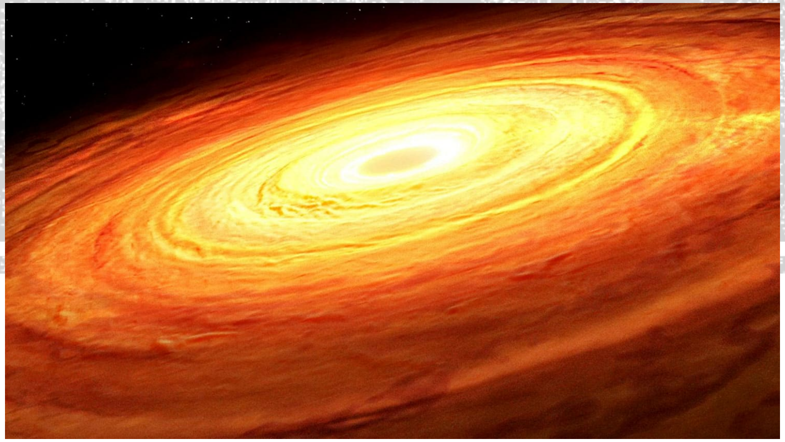
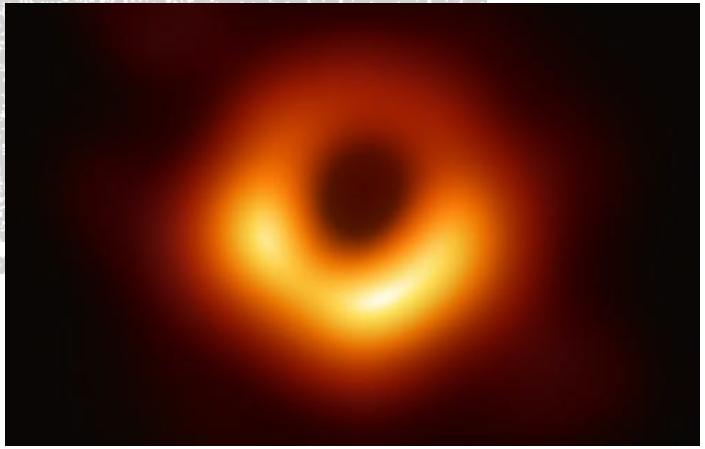
Testing rotating black holes without reflection symmetry





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- **CYC,** *JCAP* 05 (2020) 040, arXiv:2004.01440
- **CYC, HYY,** arXiv:2109.00564

International Joint Workshop on the SM and Beyond
2021 Oct. 14-15

Black holes without $\mathbb{Z}_2$ symmetry

(Pontryagin scalar)

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

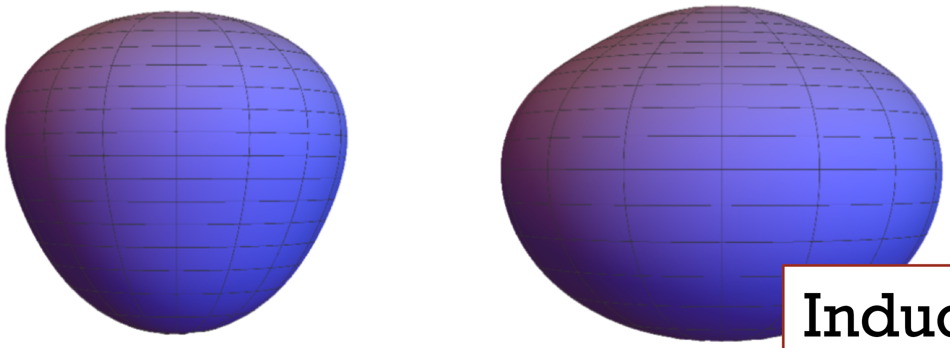
- Parity violating EFTs
- EdGB, dCS, ECG, EFT of string theory

Endlich, Gorbenko, Huang, Senatore (2017)

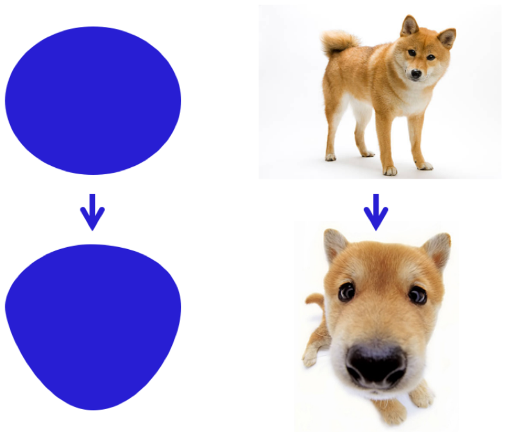
Sennett, Brito, Buonanno, Gorbenko, Senatore (2020)

Cano, Ruipérez (2017)

Cardoso, Kimura, Maselli, Senatore (2018)



Induced by **spin**



- <u>Theory-agnostic metric with $\mathbb{Z}_2$ asymmetry</u>
  - Non-GR parameters specifically for testing it

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

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

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

- If $\tilde{\epsilon}_i=0$, we get Kerr metric
- Carter-like constant: Separable geodesic eqs.

Chen (2020)

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- If $\tilde{\epsilon}_i=0$, we get Kerr metric
- Carter-like constant: Separable geodesic eqs.
- Only $\tilde{\epsilon}_1$ and $\tilde{\epsilon}_5$ are theoretically relevant (asymptotic flatness)

More on the Kerr-like metric

- In fact, if we consider the post-Newtonian parameters:

$$\beta = \gamma - \frac{\tilde{\epsilon}_1 + \tilde{\epsilon}_5}{2M^2}, \qquad \gamma = 1,$$

- The Solar System constraint: $|\beta - 1| < 2.3\times10^{-4}$, $|\gamma - 1| < 2.3\times10^{-5}$
- We then assume $\tilde{\epsilon}_1(y) = -\tilde{\epsilon}_5(y) = \tilde{\epsilon}(y)$

- In addition, we require that the $\mathbb{Z}_2$ asymmetry is induced by black hole's spin

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

Chen (2020)

Summary of the Kerr-like metric

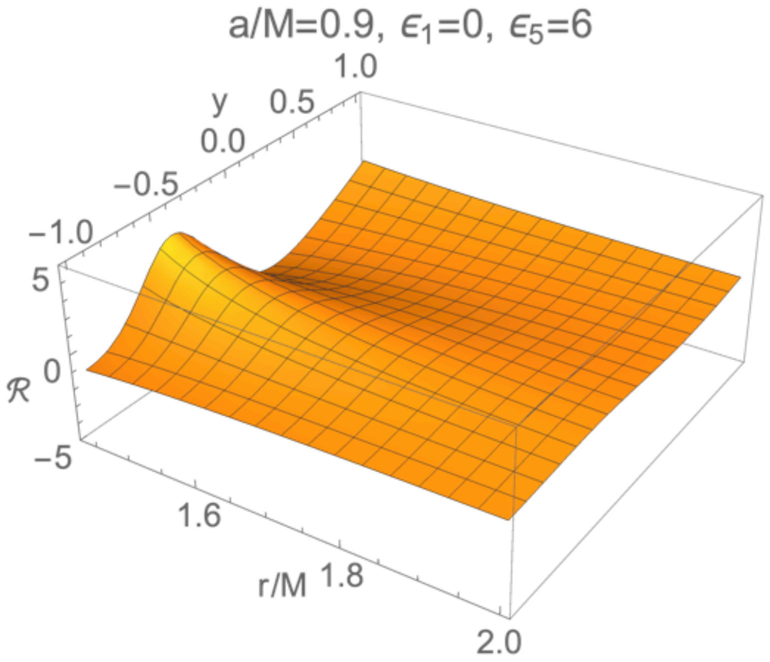
- Asymptotically reduces to Kerr
- Equatorial reflection asymmetry: possibility induced by spin
- Separable geodesic equations

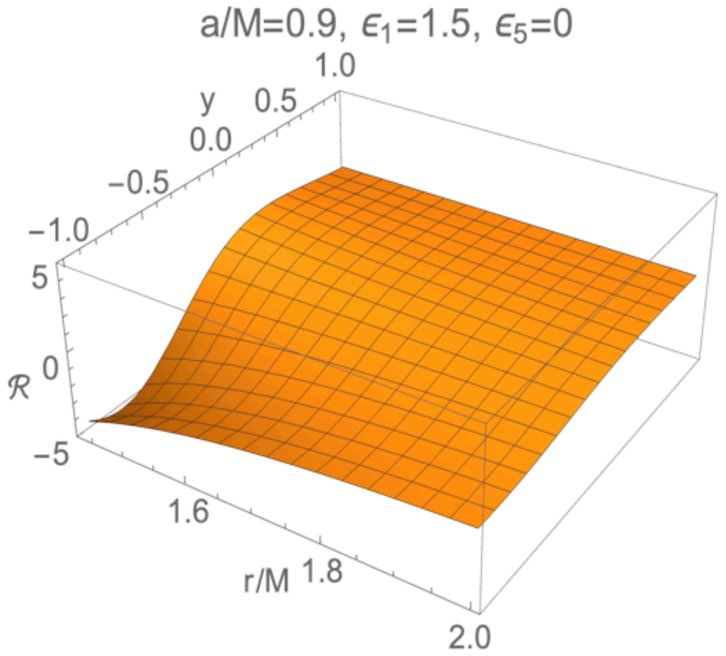
The Kerr-like metric without $\mathbb{Z}_2$ symmetry

The Ricci scalar

$$\mathcal{R}(r,y) \approx \frac{(y^2-1)(3\tilde{\epsilon}_1+\tilde{\epsilon}_5)_{,yy}+2y(3\tilde{\epsilon}_1+\tilde{\epsilon}_5)_{,y}-2(3\tilde{\epsilon}_1+\tilde{\epsilon}_5)}{r^4} + \frac{2M[12\tilde{\epsilon}_1+11\tilde{\epsilon}_5-2y\tilde{\epsilon}_{5,y}+(1-y^2)\tilde{\epsilon}_{5,yy}]}{r^5}+\mathcal{O}(r^{-6})$$

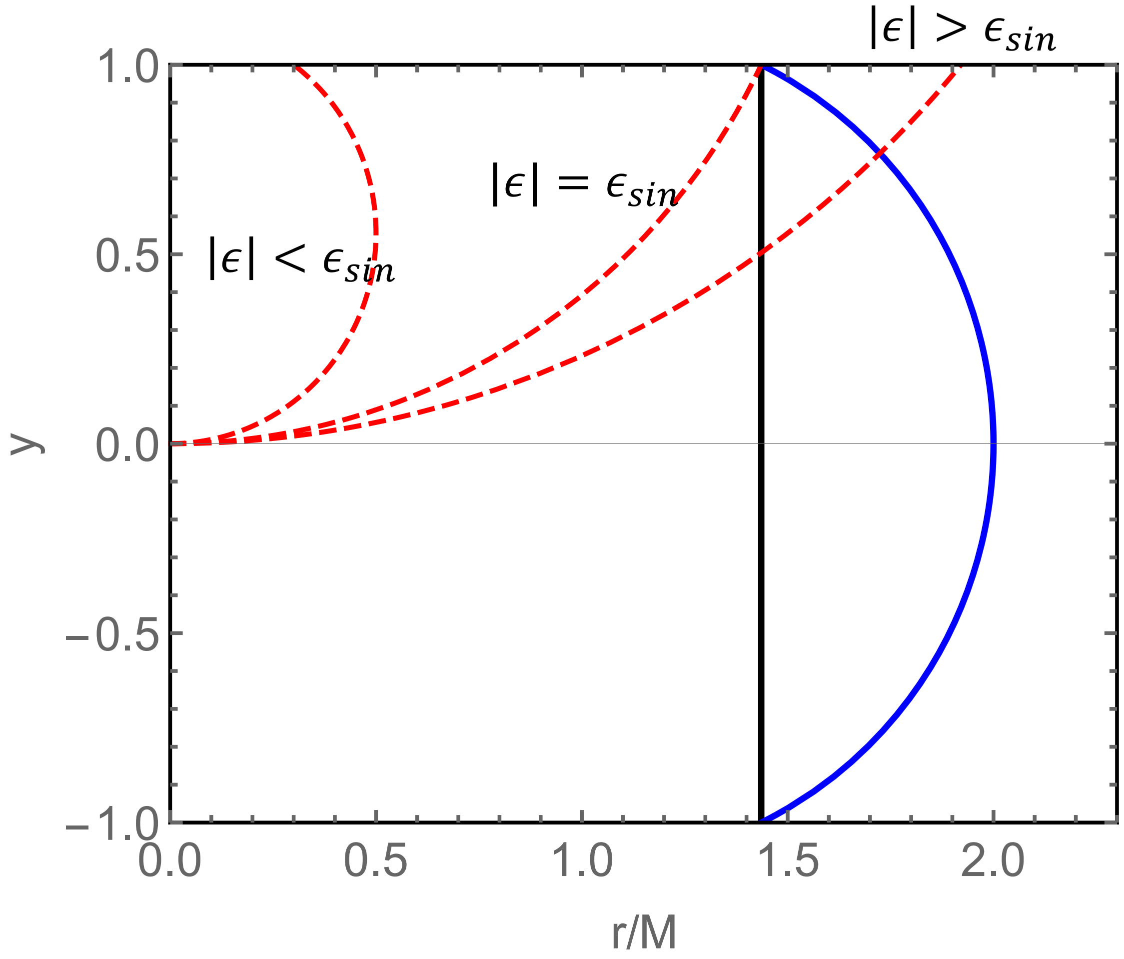
$\tilde{\epsilon}_1(y)=\epsilon_1 M^2 y$ and $\tilde{\epsilon}_5(y)=\epsilon_5 M^2 y$





Chen (2020)

Spacetime structure

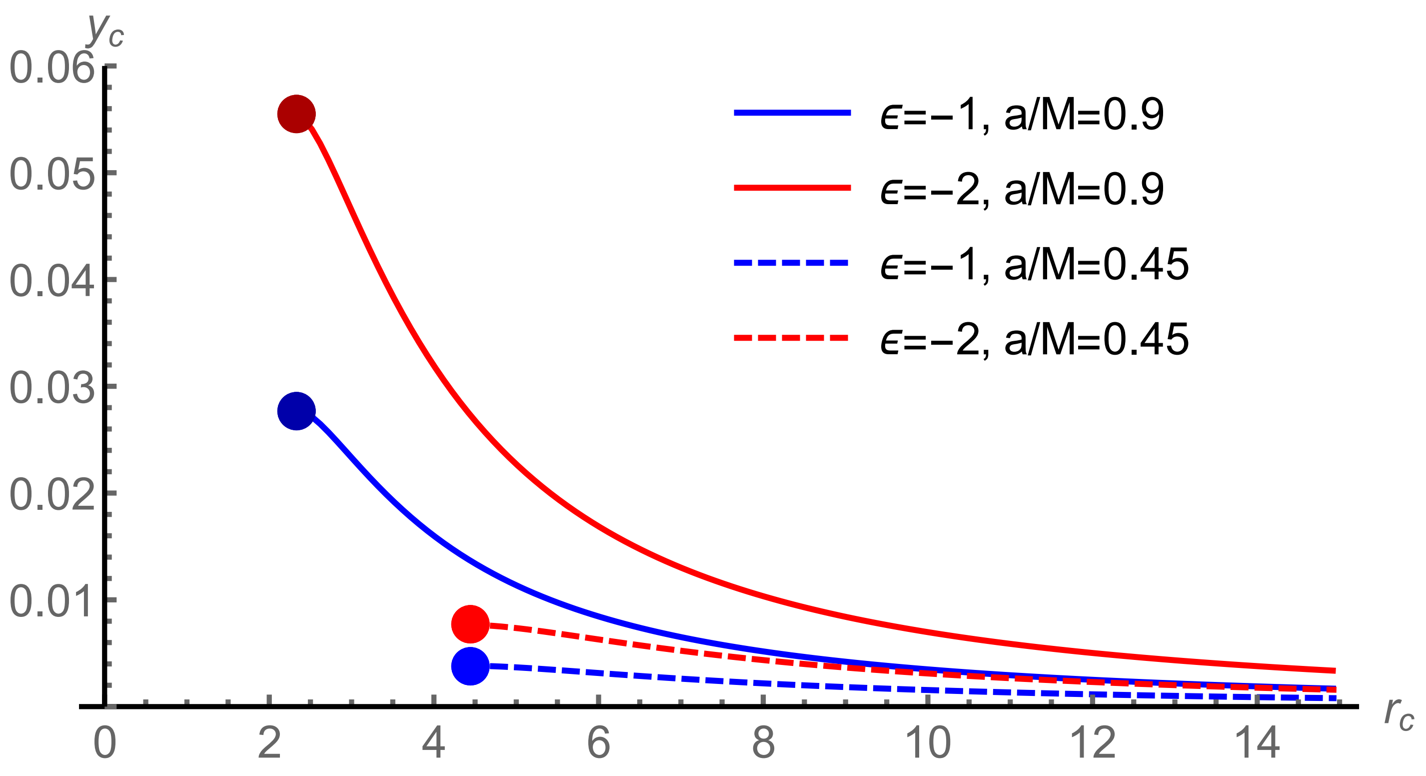


$\tilde{\epsilon}(y) = \epsilon a M y$
$a = 0.9M$

- Singularity: Ricci Scalar $\sim [r^2 + a^2y^2 + \tilde{\epsilon}(y)]^{-3}$

Chen, Yang (2021)

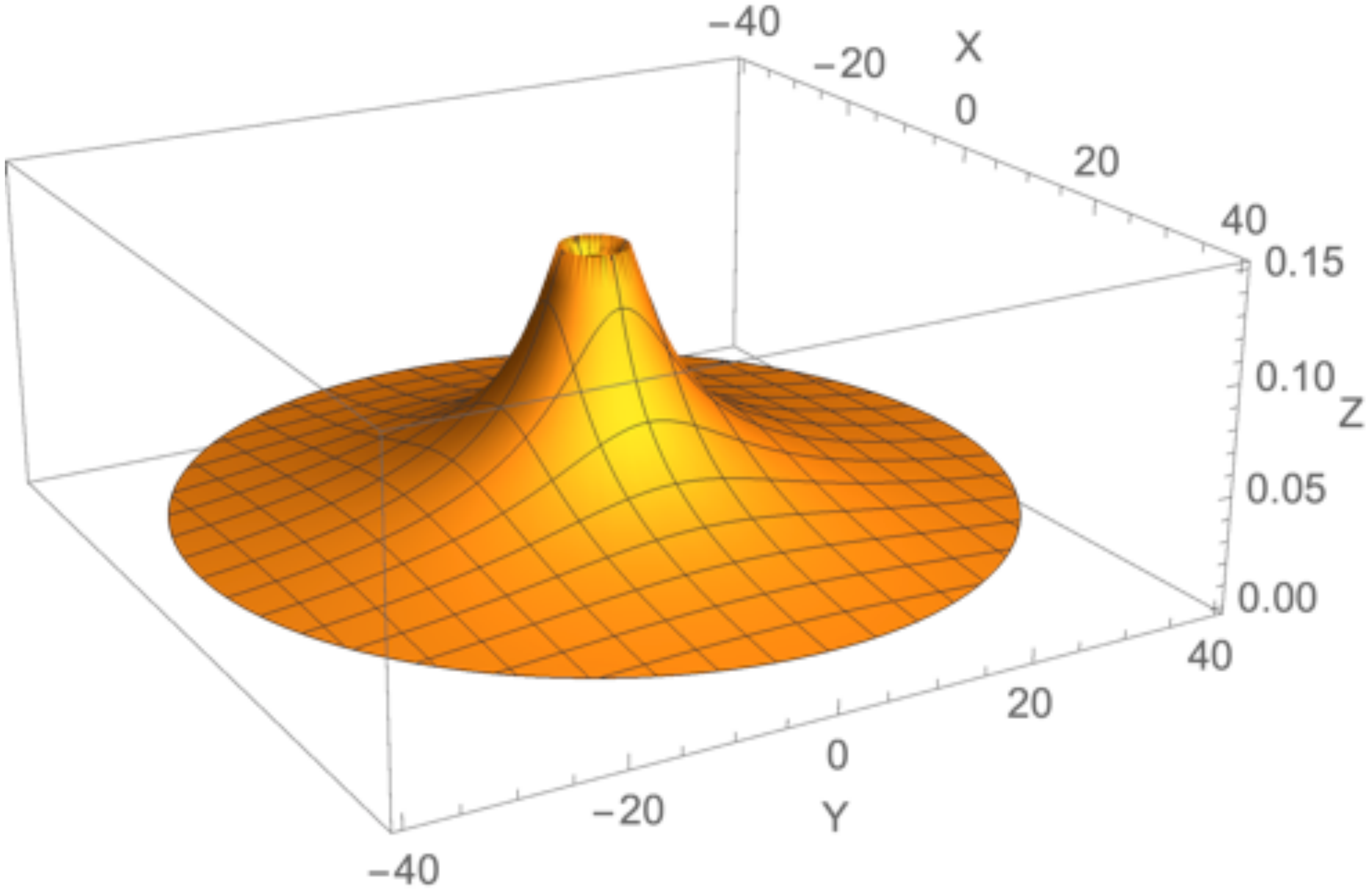
Timelike circular orbits



- Circular orbits exist, but NOT on the standard equatorial plane $y = 0$
- Instead, they have their own $y_c = y_c(r_c)$

Chen, Yang (2021)

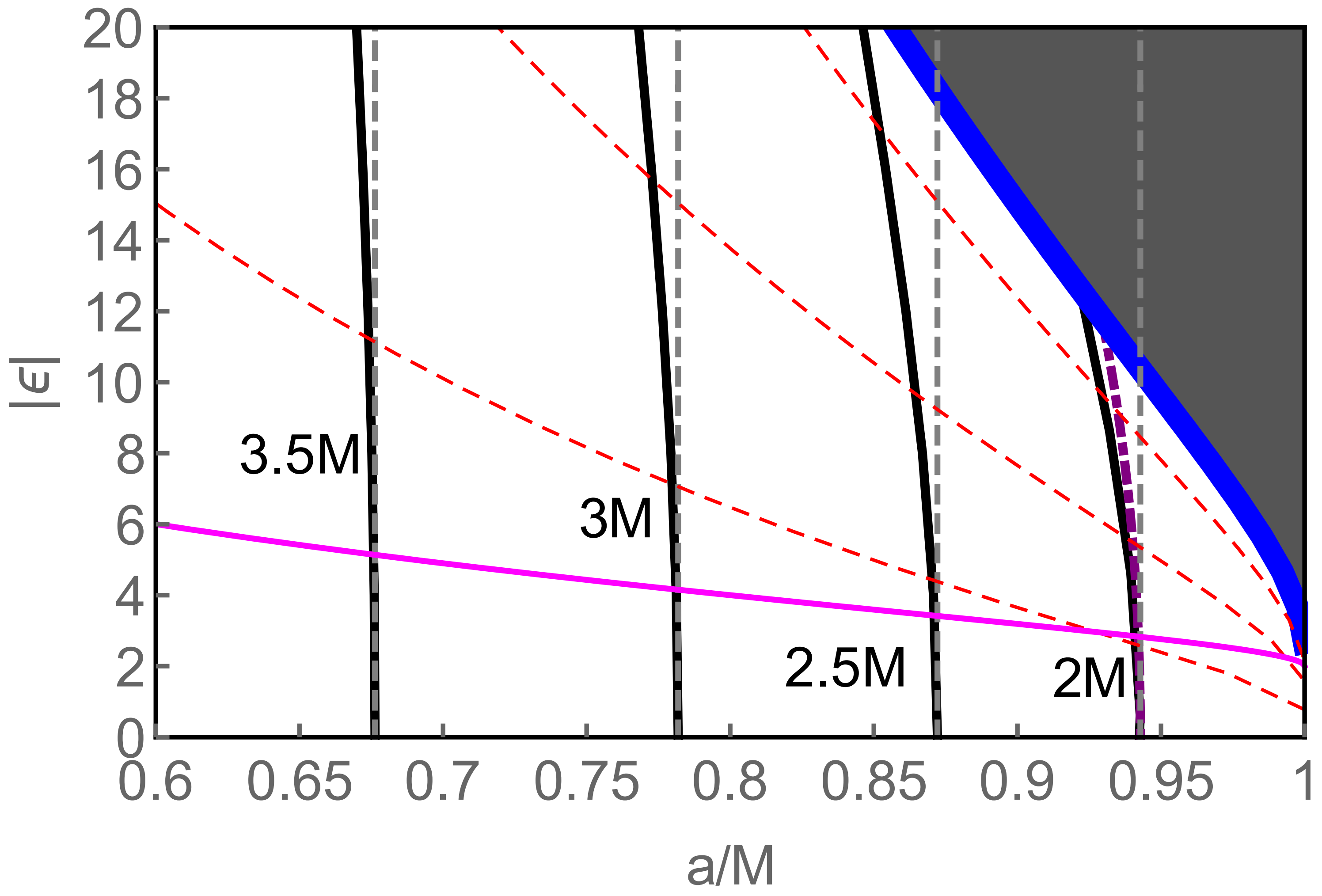
Curved accretion disk



- When $r_c \to \infty$, the orbits approach $y_c \to 0$ (asymptotic flatness)

Chen, Yang (2021)

What happen to ISCO?

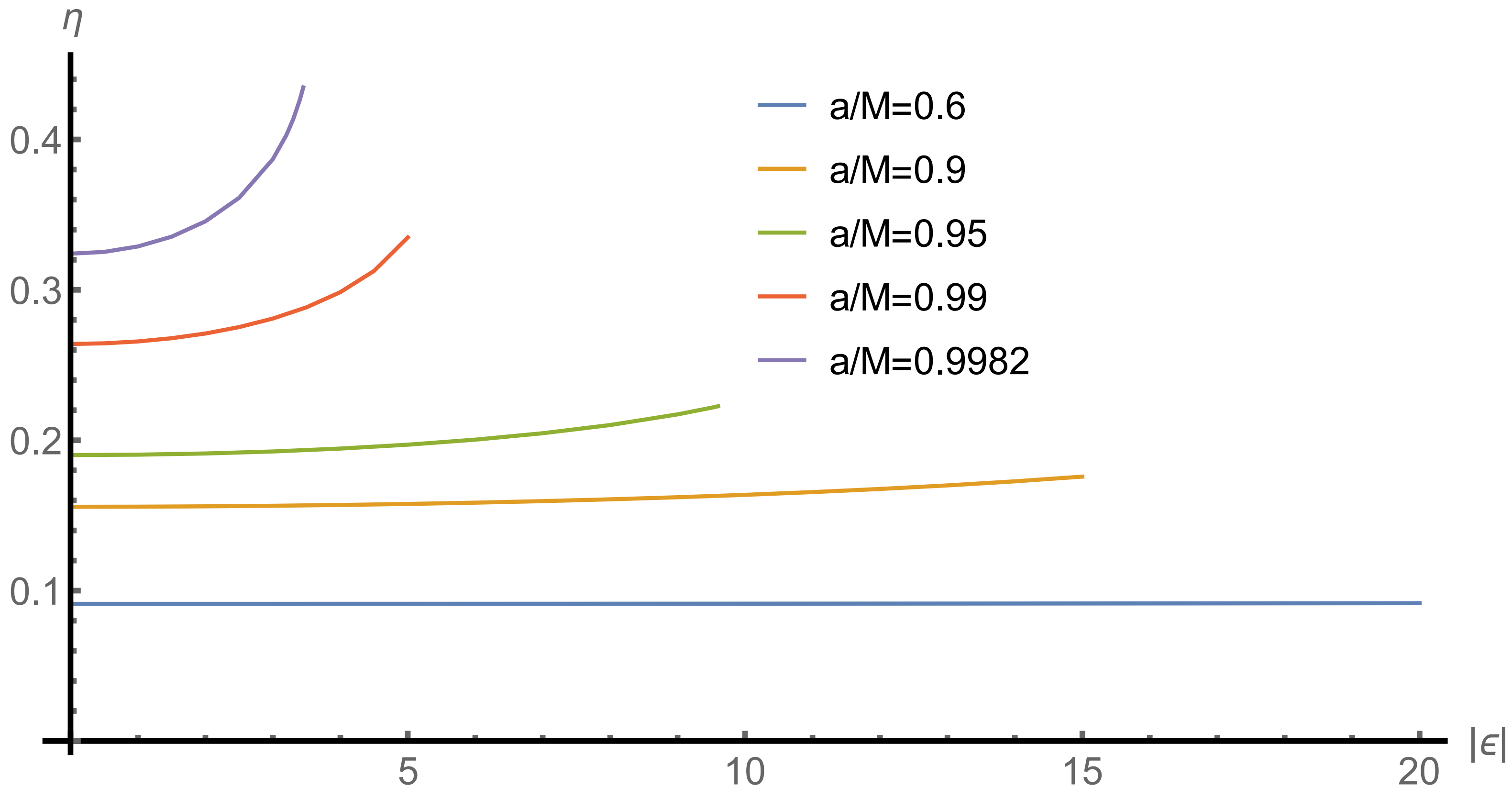


- Black: constant ISCO
- Red: constant y_c on ISCO
- Magenta: critical ϵ_{sin}
- Purple: ISCO = ergosurface
- Blue: ISCO = naked singularity

- <u>Prograde ISCOs are shrunk by ϵ</u>
  - A generic feature that is independent of the choice of $\tilde{\epsilon}(y)$ when deviations from Kerr are small

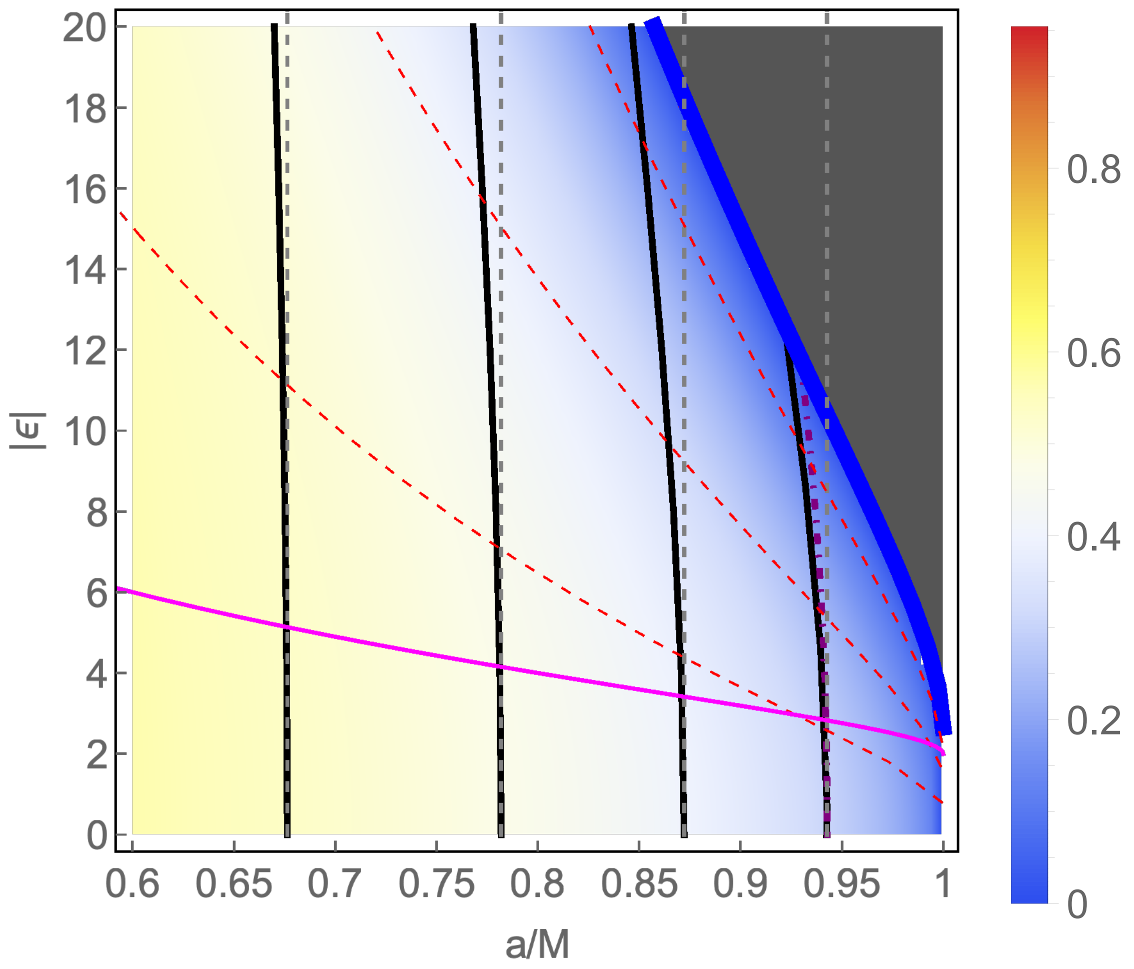
Radiative process is enhanced

- The radiative efficiency: $\eta = 1 - E_{ISCO}$



Gravitational redshifts

- Gravitational Redshift g-factor: $g = \frac{1}{1+z} = \frac{E_o}{E_e} = \frac{1}{\dot{t}(1-\lambda_o\Omega)}$



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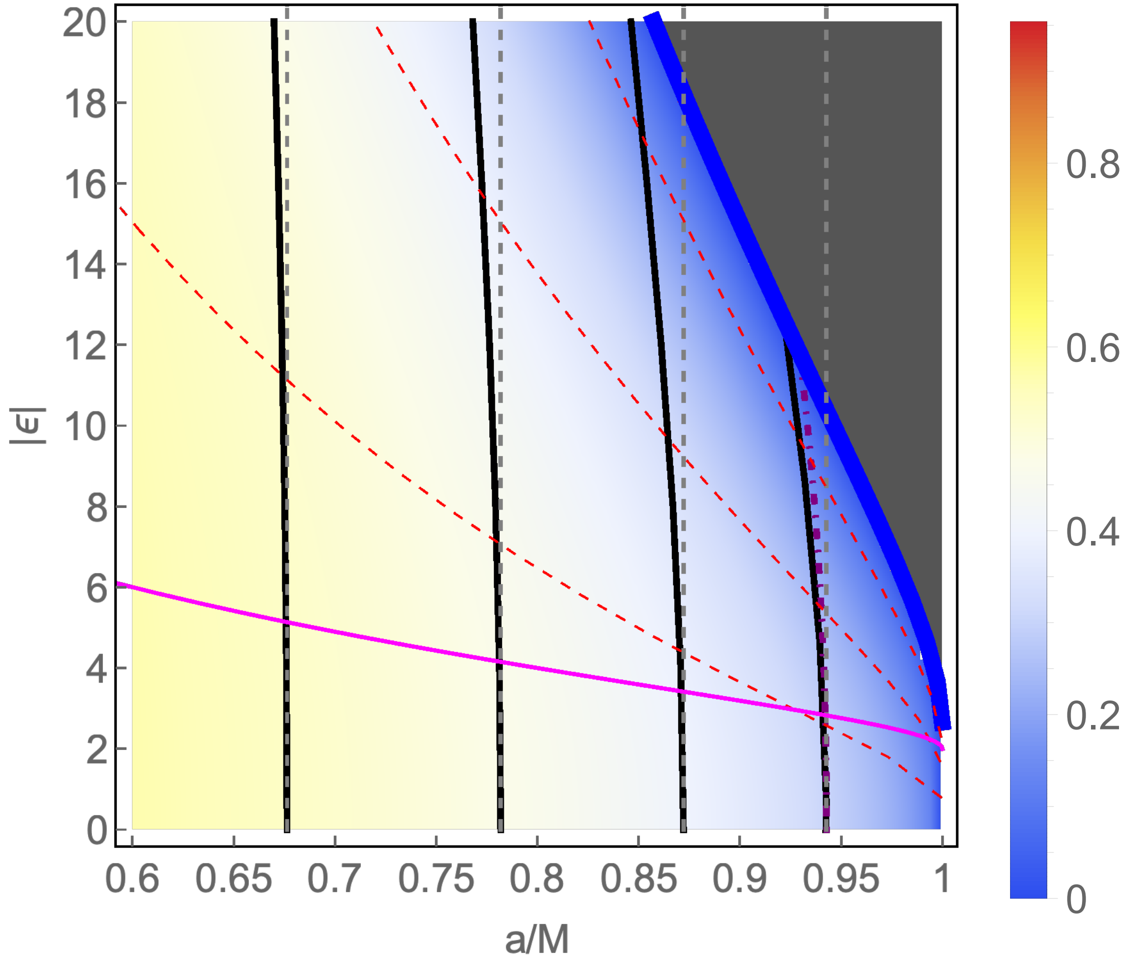
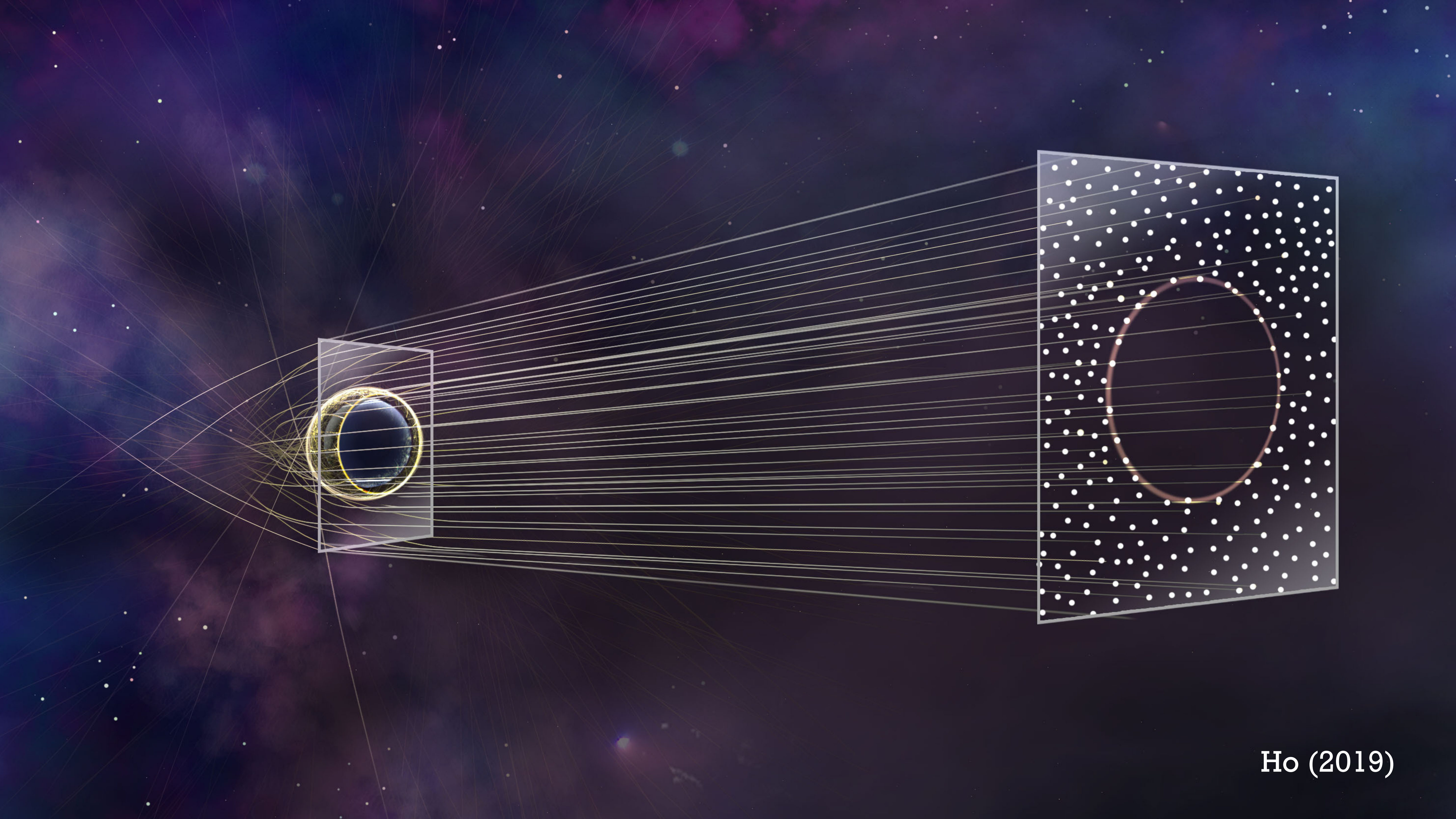
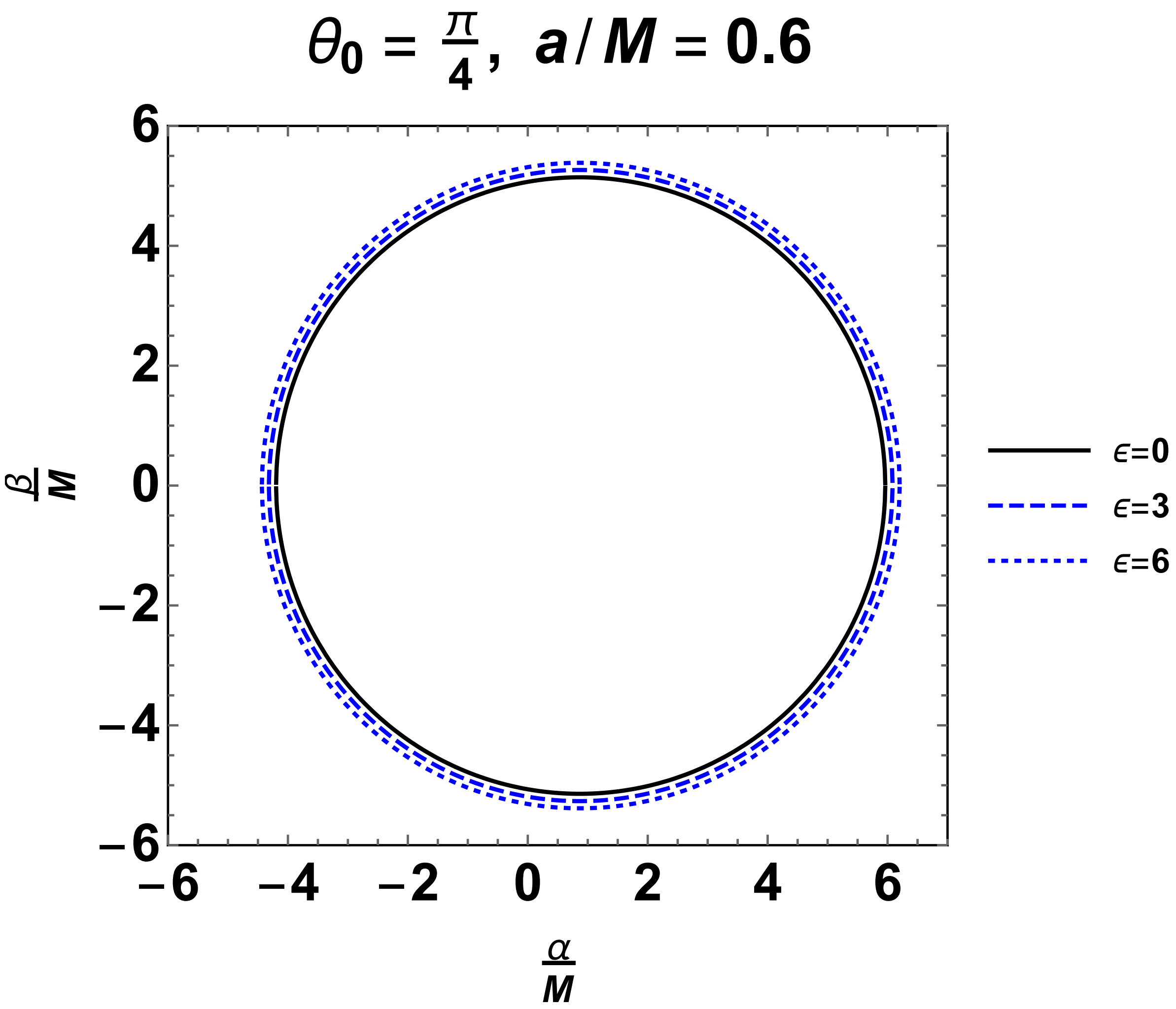


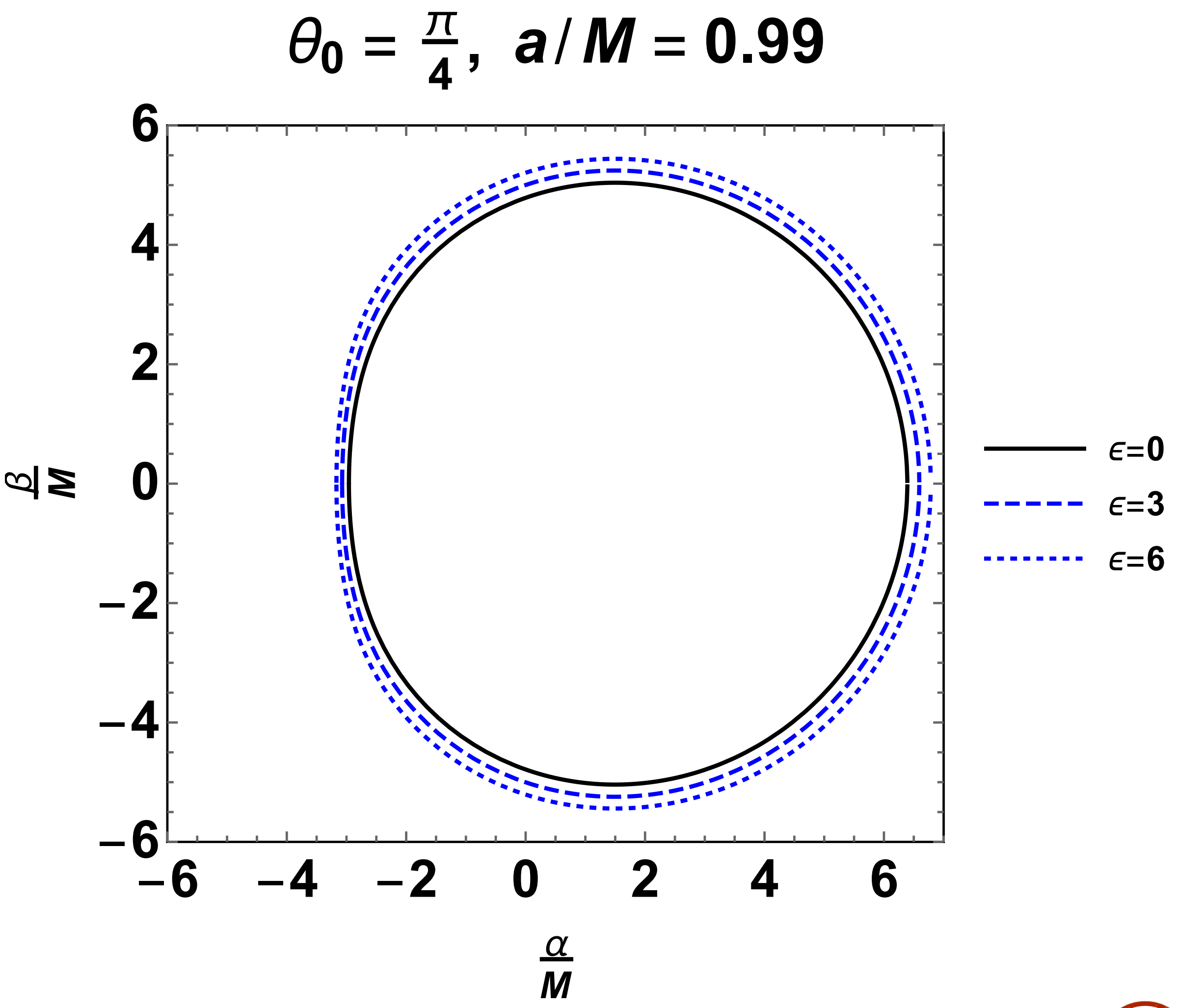
- $g = 0$ on horizon and naked singularity
- Assuming Kerr, all spin measurements based on redshifts would overestimate the true spin of Kerr-like BH
- For example: $g = 0.164$ when
  - $a = 0.99M$ for Kerr BH
  - $a = 0.85M$ and $|\epsilon| = 17.37$ for Kerr-like BH
  - This is $\sim 16.4\%$ difference!



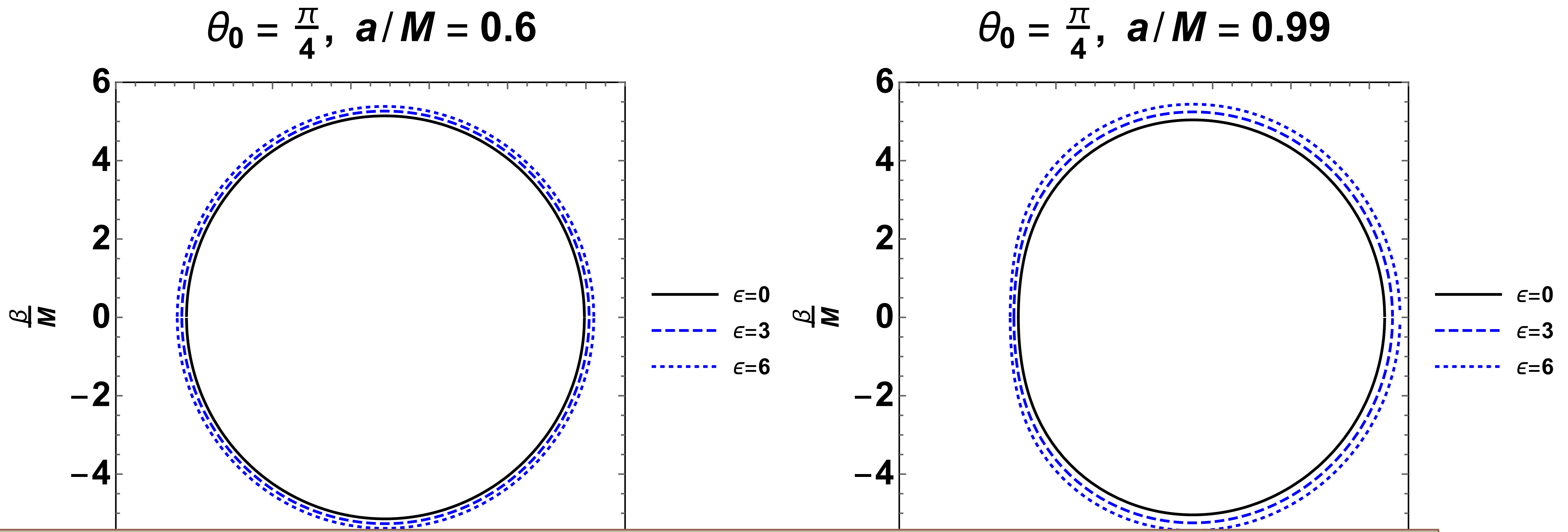
Ho (2019)

Shadow contour





Shadow contour

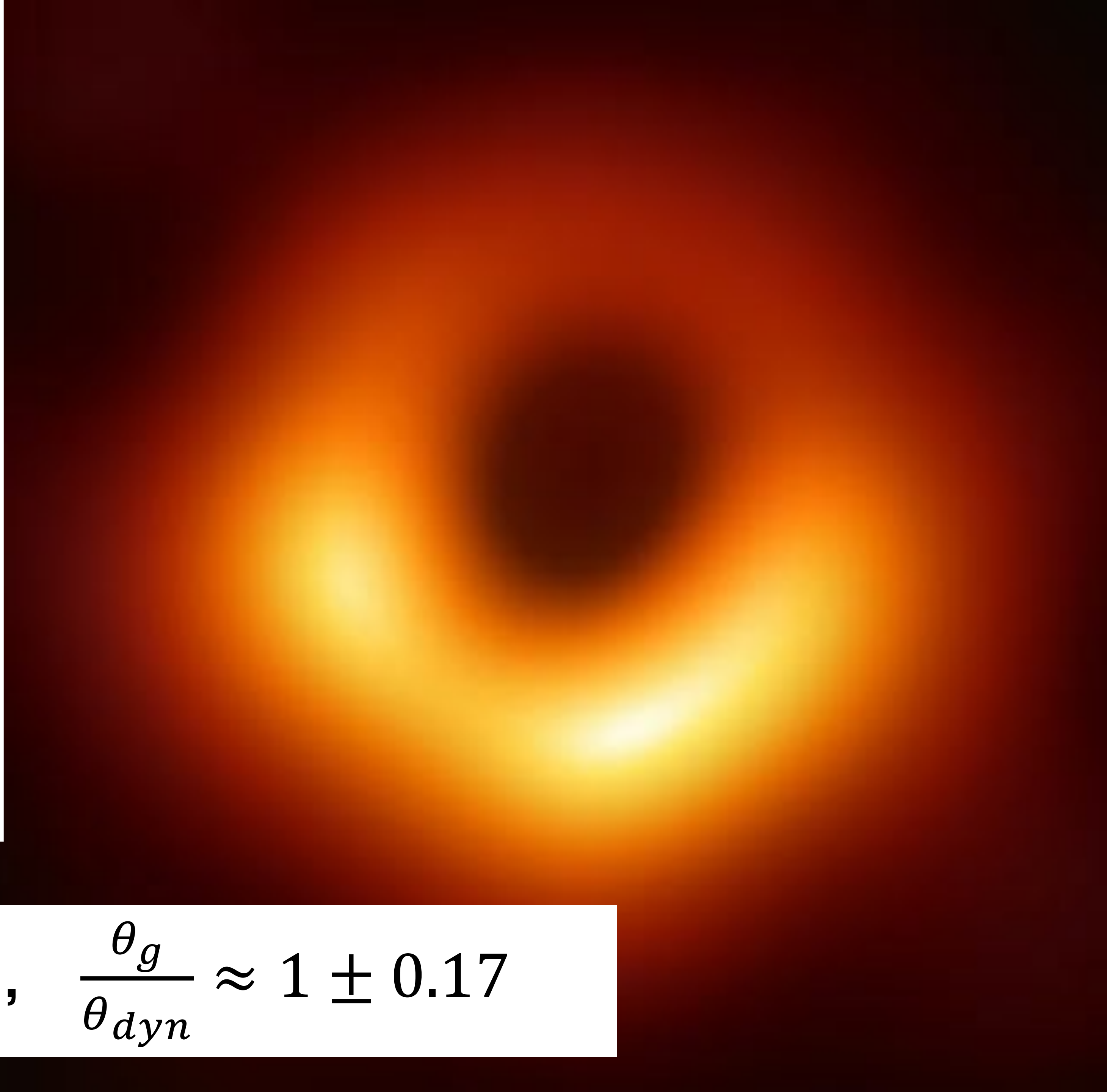


Remark:

- The contour is symmetric w.r.t. the horizontal-axis, no matter what θ_0 is!
- ϵ changes the shadow size, but does not change the shape much

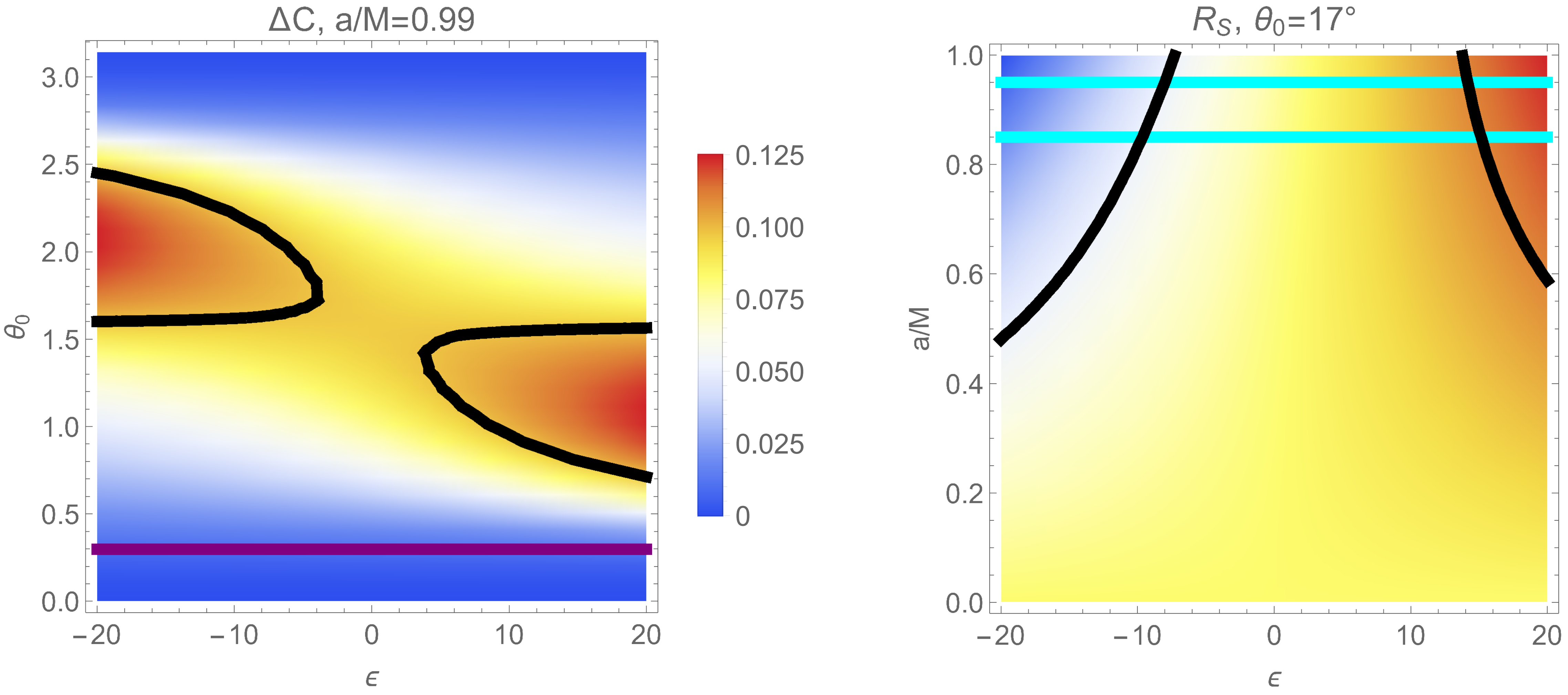
Table 1
Parameters of M87*

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



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

Conclusions

- Kerr-like metric: $\mathbb{Z}_2$ asymmetry
- Astrophysics implications:
  - Curved accretion disk
  - Smaller prograde ISCO radius
- The shadow contours:
  - Symmetric w.r.t the horizontal axis (regardless of the inclination)
  - The deviation parameter is more sensitive to the apparent size
  - Constraints from shadow size (under some astrophysical assumptions)

Future outlooks

- Disk luminosity and temperature
- Spin measurements based on continuum fitting method
  - A reliable "thin" disk model for "curved" accretion disk is necessary
- What will happen when particles enter the plunging phase?
- Realistic ring images: $n = 0, 1, 2 \dots$

Thank you for your attention!

Symmetry w.r.t the horizontal axis

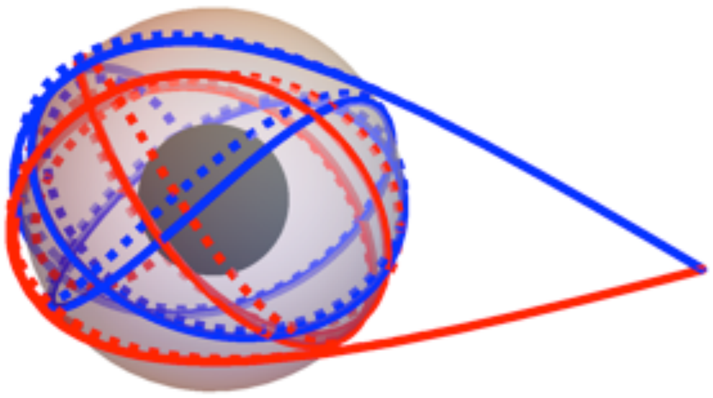
- Mathematically…

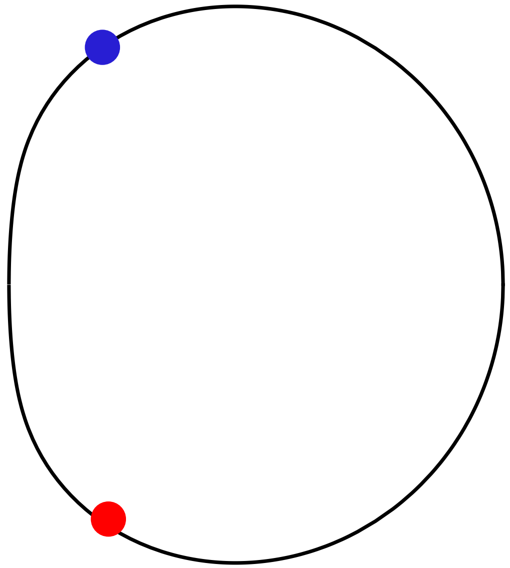
$$(A_1 + B_1)\dot{\theta}/E = \pm\sqrt{\Theta(\theta,\xi,\eta)}, \qquad \beta = \lim_{r_0\to\infty}\left(r_0^2\frac{d\theta}{dr}\right)\Big|_{r_0,\theta_0}$$

  - It is related to the separability of the geodesic equations

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

- Physically…





Chen (2020)