活動銀河核ジェットにおける シンクロトロン放射電子の空間分布

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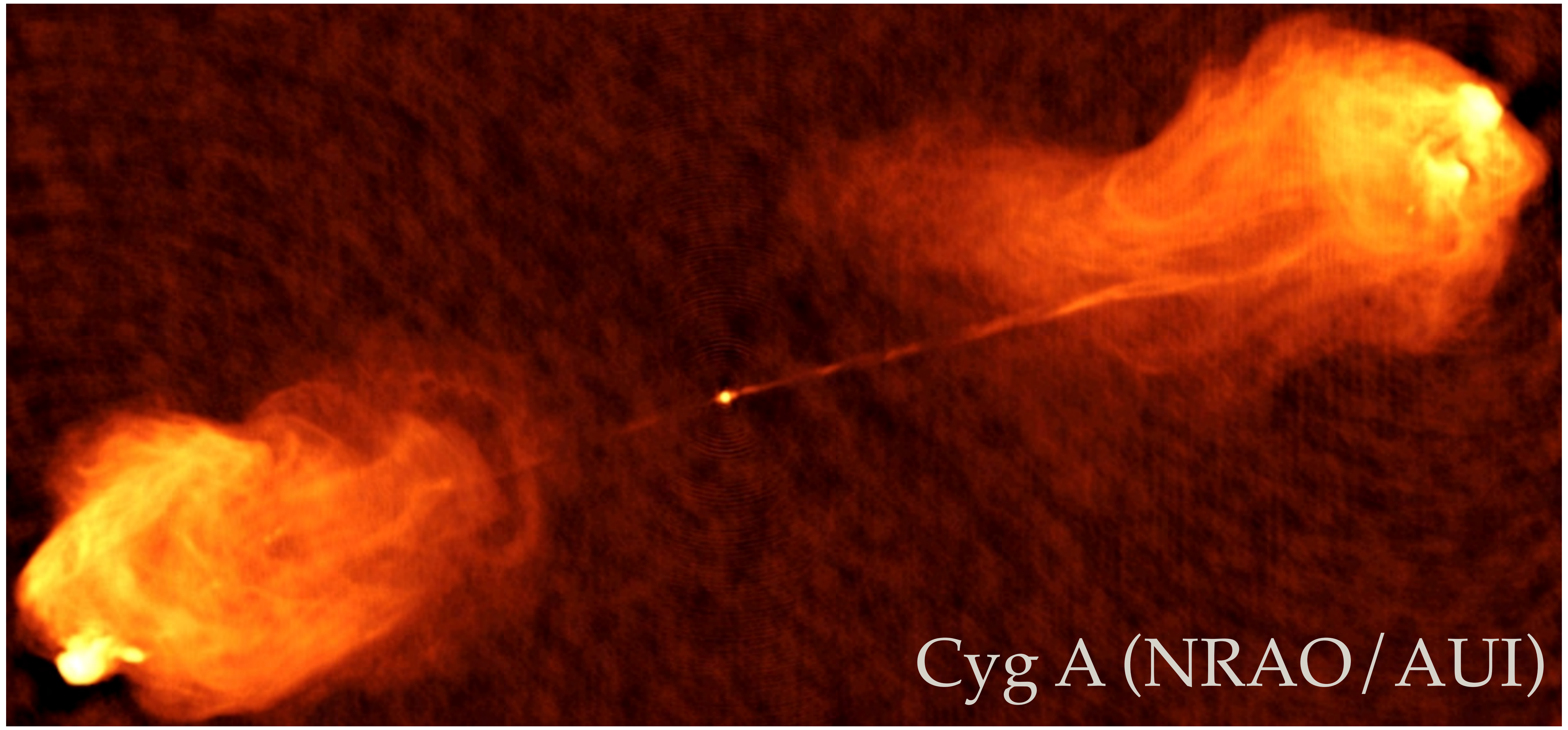
筑波大学 計算科学研究センター PD1年目

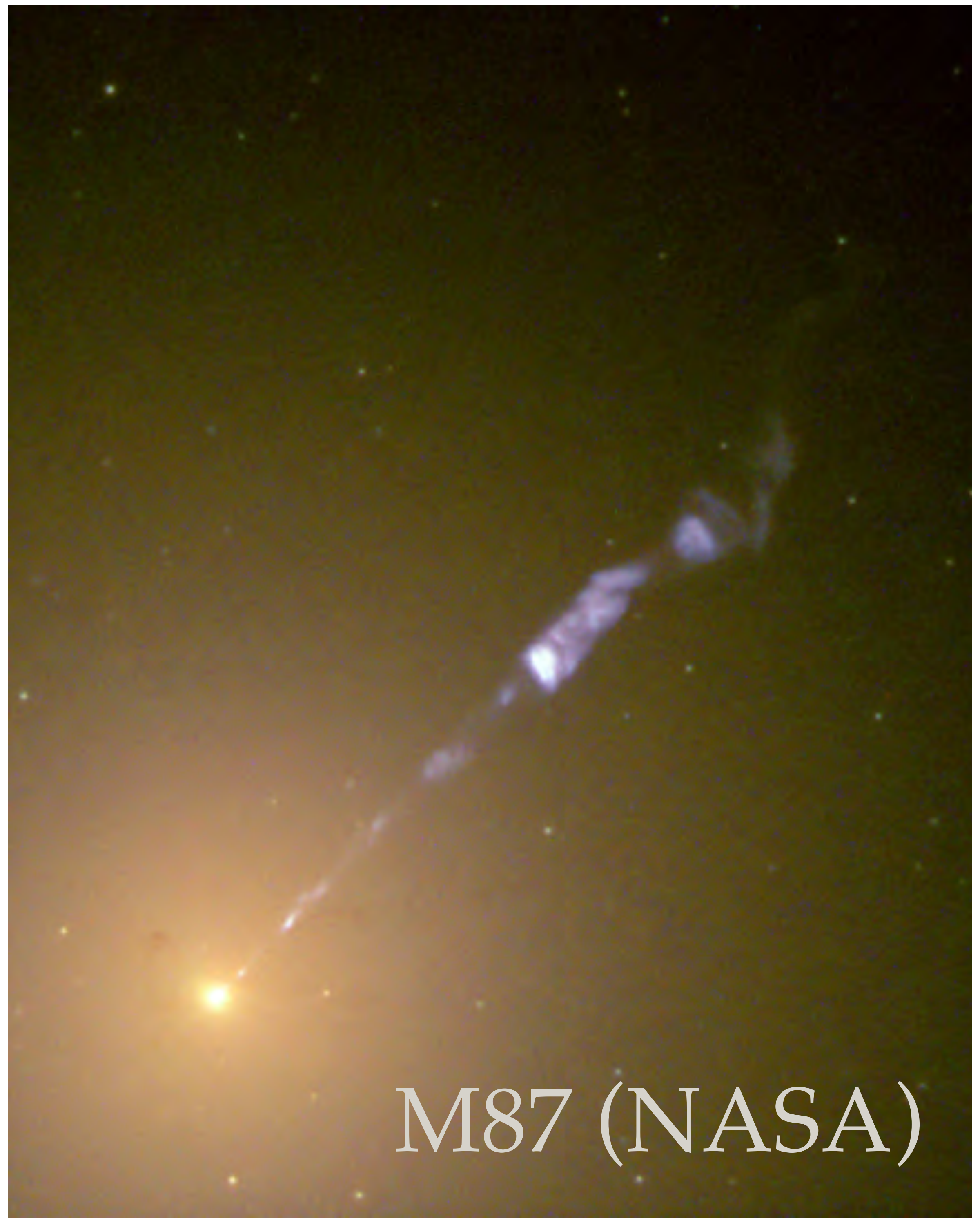
2021/06/25 14:30-15:00, 2021年度第1回 宇宙史研究センター構成員会議, online

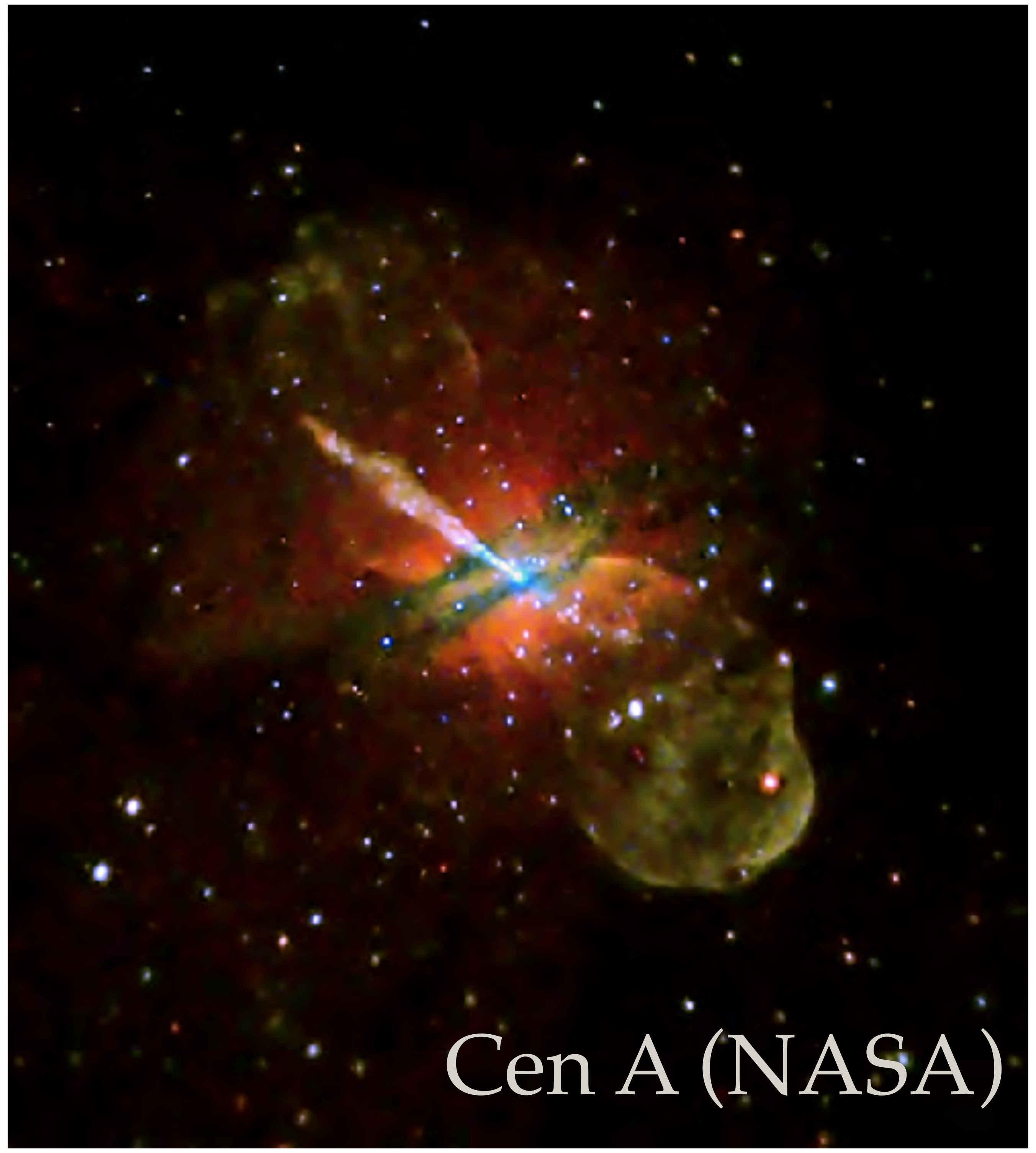
Active Galactic Nuclei jets

and their host galaxies

- collimated relativistic outflow from AGN
- extends over ~kpc - ~Mpc
- emission from radio to gamma-ray
- Almost jets belong to elliptical galaxies
- ~10% of AGN have a jet
  (radio-quiet : radio-loud = 9 : 1)
- possible heating source of galaxy clusters (cooling flow problem)







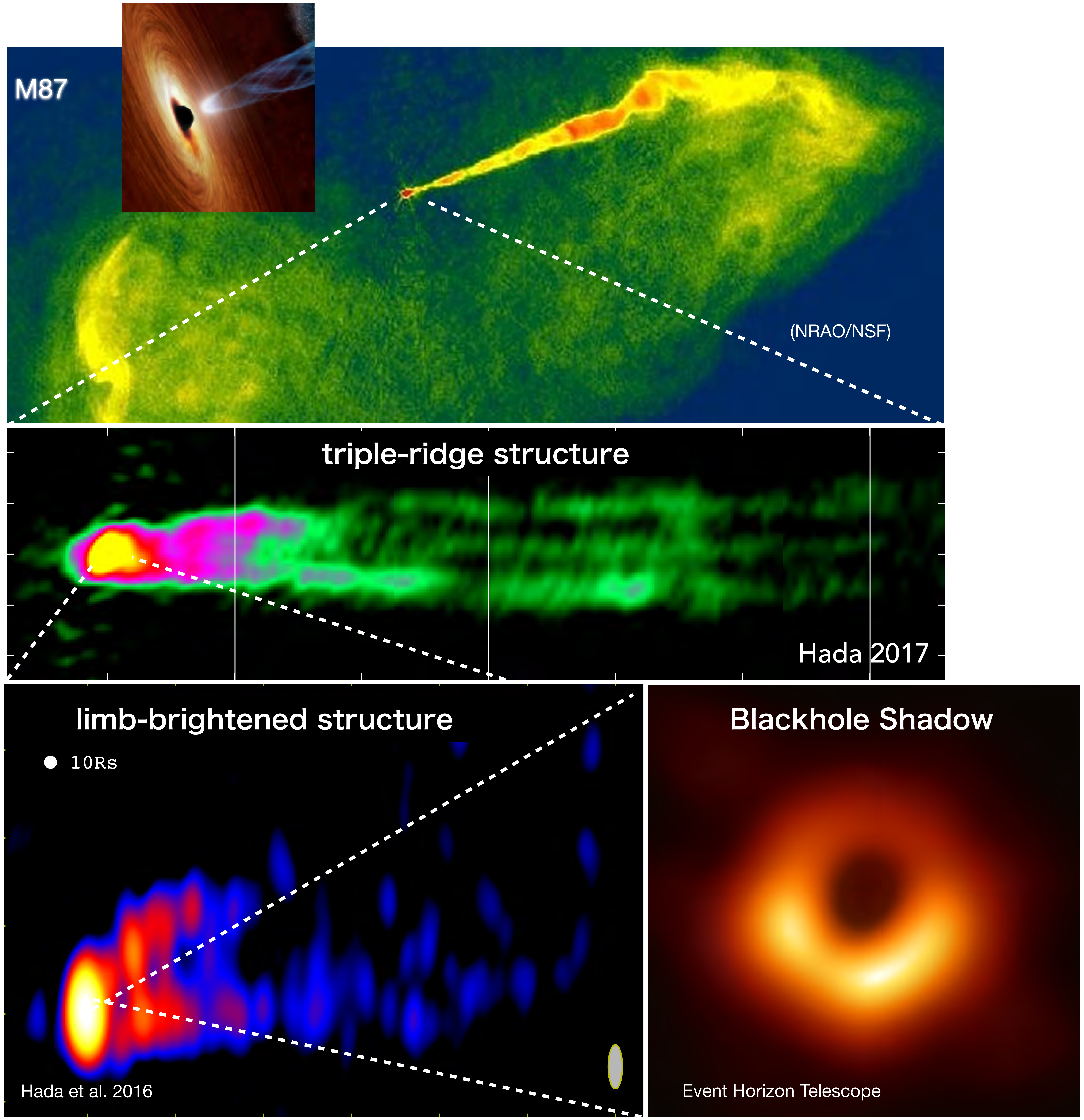
"A curious straight ray lies in a gap in the nebulosity in p.a. 20°, apparently connected with the nucleus by a thin line of matter. The ray is brightest at its inner end, which is 11″ from the nucleus."

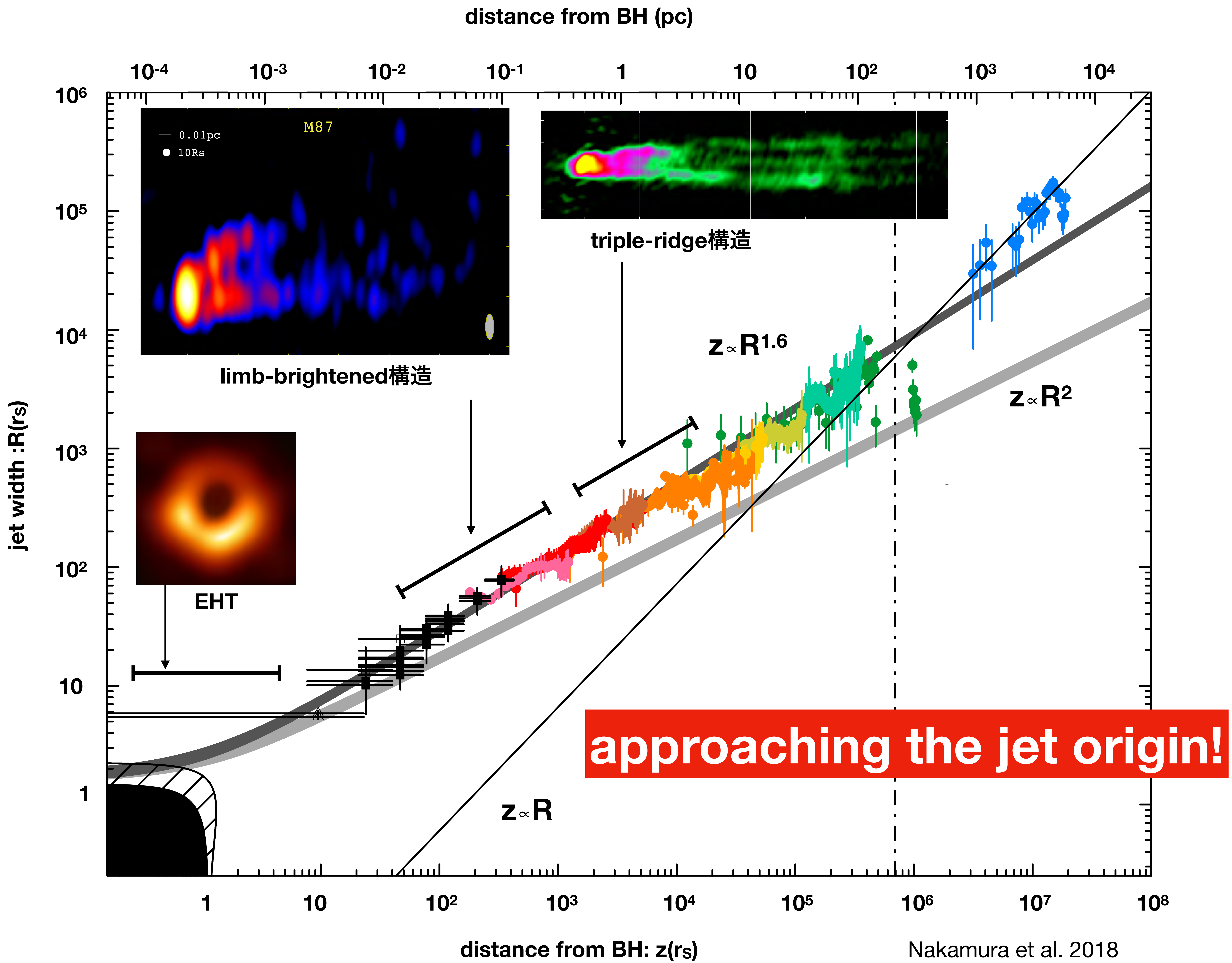
description of NGC 4486 (M87), Heber D. Curtis, 1918

Radio observations

more and more upstream

- High-resolution VLBI observations have revealed characteristic emission structures of AGN jets.
- limb-brightened: M87, Mrk 501, Mrk 421, Cyg A, 3C84
- triple-ridge: only in high-sensitivity observation of M87
- jet width profile (next slide)





Nakamura et al. 2018


A Zoom to the Black Hole in M87 - Hubble Space Telescope on Youtube
Hubble Space Telescope - visible

Jet emission near the horizon

次世代EHT観測でジェット成分の検出が期待

電波ジェットの起源に迫る観測。
BH近傍の放射イメージを理論的に予測できるか

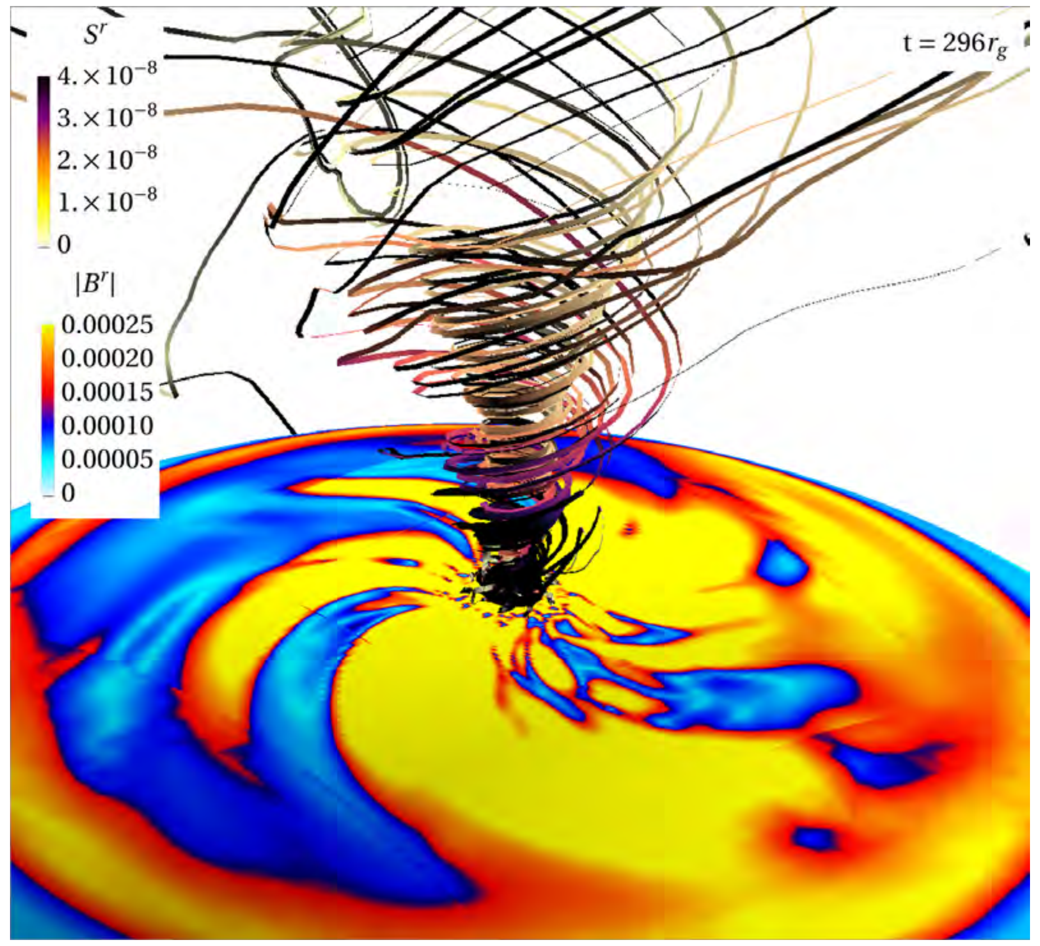
GRMHD simulations

(General Relativistic MagnetoHydroDynamic)

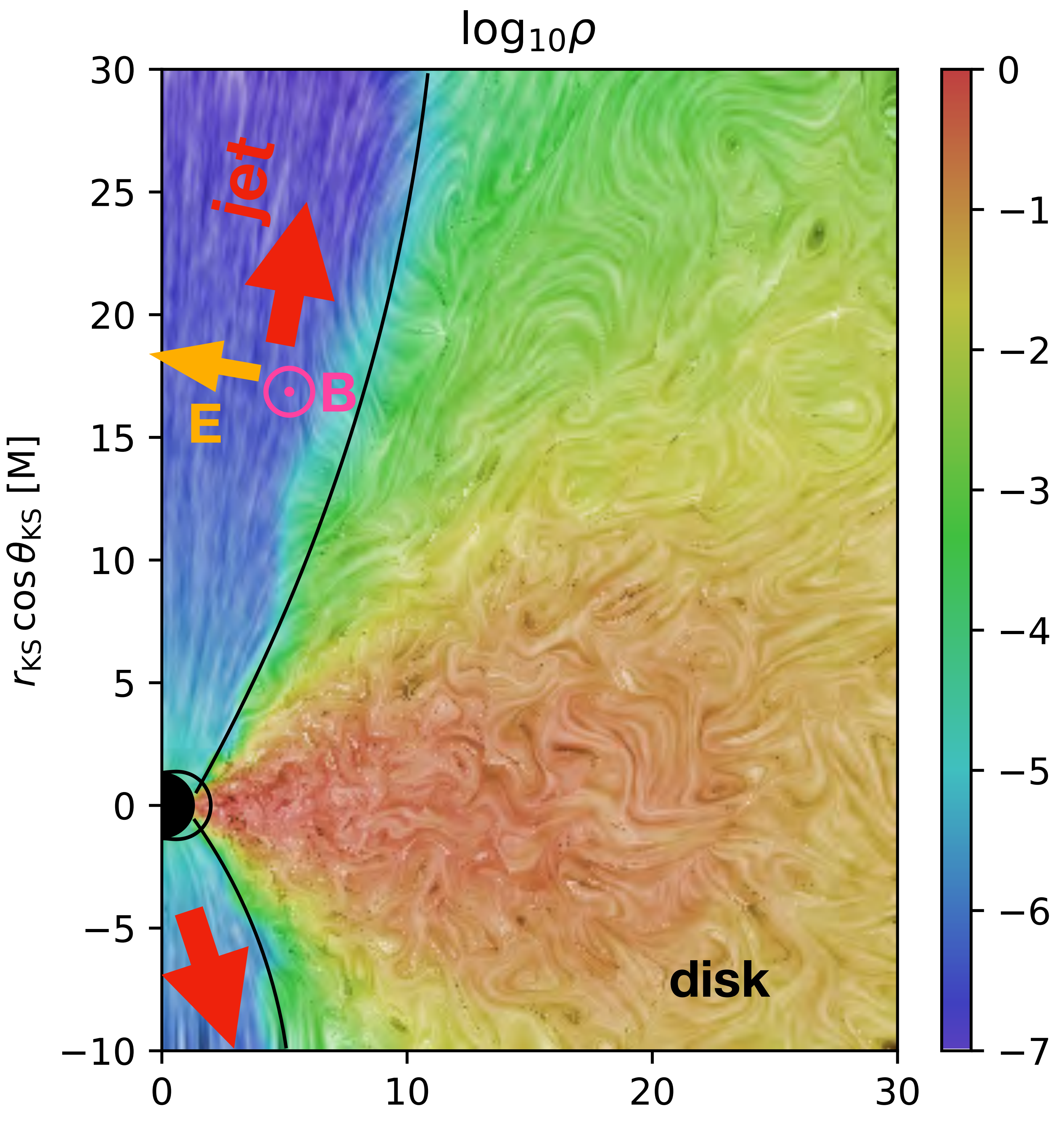
+ radiative transfer calculations

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

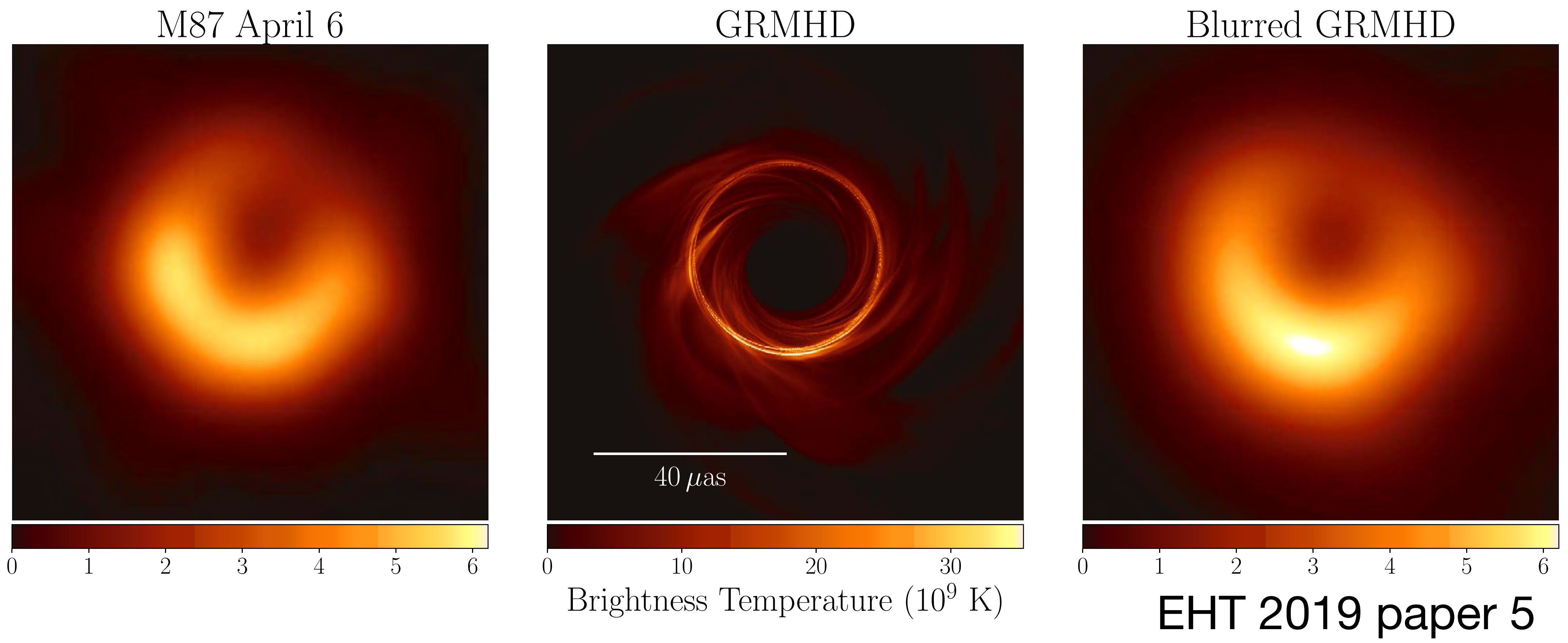
  → comparison with observations and simulations = “black hole shadow”



Mahlmann, Levinson, Aloy 2020



Porth et al. 2019

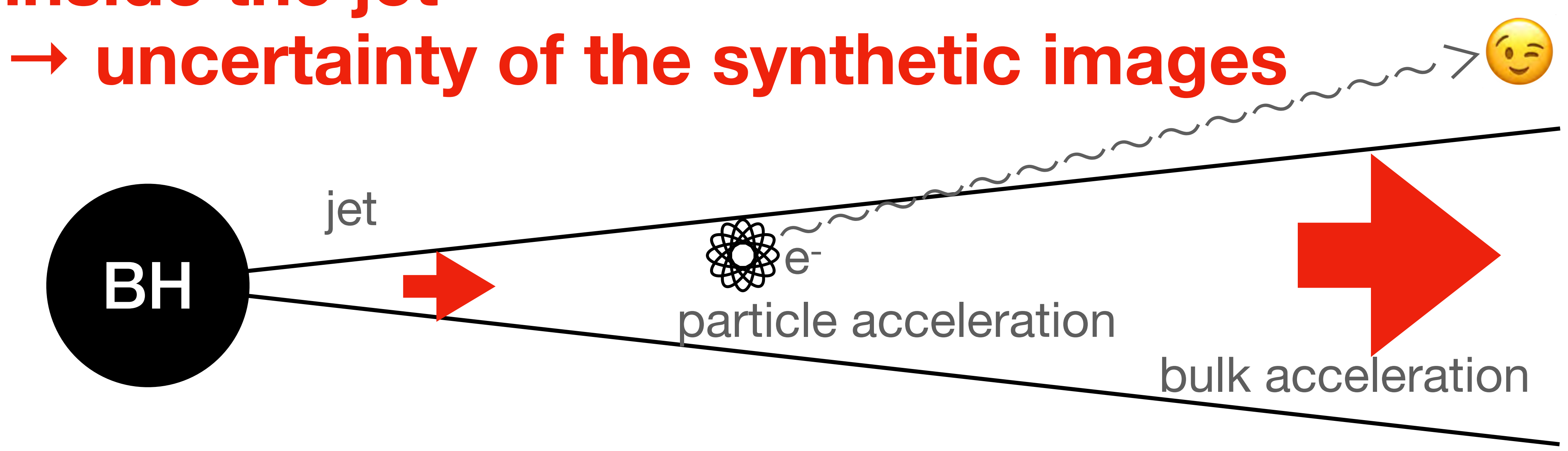


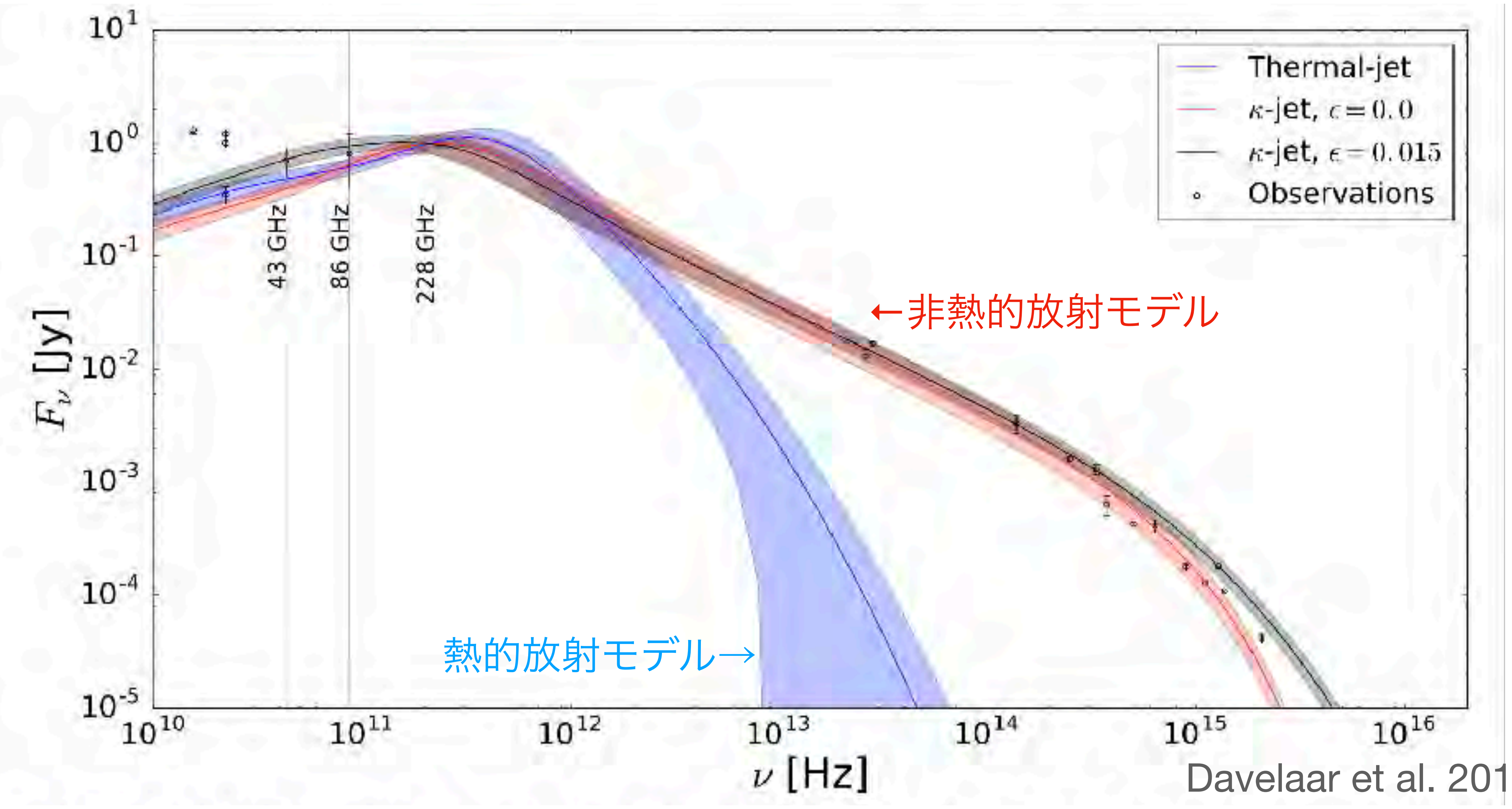
EHT 2019 paper 5

Non-thermal emission

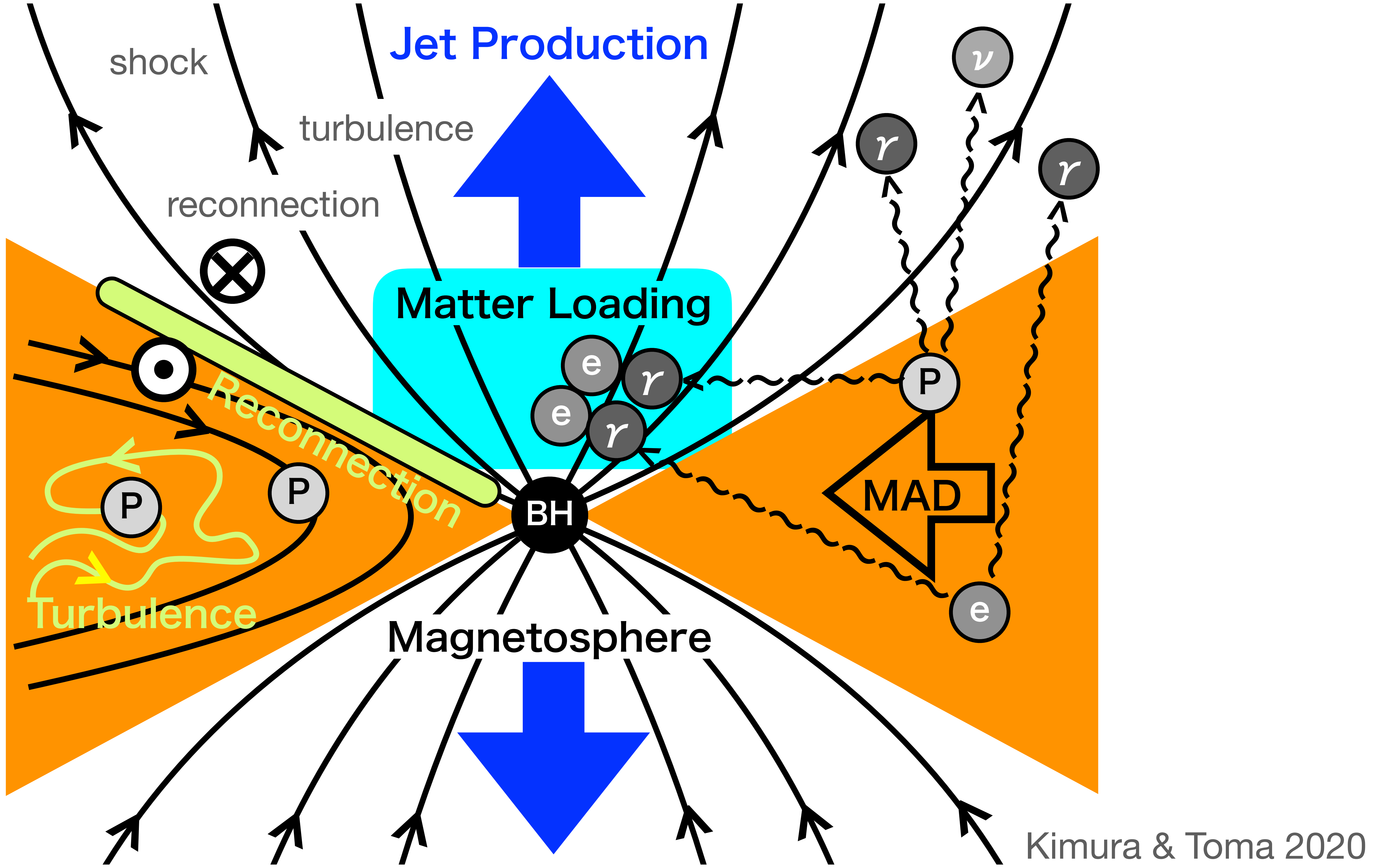
from non-thermal particles

- most GRMHD simulations consider only thermal electrons
- Emission from the jet is synchrotron emission of relativistic electrons.
- How to accelerate electrons relativistically? shock? turbulence? magnetic reconnection? pair-creation?
  → local particle physics
- What is the spatial distribution?
  → large scale dynamics of jets ←本研究
- **uncertainty of the density distribution inside the jet**
  → uncertainty of the synthetic images





Davelaar et al. 2019



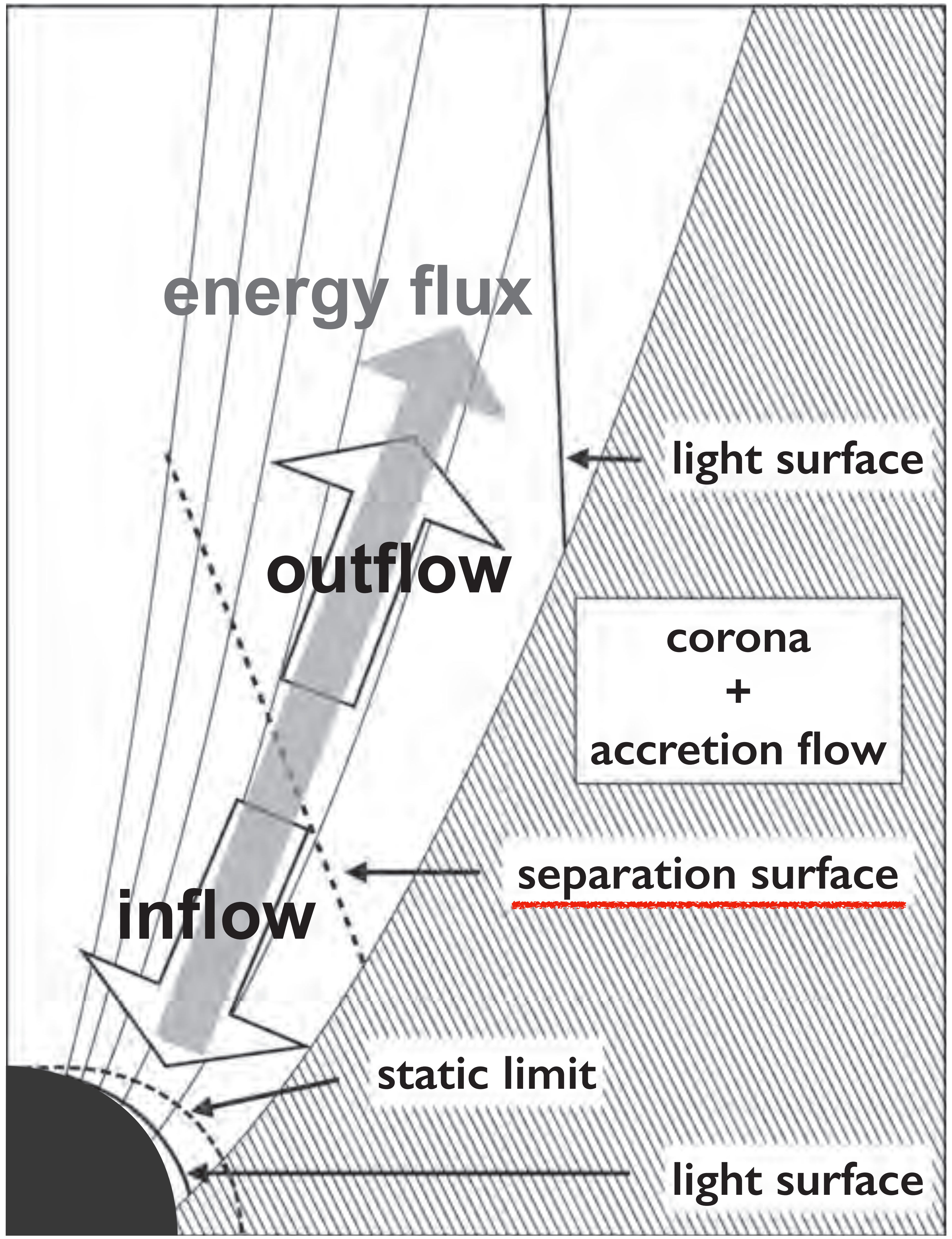
Kimura & Toma 2020

Difficulty of Jet Simulation

Density-floor problem

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



Pu et al. 2015

シミュレーションでジェットを解くのは難しそう。
放射構造を再現することに集中して、
準解析的近似解モデルを用いる。

Our Motivation

predict jet images in EHT scale

- Focus on the internal structures of jets
- Construct **a semi-analytic model which do not suffer 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 and constrain the injection mechanisms.

Basic Equations

- basic equations

Maxwell equation:

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

Energy-momentum equation:

$$\nabla_\nu T^{\mu\nu} = 0,$$

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

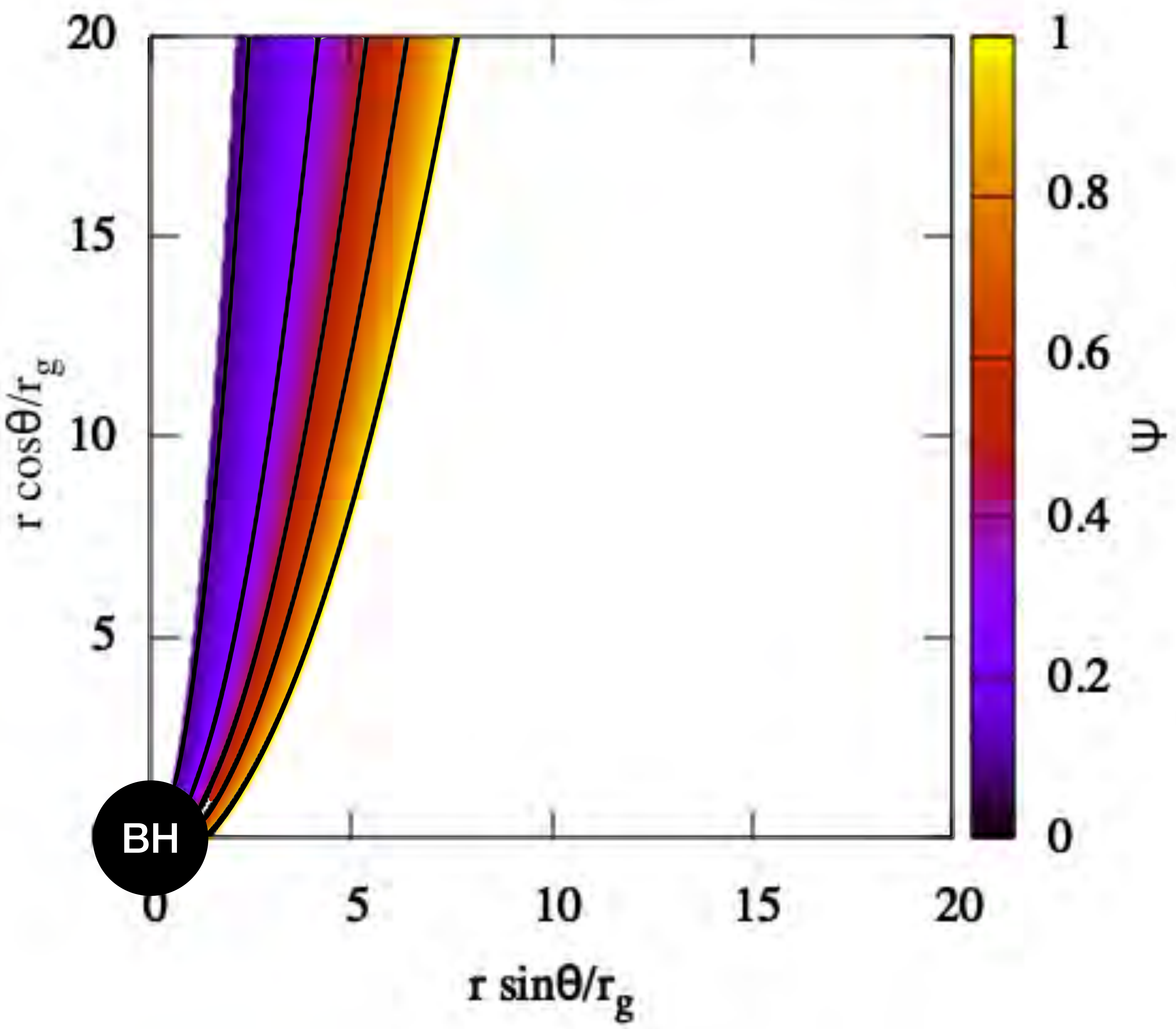
continuity equation: $(nu^\mu)_{;\mu} = 0$

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



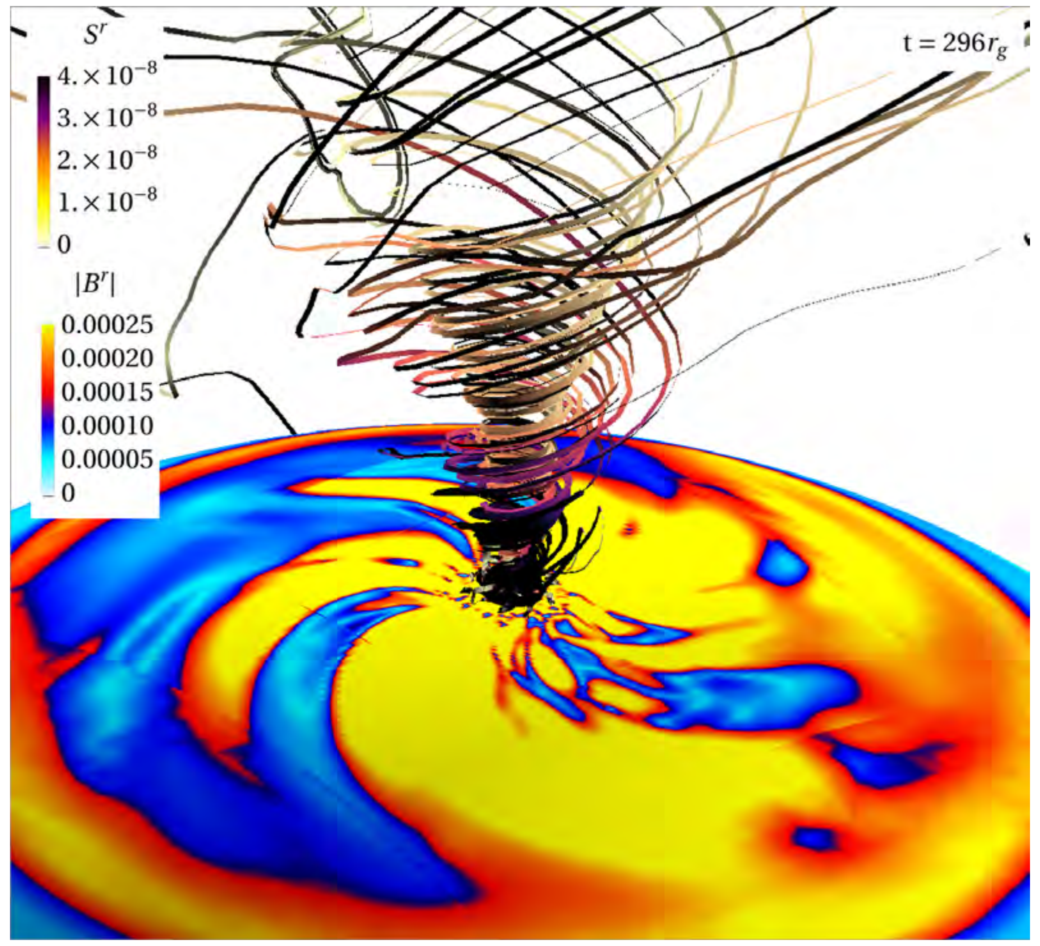
Lee & Park 2004, Beskin & Nokhrina 2006, Tchekhovskoy+2008, Pu+2015

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: $\Omega_{\mathrm{F}} = \dfrac{F_{01}}{F_{13}} = \dfrac{F_{02}}{F_{23}}$



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

If the fluid don’t move along the filed line, it rotates with Ω_{F}.

Mahlmann,Levinson, Aloy 2020

Wind Equation

- analytic solution of the Bernoulli equation

$$\sum_{i=0}^{4} A_i u_p^i = 0,$$

New formulation

- number density: $n = -\dfrac{\eta B_p}{u_p G_t}$
- toroidal field: $B_3 = -4\pi\mu\eta \dfrac{G_\phi \hat{E} + G_t \hat{L}}{M^2 - k_0}$

$$A_4 = 1$$

$$A_3 = \frac{k_0 B_p}{2\pi\mu\eta G_t}$$

$$A_2 = 1 + \hat{E}^2 k_4 + \left(\frac{k_0 B_p}{4\pi\mu\eta G_t}\right)^2$$

$$A_1 = \frac{B_p(k_0 - \hat{E}^2 k_2)}{2\pi\mu\eta G_t}$$

$$A_0 = k_0(k_0 - \hat{E}^2 k_2)\left(\frac{B_p}{4\pi\mu\eta G_t}\right)^2$$

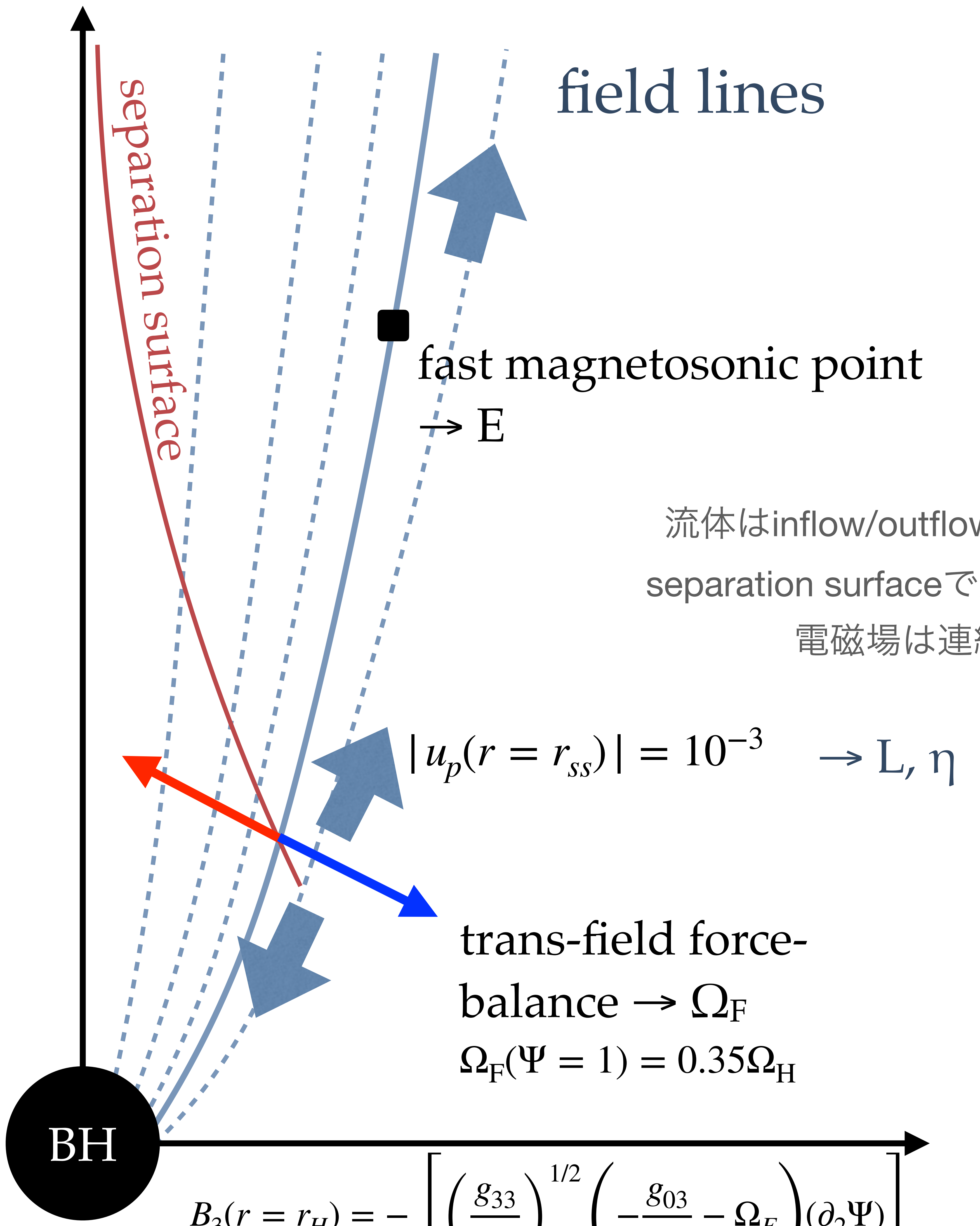
$G_t = g_{00} + \Omega_F g_{03}$ $\quad k_0 = -(g_{00} + 2\Omega_F g_{03} + \Omega_F g_{33})$ $\quad \rho_w^2 = g_{03}^2 - g_{00}g_{33}$

$G_\phi = g_{03} + \Omega_F g_{33}$ $\quad k_2 = (1 - \Omega_F L/E)^2$ $\quad k_4 = -(g_{33} + 2g_{03}L/E + g_{00}(L/E)^2)/\rho_w^2$

4 constants, 4 conditions

- constrain four integral constants by four conditions

1. regularity condition of the magnetosonic point of outflow
2. initial poloidal velocity at the separation surface
3. electromagnetic condition at the horizon (Znajek condition)
4. trans-field force balance at the separation surface (next slide)



流体はinflow/outflowで不連続、

separation surfaceで湧き出しあり

電磁場は連続的

$$B_3(r = r_H) = -\left[\left(\frac{g_{33}}{g_{22}}\right)^{1/2}\left(-\frac{g_{03}}{g_{33}} - \Omega_F\right)(\partial_2\Psi)\right]_{r=r_H}$$ → L, η

GRMHD simulationは質量流速を全面で手で与える

我々はseparation surfaceでのみ質量流速を与える

New constraining method

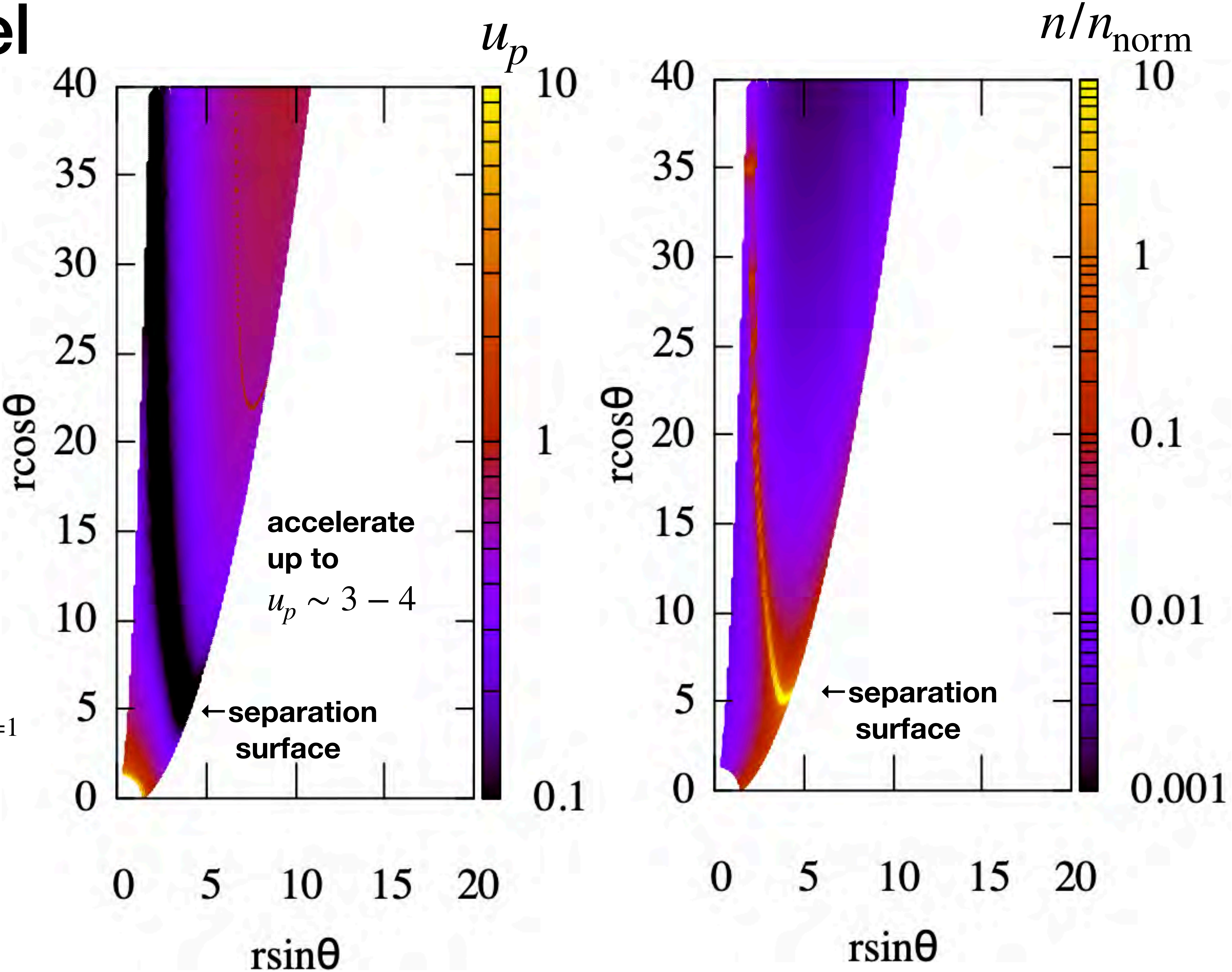
Results

Parabolic Jet Model

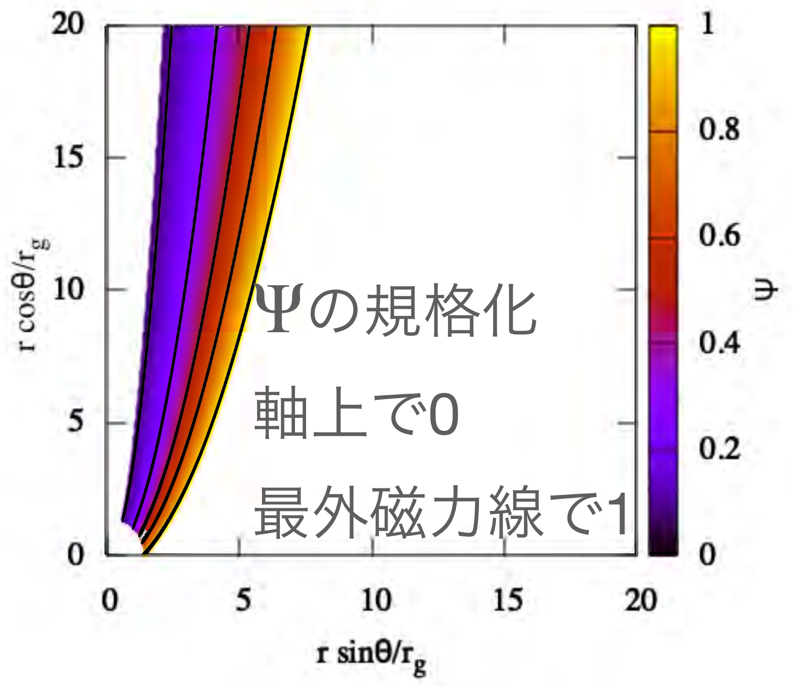
- poloidal velocity:
  $u_p^2 = u_1 u^1 + u_2 u^2$

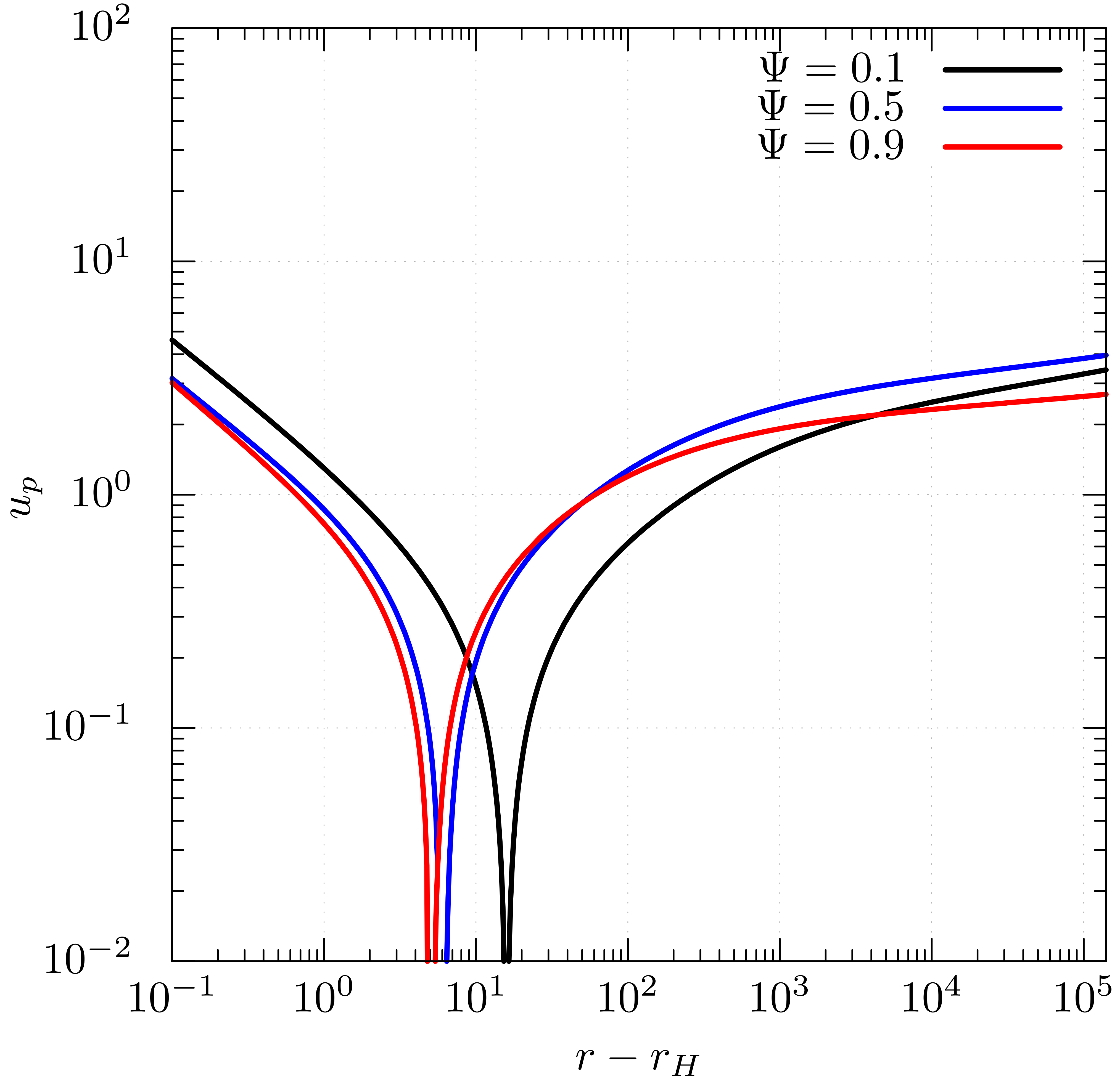
- flow accelerate from the separation surface

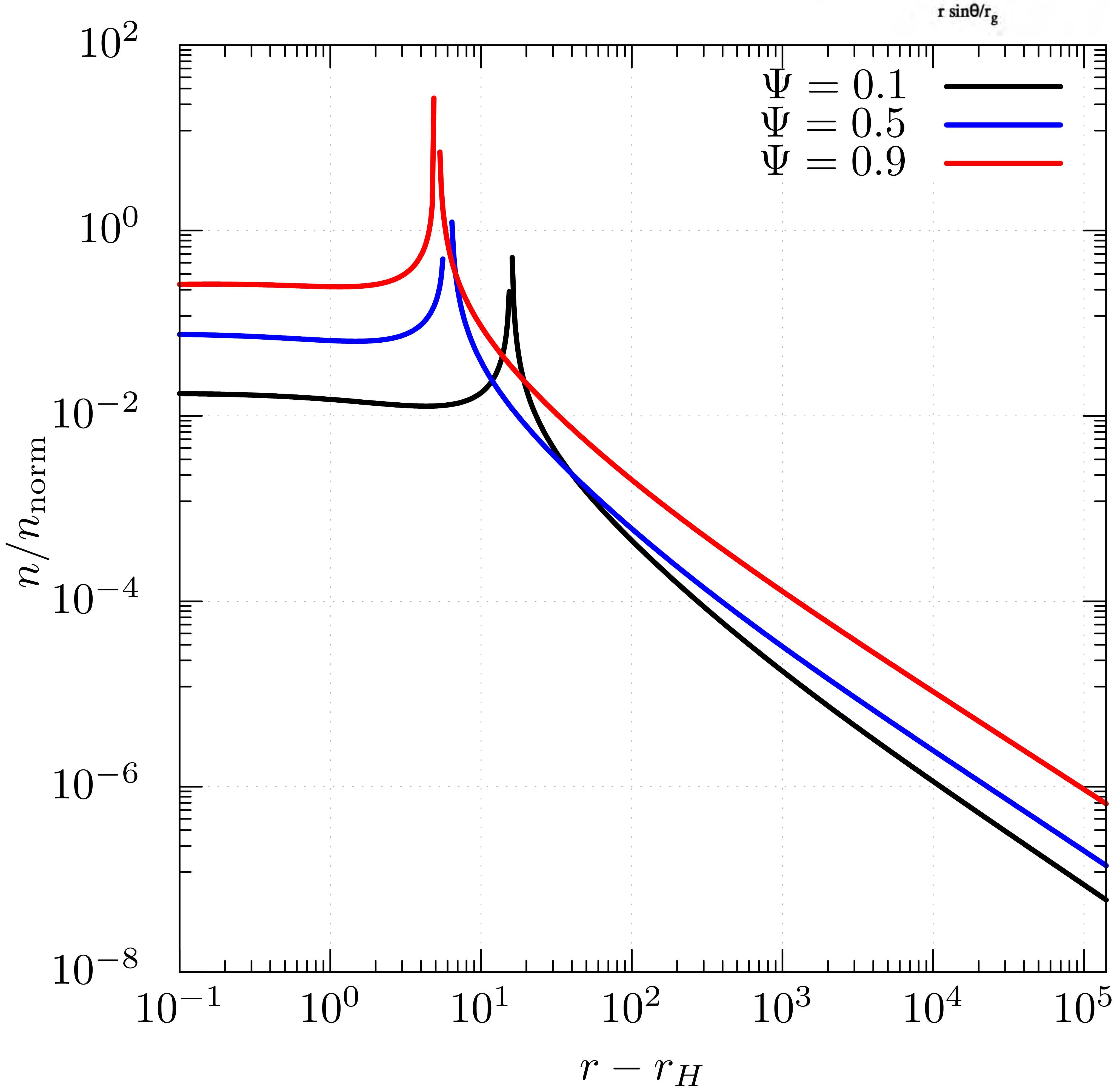
- density normalization:
  $$n_{\rm norm} = \left[\frac{B_1 B^1 + B_2 B^2 + B_3 B^3}{8\pi\mu}\right]_{r=r_{\rm ss},\Psi=1}$$



u_p and n along field lines

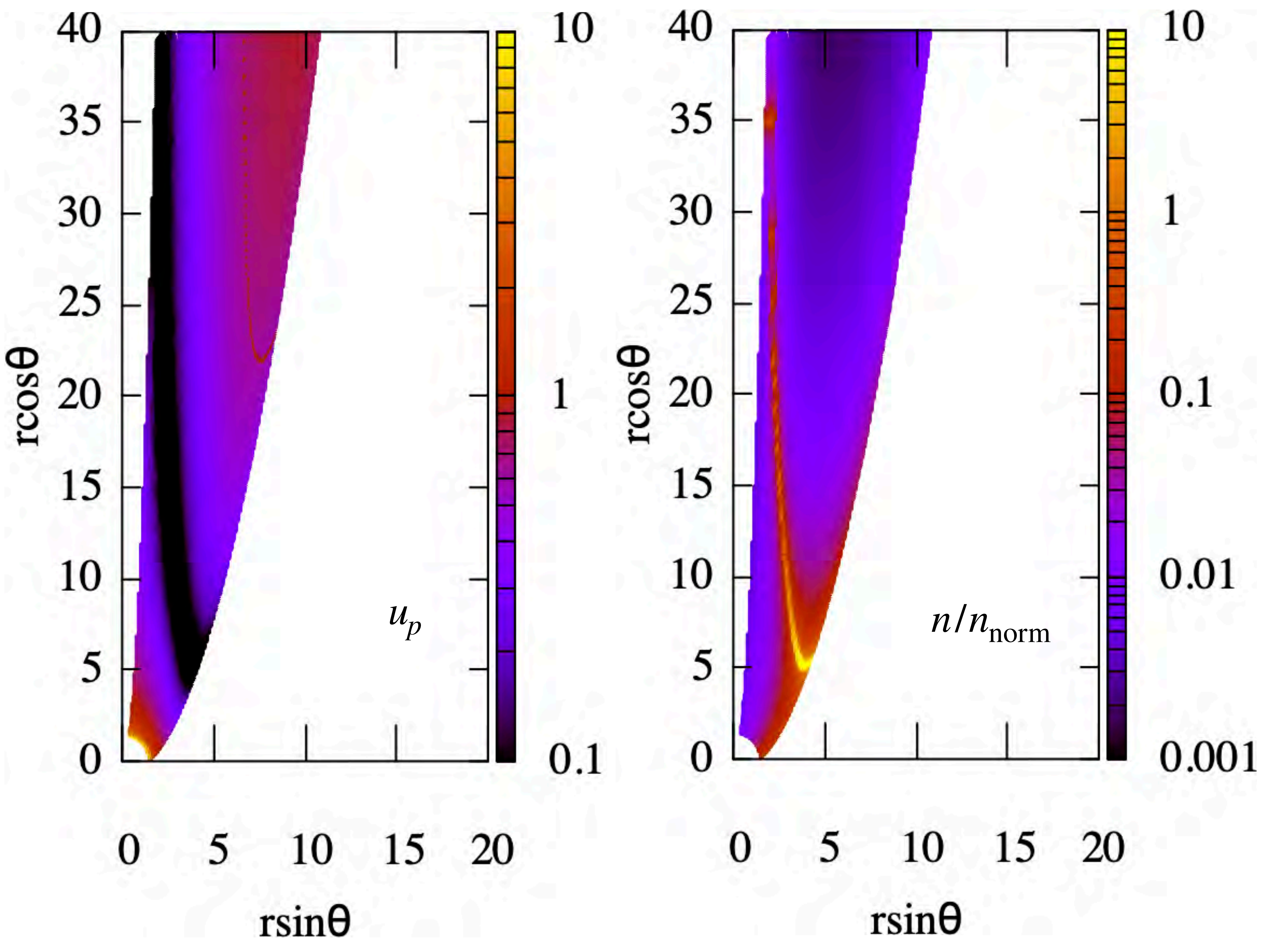






Summary

- Observations: limb-brightened/triple-ridge structure, BH shadow
- GRMHD simulation: density-floor problem → cannot simulate jets
- We have constructed the steady, axisymmetric GRMHD jet model which do not suffer the density floor problem.
- We numerically solve the force-balance between the field lines at the separation surface and analytically solve the wind equation.
- We determine **the 2D distribution of the EM field, velocity and density in a jet**.



Taiki Ogihara, T. Ogawa(Univ. of Tsukuba), K. Toma (Tohoku Univ.)
https://ui.adsabs.harvard.edu/abs/2021ApJ...911...34O/abstract

Future Prospects

- Our semi-analytic model, combined with radiative transfer calculations, may help interpret the high-resolution VLBI observations and understand the origin of jetted matter.
- reconstruct limb-brightened structure ~10r_g
- future EHT: jet origin/injection point
- No one know the emission structure of jets. Our analytic model can be adapted easier than simulations for observed structure.
- and more…
  - proper-motion / polarization
  - other limb-brightening jets