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AGN jet physics on the horizon scale

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Jet and Shock Breakouts in Cosmic Transients @ YITP; 2018/5/14-18

2018年 | プレスリリース

世界の若手研究者の活躍機会創出のため５０名規模の東北大学テニュアトラック制度を創設

2018年9月18日 16:00 | プレスリリース , 採用情報

【発表のポイント】

本学では、世界から優秀な若手研究者を集め、その中からさらに優秀な若手研究者に安定かつ独立した研究環境を提供する全国に先駆けた全学的テニュアトラック制度を創設します。

今回、本制度の創設を踏まえ、本日付けで学際科学フロンティア研究所の教員公募を開始します。

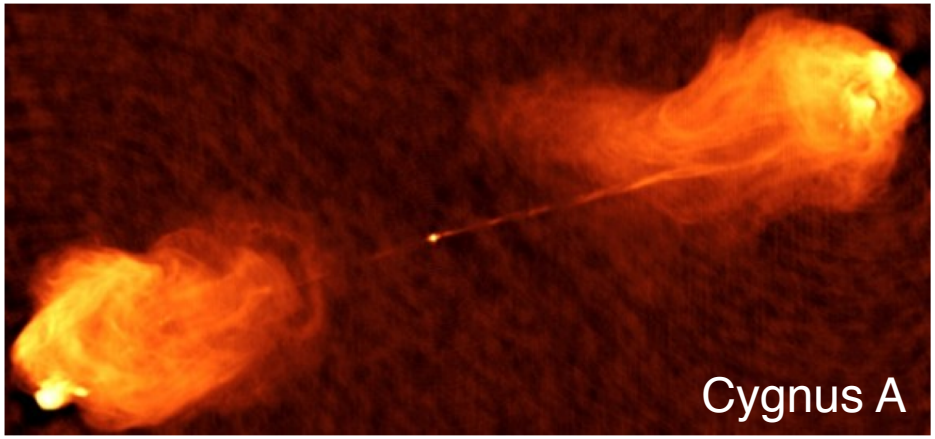
カテゴリ

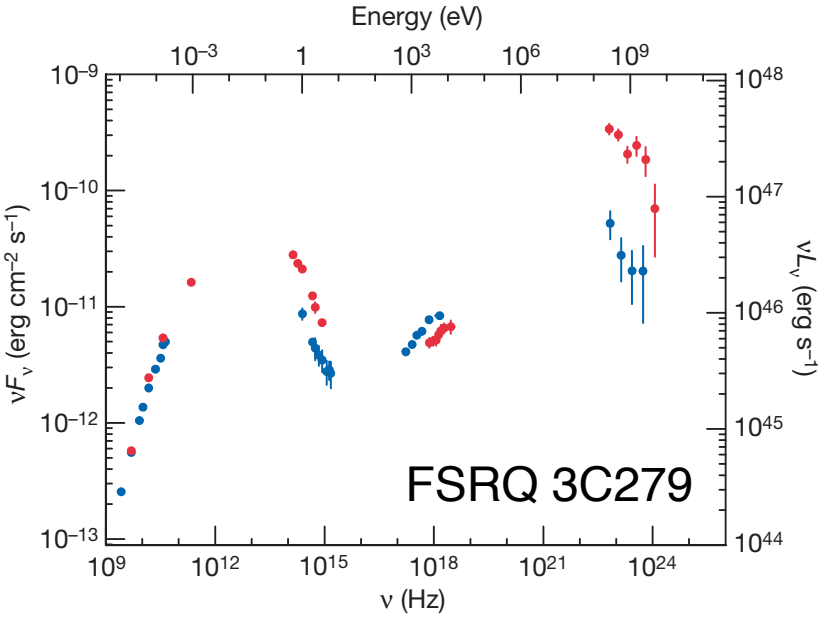
新着情報
ニュース
受賞・成果等
▶ 受賞
▶ 研究成果
▶ メディア掲載
採用情報
▶ 東北大学教員公募情報
▶ 東北大学教員の任期に関する規程
▶ 東北大学職員公募情報
▶ 東北地区国立大学法人等職員採用

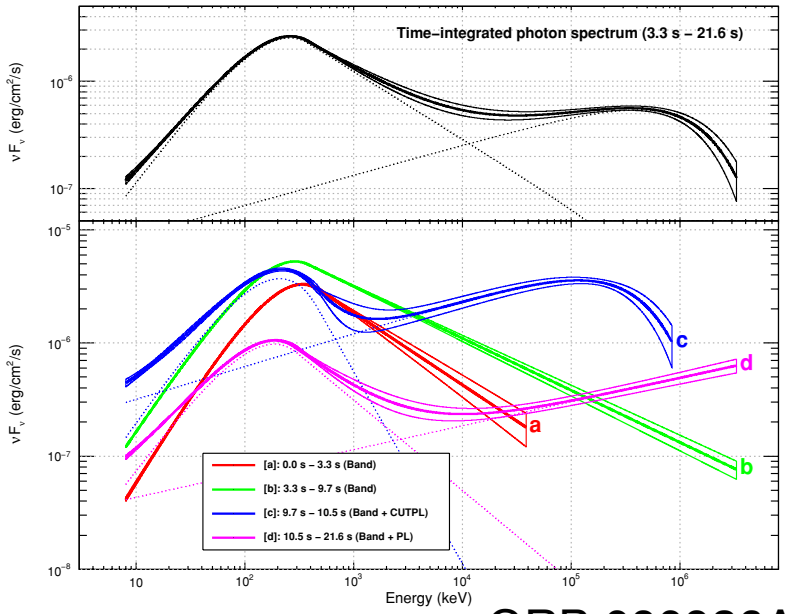
Outline

- Introduction: theoretical issues on AGN jets
  - Steady axisymmetric models
- Recent discussions in the community
  - East Asia-VLBI results & discussions
  - GRMHD simulations + GR ray-tracing

Relativistic jets







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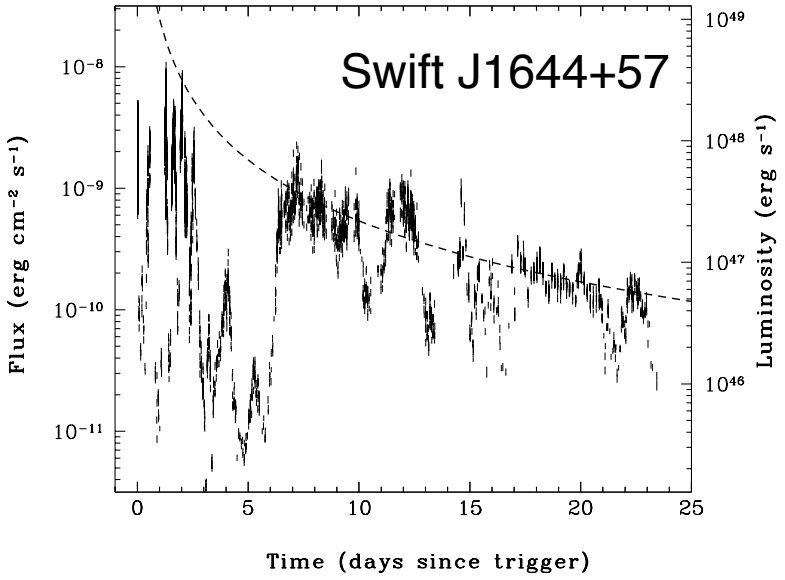
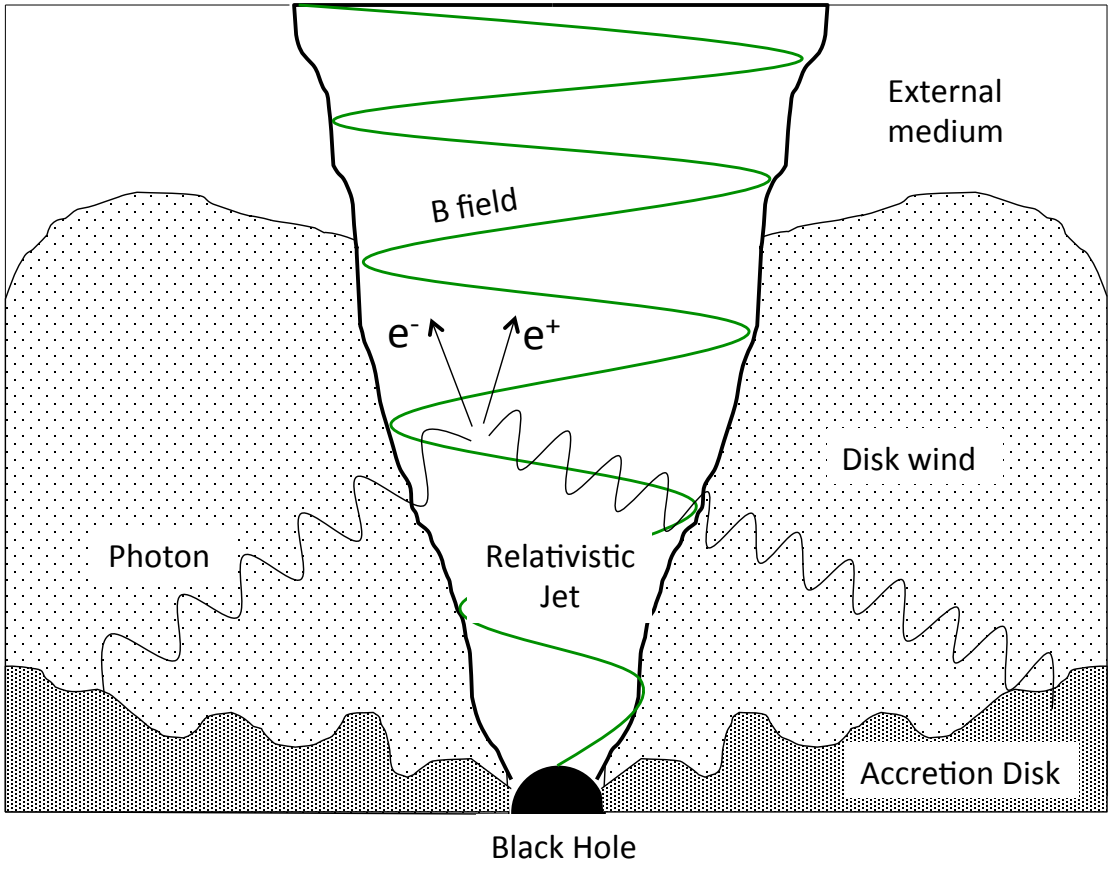


Theoretical issues

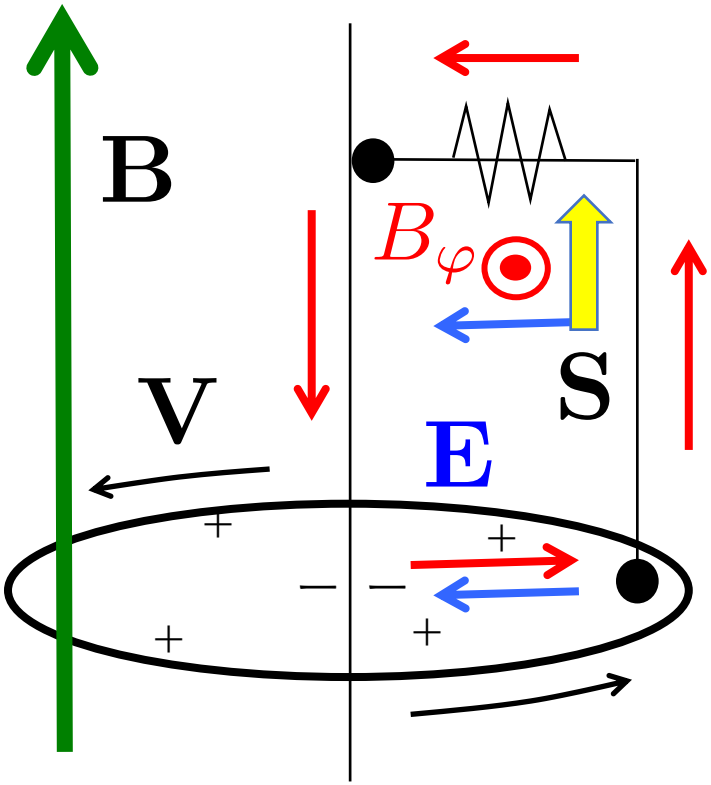
- Energy source
- Mass source
- Acceleration
- Collimation
- Stability
- Dissipation

- Classification



Koide et al. 2000; Komissarov 2001; McKinney & Gammie 2004; Barkov & Komissarov 2008; Tchekhovskoy et al. 2011; Ruiz et al. 2012; Contopoulos et al. 2013

Energy source



Conversion from
Poynting to matter

$$\nabla \cdot \mathbf{S} = -\mathbf{E} \cdot \mathbf{J} < 0$$

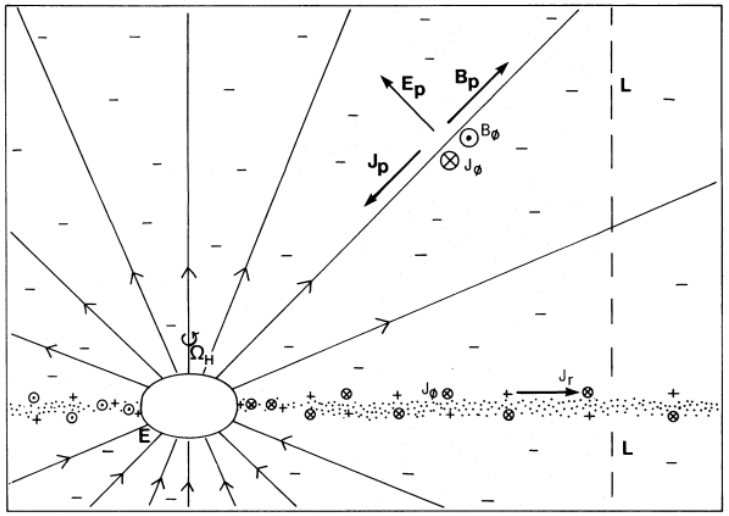
$$\nabla \cdot \mathbf{S} = 0$$

$$\nabla \cdot \mathbf{S} = -\mathbf{E} \cdot \mathbf{J} > 0$$

Conversion from
matter to Poynting

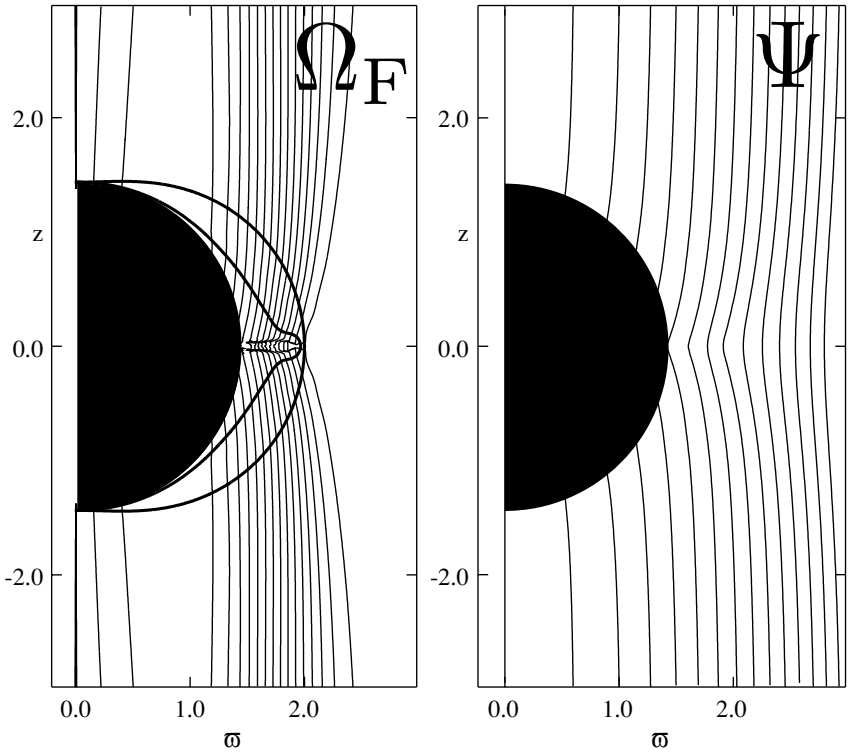
- Rotating BH or accretion disk?
- Contribution of gas pressure?

Blandford-Znajek process



$$\mathbf{E} = -\Omega_{\rm F}\mathbf{e}_\phi \times \mathbf{B}$$

Resistive force-free simulation



Ergosphere does not allow force-free plasma with no outward Poynting flux

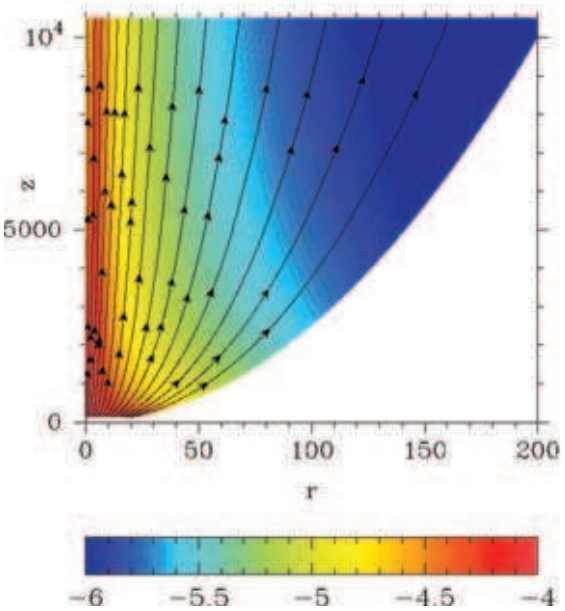
$$(B^2 - D^2)\alpha^2 = -B^2 f(\Omega_{\rm F}, r, \theta) + \frac{1}{\alpha^2}(\Omega_{\rm F} - \Omega)^2 H_\varphi^2$$

$$f(\Omega_{\rm F}, r, \theta) \equiv (\xi + \Omega_{\rm F}\chi)^2 = -\alpha^2 + \gamma_{\varphi\varphi}(\Omega_{\rm F} - \Omega)^2.$$

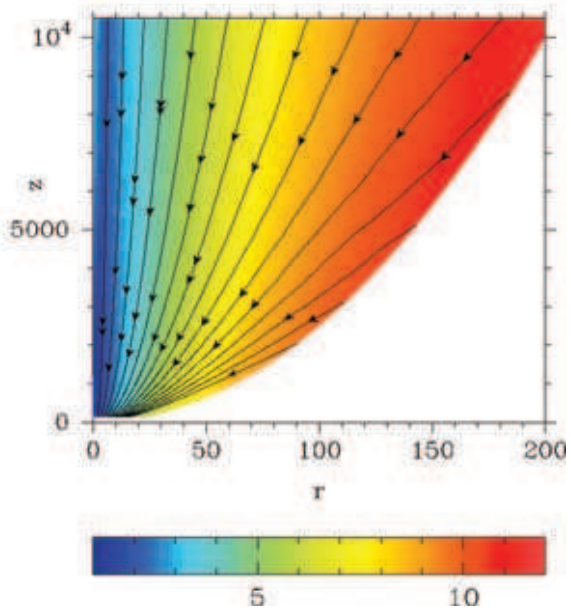
Blandford & Znajek 1977; Komissarov 2004; KT & Takahara 2014; 2016

Large-scale SRMHD simulation

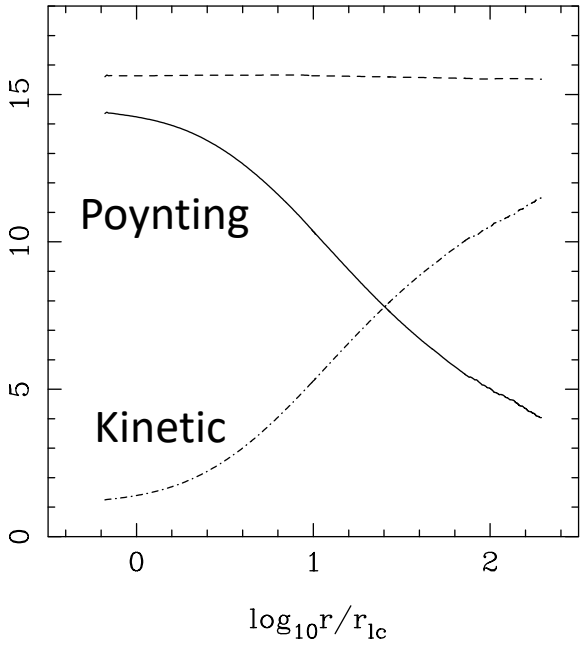
Field lines and Γρ



Current lines and Γ

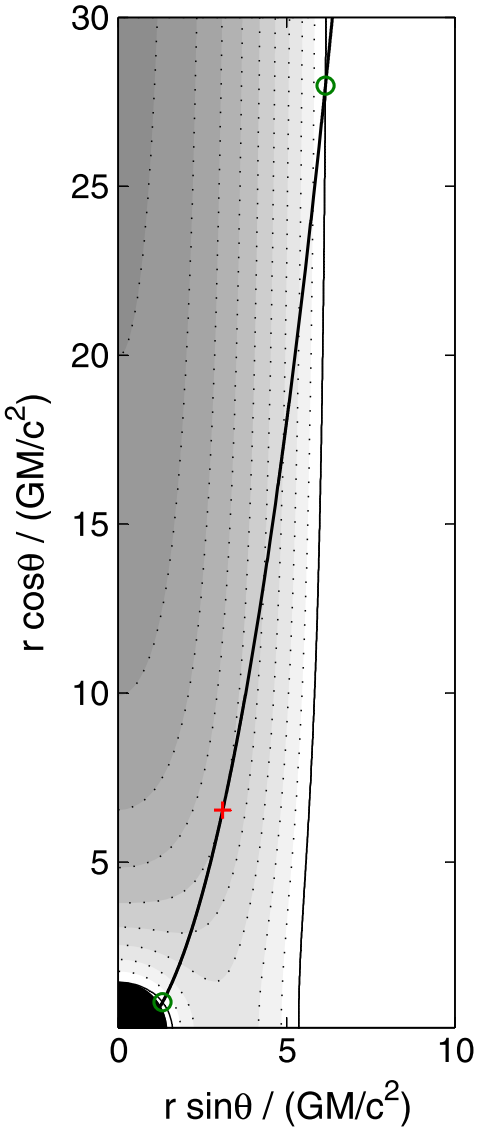


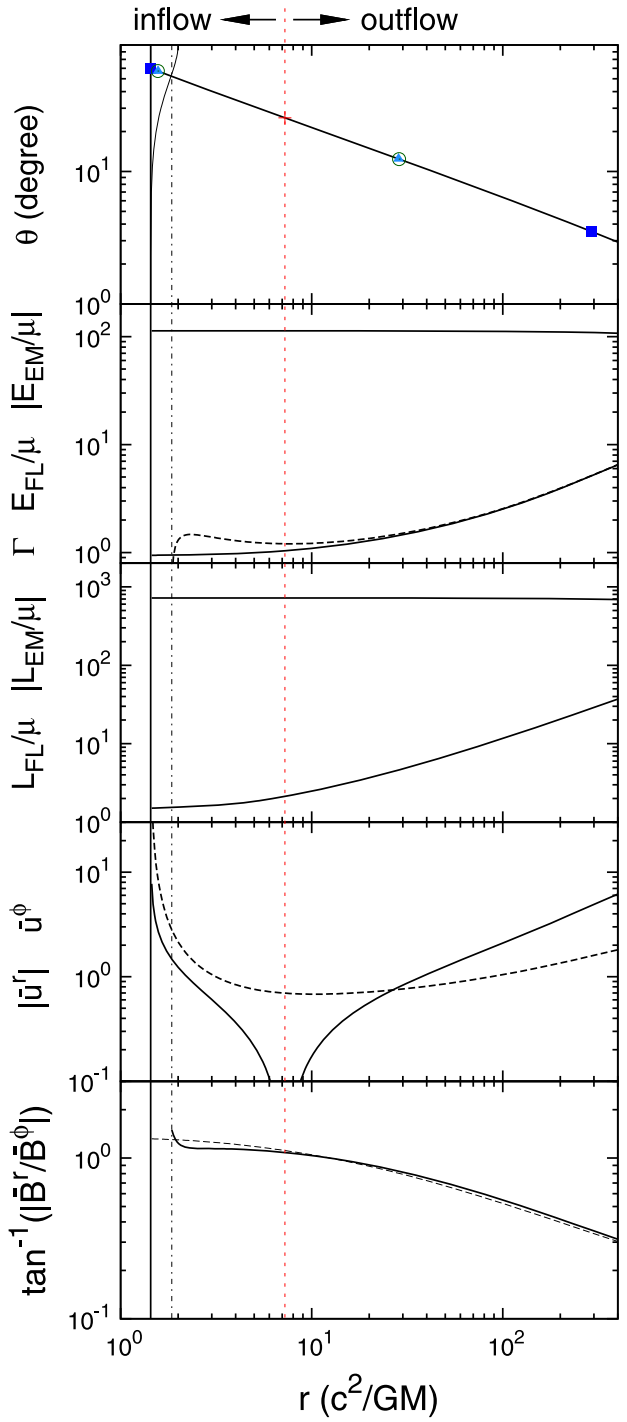
Komissarov+ 2007



- Flow near the axis is non-relativistic and self-collimated
- Then the outer part expands and accelerates
- Equipartition between Poynting and Kinetic <-> blazar emission model

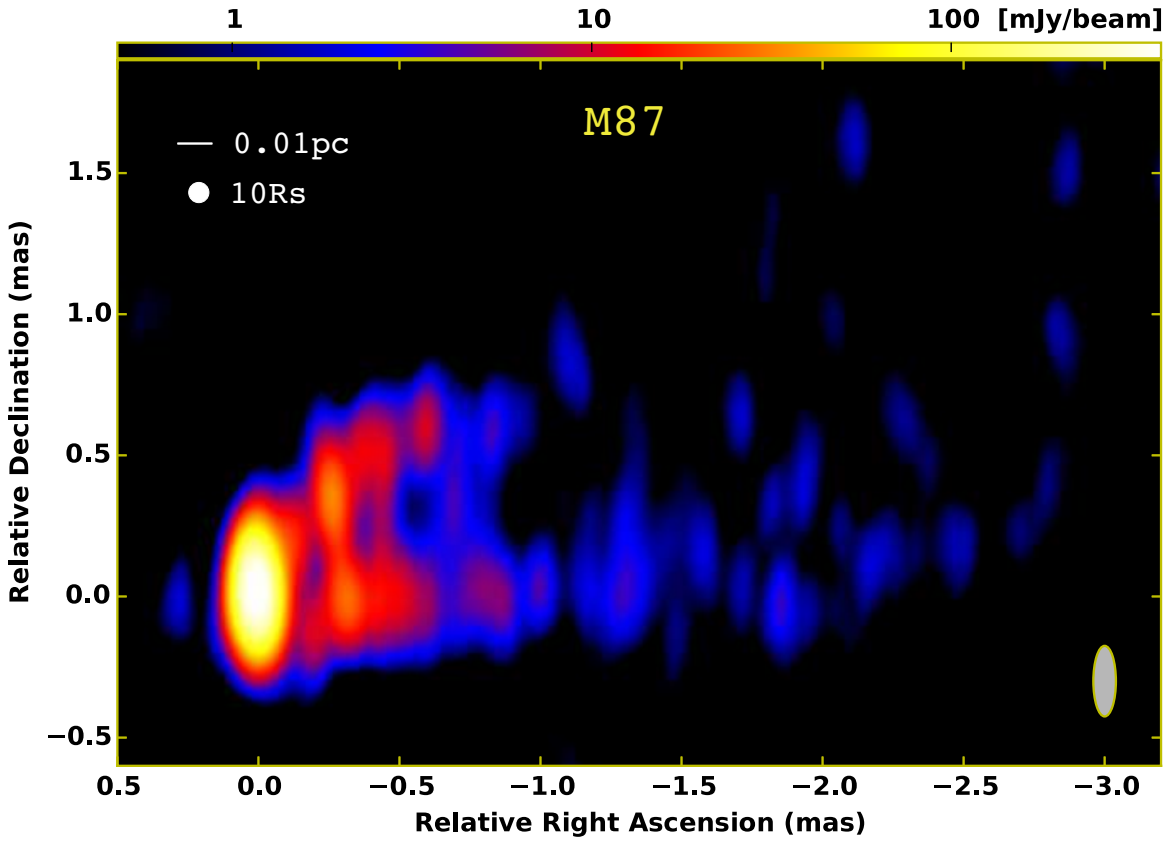
Steady GRMHD





Pu, Nakamura+ 2015; M. Takahashi+ 1990

M87 galaxy jet



- $D = 17$ Mpc
- $M_{BH} \sim 6 \times 10^9\ M_{sun}$
- $R_g \sim 4$ μas

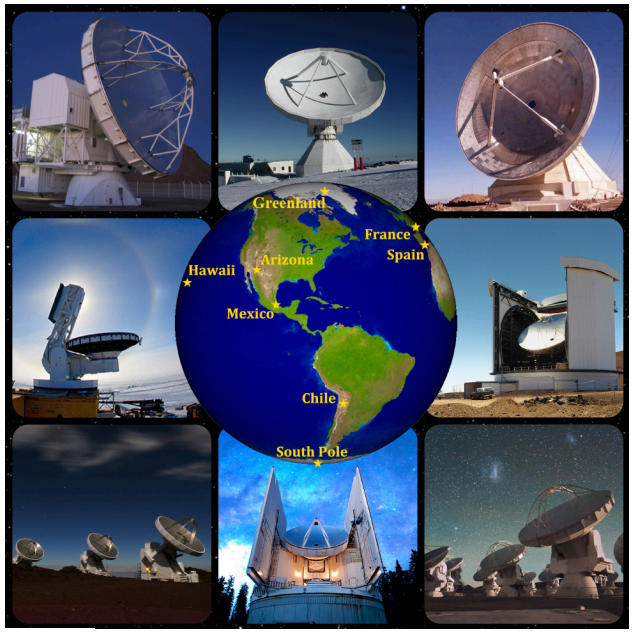
- FR-I type jet ($L_j \sim 10^{44}$ erg/s(?))
- Limb-brightening
- Superluminal blobs ($\Gamma\beta <\sim 5$)

- Probably RIAF ($L < 10^{-6}\ L_{Edd}$)

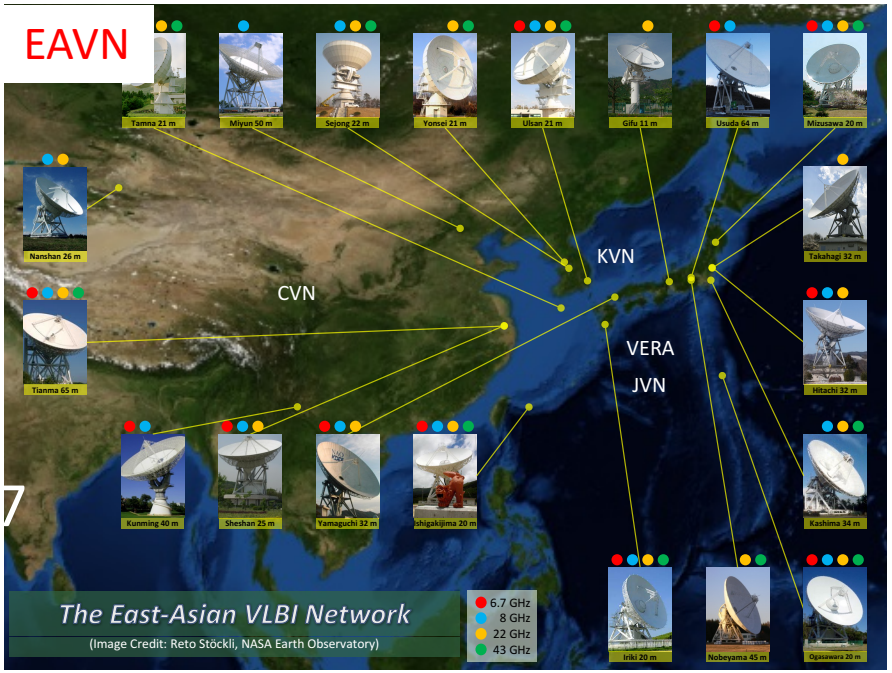
Hada, Kino, Doi et al. 2016

VLBI

Event Horizon Telescope

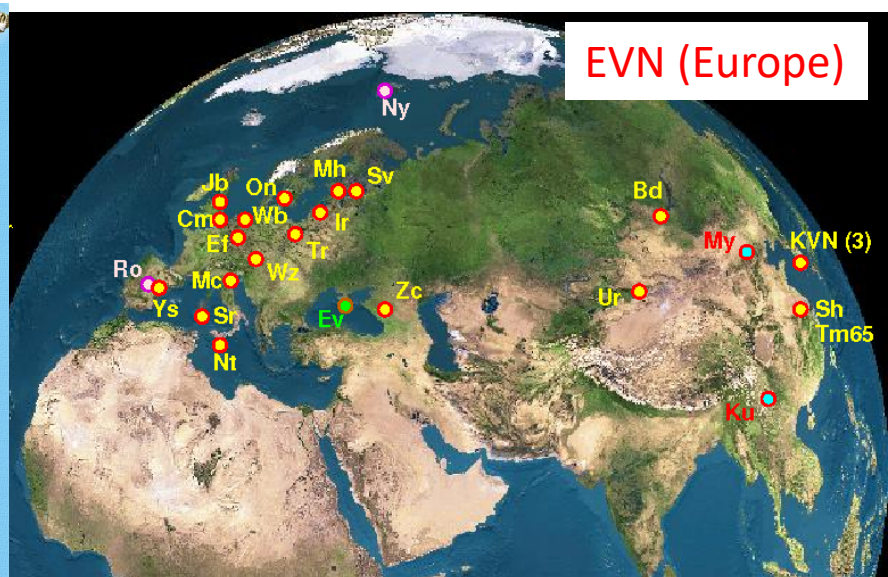


EAVN

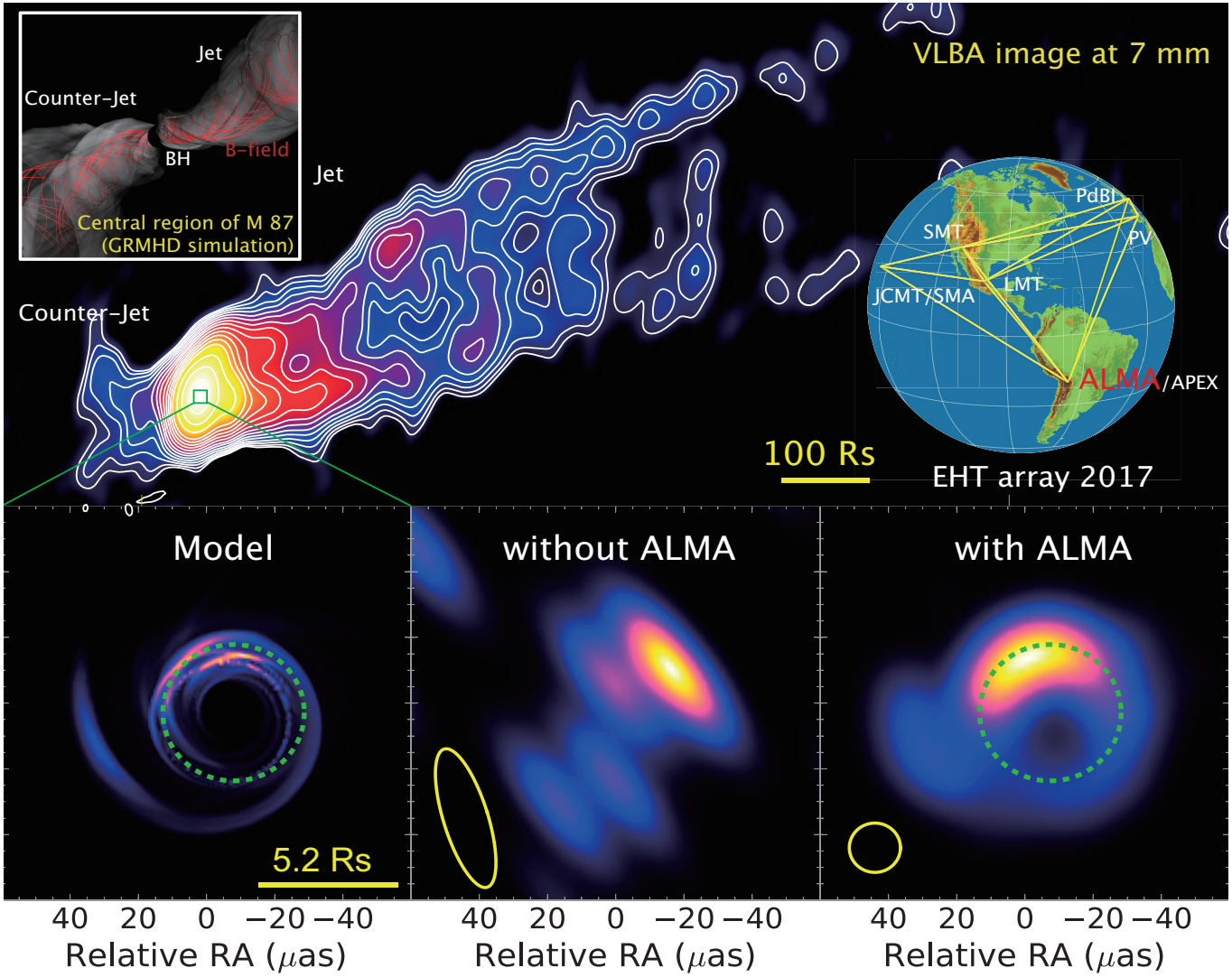


VLBA(USA)

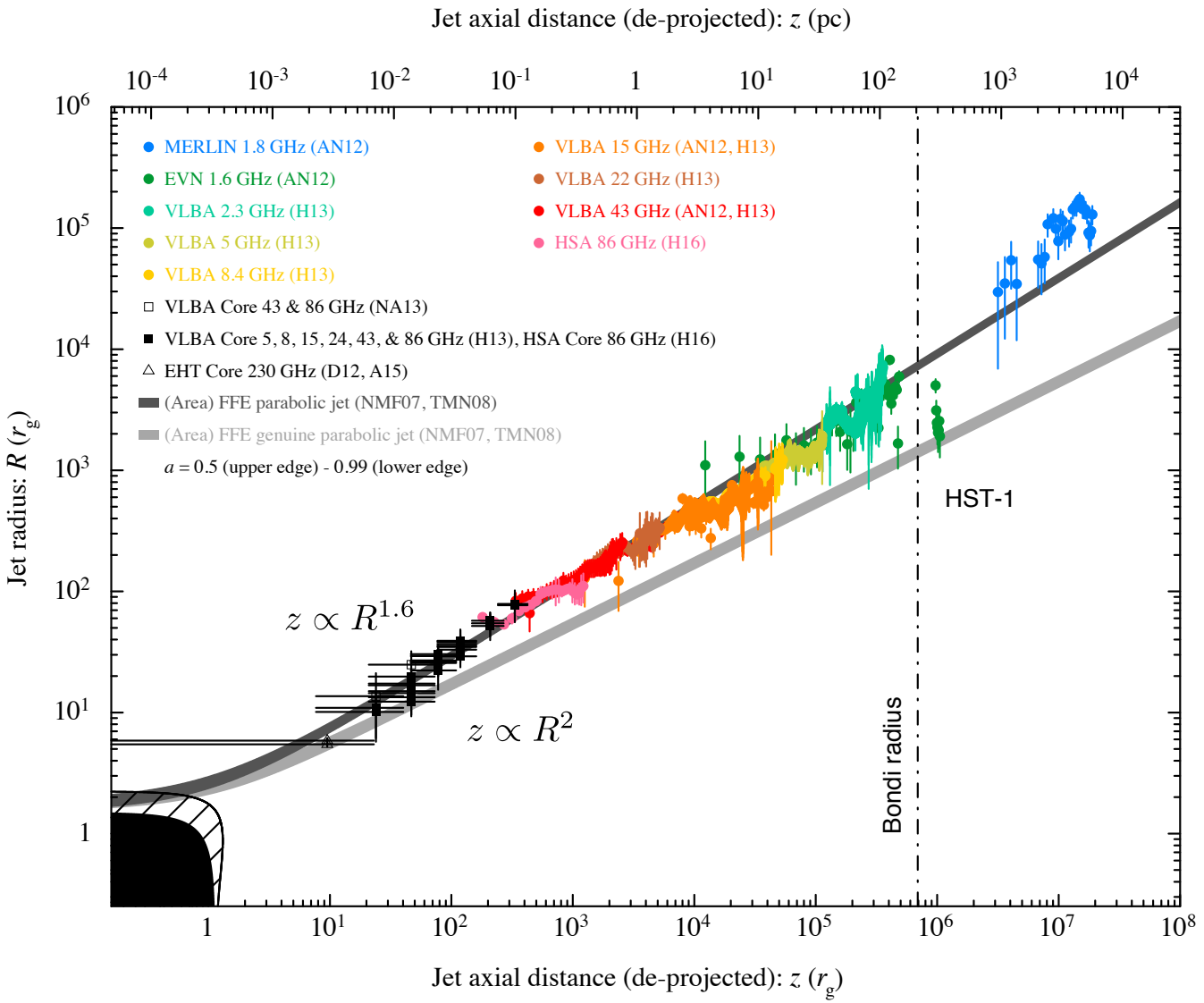
EVN (Europe)



Event Horizon Telescope

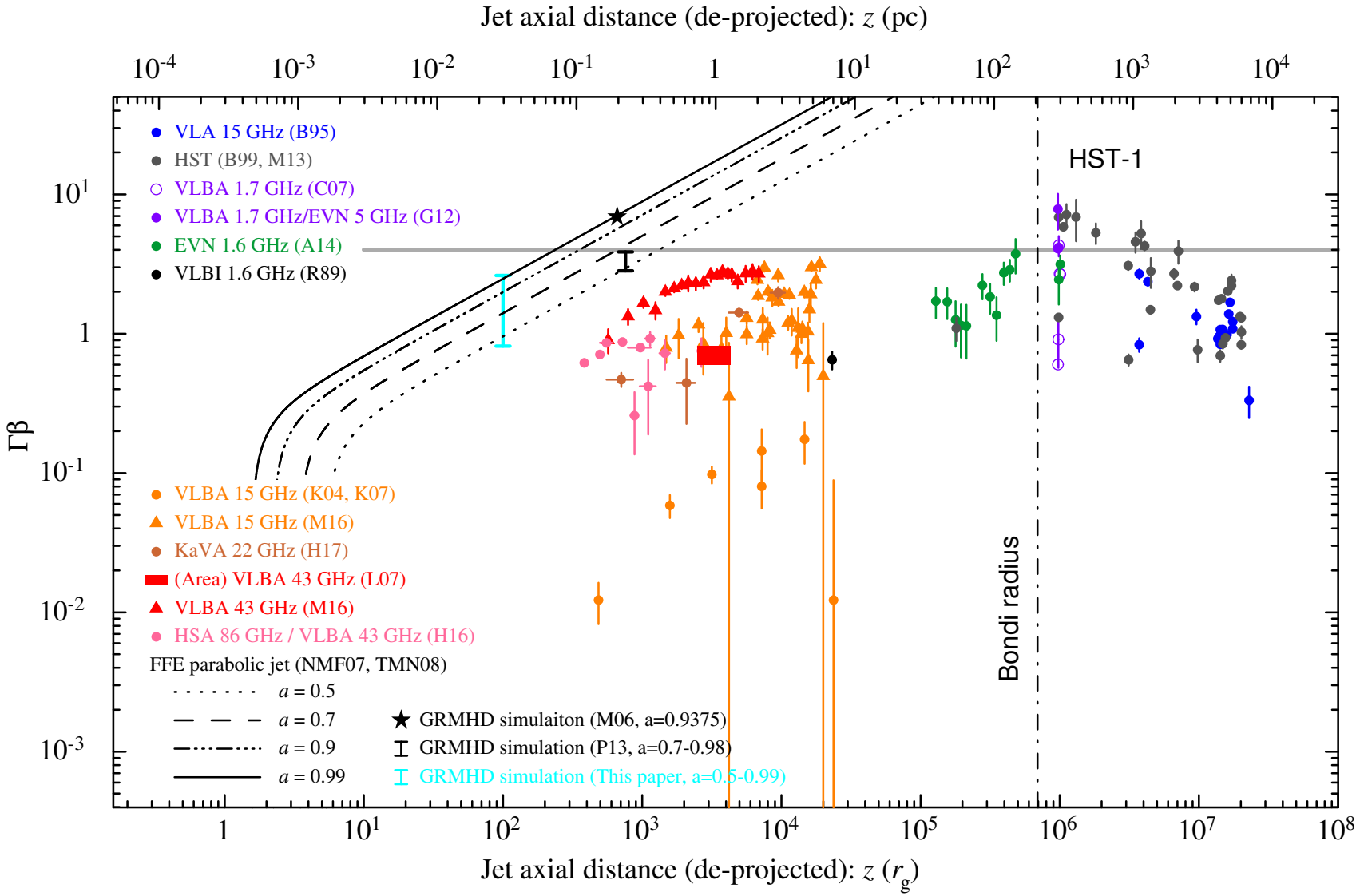


Jet width profile

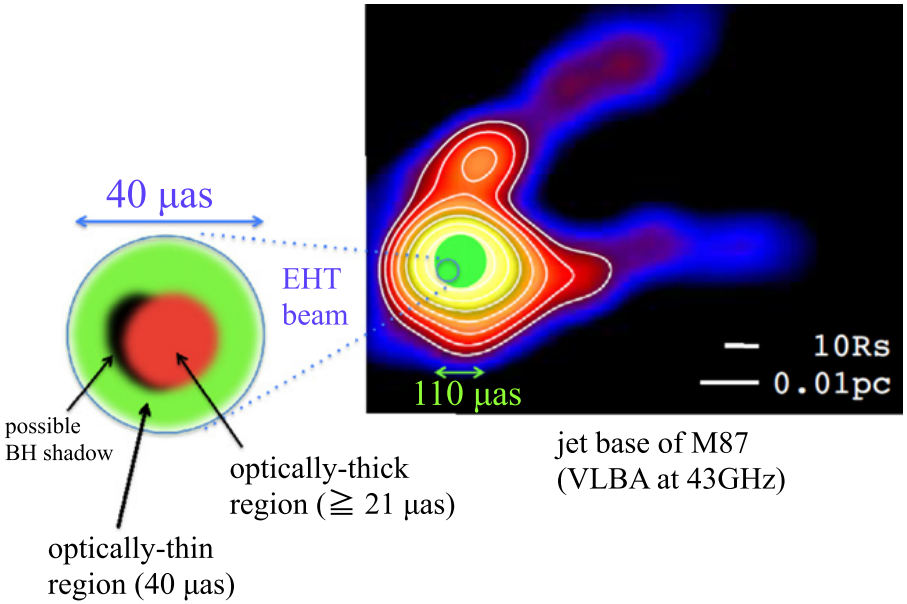


M. Nakamura, Asada, Hada, Pu, Tseng, KT, Kino, Nagai, K. Takahashi, et al. 2018

MHD velocity vs superluminal motion



Magnetic field strength estimates



$$B_{\perp} = b(p)\left(\frac{\nu_{\mathrm{ssa,obs}}}{1\ \mathrm{GHz}}\right)^{5}\left(\frac{\theta_{\mathrm{obs}}}{1\ \mathrm{mas}}\right)^{4}\left(\frac{S_{\nu_{\mathrm{ssa,obs}}}}{1\ \mathrm{Jy}}\right)^{-2} \times \left(\frac{\delta}{1+z}\right),$$

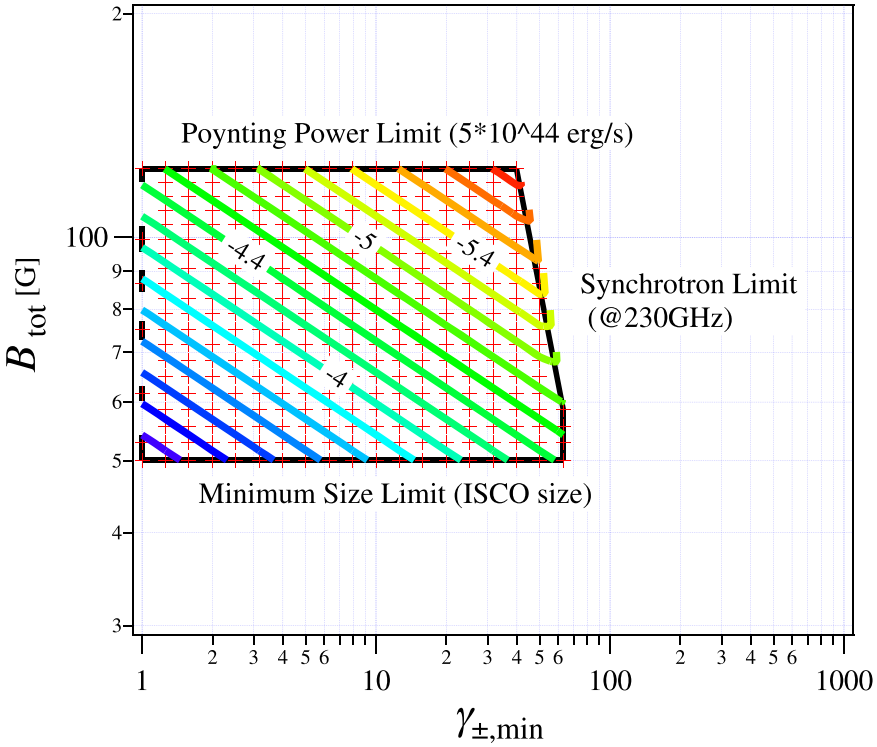
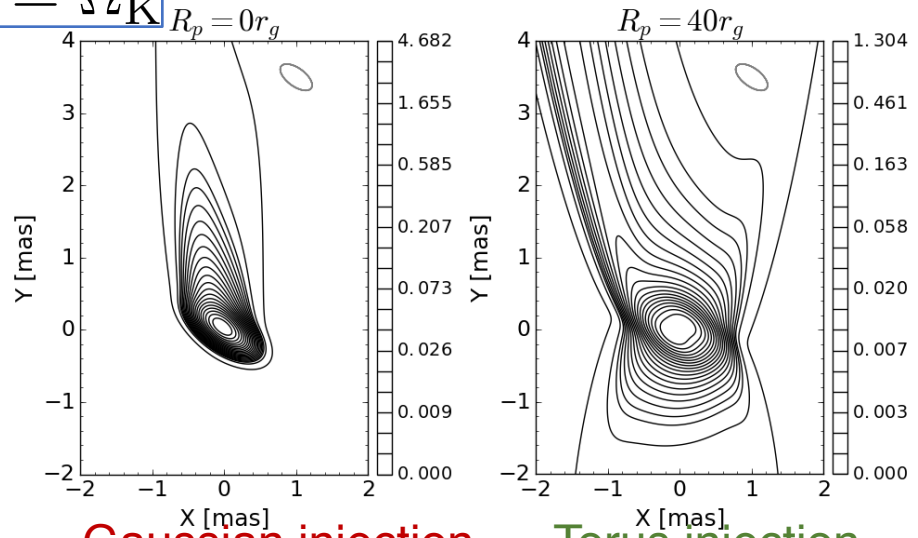


Figure 3. Allowed region of $\gamma_{\pm,\mathrm{min}}$ and B_{tot} (the red cross points enclosed by the black trapezoid). The colored contour lines show the allowed log $(U_{\pm}/U_B)$. The tags log $(U_{\pm}/U_B) = -4, -4.4, -5$, and -5.4 are marked as reference values. The physical quantities and parameters adopted are $L_{\mathrm{jet}} = 5 \times 10^{44}$ erg s^{-1} and $p = 3.0$. The minimum $\gamma_{\pm}$ is limited by $\nu_{\mathrm{syn,obs}}$ at 230 GHz.

Kino, Takahara, Hada et al. 2015

Characteristic image structure

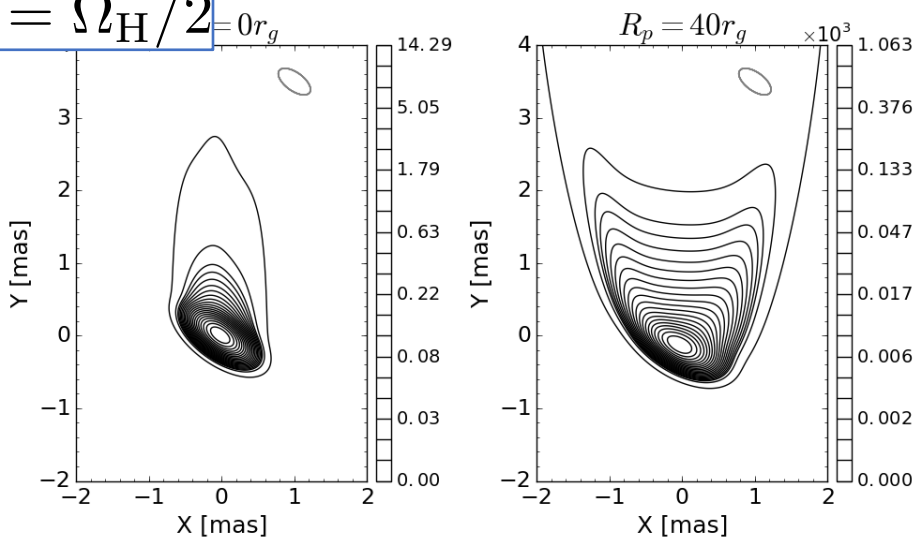
$\Omega_{\rm F} = \Omega_{\rm K}$



Gaussian injection

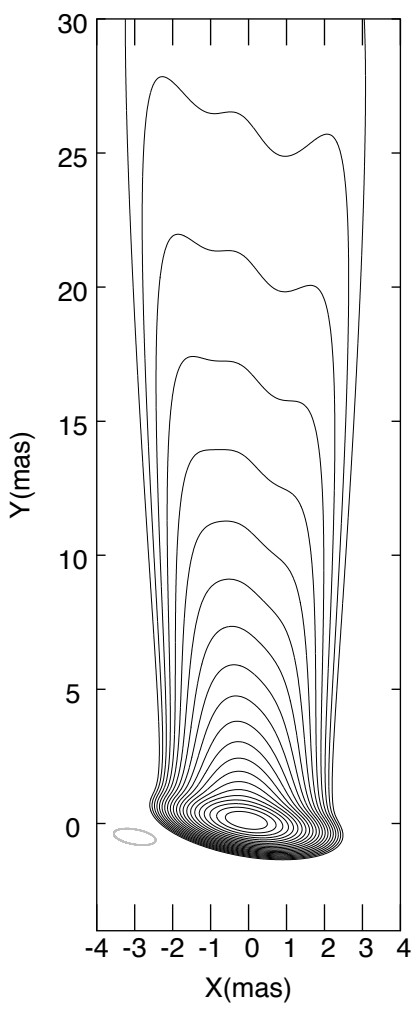
Torus injection

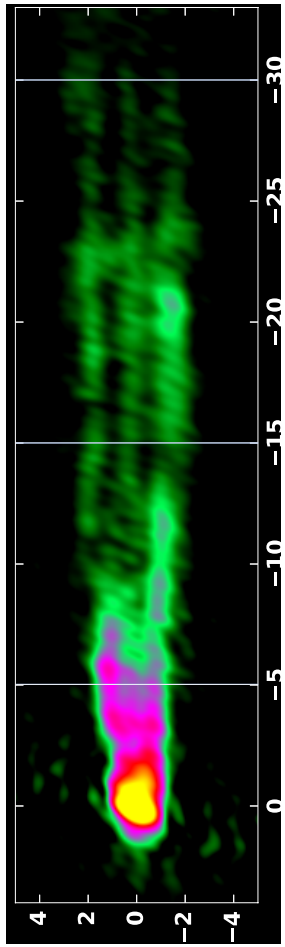
$\Omega_{\rm F} = \Omega_{\rm H}/2$



$\Omega_{\rm F} = \Omega_{\rm H}/2$

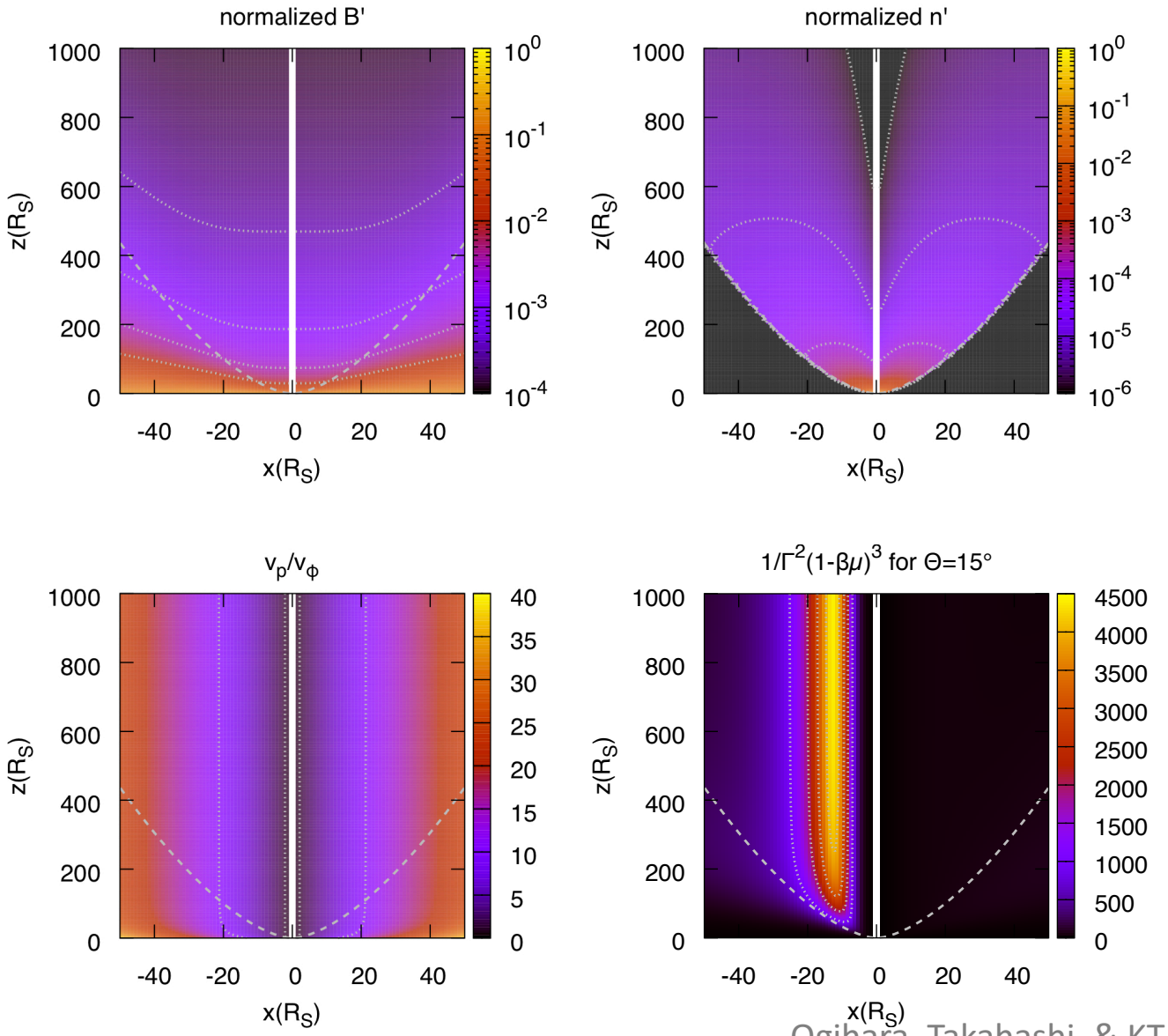
Gaussian injection; larger scale





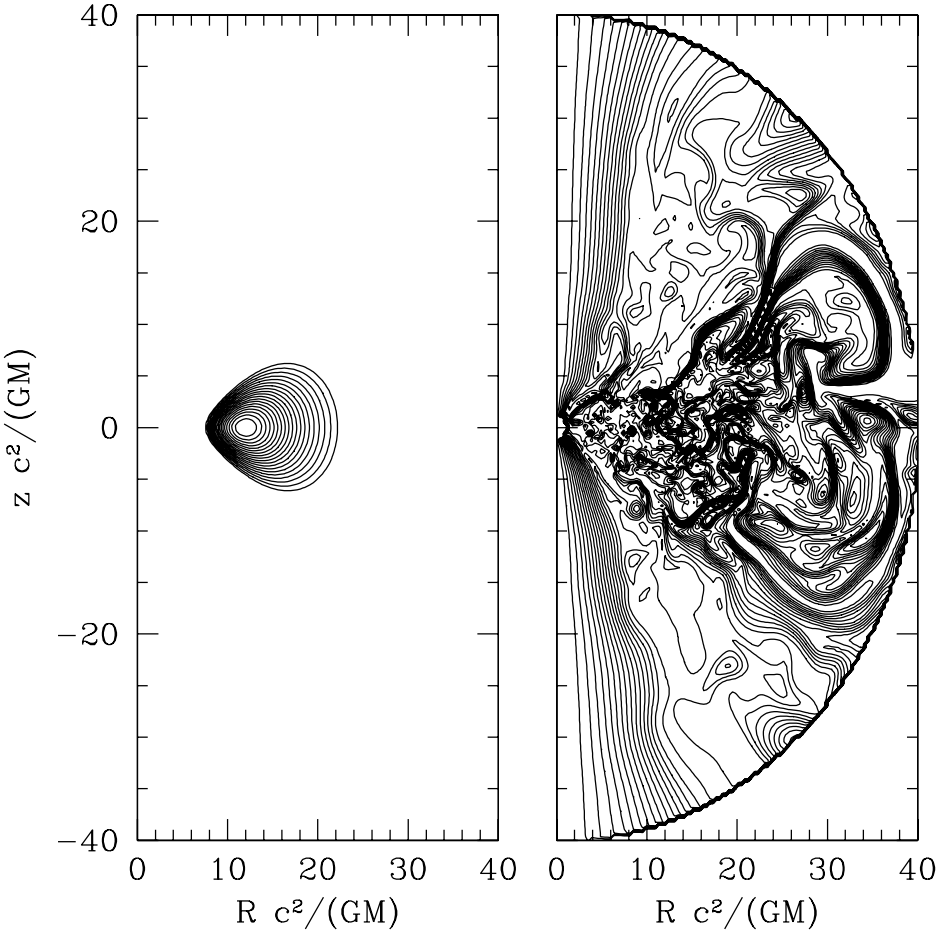
Takahashi, KT et al. 2018; Ogihara, KT & Takahashi submitted soon

Steady axisymmetric model



Ogihara, Takahashi, & KT submitted soon

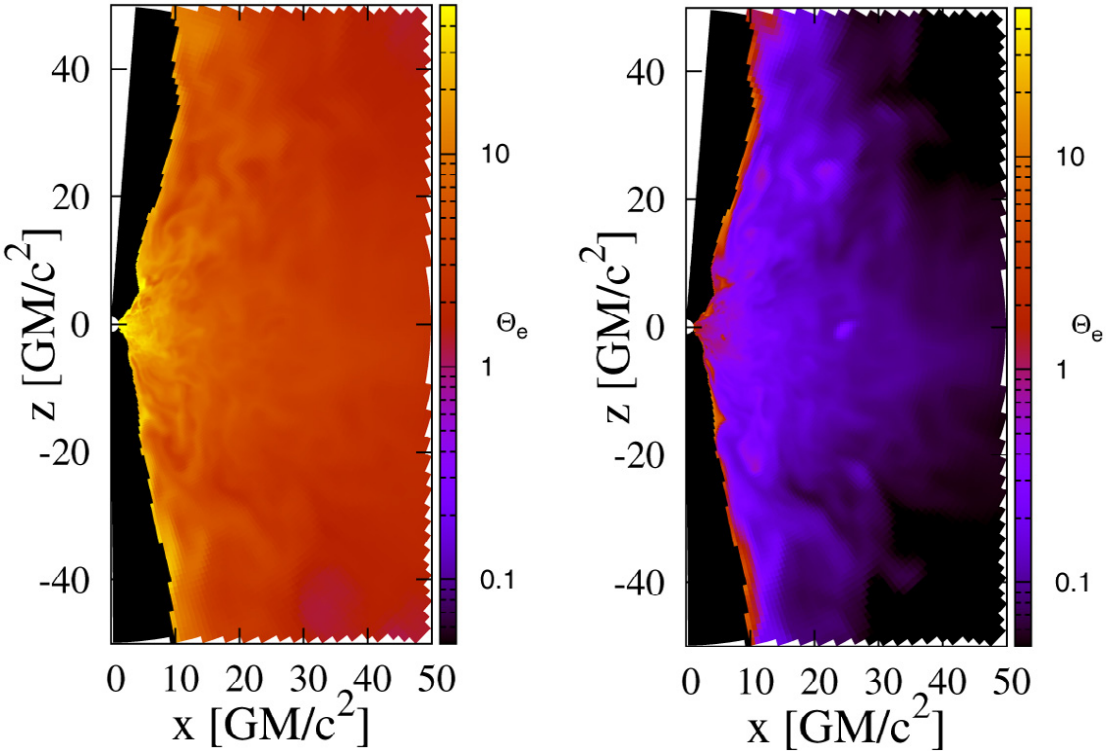
GRMHD simulations



- Initial condition: hydrodynamically equilibrium torus
- Starting with putting poloidal B loop
- Density floor: $\rho_{min} = \rho_{min}(r)$

Gammie+ 2003; McKinney & Gammie 2004; Noble+2006

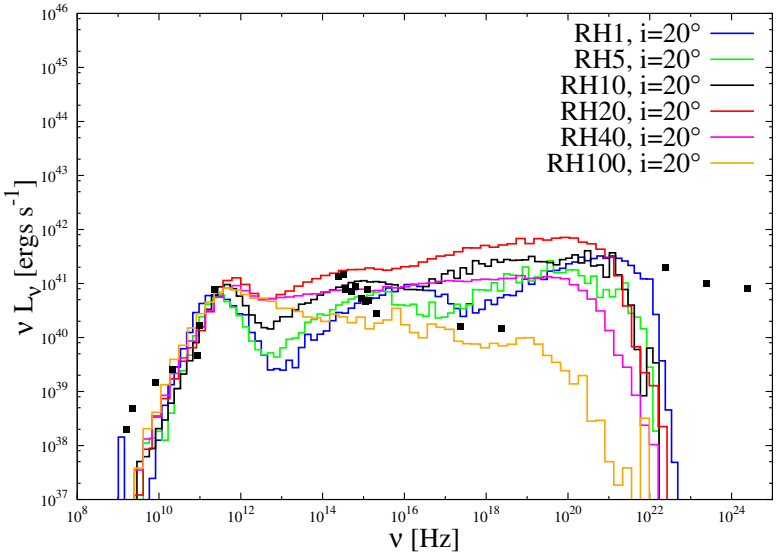
“Painting” of simulation results



$$\frac{T_p}{T_e} = R_{\rm high}\frac{b^2}{1+b^2} + R_{\rm low}\frac{1}{1+b^2}$$

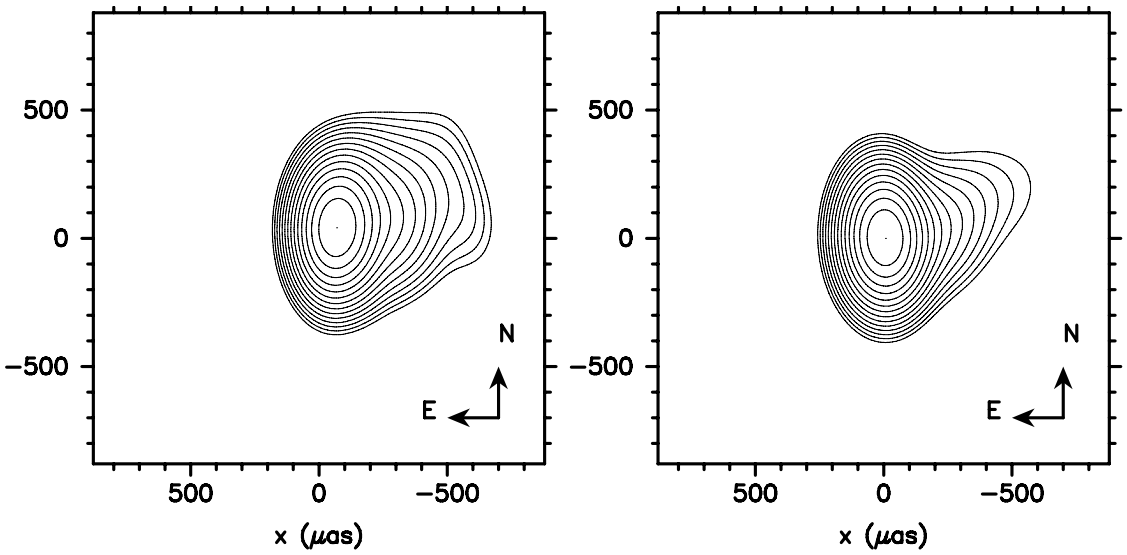
where $b = \beta/\beta_{\rm crit}$, $\beta = P_{\rm gas}/P_{\rm mag}$, sume that $\beta_{\rm crit} = 1$, and $R_{\rm high}$ and $R_{\rm lov}$

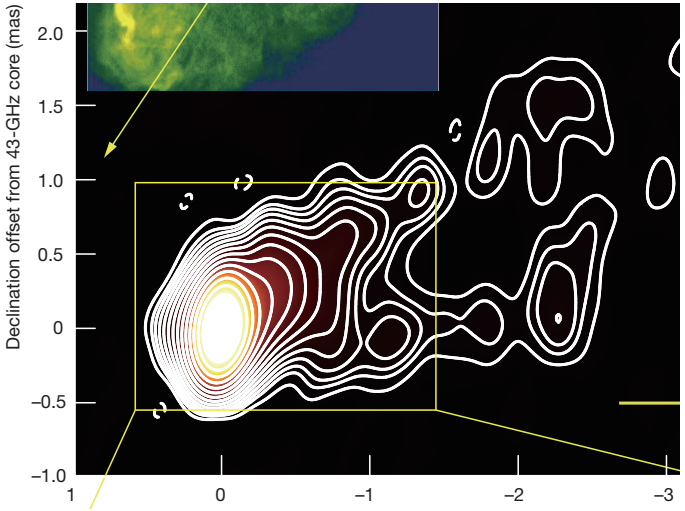
- No emission assumed from the funnel region ($\sigma > 1$)
- Based on 3D GRMHD sim. with a = 0.94

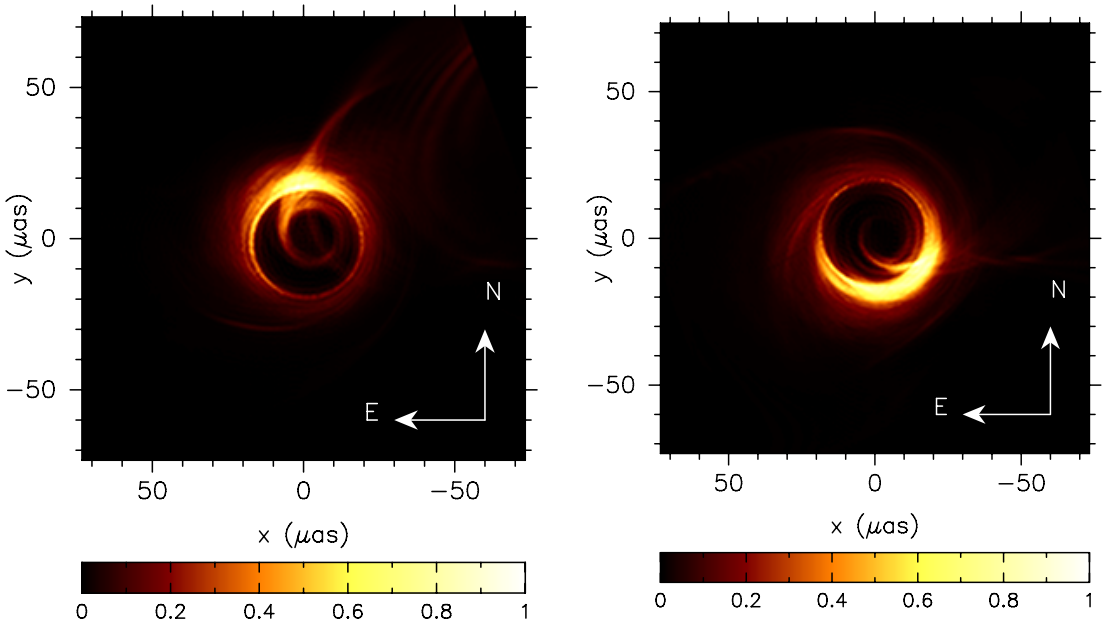


Moscibrodzka, Falke, & Shiokawa 2016

Model images at 43 GHz







Model images at 230 GHz

- Counter-jet dominant
- Asymmetric shape

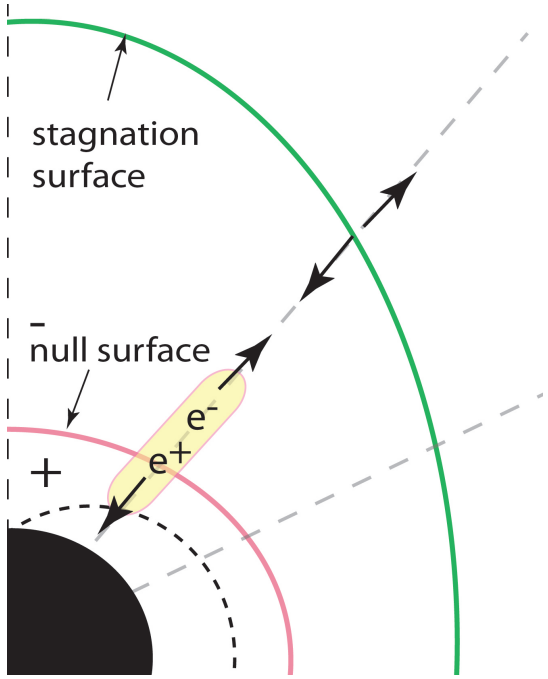
Moscibrodzka, Falke, & Shiokawa 2016; Hada, Doi, Kino et al. 2011

Pair production

number density of MeV photons in the magnetosphere:

$$n_\gamma = \frac{q_{\rm ff} 2\pi r^3 \ln(r/r_s)}{2\pi c r^2 \epsilon_\gamma} \simeq \frac{0.2 q_{\rm ff} r^3}{c r_s^2 \epsilon_\gamma} \simeq 1.4 \times 10^{11} \dot{m}^2 M_9^{-1}$$

$$n_\pm = \sigma_{\gamma\gamma} n_\gamma^2 r_s/3 \simeq 3 \times 10^{11} \dot{m}^4 M_9^{-1}\ {\rm cm}^{-3}.$$



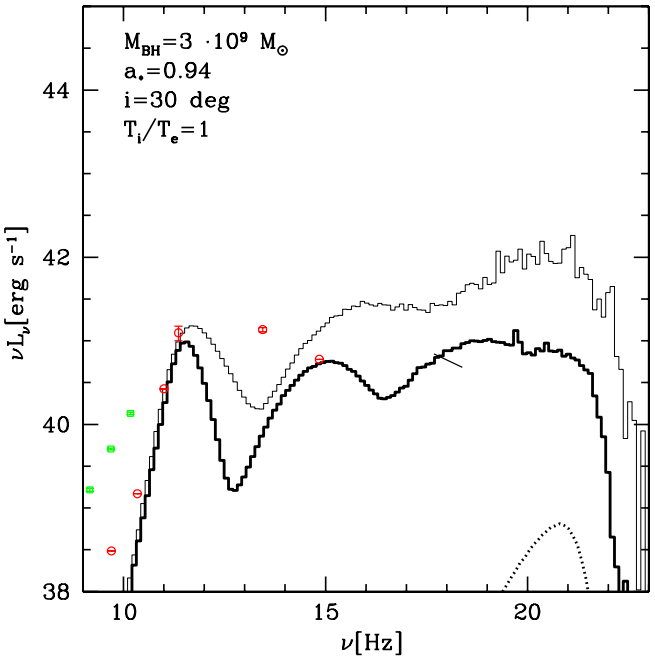


Figure 10. Model L: time-averaged spectral energy distribution. Two lines show the model with $\dot{m} = 10^{-6}$ and $T_i/T_e = 1$. $\dot{m}$ is chosen to normalize to 1.7 Jy

$$n_\pm/n_{\rm GJ} \simeq 6 \times 10^{12} \dot{m}^{7/2} M_9^{1/2}.$$

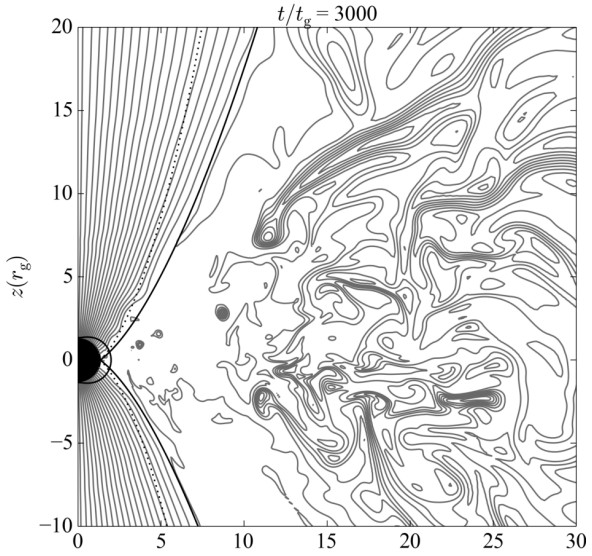
Levinson & Rieger 2011; Levinson & Segev 2017
See also Hirotani & Pu 2016; Broderick & Tchekhovskoy 2015

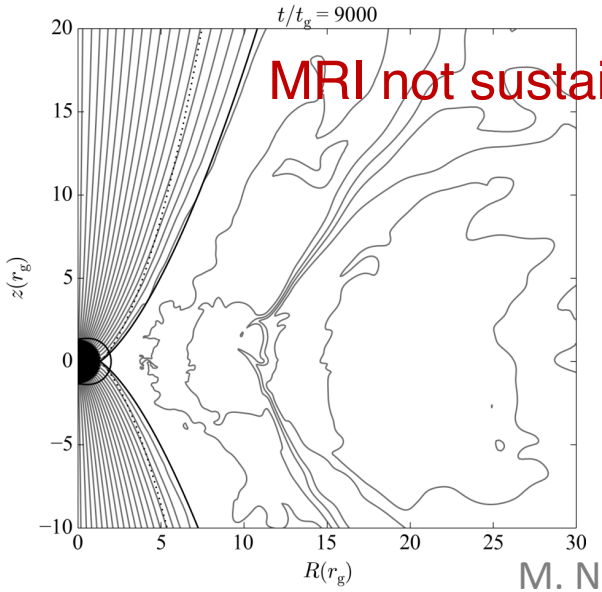
- Breakdown of MHD (pair-creation gap) at null surface and stagnation surface(?)
- Dynamic kinetic physics
  -> PIC simulation in BH magnetosphere

Moscibrodzka+2011

Levinson & Cerutti 2018

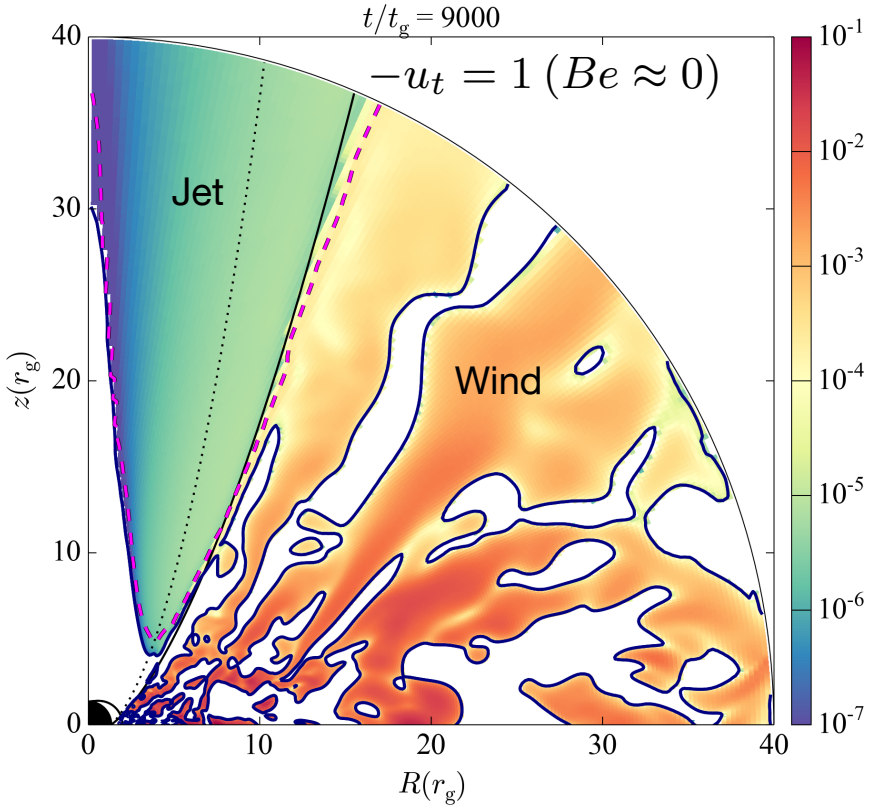
Long-term 2D simulations





MRI not sustained

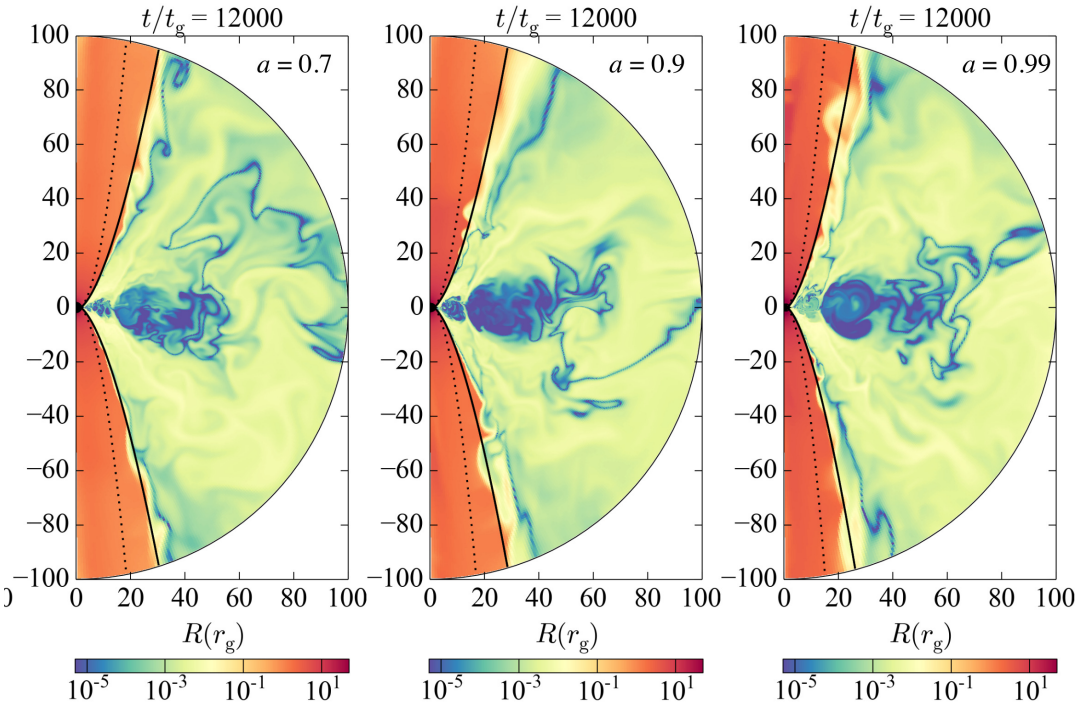
$$\dot{M}_{\rm out} = \sqrt{-g}\rho u^r (> 0)$$



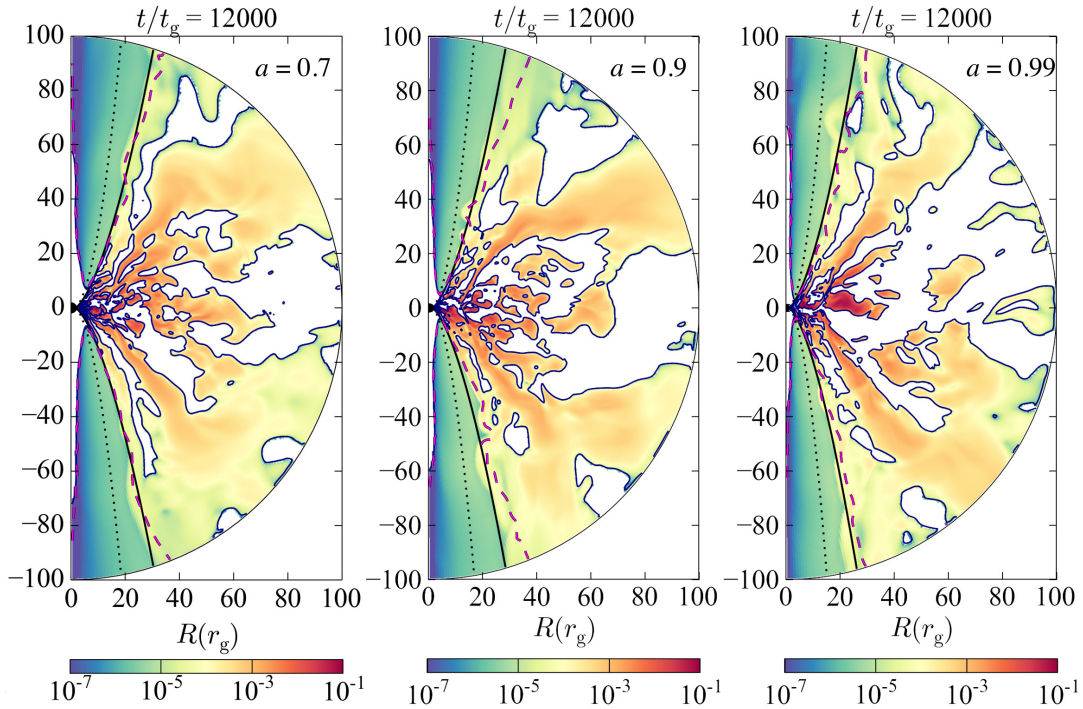
- Quasi-steady funnel shape consistent with obs: $z \propto R^{1.6}$
- Outflow-inflow structure

M. Nakamura, Asada, Hada, Pu, Tseng, KT, Kino, Nagai, K. Takahashi, et al. 2018

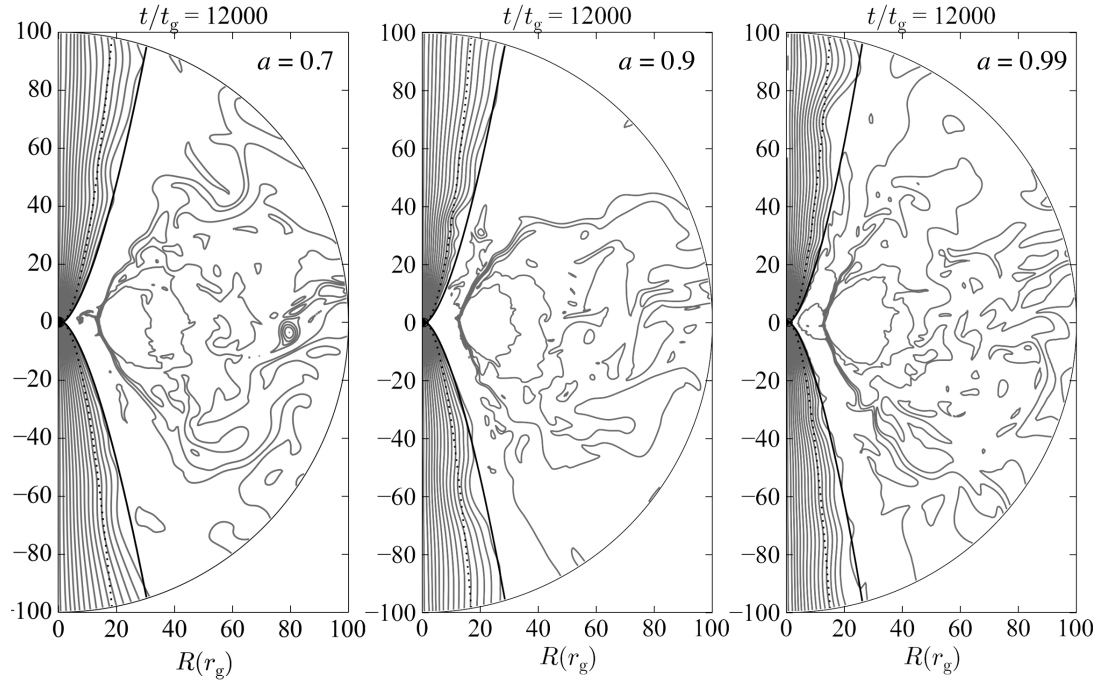
Fine grid simulations



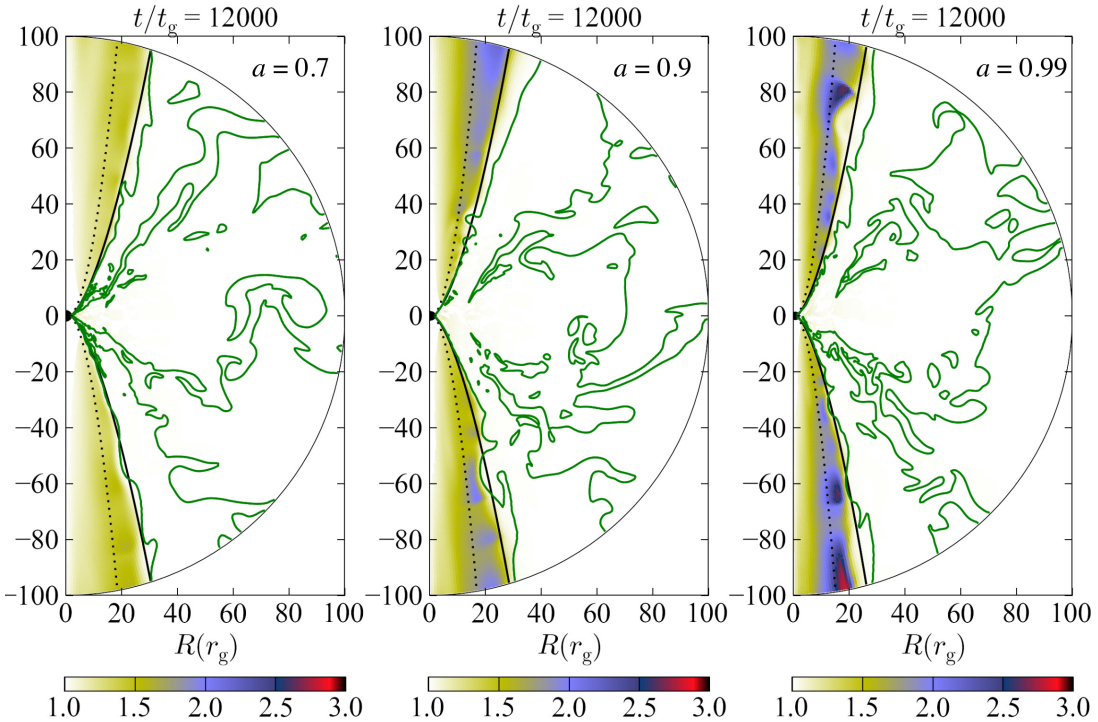
b^2/ρ



$$\dot{M}_{\rm out} = \sqrt{-g}\rho u^r (> 0)$$



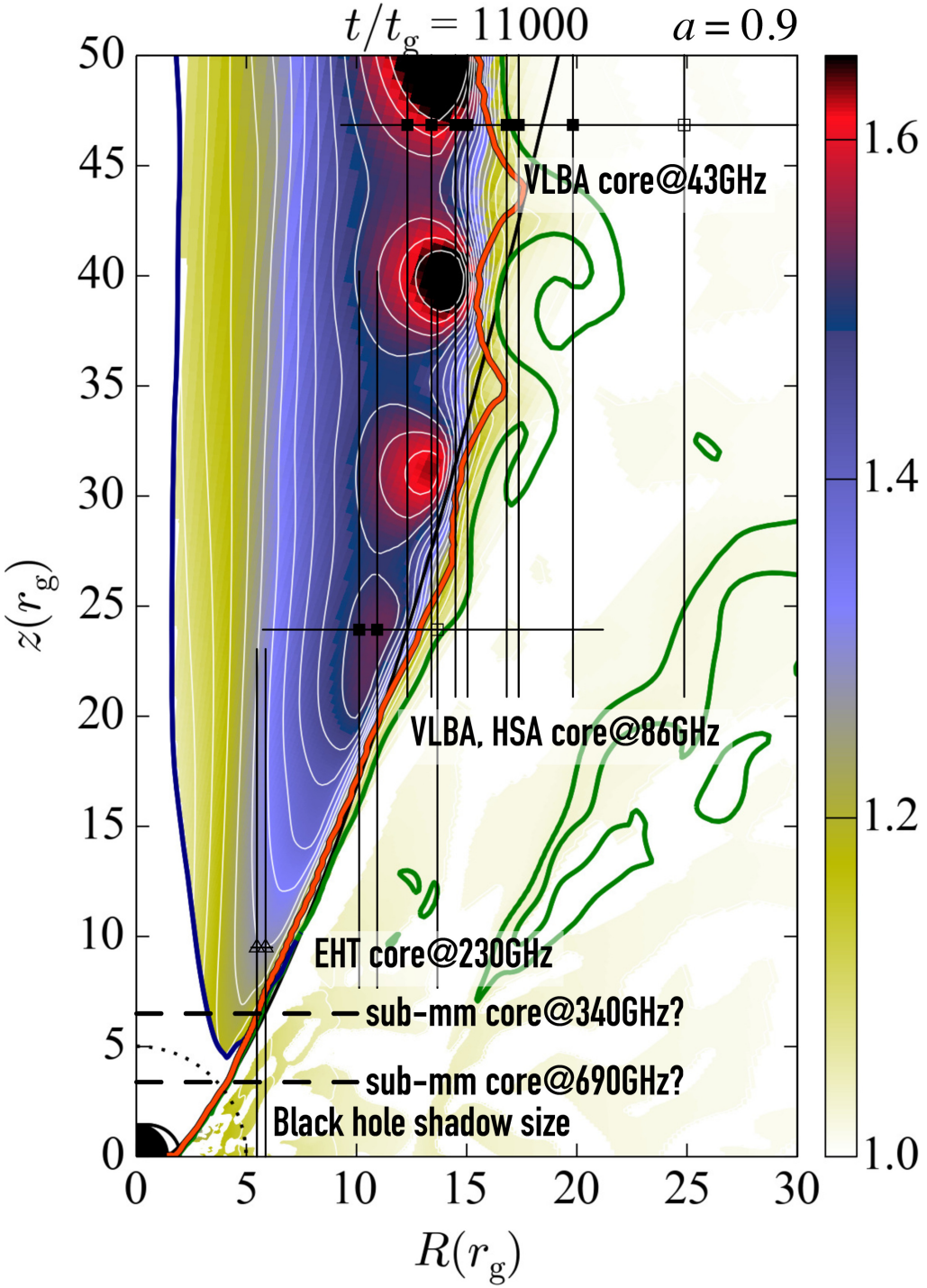
B_p



Shocks & particle acceleration??

Bulk acceleration??

Γ

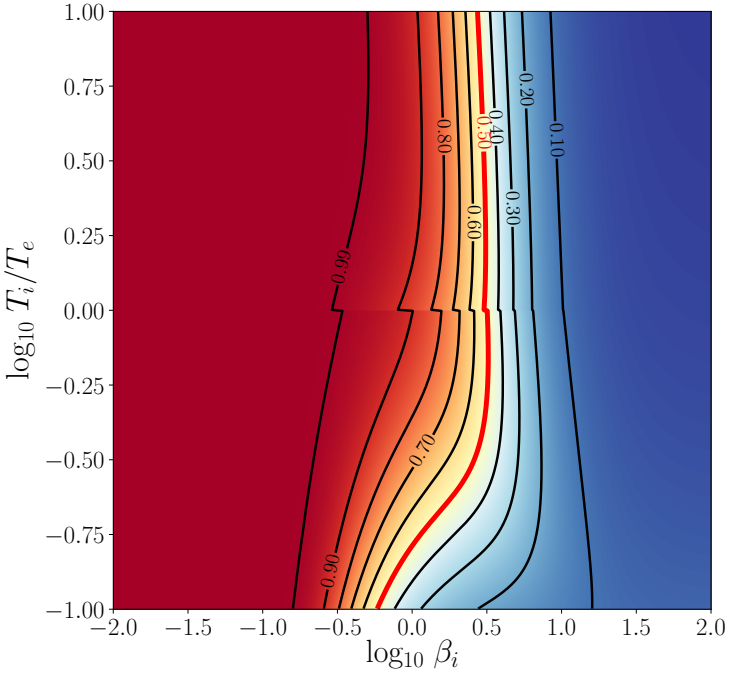


Jet is bright in the entire funnel, or not?

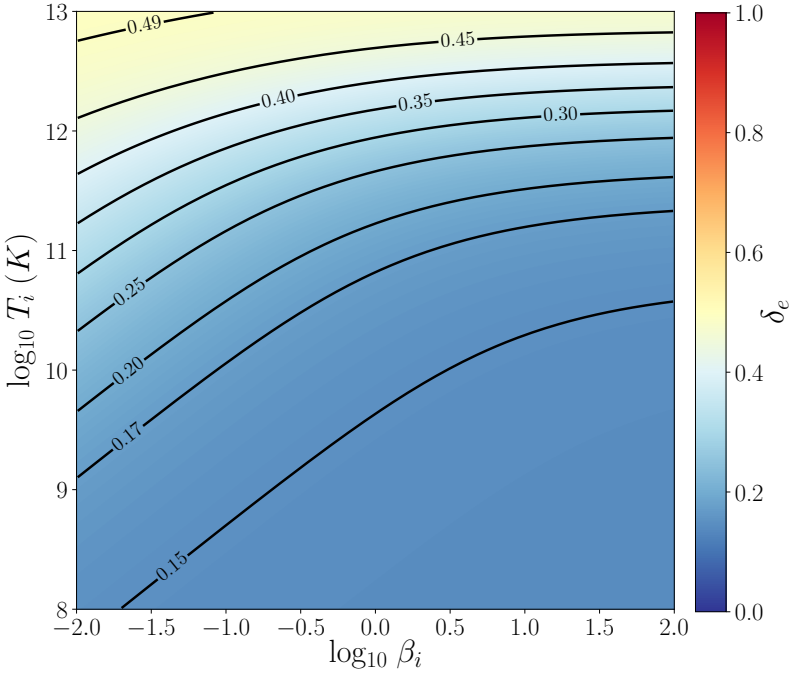
Two-temperature simulations

$$T_{\rm e}\left(ns_{\rm e}u^{\mu}\right)_{;\mu} = \delta_{\rm e}q^{\rm v} + q^{\rm C} - \hat{G}^{0},$$
$$T_{\rm i}\left(ns_{\rm i}u^{\mu}\right)_{;\mu} = (1-\delta_{\rm e})q^{\rm v} - q^{\rm C},$$

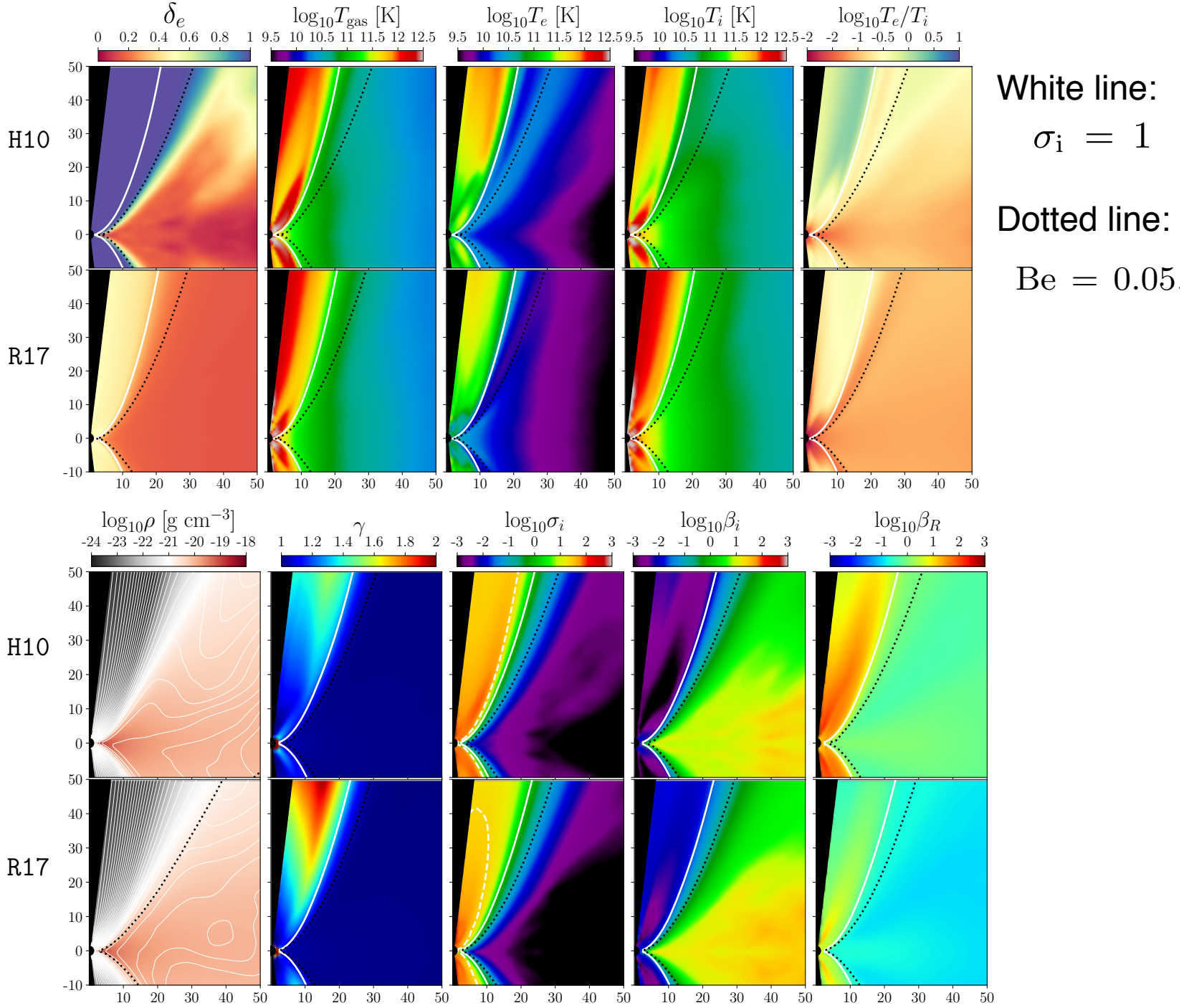
Turbulent cascade heating prescription



Reconnection heating prescription



Chael, Narayan & Johnson, arXiv:1810.01983; Howes 2010; Kawazura+2018; Rowan, Sironi & Narayan 2017

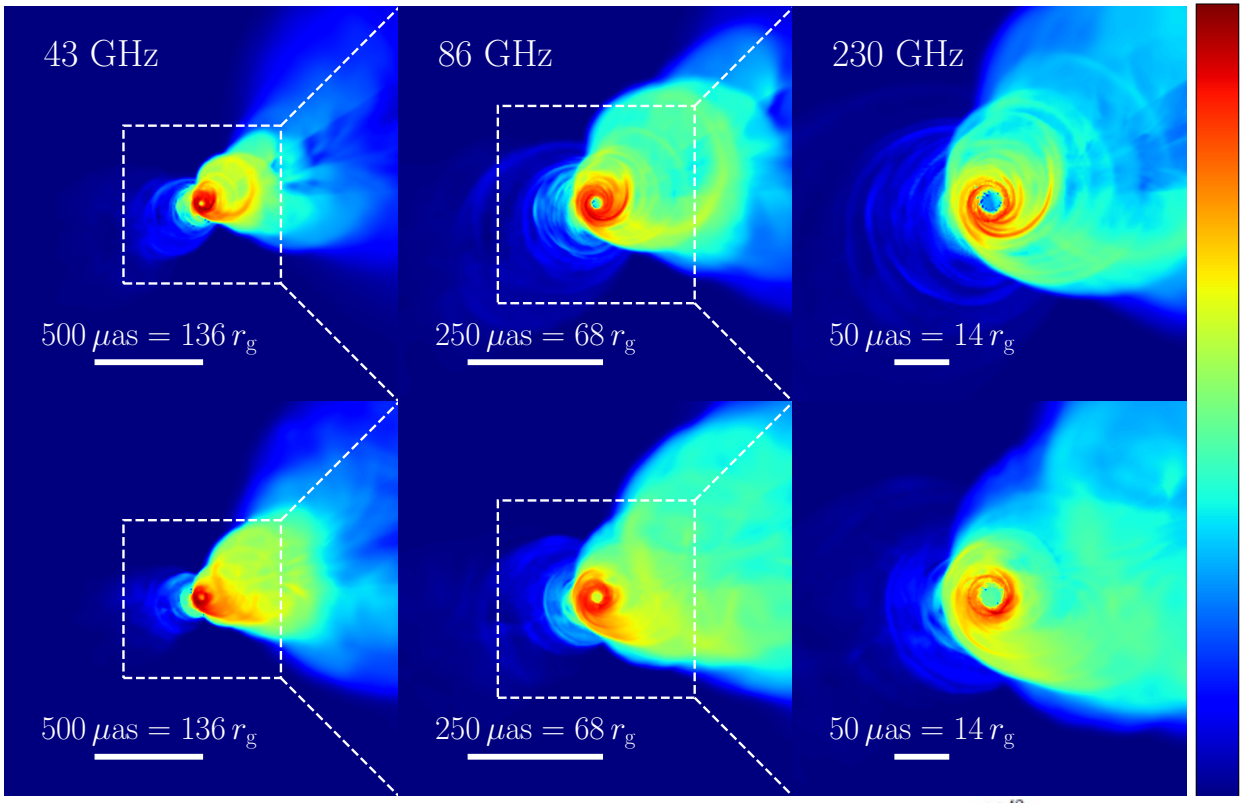


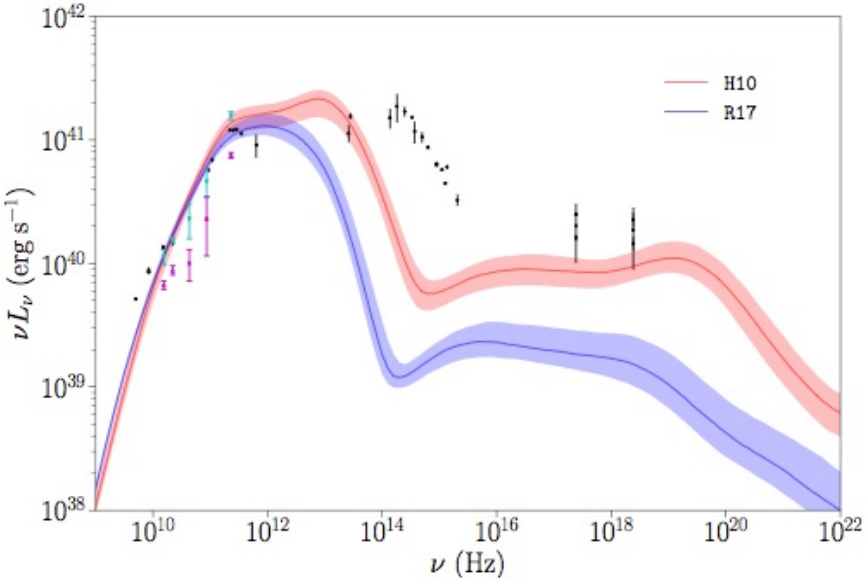
White line:

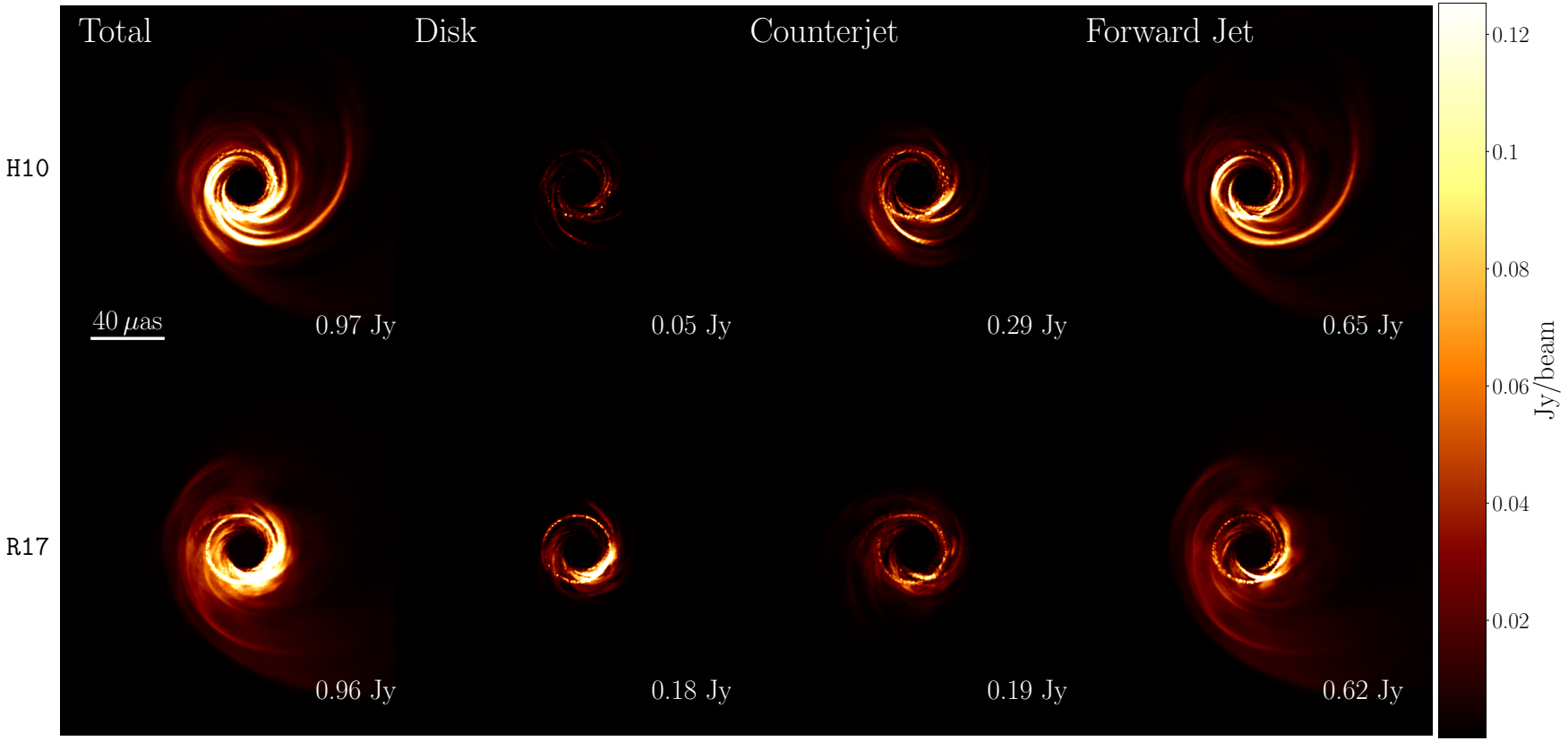
$\sigma_{\rm i} = 1$

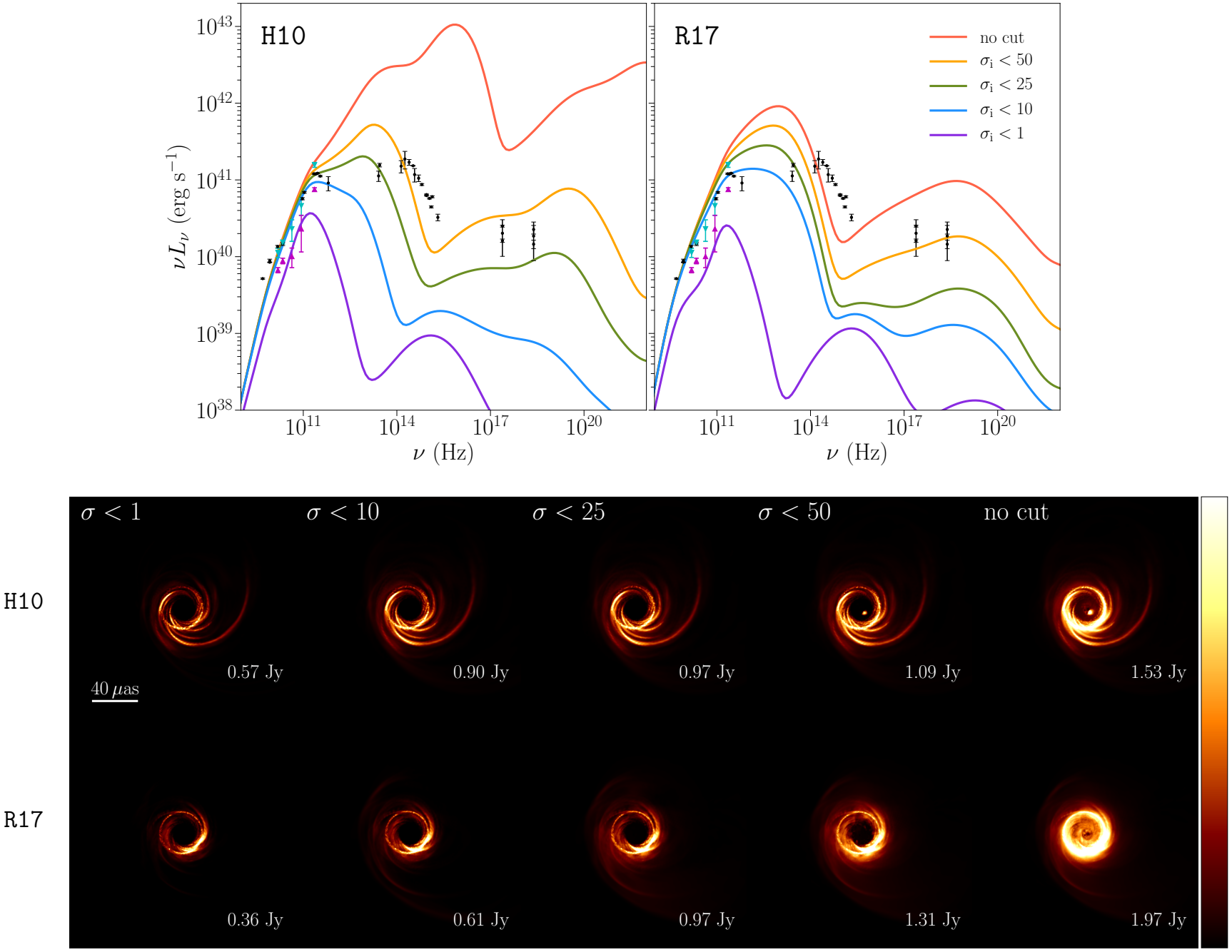
Dotted line:

${\rm Be} = 0.05$


43 GHz
86 GHz
230 GHz
H10
R17
500 μas = 136 r_g
250 μas = 68 r_g
50 μas = 14 r_g
500 μas = 136 r_g
250 μas = 68 r_g
50 μas = 14 r_g


H10
R17
νL_ν (erg s^-1)
ν (Hz)
10^42
10^41
10^40
10^39
10^38
10^10
10^12
10^14
10^16
10^18
10^20
10^22

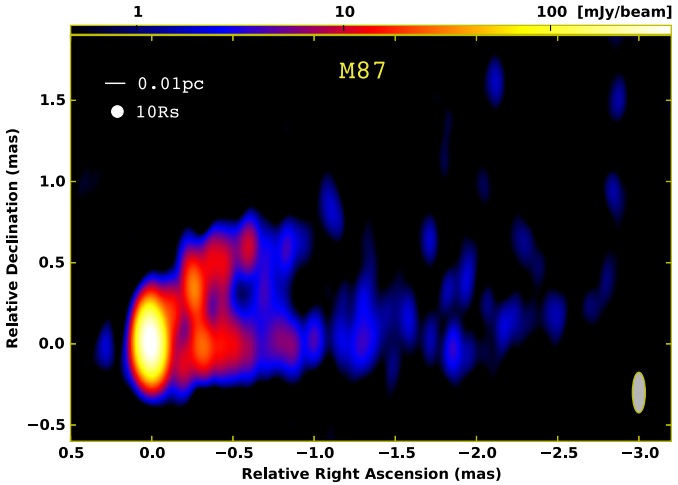

Total
Disk
Counterjet
Forward Jet
H10
R17
40 μas
0.97 Jy
0.05 Jy
0.29 Jy
0.65 Jy
0.96 Jy
0.18 Jy
0.19 Jy
0.62 Jy
0.12
0.1
0.08
0.06
0.04
0.02
Jy/beam


H10
R17
no cut
$\sigma_i < 50$
$\sigma_i < 25$
$\sigma_i < 10$
$\sigma_i < 1$
νL_ν (erg s^{-1})
ν (Hz)
$\sigma < 1$
$\sigma < 10$
$\sigma < 25$
$\sigma < 50$
no cut
40 μas
0.57 Jy
0.90 Jy
0.97 Jy
1.09 Jy
1.53 Jy
0.36 Jy
0.61 Jy
0.97 Jy
1.31 Jy
1.97 Jy

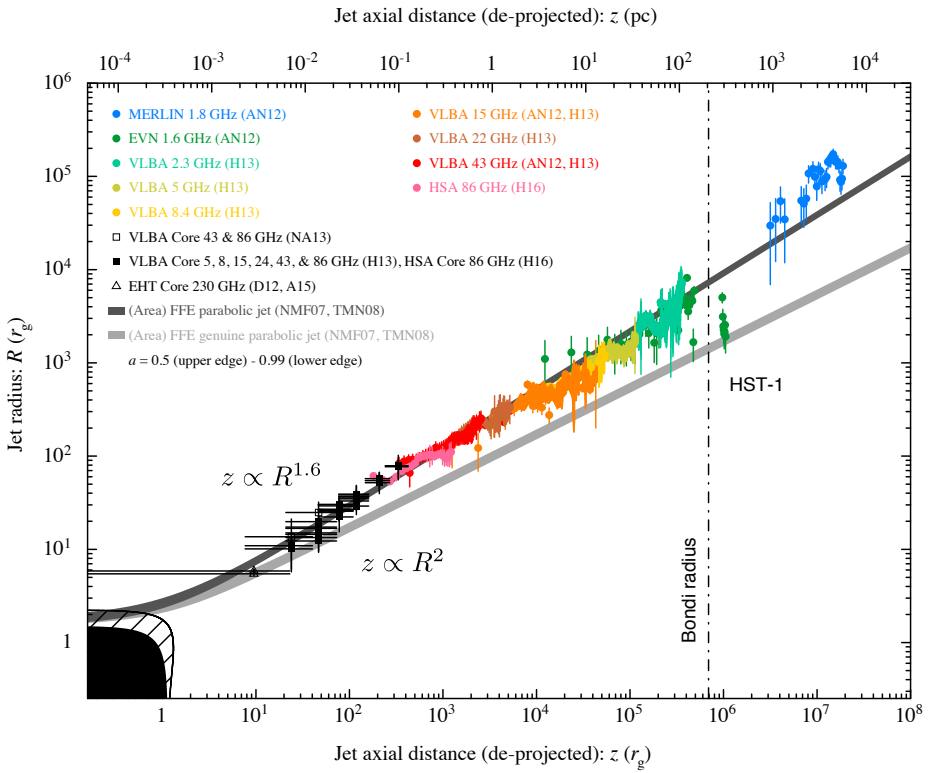
Summary

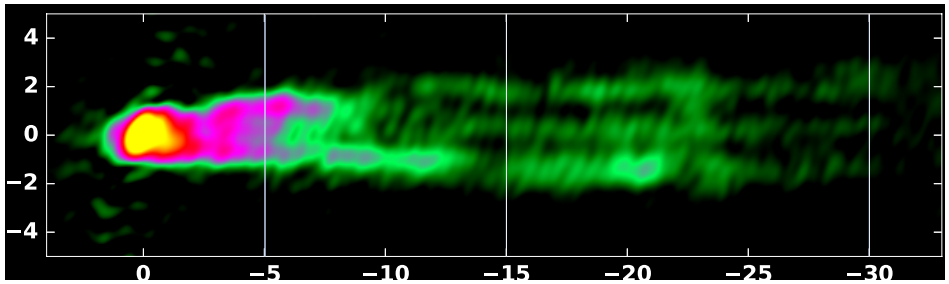
- Looking forward to the EHT data release
- For global PIC simulations of BH magnetospheres, see Kisaka-kun's talk

VLBI: recent progress for M87

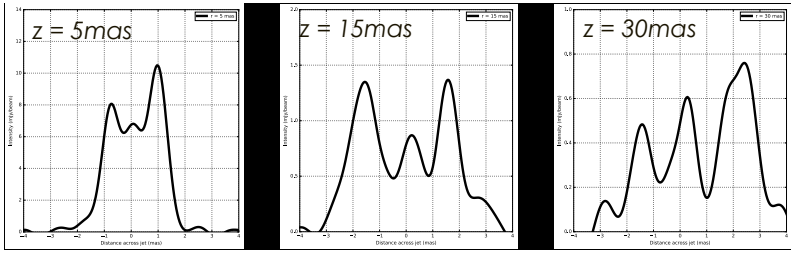


86 GHz (3.5mm); VLBA+GBT





15 GHz; VLBA+VLA



Hada et al. 2016; 2017; Nakamura, Asada et al. 2018

Agreement with force-free solution

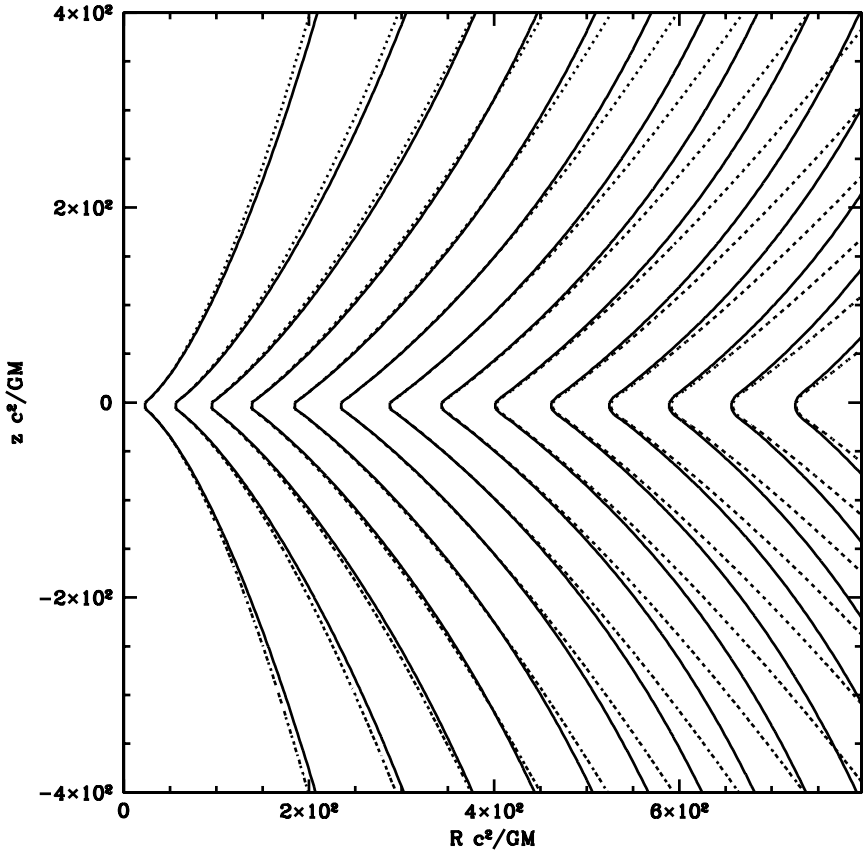


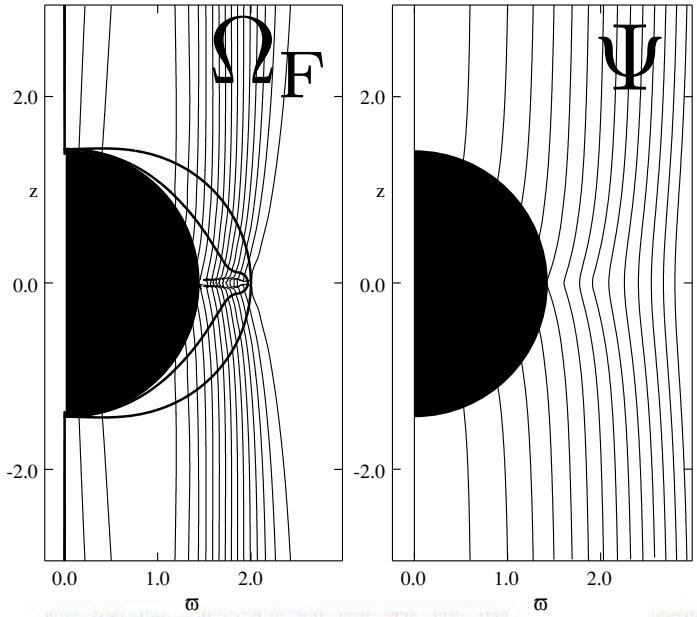
Figure 13. Field lines for the $a/M = 0.1$ GRFFE model with $\nu = 3/4$ at $t = 0$ (initial state, non-rotating solution, dotted lines) and $t = 1.2 \times 10^3 t_{\rm g}$ (final converged rotating solution, solid lines). The field lines threading the black hole show mild decollimation, as in the paraboloidal case, and the field lines from the outer regions of the disc show some collimation.

$$\Psi(r,\theta) = \left(\frac{r}{r_{\rm H}}\right)^{\kappa} (1 - \cos\theta)$$

$\kappa = 0.75$

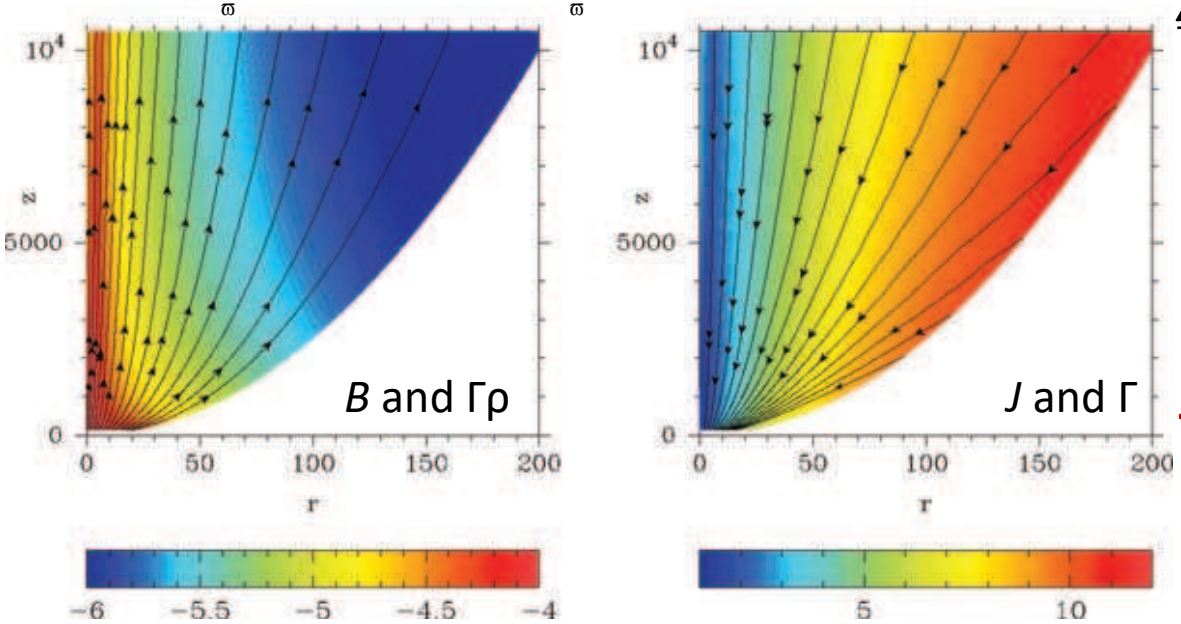
McKinney & Narayan 2007

Steady axisymmetric models



Energy source

- Conversion of rotation energy to Poynting flux
  - ➢ BH or accretion disk?
- Contribution of thermal energy?



Acceleration/collimation

- External pressure required
- Magnetic nozzle effect
- Near equipartition between Poy & Kinetic asymptotically

<-> Blazar emission models

Komissarov 04; Komissarov+ 07
see KT & Takahara 13; 14; 16