

Lensing by boson stars and shadows of Kerr black holes with scalar hair

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with: C. Herdeiro, E. Radu, H. Rúnarsson

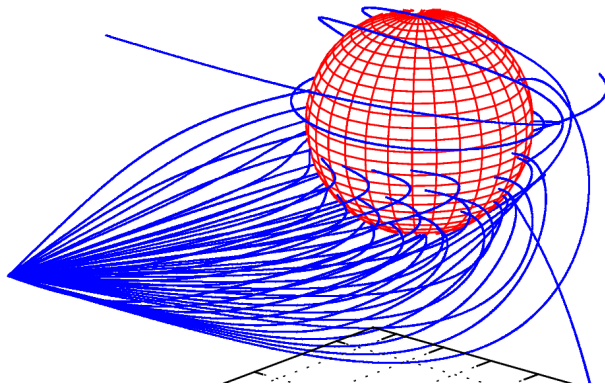
PhysRevLett.115.211102

What is a BH shadow?



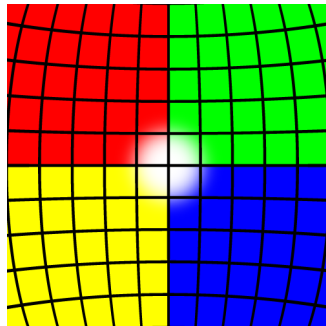
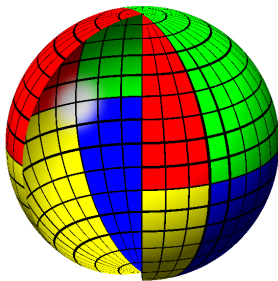
- Optical perception of a BH \rightarrow silhouette over background light.
- This dark silhouette is called a *shadow*.
- It is the fingerprint of the BH geometry.

Backwards ray-tracing



- Numerical integration of light rays yields the shadow.
- It is more efficient to evolve the rays backwards in time.
- This numerical procedure is called *backwards ray-tracing*.

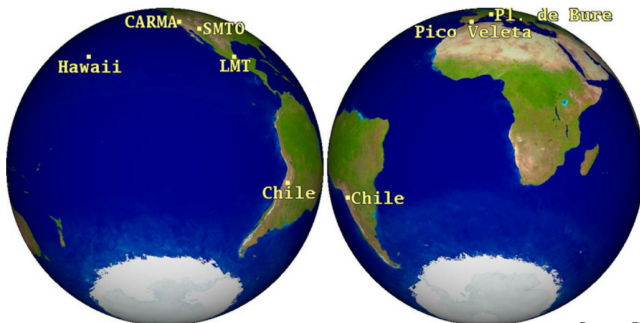
Celestial sphere



Reference: arXiv:1410.7775 [gr-qc]

- The BH and the observer are placed inside a colored sphere.
- BH is in the center of the sphere.
- The observer is in the equatorial plane.

Event Horizon Telescope



Source: Doleman et al.

- Event Horizon Telescope → international array of telescopes.
- It aims to probe Sgr A* and obtain the first images of a shadow.
- New observational templates are required!

Kerr BHs with scalar hair

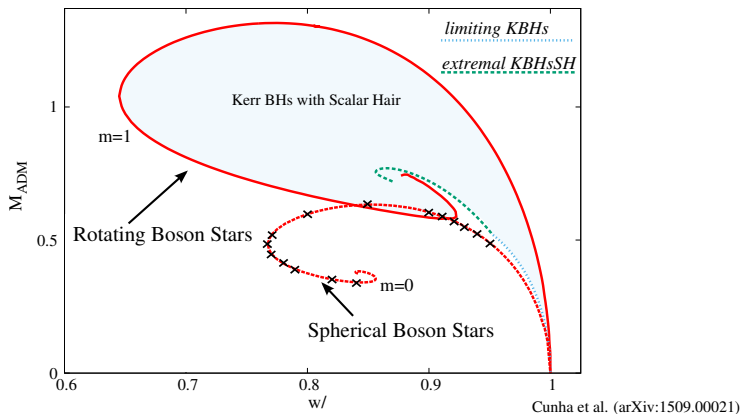
Einstein-Klein-Gordon system

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[\frac{R}{16\pi G} - \nabla_\nu \phi \nabla^\nu \phi^* - \mu^2 \phi^* \phi \right].$$

- Einstein's gravity minimally coupled to a complex scalar field ϕ .
- A stationary BH solution exists, in equilibrium with ϕ .

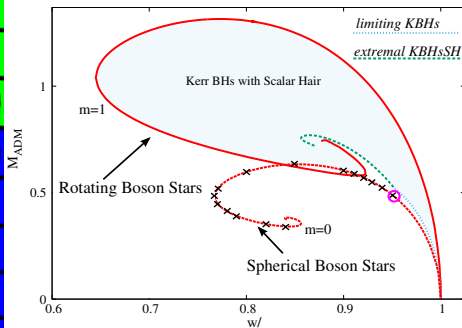
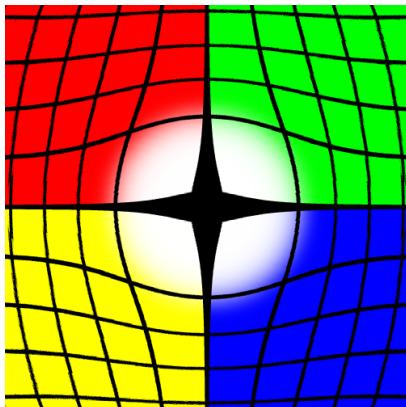
Herdeiro & Radu: PhysRevLett.112.221101

Solution space of Kerr BHs with scalar hair



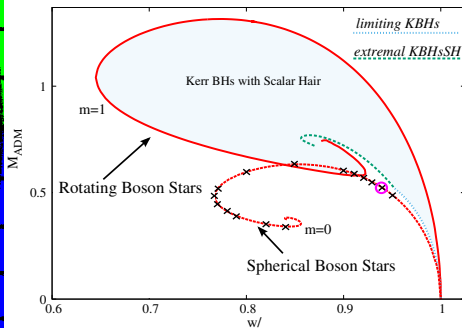
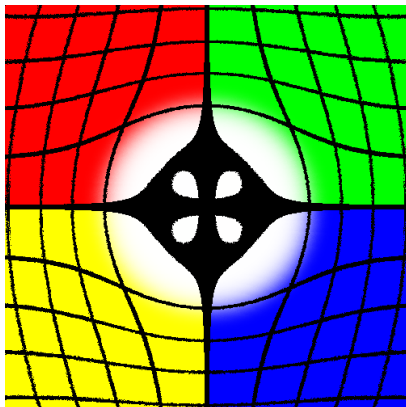
- These hairy BHs are continuously connected to Boson Stars.
- Boson Stars are self-gravitating scalar field configurations.

Lensing by spherical Boson Stars



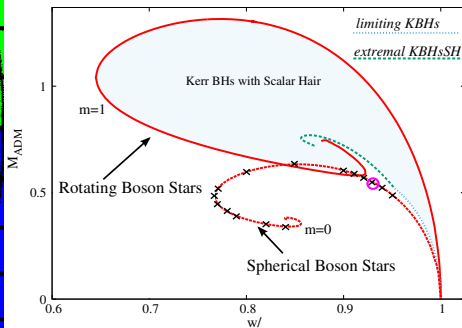
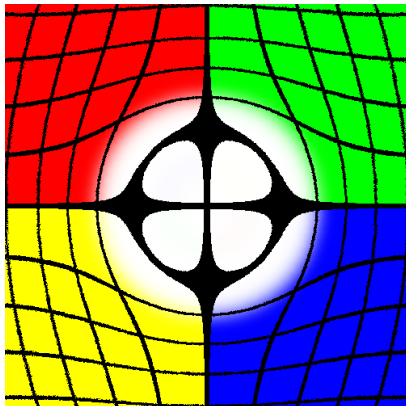
- Spherical Boson Stars have no shadows.
- Spherical Boson Stars → not continuously connected to BHs.

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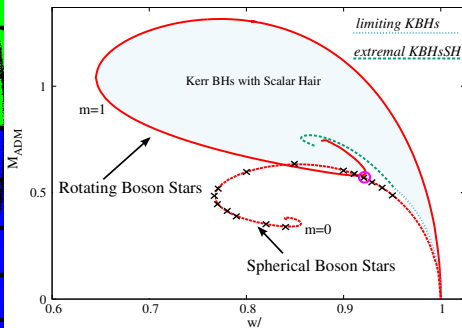
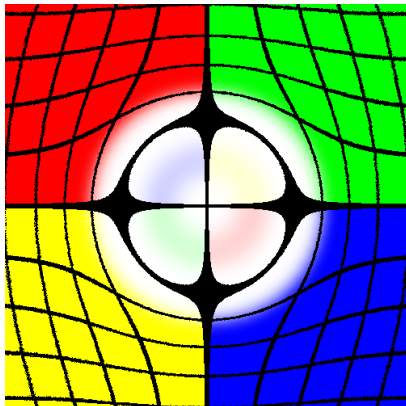
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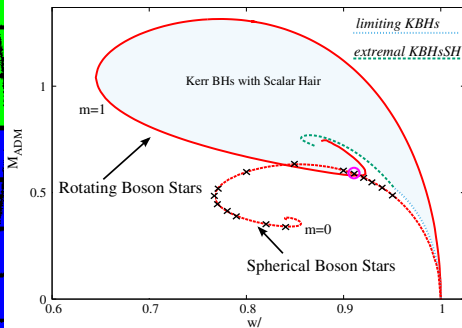
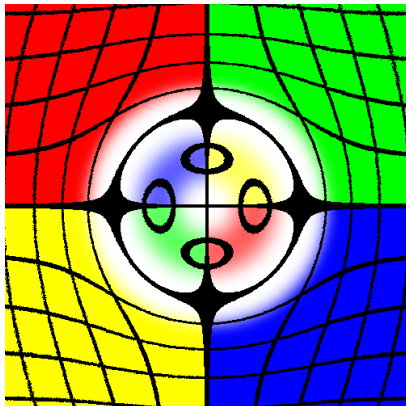
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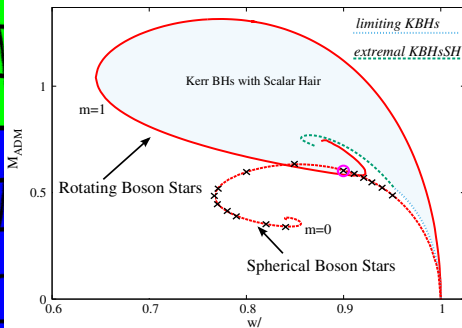
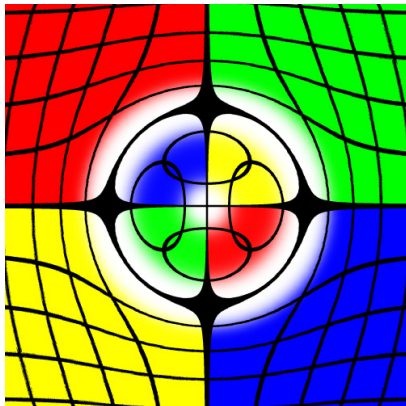
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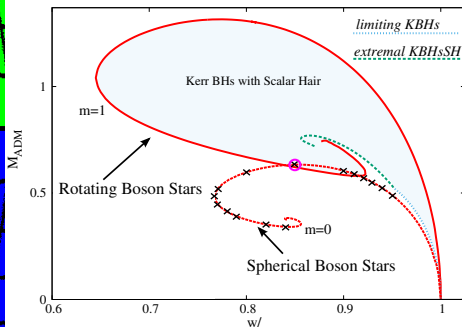
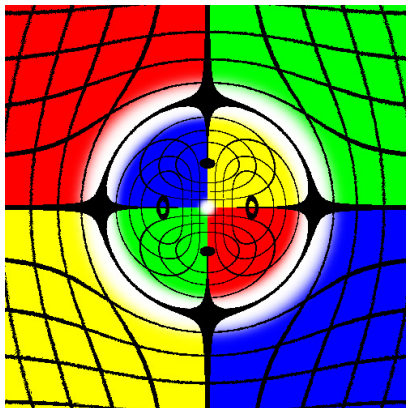
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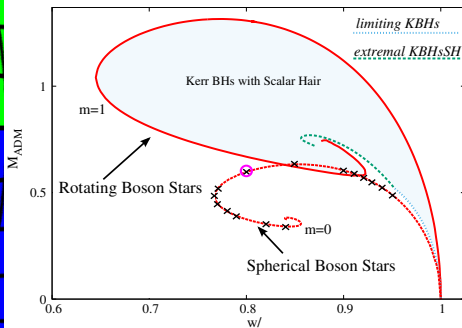
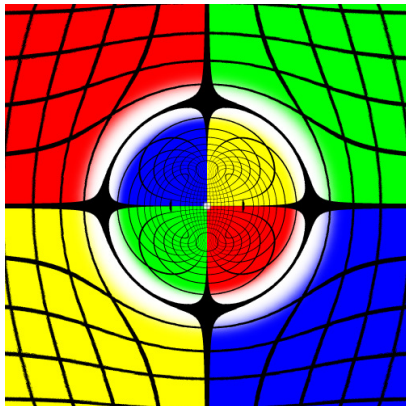
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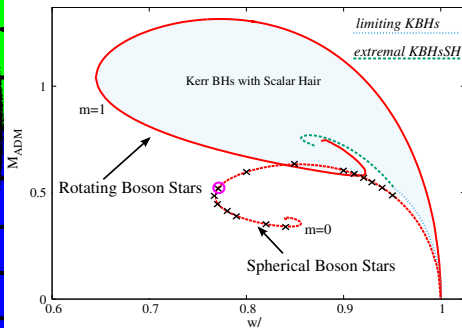
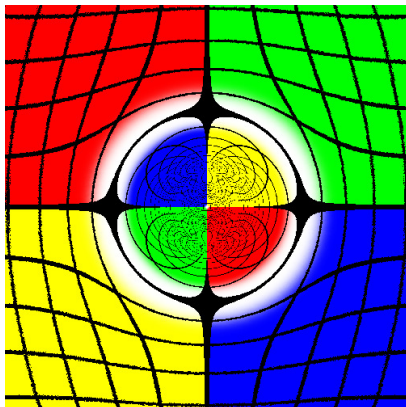
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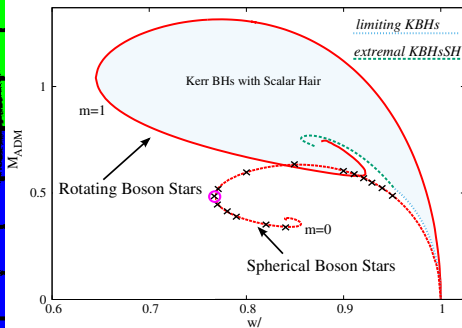
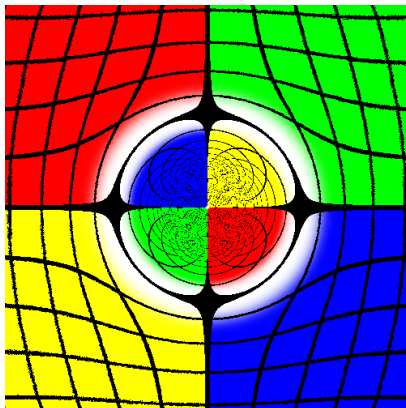
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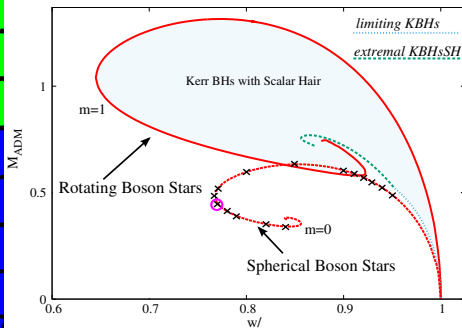
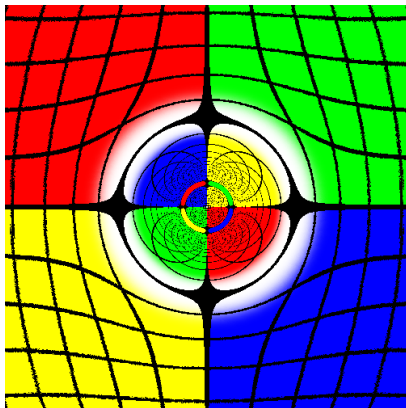
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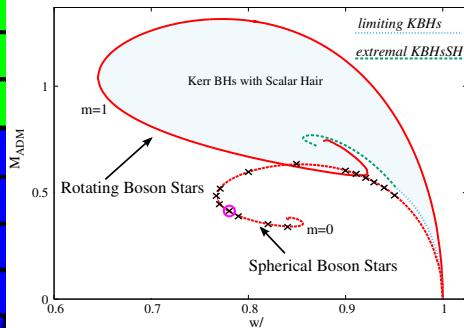
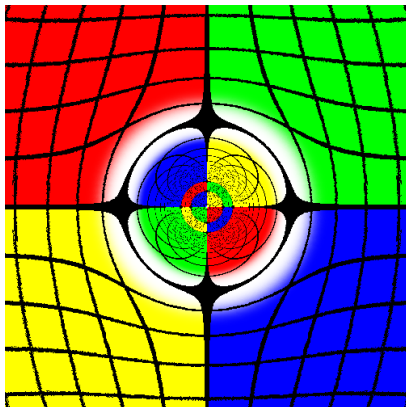
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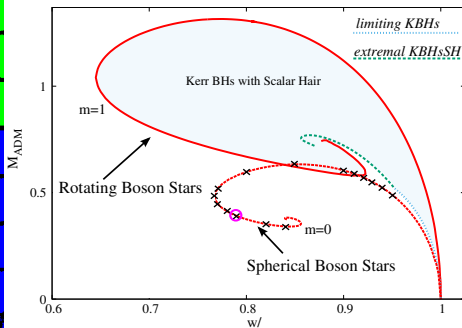
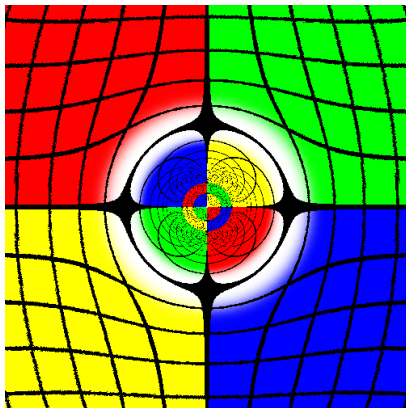
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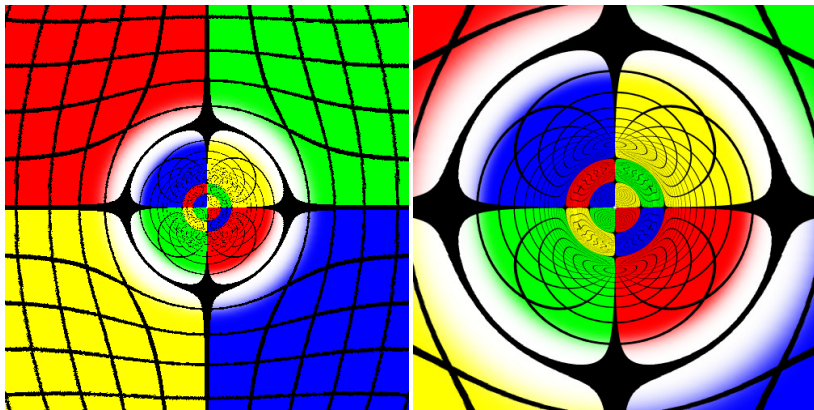
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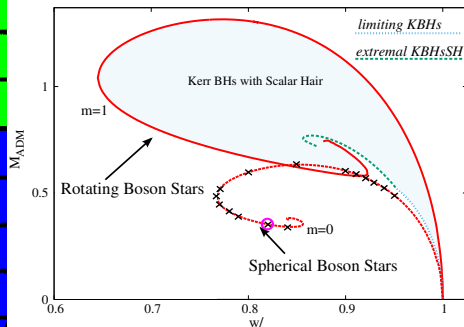
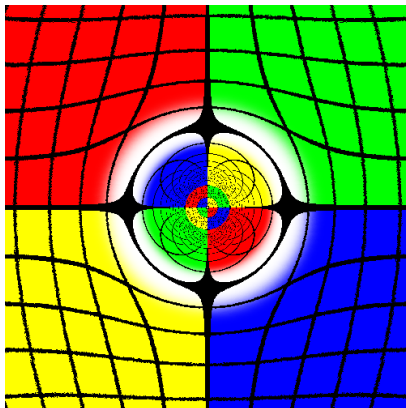
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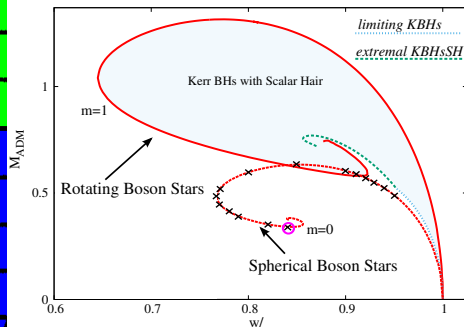
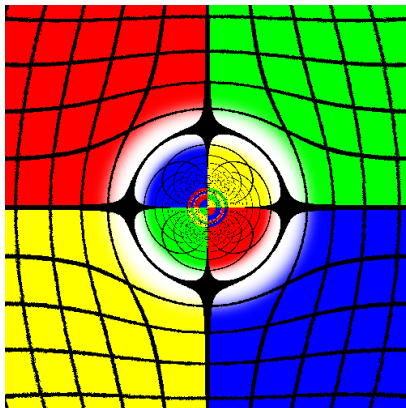
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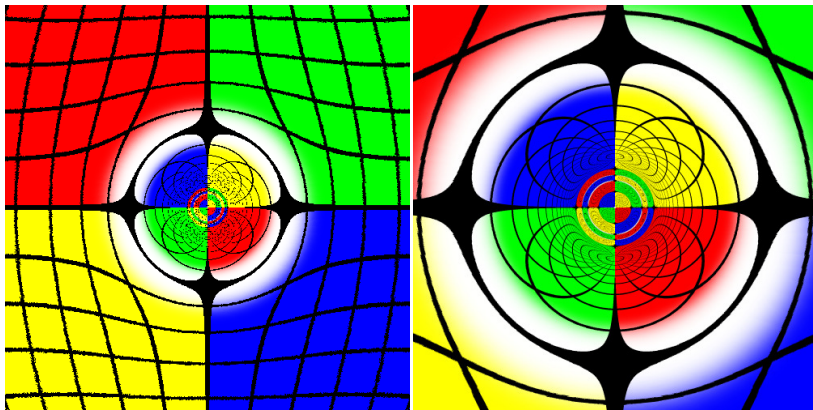
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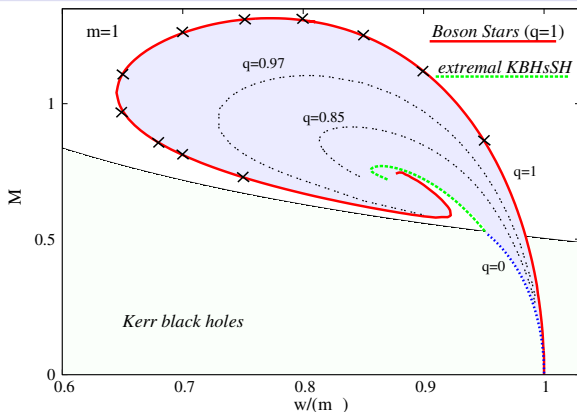
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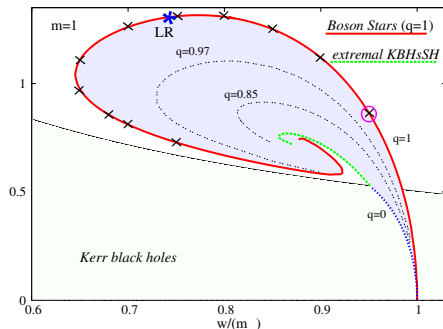
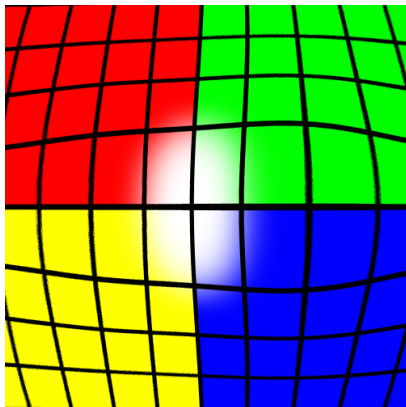
Kerr BHs with scalar hair



Source: Herdeiro & Radu

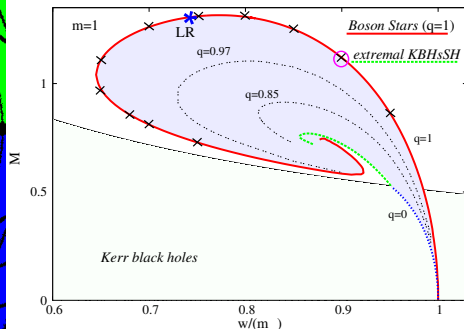
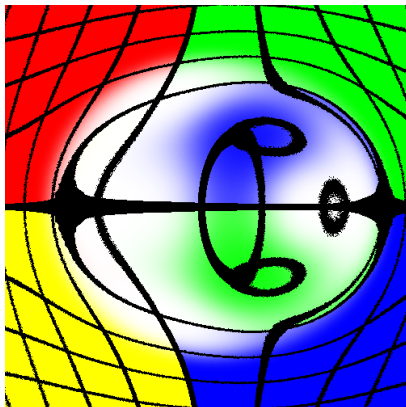
- Red curve \rightarrow rotating Boson Stars.
- These are continuously connected to hairy BHs.
- Boson Stars are self-gravitating scalar field configurations.

Lensing by rotating Boson Stars



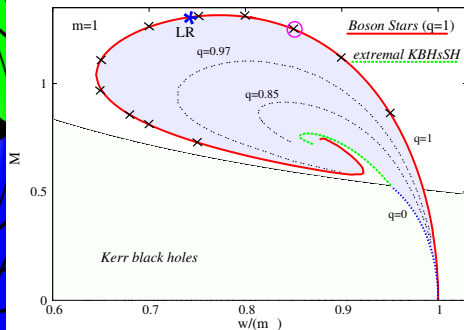
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Lensing by rotating Boson Stars



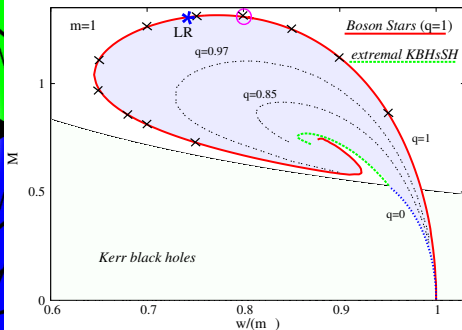
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A complex, colorful, abstract fractal-like image. It features a central circular motif with a black outline, containing a blue and yellow design. This central element is surrounded by four quadrants of different colors: red (top-left), green (top-right), blue (bottom-left), and yellow (bottom-right). The entire image is composed of intricate, overlapping black lines that create a sense of depth and complexity, resembling a fractal or a highly detailed geometric pattern. The colors are vibrant and saturated, and the overall composition is symmetrical and balanced.



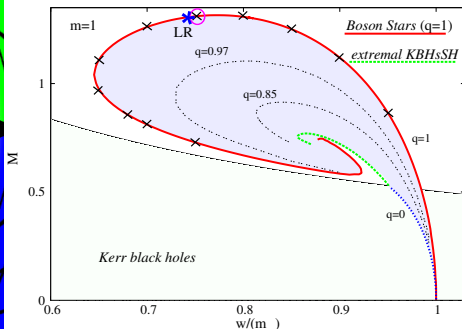
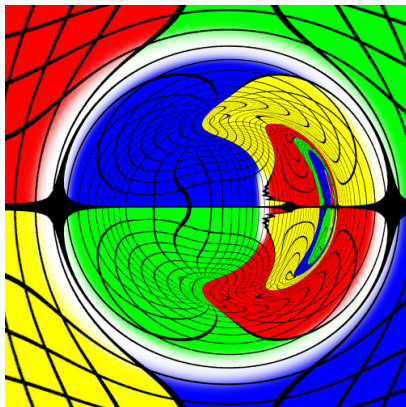
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A complex, colorful geometric pattern. At the center is a circular motif divided into four quadrants: top-left is red, top-right is yellow, bottom-left is green, and bottom-right is red. Each quadrant contains a black, swirling, wavy line pattern. This central circle is surrounded by a thick white ring, which is further enclosed by a thin black ring. The entire composition is set against a background of a black grid of lines that curve and warp around the central circular element. The colors are vibrant and saturated.



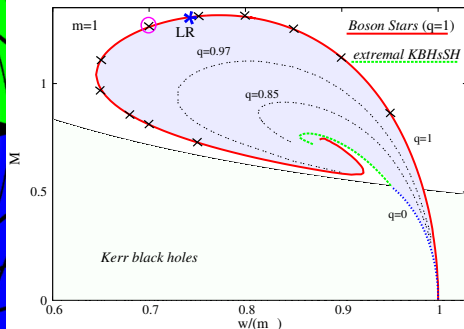
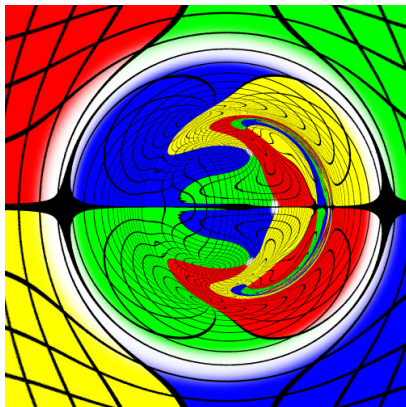
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Lensing by rotating Boson Stars



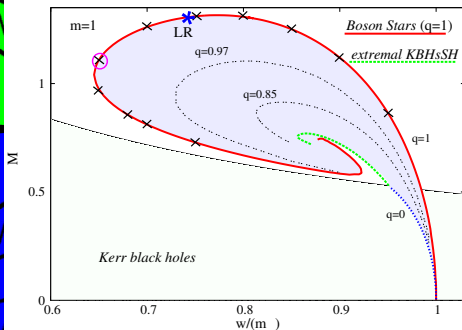
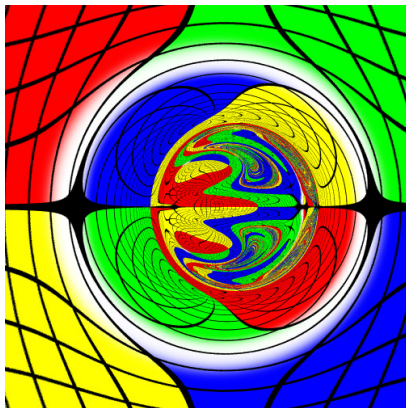
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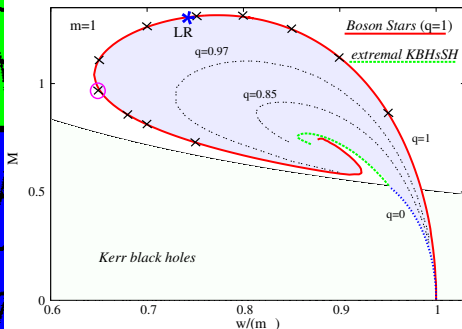
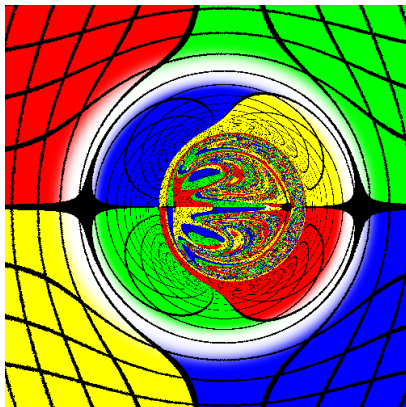
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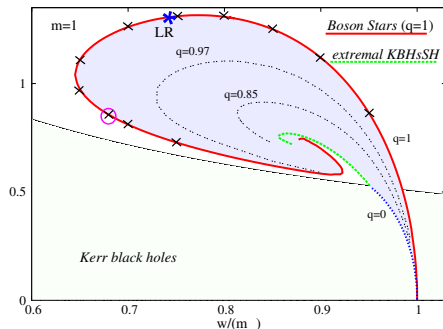
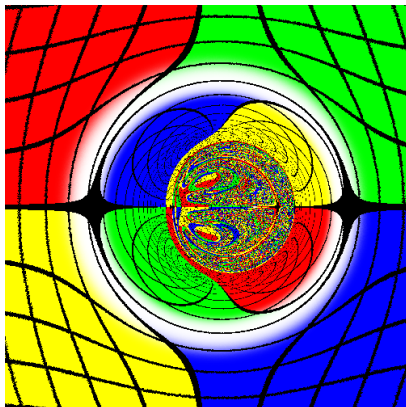
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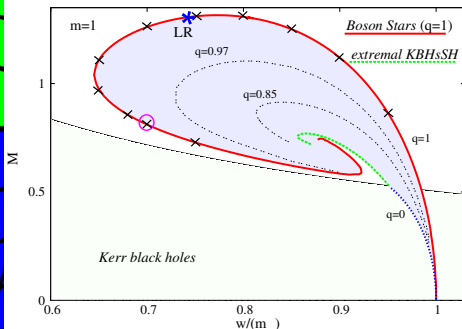
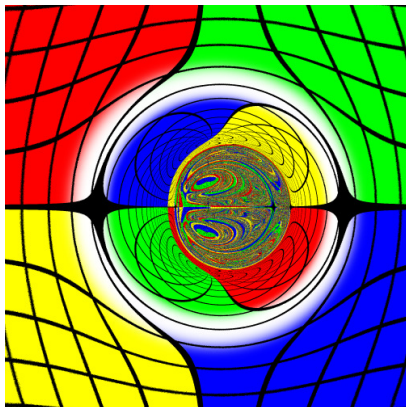
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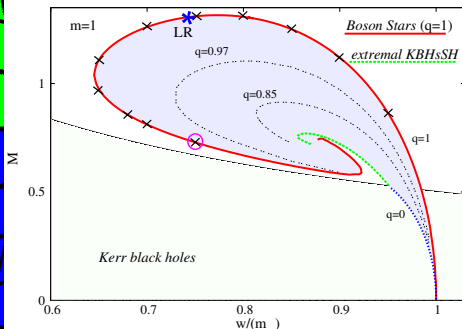
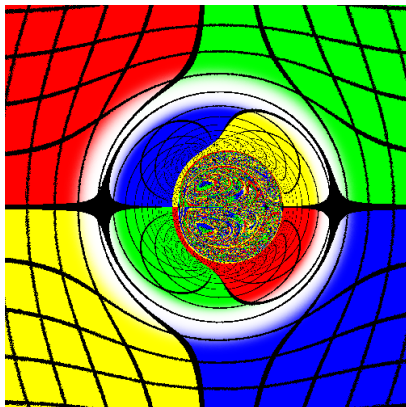
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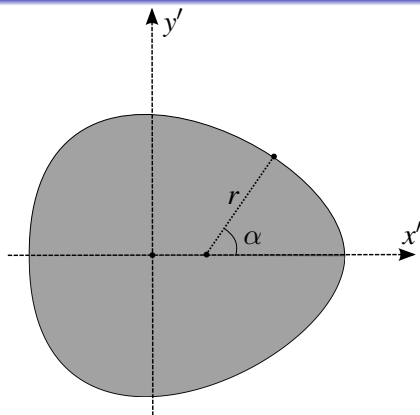
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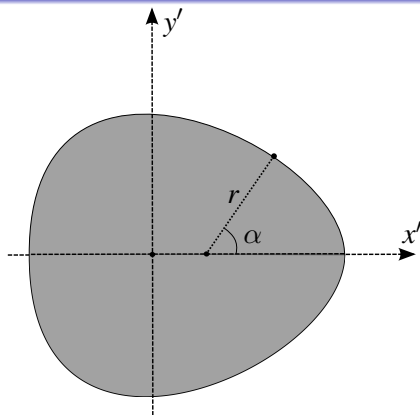
Shadow parameters



Mean radius

$$\bar{r} \equiv \frac{1}{2\pi} \int_0^{2\pi} r(\alpha) d\alpha$$

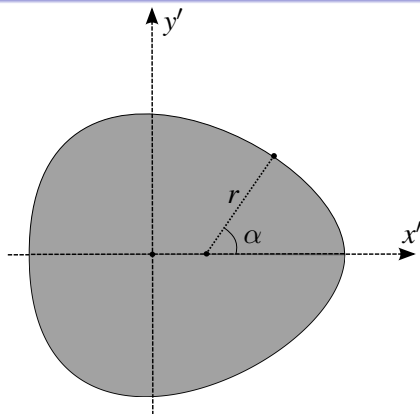
Shadow parameters



Deviation from sphericity

$$\sigma_r \equiv \sqrt{\frac{1}{2\pi} \int_0^{2\pi} [r(\alpha) - \bar{r}]^2 d\alpha}$$

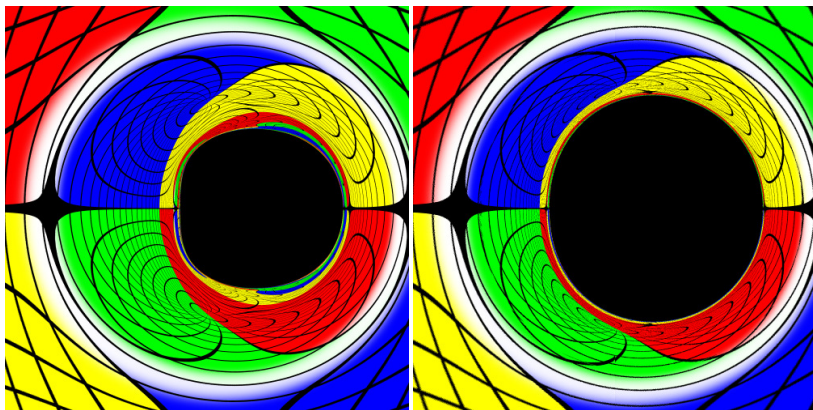
Shadow parameters



Relative deviation to a Kerr BH

$$\sigma_{Kerr} \equiv \sqrt{\frac{1}{2\pi} \int_0^{2\pi} \left[\frac{r - r_{Kerr}}{r_{Kerr}} \right]^2 d\alpha}$$

Shadows of Hairy BHs

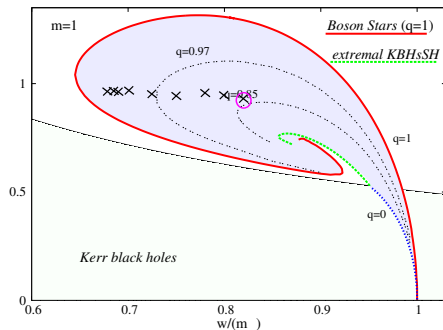
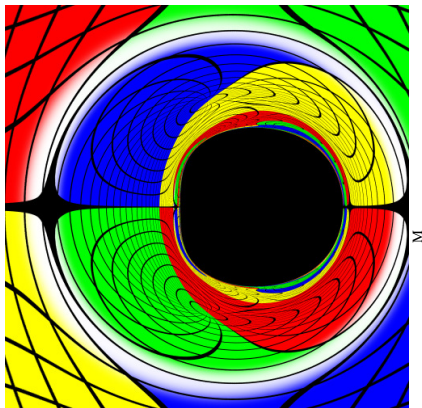


Kerr BH with scalar hair

Kerr BH (ADM)

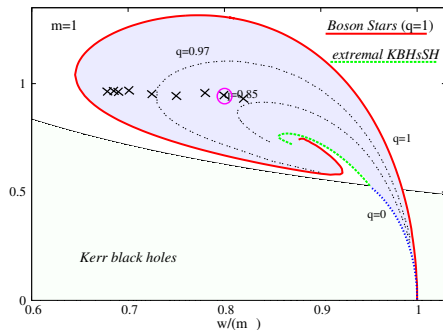
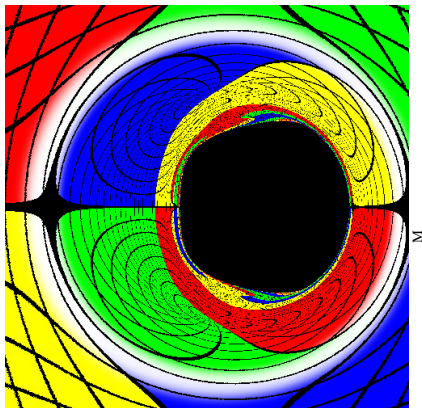
$\bar{r} (M)$	3.6	4.8
$\sigma_r / \bar{r} (\%)$	3.3	2.2
$\sigma_{Kerr} (\%)$	25.5	

Shadows of Hairy BHs



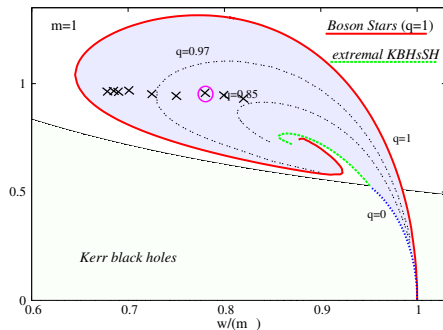
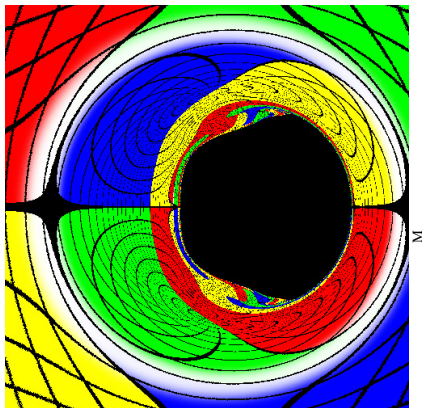
- The shadows of hairy BHs can be very distinct from Kerr's.
- These shadows are *smaller*!

Shadows of Hairy BHs



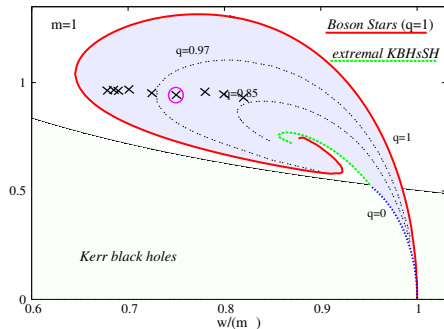
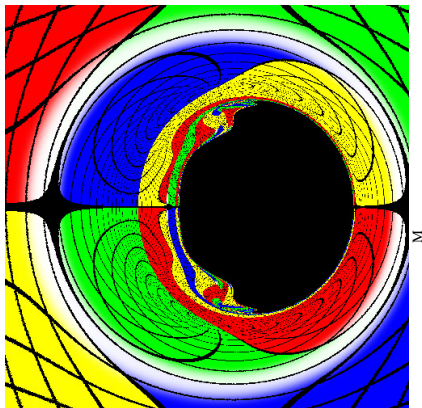
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Shadows of Hairy BHs



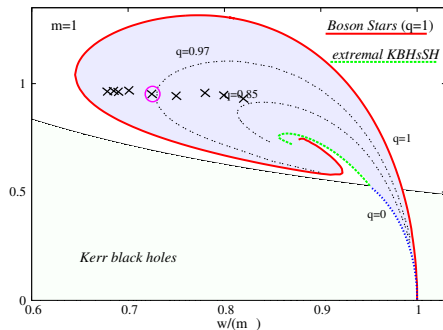
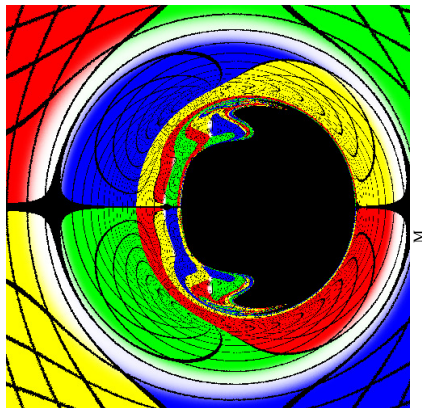
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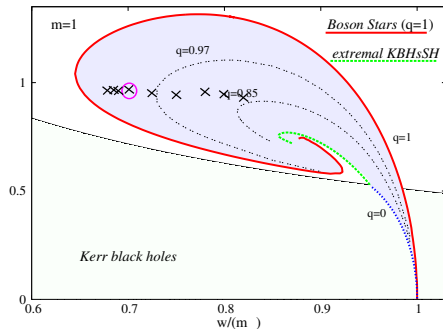
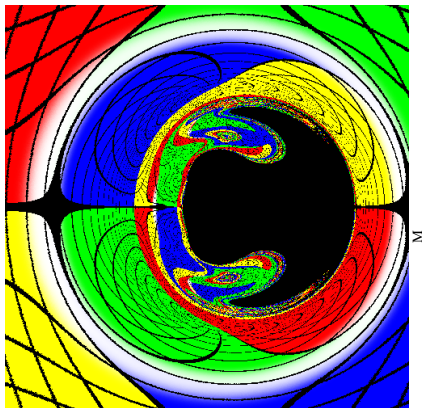
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Shadows of Hairy BHs



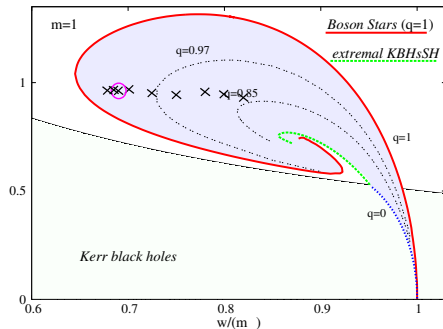
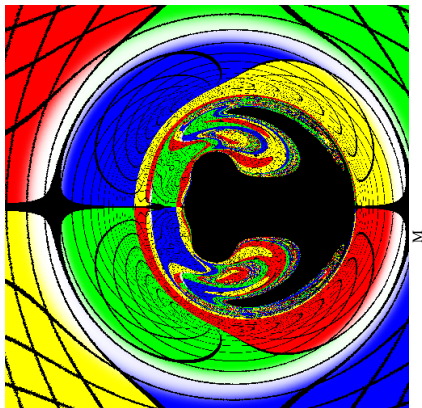
- The shadows of hairy BHs can be very distinct from Kerr's.
- These shadows are *smaller*!

Shadows of Hairy BHs



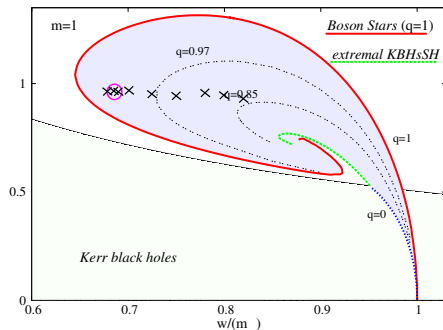
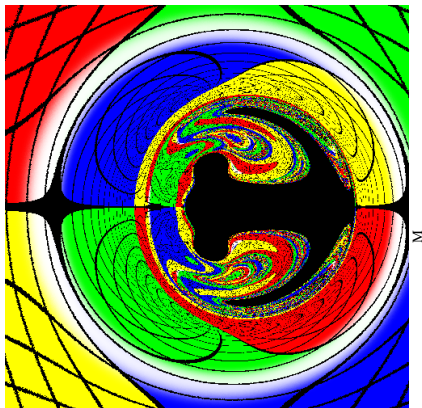
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Shadows of Hairy BHs



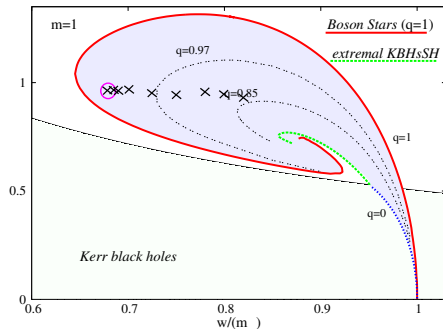
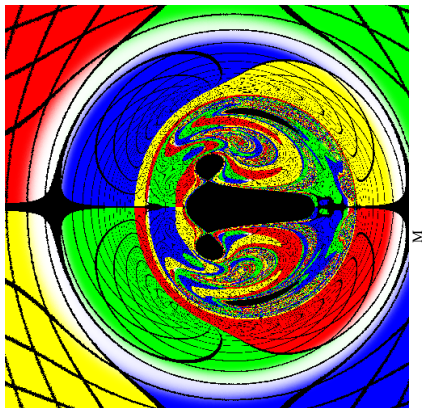
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Shadows of Hairy BHs



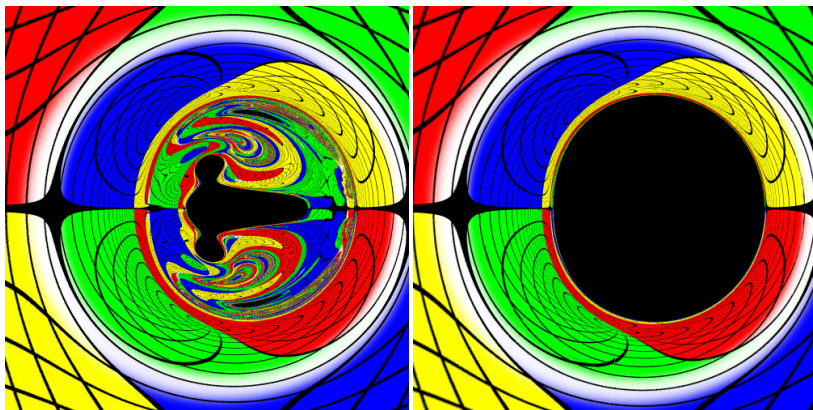
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Shadows of Hairy BHs



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Shadows of Hairy BHs

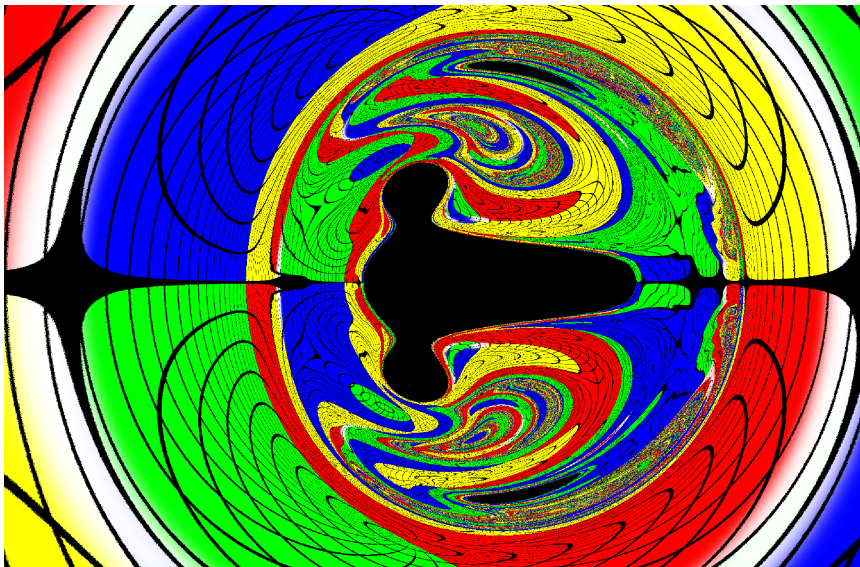


Kerr BH with scalar hair

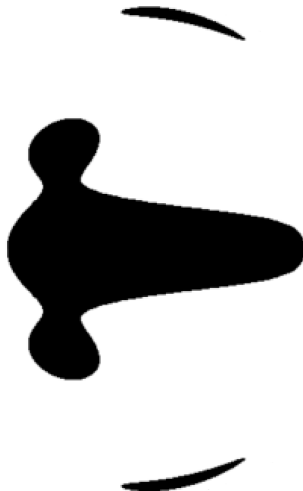
Kerr BH (ADM)

$\bar{r} (M)$	1.63	4.8
$\sigma_r / \bar{r} (\%)$	51.3	2.6
$\sigma_{Kerr} (\%)$	68.1	

Shadows of Hairy BHs



Shadows of Hairy BHs



Conclusions

- These hairy BH shadows are distinct from Kerr's.
- These shadows are in fact *smaller*.
- New shadow shapes can be obtained.
- These hairy BHs could provide observational templates.

Shadows

○○○

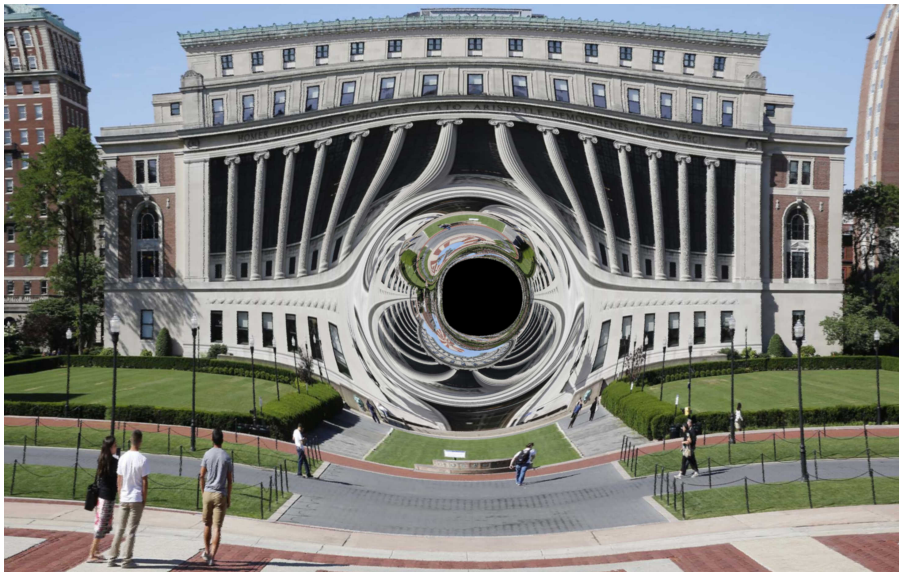
Boson Stars

○○○○

Shadows of Kerr Black Holes with scalar hair

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Thank you for your time!



Acknowledgements

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