Testing fundamental physics using black hole shadows

Che-Yu Chen

Institute of Physics, Academia Sinica, Taiwan

- **CYC,** *JCAP* 05 (2020) 040, arXiv:2004.01440
- **SB, CYC, DY,** arXiv:2012.08785

$\mathbb{Z}_2$ Asymmetry of Black Holes

(Pontryagin scalar)

$$S_{eff} = \int d^4x\sqrt{-g}\,2M_{pl}^2\left[R + \alpha C\tilde{C} + \phi\left(\beta_1 R_{GB} + \beta_2 \tilde{C}\right) + \cdots\right], \qquad C \equiv R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta} \quad \tilde{C} \equiv R_{\alpha\beta\gamma\delta}\tilde{R}^{\alpha\beta\gamma\delta}$$

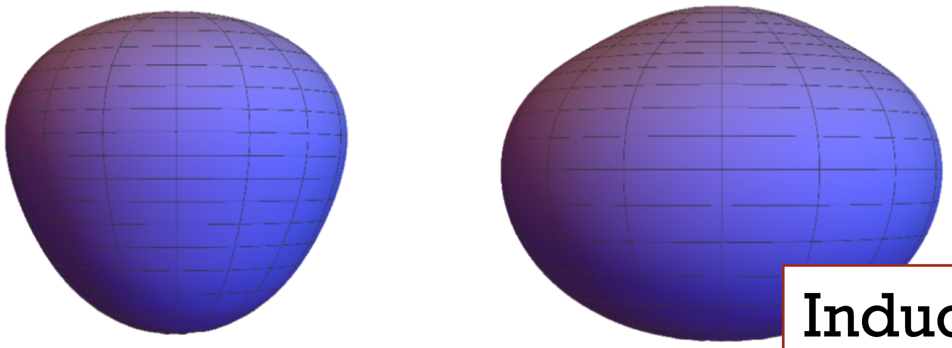
- Parity violating EFTs
- EdGB, dCS, ECG, EFT of string theory

Endlich, Gorbenko, Huang, Senatore (2017)

Sennett, Brito, Buonanno, Gorbenko, Senatore (2020)

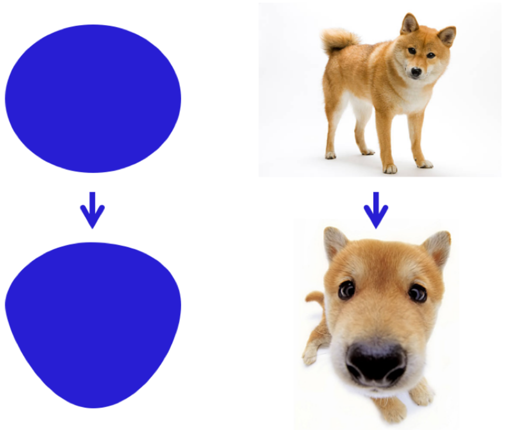
Cano, Ruipérez (2017)

Cardoso, Kimura, Maselli, Senatore (2018)



Induced by **spin**

- <u>Parametrized metric with $\mathbb{Z}_2$ asymmetry</u>



The Kerr-like metric without $\mathbb{Z}_2$ symmetry

$$g^{tt} = \frac{A_5(r) + B_5(y)}{A_1(r) + B_1(y)}, \quad g^{t\varphi} = \frac{A_4(r) + B_4(y)}{A_1(r) + B_1(y)}, \quad g^{\varphi\varphi} = \frac{A_3(r) + B_3(y)}{A_1(r) + B_1(y)}, \quad g^{yy} = \frac{B_2(y)}{A_1(r) + B_1(y)}, \quad g^{rr} = \frac{A_2(y)}{A_1(r) + B_1(y)}$$

Papadopoulos, Kokkotas (2018)

- The radial metric functions $A_i(r)$ are assumed to be Kerrian
- The polar metric functions $B_i(y)$ are Kerrian + some modifications

$$B_1 = a^2 y^2 + \tilde{\epsilon}_1(y), \qquad B_2 = 1 - \mathrm{y}^2 + \tilde{\epsilon}_2(y), \qquad B_3 = \frac{1}{1 - y^2} + \tilde{\epsilon}_3(y),$$

$$B_4 = a + \tilde{\epsilon}_4(y), \quad B_5 = a^2(1 - y^2) + \tilde{\epsilon}_5(y),$$

- If $\tilde{\epsilon}_i = 0$, we get Kerr metric

Chen (2020)

The Kerr-like metric without $\mathbb{Z}_2$ symmetry

$$g^{tt} = \frac{A_5(r) + B_5(y)}{A_1(r) + B_1(y)}, \quad g^{t\varphi} = \frac{A_4(r) + B_4(y)}{A_1(r) + B_1(y)}, \quad g^{\varphi\varphi} = \frac{A_3(r) + B_3(y)}{A_1(r) + B_1(y)}, \quad g^{yy} = \frac{B_2(y)}{A_1(r) + B_1(y)}, \quad g^{rr} = \frac{A_2(y)}{A_1(r) + B_1(y)}$$

Papadopoulos, Kokkotas (2018)

- The radial metric functions $A_i(r)$ are assumed to be Kerrian
- The polar metric functions $B_i(y)$ are Kerrian + some modifications

$$B_1 = a^2y^2 + \tilde{\epsilon}_1(y), \qquad B_2 = 1 - y^2 + \cancel{\tilde{\epsilon}_2(y)}, \qquad B_3 = \frac{1}{1-y^2} + \cancel{\tilde{\epsilon}_3(y)},$$

$$B_4 = a + \cancel{\tilde{\epsilon}_4(y)}, \quad B_5 = a^2(1-y^2) + \tilde{\epsilon}_5(y),$$

- If $\tilde{\epsilon}_i = 0$, we get Kerr metric
- Only $\tilde{\epsilon}_1$ and $\tilde{\epsilon}_5$ are theoretically relevant (asymptotic flatness)

Chen (2020)

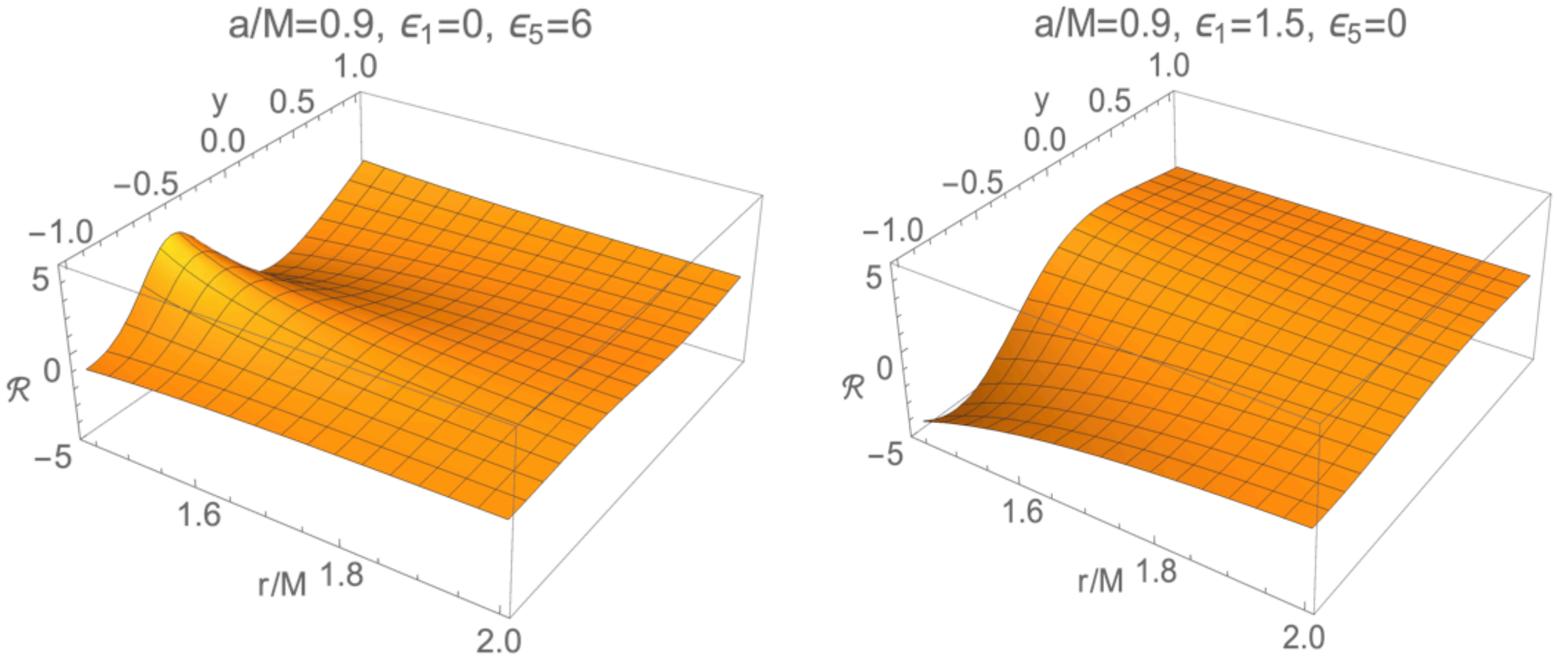
The Kerr-like metric without $\mathbb{Z}_2$ symmetry

The Ricci scalar

$$\mathcal{R}(r,y) \approx \frac{(y^2-1)(3\tilde{\epsilon}_1+\tilde{\epsilon}_5)_{,yy}+2y(3\tilde{\epsilon}_1+\tilde{\epsilon}_5)_{,y}-2(3\tilde{\epsilon}_1+\tilde{\epsilon}_5)}{r^4}$$

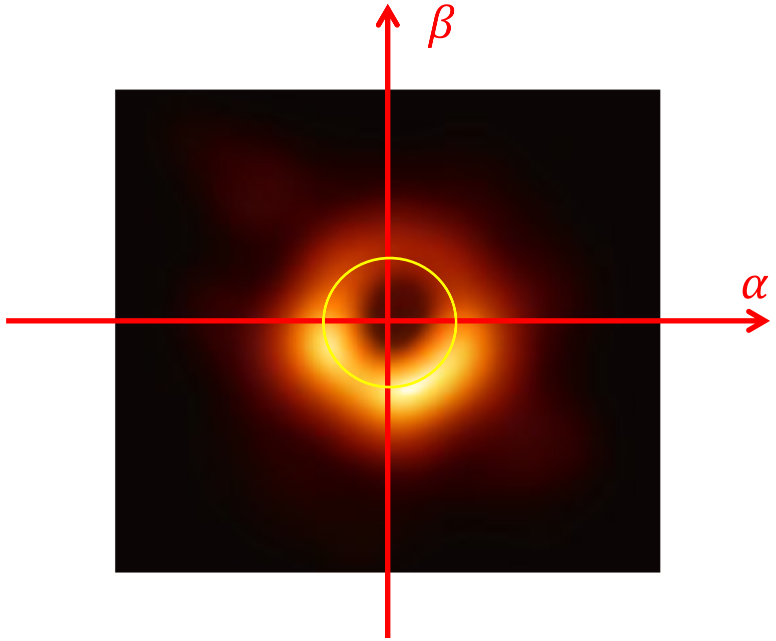
$$+\frac{2M[12\tilde{\epsilon}_1+11\tilde{\epsilon}_5-2y\tilde{\epsilon}_{5,y}+(1-y^2)\tilde{\epsilon}_{5,yy}]}{r^5}+\mathcal{O}(r^{-6})$$

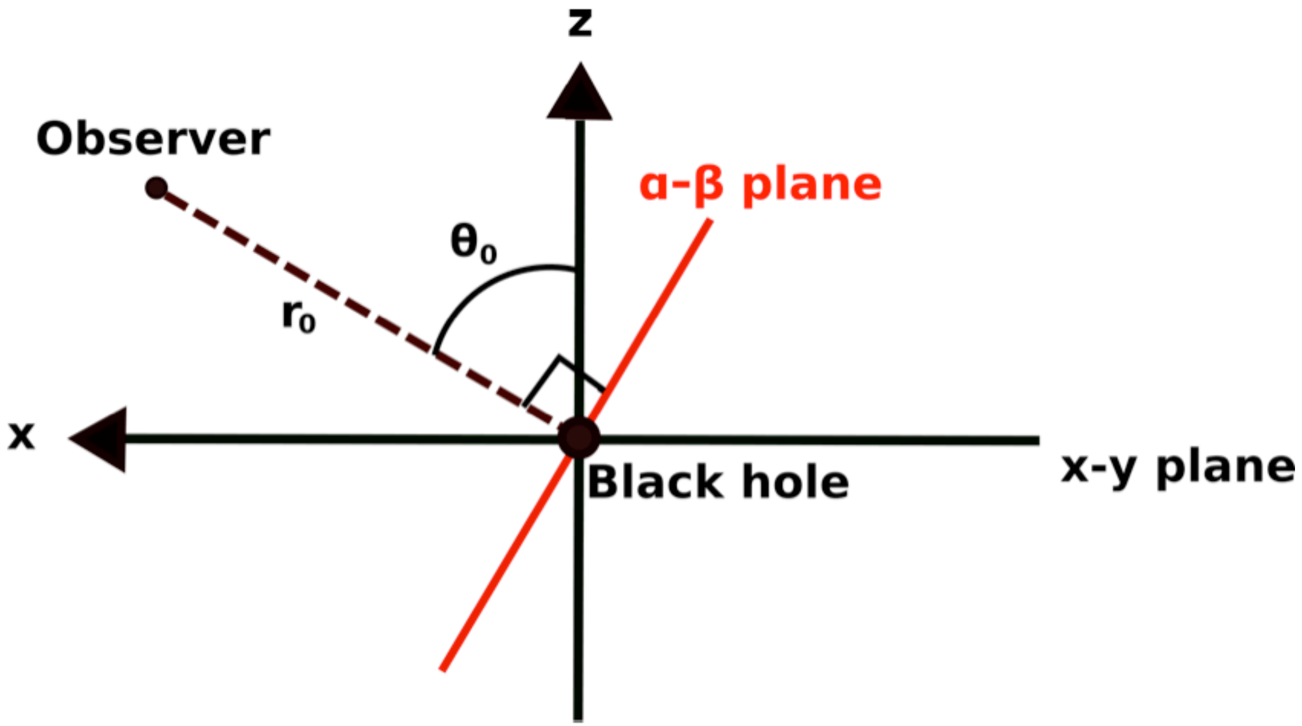
$\tilde{\epsilon}_1(y)=\epsilon_1 M^2 y$ and $\tilde{\epsilon}_5(y)=\epsilon_5 M^2 y$



Chen (2020)

Celestial coordinates (α, β)

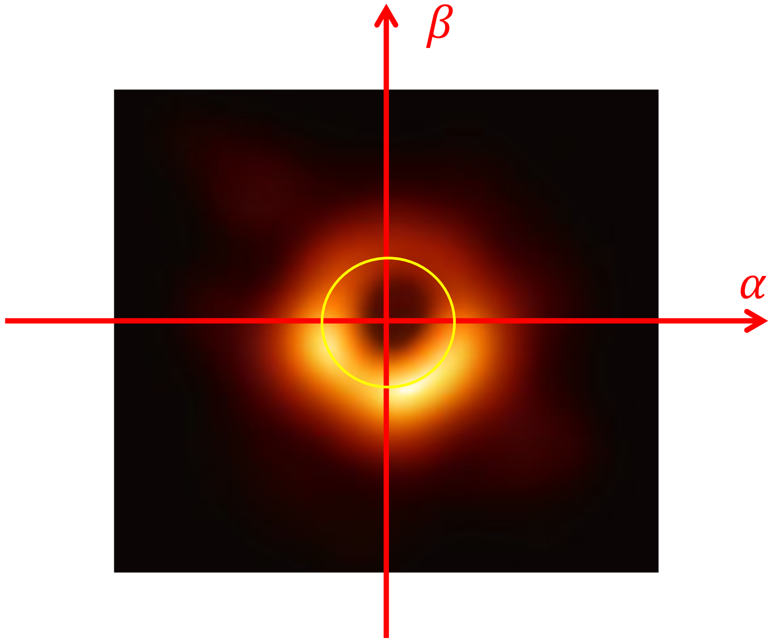


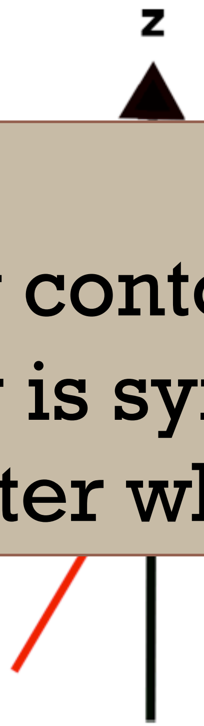


$$\alpha = \lim_{r_0\to\infty}\left(-r_0^2 \sin\theta_0 \frac{d\varphi}{dr}\right)\Big|_{r_0,\theta_0} = -\frac{\xi}{\sin\theta_0},$$

$$\beta = \lim_{r_0\to\infty}\left(r_0^2 \frac{d\theta}{dr}\right)\Big|_{r_0,\theta_0} = \pm\sqrt{\eta + a^2\cos^2\theta_0 - \xi^2\cot\theta_0 - \tilde{\epsilon}_5(y_0)}$$

Celestial coordinates (α, β)





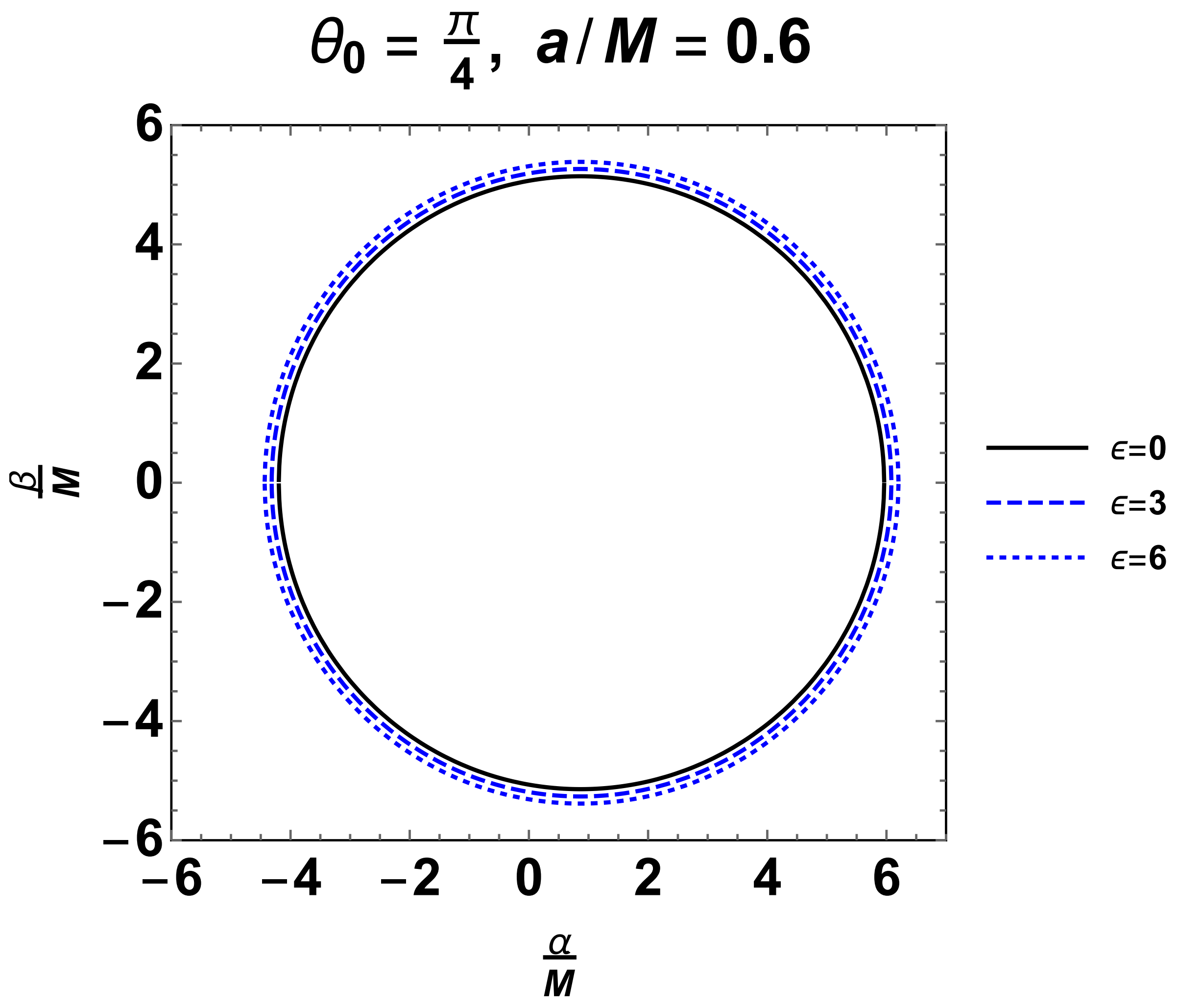
Remark:

- The shadow contour is blind to $\tilde{\epsilon}_1$
- The contour is symmetric w.r.t. α-axis, no matter what θ_0 is!

$$\alpha = \lim_{r_0 \to \infty} \left(-r_0^2 \sin\theta_0 \frac{d\varphi}{dr} \right) \bigg|_{r_0, \theta_0} = -\frac{\xi}{\sin\theta_0},$$

$$\beta = \lim_{r_0 \to \infty} \left(r_0^2 \frac{d\theta}{dr} \right) \bigg|_{r_0, \theta_0} = \pm\sqrt{\eta + a^2 \cos^2\theta_0 - \xi^2 \cot\theta_0 - \tilde{\epsilon}_5(y_0)}$$

Model: $\tilde{\epsilon}(y) = \epsilon a M y$



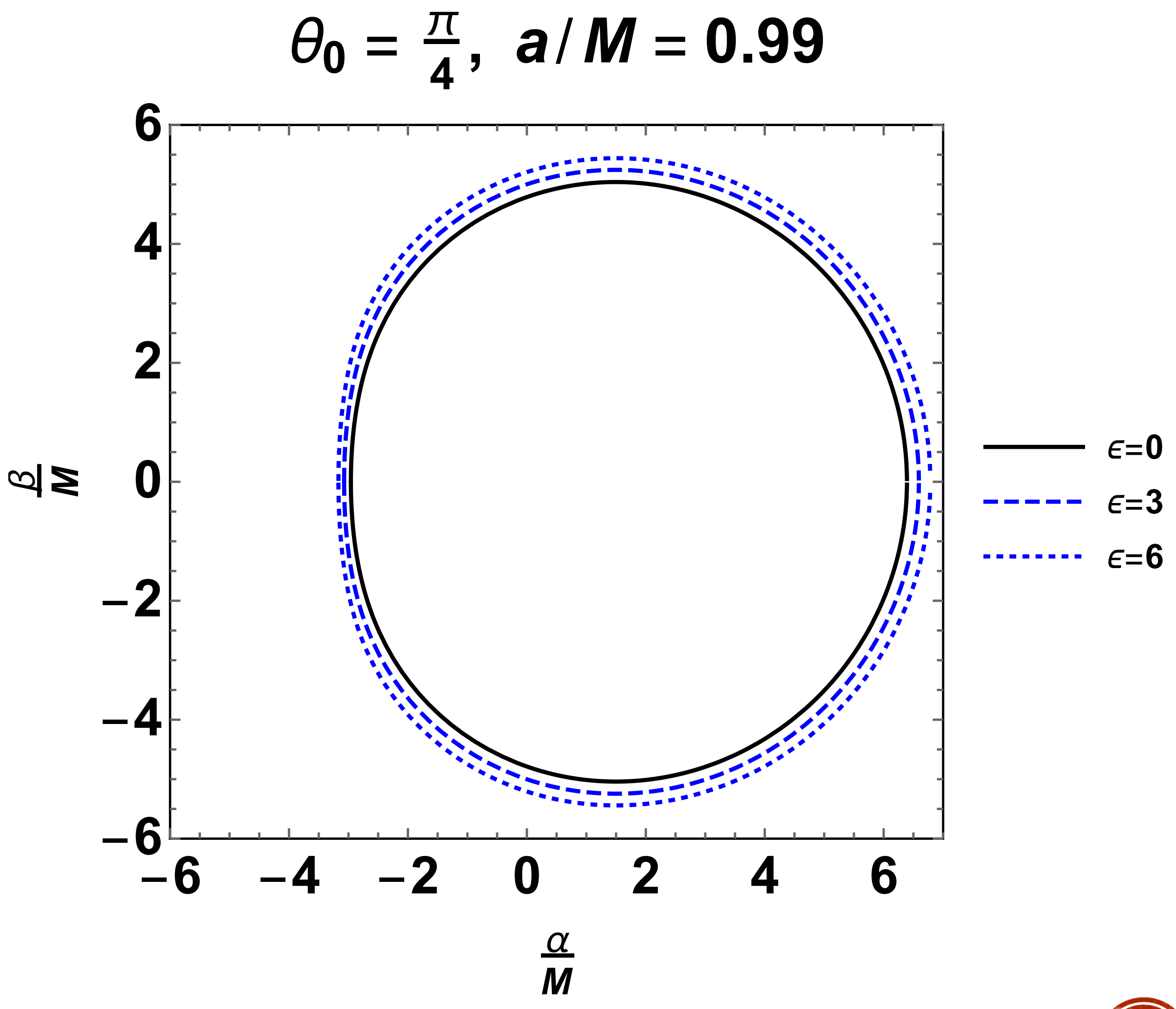
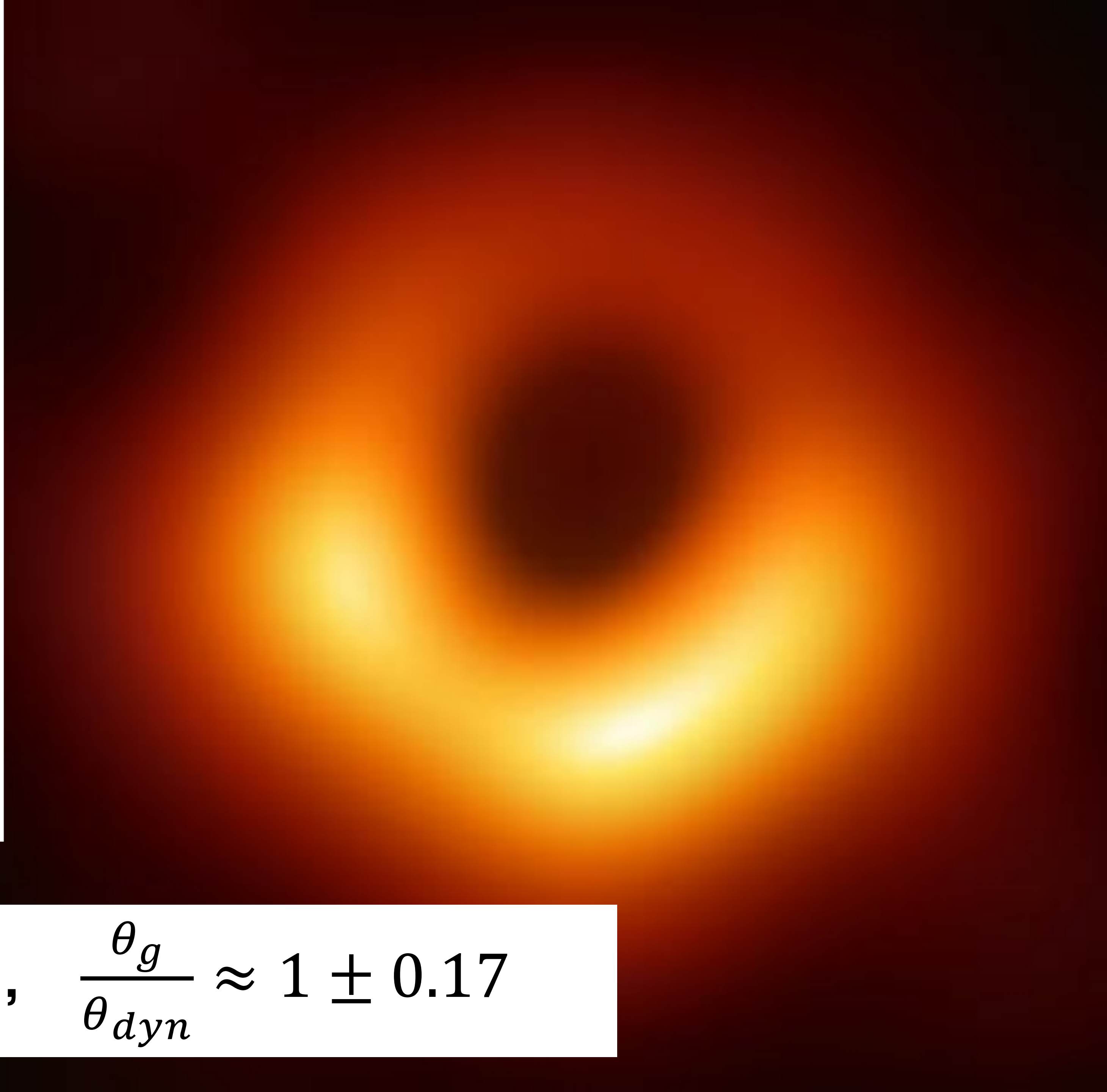


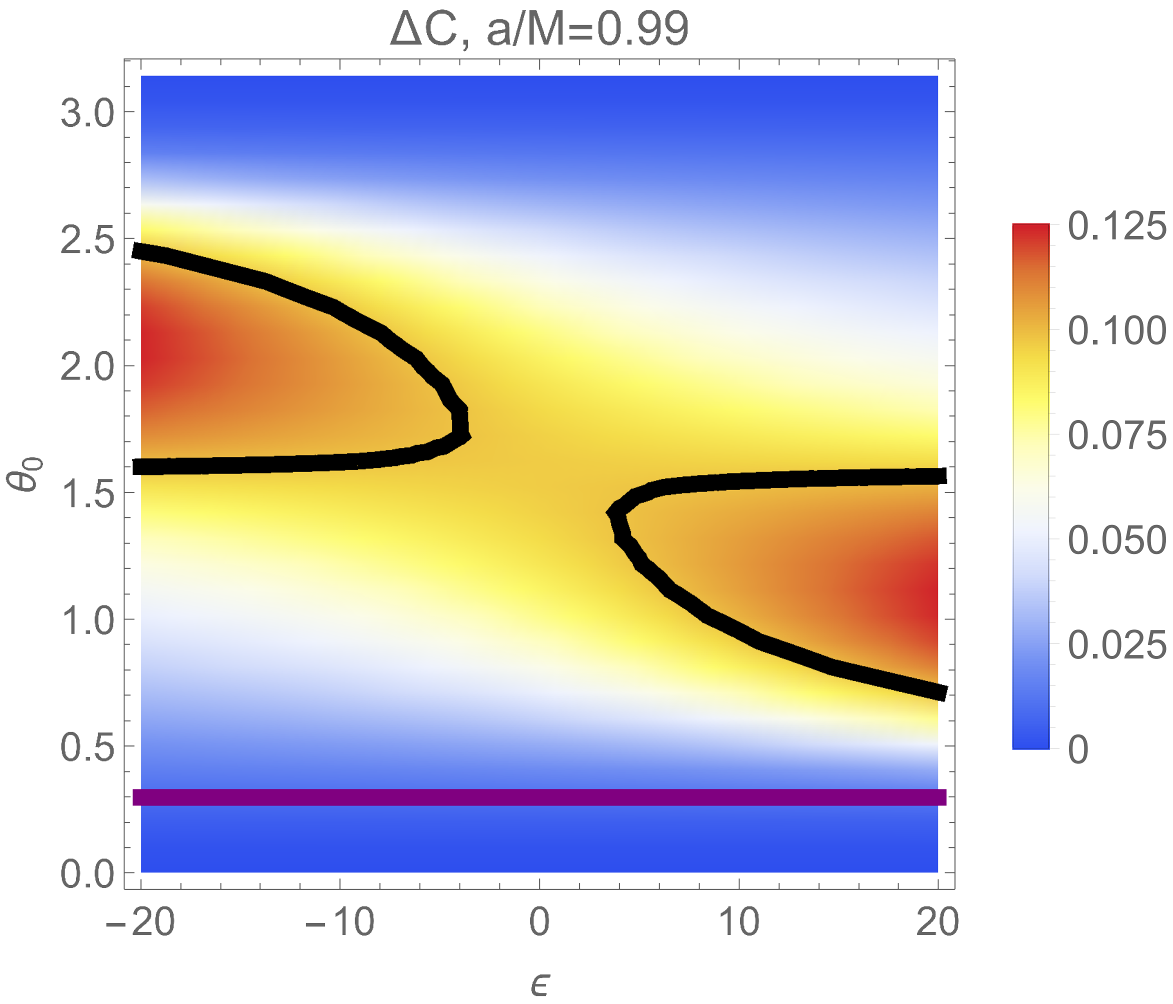
Table 1
Parameters of M87*

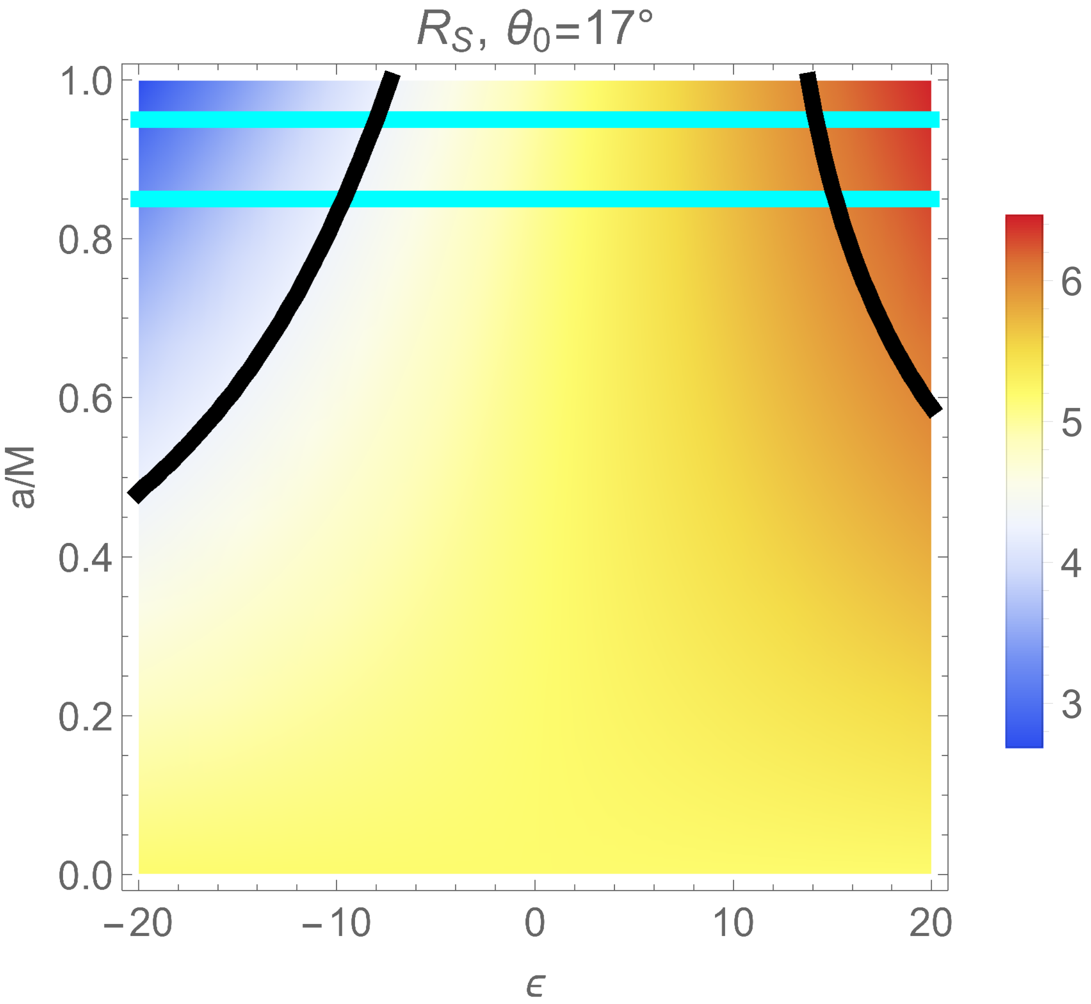
Parameter	Estimate
Ring diameter [a] d	$42 \pm 3\ \mu$as
Ring width [a]	$<20\ \mu$as
Crescent contrast [b]	$>10{:}1$
Axial ratio [a]	$<4{:}3$
Orientation PA	150°–200° east of north
$\theta_g = GM/Dc^2$ [c]	$3.8 \pm 0.4\ \mu$as
$\alpha = d/\theta_g$ [d]	$11^{+0.5}_{-0.3}$
M [c]	$(6.5 \pm 0.7) \times 10^9\ M_\odot$
Parameter	**Prior Estimate**
D [e]	(16.8 ± 0.8) Mpc
M(stars) [e]	$6.2^{+1.1}_{-0.6} \times 10^9\ M_\odot$
M(gas) [e]	$3.5^{+0.9}_{-0.3} \times 10^9\ M_\odot$



$$\Delta C < 0.1, \quad \frac{\theta_g}{\theta_{dyn}} \approx 1 \pm 0.17$$

M87* constraints





$M = 6.5{\times}10^9 M_{\odot}, \quad \theta_0 = 17°, \quad D^* = 16.8 Mpc$

The Kerr-like metric: LQG inspired BH

- LQG introduces the concept of quantum geometry: spin-networks and discrete spectrum of geometrical operators (Area, Volume)
- Effectively, we introduce semi-classical corrections by using polymerization technique (holonomy corrections along a loop)
- The polymerization scale is related to area-gap scale

- Even for non-rotating BHs, the polymerization method is not unique
- Different models have their own drawbacks
- A consistent LQG treatment to rotating spacetimes is still lacking
- Rotating BHs are important in our universe

The Kerr-like metric: LQG inspired BH

- In BMM model, a set of canonical variables (related to the metric functions) is used: (ν_k, P_k), (ν_j, P_j) Bodendorfer, Mele, Münch (2019)

$$H_{cl}\left(\nu_k, \nu_j, P_k, P_j\right) \to H_{eff}\left(\nu_k, \nu_j, \frac{\sin(\lambda_k P_k)}{\lambda_k}, \frac{\sin(\lambda_j P_j)}{\lambda_j}\right)$$

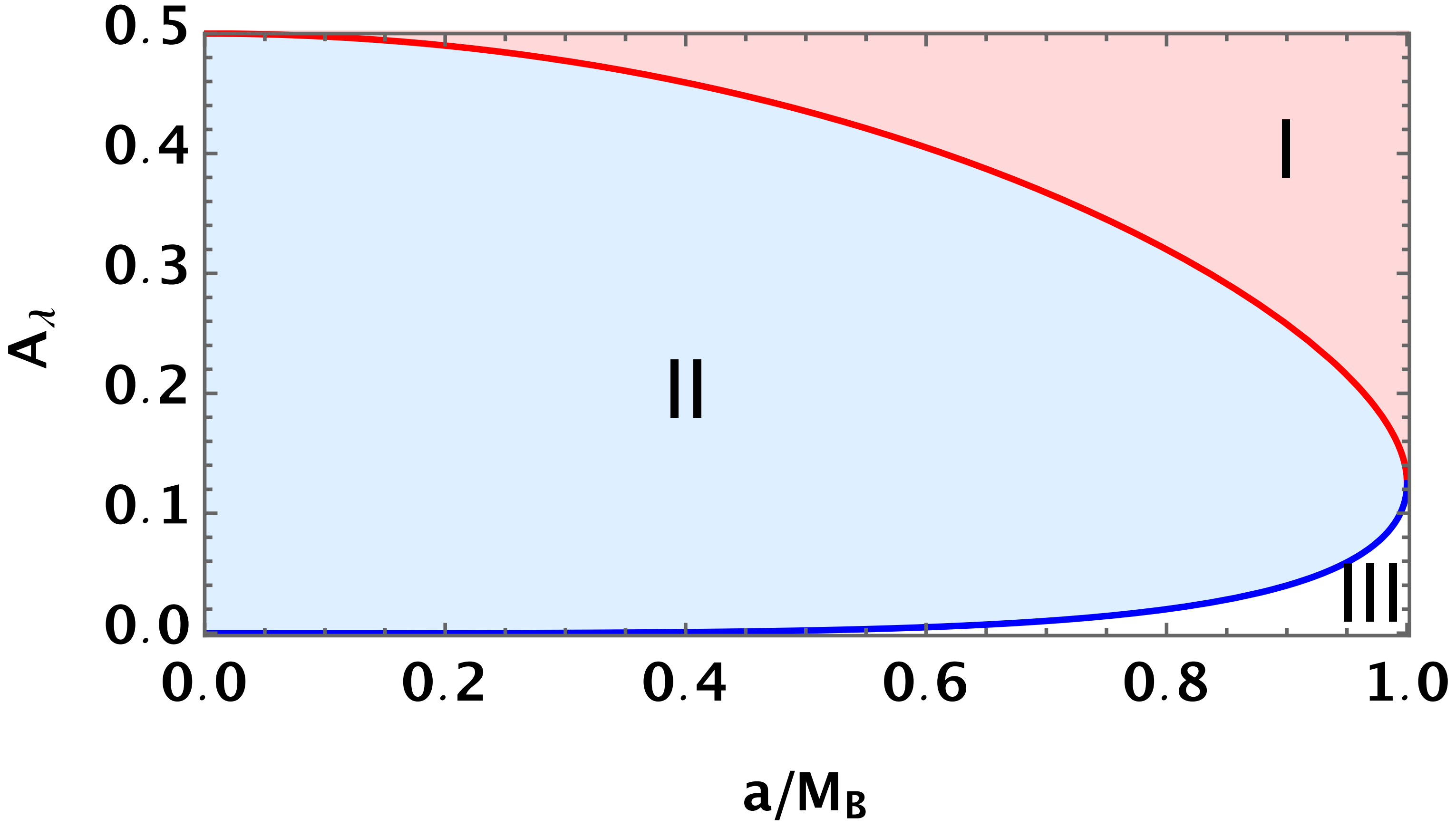
- Singularity is replaced with a transition surface connecting a black hole and a white hole regimes (very common for many LQGBHs)
- It is able to describe the exterior regimes (many LQGBHs cannot)

- We use Newman-Janis Algorithm to generate the rotating metric

Newman, Janis (1965) Azreg-Ainou (2014) SB, CYC, DY (2020)

- NB: Geodesic equations and KG equation→ Separation of variables

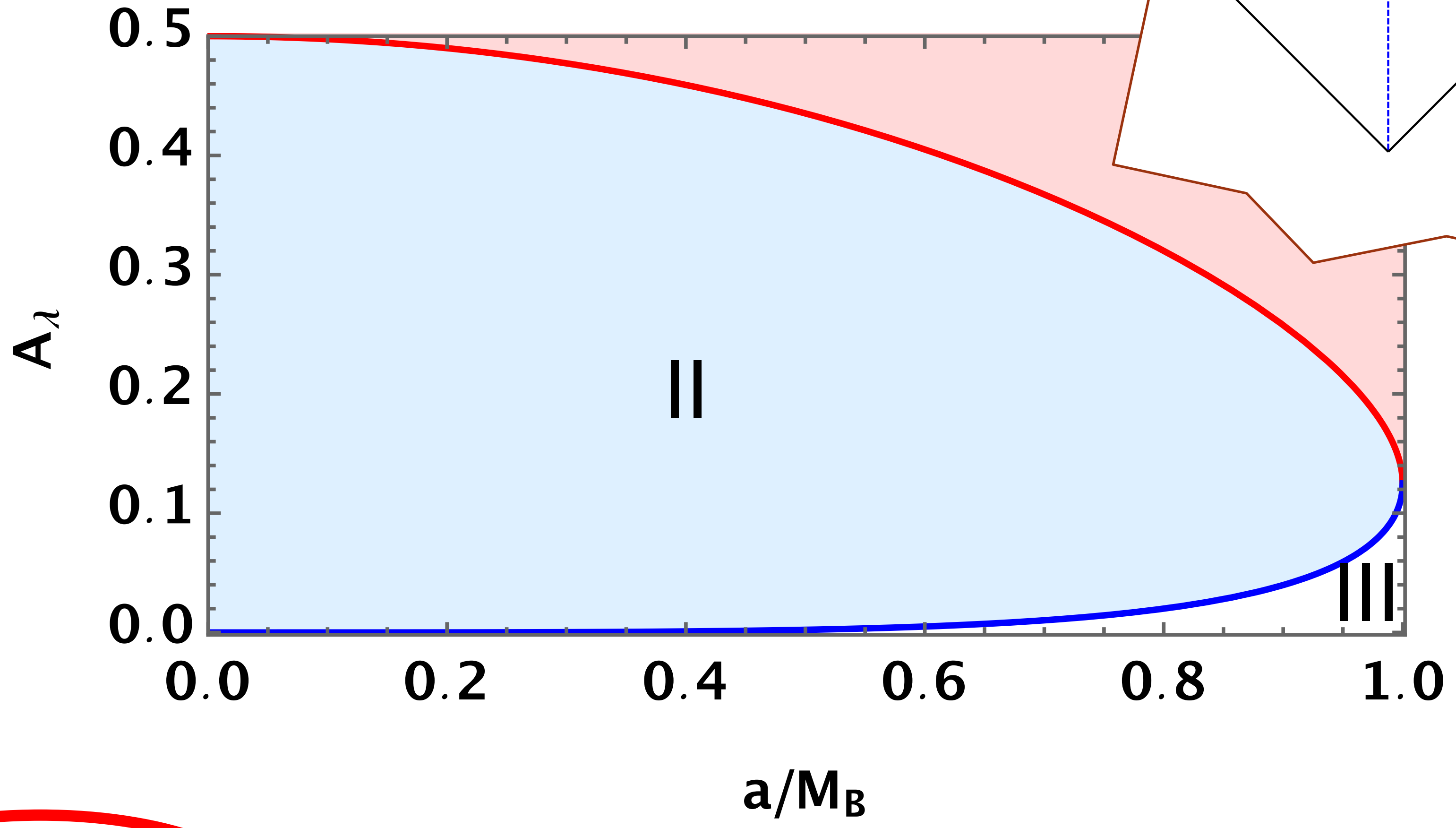
Spacetime Structure

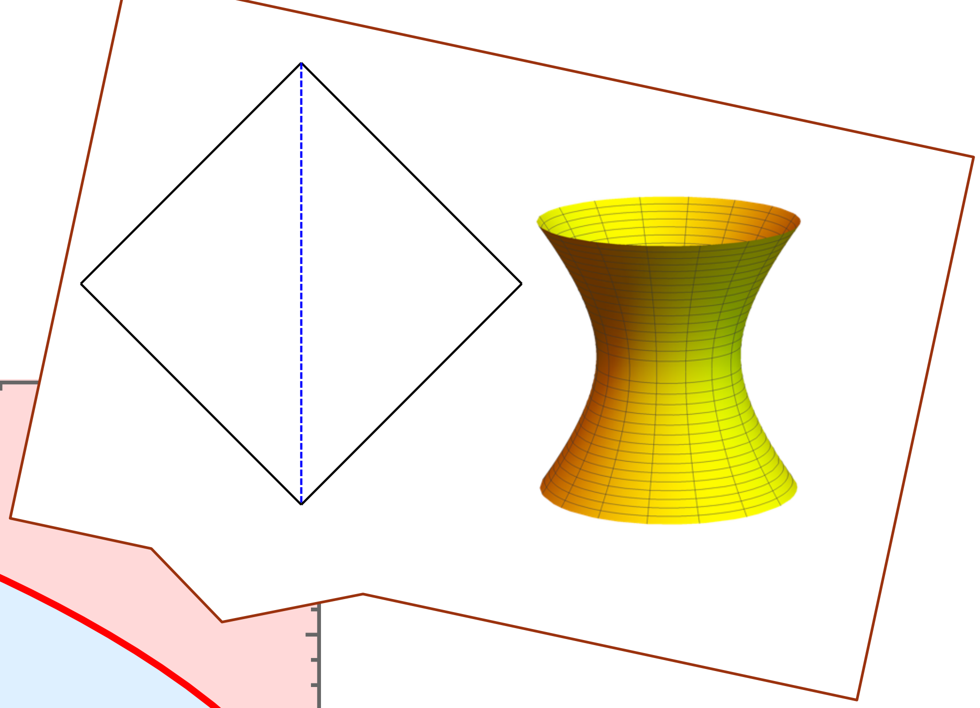


$$A_\lambda = \left(\frac{\lambda_k}{M_B^2}\right)^{\frac{2}{3}}/2$$

Region I: WH   Region II: BH with one horizon   Region III: BH with two horizons

Spacetime Structure





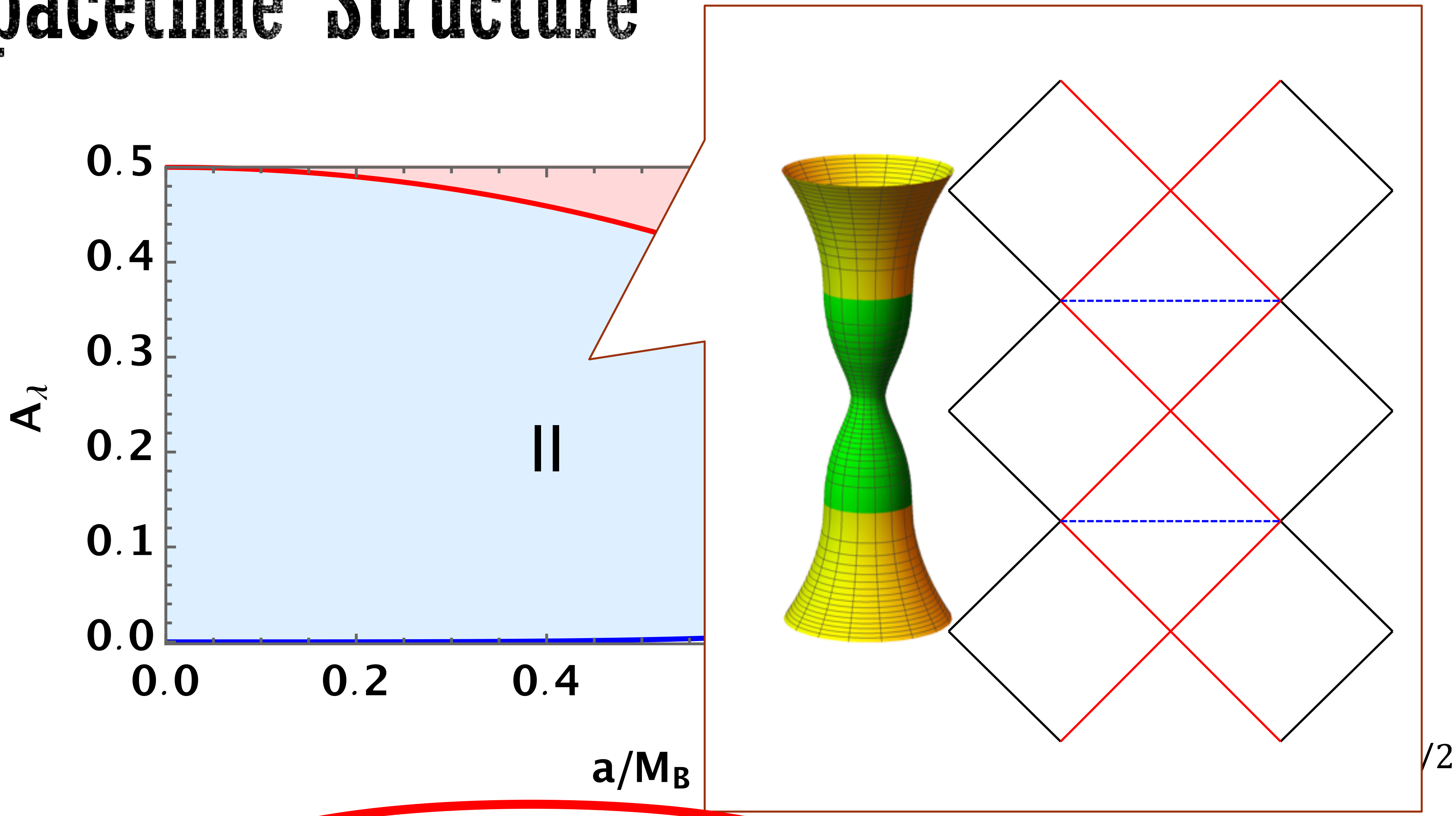
$$A_\lambda = \left(\frac{\lambda_k}{M_B^2}\right)^{\frac{2}{3}}/2$$

Region I: WH

Region II: BH with one horizon

Region III: BH with two horizons

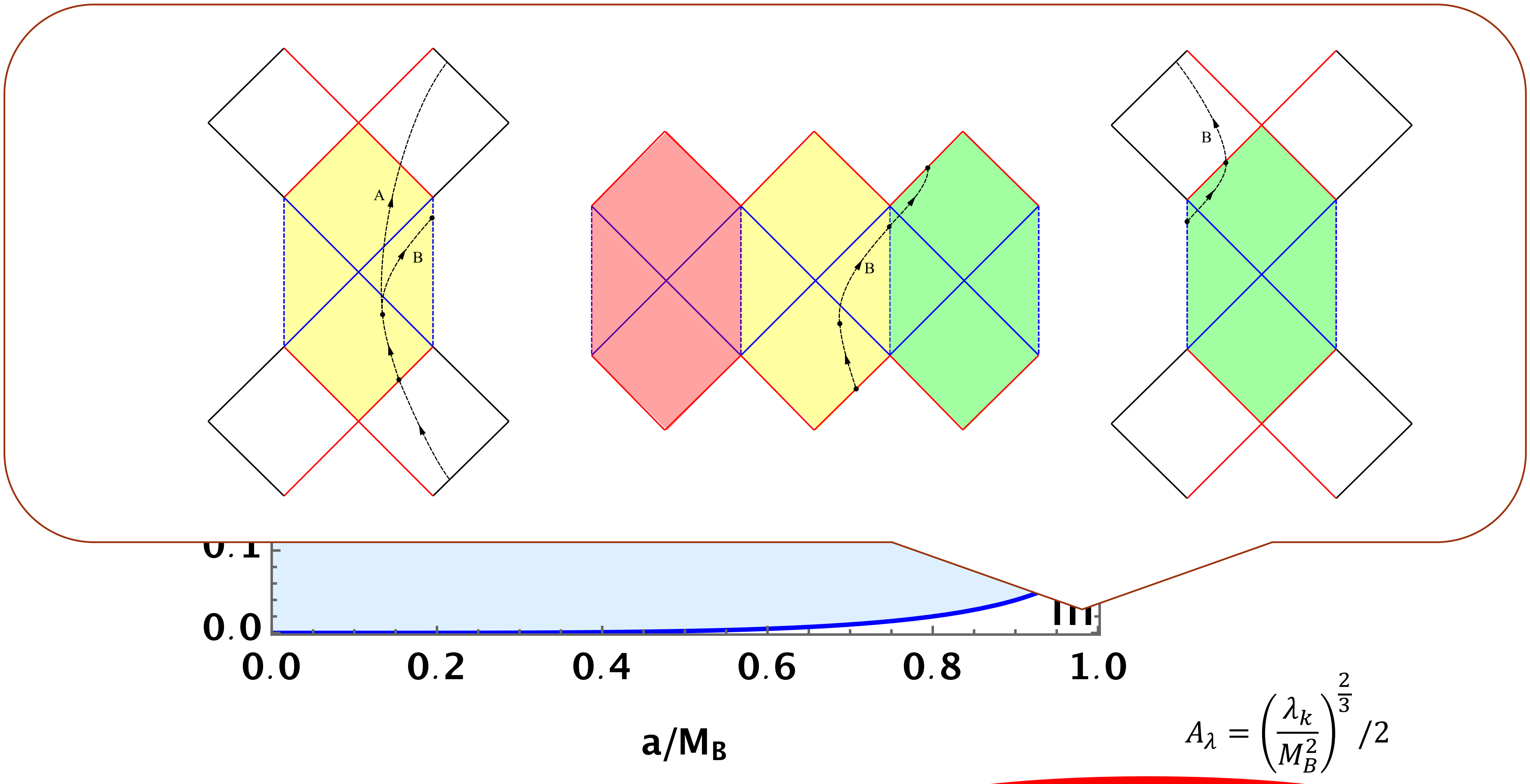
Spacetime Structure



Region I: WH

Region II: BH with one horizon

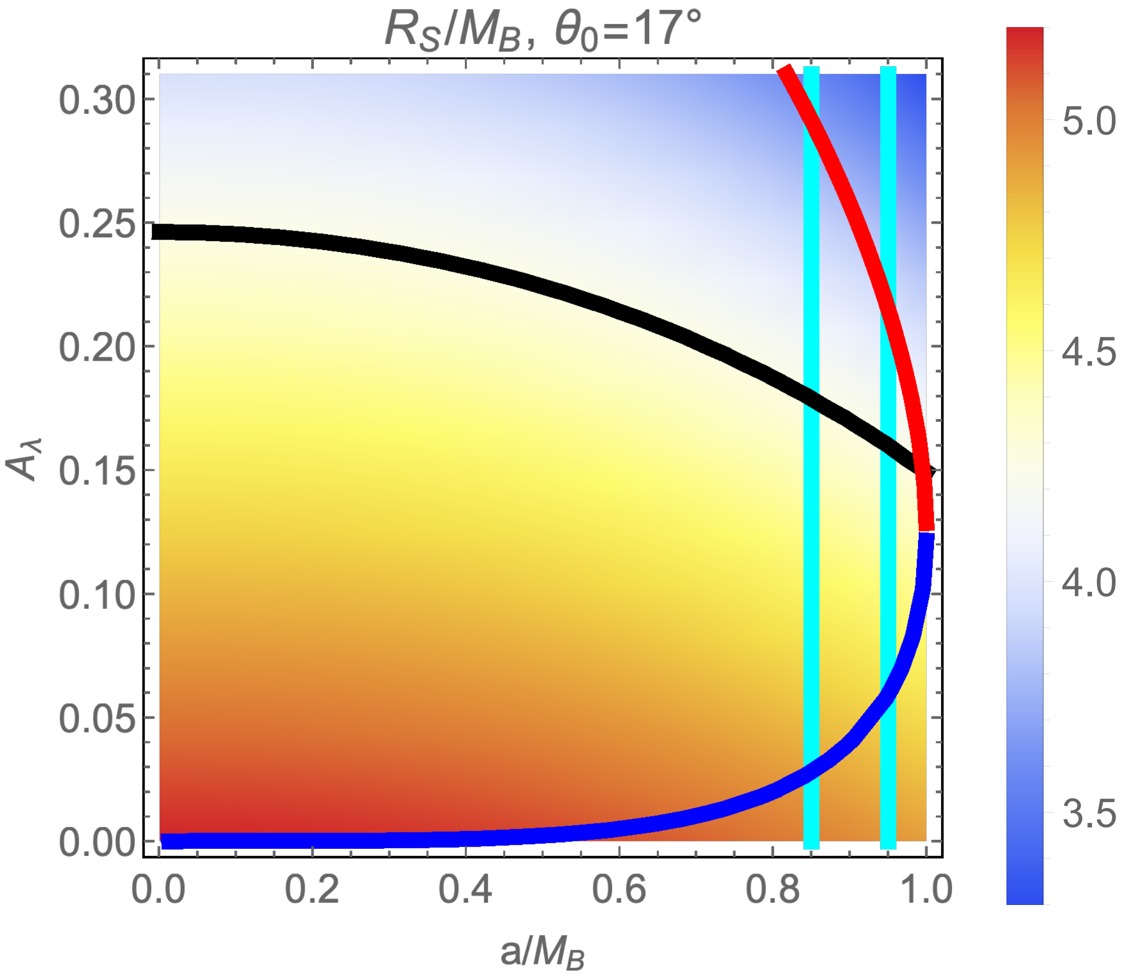
Region III: BH with two horizons

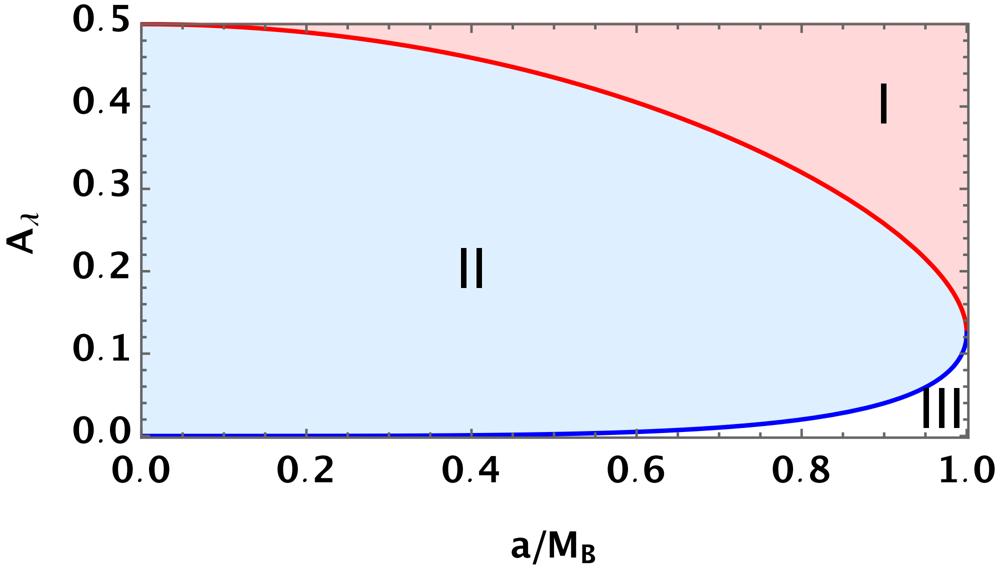


$$A_\lambda = \left(\frac{\lambda_k}{M_B^2}\right)^{\frac{2}{3}}/2$$

Region I: WH   Region II: BH with one horizon   Region III: BH with two horizons

M87* constraints





$$M = 6.5\times10^9 M_\odot, \quad \theta_0 = 17°, \quad D^* = 16.8 Mpc$$

Conclusions

- Two Kerr-like metrics: asymptotically Kerr, Solar System constraint
- Kerr-like metric I: $\mathbb{Z}_2$ asymmetry
  - $\mathbb{Z}_2$ asymmetry: induced by black hole's spin
  - $\mathbb{Z}_2$ asymmetry is quantified by a parameter ϵ
  - Good approximation to the rotating black holes in EFTs of QG
- Kerr-like metric II: LQG effective BHs
  - Nonsingular, rich spacetime structure
  - Geodesic eqs. and KG eq.: separation of variables
- The shadow contours:
  - Symmetric w.r.t the horizontal axis (regardless of the inclination)
  - The deviation parameter only alters the apparent size
  - Constraints from shadow size (under some astrophysical assumptions)

Symmetry w.r.t the horizontal axis

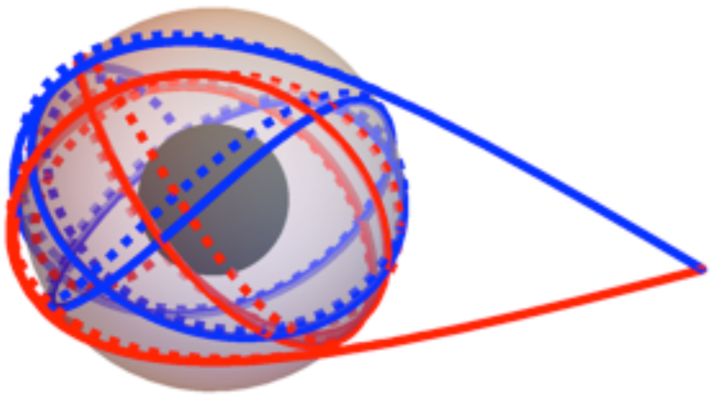
- Mathematically…

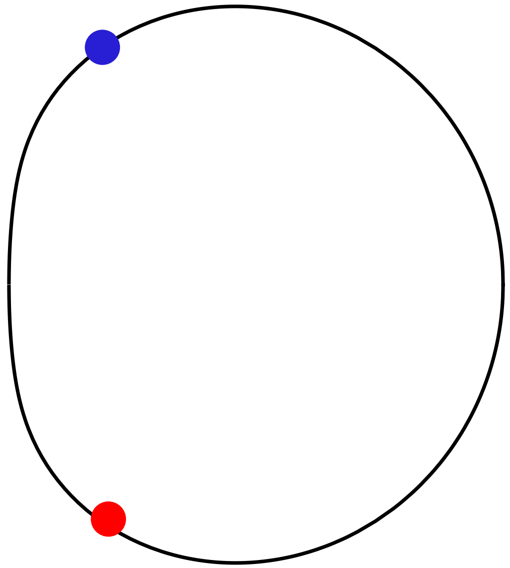
$$(A_1 + B_1)\dot{\theta}/E = \pm\sqrt{\Theta(\theta,\xi,\eta)}, \qquad \beta = \lim_{r_0\to\infty}\left(r_0^2\frac{d\theta}{dr}\right)\bigg|_{r_0,\theta_0}$$

  - It is related to the separability of the geodesic equations

Grenzebac, Perlick, Lämmerzahl (2014), Cunha, Herdeiro, Radu (2018)

- Physically…





Chen (2020)