Lensing Galaxies in the CFHT Legacy Survey

Rafael Küng[1] Prasenjit Saha[1] Elisabeth Baeten[2] Jonathan Coles[3]
Claude Cornen[2] Christine Macmillan[2] Phil Marshall[4] Anupreeta More[5]
Surhud More[5] Aprajita Verma[6] Julianne K. Wilcox[2]

[1]Physik–Institut, University of Zurich, Zurich, Switzerland
[2]Zooniverse, c/o Astrophysics Department, University of Oxford, Oxford, UK
[3]Exascale Research Computing Lab, Bruyeres-le-Chatel, France
[4]Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, USA
[5]Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa-shi, Japan
[6]Sub-department of Astrophysics, University of Oxford, Oxford, UK

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Motivation

- Strong lensing analyzes wide field surveys

- Robots are not very good at finding and modelling lenses
- Human intervention is needed!

$\Rightarrow$ SpaceWarps citizen science project
(50'000 volunteers; 11 mio classifications; 51 candidates)

SpaceWarps Results and Outlook

- CHFT Legacy Survey: 150 deg^2
- 59 candidates found (29 promising)[1]

$\Rightarrow \approx$ 1 lens every few deg^2

- DES, PanStarrs; later LSST, Euclid
- more area, better resolution

$\Rightarrow$ 10'000 lenses over 10 years ($\approx$ one per hour)

[1] [A. More et al; arXiv:1504.05587]

Outlook

A lot of computational and manpower needed

Detecting lenses:

- Robots making progress (RingFinder; ArcFinder)

in combination with

- Future SpaceWarps runs

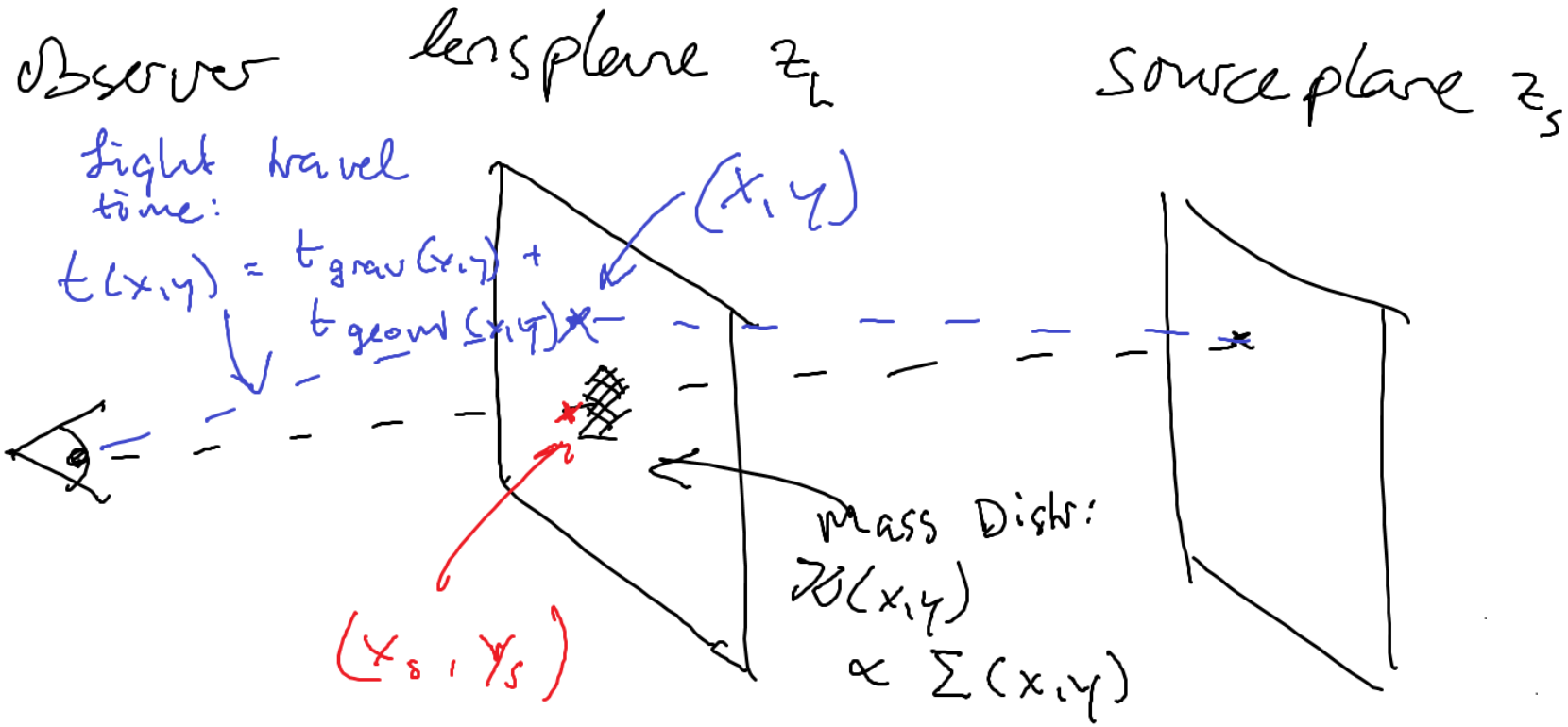
Post processing?

- Robots not there (yet?)

$\Rightarrow$ Citizen science: SpaghettiLens

Theory

Setup


Observer
lensplane z_L
Sourceplane z_S
light travel time:
$t(x,y) = t_{grav}(x,y) + t_{geom}(x,y)$
(x,y)
mass Distr:
$\mathcal{U}(x,y)$
$\propto \Sigma(x,y)$
(x_s, y_s)

Fermat's Principle

Fermat's Principle[2]

Rays of light traverse the path of stationary optical length with respect to variations of the path.

Fermat's Principle

Time t for path X:

$$t[X] = \frac{1}{c}\int_{t_1}^{t_2} n(\vec{x}(t))\sqrt{1+\left(\frac{\mathrm{d}\vec{x}(t')}{\mathrm{d}t'}\right)^2}\,\mathrm{d}t'$$

Path X where t stationary.

[2] Ghatak, Ajoy (2009), Optics

Light Travel Time

Light travel time

$$t(x,y) = t_{\text{geom}} + t_{\text{grav}} \quad (1)$$

$$t_{\text{geom}} \propto (x - x_s)^2 + (y - y_s)^2 \quad (2)$$

$$t_{\text{grav}} = \langle t_{\text{grav}}(x_\circ, y_\circ) \rangle + (1 + z_L)\frac{2G}{c^3} M(x_\bullet, y_\bullet) \quad (3)$$

$$A_t = A_{\text{geom}} + A_{\text{grav}} \tag{4}$$

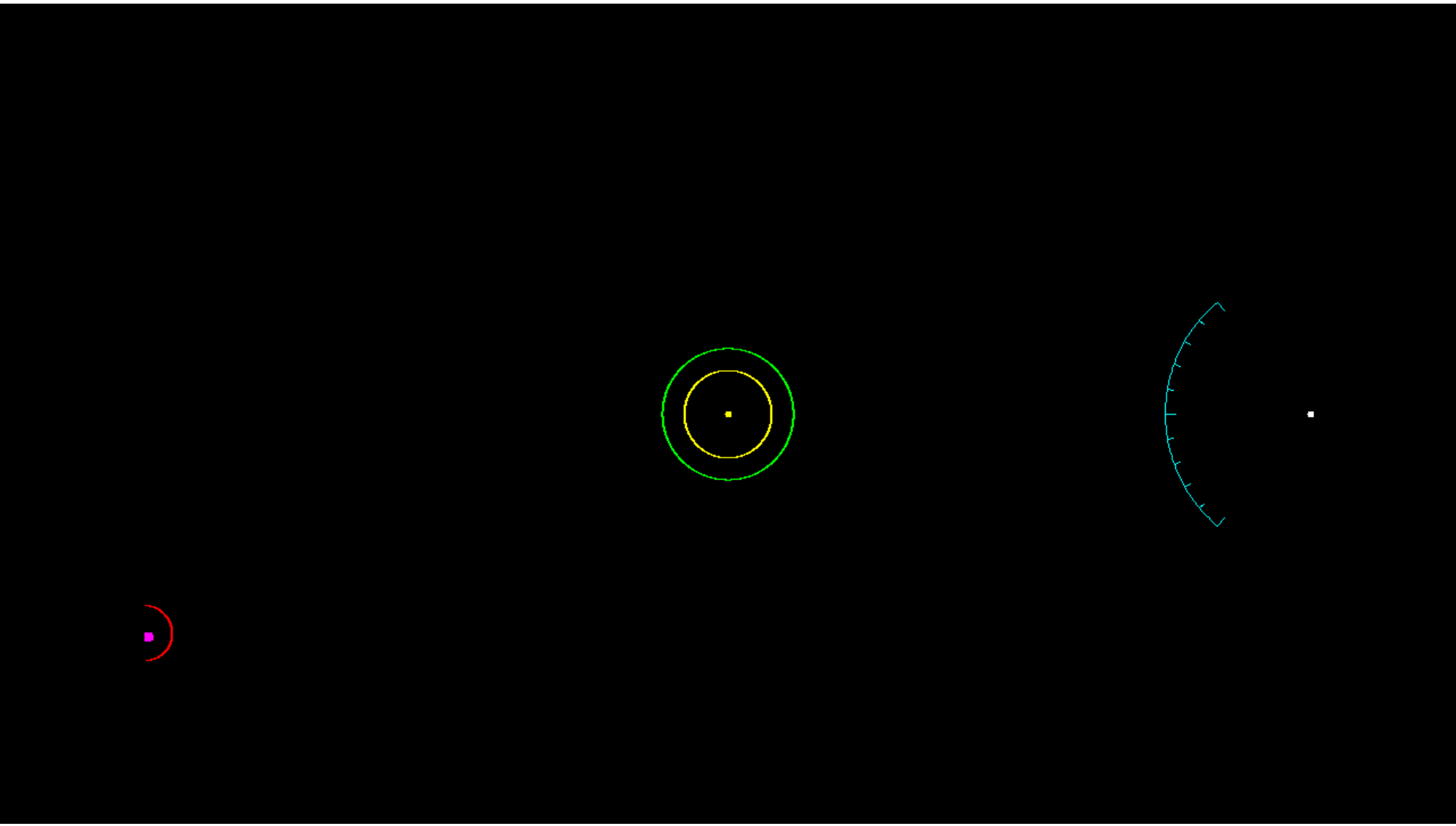
$$A_{\text{geom}} = \frac{1}{2}\left(x^2 + y^2\right) \tag{5}$$

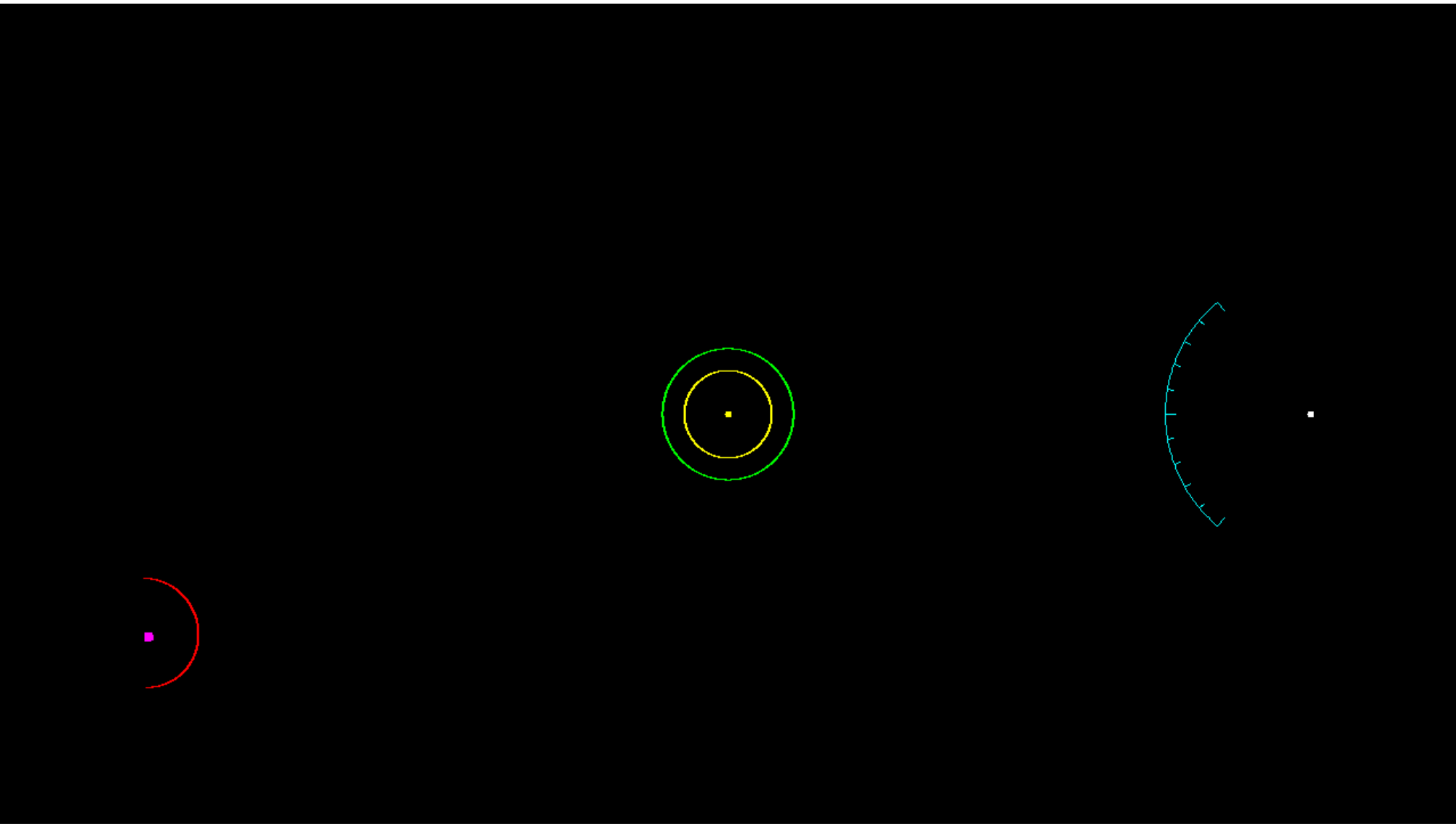
$$\nabla^2 A_{\text{grav}}(x, y) = -2\kappa(x, y) \tag{6}$$

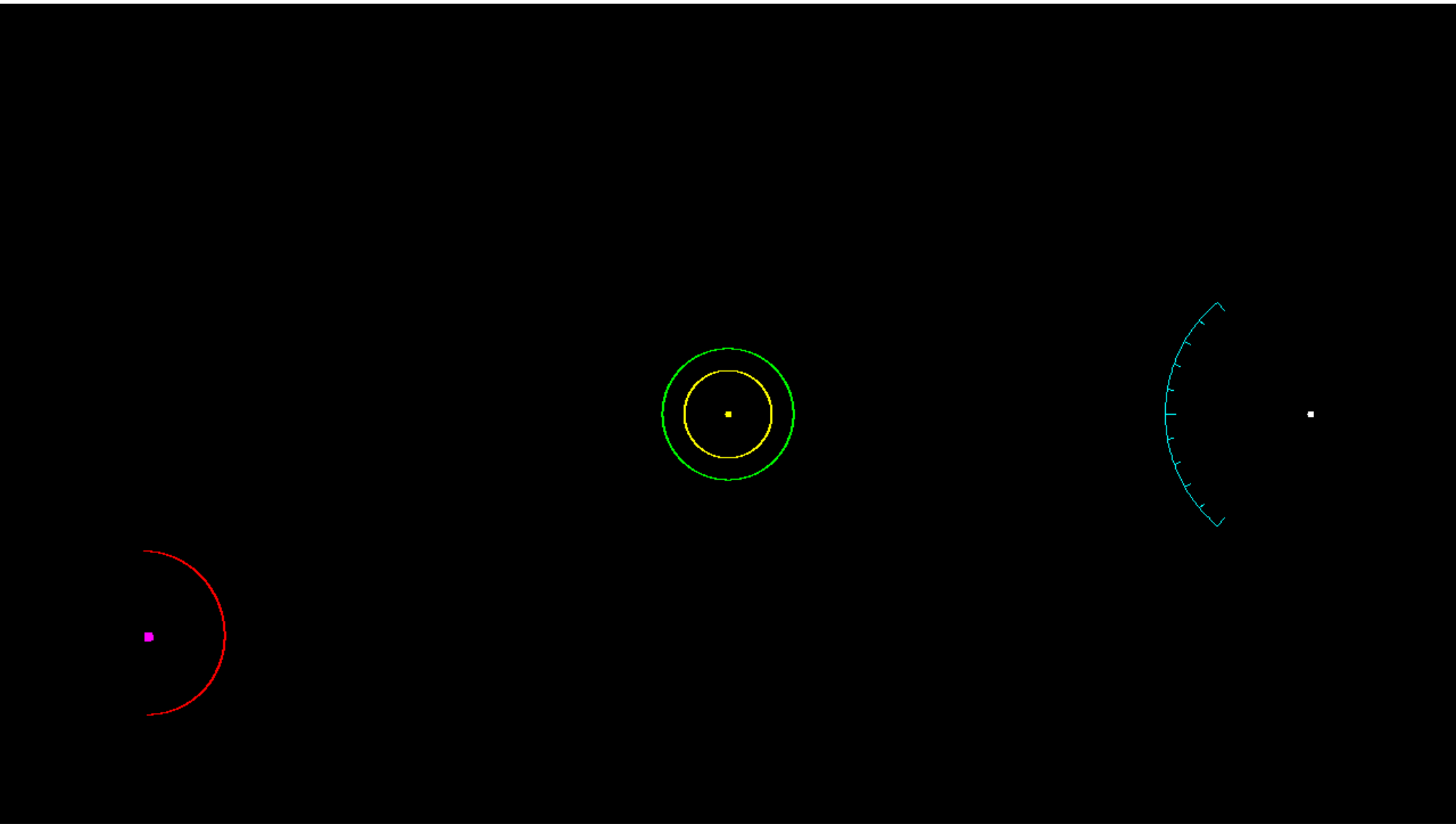
$$A = \frac{cD_L}{(1+z_L)^2}\frac{D_{LS}}{D_S} \times t \tag{7}$$

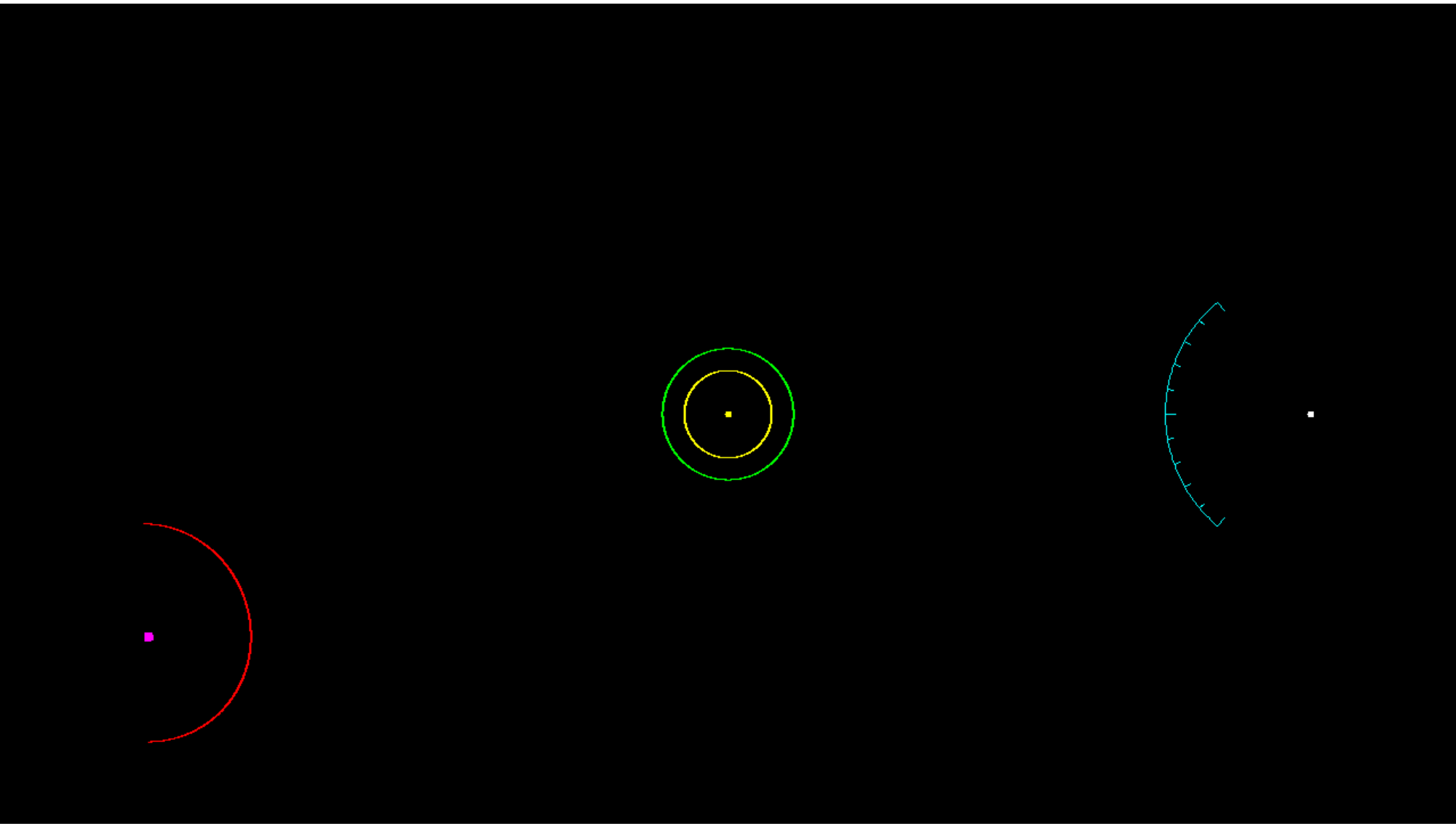
$$\kappa(x, y) = \frac{4\pi G}{c^2}\frac{D_L}{1+z_L}\frac{D_{LS}}{D_S} \times \Sigma(x, y) \tag{8}$$

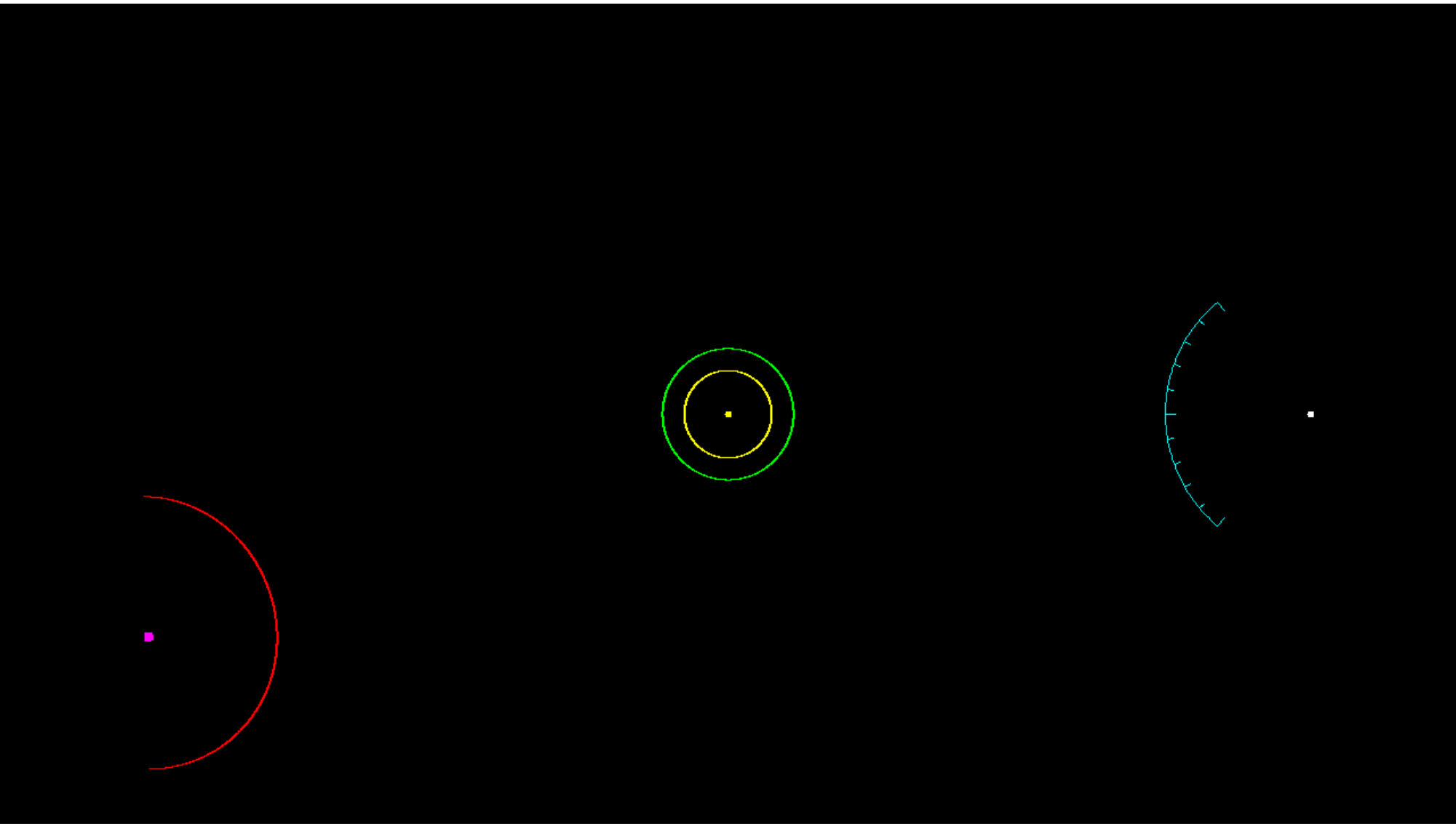
Alternative explanation

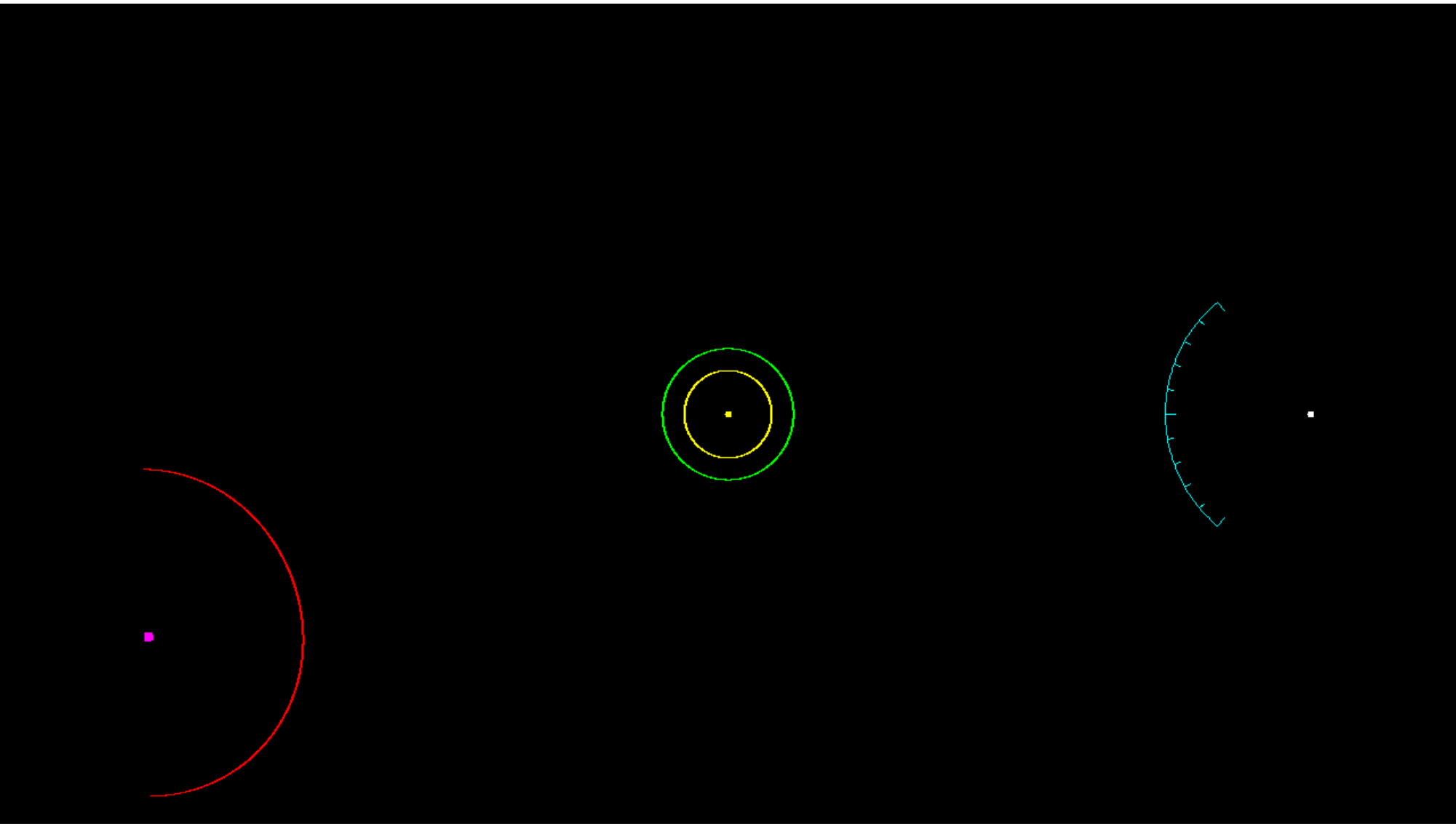


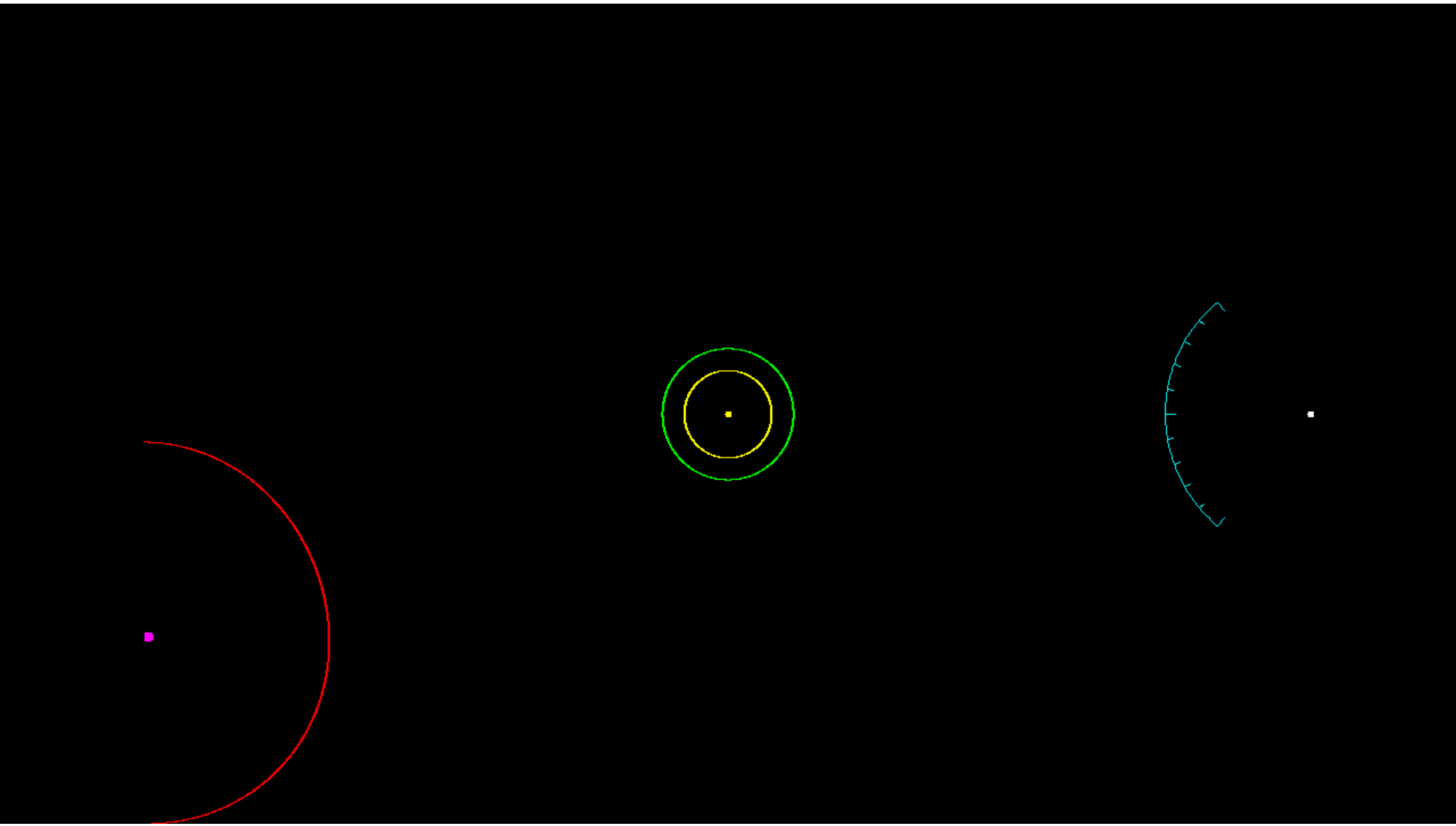


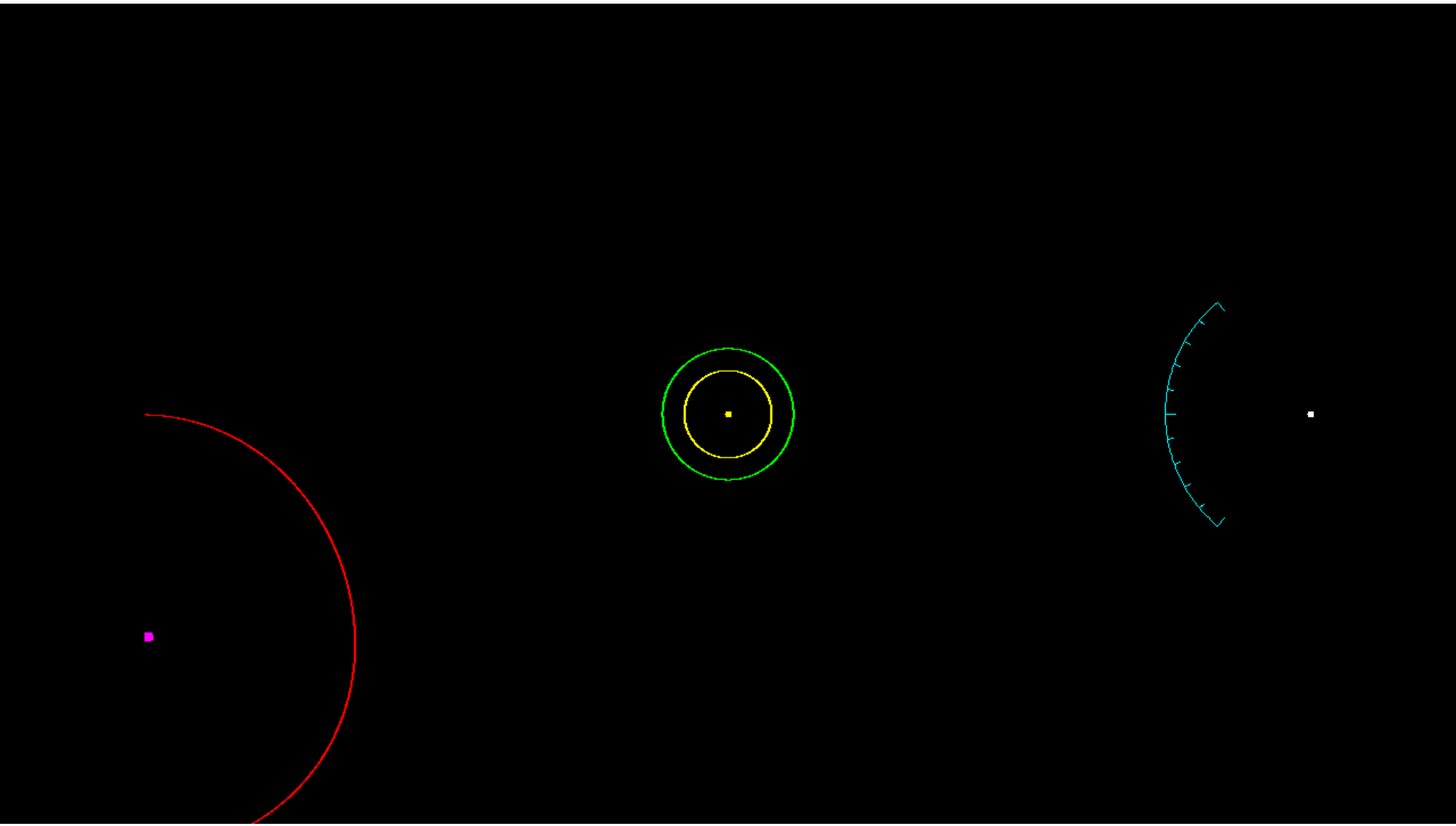


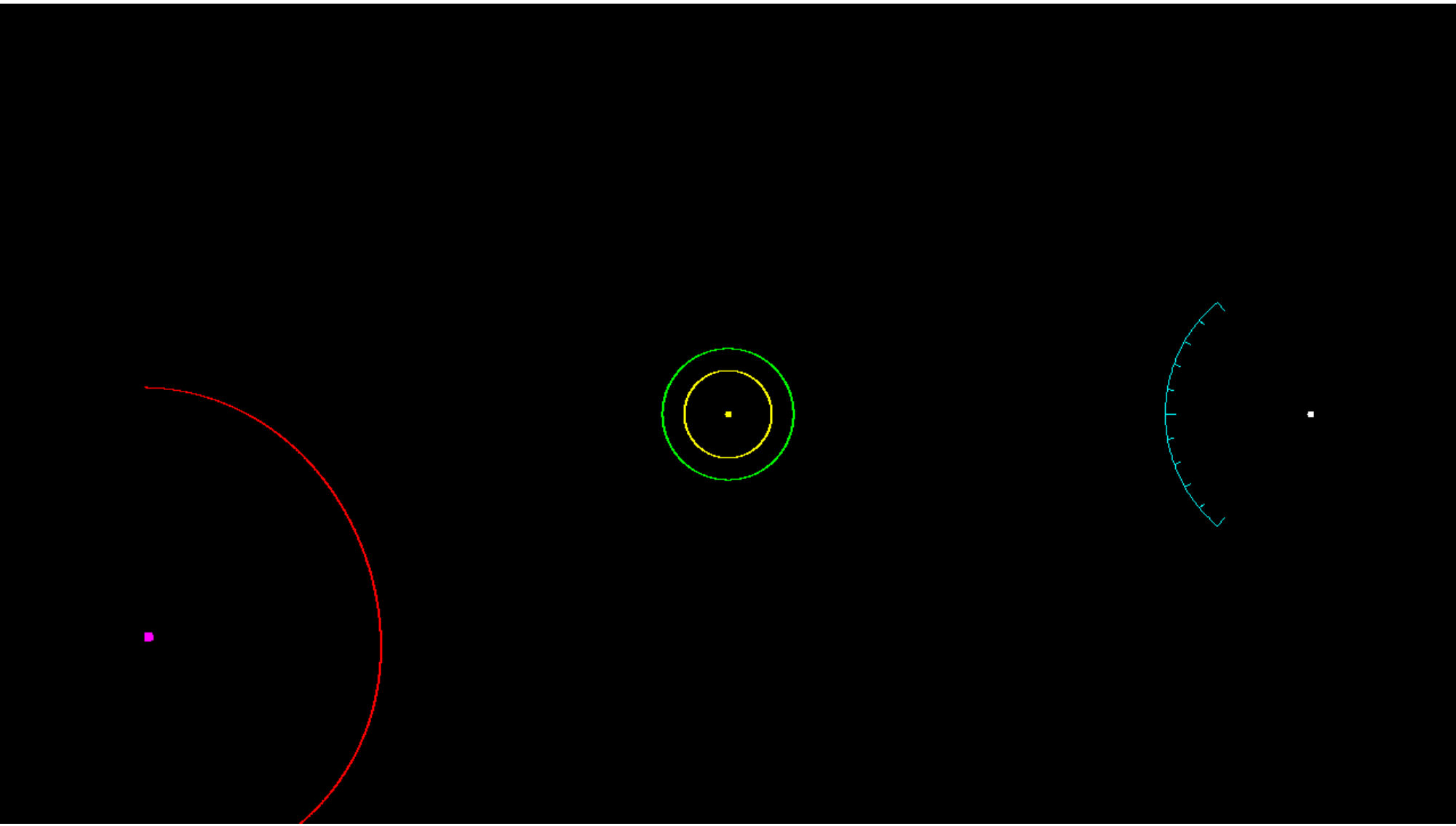


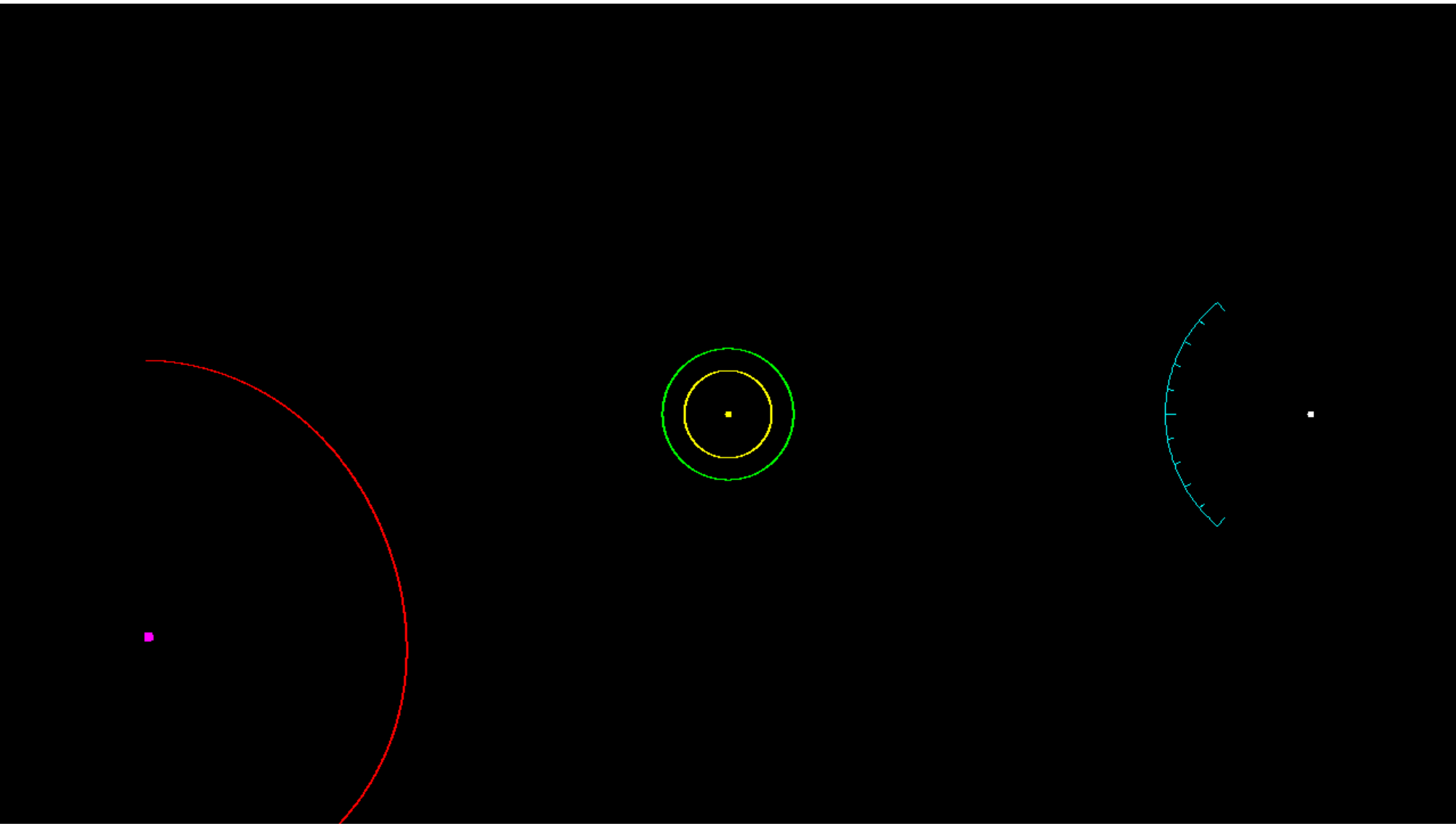


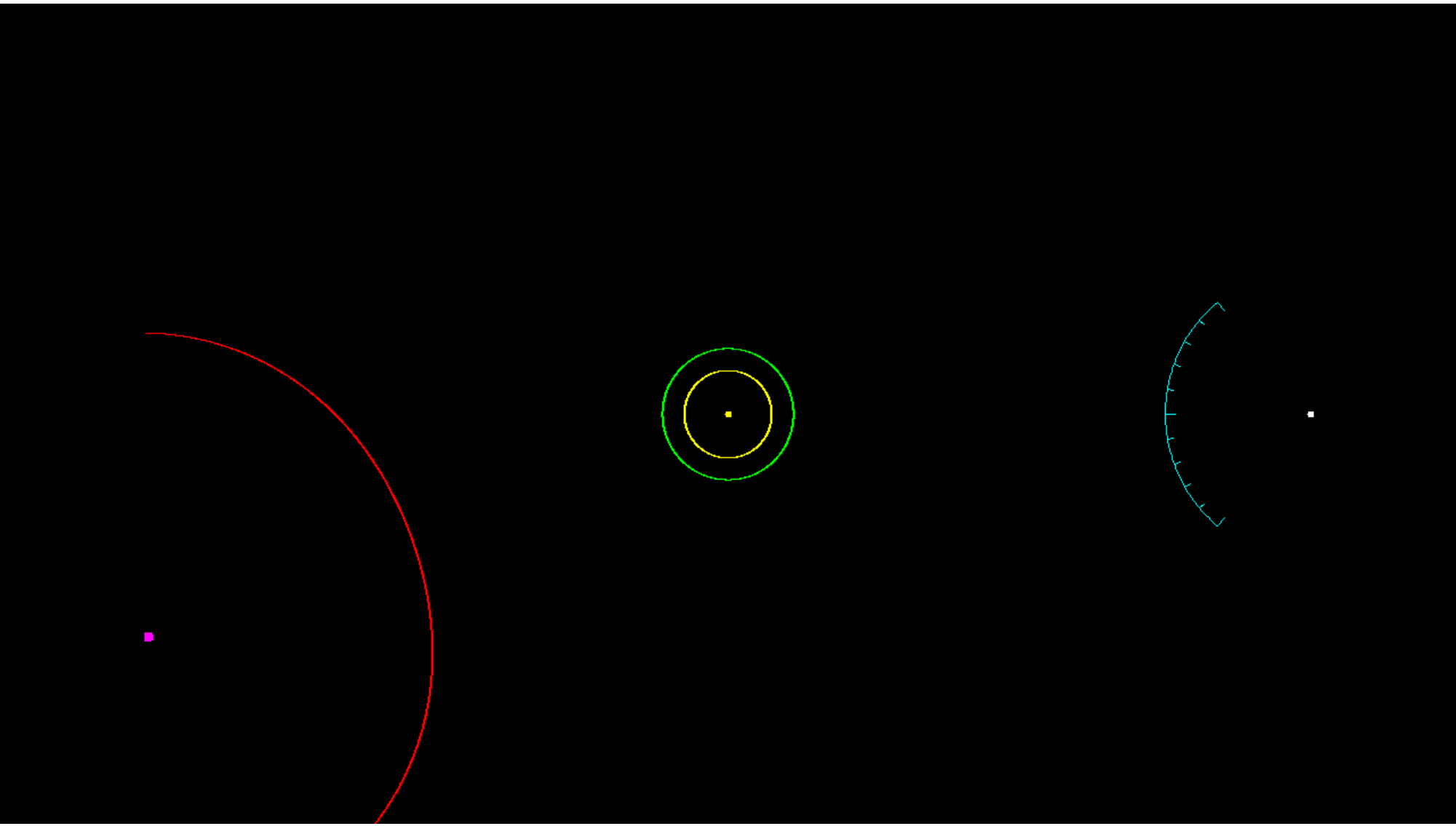


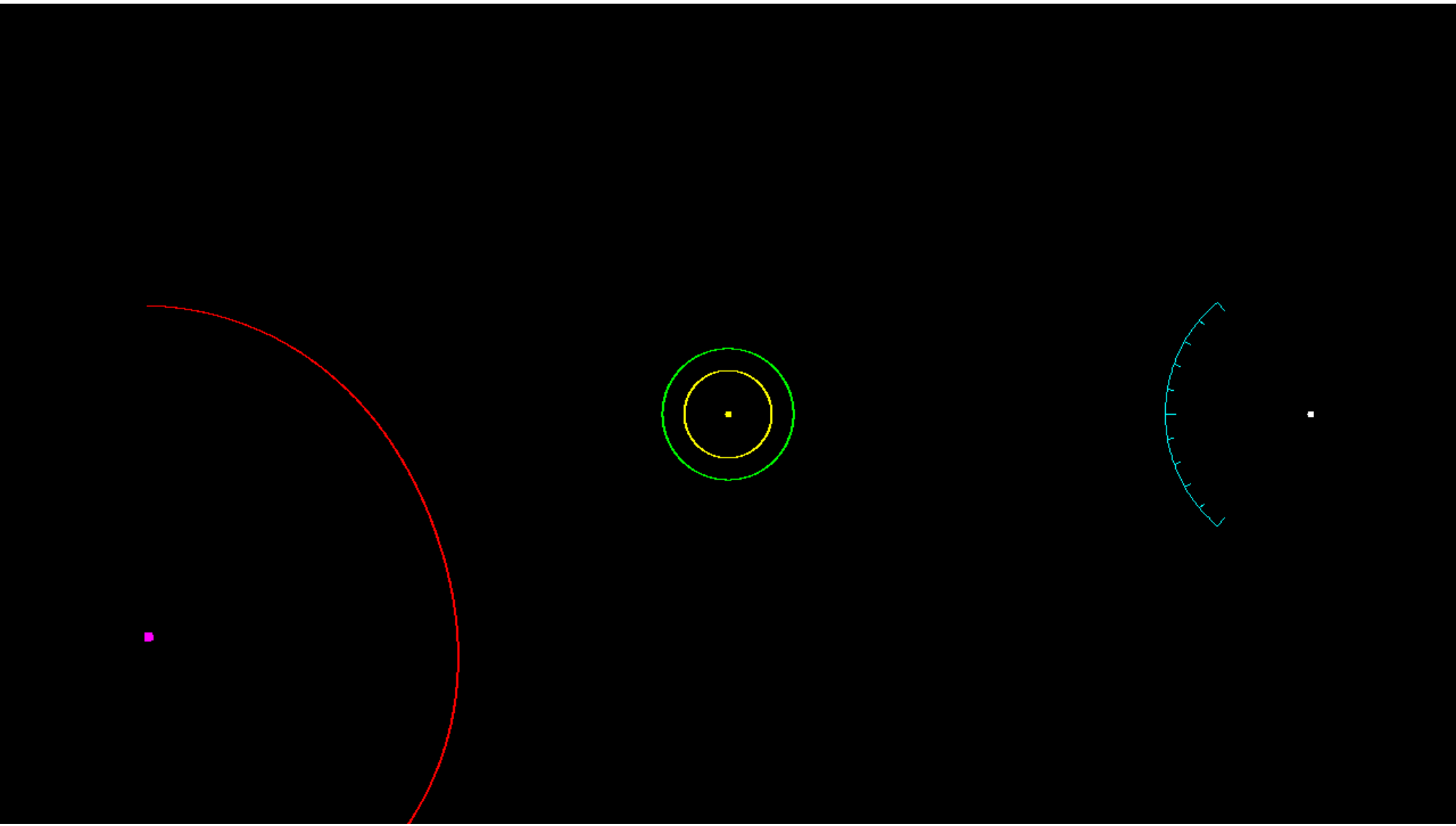


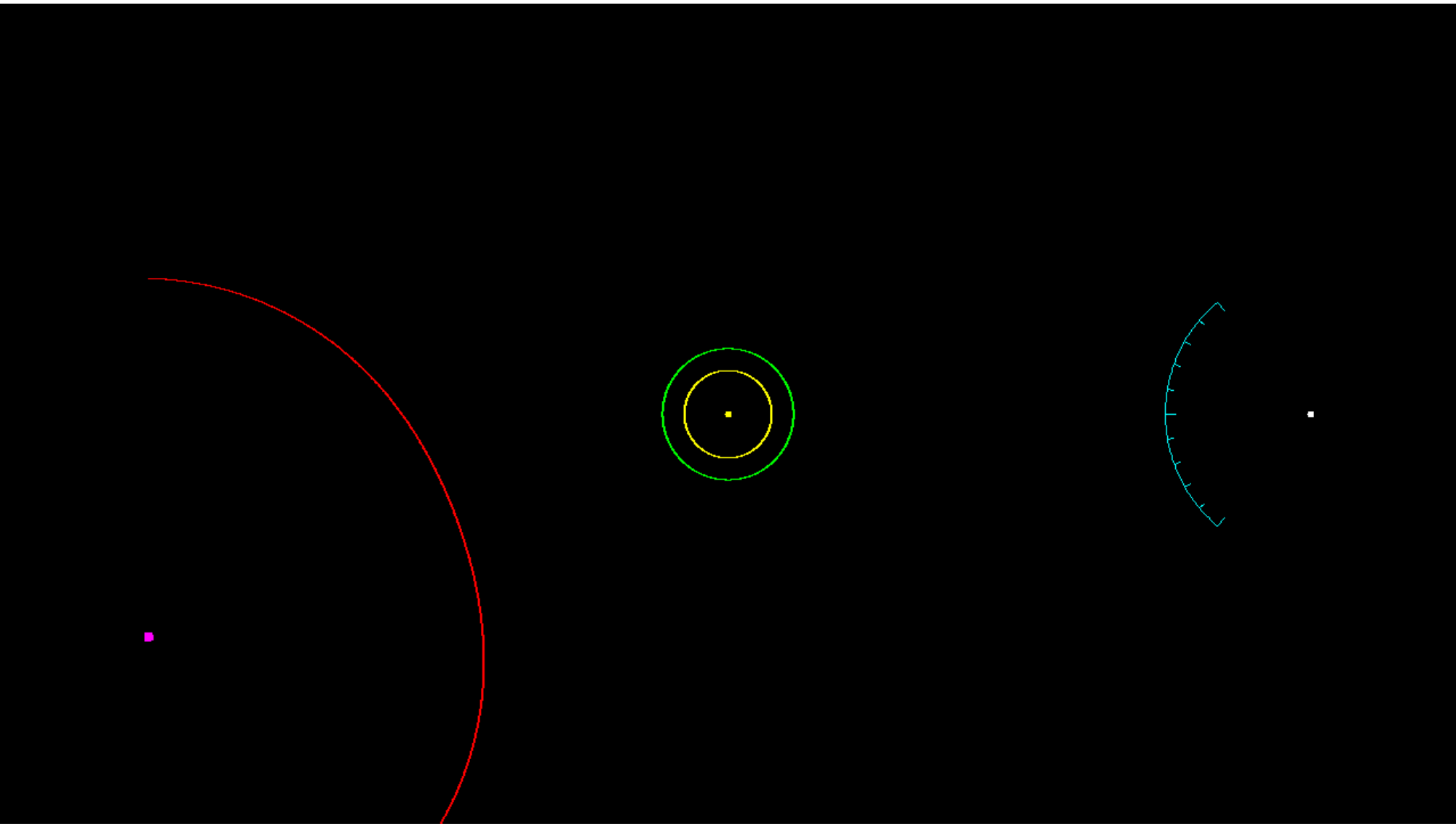


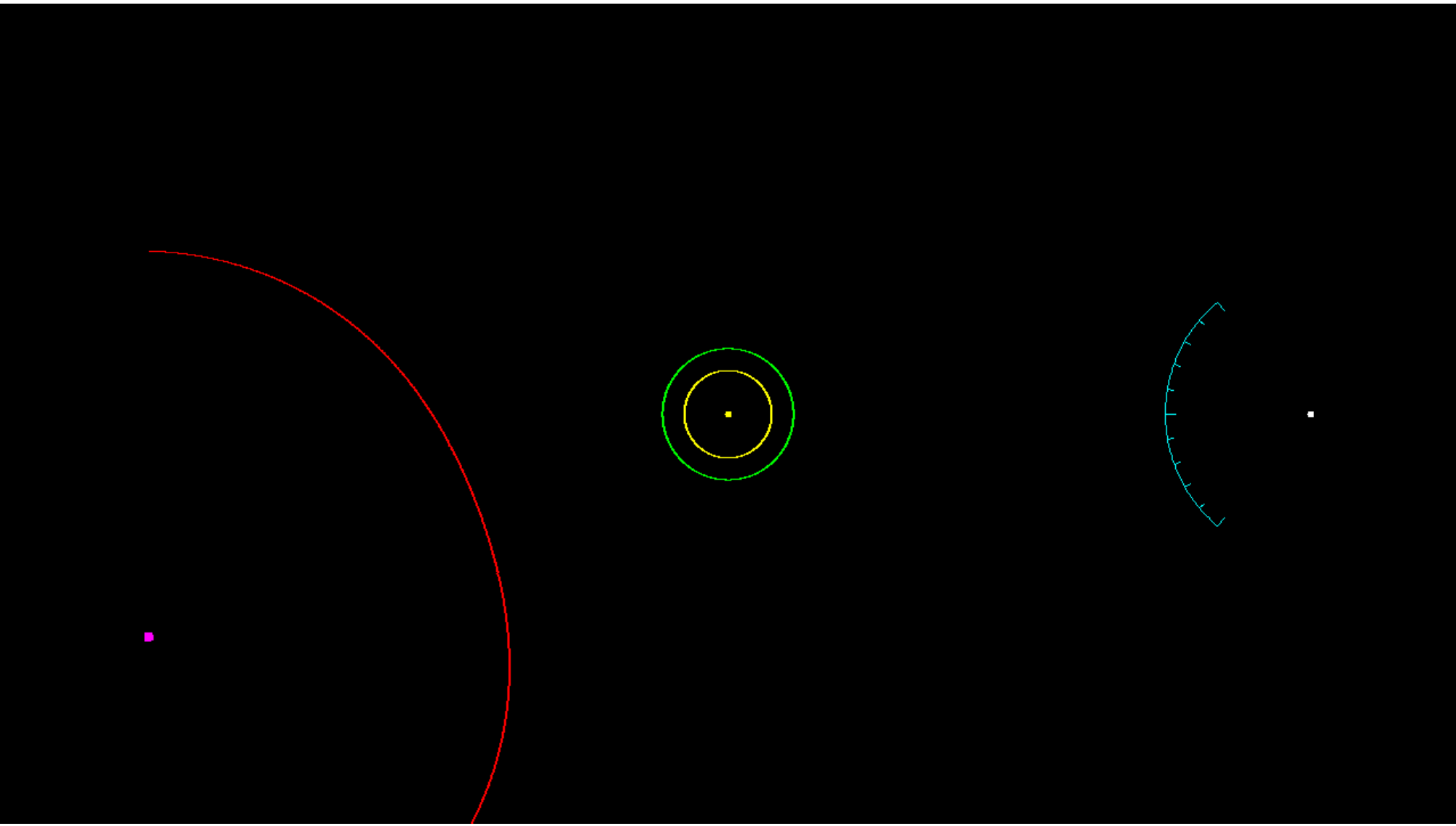


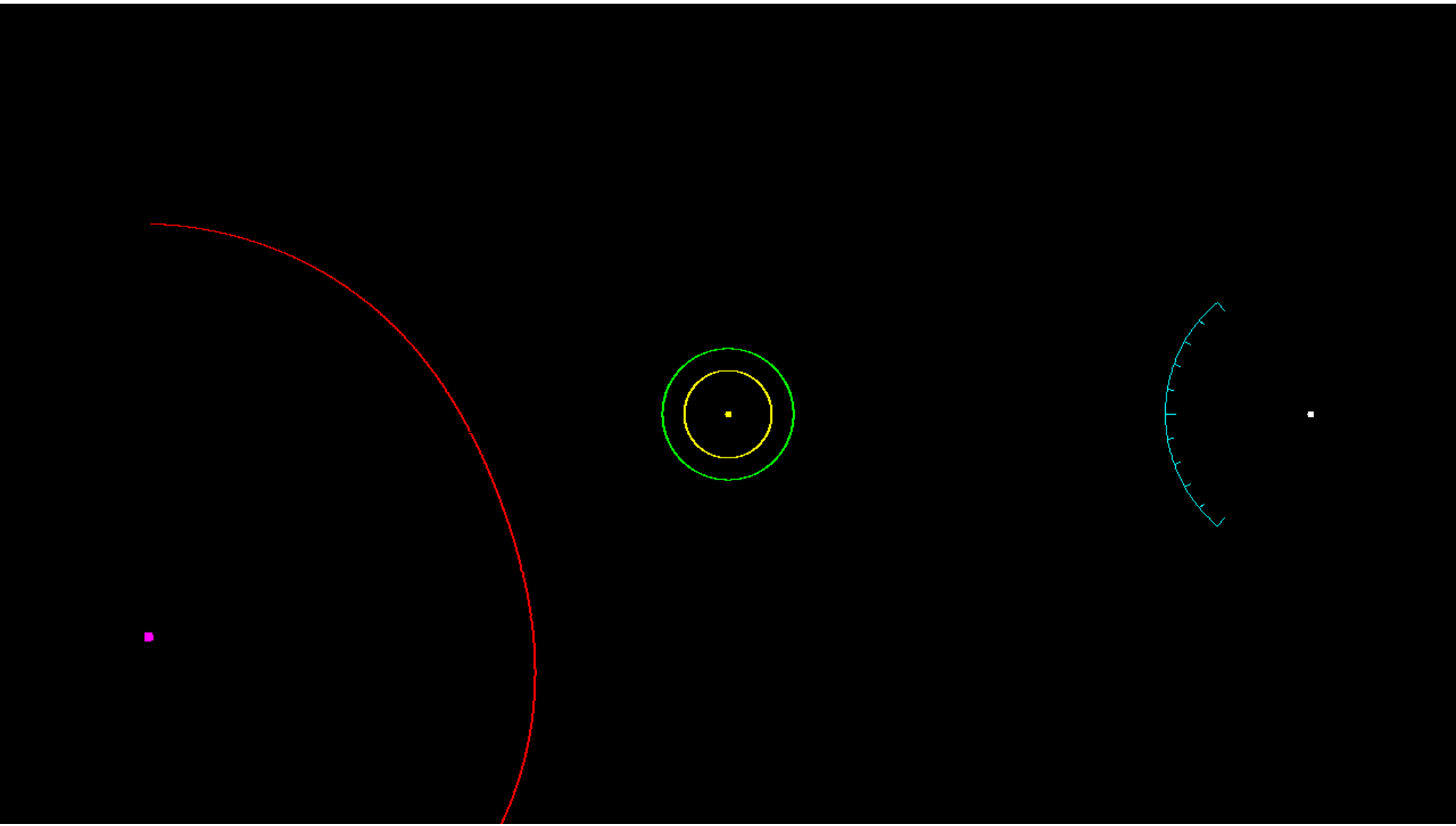


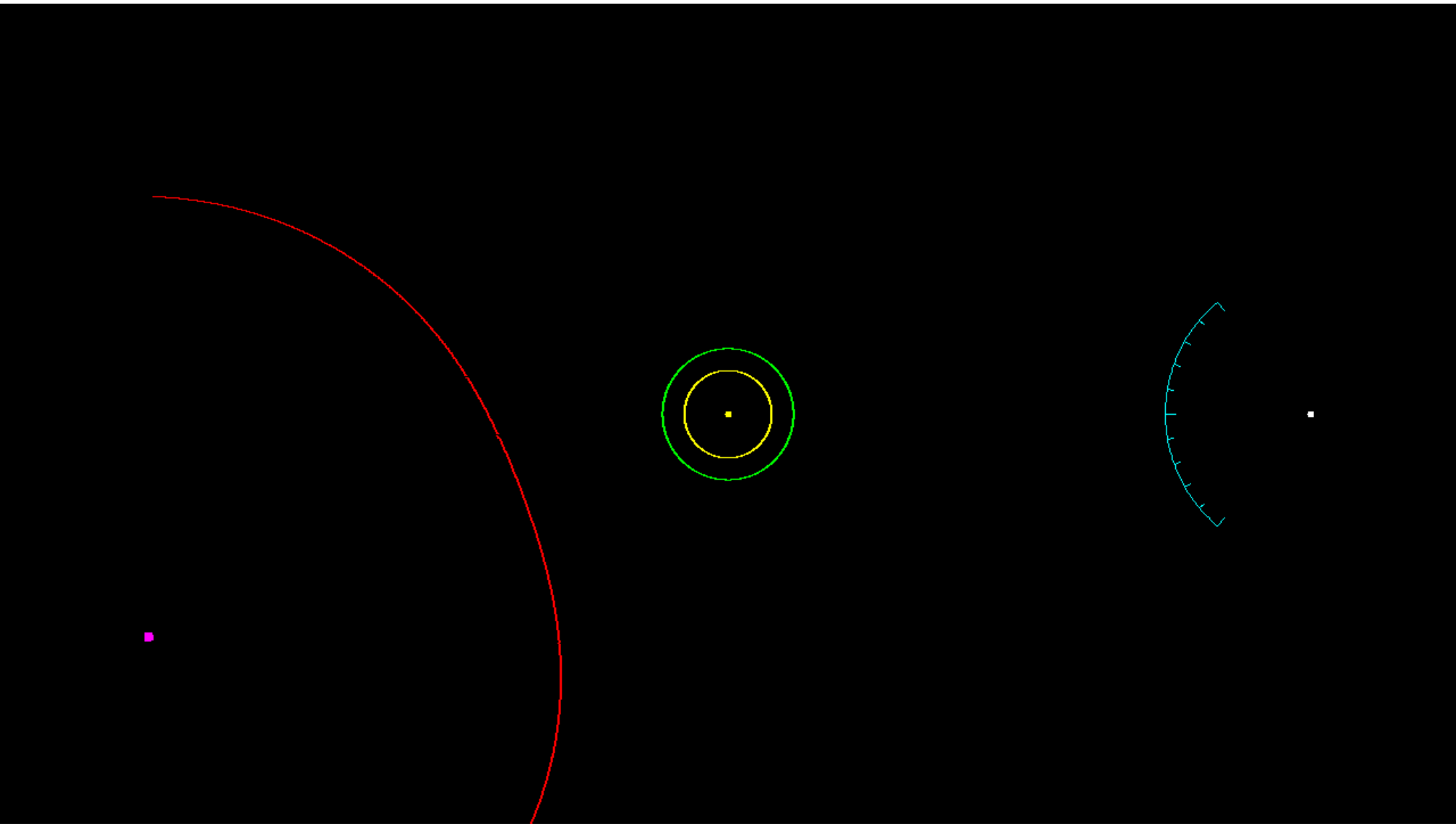


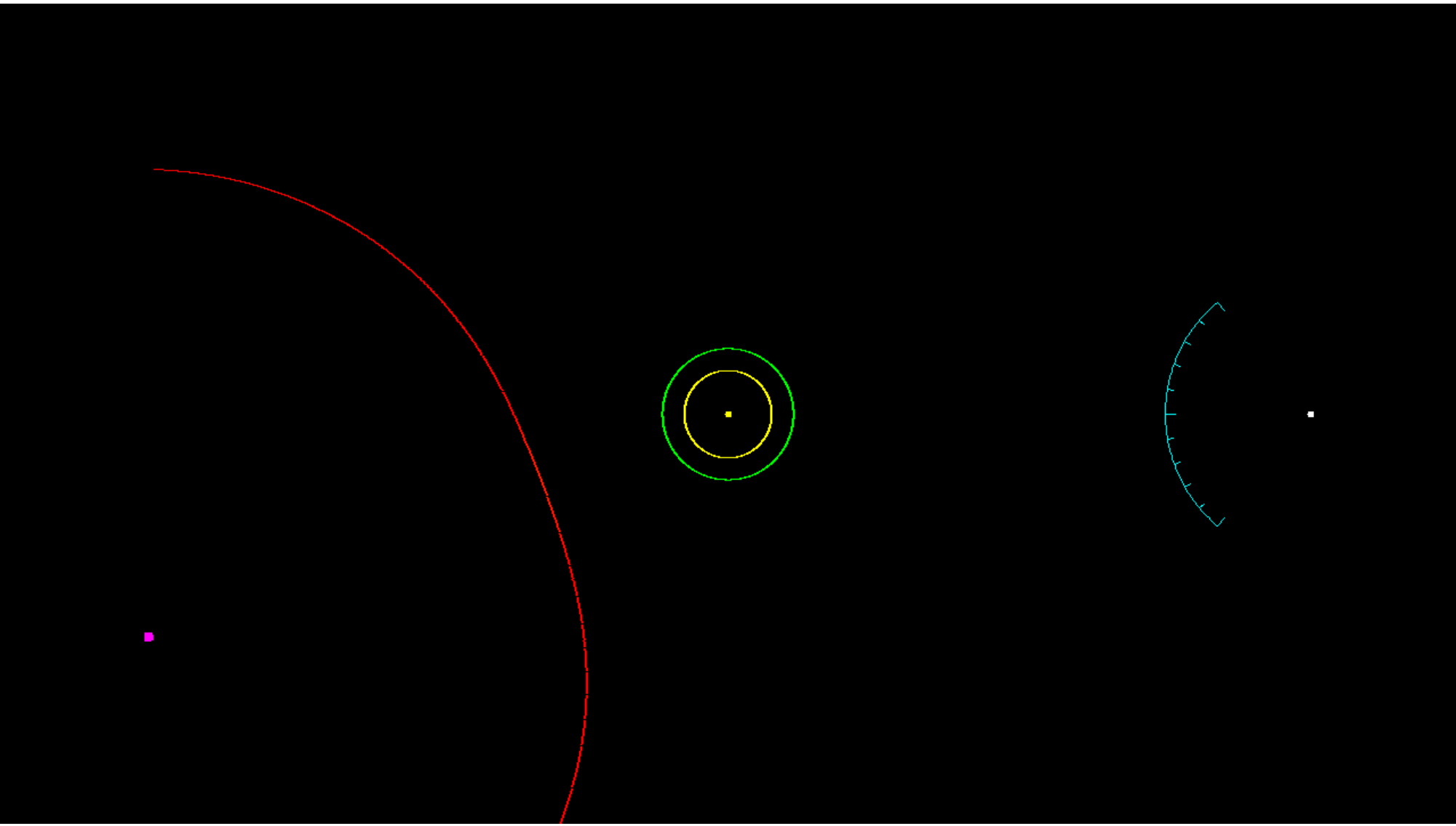


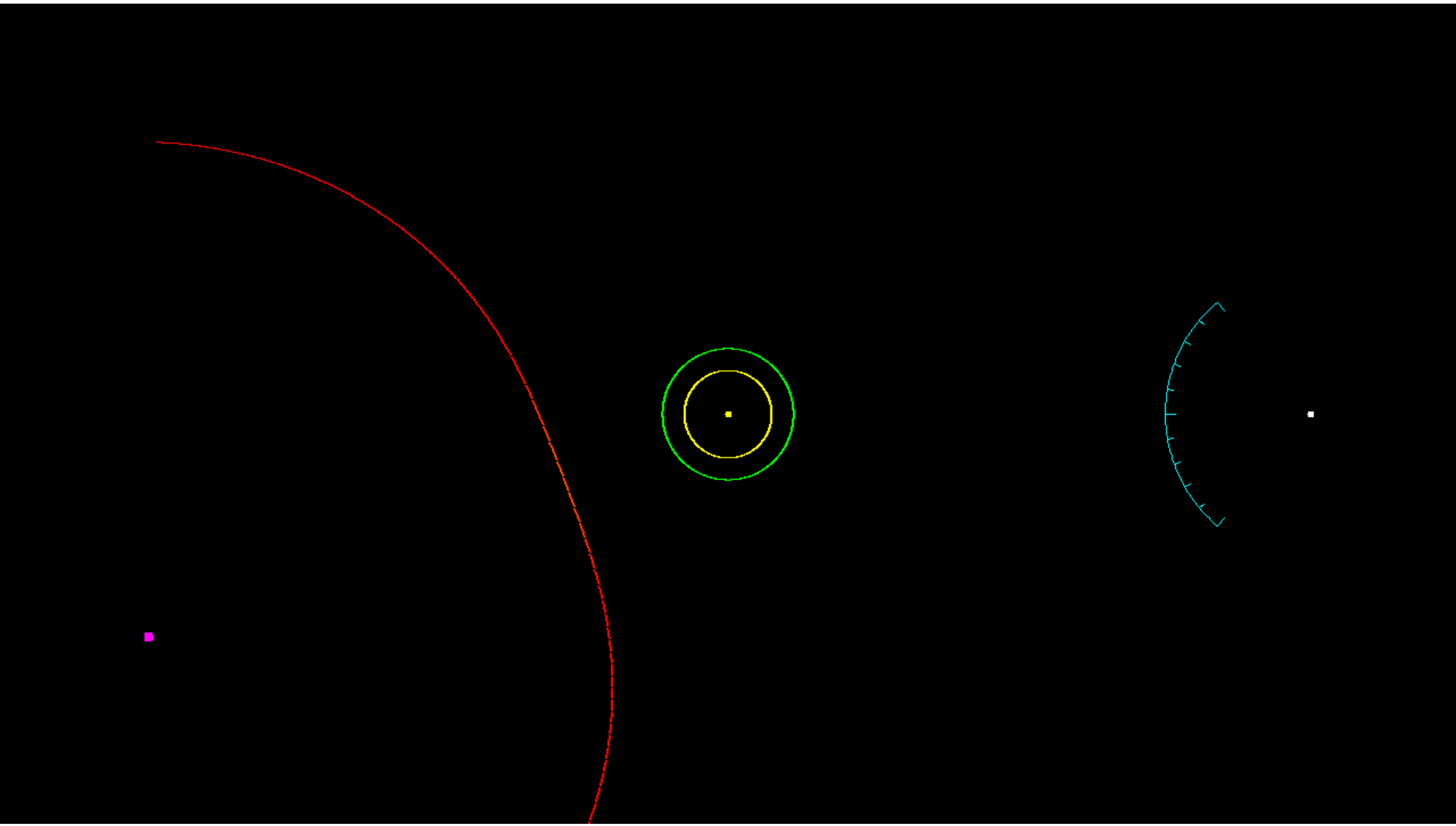


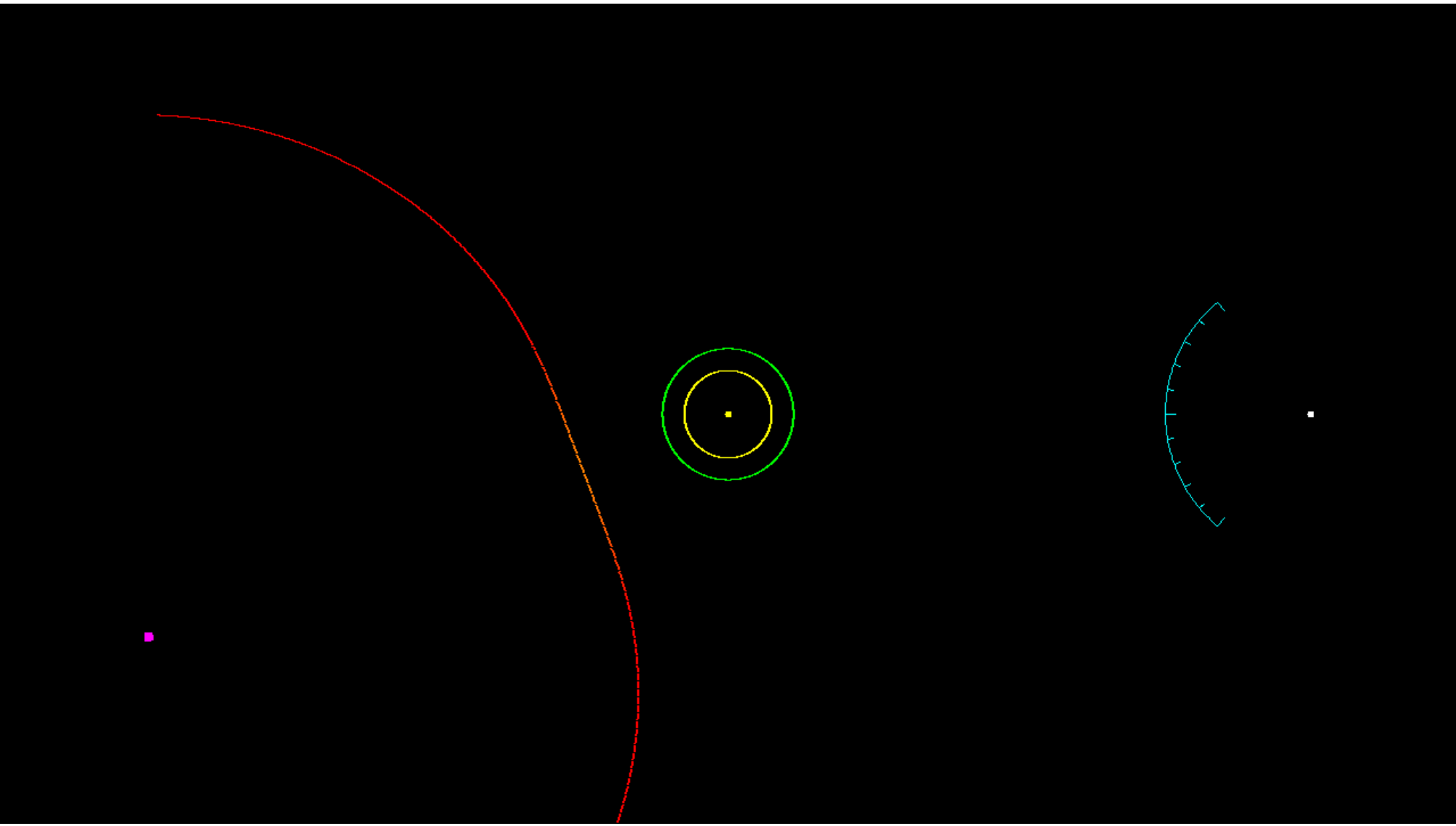


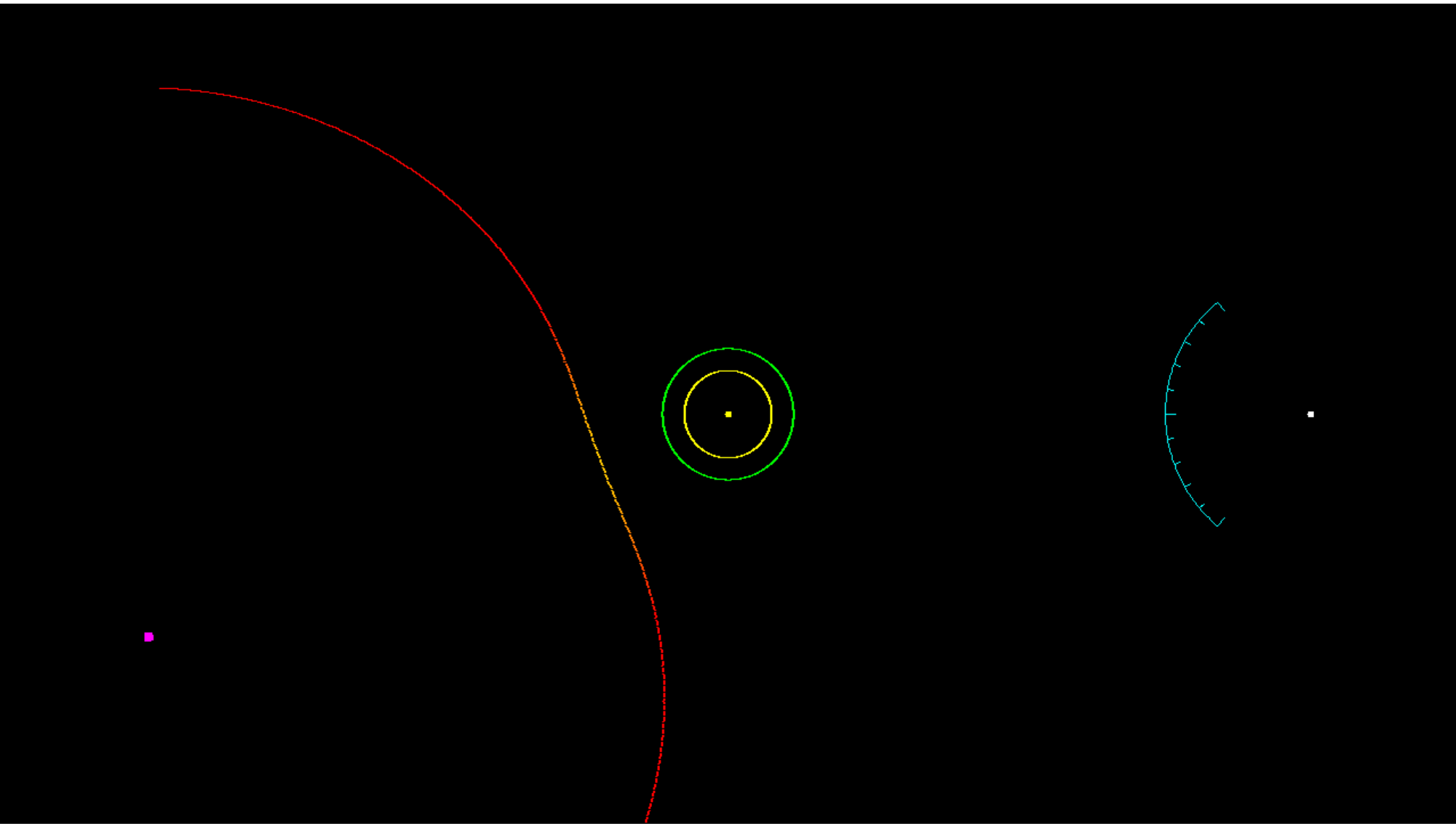


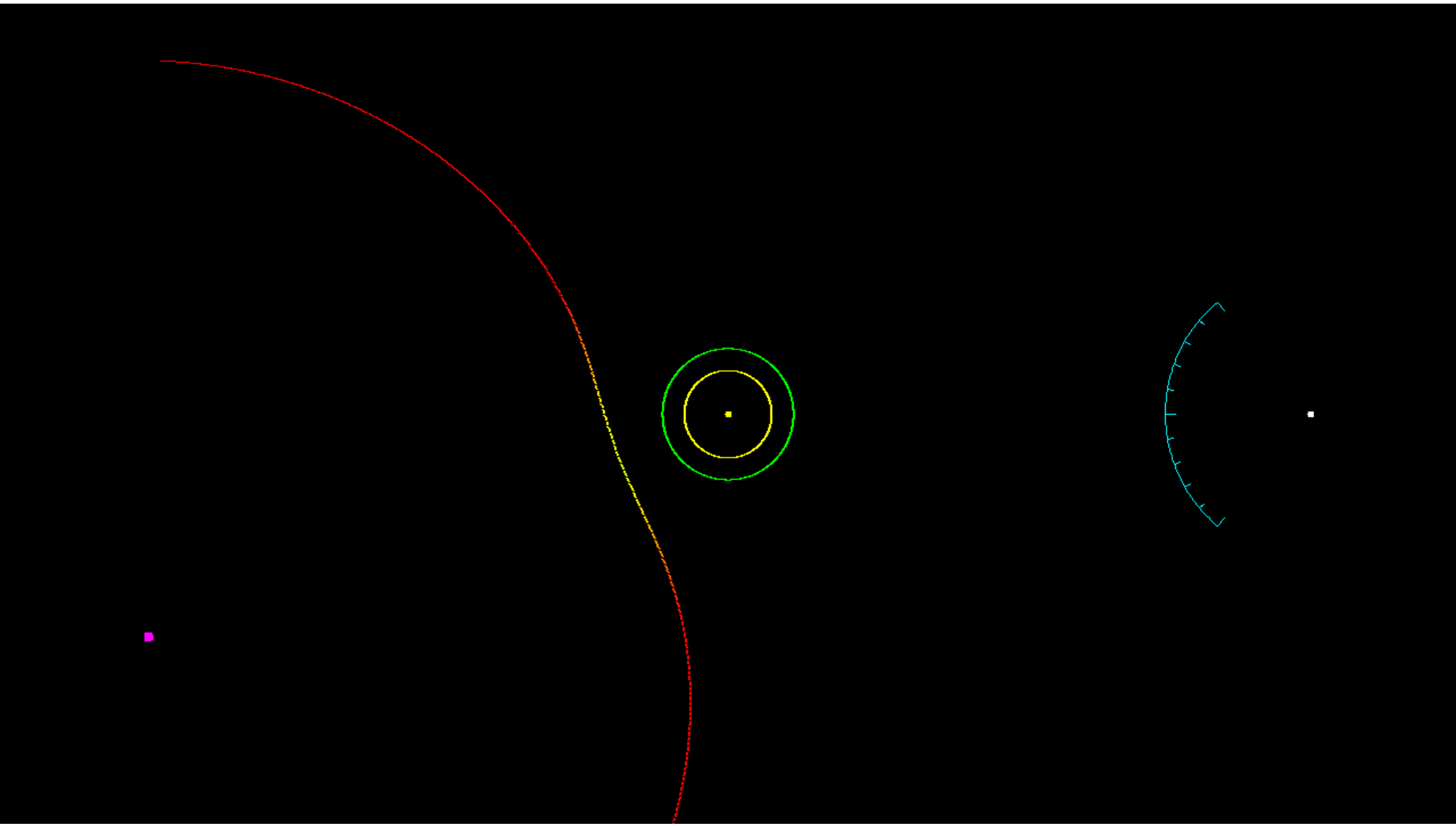


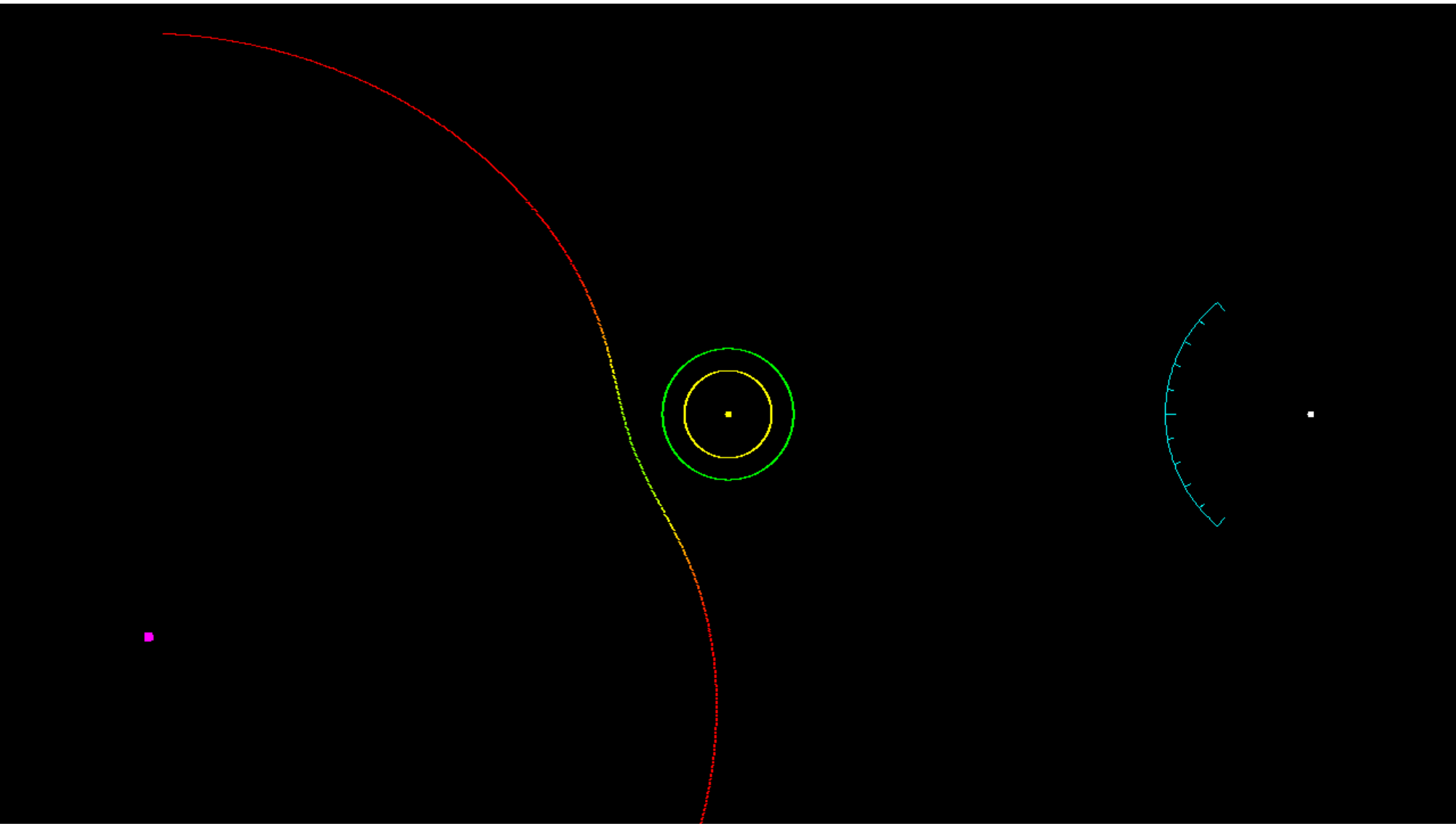


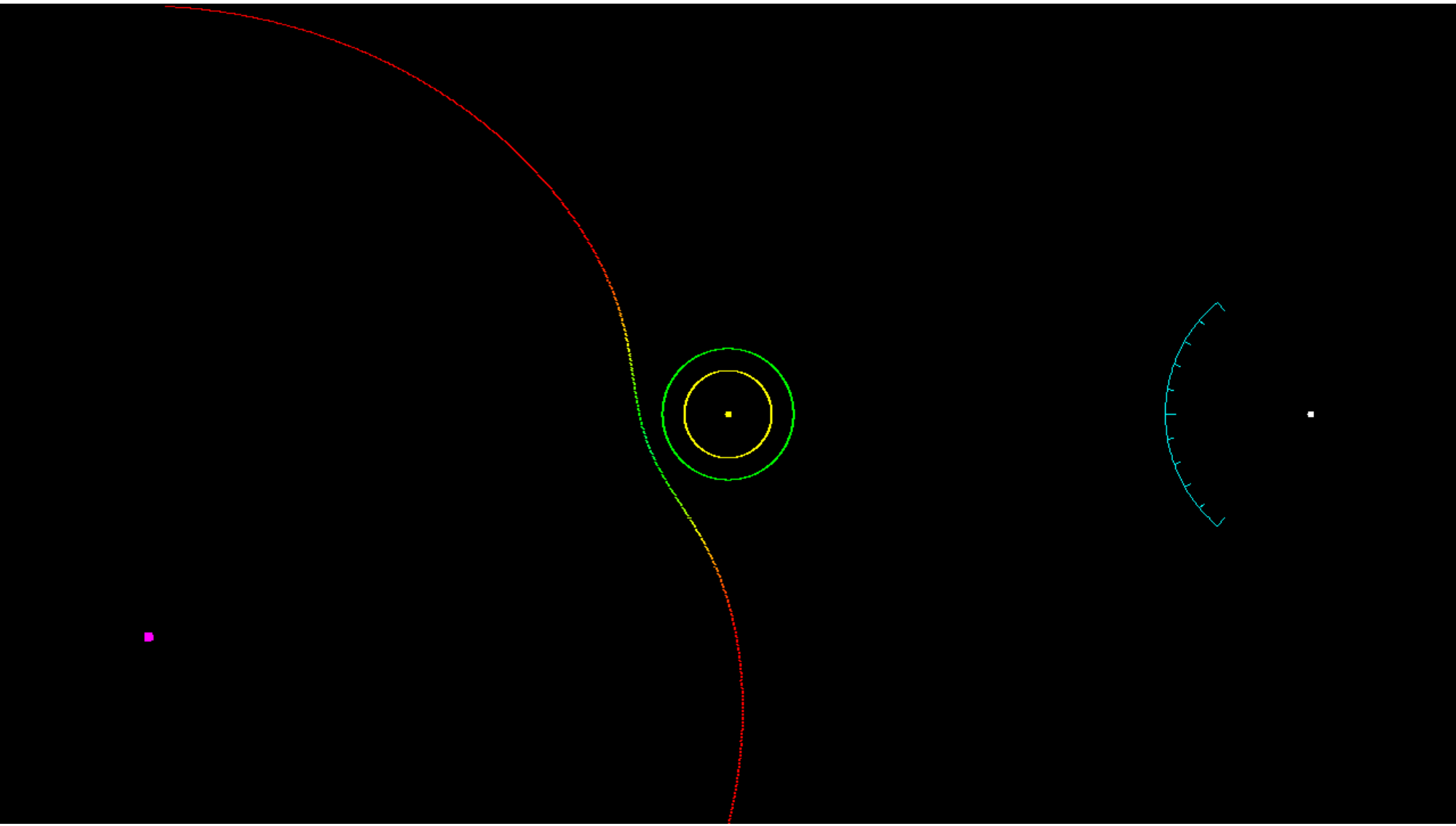


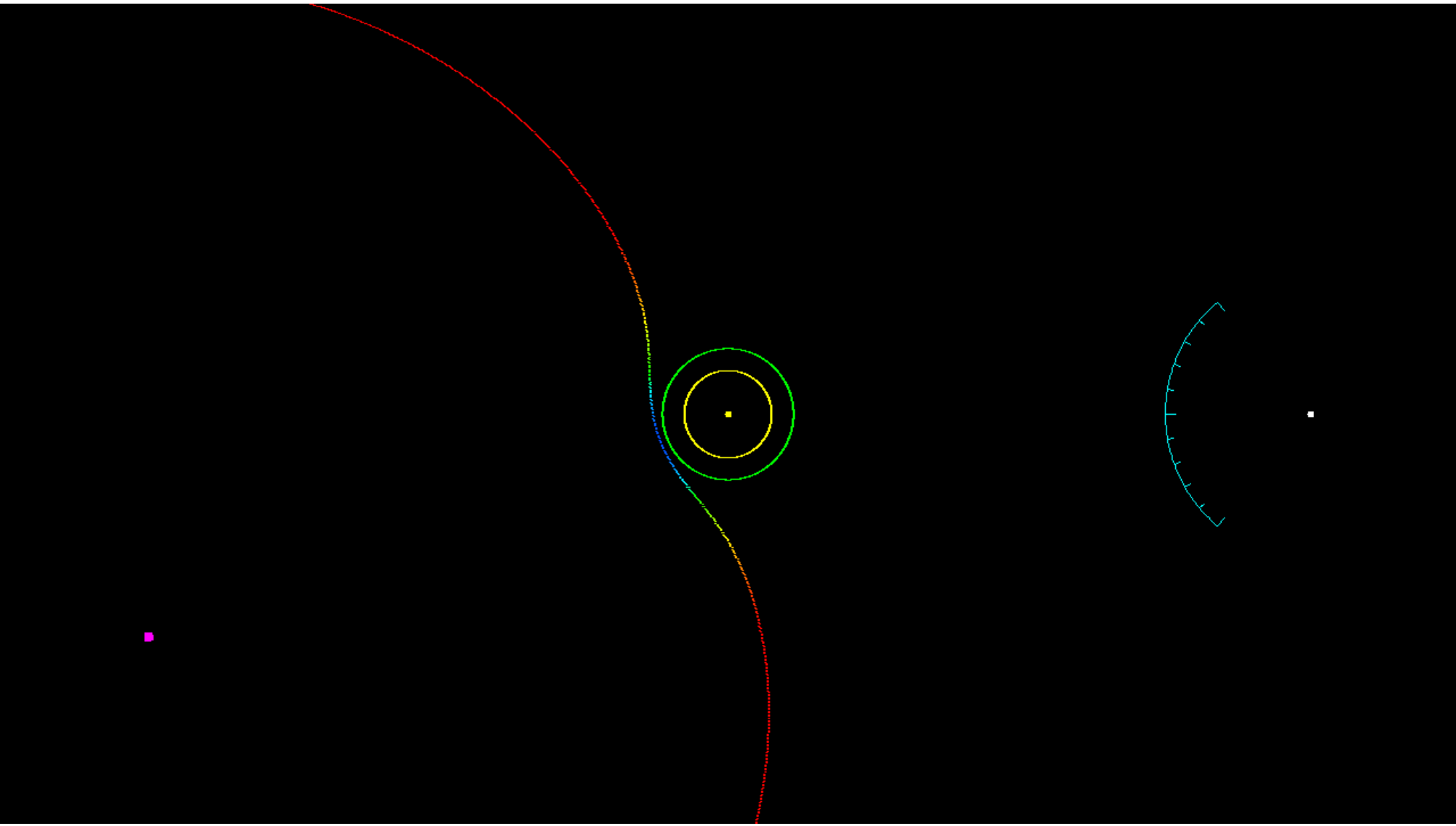


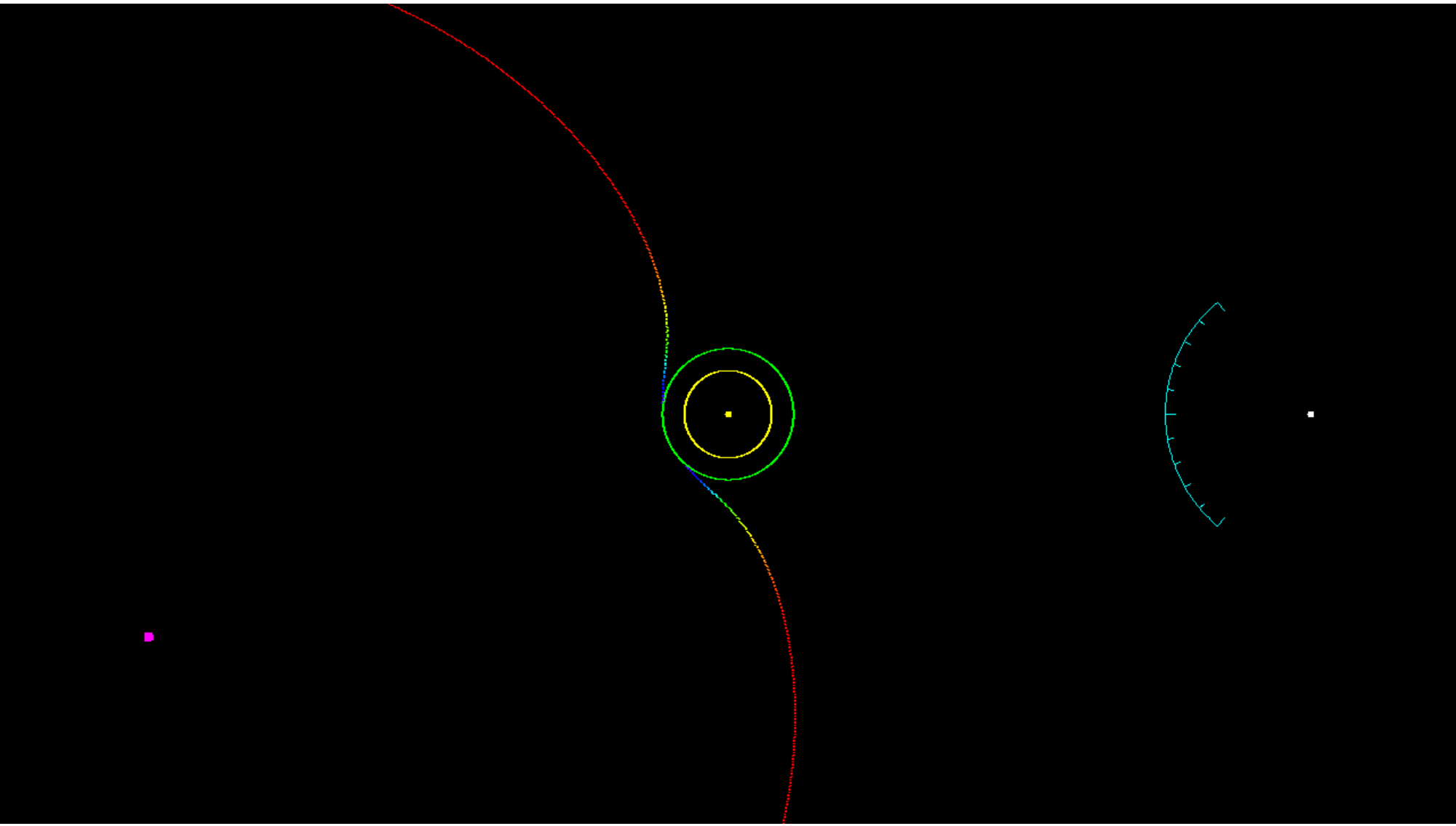


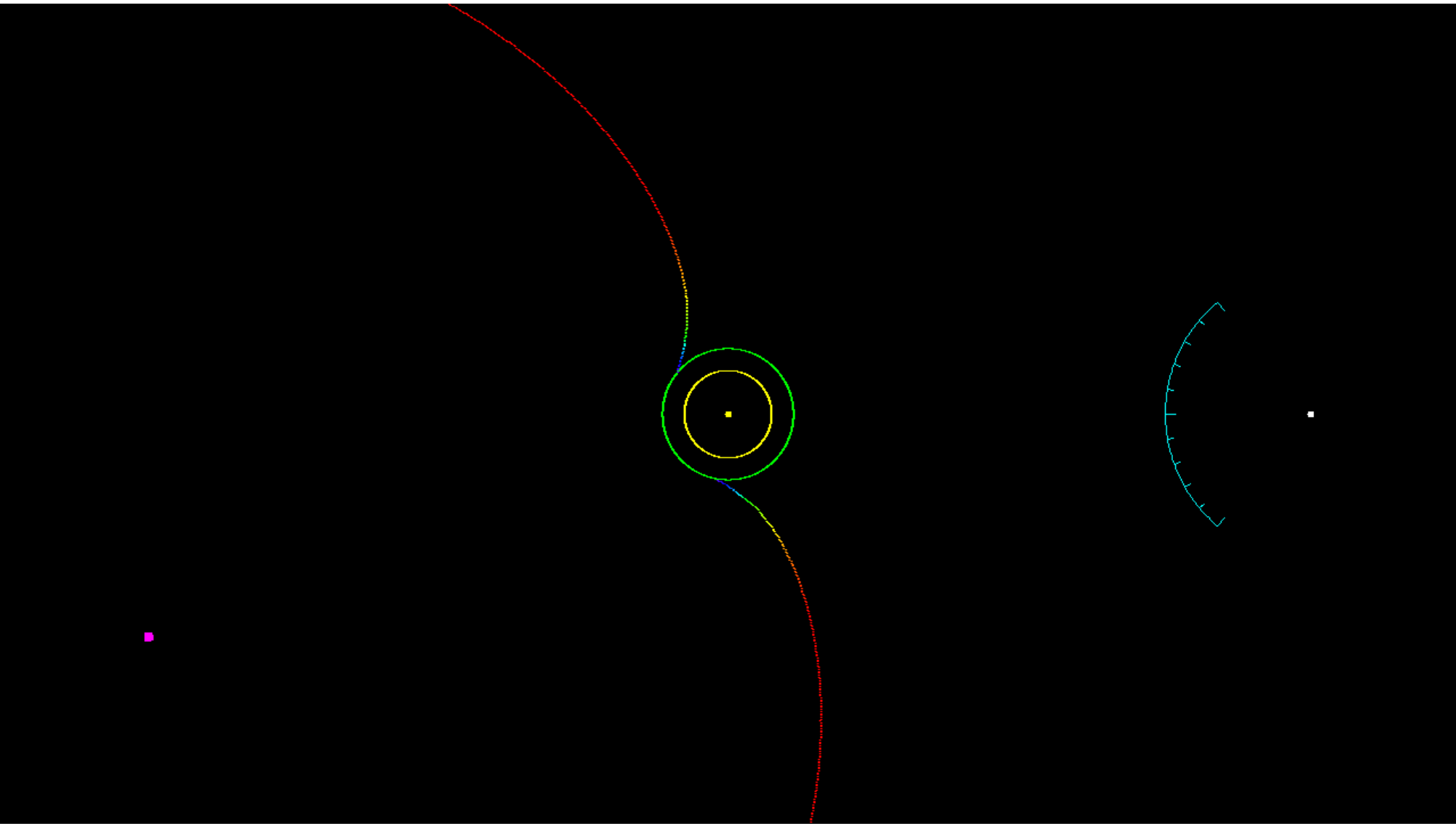


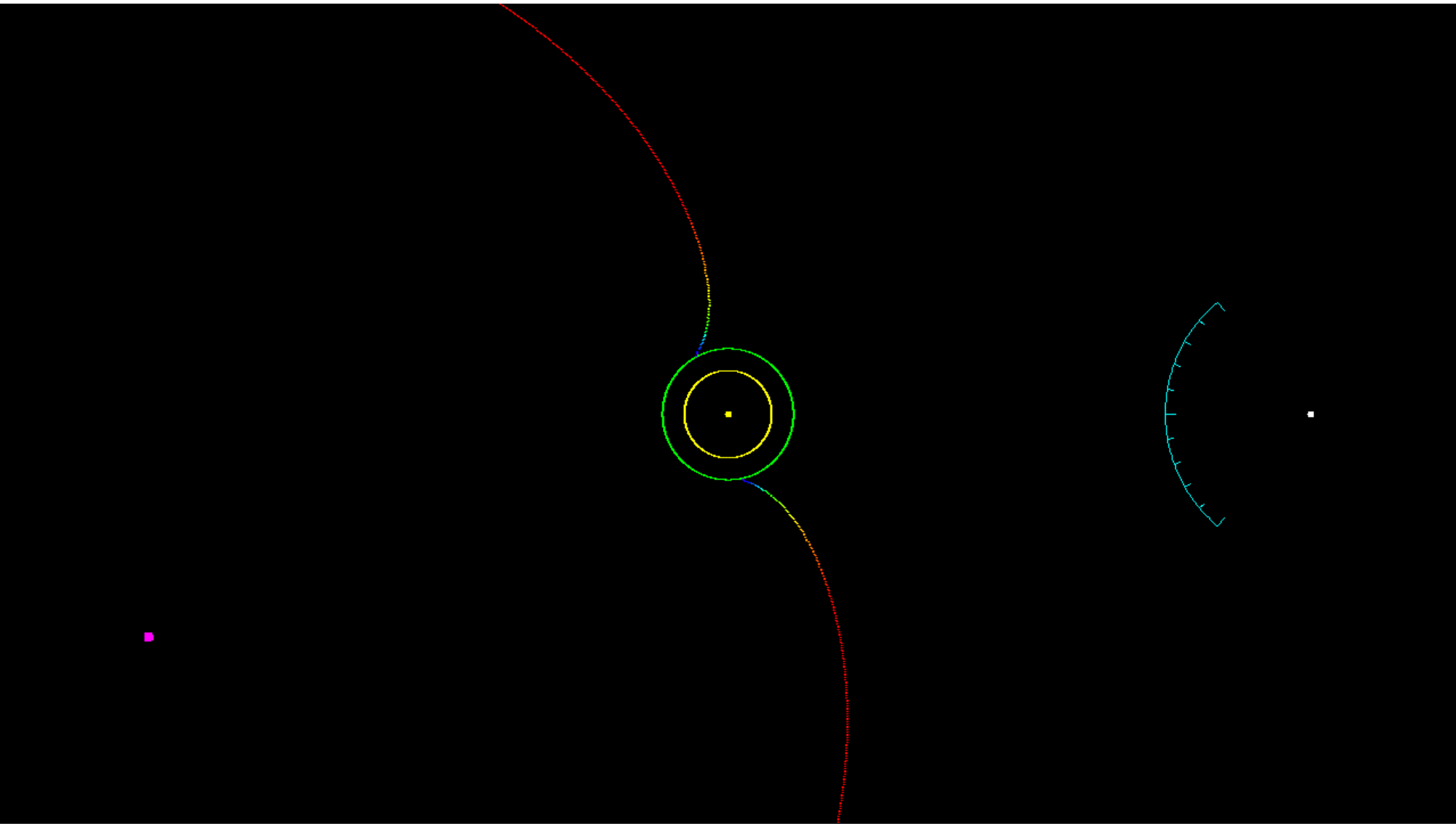


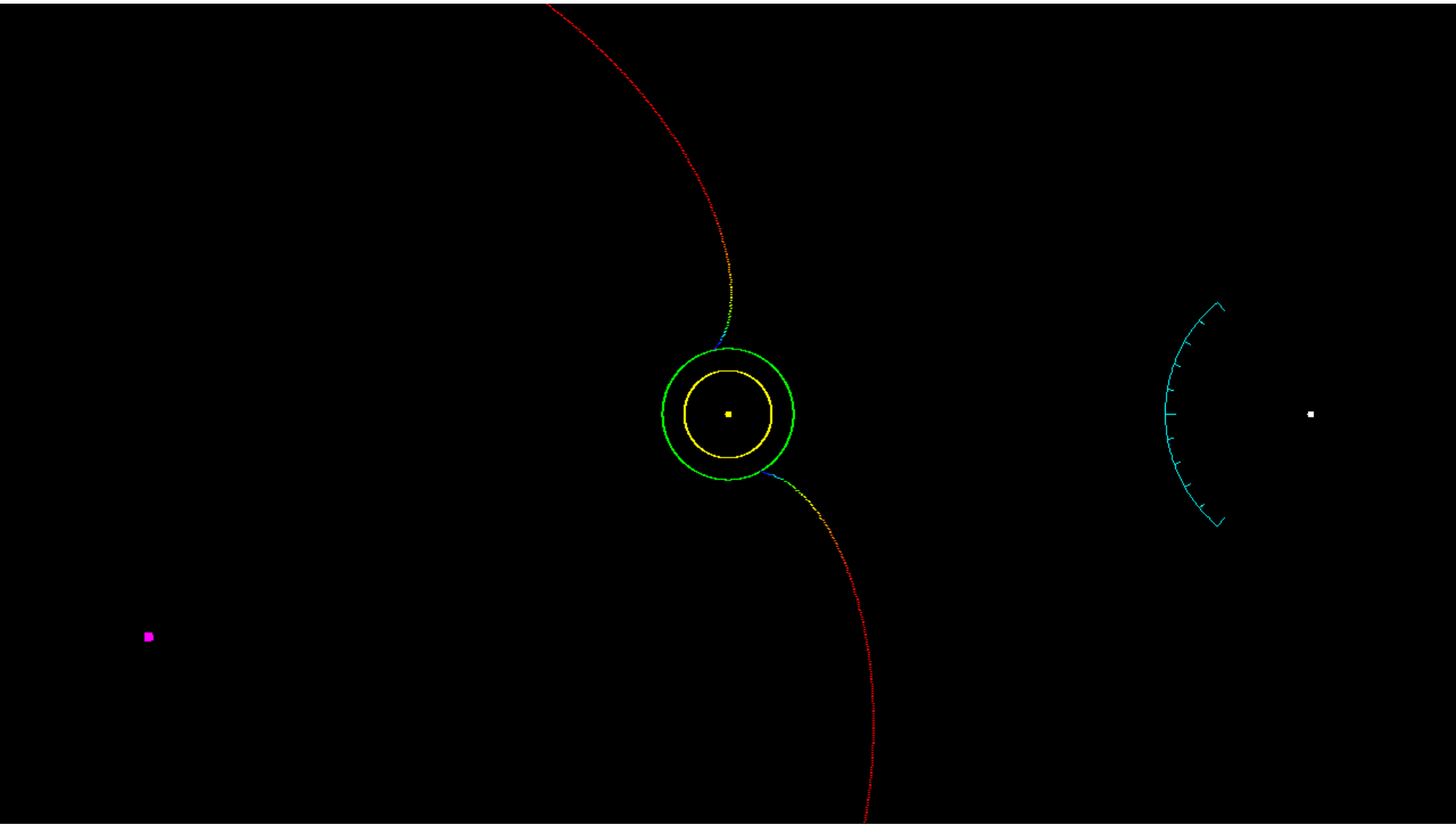


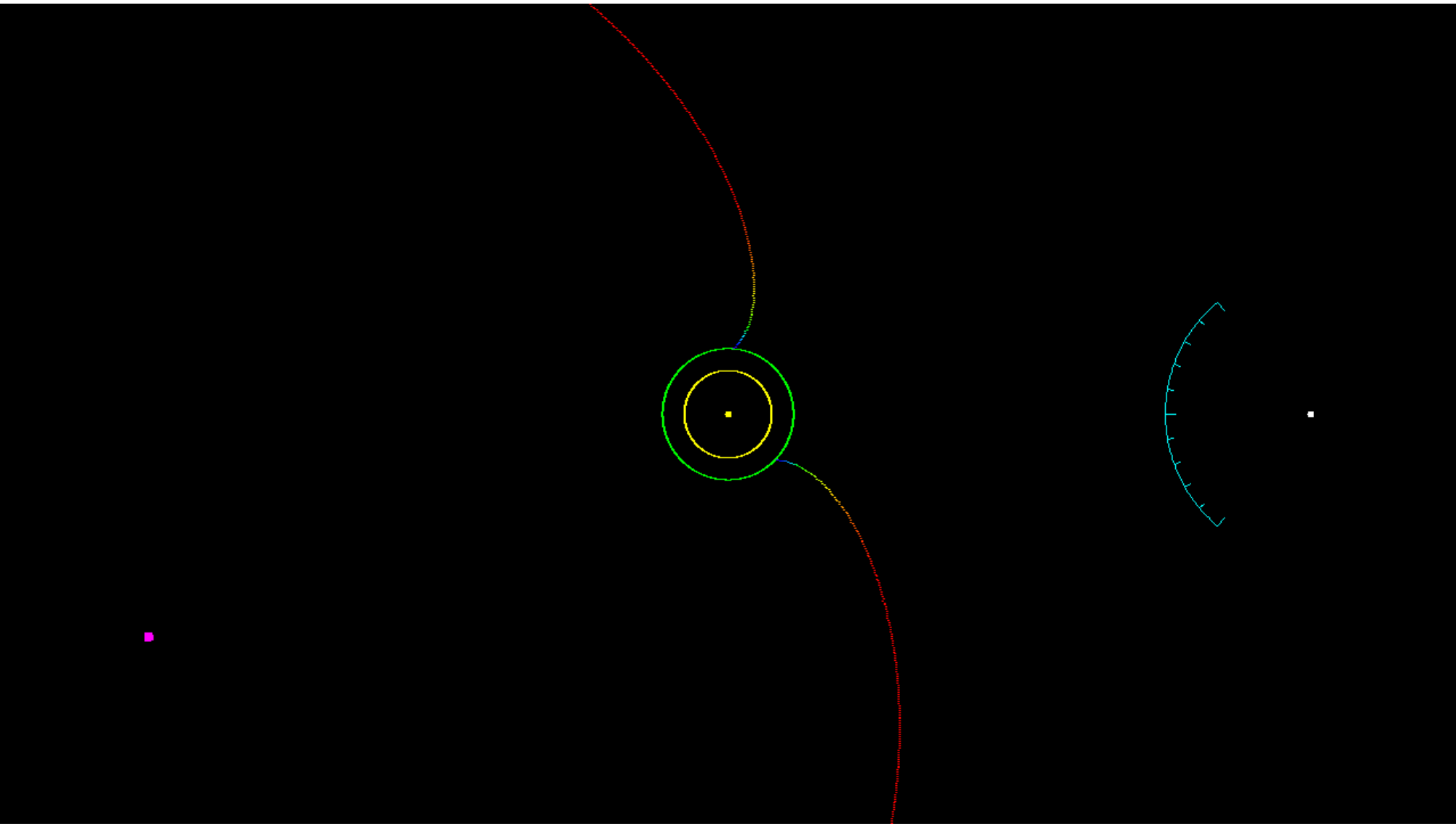


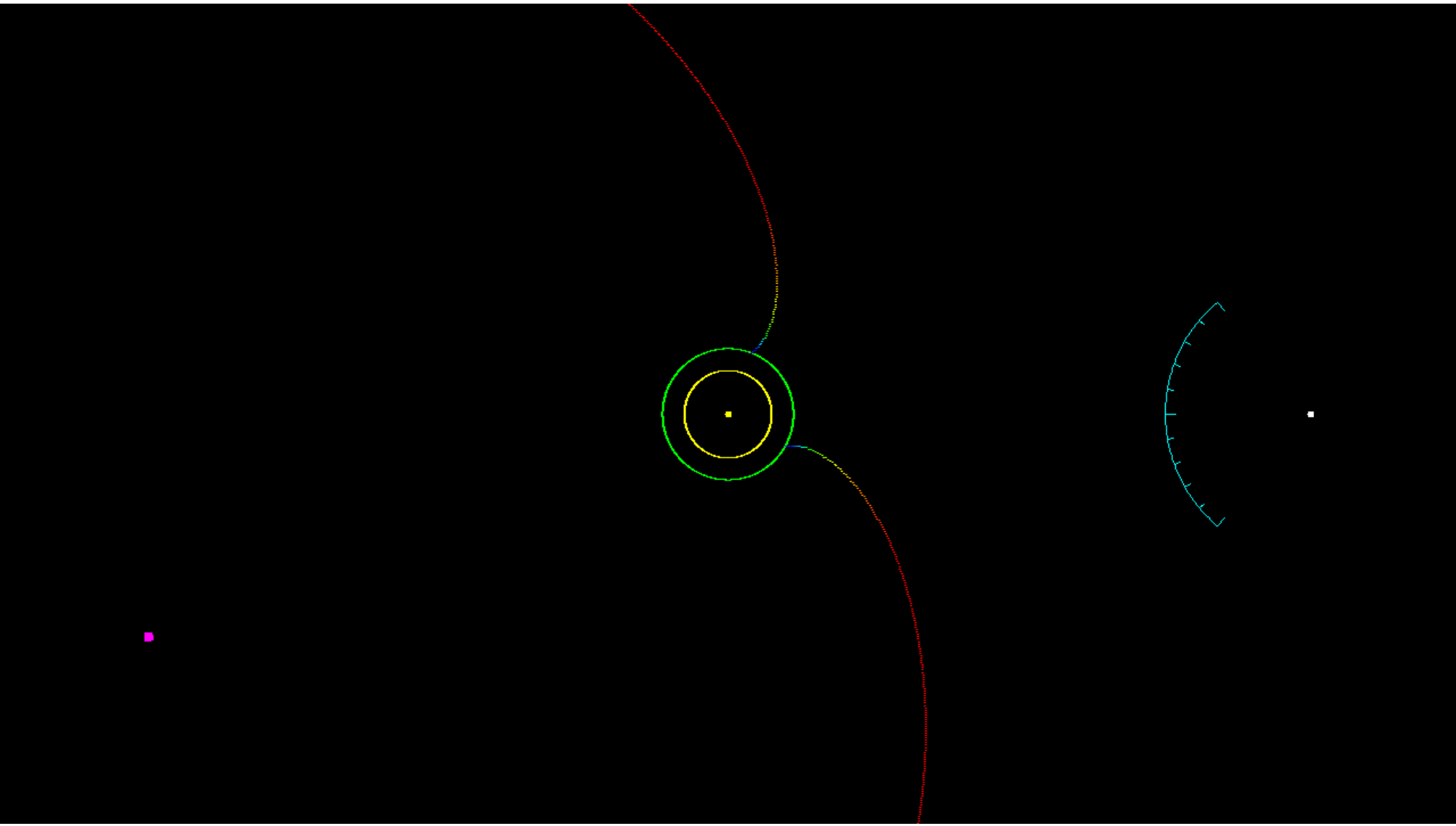


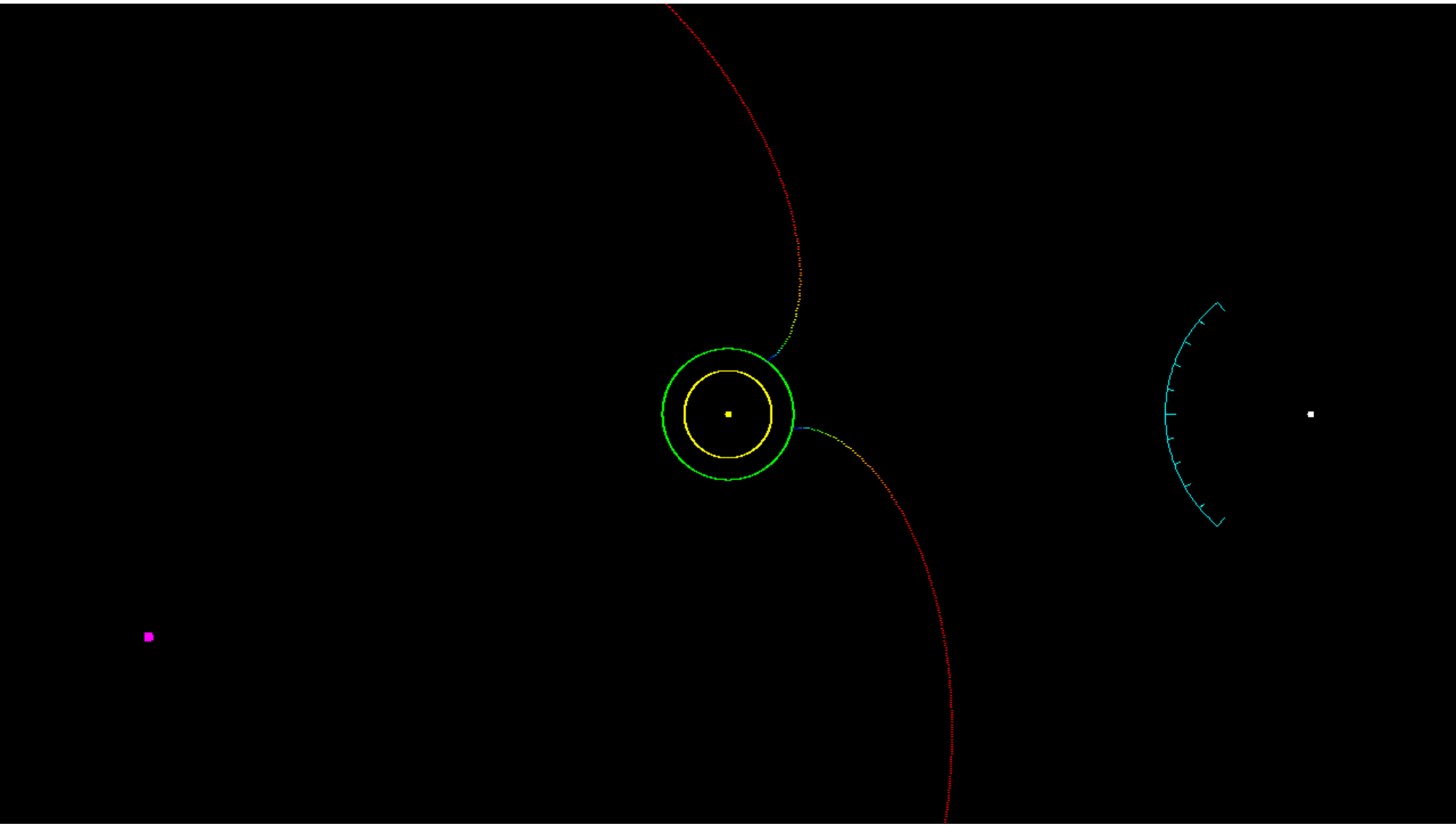


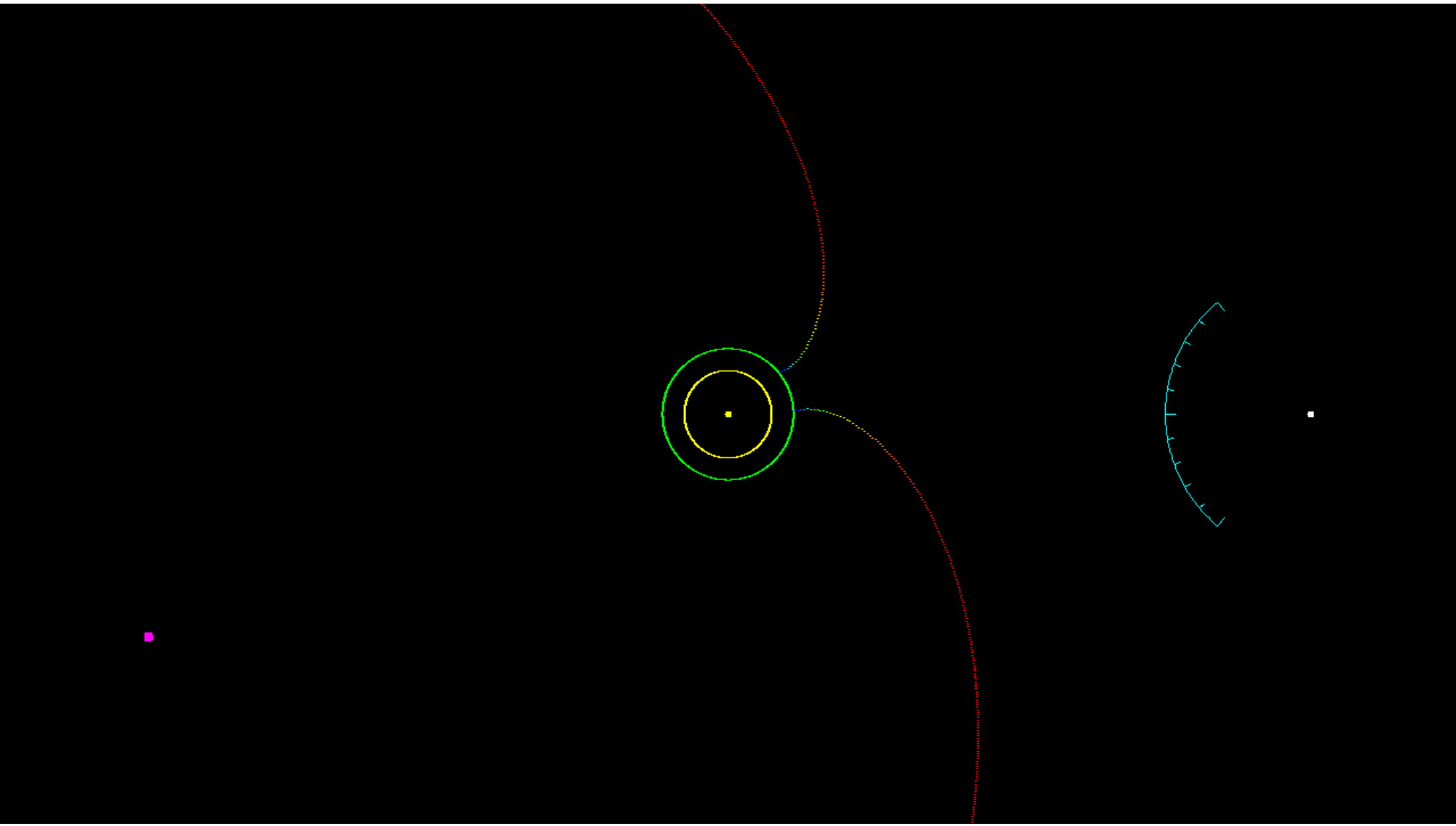


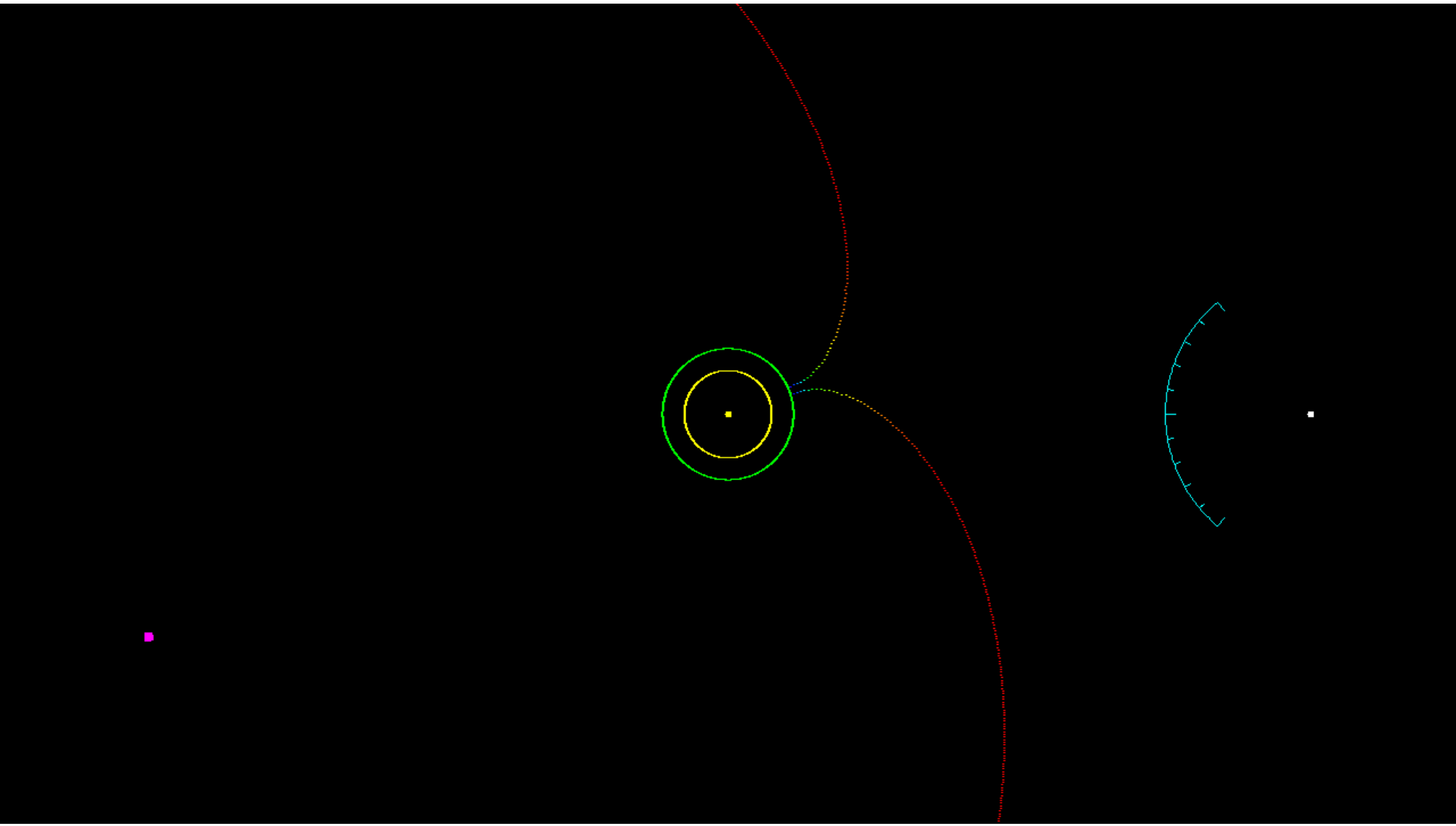


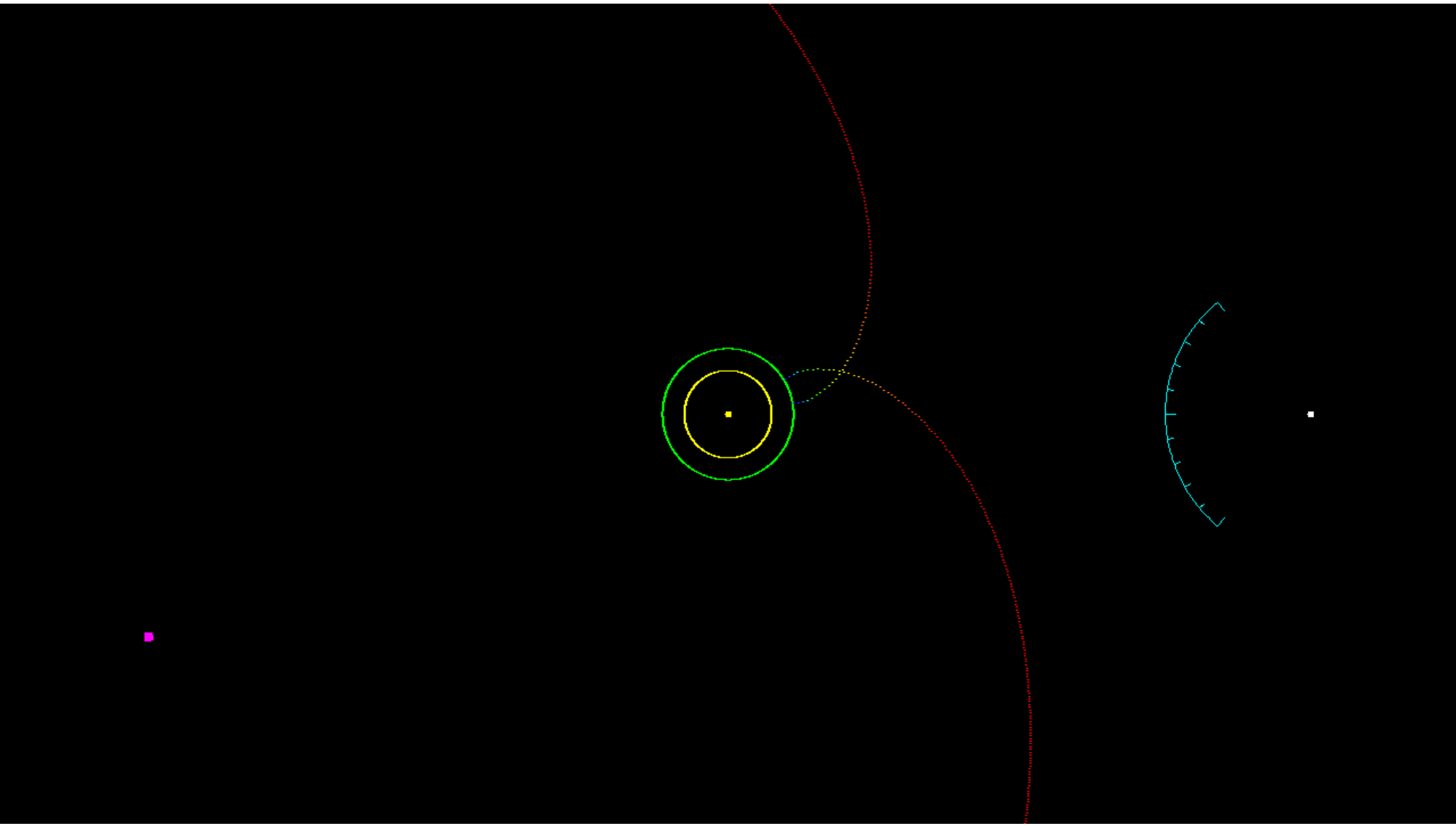


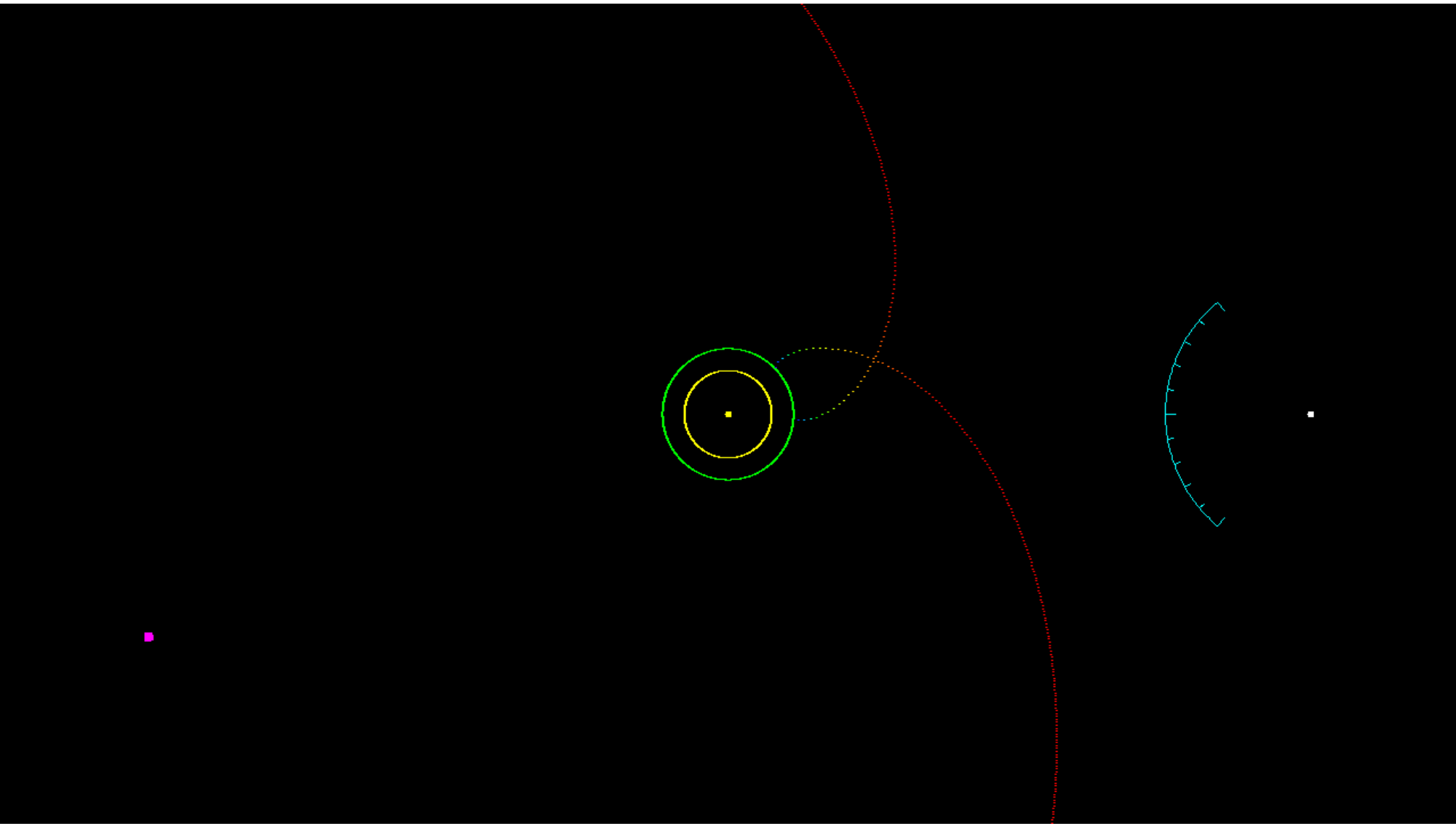


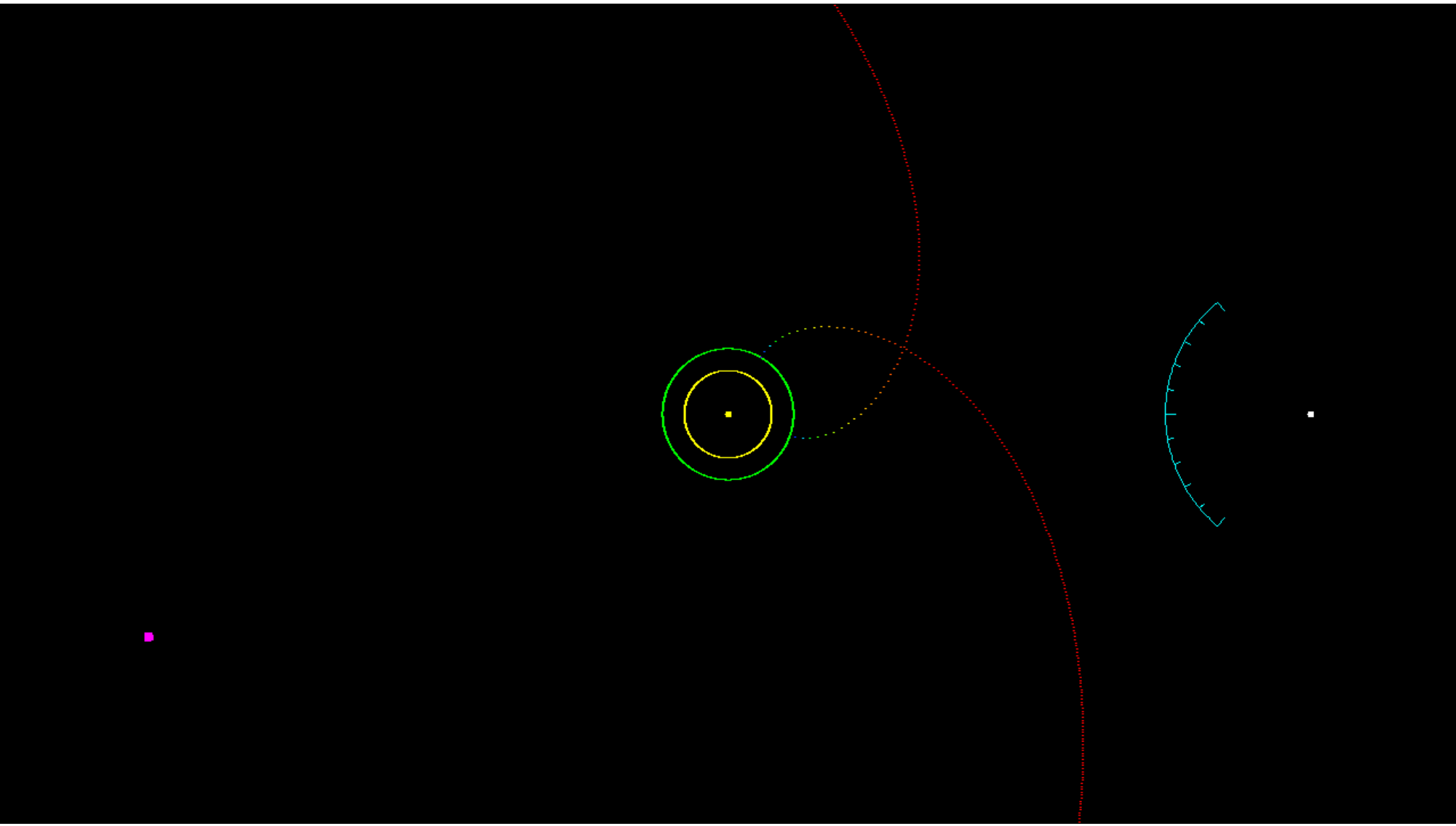


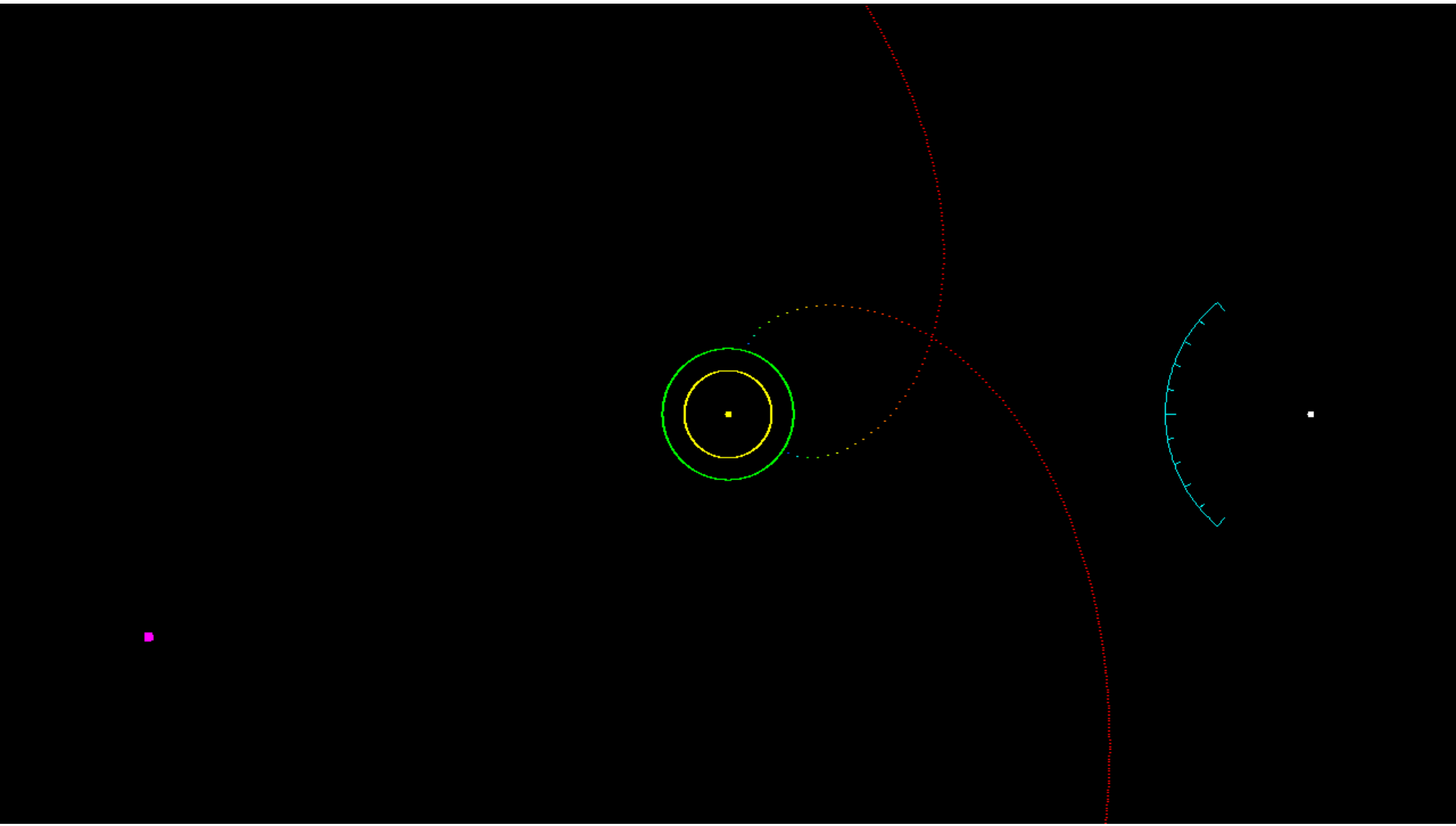


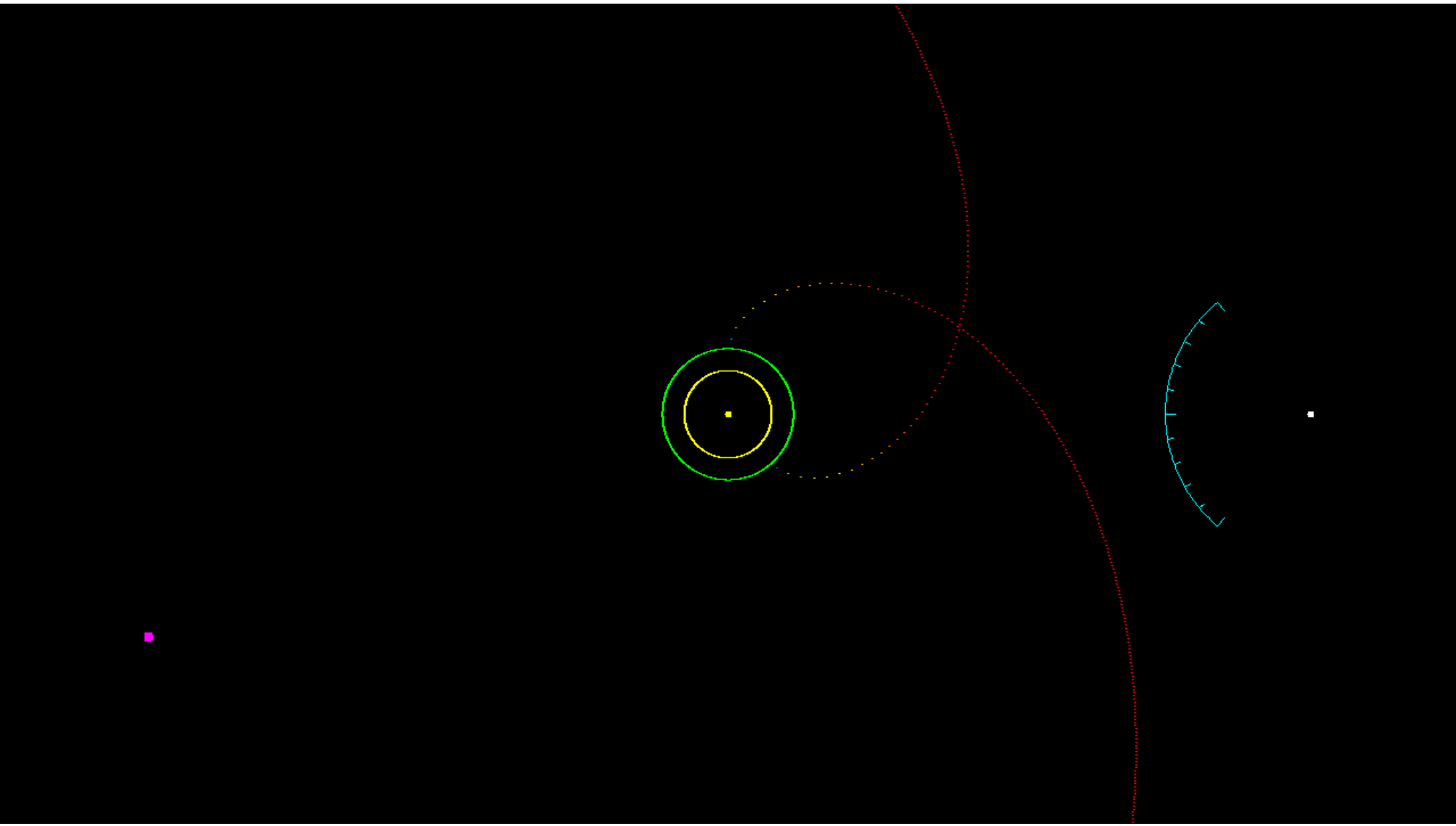


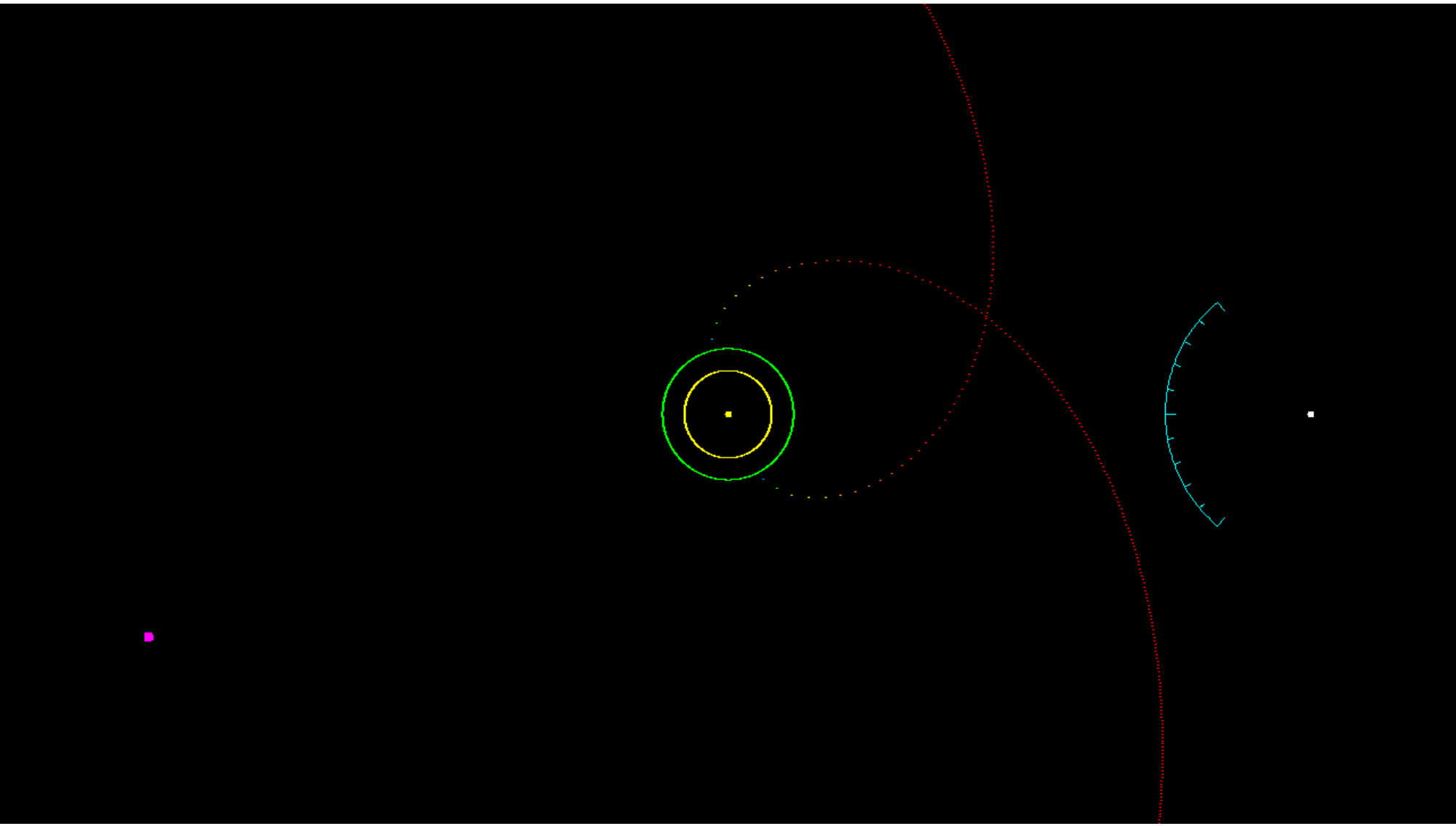


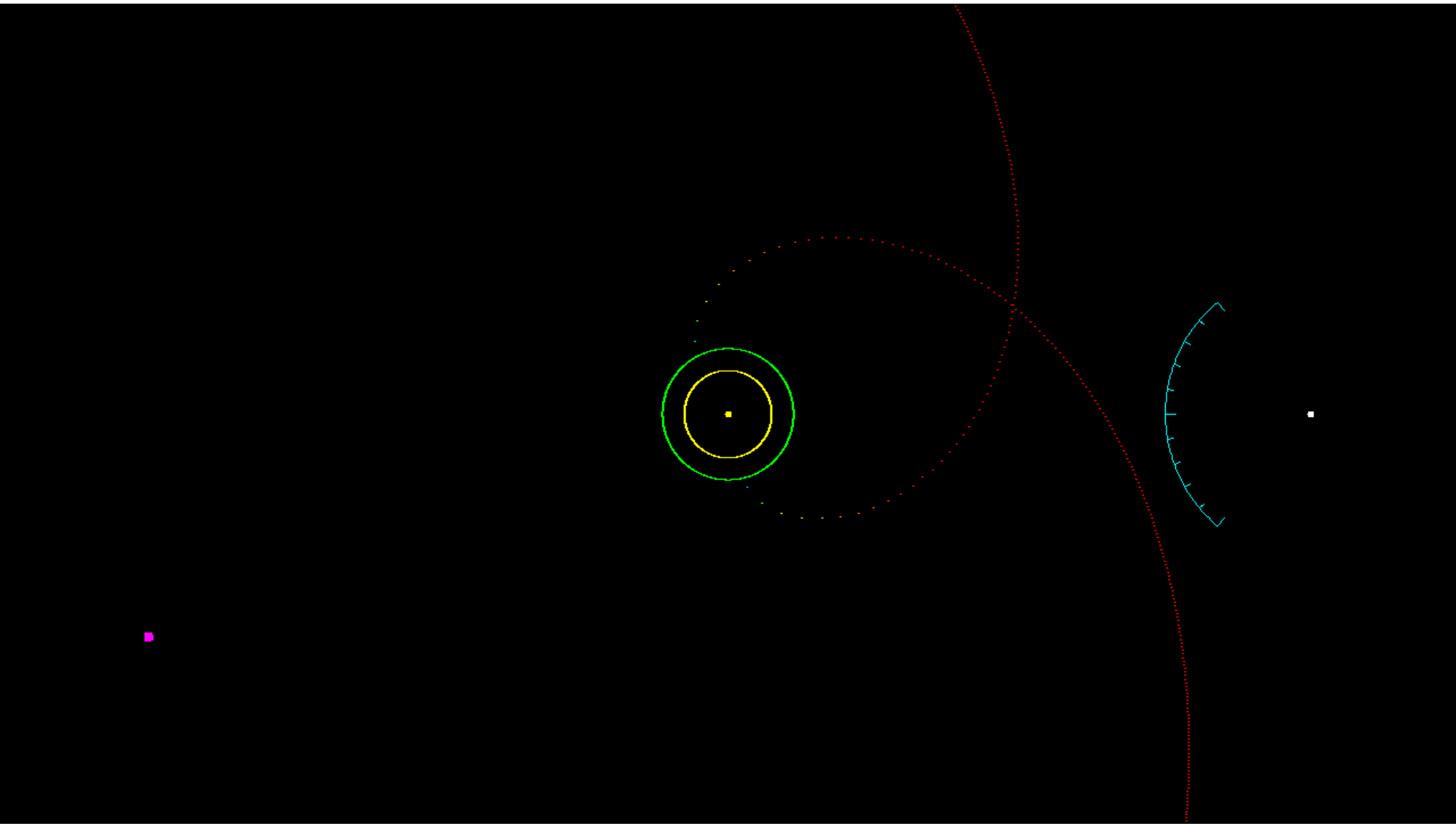


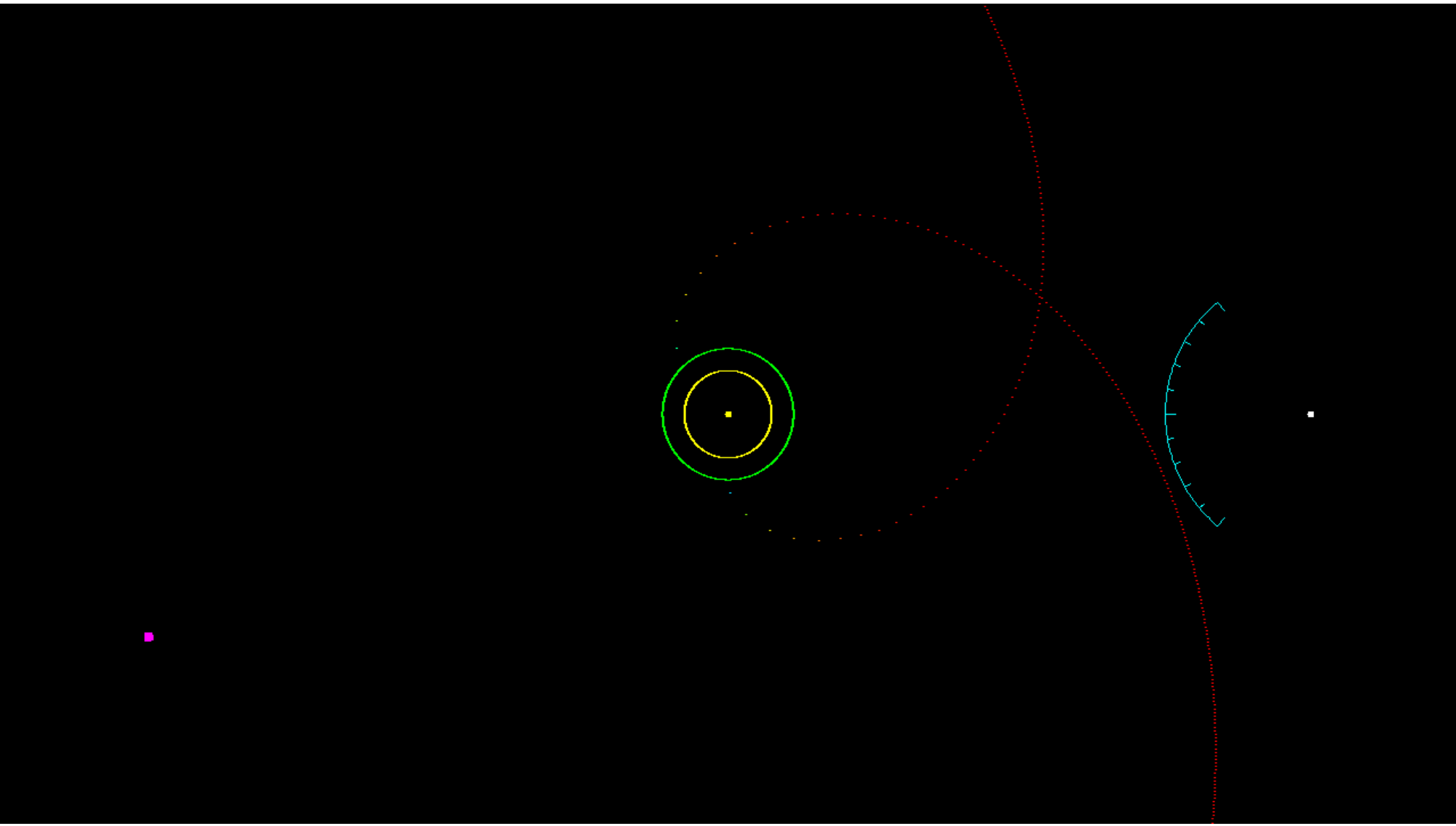


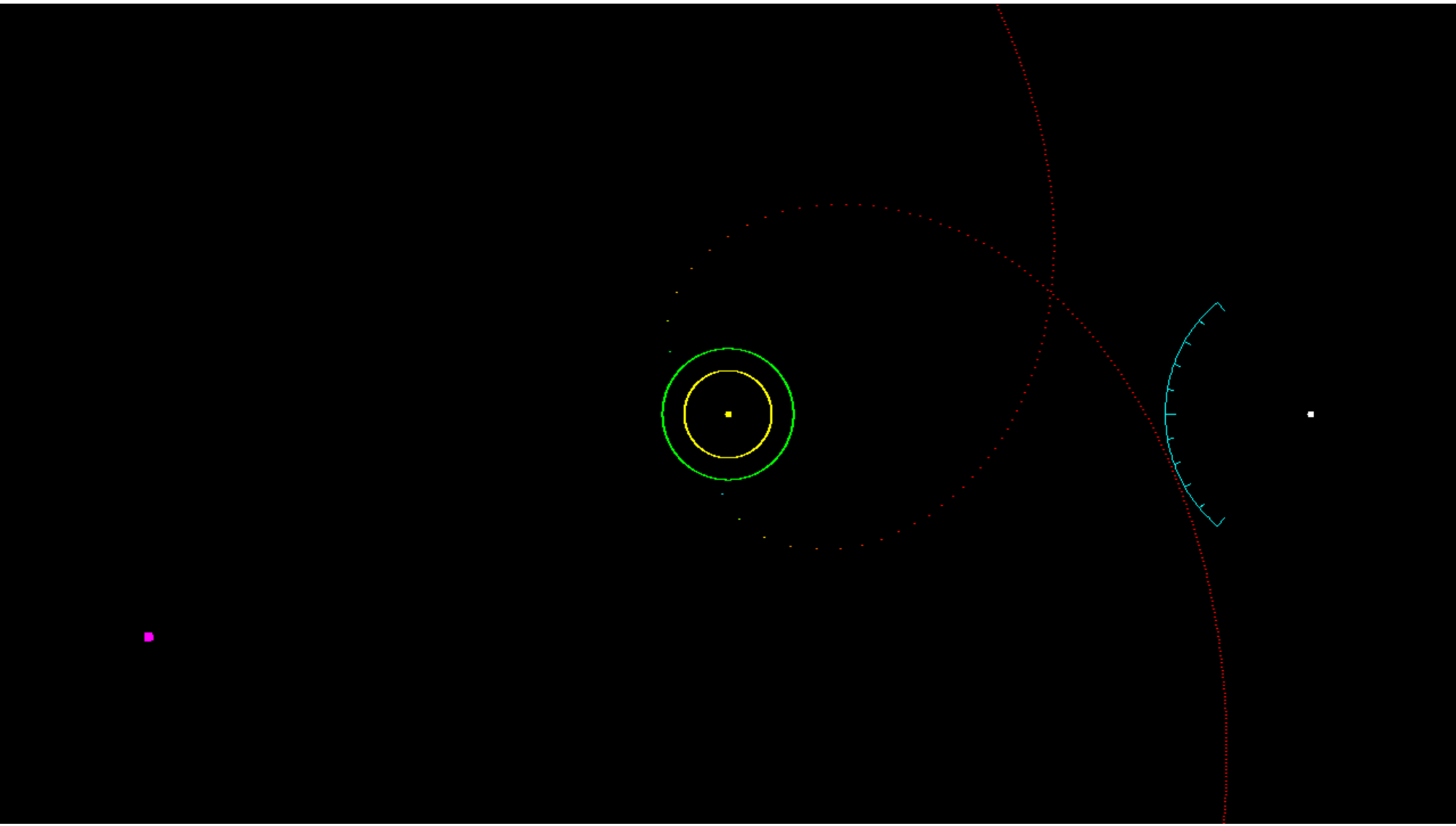


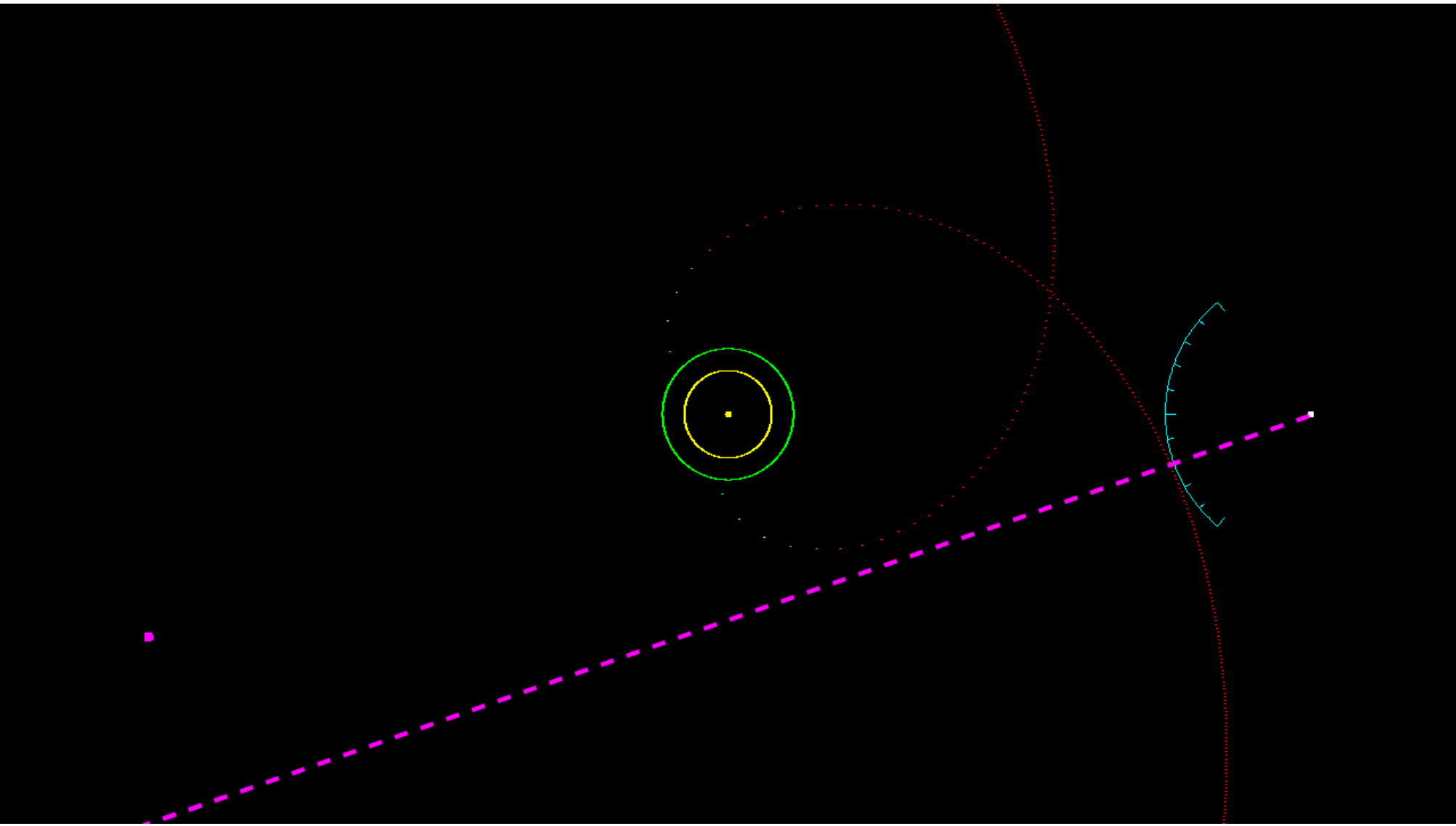


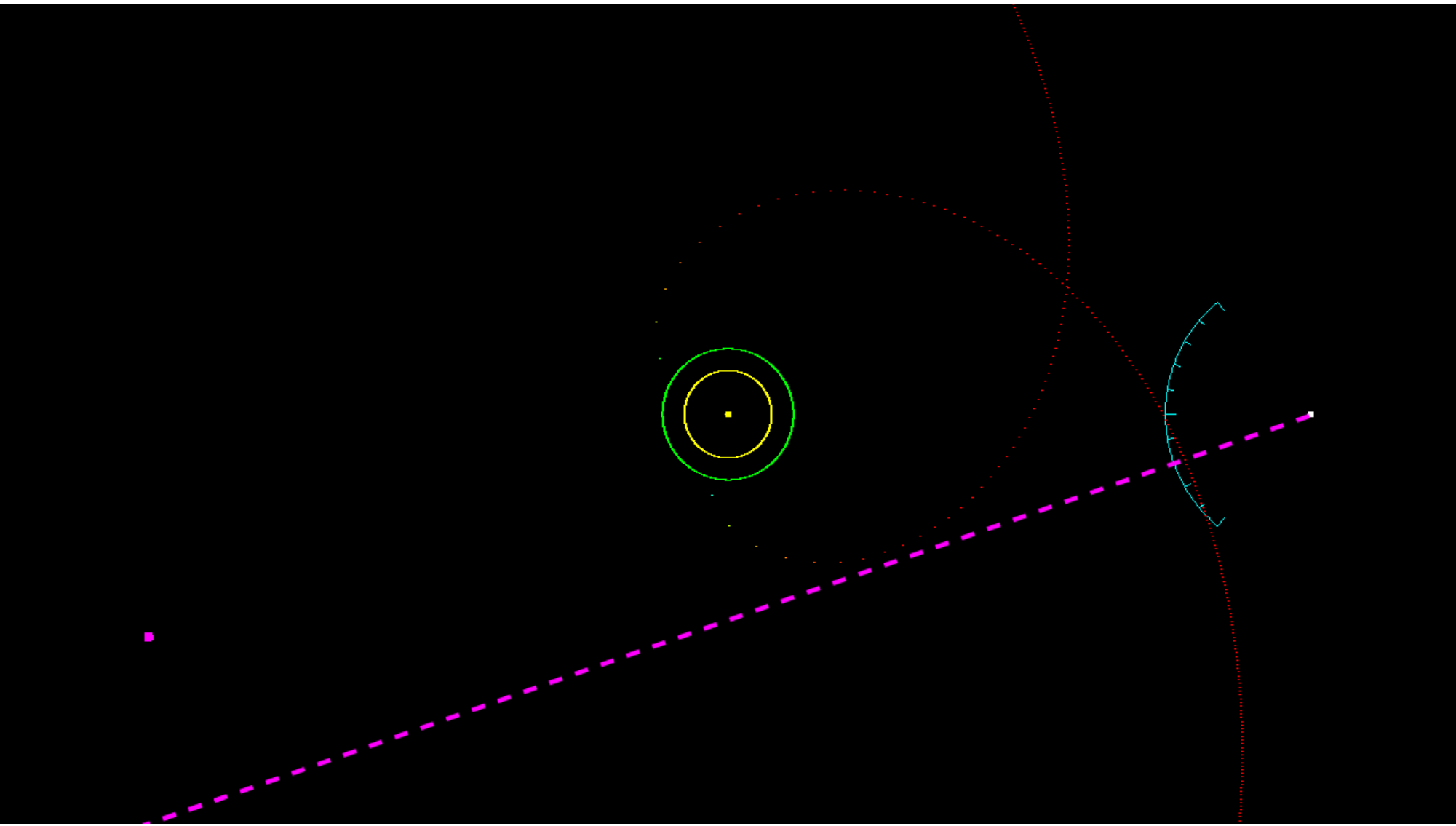


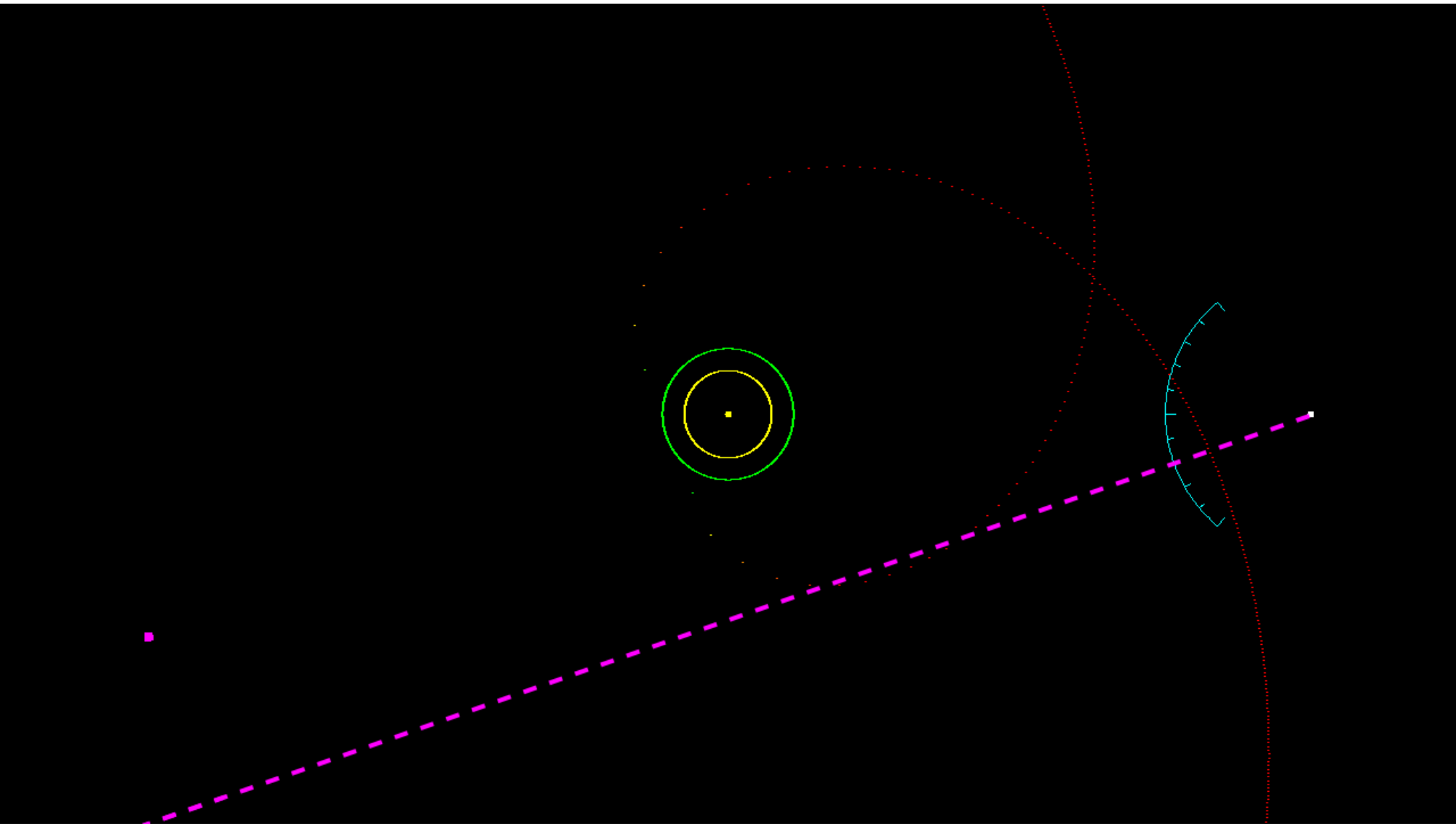


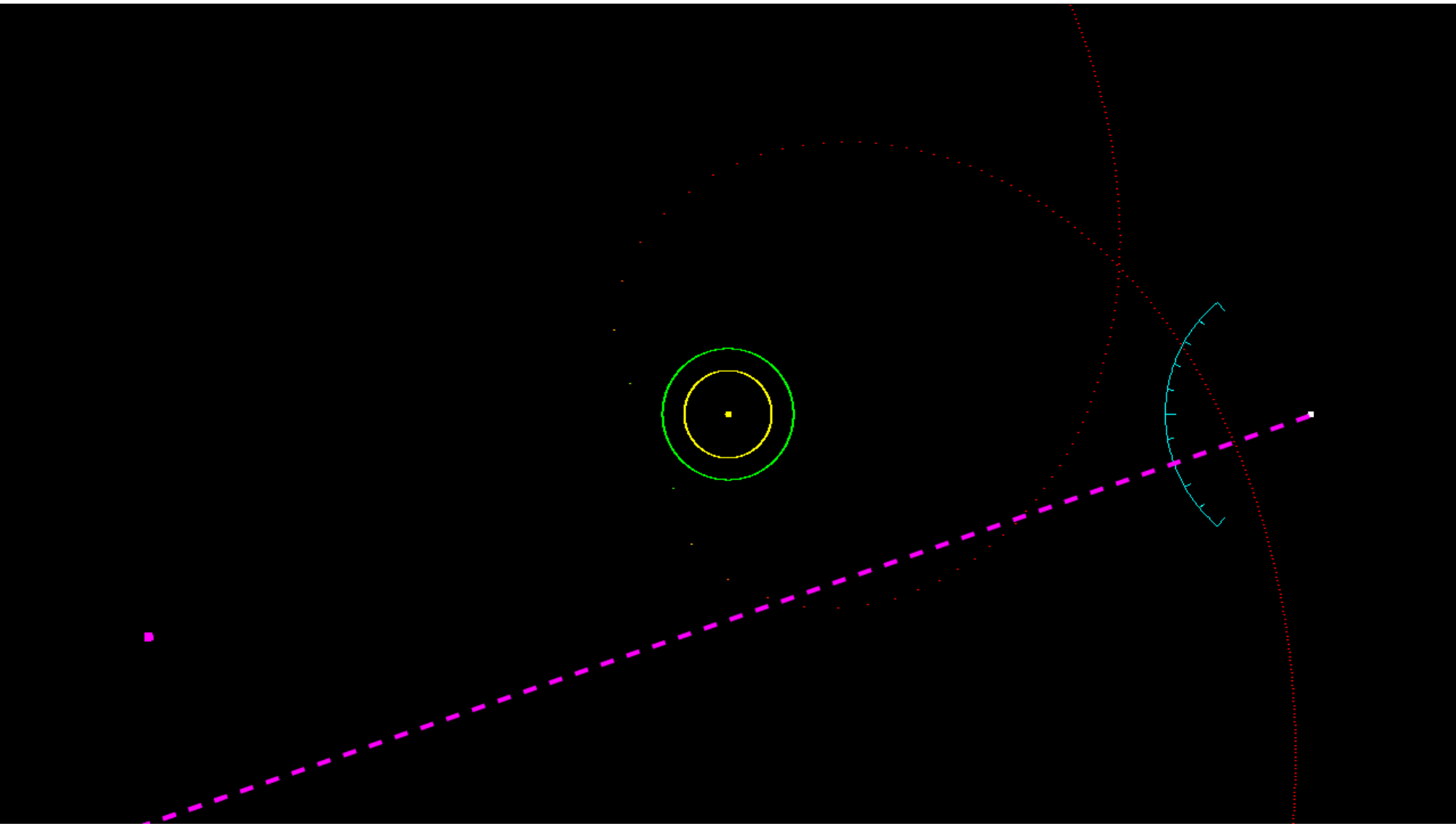


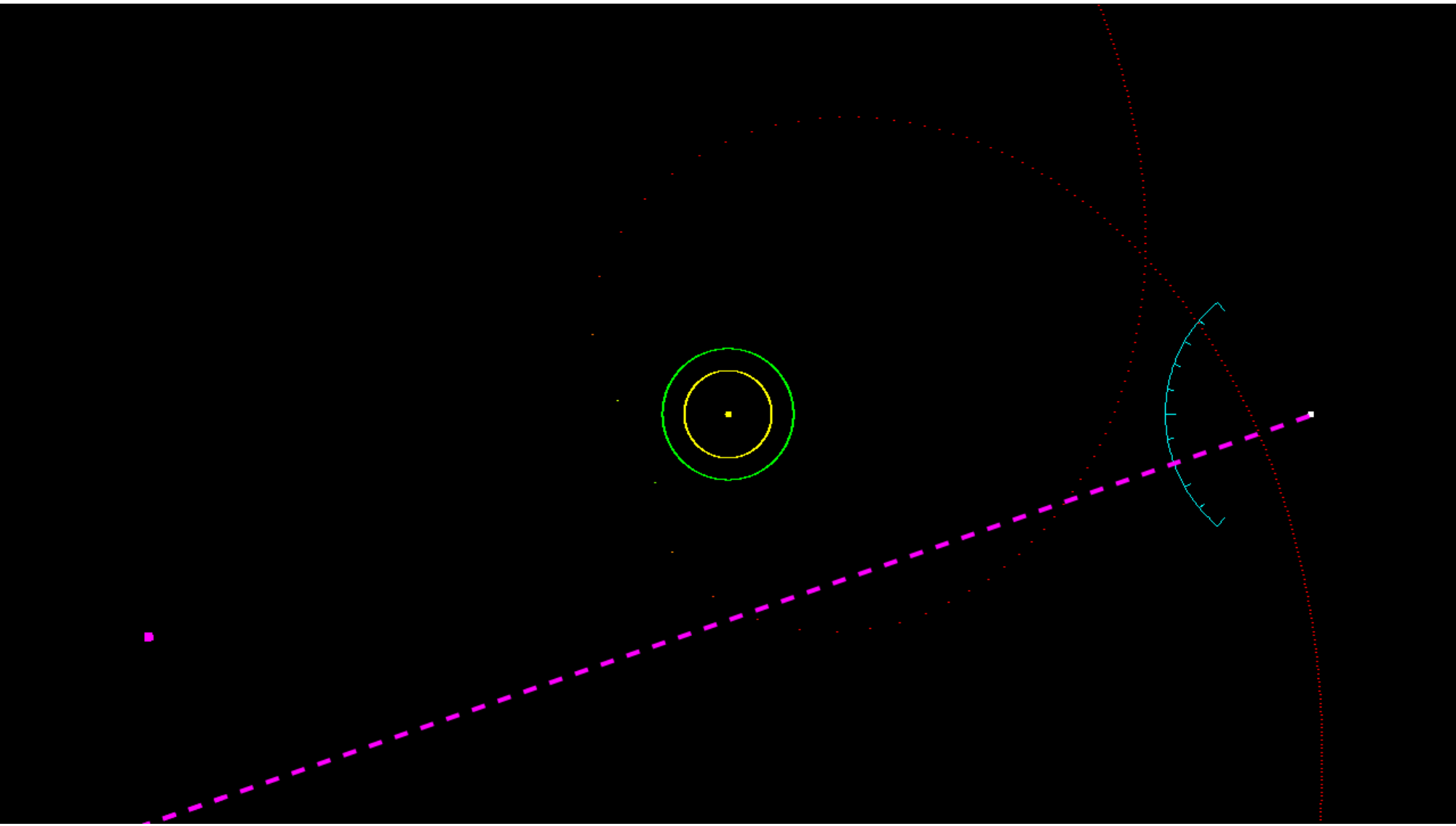


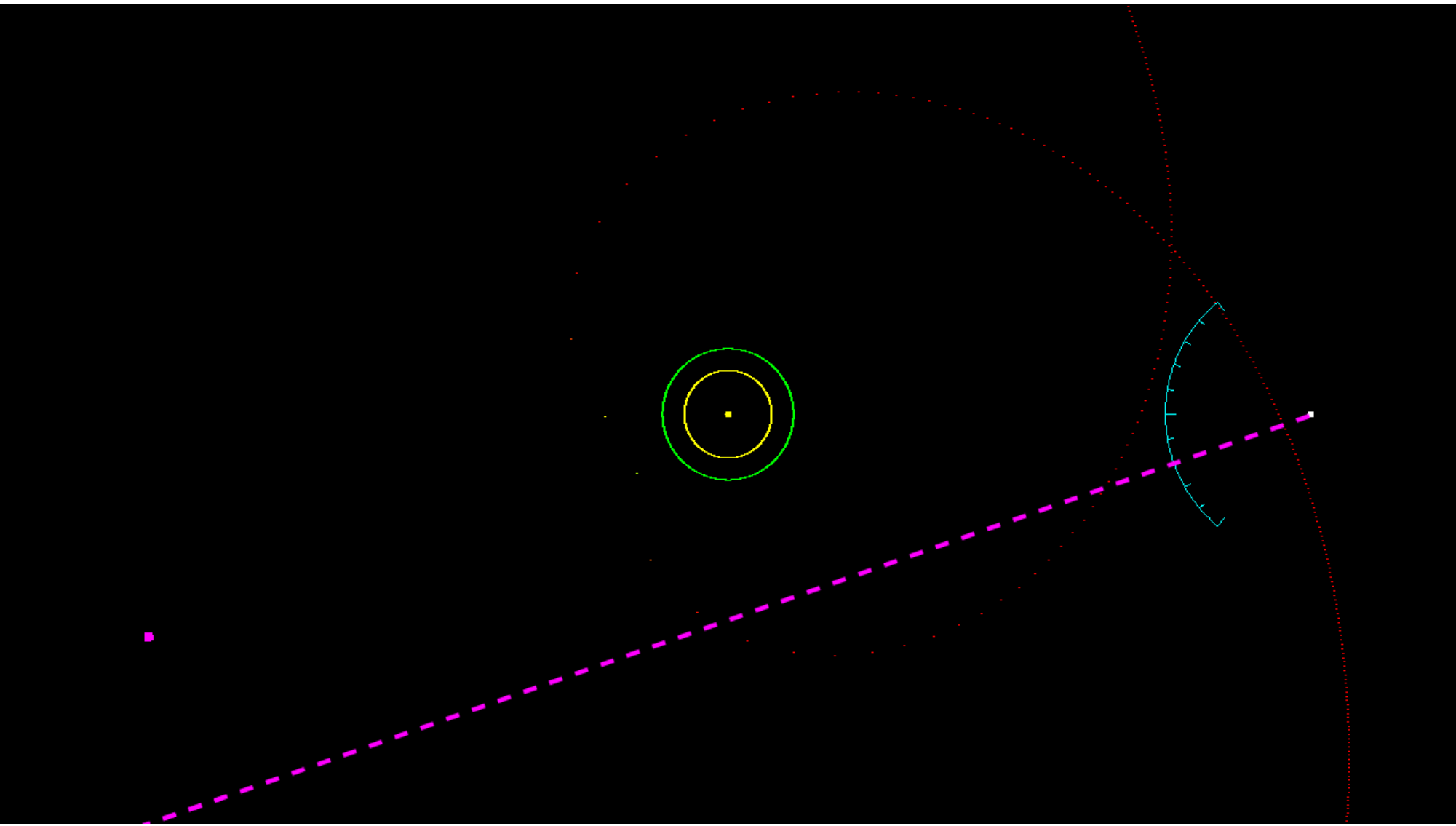


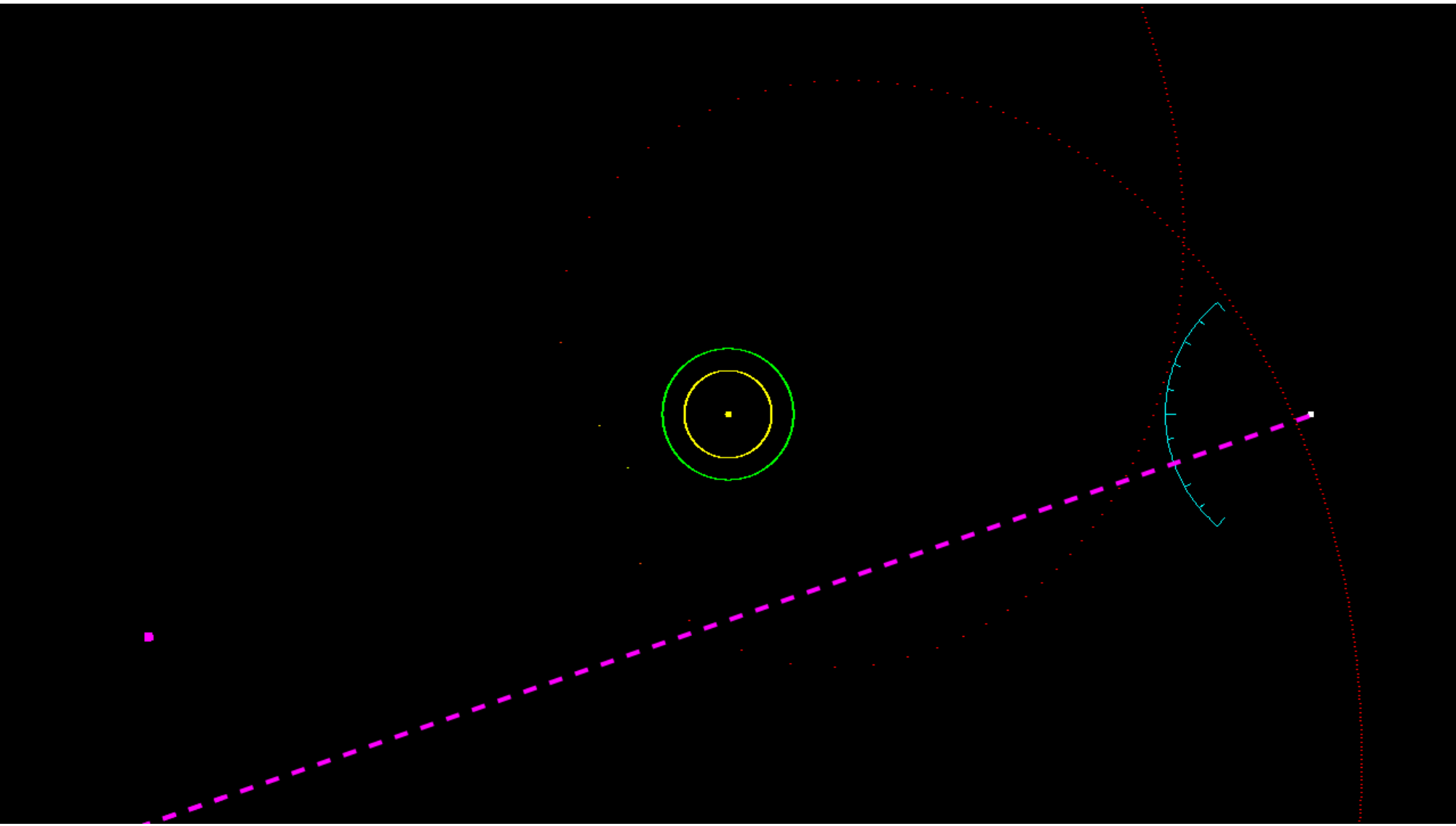


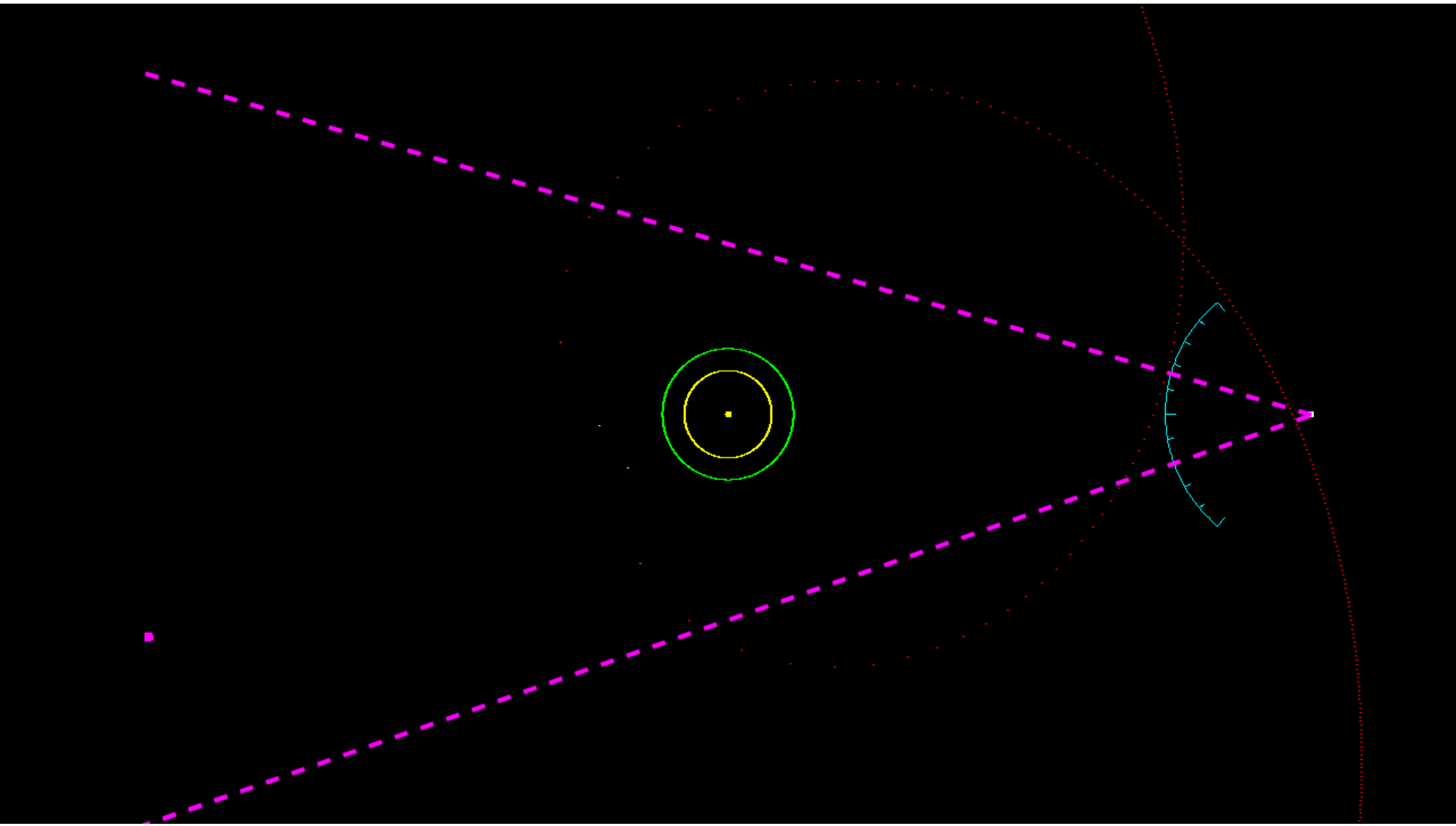


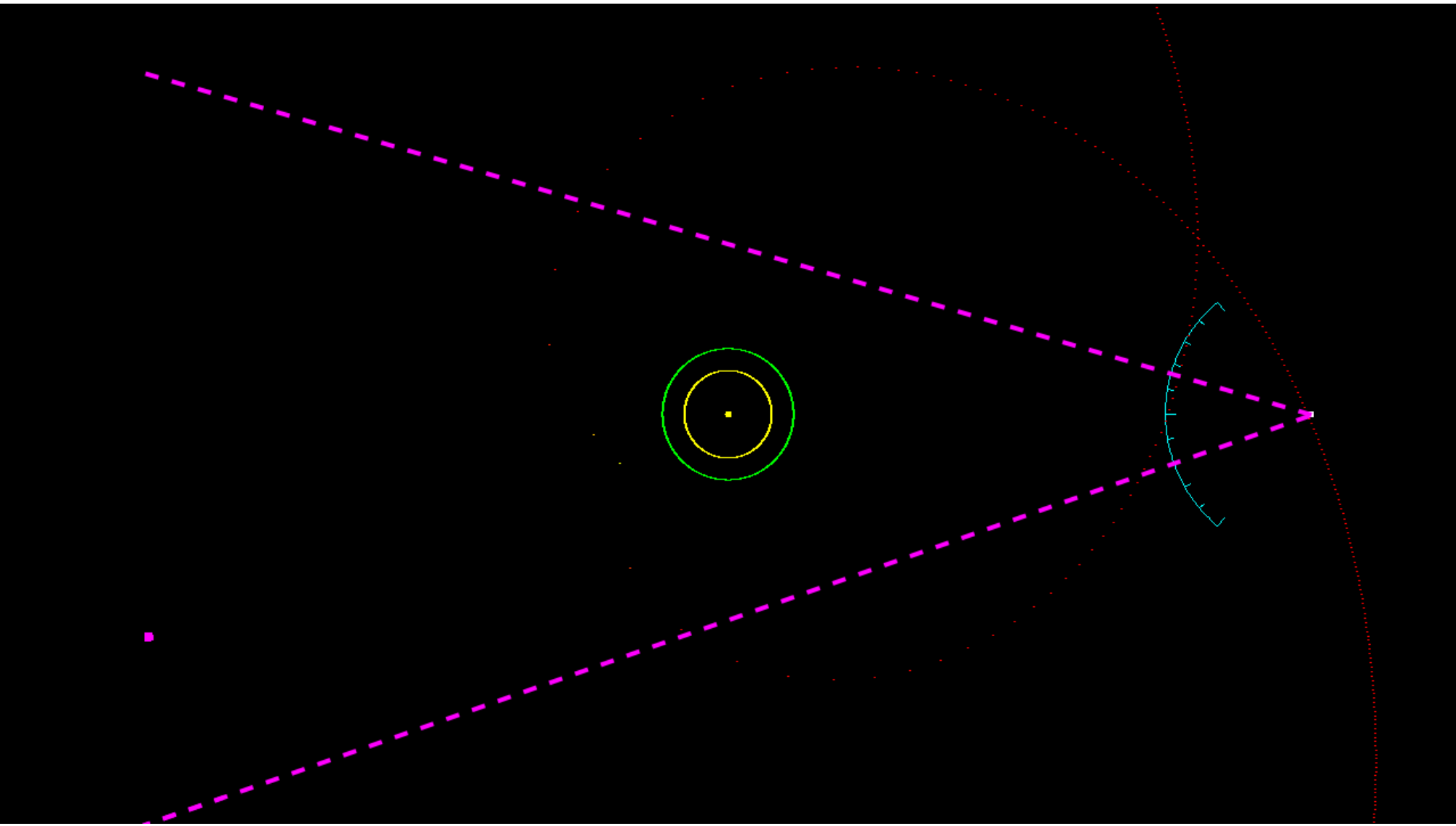


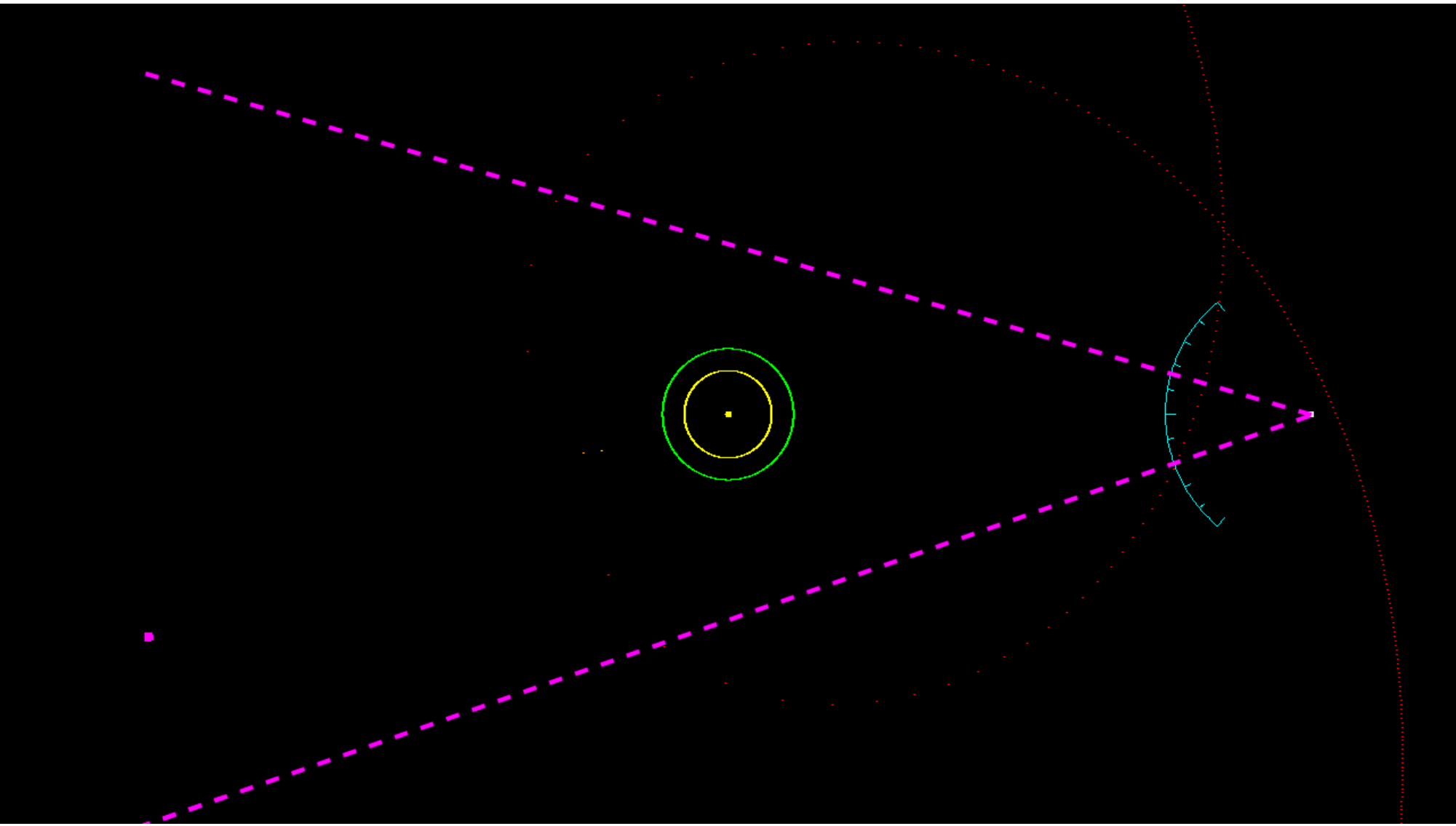


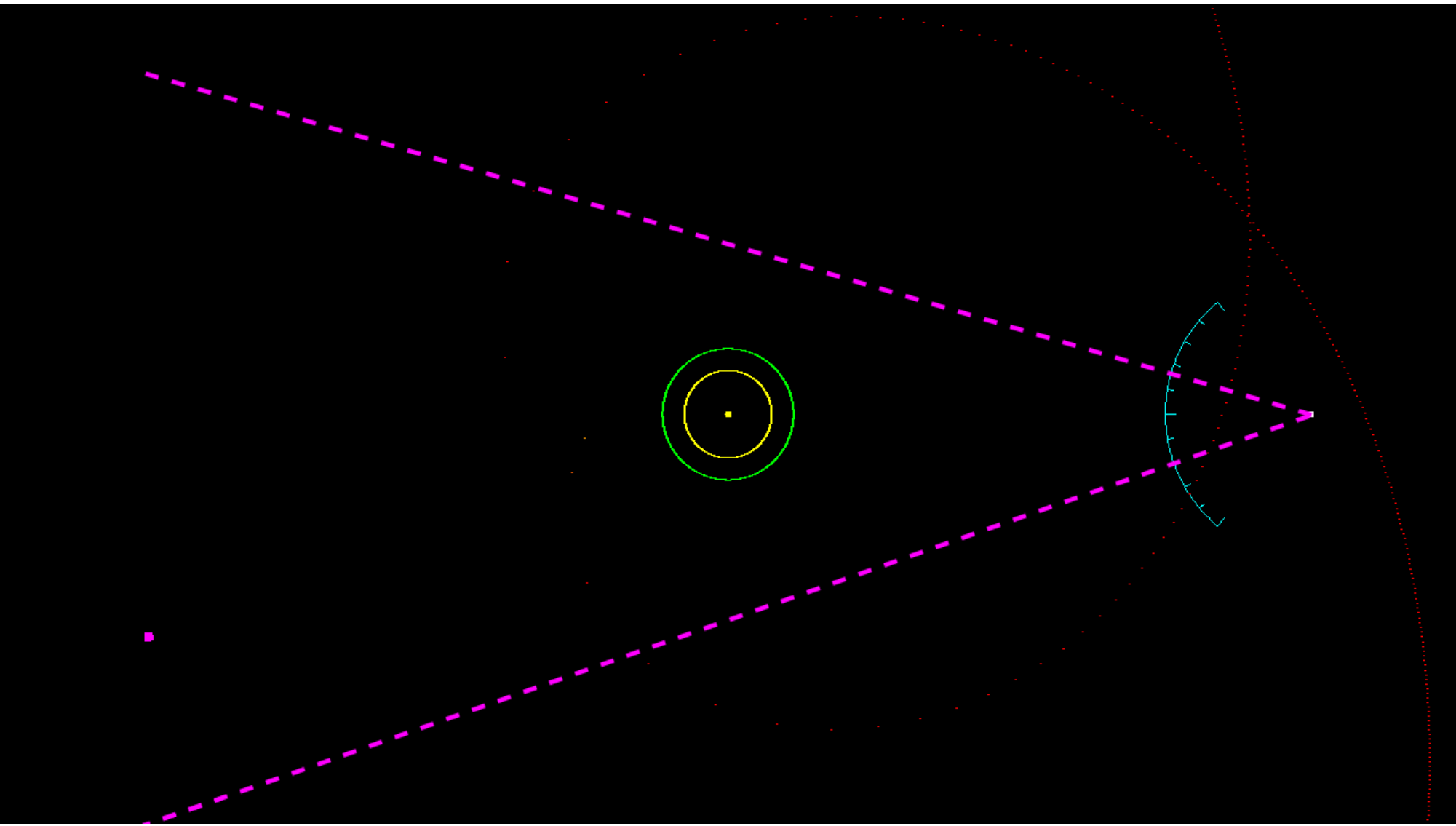


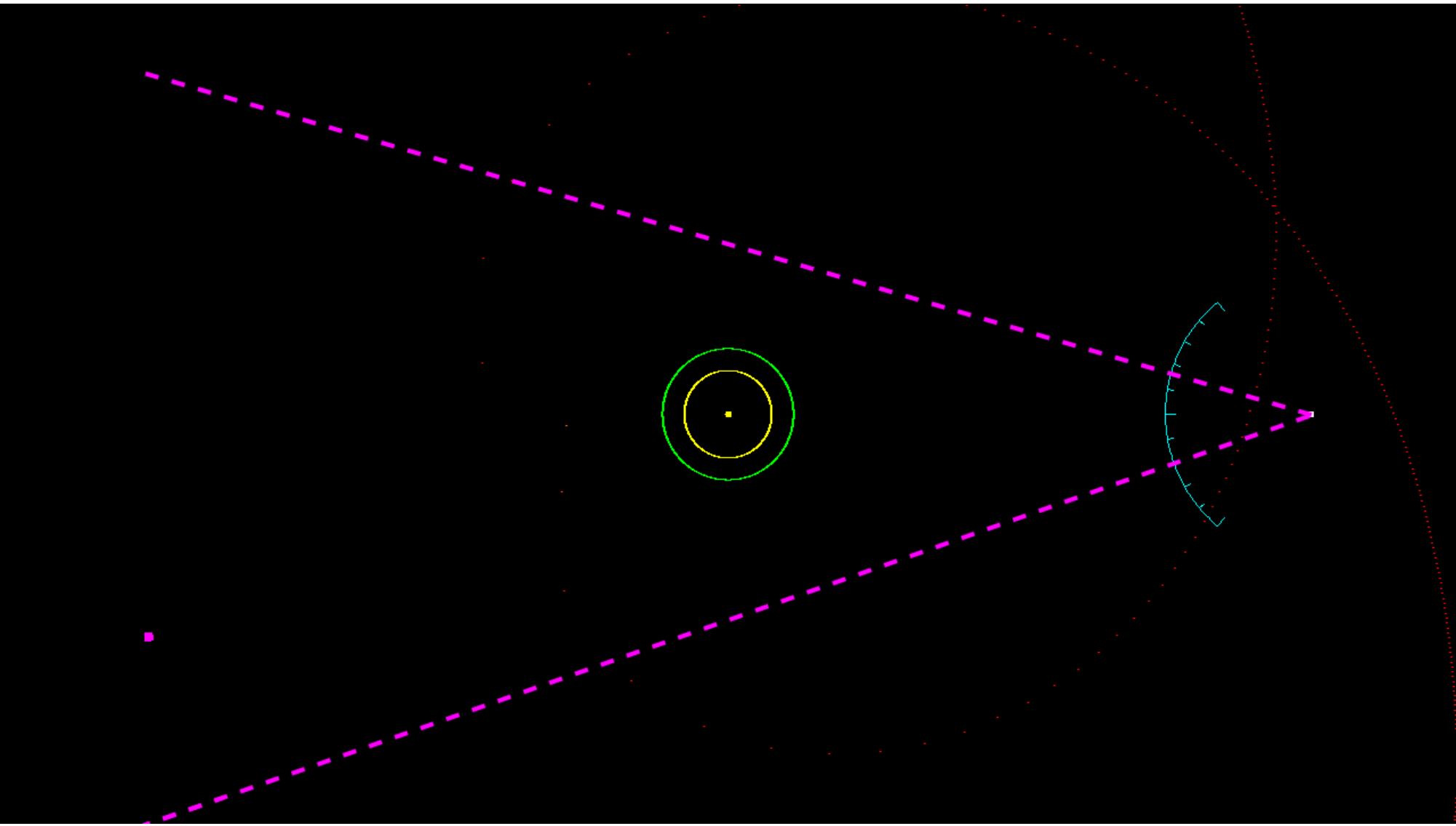




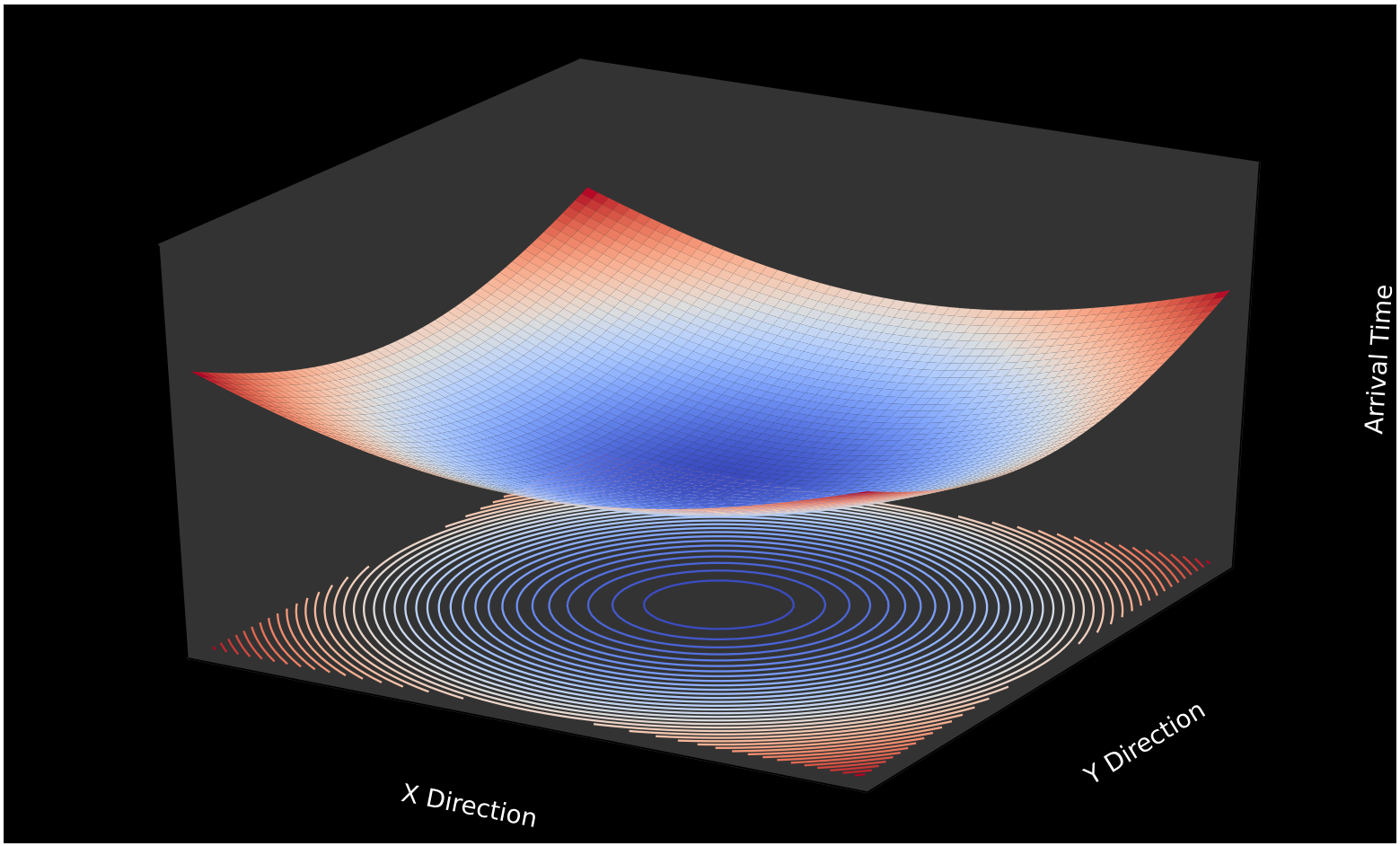


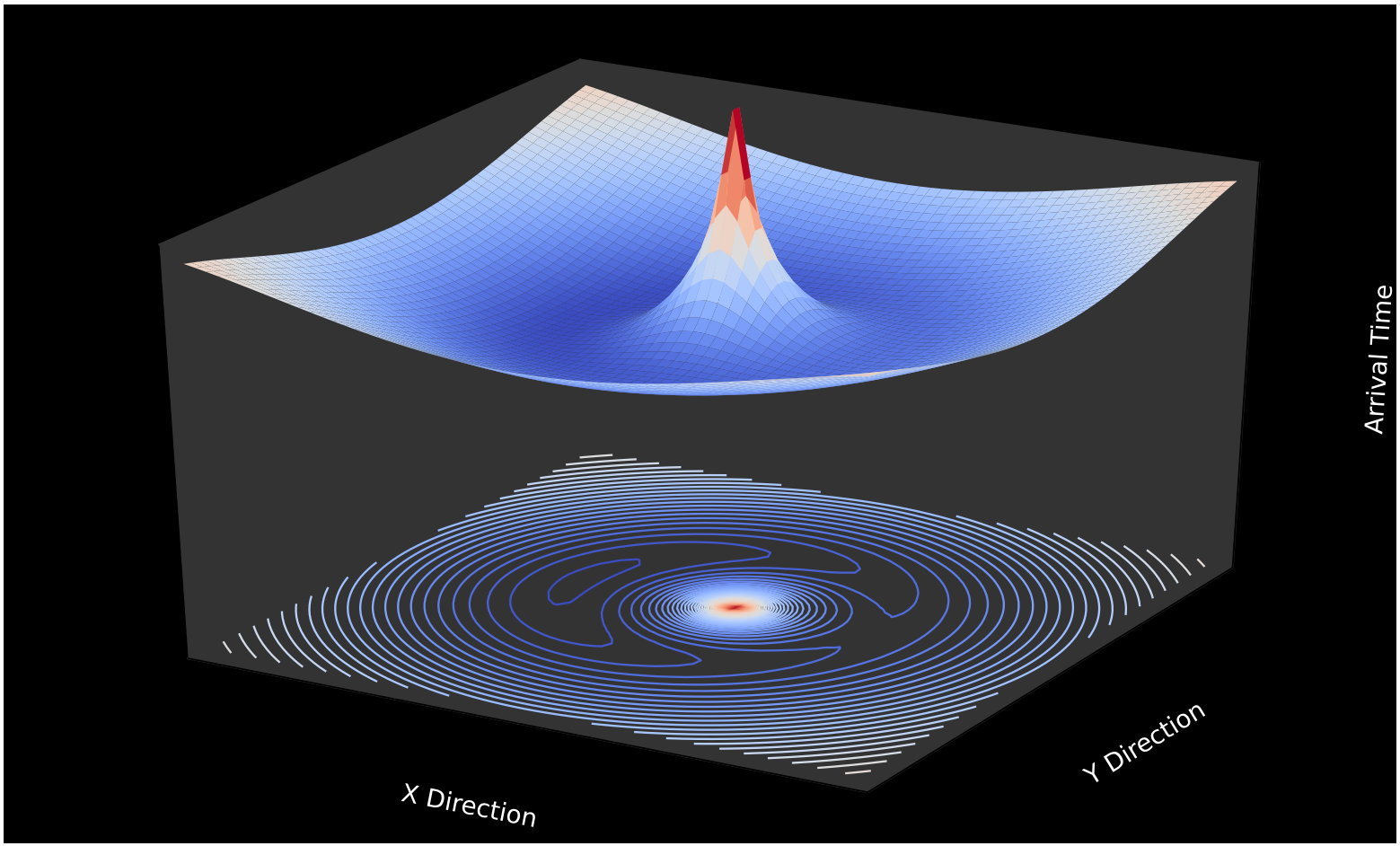


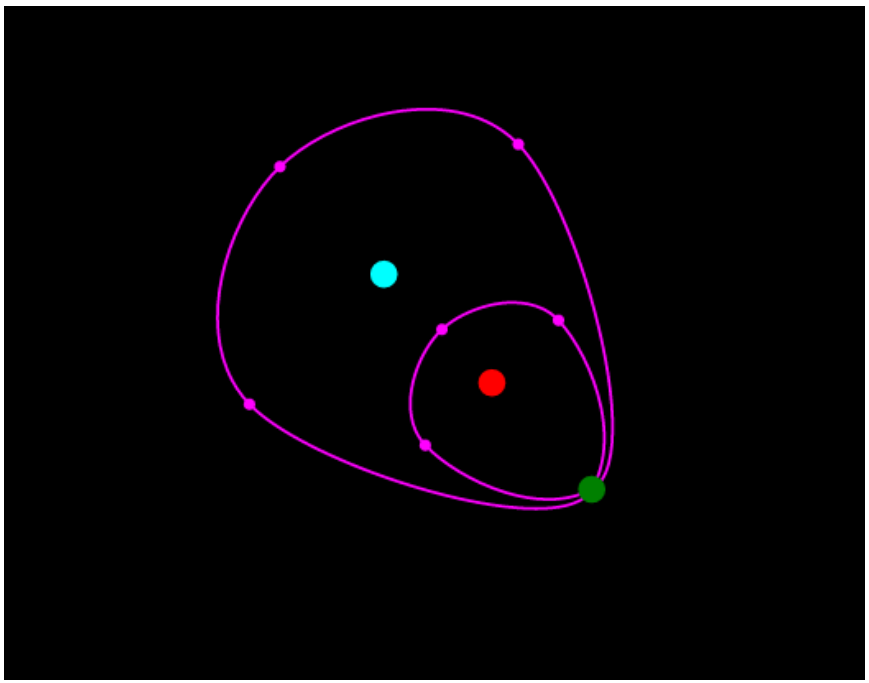




Simulation program: `gravlens` by C. Huwiler


Arrival Time
X Direction
Y Direction


Arrival Time
X Direction
Y Direction



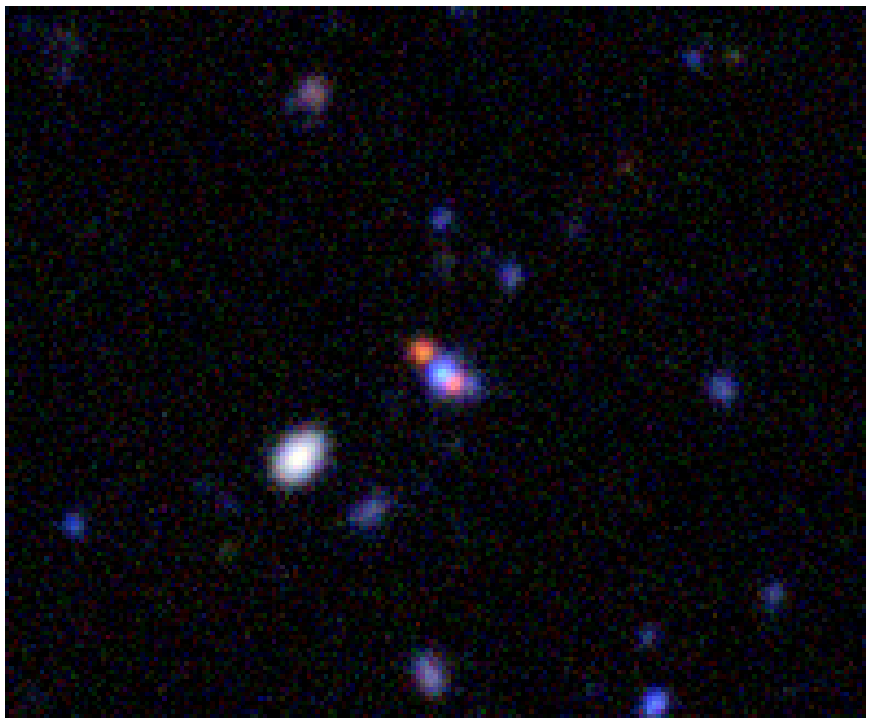
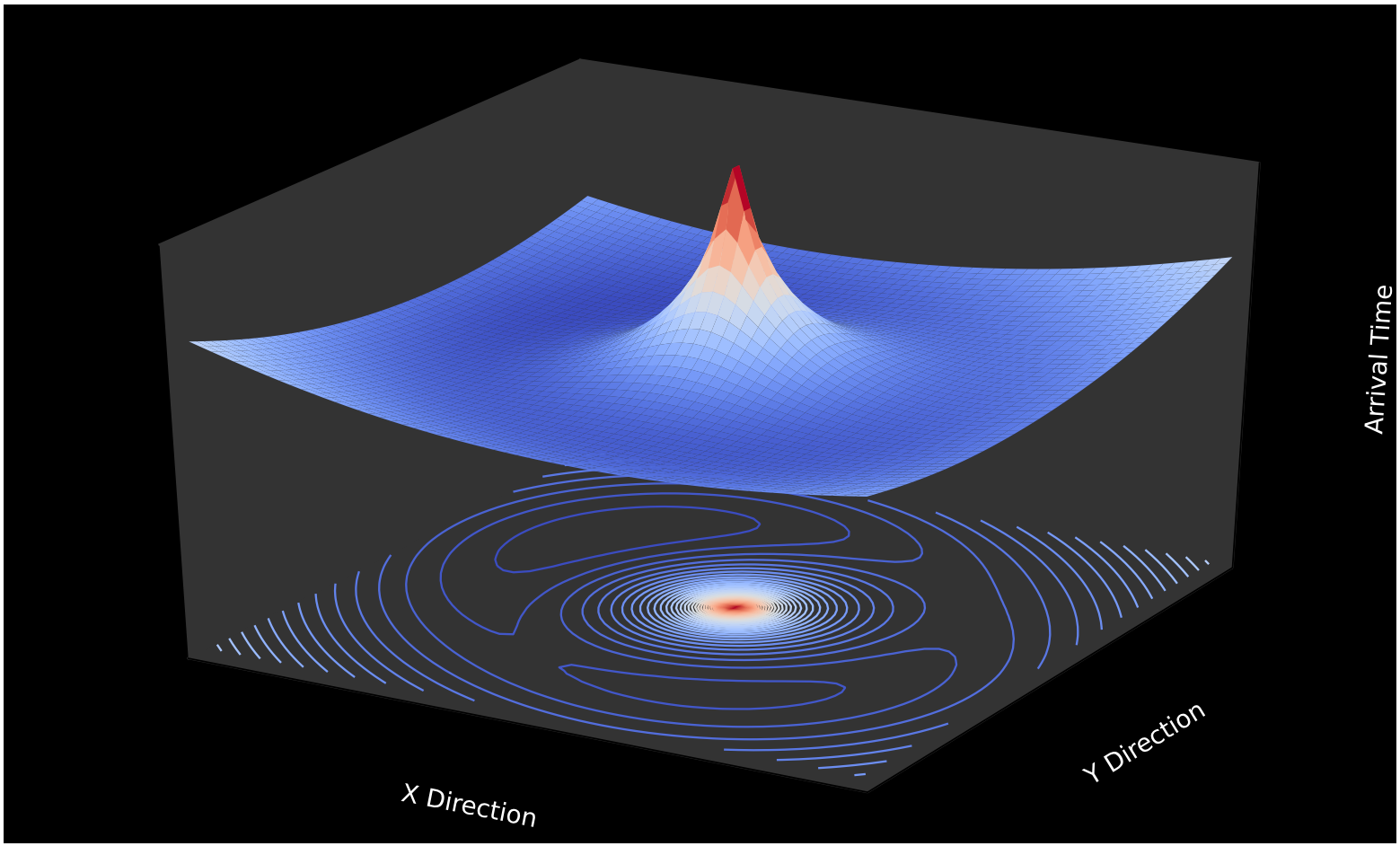
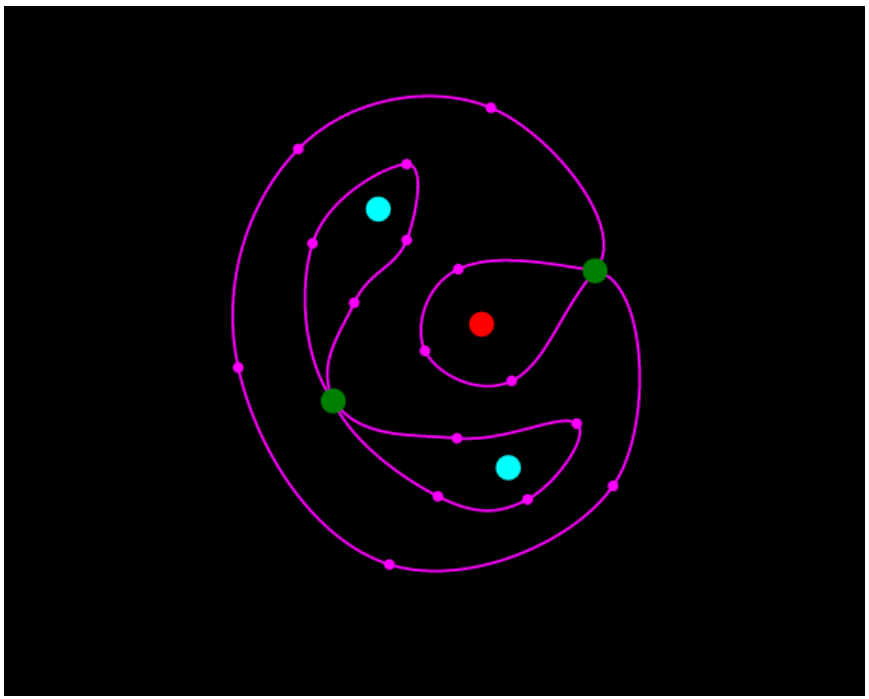


Figure: ASW0004q9e (SpaceWarps)


Arrival Time
X Direction
Y Direction



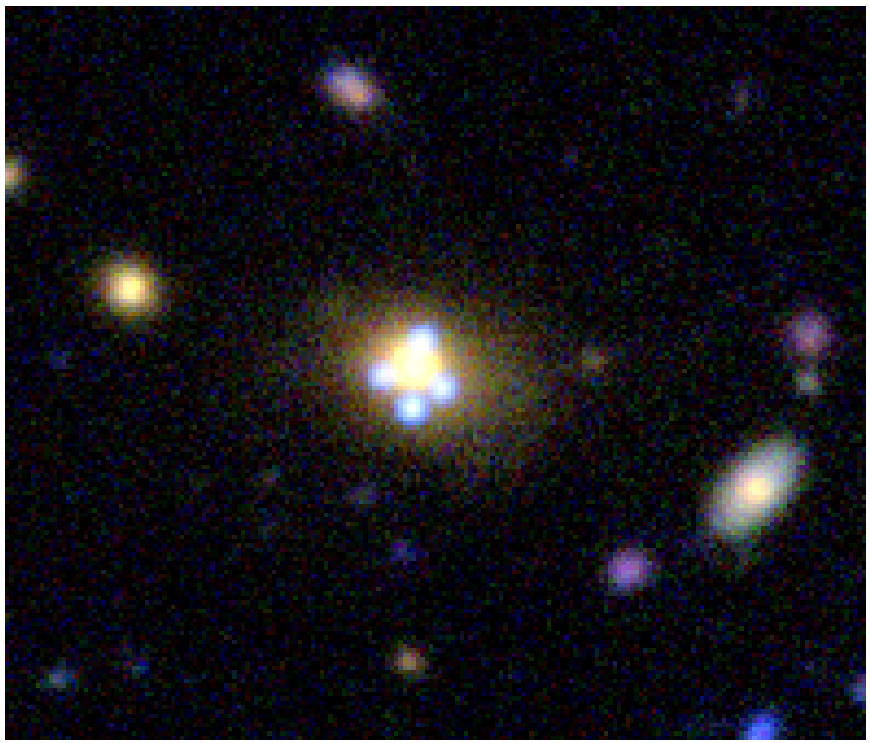
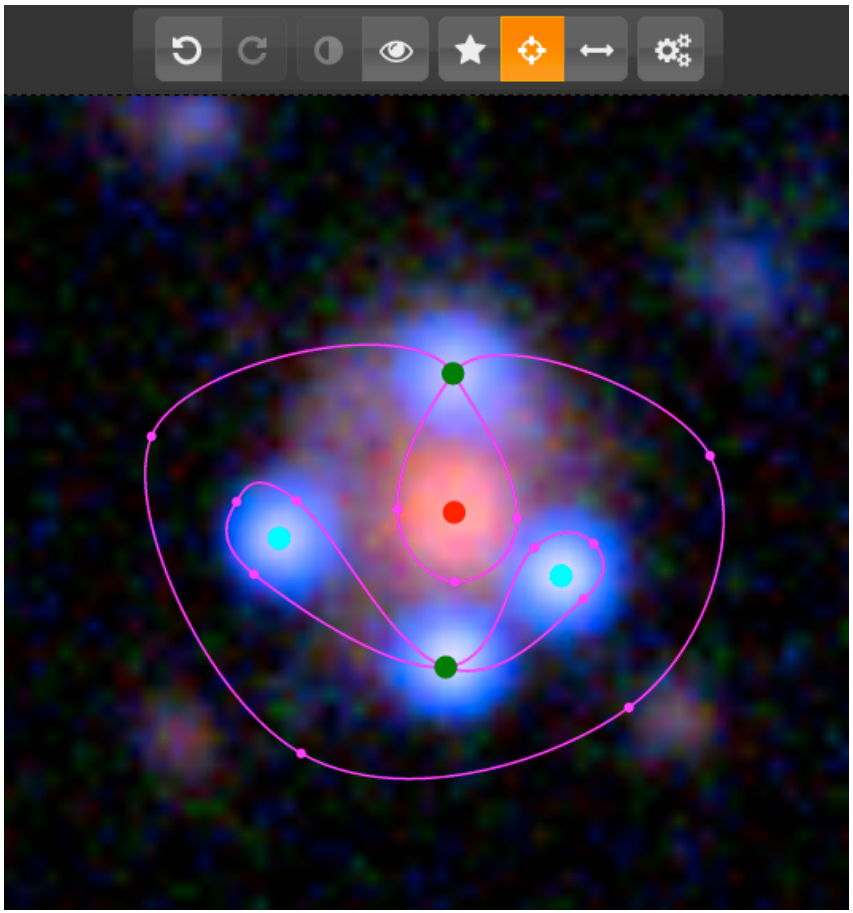


Figure: ASW0004q9e (SpaceWarps)

SpaghettiLens

- Extremal Points (Images)
- Self Intersecting Contour Lines

`http://labs.spacewarps.org/spaghetti/`



SpaghettiLens Results: Test of Performance

- Use simulated lenses
- Let volunteers model them
- Recover and compare Einstein Radii Θ_E
- Volunteers perform well!

arxiv:1502.00008

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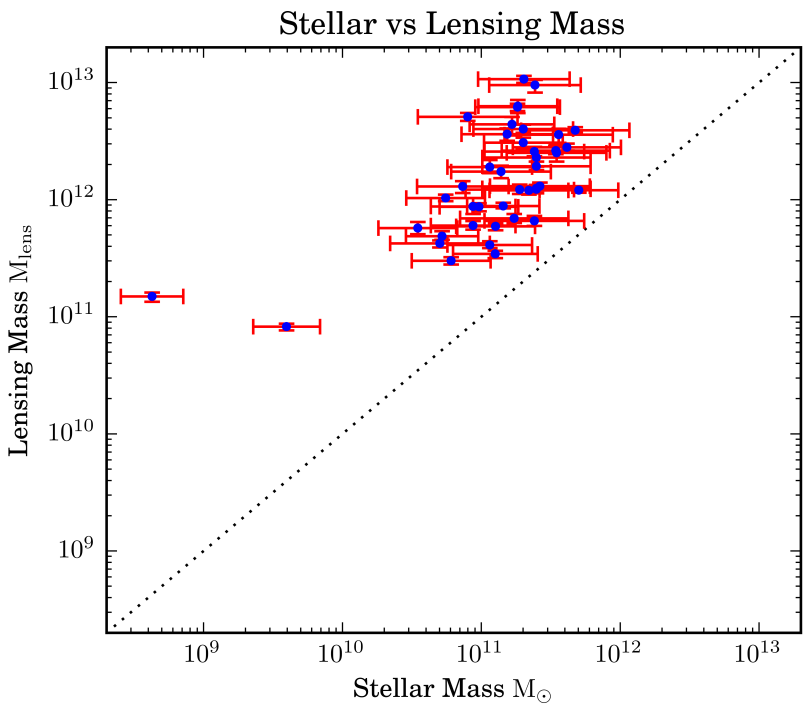
Gravitational Lens Modelling in a Citizen Science Context

Rafael Küng,[1] Prasenjit Saha,[1] Anupreeta More,[2] Elisabeth Baeten,[3]
Jonathan Coles,[4] Claude Cornen,[3] Christine Macmillan,[3] Phil Marshall,[5]
Surhud More,[2] Jonas Odermatt,[6] Aprajita Verma[7] and Julianne K. Wilcox[3]
[1] *Physik-Institut, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland*
[2] *Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa-shi 277-8583, Japan*
[3] *Zooniverse, c/o Astrophysics Department, University of Oxford, Oxford OX1 3RH, UK*
[4] *Exascale Research Computing Lab, Campus Teratec, 2 Rue de la Piquetterie, 91680 Bruyeres-le-Chatel, France*
[5] *Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, 452 Lomita Mall, Stanford, CA 94035, USA*
[6] *Kantonsschule Zug, Lüssiweg 24, 6300 Zug, Switzerland*
[7] *Sub-department of Astrophysics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK*

SpaghettiLens Results: Stellar vs Lensing Mass

- Lensing mass against the stellar mass of the candidate lens galaxies
- Stellar mass fraction of order 20 percent
- With decreasing trend for the most massive galaxies
- Expected for early type galaxies
- Outliers? Maybe non-lenses (not yet spectroscopically confirmed)



Conclusions and Outlook

Conclusions:

- SL is set up and works

We are currently working on:

- Increase the number of users
- Fit parametrized models to the free-form mass distributions[3]
- Determination of photometric red shifts
- Estimate stellar populations (using galfit, SExtractor)[4]
- Your idea!

[3] Lucy Oswald; University of Oxford
[4] Dominik Leier; University of Bologna

Questions?

Questions?

rafael.kueng@uzh.ch

Appendix