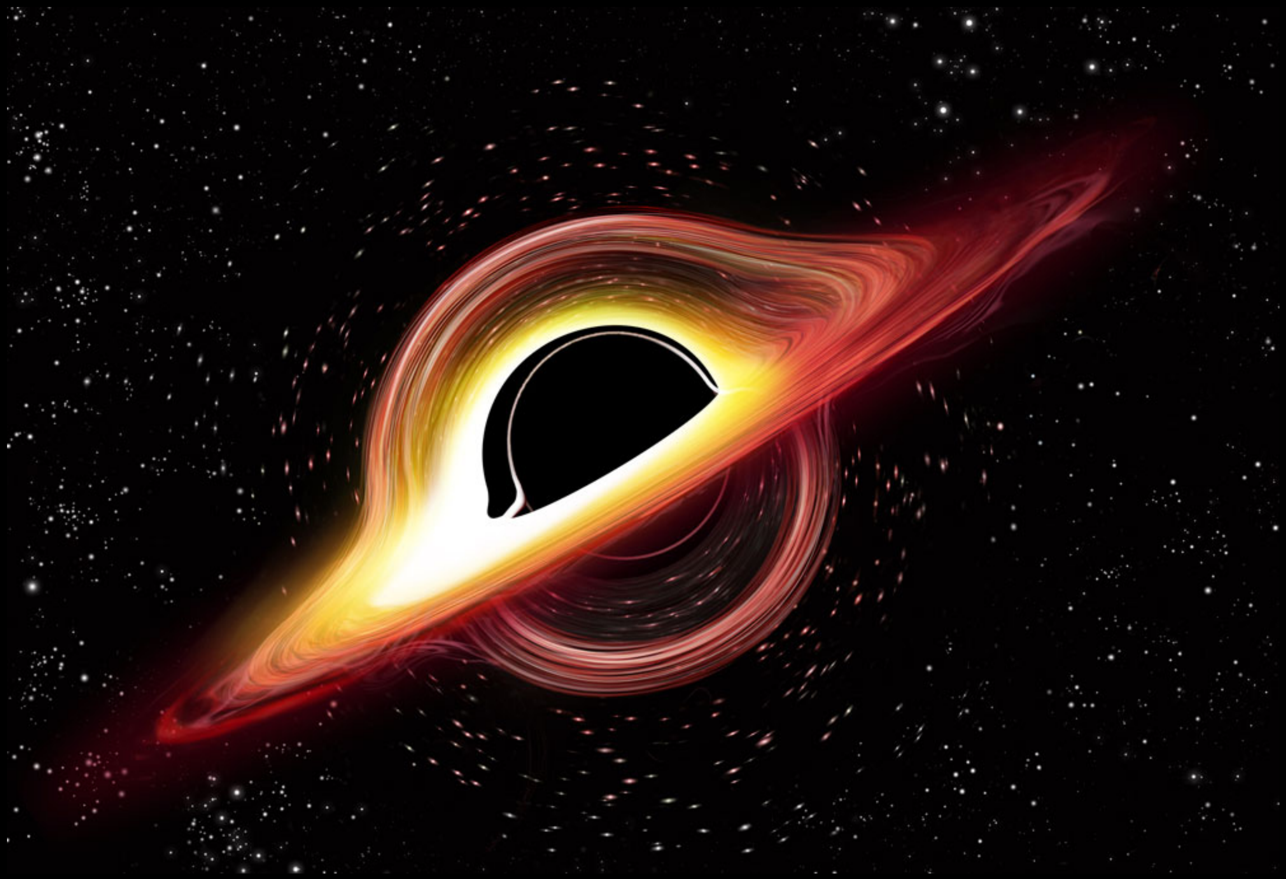
New Physics Out of the Shadow



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Based on: Bambi, Freese, Vagnozzi, **LV**, PRD **100** 044057 (2019) 1904.12983
Vagnozzi&**LV**, PRD **100** 024020 (2019) 1905.12421
Vagnozzi, Bambi, **LV**, CQG **37** 8 087001 (2020) 2001.02986

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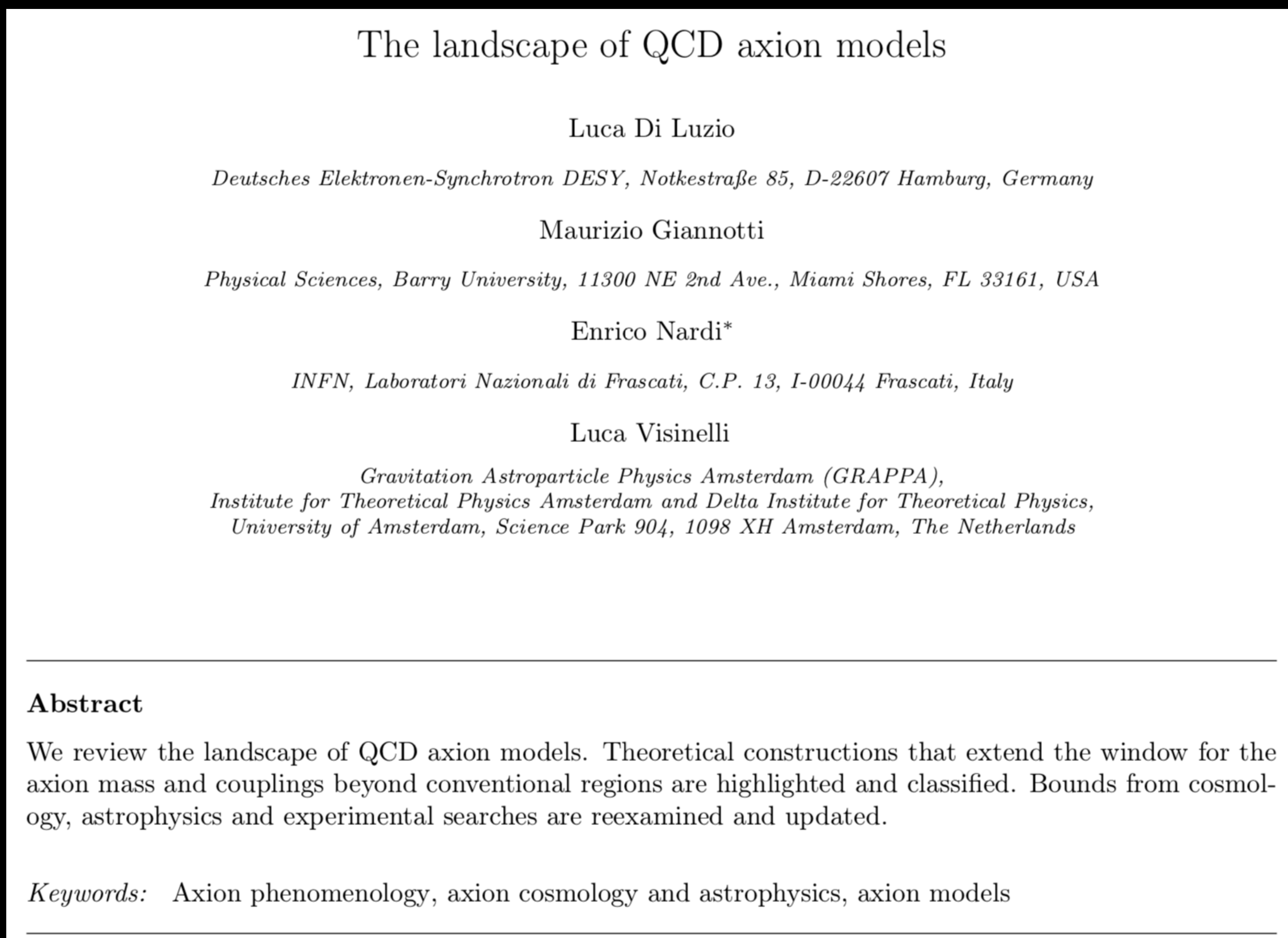
Review on QCD axion models is out!!



The landscape of QCD axion models

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Abstract

We review the landscape of QCD axion models. Theoretical constructions that extend the window for the axion mass and couplings beyond conventional regions are highlighted and classified. Bounds from cosmology, astrophysics and experimental searches are reexamined and updated.

Keywords: Axion phenomenology, axion cosmology and astrophysics, axion models

2003.01100

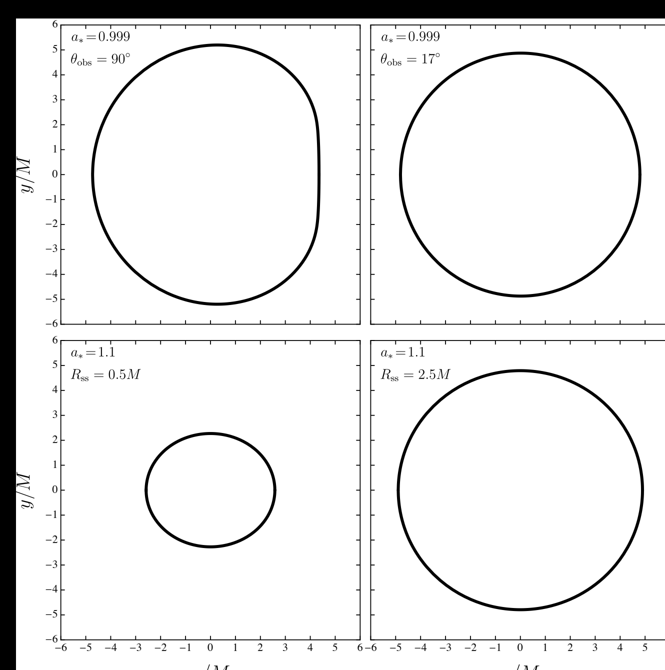
My axion talk: https://www.youtube.com/watch?v=iIfmBKMgyH8

OUTLINE

1. EHT work

2. BH shadow

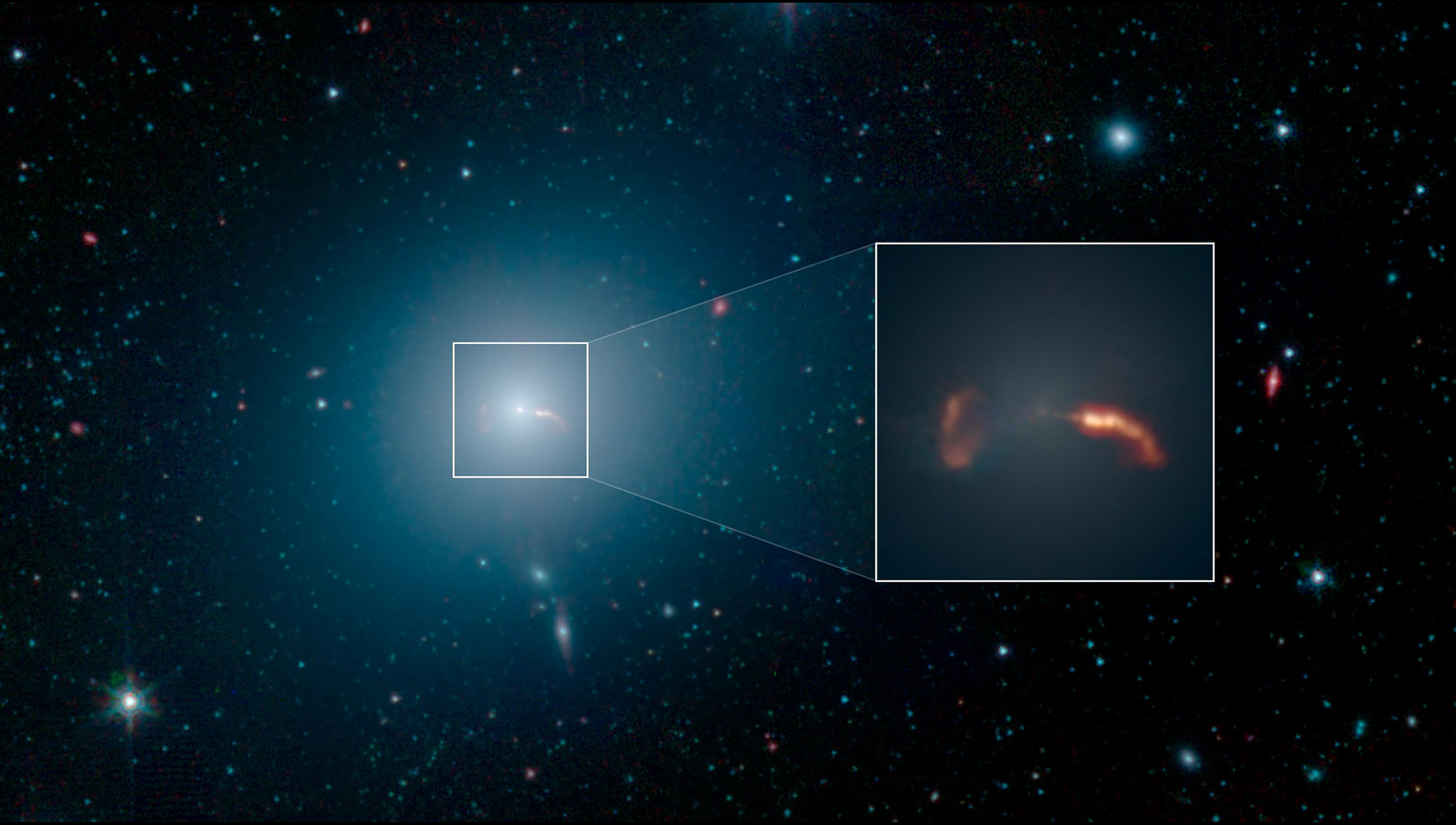
3. What to learn

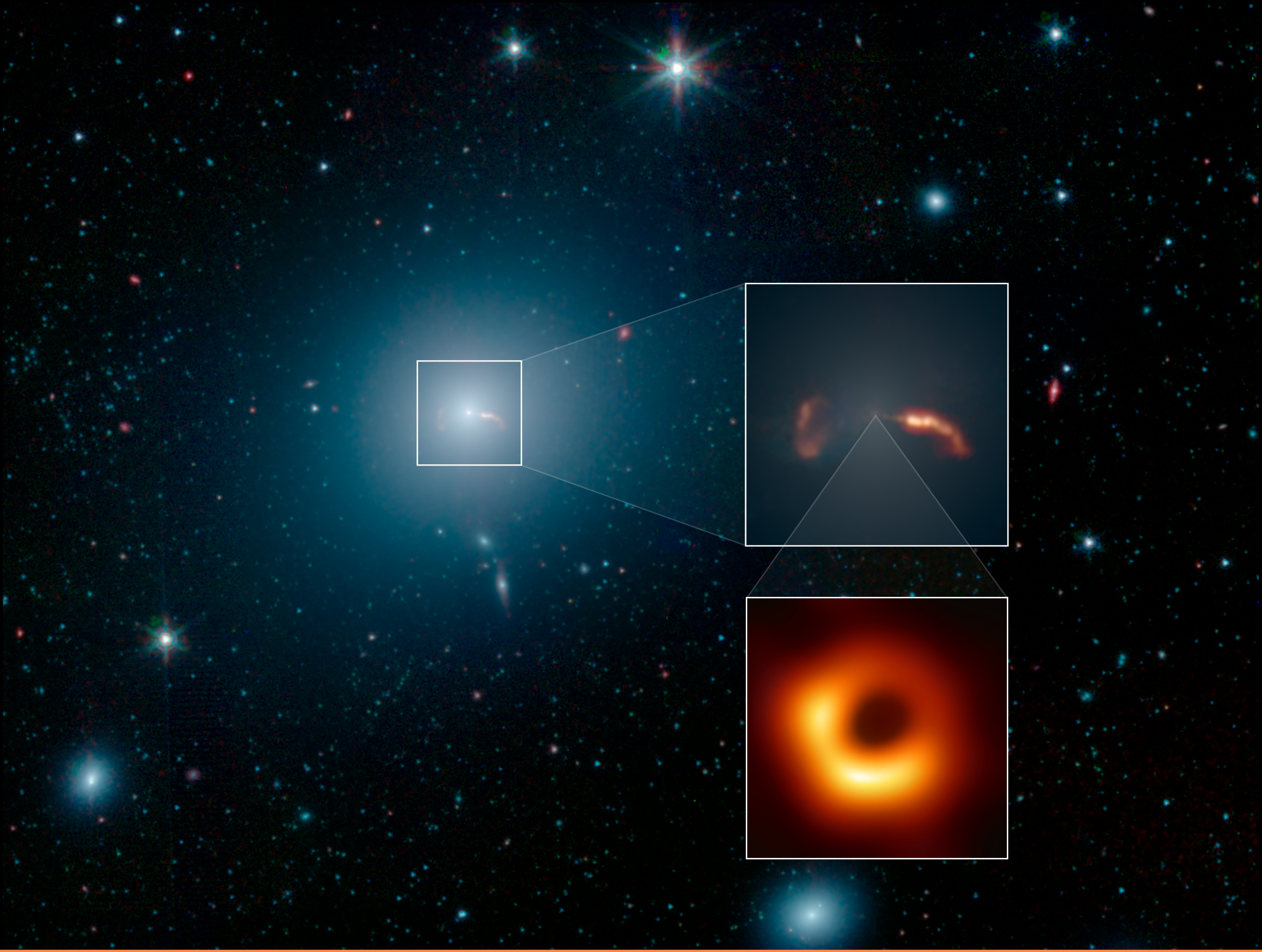


Journey begins here

M87 (or Virgo A, or NGC 4486).
55 million light-years away

Close up



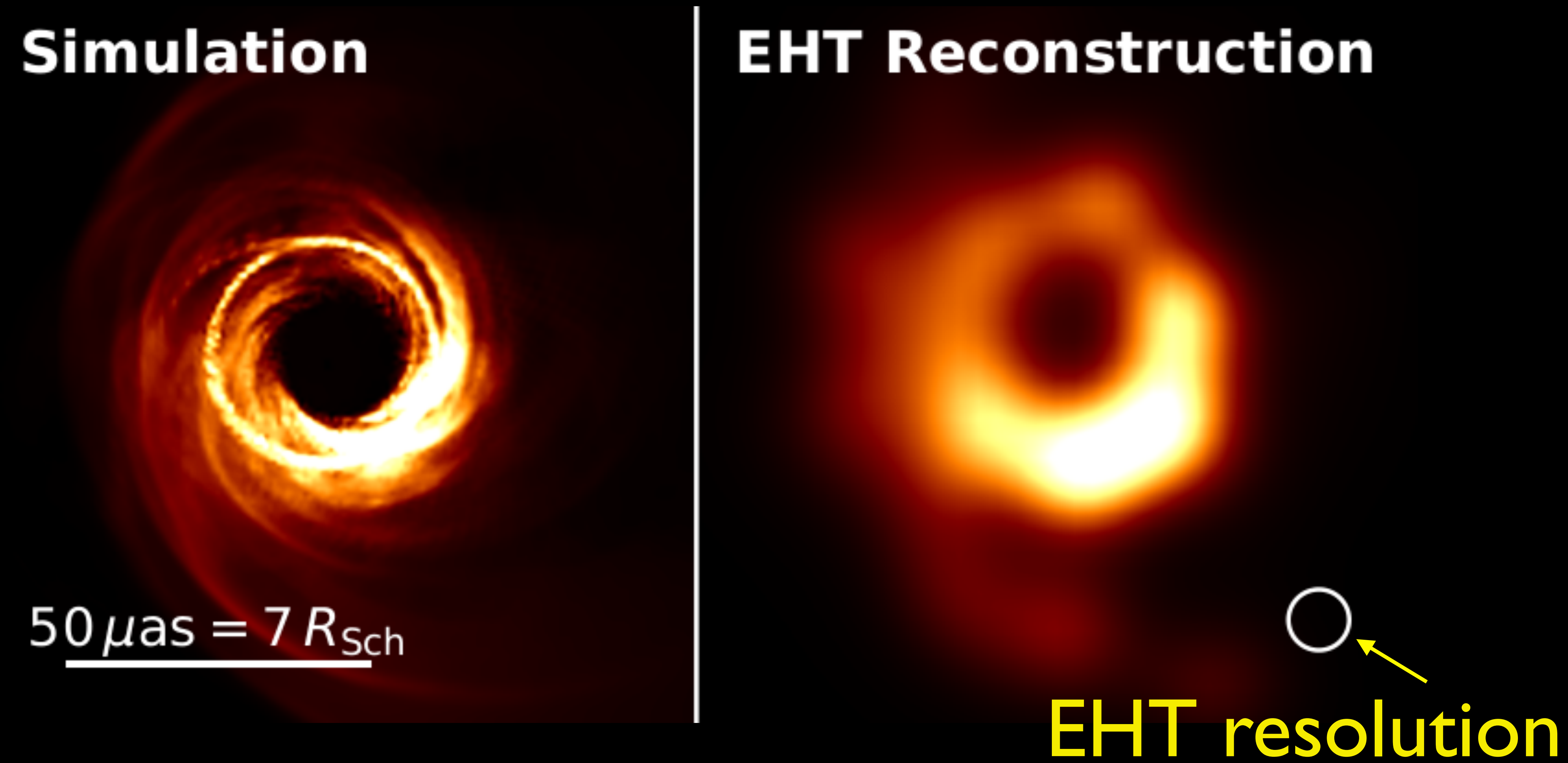


Event Horizon Telescope

VLBI observing M87* and Sagittarius A* at $\lambda = 1.3\,\mathrm{mm}$

Resolution at $10\,\mu\mathrm{arcsec}$

Event Horizon Telescope



Left: simulation of M87* at 230GHz

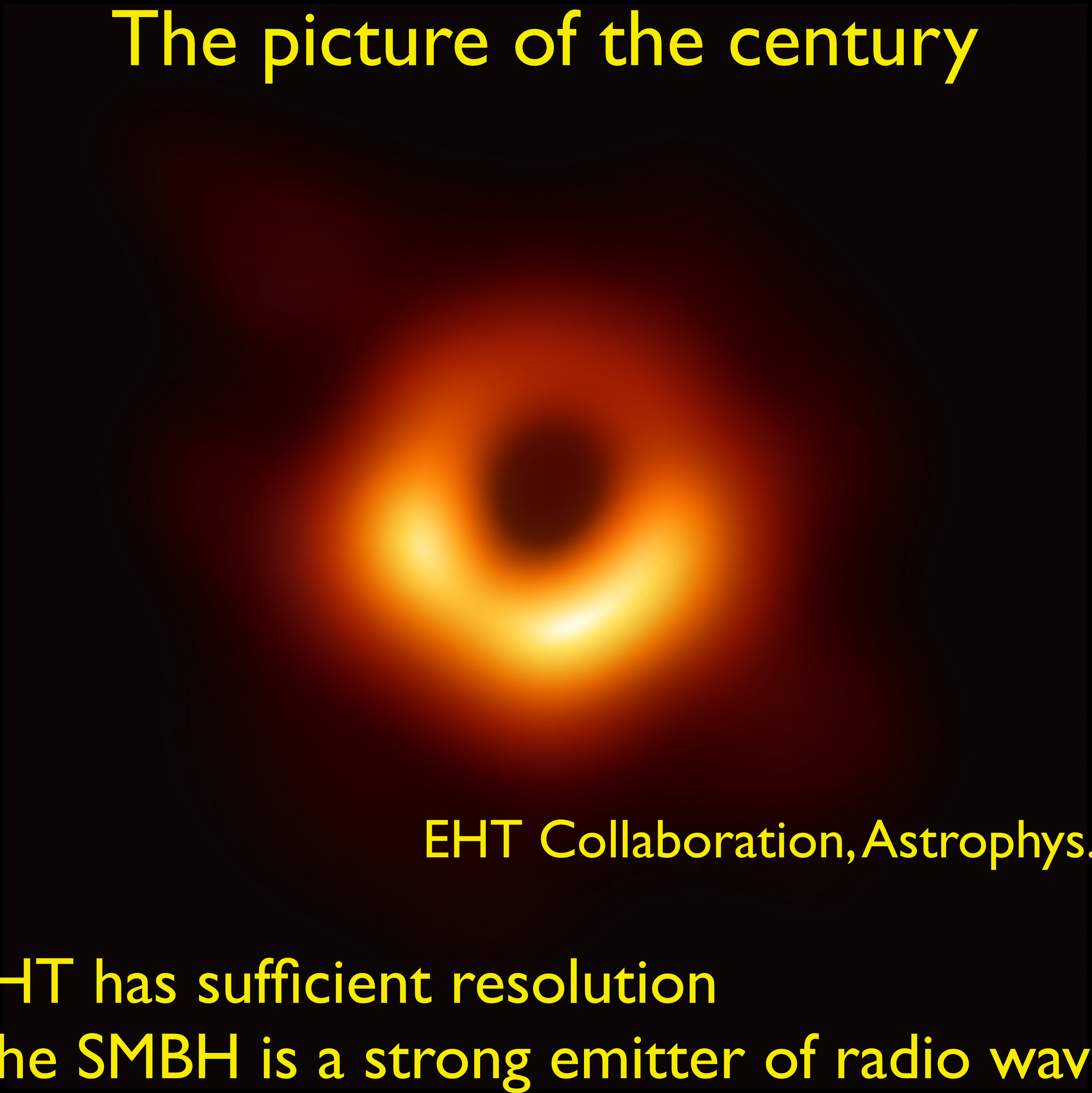
Right: Image reconstructed from simulated data using https://github.com/achael/eht-imaging

The picture of the century

EHT Collaboration, Astrophys. J. **875** (2019)

- Event Horizon Telescope (April 2019)
- 10 days acquisition + 2 years analysis

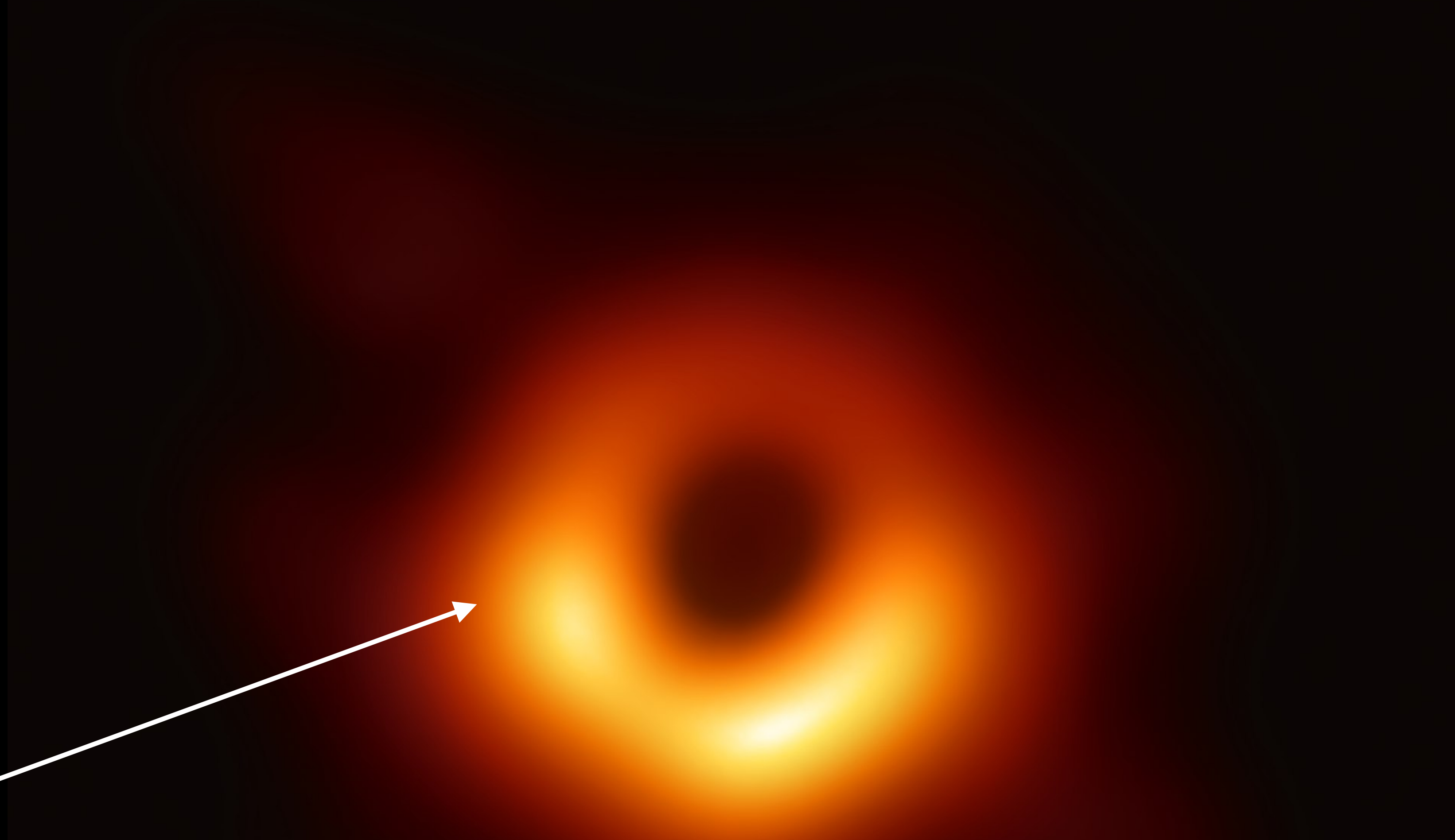
The picture of the century



EHT Collaboration, Astrophys. J. **875** (2019)

- EHT has sufficient resolution
- The SMBH is a strong emitter of radio waves
- Little foreground radio pollution

The picture of the century

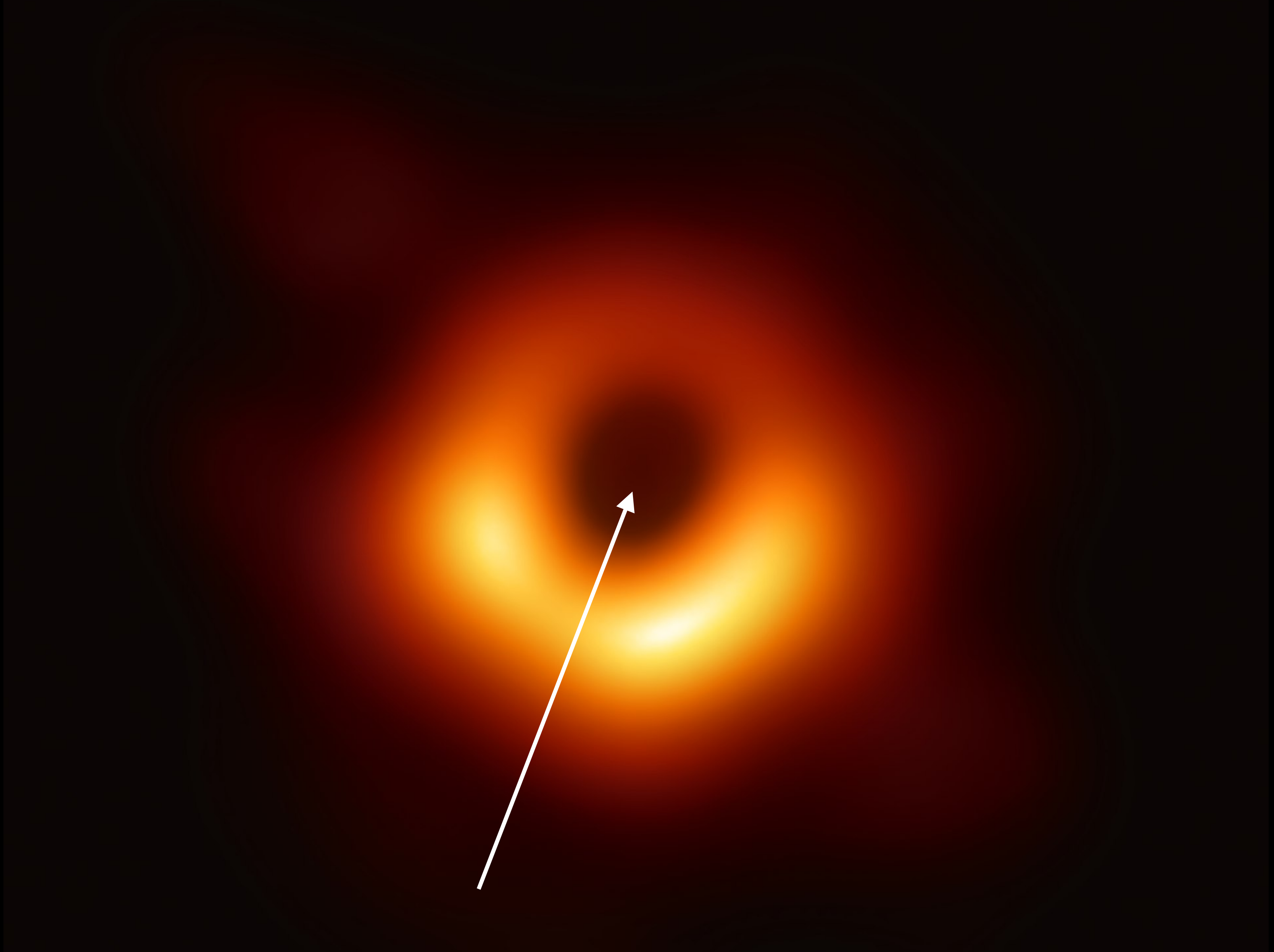


- Relativistic beaming of the plasma
- Mass $M_{\rm BH} = (6.5 \pm 0.7) \times 10^9 \, M_\odot$ from comparing the image with MHD simulations of rotating BH
- Agrees with stellar dynamics (Gebhardt+ 2011)
- Angular diameter $(42 \pm 3)\,\mu$as

The picture of the century

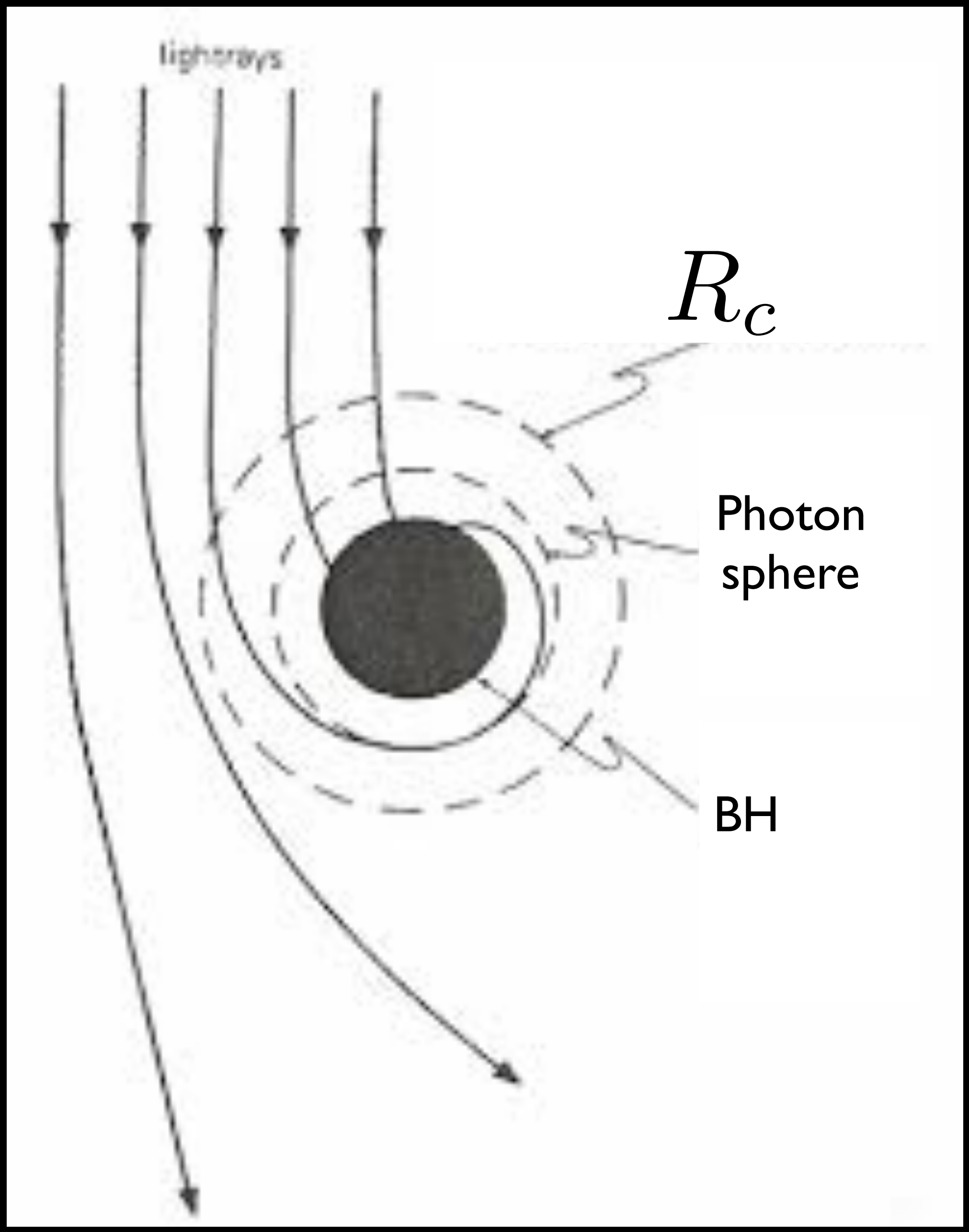
- Black hole emit Hawking radiation
- Indirect evidences is needed (motion of nearby stars, radio, GW)

The picture of the century



Shadow of a BH: dark area in the image of an optically thin region around the compact object.

Shadow ⟷ photon capture radius



Non-rotating BH:

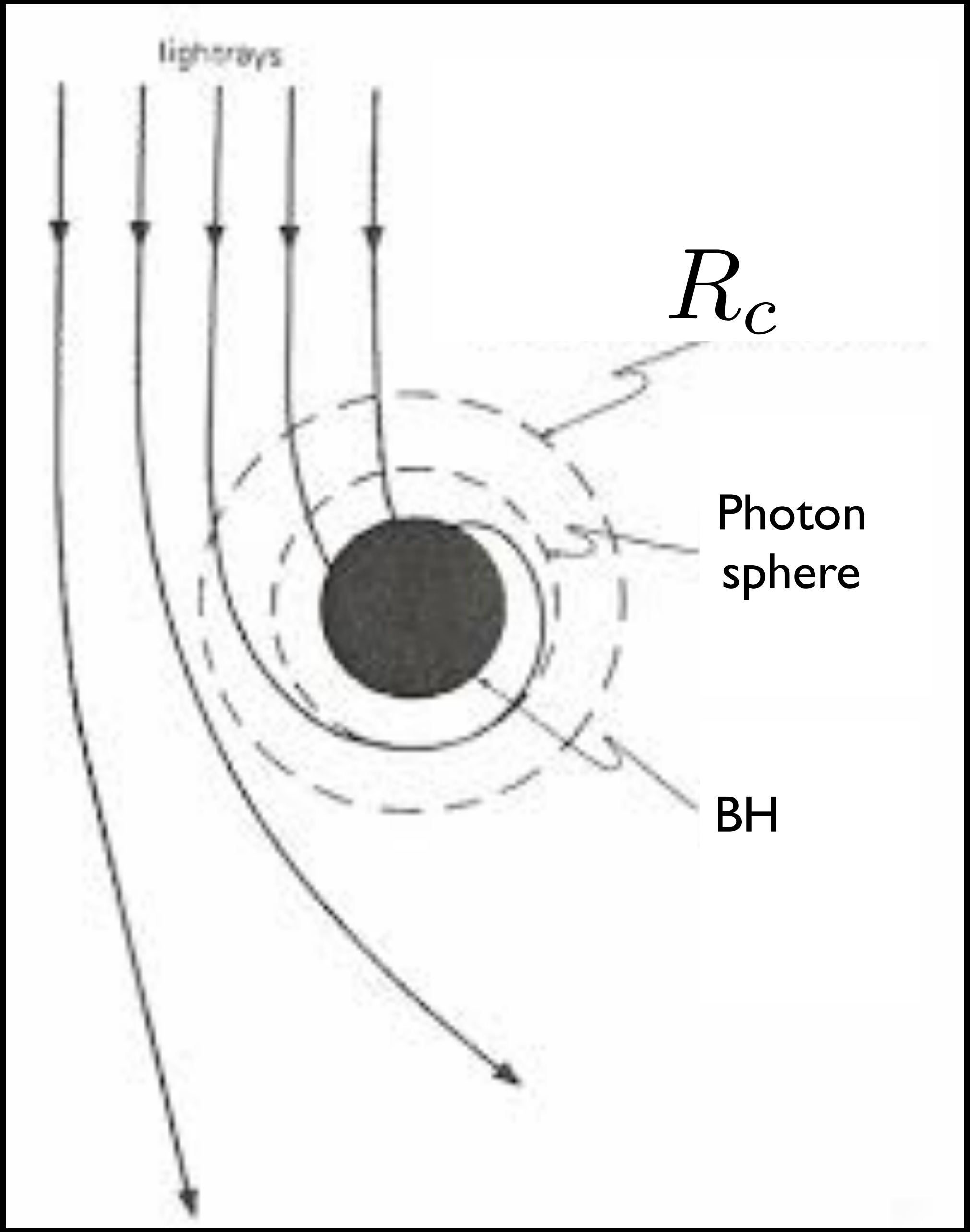
$$r_g = GM_{\rm BH}/c^2$$
$$R_s = 2r_g$$
$$R_c = \sqrt{27}r_g$$

Image angular diameter:

$$\theta = \frac{2R_c}{D} \approx 42\,\mu\text{arcsec}$$

(Measured $(42 \pm 3)\,\mu$as)

Shadow ⟷ photon capture radius

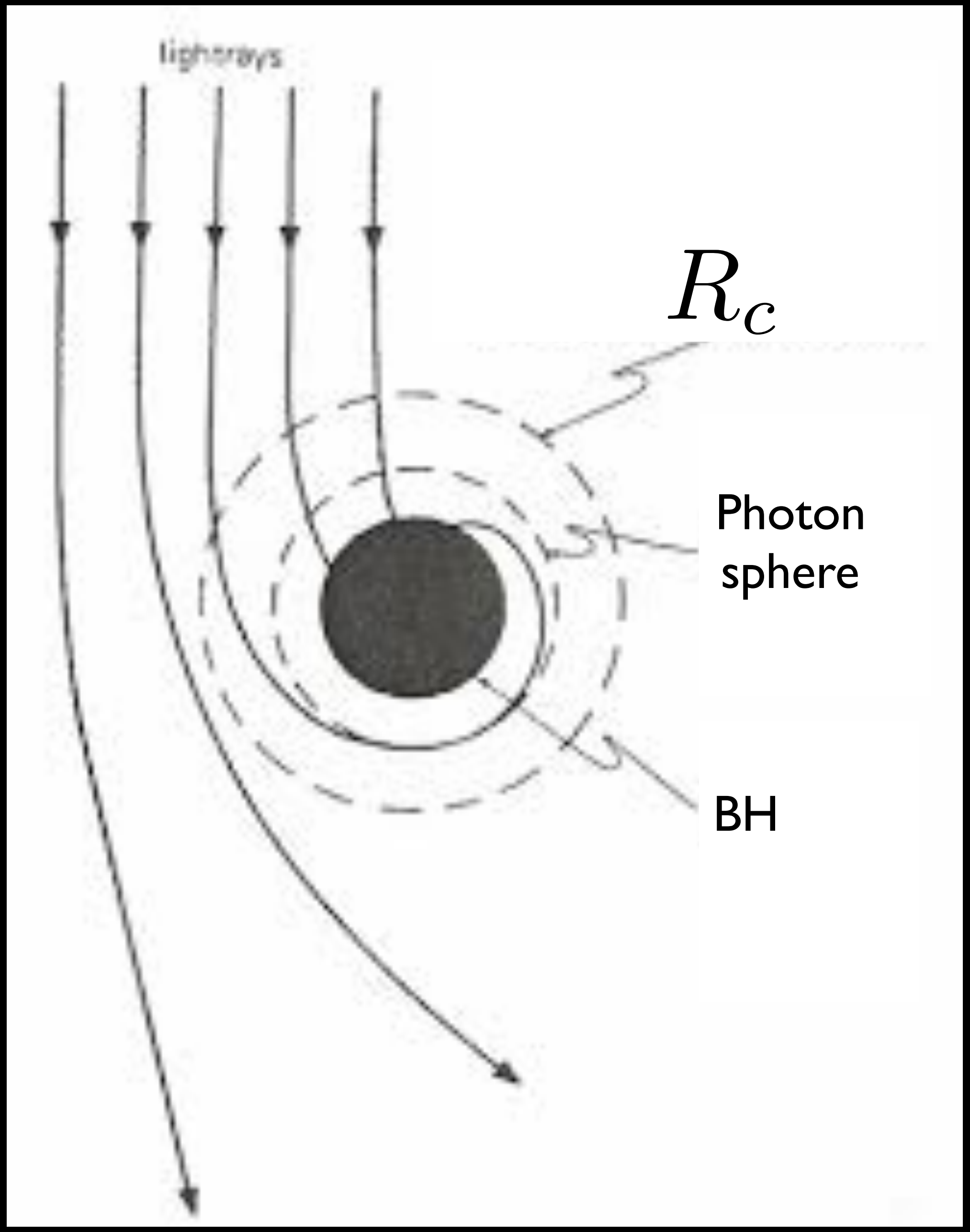


Rotating BH:

$$r_h = M + \sqrt{M^2 - a^2}$$

Kerr bound: $|a| \leq M$

Shadow ⟷ photon capture radius



Rotating BH:

Photon geodesic

$$\left(r^2 + a^2 \cos^2\theta_{\rm obs}\right)\left(\frac{dr}{d\lambda}\right) = \sqrt{\mathcal{R}}$$

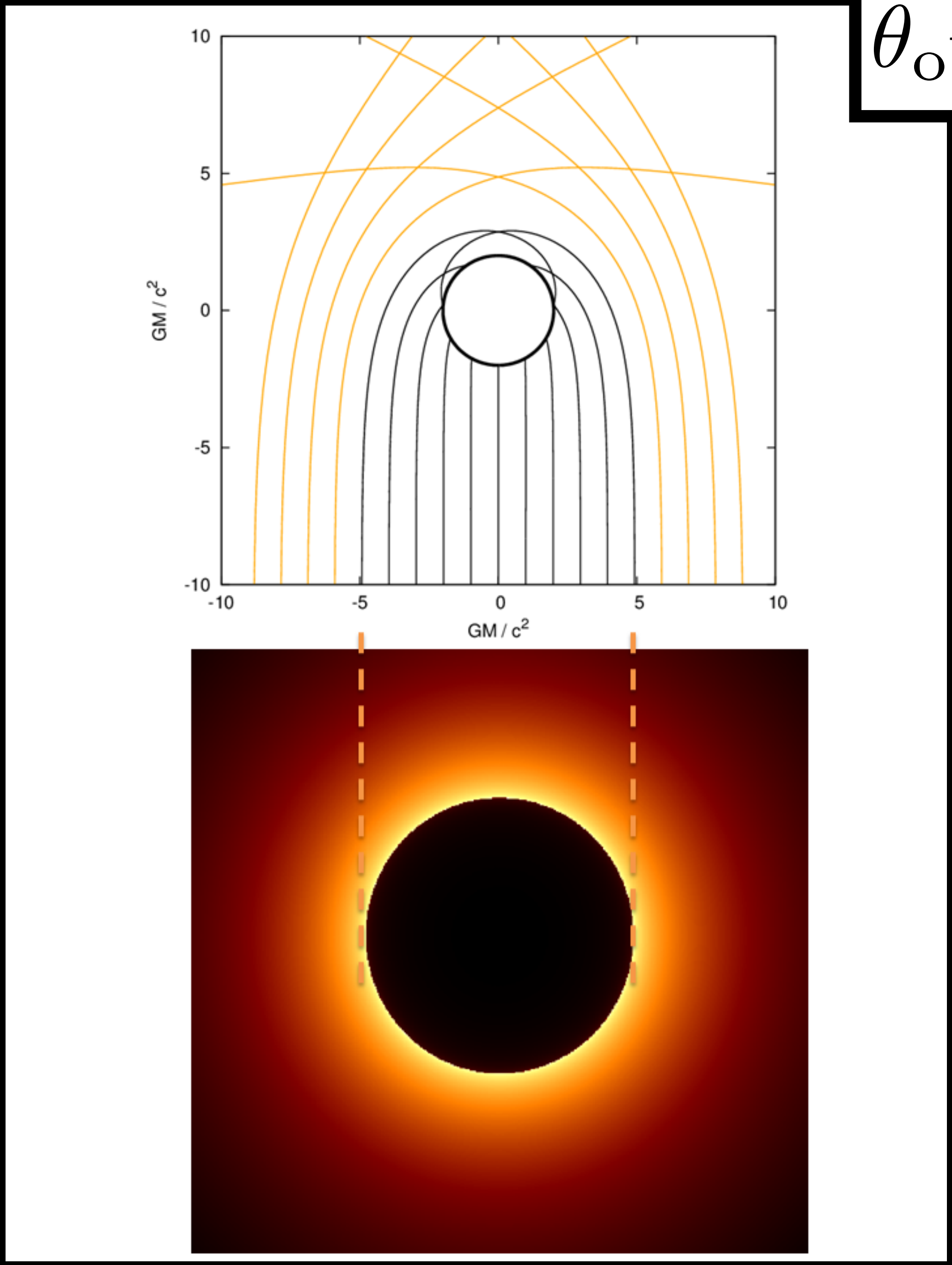
Depends only on:

- BH spin a
- Obs angle $\theta_{\rm obs}$

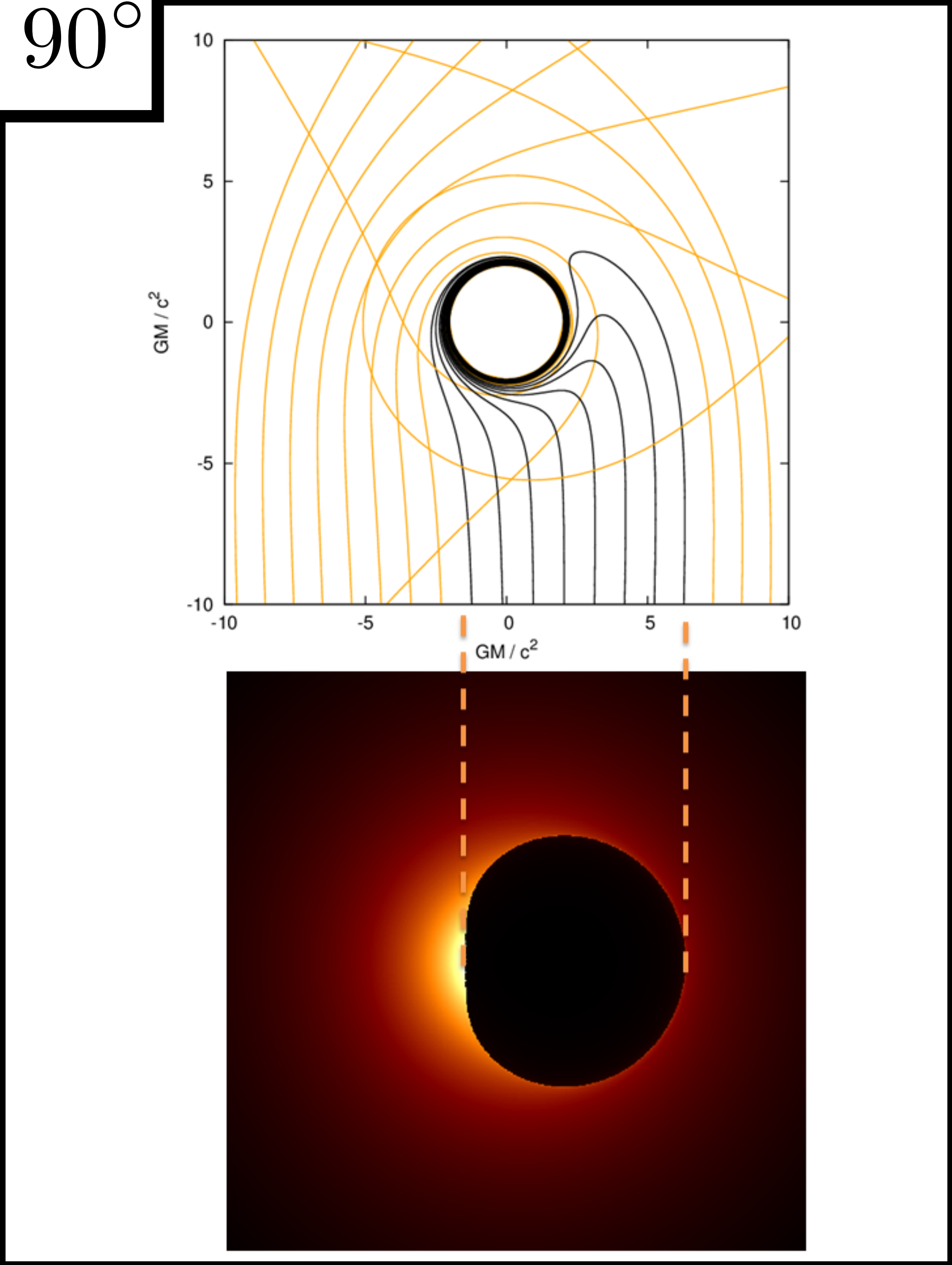
The roots of $\mathcal{R}(r) \geq 0$ define bound orbits (if exist)

Photon trajectories around a BH + shadow image

$$\theta_{\rm obs} = 90^\circ$$

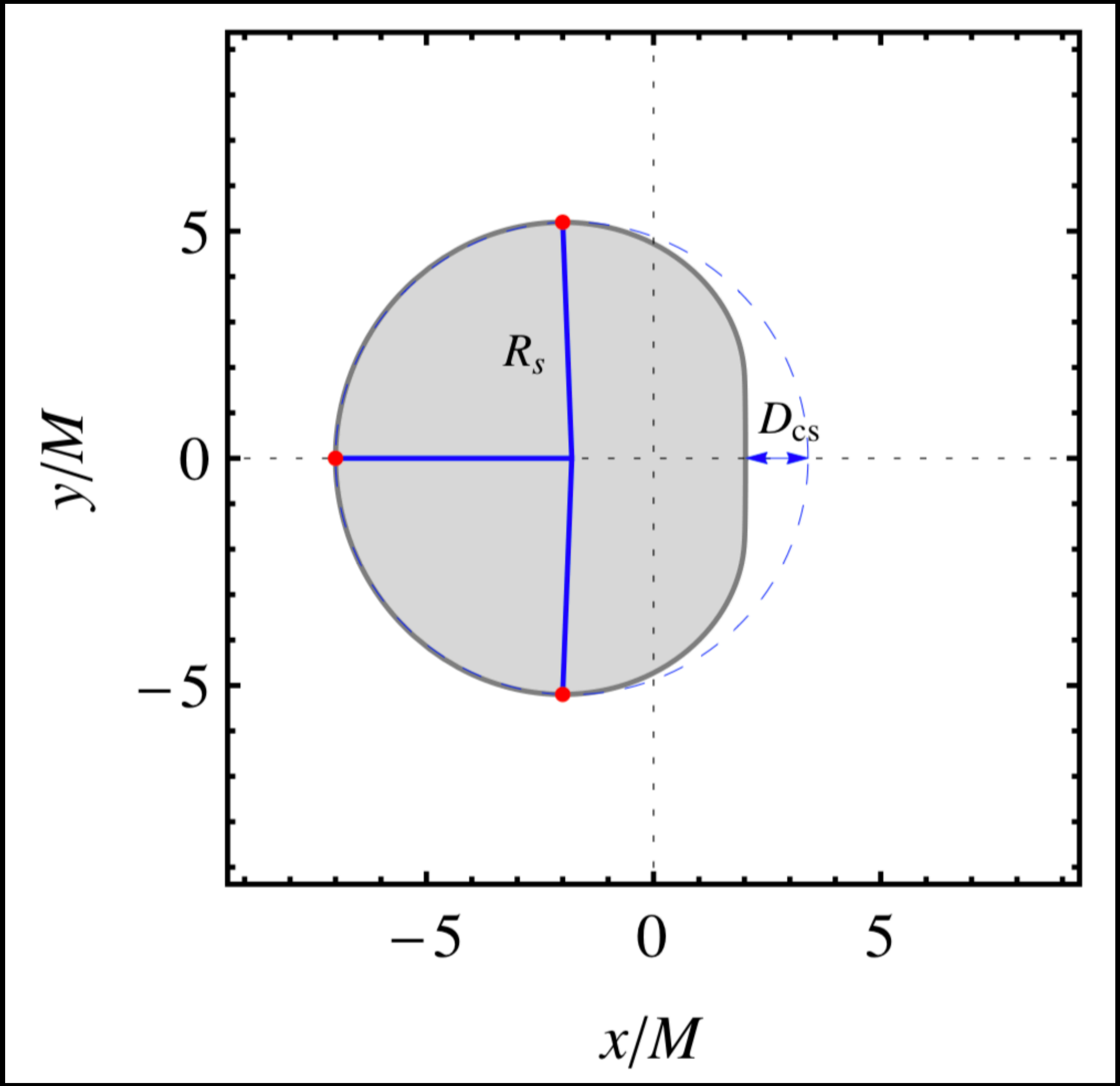


Non-rotating



Rotating

BH Shadow for rotating BH

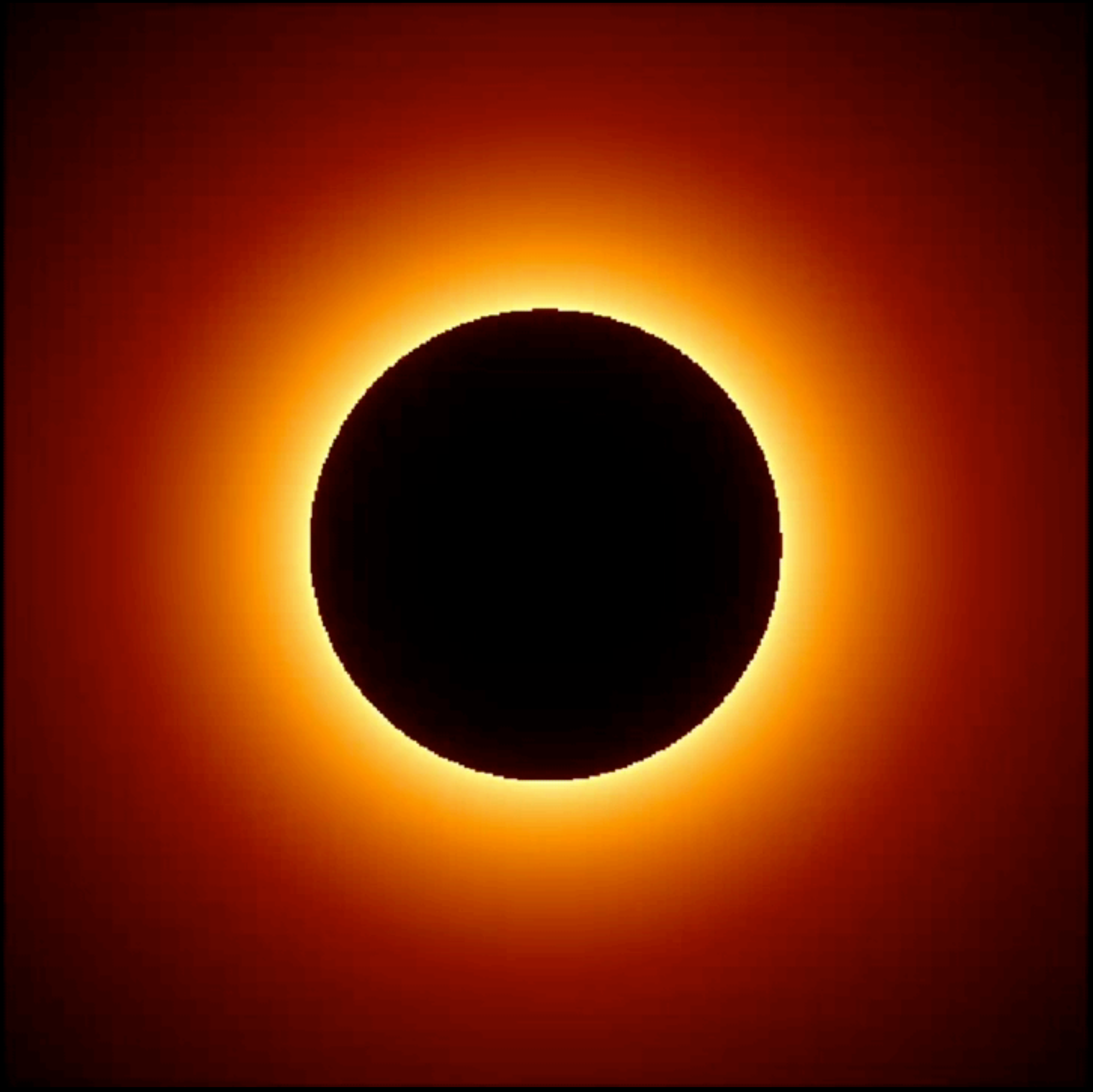


Define the distortion:

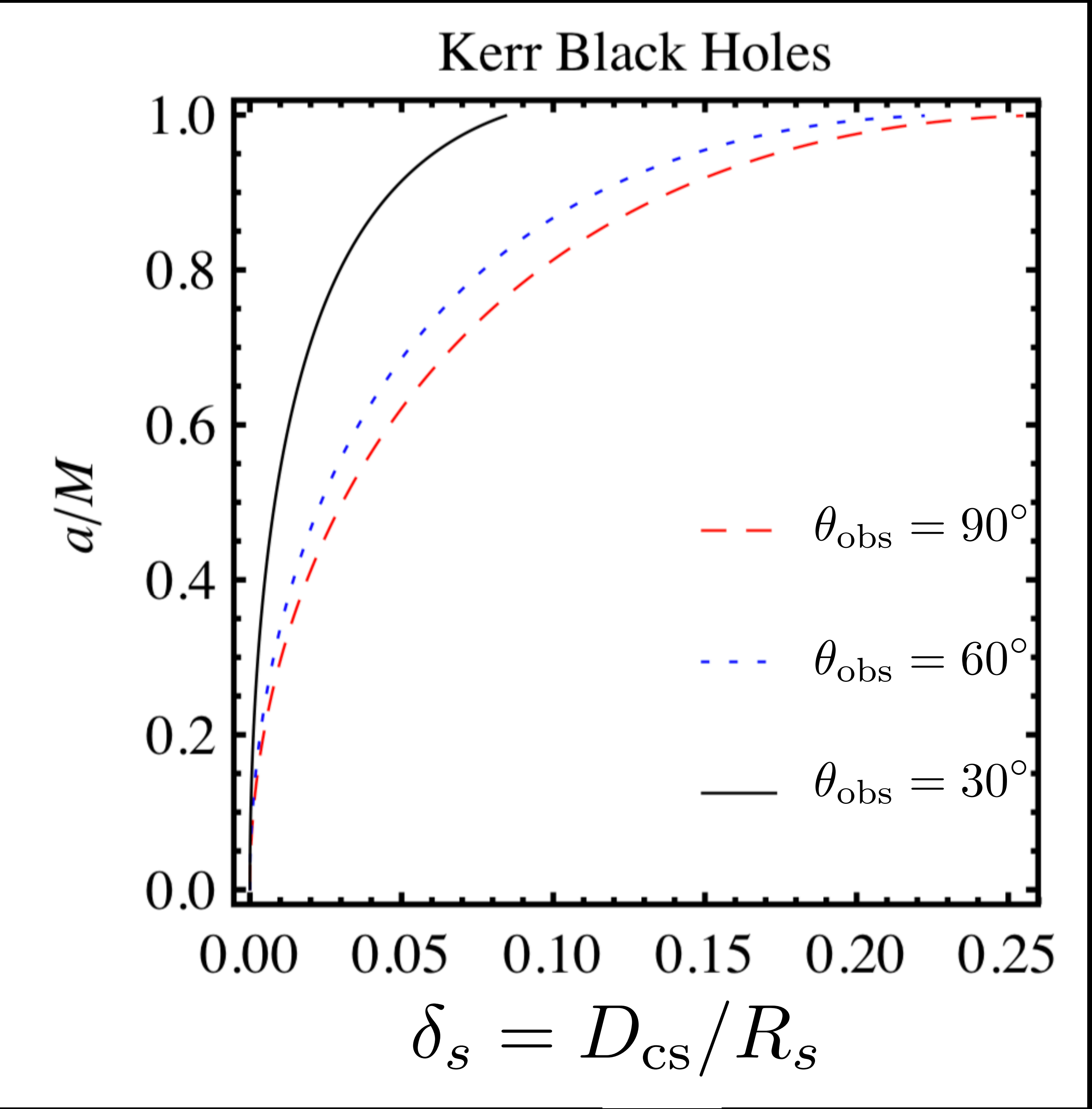
$$\delta_s = D_{\rm cs}/R_s$$

Spin-orbit is repulsive for photons with orbital angular momentum aligned to the BH spin

Photon trajectories around a BH + shadow image



Inclination matters

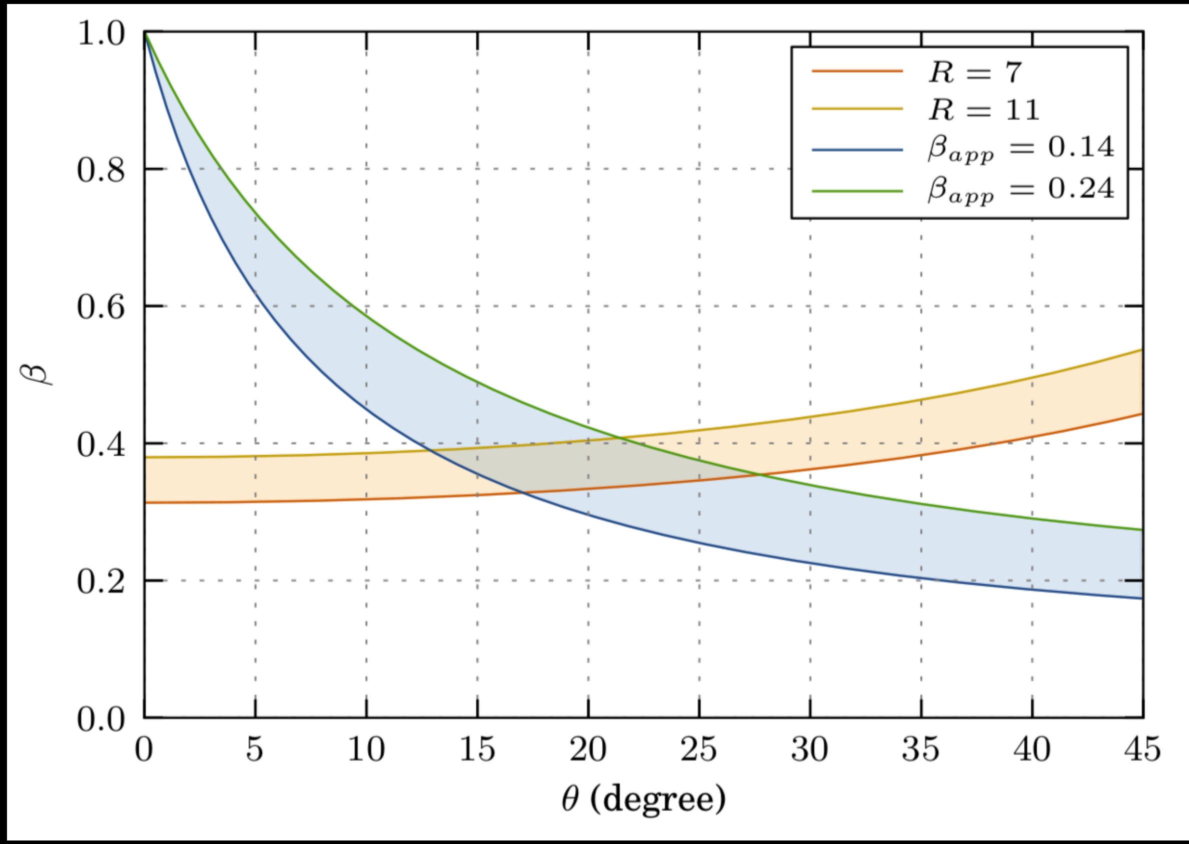


For given inclination, distortion is related to the BH spin

M87* inclination and spin

R : Jet to counter-jet intensity

$\beta_{\rm app}$: Apparent speed

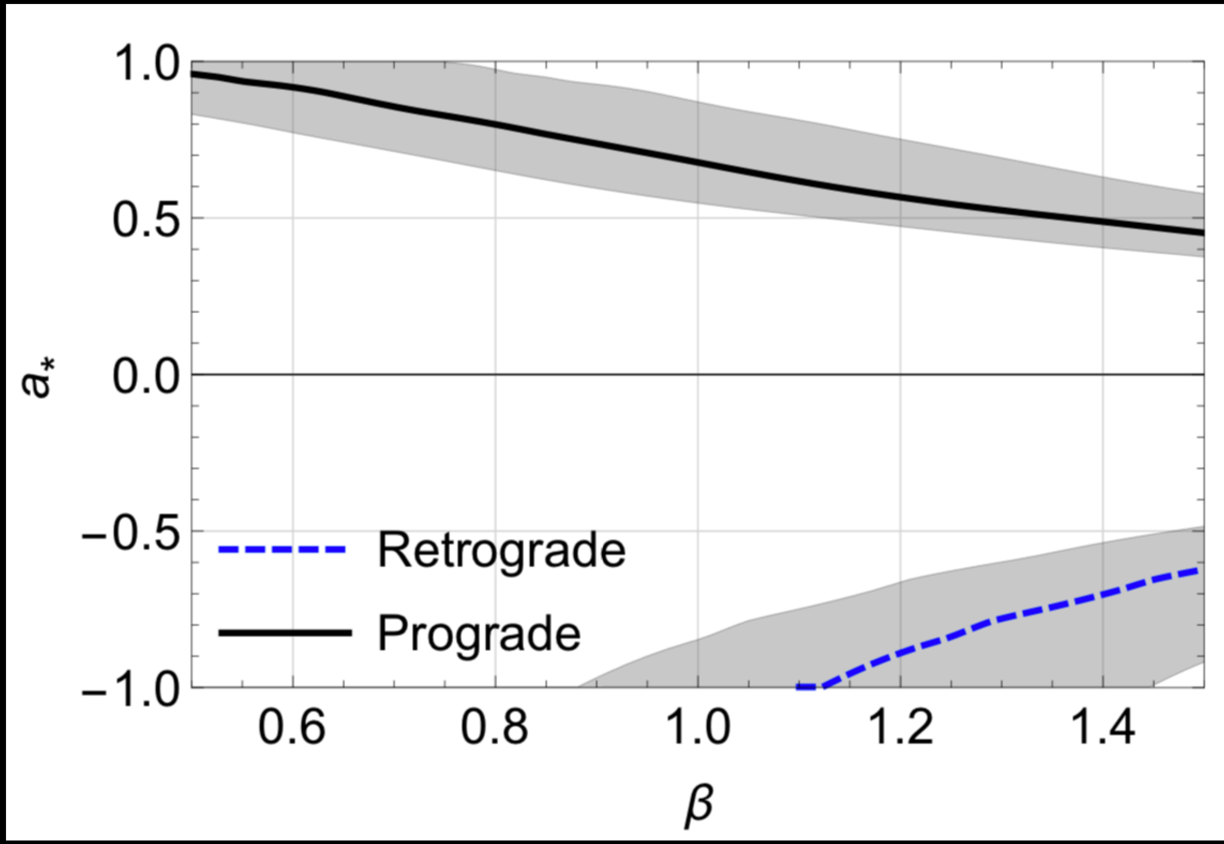


Mertens+, A&A **595** A54 (2016)

$$\theta_{\rm obs} = (17.2 \pm 3.3)^\circ$$

Accretion density radial profile

$$\rho(r) \propto r^{-\beta}$$



Nemmen, AJ **26** 880 (2019)

$|a^*| \gtrsim 0.4$ **(Prograde)**

$|a^*| \gtrsim 0.5$ **(Retrograde)**

Excerpt from EHT paper

associating to the shape of the shadow a deviation from the circularity—measured in terms of root-mean-square distance from an average radius in the image—that is $\lesssim 10\%$, we can set an initial limit of order four on relative deviations of the quadrupole moment from the Kerr value (Johannsen & Psaltis 2010). Stated differently, if Q is the quadrupole moment of a Kerr black hole and ΔQ the deviation as deduced from circularity, our measurement—and the fact that the inclination angle is assumed to be small—implies that $\Delta Q/Q \lesssim 4$ ($\Delta Q/Q = \varepsilon$ in Johannsen & Psaltis 2010).

EHT Collaboration, Astrophys. J. **875** 1 (2019)

Using the circularity to constrain the parameter space

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Katherine Freese

(UT Austin&Stockholm U.)

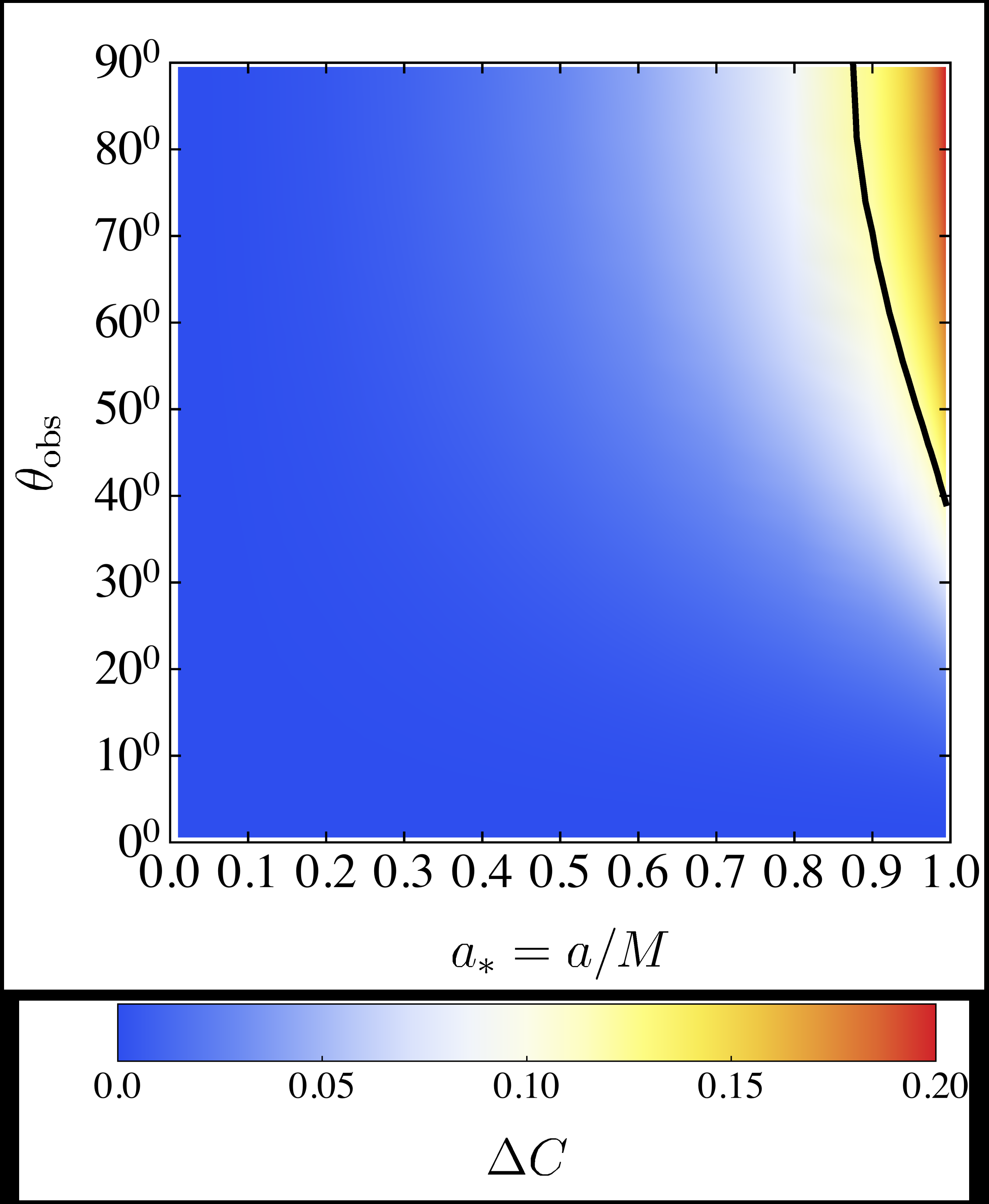
Sunny Vagnozzi

(KICC Cambridge)

$$\Delta C \equiv \frac{1}{\bar{R}}\sqrt{\frac{1}{2\pi}\int_0^{2\pi} d\phi\,\left(\ell(\phi)-\bar{R}\right)^2}$$

Bambi, Freese, Vagnozzi, **LV** Phys.Rev. D**100** 044057 (2019) 1904.12983

Using the circularity to constrain the parameter space



Can we test physics beyond GR?

Some of such exotic compact objects can already be shown to be incompatible with our observations given our maximum mass prior. For example, the shadows of naked singularities associated with Kerr spacetimes with $|a_*| > 1$ are substantially smaller and very asymmetric compared to those of Kerr black holes (Bambi & Freese 2009). Also, some commonly used types of wormholes (Bambi 2013) predict much smaller shadows than we have measured.

Superspinars

- The Kerr BH requires $a < M$
- Solutions with $a \geq M$ show a naked singularity!
- No-hair theorem: BH solutions of GR are characterised only by $M,\ a,\ Q$

Idea: maybe quantum gravity cures the GR effects and hides the singularity even for $a \geq M$

Gimon, Horava, PLB **672**, 299 (2009)

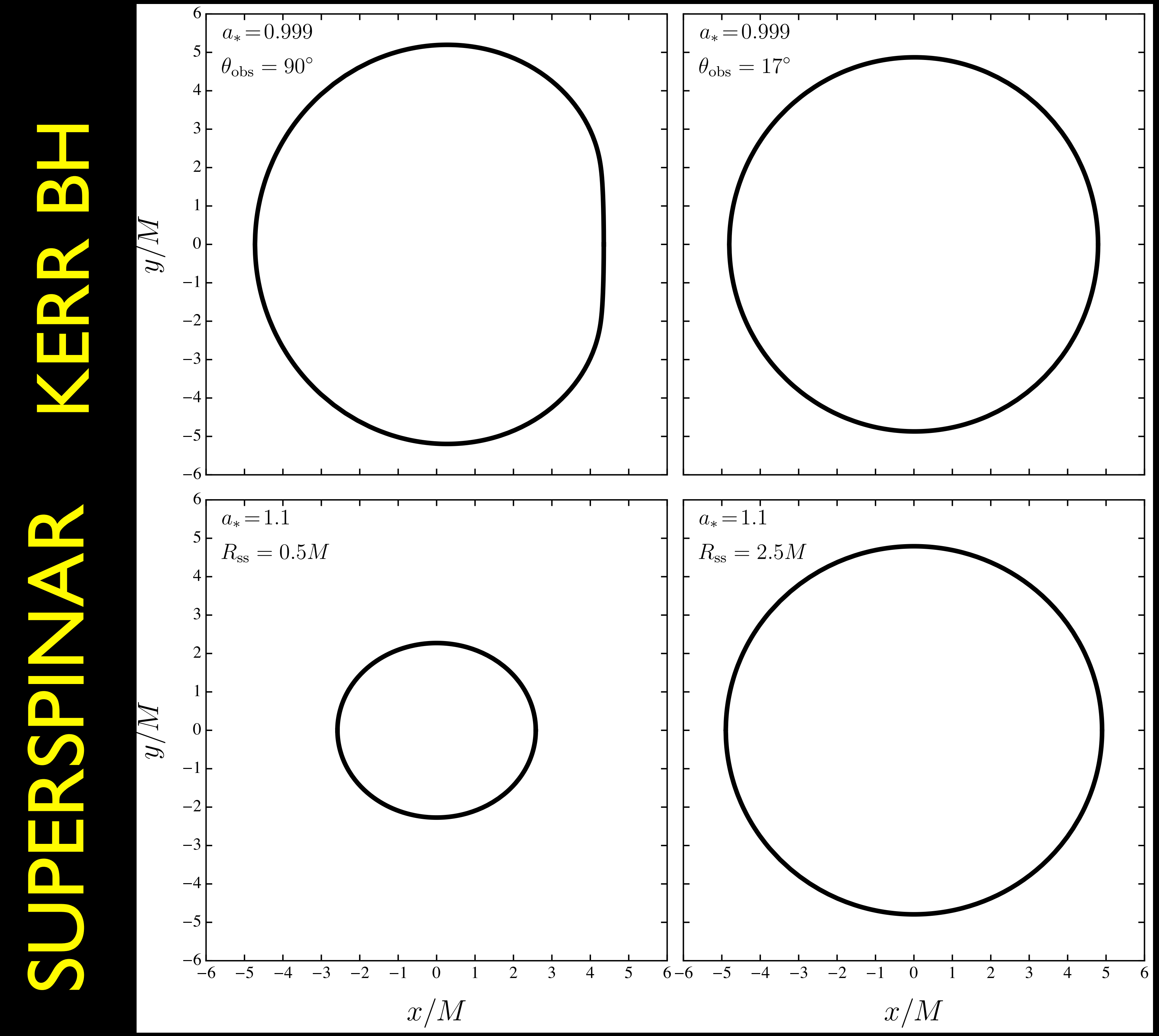
Superspinars

We introduce a new parameter $R_{\rm ss}$

The singularity at $r = 0$ is replaced by an object of finite size $R_{\rm ss}$ that covers the singularity

GR works for $r > R_{\rm ss}$

Superspinars might be remnants from a phase of the Universe when string theory was relevant



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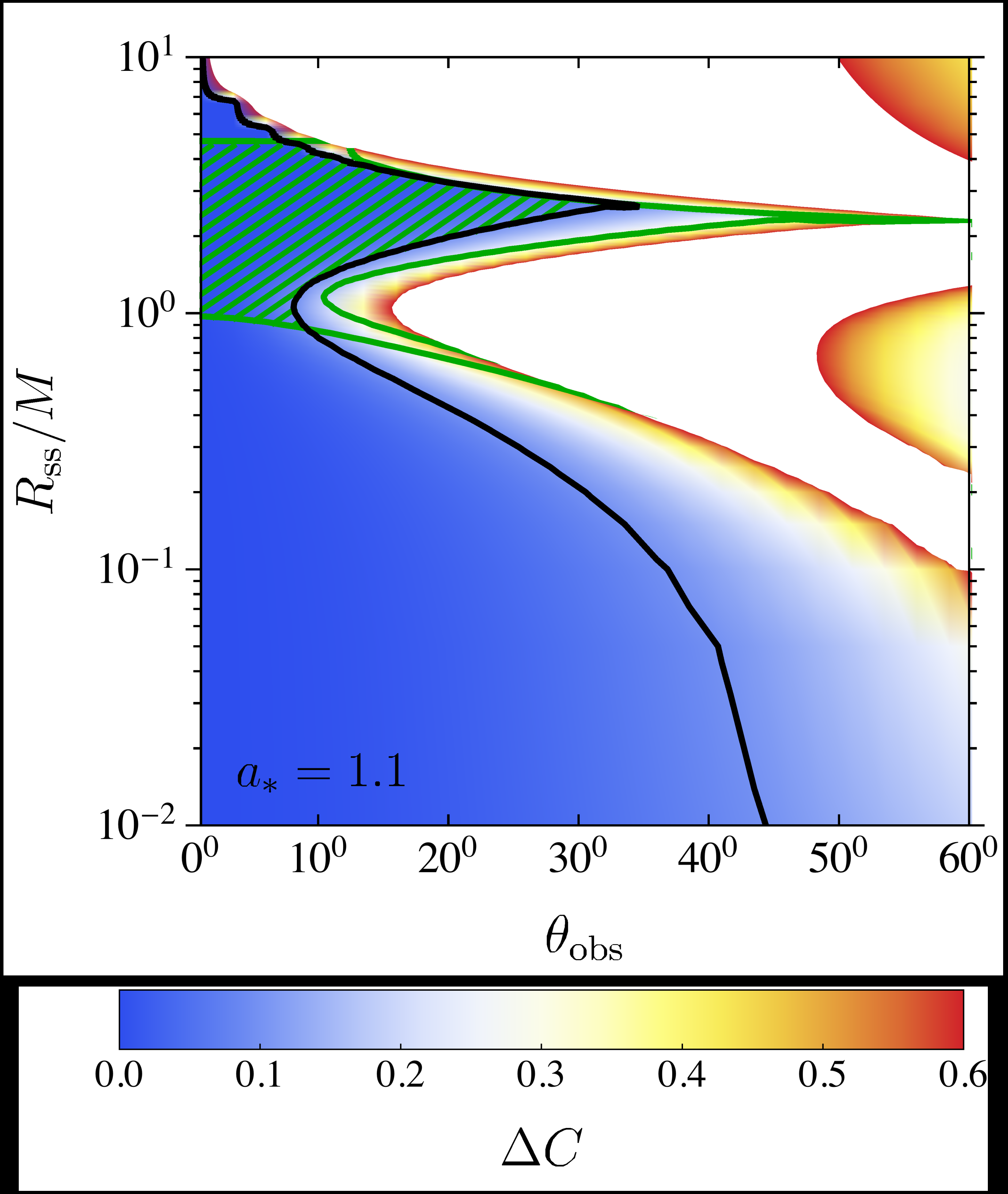

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Conclusions

- Exciting period for BH physics (GW, imaging)
- BH are gateways for new physics beyond GR
- Information on the BH characteristics extracted from the shape
- New physics (superspinars, extra dimensions…) hiding in the shadow??