

SpaghettiLens

Gravitational Lens Modelling

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26. Sept 2013



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Motivation

- Gravitational Lenses (GL) hard to find
- Let volunteers help find them: SpaceWarp
- But post processing? SpaghettiLens

Outline

1 Theory

- Fermat's Principle
- ART
- Arrival Time Surface

2 SpaghettiLens

- Demonstration
- Implementation

3 Involving Volunteers

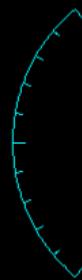
- Modelling Challenge

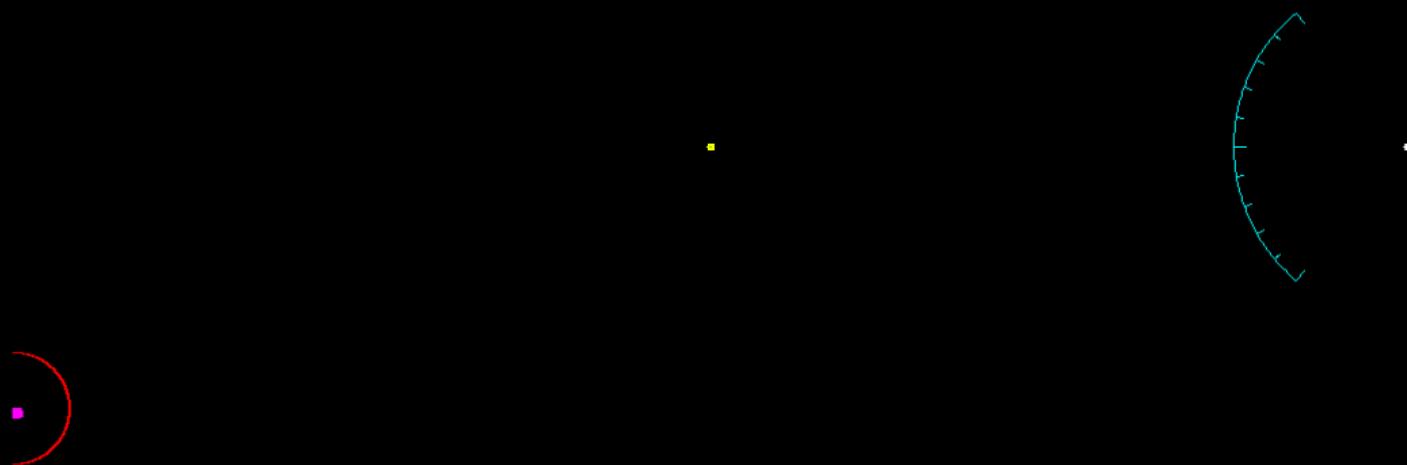
Fermat's Principle

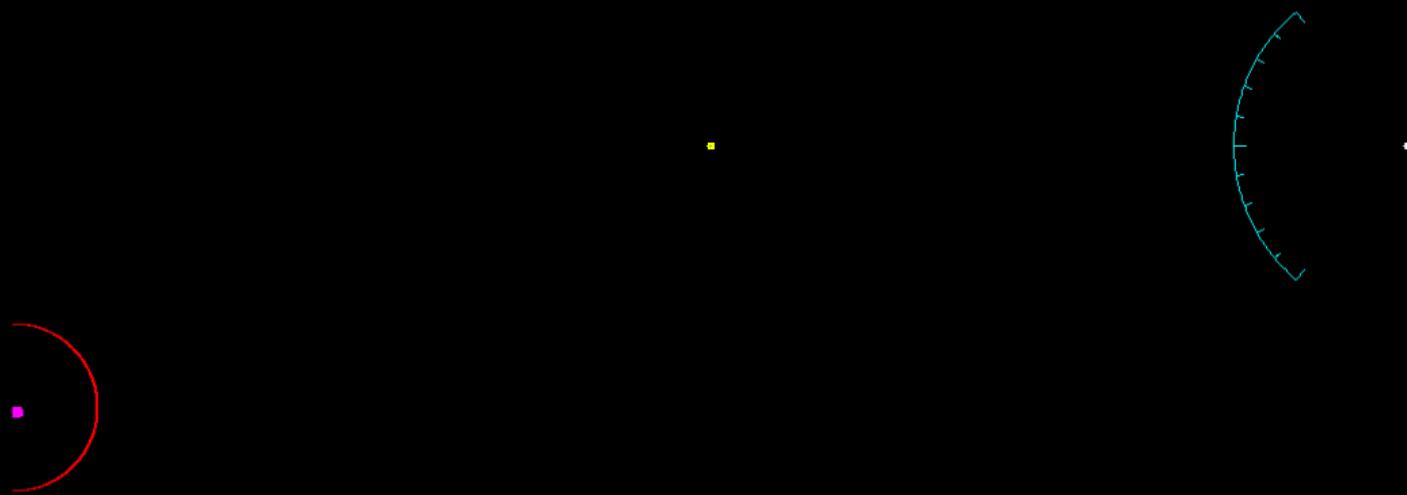
Fermat's Principle¹

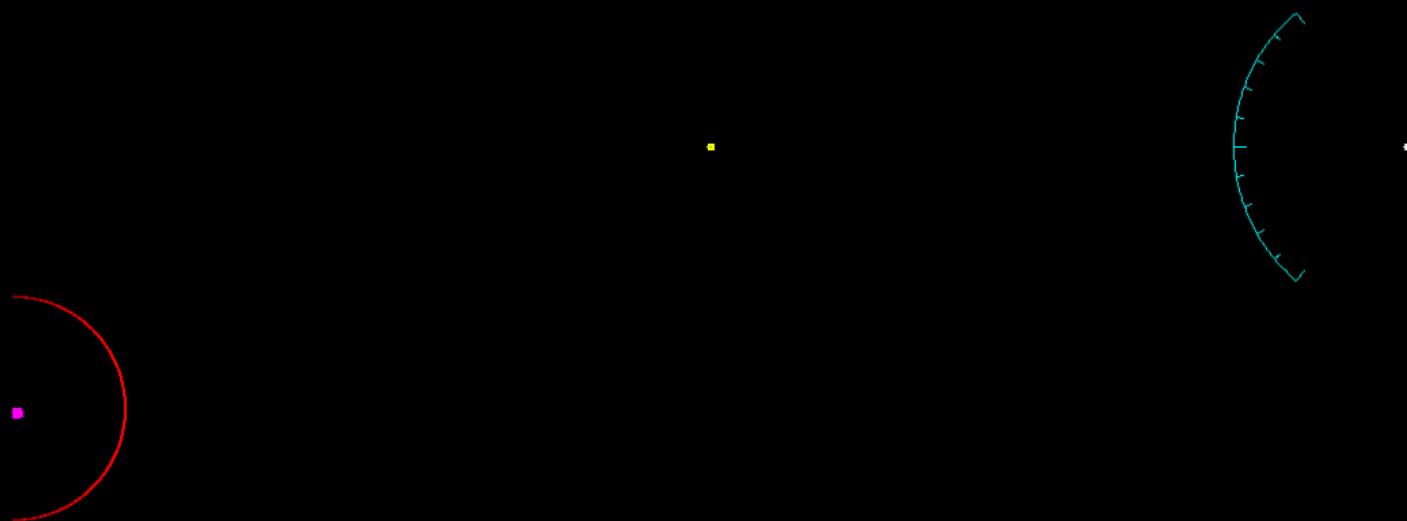
Rays of light traverse the path of stationary optical length with respect to variations of the path.

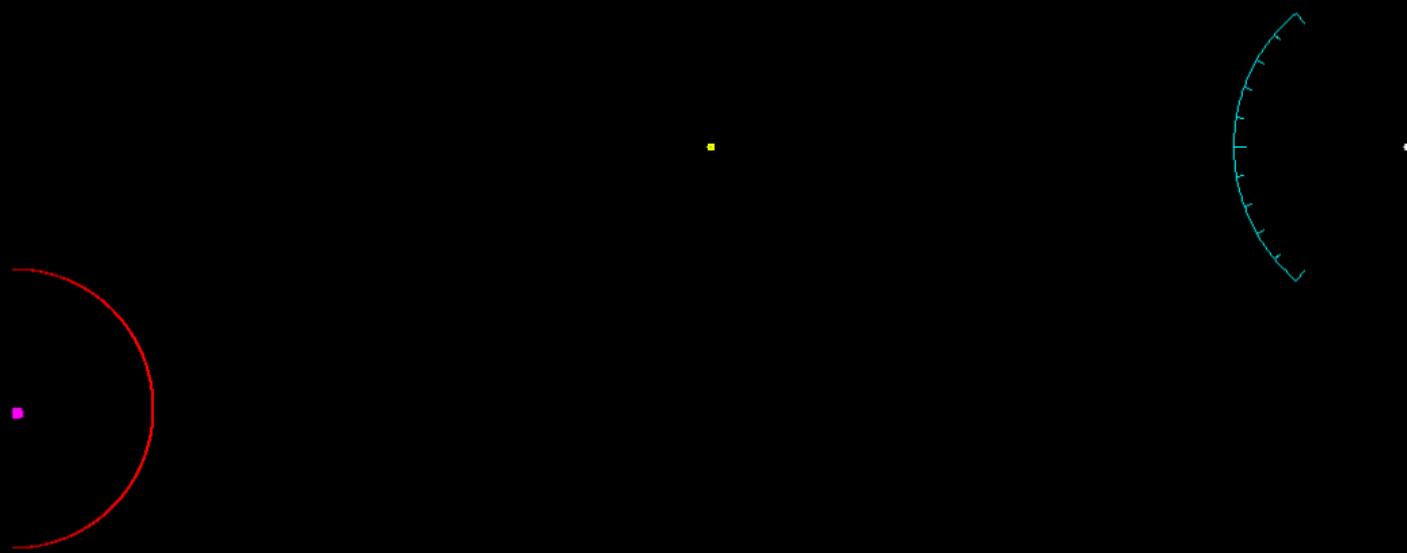
¹Ghatak, Ajoy (2009), Optics

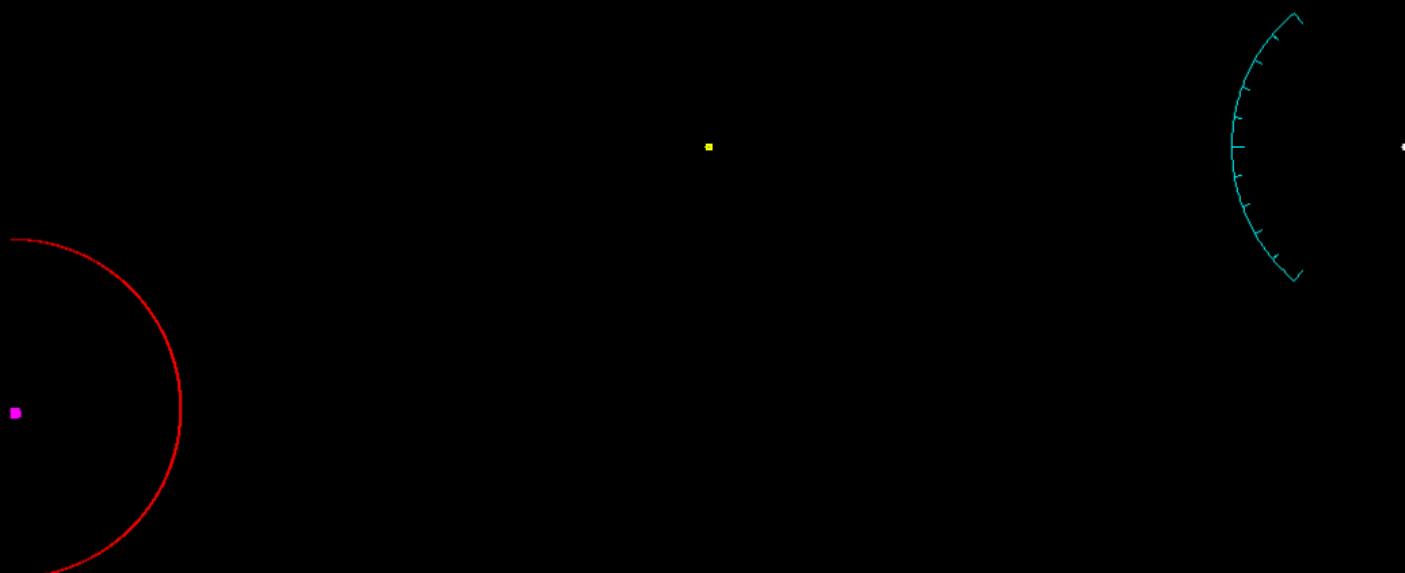


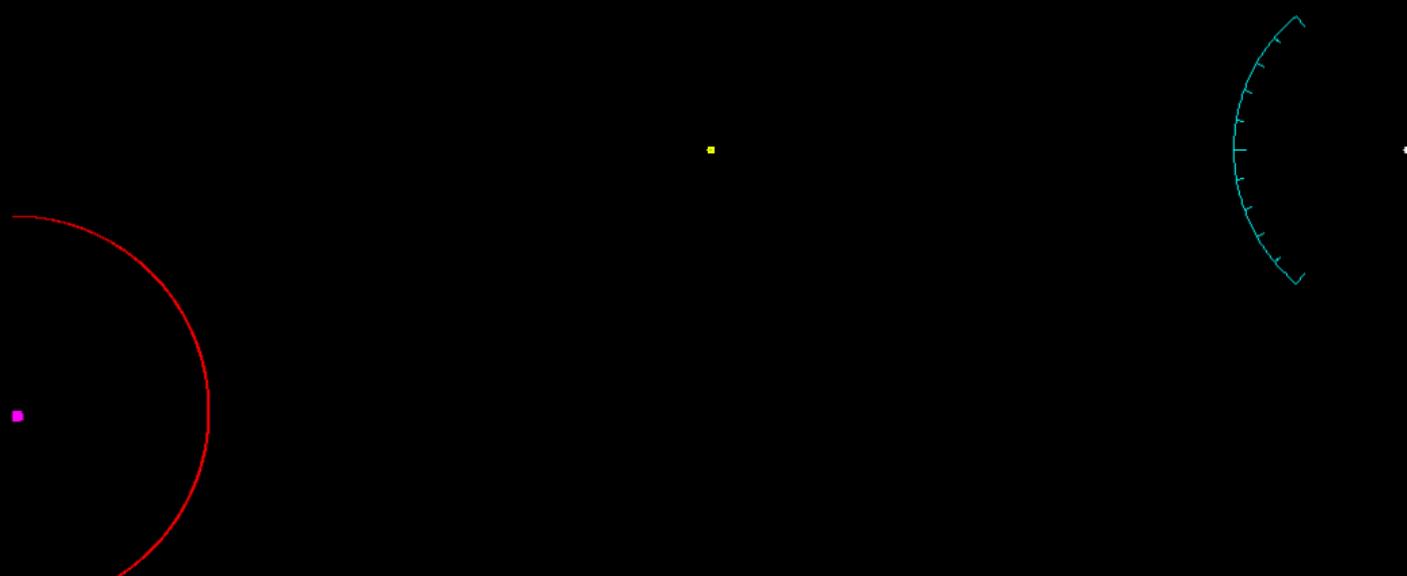


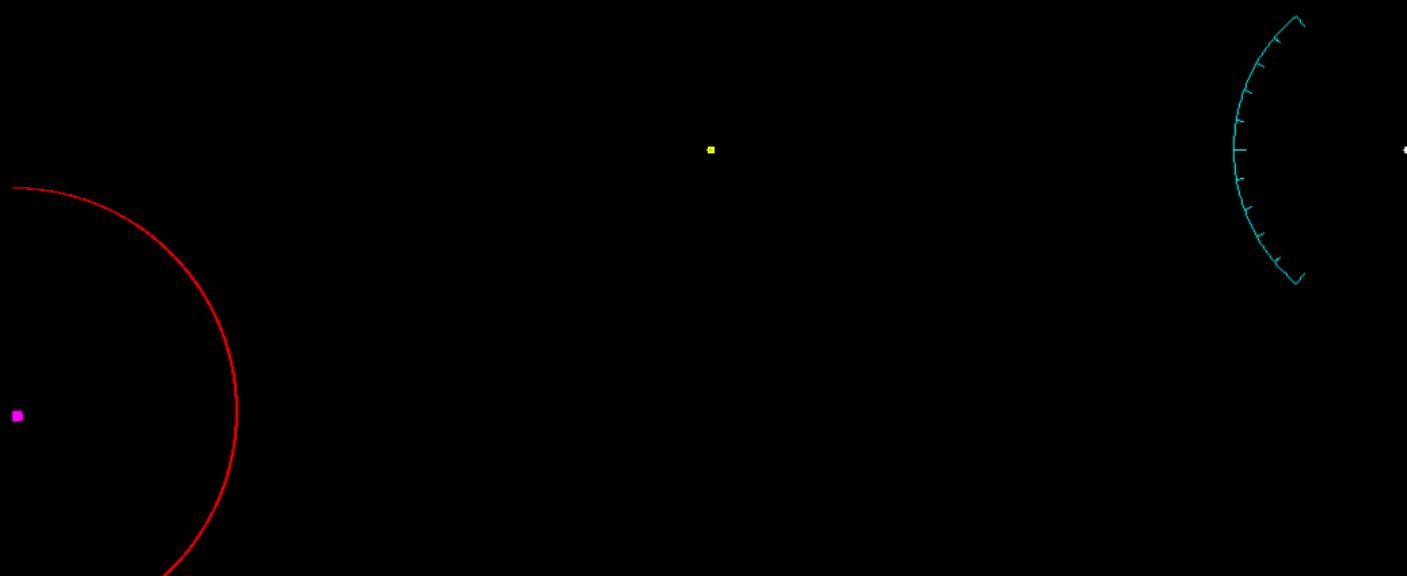


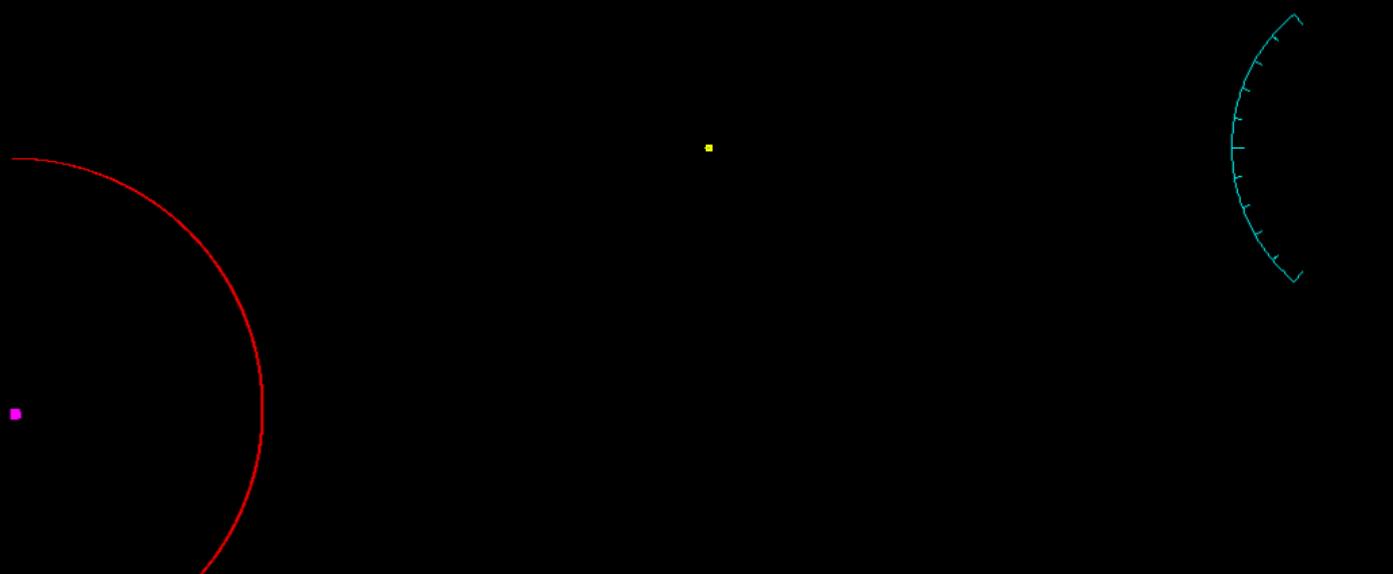


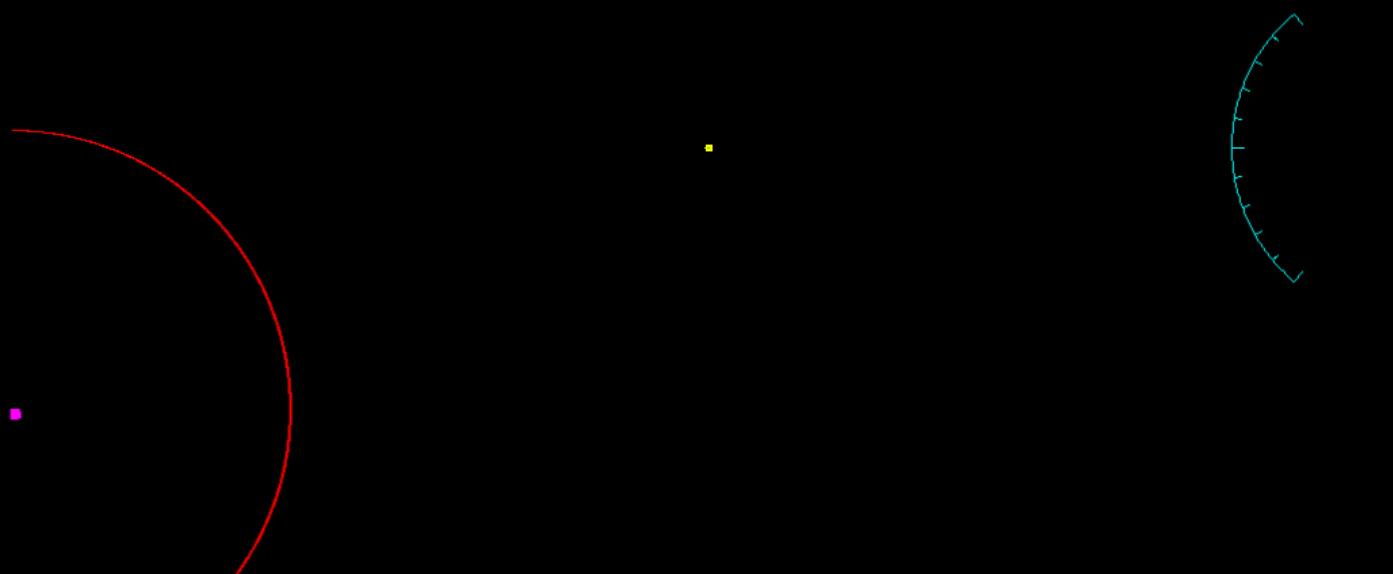


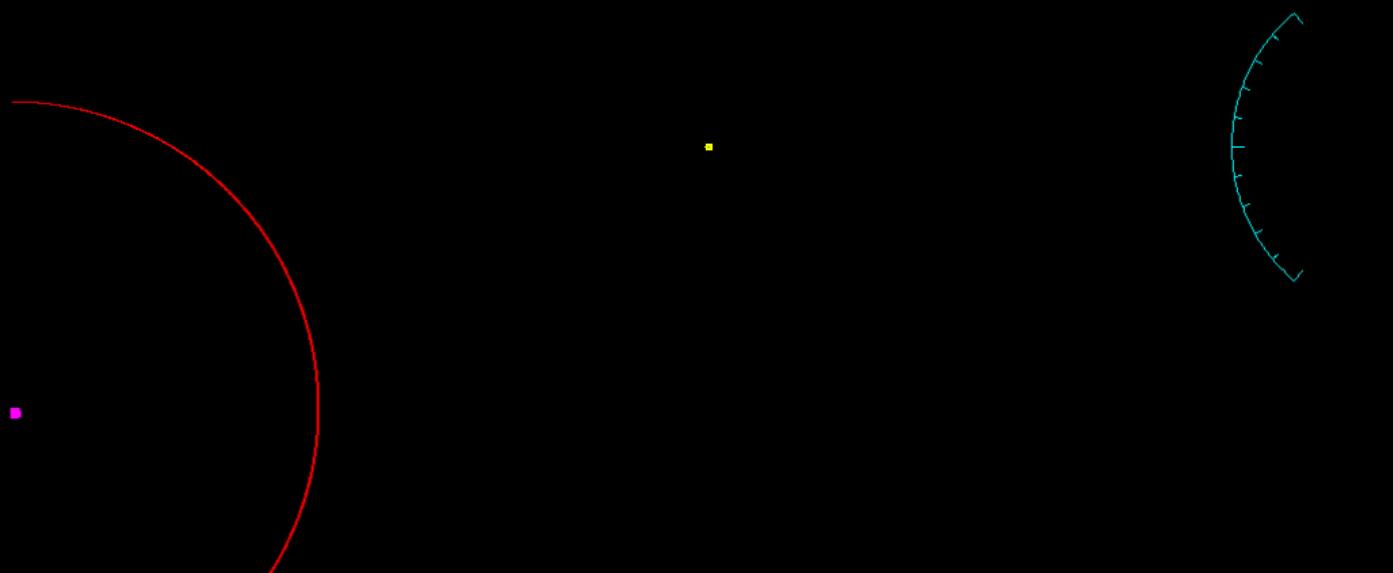


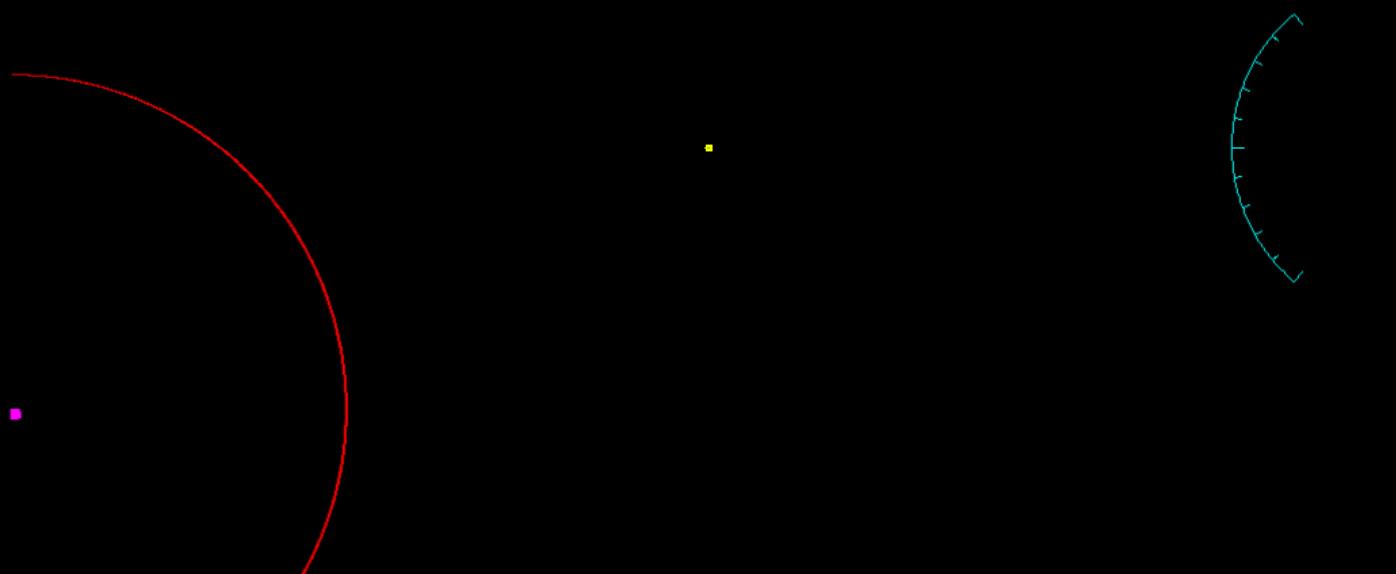


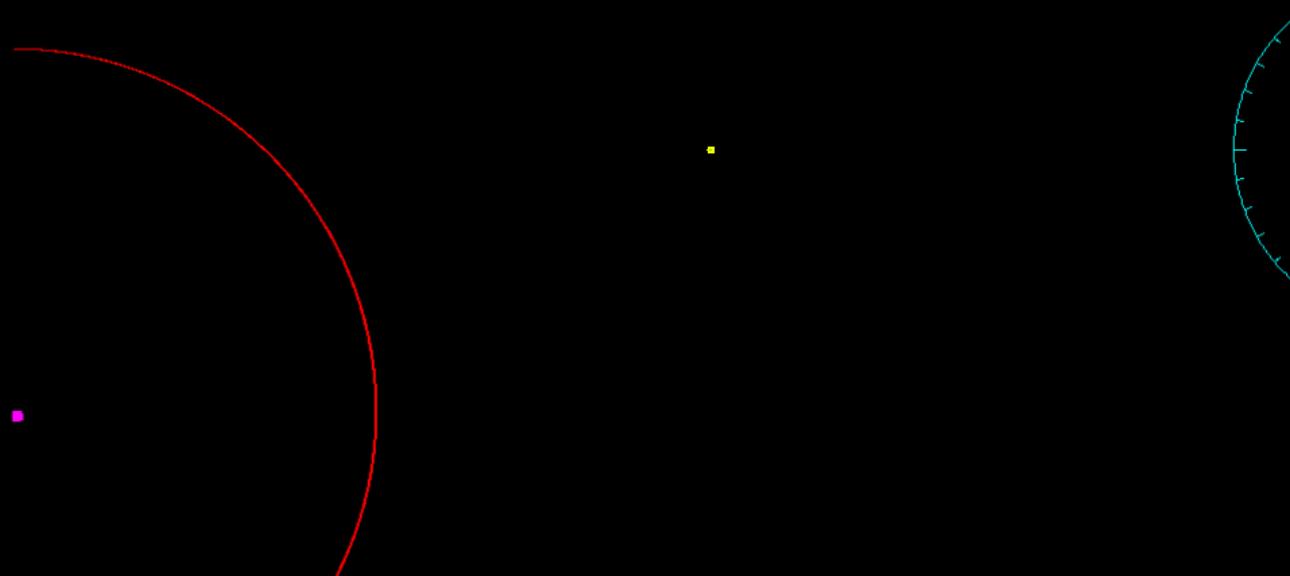


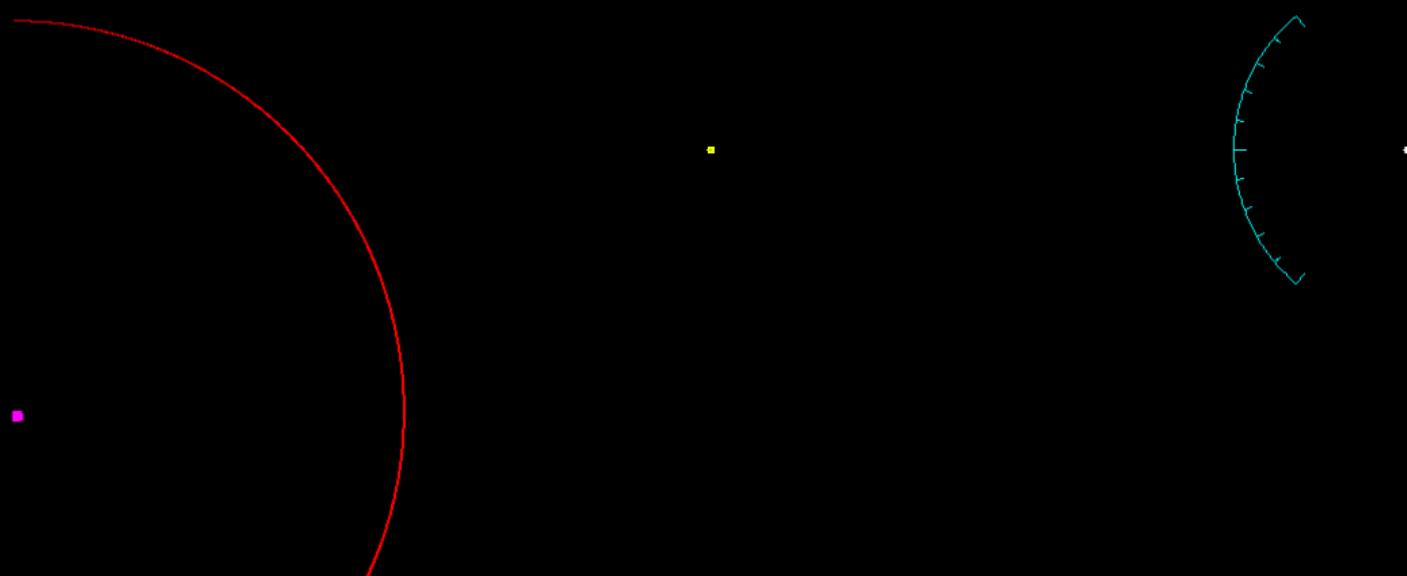




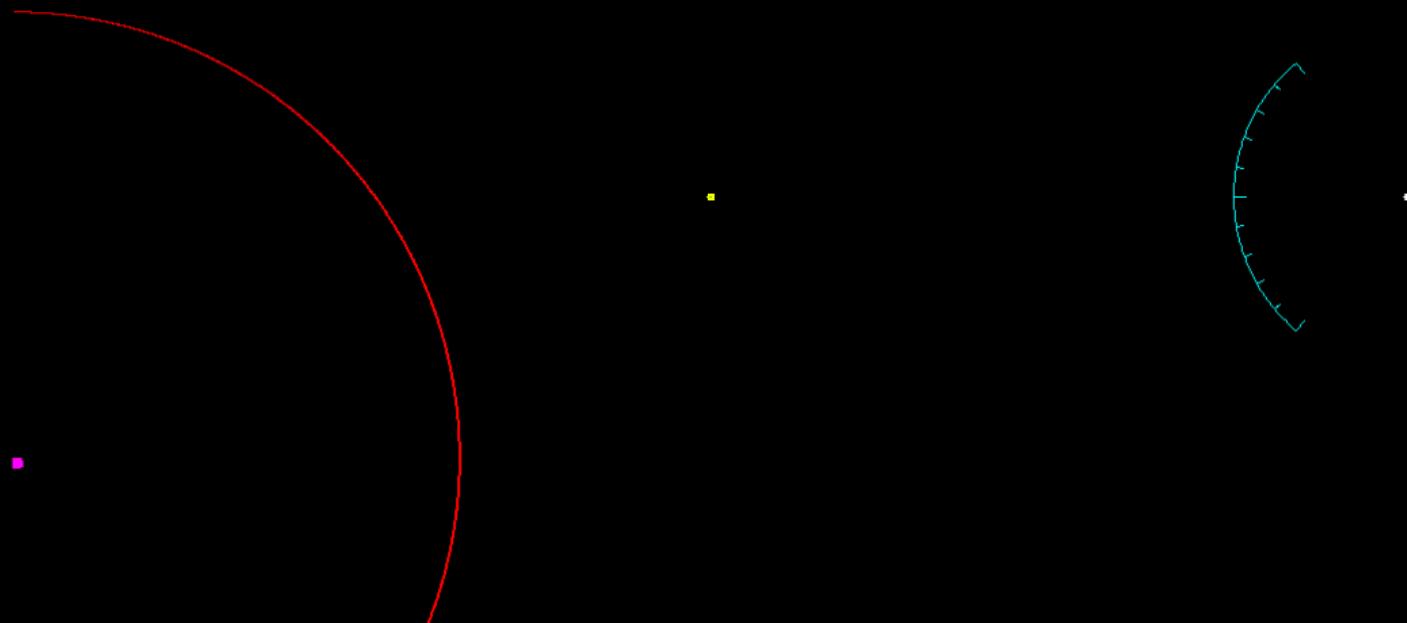


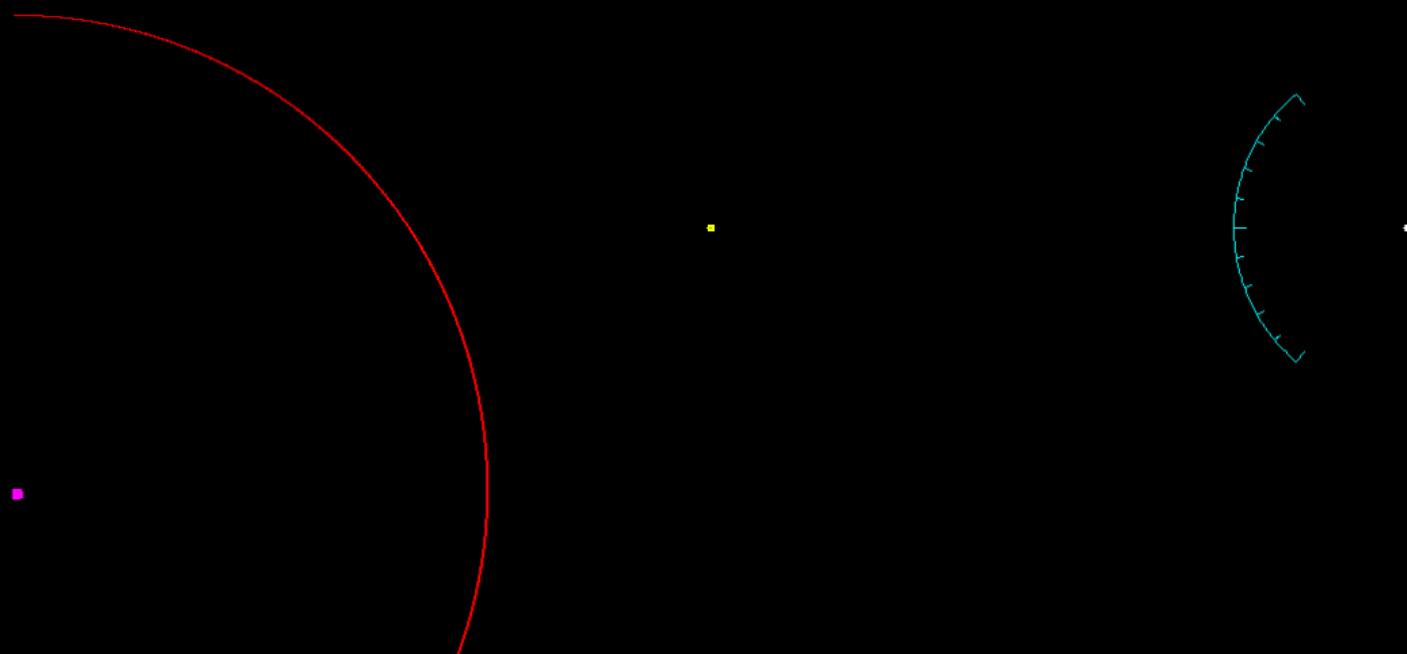


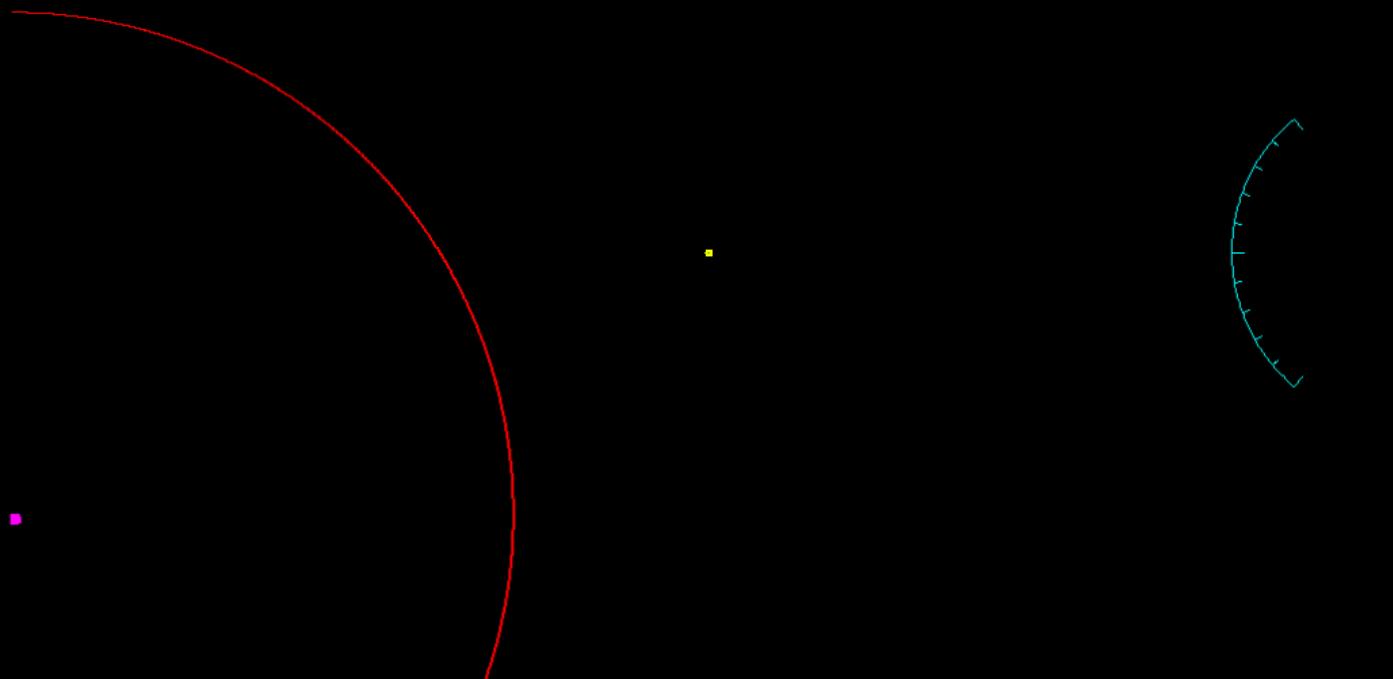


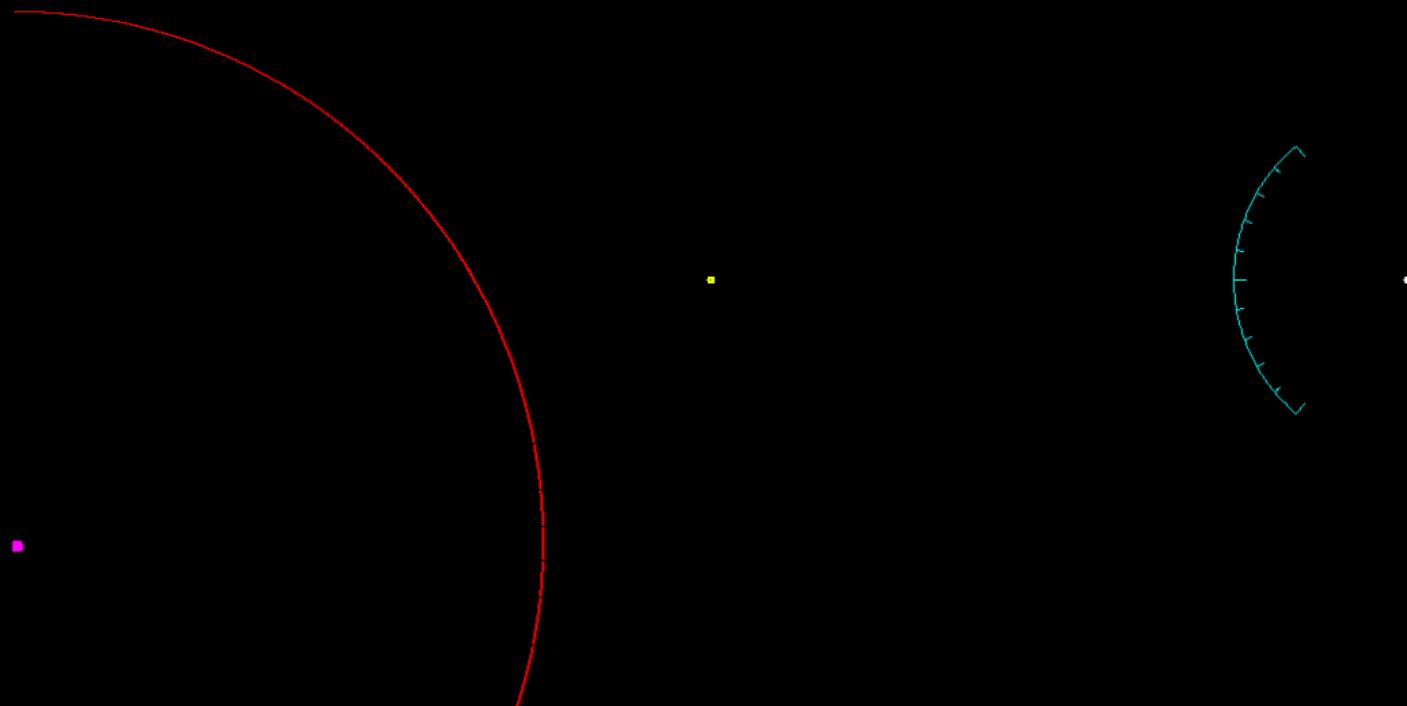


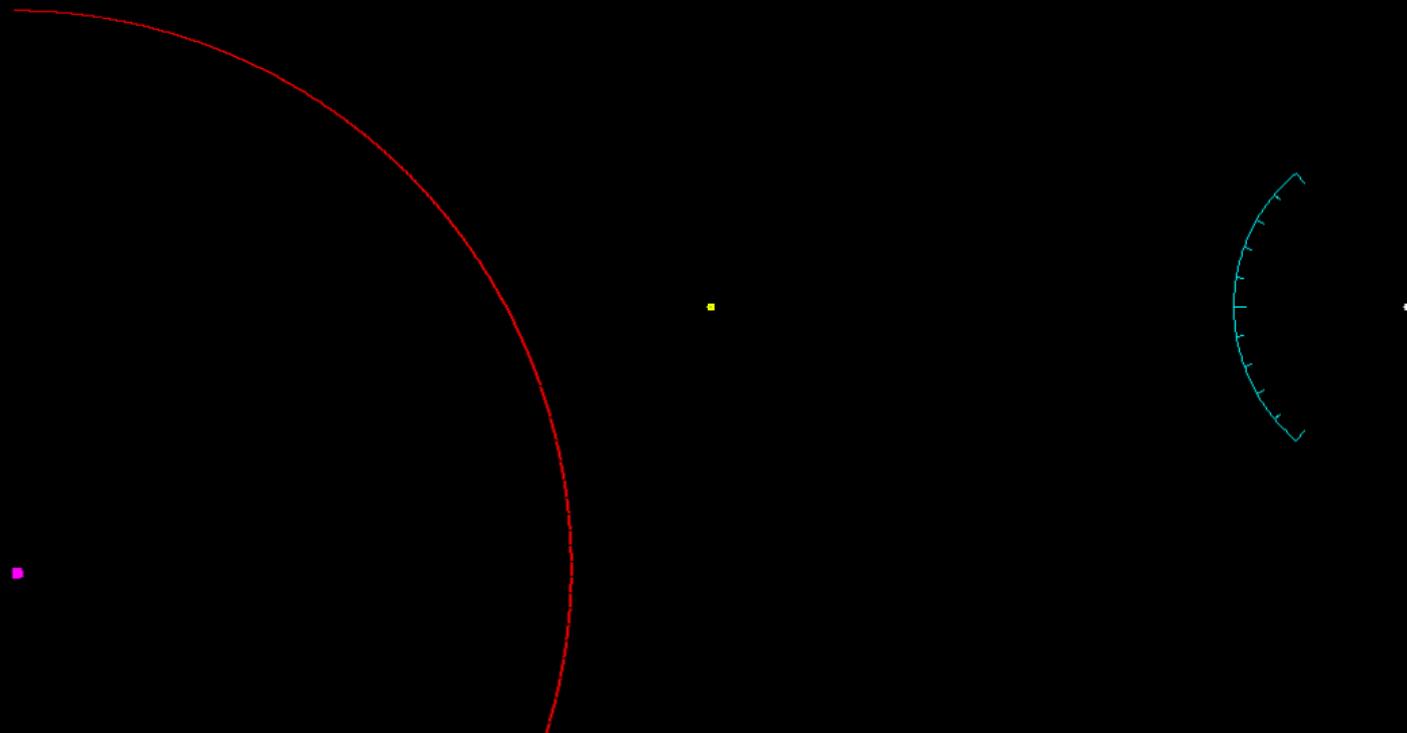


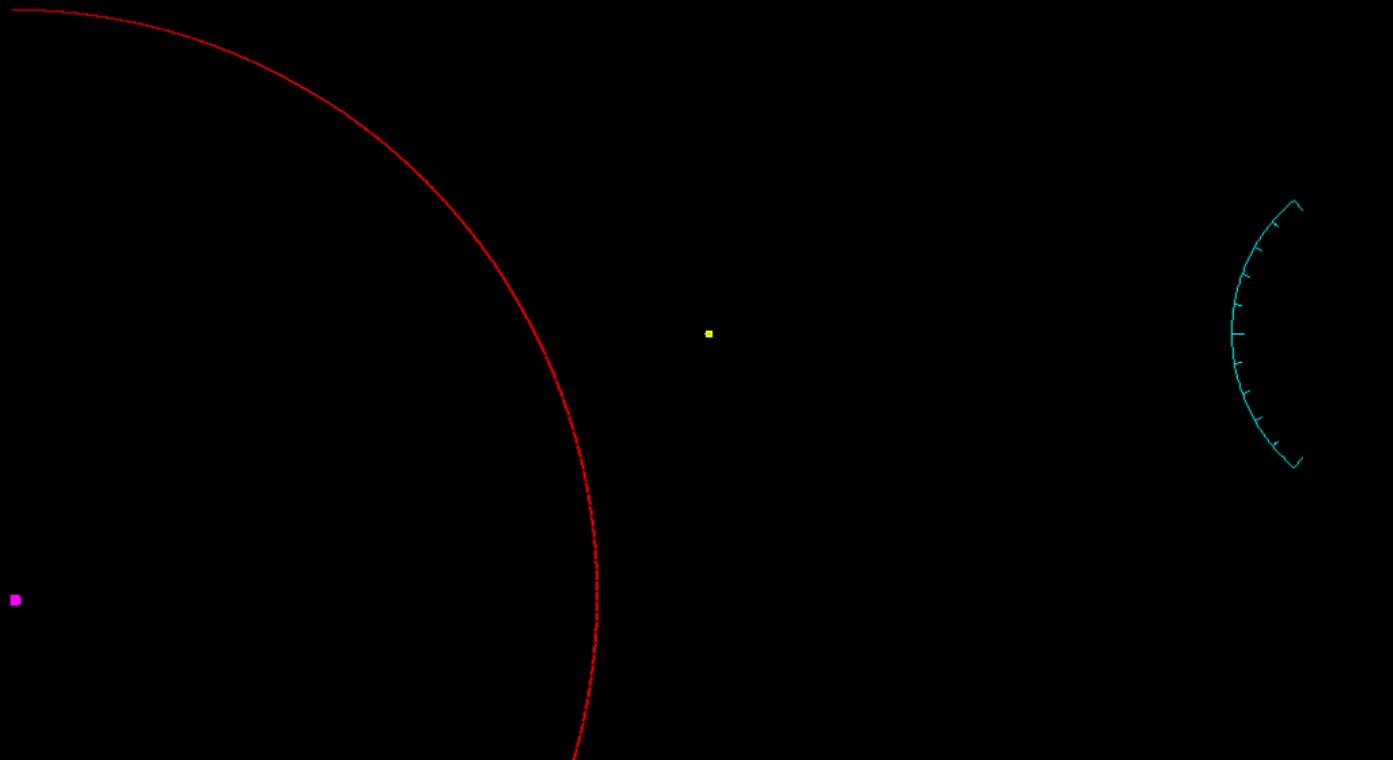


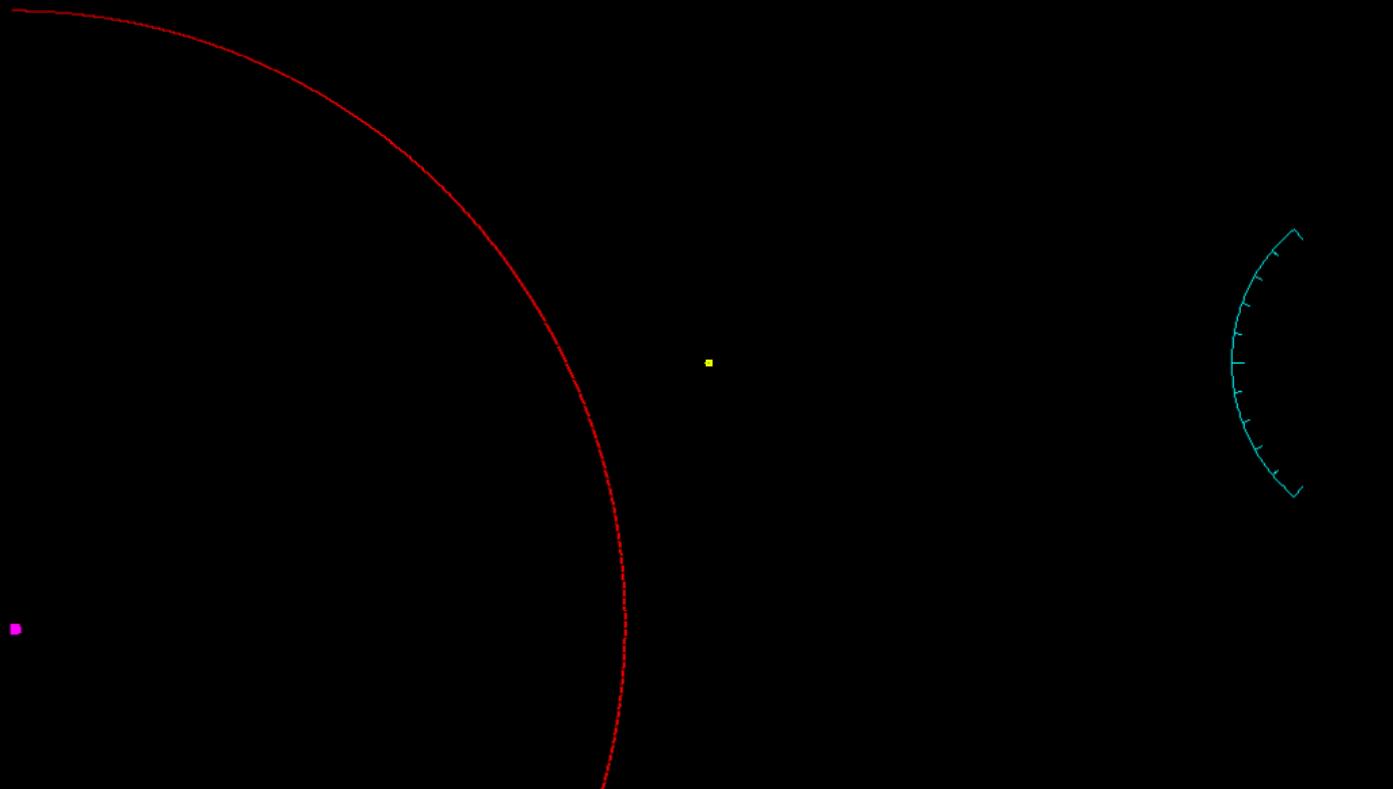


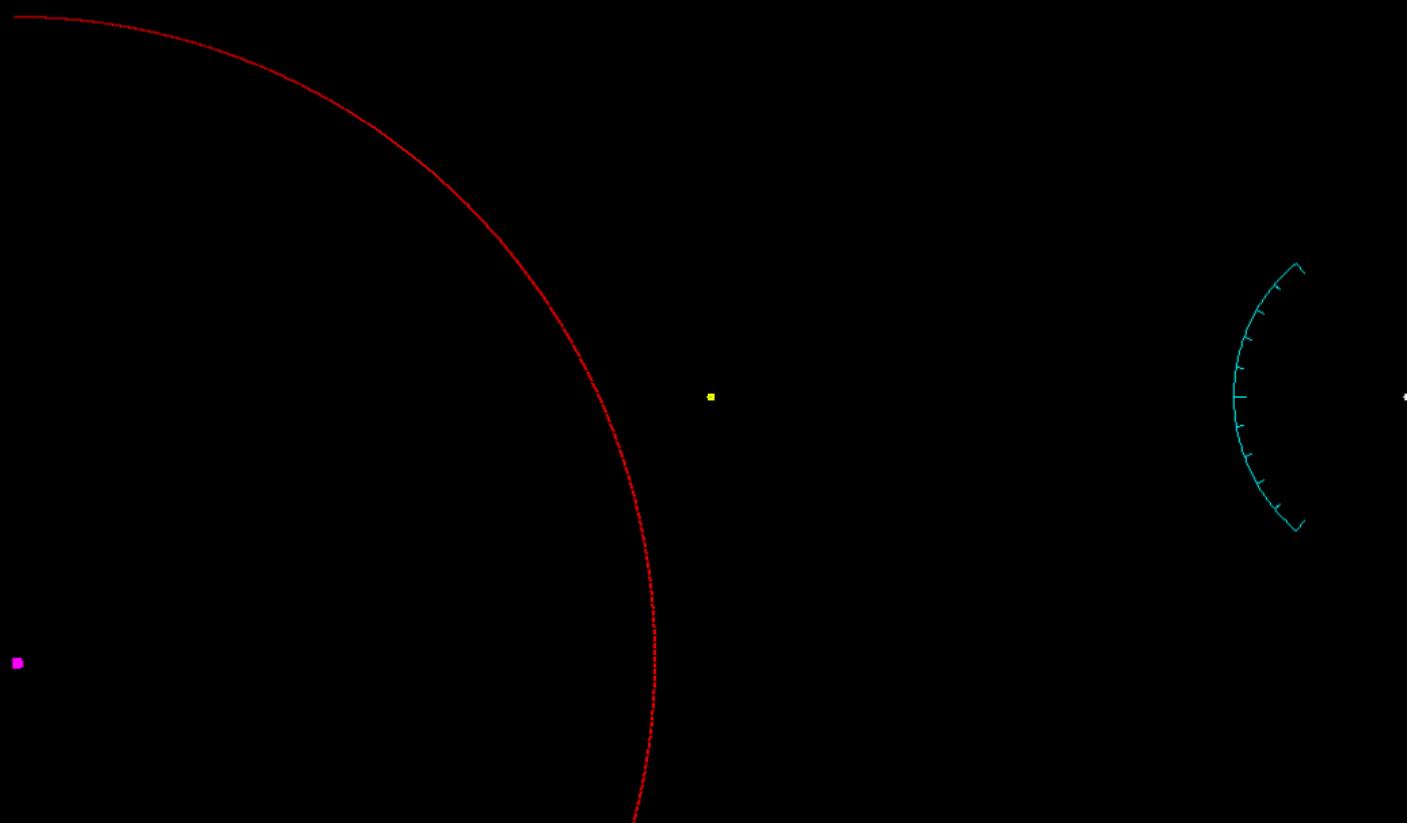


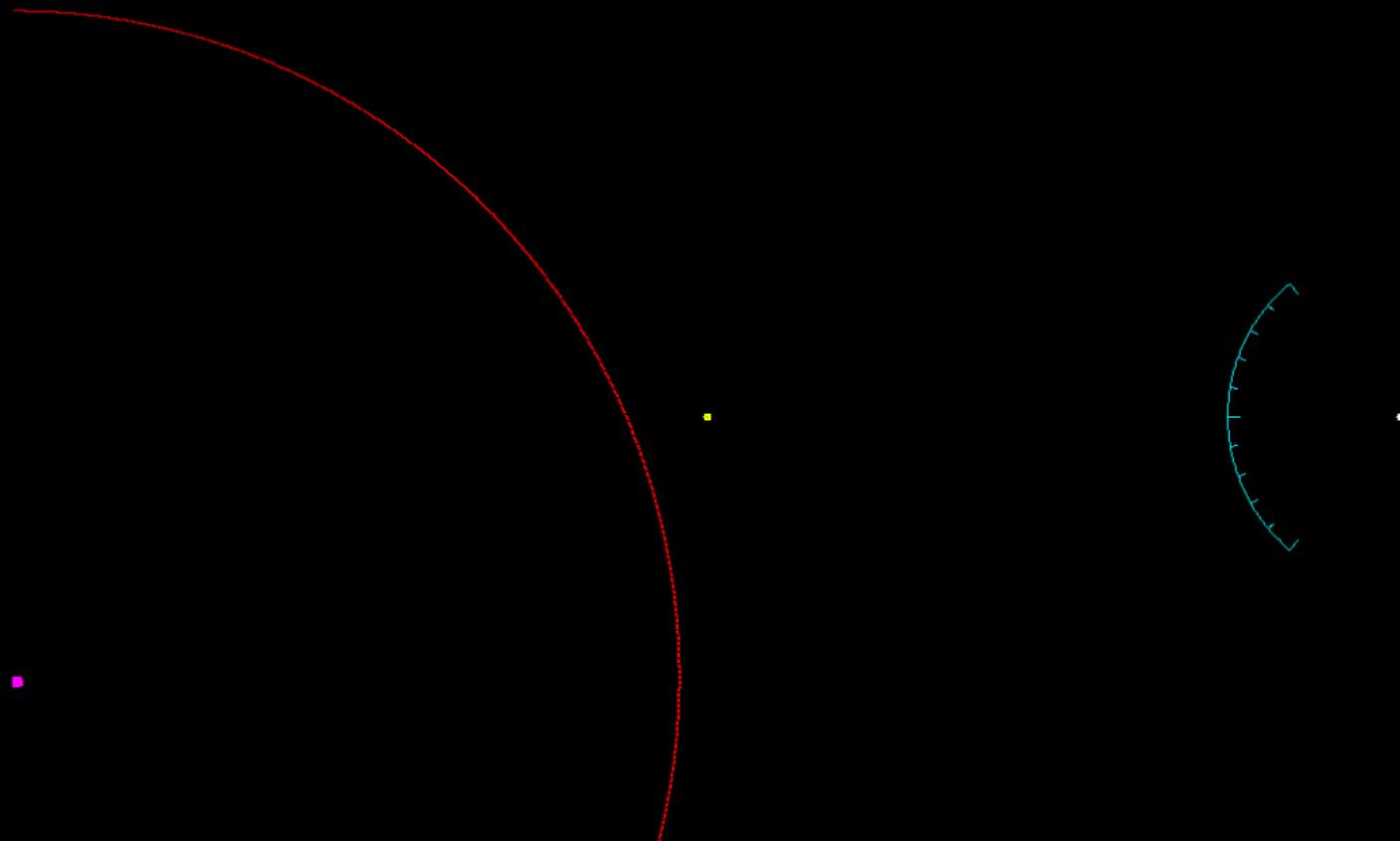


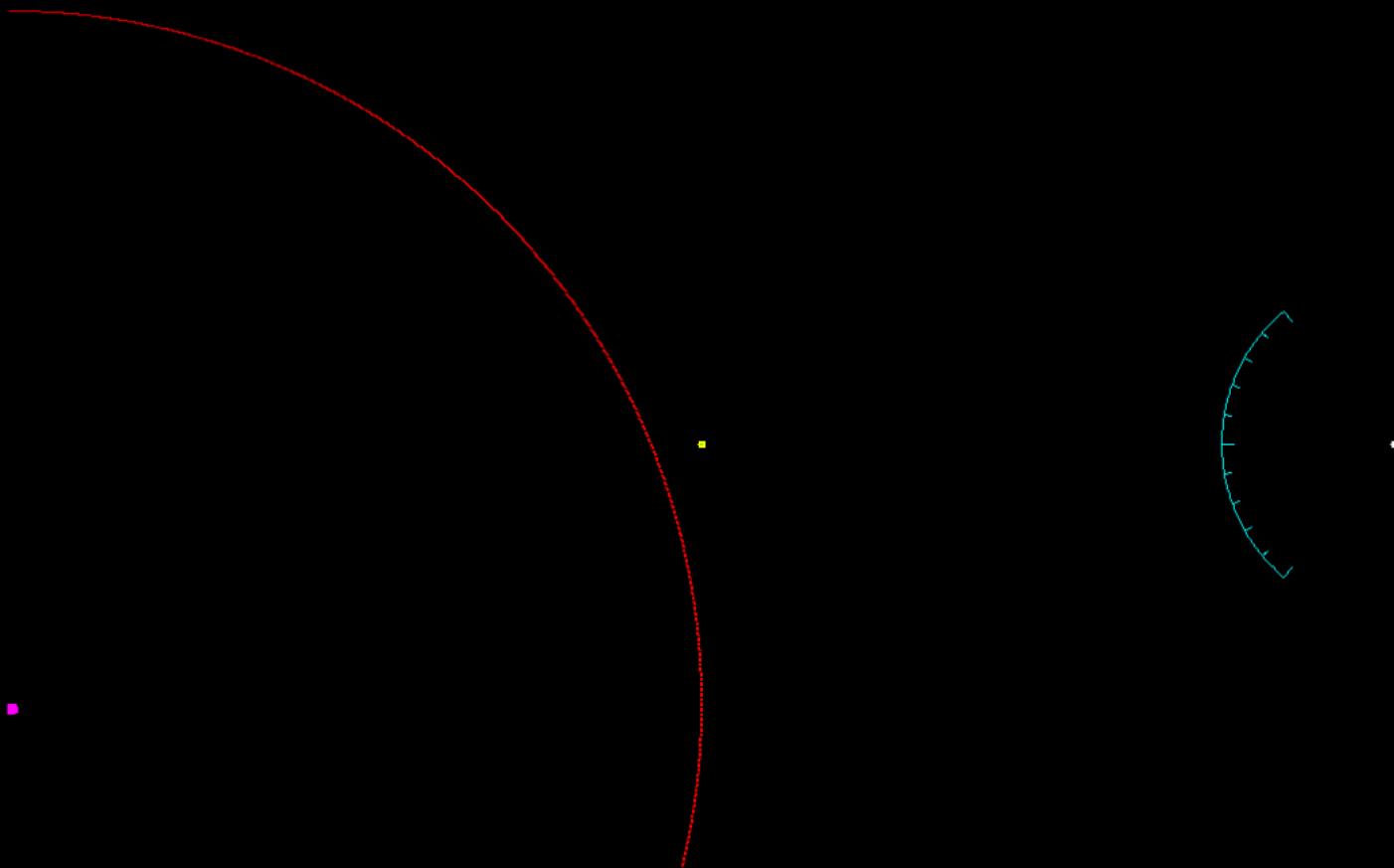


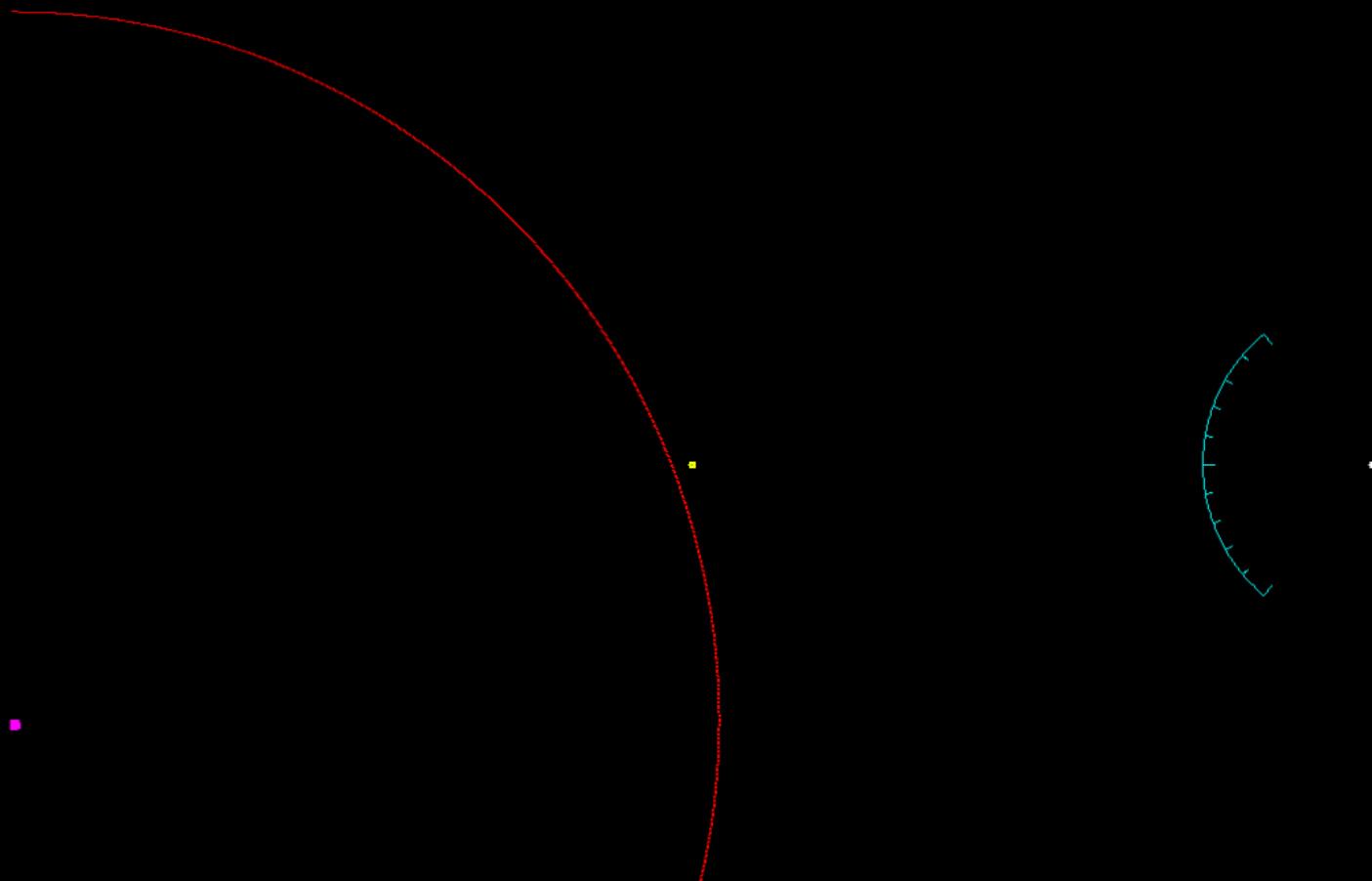


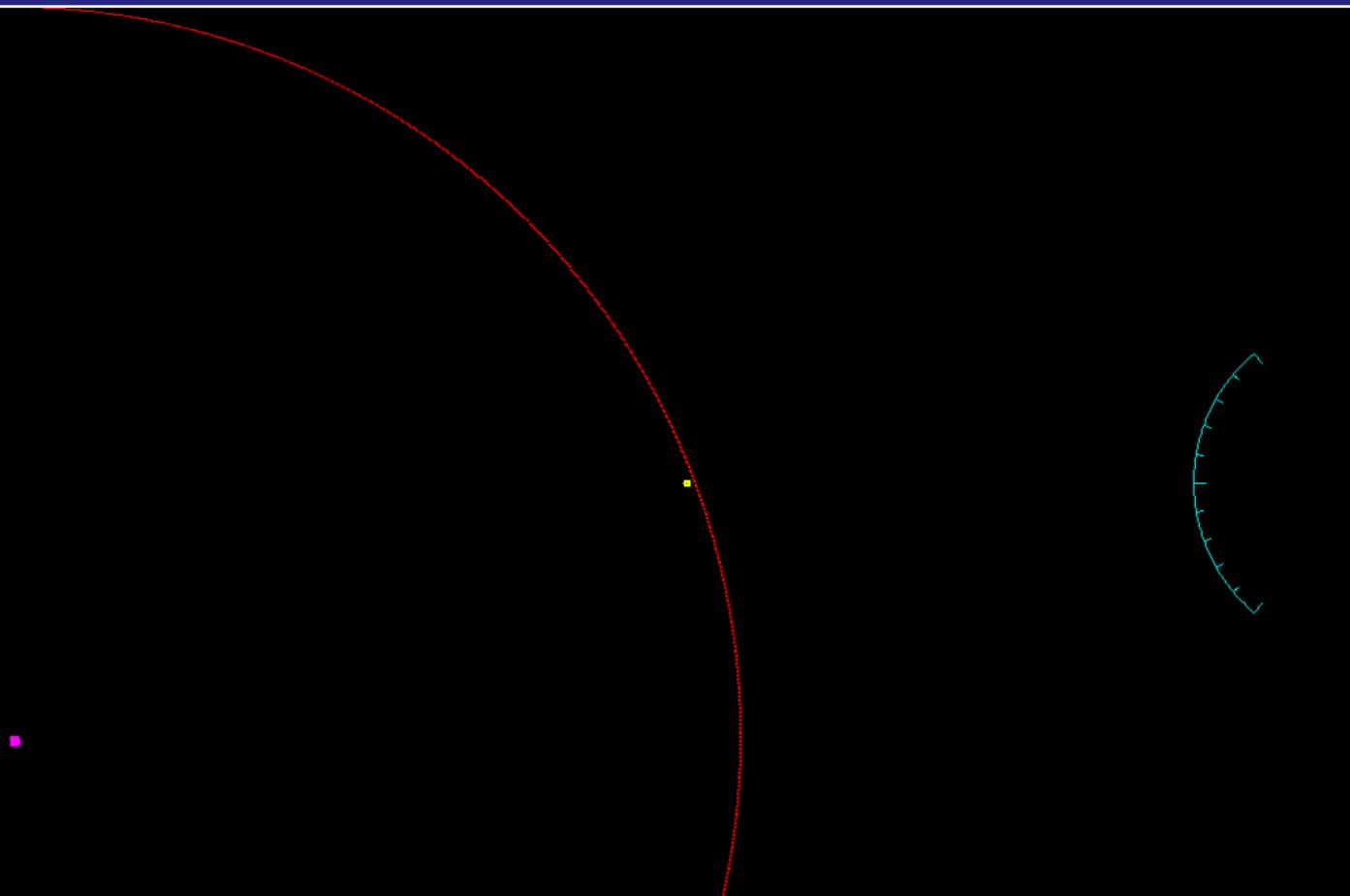


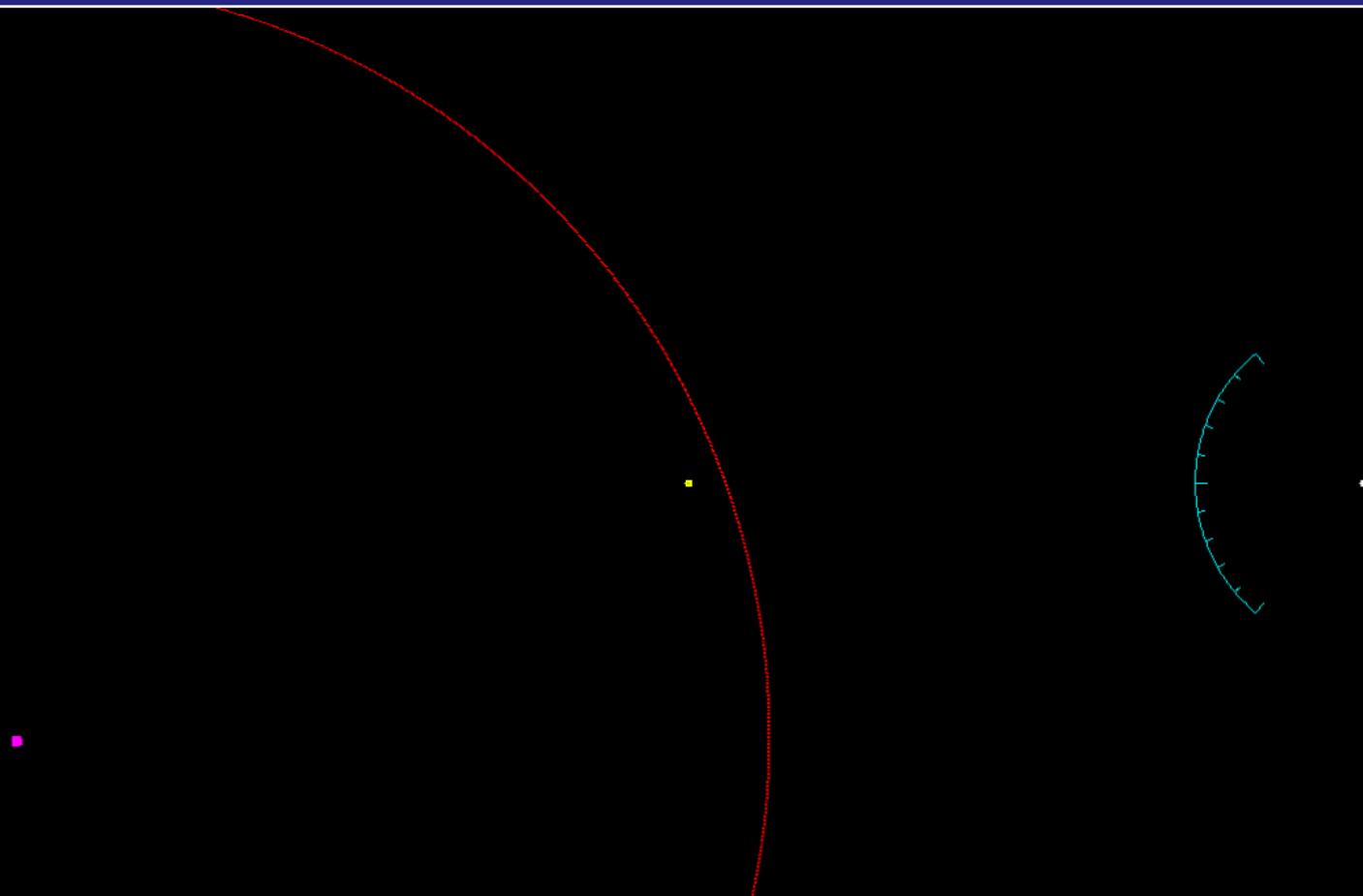


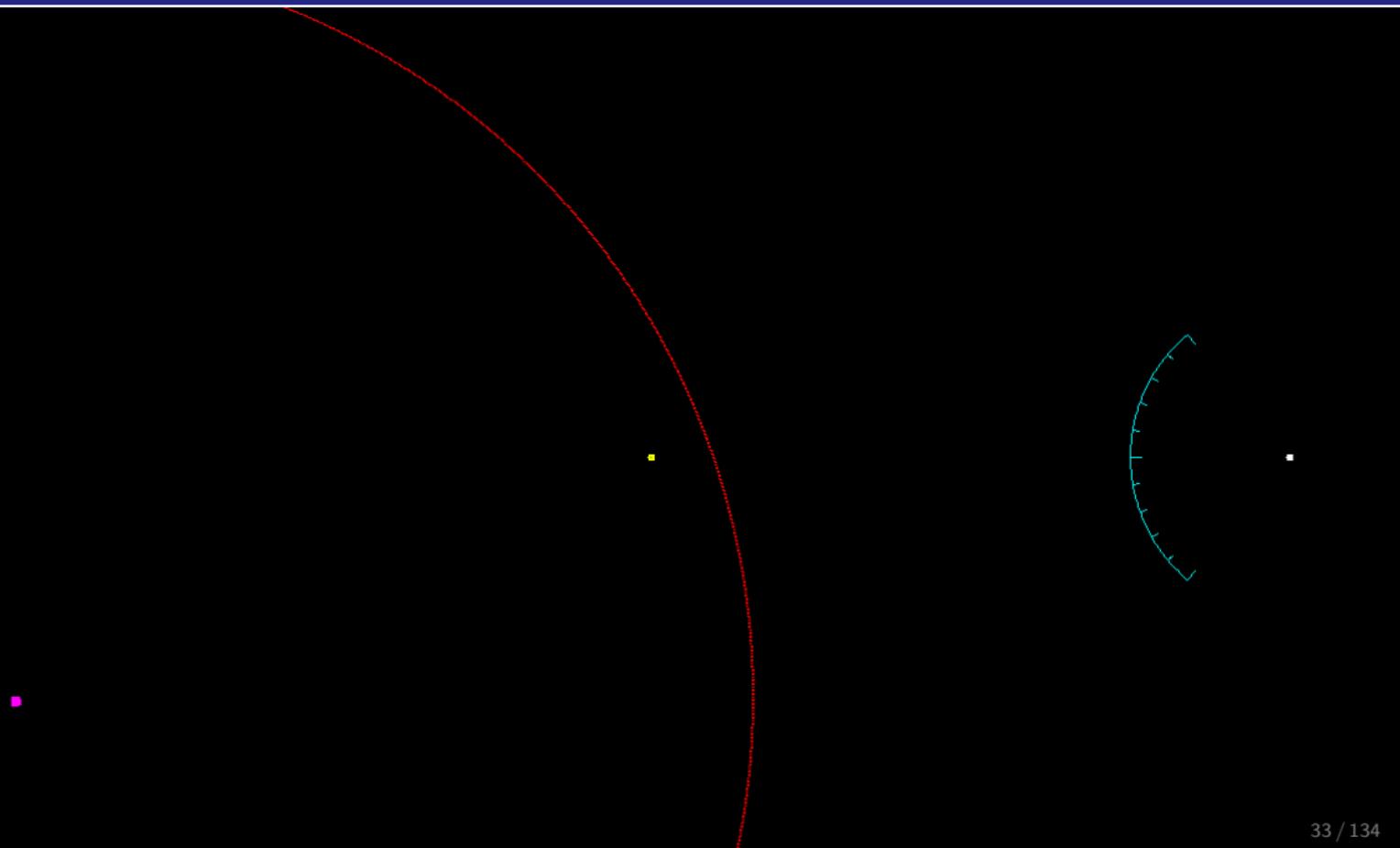


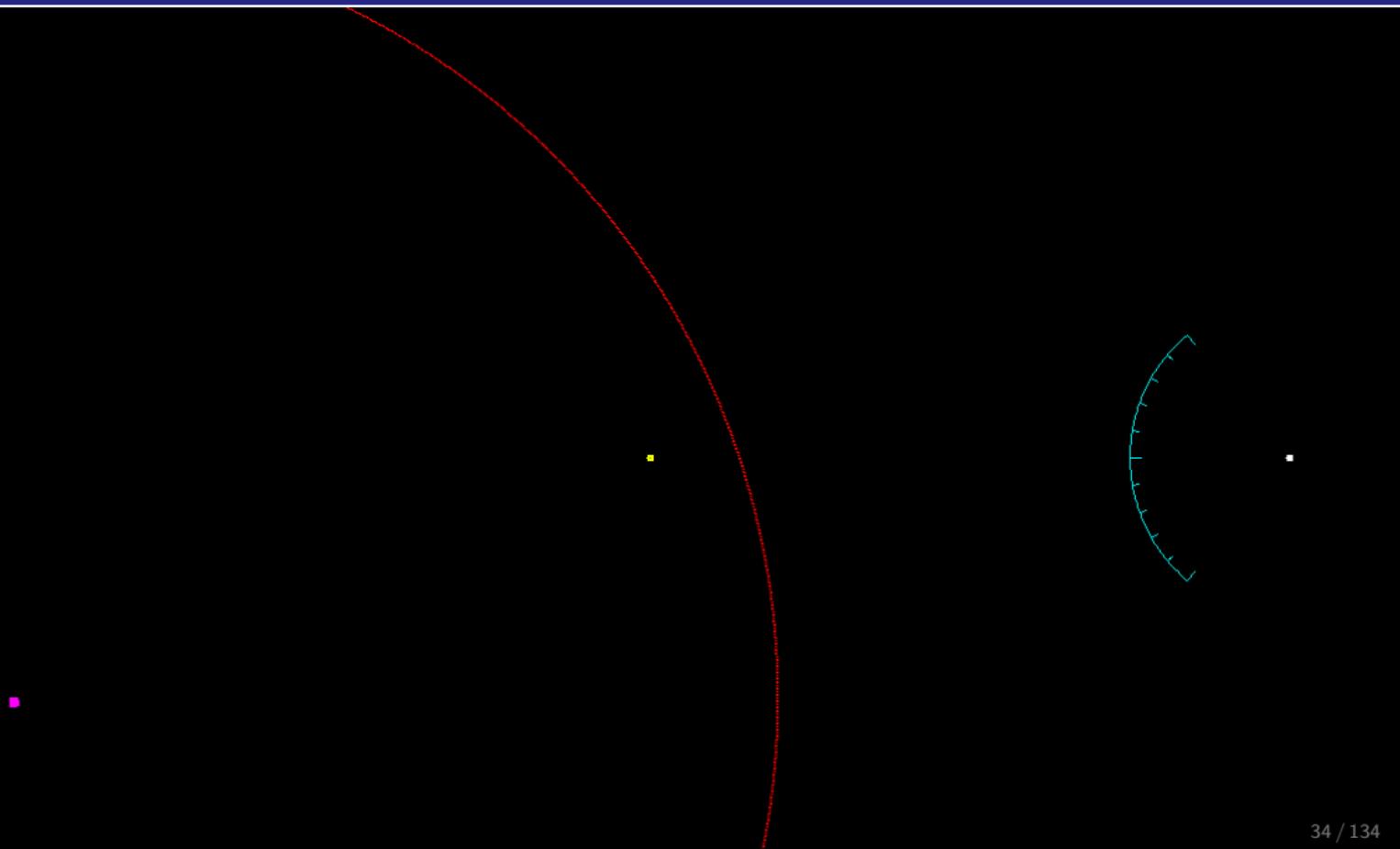


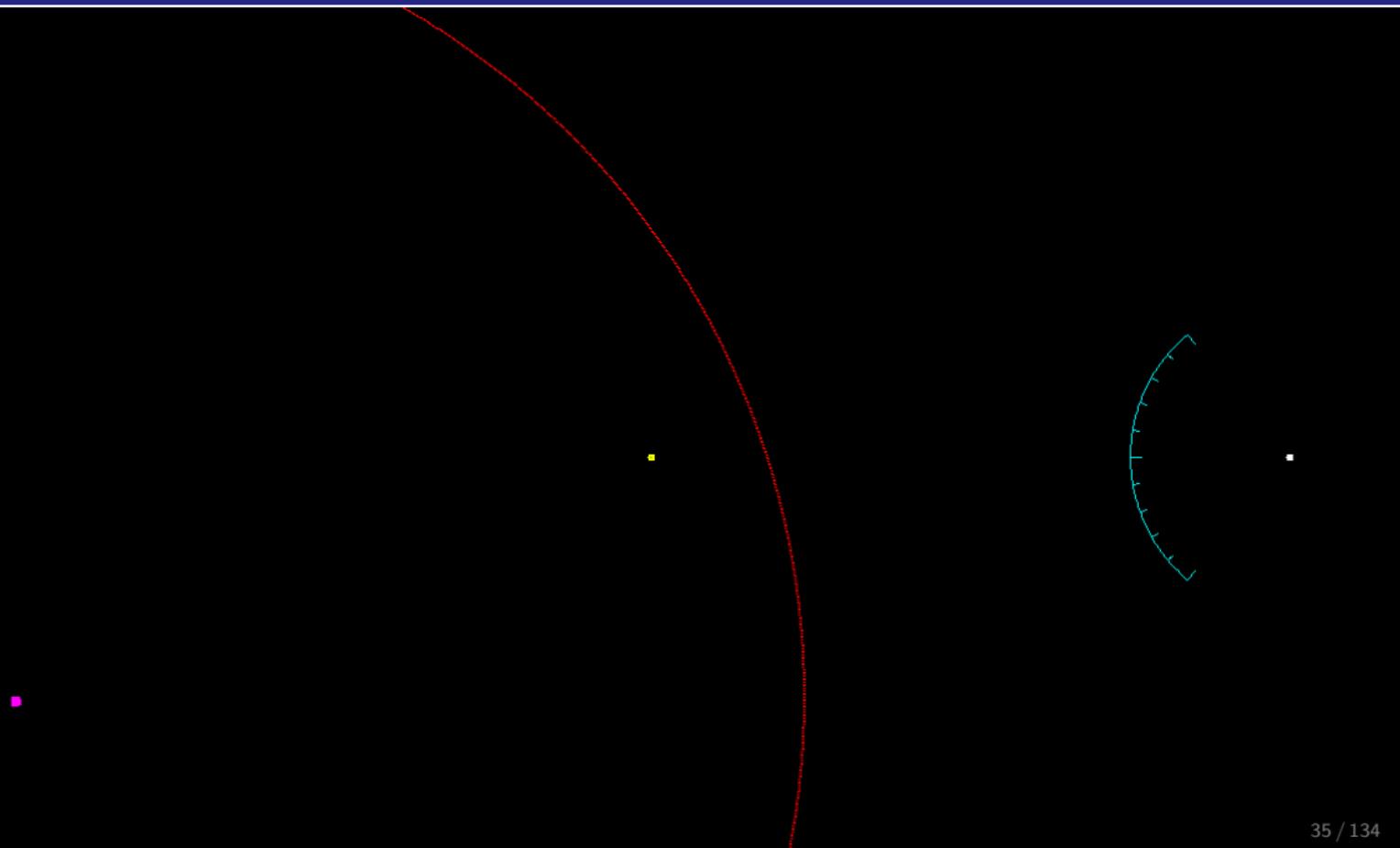




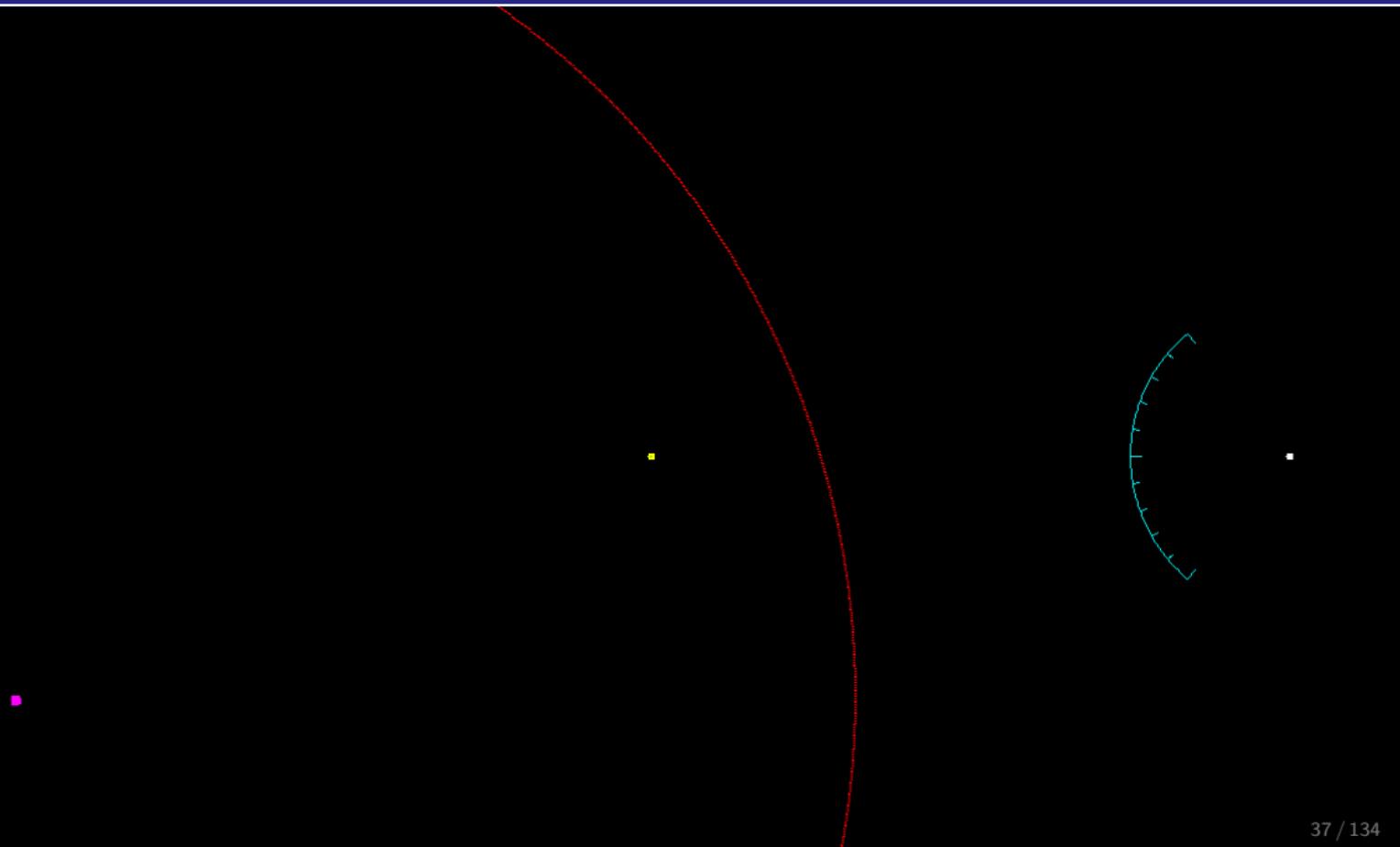


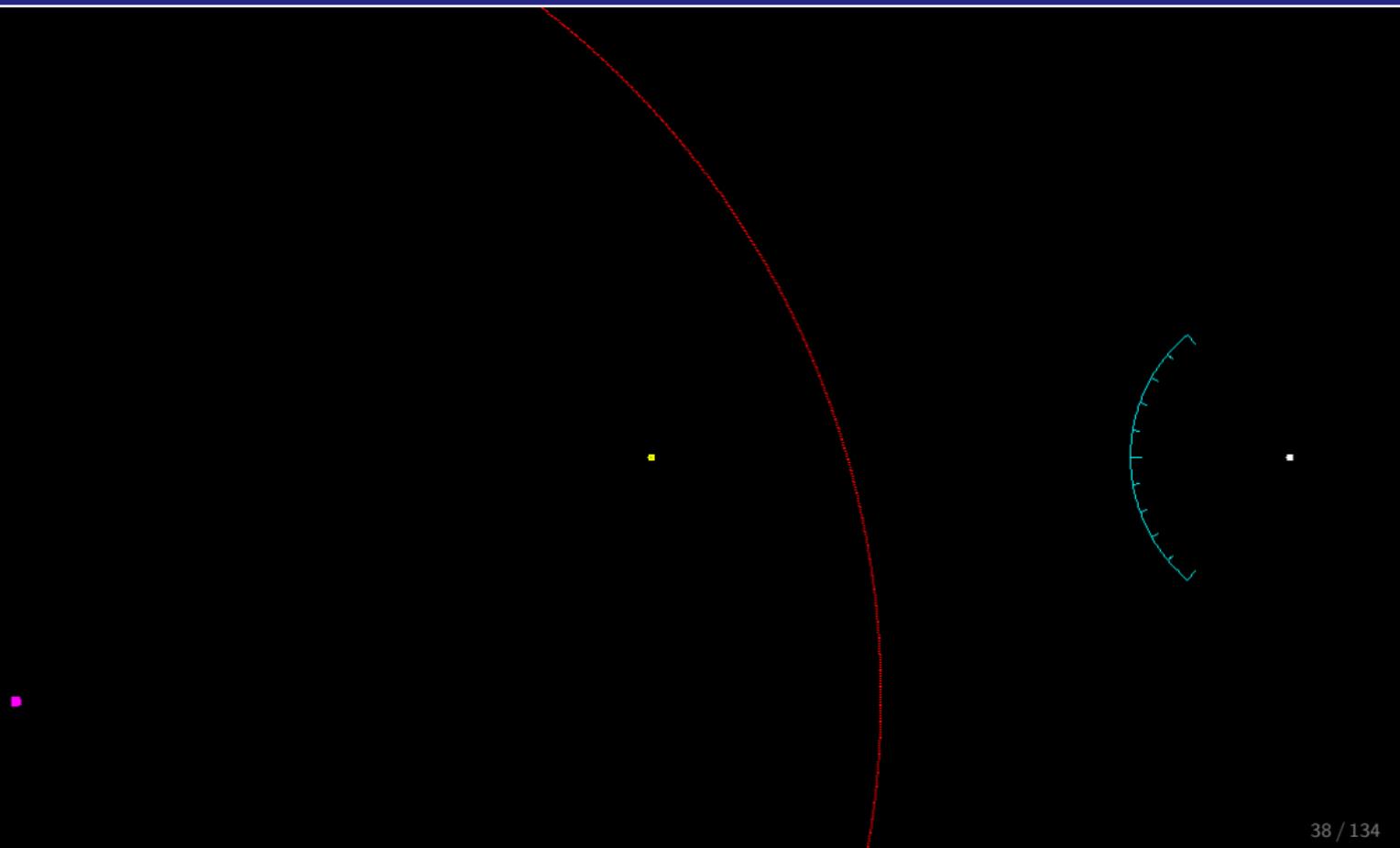


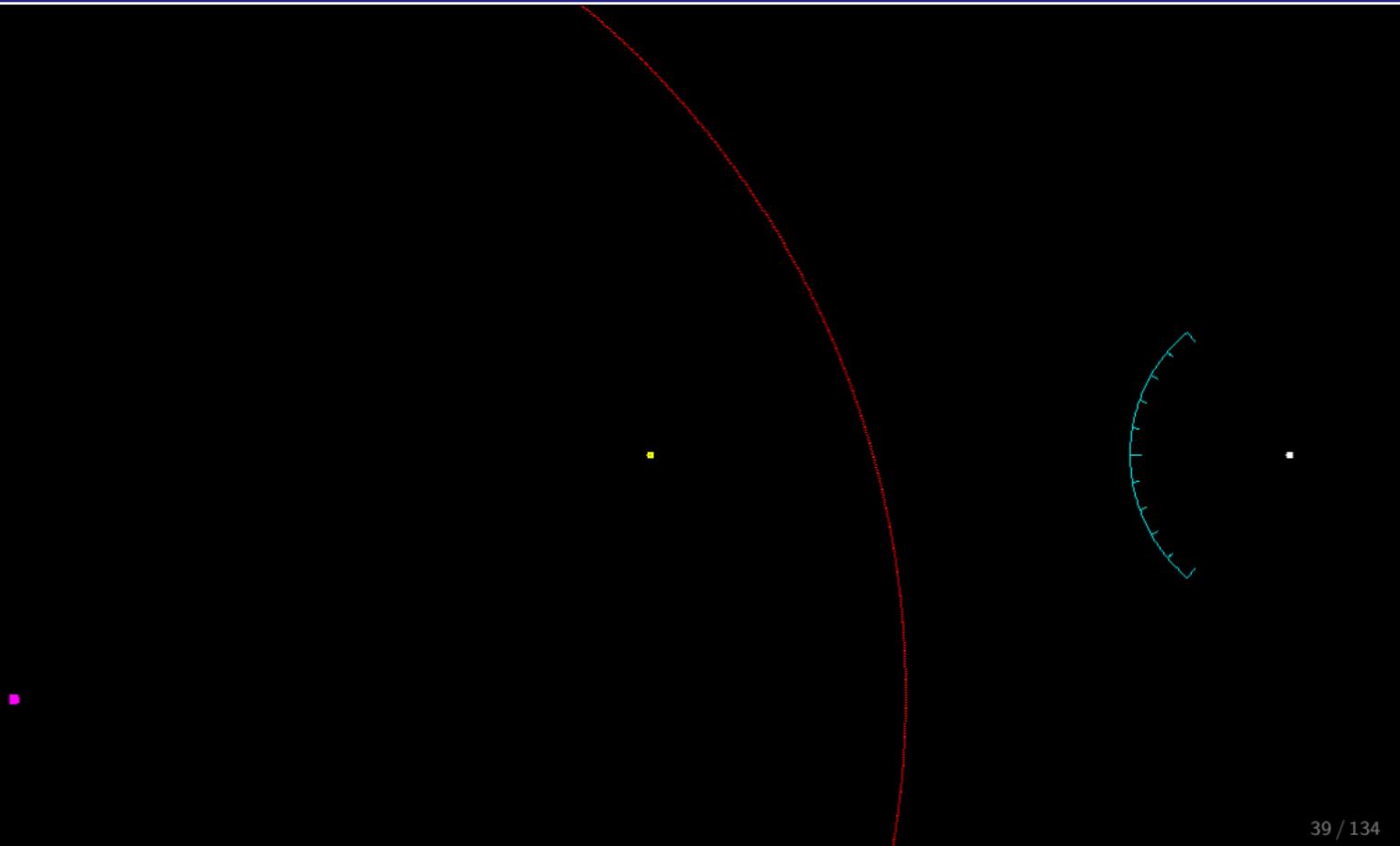


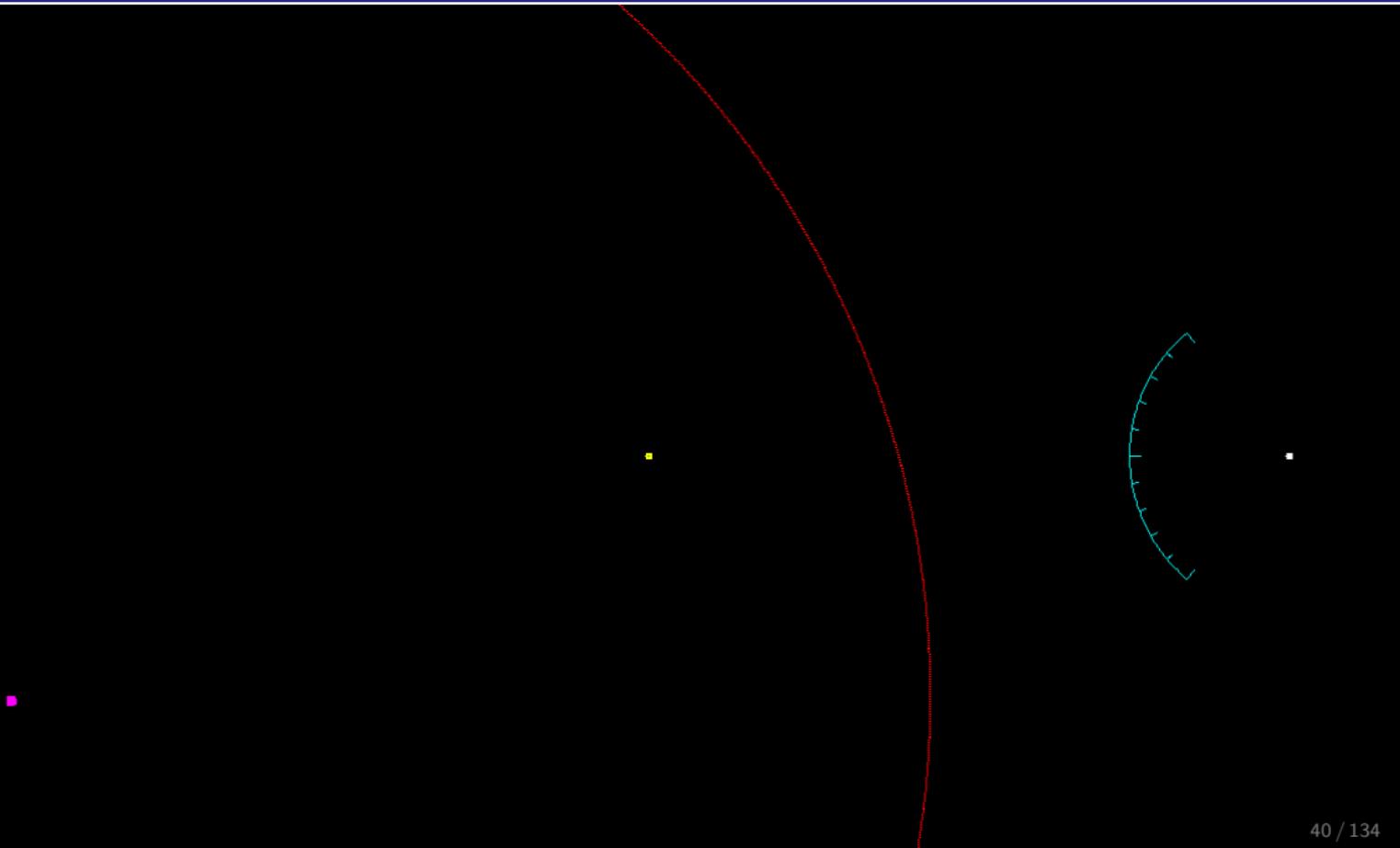


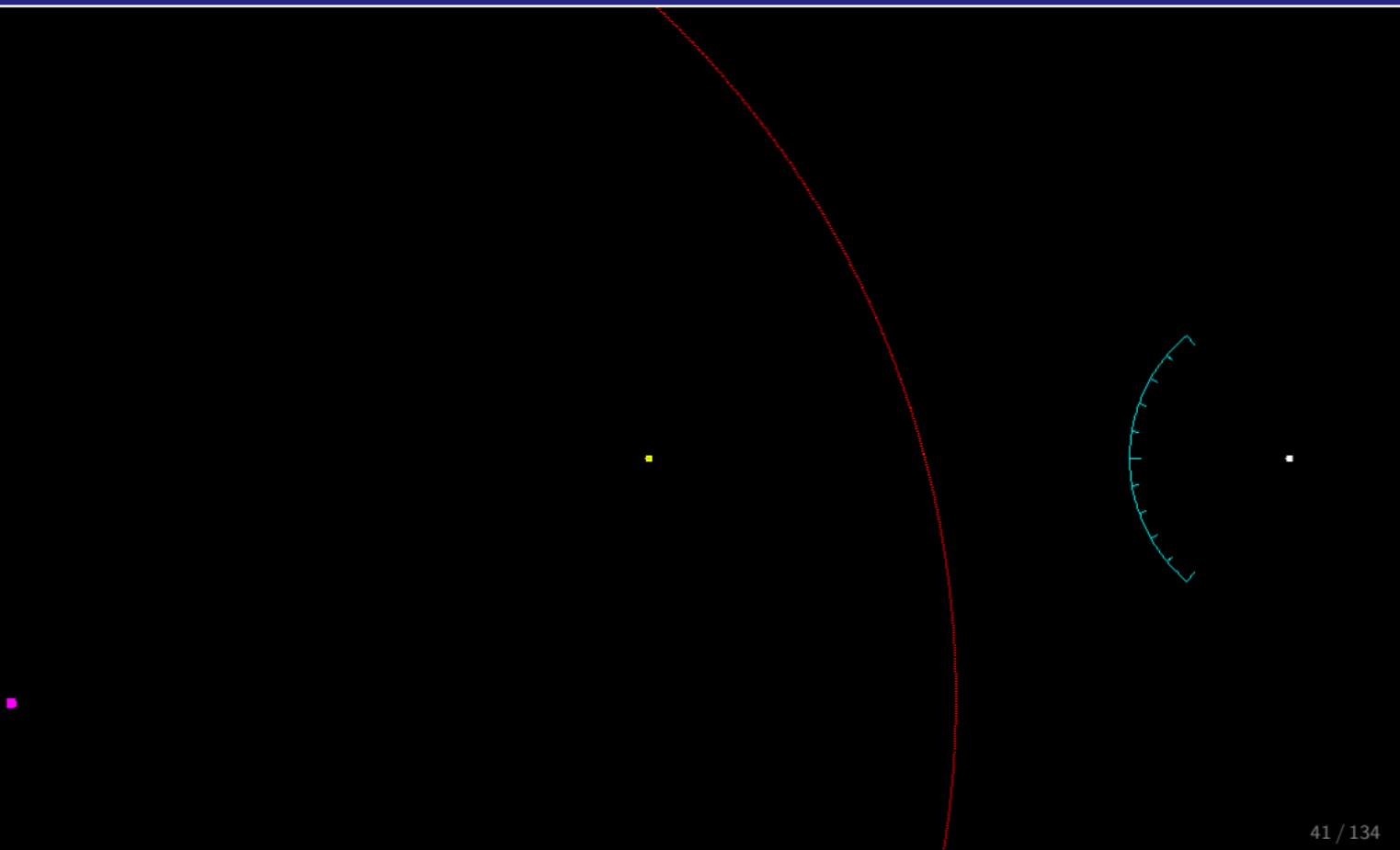


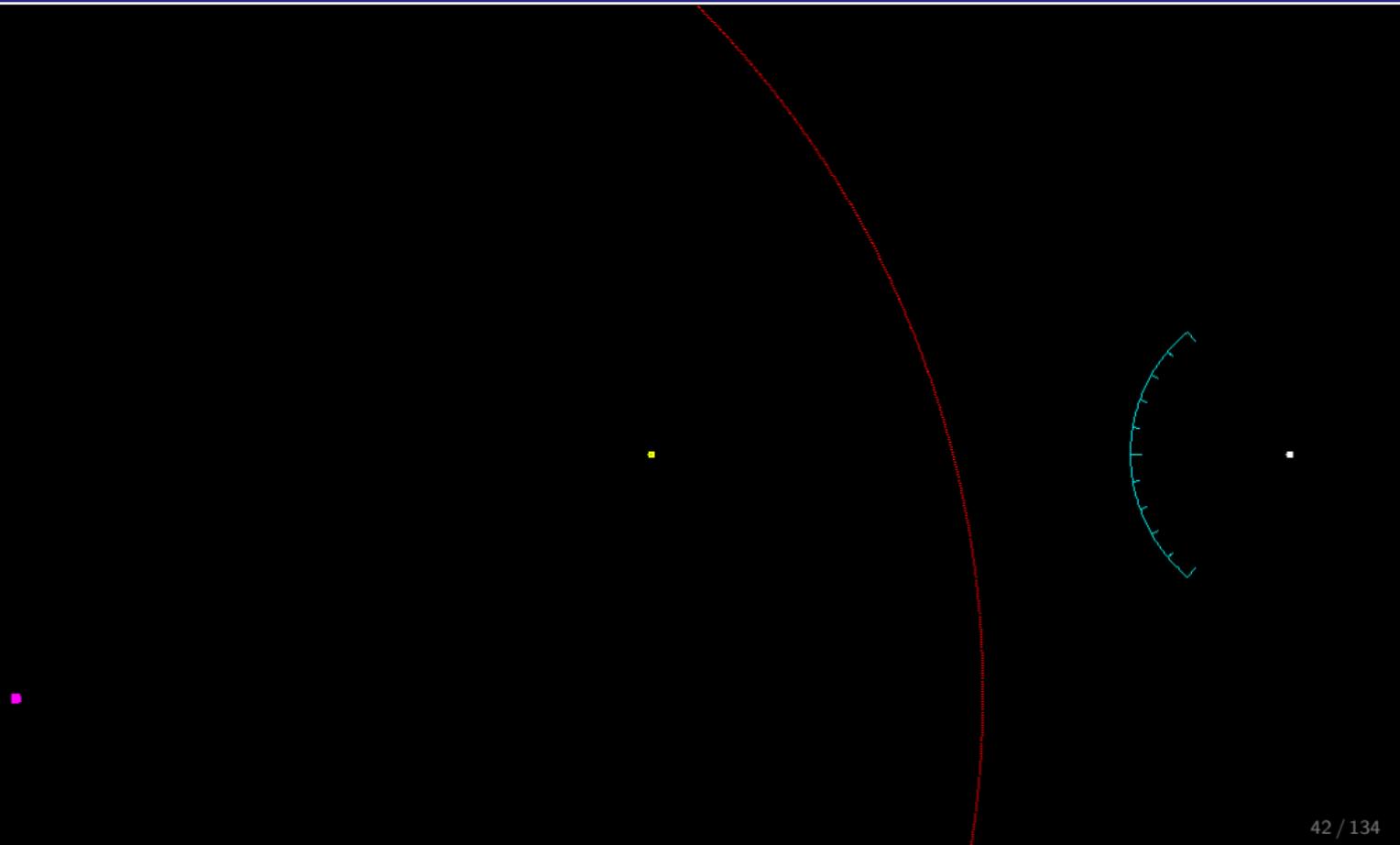




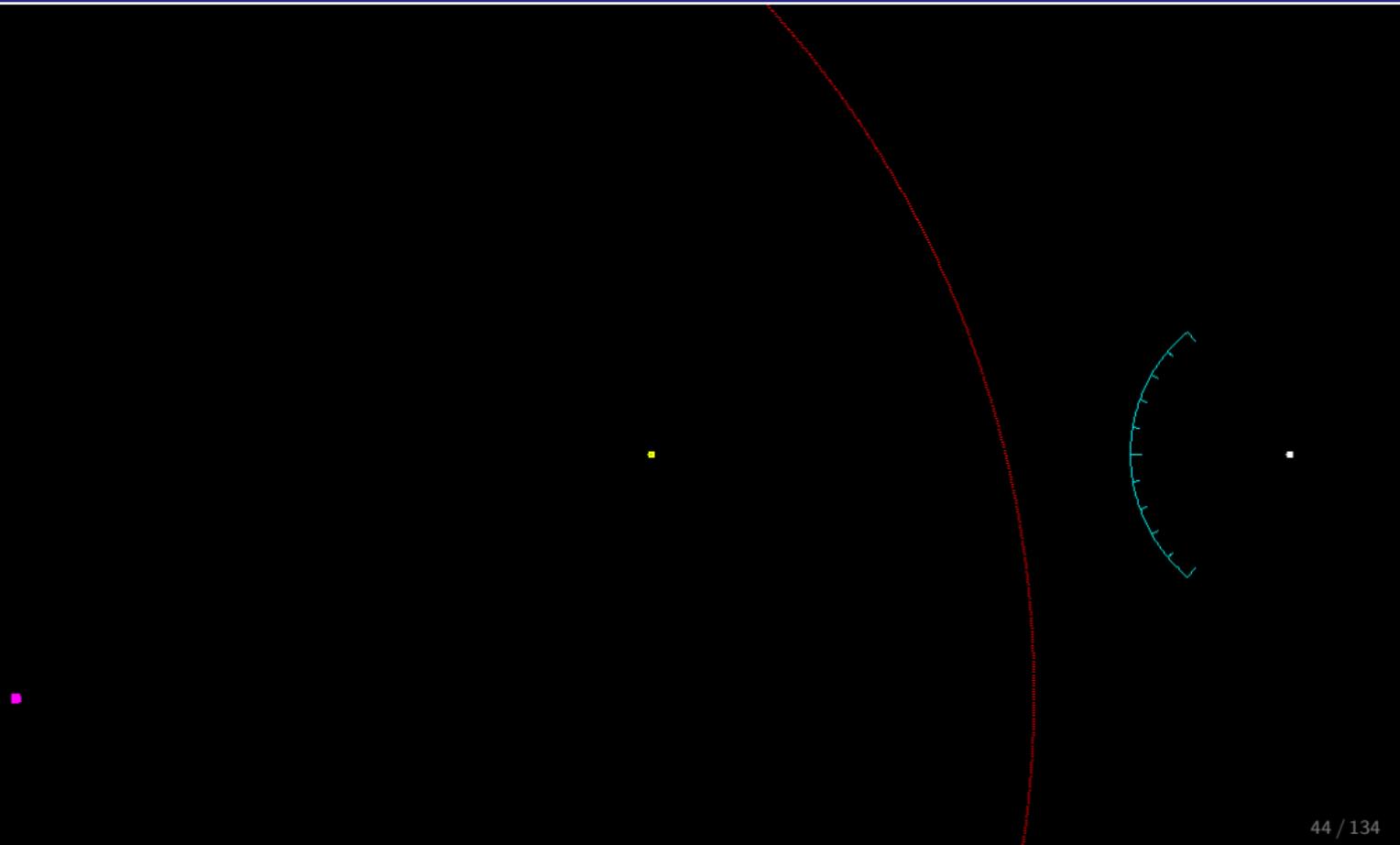






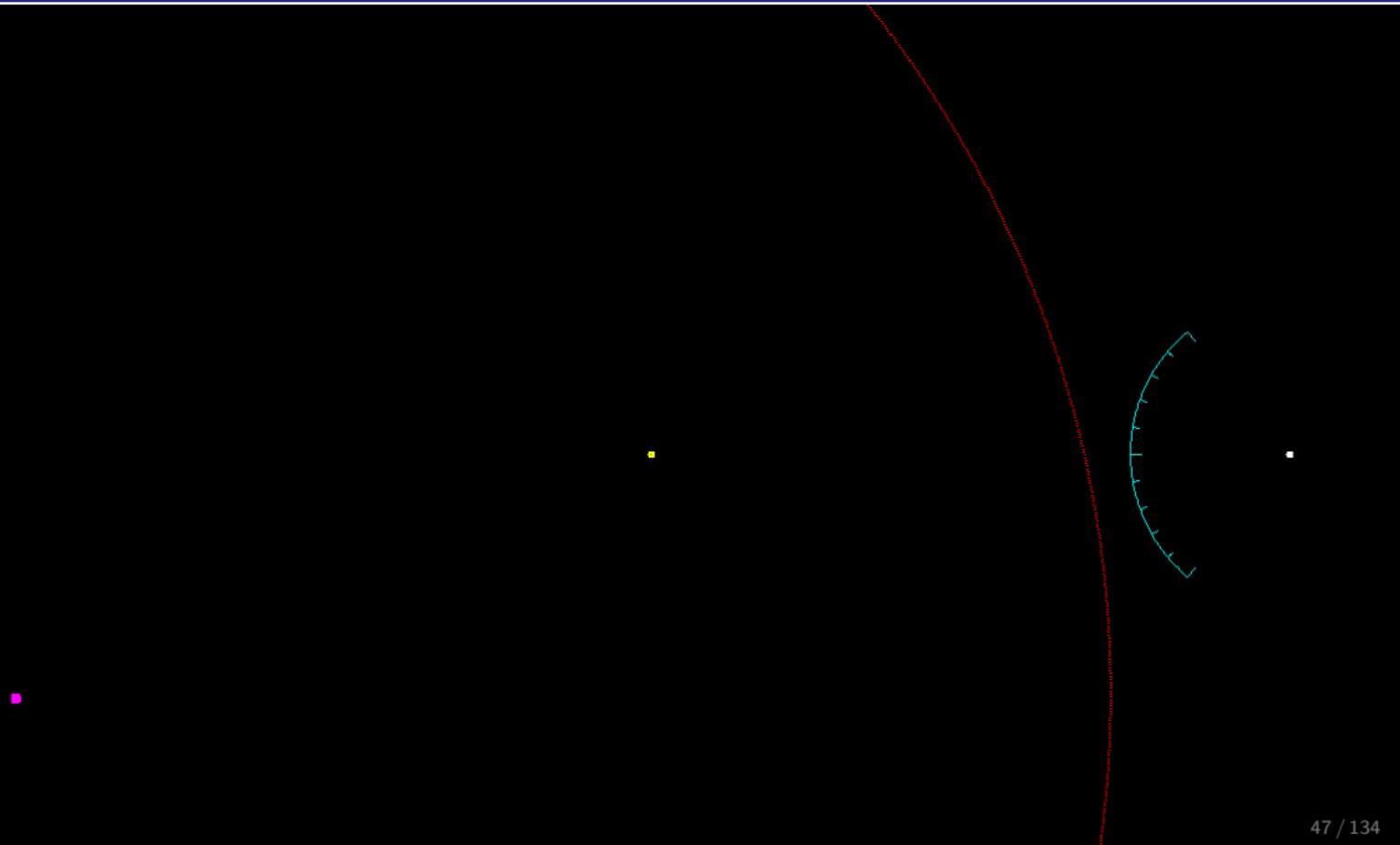


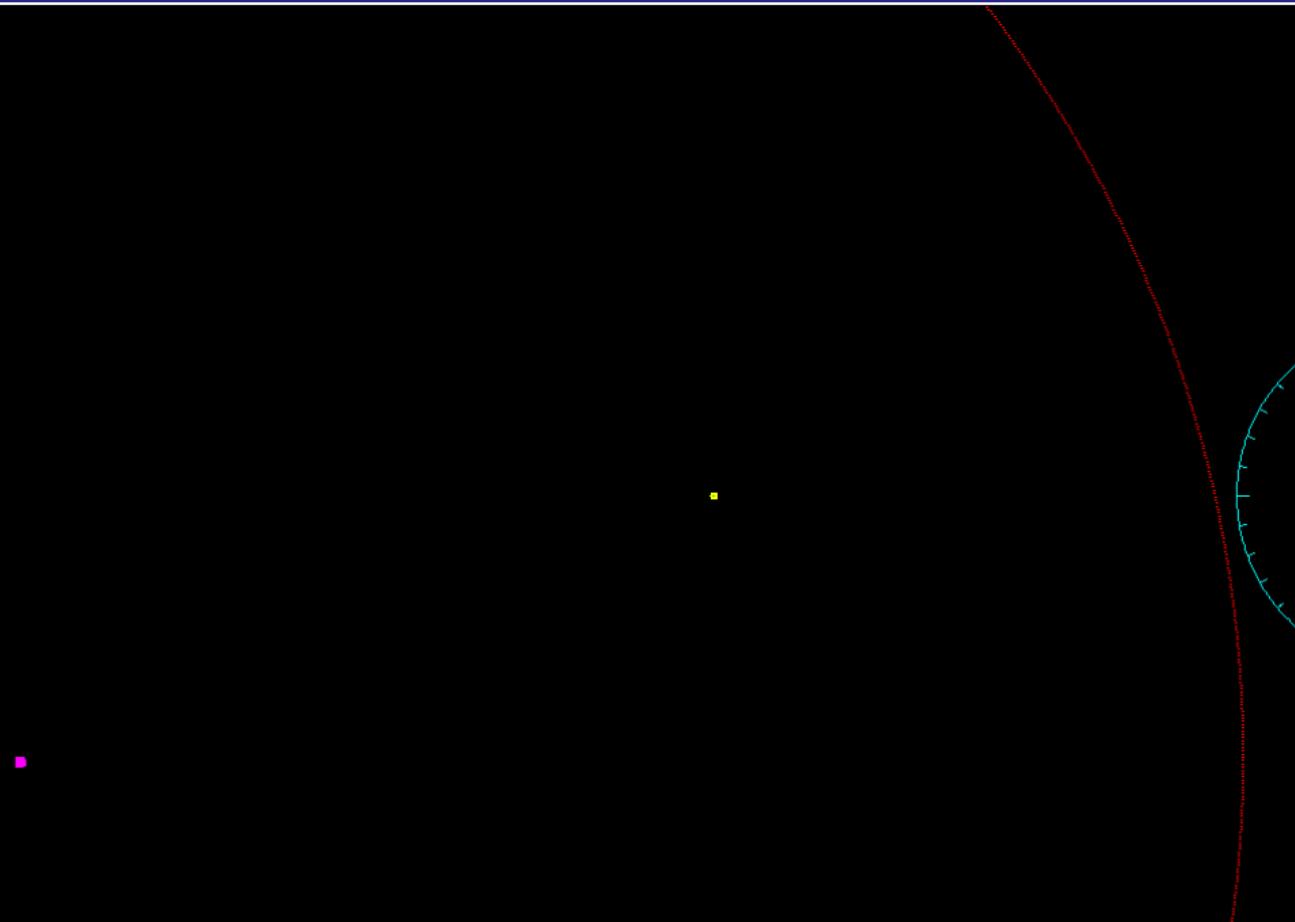


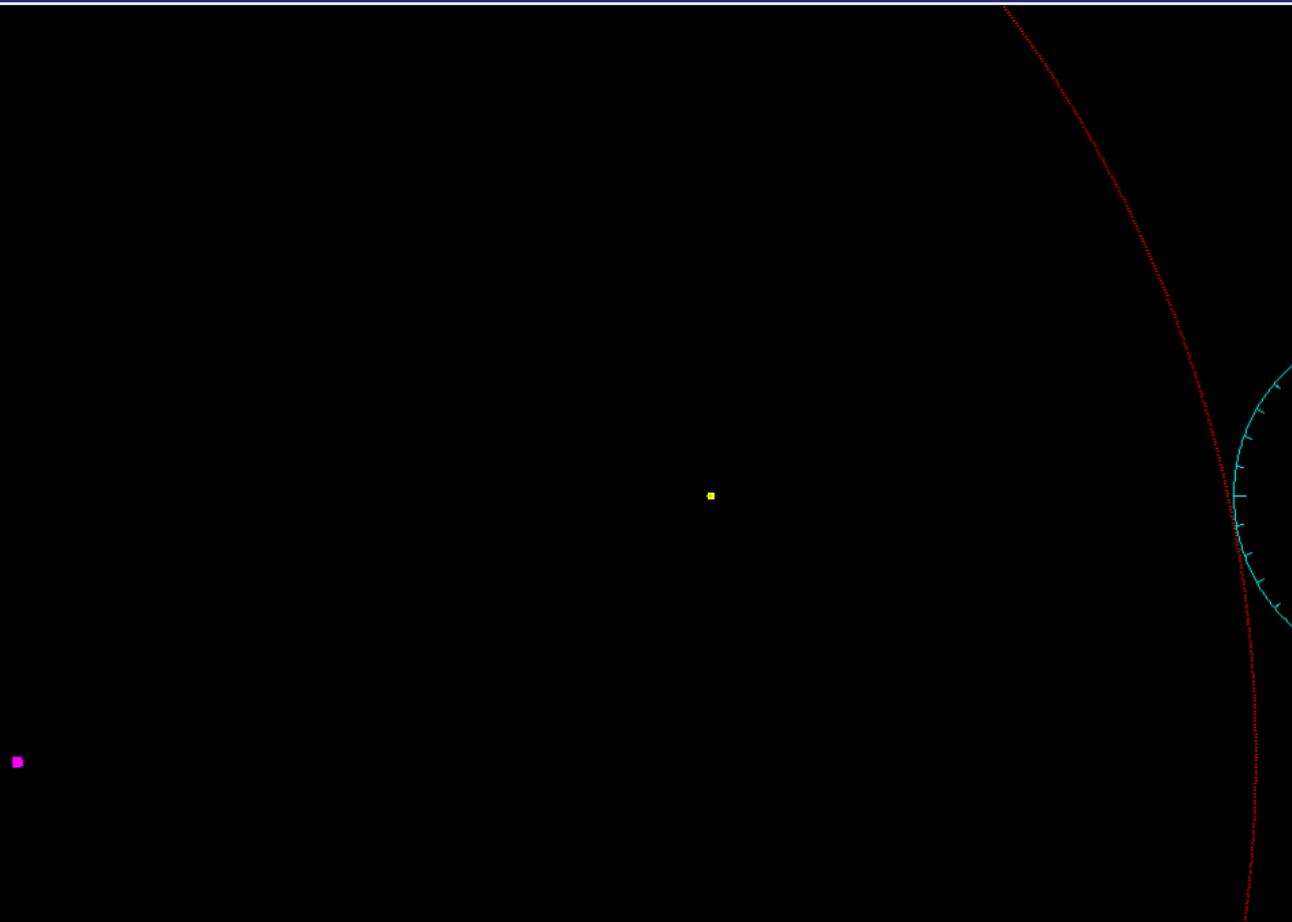


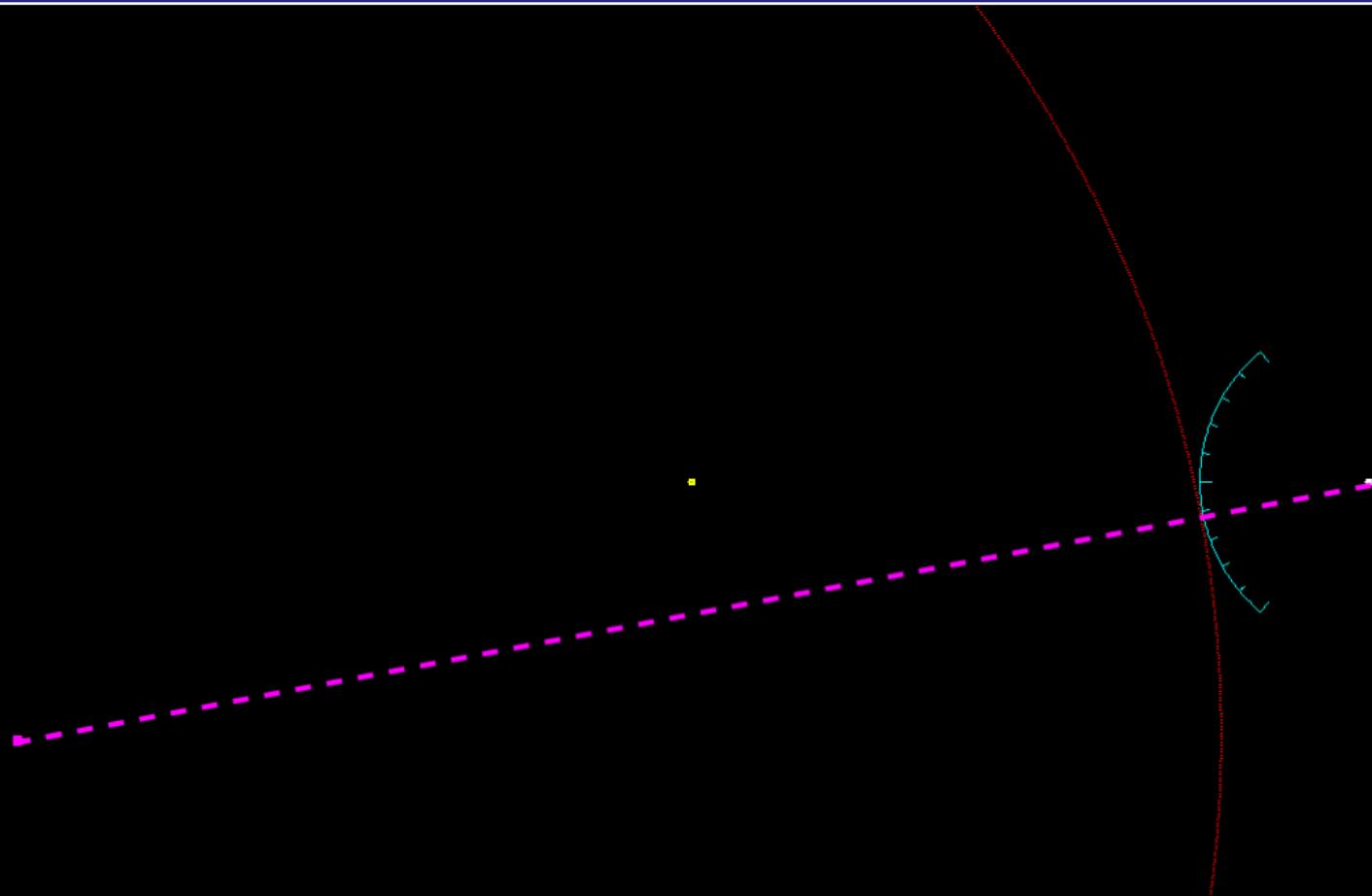


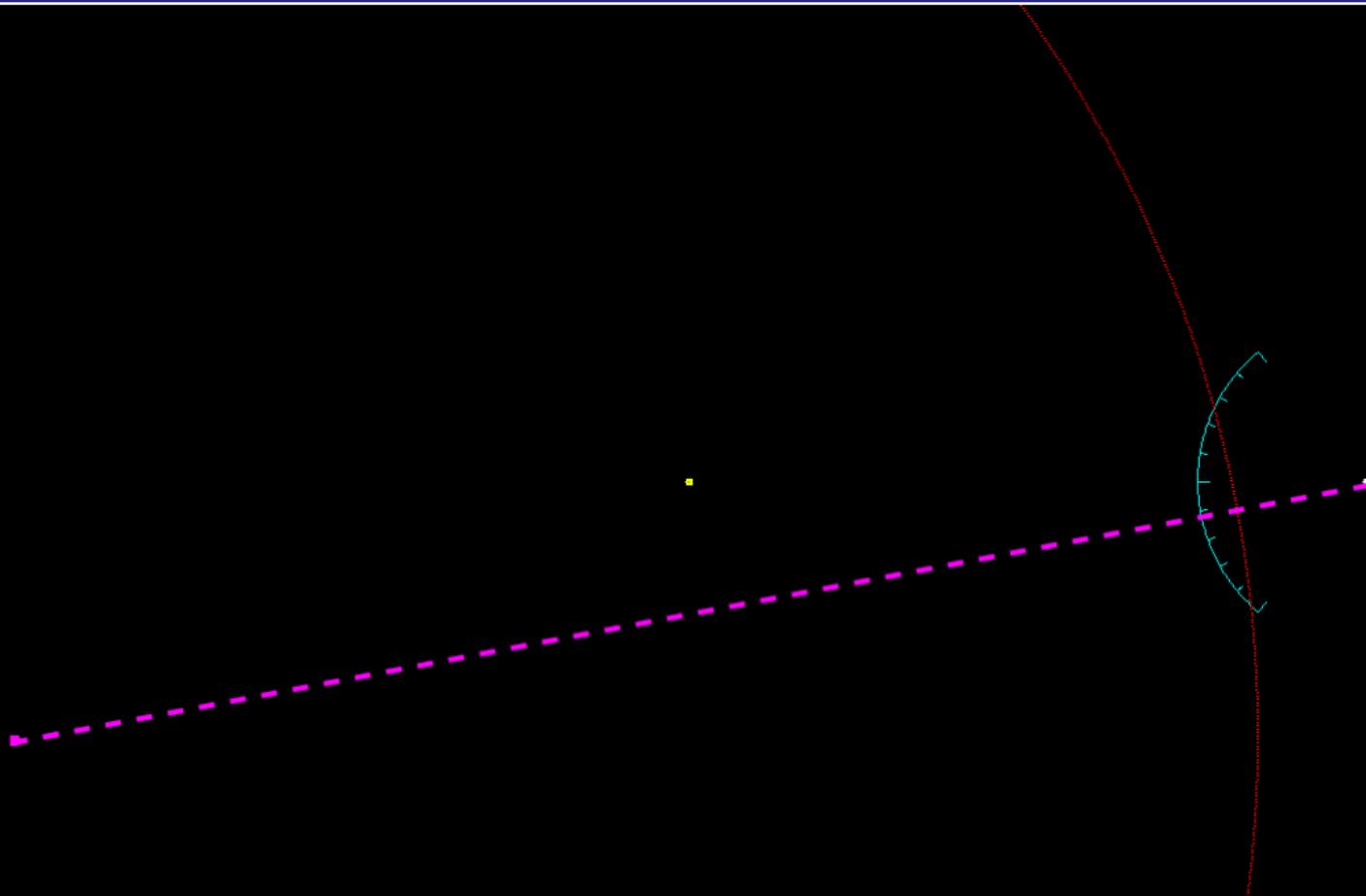


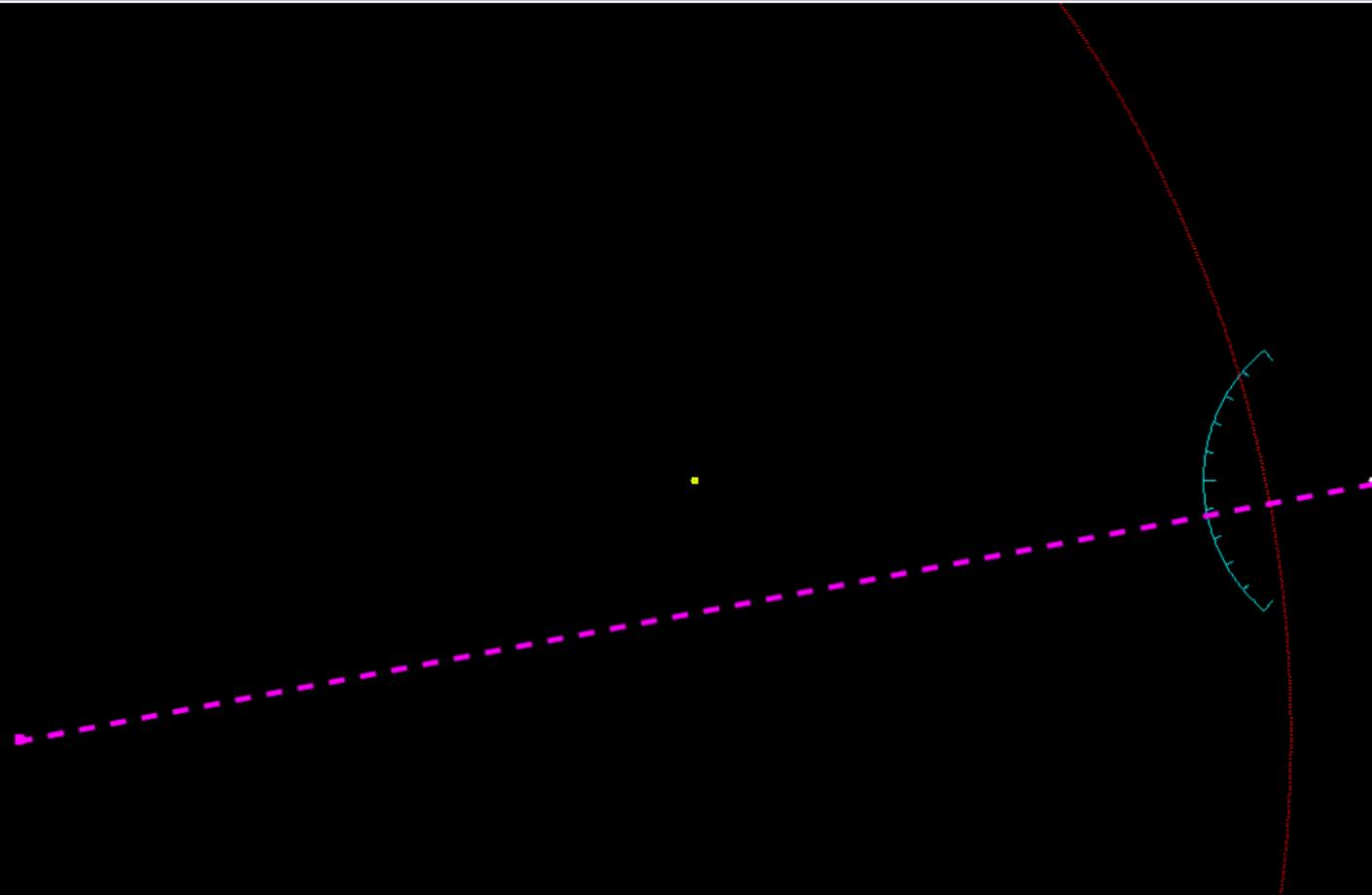


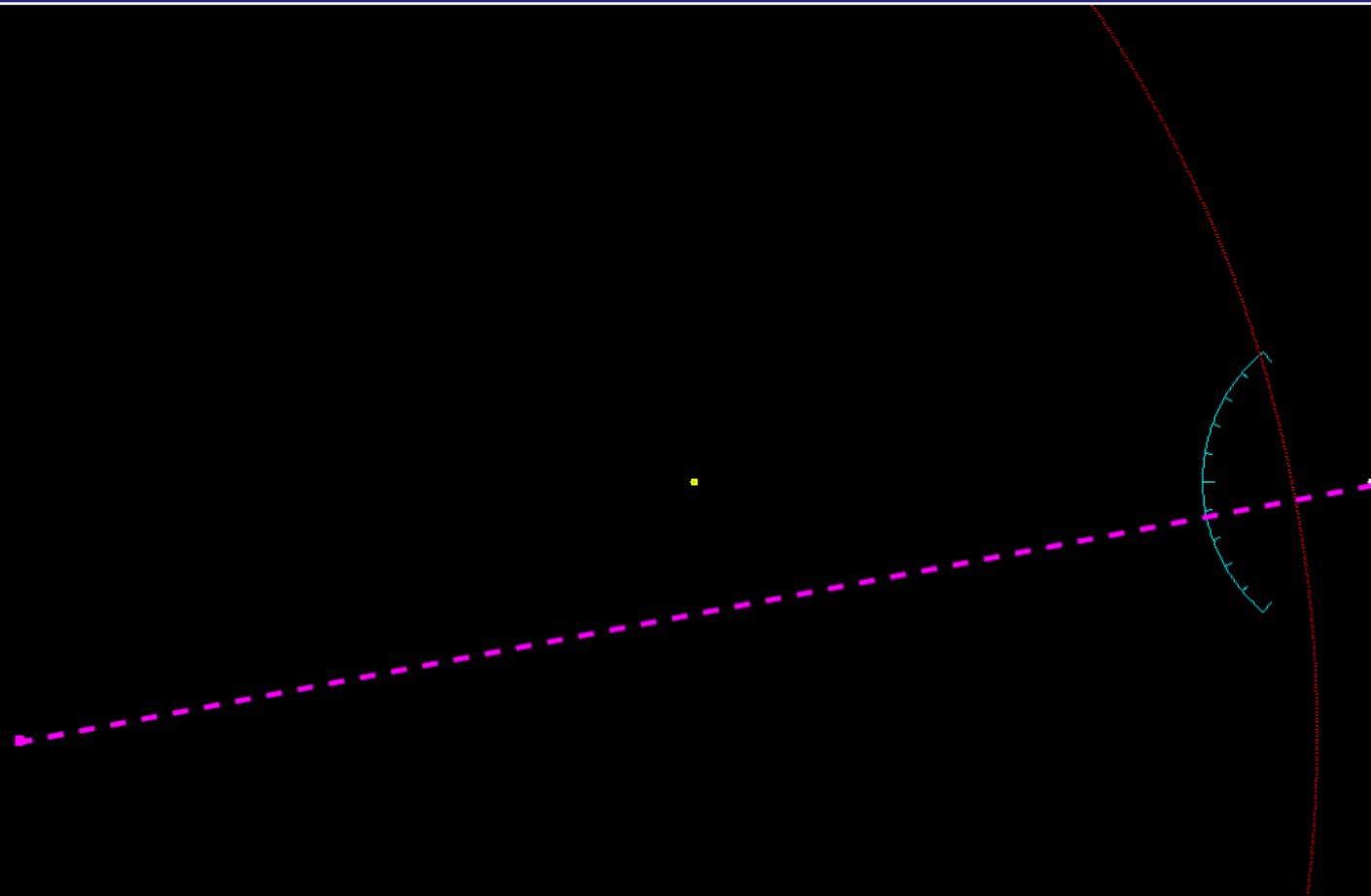


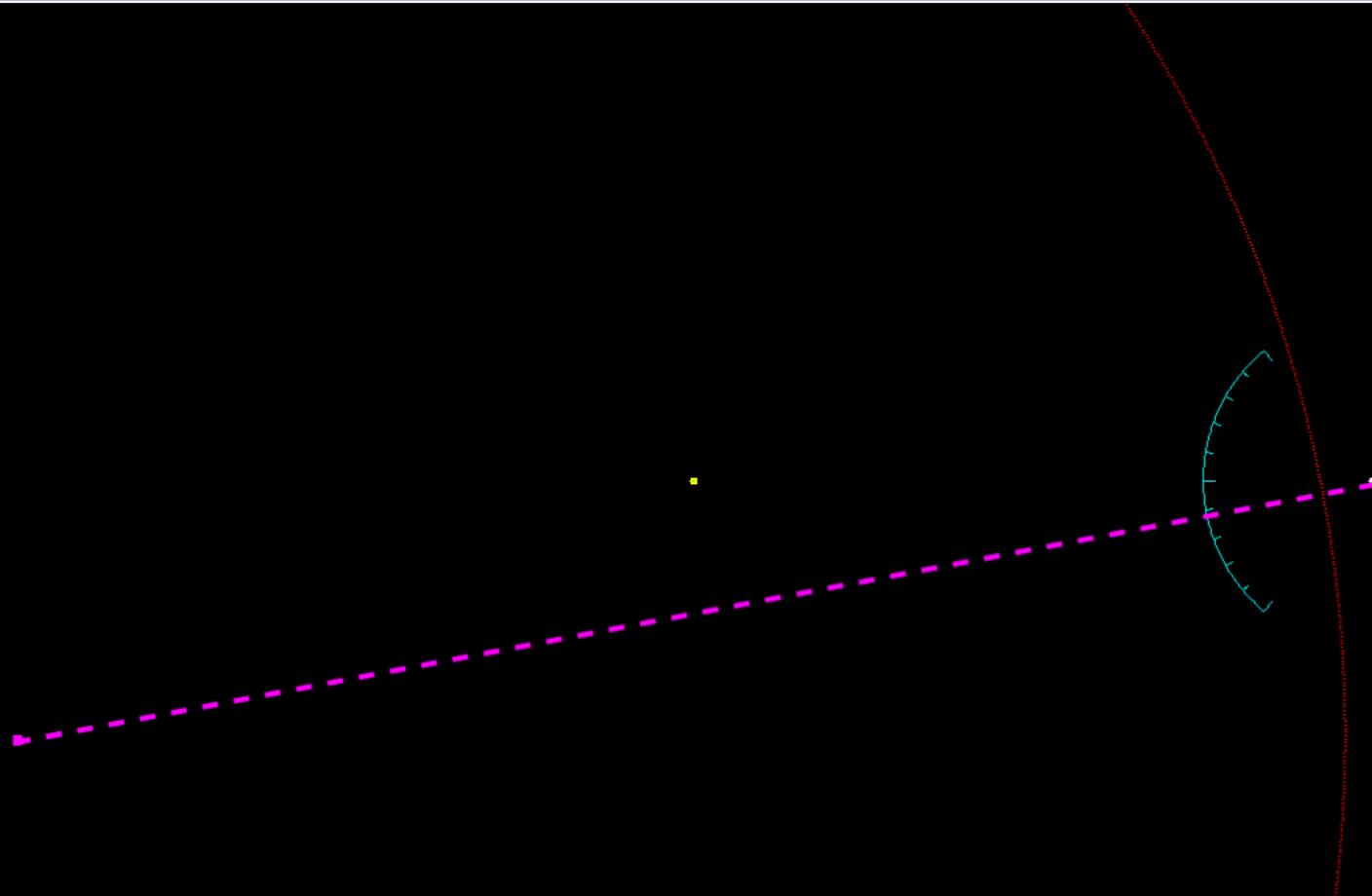


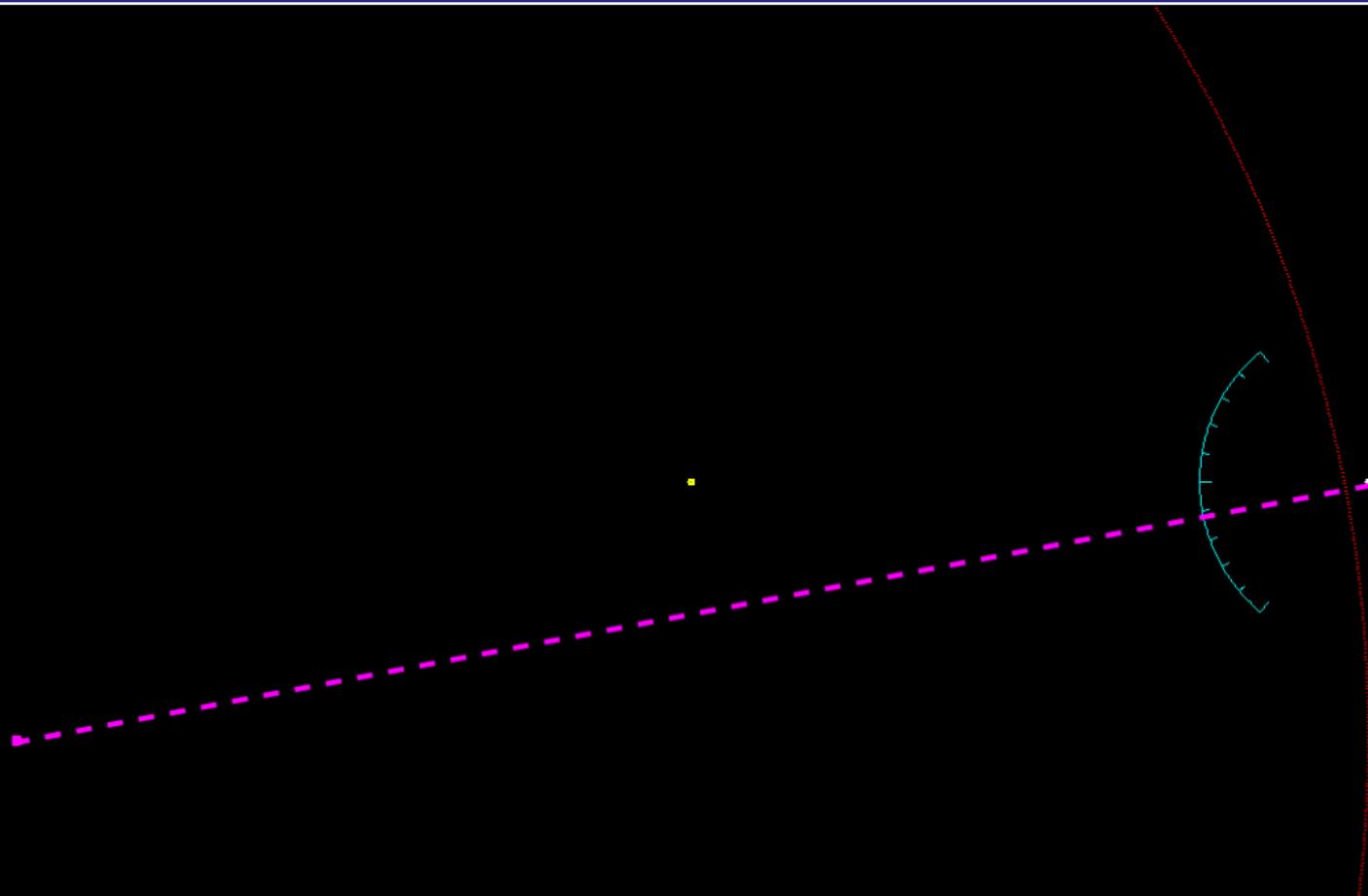










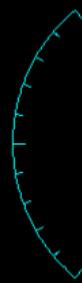


ART

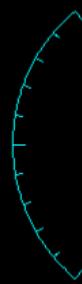
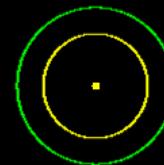
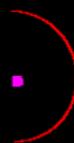
Einstein Field Equation²

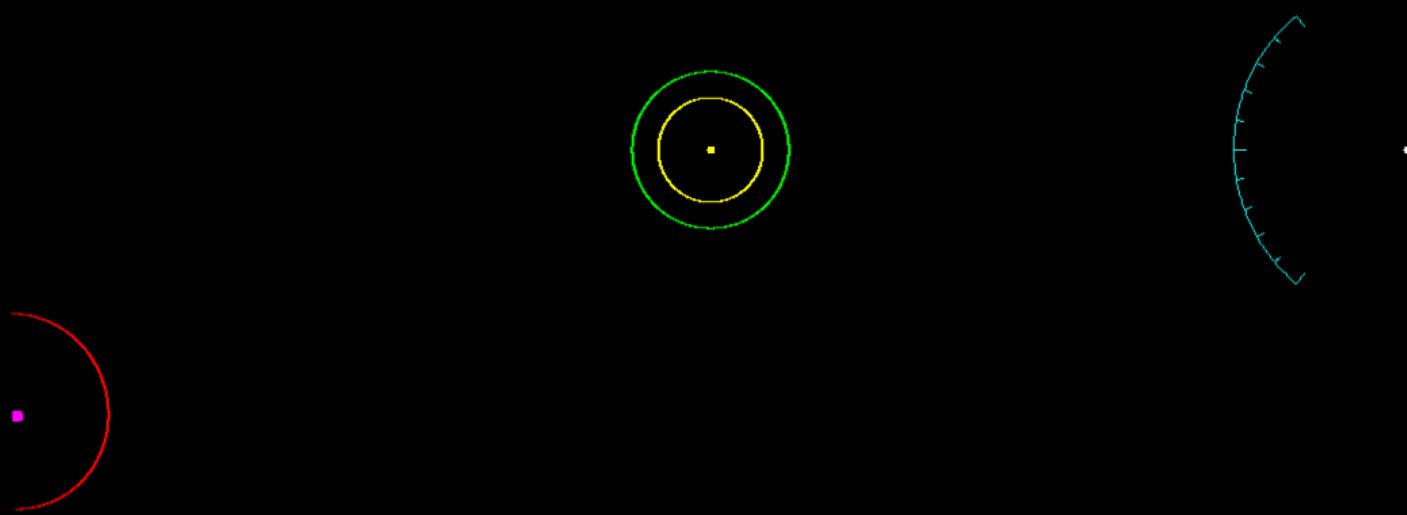
$$G_{\mu\nu} = \Lambda g_{\mu\nu} + 8\pi G T_{\mu\nu}$$

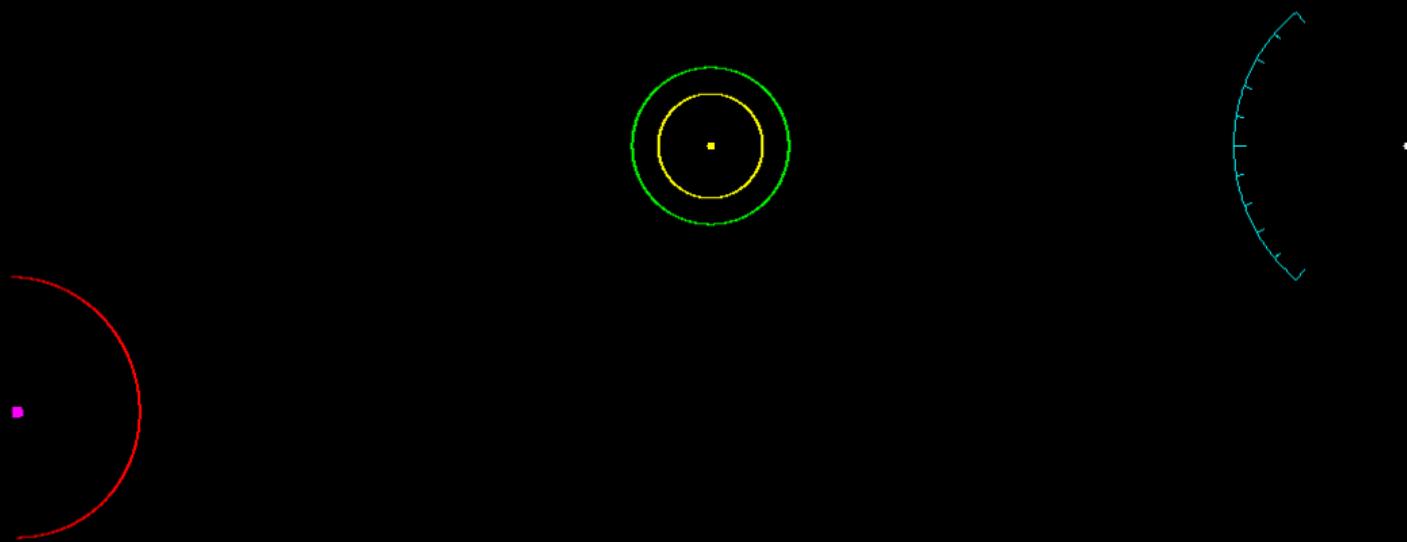
²The Wall, ITP UZH

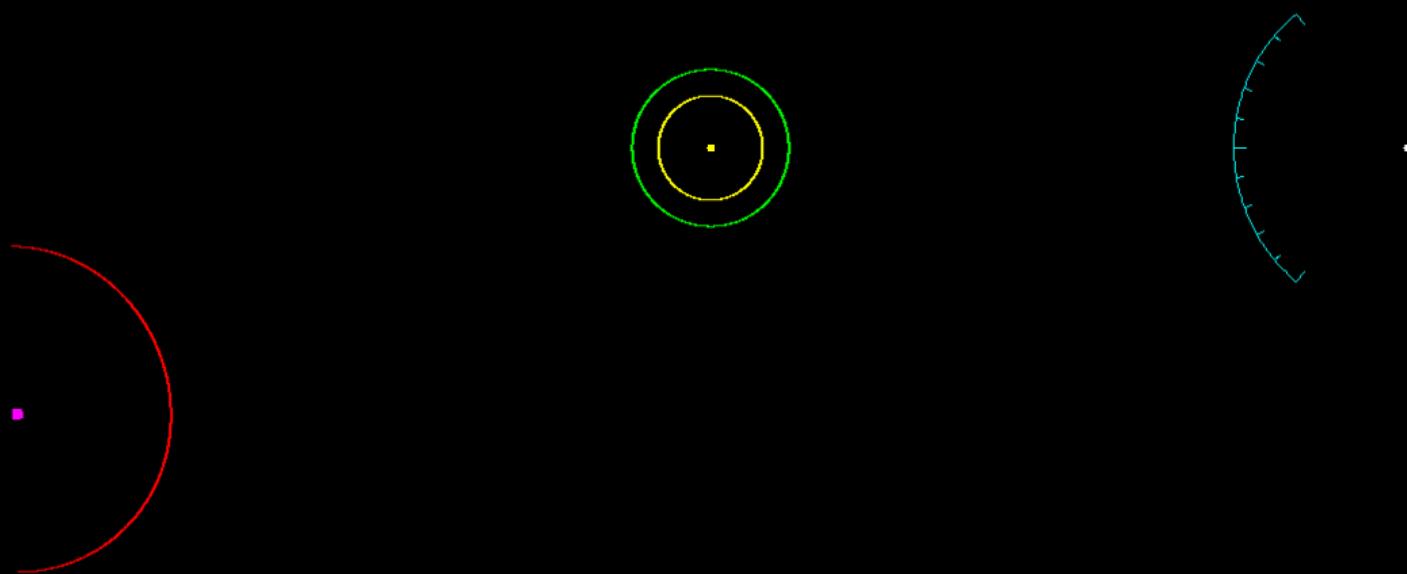


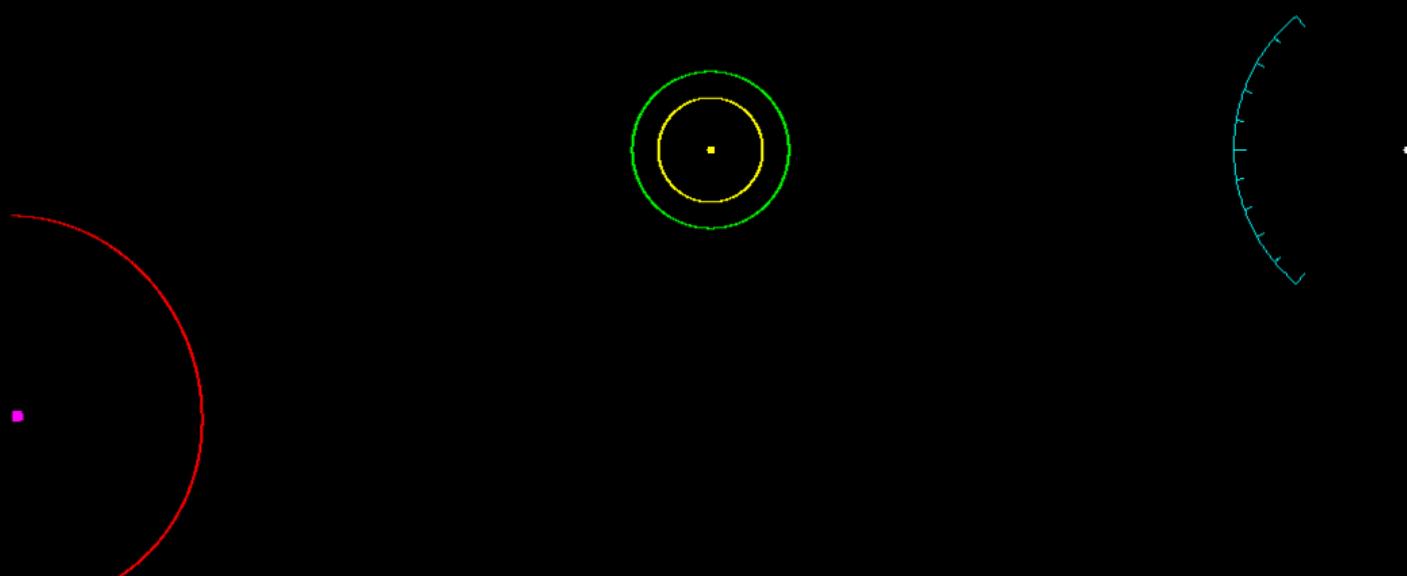
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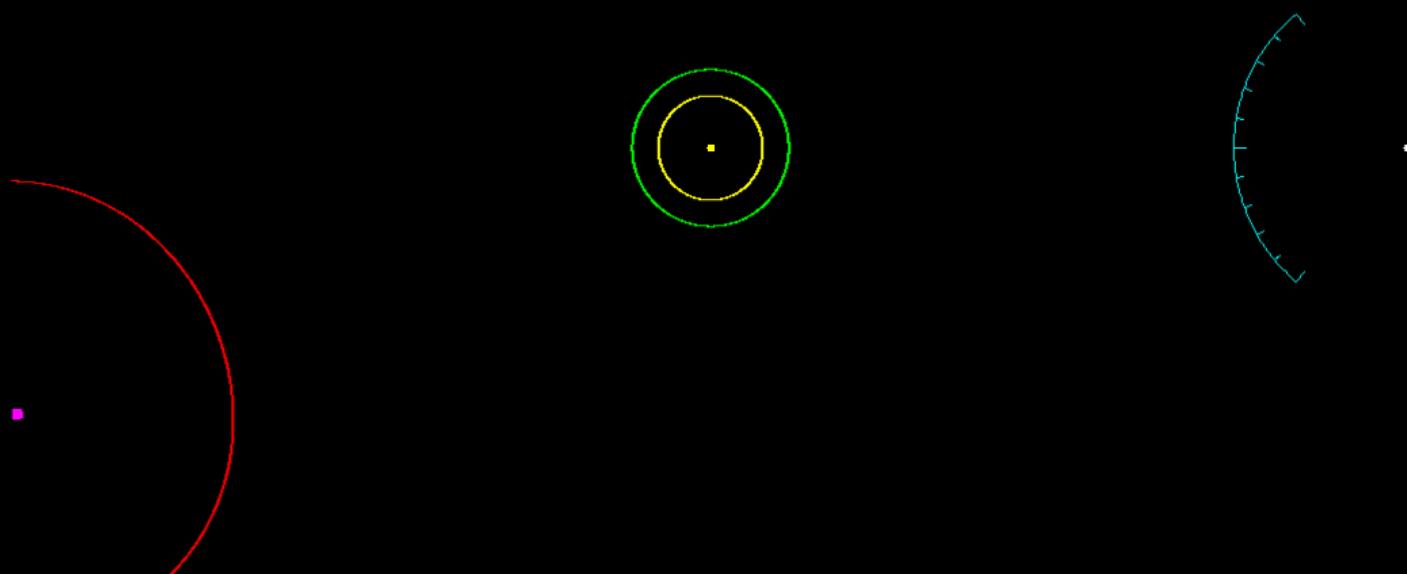


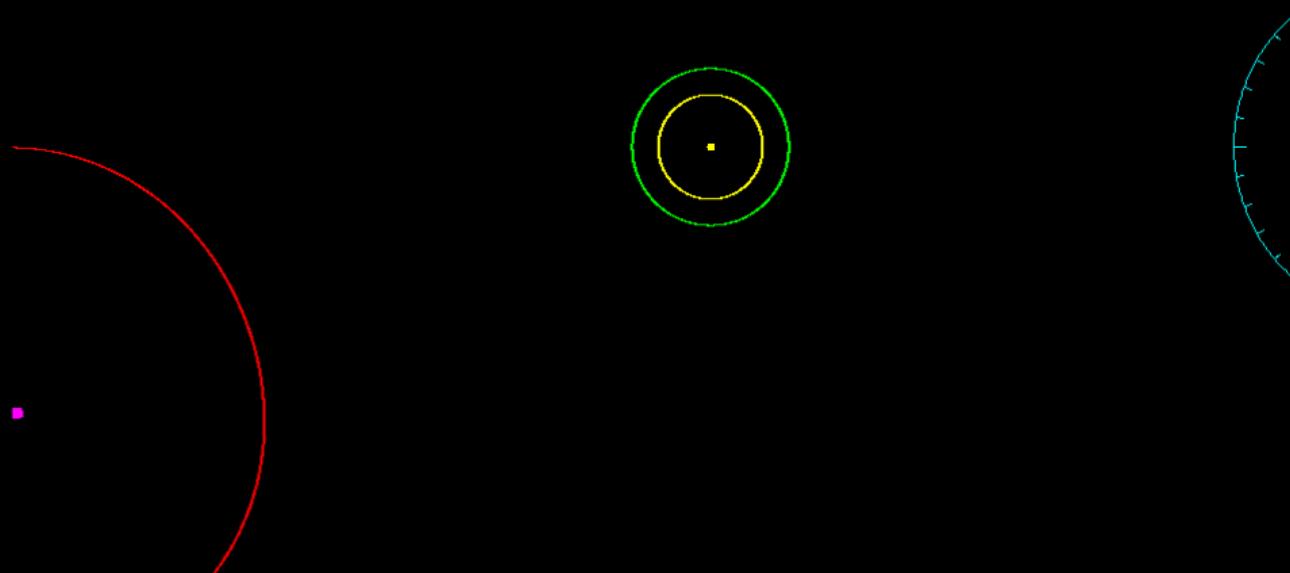


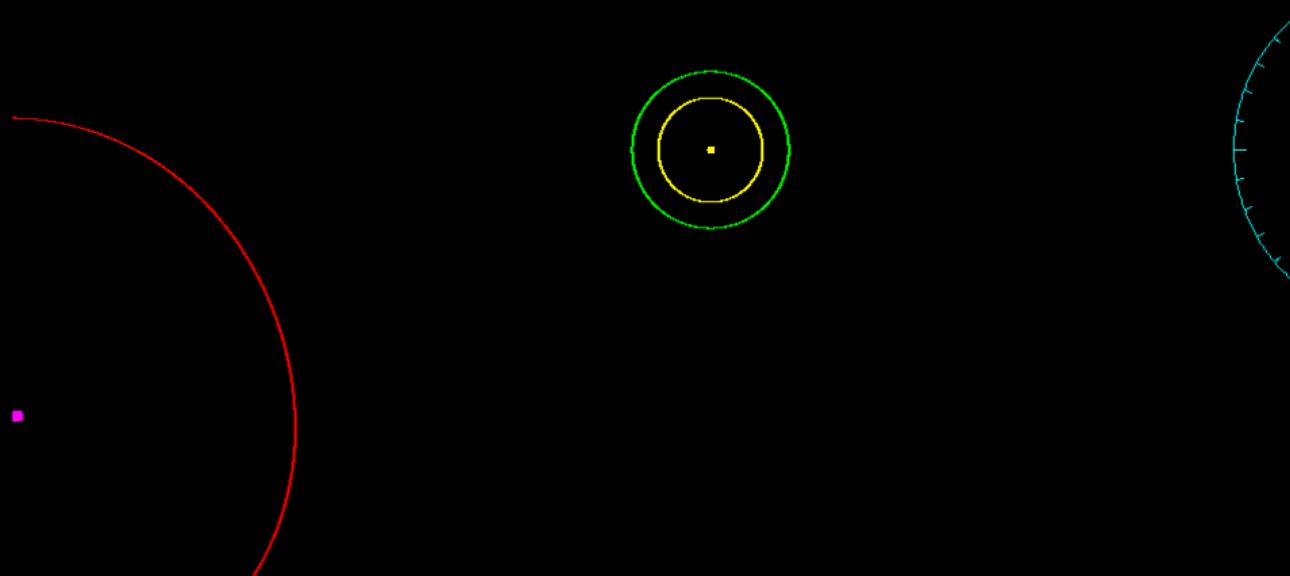


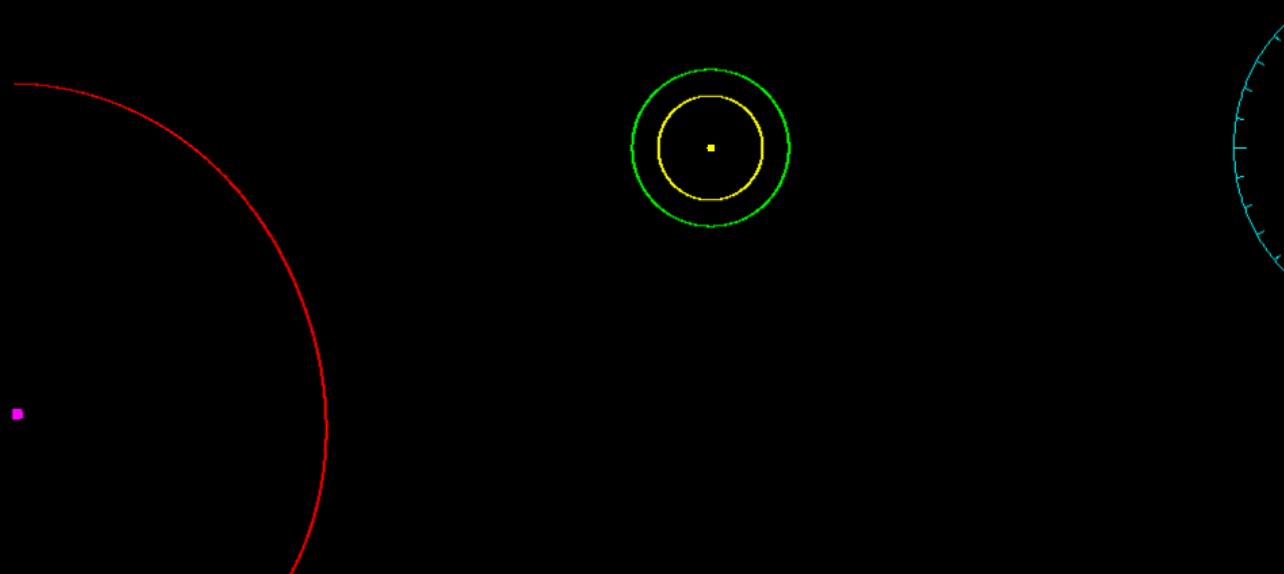


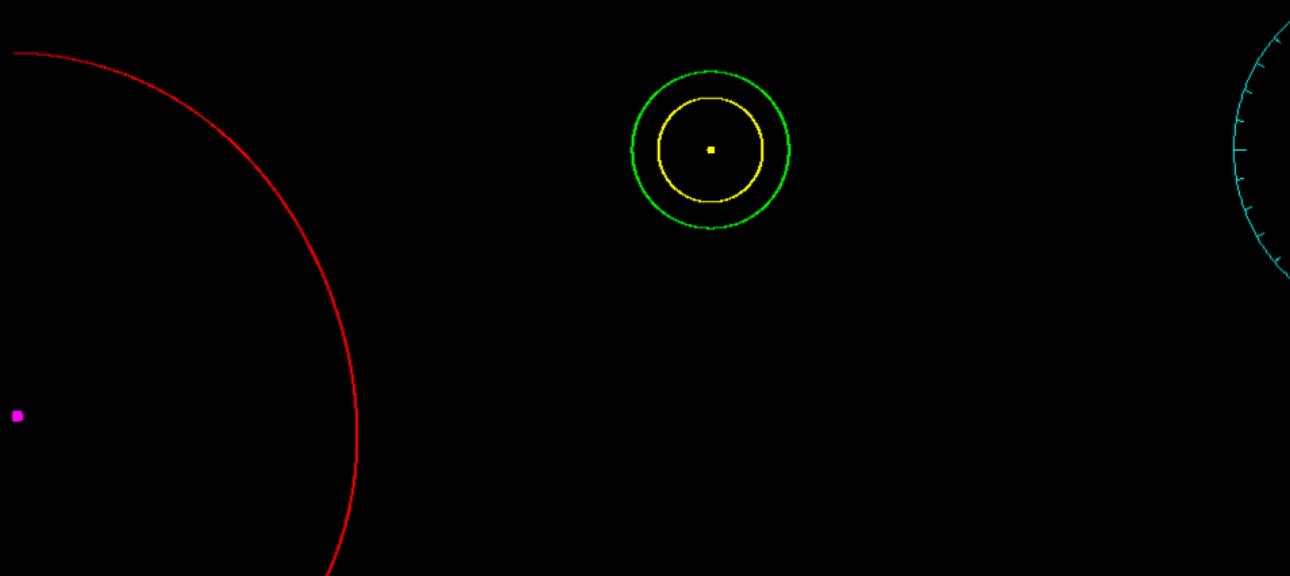


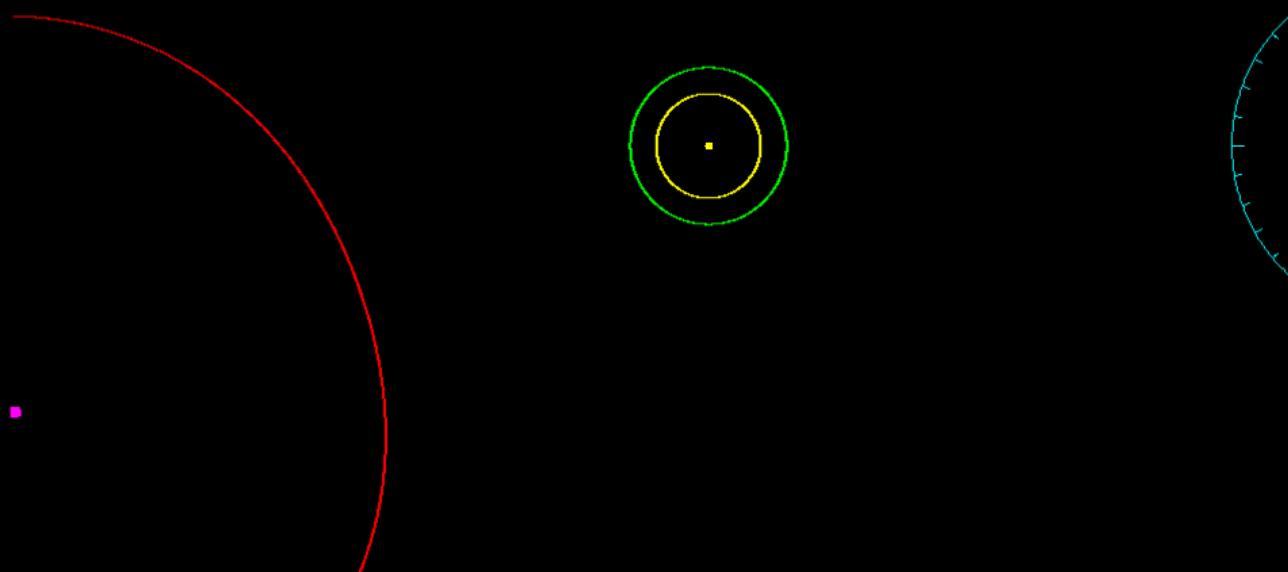


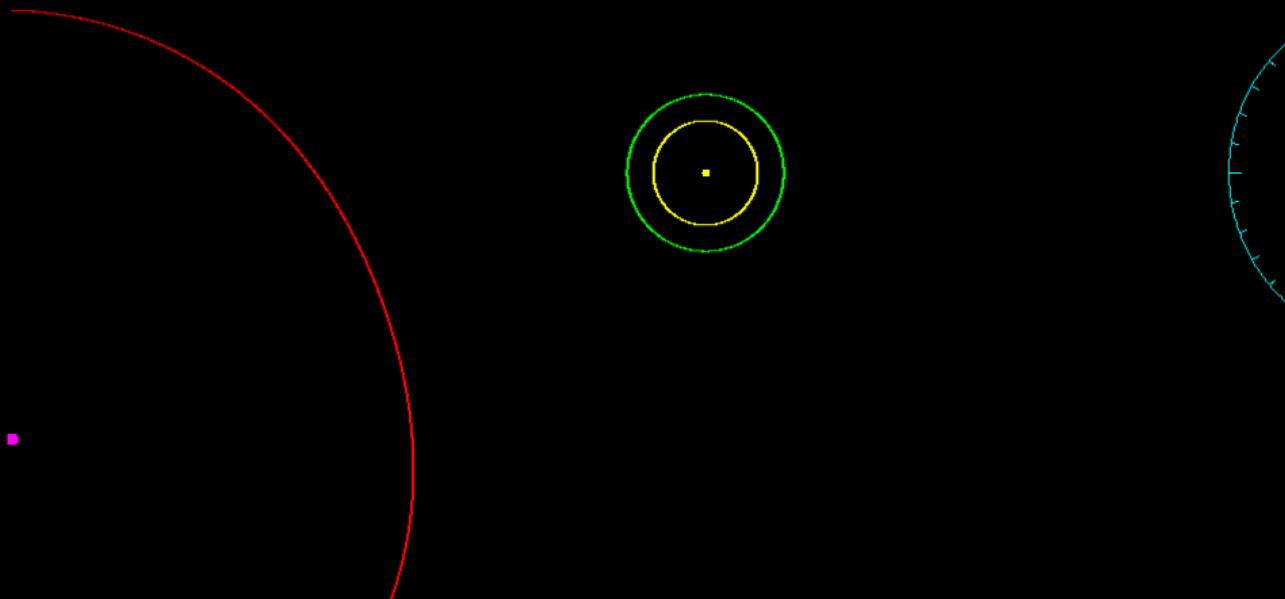


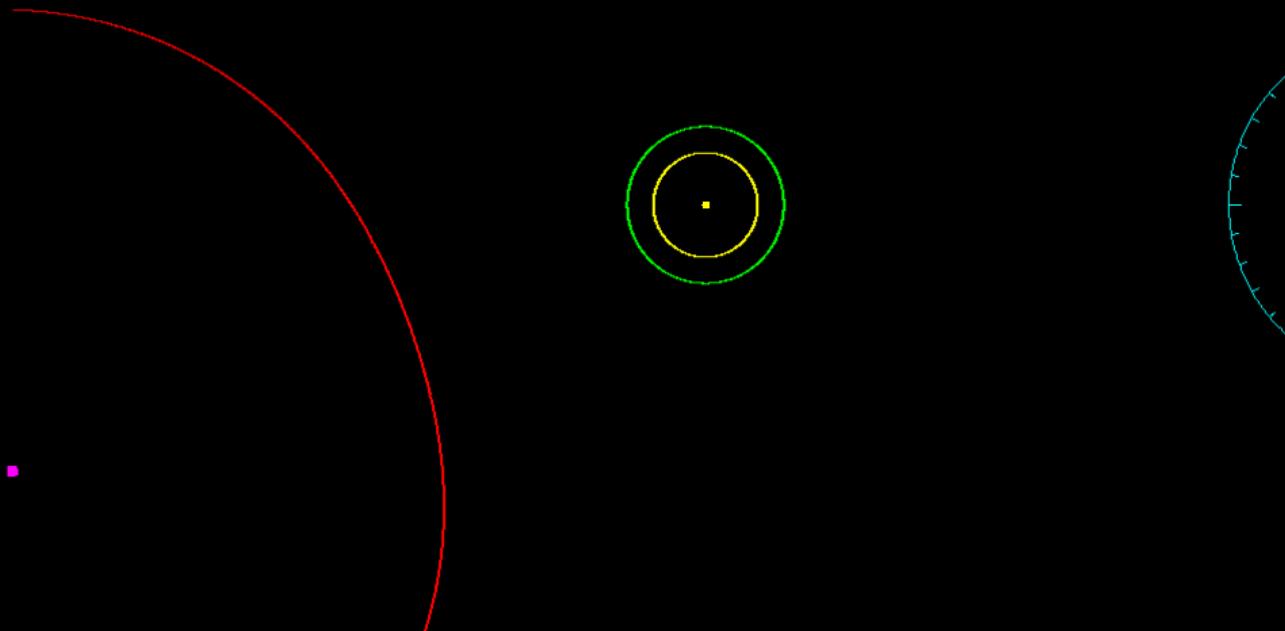


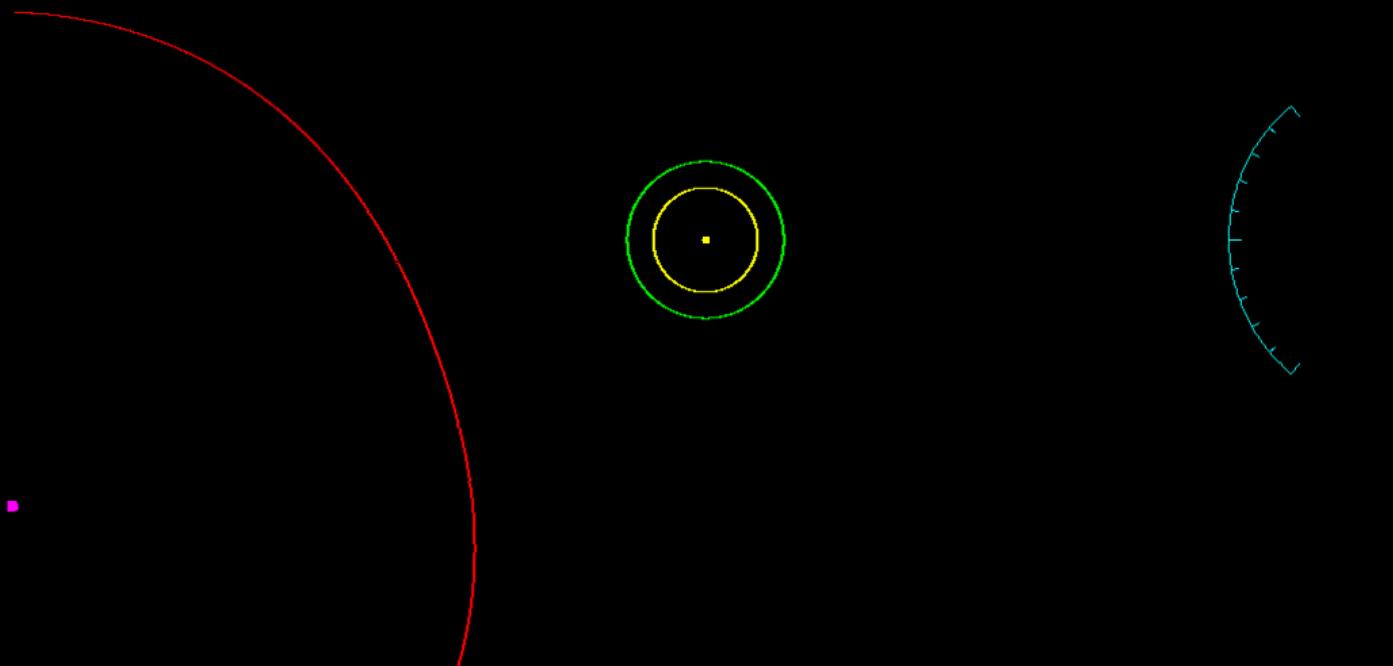


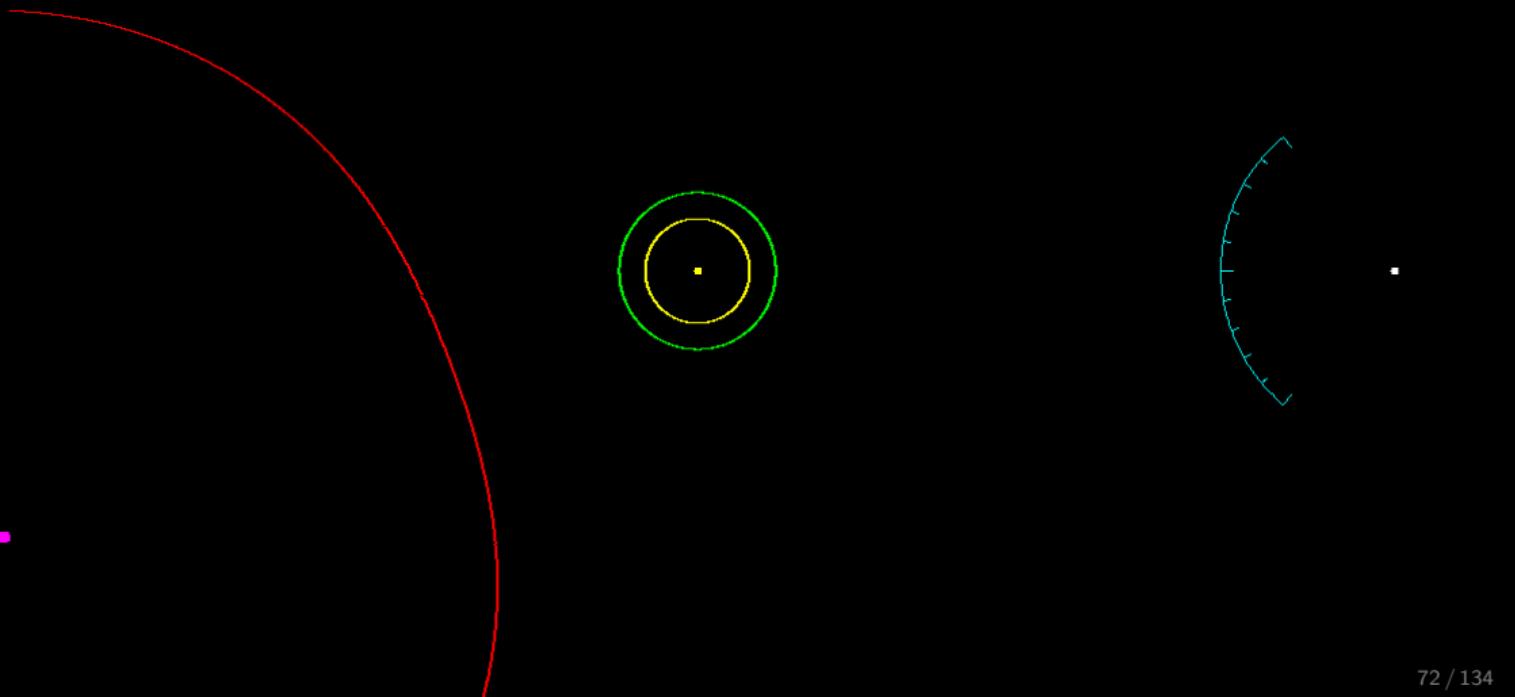


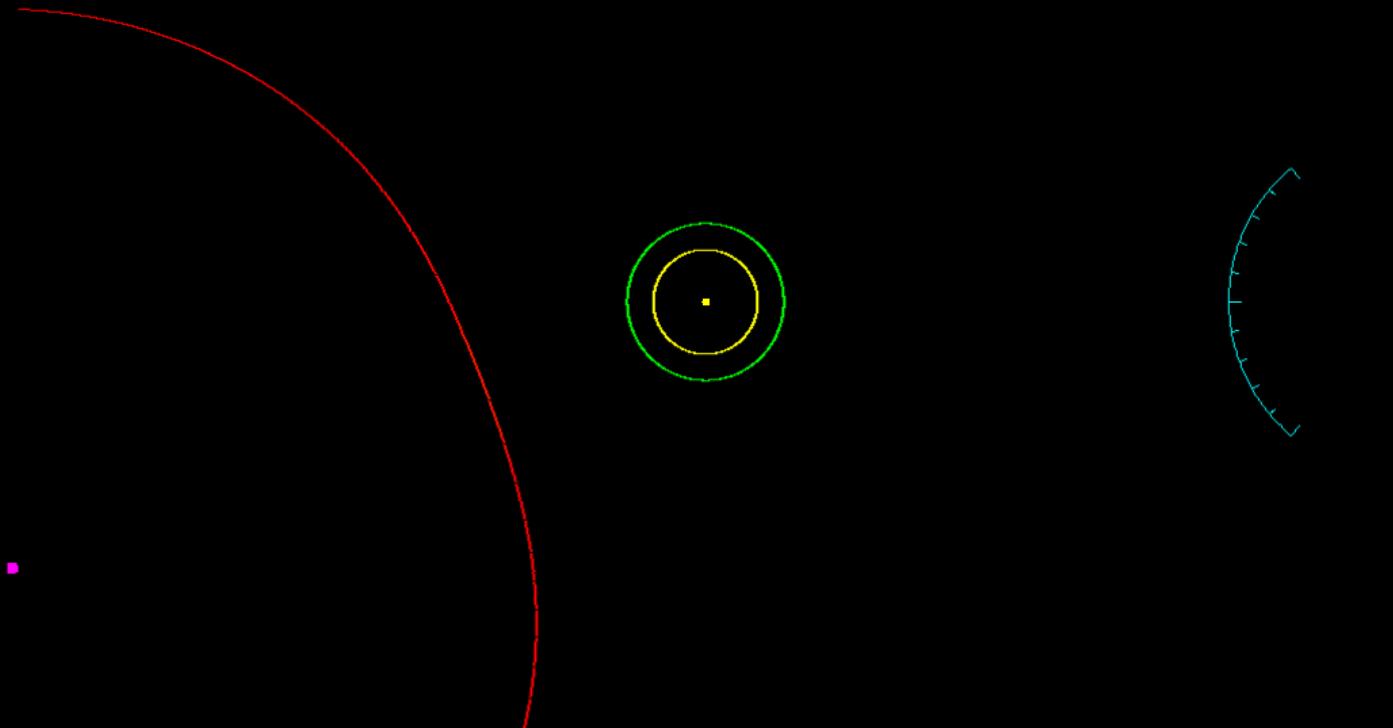


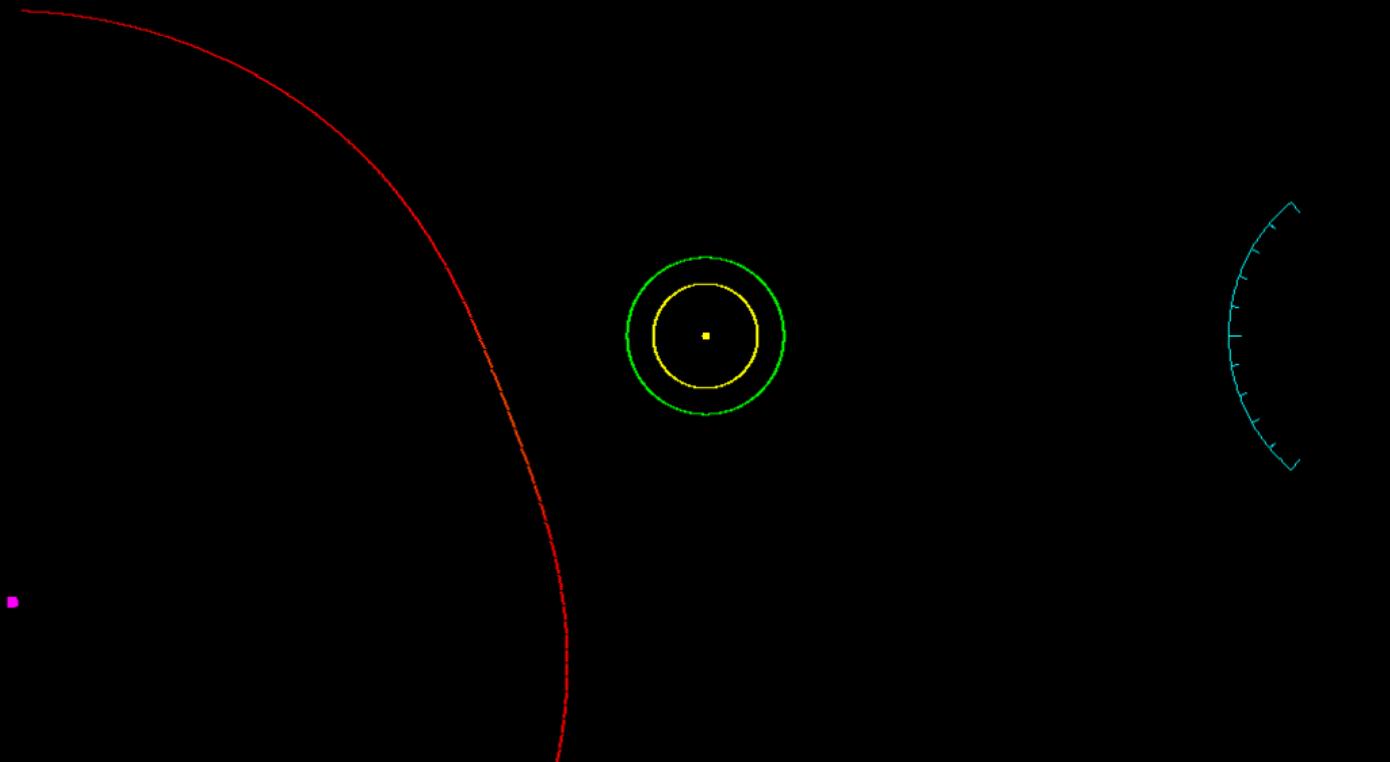


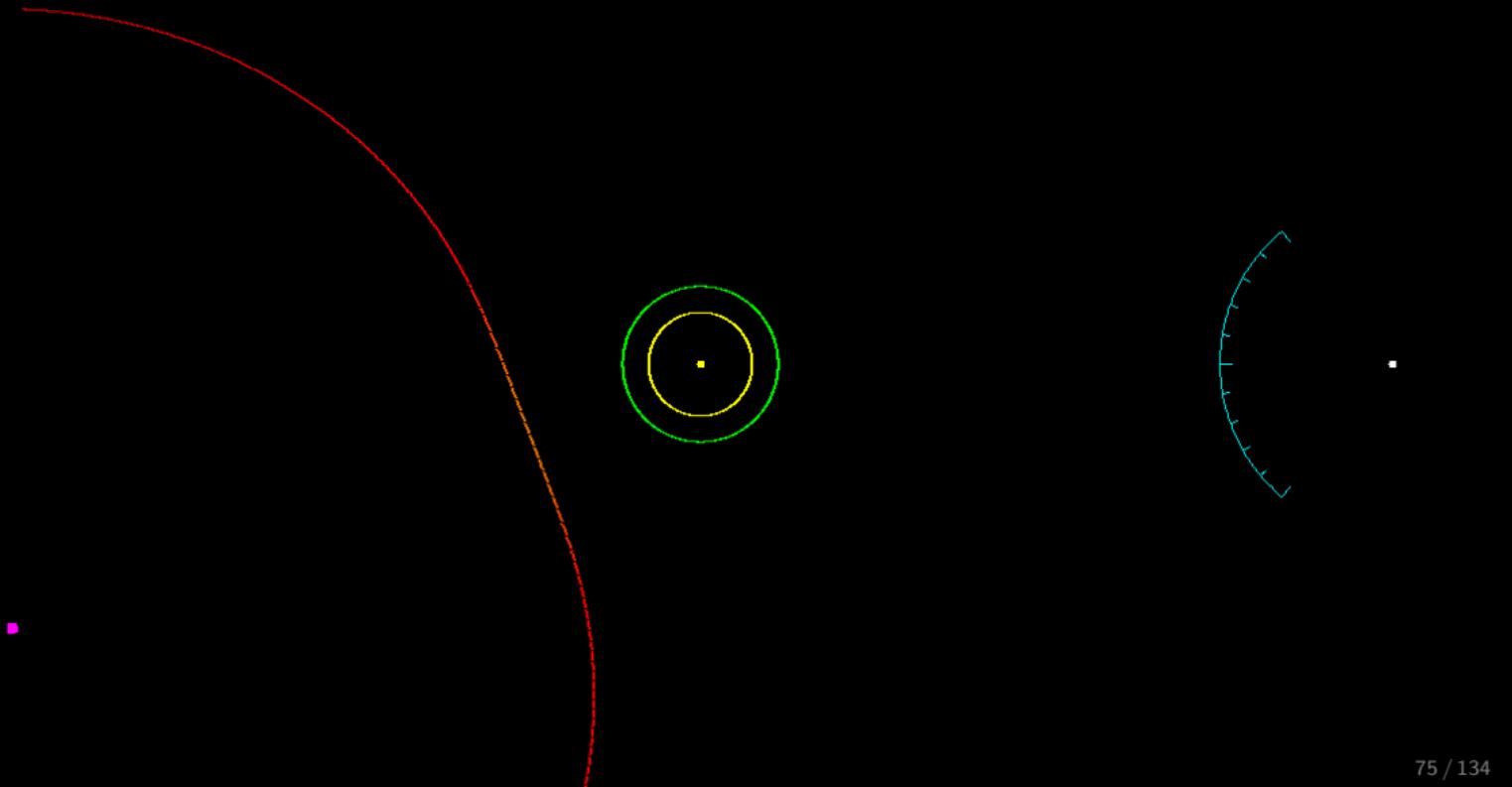


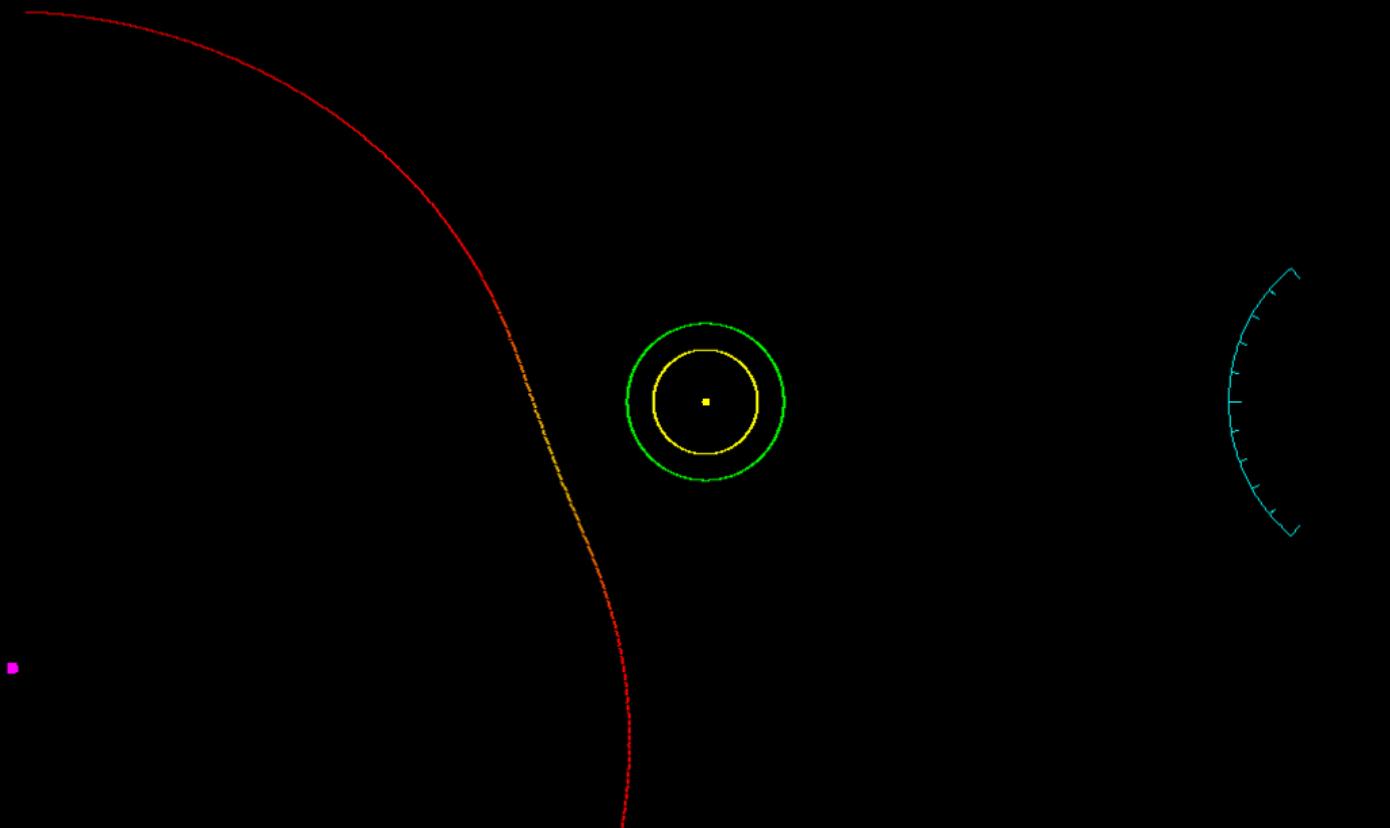


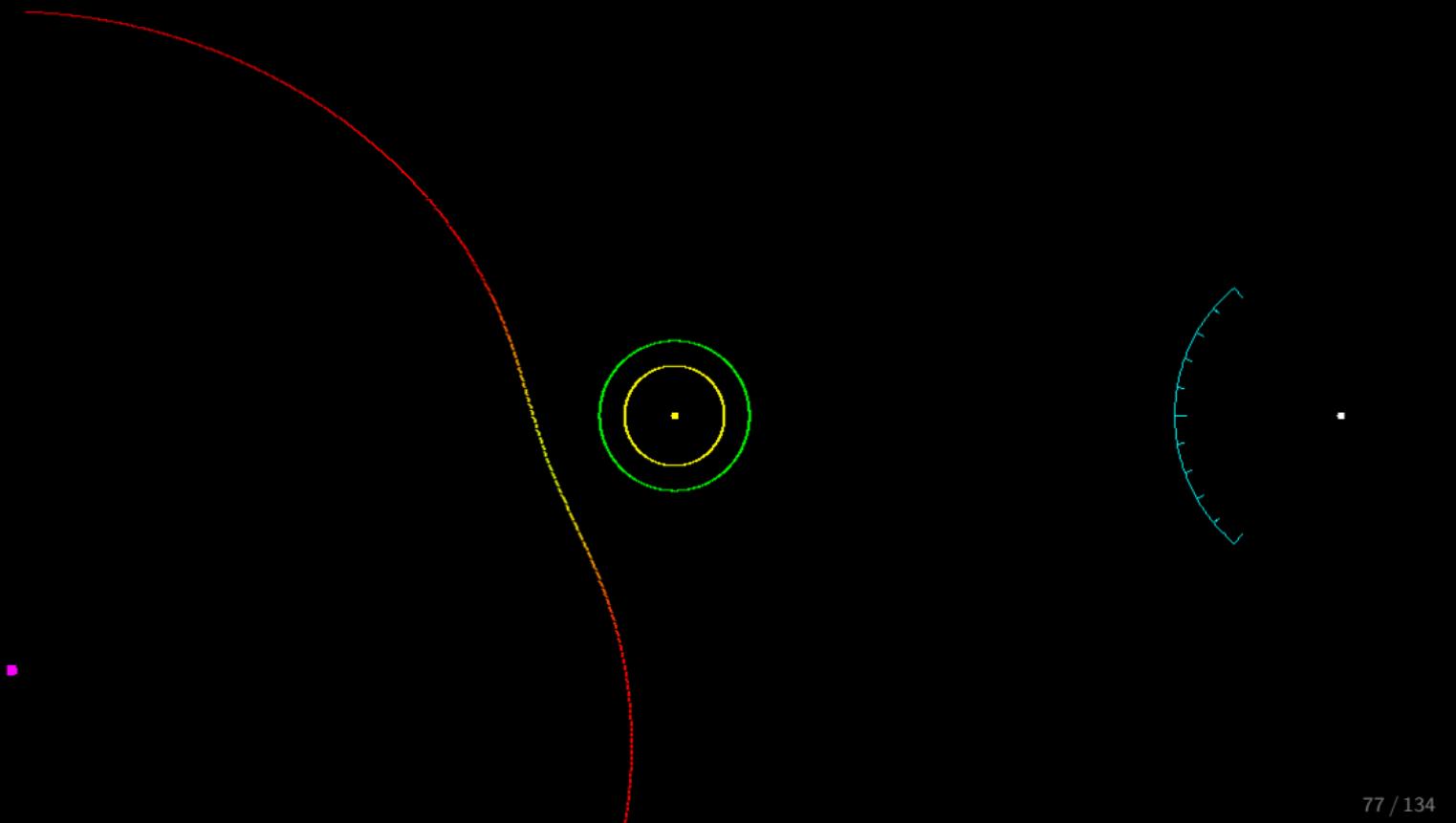


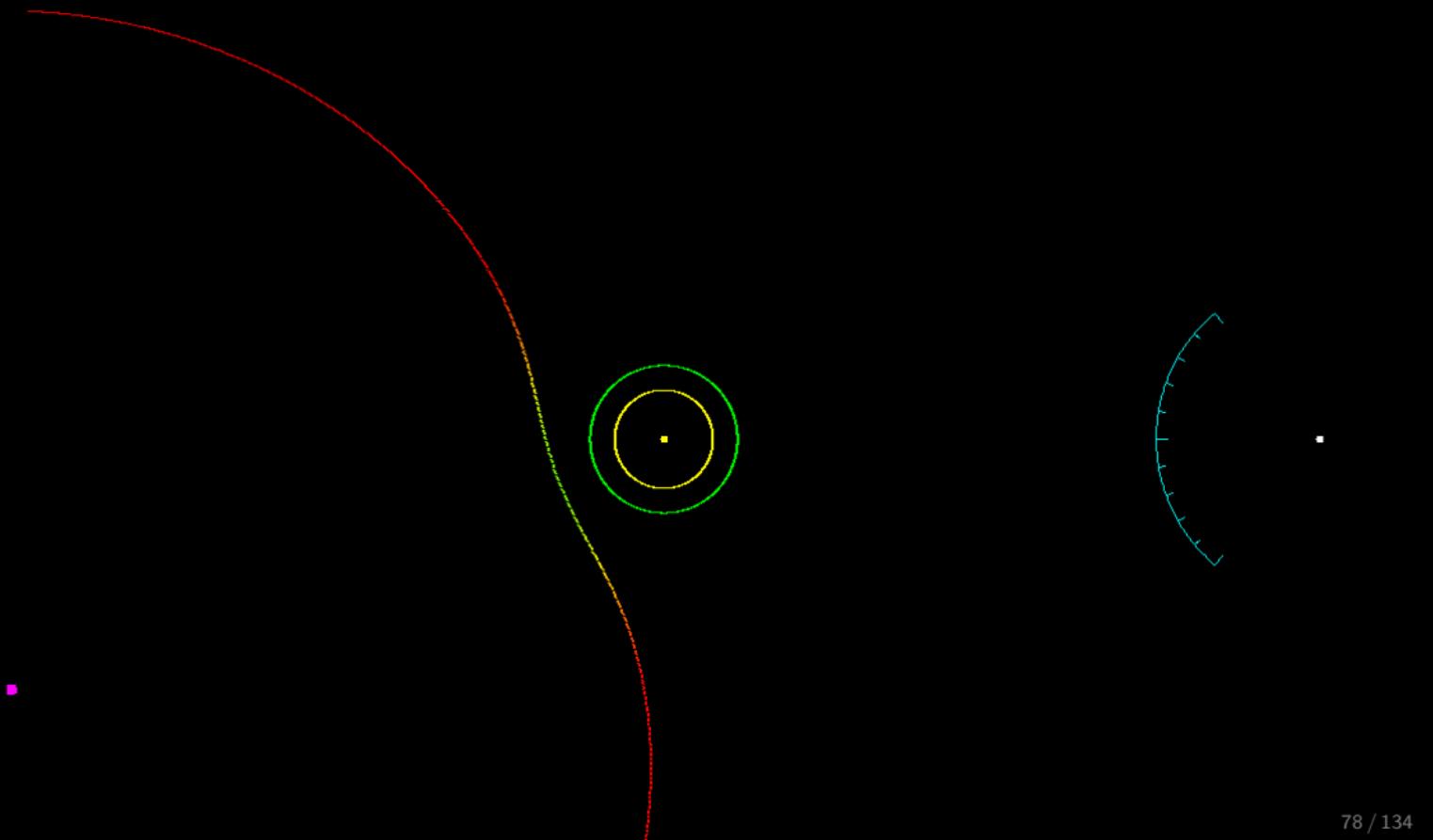


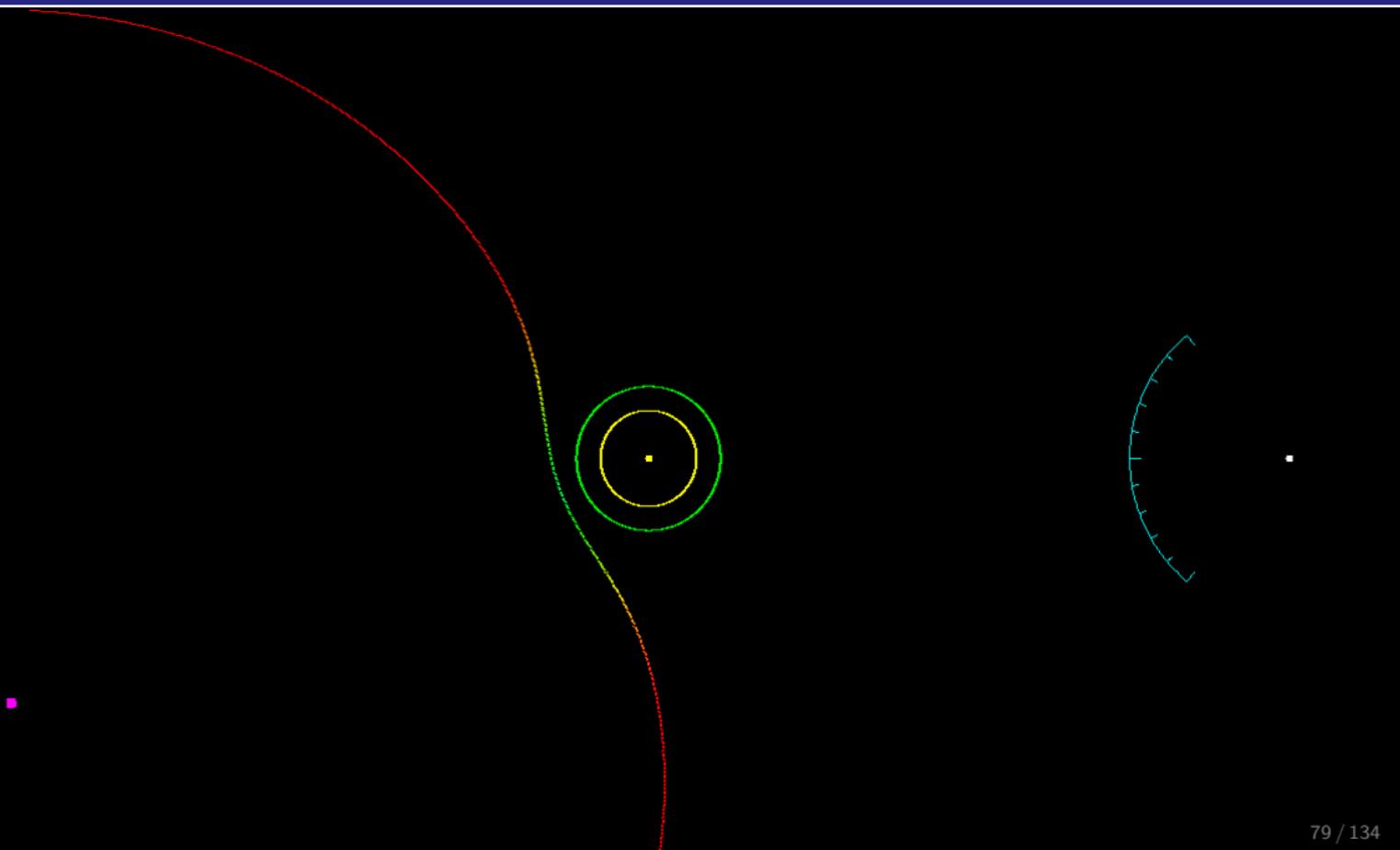


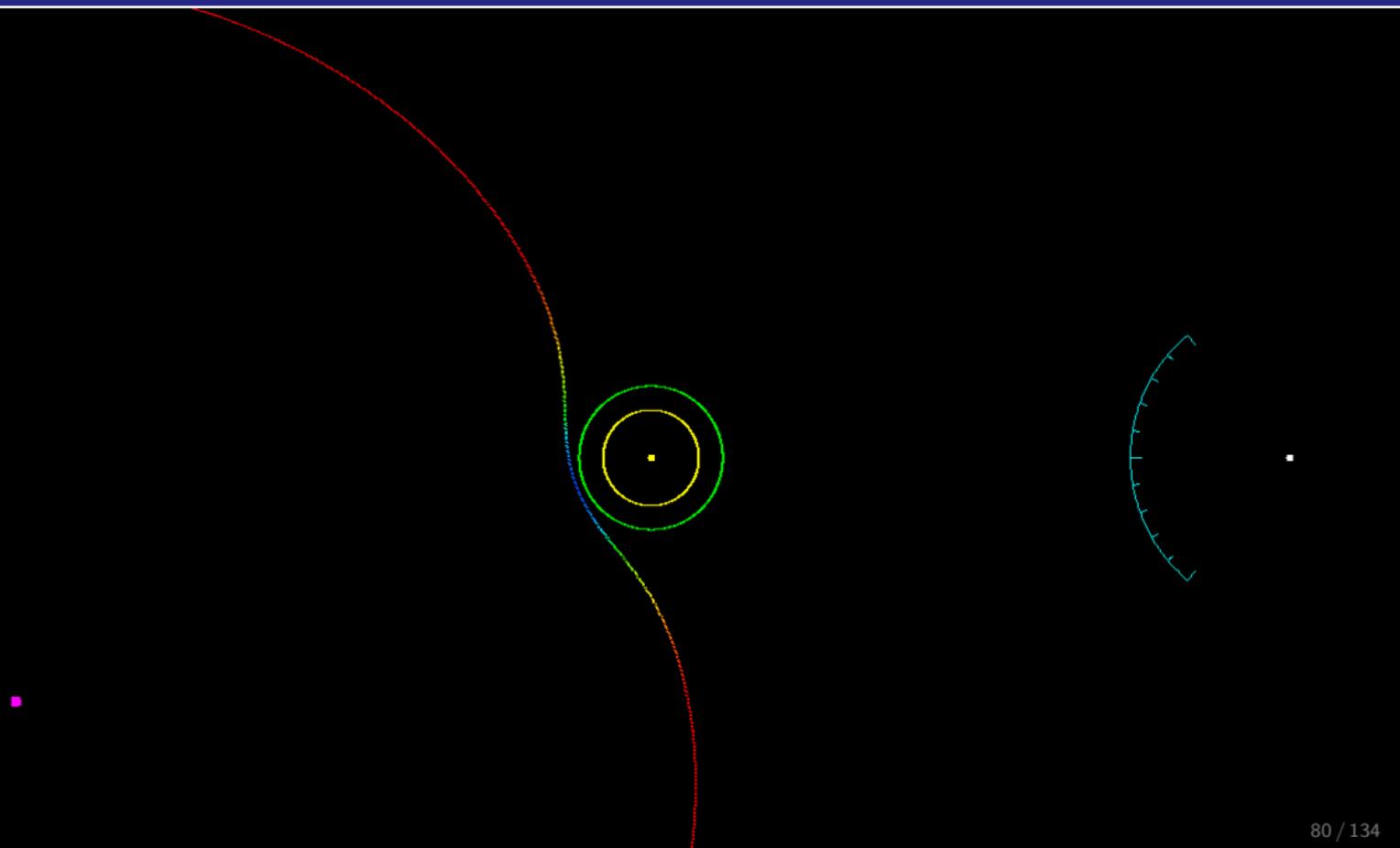


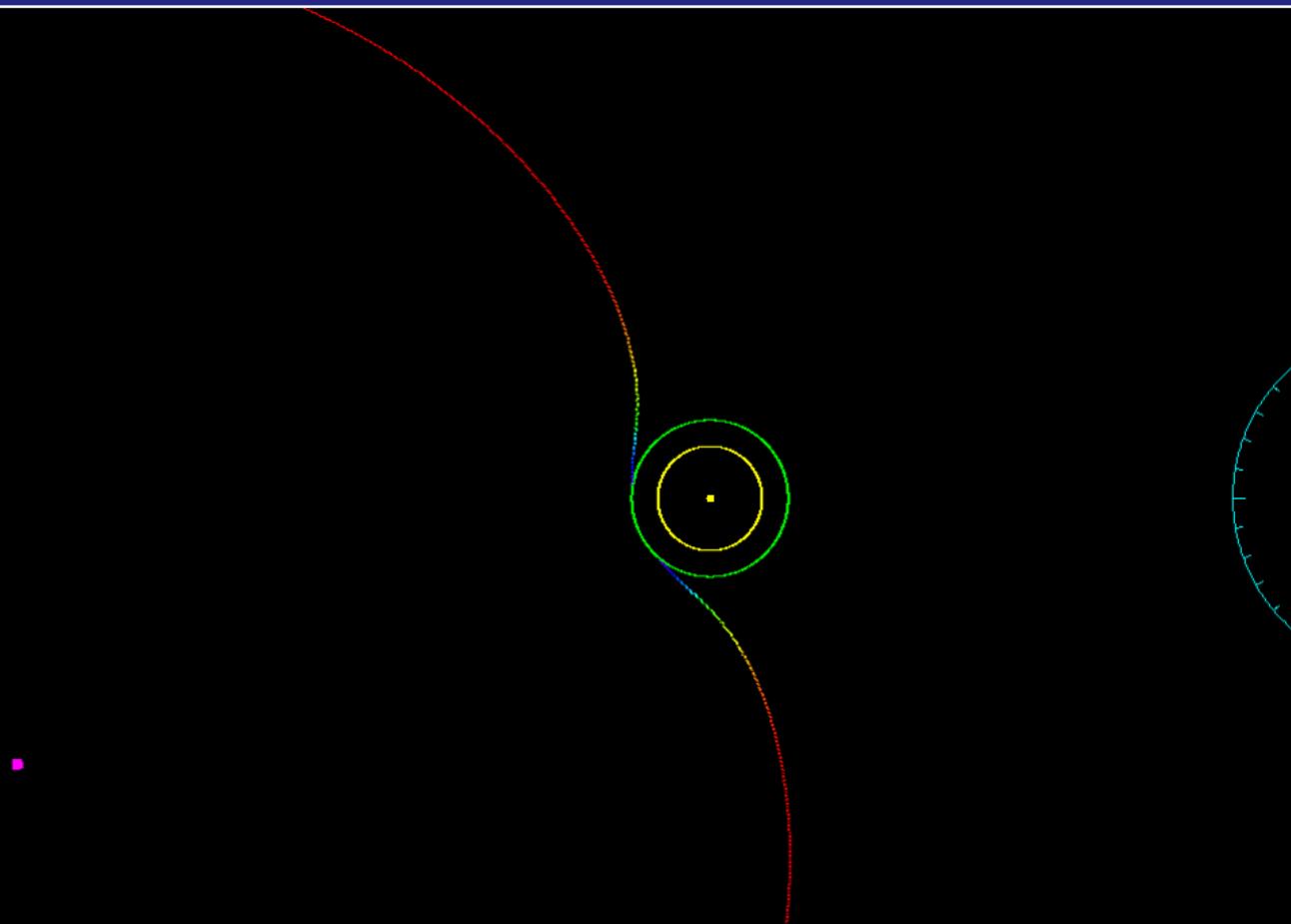


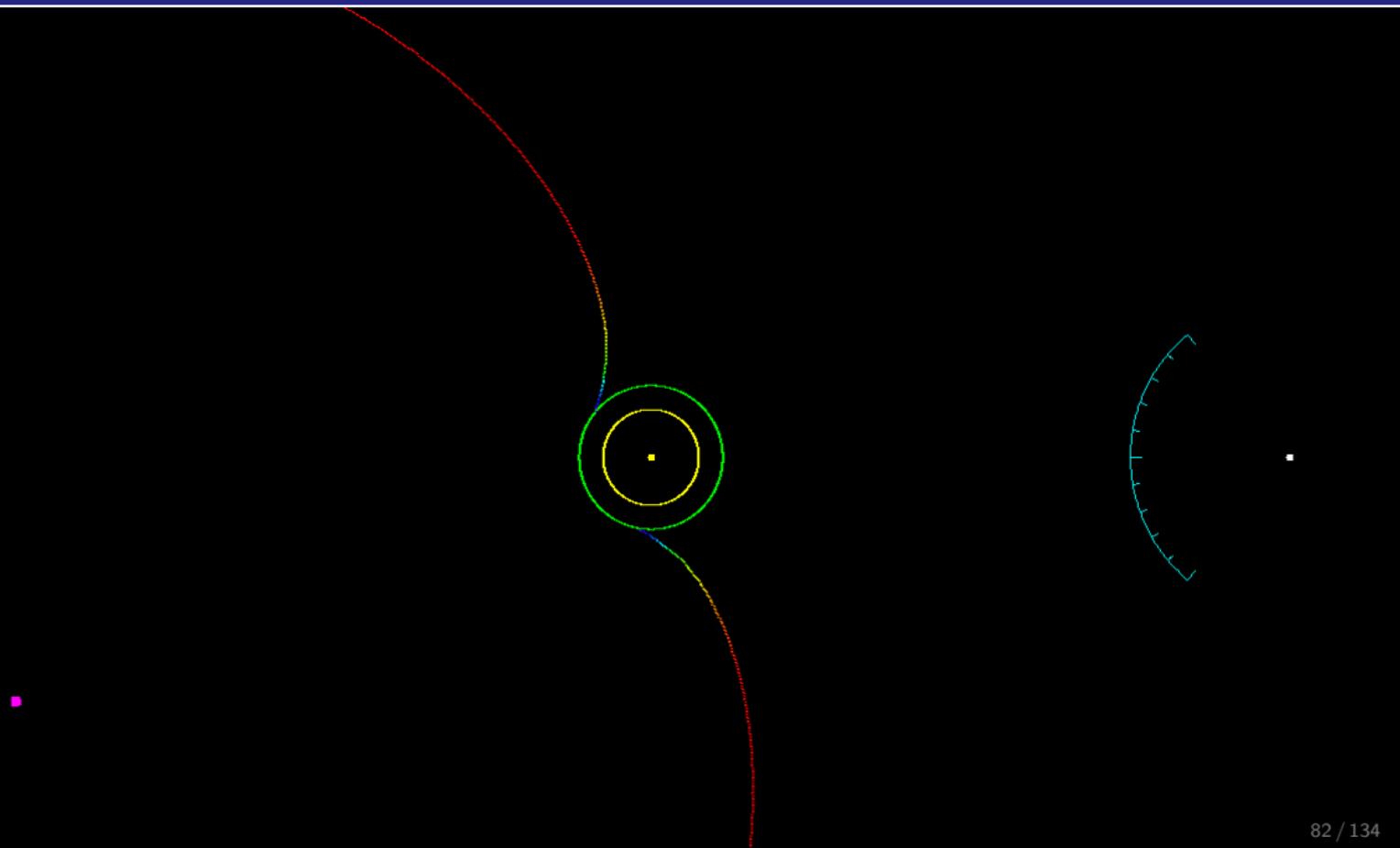


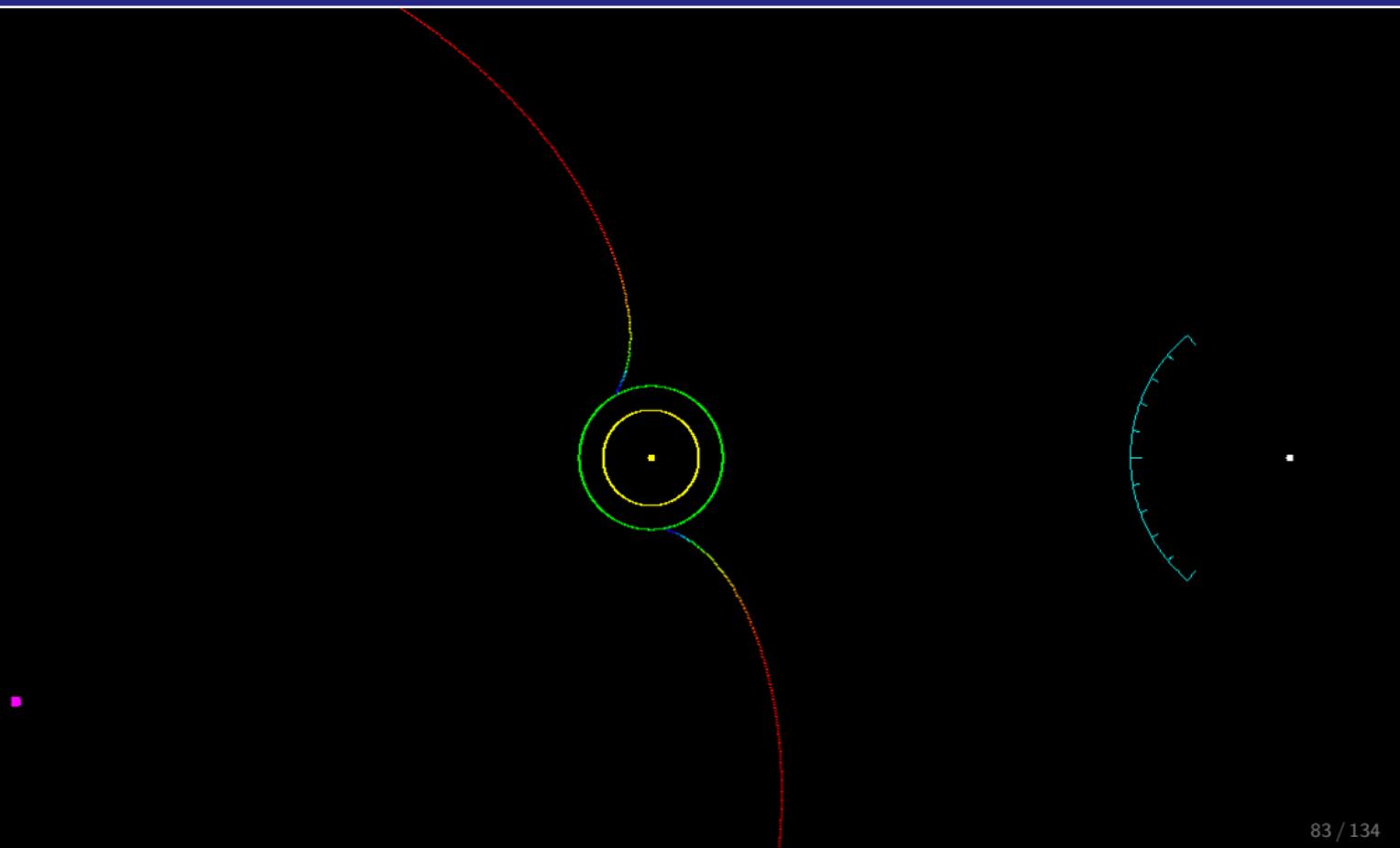


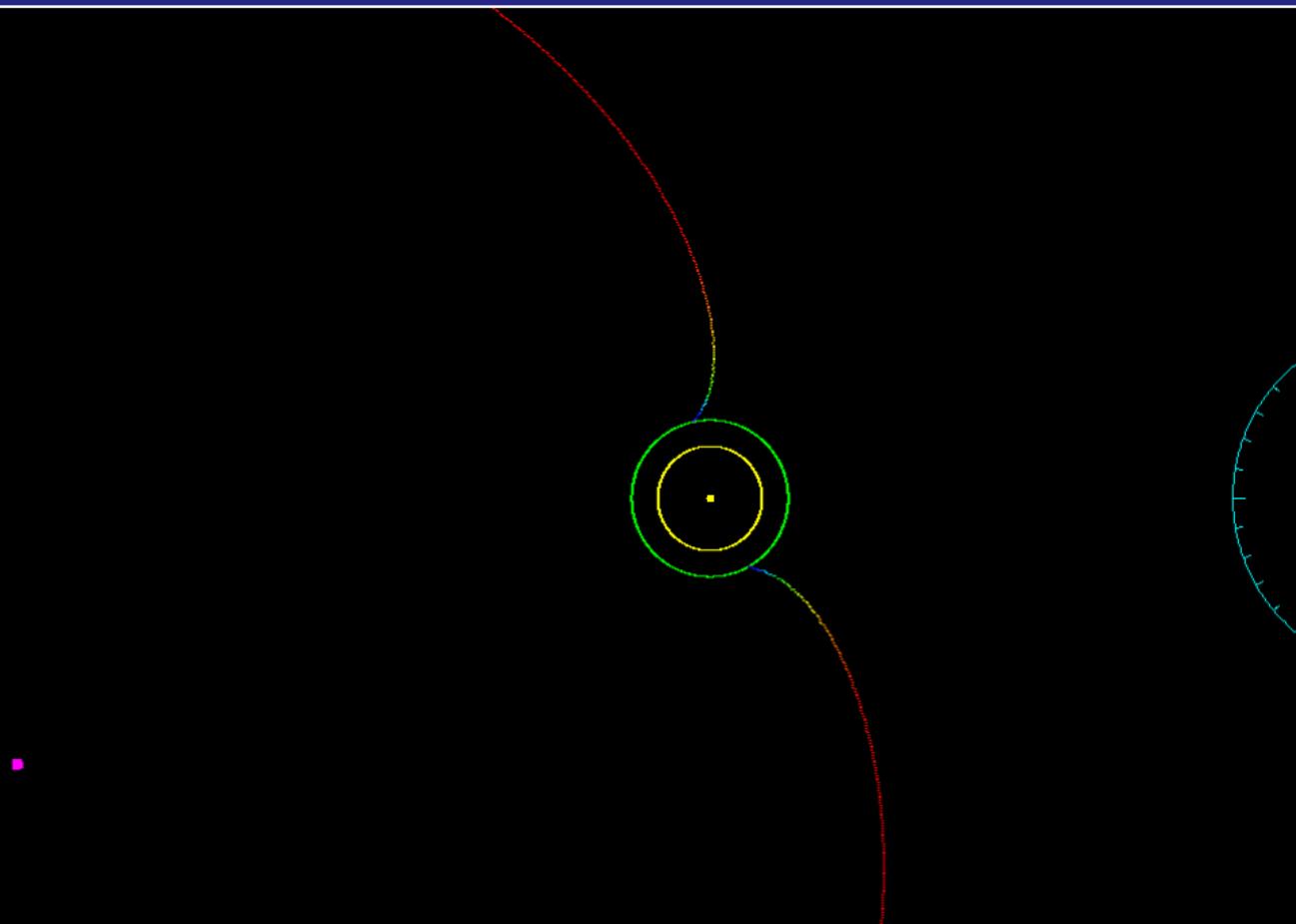


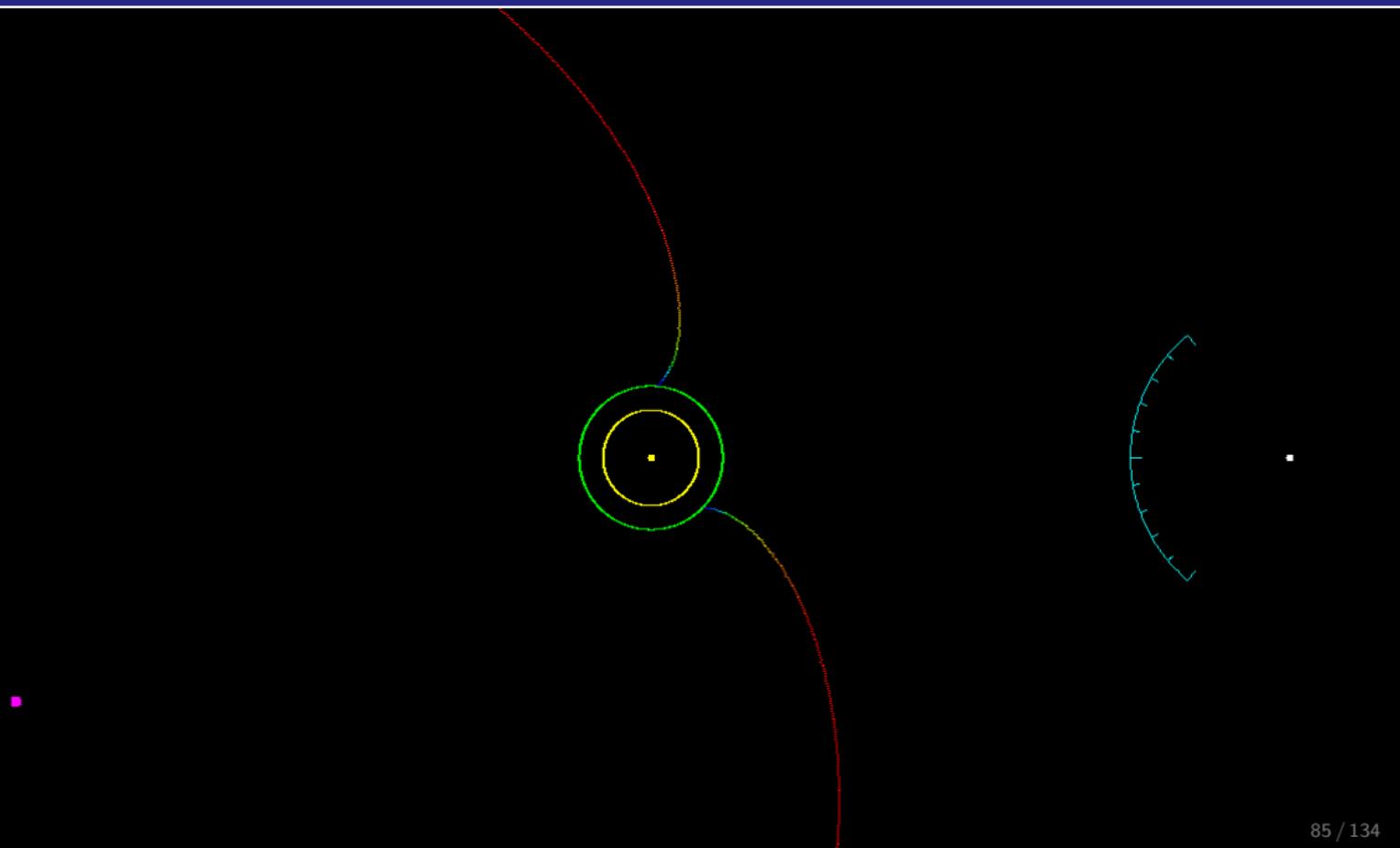


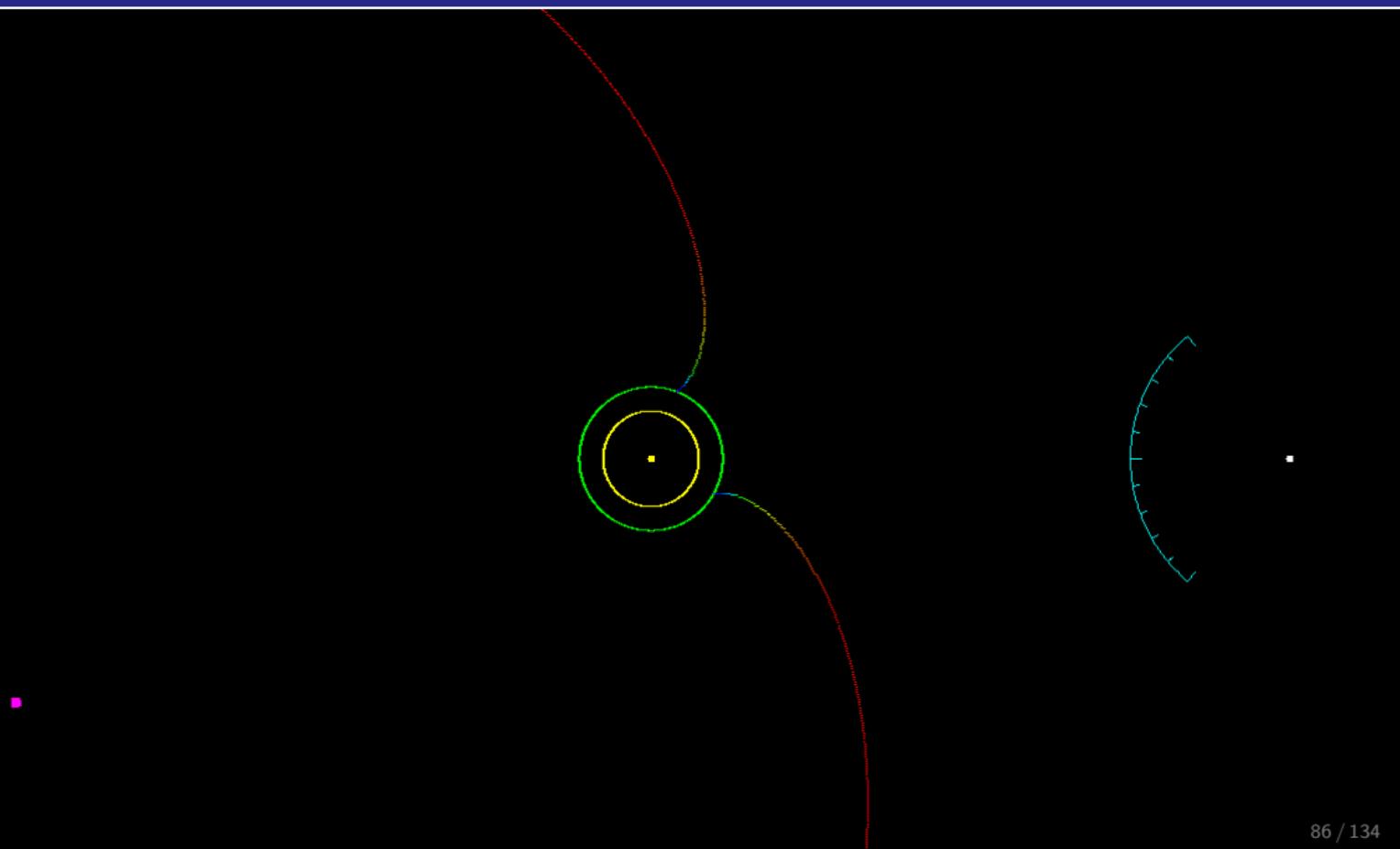


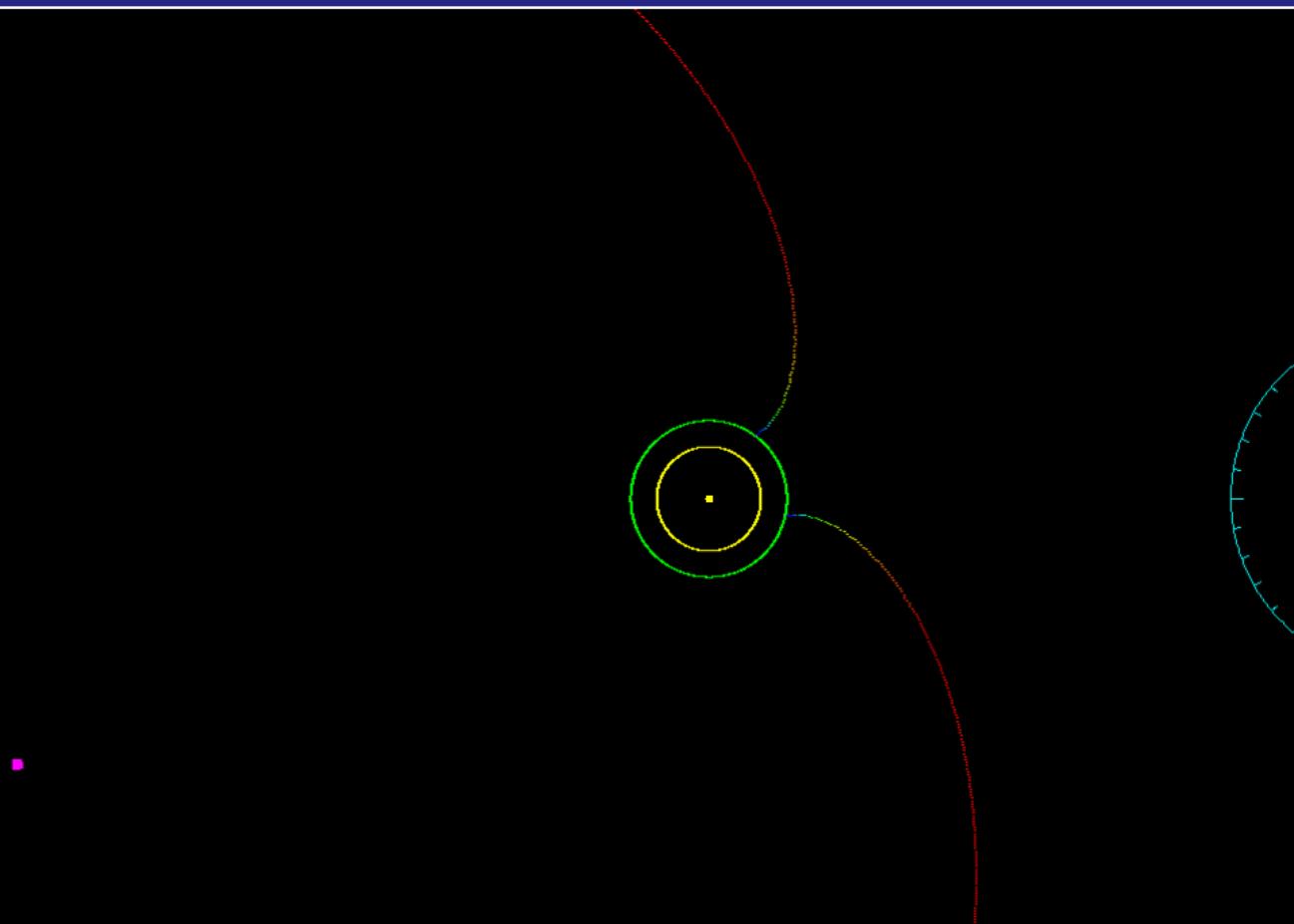


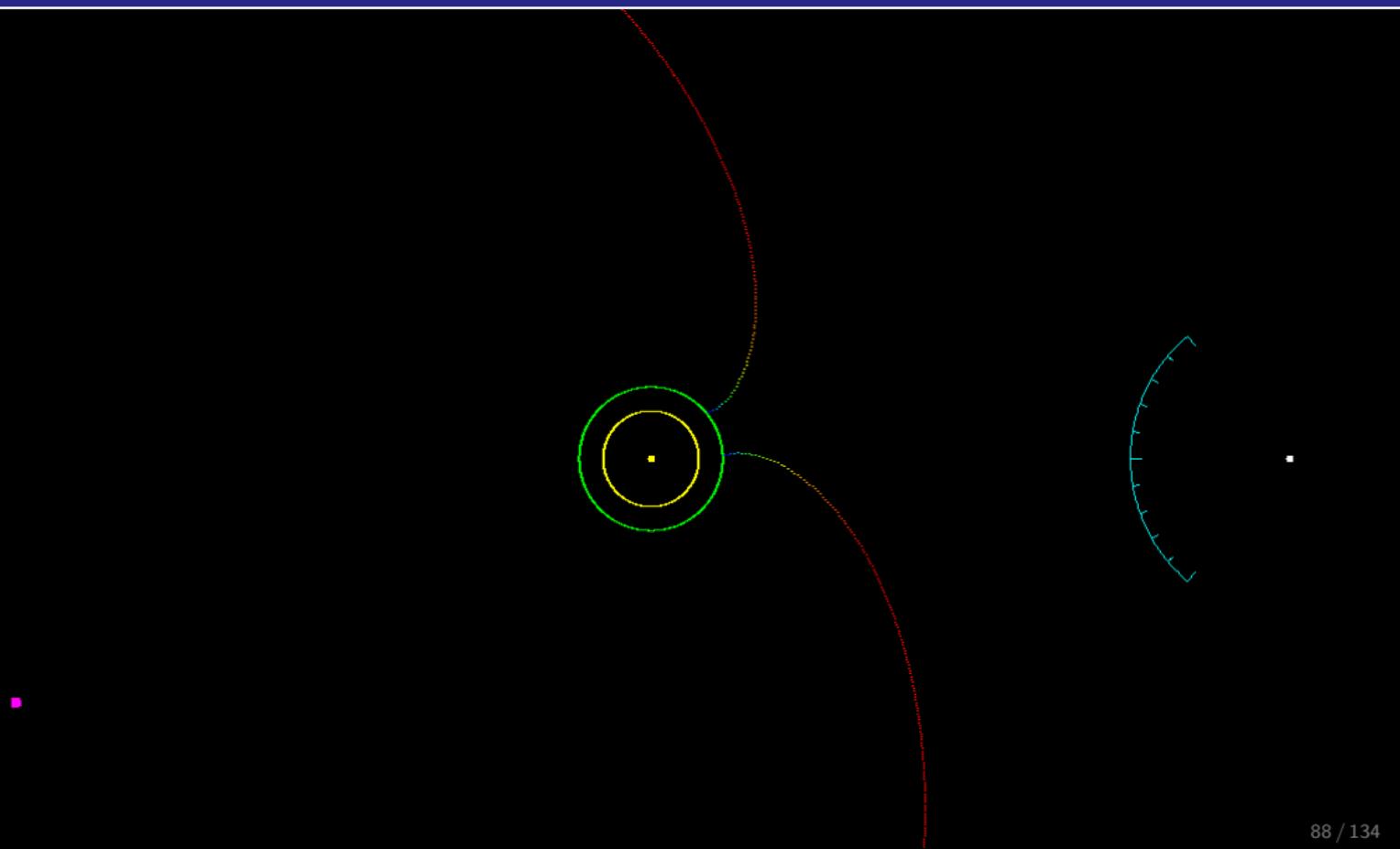


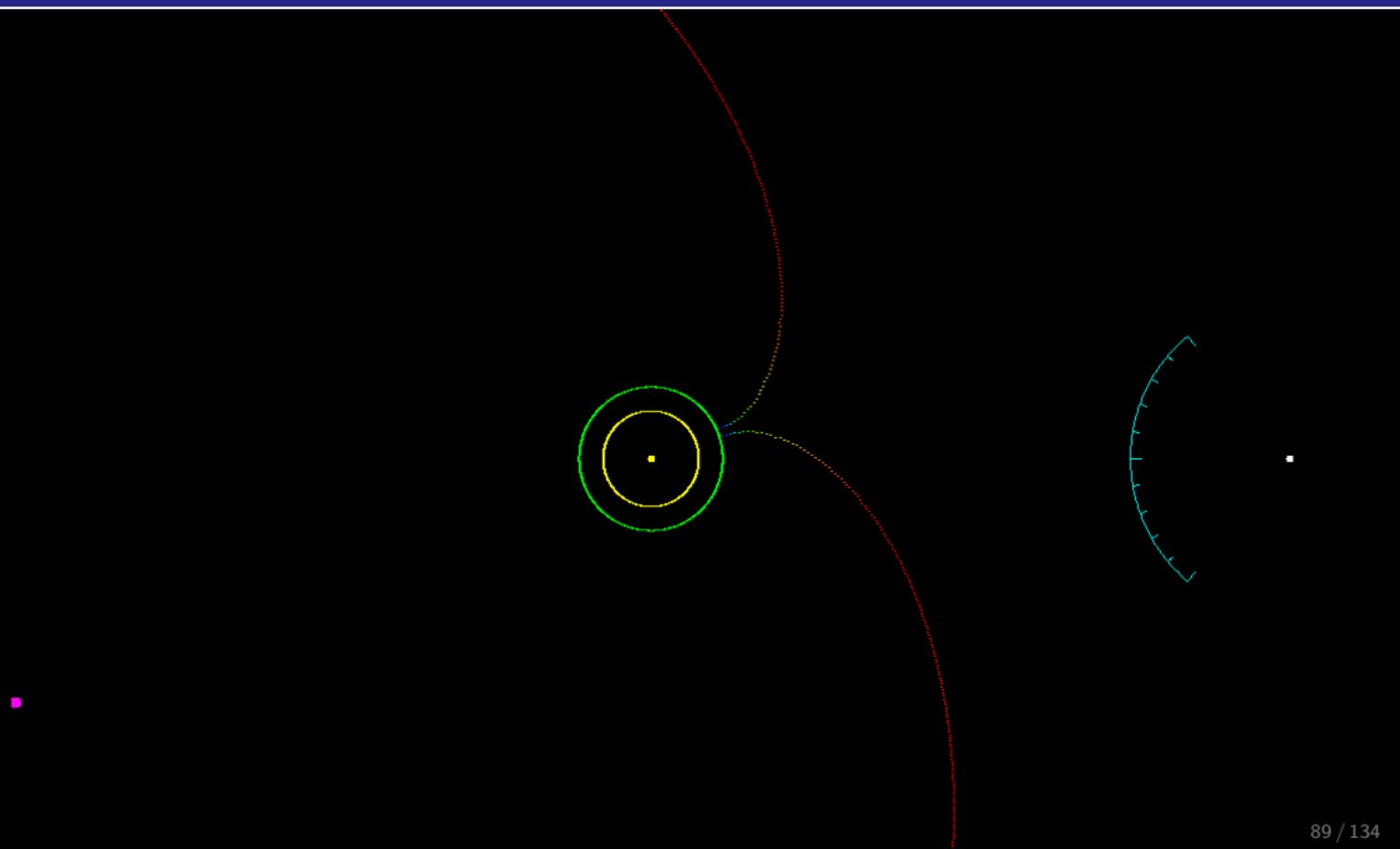


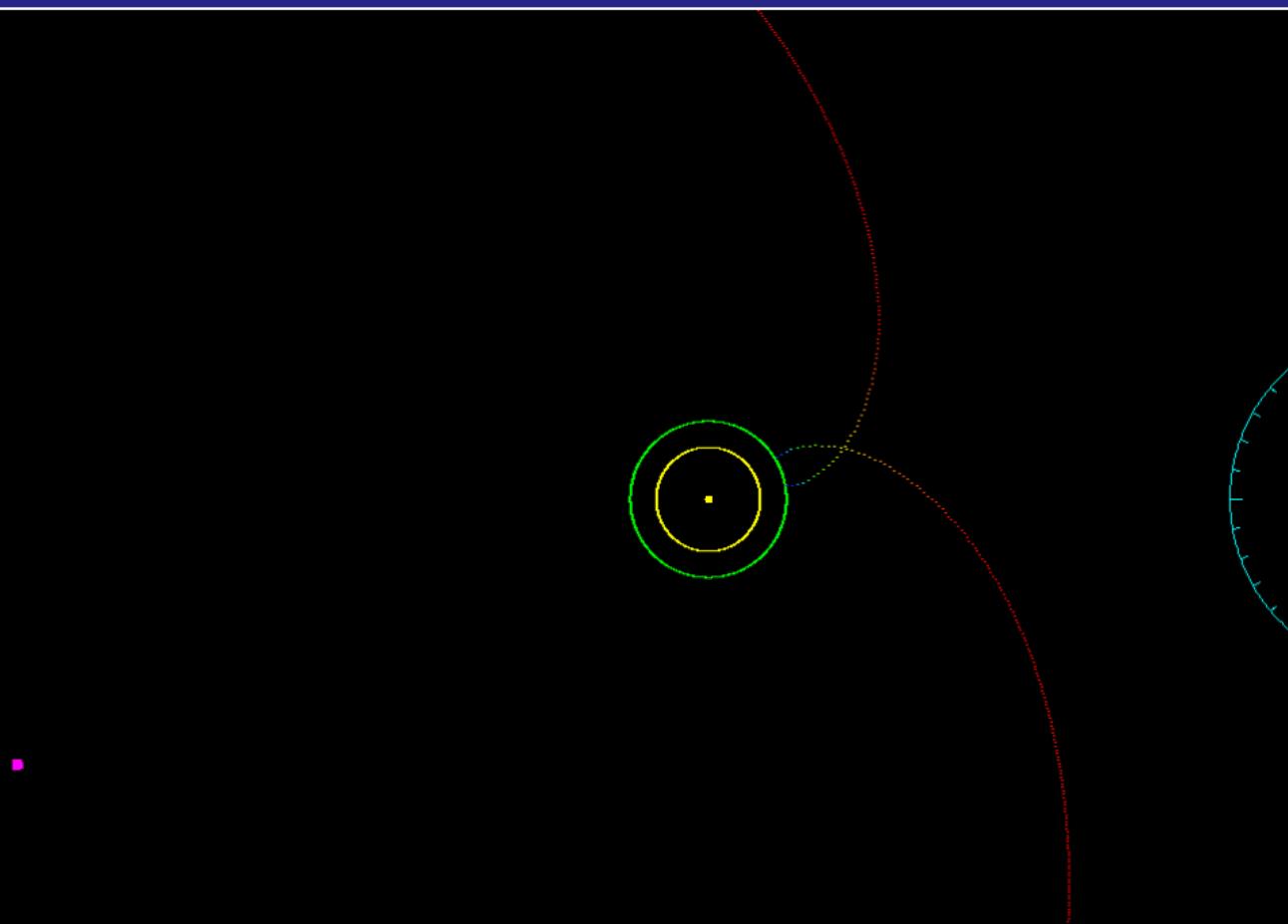


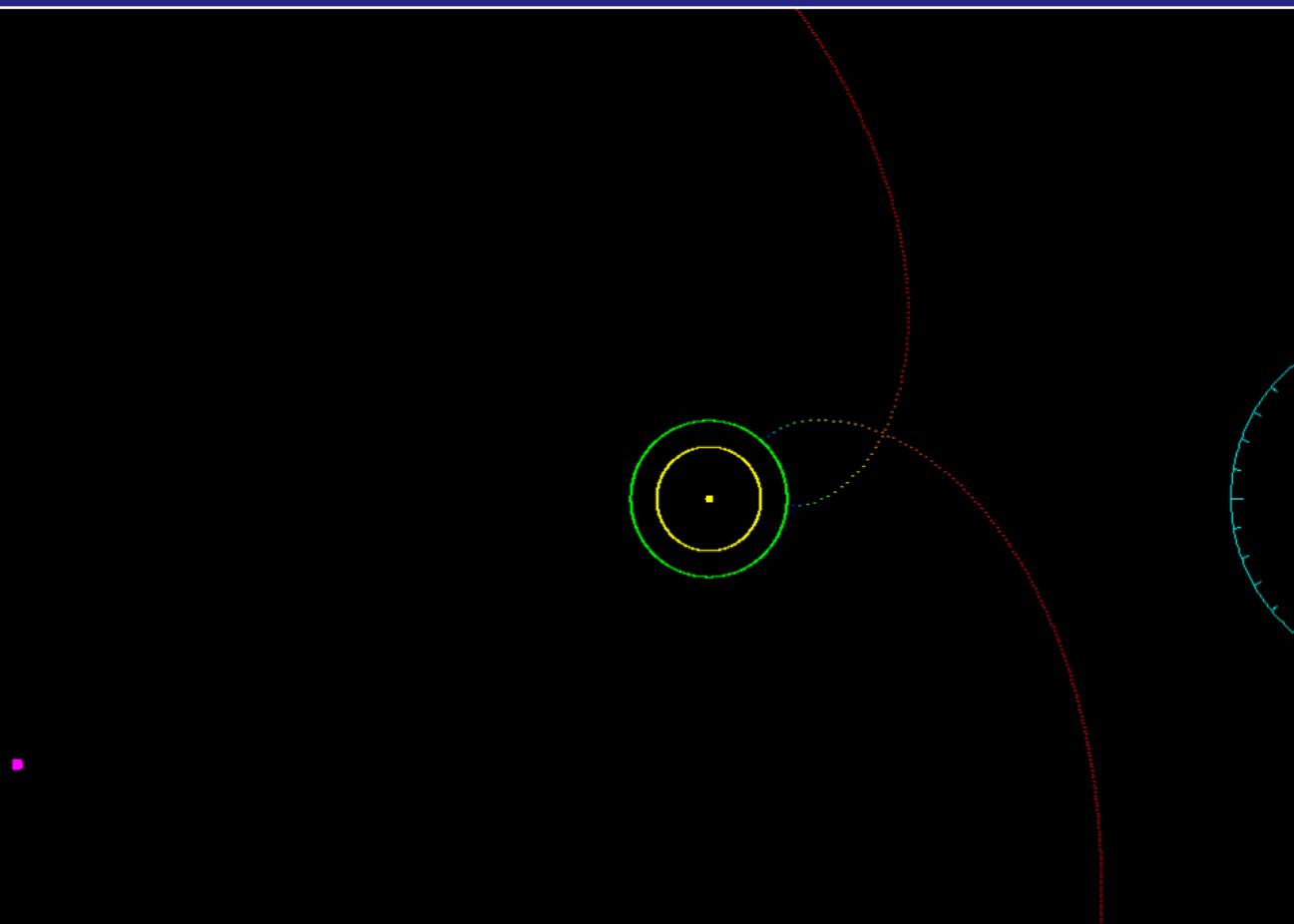


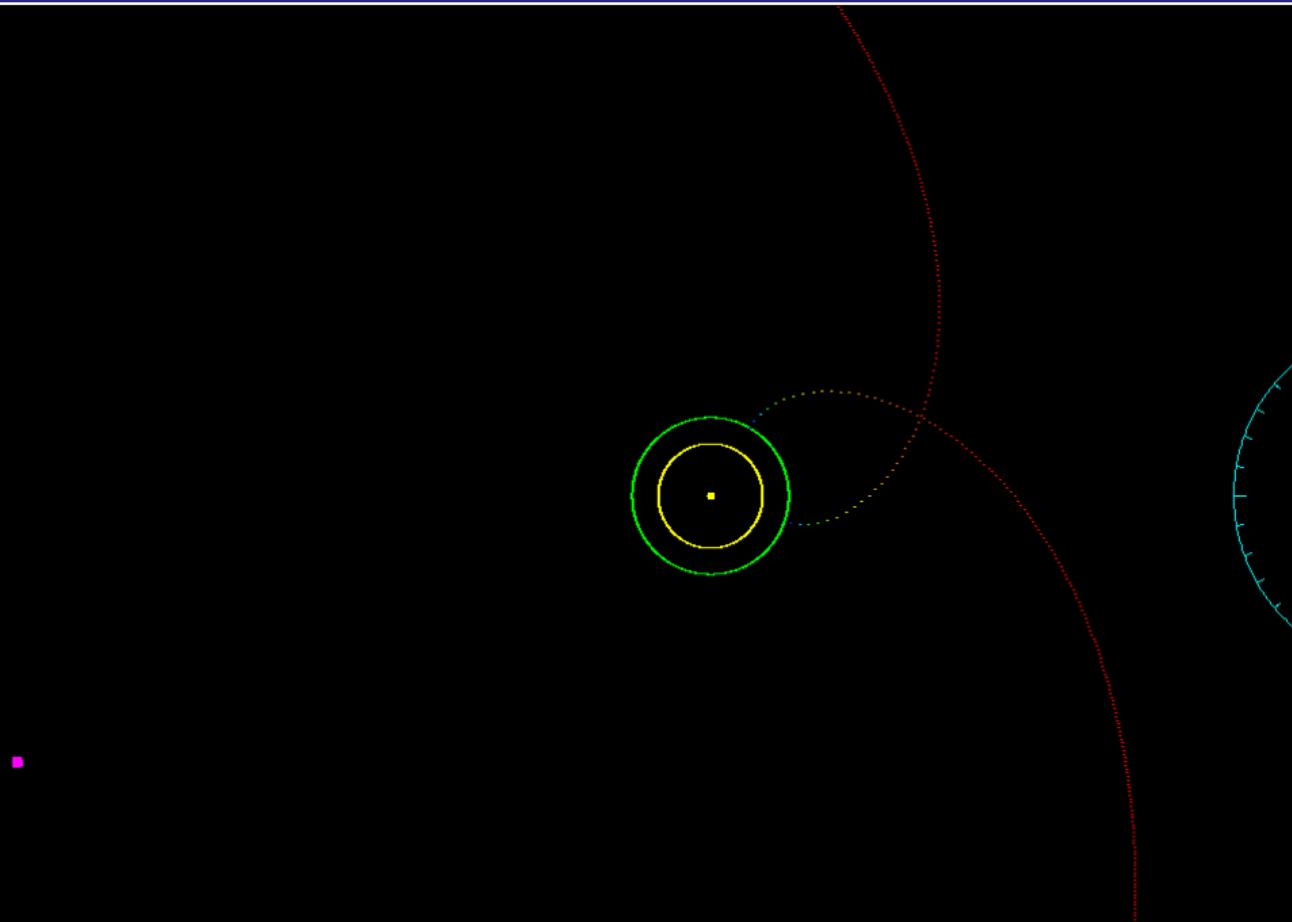


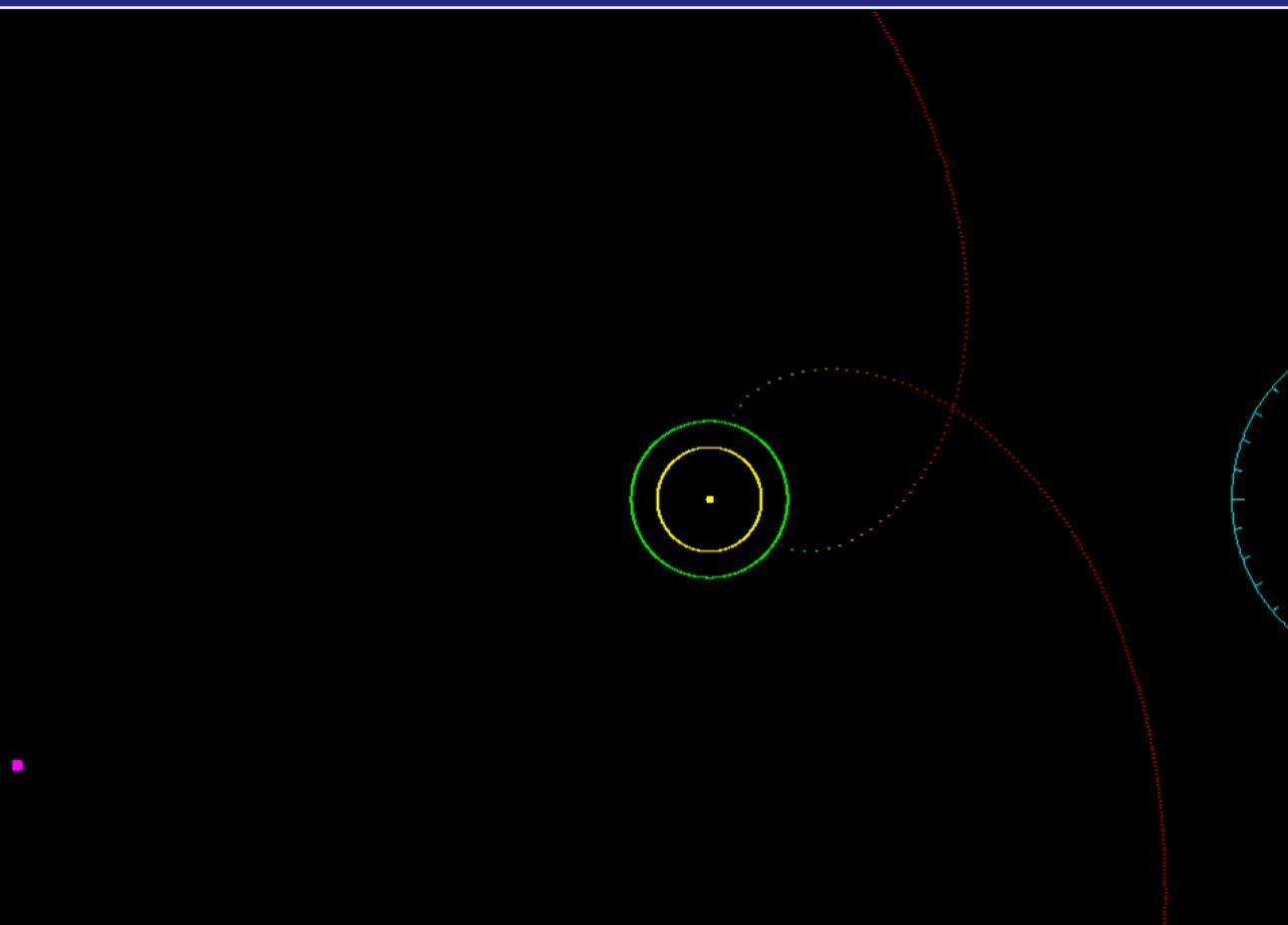


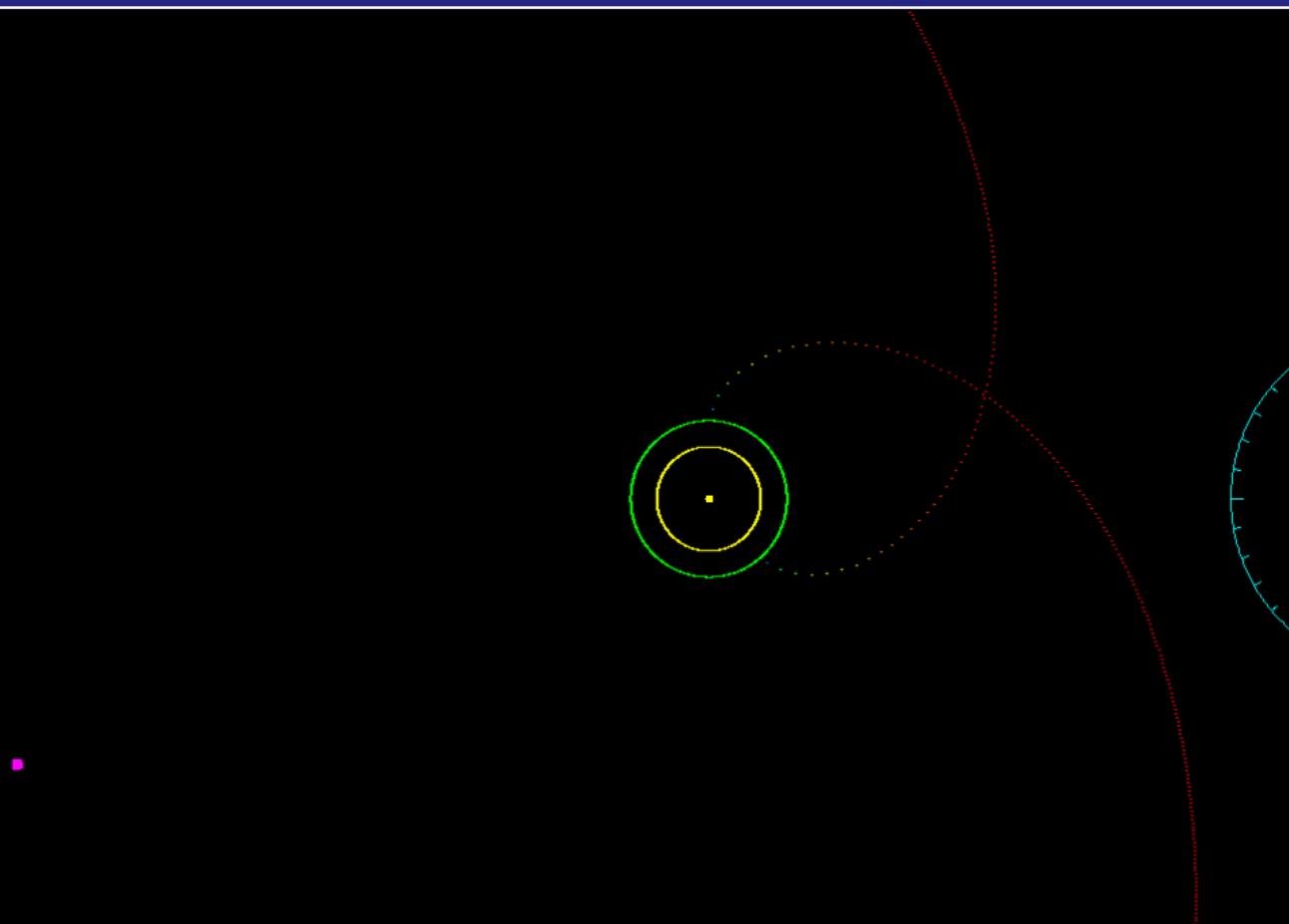


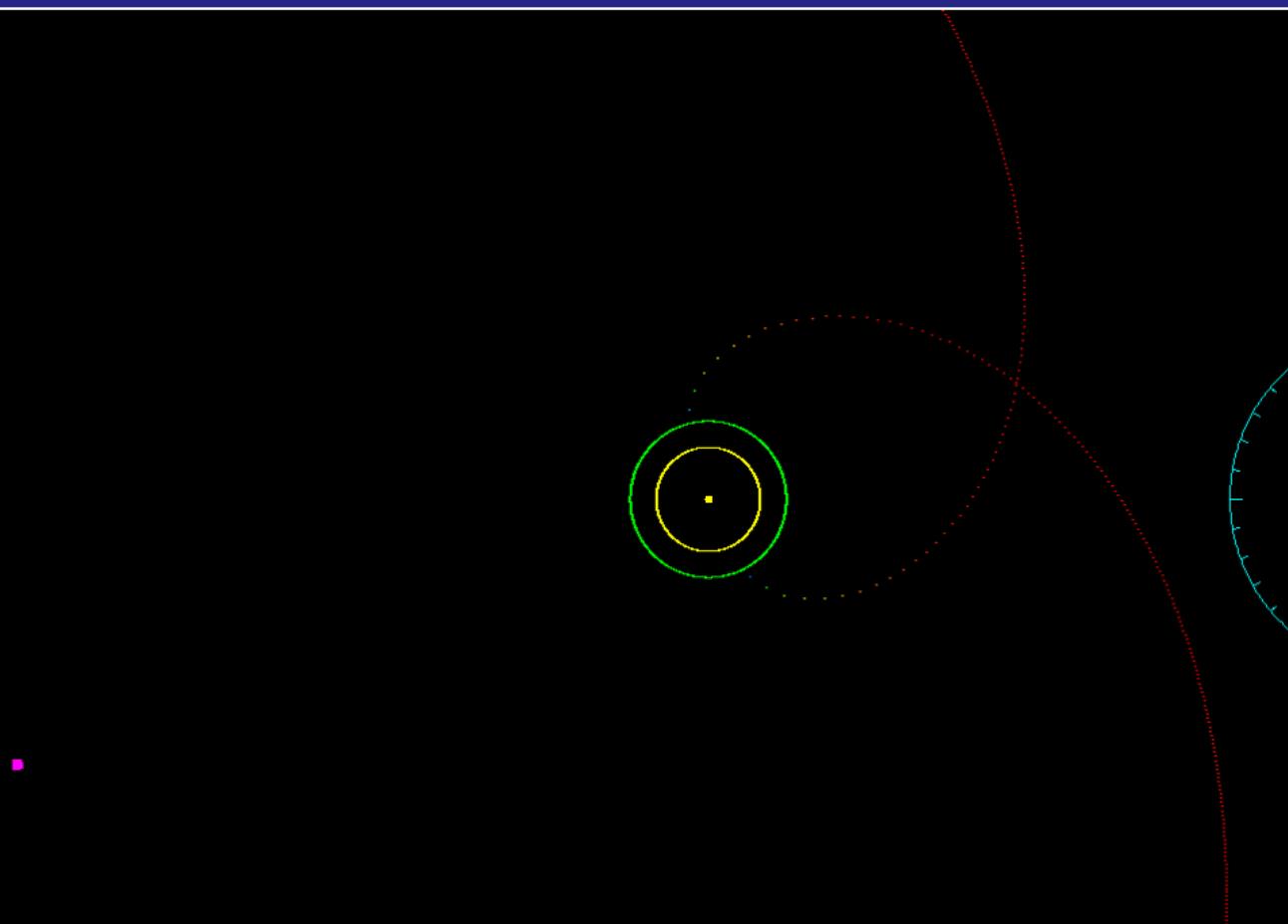


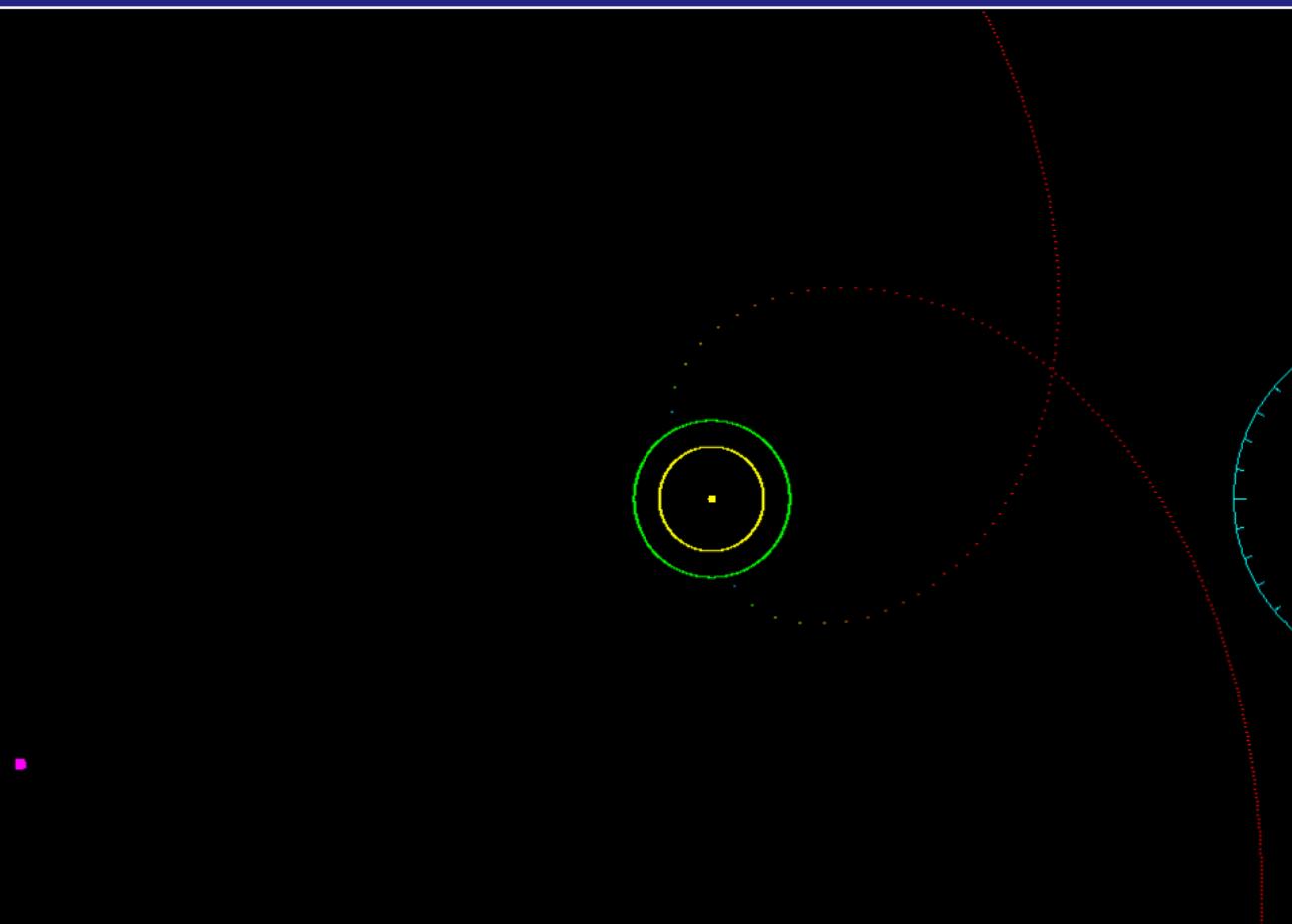


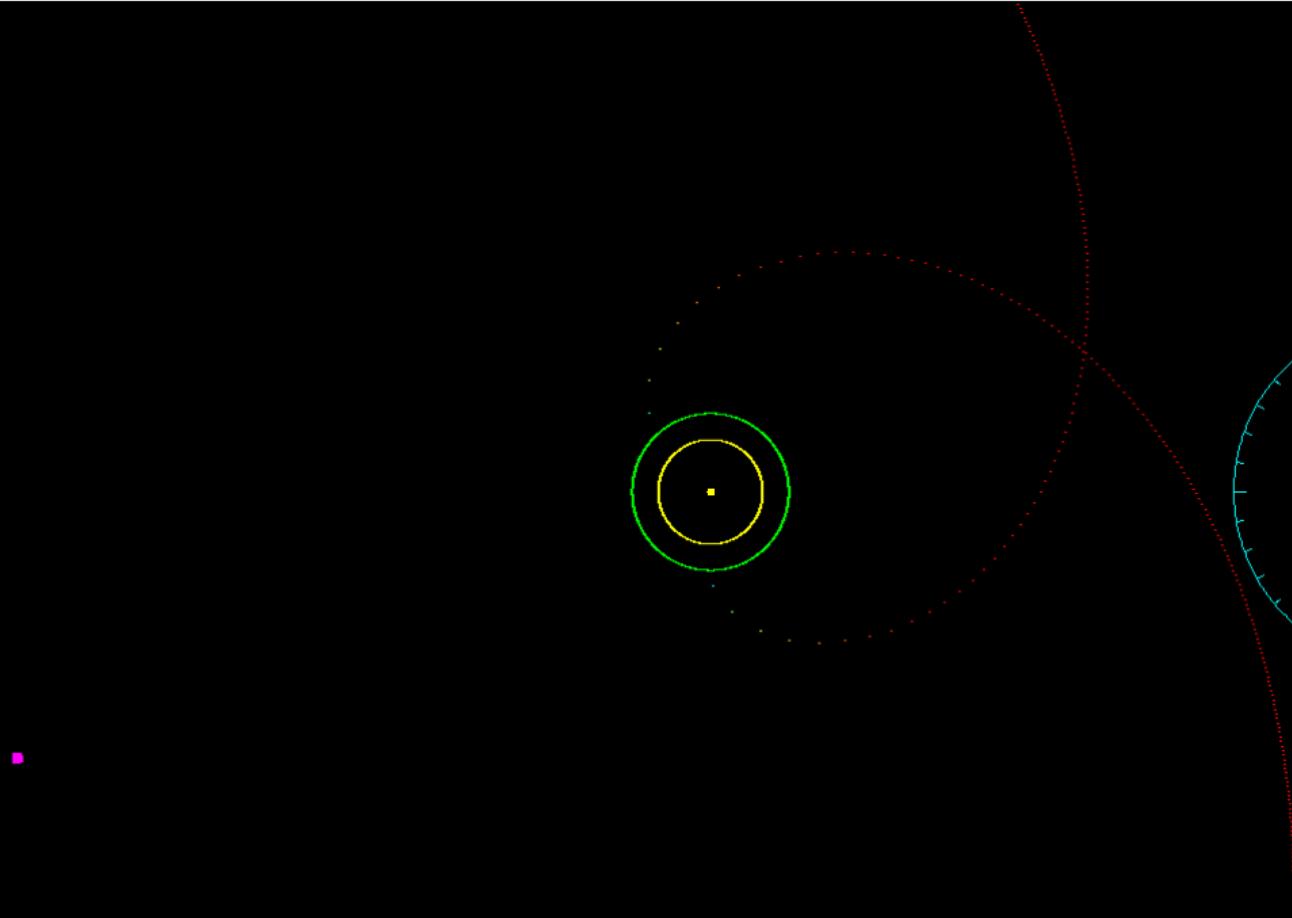


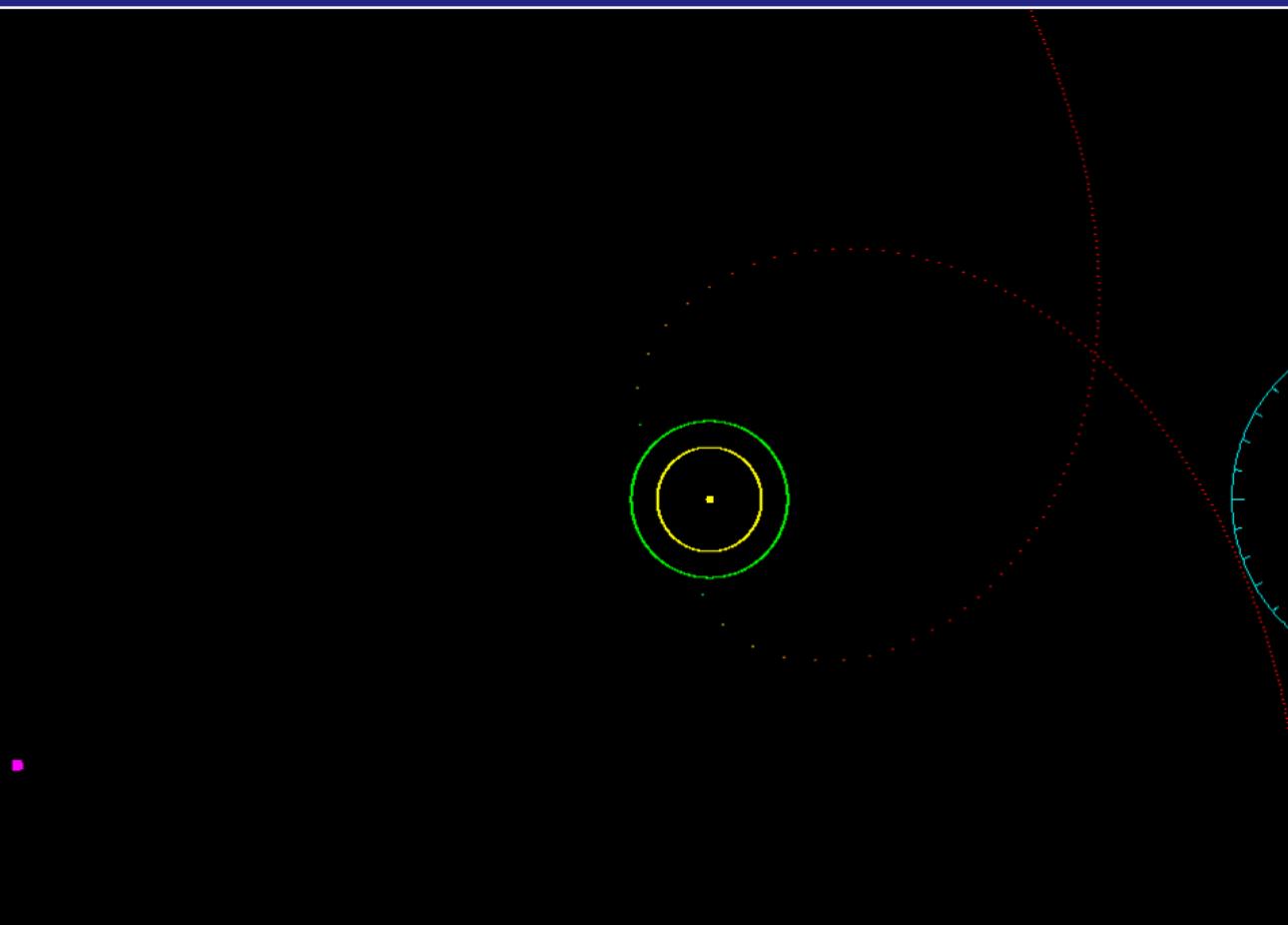


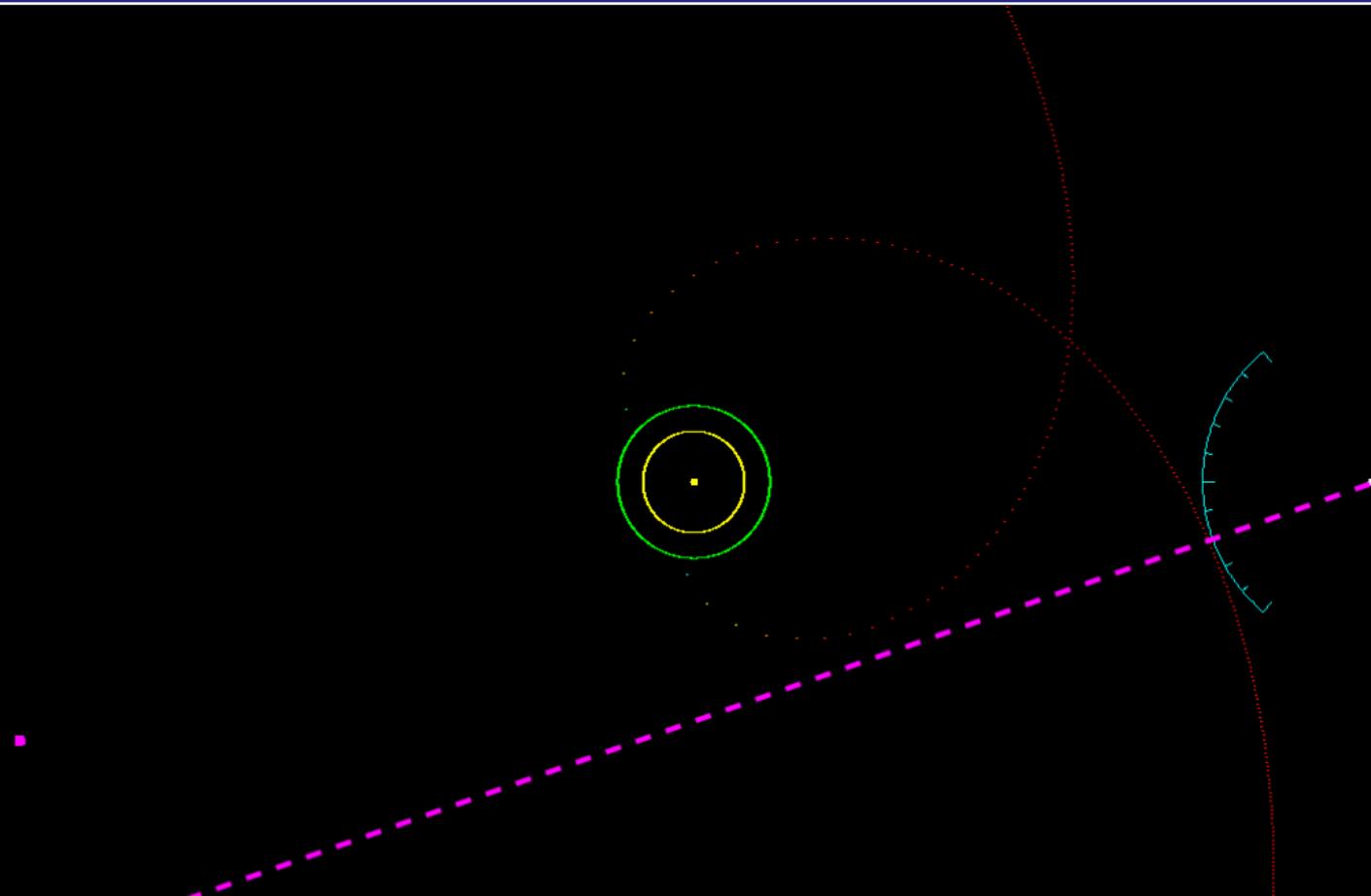


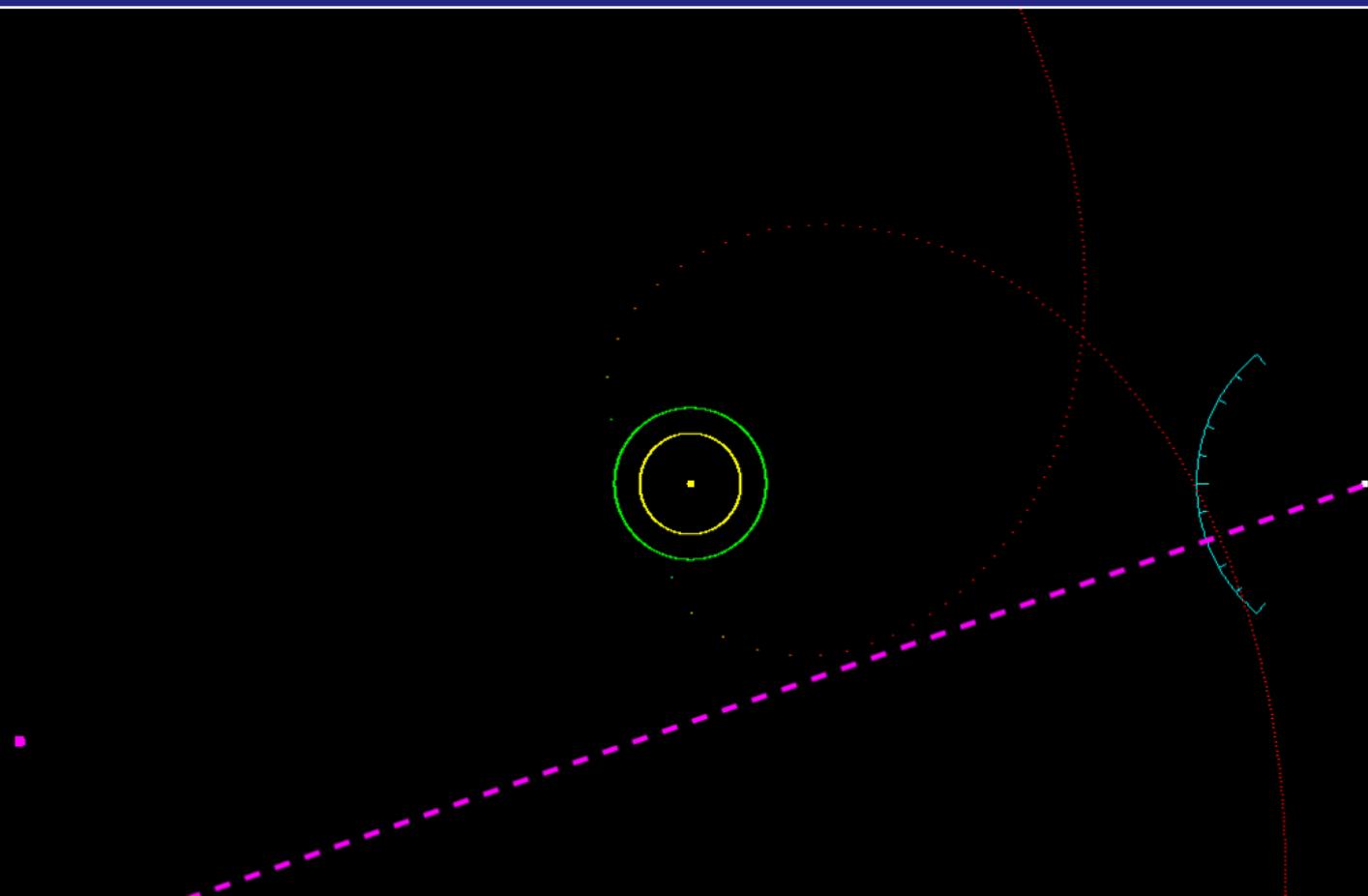


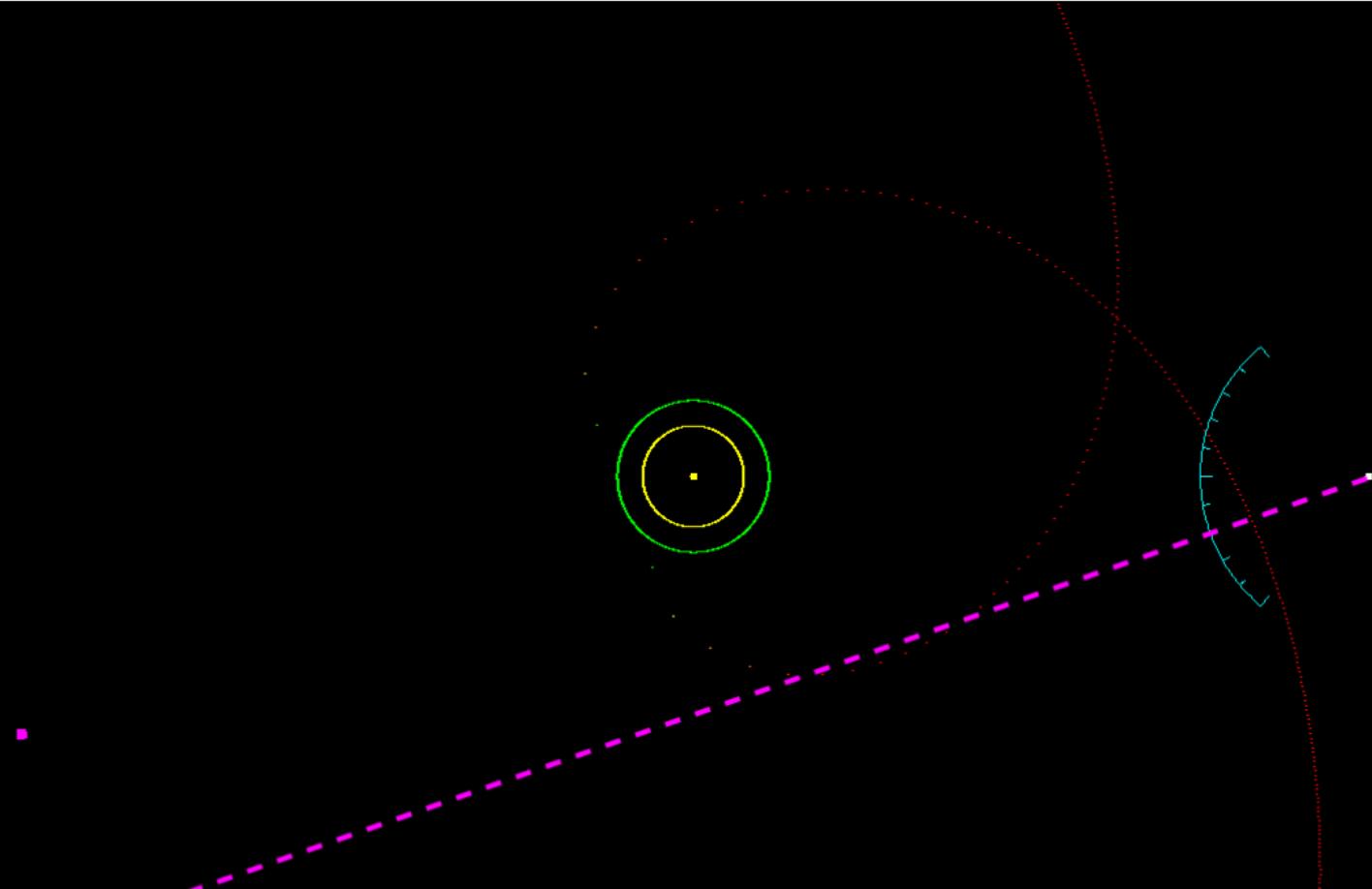


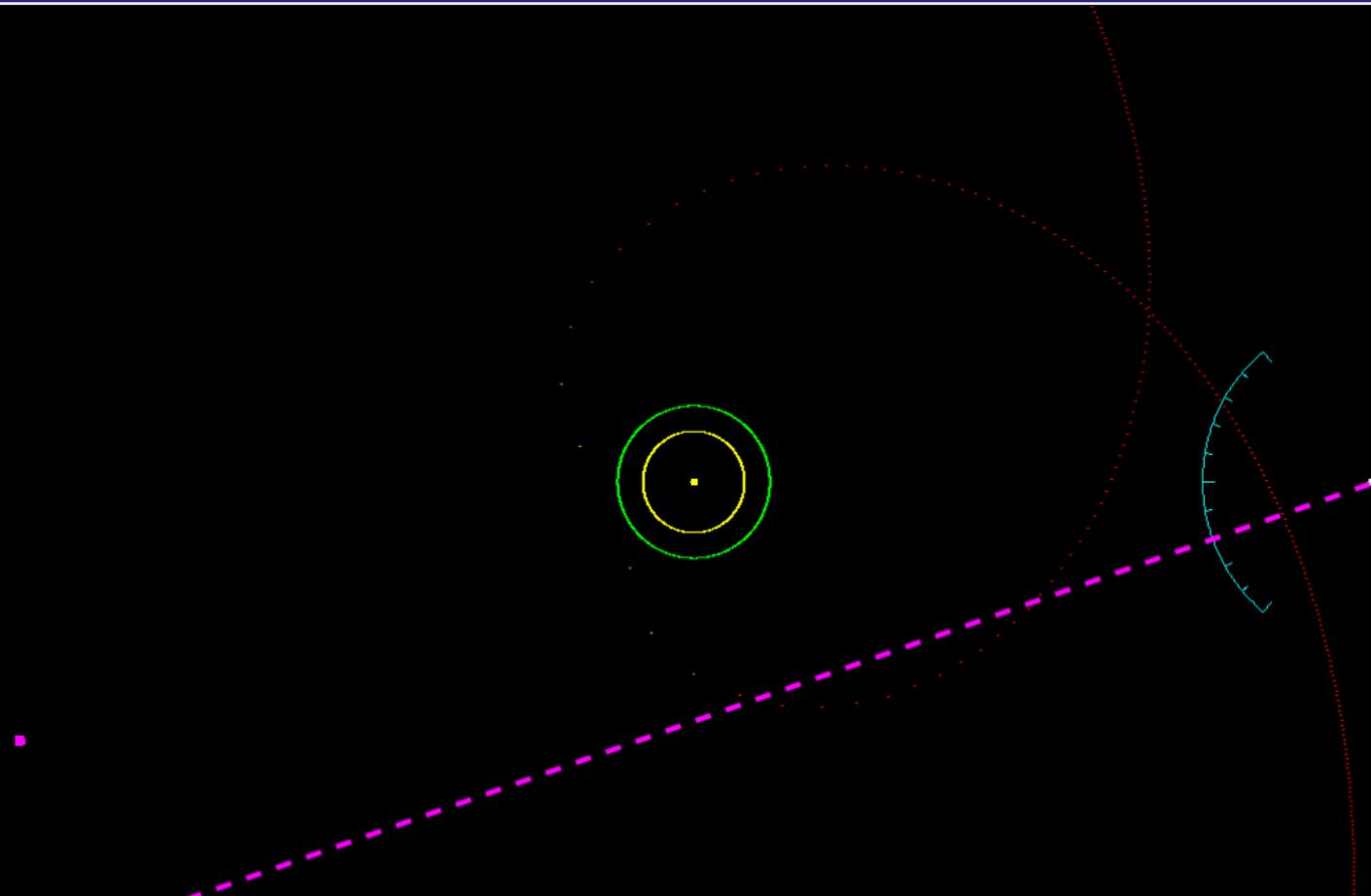


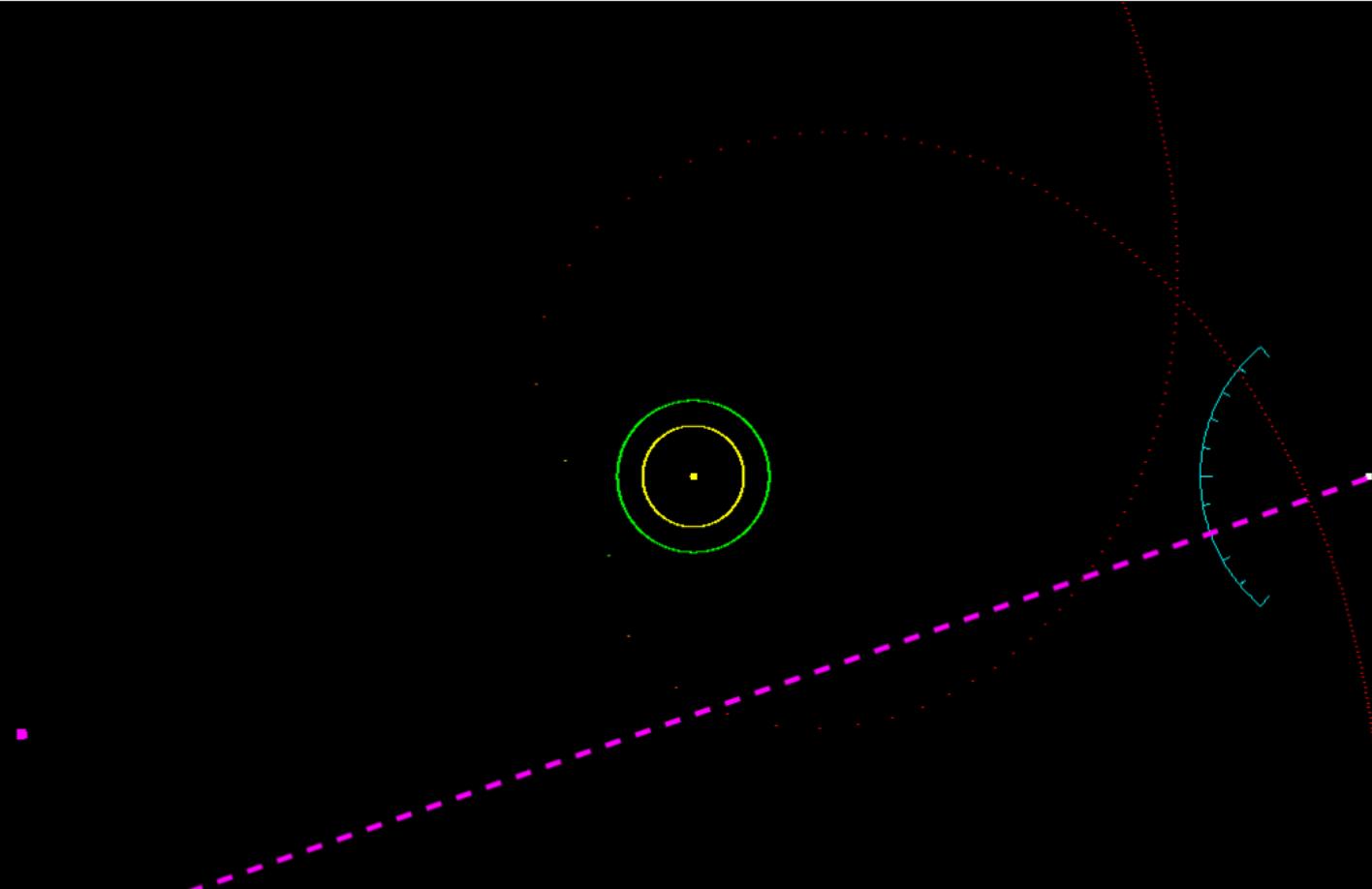


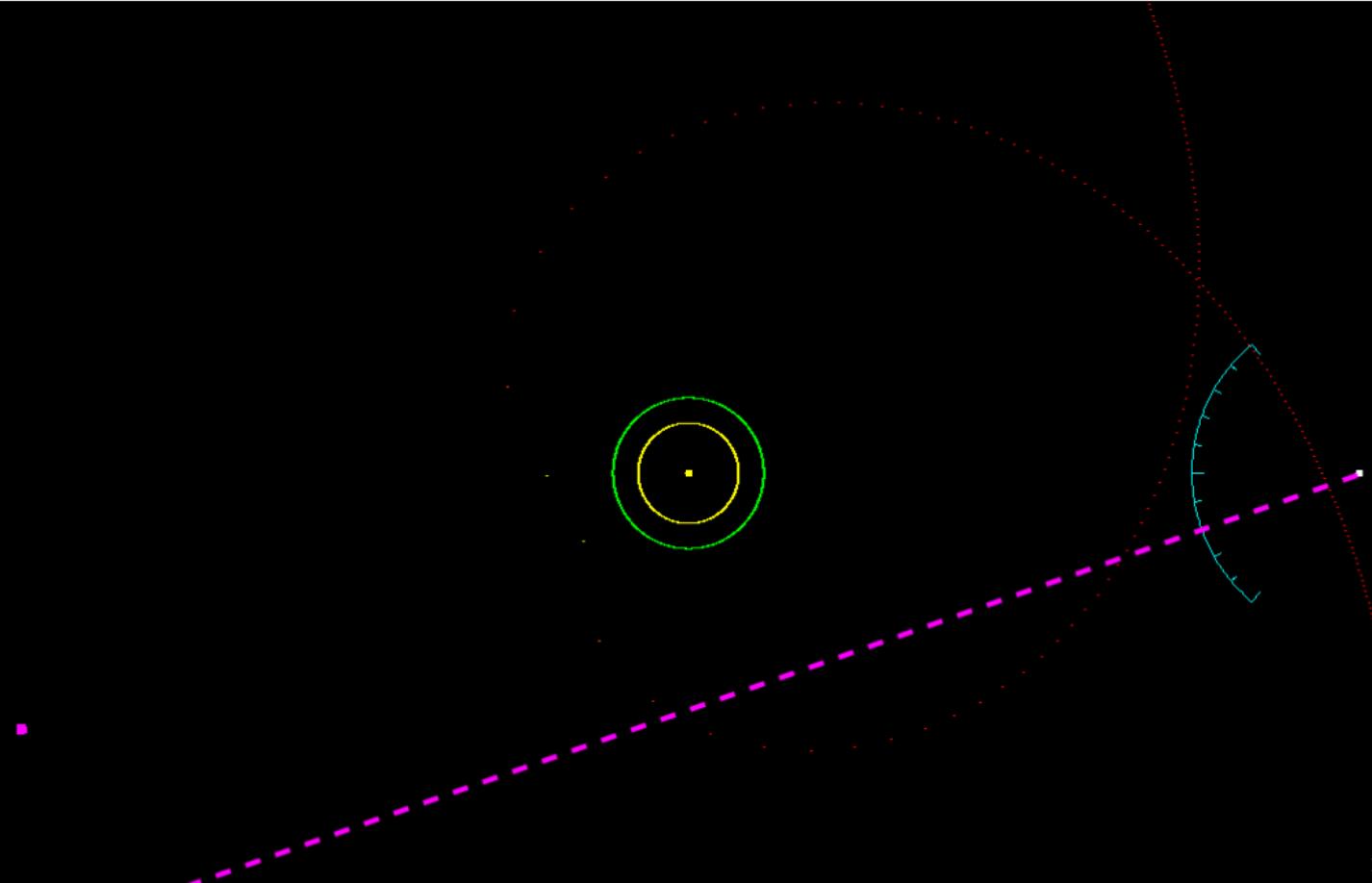


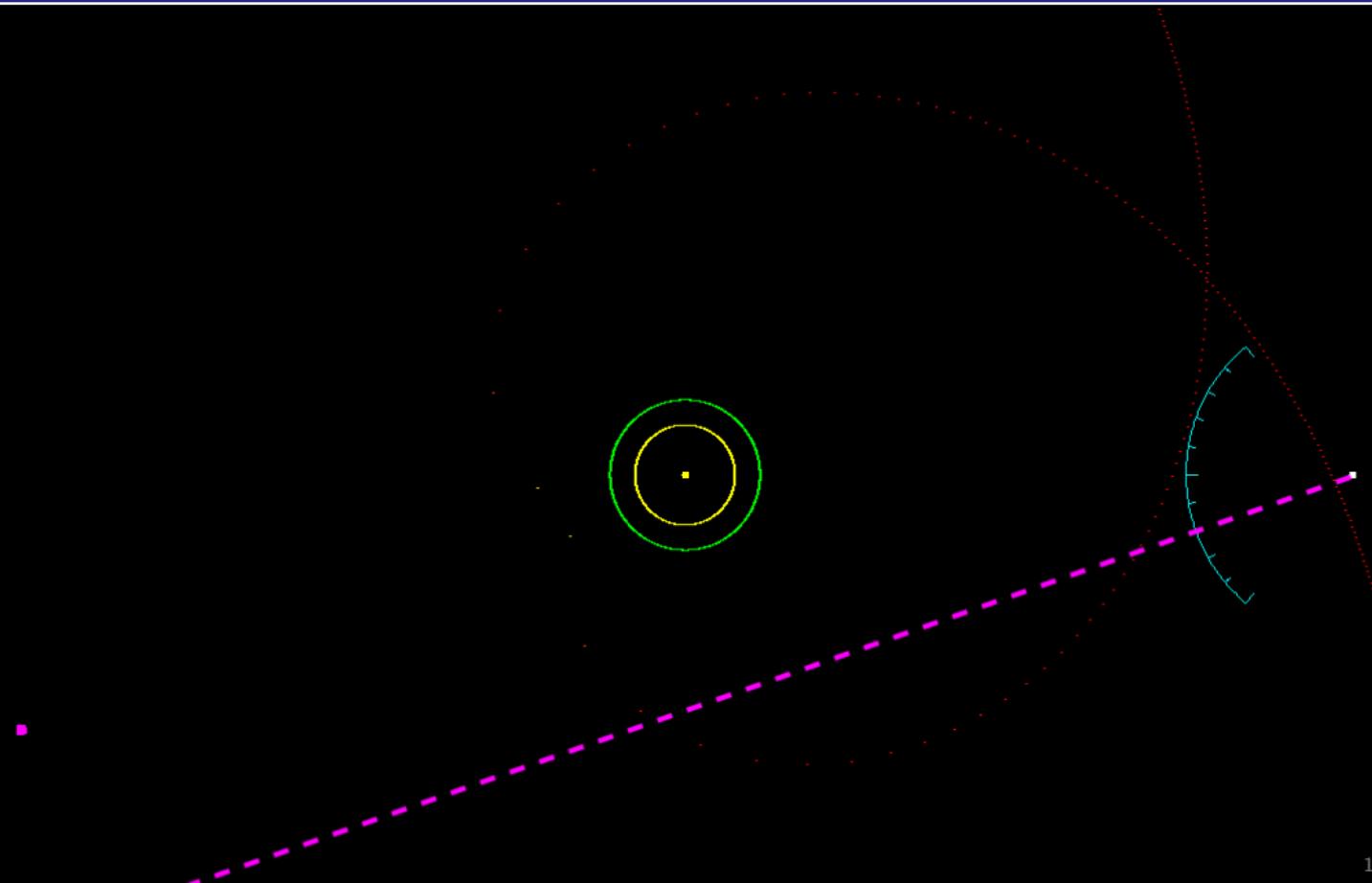


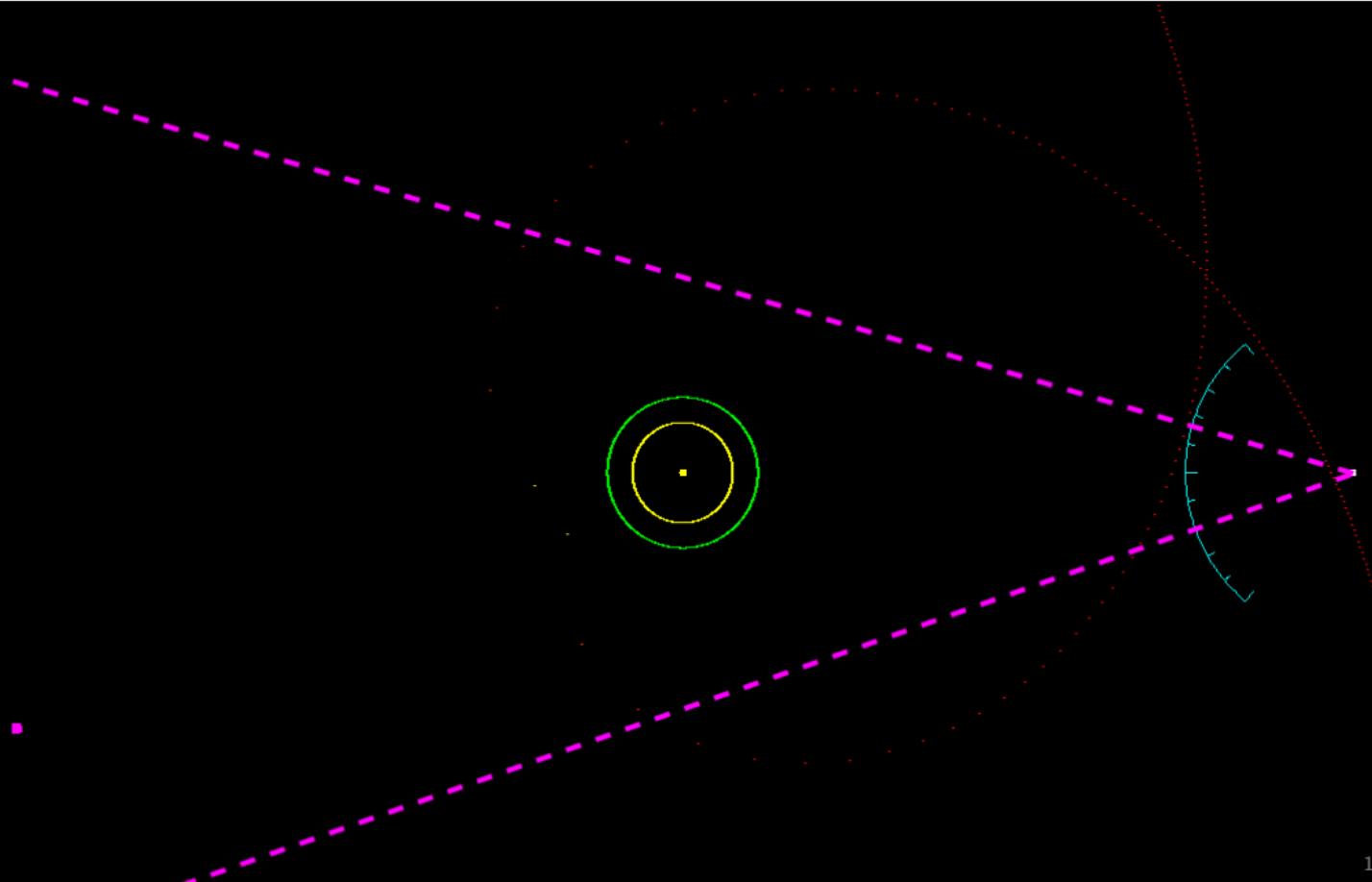


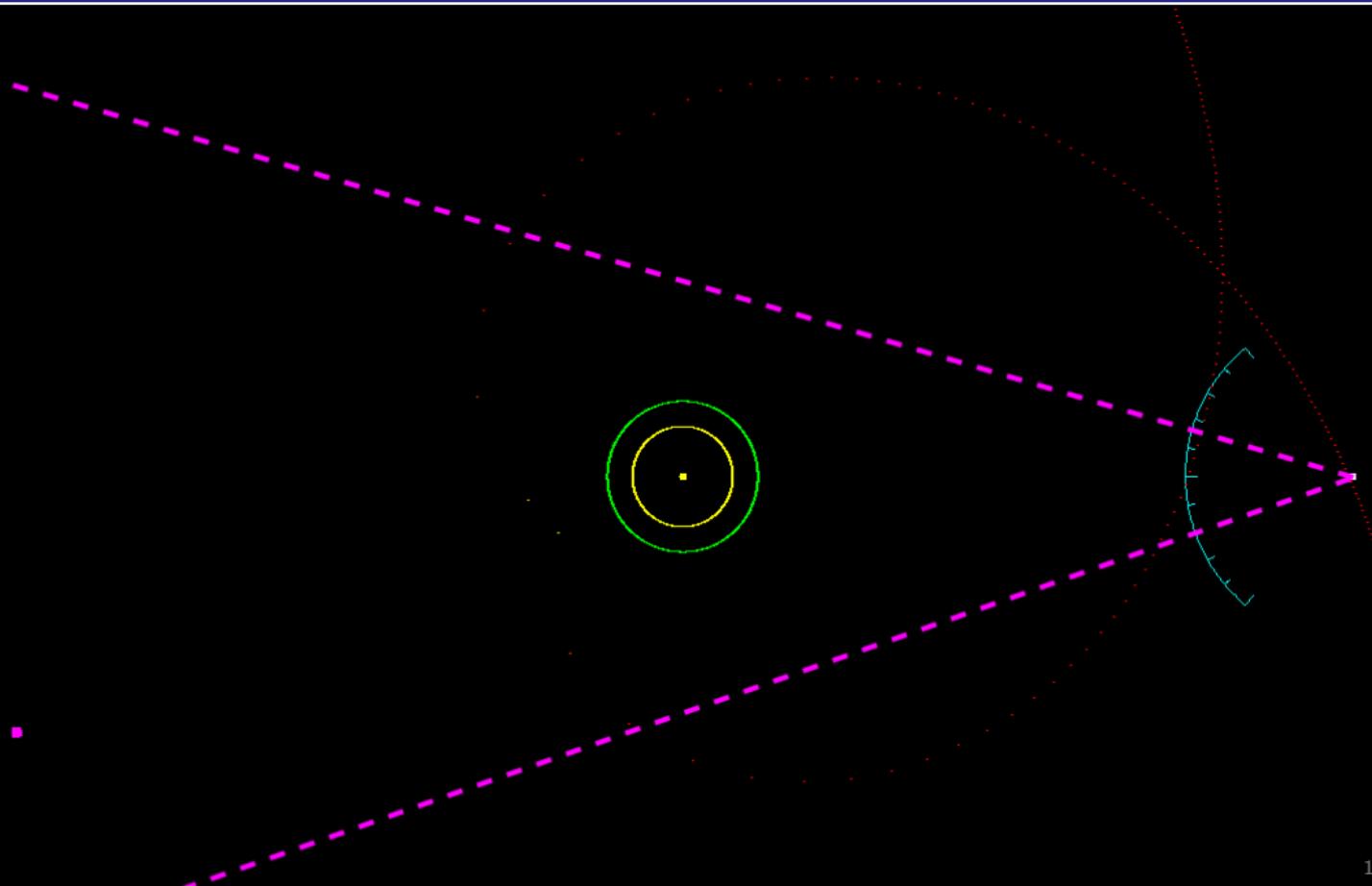


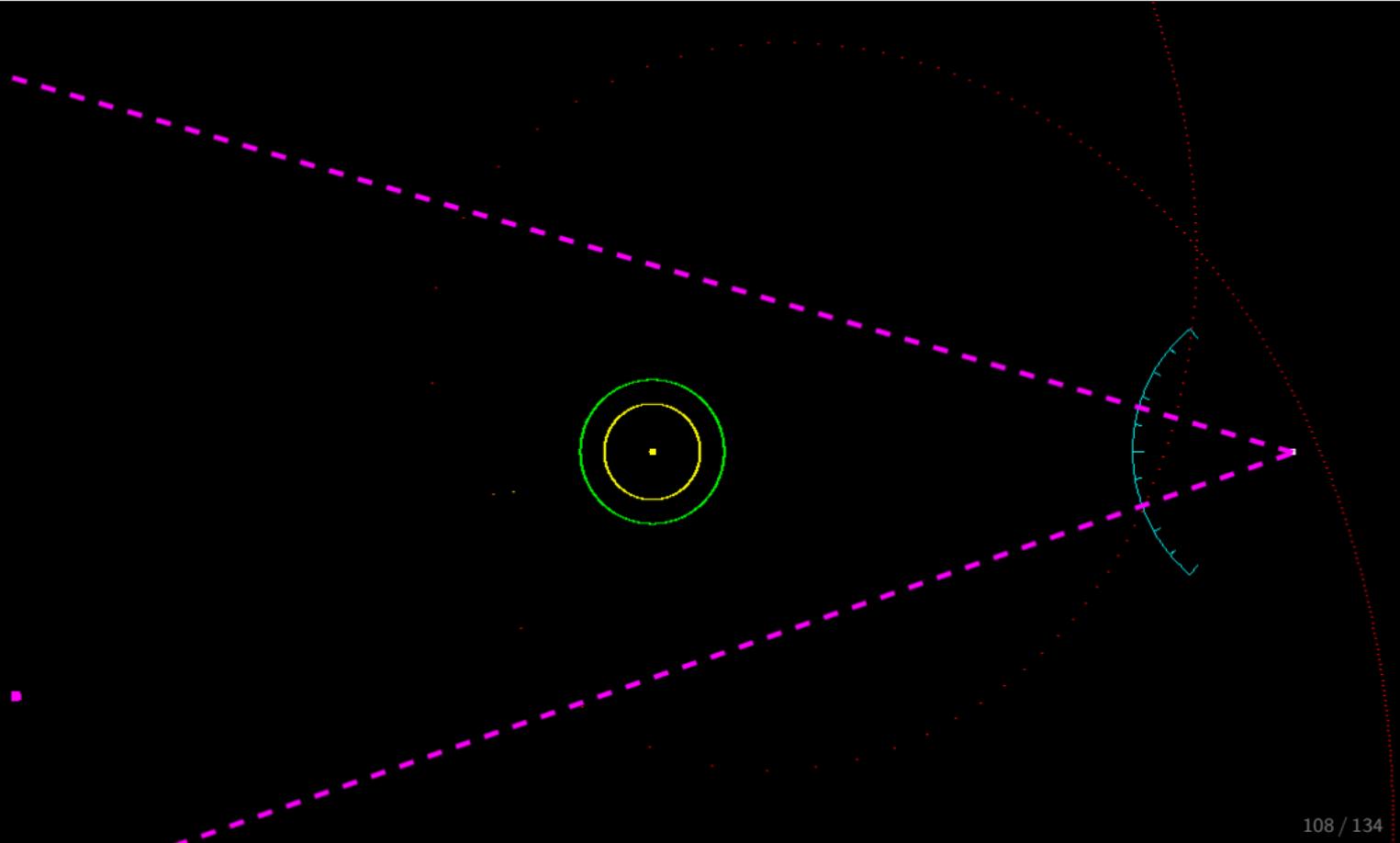


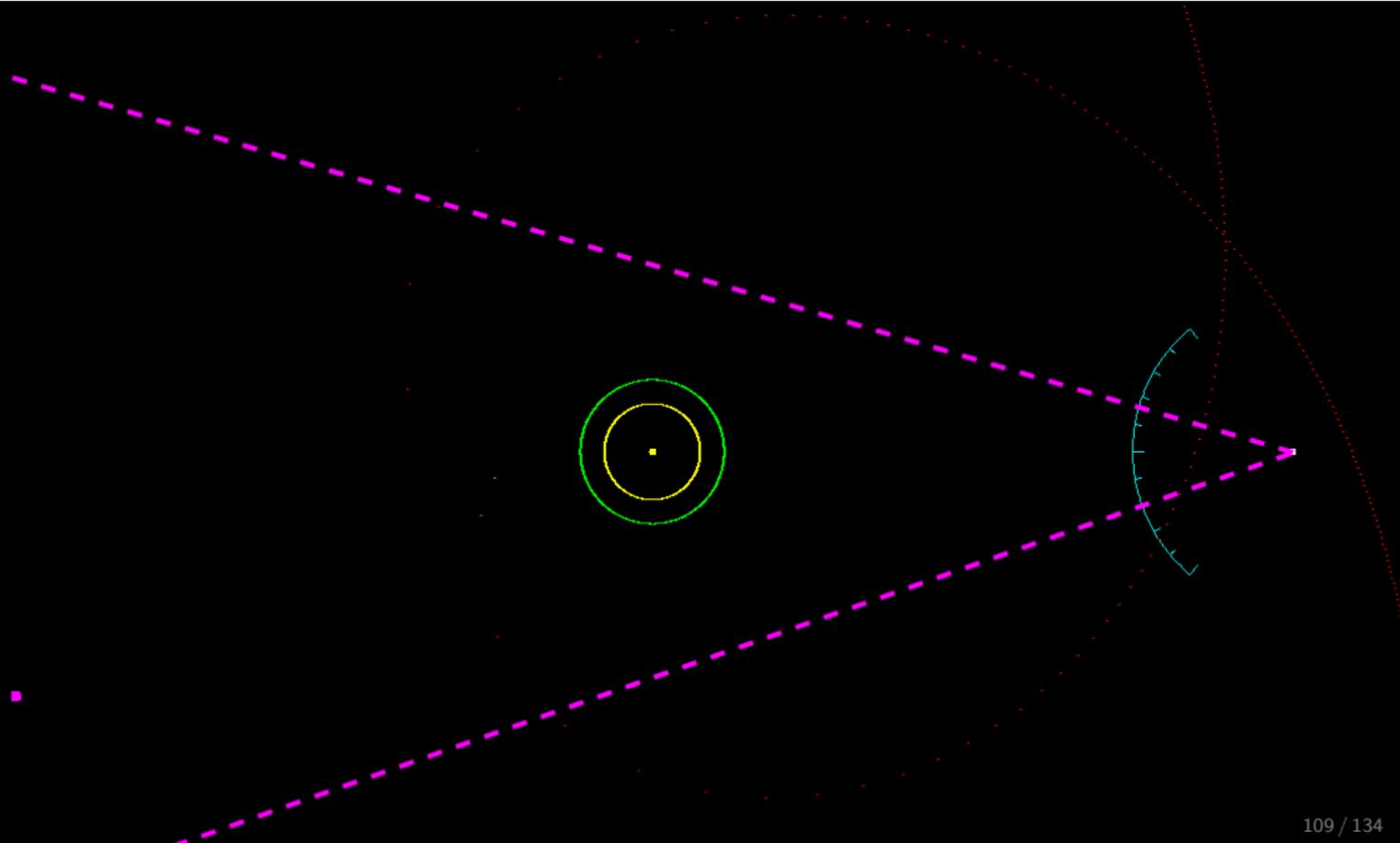


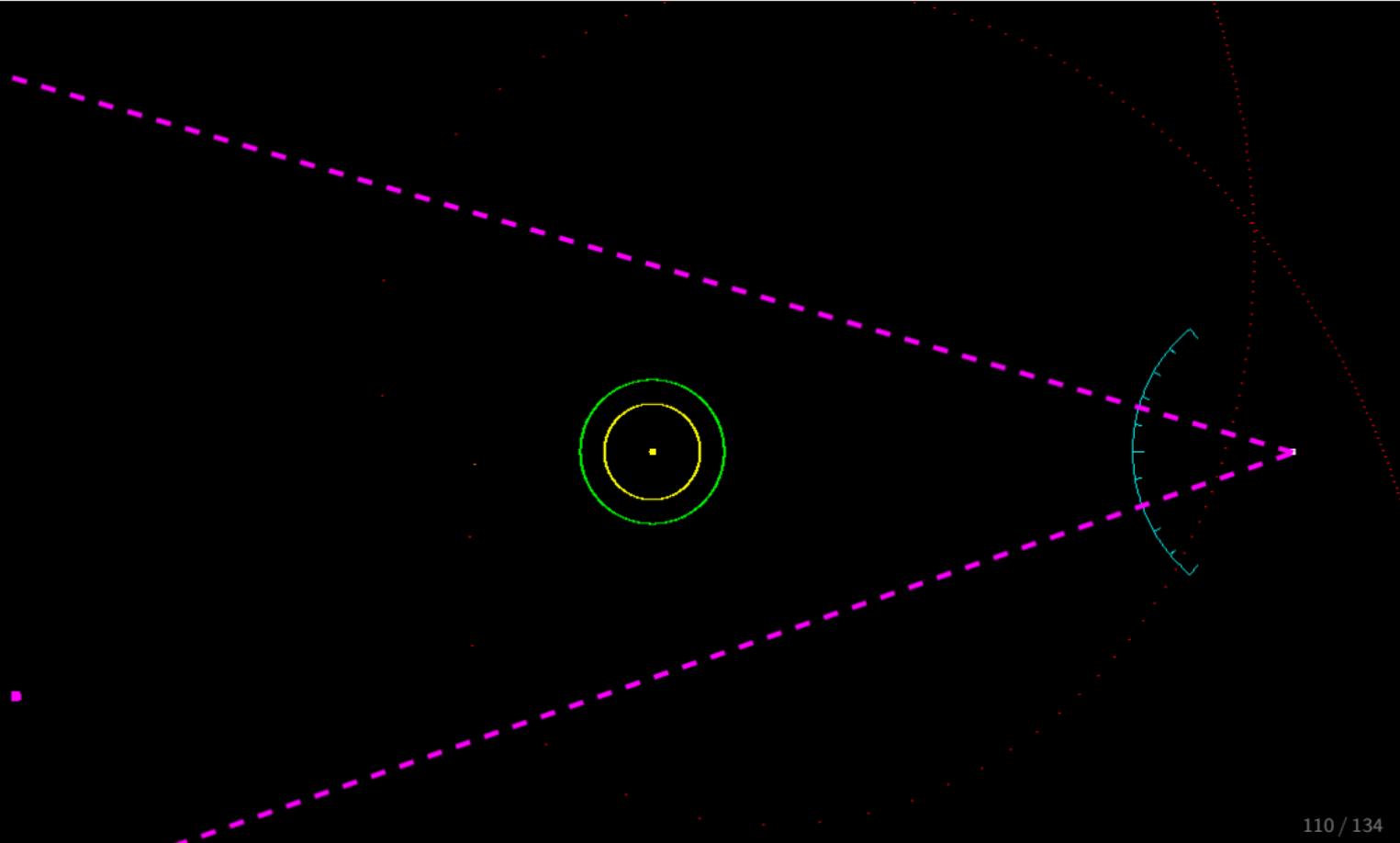




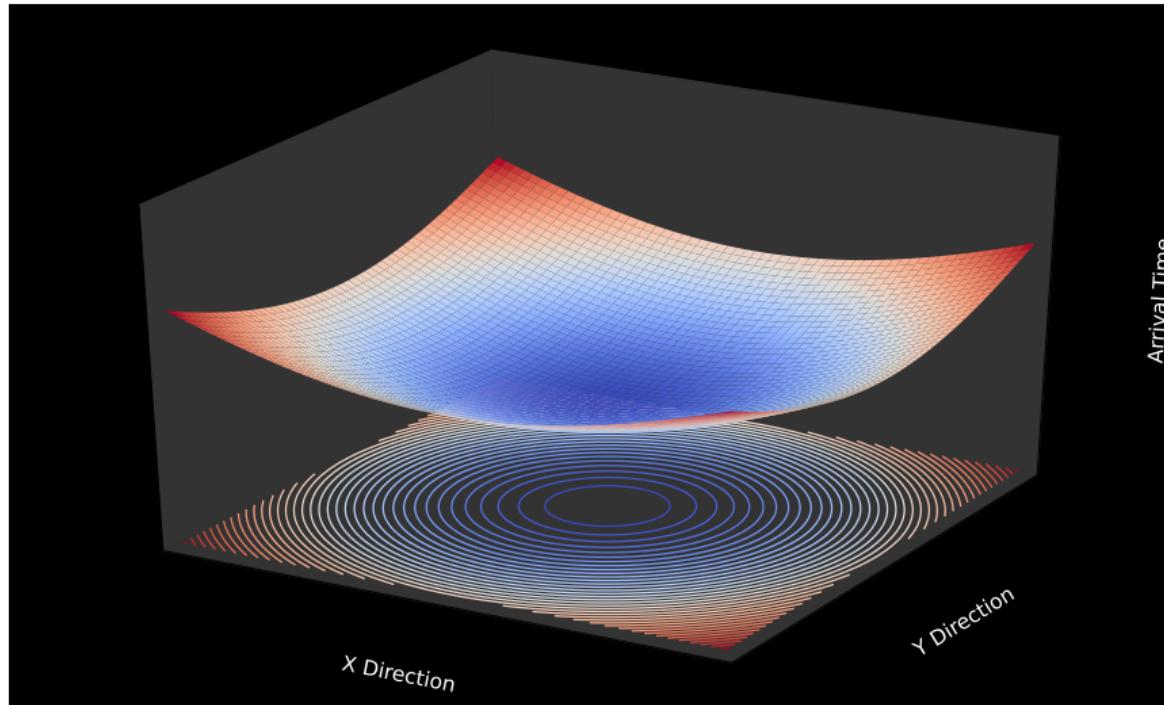


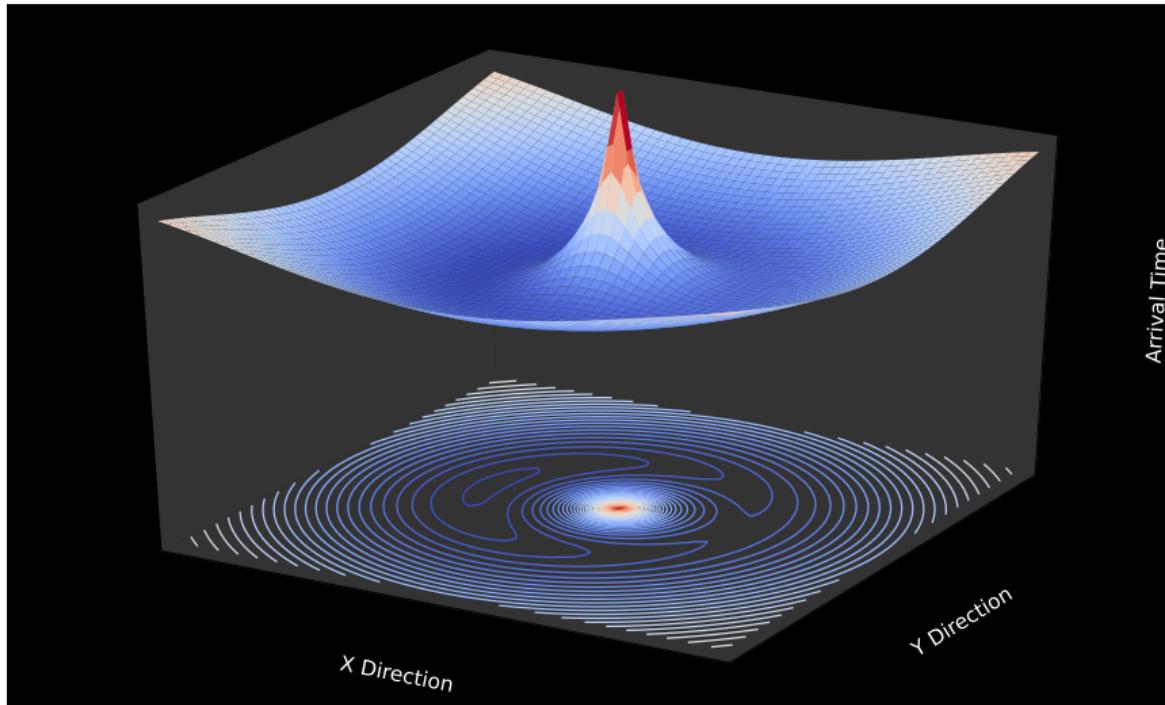






Arrival Time Surface





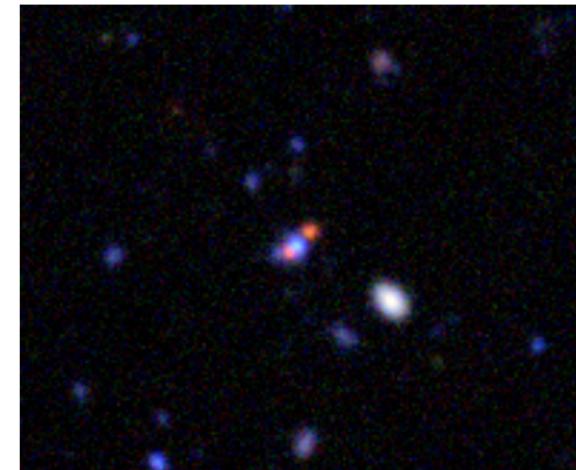
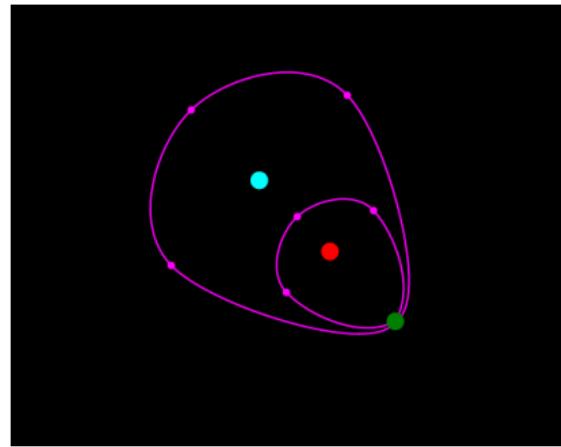
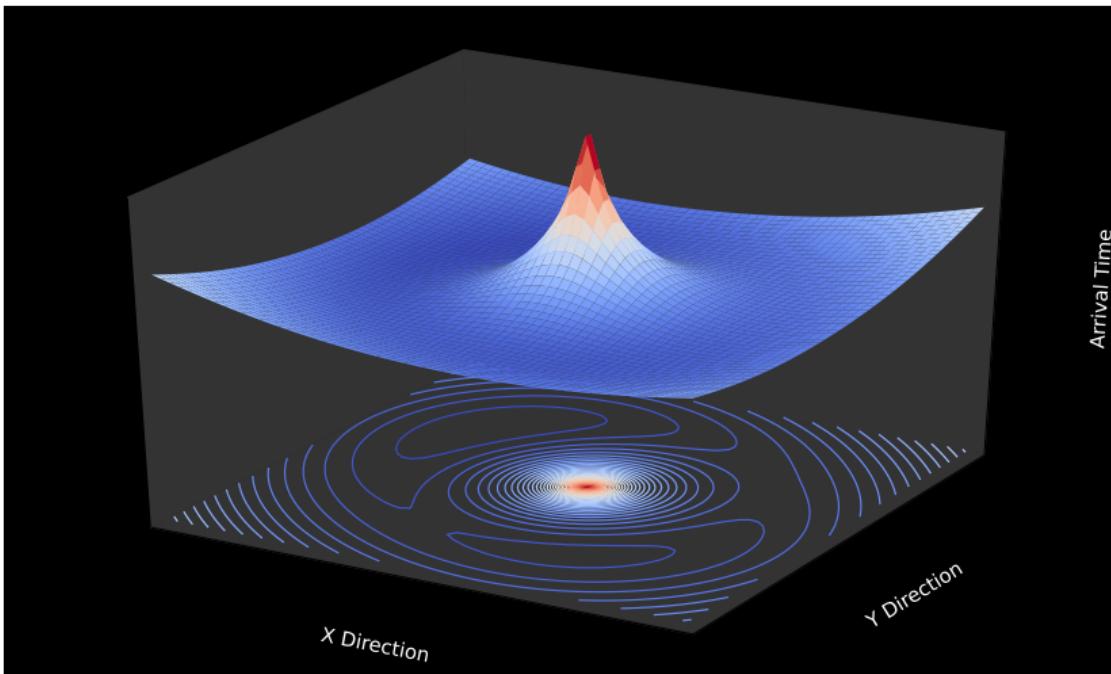


Figure : ASW0004q9e, SpaceWarp
(SW)



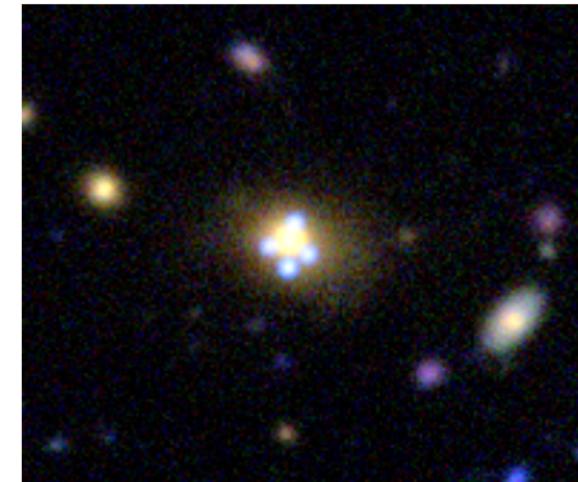
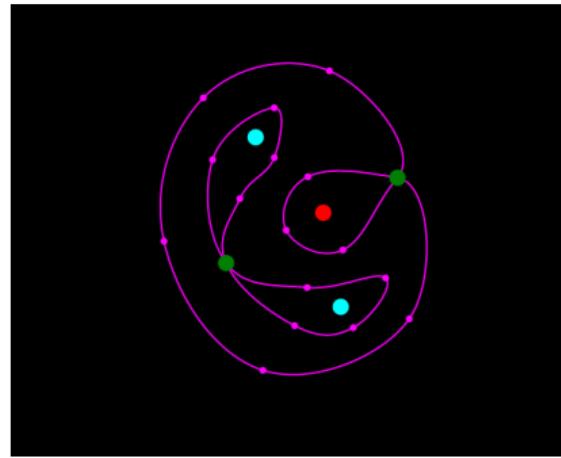
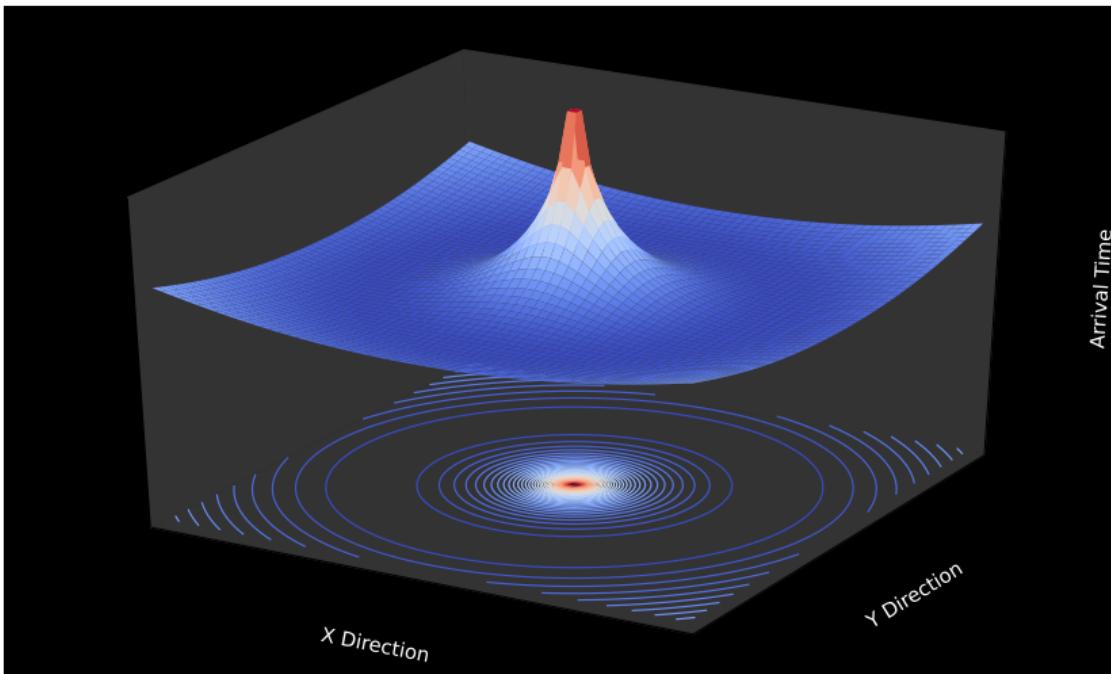


Figure : ASW0001a8c (SW)



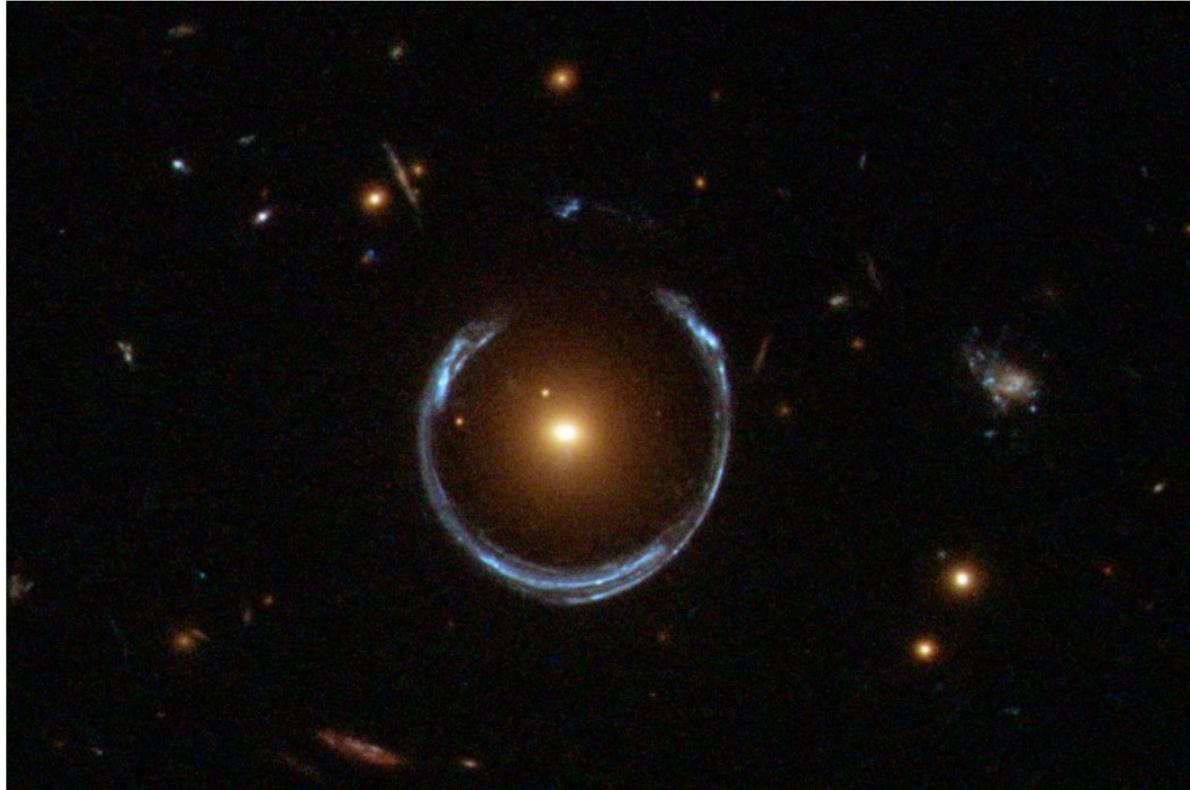
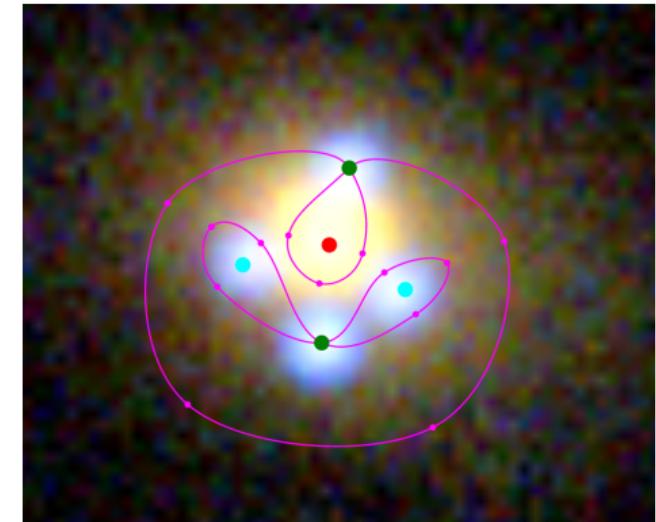


Figure : LRG 3-757 (2007, SDSS) Img: ESA/Hubble & NASA

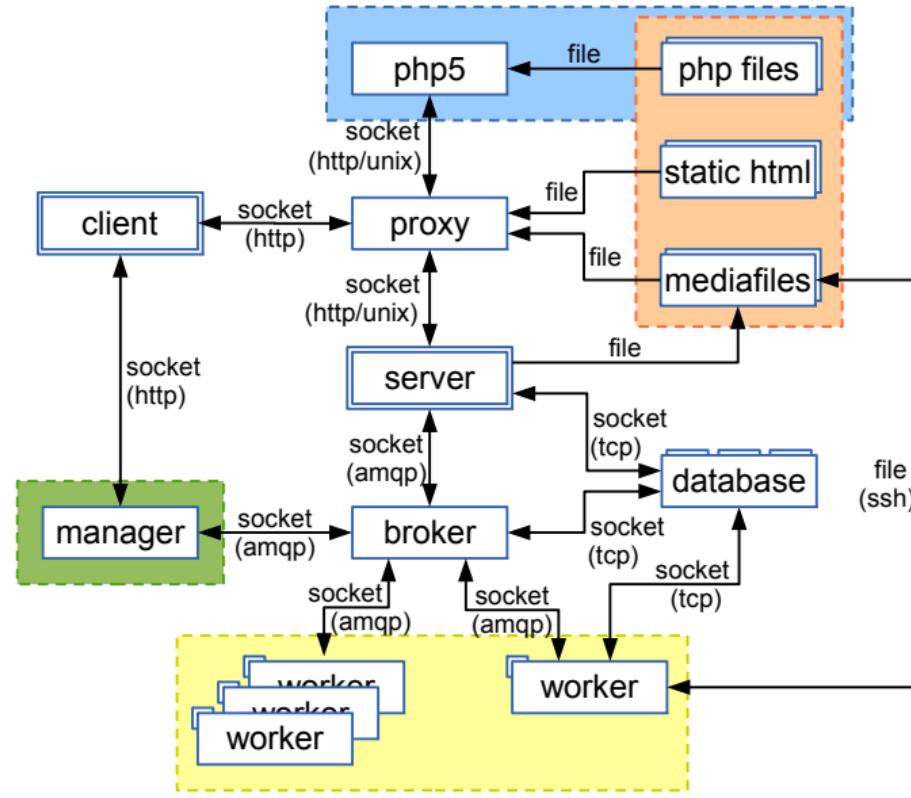
SpaghettiLens

- Extremal Points (Images)
- Self Intersecting Contour Lines

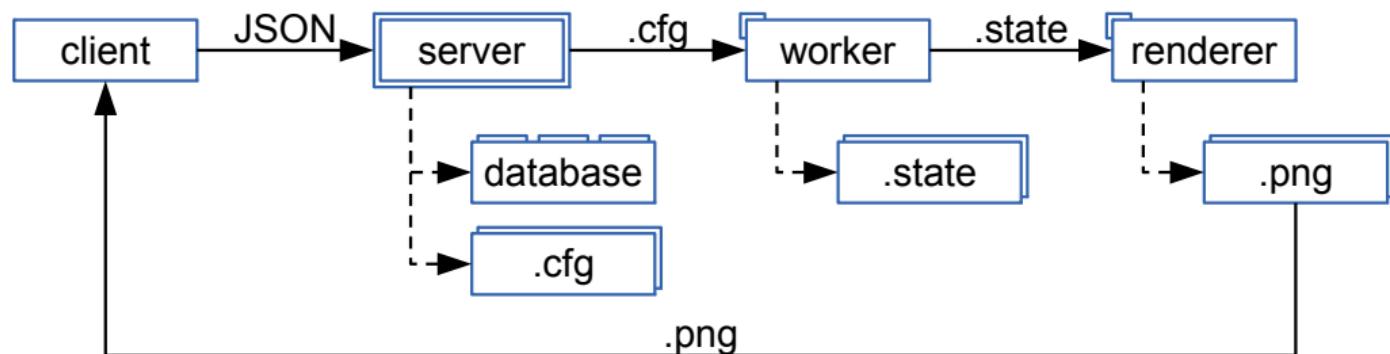
<http://mite.physik.uzh.ch/>



Implementation - Modules



Implementation - Data Flow



Modelling Challenge - Simulations

Performance evaluation of volunteers

- Selected 29 simulated lenses⁴
- Simulation parameter hidden until evaluation
- Covering a range of lens configuration

⁴Sims by Anupreeta More, using gravlens (Keeton, C. R. & Winn, J. N. 2003, ApJ, 590, 39)

Modelling Challenge – Tests

T1: Arrival time surface

- T1a: Correct identification of images
- T1b: Correct ordering

T2: Mass Distribution

Comparable mass distribution $\kappa(x, y)$ of lens

- Calculate enclosed mass $\kappa(r)$
- Determine Einstein Radius θ_E defined by $\kappa(\theta_E) = 1 \Rightarrow \theta_E$
- Compare $\theta_{E, \text{sim}}$ to $\theta_{E, \text{model}}$

Results T1

		n	p
N:	Total number of models	119	1.00
R1:	images approx. on right location	110	0.92
R2:	images with correct parity	70	0.59
E01:	inaccurate in arc	21	0.18
E02:	wrong parity in 3 img. conf.	2	0.02
E03:	identified 3 of 5 imgs.	5	0.04
E04:	modeled arc with single img.	4	0.03
E05:	π rotated	7	0.06
E06:	$\pi/2$ rotated	38	0.32
E07:	missed faint img.	1	0.01
E08:	too many imgs in arc	5	0.04
E09:	missed double img	3	0.03
E10:	too many imgs.	1	0.01

Table : T1 evaluation

Results for Model 007025 (ASW0000h2m)

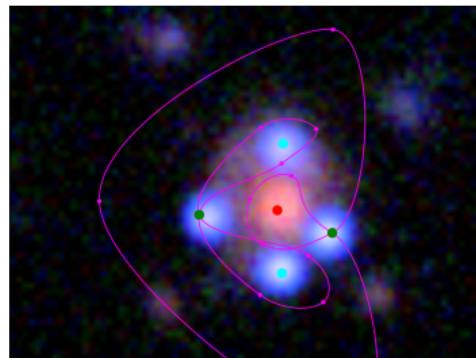


Figure : User input

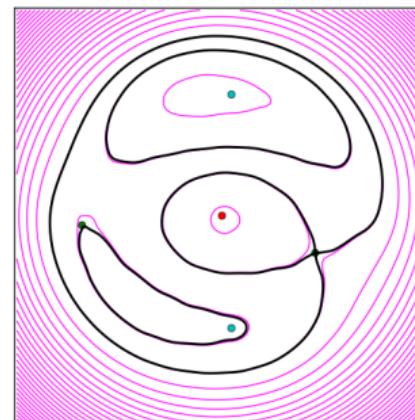


Figure : Reconstructed contour lines

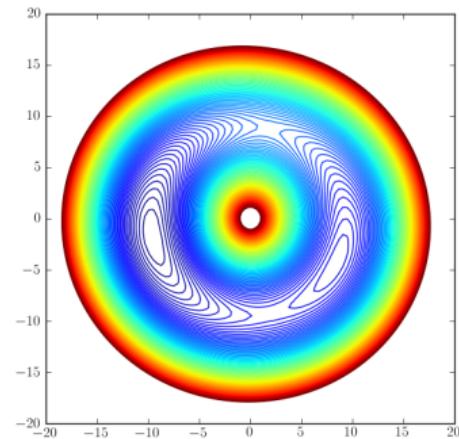
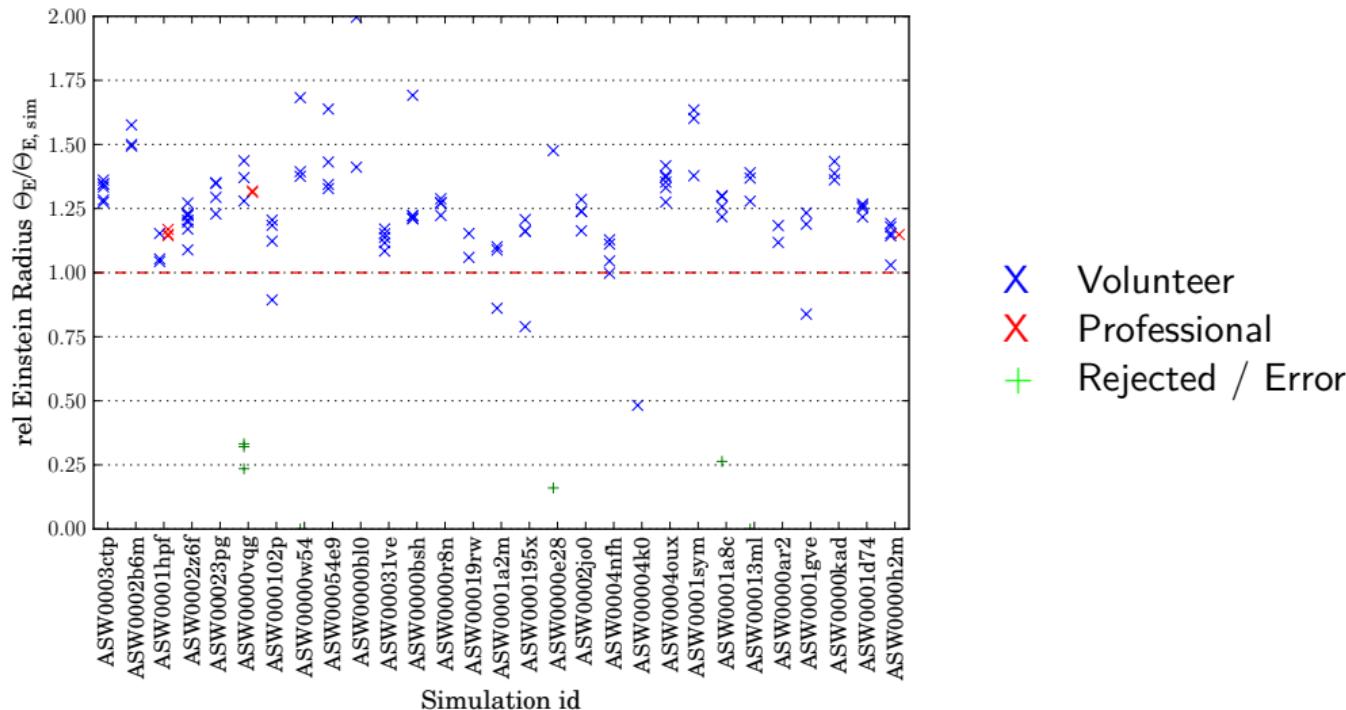
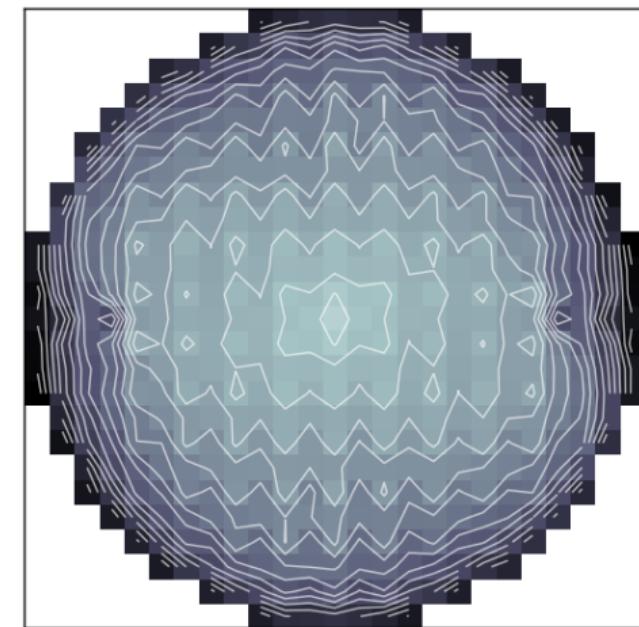
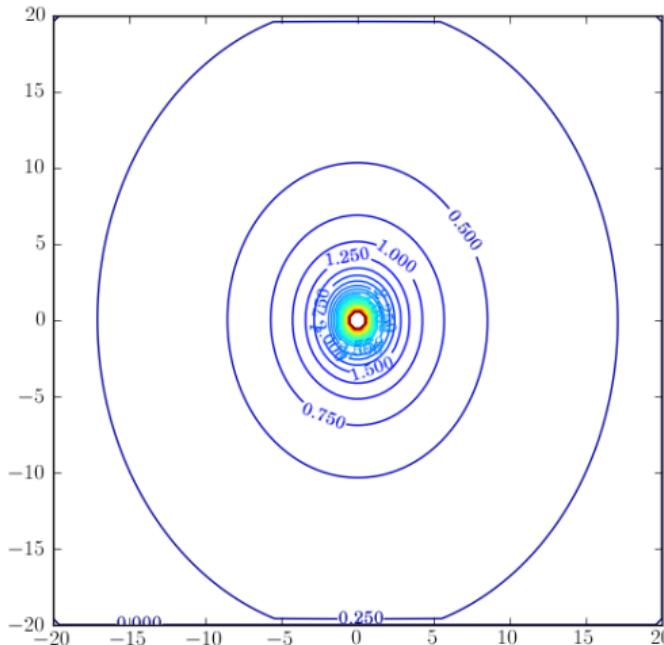


Figure : Original contour lines

Results T2



Results for Model 007025 (ASW0000h2m)



$\kappa(r)$ for Model 007025 (ASW0000h2m)

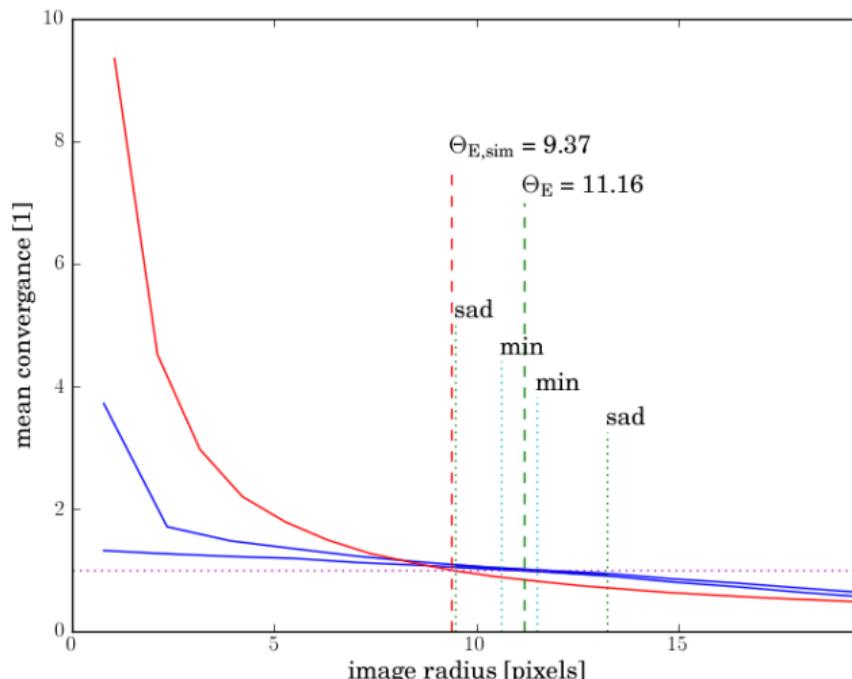


Figure : Enclosed mass $\kappa(r)$

Results for Model 006990 (ASW0004oux)

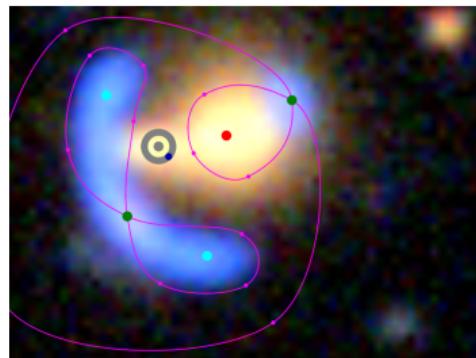


Figure : User input

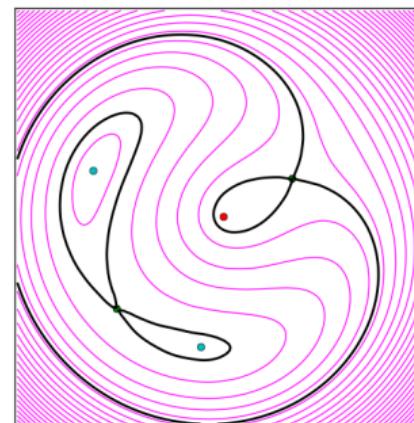


Figure : Reconstructed contour lines

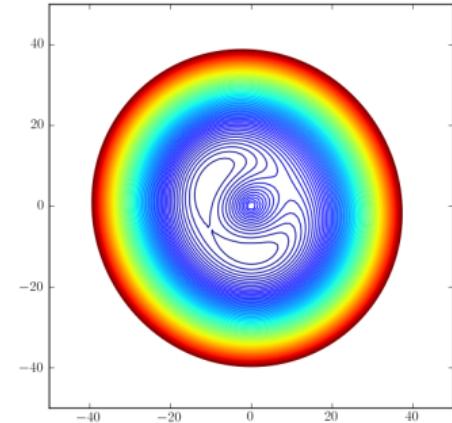
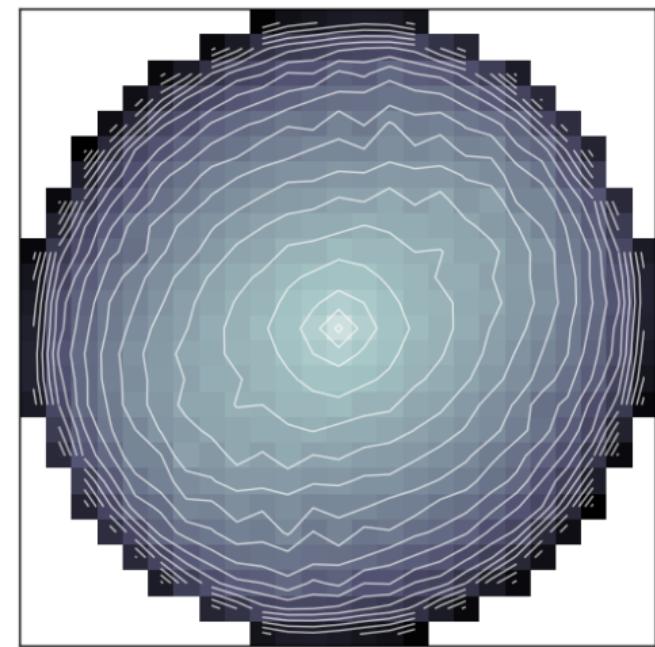
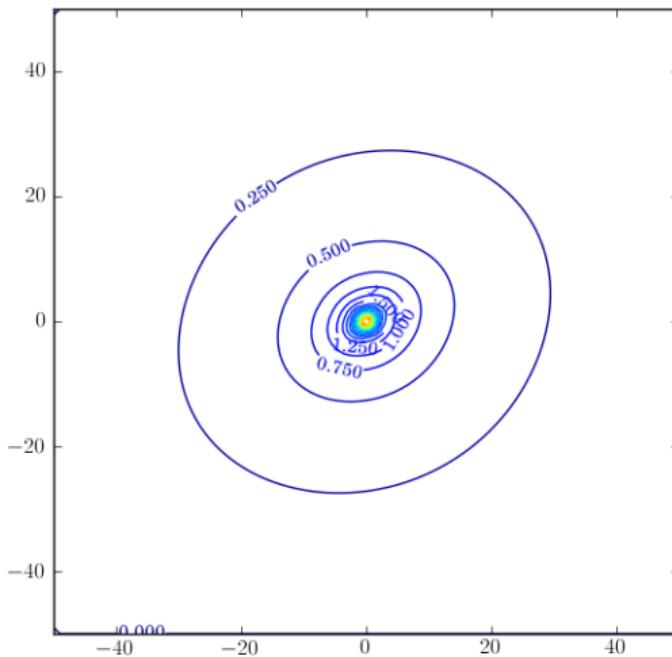


Figure : Original contour lines

Results for Model 006990 (ASW0004oux)



$\kappa(r)$ for Model 006990 (ASW0004oux)

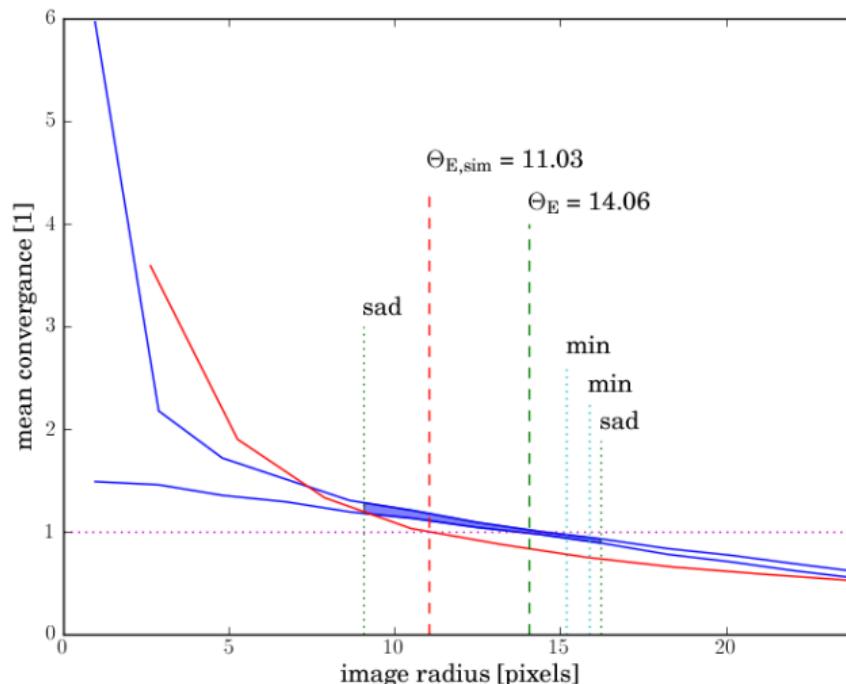


Figure : Enclosed mass $\kappa(r)$

Conclusions

- Volunteers can model lenses
- They do it comparably well to a scientist
- They like doing it
- Collaborative Modelling

The End

Questions?

Appendix

$$A_t = A_{\text{geom}} + A_{\text{grav}} \quad (1)$$

$$A_{\text{geom}} = \frac{1}{2} (x^2 + y^2) \quad (2)$$

$$\nabla^2 A_{\text{grav}} (x, y) = -2\kappa (x, y) \quad (3)$$

$$A = \frac{cD_L}{(1+z_L)^2} \frac{D_{LS}}{D_S} \times t \quad (4)$$

$$\kappa (x, y) = \frac{4\pi G}{c^2} \frac{D_L}{1+z_L} \frac{D_{LS}}{D_S} \times \Sigma (x, y) \quad (5)$$

$$(6)$$

Fermat's Principle

Fermat's Principle

Time t for path X :

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

Path X where t stationary.

