EHT Observations of Supermassive Black Holes

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on behalf of the Event Horizon Telescope Collaboration

Interplay between Particle and Astroparticle Physics (IPA2022)

Vienna, 05 September 2022

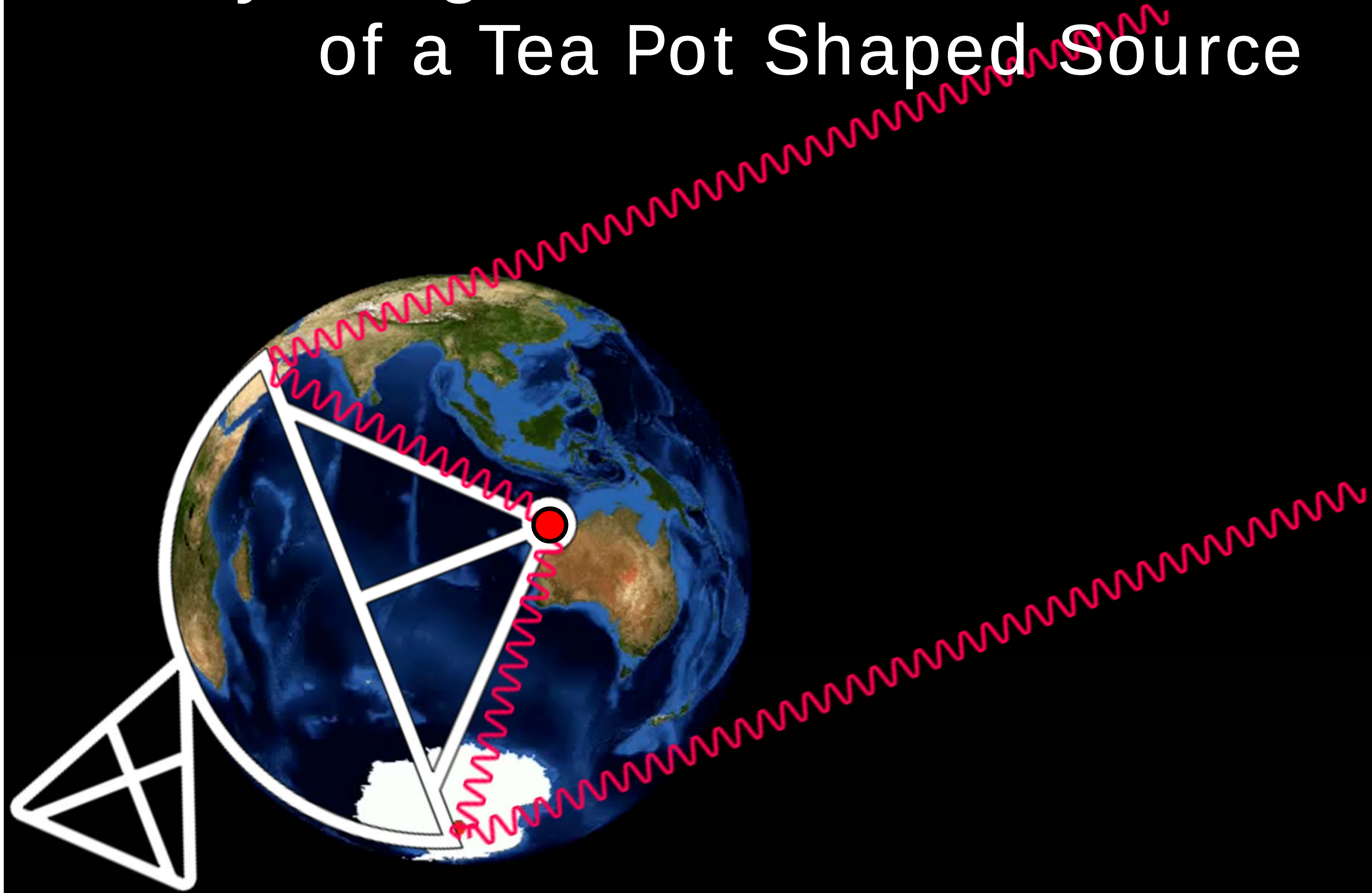
EHTC, Astrophys. J. Lett. 930 (2022) L17

Event Horizon Telescope Collaboration

Radboud University Nijmegen

EHT Collaboration Meeting, December 2021
300+ members in total

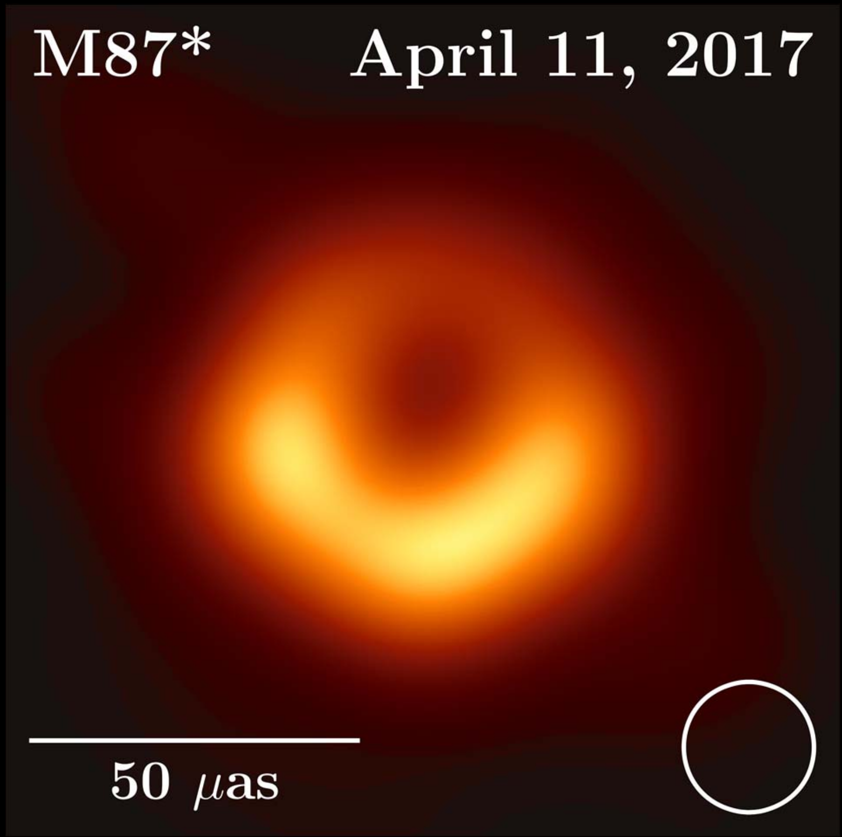
Very Large Baseline Interferometry of a Tea Pot Shaped Source

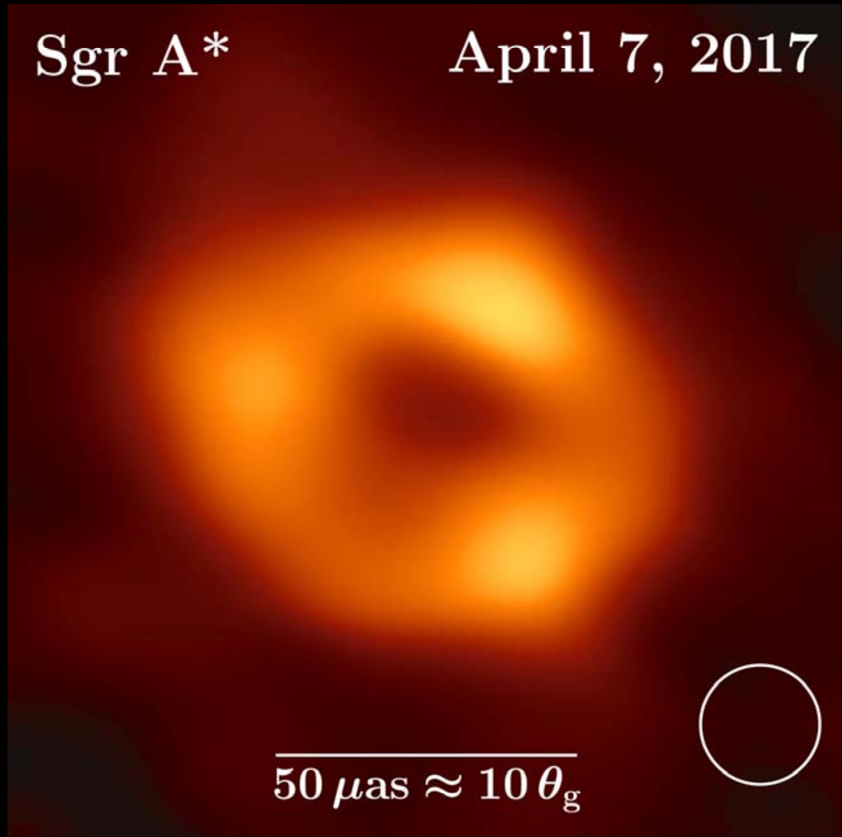


Russell’s tea pot in double Moon distance

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

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



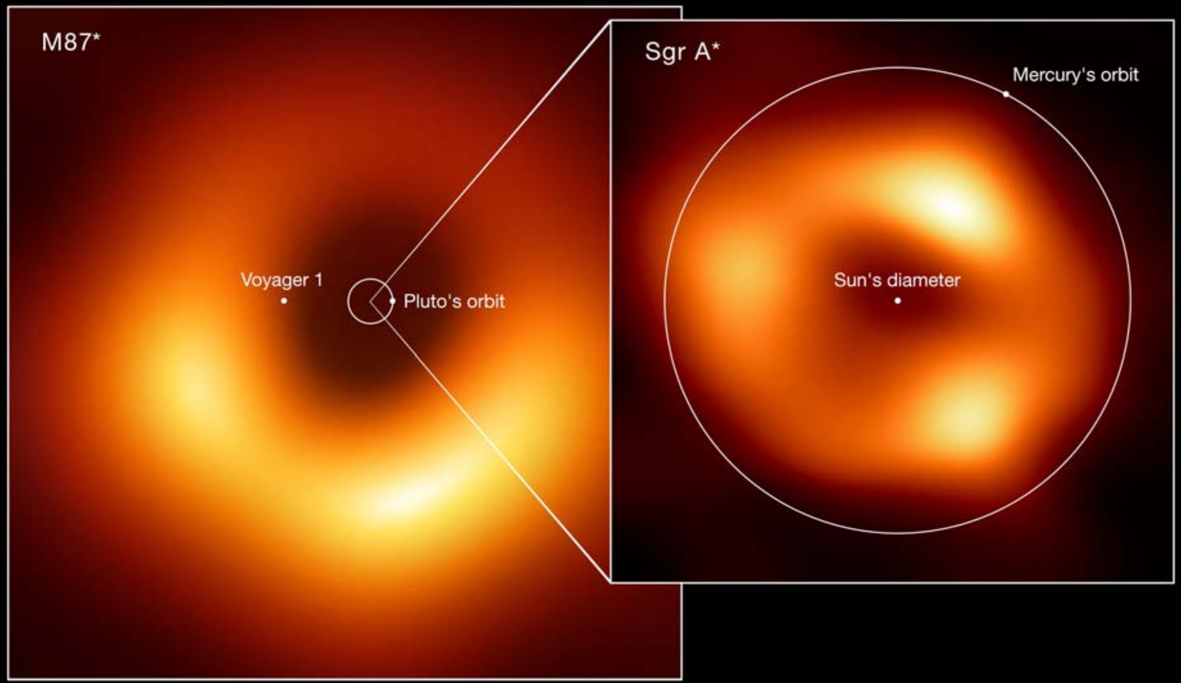


50 μas ≈ 2.4 × 10^{-10} rad

Ringlike shape and central brightness depression

EHTC, Astrophys. J. Lett. 875 (2019) L1; Astrophys. J. Lett. 930 (2022) L12

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



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

Ringlike shape and central brightness depression
⇒ Universal features from gravitational physics

Credit: L. Medeiros

How Is the Image Formed? 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.

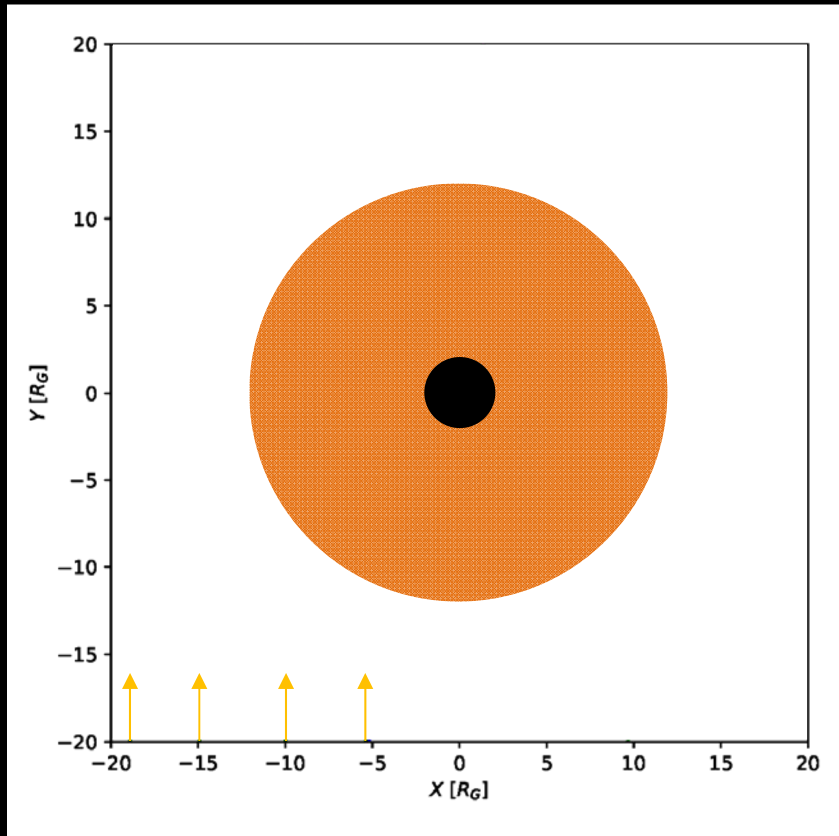
→ Trace each geodesic back towards the past and add up intensity contributions whenever it crosses emission regions.

- 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 Is the Image Formed?
Ray Tracing

Cut through
equatorial plane



Emission region

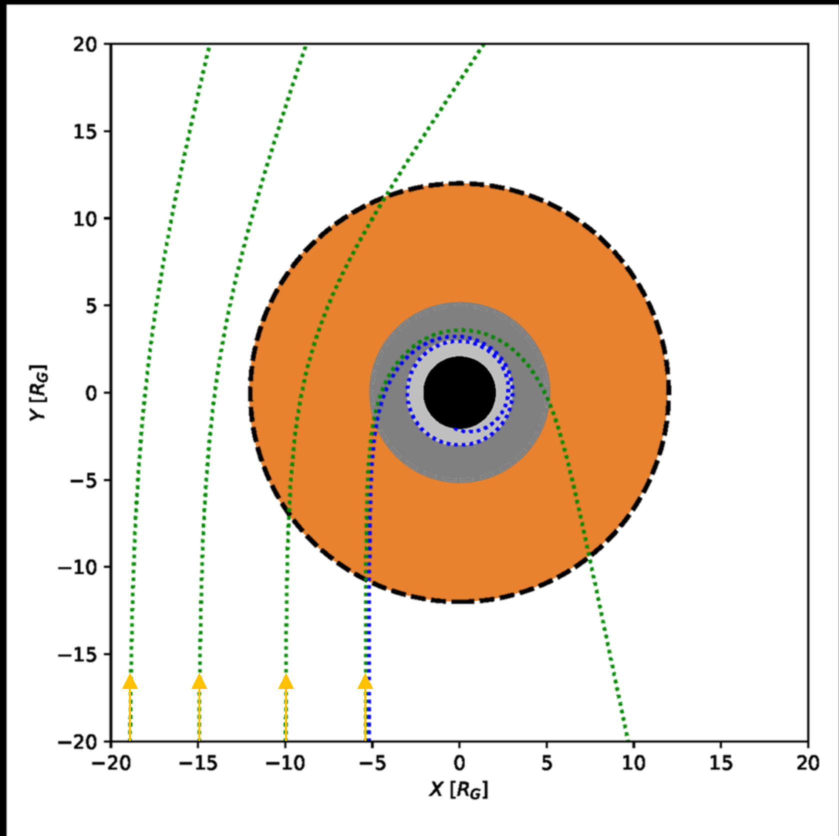
Black hole

Light rays to be
traced back

Adapted from T. Bronzwaer, H. Falcke

How Is the Image Formed?
Ray Tracing

Cut through equatorial plane



Emission region

Black hole

Instable photon orbit

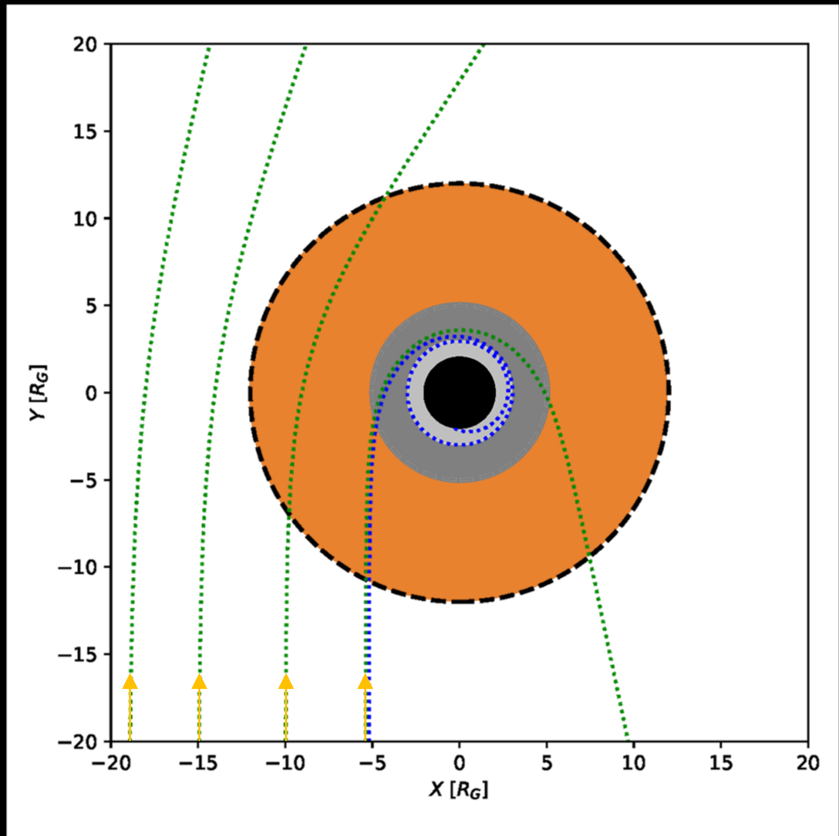
Size of the black hole shadow

Light rays to be traced back

Adapted from T. Bronzwaer, H. Falcke

How Is the Image Formed?
Ray Tracing

Cut through
equatorial plane



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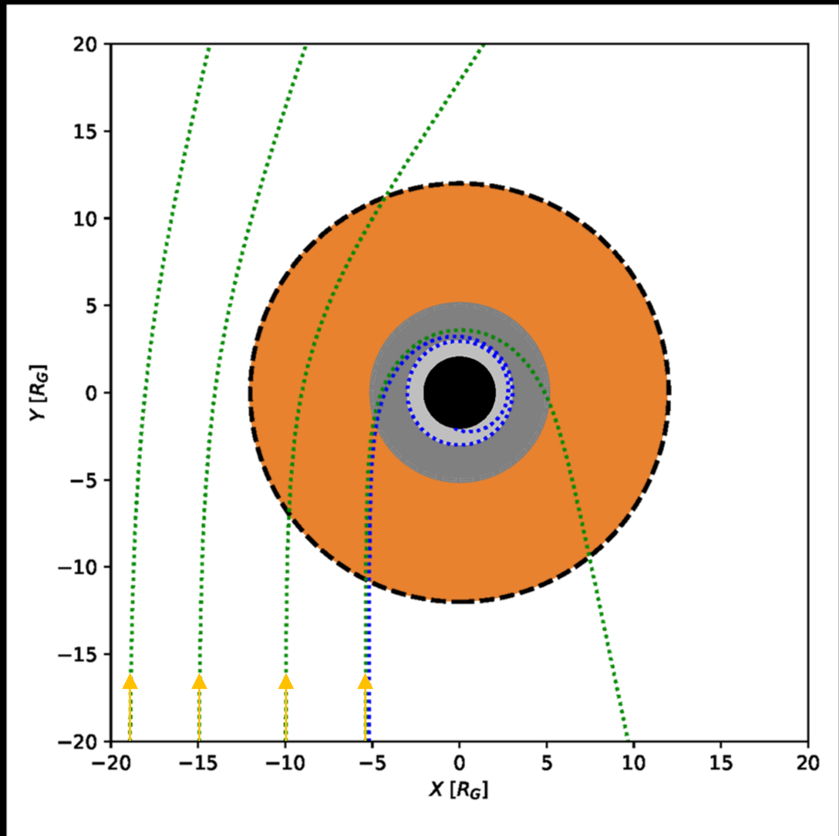

Emission region

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Instable photon
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Size of the
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Light rays to be
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Light blocking & path lengthening

Adapted from T. Bronzwaer, H. Falcke

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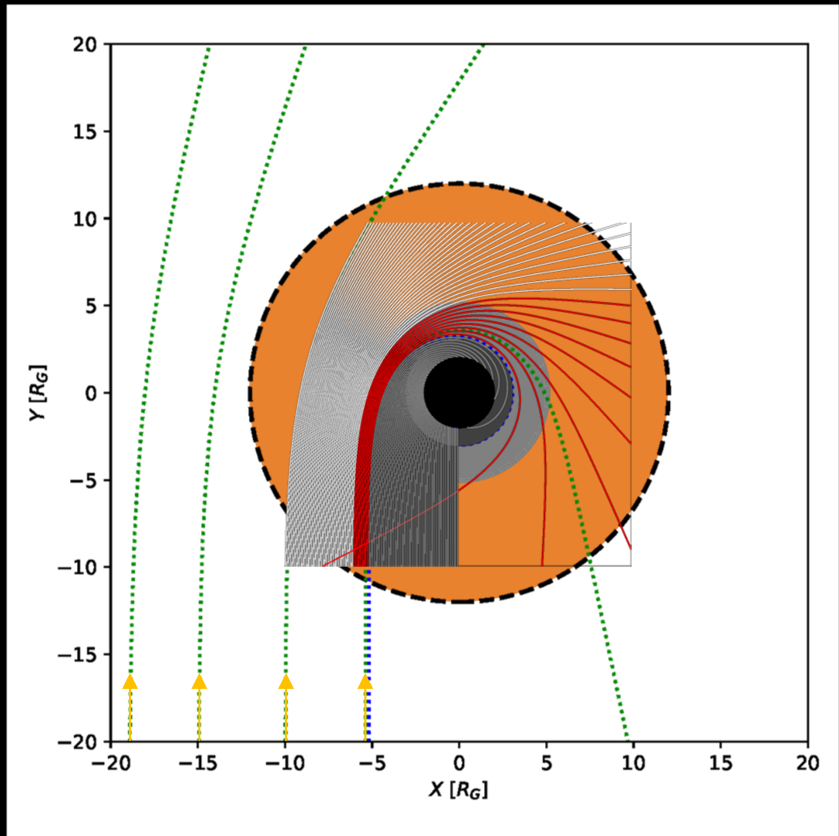


Emission region

Black hole

Size of the black hole shadow

Light rays to be traced back

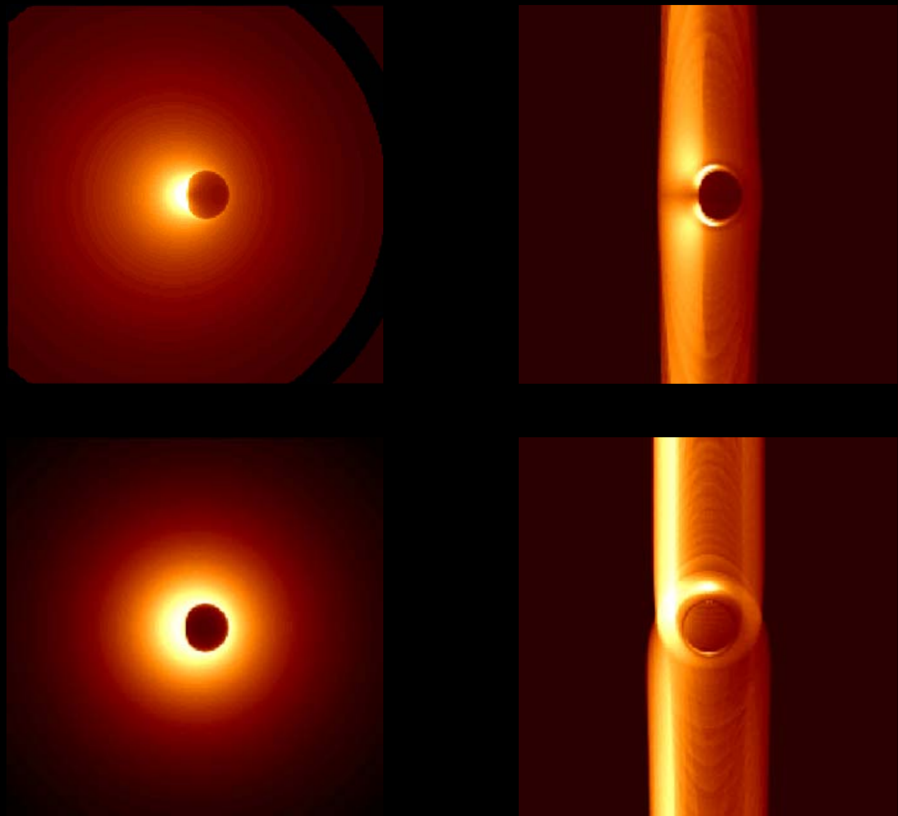
Light blocking & path lengthening

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

Gravitational Physics Imprint

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

Jet:
$a = 0.998$
$i = 90^o$
I = hollow



Accretion:
$a = 0$
$i = 90^o$
$I = r^{-2}$

Jet:
$a = 0$
$i = 45^o$
I = hollow

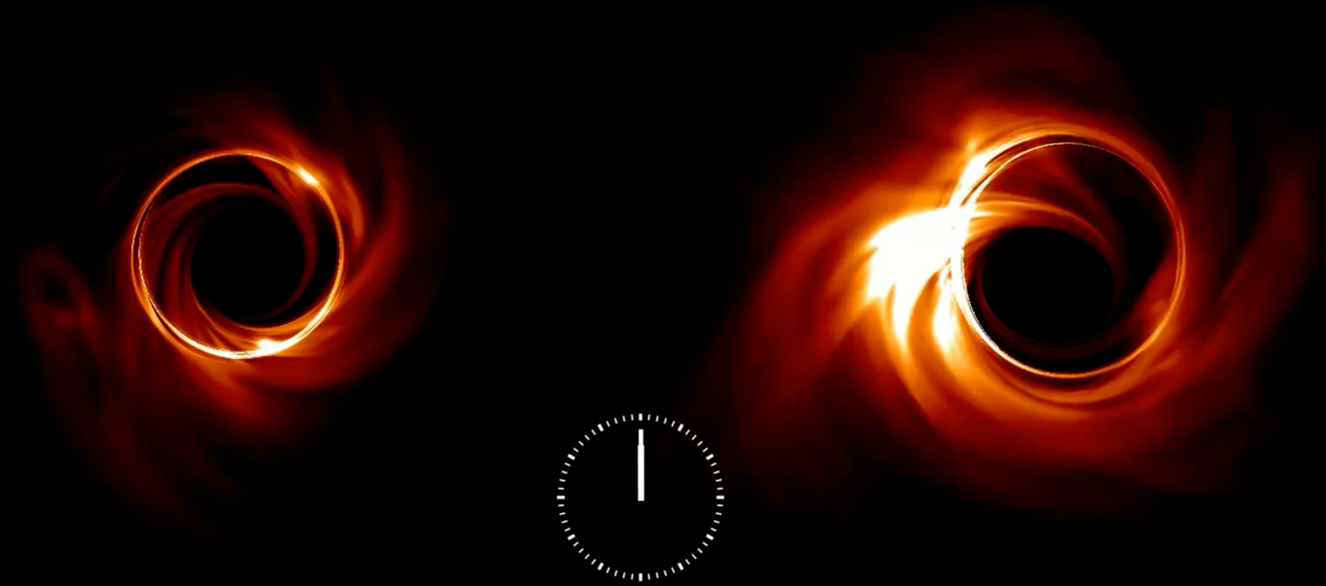
Optically thin matter covering the black hole.

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

Variability

M87* | Sgr A*



Variability time scale:
5-30 days

Simulation

Variability time scale:
5-30 min

Time-lapse evolution of best-fitting models
(hydrodynamic plasma around Kerr black hole).

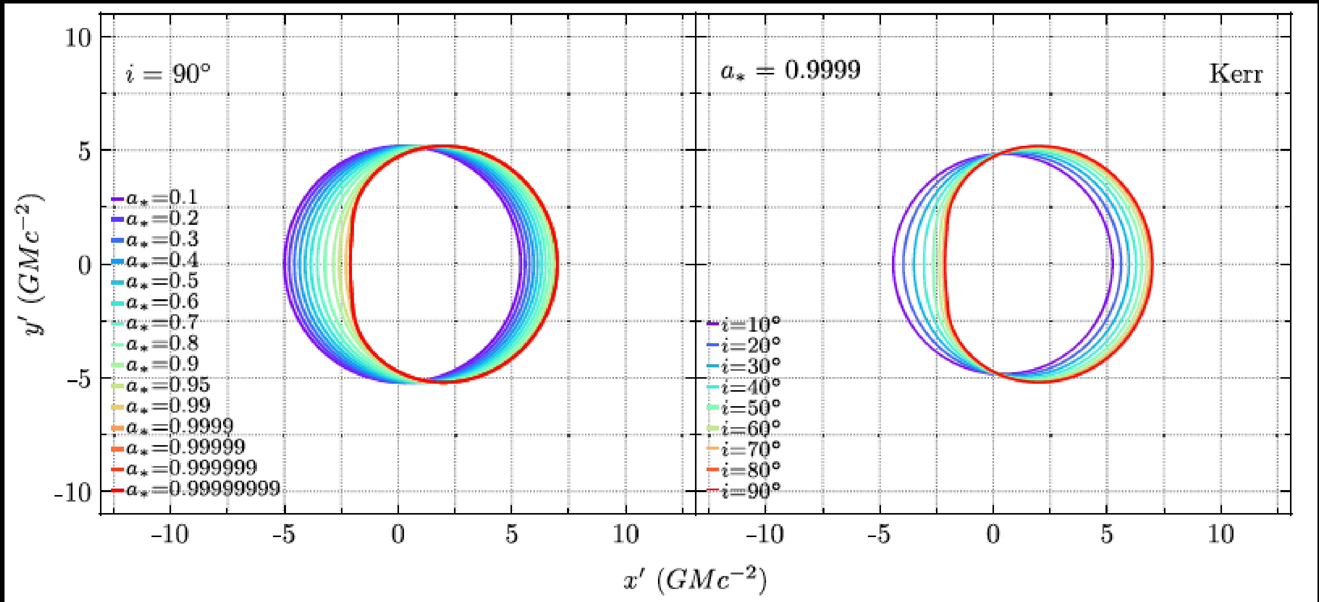
Credit: A. Joshi

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)

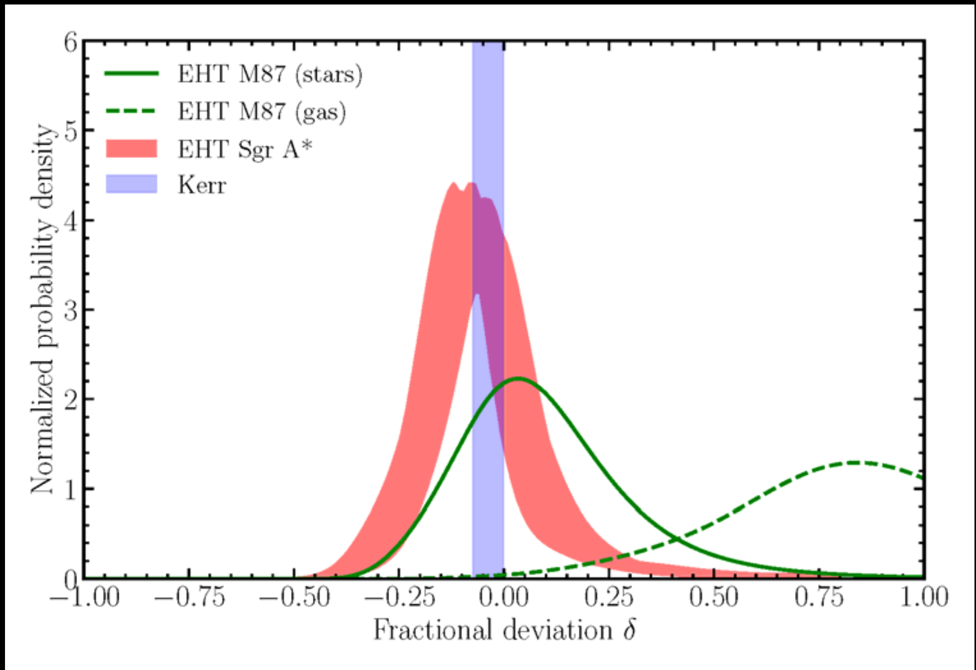
Variable spin parameter a | Variable inclination i

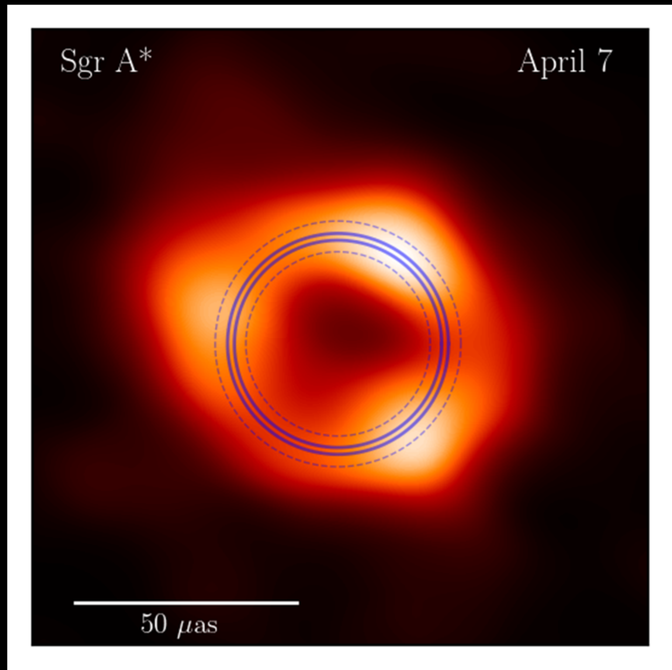


Medeiros, Özel, Psaltis, Astrophys. J. 896 (2020) 7

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 statistical inference.
  - M87*: Uncertainty in mass determination.
  - Sgr A*: More precise mass-distance prior, but higher variability.
- δ: Relative deviation of the shadow radius from the Schwarzschild value.
- Kerr reference: $0 \geq \delta \gtrsim -0.08$

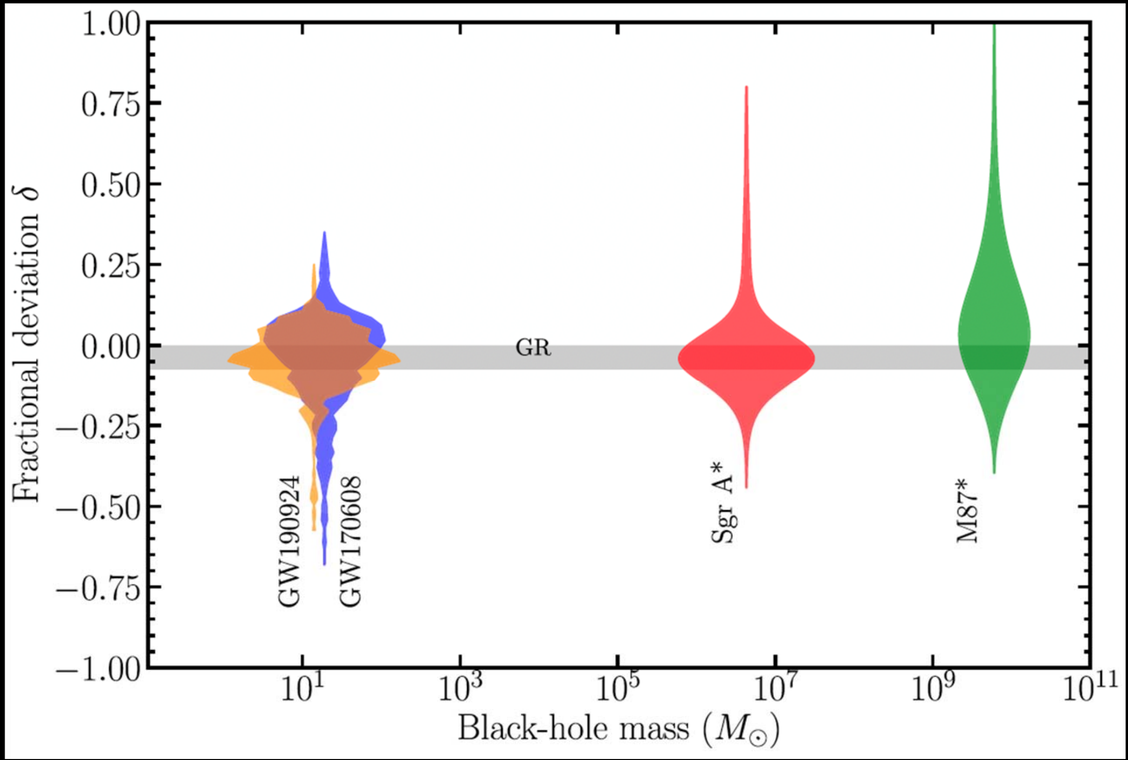




Compatibility of the Kerr Solution

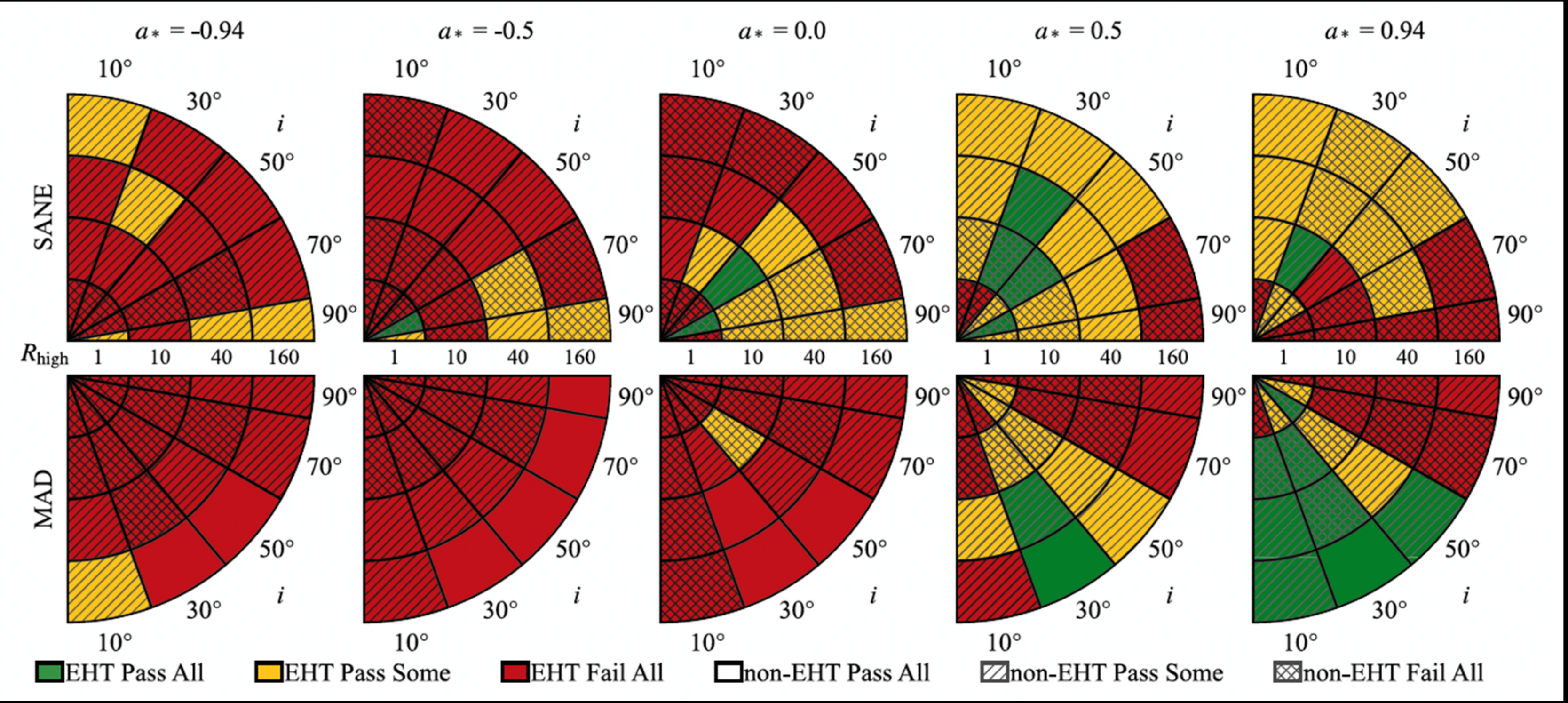
- Including GW observations from black hole mergers, the Kerr solution applies to black hole over 8 orders of magnitude.

⇒ Unlikely that GR needs corrections at these energy scales.



Best Fit Astrophysical Model (within GR)

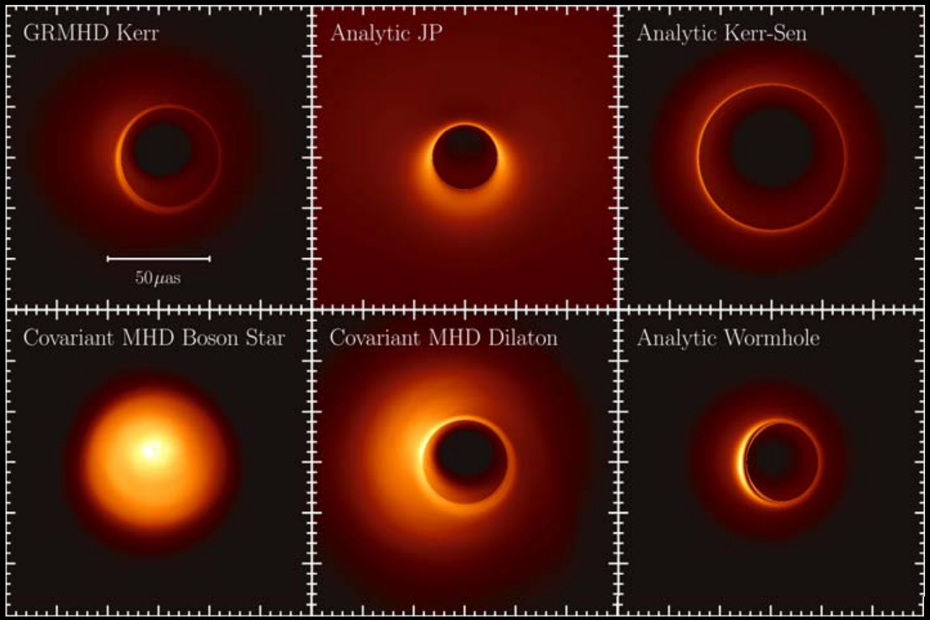
- Face-on orientation (i ~ 30°)
- Magnetically dominated accretion (MAD)
- Spinning black hole (a ≳ 0.5)
- Accretion rate: ~ 0.5-1 $\times 10^{-8}$ M_{sun}
- Jet outflow



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

Impact of Spacetime Curvature

- Images of (non-GR) compact objects differ from the GR prediction due to different spacetime curvature.

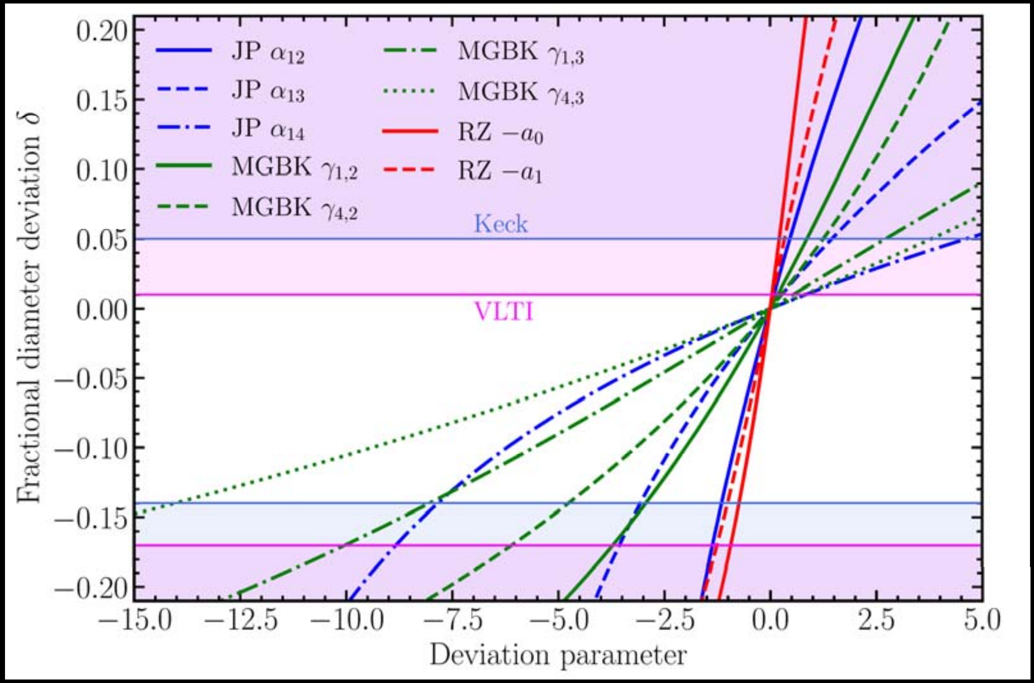


- In the following we focus on constraints on the shadow size inferred from Sgr A* observations:
  $-0.14 \leq \delta \leq 0.05$ (Keck priors), $-0.17 \leq \delta \leq 0.01$ (Gravity priors).

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

Constraints on Parametrized Metrics

- Strong-field metric parametrizations around the Kerr solution in a pathology-free manner, e.g. JP, MGBK, RZ.
  Those are independent of specific proposals of a fundamental theory of gravity.

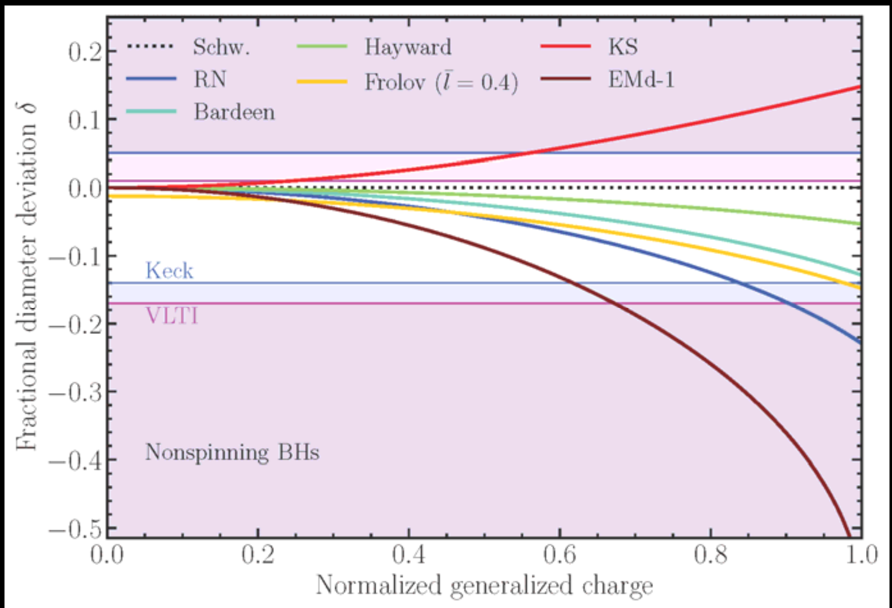


- A deviation from Kerr implies a deviation from general relativity!
- The constraints on the coefficients are versatile and apply to any metric upon expanding in the corresponding form.

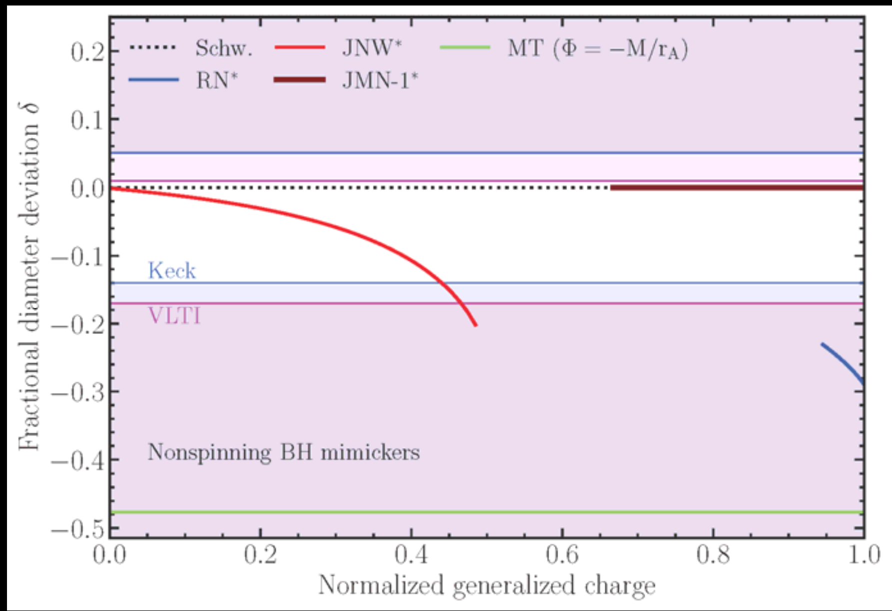
Johannsen, Psaltis, Phys. Rev. D83 (2011) 124015; Rezzolla, Zhidenko, Phys. Rev. D90 (2014) 084009; Vigeland, Yunes, Stein, Phys. Rev. D83 (2011) 104027

Constraints on Concrete Models

- Concrete non-GR black hole (mimicker) models motivated by extended theories of gravity become testable.
- Constraints on the model-specific deviation parameter (generalized "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

- Protoype of any renormalizable quantum gravity theory.

- Adding 2nd order curvature terms to GR.

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

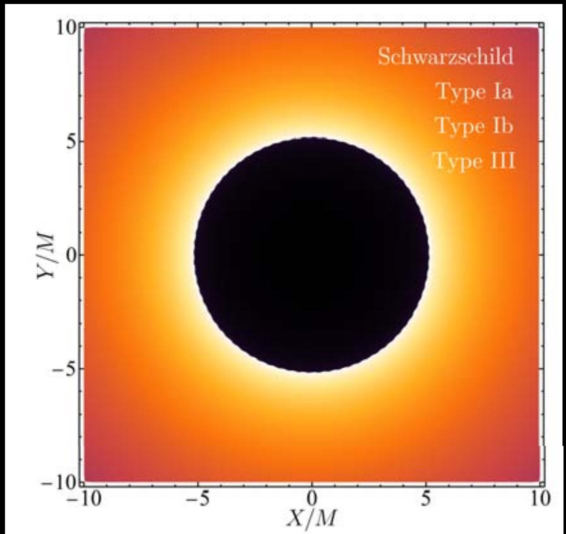
  Covers automatically 1-loop quantum corrections to GR
  (e.g. R^2 Starobinsky term).

- 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.

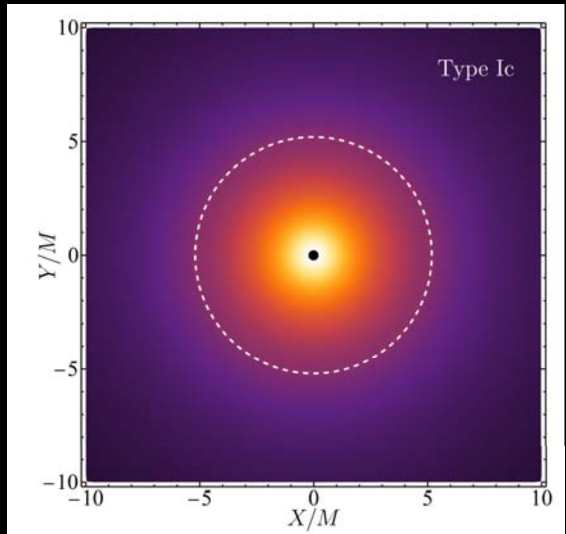
$$\begin{aligned} H_{\mu\nu} \equiv{}& \gamma \left(R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} \right) \\ & - 4\alpha \left(D^\rho D^\sigma + \frac{1}{2} R^{\rho\sigma} \right) C_{\mu\rho\nu\sigma} + 2\beta \left(R_{\mu\nu} - \frac{1}{4} R\, g_{\mu\nu} - D_\mu D_\nu + g_{\mu\nu} D^2 \right) R \\ ={}& 0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

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

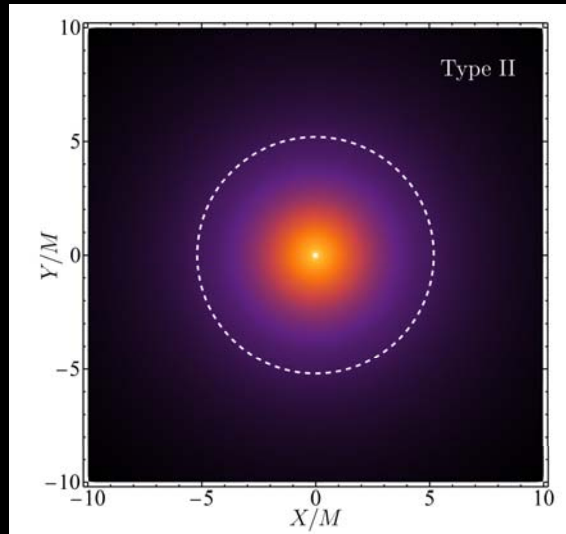
Quadratic Gravity



Black hole, wormhole, naked singularity Ia, Ib

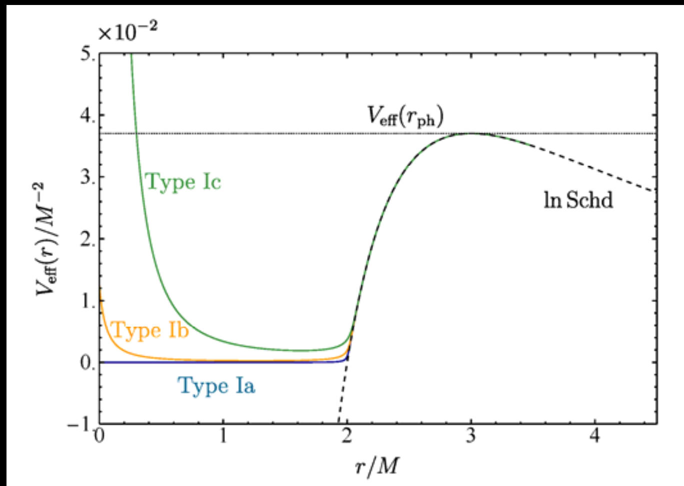


Naked singularity Ic



Naked singularity 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.

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

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

  ⇒ Shadow observations allow constraints on deviations from the Kerr black hole and on alternative theories of gravity. It also opens a door to test quantum gravity theories.

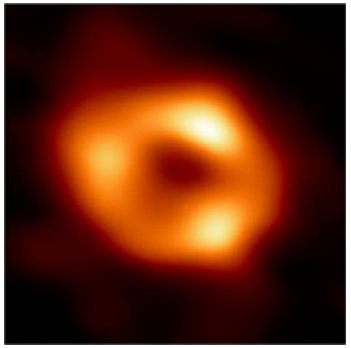
- Observation campaigns in 2018, 2021, 2022 with 3 more telescopes ⇒ higher sensitivity images.

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

  ⇒ Movies (dynamics), magnetic field investigations, higher resolution. This will allow improved opportunities to test theories of gravity.

Questions?

… apart from which operating system was used predominantly?



Ubuntu

Back Up

Generating Astrophysical Models

MAD

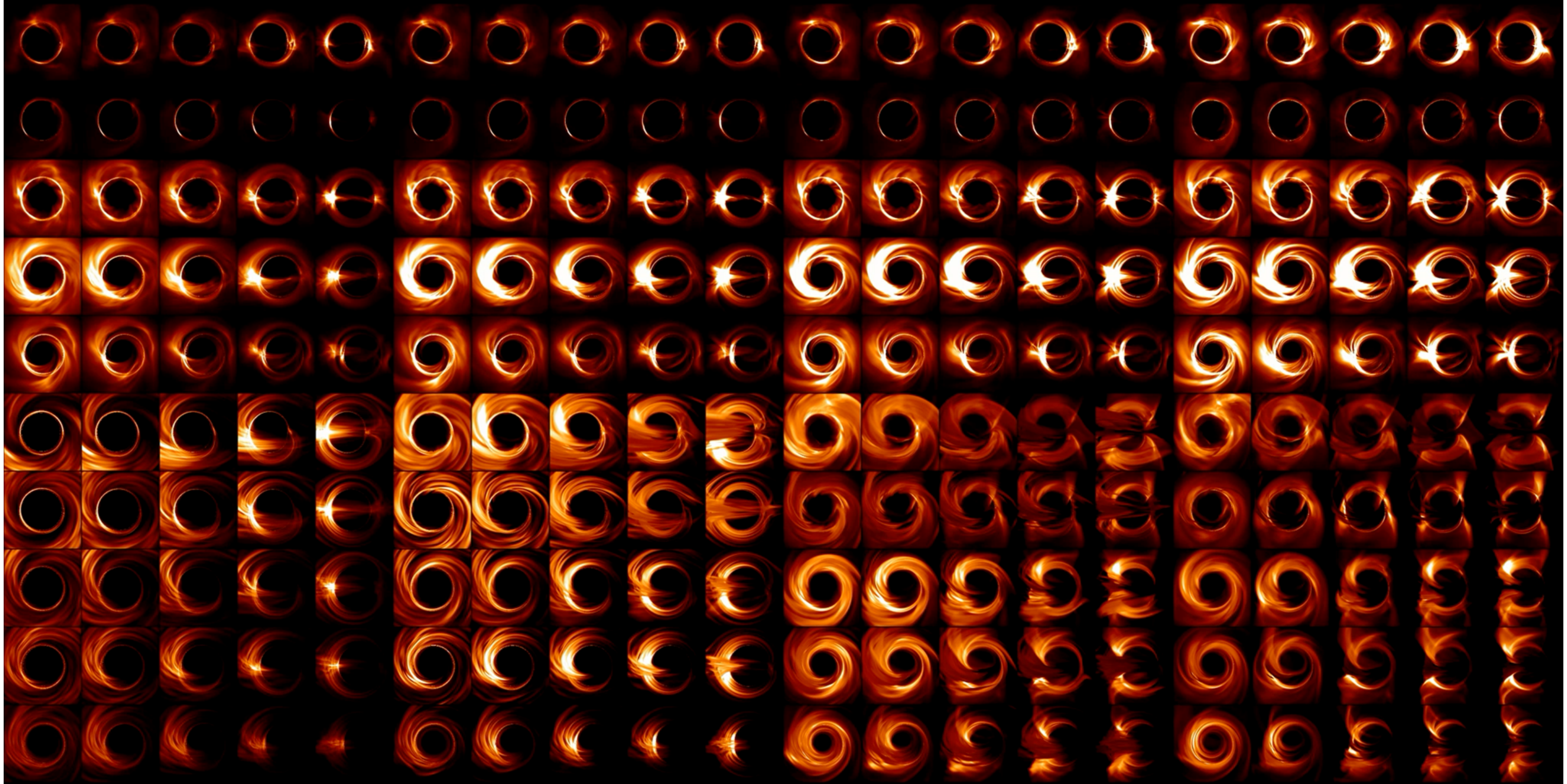
$R_{high} = 160$

$a = +0.94$

$i = 90$

Credit: B. Prather

Applying Astrophysical Constraints



Credit: B. Prather