Polarized images of charged particles in vortical motions around a magnetized Kerr black hole

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Based on arXiv: 2304.03642

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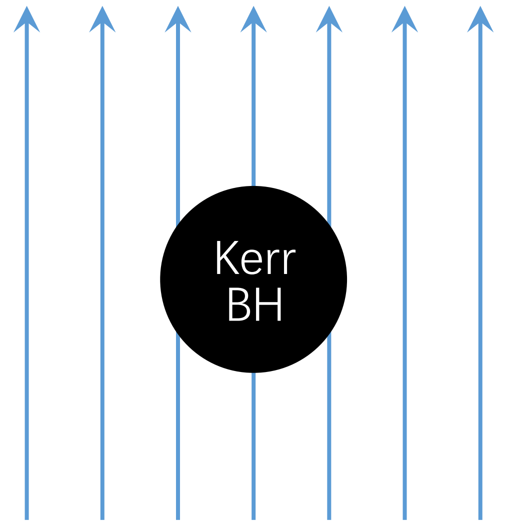
Background

- A mechanism of gamma-ray bursts [1, 2]
  - *Inner engine*

Kerr black holes + uniform magnetic field B_0

→ electric field → particle acceleration → radiation



  - Wald solution
    - Solve Maxwell's Equation in Kerr spacetime

$$A_t = -aB_0 \left[1 - \frac{r}{\Sigma}(1 + \cos^2\theta)\right]$$

$$A_\phi = \frac{1}{2} B_0 \sin^2\theta \left[r^2 + a^2 - \frac{2ra^2}{\Sigma}(1 + \cos^2\theta)\right]$$

Set $G = c = M = 1$

[1] R. Ruffini et al., arXiv: 1811.01839
[2] J. A. Rueda, R. Ruffini and R. P. Kerr, arXiv: 2203.03471

Electromagnetic field structure

$$A_t = -aB_0\left[1 - \frac{r}{\Sigma}(1 + \cos^2\theta)\right]$$

$$A_\phi = \frac{1}{2}B_0\sin^2\theta\left[r^2 + a^2 - \frac{2ra^2}{\Sigma}(1 + \cos^2\theta)\right]$$

Locally non-rotating frame (LNRF)

$$E_{(1)} = -\frac{B_0 a}{\Sigma^2 A^{\frac{1}{2}}}[(r^2 + a^2)(r^2 - a^2\cos^2\theta)(1 + \cos^2\theta) - 2r^2\sin^2\theta\,\Sigma]$$

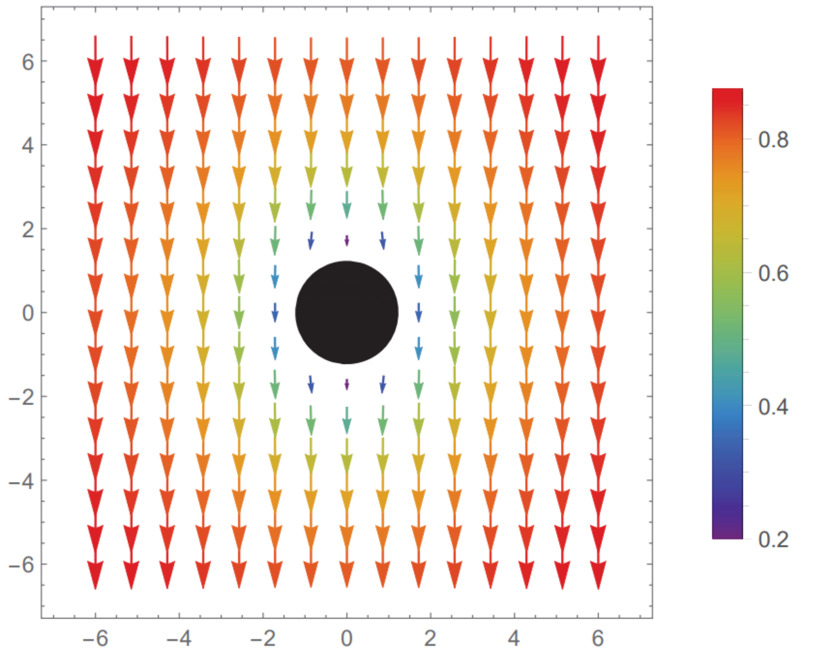
$$E_{(2)} = \frac{B_0 a \Delta^{1/2}}{\Sigma^2 A^{1/2}} 2ra^2 \sin\theta\cos\theta\,(1 + \cos^2\theta)$$

$$B_{(1)} = -\frac{B_0\cos\theta}{\Sigma^2 A^{1/2}}[(r^2 + a^2)(r^2 - a^2\cos^2\theta)(1 + \cos^2\theta) - 2r^2\sin^2\theta\,\Sigma]$$

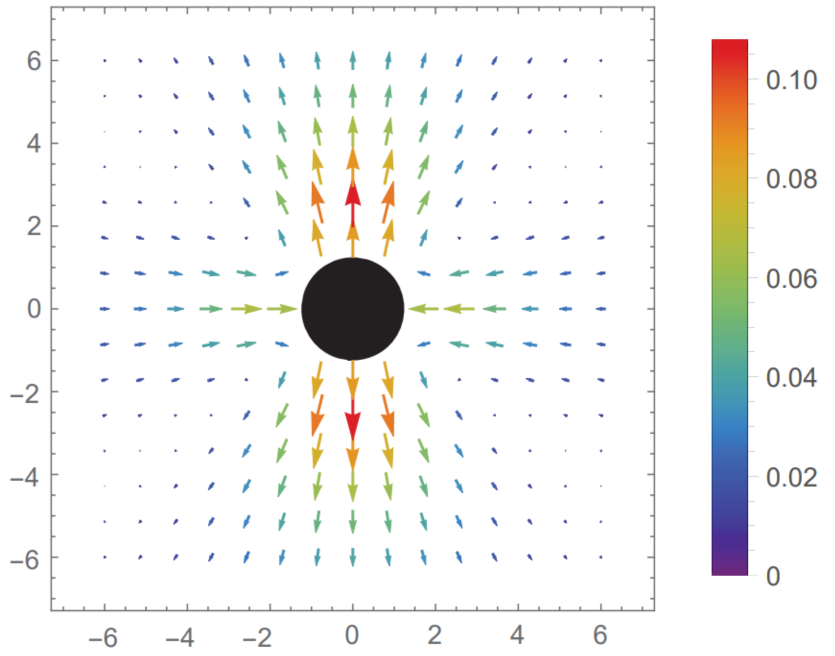
$$B_{(2)} = -\frac{\Delta^{1/2}B_0\sin\theta}{\Sigma^2 A^{1/2}}[a^2(r^2 - a^2\cos^2\theta)(1 + \cos^2\theta) + r\Sigma^2]$$

Set $G = c = M = 1$

B



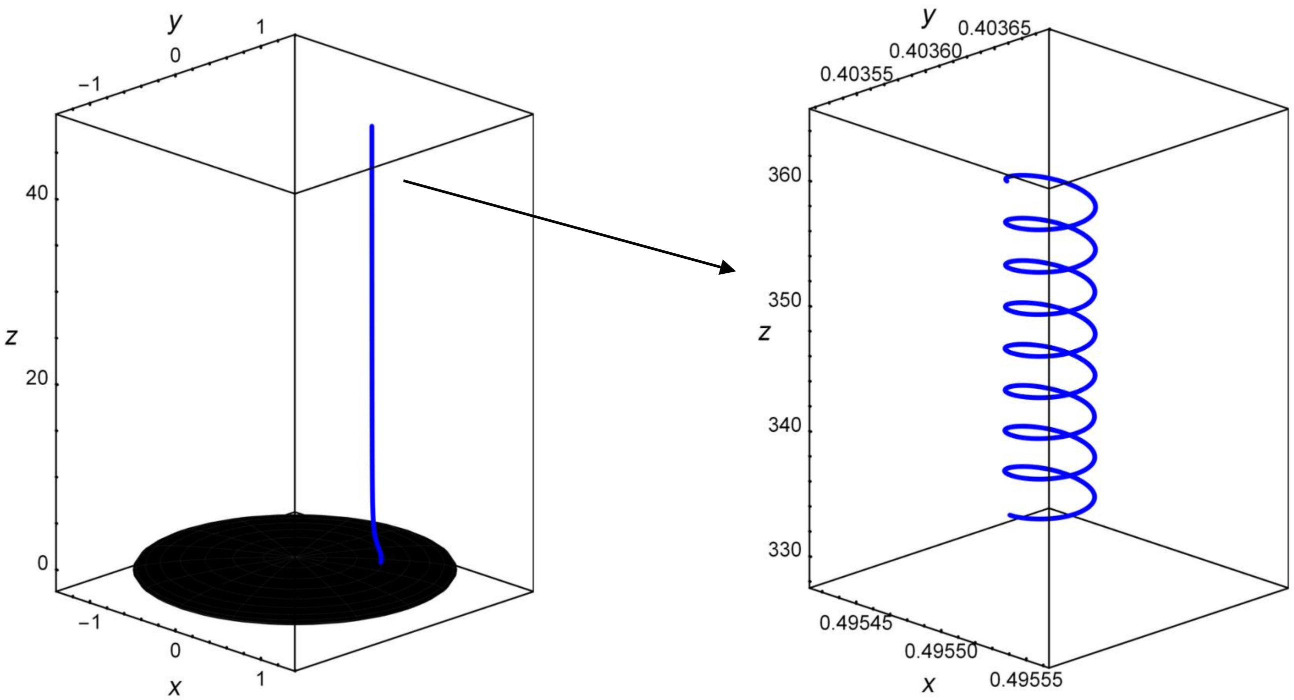
E



Dynamic of charged particles

- Electromagnetic parameter $\omega_B = \frac{qB_0}{m}$
- Numerical simulation of the particle motion
    - spontaneously vortical motion (SVM)

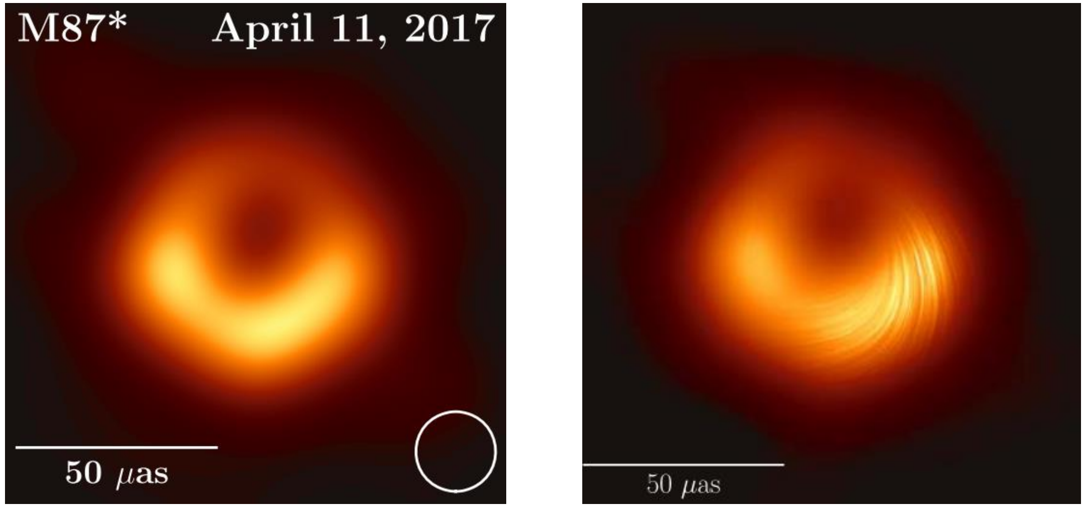
$$\omega_B = -5.59 \times 10^{12},$$
$$p_{\phi 0} = 0,$$
$$(r_0, \theta_0) = \left(2, \frac{\pi}{9}\right)$$



Questions

- What is the condition of SVM?

- As a source, can SVM radiation be detected from BH images ?



[3] Event Horizon Telescope Collaboration, K. Akiyama et al., arXiv:1906.11238
[4] Event Horizon Telescope Collaboration, K. Akiyama et al., arXiv:2105.01169

Dynamic of charged particles

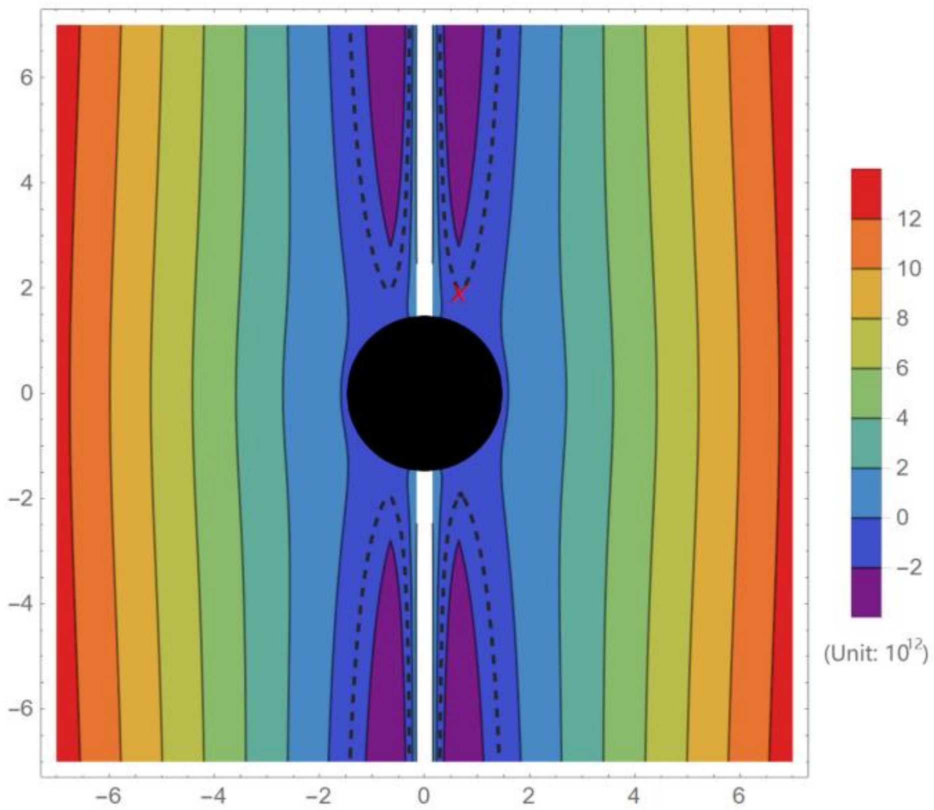
- Effective potential for SVM particles

$$V_{\text{eff}} = \frac{-\beta + \sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha}$$

$$\alpha = -g^{tt}$$

$$\beta = 2\left[g^{t\phi}\left(L - \frac{q}{m}A_\phi\right) - g^{tt}\frac{q}{m}A_t\right]$$

$$\gamma = -g^{\phi\phi}\left(L - \frac{q}{m}A_\phi\right)^2 - g^{tt}\frac{q^2}{m^2}A_t^2 + 2g^{t\phi}\frac{q}{m}A_t\left(L - \frac{q}{m}A_\phi\right) - 1$$



$\omega_B = -5.59 \times 10^{12}, (r_0, \theta_0) = \left(2, \frac{\pi}{9}\right)$

- Particles can only move in regions where V_{eff} is lower than initial V_{eff}

Set $G = c = M = 1$

Dynamic of charged particles

- Critical parameter ω_c

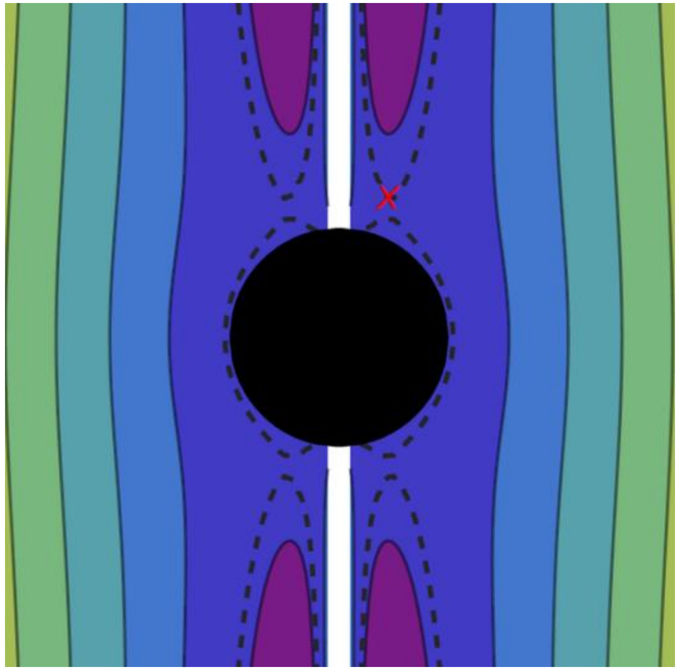
Solve $F_z^{\text{eff}} = -\partial_z V_{\text{eff}} = 0$
at the initial position

➡ ω_c

For example,
for $(r_0, \theta_0) = \left(2, \frac{\pi}{9}\right)$ & $p_{\phi_0} = 0$

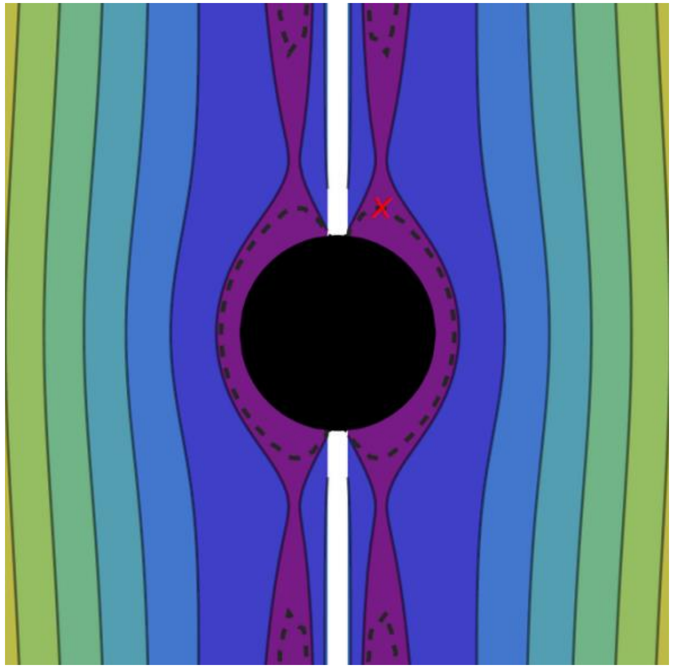
➡ $\omega_c = -1.4$

$|\omega_B| > |\omega_c|$



$\omega_B = -1.7, (r_0, \theta_0) = \left(2, \frac{\pi}{9}\right)$

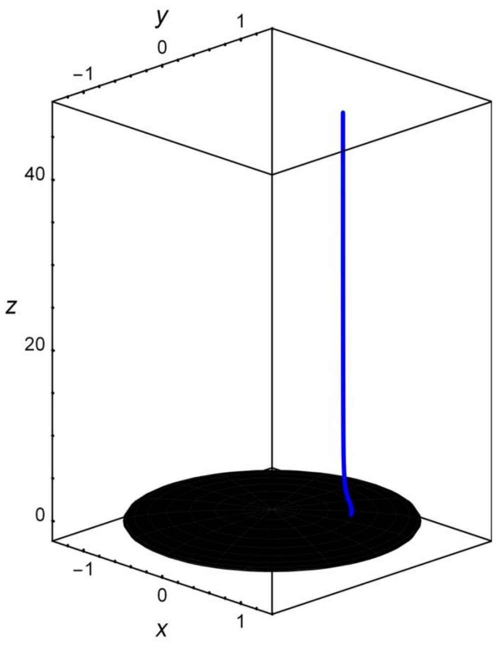
$|\omega_B| < |\omega_c|$

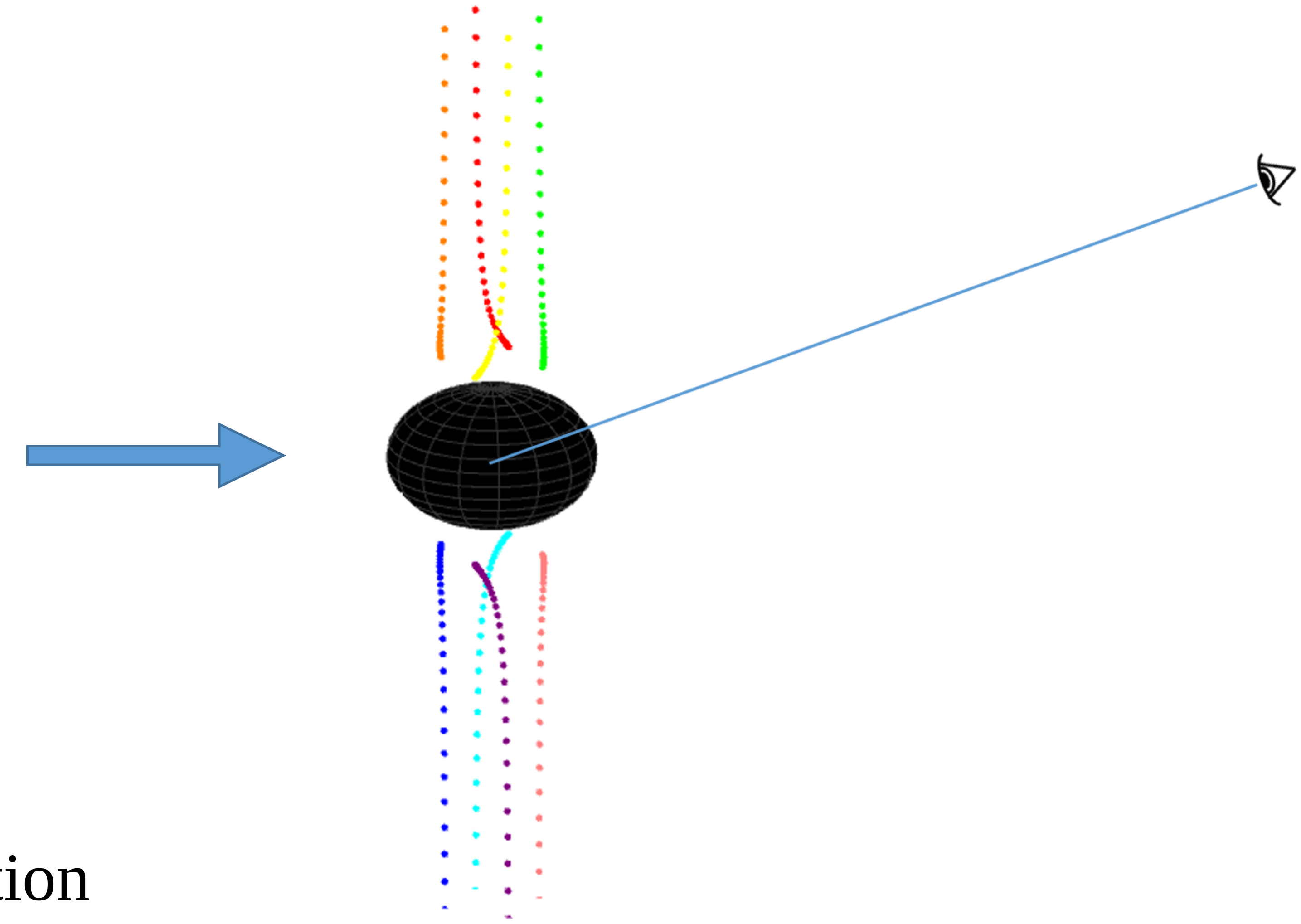


$\omega_B = -1, (r_0, \theta_0) = \left(2, \frac{\pi}{9}\right)$

Imaging method

- Backward ray-tracing

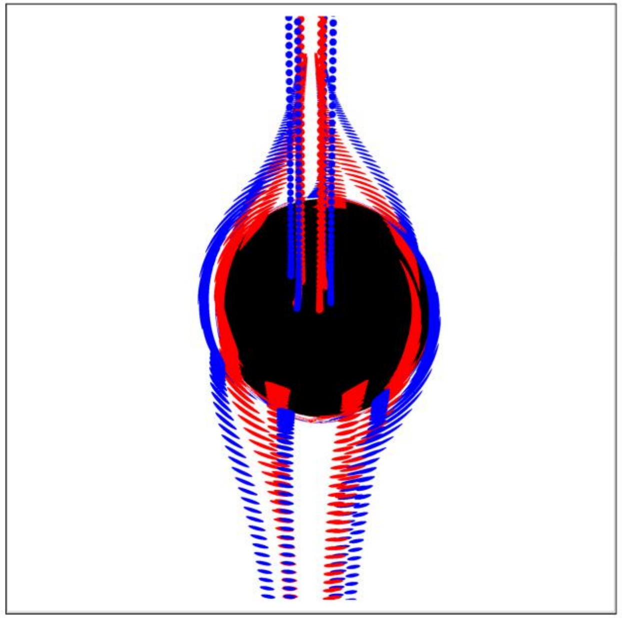


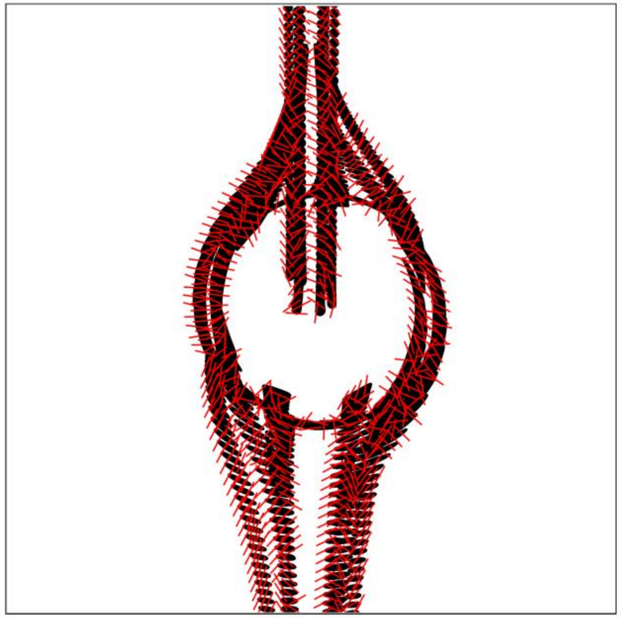


- Intensity and polarization
  - Synchrotron radiation

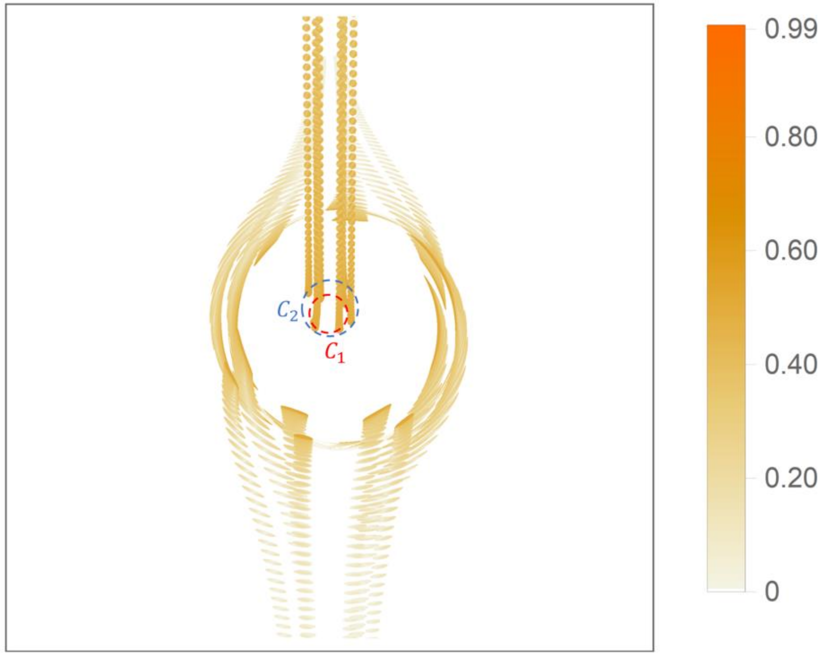
Images

- 16 trajectories
  - $r_0 = 2$ (red), $r_0 = 3$ (blue)
  - Form a ring structure





- Intensity
  - Northern hemisphere >> Southern hemisphere
  - Critical curve (ring structure) ~ primary image
  - Differ from the EHT observation



Observed at $\theta_o = 17°$

Answers

- What is the condition of SVM?

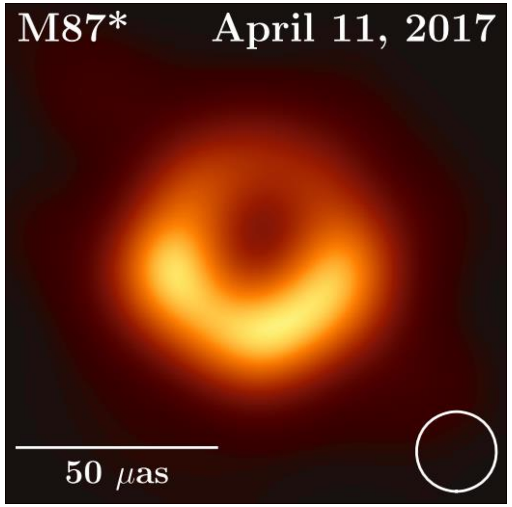
Electromagnetic Force

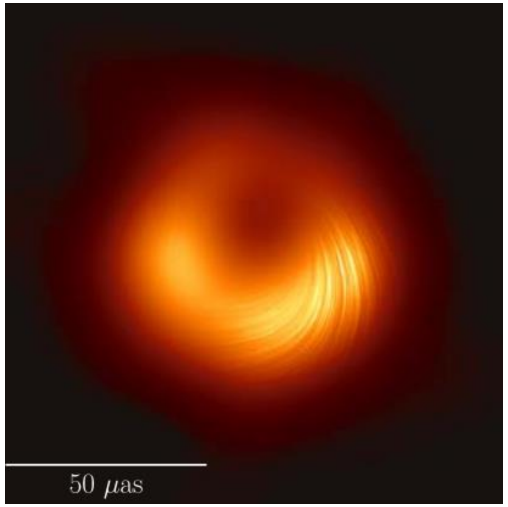
Gravity

Solve $F_z^{\text{eff}} = -\partial_z V_{\text{eff}} = 0$ at the initial position and obtain the critical parameter ω_c.

- As a source, can SVM radiation be detected from BH images ?

Probably NOT.
Images of SVM particles are quite different from EHT observations.





See our paper (arXiv:2304.03642) for more details

Thanks for listening!