Title: Probing black-hole uniqueness on supermassive scales

Speakers: Aaron Held

Series: Strong Gravity

Date: February 22, 2024 - 1:00 PM

URL: https://pirsa.org/24020089

Abstract: To set the stage, I discuss different assumptions about physics beyond GR and resulting expectations about where to look for the breakdown of the Kerr paradigm. In particular, I present counterexamples to the prevailing expectation that deviations from GR are necessarily tied to local curvature scales. This provides a motivation to probe for a potential breakdown of black-hole uniqueness, not just for solar-mass but also for supermassive black holes. I will then focus on how to leverage VLBI observations of light emitted in the accretion disk to probe the stationary and axisymmetric background spacetime. I will detail different assumptions about additional hidden symmetries of the spacetime and how to then systematically parameterize deviations. Within such a parametrization, I will demonstrate a systematic lensing-band framework to exclude spacetimes for which an observed VLBI feature cannot arise from geodesics that traversed the equatorial plane more than once. If time permits, I will also address complimentary tests with solar-mass binaries and possible pathways to achieve stable nonlinear evolution.

---

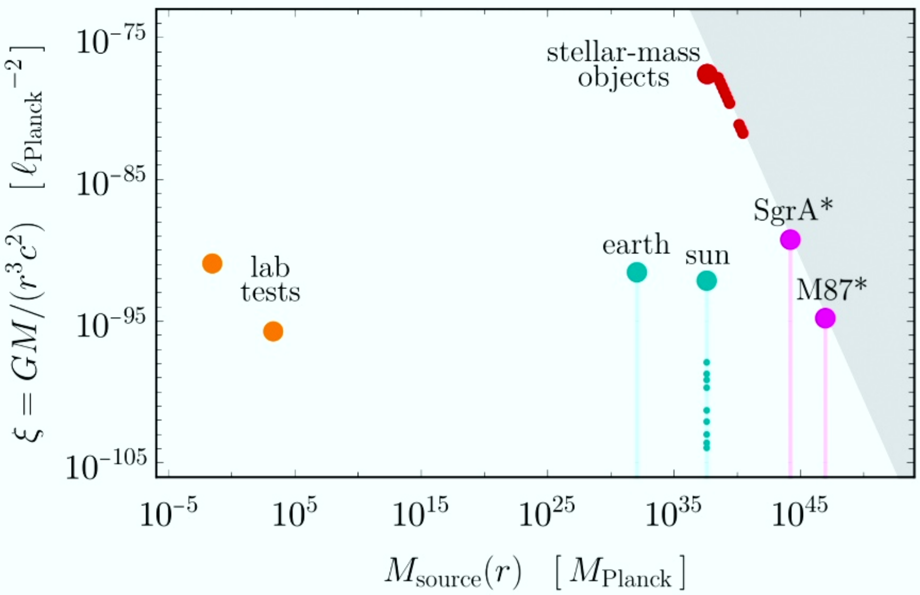
Zoom link

# Probing black-hole uniqueness on supermassive scales

**Aaron Held**

Philippe Meyer Junior Research Chair
École Normale Supérieure

22-Feb-2024: Strong-Gravity Seminar,
Perimeter Institute for Theoretical Physics




# Probing black-hole uniqueness on supermassive scales

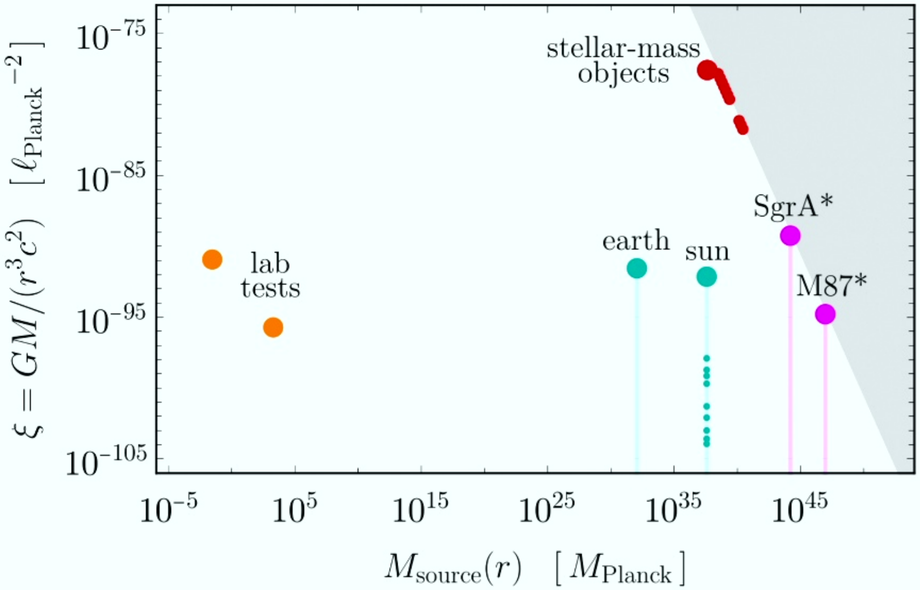

**Aaron Held**

Philippe Meyer Junior Research Chair
École Normale Supérieure


22-Feb-2024: Strong-Gravity Seminar,
Perimeter Institute for Theoretical Physics

ENS ÉCOLE NORMALE SUPÉRIEURE

FONDATION MEYER POUR LE DEVELOPPEMENT CULTUREL ET ARTISTIQUE




**Part I:**
**Where to expect new physics?**

**Part II:**
**Shadow (VLBI) observations of supermassive scales**

[ **Part III:**
**Gravitational-wave (LVK) observations of solar-mass black holes** ]

# Probing black-hole uniqueness on supermassive scales


## Aaron Held

Philippe Meyer Junior Research Chair
École Normale Supérieure


22-Feb-2024: Strong-Gravity Seminar,
Perimeter Institute for Theoretical Physics

ENS ÉCOLE NORMALE SUPÉRIEURE

FONDATION MEYER POUR LE DEVELOPPEMENT CULTUREL ET ARTISTIQUE

- **Breaking black-hole uniqueness at supermassive scales**
  Eichhorn, Fernandes, Held, Silva, 2312.11430

# Part I: Where to expect new physics?

# Scalarization in "standard" sGB theories ...

for a recent review, see, e.g., Doneva et. Al, 2211.01766

mechanism

standard example

- **Setup:** admits vacuum solutions of GR (with a constant scalar field profile)

$$S = \frac{1}{16\,\pi\,G}\int_x \left[R - (\partial\phi)^2 + \alpha_1\,F(\phi)\,\mathcal{G}\right]$$

- **Onset:** linear tachyonic instability for negative scalar mass $\left(\Box - \mu_{\rm eff}^2\right)\delta\phi = 0$

$$F[0] = 0\,, \quad F'[0] = 0\,, \quad F''[0] = \text{const}$$

- **Endpoint:** nonlinear dynamics can quench the instability and settle to a non-GR black hole

$$\mu_{\rm eff}^2 = -\alpha_1 \mathcal{G}$$

**... is tied to curvature** (or to spin)

# Scalarization in "modified" sGB theories ...

Eichhorn, Fernandes, Held, Silva, 2312.11430

mechanism

- **Setup:** admits vacuum solutions of GR (with a constant scalar field profile and a second non-dynamical scalar)
- **Onset:** linear tachyonic instability for negative scalar mass
  $(\Box - \mu_{\text{eff}}^2)\, \delta\phi = 0$

modified example

$$S = \frac{1}{16\,\pi\,G} \int_x \left[ R - (\partial\phi)^2 + \alpha_1\, F(\phi)\, \mathcal{G} - 2\alpha_2^3\, F(\phi) \left( \psi\, \mathcal{G} - \frac{\psi^2}{2} \right) \right]$$

$$F[0] = 0\,, \quad F'[0] = 0\,, \quad F''[0] = \text{const}$$

$$\mu_{\text{eff}}^2 = -\alpha_1 \mathcal{G} \;+\; \alpha_2^3\, \mathcal{G}^2$$

# Scalarization in "modified" sGB theories ...

Eichhorn, Fernandes, Held, Silva, 2312.11430

mechanism

- **Setup:** admits vacuum solutions of GR (with a constant scalar field profile and a second non-dynamical scalar)
- **Onset:** linear tachyonic instability for negative scalar mass
  $\left(\Box - \mu_{\text{eff}}^2\right) \delta\phi = 0$

modified example

$$S = \frac{1}{16\,\pi\,G} \int_x \Big[ R - (\partial\phi)^2 + \alpha_1\,F(\phi)\,\mathcal{G} \\ -2\alpha_2^3\,F(\phi)\left(\psi\,\mathcal{G} - \frac{\psi^2}{2}\right)\Big]$$

$$F[0] = 0\,, \quad F'[0] = 0\,, \quad F''[0] = \text{const}$$

$$\mu_{\text{eff}}^2 = -\alpha_1 \mathcal{G} \;+\; \alpha_2^3\,\mathcal{G}^2$$

## ... is not tied to curvature

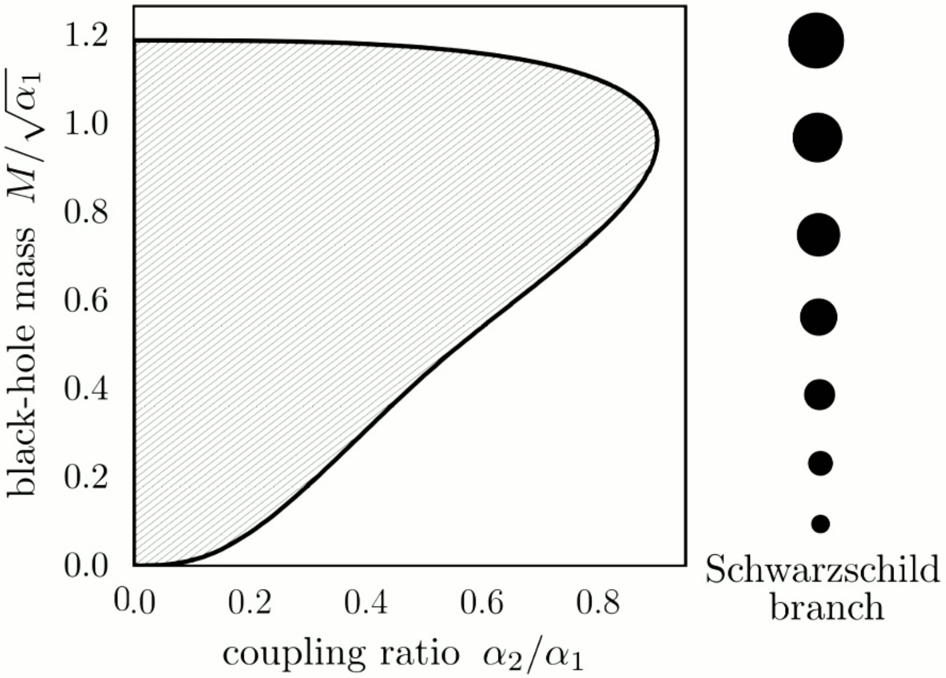
# Scalarization in "modified" sGB theories ...

Eichhorn, Fernandes, Held, Silva, 2312.11430

mechanism

- **Setup:** admits vacuum solutions of GR (with a constant scalar field profile and a second non-dynamical scalar)
- **Onset:** linear tachyonic instability for negative scalar mass $\left(\Box - \mu_{\text{eff}}^2\right)\delta\phi = 0$

Eichhorn, Fernandes, Held, Silva, 2312.11430




## ... is not tied to curvature

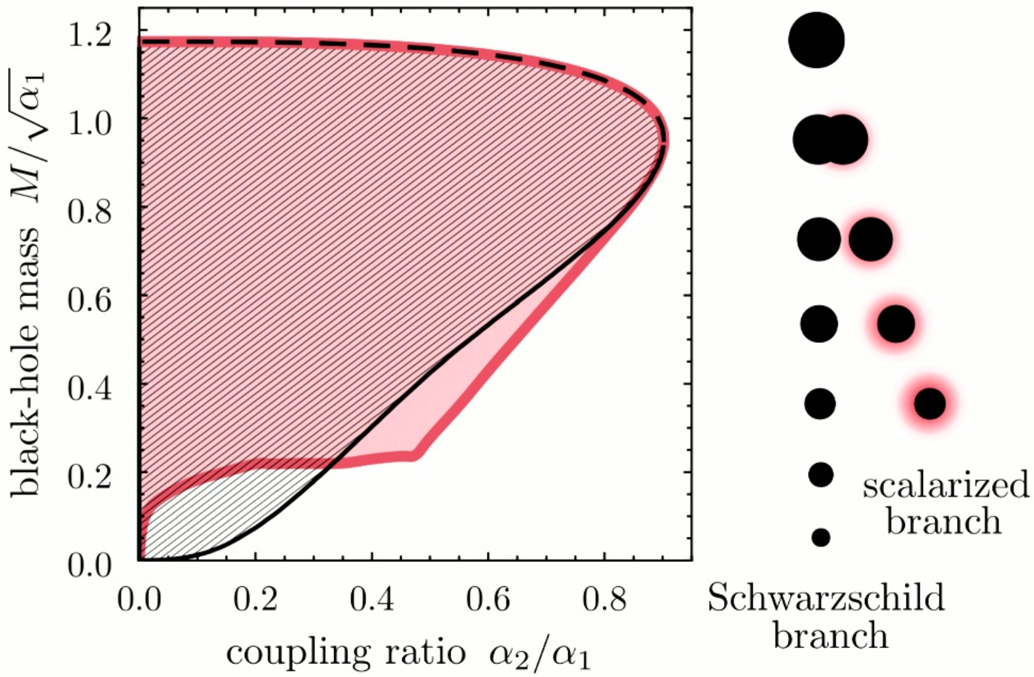
# Scalarization in “modified” sGB theories ...

Eichhorn, Fernandes, Held, Silva, 2312.11430

mechanism

- **Setup:** admits vacuum solutions of GR (with a constant scalar field profile and a second non-dynamical scalar)
- **Onset:** linear tachyonic instability for negative scalar mass $\left(\Box - \mu_{\text{eff}}^2\right)\delta\phi = 0$
- [ **Endpoint:** nonlinear dynamics might quench the instability and settle to a non-GR black hole ]

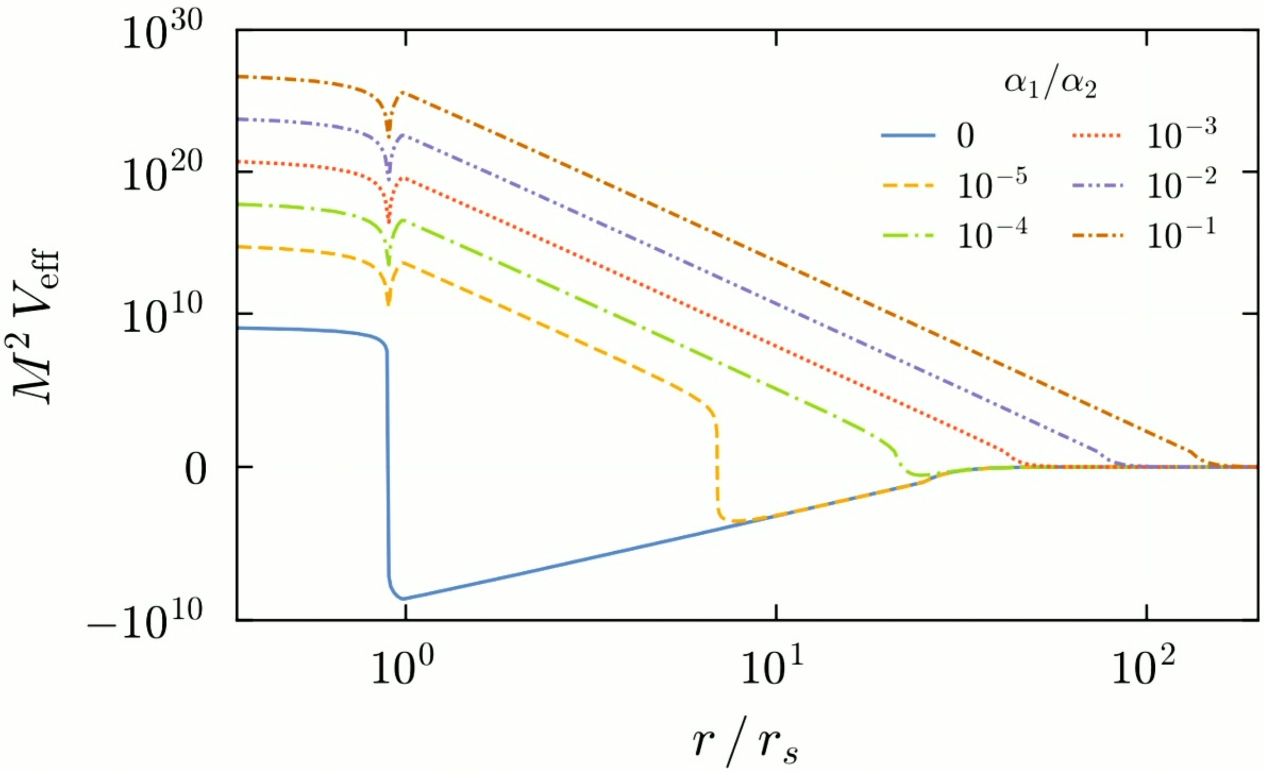
Eichhorn, Fernandes, Held, Silva, 2312.11430




... is not tied to curvature

# Scalarization of supermassive black holes ...

Eichhorn, Fernandes, Held, Silva, 2312.11430




effective potential for a neutron star of mass $\mathrm{M} = 1.4\,\mathrm{M}_\odot$ and with new-physics mass scale $\sqrt{\alpha_1} = 10^6\,\mathrm{M}_\odot$

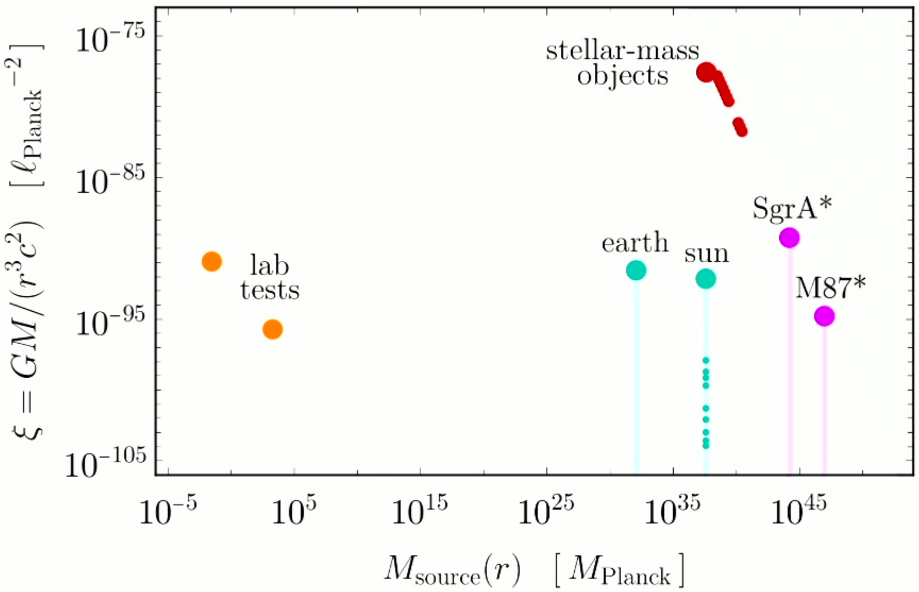
Eichhorn, Fernandes, Held, Silva, 2312.11430

# ... goes along with stable neutron stars.

# Where to go next?

- **obtain rotating solutions**
  Fernandes, Mulryne, CQG 40 (2023) 16

- **stability of and nonlinear transition to the non-GR branch**

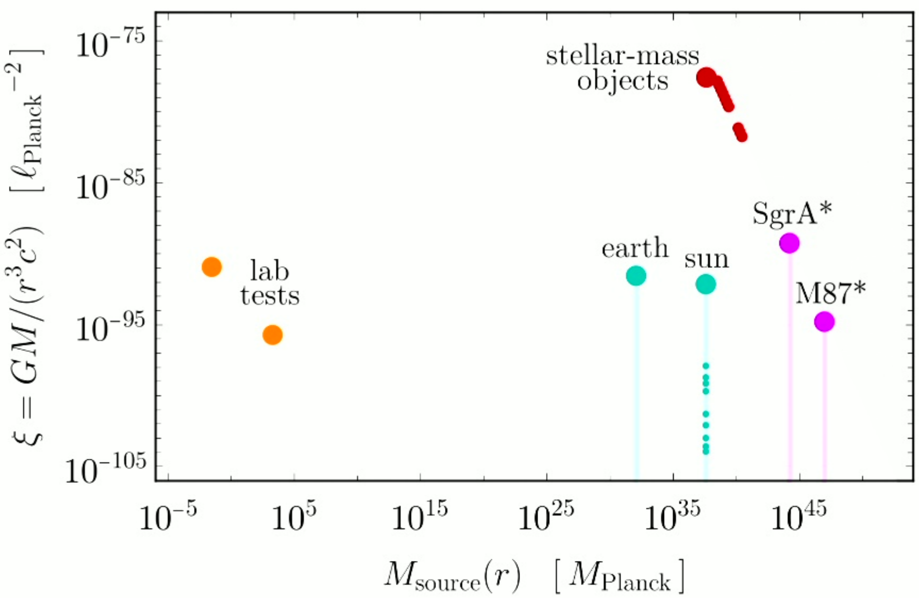


# Where to go next?

- **obtain rotating solutions**
  Fernandes, Mulryne, CQG 40 (2023) 16

- **stability of and nonlinear transition to the non-GR branch**

- **best constraints will currently come from shadow (VLBI) observations**



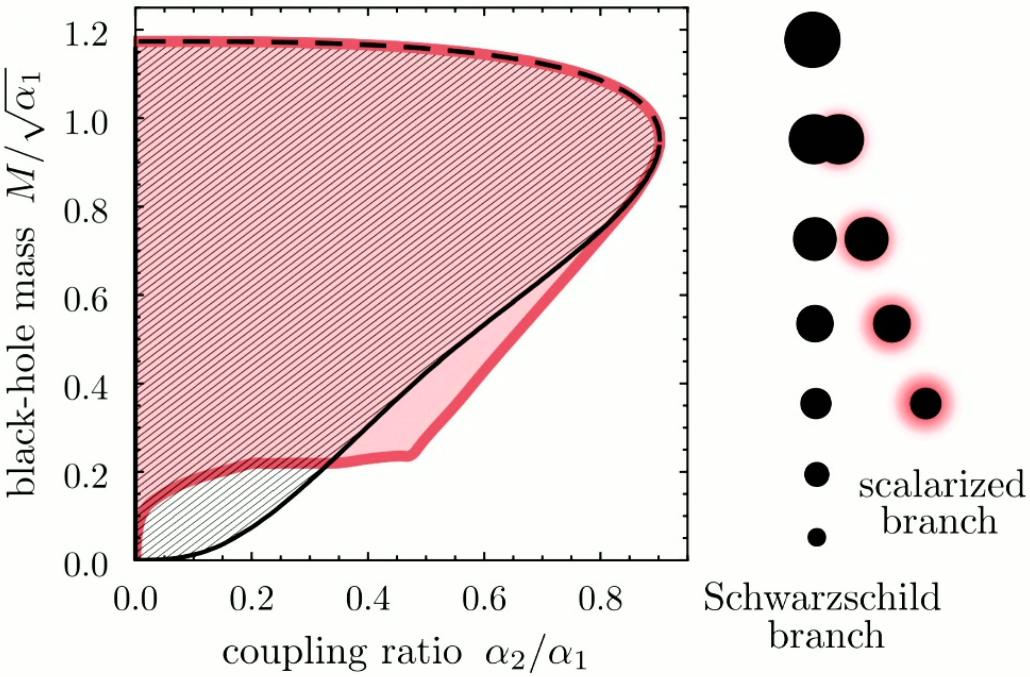
# Scalarization in "modified" sGB theories ...

Eichhorn, Fernandes, Held, Silva, 2312.11430

mechanism

- **Setup:** admits vacuum solutions of GR (with a constant scalar field profile and a second non-dynamical scalar)
- **Onset:** linear tachyonic instability for negative scalar mass $\left(\Box - \mu_{\text{eff}}^2\right)\delta\phi = 0$
- [ **Endpoint:** nonlinear dynamics might quench the instability and settle to a non-GR black hole ]

Eichhorn, Fernandes, Held, Silva, 2312.11430




## ... is not tied to curvature

# Scalarization in "modified" sGB theories ...

Eichhorn, Fernandes, Held, Silva, 2312.11430

mechanism

modified example

- **Setup:** admits vacuum solutions of GR (with a constant scalar field profile and a second non-dynamical scalar)
- **Onset:** linear tachyonic instability for negative scalar mass $\left(\Box - \mu_{\text{eff}}^2\right) \delta\phi = 0$

$$S = \frac{1}{16\,\pi\,G} \int_x \Big[ R - (\partial\phi)^2 + \alpha_1\, F(\phi)\, \mathcal{G} - 2\alpha_2^3\, F(\phi) \left( \psi\, \mathcal{G} - \frac{\psi^2}{2} \right) \Big]$$

$$F[0] = 0\,, \quad F'[0] = 0\,, \quad F''[0] = \text{const}$$

$$\mu_{\text{eff}}^2 = -\alpha_1 \mathcal{G} \;+\; \alpha_2^3\, \mathcal{G}^2$$

# ... is not tied to curvature


# Part II: Shadow (VLBI) observations of supermassive BHs

The central brightness depression:

- **What if there was no horizon?**
  Eichhorn, Held, Gold, ApJ 950 (2023) 2
  Eichhorn, Held, JCAP 01 (2023) 032

The photon ring(s):

- **How to parameterize deviations from Kerr?**
  Delaporte, Eichhorn, Held, CQG 39 (2022) 13
- **How to disentangle astrophysics and geometry?**
  Cárdenas-Avendaño, Held, 2312.06590

# Part II: Shadow (VLBI) observations of supermassive BHs

The central brightness depression:

- **What if there was no horizon?**
  Eichhorn, Held, Gold, ApJ 950 (2023) 2
  Eichhorn, Held, JCAP 01 (2023) 032

The photon ring(s):

- **How to parameterize deviations from Kerr?**
  Delaporte, Eichhorn, Held, CQG 39 (2022) 13
- **How to disentangle astrophysics and geometry?**
  Cárdenas-Avendaño, Held, 2312.06590

# Part II: Shadow (VLBI) observations of supermassive BHs

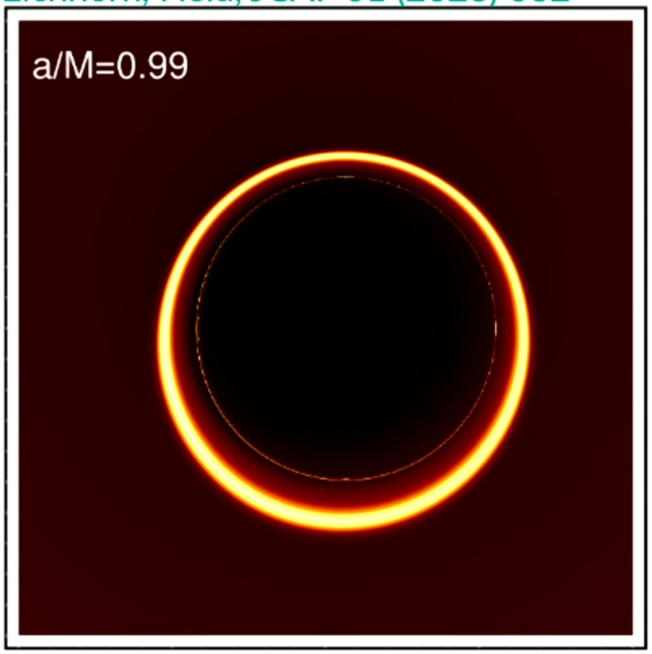
# Distinguishing black holes from horizonless objects …

**regular spacetime**
**(no curvature singularity)**
formation history is up to current research
[from charged disk a<0.98, see Thorne '74]

Eichhorn, Held, JCAP 01 (2023) 032
see also
Lamy et. Al, CQG 35 (2018) 11
for a simiar model

# Distinguishing black holes from horizonless objects …

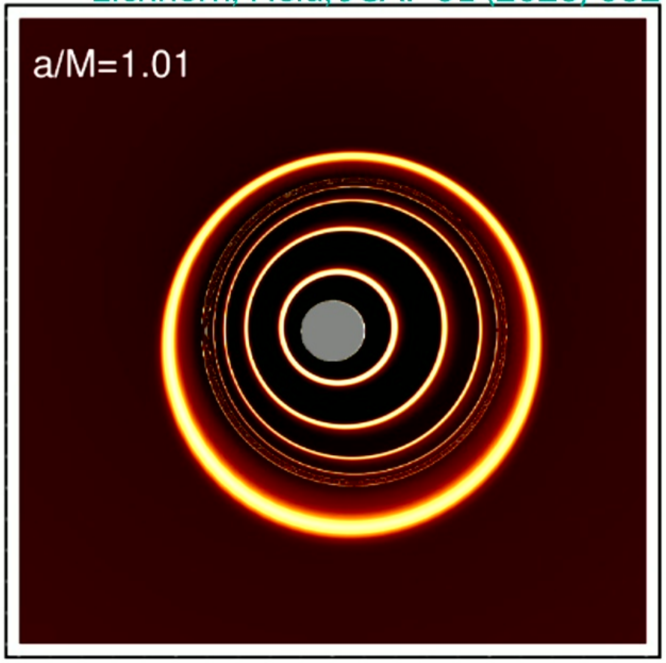
Eichhorn, Held, JCAP 01 (2023) 032




**regular spacetime**
**(no curvature singularity)**
formation history is up to current research
[from charged disk a<0.98, see Thorne '74]

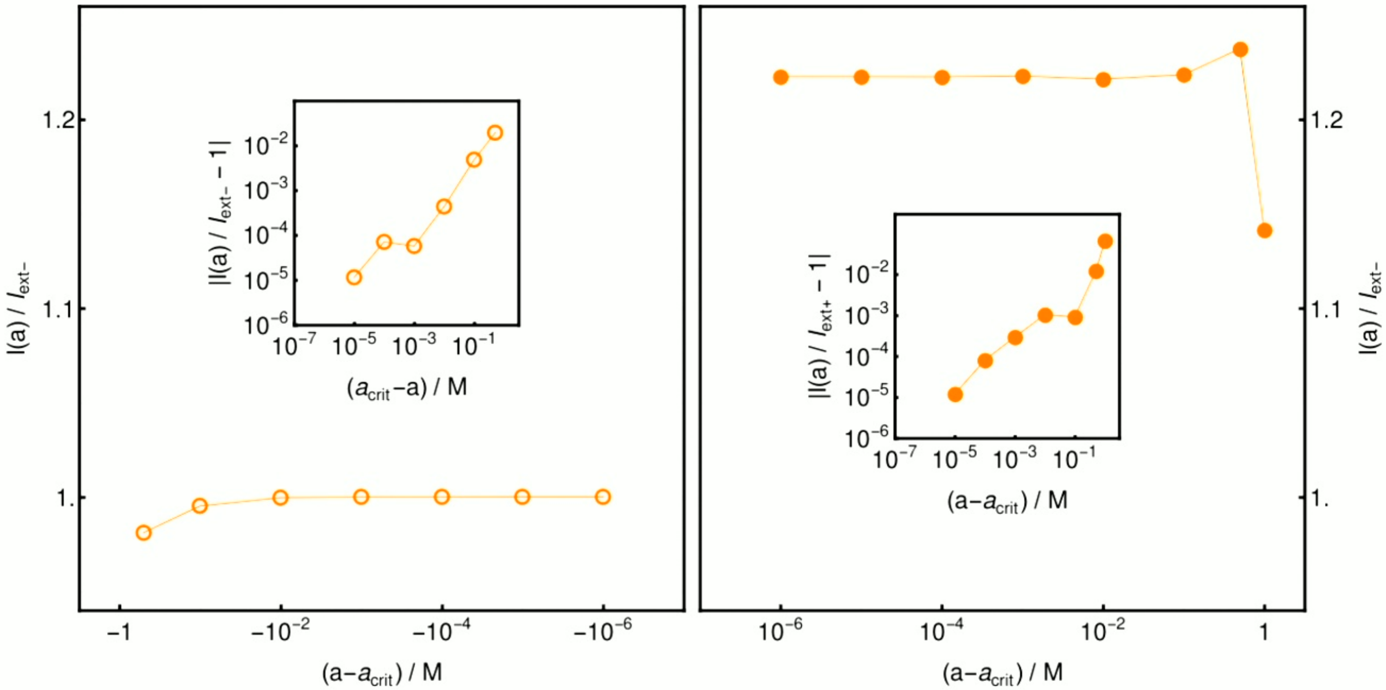
Eichhorn, Held, JCAP 01 (2023) 032
see also
Lamy et. Al, CQG 35 (2018) 11
for a simiar model

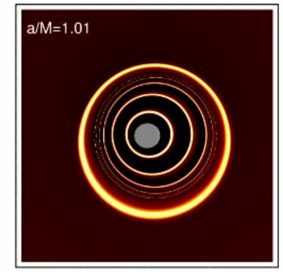
Eichhorn, Held, JCAP 01 (2023) 032



# Distinguishing black holes from horizonless objects …

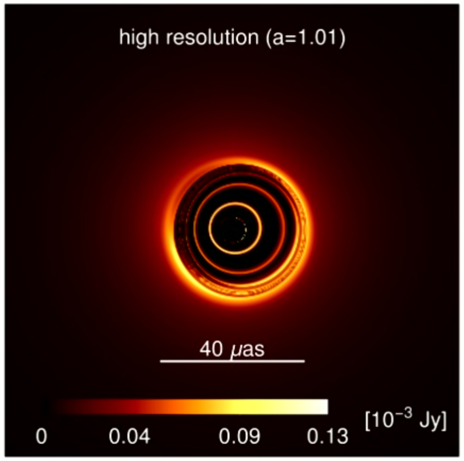
Eichhorn, Held, JCAP 01 (2023) 032

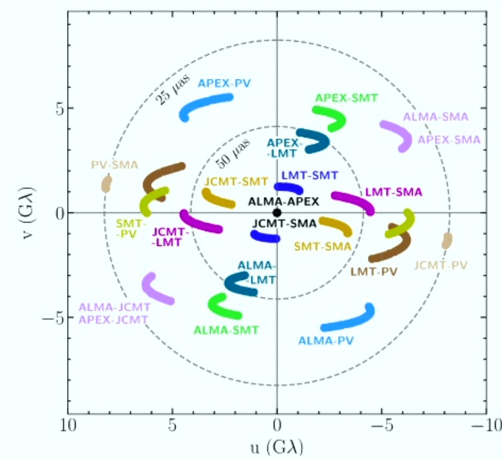



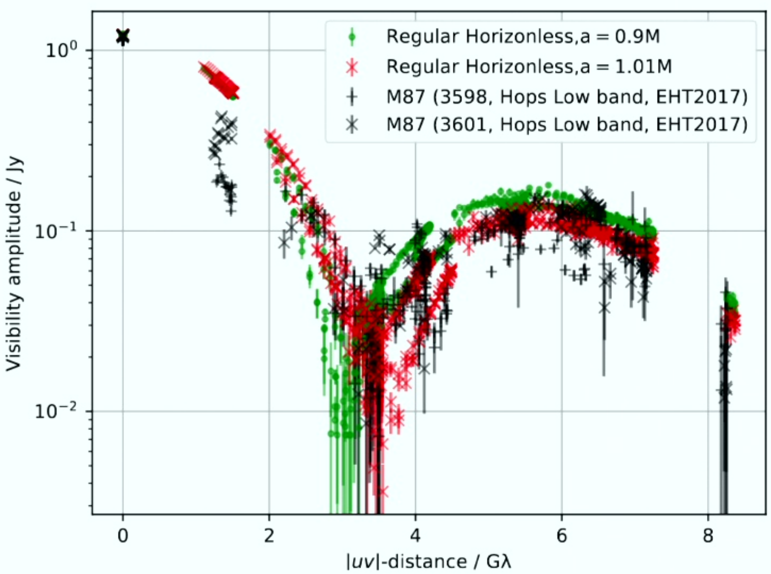
# Distinguishing black holes from horizonless objects …

Eichhorn, Held, Gold, ApJ. 950 (2023) 2, 117




EHT 2017 observing run




Eichhorn, Held, Gold, ApJ. 950 (2023) 2, 117

# Distinguishing black holes from horizonless objects …

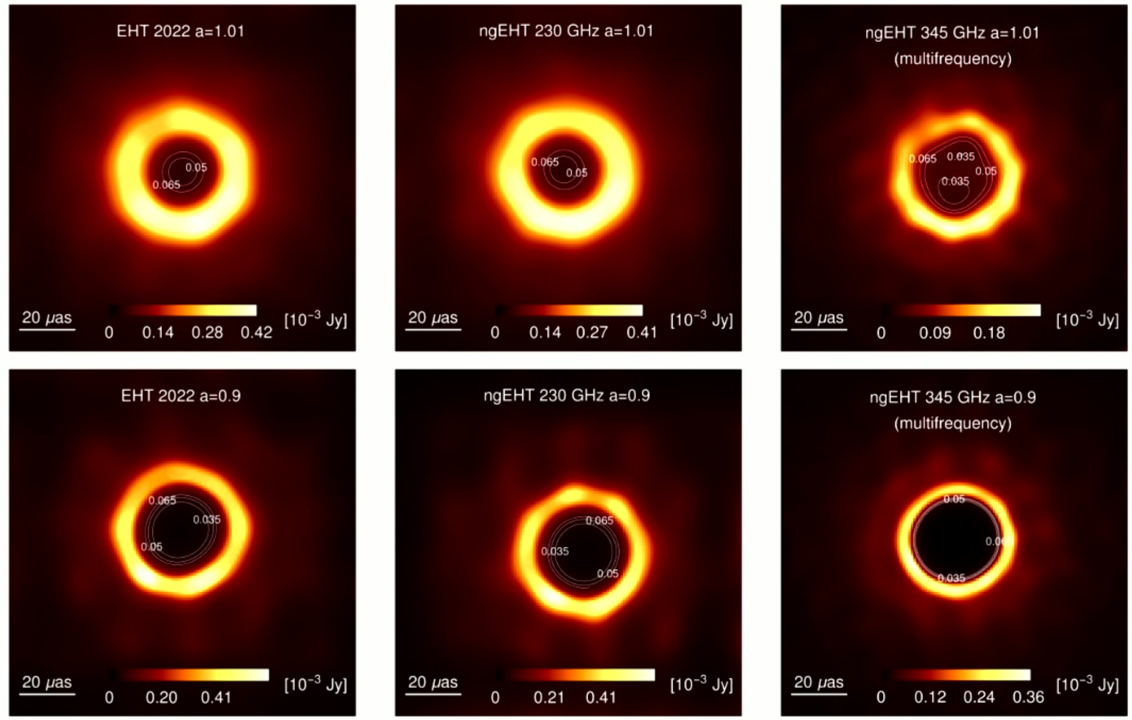
Eichhorn, Held, Gold, ApJ. 950 (2023) 2, 117

- **obtain a synthetic observation**
  eht-imaging; Chael et. Al, ApJ. 857 (2018), 23
- **fit with geometric template**
  VIDA; Tiede et. Al, ApJ. 925 (2022), 122
- **determine the brightness ratio**

$$\hat{f}_c = \frac{\text{lower 5th-percentile flux in } \mathcal{S}}{\text{mean flux in } \mathcal{R}}$$

| array configuration | $\hat{f}_c$ for $\frac{a}{M} = 1.01$ | $\hat{f}_c$ for $\frac{a}{M} = 0.9$ |
|---|---|---|
| EHT 2017 (230 GHz) | 0.226 | 0.080 |
| EHT 2022 (230 GHz) | 0.163 | 0.041 |
| ngEHT (230 GHz) | 0.166, 0.094* | 0.037 |
| ngEHT (230 GHz multifreq) | 0.269 | 0.009 |
| ngEHT (345 GHz multifreq) | 0.271 | 0.007 |

Eichhorn, Held, Gold, ApJ. 950 (2023) 2, 117



# Distinguishing black holes from horizonless objects ...

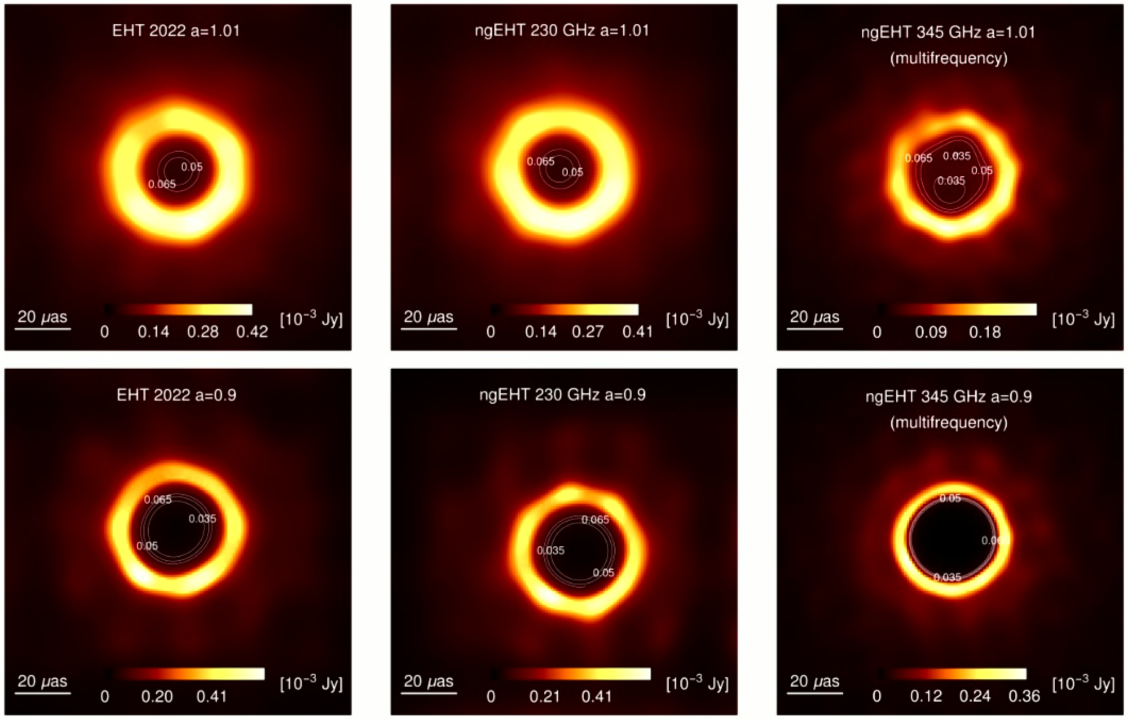
Eichhorn, Held, Gold, ApJ. 950 (2023) 2, 117

- **obtain a synthetic observation**
  eht-imaging; Chael et. Al, ApJ. 857 (2018), 23
- **fit with geometric template**
  VIDA; Tiede et. Al, ApJ. 925 (2022), 122
- **determine the brightness ratio**

$$\hat{f}_c = \frac{\text{lower 5th-percentile flux in } \mathcal{S}}{\text{mean flux in } \mathcal{R}}$$

| array configuration | $\hat{f}_c$ for $\frac{a}{M} = 1.01$ | $\hat{f}_c$ for $\frac{a}{M} = 0.9$ |
|---|---|---|
| EHT 2017 (230 GHz) | 0.226 | 0.080 |
| EHT 2022 (230 GHz) | 0.163 | 0.041 |
| ngEHT (230 GHz) | 0.166, 0.094* | 0.037 |
| ngEHT (230 GHz multifreq) | 0.269 | 0.009 |
| ngEHT (345 GHz multifreq) | 0.271 | 0.007 |

Eichhorn, Held, Gold, ApJ. 950 (2023) 2, 117




**... is / will become possible.**

The central brightness depression:

- **What if there was no horizon?**
  Eichhorn, Held, Gold, ApJ 950 (2023) 2
  Eichhorn, Held, JCAP 01 (2023) 032

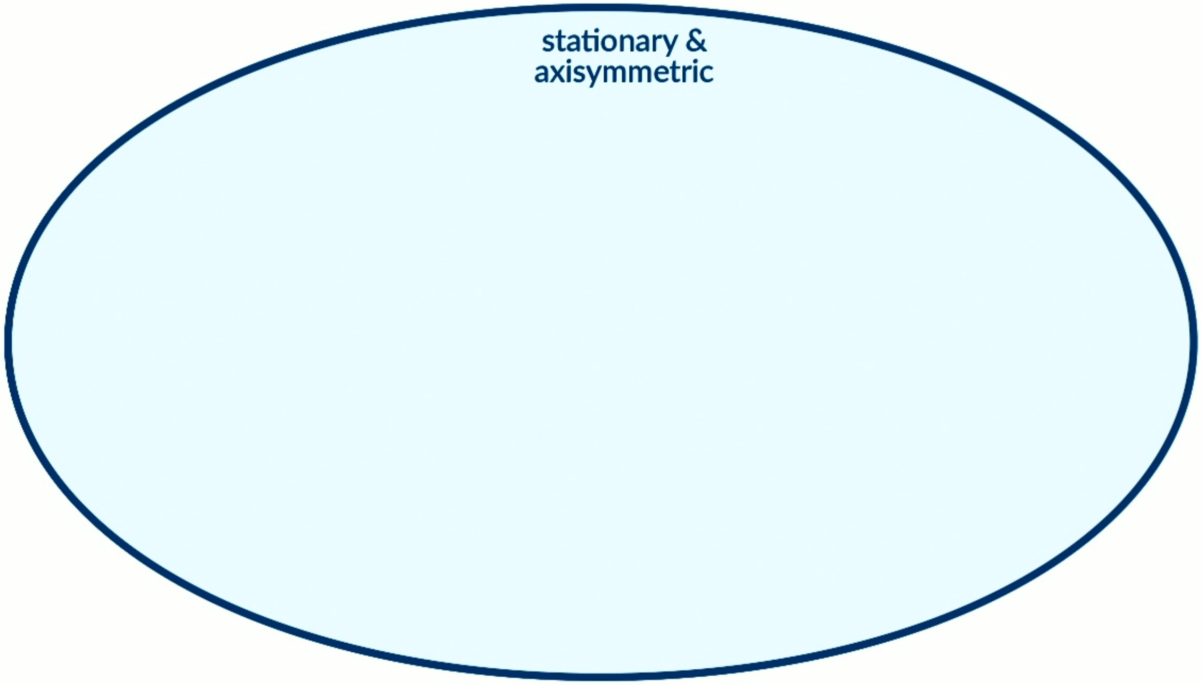
The photon ring(s):

- **How to parameterize deviations from Kerr?**
  Delaporte, Eichhorn, Held, CQG 39 (2022) 13
- **How to disentangle astrophysics and geometry?**
  Cárdenas-Avendaño, Held, 2312.06590

# Part II: Shadow (VLBI) observations of supermassive BHs

# The class of stationary & axisymmetric spacetimes …

Delaporte, Eichhorn, Held, CQG 39 (2022) 13

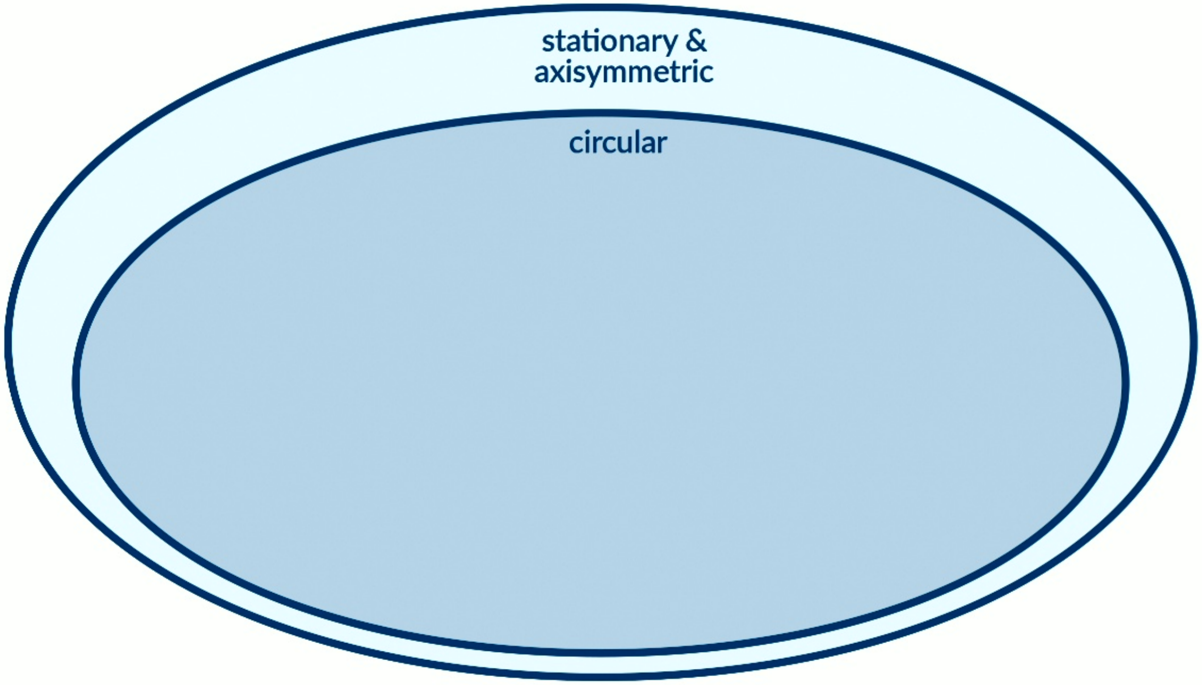


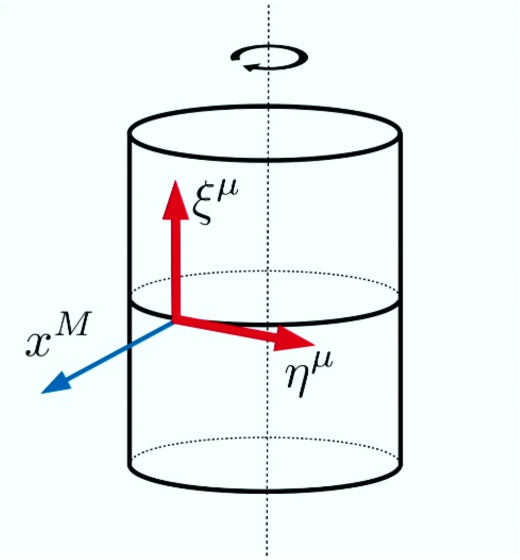

two Killing vectors

$\xi_\mu \ , \ \eta_\mu$

# The class of stationary & axisymmetric spacetimes …

Delaporte, Eichhorn, Held, CQG 39 (2022) 13

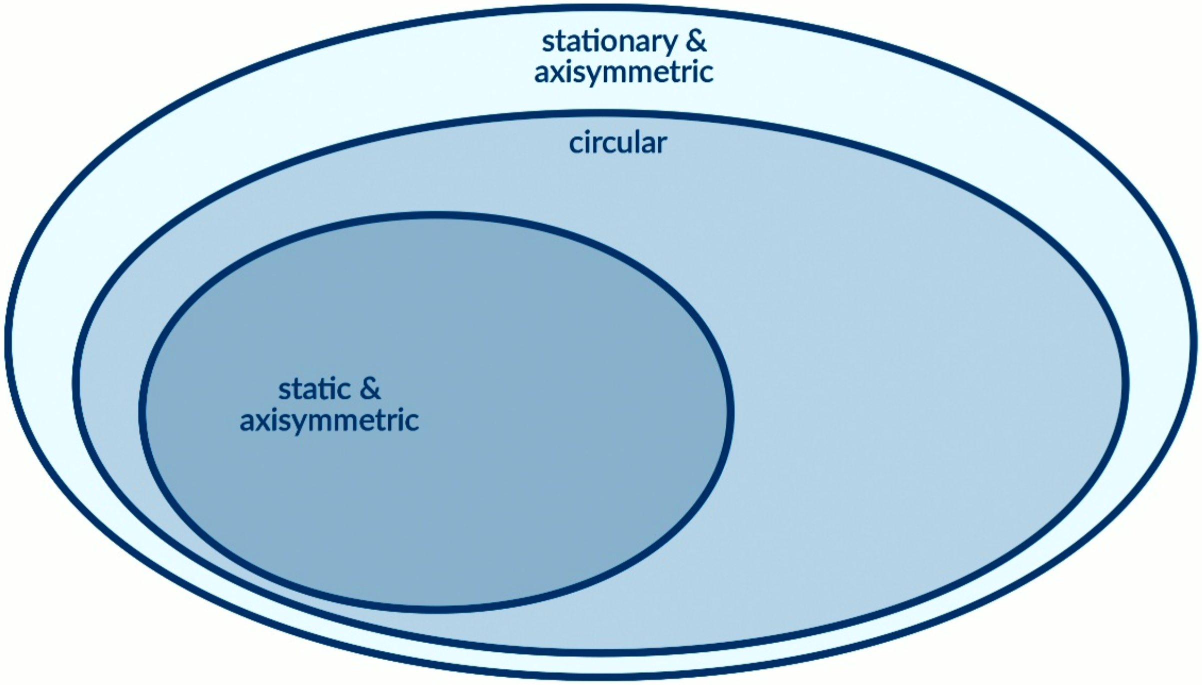



… contains a rich collection of subclasses.

# The class of stationary & axisymmetric spacetimes …

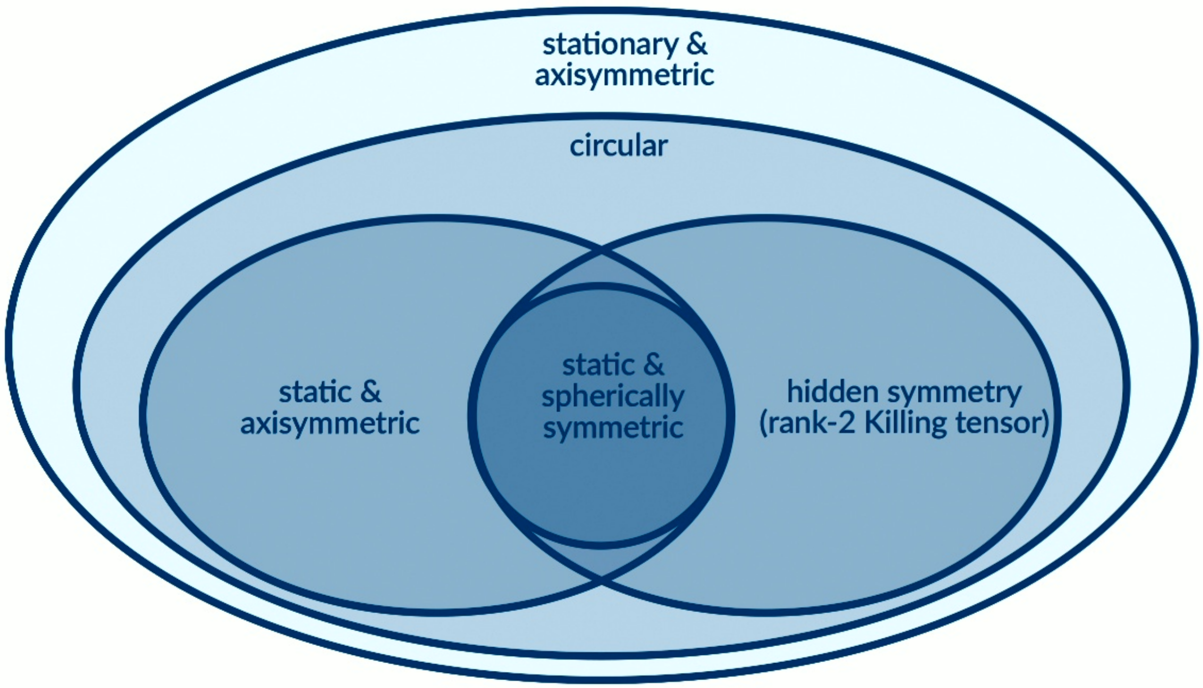
Delaporte, Eichhorn, Held, CQG 39 (2022) 13




… contains a rich collection of subclasses.

# The class of stationary & axisymmetric spacetimes ...

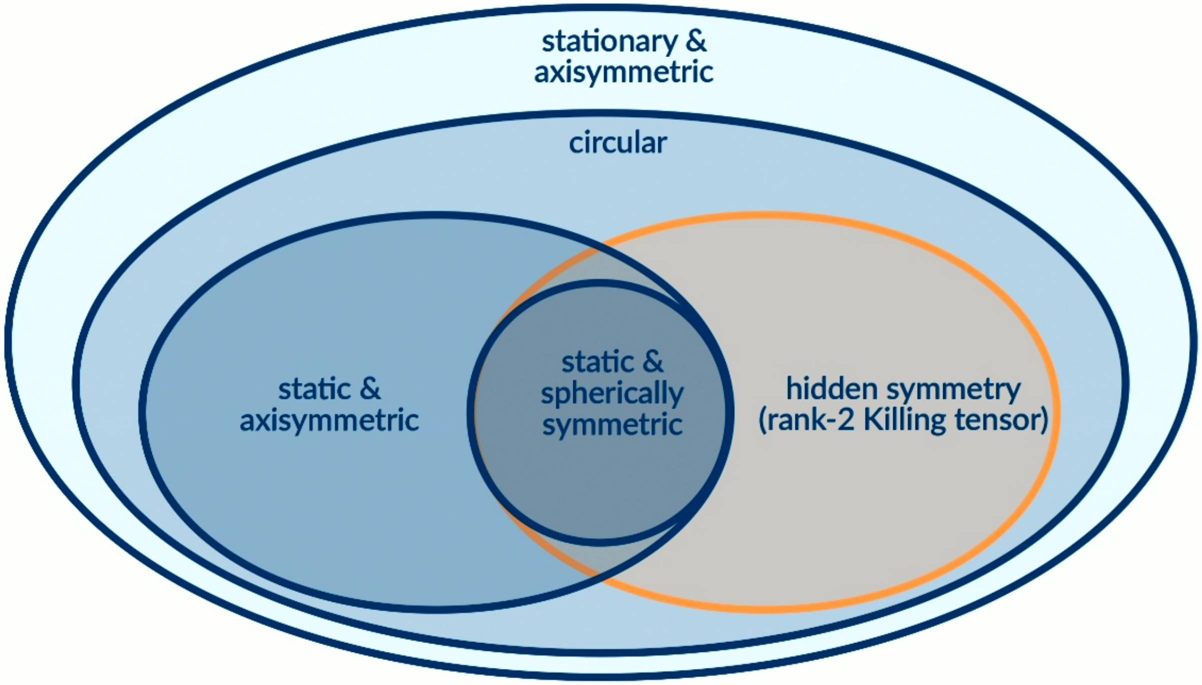
Delaporte, Eichhorn, Held, CQG 39 (2022) 13




... contains a rich collection of subclasses.

# The class of stationary & axisymmetric spacetimes …

Delaporte, Eichhorn, Held, CQG 39 (2022) 13




$$g^{\mu\nu}\partial_\mu\partial_\nu = \frac{1}{S_{x_1} + S_{x_2}}\Big[\left(G^{ij}_{x_1} + G^{ij}_{x_2}\right)\partial x_i \partial x_j + \Delta_{x_1}\partial x_1^2 + \Delta_{x_2}\partial x_2^2\Big]\,.$$

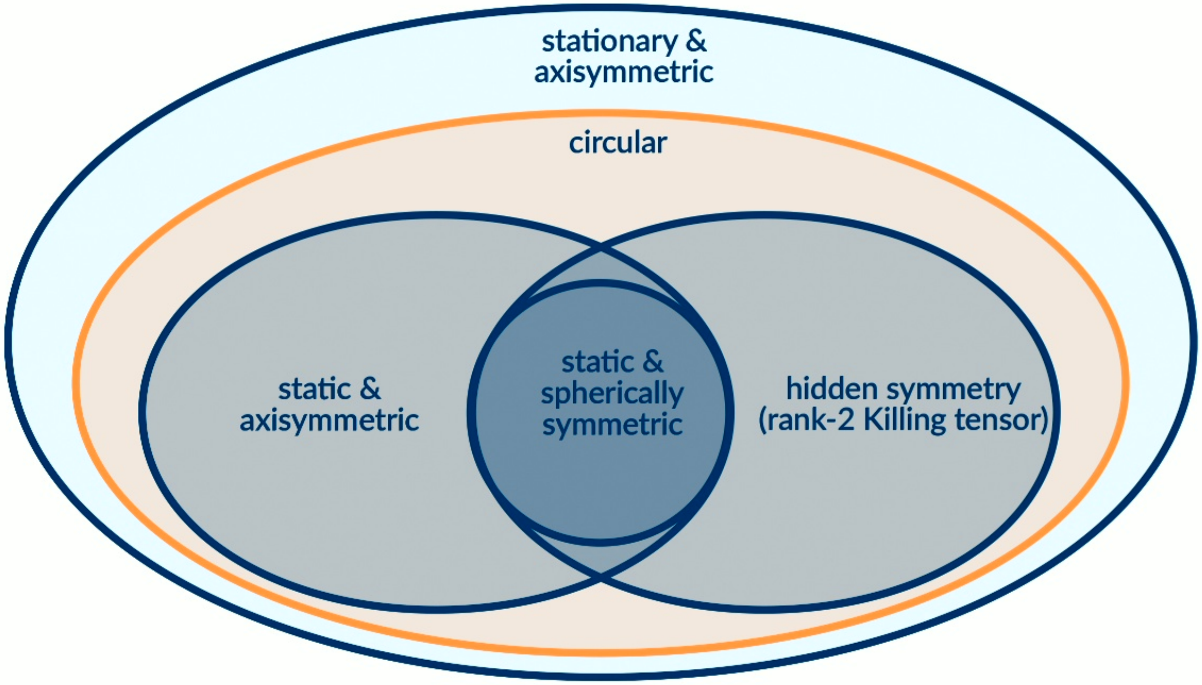
Benenti, Francaviglia '79

- rank-2 Killing tensor
- 3rd constant of motion
- separable geodesic motion
- turns out to be circular

# … contains a rich collection of subclasses.

# The class of stationary & axisymmetric spacetimes …

Delaporte, Eichhorn, Held, CQG 39 (2022) 13




surfaces of transitivity

| | | | |
|---|---|---|---|
| $g_{tt}$ | $g_{t\phi}$ | 0 | 0 |
| $g_{t\phi}$ | $g_{\phi\phi}$ | 0 | 0 |
| 0 | 0 | $g_{rr}$ | $g_{r\theta}$ |
| 0 | 0 | $g_{r\theta}$ | $g_{\theta\theta}$ |

Papapetrou '66
Kundt et.Al '66
Wald '84

meridional surfaces

+ coordinate freedom in the meridional surfaces

$$ds^2_{\text{mer}} = g_{rr}dr^2 + g_{\theta\theta}d\theta^2$$

Konoplya-Rezzolla-Zhidenko
(5 free functions)
(Kerr in Boyer-Lindquist)

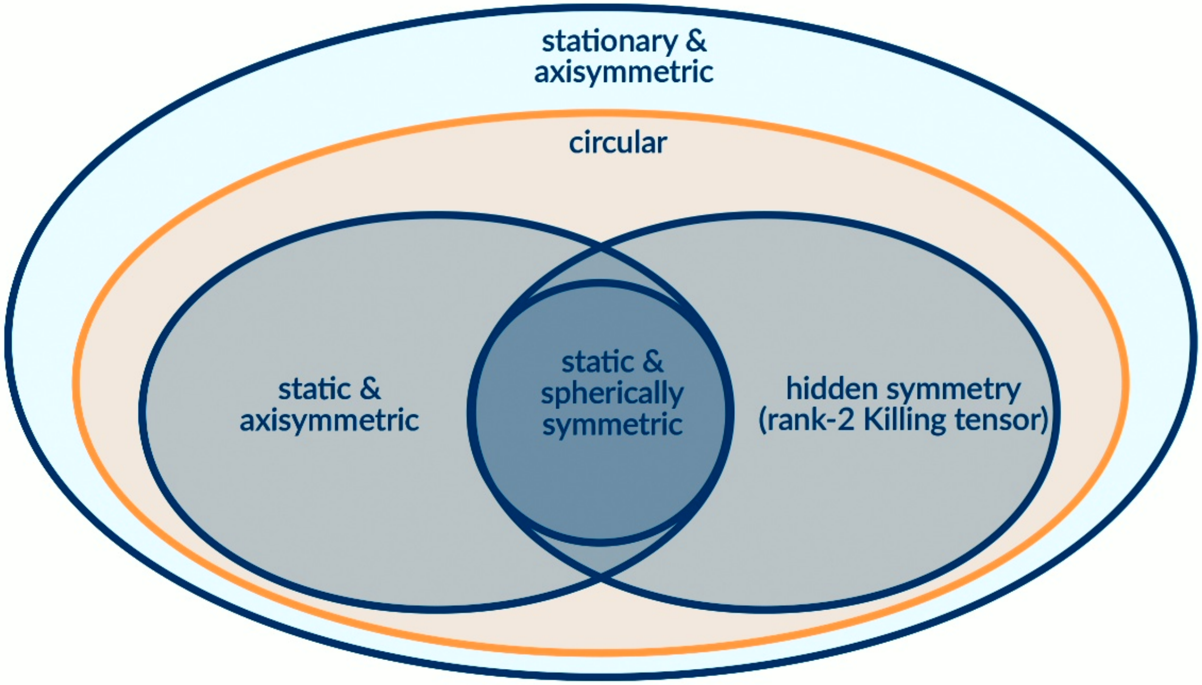
$$ds^2_{\text{mer}} = g_{\tilde{r}\tilde{r}}\left(d\tilde{r}^2 + \tilde{r}^2 d\tilde{\theta}^2\right)$$

Lewis-Papapetrou form
(4 free functions)
(Kerr not in Boyer-Lindquist)

## … contains a rich collection of subclasses.

# The class of stationary & axisymmetric spacetimes …

Delaporte, Eichhorn, Held, CQG 39 (2022) 13




surfaces of transitivity

$$\begin{pmatrix} g_{tt} & g_{t\phi} & 0 & 0 \\ g_{t\phi} & g_{\phi\phi} & 0 & 0 \\ 0 & 0 & g_{rr} & g_{r\theta} \\ 0 & 0 & g_{r\theta} & g_{\theta\theta} \end{pmatrix}$$

Papapetrou '66
Kundt et.Al '66
Wald '84

meridional surfaces

+ coordinate freedom in the meridional surfaces

$$ds^2_{\rm mer} = g_{rr} dr^2 + g_{\theta\theta} d\theta^2$$

Konoplya-Rezzolla-Zhidenko
(5 free functions)
(Kerr in Boyer-Lindquist)

$$ds^2_{\rm mer} = g_{\tilde{r}\tilde{r}} \left( d\tilde{r}^2 + \tilde{r}^2 d\tilde{\theta}^2 \right)$$

Lewis-Papapetrou form
(4 free functions)
(Kerr not in Boyer-Lindquist)

# … contains a rich collection of subclasses.

# Circular violations of black-hole uniqueness ...

$$ds^2 = -\frac{N^2(r,\theta) - W^2(r,\theta)\sin^2\theta}{K^2(r,\theta)}dt^2 - 2W(r,\theta)r\sin^2\theta dt d\phi + K^2(r,\theta)r^2\sin^2\theta d\phi^2 + \Sigma(r,\theta)\left(\frac{B^2(r,\theta)}{N^2(r,\theta)}dr^2 + r^2 d\theta^2\right)$$

Konoplya, Rezzolla, Zhidenko, 1602.02378

| | Polynomial coefficients | | | | | Leading continued fraction | | | | Subleading continued fraction | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| KRZ parameter | $\boldsymbol{\epsilon_0}$ | $\boldsymbol{a_{00}}$ | $\boldsymbol{b_{00}}$ | $k_{00}$ | $\boldsymbol{\omega_{00}}$ | $\boldsymbol{a_{01}}$ | $b_{01}$ | $k_{01}$ | $\omega_{01}$ | $a_{02}$ | $b_{02}$ | $k_{02}$ | $\omega_{02}$ | $a_{03}$ | $b_{03}$ | $k_{03}$ | $\omega_{03}$ |
| Kerr | $\frac{a^2}{r_0^2}$ | 0 | 0 | $\frac{A_{KRZ}^2}{r_0^2}$ | $\left(1+\frac{a^2}{r_0^2}\right)\frac{a}{r_0}$ | 0 | 0 | 0 | 0 | — | — | — | — | — | — | — | — |
| $\mathcal{O}(r^{-n})$ | leading asymptotics | | | | 1 | near-horizon | | | | ... | | | | ... | | | |
| KRZ parameter | $\epsilon_1$ | $a_{10}$ | $b_{10}$ | $k_{10}$ | $\omega_{10}$ | $a_{11}$ | $b_{11}$ | $k_{11}$ | $\omega_{11}$ | $a_{12}$ | $b_{12}$ | $k_{12}$ | $\omega_{12}$ | $a_{13}$ | $b_{13}$ | $k_{13}$ | $\omega_{13}$ |
| Kerr | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | — | — | — | — | — | — | — | — |
| $\mathcal{O}(r^{-n})$ | 2 | 3 | 1 | 0 | 1 | 4 | 2 | 1 | 2 | ... | | | | ... | | | |
| KRZ parameter | $\epsilon_2$ | $a_{20}$ | $b_{20}$ | $k_{20}$ | $\omega_{20}$ | $a_{21}$ | $b_{21}$ | $k_{21}$ | $\omega_{21}$ | $a_{22}$ | $b_{22}$ | $k_{22}$ | $\omega_{22}$ | $a_{23}$ | $b_{23}$ | $k_{23}$ | $\omega_{23}$ |
| Kerr | 0 | $\left(1+\frac{a^2}{r_0^2}\right)\frac{a^2}{r_0^2}$ | 0 | 0 | 0 | $-\frac{a^4}{r_0^4}$ | 0 | $-\frac{a^2}{r_0^2}$ | 0 | 0 | — | $-\frac{a^2}{r_0^2}$ | — | — | — | $\frac{a^2}{r_0^2}$ | — |
| $\mathcal{O}(r^{-n})$ | 2 | 3 | 1 | 0 | 1 | 4 | 2 | 1 | 2 | ... | | | | ... | | | |
| | ⋮ | | | | | ⋮ | | | | ⋮ | | | | | | | |

Cárdenas-Avendaño, Held, 2312.06590

# Circular violations of black-hole uniqueness ...

$$\Xi = (r_0, M, J, \beta, \gamma, a, a_{01})$$

$$g_{tt} = -\frac{\left(\Delta_{\beta\gamma} + \frac{r_0^3(r-r_0)}{r^2} a_{01}\right)\sin^2\theta - g_{t\phi}^2}{g_{\phi\phi}}$$

$$g_{rr} = \frac{\Sigma\left(1 - \frac{(1-\gamma)M}{r}\right)^2}{\left(\Delta_{\beta\gamma} + \frac{r_0^3(r-r_0)}{r^2} a_{01}\right)}$$

$$g_{\theta\theta} = \Sigma = r^2 + A^2\cos^2\theta$$

$$g_{\phi\phi} = \left[a^2 + r^2 + \frac{2Mra^2}{\Sigma}\left(\frac{A}{a} - \frac{(a^2 + r_0^2)\cos^2\theta}{2\,M\,r_0}\right)\right]\sin^2\theta$$

$$g_{t\phi} = -\frac{2MrA\sin^2\theta}{\Sigma}$$

$$\Delta_{\beta\gamma} = \frac{(r - r_0)\left[\Delta - 2M^2(\beta - \gamma + \frac{r_0}{M}) + r_0(r + r_0)\right]}{r}$$

- tell apart horizon location and asymptotic mass — $r_0$, $M$
- tell apart horizon spin and asymptotic angular momentum — $a$, $J$
- probe leading PPN asymptotic corrections — $\beta$, $\gamma$
- probe further near-horizon corrections such as — $a_{01}$

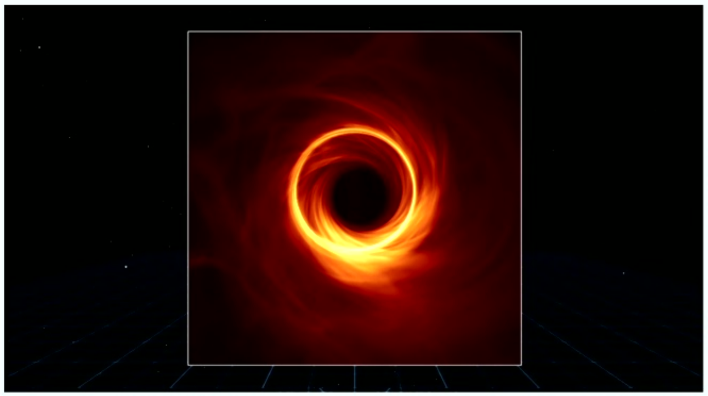
**have to deal with large parameter spaces**

## ... require an efficient tool.

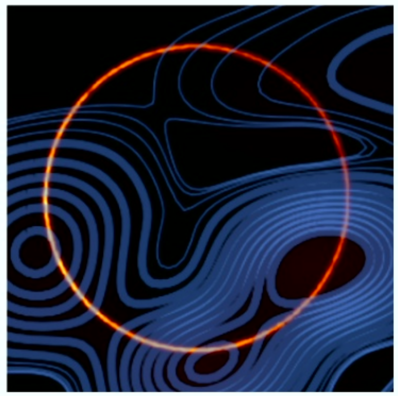
# Separate geometry from astrophysics ...

observation

geometry



Credit: M. Johnson et. Al, Sci.Adv. 6 (2020)



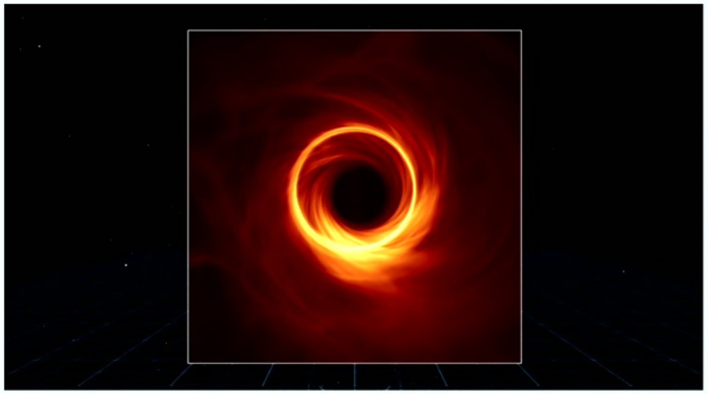
Broderick et. Al
ApJ 935 (2022) 61

need for a
fast & astrophysics-independent
way to exclude geometries

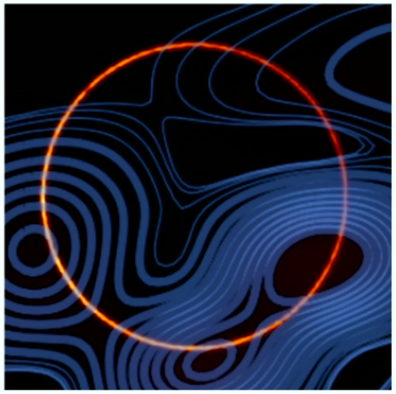
## ... via geometric lensing bands.

# Separate geometry from astrophysics ...

observation

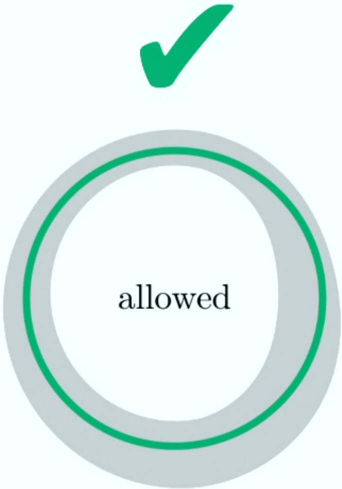


Credit: M. Johnson et. Al, Sci.Adv. 6 (2020)



Broderick et. Al
ApJ 935 (2022) 61

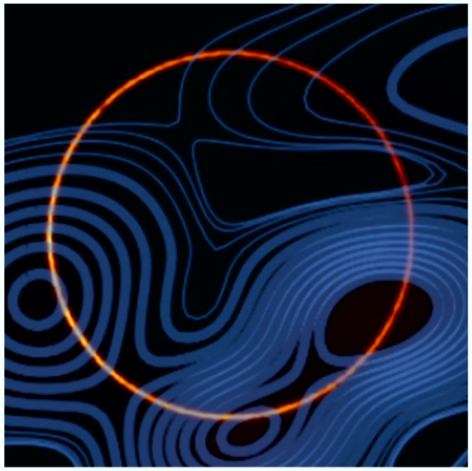
geometry



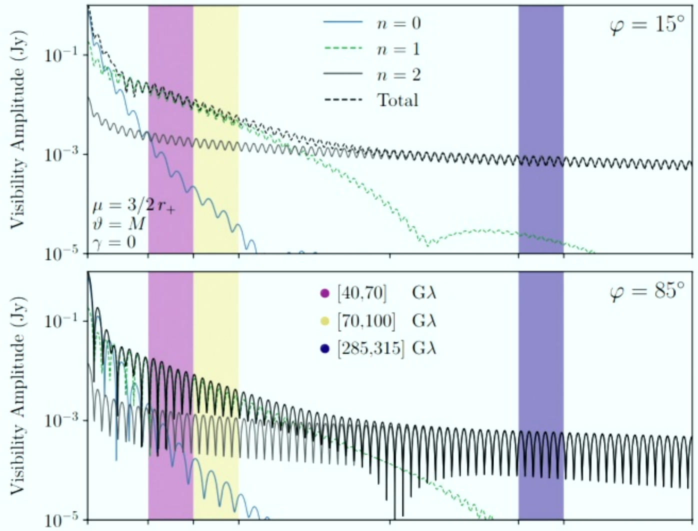

# ... via geometric lensing bands.

# Observational constraints on the 1st lensed image …

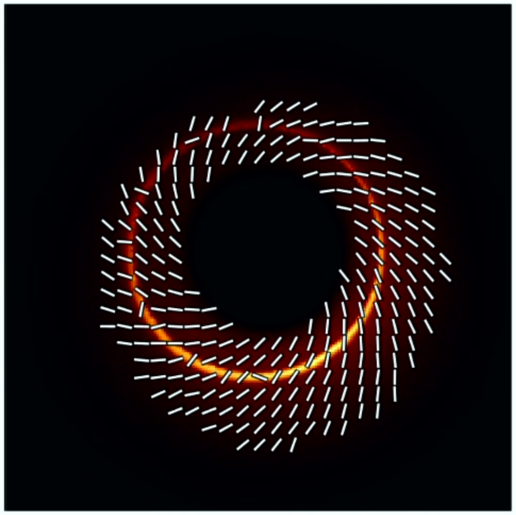
## hybrid imaging algorithms
[Broderick et. Al 2022 ApJ 935 61]



## interferometric diameter
[Avendano, Lupsasca 2305.12956]

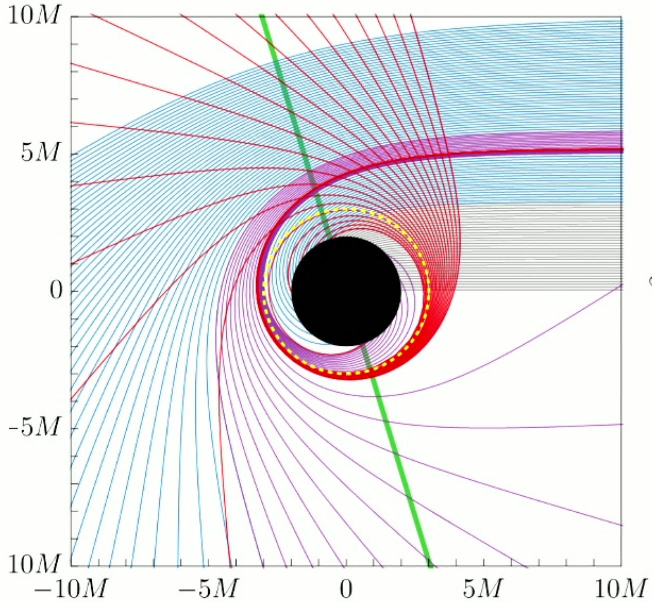



## polarimetry
[Palumbo et. Al 2307.05293]

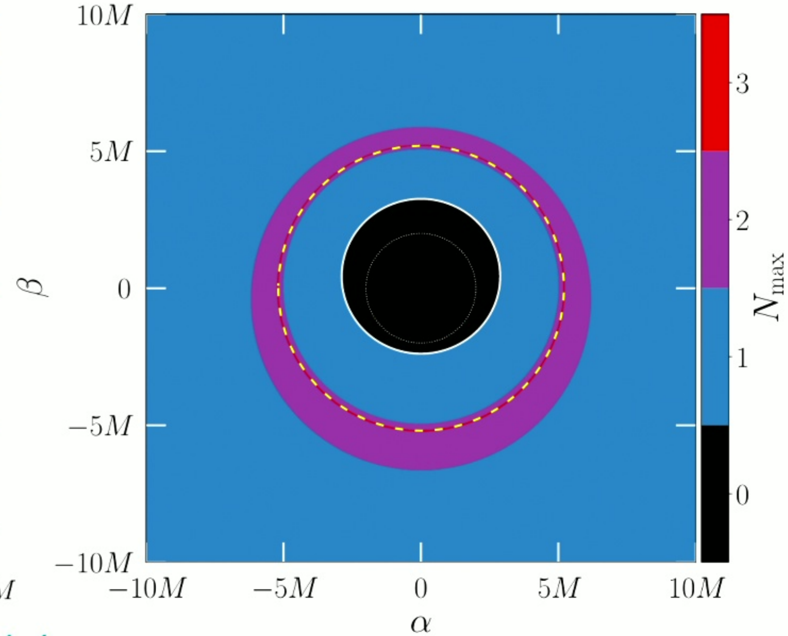


# … will tighten in the near future.

# Detecting a “lensed image” …



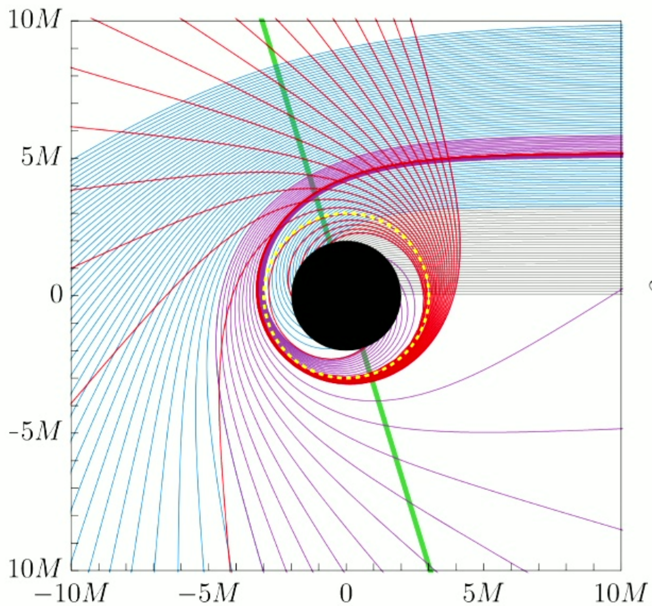

Chael, Johnson, Lupsasca ApJ 918 (2021) 1, 6

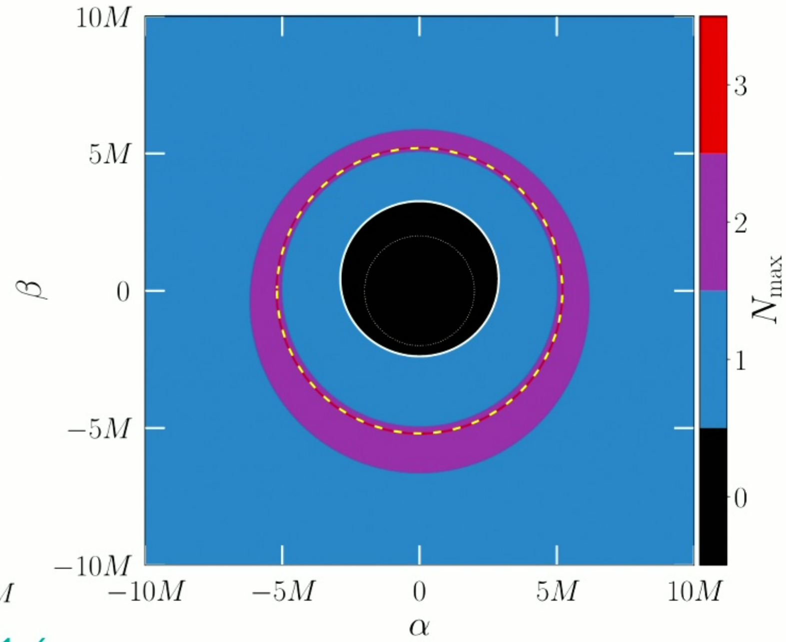



number of times the ray has crossed the equatorial plane

## … rests on some precise definition of “lensed image”.

# Detecting a “lensed image” …



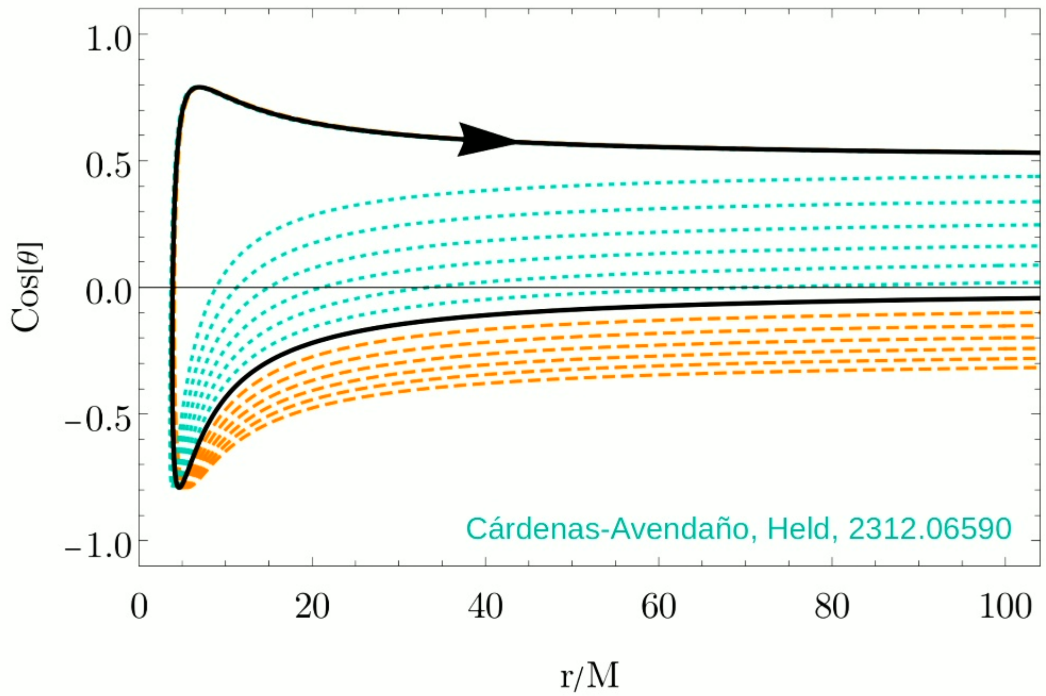

Chael, Johnson, Lupsasca ApJ 918 (2021) 1, 6

number of times the ray has crossed the equatorial plane

number of turning points in azimuthal angle

# … rests on some precise definition of “lensed image”.

# Detecting a “lensed image” …



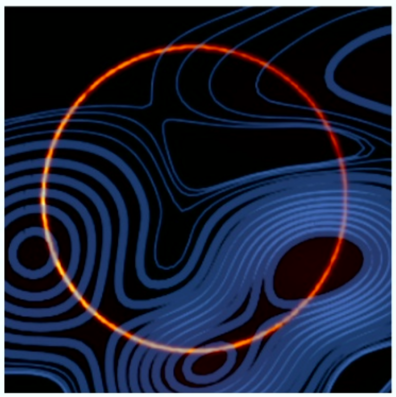

number of times the ray has crossed the equatorial plane

number of turning points in azimuthal angle

… rests on some precise definition of “lensed image”.

# Separate geometry from astrophysics ...

observation

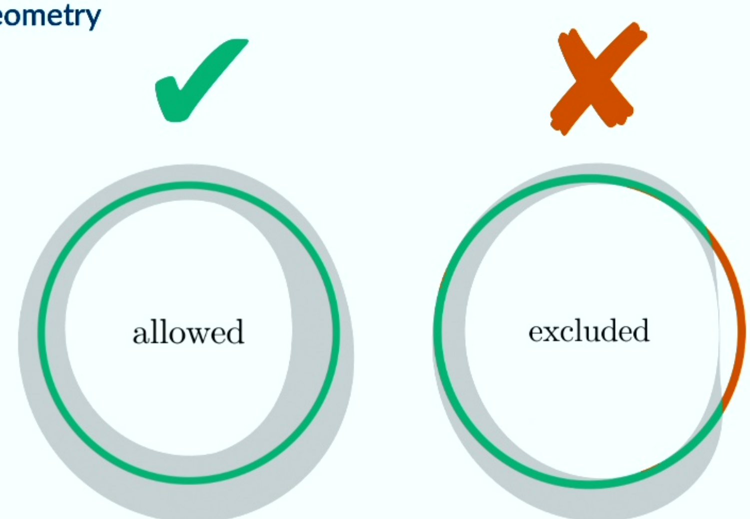


Broderick et. Al
ApJ 935 (2022) 61

**We exclude spacetimes for which an observed VLBI feature cannot arise from geodesics that traversed the equatorial plane more than once**

Cárdenas-Avendaño, Held, 2312.06590

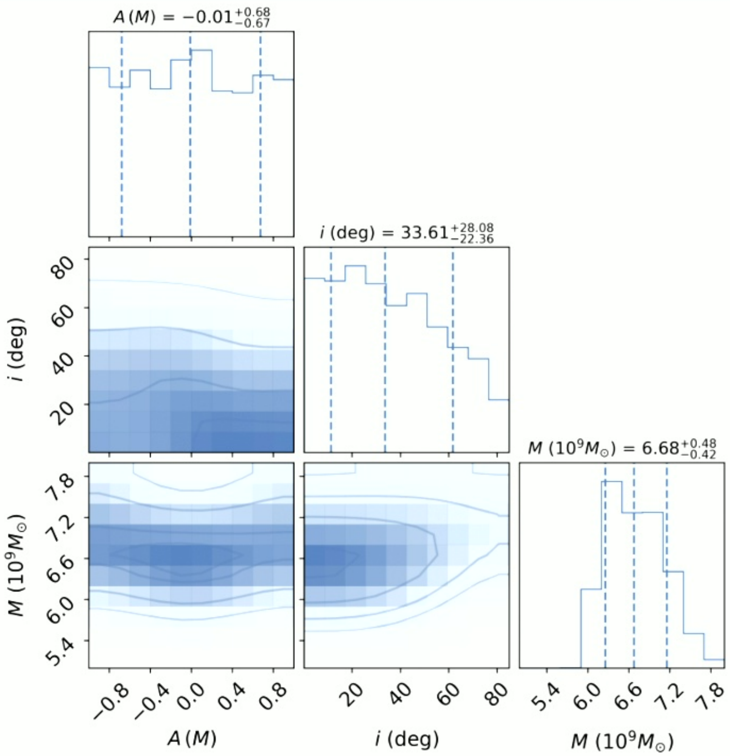
geometry




# ... via geometric lensing bands.

# Results on Kerr spacetime …

Cárdenas-Avendaño, Held, 2312.06590

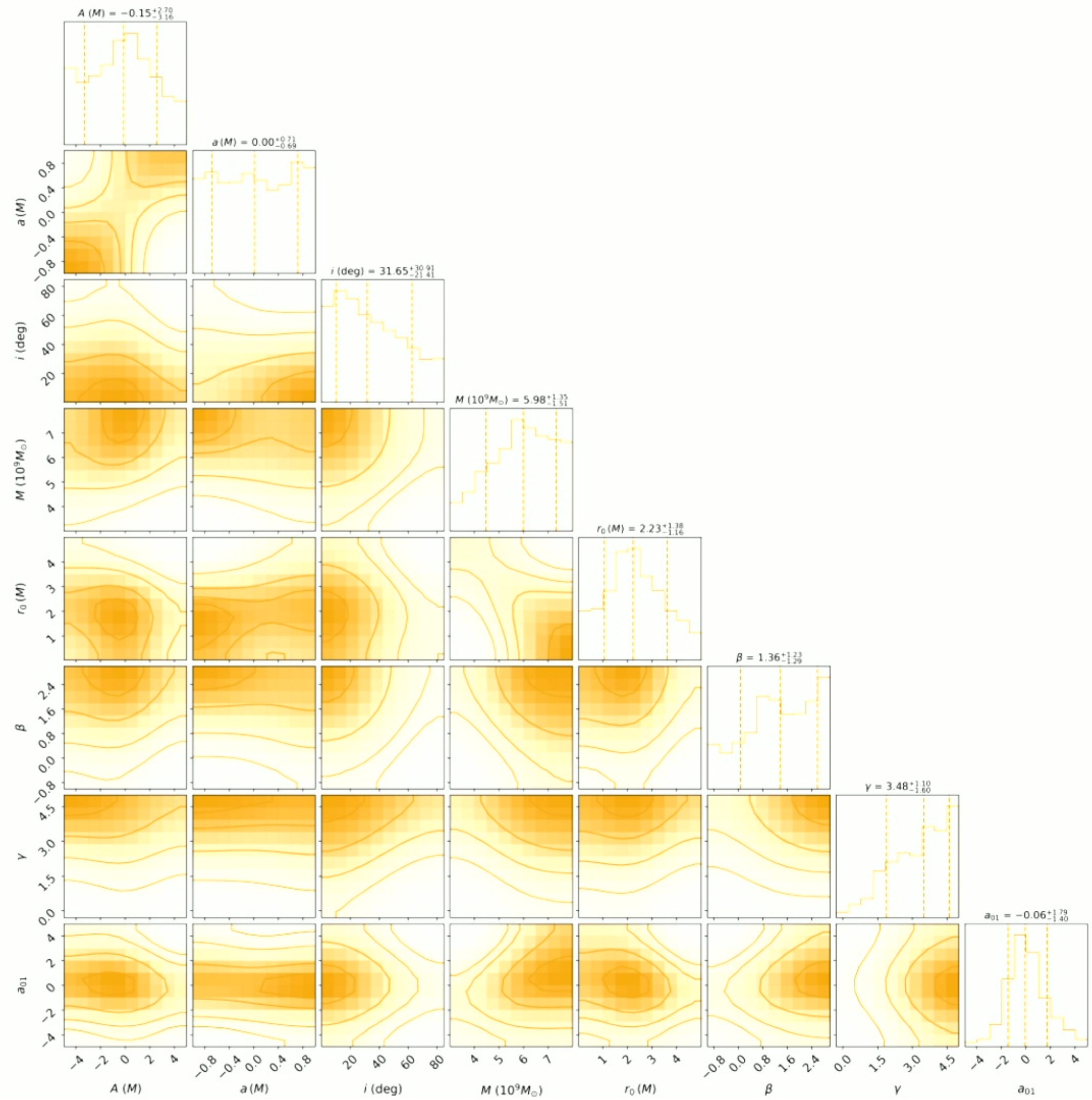



- projected constraint on the mass (from photon-ring size)
  see, e.g., EHT M87* paper I
- result/method disfavors high inclination
- correlation between mass and spin
  Broderick et. Al, AJ 935, 61 (2022), AJ 927, 6 (2022)

## 7-parameter family of deviations

$$\Xi = (r_0, M, J, \beta, \gamma, a, a_{01})$$

- horizon location: $r_0$
- asymptotic mass: $M$
- horizon spin: $a$
- angular momentum: $J$
- leading PPN corrections $\beta$ , $\gamma$
- tower of strong-gravity parameters $a_{01}$



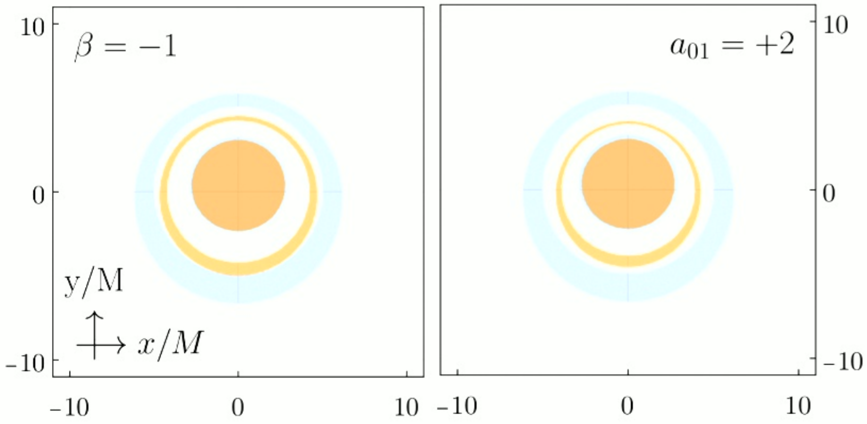
# Tests on deviations from Kerr spacetime …

Cárdenas-Avendaño, Held, 2312.06590

- separate (projected) constraints on mass and horizon size
- very degenerate “size constraint”
- (at least partially) broken by “shape constraints”

# Tests on deviations from Kerr spacetime ...

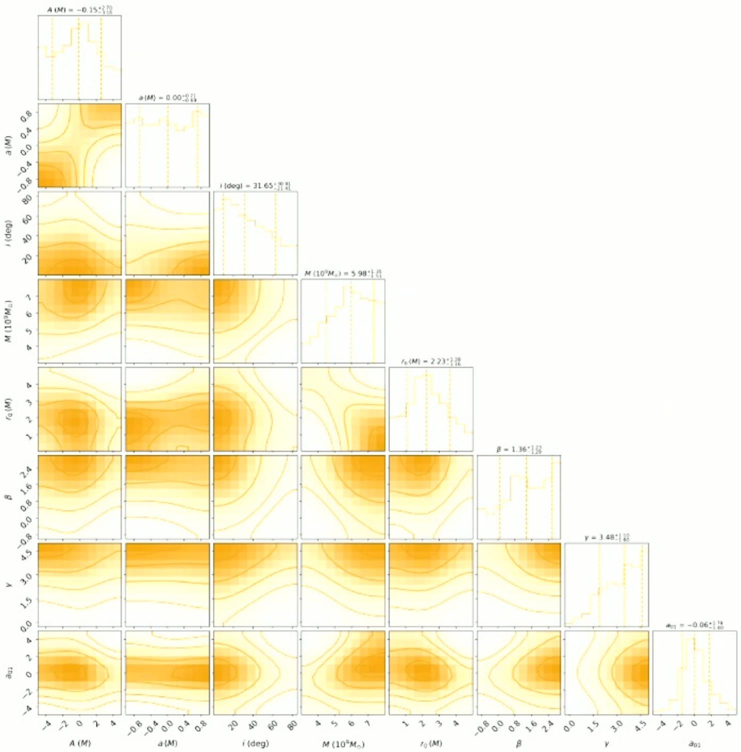
Cárdenas-Avendaño, Held, 2312.06590




- separate (projected) constraints on mass and horizon size
- very degenerate "size constraint"
- (at least partially) broken by "shape constraints"

# Tests on deviations from Kerr spacetime ...

Cárdenas-Avendaño, Held, 2312.06590



- separate (projected) constraints on mass and horizon size
- very degenerate “size constraint”
- (at least partially) broken by “shape constraints”

# ... quantify constraints of black-hole uniqueness.

# Where to go next?

- constrain specific theories

Eichhorn, Fernandes, Held, Silva, 2312.11430
see also
Gyulchev et. Al, 2402.08469
ngEHT white paper, 2312.02130

- include non-circular deviations

Delaporte, Eichhorn, Held, CQG 39 (2022) 13
see also
Gourgoulhon, Bonazzola, PRD 48 (1993) 6

- account for off-equatorial emission

- explore mild astrophysics priors

# Scalarization in "modified" sGB theories ...

Eichhorn, Fernandes, Held, Silva, 2312.11430

mechanism

- **Setup:** admits vacuum solutions of GR (with a constant scalar field profile and a second non-dynamical scalar)
- **Onset:** linear tachyonic instability for negative scalar mass
  $\left(\Box - \mu_{\text{eff}}^2\right) \delta\phi = 0$

modified example

$$S = \frac{1}{16\,\pi\,G} \int_x \Big[ R - (\partial\phi)^2 + \alpha_1\, F(\phi)\, \mathcal{G} - 2\alpha_2^3\, F(\phi) \left( \psi\, \mathcal{G} - \frac{\psi^2}{2} \right) \Big]$$

$$F[0] = 0\,, \quad F'[0] = 0\,, \quad F''[0] = \text{const}$$

$$\mu_{\text{eff}}^2 = -\alpha_1 \mathcal{G} \; + \; \alpha_2^3\, \mathcal{G}^2$$

... is not tied to curvature