Solar electrons in the Heliosphere

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1. Galactic cosmic Rays (GCRs)

2. Anomalous cosmic rays (ACRs), that originate as interstellar neutral atoms traveling into the heliosphere, ionized by solar UV and carried out as pickup ions in the solar wind to be finally accelerated to energies as high as 100 MeV/nucleon presumably close to the solar wind termination shock or in the heliosheath.

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2. Anomalous cosmic rays (ACRs)

3. Solar energetic particles (SEPs) that originate near the Sun in association with intense solar flares and large coronal mass ejections (CMEs). Occasionally, SEP events are observed at very high energies reaching GeV for protons and 100 MeV for electrons.

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2. Anomalous cosmic rays (ACRs)
3. Solar energetic particles (SEPs)
4. Energetic particles accelerated by other shocks and disturbances in the solar wind such as shocks formed in the solar wind stream interaction regions (SIRs) or corotating interaction regions (CIRs).

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4. Particles accelerated by SIRs or CIRs
5. Energetic particles accelerated in planetary magnetospheres, such as Jovian electrons observed in the inner heliosphere at energies from a few hundred keV to less than about 30 MeV.

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The study of these particle populations at different latitudes and under different heliospheric conditions provides information about:

- the global structure of the heliosphere during solar minimum and solar maximum conditions
- the mechanisms of particle propagation in the heliosphere
- properties of solar source regions (charge states, composition).

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The intensities of all particle populations which propagate through the heliosphere are affected by

- variations in the level of solar activity,
- the characteristics of the solar wind,
- the properties of the interplanetary magnetic field

Changes in these properties result in

- short-term and long-term modulations of GCRs and ACRs,
- variations in latitudinal and radial gradients of particle intensities,
- and changes in the energy spectra and composition of the heliospheric energetic particle population.

This lecture will deal with SEP electrons.

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- The structure of the heliospheric magnetic field
- Electron propagation
  - Adiabatic focusing
  - Pitch angle scattering
- In situ electrons observed near the Earth
  - Inversion of observed electron profiles
  - In-situ and hard x-rays
  - The electron "delay" problem: type III bursts flares and CMEs
- Prospects

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Electrons from the Sun will propagate in the interplanetary magnetic field.

In the absence of large-scale disturbances like CMEs and shocks, the interplanetary magnetic field can be described as a smooth average field due to the steady solar wind flow.

The magnetic field in the solar wind is "frozen" in the plasma, and is carried by the solar wind flow.

The Sun rotates, so although the wind flowing from a given region in the corona propagates radially, the solar wind will have a spiral structure.

Example:

- solar wind source initially at west limb (view from above)
- slow wind (400 km/s)
- radial flow in the ecliptic plane

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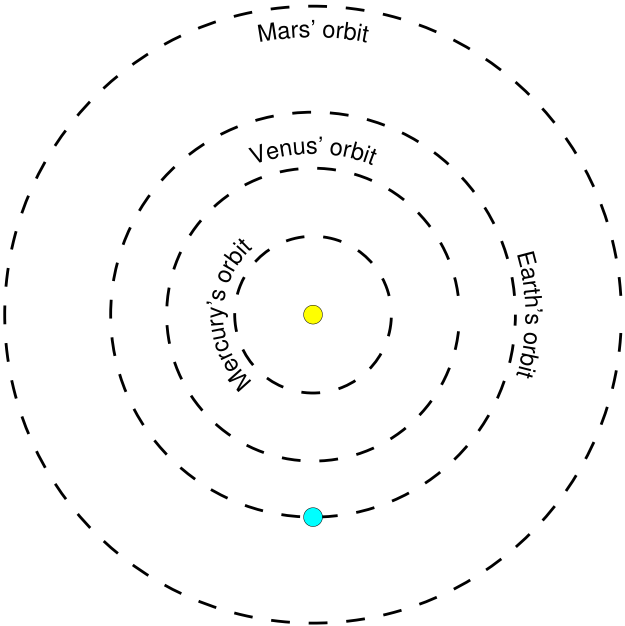
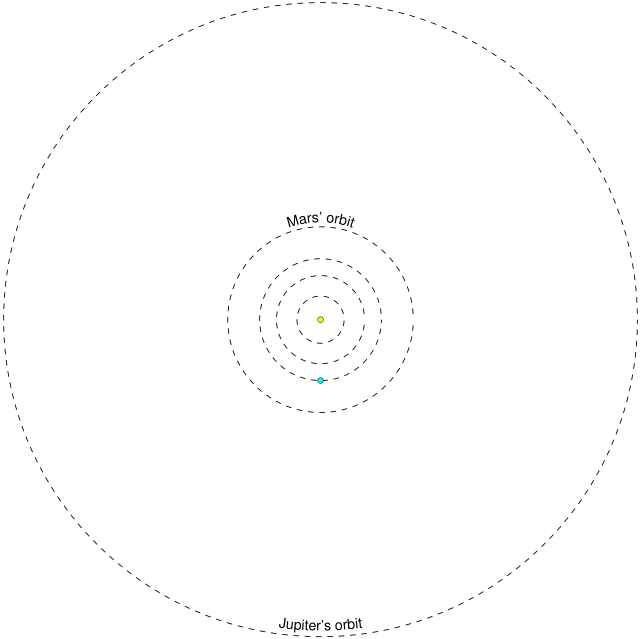
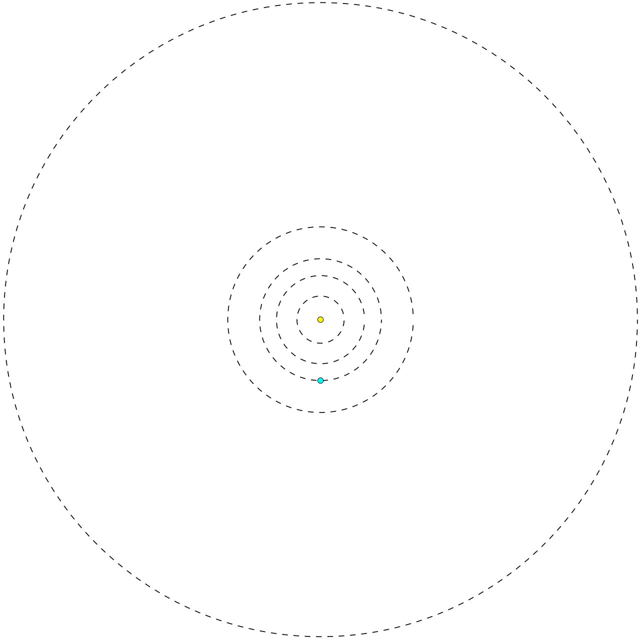
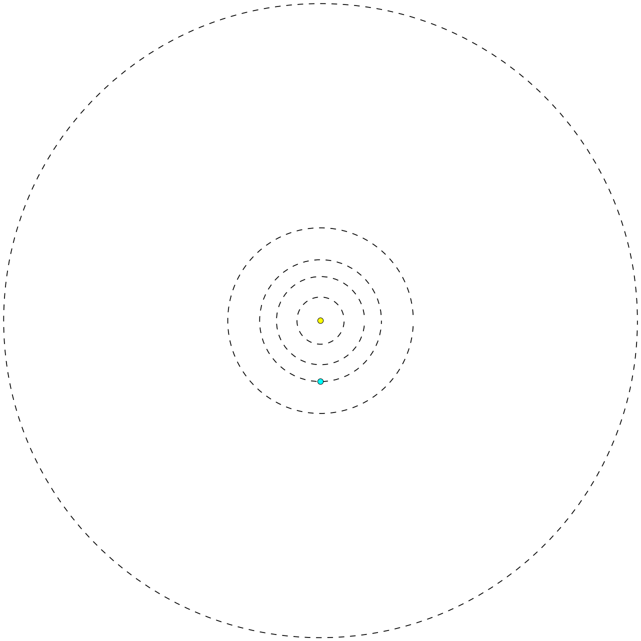
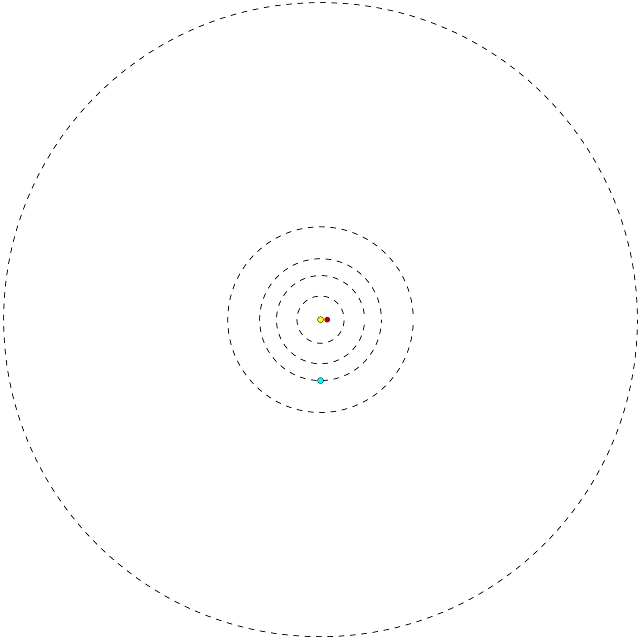


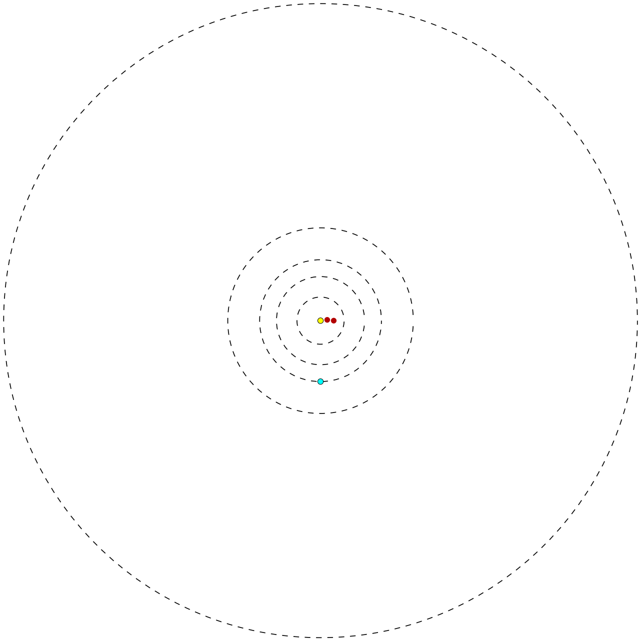
Mars' orbit
Venus' orbit
Mercury's orbit
Earth's orbit

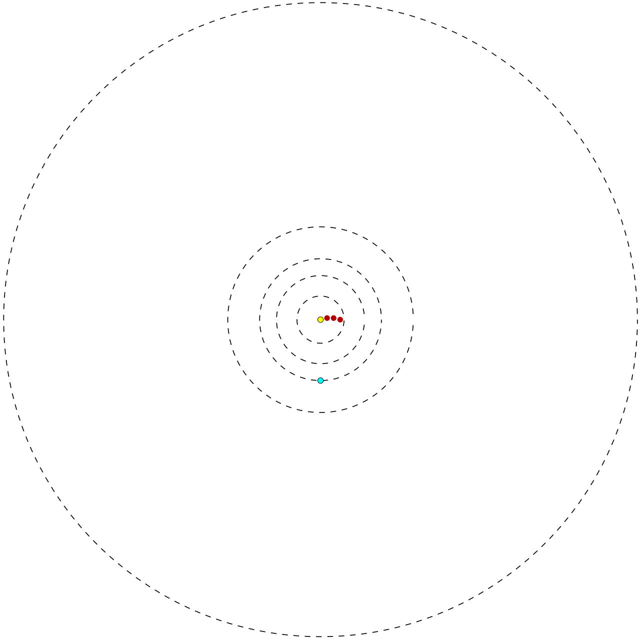

Mars’ orbit
Jupiter’s orbit

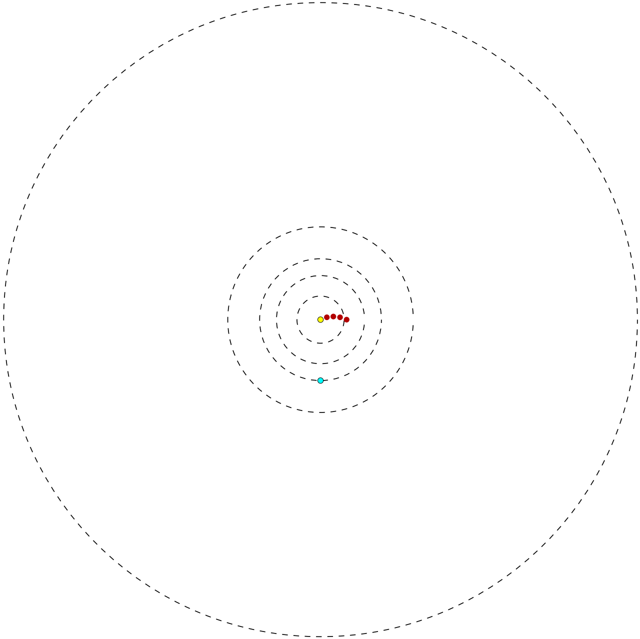


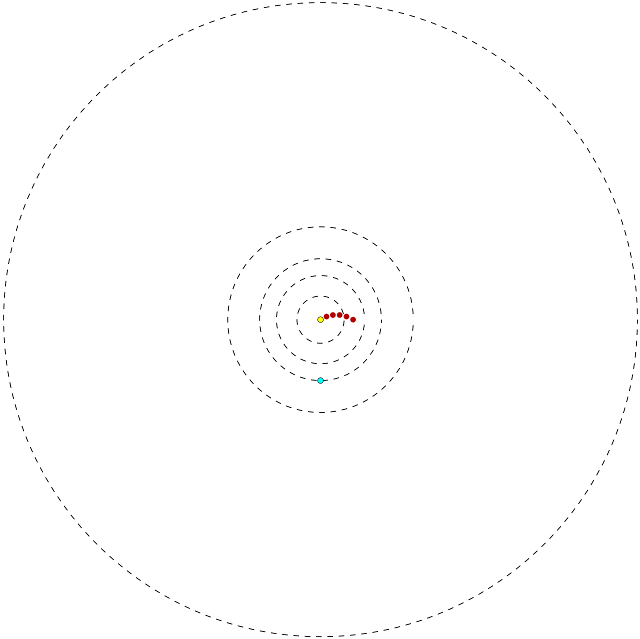


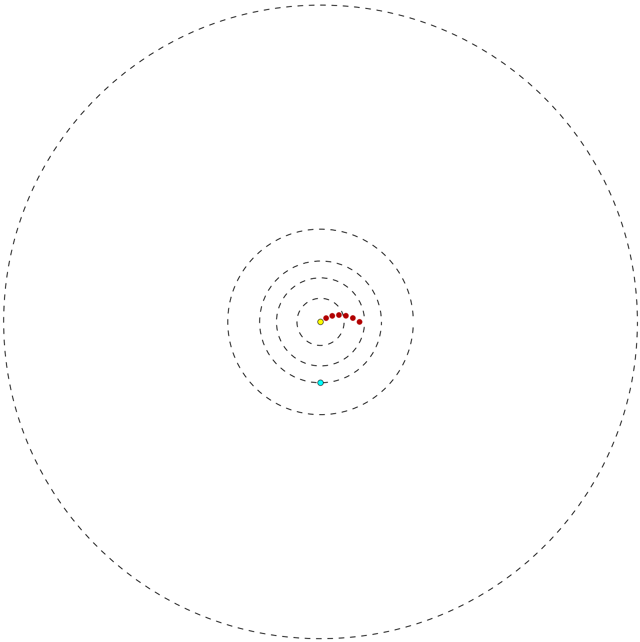


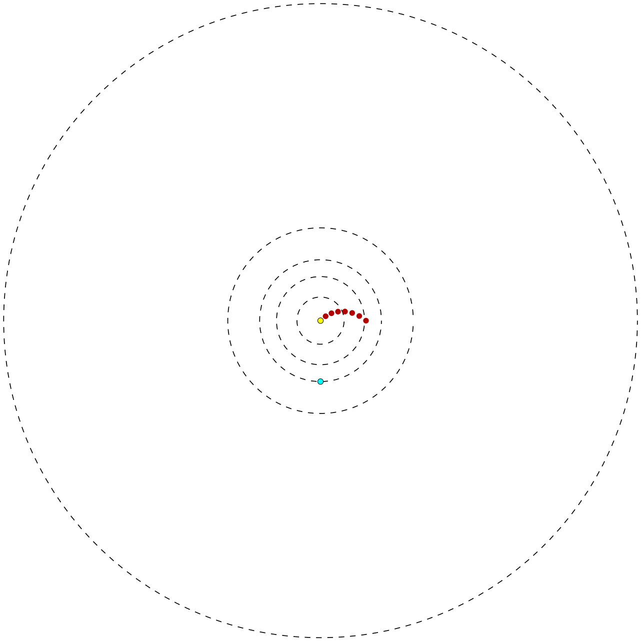


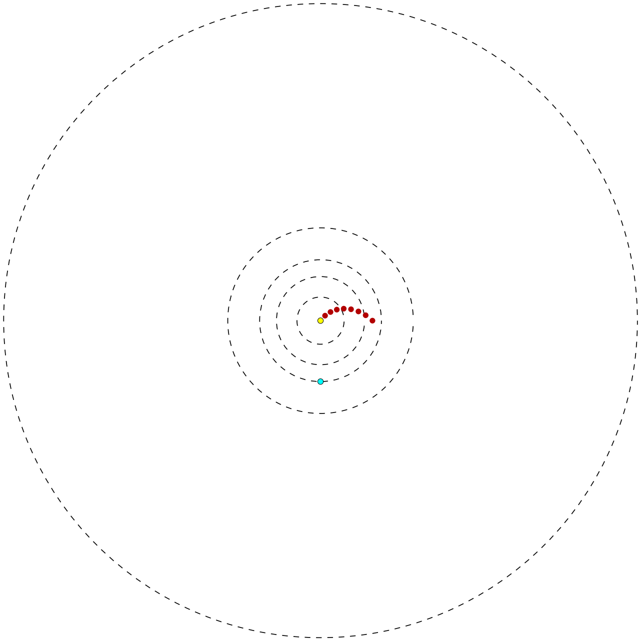


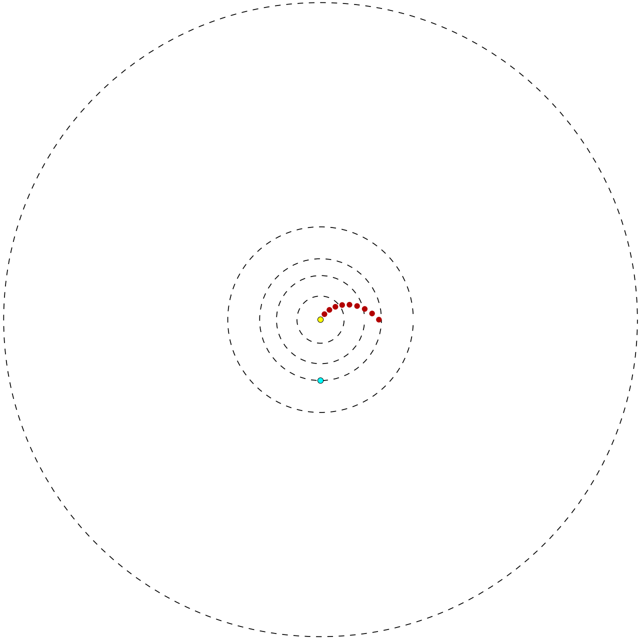


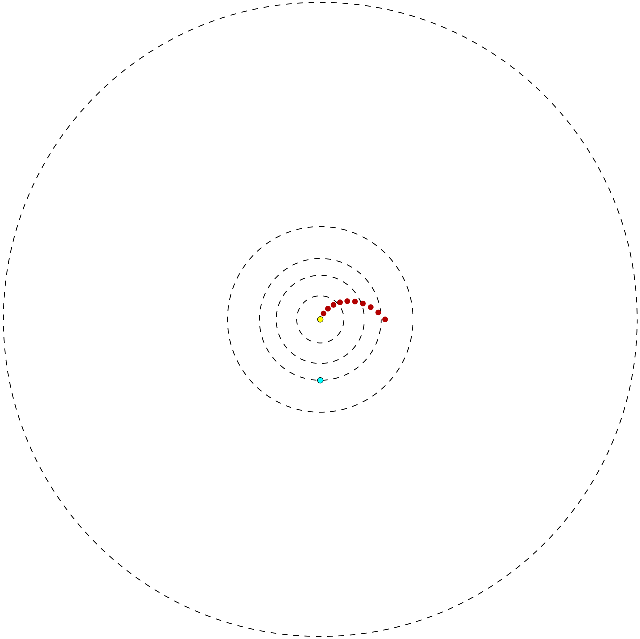


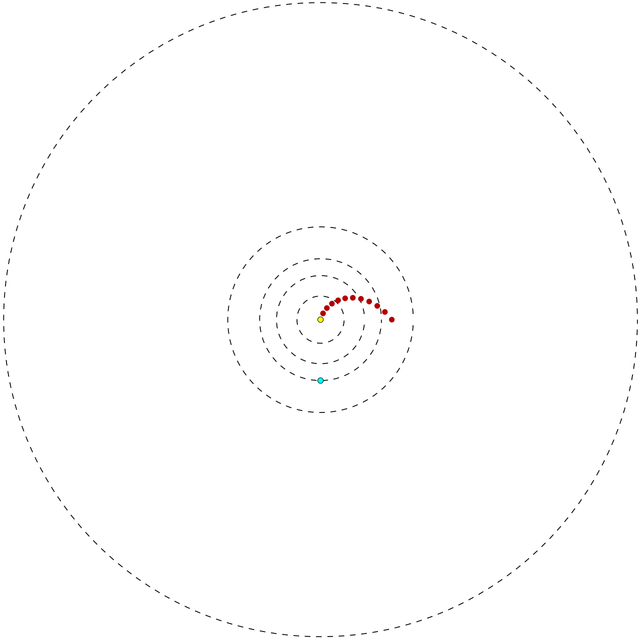


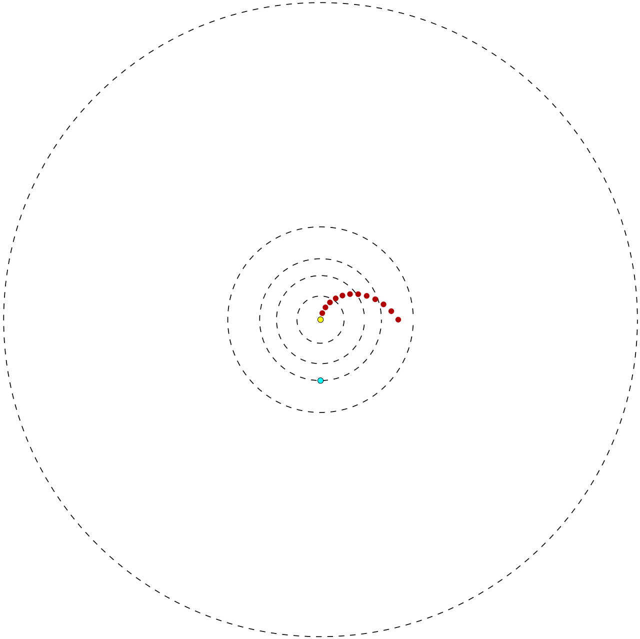


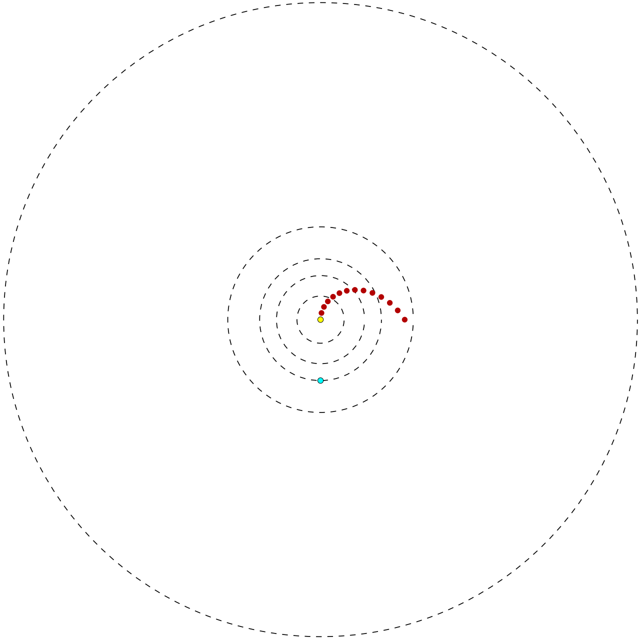


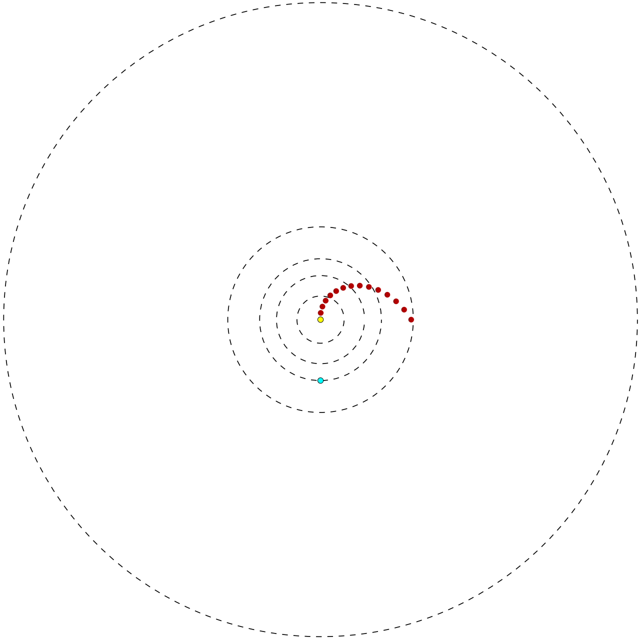


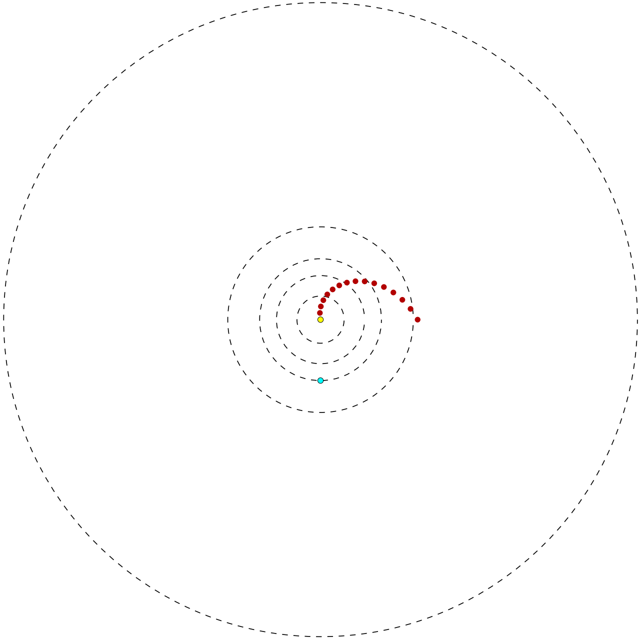


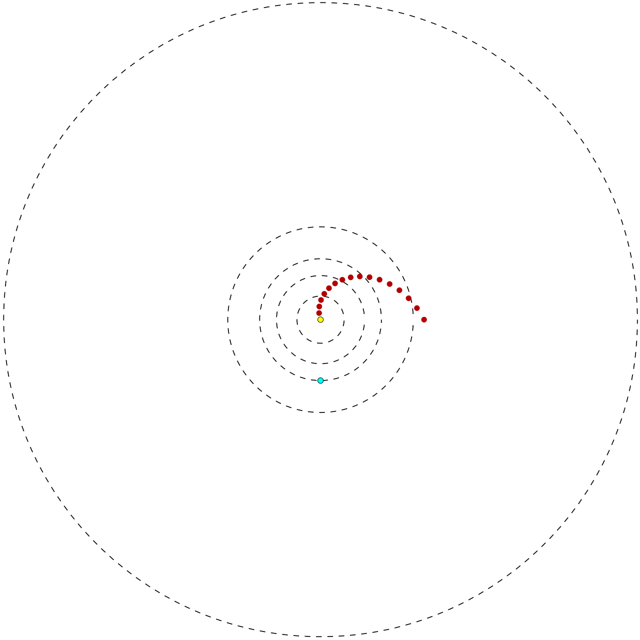


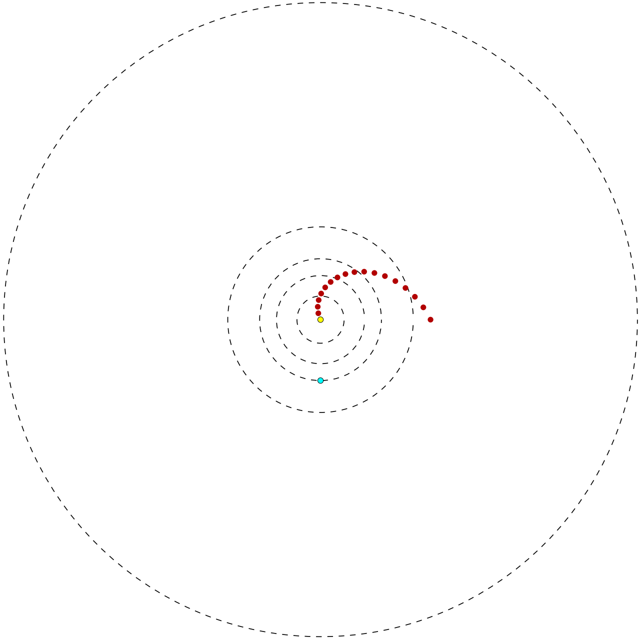


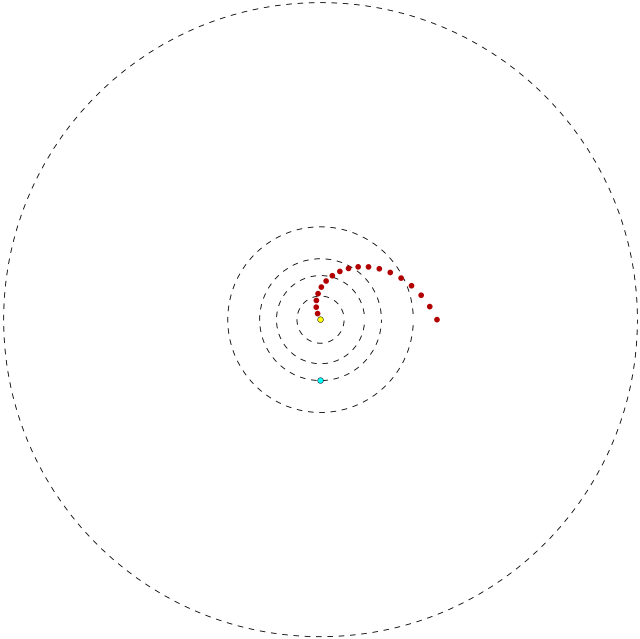


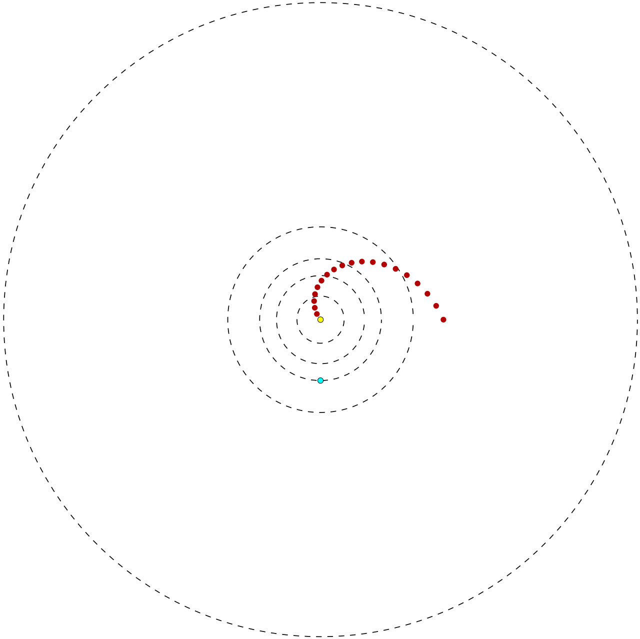


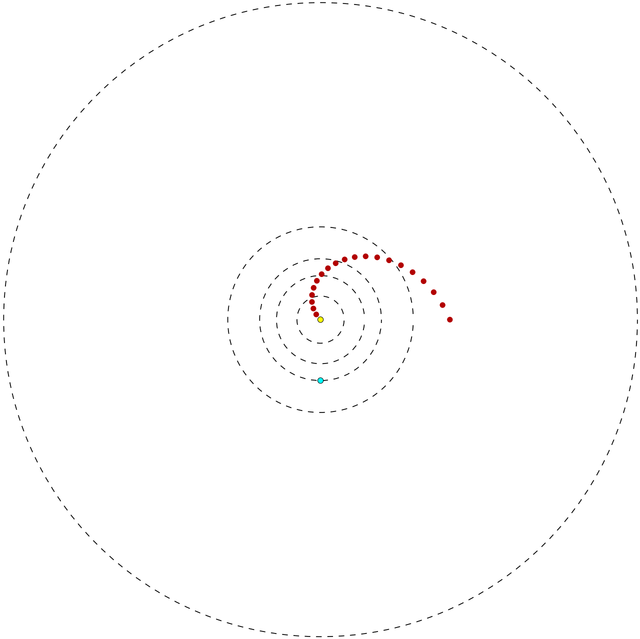


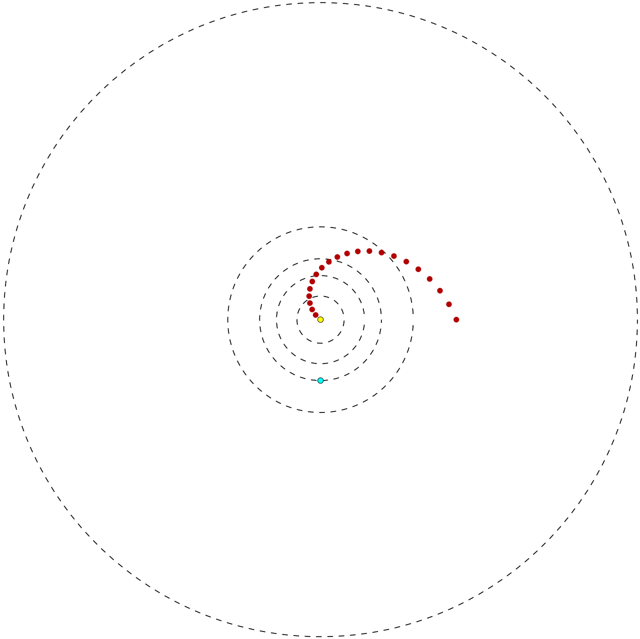


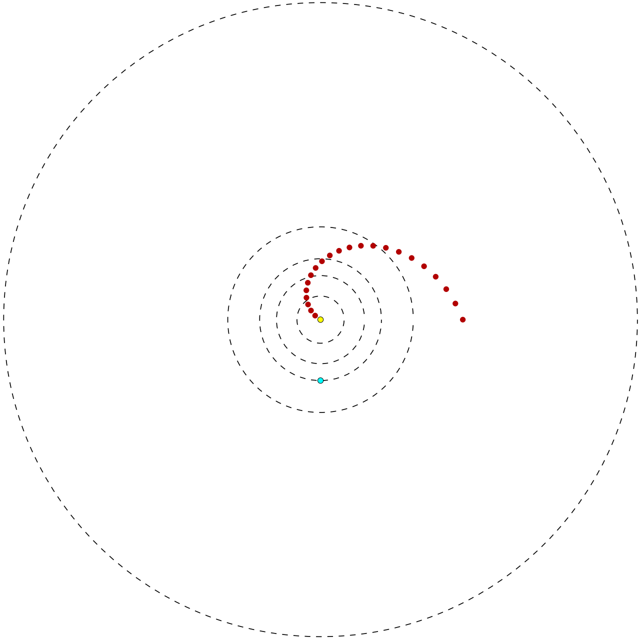


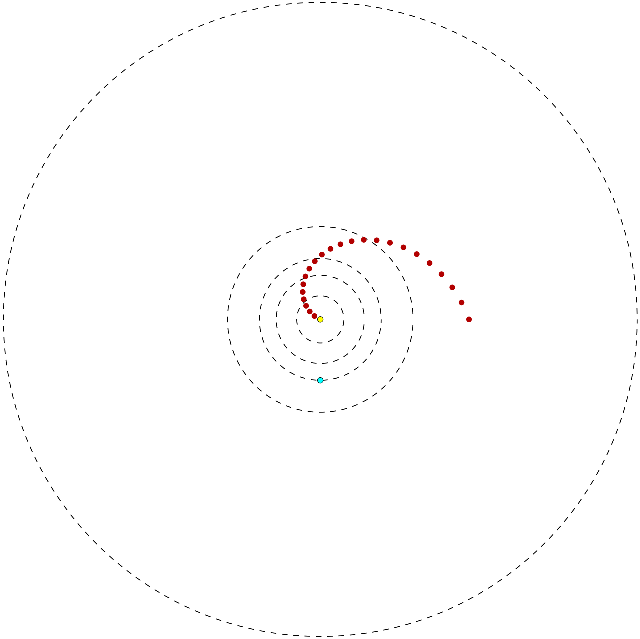


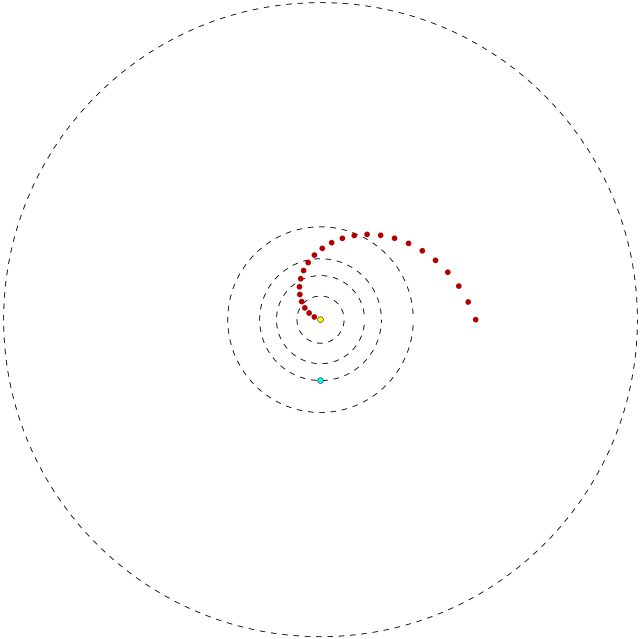


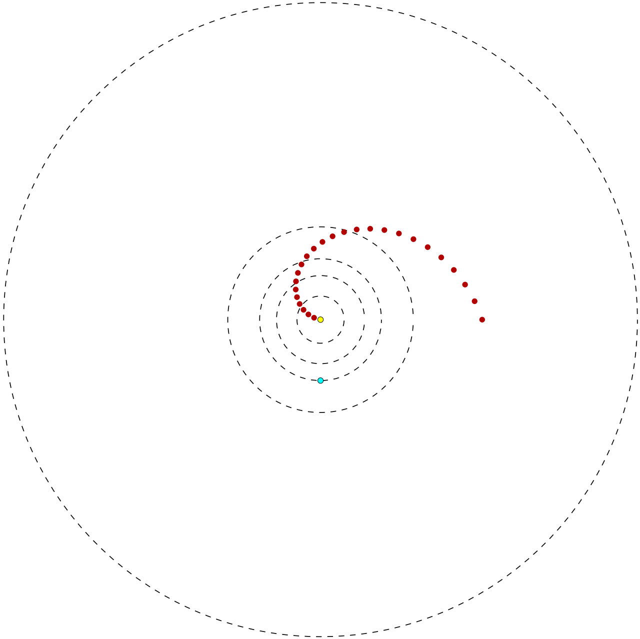


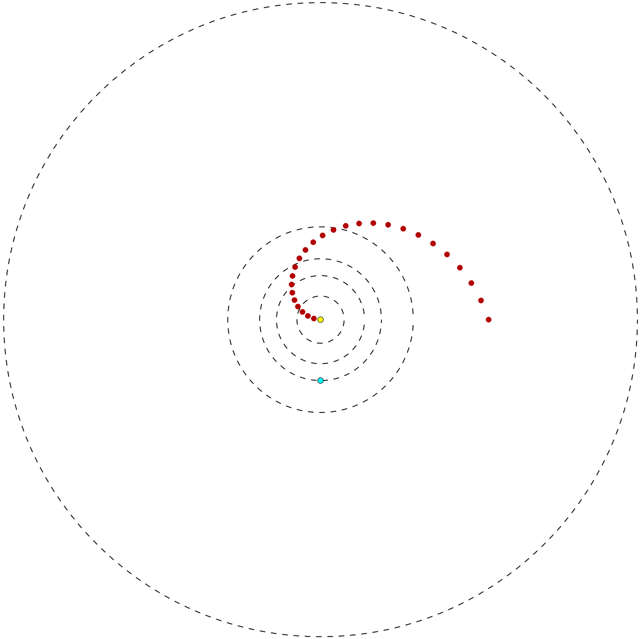


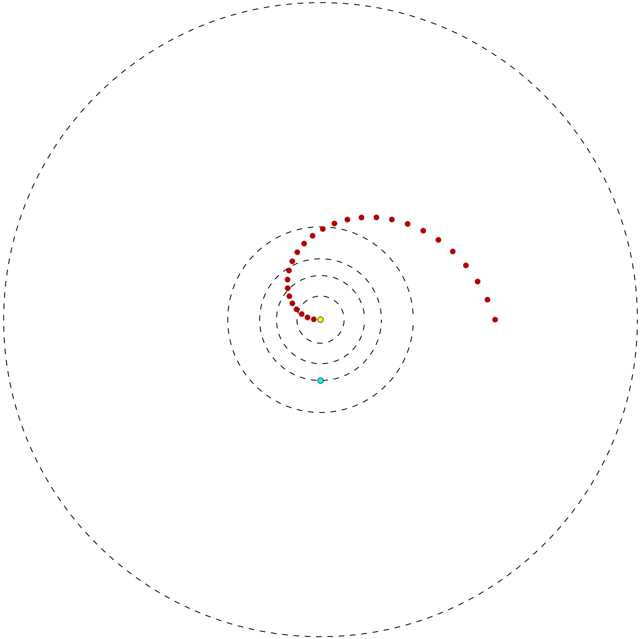


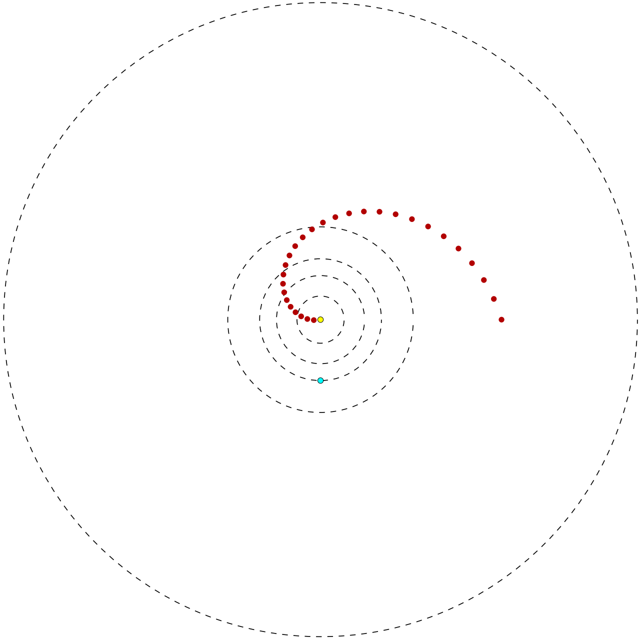


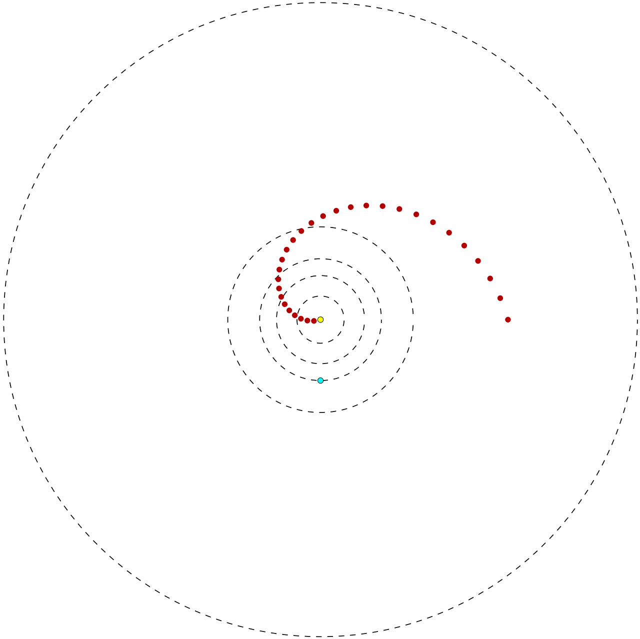


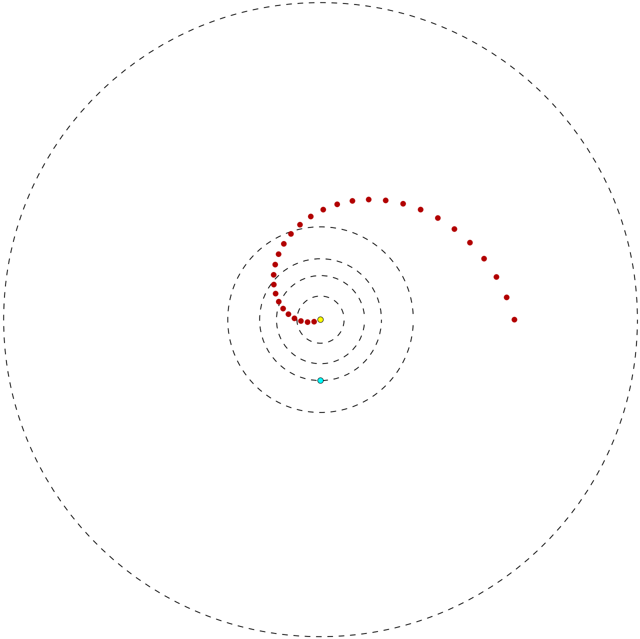


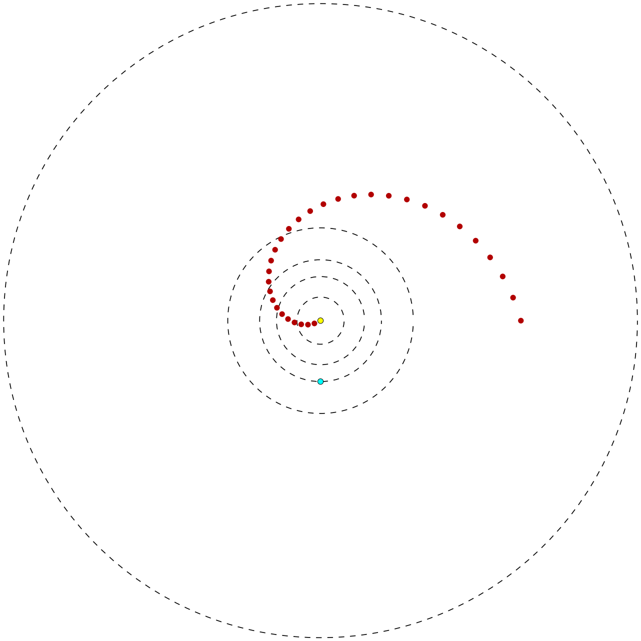


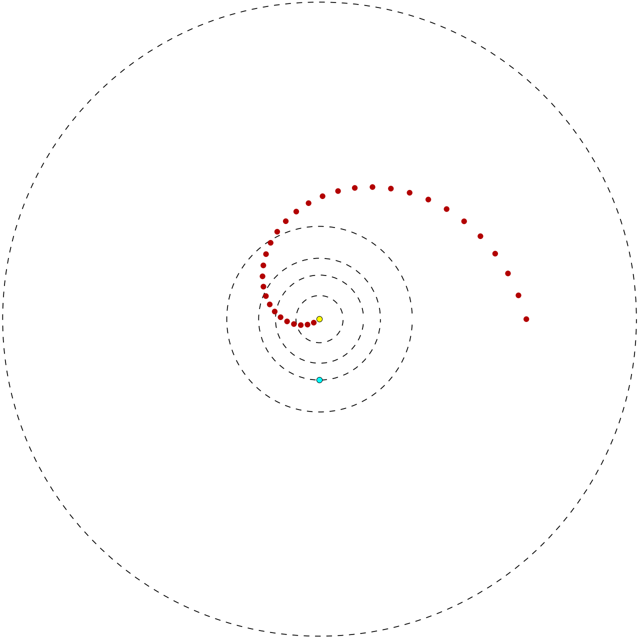


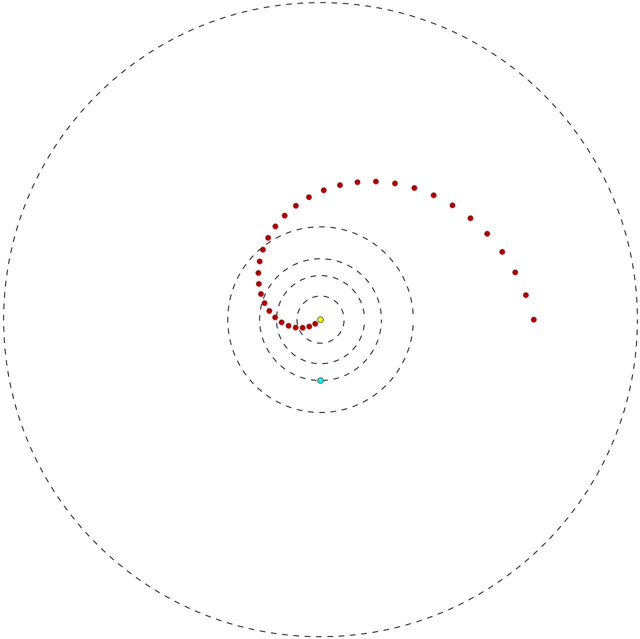


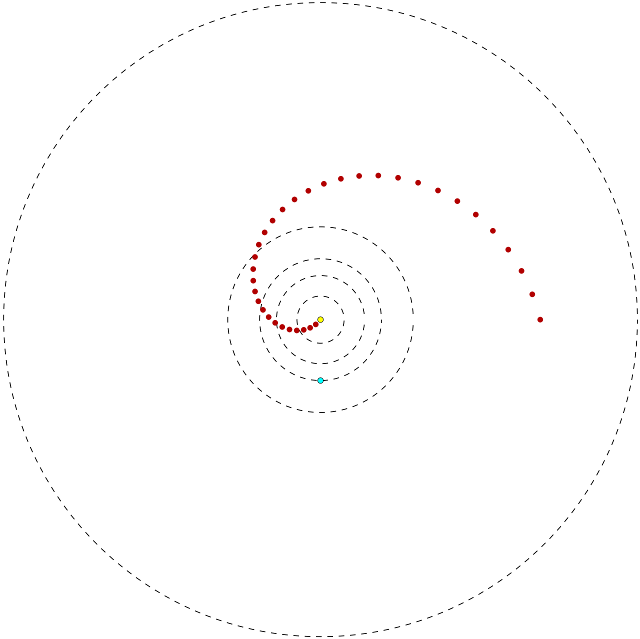


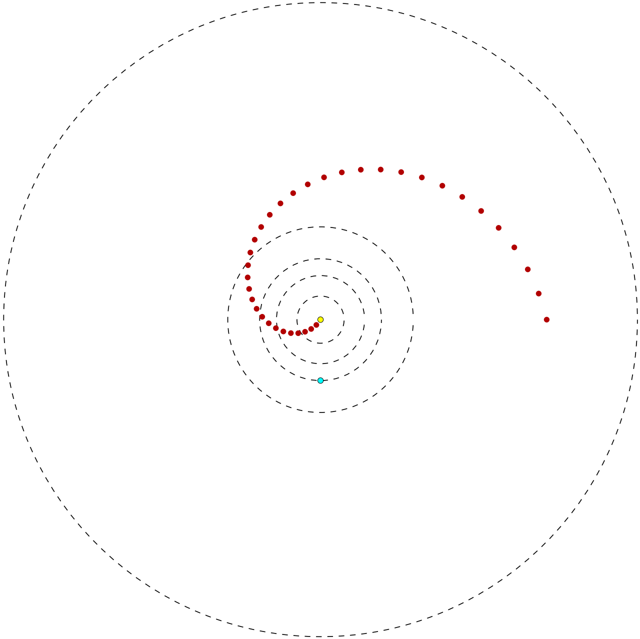


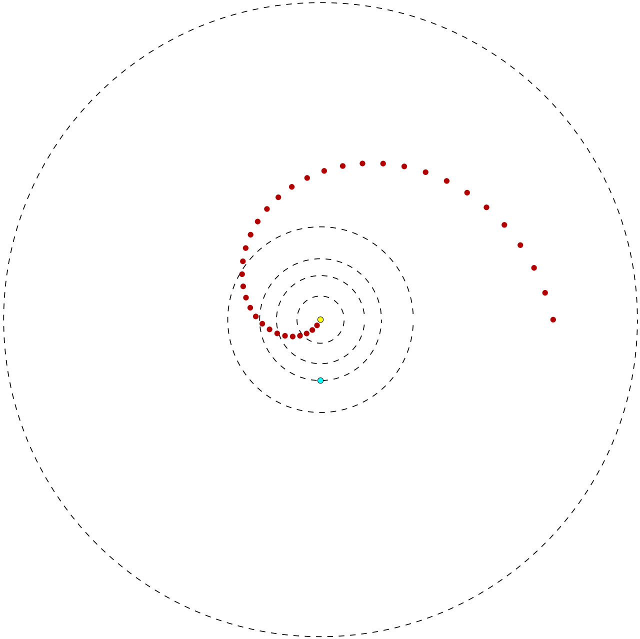


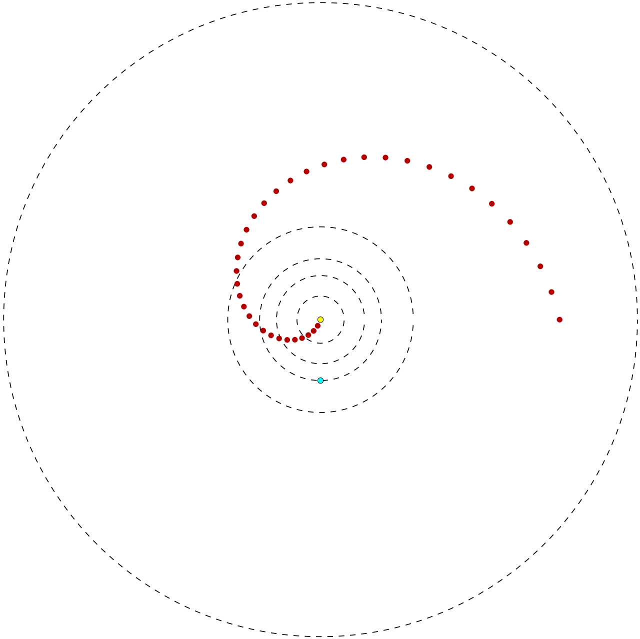


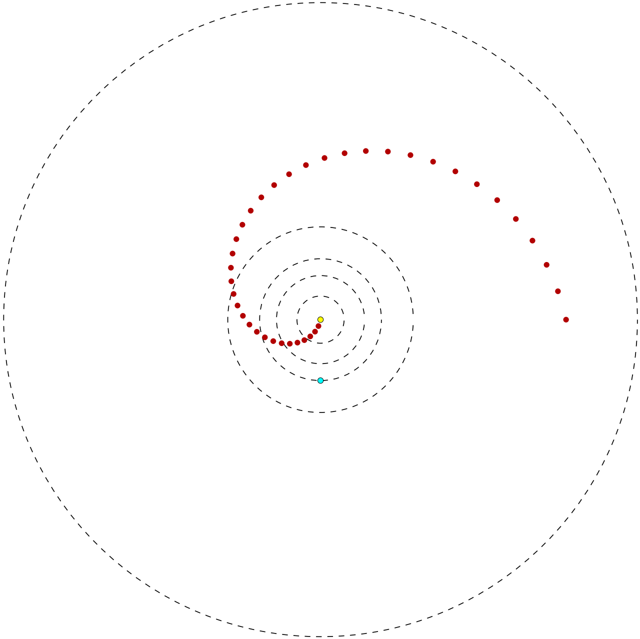


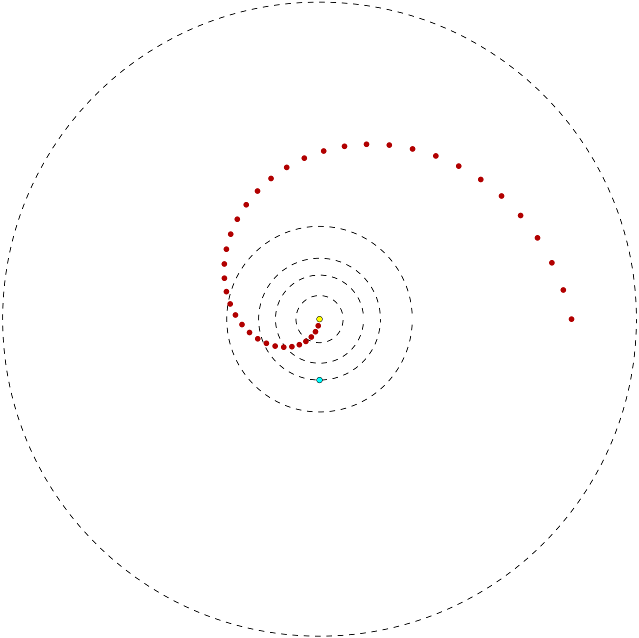


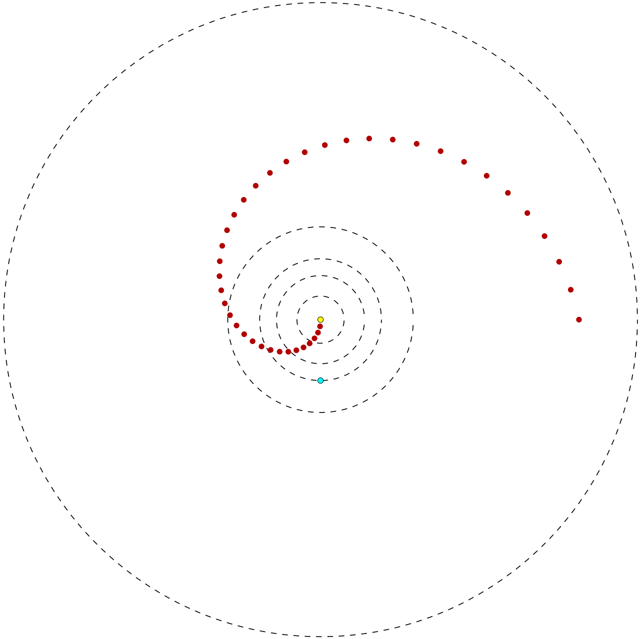


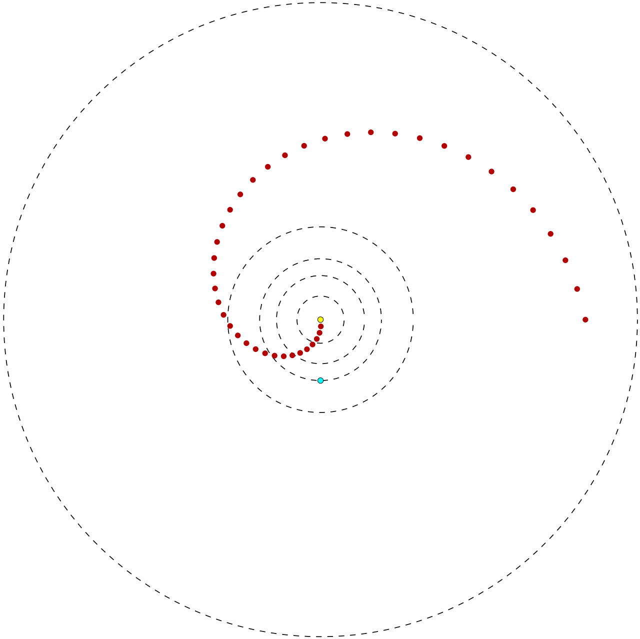


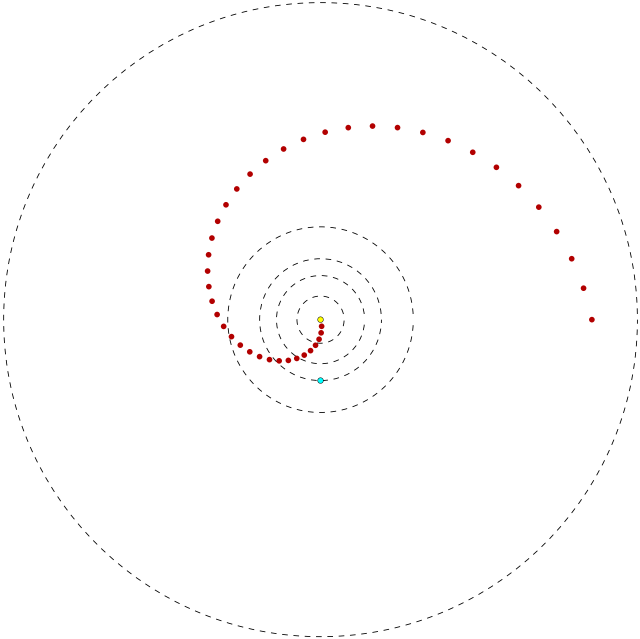


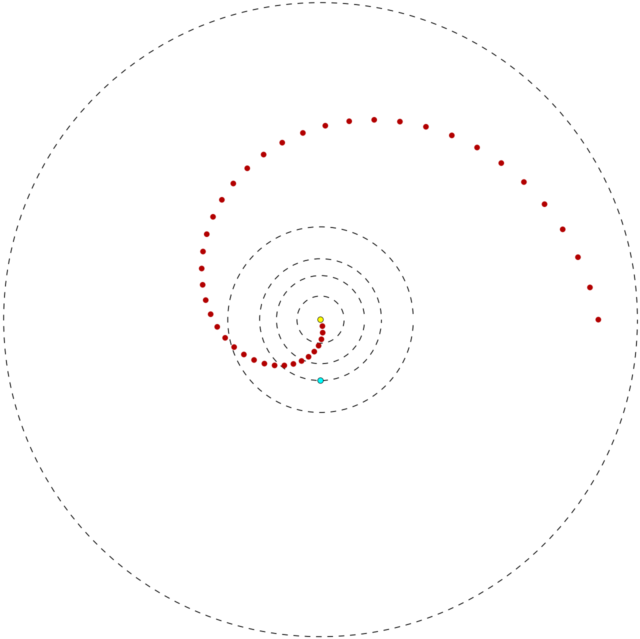


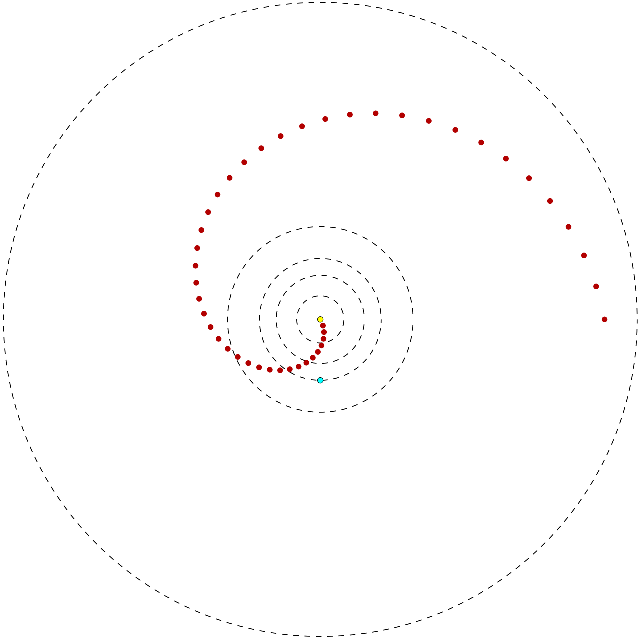


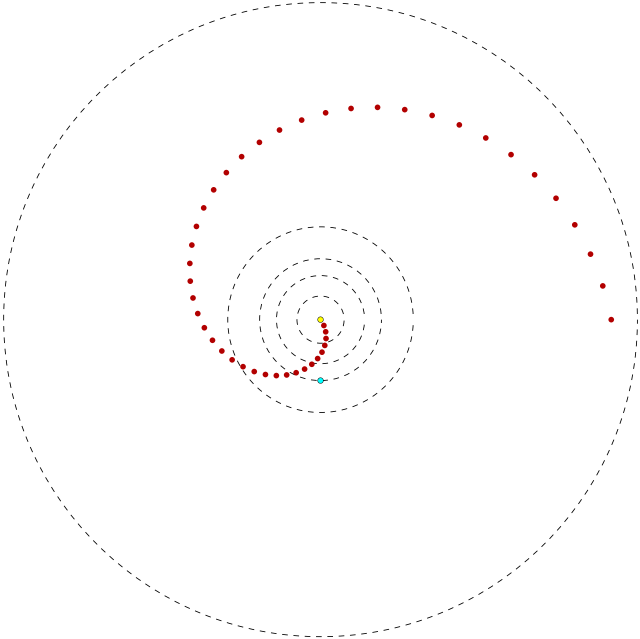


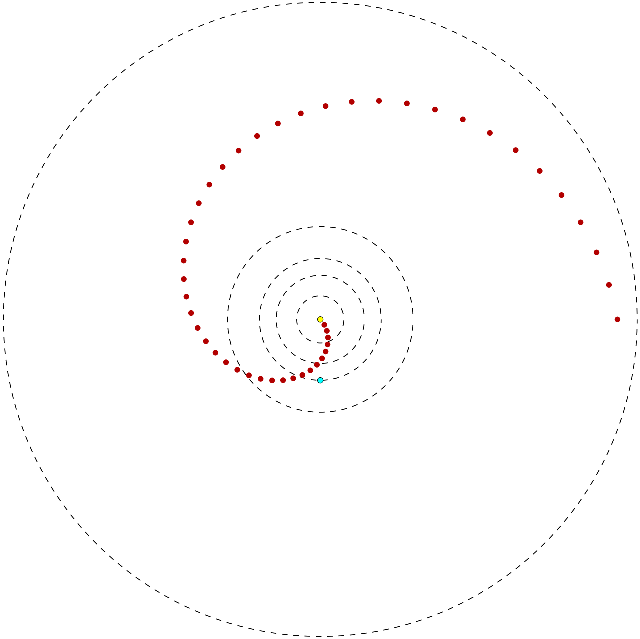


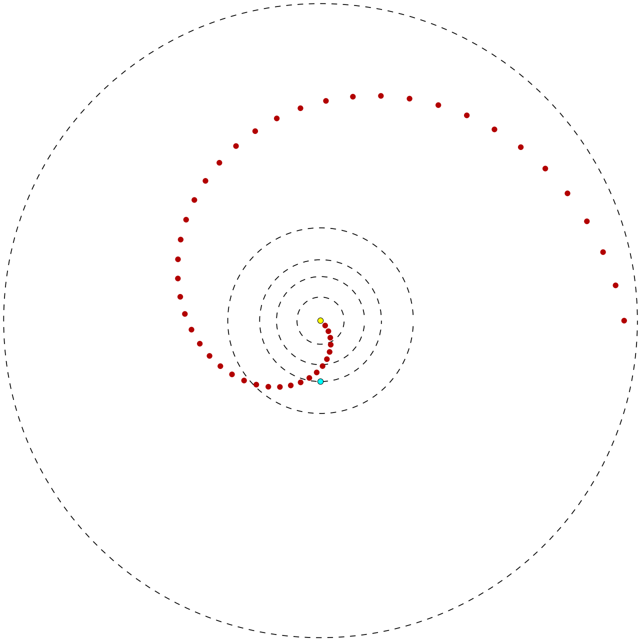


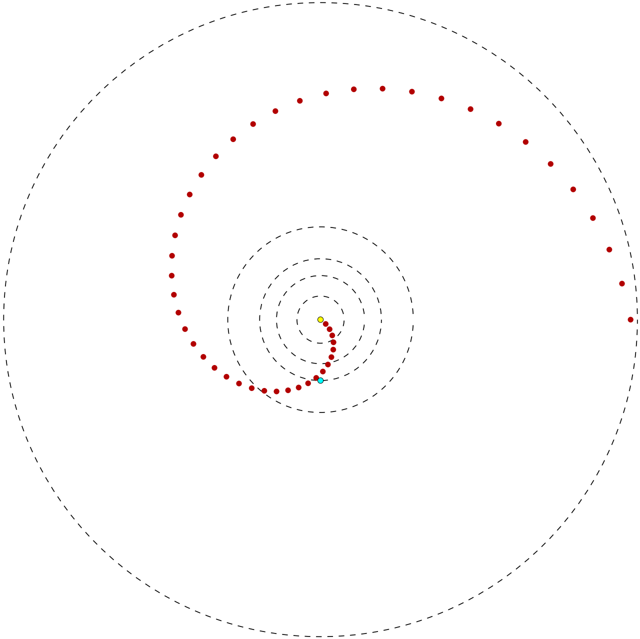


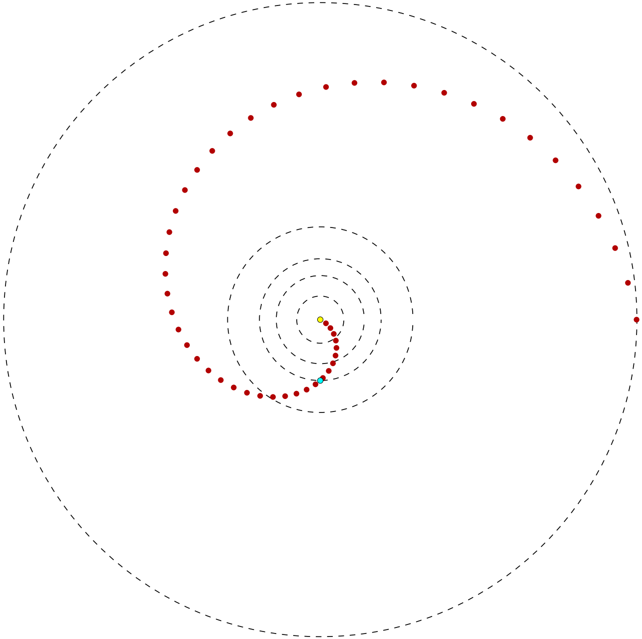


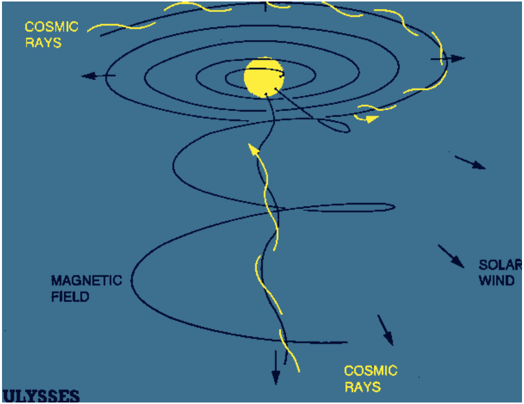










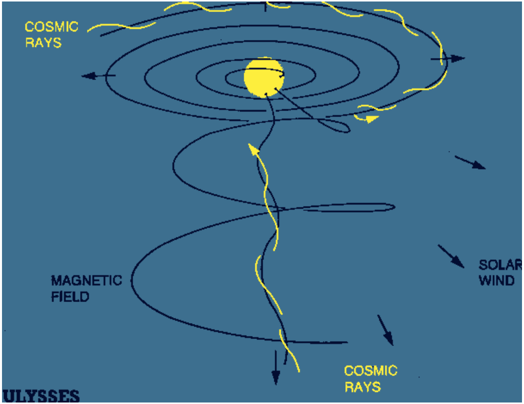


Up to Mercury's orbit the interplanetary magnetic field is nearly radial.

The typical spiral length near Earth is ≈ 1.2 AU.

Particles in the ecliptic plane need to travel huge distances to reach radial distances of a few AU from the Sun center.

Fast wind from coronal holes, complicates this picture: around the Earth orbit the fast wind catches the slow wind.



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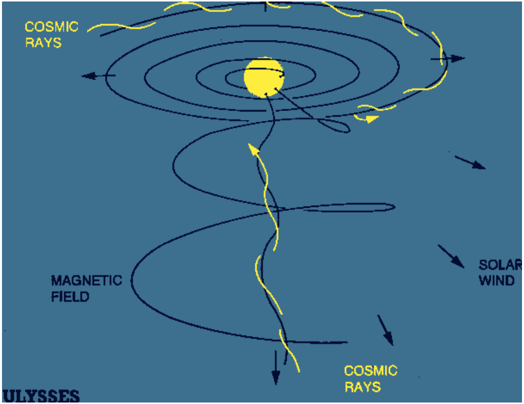

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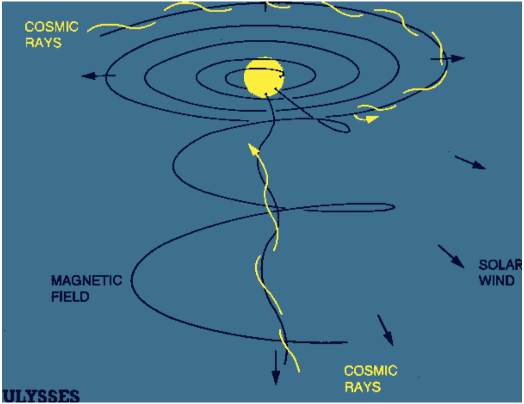

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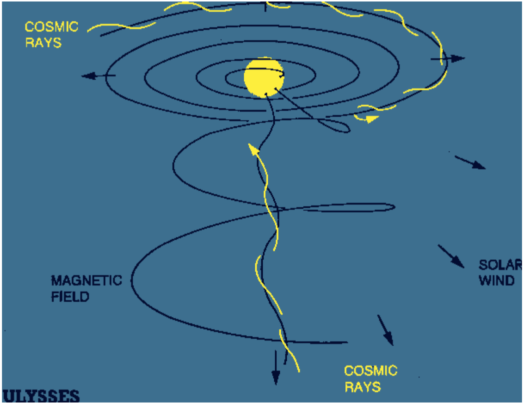

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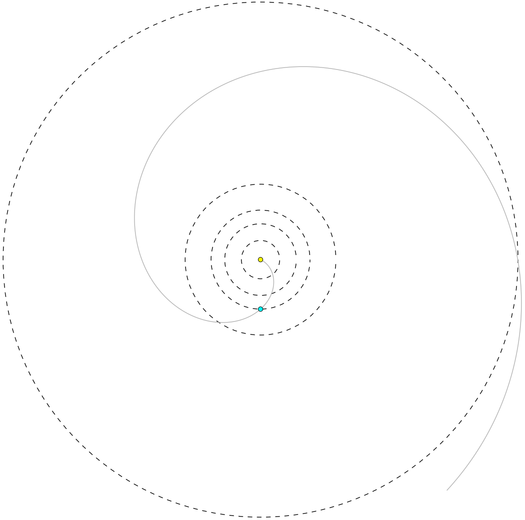
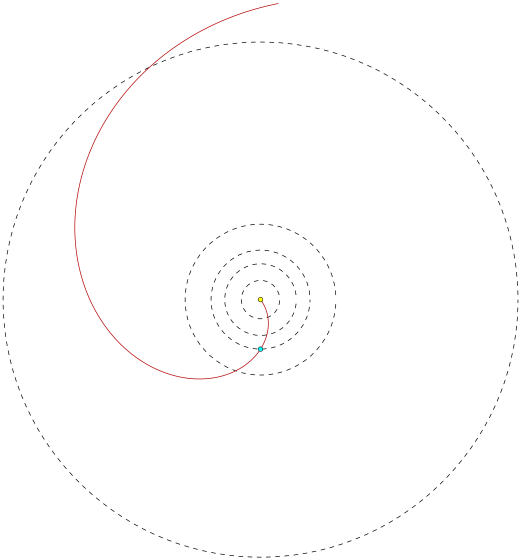


gray - 400 km/s solar wind

red - 700 km/s solar wind



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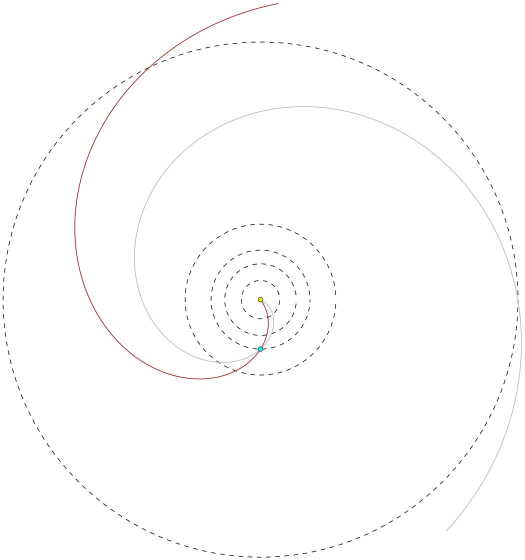
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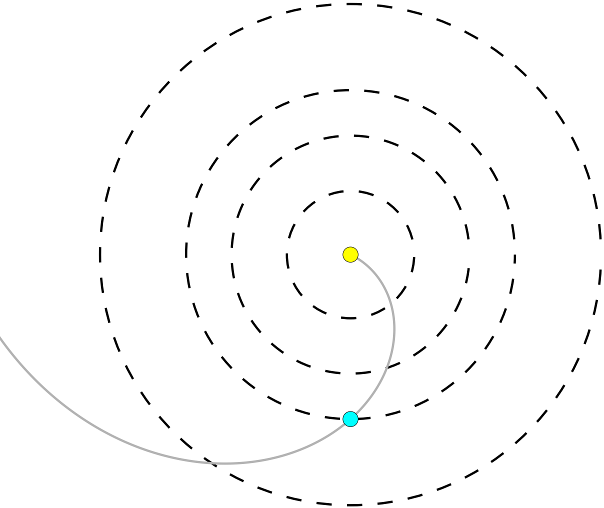

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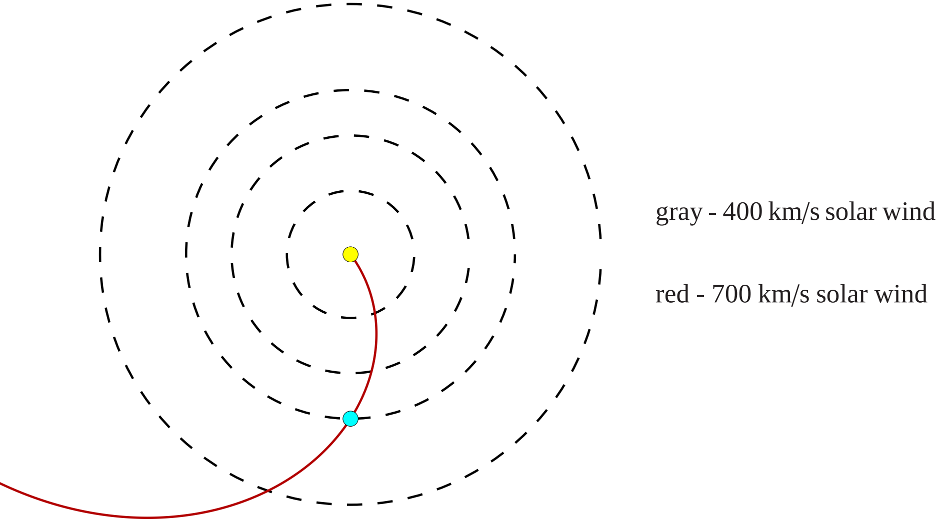
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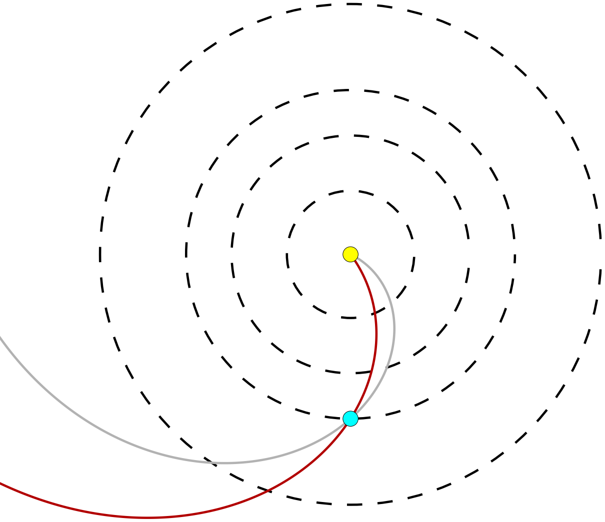

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When the fast wind “catches” the slow wind a corating interaction region (CIR) will develop, bound by a pair of reverse and forward shocks.

CIRs, iCMEs and iCME-associated shocks, and other features in the solar wind affect article propagation (GCR modulation).

In what follows I will consider only the ideal situation: large scale spiral magnetic field, with small scale irregularities. The real picture is much more complicated.

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With no solar wind effects included, particle propagation is based on the model of focused transport illustrated by the equation (Roelof, 1969)

$$\frac{\partial f}{\partial t} + \mu v \frac{\partial f}{\partial z} f + \frac{1-\mu^2}{2L} v \frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}\left(D_{\mu\mu}(\mu) \frac{\partial f}{\partial \mu} \right) = Q(z, \mu, t)$$

- z is the coordinate of the observer along the magnetic field line, μ is the cosine of pitch angle, t the time, v is the particle velocity
- $f = f(z, , t)$ particles phase space density
- $L(z)$ is the focusing length of the field
- v pitch angle diffusion coefficient
- $Q(z, , t)$ is the source function.

References: Ruffolo (1991). ApJ 382:688-698. Ruffolo (1995). ApJ 442:861-874. Kocharov et al (1998). Solar Physics 182:192:215

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The equation includes terms describing the streaming of particles along the field lines, and terms describing the change of the particles' pitch angles.

$L(z) = (1/B)(\partial B)(\partial z)$, the focusing length in the diverging magnetic field B, characterizes the systematic forces caused by magnetic mirroring.

Conservation of a particle's first adiabatic invariant

$$(1-\mu^2)/B(r)$$

leads to an increase of μ as the particle propagates away from the Sun.

(In what follows I define $\mu > 0$ to be outward from the Sun.)

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The equation includes terms describing the streaming of particles along the field lines, and terms describing the change of the particles' pitch angles.

$L(z) = (1/B)(\partial B)(\partial z)$, the focusing length in the diverging magnetic field B, characterizes the systematic forces caused by magnetic mirroring.

Conservation of a particle's first adiabatic invariant

$$(1-\mu^2)/B(r)$$

leads to an increase of μ as the particle propagates away from the Sun.

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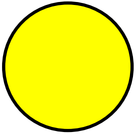

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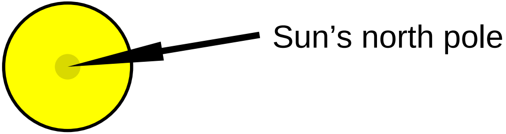

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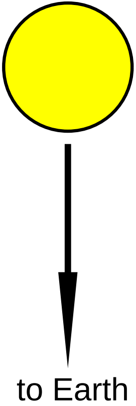

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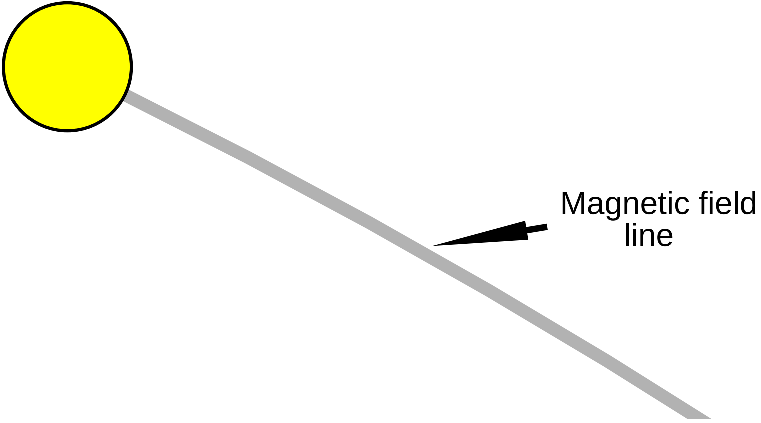

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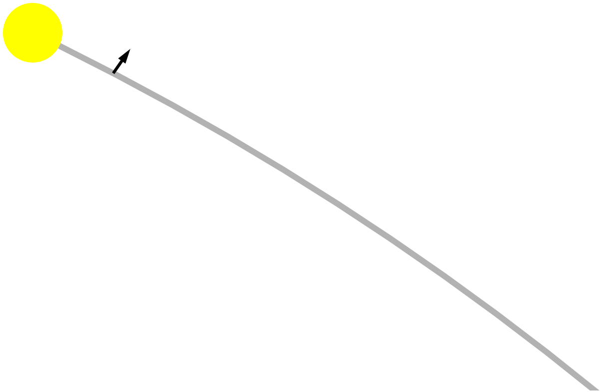

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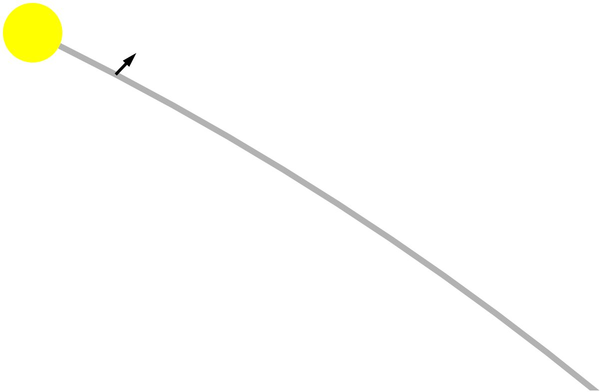

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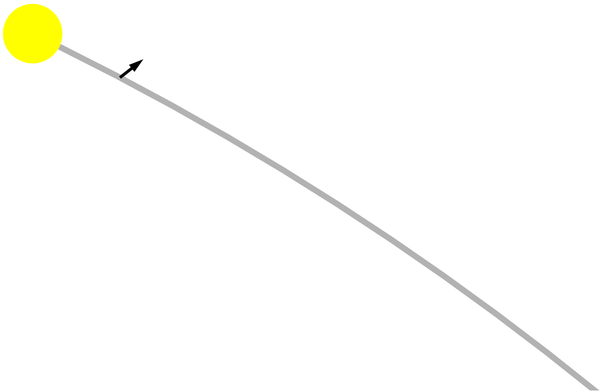

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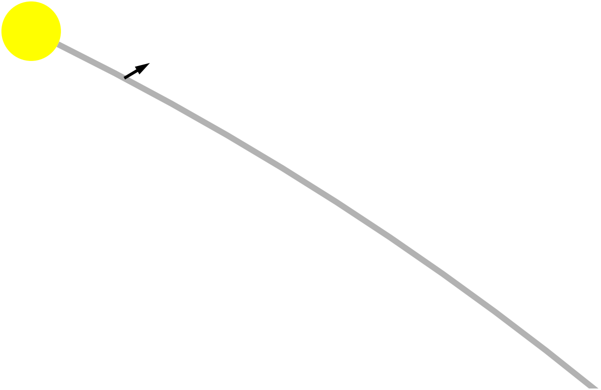

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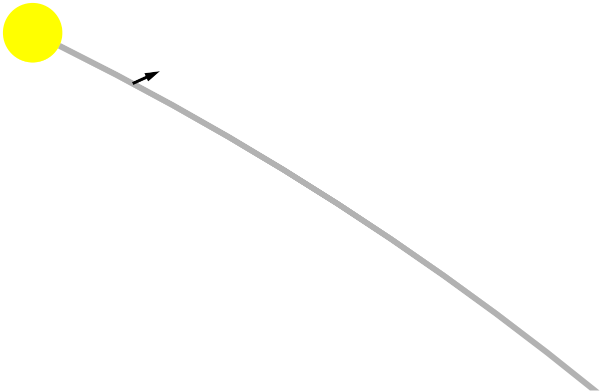

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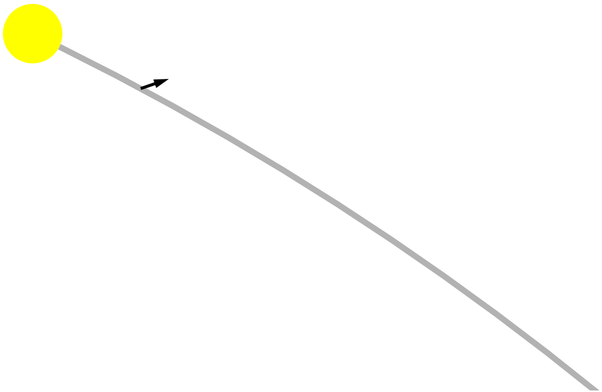

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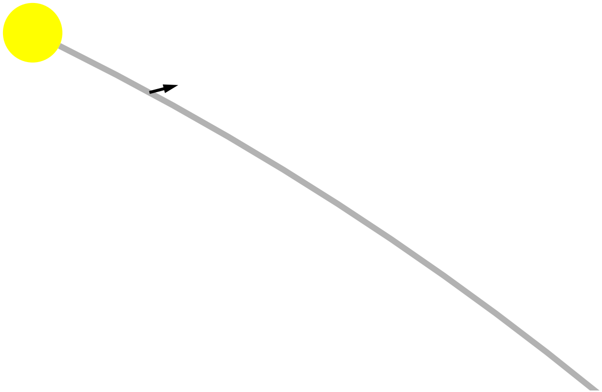

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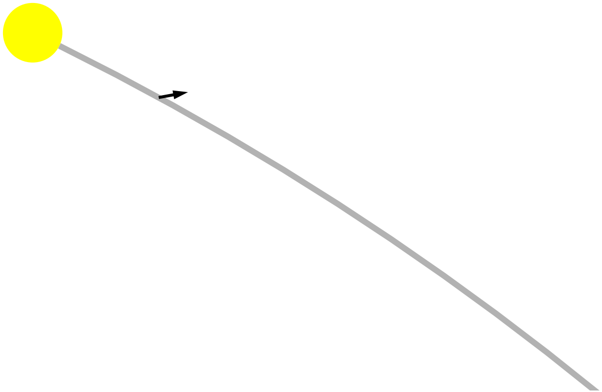

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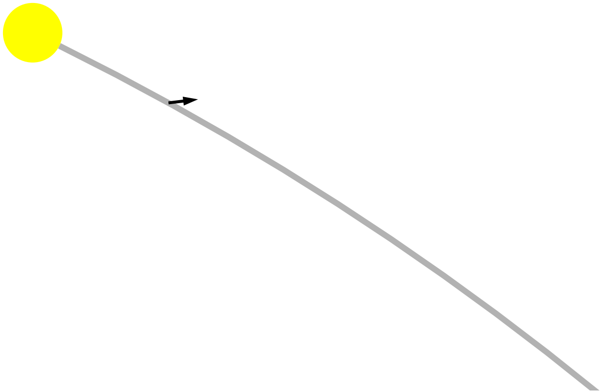

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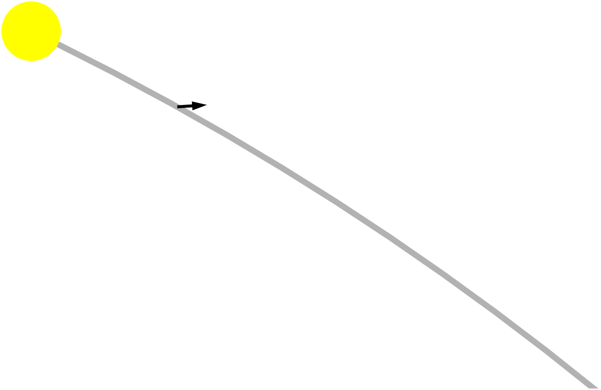

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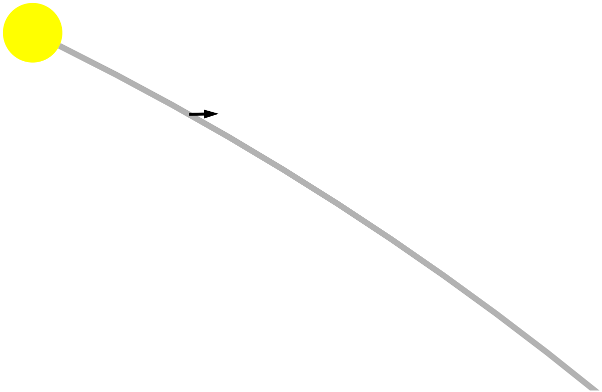

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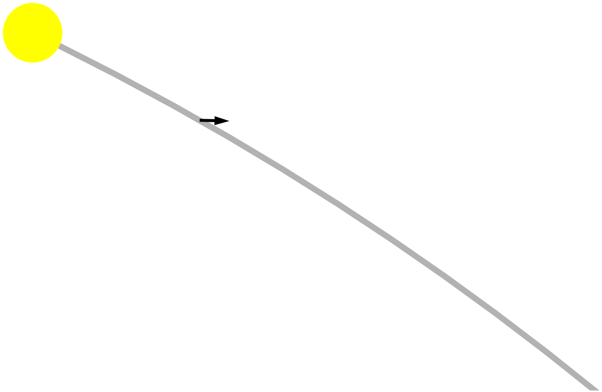

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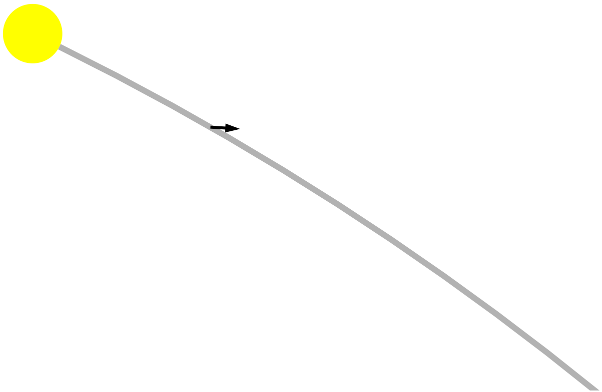

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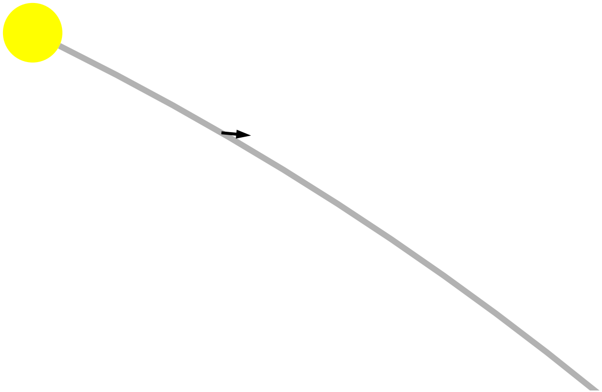

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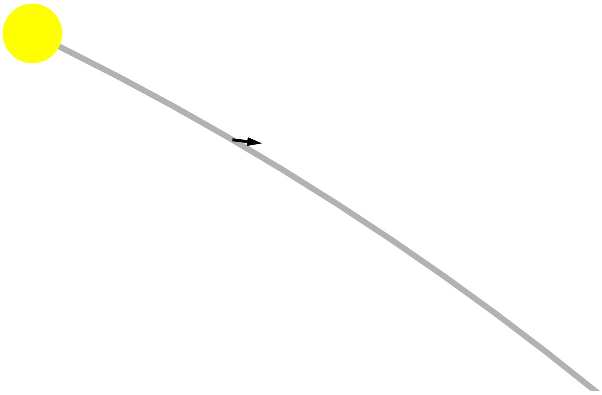

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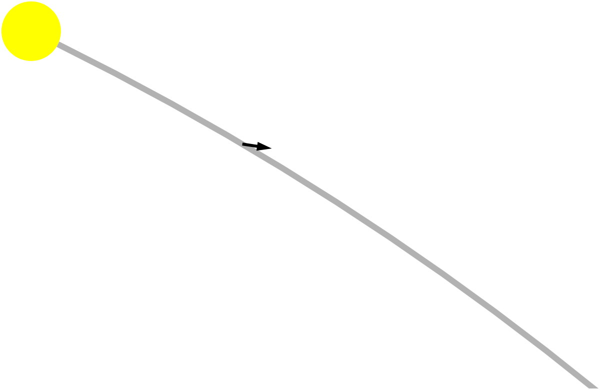

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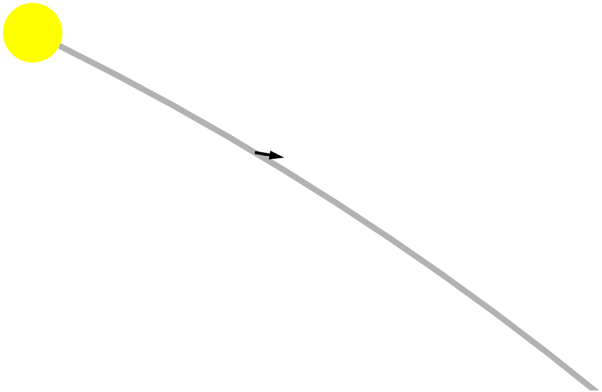

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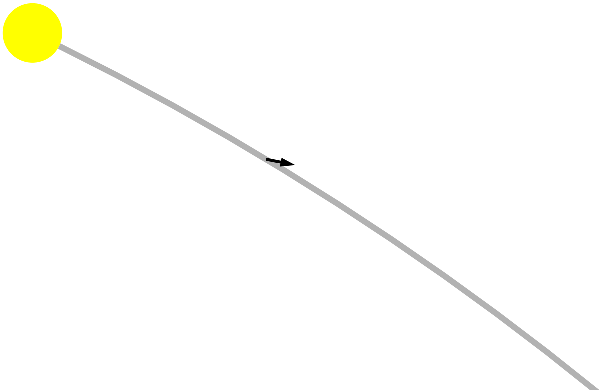

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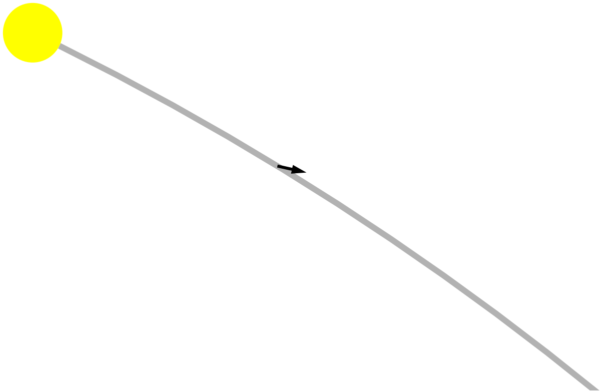

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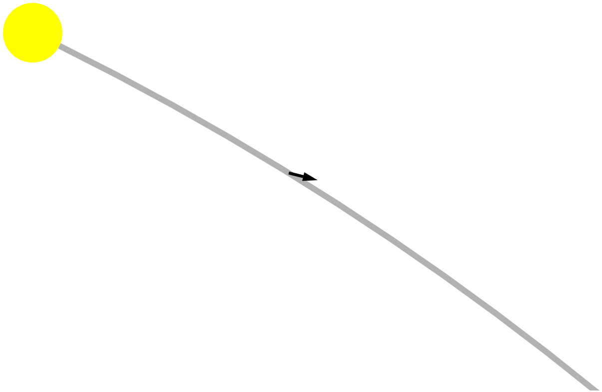

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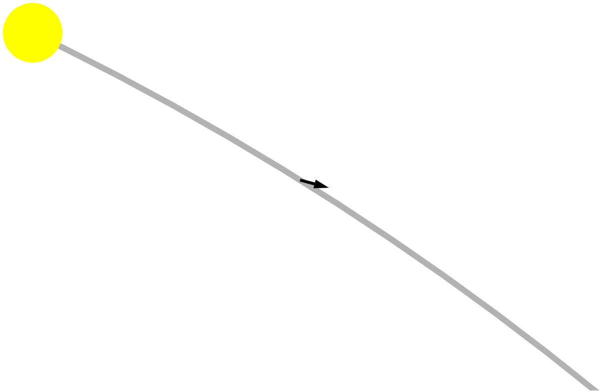

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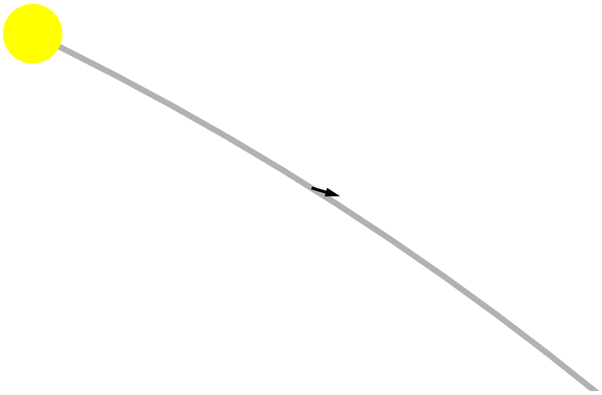

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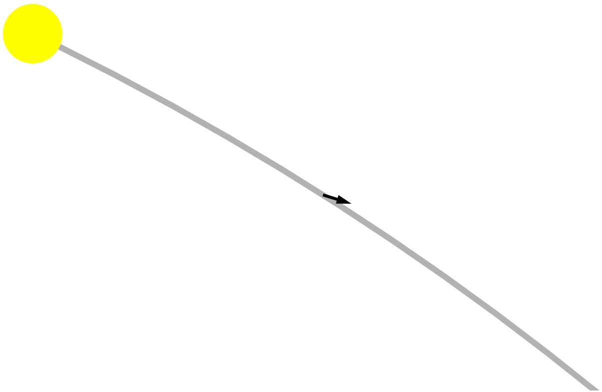

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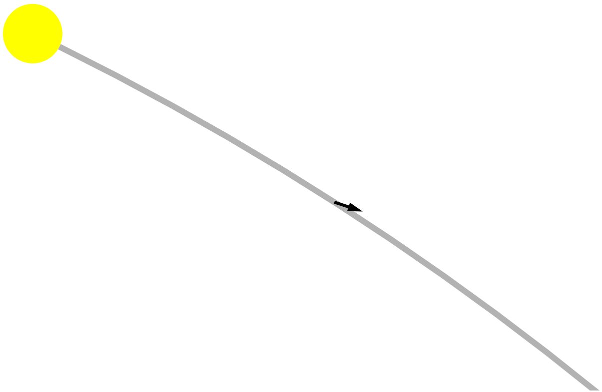

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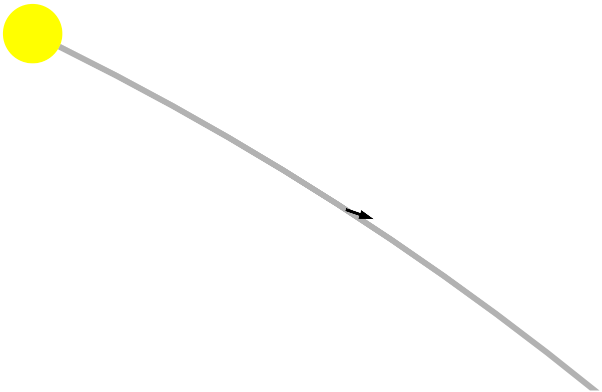

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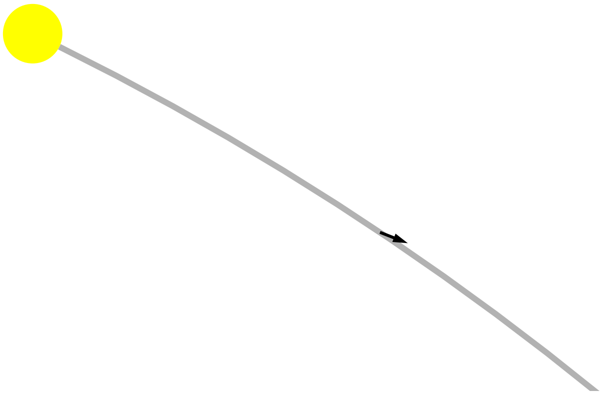

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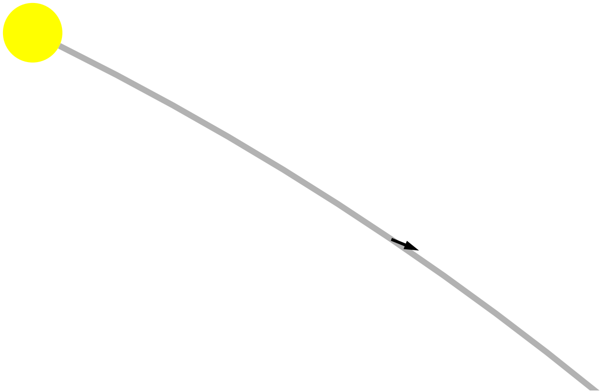

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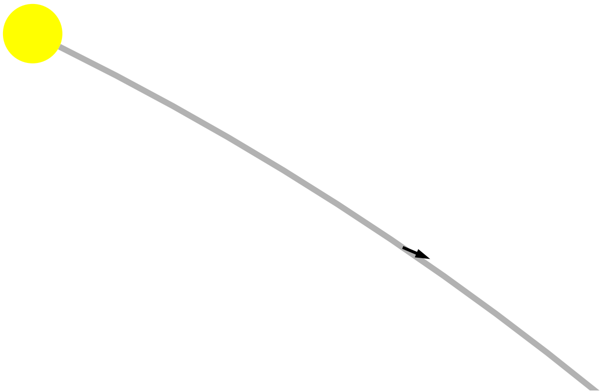

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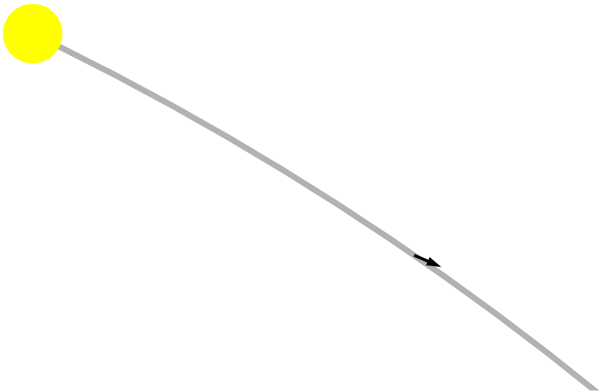

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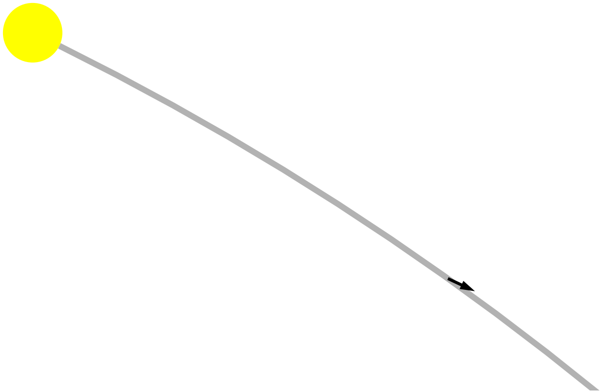

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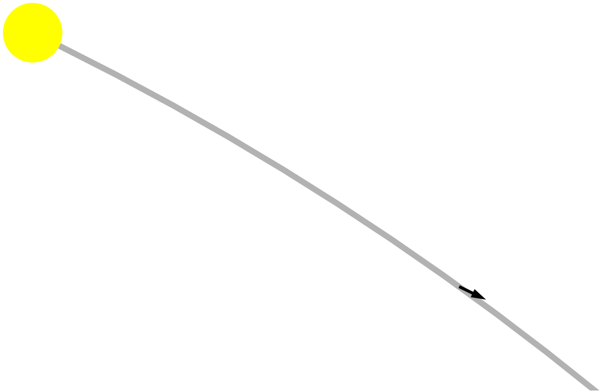

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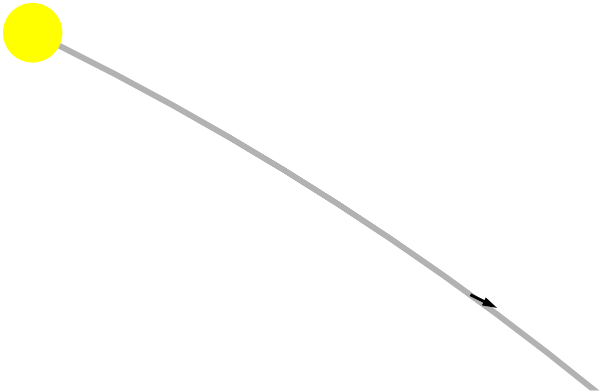

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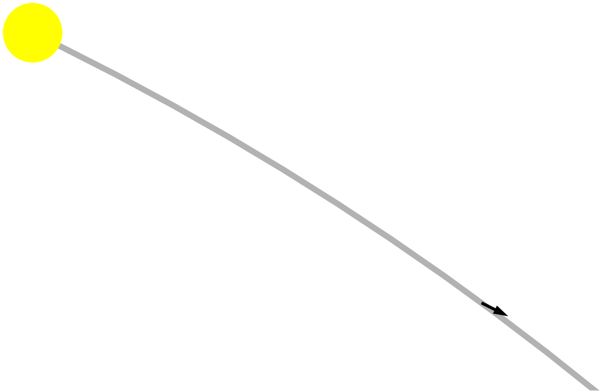

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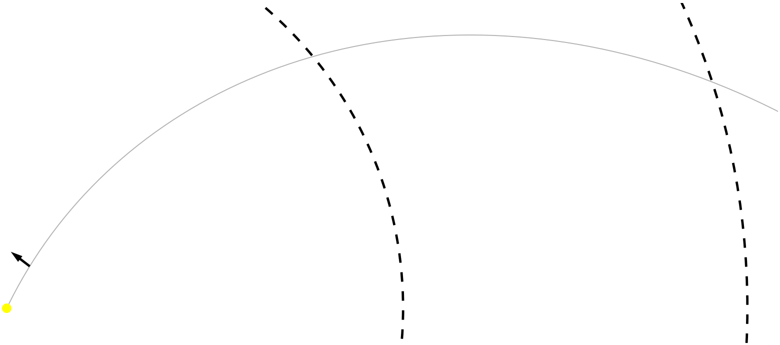

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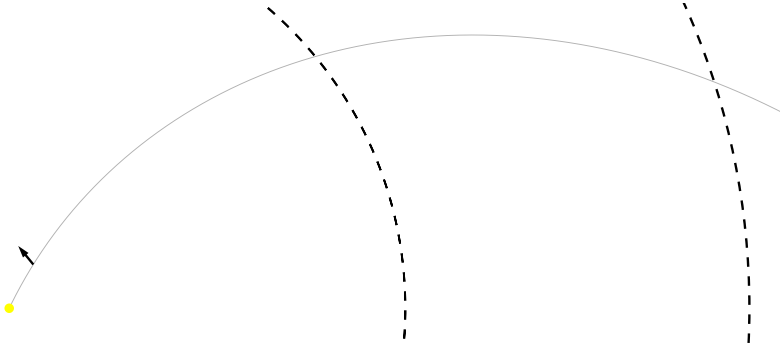

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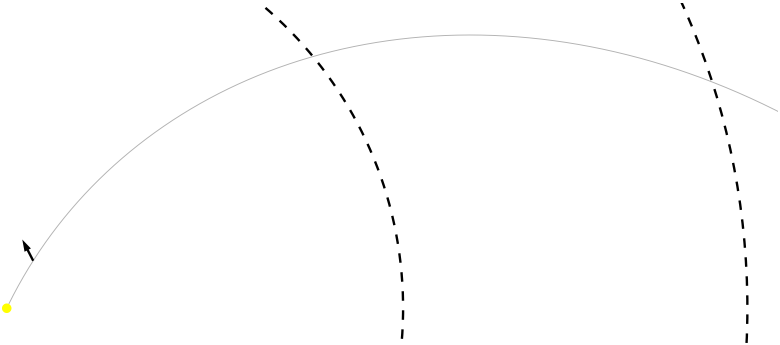

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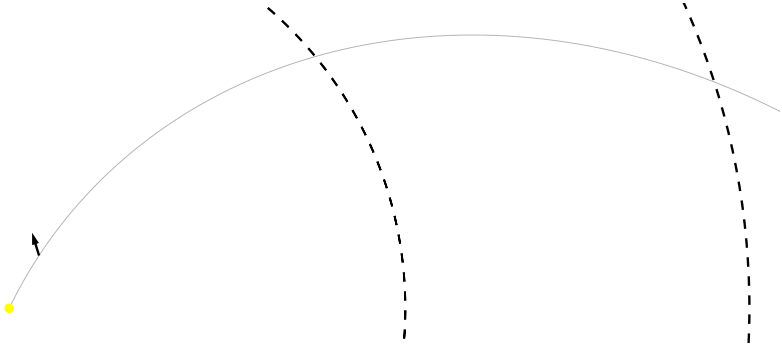

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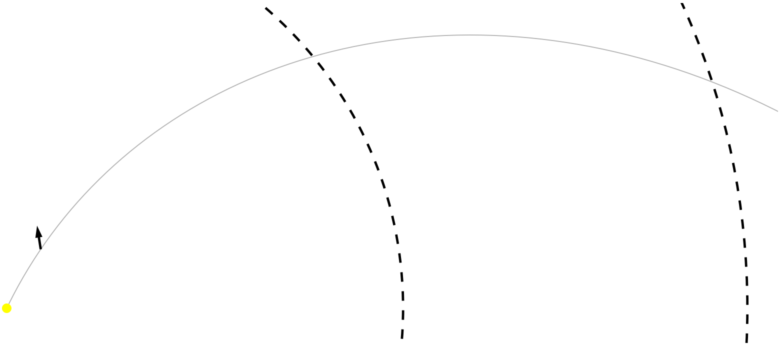

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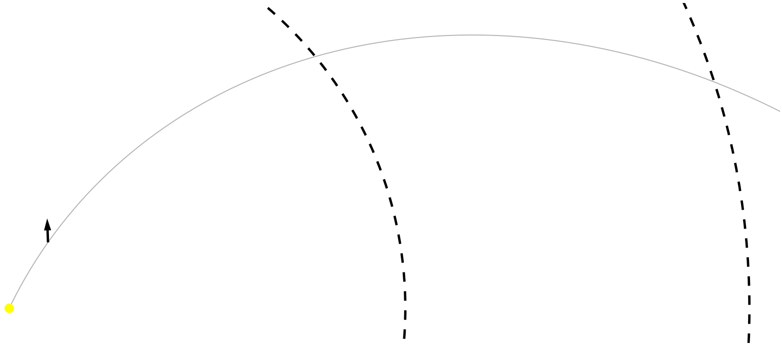

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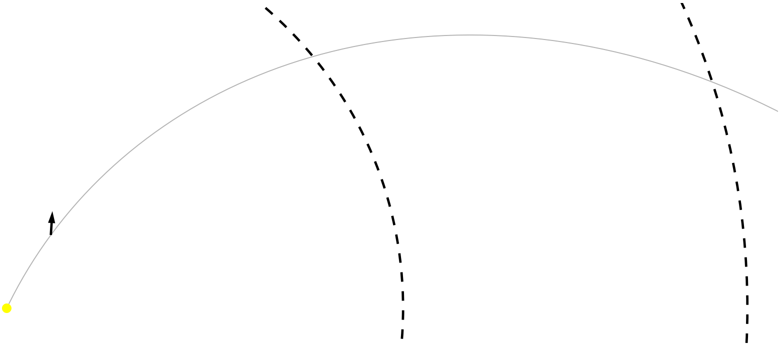

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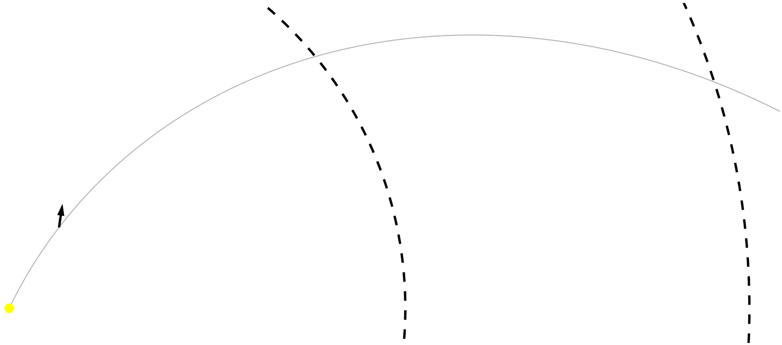

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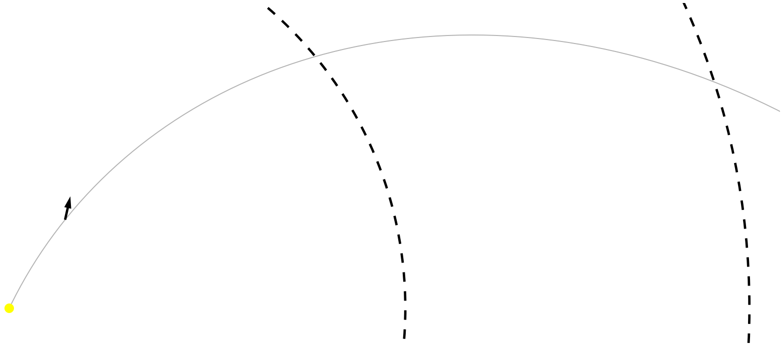

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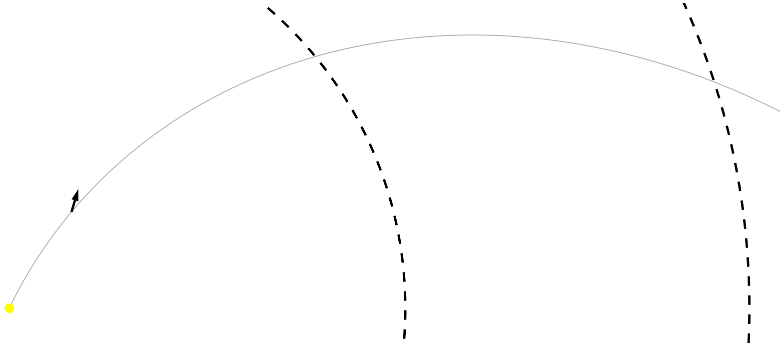

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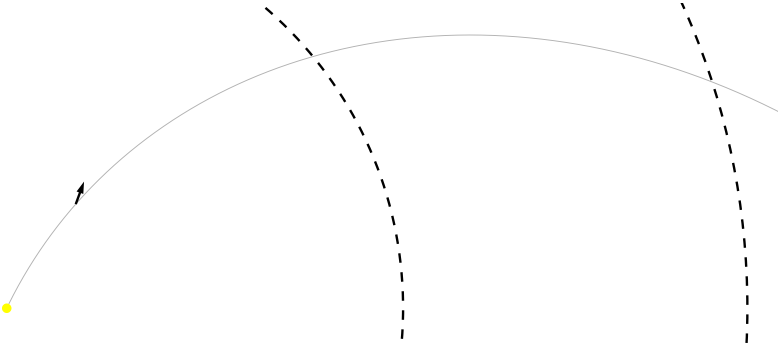

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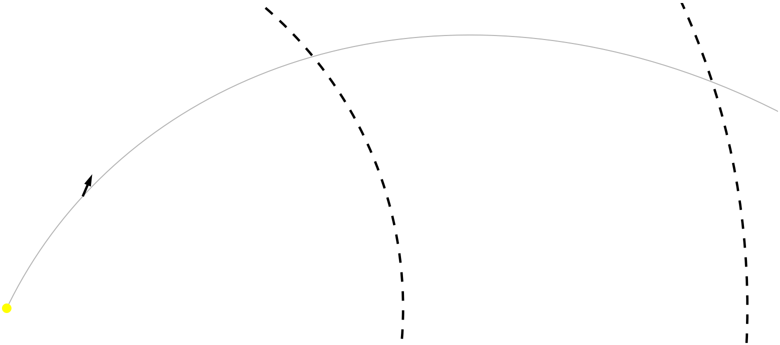

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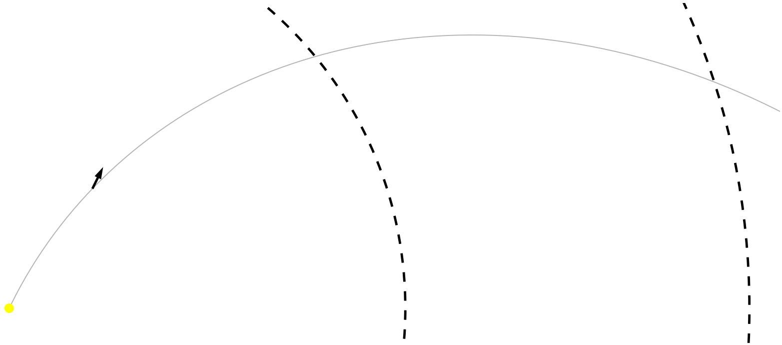

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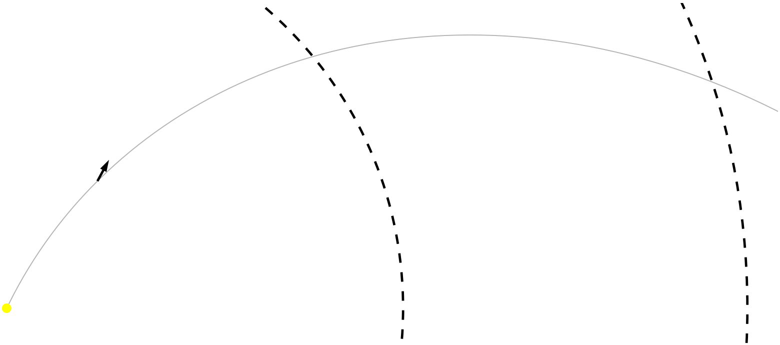

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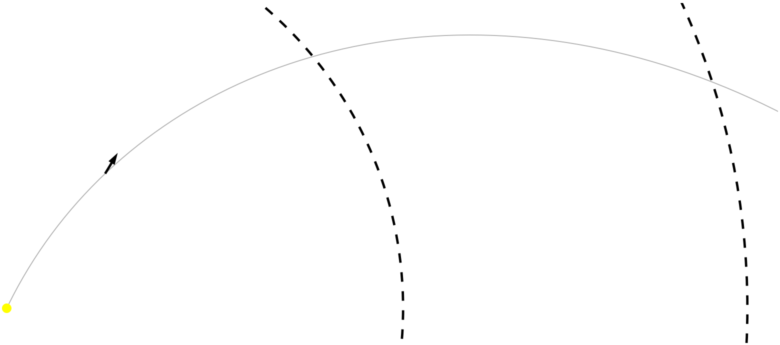

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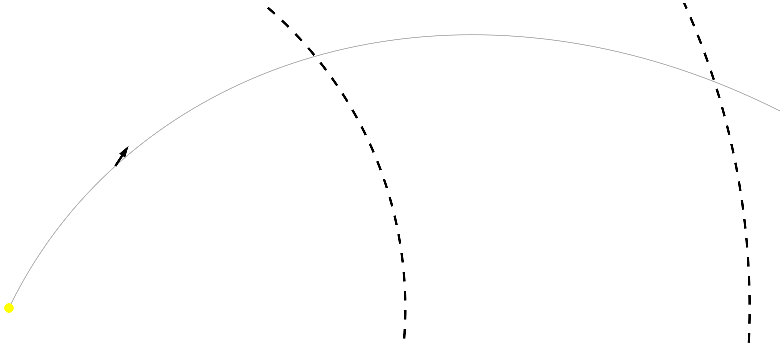

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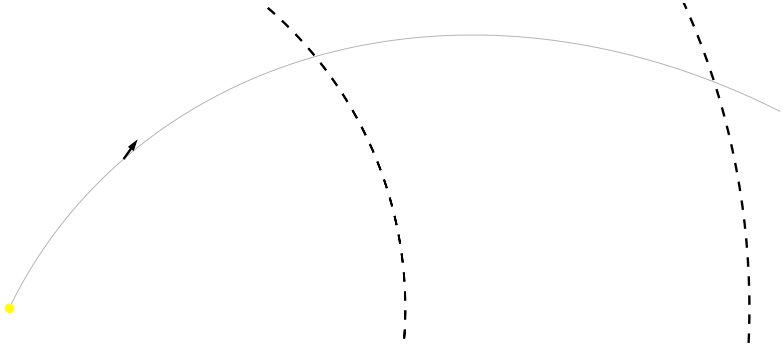

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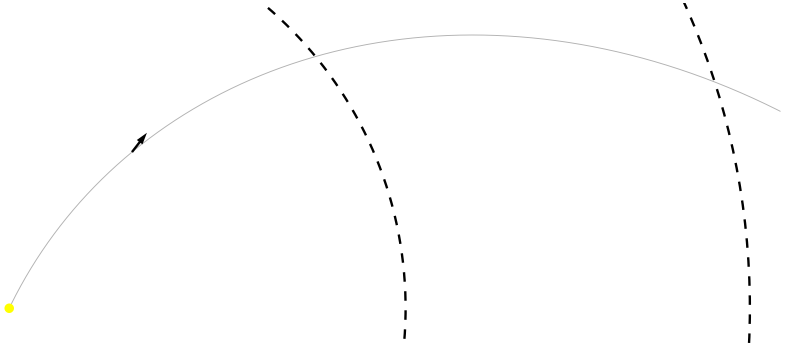

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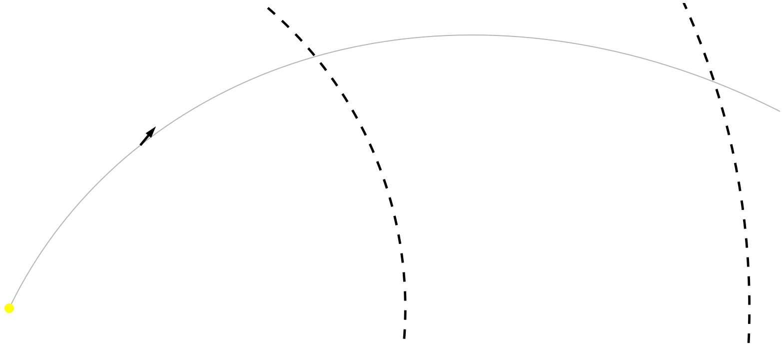

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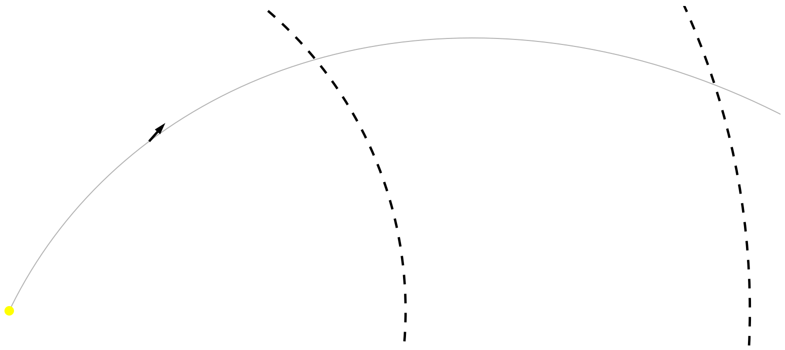

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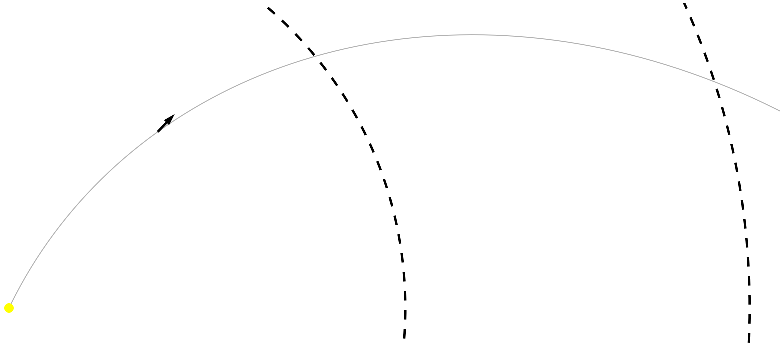

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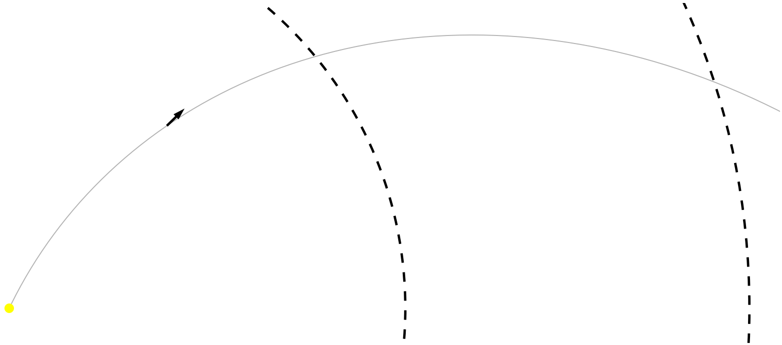

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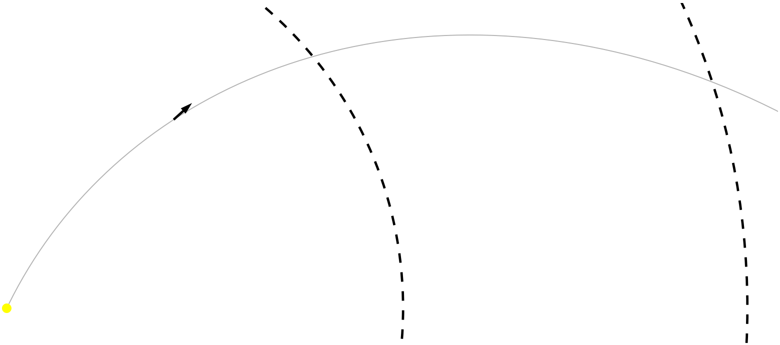

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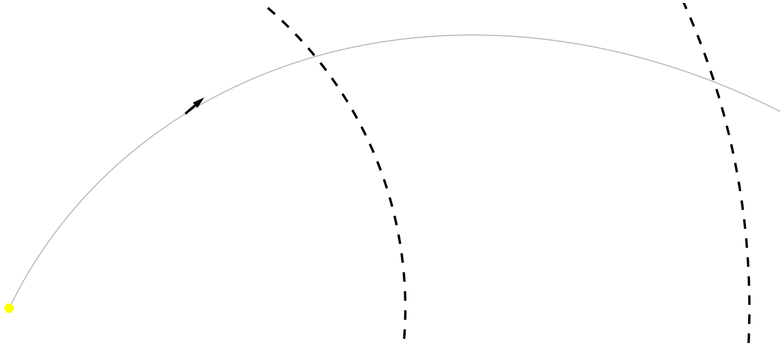

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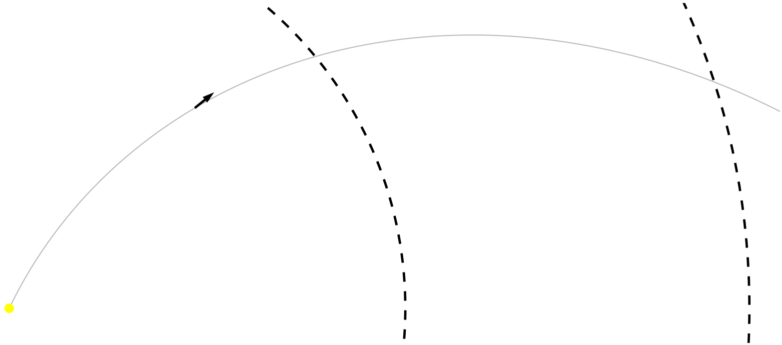

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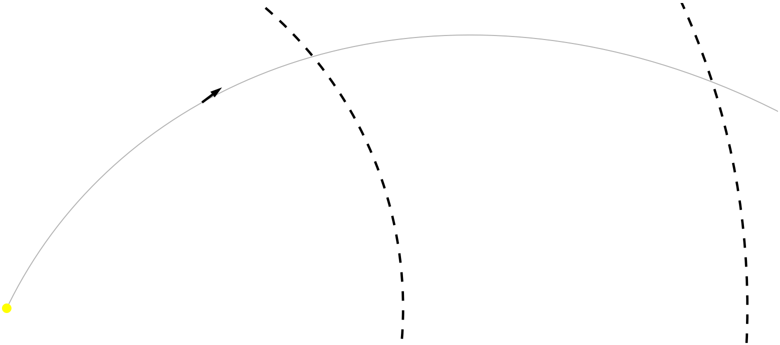

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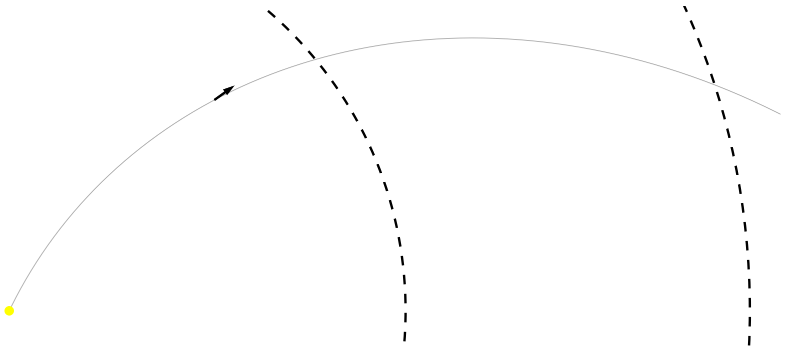

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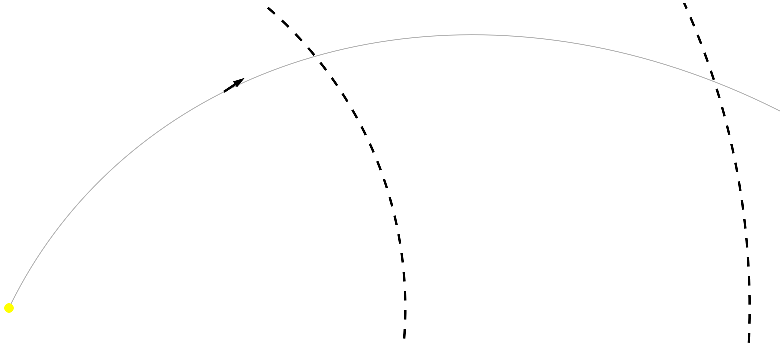

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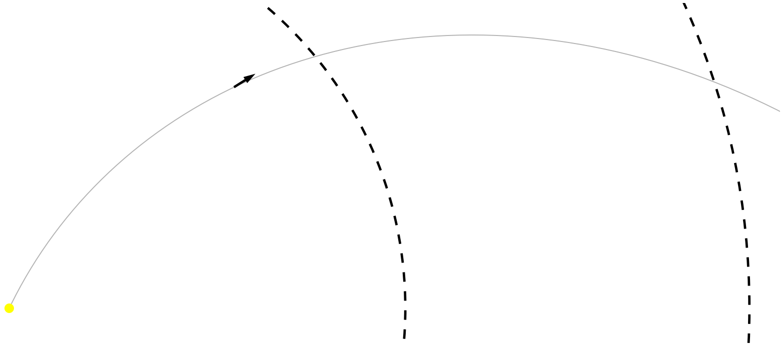

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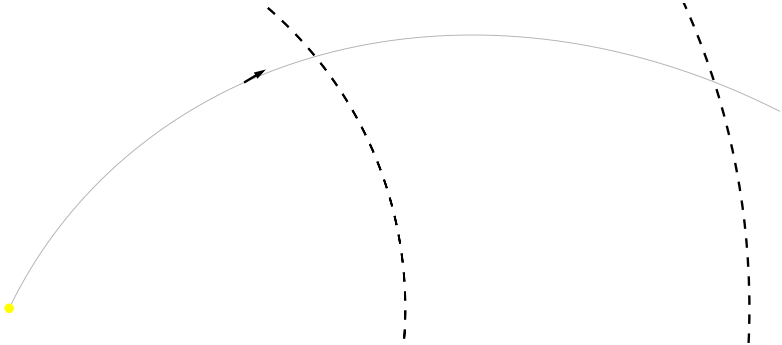

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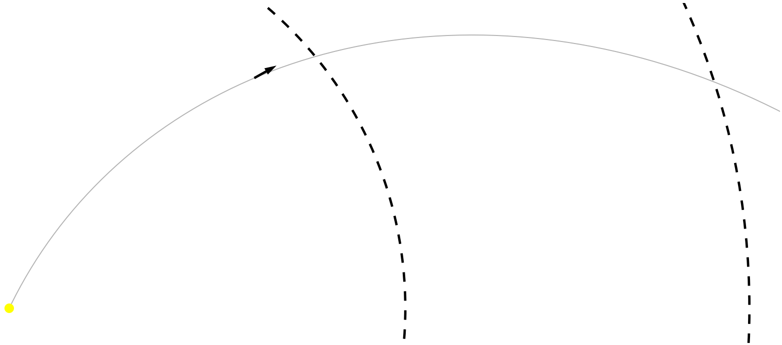

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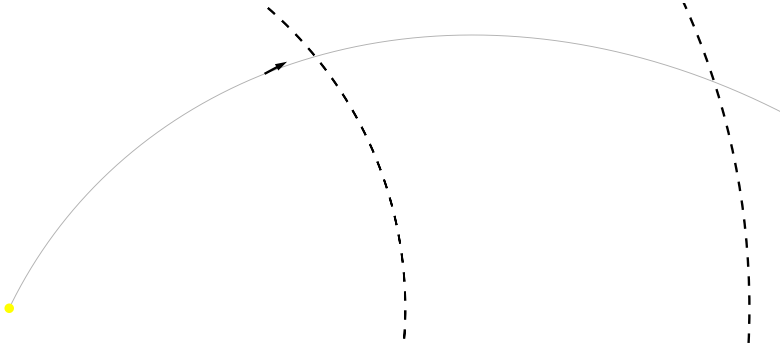

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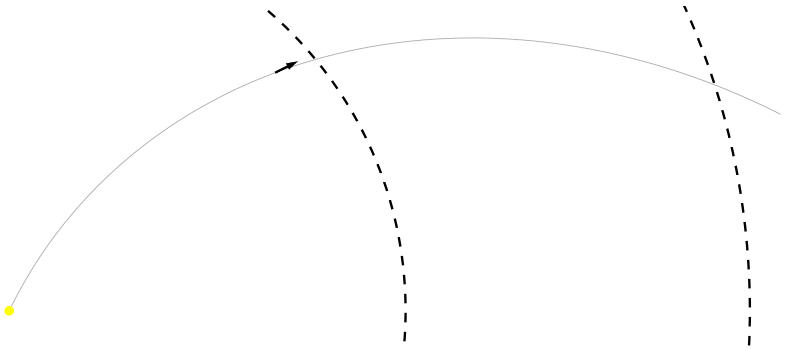

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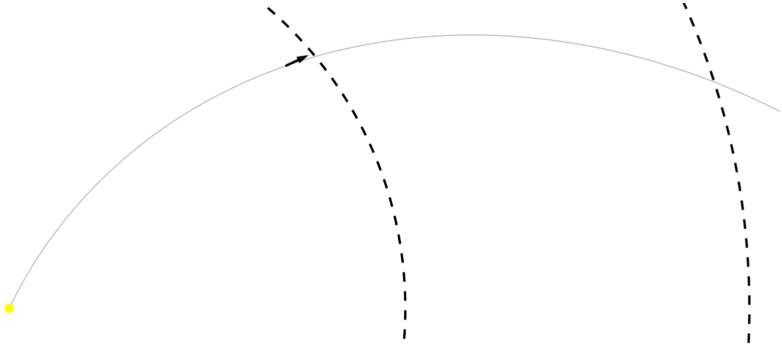

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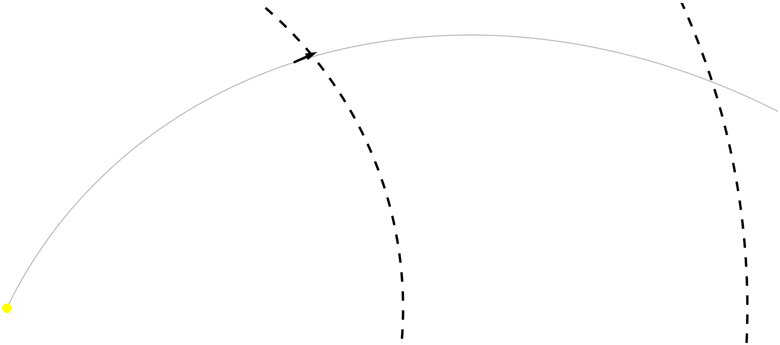

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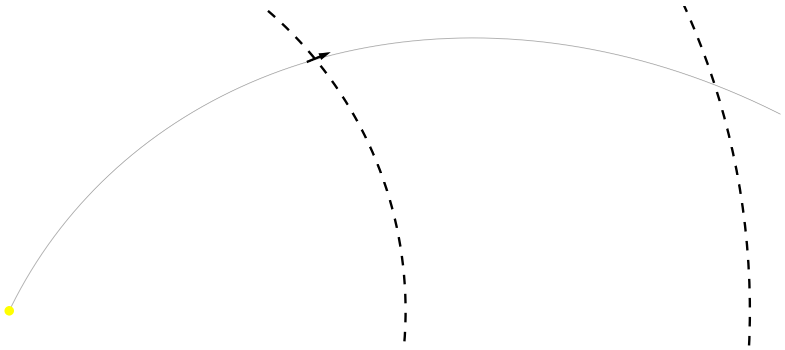

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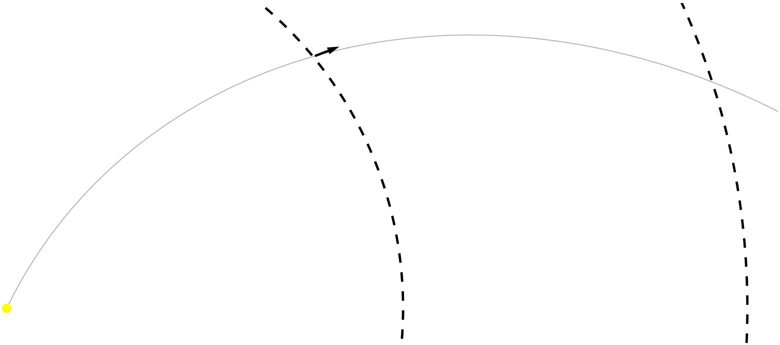

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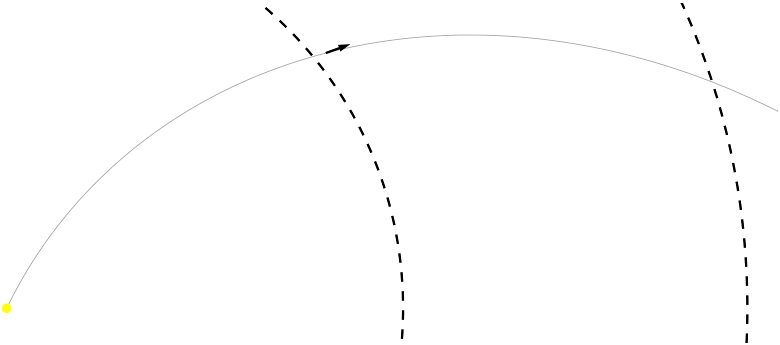

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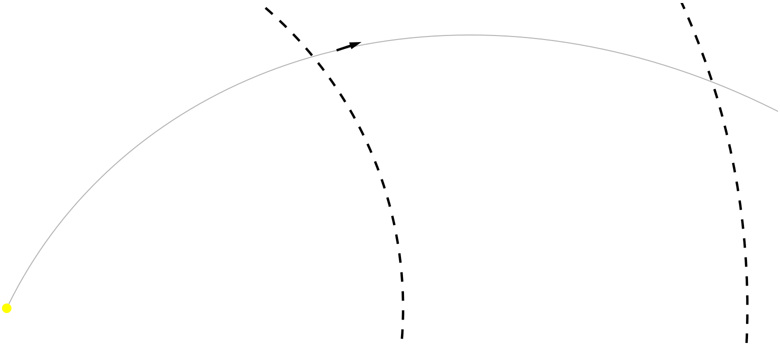

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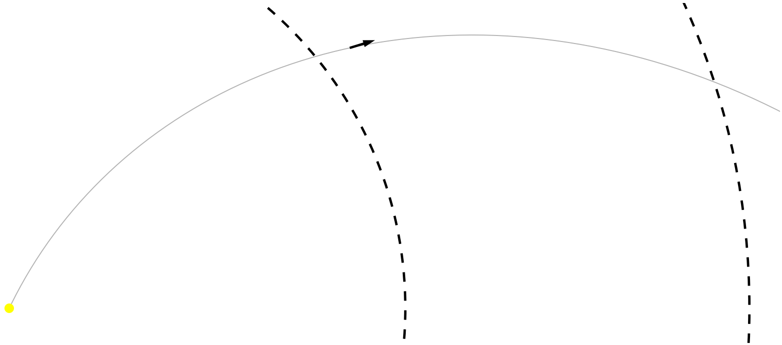

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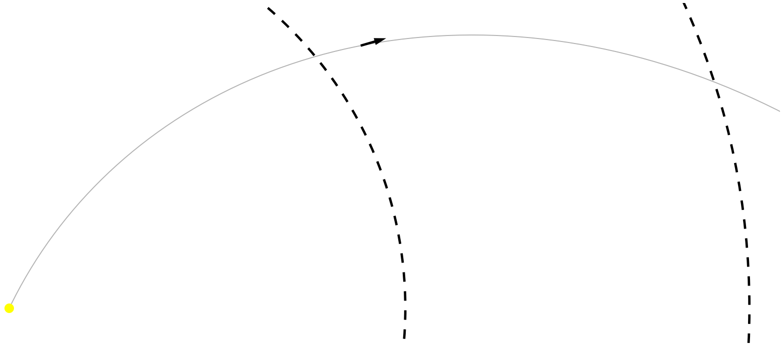

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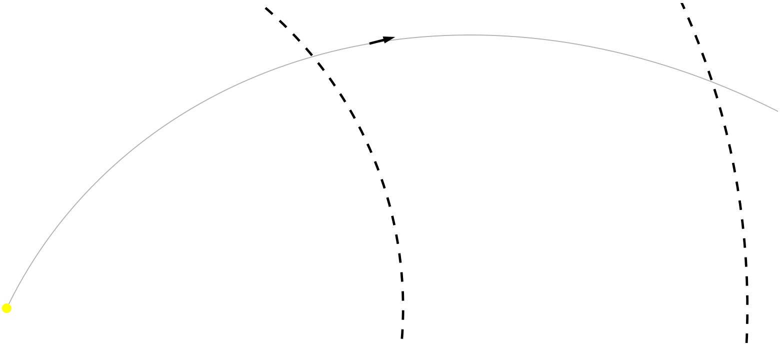

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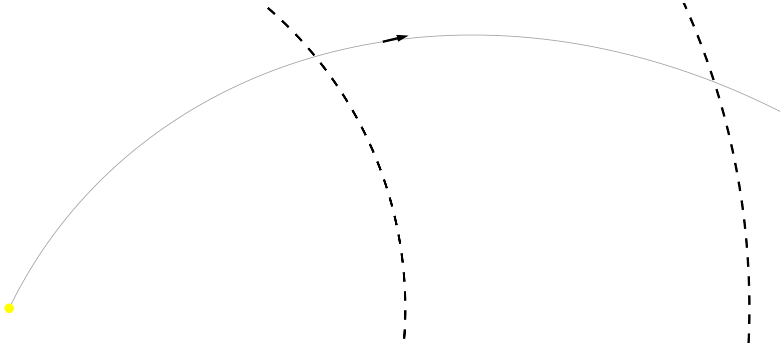

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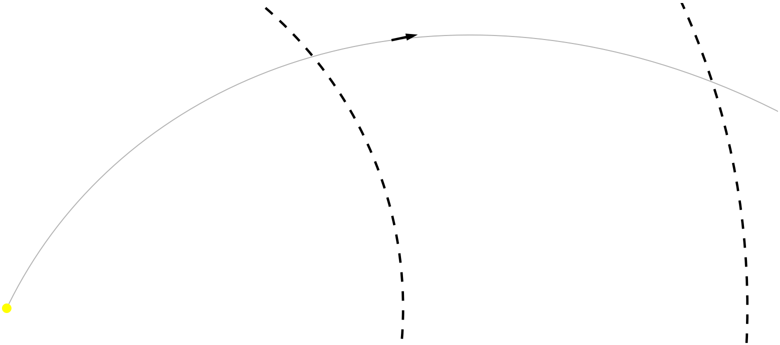

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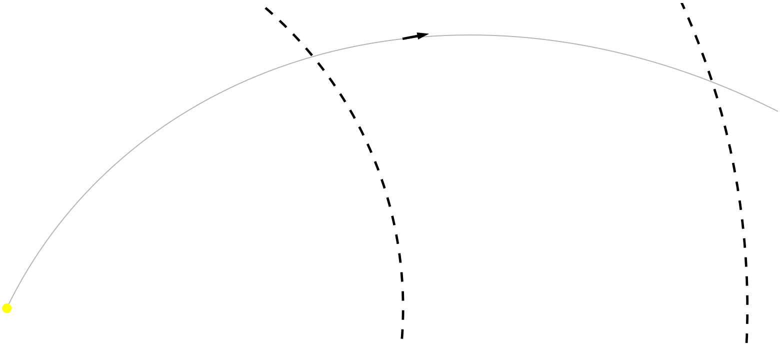

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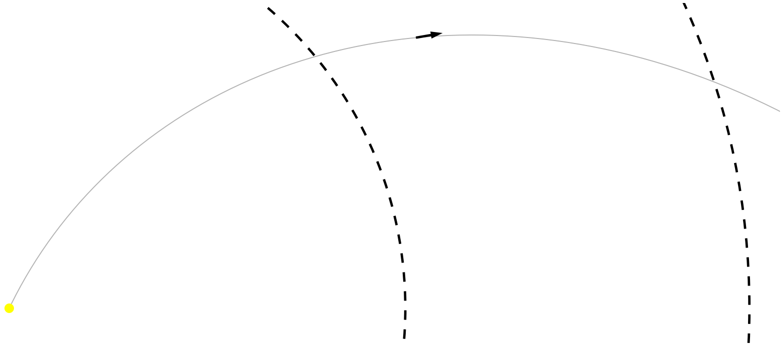

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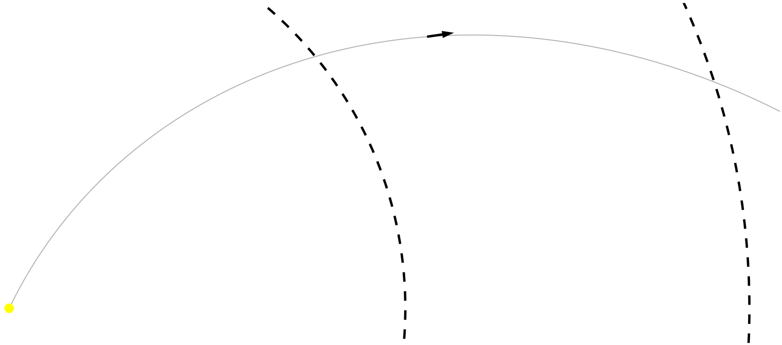

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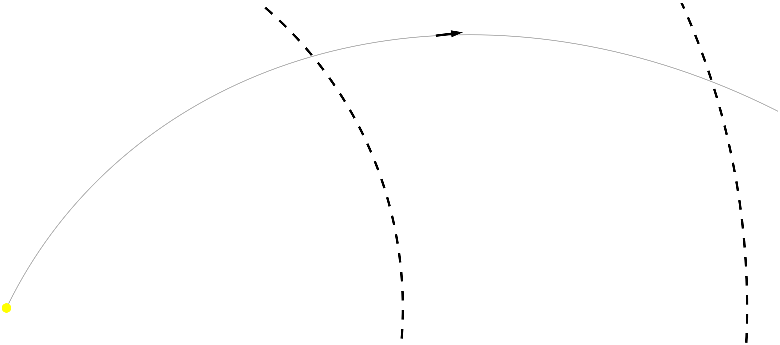

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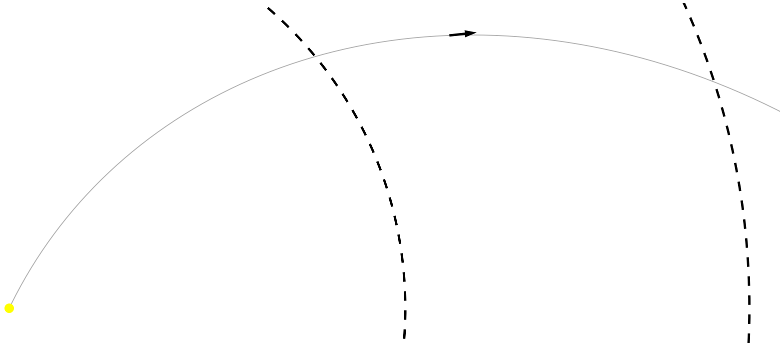

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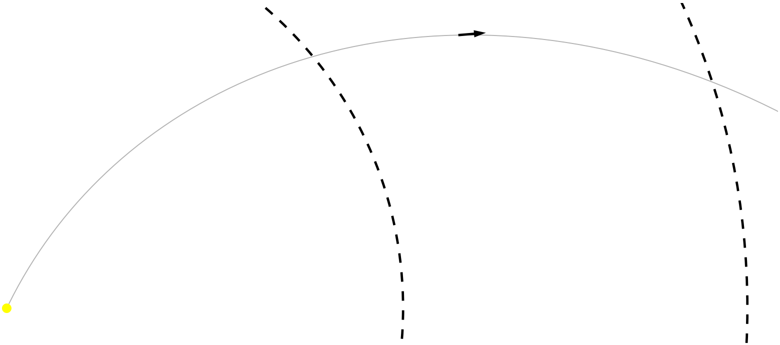

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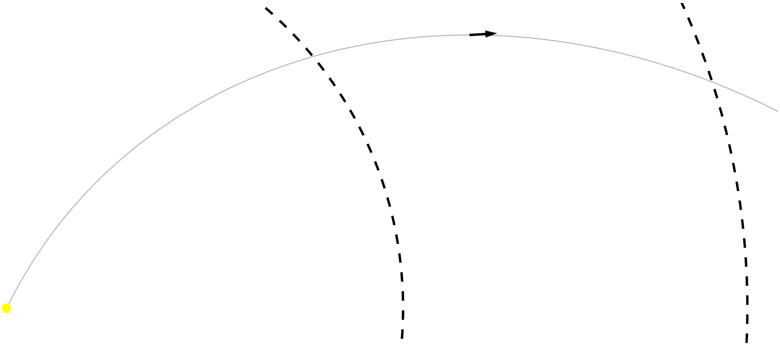

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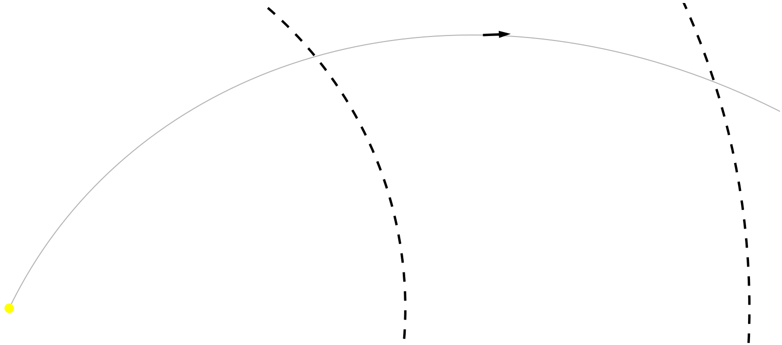

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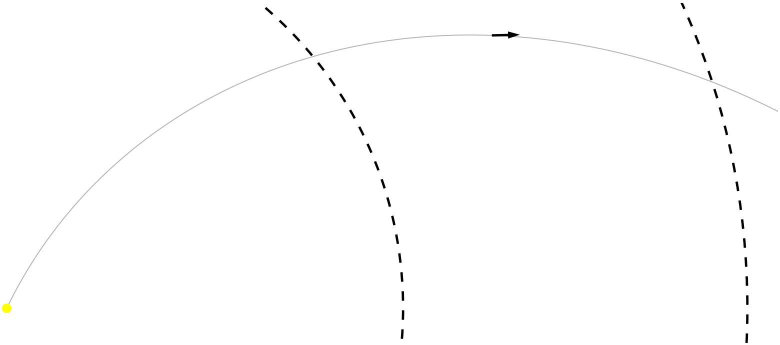

What about particles propagating towards the Sun?

Example:

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- outward motion, initial $\mu \approx -0.95$
- spiral magnetic field (solar wind 400 km/s)
- magnetic field intensity varying as R^{-2}

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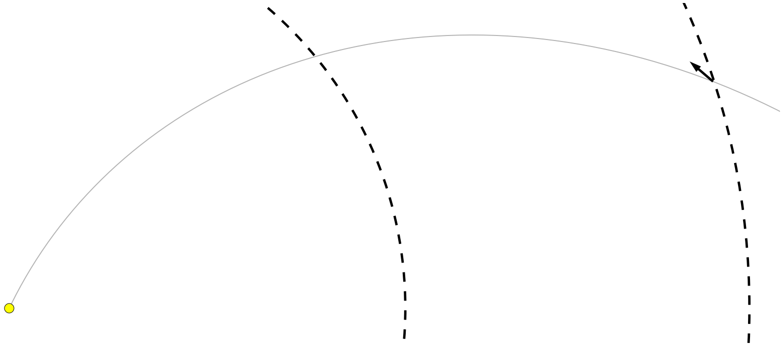

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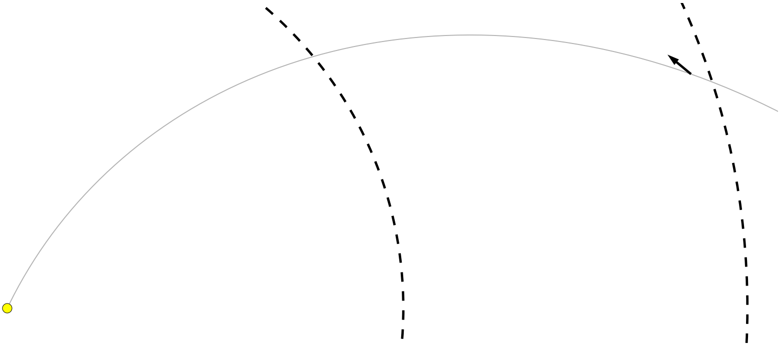

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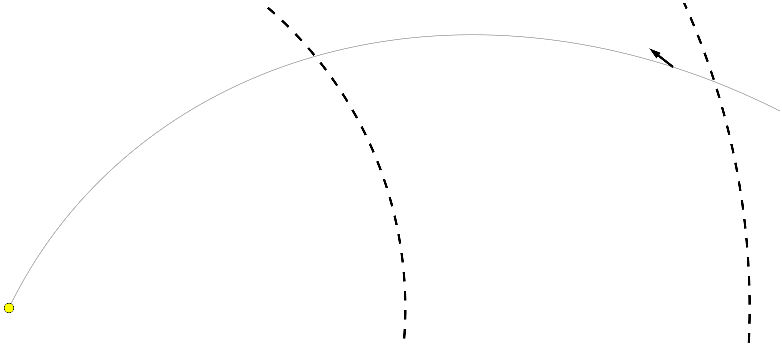

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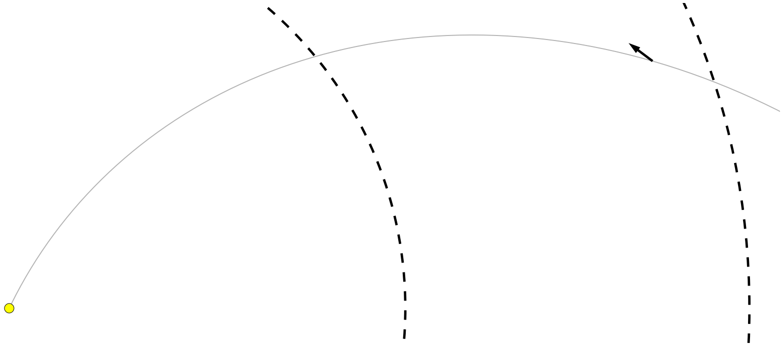

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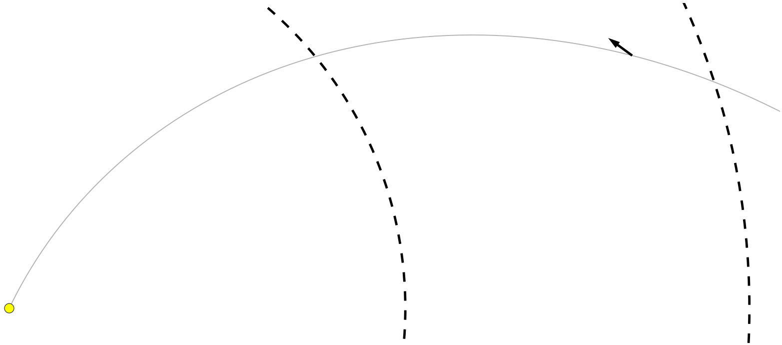

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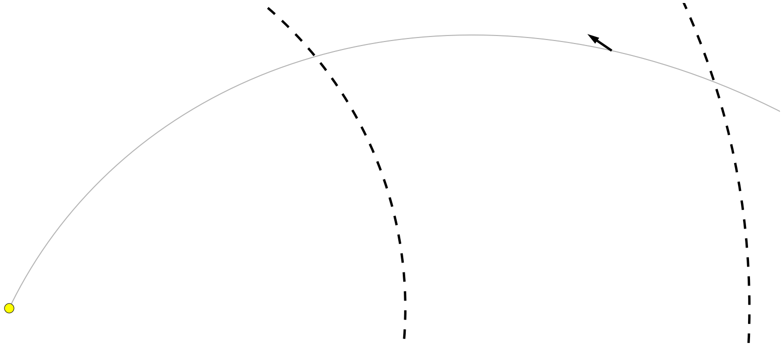

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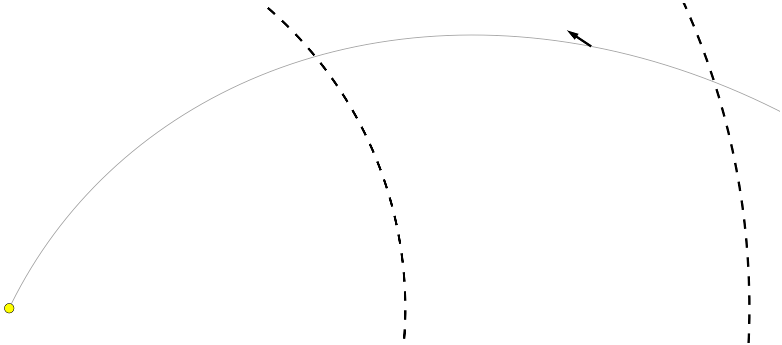

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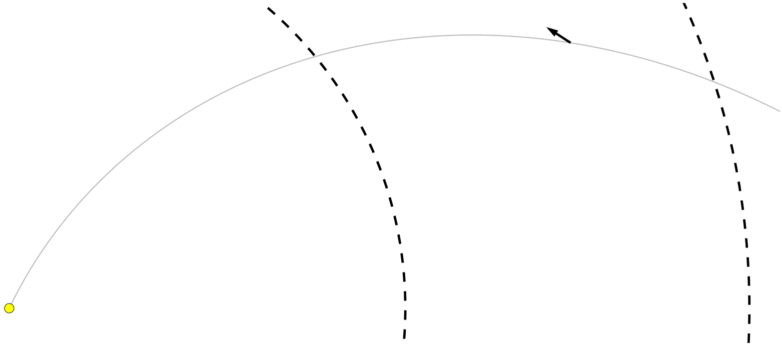

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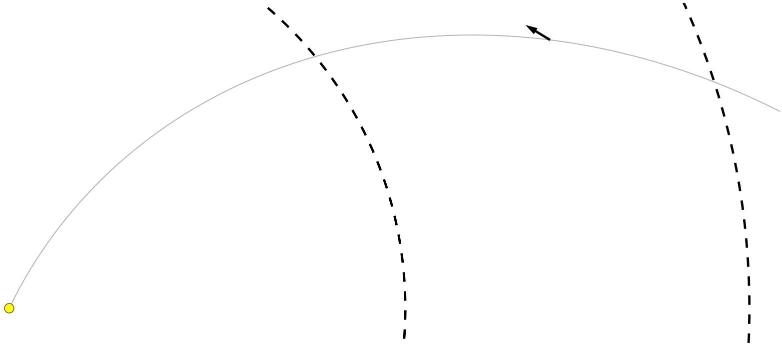

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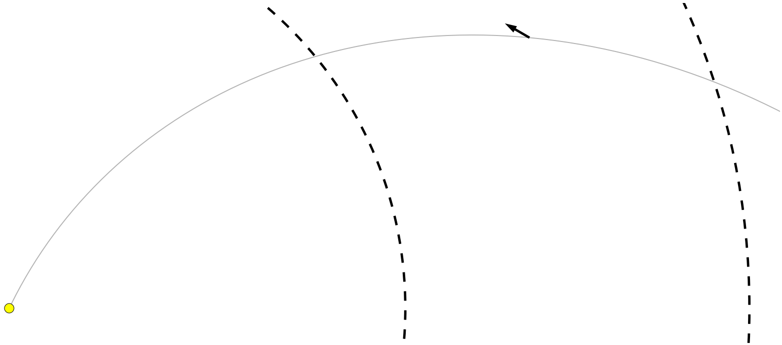

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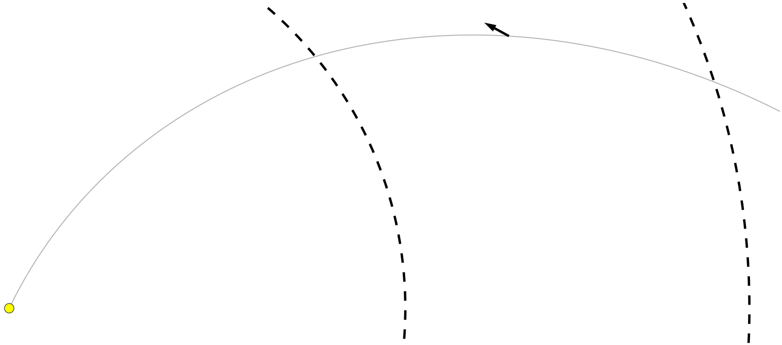

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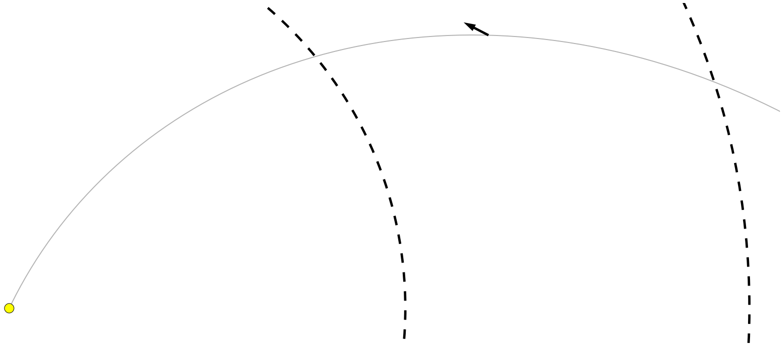

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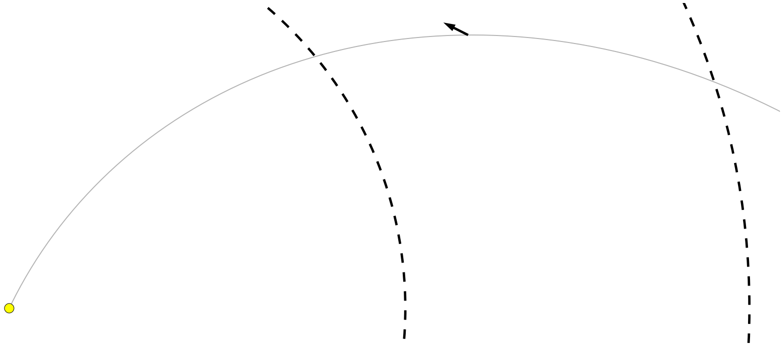

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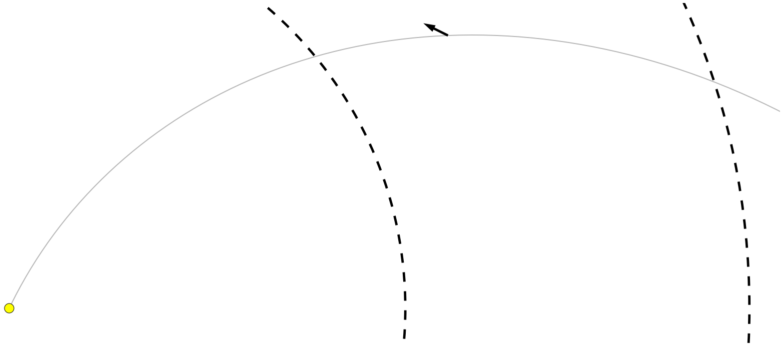

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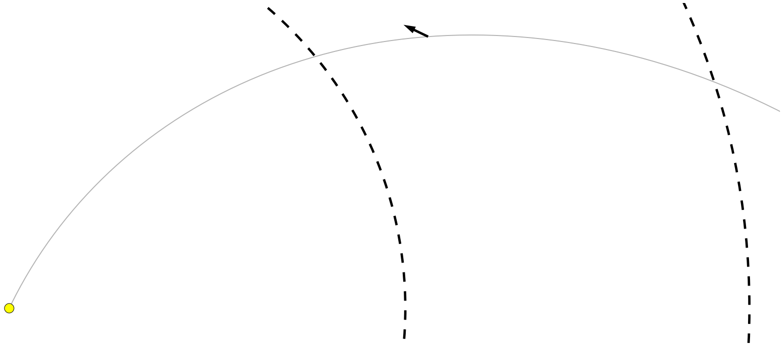

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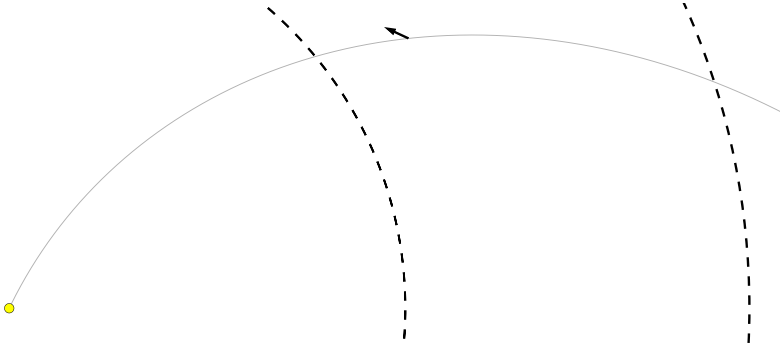

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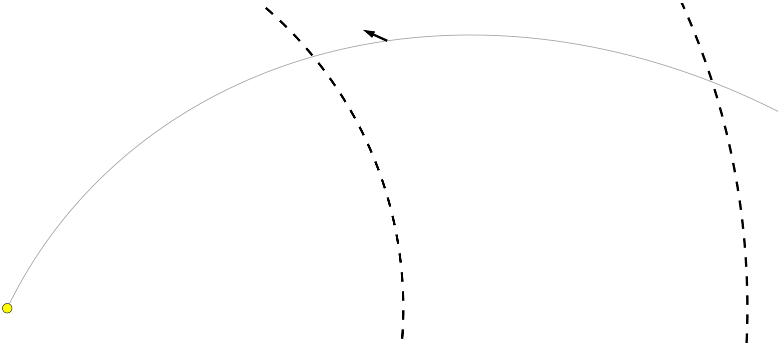

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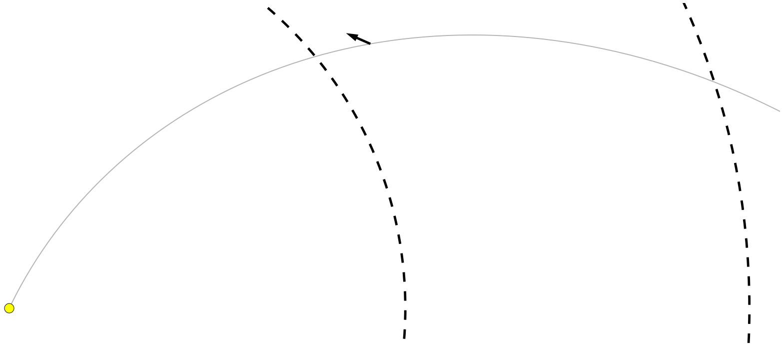

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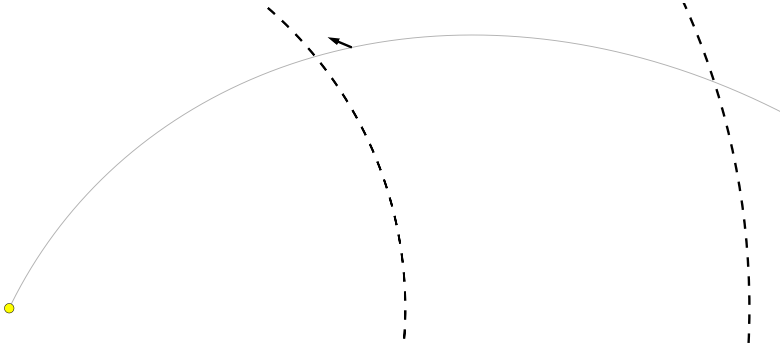

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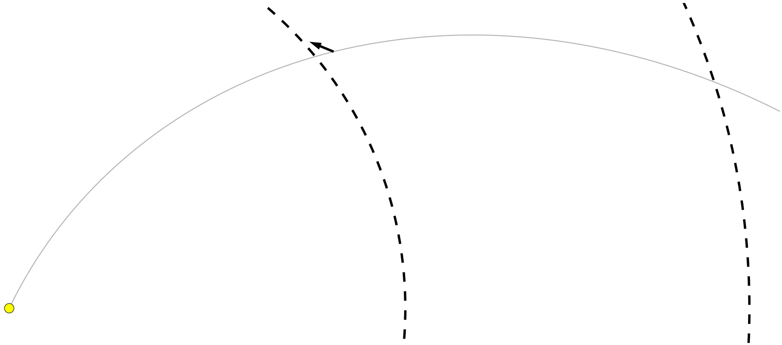

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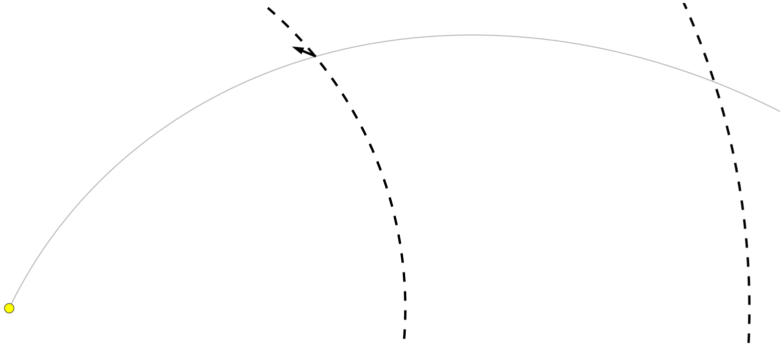

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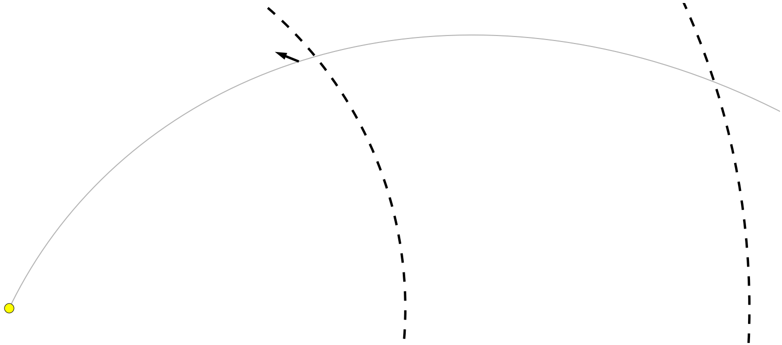

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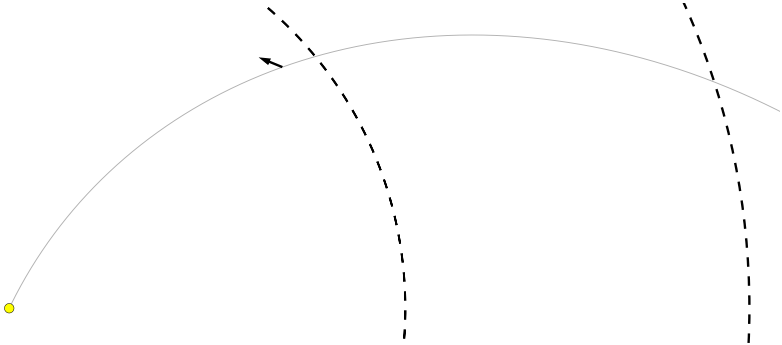

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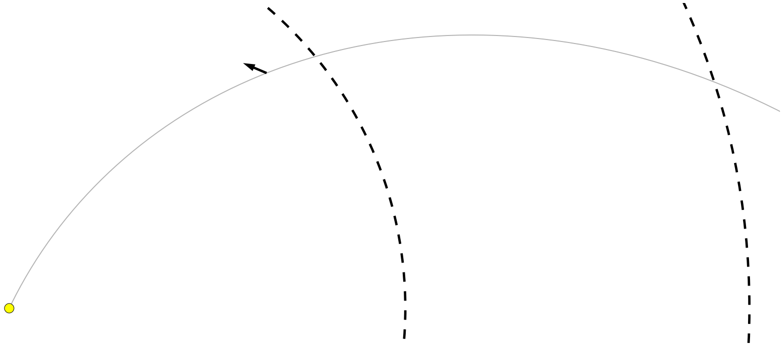

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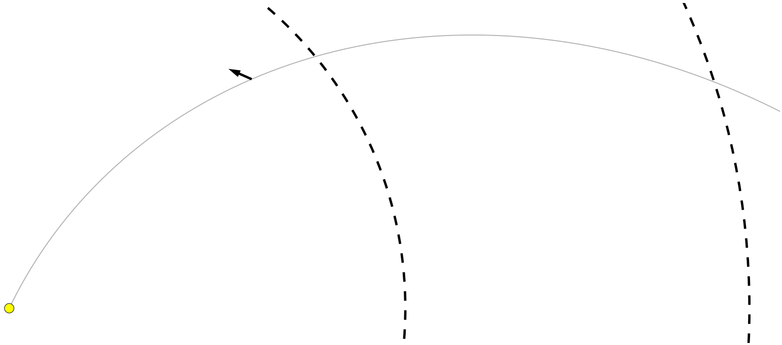

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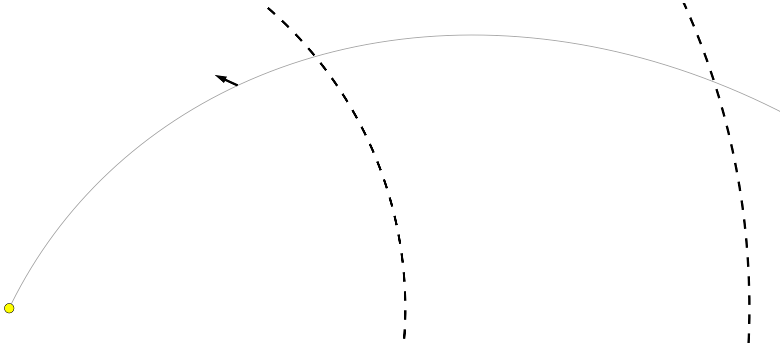

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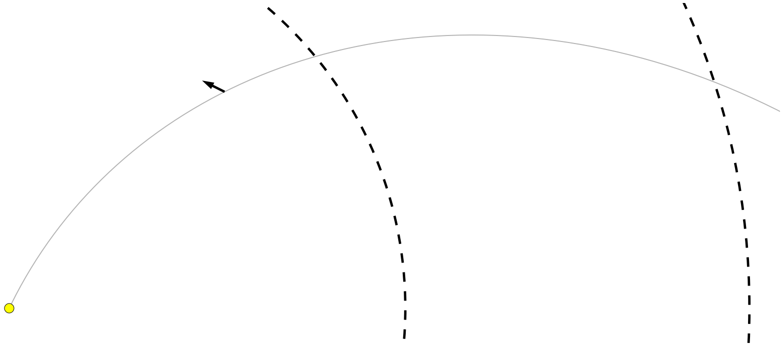

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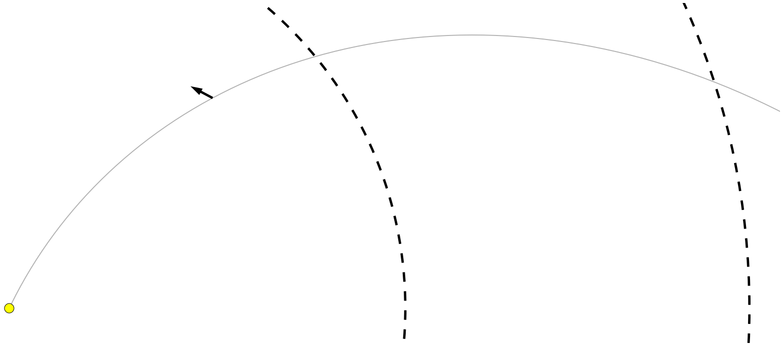

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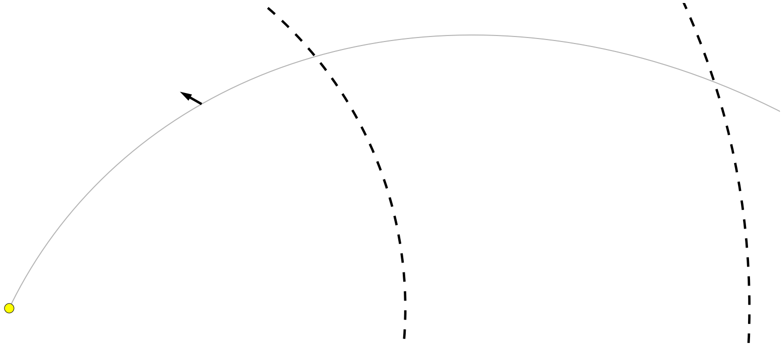

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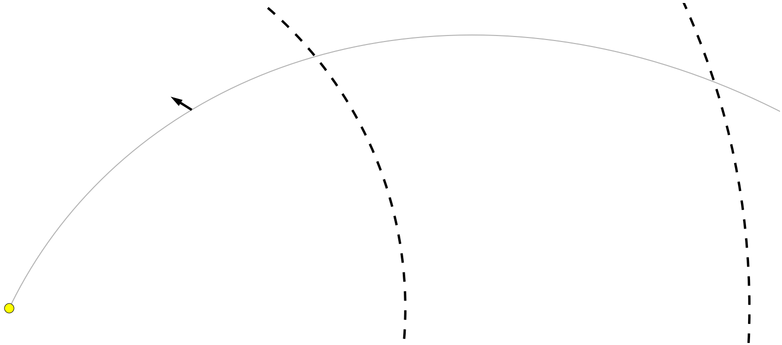

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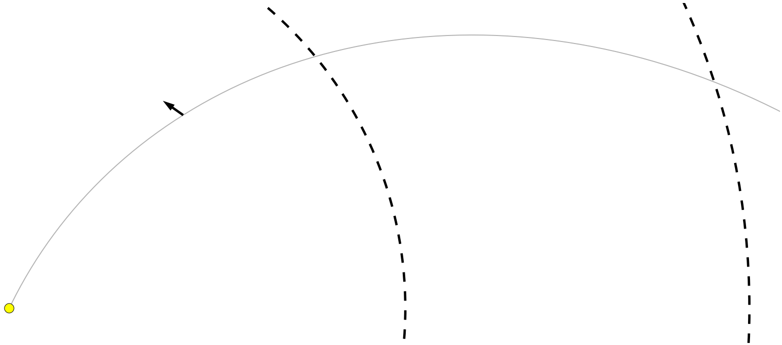

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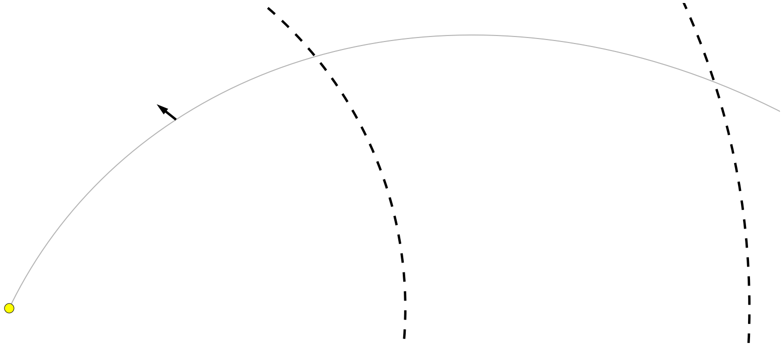

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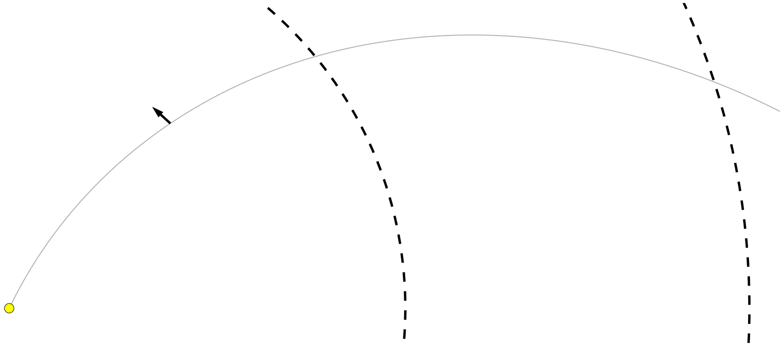

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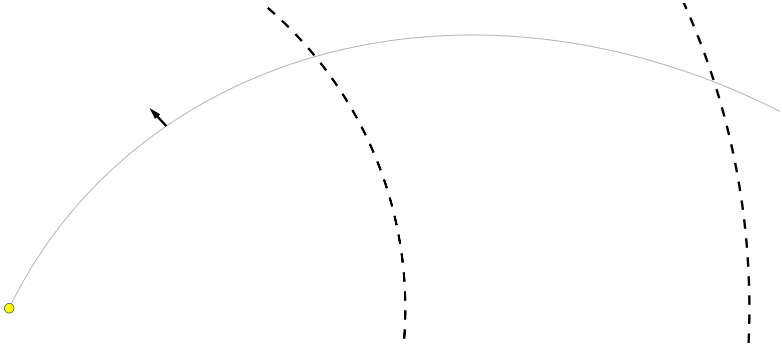

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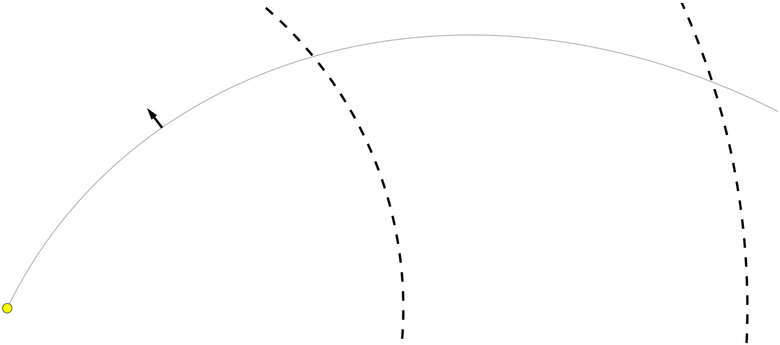

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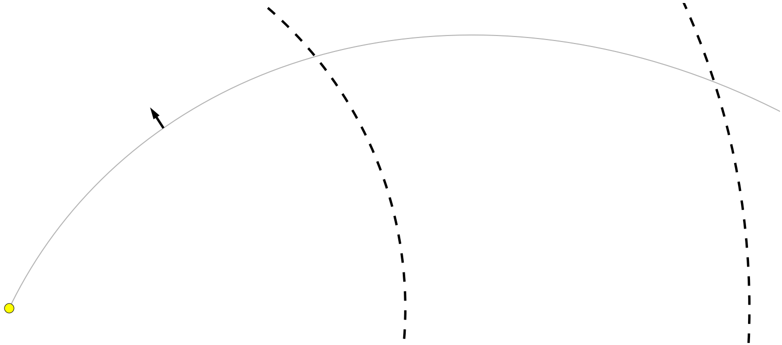

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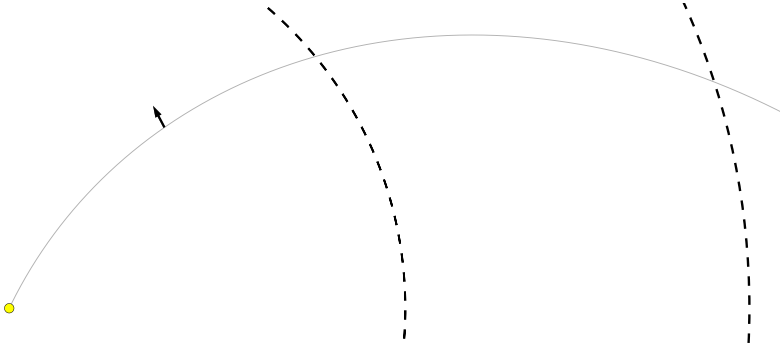

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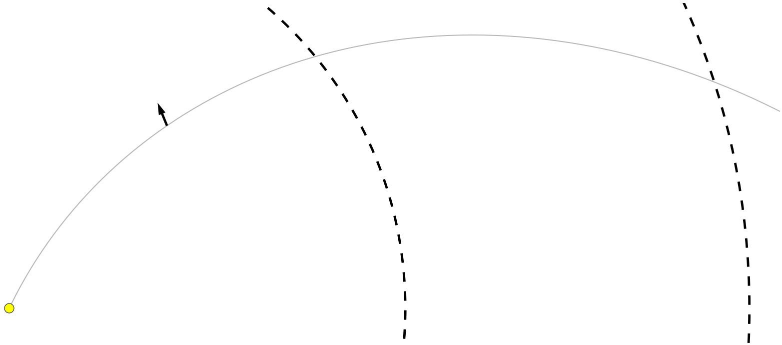

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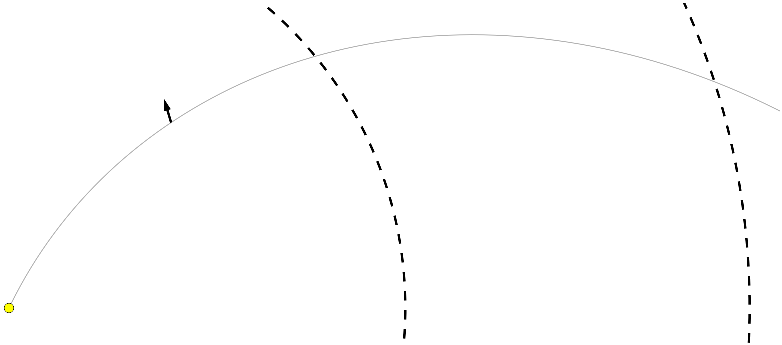

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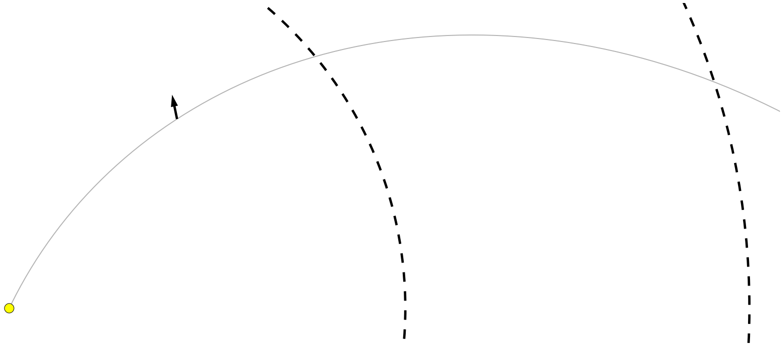

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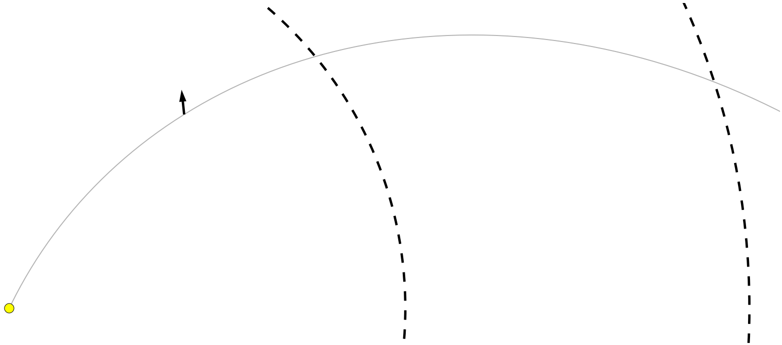

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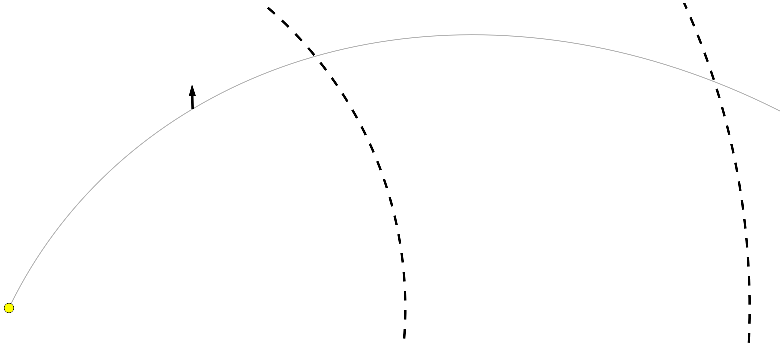

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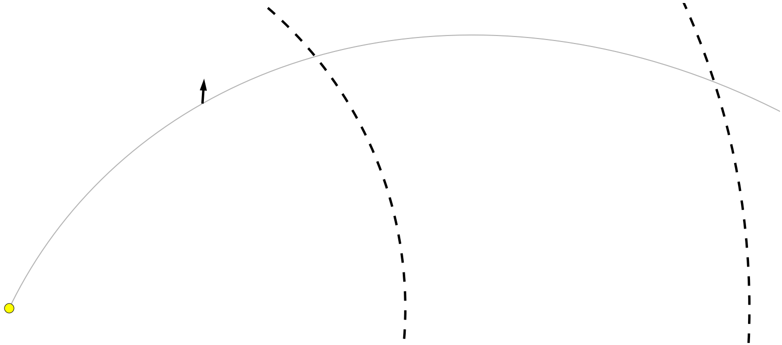

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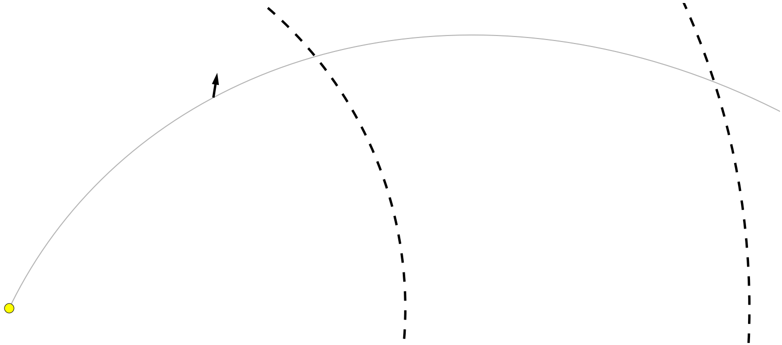

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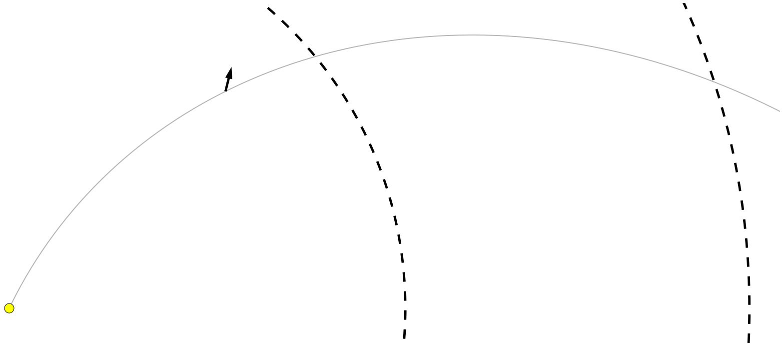

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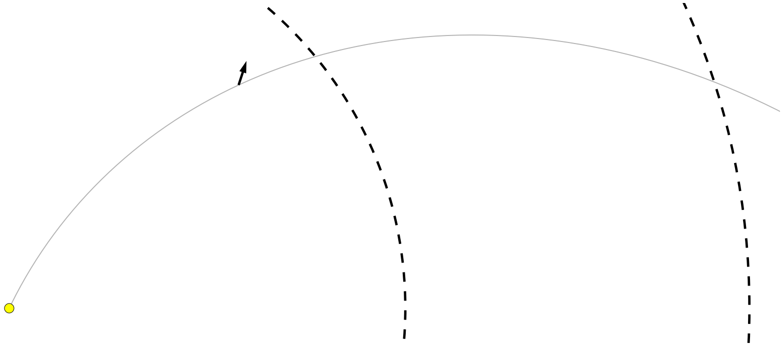

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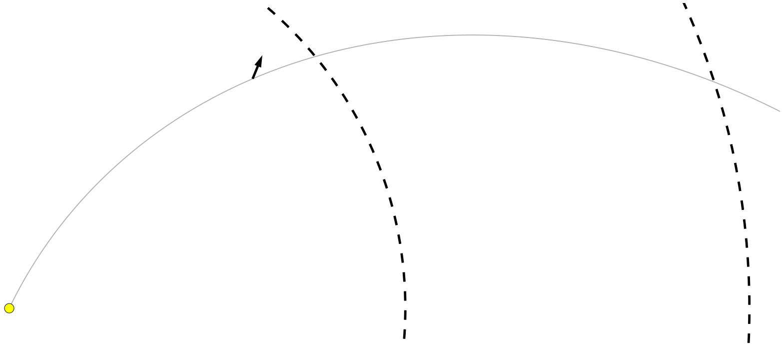

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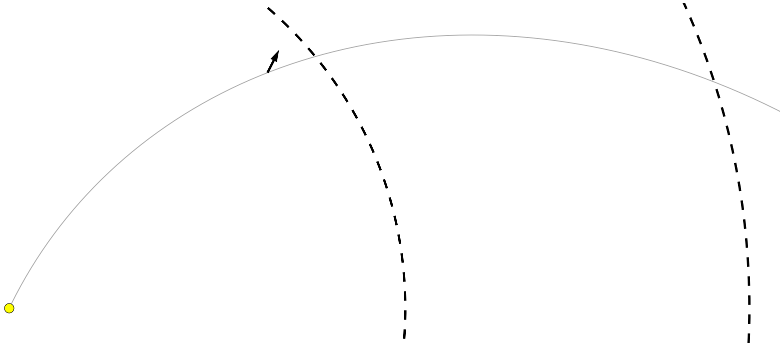

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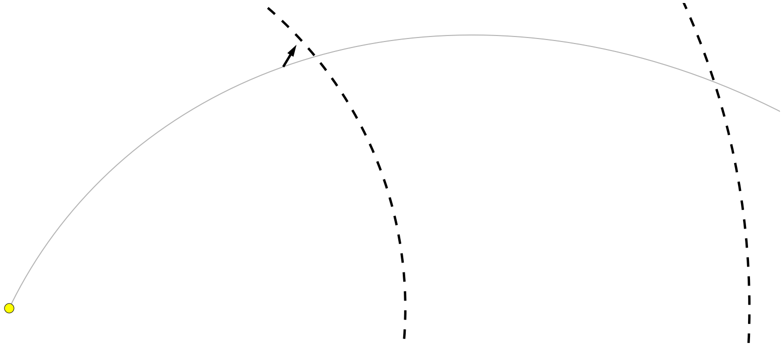

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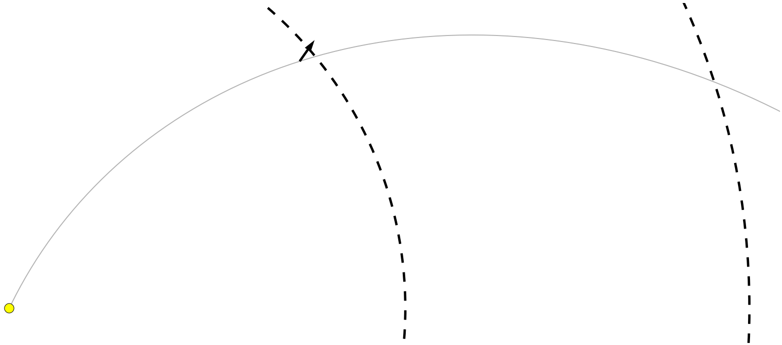

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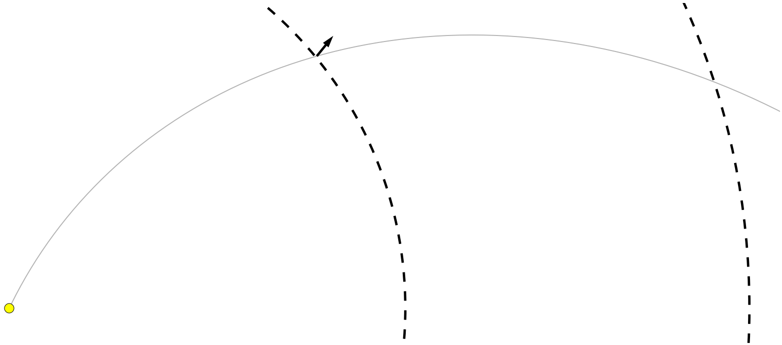

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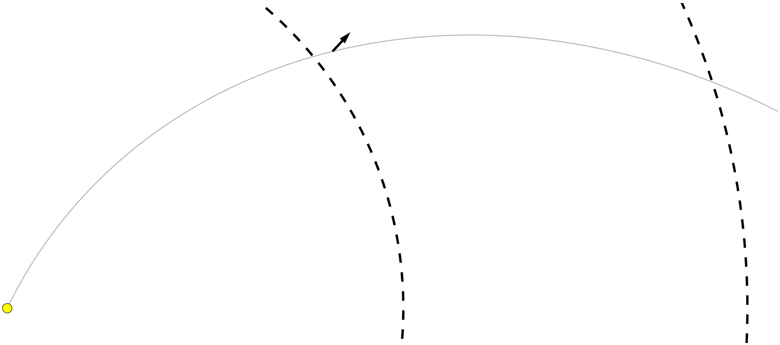

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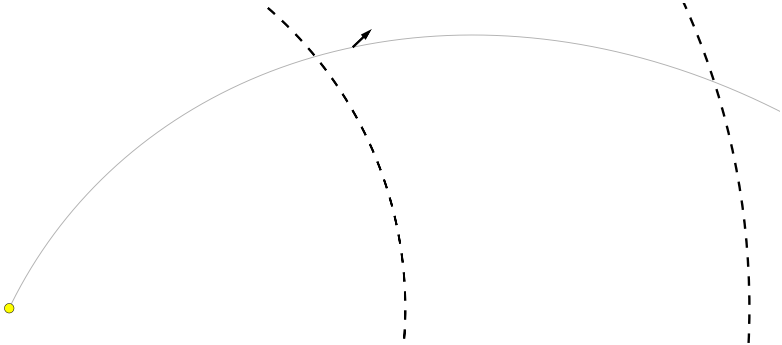

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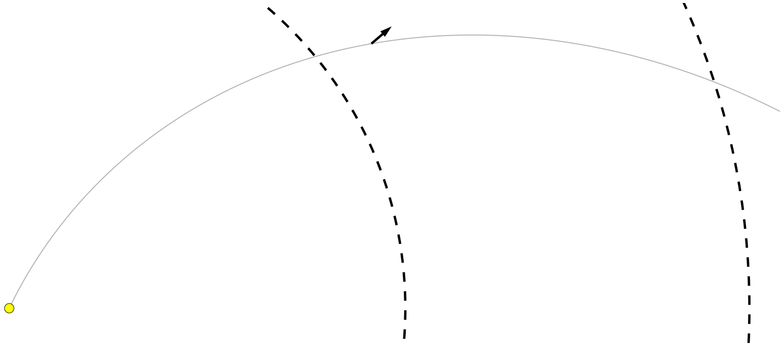

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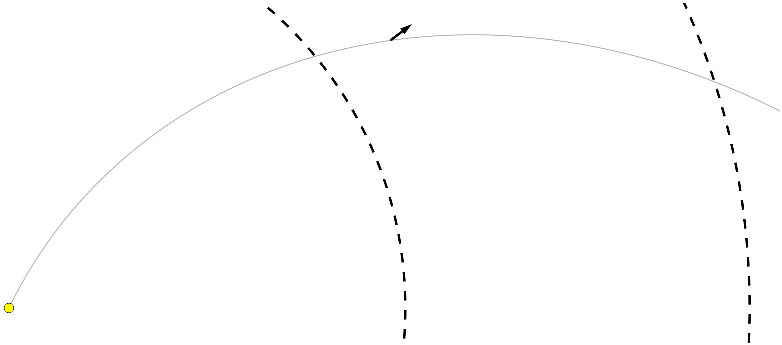

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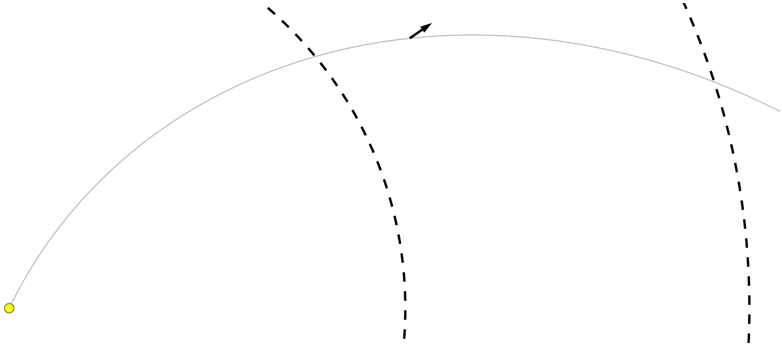

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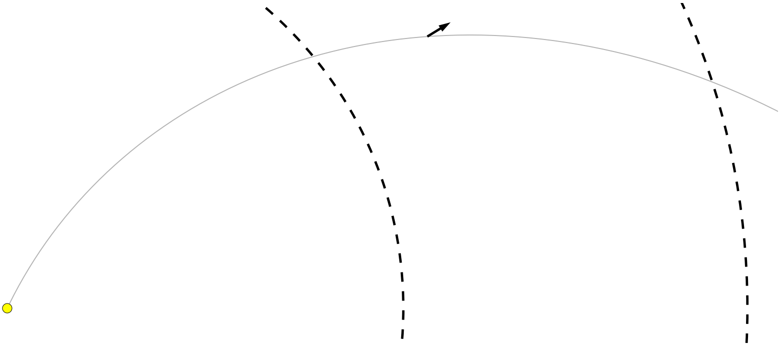

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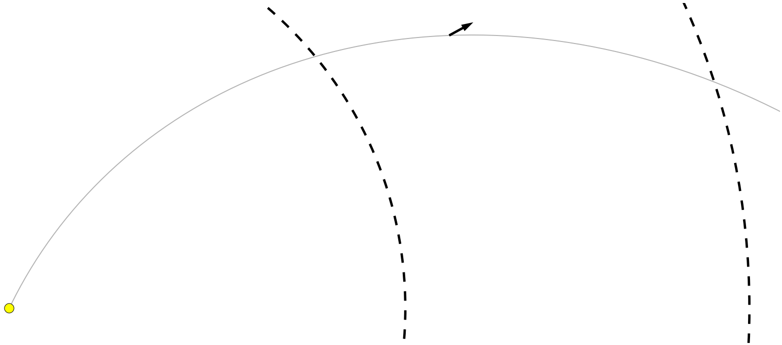

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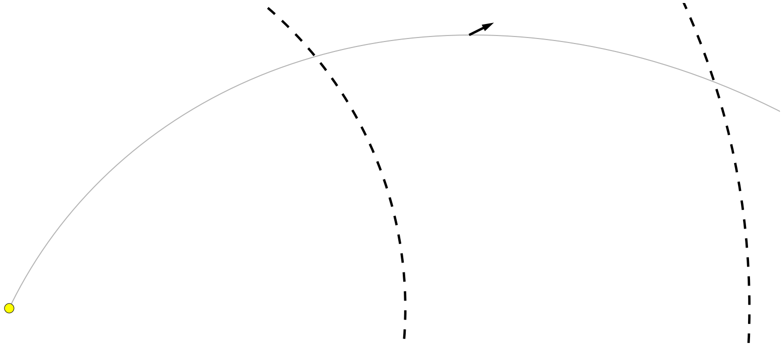

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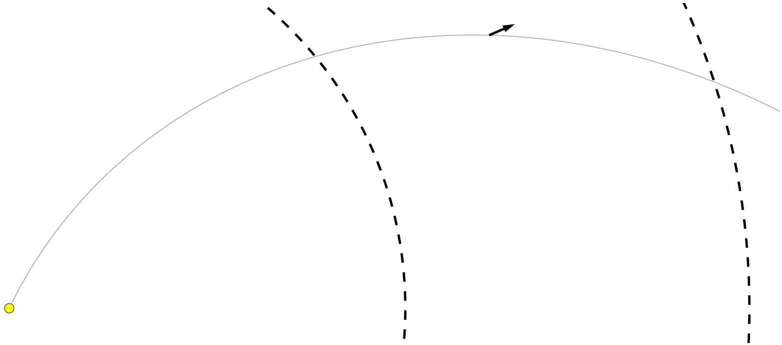

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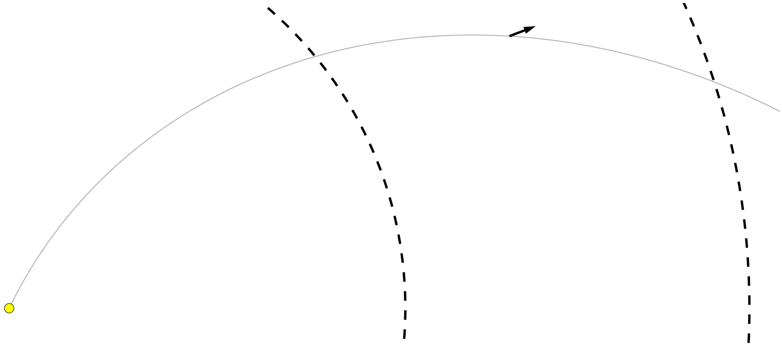

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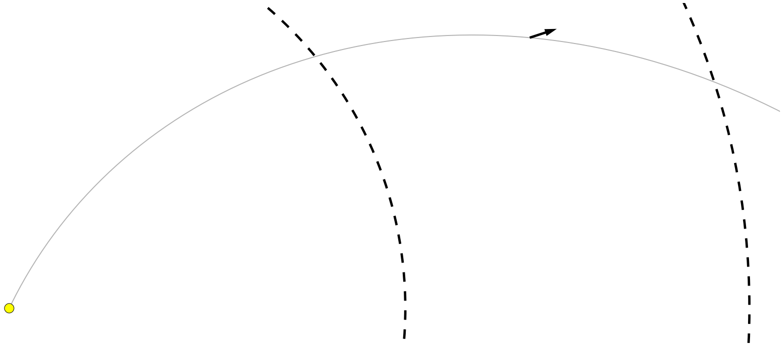

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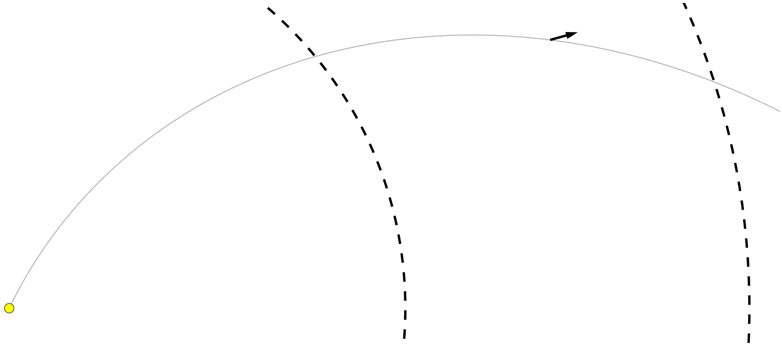

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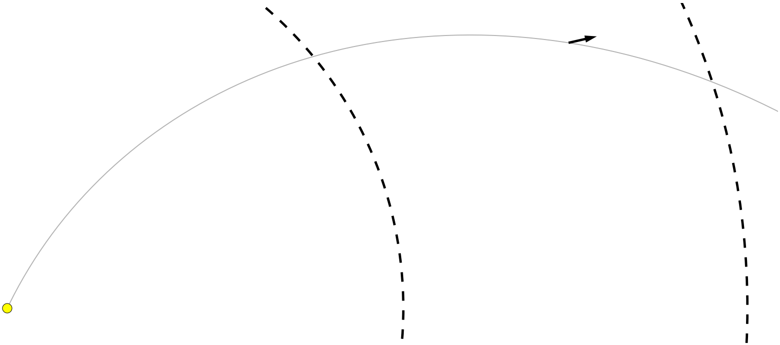

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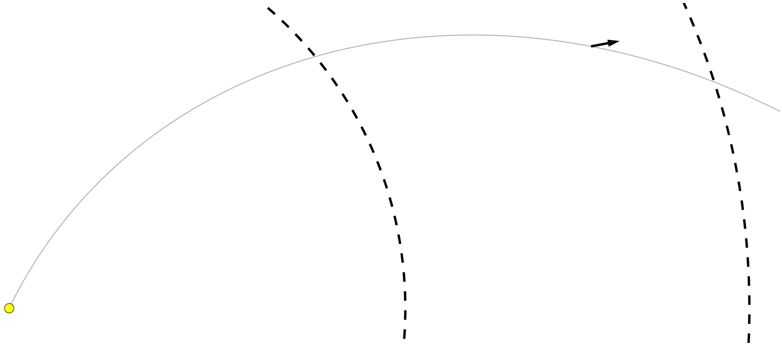

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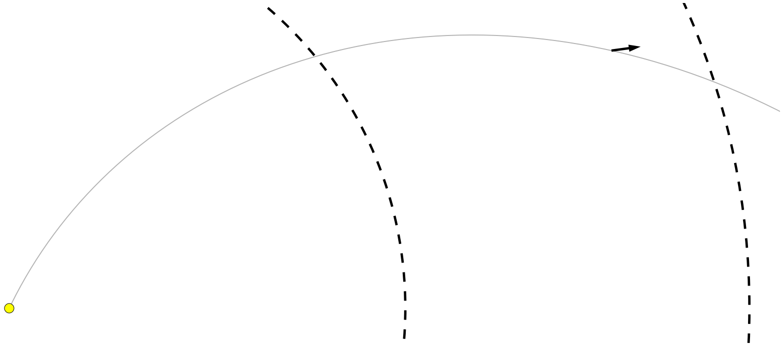

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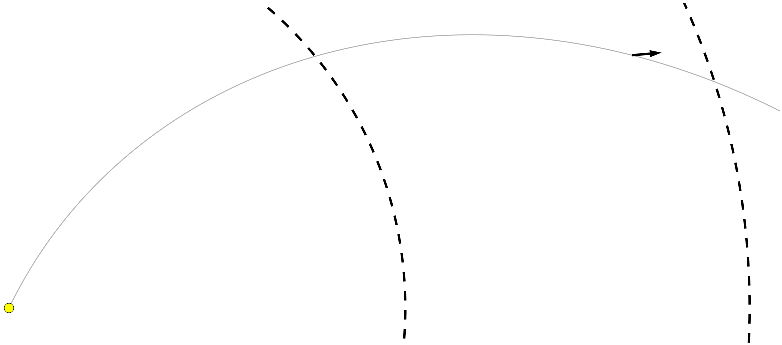

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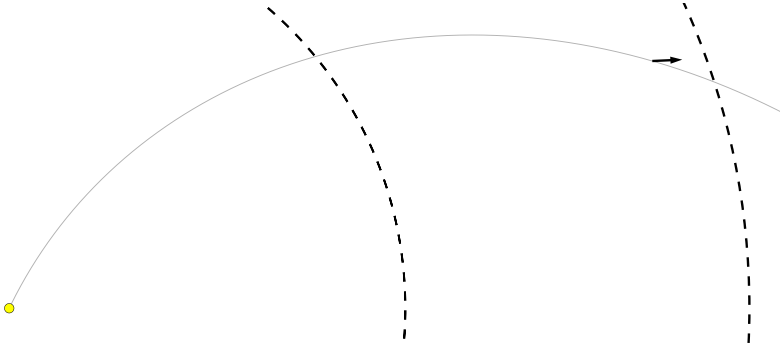

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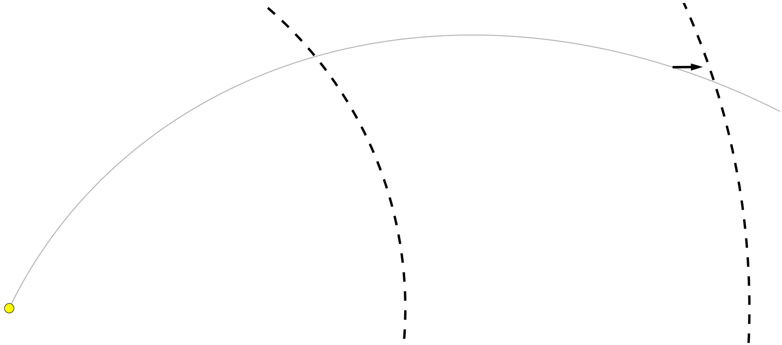

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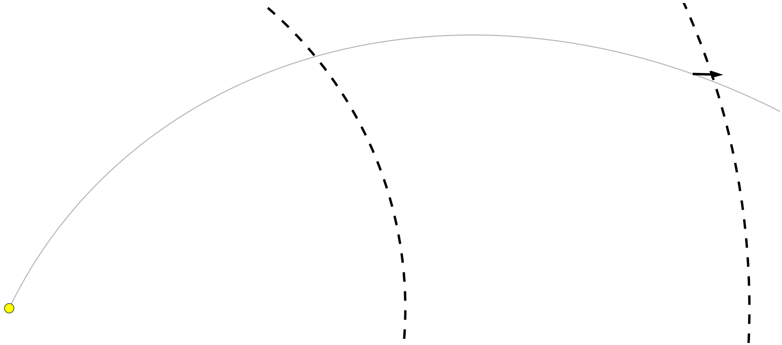

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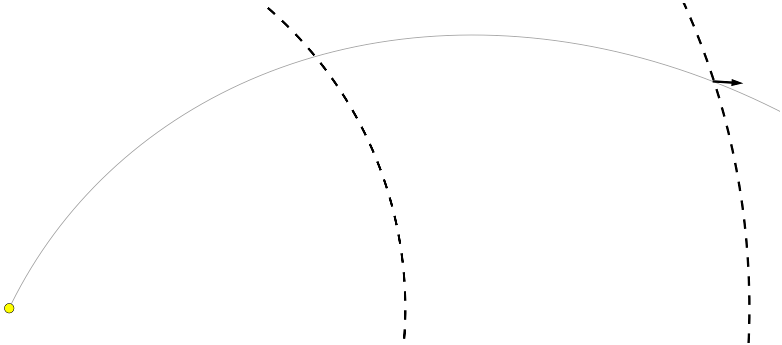

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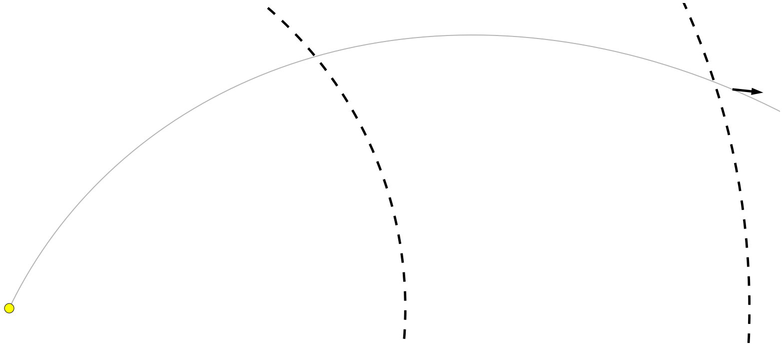

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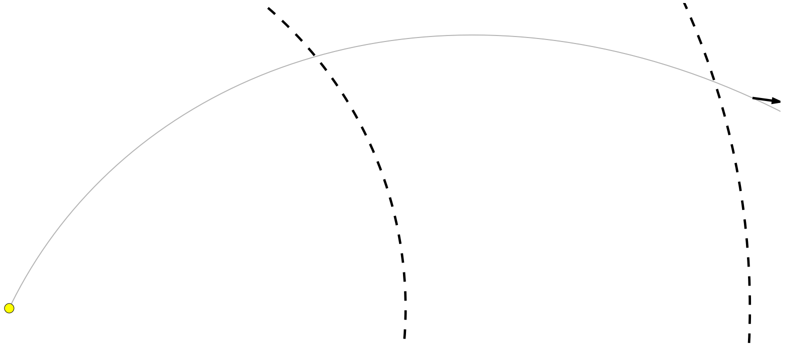

Problem

Consider $B \propto R^{-2}$

consider a particle at Venus with $\mu = -0.95$

at what distance will it sent back?

what is the minimum $|\mu|$ for a particle, sent from Mars towards the Sun, to reach the orbit of Mercury?

Orbit of Mercury: .38709821 AU. Orbit of Mars: 1.52366231 AU.

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Particles are subject to small-angle scatterings off magnetic turbulence.

Kinetic approach (Kocharov 1998), parametrized by a mean free path λ, isotropic scattering, scattering centers frozen in the solar wind.

- a time step is chosen such that the particle only travels a very small fraction if λ
- after each time step the position of the particle and its pitch angle are updated using only the effects of adiabatic focusing
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Focused transport with scattering.

Example:

- 50 electrons, with 100 keV, released from 3 Rs in ecliptic plane
- outward motion, initial μ uniform in]0,1[
- spiral magnetic field (solar wind 400 km/s)
- magnetic field intensity varying as R^{-2}
- constant mean free path $\lambda = 1$ AU

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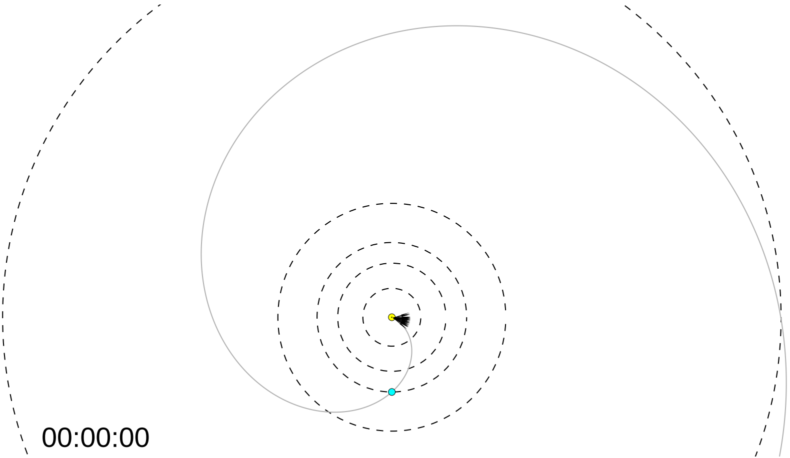
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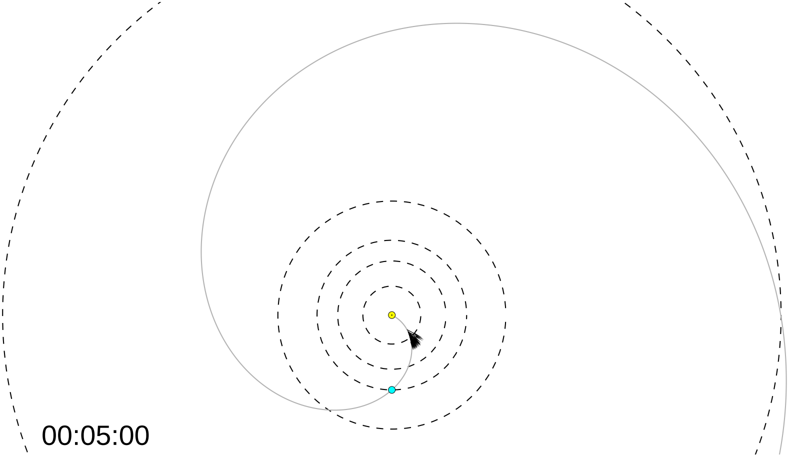
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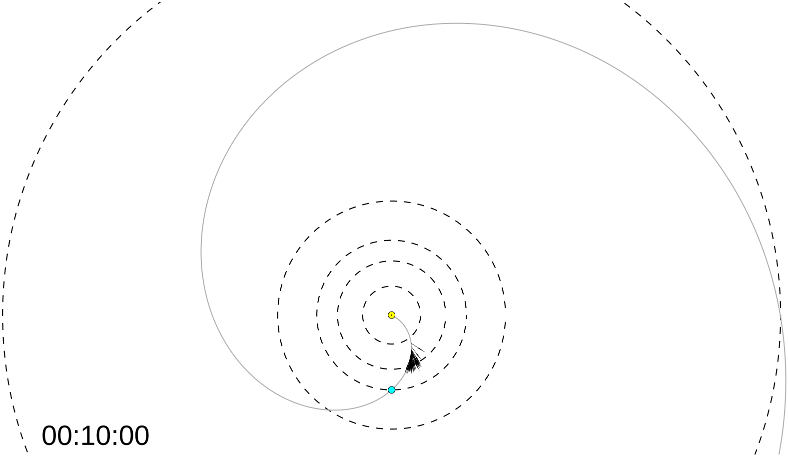
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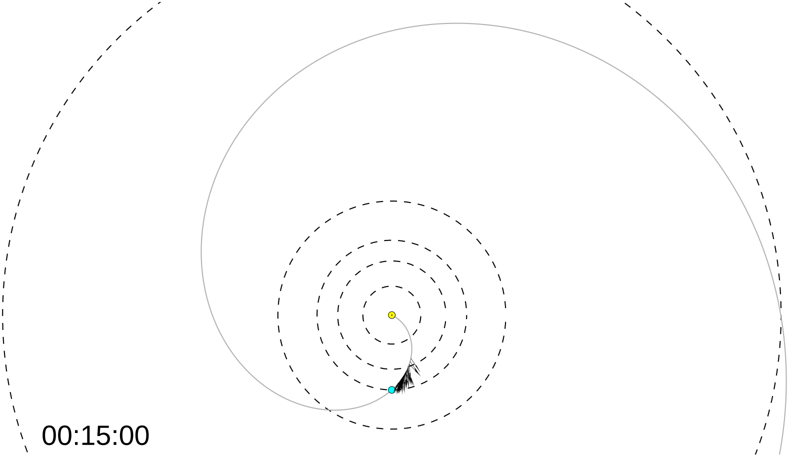
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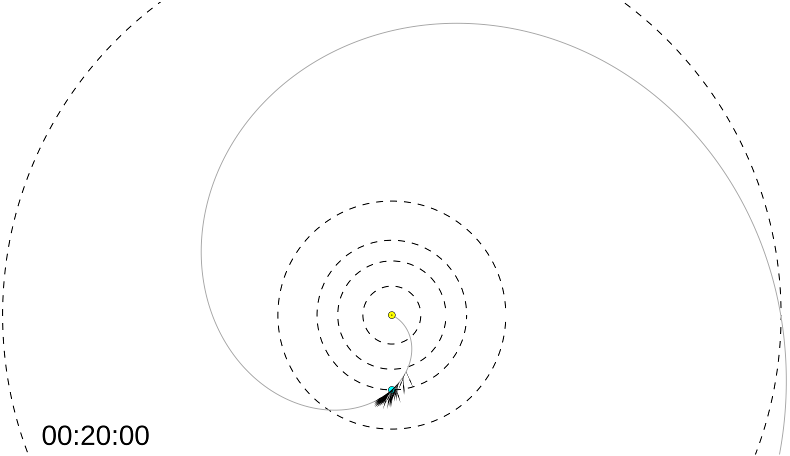
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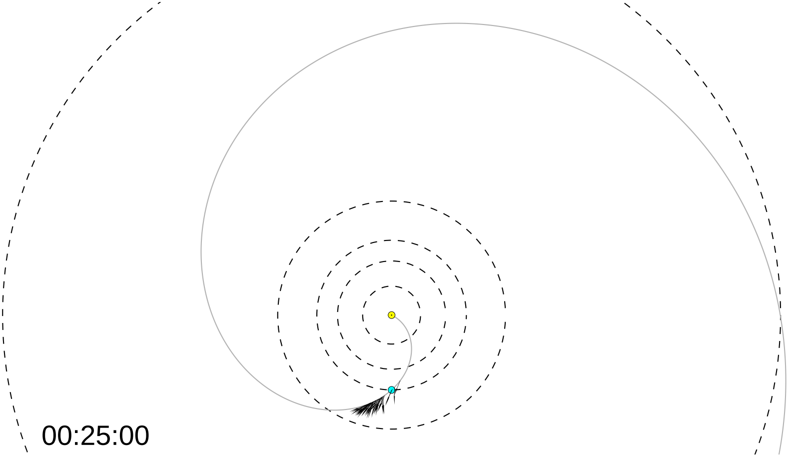
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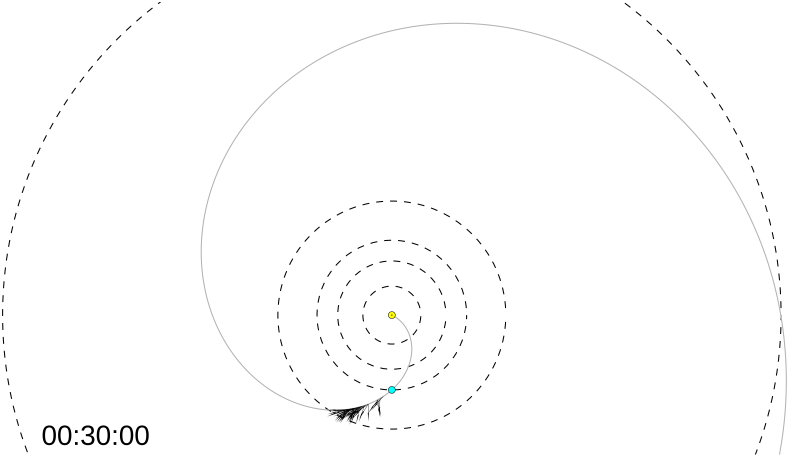
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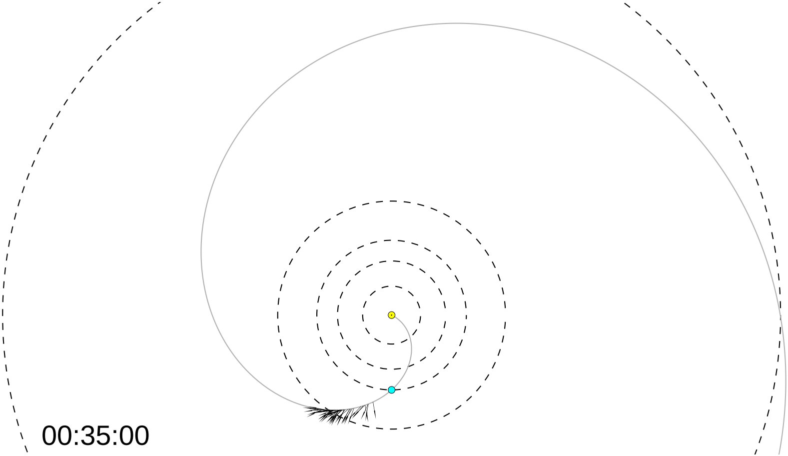
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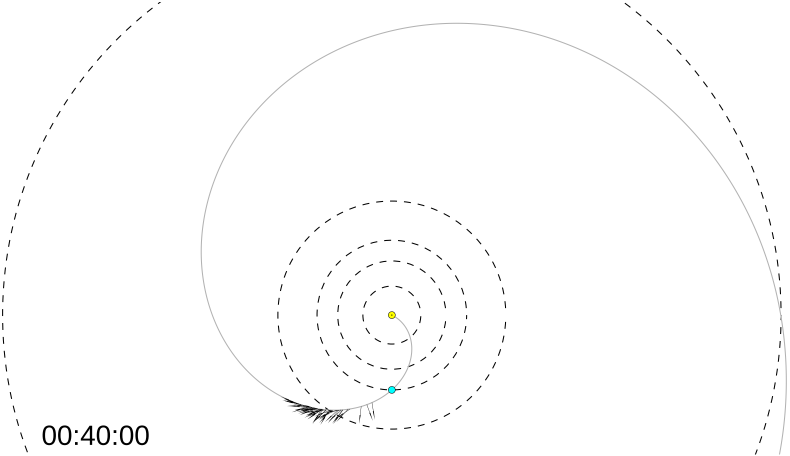
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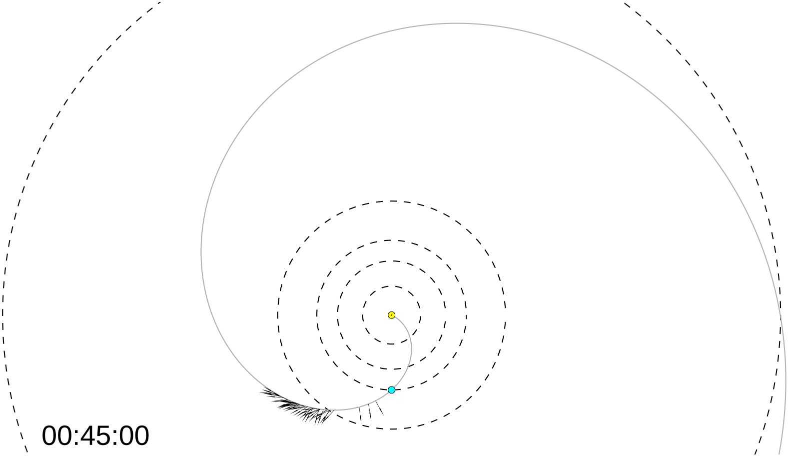
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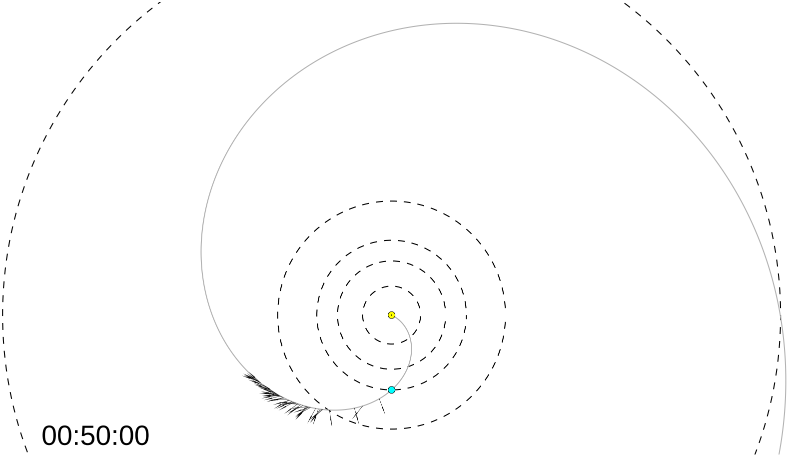
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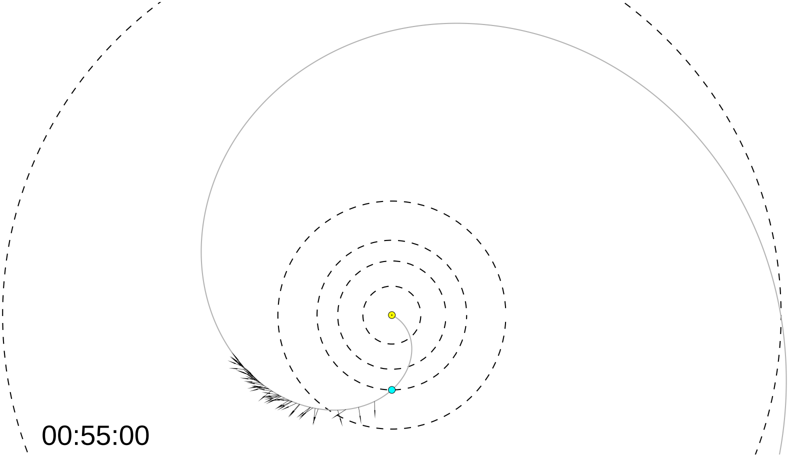
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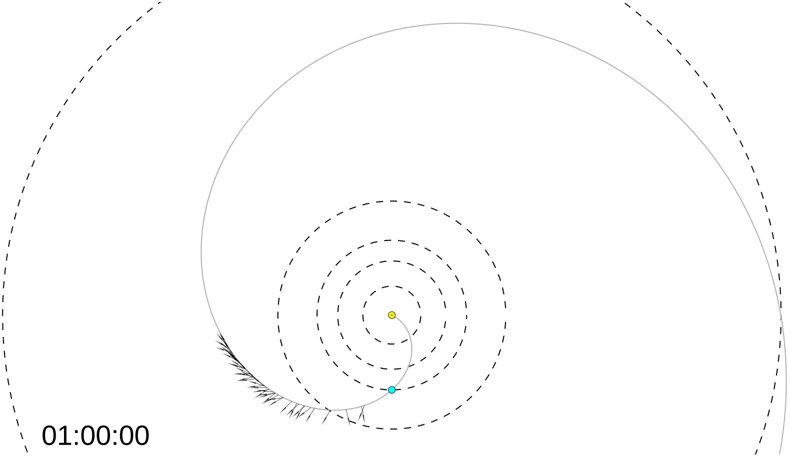
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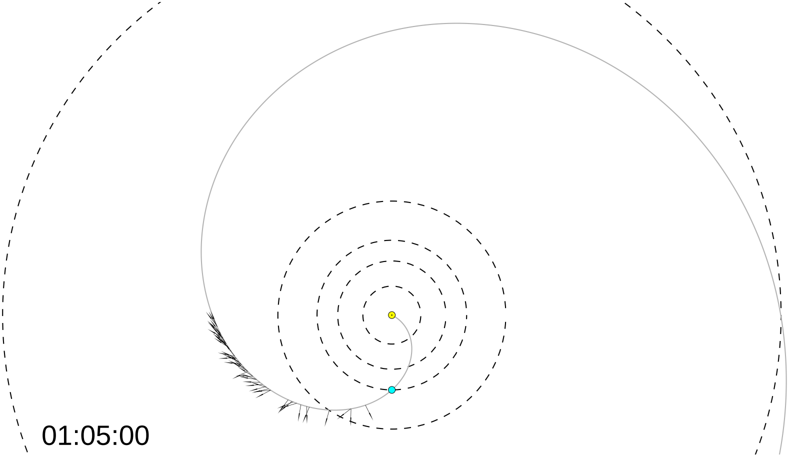
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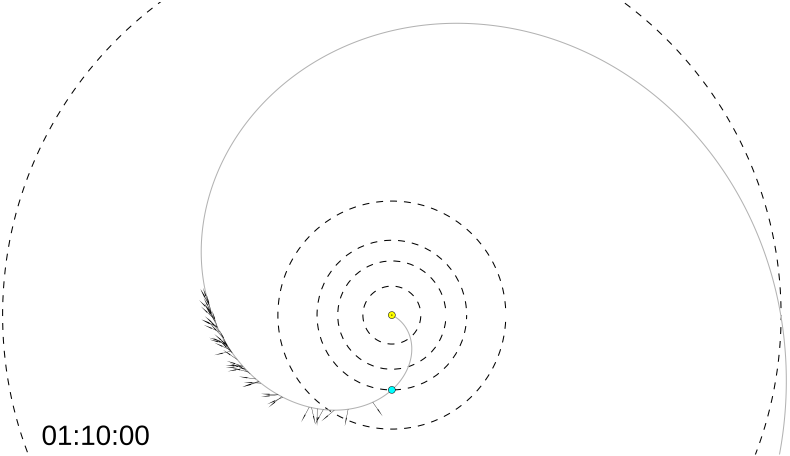
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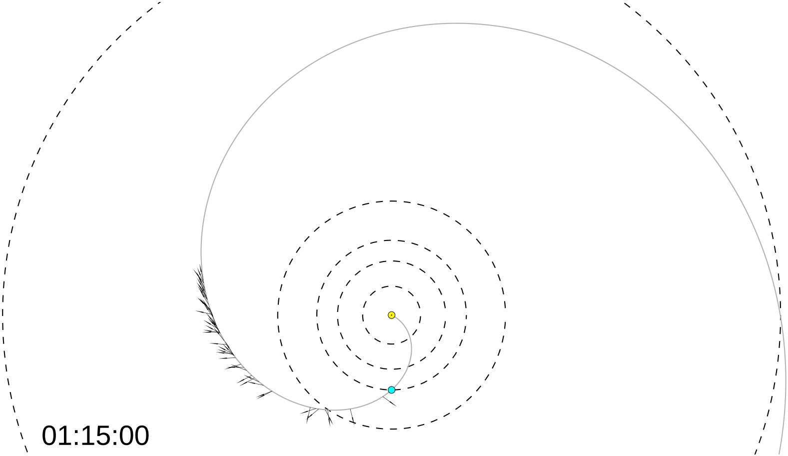
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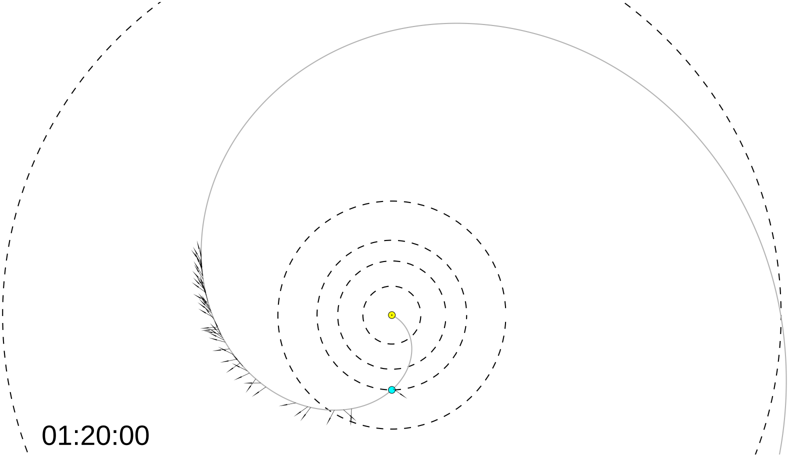
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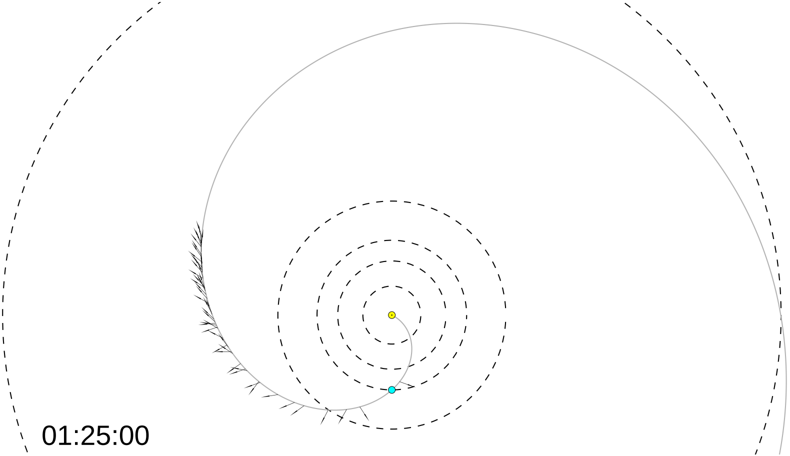
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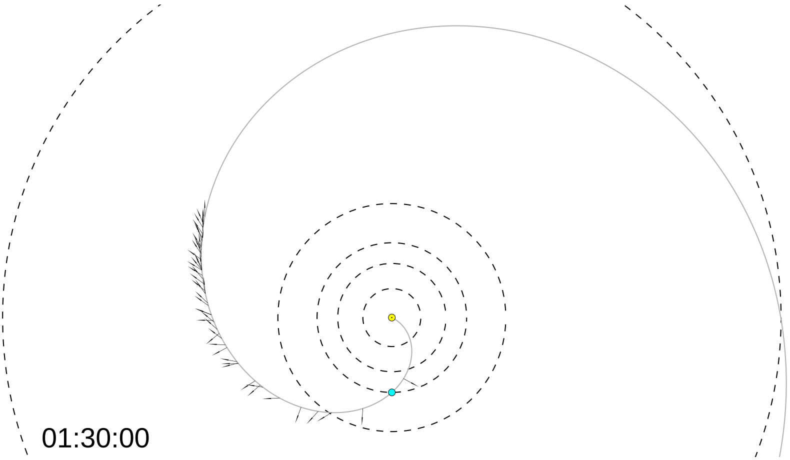
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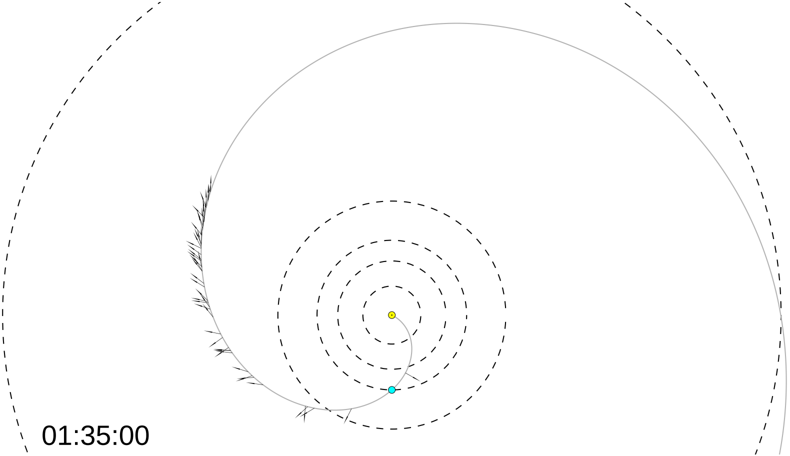
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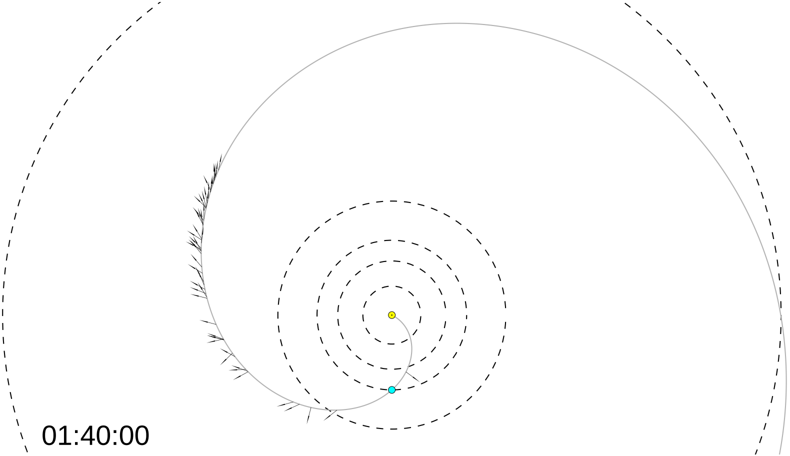
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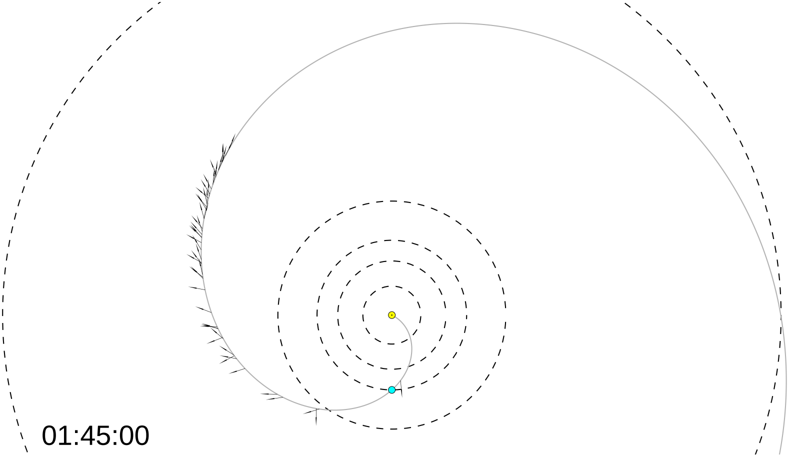
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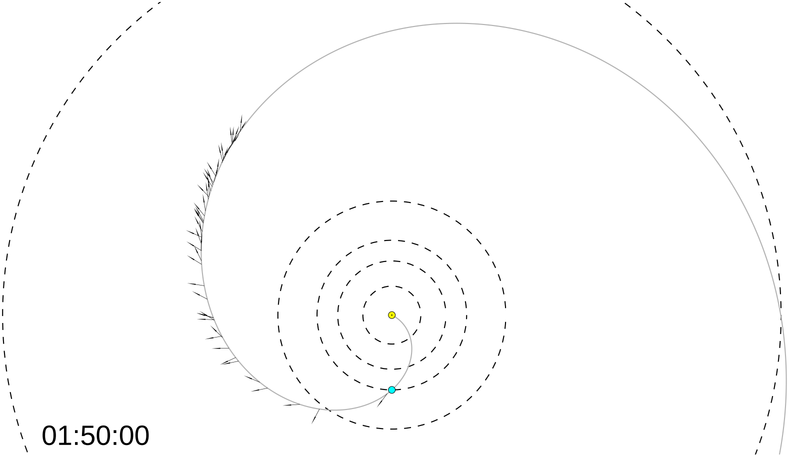
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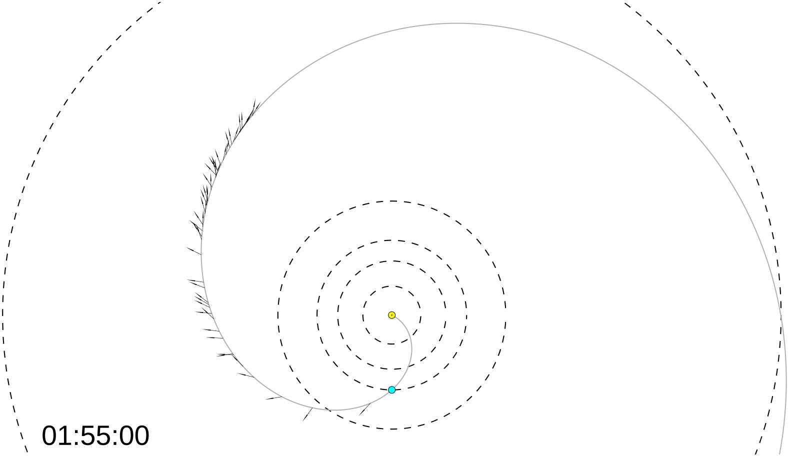
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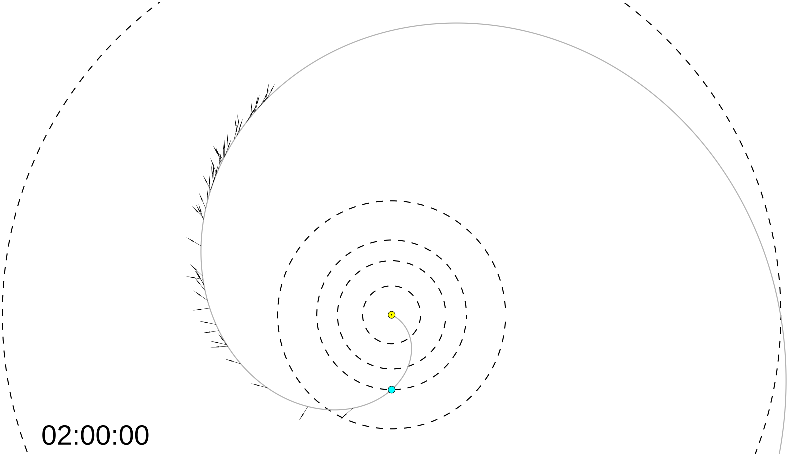
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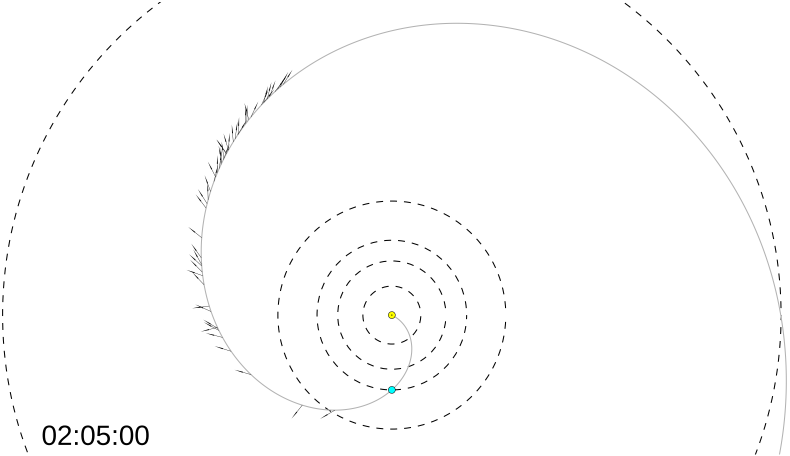
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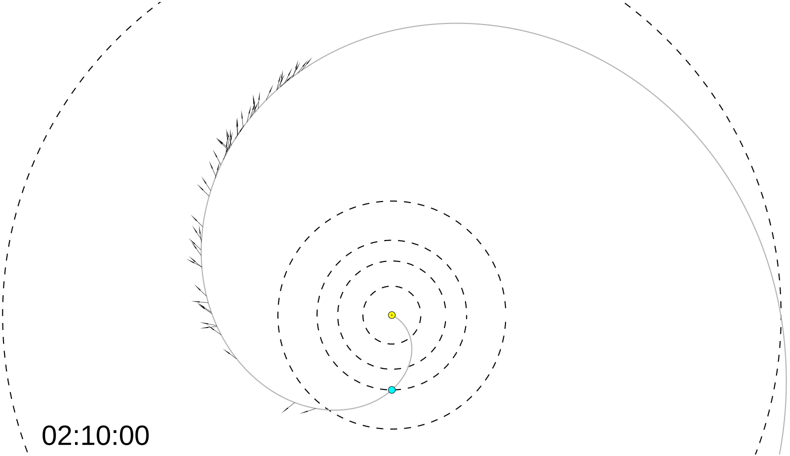
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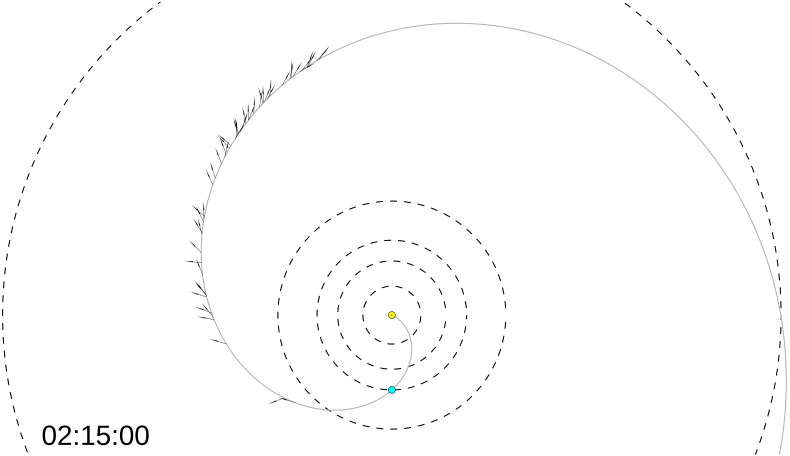
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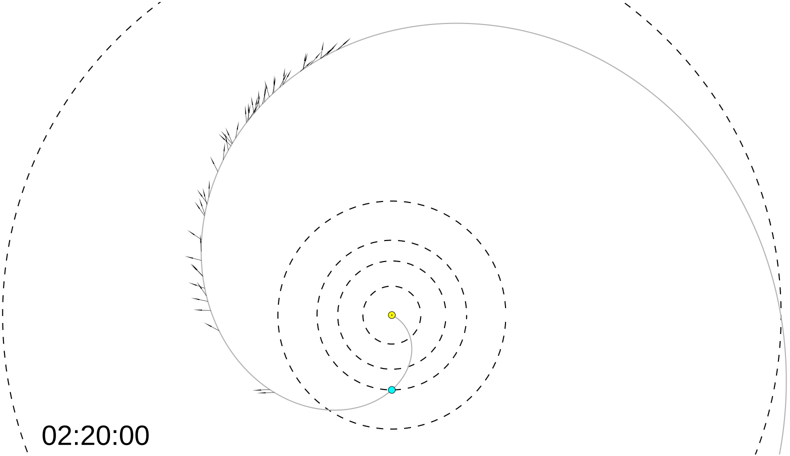

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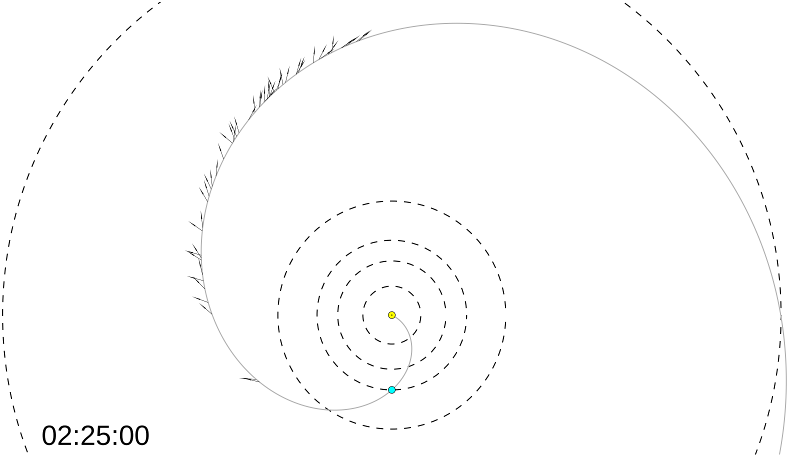
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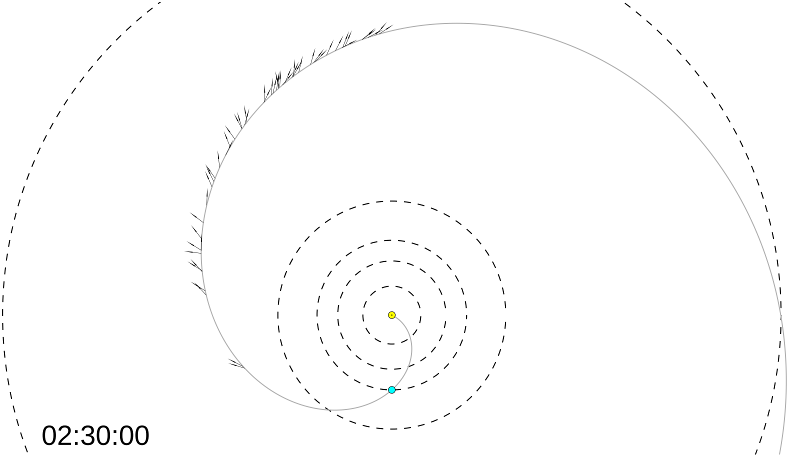
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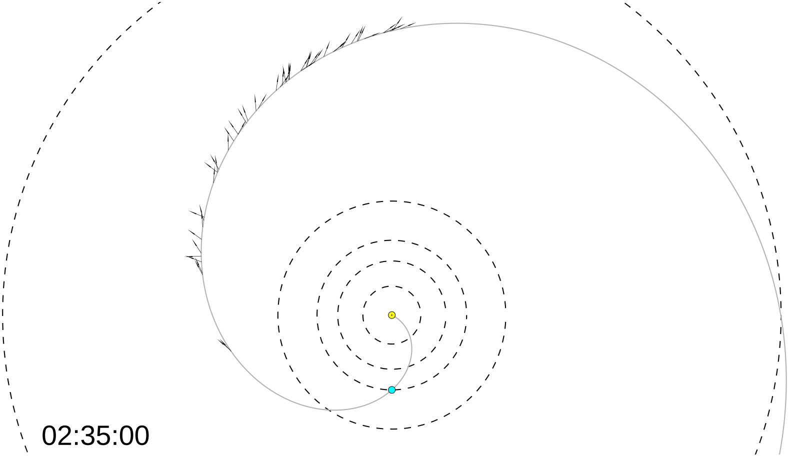
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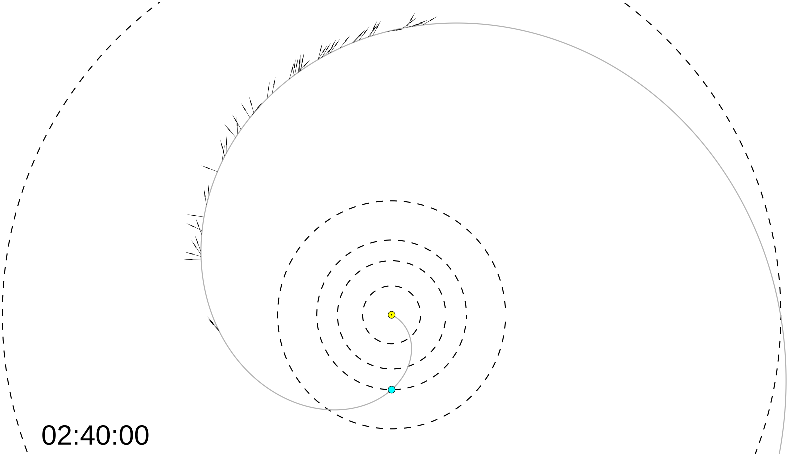
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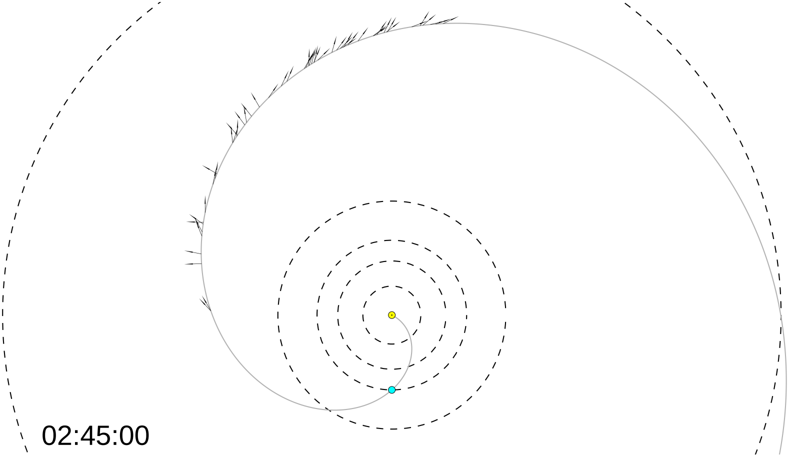
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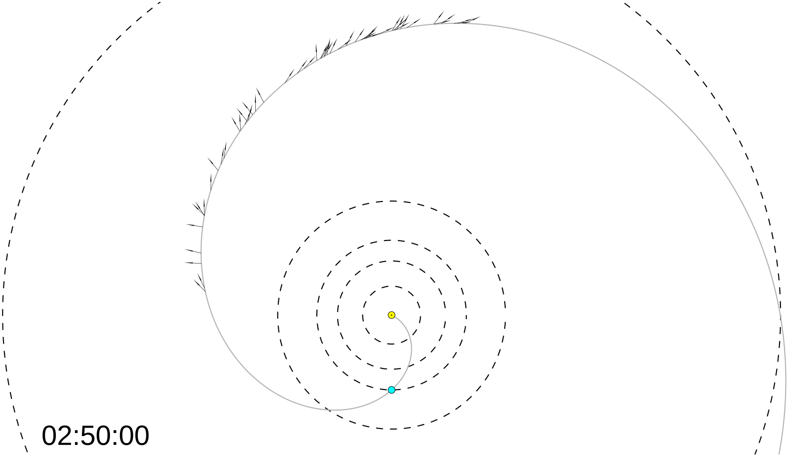
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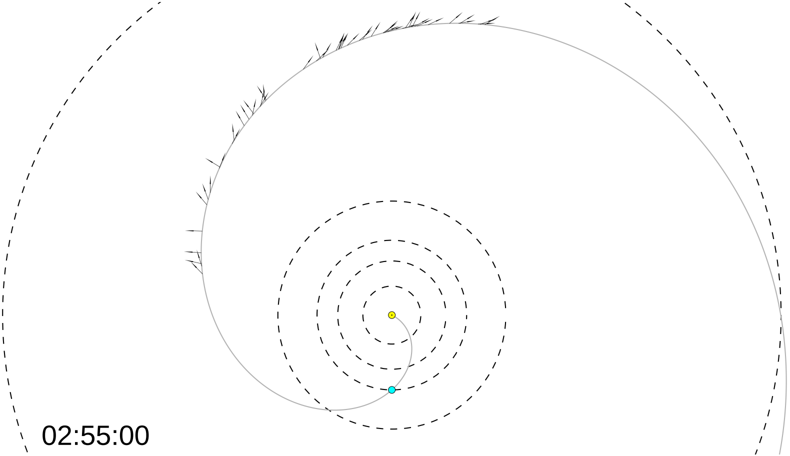
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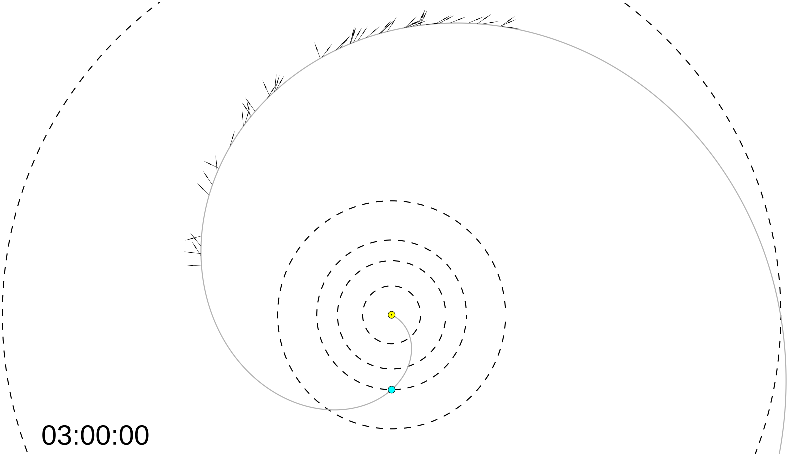

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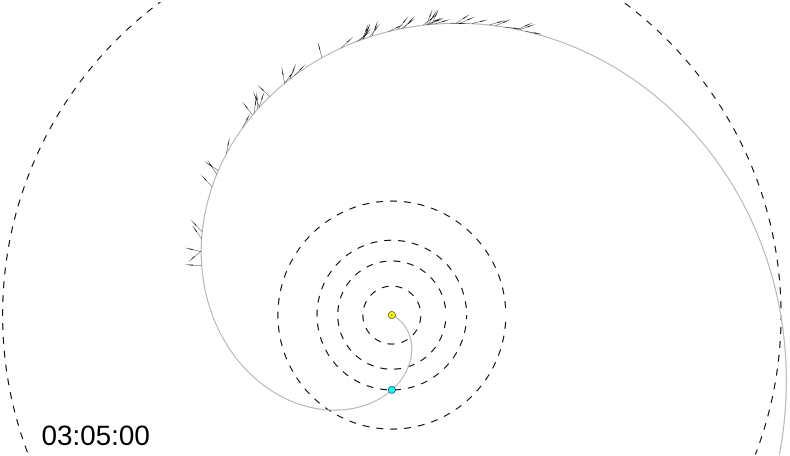
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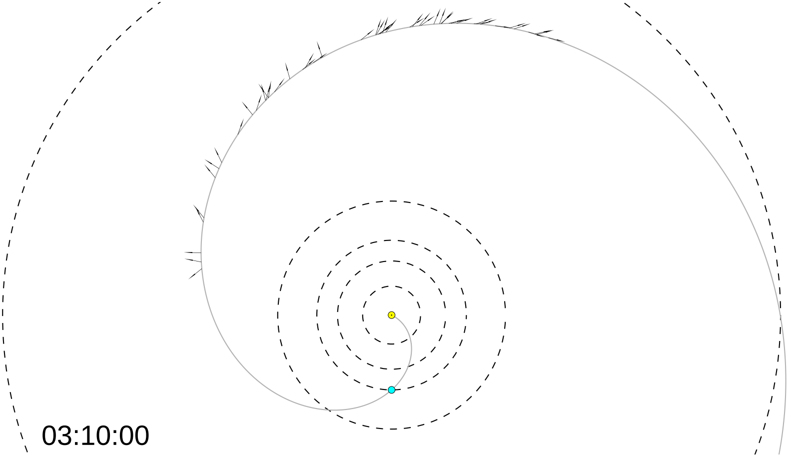
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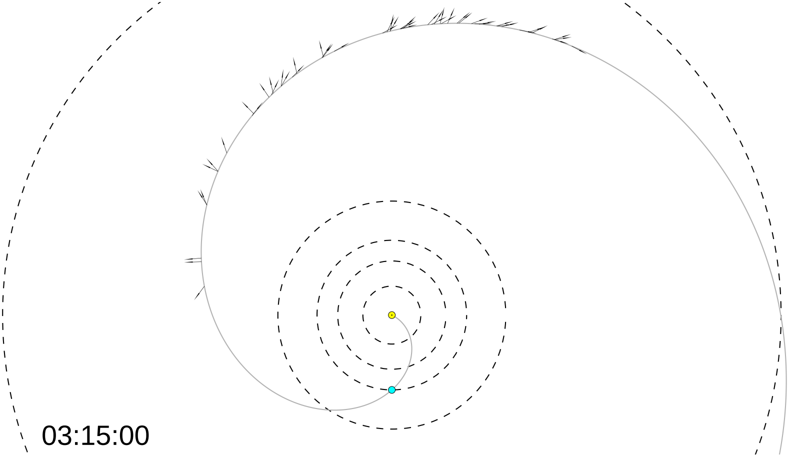
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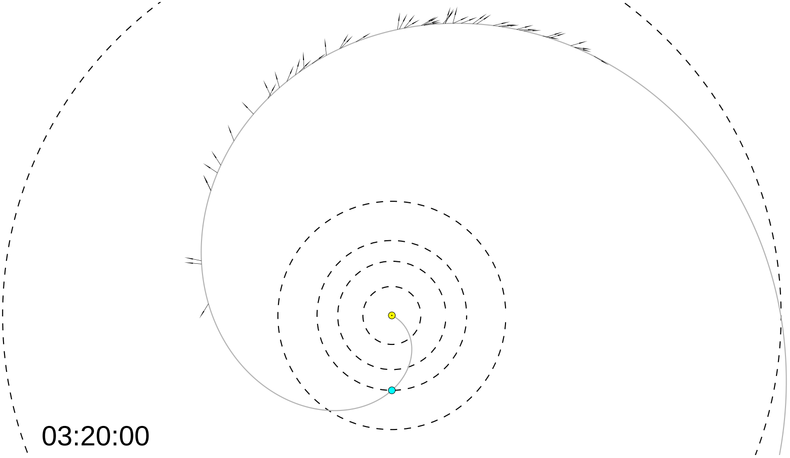
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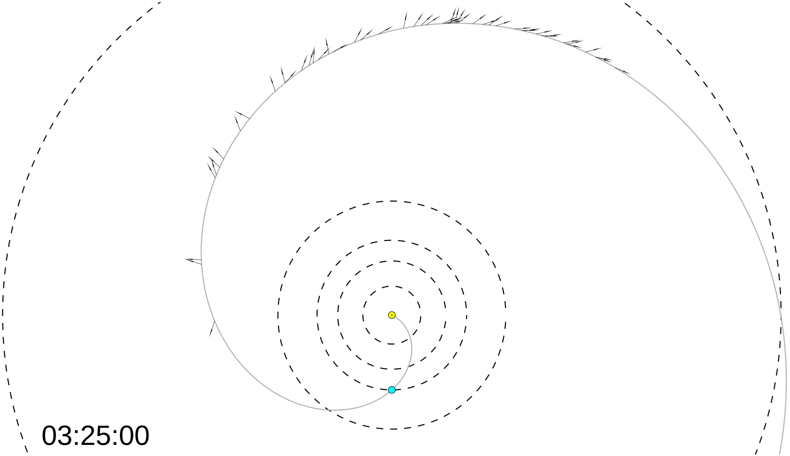
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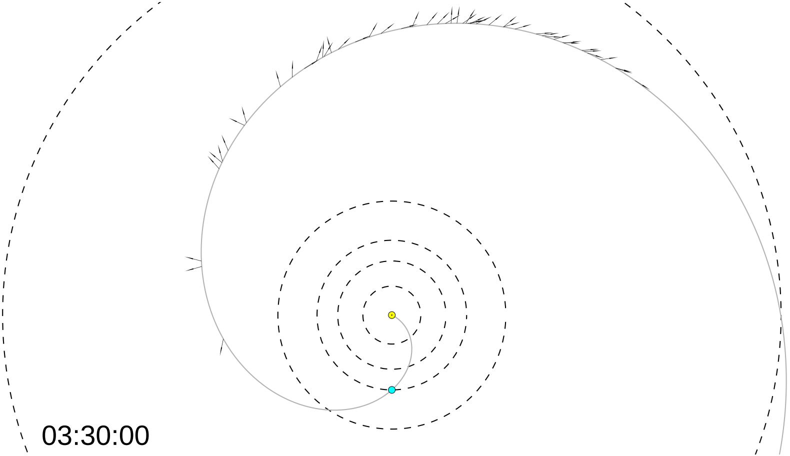
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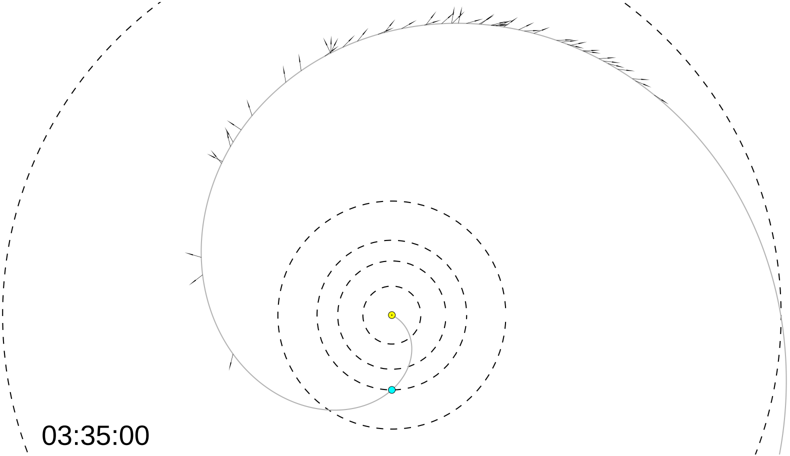
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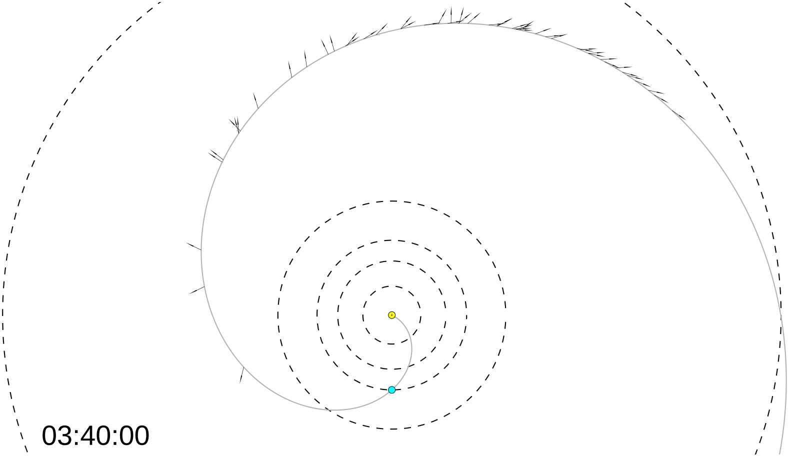
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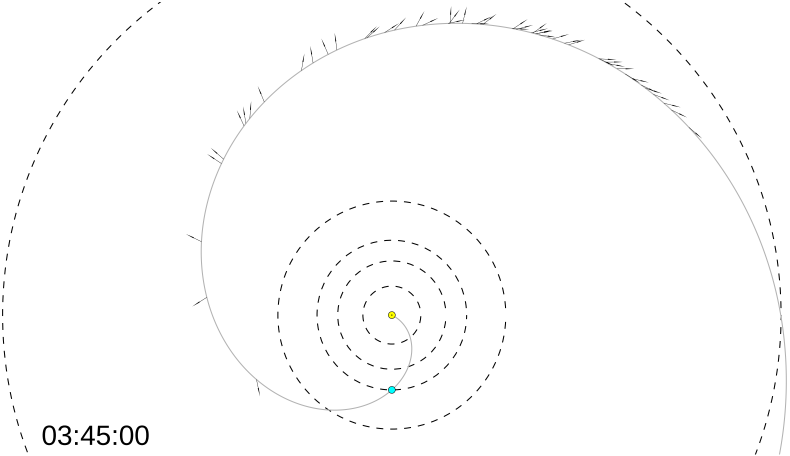
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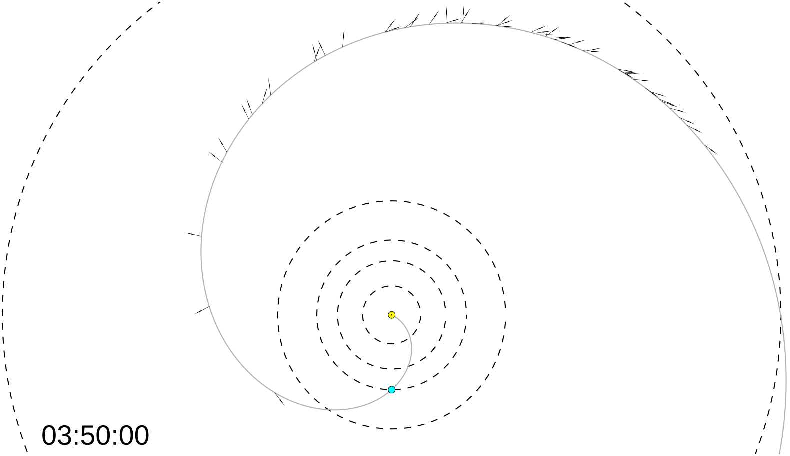
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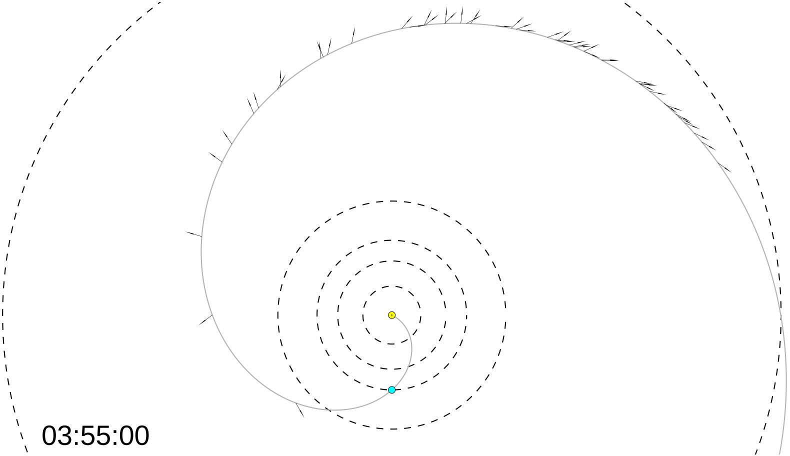
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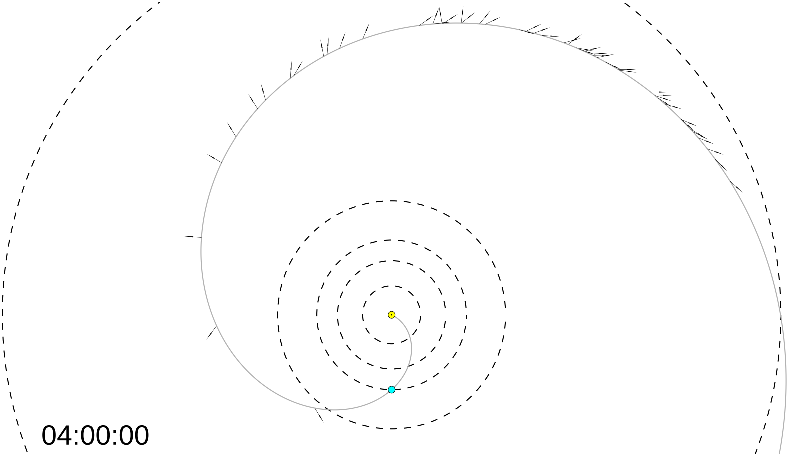
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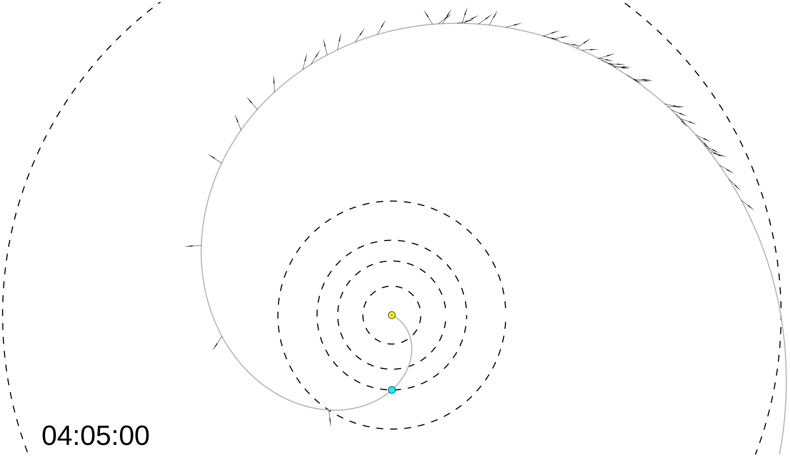
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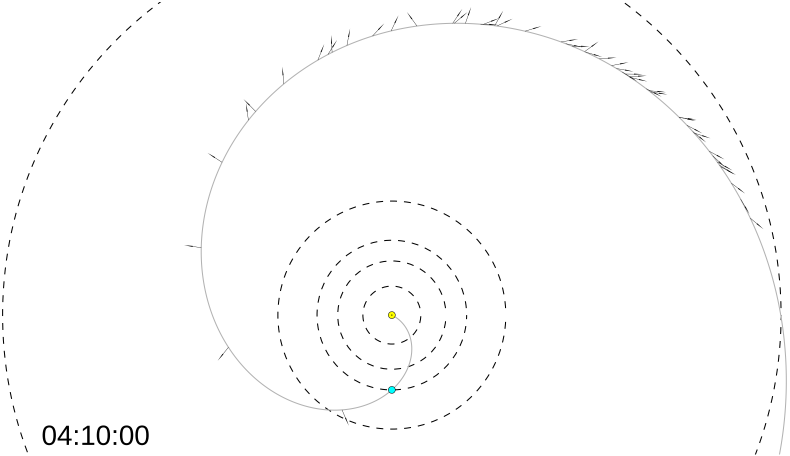

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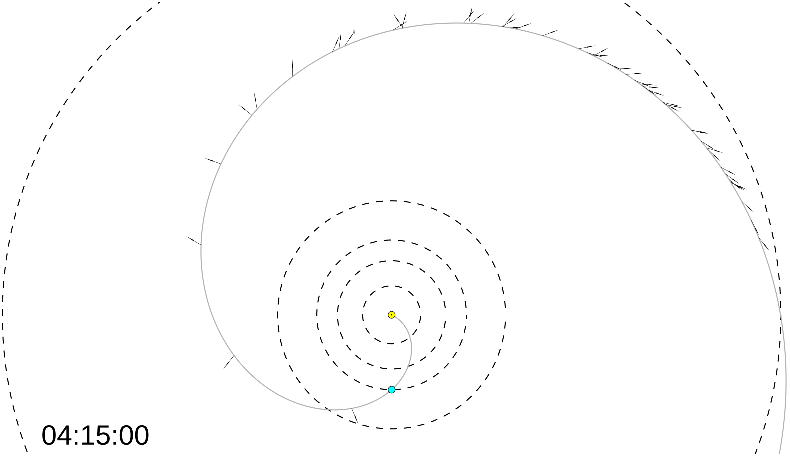
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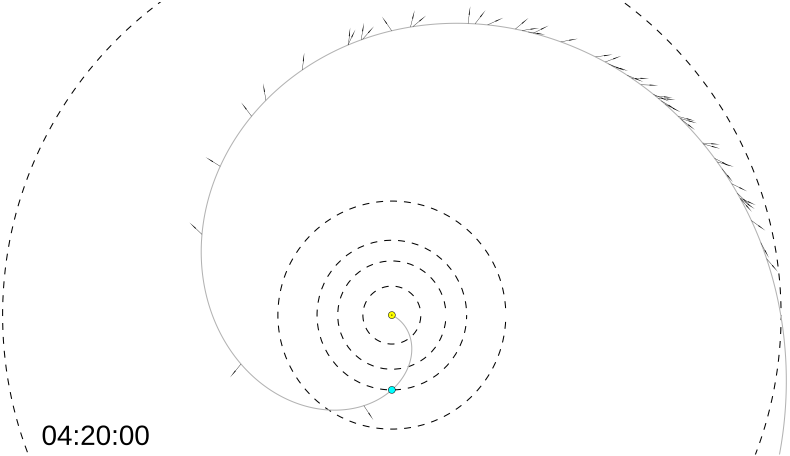
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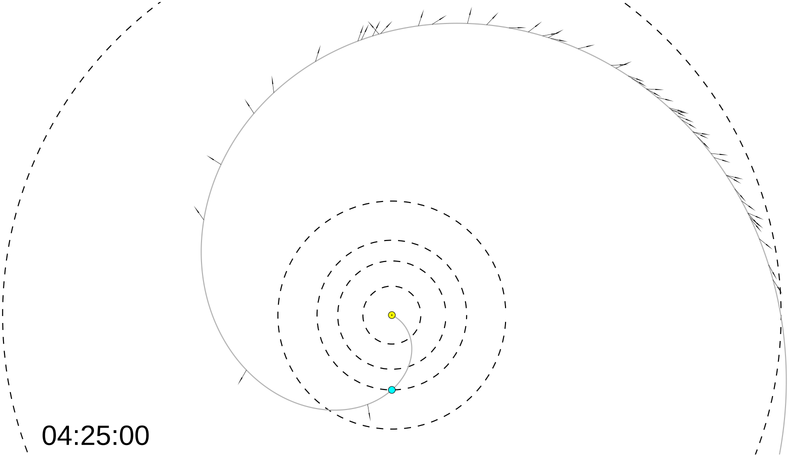
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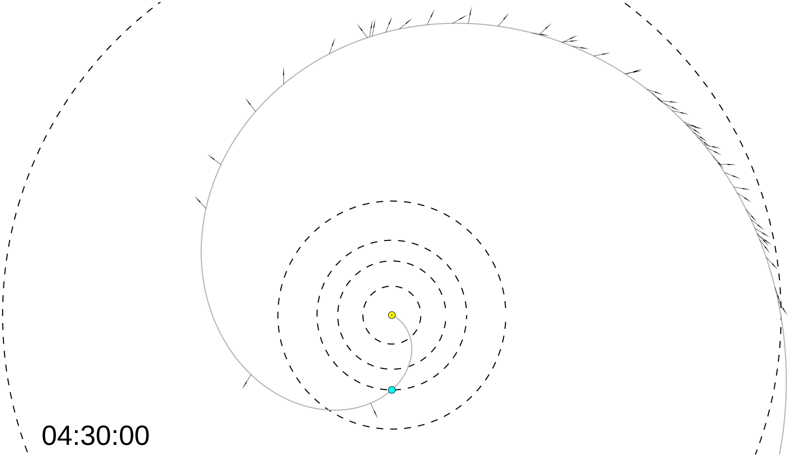
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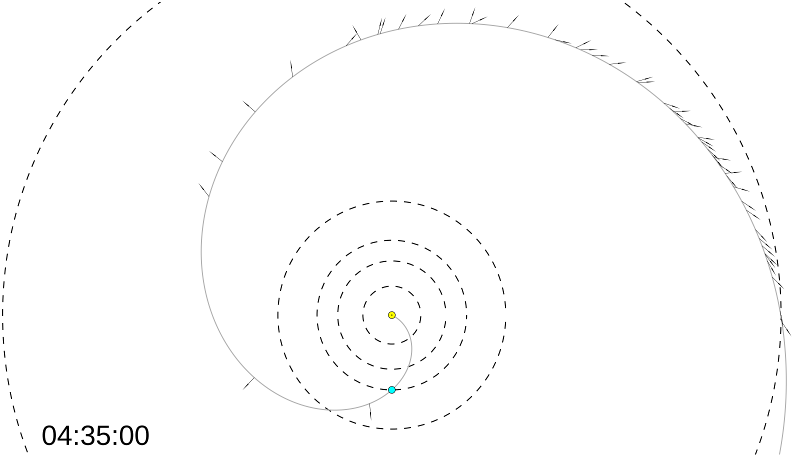
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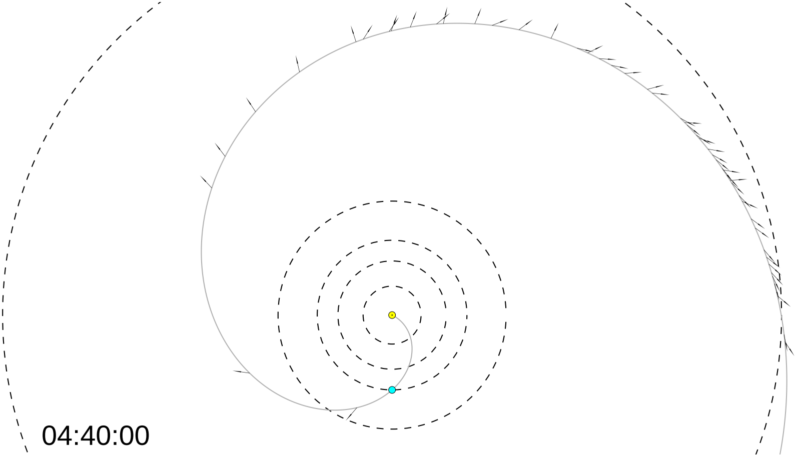
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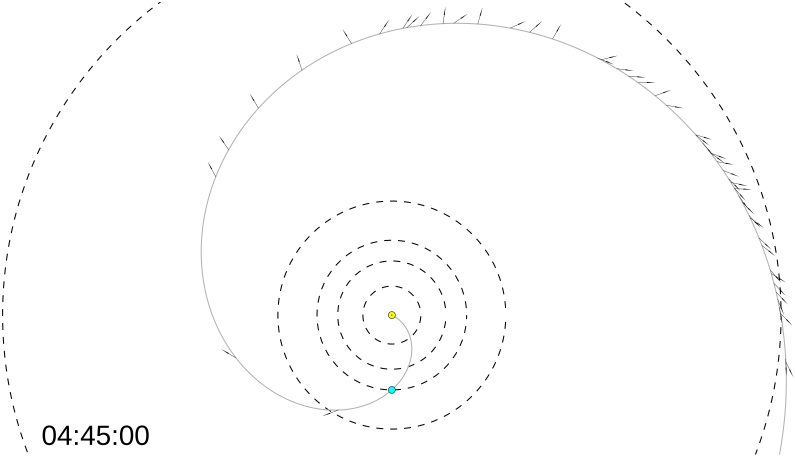
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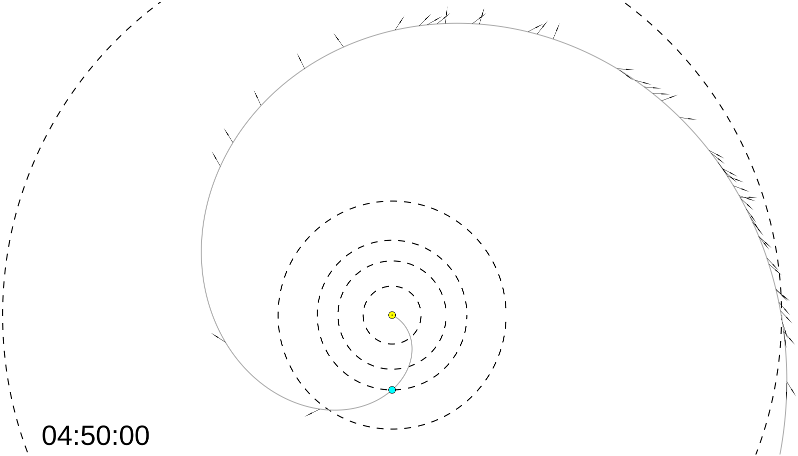
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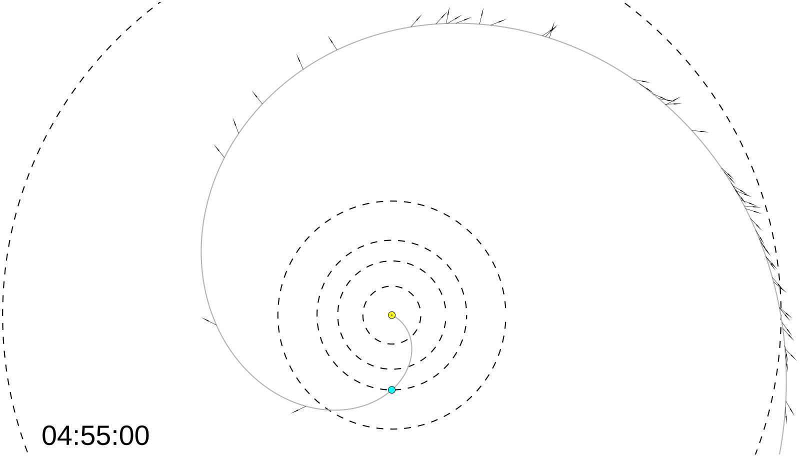
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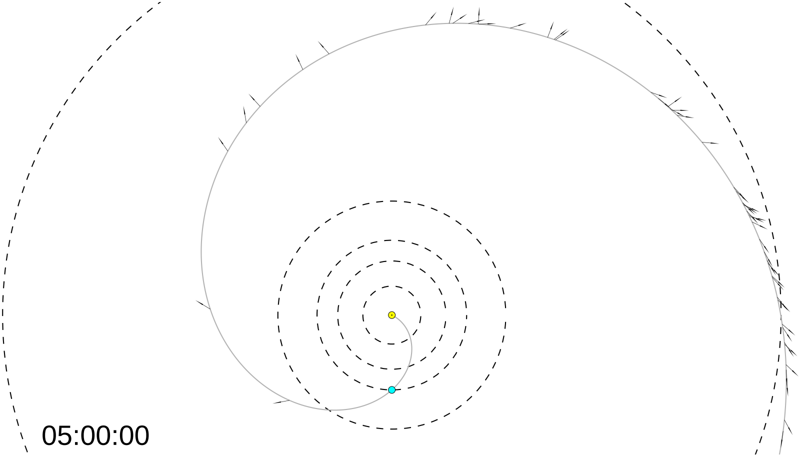
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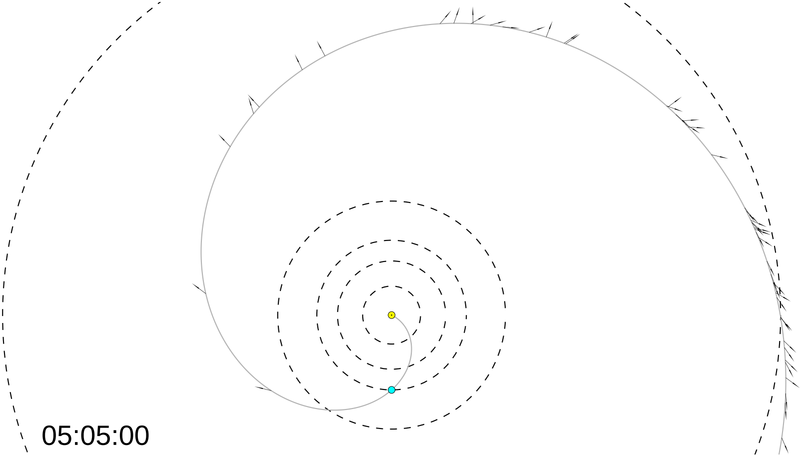
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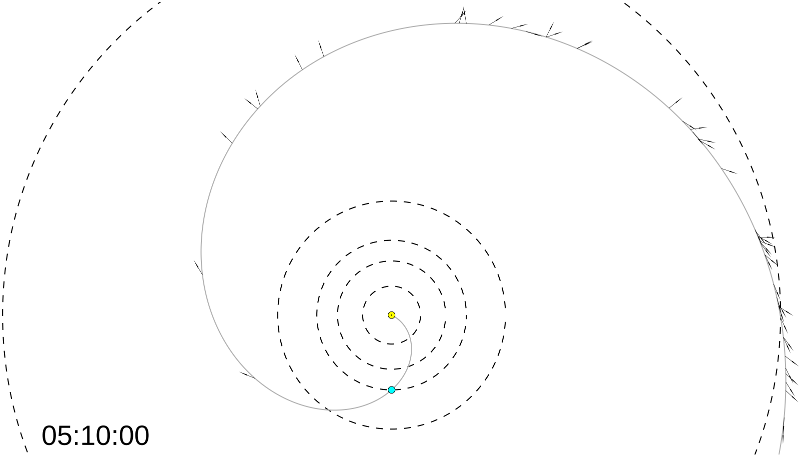
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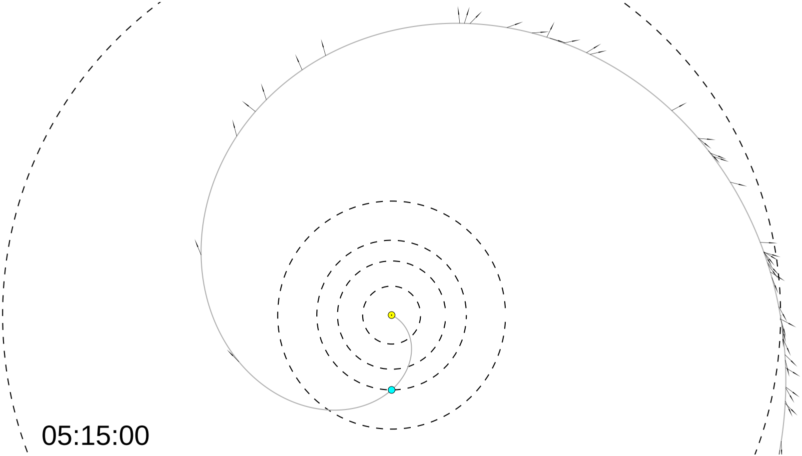
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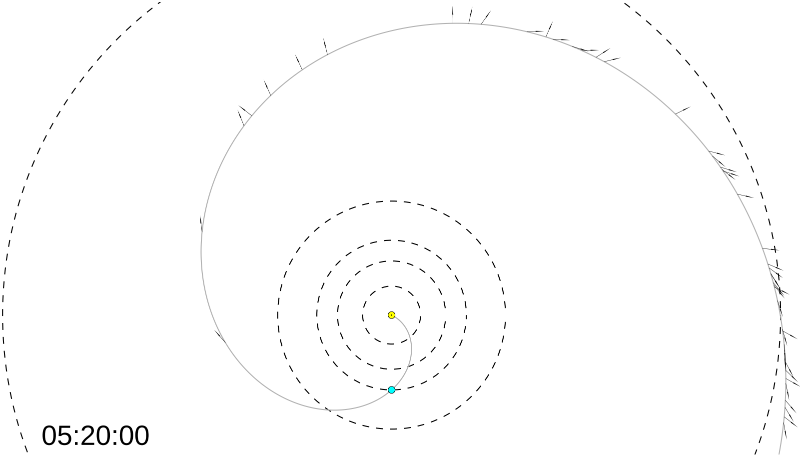
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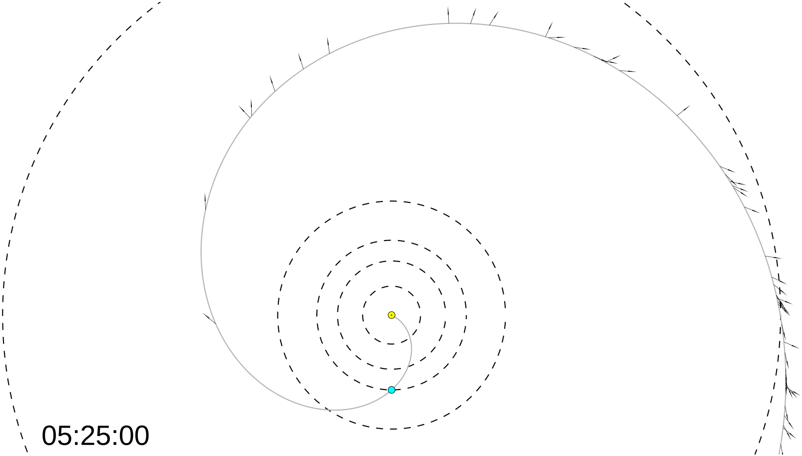
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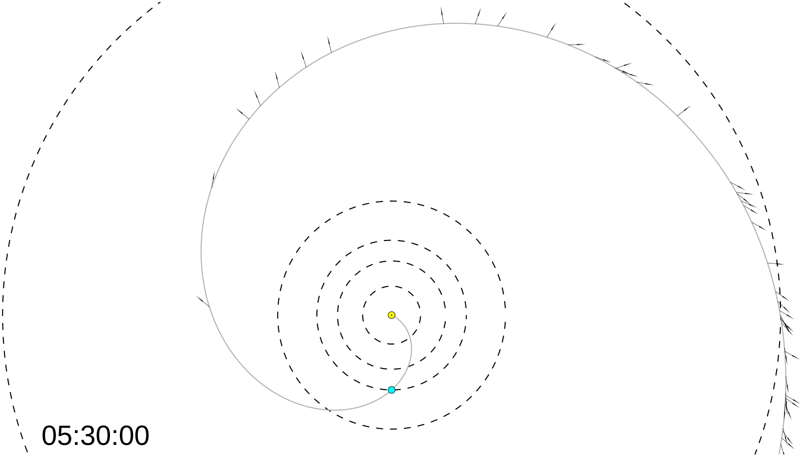
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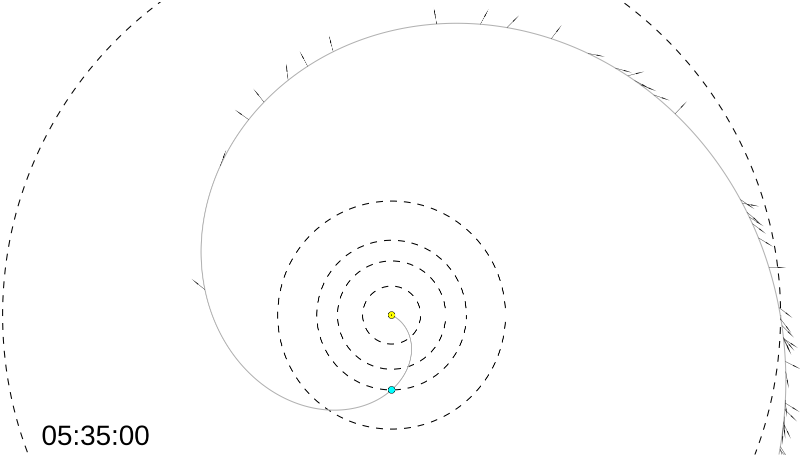
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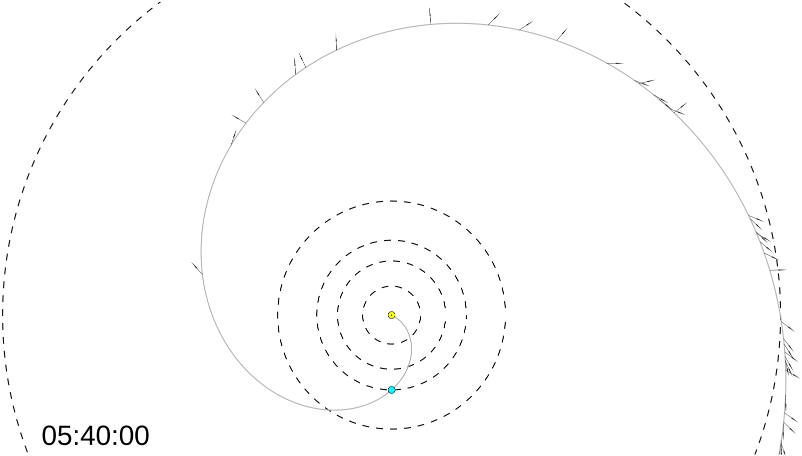
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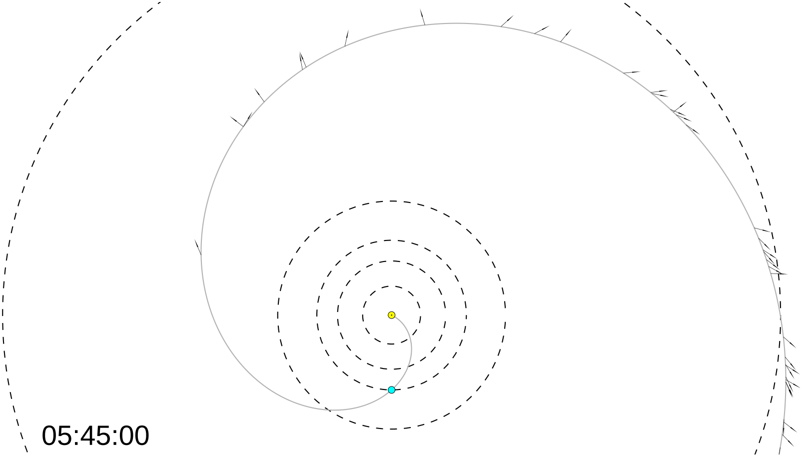
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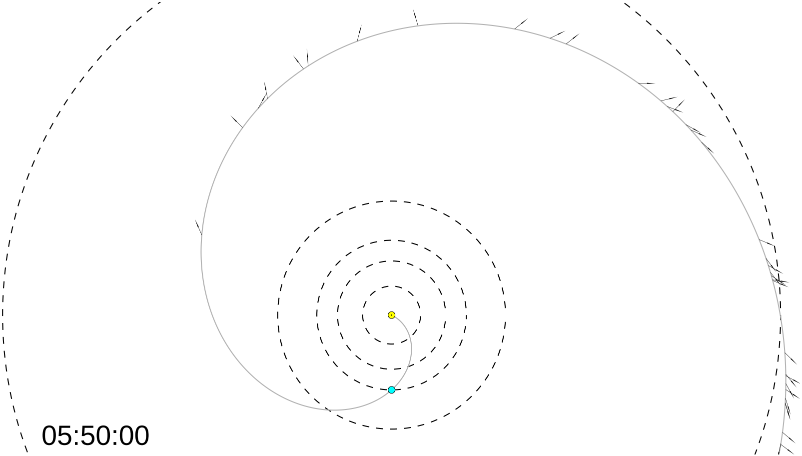
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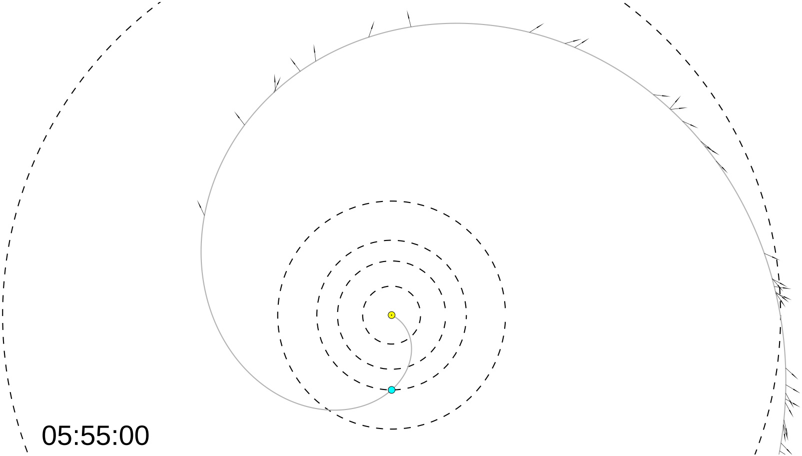
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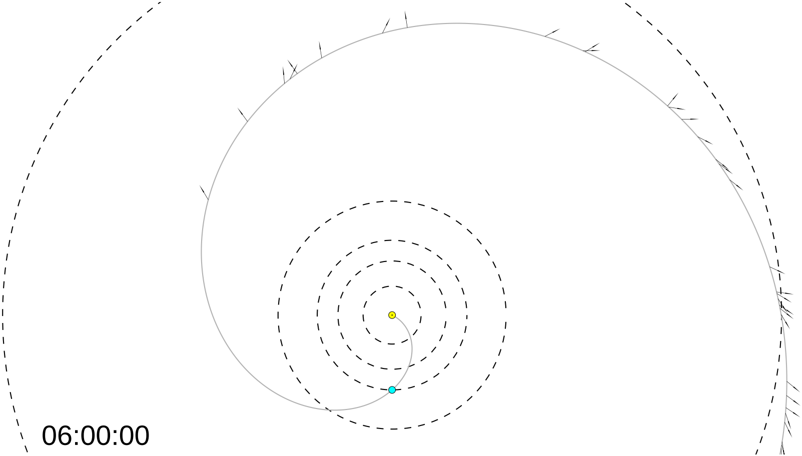
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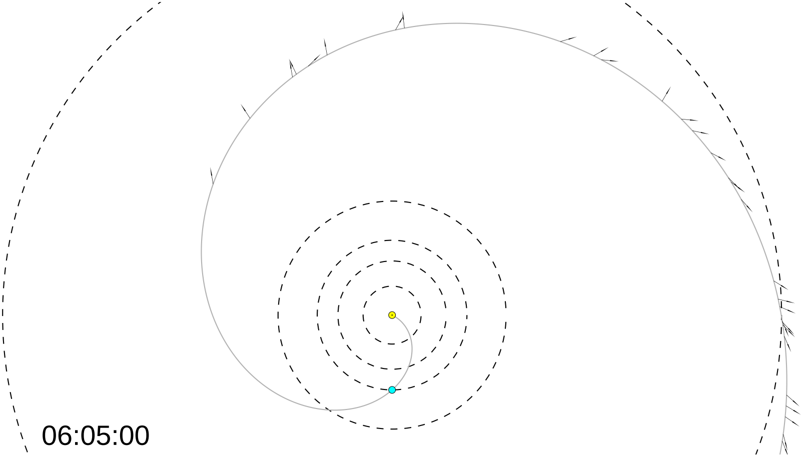
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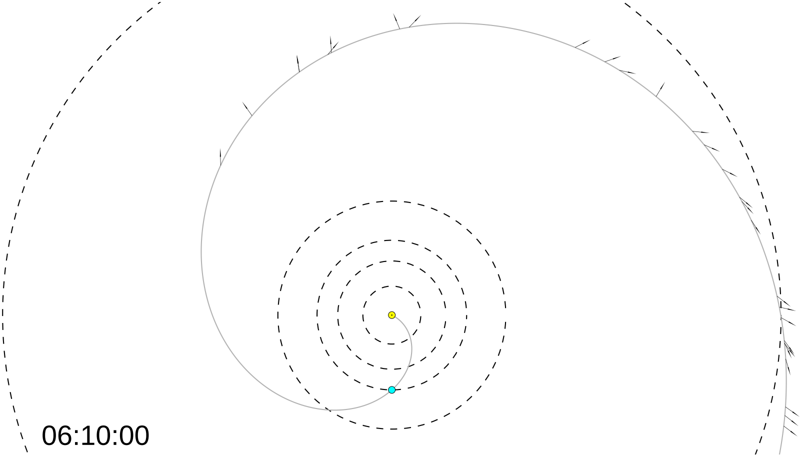
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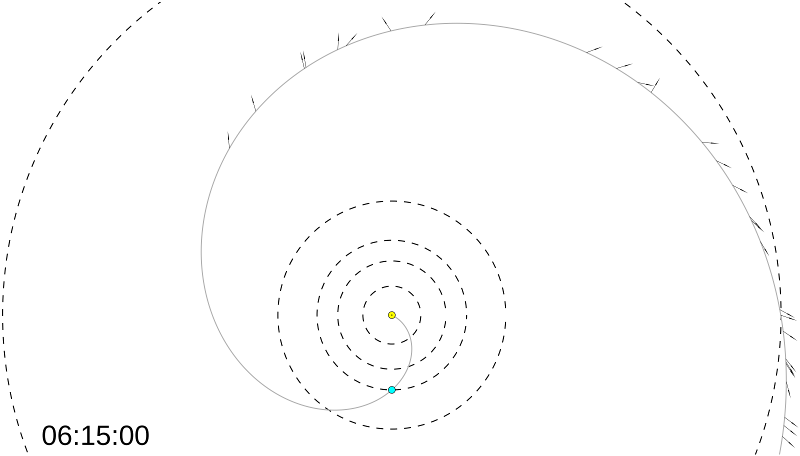
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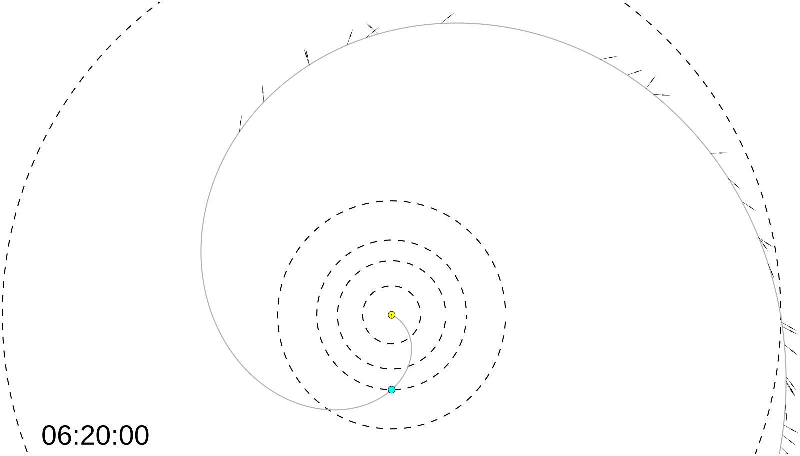

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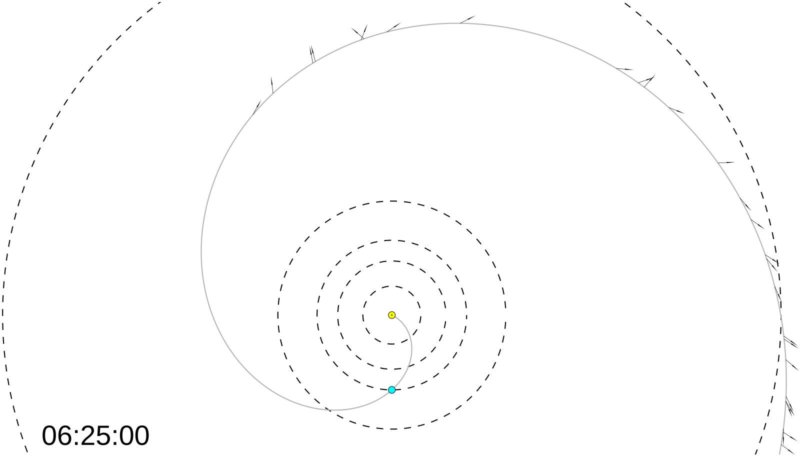
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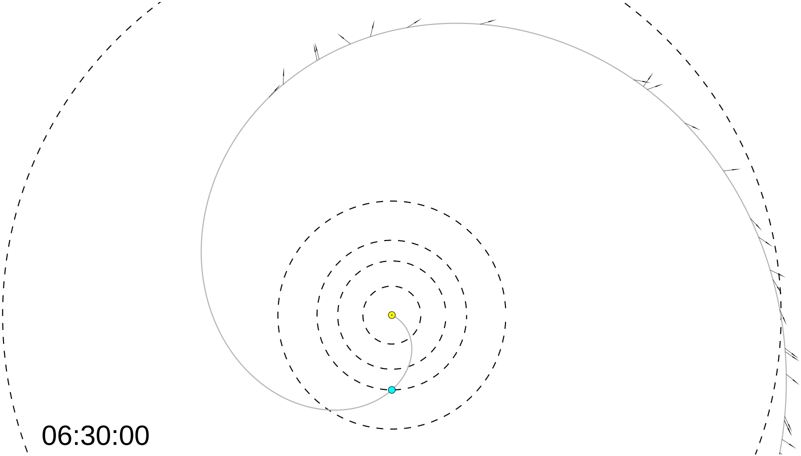

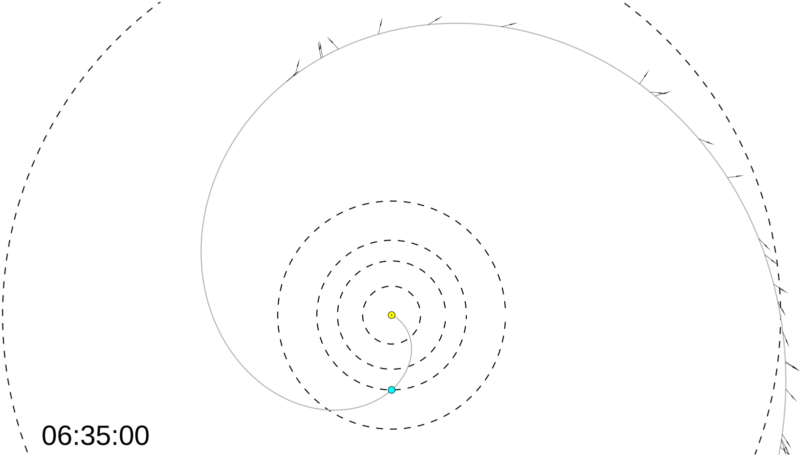
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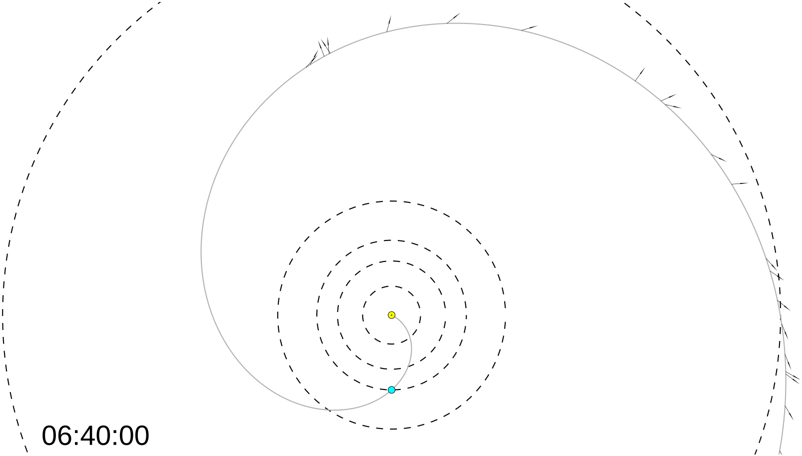
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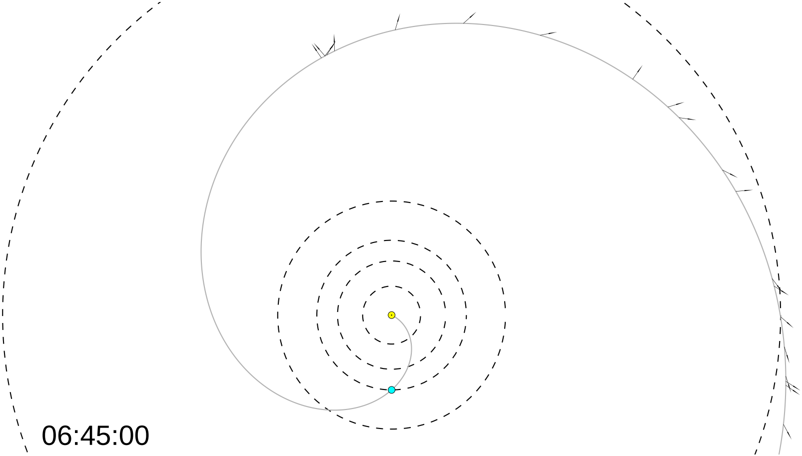
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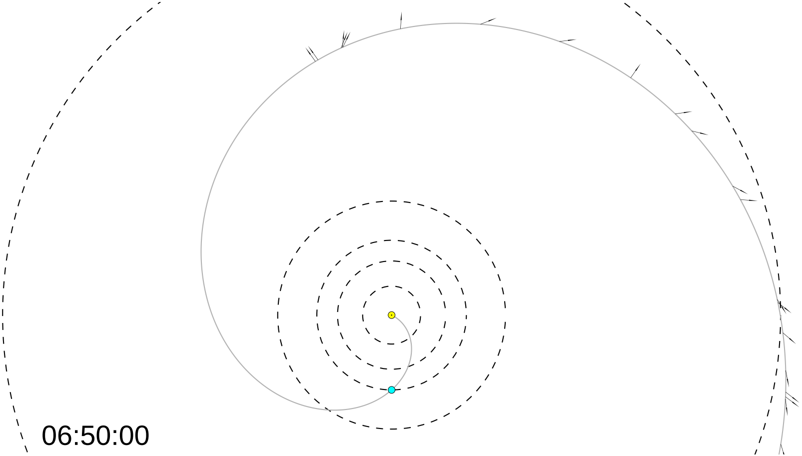
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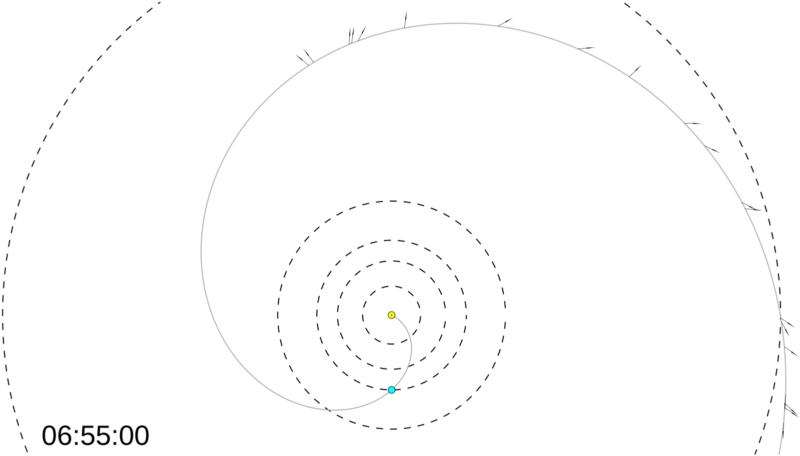
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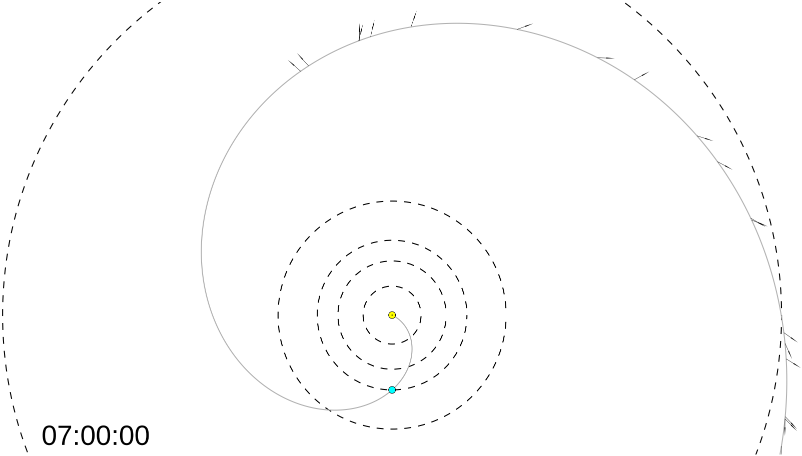
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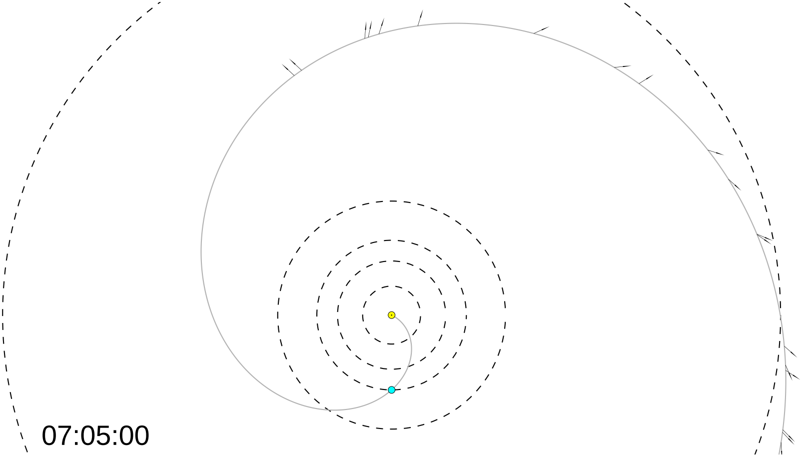
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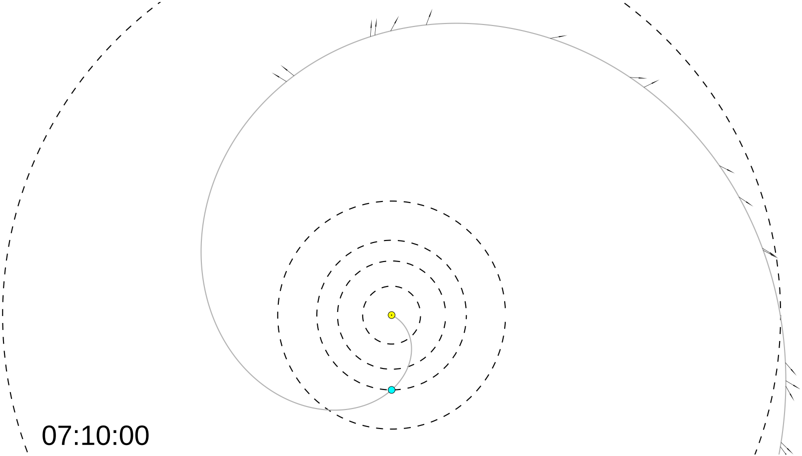

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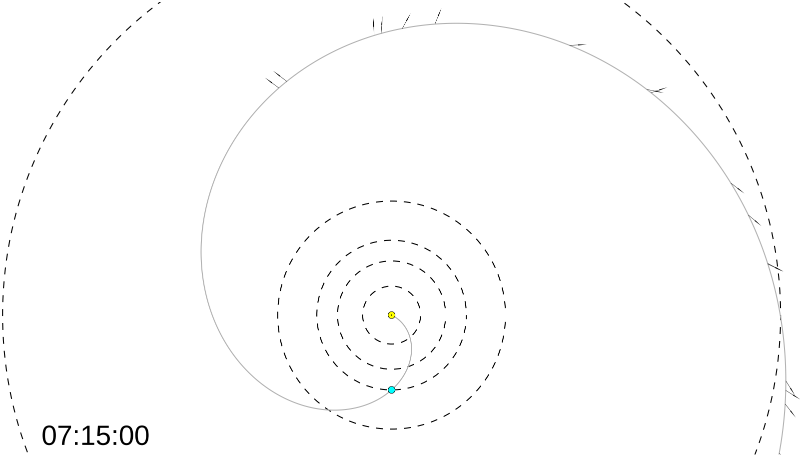
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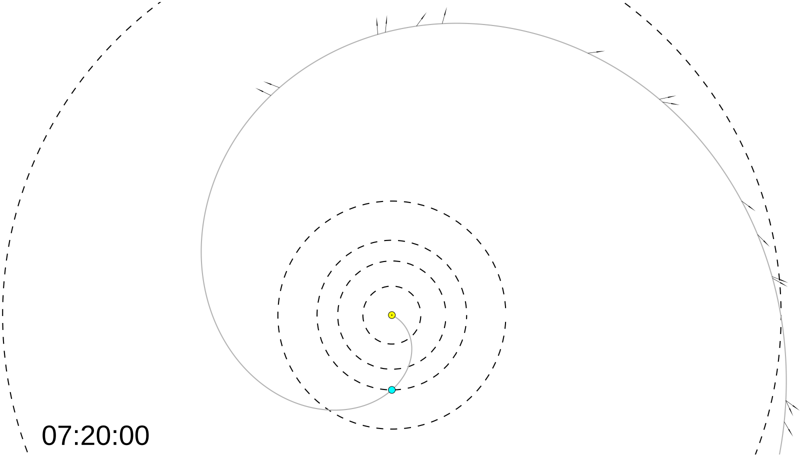
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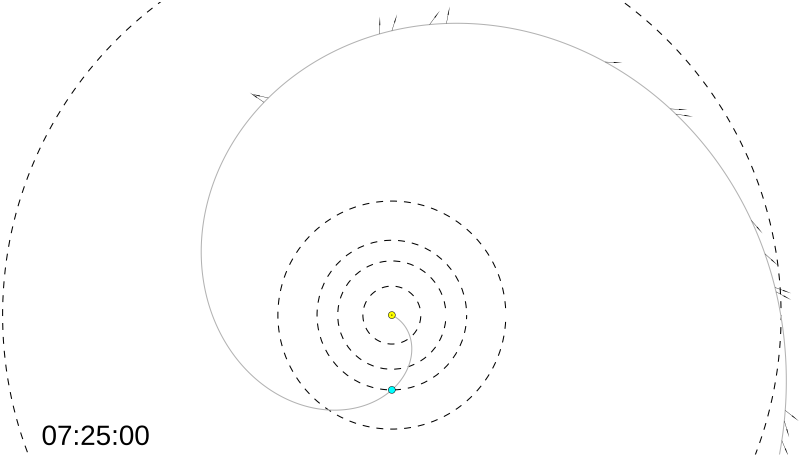
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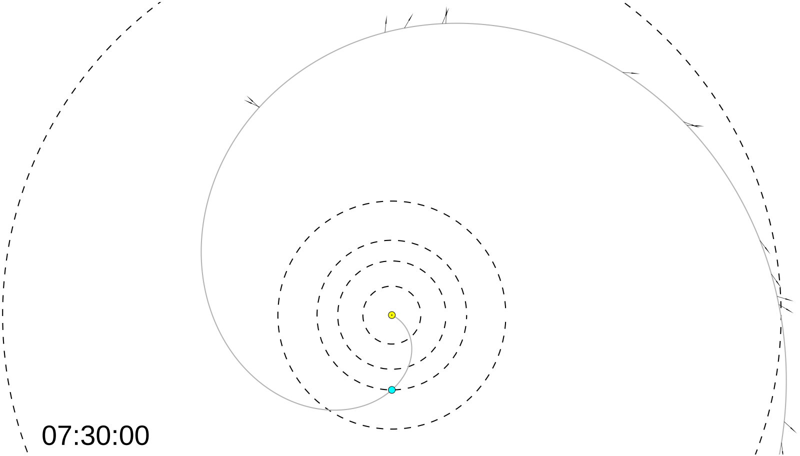
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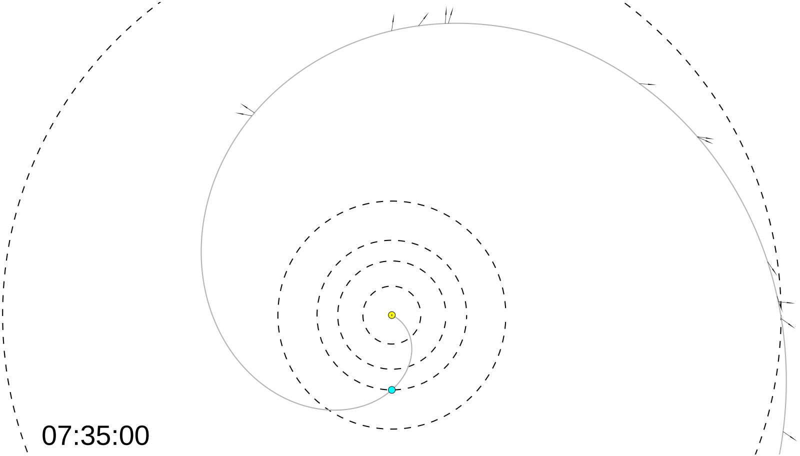
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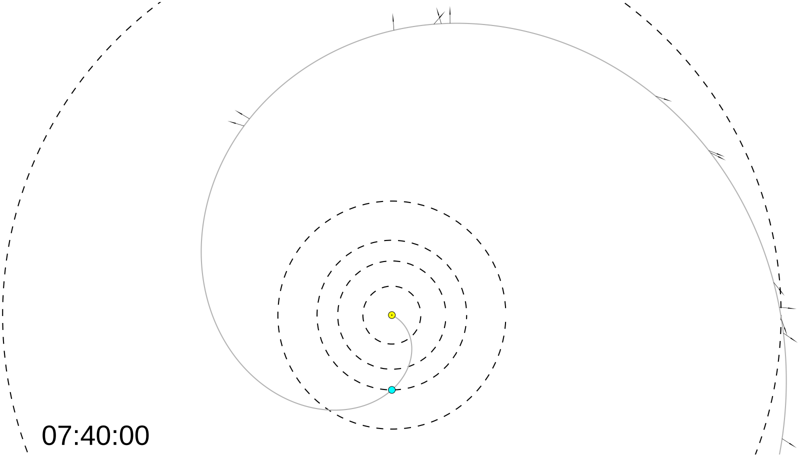

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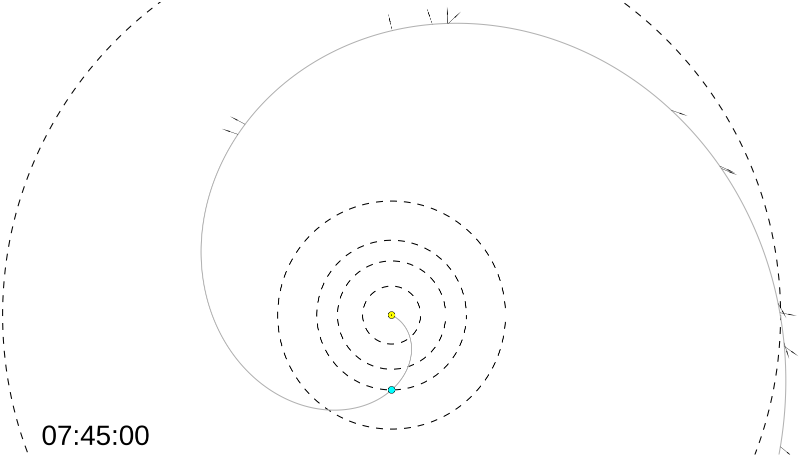
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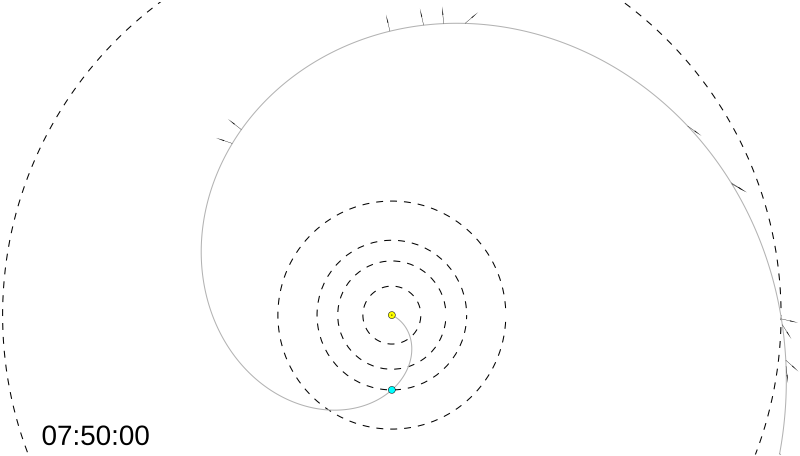
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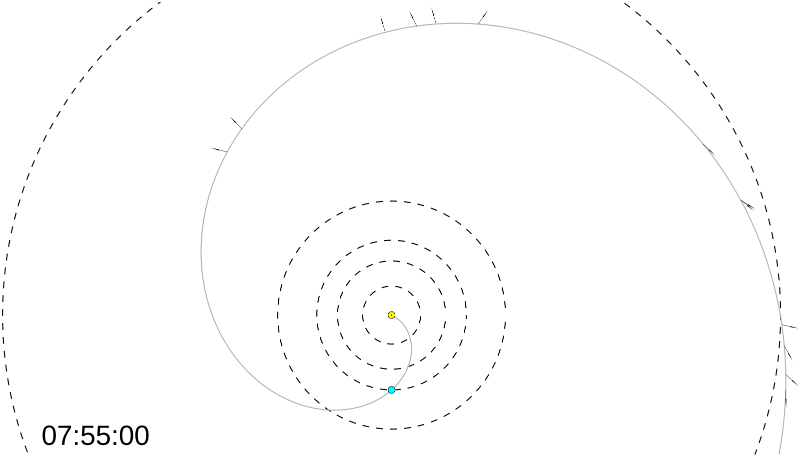
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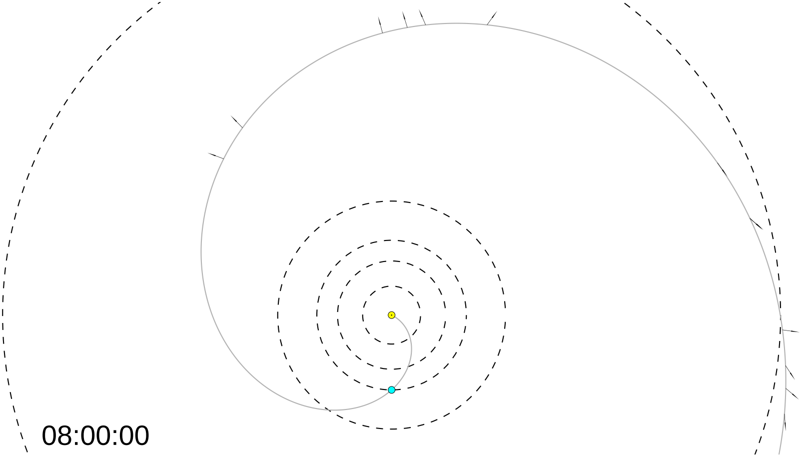
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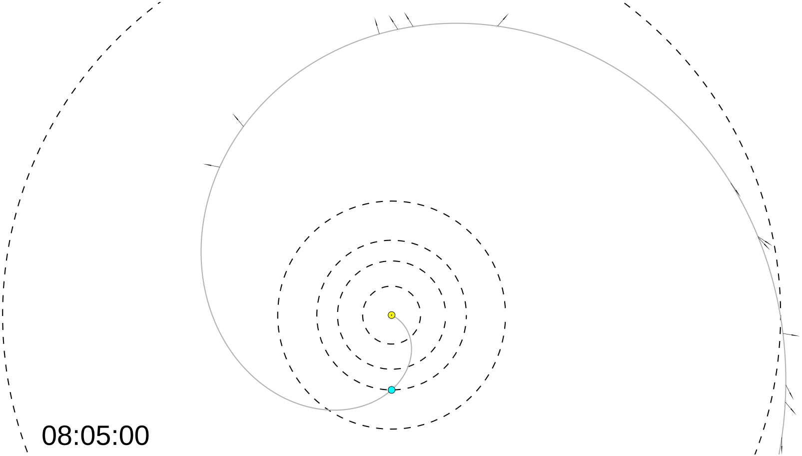
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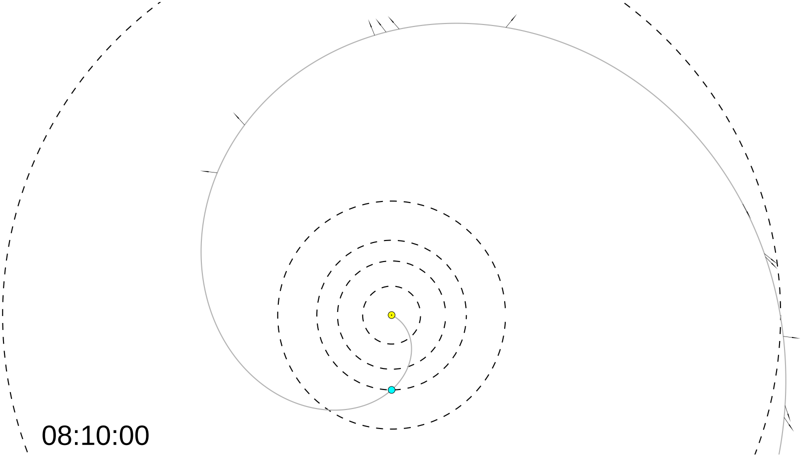
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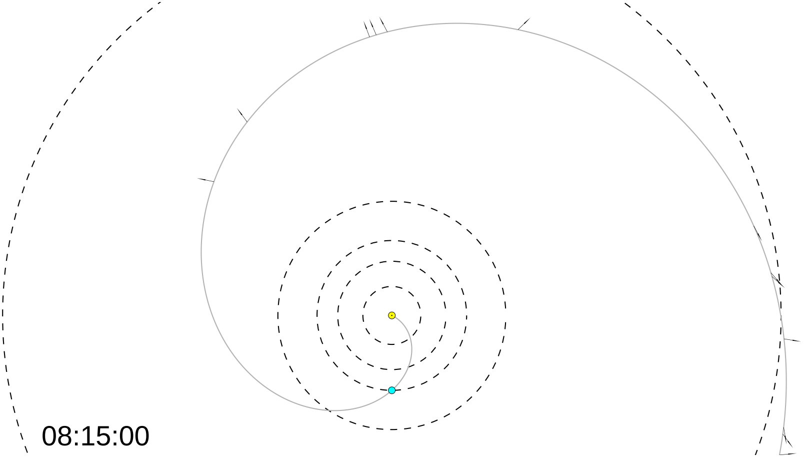
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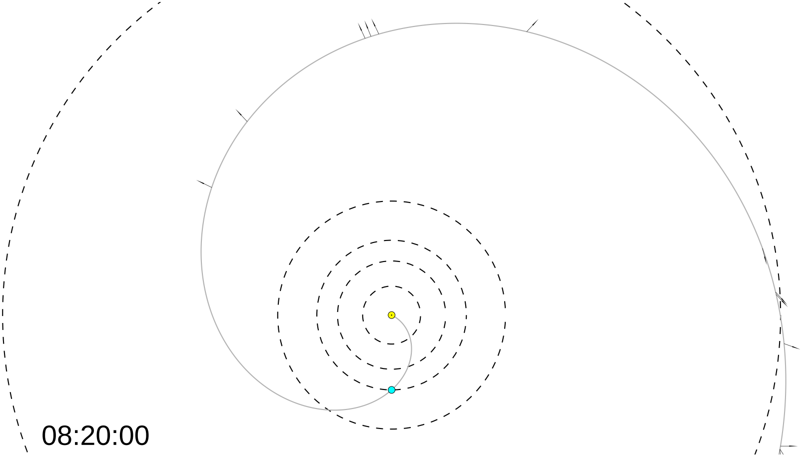
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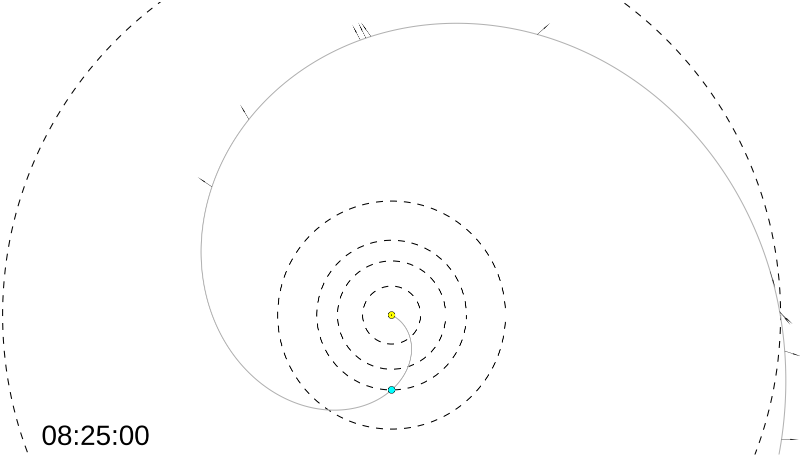
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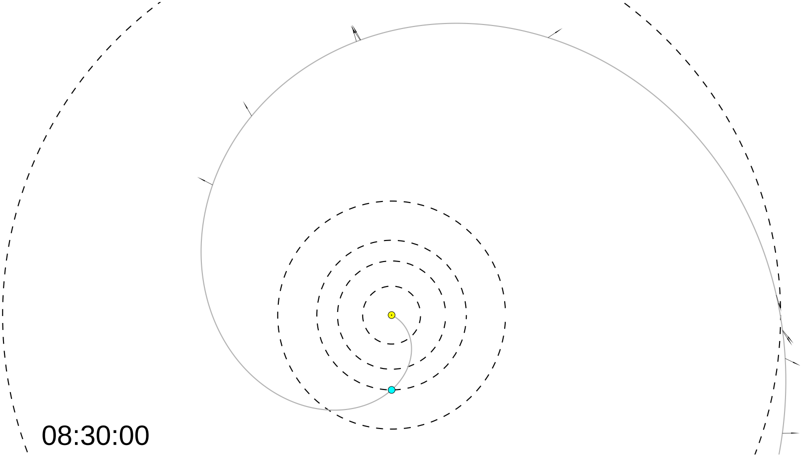
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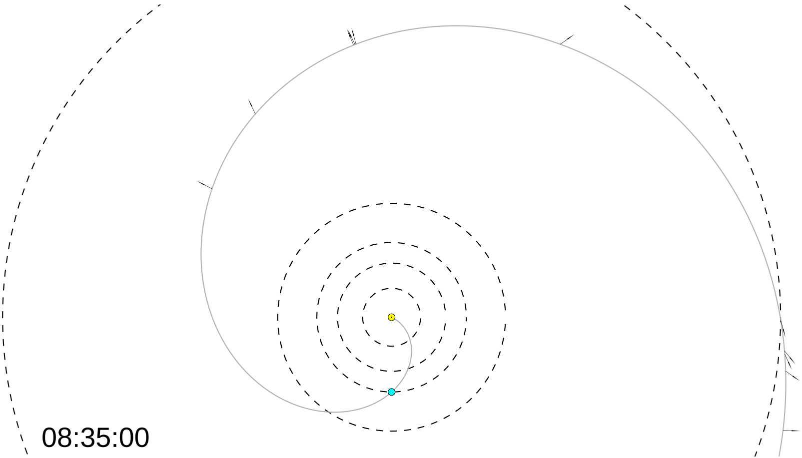
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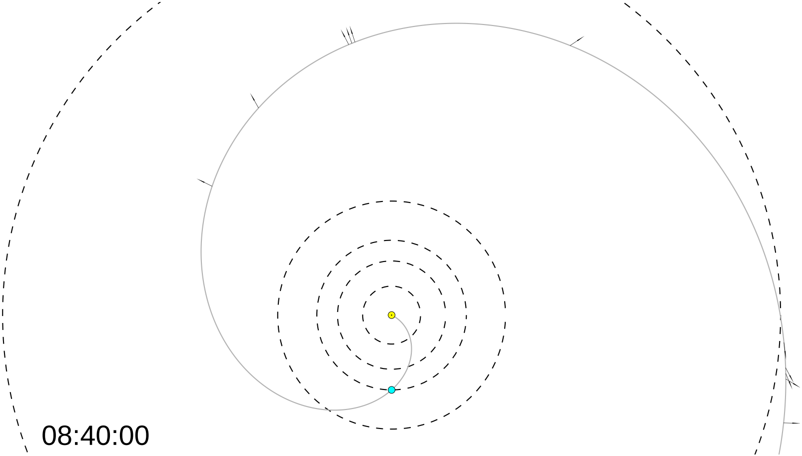
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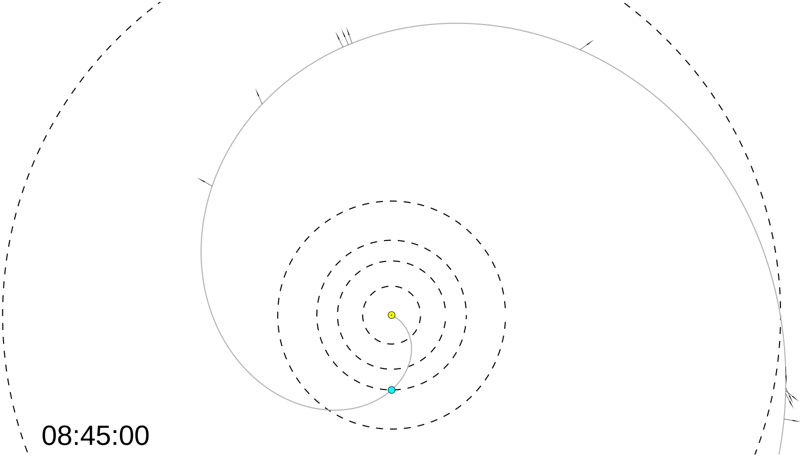
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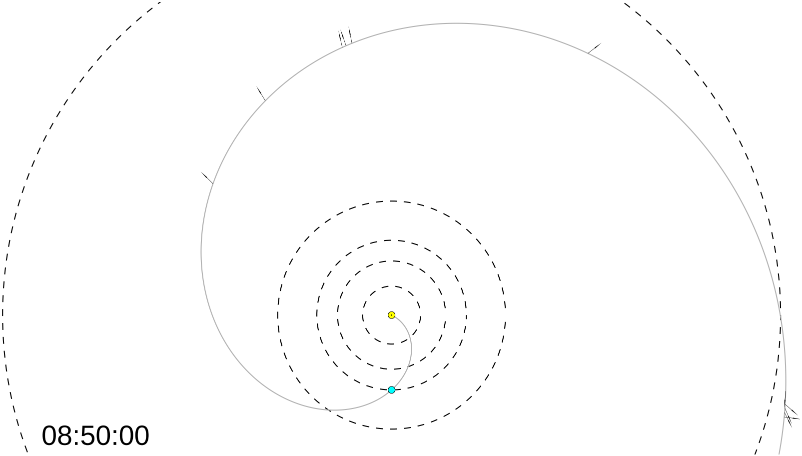
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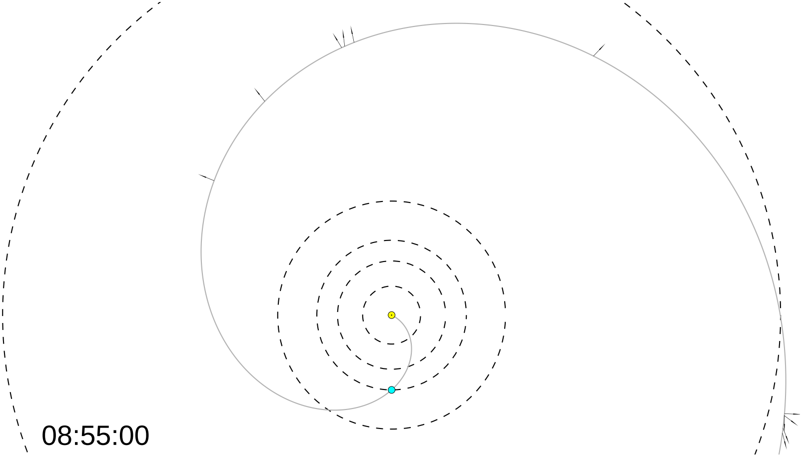
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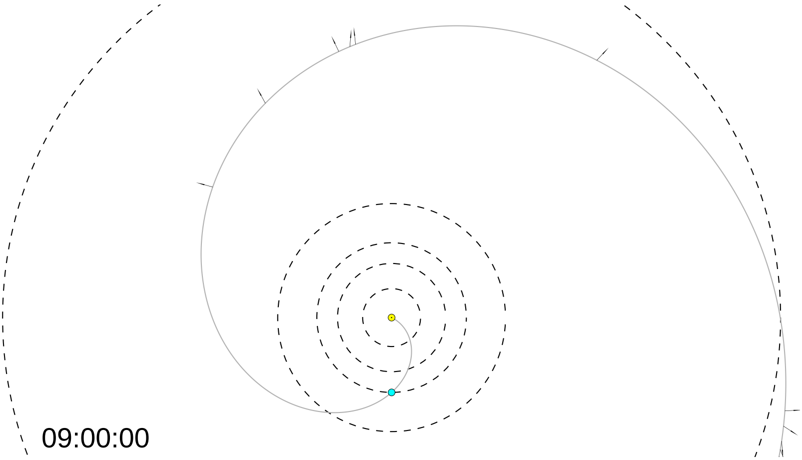
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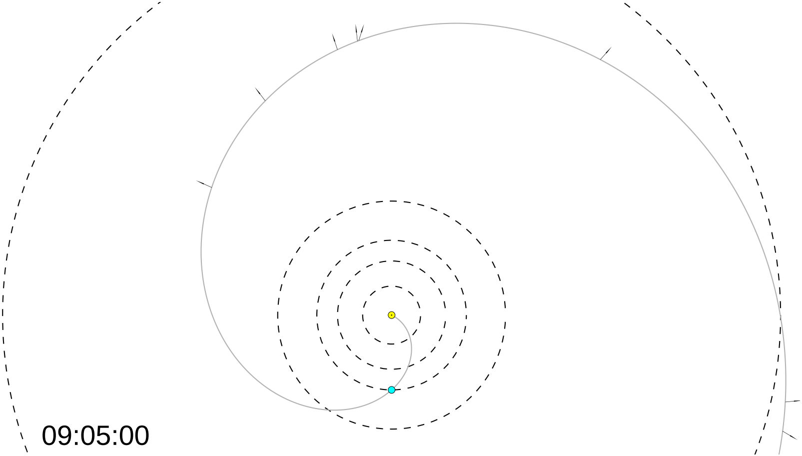
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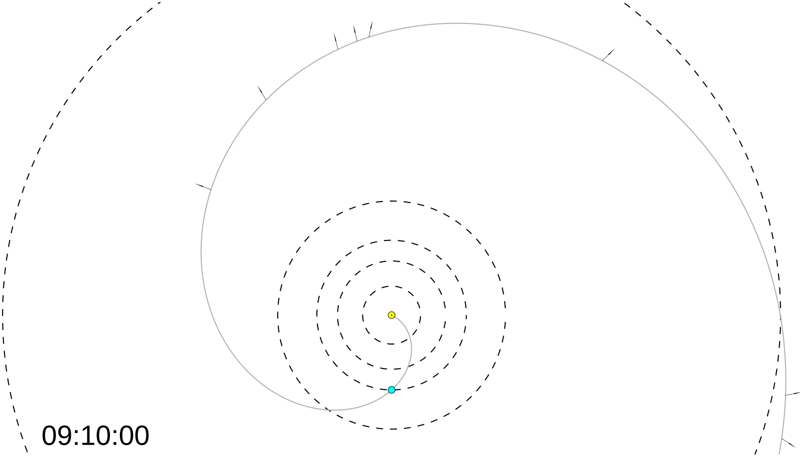
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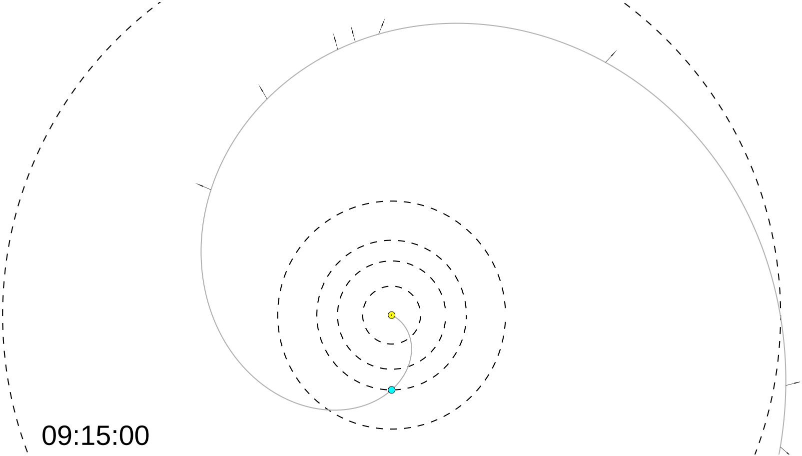
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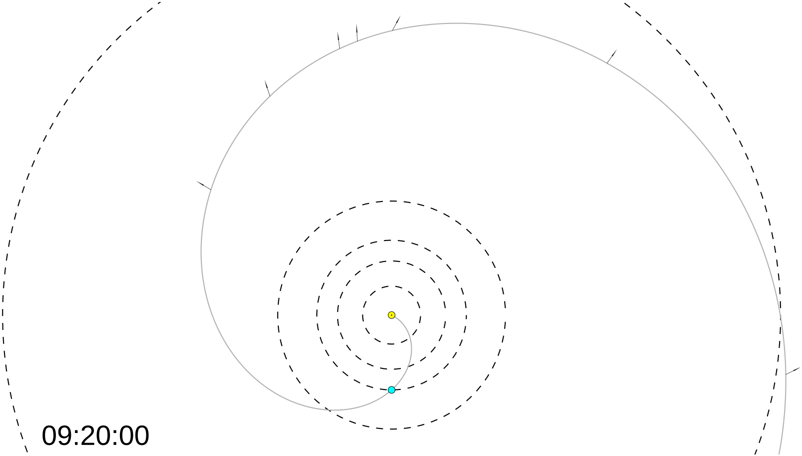
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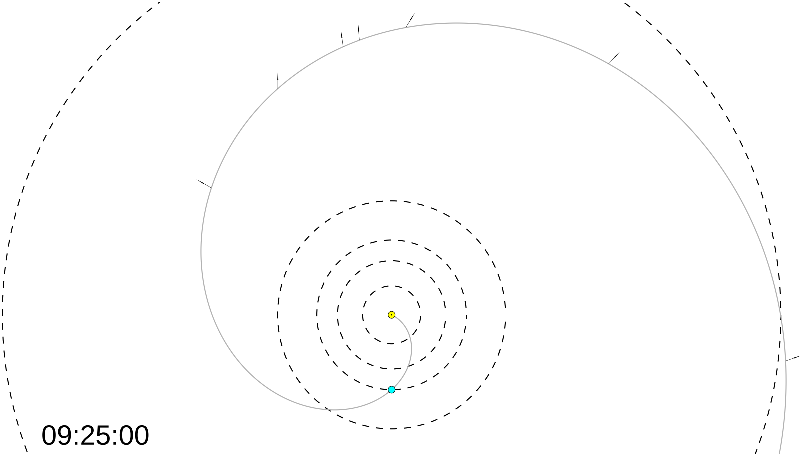
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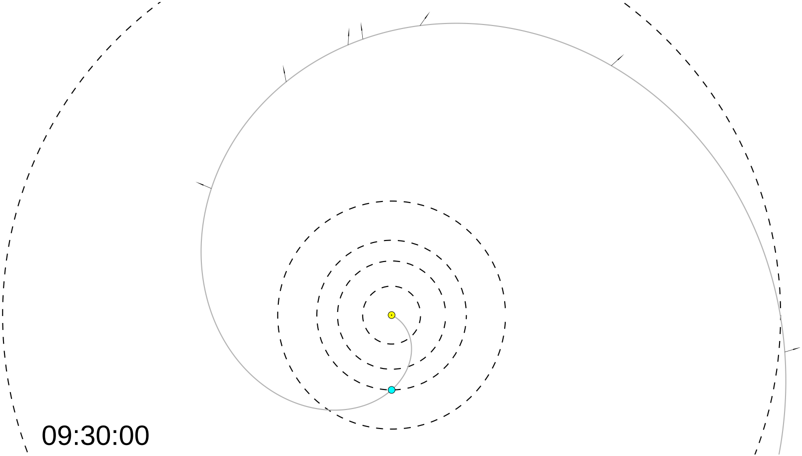
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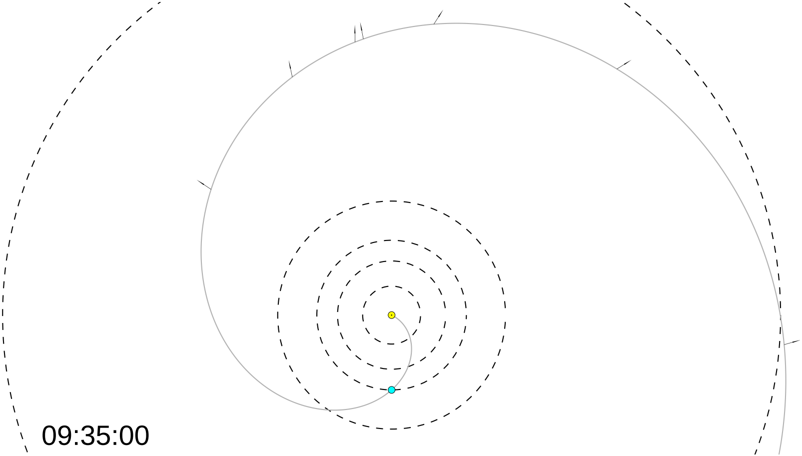
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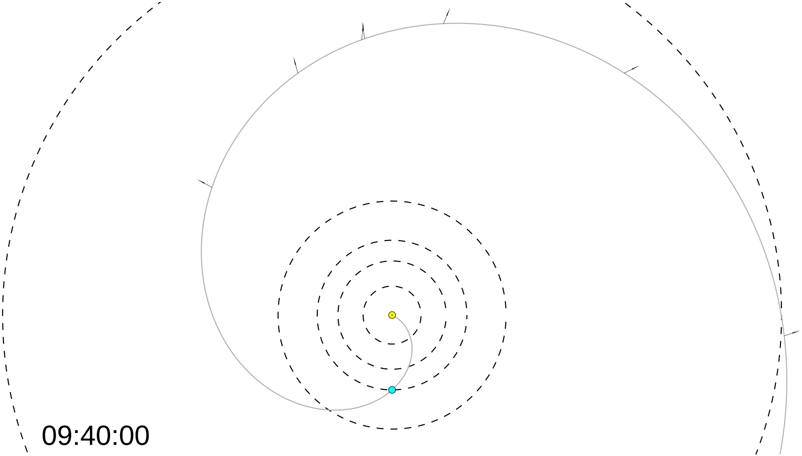

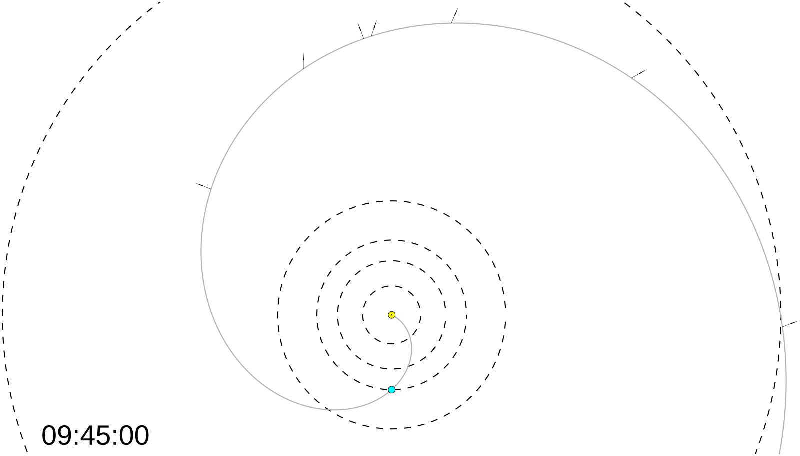
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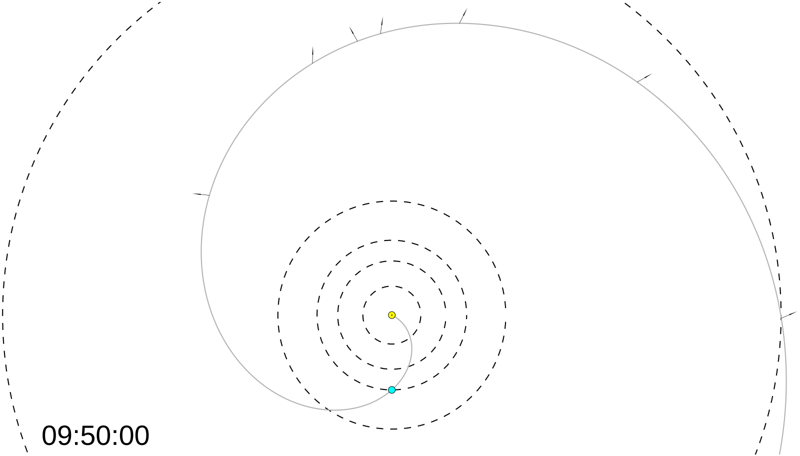
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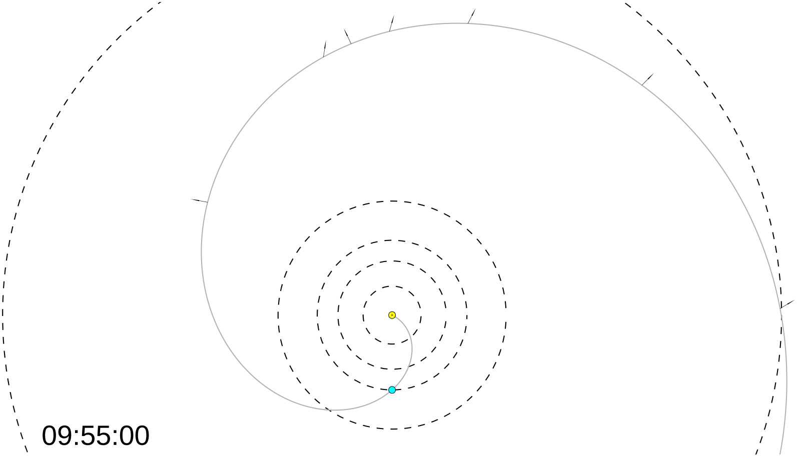
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Focused transport with scattering.

Example:

- 50 electrons, with 100 keV, released from 3 Rs in ecliptic plane
- outward motion, initial μ uniform in]0,1[
- spiral magnetic field (solar wind 400 km/s)
- magnetic field intensity varying as R^{-2}
- constant mean free path $\lambda = 0.5$ AU

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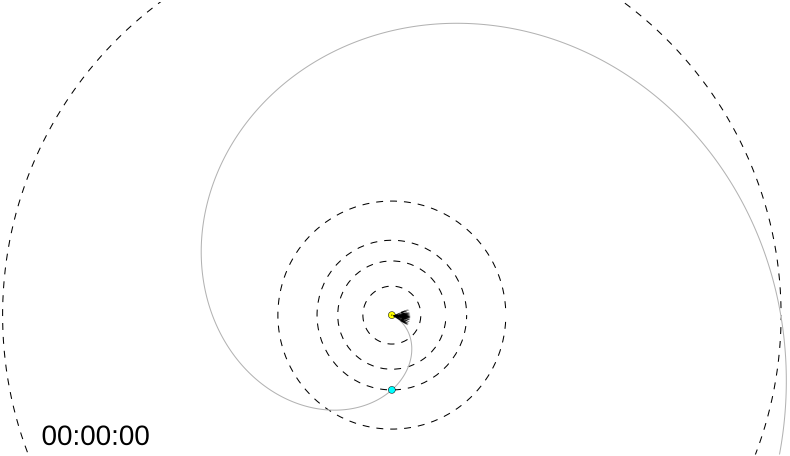
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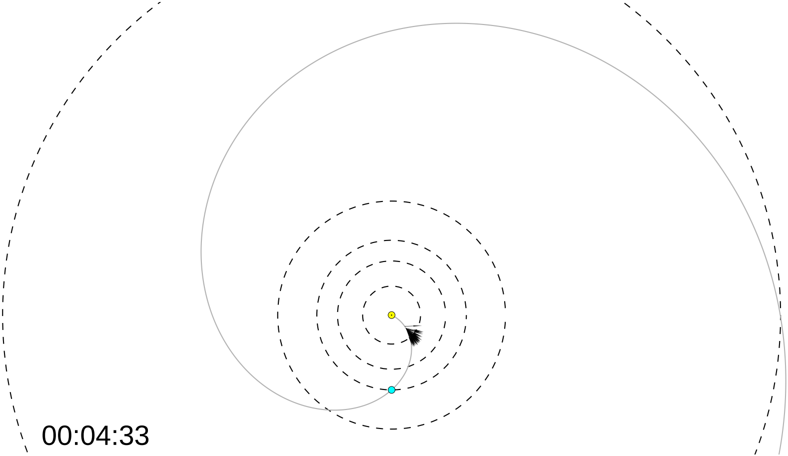
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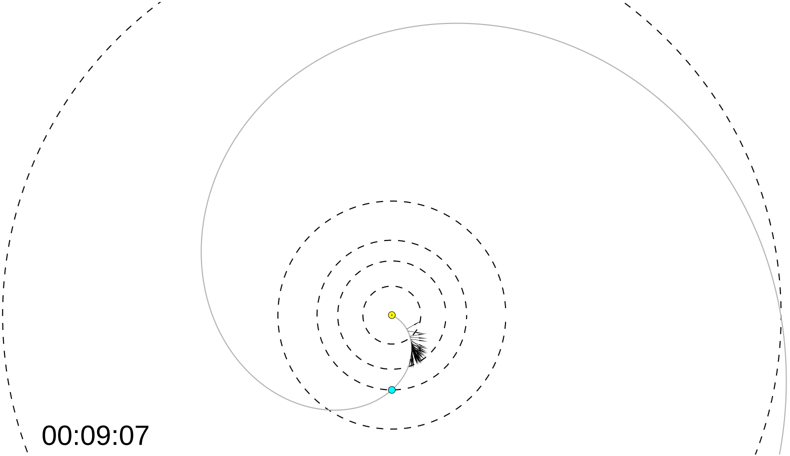
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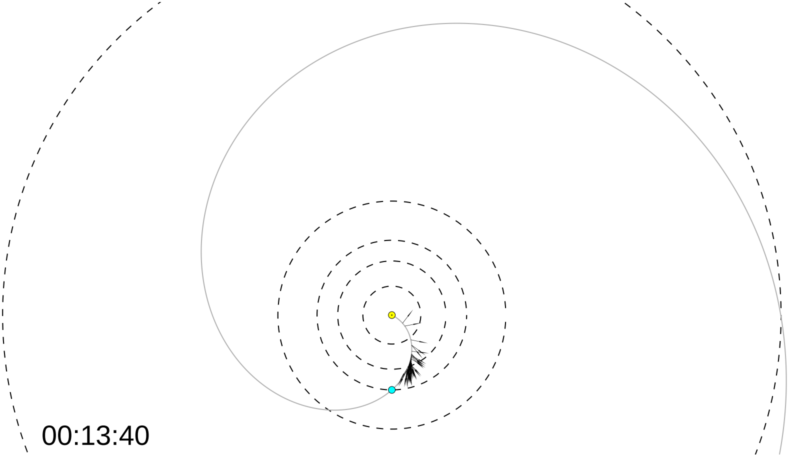
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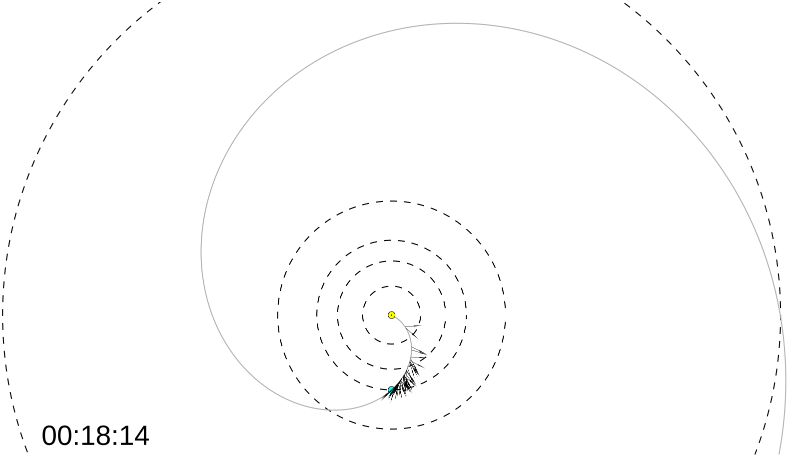
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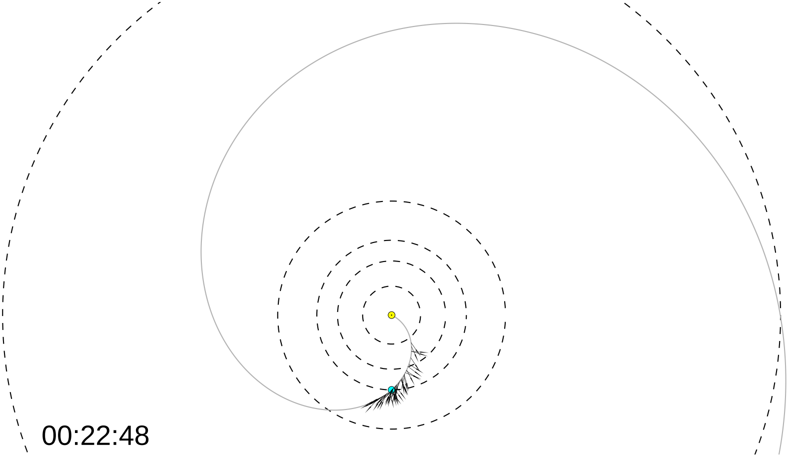
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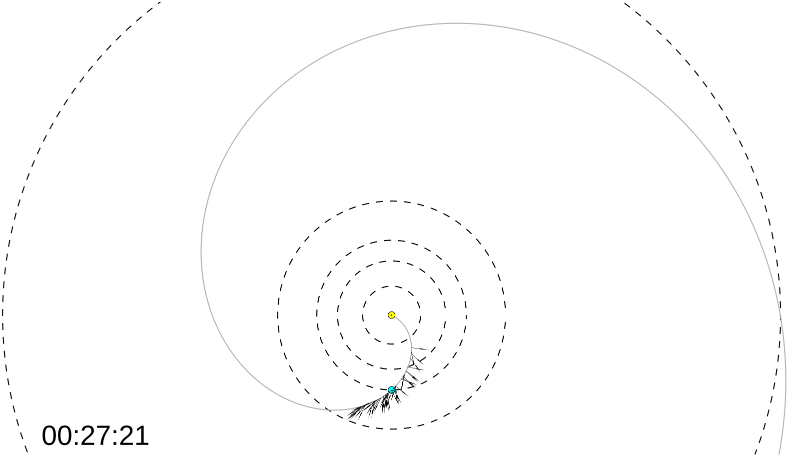
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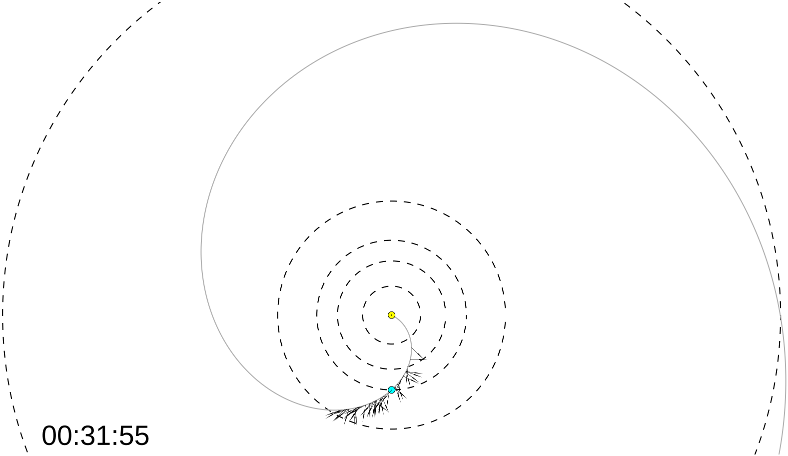
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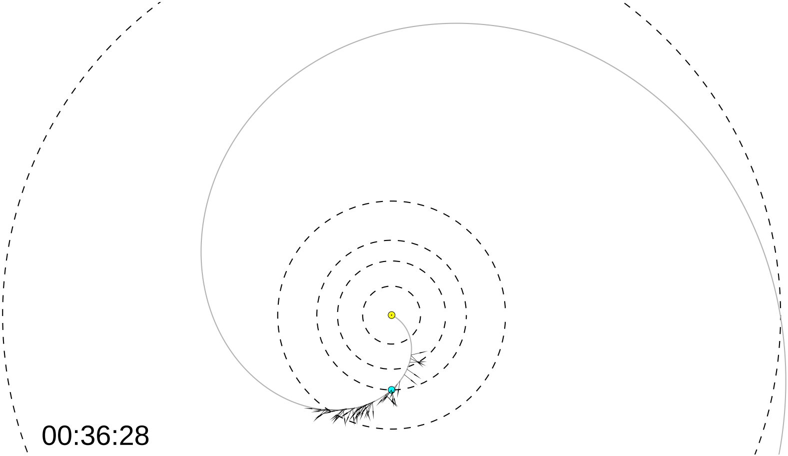
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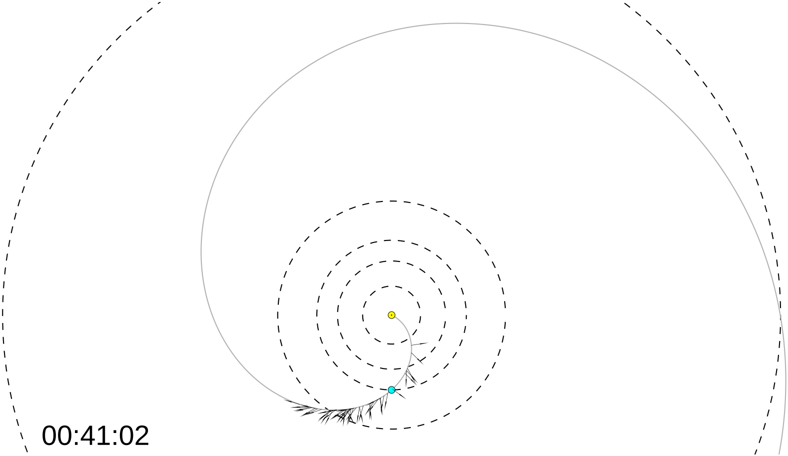
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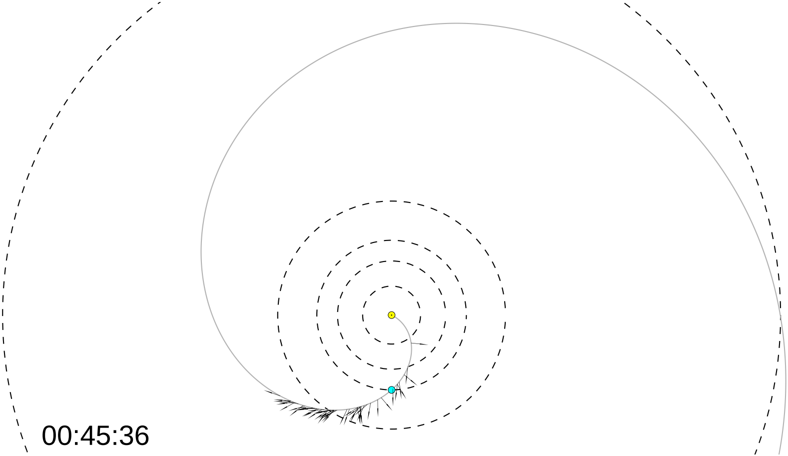
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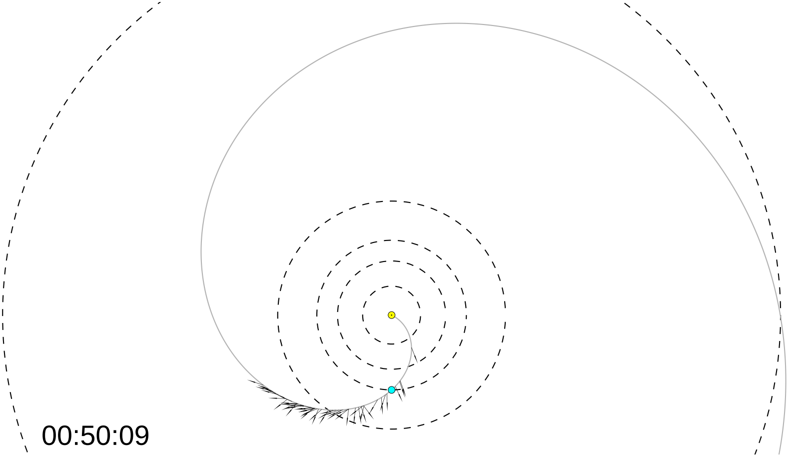
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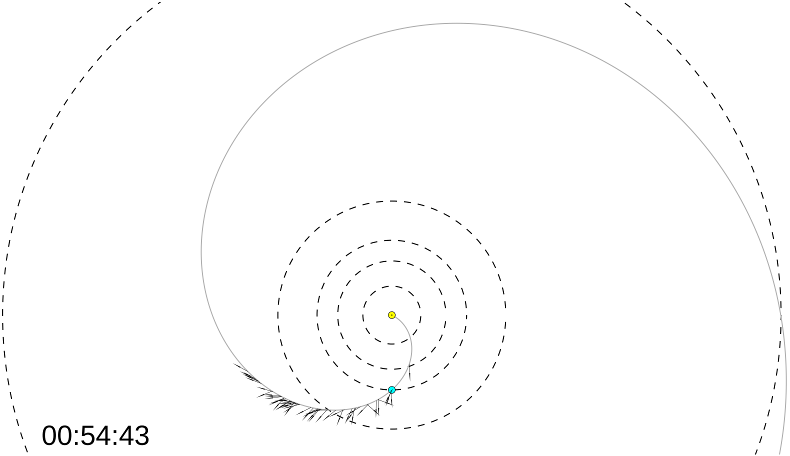
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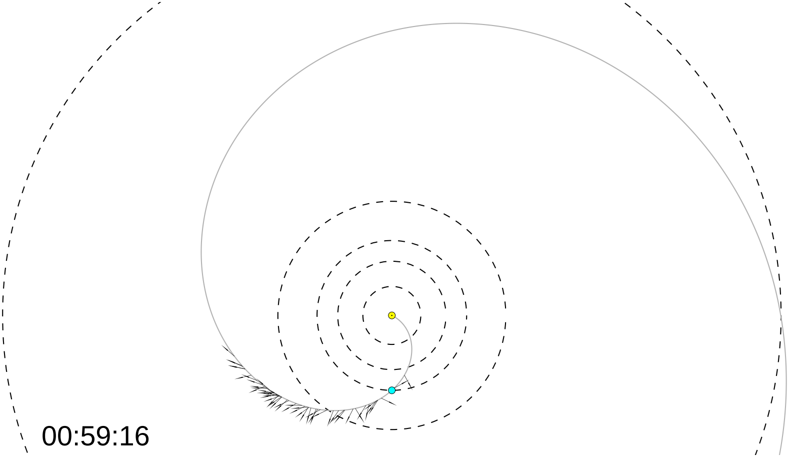
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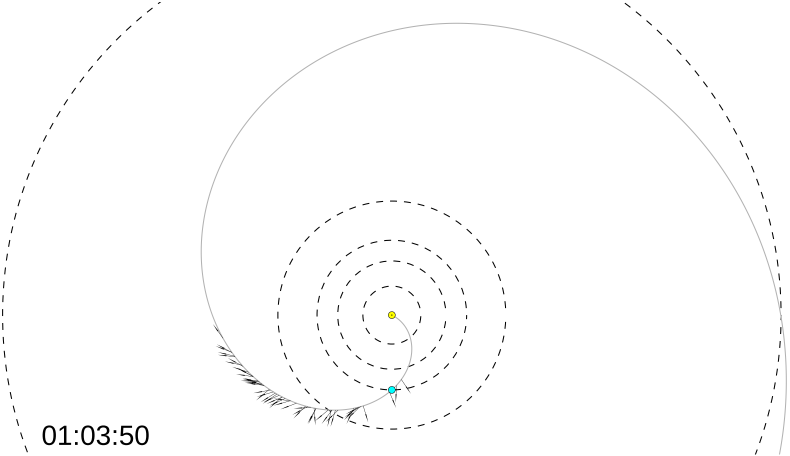
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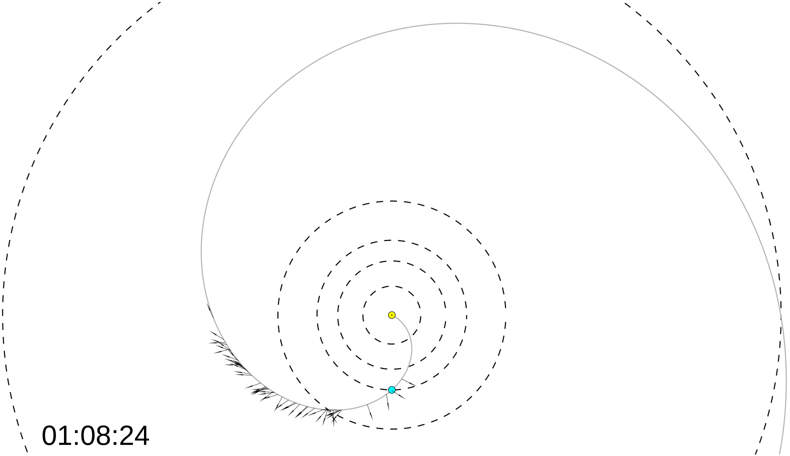
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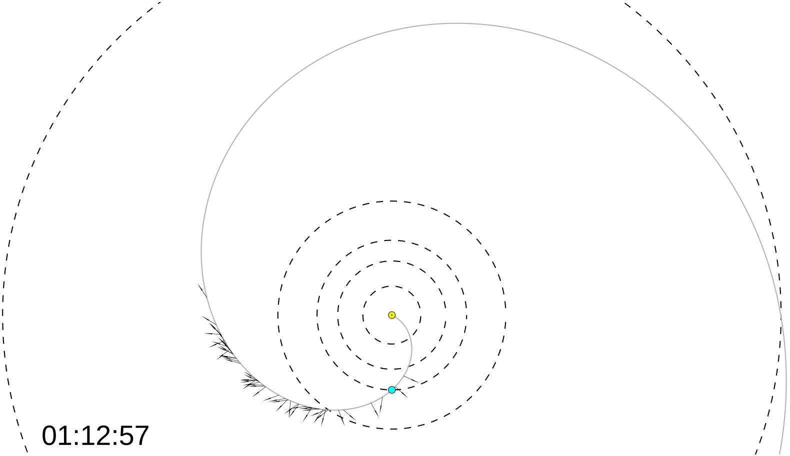
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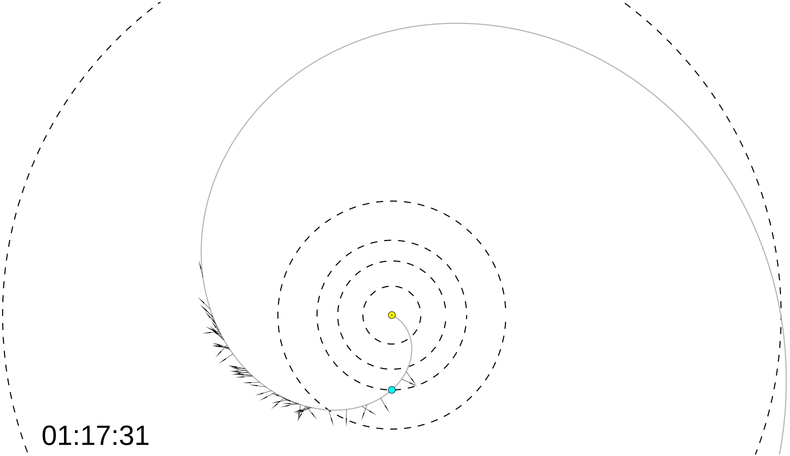
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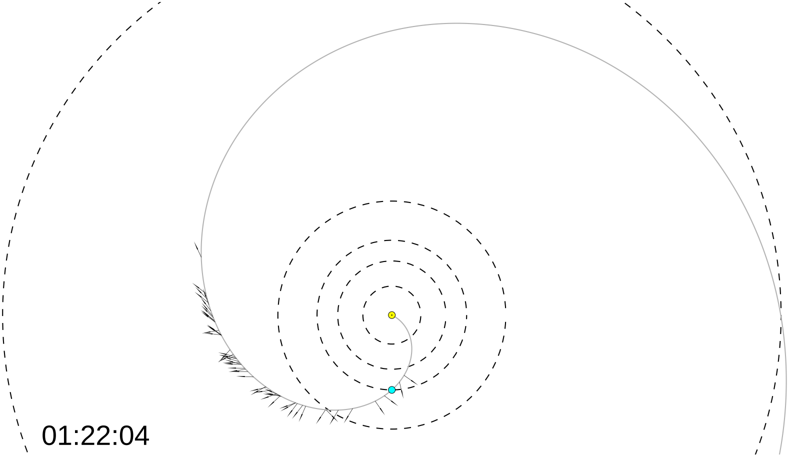
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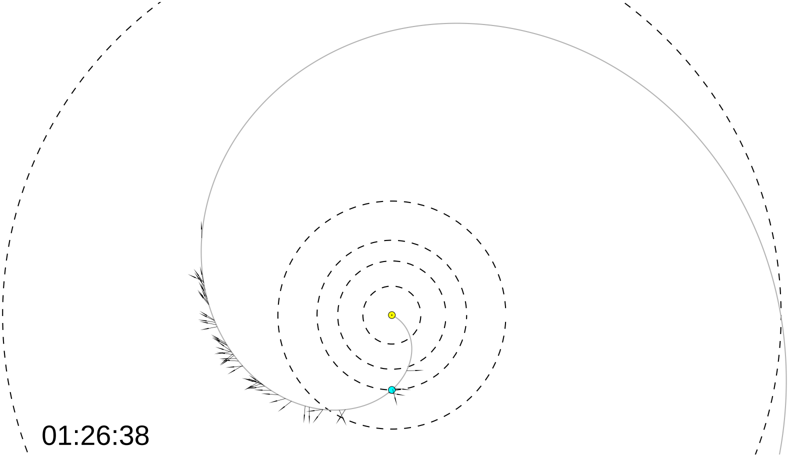
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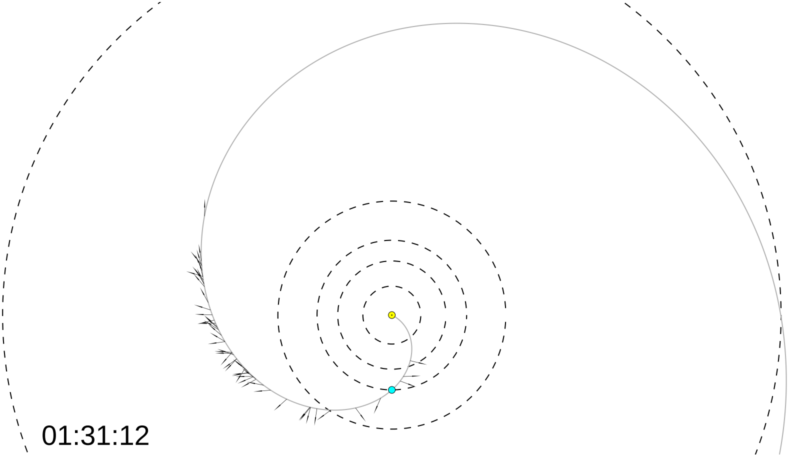
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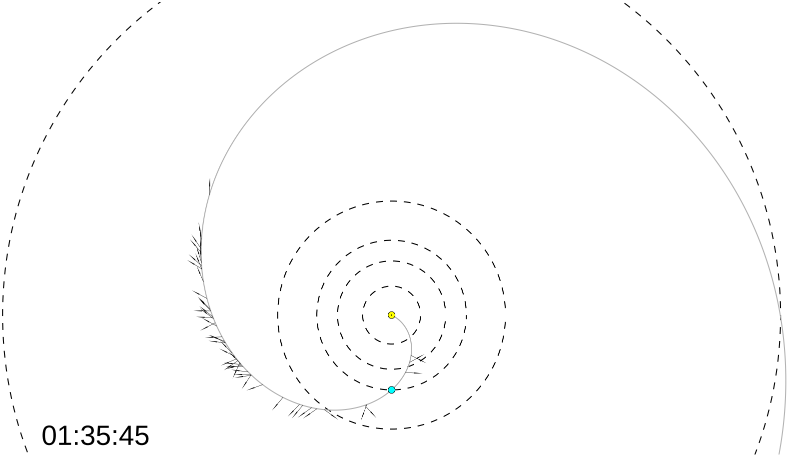
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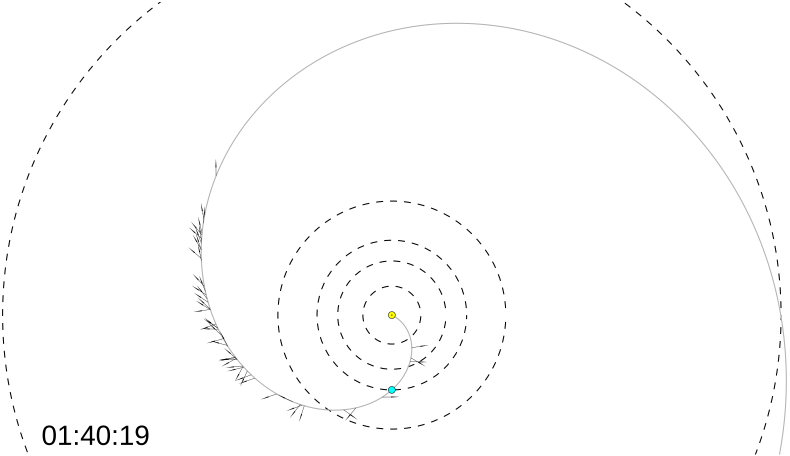
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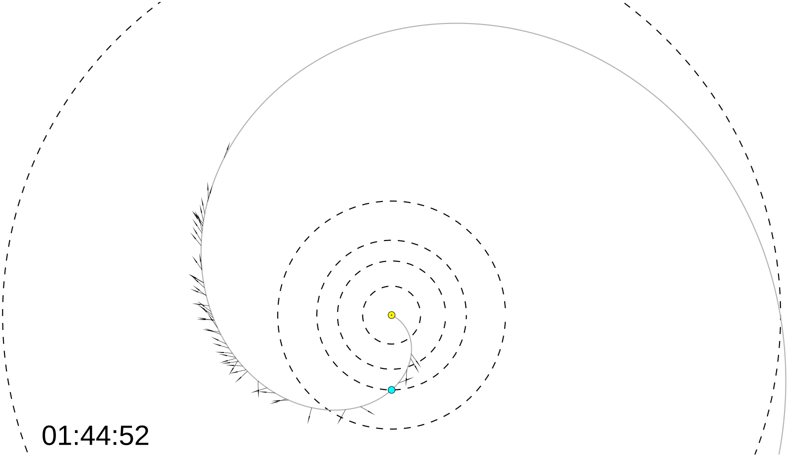

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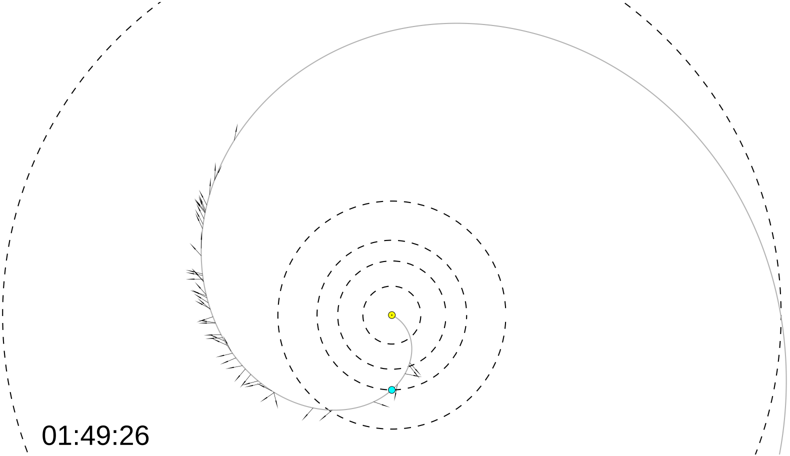
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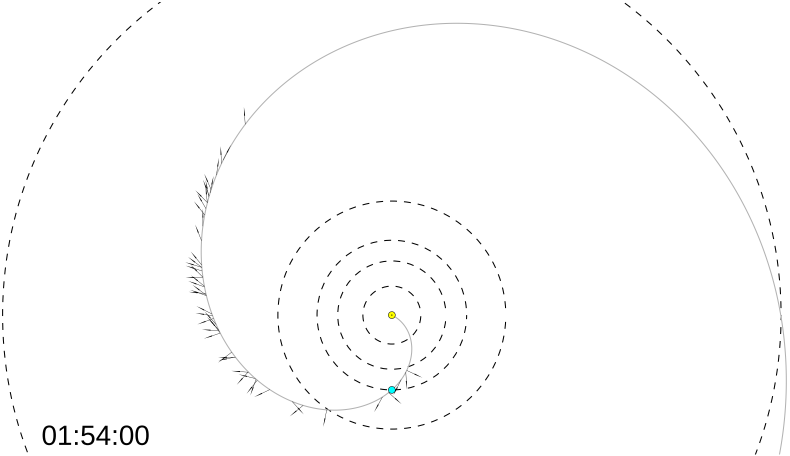
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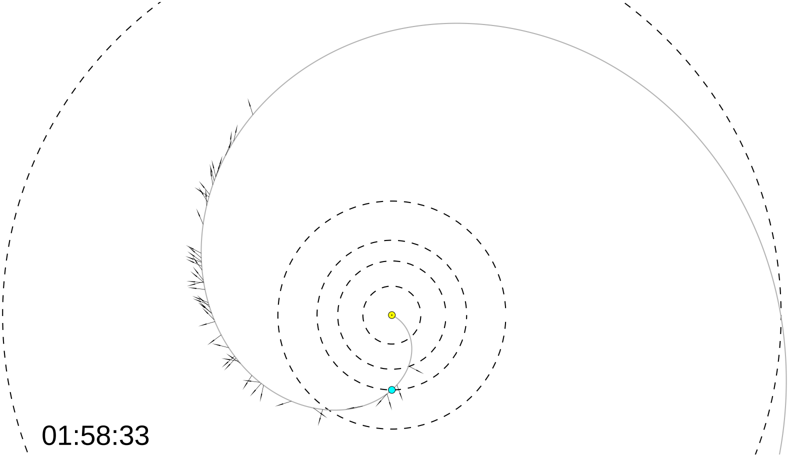
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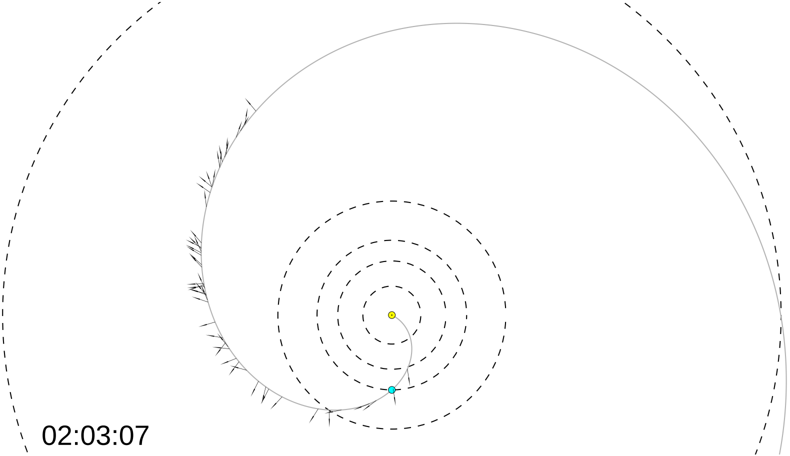
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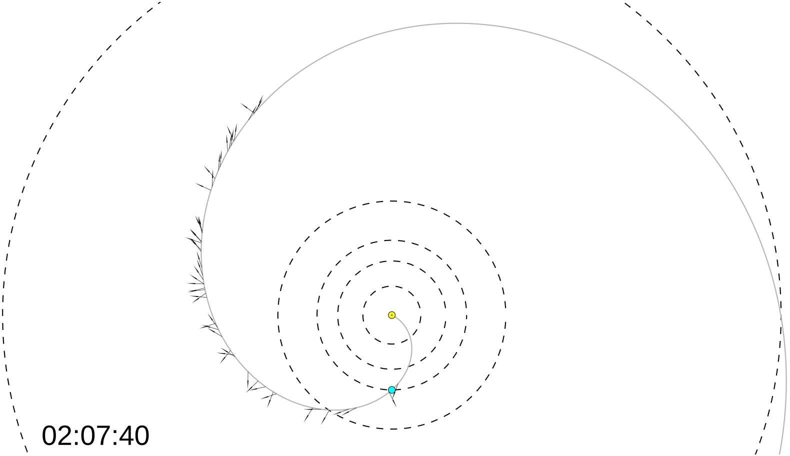
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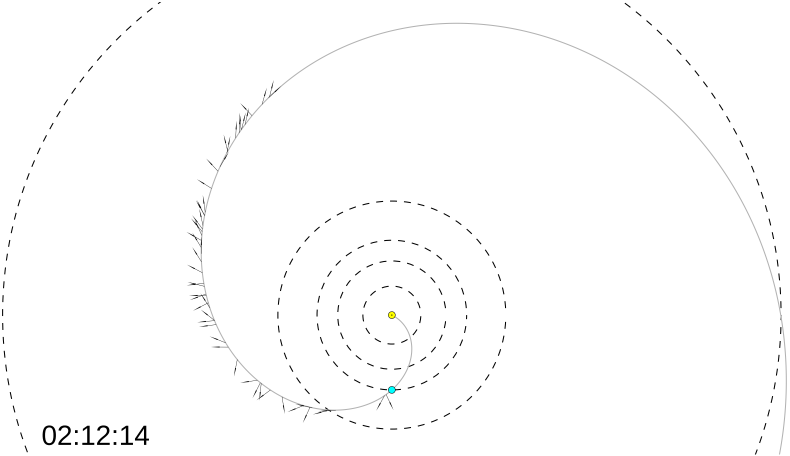

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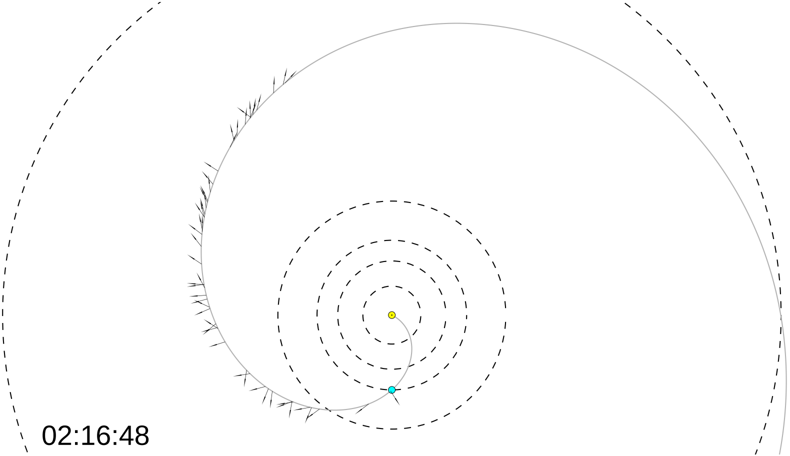
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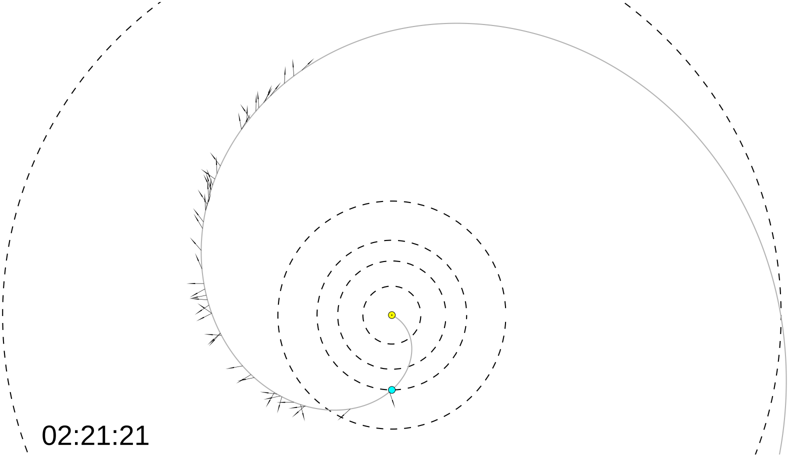
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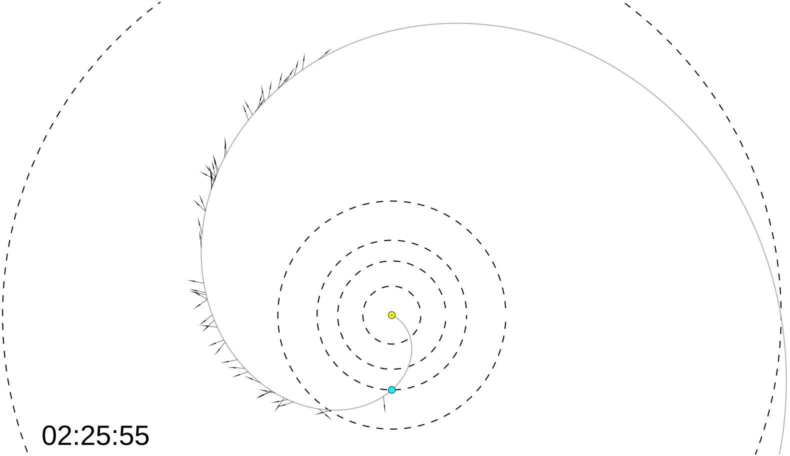
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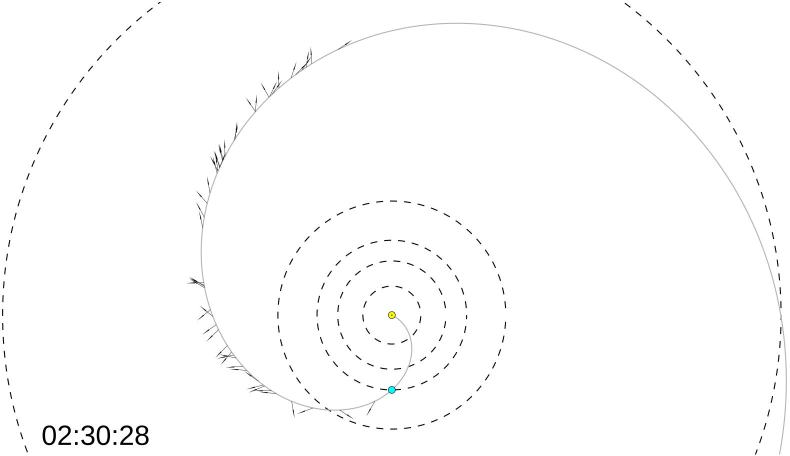
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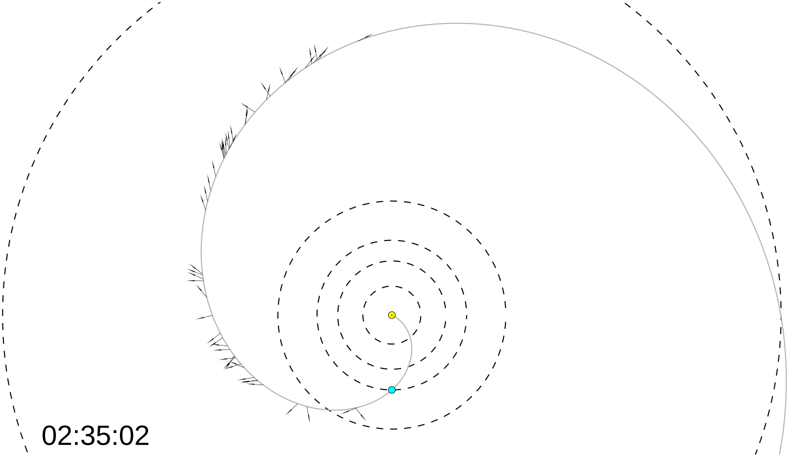

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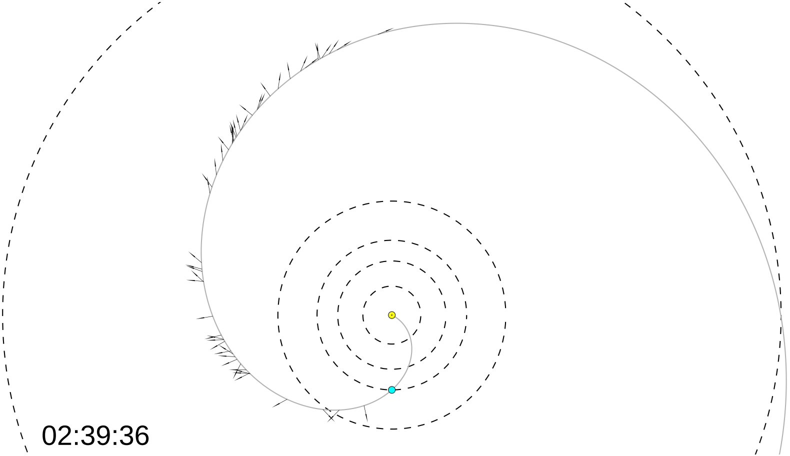
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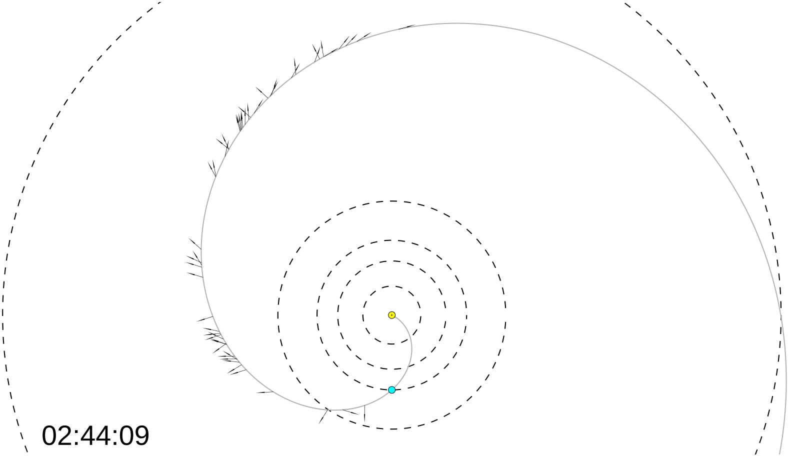
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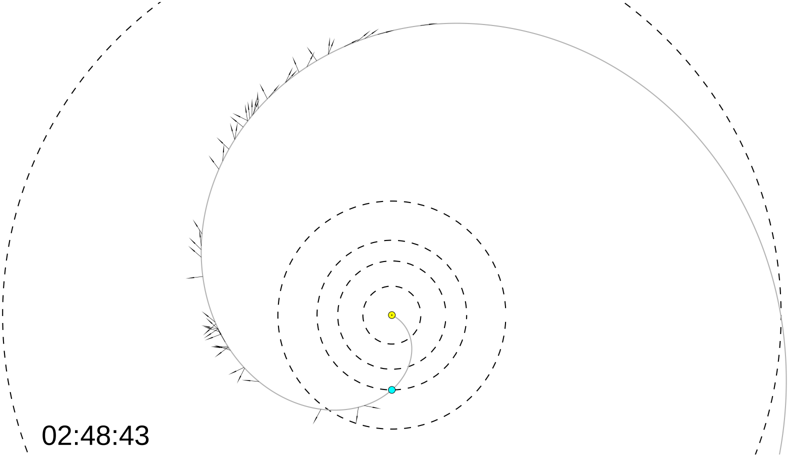
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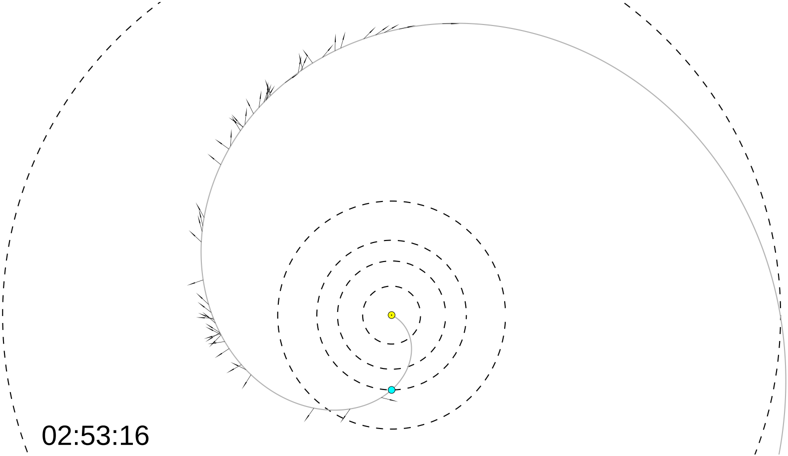
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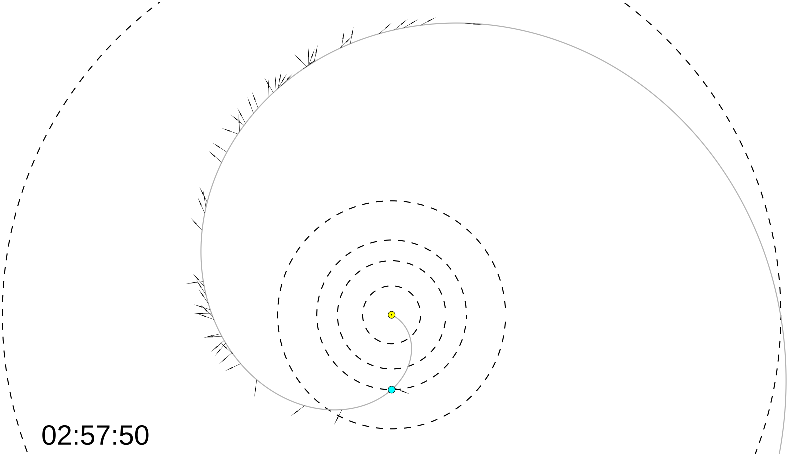
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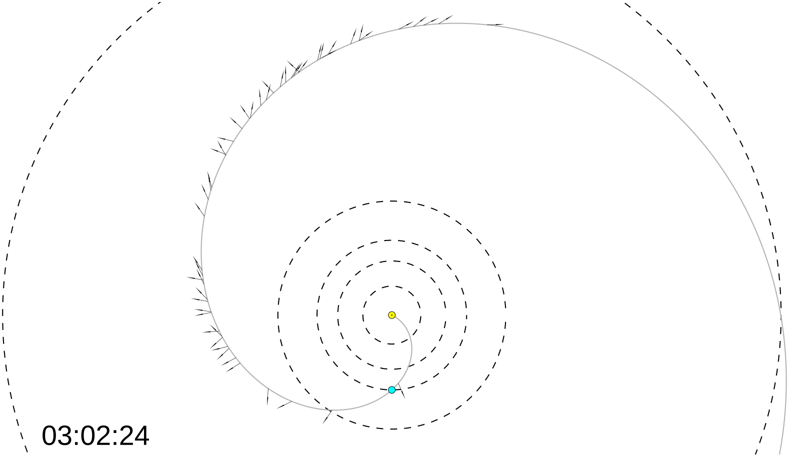
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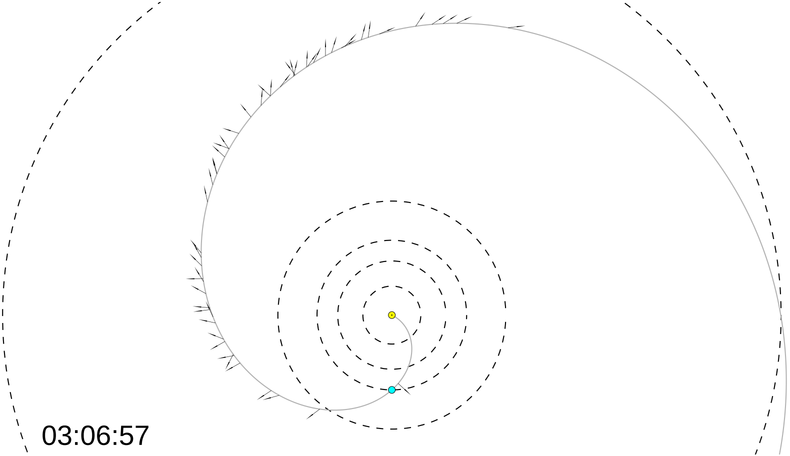
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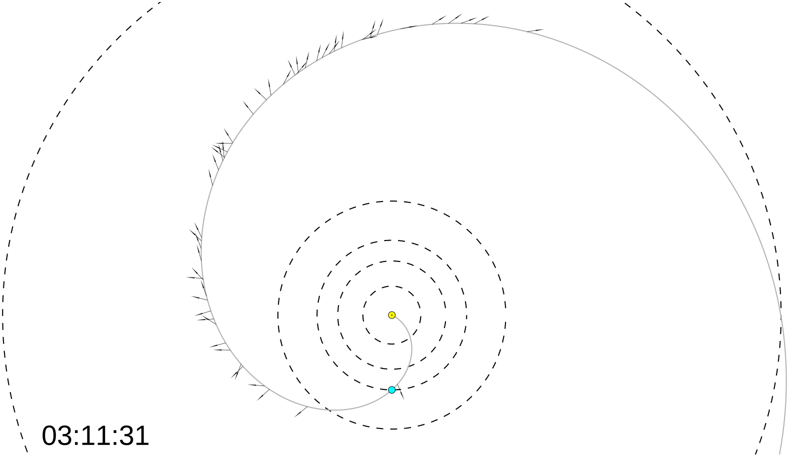
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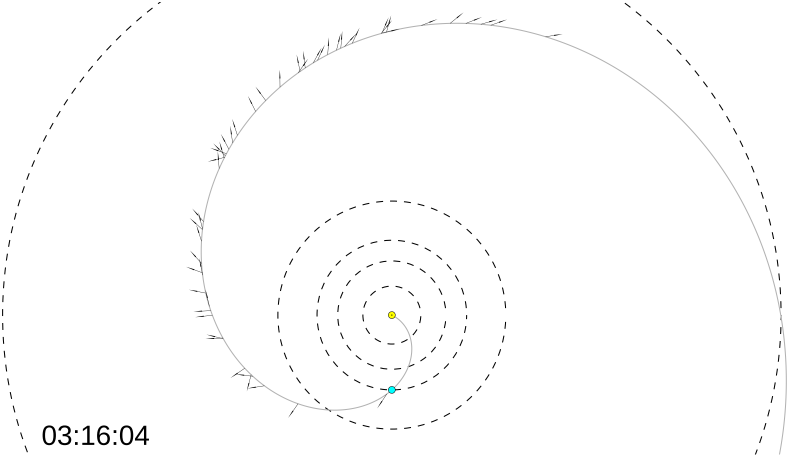
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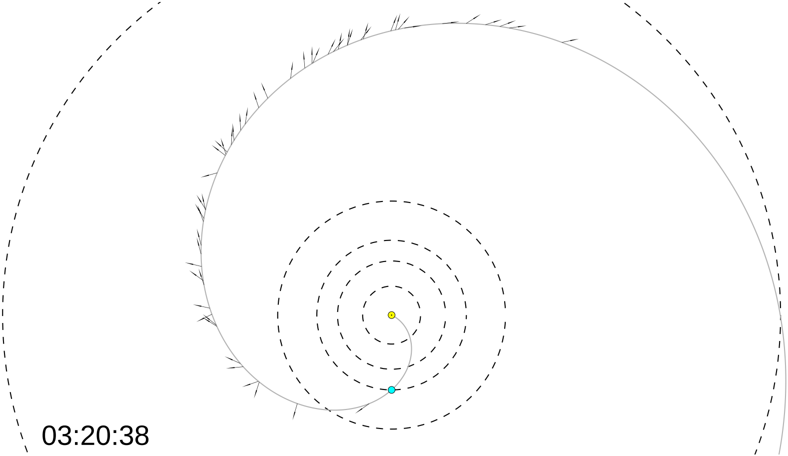
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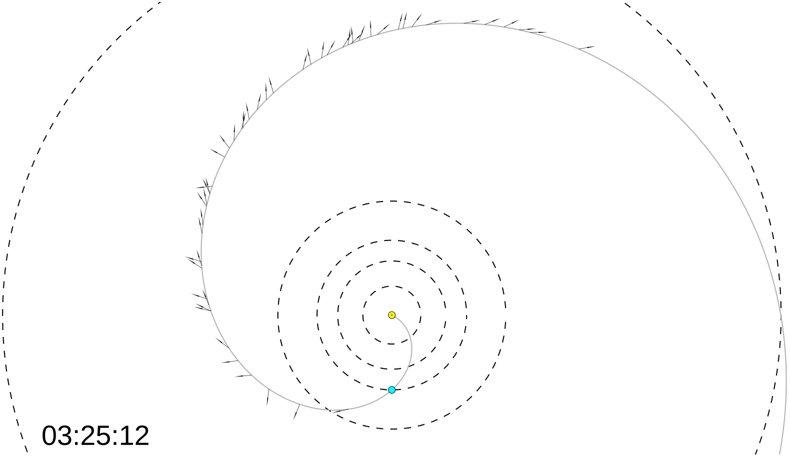
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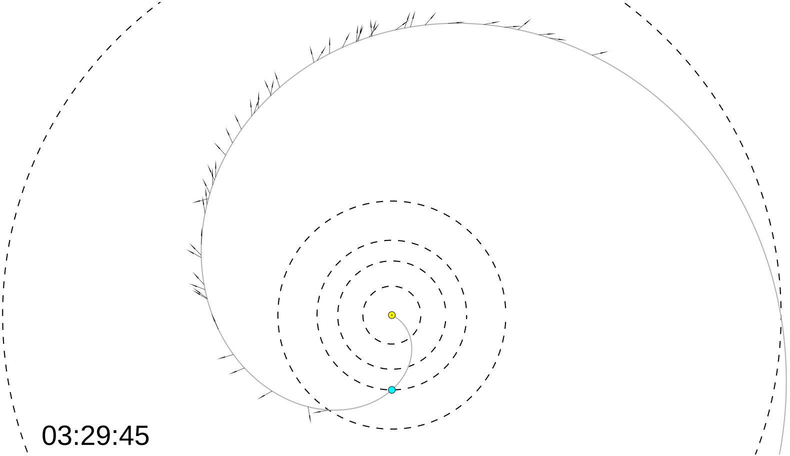
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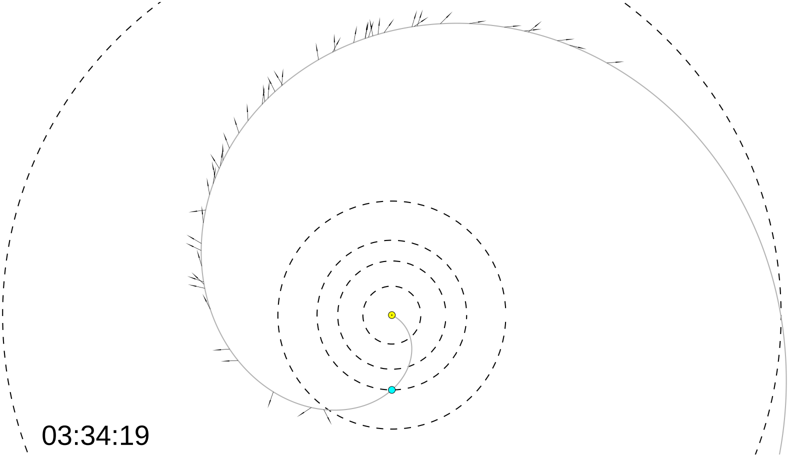
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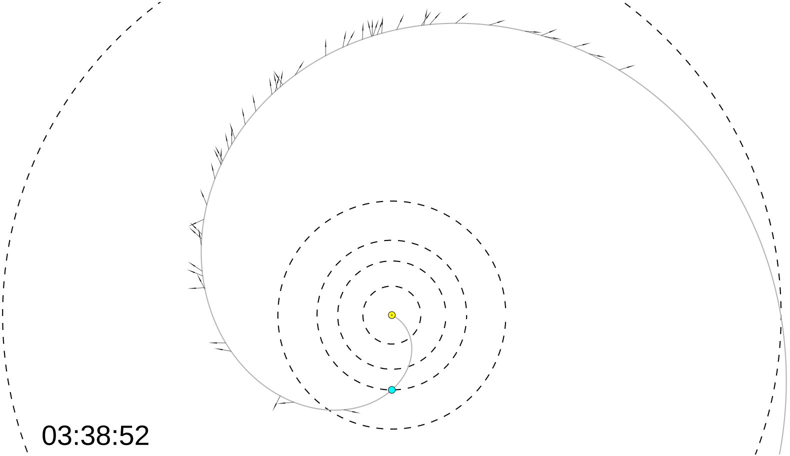
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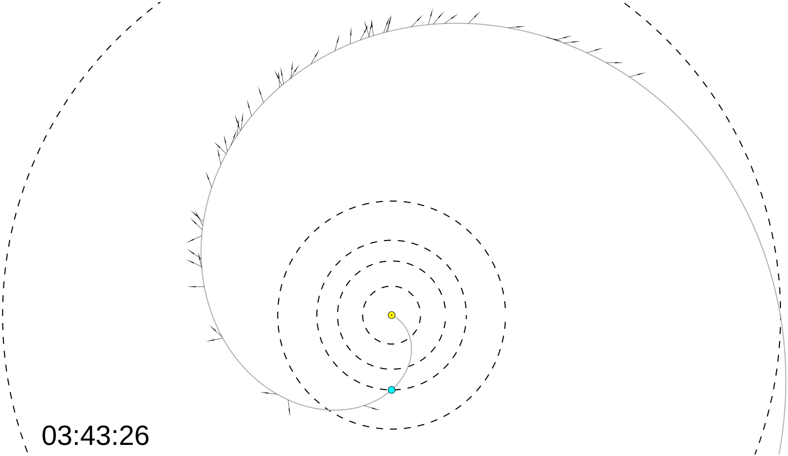
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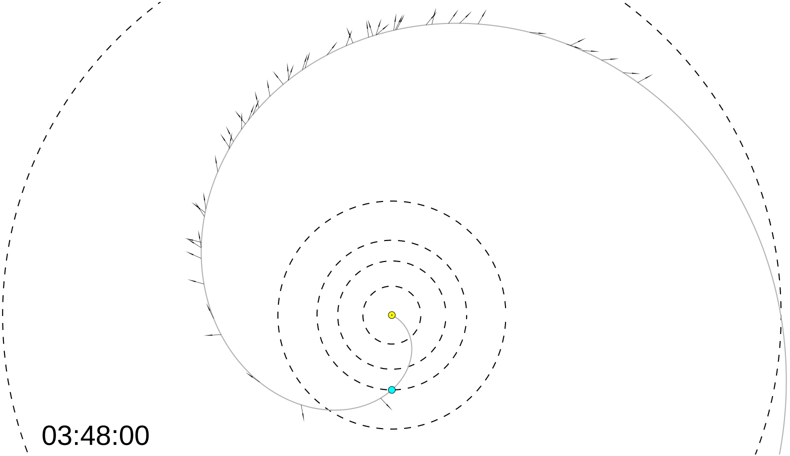
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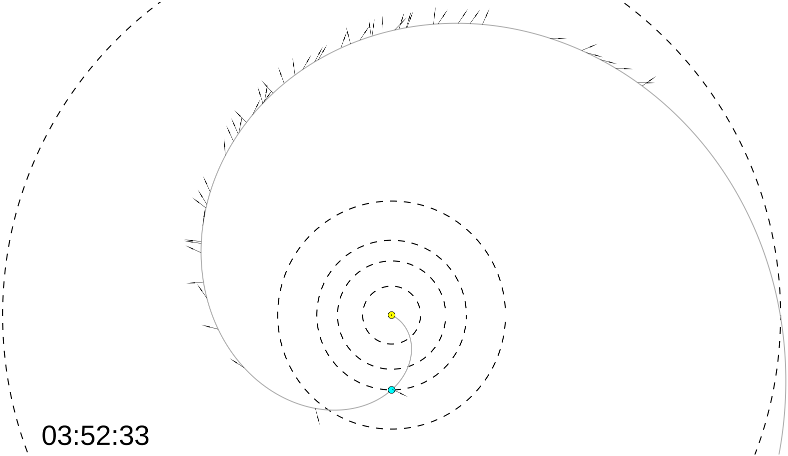
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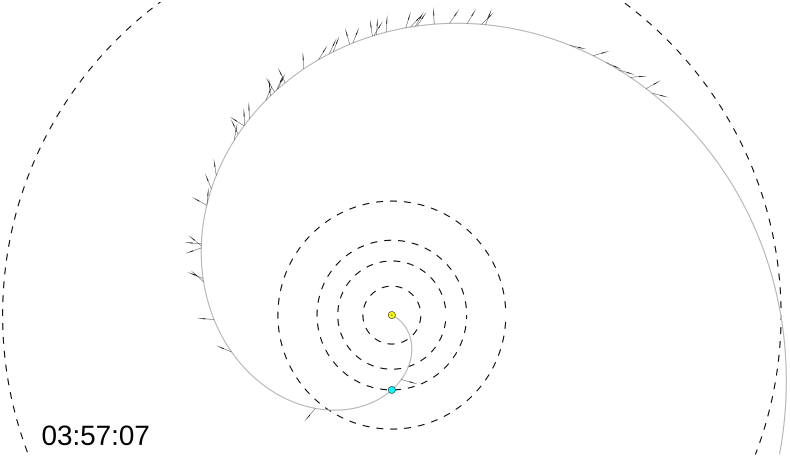
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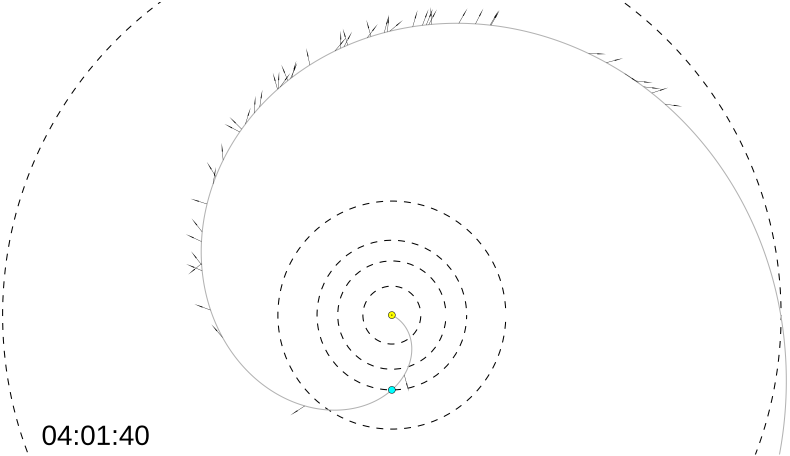
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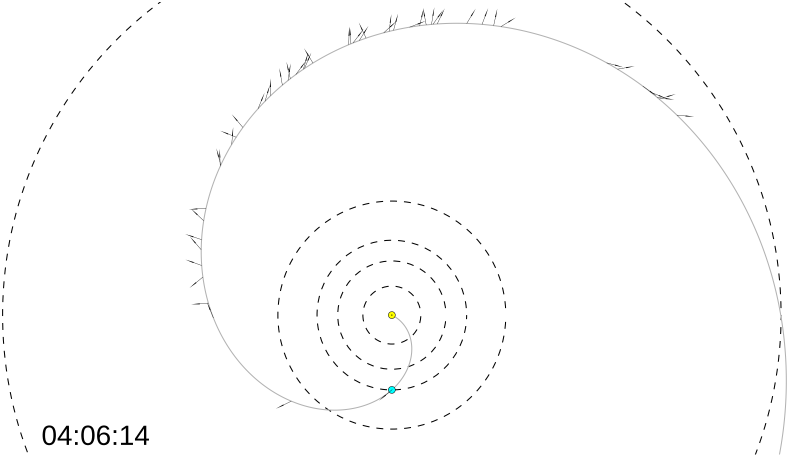
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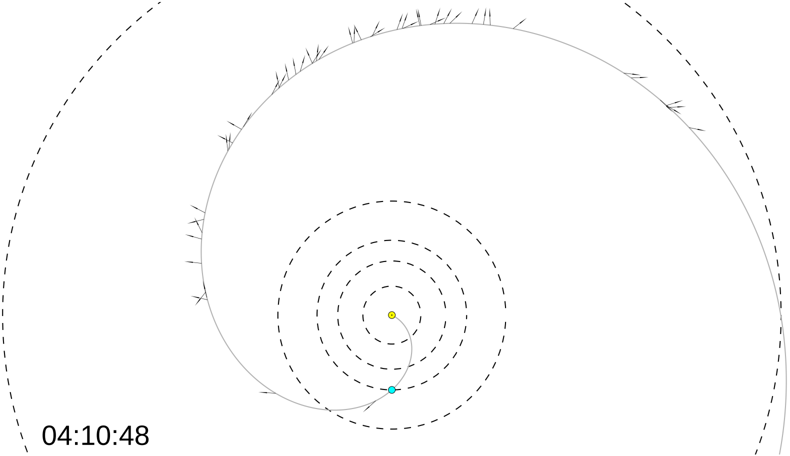

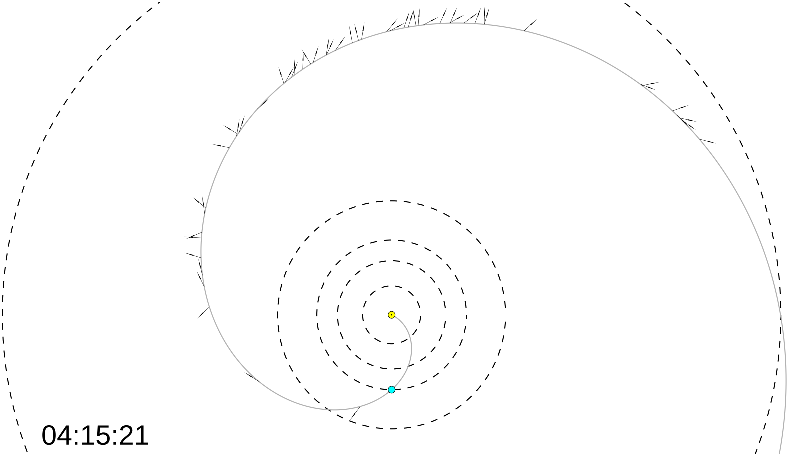
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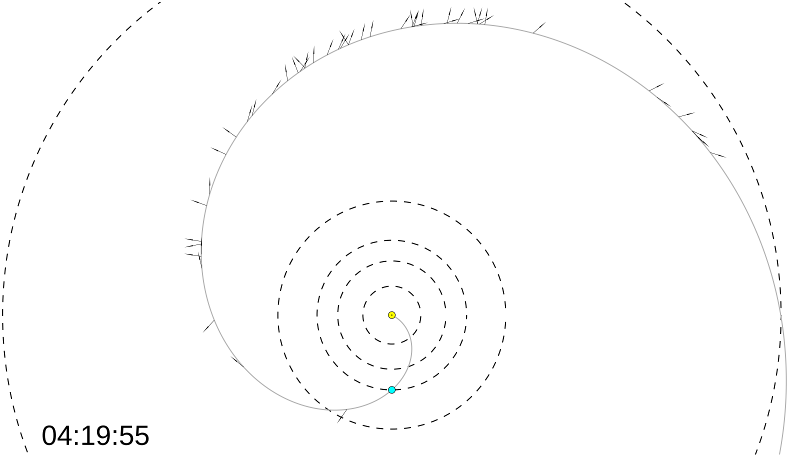
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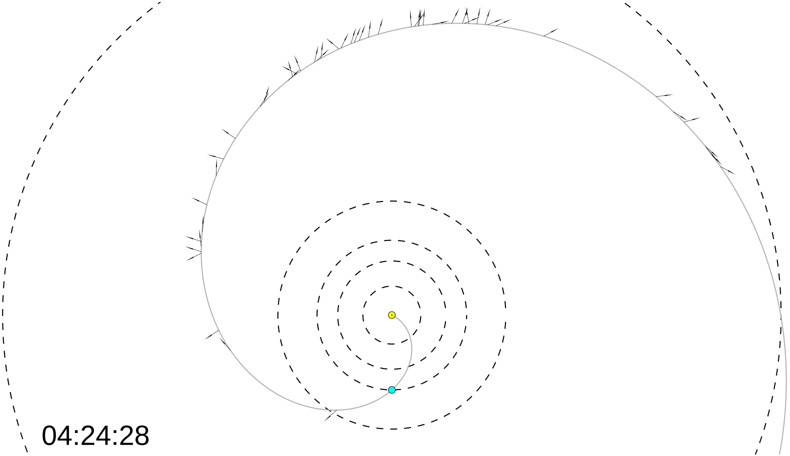
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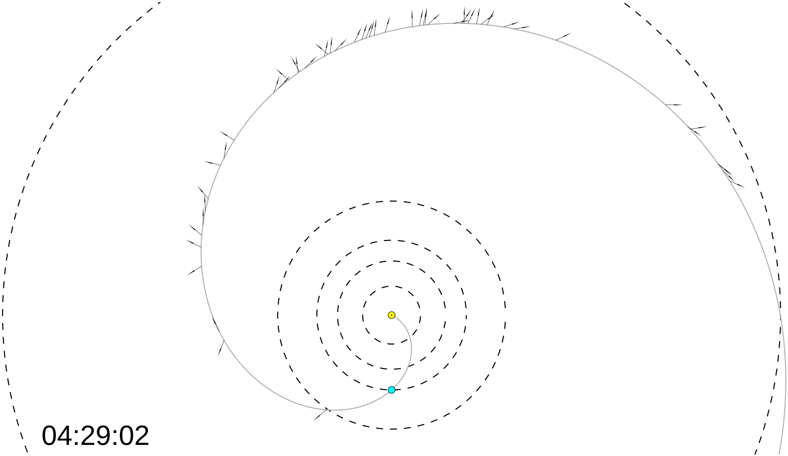
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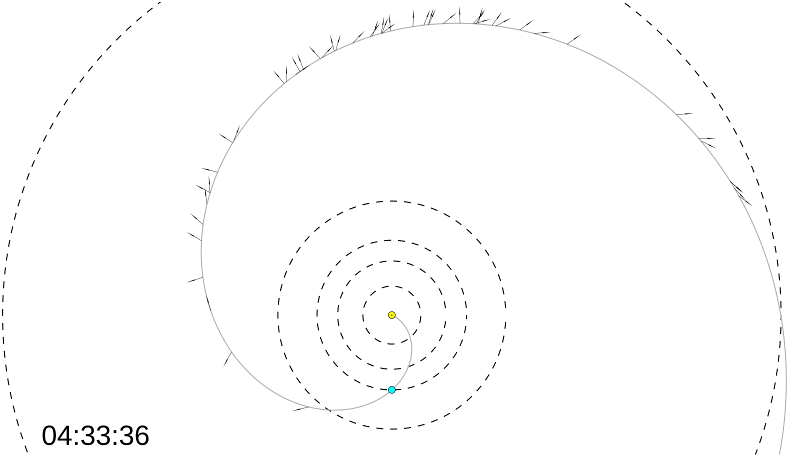

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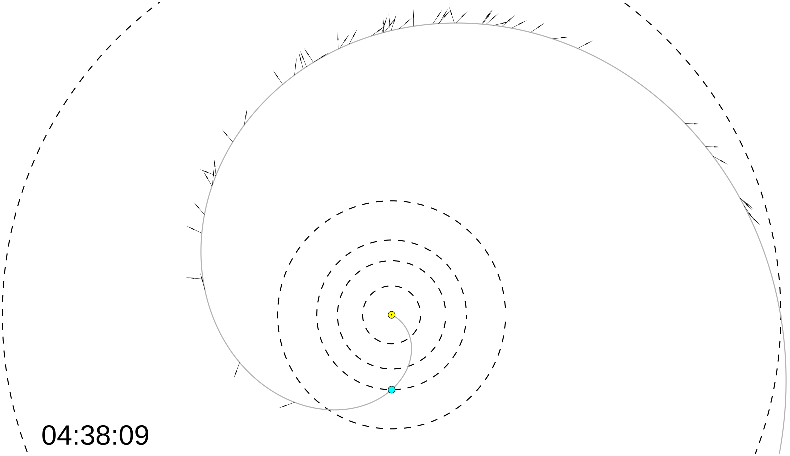
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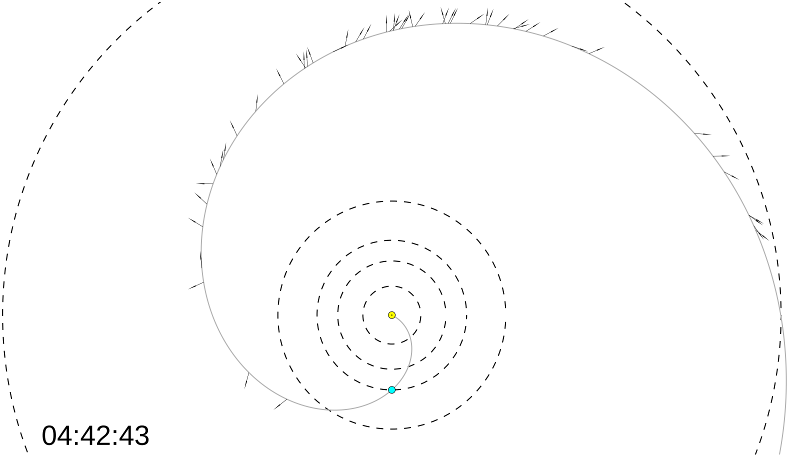
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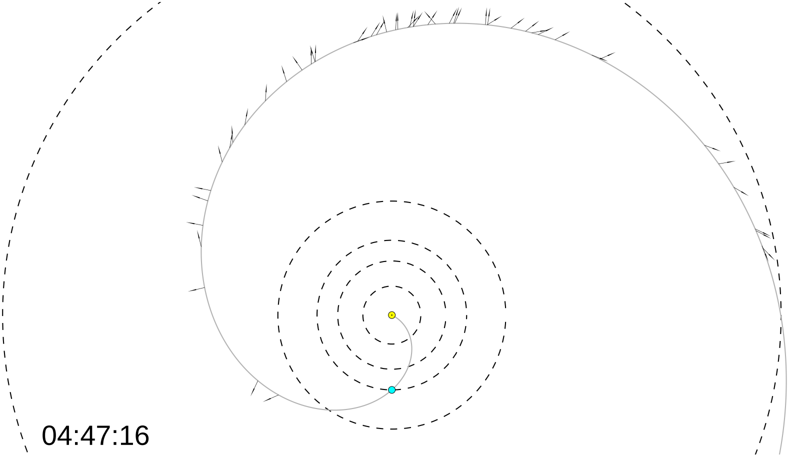
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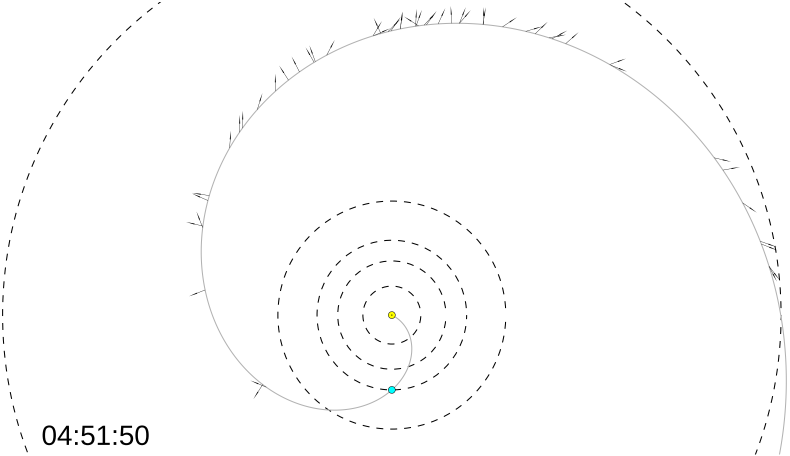
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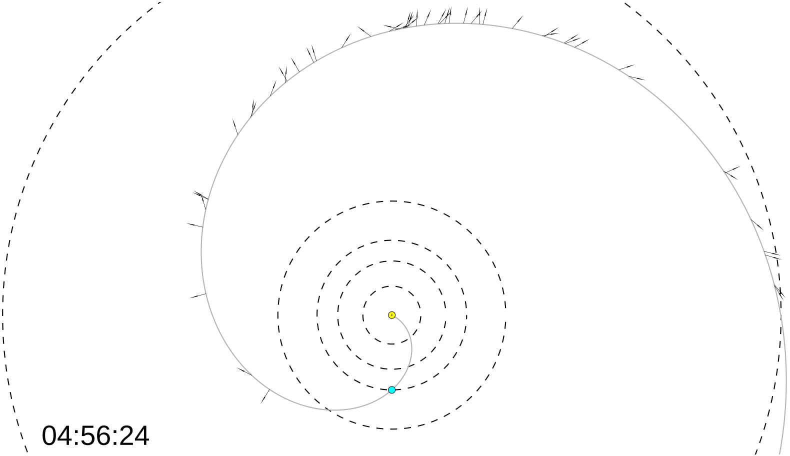
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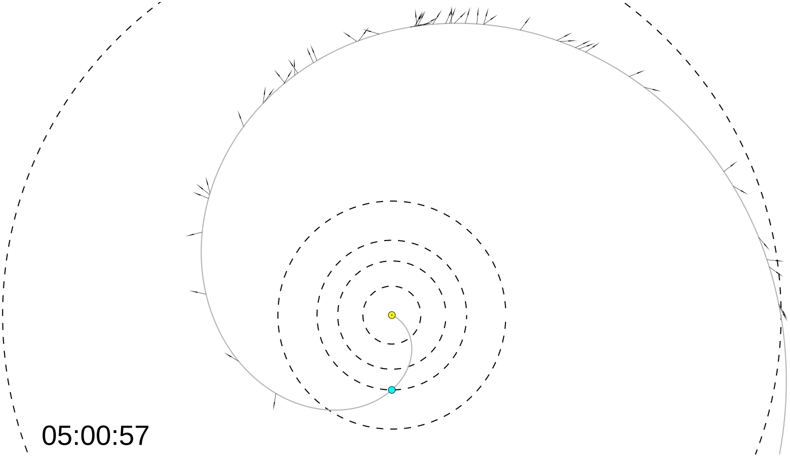
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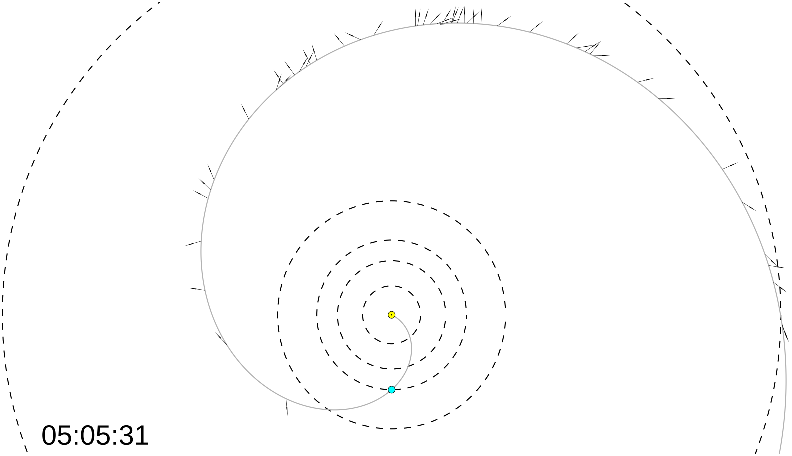
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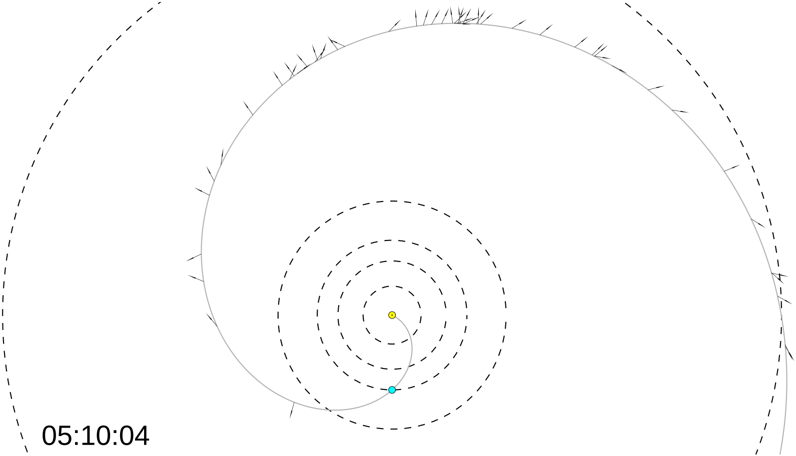
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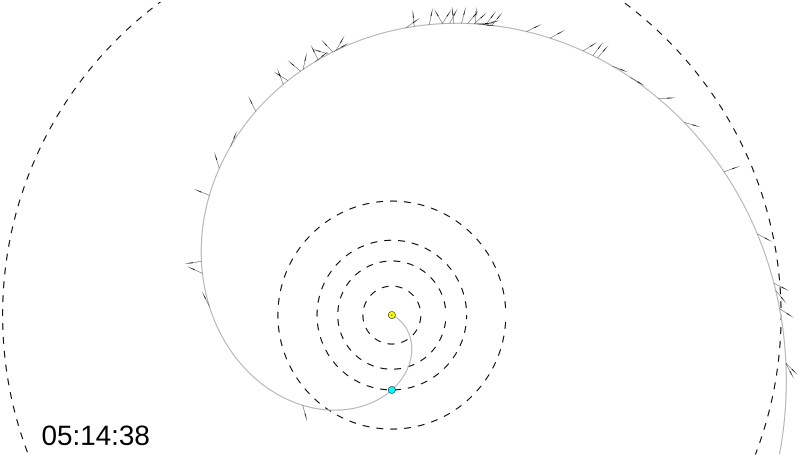

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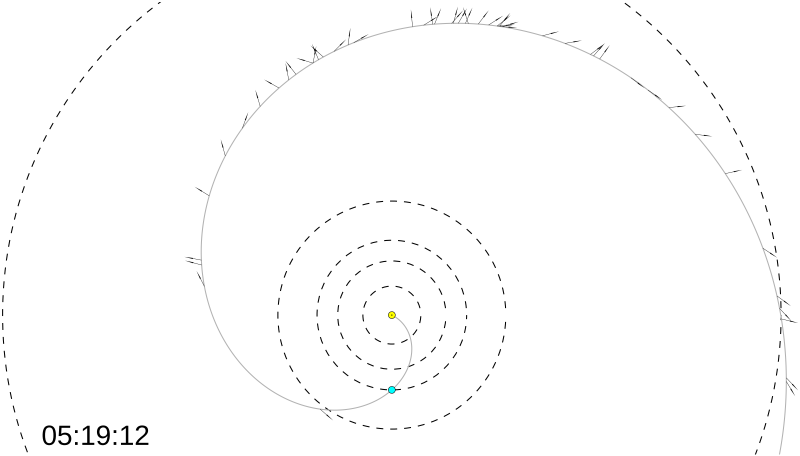
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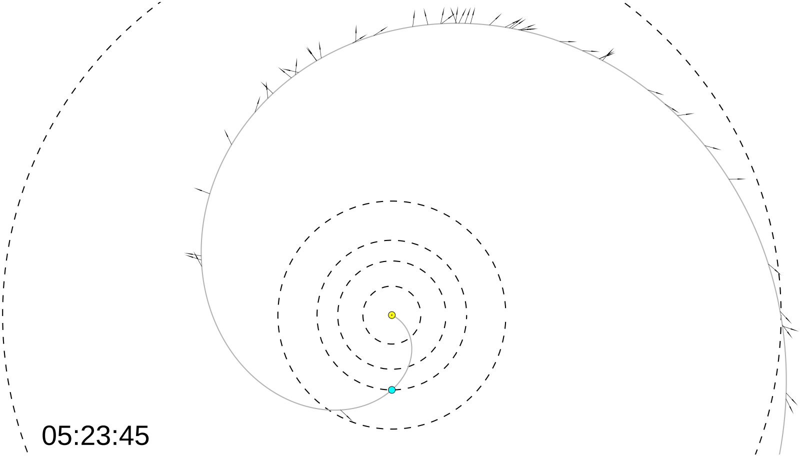
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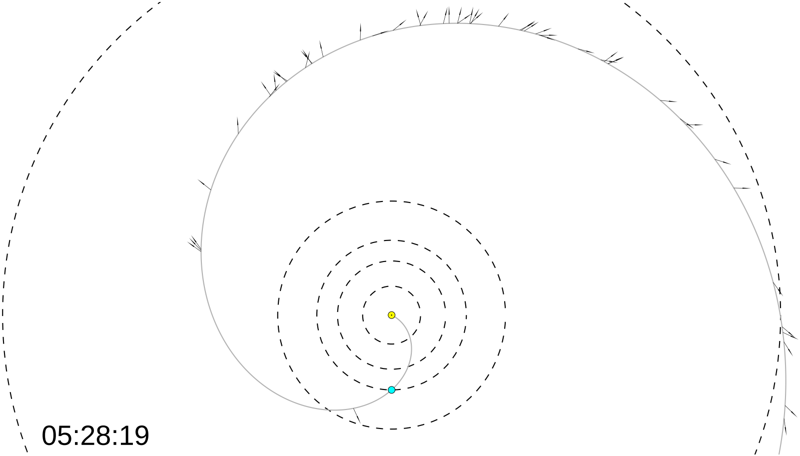
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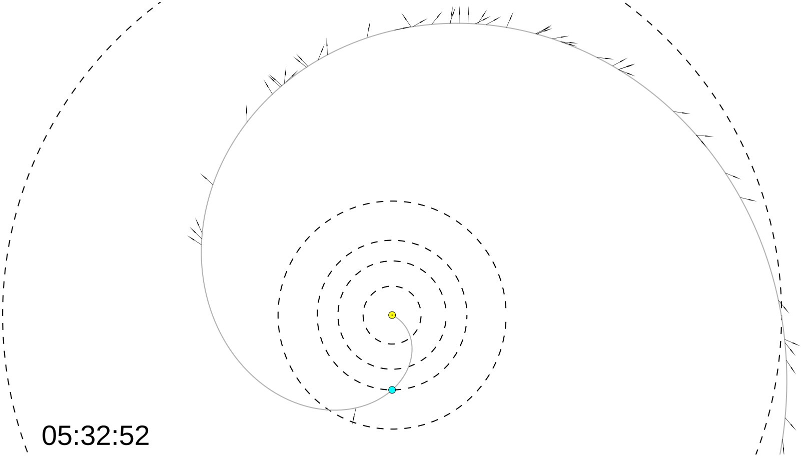
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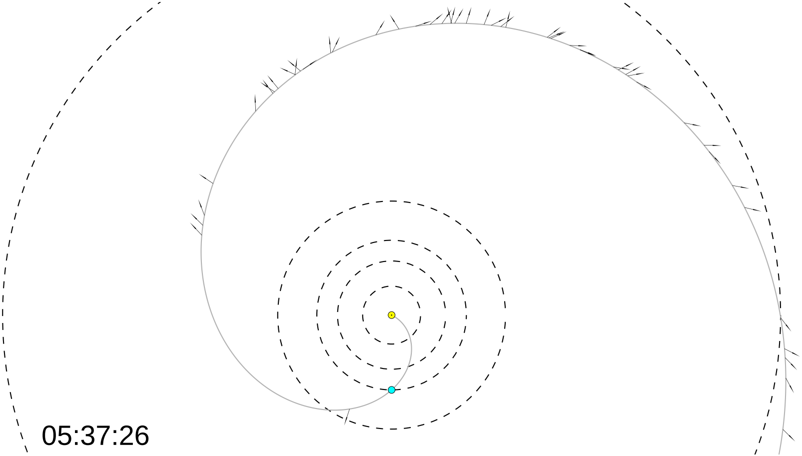
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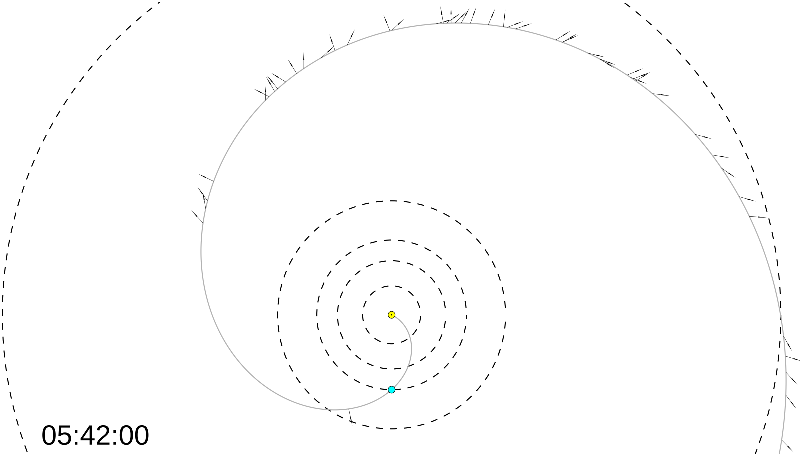
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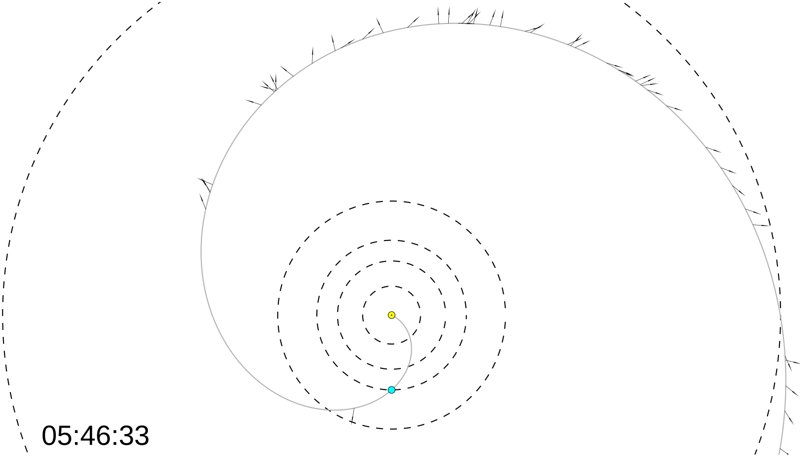

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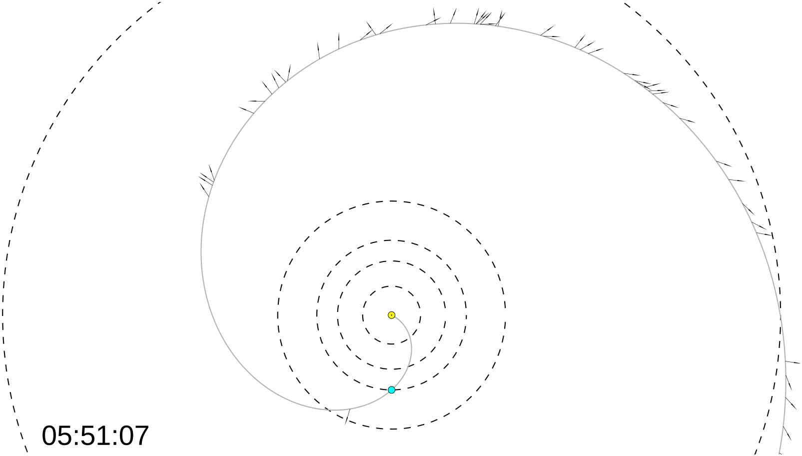
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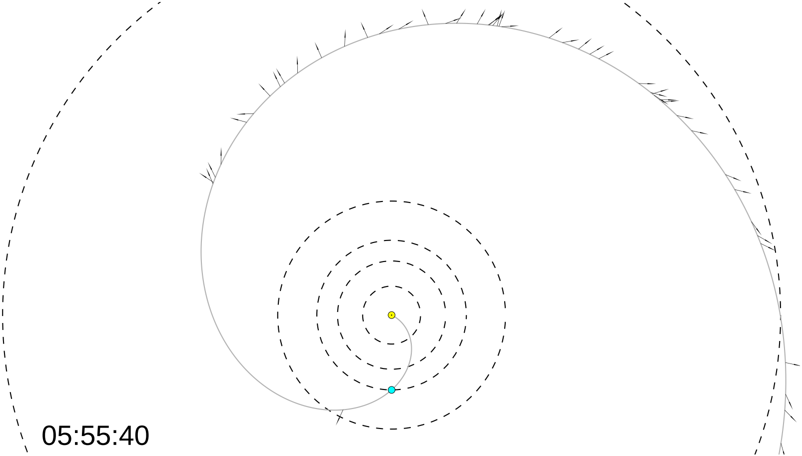
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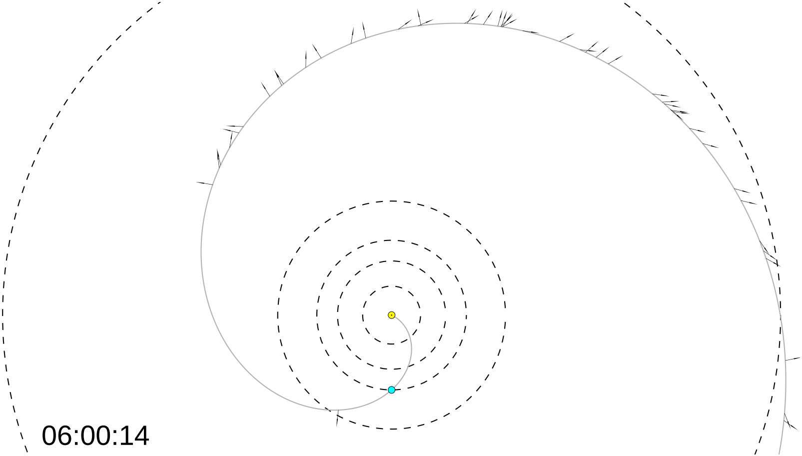

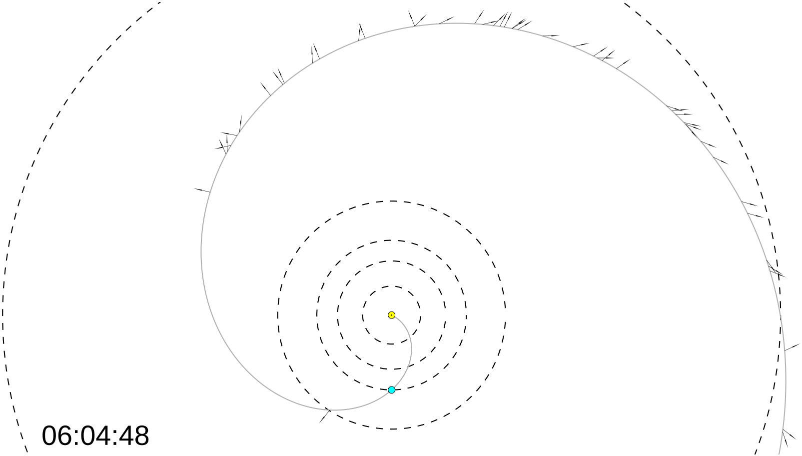

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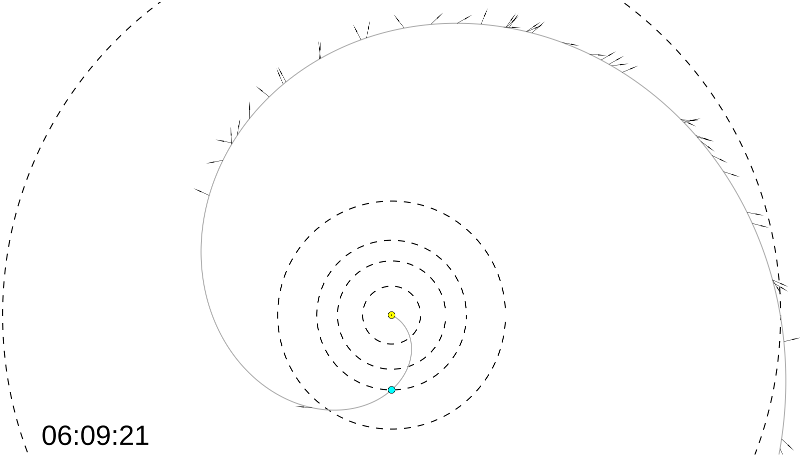
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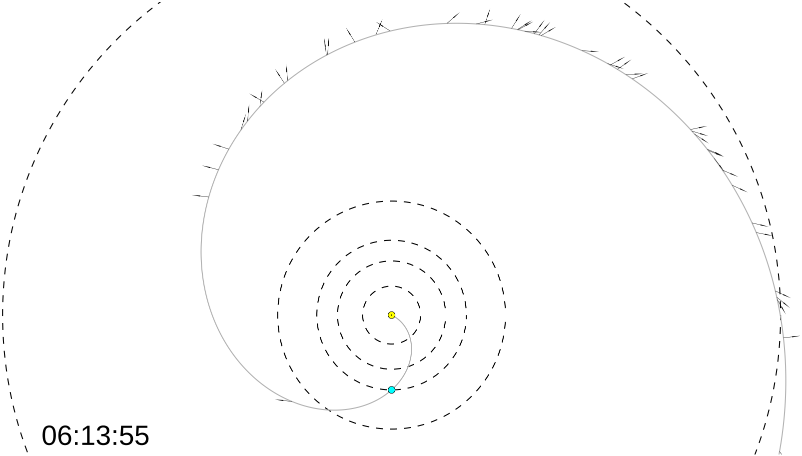
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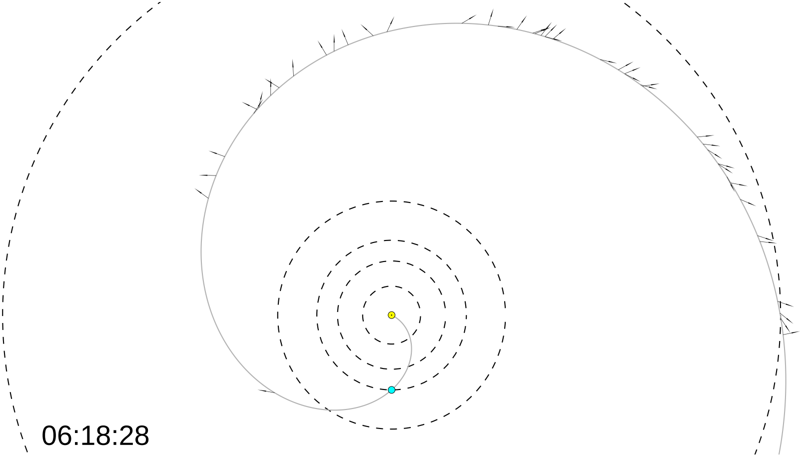

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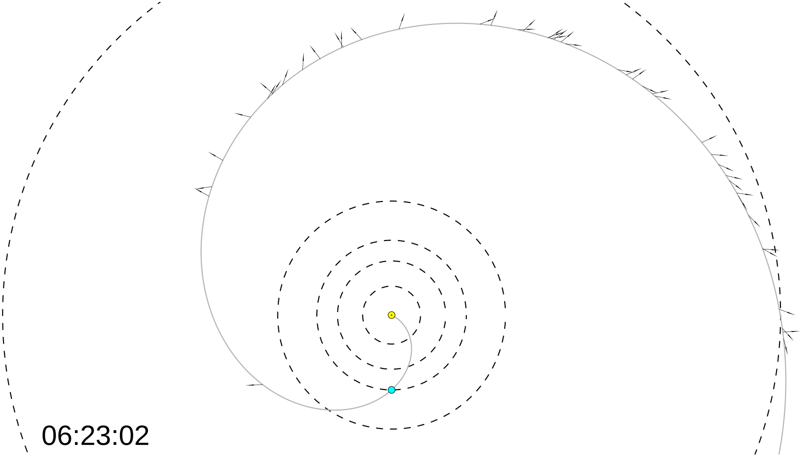
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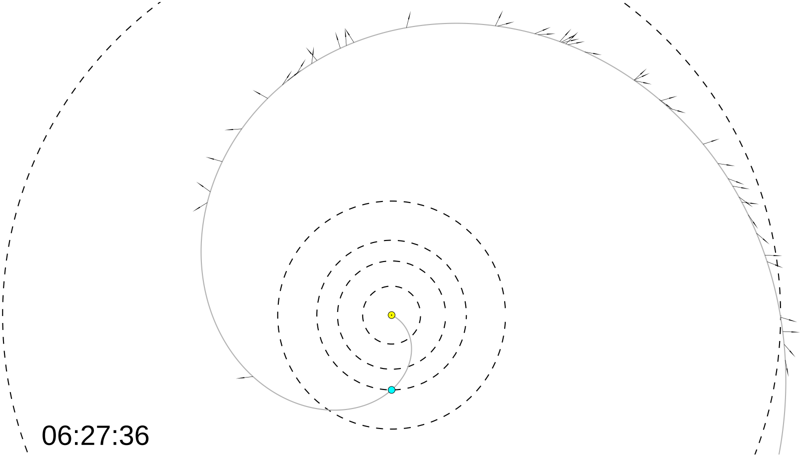

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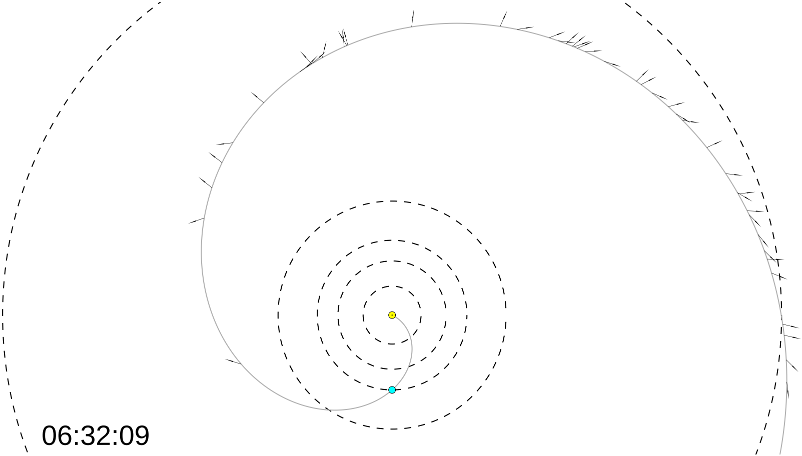
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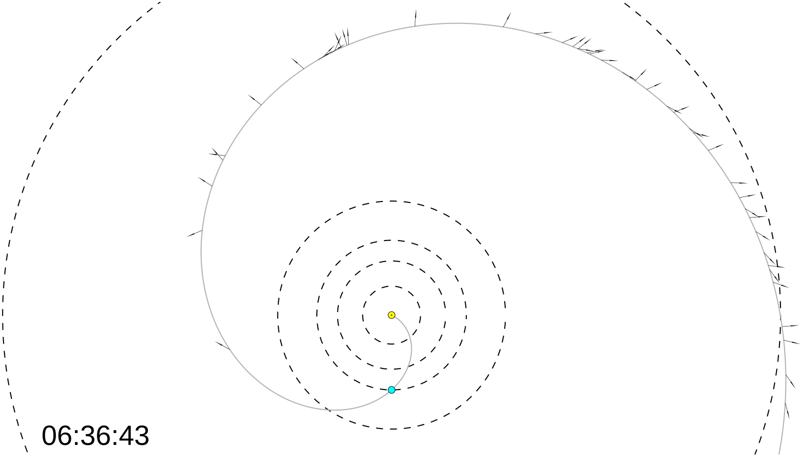
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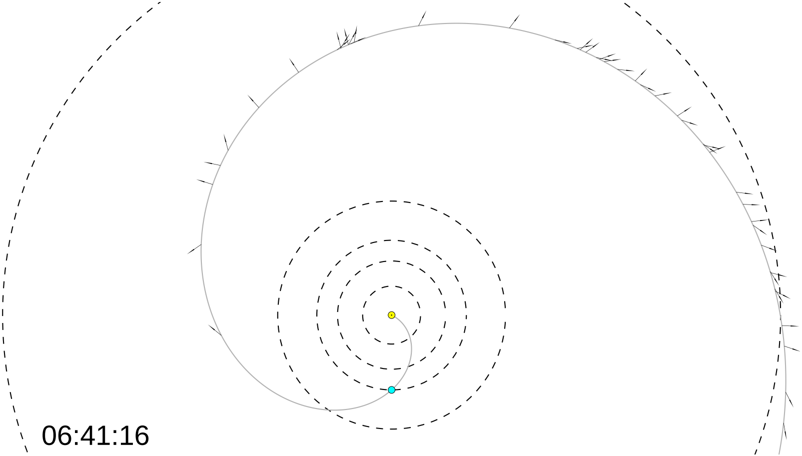
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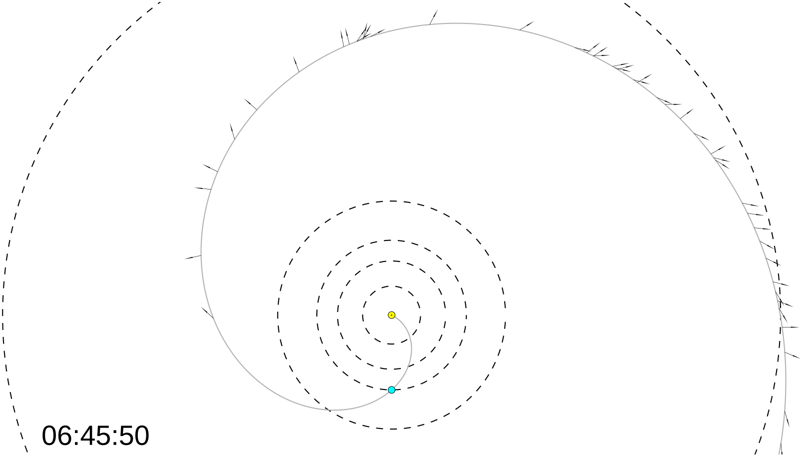
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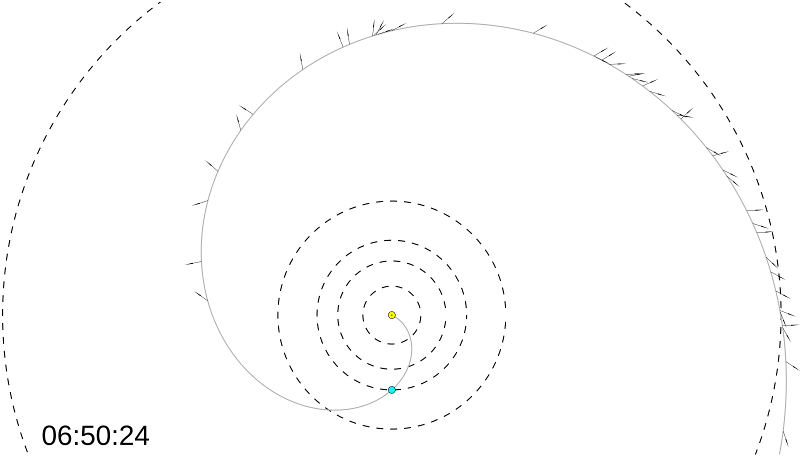
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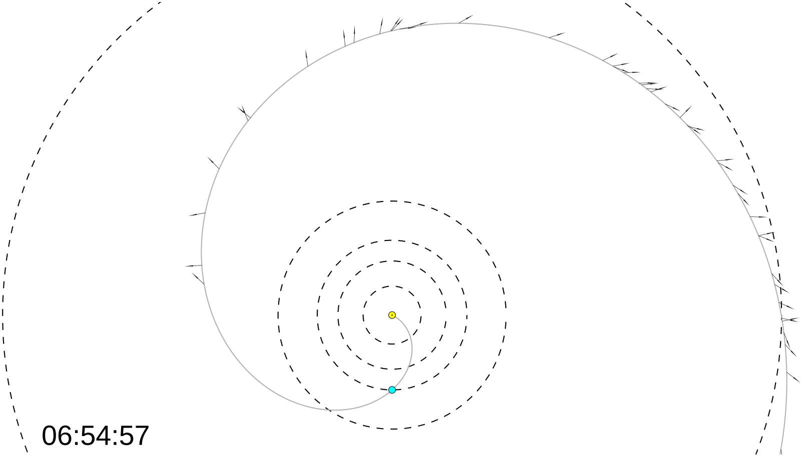
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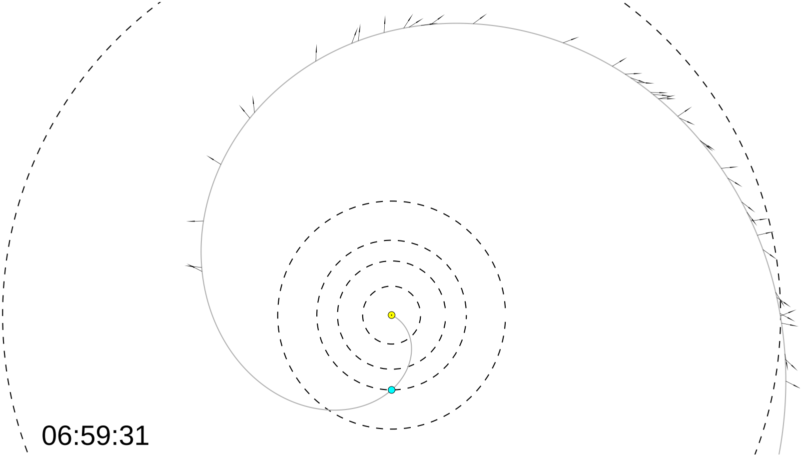
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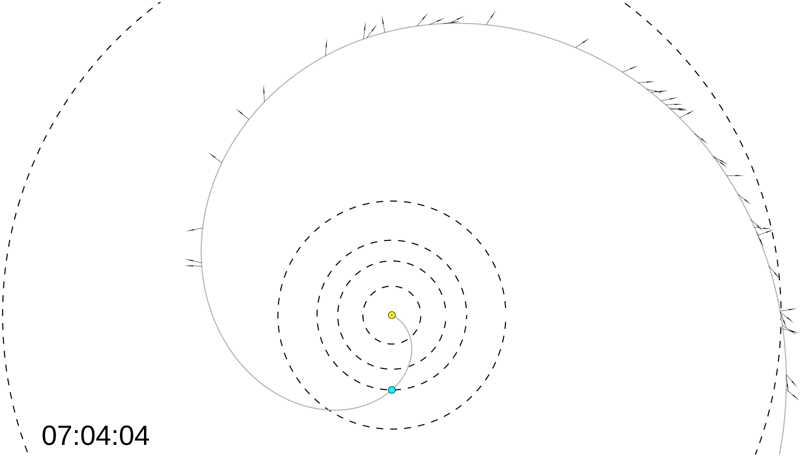

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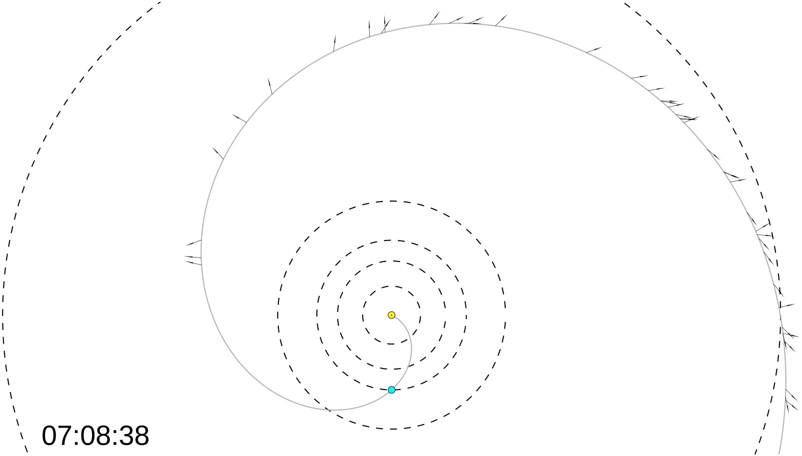
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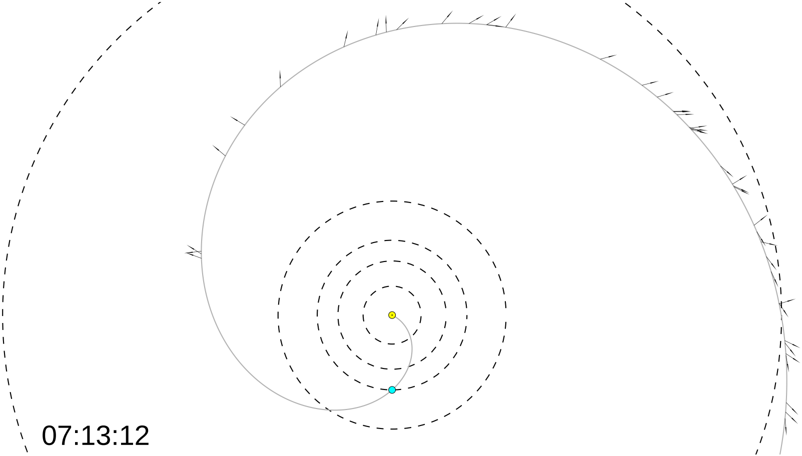
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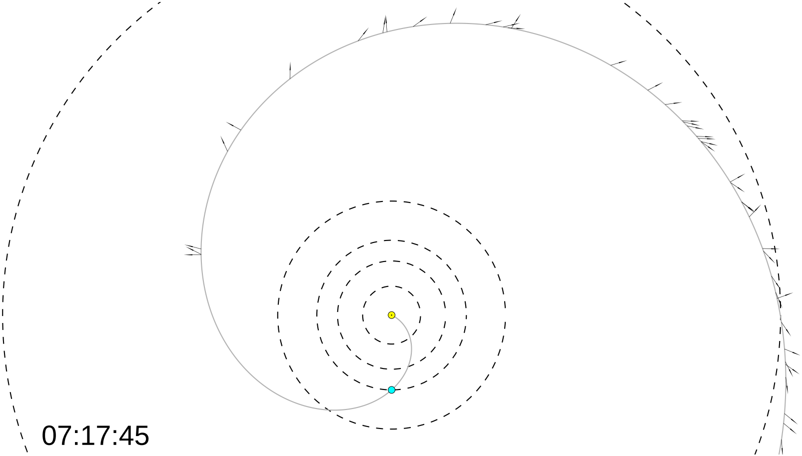
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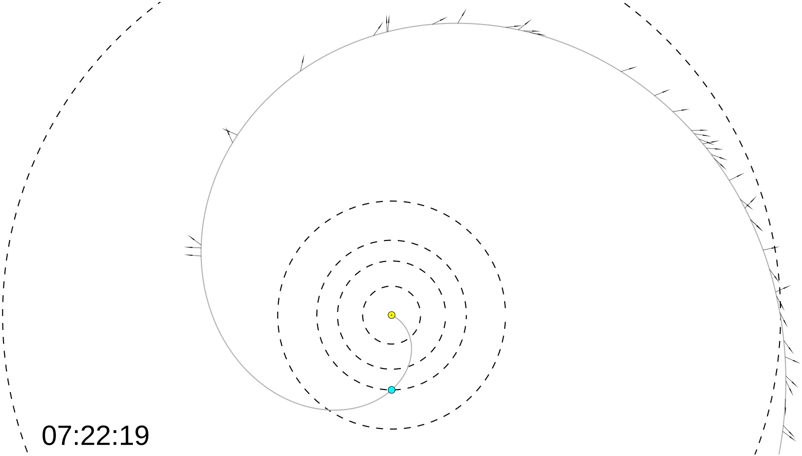
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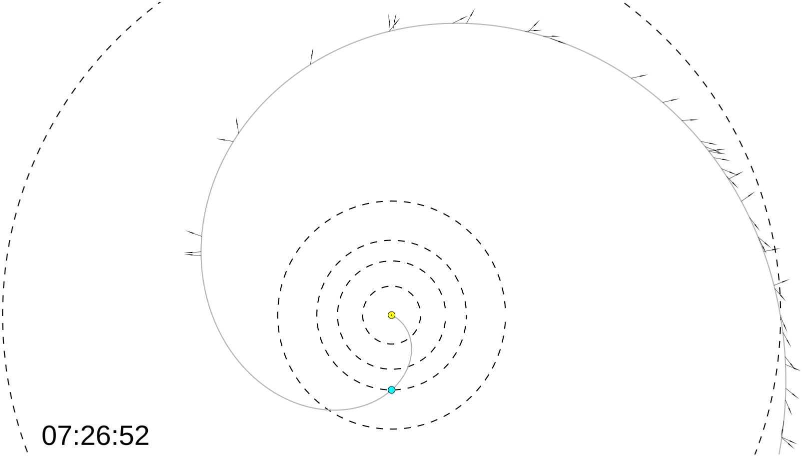
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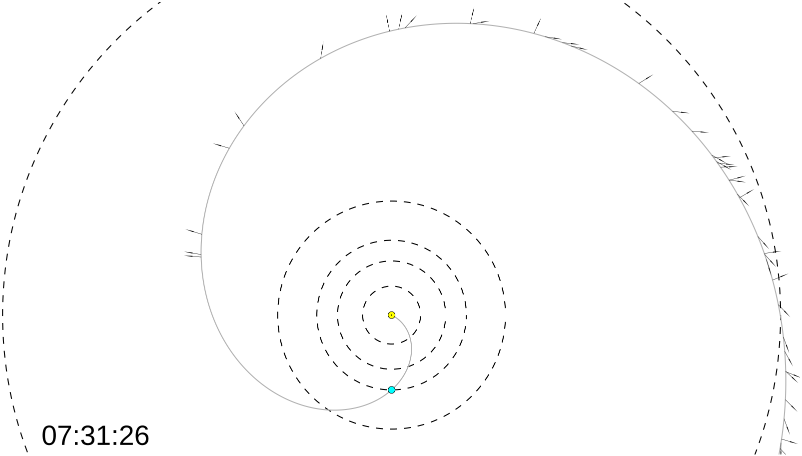
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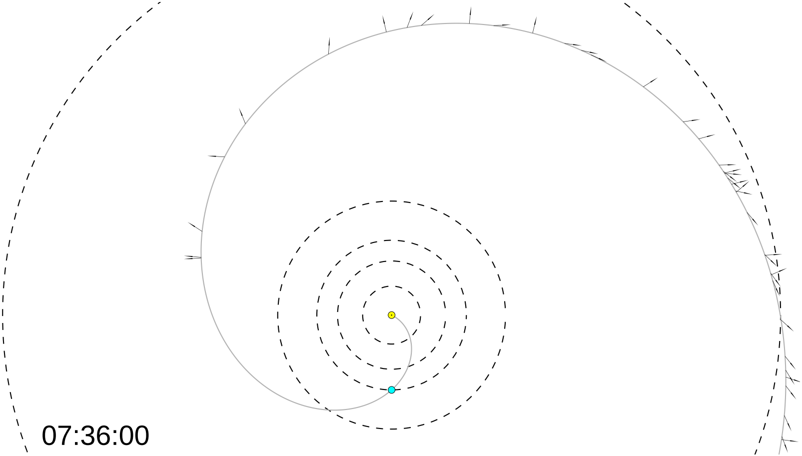
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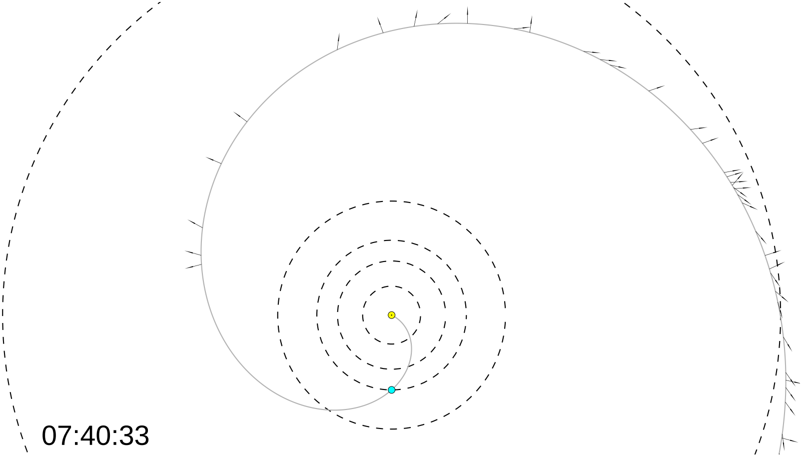
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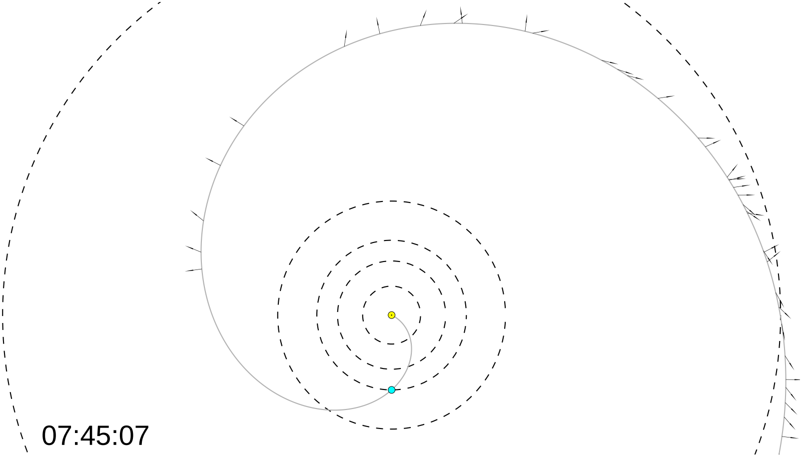
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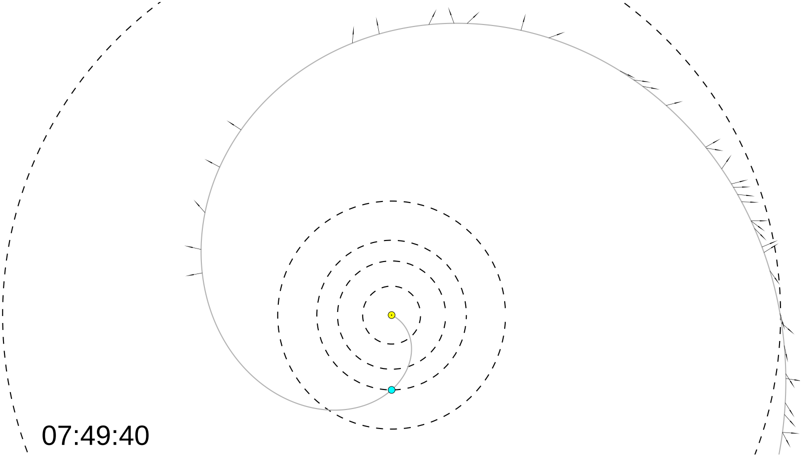
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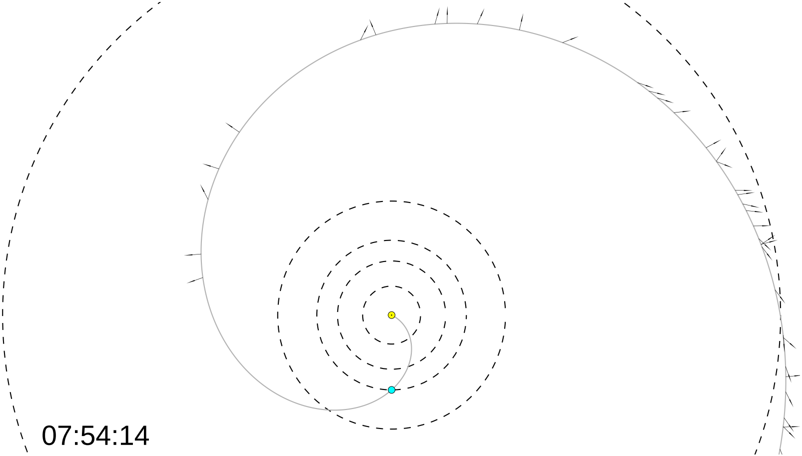

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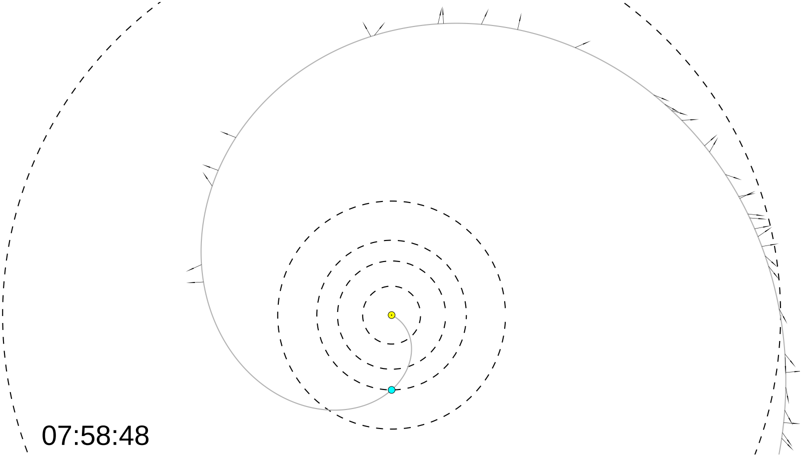
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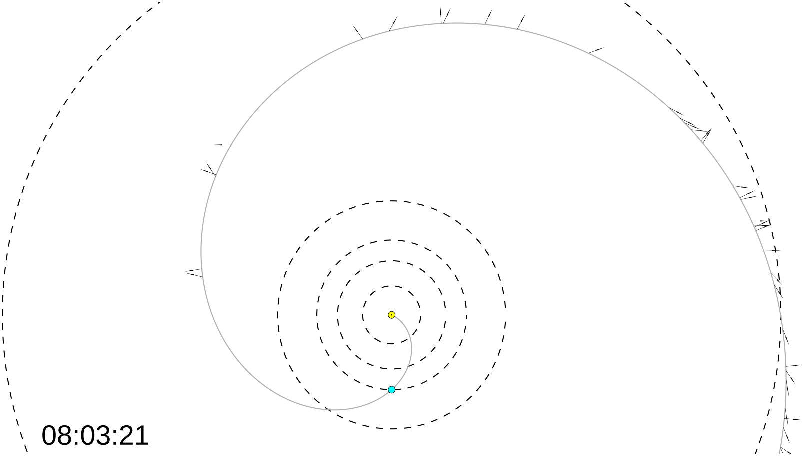
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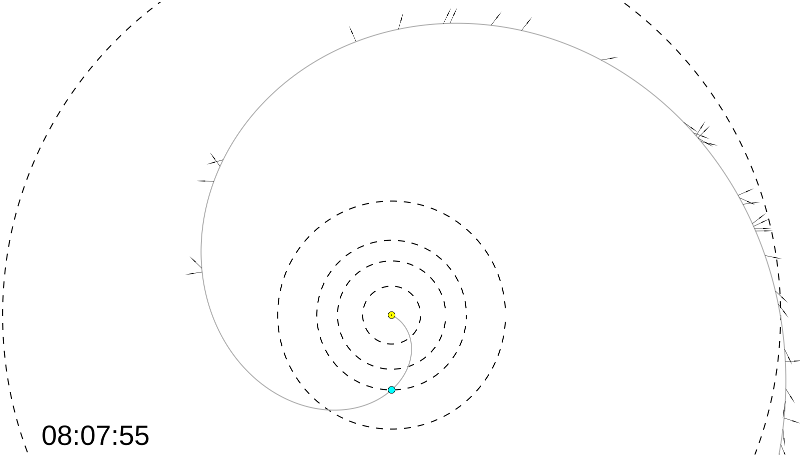

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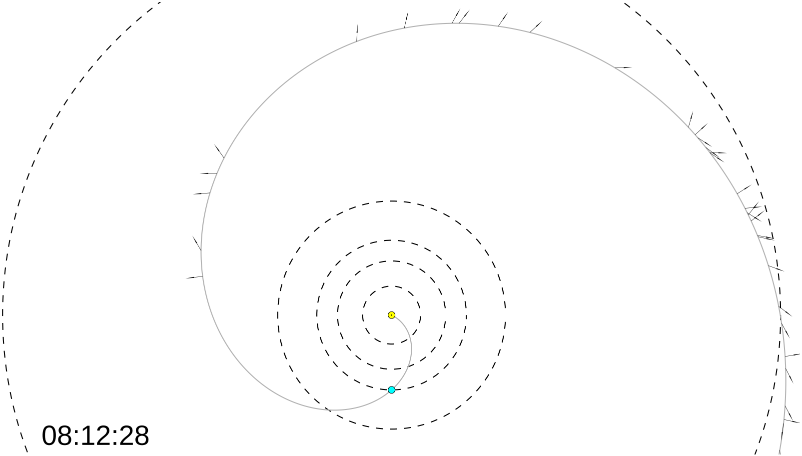
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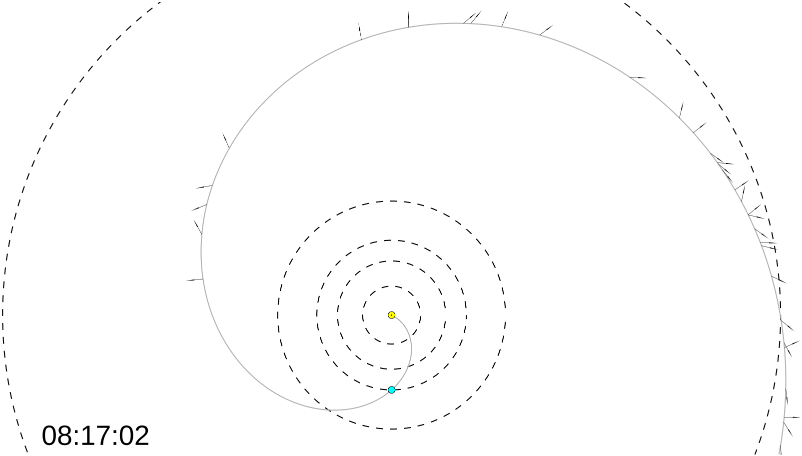
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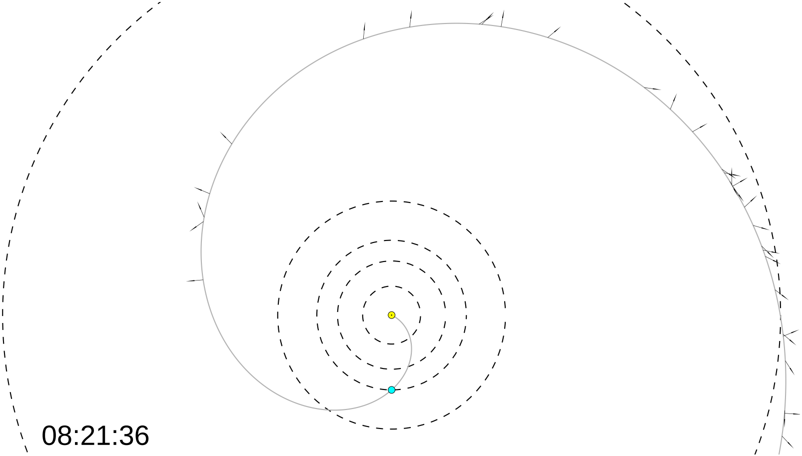
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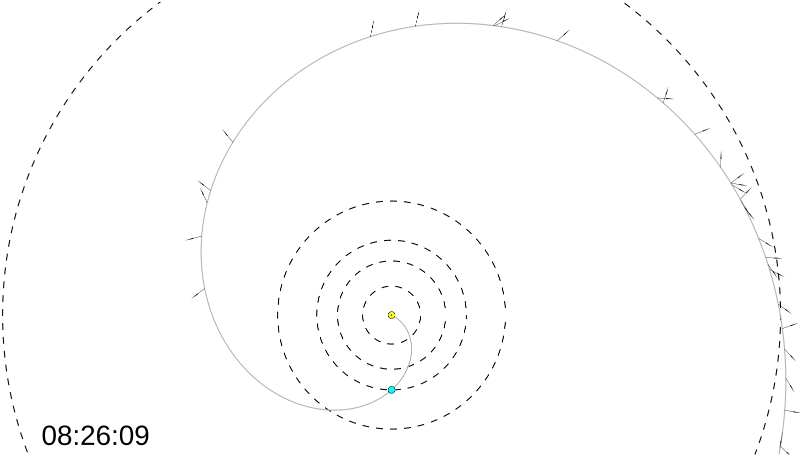
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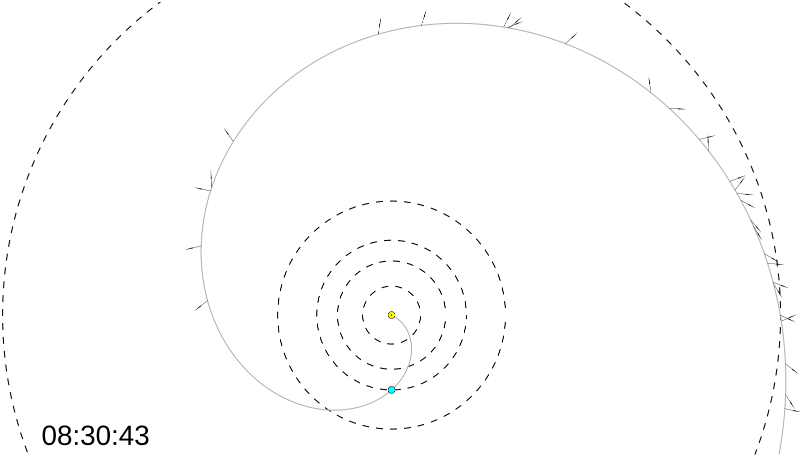

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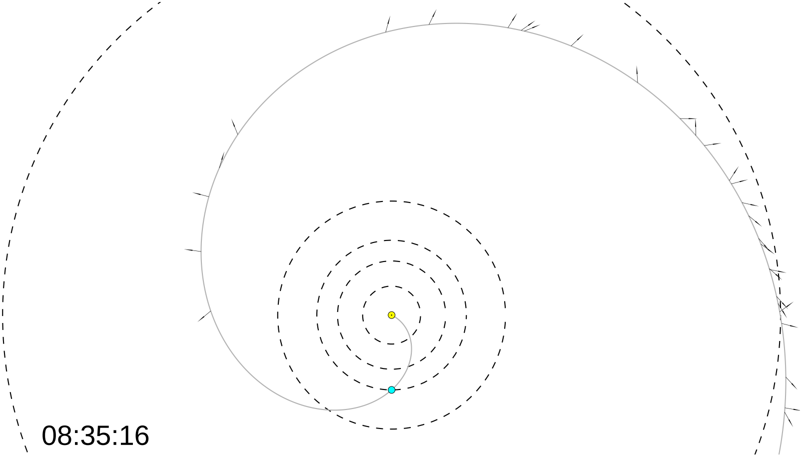
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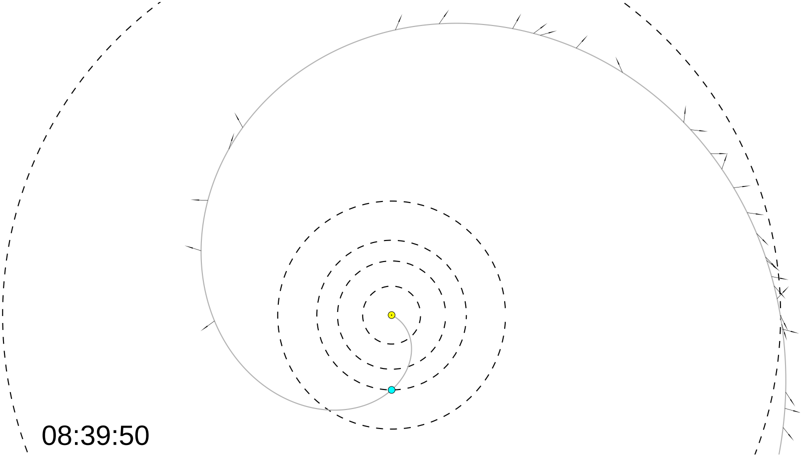
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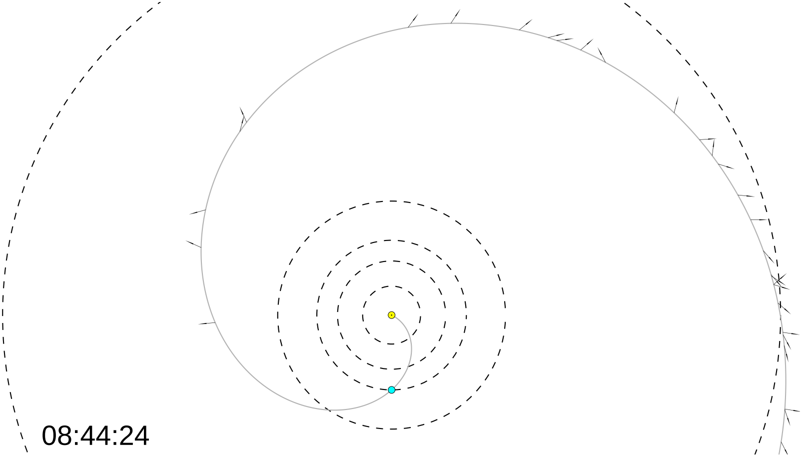
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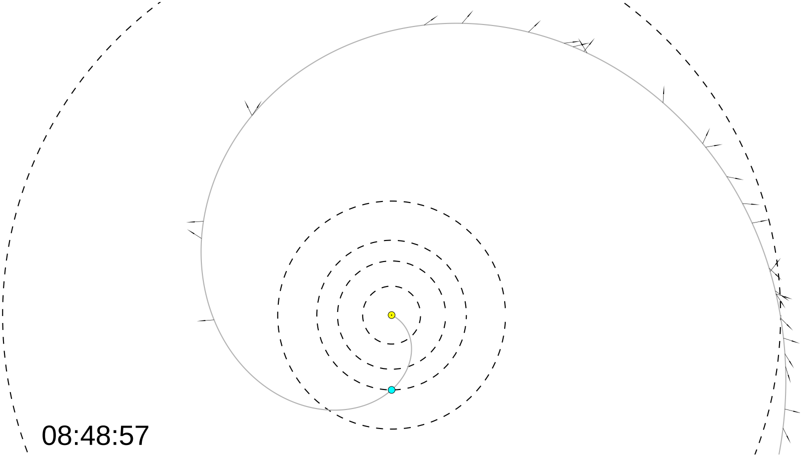
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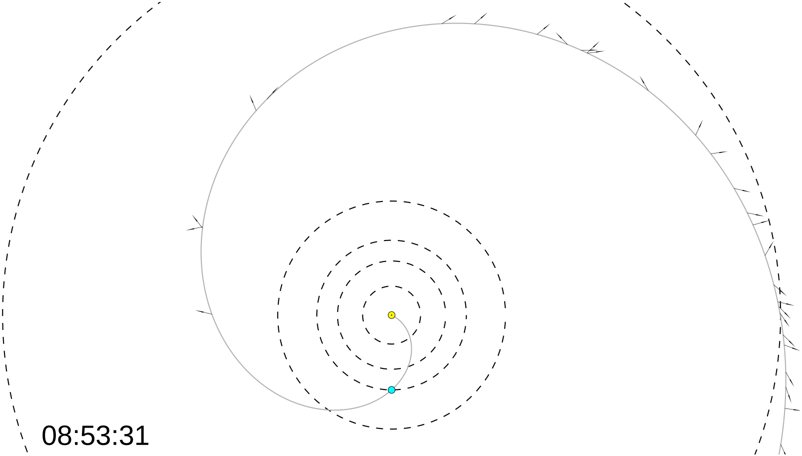
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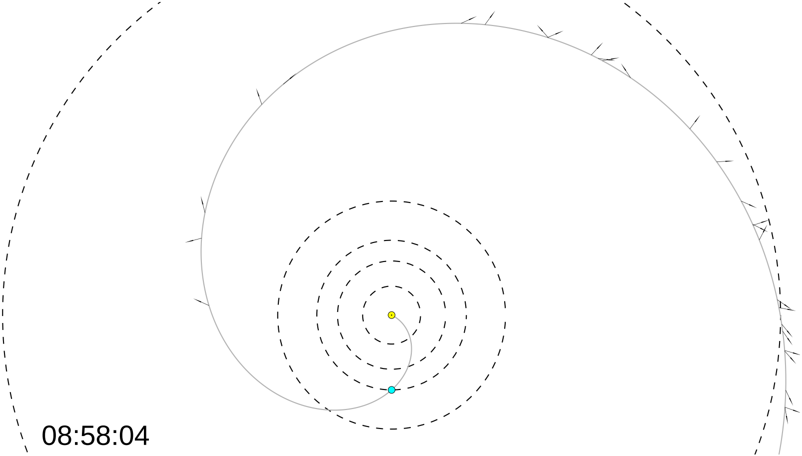
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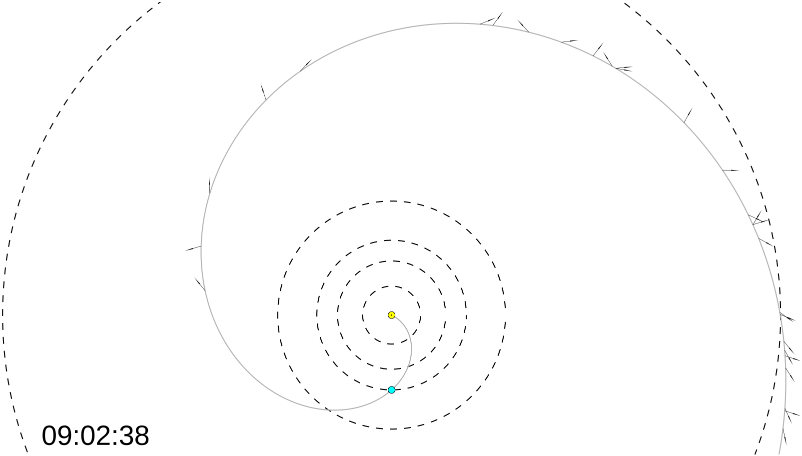
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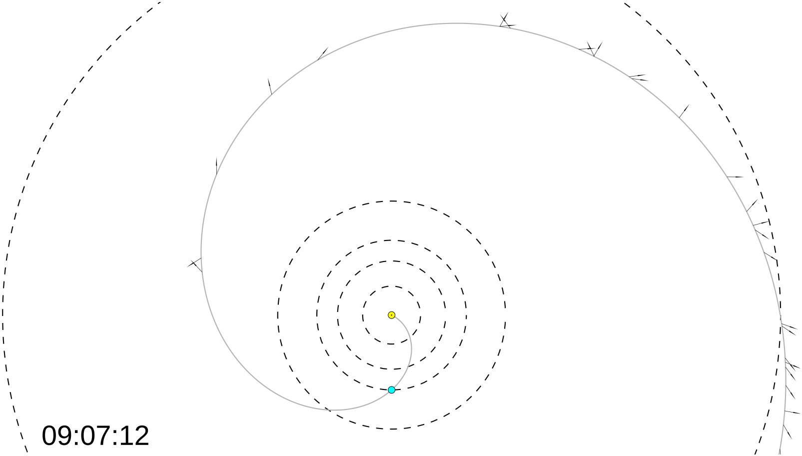

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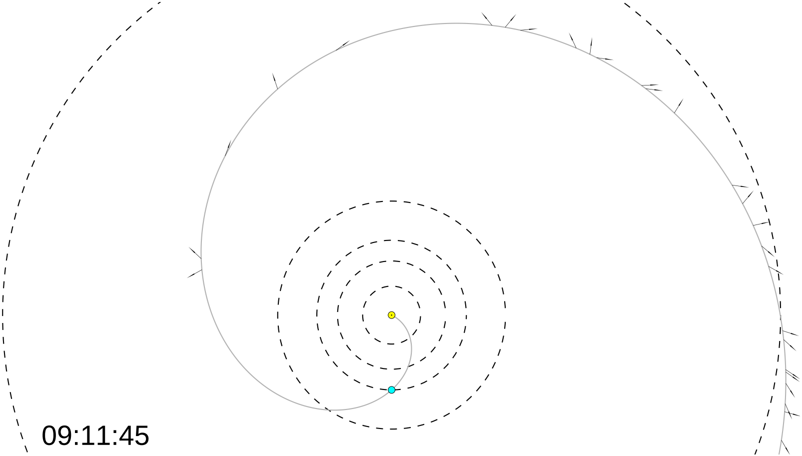
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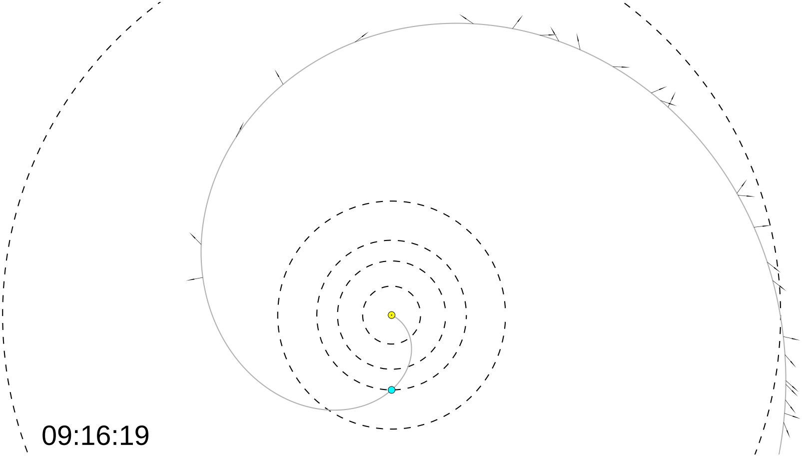
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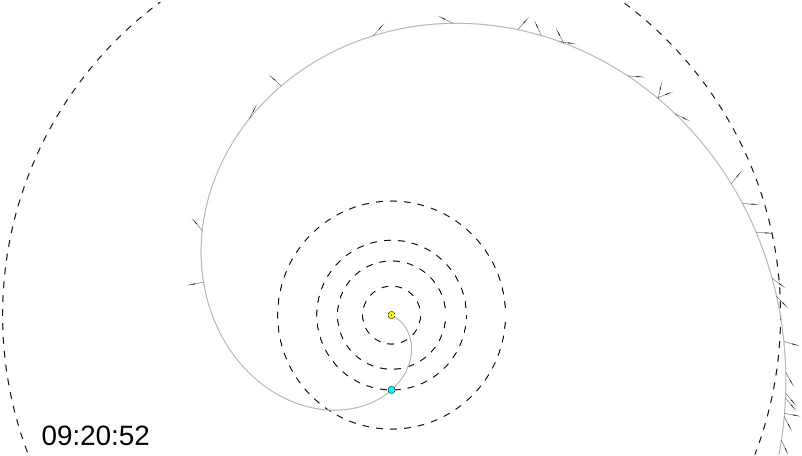
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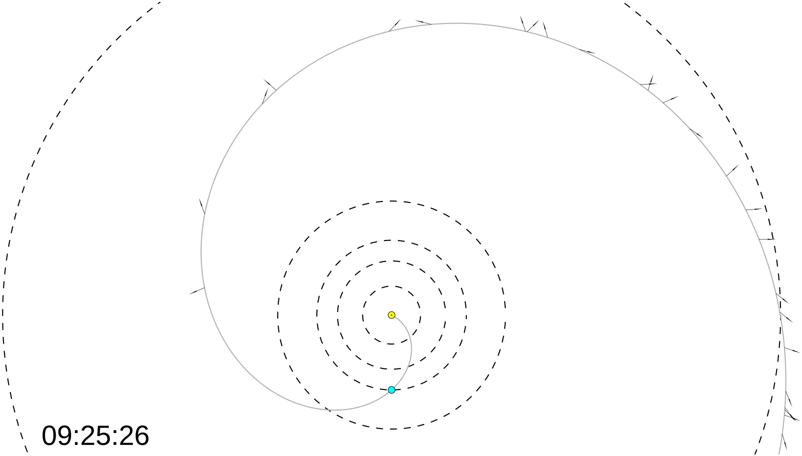

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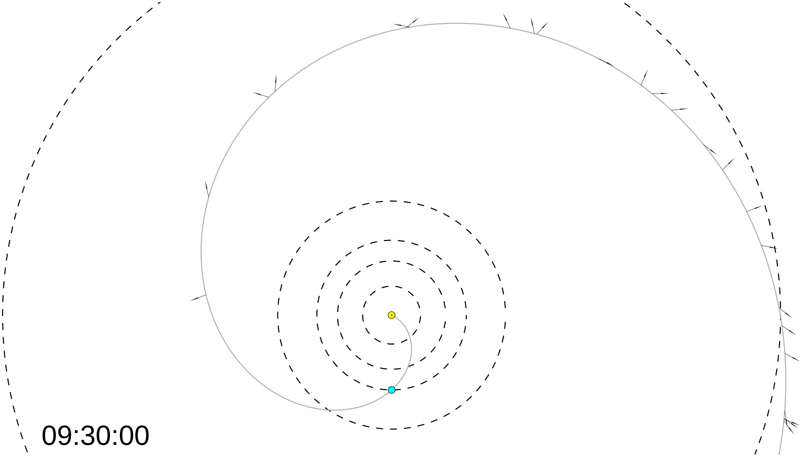
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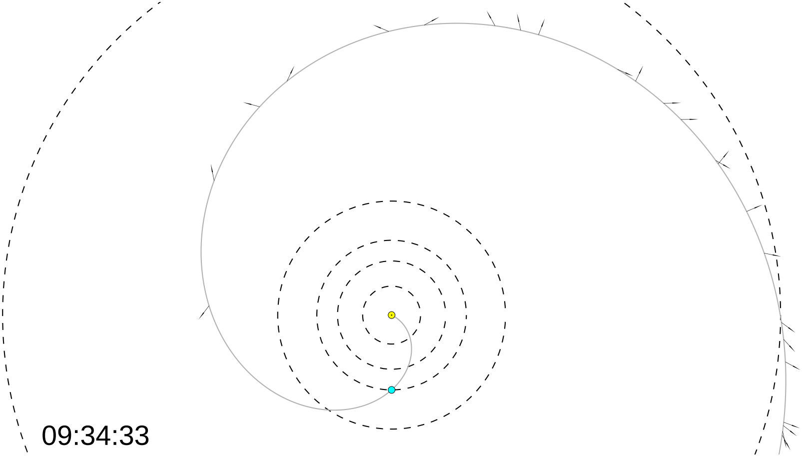
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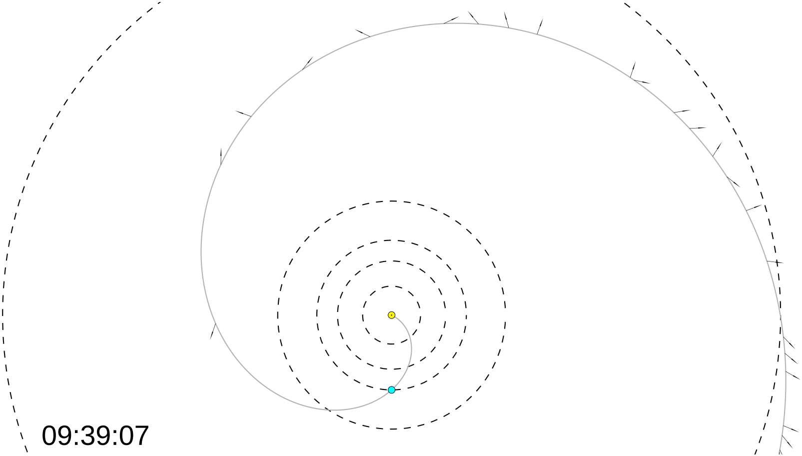
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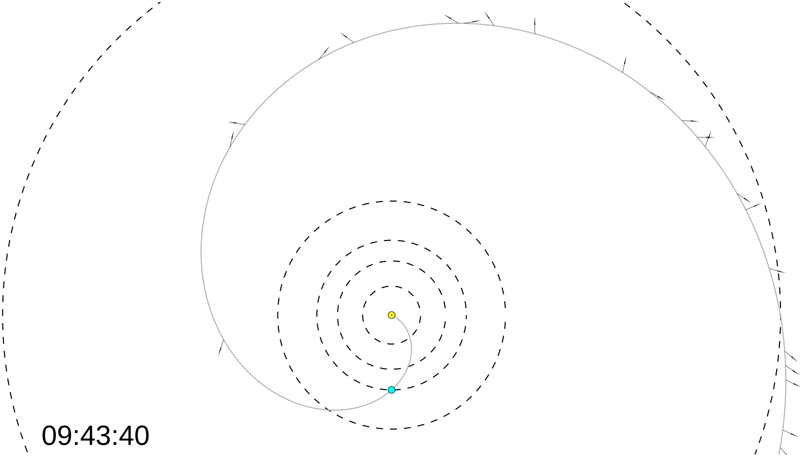
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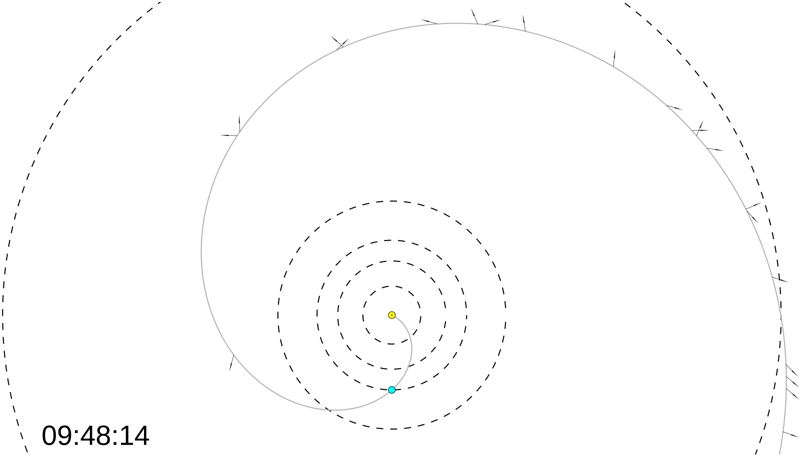
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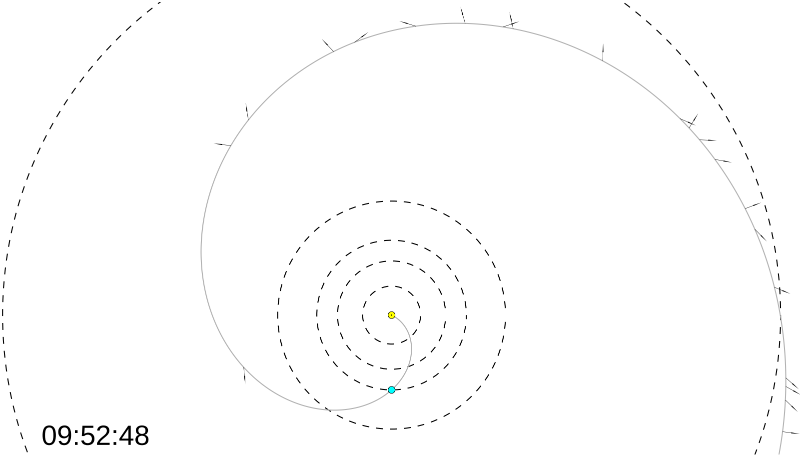
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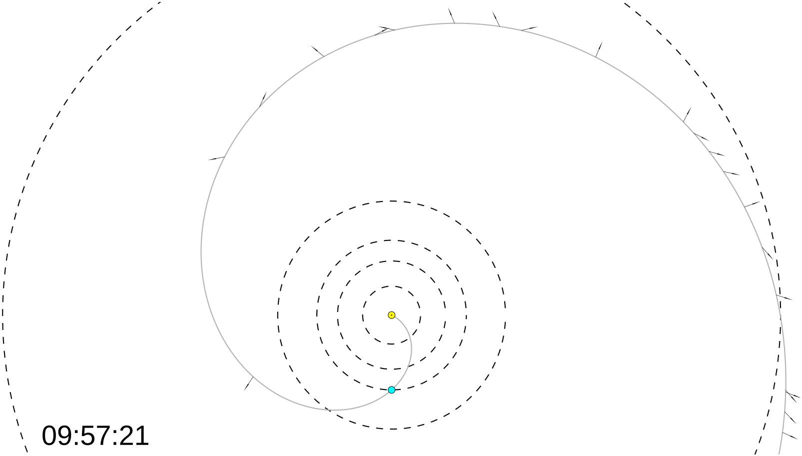

Focused transport with scattering.

Example:

- 50 electrons, with 100 keV, released from 3 Rs in ecliptic plane
- outward motion, initial μ uniform in]0,1[
- spiral magnetic field (solar wind 400 km/s)
- magnetic field intensity varying as R^{-2}
- constant mean free path $\lambda = 0.1$ AU

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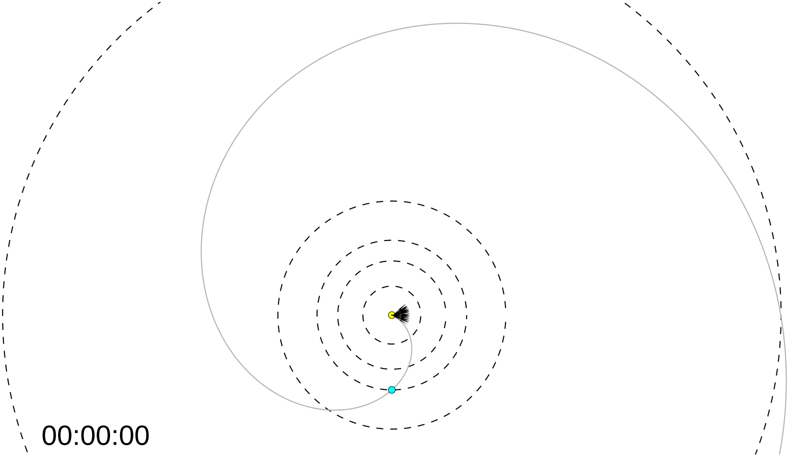
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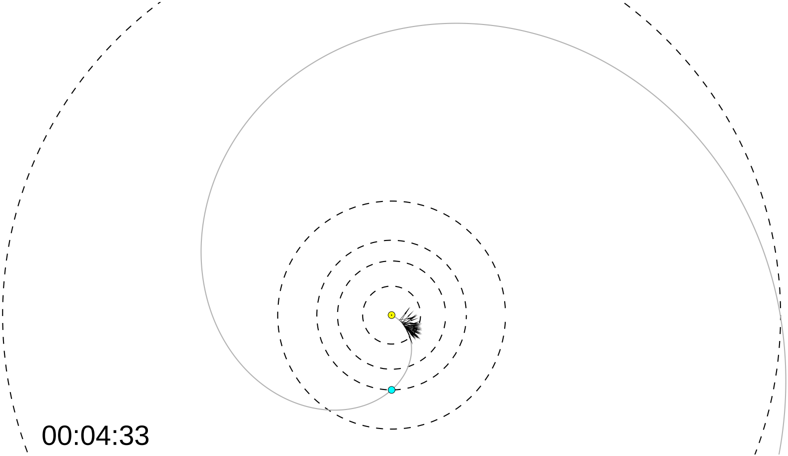
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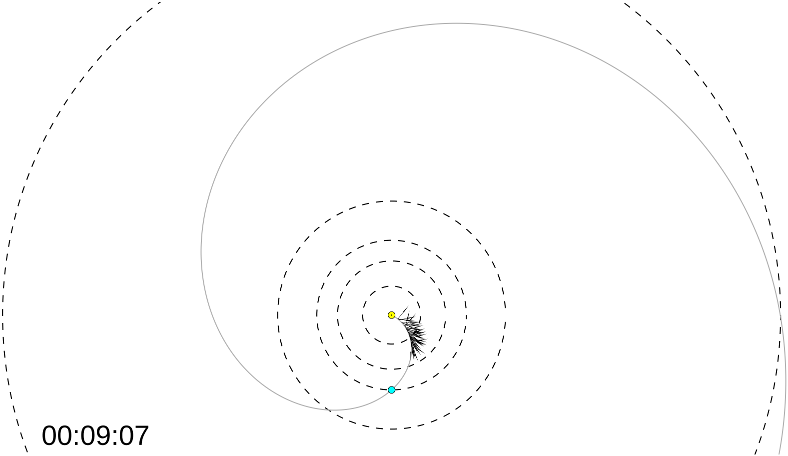
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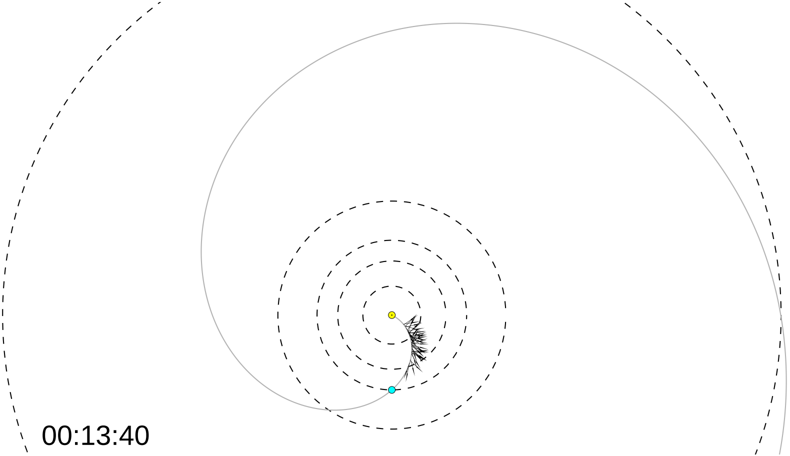
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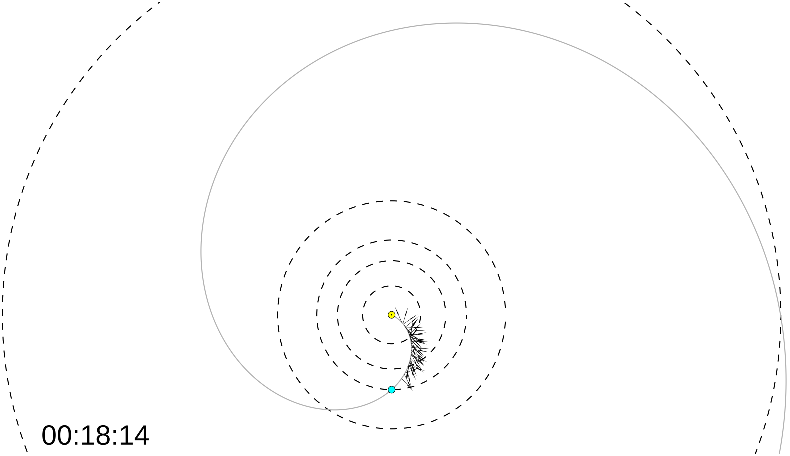
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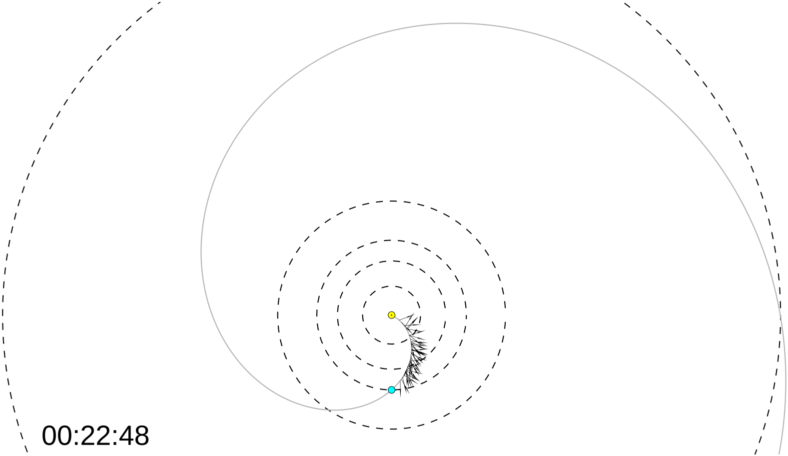
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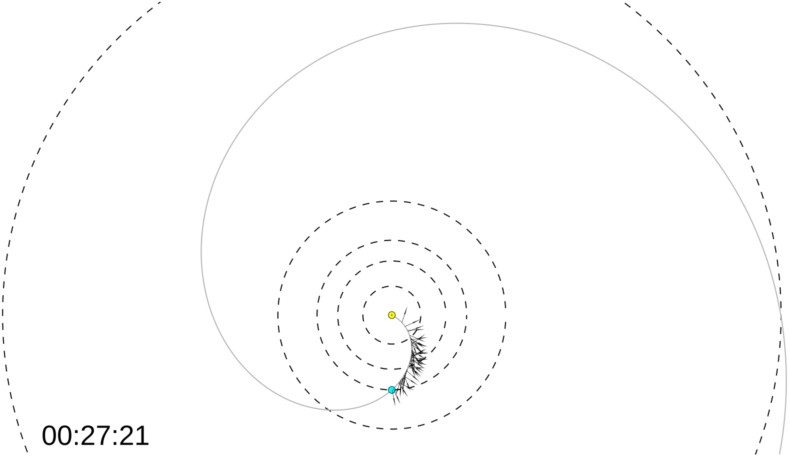
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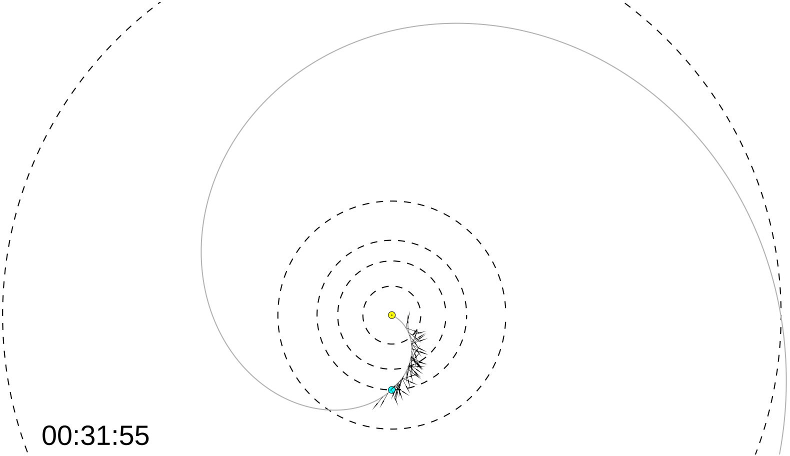
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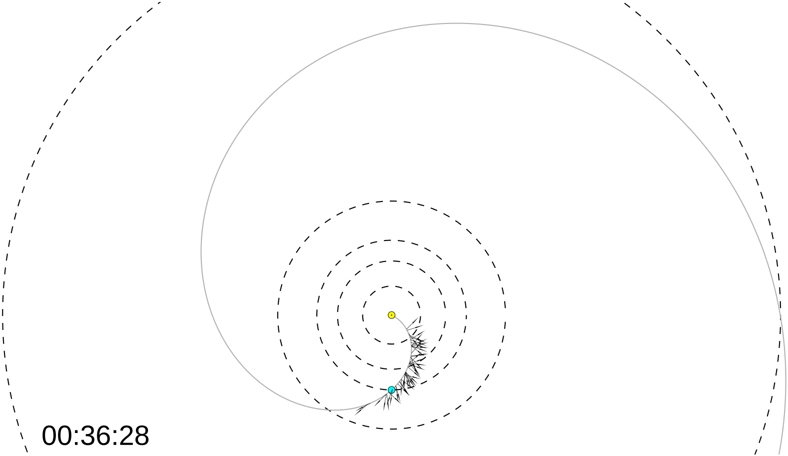
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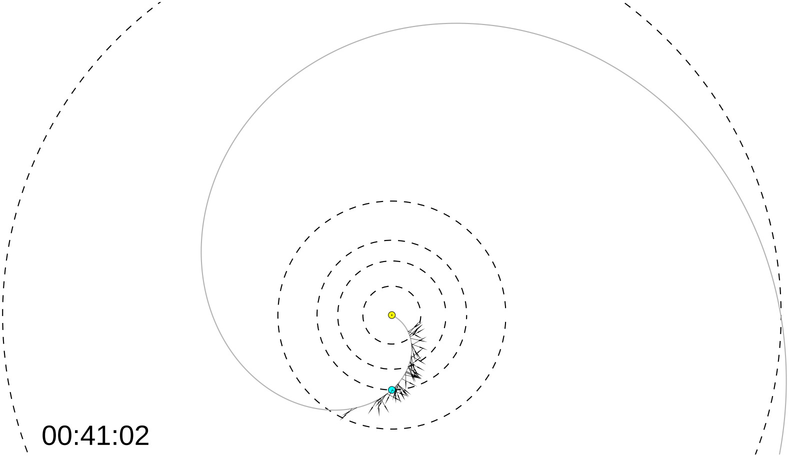
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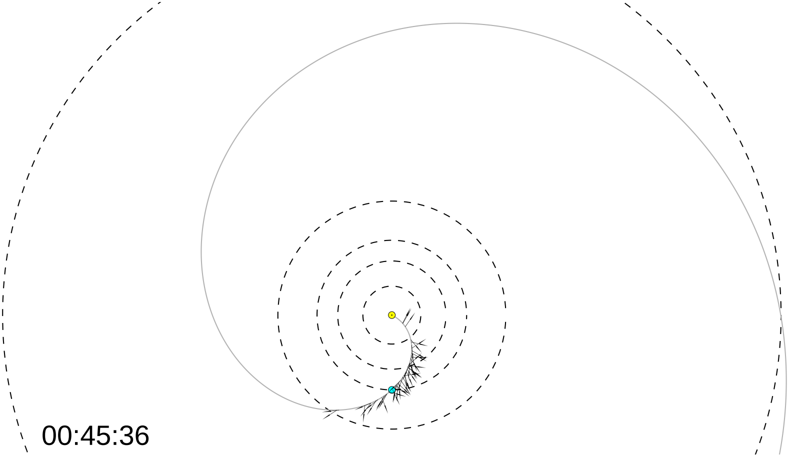
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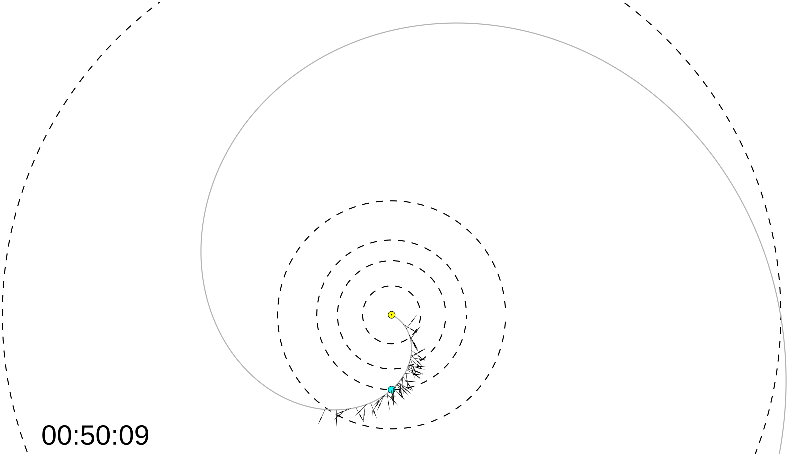
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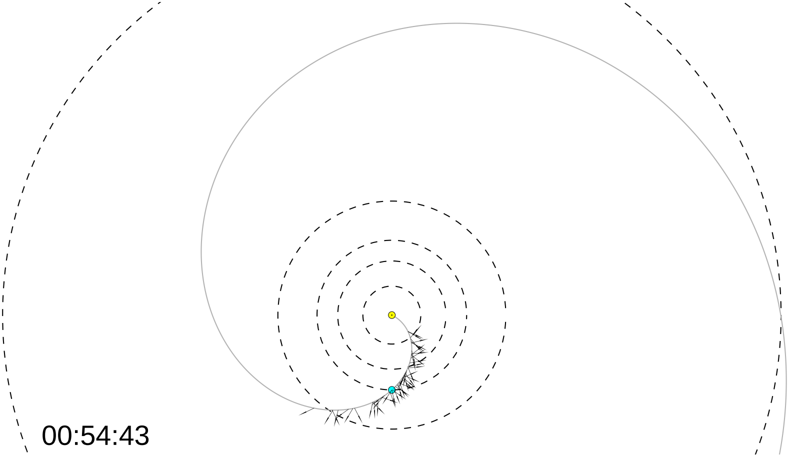
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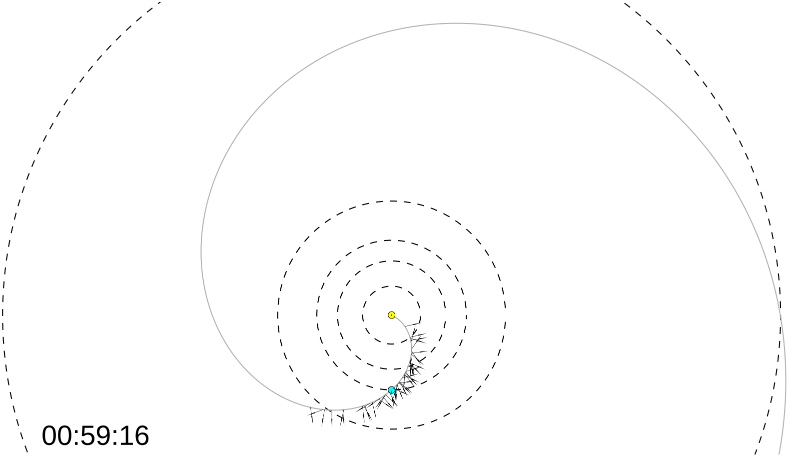
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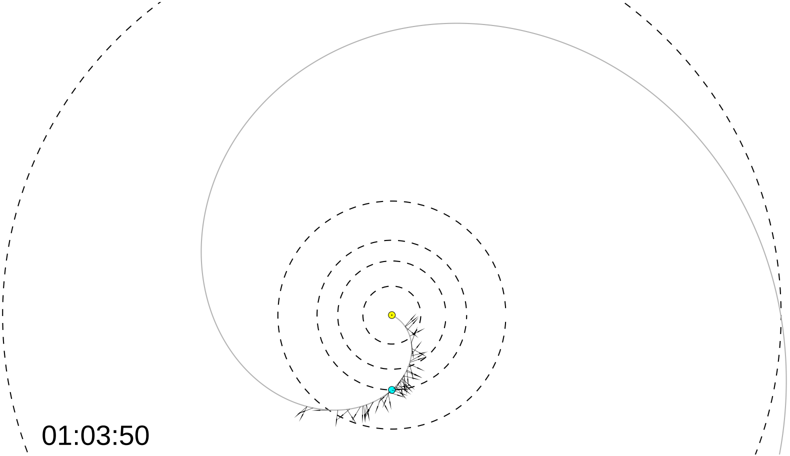
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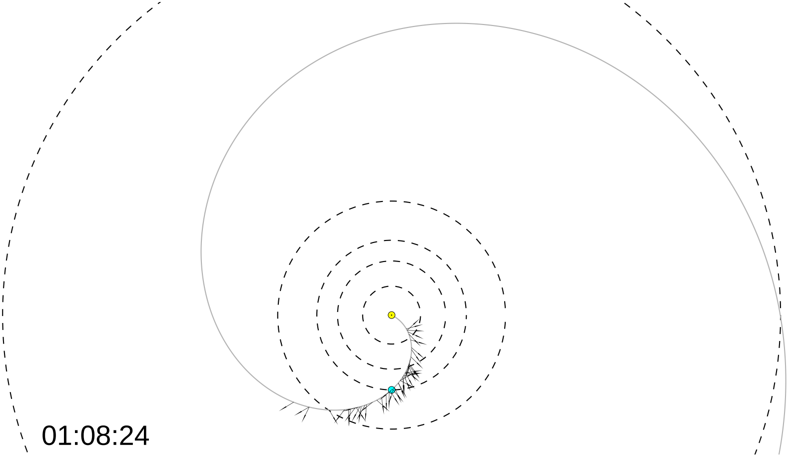
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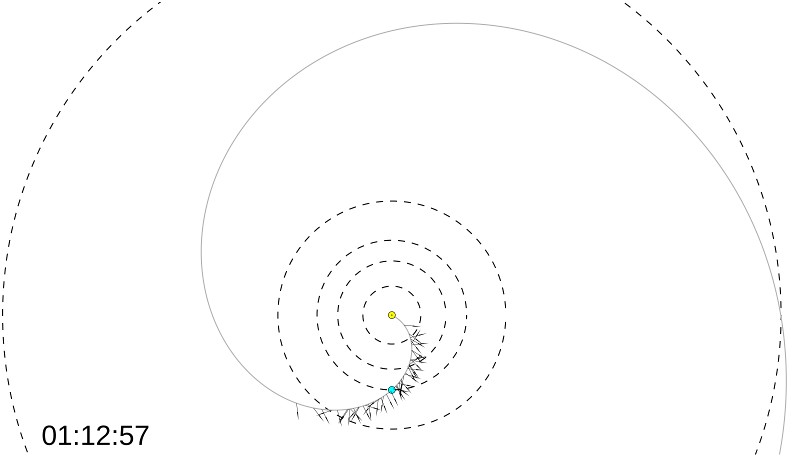
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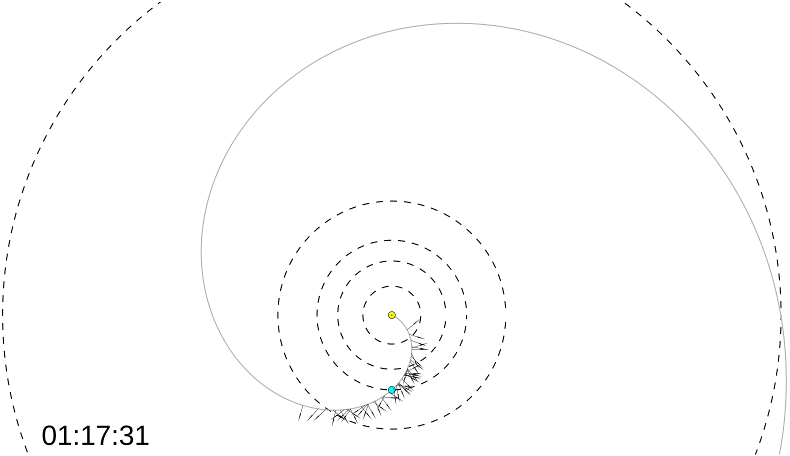
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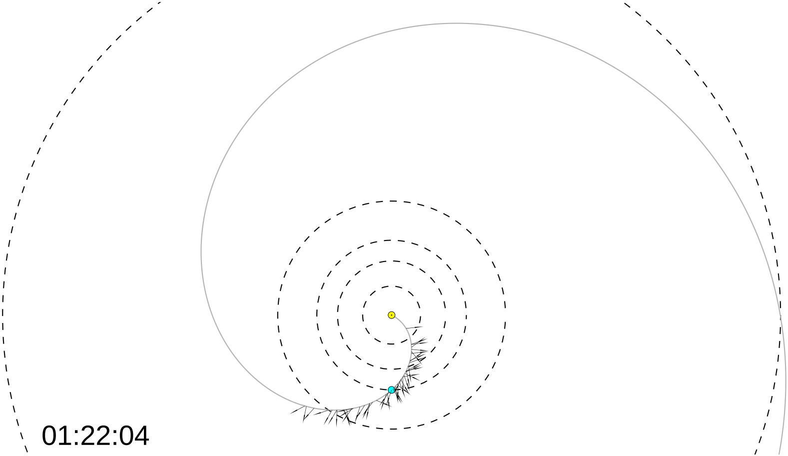

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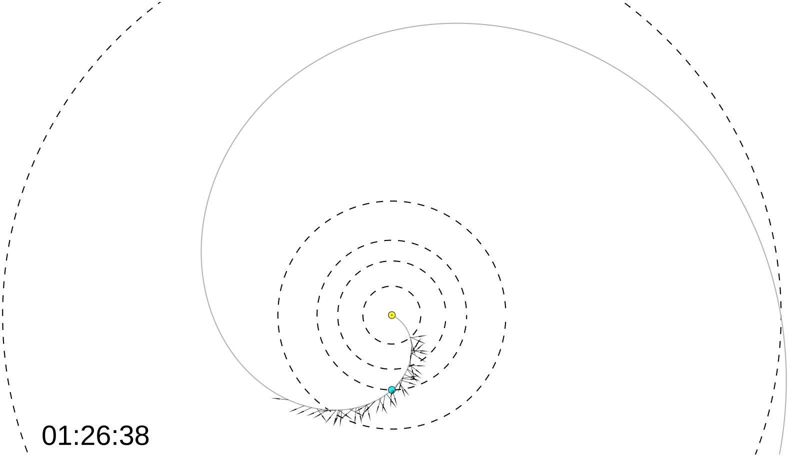
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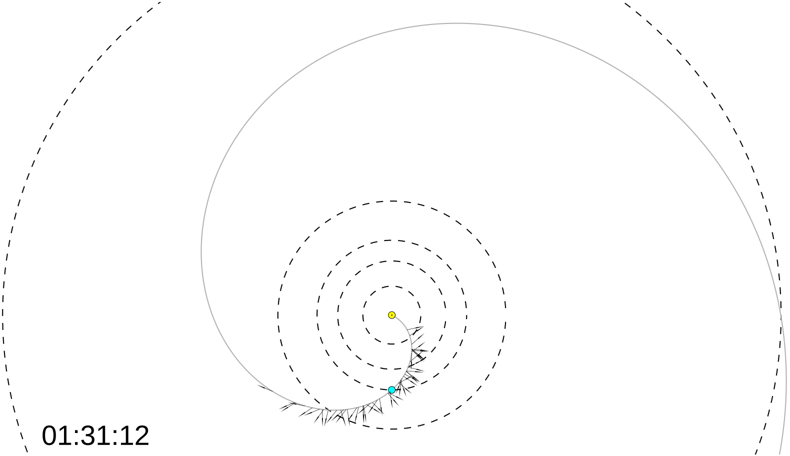
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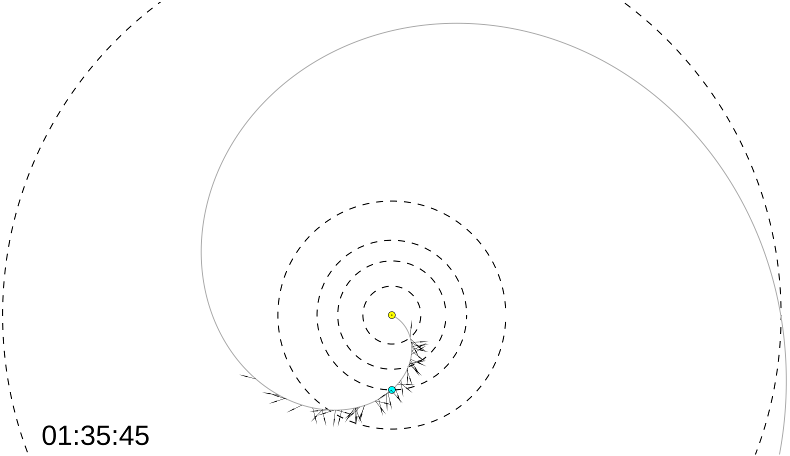
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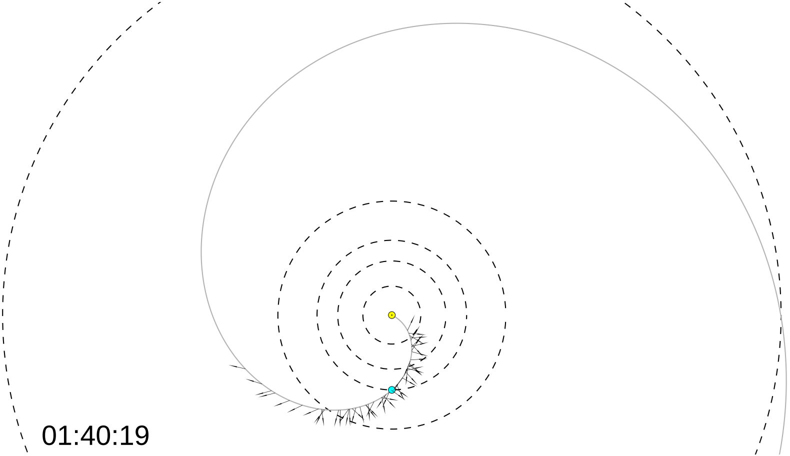
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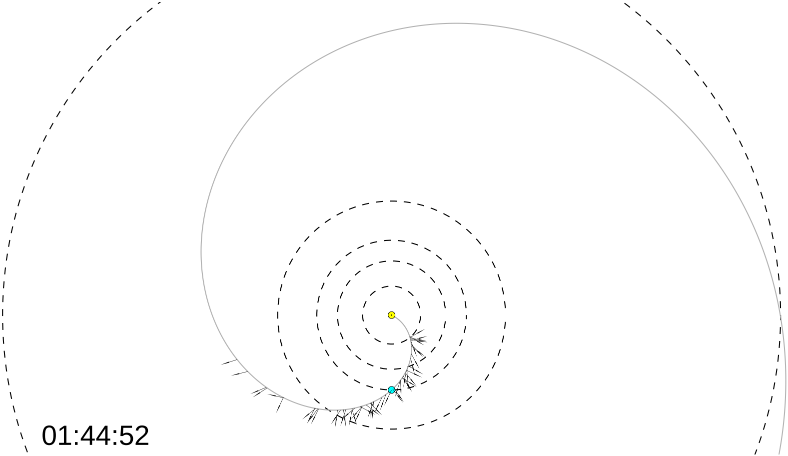
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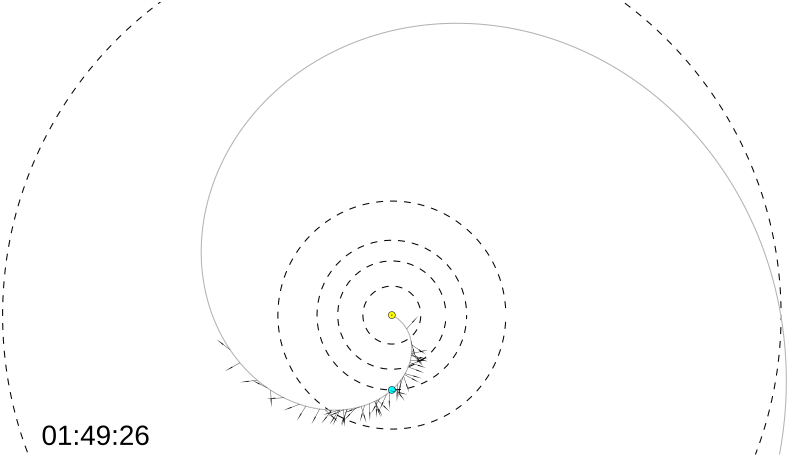
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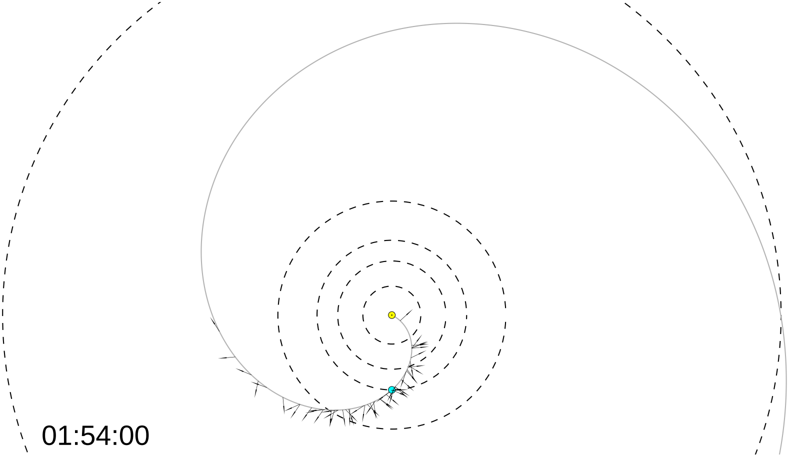
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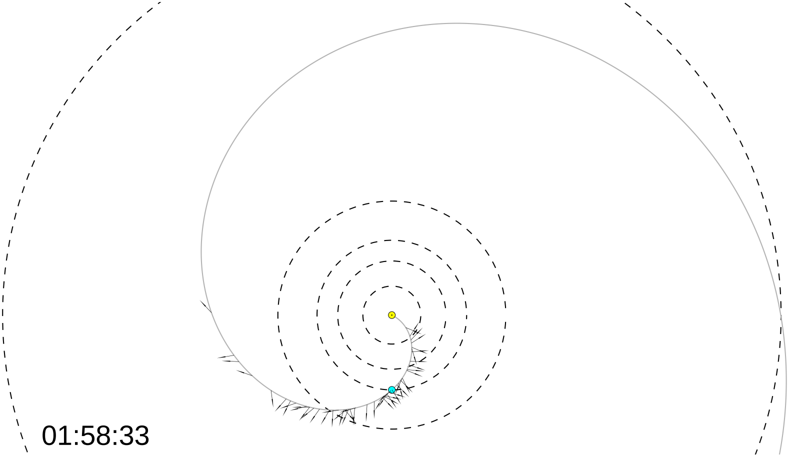
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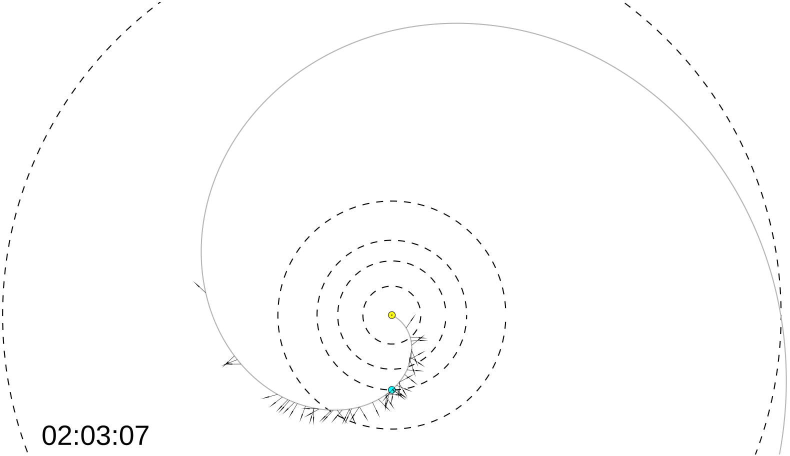
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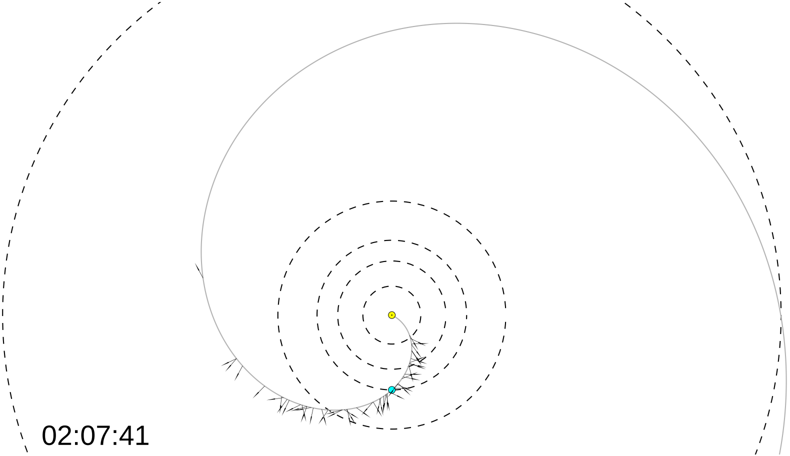
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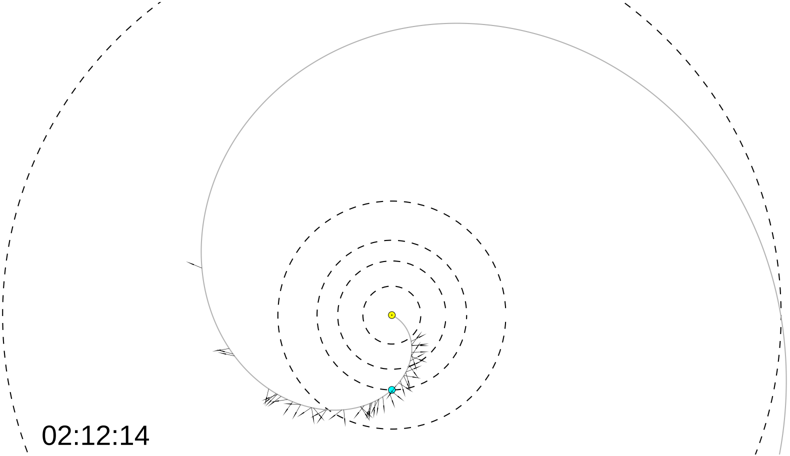
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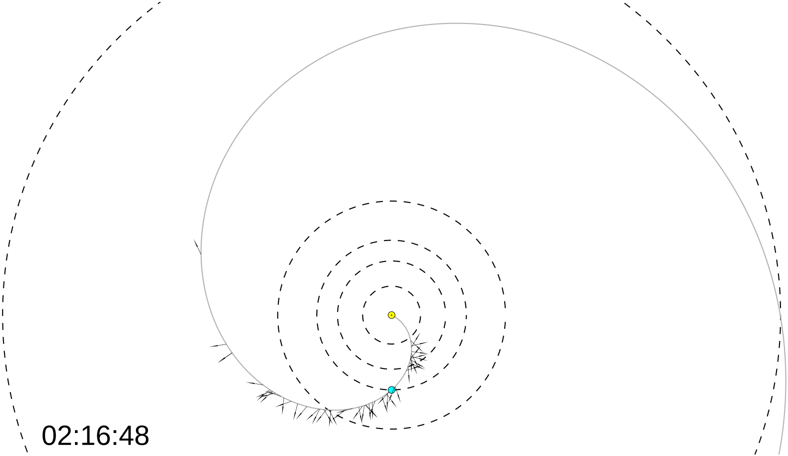
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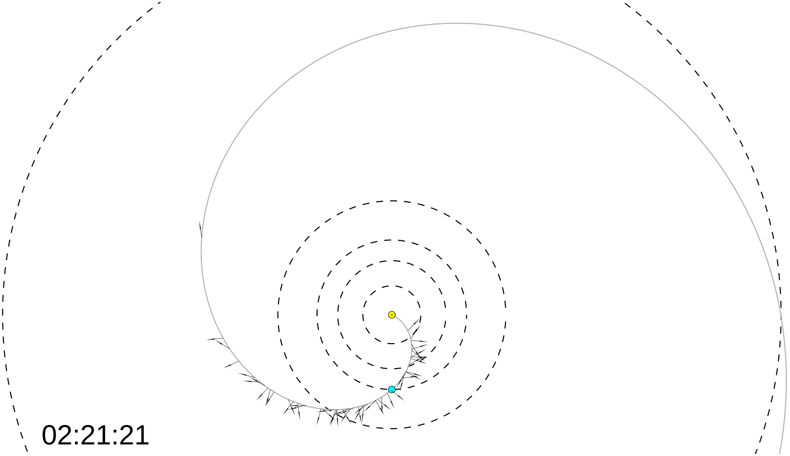
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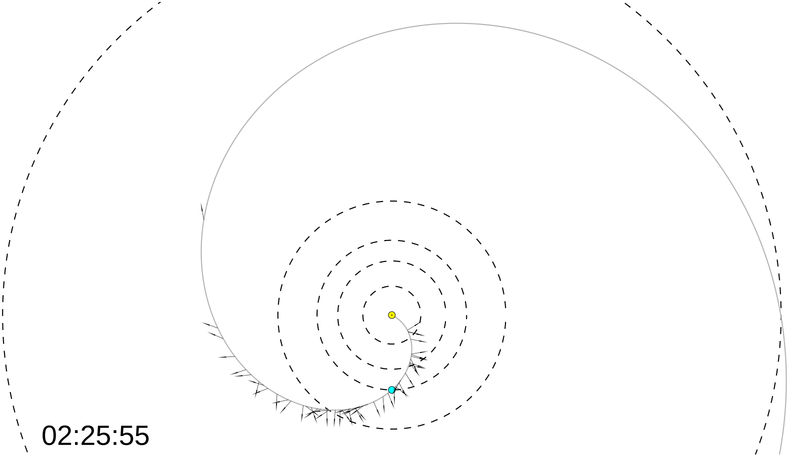
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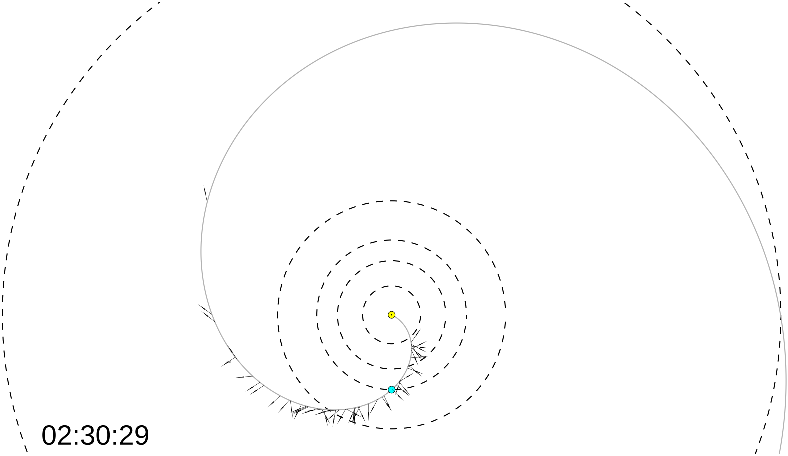
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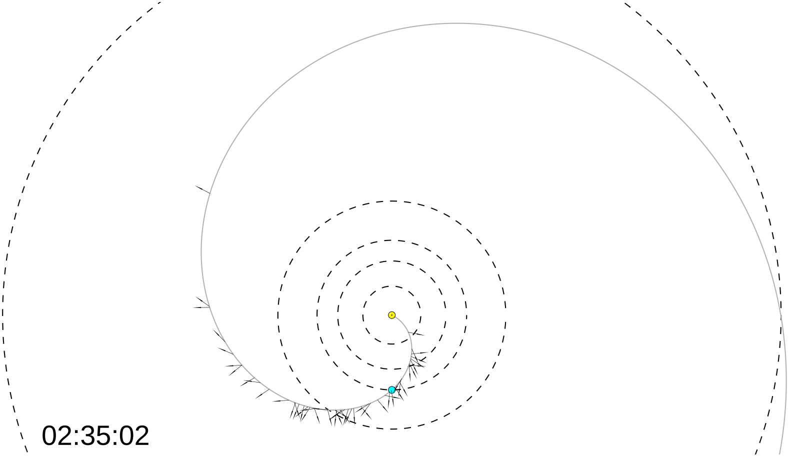

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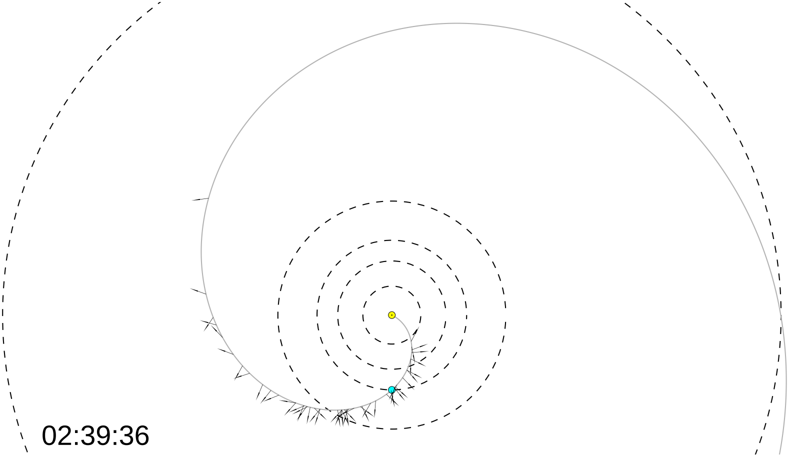
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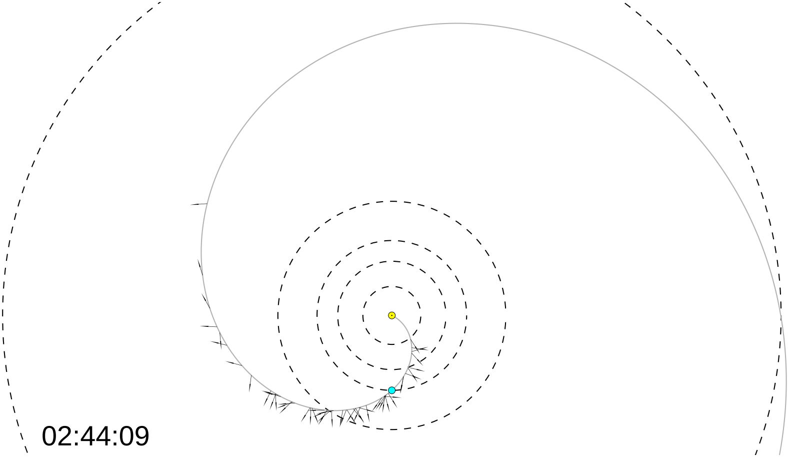
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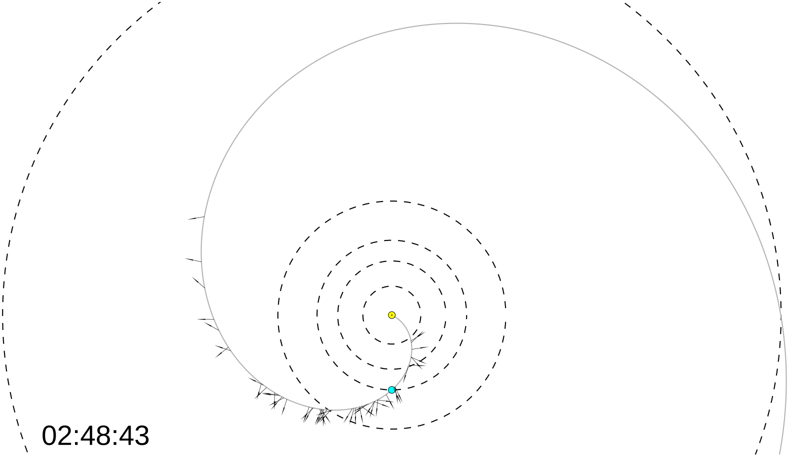
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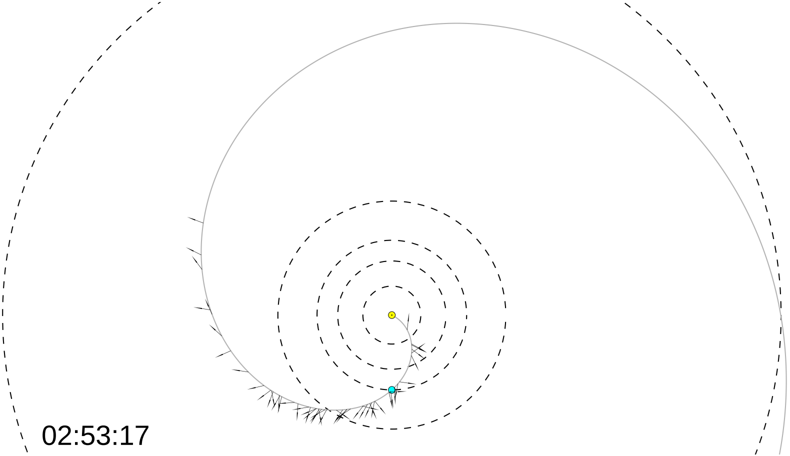
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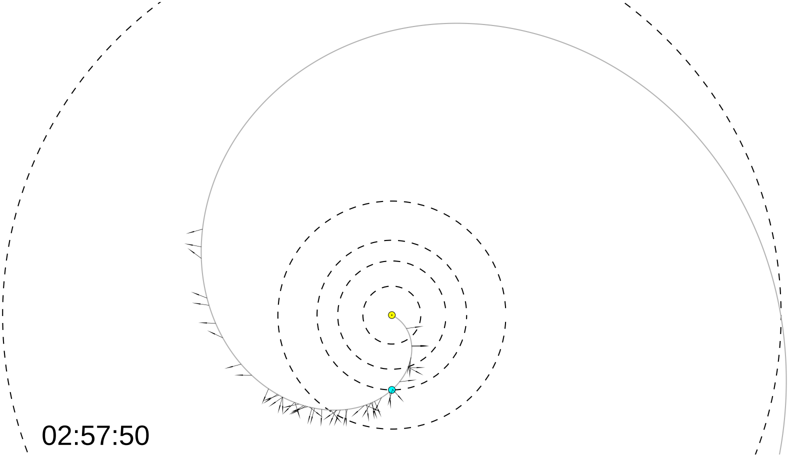
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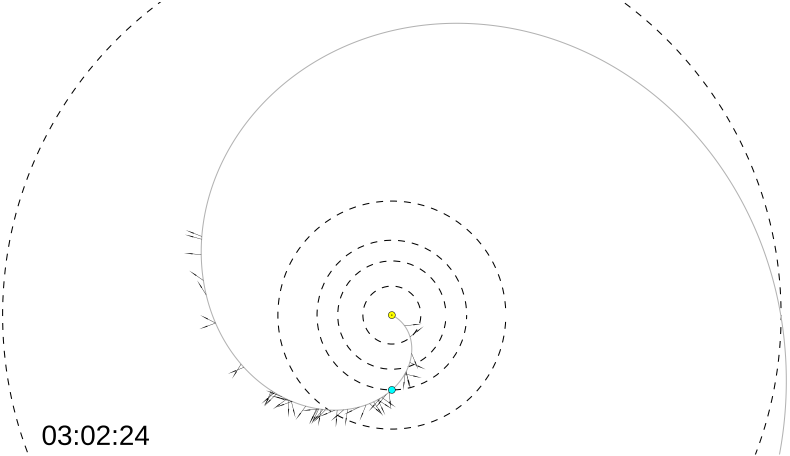

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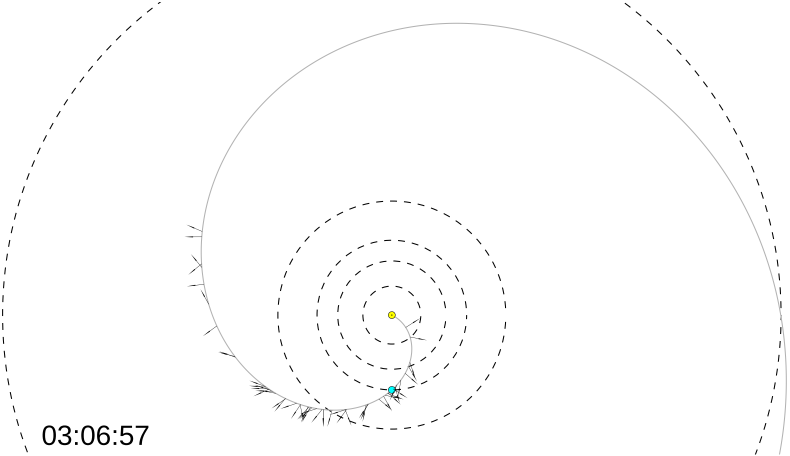
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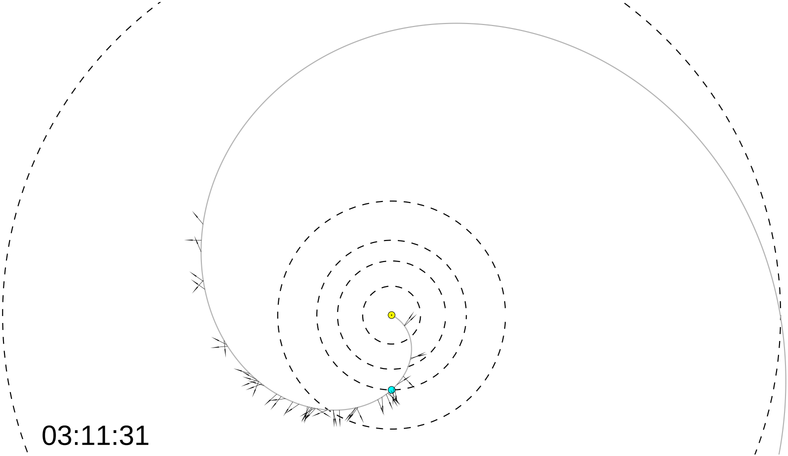
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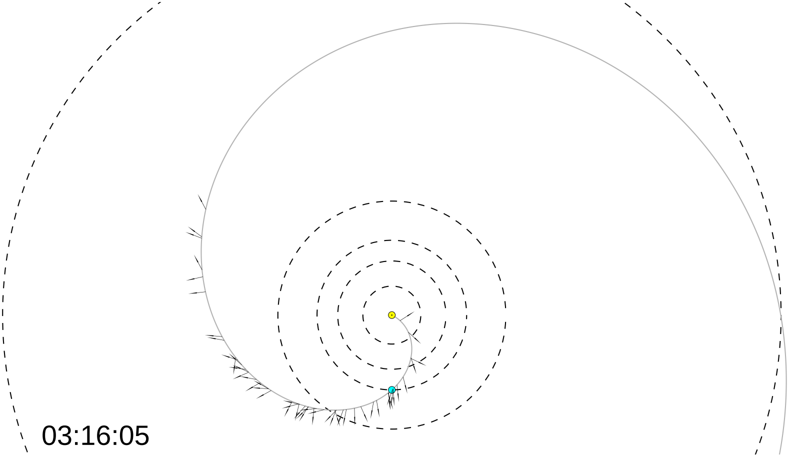

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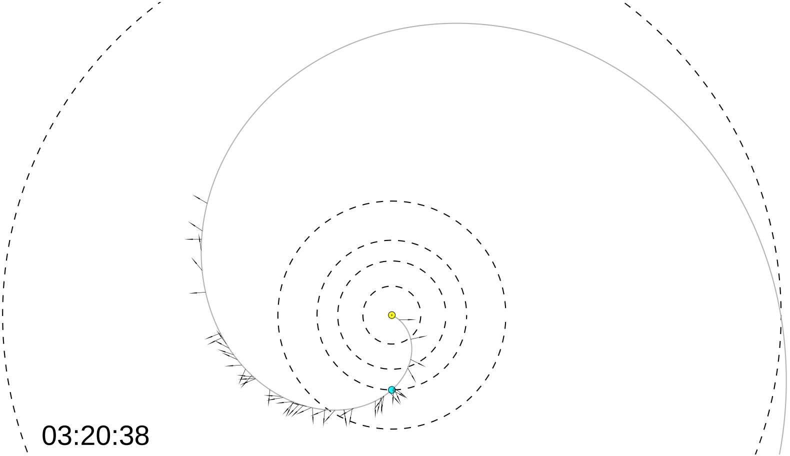
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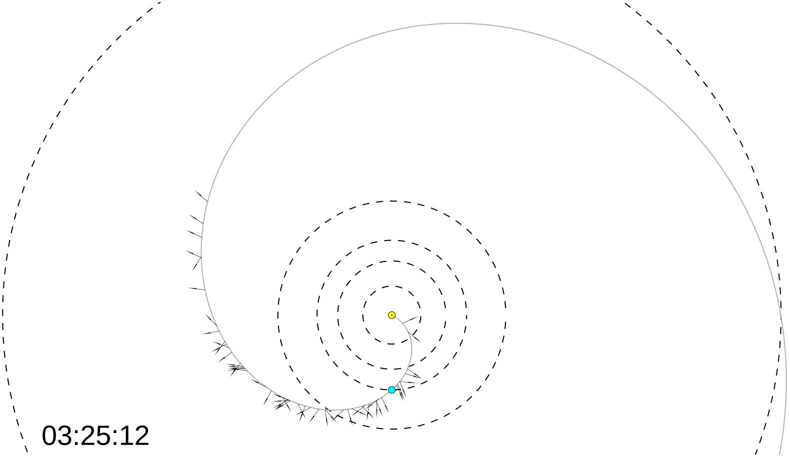
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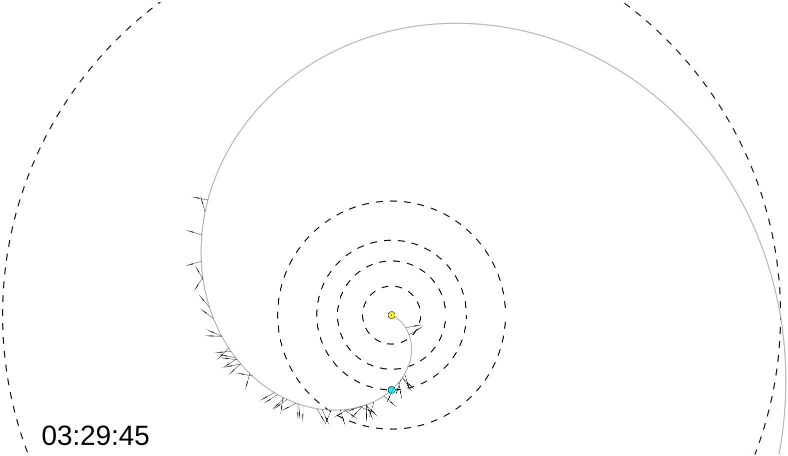
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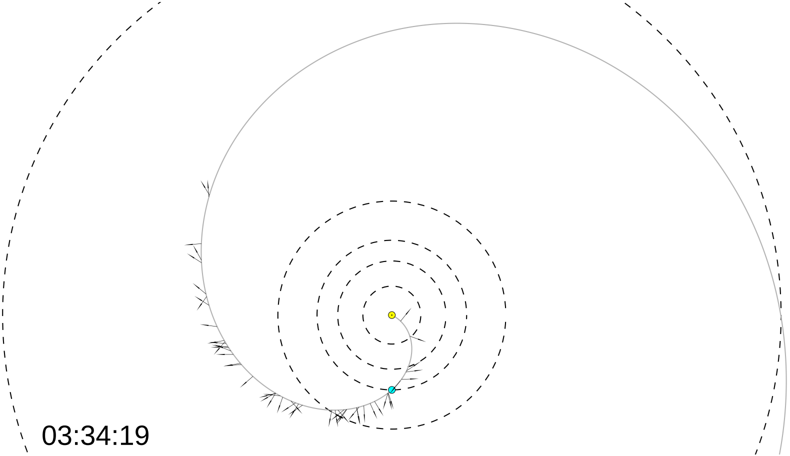
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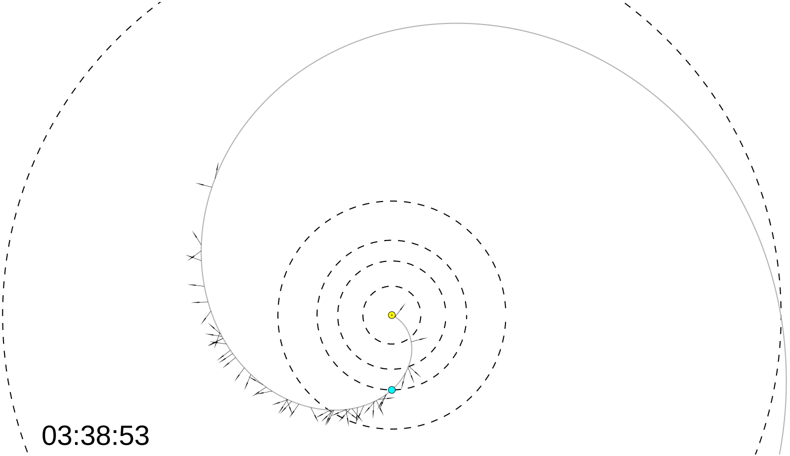
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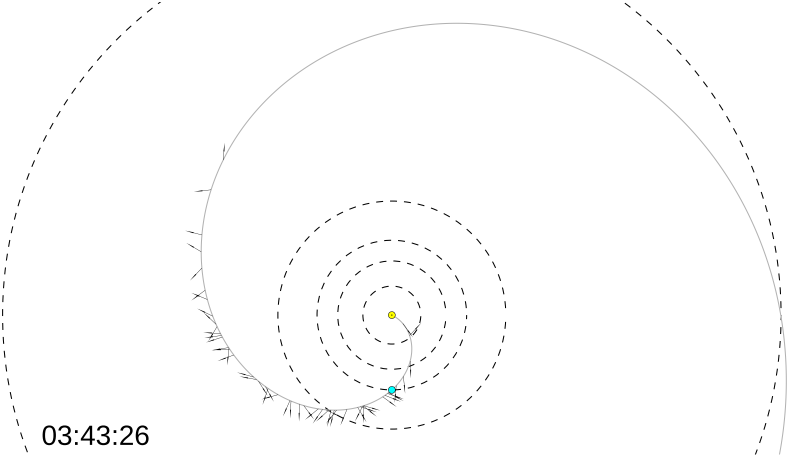
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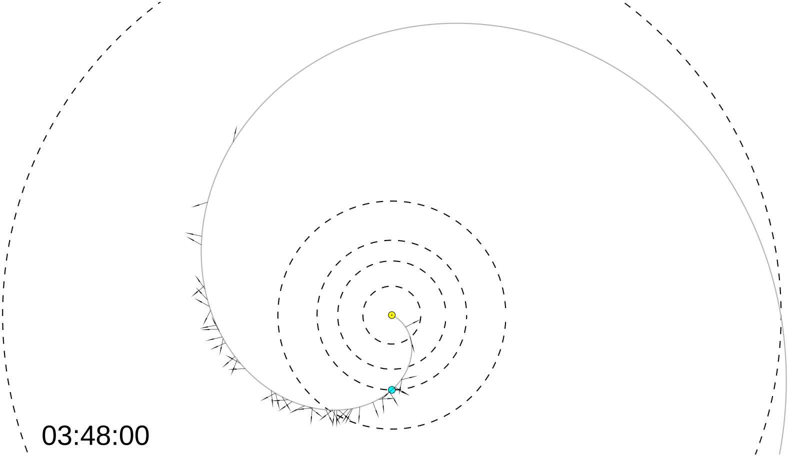
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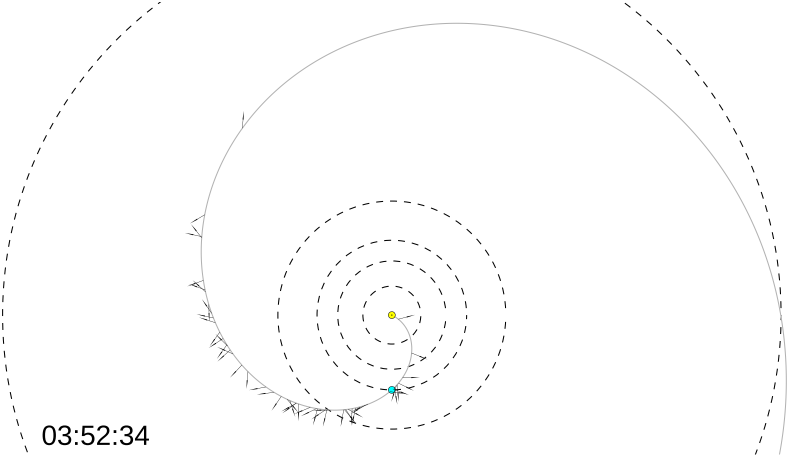
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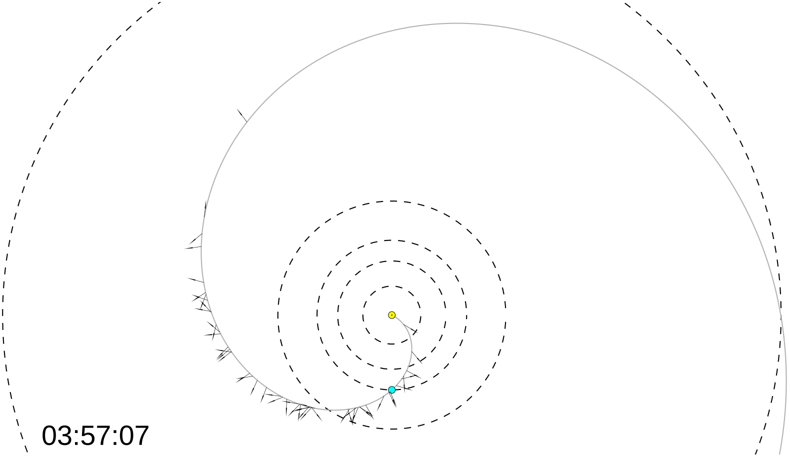
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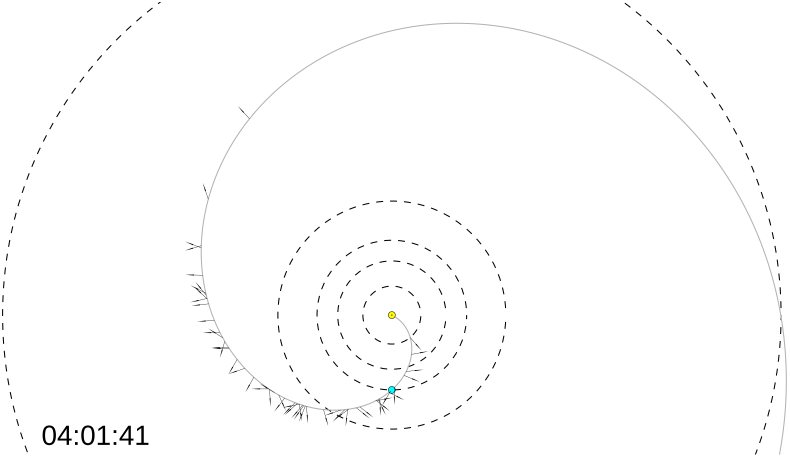

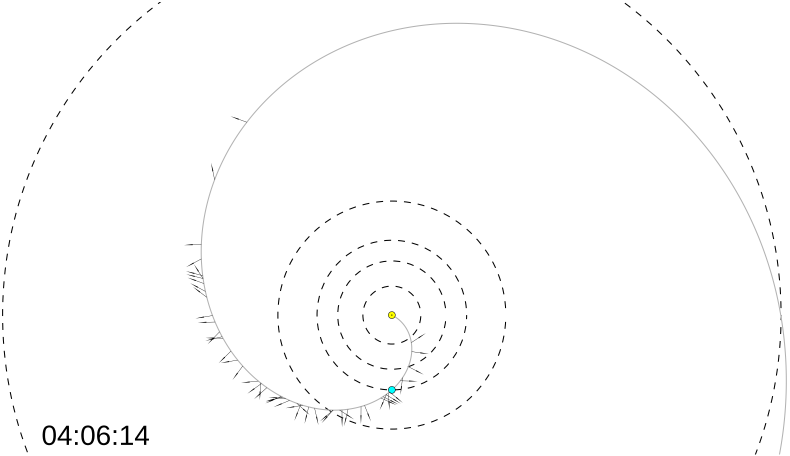

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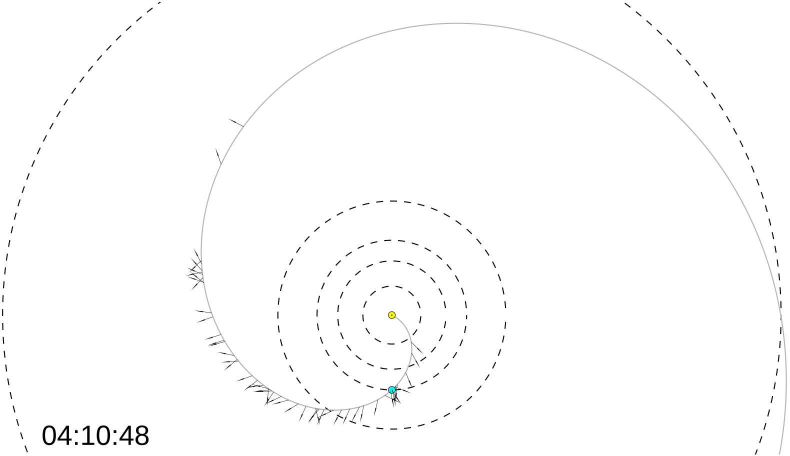
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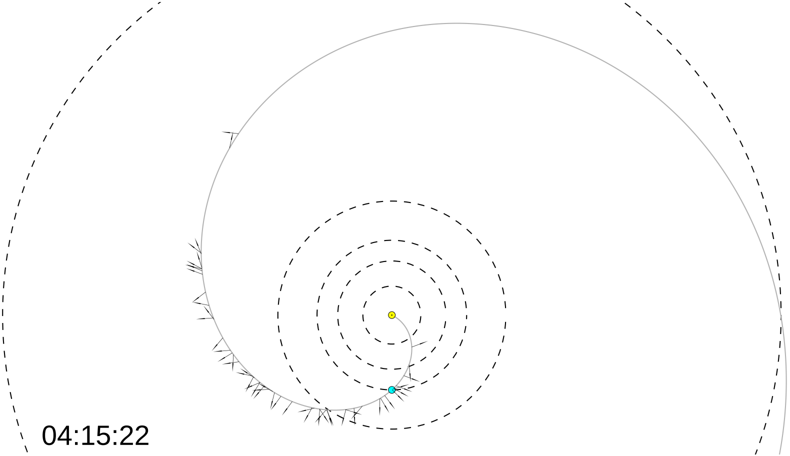

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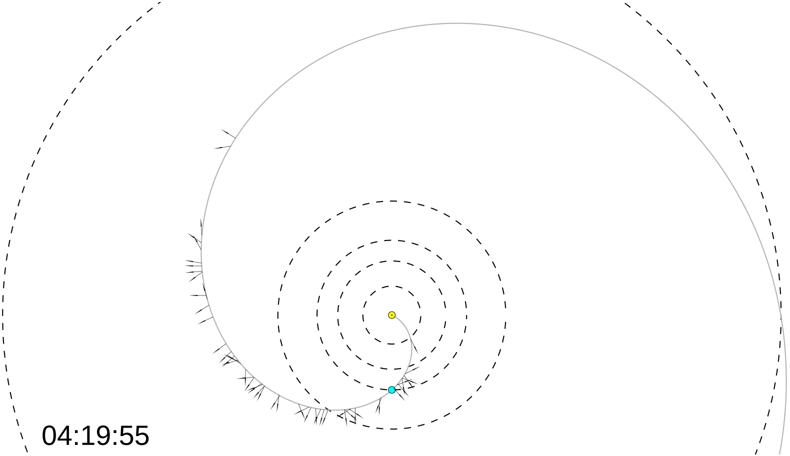

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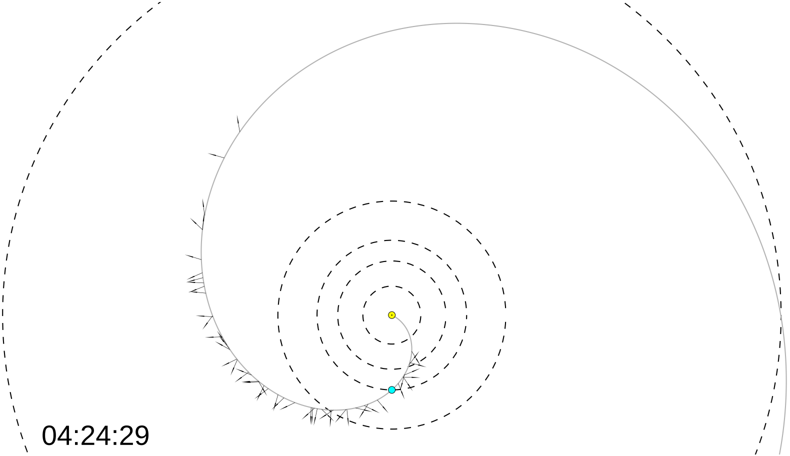
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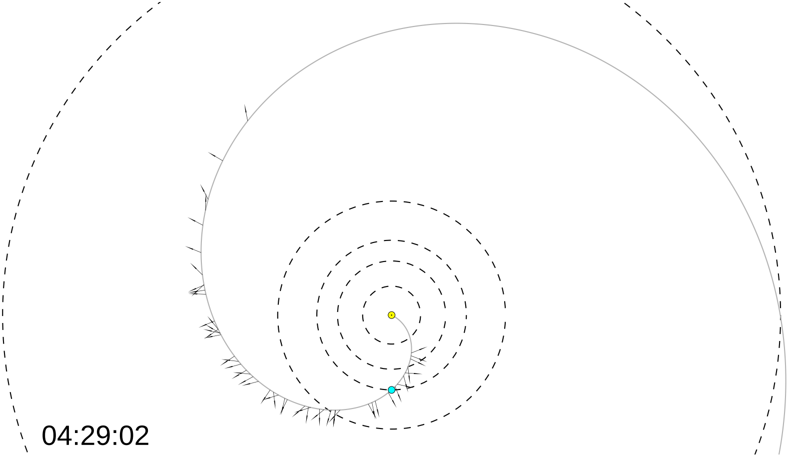
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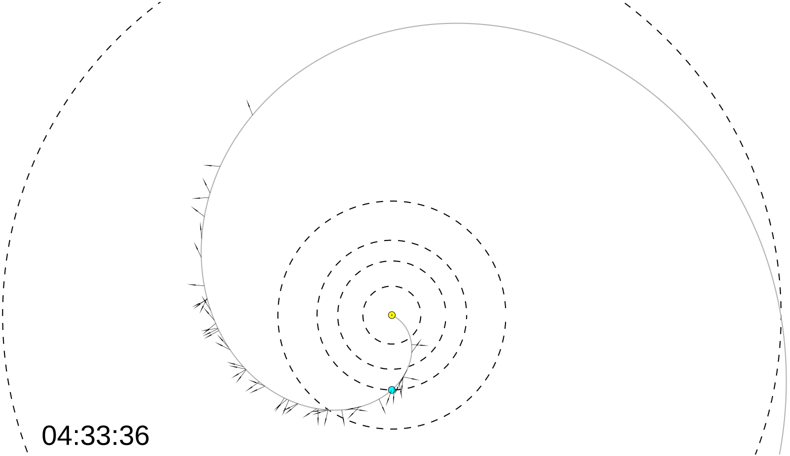
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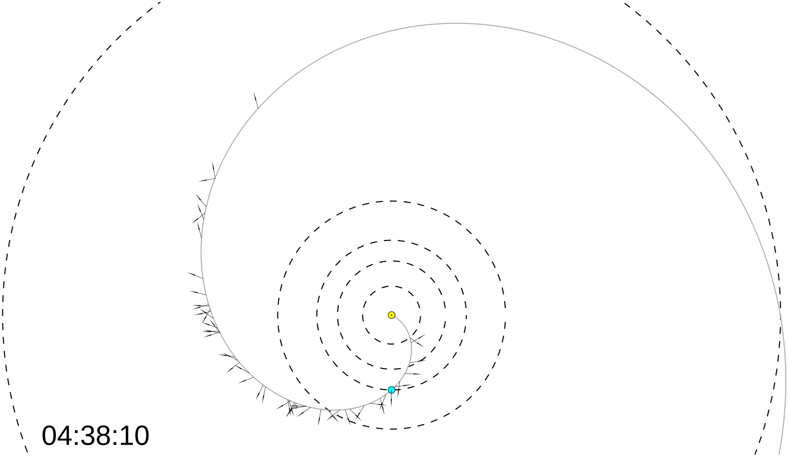
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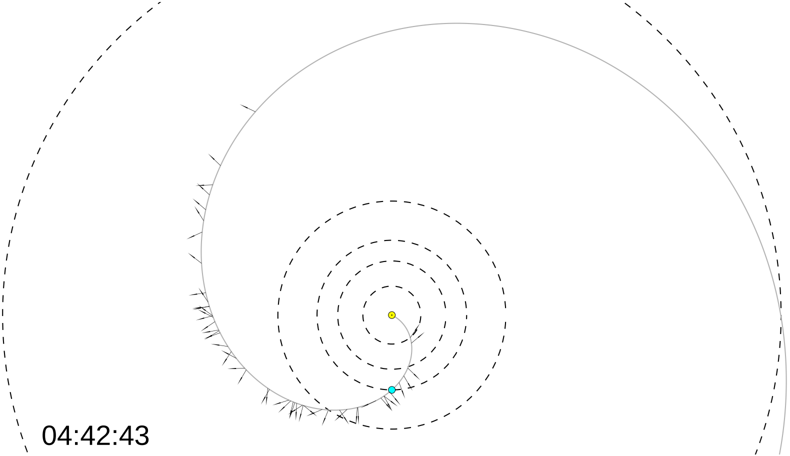
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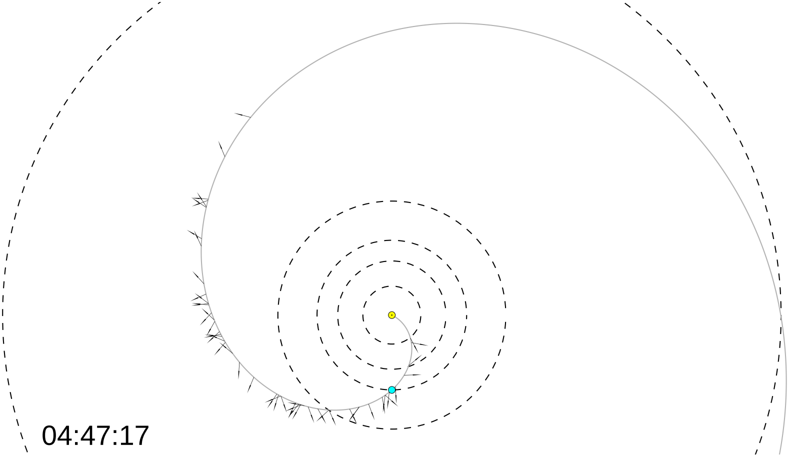
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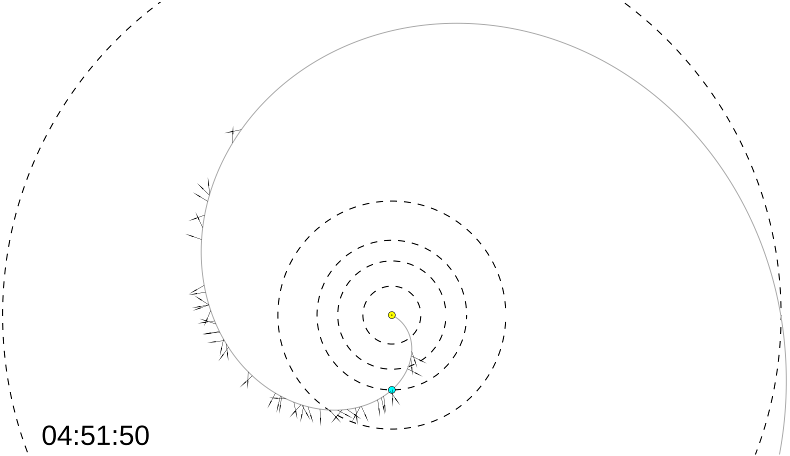
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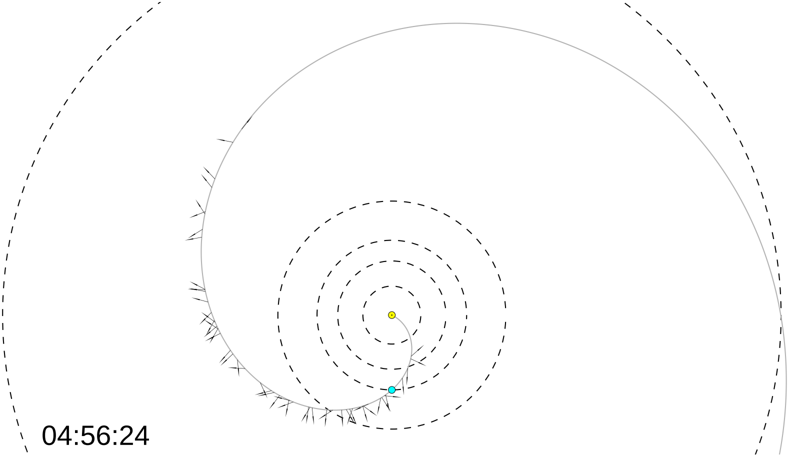
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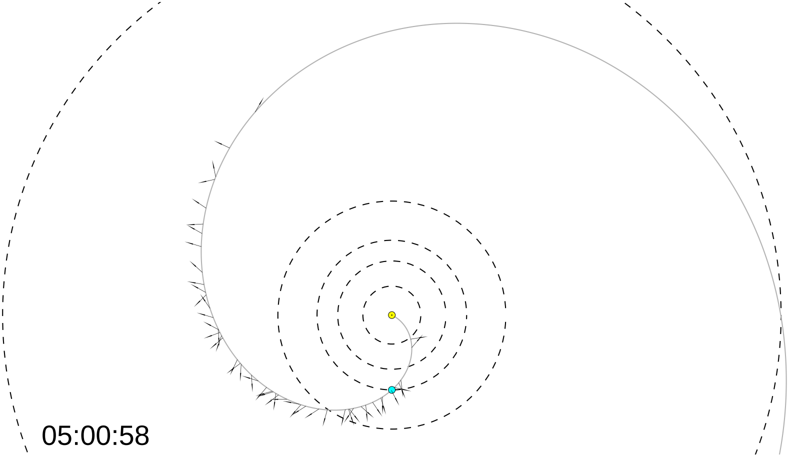
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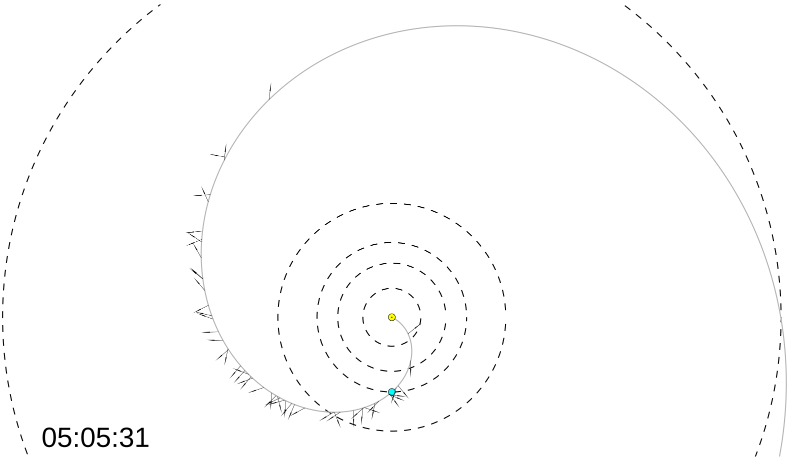
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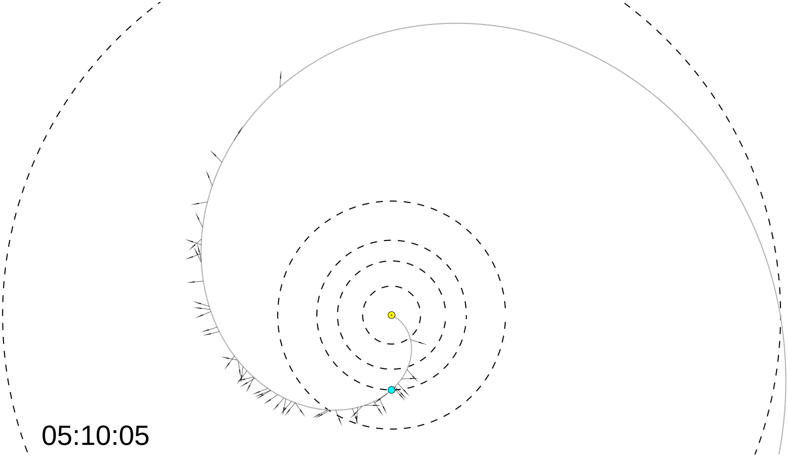
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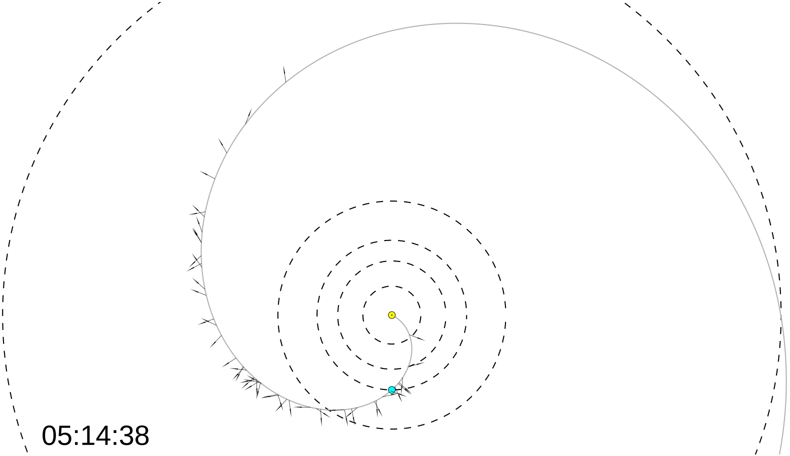

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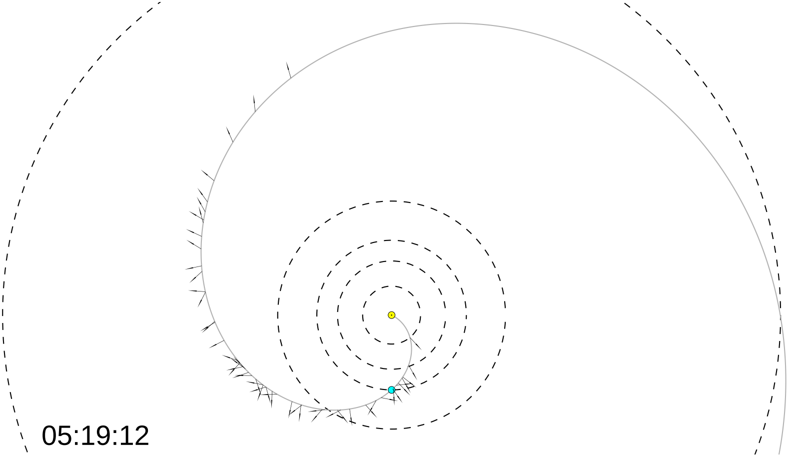

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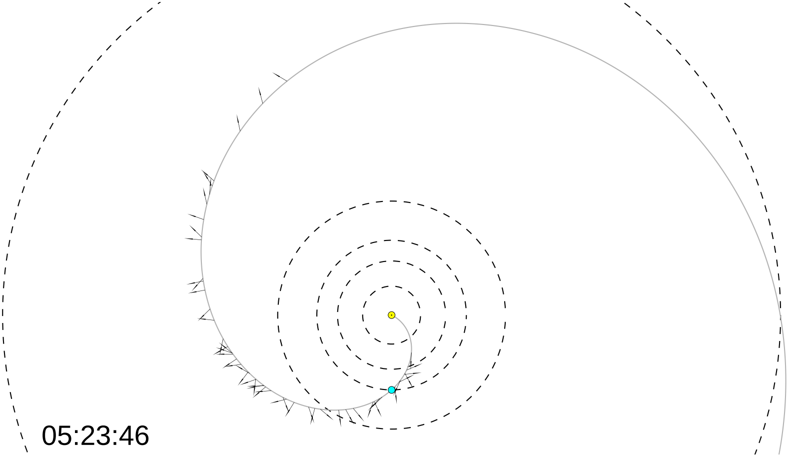
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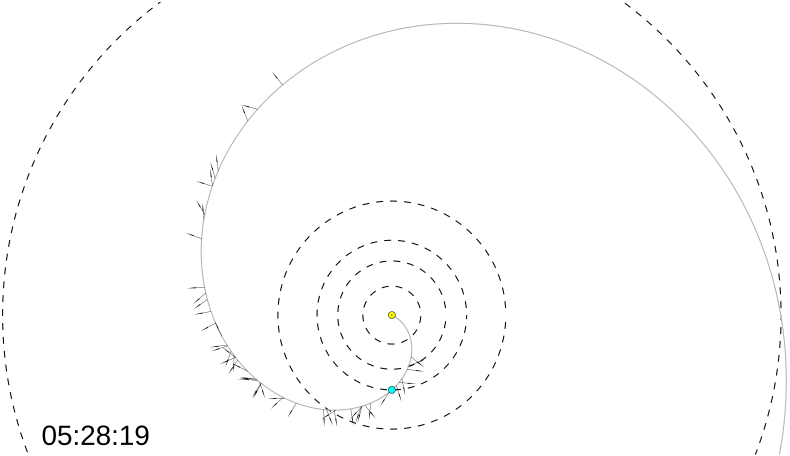
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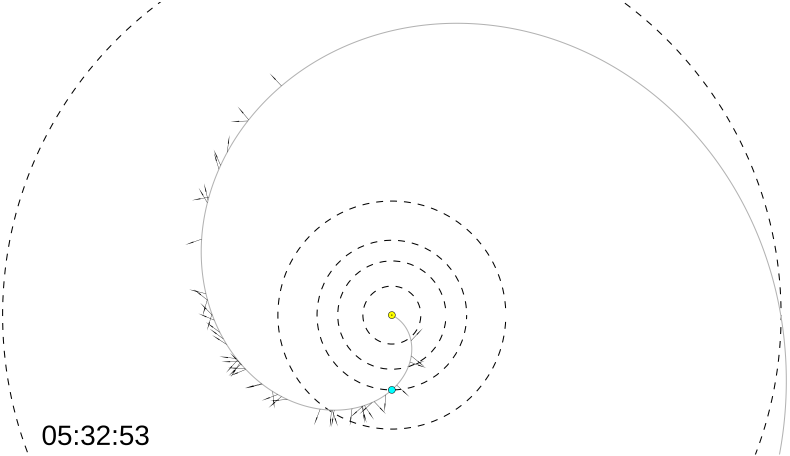
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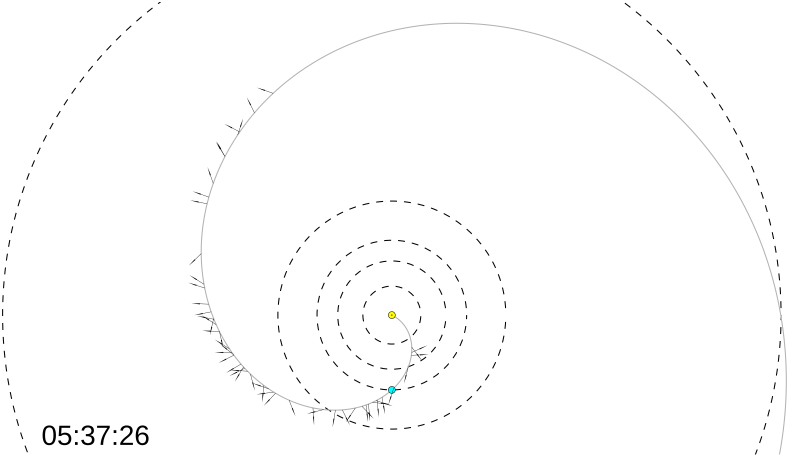
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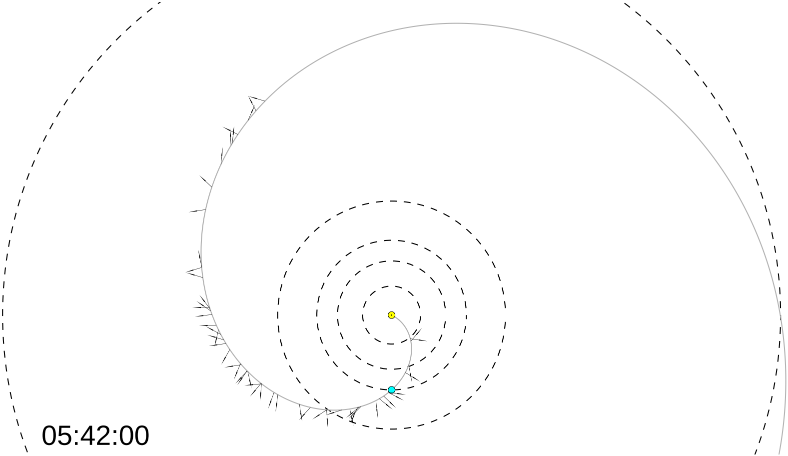
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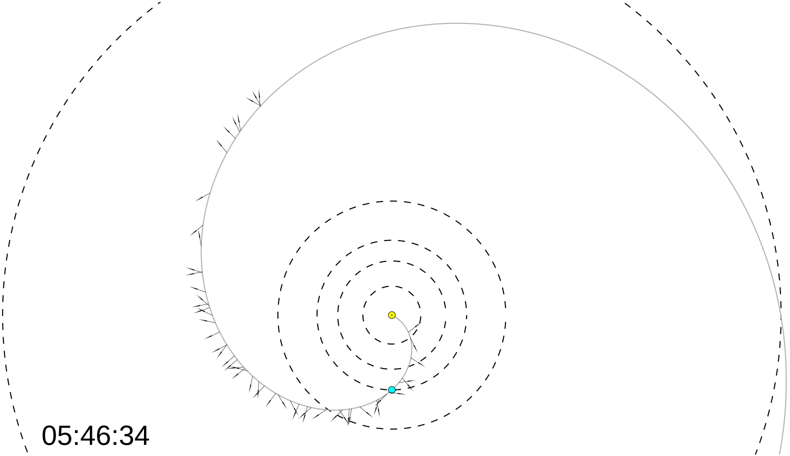
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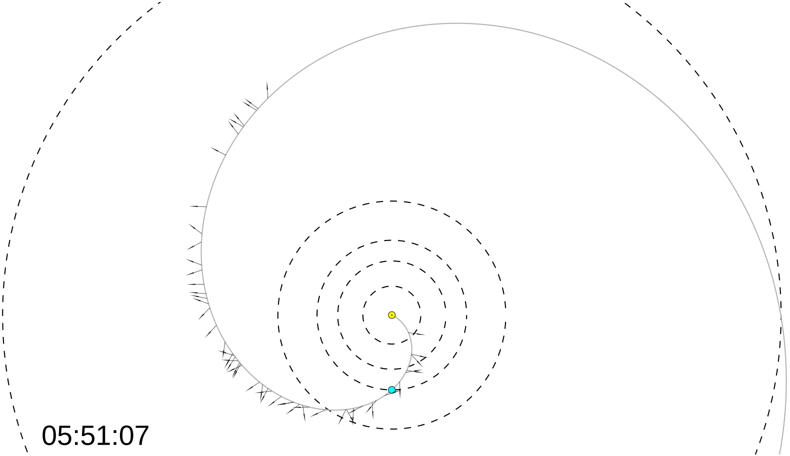
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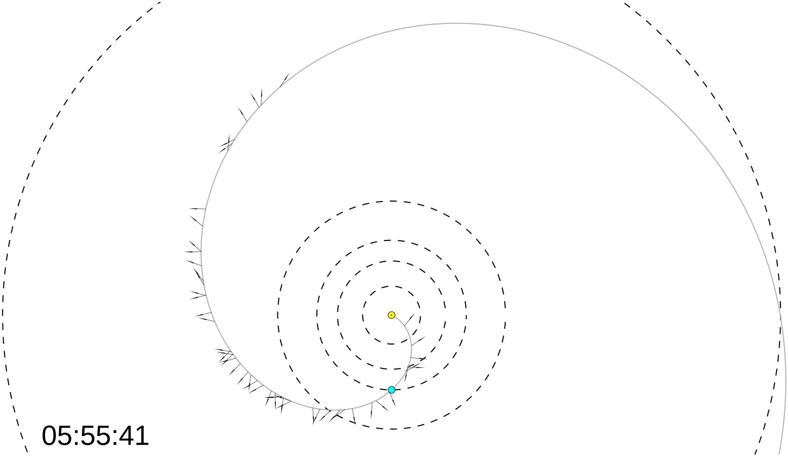
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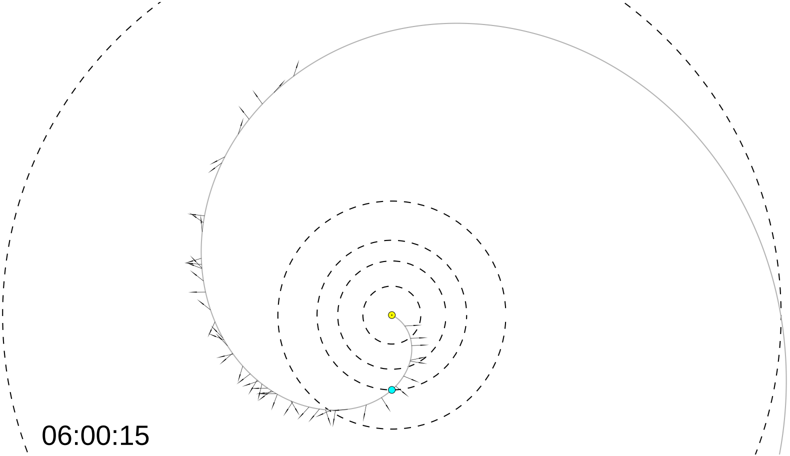
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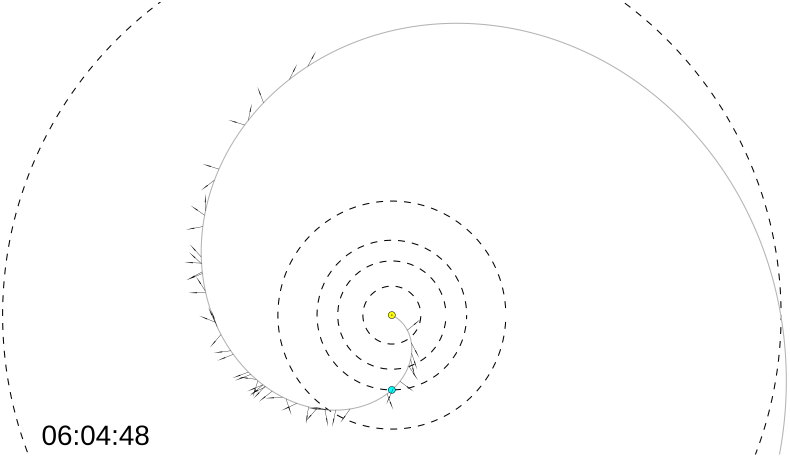
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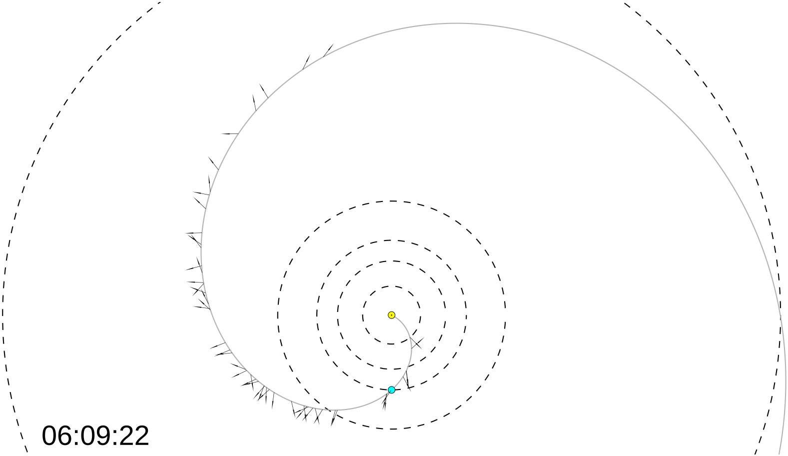
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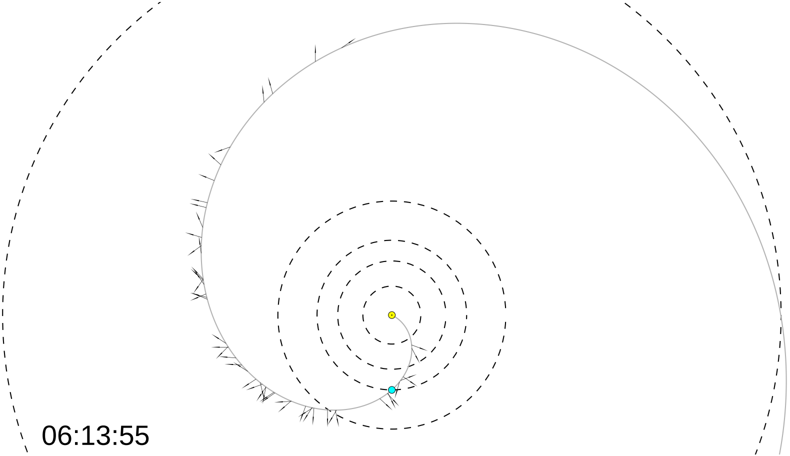
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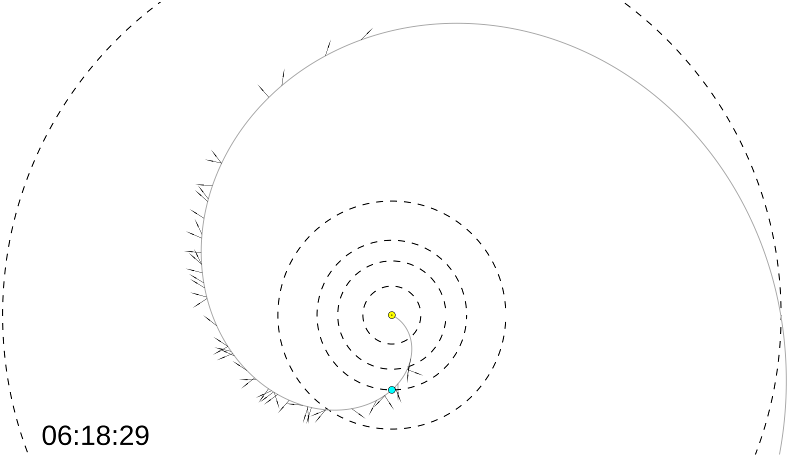
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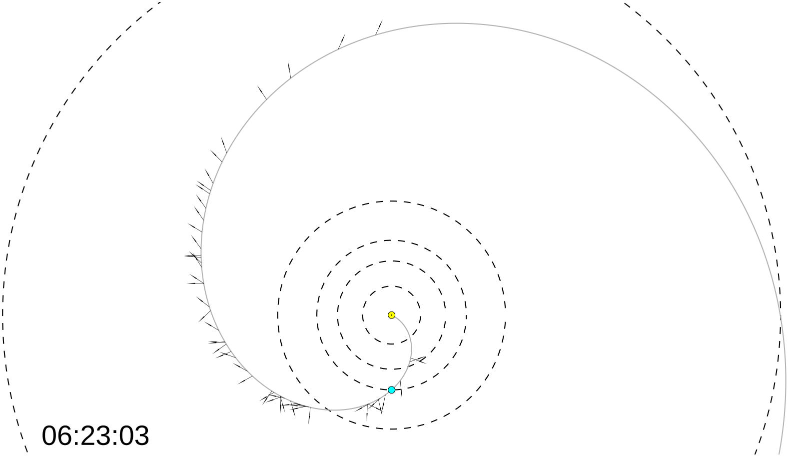
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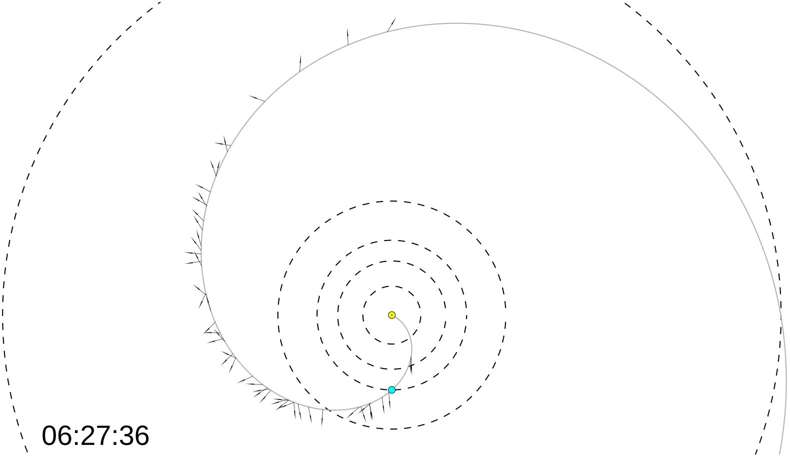
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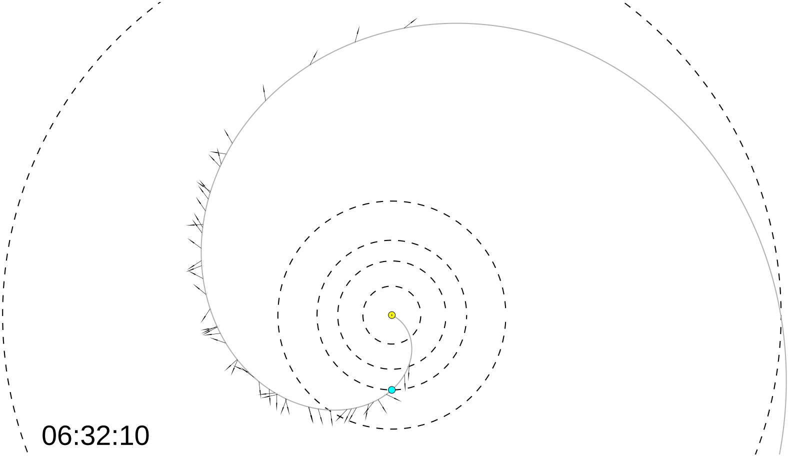
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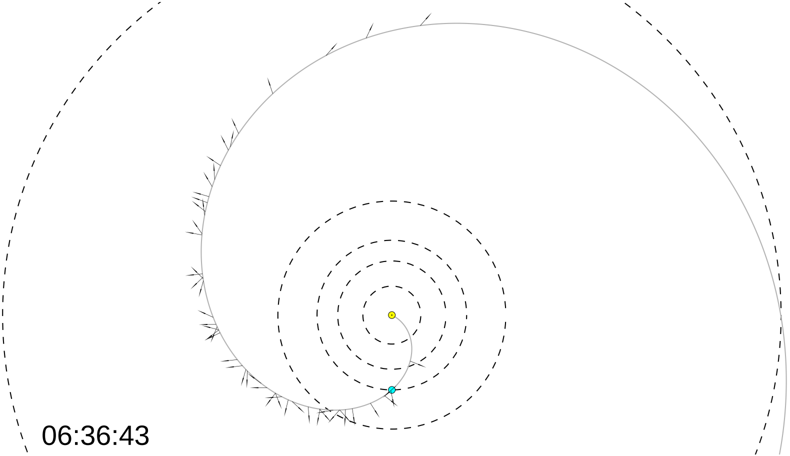
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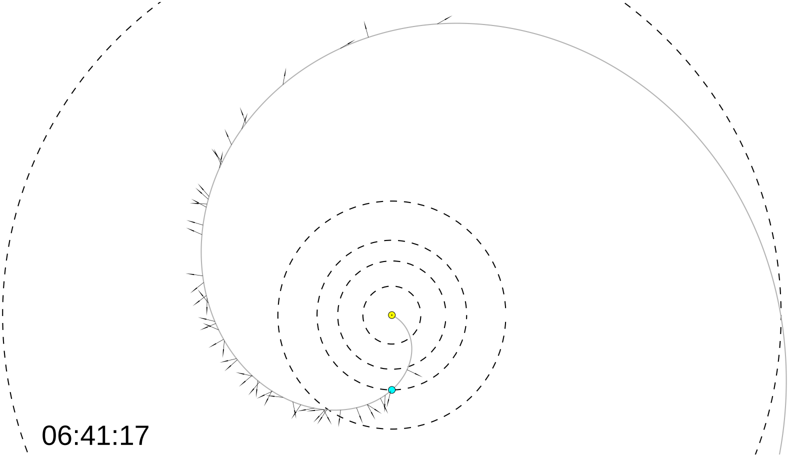
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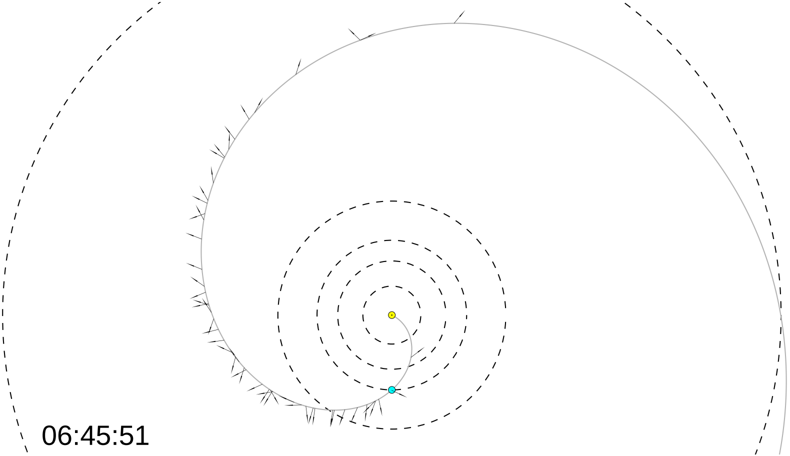
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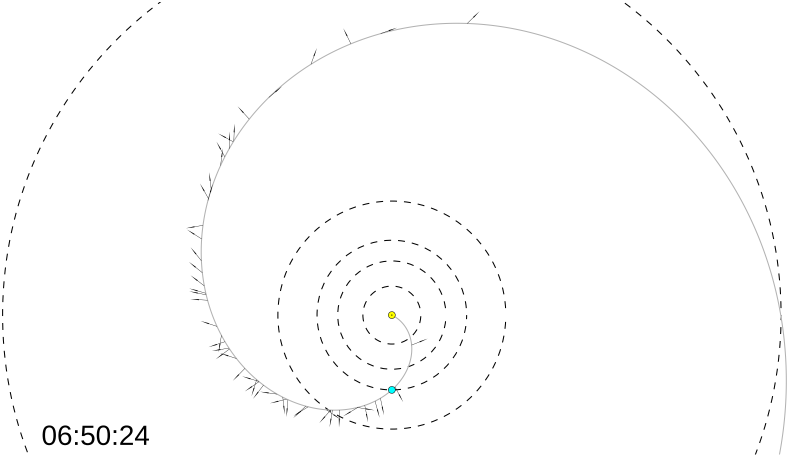
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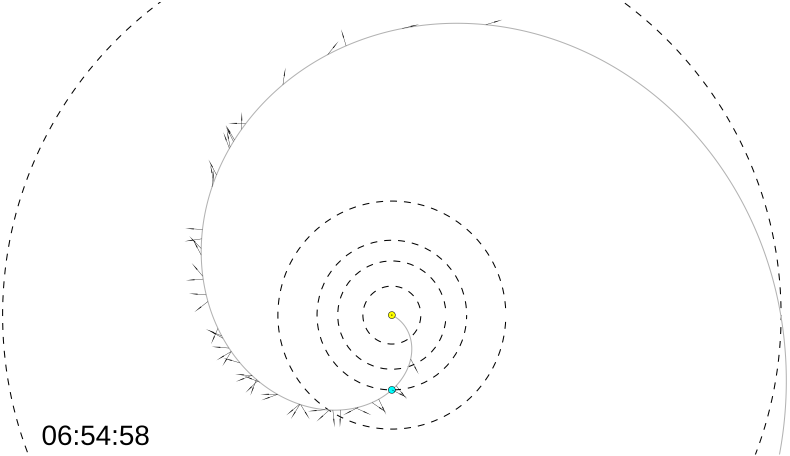
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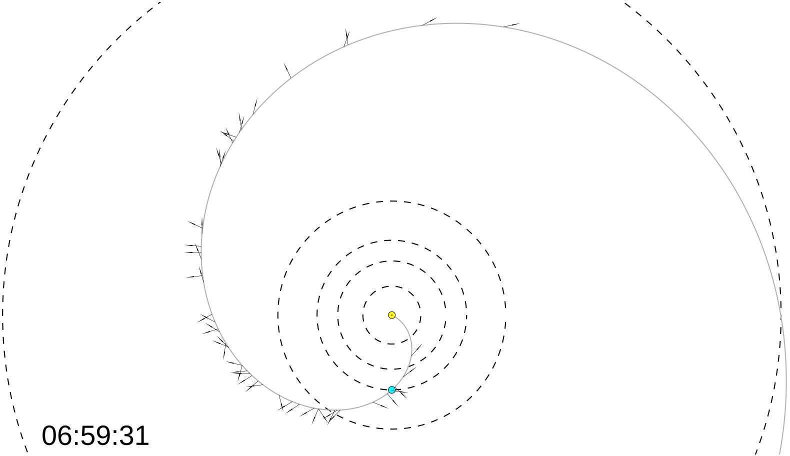

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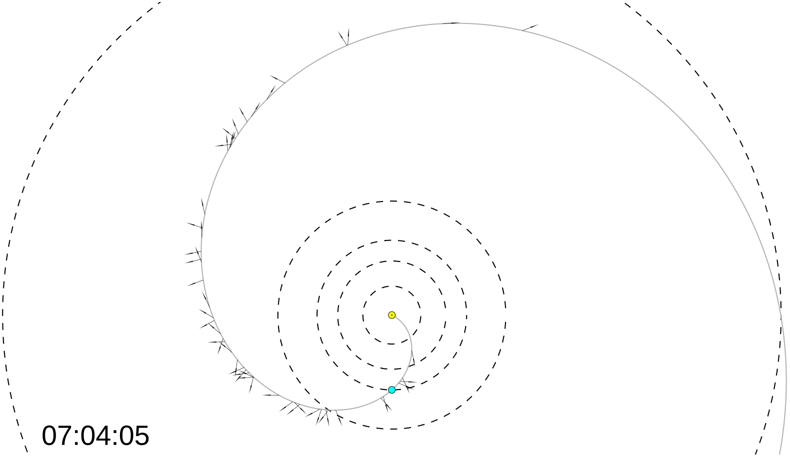
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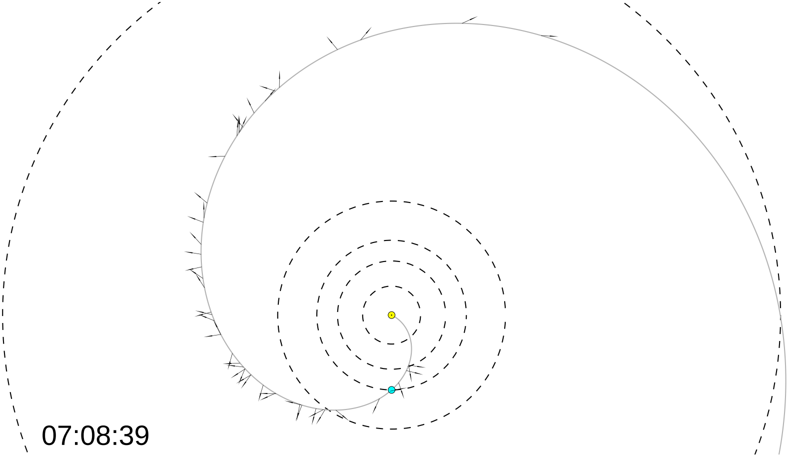
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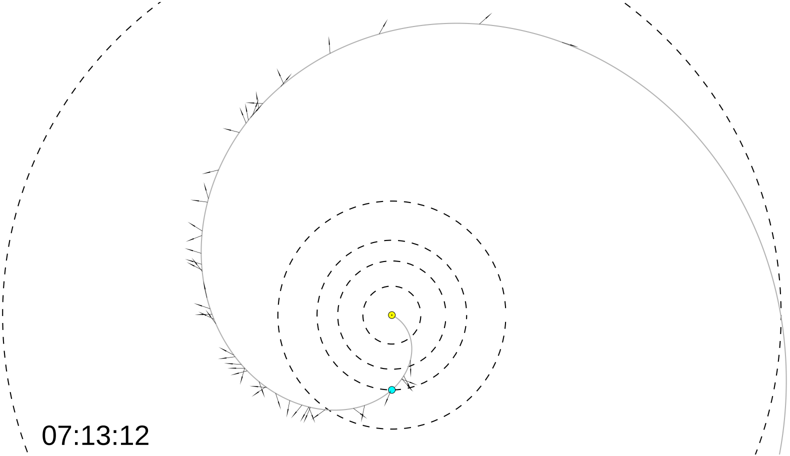
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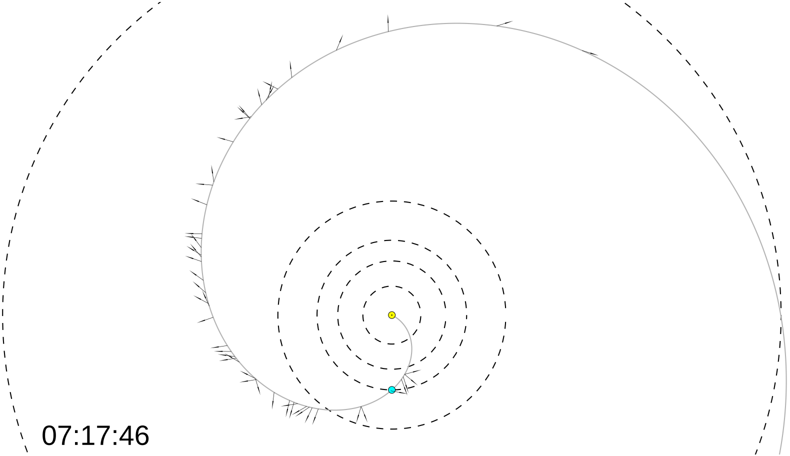
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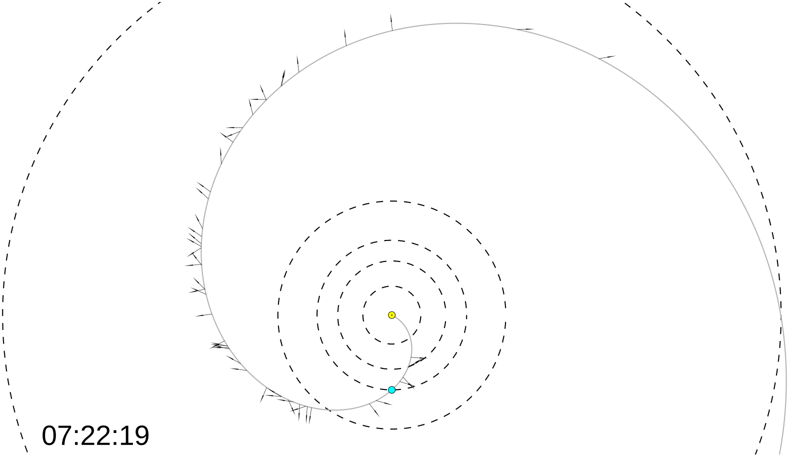
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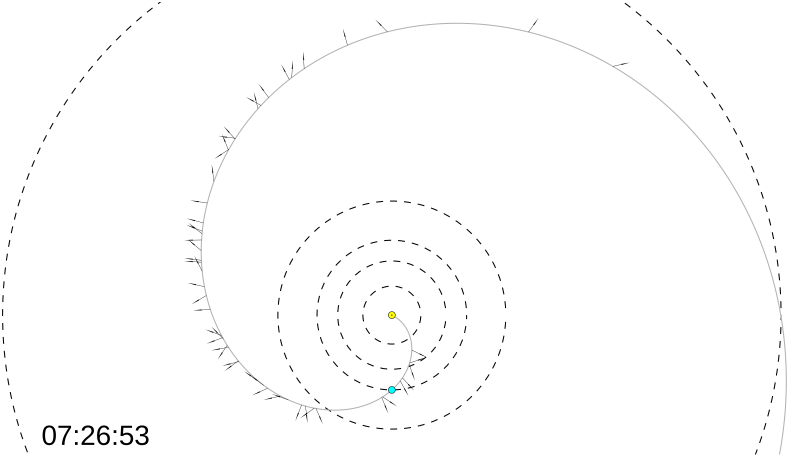
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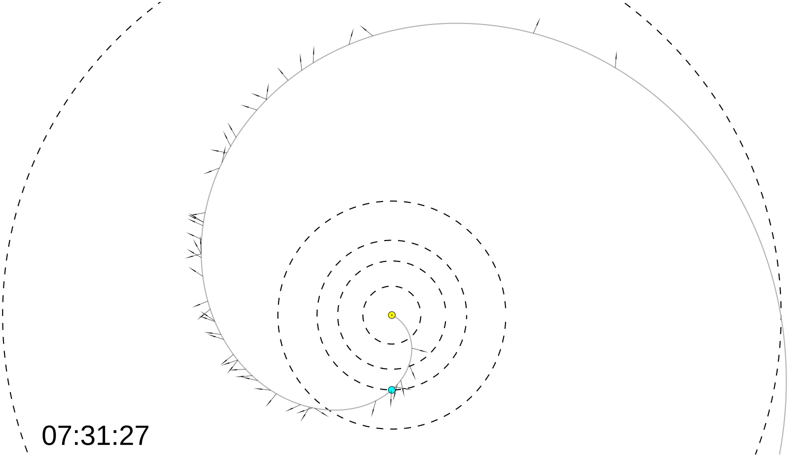
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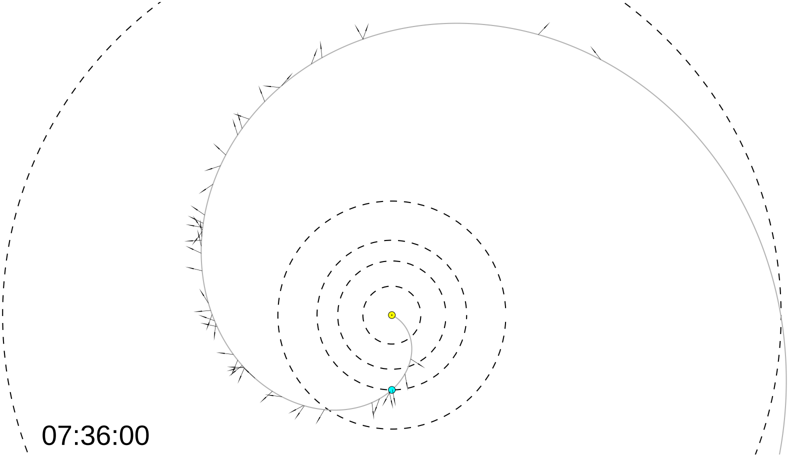
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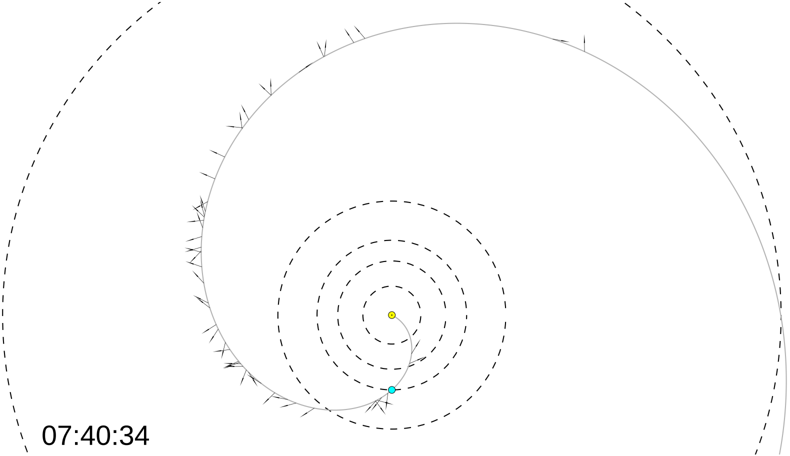
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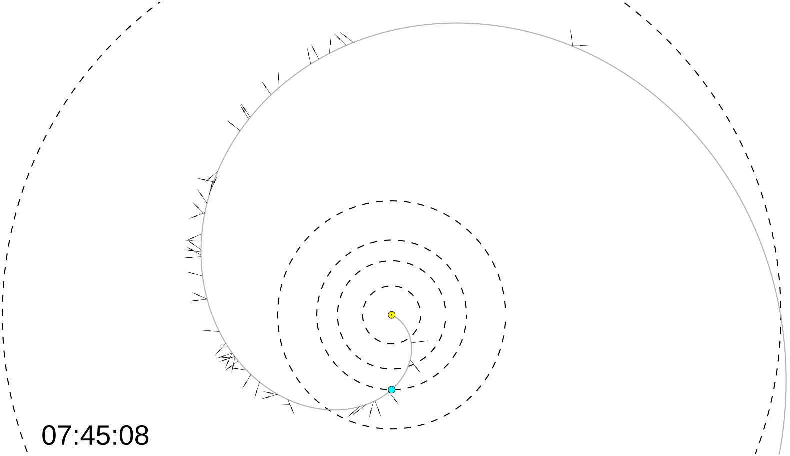
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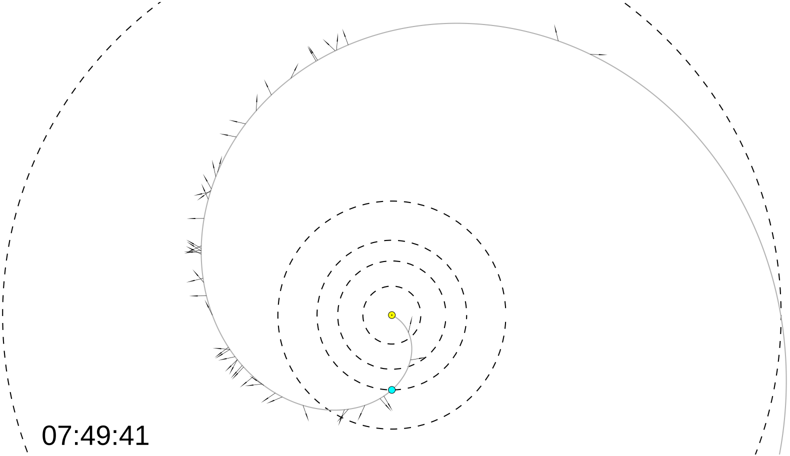
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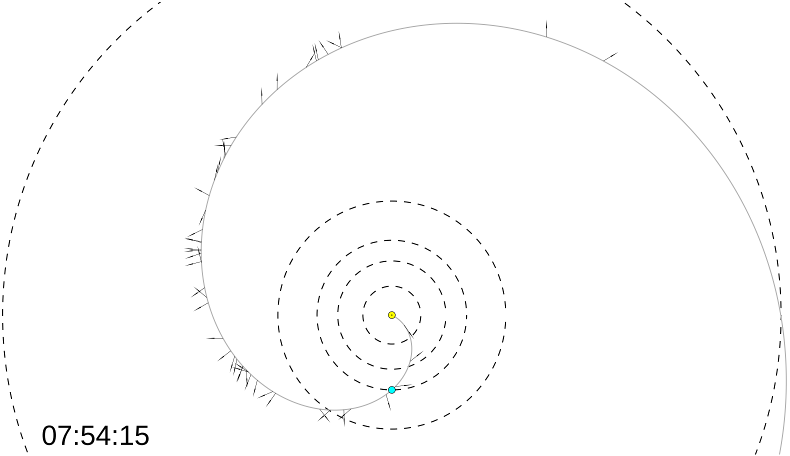
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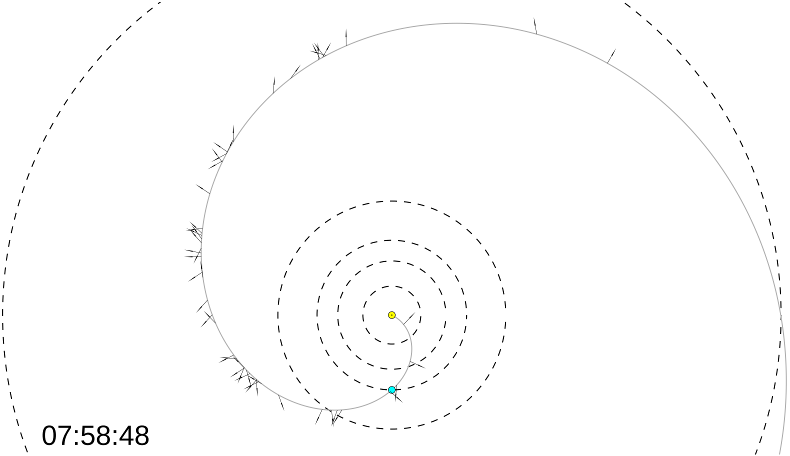
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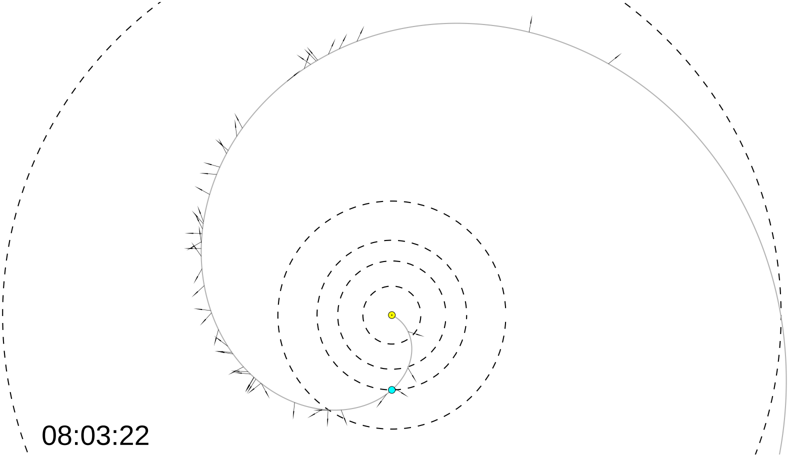
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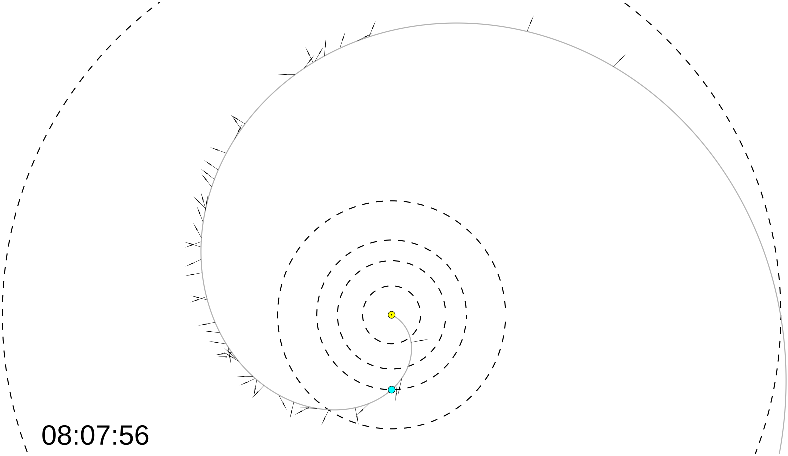
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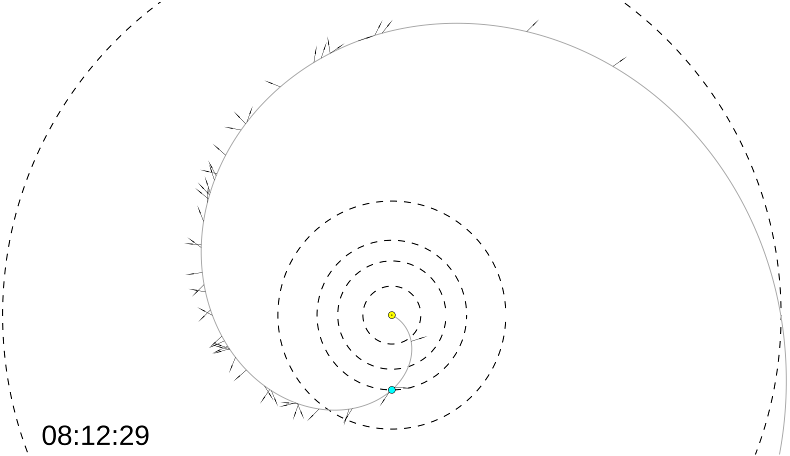
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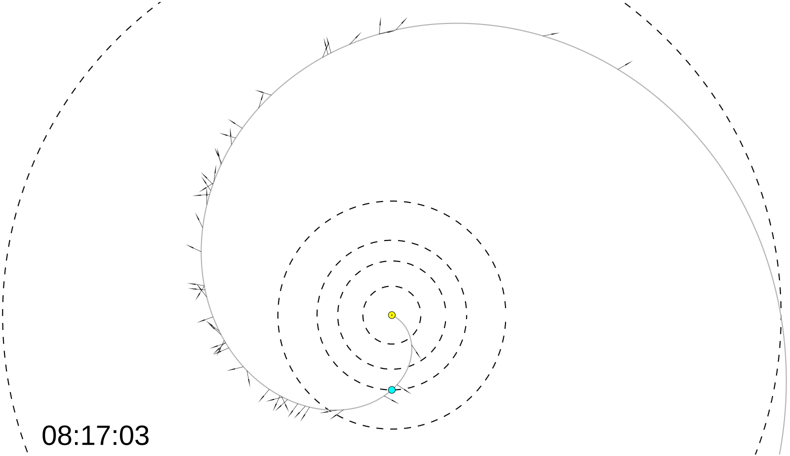
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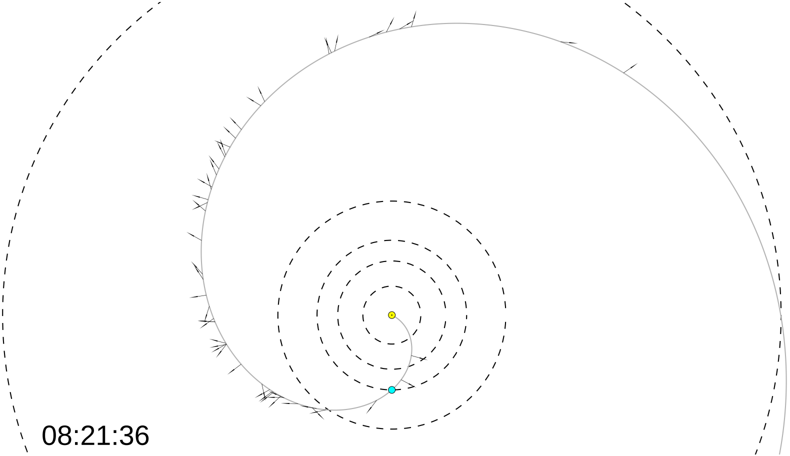
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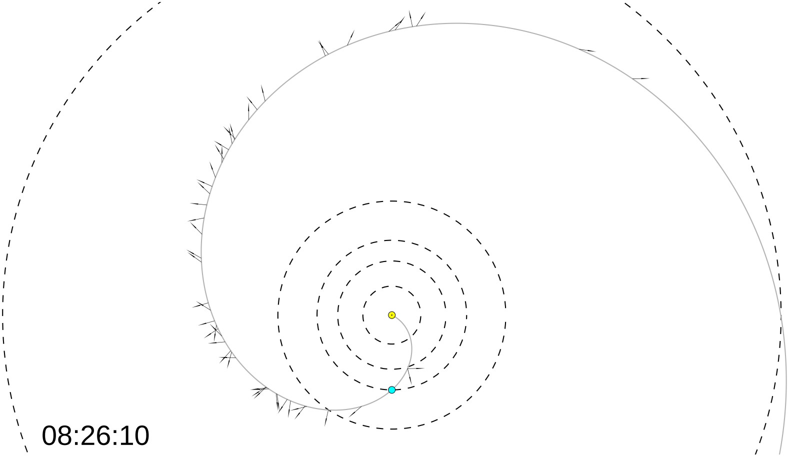
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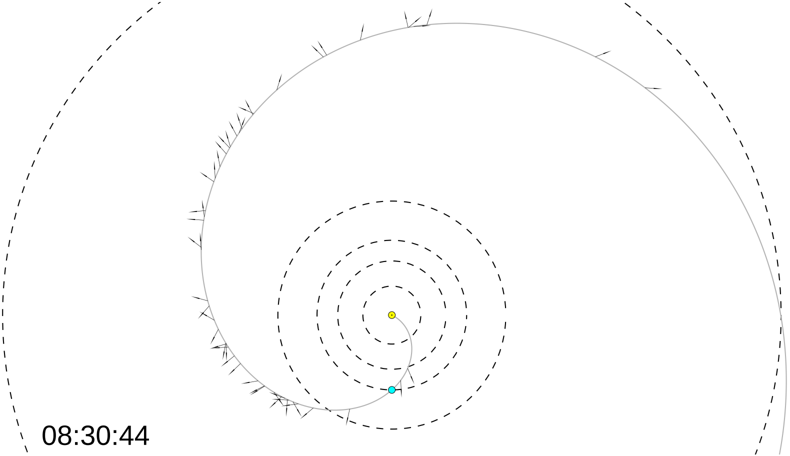

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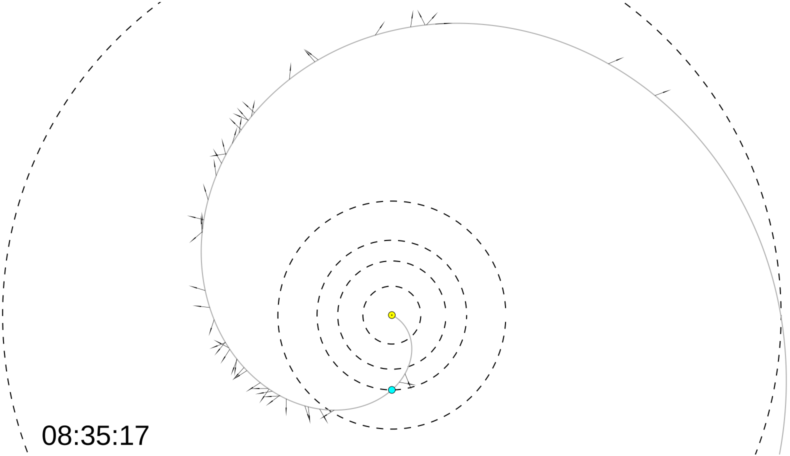
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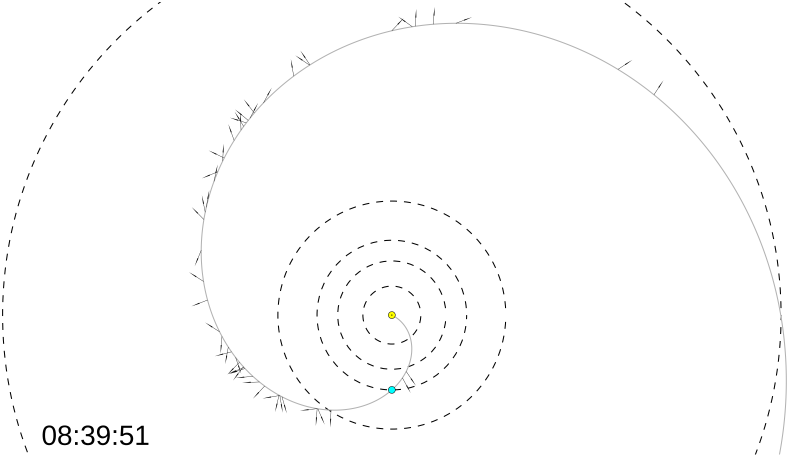
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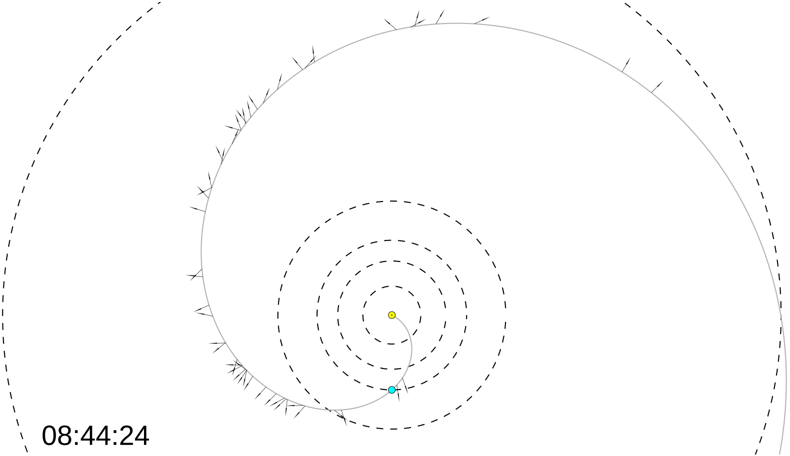
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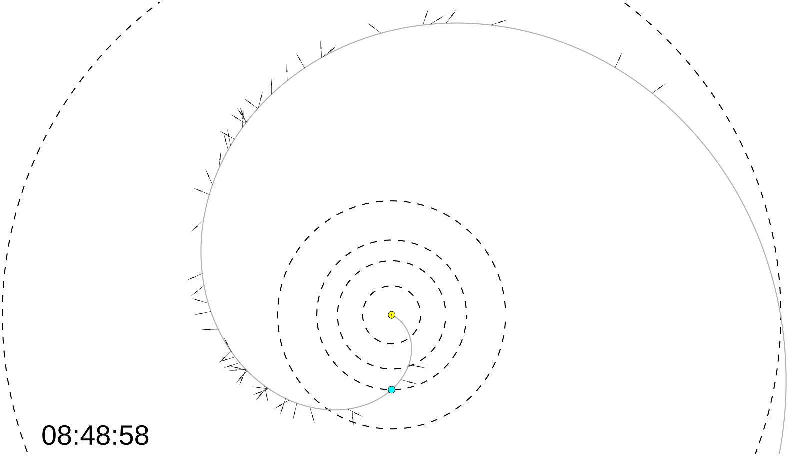
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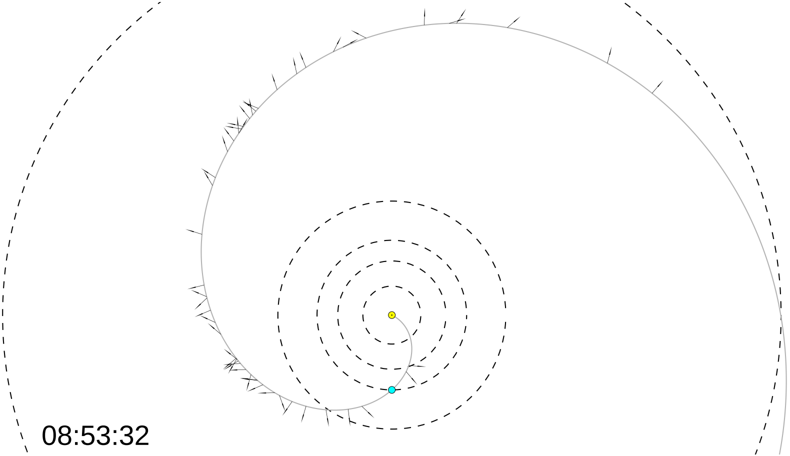
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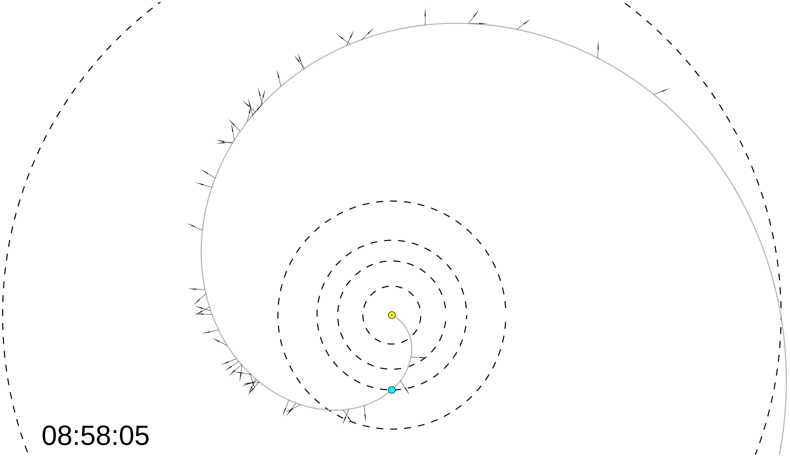

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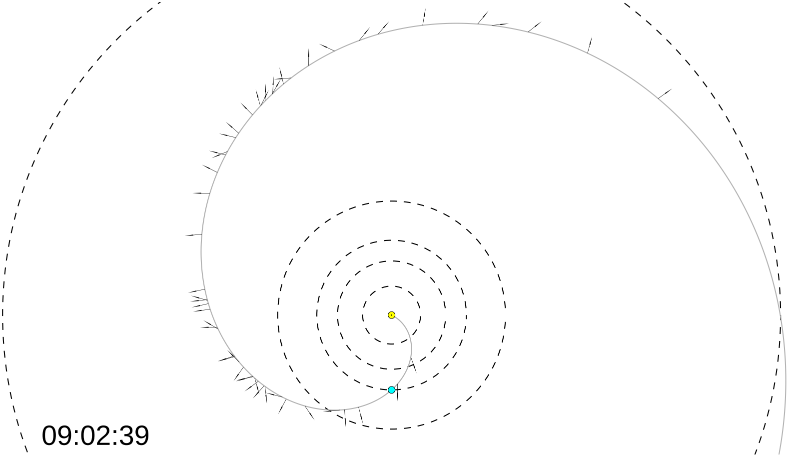
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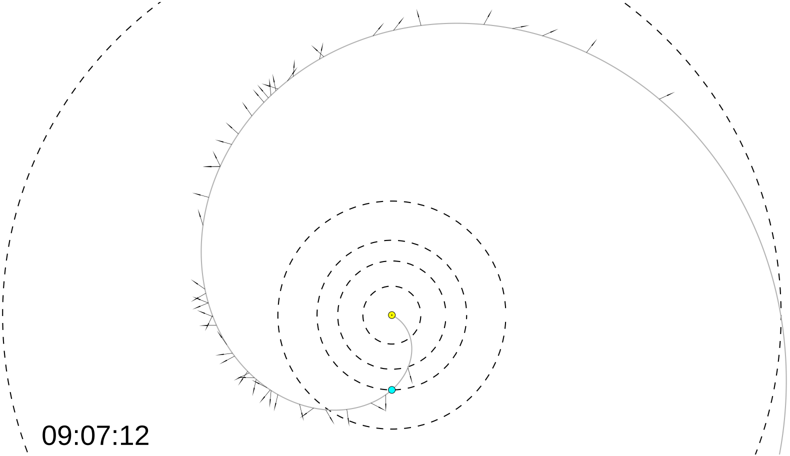
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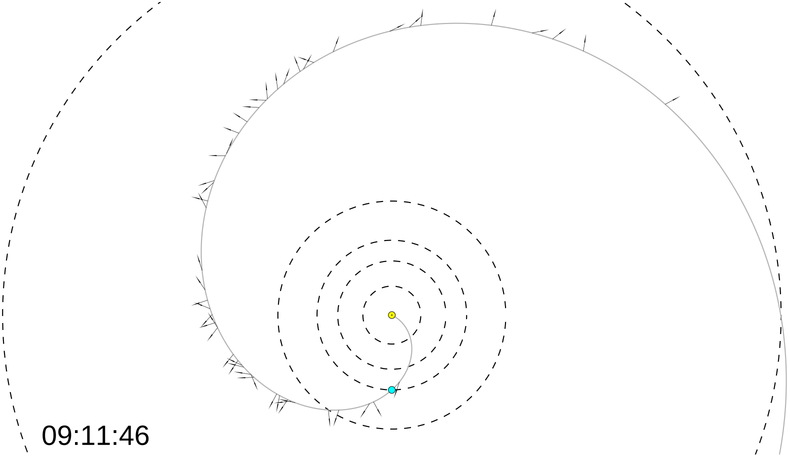
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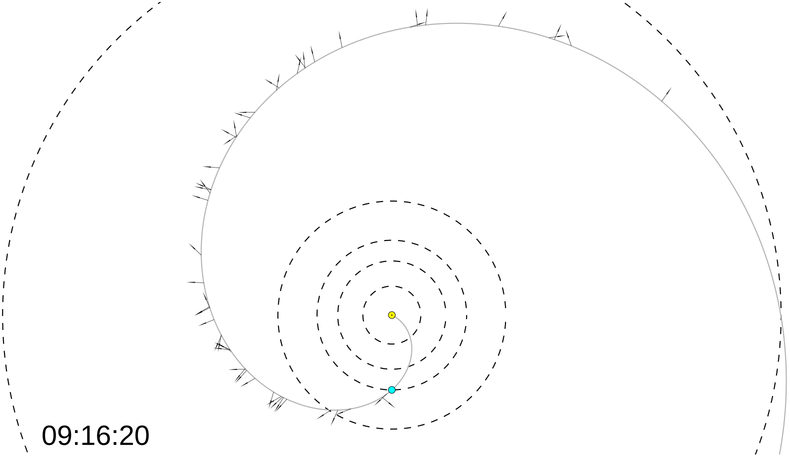

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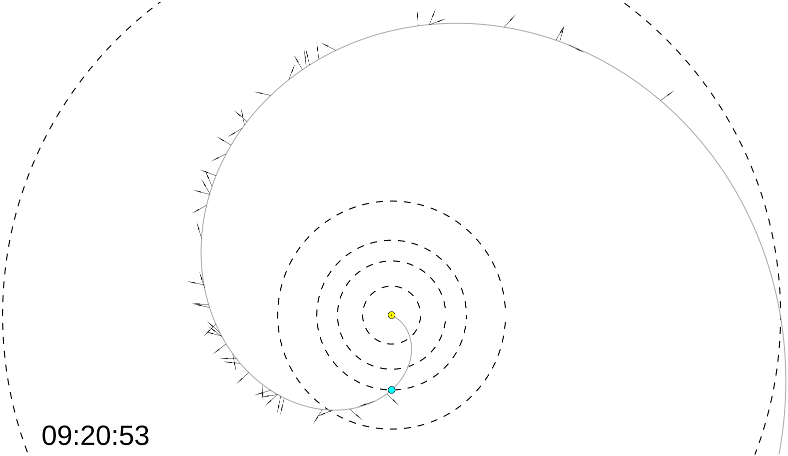
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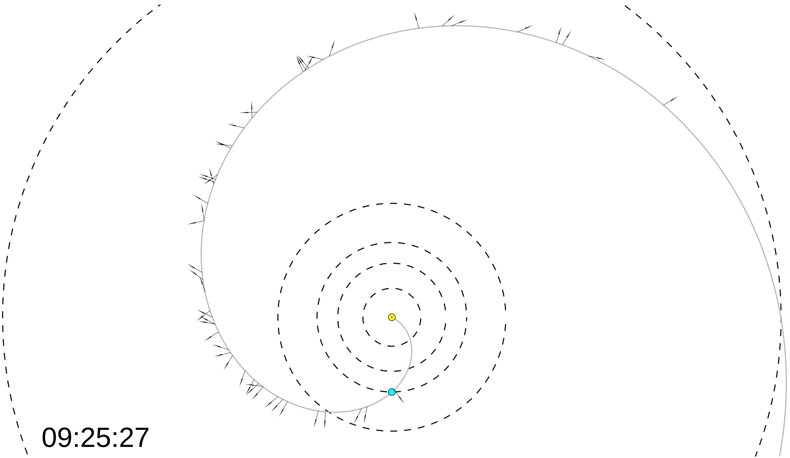
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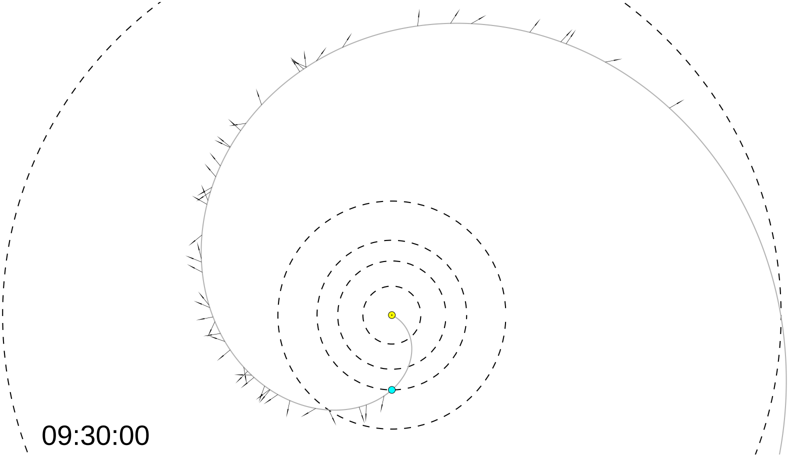
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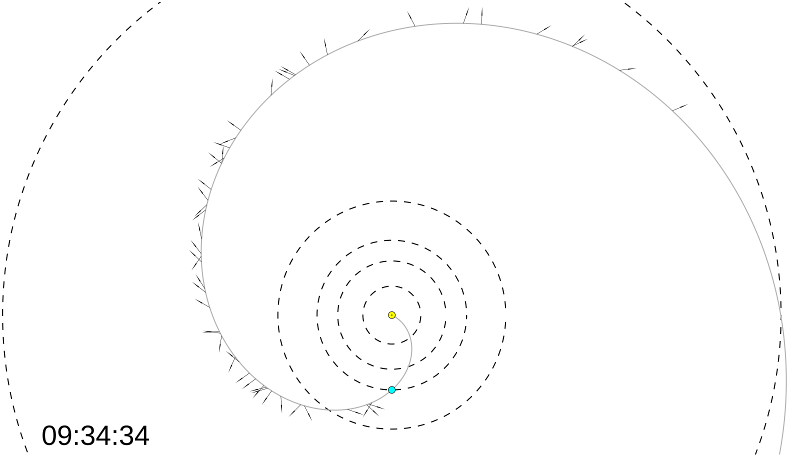
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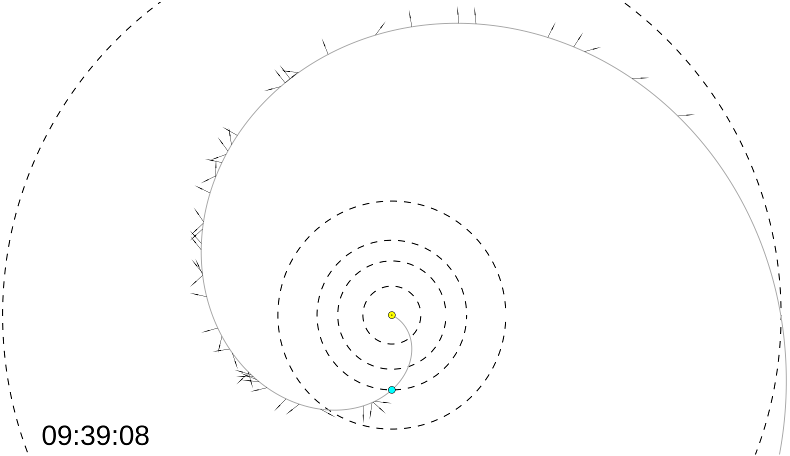
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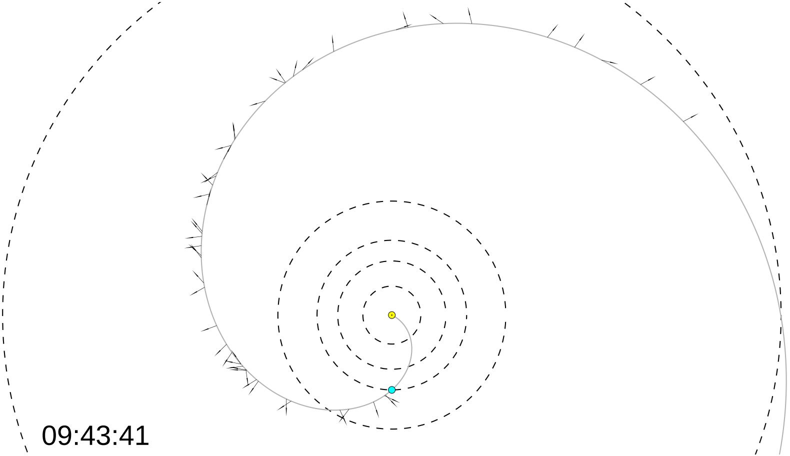
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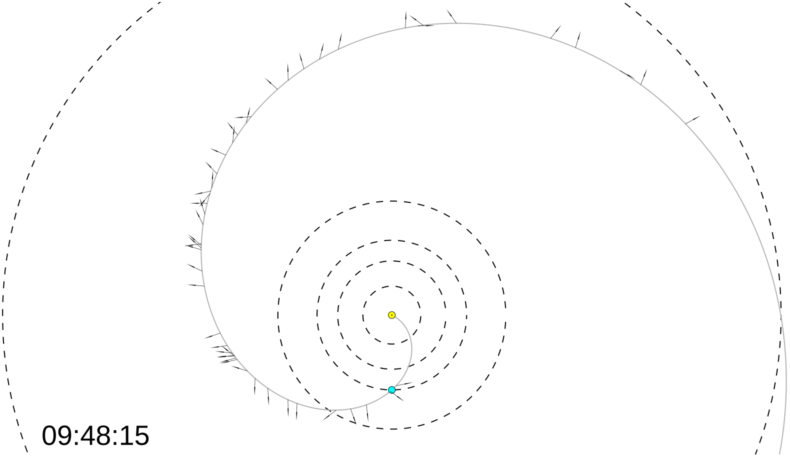
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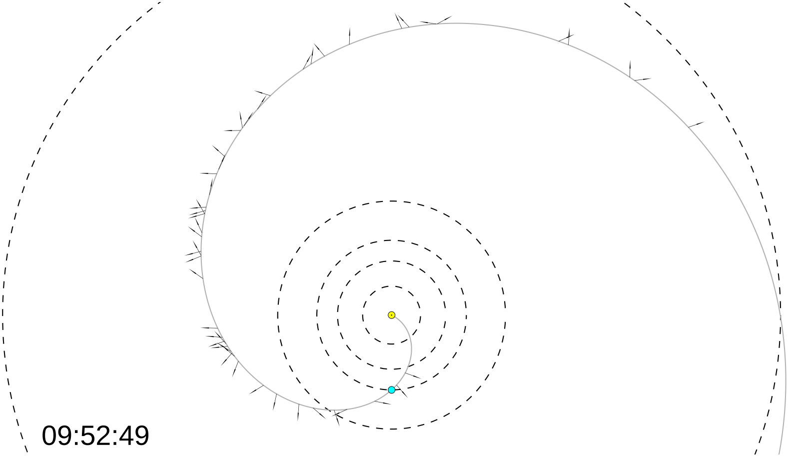
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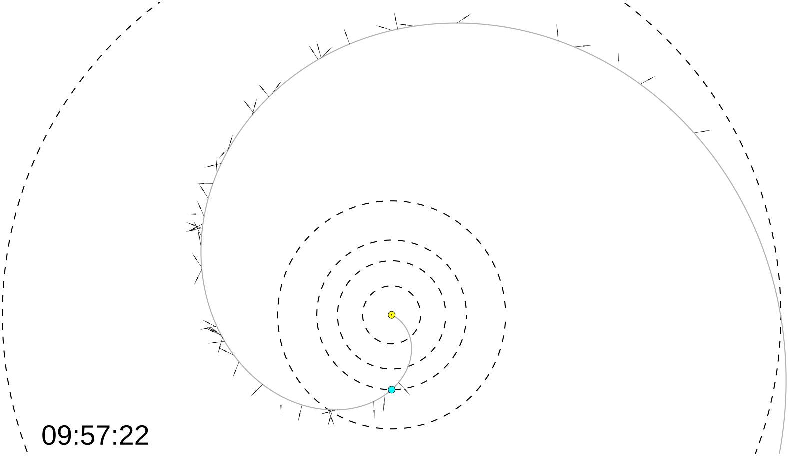
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Focused transport with scattering.

Example:

- 50 electrons, with 100 keV, released from 3 Rs in ecliptic plane
- outward motion, initial μ uniform in]0,1[
- spiral magnetic field (solar wind 400 km/s)
- magnetic field intensity varying as R^{-2}
- constant mean free path $\lambda = 0.05$ AU

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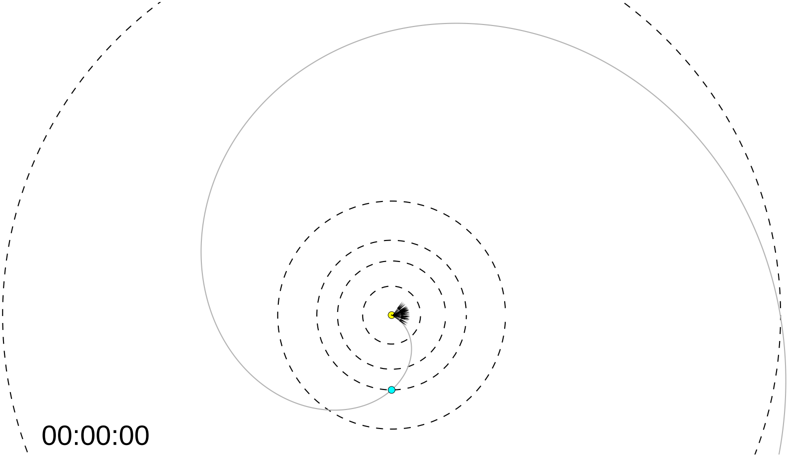
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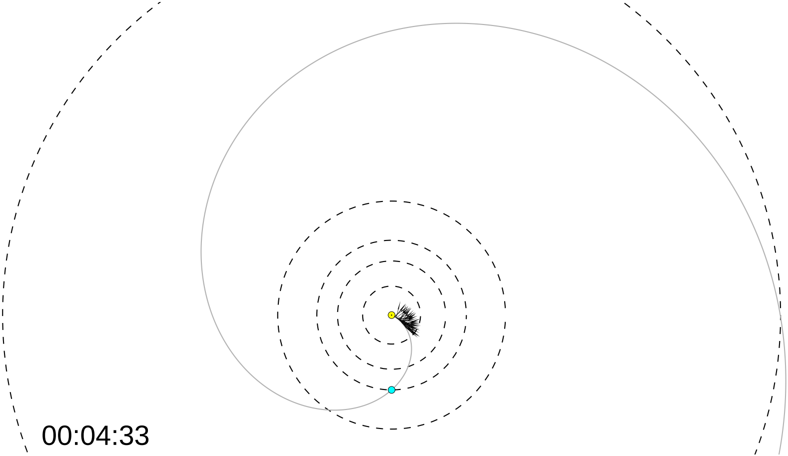
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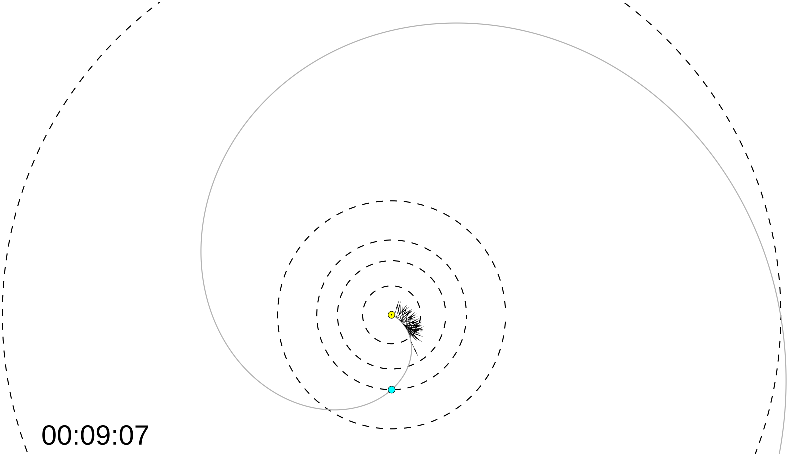
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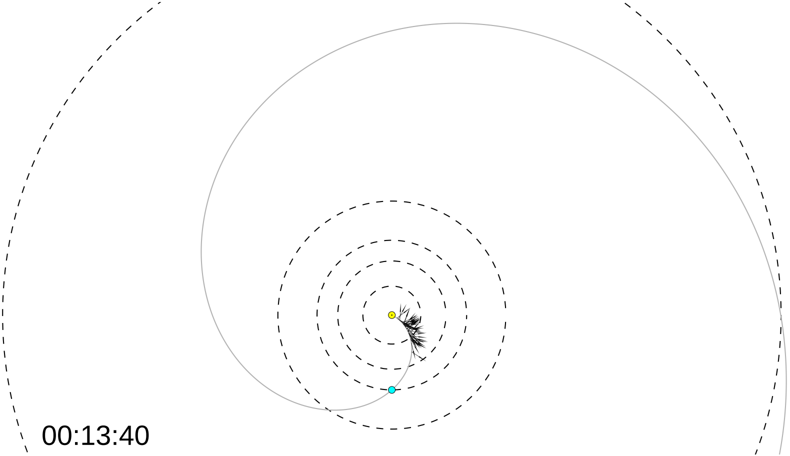
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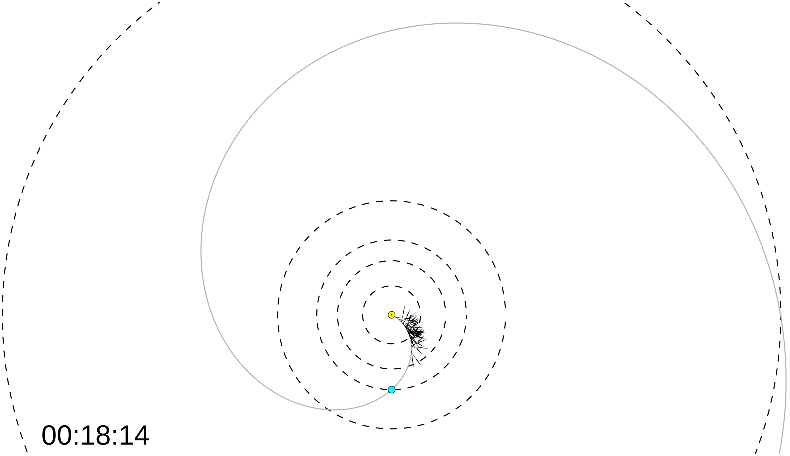
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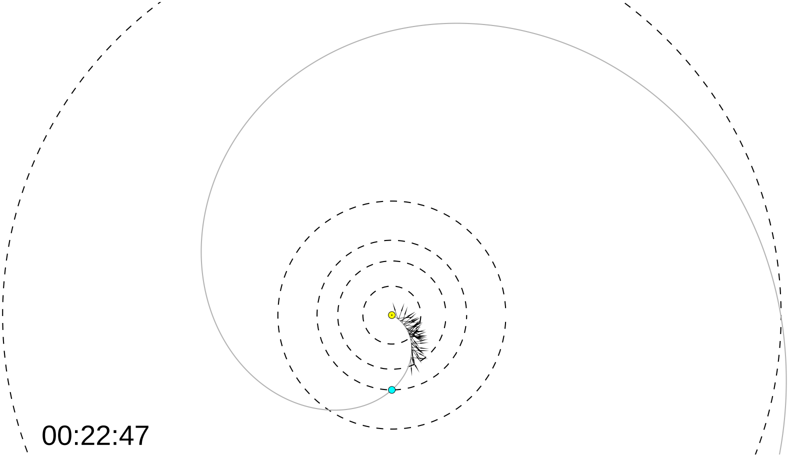
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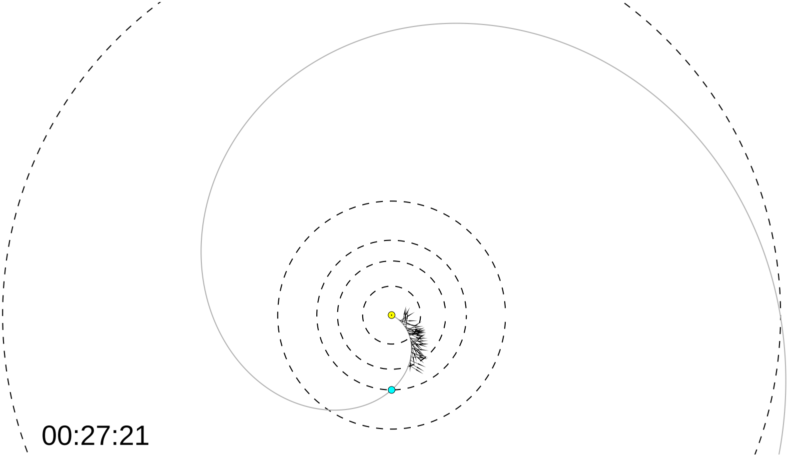
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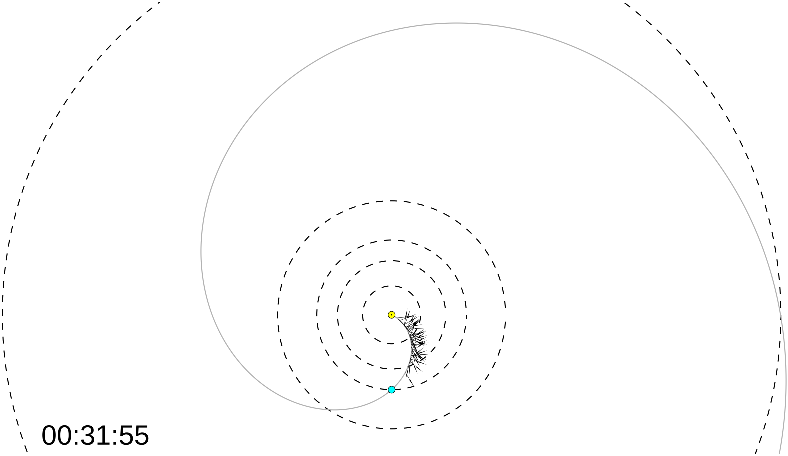
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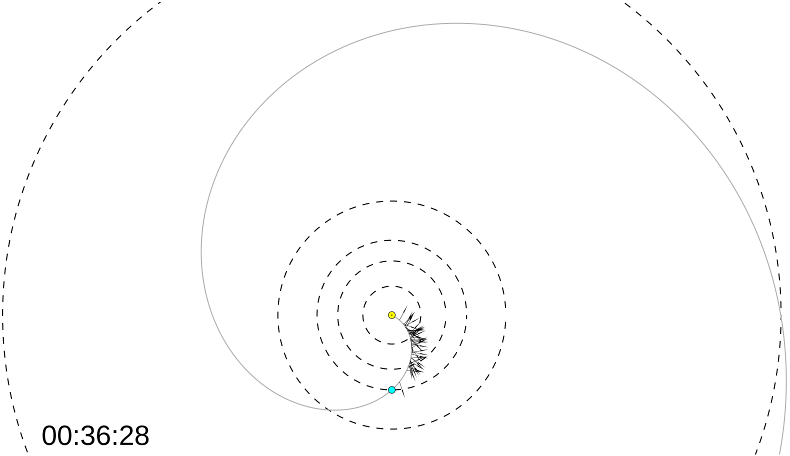
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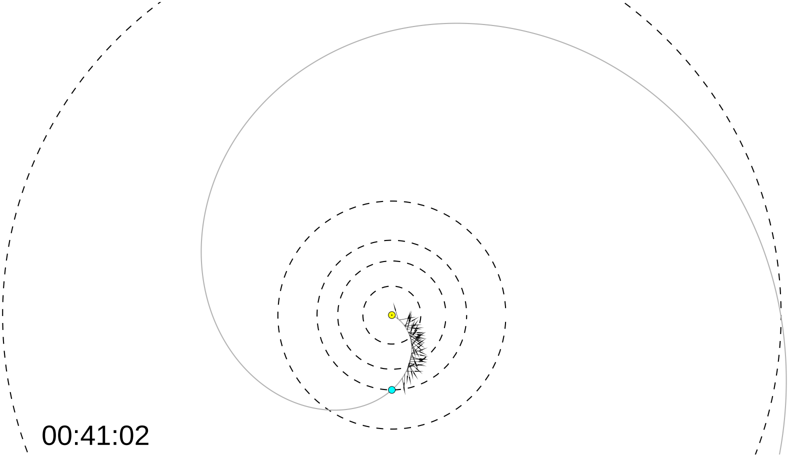
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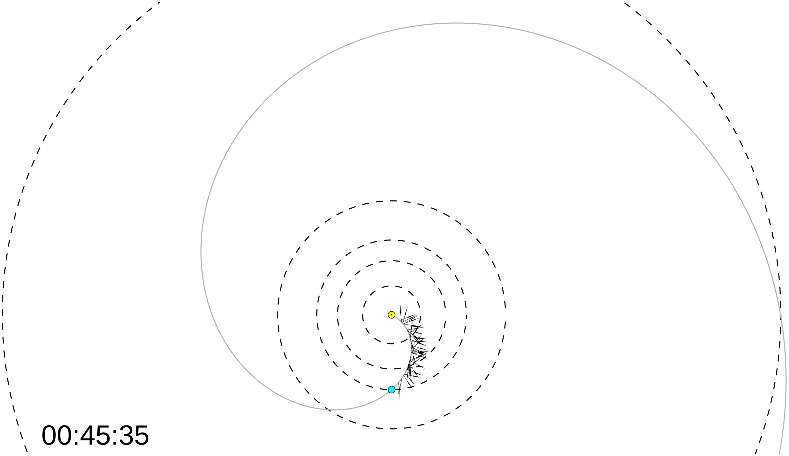
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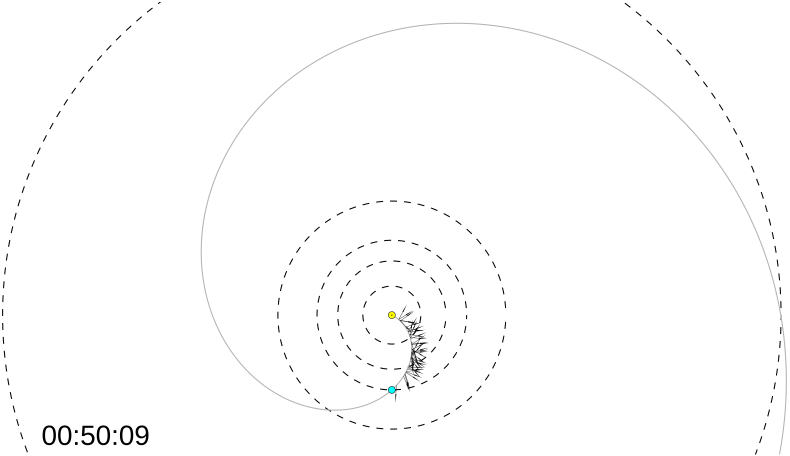
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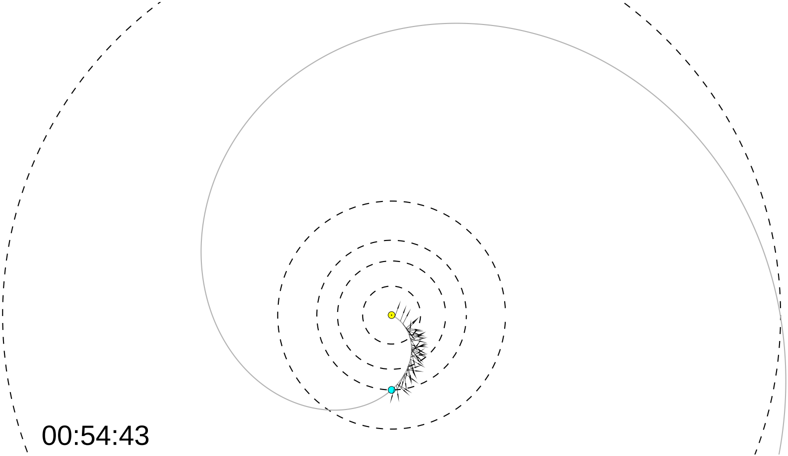

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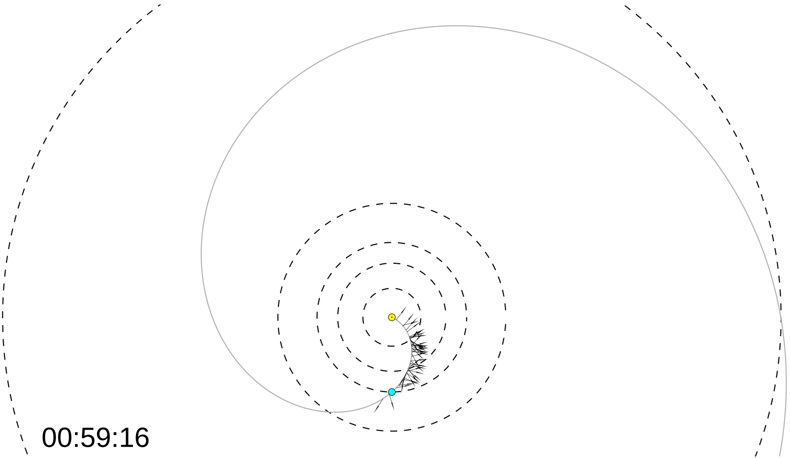
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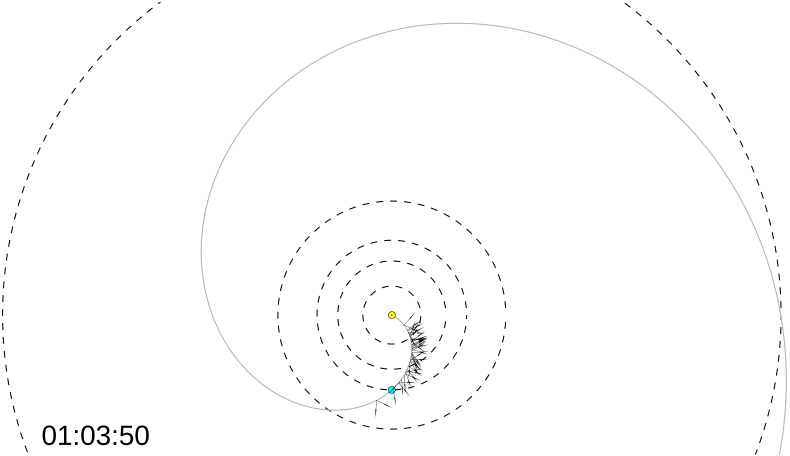
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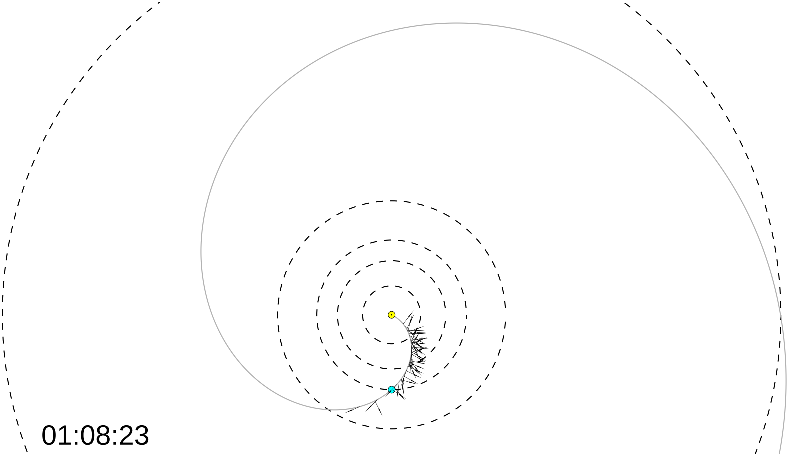
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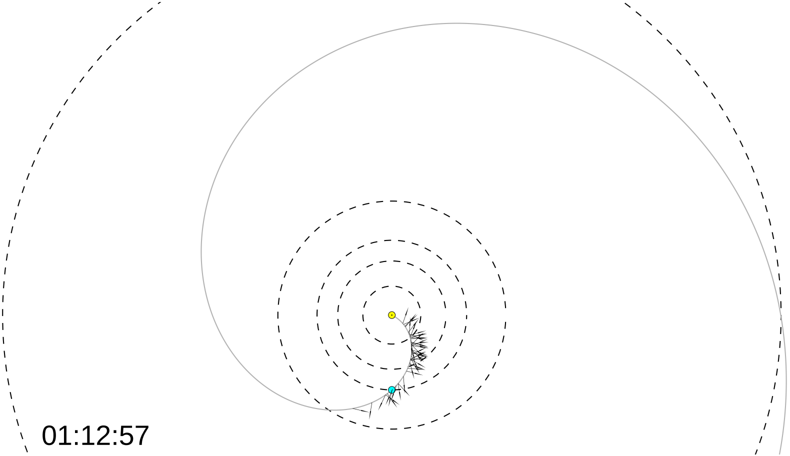
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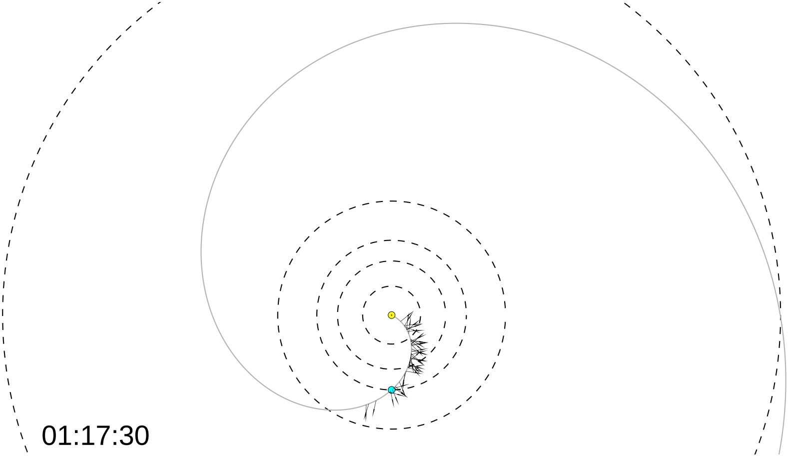
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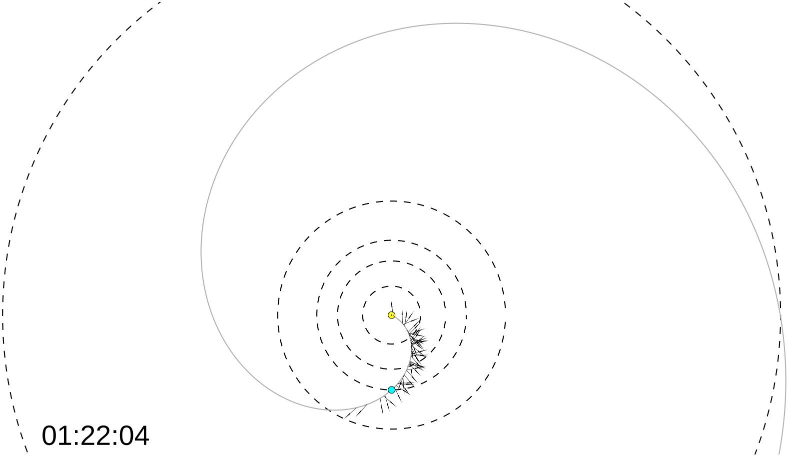
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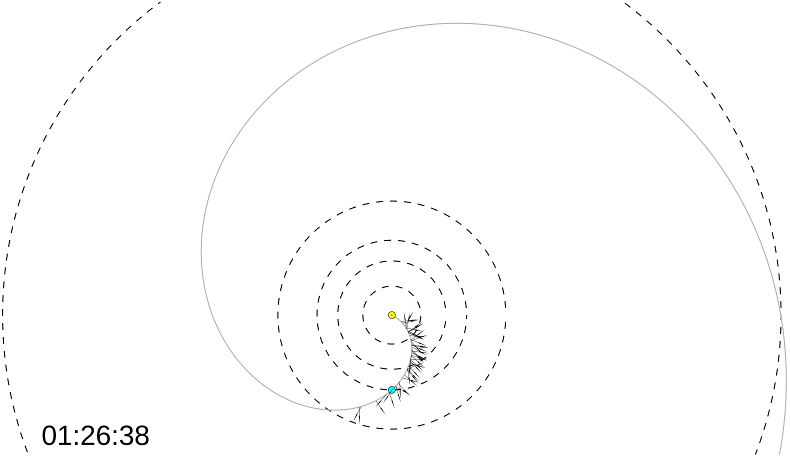
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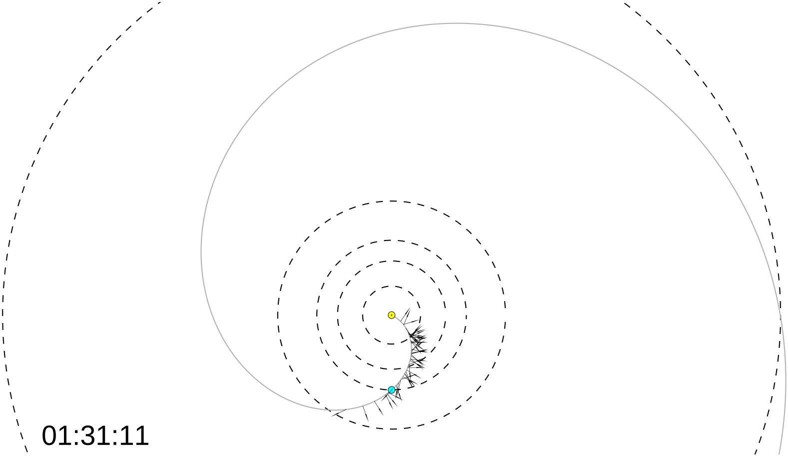
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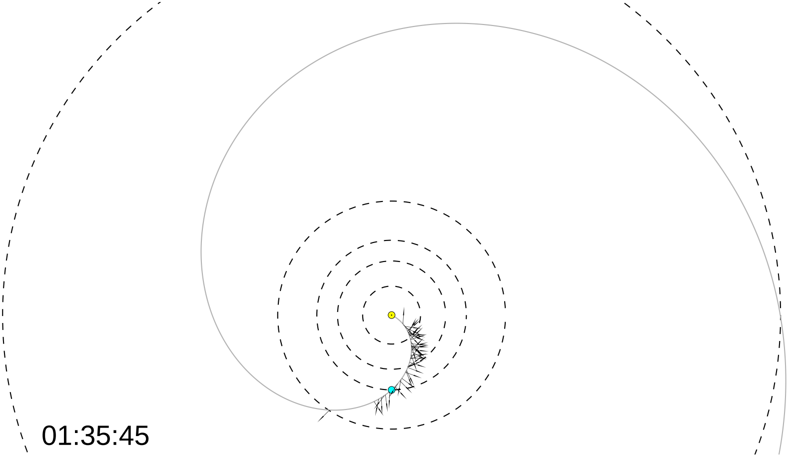
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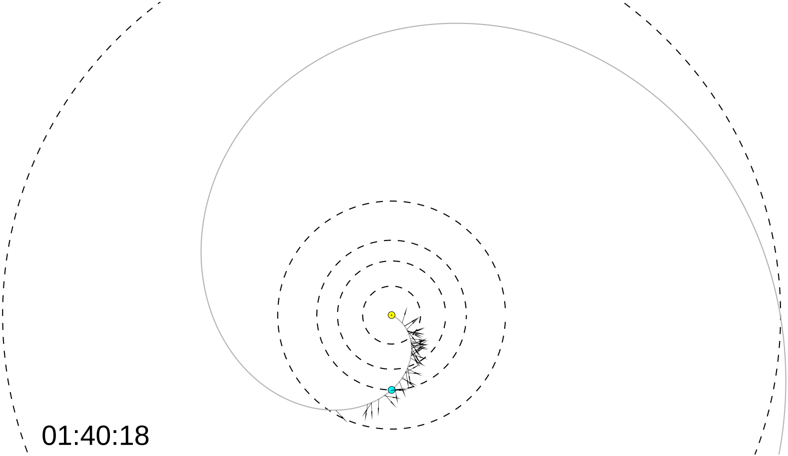
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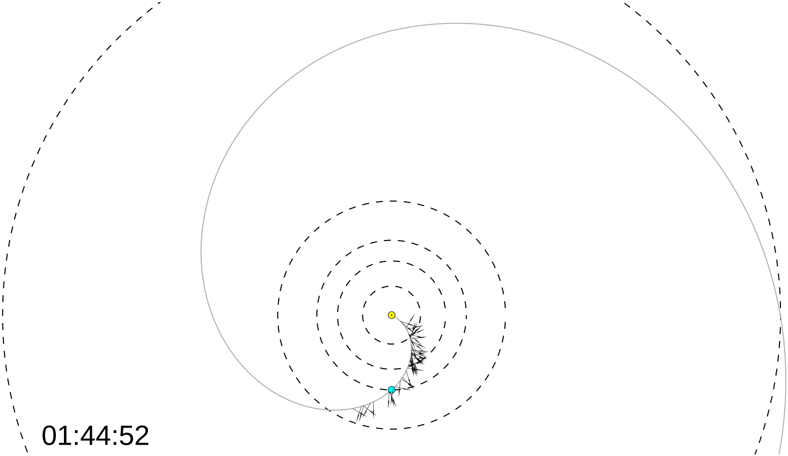
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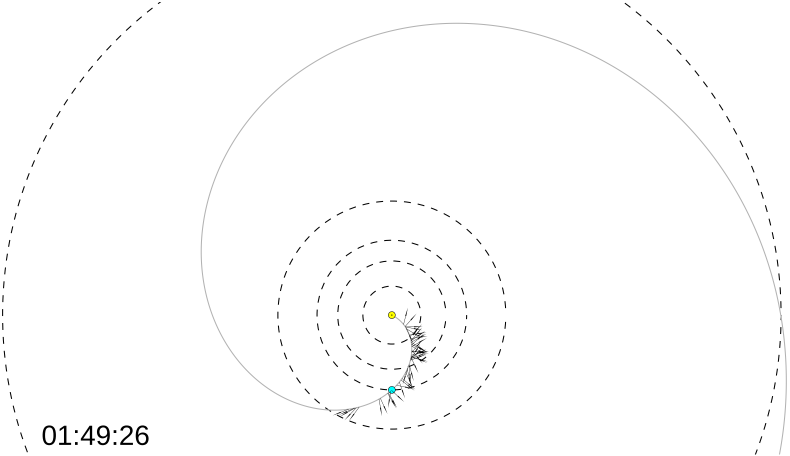
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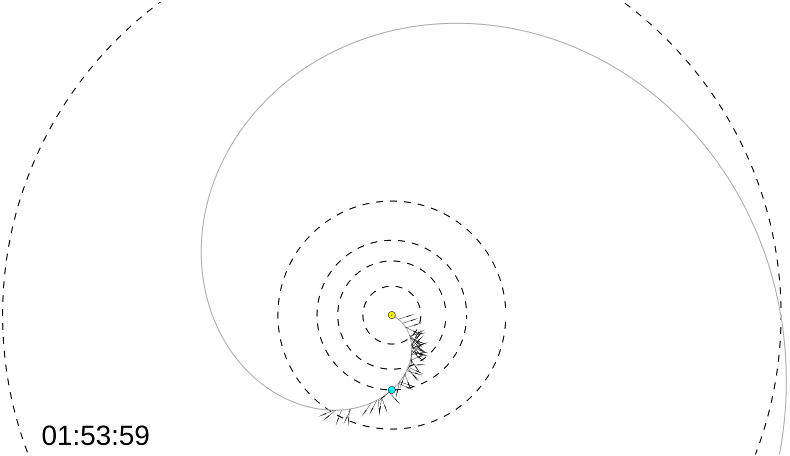
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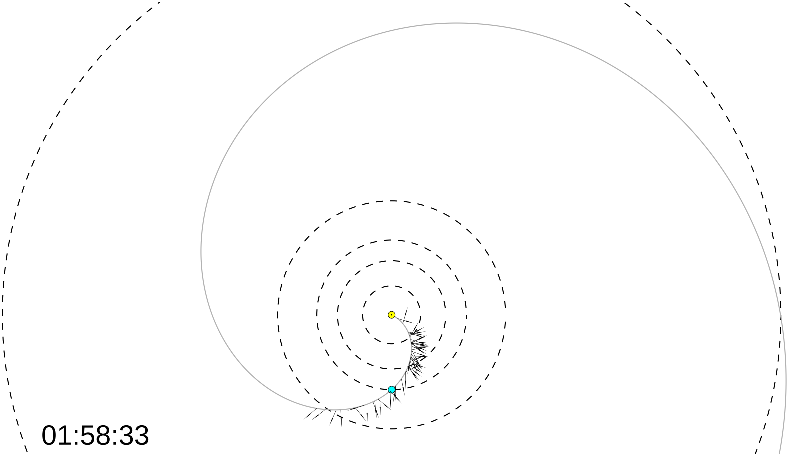
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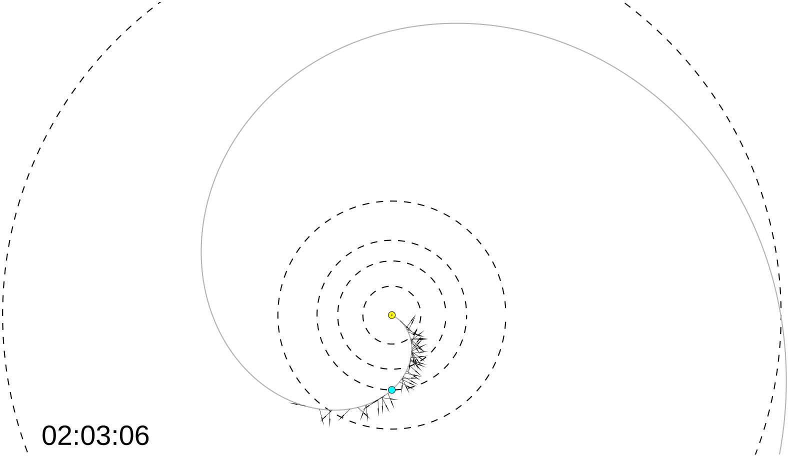
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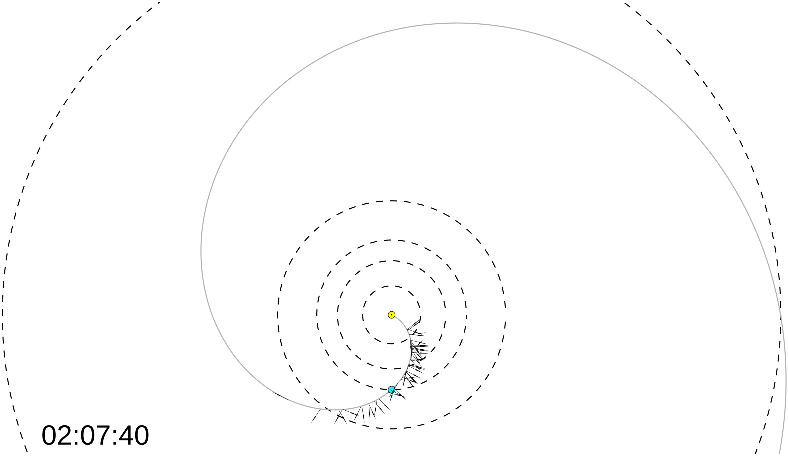
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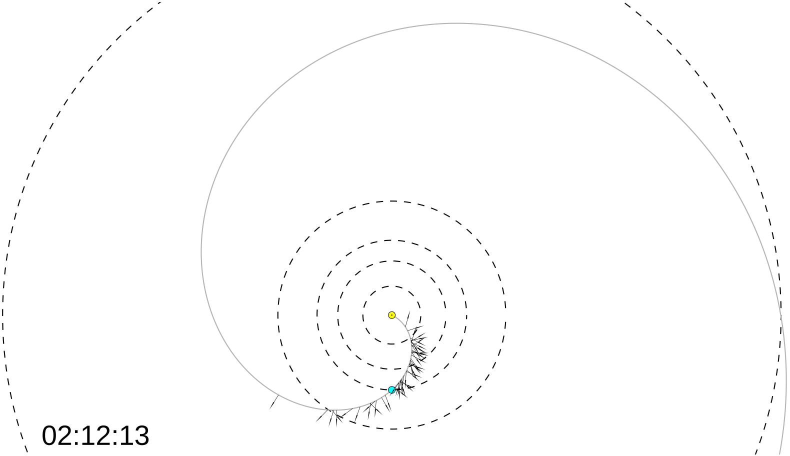
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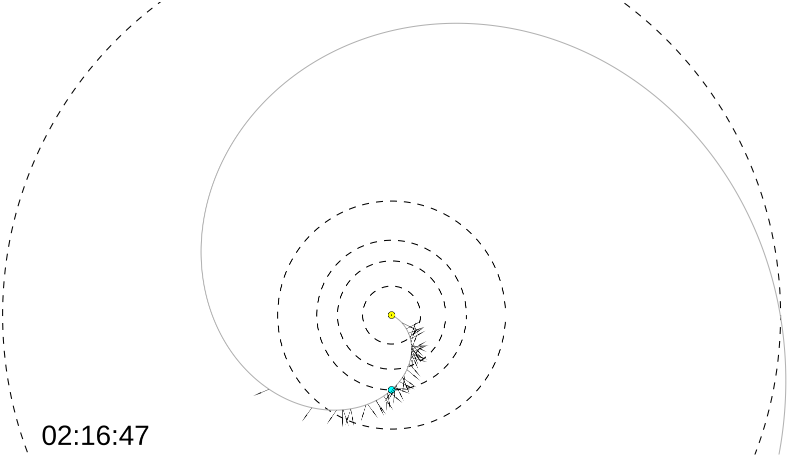
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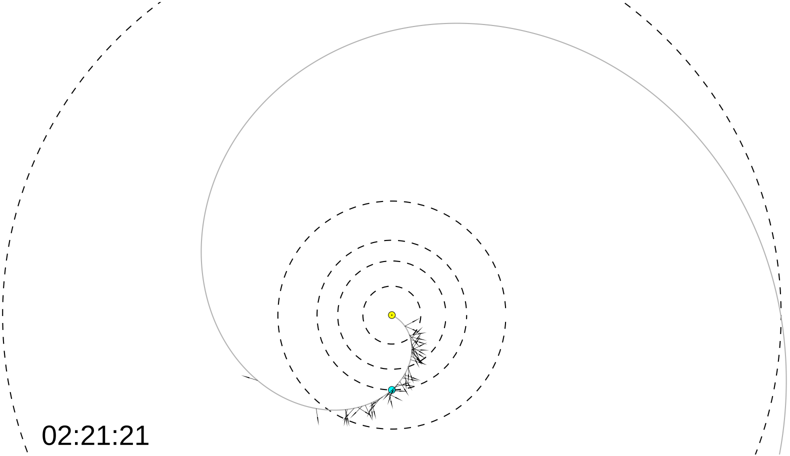
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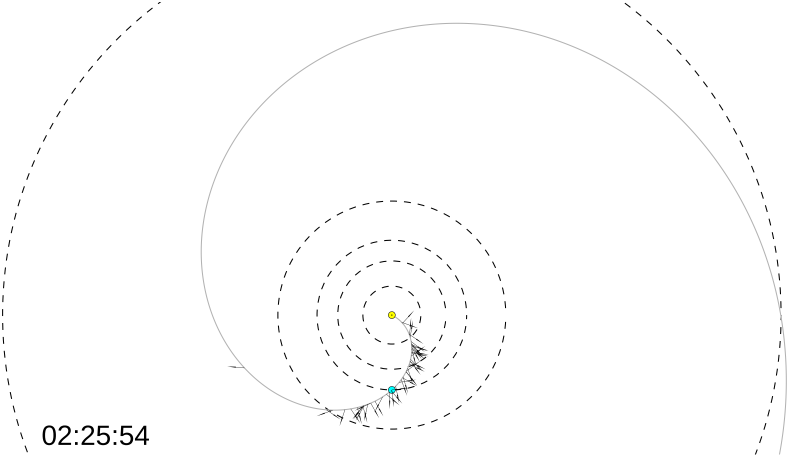
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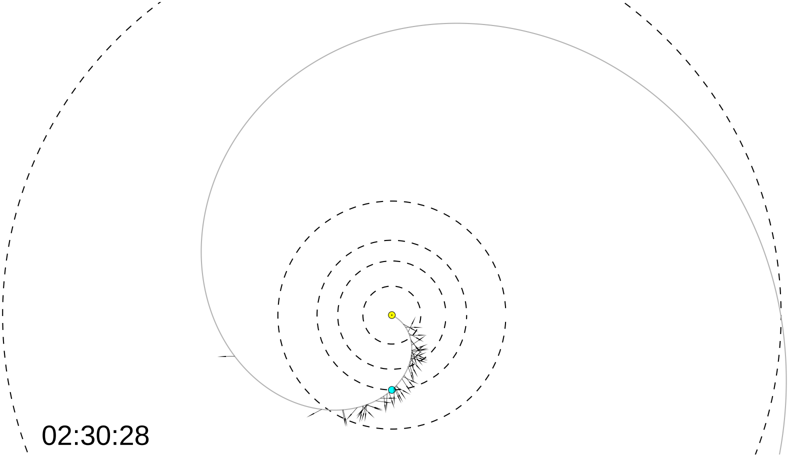
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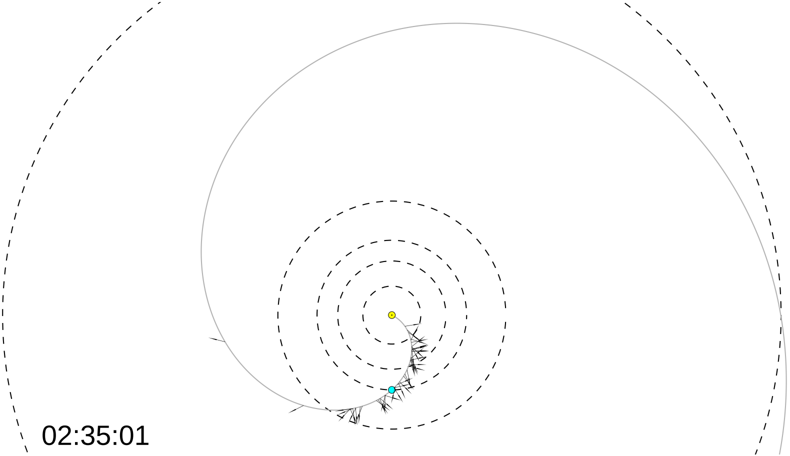
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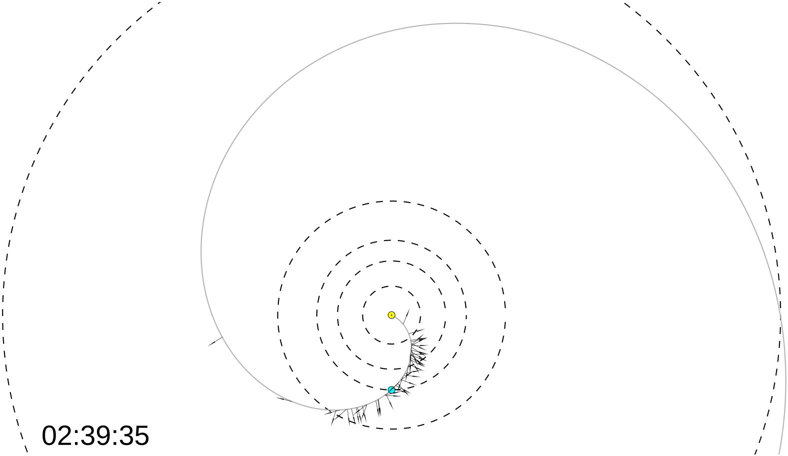
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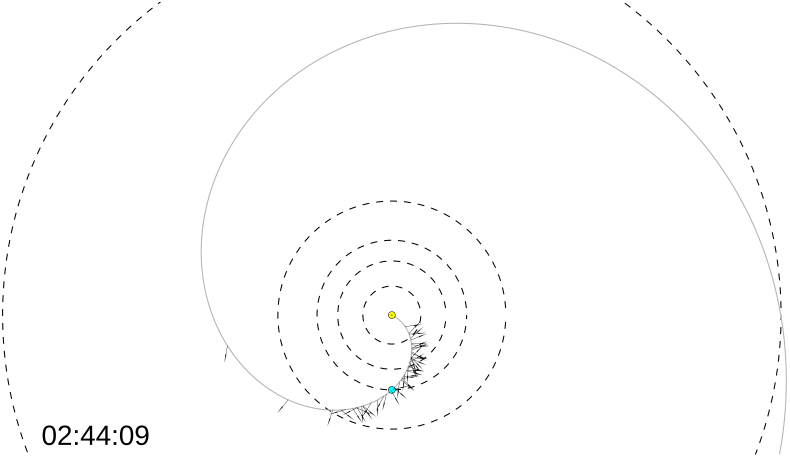
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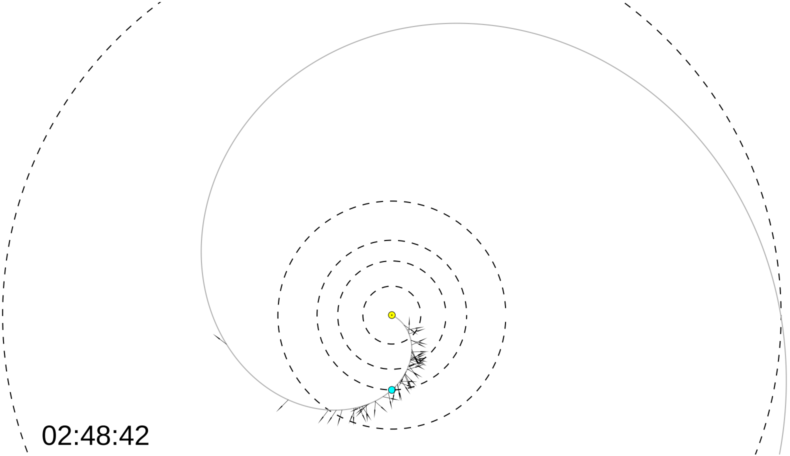
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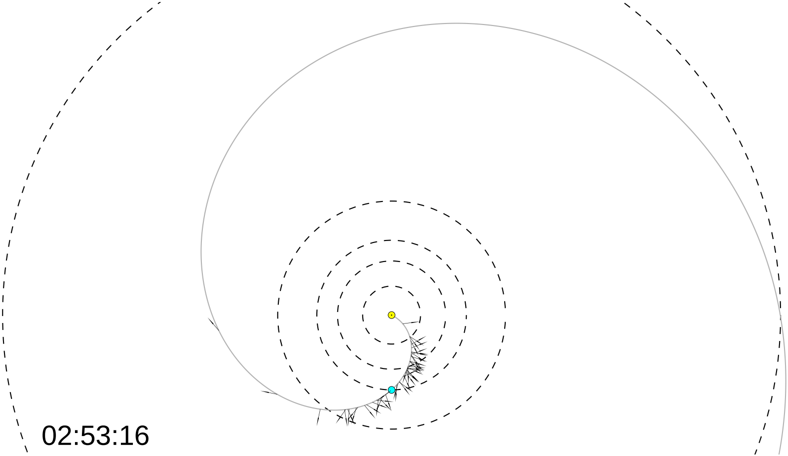
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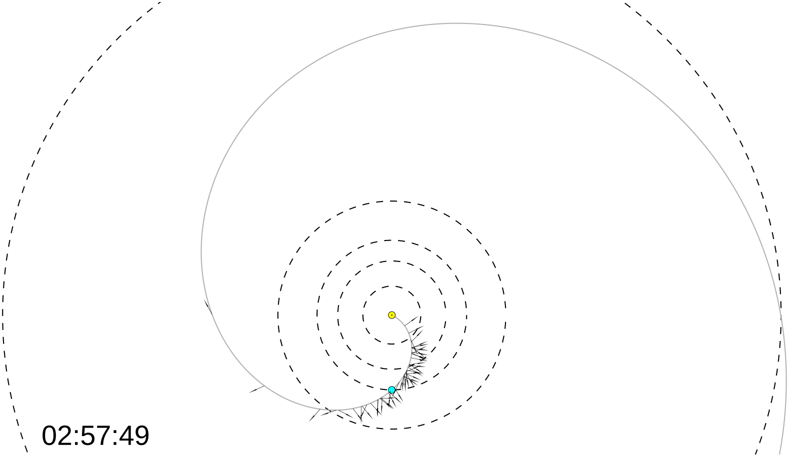
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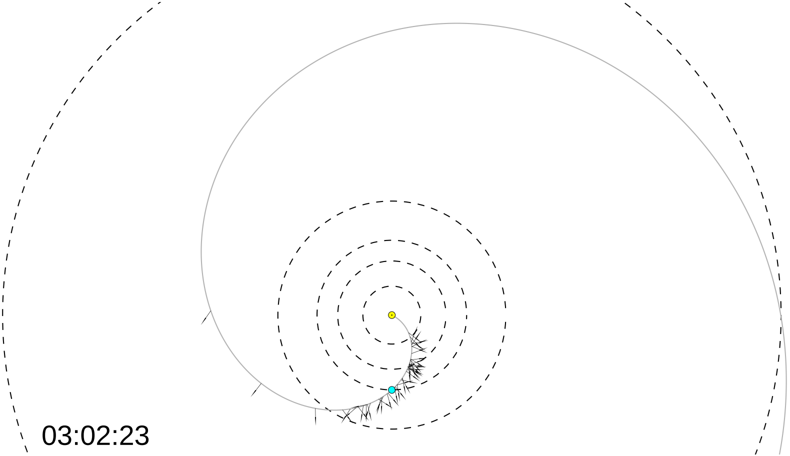
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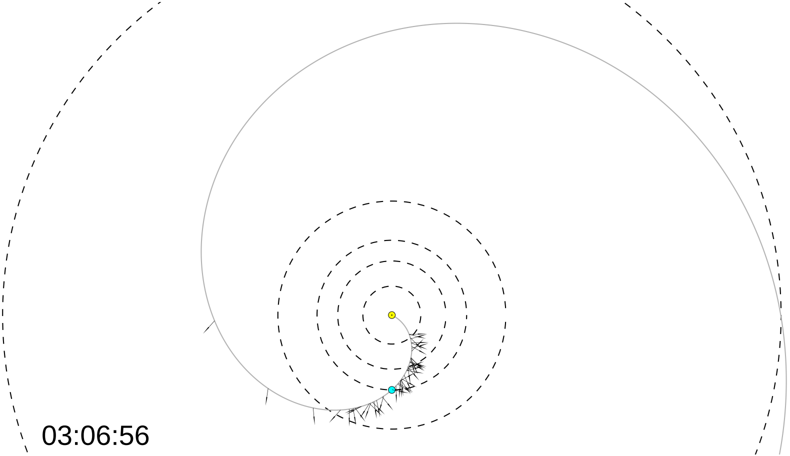
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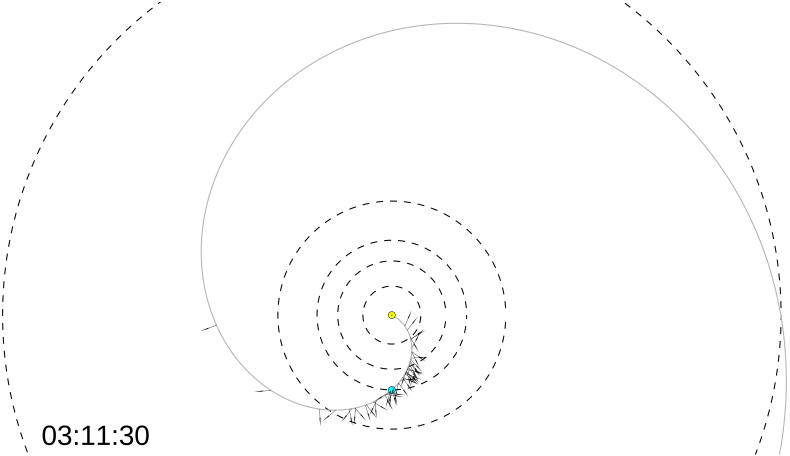
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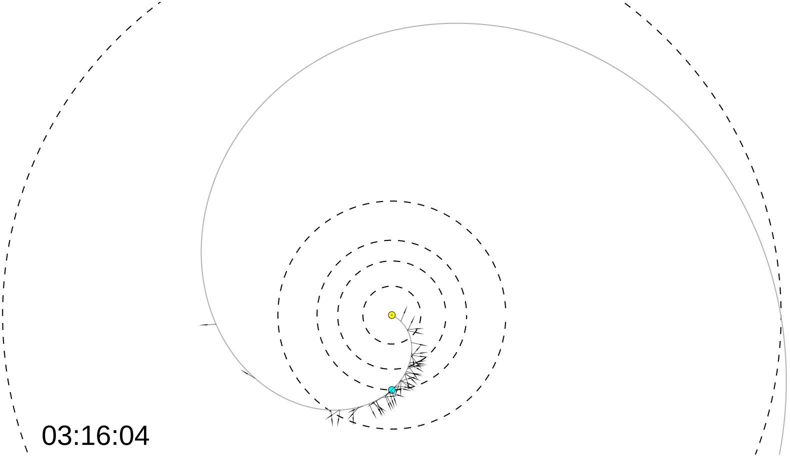
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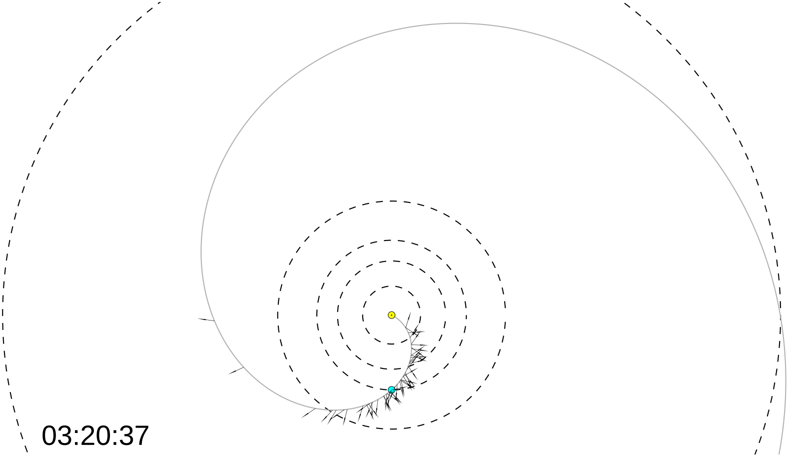
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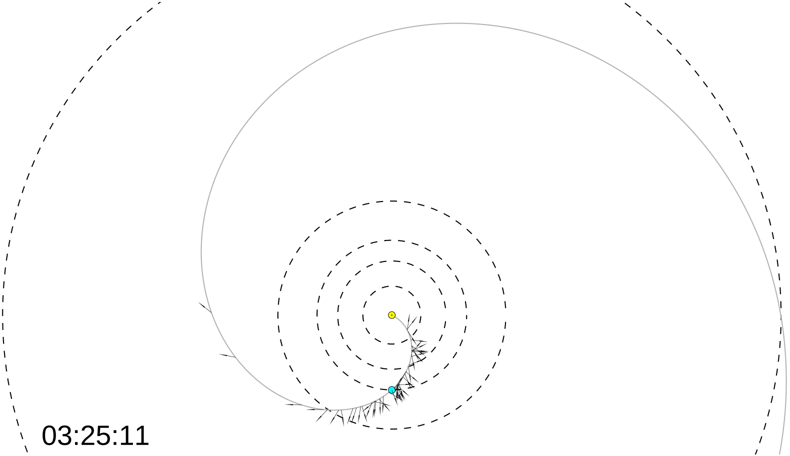
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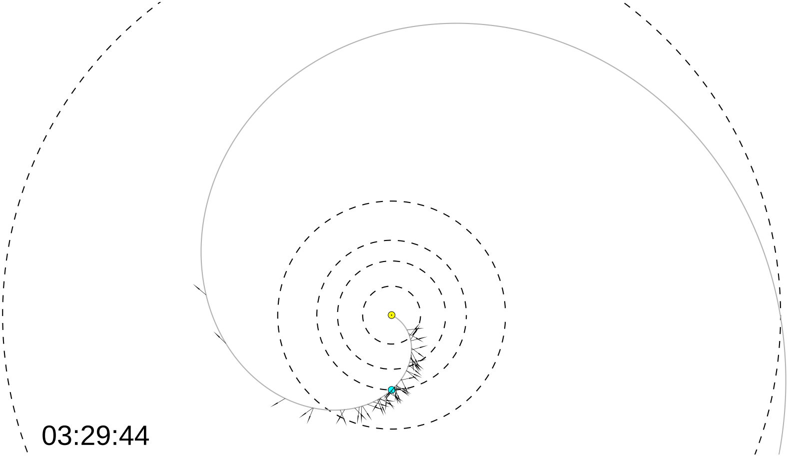
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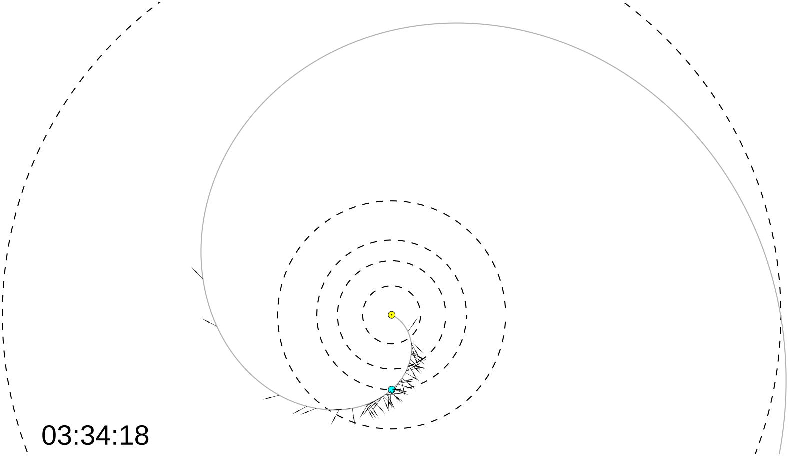
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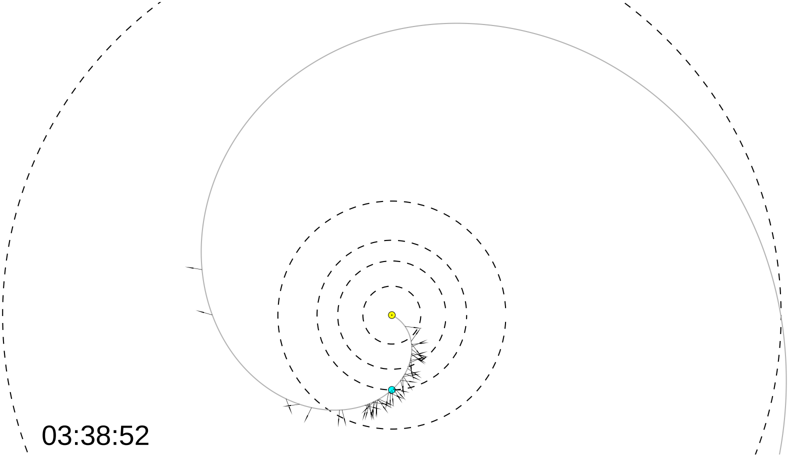
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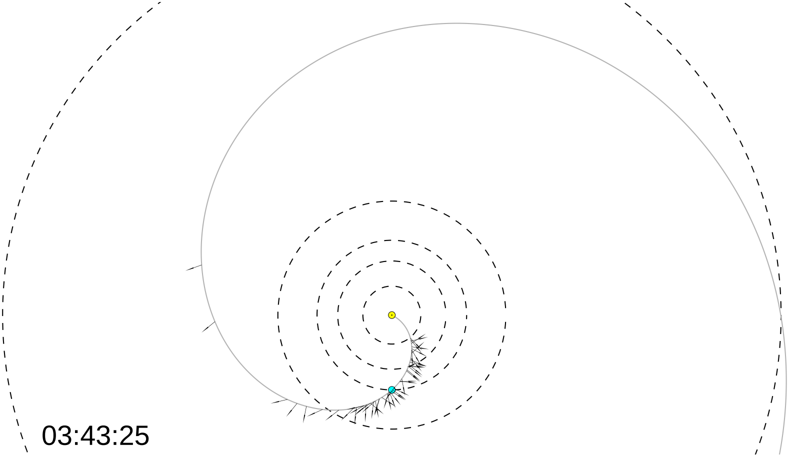

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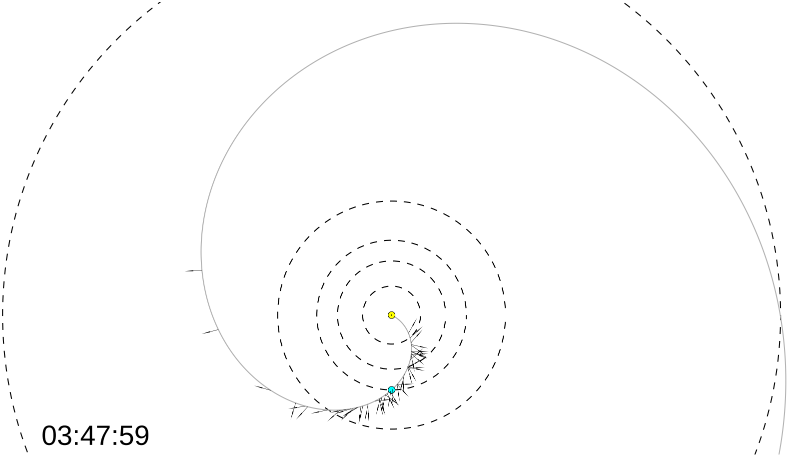
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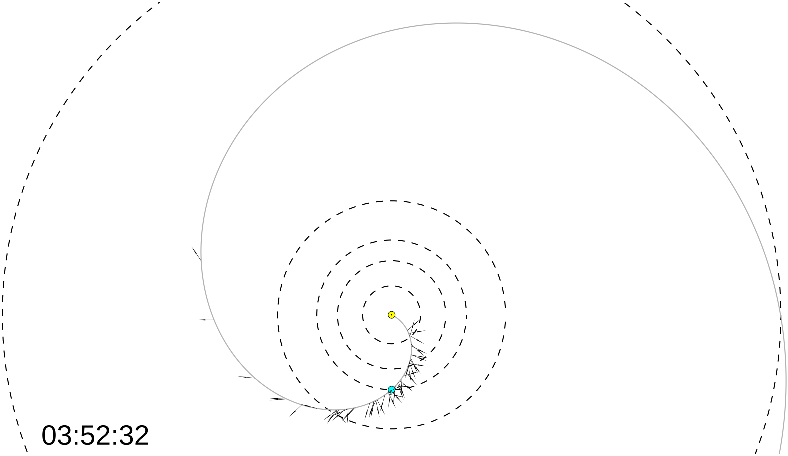
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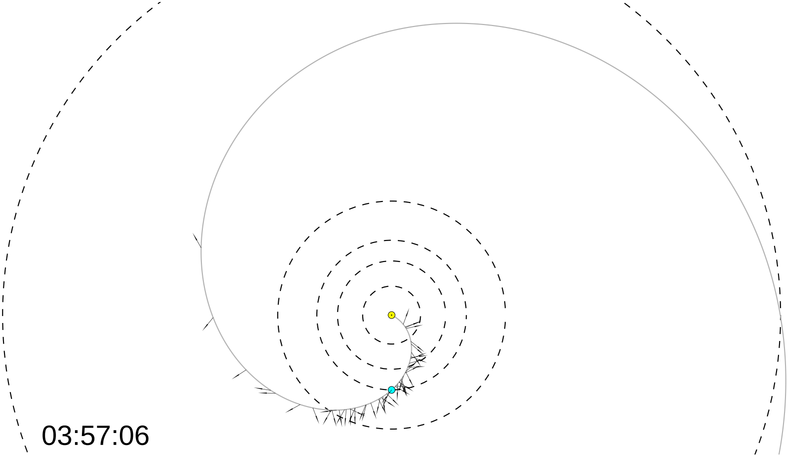
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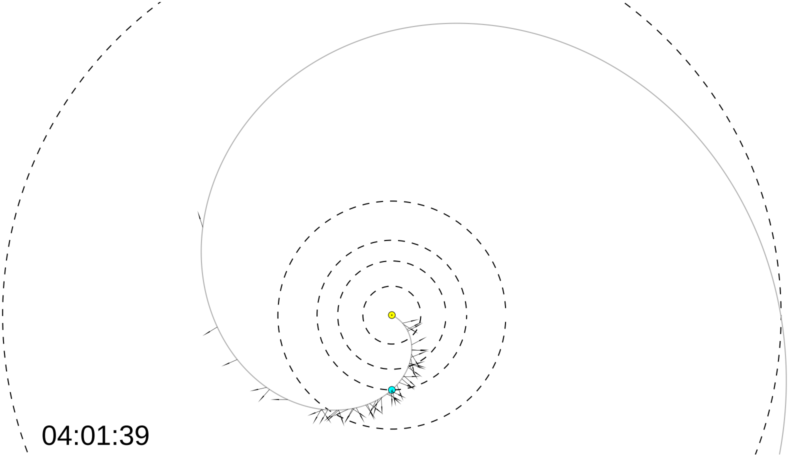
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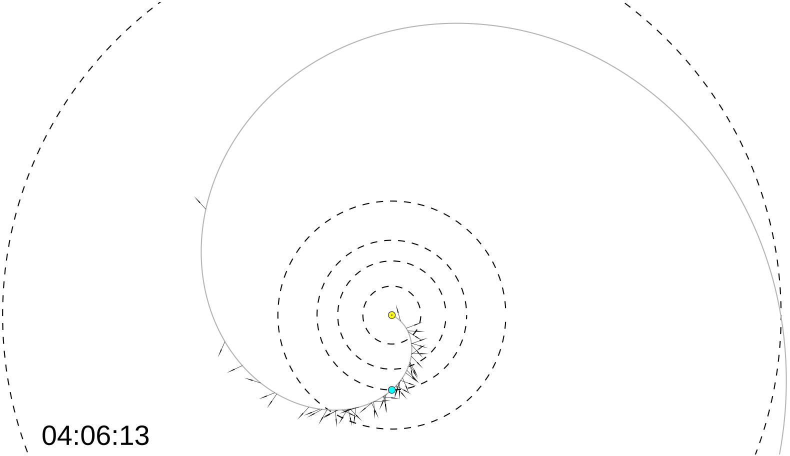
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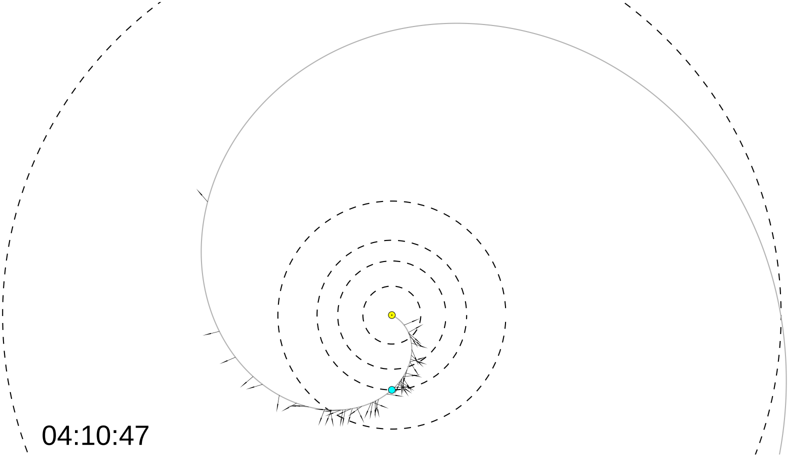
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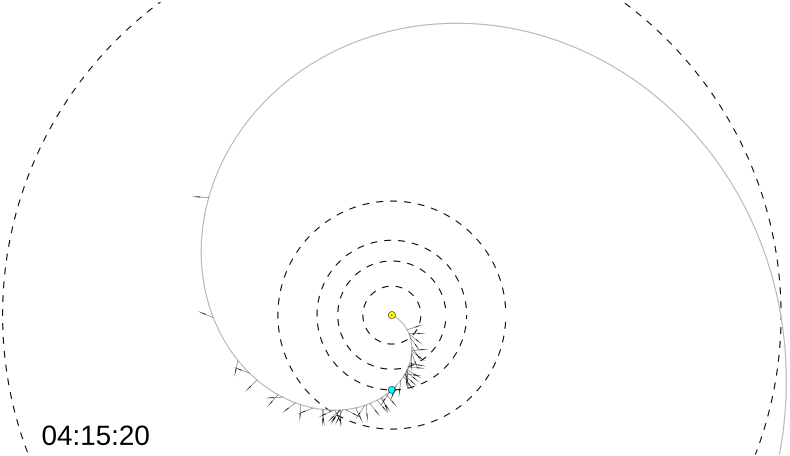
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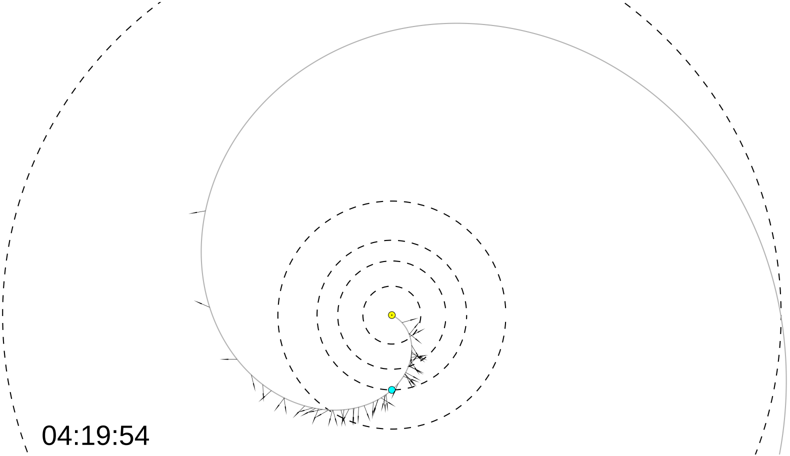
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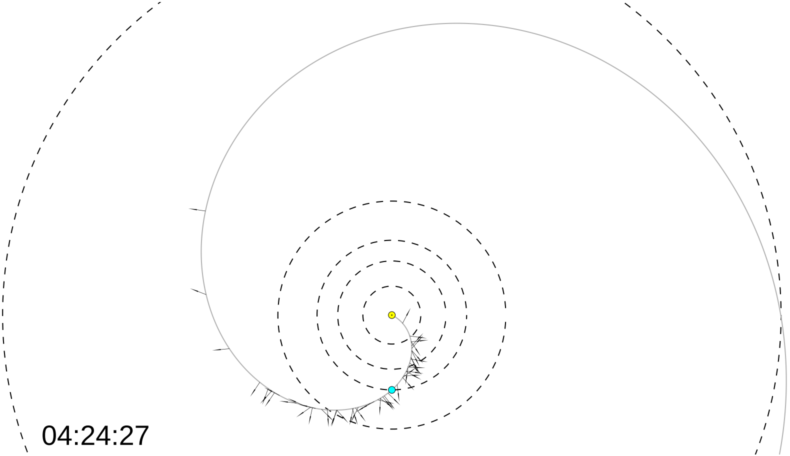
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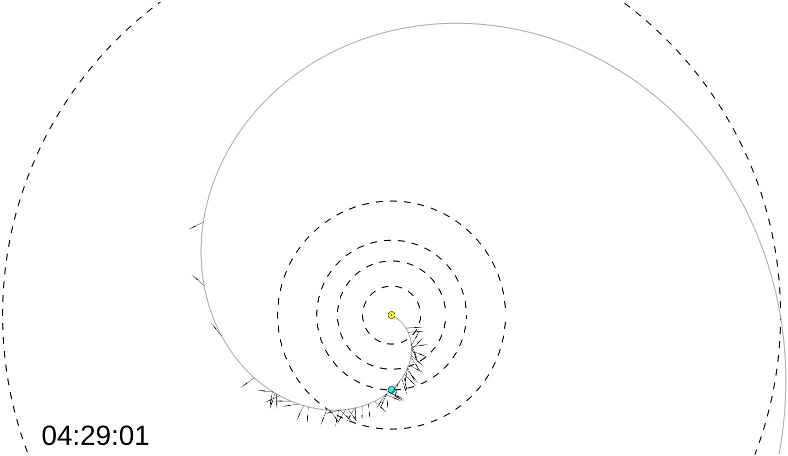
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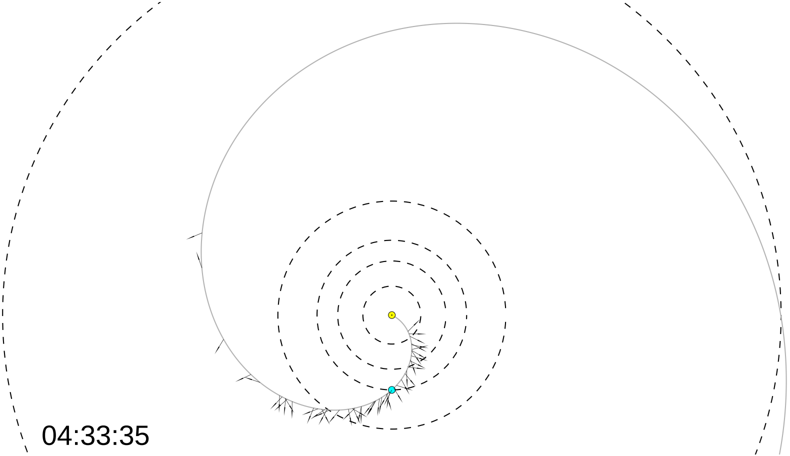
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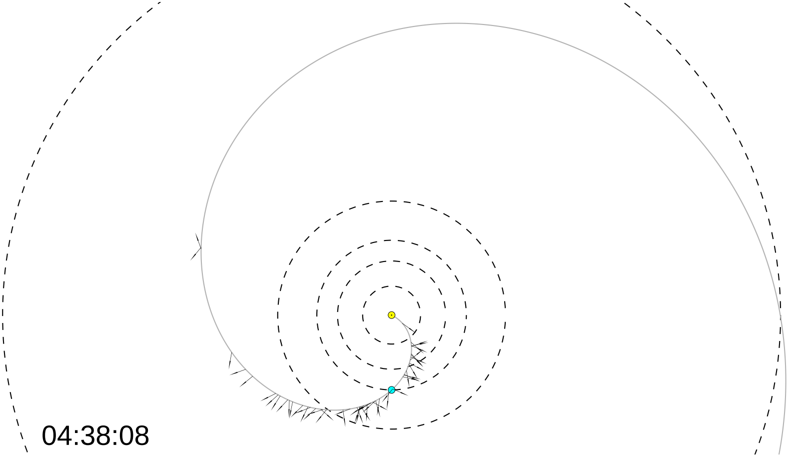

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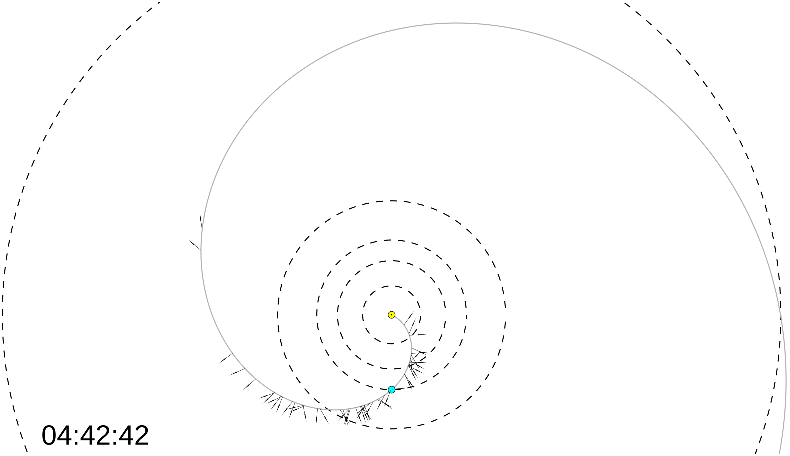
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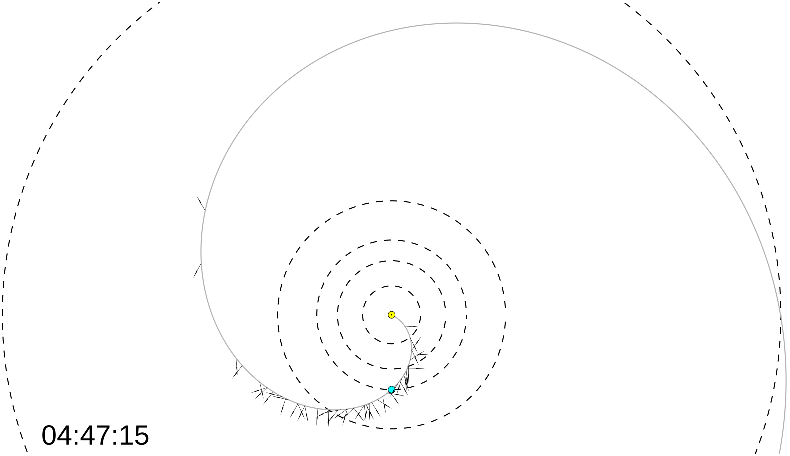

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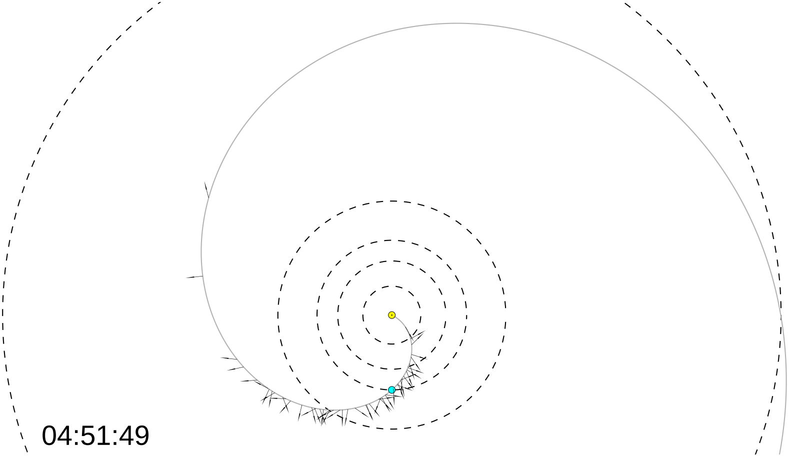
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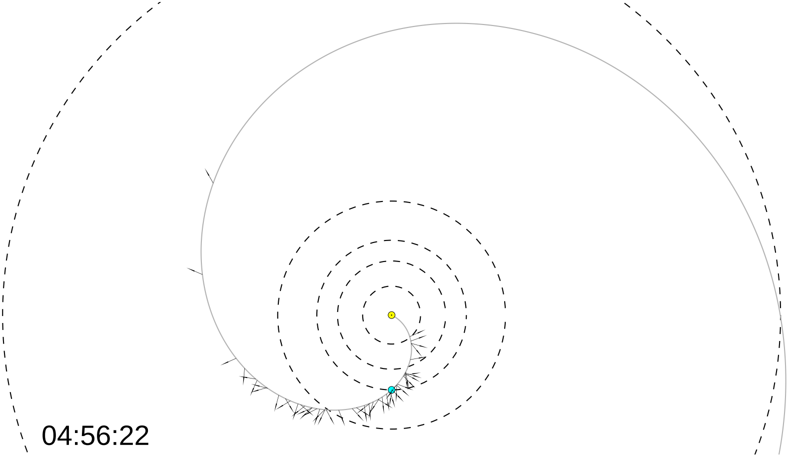
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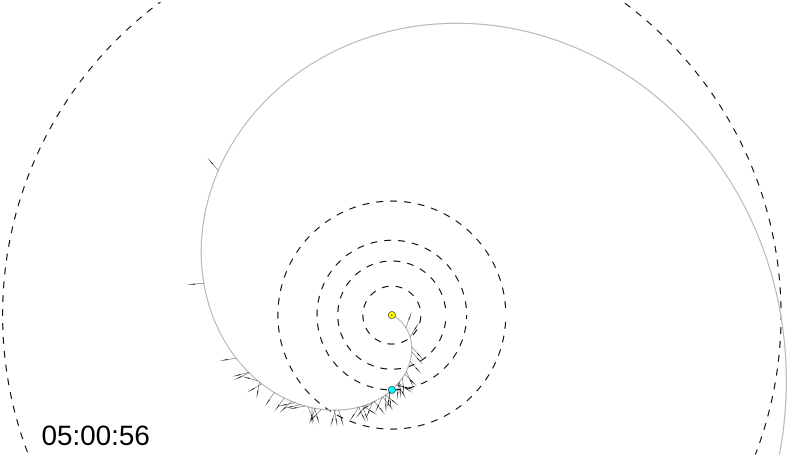
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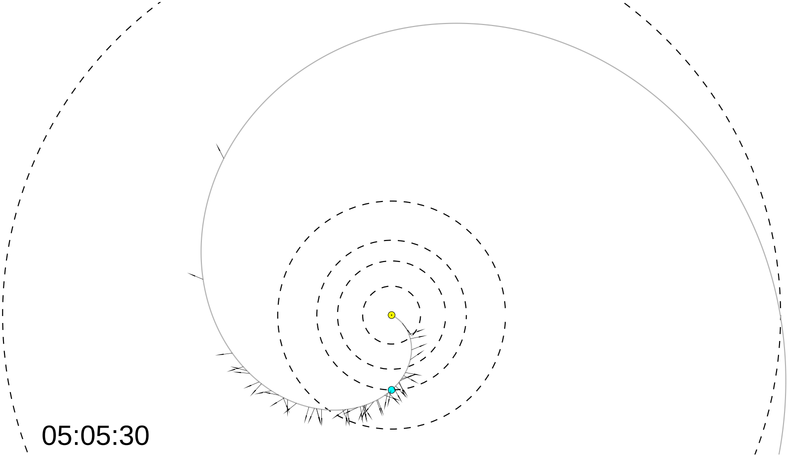
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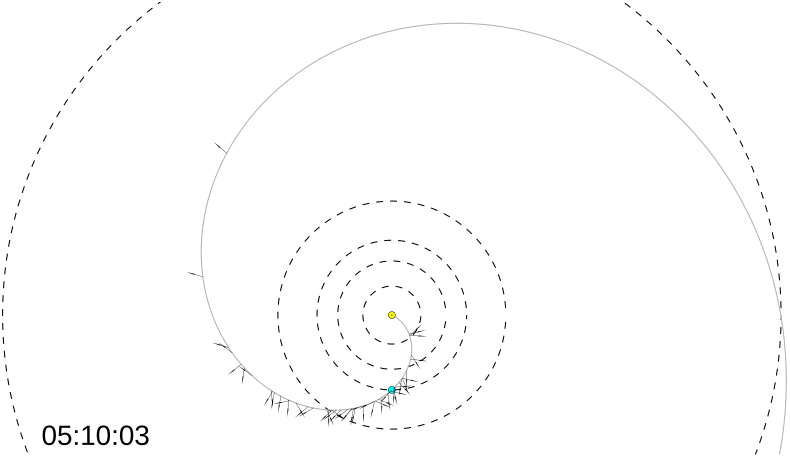
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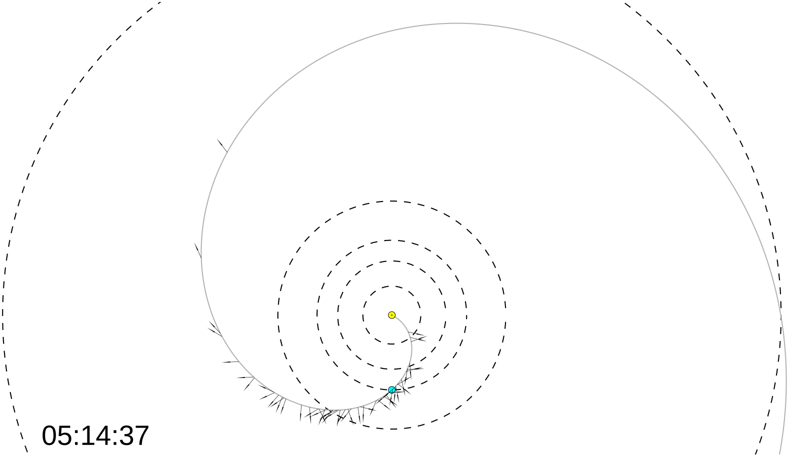
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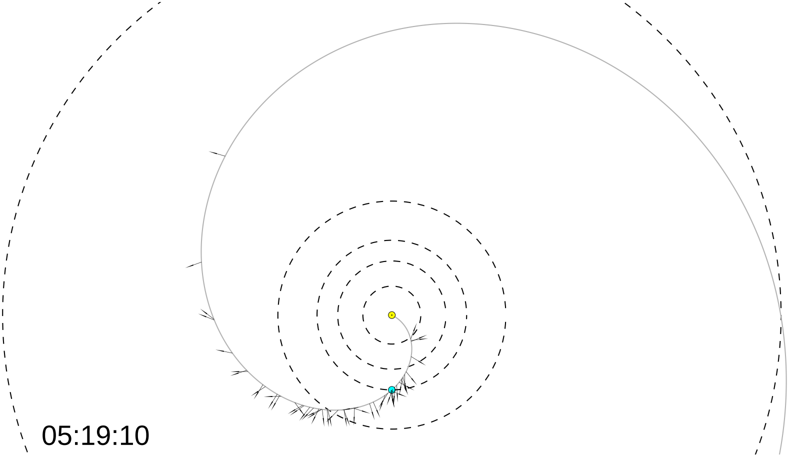
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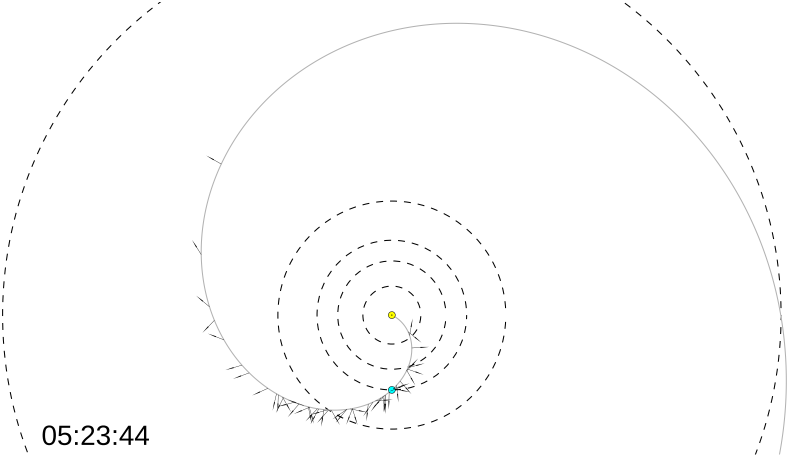
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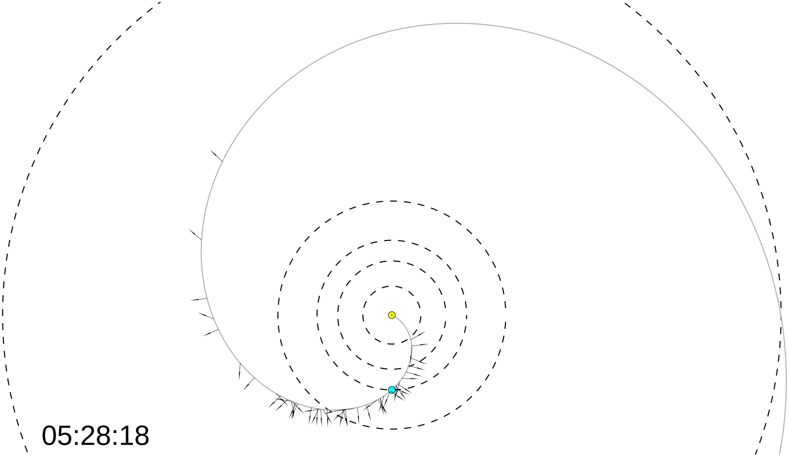
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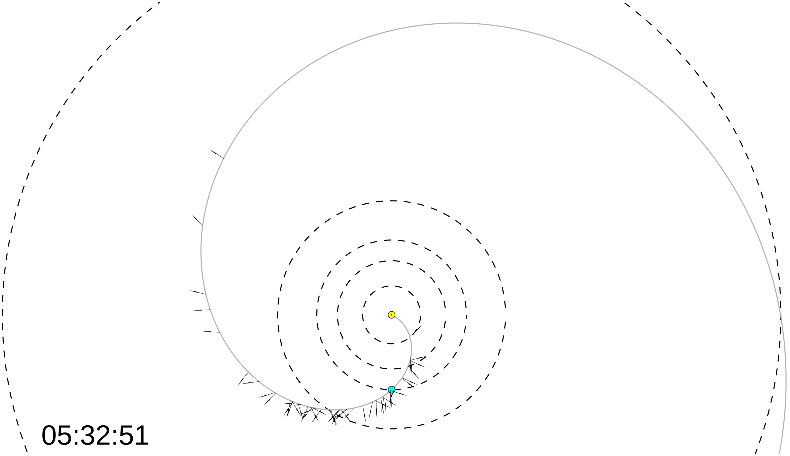
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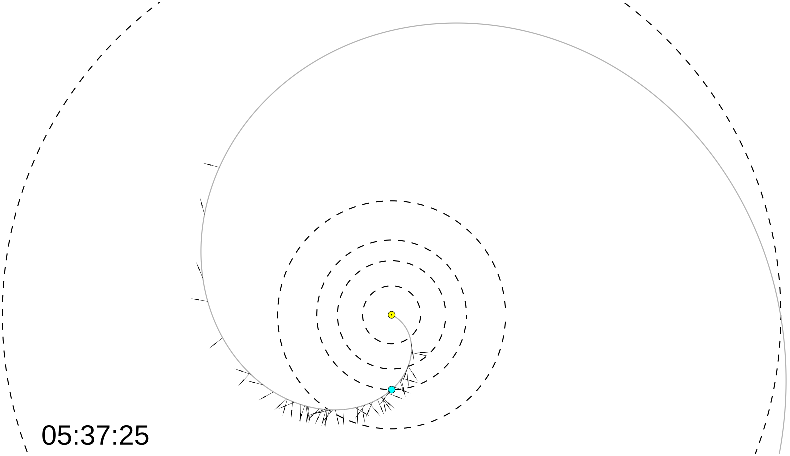
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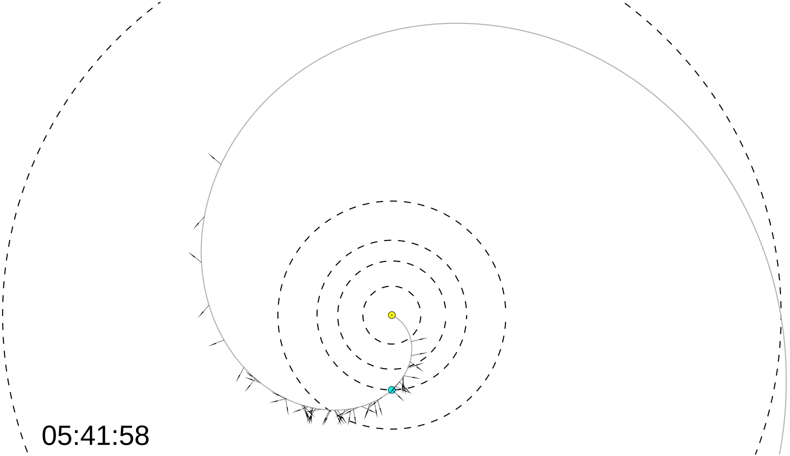
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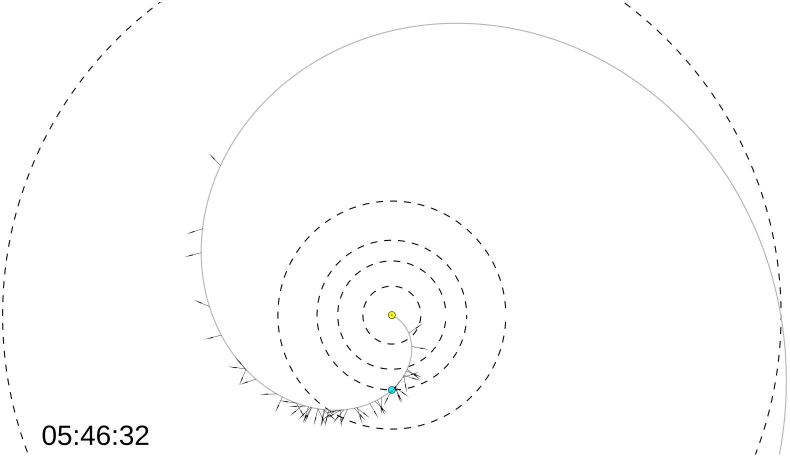
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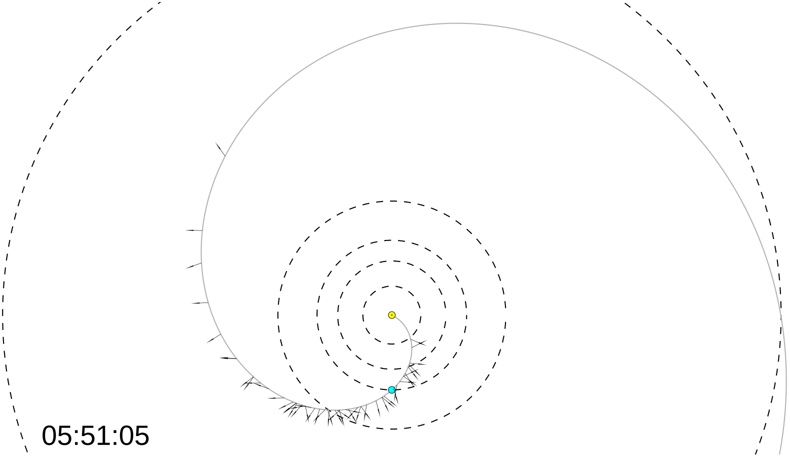
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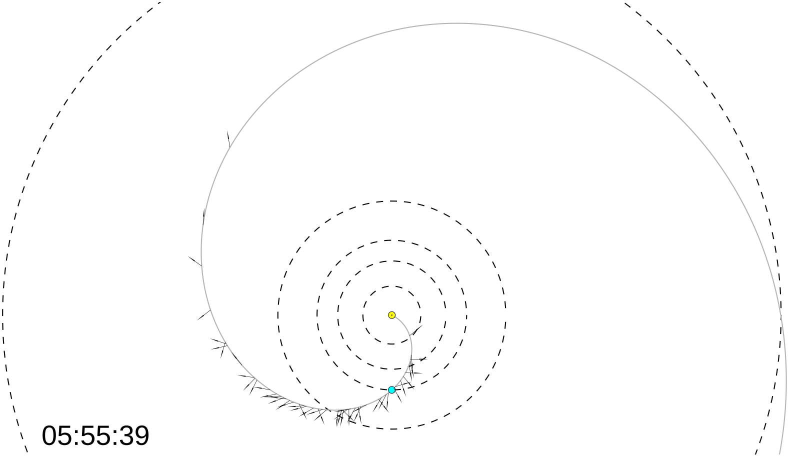
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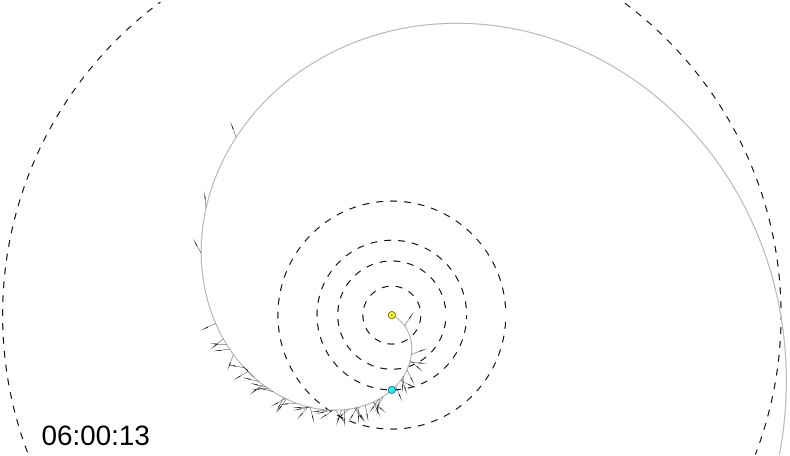
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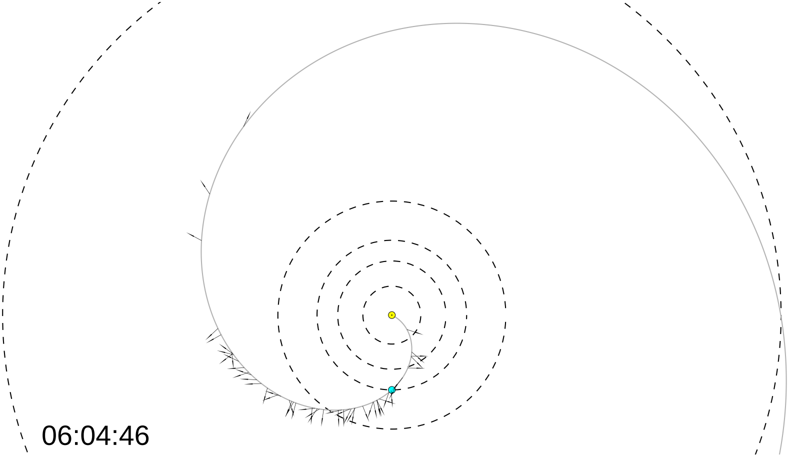
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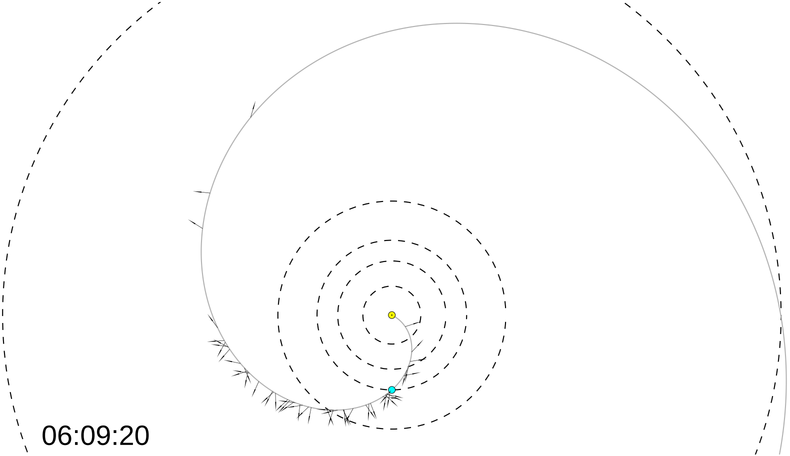
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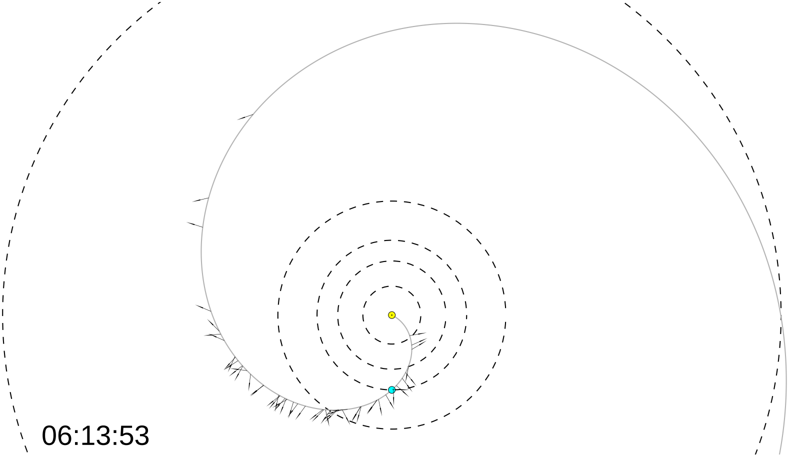
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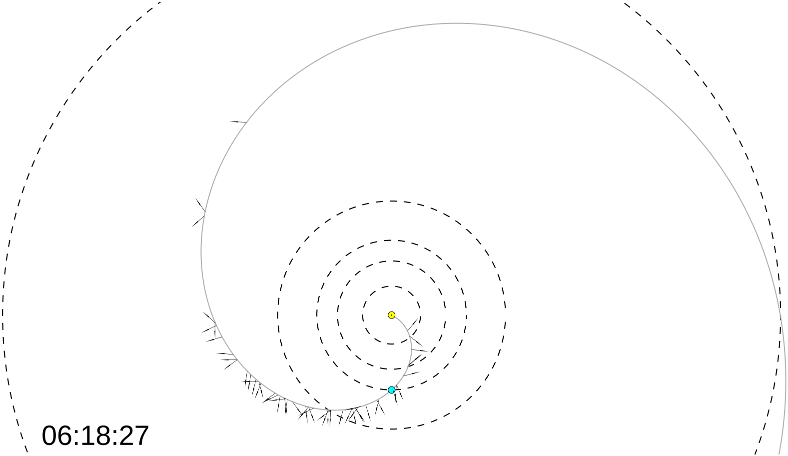
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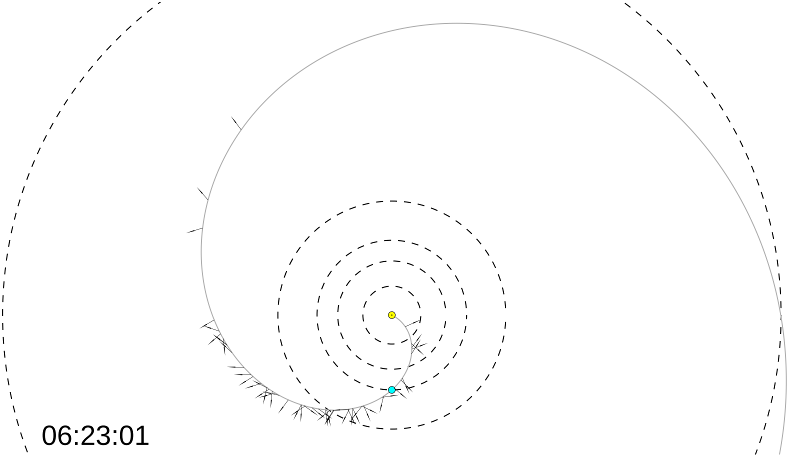
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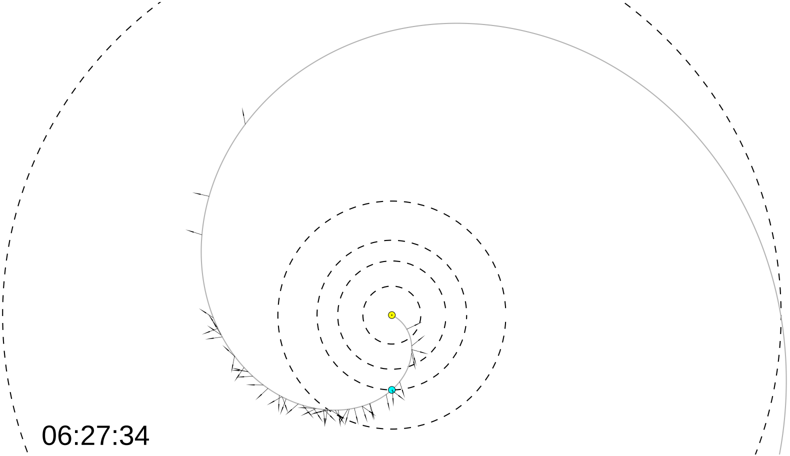
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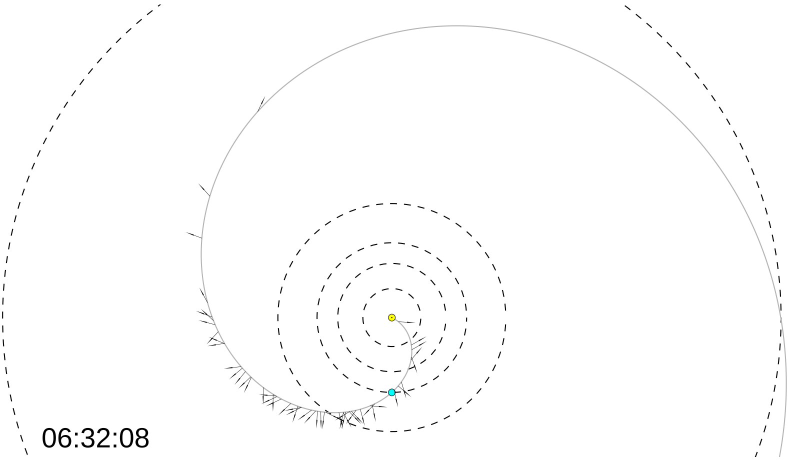
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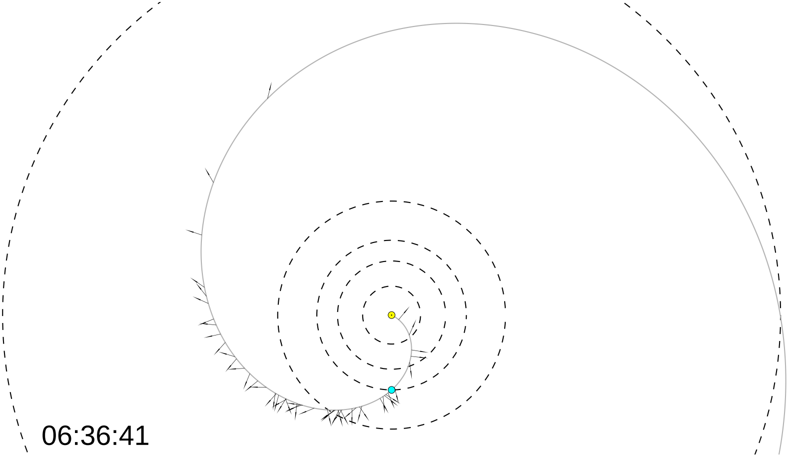
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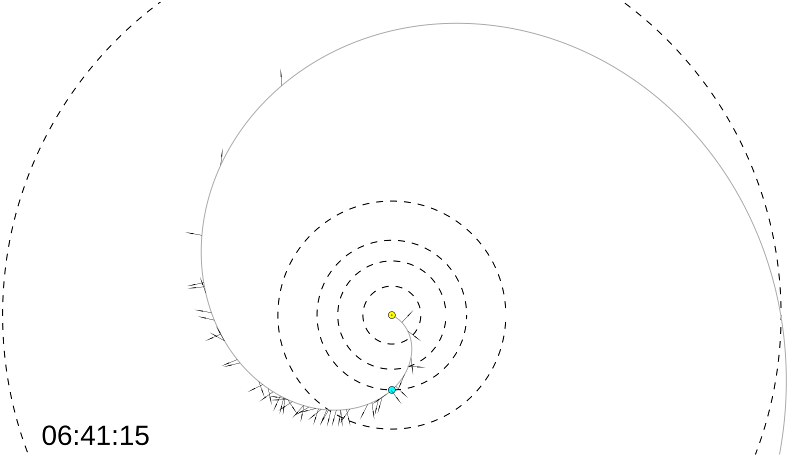
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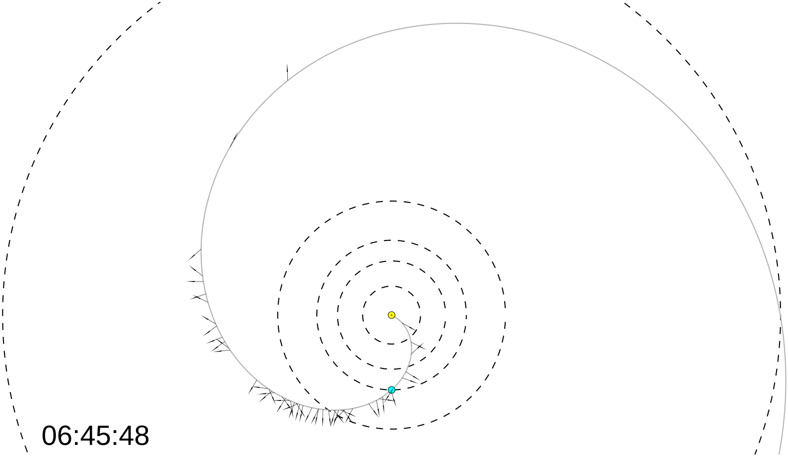
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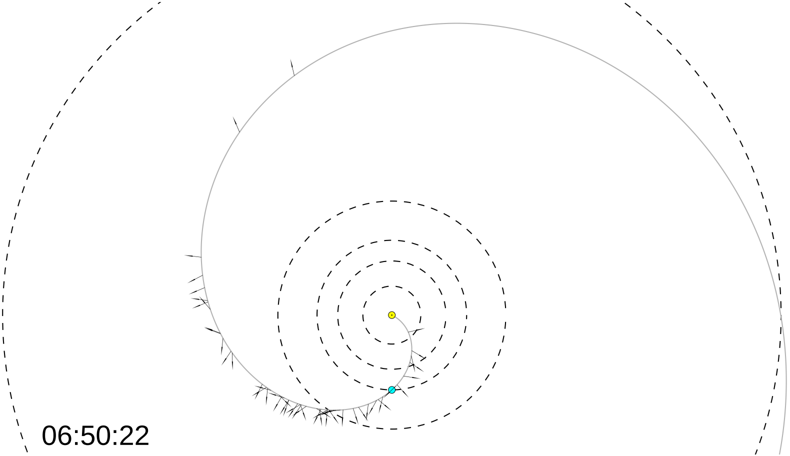
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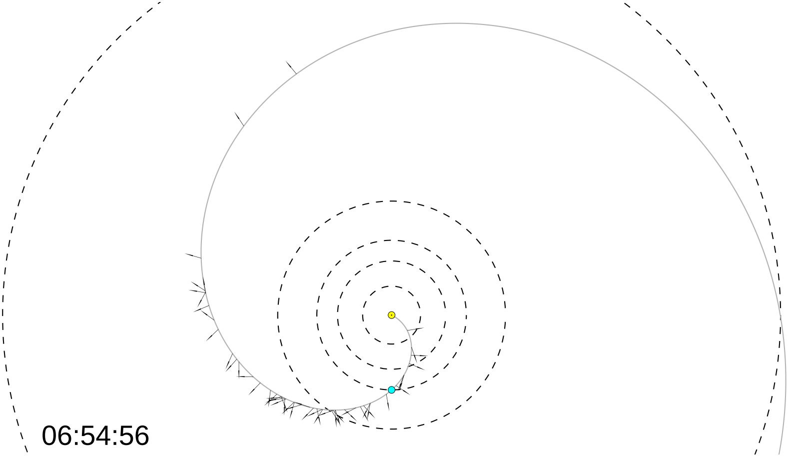
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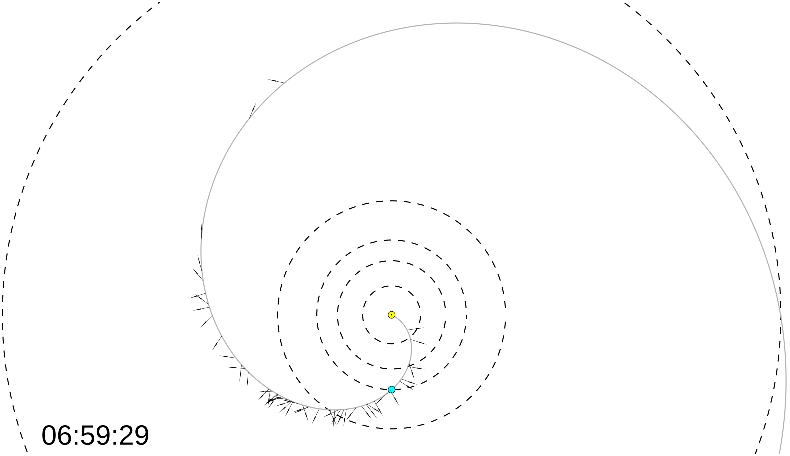
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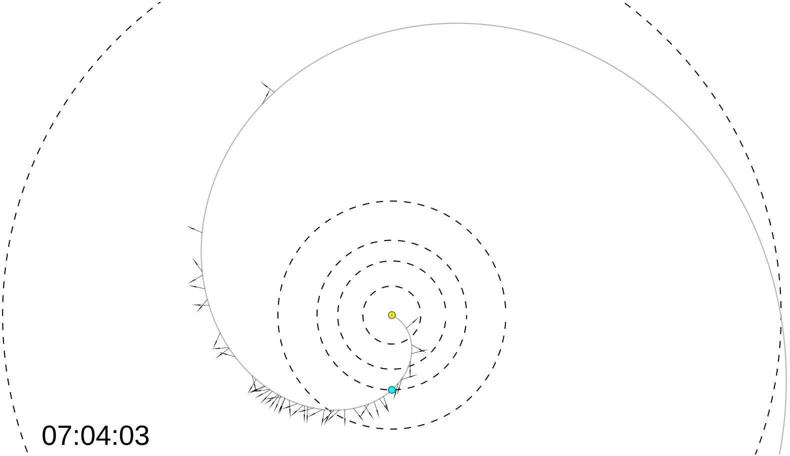
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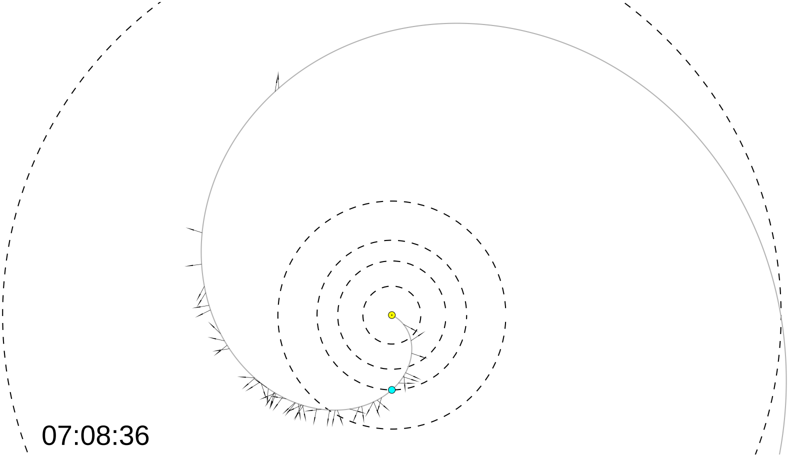
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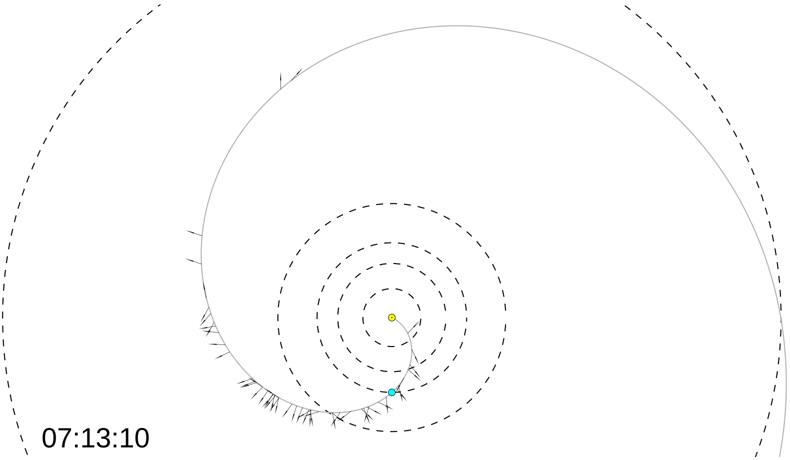
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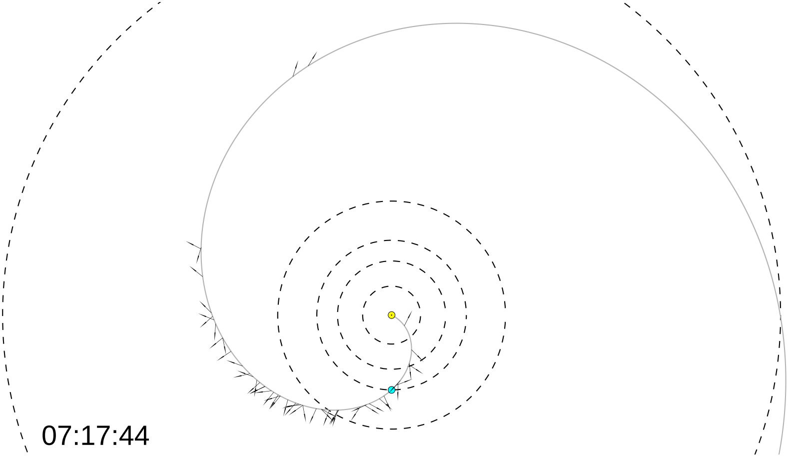
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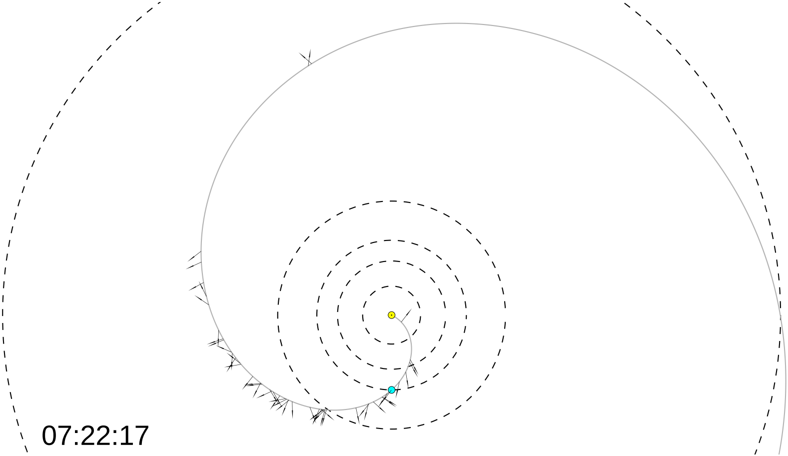
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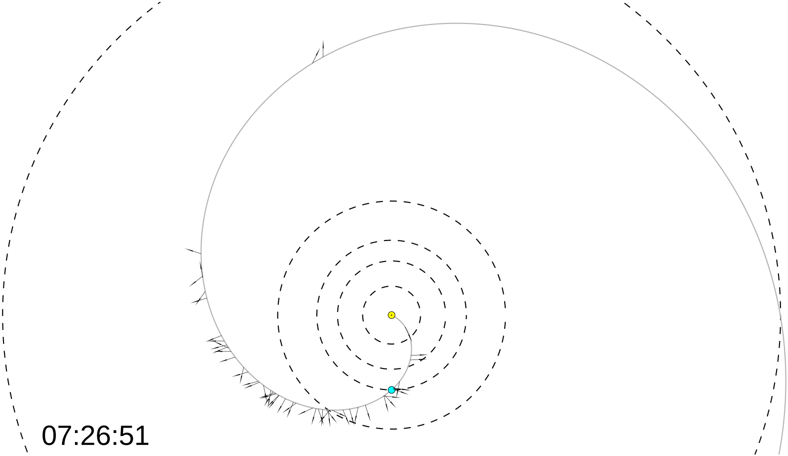
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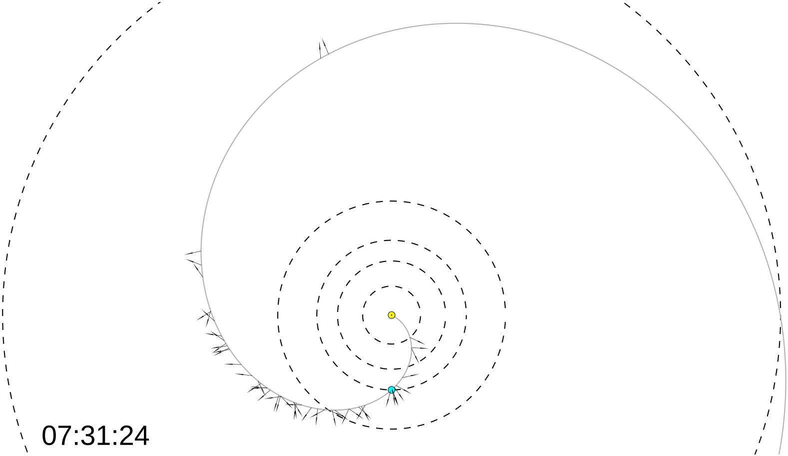

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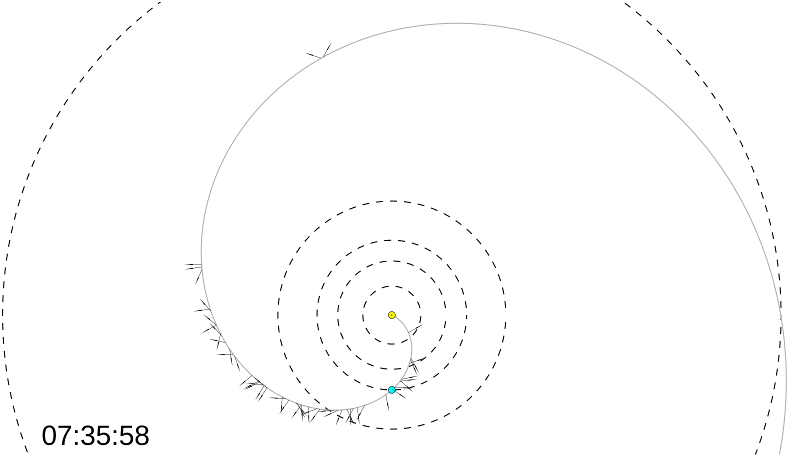

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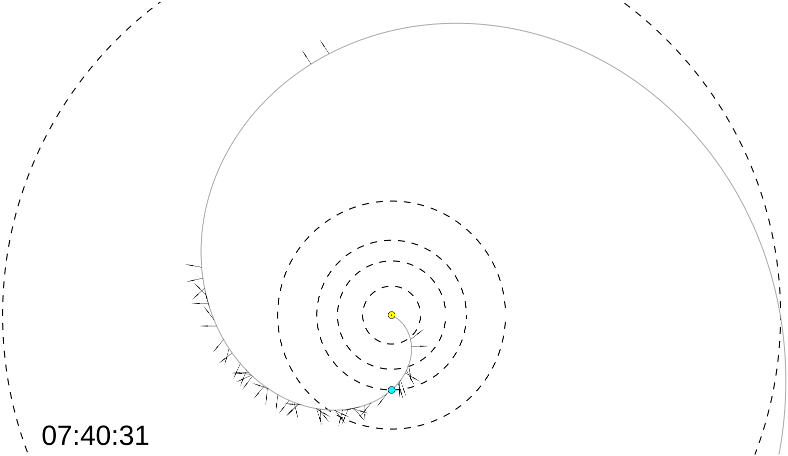
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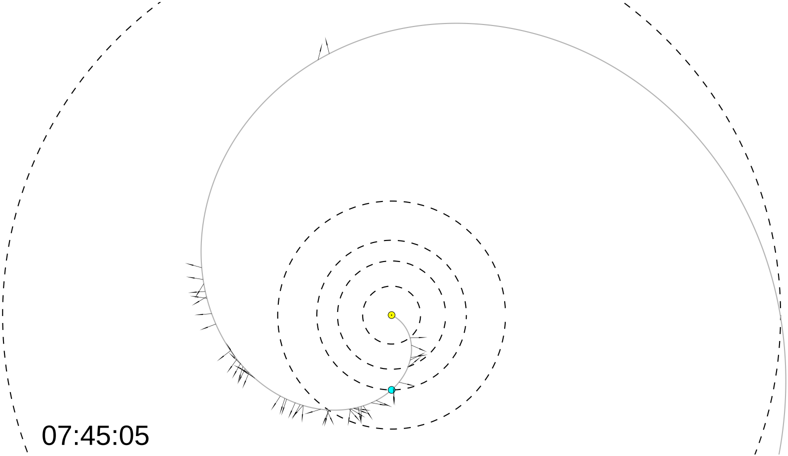
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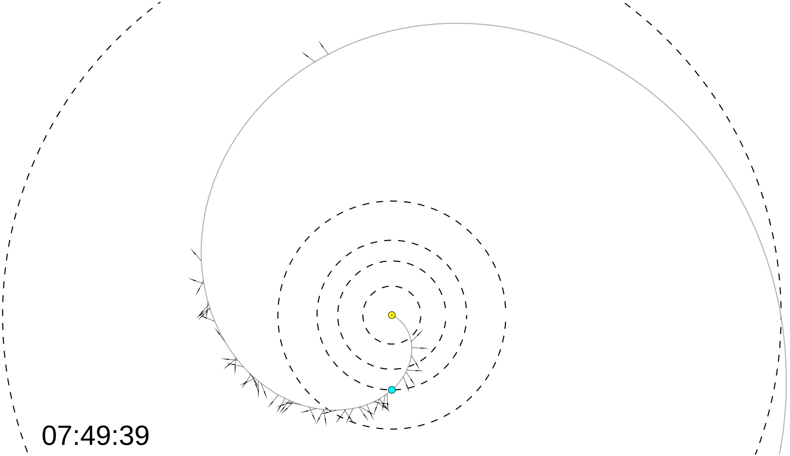

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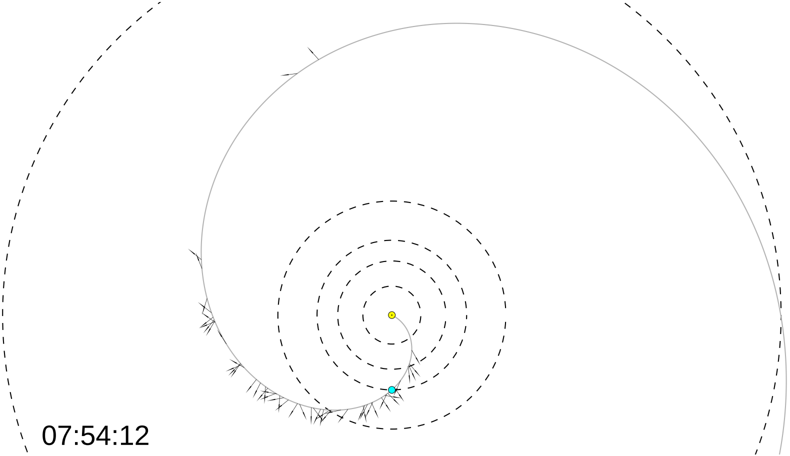
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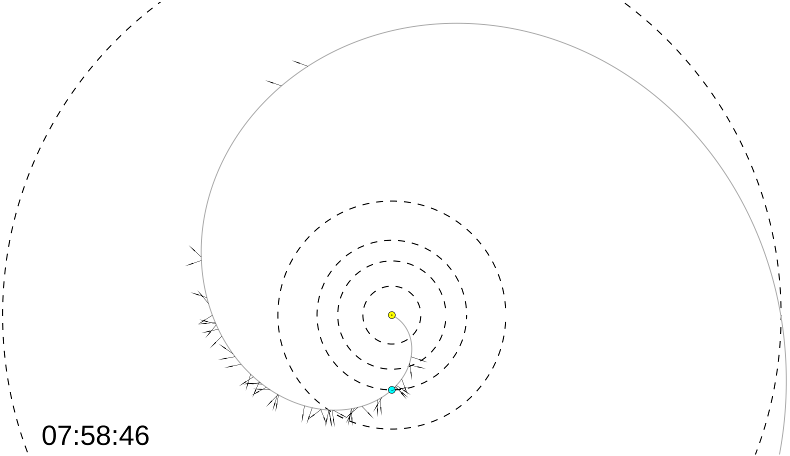
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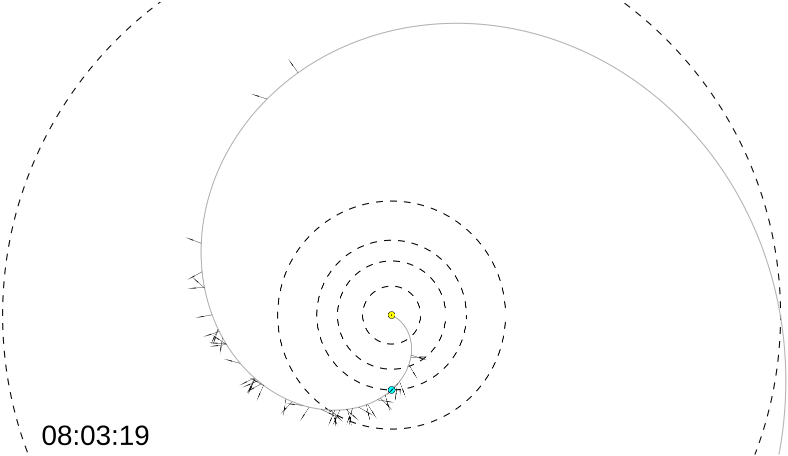
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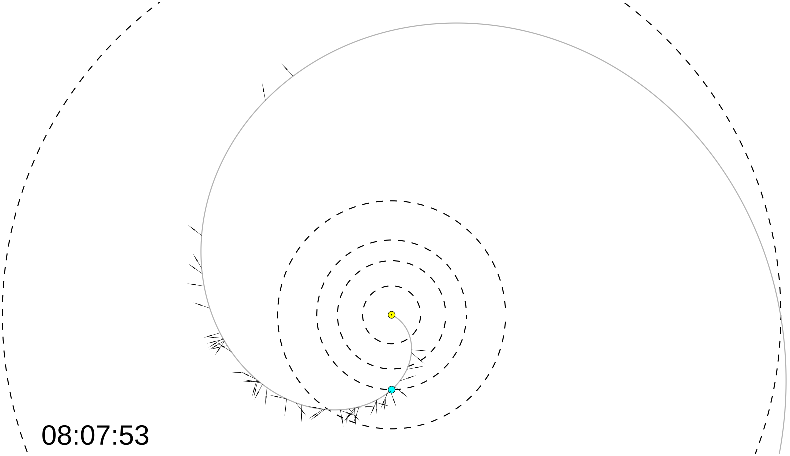
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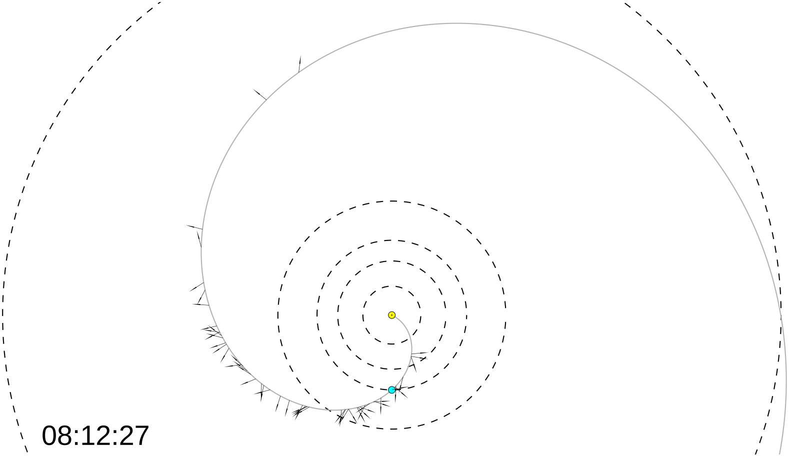
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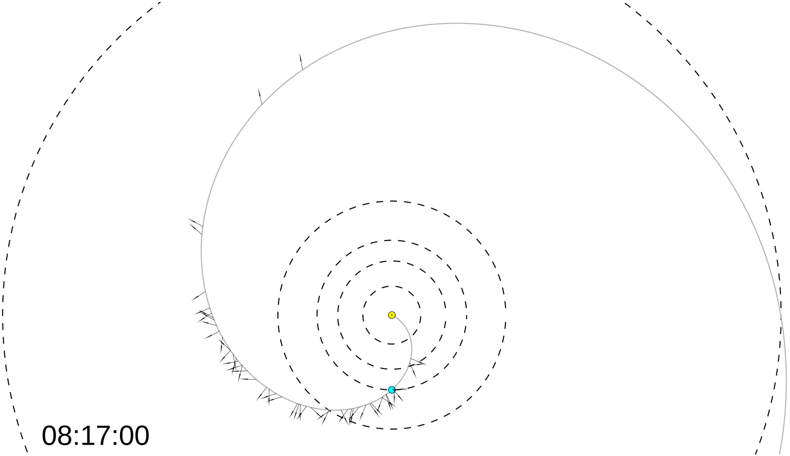
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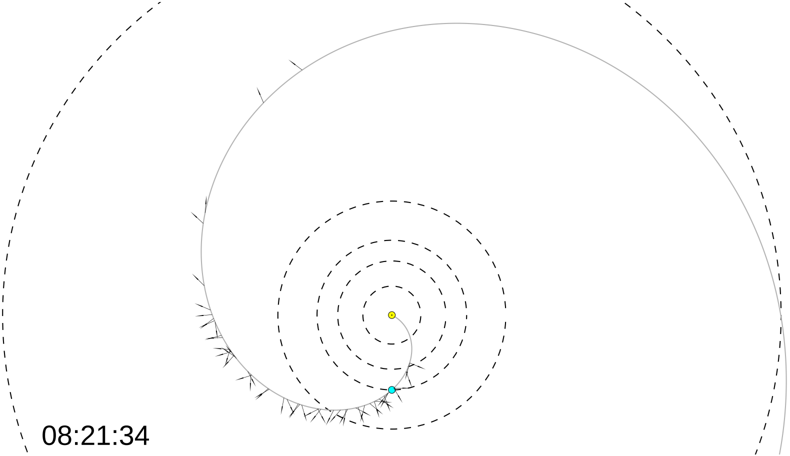
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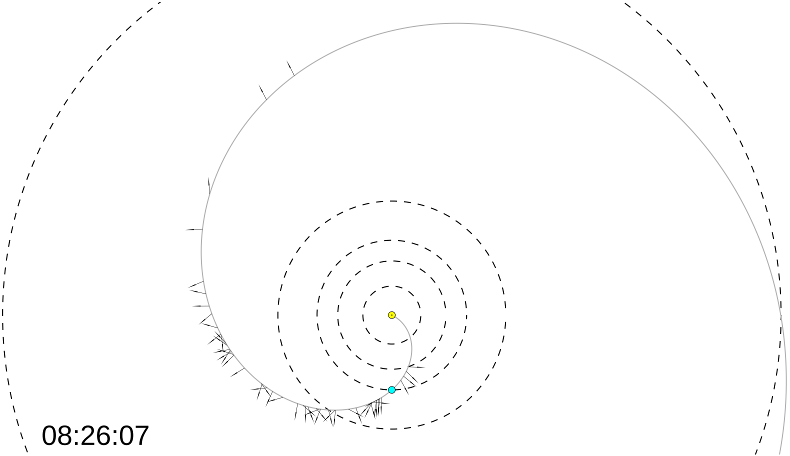
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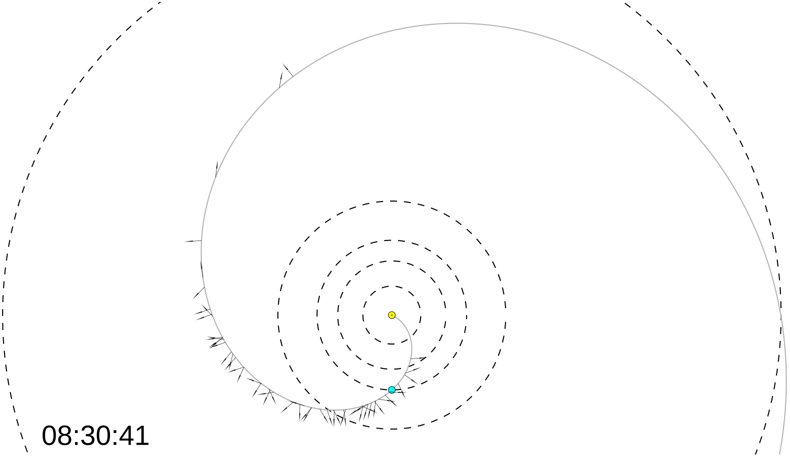
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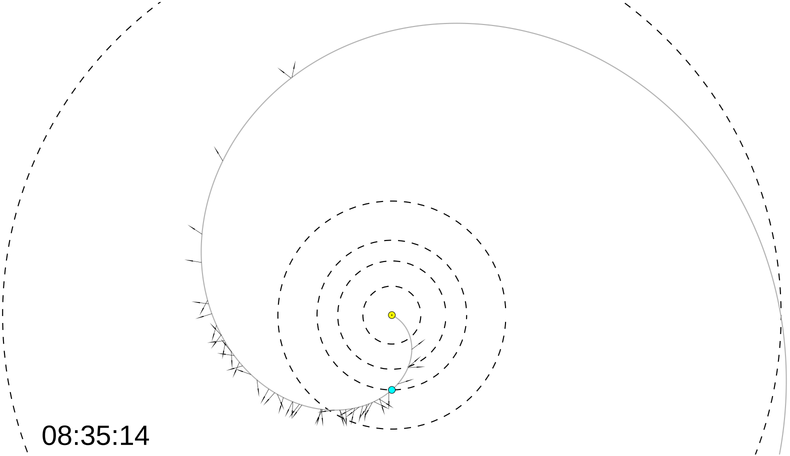
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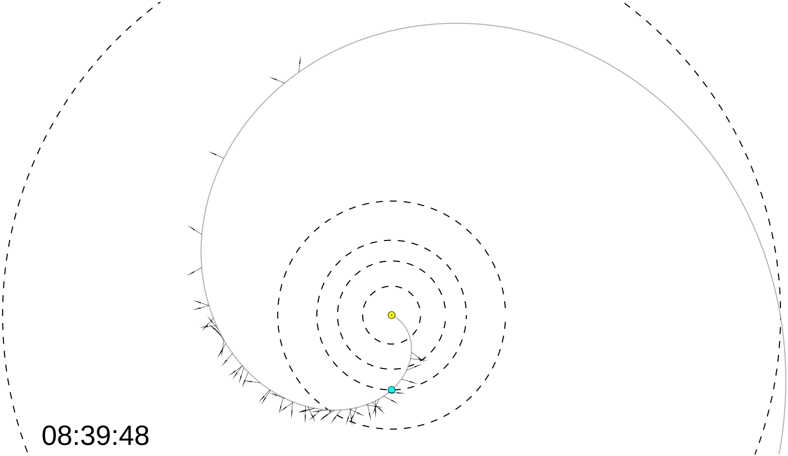
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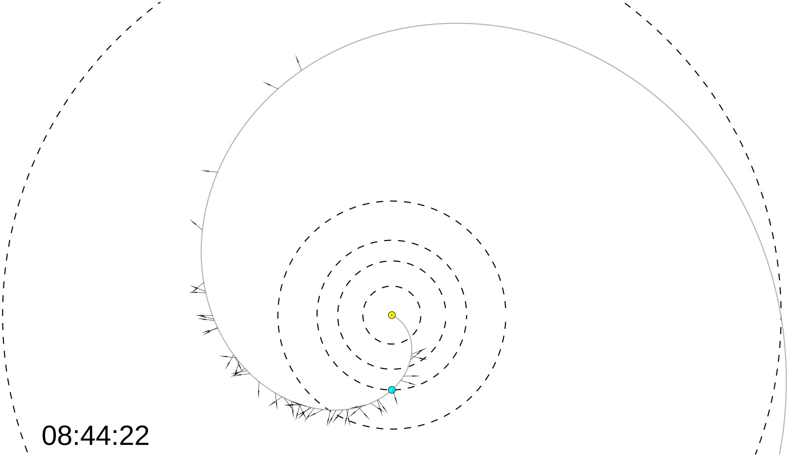
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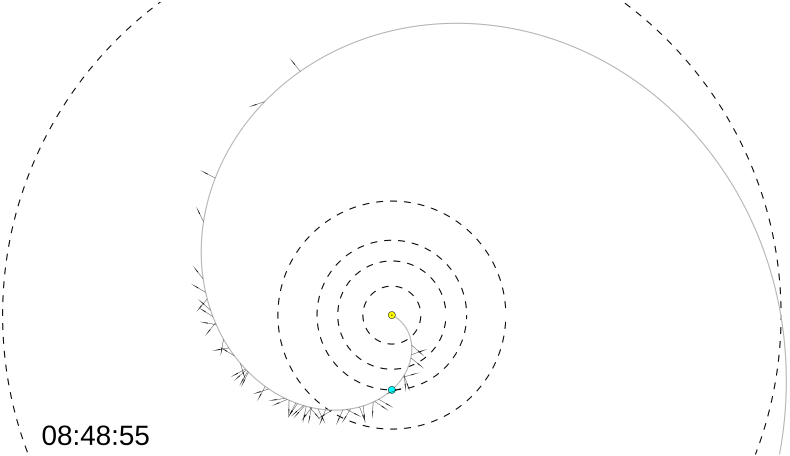
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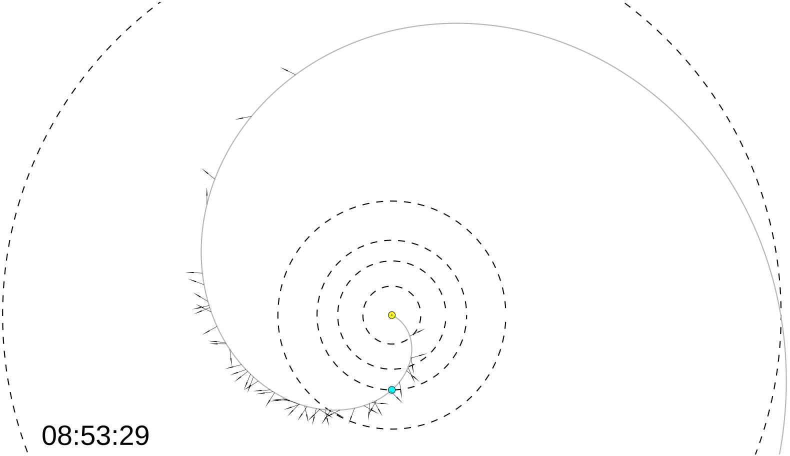
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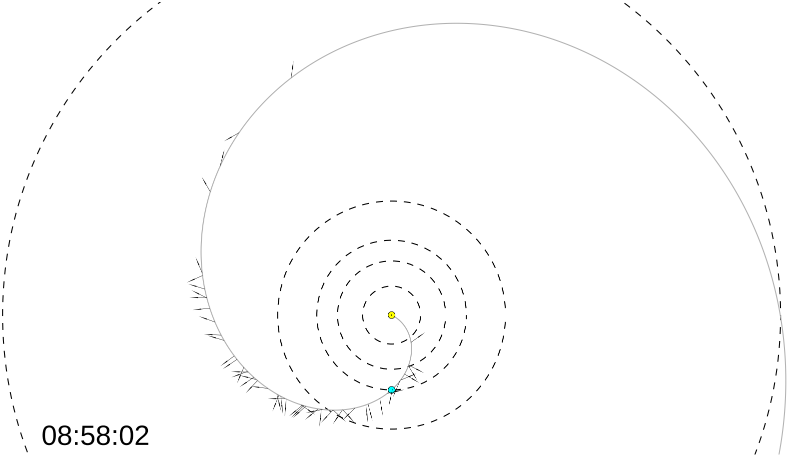
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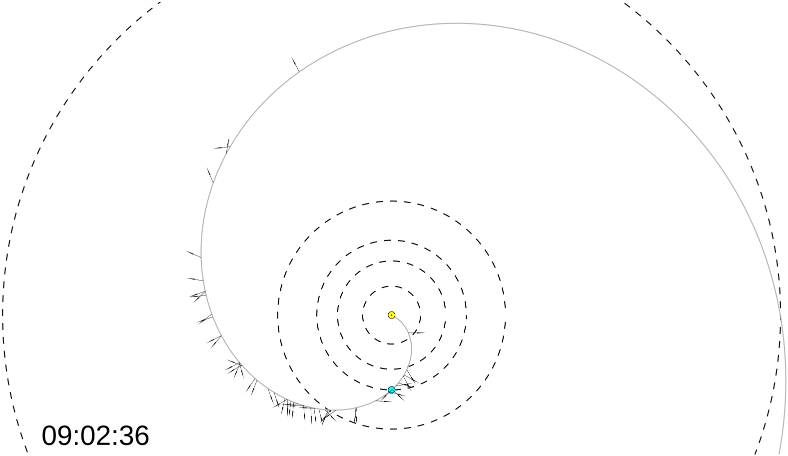
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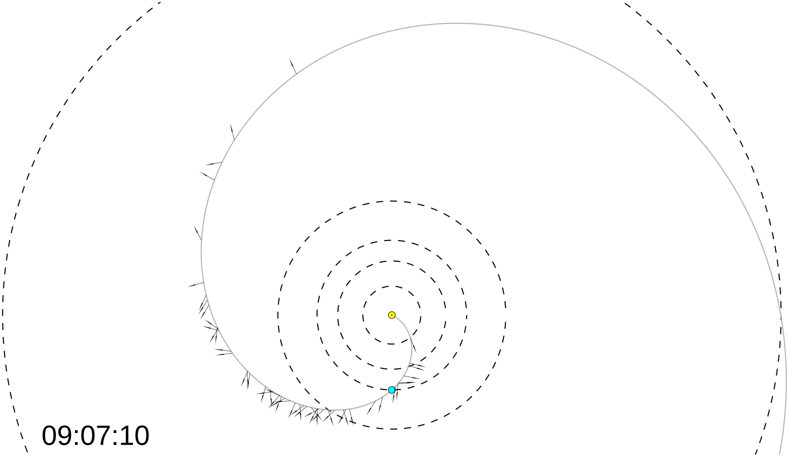
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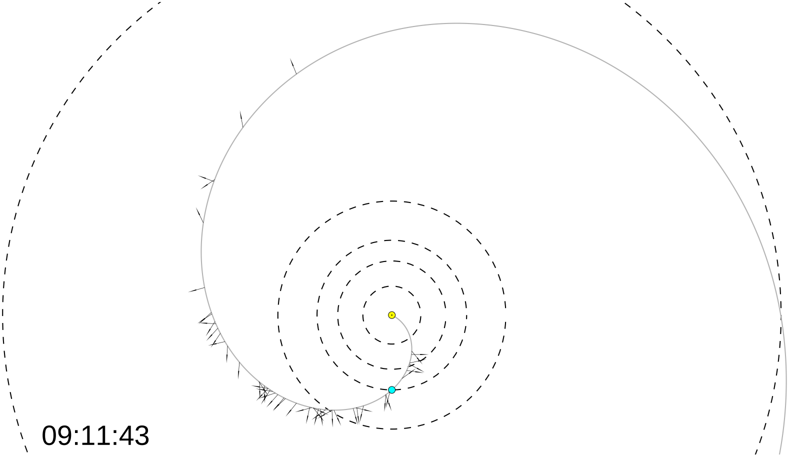
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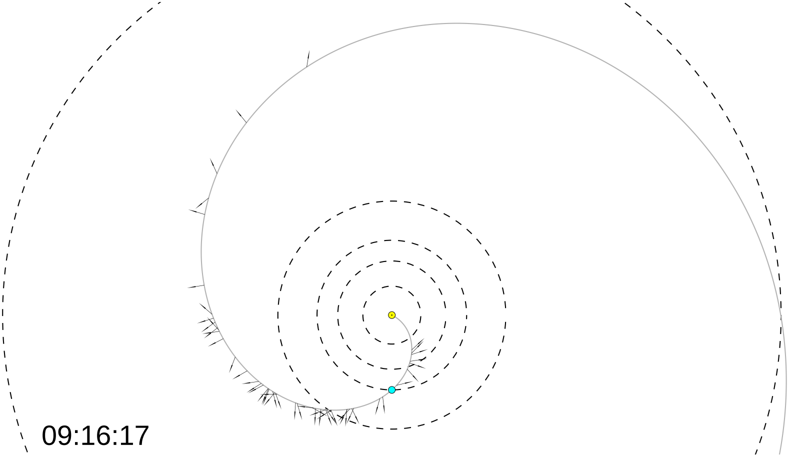

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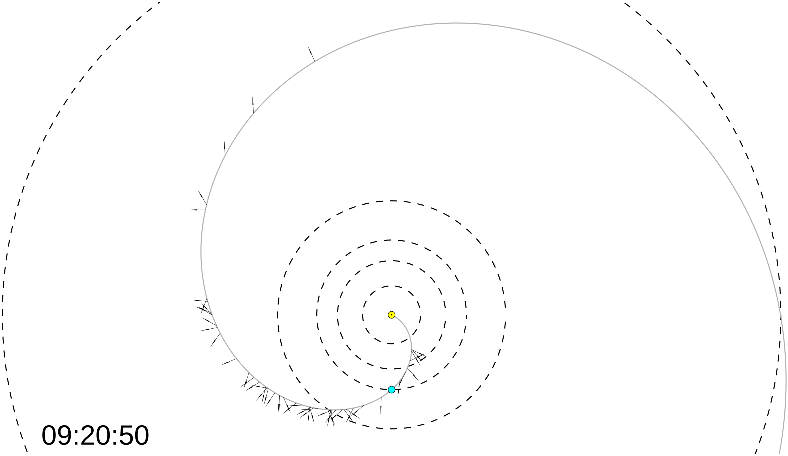
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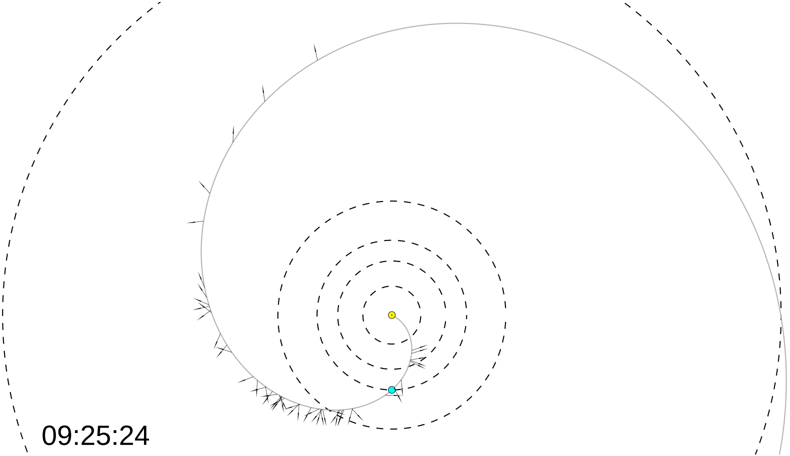
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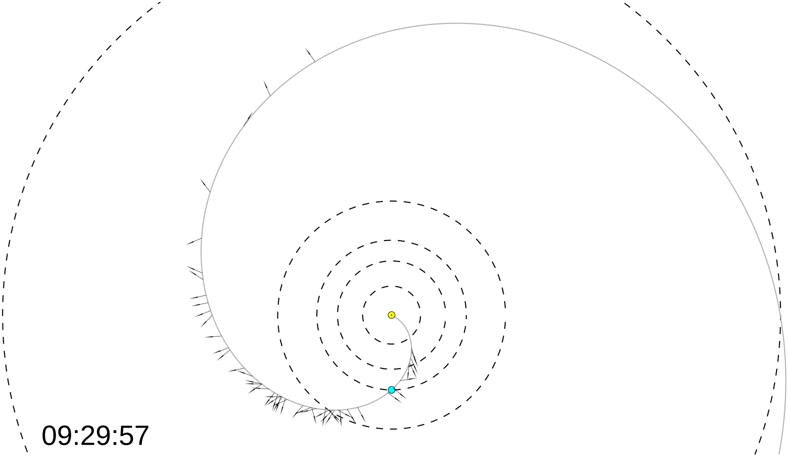
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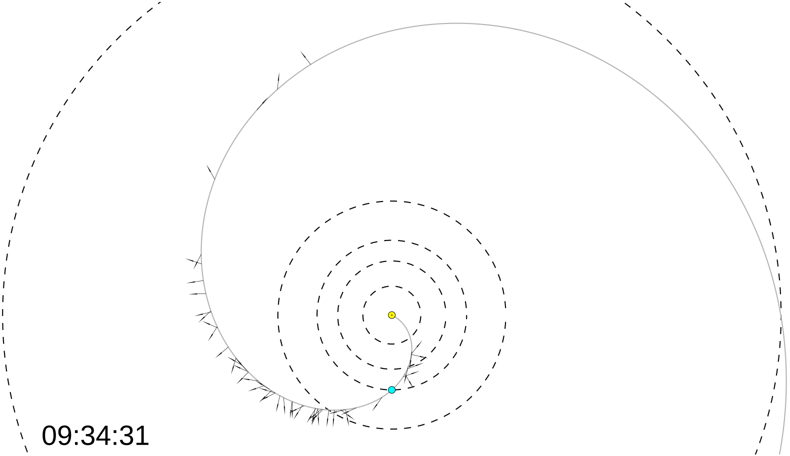
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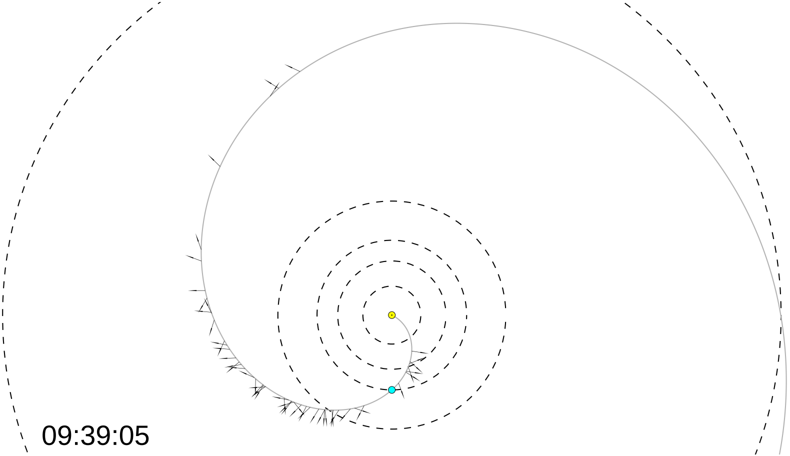
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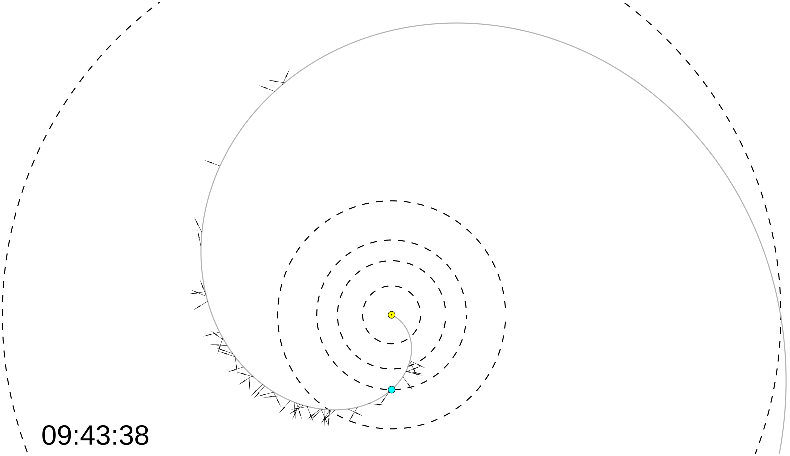
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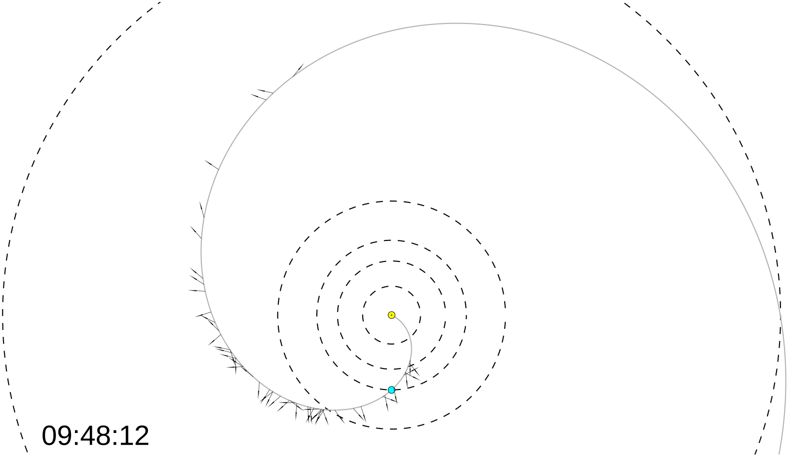
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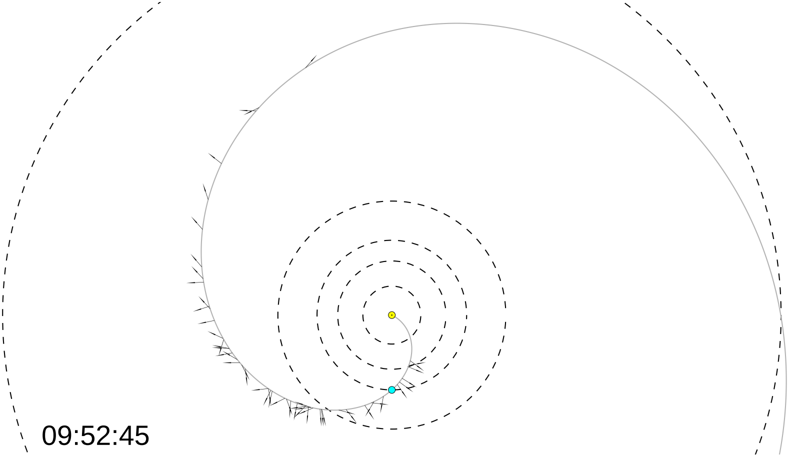
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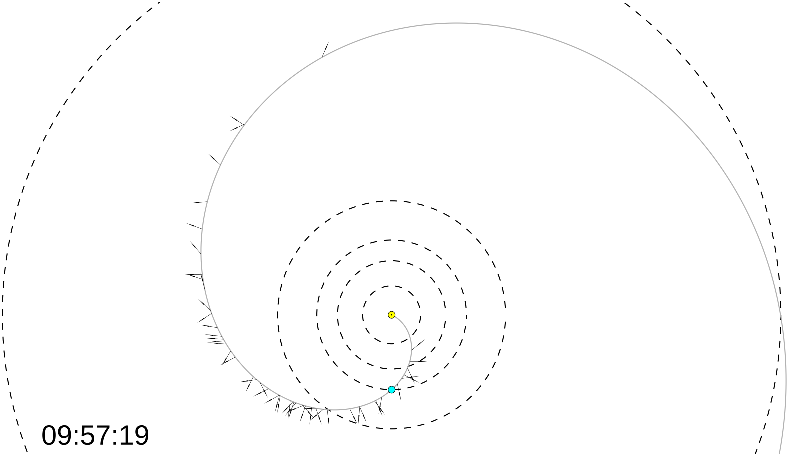
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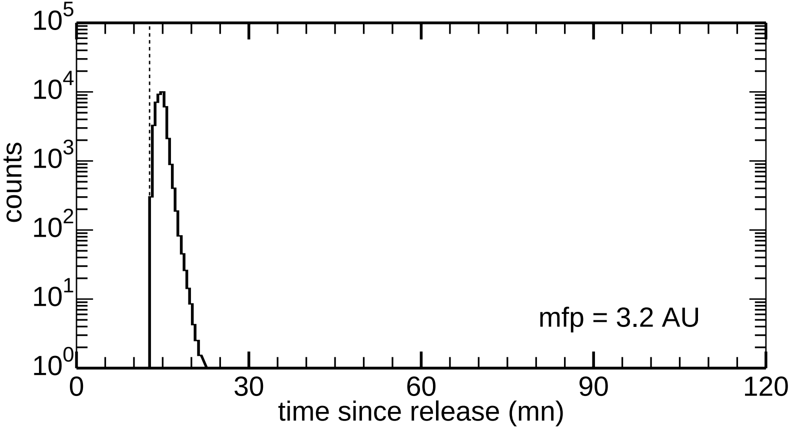
Individual particles “lose their memory”, one has to use statistical properties, like total flux and total anisotropy as a function of time to reconstruct the history of a particle event back at the Sun:



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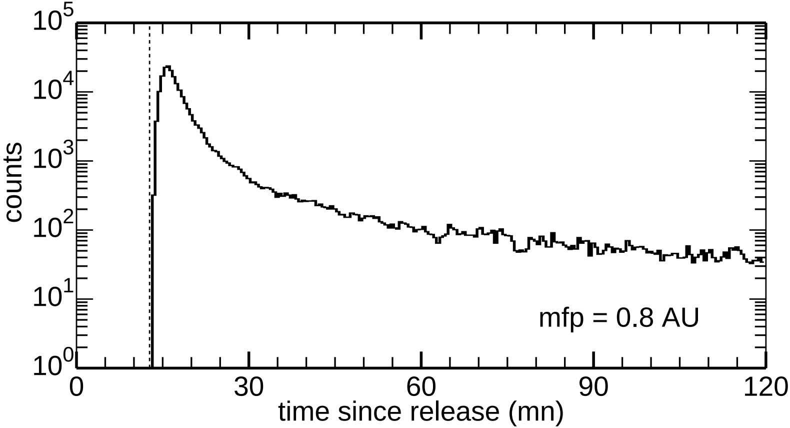

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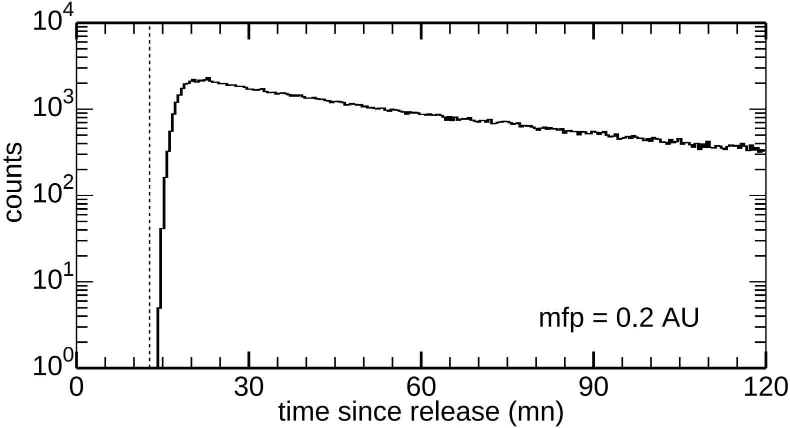

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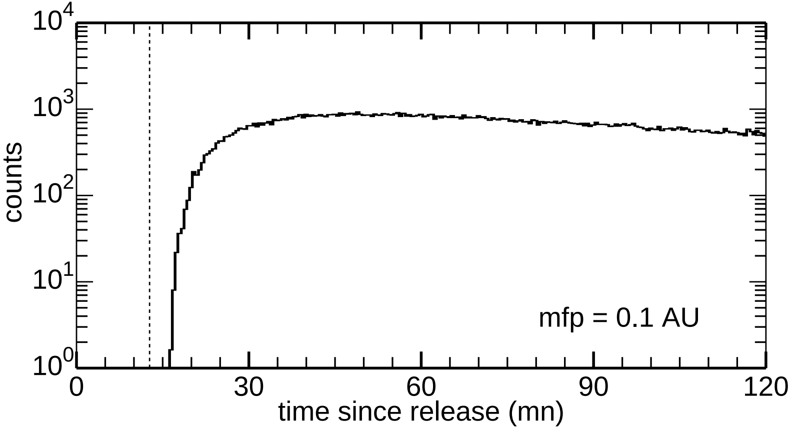

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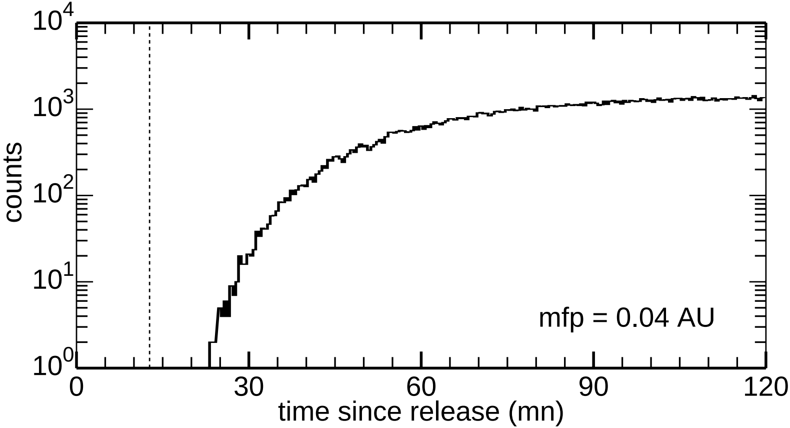

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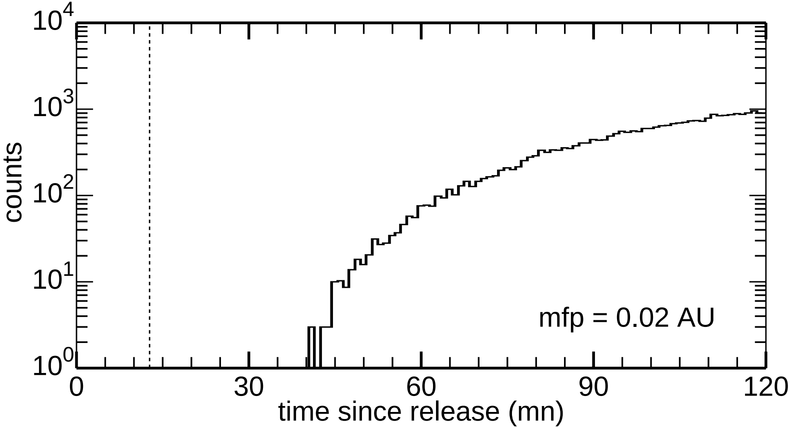

Electron telescopes measure the particle energy, $E(R,t)$ and the particle pitch angle (if magnetometer data are available). From these it is possible to build the directional flux, $F(\mu,t;R,E)$ and, depending on the instrument, it is also possible to recover the total flux:

$$I(t;R,E) = \frac{1}{2}\int_{-1}^{1} F(\mu,t;R,E)d\mu$$

Other important quantities are the total anisotropy:

$$A(t;R,E) = <\mu F(\mu,t;R,E)>_{\mu} = \frac{1}{2}\int_{-1}^{1} \mu F(\mu,t;R,E)d\mu$$

And the average anisotropy:

$$a(t;R,E) = A(t;R,E)/I(t;R,E)$$

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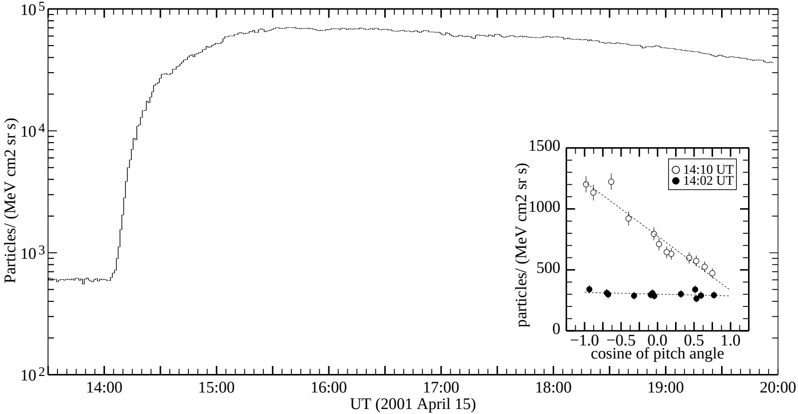
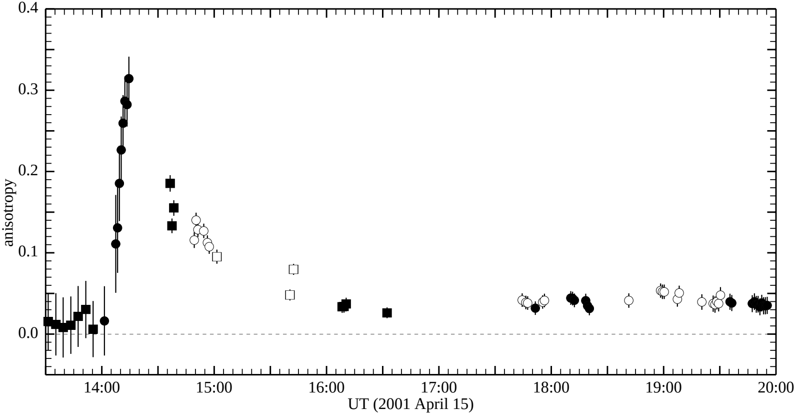


200 keV electrons from EPAM/ACE. Long duration event, with anisotropic onset. Slow rise and long duration could be related to long-lasting injection at the Sun. Particles from anti-sunward direction at the onset suggest the reason is very strong scattering.



200 keV electrons from EPAM/ACE. Average pitch angle (anisotropy).

Modeling propagation effects

Kinetic treatment: 1 million particles generated randomly. Solar wind effects included, adiabatic focusing and isotropic scatter (mean free path does not depend on the pitch angle).

for each λ the injection function is determined (deconvolution not a fit)

for each the average anisotropy is computed using the injection function above

for each lambda the sum of the quadratic difference between observed and model anisotropies is computed.

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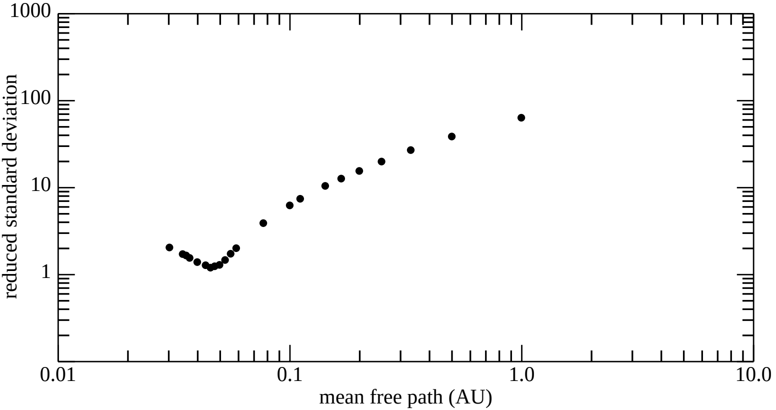
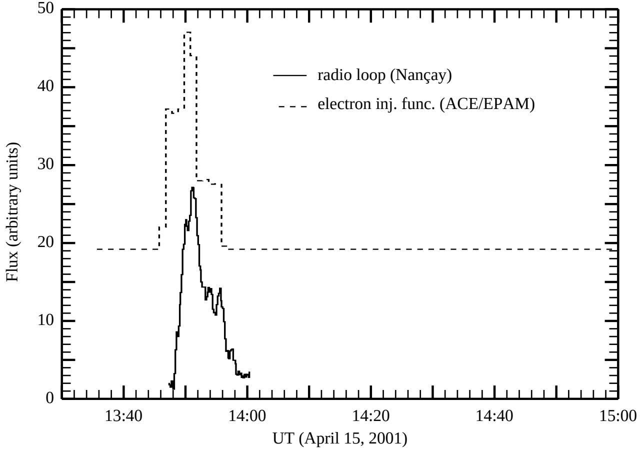


Data are enough to chose between the different models.
Mean free path is ≈ 0.045 AU.

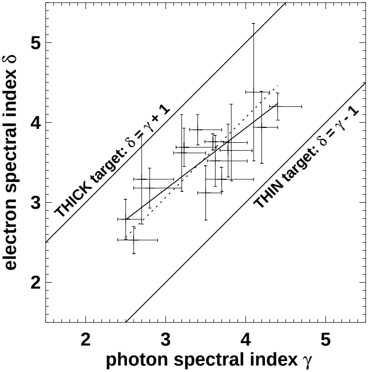


Injection function peaks and drops relatively fast. It coincides with remote observations of gyro-synchrotron emissions.

Ref: Maia et al (2007). ApJ 660:874-881.

In-situ electrons and remote observations

The good association of electron events with electron-rich ^{3}He events suggests that flare electrons reach Earth orbit.



Electron events seen by WIND/3DP with inferred release coinciding with HXR emission seen by RHESSI

Good spectral correlation

Only about 1% of flare electrons are relased into the IM.

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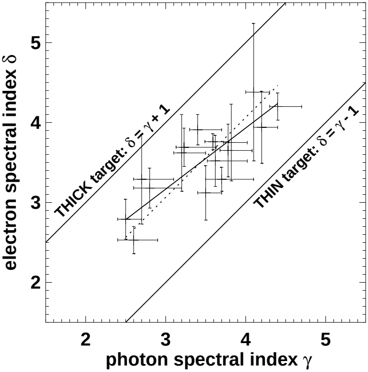

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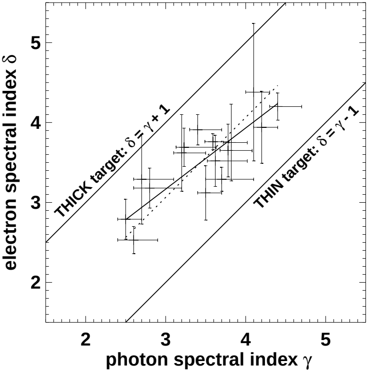

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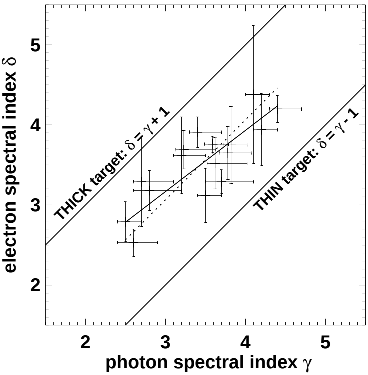

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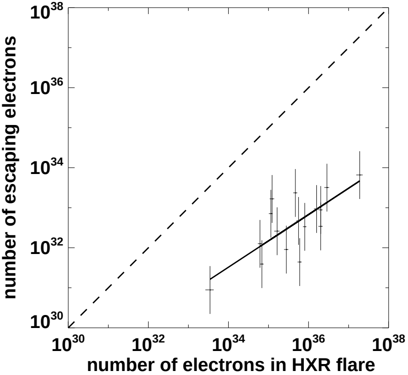

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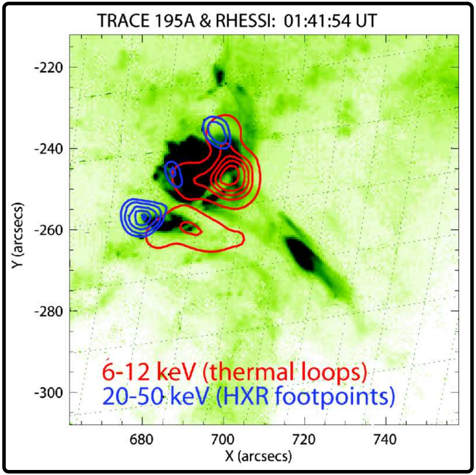
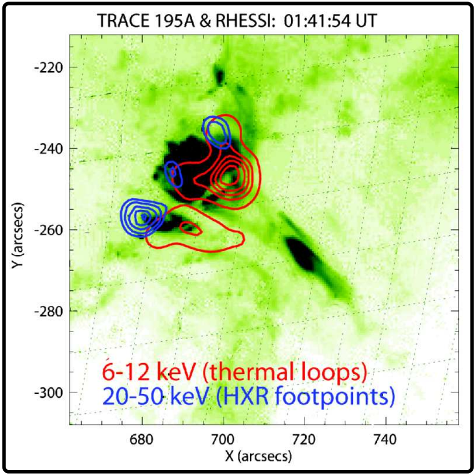
Ref: Krucker et al (2007). ApJ 663:L109-L112.



Trace EUV observations of one of Krucker et al (2007) events. Note the EUV jets.

RHESSI contours superposed: thermal loops with HXR footpoints.



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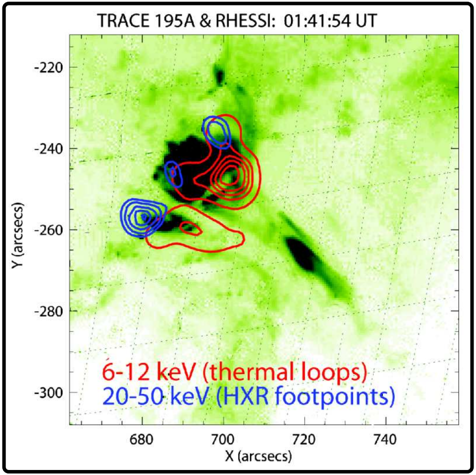

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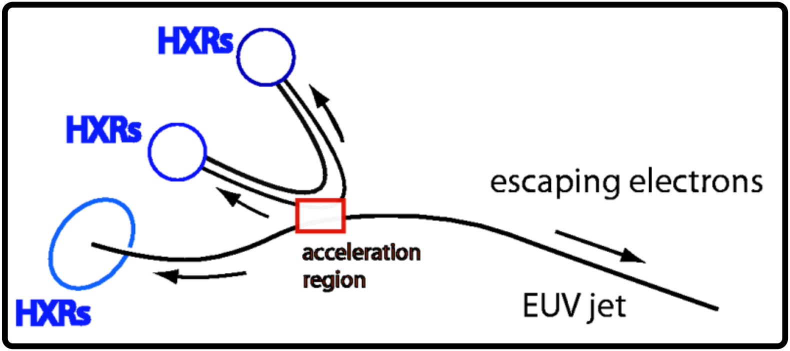
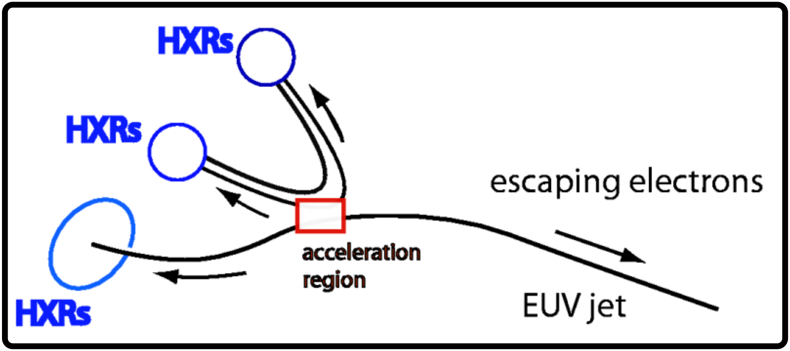


Observations suggest imple magnetic reconnection models with newly emerging flux tubes that reconnect with previously open field lines, also known as interchange reconnection.

Yet, many in-situ electron events do not agree in time with the HXR burst, and those do not show the same kind of spectral index correlation.



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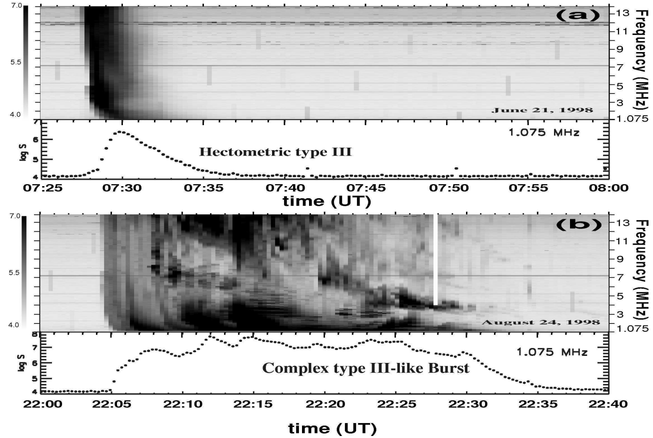

Type III bursts are signatures of electron beams propagating in the corona, then in the IM. There is a near one to one association between a solar electron event seen in situ, and a type III occuring close to the expected time for the release of the in-situ detected particles.

The association between type III bursts and impulsive electron events was revisited in recent years. Krucker et al. (1999), ApJ 519,864.

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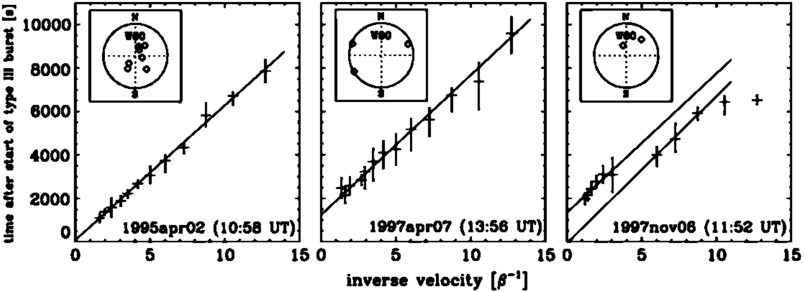

Inferred release time 100 keV electrons delayed by 10 mn from onset times of type III bursts at frequencies 10 MHz.

Verified also for 79 beam-like events seen by EPAM on ACE. Haggerty and Roelof (2002), ApJ 579, 841-853.

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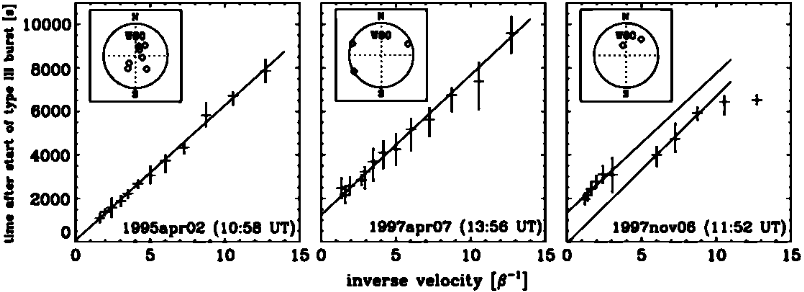

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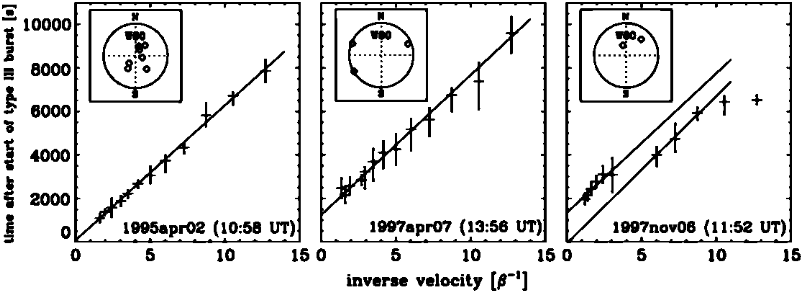

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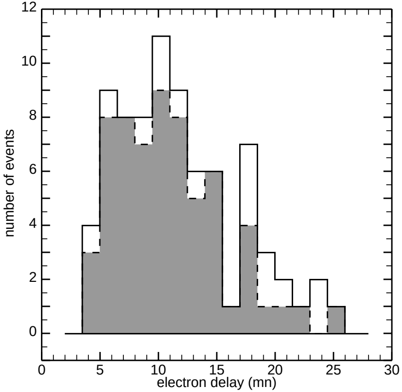

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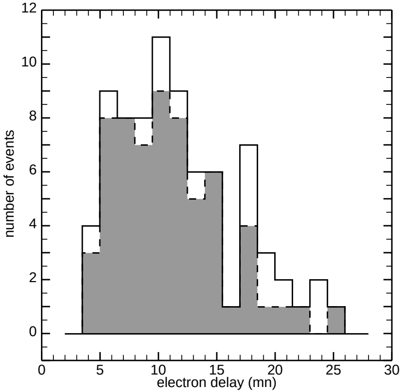

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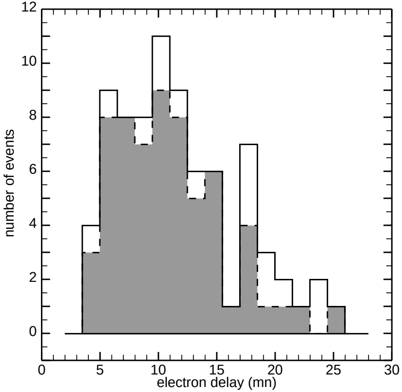

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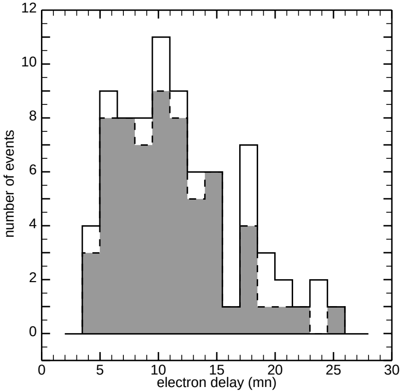

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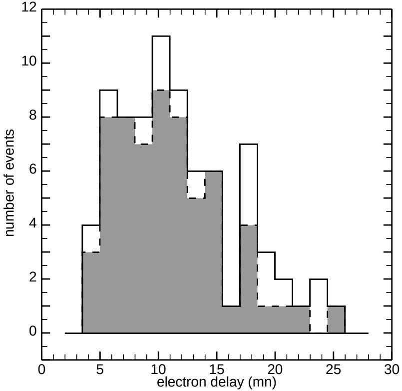

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Possible explanations:

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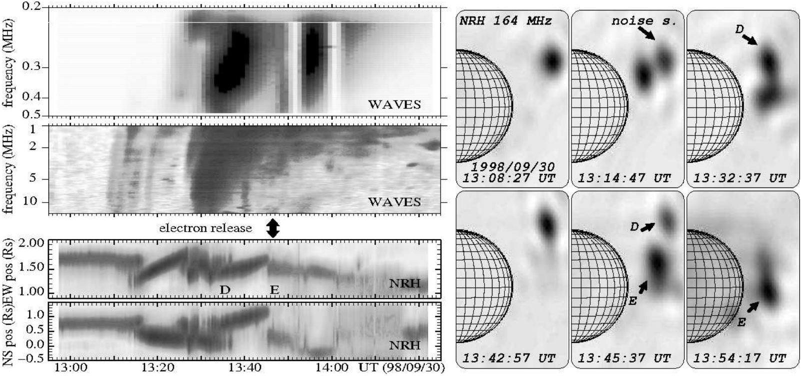

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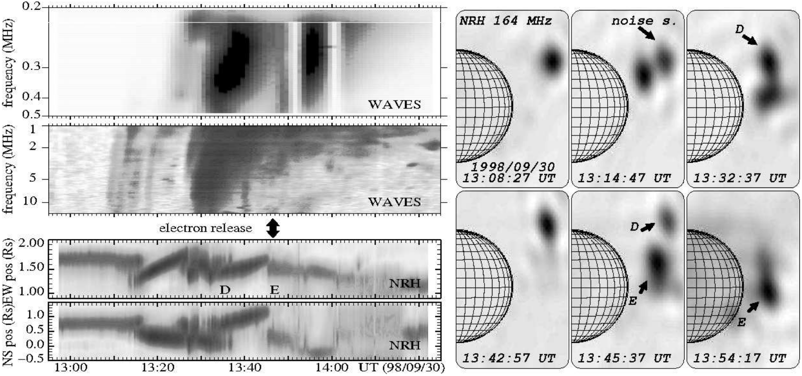

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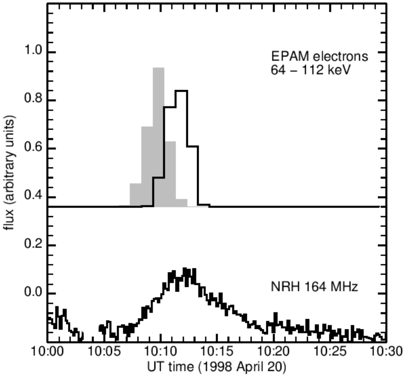

Inferred release function for the electrons (full deconvolution).

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Flux plot, radio emissions 164 MHz, south flank of radio loop.

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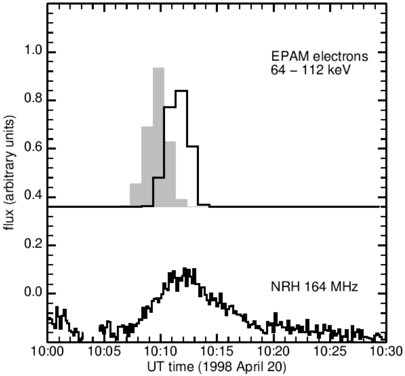

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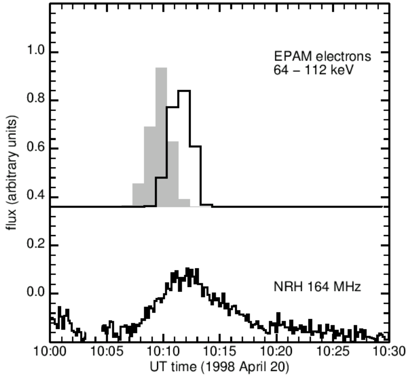

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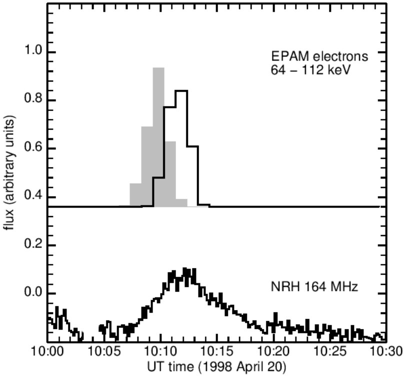

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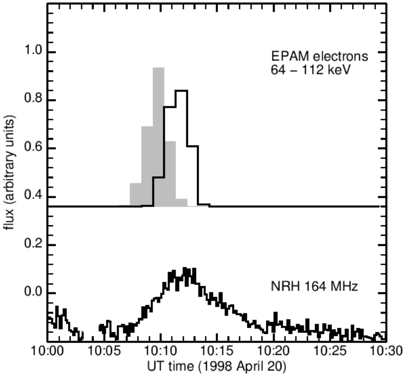

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