General Relativistic Radiation MHD simulations of Super-Eddington Accretion Flows onto Magnetized Neutron Stars; Powerful Outflows and Thermal Emission

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Summary of this talk

Motivation : Galactic ULX pulsar, Swift J0243.6+6124

- Thermal emission (Tao+2019)
- Magnetic field strength of the NS $B_{\rm NS}$ and mass accr. rate $\dot{M}_{\rm in}$

Method

2D General Relativistic Radiation MHD (GR-RMHD) simulations of super-Eddington accr. flows around NS with dipole magnetic fields

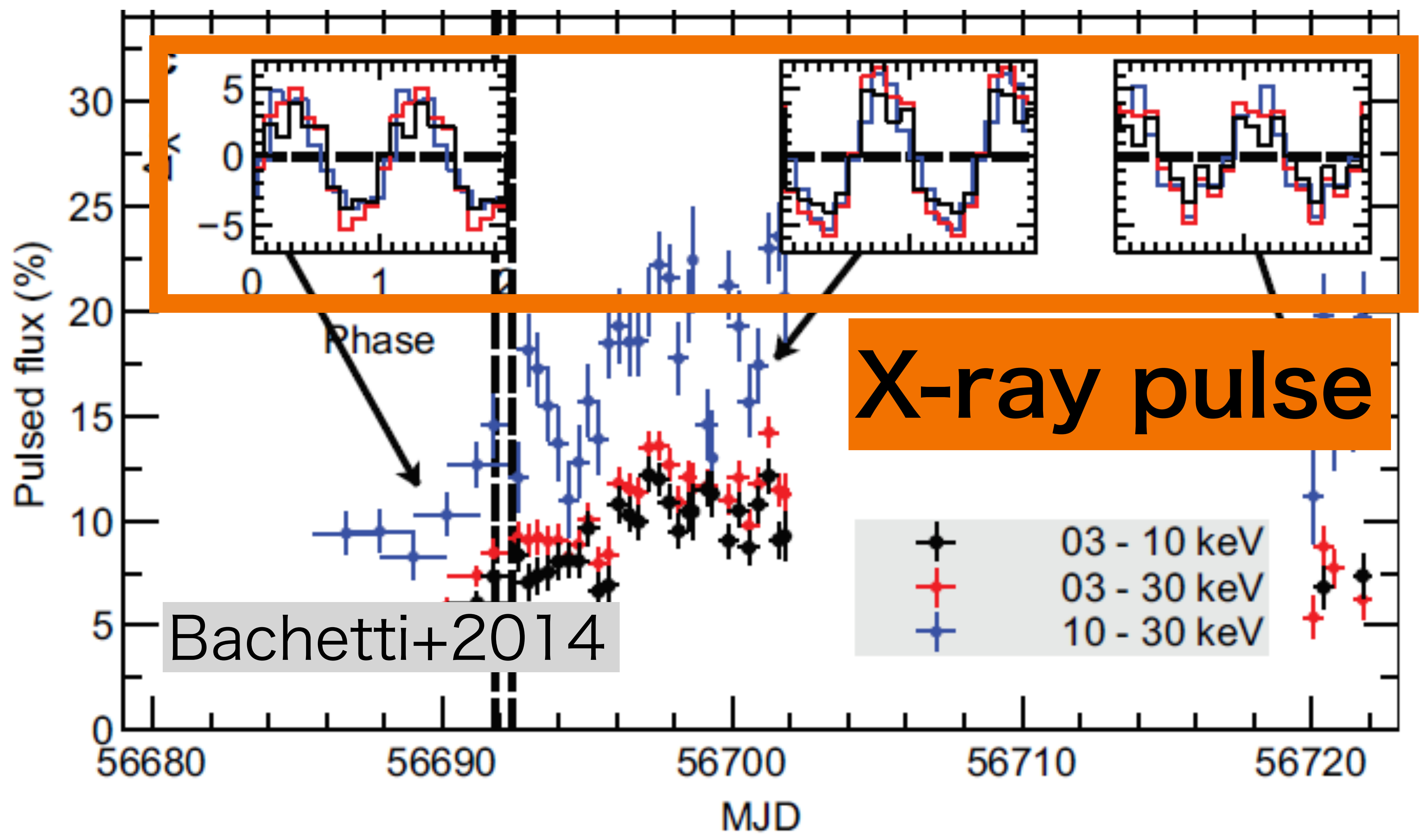
Result & Conclusion

- ☑ The observed thermal emission can be reproduced by optically thick outflow launched from the accr. disk.
- ☑ $3\times10^{11}\ {\rm G} \lesssim {\rm B_{NS}} \lesssim 4\times10^{12}\ {\rm G},\ \ 130\dot{M}_{\rm Edd} < \dot{M}_{\rm in} < 1200\dot{M}_{\rm Edd}$ in Swift J0243.6+6124.

Super-Eddington accretion onto the neutron star

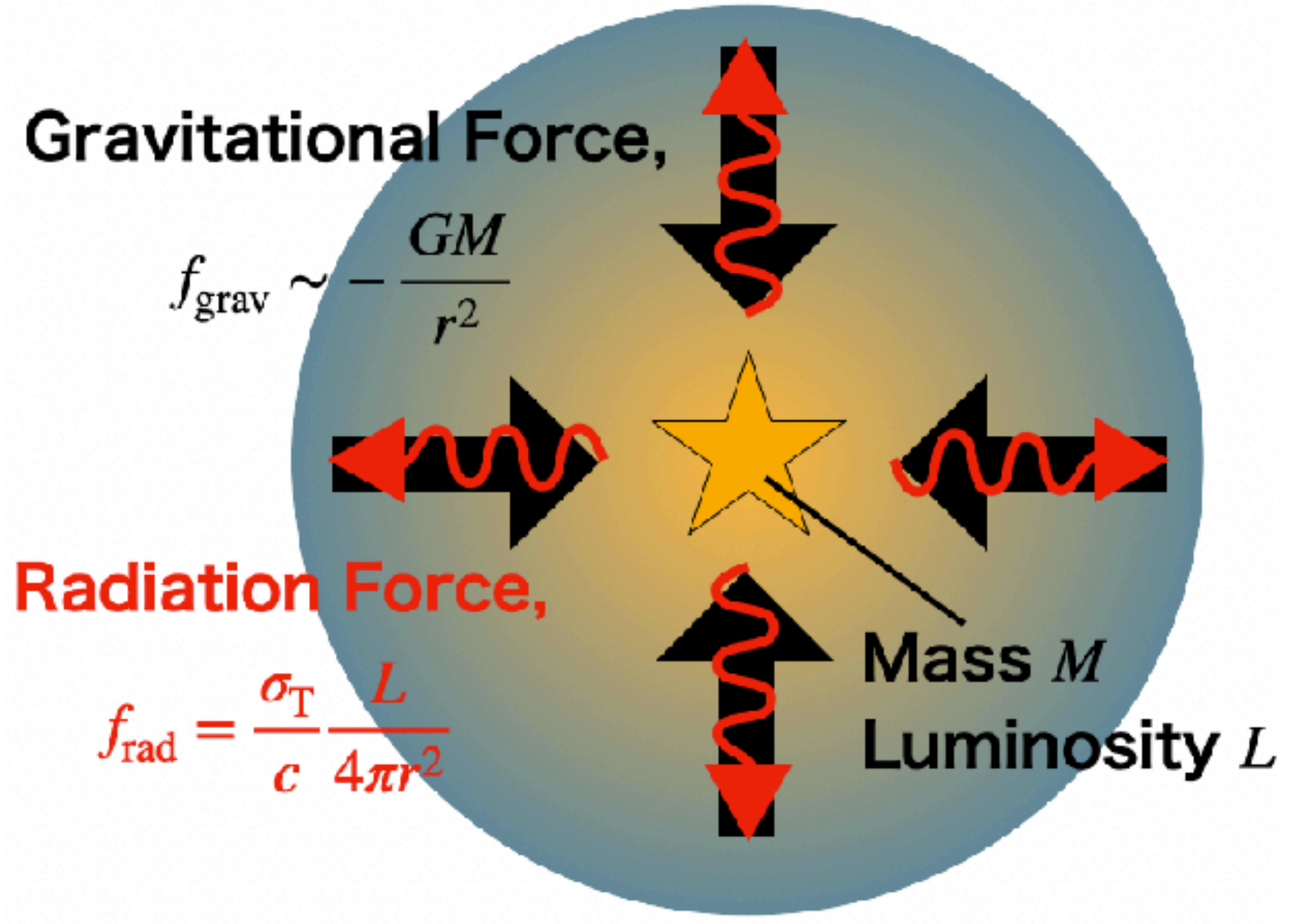
UltraLuminous X-ray Pulsars (ULX Pulsars)

X-ray pulsar with $L > 10^{39}$ erg/s $\sim 10 L_{\rm Edd}$



- **X-ray pulse is detected**
  → magnetized neutron star (NS) ?
- **Large X-ray luminosity**
  → **super-Eddington accr., $\dot{M}_{\rm in} > L_{\rm Edd}/c^2$?**

Eddington limit $L_{\rm Edd}$ & $\dot{M}_{\rm Edd}$



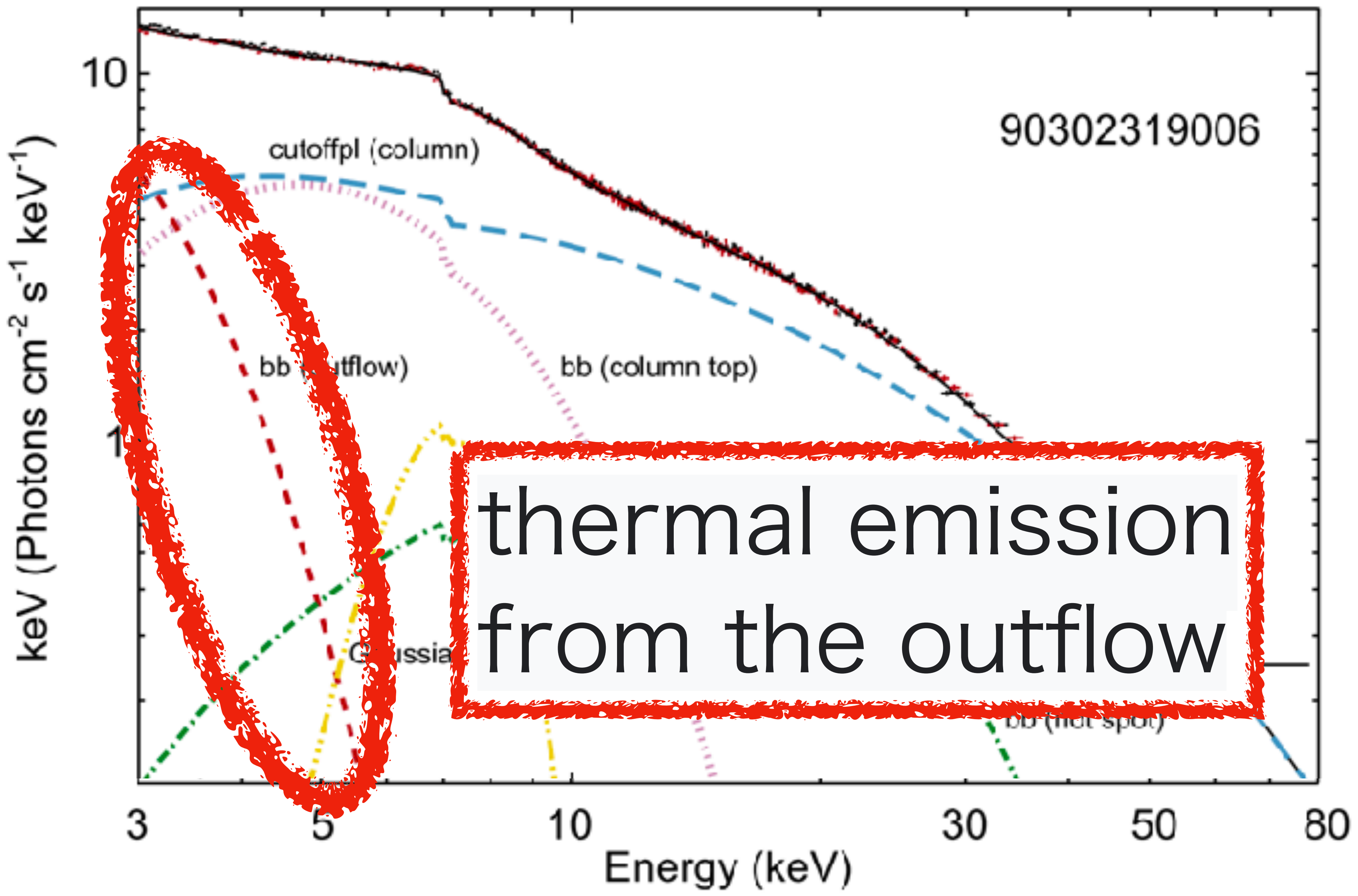
We would naively impose $f_{\rm grav} > f_{\rm rad}$

$$L < L_{\rm Edd} = 1.25 \times 10^{39}\ [{\rm erg\ s^{-1}}]\left(\frac{M}{10M_\odot}\right)$$

$$\dot{M}_{\rm in} < L_{\rm Edd}/c^2 = 1.4 \times 10^{18}\ [{\rm g\ s^{-1}}]\left(\frac{M}{10M_\odot}\right)$$

Galactic ULX Pulsar, Swift J0243.6+6124

- **Outflows driven by super-Eddington accr. onto magnetized NS**



Radiation spectrum (Tao+2019)

Thermal emission

$T_{\rm bb}$: $\sim 10^7$ K, $R_{\rm bb}$: 100-500km

$T_{\rm bb}$: blackbody temperature

$R_{\rm bb}$: blackbody radius

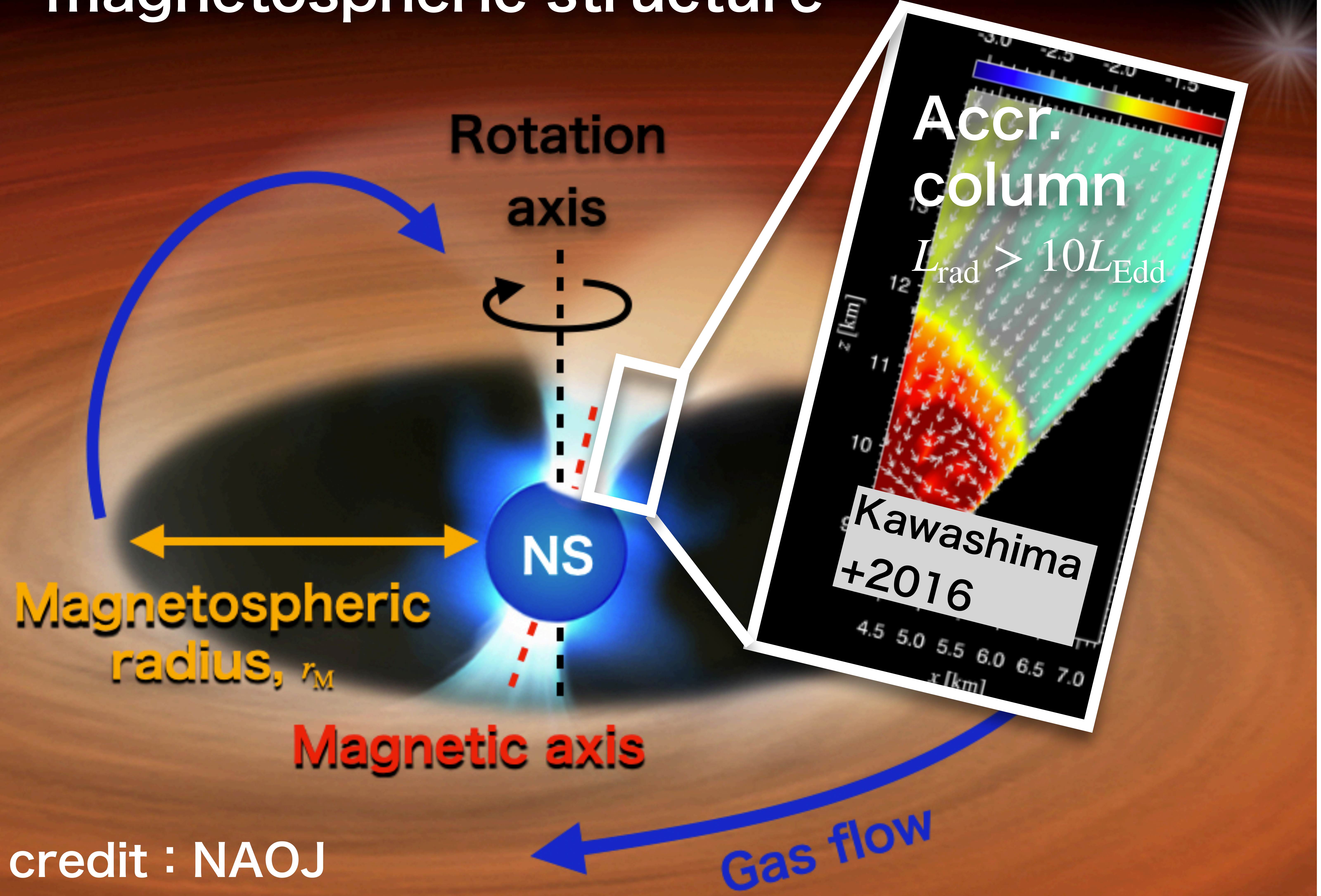
- **Magnetic field strength of NS,** $B_{\rm NS} \lesssim 6 \times 10^{12}$ G (Tsygankov+2018)

This study

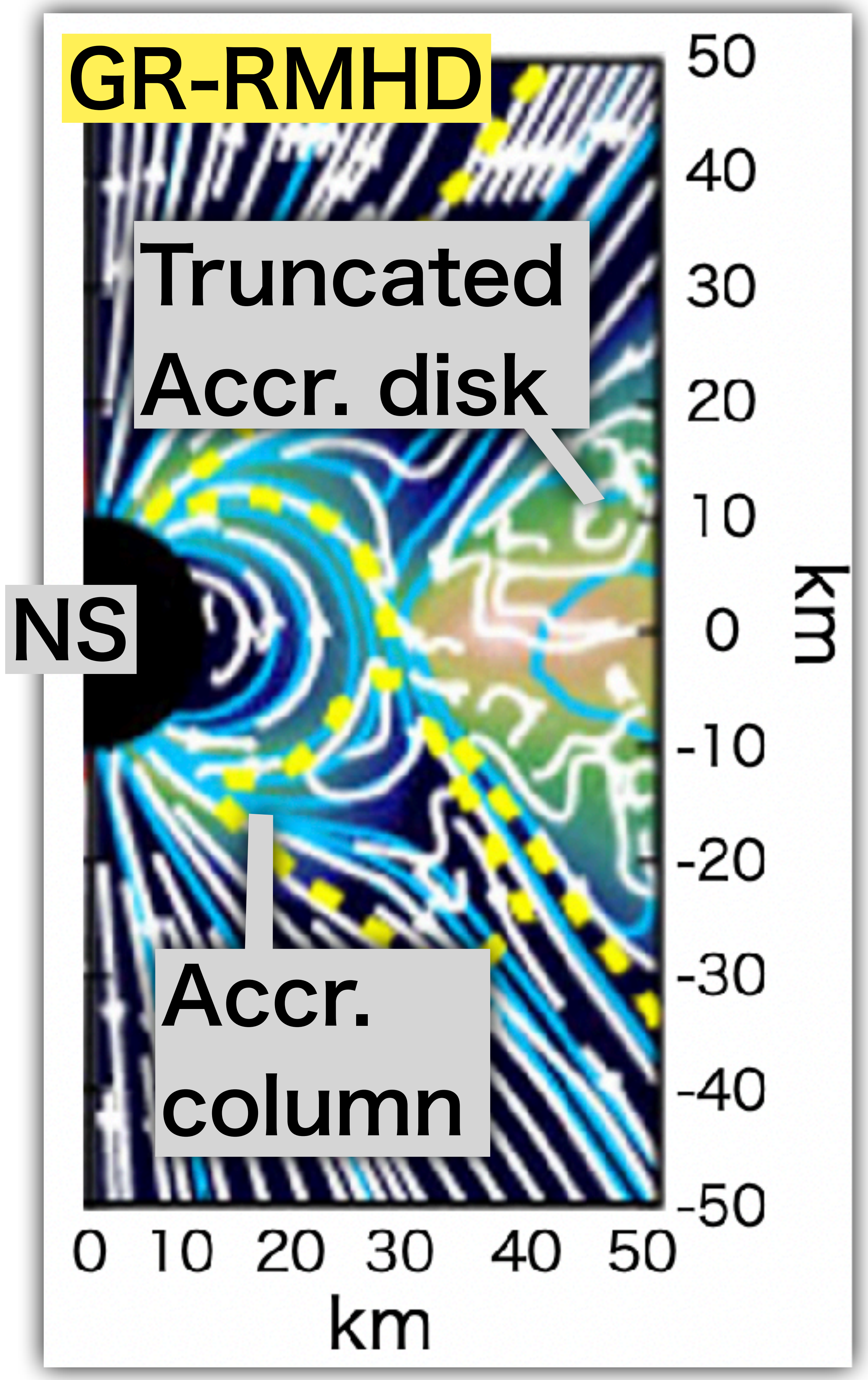
We investigate with GR-RMHD simulations whether the super-Eddington accr. onto magnetized NSs can reproduce this thermal emission or not. A limit of $B_{\rm NS}$ and $\dot{M}_{\rm in}$ can be obtained from this thermal emission.

Hydrodynamical Simulations around magnetized NSs

B_{NS} and $\dot{M}_{in}$ determine the magnetospheric structure



Takahashi & Ohsuga 2017 (see also, Abarca+2021)



Basic equations of GR-RMHD

ρ mass density, u^μ four velocity of the gas
g determinant of metric, B^i magnetic three vector
b^μ covariant magnetic field, $T^{\mu\nu}$ ideal MHD energy-momentum tensor, $R^{\mu\nu}$ radiation energy-momentum tensor, $\kappa_{\rm abs}$ free-free, $\kappa_{\rm sca}$ electron scattering,
$\Gamma^\mu_{\alpha\beta}$ Christoffel symbol, $G^\mu{}_{\rm comp}$ thermal Compton,
$\hat{B}$ Black-body intensity, $\bar{E}_{\rm R}$ radiation energy in radiation rest-frame, $u_{\rm R}{}^\mu$ four velocity of radiation

We use GR-RMHD code UWABAMI (Takahashi & Ohsuga 2017)

Mass cons. $\partial_t\left(\sqrt{-g}\rho u^t\right) + \partial_i\left(\sqrt{-g}\rho u^i\right) = 0$

Gauss law $\partial_i\left(\sqrt{-g}B^i\right) = 0$

Induction eq. $\partial_t\left(\sqrt{-g}B^i\right) = -\partial_j\left[\sqrt{-g}\left(b^j u^i - b^i u^j\right)\right]$

Energy-momentum cons. for ideal MHD $\partial_t\left(\sqrt{-g}T^t_\nu\right) + \partial_i\left(\sqrt{-g}T^i_\nu\right) = \sqrt{-g}T^\kappa_\lambda\Gamma^\lambda_{\nu\kappa} + \sqrt{-g}G_\nu$

Energy-momentum cons. for radiation $\partial_t\left(\sqrt{-g}R^t_\nu\right) + \partial_i\left(\sqrt{-g}R^i_\nu\right) = \sqrt{-g}R^\kappa_\lambda\Gamma^\lambda_{\nu\kappa} - \sqrt{-g}G_\nu$

Interaction term between the MHD and the radiation

Radiation force $G^\mu = -\rho\kappa_{\rm abs}\left(R^\mu{}_\alpha u^\alpha + 4\pi\hat{B}u^\mu\right) - \rho\kappa_{\rm sca}\left(R^\mu{}_\alpha u^\alpha + R^\alpha{}_\beta u_\alpha u^\beta u^\mu\right) + G^\mu{}_{\rm comp}$

M1-closure $R^{\mu\nu} = \frac{4}{3}\bar{E}_R u_R{}^\mu u_R{}^\nu + \frac{1}{3}\bar{E}_R g^{\mu\nu}$

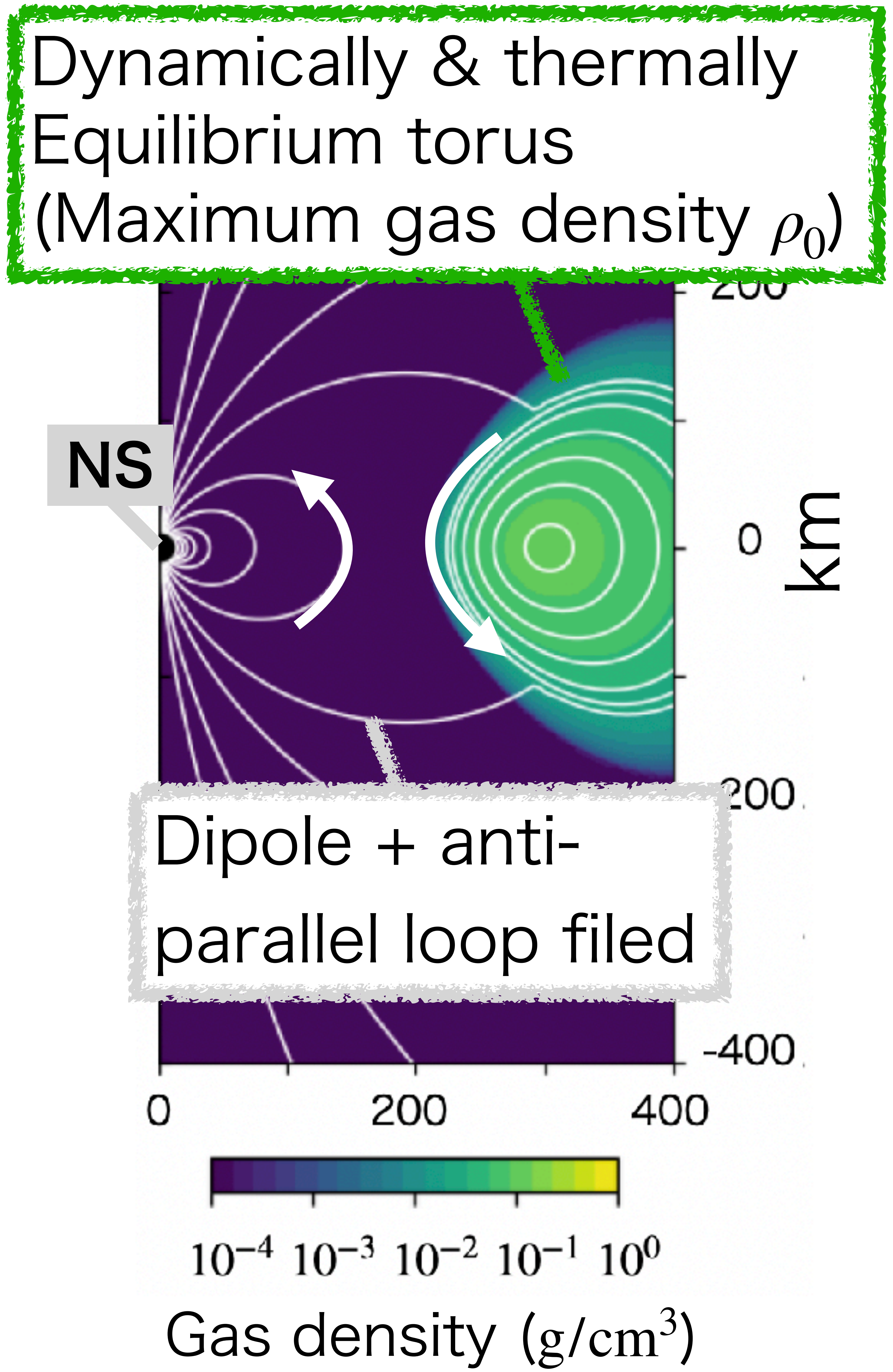
Sadowski+ 2013, 2014

We numerically solve 12 PDE (+ EOS)

$$\partial_t\mathcal{U} + \partial_j\mathcal{F}^j = \mathcal{S}$$

$$\mathcal{U} = \sqrt{-g}\begin{pmatrix}\rho u^0\\ T^0_\nu\\ B^i\\ R^0_\nu\end{pmatrix},\quad \mathcal{F}^j = \sqrt{-g}\begin{pmatrix}\rho u^j\\ T^j_\nu\\ b^i u^j - b^i u^j\\ R^j_\nu\end{pmatrix},\quad \mathcal{S} = \begin{pmatrix}0\\ \sqrt{-g}\Gamma^\alpha_{\nu\beta}T^\beta_\alpha + \sqrt{-g}G_\nu\\ 0\\ \sqrt{-g}\Gamma^\alpha_{\nu\beta}R^\beta_\alpha - \sqrt{-g}G_\nu\end{pmatrix}$$

Simulation setup & model



Computational domain & resolution

2D simulation

$r = [10\ \mathrm{km},\ 2100\ \mathrm{km}]$, $\theta = [0,\ \pi]$, $(N_r,\ N_\theta,\ N_\phi) \geq (592{,}412,\ 1)$

Non-rotating Neutron Stars (NS)

- $M_{\mathrm{NS}} = 1.4\ M_\odot$
- $r_{\mathrm{NS}} = 10$ km
- dipole magnetic field
- Kinetic and thermal energy are immediately converted into radiation energy at the NS surface.
- Radiation fields become isotropic at the NS surface.

Treatment of high magnetized region

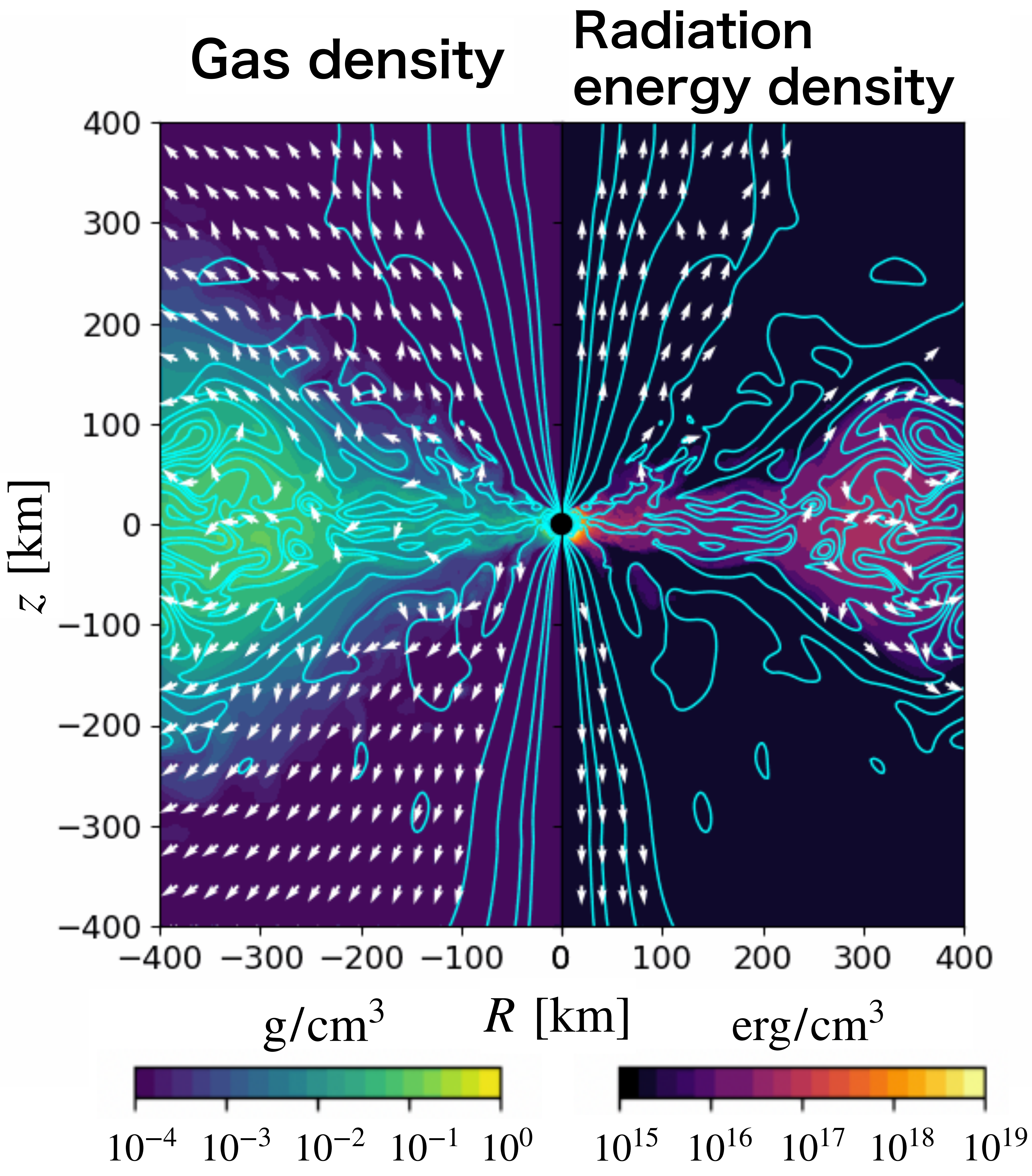
κ_{abs} and κ_{es} are set to zero in $\sigma = b^2/4\pi\rho c^2 > 10$

Model parameter

corresponding to changing $\dot{M}_{\mathrm{in}}$

$B_{\mathrm{NS}} = 3.3 \times 10^{9-10}$ [G], $\rho_0 = 0.01 - 1$ [g/cm^3]

Overview : accretion disk, column and outflow



Solid lines : magnetic field lines

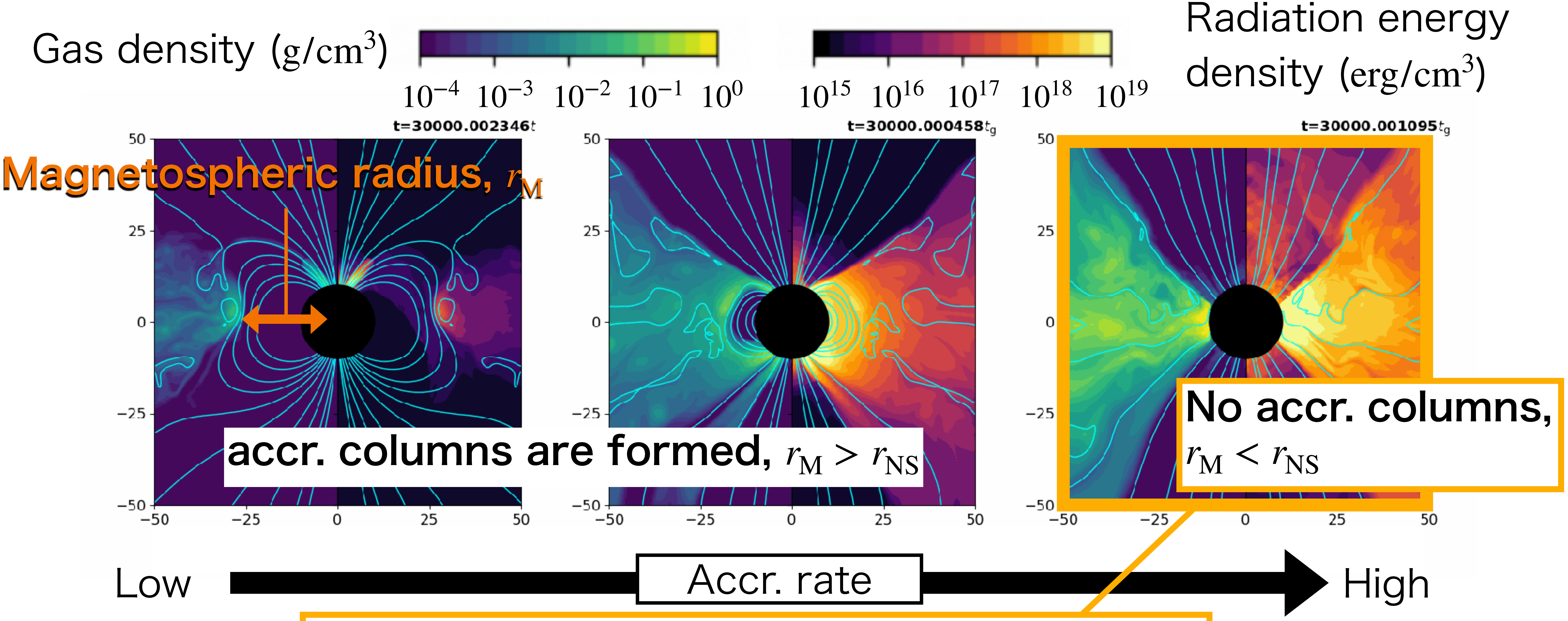
Vector Left : gas velocity (outflow rate $> 100\dot{M}_{\rm Edd}$)

Right : radiative flux ($L_{\rm rad} > 100 L_{\rm Edd}$)

- **The accr. disk** is formed around the magnetized NS.
- **Powerful outflows**, driven by radiation force and centrifugal force, are launched from the accr. disk.
- The accr. disk is truncated by the dipole magnetic field of the NS, and then **accr. columns** are formed near the poles. At the same time, the angular momentum of the accreting gas is transported to the NS through the dipole magnetic field (**spin-up**).

The magnetospheric radius, $r_{\rm M}$ (model with $B_{\rm NS} = 10^{10}$ G)

($r_{\rm M}$ in high $\dot{M}_{\rm in}$ model) < ($r_{\rm M}$ in low $\dot{M}_{\rm in}$ model)



The accr. disk reaches the NS surface without being truncated. **Pulsation may not occur.**

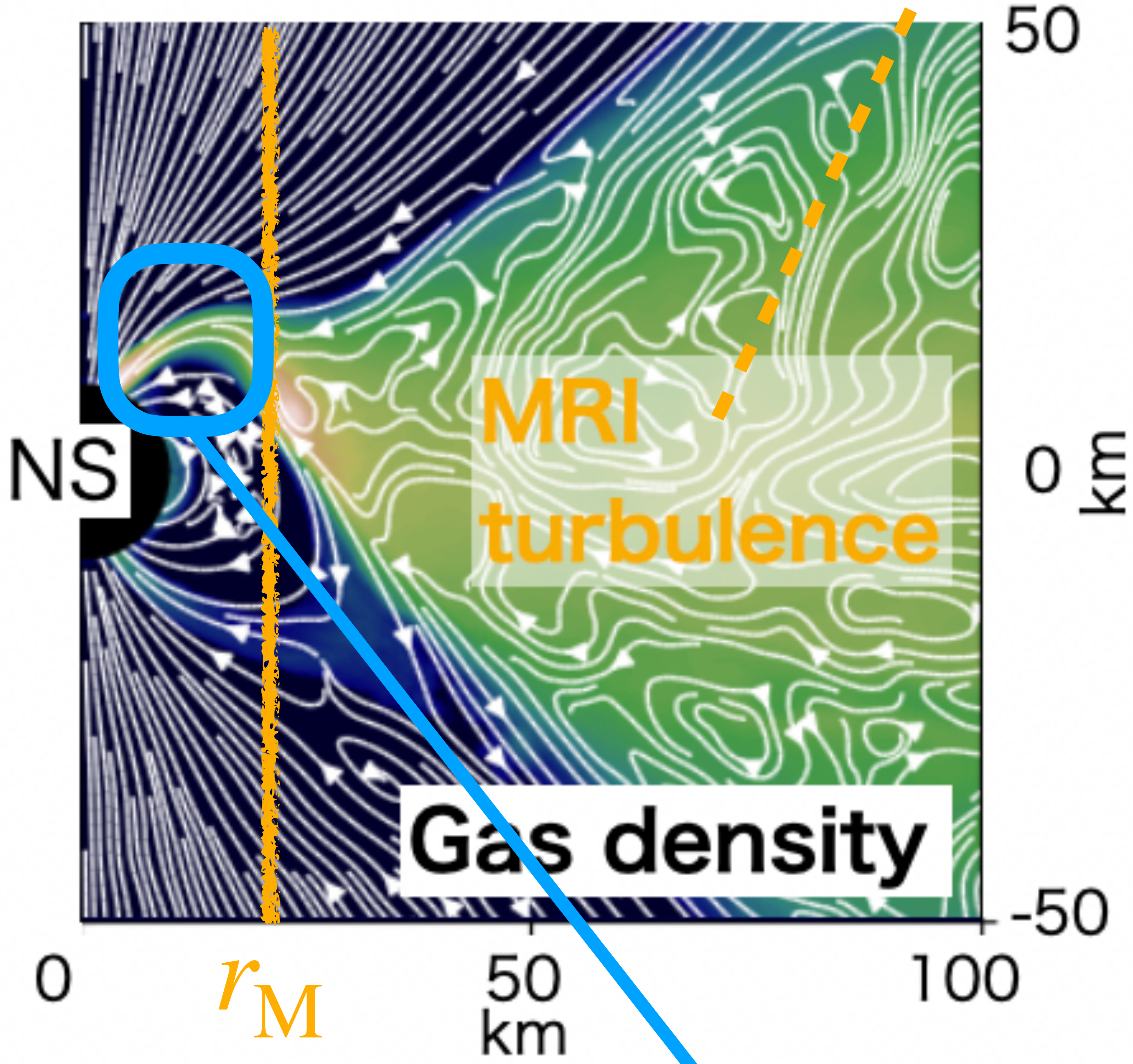
The angular momentum flux $\dot{L}$ and spin-up rate $\dot{P}$

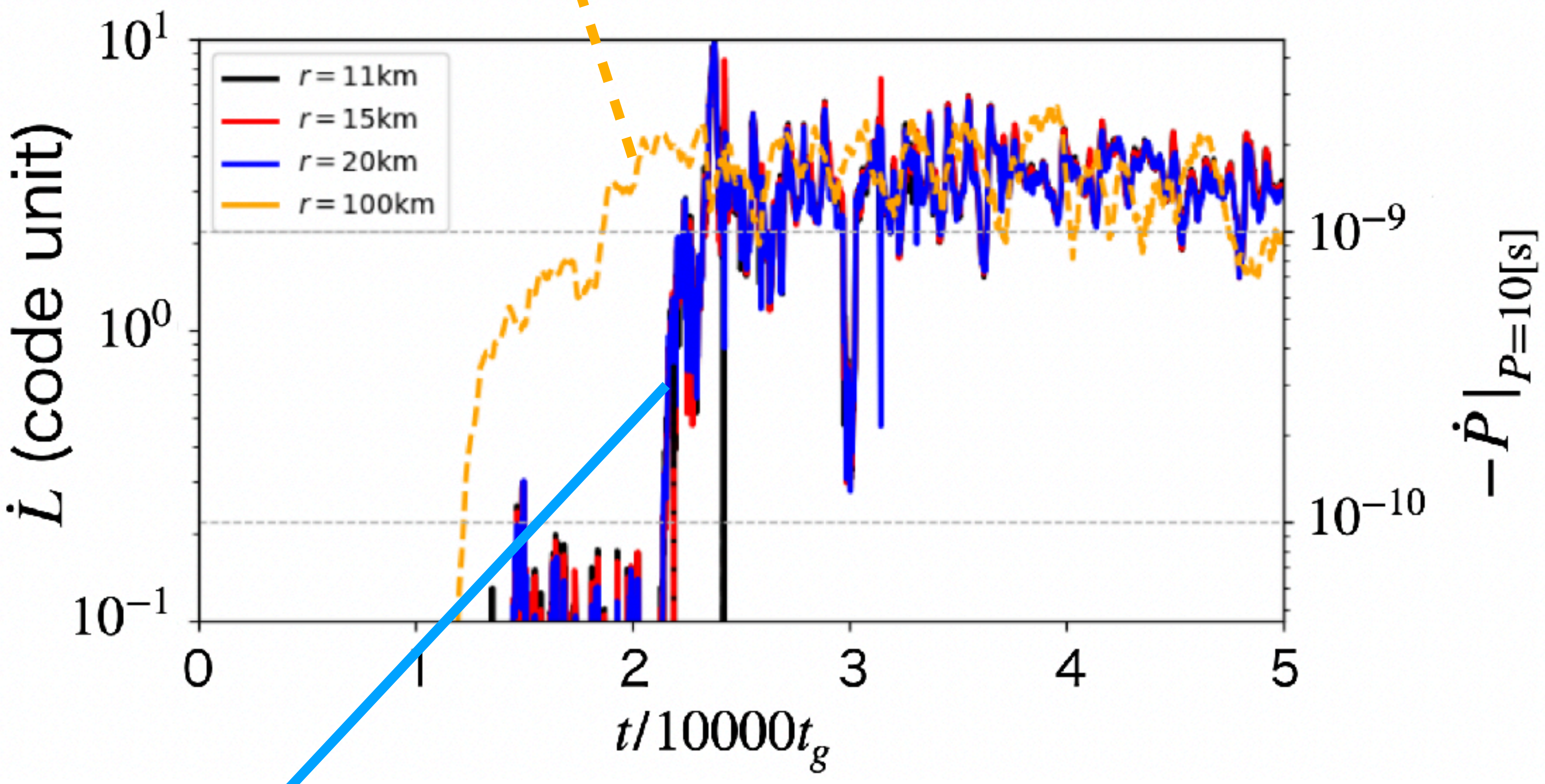
$$\dot{L} = \int T_{\rm EM}{}^{r}{}_{\phi} d\Omega \ , \quad T_{\rm EM}{}^{\mu\nu} = b^2 u^\mu u^\nu + \frac{b^2}{2} g^{\mu\nu} - b^\mu b^\nu \ , \quad \dot{P} = -\frac{\dot{L}}{M_{\rm NS} l_{\rm NS}} P$$

$l_{\rm NS}$: angular momentum of NS
P : rotation period

Outward $\dot{L}$ dominates outside the magnetospheric radius

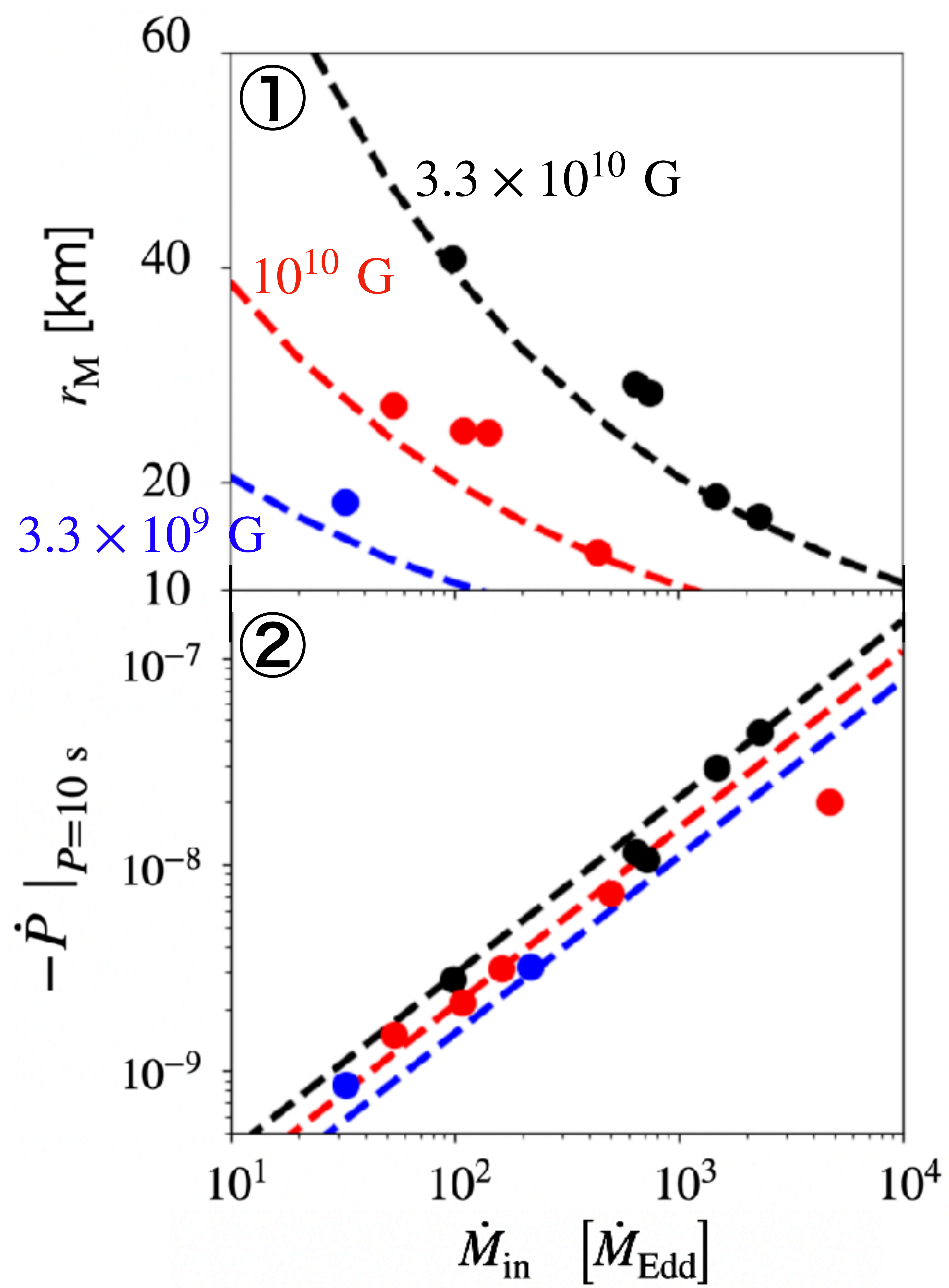
Solid : inward flux
dashed : outward flux





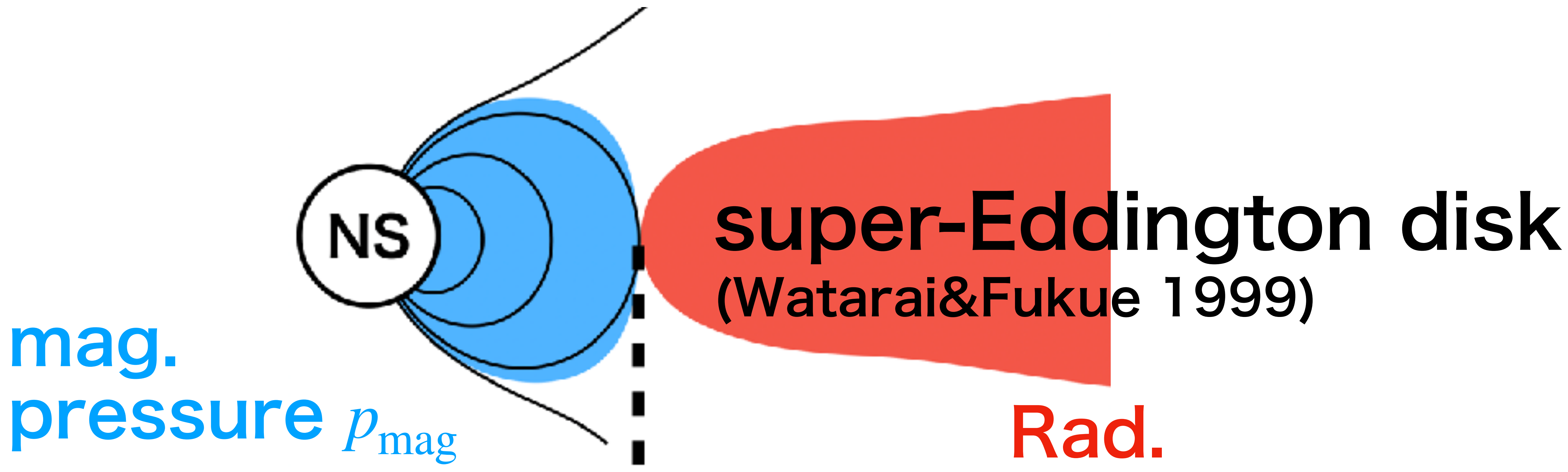
Inside r_M, the inward $\dot{L}$ is dominant. This inward $\dot{L}$ causes NS to spin up.

The comparison between numerical Models and analytical formulas



analytical model (dashed line; Takahashi&Ohsuga 2017)

① At $r = r_M$, p_{mag} balances with p_{rad}



$$r_M \propto \dot{M}_{in}^{-2/7} B_{NS}^{4/7}$$

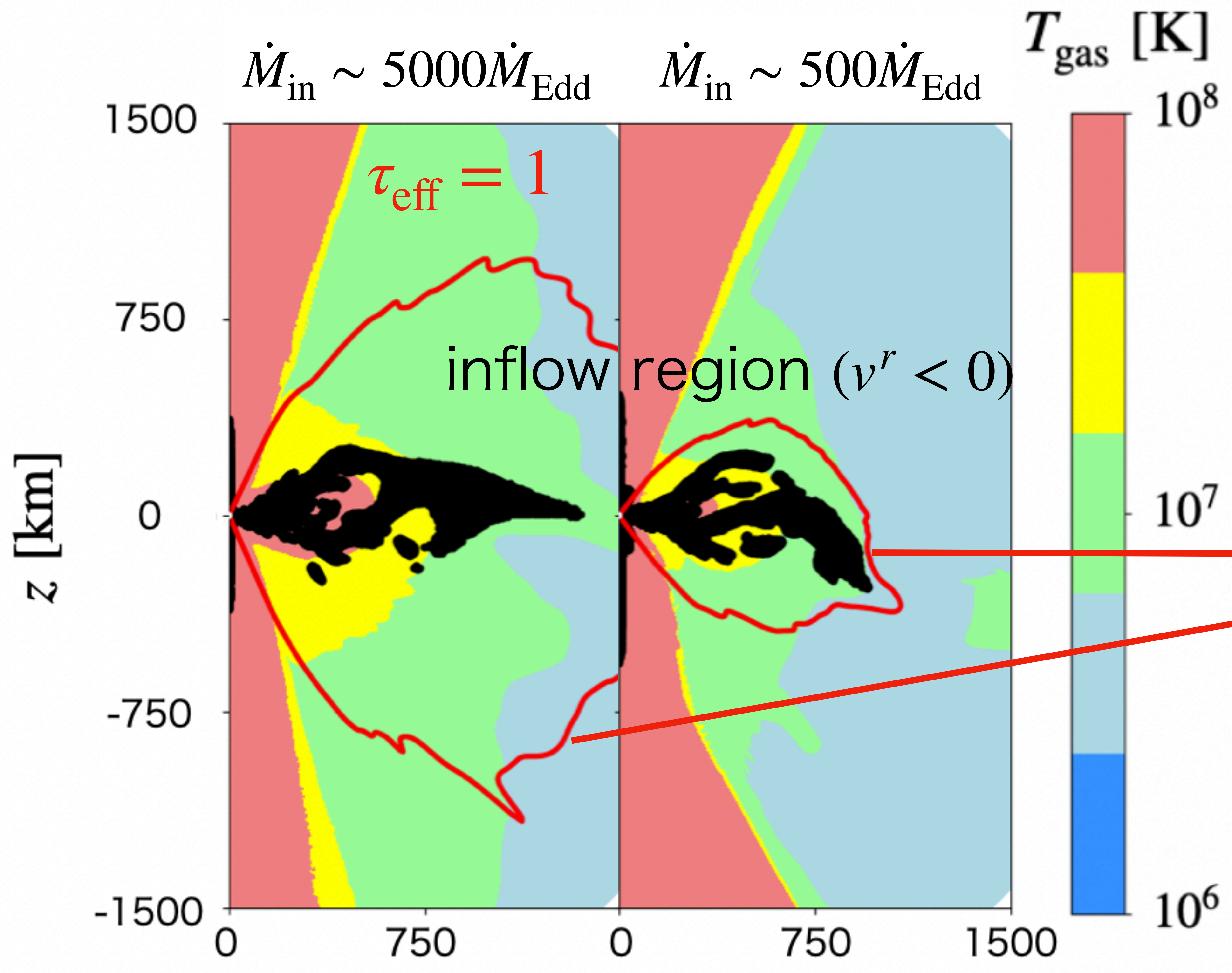
② $-\dot{P} = \dot{M}_{in} l_{Kep}(r_M) \propto \dot{M}_{in}^{6/7} B_{NS}^{2/7} P^2$

Keplerian angular momentum at r_M is transported to NS without dissipation

Resulting r_M and $\dot{P}$ are roughly comparable to analytical model.

Outflows and photospheres

Outflows launched from the accr. disk is effectively optically thick



Effective photosphere

$$\tau_{\rm eff} = \int_r^{r_{\rm out}} \sqrt{\kappa_{\rm abs}(\kappa_{\rm abs} + \kappa_{\rm sca})}\, dr$$

The size of the photosphere increases as $\dot{M}_{\rm in}$ increases

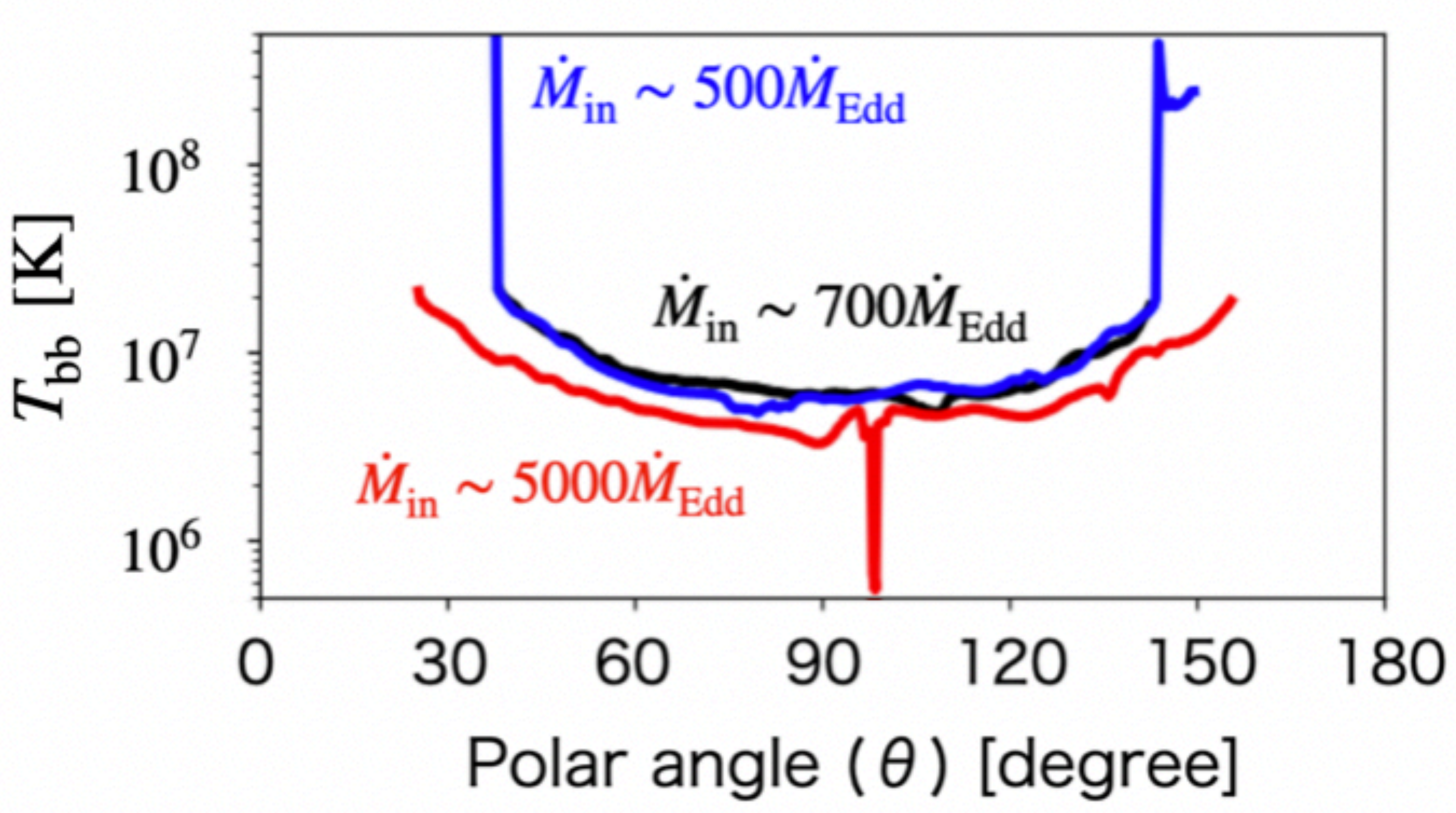
It is expected that blackbody radiation with a temperature of 10^7 K can be observed

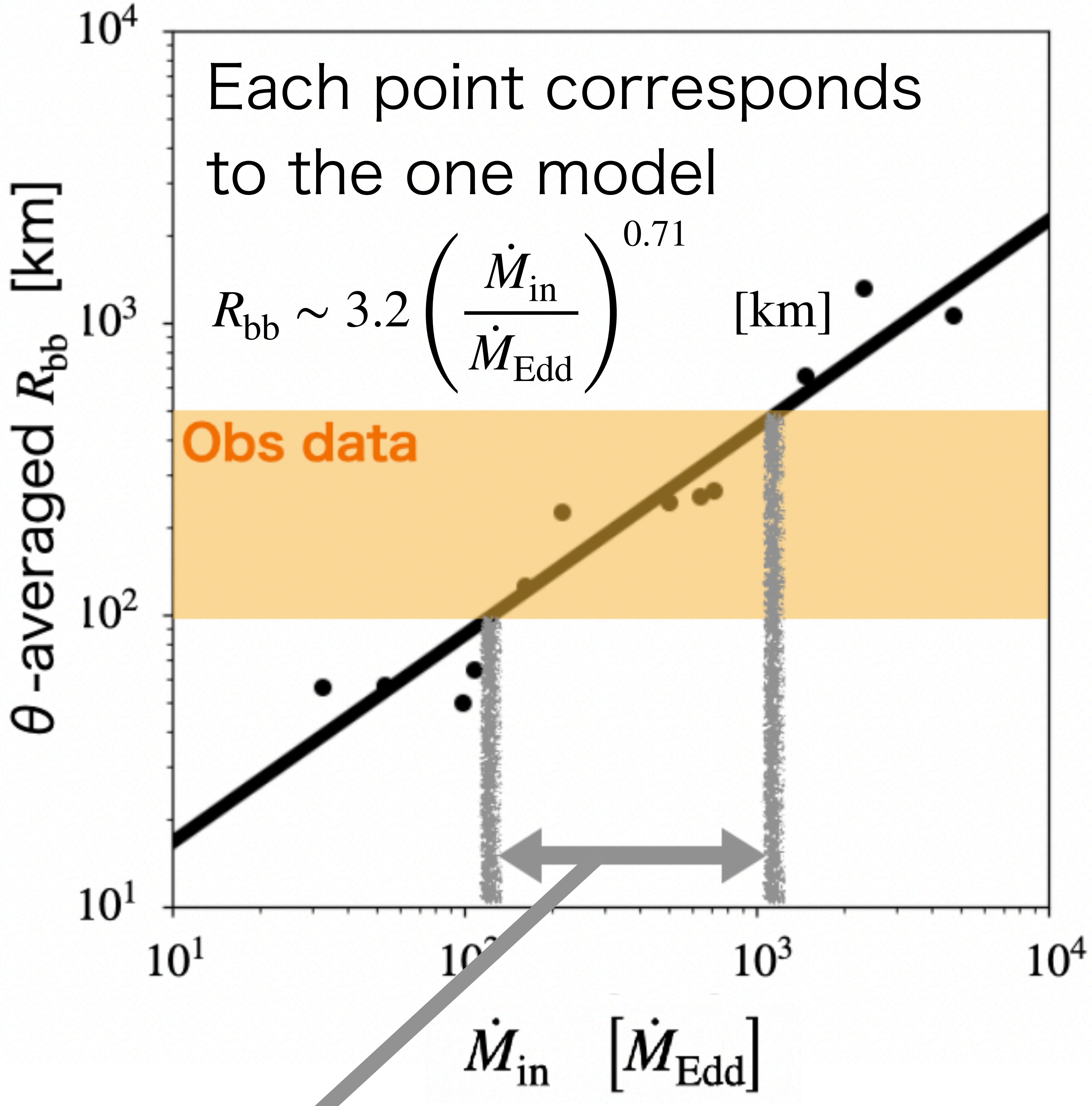
The dependence of the blackbody radius on $\dot{M}_{\rm in}$

Blackbody temperature & radius

$$T_{\rm bb} = T_{\rm gas}(r_{\rm th}) \sim 10^7 \ {\rm K}, \quad R_{\rm bb} = \left(\frac{L_{\rm rad}^{\rm ISO}}{4\pi\sigma T_{\rm bb}^4}\right)^{1/2}$$

$r_{\rm th}$: the radius of the photosphere





$R_{\rm bb} = 100 - 500$ km **can be explained with** $130\dot{M}_{\rm Edd} < \dot{M}_{\rm in} < 1200\dot{M}_{\rm Edd}$

Discussion; magnetic field strength at the NS surface

Magnetospheric radius : $r_M \sim 2.0 \times 10^6$ [cm] $\left(\frac{\dot{M}_{in}}{10^2 \dot{M}_{Edd}}\right)^{-2/7} \left(\frac{B_{NS}}{10^{10}\ G}\right)^{4/7}$

Observable quantities

Spin-up rate : $\dot{P} \sim -2.2 \times 10^{-11}$ [s · s^{-1}] $\left(\frac{\dot{M}_{in}}{10^2 \dot{M}_{Edd}}\right)^{6/7} \left(\frac{B_{NS}}{10^{10}\ G}\right)^{2/7} \left(\frac{P}{1\ s}\right)^{2}$

Mass accretion rate for the thermal emission : $130\dot{M}_{Edd} < \dot{M}_{in} < 1200\dot{M}_{Edd}$

Adapting the observational data of galactic ULX Pulsar ($\dot{P} = 2 \times 10^{-8}$ s s^{-1}, $P = 9.8$ s)

$$10^{10}\ G \lesssim B_{NS} \lesssim 4 \times 10^{12}\ G$$

consistent with the previous study

📍 Using the observed data when the luminosity is below L_{Edd}, we get $3 \times 10^{11}\ G \lesssim B_{NS} \lesssim 4 \times 10^{12}\ G$ (see Inoue et al. 2023 in detail)

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- ☑ The observed thermal emission can be reproduced by optically thick outflow launched from the accr. disk.
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