General relativistic radiation-MHD simulations of supercritical accretion flows and outflows around magnetized neutron stars

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Ultra-Luminous X-ray Sources (ULXs)

Off-nuclear, compact, X-ray sources of which X-ray luminosity exceeds the Eddington luminosity for the stellar mass black holes, $\sim 10^{39}$ erg s^{-1}.

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It has been thought to be either

- **stellar mass black hole + Supercritical accretion**
  (King+2001, Watarai+2001, ・・・)

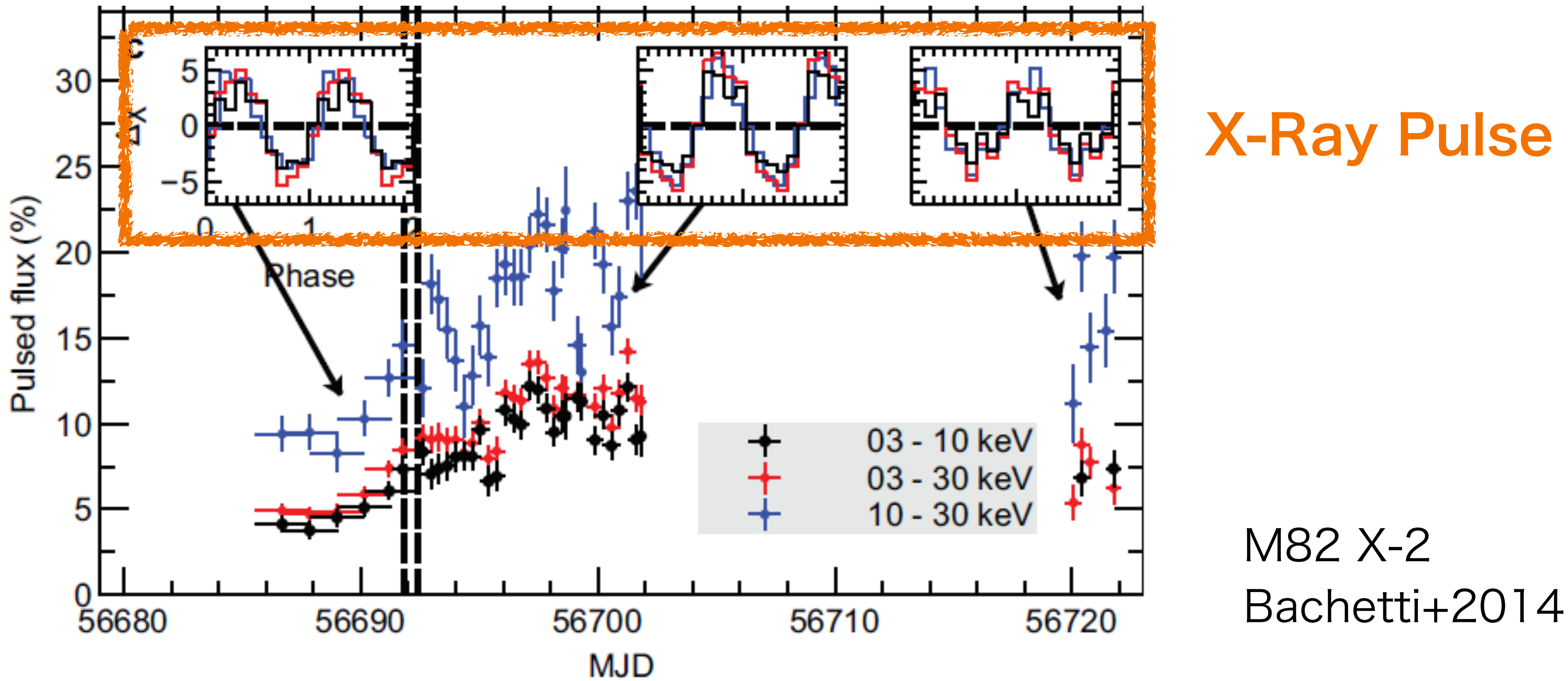
or

- **Intermediate-mass black hole + Sub-Eddington accretion**
  (Colbert & Mushotzky 1999, Makishima+2000, ・・・)

However, it has not been settled yet . . .

Ultra-Luminous X-ray Pulsar (ULX Pulsar)

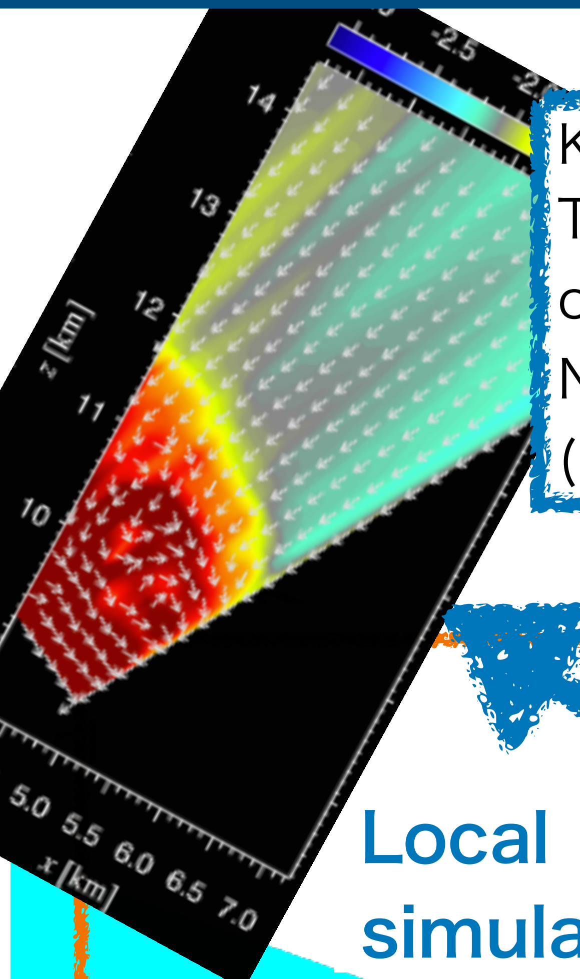
The central objects of some ULXs turned out to be neutron stars (NSs) since recent X-ray observations detected the pulsed emission.



M82 X-2
Bachetti+2014

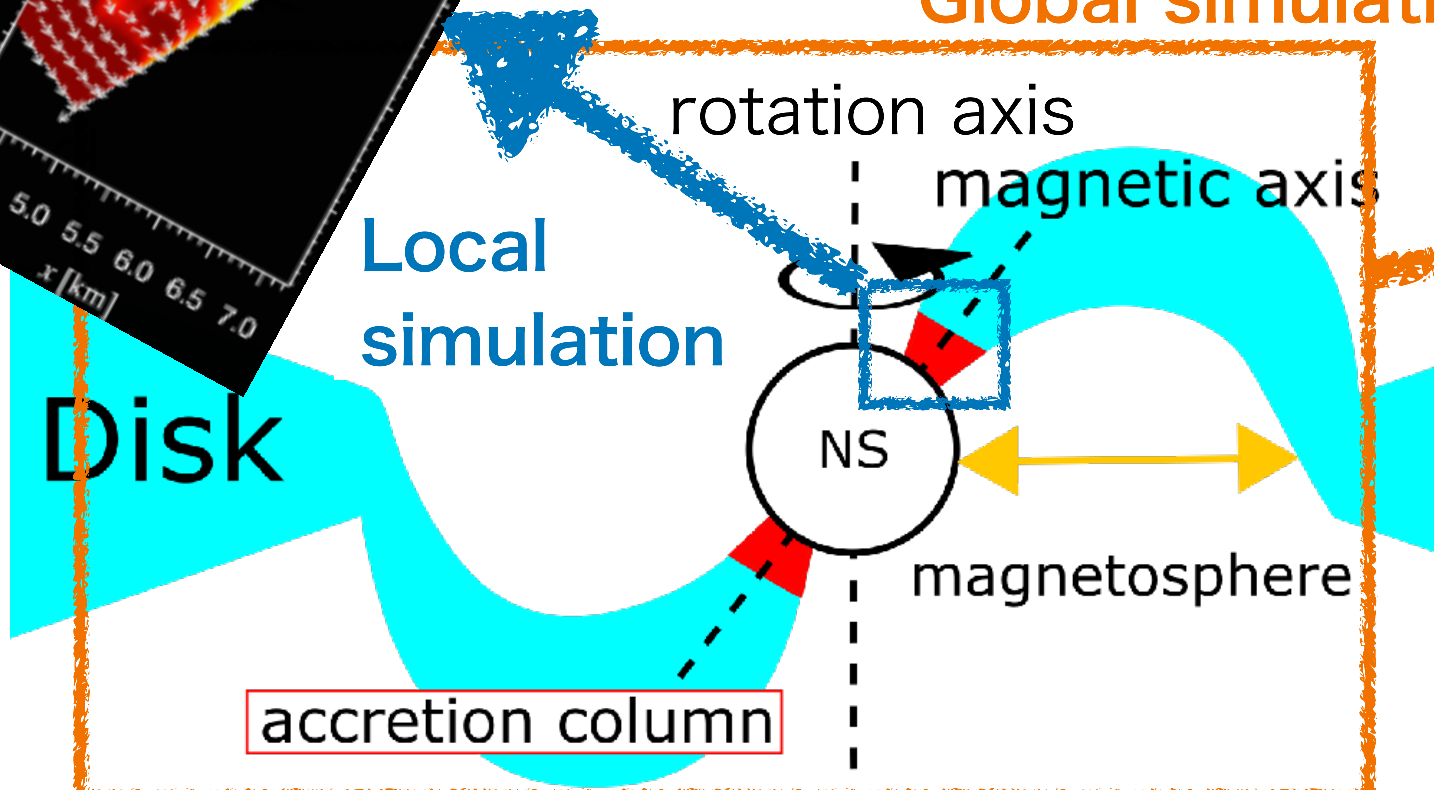
- The mass of an NS is $(1.4-3)M_{\odot}$, and therefore the matter should accrete at the **supercritical rate** where the mass accretion rate exceeds the critical mass accretion rate, $\dot{M}_{\rm Edd} \sim 10^{17}$ g s^{-1}.
- There are still debates on the magnetic field strength in ULX Pulsars, from 10^{10} G (see e.g., King + 2017) to 10^{15} G (see e.g., Mushtukov+2015).

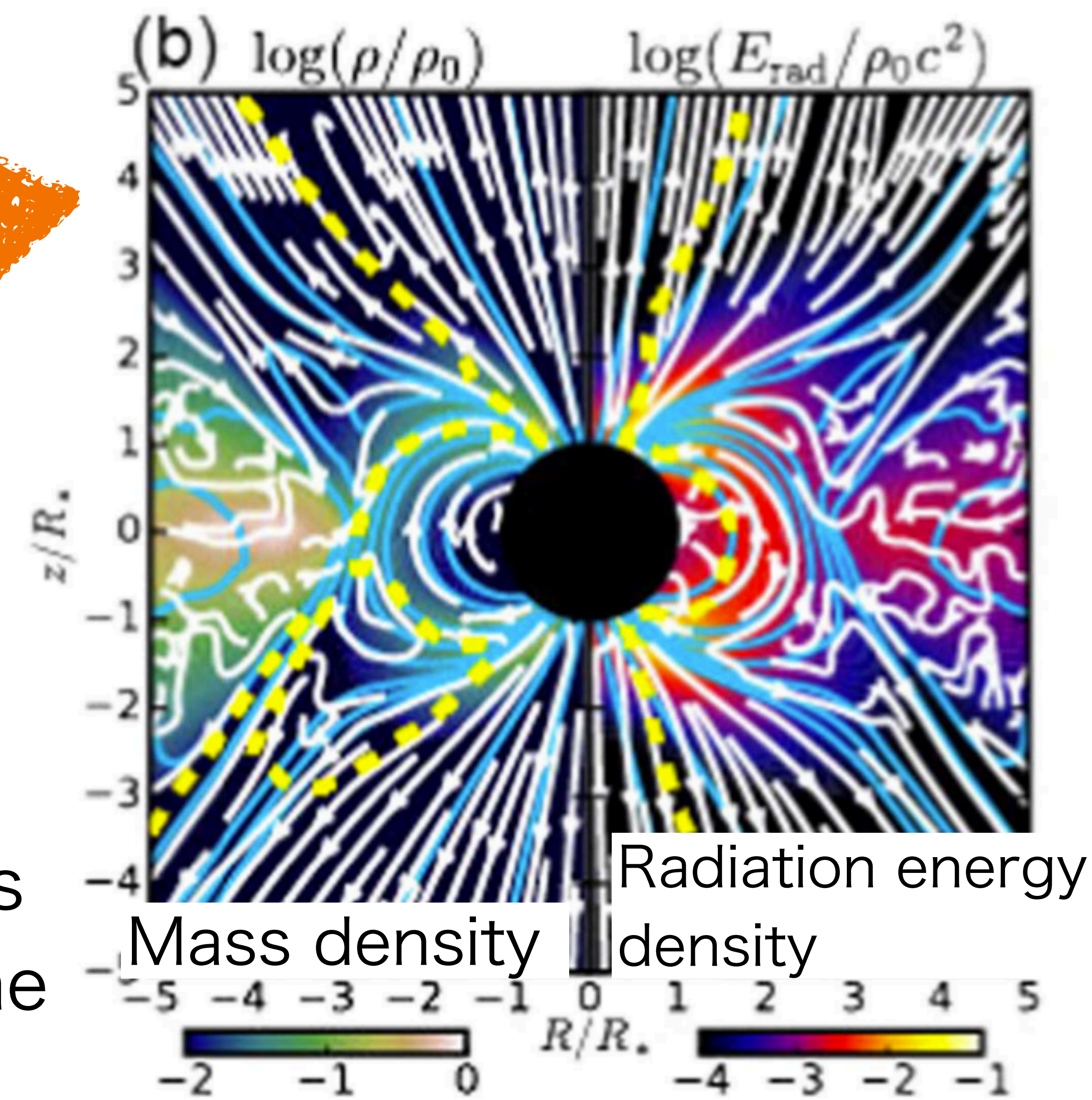
Numerical Simulations around magnetized NSs



Kawashima+2016
They showed that the luminosity of side wall of the column near the NS exceeds the critical luminosity (Eddington luminosity).

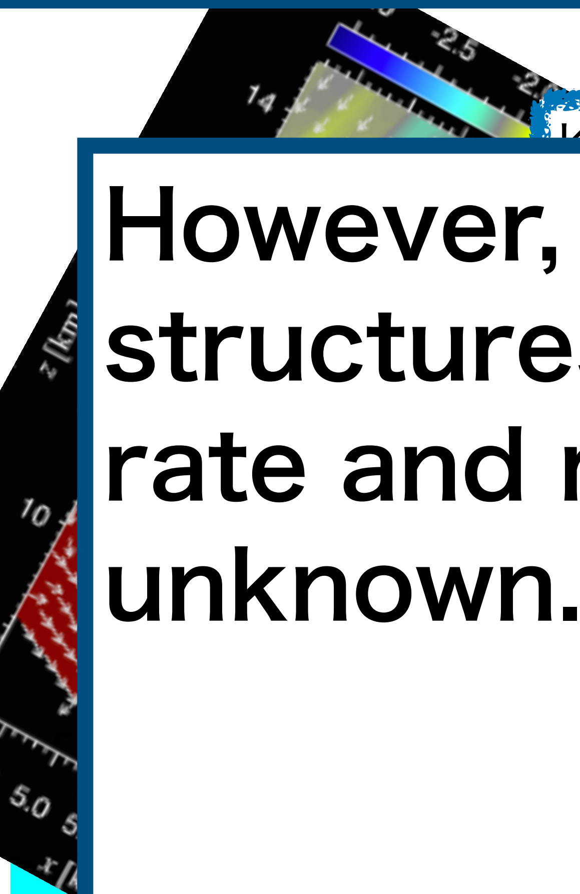
Takahashi & Ohsuga 2017
They showed that the supercritical accretion disk was truncated by the dipole magnetic field of a neutron star, and formed the accretion columns on the magnetic poles.





The magnetic field strength and the mass accretion rate of a neutron star determine the magnetospheric structure.

Numerical Simulations around magnetized NSs



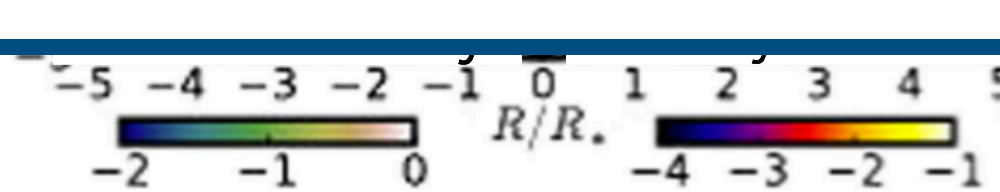
Kawashima 2016

However, the dependence of magnetospheric structures and outflows on the mass accretion rate and magnetic field strength of the NS is still unknown.

↓

We perform General Relativistic Radiation-MHD (GR-RMHD) simulations of supercritical accretion flows onto the magnetized neutron stars, and investigate the magnetospheric structure and outflows.

accretion rate of a neutron star determine
the magnetosphere structure.



GR-RMHD equation

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, synchrotron opacity

$\kappa_{\rm sca}$ 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

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

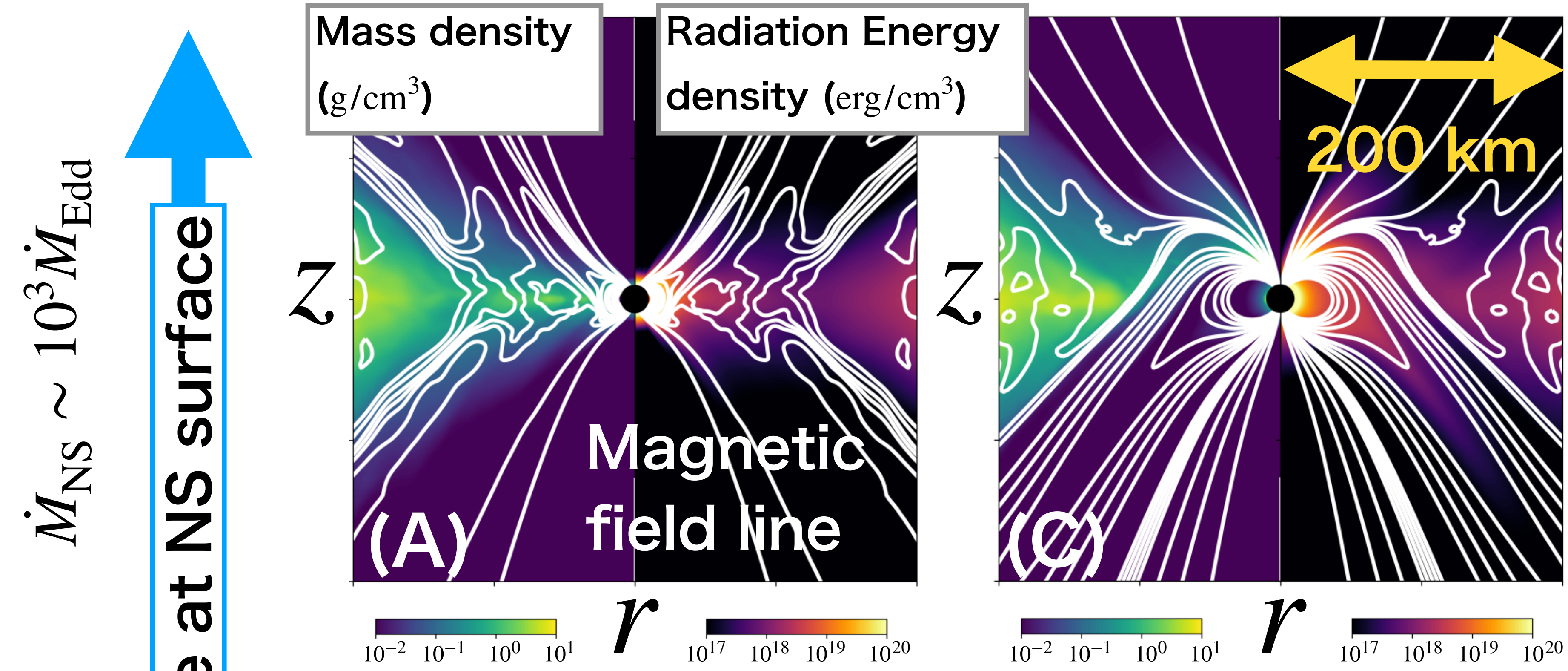
Radiation four force $G^\mu=-\rho\kappa_{\rm abs}\left({R^\mu}_\alpha u^\alpha+4\pi\hat{B}u^\mu\right)-\rho\kappa_{\rm sca}\left({R^\mu}_\alpha u^\alpha+{R^\alpha}_\beta u_\alpha u^\beta u^\mu\right)+{G^\mu}_{\rm comp}$

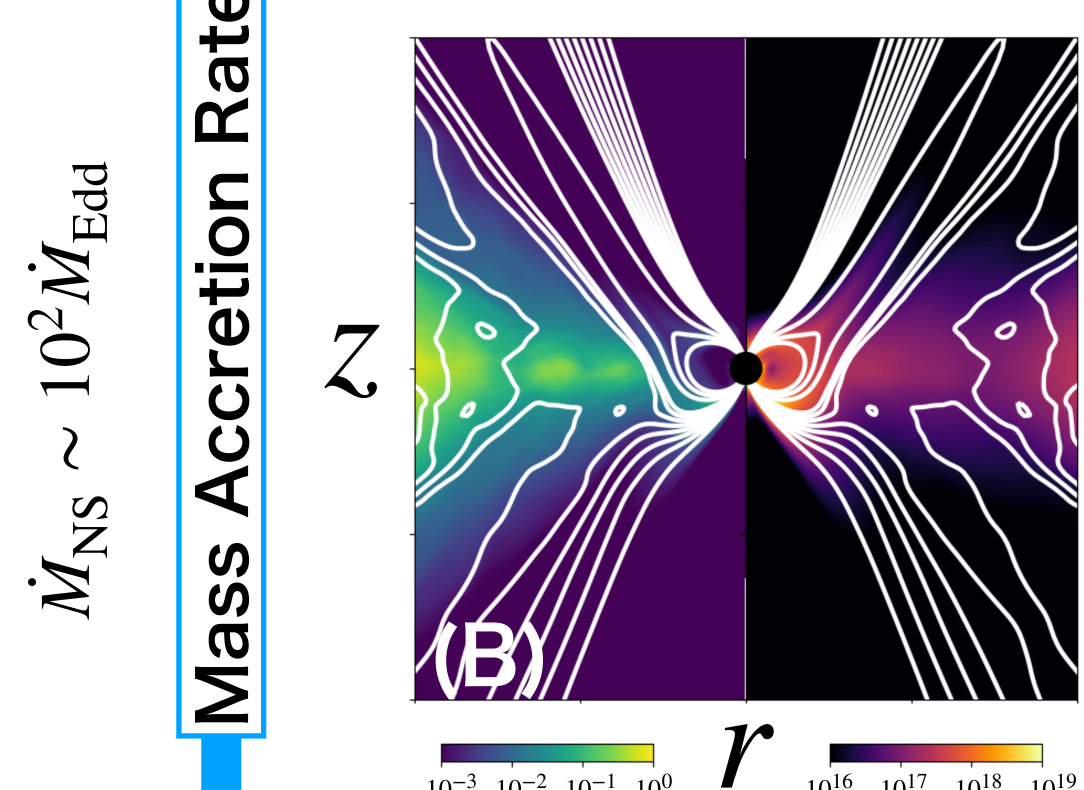
M1-closure $R^{\mu\nu}=\frac{4}{3}\bar{E}_R {u_R}^\mu {u_R}^\nu+\frac{1}{3}\bar{E}_R g^{\mu\nu}$

Sadowski+ 2013, 2014

- Boyer-Lindquist Metric
- Mass and radius of the NS are $1.4\ M_\odot$ and 10km, respectively
- The NS has the magnetic dipole filed
- spin parameter is set to be zero.
- The magnetic axis coincides with the rotation axis (Axisymmetric structure).

The dependence of magnetospheric radius on the mass accretion rate and the magnetic field strength of NSs





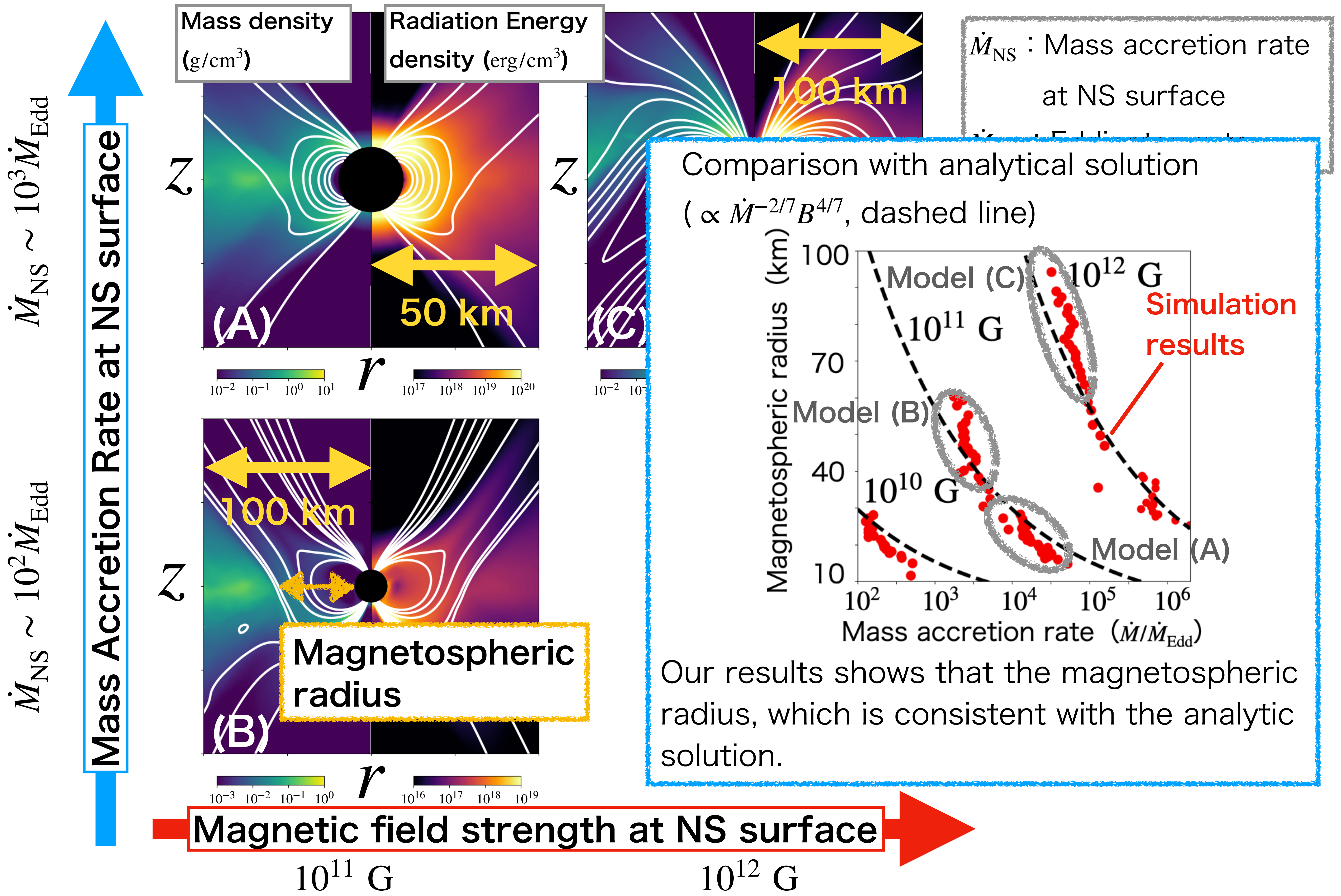
$\dot{M}_{NS}$: Mass accretion rate at NS surface

$\dot{M}_{Edd}$: Critical mass accretion rate, $\sim 10^{17}$ g s^{-1}

the accretion disk is truncated by dipole magnetic field of NS.

Magnetosphere of the NS becomes large (small) in the case of small (large) accretion rate and strong (weak) magnetic field.

The dependence of magnetospheric radius on the mass accretion rate and the magnetic field strength of NSs (Enlarged View)



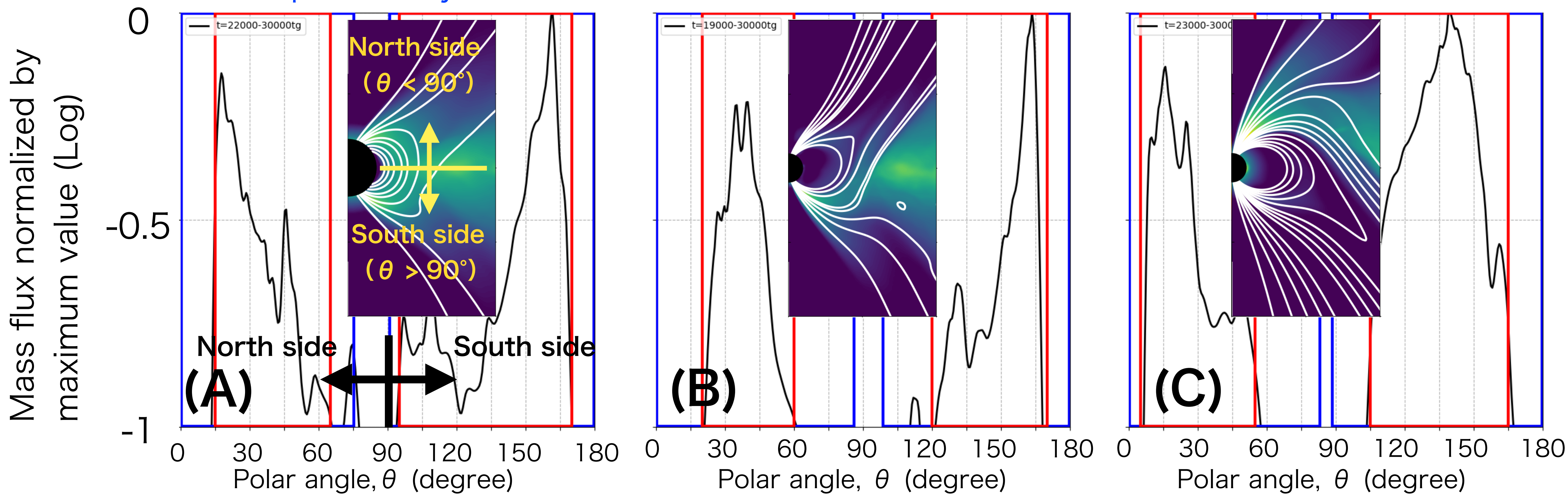
Our results shows that the magnetospheric radius, which is consistent with the analytic solution.

The dependence of outflows on magnetospheric structures

These figure show the time averaged mass flux of each models at r = 2000 km.

The blue frame shows the region where the velocity of gases exceeds the escape velocity

The red frame shows the region where the mass flux is larger than 10% of maximum value (Outflow region).



The side where the accretion column is formed：

The peak of outflow, θ_{peak}, is near the rotation axis.

Offset angle between rotation axis and θ_{peak} is about 15°.

The side where the accretion column is not formed (model B and C)：

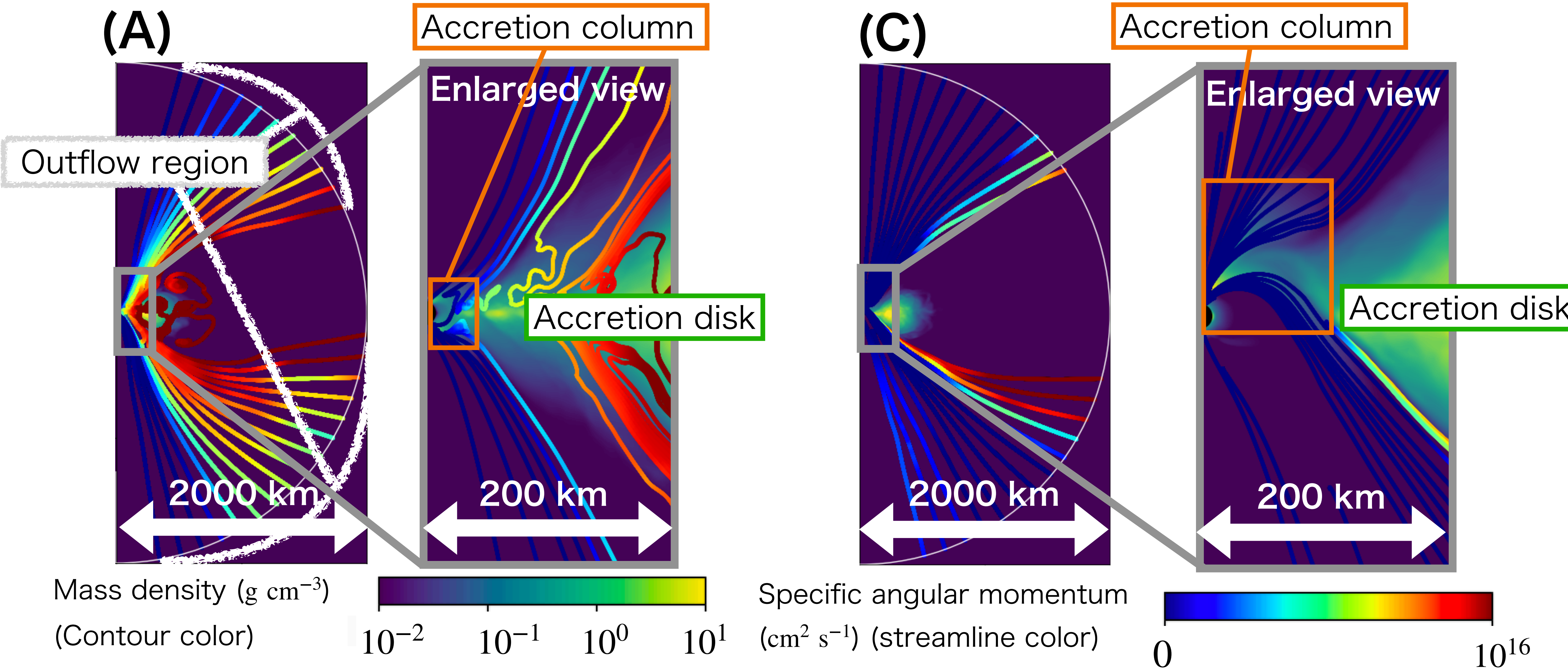
Outflow extends to the relatively wide angle away from the rotation axis.

Offset angle between rotation axis and θ_{peak} is >30°.

We define the region surrounded by the red frame as outflow region.

The origin of outflows depends on magnetospheric structures

The lines indicate the streamlines of the outflow regions. The color of the lines means the specific angular momentum of the outflowing matter.



Model A (small magnetosphere)

The outflow with larger angular momentum is originated from the disk (see red lines) and the matter comes from the accretion columns has smaller angular momentum (blue lines).

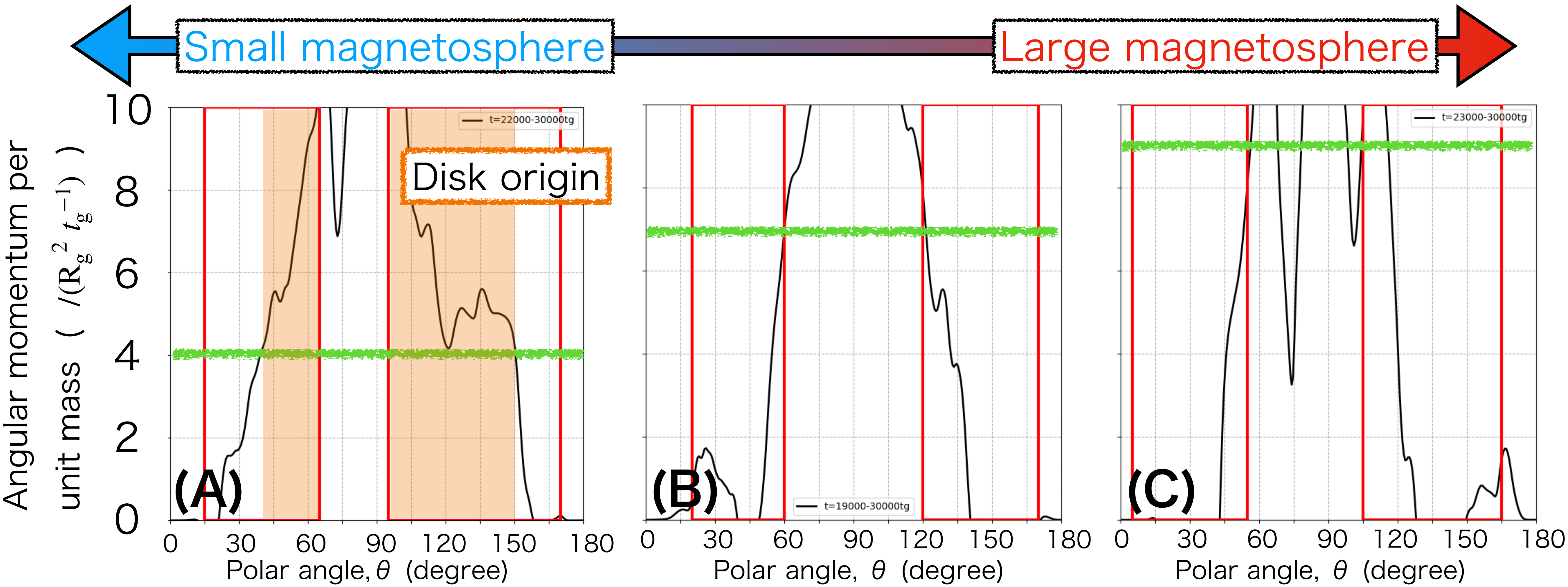
Model C (large magnetosphere)

Most of the outflowing matter has small angular momentum and is launched near the accretion column.

The dependence of components of outflows on magnetospheric structures

The red frame shows the Outflow region.

Angular momentum profiles of outflows at r = 2000km.



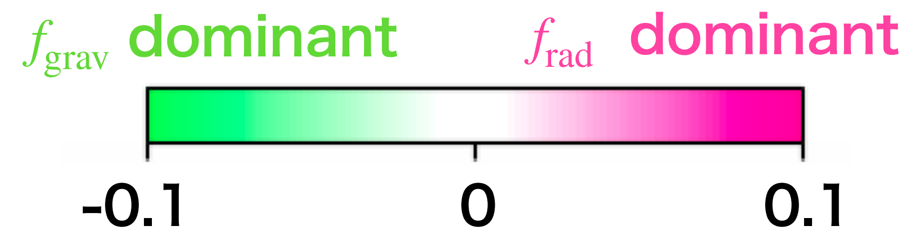
Green line shows the Keplerian angular momentum at the magnetospheric radius.

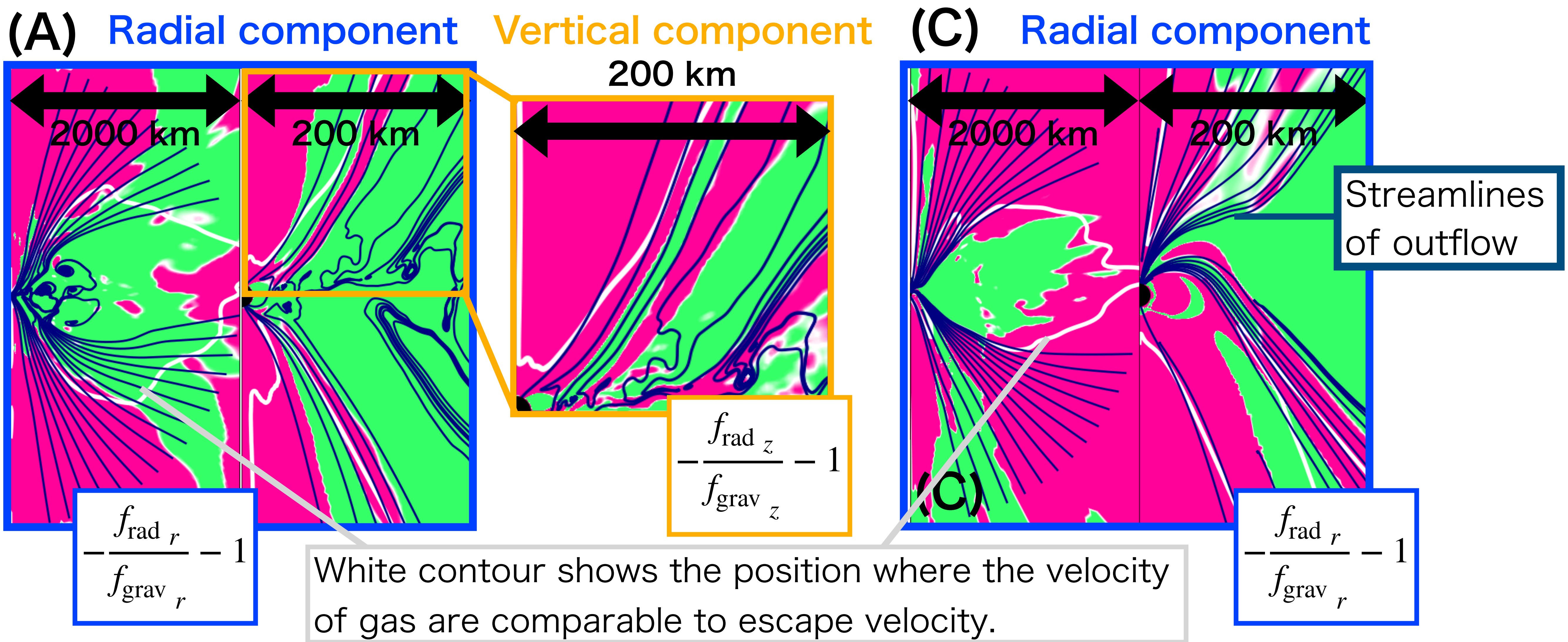
- In the model A, outflows in 40°< θ <65° and 95°< θ <150° may be disk origin since the angular momentum is larger than Keplerian angular momentum at the magnetospheric radius.
- In the model B and C (Large magnetosphere case), the angular momentum of the gas is small, and therefore most of the components of outflows may come from inside the magnetosphere, probably accretion column (see previous slide).

$R_g \sim 2.1 \times 10^5$ cm, $t_g \sim 7 \times 10^{-6}$ s

What are outflows driven by ?

We compared the radiation force $f_{\rm rad}$ and gravitational force $f_{\rm grav}$.





- **In the magenta region**, the radiation force becomes larger than the gravitational force.
- Outflow may be mainly driven by radiation force.

Summary

We performed General-Relativistic Radiation MHD simulation of supercritical accretion flows onto the magnetized neutron stars.

The resulting magnetospheric radius roughly depends on the mass accretion rate and the strength of the magnetic fields as ($\propto \dot{M}^{-2/7}B^{4/7}$), which is consistent with the analytic solution.

The structure of the outflow and accretion column depend on the magnetospheric radius.

Small magnetosphere case

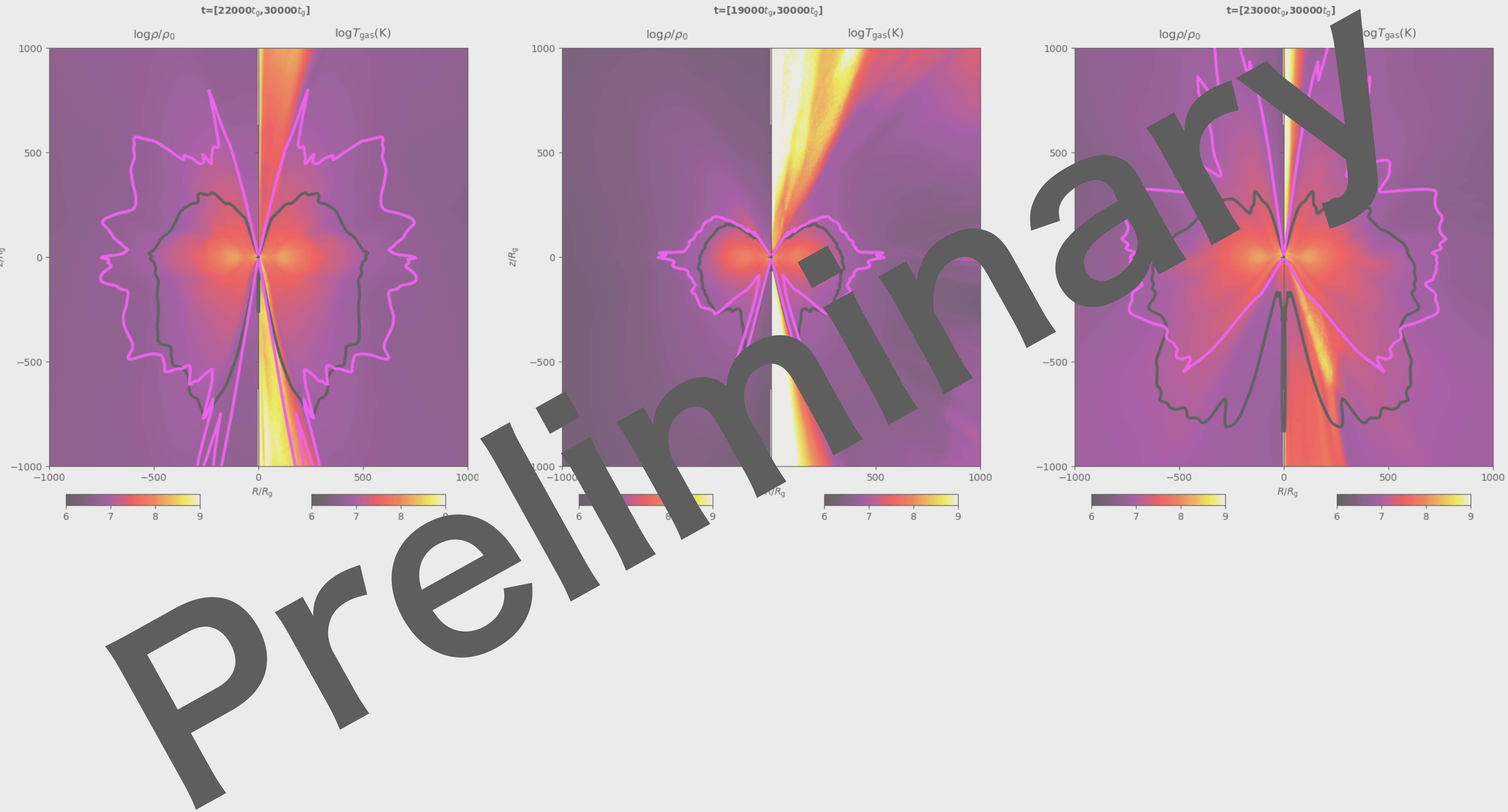
- Accretion columns form at both the north and south poles.
- Outflowing matter comes from both the disk and the accretion columns.

Large magnetosphere case

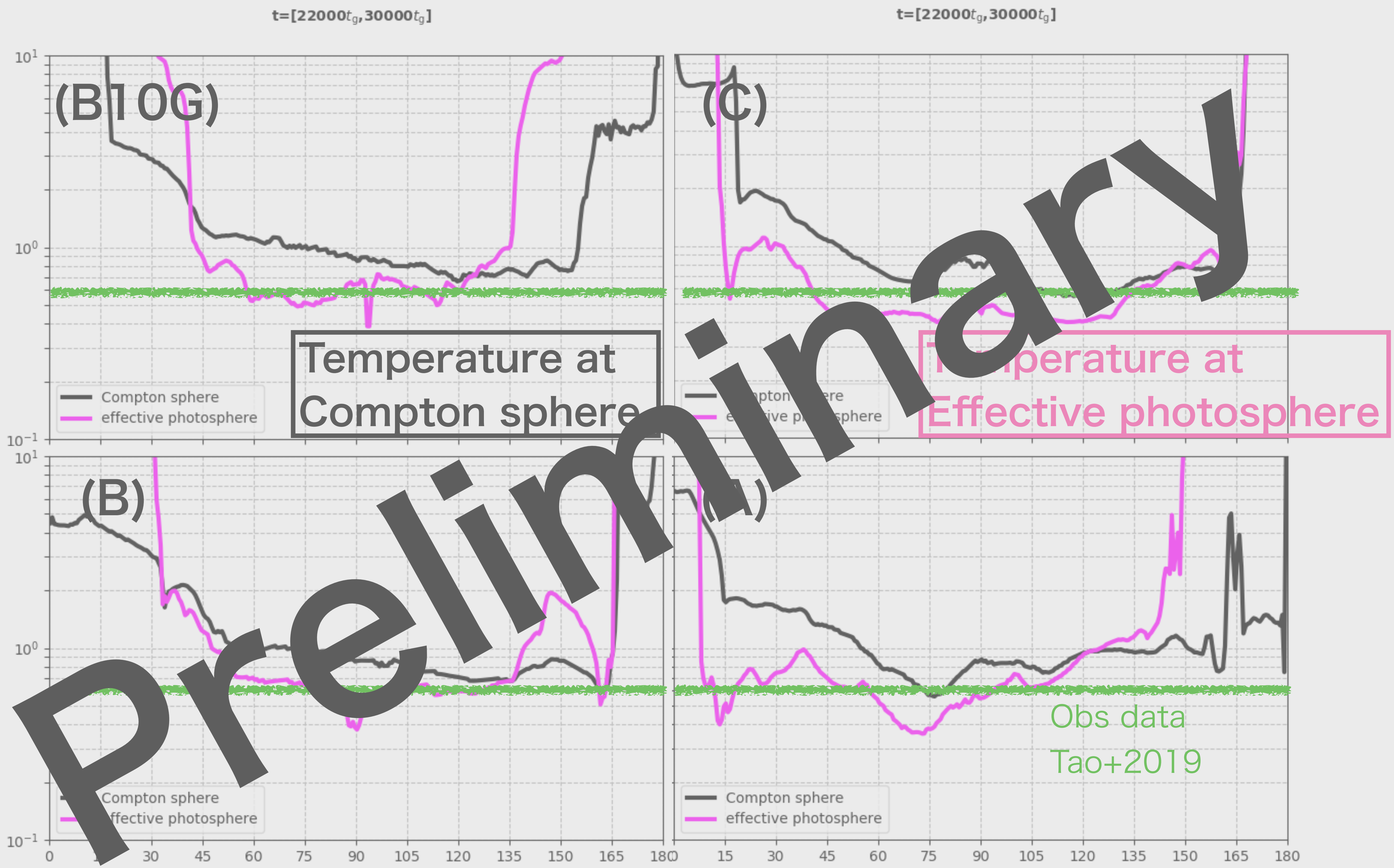
- Accretion column forms at either the north or south poles.
- Matter of the outflows is launched at the accretion column.

Outflow is probably driven by radiation force.

Effective photosphere and Compton sphere



Outflow temperature



Resulting gas temperatures are consistent with observed outflow temperature

Outflow velocity