

Shadows of Kerr black holes with synchronized Proca hair

Ivo Sengo

December 20th, 2022 (XV Black Holes Workshop)

In collaboration with: Carlos Herdeiro, Pedro Cunha and Eugen Radu (U. Aveiro)

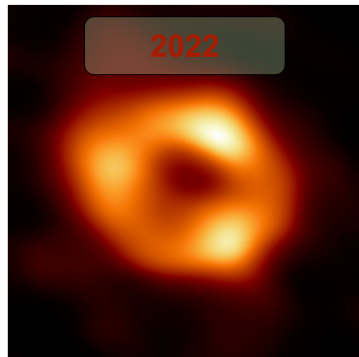
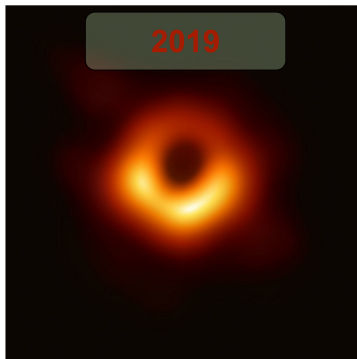
ArXiv: [2209.06237](https://arxiv.org/abs/2209.06237)

Gr@v

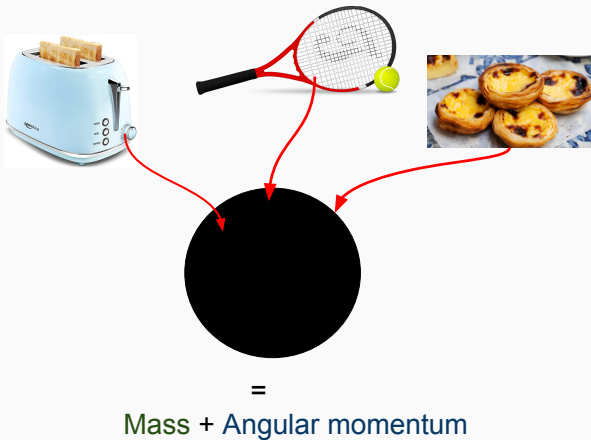
FCT
Fundação
para a Ciência
e a Tecnologia



The beginning of a new era



The Kerr hypothesis



Hairy black hole solutions

Mass + Angular momentum +



???

Hairy black hole solutions can be obtained by minimally coupling gravity to a (time dependent) bosonic field. Like, for instance, **scalar fields**[1403.2757]:

Hairy black hole solutions

Mass + Angular momentum +



???

Hairy black hole solutions can be obtained by minimally coupling gravity to a (time dependent) bosonic field. Like, for instance, **scalar fields**[1403.2757]:

$$S = \int d^4x \sqrt{-g} \left(\frac{R}{16\pi} - \nabla_\mu \phi \nabla^\mu \phi^* - \mu^2 \phi^* \phi \right) \quad (1)$$

Proca hair – a viable alternative

Mass + Angular momentum +



???

We will focus on the **Proca model** [2004.09536]:

Proca hair – a viable alternative

Mass + Angular momentum +

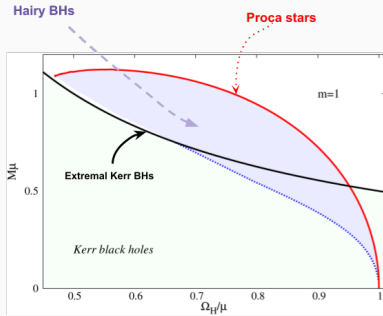


???

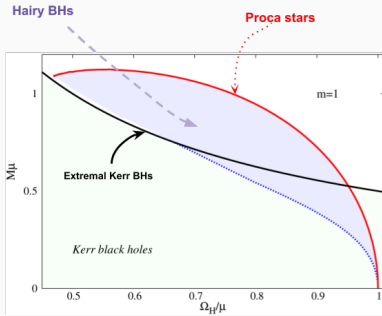
We will focus on the Proca model [2004.09536]:

$$S = \int d^4x \sqrt{-g} \left(\frac{R}{16\pi} - \frac{1}{4} F_{\alpha\beta} \bar{F}^{\alpha\beta} - \frac{1}{2} \mu^2 A_\alpha \bar{A}^\alpha \right) \quad (2)$$

KBHsPH domain of existence

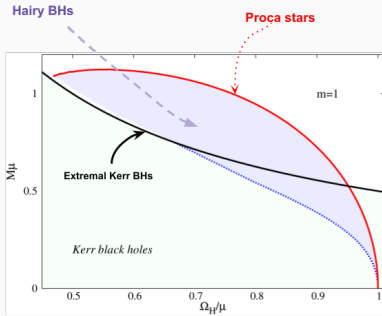


KBHsPH domain of existence



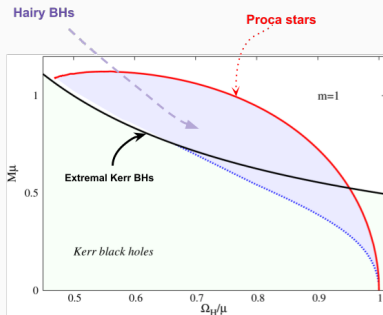
- Proca stars can mimic the shadow of BHs [2102.01703]

KBHsPH domain of existence



- Proca stars can mimic the shadow of BHs [2102.01703]
- Proca stars, unlike scalar boson stars, are dynamically stable [1907.12565]

KBHsPH domain of existence



- Proca stars can mimic the shadow of BHs [2102.01703]
- Proca stars, unlike scalar boson stars, are dynamically stable [1907.12565]
- Proca stars are consistent with some GW events [2009.05376]

The ray-tracing setup

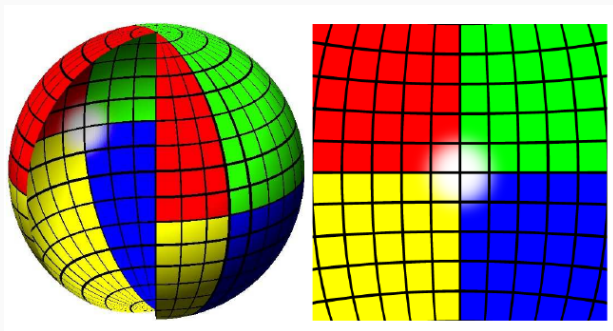
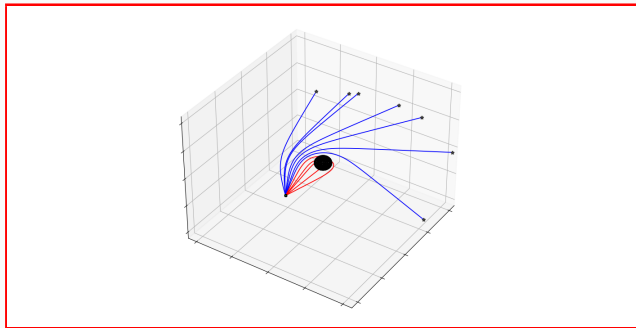
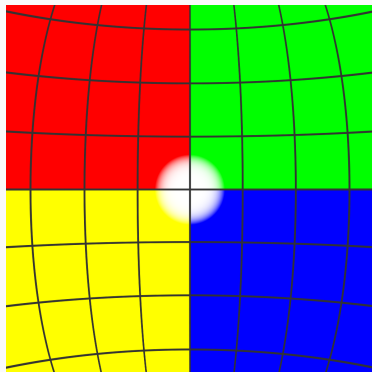


Figure 1: Setup as in [arXiv:1410.7775](https://arxiv.org/abs/1410.7775)

Drawing black hole images on a computer

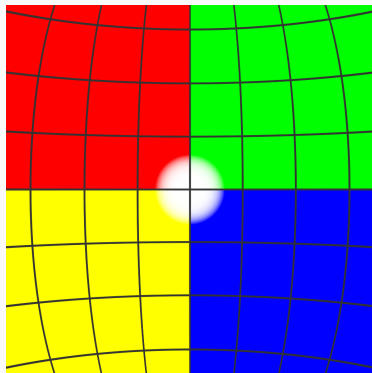


Black hole images

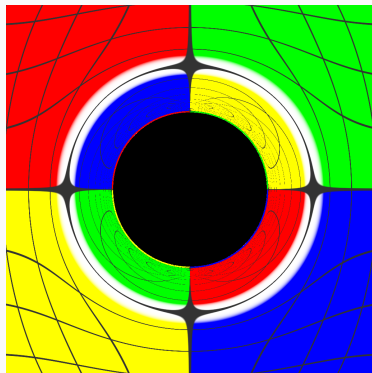


(a) without black hole

Black hole images

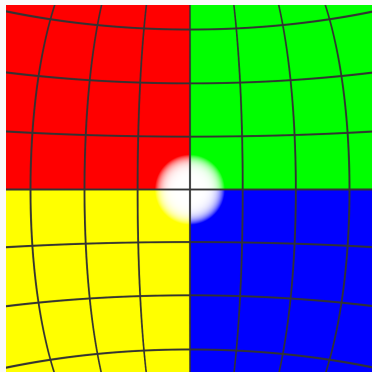


(a) without black hole

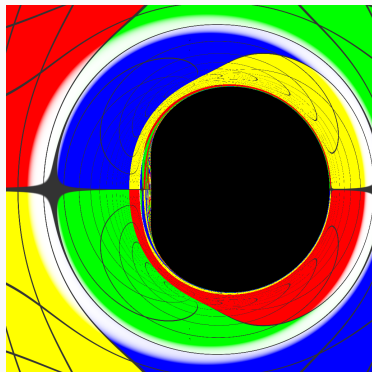


(b) with black hole (Schwarzschild)

Black hole images

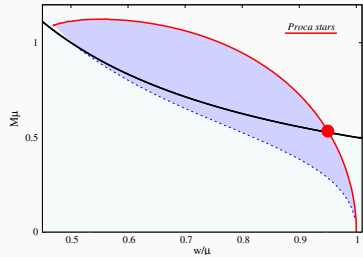
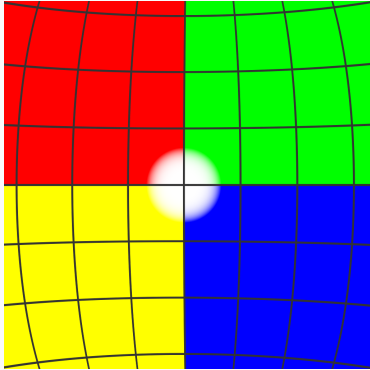


(a) without black hole

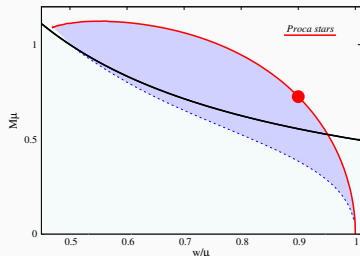
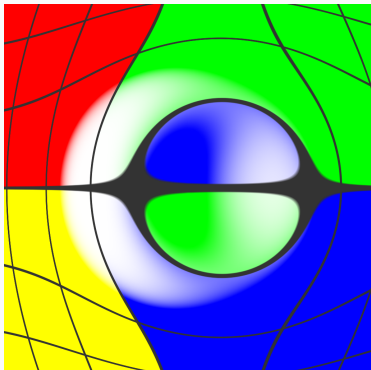


(b) with black hole (extremal Kerr)

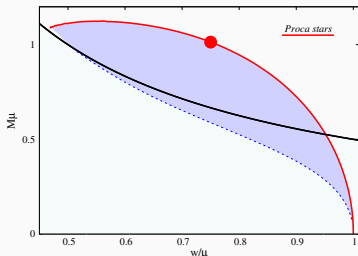
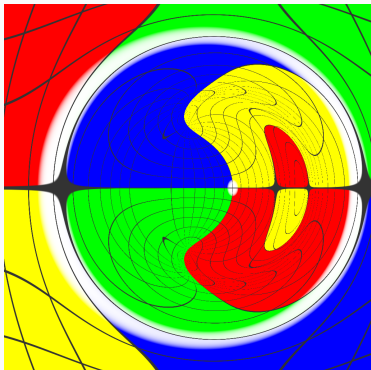
Lensing by Proca stars



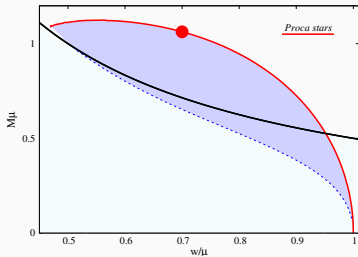
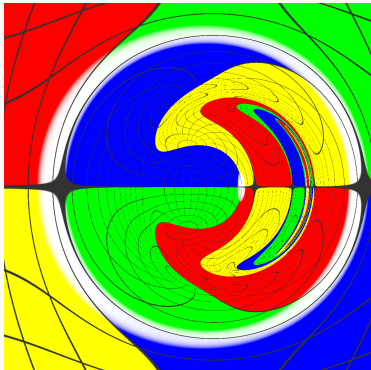
Lensing by Proca stars: Einstein ring



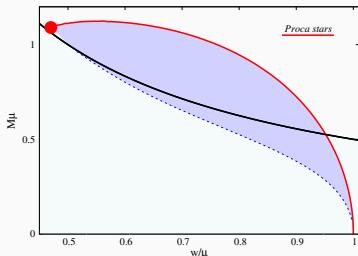
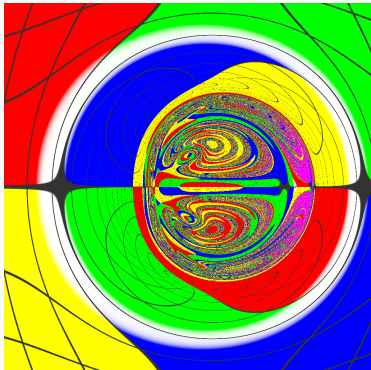
Lensing by Proca stars: Multiple Einstein rings



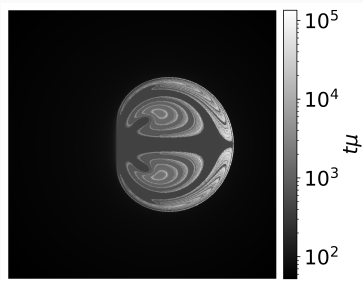
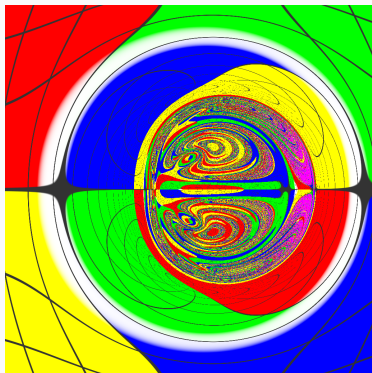
Lensing by Proca stars: light rings



Lensing by Proca stars: chaos

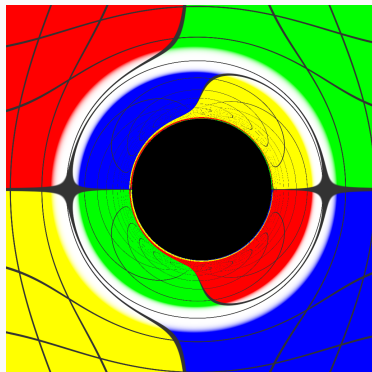


Lensing by Proca stars: chaos

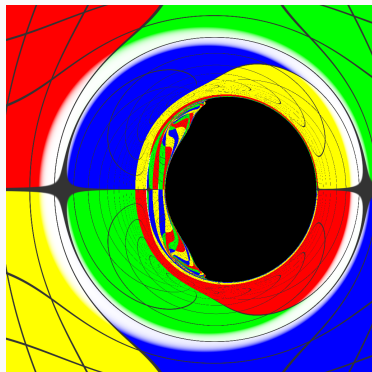


(For more about chaotic lensing: [1609.01340](#))

Lensing by Kerr BHs with Proca hair

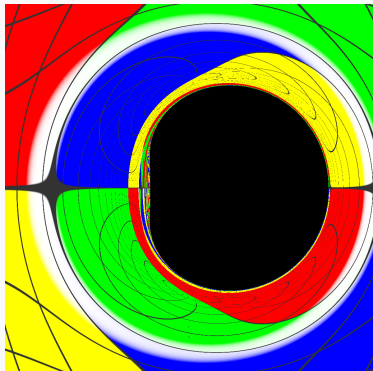


(a) small amount of hair



(b) large amount of hair

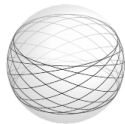
Kerr spherical photon orbits



(a)



(b)



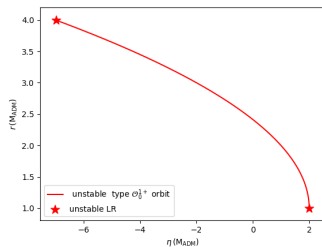
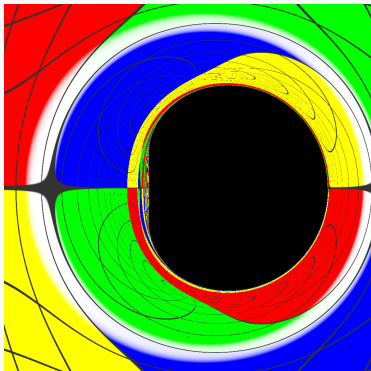
(c)



(d)

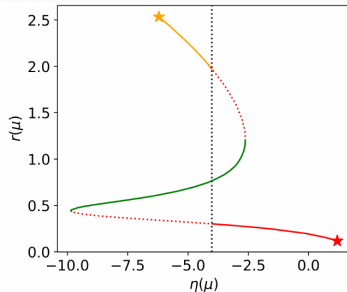
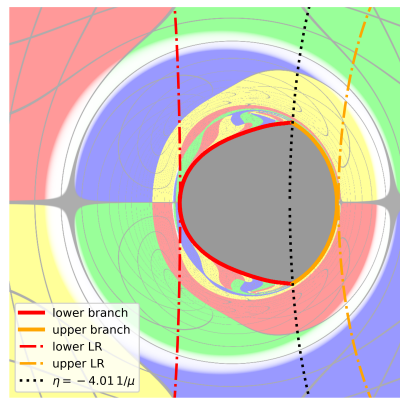
(a) arXiv:2007.04022

Kerr spherical photon orbits

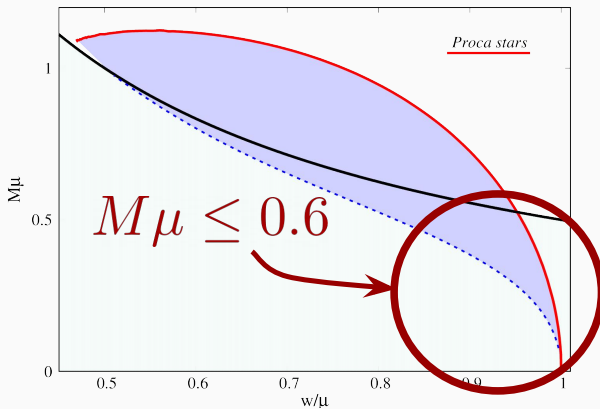


Fundamental photon orbits

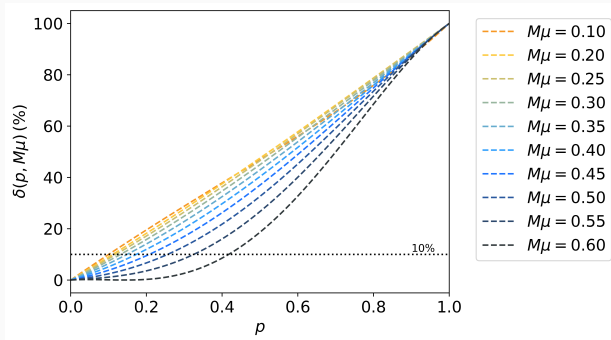
In coordinates adapted to stationarity and axi-symmetry, we can define these FPOs simply as geodesics that are periodic in (r, θ) space[1705.05461].



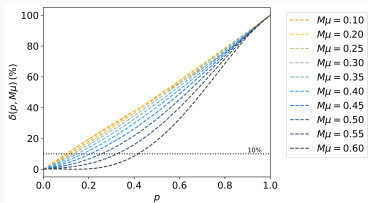
Astrophysically viable region



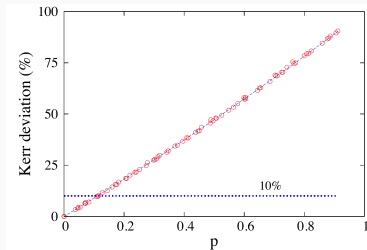
What can we learn from EHT



What can we learn from EHT

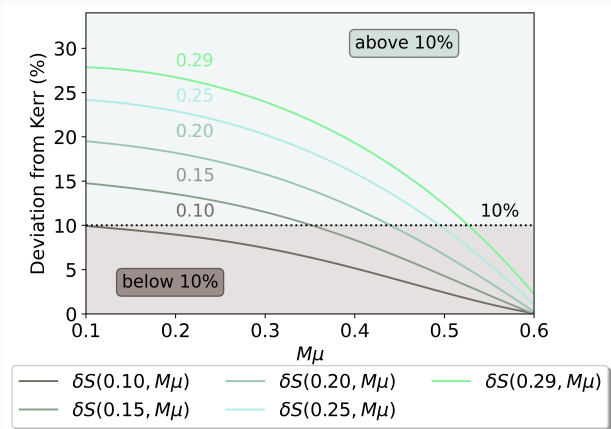


(a) Proca case

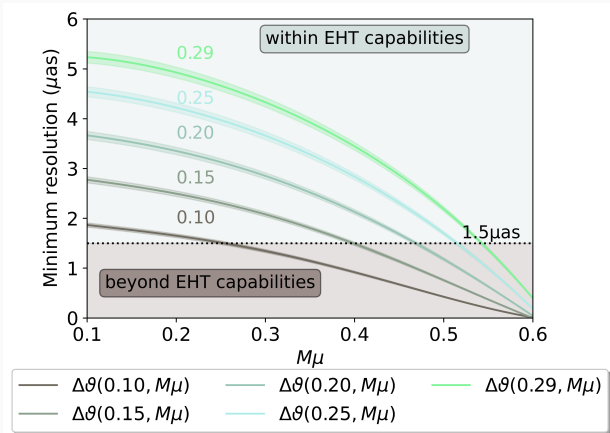


(b) Scalar case (arXiv:1909.08039)

What can we learn from EHT



What can we learn from EHT



CONCLUSIONS

- Some solutions of the Proca model show **intriguing lensing properties**, not found in Kerr black holes;
- **Fundamental photon orbits** constitute a useful tool in analysing these lensing images;
- Kerr black holes with Proca hair can have up to **40% of the mass outside the horizon**, while still having a shadow that deviates just slightly from the Kerr ones.
- It would be interesting to explore why...