2024引力与宇宙学专题研讨会

Images of Konoplya-Zhidenko rotating black holes with magnetized Accretion Disks

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2024.11.17 中国科技大学

Outline

1. Introduce of black hole images

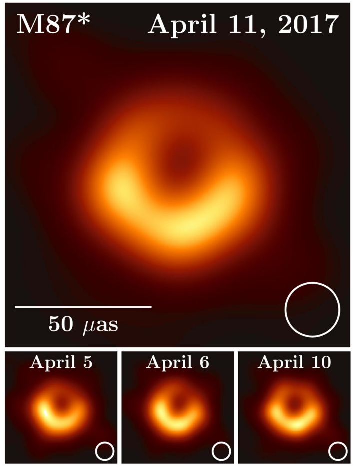
2. Images of Konoplya-Zhidenko black holes

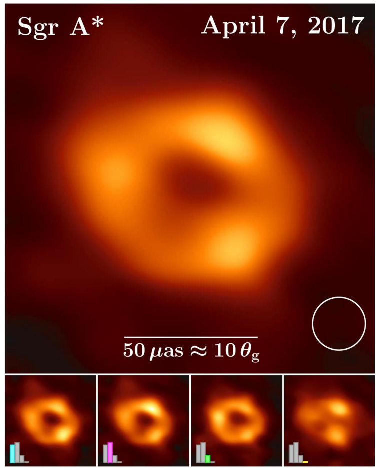
   - Geometrically thick magnetized equilibrium tori

   - Dynamically thick magnetized accretion disk

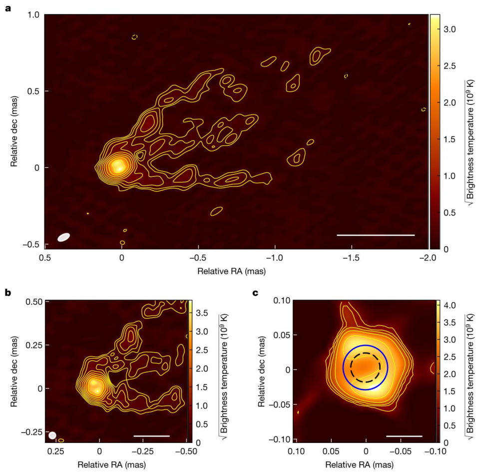
3. Summary

1.Observational Images of M87 and SgrA*

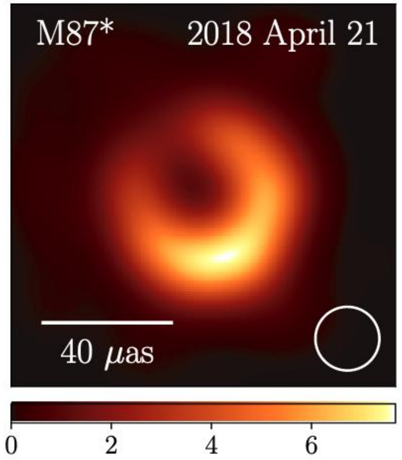




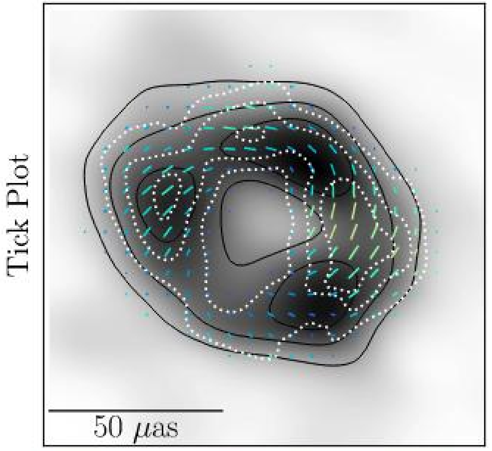
2019 *ApJL* **875** L1
2022 *ApJL* **930** L12
Event Horizon Telescope Collaboration, et al.

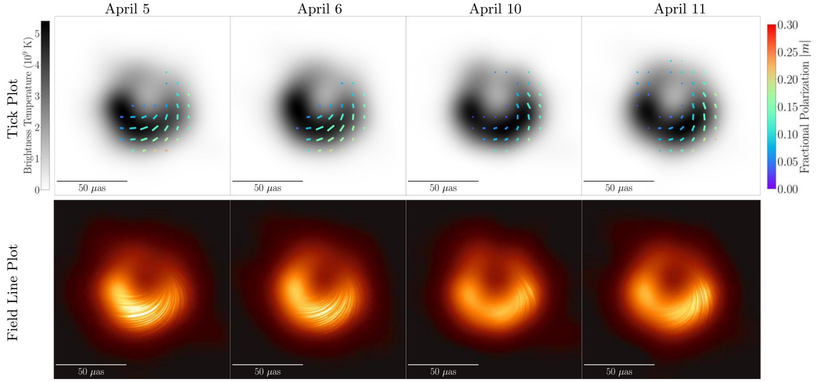


2023 *Nature* **616** 686
Lu, R. S., Asada, K., Krichbaum, T. P., et al.

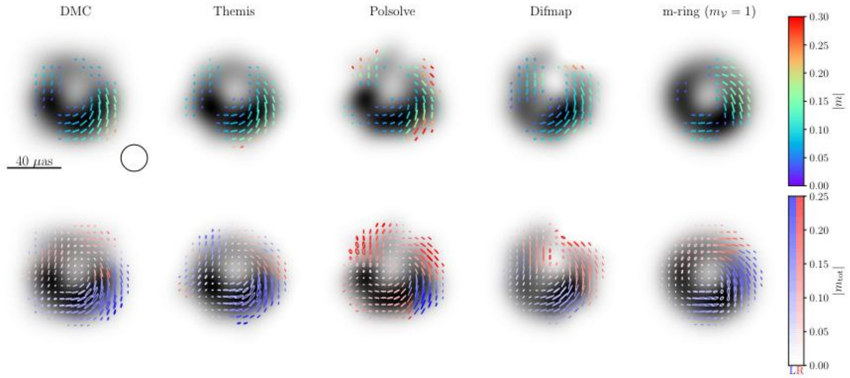


2024 *A&A* **681** A79
EHT Collaboration, et al.

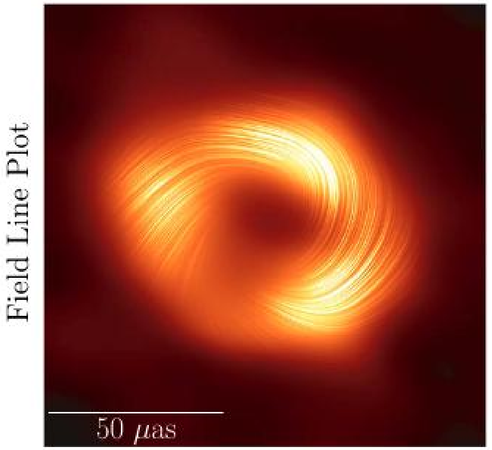




2021 *ApJL* **910** L12 EHT Collaboration, et al.



2023 *ApJL* **957** L20 EHT Collaboration, et al.



2024 *ApJL* **964** L25 EHT Collaboration, et al.

事件视界望远镜项目组 (EHT)

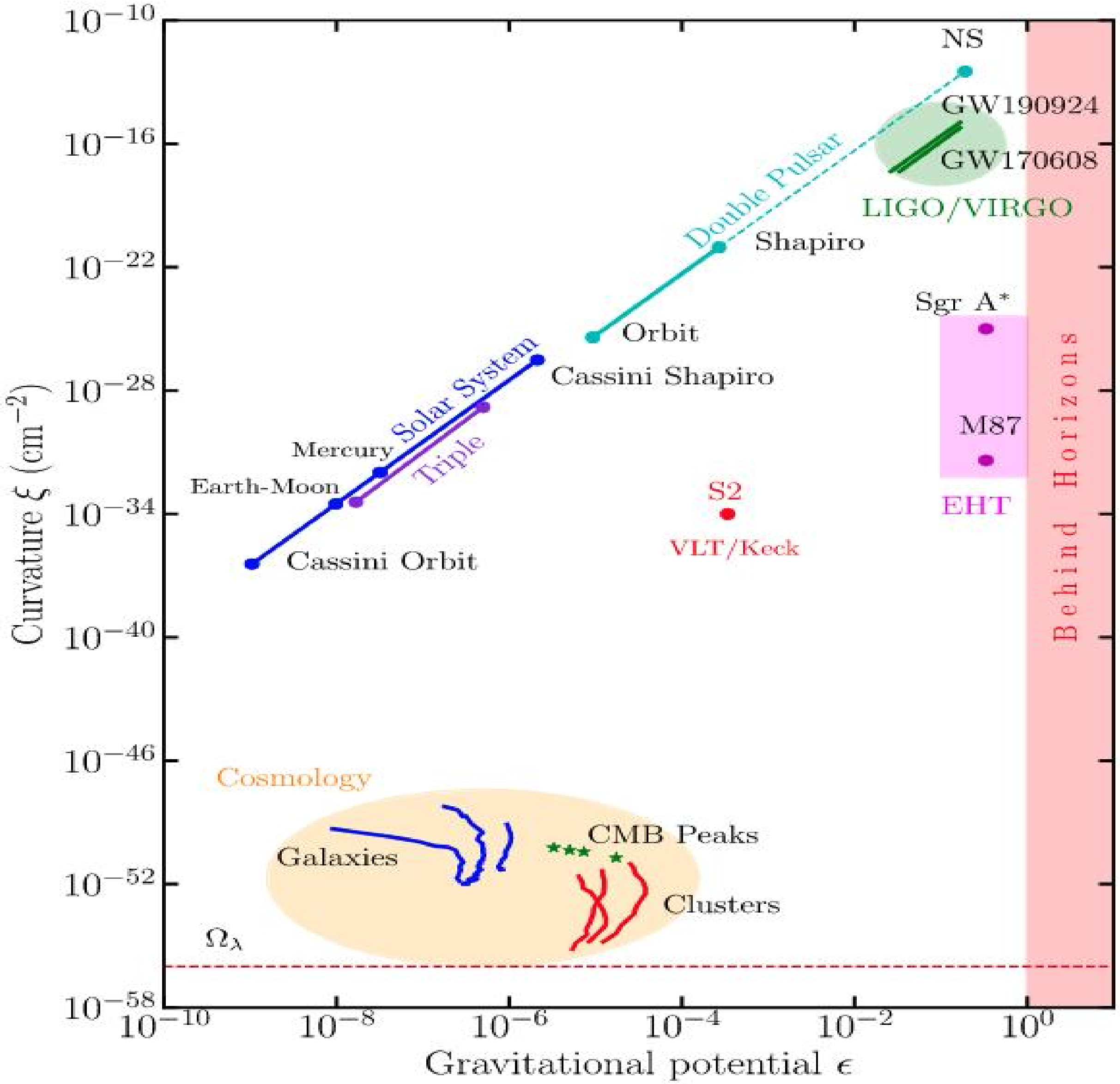
2020年突破奖----基础物理学奖

直接验证了黑洞的存在

有助于检验包括广义相对论在内的引力理论。

有助于理解强引力场中物质的分布和运动及其相关物理。

Testing the Theory of Gravity



- **[Non-rotating Dilaton BH,** GRMHD**]** Mizuno Y., et al., 2018, NatAs, 2, 585.
- **[Equivalence Principle]** Yan S.F., et al., 2020, PhRvR, 2, 023164.
- **[STVG,** Polarization**]** Qin X., et al., 2022, ApJ, 938, 2.
- **[Axion,** Polarization**]** Chen Y., et al., 2022, NatAs, 6, 592.
- **[Horndeski Gravity]** Afrin M., et al.,2022, ApJ, 932, 51.
- **[Lorentz symmetry]** Khodadi M., et al., 2022, PhRvD, 106, 104050.
- **[Modified Gravity]** Kuang X.M., et al., 2022, PhRvD, 106, 064012.
- **[Loop Quantum Gravity,** GRMHD**]** Jiang H.-X., et al., 2024, JCAP, 101.
- **[Naked singularity,** GRMHD**]** Dihingia I.~K., et al., 2024, arXiv:2410.13406.
- **[Wormholes,** GRMHD**]** Combi L., et al., 2024, PhRvD, 109, 103034.

2022 *ApJL* **930** L17 EHT Collaboration, et al.

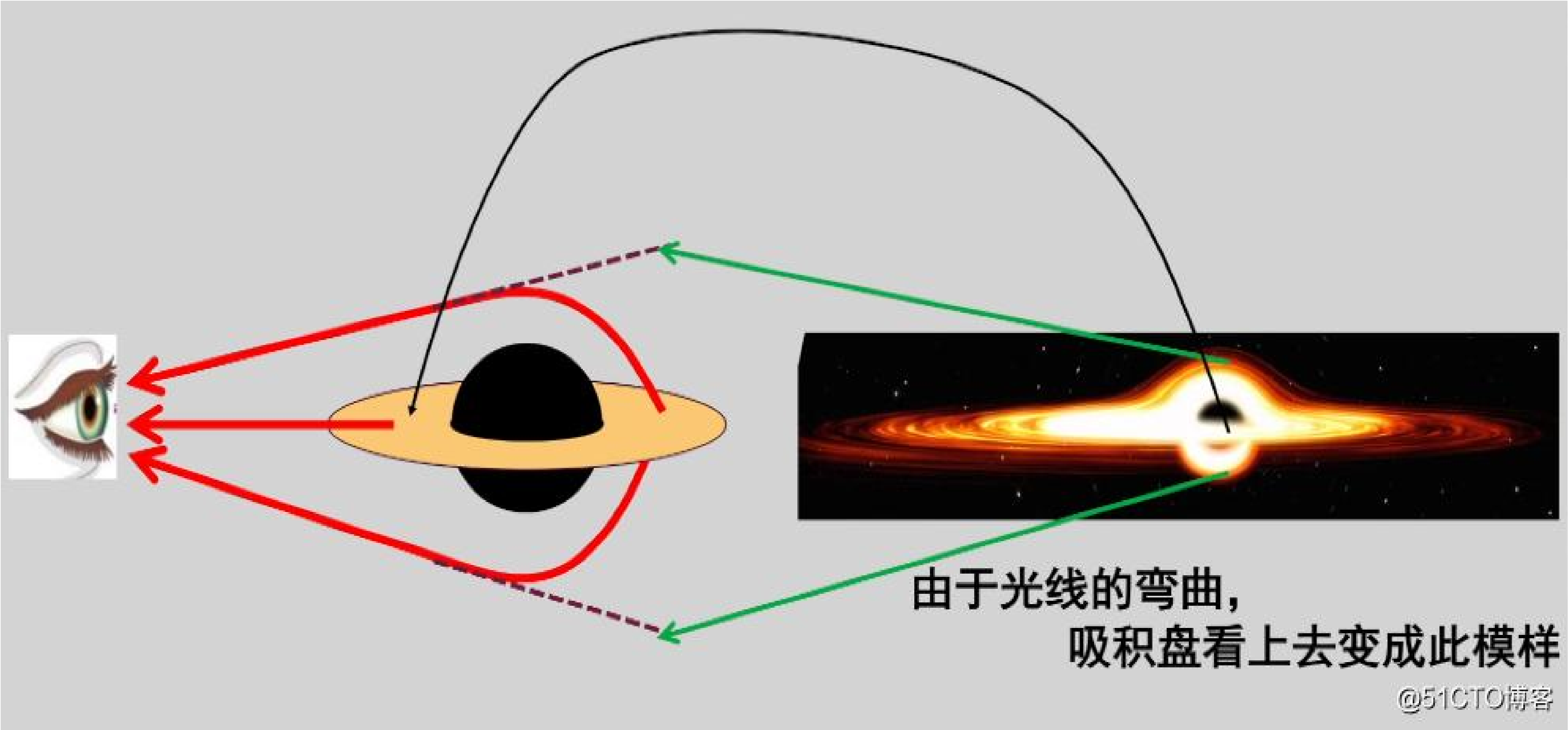
黑洞图像取决于：

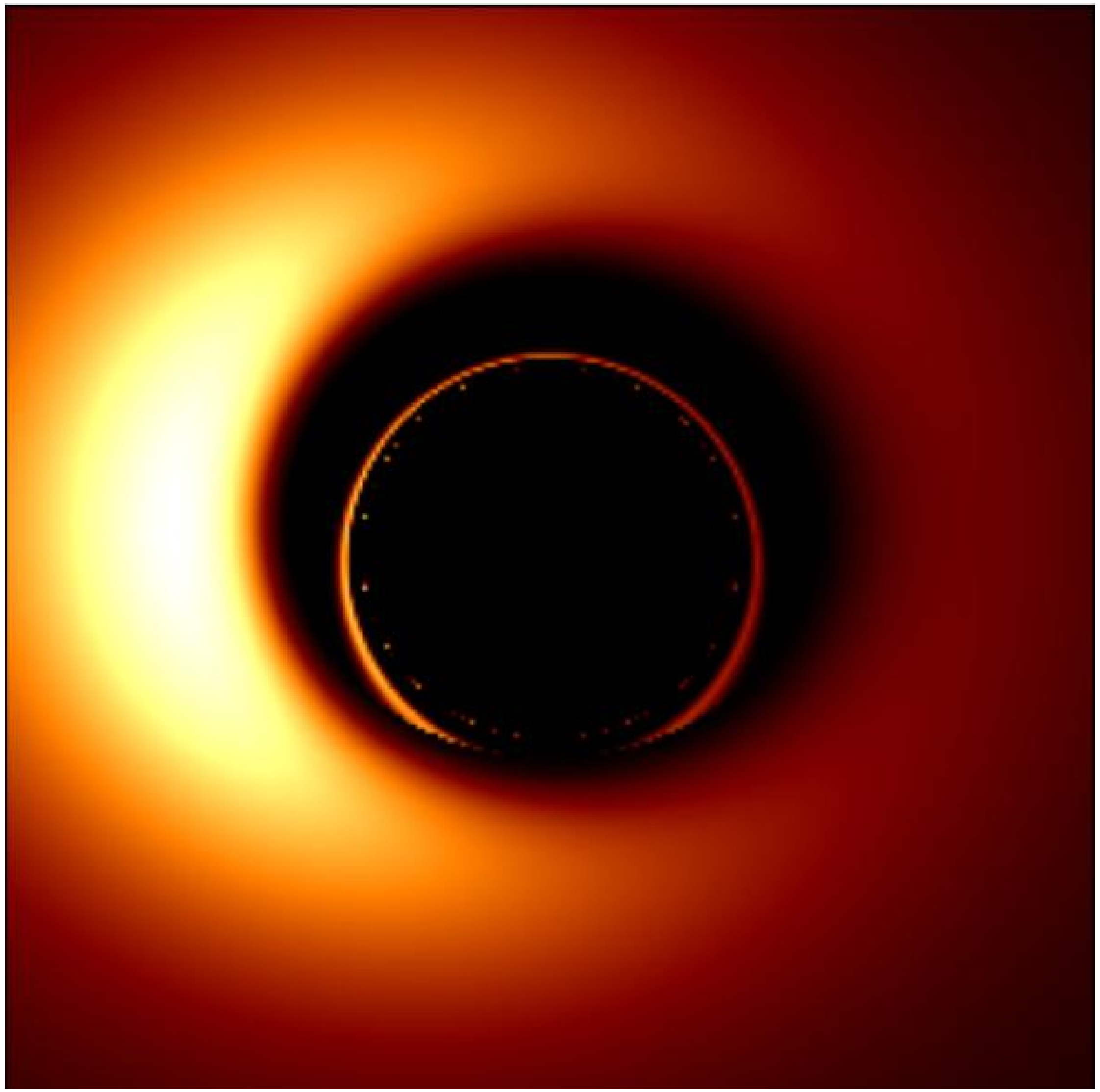
黑洞本身的时空特征

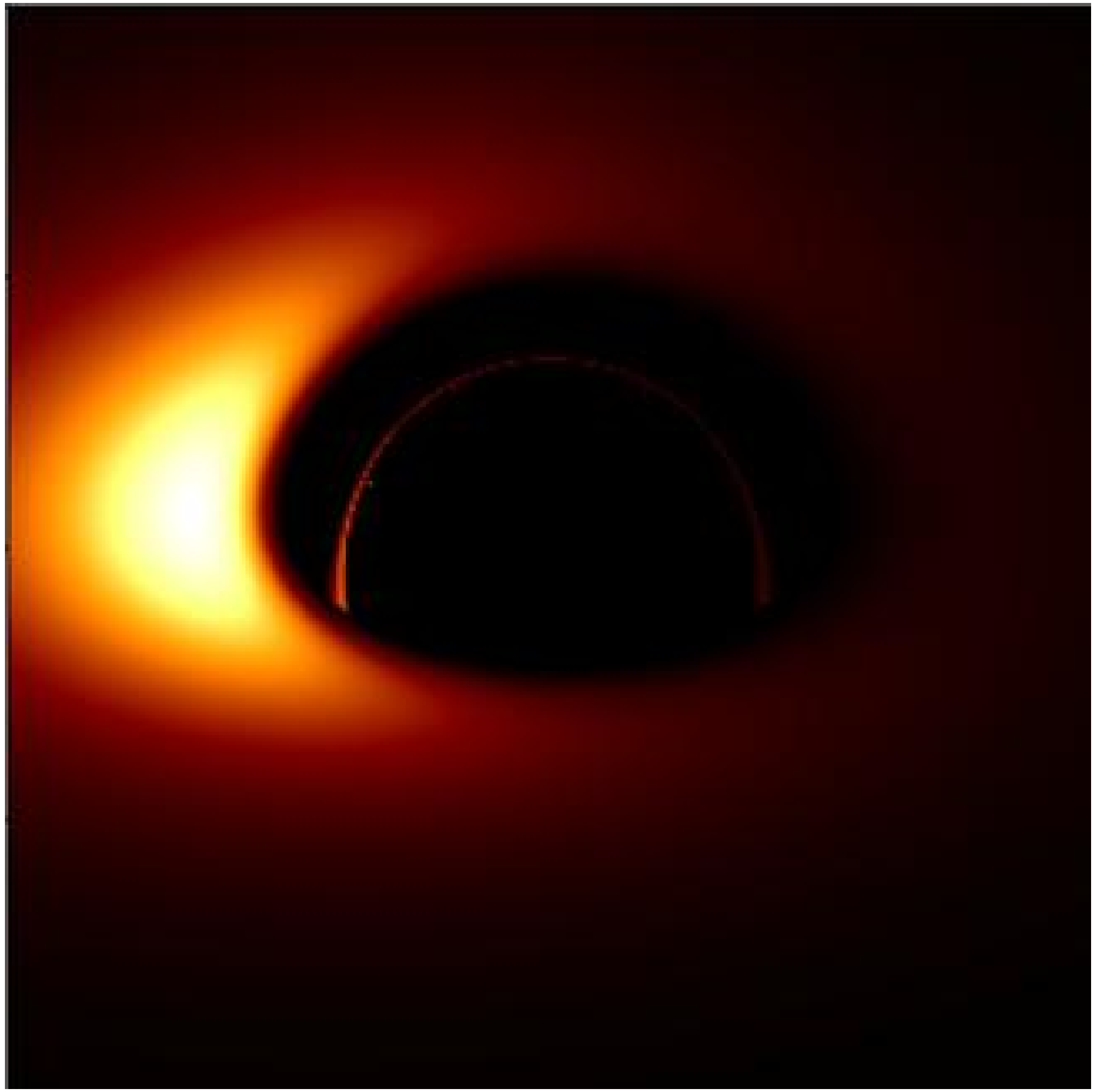
吸积盘中的流体动力学过程以及辐射机制

辐射在黑洞时空中的传输过程

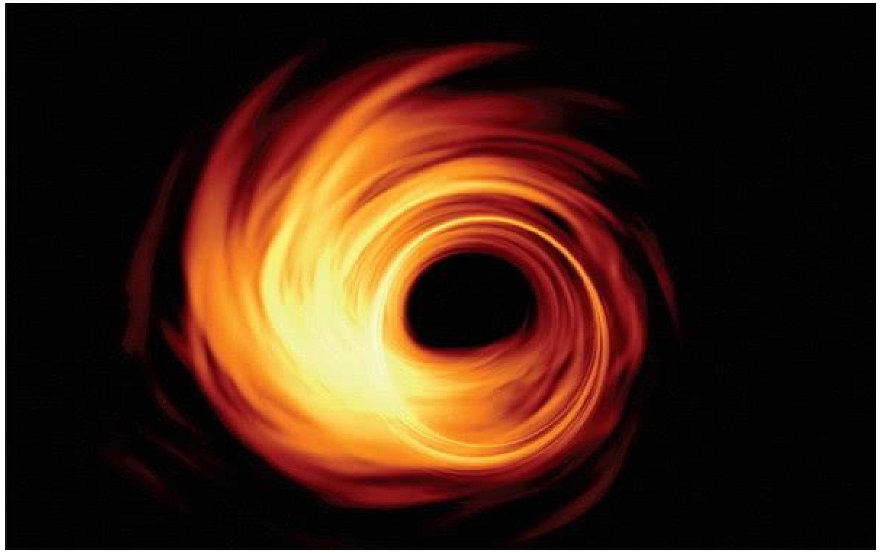
薄盘

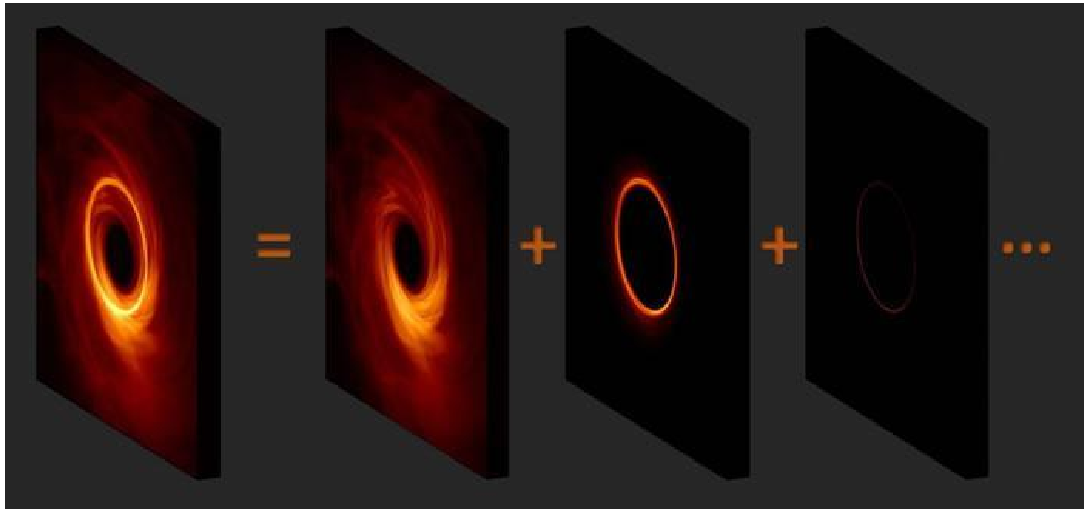


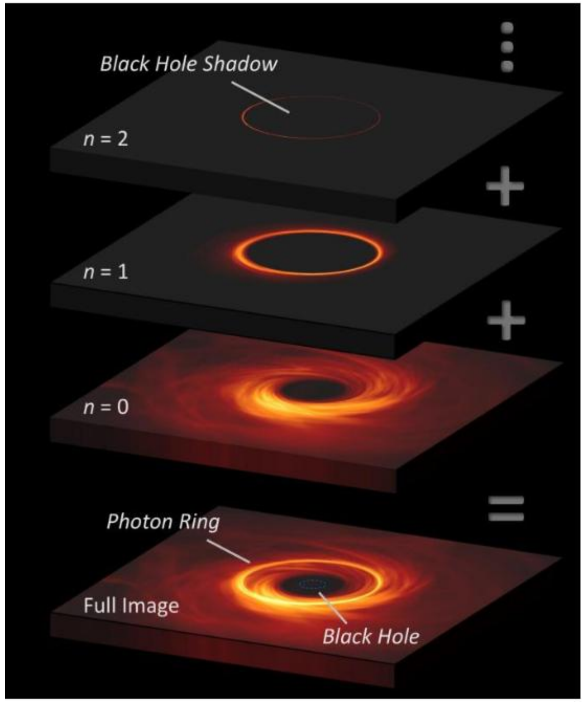




黑洞几何厚盘图像一般特征







检验非爱因斯坦引力理论的思路

1. 找出非爱因斯坦引力理论的黑洞解及其可观测的特征信息

2. 在Kerr黑洞时空直接加入一些偏离参数：可观测的特征信息

2.Konoplya-Zhidenko BH Metric

Konoplya R., Zhidenko A., PhLB, 756, 350 (2016)

$$ds^2 =-\left(1-\frac{2Mr^2+\eta}{r\rho^2}\right)^2 dt^2+\frac{\rho^2}{\Delta}dr^2+\rho^2 d\theta^2+$$

$$sin^2\theta\left[r^2+a^2+\frac{(2Mr^2+\eta)a^2 sin^2\theta}{r\rho^2}\right]d\phi^2$$

$$-2\left(\frac{2Mr^2+\eta}{r\rho^2}\right)a sin^2\theta dt d\phi$$

$$\Delta=r^2-2Mr+a^2-\frac{\eta}{r} \qquad \rho^2=r^2+a^2 cos^2\theta$$

Static deformation from Kerr BH $M \rightarrow M+\frac{\eta}{2r^2}$

$$\eta_1=\frac{2}{27}\left(\sqrt{4M^2-3a^2}-2M\right)^2\left(\sqrt{4M^2-3a^2}+M\right)$$

$$\eta_2=-\frac{2}{27}\left(\sqrt{4M^2-3a^2}+2M\right)^2\left(\sqrt{4M^2-3a^2}-M\right)$$

Horizons	Parameter range
0	$\eta<\eta_2<0$ or $\lvert a\rvert>\frac{2\sqrt{3}}{3}$ & $\eta<0$
1	$\eta>\eta_1$ or $0<\eta<\eta_2$ or $\lvert a\rvert>\frac{2\sqrt{3}}{3}$ & $\eta>0$
2	$\eta_2\leq\eta\leq 0$ or $\eta=\eta_1$
3	$0<\eta<\eta_1$ & $\eta_2<0$ or $\eta_2<\eta<\eta_1$ & $\eta_2>0$

几何厚盘成像要解决的问题：

（1）盘的几何形状、物质分布和动态演化及亮度分布

3+1 GRMHD equations

Valencia Formulation: No Christoffel symbols but only metric derivatives on the rhs

Conserved Form

$$\partial_t(\sqrt{\gamma}\mathbf{U}) + \partial_i(\sqrt{\gamma}\mathbf{F}^i) = \sqrt{\gamma}\mathbf{S}$$

Metric : $ds^2 = -\alpha^2 dt^2 + \gamma_{ij}(dx^i + \beta^i dt)(dx^j + \beta^j dt)$

α: lapse function, β^i: shift vector

Primitive variables　Conserved variables　Flux

$$\mathbf{P} = \begin{bmatrix} \rho \\ \Gamma v^j \\ p \\ B^j \\ \phi \end{bmatrix} \quad \mathbf{U} = \begin{bmatrix} D \\ S_j \\ \tau \\ B^j \\ \phi \end{bmatrix} \quad \mathbf{F}^i = \begin{bmatrix} \mathcal{V}^i D \\ \alpha W^i_j - \beta^i S_j \\ \alpha(S^i - v^i D) - \beta^i \tau \\ \mathcal{V}^i B^j - B^i \mathcal{V}^j - B^i \beta^j \\ \alpha B^i - \phi \beta^i \end{bmatrix}$$

transport velocity

$$\mathcal{V}^i = \alpha v^i - \beta^i$$

Magnetic field 4-vector

$$b^0 = \Gamma(B^i v_i)/\alpha, \quad b^i = (B^i + \alpha b^0 u^i)/\Gamma$$

Source term

$$\mathbf{S} = \begin{bmatrix} 0 \\ \frac{1}{2}\alpha W^{ik}\partial_j\gamma_{ik} + S_i\partial_j\beta^i - U\partial_j\alpha \\ \frac{1}{2}W^{ik}\beta^j\partial_j\gamma_{ik} + W^j_i\partial_j\beta^i - S^j\partial_j\alpha \\ -B^i\partial_i\beta^j - \alpha\gamma^{ij}\partial_i\phi \\ -\alpha\kappa\phi - \phi\partial_i\beta^i - \frac{1}{2}\phi\gamma^{ij}\beta^k\partial_k\gamma_{ij} + B^i\partial_i\alpha \end{bmatrix}$$

$$D := \rho\Gamma$$

$$S_j := (\rho h + b^2)\Gamma^2 v_j - \alpha b^0 b_j$$

$$\tau := (\rho h + b^2)\Gamma^2 - (p + b^2/2) - \alpha^2(b^0)^2 - D$$

Energy-momentum tensor

$$T^{\mu\nu} = (\rho h + b^2)u^\mu u^\nu + (p + \frac{b^2}{2})g^{\mu\nu} - b^\mu b^\nu$$

$$W^{ij} := h^i_\mu h^j_\nu T^{\mu\nu}$$

For AMR grid, we solve “Augmented Faraday’s law”

$$\nabla_\nu(F^{*\mu\nu} - \phi g^{\mu\nu}) = -\kappa n^\mu \phi$$

广义相对论磁流体动力学

（2）盘上的辐射及其传输

- Observer $(t_0, r_0, \theta_0, \phi_0)$

- Geodesic equation

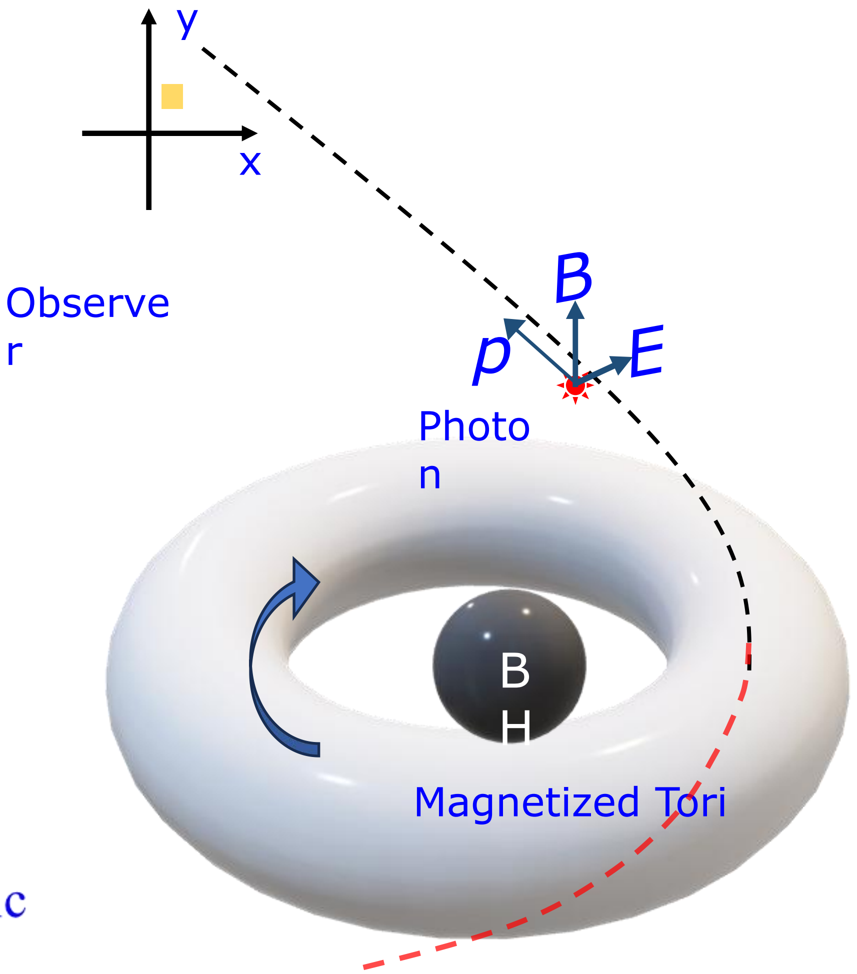
$$\ddot{x}^\mu + \Gamma^\mu_{\alpha\beta}\dot{x}^\alpha\dot{x}^\beta = 0$$

- Radiative transfer equation

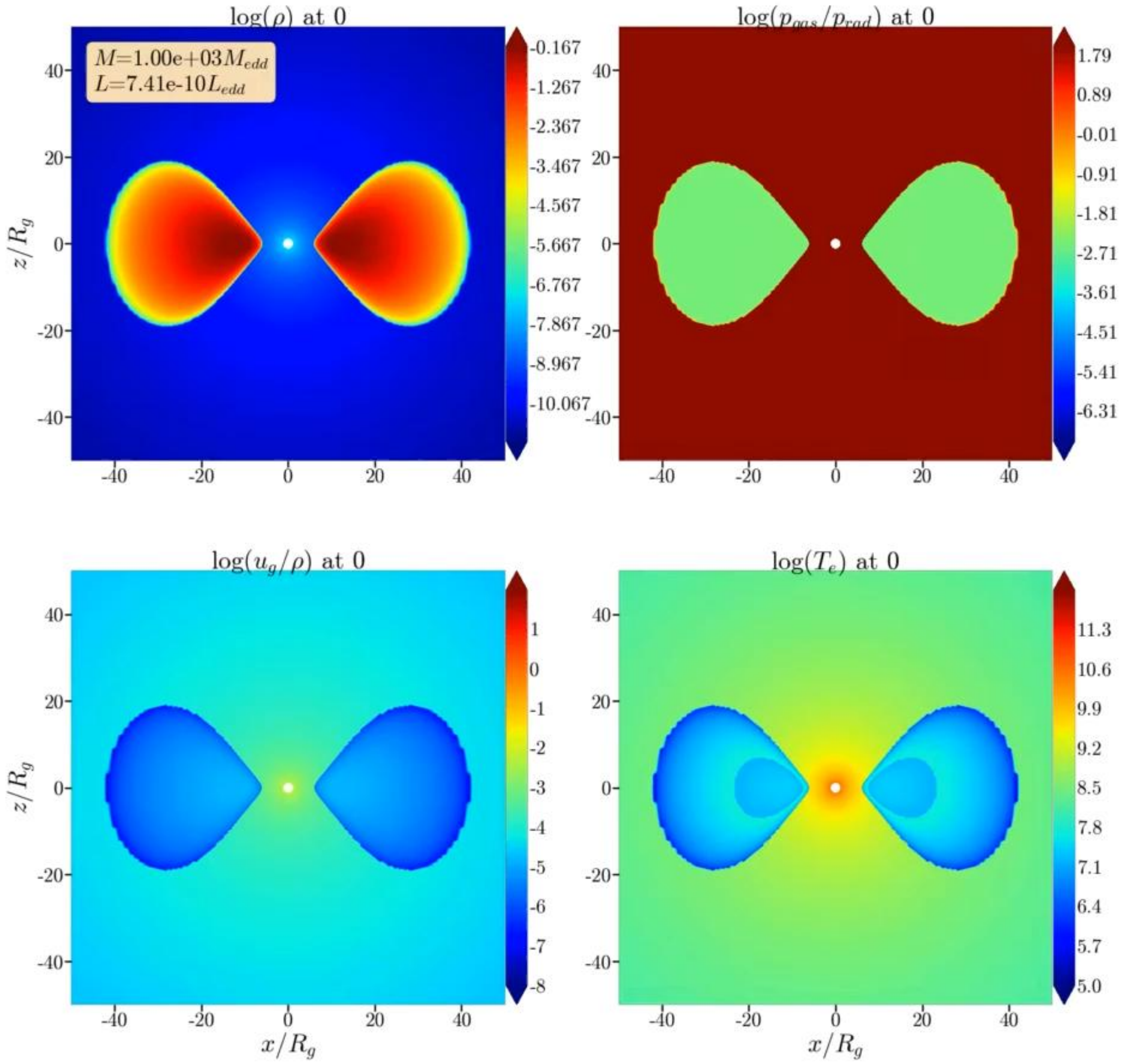
$$\frac{d\mathbb{I}\_\nu}{d\lambda} = L\frac{u_a(p_{obs})k^a(p_{obs})}{\nu_0}(\mathbb{J}_\nu - \mathbb{I}_\nu\mathbb{M}_\nu)$$

- Radiation type

Synchrotron emission from hot relativistic electrons



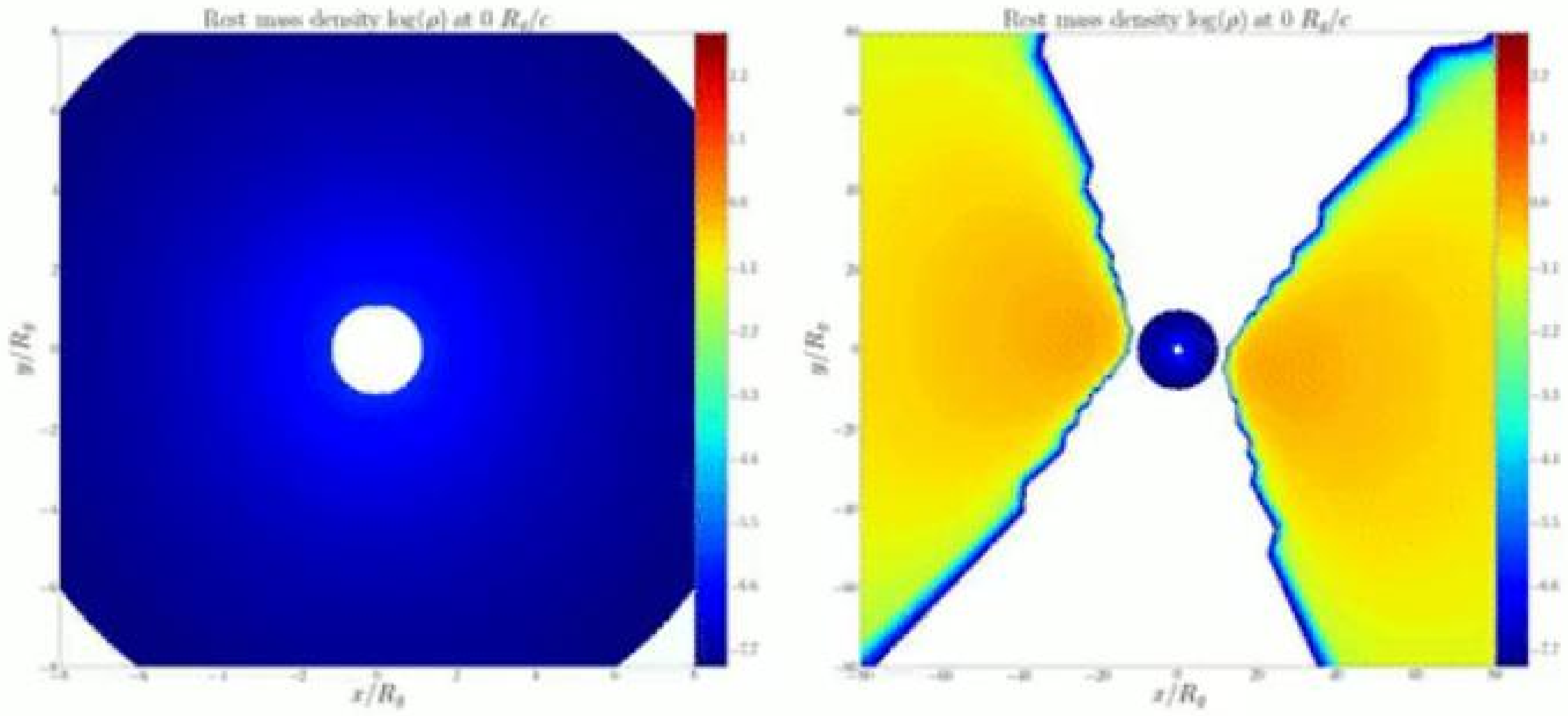
（3）要借助高精度的数值模拟



CPU144

2.6万元

Liska et al. 2023, arXiv:2309.15926.



缺点：复杂、算力要求高、烧钱、不便做一般性讨论

a) Geometrically thick magnetized equilibrium tori

- Basic Equations
  - $\nabla_\alpha T^{\alpha\beta} = 0, \quad \nabla_\alpha {}^*F^{\alpha\beta} = 0, \quad \nabla_\alpha \rho u^\alpha = 0$
  - Ideal relativistic MHD:

$$T^{\alpha\beta} = (h + b^2)u^\alpha u^\beta + \left(p + \frac{1}{2}b^2\right)g^{\alpha\beta} - b^\alpha b^\beta$$

  - enthalpy h, pressure p, 4-velocity u^α, magnetic field 4-vector b^α
  - $\Omega = u^\phi / u^t, \quad l = -u_\phi / u_t$
- Assumptions
  - Flow is both stationary and axisymmetric

$$g_{\mu\nu,t} = g_{\mu\nu,\phi} = 0, \quad f_{,t} = f_{,\phi} = 0$$

  - Velocity, magnetic field is purely azimuthal

$$u^r = u^\theta = 0, \quad b^r = b^\theta = 0$$

- Equipotential Surface
  - For a barotropic equation of state

$$h = h(p), \quad \tilde{h} = \tilde{h}(\tilde{p}_m), \quad \Omega = \Omega(l)$$

$$W - W_{in} + \int_0^p \frac{dp}{h} + \int_0^{\tilde{p}_m} \frac{d\tilde{p}_m}{\tilde{h}} = 0$$

where $W = ln|u_t| + \int_l^{l_\infty} \frac{\Omega dl}{1 - l\Omega}$ (potential)

  - Simplest case $\quad l = l_0$
  - Equation of state $\quad p = Kh^\kappa, \quad \tilde{p}_m = K_m \tilde{h}^\eta$

$$W - W_{in} + \frac{\kappa}{\kappa - 1}\frac{p}{h} + \frac{\eta}{\eta - 1}\frac{p_m}{h} = 0$$

Komissarov S.S., 2006, MNRAS, 368, 993.

该模型的优点:

盘的形状完全由黑洞度规和流体的比角动量决定。

盘上物质的分布

$$p = Kh^{\kappa}, \quad \tilde{p}_m = K_m \tilde{h}^{\eta}$$

$$W - W_{in} + \frac{\kappa}{\kappa - 1}\frac{p}{h} + \frac{\eta}{\eta - 1}\frac{p_m}{h} = 0$$

- Dimensionless parameter

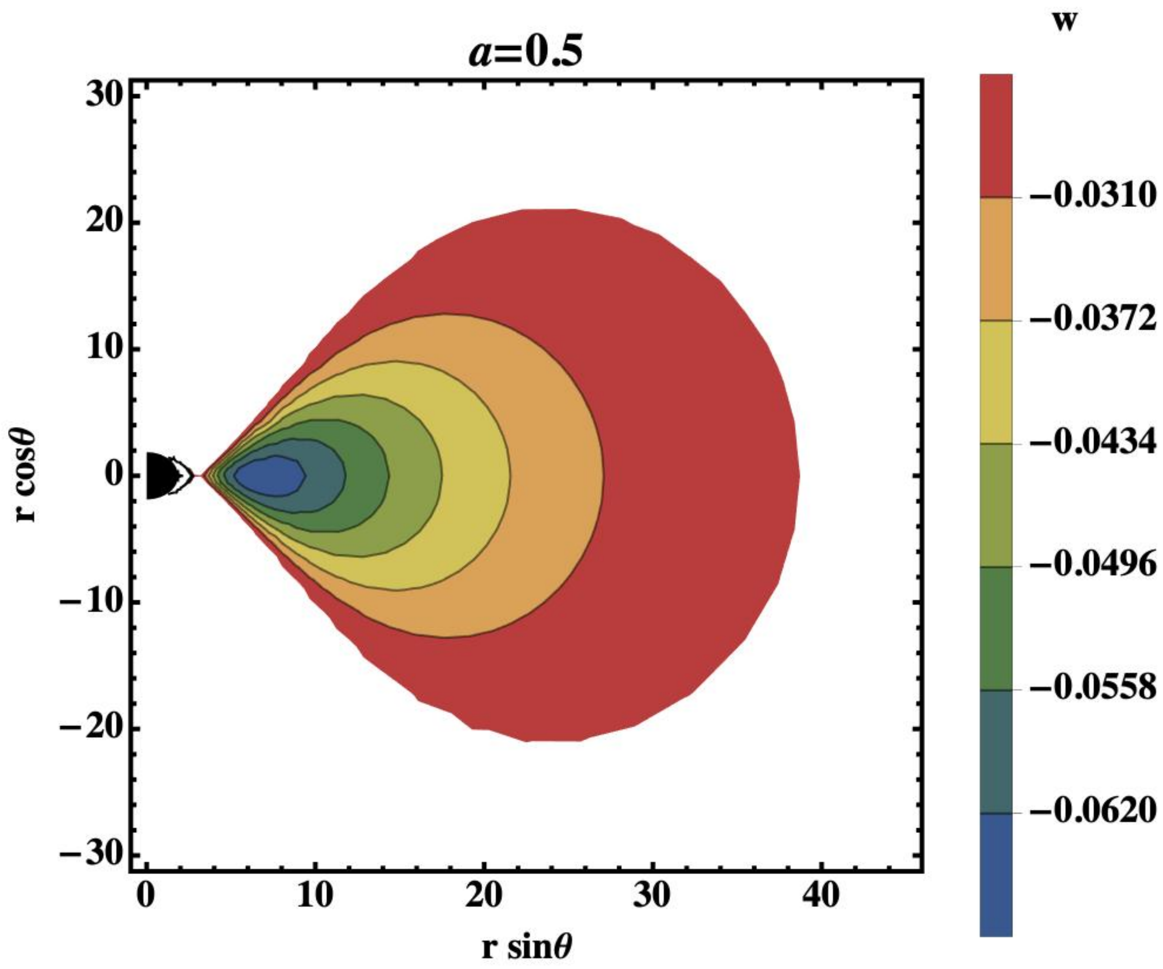
➢ Specific angular momentum

$$\lambda \equiv \frac{l_0 - l_{ms}}{l_{mb} - l_{ms}}, \quad 0 \le \lambda \le 1$$

➢ Potential

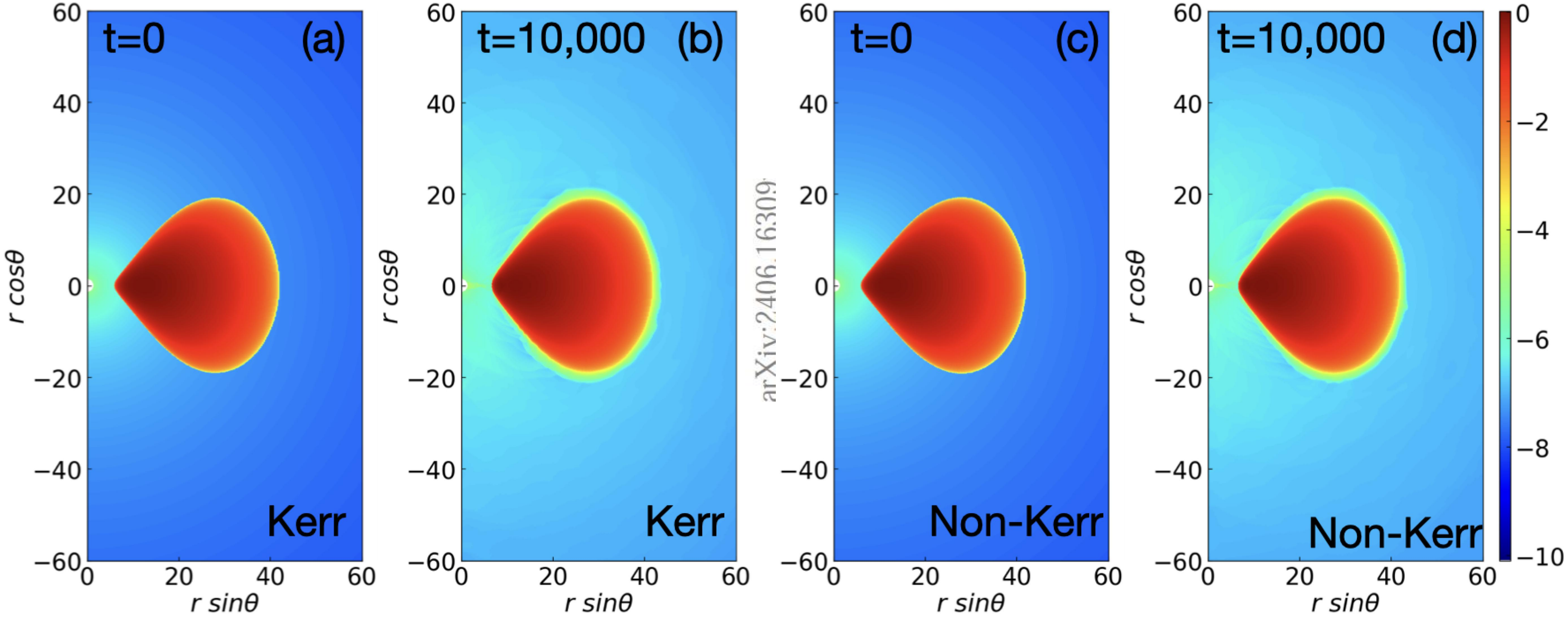
$$w(r,\theta) \equiv \frac{W(r,\theta) - W_{cusp}}{W_c - W_{cusp}}$$

Magnetized Tori



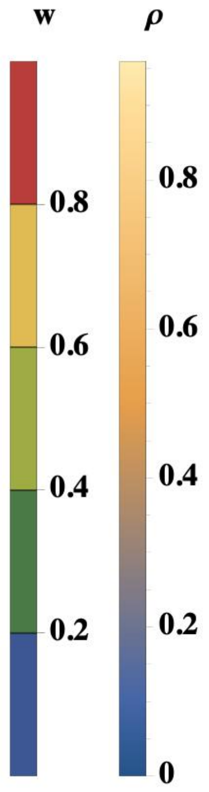
Parameters	Values
l_0	3.36
$\beta = p/p_m$	10
$\kappa,\ \eta$	4/3
r_{cusp}	3.01
r_c	6.74
W_{cusp}	-0.023
W_c	-0.067

该模型动力学演化稳定性好



arXiv:2406.16309

Equipotential surfaces and density distribution diagram



平衡环吸积盘的辐射：热电子，同步辐射

假设盘为低密度高温度盘，离子无碰撞

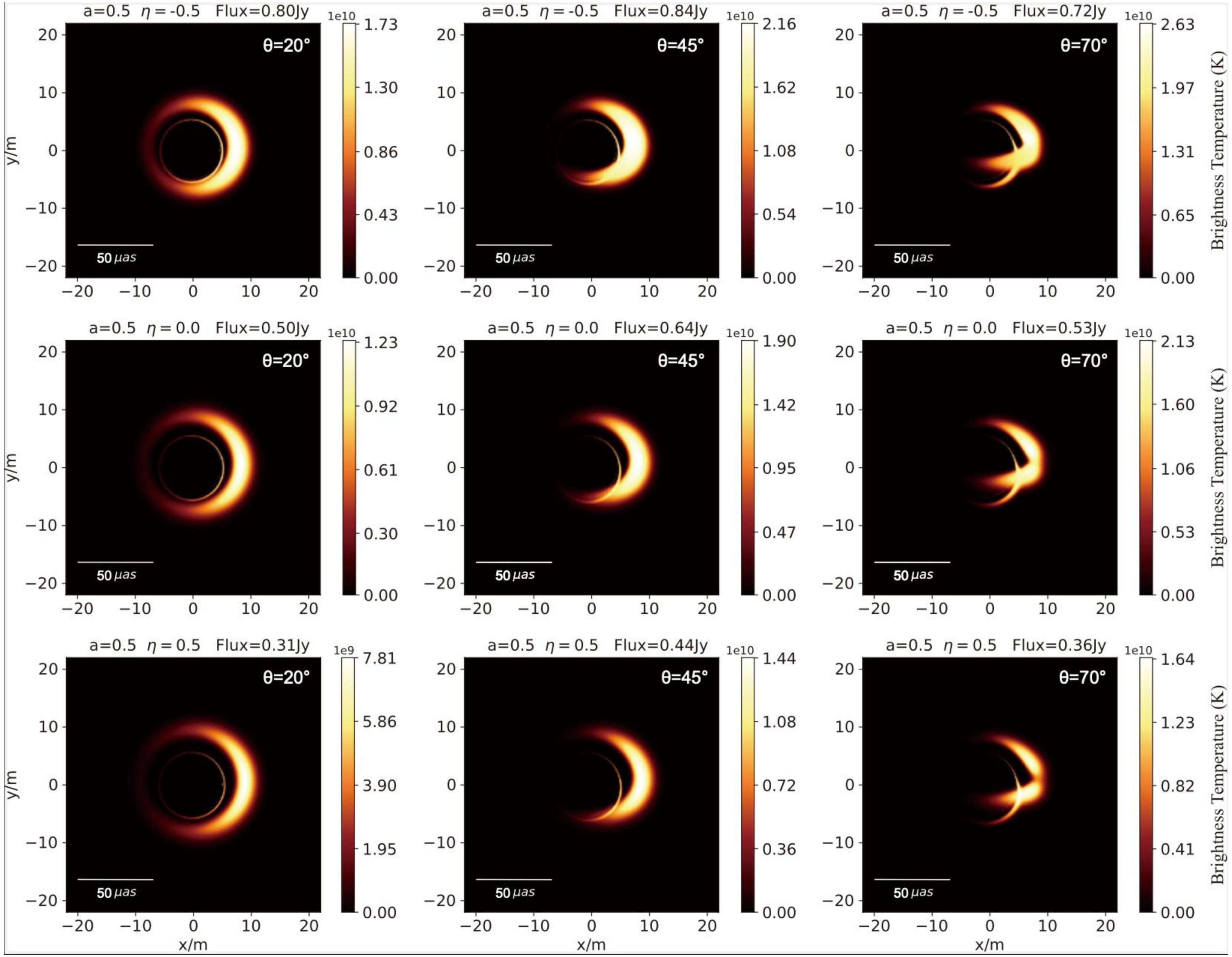
电子温度 $$T_e = \frac{2m_p u}{3k_B \rho (2+R)},$$

离子与电子温度比 $$R \equiv T_i/T_e$$

$$R = R_{high}\frac{\beta^2}{1+\beta^2} + \frac{1}{1+\beta^2},$$

β 等离子磁化参数

Images at different inclinations and parameters

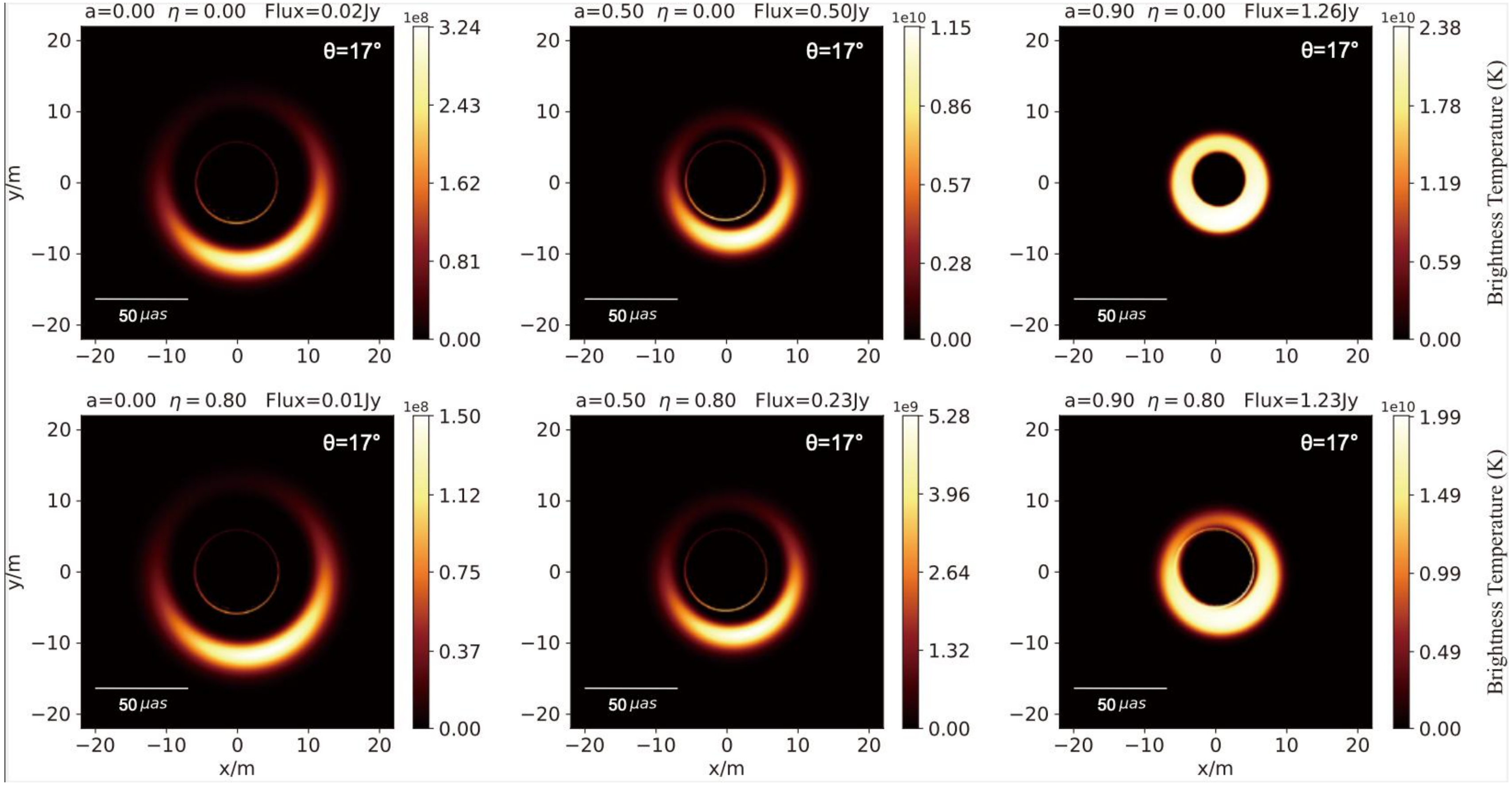


亮温

$$T_b = S\lambda^2/(2k_B\Omega),$$

ARCMANCER

Images with different η parameters at $\theta = 17°$ and $PA = 288°$

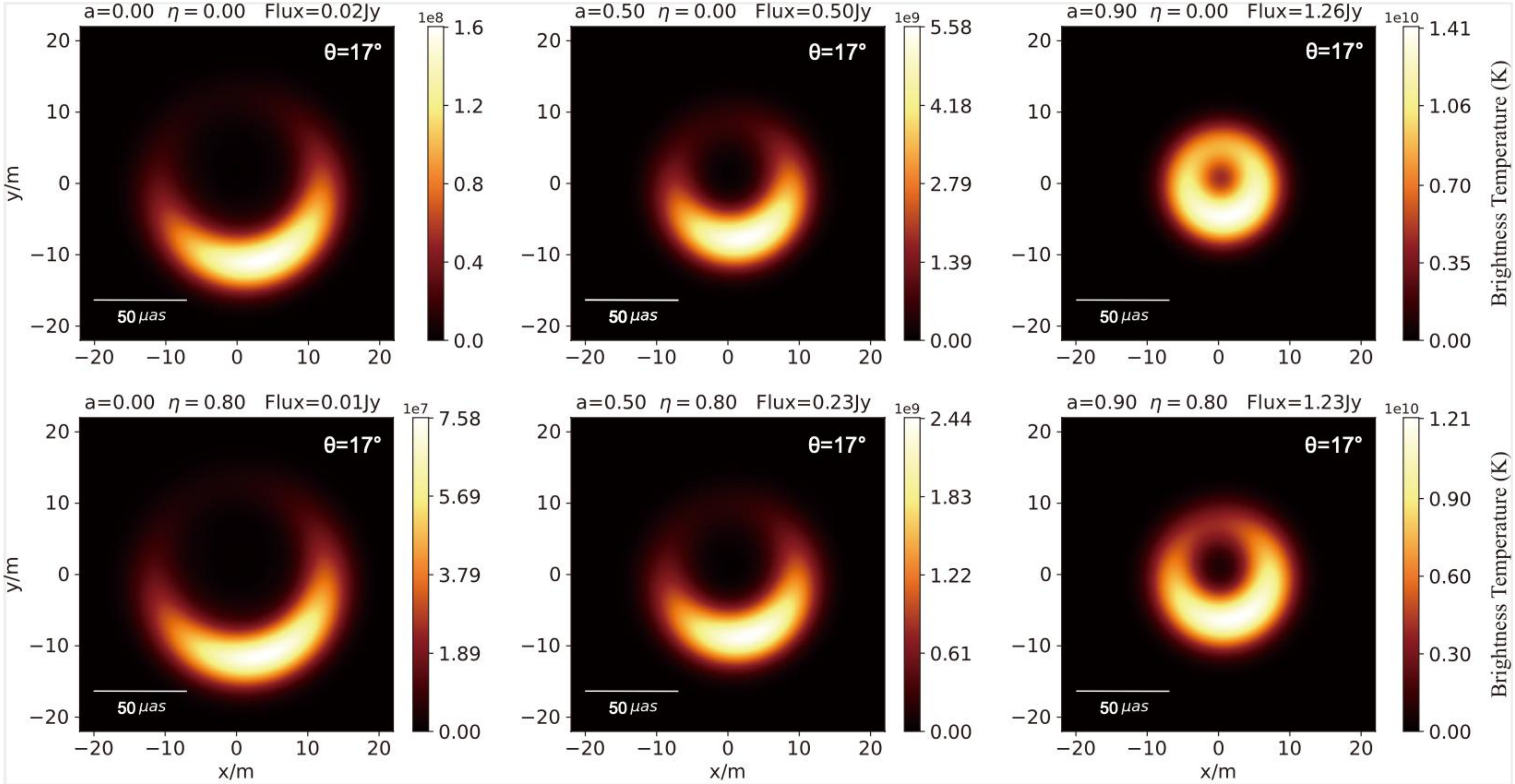


图像特征：

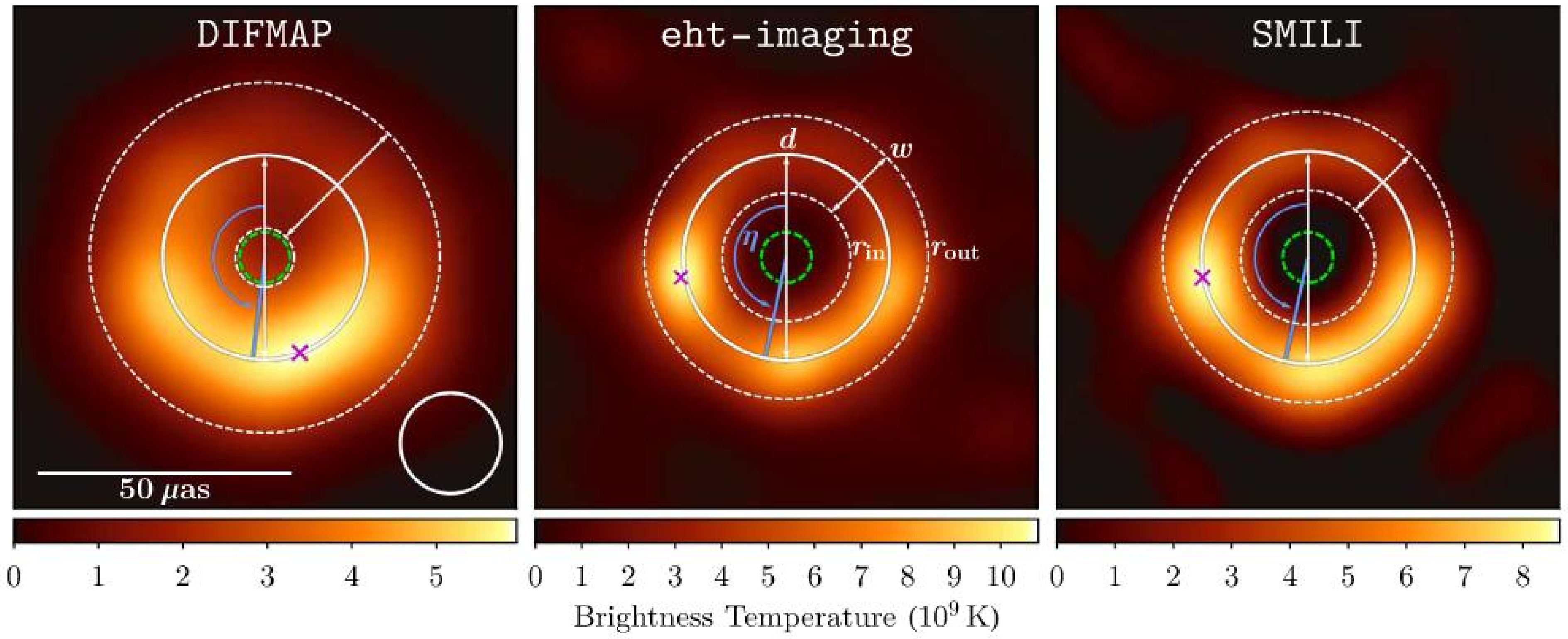
偏离参数使亮环变大

明亮区域位于光子环外面。主要原因为平衡环位于ISCO外面。

Images convolved with a $20\mu as$ FWHM Gaussian beam



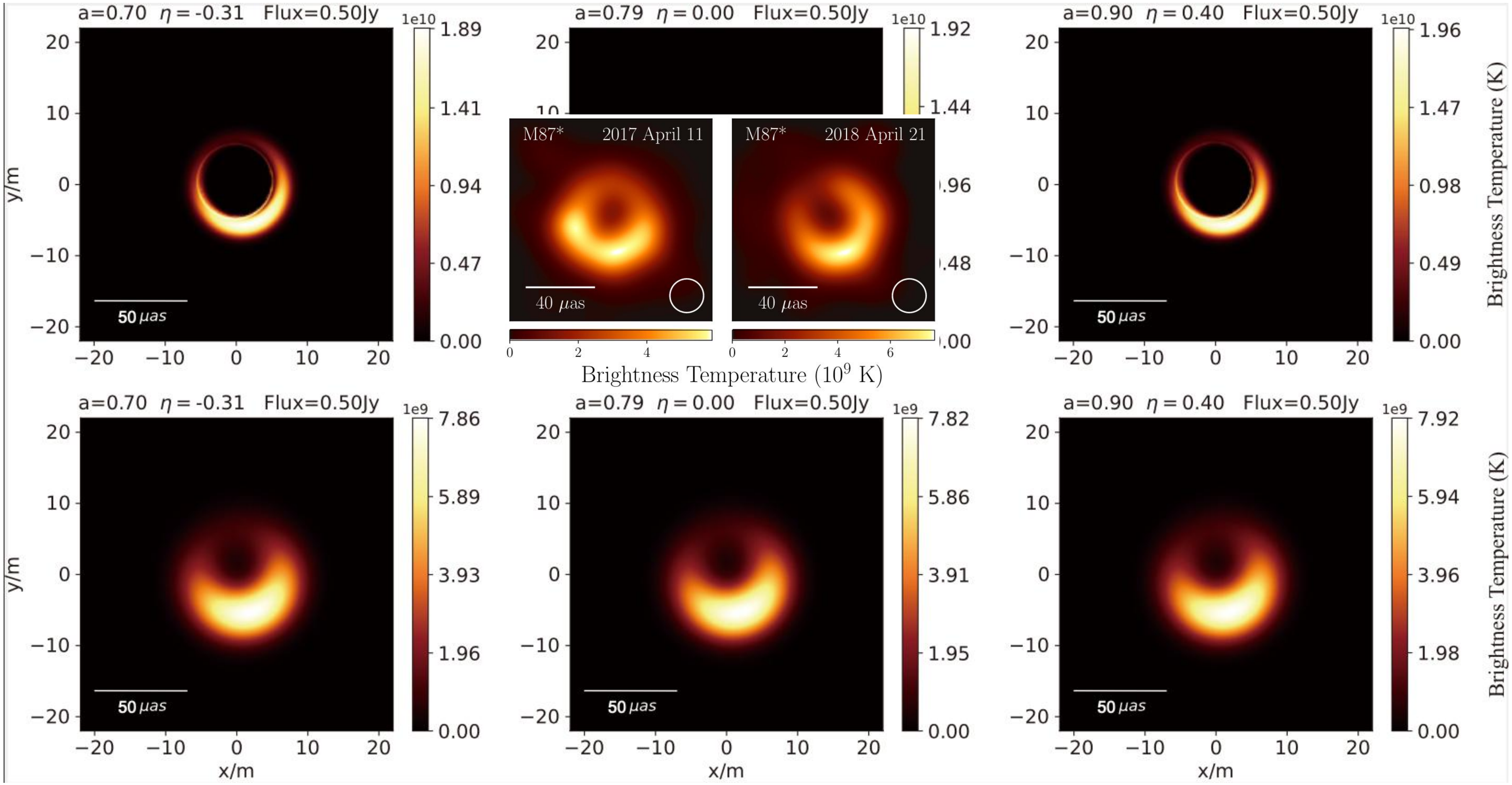
Estimated ring properties overlaid on the fiducial images



Event Horizon Telescope Collaboration, et al., 2019, ApJL, 875, L4.

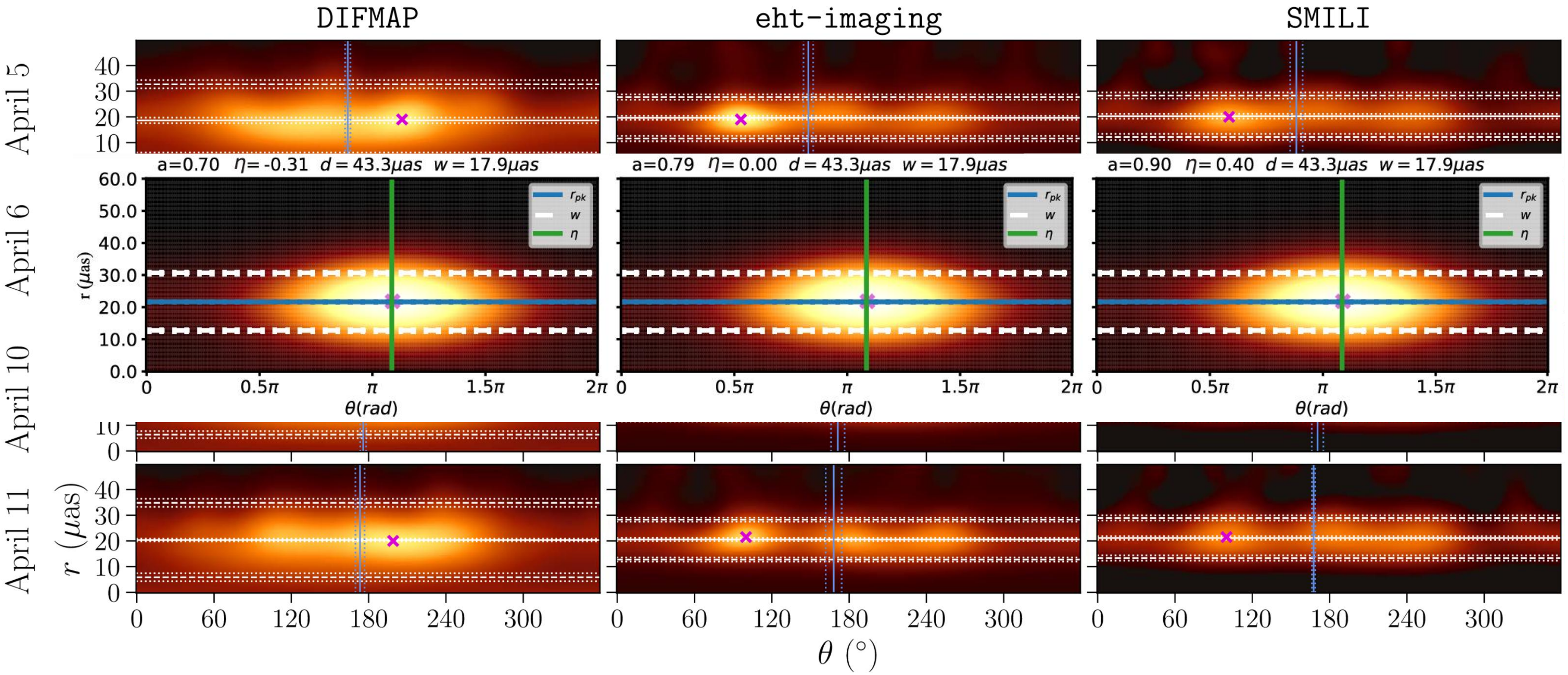
Ring diameter d: $42 \pm 3\ \mu as$ (2017) $43.3^{+1.5}_{-3.1}\ \mu as$ (2018)

Images with different α parameters at $d = 43.3\mu ms$



$n_e \sim 2 \times 10^6 cm^{-3}$ $T_e \sim 3 \times 10^{10} K$ $B \sim 11\ G$

Unwrapped ring profiles of the images



Event Horizon Telescope Collaboration, et al., 2019, ApJL, 875, L4.

b) 动态吸积盘
GRMHD simulation

- Basic Equations
  - ➢ $\nabla_\alpha T^{\alpha\beta} = 0,\quad \nabla_\alpha {}^*F^{\alpha\beta} = 0,\quad \nabla_\alpha \rho u^\alpha = 0$
  - ➢ Ideal relativistic MHD:

$$T^{\alpha\beta} = (h + b^2)u^\alpha u^\beta + \left(p + \frac{1}{2}b^2\right)g^{\alpha\beta} - b^\alpha b^\beta$$

  - ➢ Conservation form

$$\partial_t(\sqrt{-g}\,\rho u^t) = -\,\partial_i(\sqrt{-g}\,\rho u^i)$$

$$\partial_t(\sqrt{-g}T^t{}_\nu) = -\,\partial_i(\sqrt{-g}T^i{}_\nu) + \sqrt{-g}T^\kappa{}_\lambda \Gamma^\lambda{}_{\nu\kappa}$$

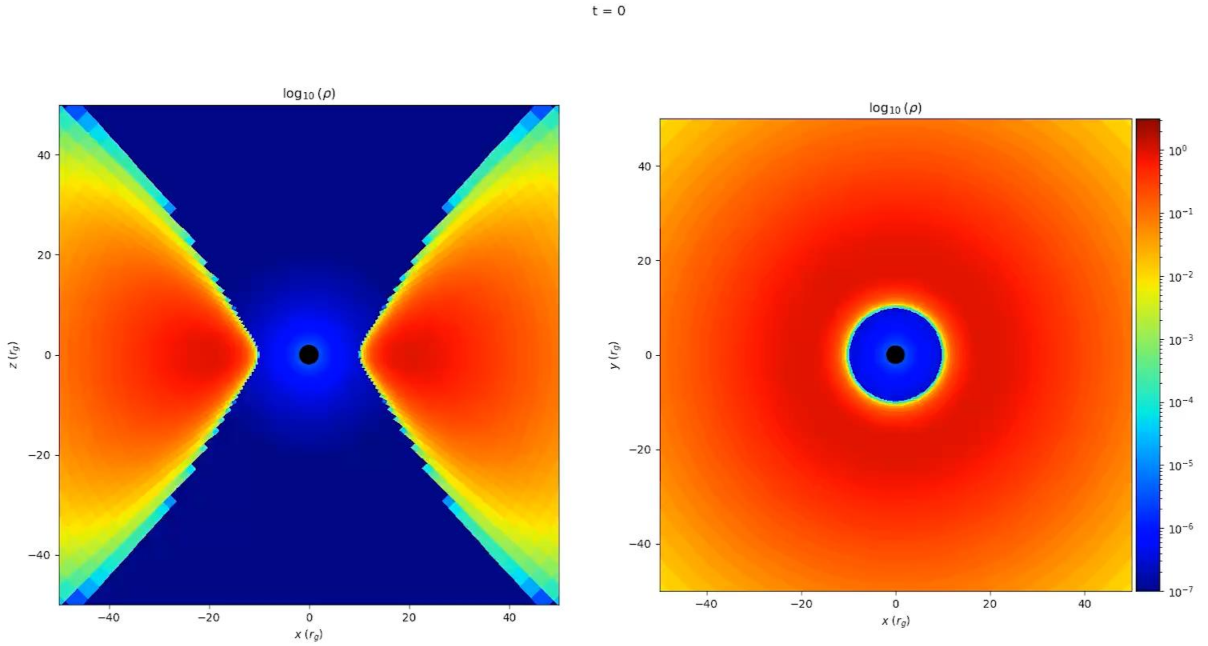
$$\partial_t(\sqrt{-g}B^i) = -\,\partial_j[\sqrt{-g}\,(b^j u^i - b^i u^j)]$$

$$\partial_i(\sqrt{-g}B^i) = 0$$

- Initial conditions
  - ➢ Fishbone-Moncrief torus
  - ➢ Parameter: $a = 0.5/0.9375,\ \eta = 0/0.5$
  - ➢ $r_{in} = 10,\ r_{max} = 20,\ \gamma = 4/3$
  - ➢ SANE: $A_\phi = \max\left[\frac{\rho}{\rho_{\max}} - 0.2, 0\right]$
  - ➢ Resolution: 128*96*96

$log_{10}\,\rho$

$a = 0.5, \eta = 0$



$a = 0.5, \eta = 0.5$

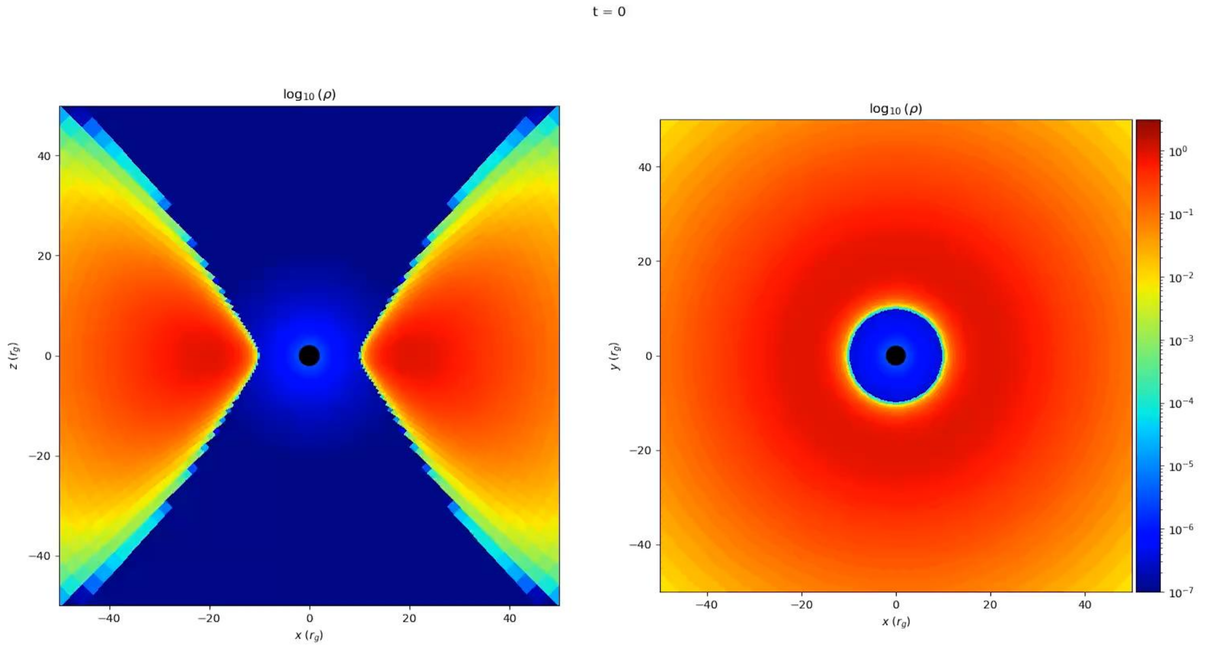
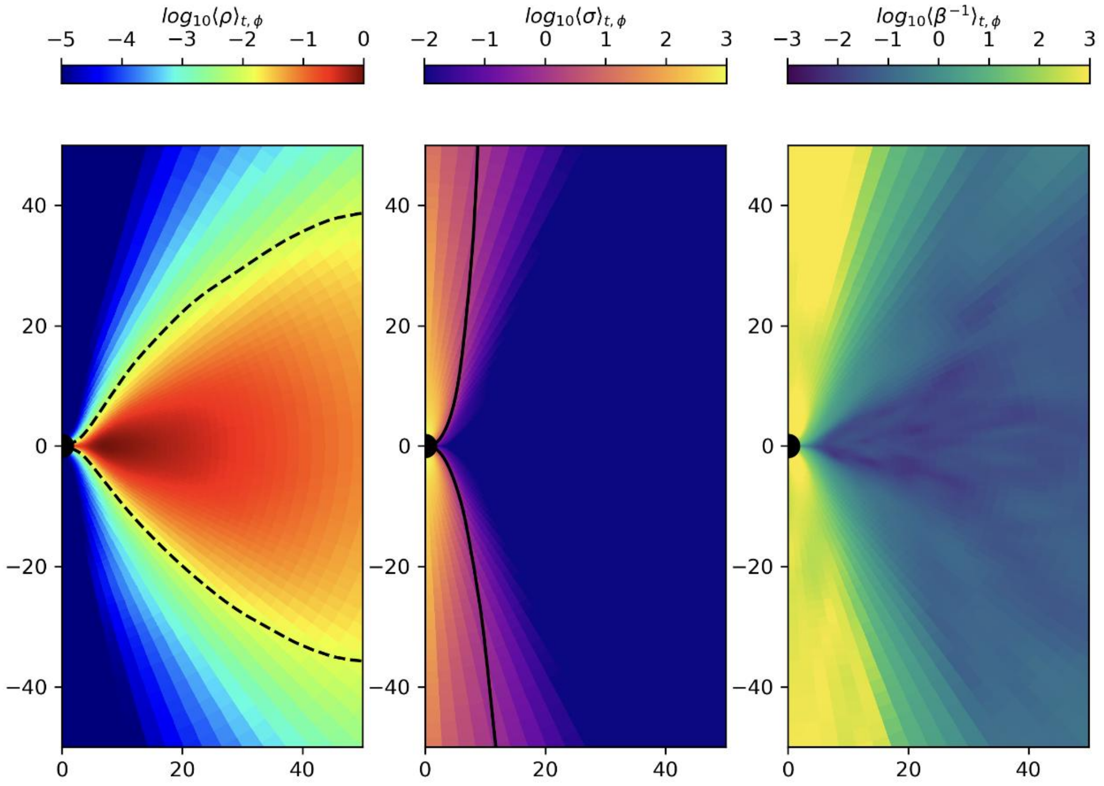
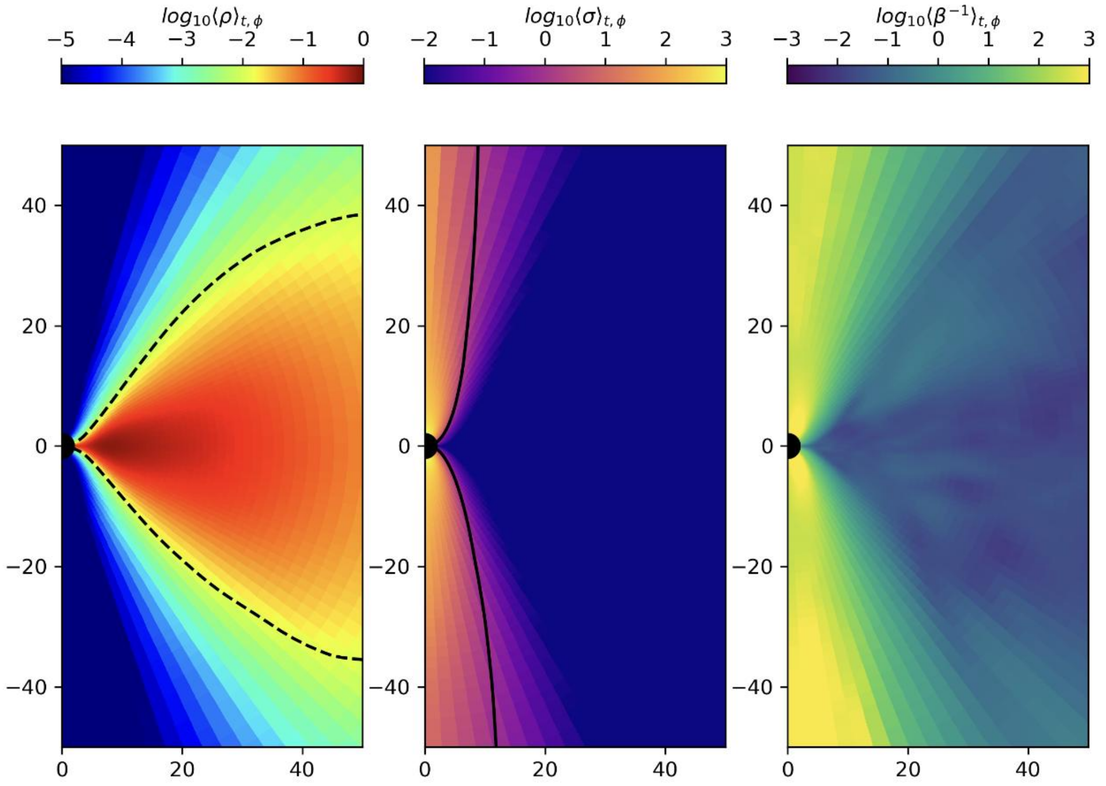


Image averaged in t and φ directions

$\sigma = b^2/\rho \quad \beta = P_{gas}/P_{mag}$



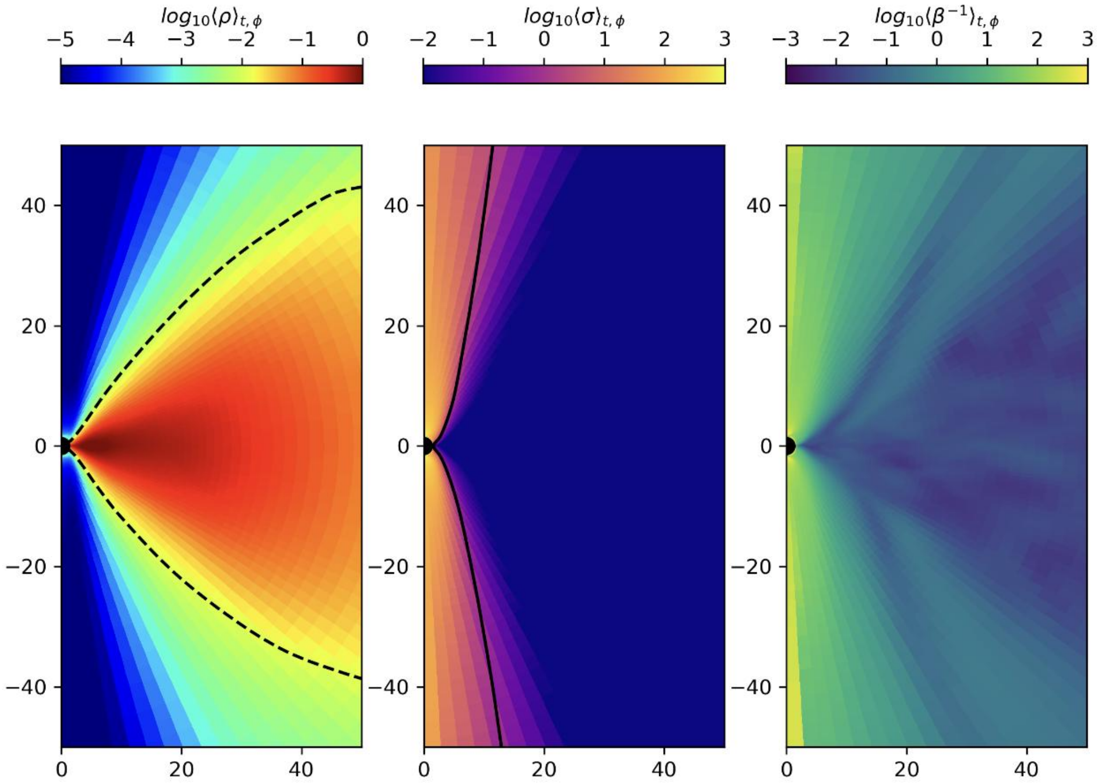
$a = 0.5, \eta = 0$



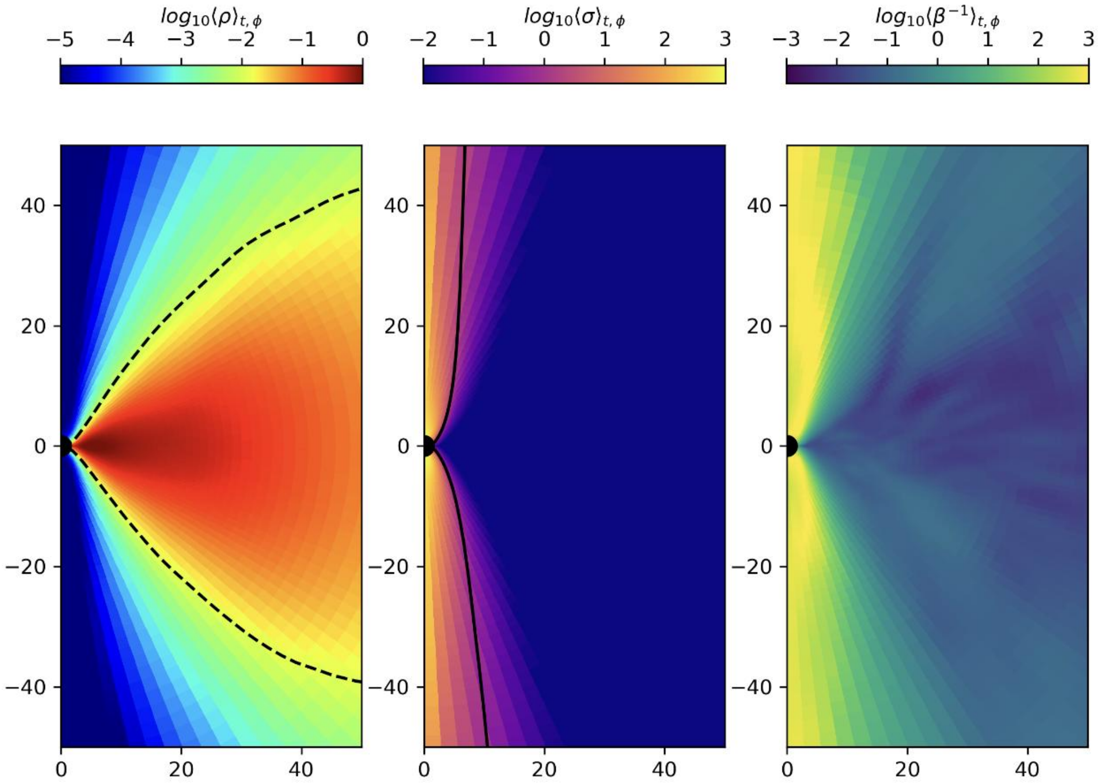
$a = 0.5, \eta = 0.5$

Image averaged in t and φ directions

$\sigma = b^2/\rho \quad \beta = P_{gas}/P_{mag}$

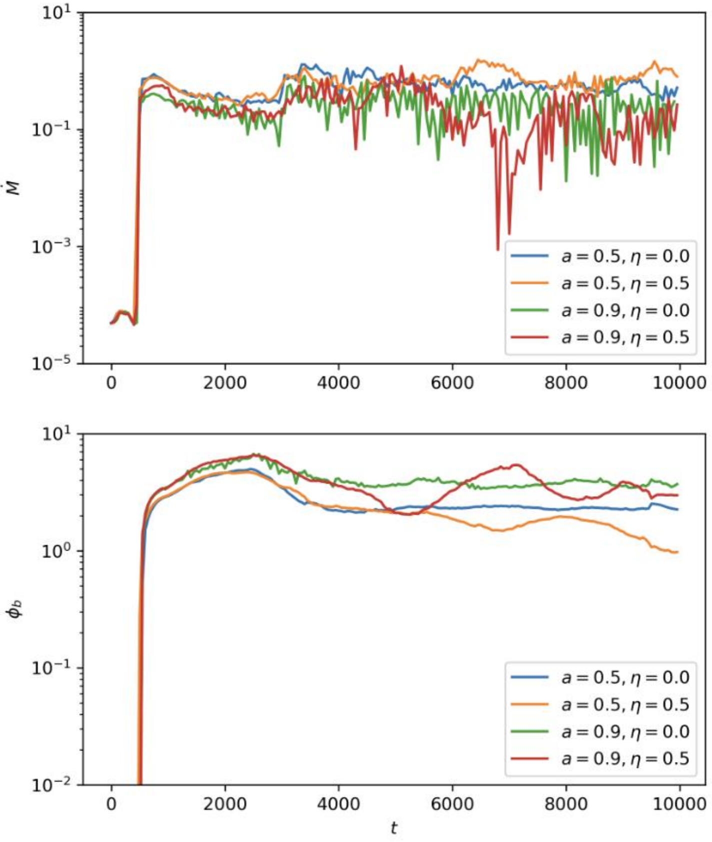


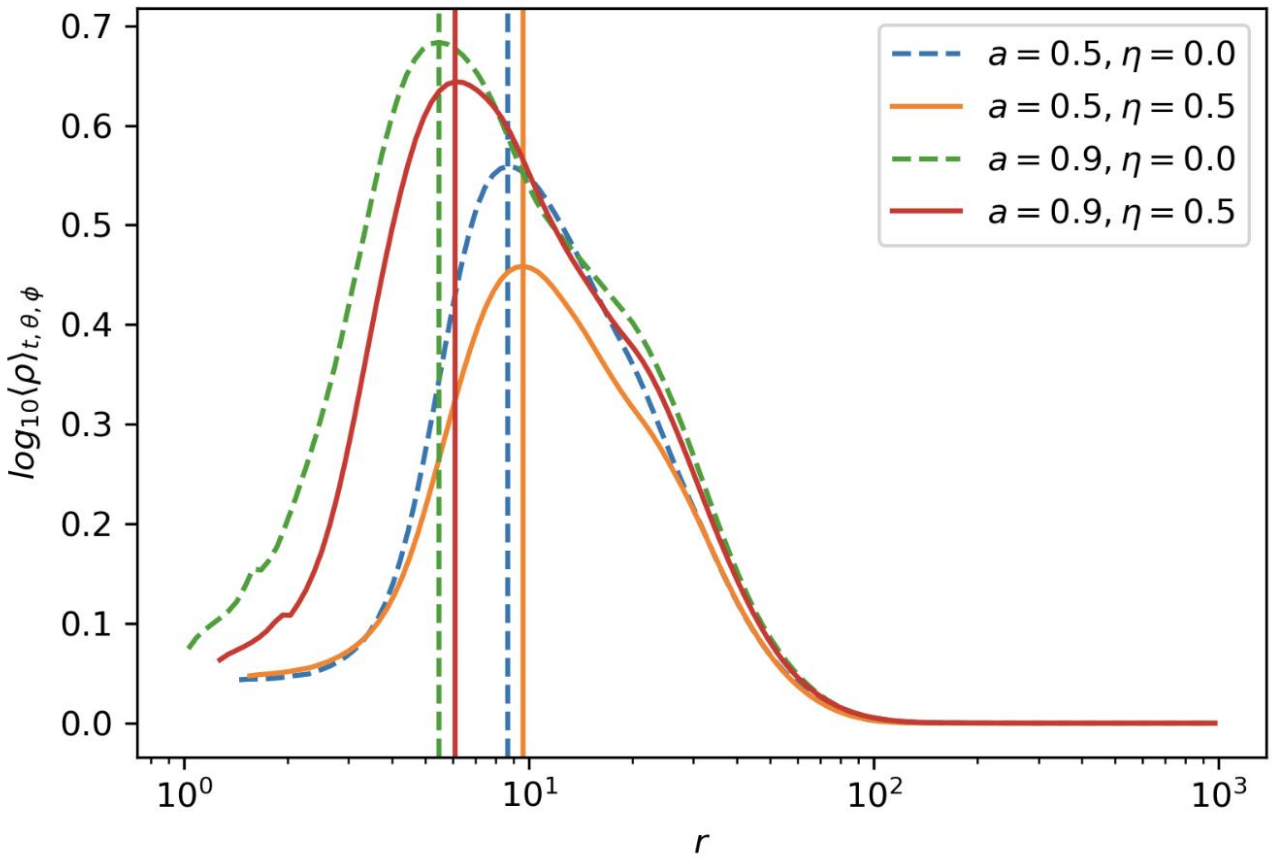
$a = 0.9, \eta = 0$



$a = 0.9, \eta = 0.5$

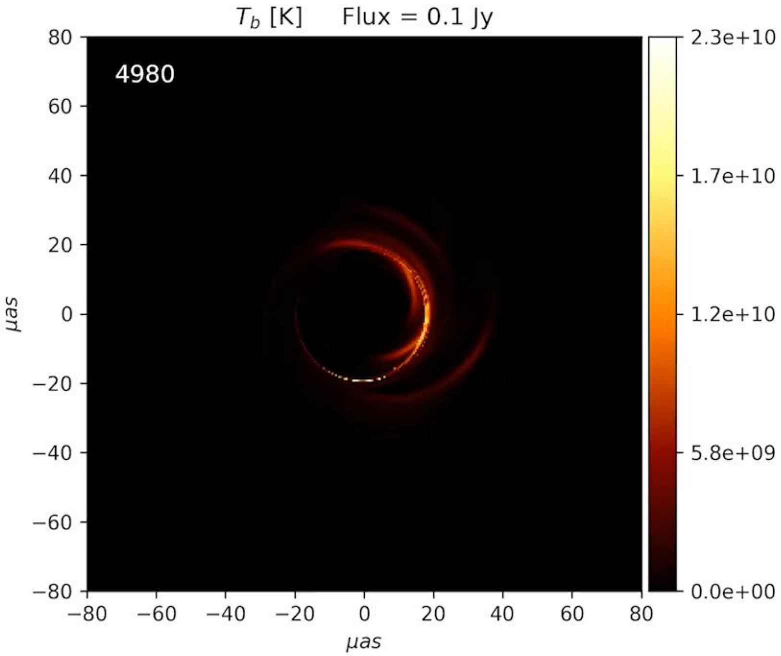
Accretion rate, magnetic flux, and radial matter distribution

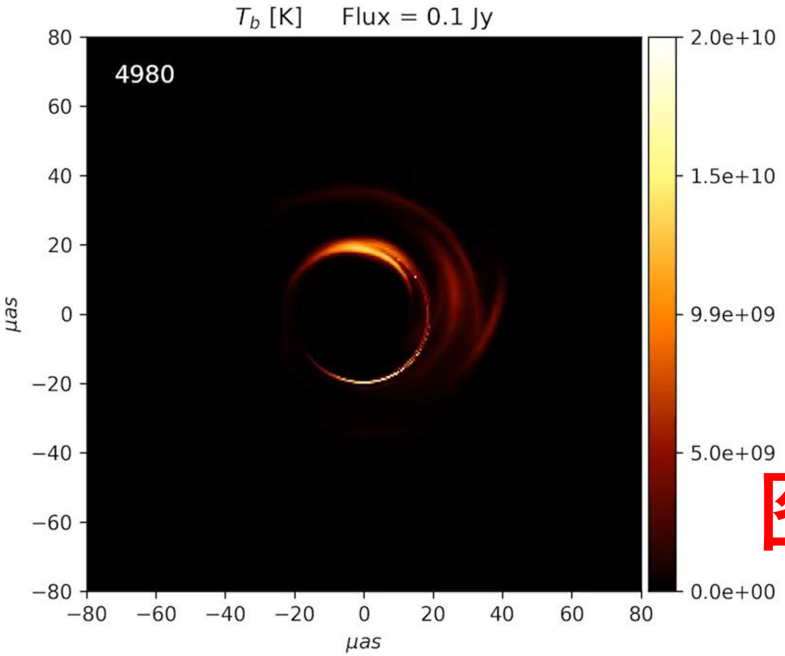




$$\dot{M} = -\int_0^{2\pi}\int_0^{\pi} \rho\, u^r \sqrt{-g}\,\mathrm{d}\theta\mathrm{d}\phi \qquad \phi_{\mathrm{BH}} = \frac{\Phi_{\mathrm{BH}}}{\sqrt{\dot{M}}} \qquad \Phi_{\mathrm{BH}} = \frac{1}{2}\int_0^{2\pi}\int_0^{\pi} |\star F^{rt}|\sqrt{-g}\,\mathrm{d}\theta\mathrm{d}\phi$$

$a = 0.5, \eta = 0$



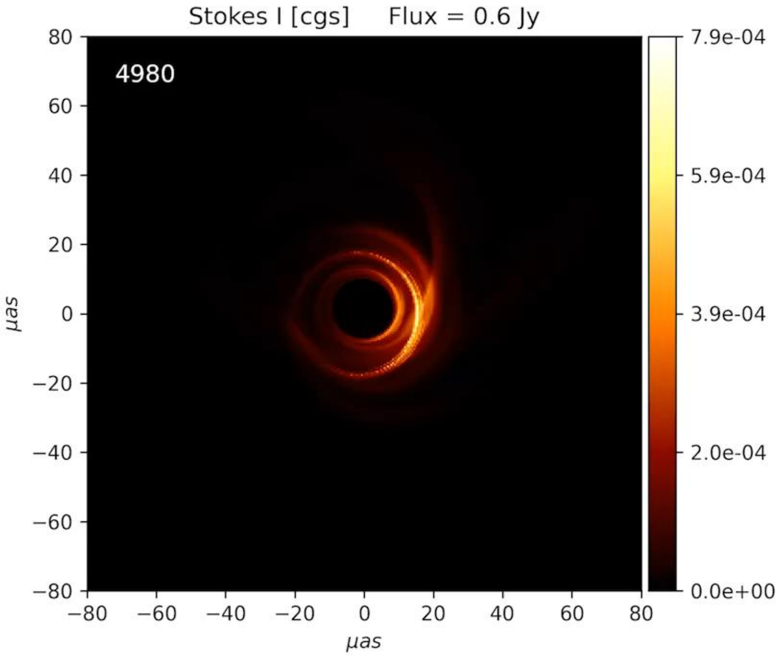


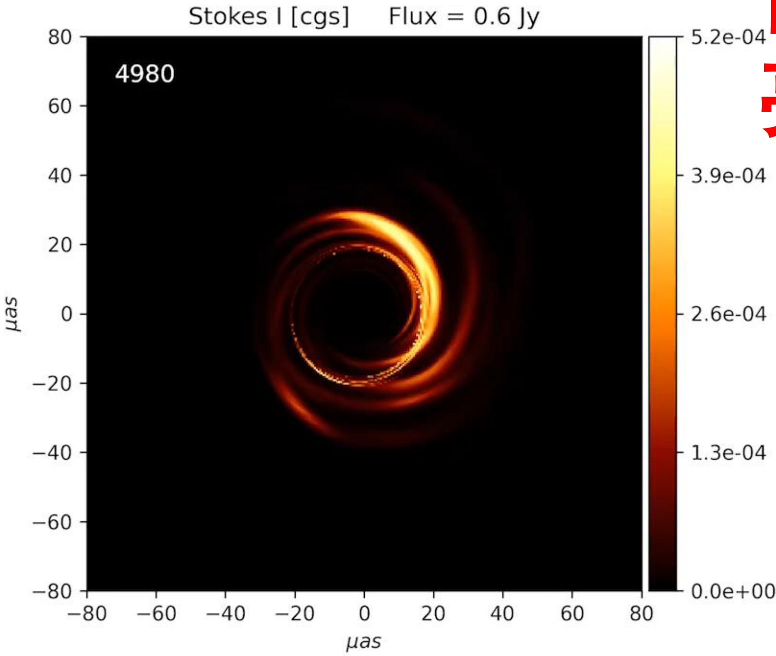
$a = 0.5, \eta = 0.5$

图像特征：

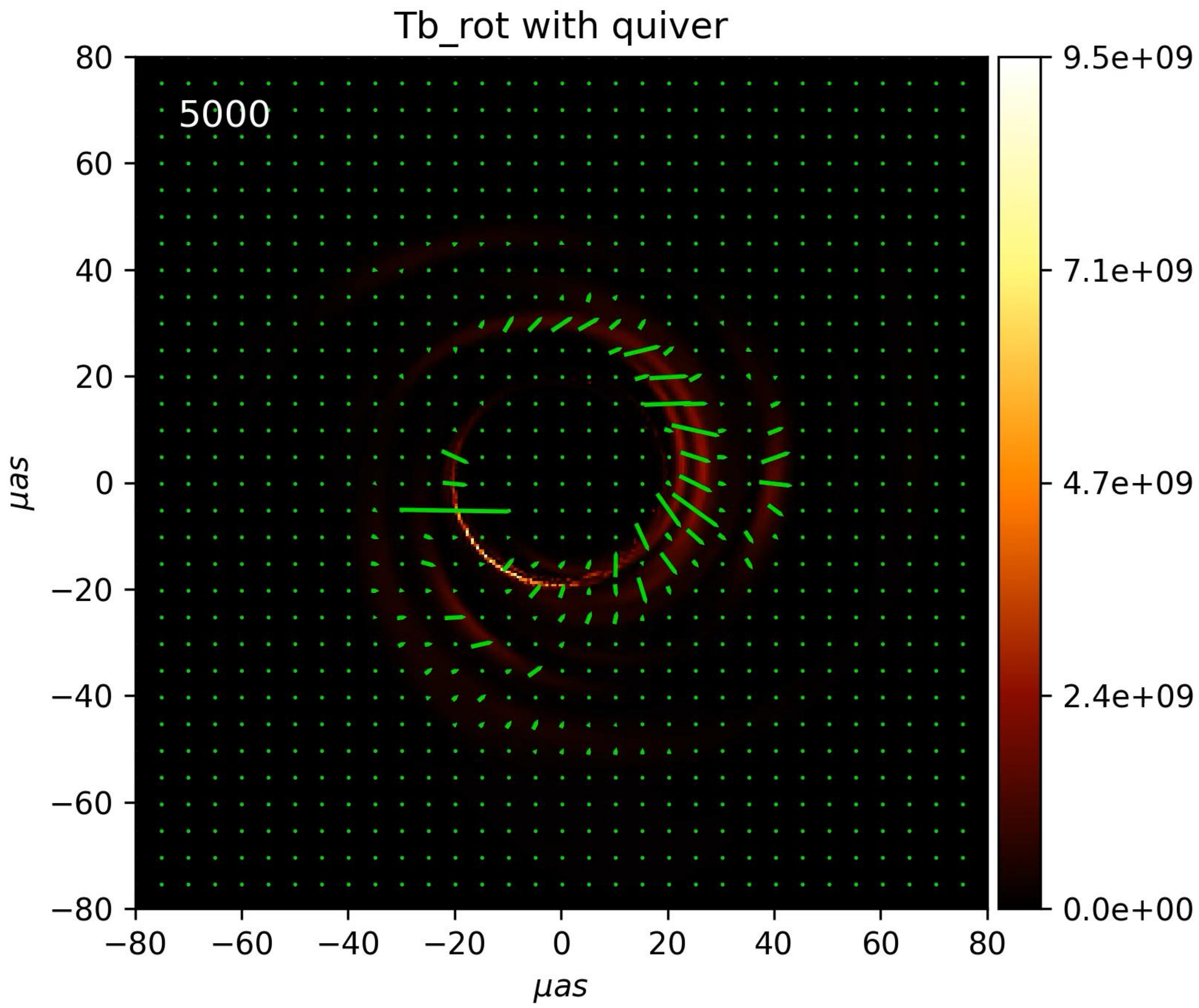
偏离参数使亮环变大

$a = 0.9, \eta = 0$

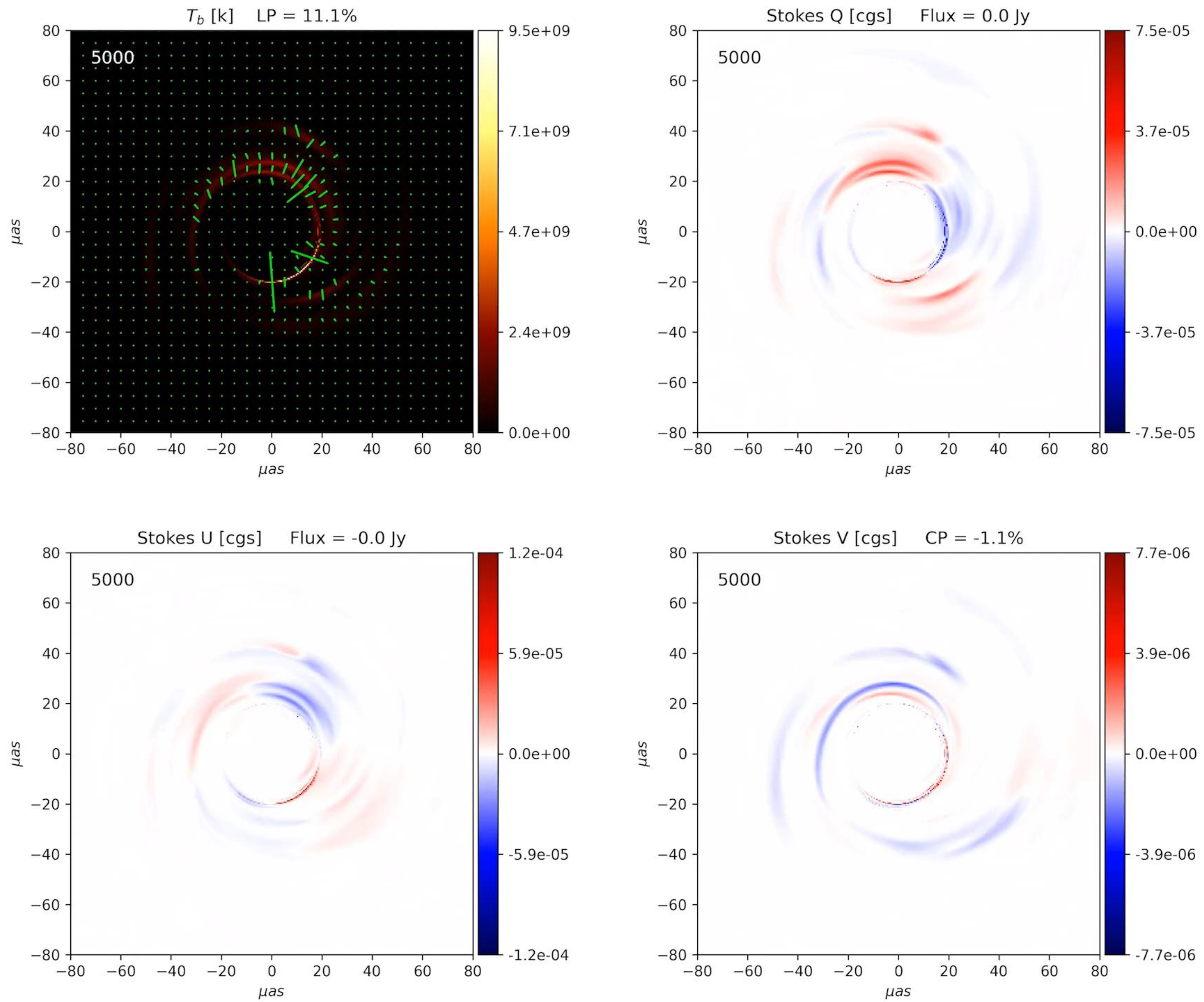




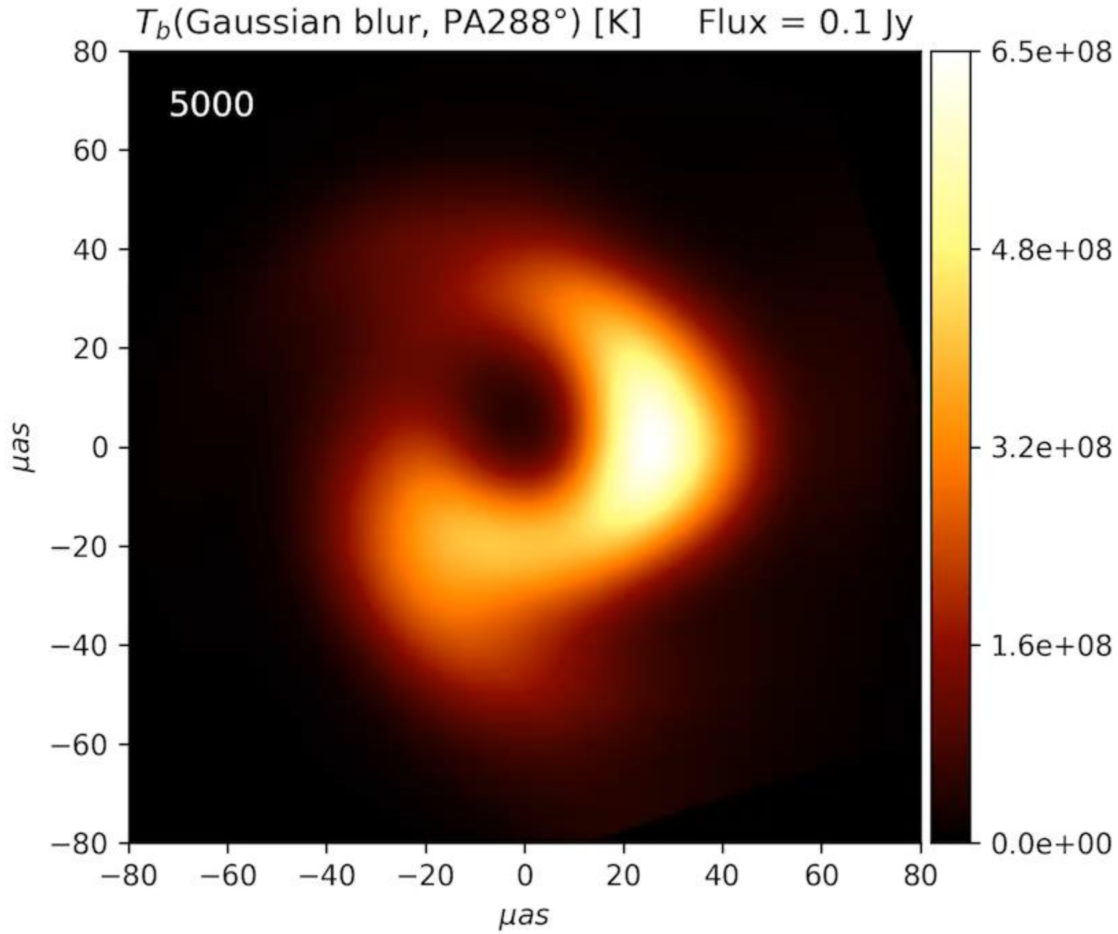
$a = 0.9, \eta = 0.5$

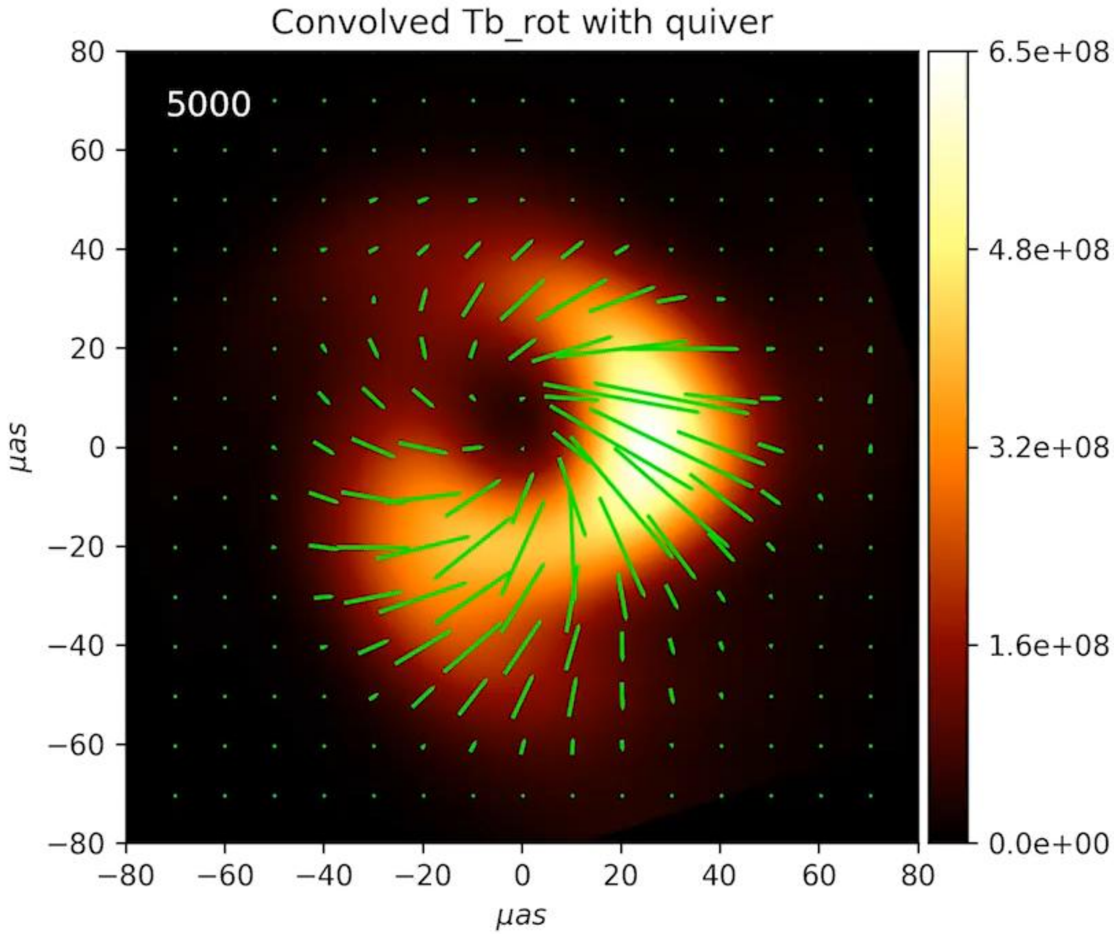


Tb_rot with quiver
5000
80
60
40
20
0
−20
−40
−60
−80
−80
−60
−40
−20
0
20
40
60
80
μas
μas
9.5e+09
7.1e+09
4.7e+09
2.4e+09
0.0e+00



T_b [k] LP = 11.1%
Stokes Q [cgs] Flux = 0.0 Jy
Stokes U [cgs] Flux = -0.0 Jy
Stokes V [cgs] CP = -1.1%
5000
μas
9.5e+09
7.1e+09
4.7e+09
2.4e+09
0.0e+00
7.5e-05
3.7e-05
-3.7e-05
-7.5e-05
1.2e-04
5.9e-05
-5.9e-05
-1.2e-04
7.7e-06
3.9e-06
-3.9e-06
-7.7e-06


T_b(Gaussian blur, PA288°) [K]   Flux = 0.1 Jy
5000
μas
μas
6.5e+08
4.8e+08
3.2e+08
1.6e+08
0.0e+00


Convolved Tb_rot with quiver
5000
μas
μas
6.5e+08
4.8e+08
3.2e+08
1.6e+08
0.0e+00

3. Summary

1. 研究了Konoplya-Azhidenko黑洞周围两种几何厚吸积盘的图像特征

2. 黑洞的旋转参数使几何厚吸积盘的图像变小。

3. 偏离参数使几何厚吸积盘的图像变大。


Thank you!
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