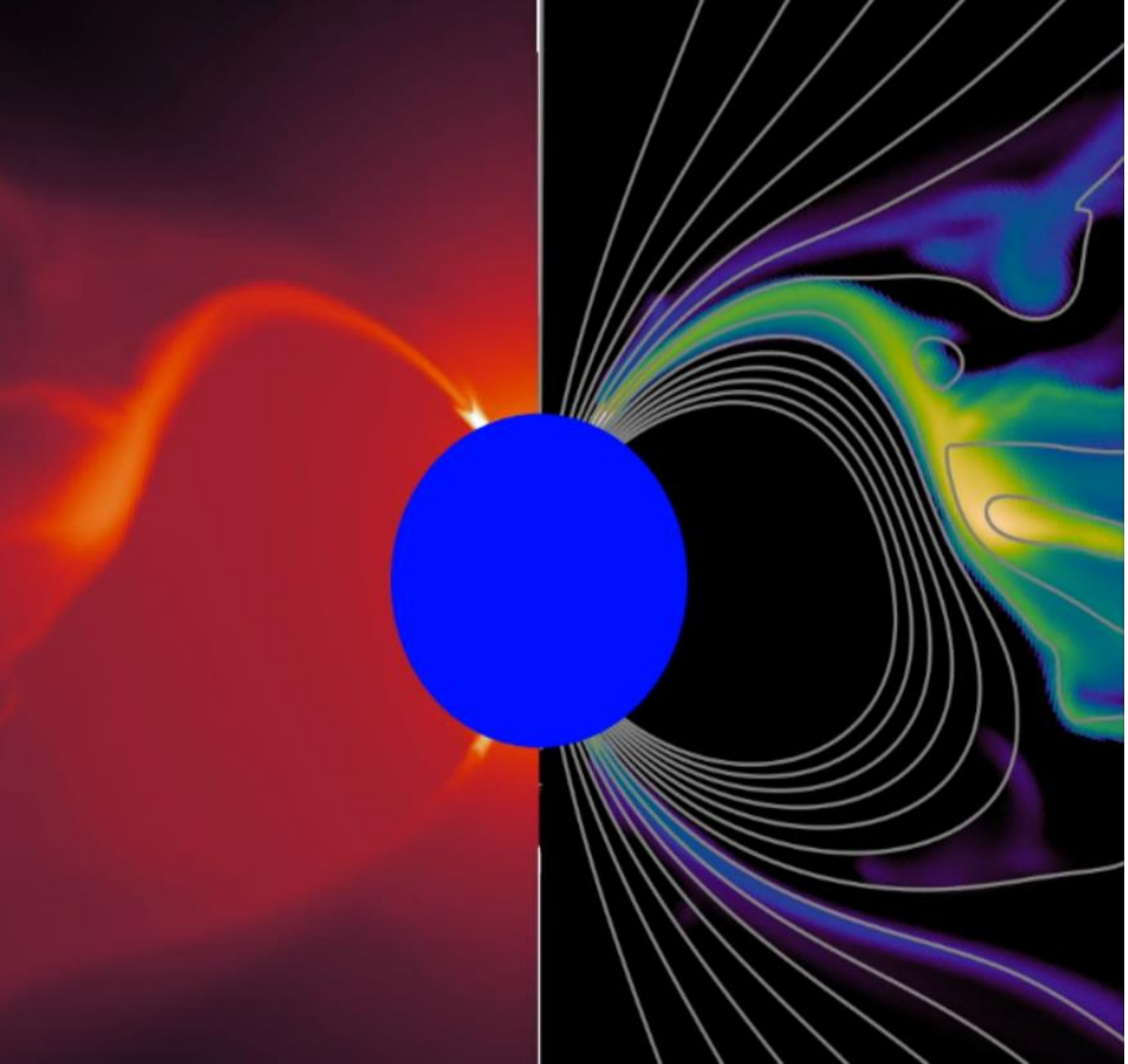

Energy flow and radiation luminosity in the simulations of neutron star Ultraluminous X-ray sources

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Neutron star Ultraluminous X-ray Sources (NS-ULXs)

- ULXs: Non-nuclear extra-galactic sources that emit X-rays at luminosities exceeding 10^{39} erg s^{-1}, above the critical Eddington luminosity for a compact object with a mass less than 10 solar mass.
  - Super-Eddington accretion onto stellar mass objects (neutron stars and black holes),
  - Supper-Eddington radiation in the radii between magnetosphere and spherization radius,

$$L \simeq L_{Edd} [1 + \ln \dot{M} / \dot{M}_{Edd}],$$ *(Shakura & Sunyaev, 1973).*

  - Radiation pressure causes the outflow and resulting beaming *(King et al. 2001).*
  - *King. et.al, 2001:* ULXs powered by extremely high accretion rate onto compact objects in high-mass X-ray binaries (HMXBs) in a transient stage.

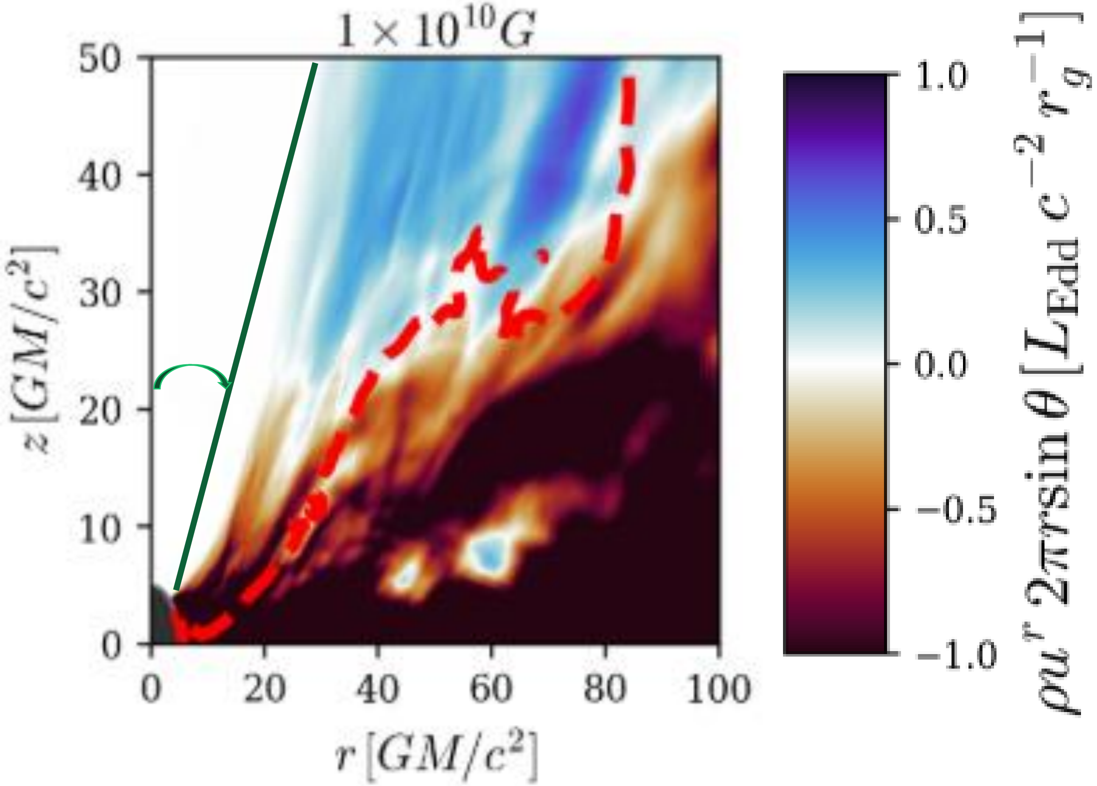
Beaming emission

- KLK model (studied by King, Lasota & Kluźniak, 2017; King & Lasota, 2019, 2020):
  - ✓ The compact object emits its radiation within a fraction b of the unit sphere, causing the luminosity to be overestimated by a factor of 1/b
  - ✓ when b<<1 then the inferred isotropic luminosity, $L_{iso} \sim L/b$

$L_{iso} = 4\pi d^2 F^r_{rad}$

F^r_{rad}: radiation flux in optically thin cone-like region

d: distance between source and detector



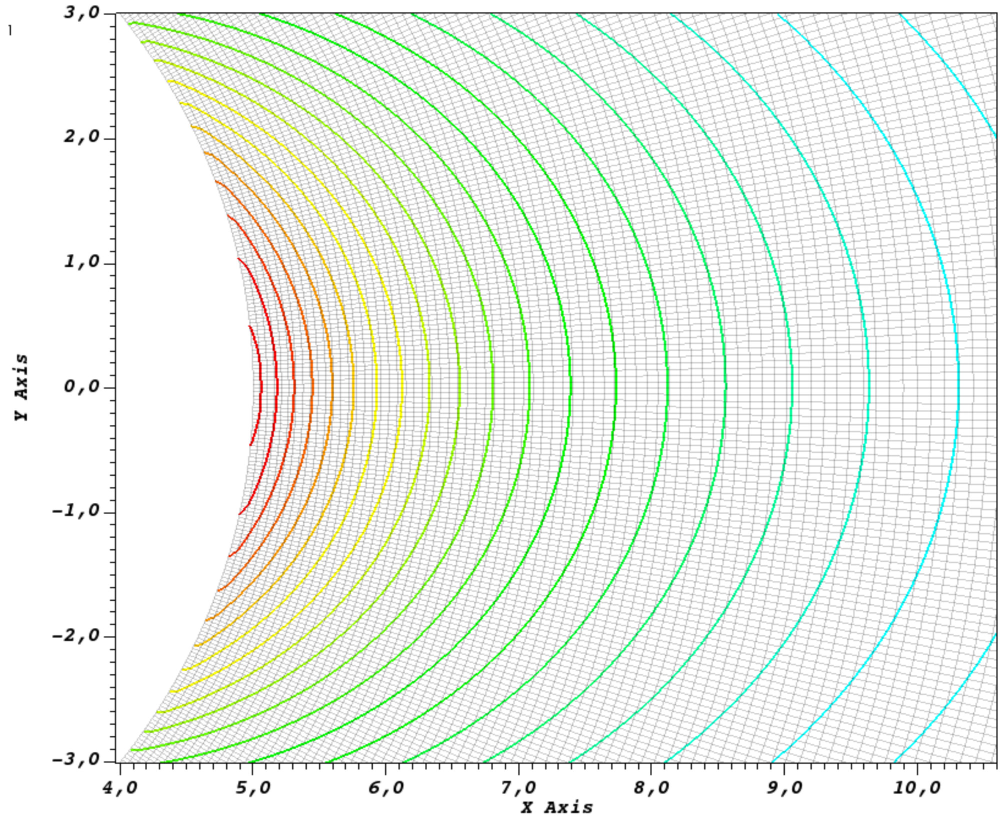
Simulation details

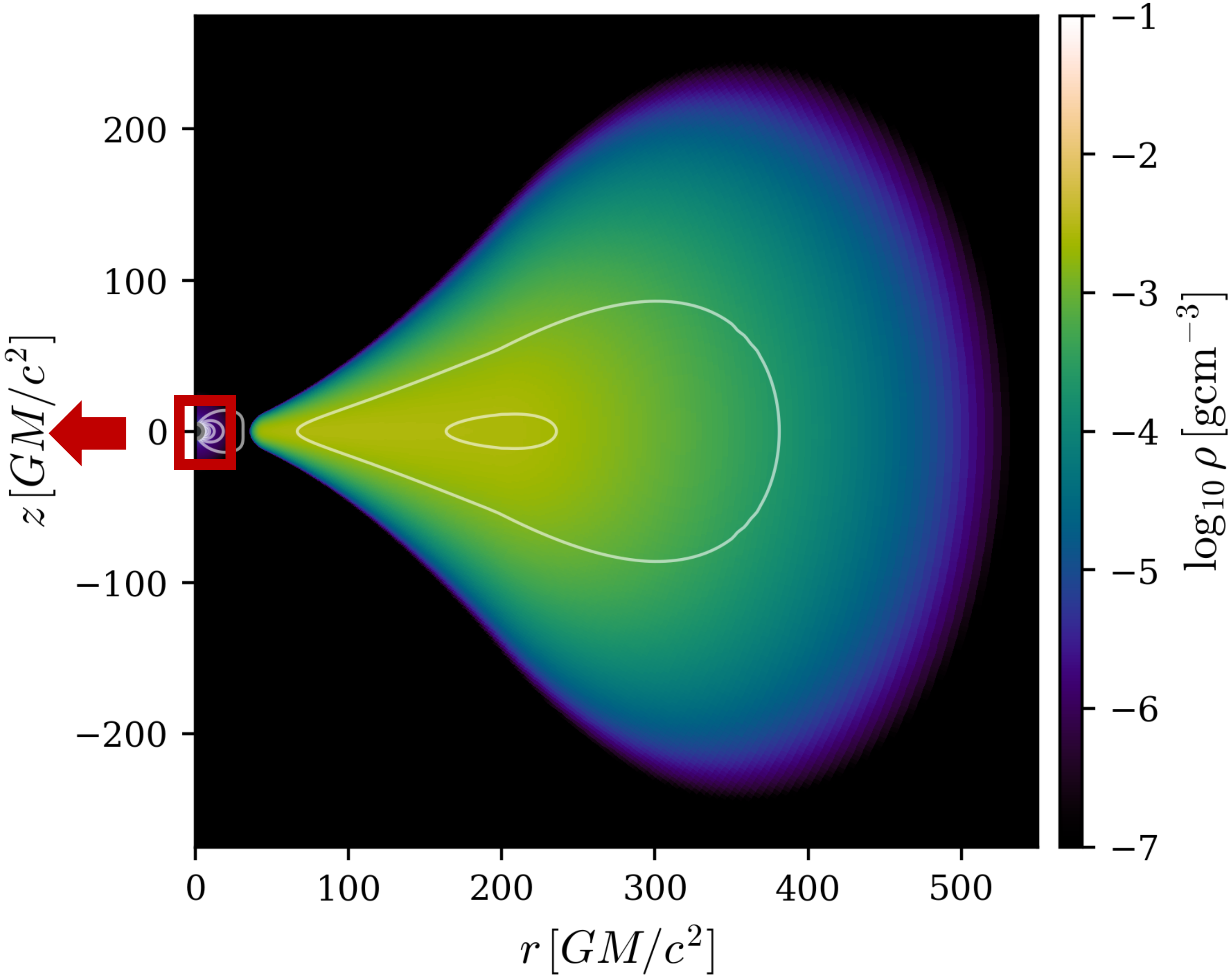
- General relativistic radiative magnetohydrodynamic (GRRMHD) code, KORAL.
- Conservation of mass ne energy-momentum tensor:

$$\nabla_\mu(\rho u^\mu) = 0 \quad \& \quad \nabla_\mu(T^\mu{}_\nu + R^\mu{}_\nu) = 0$$

- Neutron star: mass 1.4 $M_\odot$ and radius $5r_g$ ($r_g = GM/c^2$) with dipole magnetic field
- Torus: Equilibrium torus with loop magnetic field with $\boldsymbol{\beta} = (P_{gas}+P_{rad})/P_{mag} = 10$
- Resolution: $N_r \times N_\theta \times N_\varphi = 512 \times 510 \times 1$ with logarithmic spacing in r direction
- Schwarzschild metric
- Boundary condition: energy reflective surface for the neutron star with albedo 0.75

Initial setup



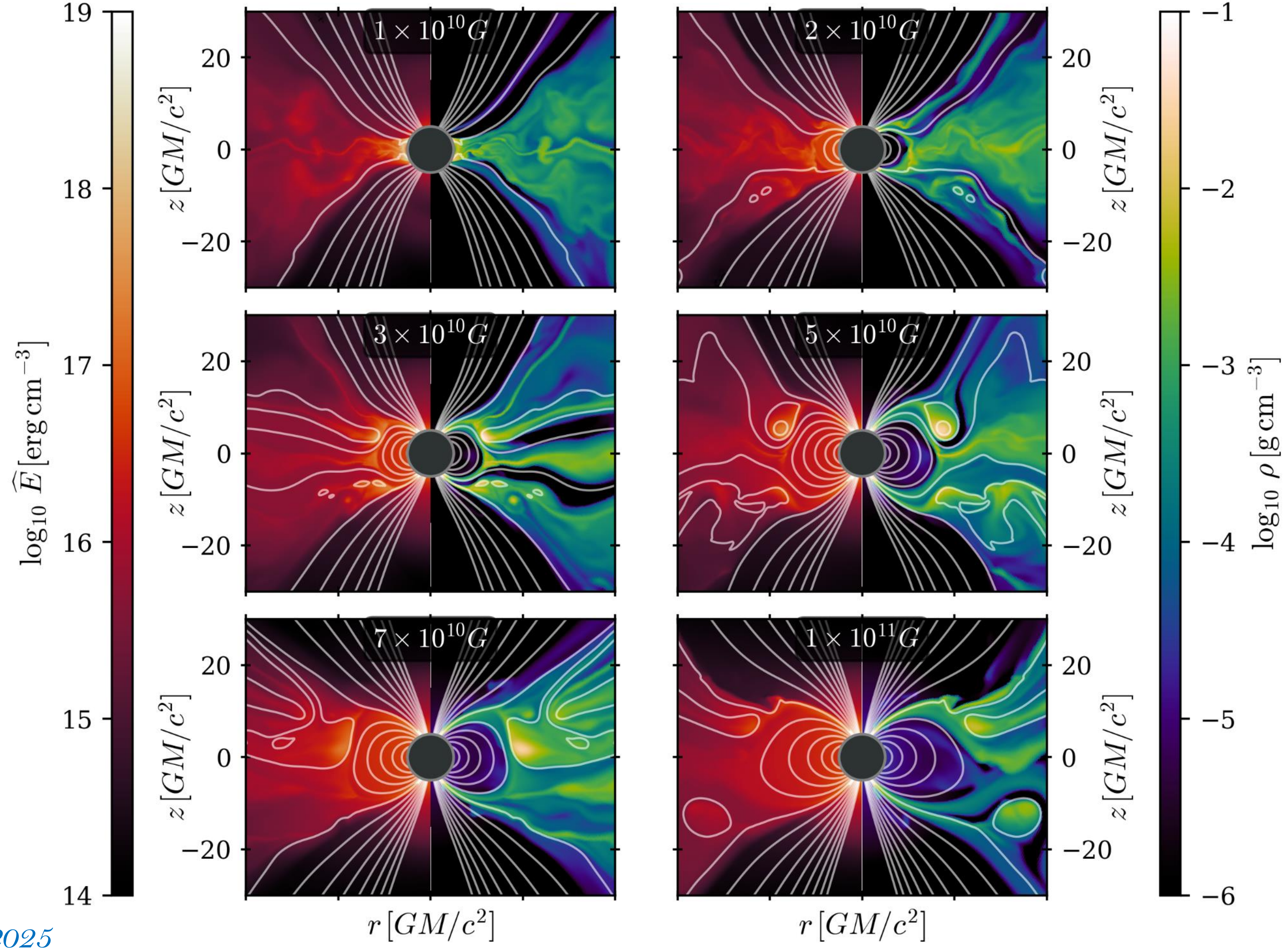


Models

B [G]	$\dot{M}$ [L_{Edd} c^{-2}]	$\dot{M}_{out}$ [L_{Edd} c^{-2}]	L/L_{Edd}	b_{min}	L_{iso}/L_{Edd}	R_A/r_g
1×10^{10}	257	325	2.10	0.016	115	5.25
2×10^{10}	320	317	1.97	0.020	100	6.85
3×10^{10}	345	250	1.90	0.023	90	10.15
5×10^{10}	355	150	1.55	0.026	68	13.30
7×10^{10}	430	190	1.50	0.045	45	15.85
1×10^{11}	490	80	1.49	0.083	39	17.39

3×10^{10}	144	30	1.14	0.050	40	11.85
3×10^{10}	1000	3600	2.5	0.010	185	8.10

Models



Kayanikhoo et al., APJ, 2025

Time-averaged data

Time averaged data over the periods from $t = 15\,000\ t_g$ to $50\,000\ t_g$

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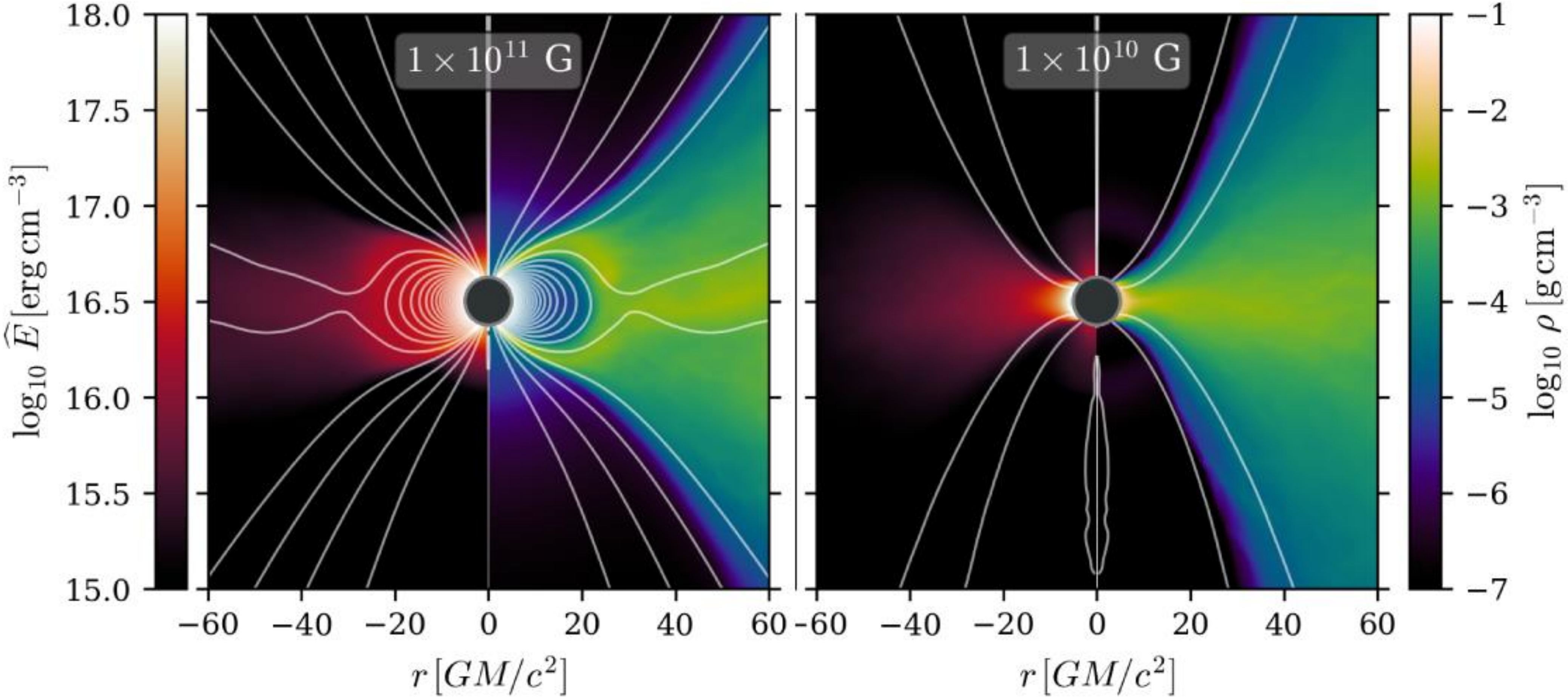
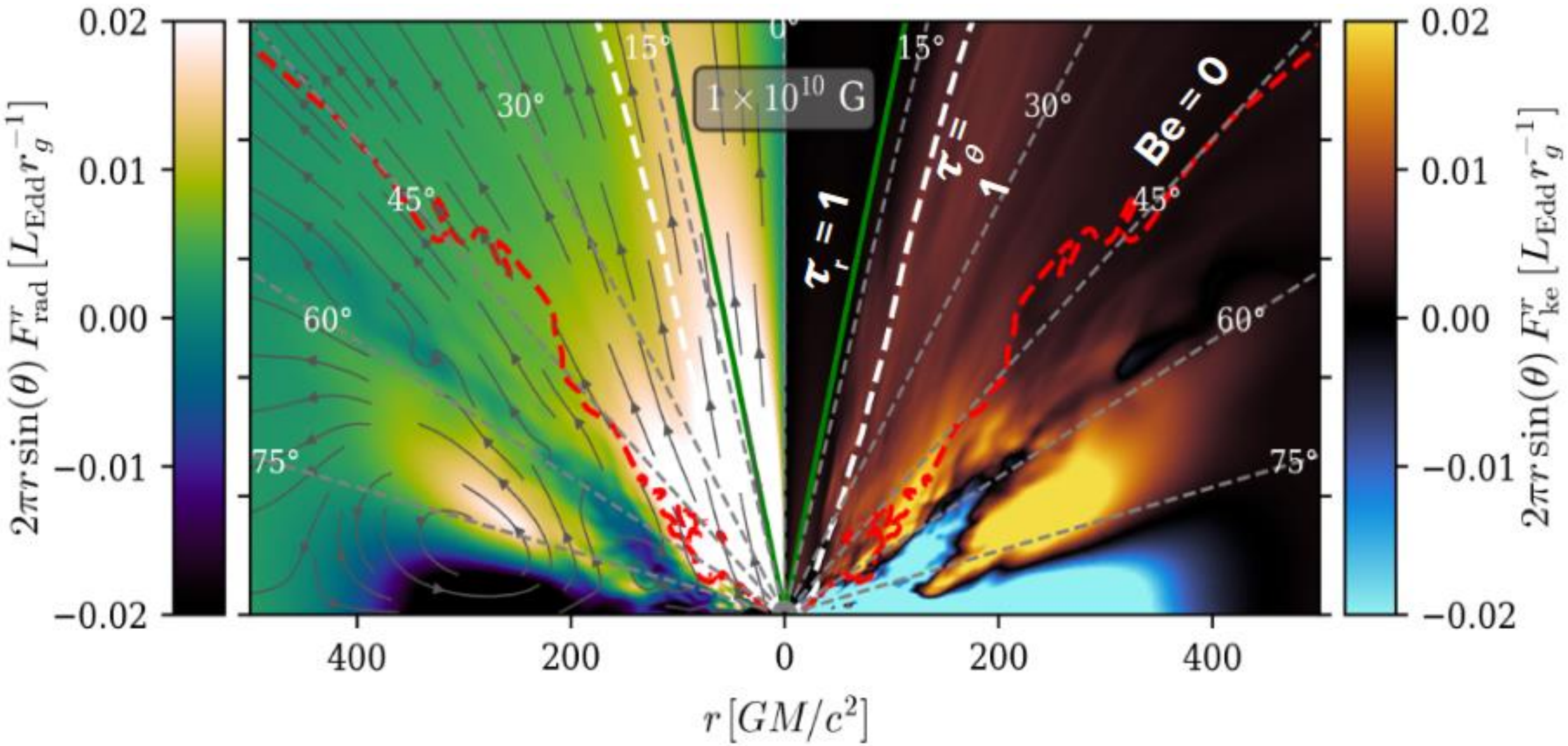


Different regions

$$Be = -\frac{T^t{}_t + R^t{}_t + \rho u^t}{\rho u^t},$$

$T^t{}_t$ and $R^t{}_t$ are MHD and radiation energy densities, $\boldsymbol{\rho}$ is the mass-density and u^t is time component of 4-velocity



$$\tau_{\rm r}(r) = \int_r^{r_{\rm out}} \rho \kappa_{\rm es} \sqrt{g_{\rm rr}}\, dr,$$

whit r_{out} the outer boundary of simulations,
κes = 0.34 cm g^{-1} , the electron scattering opacity for solar composition

Radiation and kinatic efficiency

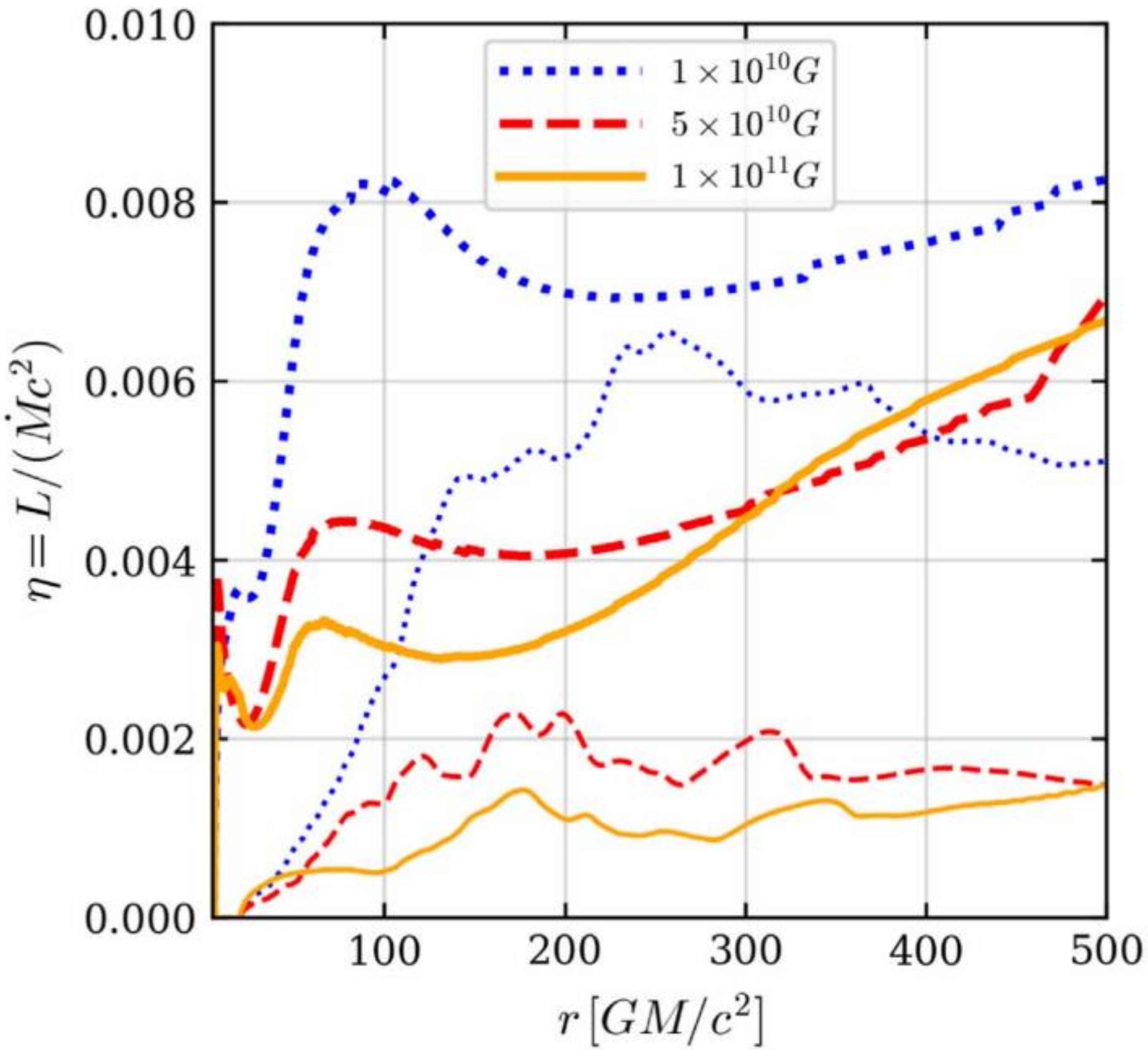
$$L_{\mathrm{r}} = -2\pi \int R^r{}_t \sqrt{-g}\, d\theta|_{\tau_{\mathrm{r}}<1}.$$

$$L_{\mathrm{KE}} = -2\pi \int (u_t + \sqrt{-g_{tt}})\rho u^r \sqrt{-g}\, d\theta\Big|_{Be>0,\, u^r>0}$$

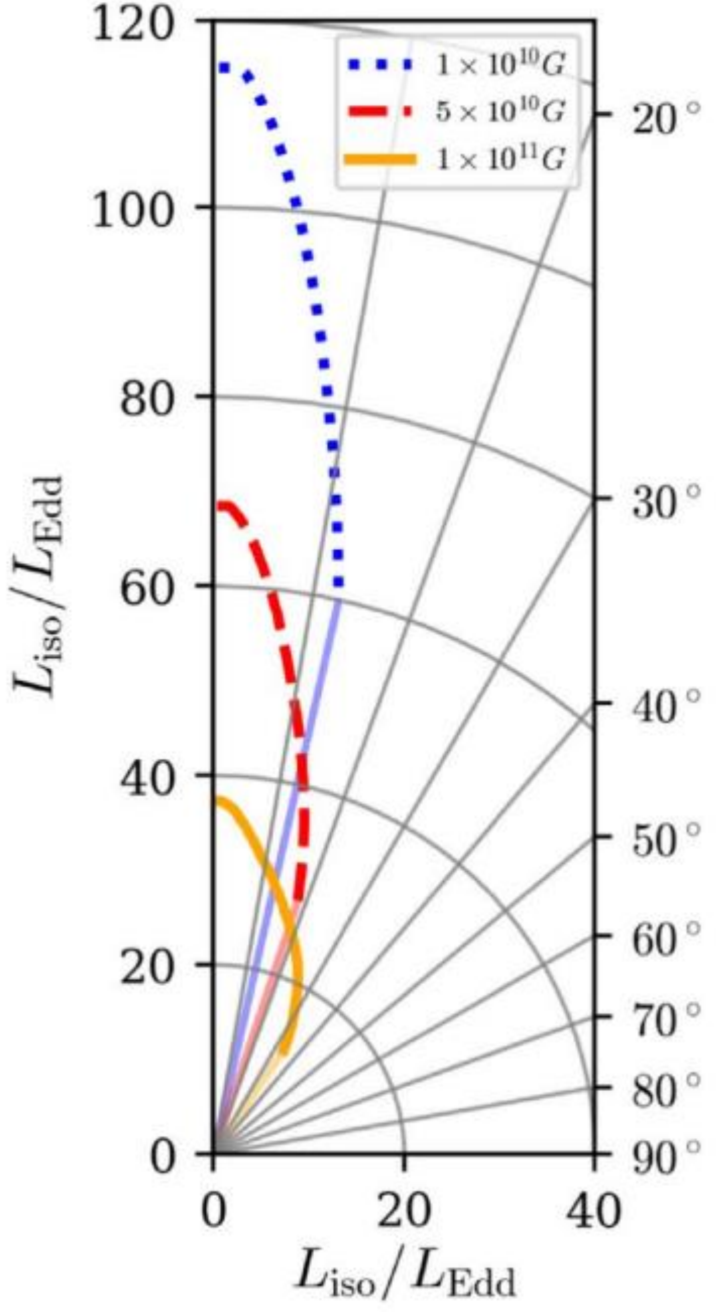
$$\eta = L/(\dot{M}c^2)$$

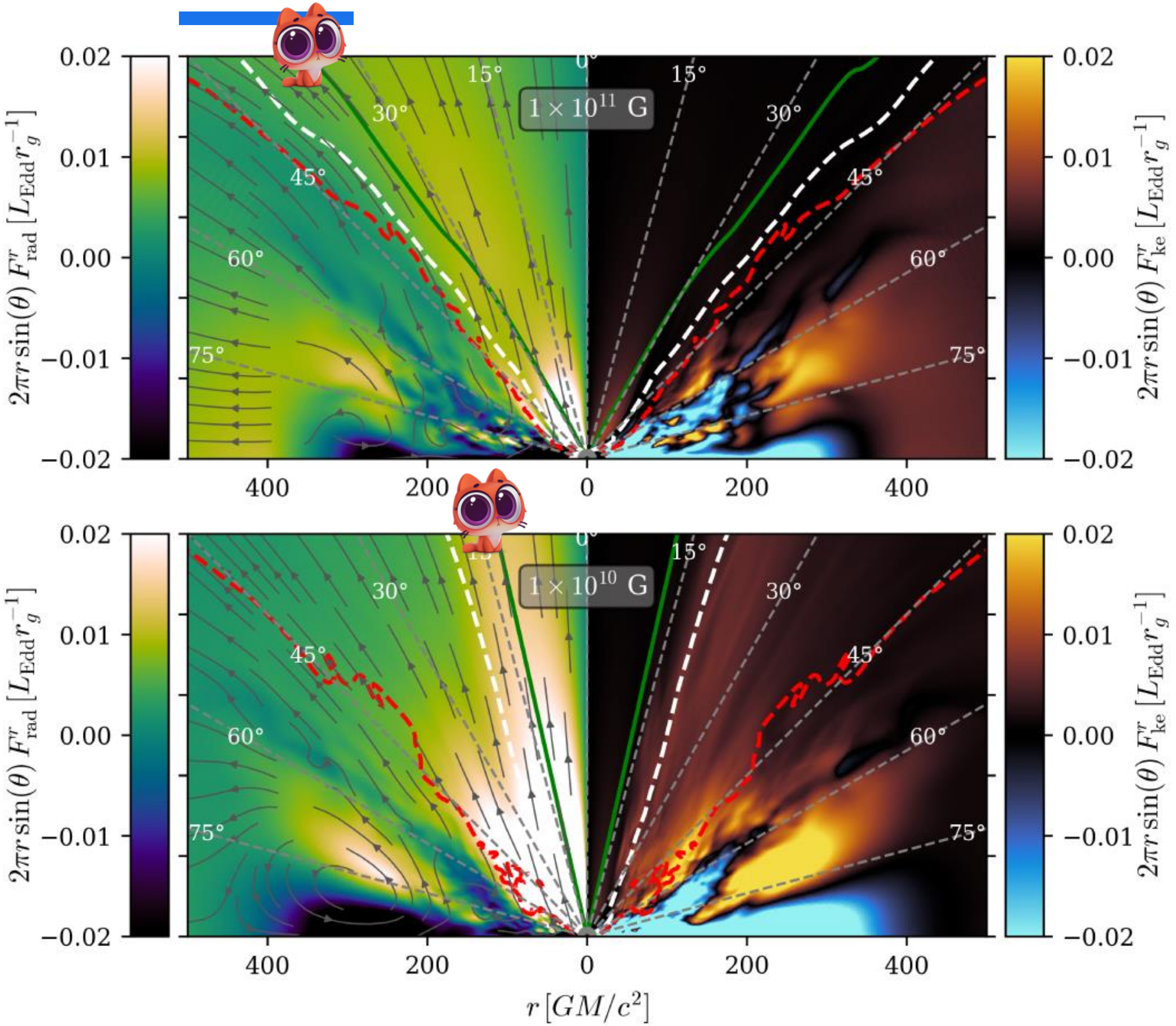
Weaker magnetic field

- more powerful outflows
- higher radiation efficiency



Beaming and apparent luminosity





Conclusions

- The simulation with a **weak dipole** (10^{10} G) compared to strong dipole (10^{11} G):
  - ✓ More powerful outflow
  - Higher radiation efficiency
  - Higher apparent luminosity
- 10^{10} G =>> the apparent luminosity about 120 Eddington luminosity.
- 10^{11} G =>> the apparent luminosity about 40 Eddington luminosity.
- Increasing **accretion rate** in simulation with a fixed magnetic dipole strength:
  - More powerful outflow
  - lower radiation efficiency
  - Higher apparent luminosity

The simulation with dipole strength 10^{10} G and accretion rate of 1000 Eddington units gives the apparent luminosity of 250 Eddington luminosity.