Full Presentation

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Proca Stars that can mimic Schwarzschild shadow

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Carlos A.R. Herdeiro, Eugen Radu, Pedro V.P. Cunha, Nicolas Sanchis-Gual

Introduction: Black Hole mimicker

- With all the new observational EHT like evidences, one question arises:

- Typically, the shadow is associated with the LR and illumination source (accretion disk)
- LRs have been shown to be a generic feature of stationary BHs
- And to have an important impact on the ringdown and shadow

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- Can a dynamically robust, horizonless object mimick a BH image?

Introduction: Boson Stars

- A Boson Star is an hypothetical astronomical object formed out of bosons
- For this stars to exist, one needs a stable boson
- Compact Boson Stars are often studied involving massive complex scalar fields with **U(1)** global symmetry
- They may be described as an everywhere regular lump of scalar or vector boson

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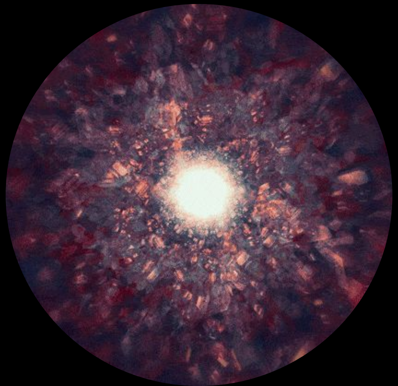

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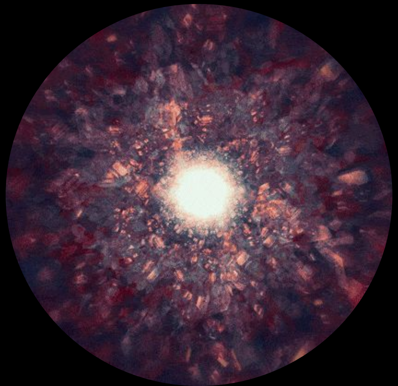

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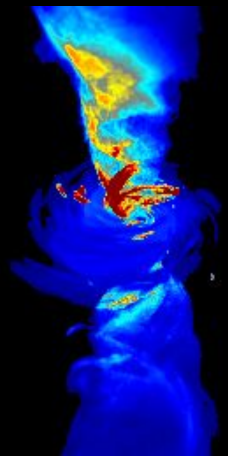
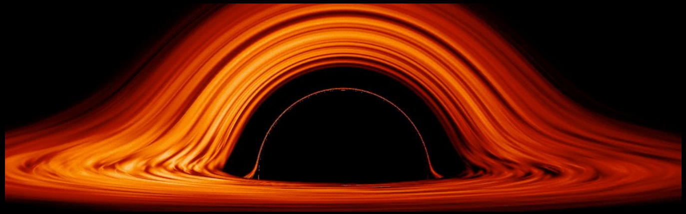


blackholecam.org/

Black Hole Mimicker

Black Hole mimicker

- 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
- Which is determined by the innermost stable circular orbit (ISCO) of the BH
- However, for spherical BSs there is no ISCO



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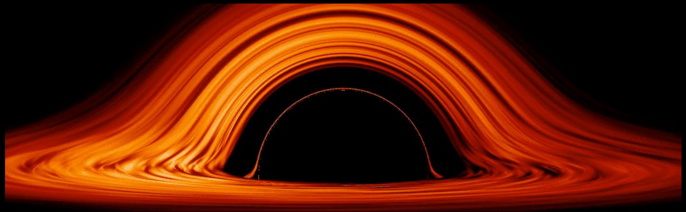

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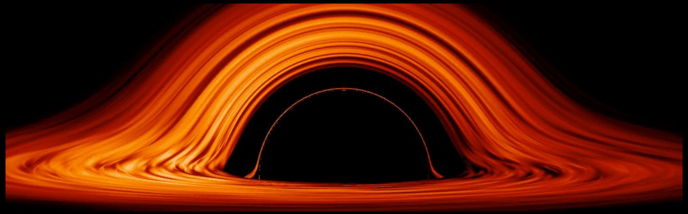

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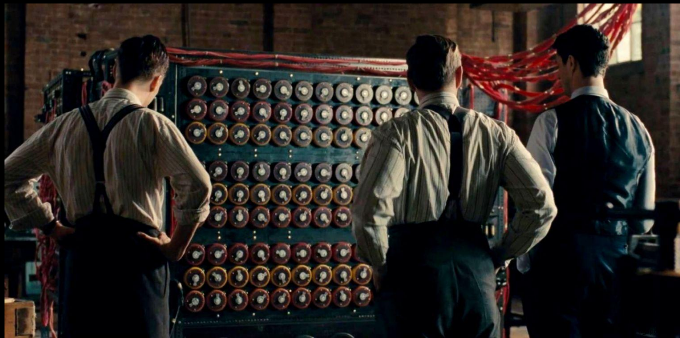

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- Show that the angular velocity of the orbits, Ω, attains a maximum at some areal radius R_Ω
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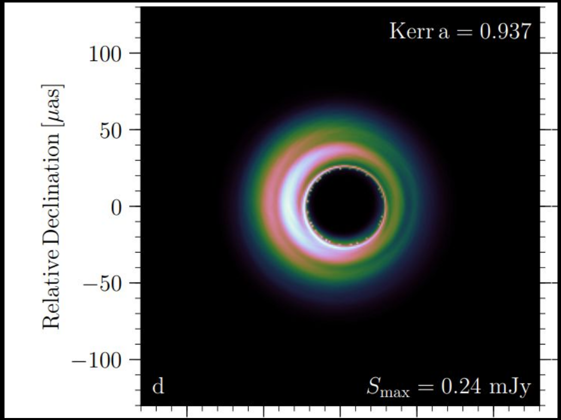

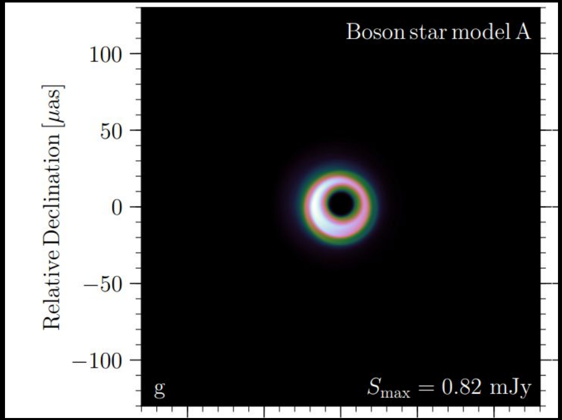

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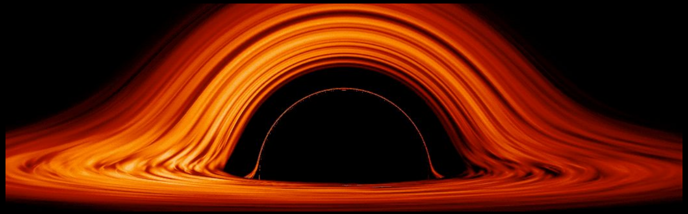

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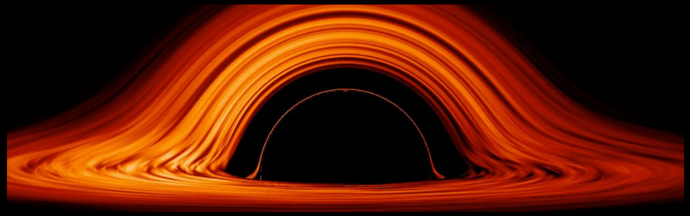

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- The objective of this work is to assess if stable and dynamically robust BS can yield the same shadow as a BH.

The Model

The model: Lagrangean

- The Einstein-matter action, where the matter part describes a spin-$s = 0, 1$ classical field minimally coupled to Einstein's gravity

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

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$$\mathcal{L}_0 = -\frac{1}{2}g^{\alpha\beta}\left(\bar{\Phi}_{,\alpha}\Phi_{,\beta} + \bar{\Phi}_{,\beta}\Phi_{,\alpha}\right) - U_i\left(|\Phi|^2\right) ,$$

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$$\mathcal{L}_1 = -\frac{1}{4} F_{\alpha\beta} \bar{F}^{\alpha\beta} - V(\mathbf{A}^2)$$

The model: Ansatz

- For the metric ansatz

$$ds^2 = -N\sigma^2 dt^2 + \frac{dr^2}{N} + r^2 d\Omega_2^2 \qquad N(r) = 1 - \frac{2m(r)}{r}$$

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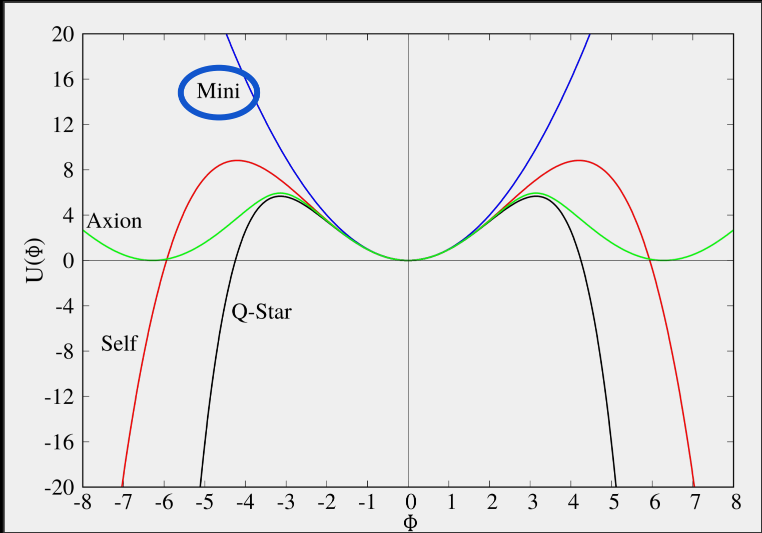
For the vector fields $A : s = 1$

$$A = \left[f(r)dt + i\,g(r)dr\right]e^{-i\omega t}$$

The model: Potentials

- The self-interaction potentials

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



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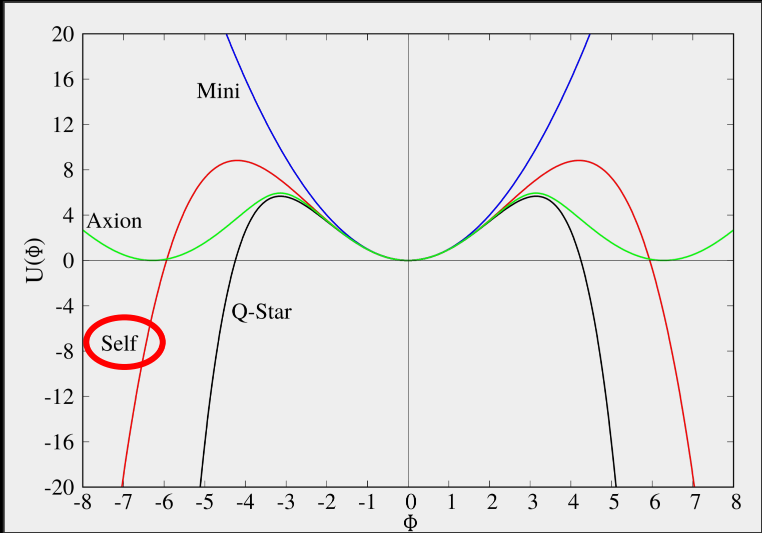
$$U_{\text{poly}} = \mu_S^2 \Phi^2 + \lambda \Phi^4$$



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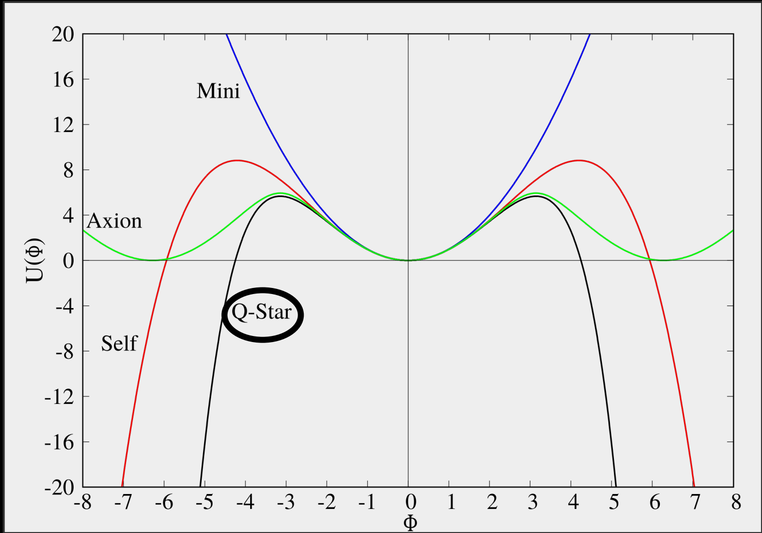
$$U_{\text{poly}} = \mu_S^2 \Phi^2 + \lambda \Phi^4 + \gamma \Phi^6$$



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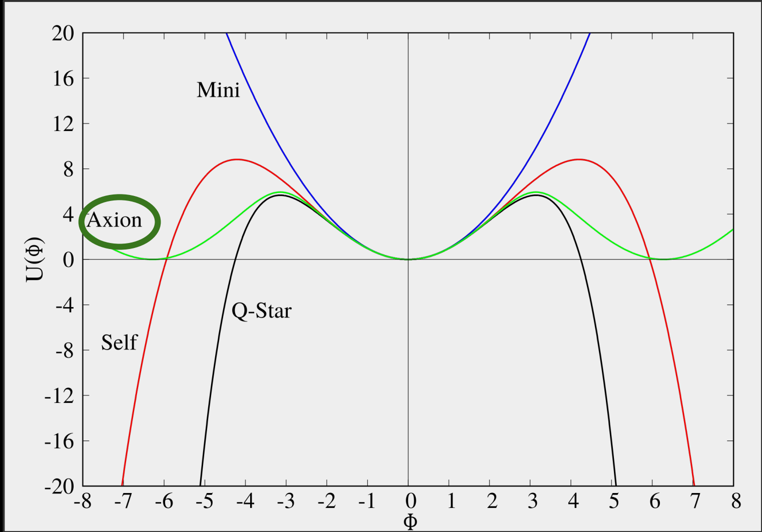

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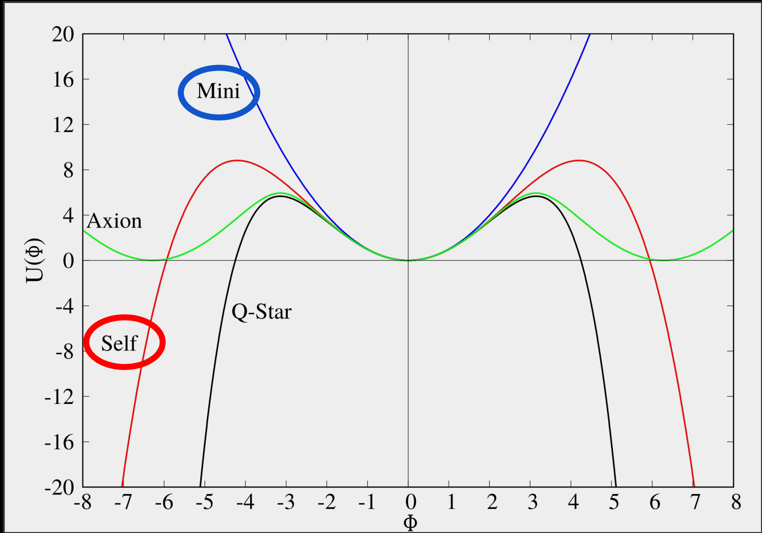
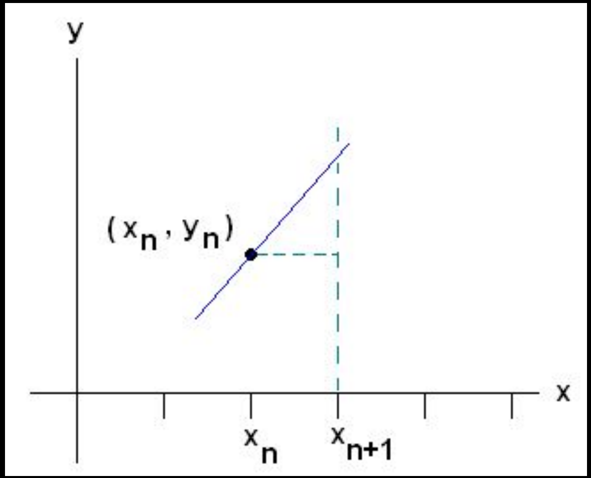
$$V = \frac{\mu_P^2}{2}\mathbf{A}^2 + \frac{\lambda_P}{4}\mathbf{A}^4$$



Numerical Procedure: Integrator

- The, in house developed, integrator consists on a parallelized adaptive step *(5)6-0* Runge-Kutta method



Light Rings
and
Timelike Circular Orbits

Geodesic motion

- The radial geodesic equation for a particle around a BS,

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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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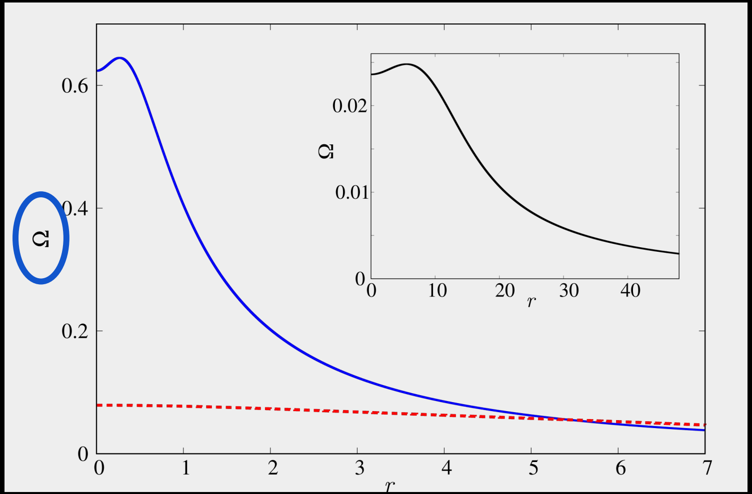

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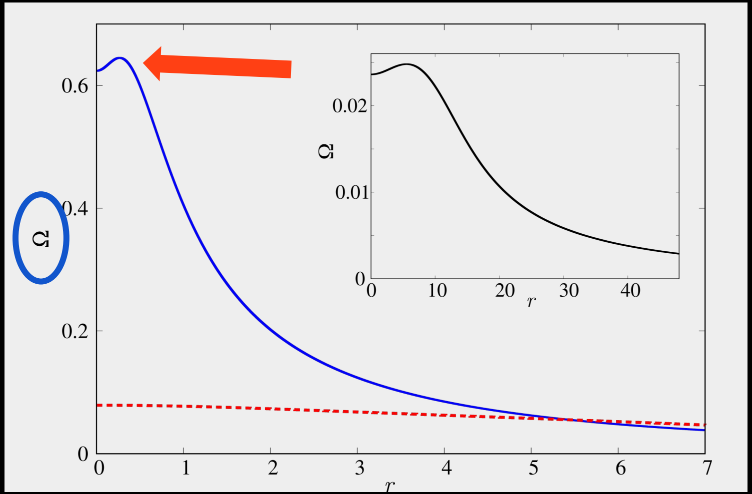

Geodesic motion: Keeping up

- Does it provide a similar scale, for a BS and a Schw. BH?

- Moving along the spiral, the ADM mass and frequency undergo oscillations
- The field amplitude at the origin, on the other hand, grows monotonically
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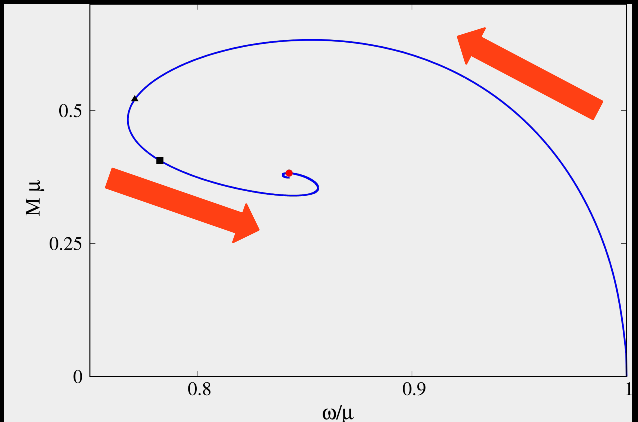

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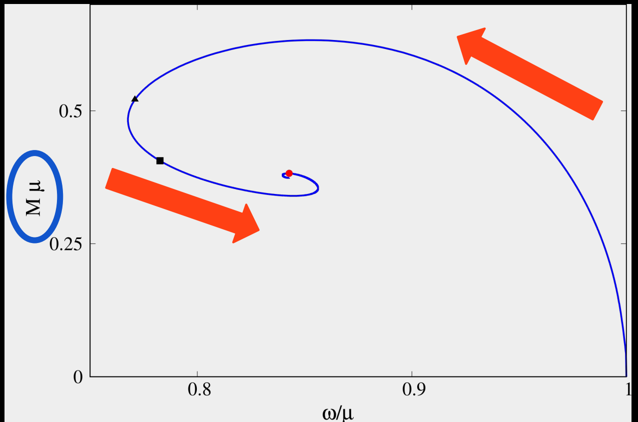

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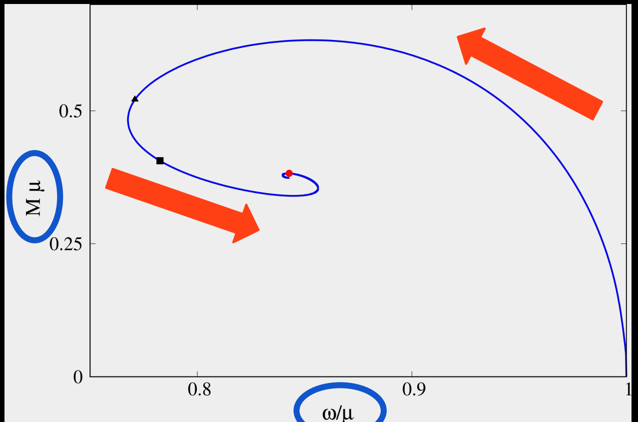

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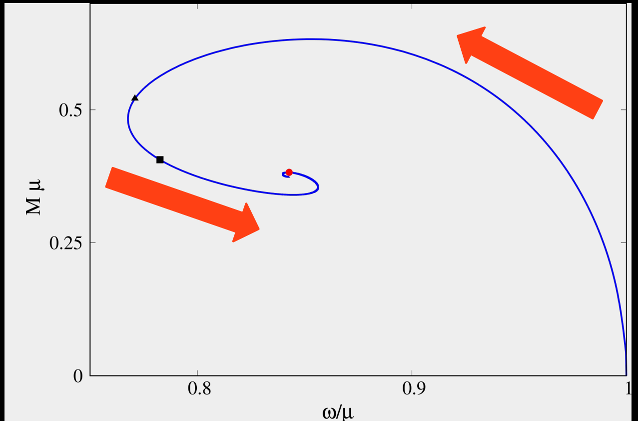


Geodesic motion: Keeping up

- Does it provide a similar scale, for a BS and a Schw. BH?

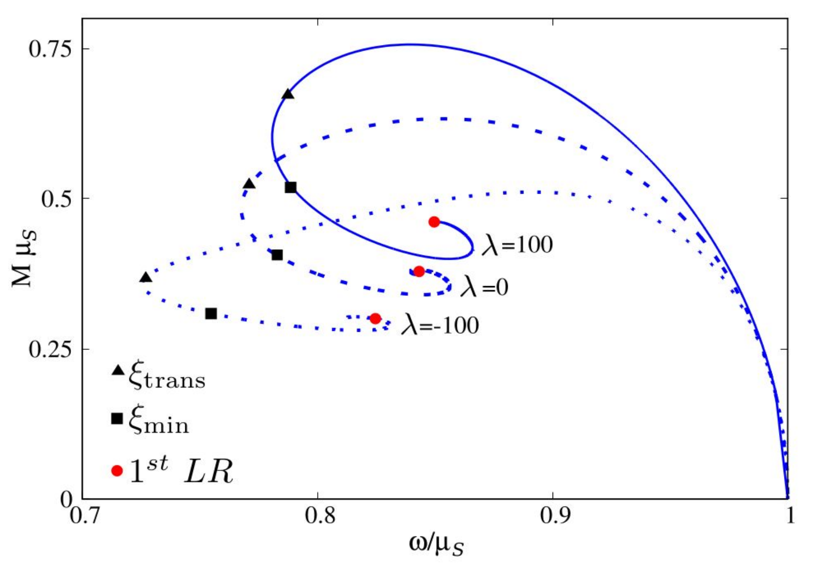
$$\xi \equiv \frac{R_{ISCO}}{R_{\Omega}}$$

- Moving along the spiral, the ADM mass and frequency undergo oscillations
- The field amplitude at the origin, on the other hand, grows monotonically
- To uniquely label the solutions, let us introduce

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

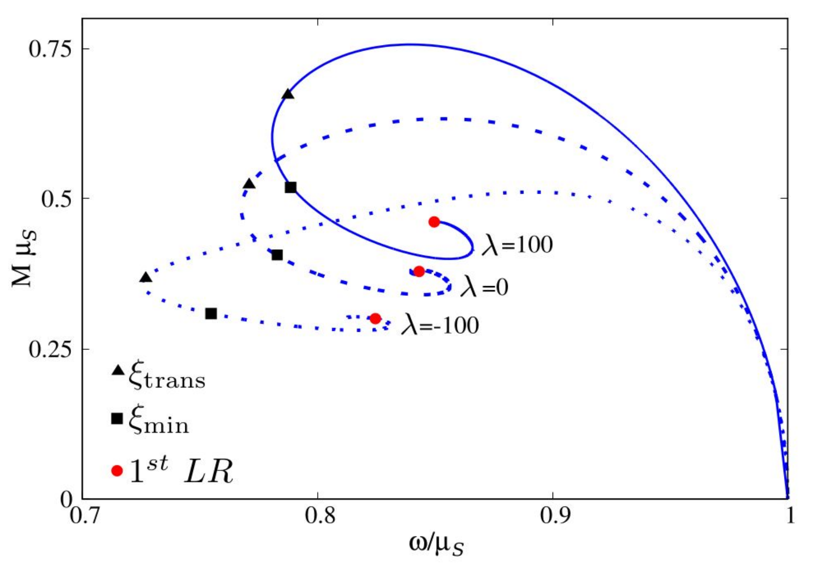
Numerical Results

Boson Stars: Polynomial Scalar



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

Boson Stars: Polynomial Scalar



There is no stable ultracompact Boson Star solution

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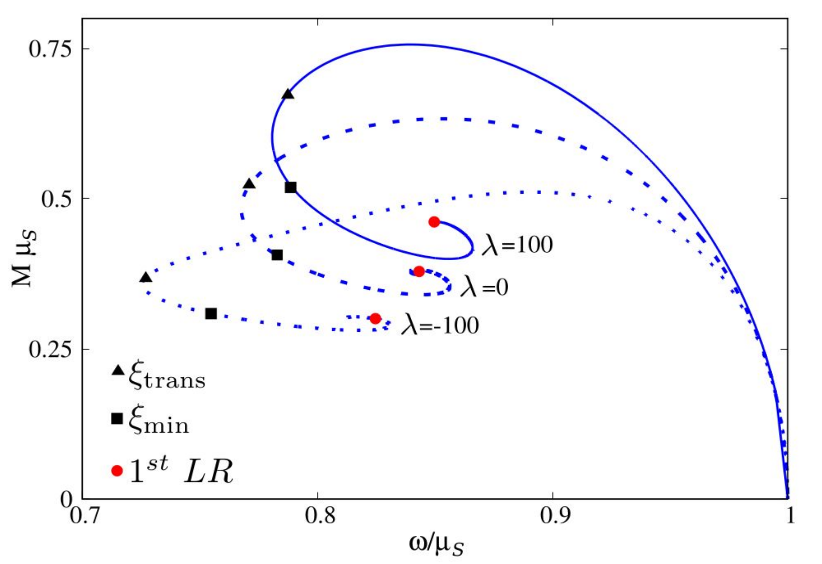
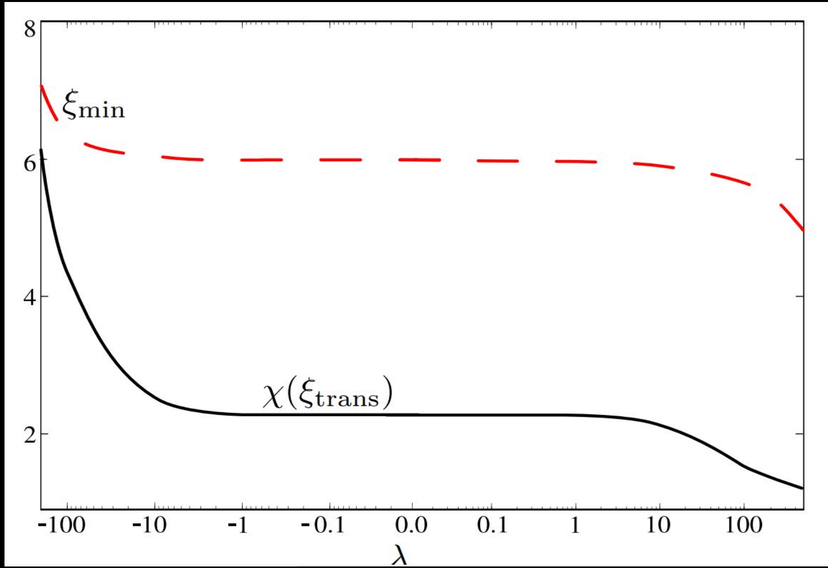
Boson Stars: Polynomial Scalar





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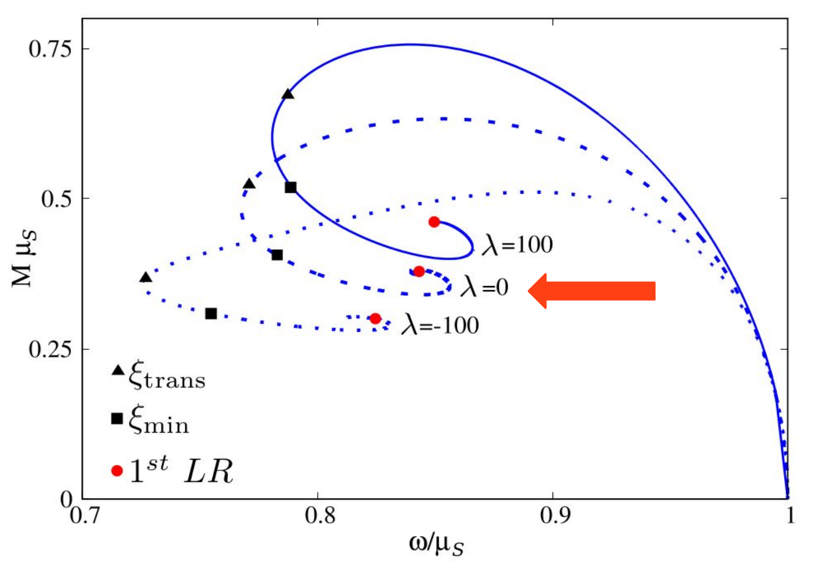

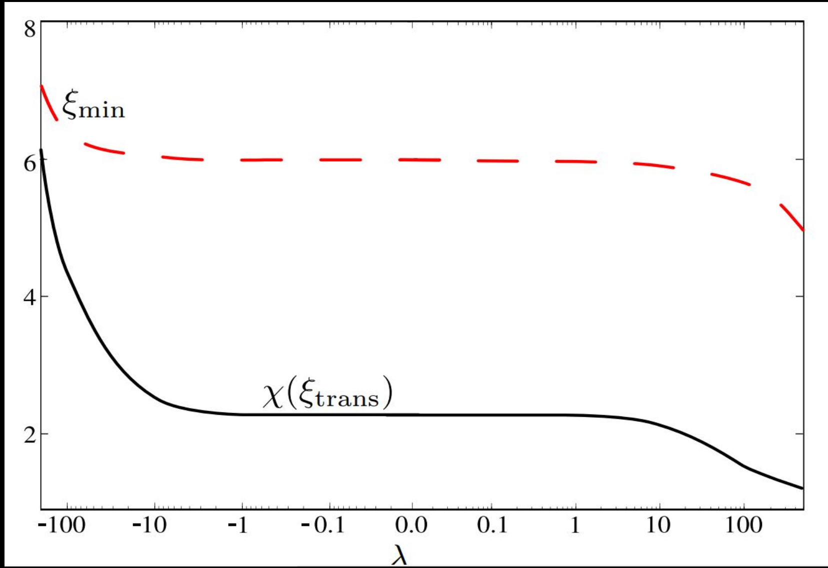

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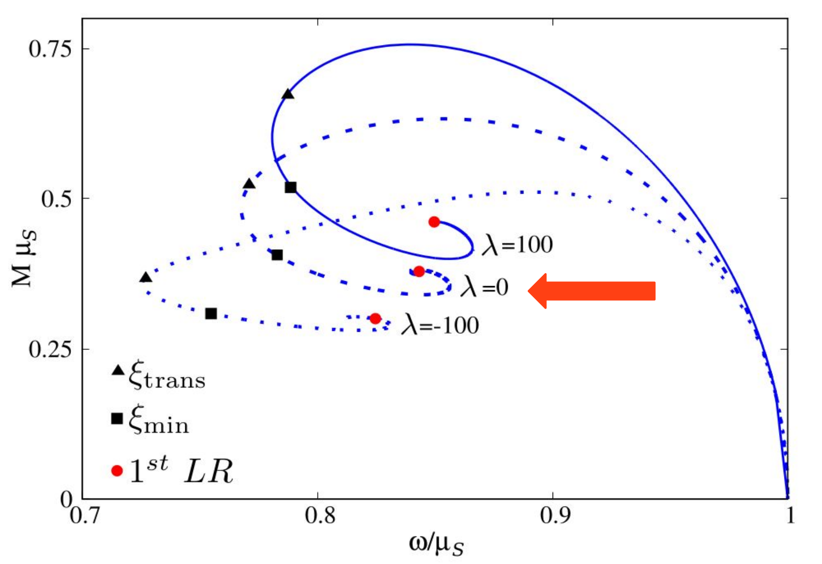

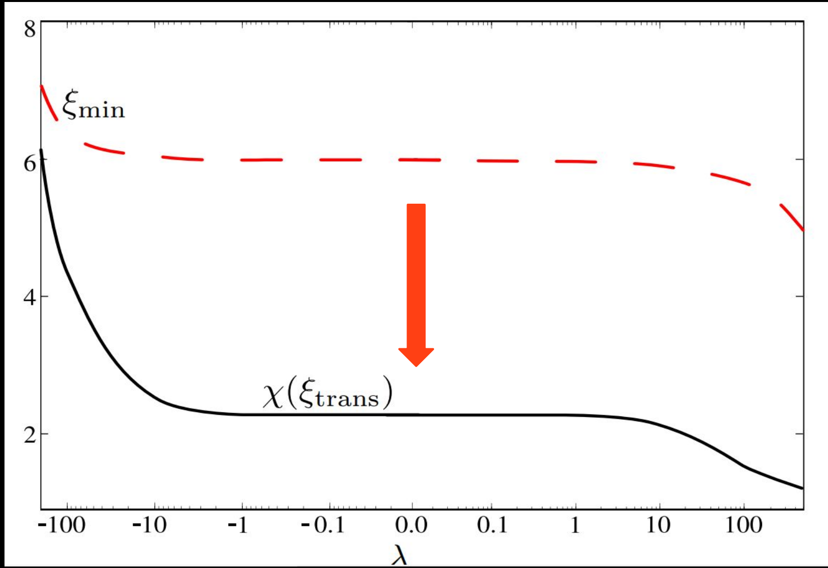

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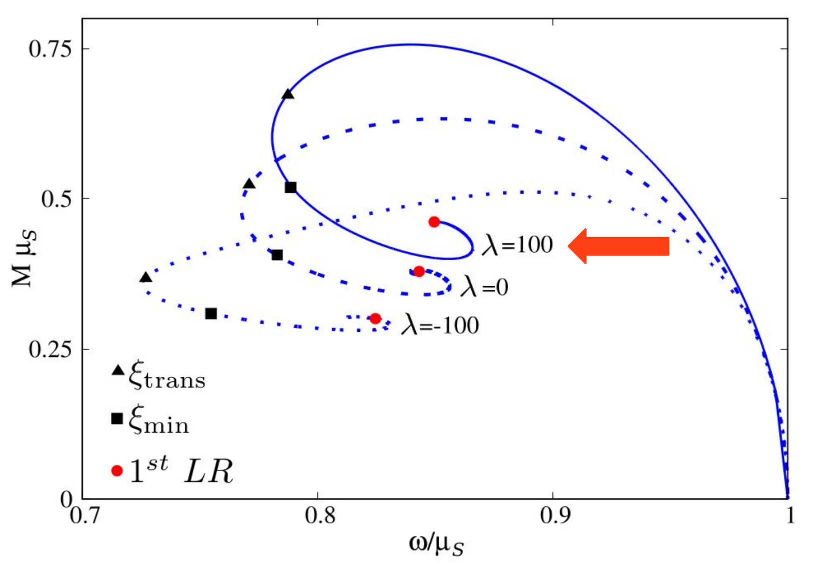

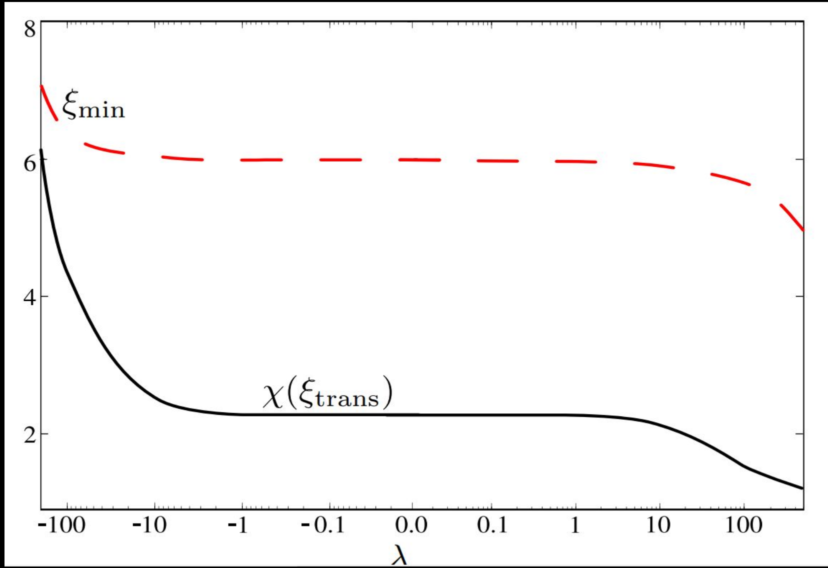

$$U_{\rm poly} = \mu_S^2 \Phi^2 + \lambda \Phi^4$$

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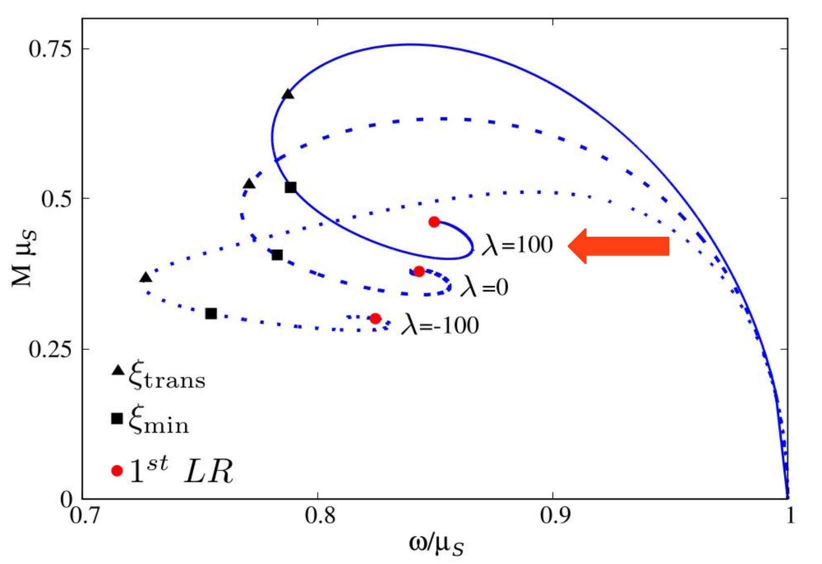

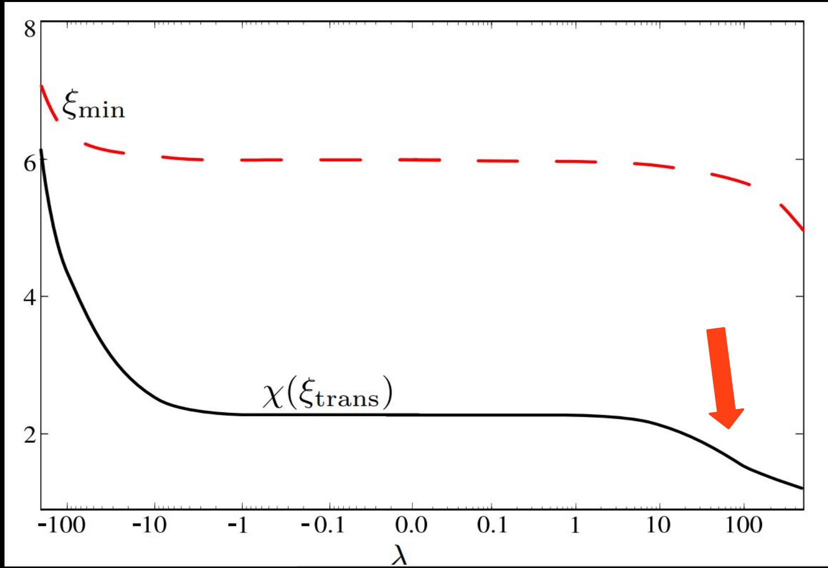

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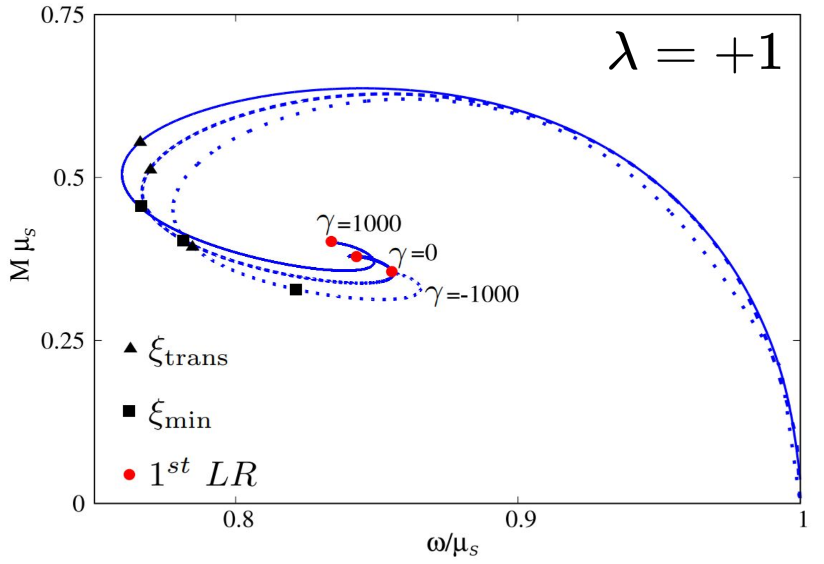

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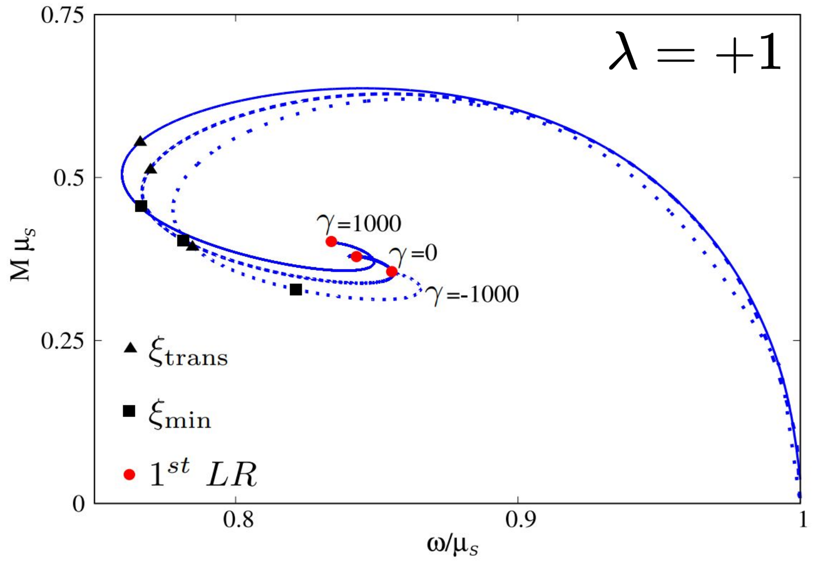

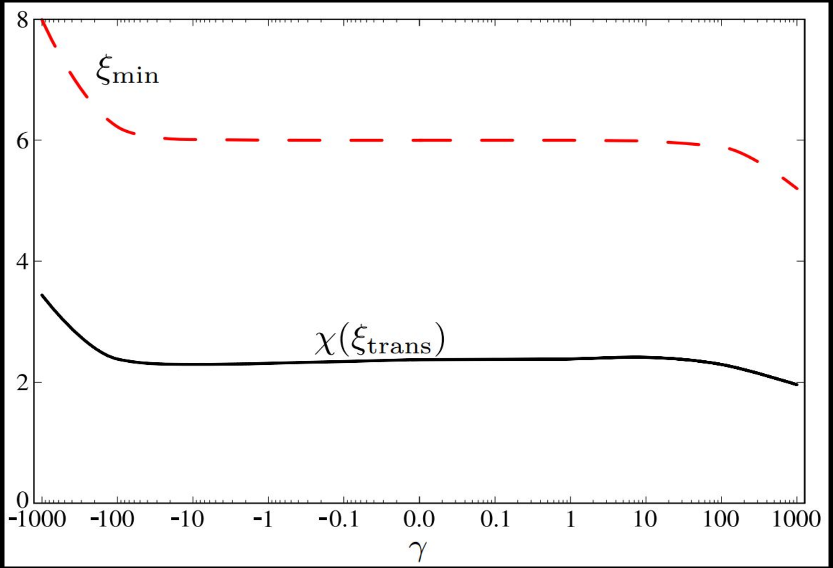

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Boson Stars: Polynomial Scalar

- This analysis and the one in the previous subsection, suggest that a simultaneous increase
- To test this hypothesis: $\lambda = 100$ and $\gamma = 1000$
- $\chi(\xi_{trans}) = 1.51$
- However R_Ω is still fairly below the ISCO radius of the comparable BH:
- $\xi_{min} = 5.09$

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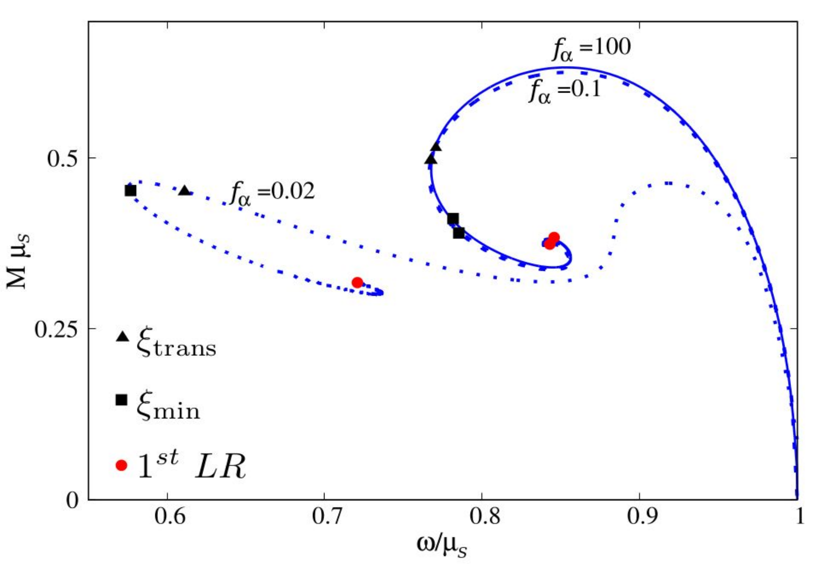
Boson Stars: Axion Scalar



$$U_{\text{axion}} = \frac{2\mu_S^2 f_\alpha^2}{\hbar B}\left[1 - \sqrt{1 - 4B\sin^2\left(\frac{\Phi\sqrt{\hbar}}{2f_\alpha}\right)}\,\right]$$

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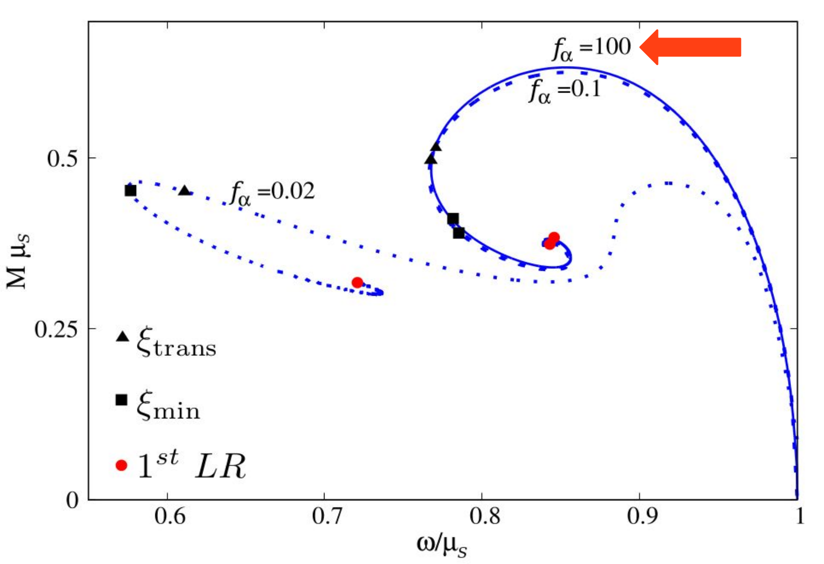

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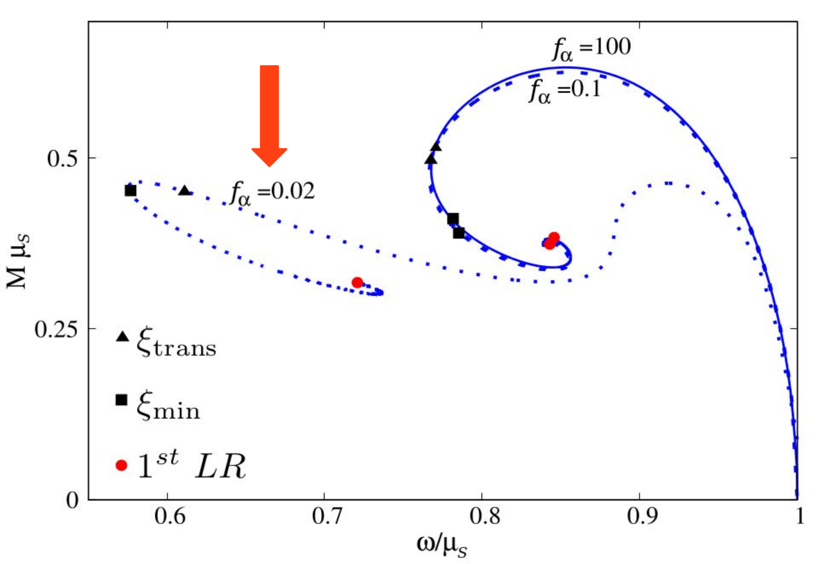

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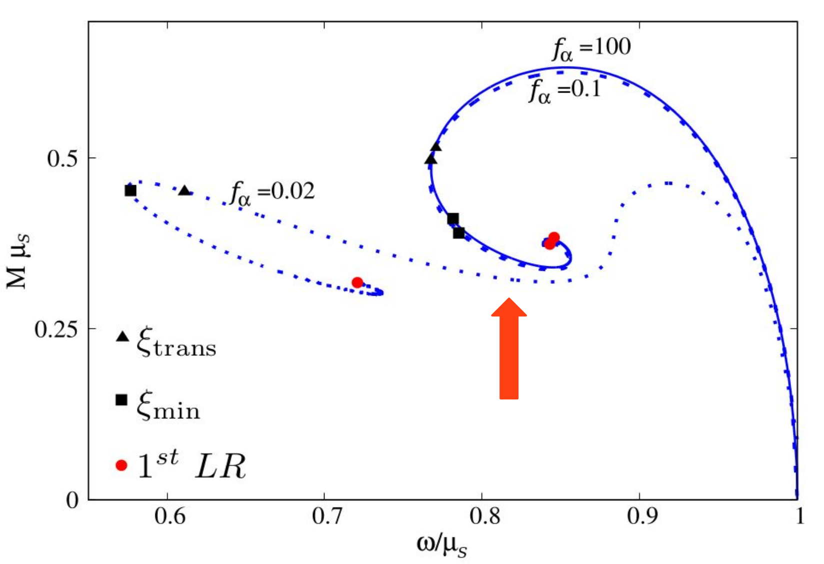

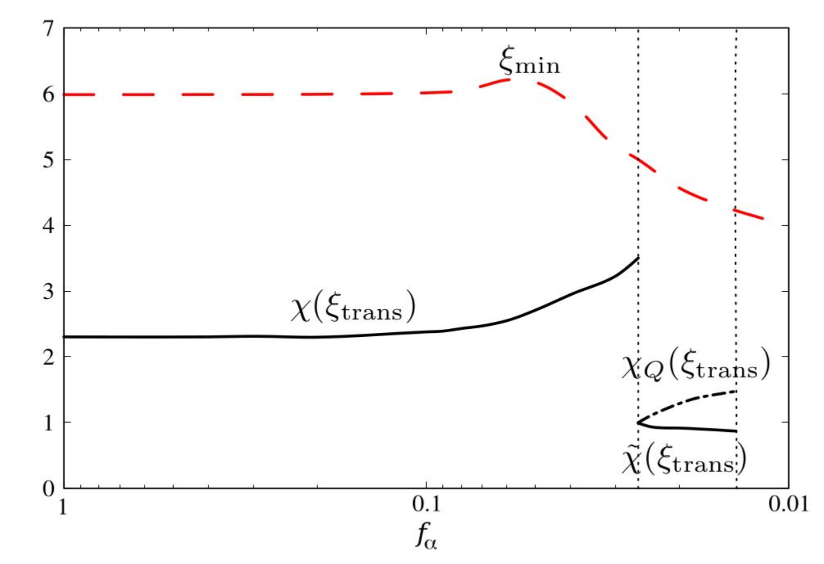

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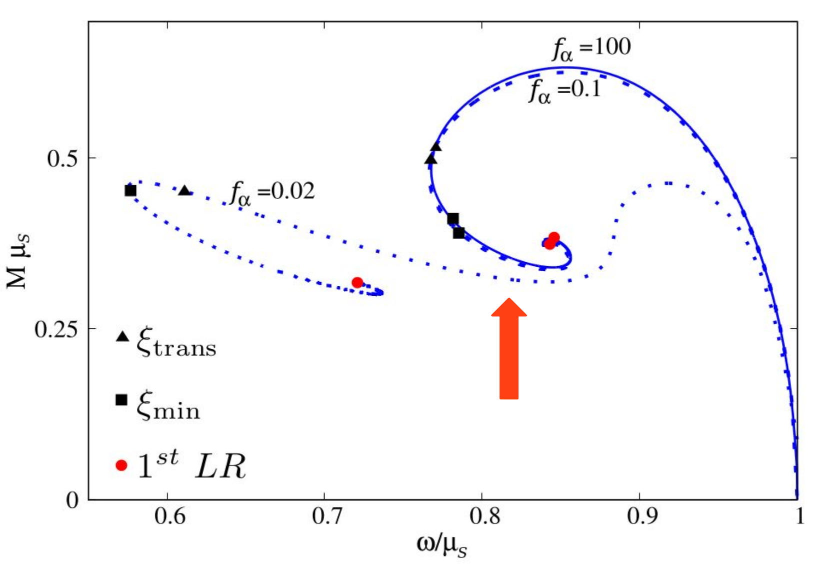
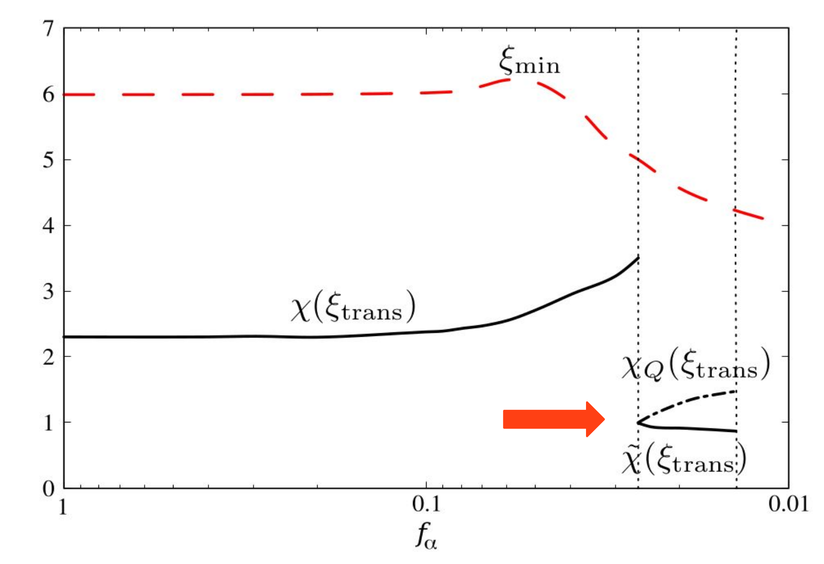
Boson Stars: Stability





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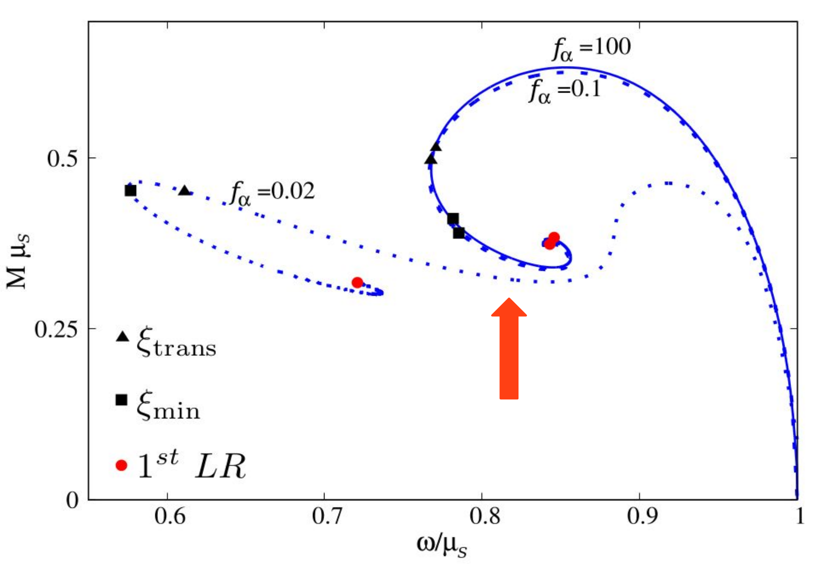

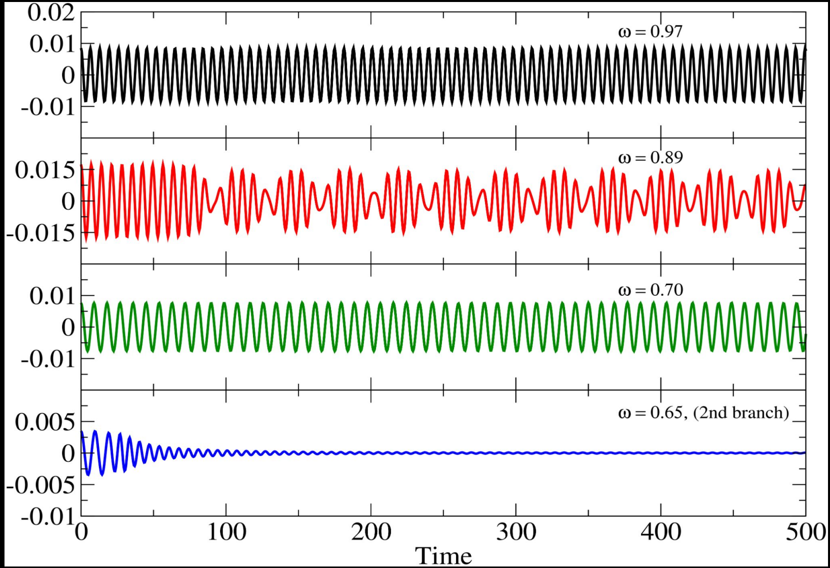

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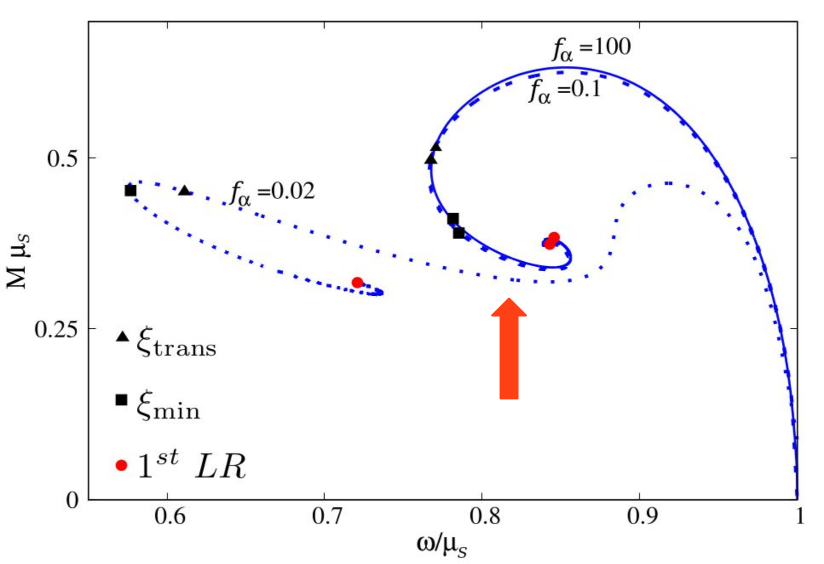

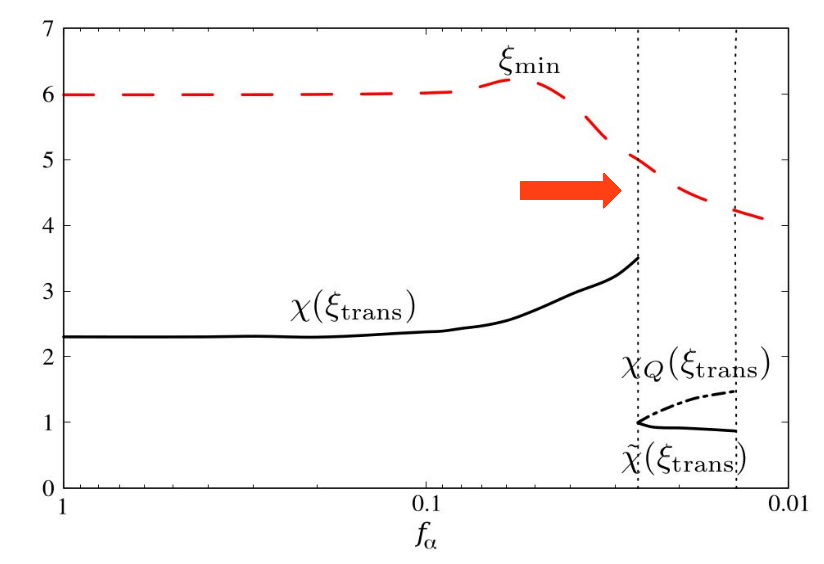

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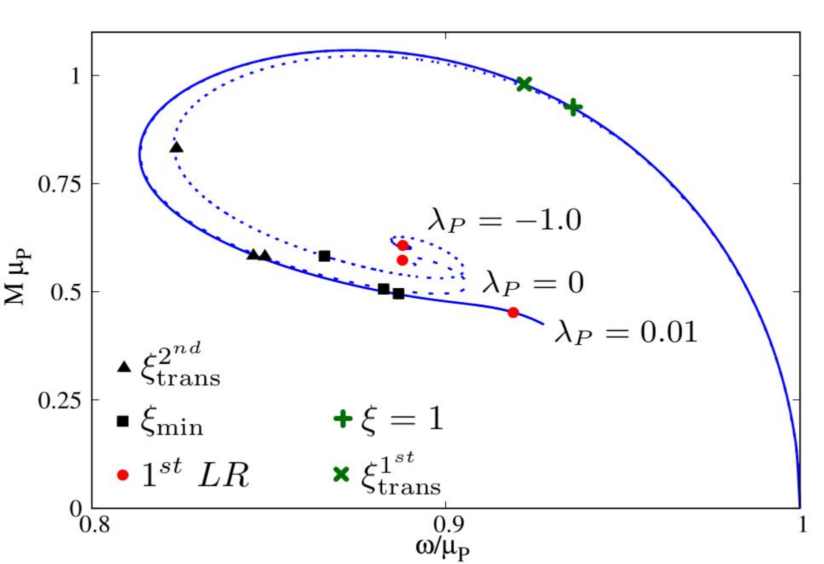
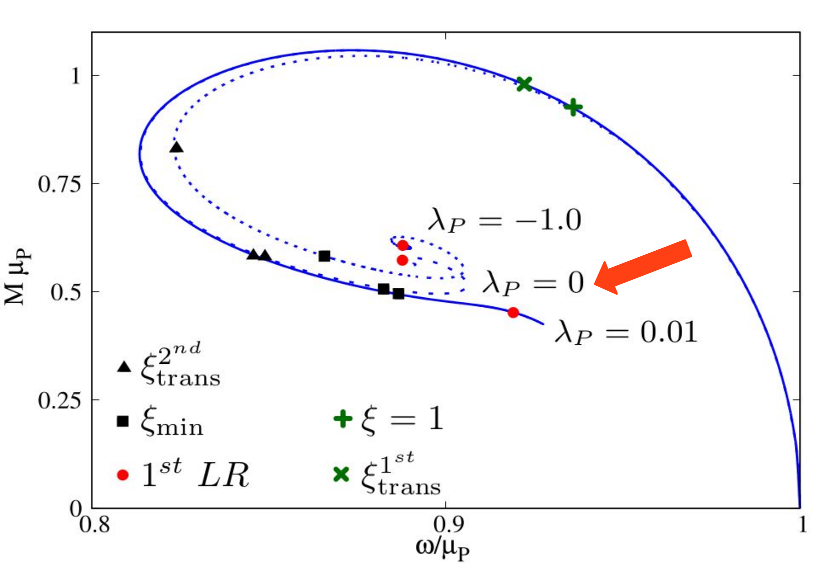
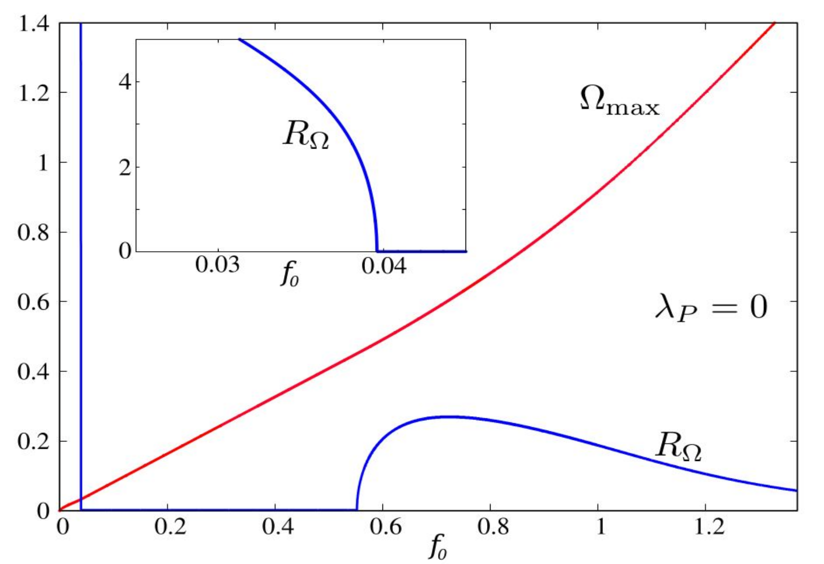
Boson Stars: Proca



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

Boson Stars: Proca





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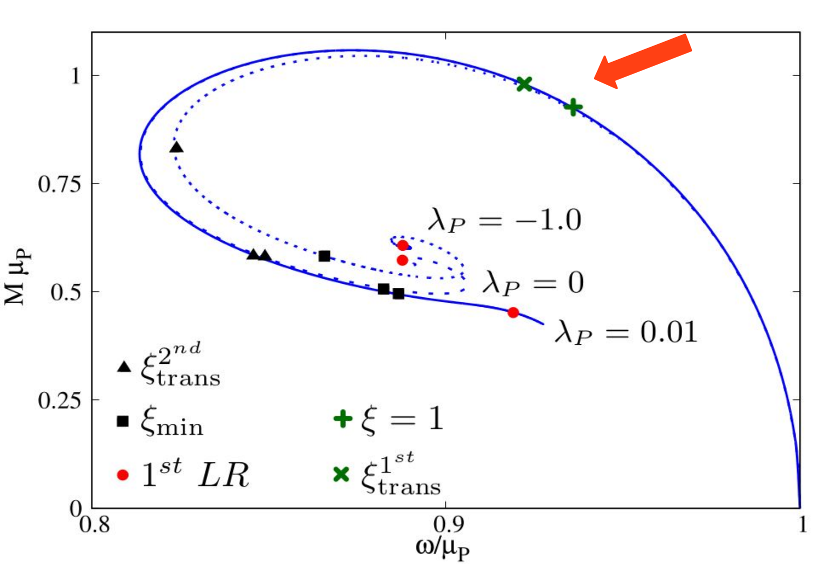

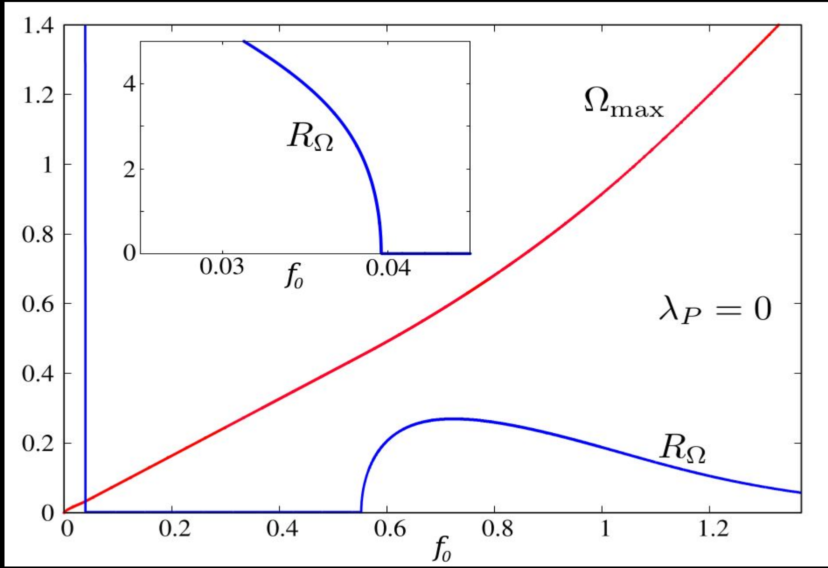

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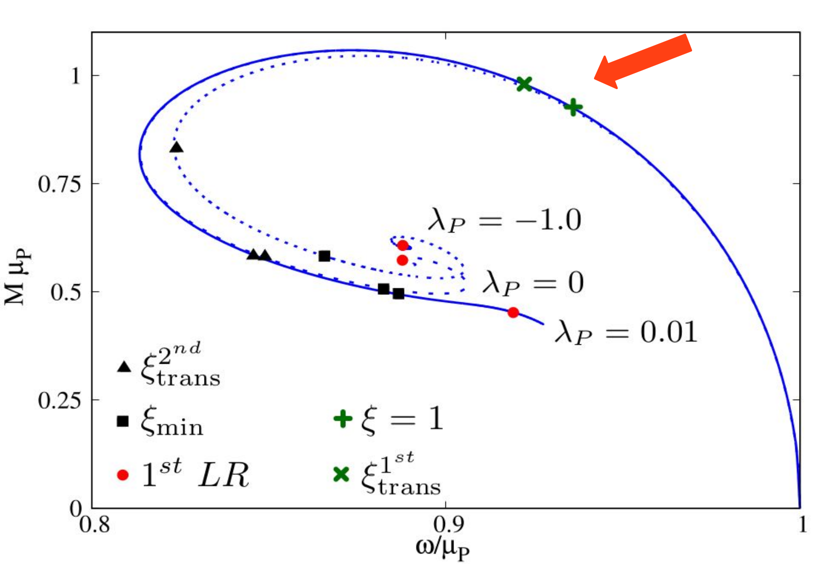

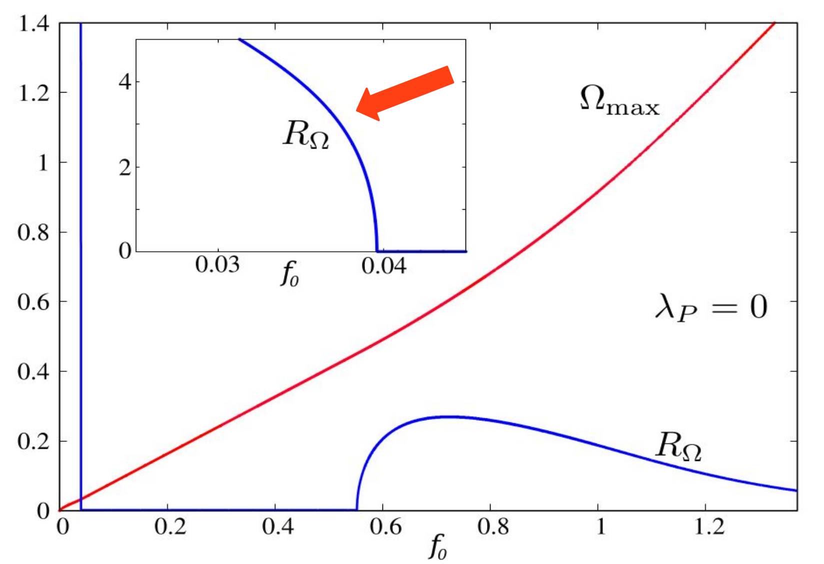

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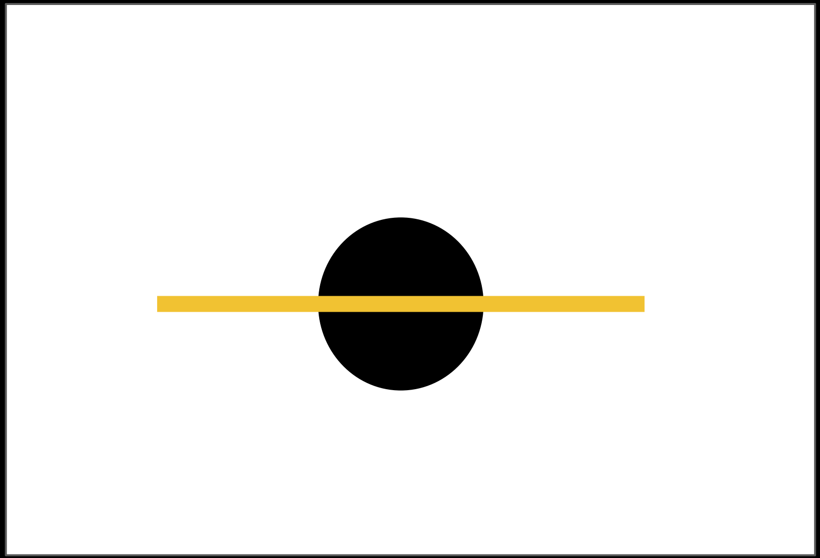
Shadow

Shadow: BH vs PS



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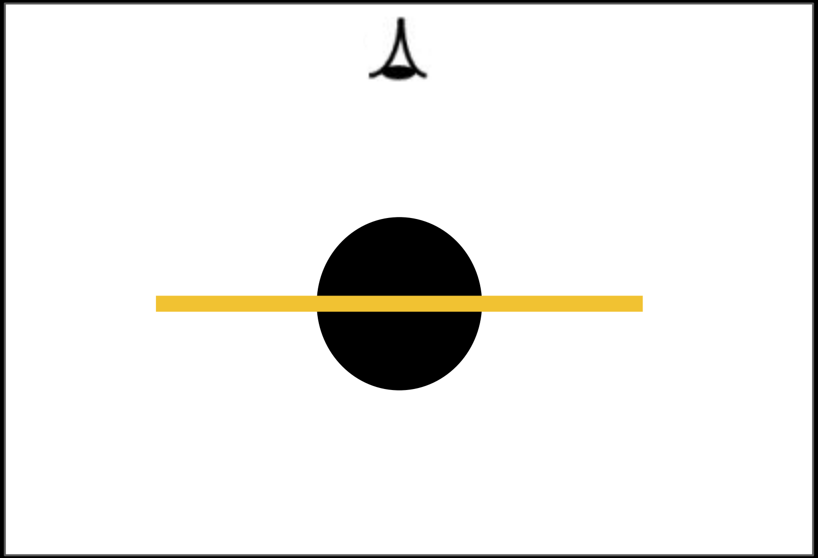

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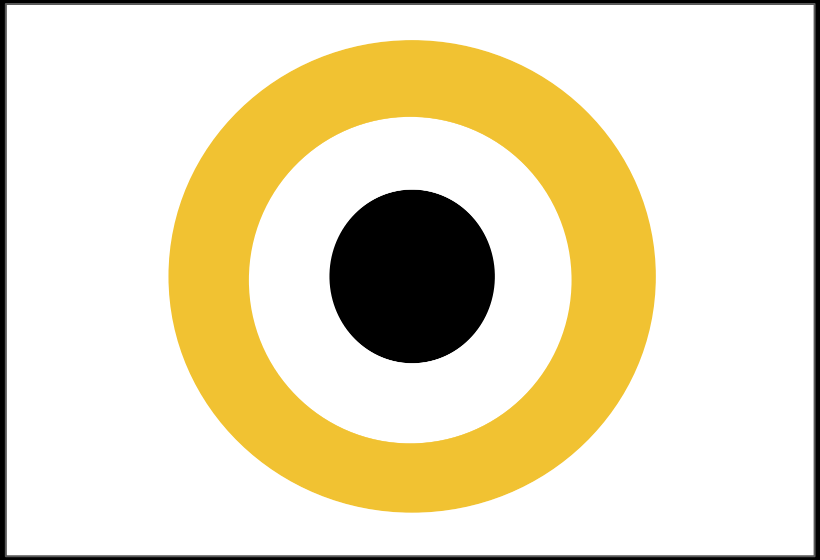

Shadow: BH vs PS

BH

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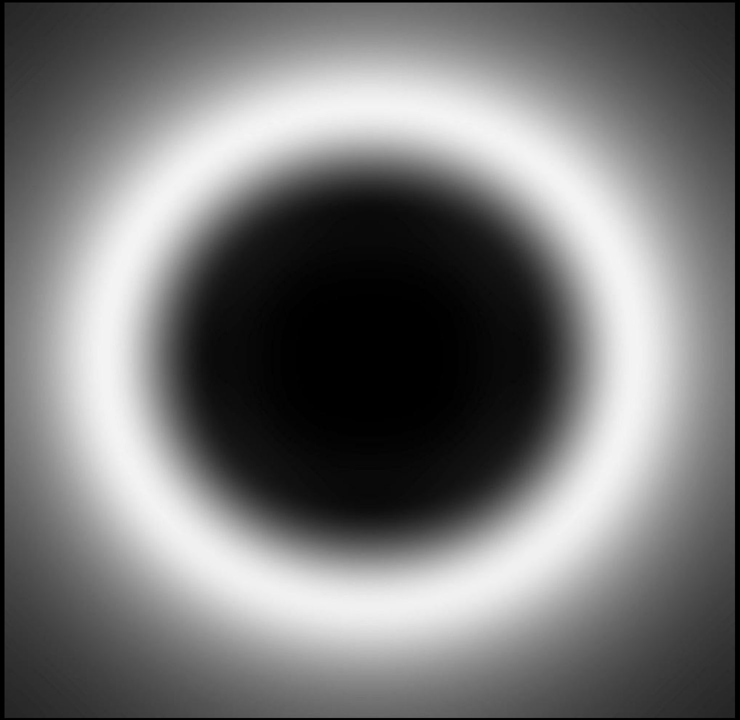
PS



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BH

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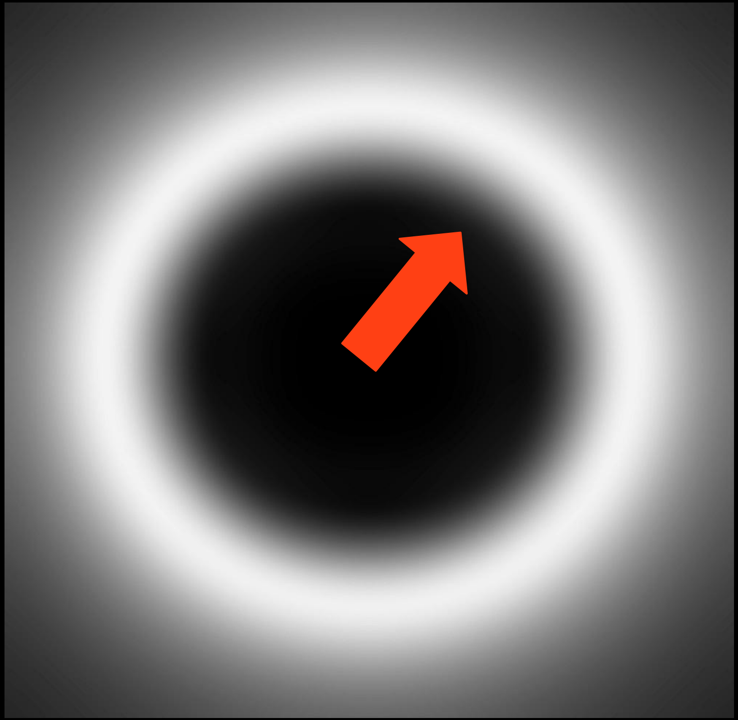

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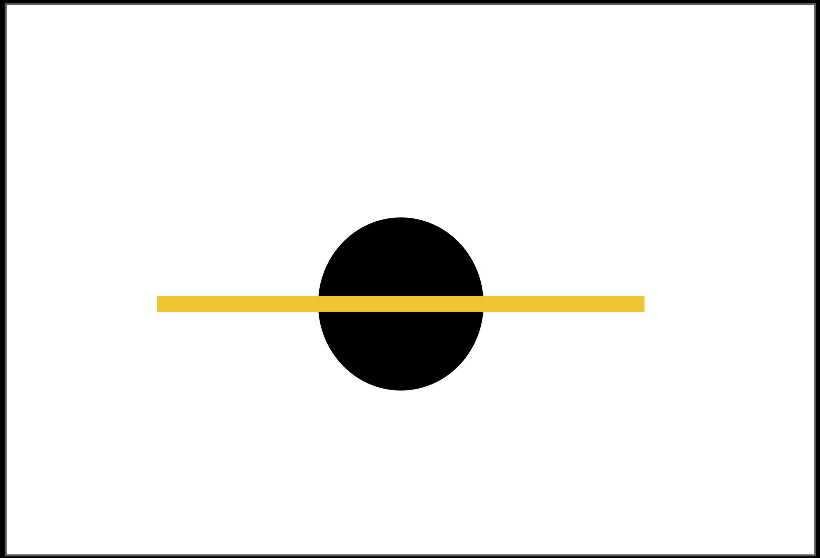

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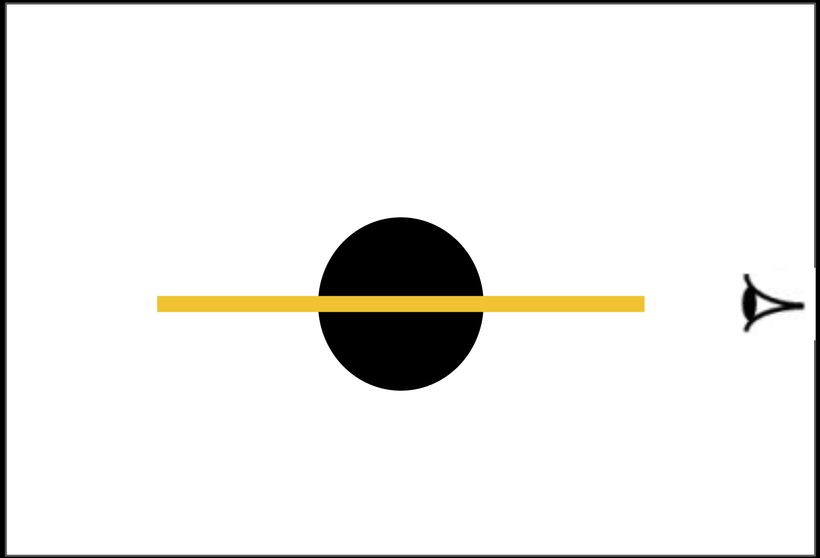

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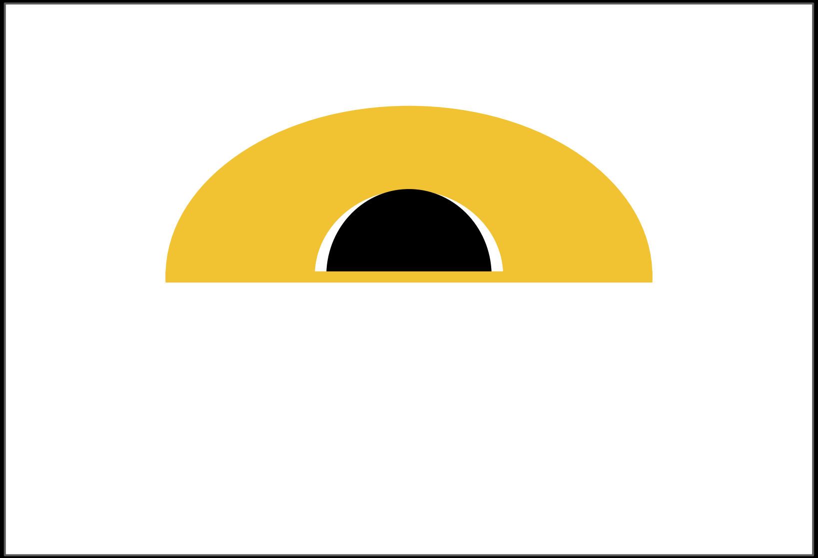

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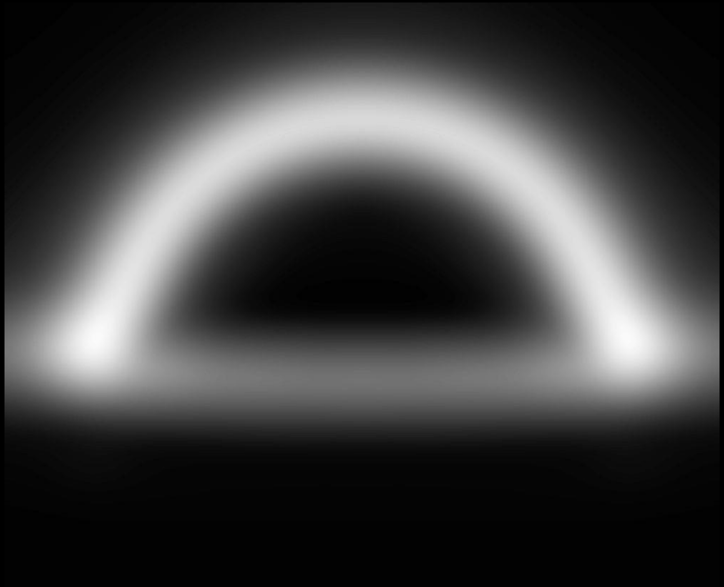

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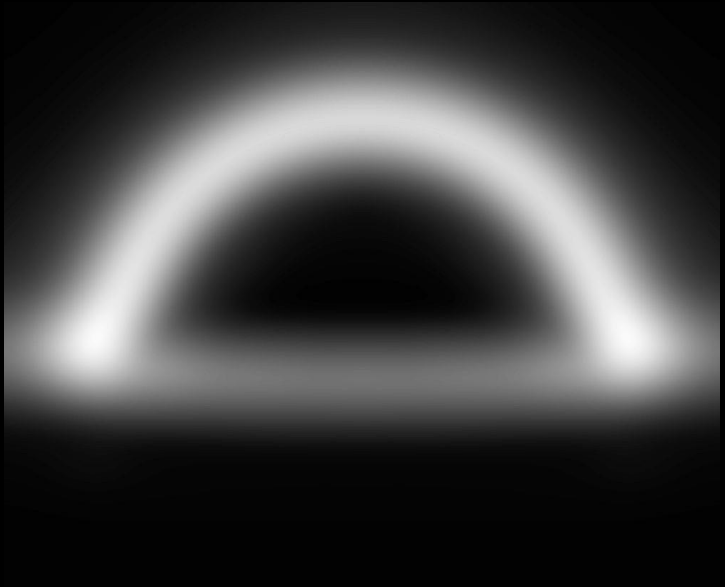
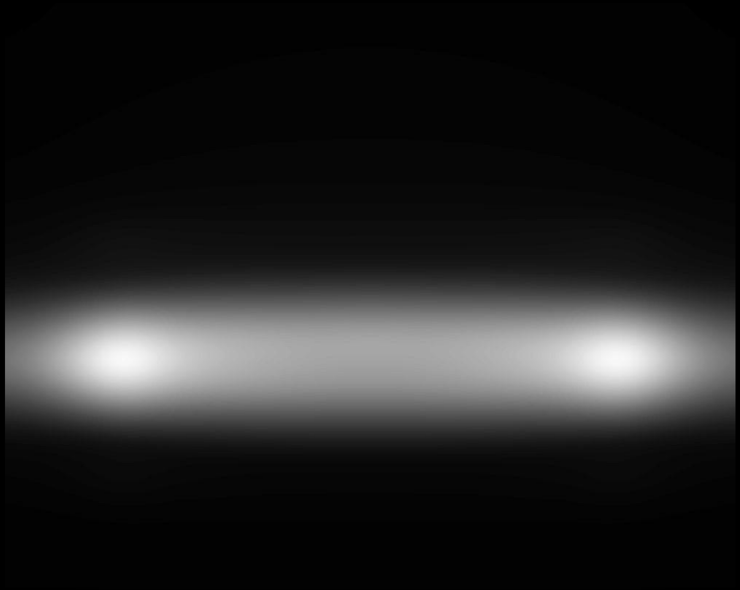


PS



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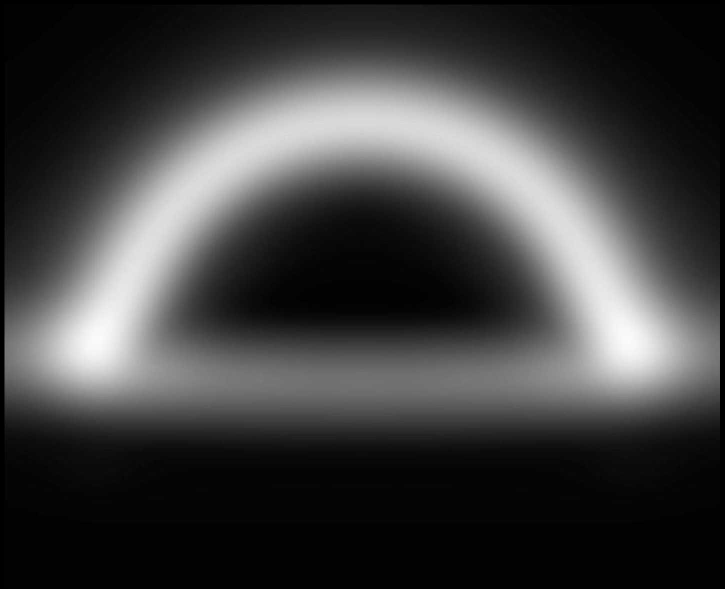
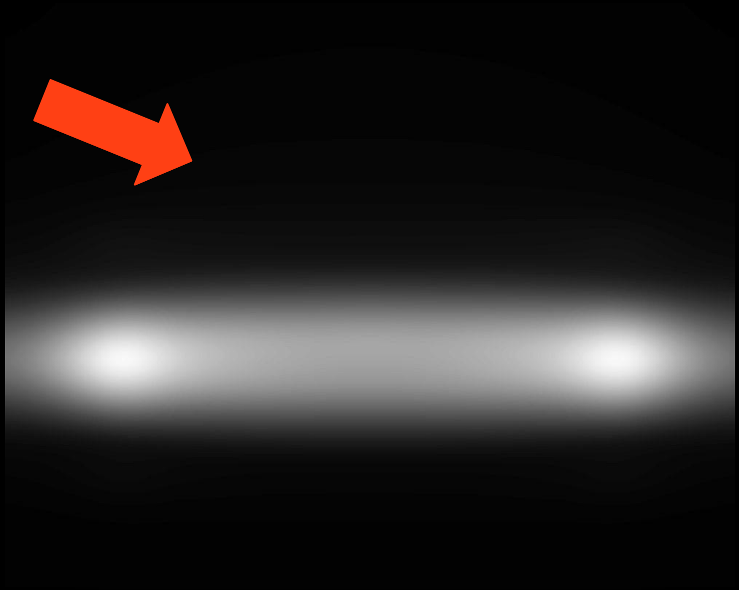


PS



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- In the case of spherically stable scalar BSs:
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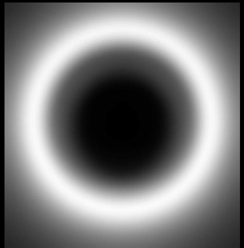
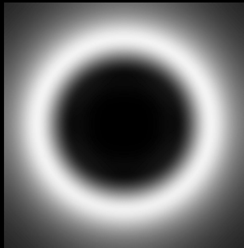
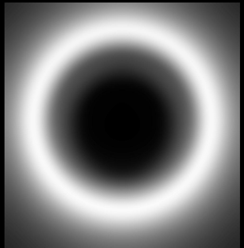
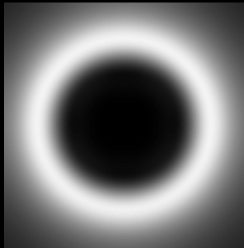




Conclusion

- Can a dynamically robust, horizonless object mimick a BH image?

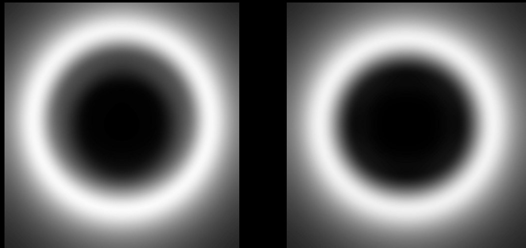




Conclusion

- Can a dynamically robust, horizonless object mimick a BH image?

Yes

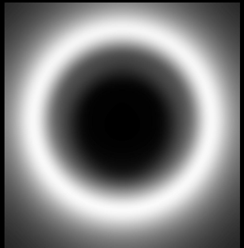


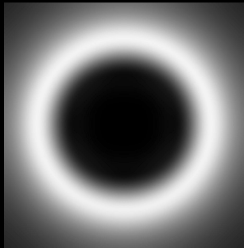
Conclusion

- Can a dynamically robust, horizonless object mimick a BH image?

Yes

But only under certain observational conditions





Conclusion

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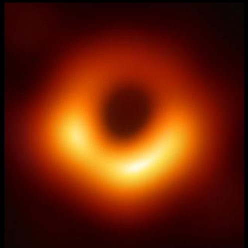

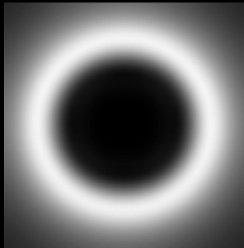

Thank You!

Obrigado!

The imitation game: Proca Stars that can mimic Schwarzschild shadow

doi.org/10.1088/1475-7516/2021/04/051

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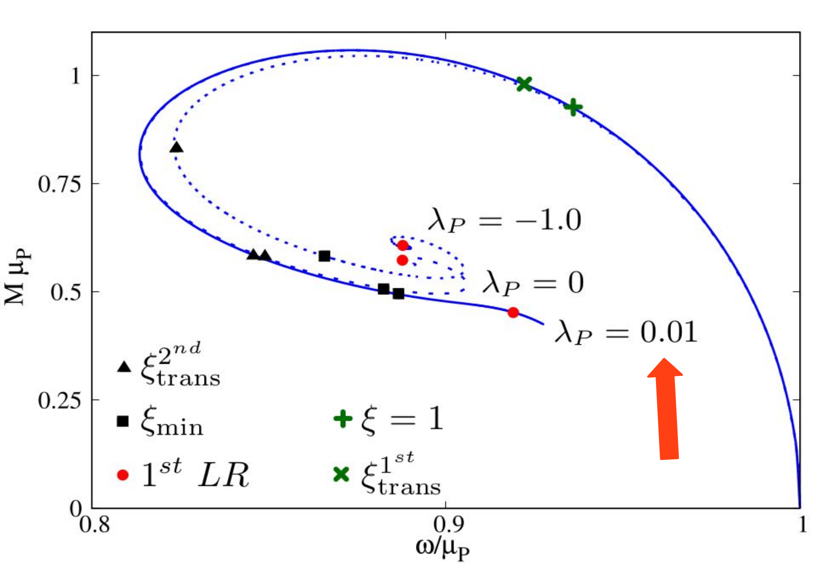
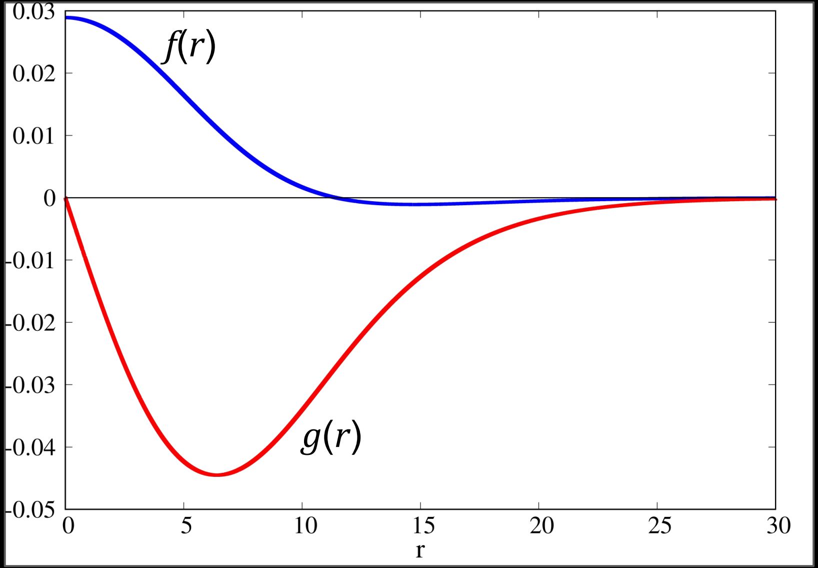
Proca Stars

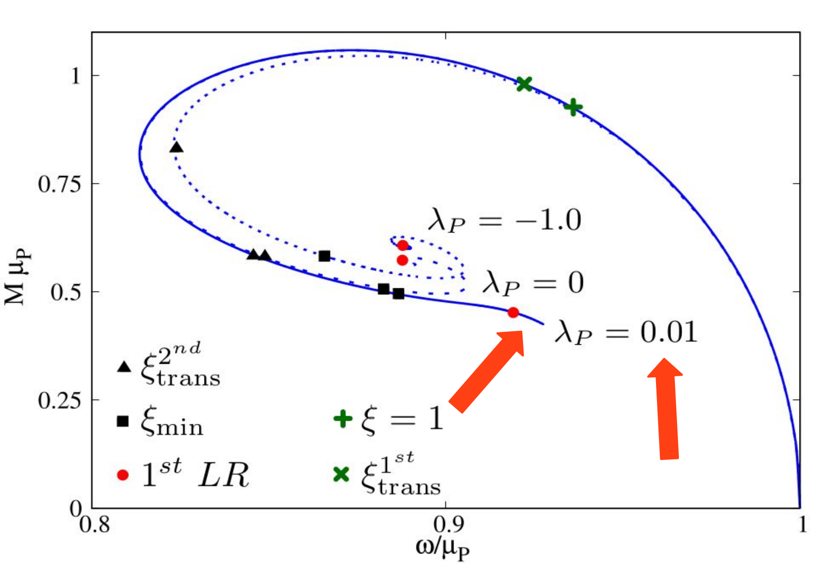
Boson Stars: Proca

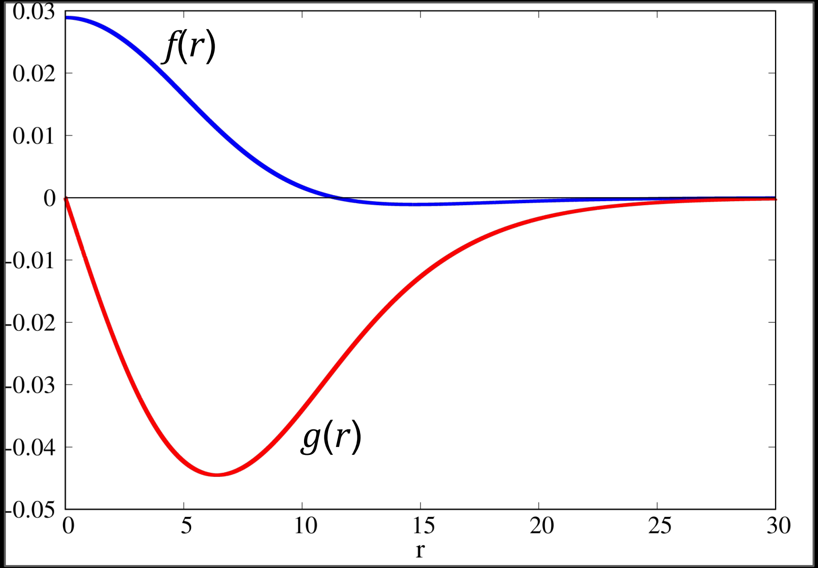




$$V = \frac{\mu_P^2}{2}\mathbf{A}^2 + \frac{\lambda_P}{4}\mathbf{A}^4$$

Boson Stars: Proca





$$V = \frac{\mu_P^2}{2}\mathbf{A}^{\ 2} + \frac{\lambda_P}{4}\mathbf{A}^{\ 4}$$