

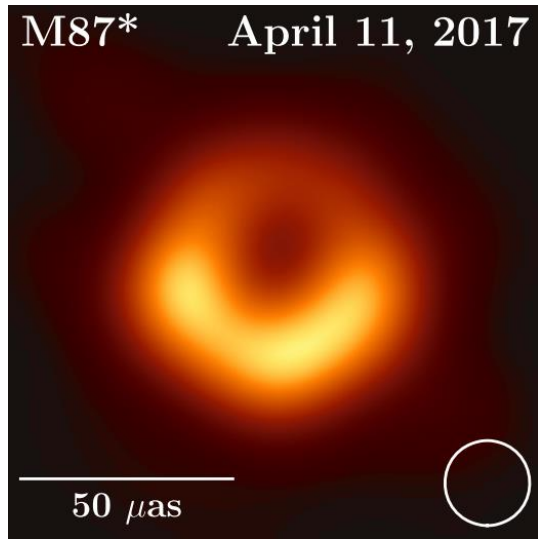
# Observational signatures of rotating black holes in the semiclassical gravity with trace anomaly

张震宇

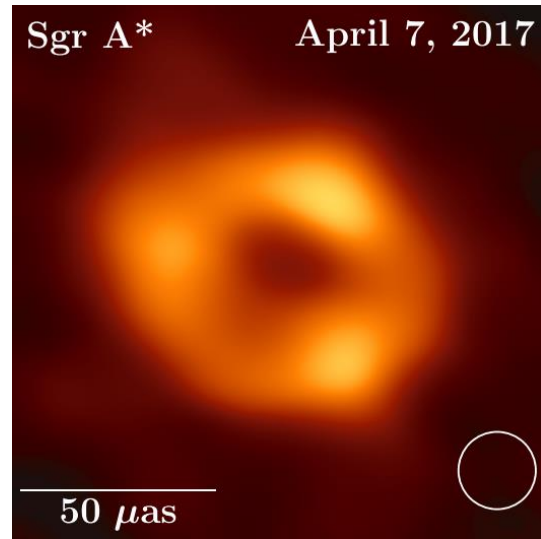
北京大学物理学院

arXiv: 2305.14924

合作者: 侯业辉、郭敏勇



[1]

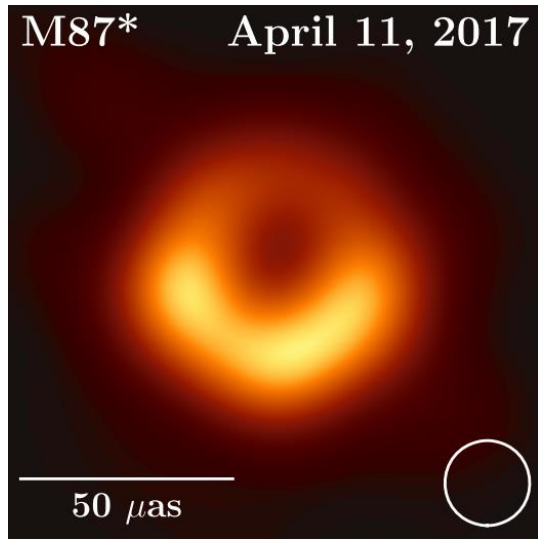


[2]

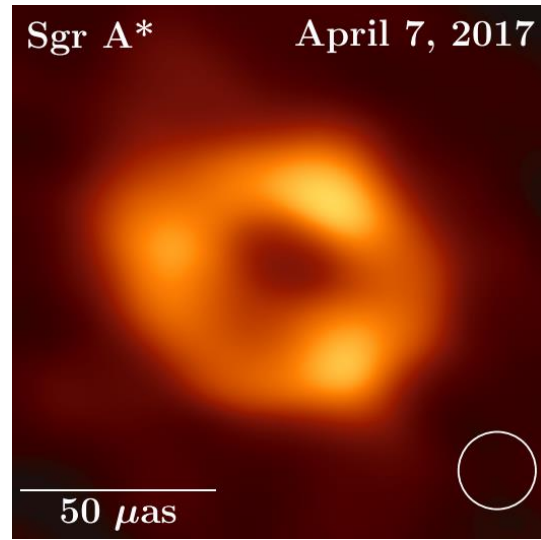
Spacetime information?

[1] The Event Horizon Telescope Collaboration et al. First M87 Event Horizon Telescope Results. *Astrophys.J.Lett.* 875 (2019).

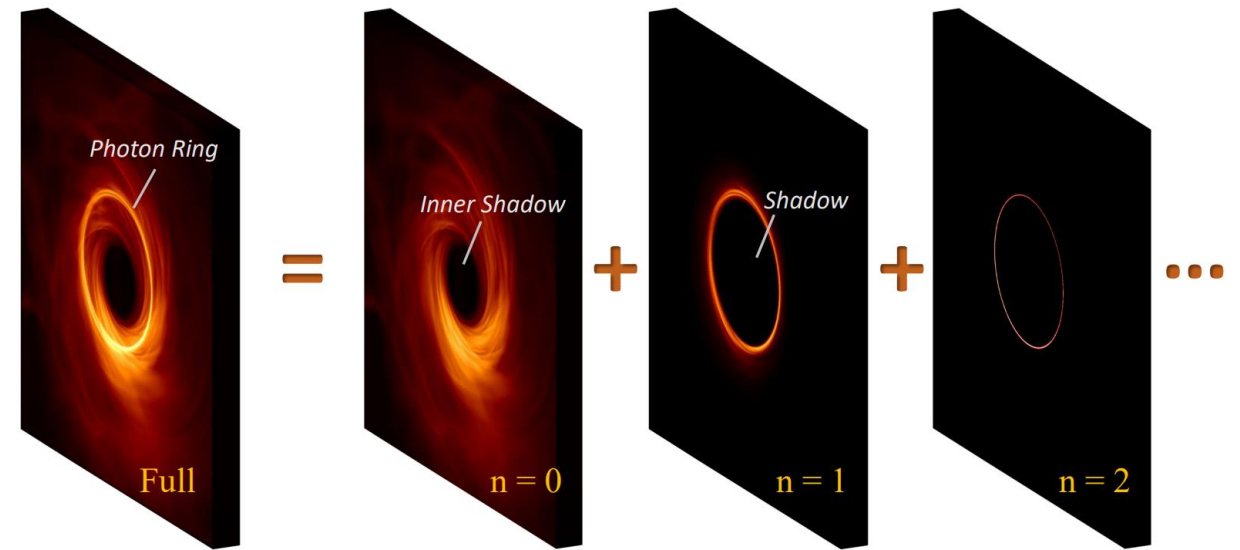
[2] The Event Horizon Telescope Collaboration et al. First Sagittarius A\* Event Horizon Telescope Results. *Astrophys.J.Lett.* 930 (2022).



[1]



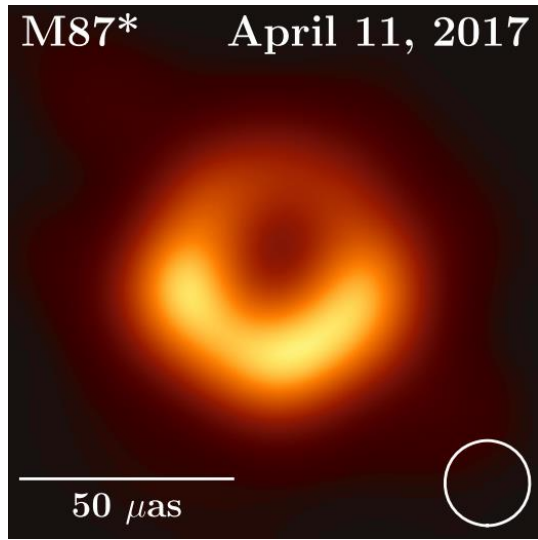
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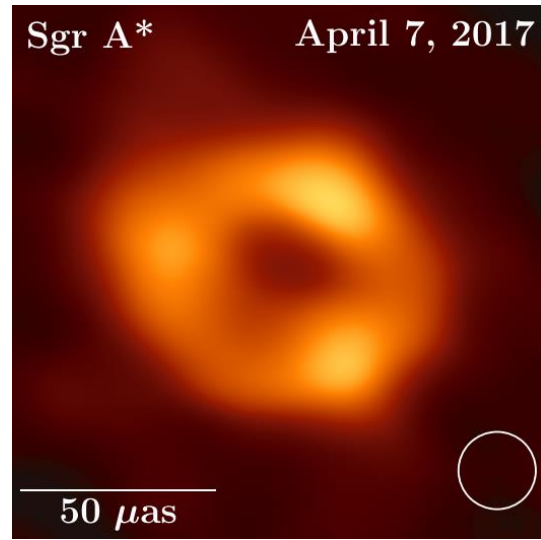
Spacetime information?

Photon ring (well-known) → High-order images

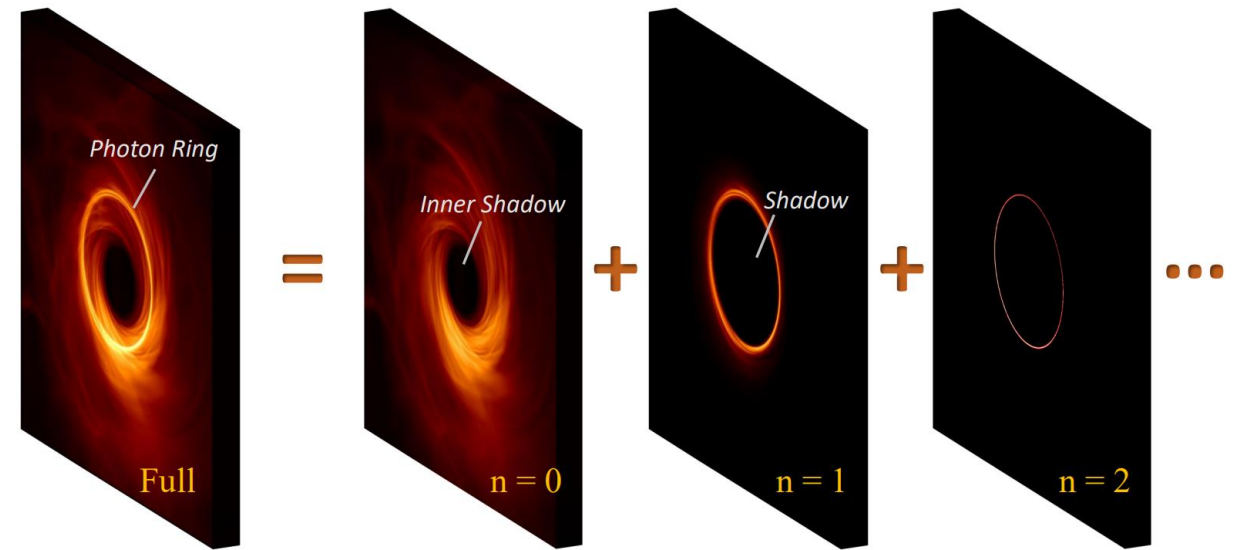
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 [2] The Event Horizon Telescope Collaboration et al. First Sagittarius A\* Event Horizon Telescope Results. *Astrophys.J.Lett.* 930 (2022).  
 [3] M. D. Johnson, K. Akiyama et al. Key Science Goals for the Next-Generation Event Horizon Telescope. *Galaxies* 11 (2023) 61.



[1]



[2]



[3]

Spacetime information?

(in some cases)

Photon ring (well-known)  $\longrightarrow$  High-order images

Near-horizon source  $\longrightarrow$  Every-order images

[1] The Event Horizon Telescope Collaboration et al. First M87 Event Horizon Telescope Results. *Astrophys.J.Lett.* 875 (2019).

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[3] M. D. Johnson, K. Akiyama et al. Key Science Goals for the Next-Generation Event Horizon Telescope. *Galaxies* 11 (2023) 61.

# Contents

- Background
  - Metric
- Light Rings
- Black hole shadows
  - Ray tracing
- Images with a thin disk
  - Disk model
  - Intensity accumulation
- Summary

# Background

- Type A trace anomaly [4, 5]

$$g^{\mu\nu} \langle T_{\mu\nu} \rangle = \frac{\alpha}{2} (R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma})$$

- Semiclassical gravity

$$R^{\mu\nu} - \frac{1}{2}g^{\mu\nu}R = 8\pi G \langle T_{\mu\nu} \rangle$$

- Black hole solution [6]

$$M = \frac{2m_0}{1 + \sqrt{1 - \frac{8\alpha r \xi m_0}{\Sigma^3}}}$$

$$\begin{aligned}\Sigma &= r^2 + a^2 \cos^2 \theta \\ \xi &= r^2 - 3a^2 \cos^2 \theta\end{aligned}$$

[4] S. Deser and A. Schwimmer, Geometric classification of conformal anomalies in arbitrary dimensions, Phys. Lett. B 309 (1993) 279–284.

[5] D. M. Capper and M. J. Duff, Trace anomalies in dimensional regularization, Nuovo Cim. A 23 (1974) 173–183.

[6] P. G. S. Fernandes, Rotating black holes in semiclassical gravity, Phys. Rev. D 108 no. 6, (2023) L061502.

# Light rings

- Effective potential

$$V_{eff}(r) \equiv \left(\frac{dr}{d\lambda}\right)^2 = E^2 - \mu^2 + \frac{2M\mu^2}{r} + \frac{a^2(E^2 - \mu^2) - L^2}{r^2} + \frac{2M(L - aE)^2}{r^3}$$

- For photons

$$V_{eff}(r) = 1 + \frac{a^2 - l^2}{r^2} + \frac{2M(l - a)^2}{r^3}$$

- Light ring conditions

$$V_{eff} = 0, \quad \partial_r V_{eff} = 0$$

- LRs are unstable

$$\partial_r^2 V_{eff} > 0$$

# Light Rings

- Results

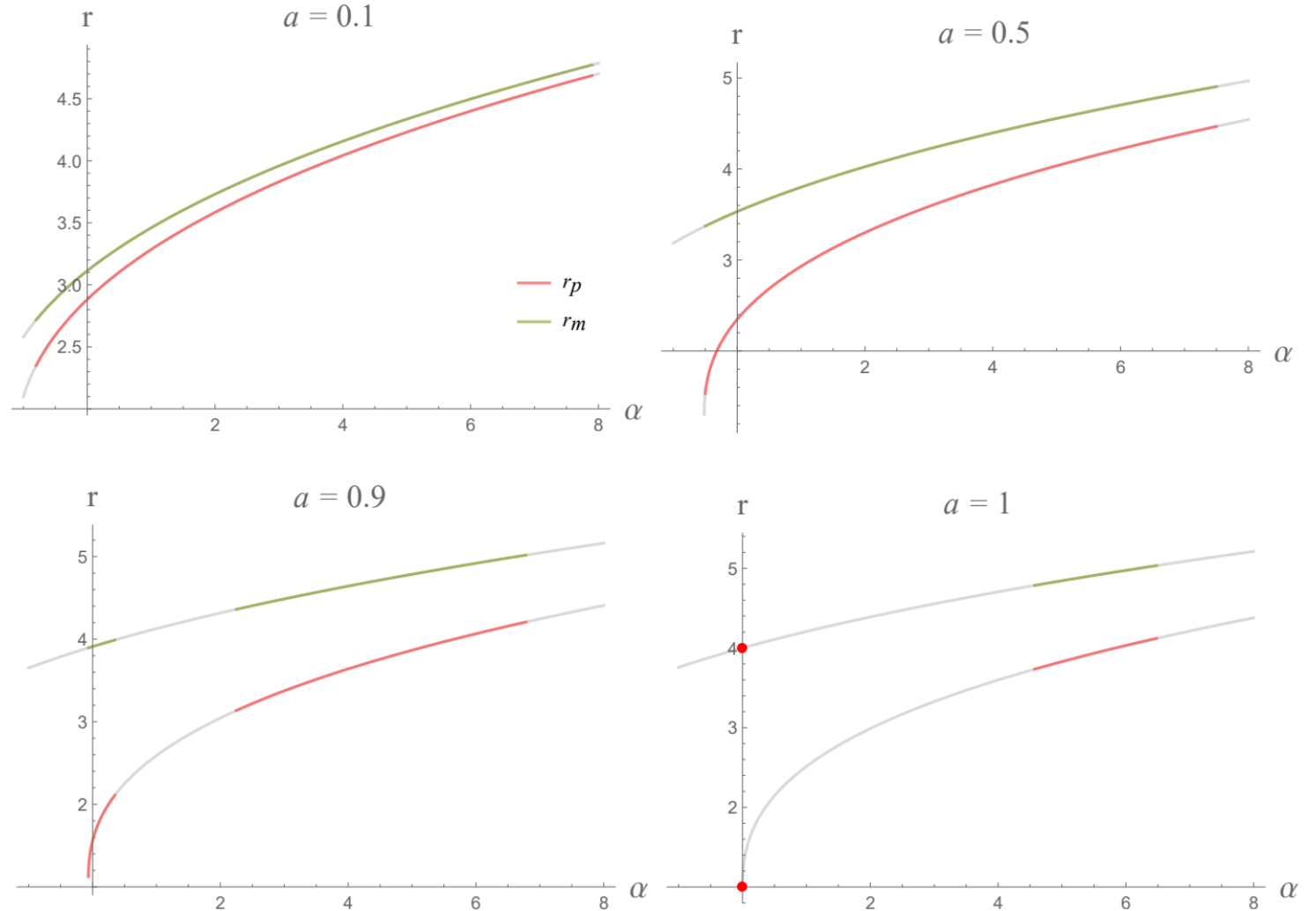
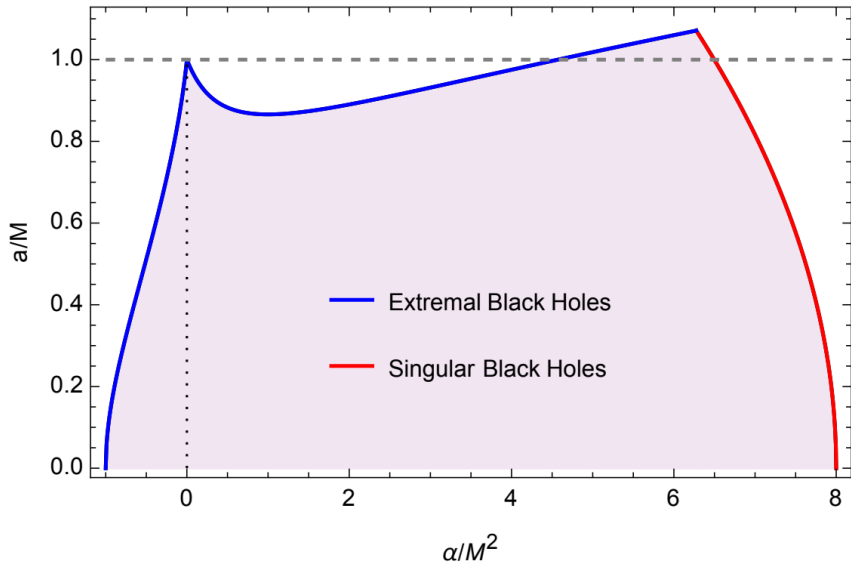


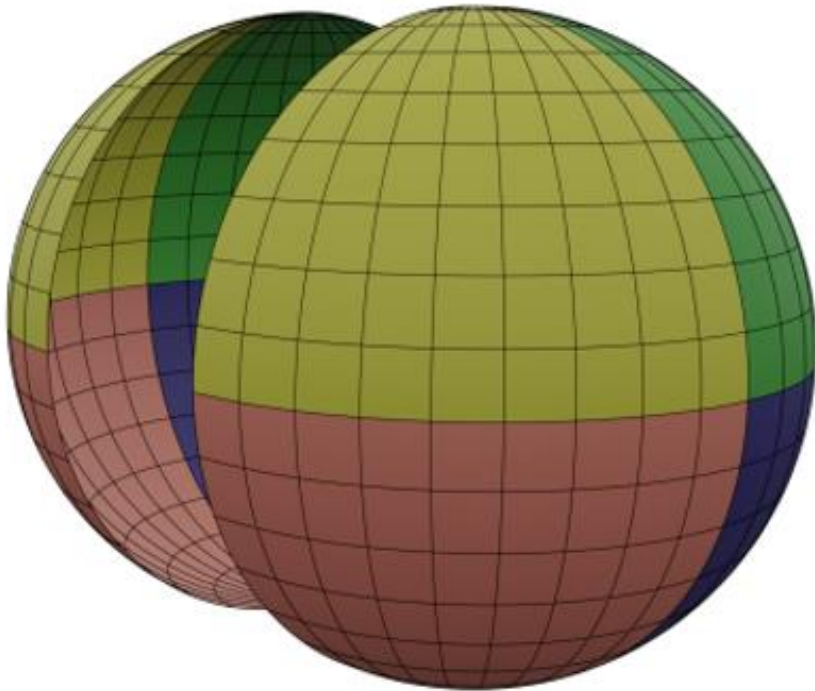
Figure 2: LRs as functions of  $\alpha$ , under different spin parameters. The red and orange colors denote the prograde orbit and retrograde orbit, respectively.

[6]

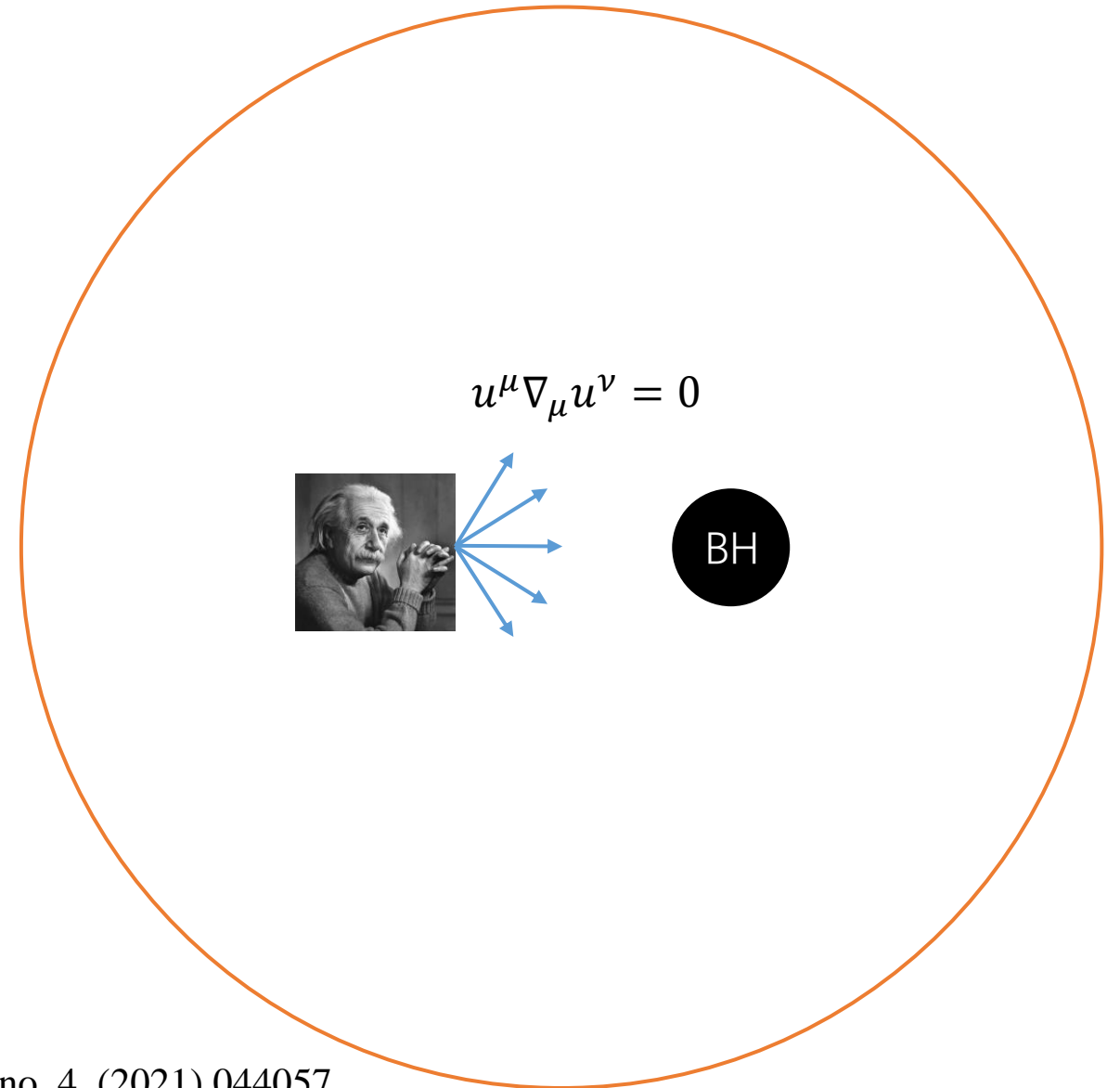


# Black hole shadows

- Celestial light source & ray tracing

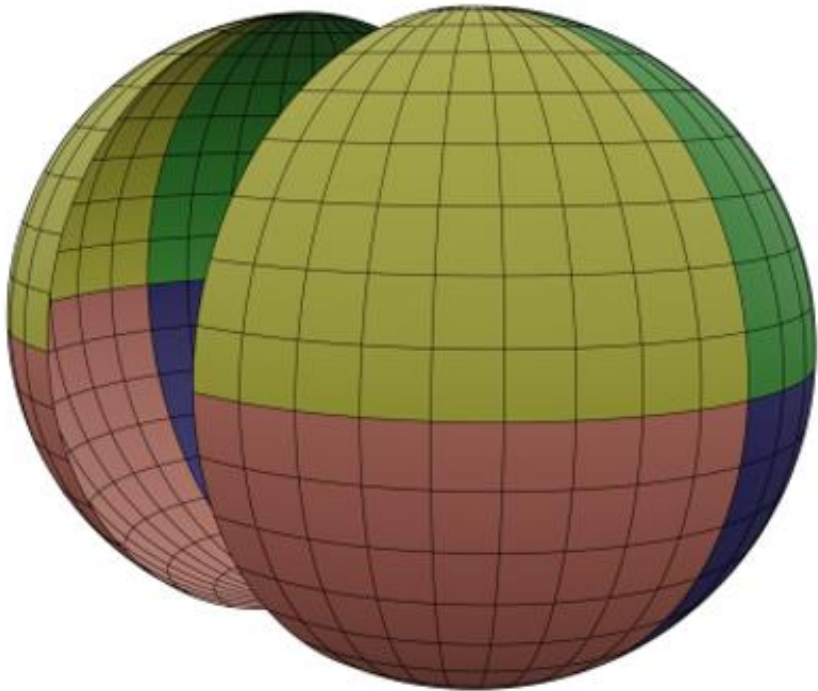


[7]

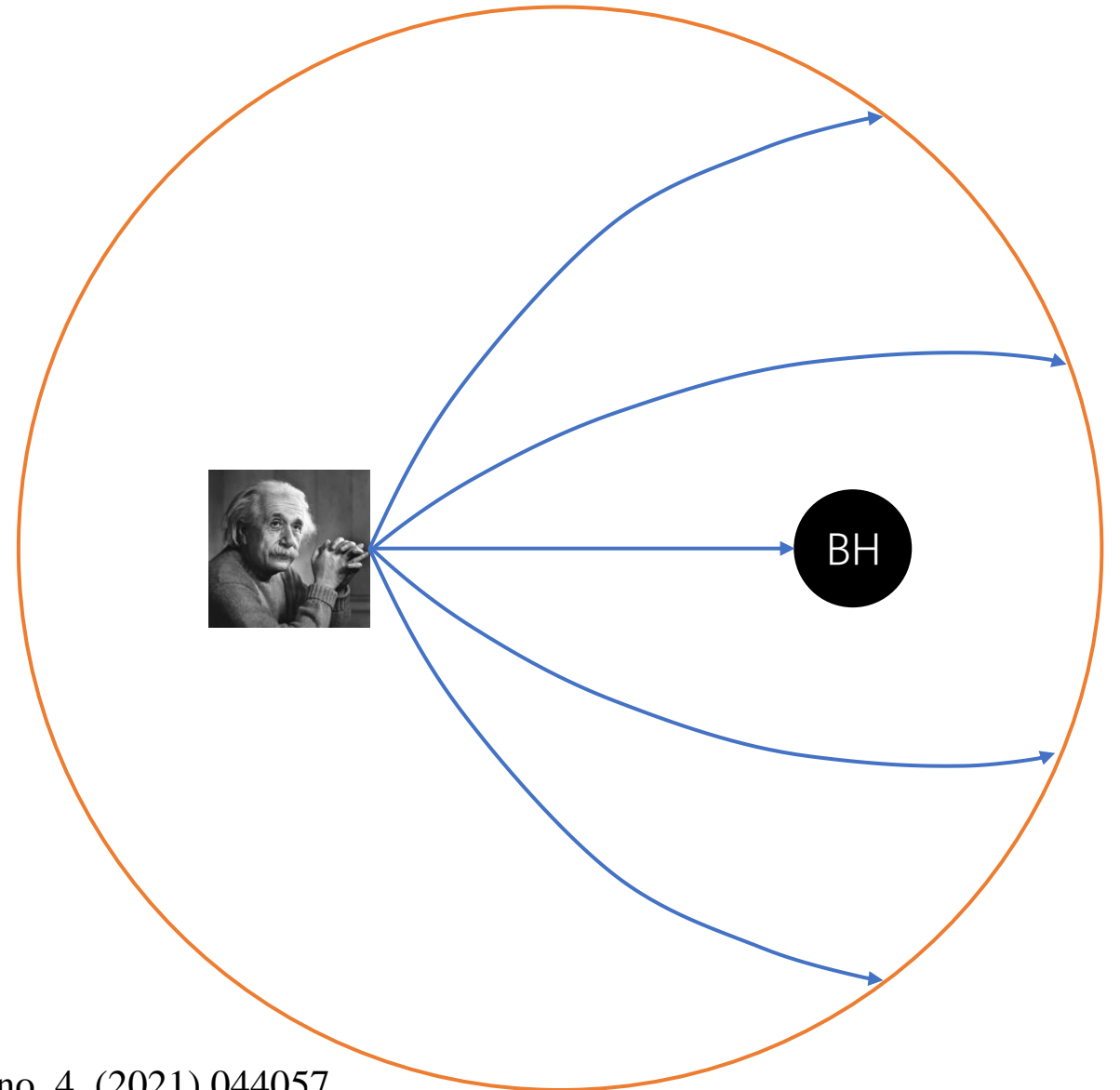


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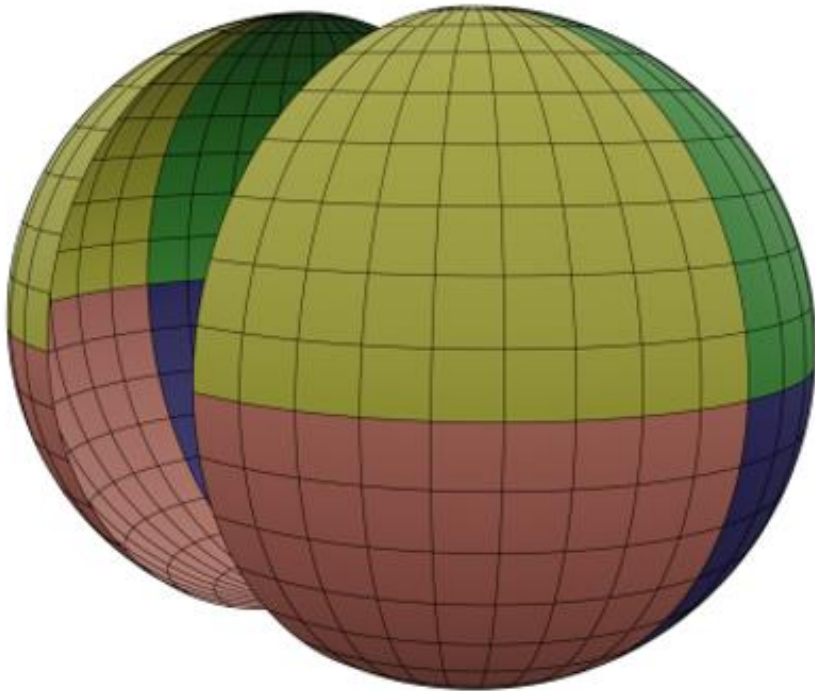


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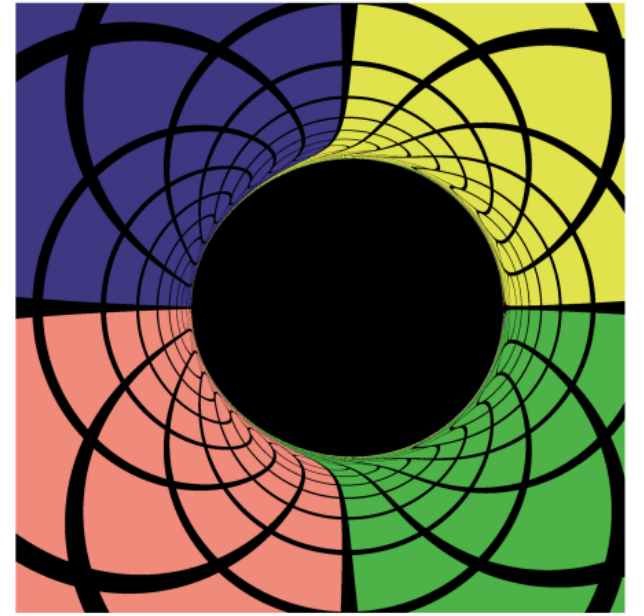
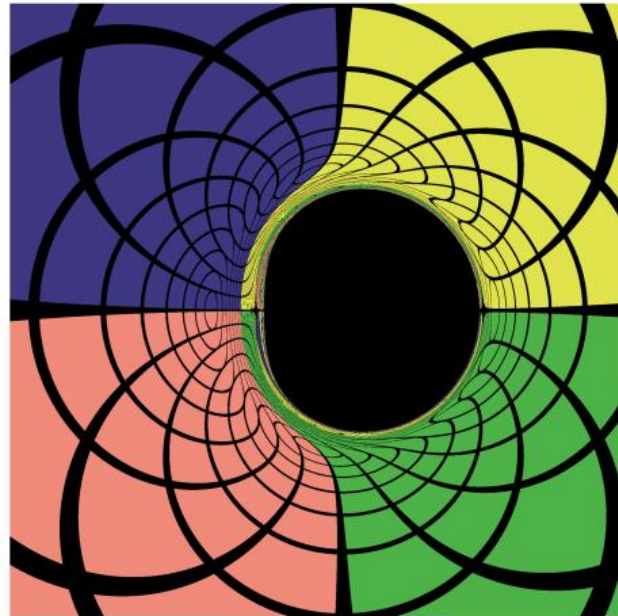


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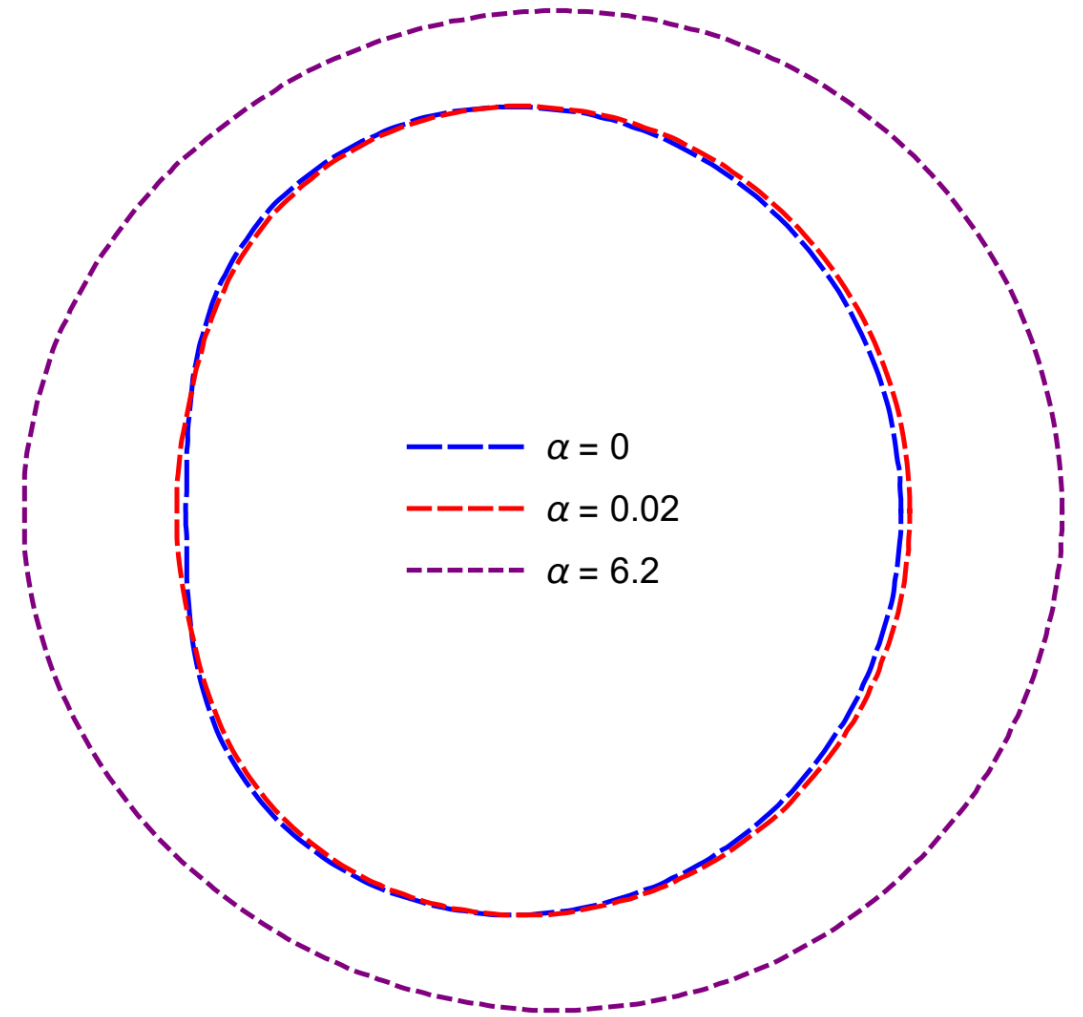


[7]



# Black hole shadows

- Main results
  - For high-spin case, NHEK line [8] disappear



$$a = 0.99, \theta_o = 90^\circ$$

[8] S. E. Gralla, A. Lupsasca, and A. Strominger, Observational Signature of High Spin at the Event Horizon Telescope, Mon. Not. Roy. Astron. Soc. 475 no. 3, (2018) 3829–3853.

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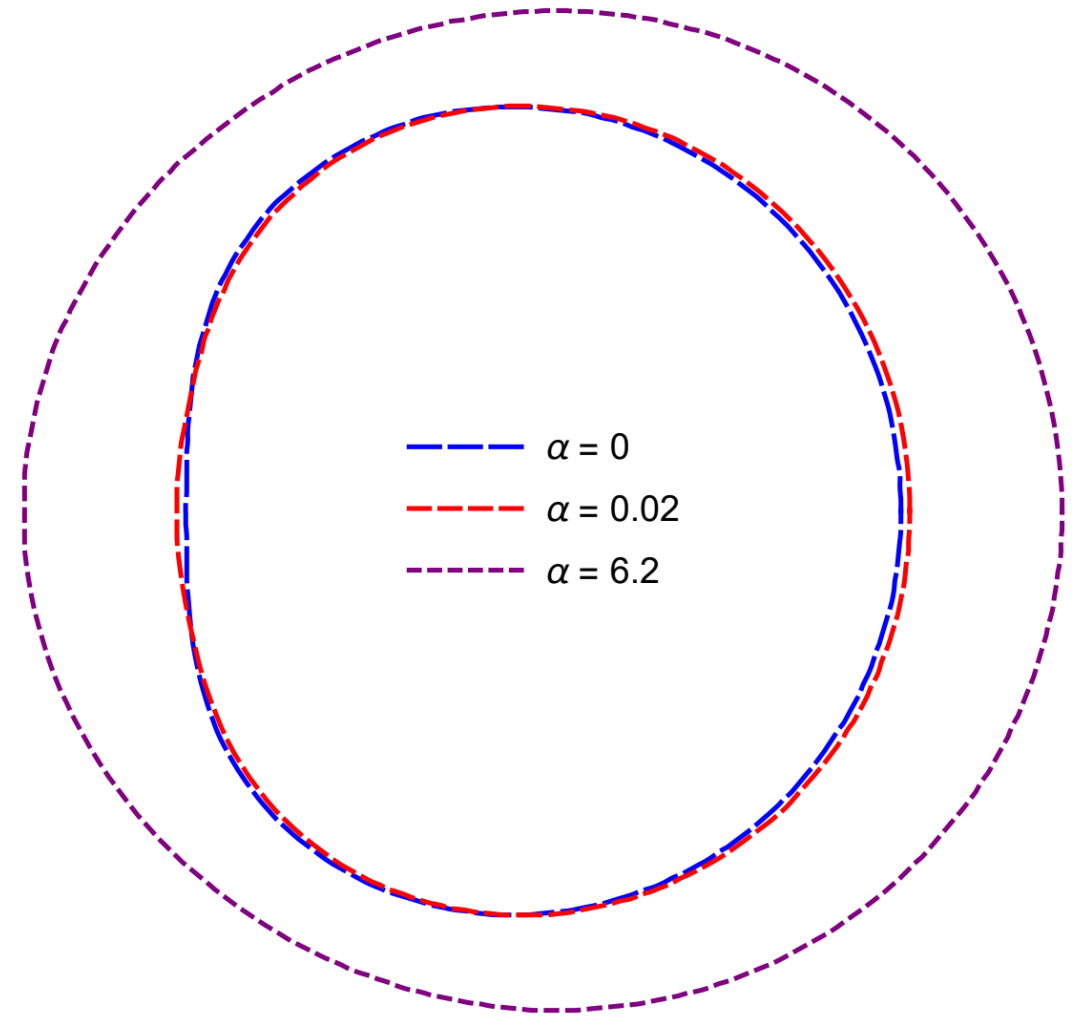
- For high-spin case, NHEK line disappear

NHEK line [8] :

An edge-on observer can observe a vertical line segment within the left contour of the shadow.

↑  
Near-Horizon-Extreme-Kerr geometry

↑  
Global degeneracy of the horizons ( $r_+ = r_-$ ) [9]



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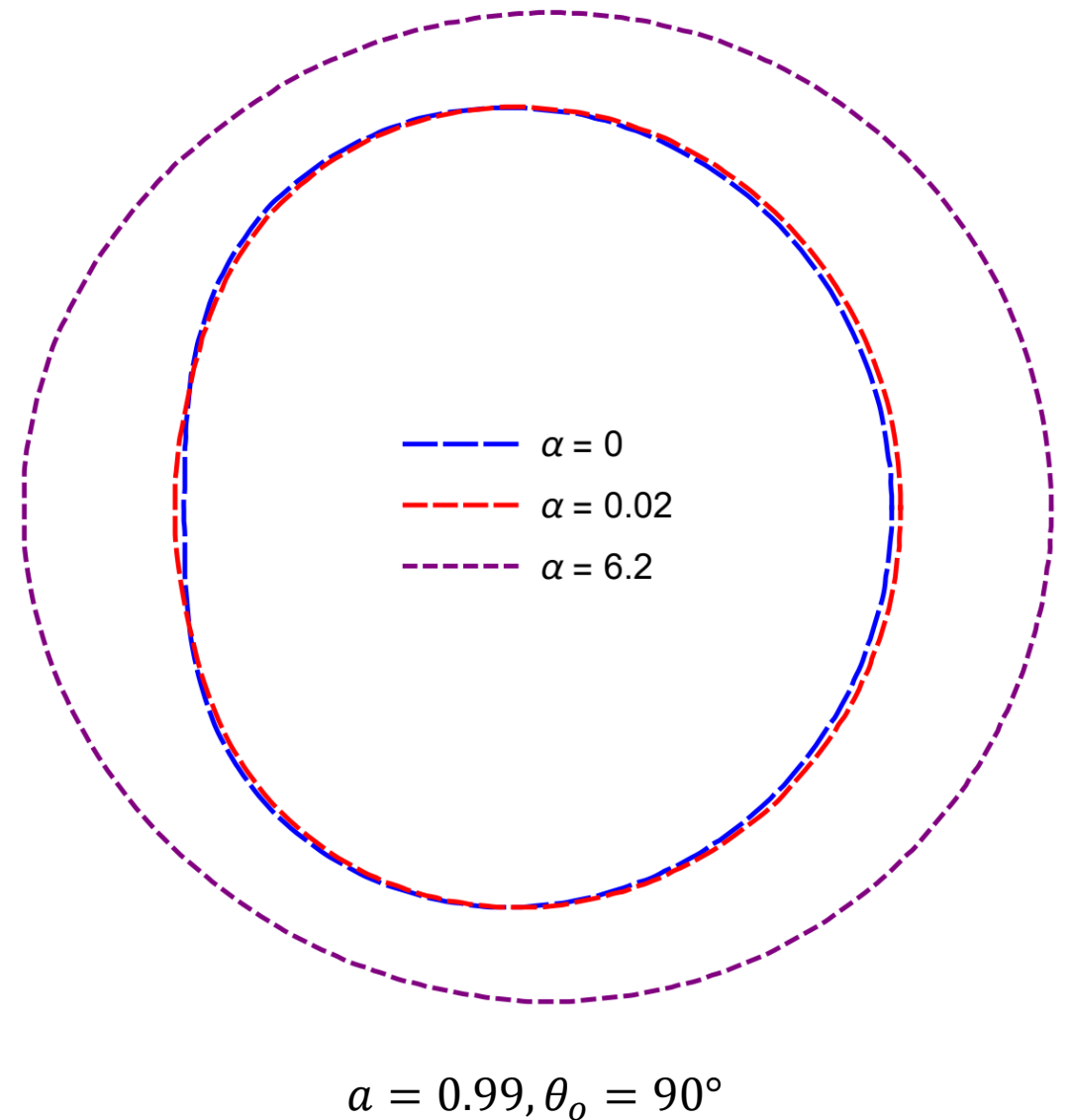
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Quantum correction (parameter  $\alpha$ )



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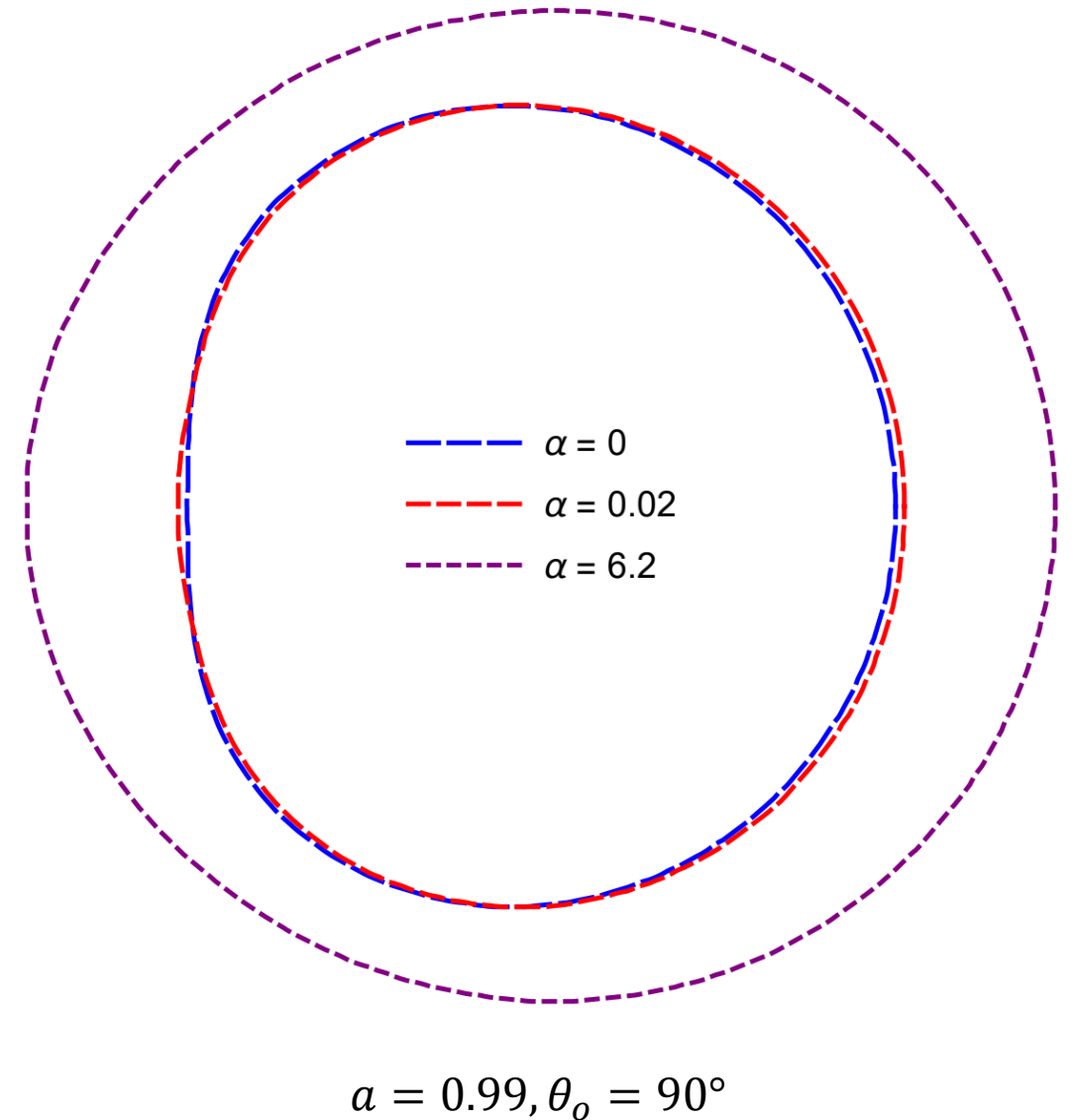
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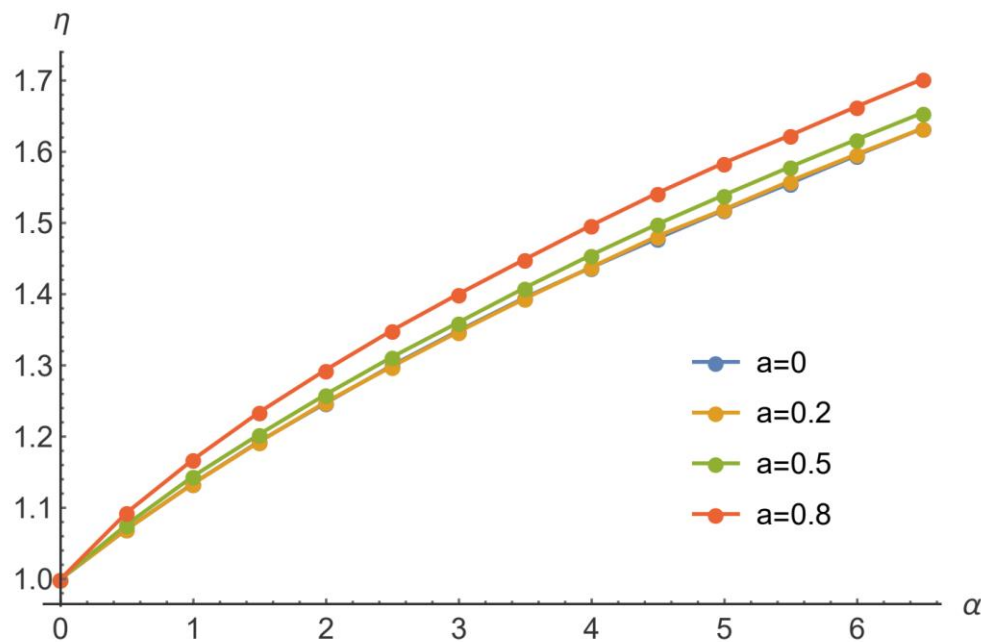
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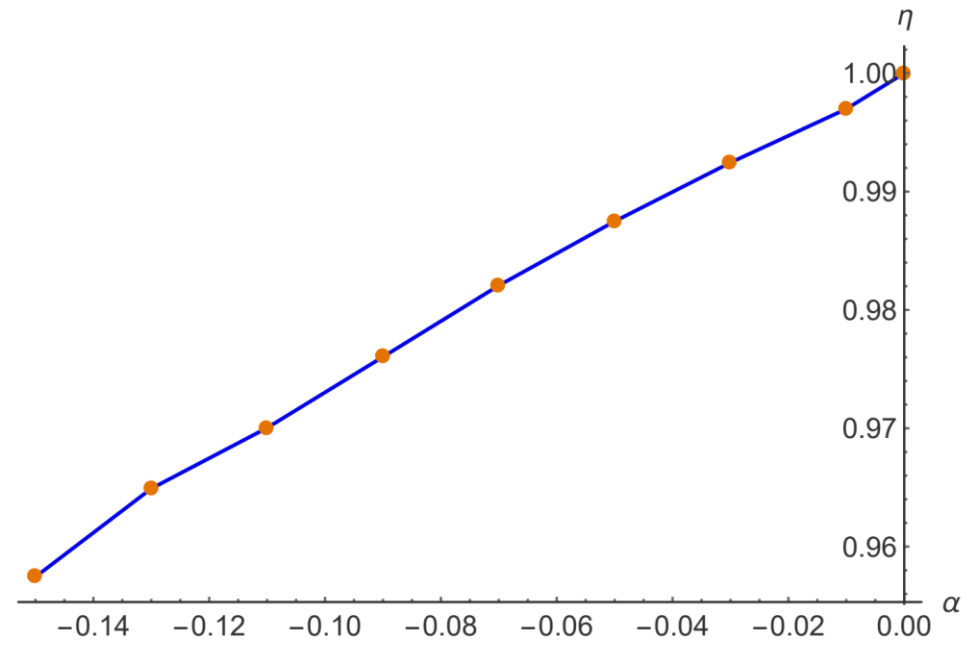
- For high-spin case, NHEK line disappear

- Area ratio  $\eta \equiv S_{BH}/S_{Kerr}$

- Monotonically increasing function of quantum-corrected parameter  $\alpha$



$\alpha \geq 0, \theta_o = 90^\circ$

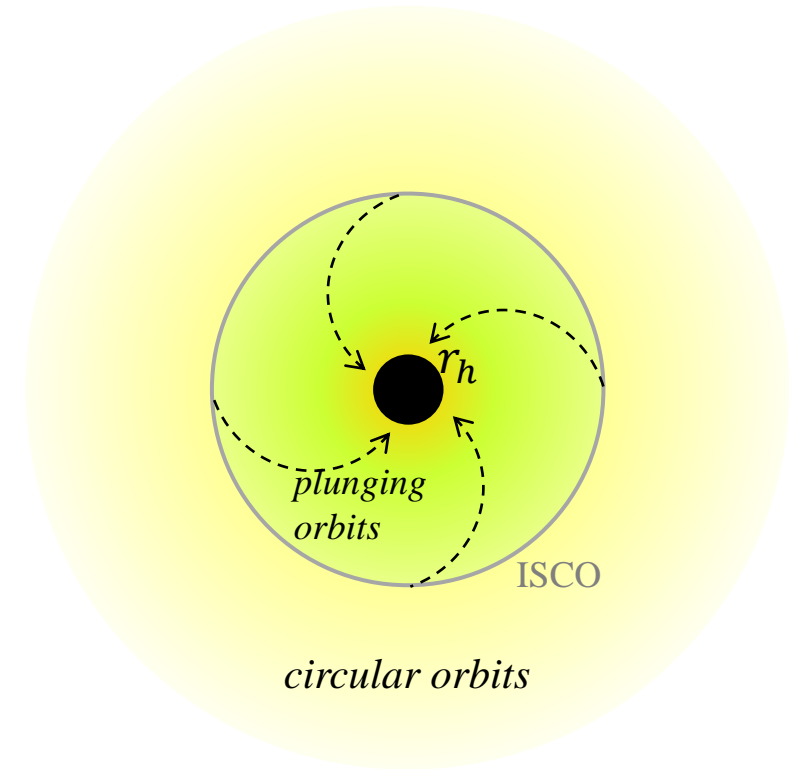


$\alpha \leq 0, a = 0.8, \theta_o = 90^\circ$



# Images with a thin disk

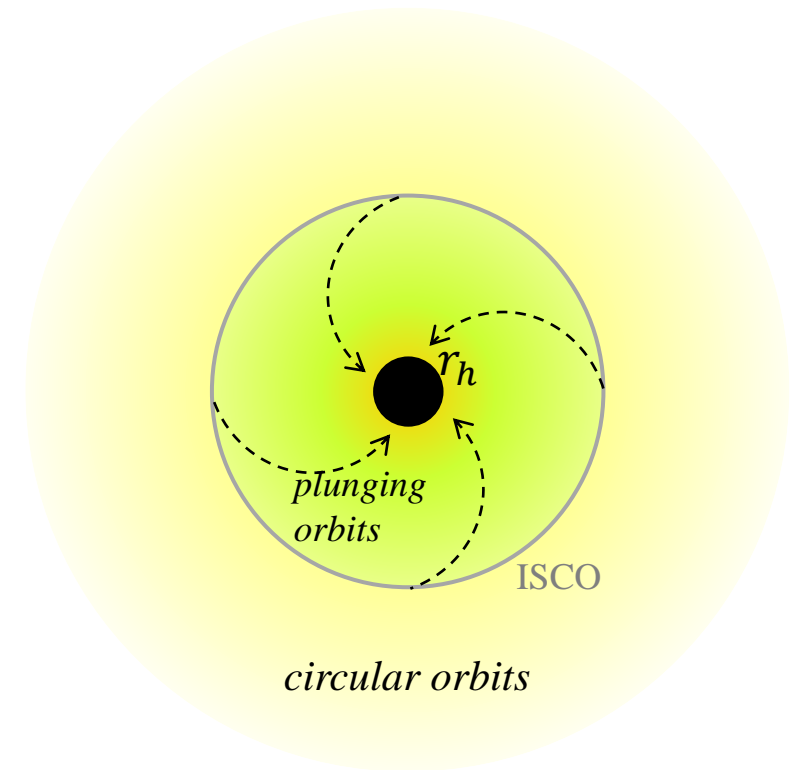
- Disk model (geometrically and optically thin)
  - placed on the equatorial plane
  - Outside the ISCO: circular orbits
  - Inside the ISCO: falls from the ISCO to the horizon



# Images with a thin disk

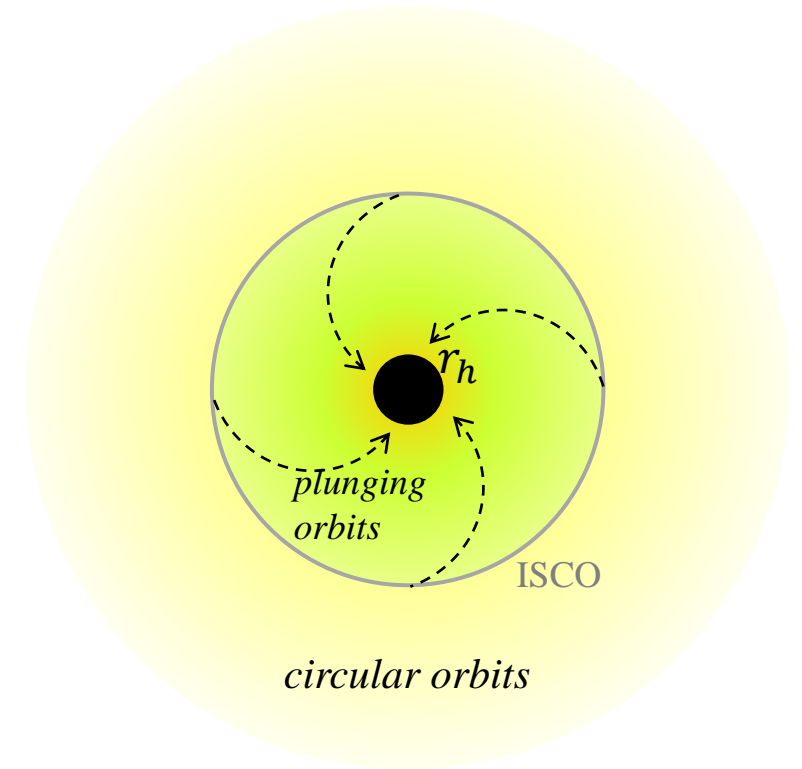
- Disk model (geometrically and optically thin)
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- Emissivity [10]  $J = \exp\left(-\frac{1}{2}z^2 - 2z\right)$   
 $z = \ln\left(\frac{r}{r_H}\right)$

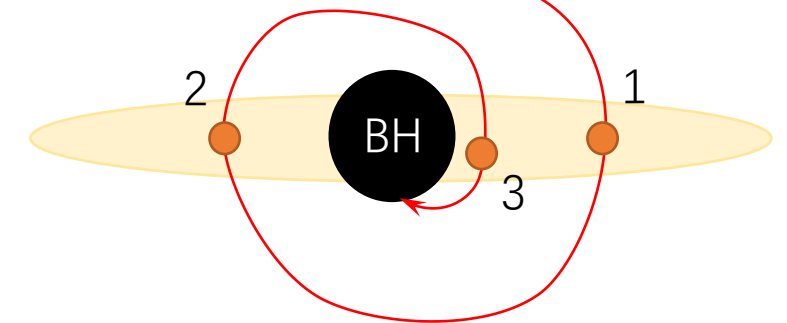
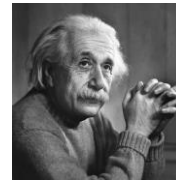


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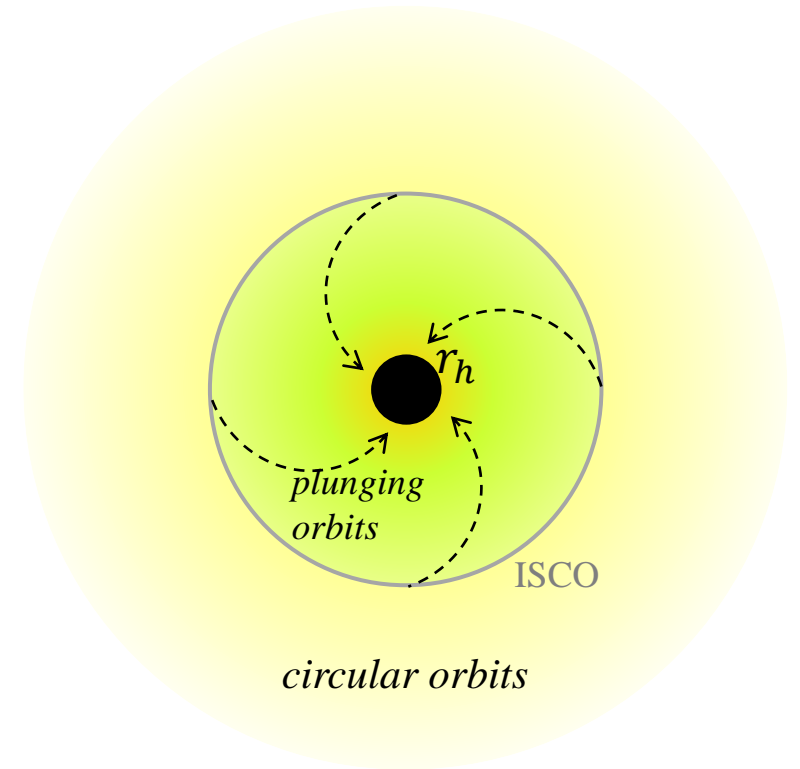
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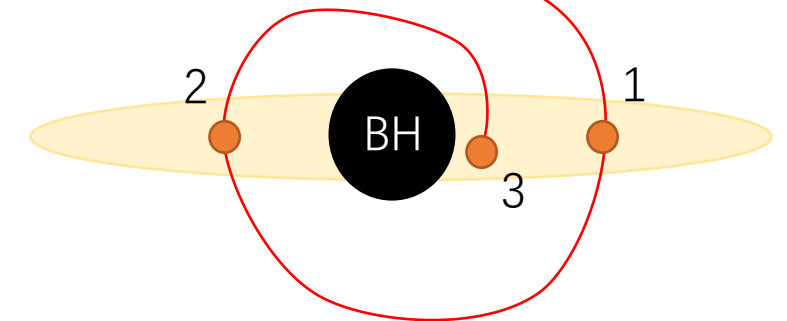
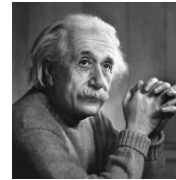
- Intensity  $I_{\nu_o} = \sum_{n=1}^N g_n^3 J_n$

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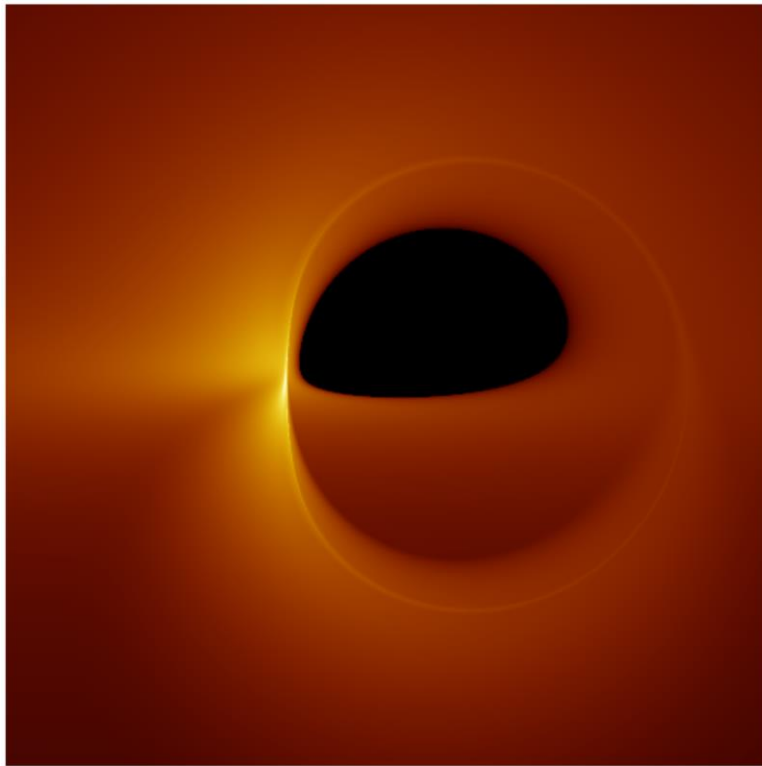


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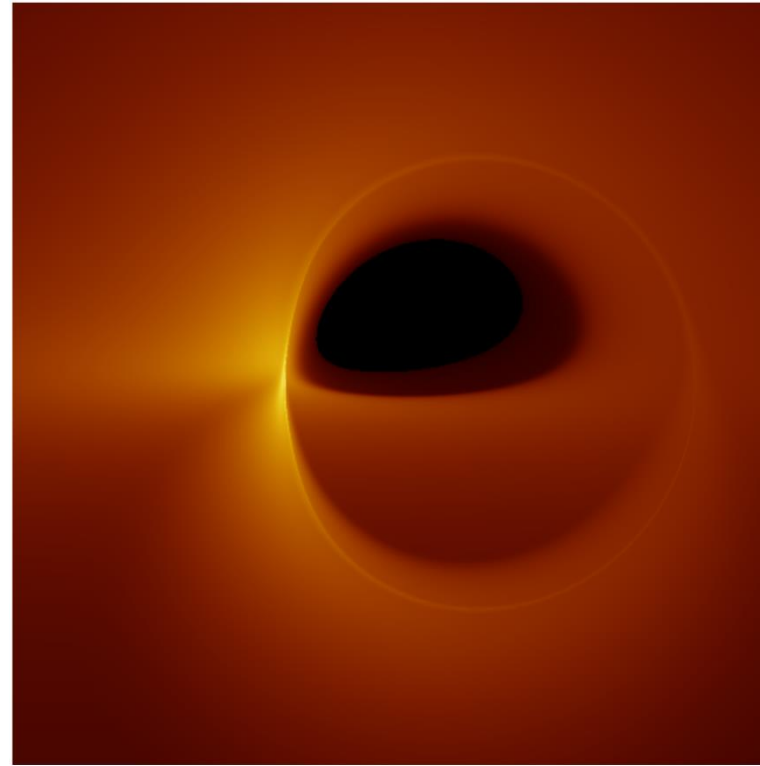
# Images with a thin disk

- Results

- Intensity : a smaller *inner shadow* [10]



$$a = 0.99, \alpha = 0, \theta_o = 80^\circ$$

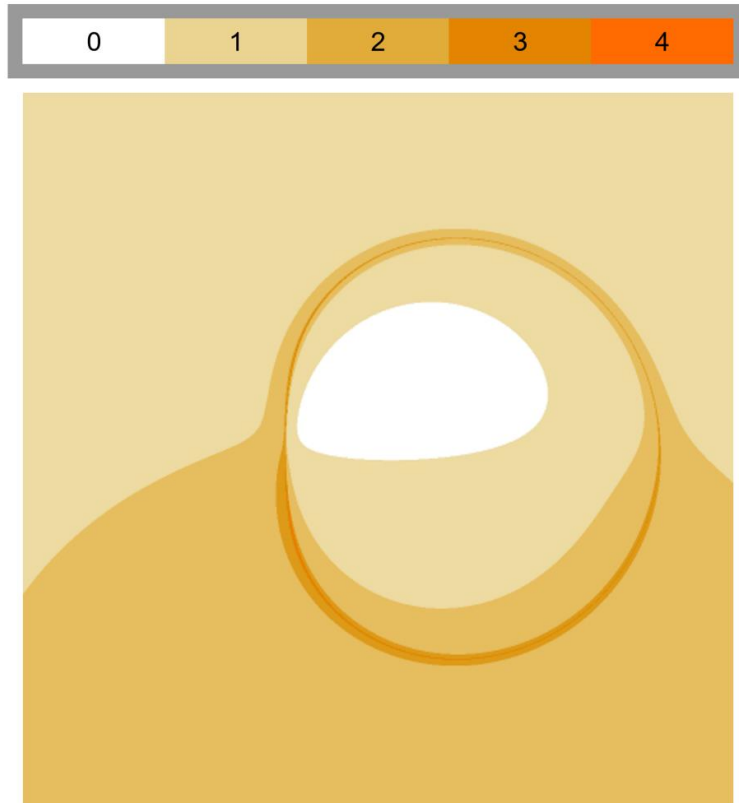


$$a = 0.99, \alpha = 0.02, \theta_o = 80^\circ$$

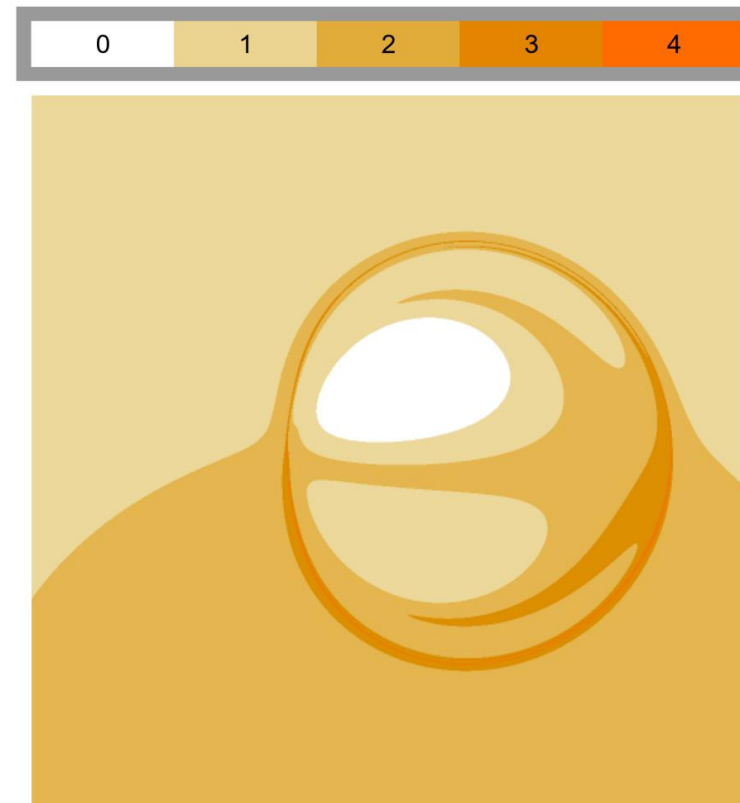
# Images with a thin disk

- Results

- Number of times the light rays intersect the disk



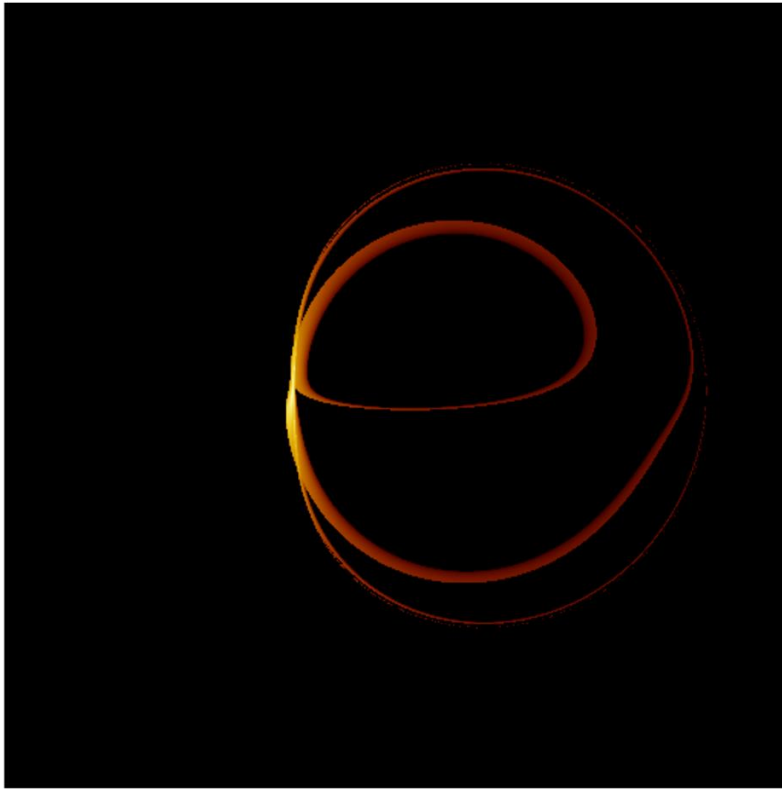
$$a = 0.99, \alpha = 0, \theta_o = 80^\circ$$



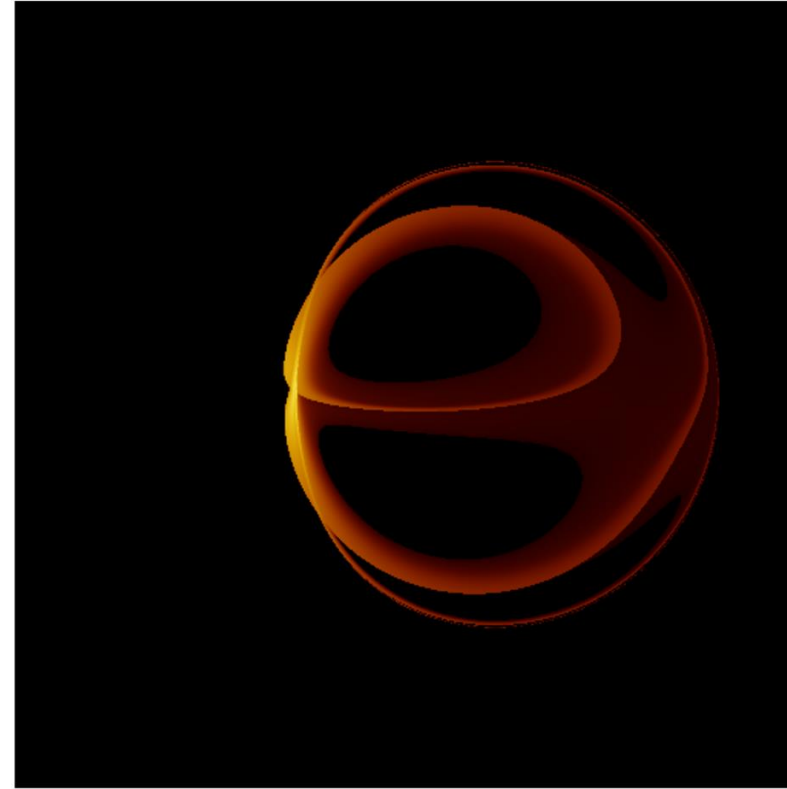
$$a = 0.99, \alpha = 0.02, \theta_o = 80^\circ$$

# Images with a thin disk

- Results
  - Only inner-ISCO region



$$a = 0.99, \alpha = 0, \theta_o = 80^\circ$$



$$a = 0.99, \alpha = 0.02, \theta_o = 80^\circ$$

# Summary

- We explore the observational signature of a rotating black holes in the semiclassical gravity with trace anomaly.
- For high-spin black holes, the NHEK line was highly susceptible to disruption by the quantum correction effect.
- Our study highlights the importance of near-horizon emission sources in detecting the effects of quantum corrections by black hole images.

See our paper  
(arXiv:2305.14924)  
for more details

Thanks for listening!



# Appendix

$$u^\mu = u_{\text{out}}^t(1, 0, 0, \Omega_s),$$

where

$$u_{\text{out}}^t = \sqrt{-\frac{1}{g_{\phi\phi}\Omega_s^2 + 2g_{t\phi}\Omega_s + g_{tt}}} \Big|_{\theta=\pi/2}, \quad \Omega_s = \frac{-\partial_r g_{t\phi} + \sqrt{(\partial_r g_{t\phi})^2 - \partial_r g_{\phi\phi}\partial_r g_{tt}}}{\partial_r g_{\phi\phi}} \Big|_{\theta=\pi/2}.$$
$$u_{\text{in}}^t = (-g^{tt}E_{\text{ISCO}} + g^{t\phi}L_{\text{ISCO}}) \Big|_{\theta=\pi/2}, \quad u_{\text{in}}^\phi = (-g^{t\phi}E_{\text{ISCO}} + g^{\phi\phi}L_{\text{ISCO}}) \Big|_{\theta=\pi/2},$$
$$u_{\text{in}}^r = -\sqrt{-\frac{g_{tt}u_{\text{in}}^t u_{\text{in}}^t + 2g_{t\phi}u_{\text{in}}^t u_{\text{in}}^\phi + g_{\phi\phi}u_{\text{in}}^\phi u_{\text{in}}^\phi + 1}{g_{rr}}} \Big|_{\theta=\pi/2}, \quad u_{\text{in}}^\theta = 0,$$

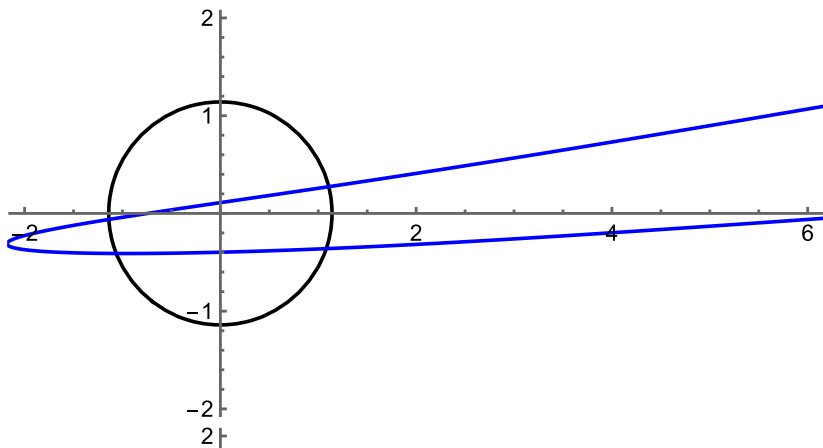
where  $E_{\text{ISCO}}$  and  $L_{\text{ISCO}}$  is the conserved energy and angular momentum at the ISCO.

See our paper  
(arXiv:2305.14924)  
for more details

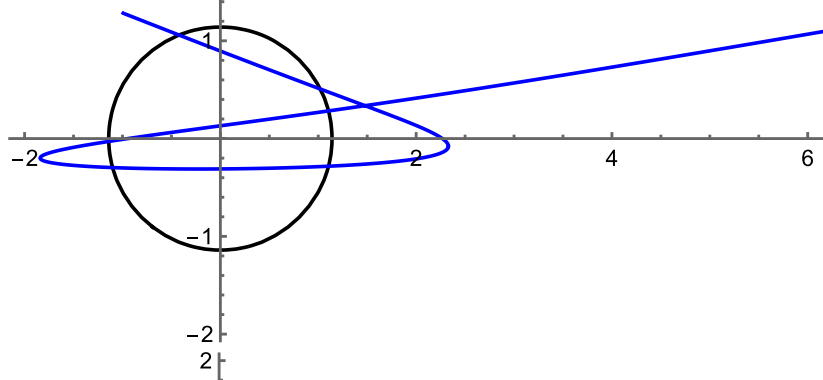
Thanks for listening!

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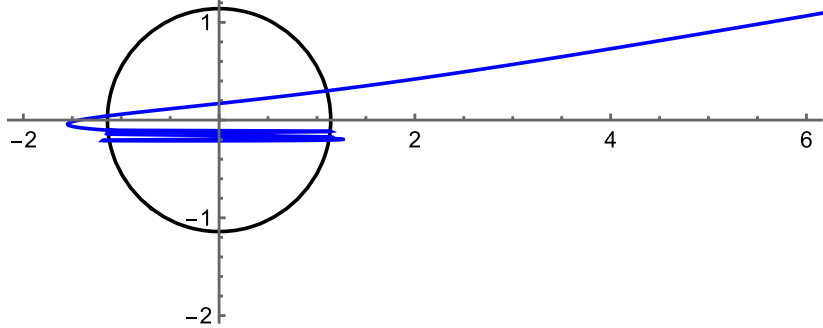
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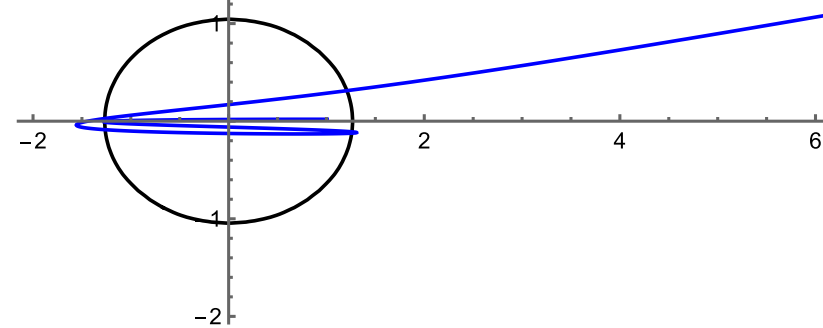
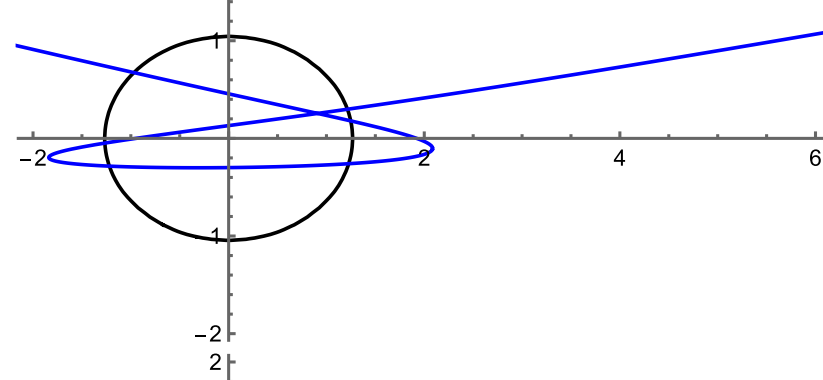
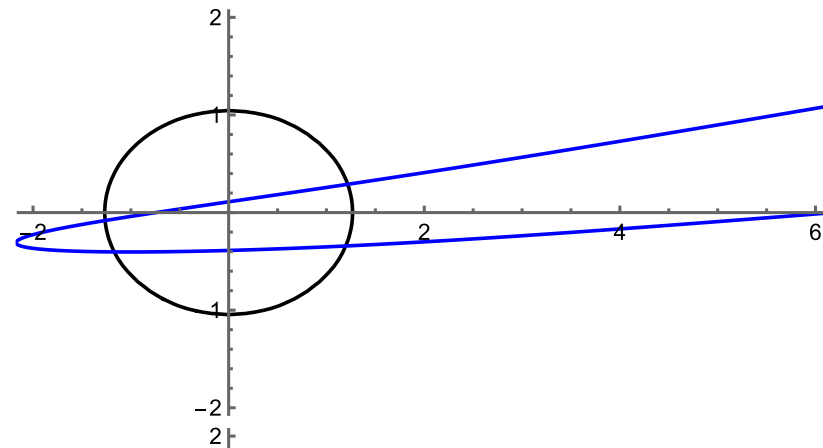
155,256

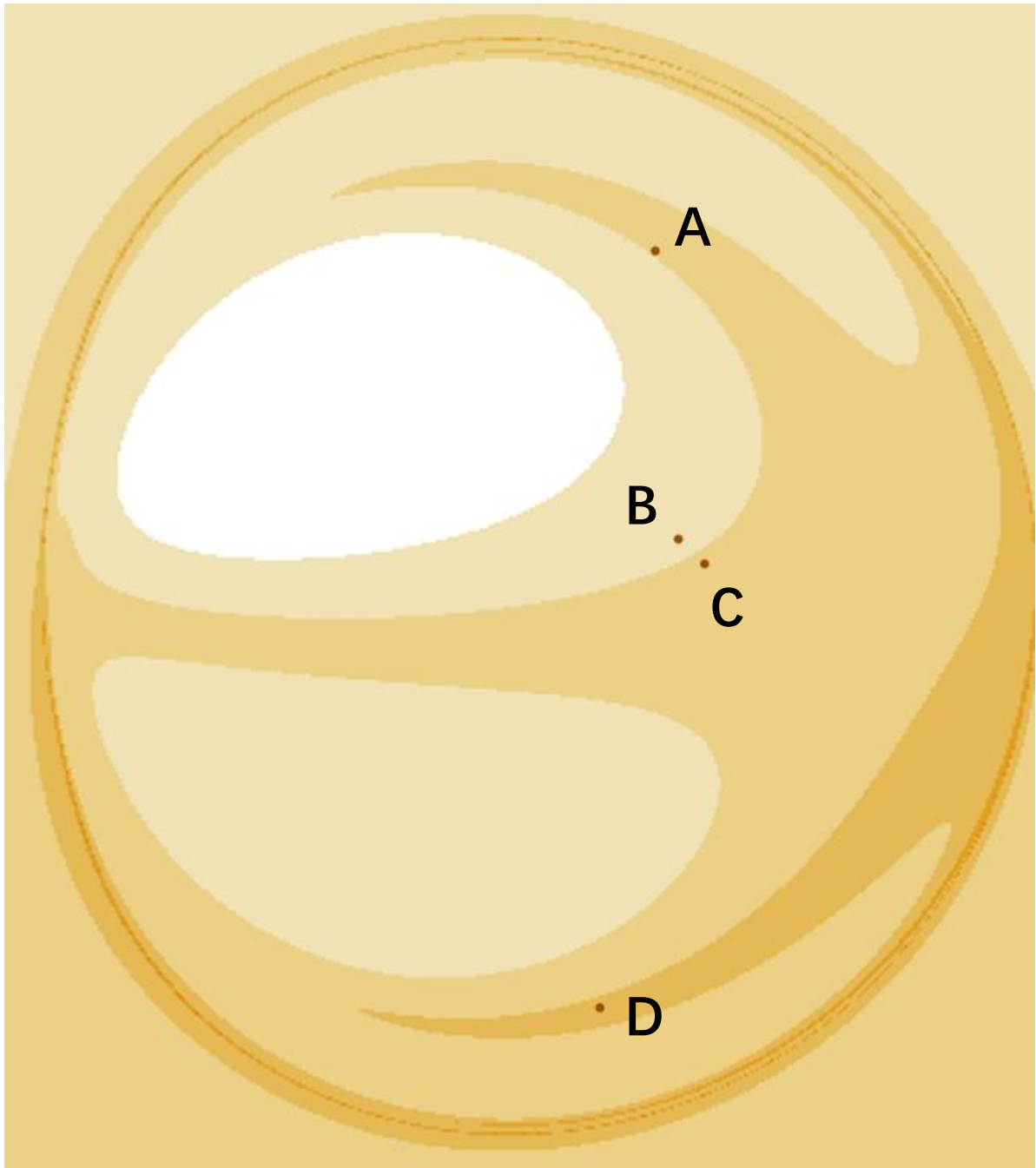


176,256

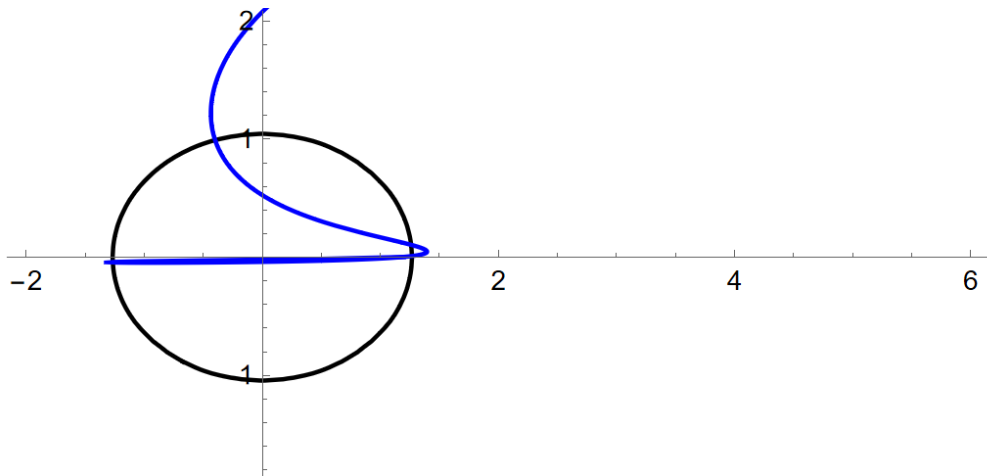
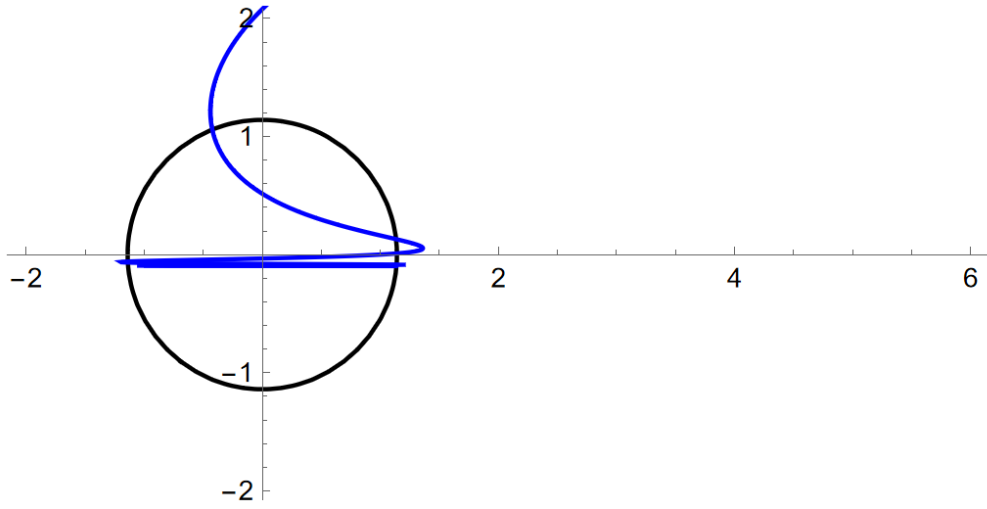


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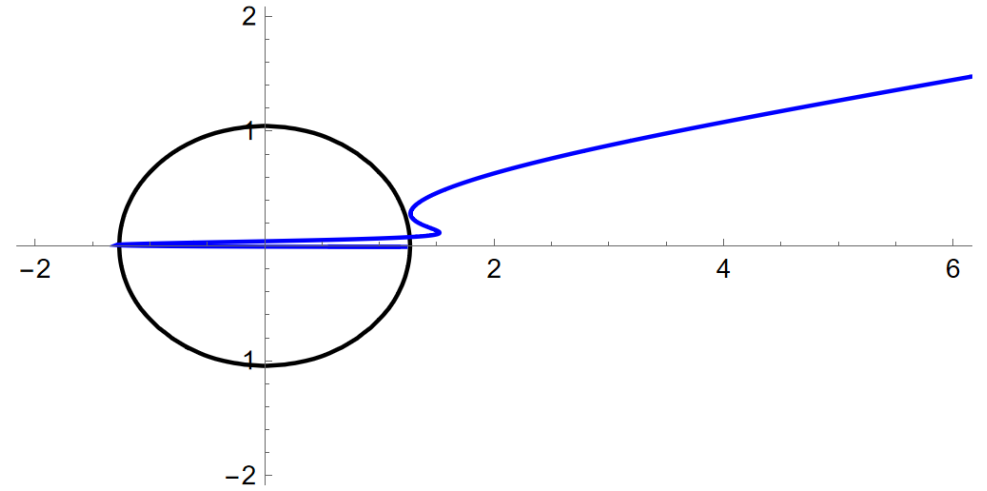
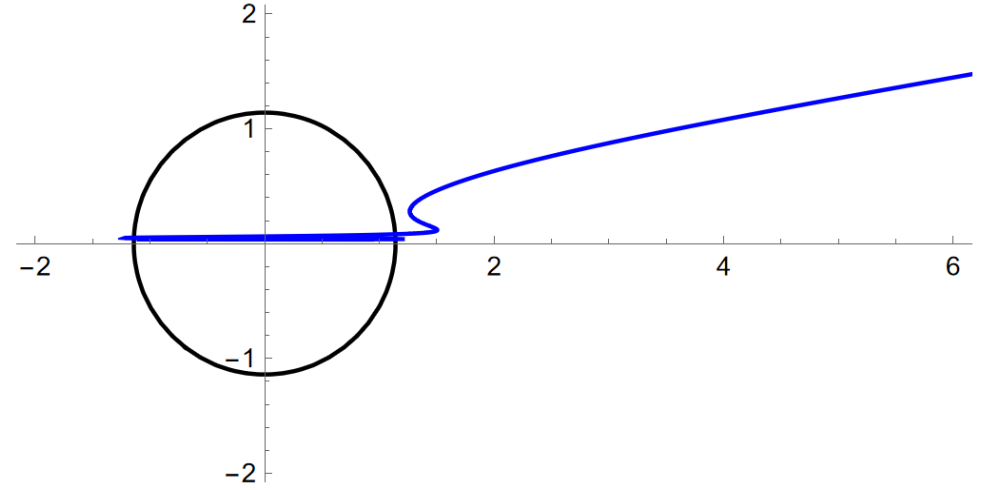




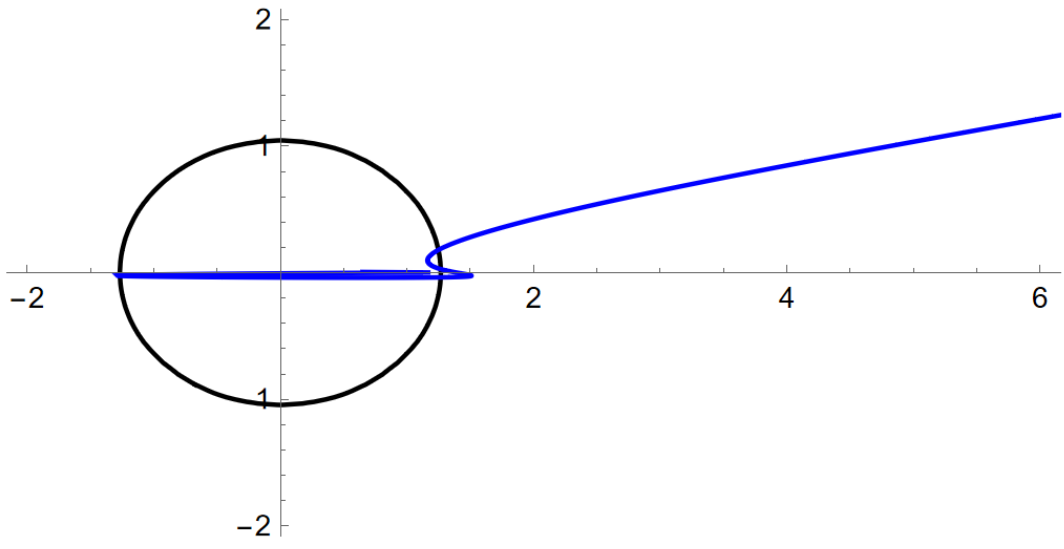
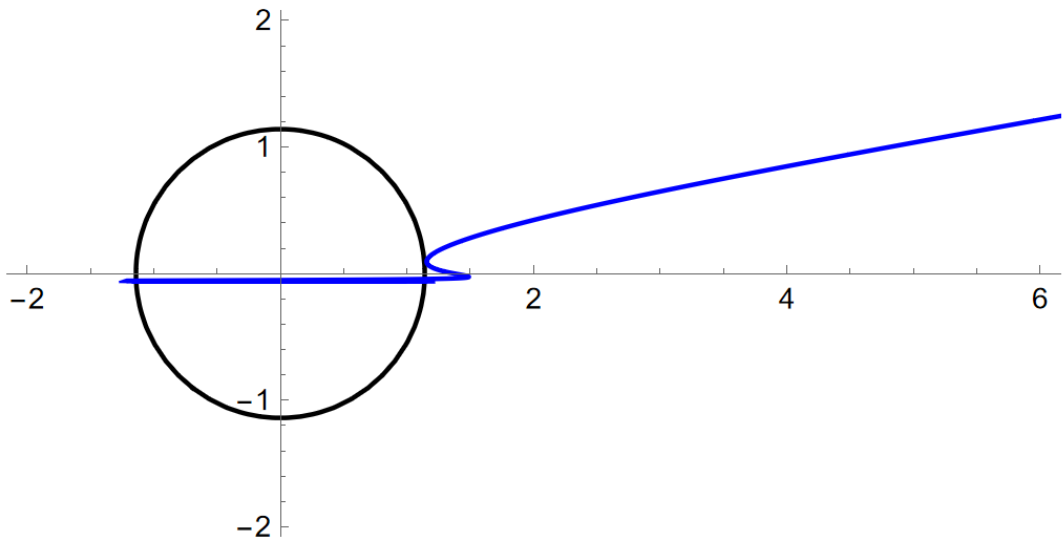
**A**



**B**



**C**



**D**

