Tests of General Relativity with observations of the photon ring

Aaron Held

Philippe Meyer Junior Research Chair
École Normale Supérieure

November 19 2024: GRAVITY+ workshop,
Meudon, November 19 – November 21 2024

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FONDATION MEYER POUR LE DEVELOPPEMENT CULTUREL ET ARTISTIQUE

The central brightness depression:

- **presence of a horizon**
  Eichhorn, Held, Gold, ApJ 950 (2023) 2
  Eichhorn, Held, JCAP 01 (2023) 032

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The central brightness depression:

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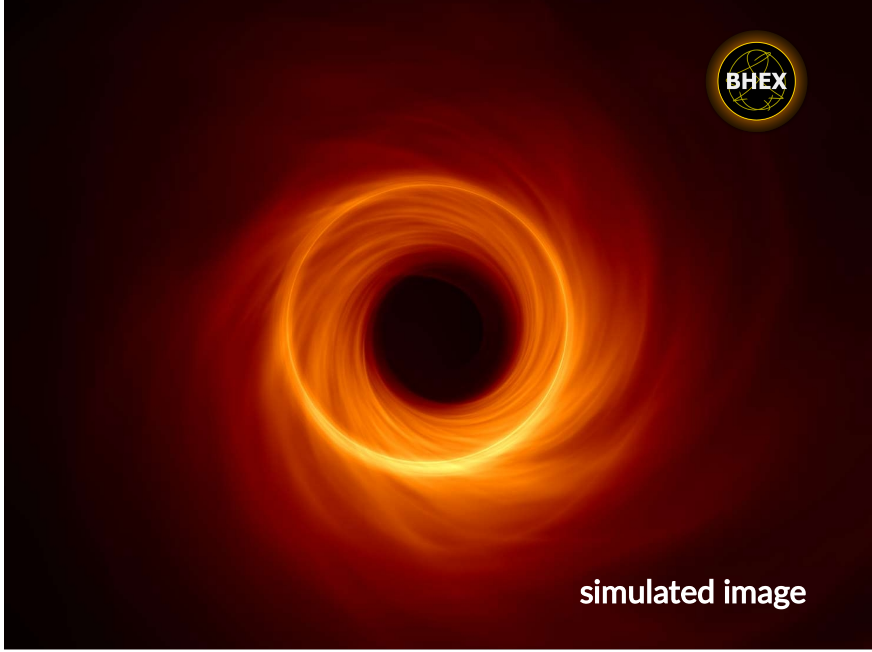
  Eichhorn, Held, Gold, ApJ 950 (2023) 2
  Eichhorn, Held, JCAP 01 (2023) 032

Lensed emission feature: photon ring(s):

- **map out (near-horizon) spacetime geometry**
  Cárdenas-Avendaño, Held, PRD 109 (2024) 6, 064052



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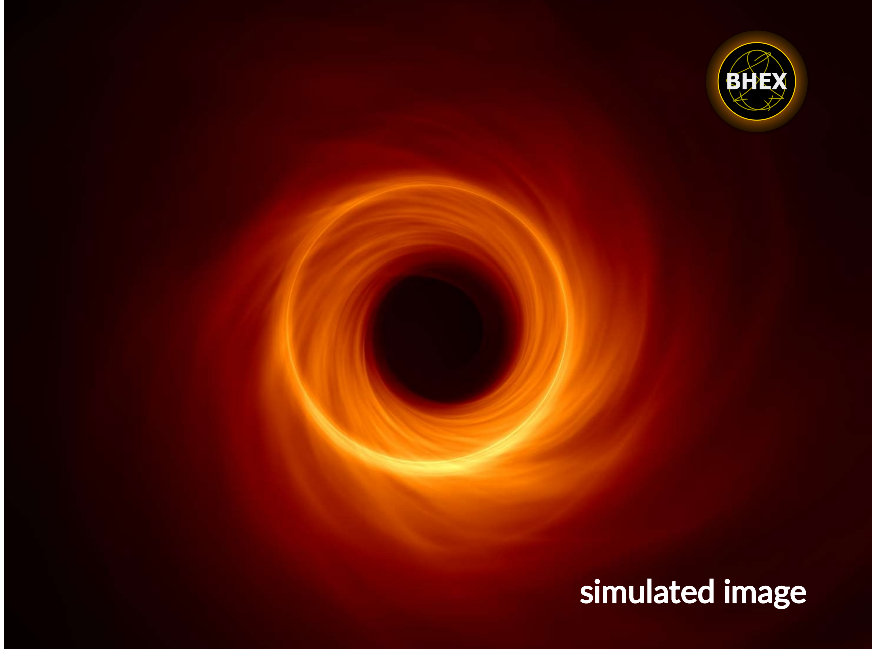
1) **The Black Hole Explorer**
NASA SMEX proposal

2) **Deviations from Kerr spacetime**
Delaporte, Eichhorn, Held, CQG 39 (2022) 13

3) **Lensing-band constraints**
Cárdenas-Avendaño, Held, PRD 109 (2024) 6, 064052



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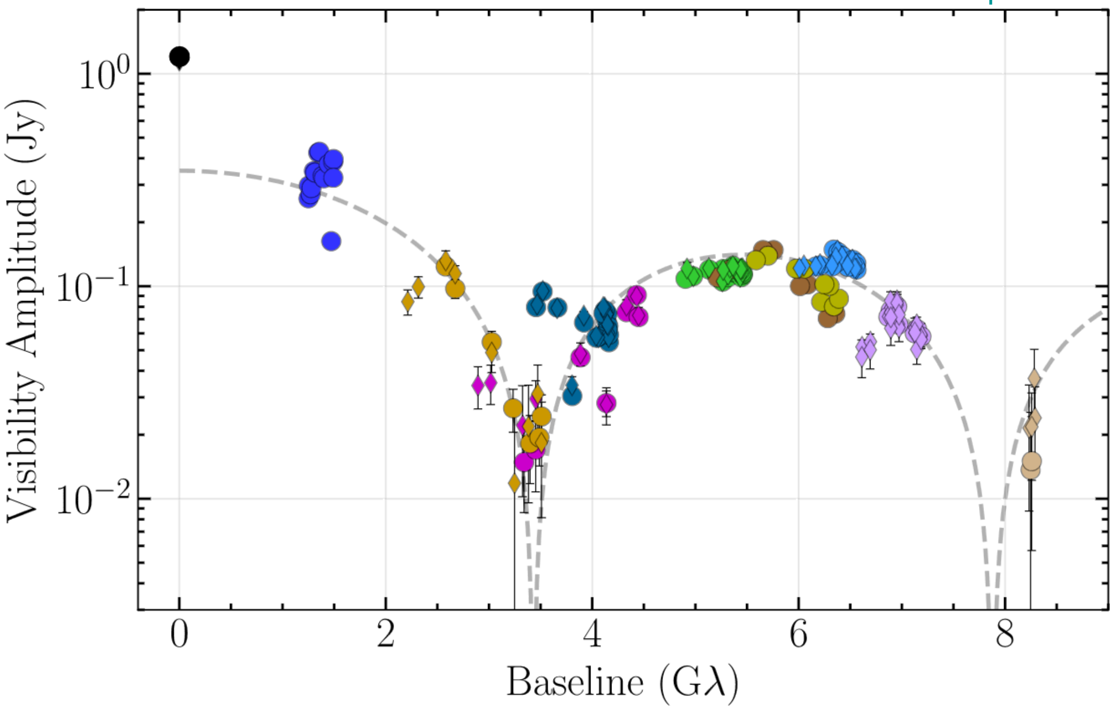
Part I: The Black-Hole Explorer

The Event Horizon Telescope (EHT) ...

EHT: earth-based VLBI

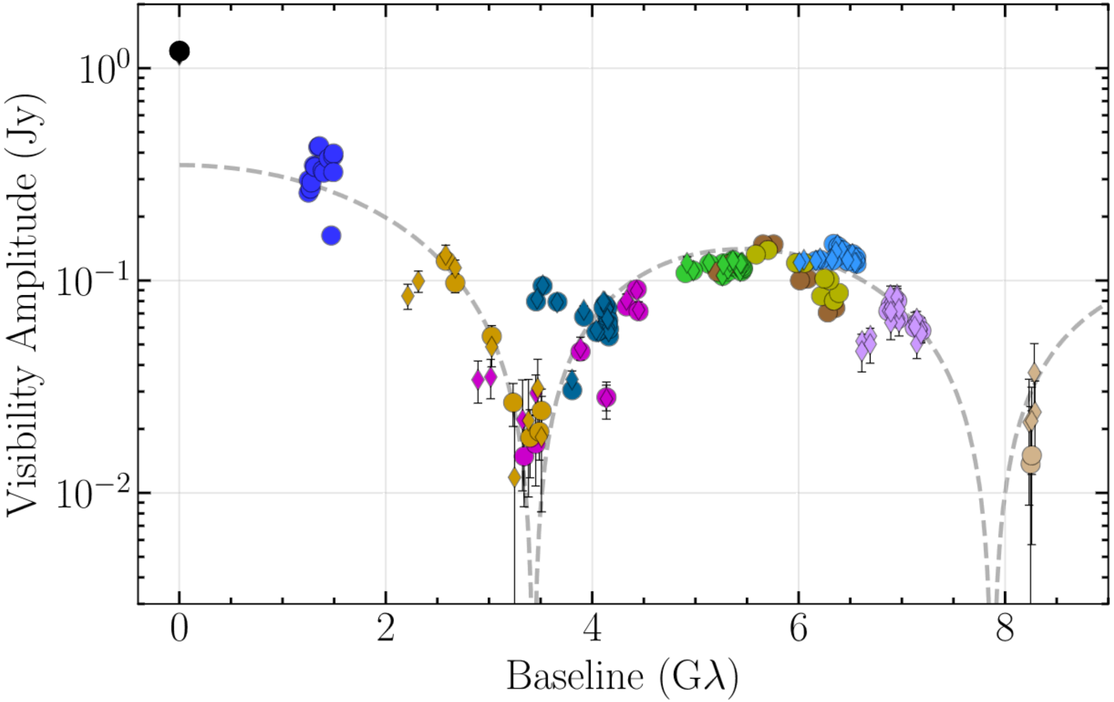
Event Horizon Telescope 2019



The Event Horizon Telescope (EHT) ...

EHT: earth-based VLBI

Event Horizon Telescope 2019

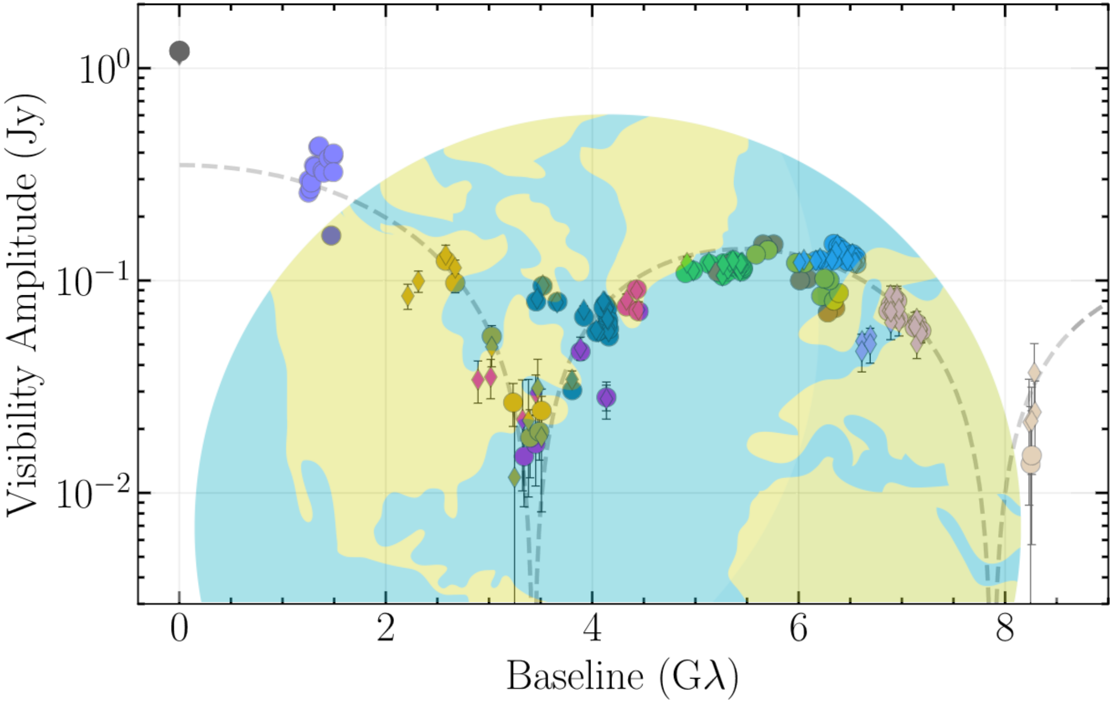


... resolves the central brightness depression.

The Event Horizon Telescope (EHT) …

EHT: earth-based VLBI

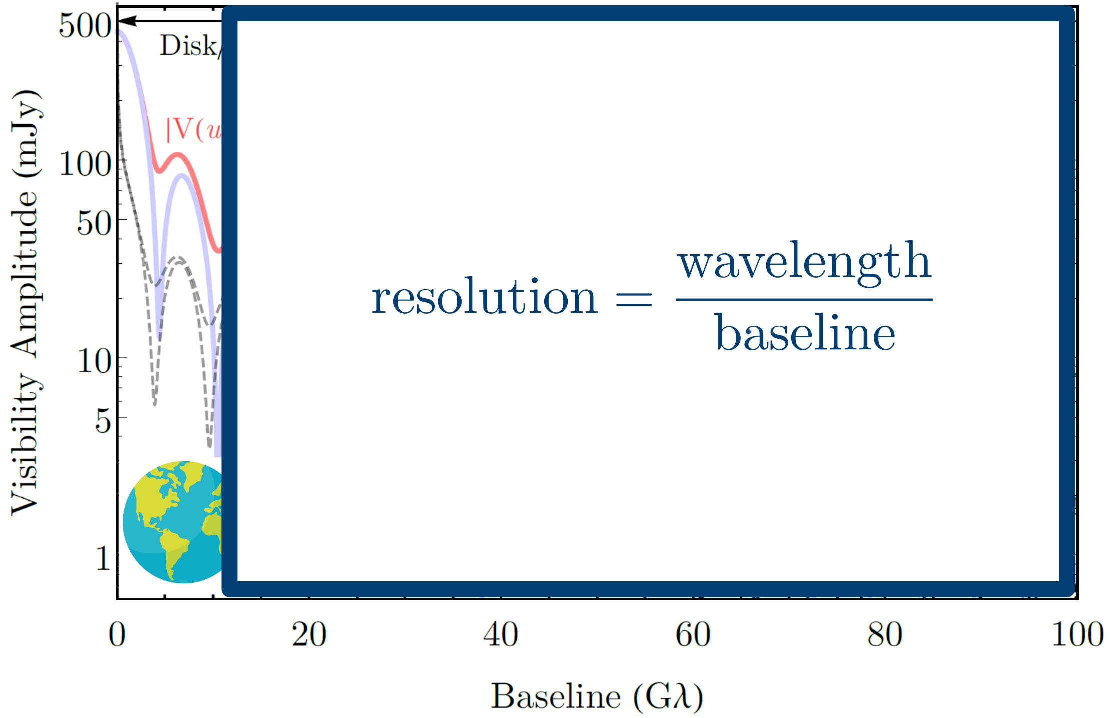
Event Horizon Telescope 2019



… is limited by the diameter of earth.

The Event Horizon Telescope (EHT) ...

EHT: earth-based VLBI



$$\text{resolution} = \frac{\text{wavelength}}{\text{baseline}}$$

... is limited by the diameter of earth.

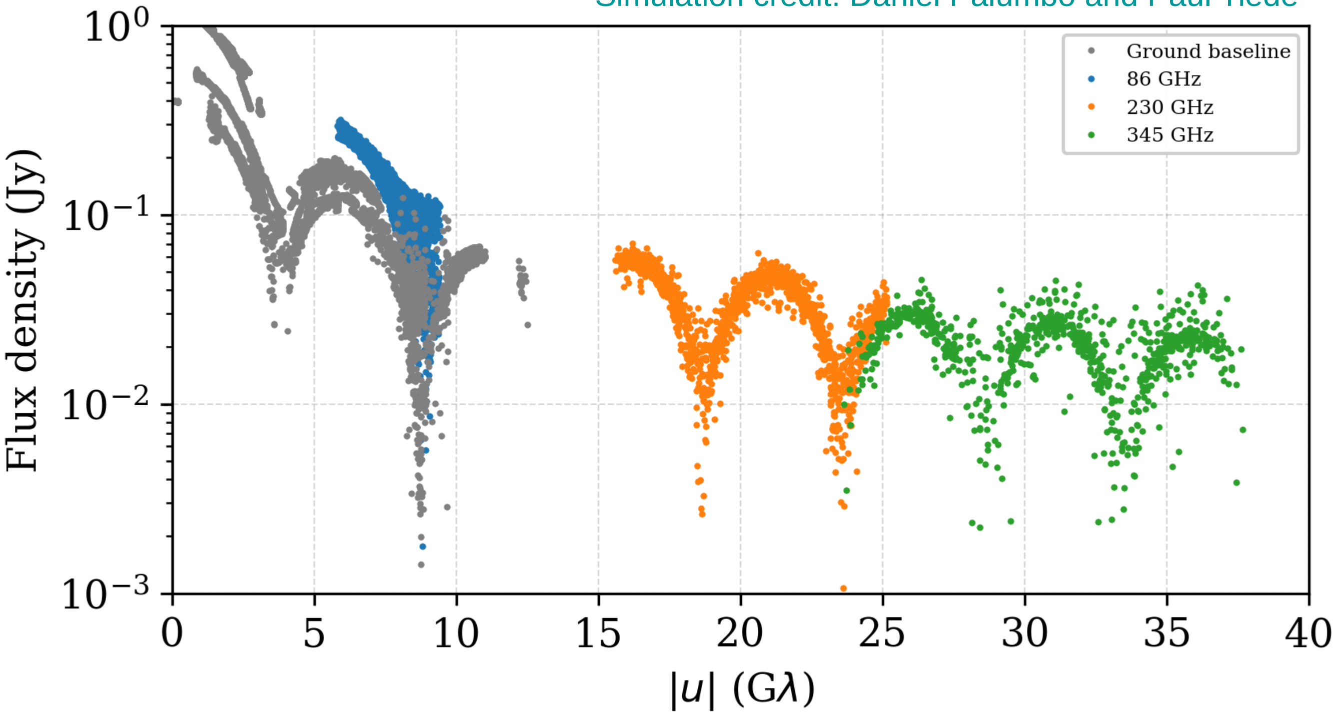
The Black Hole Explorer …

- 3.5m antenna satellite
- ~20,000 km altitude orbit
- simultaneous dual-band observations (86 + 230/345 GHz)
- 2+ years observation time
- 100 Gbps laser downlink

BHEX

The Black Hole Explorer …

Simulation credit: Daniel Palumbo and Paul Tiede



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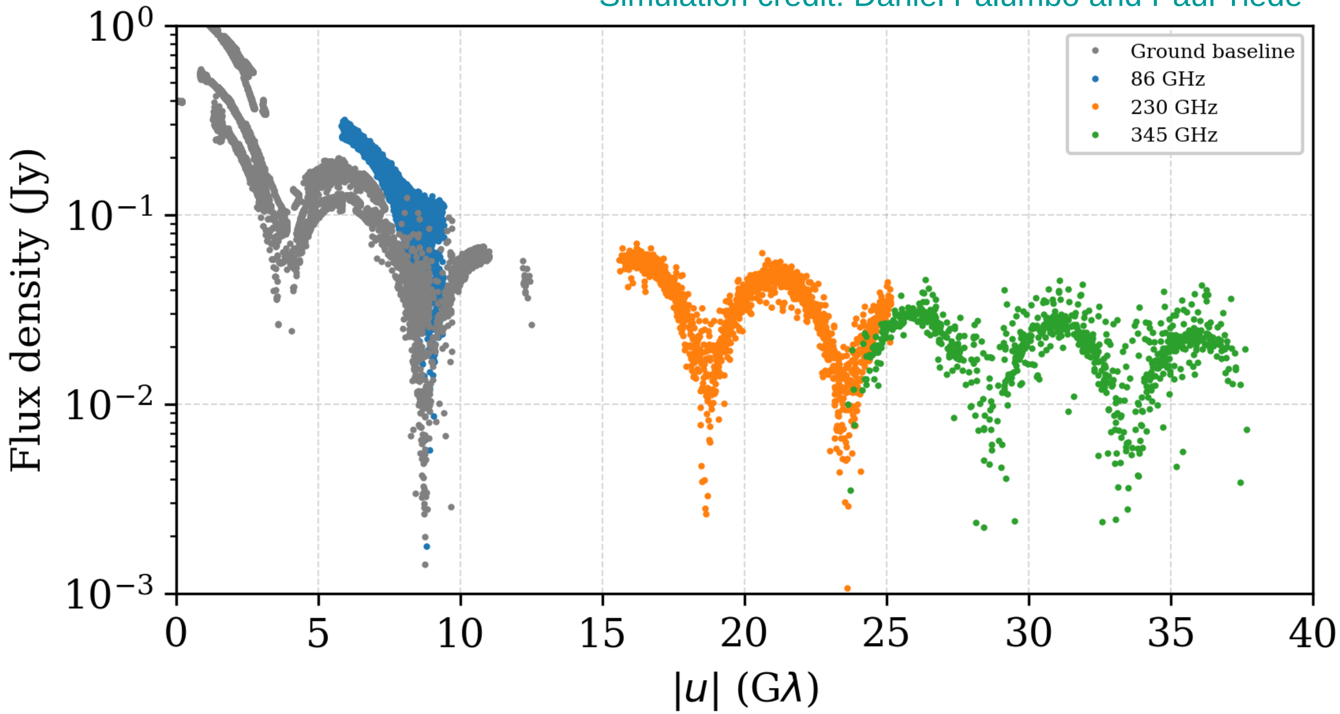
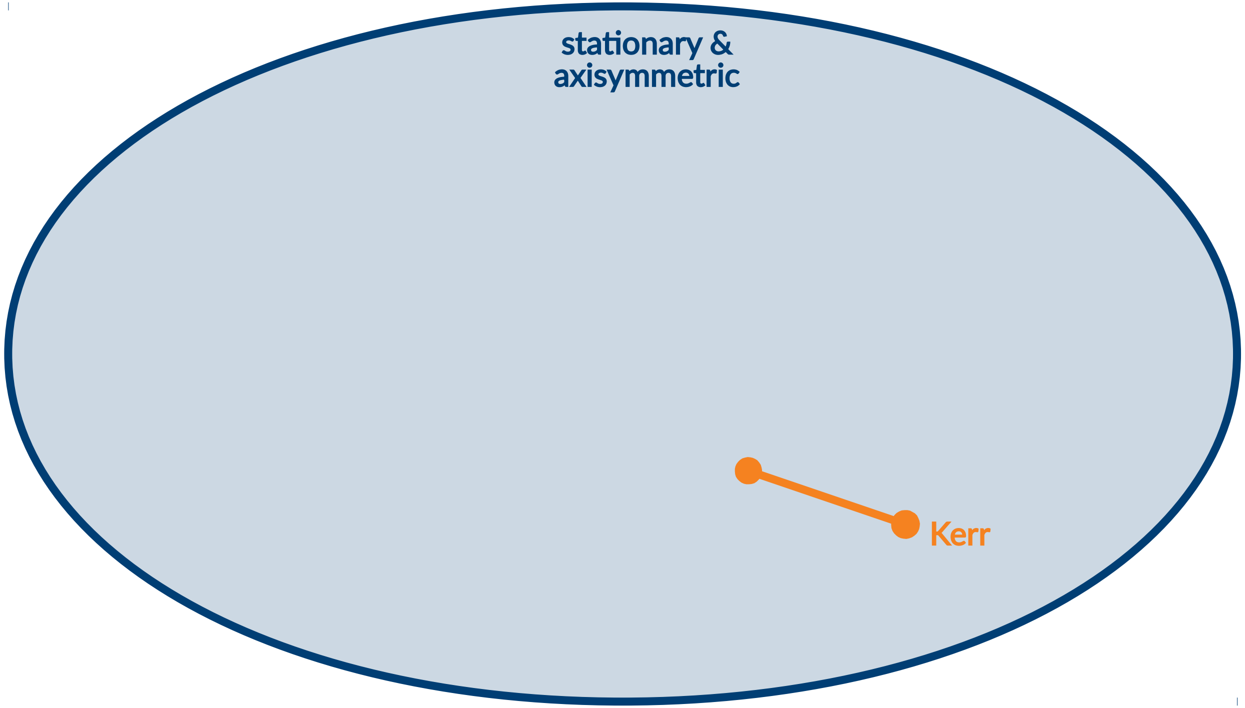


… will resolve the first lensed image.

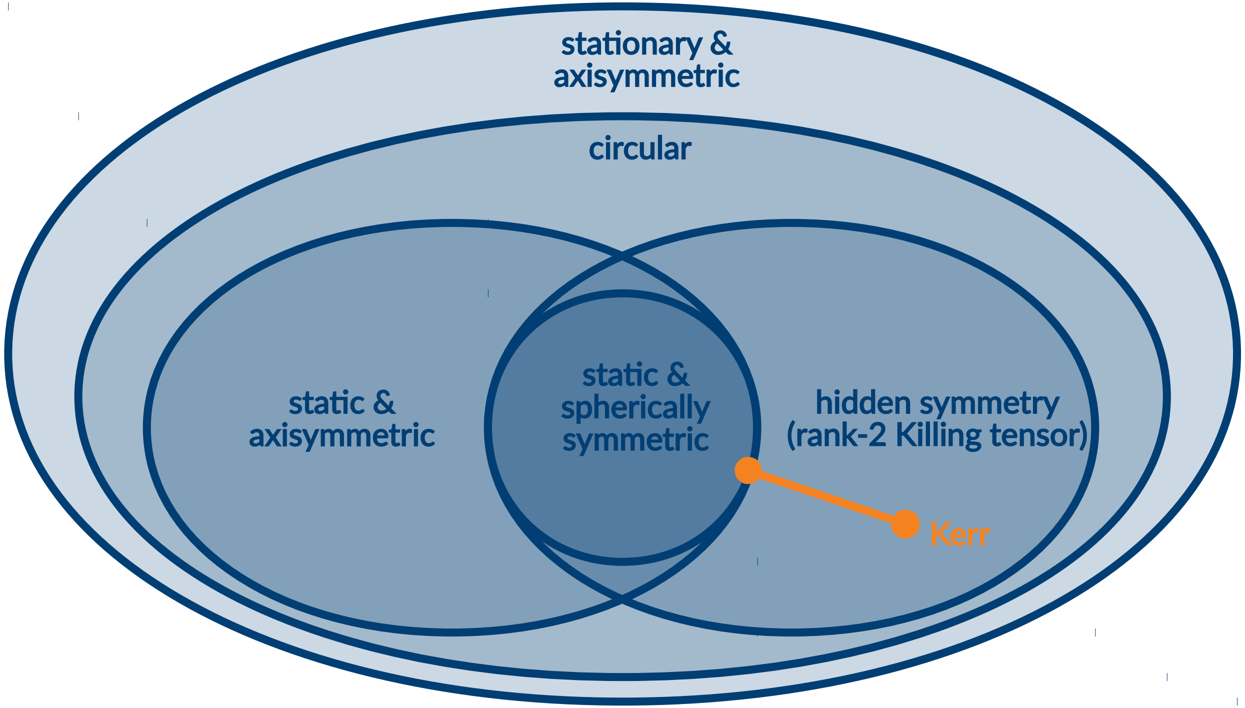
Part II: Parameterising deviations from Kerr spacetime

Kerr black holes ...



two Killing vectors
$\xi_\mu \ , \ \eta_\mu$

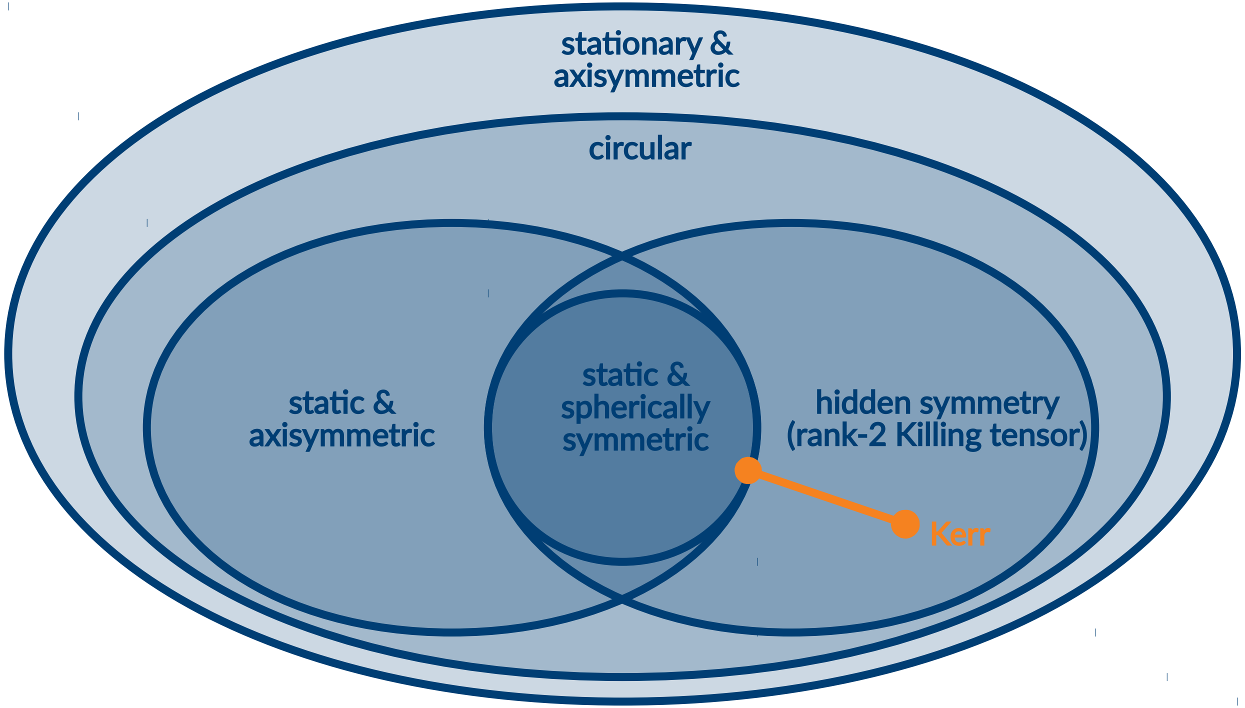
Kerr black holes ...



... are very special.

Deviations from the Kerr paradigm ...

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



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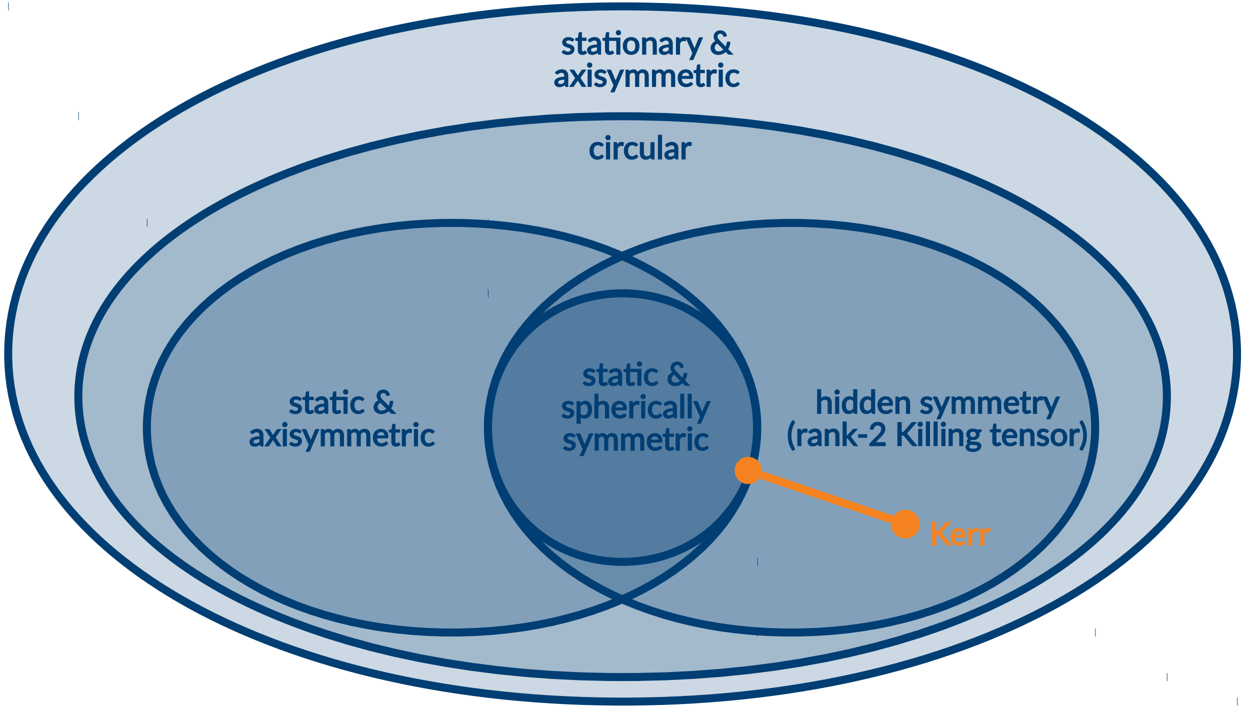
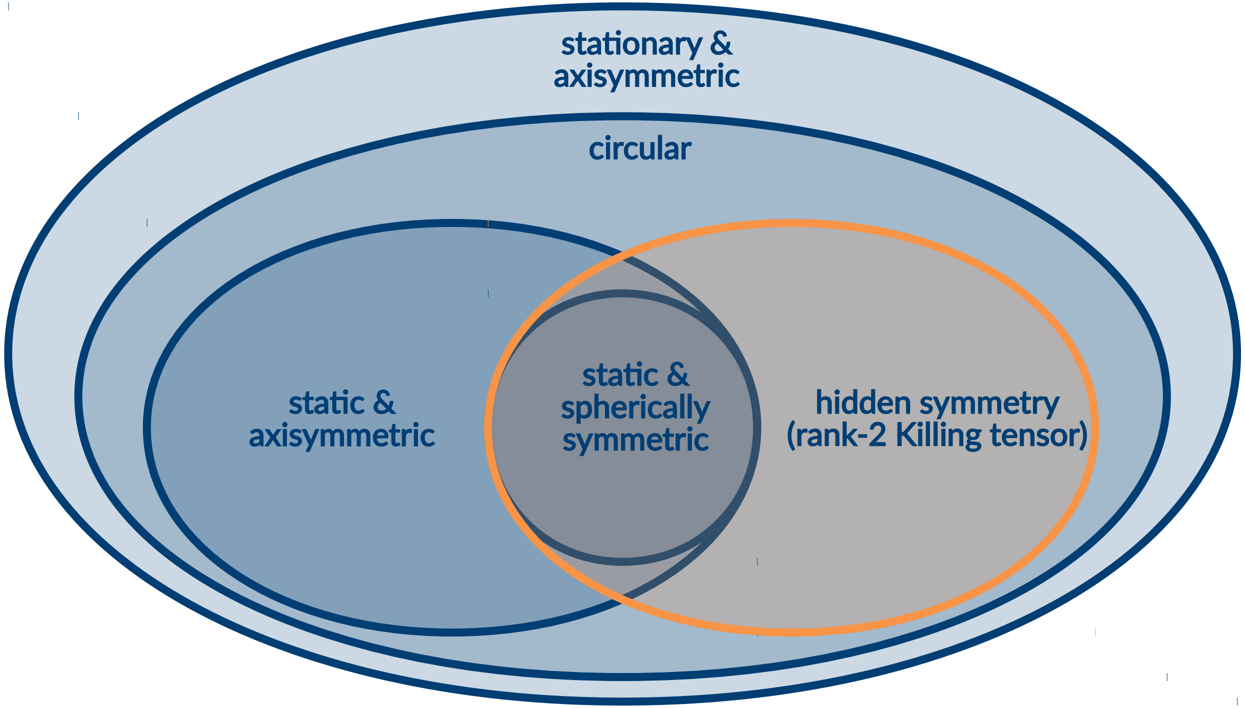


... require systematic parameterisation.

Deviations from the Kerr paradigm ...

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



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

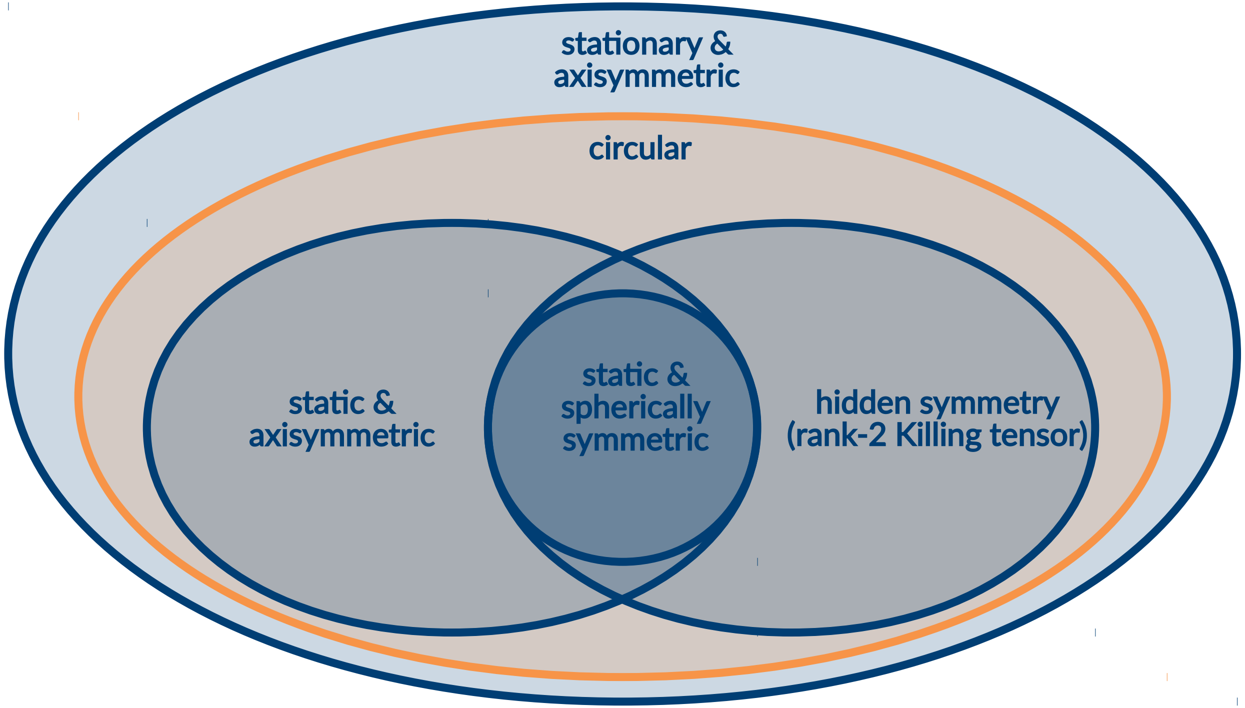
Benenti, Francaviglia '79

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

... require systematic parameterisation.

Deviations from the Kerr paradigm ...

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



$$\begin{array}{c} \text{surfaces of transitivity} \\ \\ \\ \end{array} \begin{array}{cccc} g_{tt} & g_{t\phi} & 0 & 0 \\ g_{t\phi} & g_{\phi\phi} & 0 & 0 \\ 0 & 0 & g_{rr} & g_{r\theta} \\ 0 & 0 & g_{r\theta} & g_{\theta\theta} \end{array} \begin{array}{c} \\ \\ \text{meridional surfaces} \\ \end{array}$$

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

+ coordinate freedom in the meridional surfaces

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

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

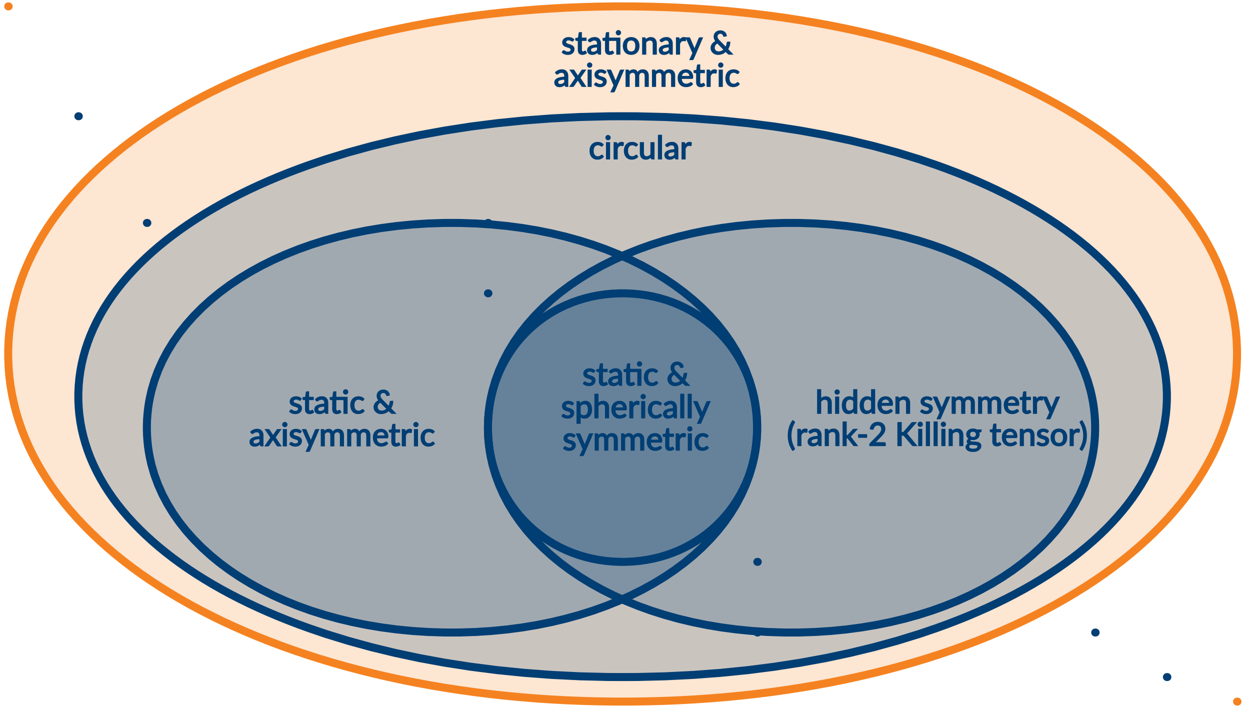
$$ds^2_{\mathrm{mer}} = g_{\tilde{r}\tilde{r}}\left(d\tilde{r}^2 + \tilde{r}^2 d\tilde{\theta}^2\right)$$

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

... require systematic parameterisation.

Deviations from the Kerr paradigm …

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



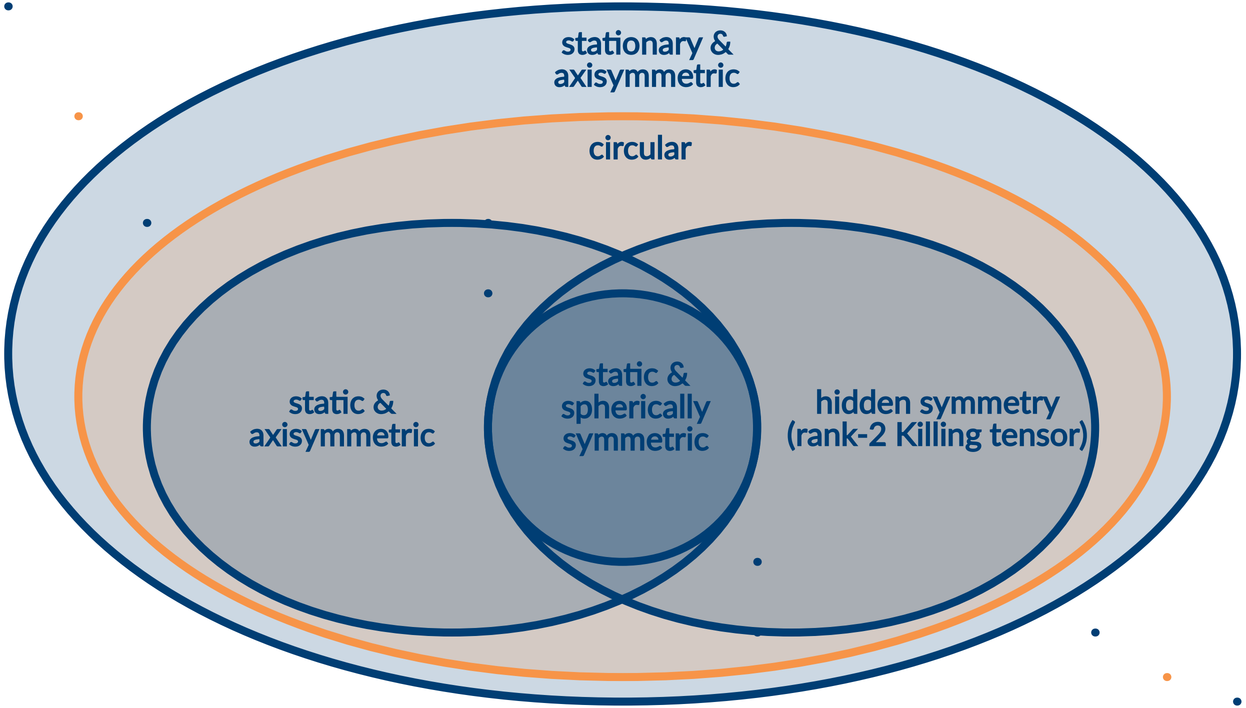
$$\begin{matrix} g_{tt} & g_{tr} & g_{t\theta} & g_{t\phi} \\ & g_{rr} & g_{r\theta} & g_{r\phi} \\ & & g_{\theta\theta} & g_{\theta\phi} \\ & & & g_{\phi\phi} \end{matrix}$$

- in general 10 free functions
- 8 free functions (meridional coordinate freedom)
  Gourgoulhon, Bonazzola ‘93
- 6 free functions (general coordinate freedom)
  Petrov ‘61, Ayón-Beato et.Al ‘06

… require systematic parameterisation.

Deviations from the Kerr paradigm …

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



surfaces of transitivity

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

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

meridional surfaces

+ coordinate freedom in the meridional surfaces

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

… require systematic parameterisation.

Circular deviations from Kerr spacetime ...

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

Konoplya, Rezzolla, Zhidenko, 1602.02378

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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}	ω_{01}	a_{02}	b_{02}	k_{02}	ω_{02}	a_{03}	b_{03}	k_{03}	ω_{03}
Kerr	$\frac{a^2}{r_0^2}$	0	0	$\frac{A_{\mathrm{KRZ}}^2}{r_0^2}$	$\left(1+\frac{a^2}{r_0^2}\right)\frac{a}{r_0}$	0	0	0	0	—	—	—	—	—	—	—	—
$\mathcal{O}(r^{-n})$	1	2	1	0	1	3	2	1	2	...				...			
KRZ parameter	ϵ_1	a_{10}	b_{10}	k_{10}	ω_{10}	a_{11}	b_{11}	k_{11}	ω_{11}	a_{12}	b_{12}	k_{12}	ω_{12}	a_{13}	b_{13}	k_{13}	ω_{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	ϵ_2	a_{20}	b_{20}	k_{20}	ω_{20}	a_{21}	b_{21}	k_{21}	ω_{21}	a_{22}	b_{22}	k_{22}	ω_{22}	a_{23}	b_{23}	k_{23}	ω_{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	...				...			
	$\vdots$					$\vdots$				$\vdots$							

Cárdenas-Avendaño, Held, 2312.06590

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Konoplya, Rezzolla, Zhidenko, 1602.02378

	Polynomial coefficients					Leading continued fraction				Subleading continued fraction							
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Kerr	$\frac{a^2}{r_0^2}$	0	0	$\frac{A_{\mathrm{KRZ}}^2}{r_0^2}$	$\left(1+\frac{a^2}{r_0^2}\right)\frac{a}{r_0}$	0	0	0	0	—	—	—	—	—	—	—	—
$\mathcal{O}(r^{-n})$	1	2	1	0	1	3	2	1	2	$\cdots$				$\cdots$			
KRZ parameter	ϵ_1	a_{10}	b_{10}	k_{10}	ω_{10}	a_{11}	b_{11}	k_{11}	ω_{11}	a_{12}	b_{12}	k_{12}	ω_{12}	a_{13}	b_{13}	k_{13}	ω_{13}
Kerr	0	0	0	0	0	0	0	0	0	—	—	—	—	—	—	—	—
$\mathcal{O}(r^{-n})$	2	3	1	0	1	4	2	1	2	$\cdots$				$\cdots$			
KRZ parameter	ϵ_2	a_{20}	b_{20}	k_{20}	ω_{20}	a_{21}	b_{21}	k_{21}	ω_{21}	a_{22}	b_{22}	k_{22}	ω_{22}	a_{23}	b_{23}	k_{23}	ω_{23}
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$\mathcal{O}(r^{-n})$	2	3	1	0	1	4	2	1	2	$\cdots$				$\cdots$			
	$\vdots$					$\vdots$				$\vdots$							

leading asymptotics

near-horizon

Cárdenas-Avendaño, Held, 2312.06590

Circular deviations from Kerr spacetime ...

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

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

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

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

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

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

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

- tell apart **horizon location** and **asymptotic mass** r_0 M

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- tell apart **horizon location** and **asymptotic mass** — r_0, M
- tell apart **horizon spin** and **asymptotic angular momentum** — a, J

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- probe further **near-horizon** corrections such as — a_{01}

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have to deal with **large parameter spaces**

Circular deviations from Kerr spacetime ...

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- probe leading **PPN** asymptotic corrections β , γ
- probe further **near-horizon** corrections such as a_{01}

have to deal with **large parameter spaces**

... **require an efficient tool.**

Part III: Lensing-band constraints

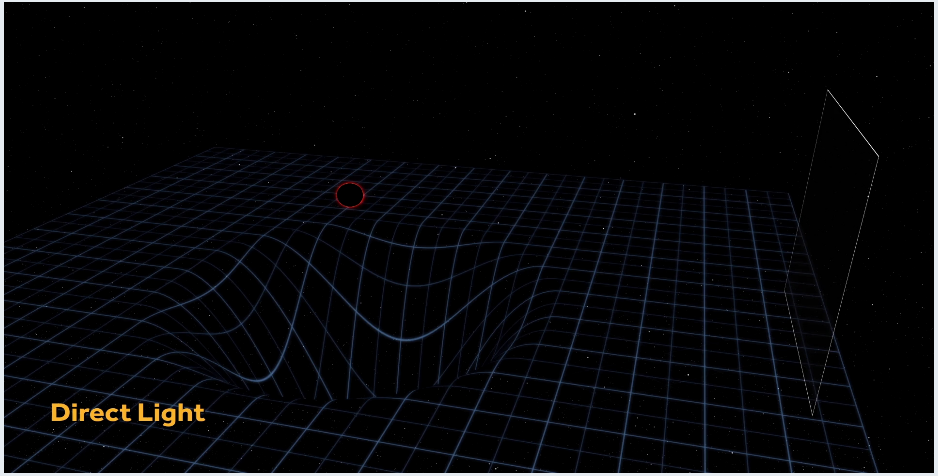
Separate geometry from astrophysics ...

observation

geometry

Separate geometry from astrophysics ...

observation

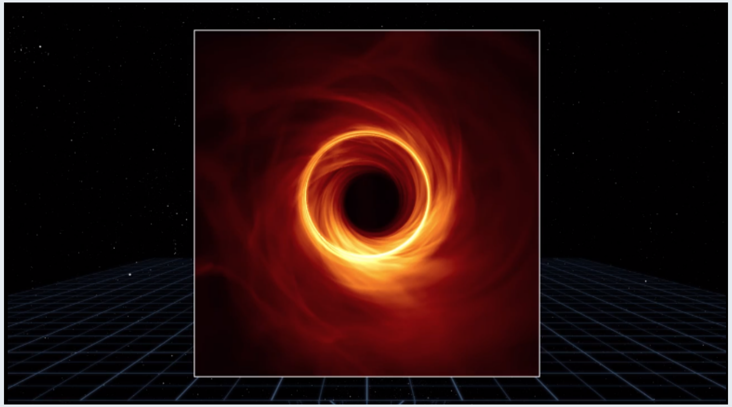


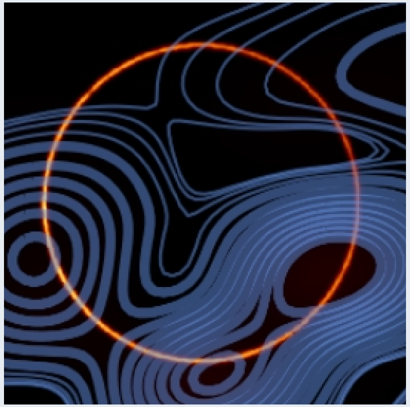
Credit: CfA Harvard & Smithsonian and Vanderbilt University

geometry

Separate geometry from astrophysics ...

observation





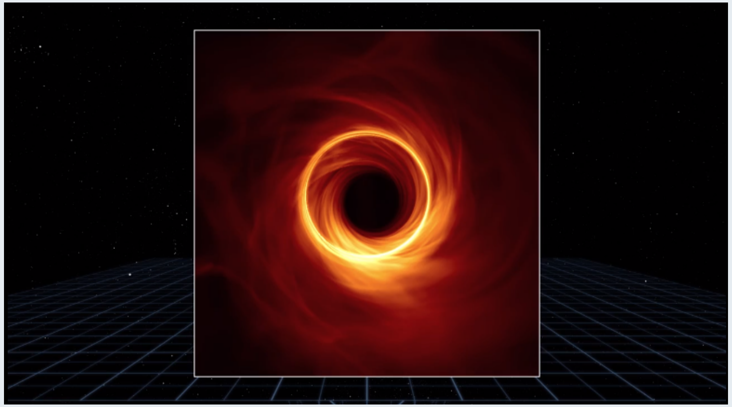
Credit: M. Johnson et. Al, Sci.Adv. 6 (2020)

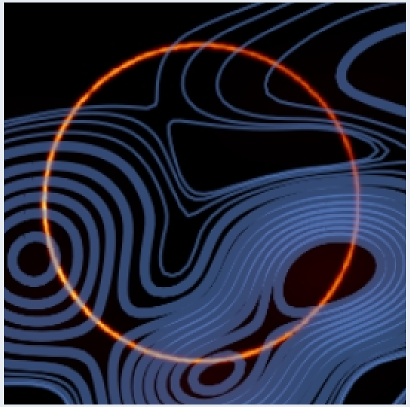
Broderick et. Al, ApJ 935 (2022)
Tiede et.Al, Galaxies 10, 111 (2022)

geometry

Separate geometry from astrophysics …

observation





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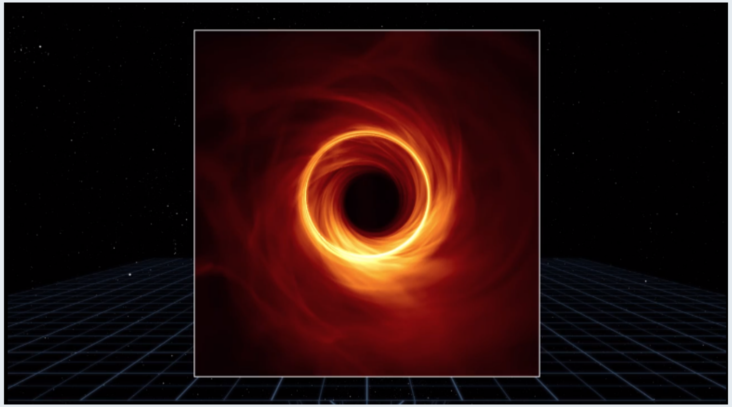
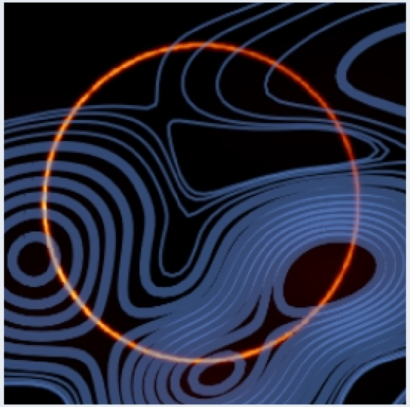
geometry

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

Separate geometry from astrophysics ...

observation





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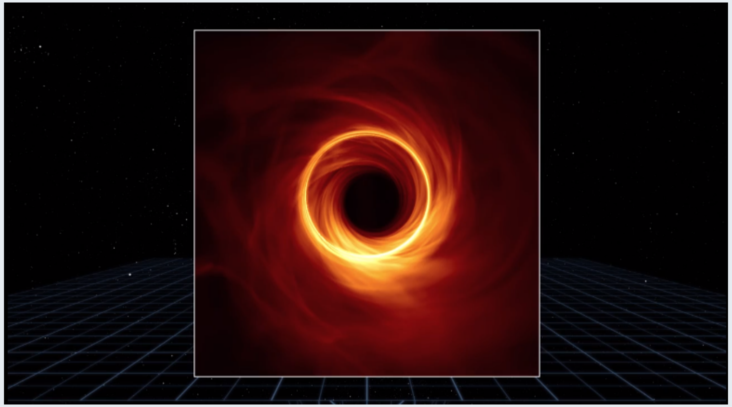
geometry

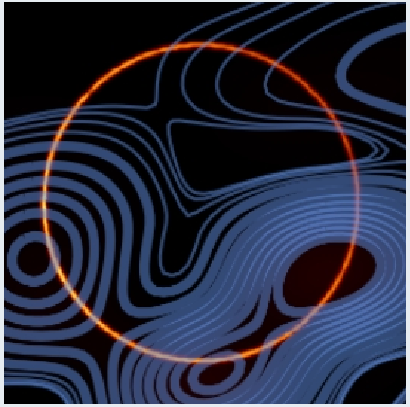
need for a
fast & astrophysics-independent
way to exclude geometries

... via geometric lensing bands.

Separate geometry from astrophysics ...

observation





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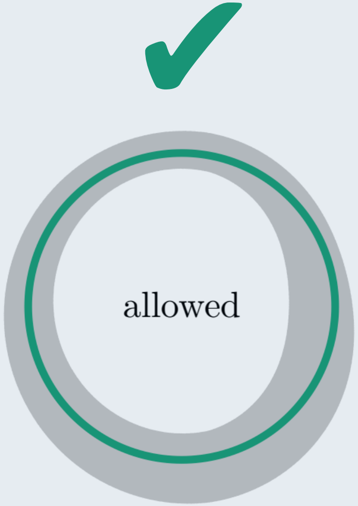
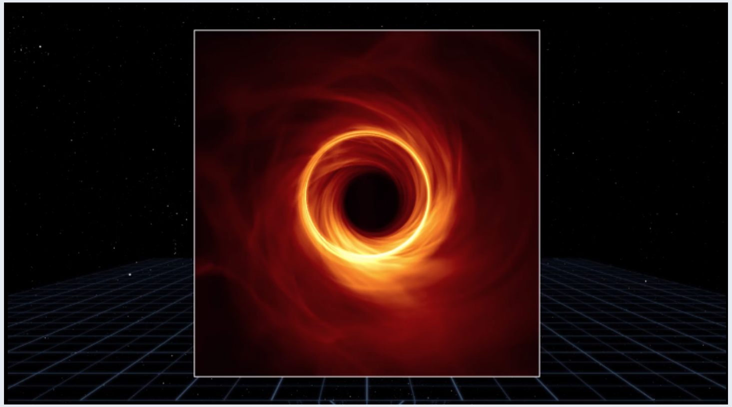
geometry

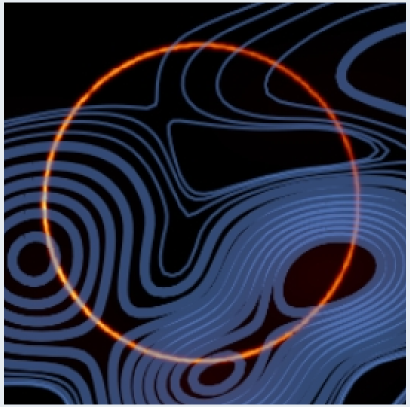


... via geometric lensing bands.

Separate geometry from astrophysics …

observation





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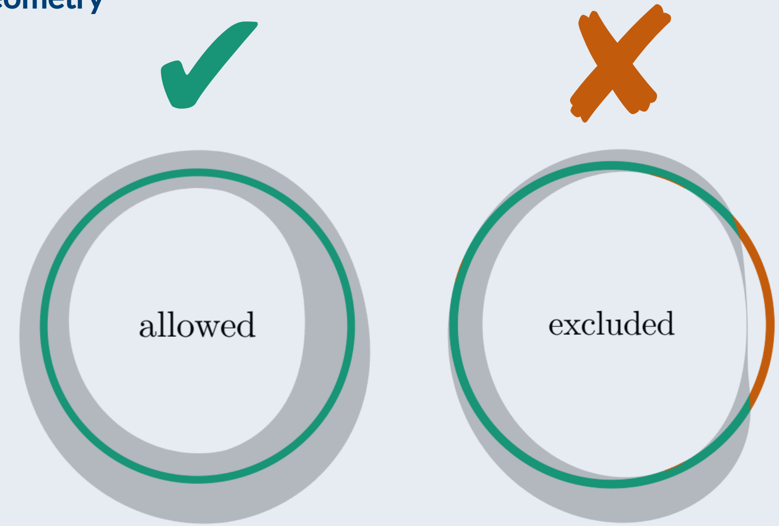
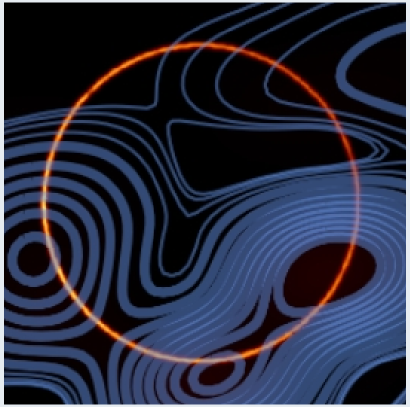
geometry



… via geometric lensing bands.

Separate geometry from astrophysics ...

observation

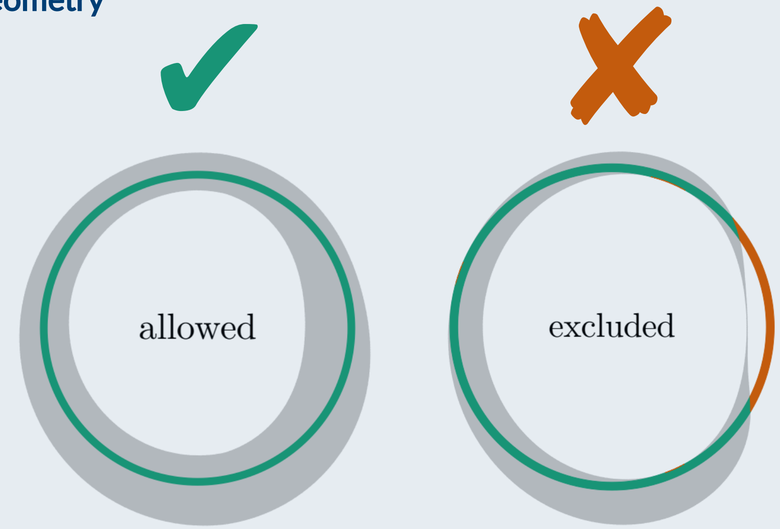


Broderick et. Al
ApJ 935 (2022) 61

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



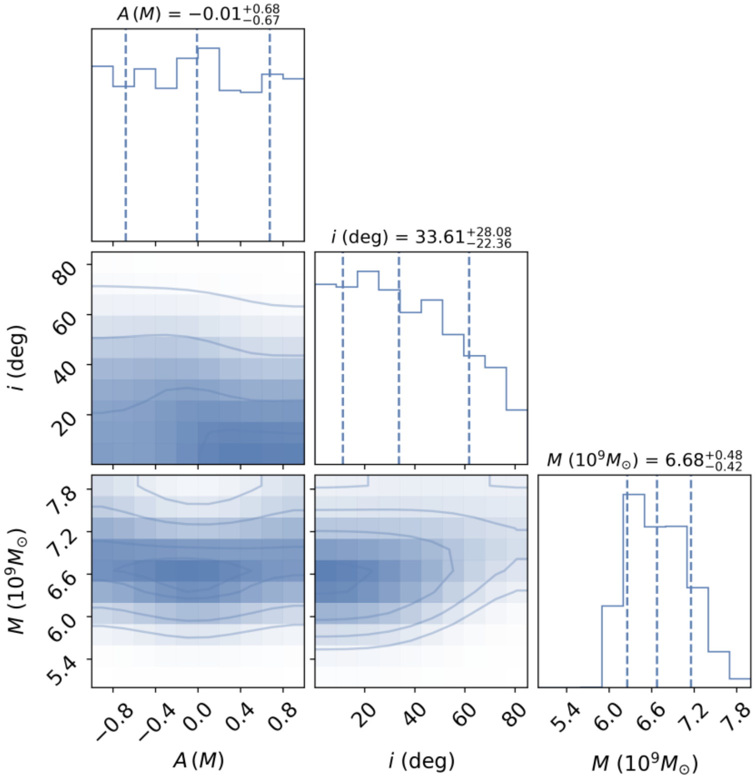
... via geometric lensing bands.

Benchmark with Kerr spacetime ...

Cárdenas-Avendaño, Held, 2312.06590

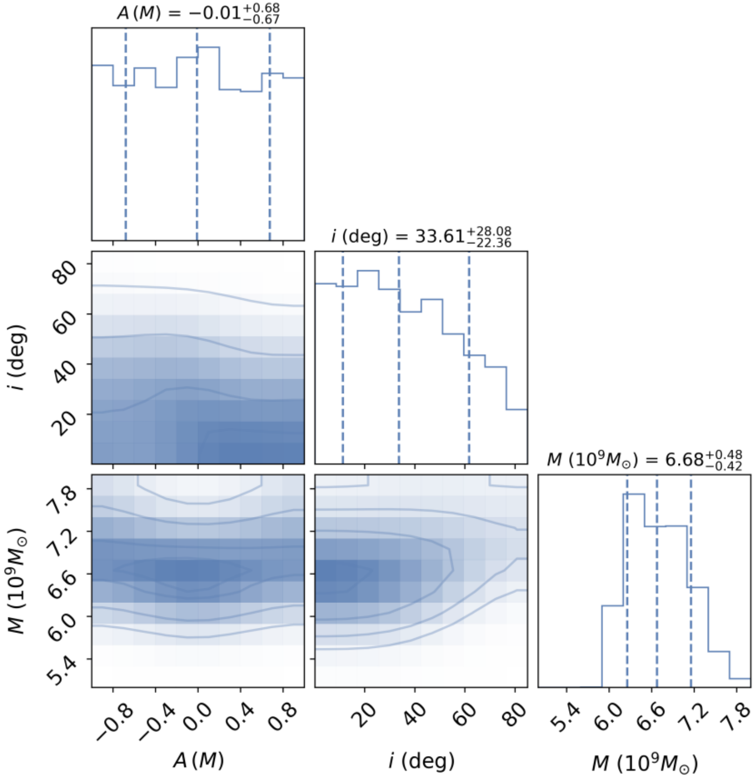
Benchmark with Kerr spacetime ...

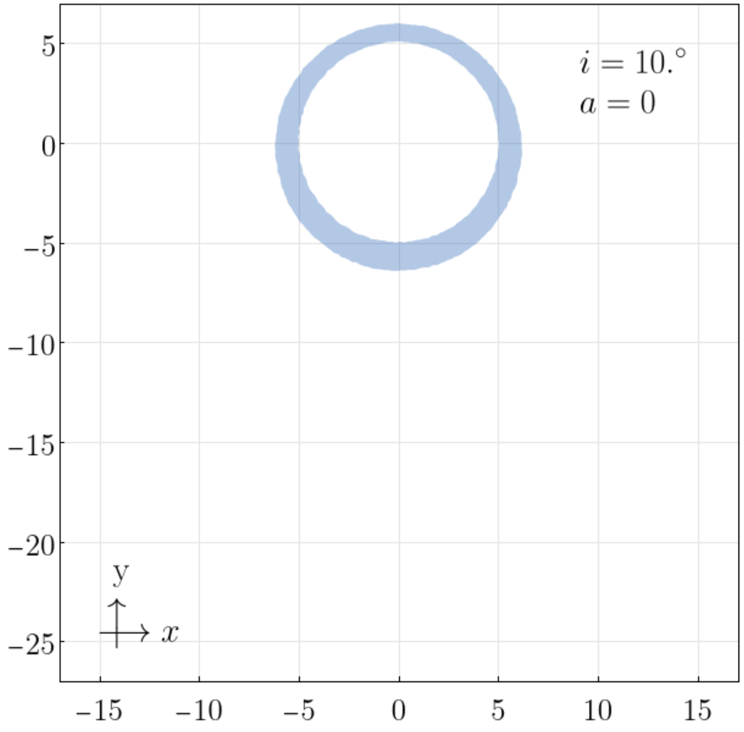
Cárdenas-Avendaño, Held, 2312.06590



Benchmark with Kerr spacetime …

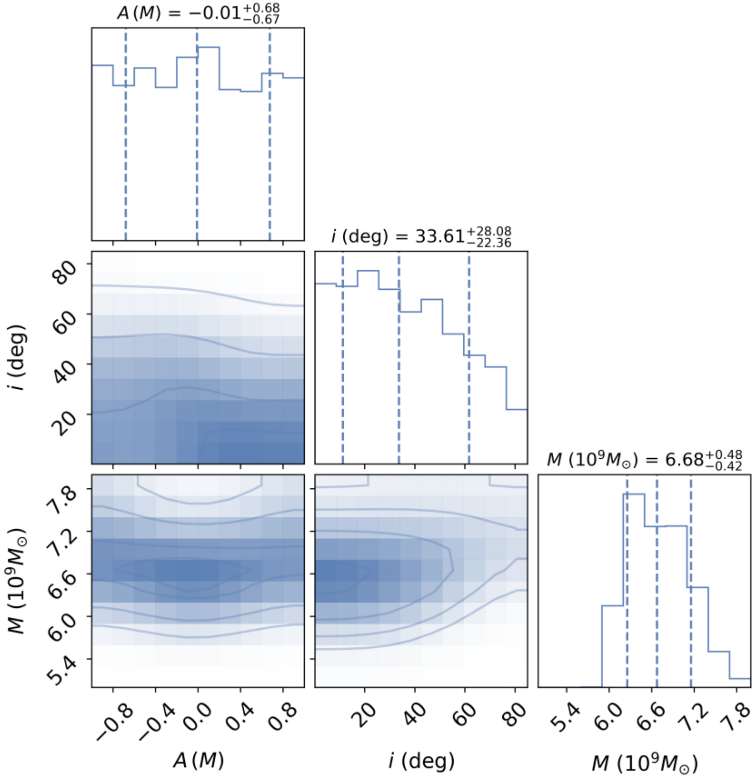
Cárdenas-Avendaño, Held, 2312.06590

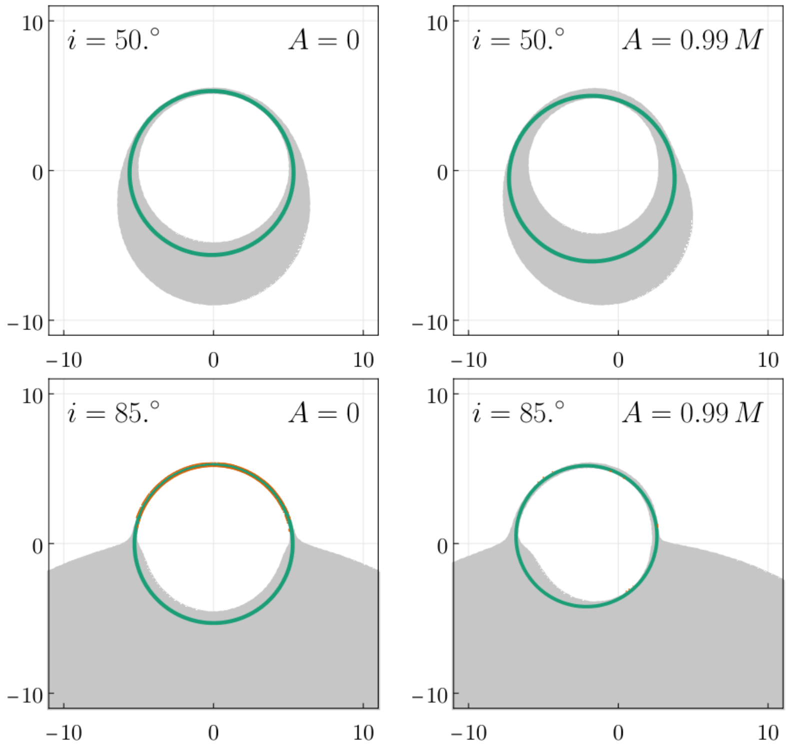




Benchmark with Kerr spacetime ...

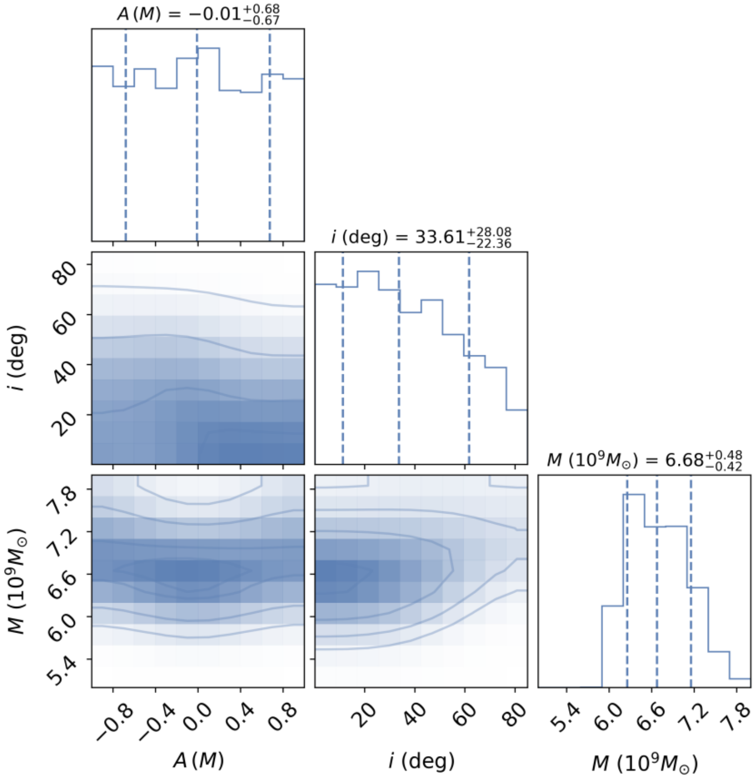
Cárdenas-Avendaño, Held, 2312.06590





Benchmark with Kerr spacetime …

Cárdenas-Avendaño, Held, 2312.06590

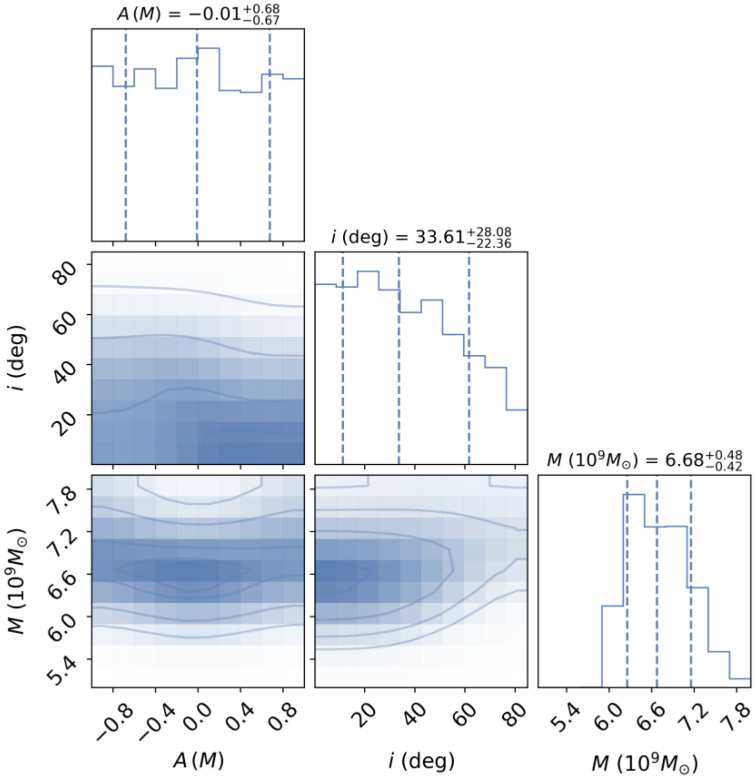


- projected constraint on the mass (from photon-ring size)
  see, e.g., EHT M87* paper I

- correlation between mass and spin
  Broderick et. Al, AJ 935, 61 (2022), AJ 927, 6 (2022)

Benchmark with Kerr spacetime ...

Cárdenas-Avendaño, Held, 2312.06590



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... recover previous work.

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 β , γ
- tower of strong-gravity parameters a_{01}

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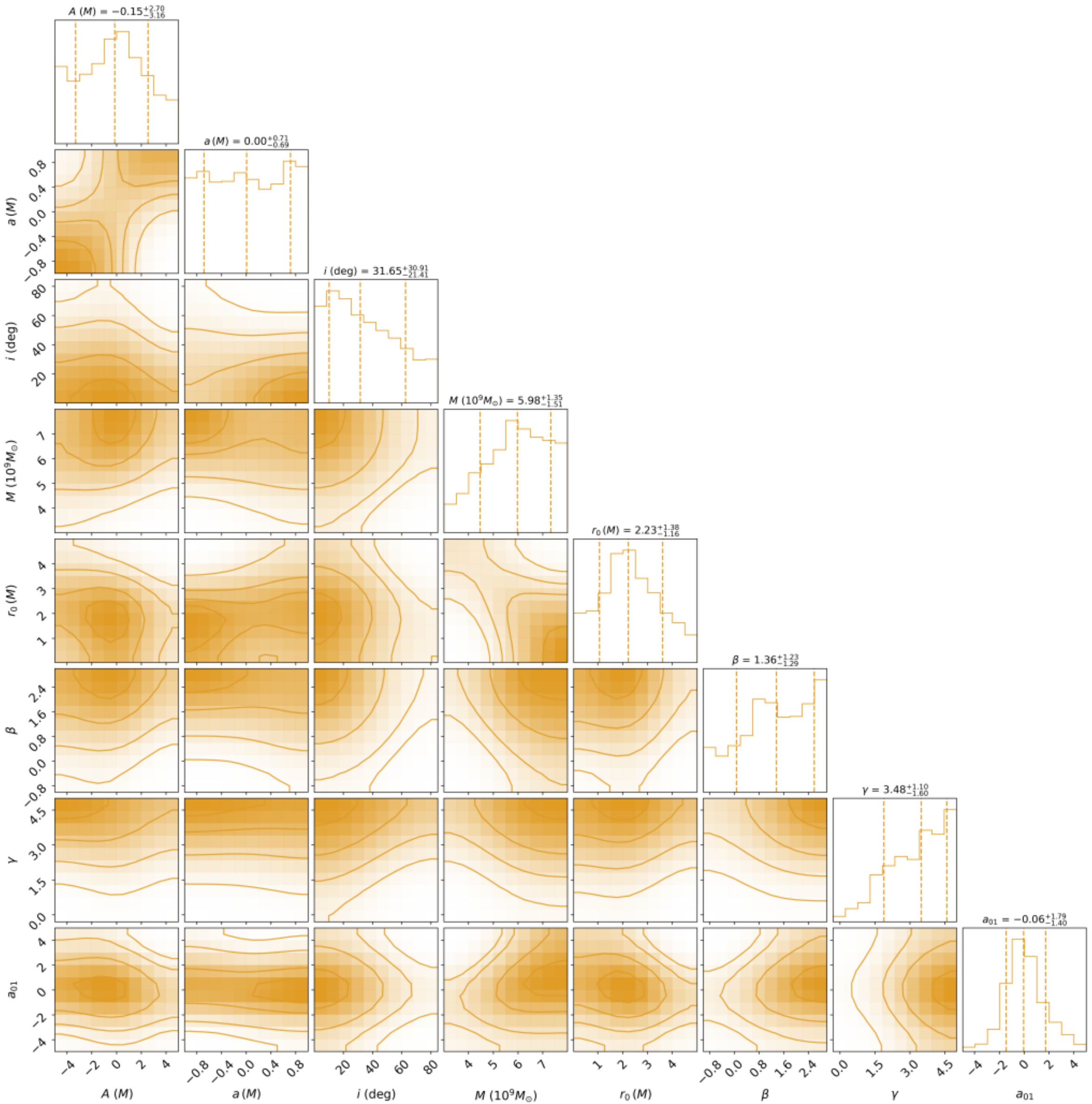

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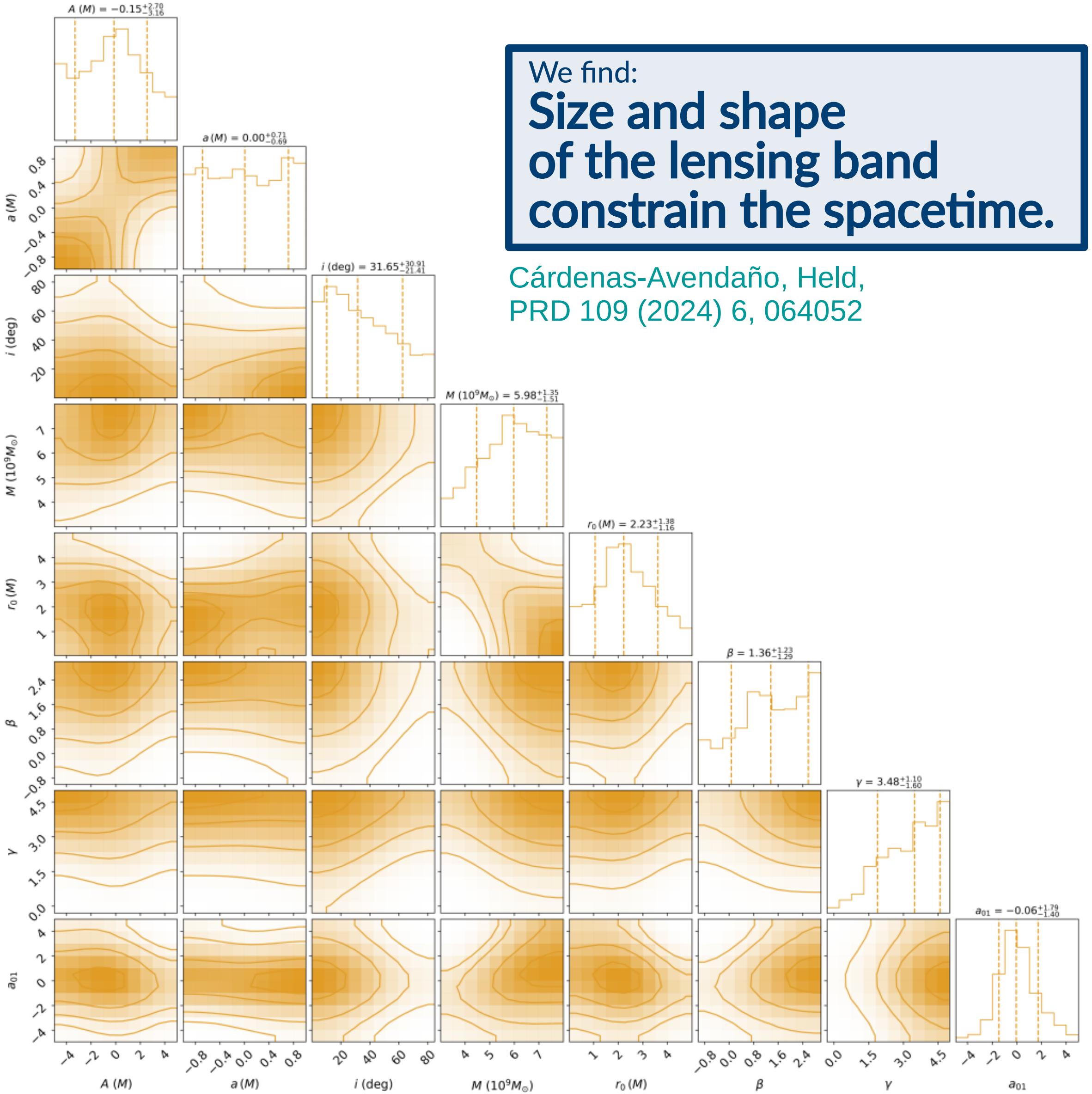

We find:
Size and shape of the lensing band constrain the spacetime.

Cárdenas-Avendaño, Held,
PRD 109 (2024) 6, 064052