NEB-21

September 3rd, 2025

Using shadow observations to distinguish black holes from ultra-compact objects

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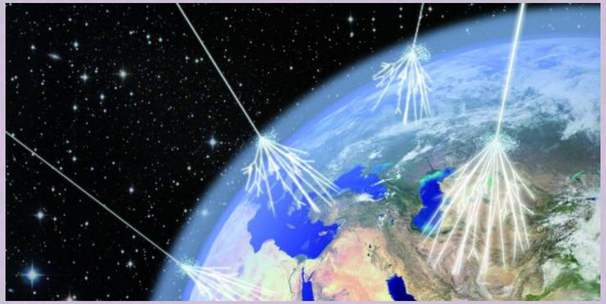
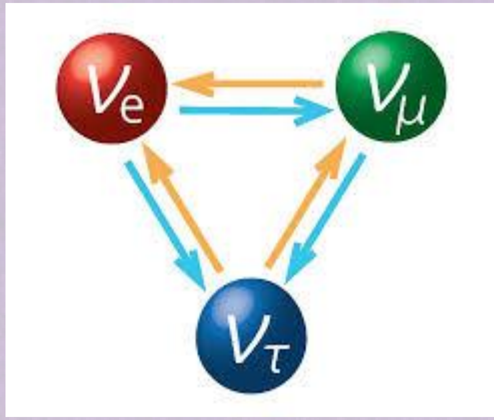
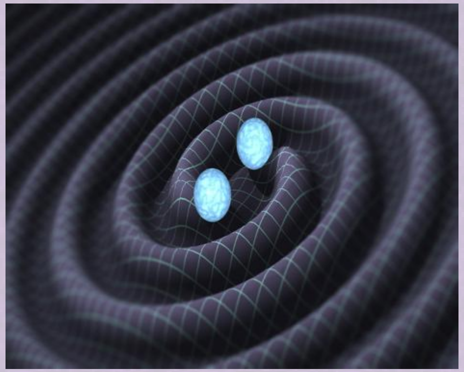
- In the last few years we have witnessed the dawn of multimessenger astronomy, namely, astronomy with different carriers (light, gravitational waves, cosmic rays and neutrinos)

Cosmic rays



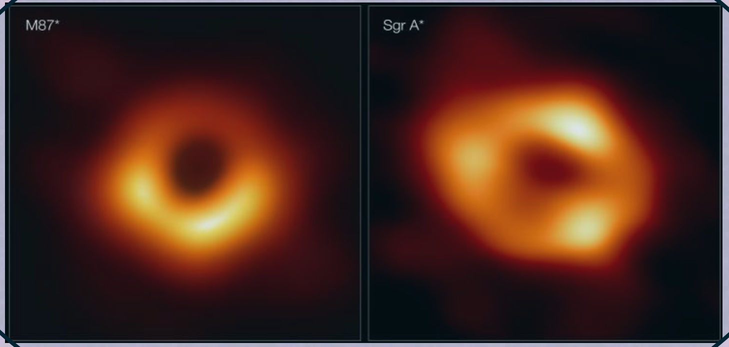


Neutrinos



GWs from BH mergers

Shadows



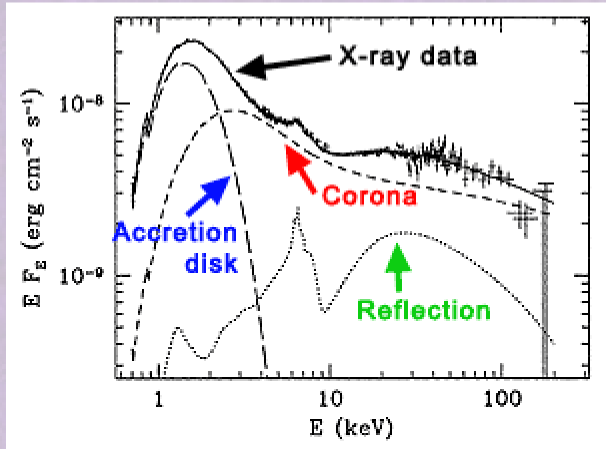
Several messengers

Quantity and quality of data

Large international collaborations

A. Adazzi et al (including DRG), Prog. Part. Nuc. Phys 125 (2022) 103948

X-ray spectroscopy

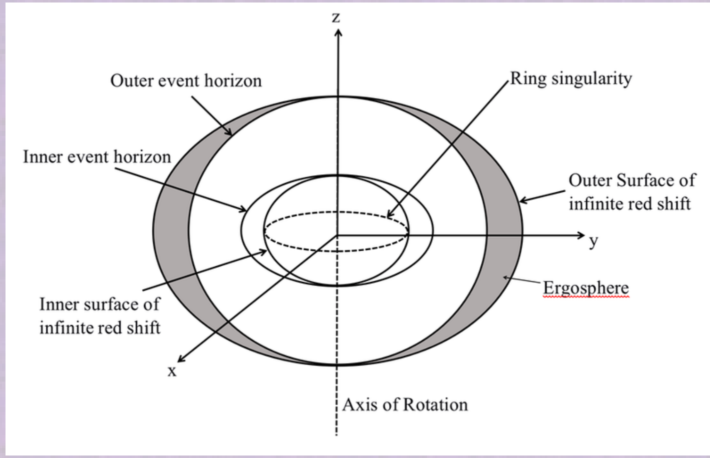


- **Great hopes have been placed in the tools provided by this new era to help us unveil the nature of compact objects**

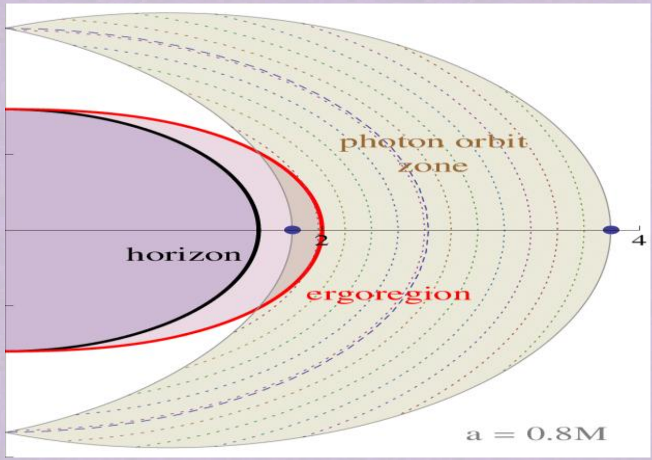
The Kerr hypothesis

- **The Kerr solution is the unique axi-symmetric, vacuum solution of Einstein field's equations**
- **It is described by solely two parameters: mass and angular momentum (electric charge is neglected in physically realistic astrophysical environments)**

Theoretically disputable on its inner regions (singularity problem, closed time-like curves, mass inflation, information loss problem)…



(Credit to Caio Macedo)



Ultra-compact object (UCO): Any object compact enough to develop regions of unstable bound geodesics

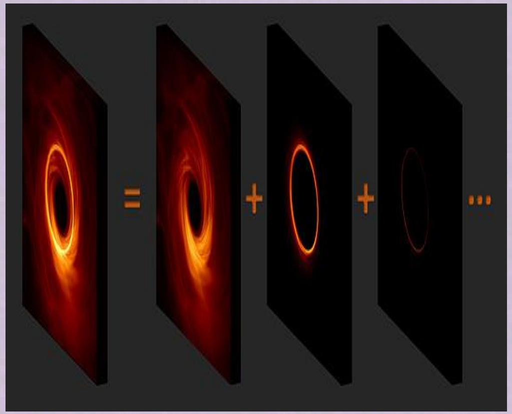
But observationally successful on its external region (X-ray spectroscopy, orbits of S-stars, GWs, shadows)

- **How these two views can be reconciled?. Can we connect the troublesome theoretical modeling of the internal region with the verifiable phenomena associated to the external region?**
- **The Kerr hypothesis states the universality of Kerr black holes. Can it be disputed?**

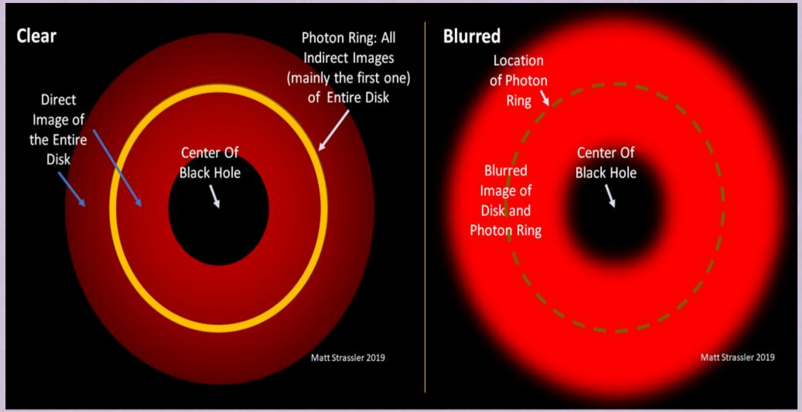
BH imaging (aka ``shadows”)

- **The theoretical analysis and the results of General Relativistic MagnetoHydroDynamic (GRMHD) simulations agree on the existence of TWO universal and persistent features in black hole images illuminatedby its accretion disk**

A bright ring of radiation comprised of the disk’s direct emission and a series of stacked rings (photon rings) on top of it, blurred due to limited resolution

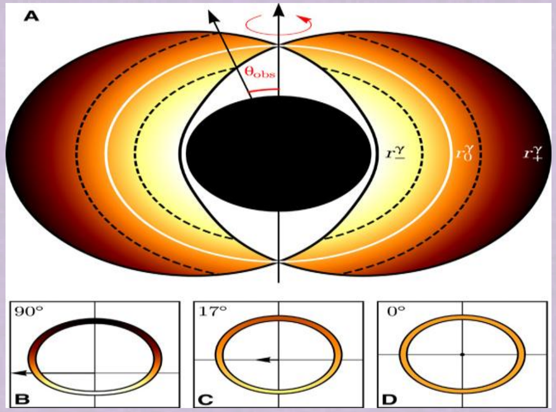


(Credit to Matt Strassler)



(Credit to G.Wong and M. Johnson)

These two features have their origin in the surface of unstable bound geodesics: the photon shell

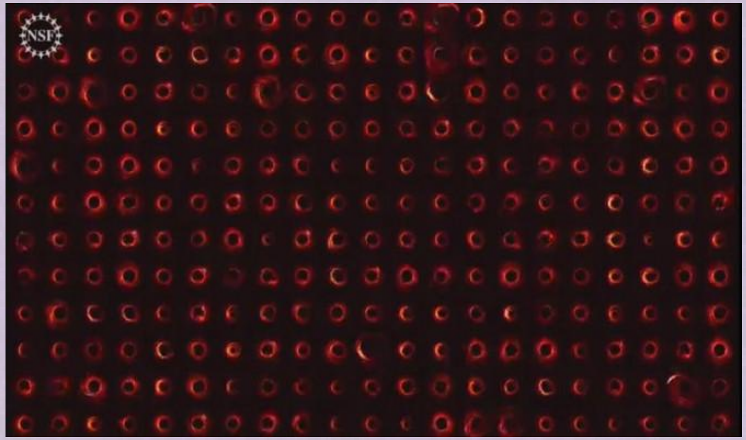


M. D. Johnson et al. *Sci.Adv.* 6 (2020) 12, eaaz1310

For spherically symmetric BHs, it degenerates into the photon sphere

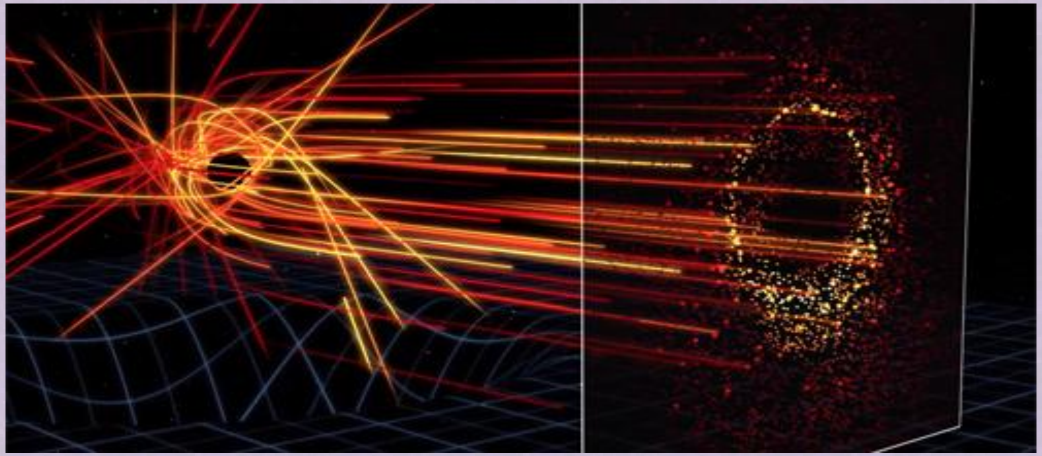
A central brightness depression (shadow) caused by the much shorted path-length of photons intersecting the BH event horizon

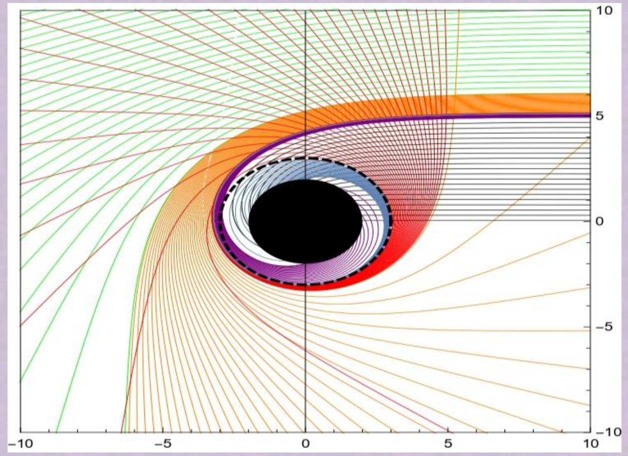
The features of the photon ring(s) and the shadow are dependent on the space-time geometry and the accretion disk physics, enabling studies of both via GRMD simulations of the accretion flow



A blossoming field of research peering into the strong-field regime of gravity!

- **Ray-tracing is the procedure by which all light rays arriving to the observer's screen are backtracked to the region of the sky the came from**
- **For BH imaging, the collection of points in the sky is identified with the accretion disk surrounding the BH**





M. Guerrero, G. J. Olmo, DRG, D. Saez-Gomez,, JCAP 08 (2021) 036

- **For a spherically symmetric line element of the form** $ds^2 = -A(x)dt^2 + B(x)dx^2 + r^2(x)d\Omega^2$

the geodesic equation reads as

$$AB\left(\frac{dx}{d\lambda}\right)^2 = \frac{1}{b^2} - V(r)$$ (Scattering problem)

$$V(r) = \frac{A(x)}{r^2(x)}$$ Effective potential

$$b = \frac{L}{E}$$ Impact parameter

$$\frac{d\phi}{dx} = \mp \frac{b}{r^2(x)} \frac{AB}{\sqrt{1 - \frac{b^2 A(x)}{r^2(x)}}}$$ (Deflection angle)

$$E = -A\frac{dt}{d\lambda}$$ Energy

(Conserved quantities)

$$L = r^2(x)\frac{d\phi}{d\lambda}$$ Angular momentum

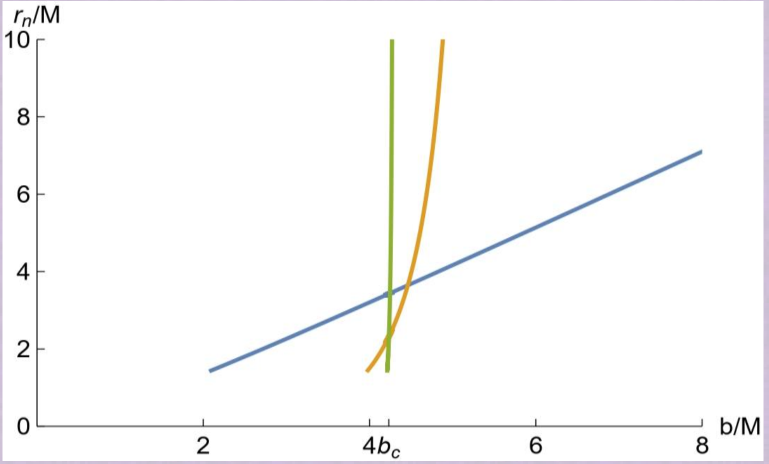
Plane $\theta = \pi/2$ (spherical symmetry, no loss of generality)

$$r_{ps}A'_{ps} - 2A_{ps} = 0$$

$$b_{ps} = \frac{r_{ps}}{A_{ps}^{1/2}}$$

Photon sphere of unstable bound geodesics

- Output of the ray-tracing is the transfer function: $r_n(b)$ the radial location of the equatorial disk crossed by the photon
- Here the integer part of $n = \frac{\phi}{\pi}$ determines the (half-)number of times each photon has winded around the black hole
- This relation allows to trade dependences in b with those in r, the latter appearing in the illumination profiles



V. Perlick, O. Y. Tsupko, Phys. Rept. 947 (2022) 1

$n = 0$ (blue) denotes the disk's direct emission

$n = 1, 2, \ldots$ (orange and green) denote the photon rings: sucessive images of the back and front of the disk

The slope of the transfer function indicates the demagnification of each photon ring

- The accretion disk physics is governed by the radiative transfer equation: $$\frac{d}{d\lambda}\left(\frac{I_\nu}{\nu^3}\right) = \left(\frac{j_\nu}{\nu^2}\right) - (\nu\alpha_\nu)\left(\frac{I_\nu}{\nu^3}\right)$$
- Furthermore, two key ingredients of the disk are needed

  - *Optical properties*. To what extent is it transparent to its own radiation?. If opacity is absolute, no photon ring can exist
  - *Geometrical properties*. Its thickness (radial extend vs height) interpolates between infinitesimally-thin and spherical

I_ν Intensity

j_ν Emissivity

α_ν Absorptivity

R. Gold et al. *Astrophys.J.* 897 (2020) 2, 148

GRMHD simulations fix these coefficients and generate images of the accretion flow around a BH

- **As with gravitational waves, adapting numerical codes to each theory of gravity + matter is very costly**
- **Alternative: use semi-analytic models that can successfully reproduce results of GRMHD simulations, based on a few parameters, to significantly reduce the complexity of the problem and the waste of computational resources**

"GLM" models

S. E. Gralla, A. Lupsasca and D. P. Marrone
Phys. Rev. D 102 (2020) no.12, 124004

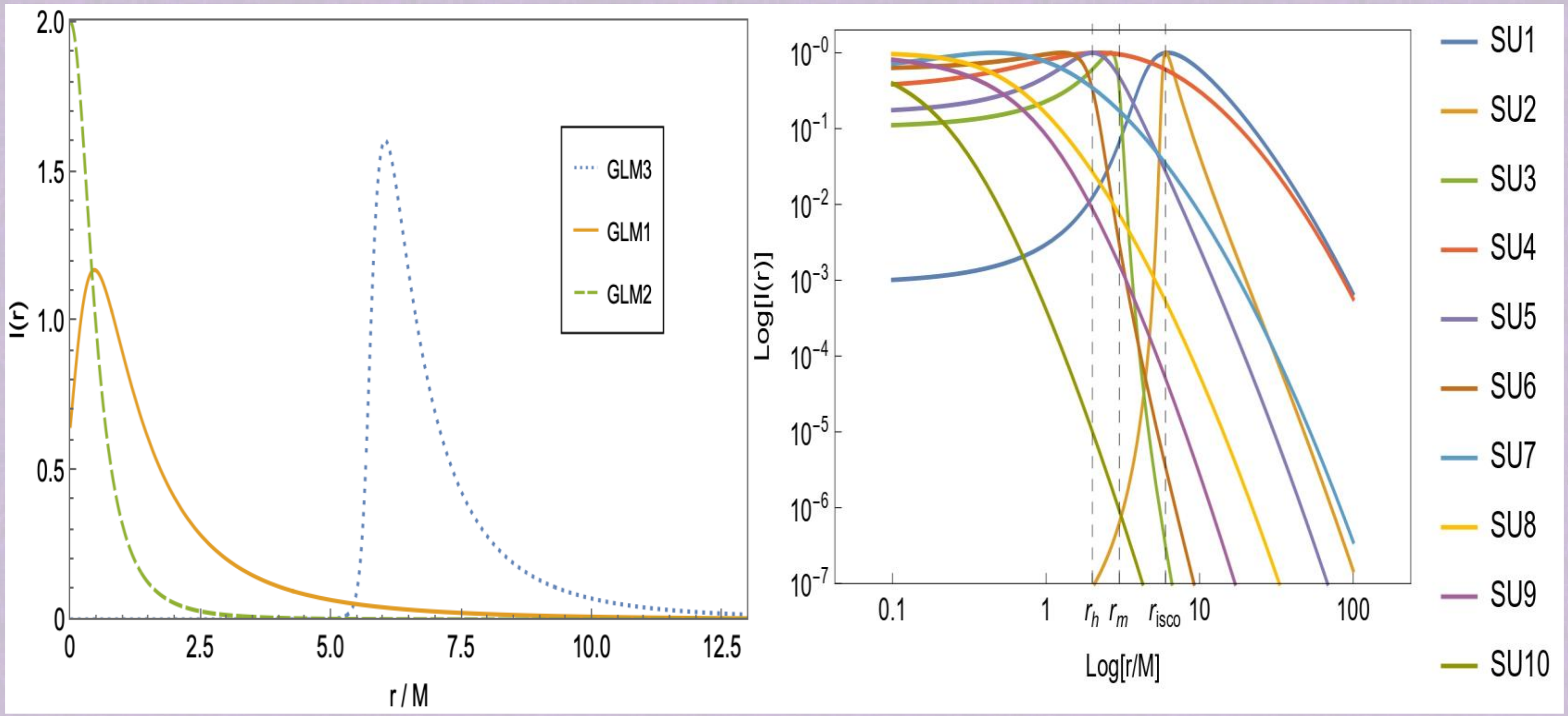
Based on Johnson's Standard Unbound Profile
(SU models)

$$I(r;\gamma,\mu,\sigma) = \frac{\exp\left(-\frac{1}{2}\left(\gamma + \operatorname{arcsinh}\left(\frac{r-\mu}{\sigma}\right)\right)^2\right)}{\sqrt{(r-\mu)^2+\sigma^2}}$$

γ Peak's location

μ Profile's width

σ Profile's asymmetry



Our assumptions:

- Infinitesimally-thin
- Optically thin up to n=2 ring
- Monochromatic emission in the disk's frame

$$I_{ob} = \sum_{n=0} A^2(r) I(r)\Big|_{r=r_m(b)}$$

I. De Martino, R. Della Monica, DRG, Phys.Rev.D 108 (2023) 12, 124054

Gravitational redshift +
Multiple crosses of the disk (up to n=2)

Evaluated at $r_n(b)$

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Generation of images

Diego Rubiera-García

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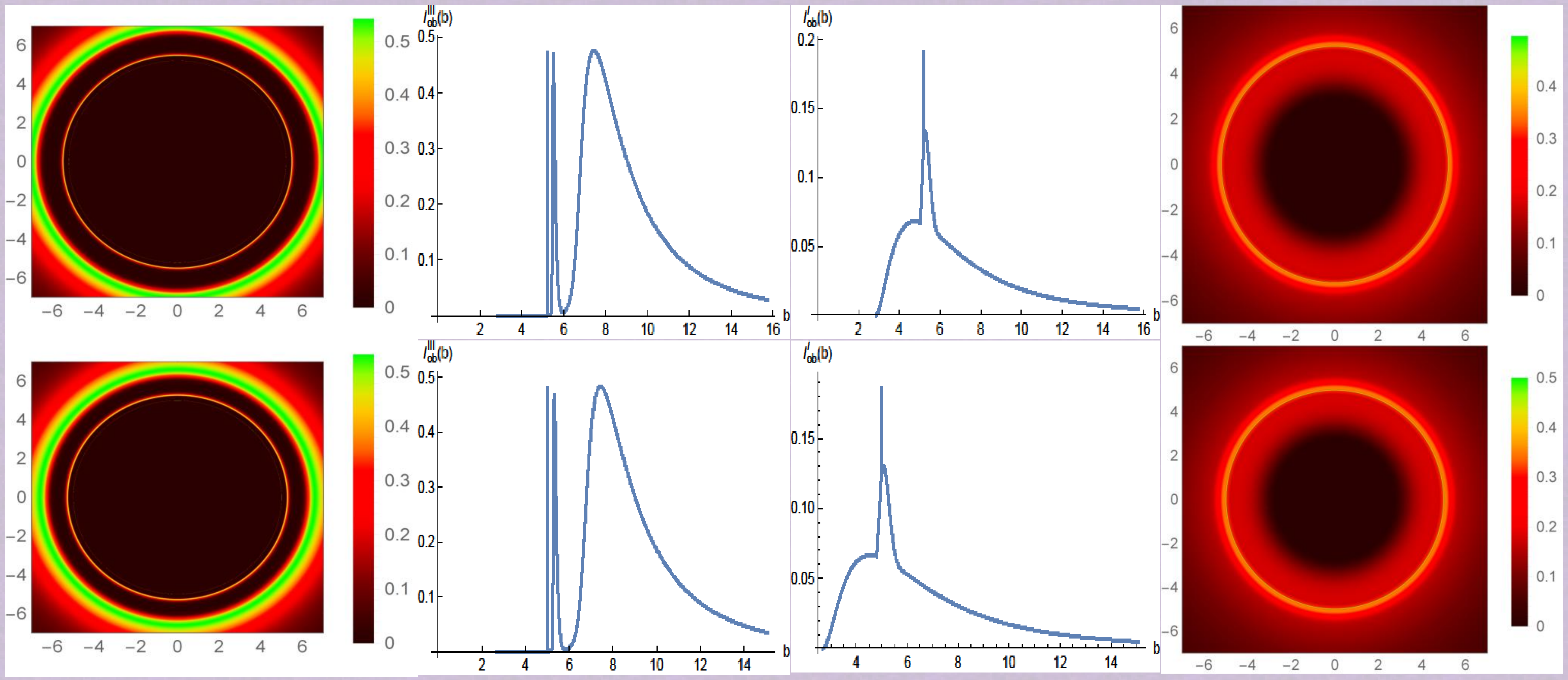
- **Optical appearance of black holes typically dominated by a series of bright rings (direct emission + photon rings) surrounding a central brightness depression (``shadow")**
- **Differences with optical appearances of modified black holes in GR or modified gravity can be very tiny. Detectable?**

Schwarzschild black hole

Imaged generated with GRAVITYp code.
*Samples available at **Wolfram web**; Tutorials in YouTube at **Modified Gravity** channel*

GLM3
(Peak at ISCO)

GLM1
(Peak at horizon)



GLM3
(Peak at ISCO)

GLM1
(Peak at horizon)

$$S = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\left(R + \alpha R^2 + \beta R_{\mu\nu}R^{\mu\nu}\right)$$

Black hole in Quadratic gravity in Palatini formulation with Maxwell field

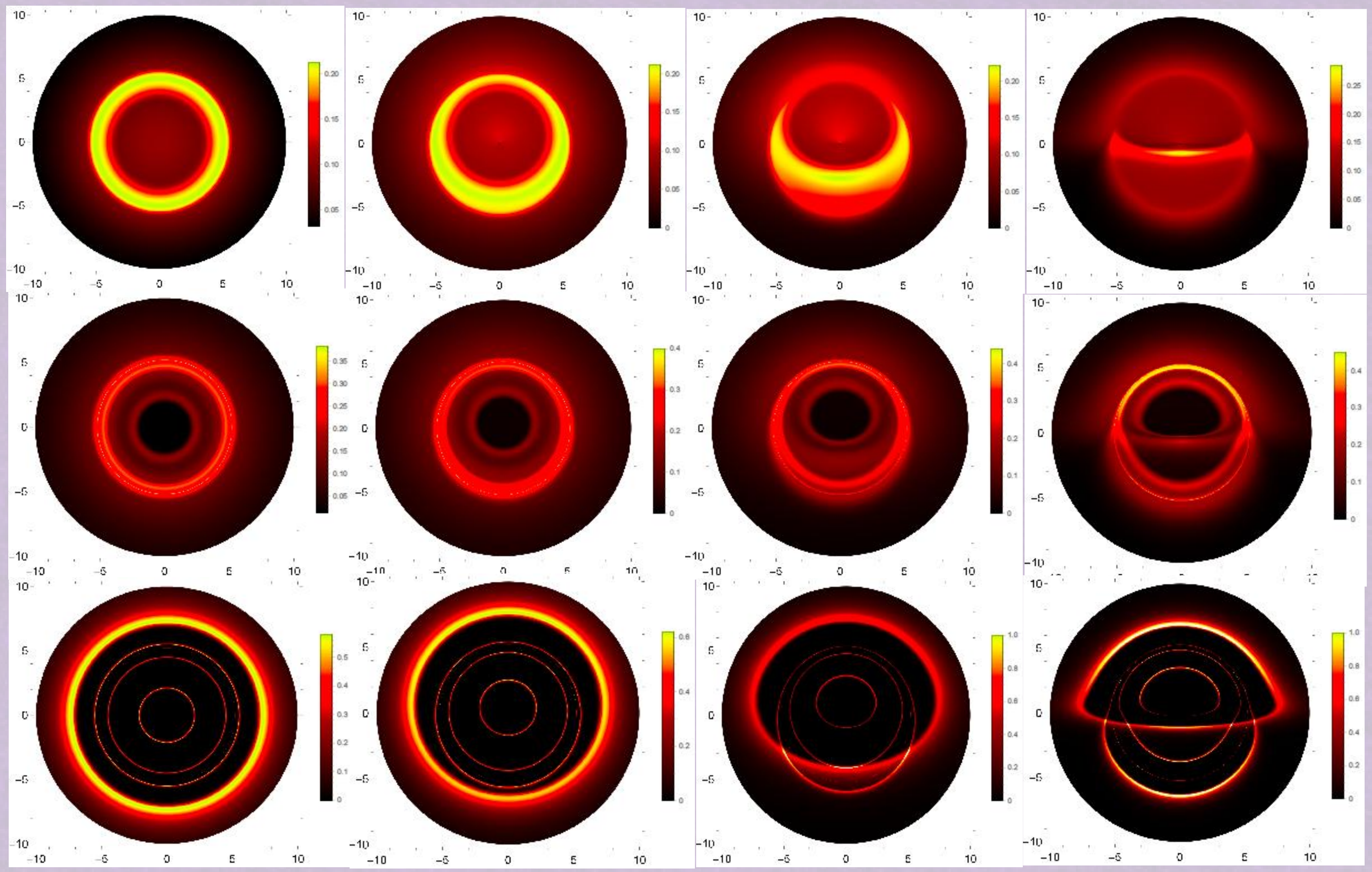
$g_{\mu\nu}, \Gamma^{\gamma}_{\alpha\beta}$ independent

G. J. Olmo, J. L. Rosa, D. Saez-Gomez, DRG, Class.Quant.Grav. 40 (2023) 174002

- Boson stars are hypothetical ultra-compact objects supported by (complex) scalar fields,
- Long lived? Stable?. Critically dependent on their potential, parameters, and compactness! $\mathcal{S} = \int d^4x \sqrt{-g} \left[\frac{R}{2\kappa^2} - \frac{1}{2}\partial_\mu \Phi^* \partial^\mu \Phi - \frac{1}{2} V(|\Phi|) \right]$
- Typical choices: quartic potential and solitonic potential

C. Macedo, J. L. Rosa, DRG, Phys.Rev.D 108 (2023) 4, 044021

Face-on | 20 degrees | 50 degrees | 80 degrees



Solitonic potential
Medium-compactness
Central disk model

Photon ring
No shadow
Different from BH images

Solitonic potential
High-compactness
Central disk model

Usual photon rings
Shadow
Similar to BH images

Solitonic potential
High-compactness
ISCO disk model

Many photon rings
Shadow
Different from BH images

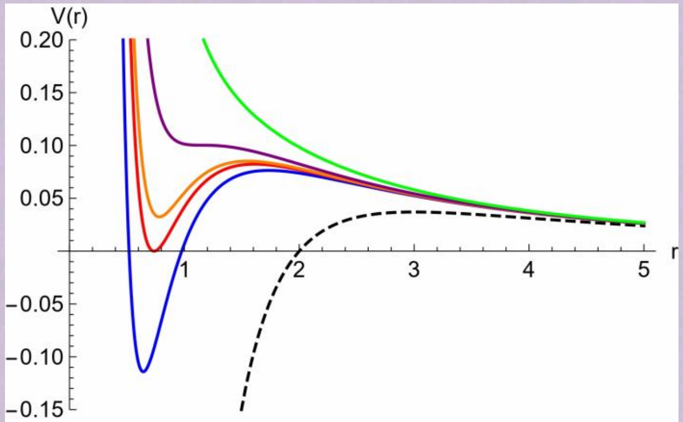
- **For UCOs, photon spheres always come in pairs: one unstable, one stable**
- **A multi-ring structure due to additional light trajectories circling the two photon spheres**
- **Time delay effect in time-averaged images may influence actual luminosity of innermost rings**

9 SU models decreasing peak of emisión from ISCO to center

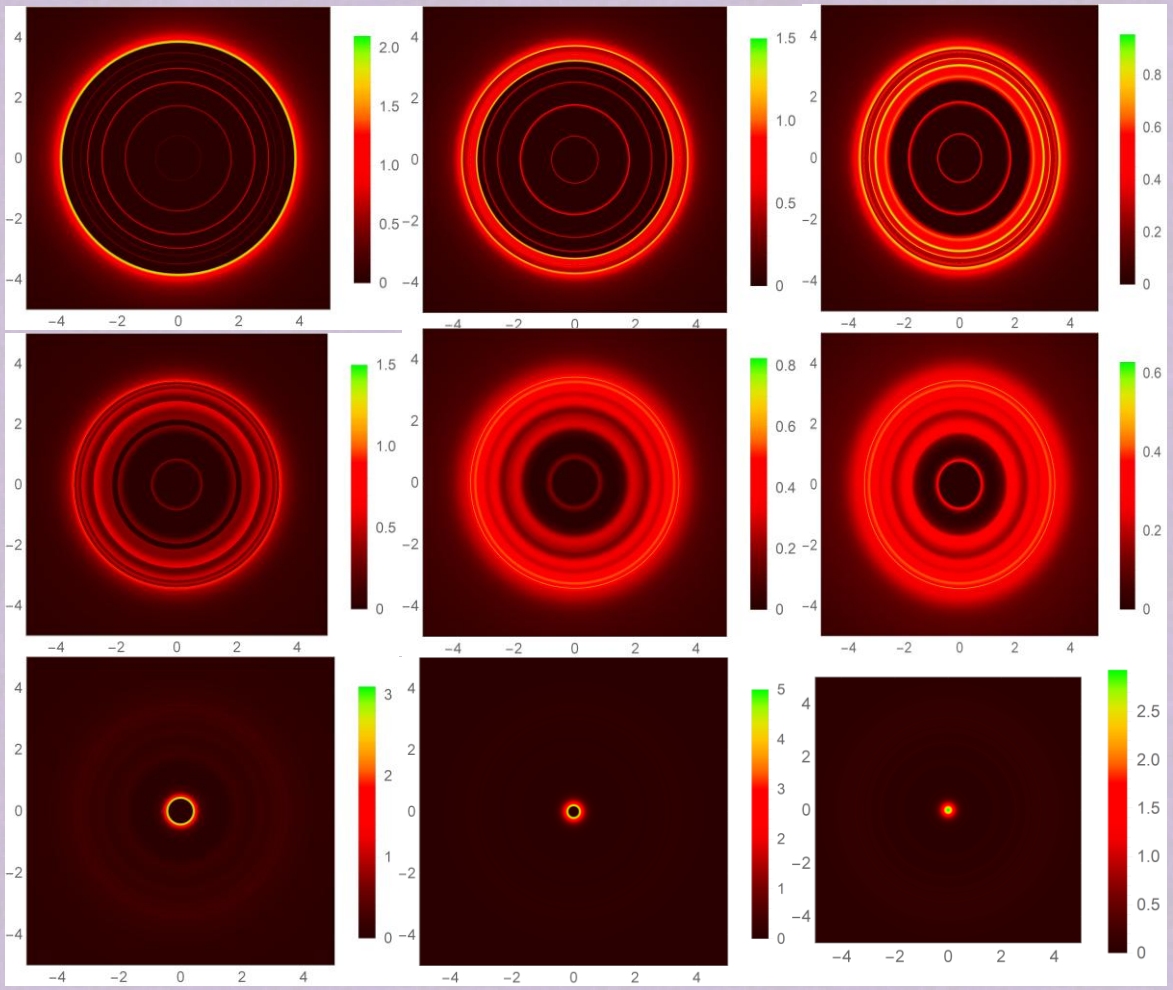
$$A(r) = 1 - \frac{2Me^{-l/r}}{r} \,,$$

A toy-model with an infinite central potential barrier

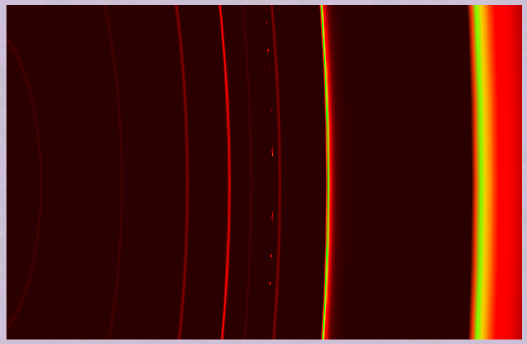
A. Simpson and M. Visser, JCAP 03 (2022) 011.



M. Guerrero, G. J. Olmo, D. Saez-Gomez, DRG, Phys.Rev.D 106 (2022) 4, 044070



Many additional photon rings, up to 9 clearly visible and isolated, from n=6 imaging



Universal expectations on photon rings and shadows of black holes not fulfilled!

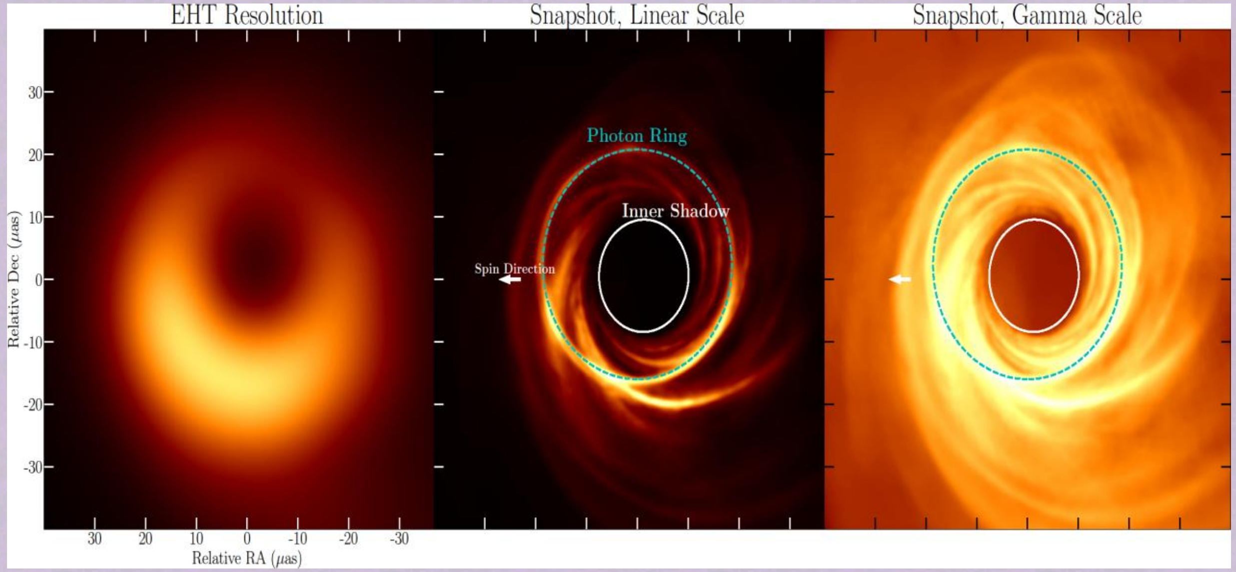
- **Theoretically, the shadow is defined by the critical curve, to which the sequence of photon rings converges in the limit $n \to \infty$**
- **However, the central brightness depression only coincides with the critical curve for spherical disk models.**
- **In thin or thick disks, i.e., as long as there are gaps in the emission region, the shadow radius will be reduced**
- **The minimum shadow radius is determined by the geometry alone: the inner shadow, a redshifted image of the event horizon**

A. Chael, M. D. Johnson, A. Lupsasca, *Astrophys.J.* 918 (2021) 1, 6,

- The shadow's radius r_{sh} is not directly observable due to the fact that the EHT cannot measure brightness below $\sim 10\%$ of its peak luminosity
- EHT claims that the size of the direct emission can act as a proxy of the shadow's size
- Using data on M/D for Sgr A* and M87 it reports the constraint

$$4.21 \lesssim \frac{r_{sh}}{M} \lesssim 5.66 \quad (\text{at } 2\sigma)$$

K. Akiyama et. al.
The Astrophysical Journal 930 (2022) L17

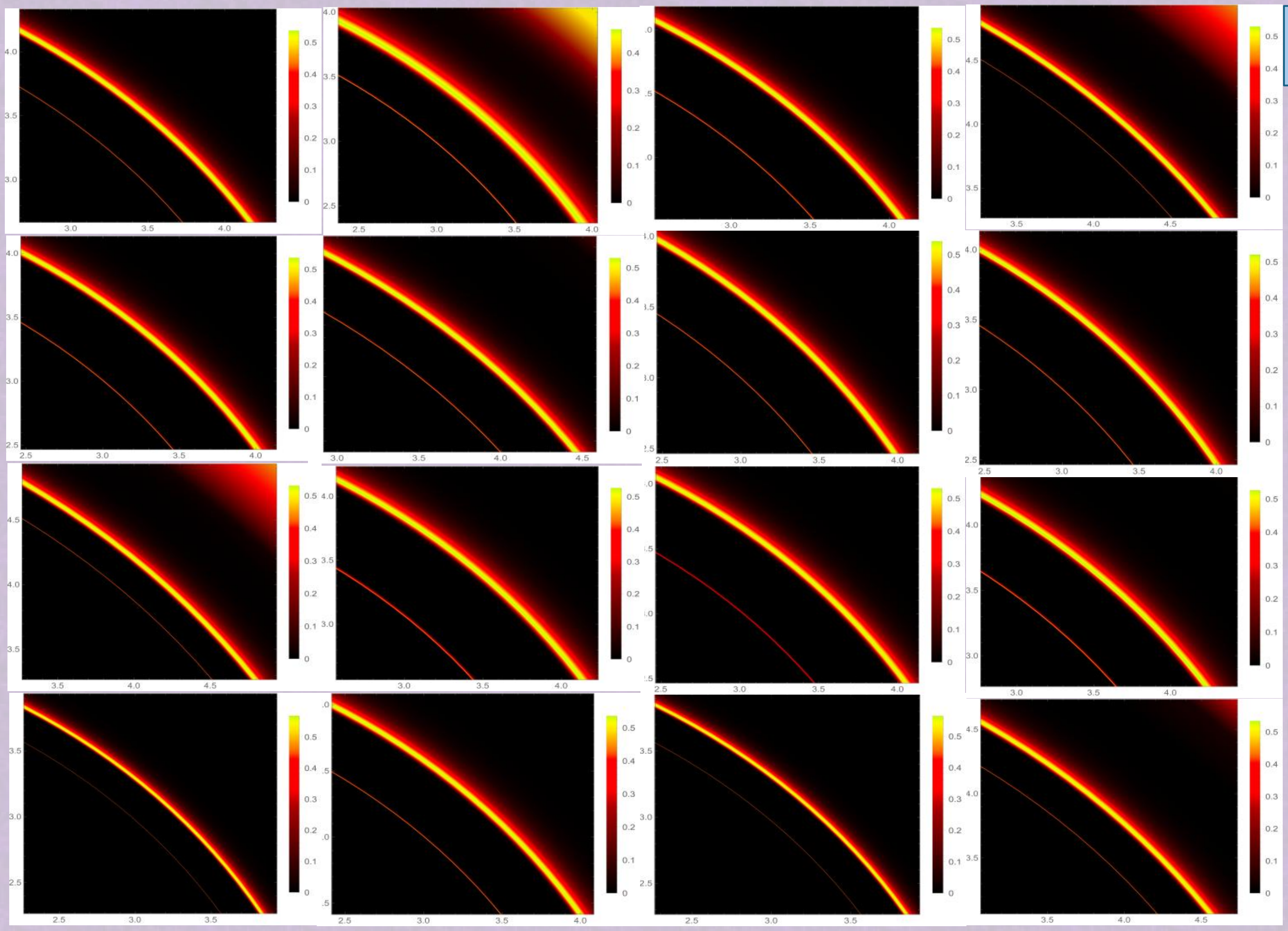


Magnetically arrested simulation of M87

Caveats: calibration factors accounting for theoretical and observational uncertainties; GR as gravity theory; Kerr as default solution; accretion disk modelling, etc

S. Vagnozzi et. al.
Class.Quant.Grav. 40 (2023) 16, 165007
60+ geometries constrained with this observation!

- **Photon rings are self-similar images of the source, redshifted in the background geometry of the black hole**
- **They approach the critical curve in the limit $n \to \infty$ but interferometric projects (i.e. ngEHT) may go up to n=1 (maybe n=2)**



L. D. Silva, G. J. Olmo, DRG, D. Saez-Gomez, Phys.Rev.D 108 (2023) 8, 084055 → Photon rings of 16 geometries!

Photon rings satisfy universal scaling relations describing the radial drift of unstable bound geodesics, driven by critical exponents dependent only on the background geometry

For a photon starting at a location $r_0 = r_{ps} + \delta r$ it drifts away, after n half-turns, to

$$r = r_0 e^{\gamma_{ps} n}$$

$$\gamma_{ps} = \pi \frac{1}{B_{ps}^{1/2} A'_{ps}} \left[A'^2_{ps} - 2 A_{ps} A''_{ps} \right]^{1/2}$$

This parameter is dubbed as the Lyapunov exponent.

It controls the flux ratio between sucessive photon rings in the limit $n \to \infty$

$$\frac{I_{n+1}}{I_n} \propto e^{-\gamma_{ps}}$$

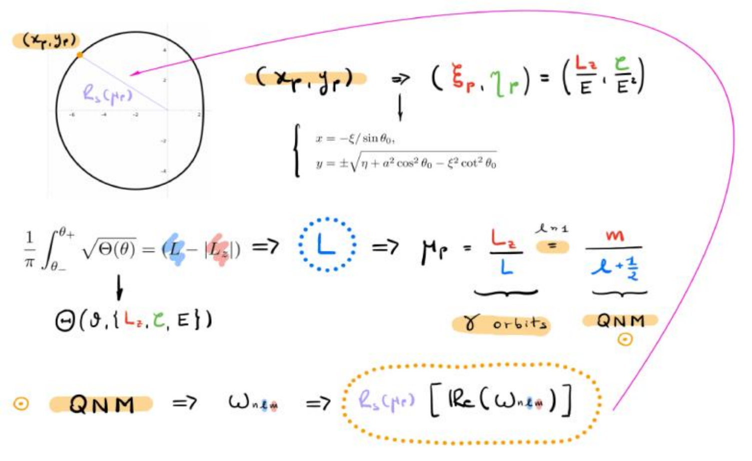
Measurement of two successive photon rings provides info on the background geometry!

- **Gravitational waves are perturbations on the fabric of space-time, with quasi-normal modes encapsulating the way a black hole ``rings" upon a perturbation (simulated via e.g. a scalar or Dirac field)**
- **Black Hole Imaging is the optical appearance of a black hole when surrounded by its accretion disk**
- **Despite being seemingly different phenomena…they turn out to be related!**

Eikonal limit

$$l \gg n$$

It works for axially symmetric BHs too!



QNM frequency

Angular velocity of unstable bound geodesics

$$\omega = \omega_R + i\omega_I = \left(l + \frac{1}{2}\right)\Omega_R - i\left(n + \frac{1}{2}\right)\Omega_I$$

QNM damping time

Lyapunov time-scale of unstable bound geodesics

$$\Omega_R = \frac{1}{b_c}$$

$$\Omega_I = |\lambda|$$

$$\gamma = \pi b_{ps}|\lambda|$$

$$r_{sh} = \frac{\left(l + \frac{1}{2}\right)}{\omega_R}$$

Shadow radius correlates with QNM frequency

$$\gamma_{ps} = \frac{\pi b_{ps}\omega_I}{\left(n + \frac{1}{2}\right)}$$

Photon rings luminosity frequency correlates with QNM damping time

D. Pedrotti, S. Vagnozzi
Phys.Rev.D 110 (2024) 8, 084075

Correlation between sets of observables on each side of of the correspondence!

Several caveats but still to be fully exploited!

Usefulness of the correspondence?

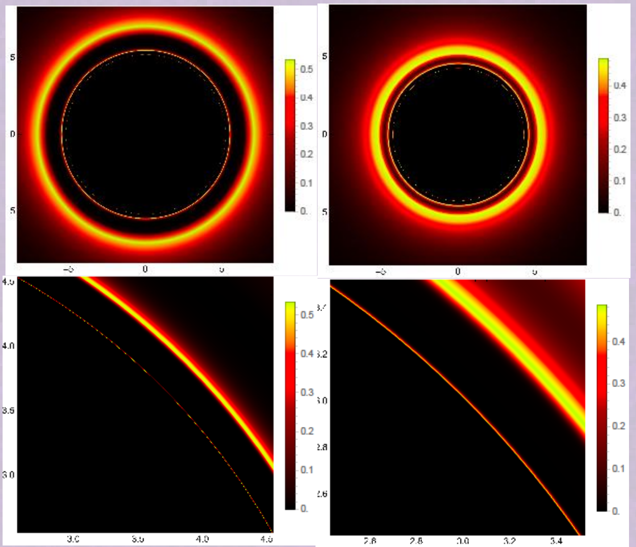
- **We check the usefulness of the correspondence with two simple, naïve space-times**

- **For black holes we pick a scale-dependent gravity space-time with a single extra parameter**

$$A(x) = 1 - \frac{2}{r}\left(1+\frac{\epsilon}{6r}\right)^{-3},$$

B. Koch et. al. (including DRG), 2506.15944 [gr-qc]

Schwarzschild   BH with $\epsilon = 1.0$



Reduced size of the central brightness depression

Relatively brighter photon rings, up to a factor ~ 1.5

QNM frecuencies reproduce results from BH imaging for large l!

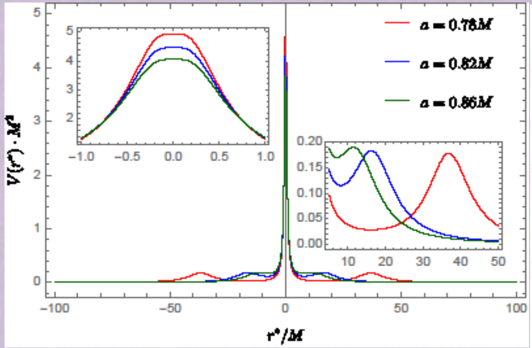
Case	Overtone	Ω_c	$\lvert\lambda\rvert$	b_c^{QNM}	$\frac{b_c^{BHI}}{b_c^{QNM}}$	$\frac{\gamma_{ps}^{BHI}}{\gamma_{ps}^{QNM}}$
$\epsilon = 0$, $\ell = 10$	$n=0$	0.1925	0.1925	5.1946	1.0003	0.9999
	$n=1$	0.1920	0.1927	5.2077	0.9977	0.9963
	$n=2$	0.1910	0.1931	5.2337	0.9928	0.9892
	$n=3$	0.1896	0.1937	5.2728	0.9854	0.9787
$\epsilon = 1.0$, $\ell = 10$	$n=0$	0.2363	0.2012	4.2309	0.9997	1.0070
	$n=1$	0.2352	0.2013	4.2373	0.9988	0.9978
	$n=2$	0.2352	0.2016	4.2499	0.9958	0.9933
	$n=3$	0.2342	0.2021	4.2688	0.9914	0.9868

Table 1: Values of the parameter Ω_c and of $|\lambda|$ as well as the inferred values from QNM analysis on b_c^{QNM} using the correspondence QNM-BHI and the ratios b_c^{BHI}/b_c^{QNM} and $\gamma_{ps}^{BHI}/\gamma_{ps}^{QNM}$. Data for QNM extracted from scalar field perturbations

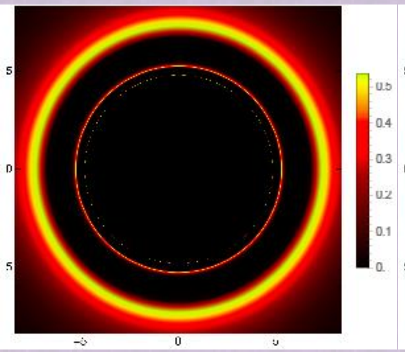
- **For UCOs, we pick a generalization of the black bounce proposal, interpolating between black holes and traversable wormholes**

$$A(r) = 1 - \frac{2Mr^2}{(r^2+a^2)^{3/2}} \quad ; \quad \Sigma(r) = \sqrt{r^2+a^2}.$$

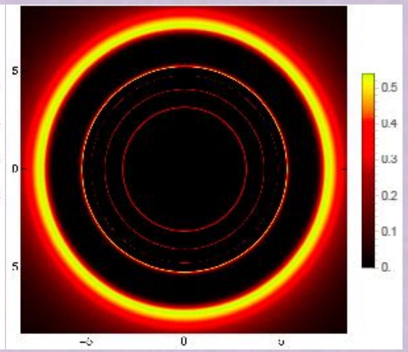
$V_{QNM}(r^\star)$



BH with a=0.76



WH with a=0.78



Trapping potential **produces echoes** with damped frequencies

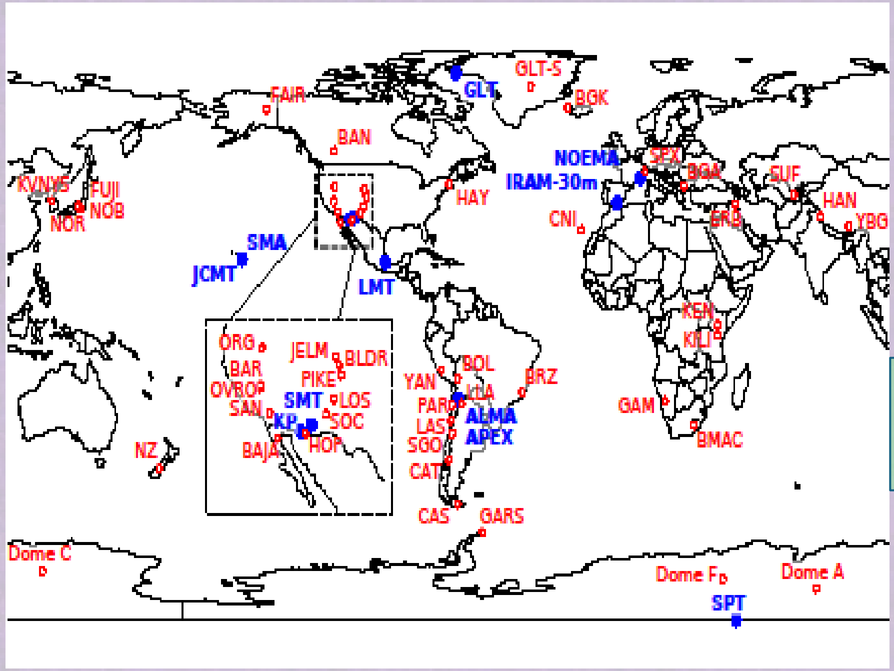
Trajectories with up to n=3 **generate two additional visible rings** in the WH case

How to correlate both features?

A. Duran-Cabeces, D. Saez-Gomez, DRG, 2506.18014 [gr-qc]

Message to take home

- **Theoretical concepts (photon shell, shadow's size, Lyapunov index) are very useful, but need to be put in direct correlation with observables (photon ring, brightness depression)**
- **GRMHD models are though to implement; semi-analytical models reduce complexities while keeping main observables**
- **Two black hole space-times can be very similar in their direct emisión, but deviate strongly in their photon ring structure**
- **UCOs may produce additional visible rings and a shadow reduction. Might they mimic BHs?**
- **Advances in very-long baseline interferometry are expected to be able to resolve the n=1 ring and (perhaps) the n=2?**

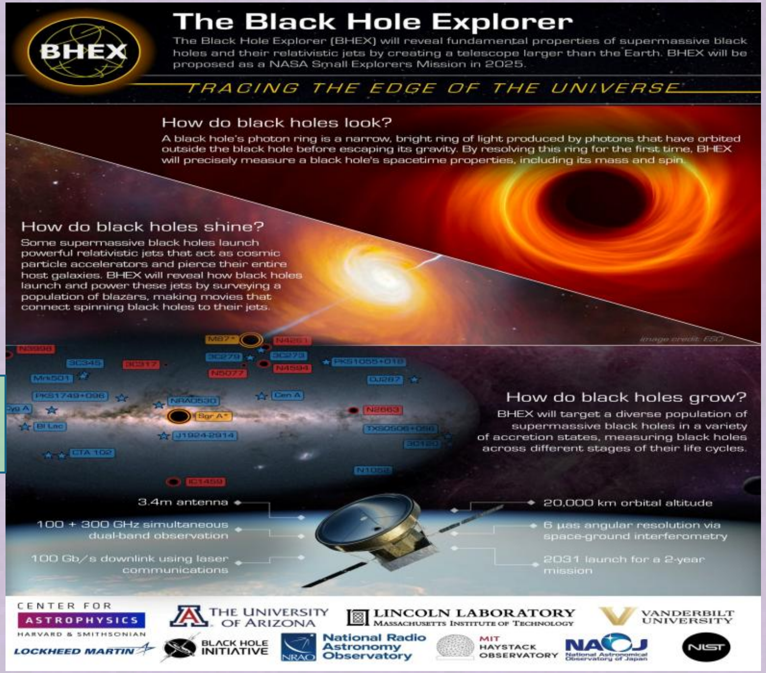


Next-generation Event Horizon Telescope, ground-based, date?

A. Lupsasca et al.
Proc. SPIE Int Soc. Opt. Eng. 13092 (2024) 130926Q

Black Hole Explorer, space-based, 2031

M. D. Johnson et. al.
Galaxies 11 (2023) 61



- **Correspondence QNM-BHI can provide some clues for both black holes and UCOs**

Work funded by the Spanish National Grants PID2022-138607NBI00 and CNS2024-154444, funded by MICIU/AEI/10.13039/501100011033 (``ERDF A way of making Europe" and ``PGCGeneración de Conocimiento“)

Thank you very much for your attention!

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