Matter density distribution of GRMHD jets driven by black holes

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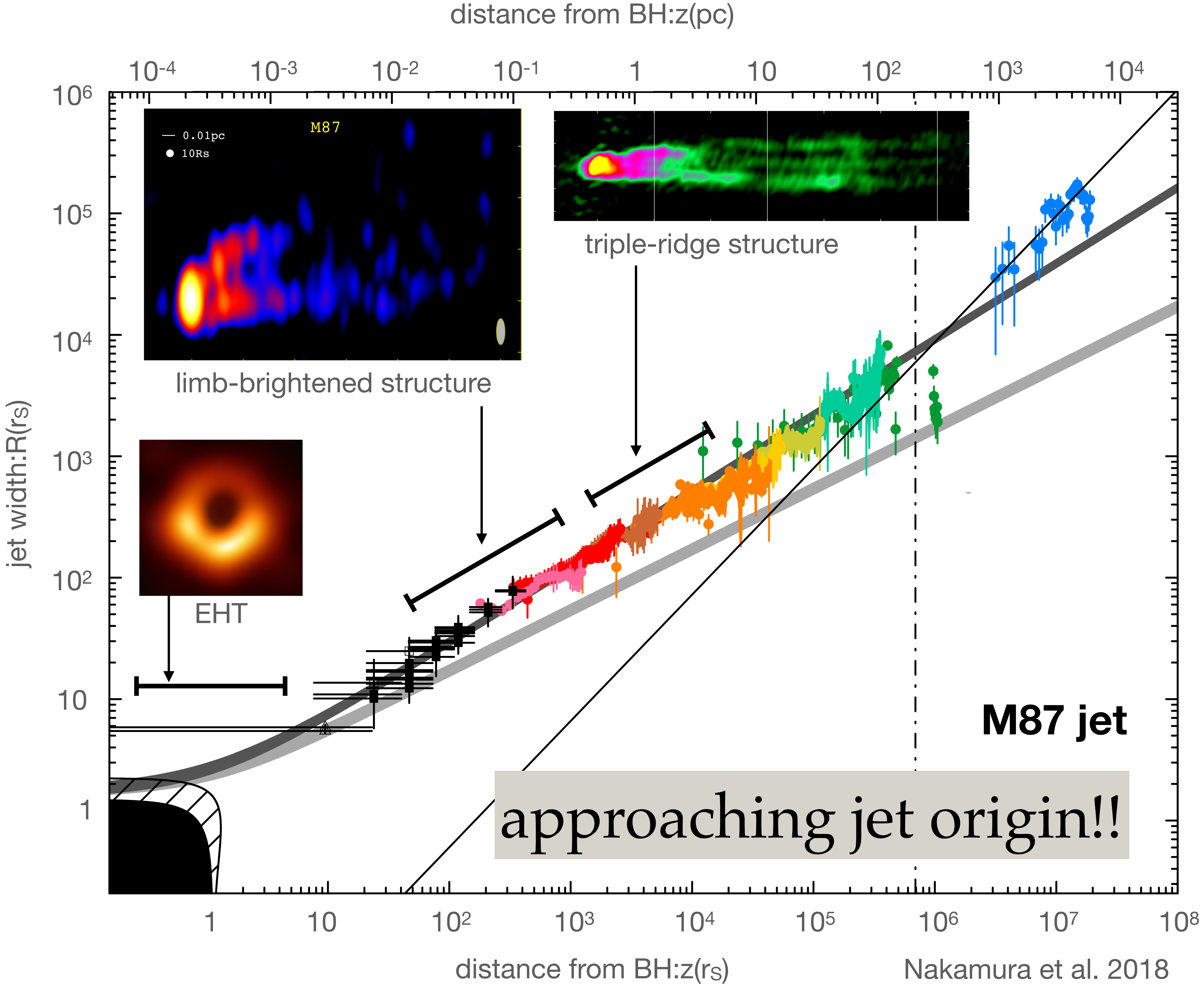
Radio observations

The jet origin is near the BH.

- High-resolution VLBI observations have resolved jets and revealed detailed emission structures.
- limb-brightened: M87, Mrk 501, Mrk 421, Cyg A, 3C84
- triple-ridge: only in high-sensitivity observation of M87
- jet width profile
- Jet emission near the horizon is not observed yet.

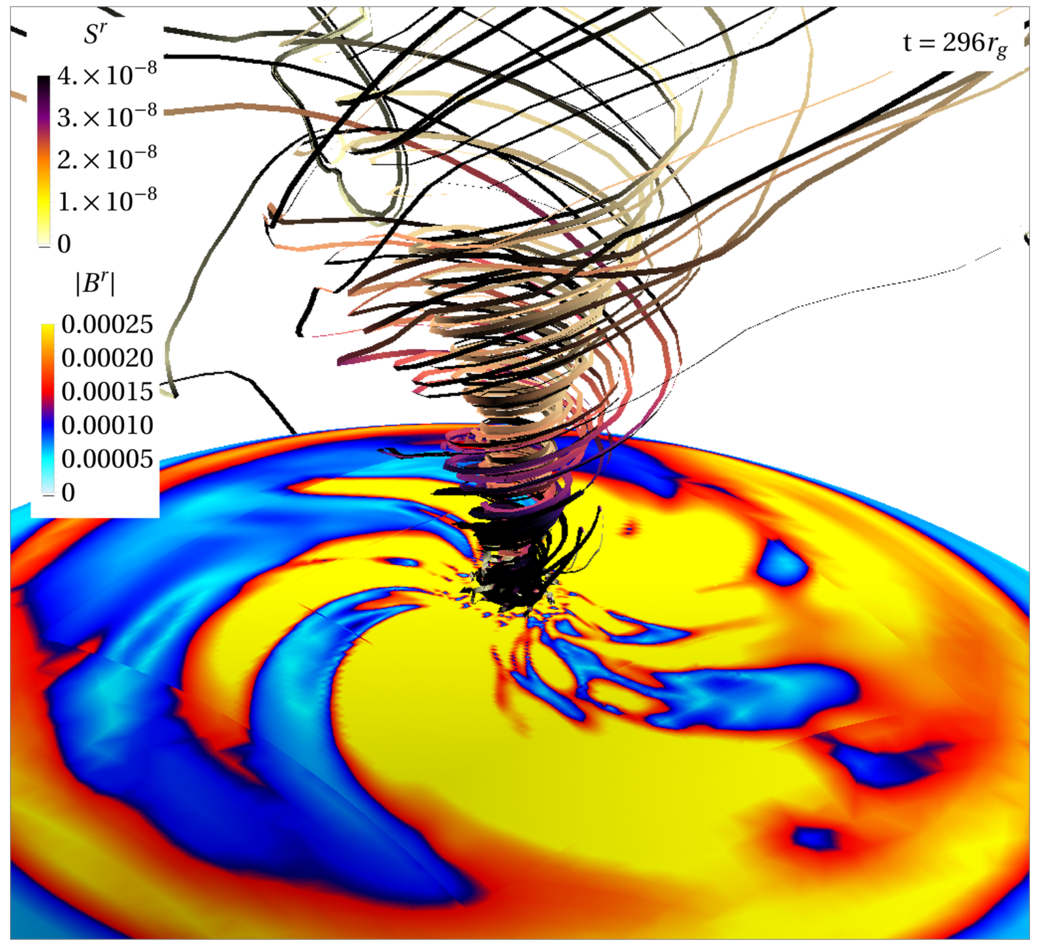


GRMHD simulations

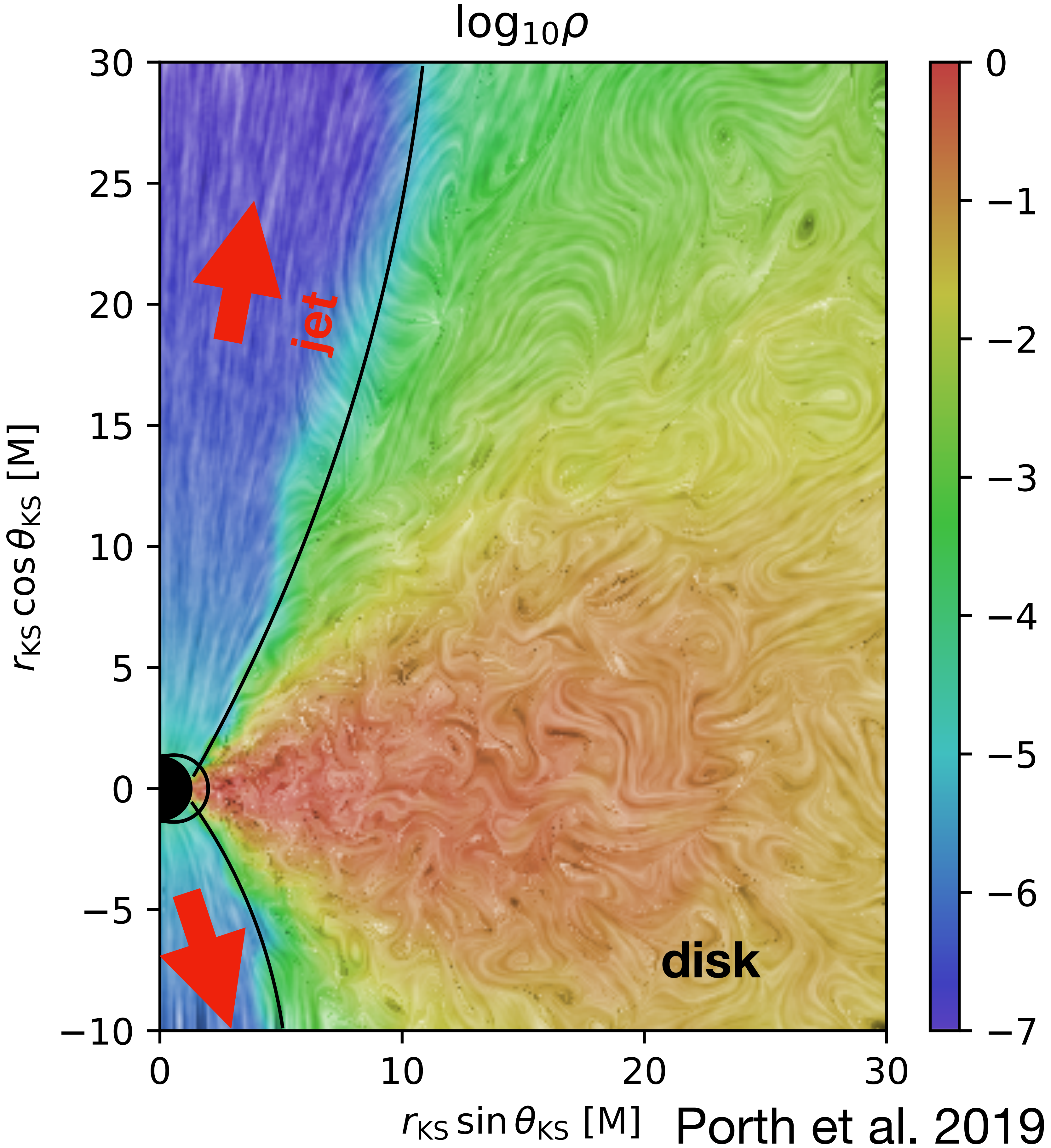
comparison to observations

- The plausible jet launching mechanism is the Blandford-Znajek process.
    - rotational energy of BH
      → Poynting flux
      → kinetic energy
- GRMHD simulations supports the BZ process.
- Combining with radiative transfer calculations, one can create synthetic images.

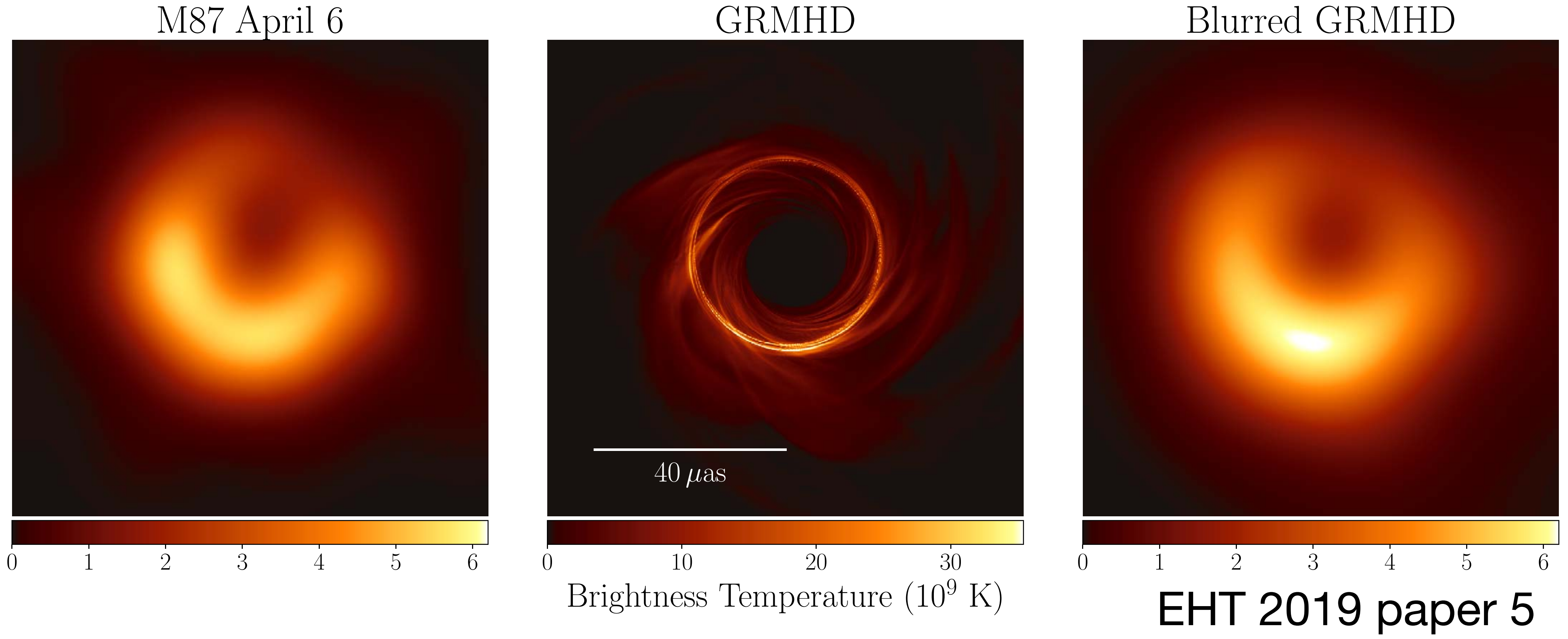
  → compare theoretical models with observations = “black hole shadow”



Mahlmann, Levinson, Aloy 2020



Porth et al. 2019

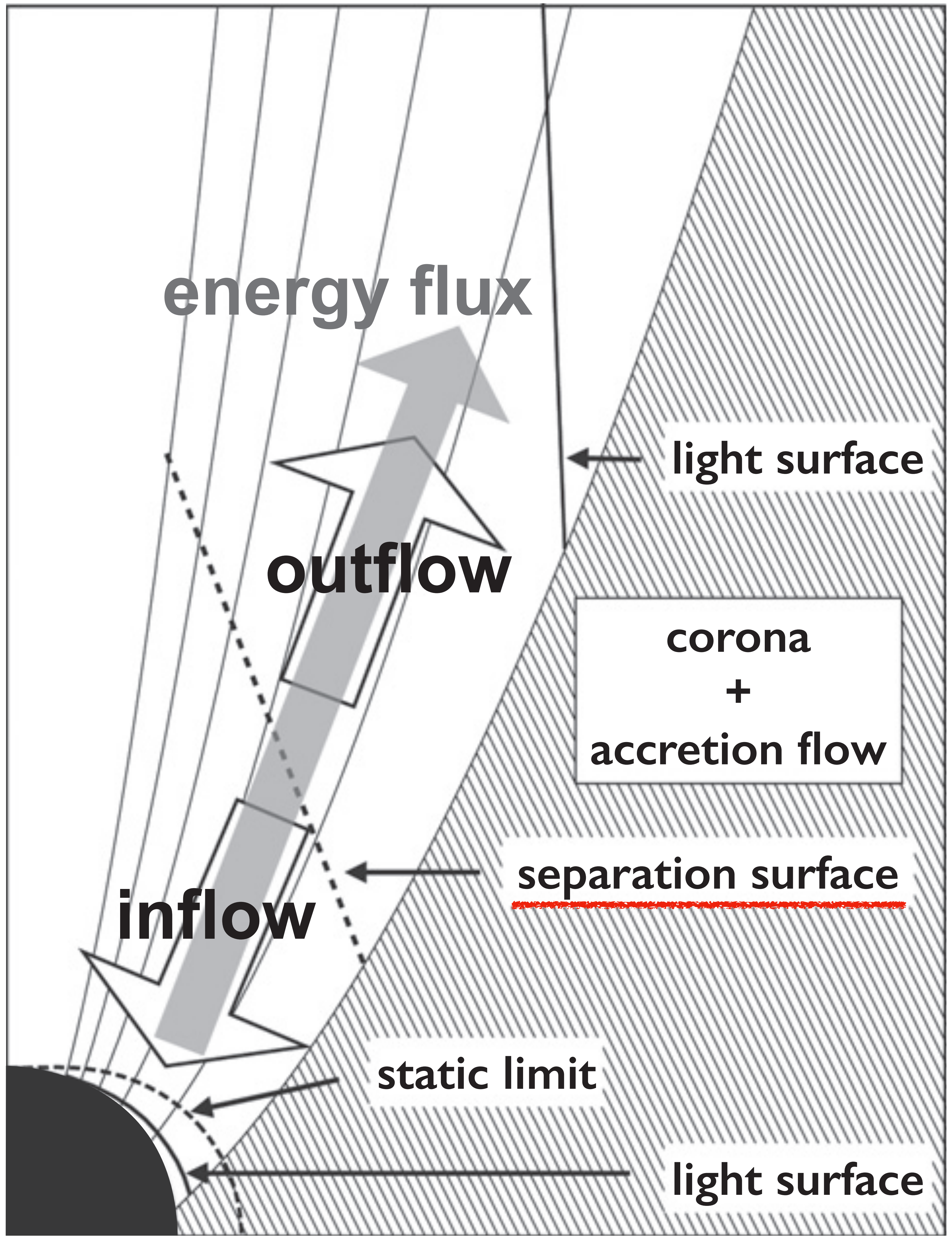


EHT 2019 paper 5

Density-floor
in GRMHD simulations

- Thermal plasma cannot dissipate into the highly magnetized region.
- In GRMHD simulations, the separation surface between the inflow and outflow emerges at the balanced surface of the gravity and the Lorentz force.
- **Density becomes very low in the jet.** Due to the numerical difficulty, density is replaced by "floor values" in simulations.

  e.g., $\rho_{0;min} = 10^{-4} r^{-3/2}$, $u_{\rm min} = 10^{-6} r^{-5/2}$
  (McKinney & Gammie 2004)

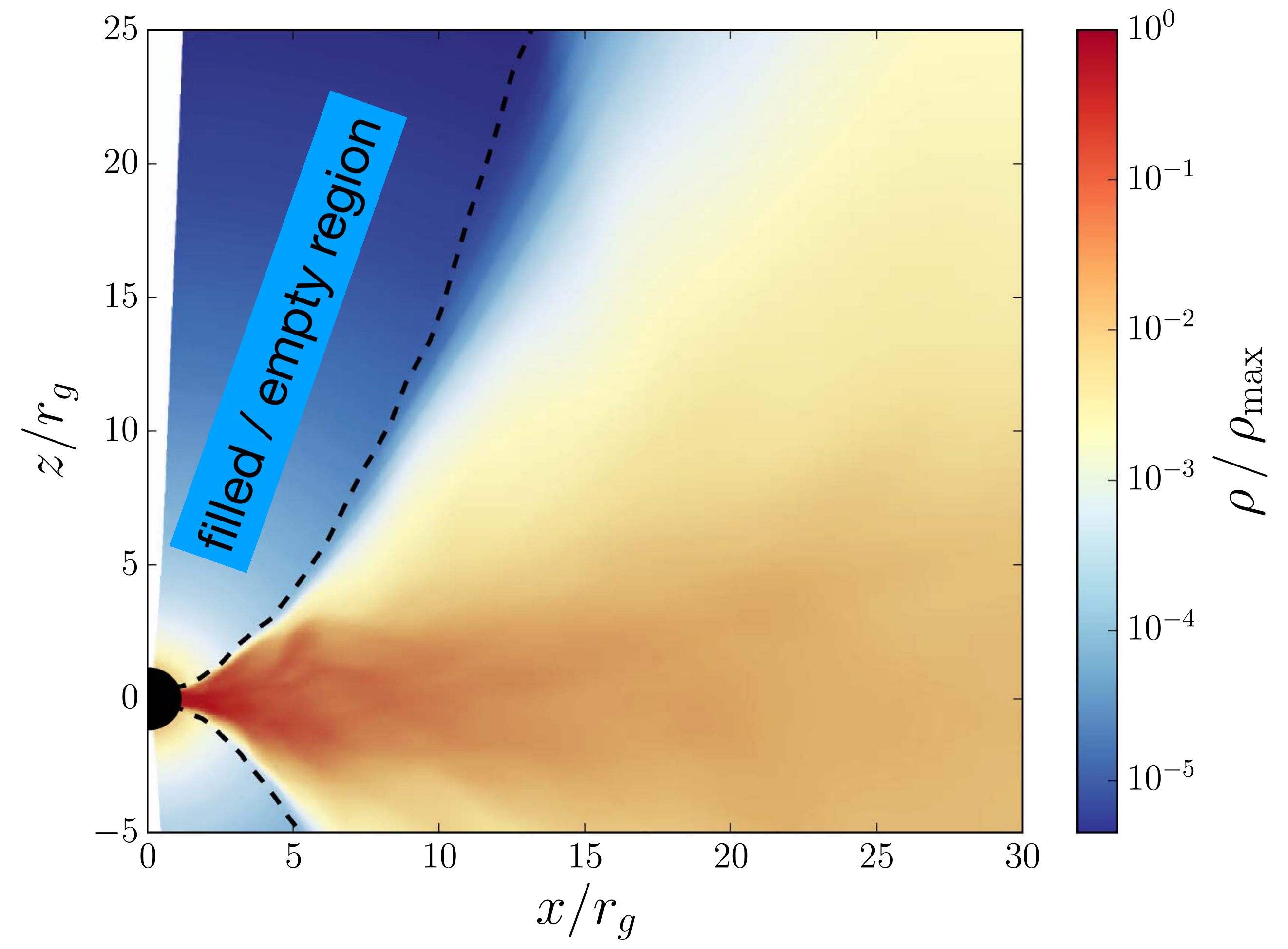


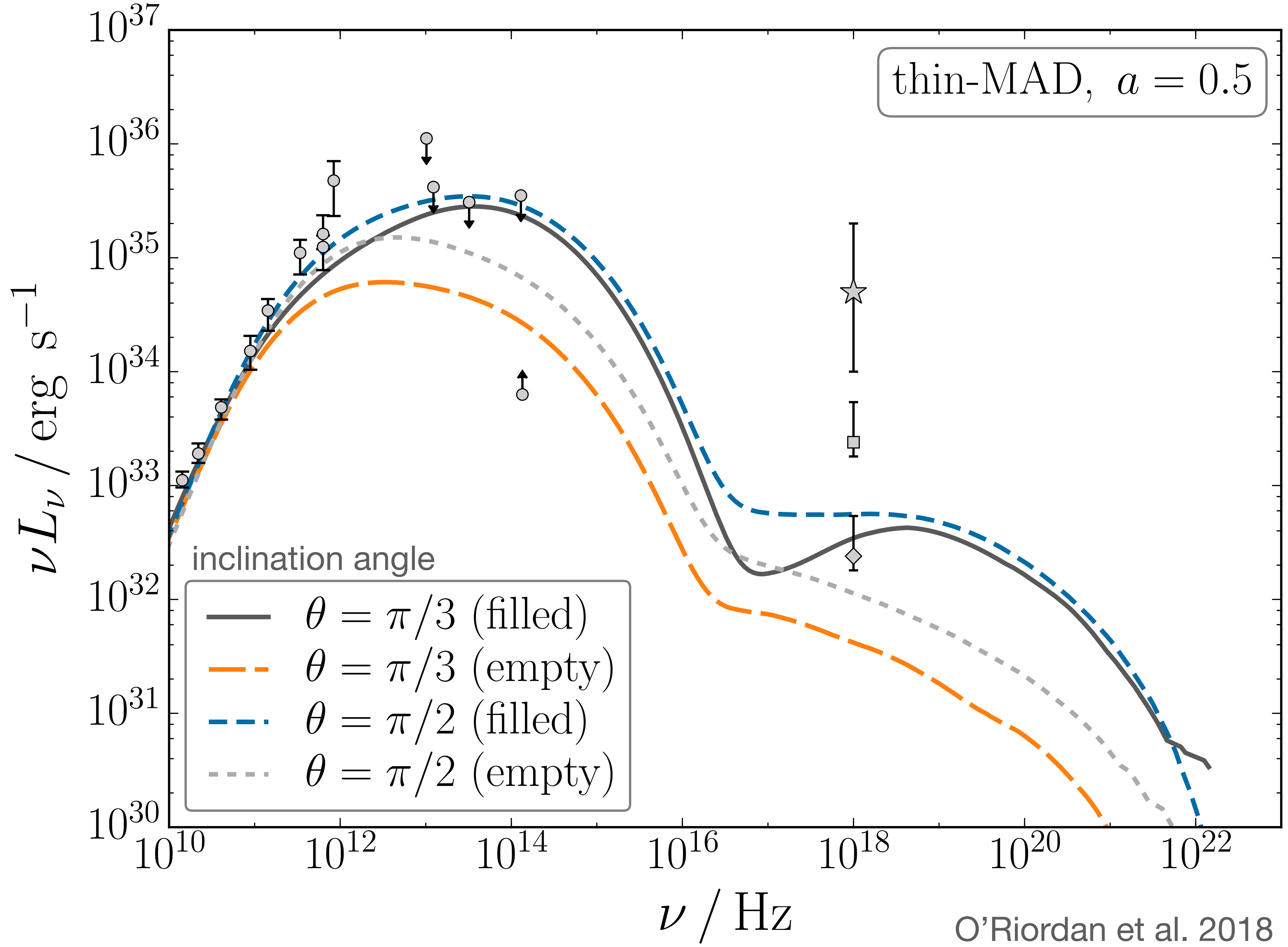
Pu et al. 2015

Density-floor

effect on observations

- O'Riordan et al. 2018
  - 3D GRMHD simulation
  - calculate spectra for Sgr A*
  - filled / empty highly-magnetized funnel region
  - radio spectrum do not change significantly because the emission comes from the funnel edge.
  - IR and optical flux are enhanced in the filled case relative to the empty funnel case.



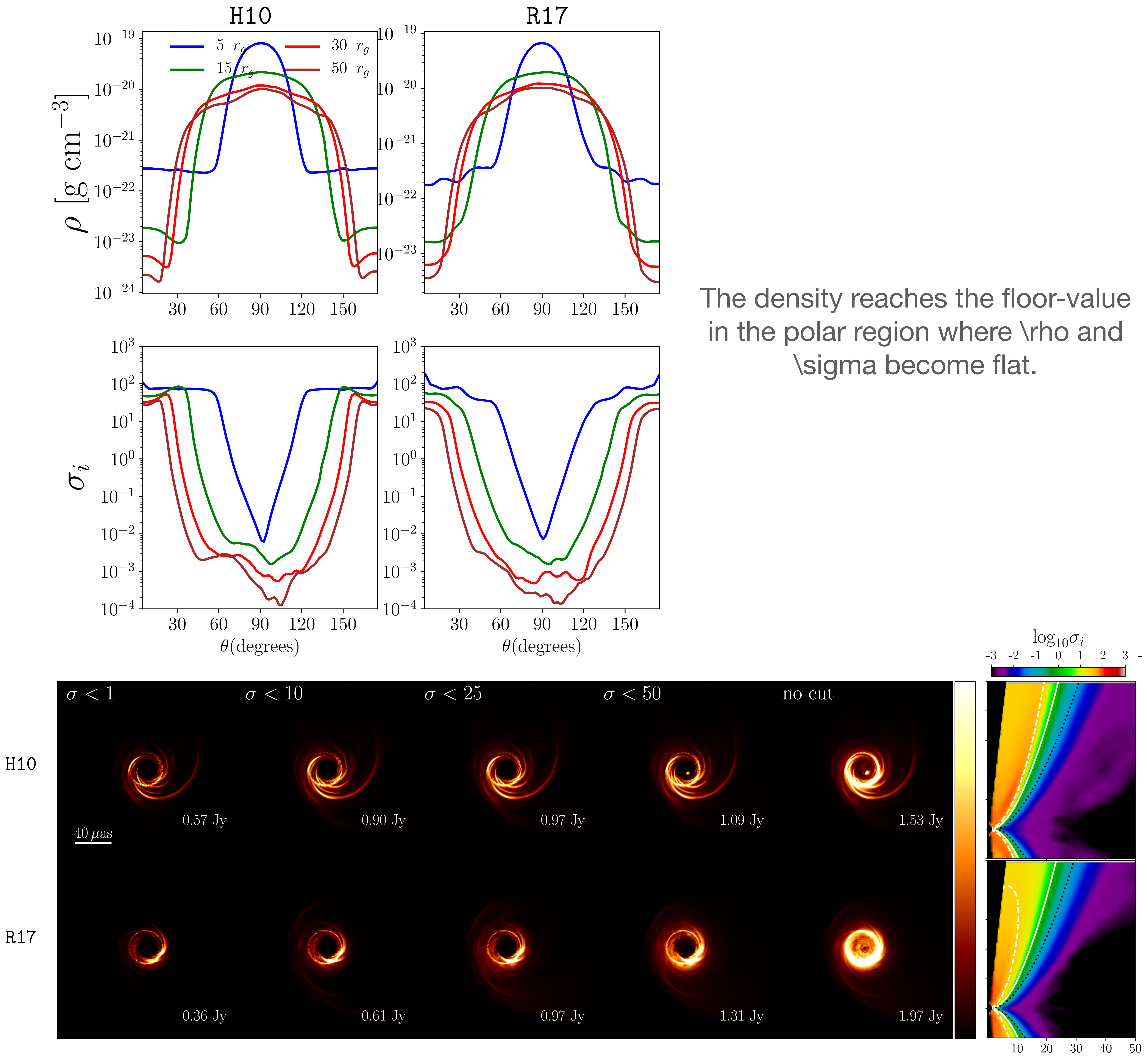


O'Riordan et al. 2018

Density-floor

effect on observations

- Chael et al. 2019
  - 3D GRMHD simulation
  - ignore a region $\sigma > \sigma_{\rm cut}$ when calculate radiative transfer
  - no σ cut model: spectrum change at $\nu \gtrsim 230\,\mathrm{GHz}$
  - brighter ring/jet
- **The emission from the funnel region is not explored much.**



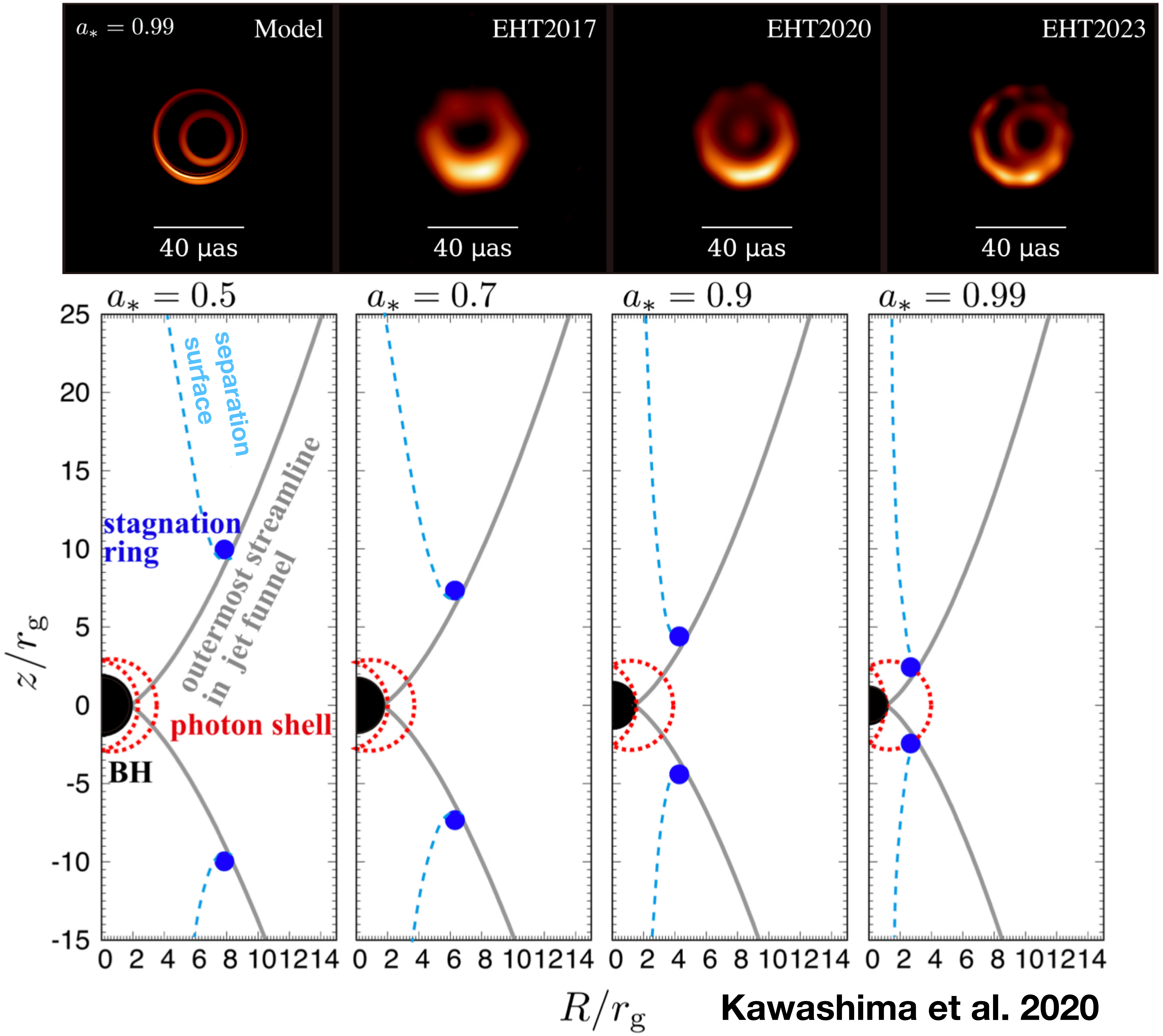
The density reaches the floor-value in the polar region where \rho and \sigma become flat.

Chael et al. 2019

Emission from Jet Origin

EHT scale observation

- Kawashima et al. 2020
  - radiative transfer calculation of the emission from the separation surface
  - reproduce the ring structure of EHT observation in 2017
  - In future observations, additional ring may be seen.
- **Emission from the jet may also be important to interpret the future EHT observations.**

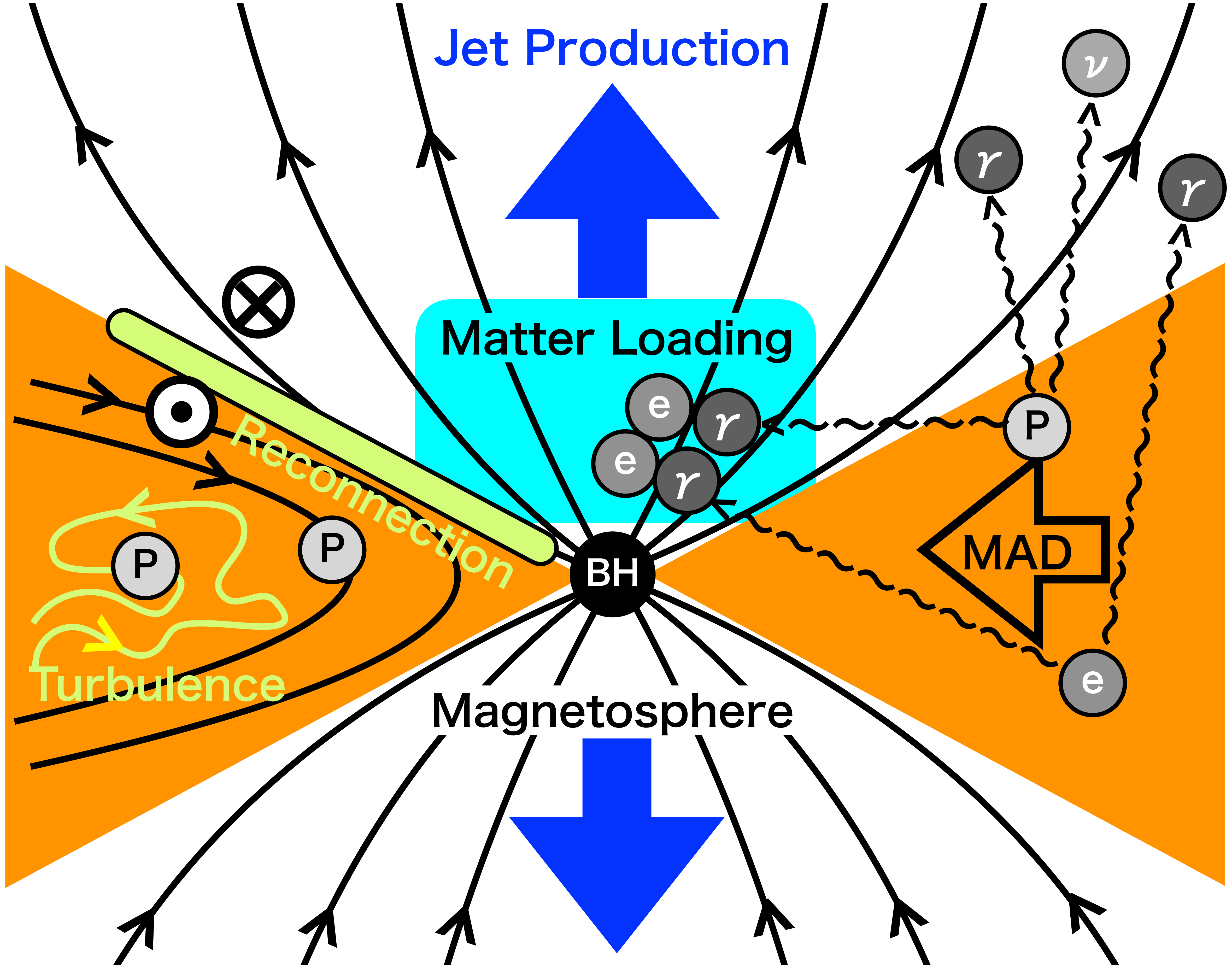


Kawashima et al. 2020

Injection Mechanisms

not conclusive

- steady jets require an injection mechanism
  - pair-creation in jet?
    (Levinson & Rieger 2011, Kimura & Toma 2020)
  - pair cascade?
    (Broderick & Tchekhovskoy 2015, Kisaka+2020)
  - reconnection at jet edge?
    (Dexter+14, Parfrey+15, Nathanail+20)
  - decay of relativistic non-charged particles?
    (Toma & Takahara 2012)
- **uncertainty of the density distribution inside the jet**
  → uncertainty of the synthetic images



Kimura & Toma 2020

Our Motivation

predict jet images in EHT scale

- Focus on the internal structures of jets
- Construct **a semi-analytic model which do not suffer from the density floor problem**
- Determine the density distribution in a jet near the black hole
- In future, our jet model combined with radiative transfer calculations predicts/reproduce observed jet images

2. steady, axisymmetric, GRMHD jet model

Basic Equations

- basic equations

Maxwell equation:
$\nabla_\nu F^{\mu\nu} = J^\mu, \ \nabla_\nu * F^{\mu\nu} = 0$

Energy-momentum equation:

$$\nabla_\nu T^{\mu\nu} = 0,$$
$$T^{\mu\nu} = \rho u^\mu u^\nu + \frac{1}{4\pi}\left(F^{\mu\lambda}F^\nu_\lambda - \frac{1}{4}g^{\mu\nu}F^{\lambda\sigma}F_{\lambda\sigma}\right)$$

continuity equation: $(nu^\mu)_{;\mu} = 0$

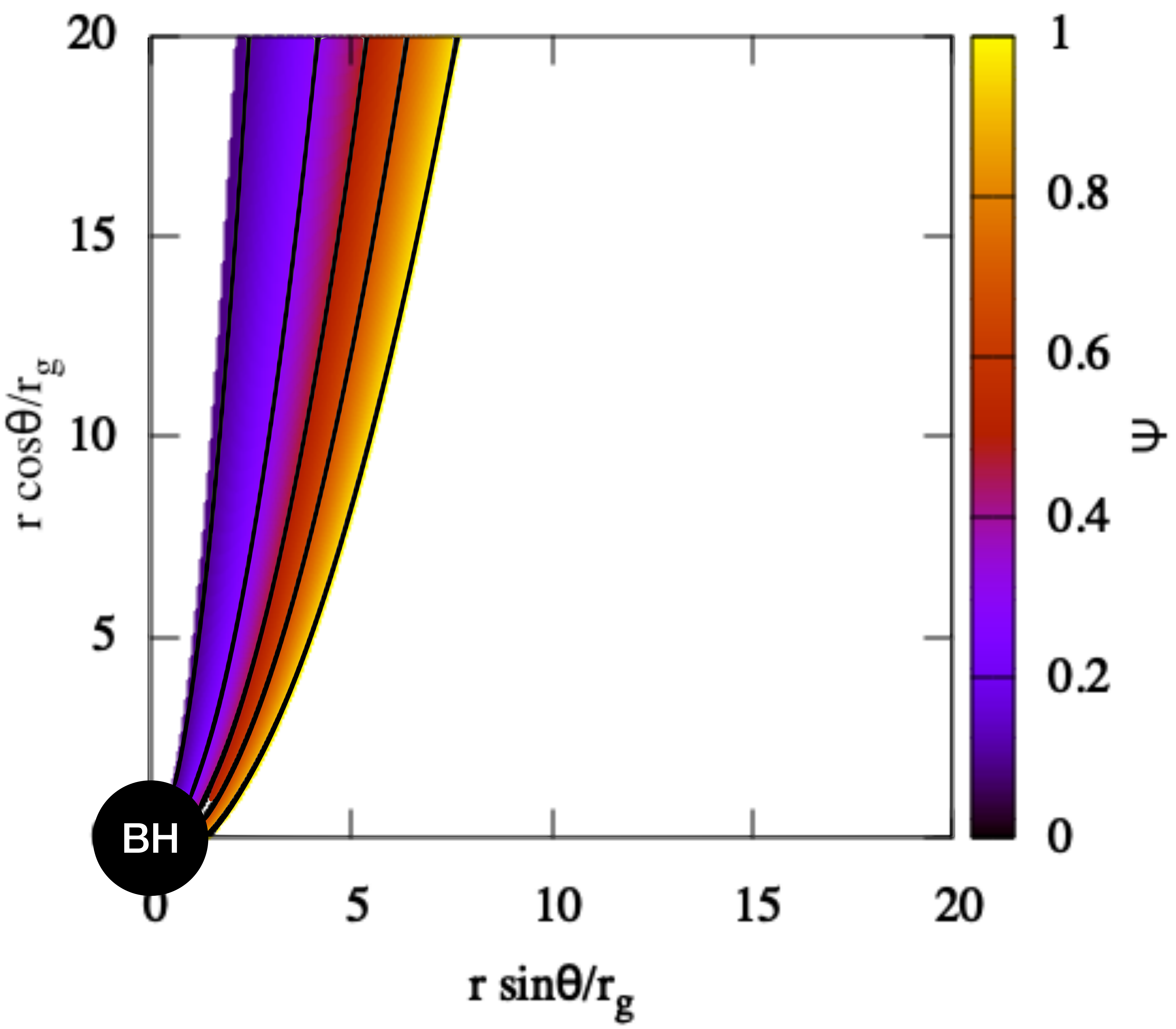
ideal MHD condition: $u^\nu F_{\mu\nu} = 0$

- Boyer-Lindquist coordinate in Kerr spacetime
- steady, axisymmetric $\partial_0 = 0, \partial_3 = 0$
- divide the basic equations into the parallel component to the field line (Bernoulli eq.) and the perpendicular component (Grad-Shafranov eq.)

Field Line Configuration

- flux function:
  $\Psi(r,\theta) = C[(r/r_H)^\nu(1-\cos\theta) + (1/4)\epsilon r\sin\theta]$
  - $\nu = 1$: parabolic field shape force-free solution
  - $\epsilon = 10^{-4}$: MHD deviation
  - C: constant. $\Psi(r_{\rm H}, \pi/2) = 1$
- consistent with results of GRMHD simulations

Lee & Park 2004, Beskin & Nokhrina 2006, Tchekhovskoy+2008, Pu+2015



Integral Constants

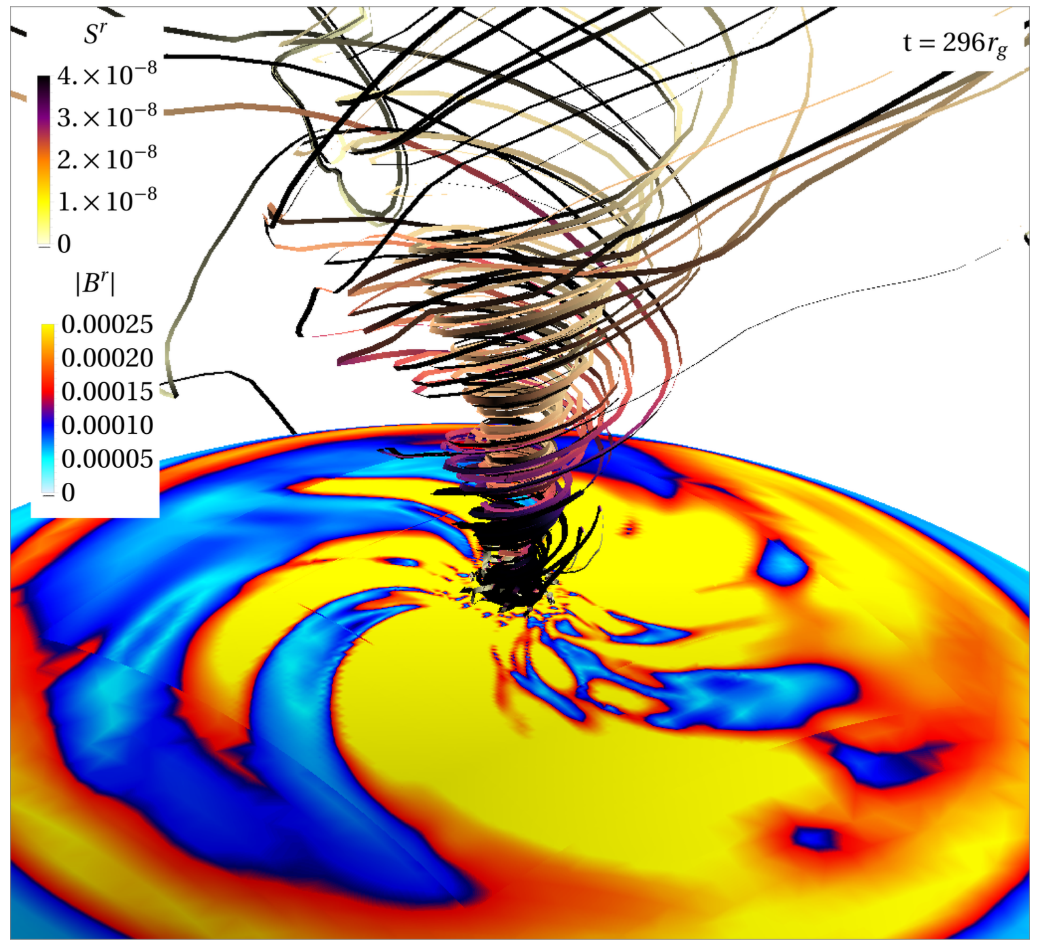
- 4 constant quantities along a field line

1. Energy flux per the rest-mass energy : $\hat{E} = -u_0 + \dfrac{\Omega_F B_3}{4\pi\mu\eta}$
2. Angular momentum flux per the rest-mass energy: $\hat{L} = u_3 + \dfrac{B_3}{4\pi\mu\eta}$
3. mass flux per magnetic field flux: $\eta = -\dfrac{nu_1}{B_1}G_t = -\dfrac{nu_2}{B_2}G_t$

   $G_t = g_{00} + \Omega_F g_{03}$
4. “angular velocity” of the field line: $\Omega_{\rm F} = \dfrac{F_{01}}{F_{13}} = \dfrac{F_{02}}{F_{23}}$

$$\mathbf{v}_d = \frac{\mathbf{E}\times\mathbf{B}}{B^2} = R\Omega_F\mathbf{e}_\phi - R\Omega_F\frac{B_\phi}{B^2}\mathbf{B}.$$

If the fluid don’t move along the filed line, it rotates with $\Omega_{\rm F}$.

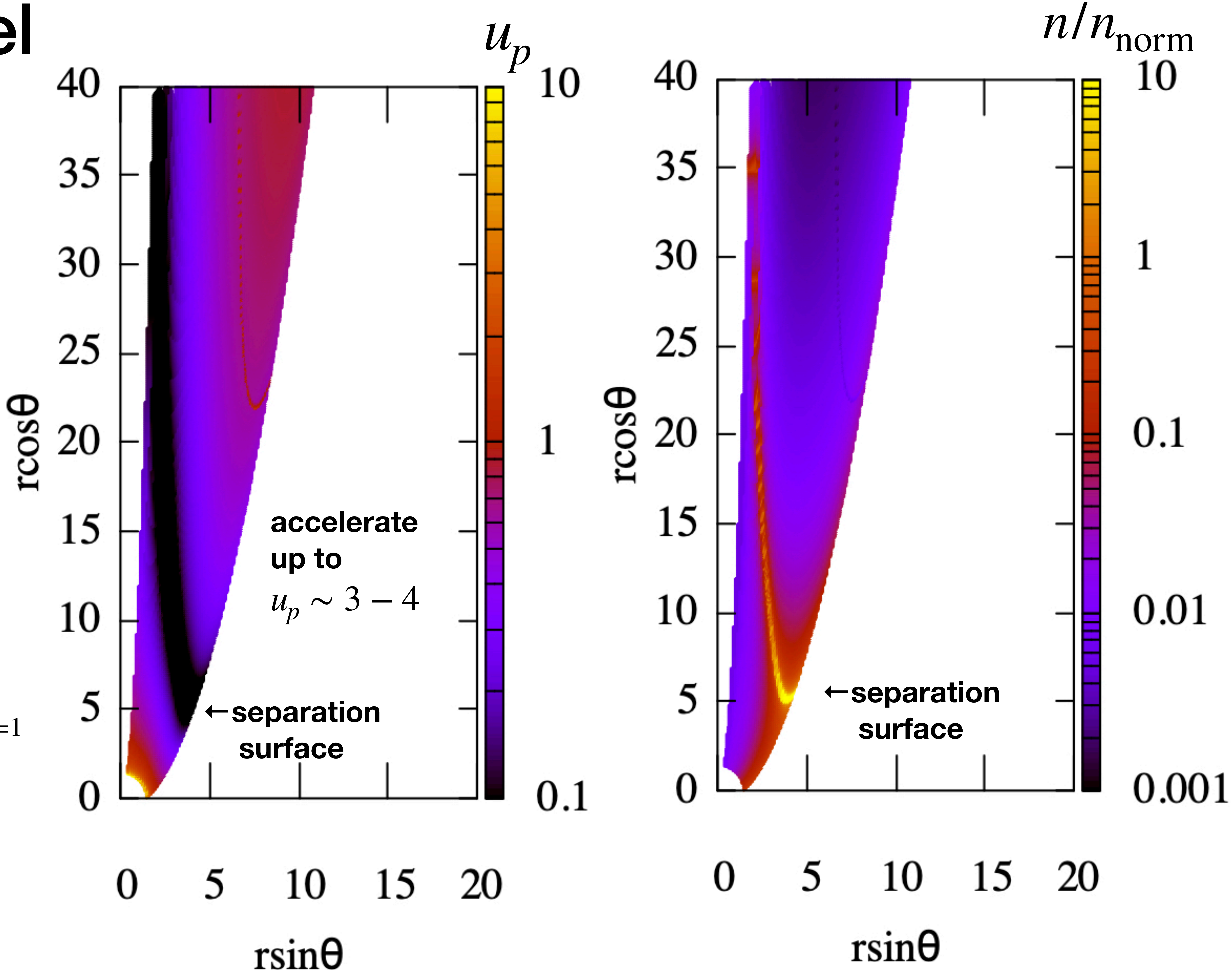


Mahlmann,Levinson, Aloy 2020

3. Results

Parabolic Jet Model

- poloidal velocity:
  $u_p^2 = u_1 u^1 + u_2 u^2$
- flow accelerate from the separation surface
- density normalization:
  $n_{\rm norm} = \left[\frac{B_1 B^1 + B_2 B^2 + B_3 B^3}{8\pi\mu} \right]_{r=r_{\rm ss}, \Psi=1}$

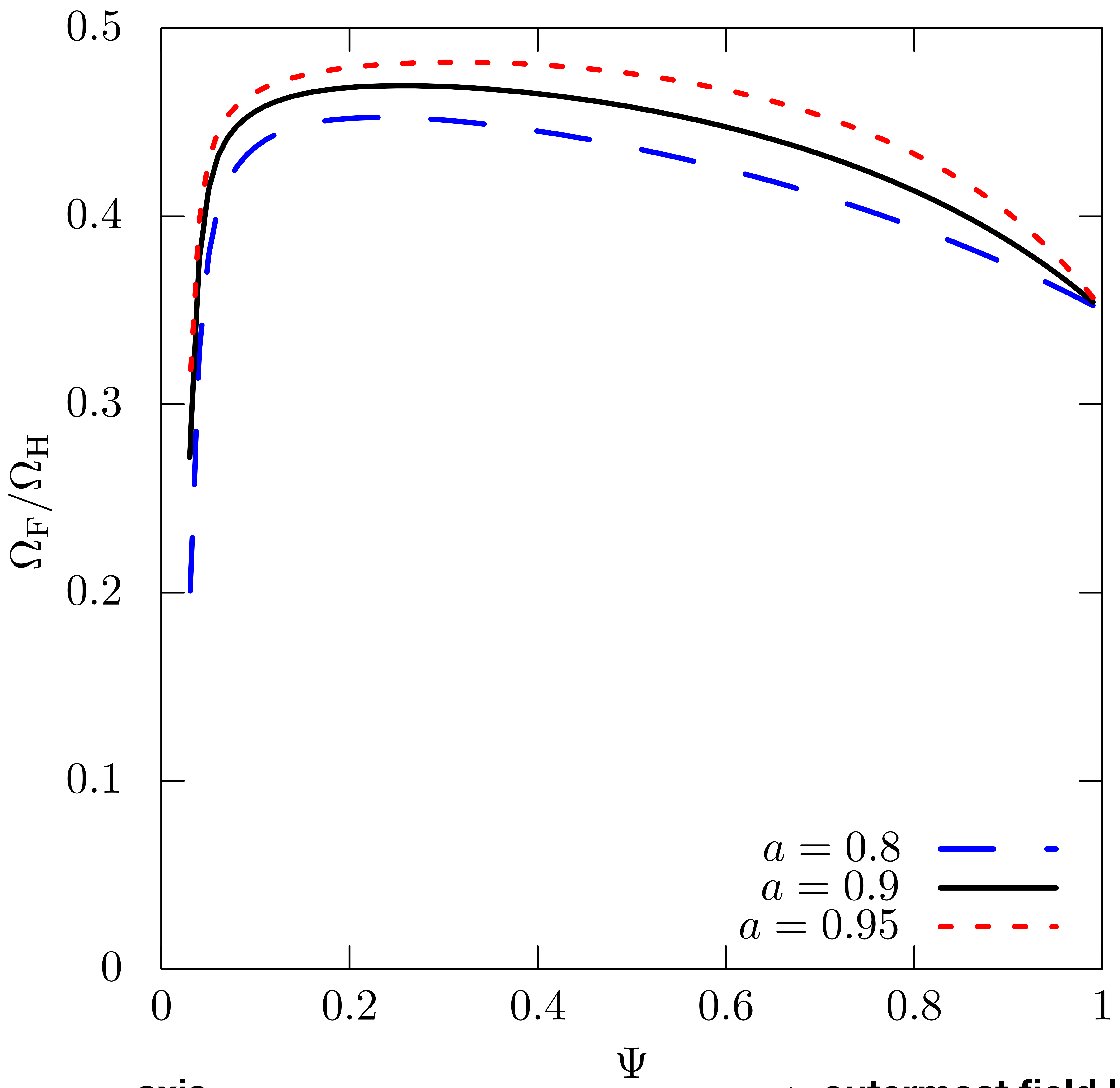


Distribution of Integral Constants and Density

- Ω_F approaches $0.5\Omega_\mathrm{H}$ toward the axis like the parabolic force-free analytic solution.

- $\eta E = -\dfrac{\rho u_0 u_p G_t}{B_p} + \dfrac{\Omega_F B_3}{4\pi} \propto \sin^2\theta$
  dependence of B_3 at the horizon
  → EM dominant jet

- **density: concentrate at $\Psi = 1$**
  - The density contrast becomes higher when the BH spin is larger.



axis ------------------> outermost field line

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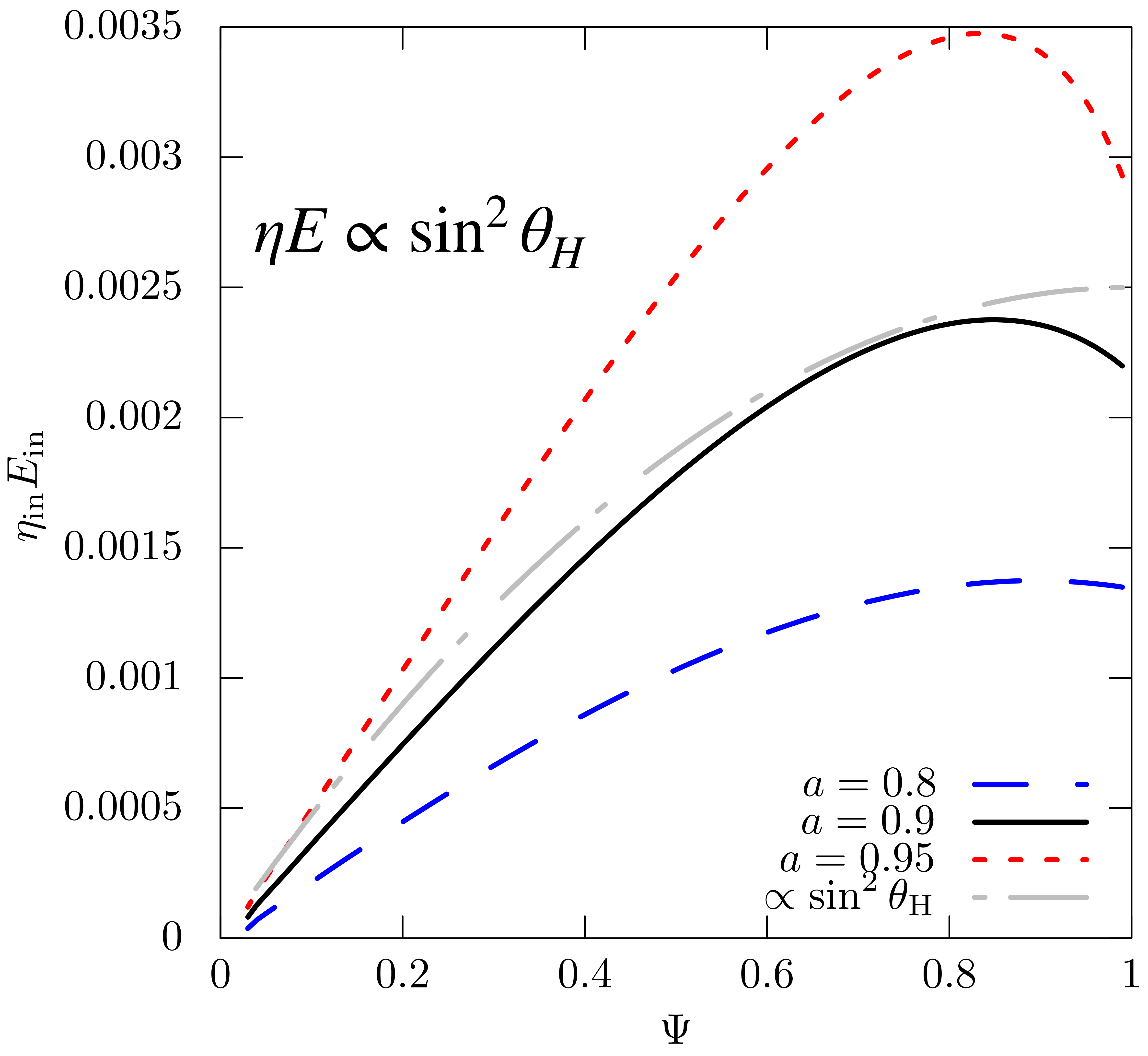

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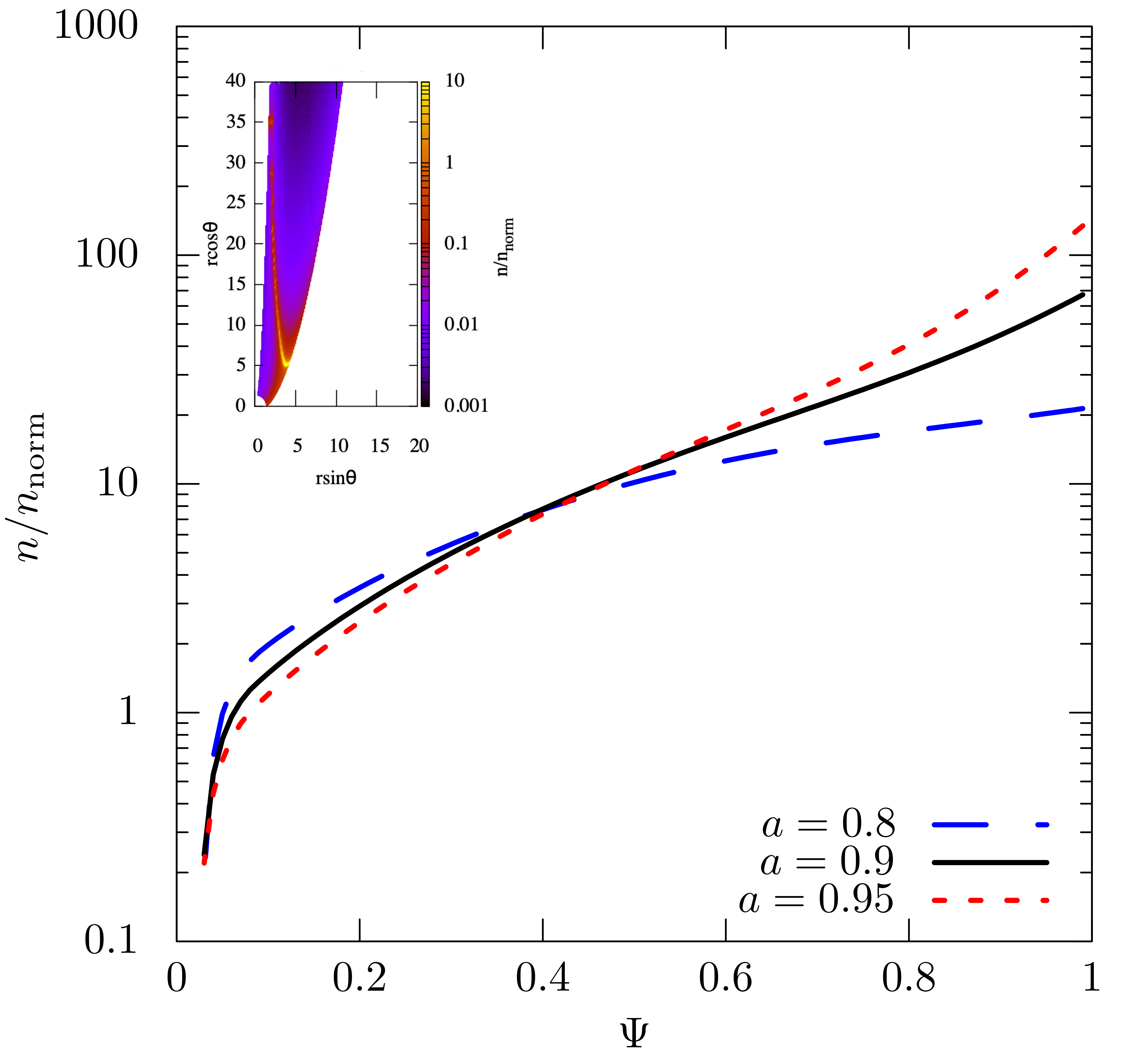
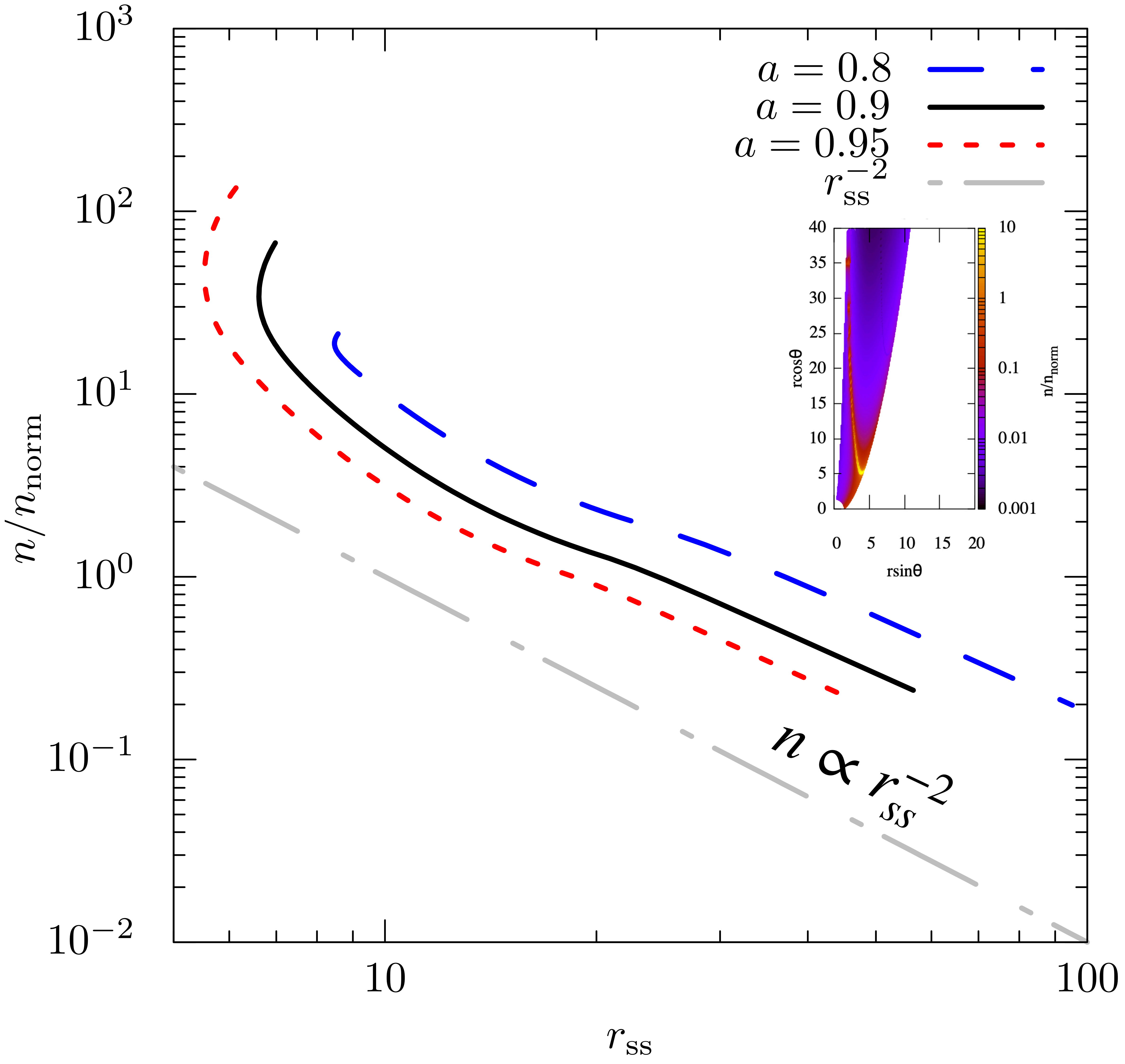


axis ----------------------> outermost field line

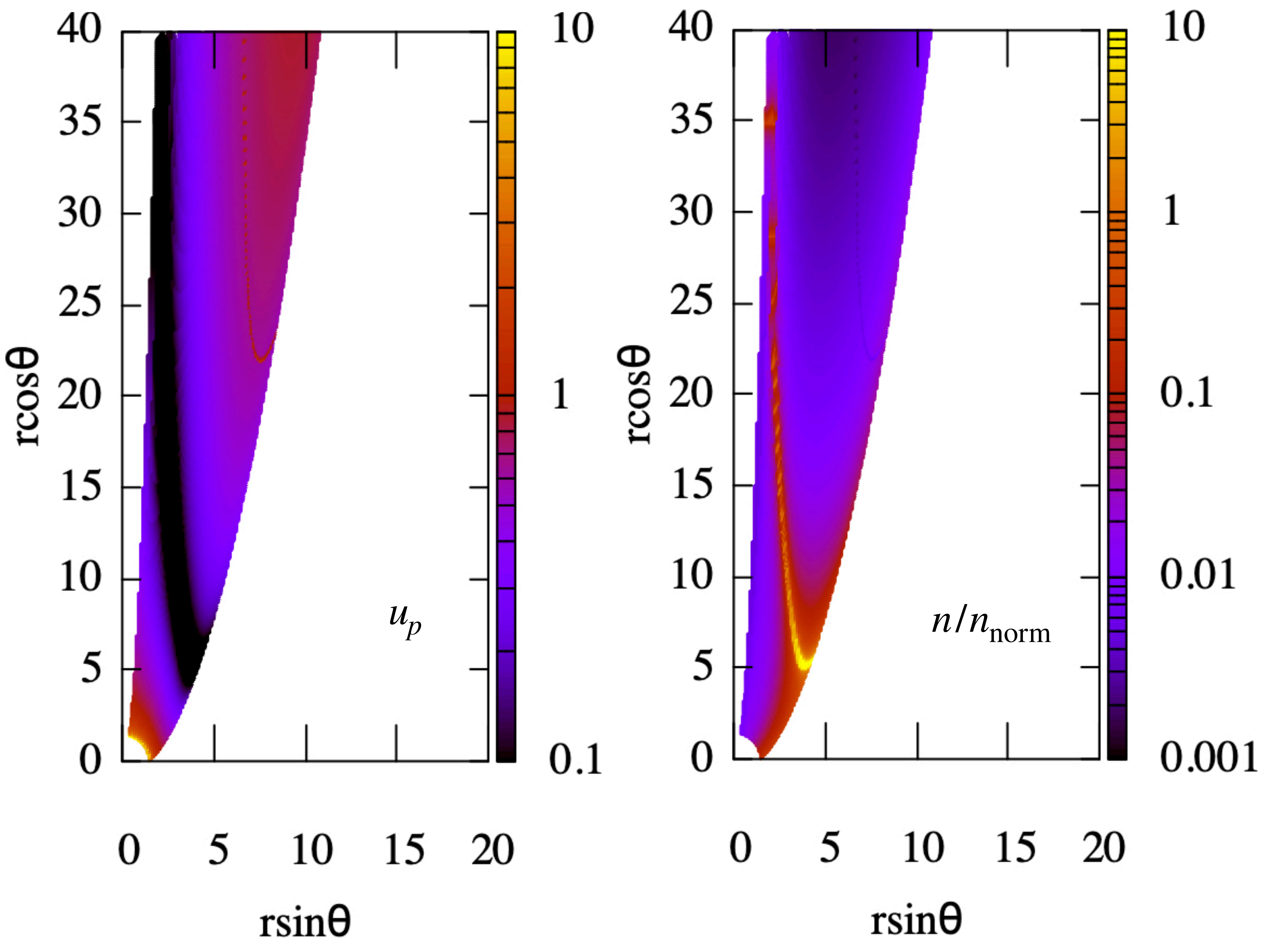
Density on the Separation Surface

- our result: $n \propto r_{ss}^{-2}$
- **This dependence may change if we change initial velocity distribution $u_{p,ss}(\Psi)$.**
- photon-photon pair creation model
  - $n \propto r^{-6}$ for compact source near BH (Moscibrodzka+ 2011, Wong, Ryan, Gammie 2020)
  - $n \propto r^{-4}$ for distant sources (Kimura & Toma 2020)



Summary

- High resolution VLBI observations have resolved emission structures of jets.
- We have constructed the steady, axisymmetric GRMHD jet model which do not suffer from the density floor problem.
- We numerically solve the force-balance between the field lines at the separation surface and analytically solve the distributions of velocity and density along the field lines.
- We determine **the 2D distribution of the EM field, velocity and density in a jet**.
- Our semi-analytic model, combined with radiative transfer calculations, may help interpret the high-resolution VLBI observations and understand the origin of jetted matter.



Ogihara, Ogawa, Toma, ApJ submitted