Polarization patterns of the hotspots plunging into a Kerr black hole

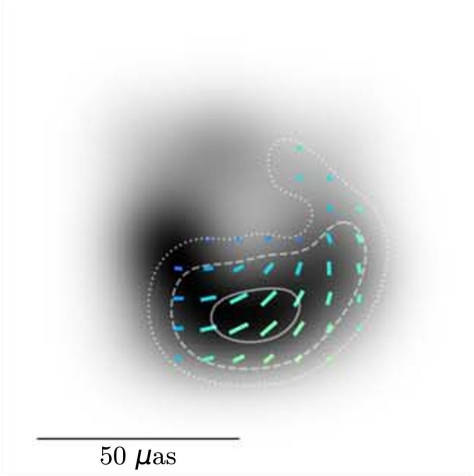
Zhenyu Zhang
School of physics, Peking university
Based on arXiv: 2407.14897
Accepted by PRD
Collaborate with: B. Chen, Y. Hou, and Y. Song

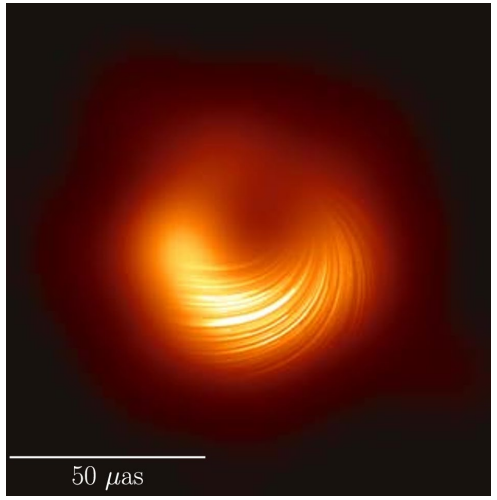
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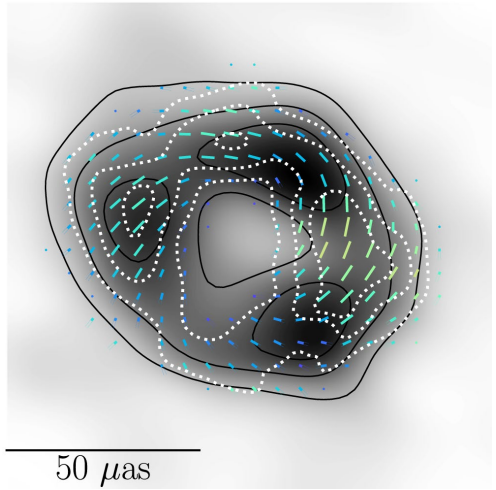
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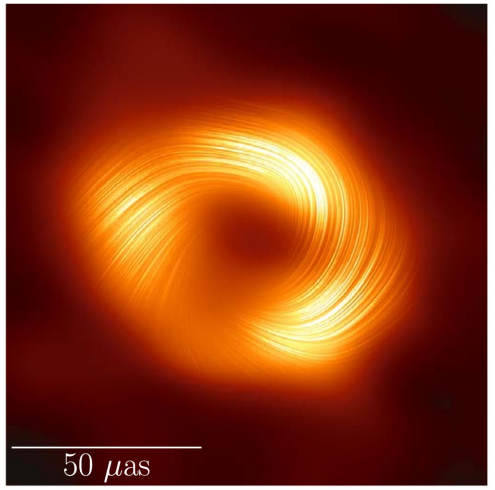
Observed polarization patterns

- EHT [1,2]

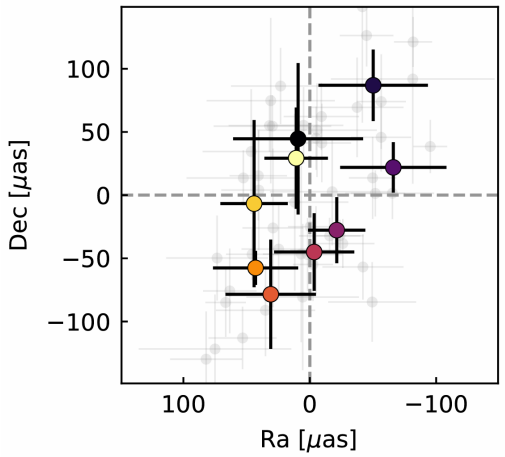


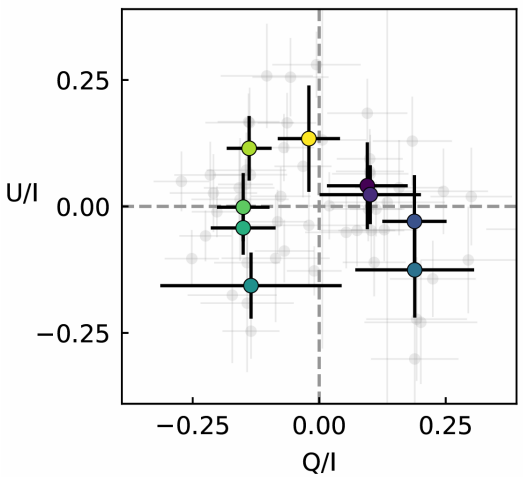


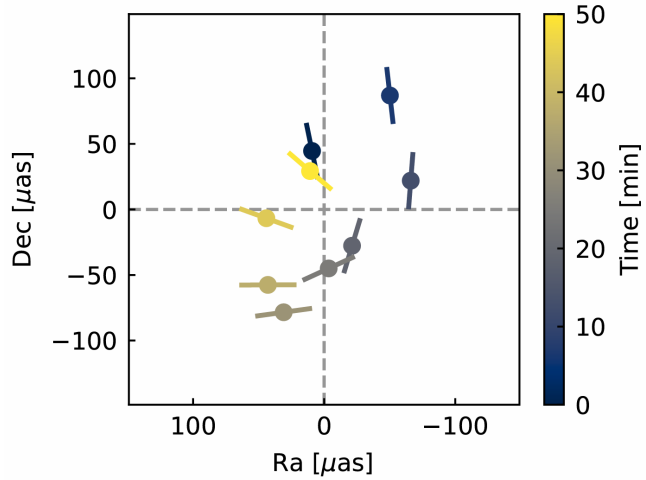




- GRAVITY [3]



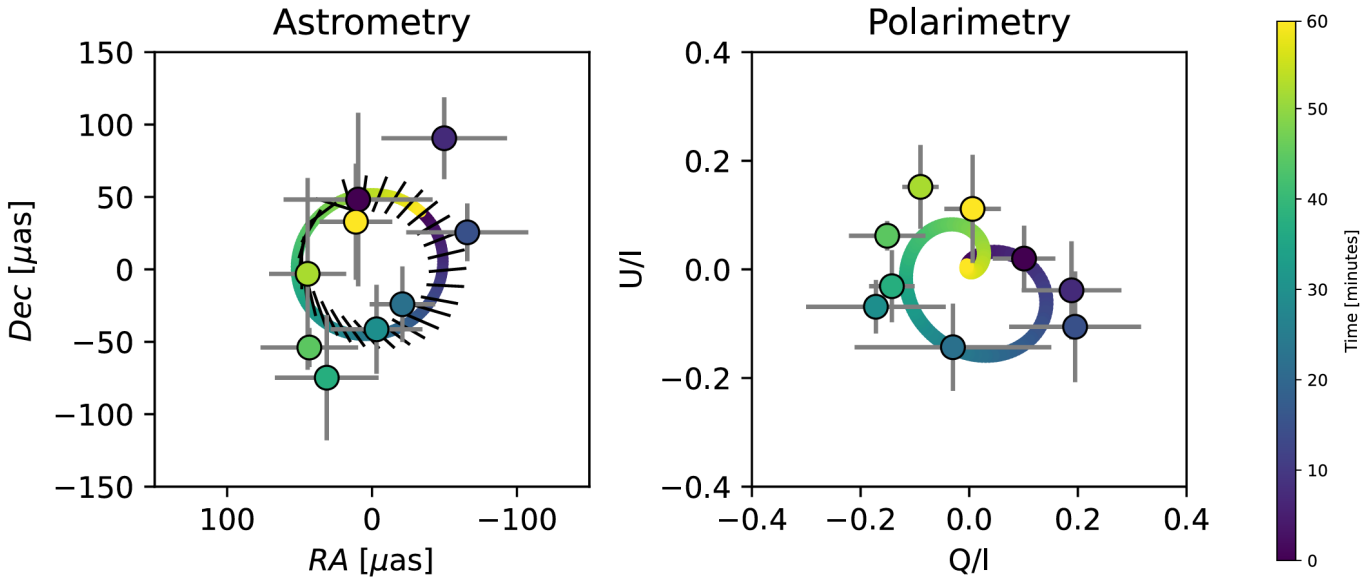




[1] EHT collaboration, Astrophys.J.Lett. 964 (2024) 2, L25
[2] EHT collaboration, Astrophys.J.Lett. 910 (2021) 1, L12
[3] GRAVITY Collaboration, Astron.Astrophys. 677 (2023) L10

Hotspot model

- EHT [4,5]
- GRAVITY [3]

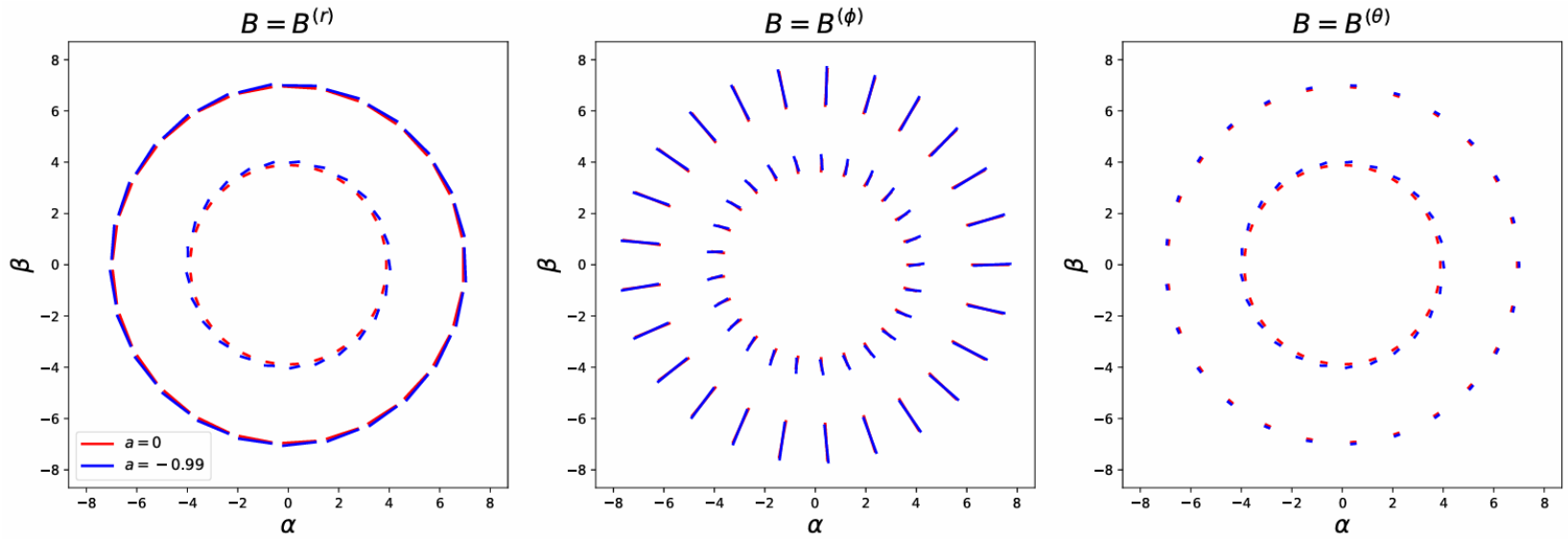


[3] GRAVITY Collaboration, Astron.Astrophys. 677 (2023) L10
[4] EHT collaboration, Astrophys.J.Lett. 964 (2024) 2, L25
[5] EHT collaboration, Astrophys.J.Lett. 910 (2021) 1, L12

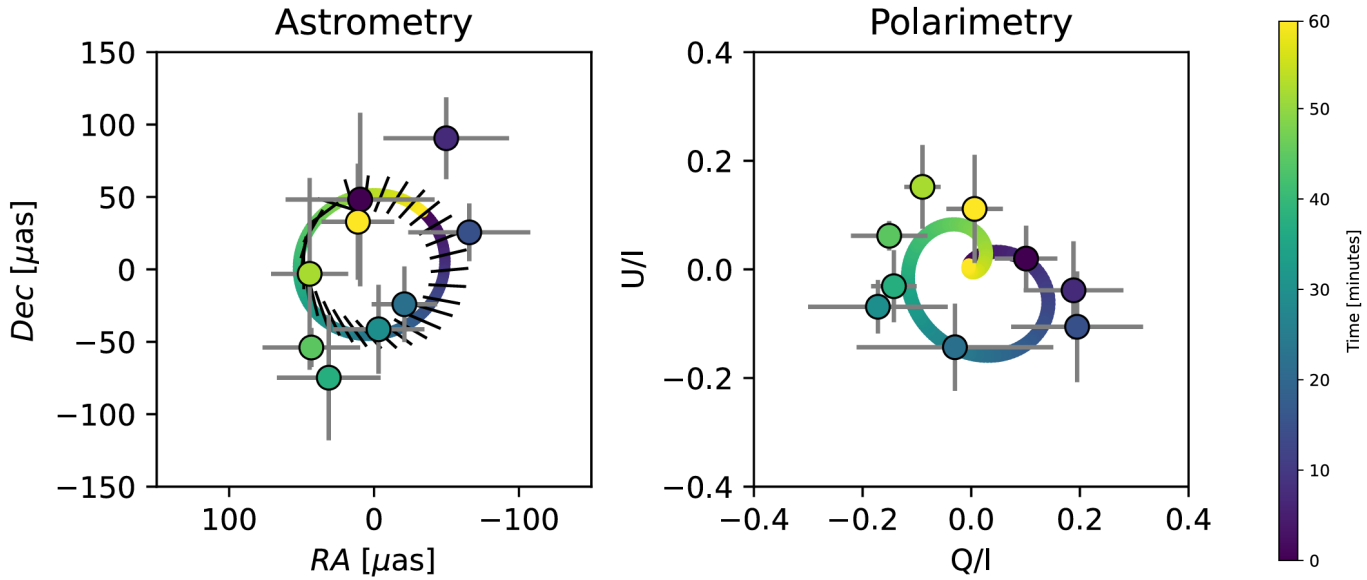
Hotspot model

- EHT [4,5]

"ring model":
time-averaged hotspot

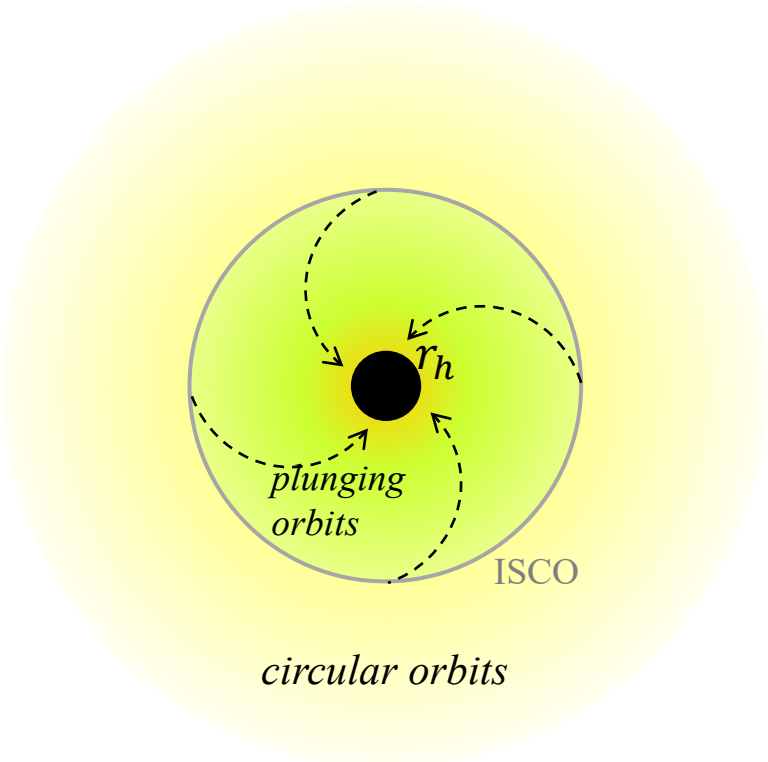


- GRAVITY [3]

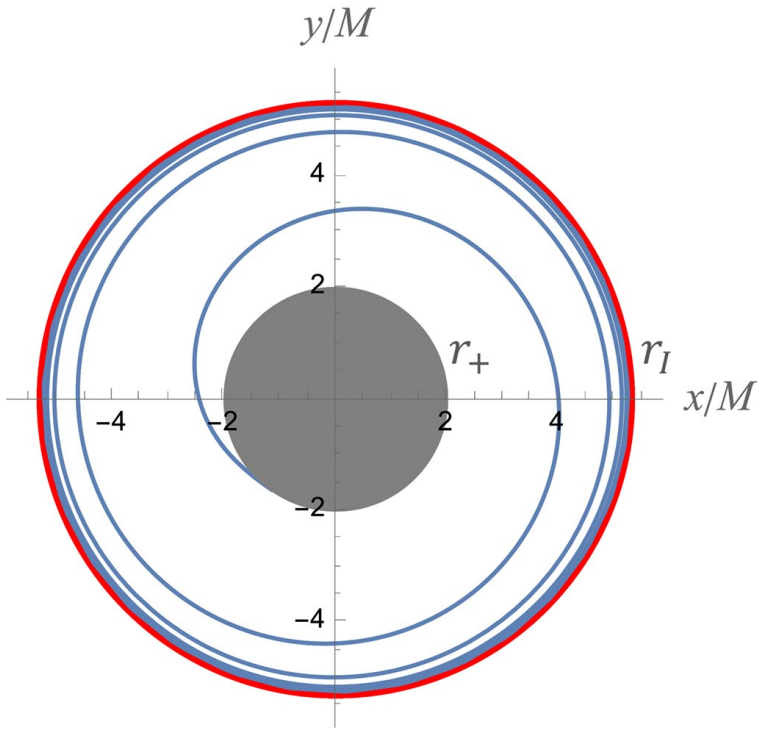


[3] GRAVITY Collaboration, Astron.Astrophys. 677 (2023) L10
[4] EHT collaboration, Astrophys.J. 912 (2021) 1, 35
[5] Zachary Gelles et al., Phys.Rev.D 104 (2021) 4, 044060

Plunging from the ISCO



(Credit: Y. Hou)



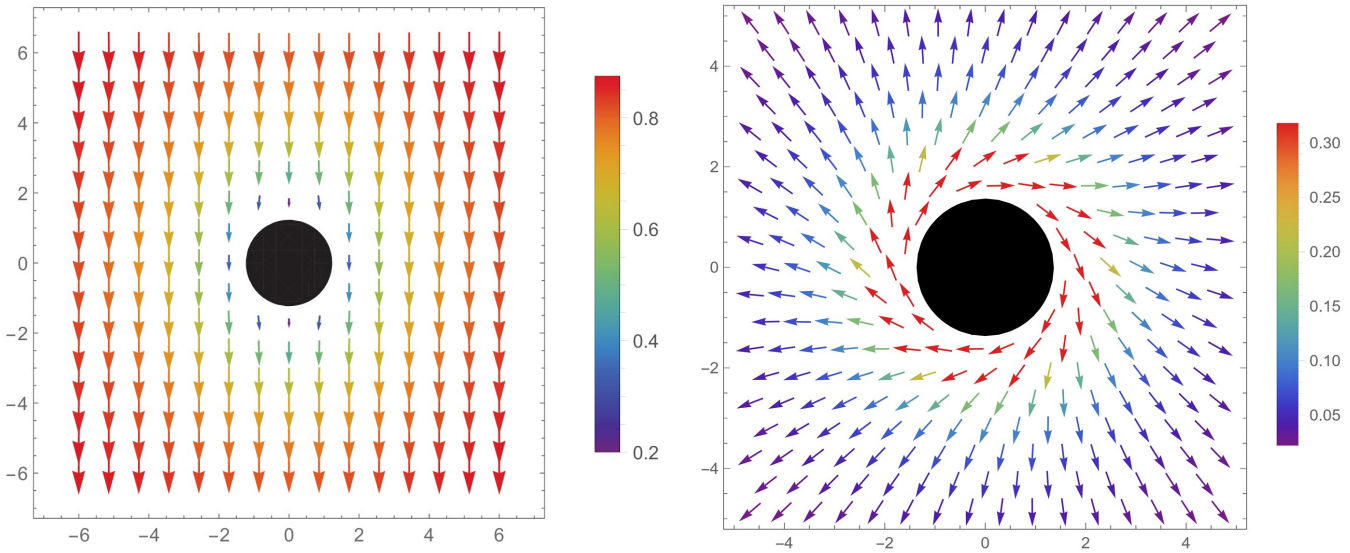
- It is a reasonable model of the accretion flow inside the ISCO.
- Previous studies focused only on the intensity instead of the polarization in this region.
- It can provide a possible explanation for the disappearance of hotspots.

Emission

- Thermal synchrotron radiation
  - Polarization vector: $\vec{f} \propto \vec{p} \times \vec{B}$
  - Covariant form: $f^{\mu} = -\frac{\epsilon^{\mu\nu\alpha\beta} U_{\nu} p_{\alpha} (B_{\perp})_{\beta}}{U \cdot p \sqrt{B_{\perp}^2}}, \quad B_{\perp}^{\mu} = B^{\mu} - \frac{B \cdot p}{(U \cdot p)^2} [p^{\mu} + (U \cdot p) U^{\mu}]$
  - Intensity: $I \propto B_{\perp}^2$

Emission

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  - Intensity: $I \propto B_{\perp}^2$
- Global magnetic field
  - Vertical [6]: $A^{\mu} \partial_{\mu} = aB \partial_t + \frac{B}{2} \partial_{\phi}$
  - Radial [7]: $A_{\mu} dx^{\mu} = A_{\phi} d\phi$



[6] R. M. Wald, Phys.Rev.D 10 (1974) 1680-1685
[7] Y. Hou et al., JCAP 02 (2024) 030

From source to observer

- Light propagation
  - Face-on:

$$\rho = \frac{r_s}{M} + 1 + \frac{a^2 - M^2}{2Mr_s} + \frac{50M^2 - 2a^2 - 15M^2\pi}{4r_s^2} + \mathcal{O}(M^3/r_s^3)$$

a new fitting function for φ direction

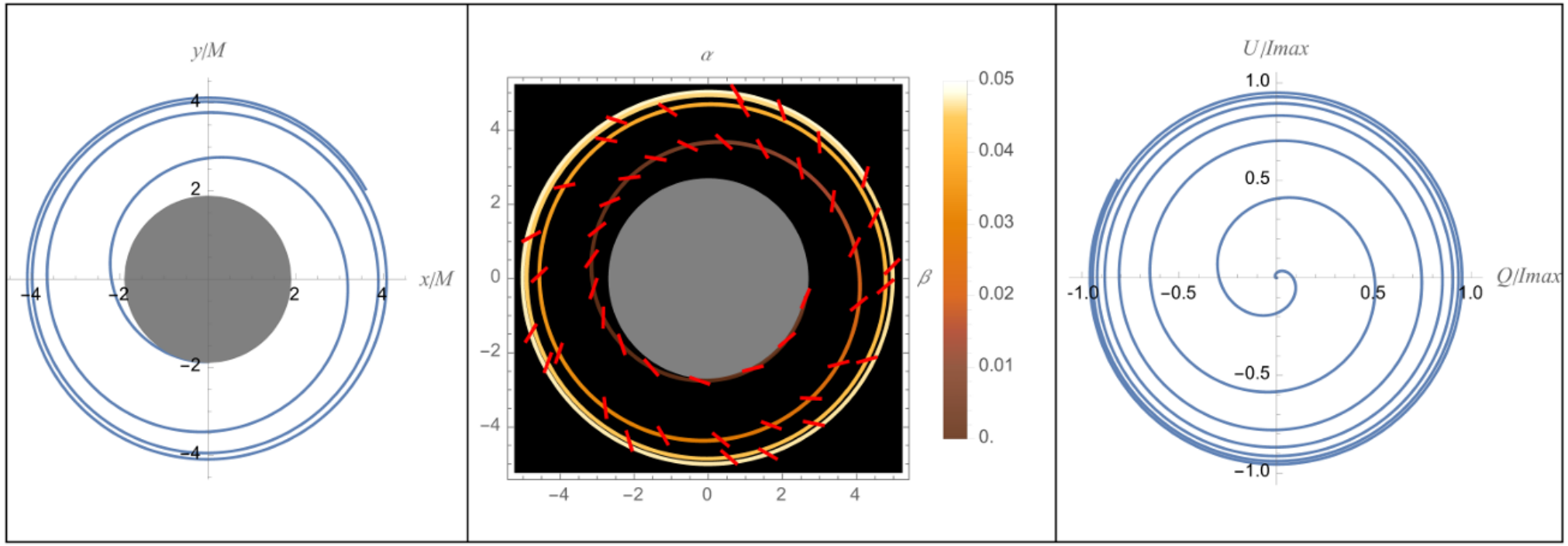
$$\Delta\varphi \approx \begin{cases} \dfrac{2Ma}{r_s^2}\left[1 - \dfrac{\tilde{\beta}}{(\frac{r_s}{r_+} - 1)^{\tilde{\alpha}}} \ln\left(\dfrac{r_s}{r_+} - 1\right)\right], & r_s < r_I\,, \\ \dfrac{2Ma}{r_s^2}\left[1 + \dfrac{\tilde{\gamma}}{(\frac{r_s}{r_+} - 1)}\right], & r_s \geq r_I\,, \end{cases} \qquad \begin{cases} \tilde{\alpha} = 0.035(1 - a_\star) + \dfrac{0.0059}{(1 - a_\star)^{0.4577}} + 0.1163\,, \\ \tilde{\beta} = 0.2093 \arctan\left(a_\star^{12}\right) + 0.3467\,, \\ \tilde{\gamma} = 0.07815 \arctan\left(a_\star^{3}\right) + 0.0983\,. \end{cases}$$

  - Inclined: GRRT

- Polarization transformation: Penrose-Walker constant

Results: vertical magnetic field

$a = 0.5M$



Trajectory

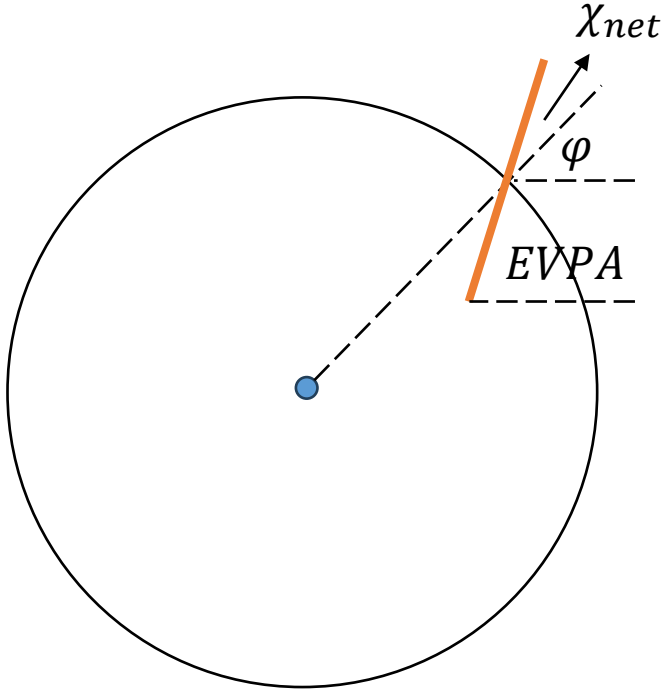
Polarized image
(0th)

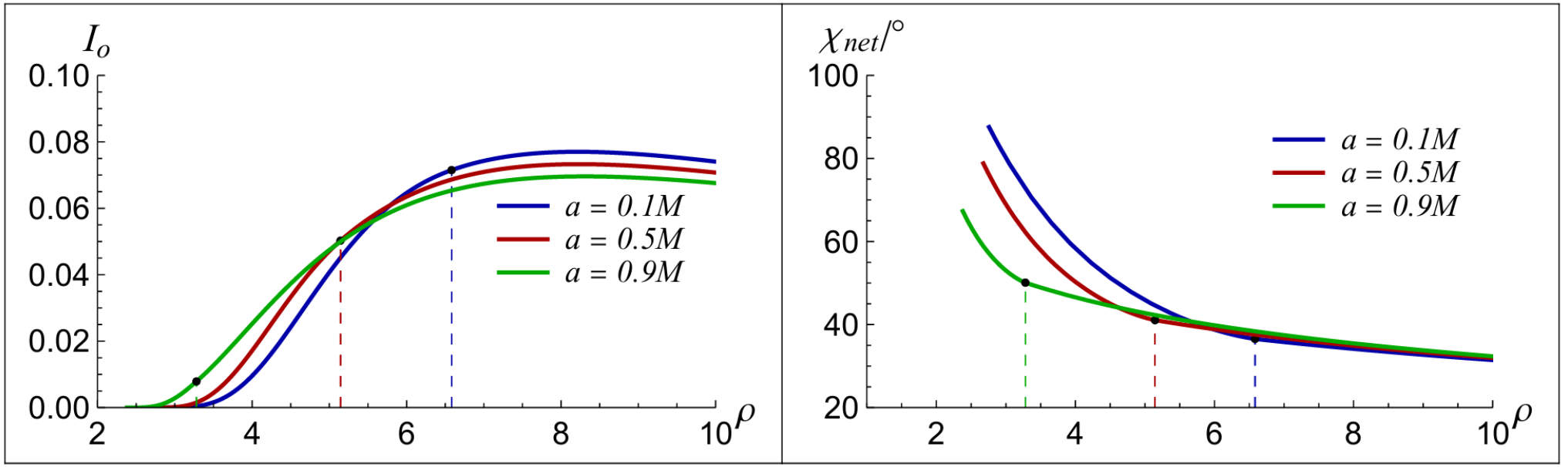
Q-U structure

Results: vertical magnetic field

To quantitatively analyze the polarization, we define

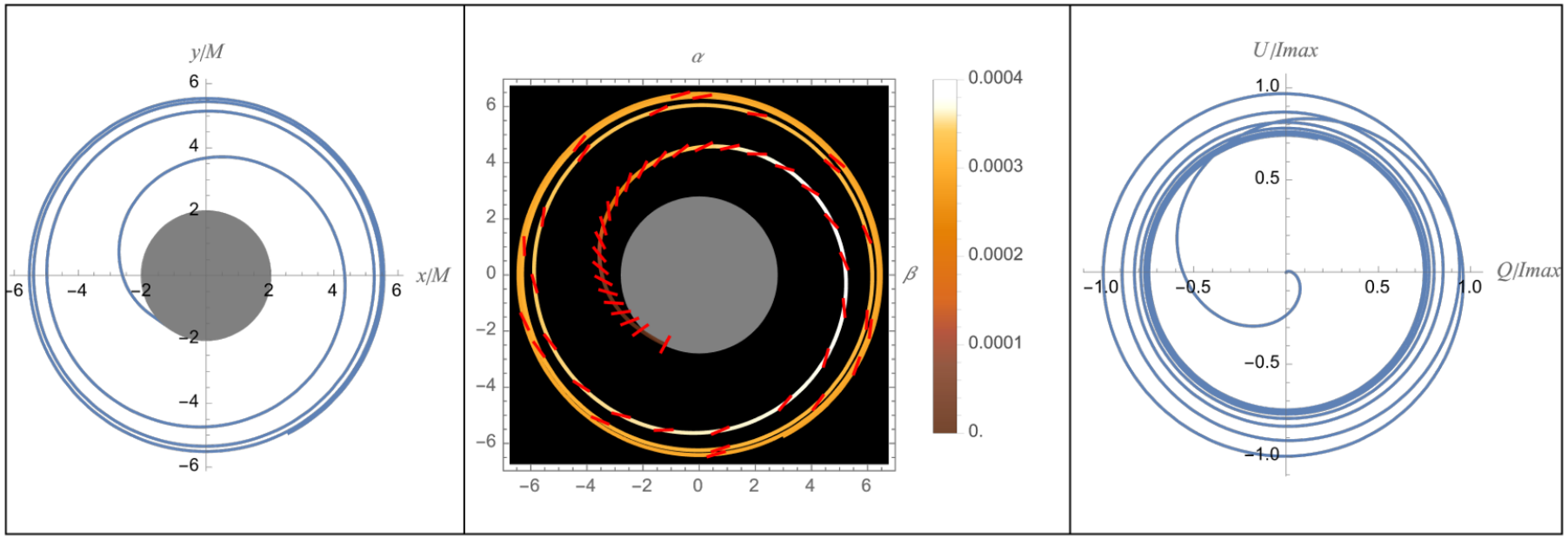
$$\chi_{net} = EVPA - \varphi$$

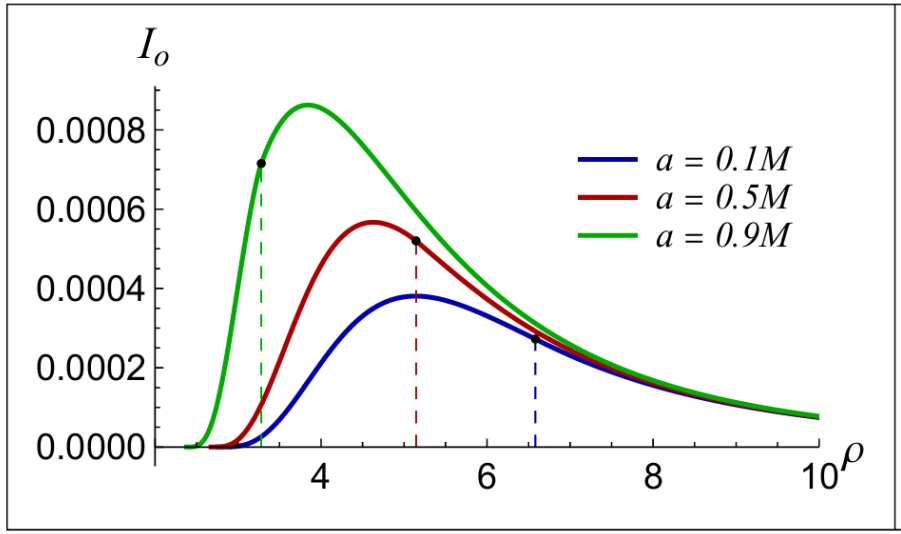


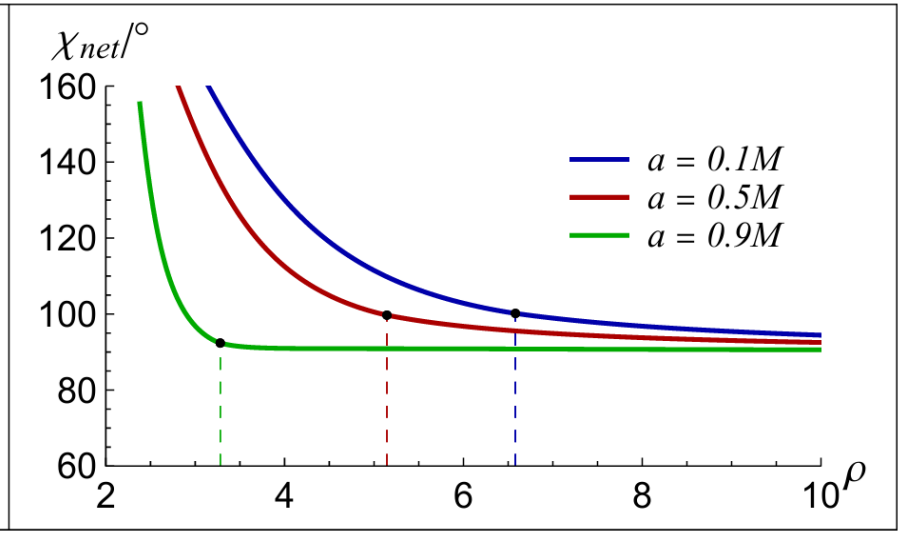


Results: radial magnetic field

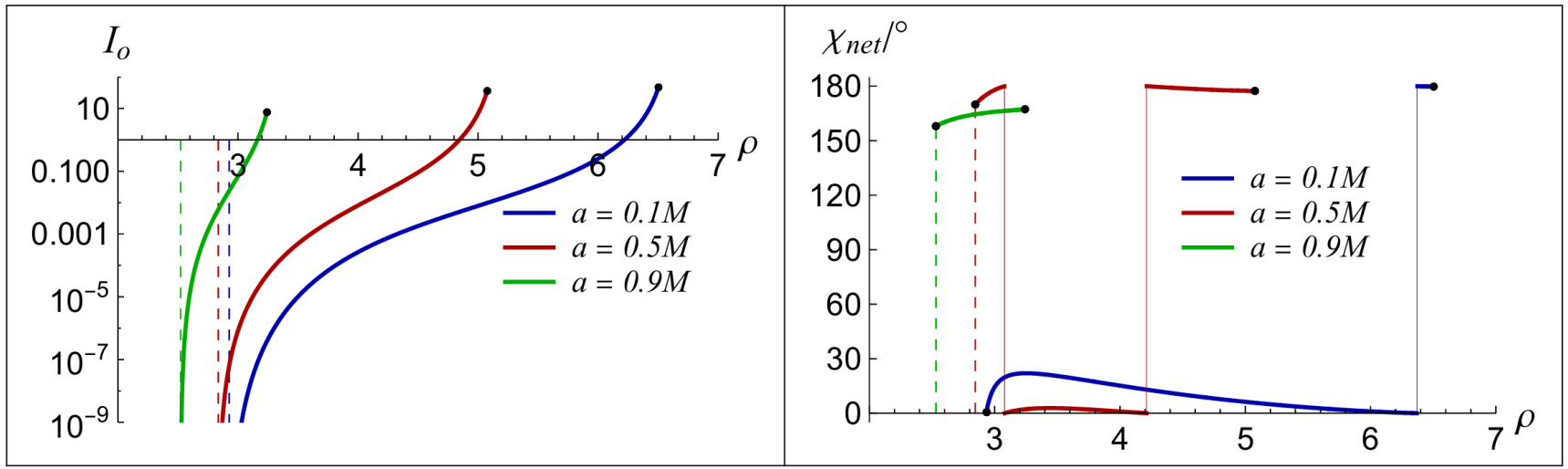
$a = 0.1M$

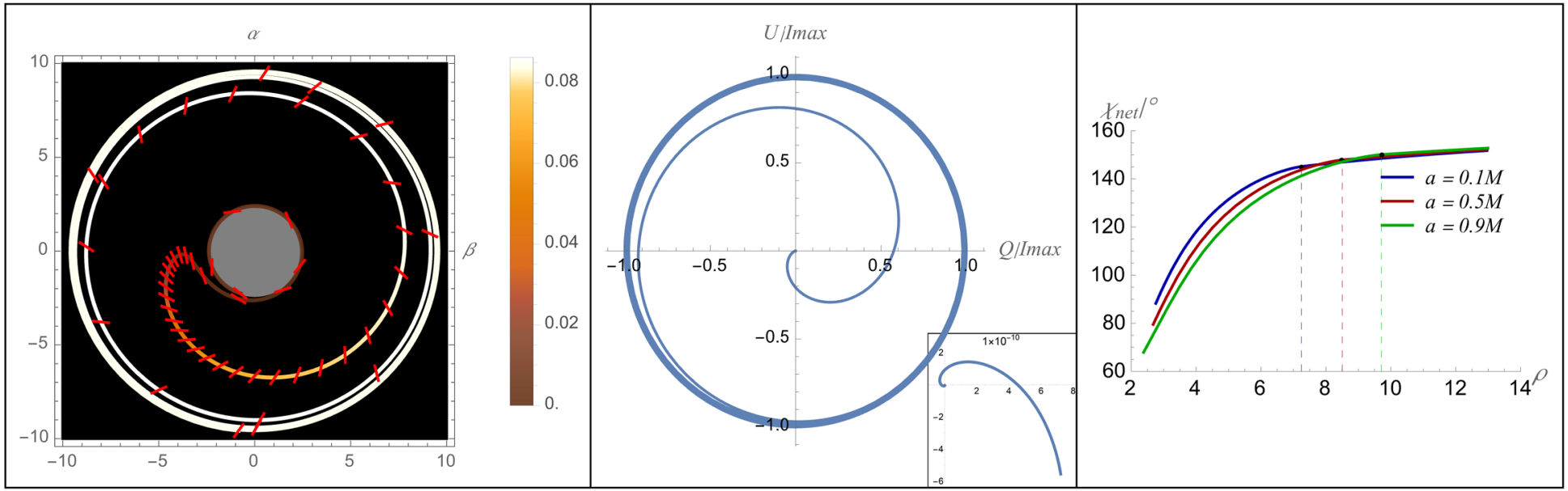






Results: accretion flow & retrograde orbit





Summary

- We studied the polarized images of hotspots plunging into a Kerr BH.

- Highlights
  - We used global magnetic field configurations.
  - We developed a new approximate function for imaging.
  - We emphasized the importance of intra-ISCO radiation.

Summary

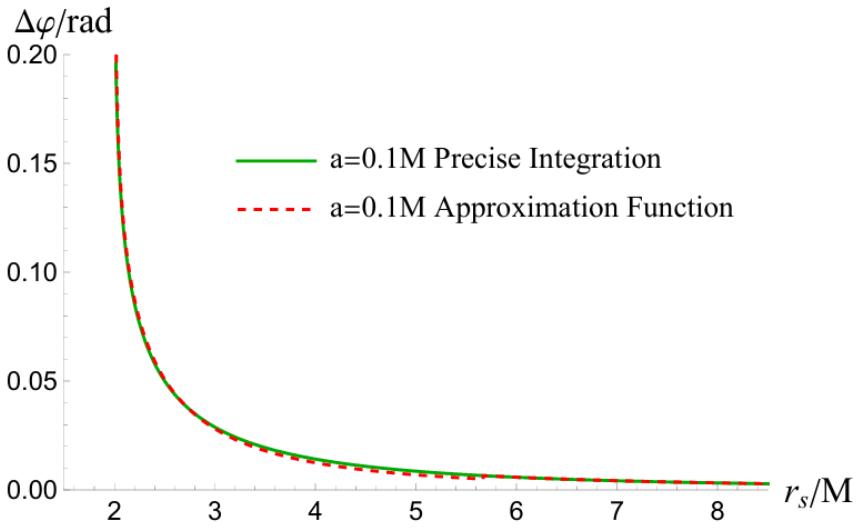
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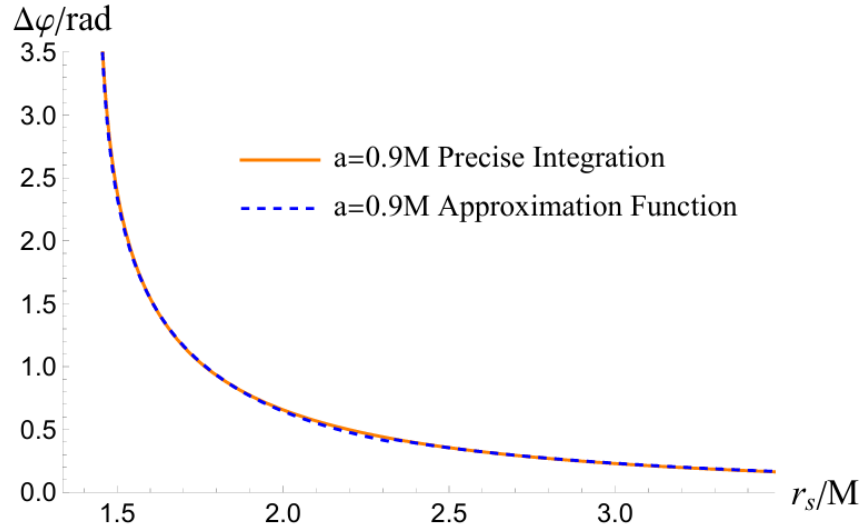
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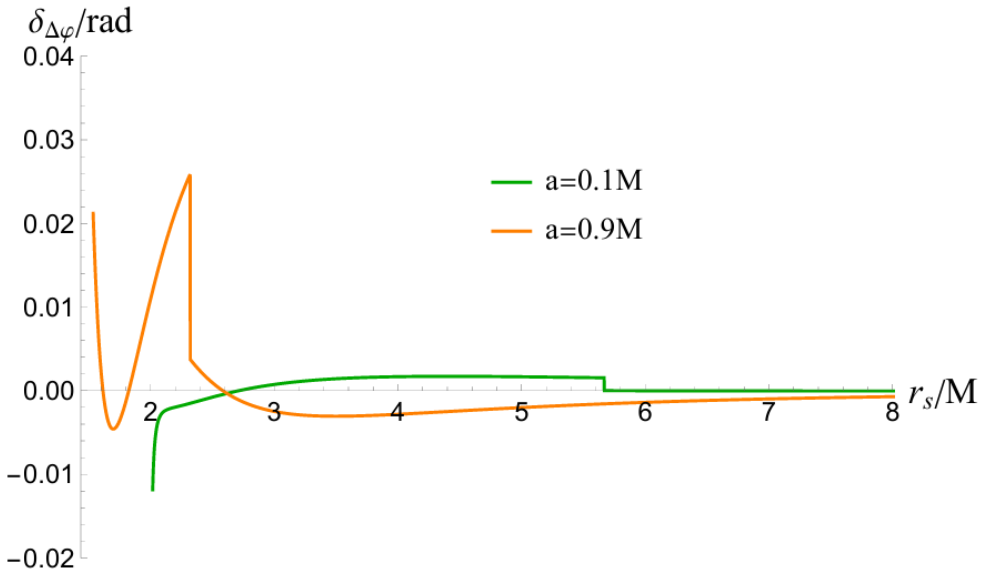
- See our paper (arXiv:2407.14897) for more details and results.

Thanks for listening!

Appendix


Δφ/rad
0.20
0.15
0.10
0.05
0.00
2
3
4
5
6
7
8
r_s/M
a=0.1M Precise Integration
a=0.1M Approximation Function


Δφ/rad
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1.5
2.0
2.5
3.0
r_s/M
a=0.9M Precise Integration
a=0.9M Approximation Function

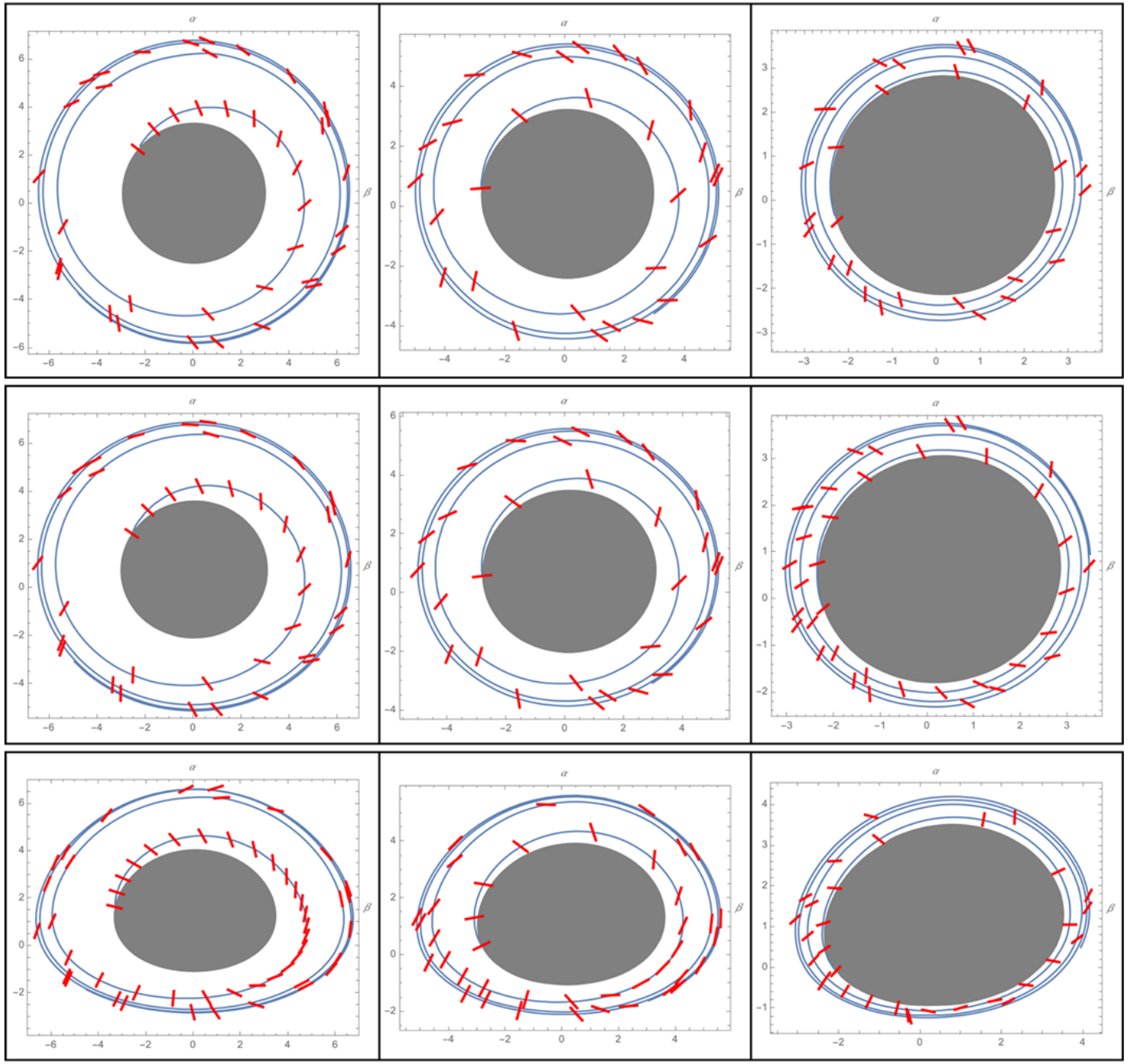

$\delta_{\Delta\varphi}$/rad
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
2
3
4
5
6
7
8
r_s/M
a=0.1M
a=0.9M

Appendix

ideal-MHD condition [55], resulting in

$$B^t = -\frac{\Psi}{\sqrt{-g}}\left(U_r + \frac{U^\phi}{U^r}L\right), \quad B^r = -\frac{\Psi}{\sqrt{-g}}E\,, \quad B^\phi = -\frac{\Psi}{\sqrt{-g}}\frac{U^\phi}{U^r}E\,.$$

Appendix



Appendix

