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Boson Stars that mimic Black Holes

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Can a dymically robust, horizonless object mimic a BH?

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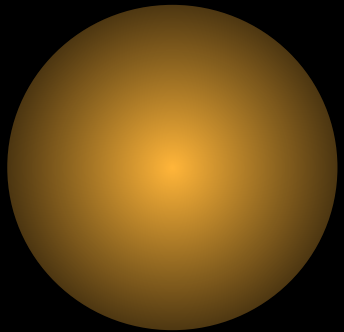
- A Boson Star is an hypothetical astronomical object made out of bosons
- For this stars to exist, one needs a stable boson
- Compact BSs are usually contain a massive complex scalar fields with **U(1)** global symmetry
- They are everywhere regular lumps of scalar or vector boson



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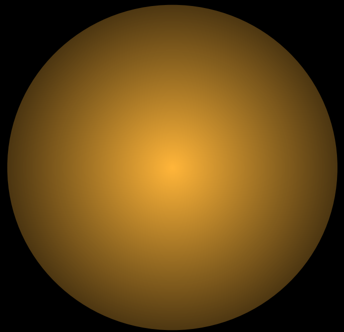

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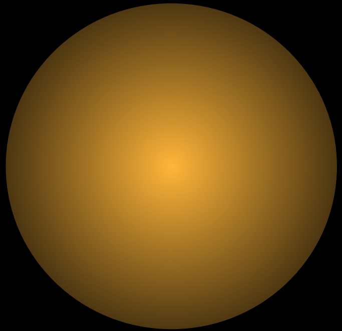

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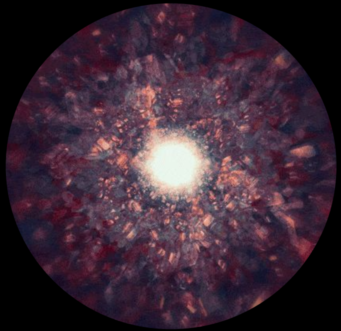

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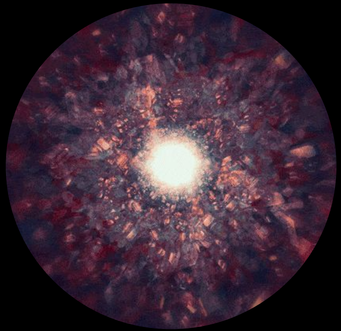

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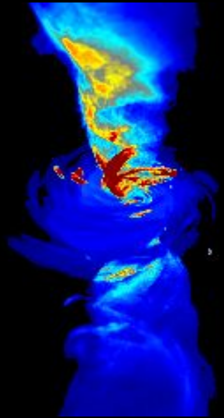

The Model

The model: Lagrangean

- The Einstein-matter action, with a spin-$s = 0, 1$ classical field

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[\frac{R}{16\pi G} + \mathcal{L}_s \right] ,$$

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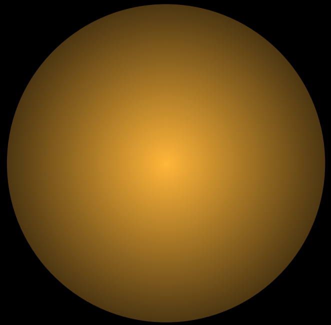

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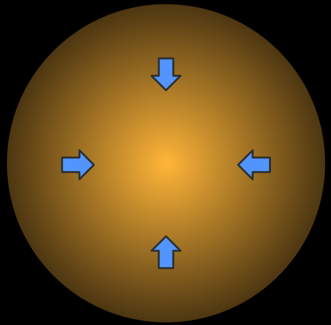

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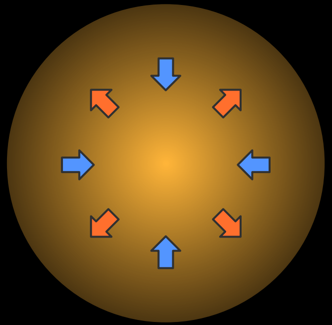

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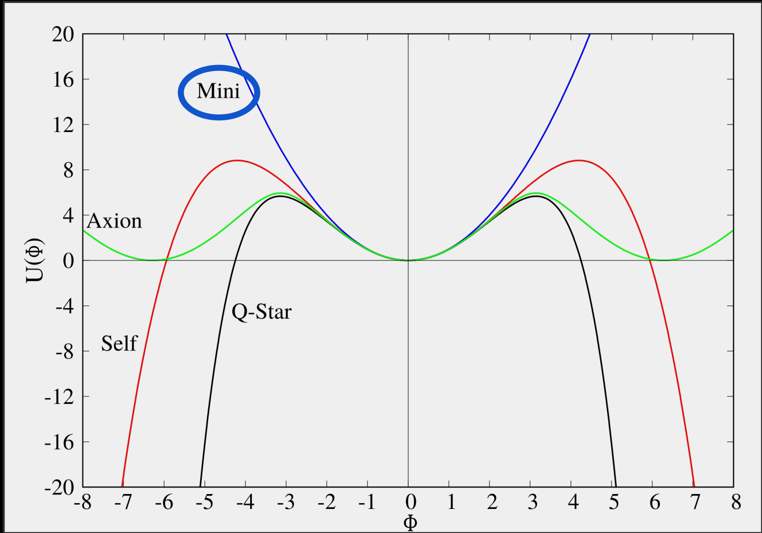
The model: Potentials

- The self-interaction potentials

$$U_{\text{poly}} = \mu_S^2 \Phi^2$$



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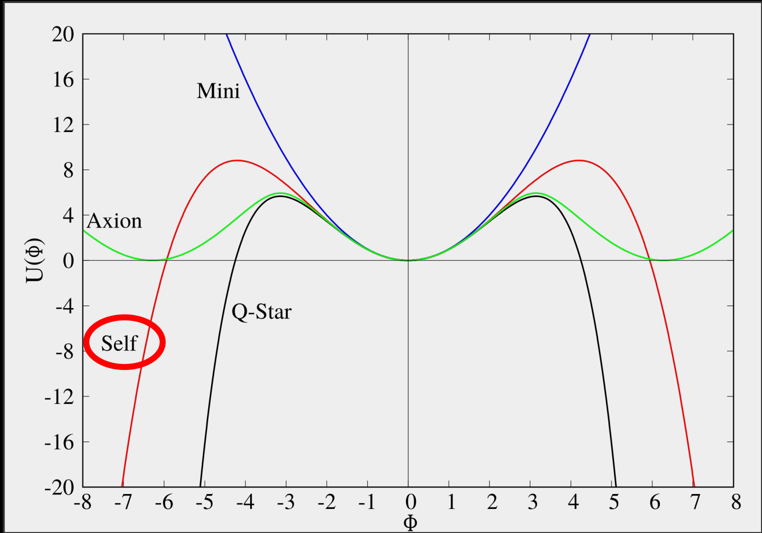
$$U_{\text{poly}} = \mu_S^2 \Phi^2 + \lambda \Phi^4$$



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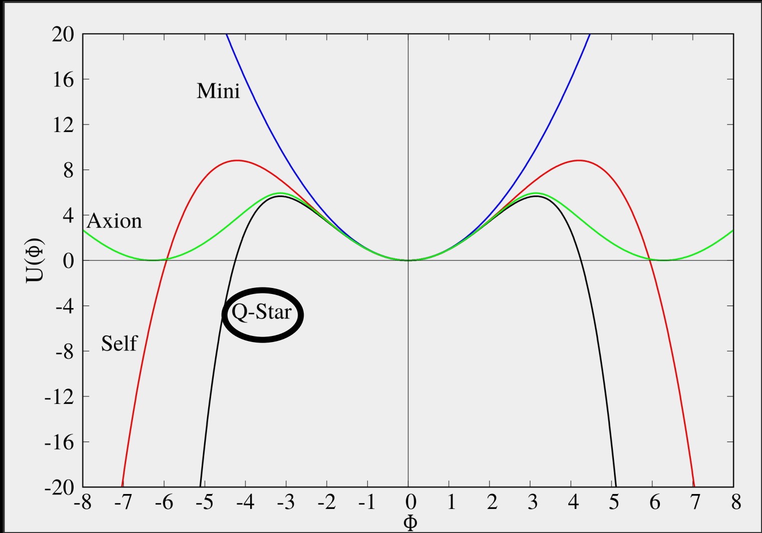

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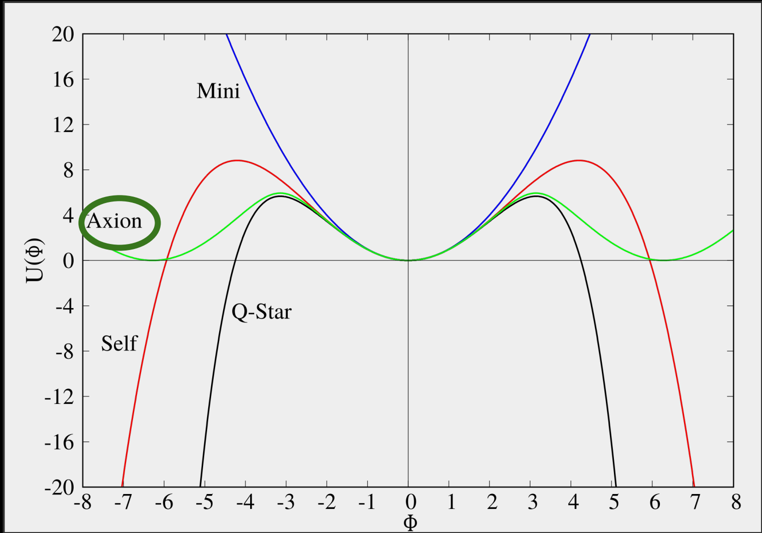

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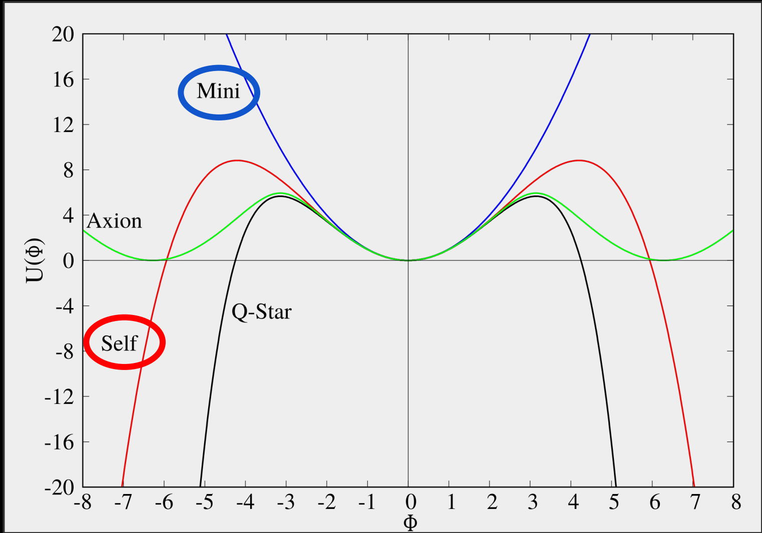

Numerics

- We developed a numerical solver to tackle the systems of ODEs
- It is written in C where:
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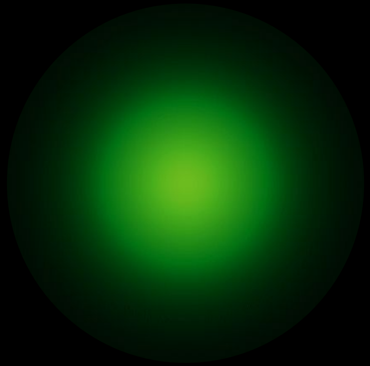
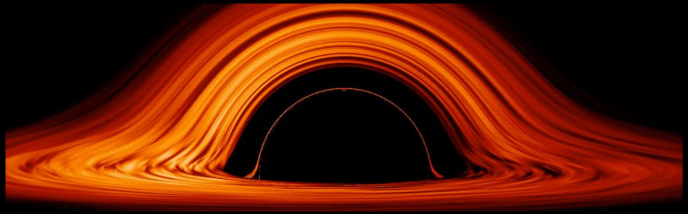


Imaging

Black Hole Shadow

- If the source of light in the vicinity of the BS has the same morphology as it would have around a BH, the observational image could be similar
- A key feature is the cut-off in the emission due to the disk's inner edge
- Determined by the innermost stable circular orbit (ISCO) of the BH
- However, for spherical BSs there is no ISCO



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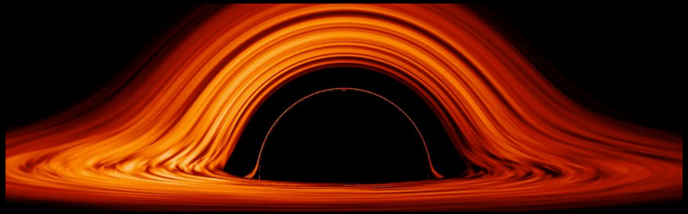

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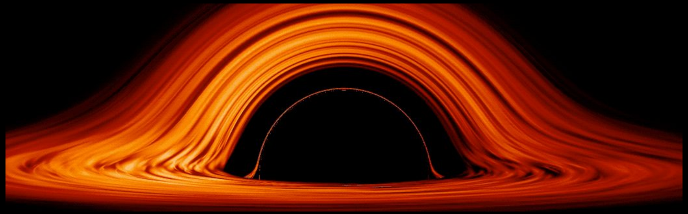

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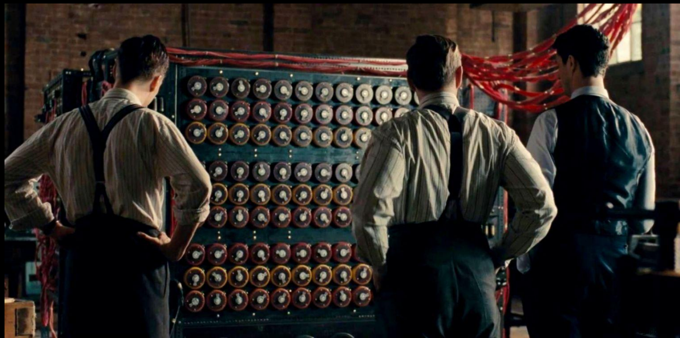

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- Show that the angular velocity of the orbits, Ω, attains a maximum at some areal radius R_Ω
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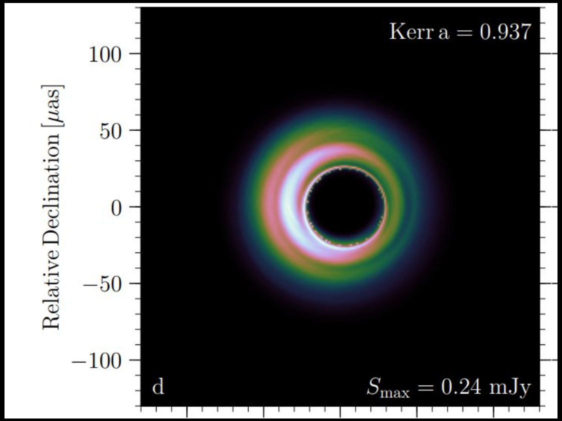

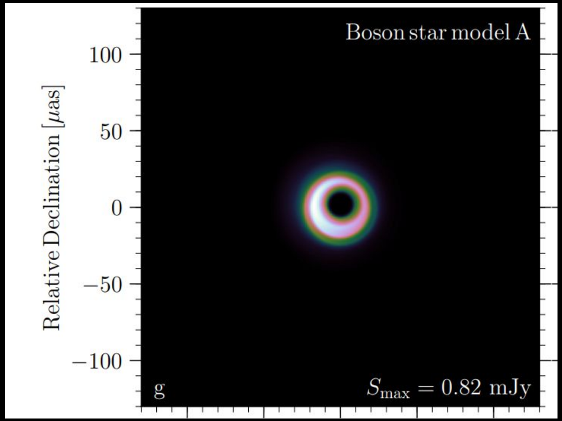

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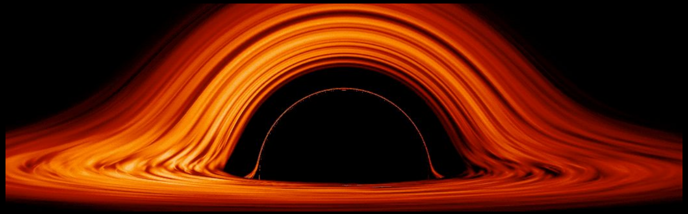

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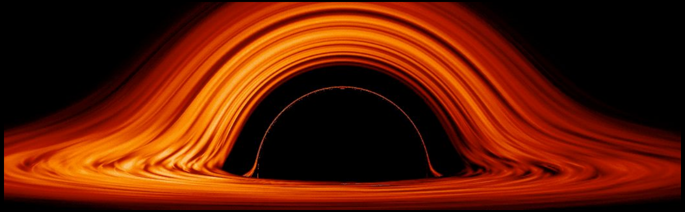

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- The objective of this work is to assess if **stable and dynamically robust** BS can yield the same shadow as a BH.

Light Rings
and
Timelike Circular Orbits

Geodesic motion

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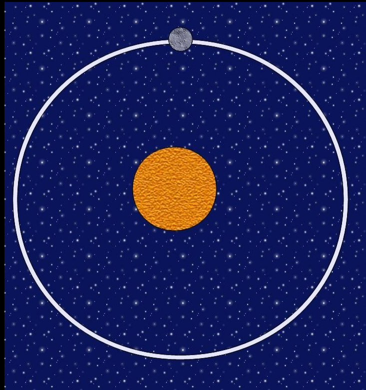
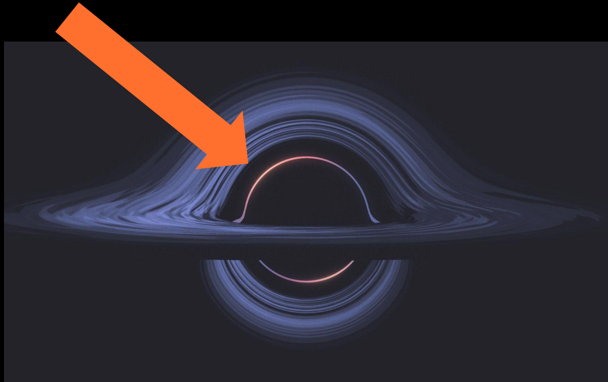
- For a circular orbit, $\dot{r} = 0 = \ddot{r}$



Geodesic motion: Light Rings $k = 0$

- Let us first consider null geodesics ($k = 0$)

$$-r\sigma\left(\frac{-2m'}{r}+\frac{2m}{r^2}\right)+2\left(1-\frac{2m}{r}\right)\left(\sigma-r\sigma'\right)=0\,.$$



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- In other words, the first ultracompact BS

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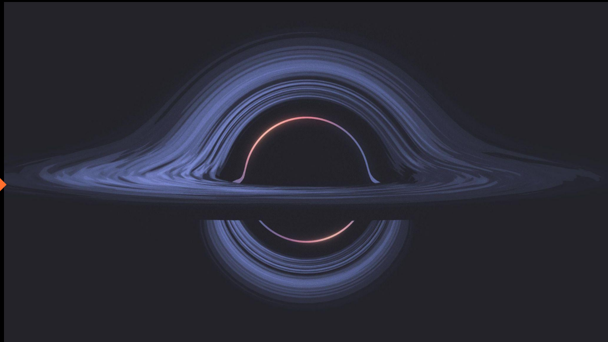
Geodesic motion: Timelike Circular Orbits $k = -1$

- Let us now consider timelike geodesics ($k = -1$)
- The angular velocity Ω along these orbits is
- As already mentioned, BS do not have an ISCO



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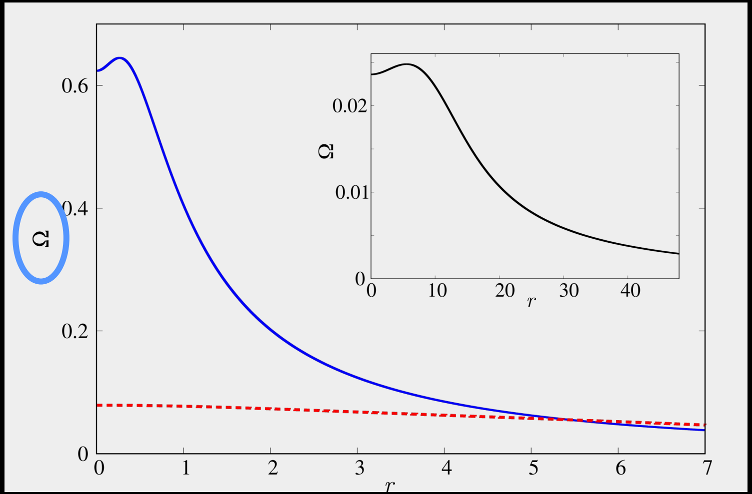

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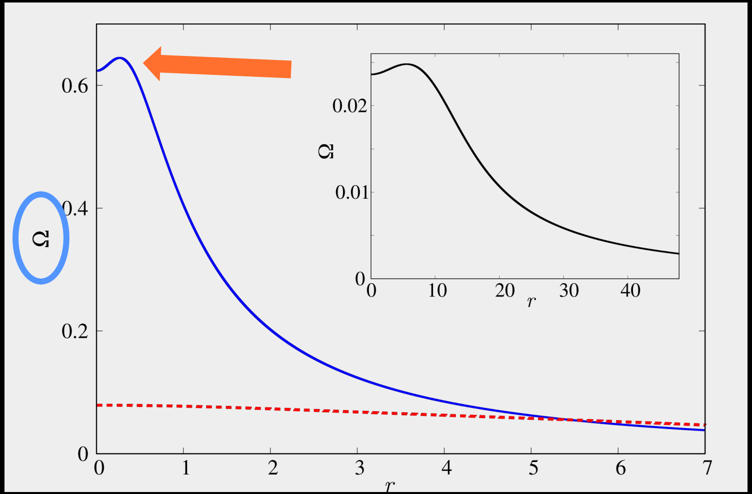

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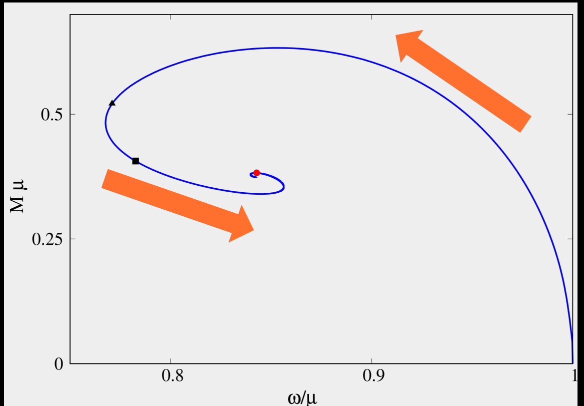

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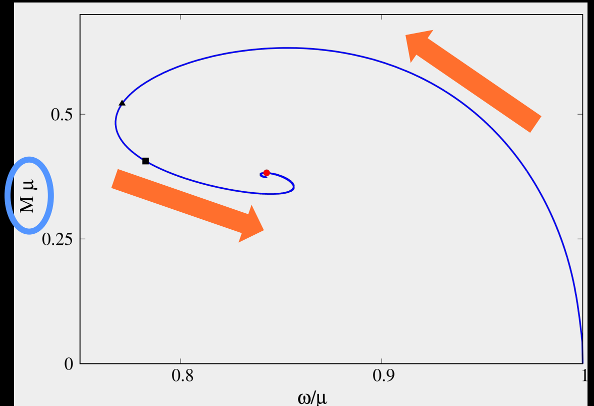

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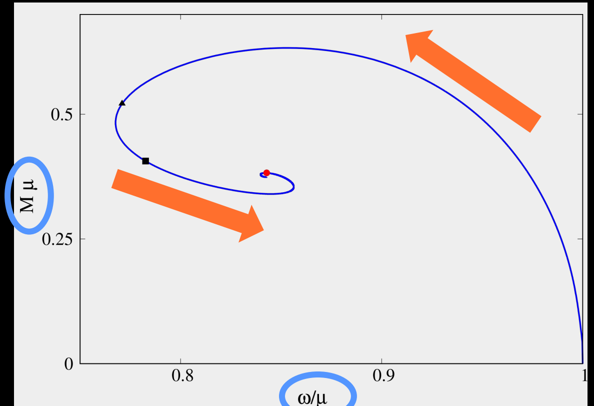

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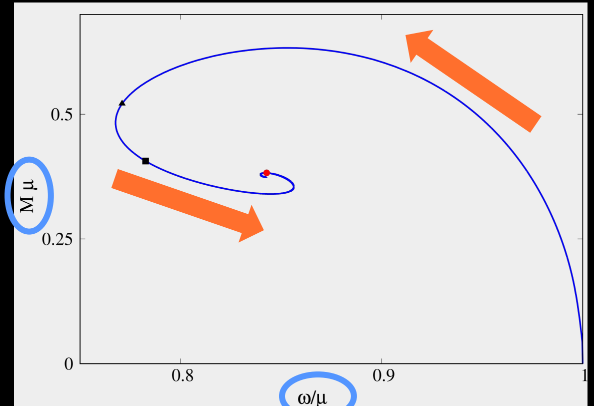

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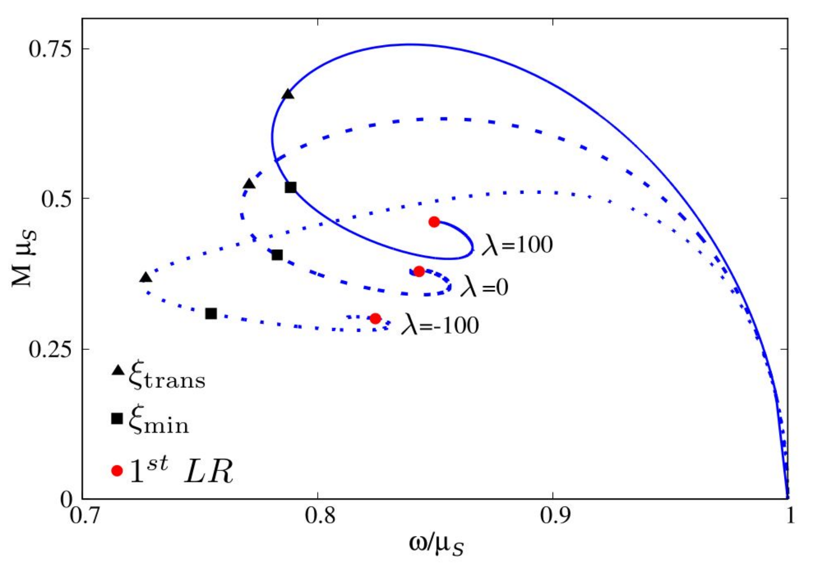
$$\chi(x) \equiv \frac{\varphi_0(x)}{\varphi_0(M_{\max})} \quad [\text{scalar}] \qquad \text{or} \qquad \chi(x) \equiv \frac{f_0(x)}{f_0(M_{\max})} \quad [\text{vector}] \,,$$

Numerical Results

Boson Stars: Polynomial Scalar



$$U_{\text{poly}} = \mu_S^2 \Phi^2$$

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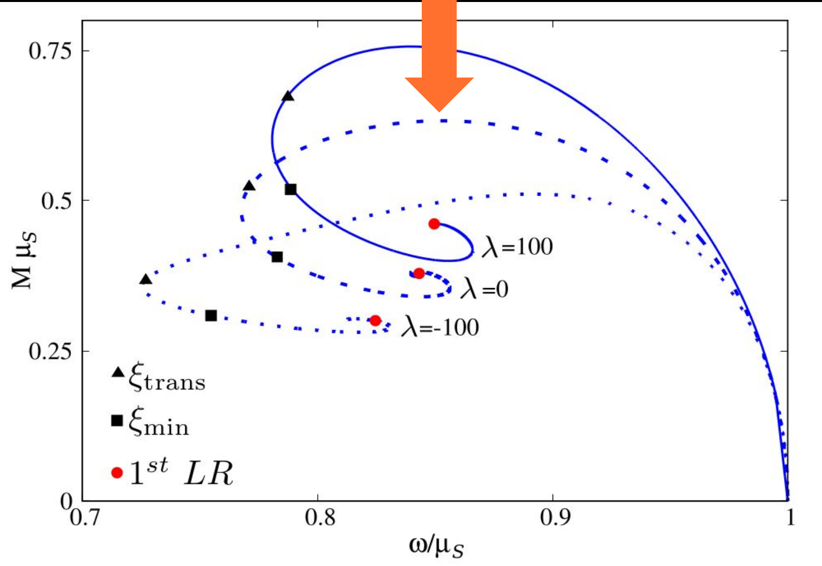

Solutions are stable up to the first maximum of the mass

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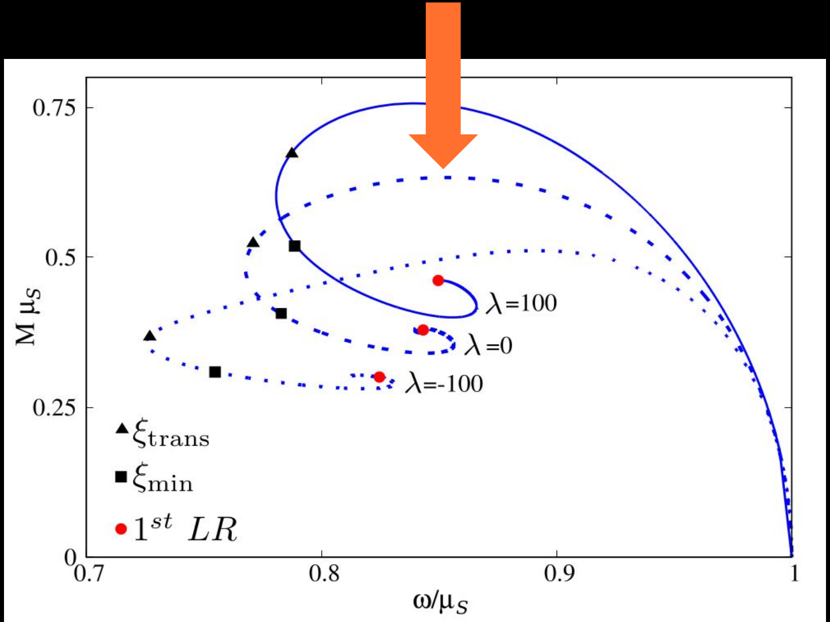

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There is no stable ultracompact Boson Star solution

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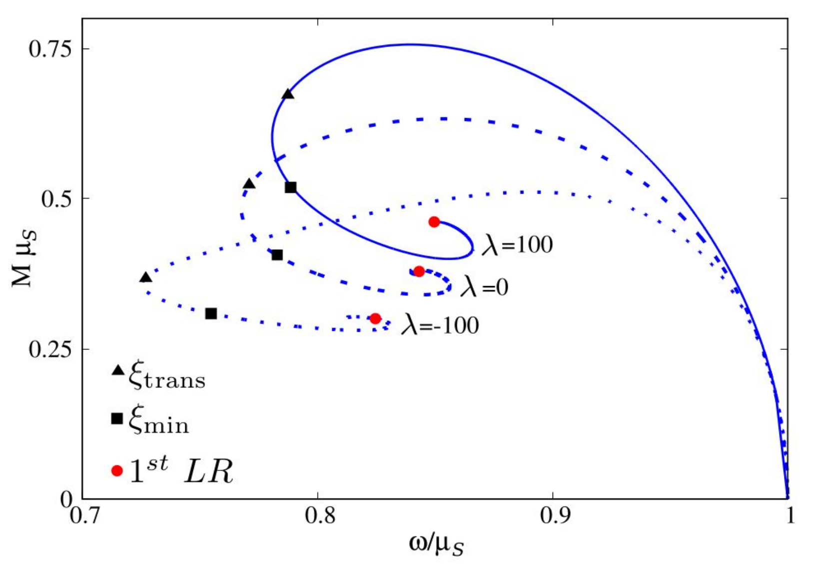

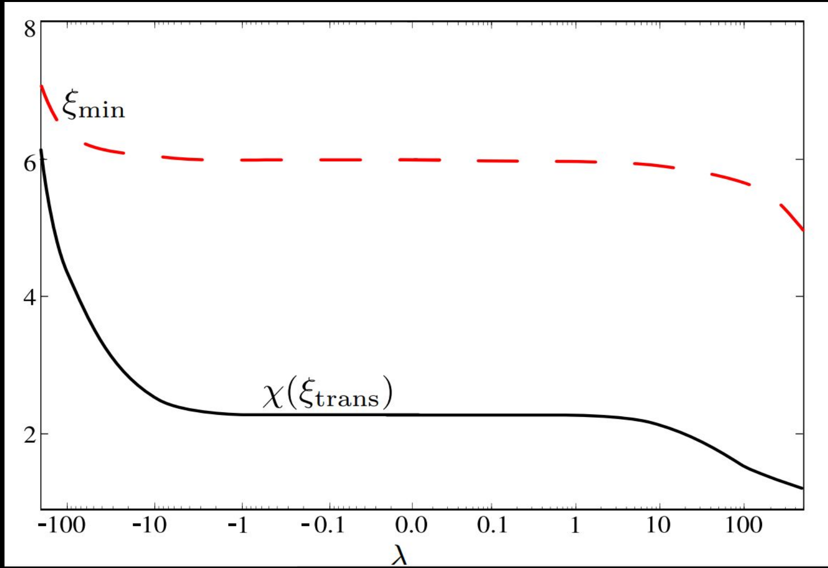

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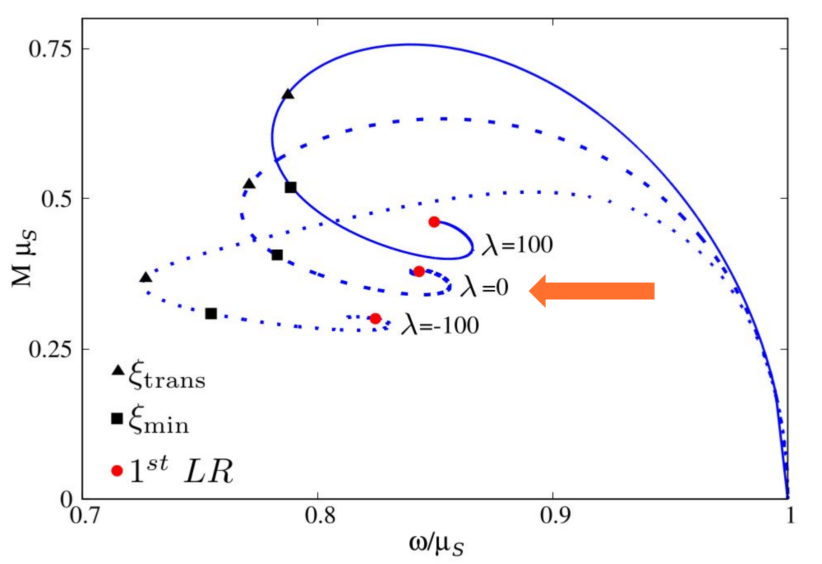

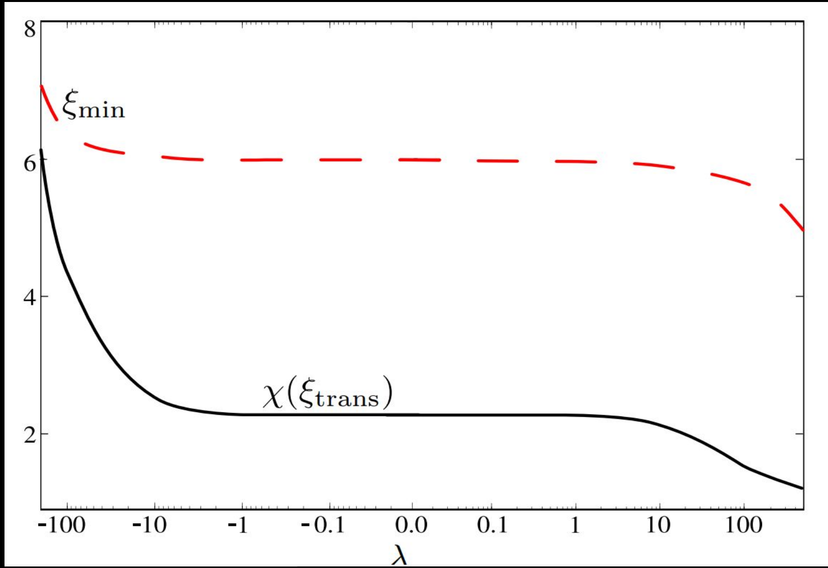

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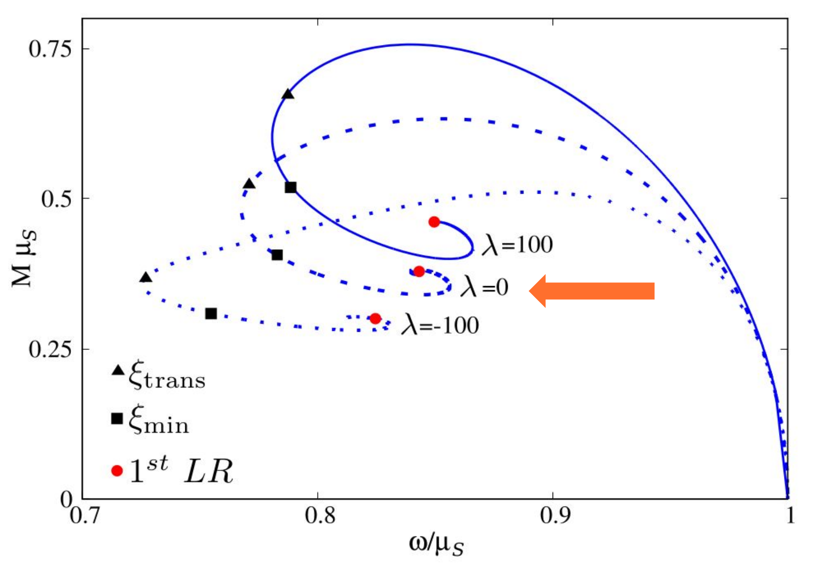

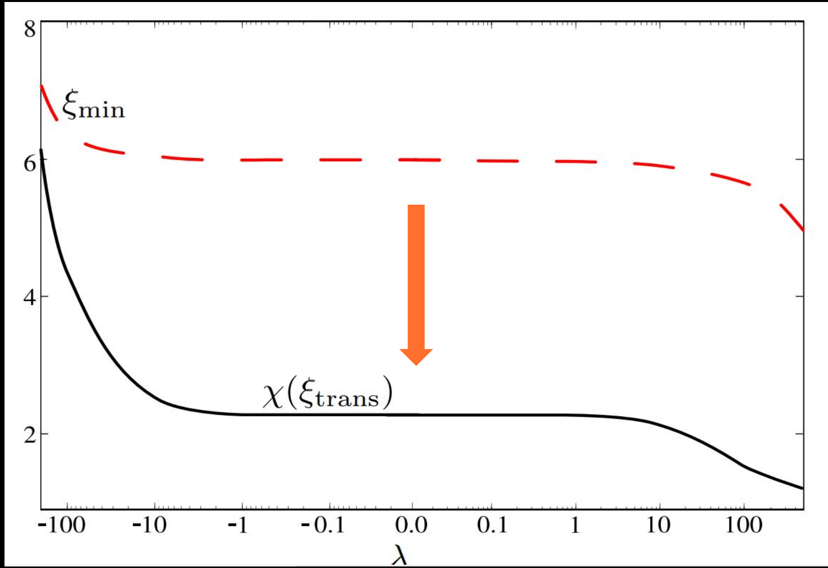

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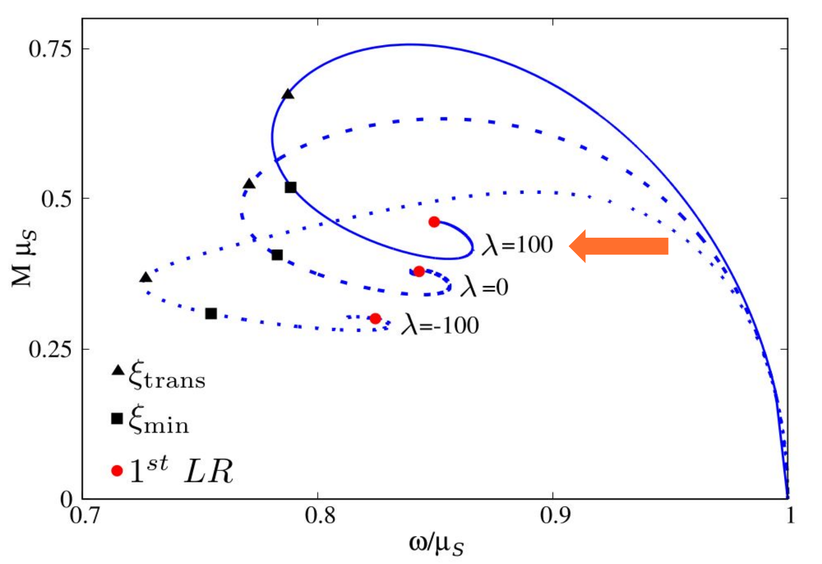

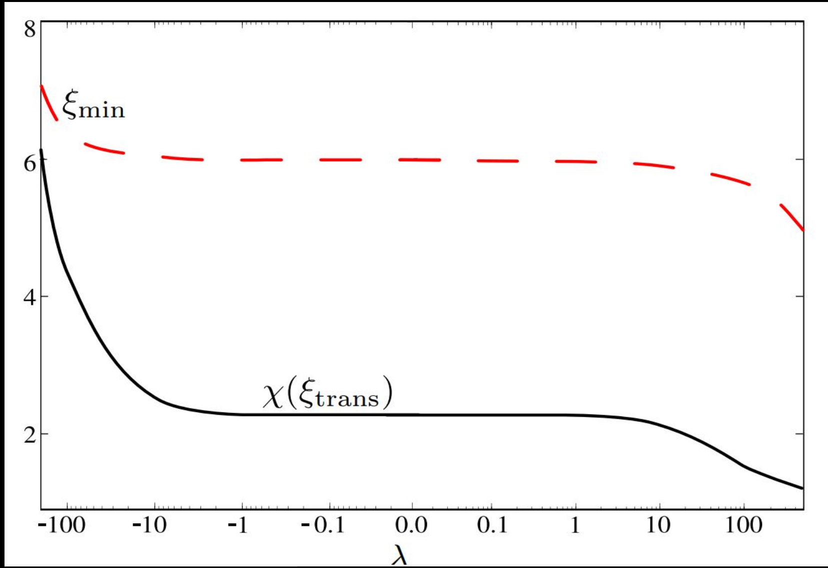

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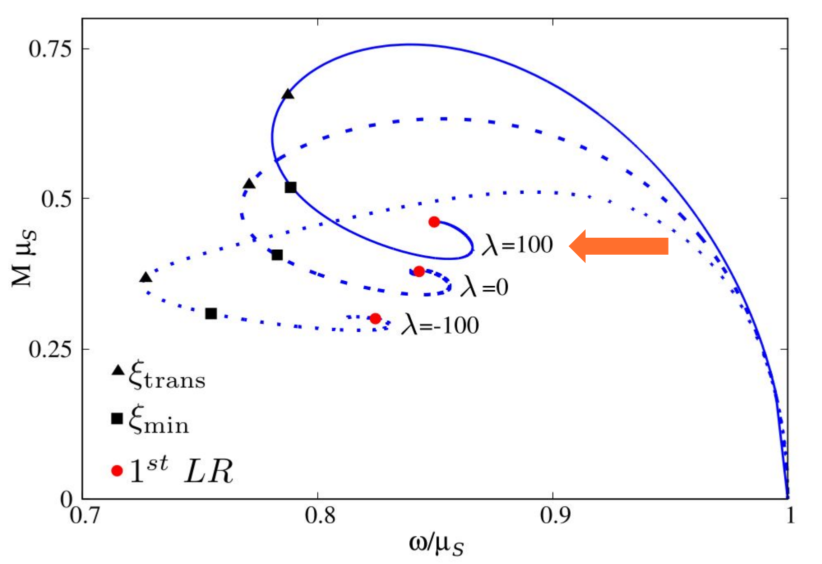

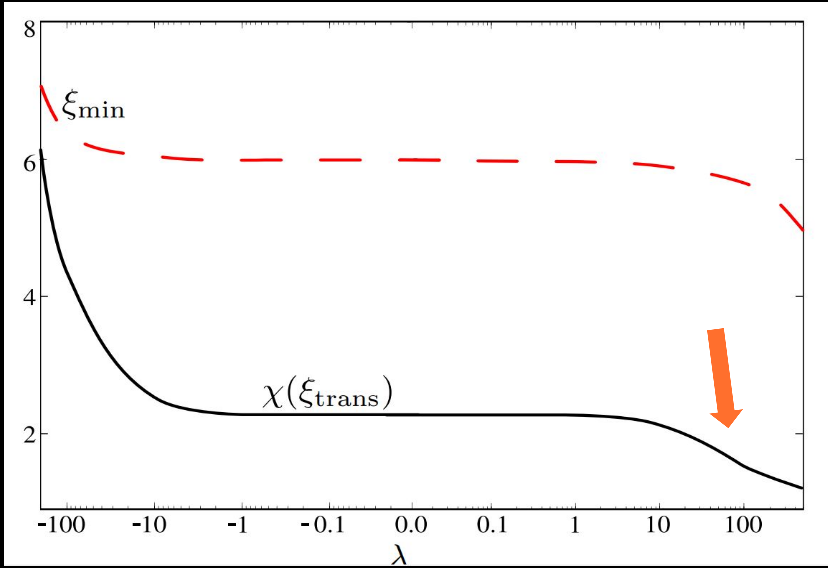

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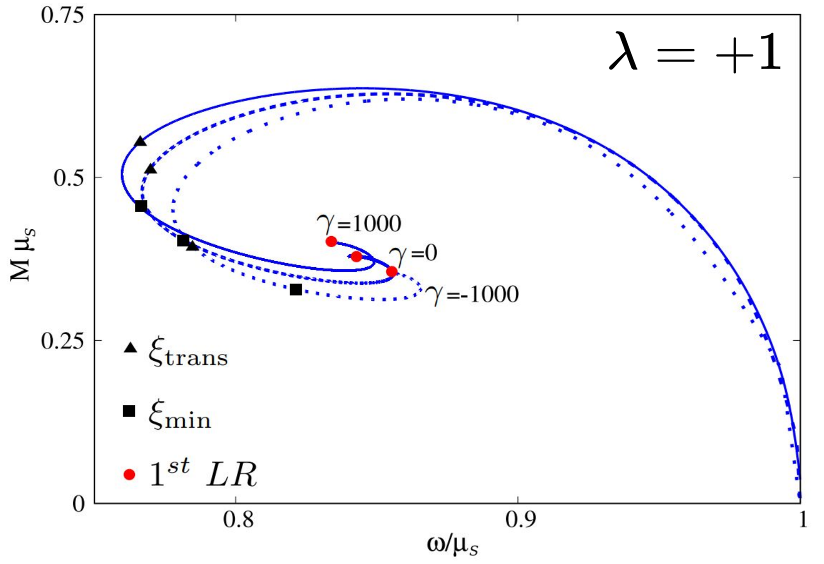

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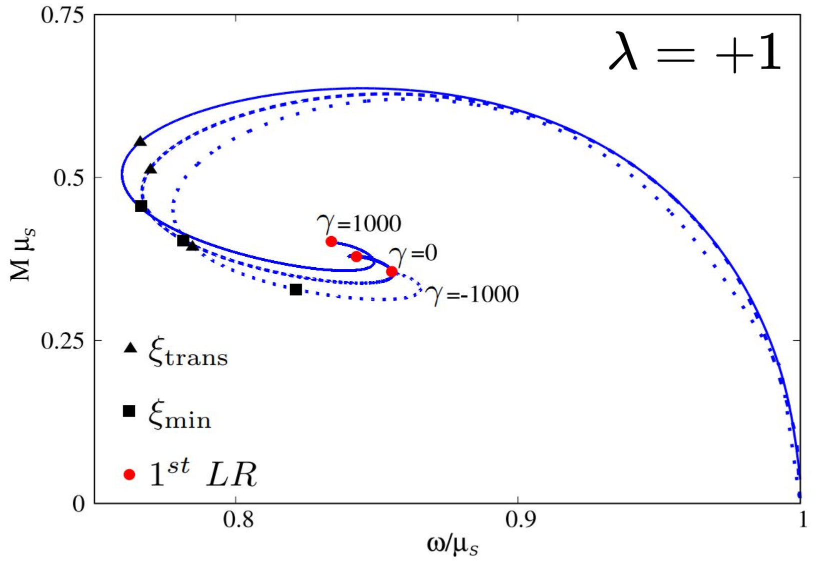

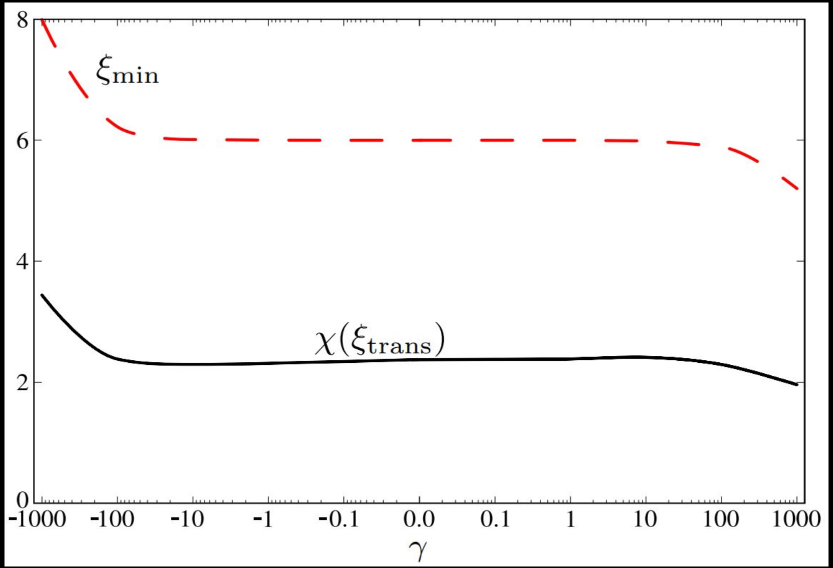

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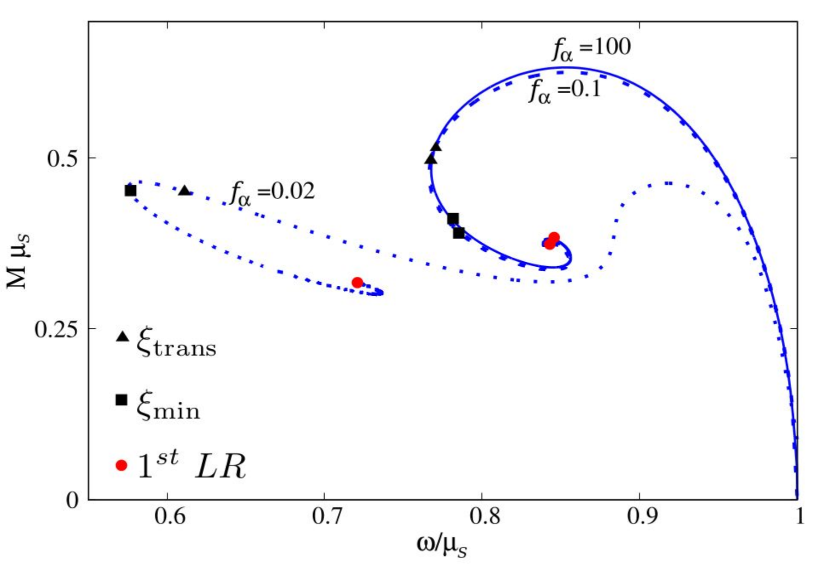

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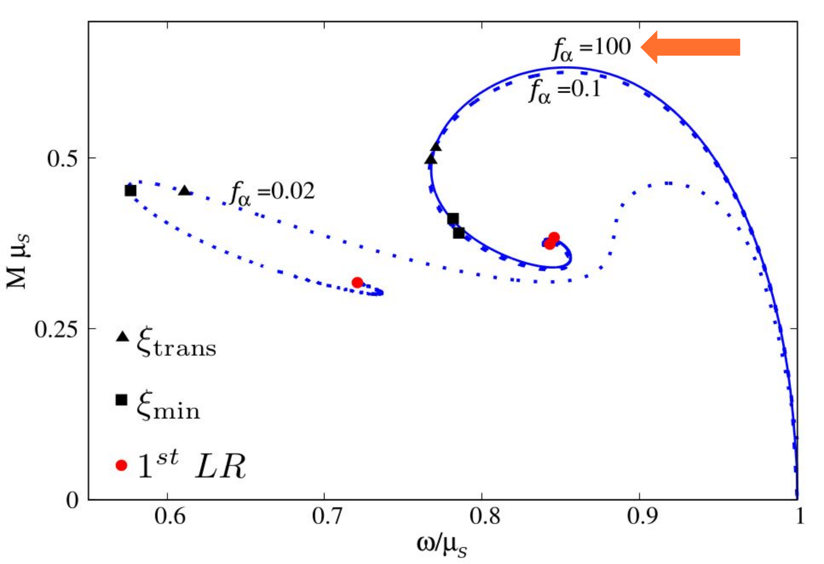

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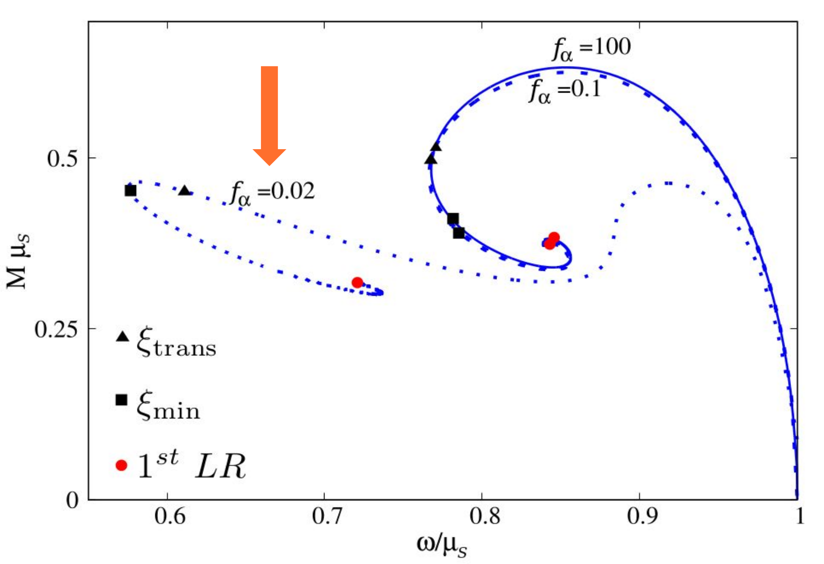

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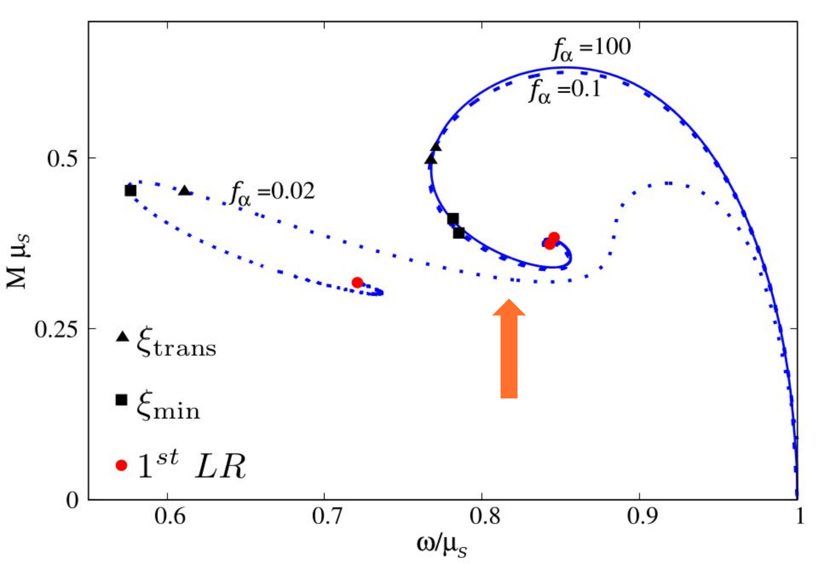

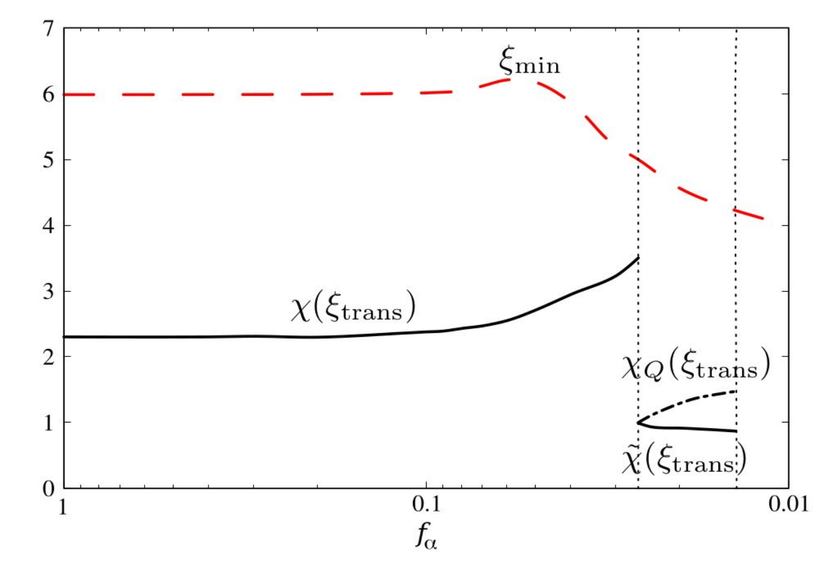

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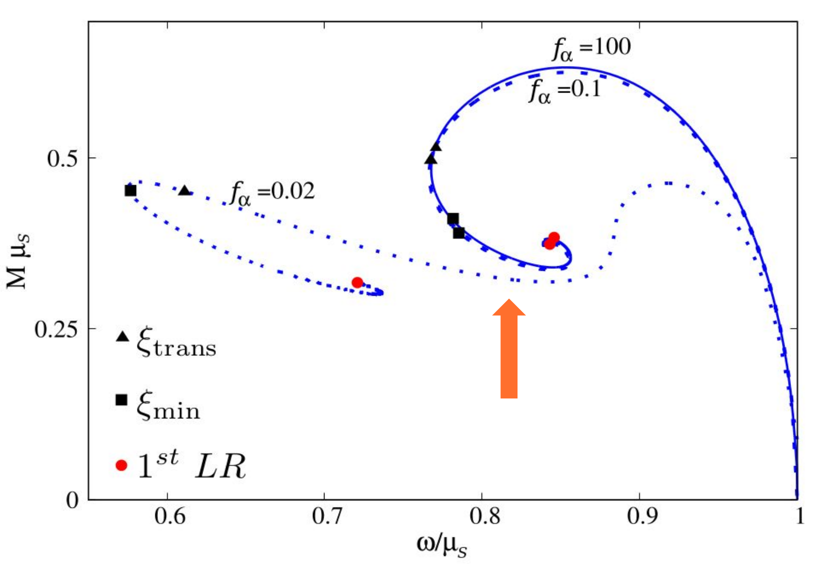

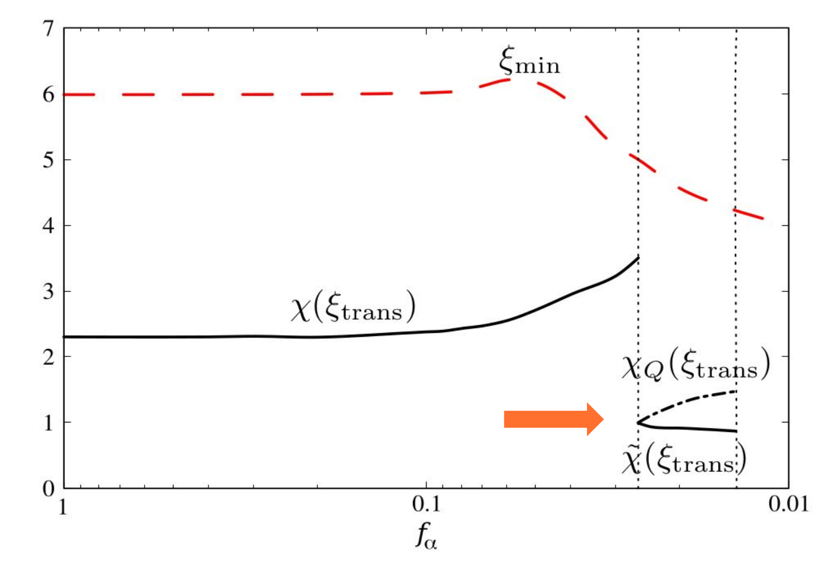

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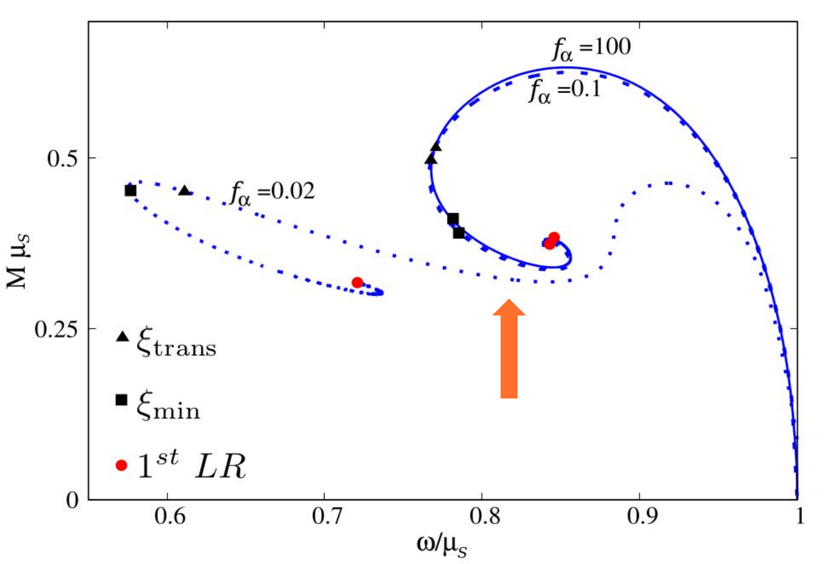

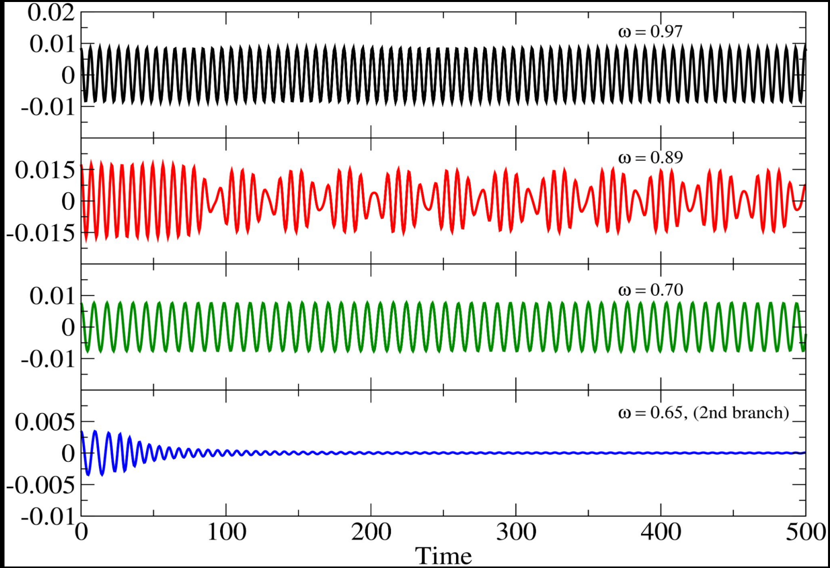

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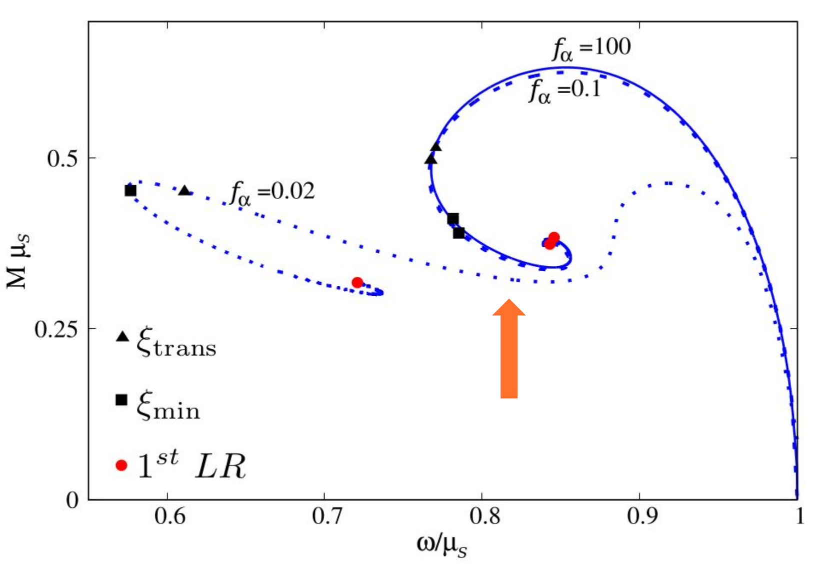

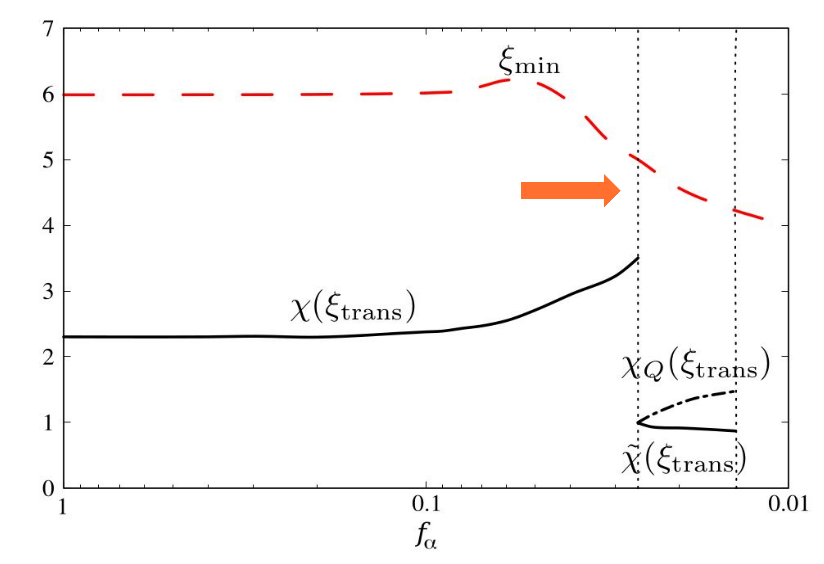

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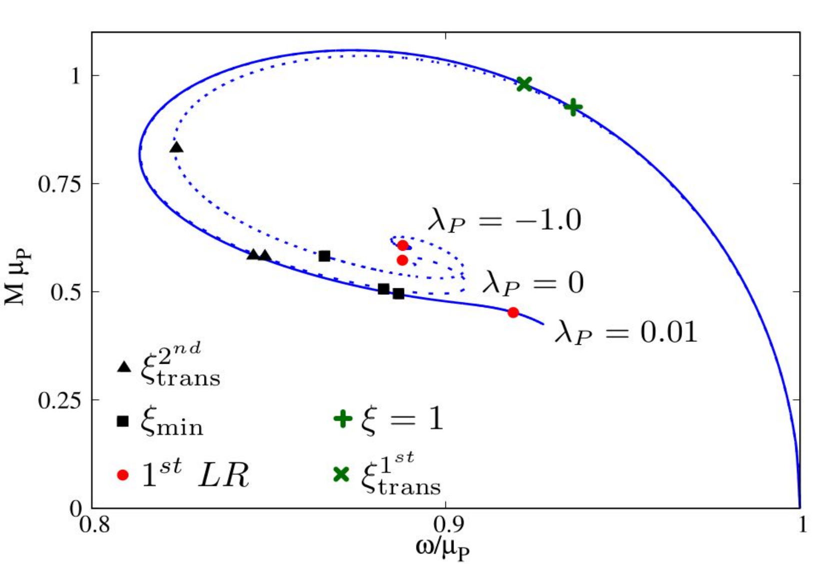

$$V = \frac{\mu_P^2}{2}\mathbf{A}^{\,2}$$

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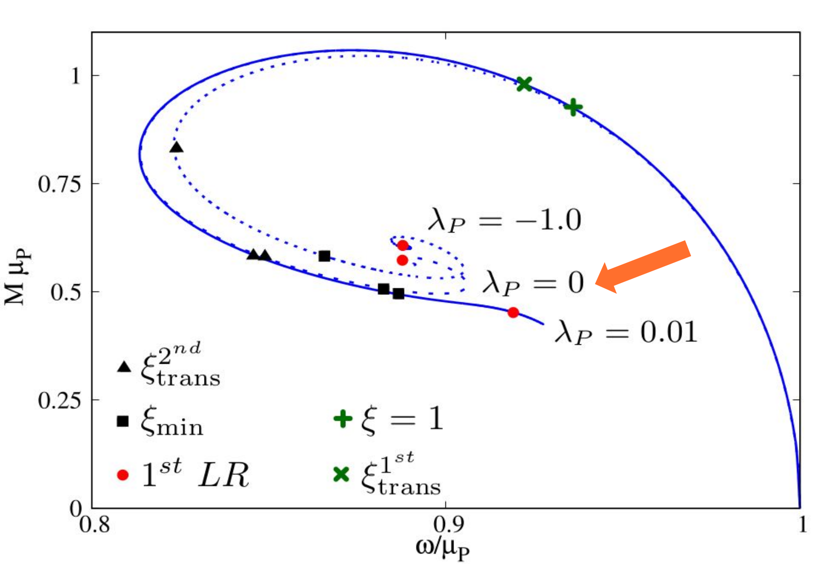

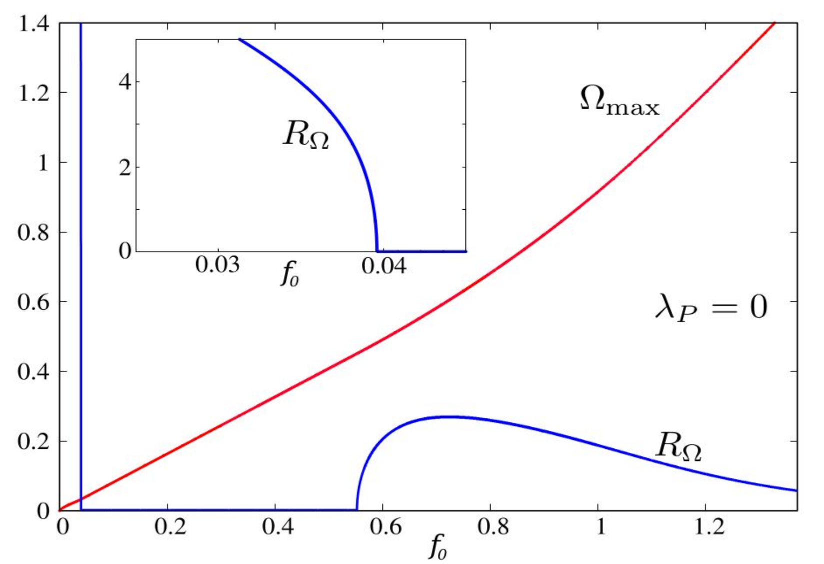

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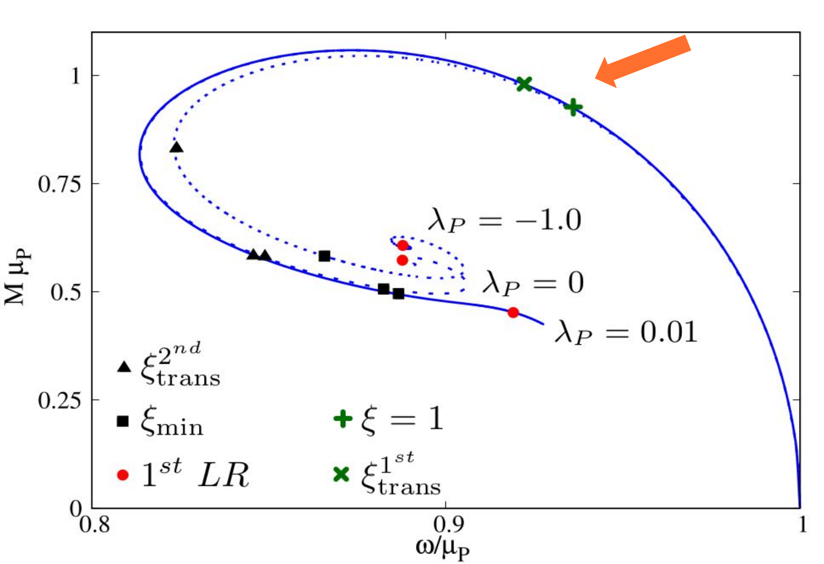

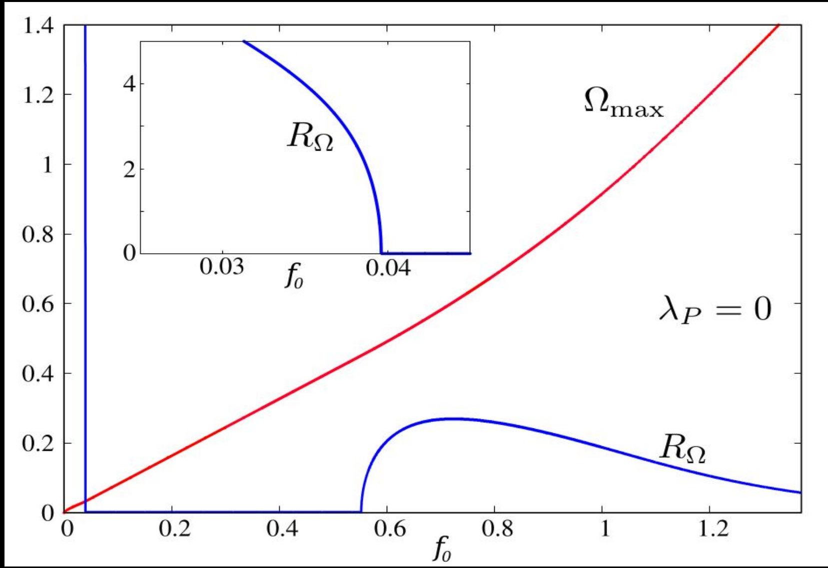

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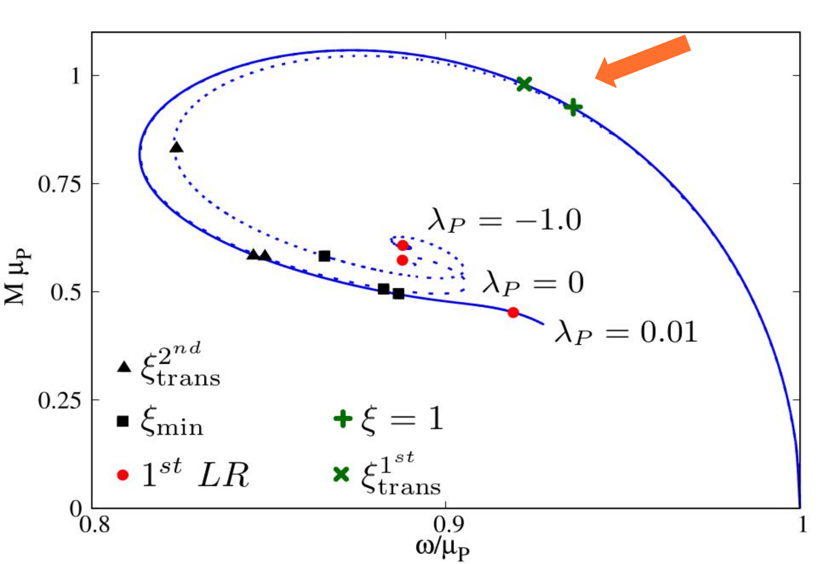

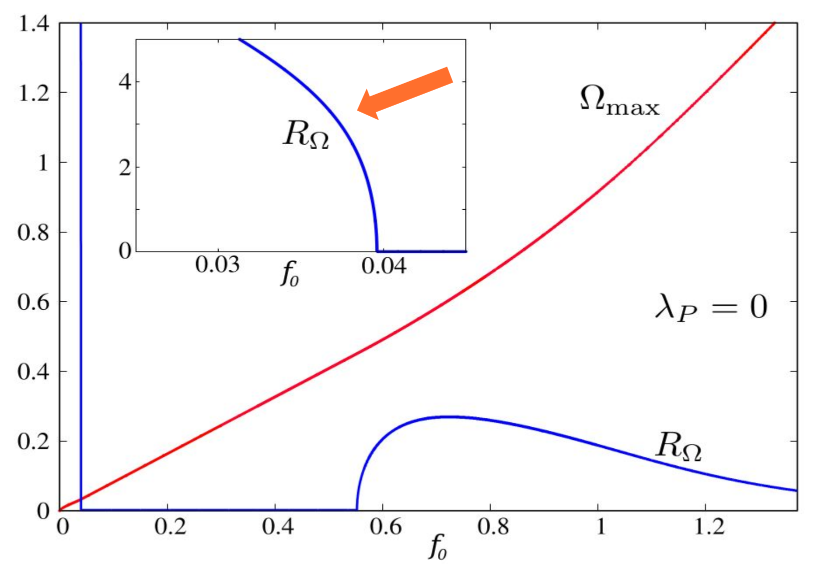

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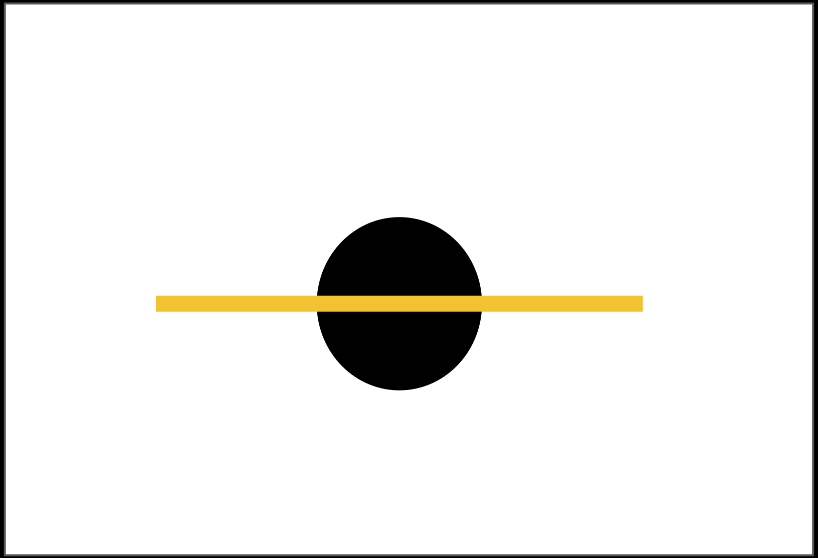
Shadow

Shadow: BH vs PS



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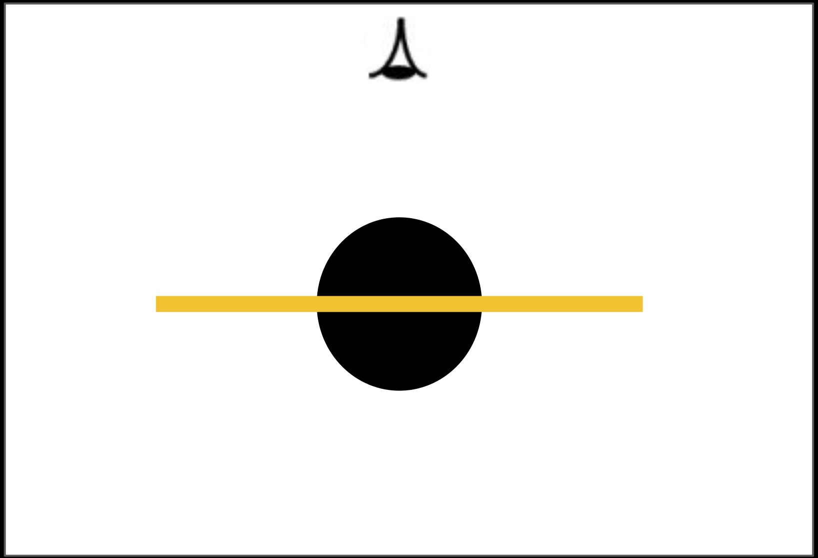

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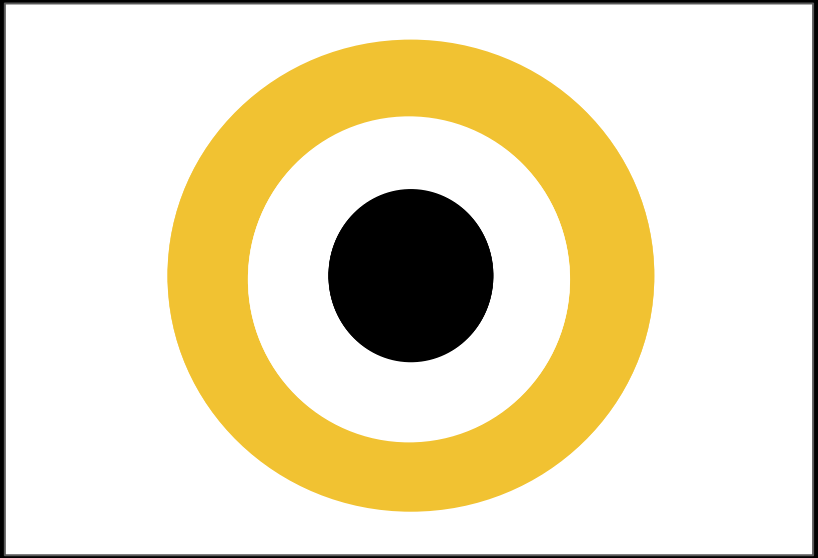

Shadow: BH vs PS

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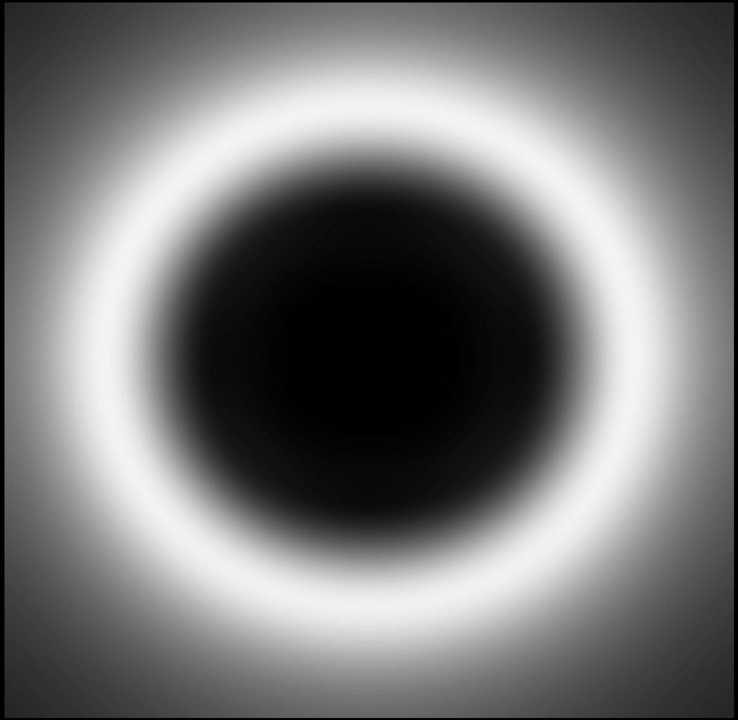

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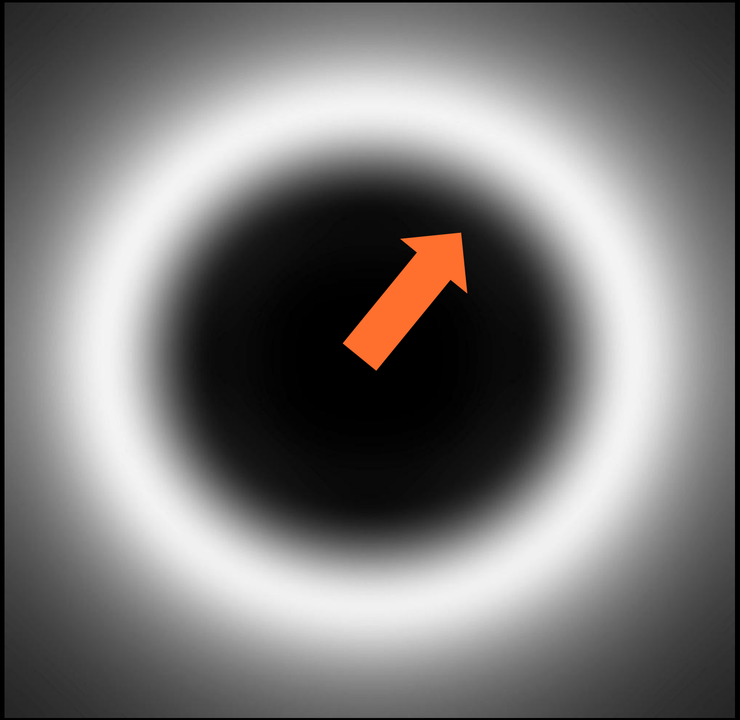

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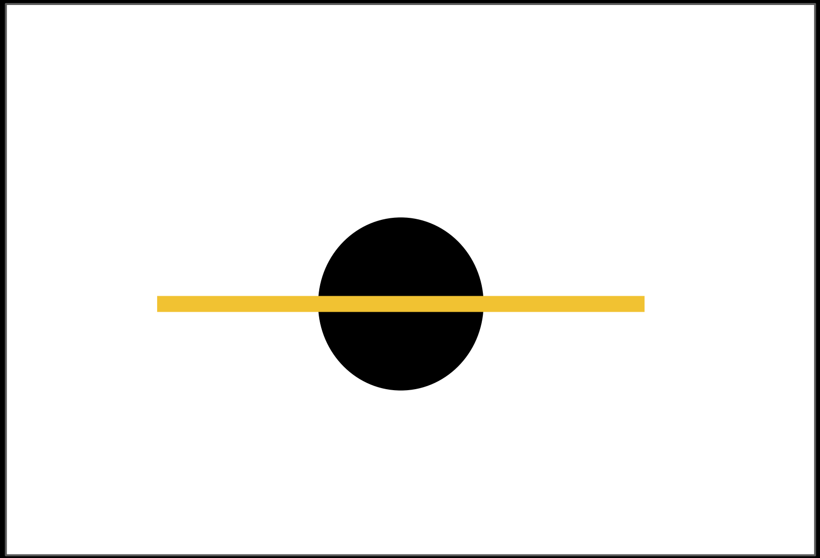

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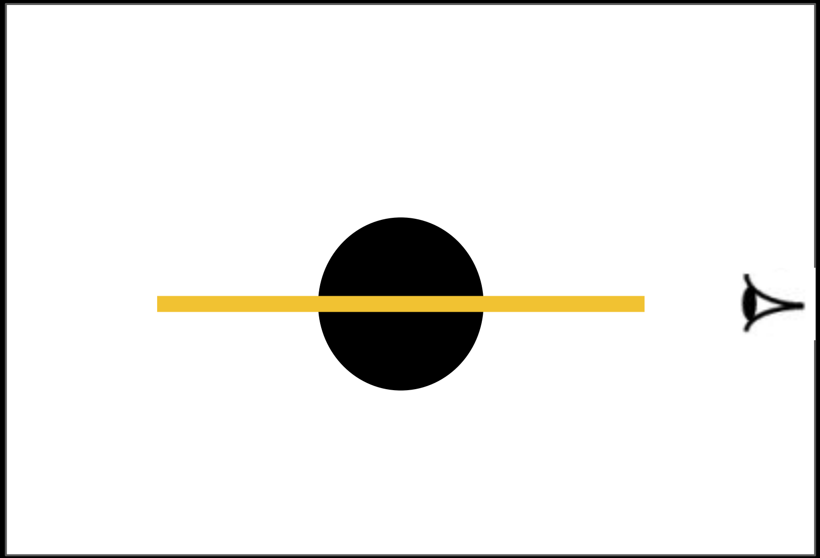

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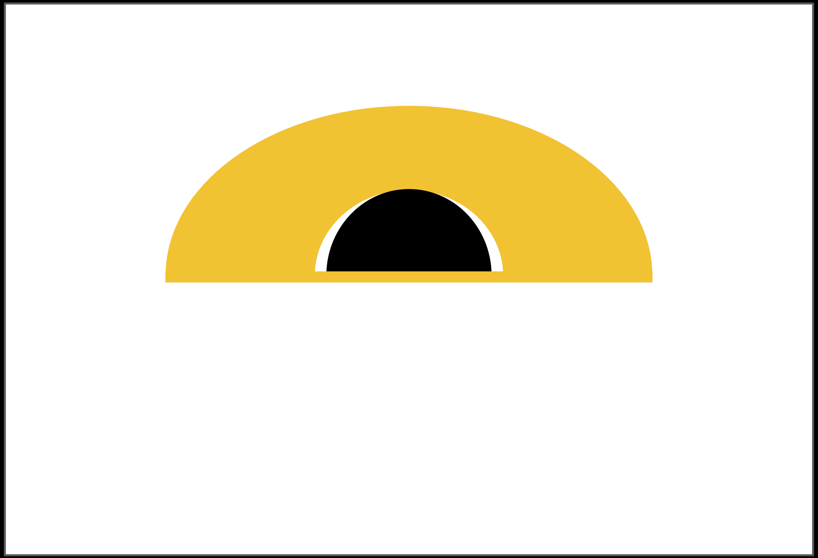

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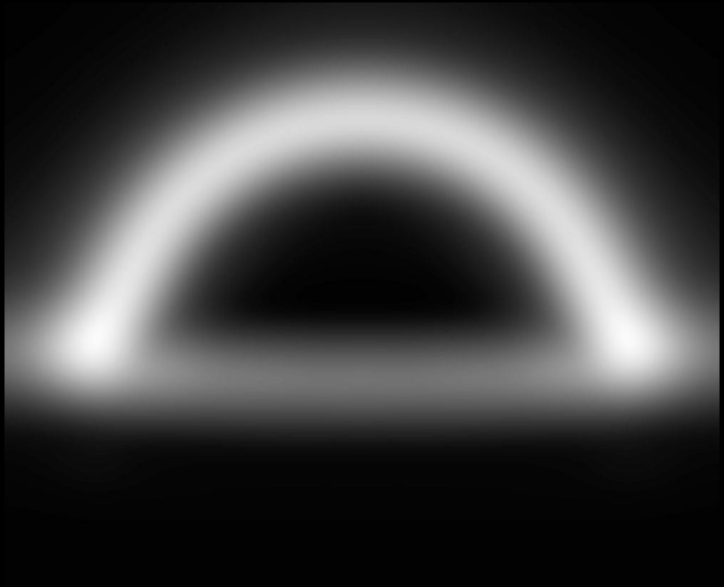

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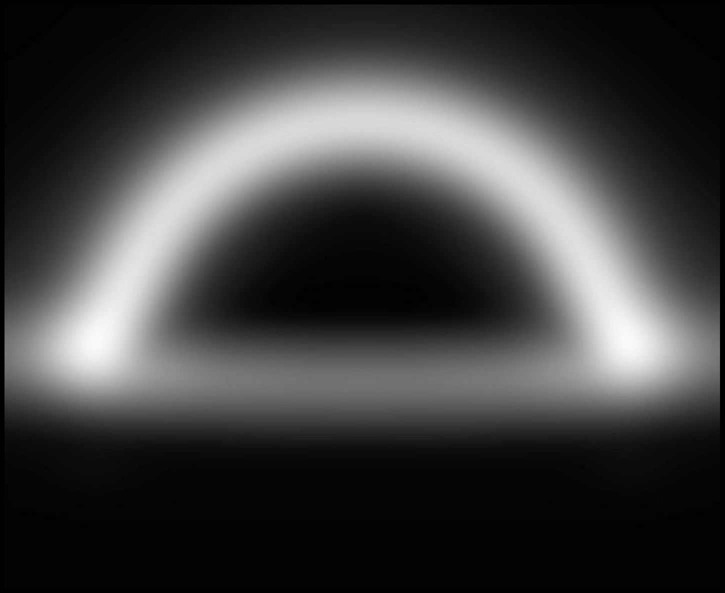
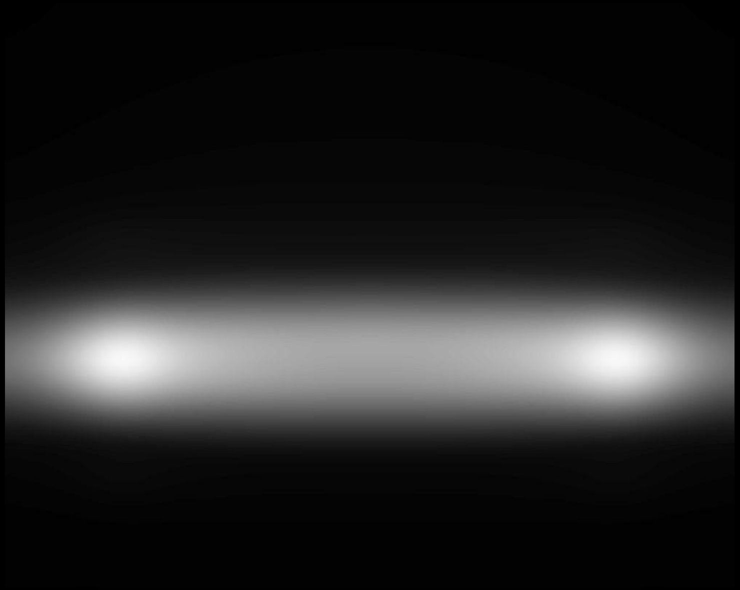
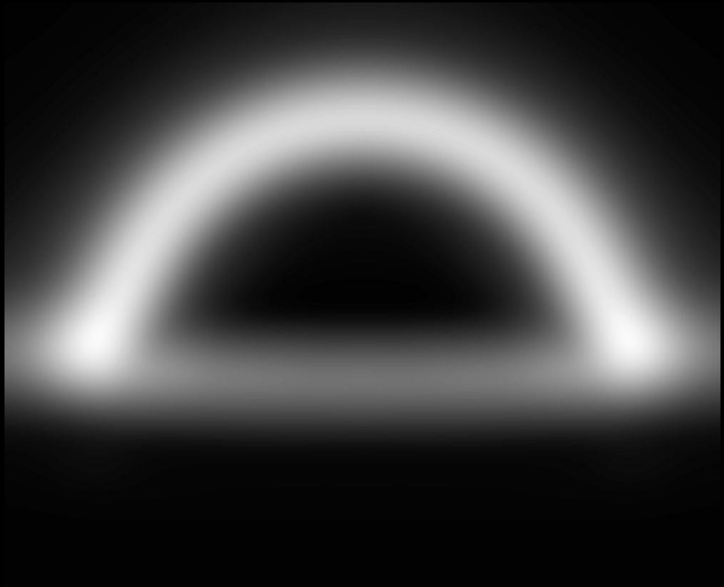


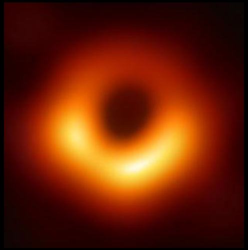
PS



Shadow: BH vs PS

BH





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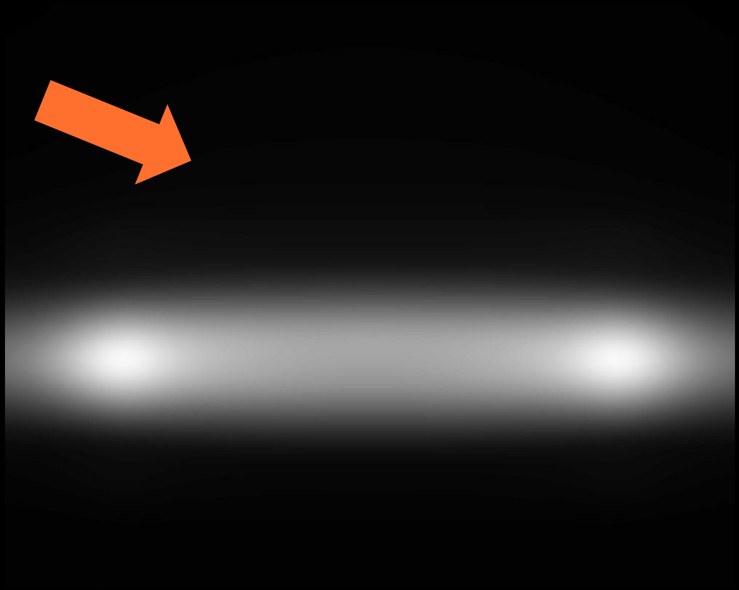

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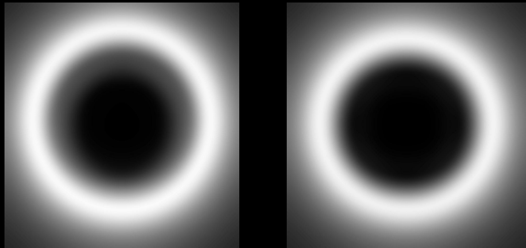

Kinematics

Black Hole mimicker

- In the absence of an illumination, direct observations are impossible
- However, the gravitational potential still exist allowing the orbiting luminous objects
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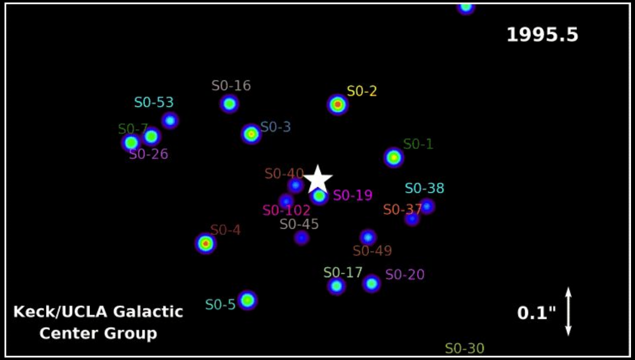

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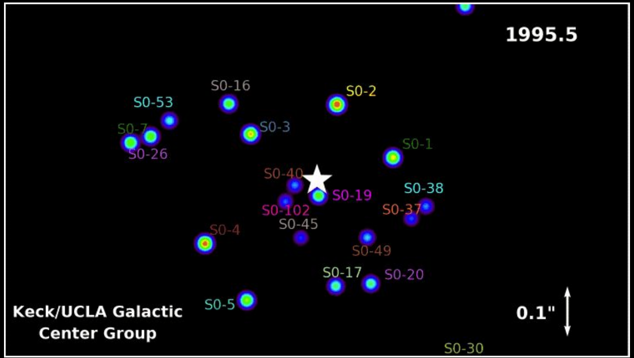

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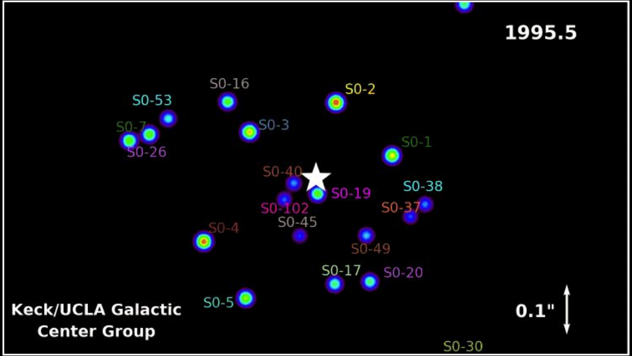

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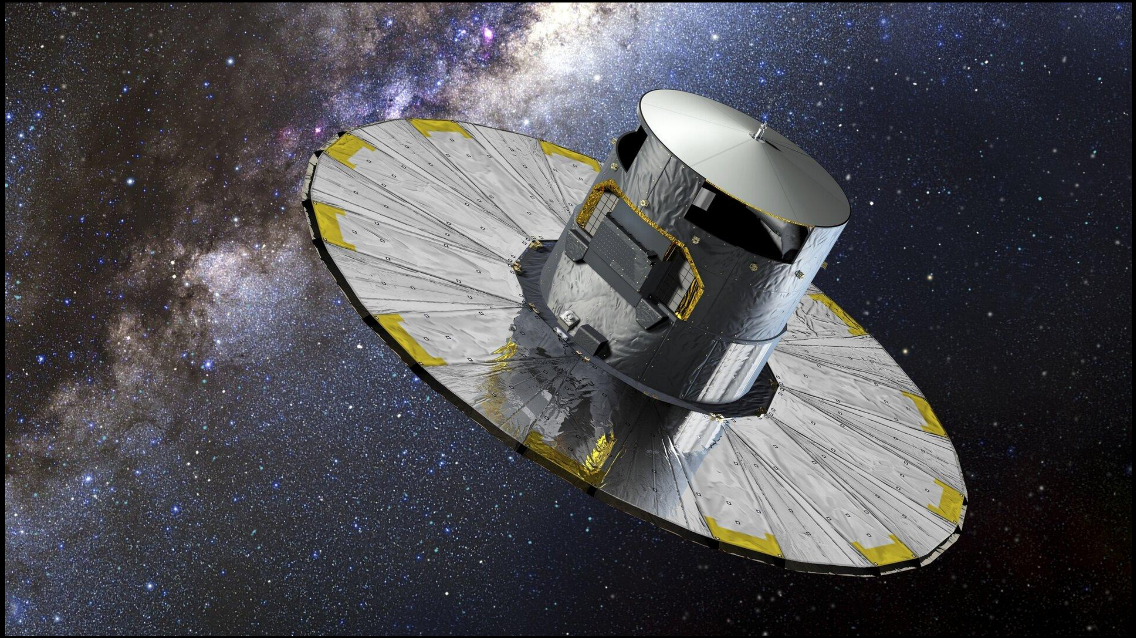
Observation: GAIA



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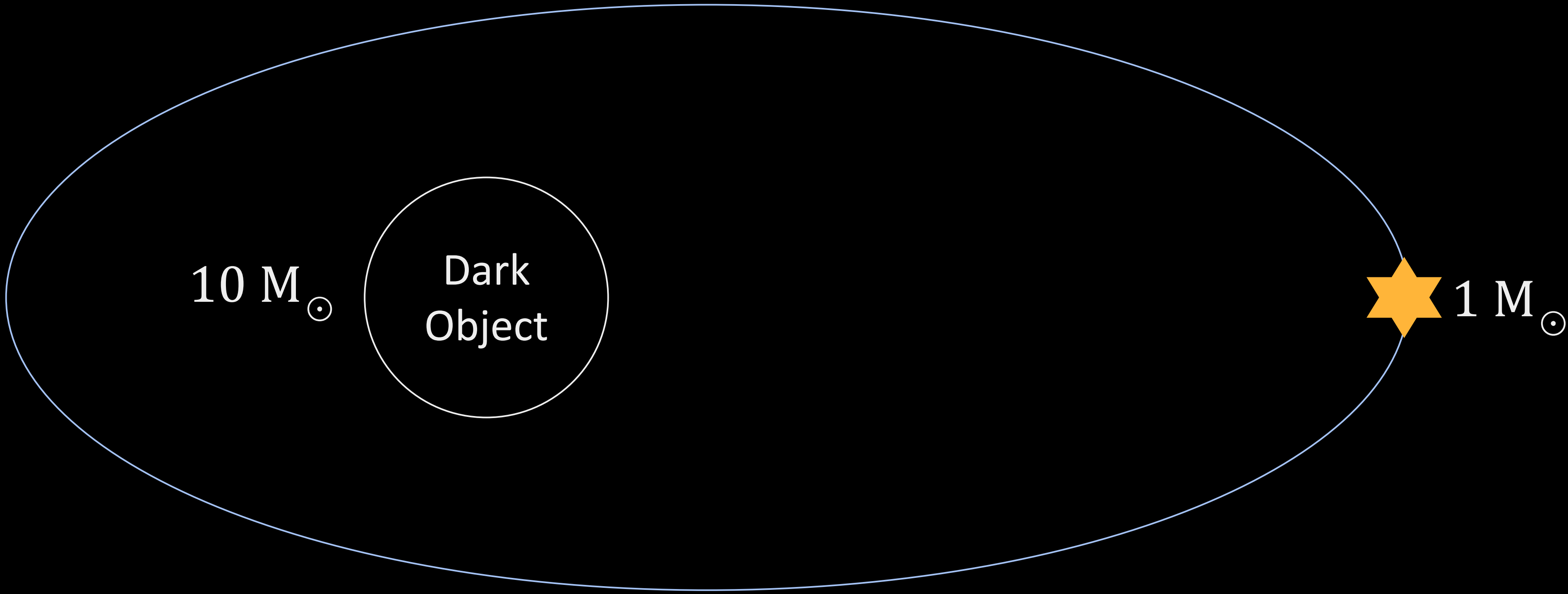

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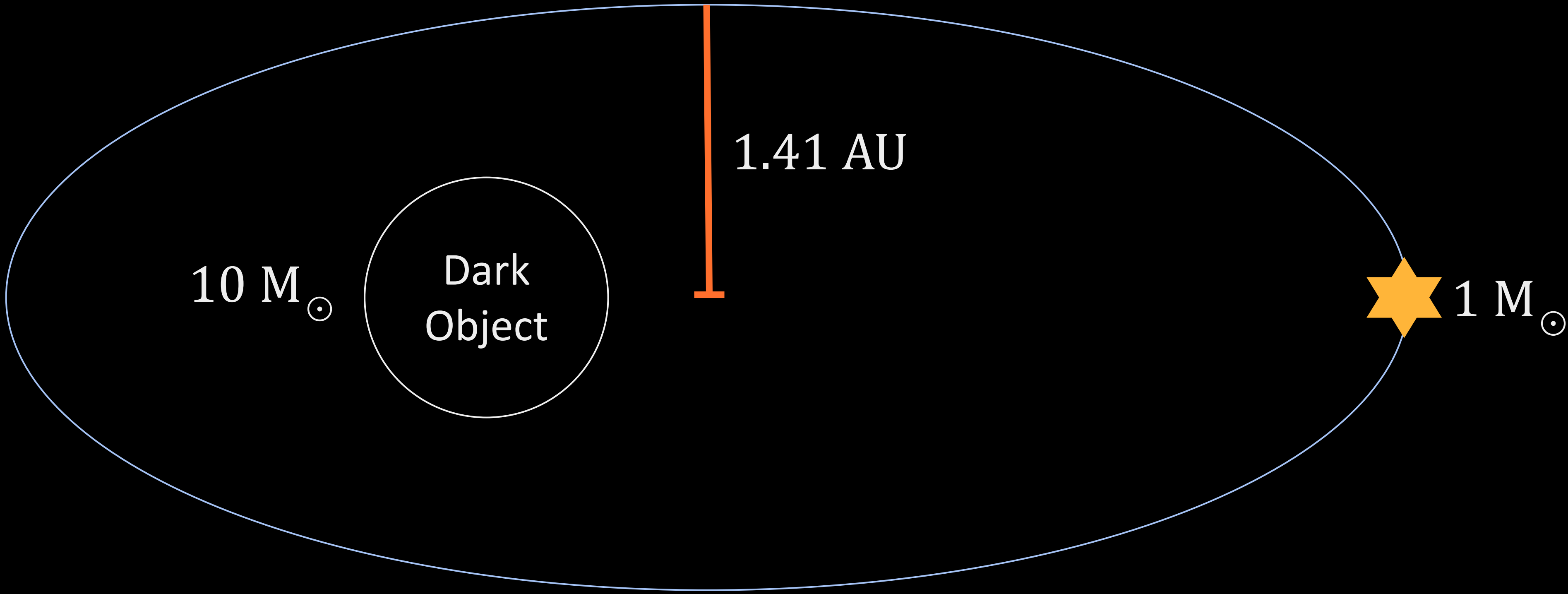

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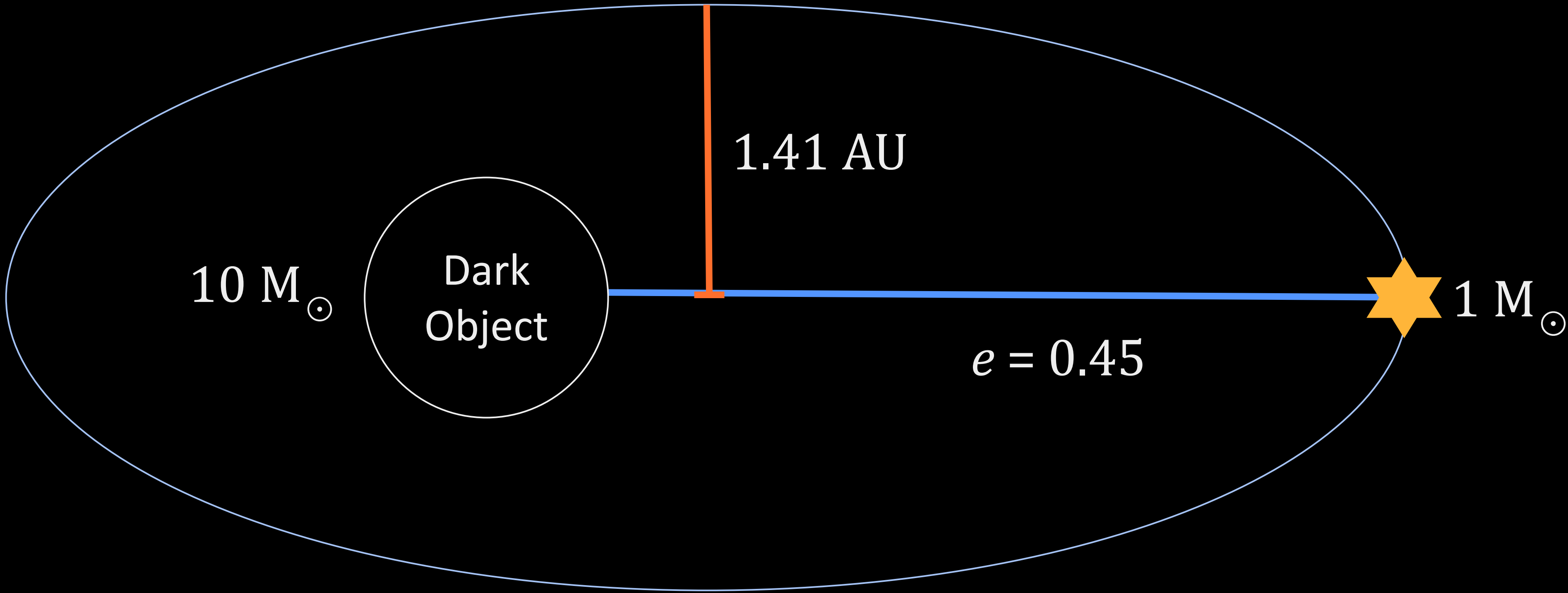

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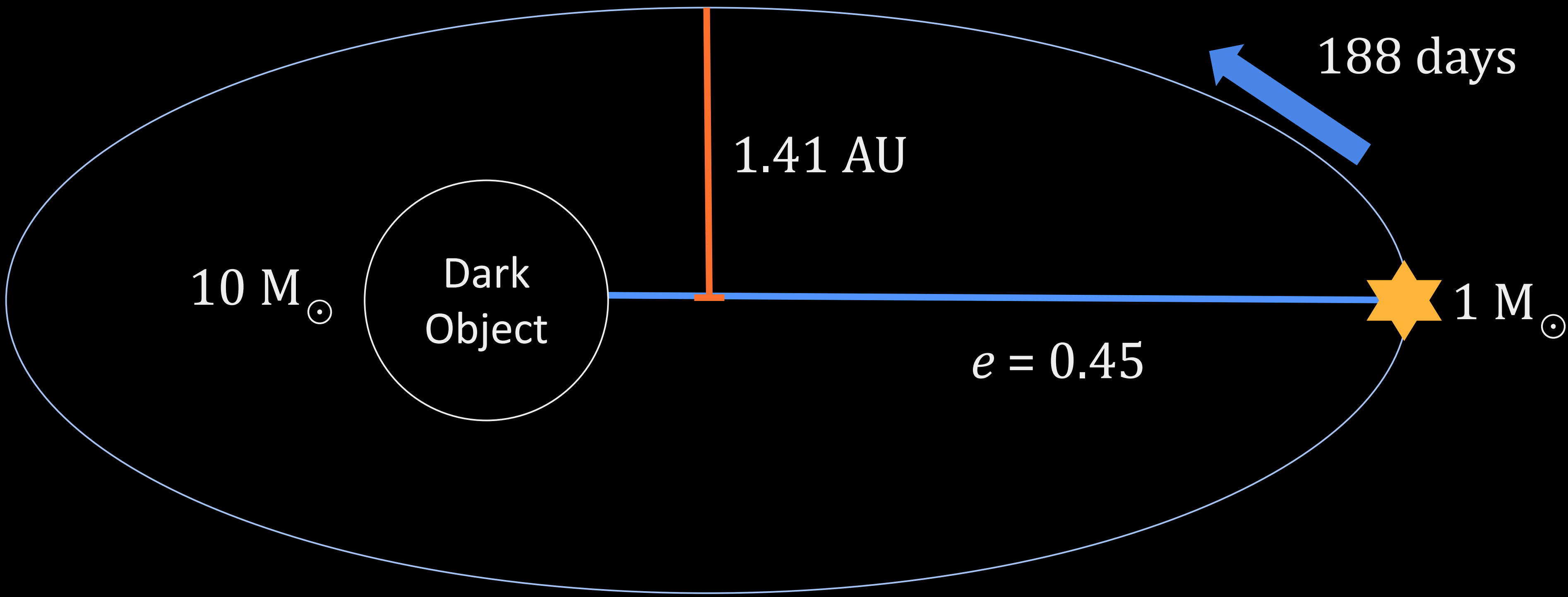

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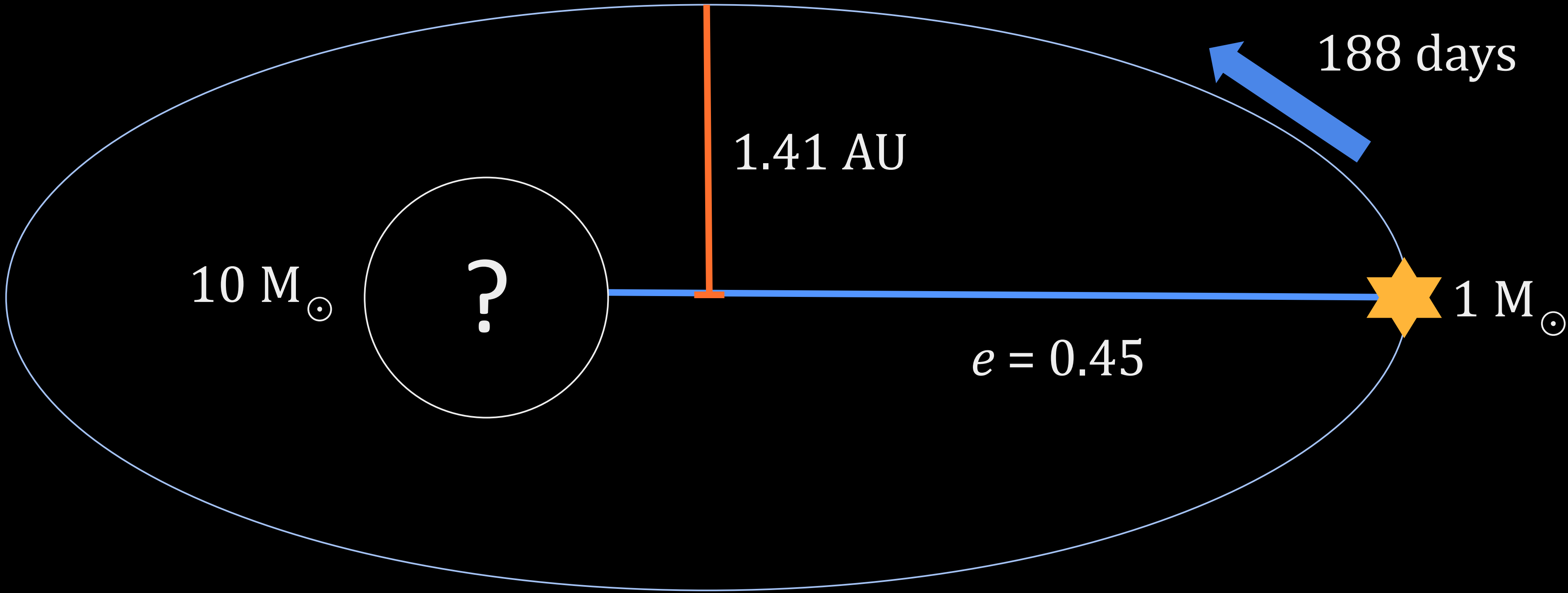
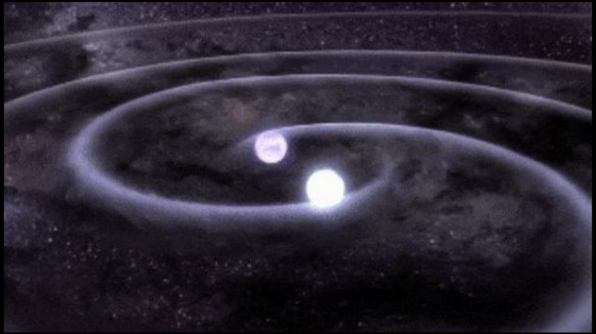


System



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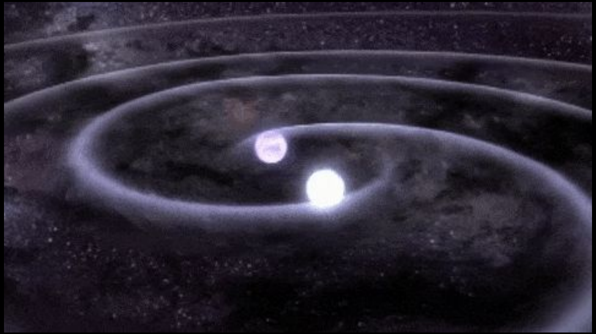

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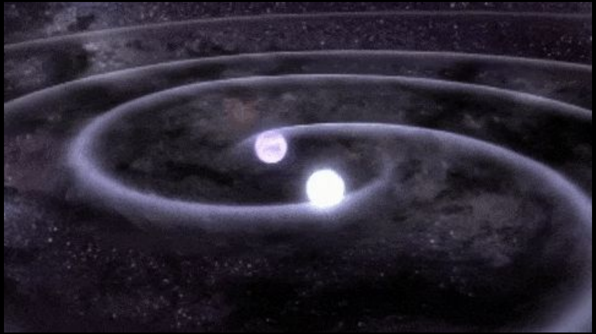

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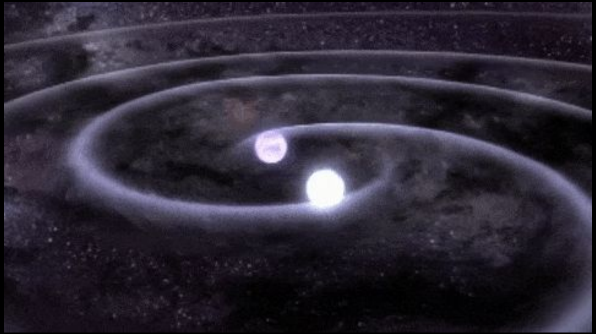

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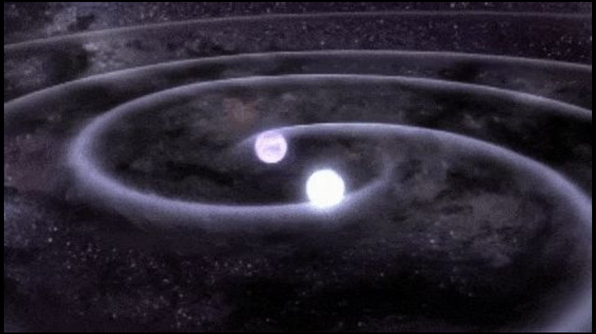

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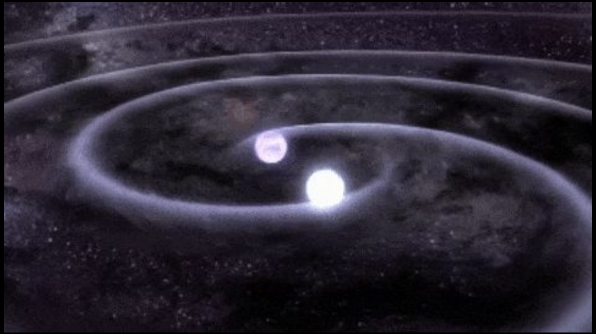

Mass range
Formation
Stability

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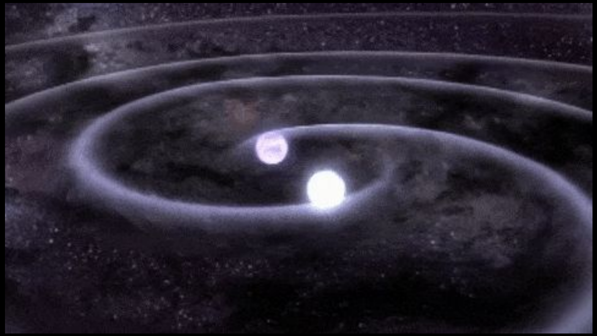

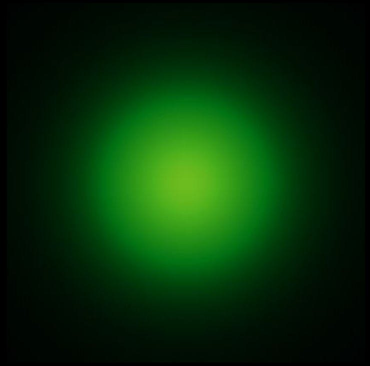

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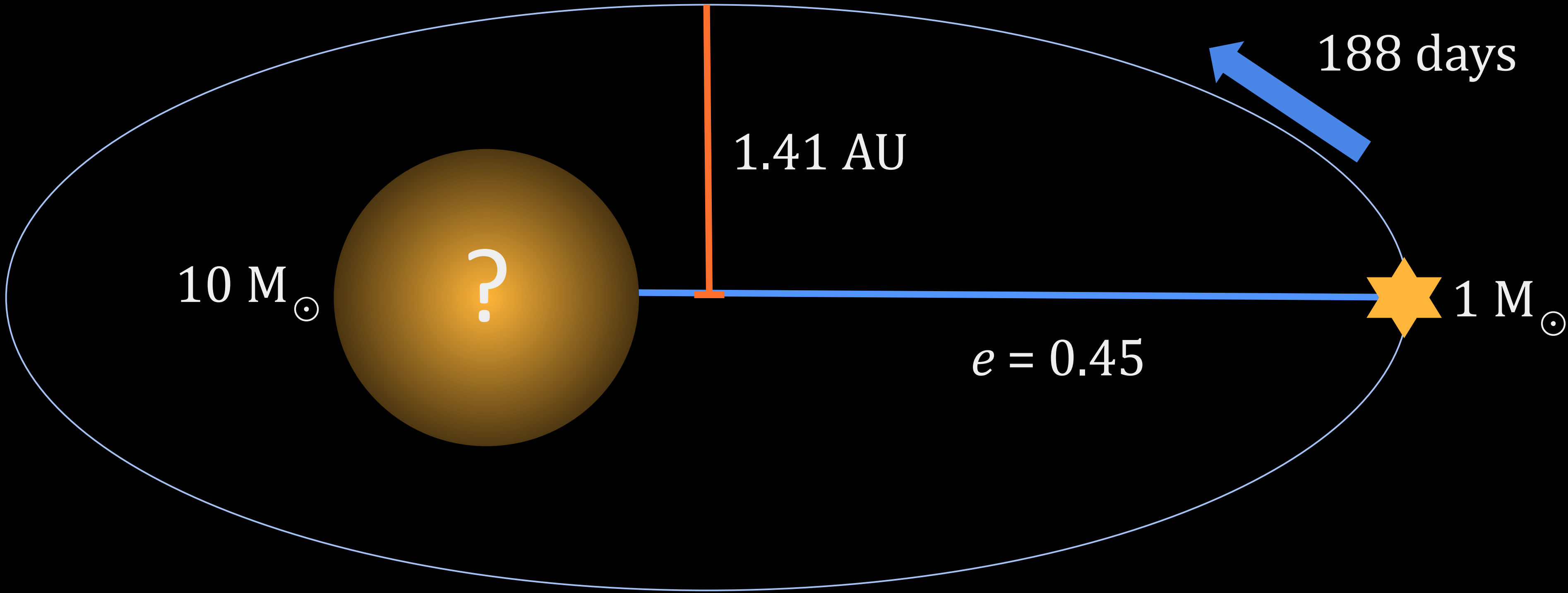
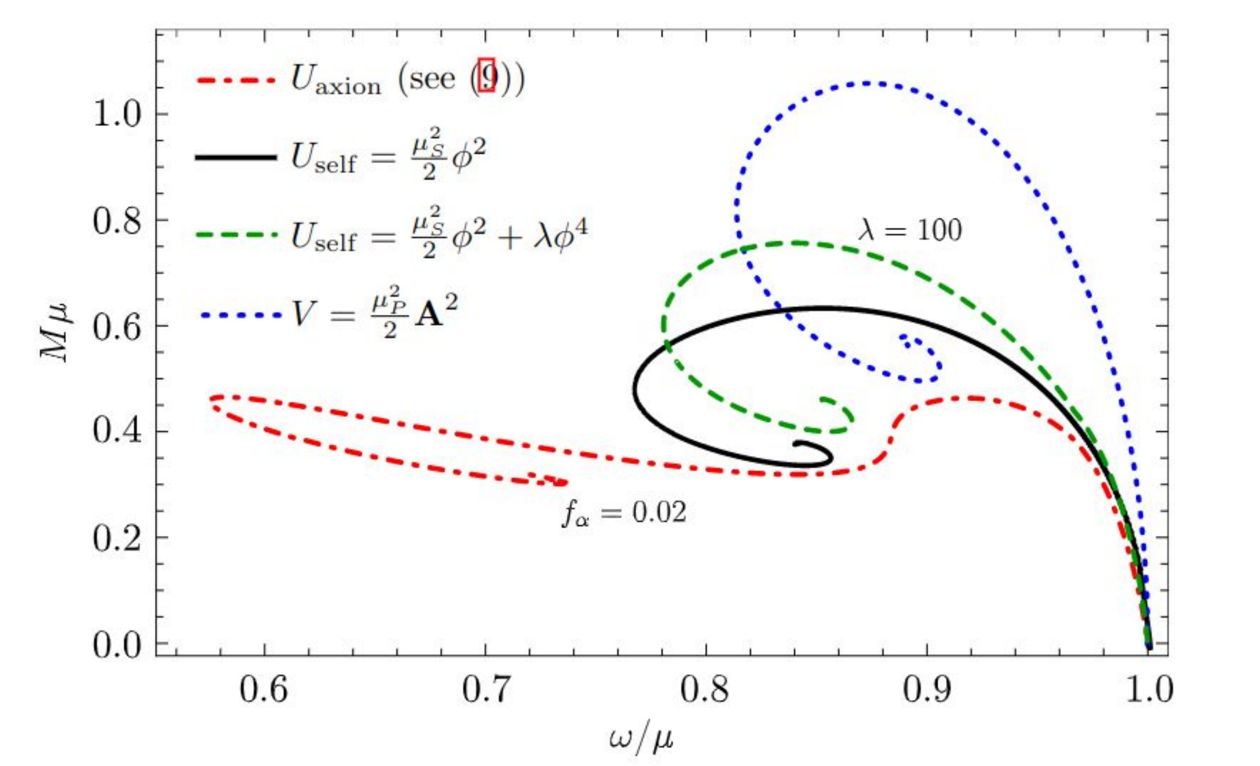


Boson Star



U_{axion} (see [9])
$U_{\text{self}} = \frac{\mu_S^2}{2}\phi^2$
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0.8
1.0
0.6
0.7
0.8
0.9
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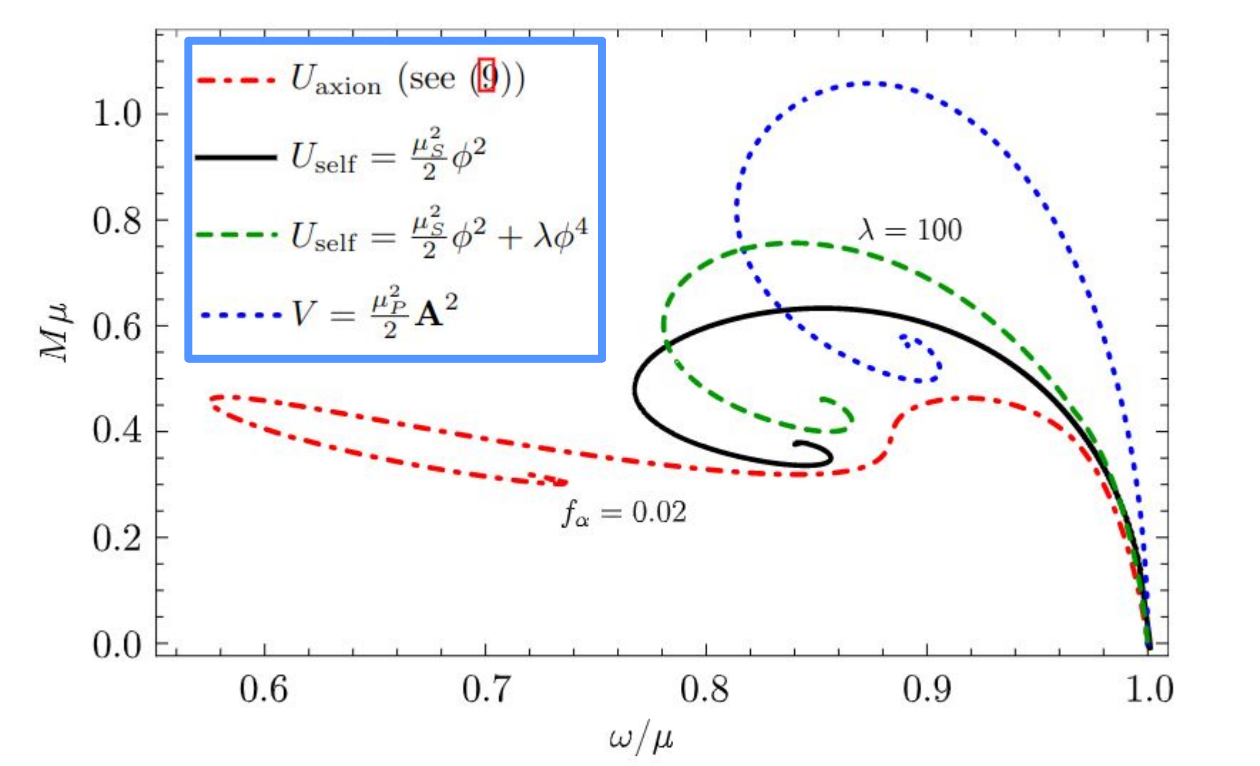

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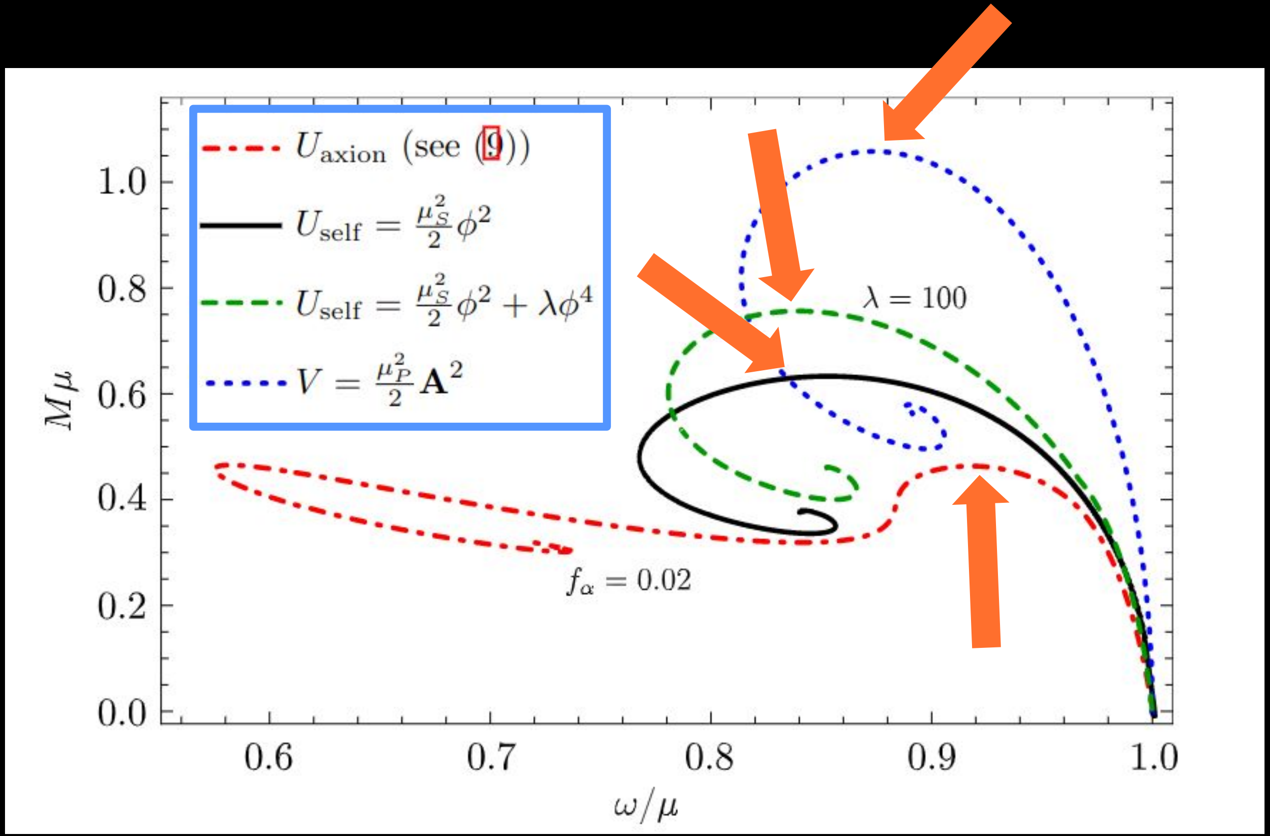

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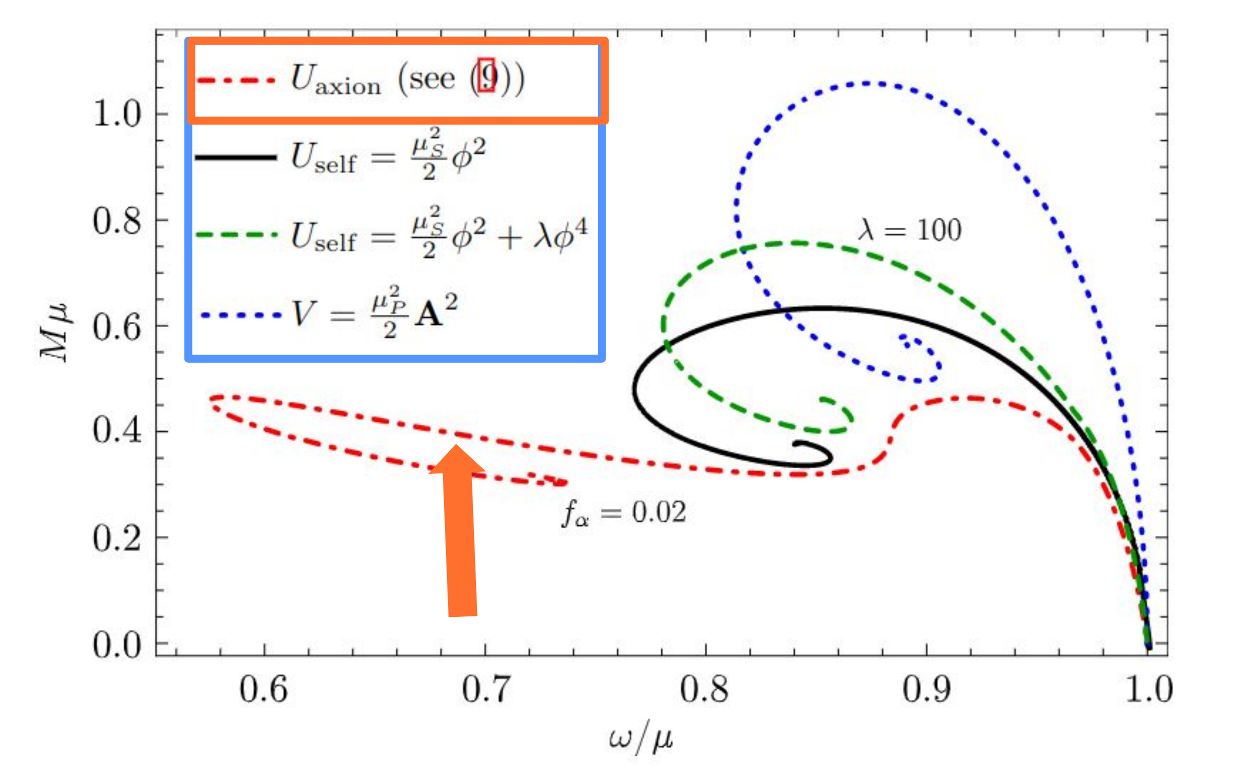

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Orbits

Geodesic motion: Timelike Circular Orbits $k = -1$

- Let us now consider timelike geodesics ($k = -1$)
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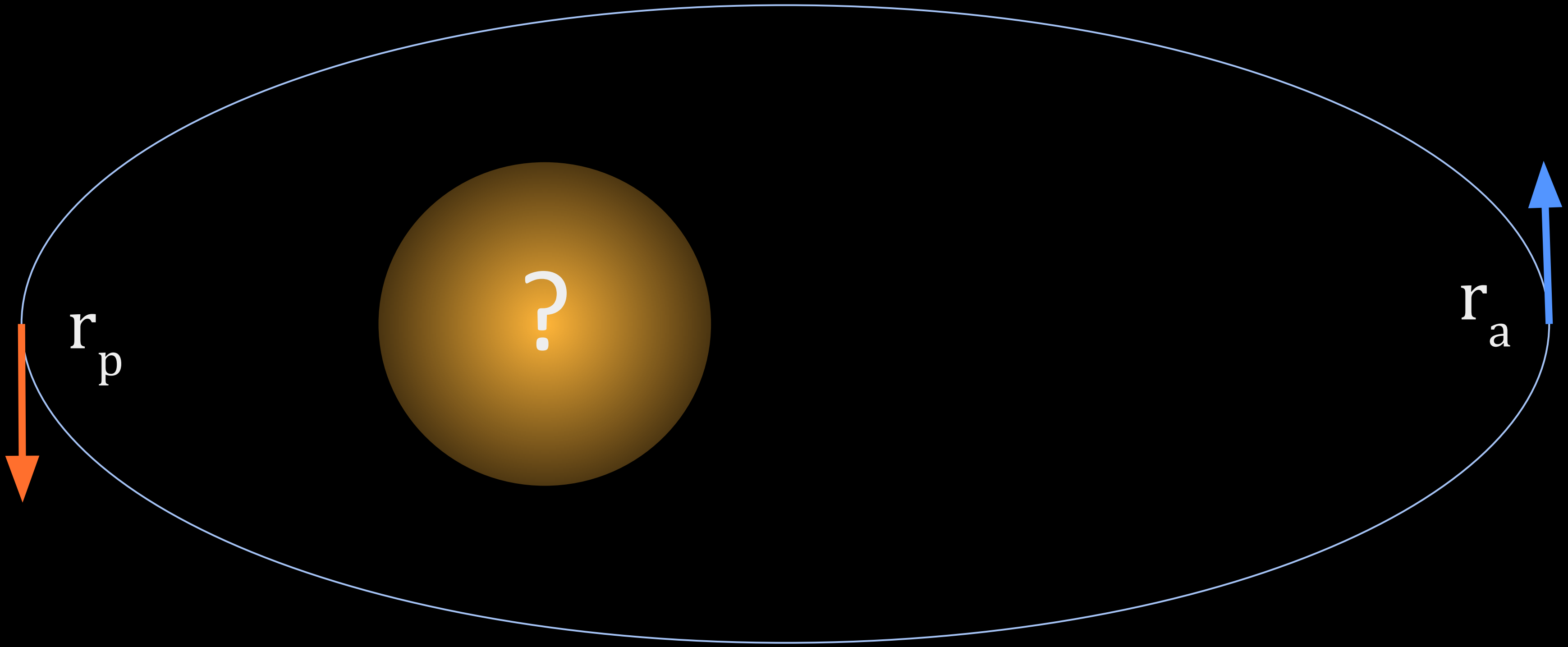

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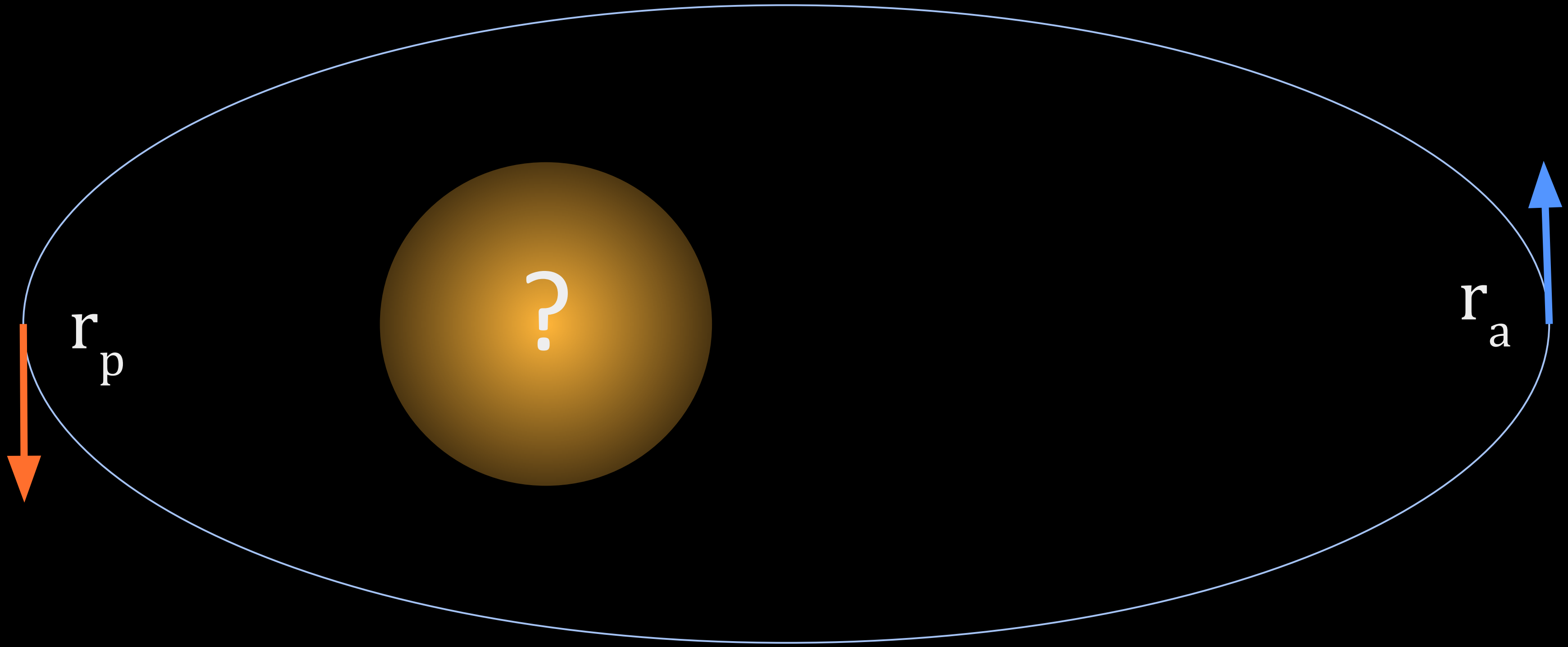

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$$c = 63241\ \mathrm{AU}\cdot\mathrm{yr}^{-1}\,,\ \mathrm{G} = 39.748\ \mathrm{AU}^3\cdot\mathrm{M}_\odot\cdot\mathrm{yr}^{-2}\,,\ \mathrm{M}_{\mathrm{Pl}} = 1.094\times10^{-38}\ \mathrm{M}_\odot$$

Orbits: Class I

Scalar

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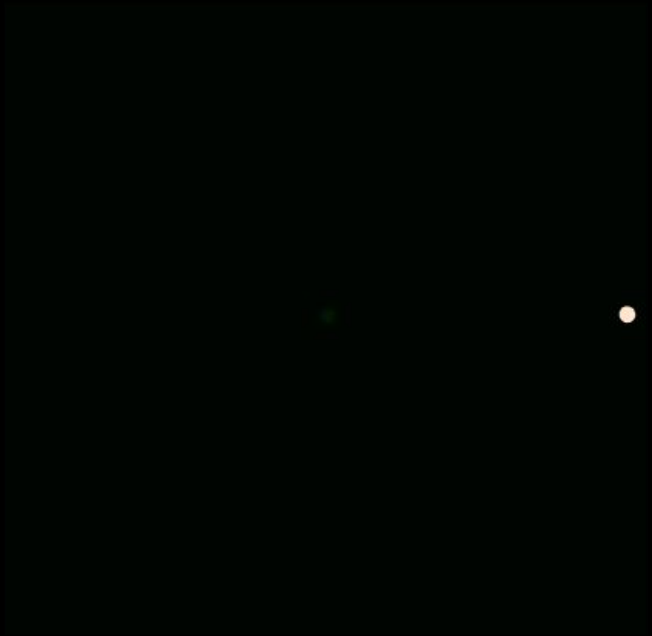
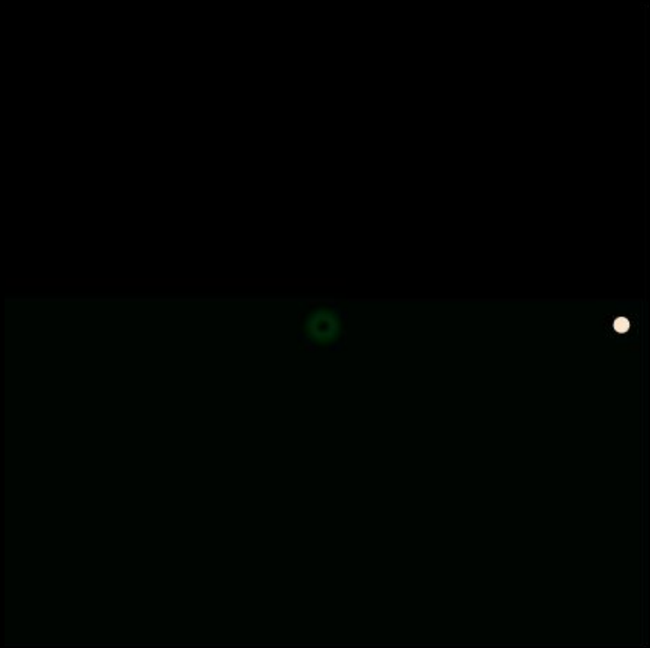
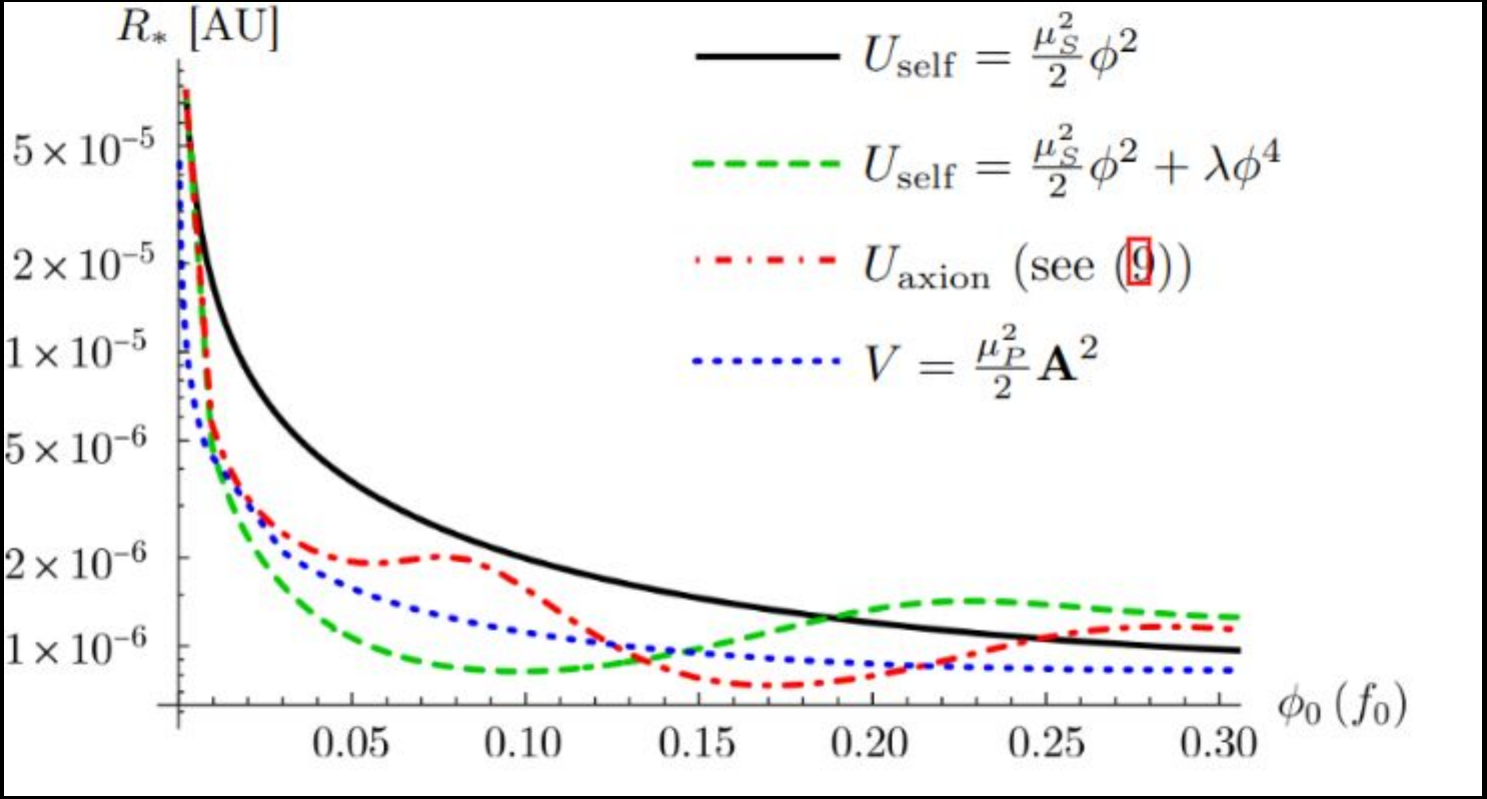
Scalar



Vector



Orbits: Class I



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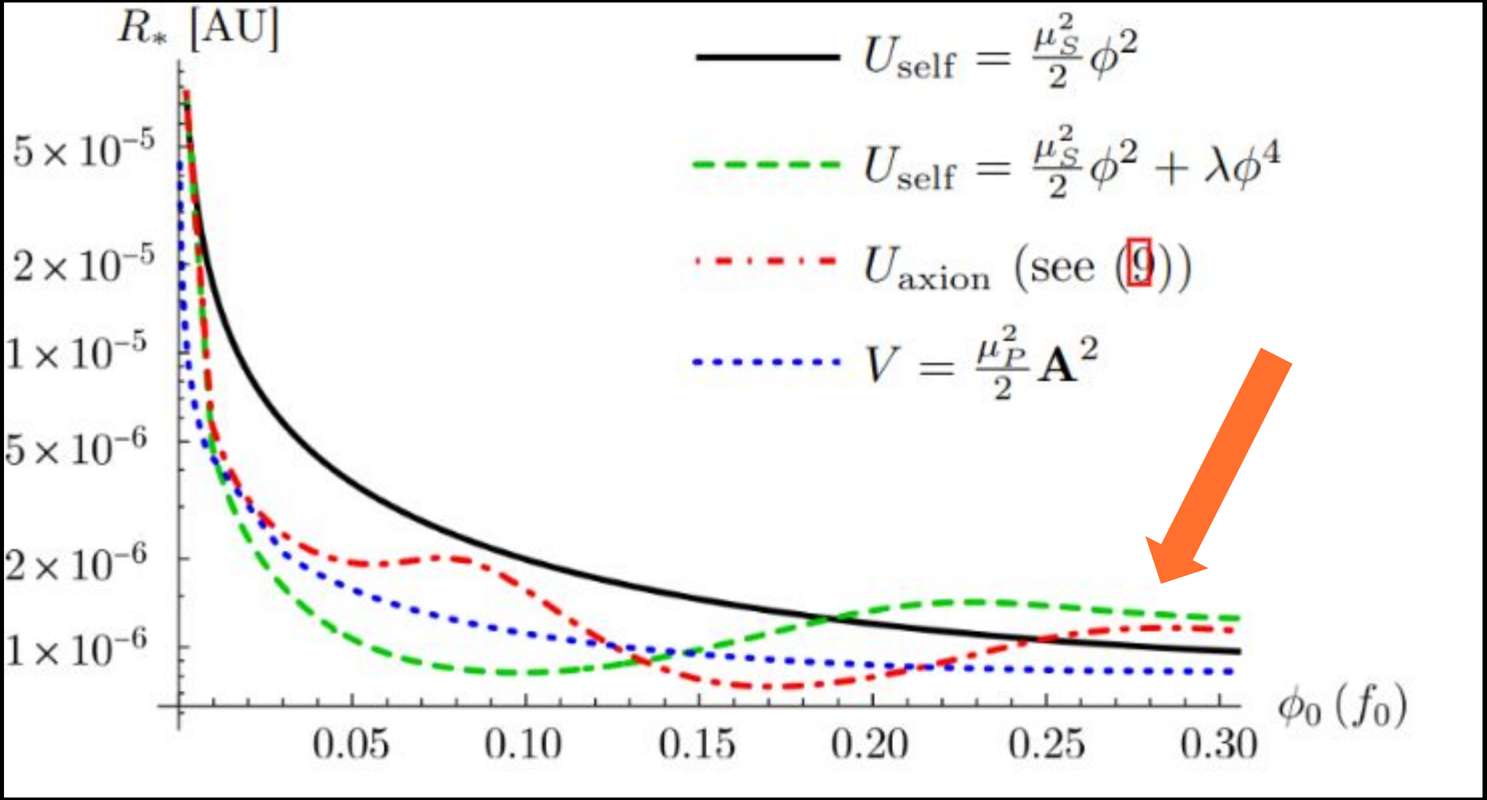

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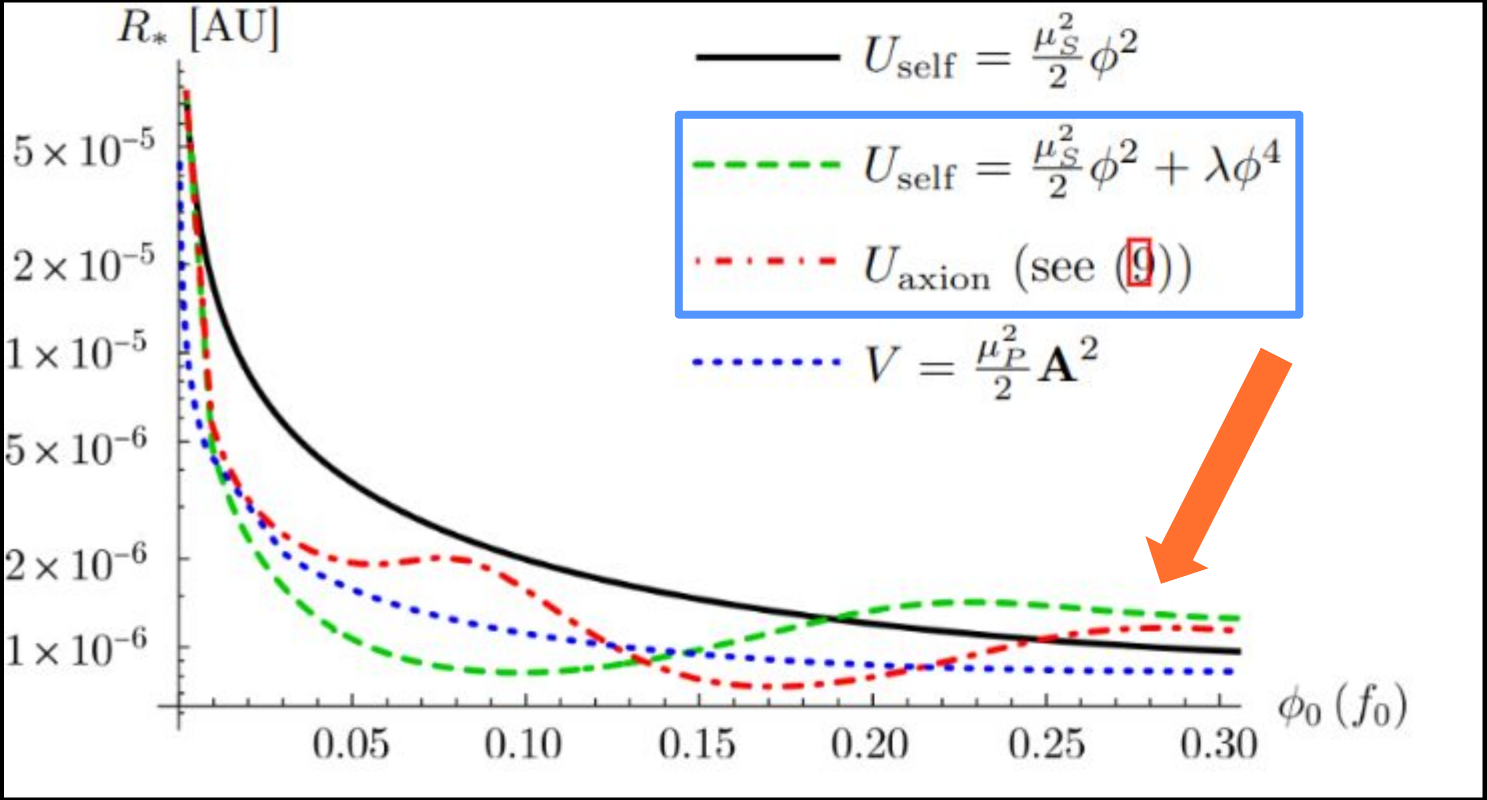

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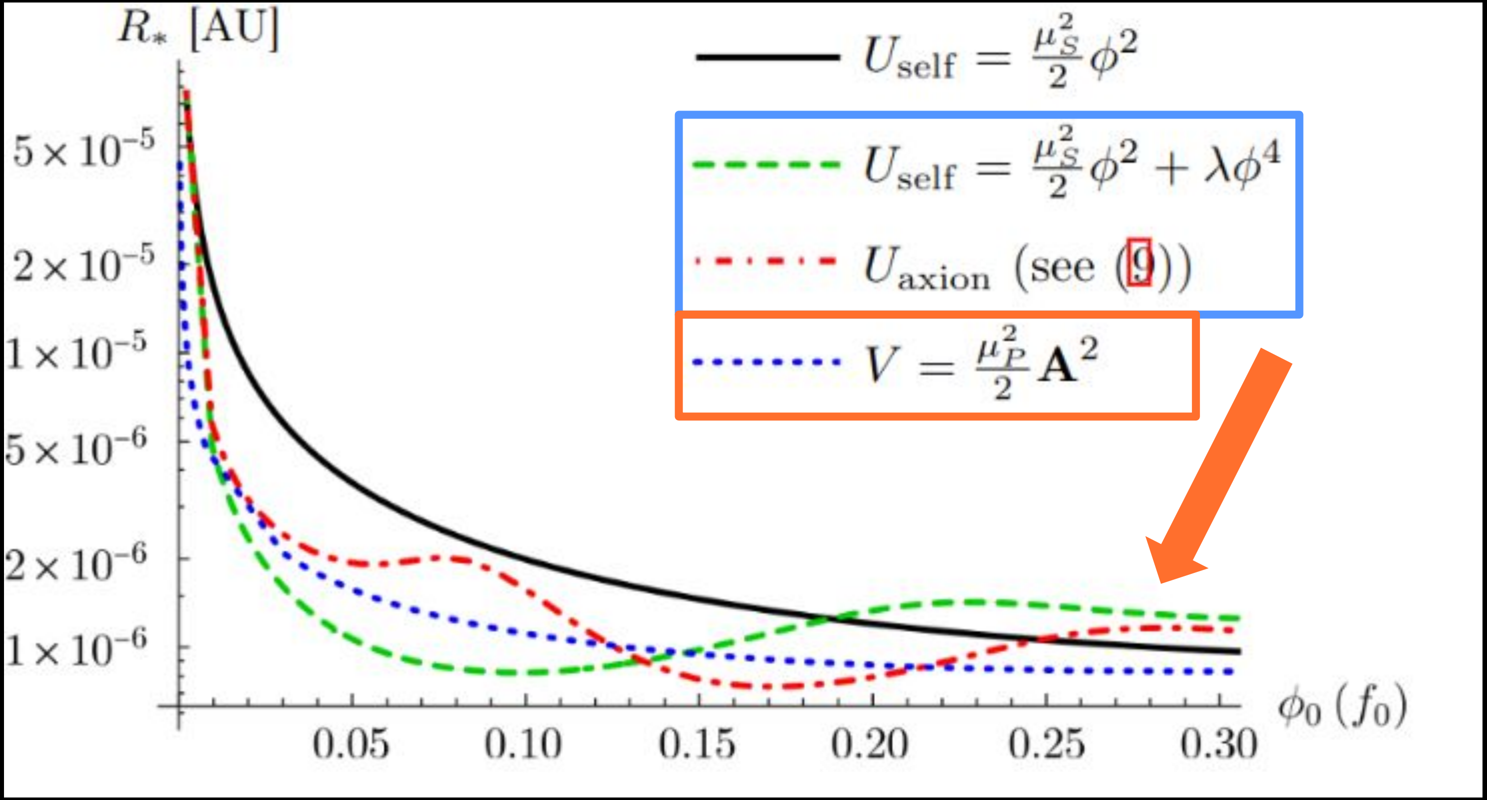

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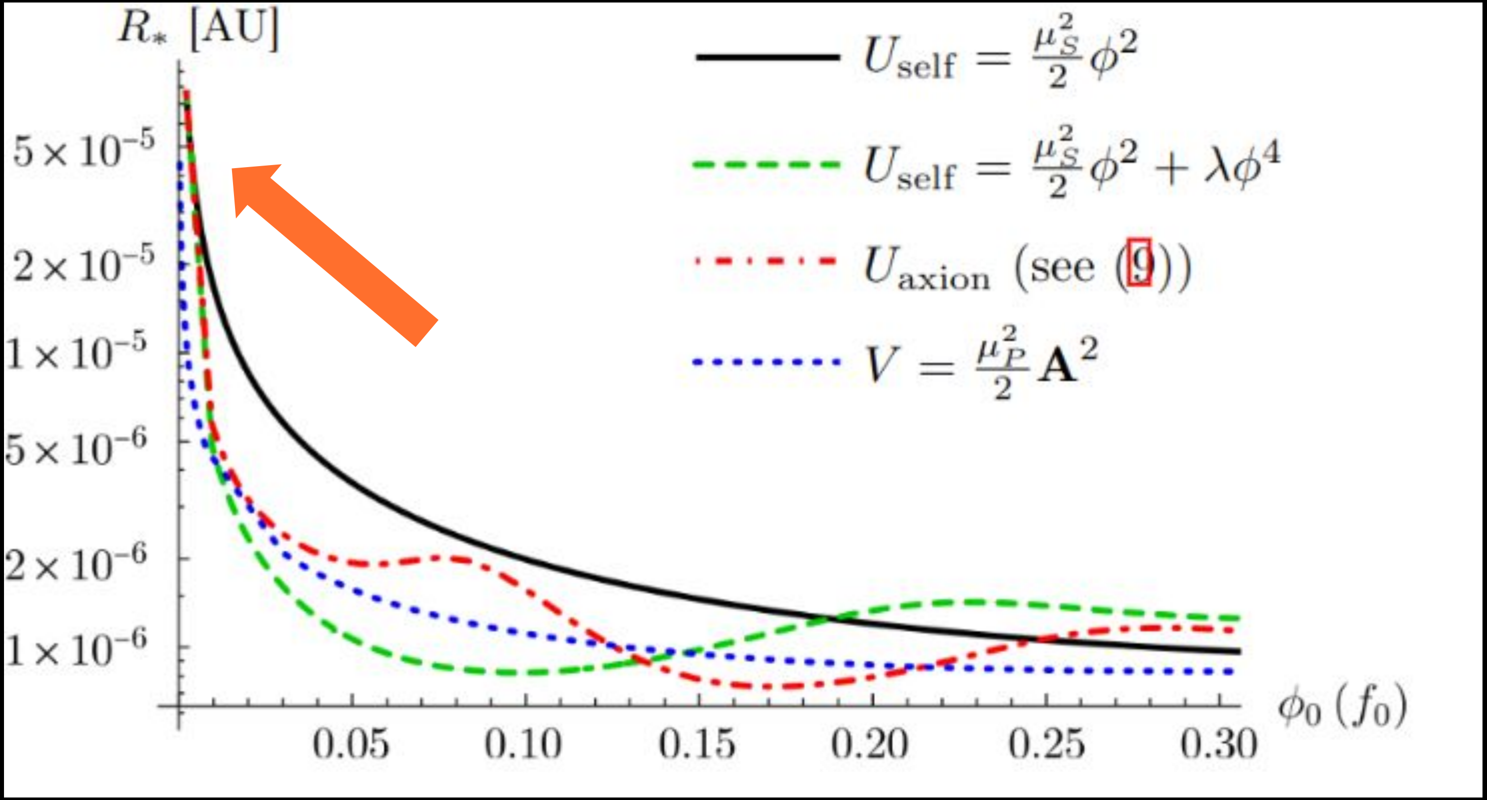

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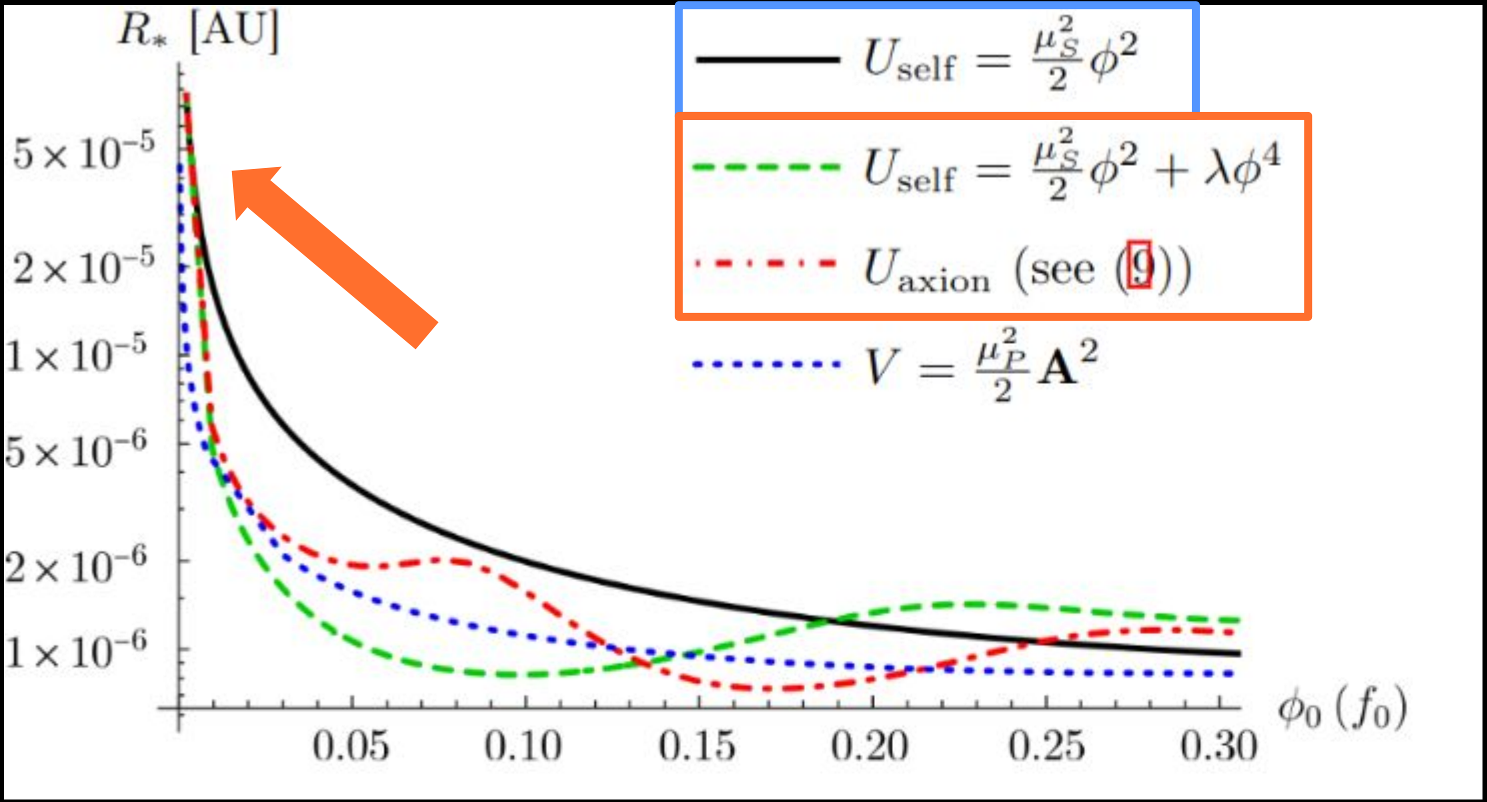

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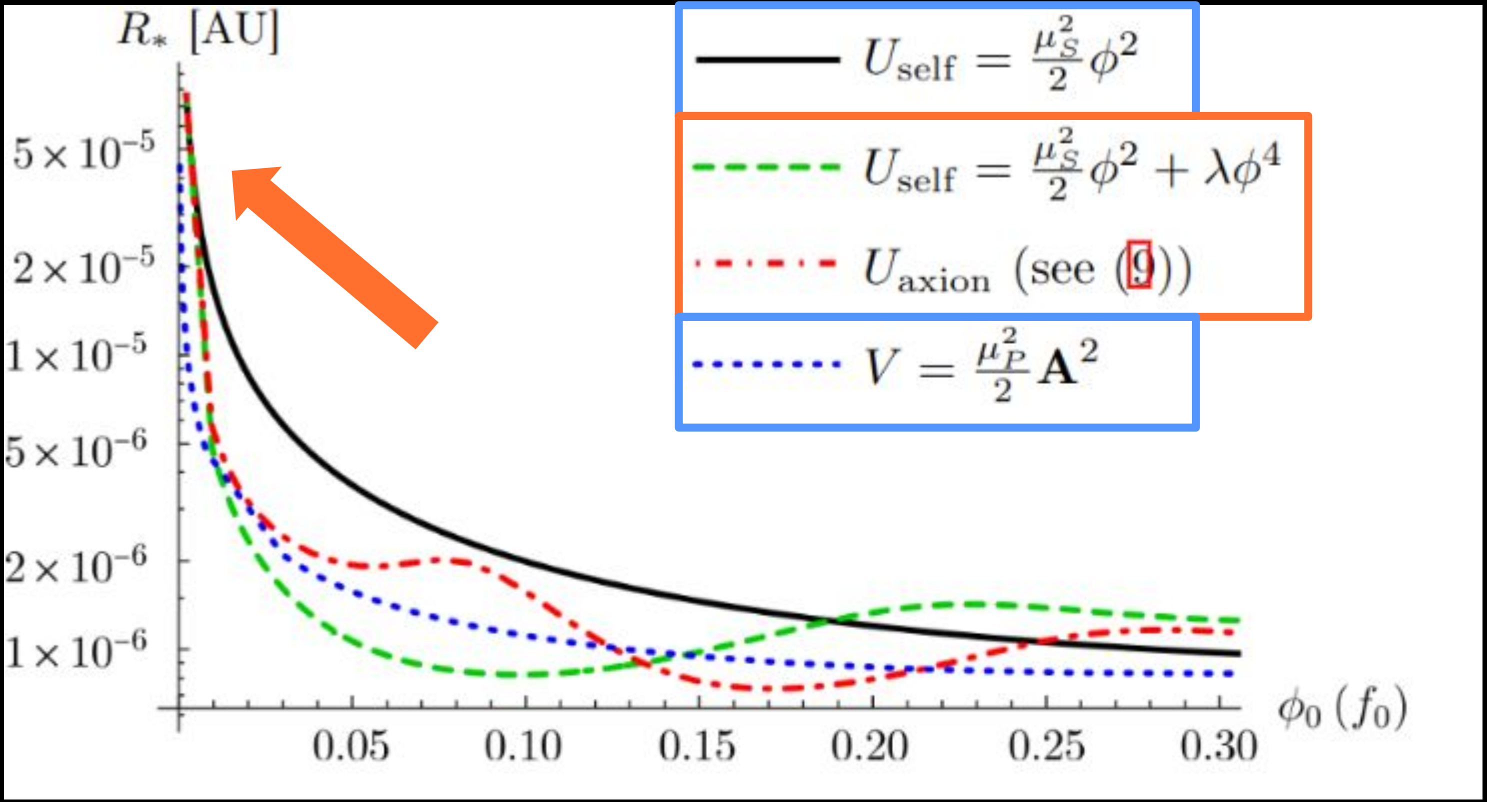

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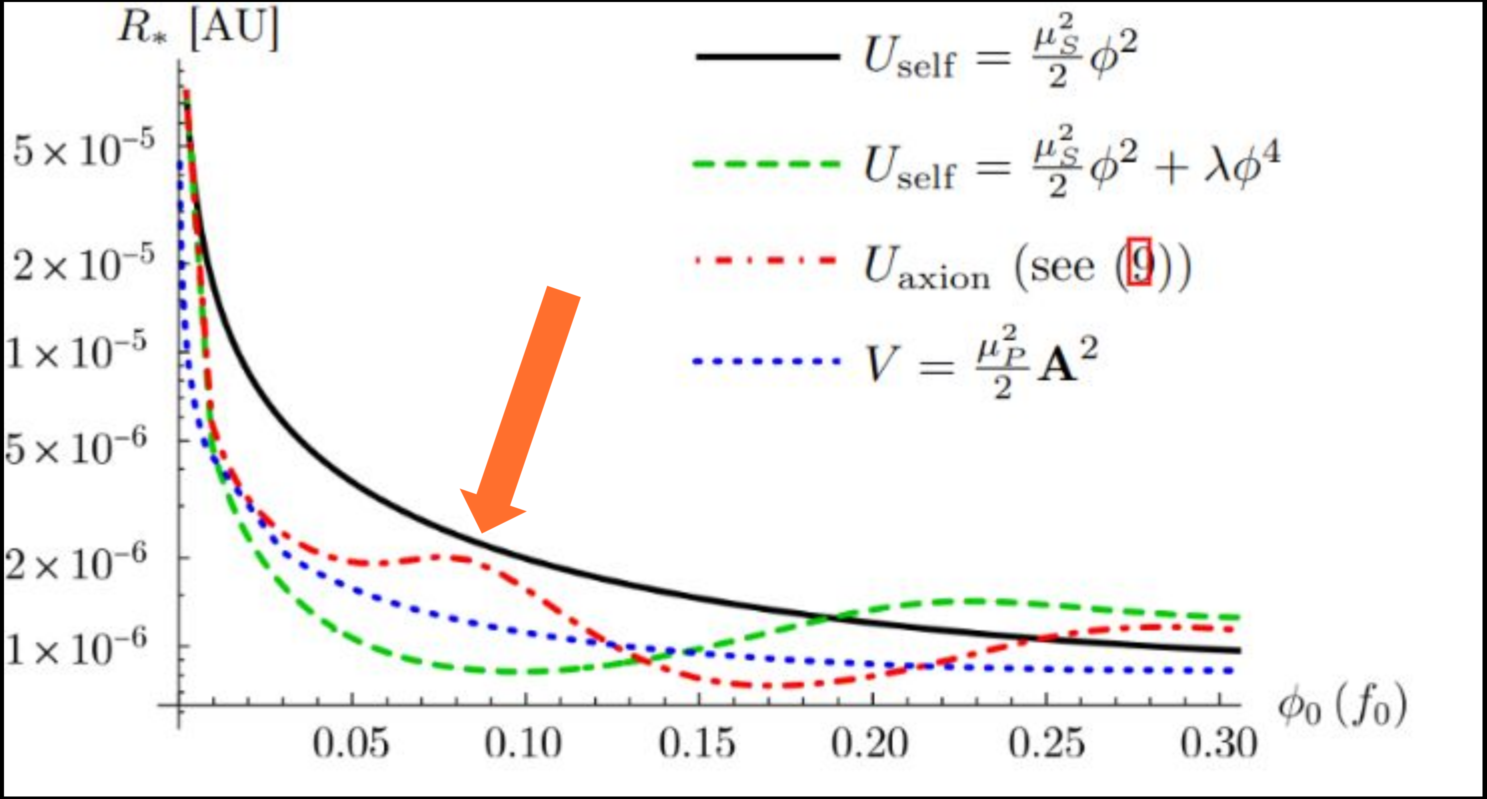

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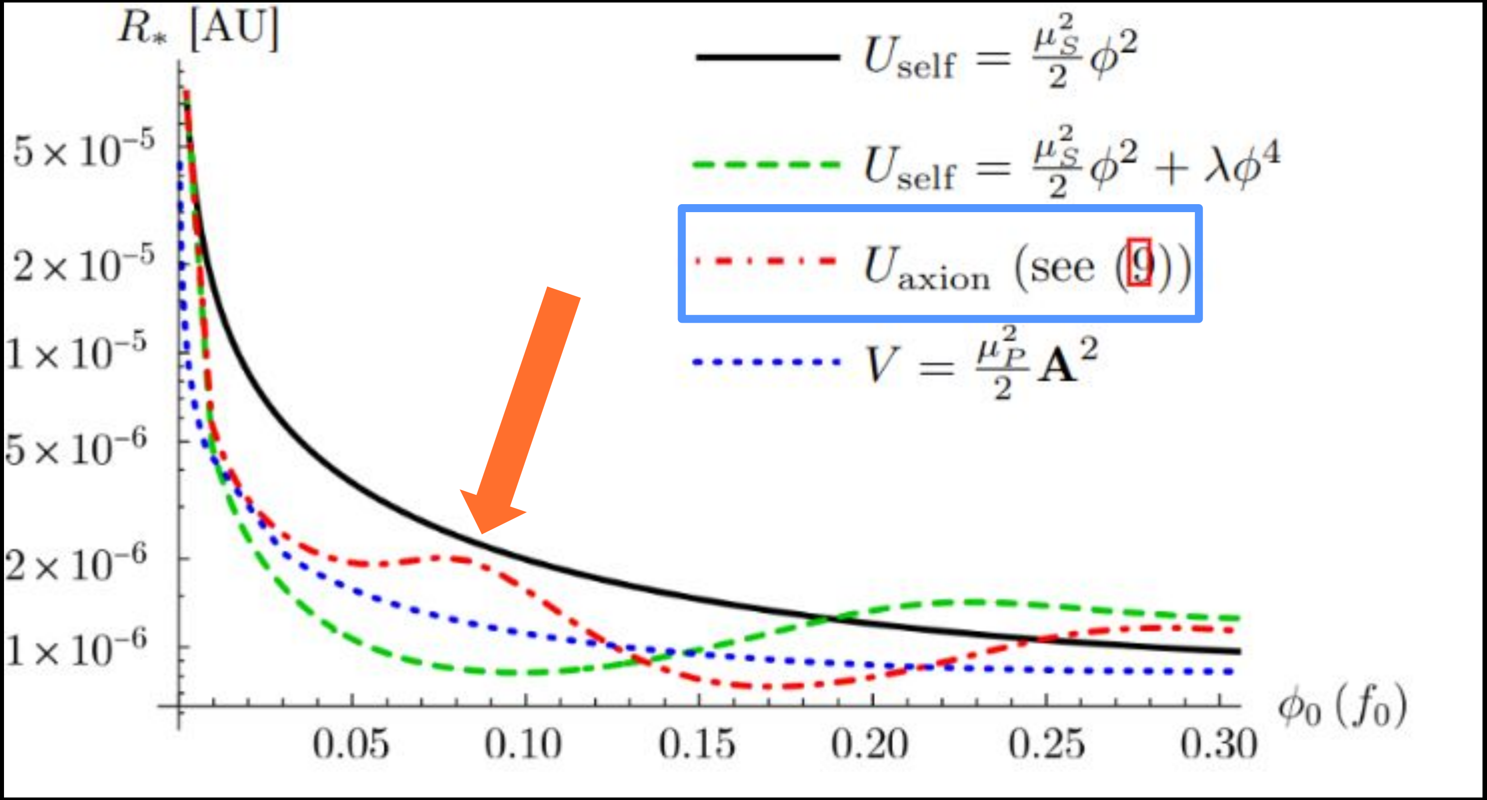

Orbits: Class I

Boson star characteristics - Case I				
Model	Potential	Boson mass (μ) at $M_{\rm Max}$ [GeV/c^2]	Radius R_* at $M_{\rm Max}$ [km]	Interaction coupling (λ)
Scalar, non-interacting	$U_{\rm self} = \frac{\mu_S^2}{2}\phi^2$	10^{-20}	134	$\lambda = 0$
Scalar, self-interacting	$U_{\rm self} = \frac{\mu_S^2}{2}\phi^2 + \lambda\phi^4$	10^{-20}	87	$\lambda = 100$
Scalar, axion-like	$U_{\rm axion}$ (see (9))	10^{-19}	317	$f_\alpha = 0.02$
Vector	$V = \frac{\mu_P^2}{2}\mathbf{A}^2$	10^{-20}	124	0

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Scalar, non-interacting	$U_{\rm self} = \frac{\mu_S^2}{2}\phi^2$	10^{-20}	134	$\lambda = 0$
Scalar, self-interacting	$U_{\rm self} = \frac{\mu_S^2}{2}\phi^2 + \lambda\phi^4$	10^{-20}	87	$\lambda = 100$
Scalar, axion-like	$U_{\rm axion}$ (see (9))	10^{-19}	317	$f_\alpha = 0.02$
Vector	$V = \frac{\mu_P^2}{2}\mathbf{A}^2$	10^{-20}	124	0

Orbits: Class I

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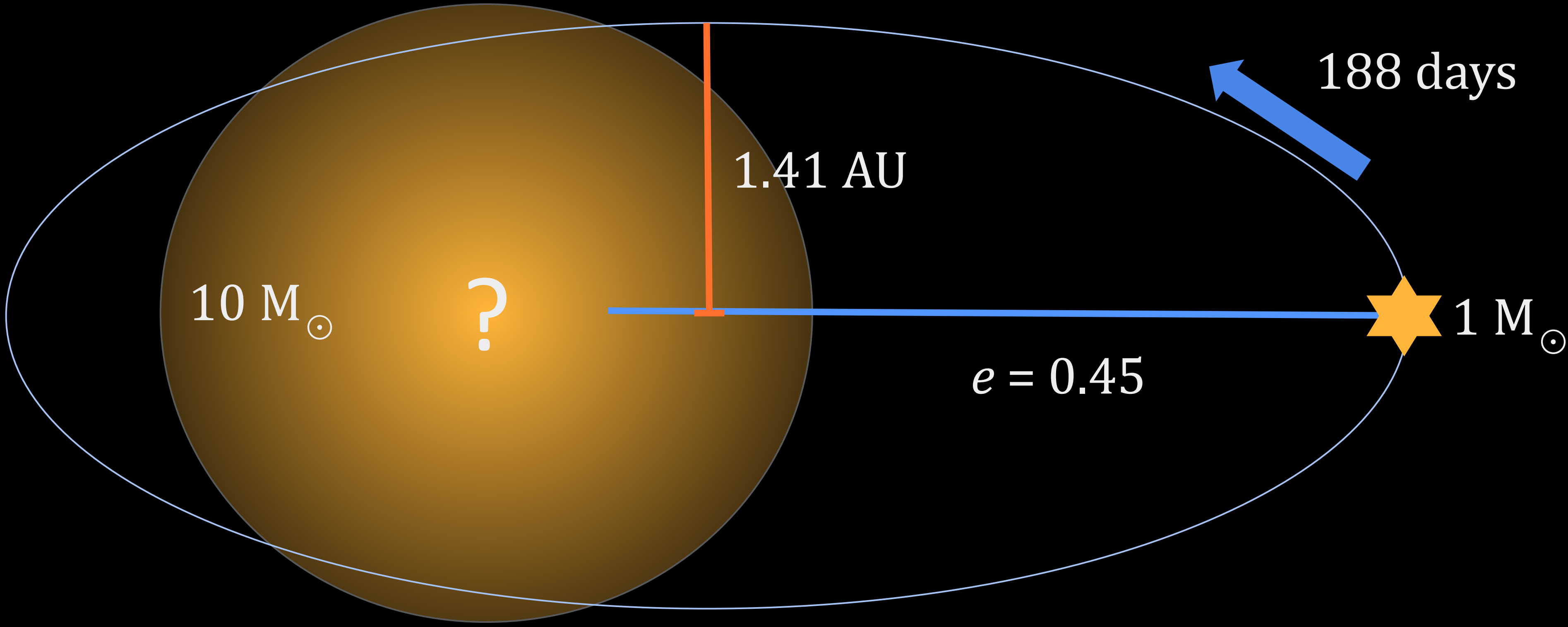
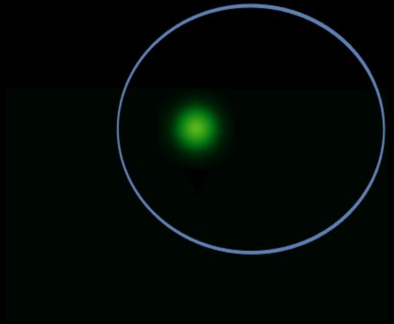
Orbits: Class II



Class II: Scalar



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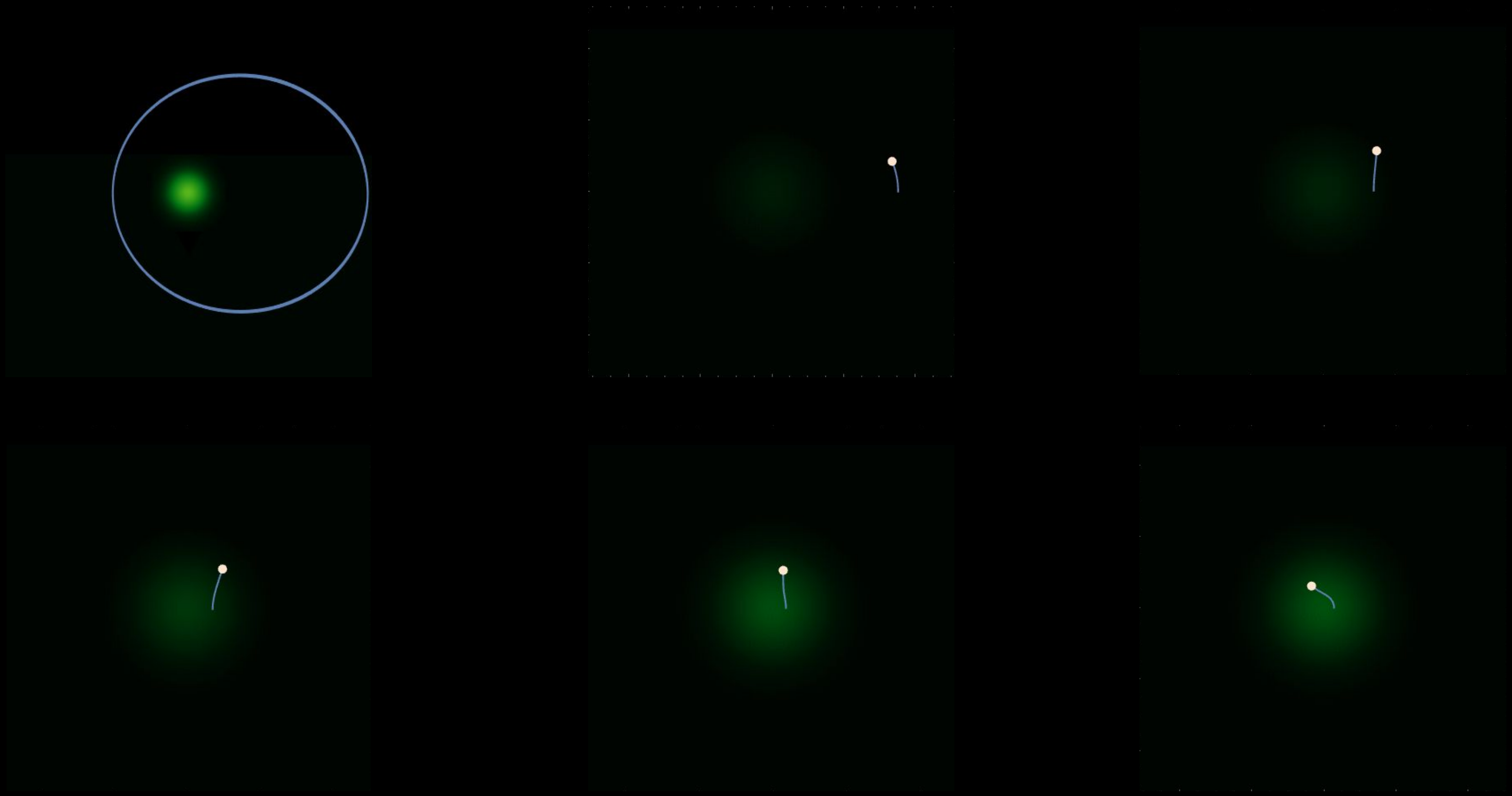
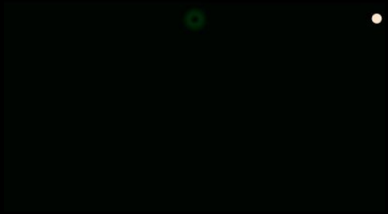
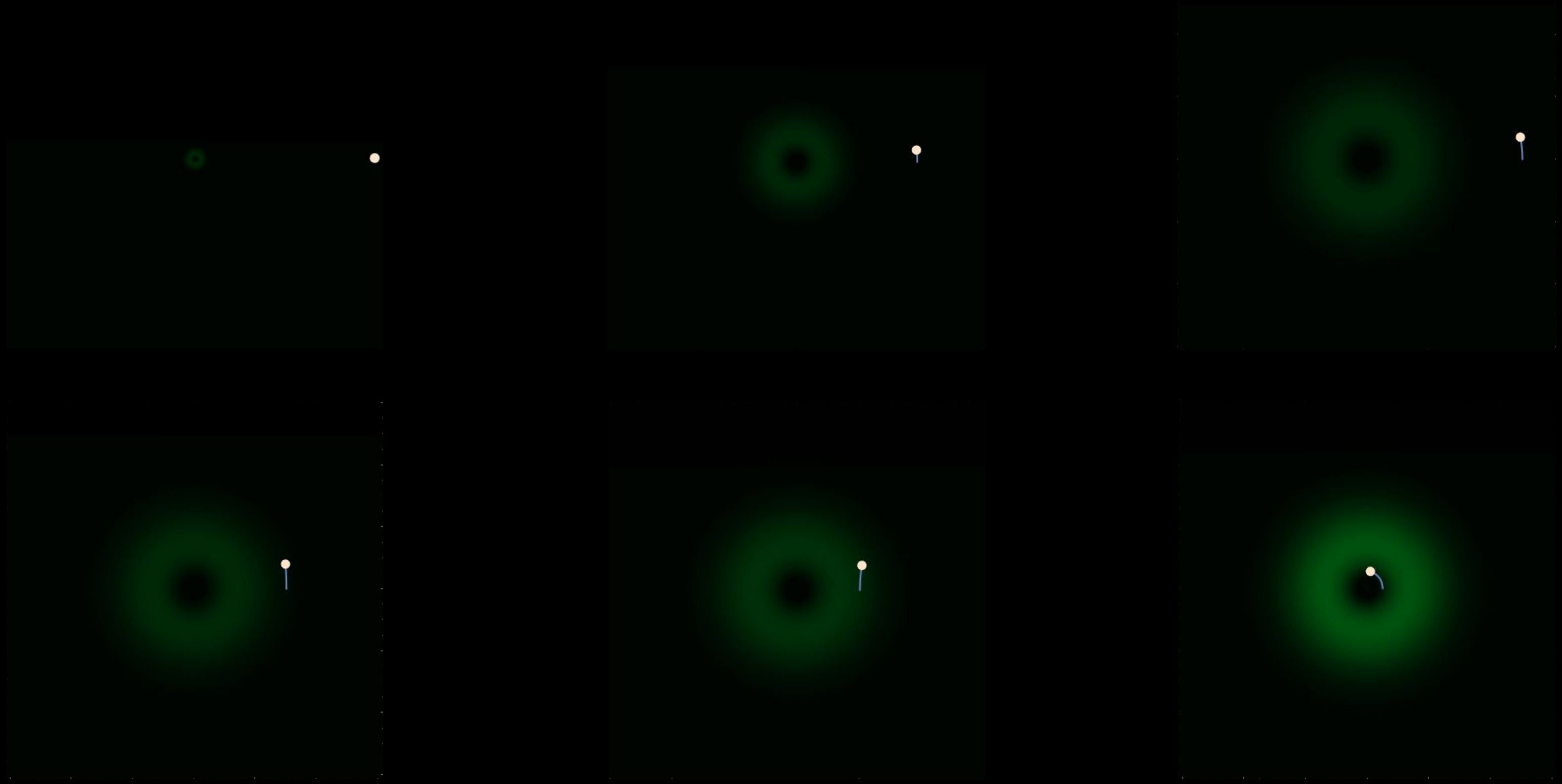


Class II: Vector



Class II: Vector



Summary

- Models with dynamically robust spherical BSs, can reproduce the observations made by GAIA
- The largest boson star radii occurs in the stable region
- In this part, the mass is the leading term

- Axionic stars may have the orbiting star inside the matter distribution
- In this case, orbits become highly eccentric and pressessing
- Hence, being ruled out by current observations

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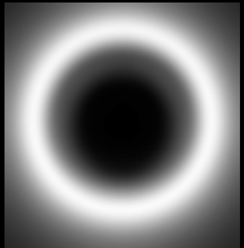
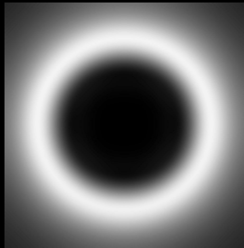
Image

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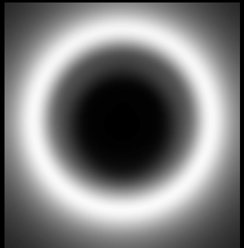

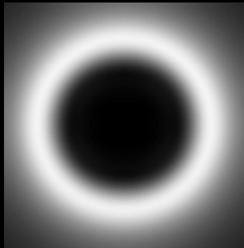

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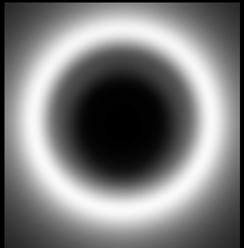
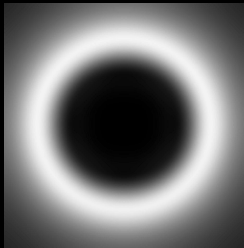
But only under certain observational conditions





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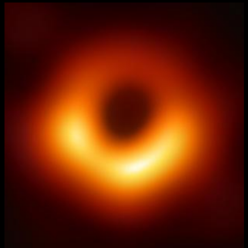

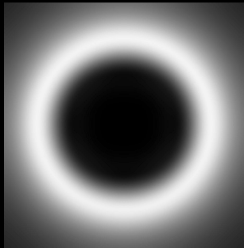

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A Boson star can mimic a BH’s phenomonology

Thank You!

Děkuji!

FZU ceico
Czech Academy of Sciences
GAČR
CZECH SCIENCE FOUNDATION
czechLISA
Czech participation in the LISA mission

Boson Stars that mimic Black Holes

doi.org/10.1088/1475-7516/2021/04/051
arXiv:2304.09140

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