EHT Constraints on Theories of Gravity

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on behalf of the Event Horizon Telescope Collaboration

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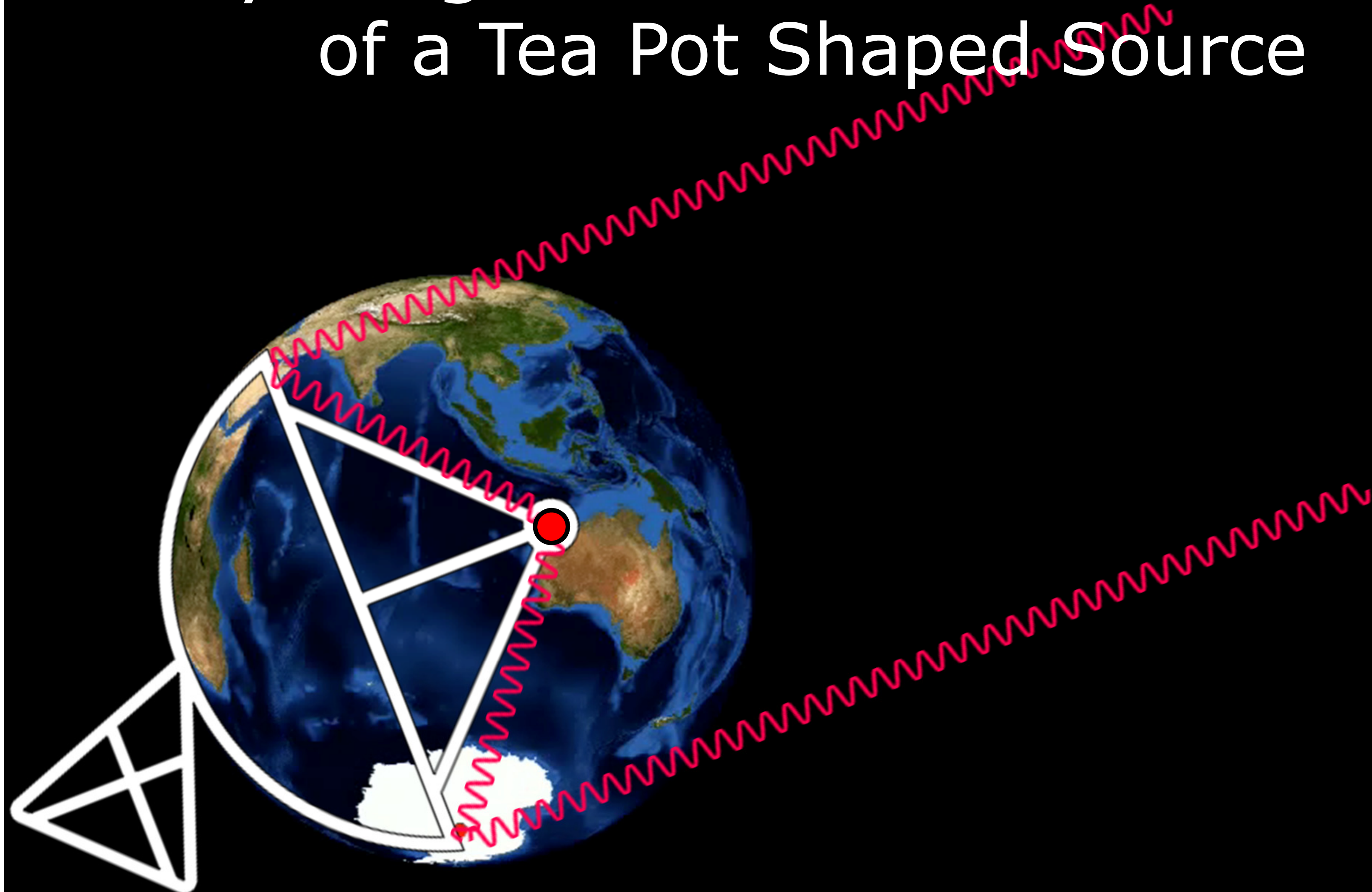
EHTC, Astrophys. J. Lett. 930 (2022) L17

Event Horizon Telescope Collaboration

Radboud University Nijmegen

EHT Collaboration Meeting, December 2021
300+ members in total

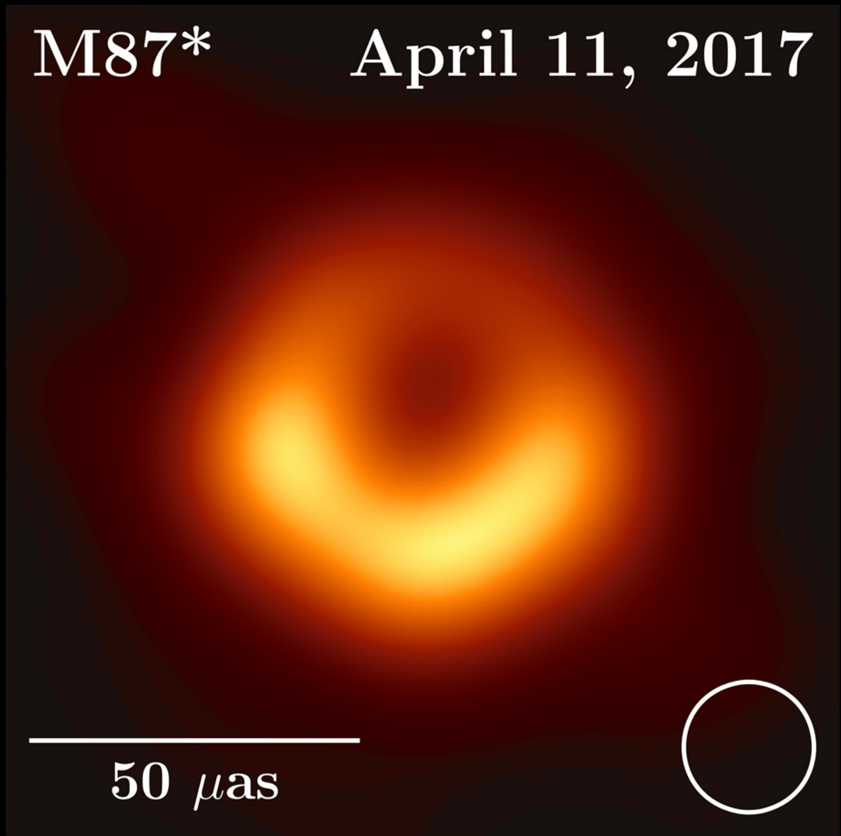
Very Large Baseline Interferometry of a Tea Pot Shaped Source

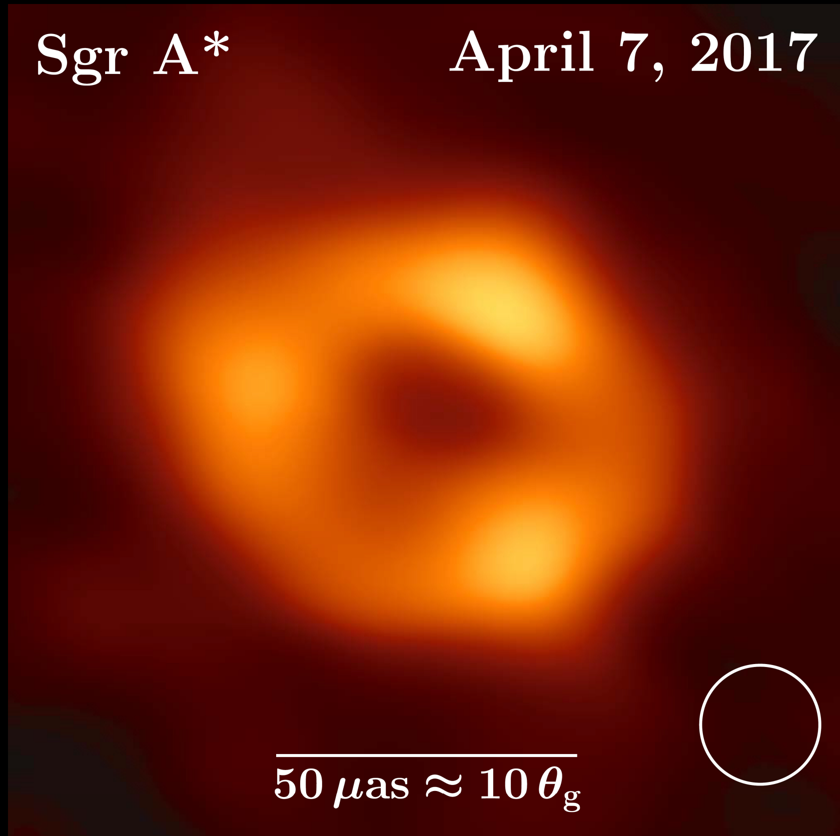


Tea pot in double Moon distance

Credit: F. Roelofs, S. Issaoun, C. Brinkerink; H. Falcke

EHT Images of Supermassive Black Holes
Comparing M87* and Sgr A*

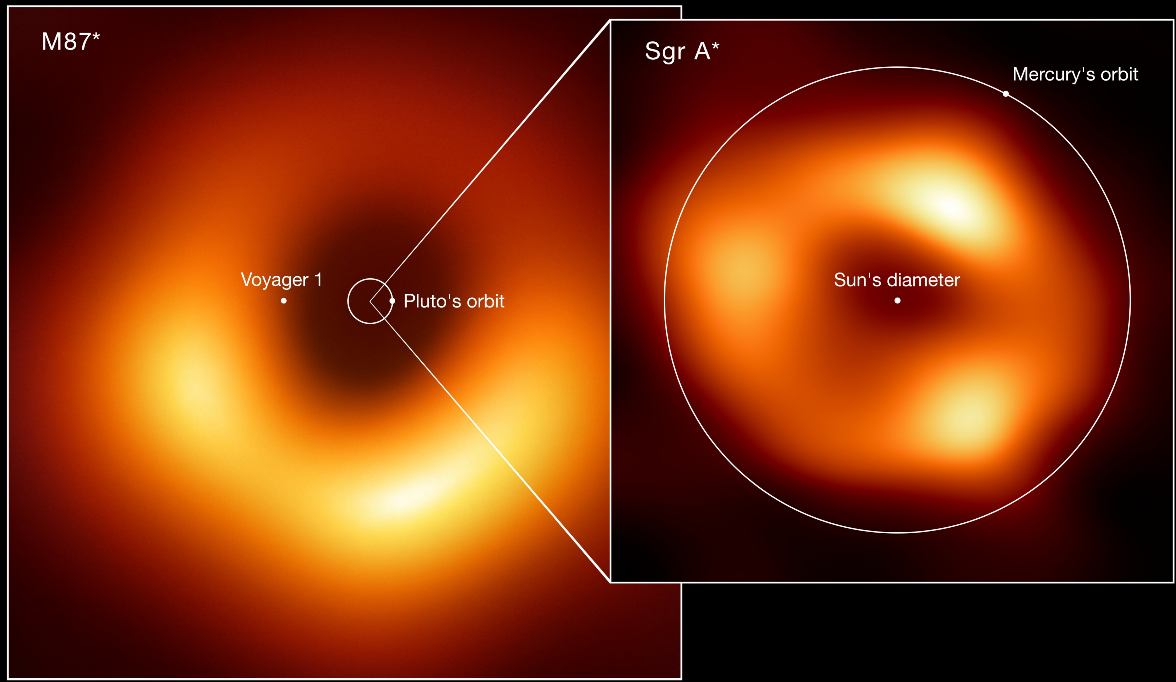




50 μas $\approx 2.4 \times 10^{-10}$ rad

Ringlike shape and central brightness depression

EHT Images of Supermassive Black Holes Comparing M87* and Sgr A*



Mass, Distance, Light-crossing time: $\times 1000$
Mass accretion rate: $\times 100{,}000$
Host galaxy: elliptic (with prominent jet) vs. spiral

Ringlike shape and central brightness depression
$\Rightarrow$ Universal features from gravitational physics

Credit: L. Medeiros

How Does the Image Come Together? Ray Tracing

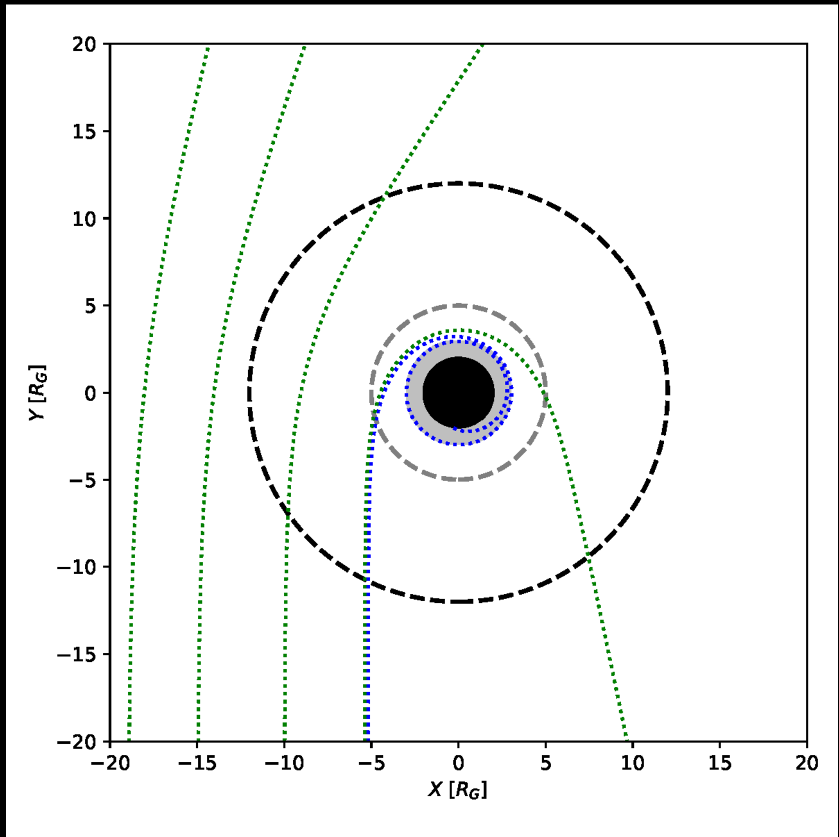
- Black hole is illuminated by radiation from surrounding matter (accretion disk, jet). Optically thin at $\lambda = 1.3$ mm.
- Classify the emitted light according to the position where it hits the observer's screen.
- The total intensity, which an observer measures along a certain line of sight, results from all emissions along the corresponding light trajectory.

$\Rightarrow$ Trace each geodesic back towards the past and add up intensity contributions whenever it crosses emission regions.

- 2 main effects:
  - Light blocking $\Rightarrow$ shadow [magnified by light bending]
  - Path lengthening $\Rightarrow$ bright photon ring

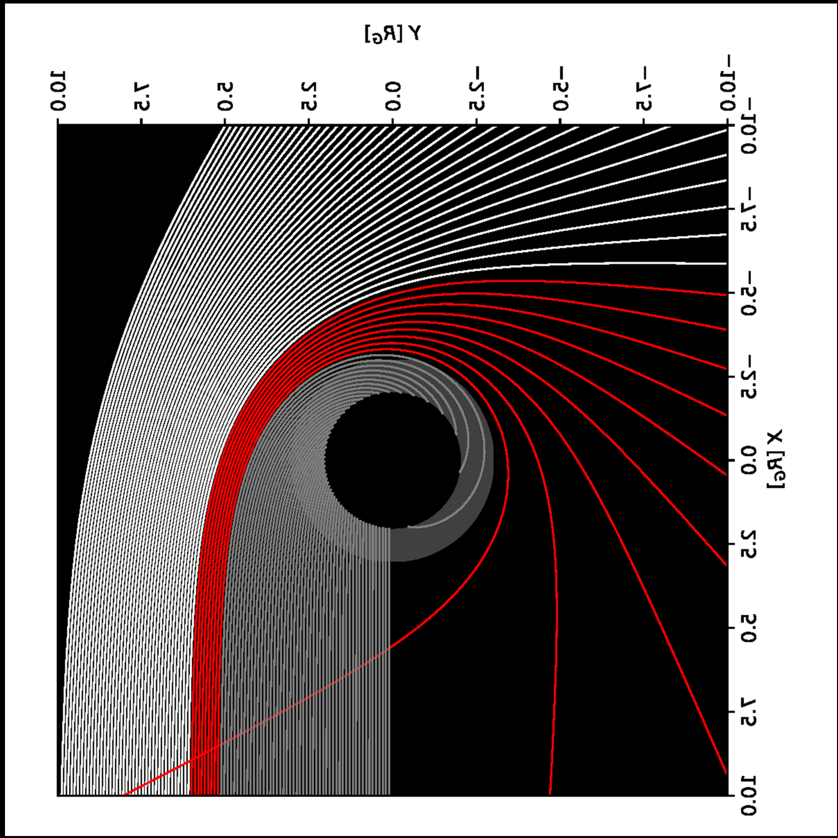
Bronzwaer, Falcke, Astrophys. J. 920 (2021) 155

How Does the Image Come Together? Ray Tracing



Credit: T. Bronzwaer, H. Falcke

How Does the Image Come Together? Ray Tracing

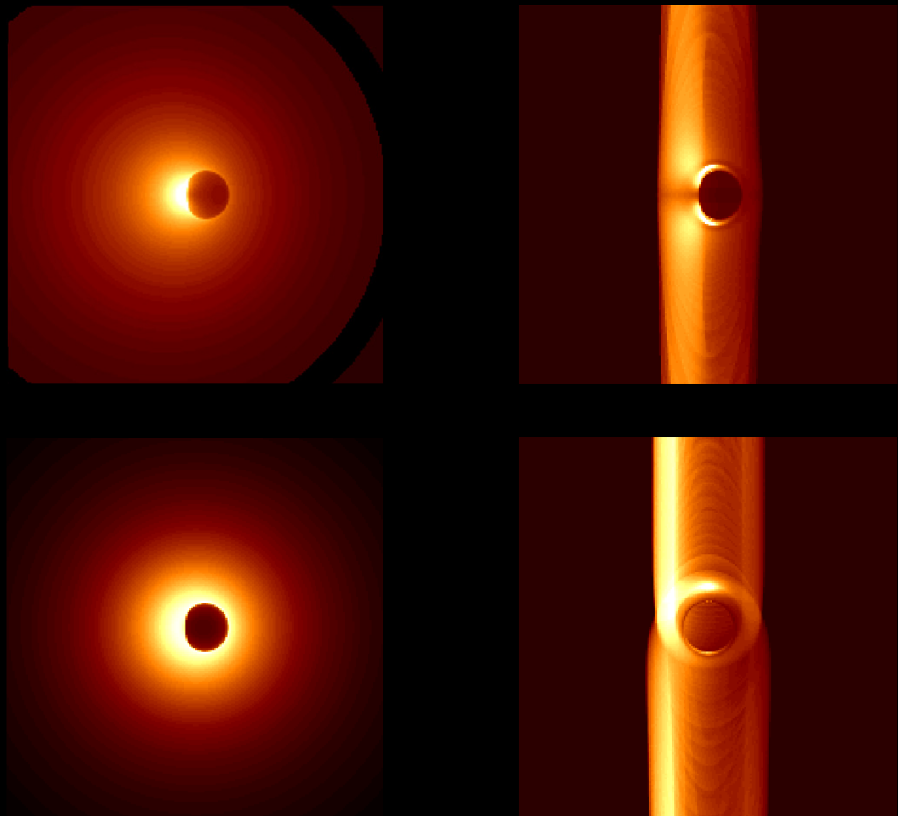


Bronzwaer, Falcke, Astrophys. J. 920 (2021) 155

Gravitational Physics Imprint

Accretion:
a = 0.998
i = 90º
I = r^{-2}

Accretion:
a = 0
i = 90º
I = r^{-2}



Jet:
a = 0.998
i = 90º
I = hollow

Jet:
a = 0
i = 45º
I = hollow

Optically thin matter covering the black hole.

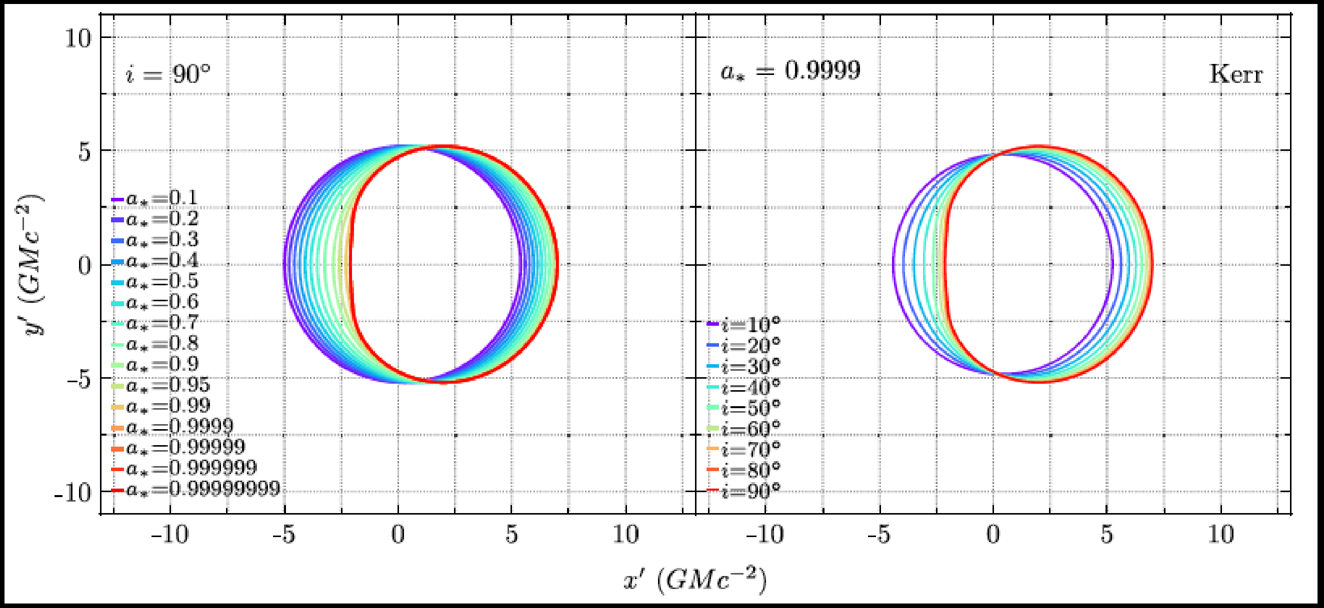
Independent of astrophysical situation,
the image shows a shadow of roughly the same size.

Falcke, Melia, Agol, Astrophys. J. Lett. 528 (2000) L13; AIP Conf. Ser. 522 (2000) 317

GR Prediction

Unique solution according to GR (“no hair theorem”):
Kerr black hole

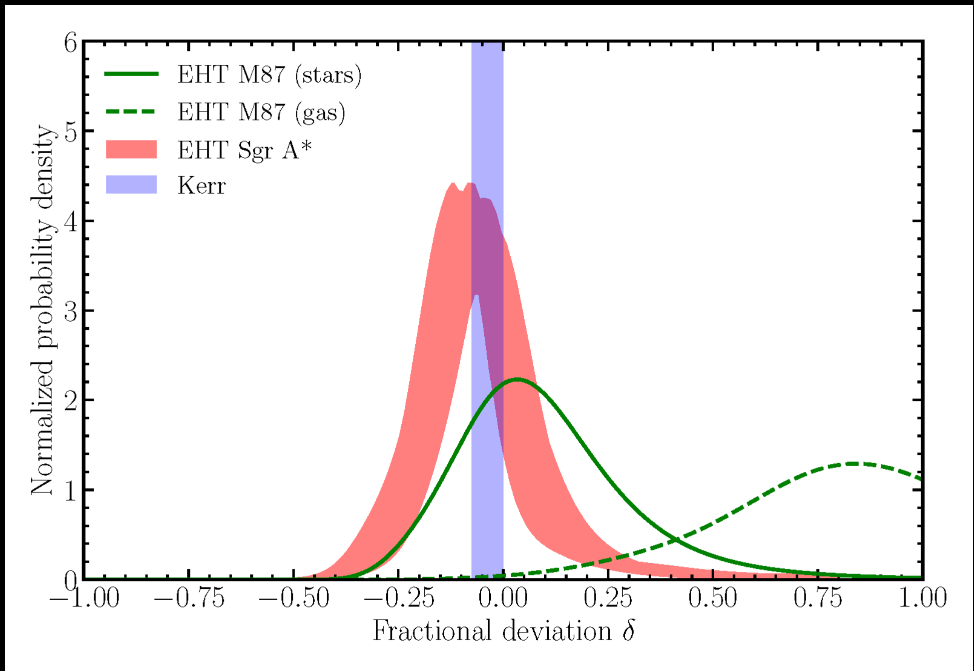
- Vacuum
- Stationary
- Axisymmetric
- Electrically uncharged
- Asymptotically flat
- Covered by a horizon
- Pathology-free
  (CTCs, metric signature
  change outside the horizon)

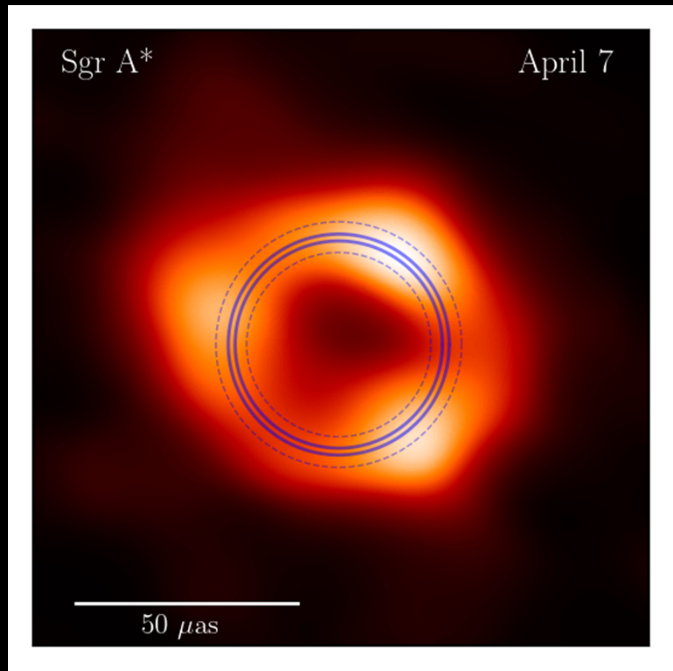


Medeiros, Özel, Psaltis, Astrophys. J. 896 (2020) 7

Compatibility of the Kerr Solution with EHT Observations

- Test of the Kerr solution based on the shadow diameter, extracted from the image via calibration and Bayesian inference.
- δ: Relative deviation of the shadow radius from the Schwarzschild value.
- Kerr: 0 ≥ δ ≳ -0.08

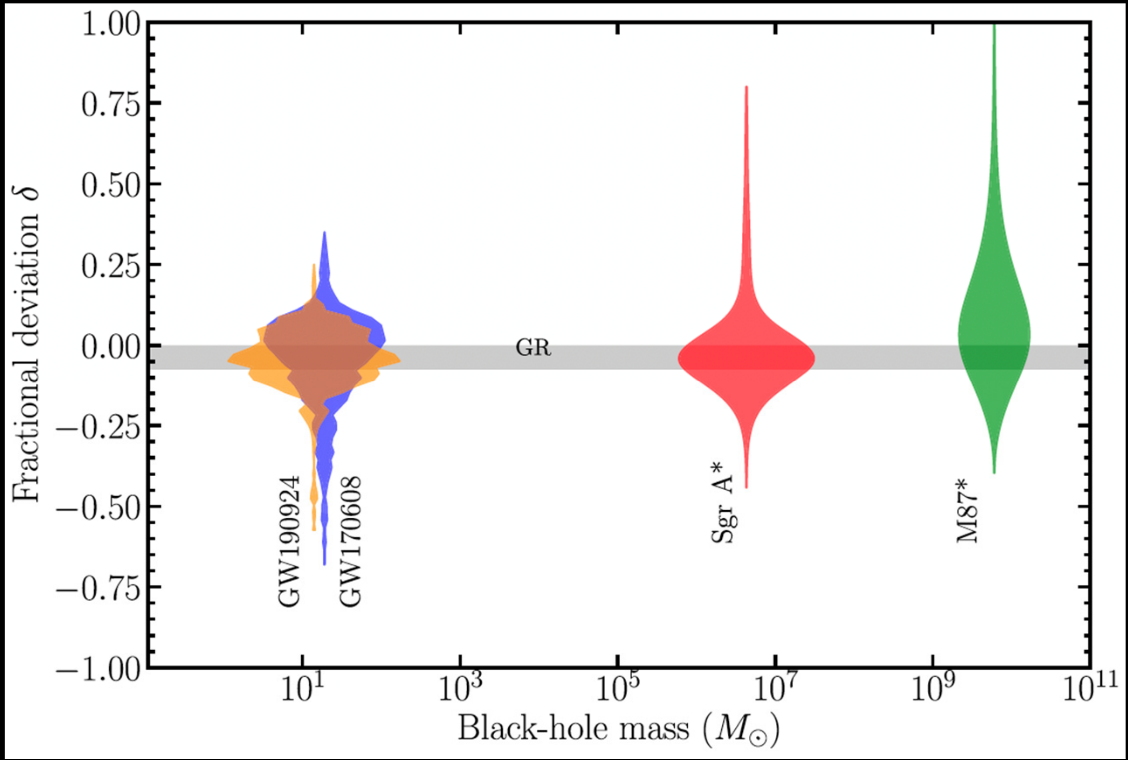




Compatibility of the Kerr Solution

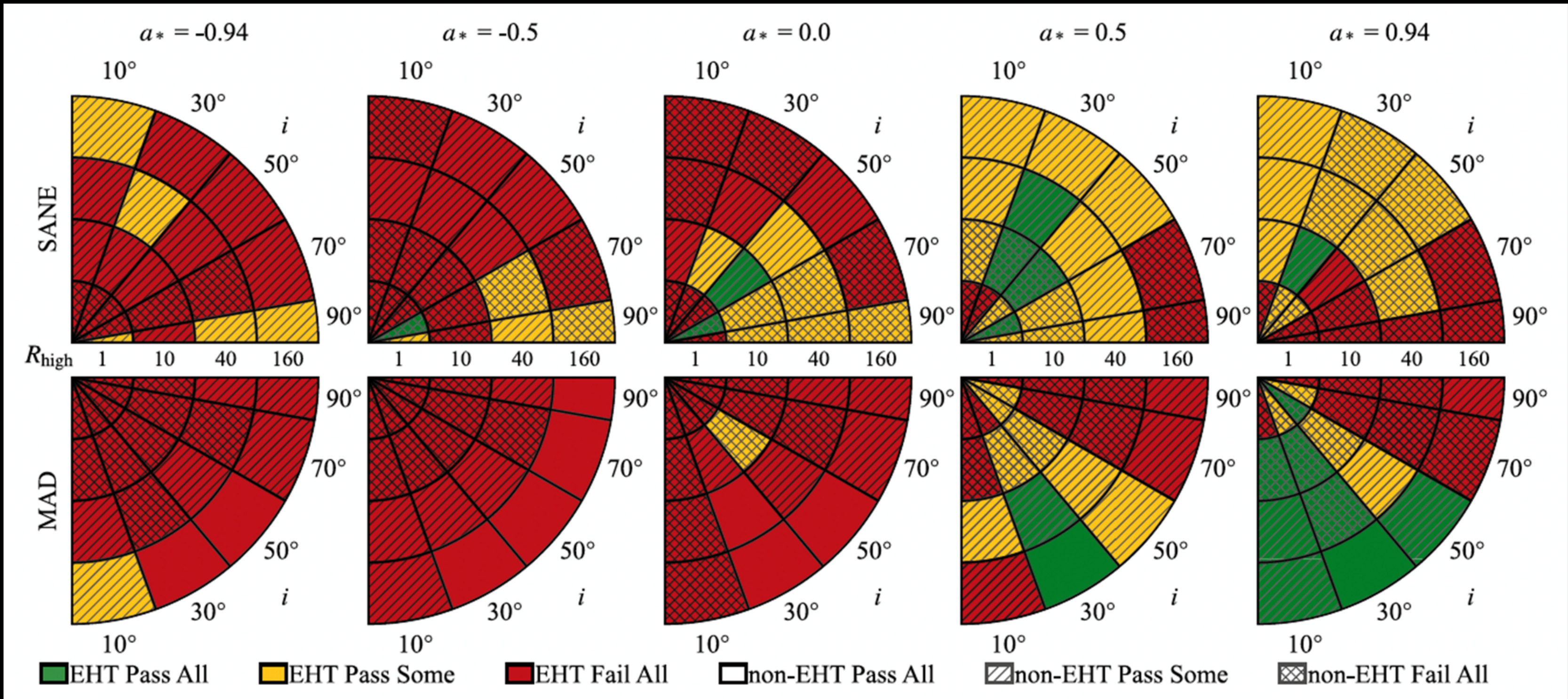
- Including GW constraints, the Kerr solution applies to black hole observations over 8 orders of magnitude.

⇒ Unlikely that the fundamental theory of gravity has a scale in this regime.



Best Fit Astrophysical Model (within GR)

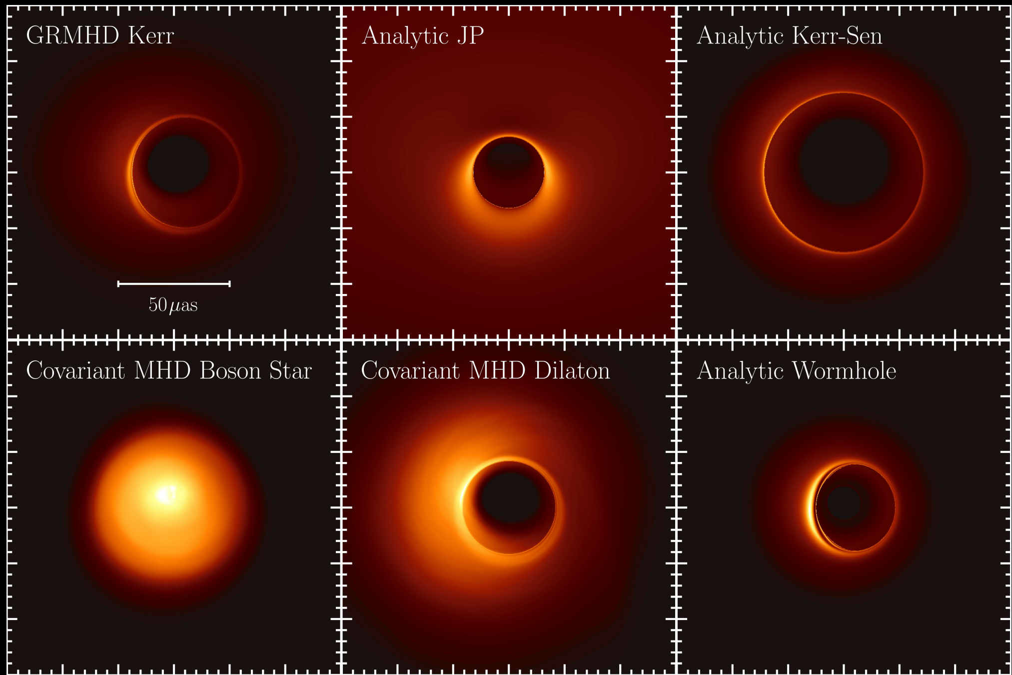
- Face-on orientation (i ~ 30°)
- Magnetically dominated accretion (MAD)
- Spinning black hole (a ≳ 0.5)
- Accretion rate: ~ 0.5-1 $\times 10^{-8}$ M_{sun}
- Jet outflow



EHTC, Astrophys. J. Lett. 930 (2022) L16

Constraints from Sgr A*

- There is a variety of images possible for compact objects with or without event horizons.

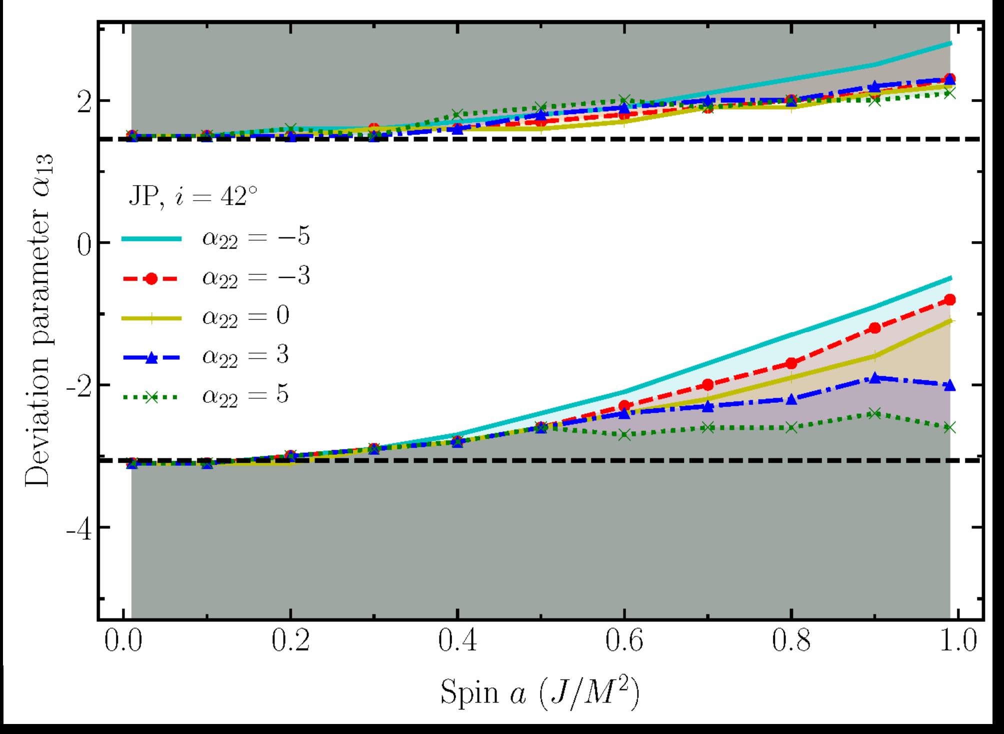


- In the following we focus on constraints based on the shadow size.

see also Mizuno et al., Nature Astron. 2 (2018) 585

Constraints on Parametrized Metrics

- Strong-field metric parametrizations around Kerr solution in a pathology-free manner.
  They are agnostic to the fundamental theory of gravity, e.g. JP (see also MGBK, RZ).

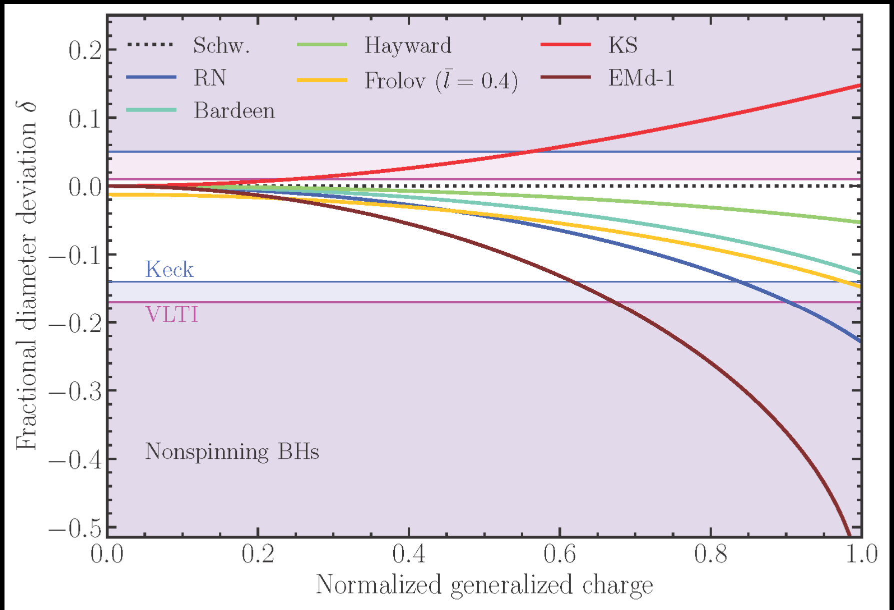


- A deviation from Kerr implies a deviation from general relativity!
- The constraints on the coefficients are versatile and apply to any metric upon expanding in the corresponding form.

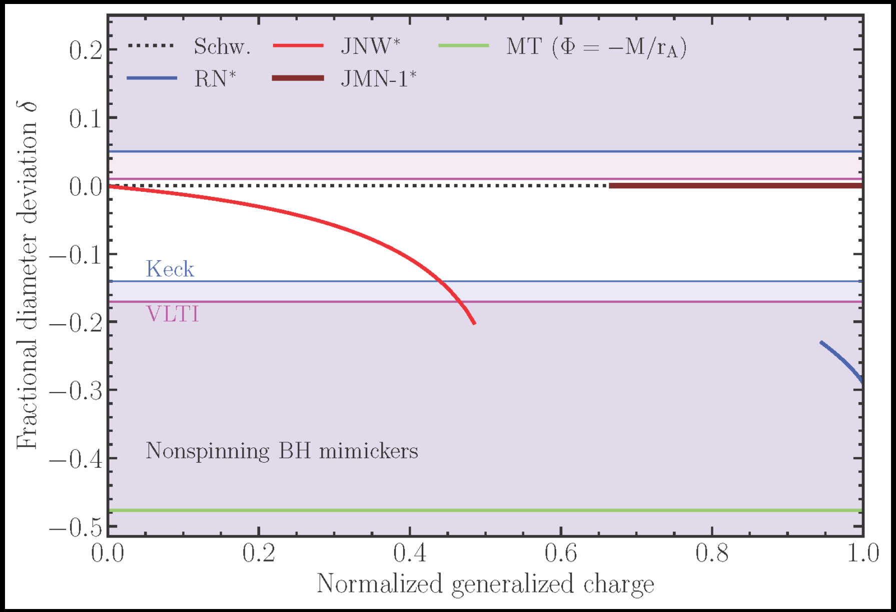
Johannsen, Psaltis, Phys. Rev. D83 (2011) 124015; Rezzolla, Zhidenko, Phys. Rev. D90 (2014) 084009; Vigeland, Yunes, Stein, Phys. Rev. D83 (2011) 104027

Constraints on Concrete Models

- Concrete models based on certain energy distributions or modified theories of gravity.
- Nonspinning objects with an additional parameter ("charge"):



Black holes



Naked singularities, wormhole

see also EHTC, Phys. Rev. D103 (2021) 104047;
Kocherlakota, Rezzolla, Mon. Not. Roy. Astron. Soc. 513 (2022) 1229

Quadratic Gravity

- Adding higher curvature terms to GR to approach quantum gravity.

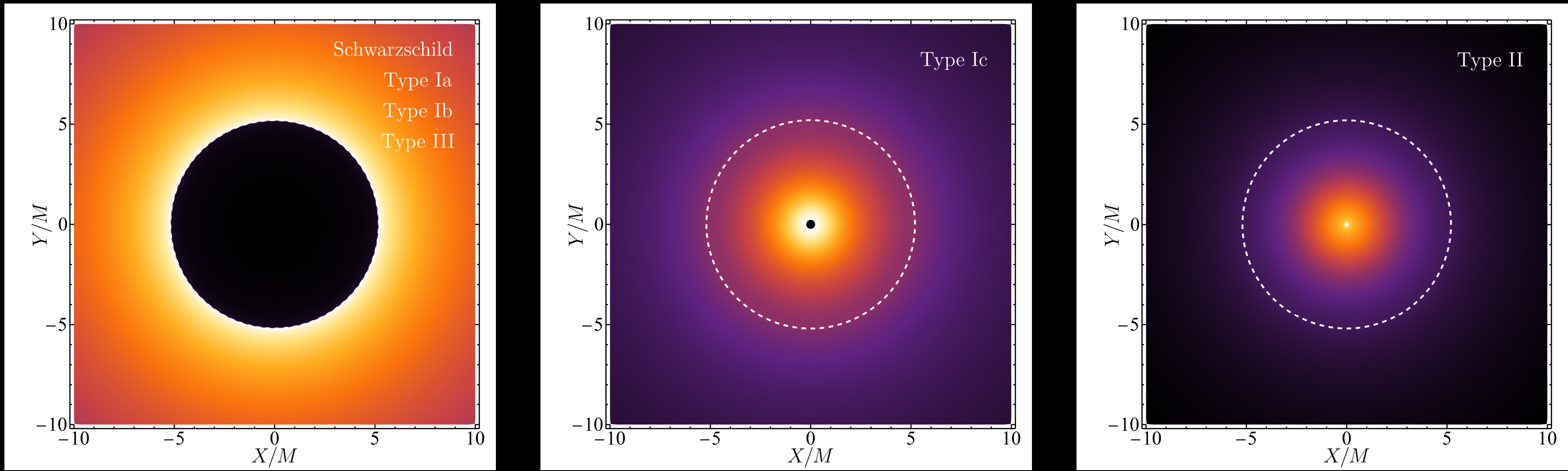
$$S = \frac{1}{16\pi} \int \mathrm{d}^4x \sqrt{-g} \left[\gamma R - \alpha C_{\mu\nu\rho\sigma} C^{\mu\nu\rho\sigma} + \beta R^2 \right]$$

- Interpretation:
  - Exact: Renormalizable gravitational theory.
  - As an expansion: First order quantum corrections, 1-loop order (see also Starobinsky inflation).
- Rich phase space even for
static, spherically symmetric, asymptotically flat vacuum spacetimes
(in contrast to the no hair theorem in GR):
naked singularities, wormholes, only few black hole solutions.

$$H_{\mu\nu} \equiv \gamma \left(R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} \right) - 4\alpha \left(D^\rho D^\sigma + \frac{1}{2} R^{\rho\sigma} \right) C_{\mu\rho\nu\sigma} + 2\beta \left(R_{\mu\nu} - \frac{1}{4} R \, g_{\mu\nu} - D_\mu D_\nu + g_{\mu\nu} D^2 \right) R = 0$$

Daas, Kuijpers, Saueressig, Wondrak, Falcke, arXiv:2204.08480 [gr-qc]

Quadratic Gravity

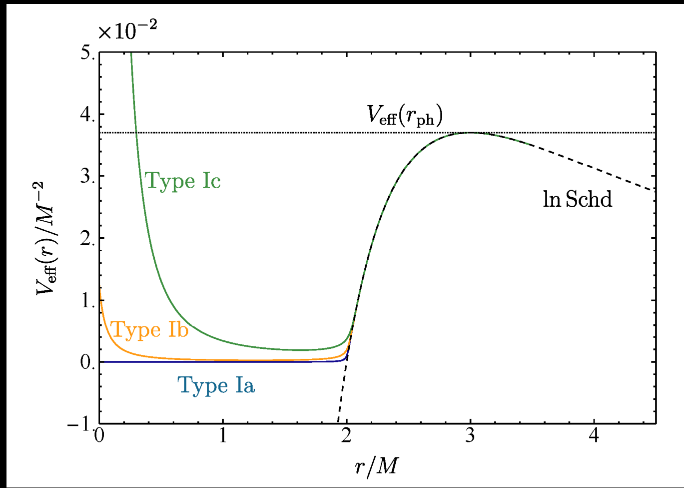


Black hole, wormhole, naked sing. Ia, Ib

Naked sing. Ic

Naked sing. II

- Phase space of quadratic gravity can be constrained.
- Shadow can arise also in naked singularity spacetimes.
- Quantum effects reach out until horizon scale.



Daas, Kuijpers, Saueressig, Wondrak, Falcke, arXiv:2204.08480 [gr-qc]

Conclusions and Outlook

- The second shadow observation is further evidence for the existence of supermassive black holes.

  ⇒ Compatibility of strong field tests with the GR prediction (= Kerr black hole) over 8 orders of magnitude (incl. GW signals from solar mass BHs).

- The presence of a shadow and the value of its radius are a direct consequence of gravitational physics.

  ⇒ Constraints on deviations from the Kerr black hole, on specific matter configurations, and on alternative theories of gravity. Opens a door to test quantum gravity theories.

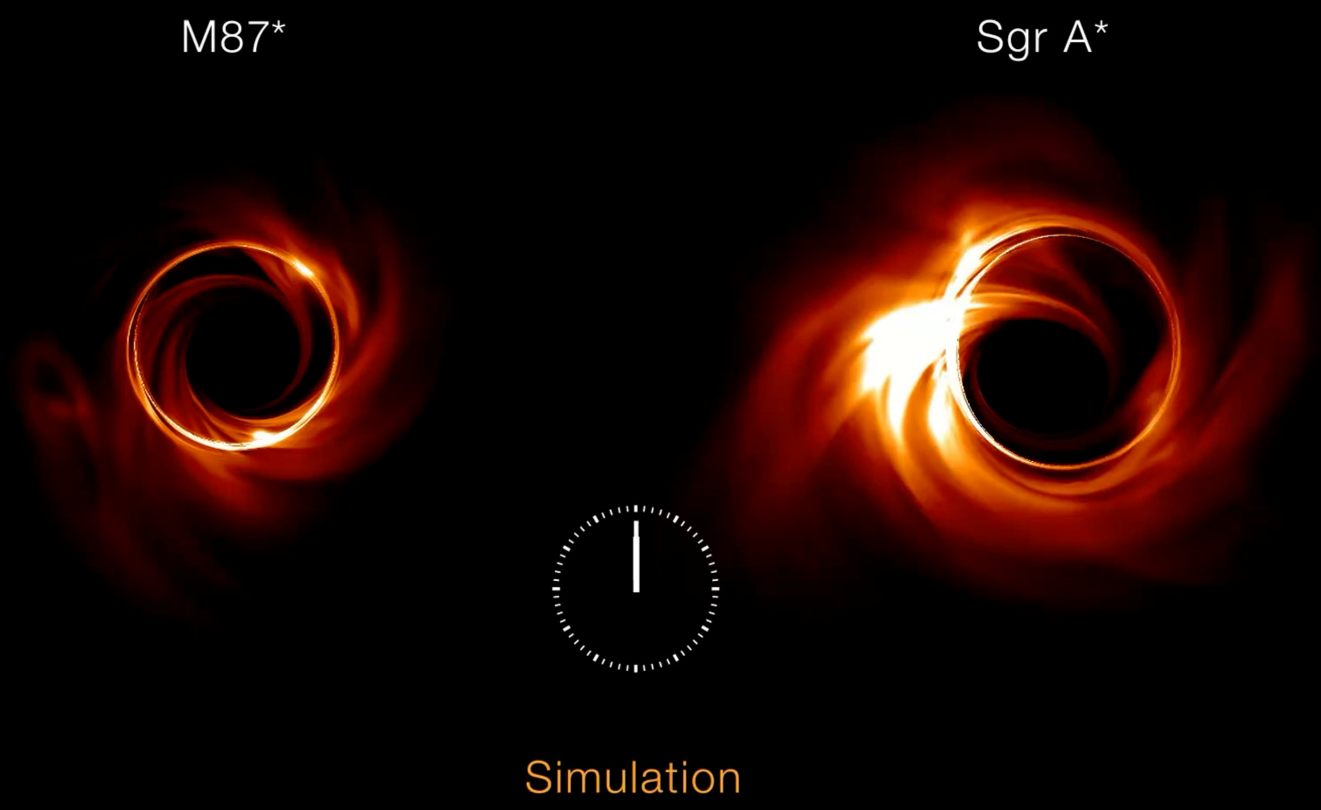
- Data available from observation campaigns in 2018, 2021, 2022 with 3 more telescopes ⇒ higher sensitivity images.

  Future campaigns: further telescopes (e.g. African mm Telescope), multi-wavelength input, higher frequency, space-based VLBI.

  ⇒ Movies (dynamics), magnetic fields, higher resolution.
  Diverse opportunities to test theories of gravity.

Back Up

Variability Time Scales



Credit: A. Joshi

Generating Astrophysical Models

MAD

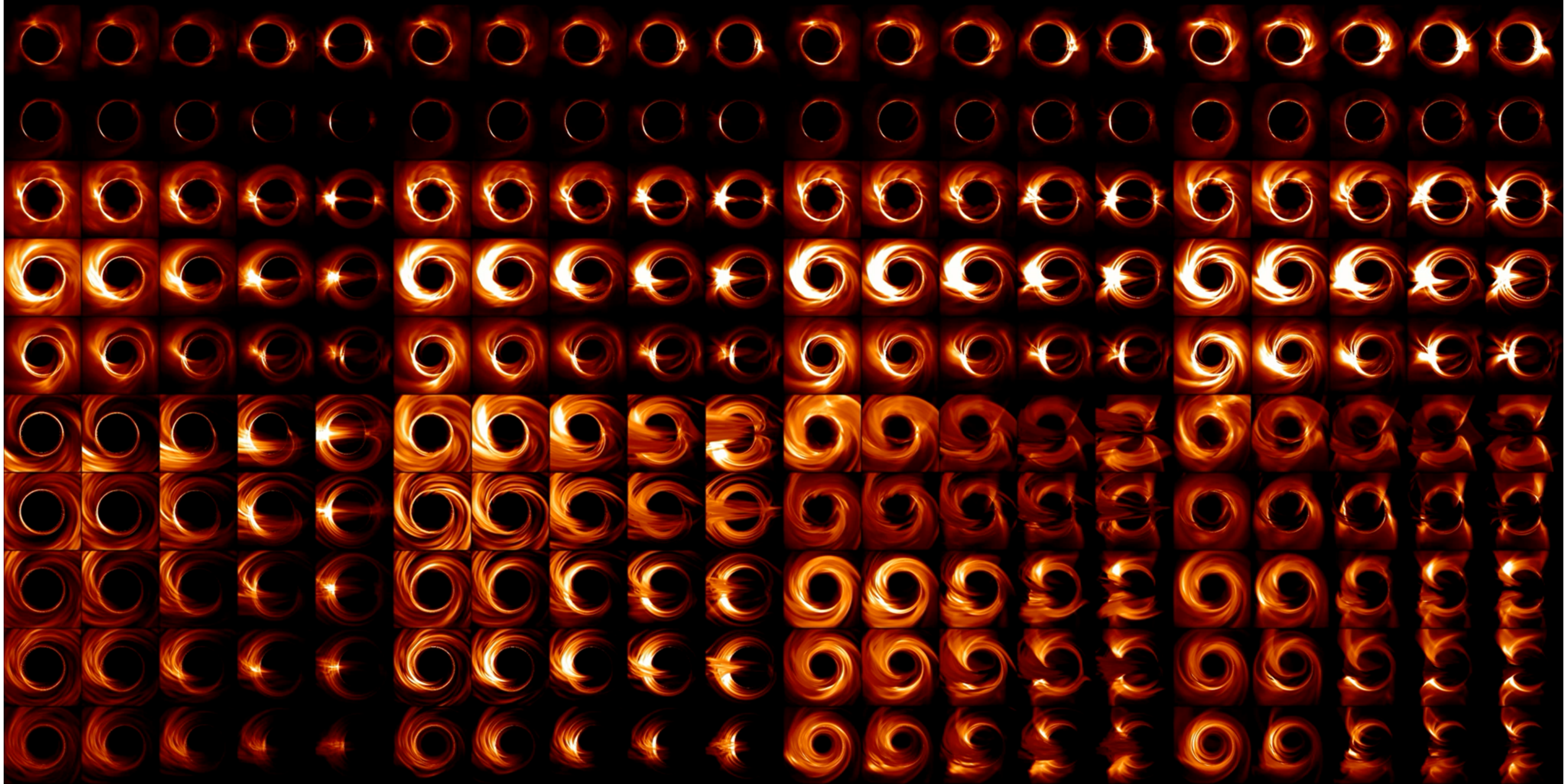
$R_{high} = 160$

$a = +0.94$

$i = 90$

Credit: B. Prather

Applying Astrophysical Constraints



Credit: B. Prather