Relativistic radiation magnetohydrodynamic simulations of accretion disks

~Accretion to Black Hole and Neutron Star~

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Outlines

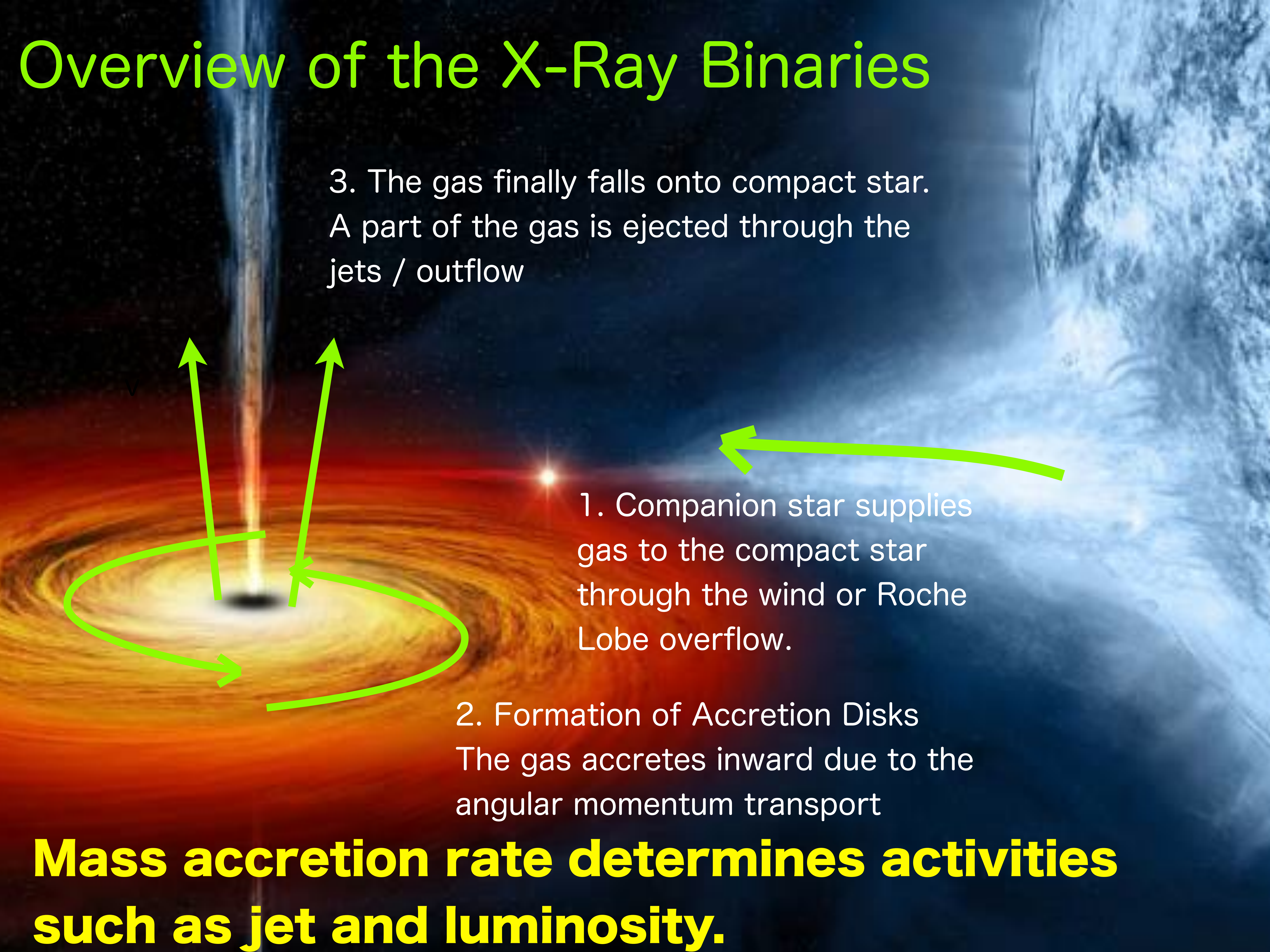
1. Formation processes of jets from BH accretion disk

radiatively accelerated outflow from supercritical accretion disks and standard disks

2. Accretion to Neutron star

Neutron star can be more powerful than black hole?

Overview of the X-Ray Binaries



3. The gas finally falls onto compact star.
A part of the gas is ejected through the jets / outflow

1. Companion star supplies gas to the compact star through the wind or Roche Lobe overflow.

2. Formation of Accretion Disks
The gas accretes inward due to the angular momentum transport

Mass accretion rate determines activities such as jet and luminosity.

Is the supercritical Accretion feasible?

Supercritical Accretion:

Accretion rate exceeds the Eddington limit.

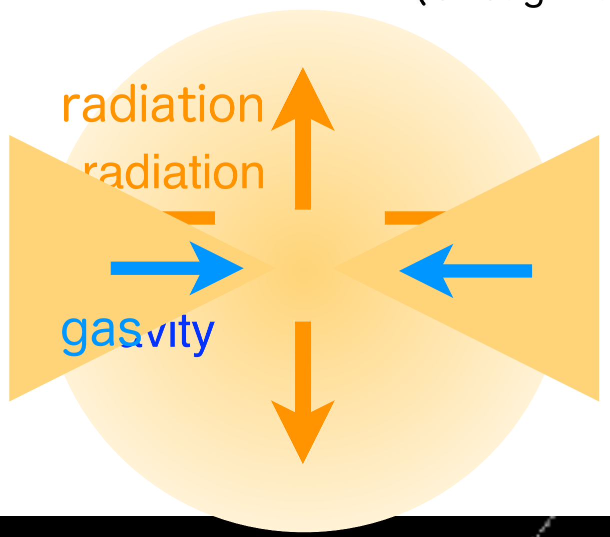
Consider the spherical accretion to the compact star.

And the the central star irradiates the accreting gas.

Radiation force < Gravity force

$$\frac{L}{4\pi r^2 c}\sigma_T < \frac{G M_{\rm BH} m_p}{r^2}$$

(Ohsuga '05, '09)



gravity > radiation, gas accretes towards the star.

gravity < radiation, gas is blown away.

Eddington luminosity

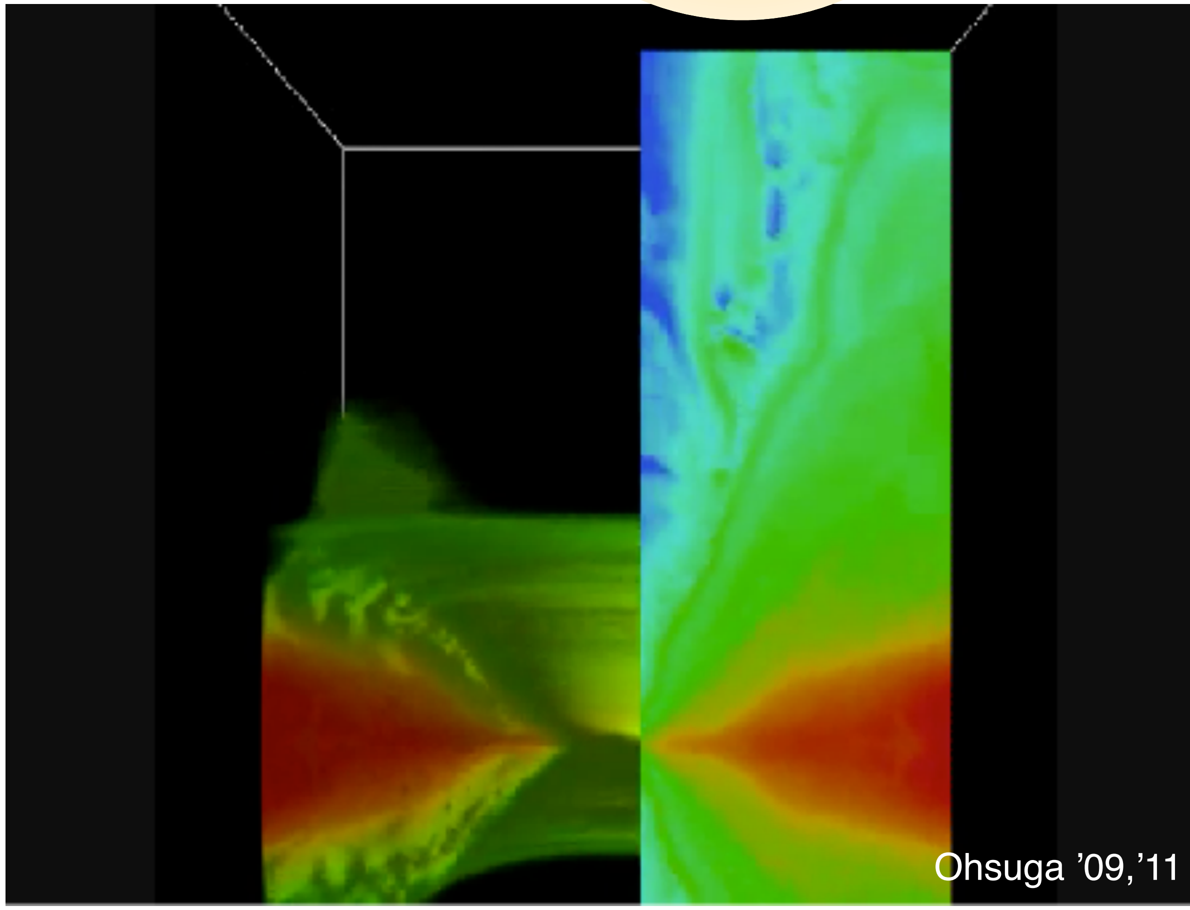
$$L < L_E = \frac{4\pi G M_{\rm BH} m_p c}{\sigma_t}$$

$$= 1.3 \times 10^{38} \left(\frac{M_{\rm BH}}{10 M_\odot}\right) \ {\rm erg\ s^{-1}}$$

This source is powered by mass accretion, we can compute the corresponding mass accretion rate

Critical Accretion rate

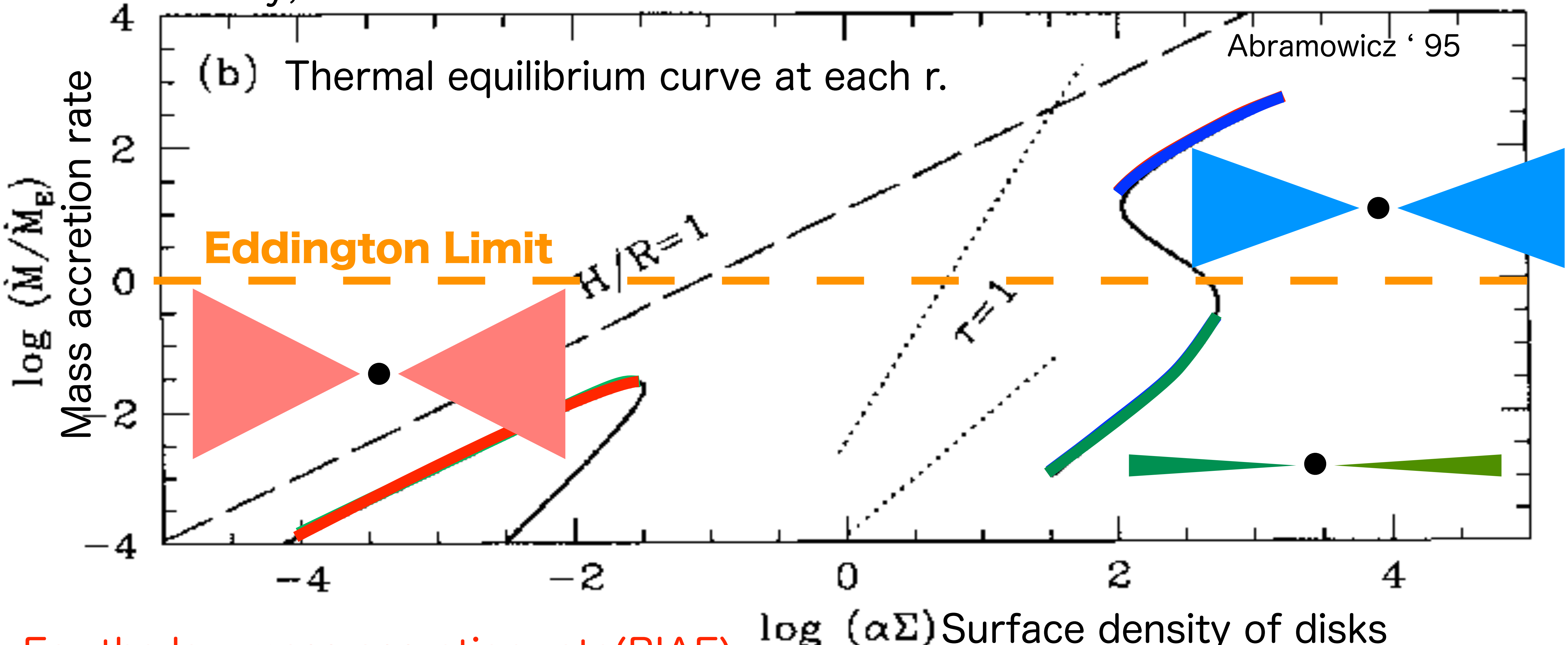
$$\dot{M}_{\rm crit} = L_{\rm E}/c^2 = 1.4 \times 10^{18} \left(\frac{M}{10 M_\odot}\right) \ {\rm g\ s^{-1}}$$



Supercritical accretion would be possible for black hole.

Three States of Accretion Disks

Theoretically, there are three distinct accretion modes.



For the low mass accretion rate(RIAF),

optically thin, geometrically thick disk → Low hard state/LLAGN

For the middle mass accretion rate(Standard Disks),

optically thick, geometrically thin -> High soft state/Seyfert

For the high mass accretion rate (Slim Disks/ Supercritical Accretion Disks),

optically thick, geometrically thick -> ULX?/NLSI

Disk state changes according to the mass accretion rate.

How the jet is accelerated?

There are two models for explaining jet acceleration

MHD model

Blandford & Payne 1982, Uchida & Shibata '85
Shibata & Uchida '86,Kudoh & Shibata '97

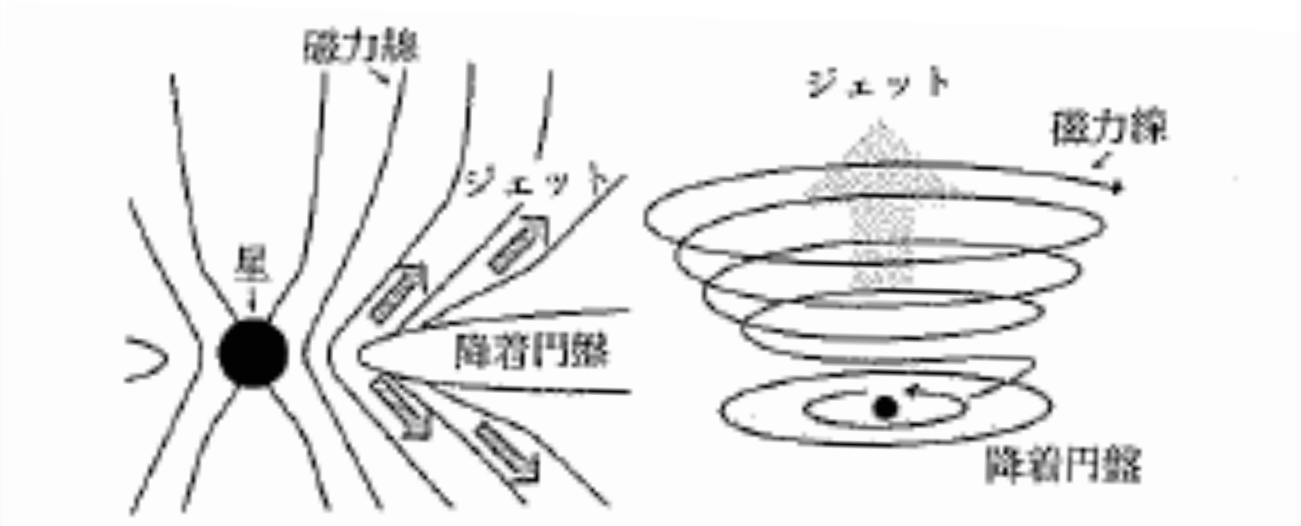


図 10.2 降着円盤から噴出する磁気流体ジェットの模式図．左：子午面内での断面図．右：磁力線を立体的に描いたもの

Jet is accelerated by the magnetic pressure or the magnetocentrifugal force.

The jet acceleration is well studied using MHD simulations.

Expected in RIAF state

rad. model

Lynden-Bell'81, Sikora & Wilson '81, Calvani & Nobili '83, Eggum '85, Tajima & Fukue '96

acc. : rad. force
coll. : radiation drag
←relativistic effect (v/c)

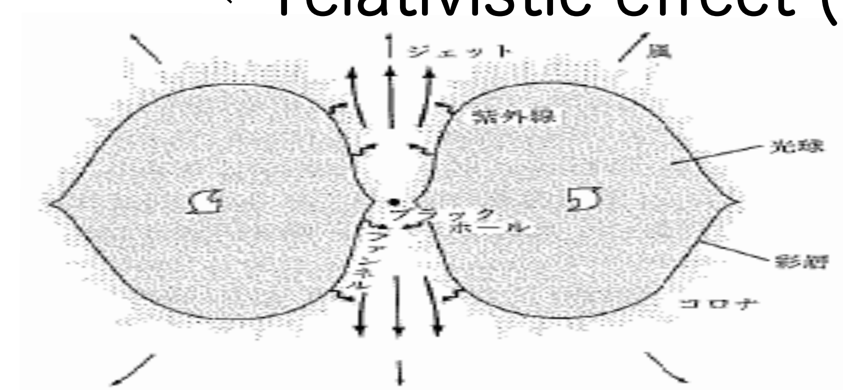


図 9.14 降着トーラスとファンネル

Jet is accelerated by the radiation pressure force.
This process works when the accretion rate is high (radiation pressure dominate).
This model is not well understood.

Expected in Slim disk?

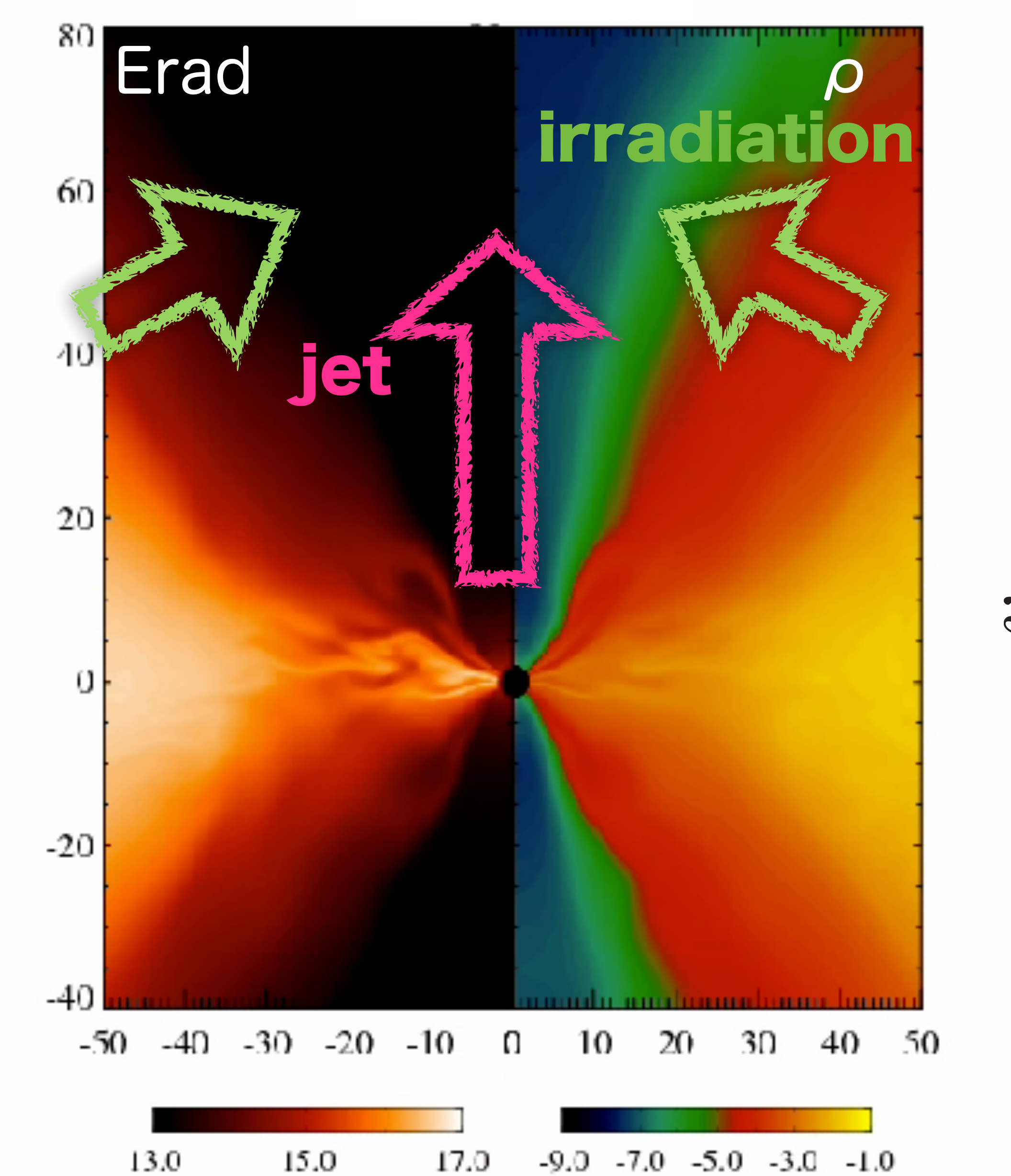
Which model is feasible for jet formation from supercritical accretion disks? Radiation MHD simulation is necessary.

Jets from Supercritical Accretion Disks

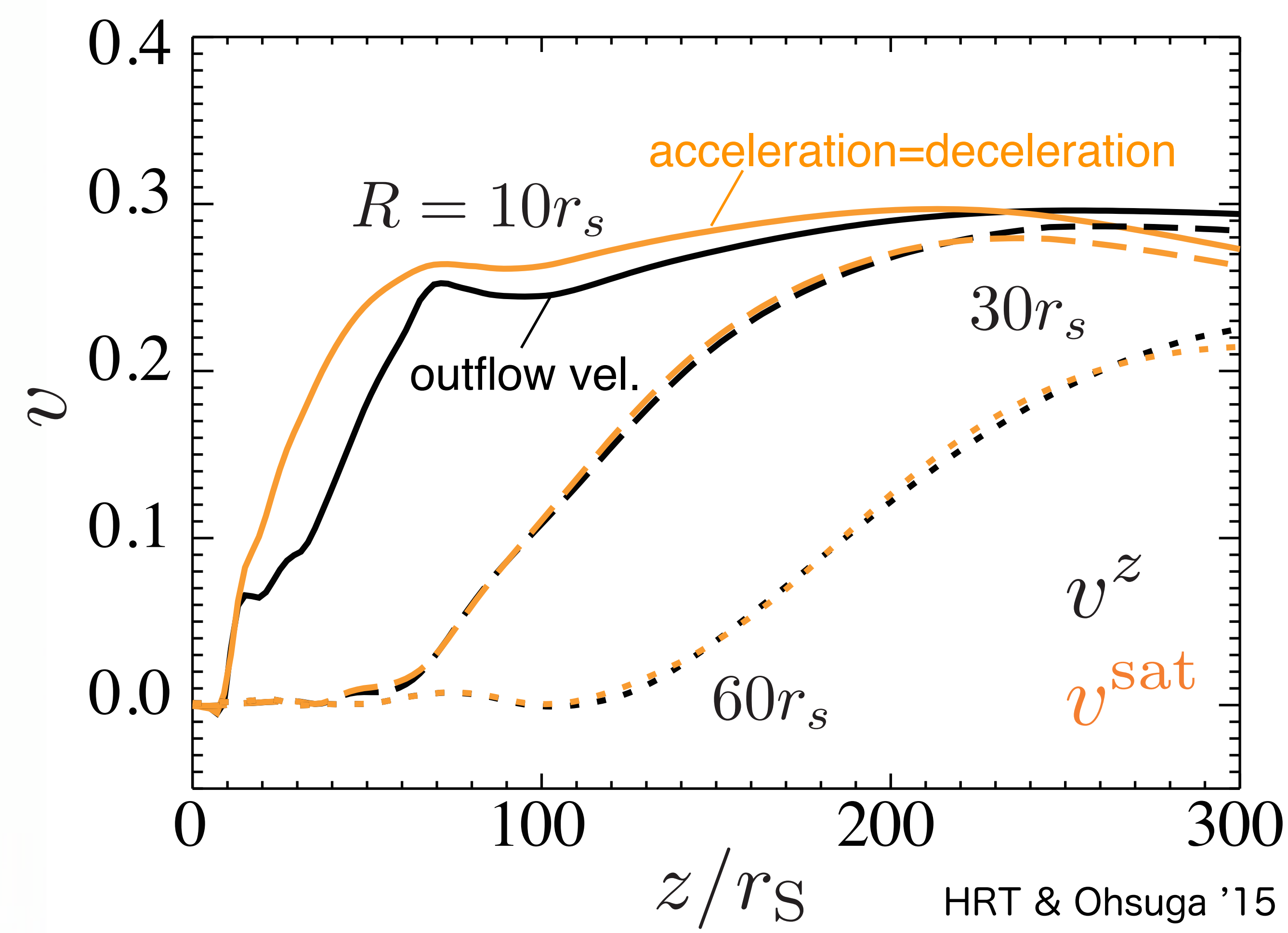
Black Hole mass is assumed to be 10 solar mass. **Takahashi & Ohsuga '15**

Mass accretion rate ~10^2 - 10^3 Eddington value →supercritical A.D.

Jet is accelerated by radiation pressure force



vertical structure of outflow velocity (black curves)



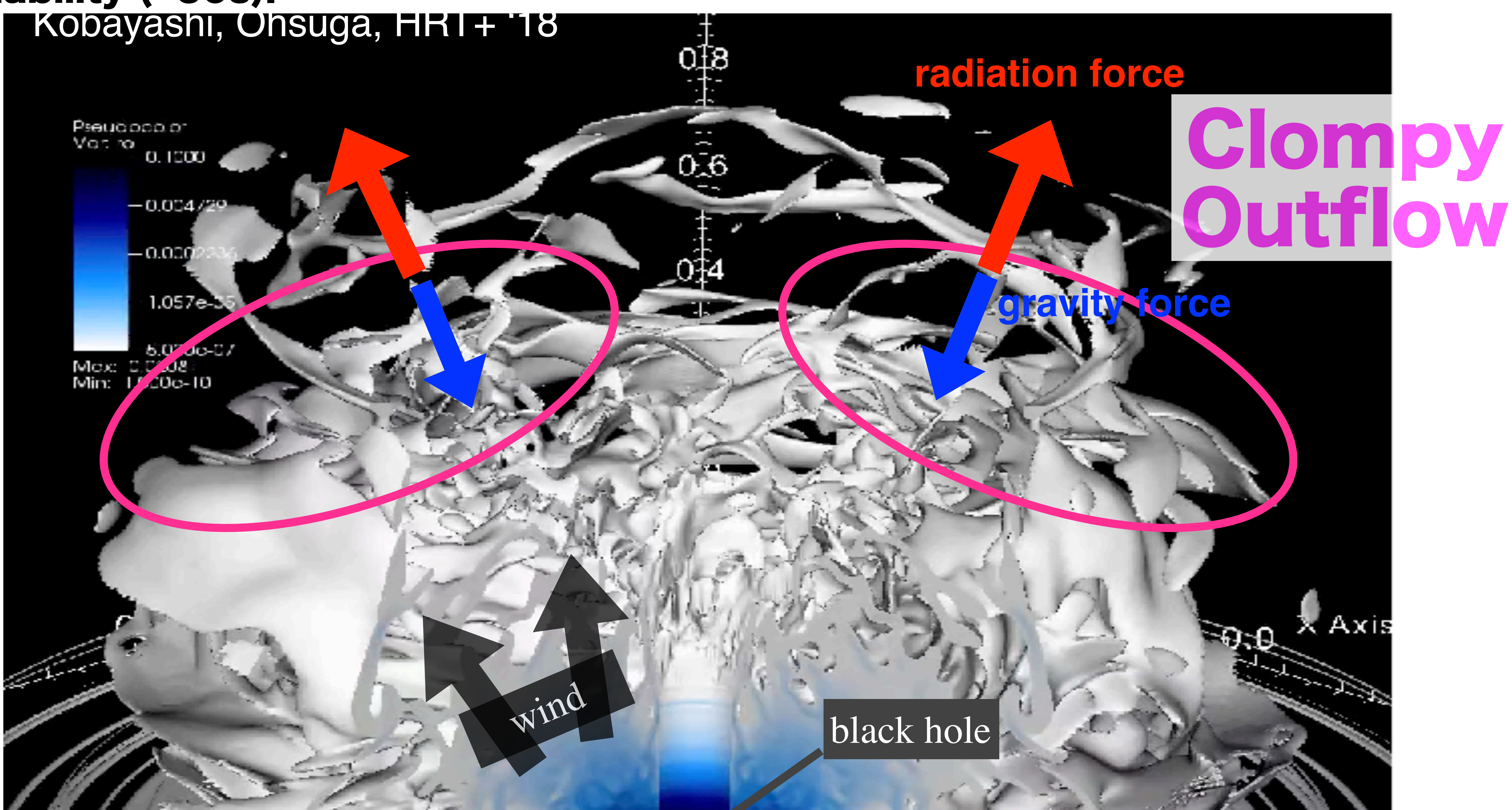
The gas is pushed by the radiation from the inner disks, → acceleration.

The jet collides with the radiation ejected from the outer disks, → deceleration.

The jet has the terminal velocity, which is about 0.3c -> consistent with SS433

3D view: Clumpy Outflow

We also performed 3D non-relativistic RMHD simulations with a large simulation box.
Optically thick, clumpy outflow is formed.
The outflow is accelerated by radiation force, which directs opposite to gravity force.
Then the outflow fragments due to the Rayleigh-Tayler instability.
Optically thick clumpy outflow shields the X-ray, it would be responsible for X-ray variability (~50s).



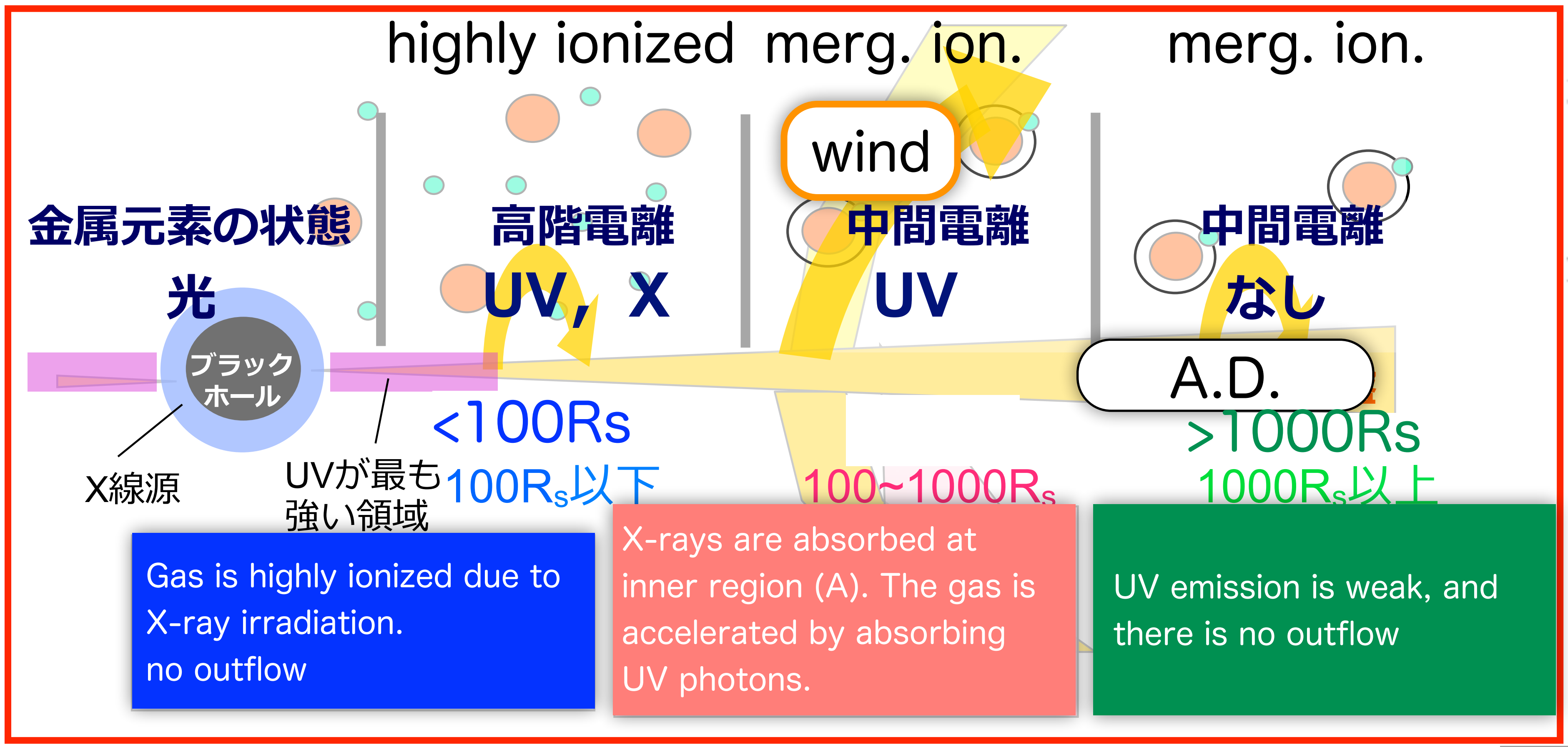
Another Process of Radiative Acceleration

For the SMBH, the **line force** would power outflow

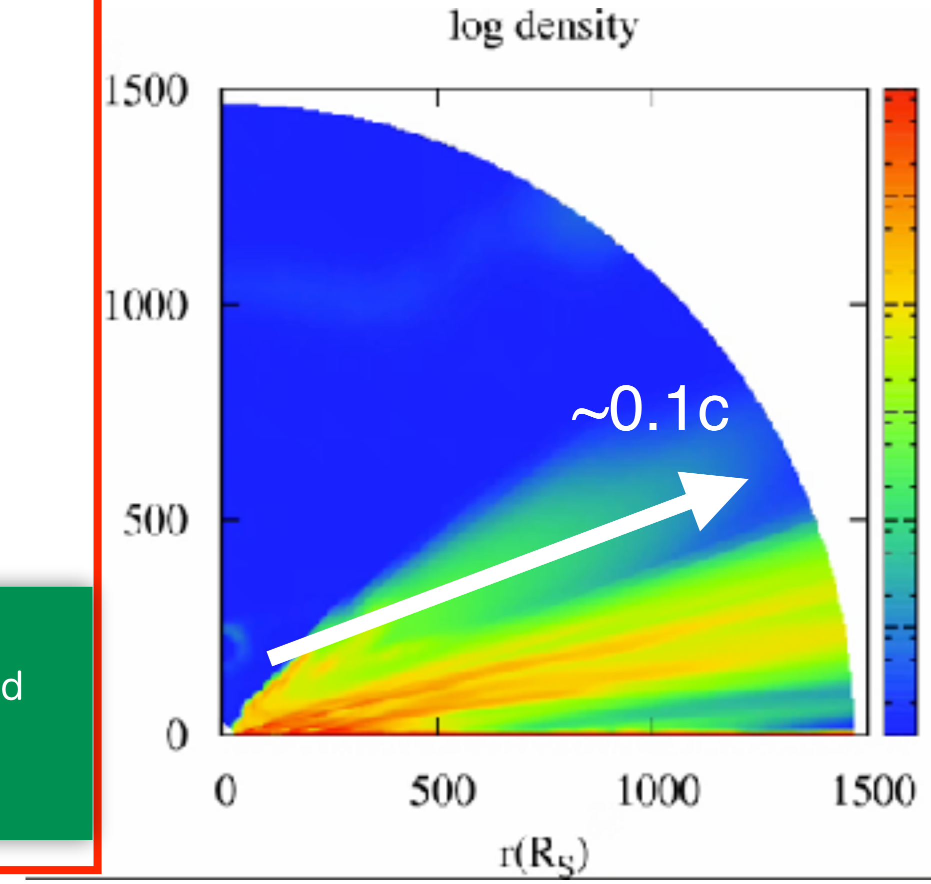
Line force : particles get momentum through absorption lines

disk temperature: ~10^8 K for stellar mass black hole -> fully ionized

~ 10^6 K for SMBH -> partially ionized



Radiation HD Sim.



Close to BH: X-ray photons ionize the gas and outflow fails.

In the middle region: X-ray photons are shielded by the failed outflow

-> the gas is accelerated by absorbing the UV photons.

This line driven wind is efficient for the supermassive black holes

Nomura, Ohsuga, Takahashi, Wada Yoshida '16

General Relativistic Radiation MHD

mass cons.	$\partial_t\left(\sqrt{-g}\rho u^t\right)+\partial_i\left(\sqrt{-g}\rho u^i\right)=0$
Gauss's 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 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 fource	$G^\mu=-\rho(\kappa_a+\kappa_s)R^{\mu\nu}u_\nu-\rho(\kappa_s R^{\alpha\beta}u_\alpha u_\beta+\kappa_a 4\pi B)u^\mu$
M1-closure	$R^{\mu\nu}=\frac{4}{3}\bar{E}_R u^\mu_R u^\nu_R+\frac{1}{3}\bar{E}_R g^{\mu\nu}$ (see, Sadowski'13)

We solve MHD equations in the Kerr-Schild metric.

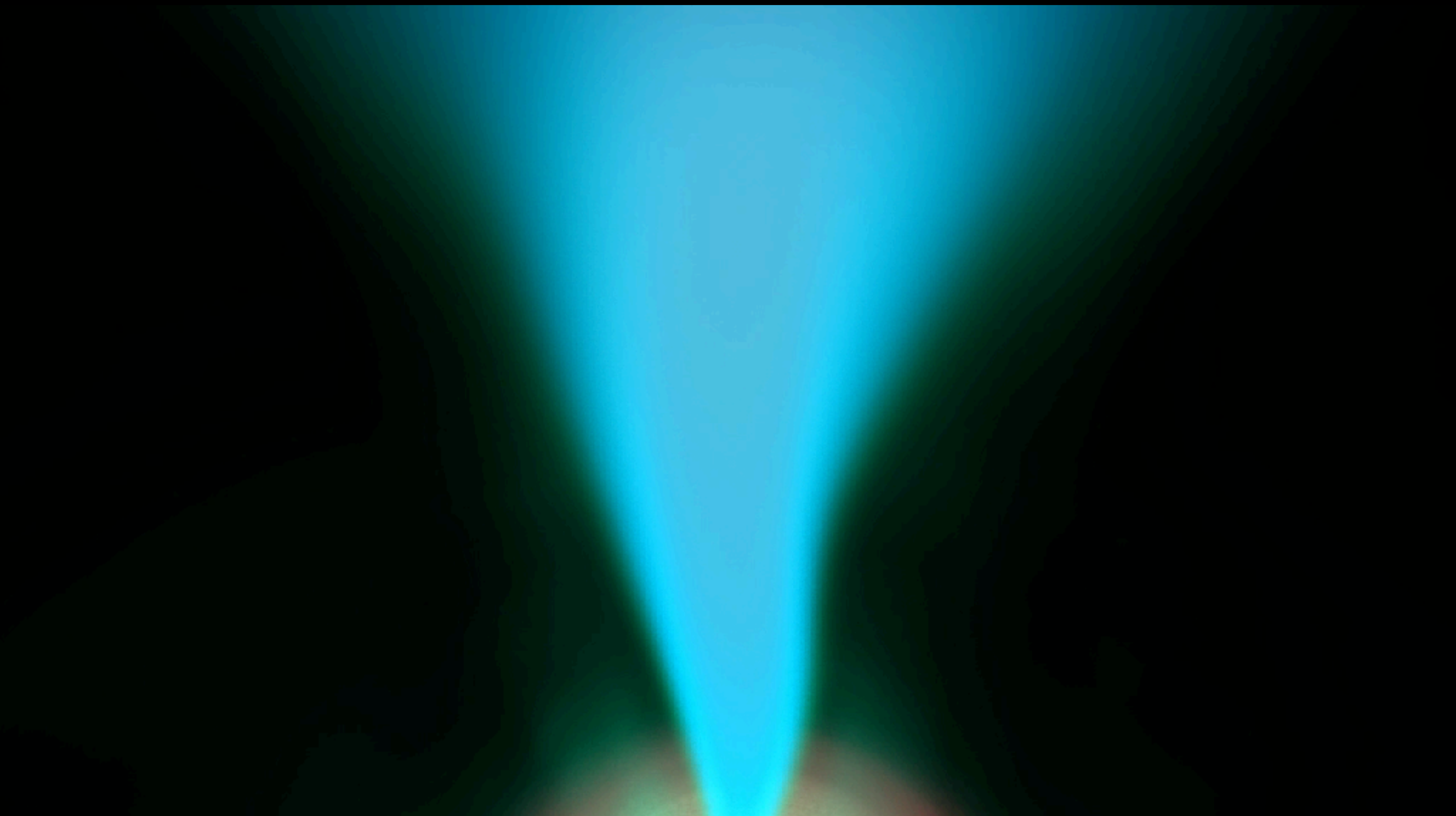
The radiation transfer is also solved by assuming M-1 approximation.

We consider the free-free emission and electron scattering for the source of opacity.

3D GRRMHD

シミュレーション：高橋博之，大須賀健
可視化：中山弘敬
国立天文台４次元デジタル宇宙プロジェクト

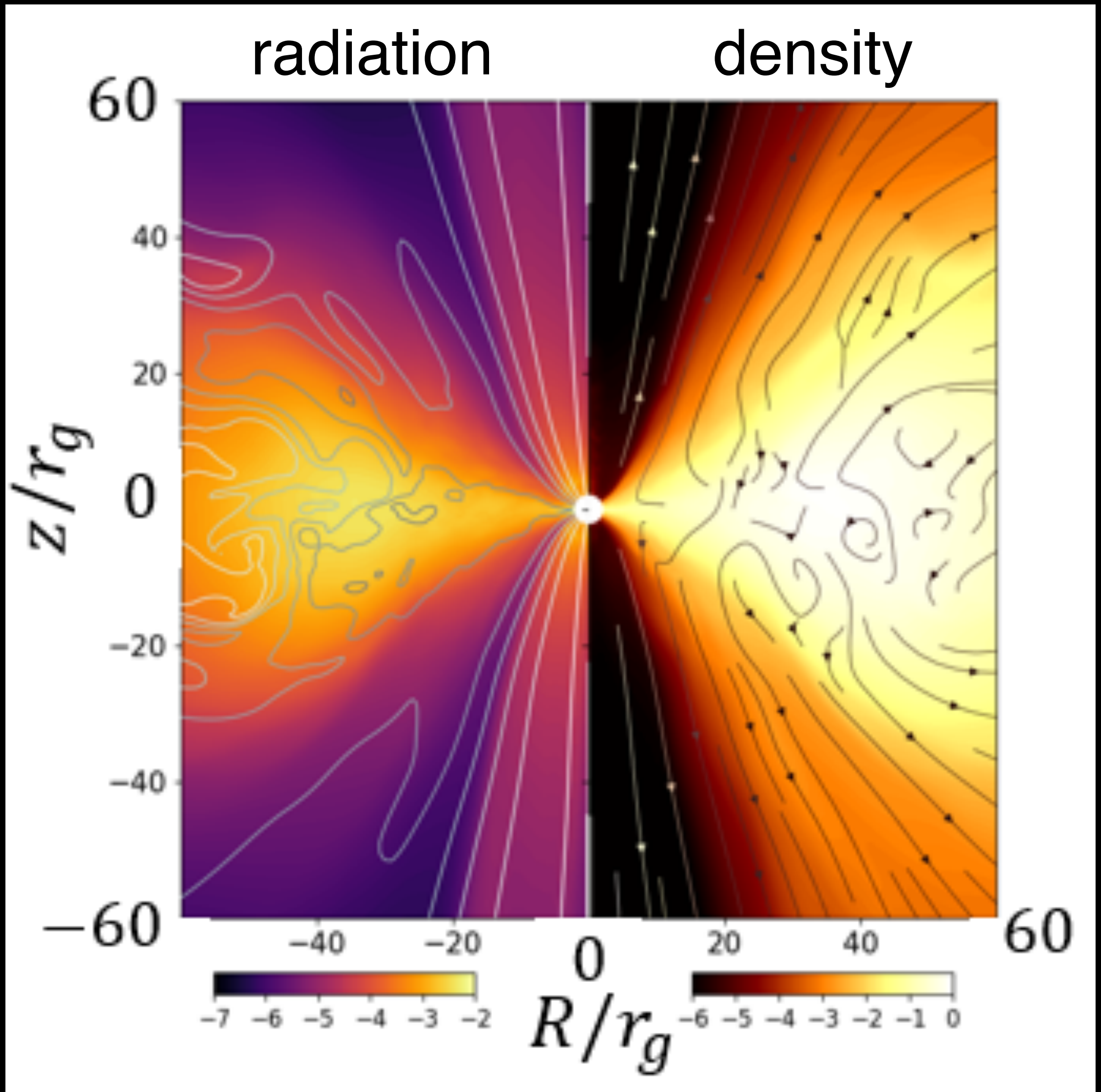
We performed 3D GRRMHD simulations of supercritical accretion disk ($\dot{M} \simeq 100\dot{M}_{\rm crit}$).
The outflow speed is 0.4-0.5c driven by radiation force.

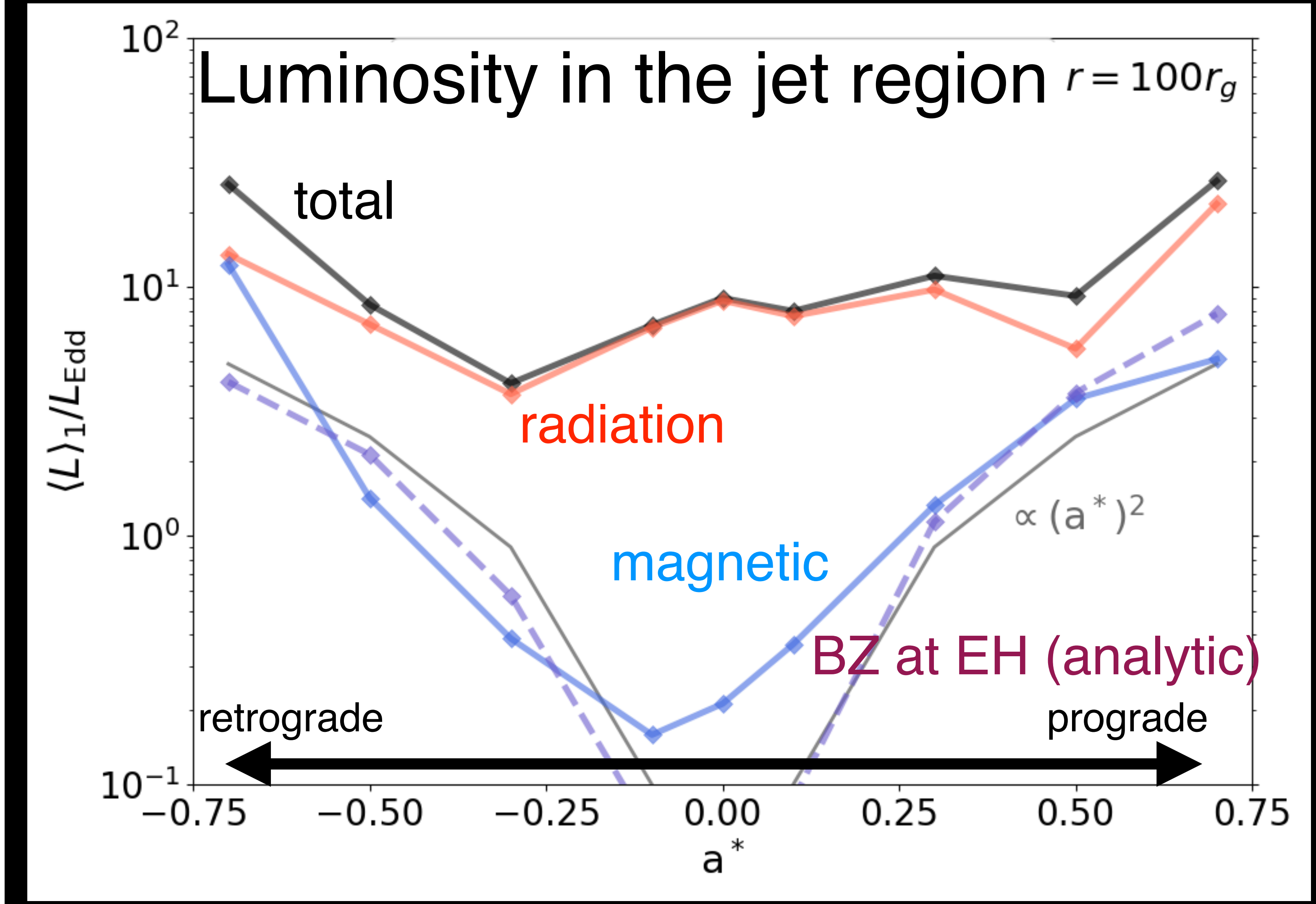


Full version of the movie will be available soon (https://4d2u.nao.ac.jp)

See Poster by Utsumi: Spin dependence

We perform GRRMHD simulations of supercritical accretion disks $\dot{M} \simeq 100\dot{M}_{\rm crit}$ with different black hole spin.





The radiation luminosity exceeds magnetic power. The outflow might be powered by liberation of gravitational energy of accretion disks.

The BZ power increases with BH spin. We think the jet will be powered by BZ process for highly rotating blackhole even in high mass accretion rate.

Brief Summary 1:

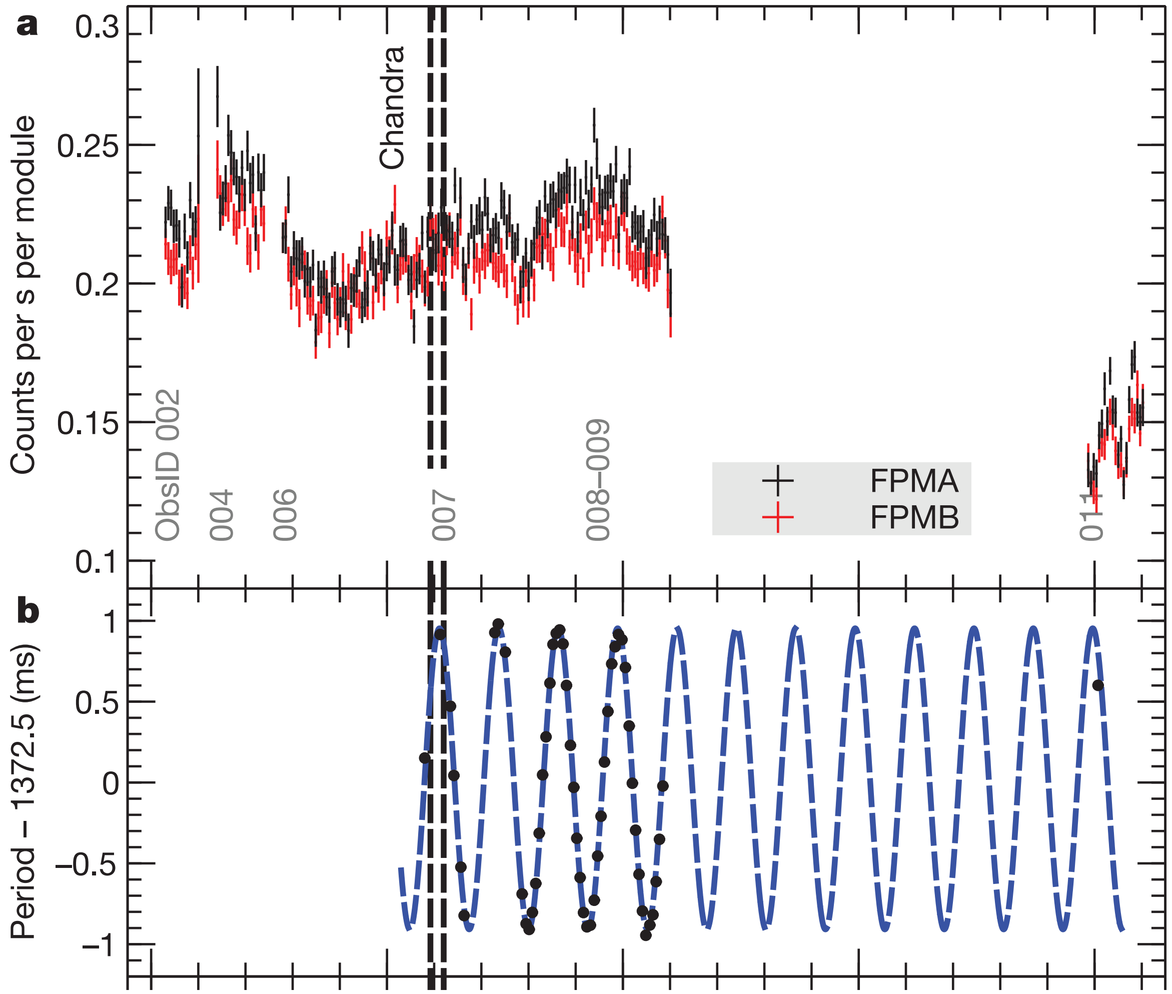
We performed radiation magnetohydrodynamic simulations to study the disk structure near the black hole.

- supercritical accretion is feasible.
- strong outflow is powered by radiation force.
- outflow velocity is about 40-50% of light speed, which is determined by the balance between radiation pressure force and radiative drag force.
- For SMBH, the line driven wind is formed for sub Eddington case.

2. Accretion to Neutron Star

Why Neutron Star?

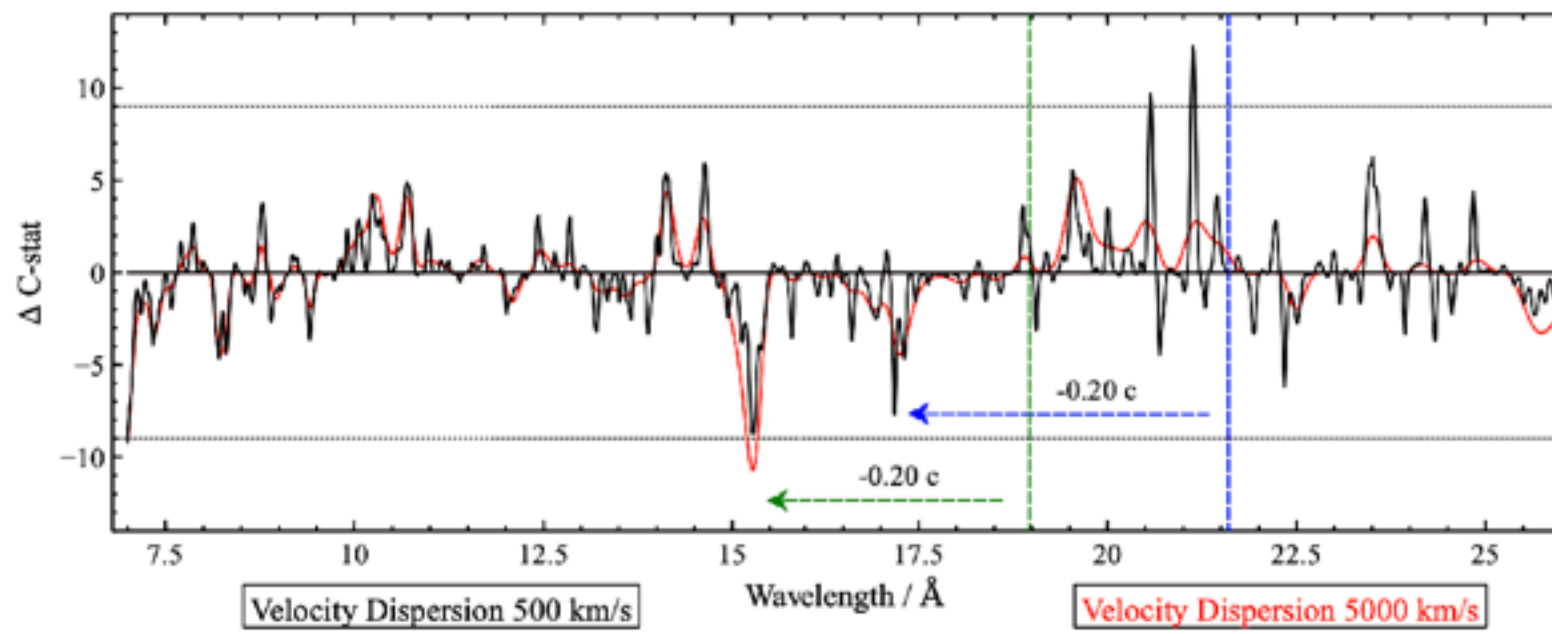
X-ray pulsation has been detected from M82 X-2 of ULX



Bachetti '14

Some of ULX can be originated from Neutron star.

Some of ULX pulsar have a Fast outflow (e.g., NGC300 ULX-1)



Kosec '18

Blue shifted absorption lines are detected.

The corresponding outflow velocity is 0.22c.

The estimated kinetic power is 10^{41} erg/s .

Supercritical accretion takes place in ULX pulsars.

Neutron star can be a powerful source similar to black hole

see, also Miller 16, King & Lasota '16

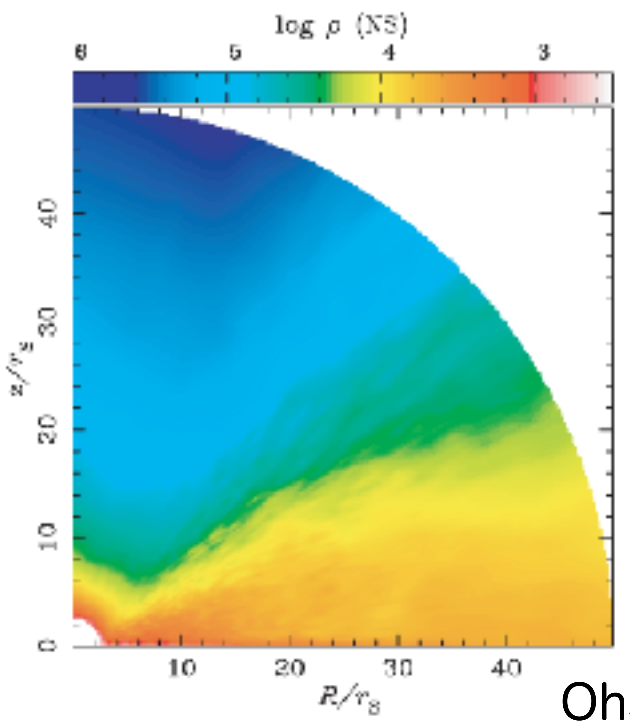
Is supercritical accretion possible to Neutron Star?

Which is powerful, NS and BH?

Previous work

There are previous works on mass accretion onto the neutron star.
But there are some problems to consider the ULX pulsars.

weakly magnetized NS



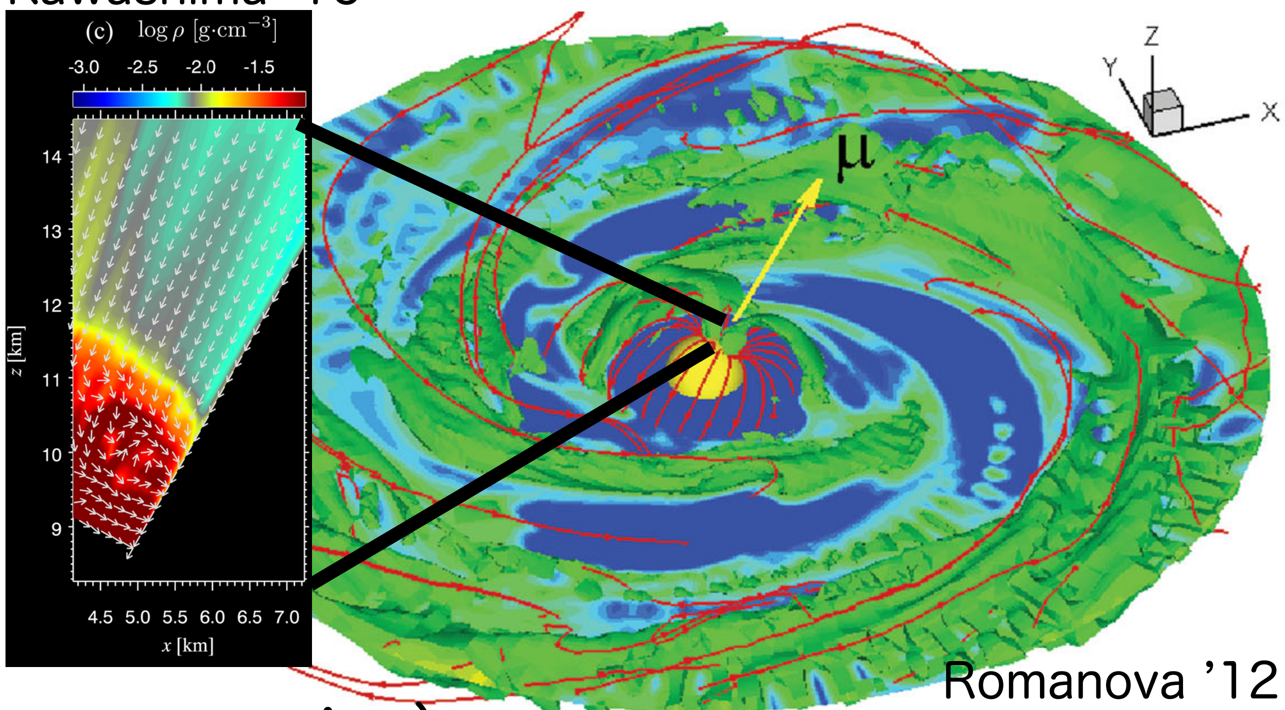
Ohsuga '07

assumption)

- α-viscosity (no B field)
- diffusion approximation
- ignore Compton scattering
- ignore relativistic effects

strongly magnetized NS

Kawashima '16



Romanova '12

assumption)

- global simulation
  ignore radiation effects
  = low accretion rate
- local simulation
  ignore interaction between disk
  and B field

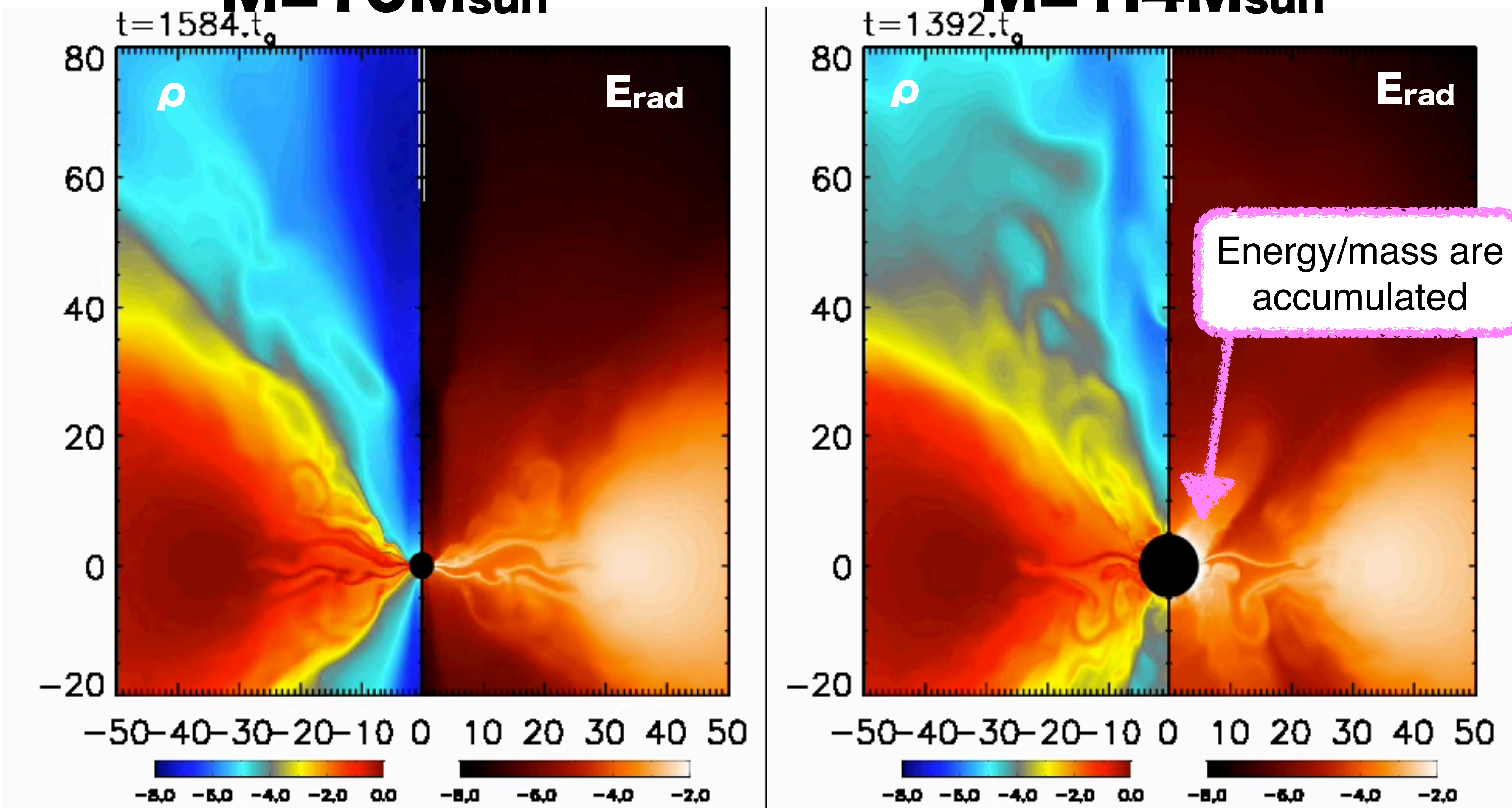
To study the supercritical accretion to the neutron star, we should perform global GR-RMHD simulations.

Accretion to Neutron Star

We performed GR-RMHD simulations of supercritical accretion onto the non-rotating blackhole and non-rotating neutron star.

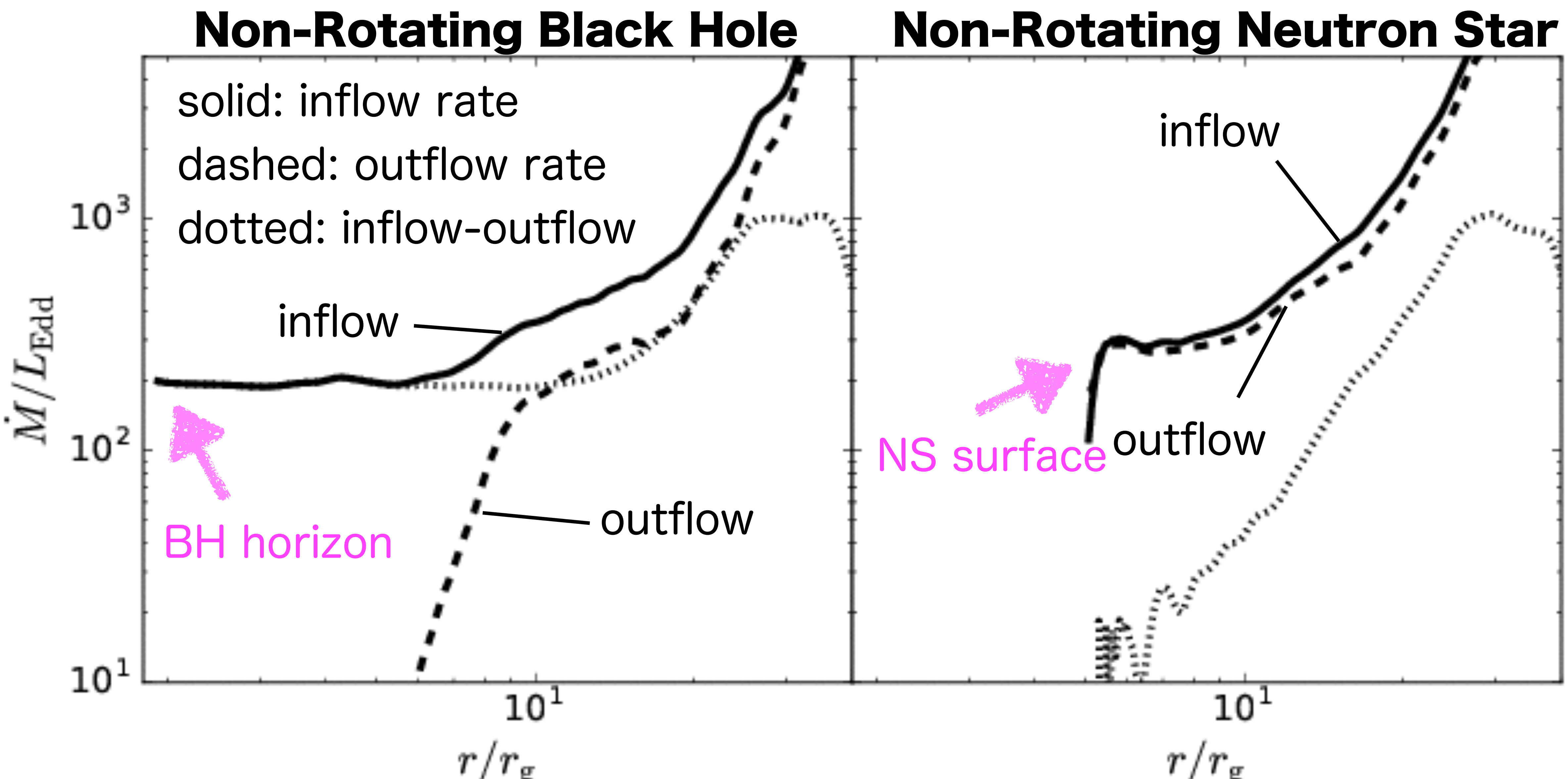
Non-Rotating BH
M=10Msun

Non-Rotating NS
M=1.4Msun



Inflow and Outflow

Takahashi & Ohsuga '16



For the black hole,

The mass accretes toward black hole r = 2rg.

The strong outflow is ejected beyond r >~ 6 rg.

For Neutron star,

Mass inflow/outflow are suddenly dropped around the NS surface.

Strong outflow is ejected very close to the neutron star surface

def. of outflow/inflow rate

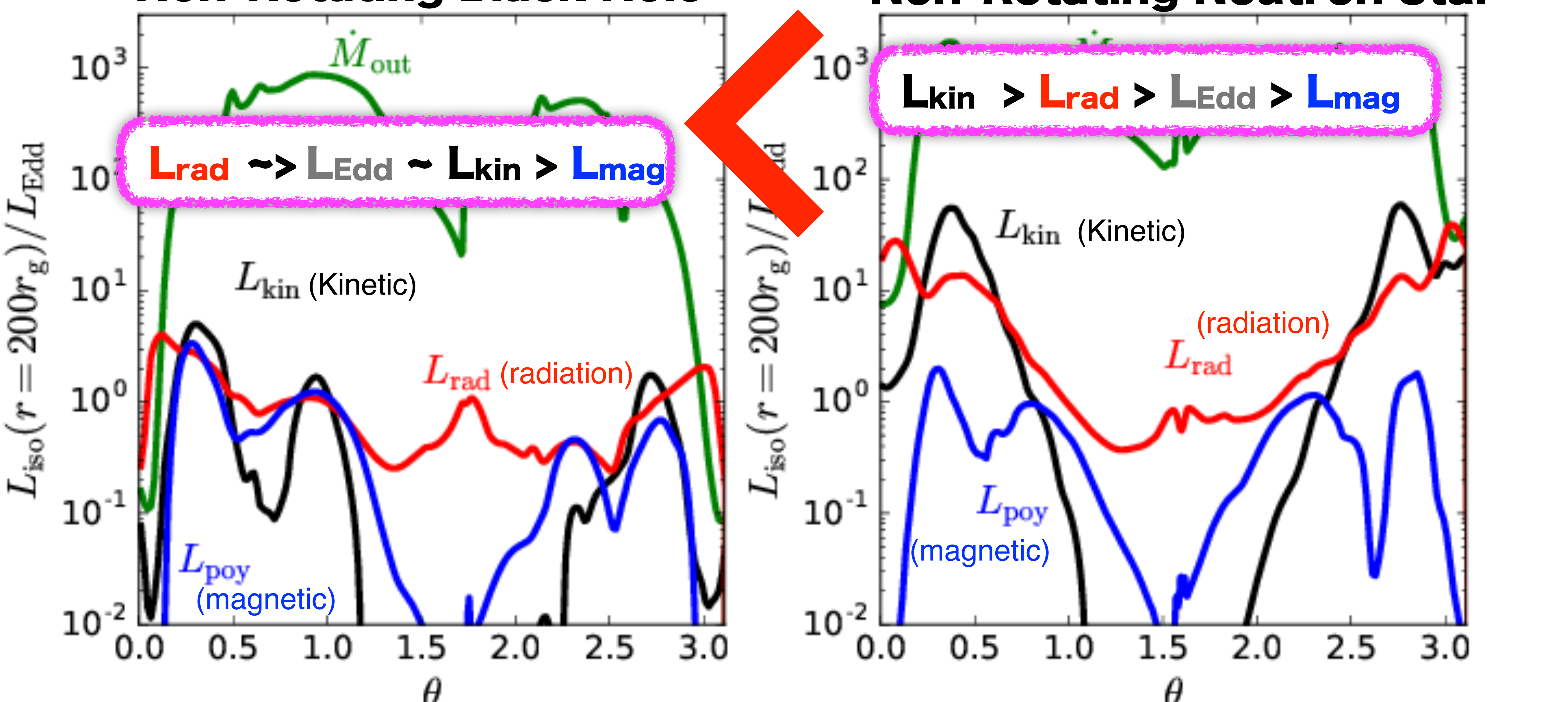
$$\dot{M}_{\rm out} \equiv \int \rho u^r \theta(u^r)\sqrt{-g}d\theta d\phi$$

$$\dot{M}_{\rm in} \equiv \int \rho u^r \theta(-u^r)\sqrt{-g}d\theta d\phi$$

Isotropic luminosity at r=200 r_g

Takahashi & Ohsuga '16

Non-Rotating Black Hole **Non-Rotating Neutron Star**

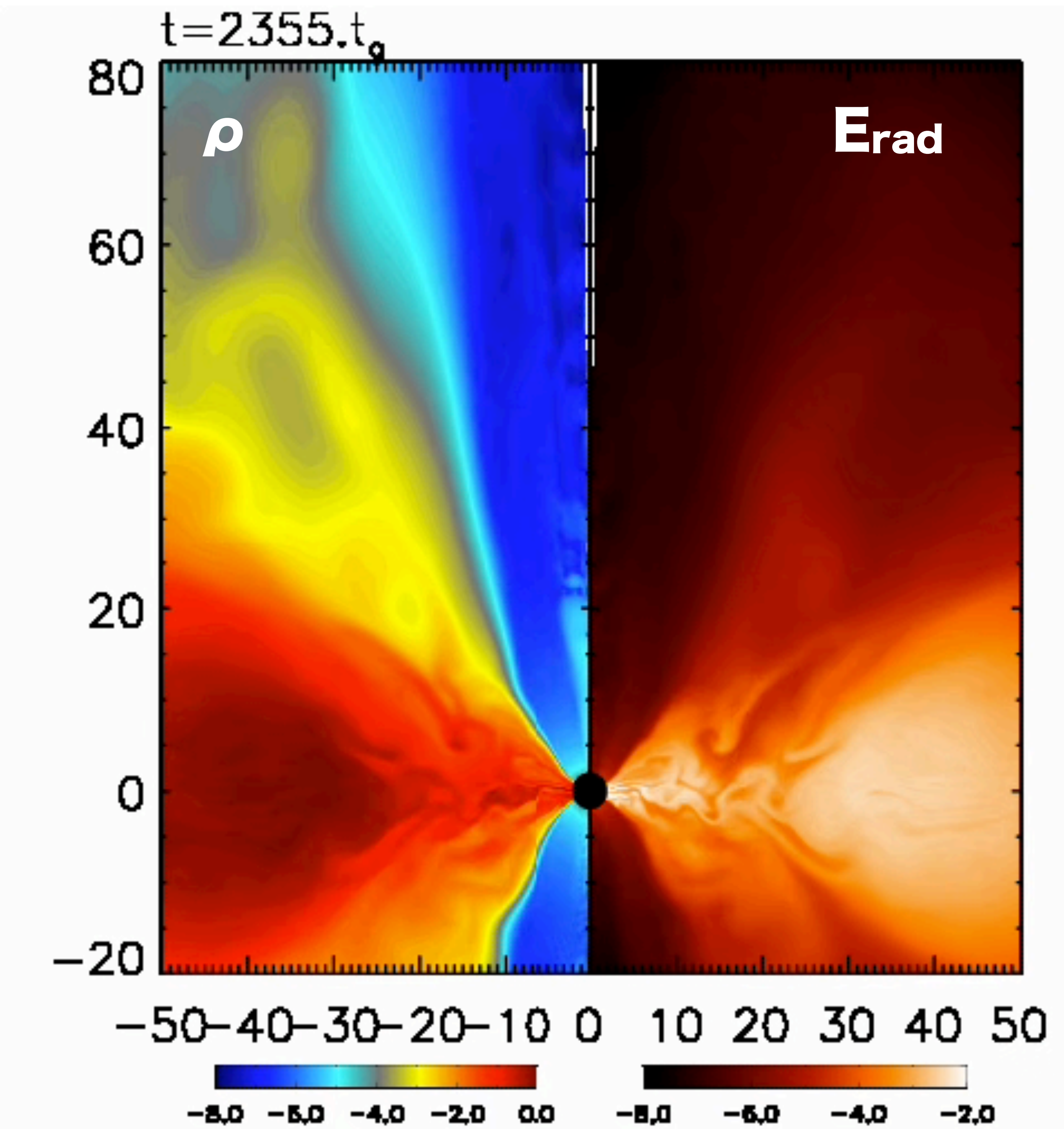


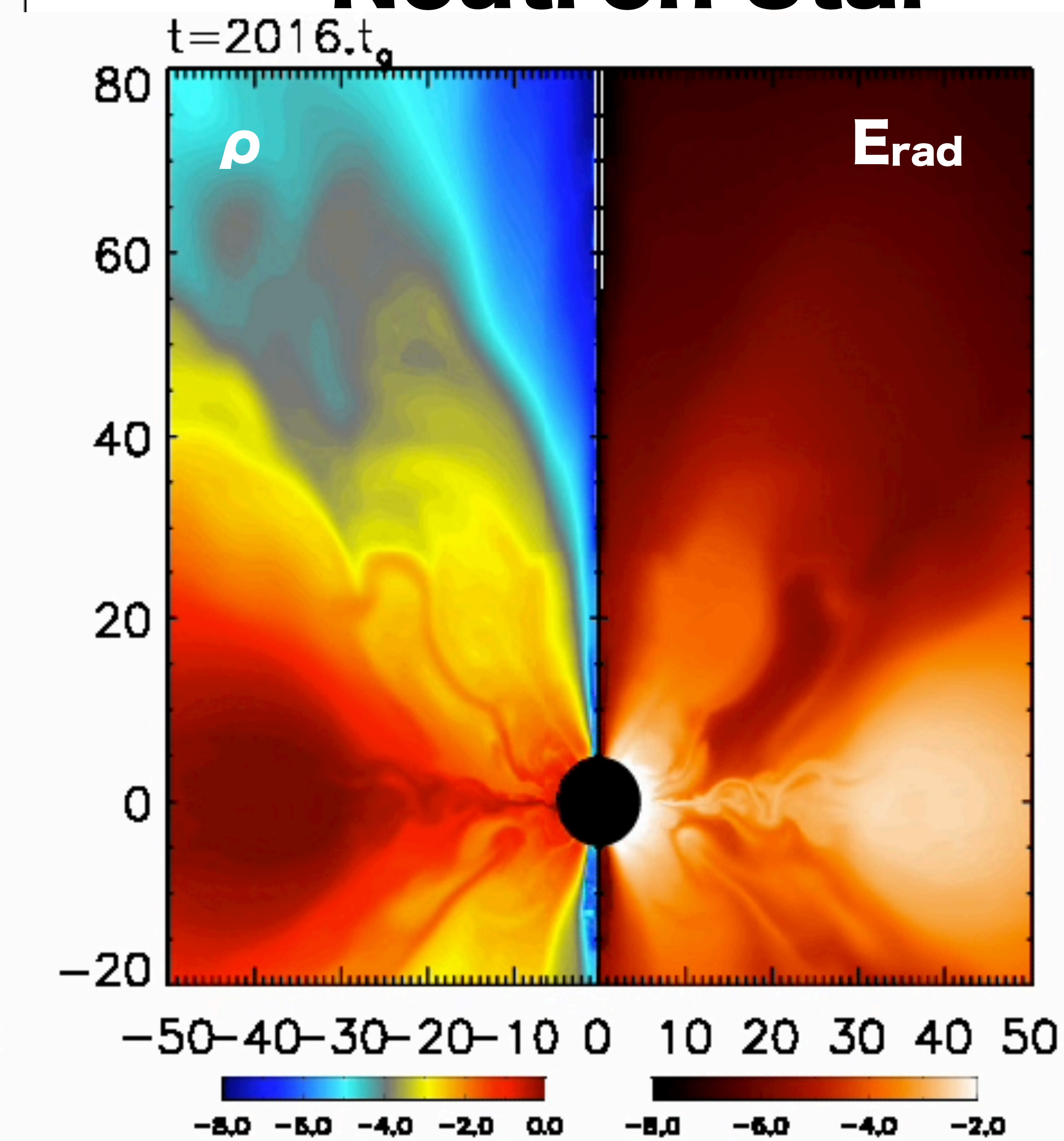
In both case, the isotropic luminosity has a peak near the rotation axis, which exceeds the Eddington value.

For the non-rotating black hole, the radiative luminosity is comparable to the kinetic luminosity. For the Neutron star, kinetic luminosity exceeds the radiative luminosity.

The neutron star can be more powerful than the black hole.

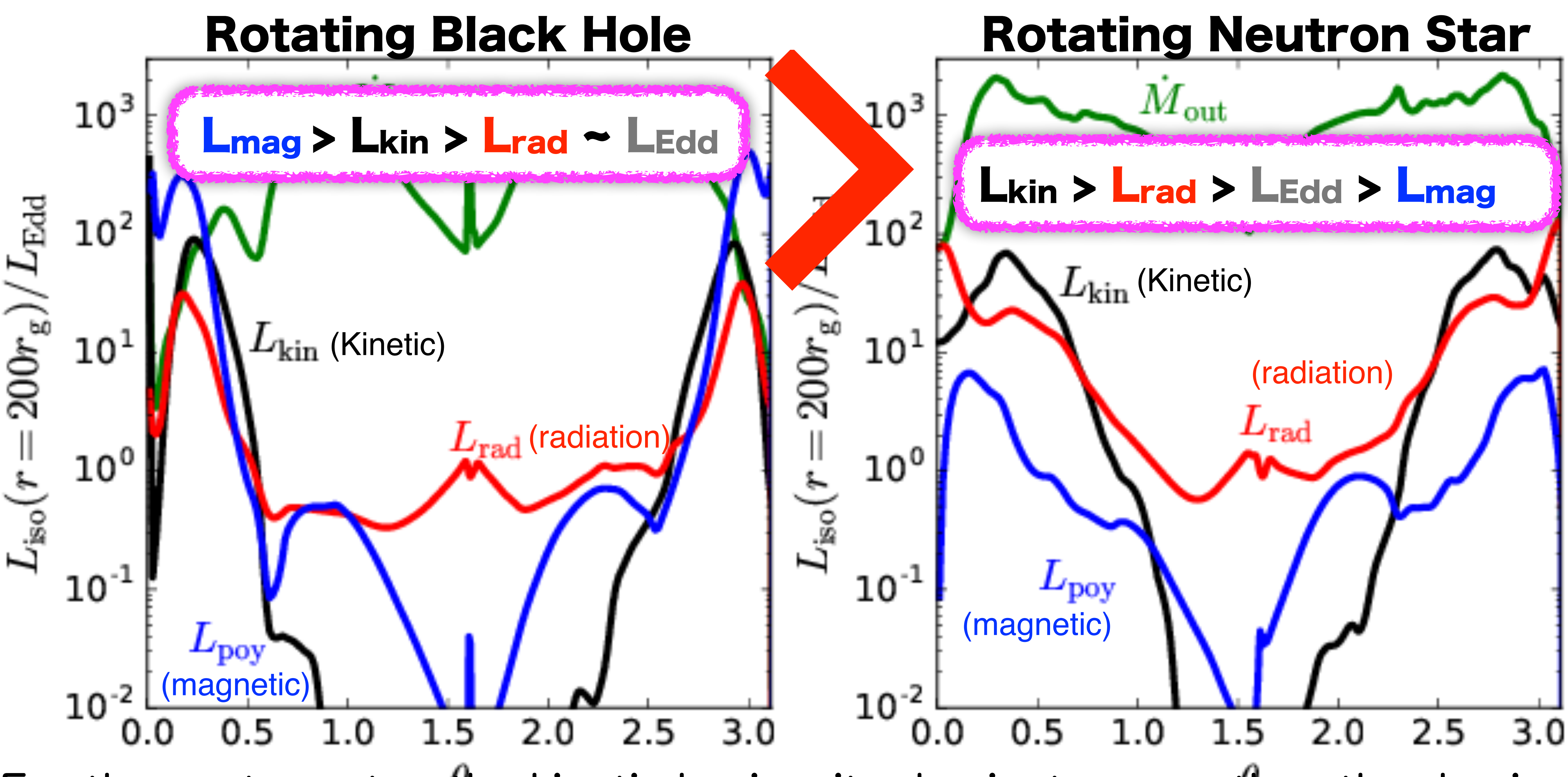
Rotating case





Isotropic luminosity from rotating objects

Takahashi & Ohsuga '16

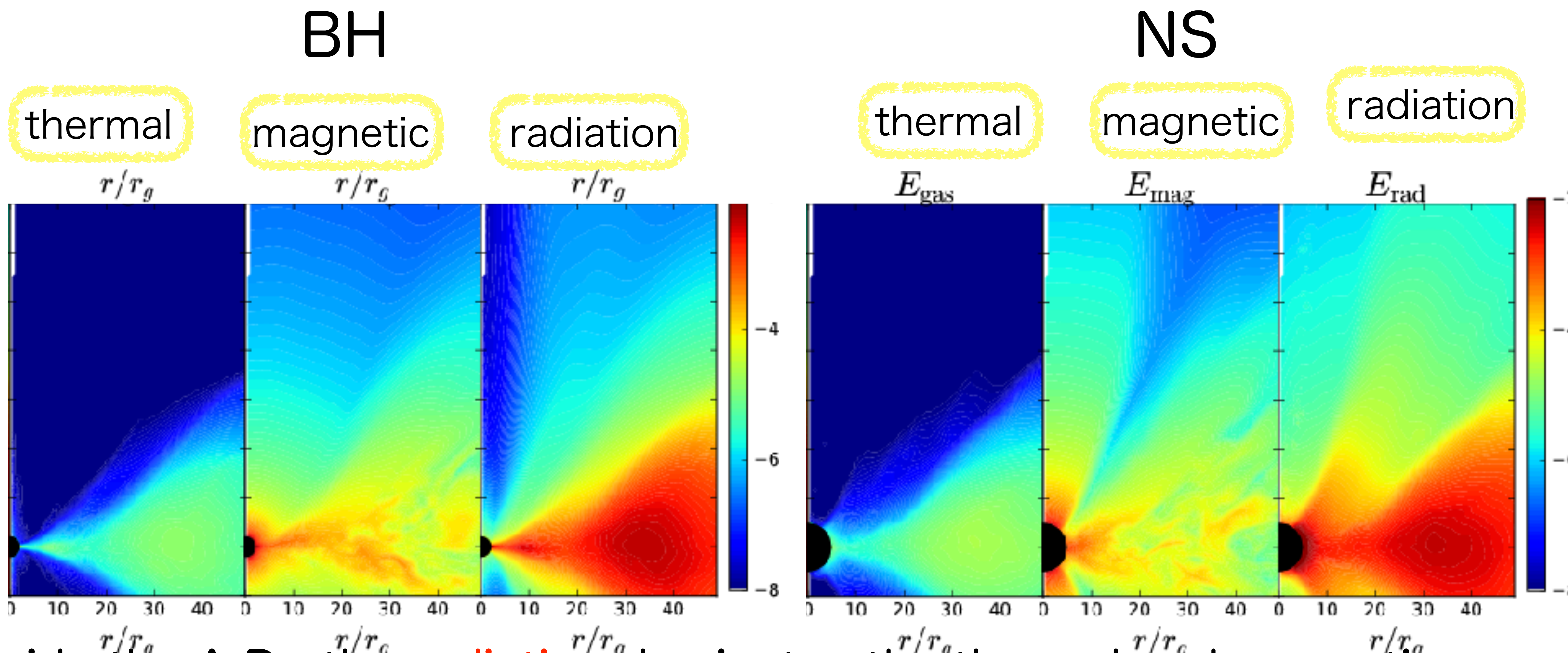


For the neutron star, the kinetic luminosity dominates over the other luminosities. The total luminosity much exceeds the Eddington value. These are consistent with the non-rotating case.

For the black hole, the magnetic power dominates over the other luminosities due to the Blandford-Znajek effects.

Rotating BH is the most powerful in these system, the NS is second strongest.

Why the Supercritical Accretion feasible?



Inside the A.D., the radiation dominates the thermal and magnetic energy (supercritical accretion).

The radiation can escapes from the disk surface or is swallowed by BH.

For the neutron star, the radiation is not swallowed by the neutron star.

The radiation energy is accumulated on its surface.

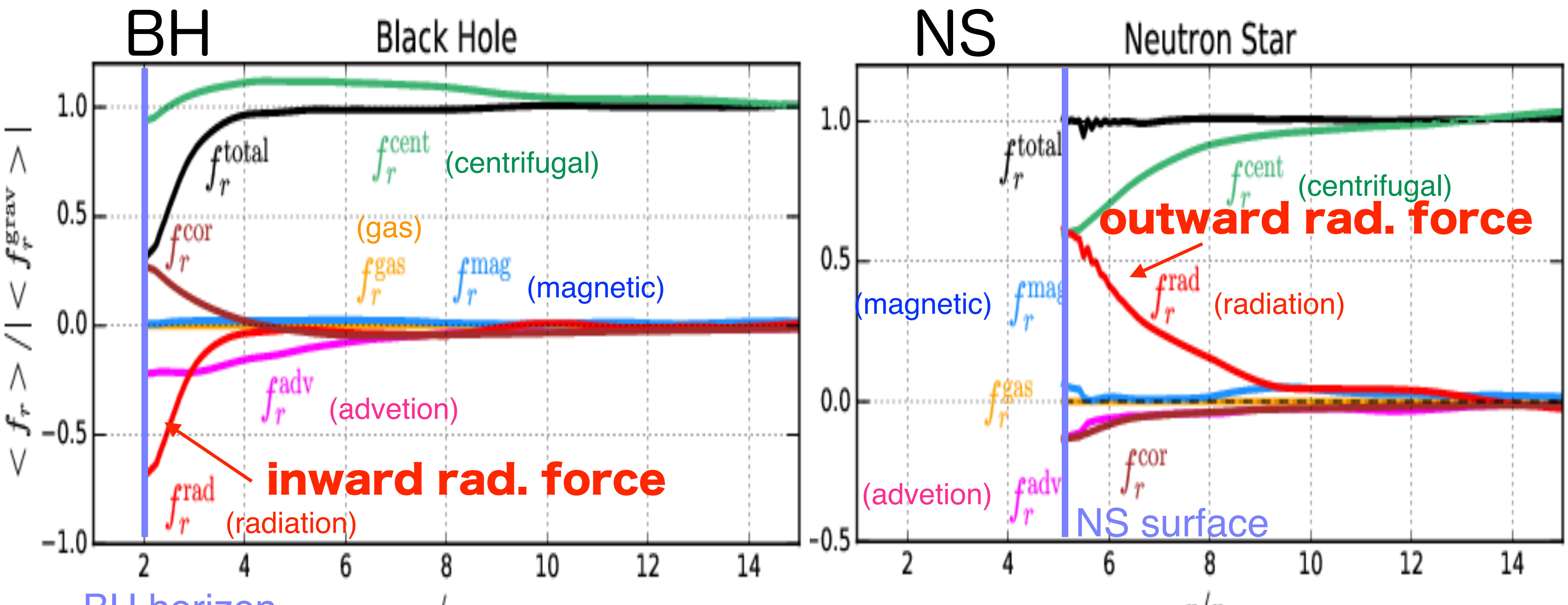
Why can the accretion rate exceed Eddington limit?

Takahashi, Mineshige & Ohsuga '18

Why the Supercritical Accretion feasible?

radial force on the equatorial plane

$$u^r \partial_r u_r = -f_{\rm grav} + f_{\rm cent} + f_{\rm rad} + f_{\rm cor} + f_{\rm mag}$$



Far from the central star, centrifugal force balances the gravity force

BH: the radiation is swallowed by BH. -> inward radiation force

NS: close to the NS, the outward rad. force due to the accumulation of rad. energy. the radiation force is about a few 10% of grav. force.

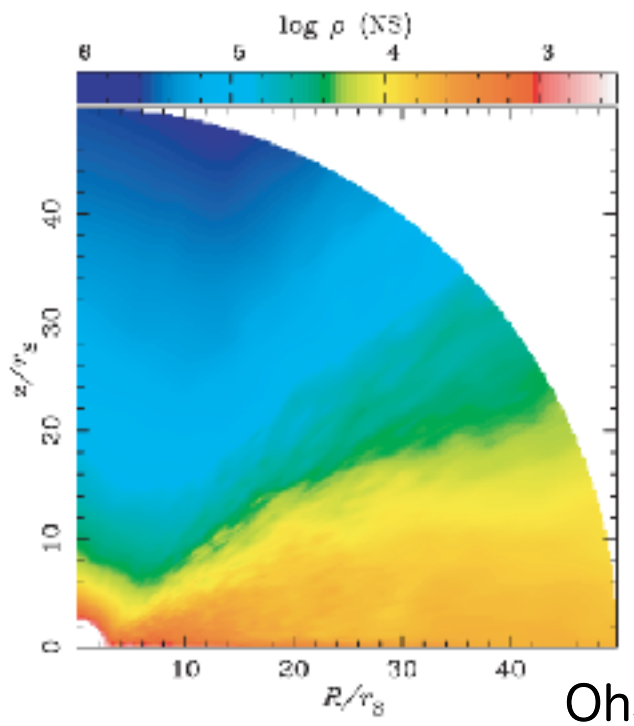
This is because the radiation is almost isotropic close to NS. Thus the radiation force not such a strong to halt gas accretion.

Takahashi, Mineshige & Ohsuga '18

Previous work

There are previous works on mass accretion onto the neutron star.

weakly magnetized NS



Ohsuga '07

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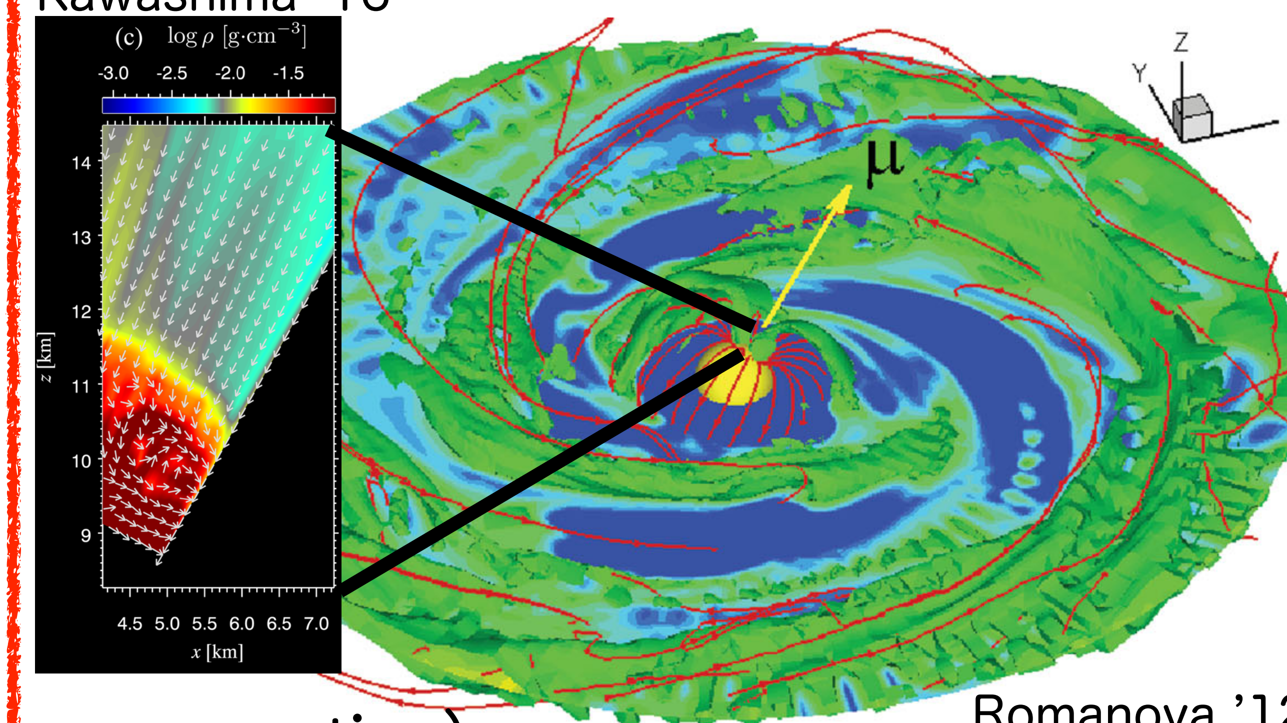

Romanova '12

assumption)

- global simulation
  ignore radiation effects
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- local simulation
  ignore interaction between disk
  and B field

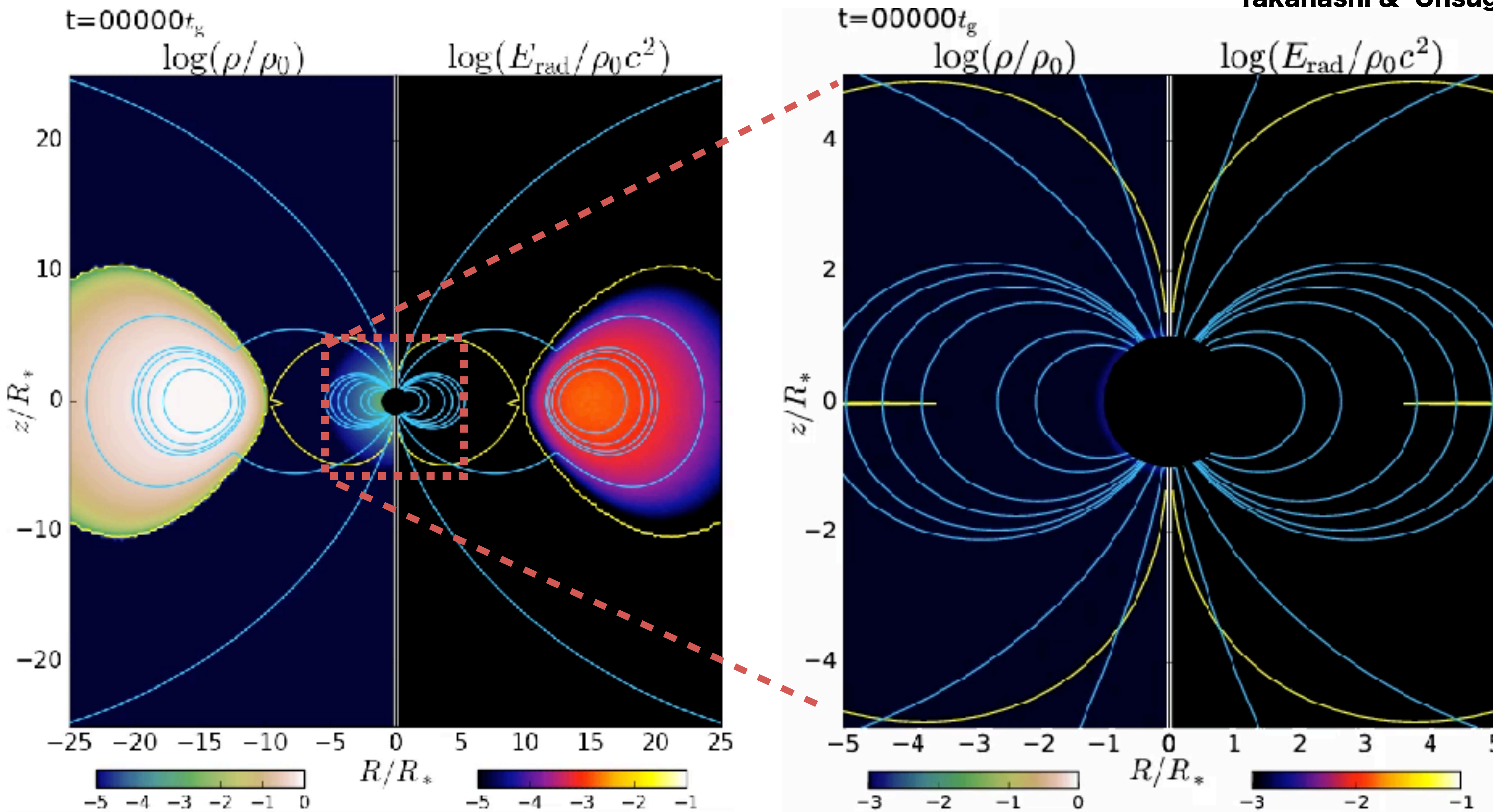
Supercritical Accretion onto Strong B NS?

Accretion onto Magnetized NS

We included the dipole magnetic field of the NS. $B_0 = 10^{10}$ Gauss.

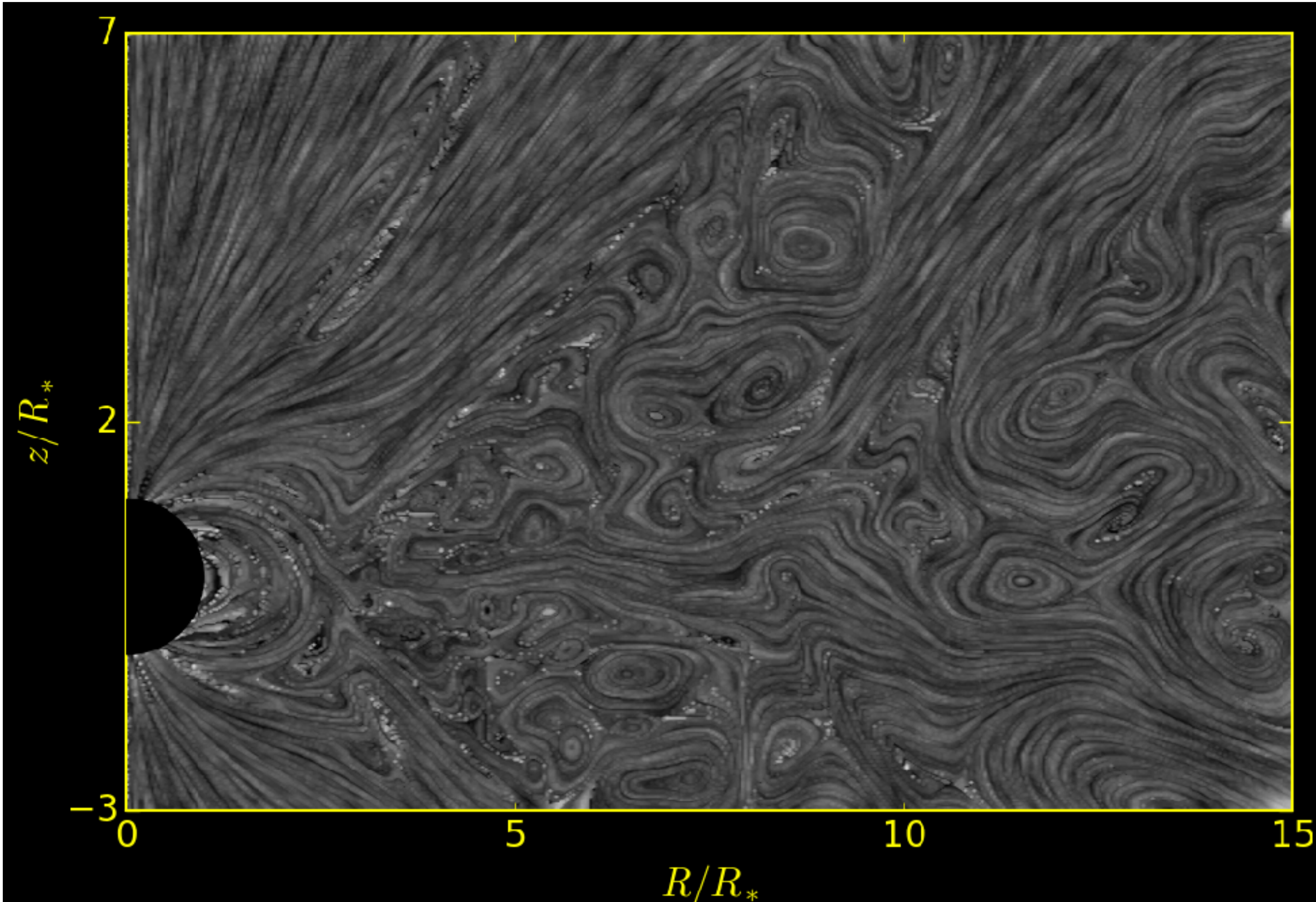
NS is assumed to be **non-rotating**.

Takahashi & Ohsuga '17

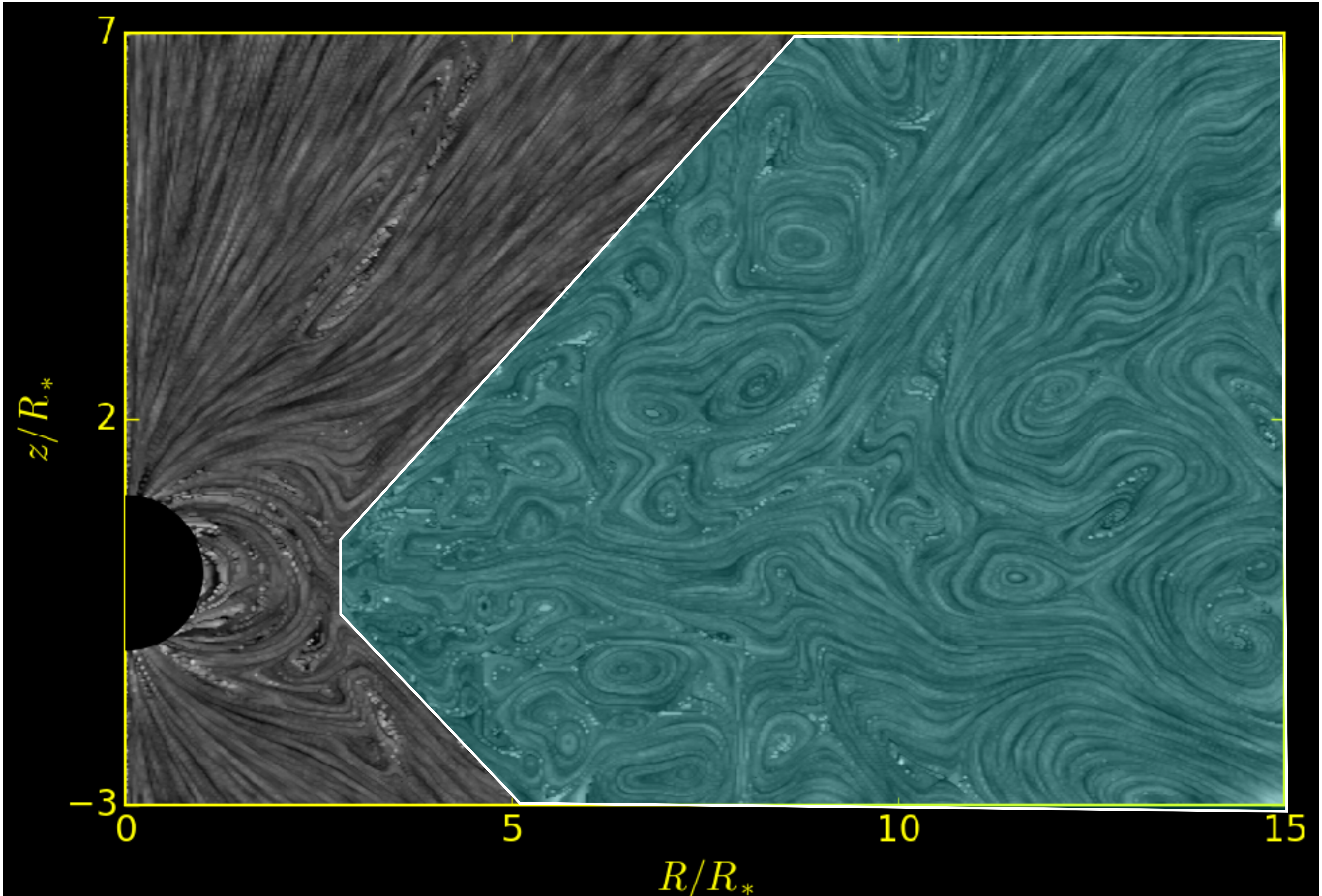


Accretion disks are formed far from the neutron star.
Strong gas and radiation outflows are ejected from accretion disks.

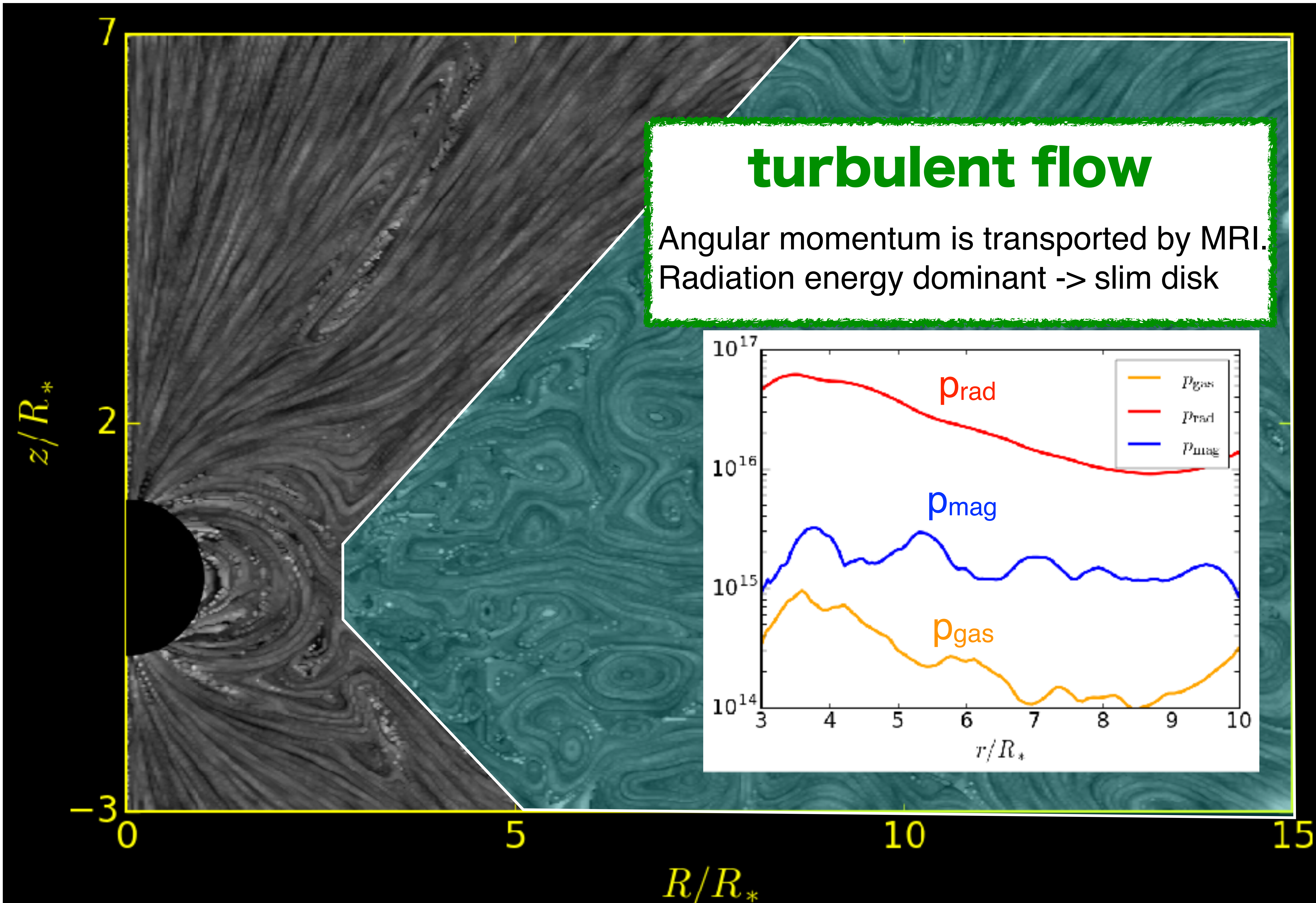
Stream lines



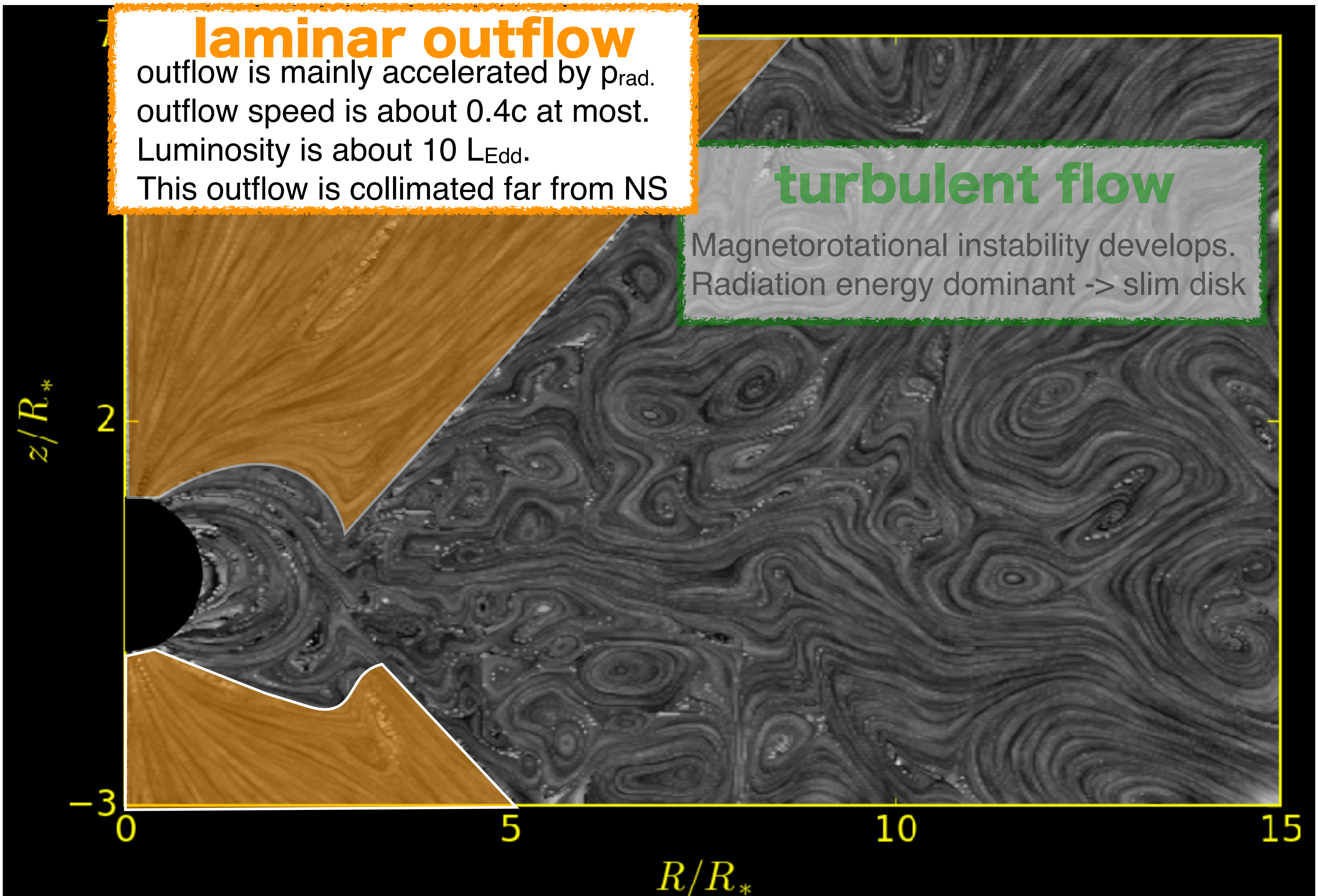
Stream lines



Stream lines



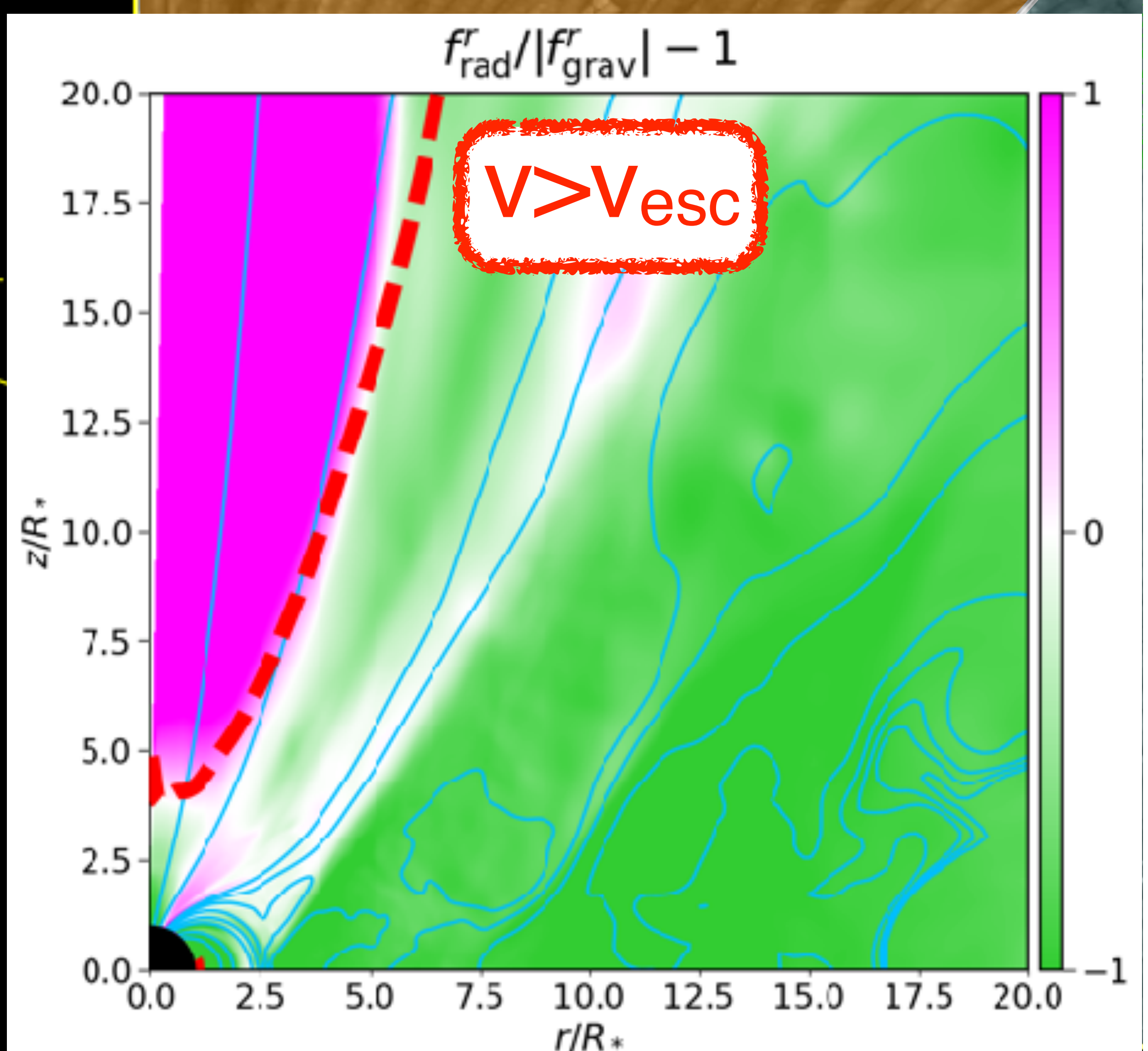
Stream lines

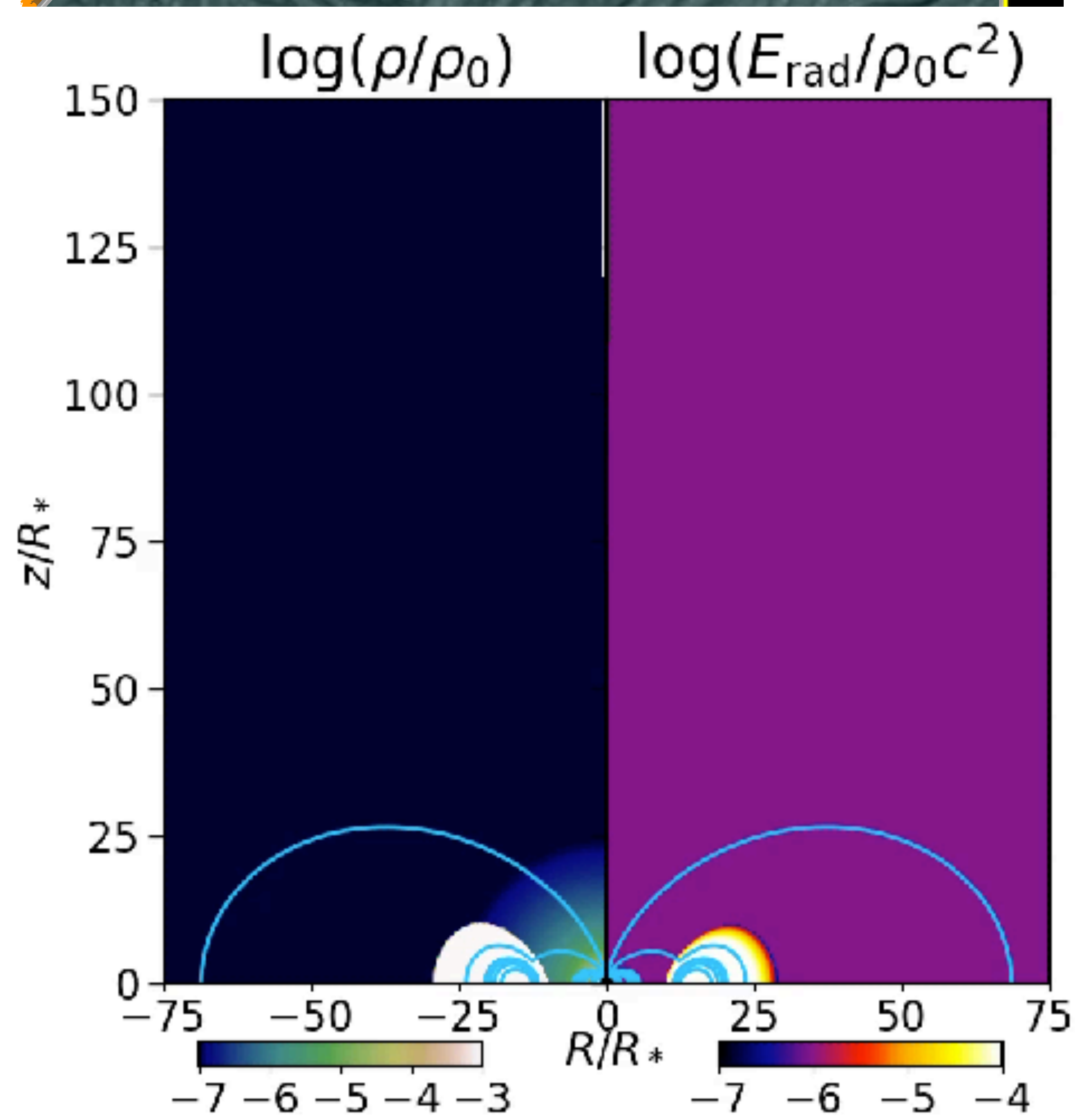


Stream lines

laminar outflow

outflow is accelerated by p_{rad}.
outflow speed is about 0.4c.
Luminosity is about 10 L_{Edd}.
This outflow is roughly collimated far from NS





z/R*
0
5
10
15
R/R*

Reconnection Outflow1

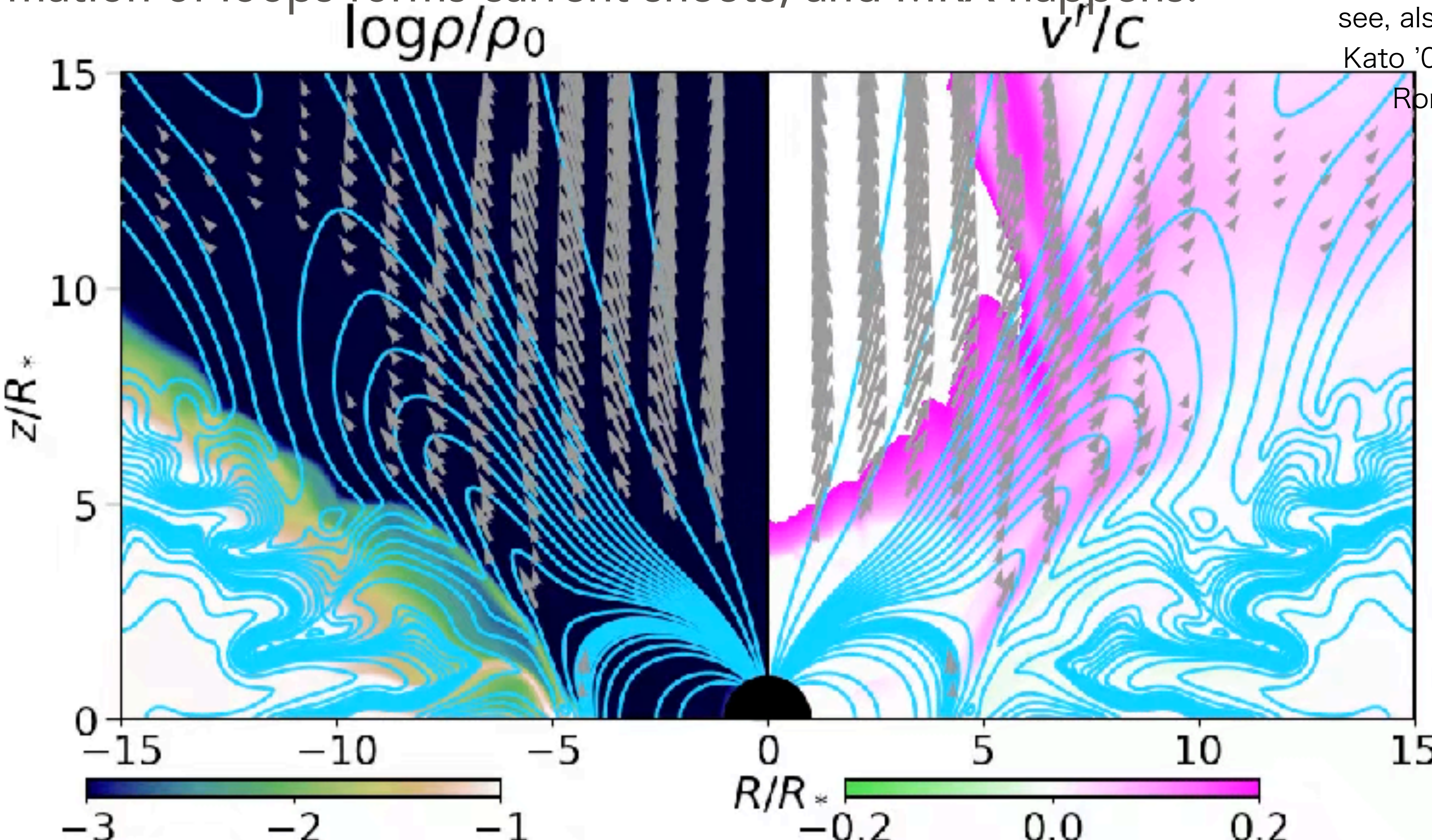
We observed two types of Magnetic reconnection driven outflow.

The accretion disks push the dipole field, and field lines are twisted.

The deformed magnetic loops inflate in 45° degree direction.

The deformation of loops forms current sheets, and MRX happens.

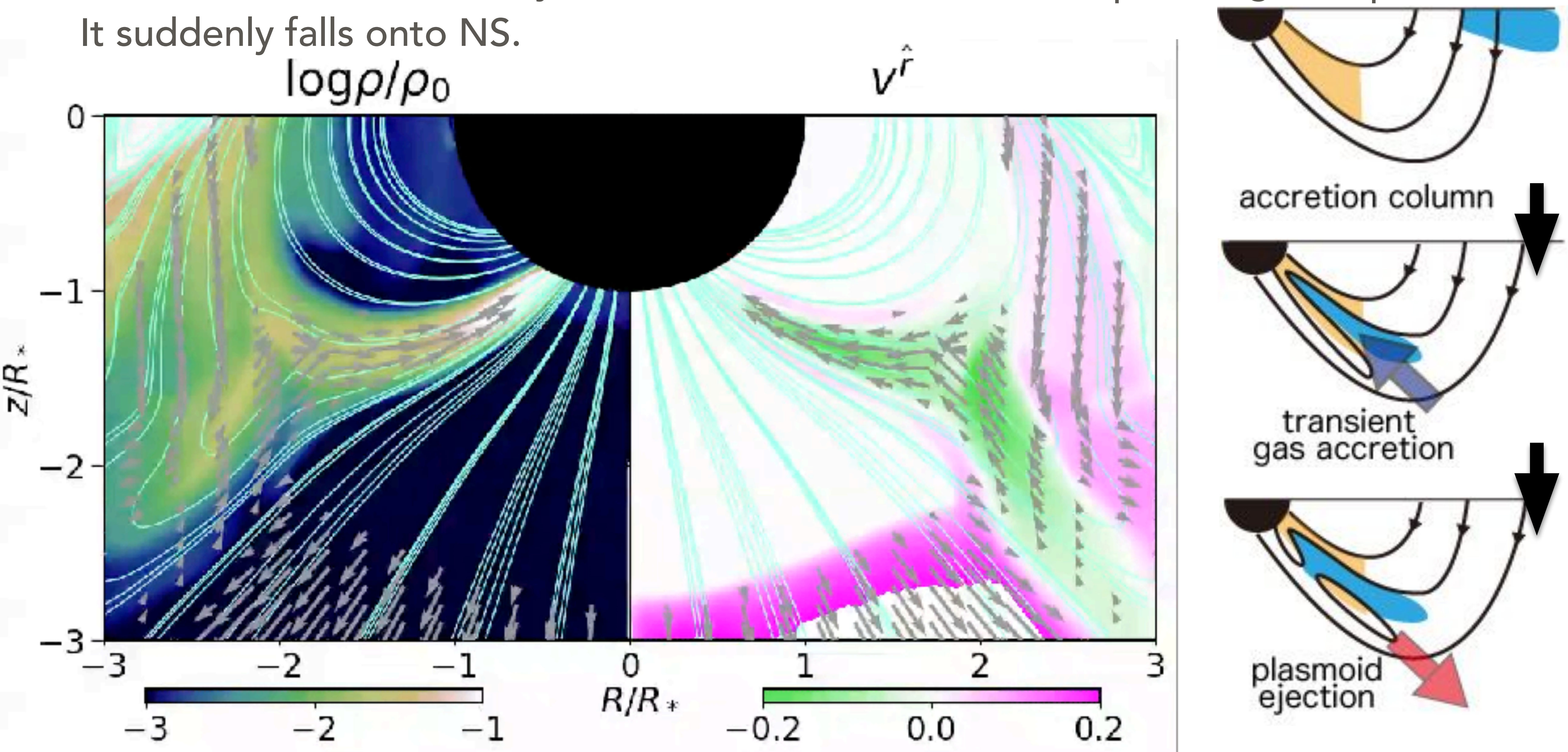
see, also Hayashi ''96, Kato '04, Ferreira'06, Romanova'12



This type of outflow takes place when the accretion disk pushes the dipole field.
When the radiation pressure balances the magnetic pressure, field lines are no more twisted.
-> This process occurs when the mass accretion rate increases.
-> This type of outflow is a transient nature.

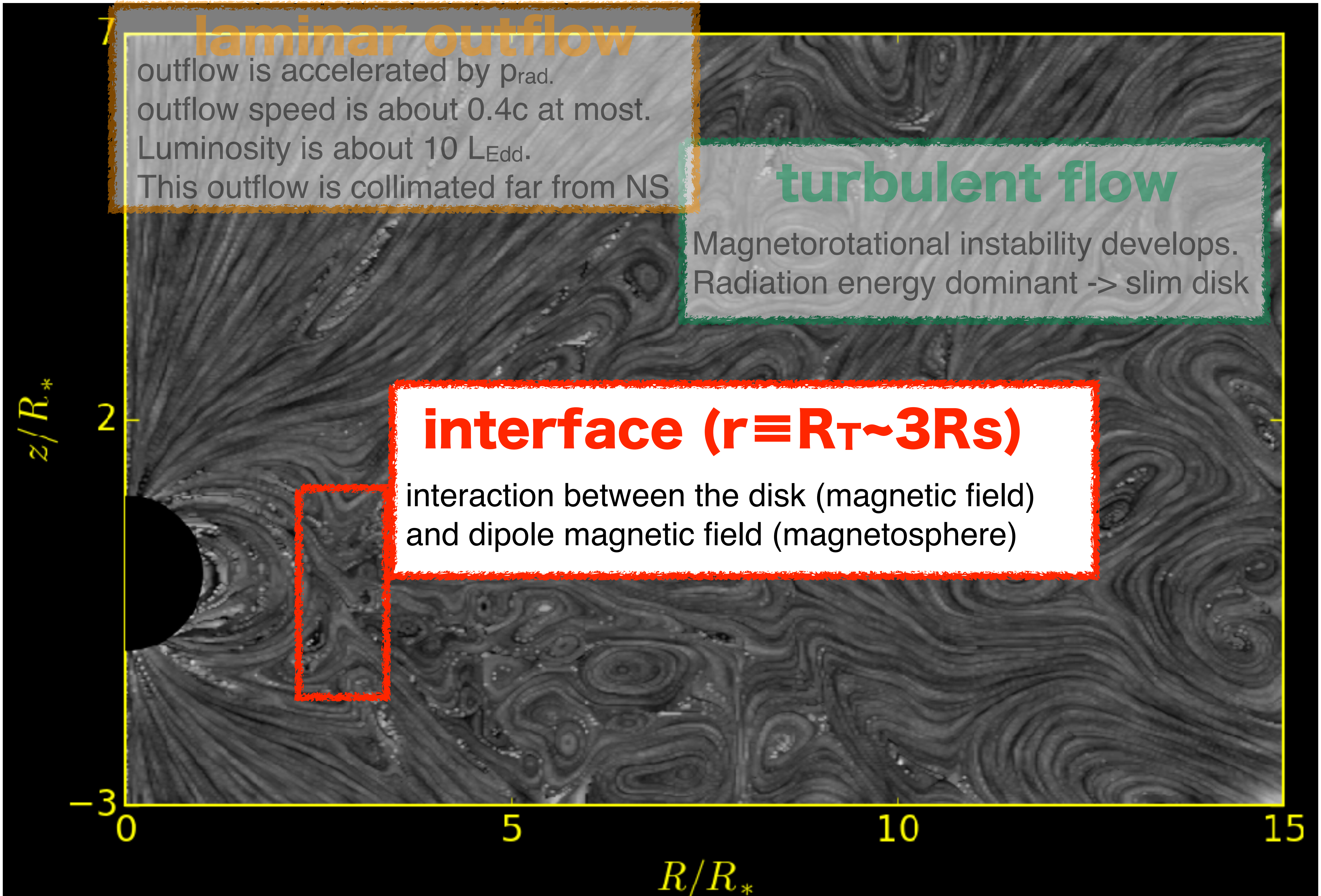
Reconnection Outflow 2

Second type of MRX-driven outflow occurs when mass falls onto the NS.
Gas accretion is not steady, but it is accumulated on the top of magnetosphere.
It suddenly falls onto NS.

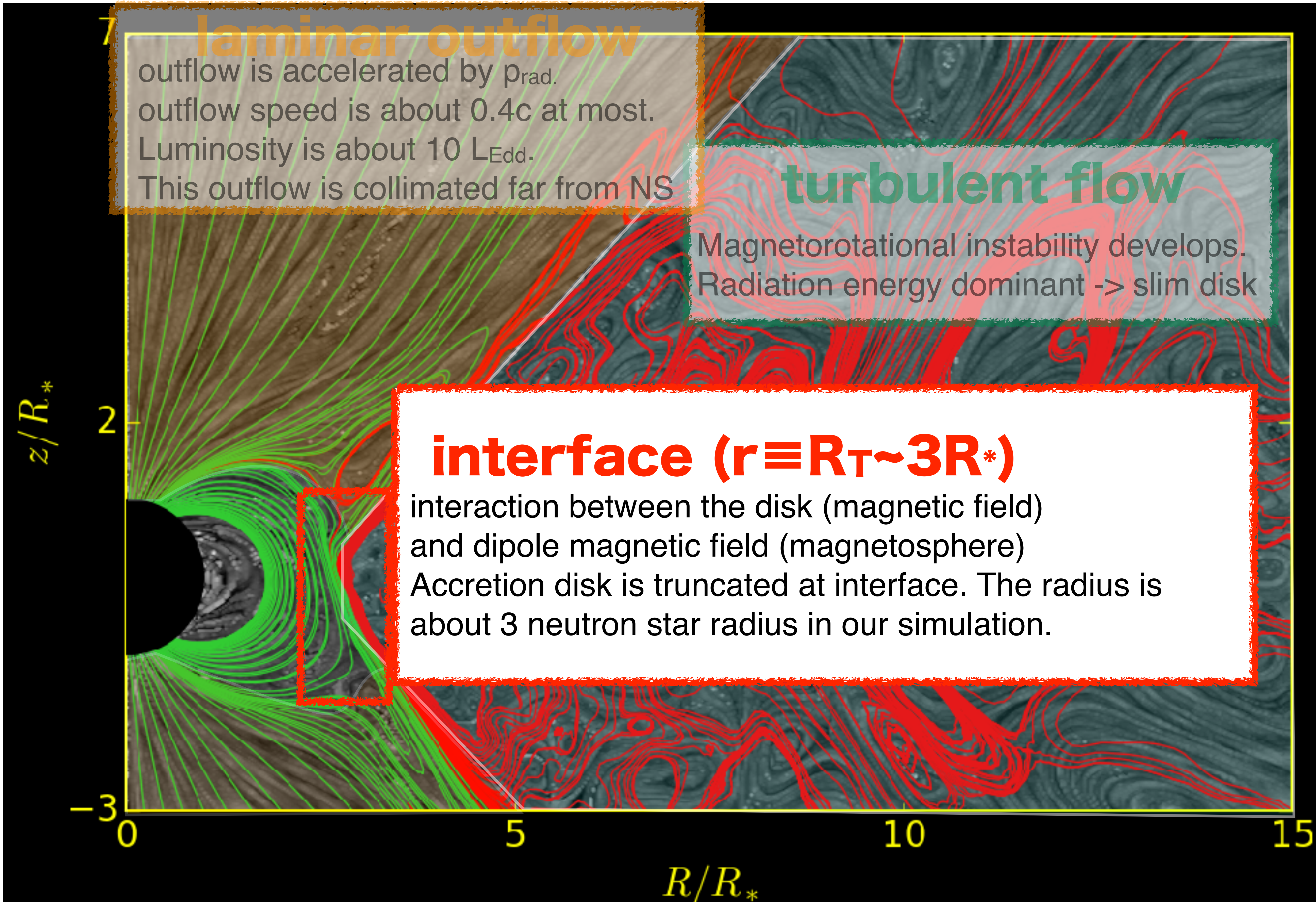


The magnetic field is folded due to the sudden accretion. The magnetic reconnection takes place in the current sheet.
The outflow velocity is 0.3c ~ Alfvén velocity.
The reconnection outflow is responsible for mass loading to outflow region.

Stream lines

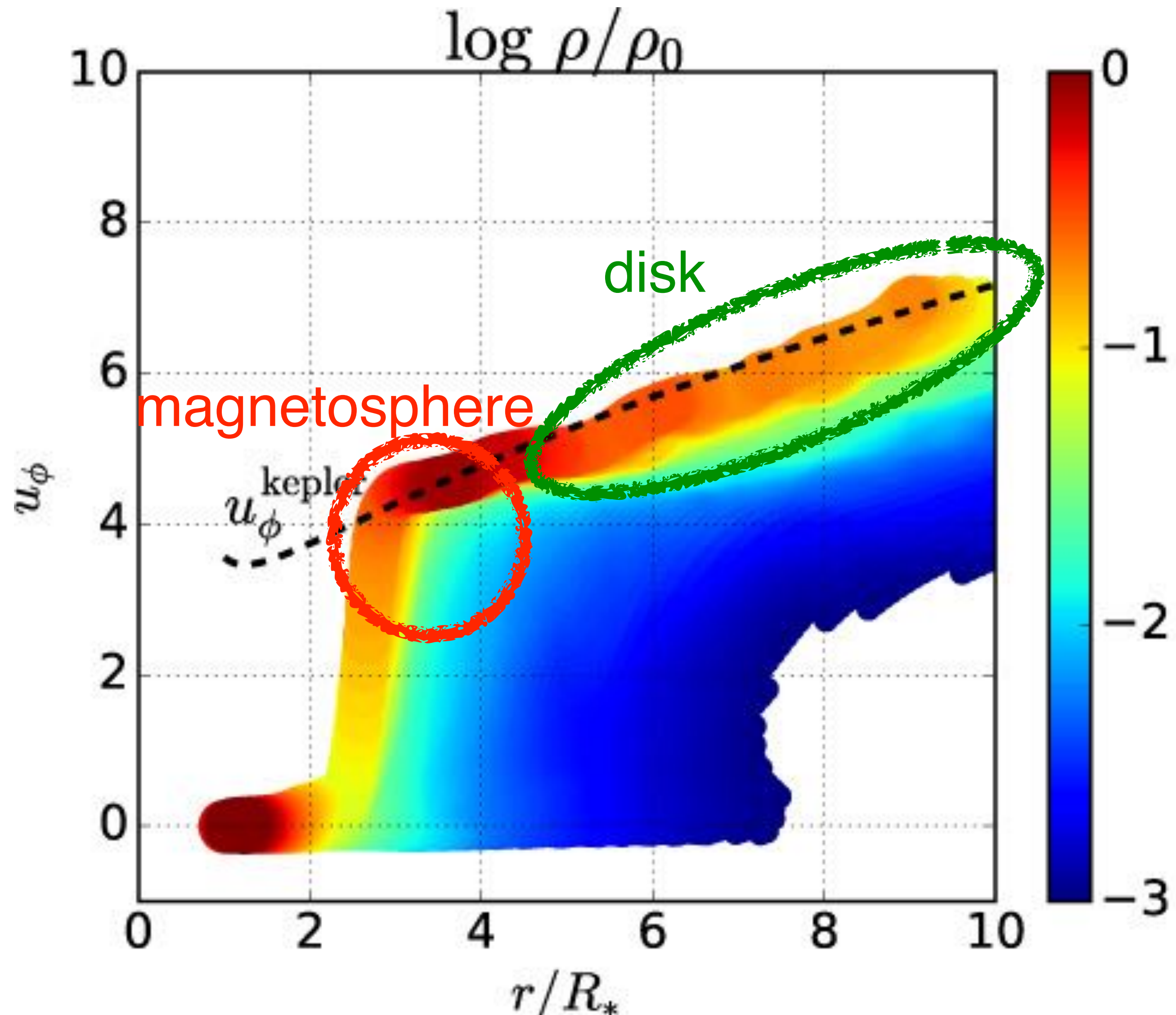


Stream lines

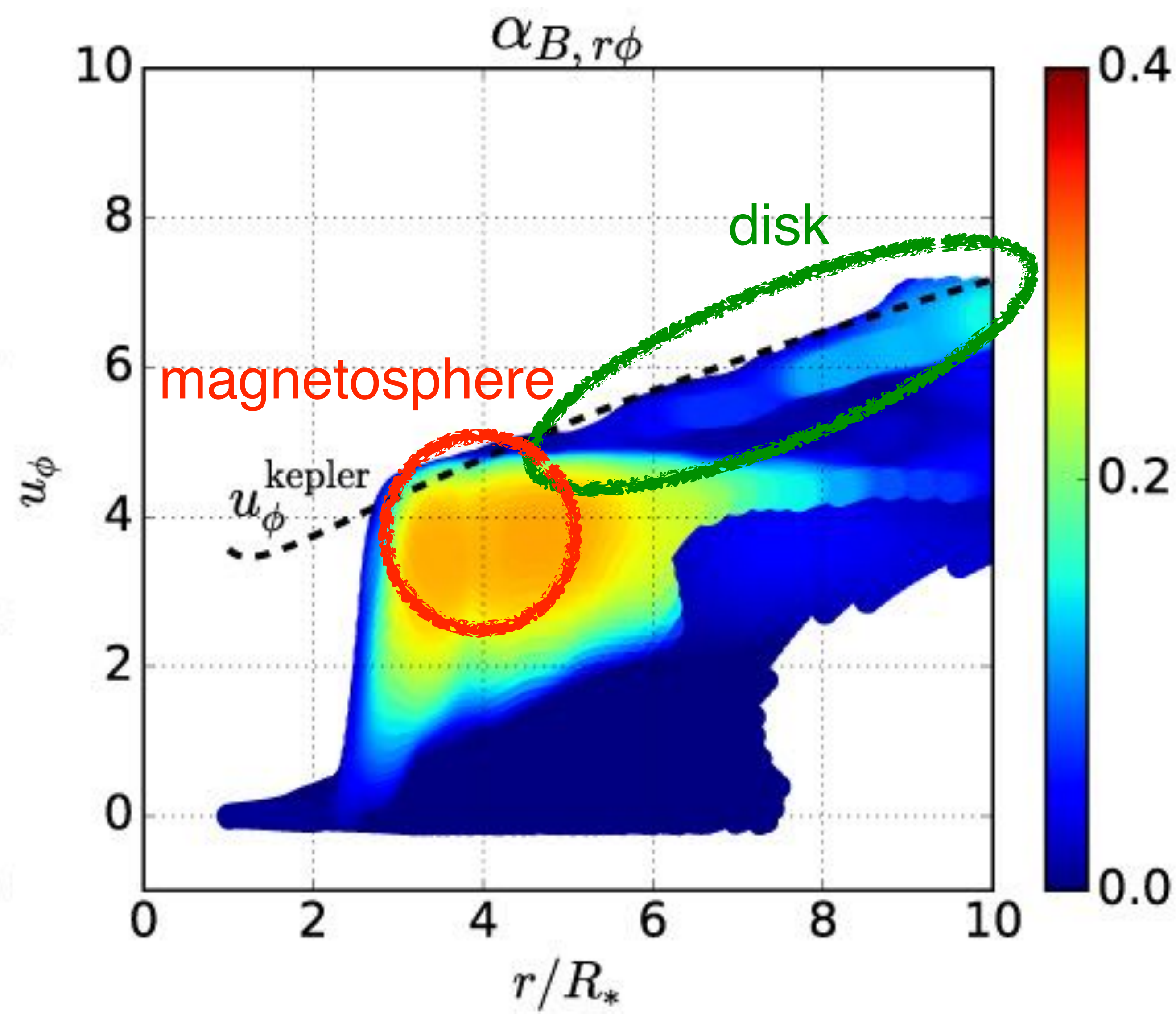


interaction between disk and dipole field

angular momentum dist.



viscous parameter dist.



Disk (r > 4R*):

most of gas has Keplerian angular momentum.

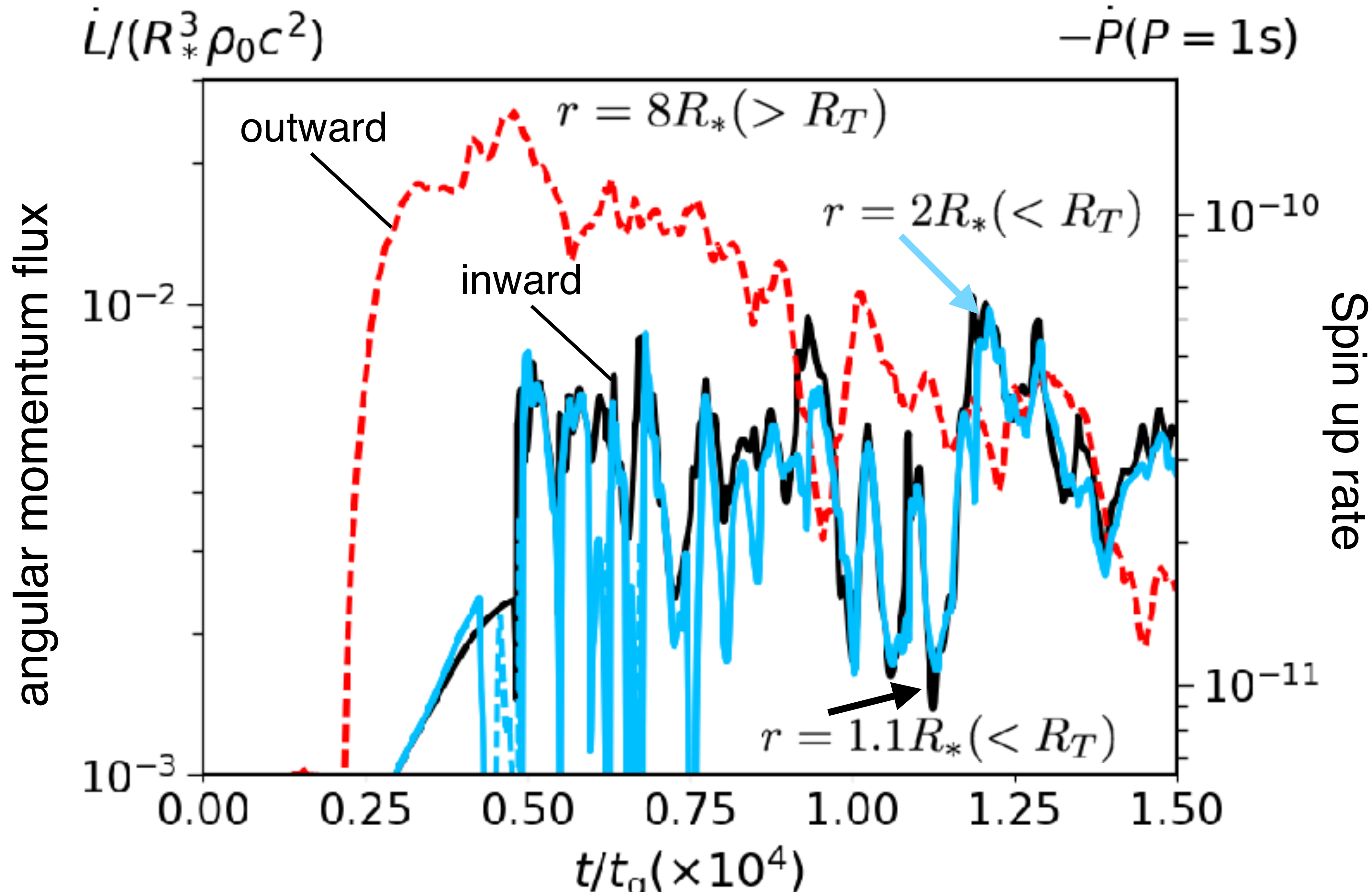
α viscosity is about 0.01 - 0.1, which is consistent with previous studies of accretion disks (ADAF and Slim disk)

At the magnetospheric radius (r~3 R_*)

Angular momentum suddenly drops to zero due to the magnetic braking.

α viscosity is larger than 0.1. <- larger than turbulent viscosity.

angular momentum flux

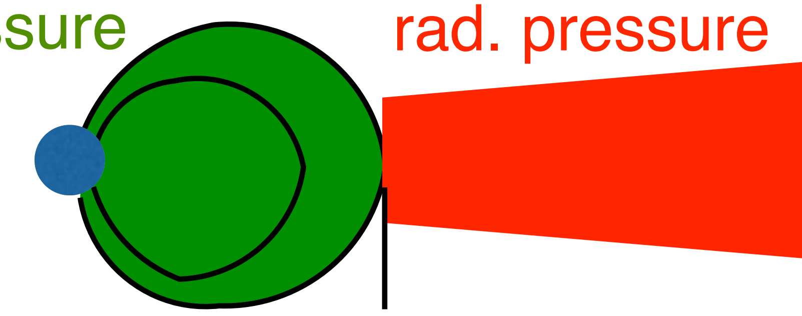


Far from truncation radius, angular momentum is transported outward.
Inside truncation radius, angular momentum is transported inward.
Assuming NS rotation period ~ 1s, spin up rate is about $3\text{x}10^{-11}$ s s^{-1}.
This value is consistent with observed spin up rate.

Discussion: Spin up rate of NS

We observed a truncation of accretion disks and spin up of NS.

$$r = r_\mathrm{T} \simeq 3R_*$$
$$\dot{P}(P = 1\mathrm{s}) = -3 \times 10^{-11}\ \mathrm{s\ s^{-1}}$$



- $p_\mathrm{mag} = p_\mathrm{rad}$ @ magnetospheric radius r_M

$$p_\mathrm{mag} = \frac{B_*^2}{8\pi}\left(\frac{r}{R_*}\right)^{-6},\ p_\mathrm{rad} = aT_\mathrm{rad}^4,\ T_\mathrm{rad} = \left(\frac{cGM_*\dot{M}}{4\pi r^4}\right)^{1/4}$$

Watarai & Fukue '99

magnetospheric radius

$$\frac{r_\mathrm{M}}{R_*} = 2\left(\frac{\dot{M}}{10^2 L_\mathrm{Edd}/c^2}\right)^{-2/7}\left(\frac{B_*}{10^{10}\ \mathrm{G}}\right)^{4/7}\left(\frac{M_*}{1.4M_\odot}\right)^{-3/7}\left(\frac{R_*}{10\ \mathrm{km}}\right)^{5/7}$$

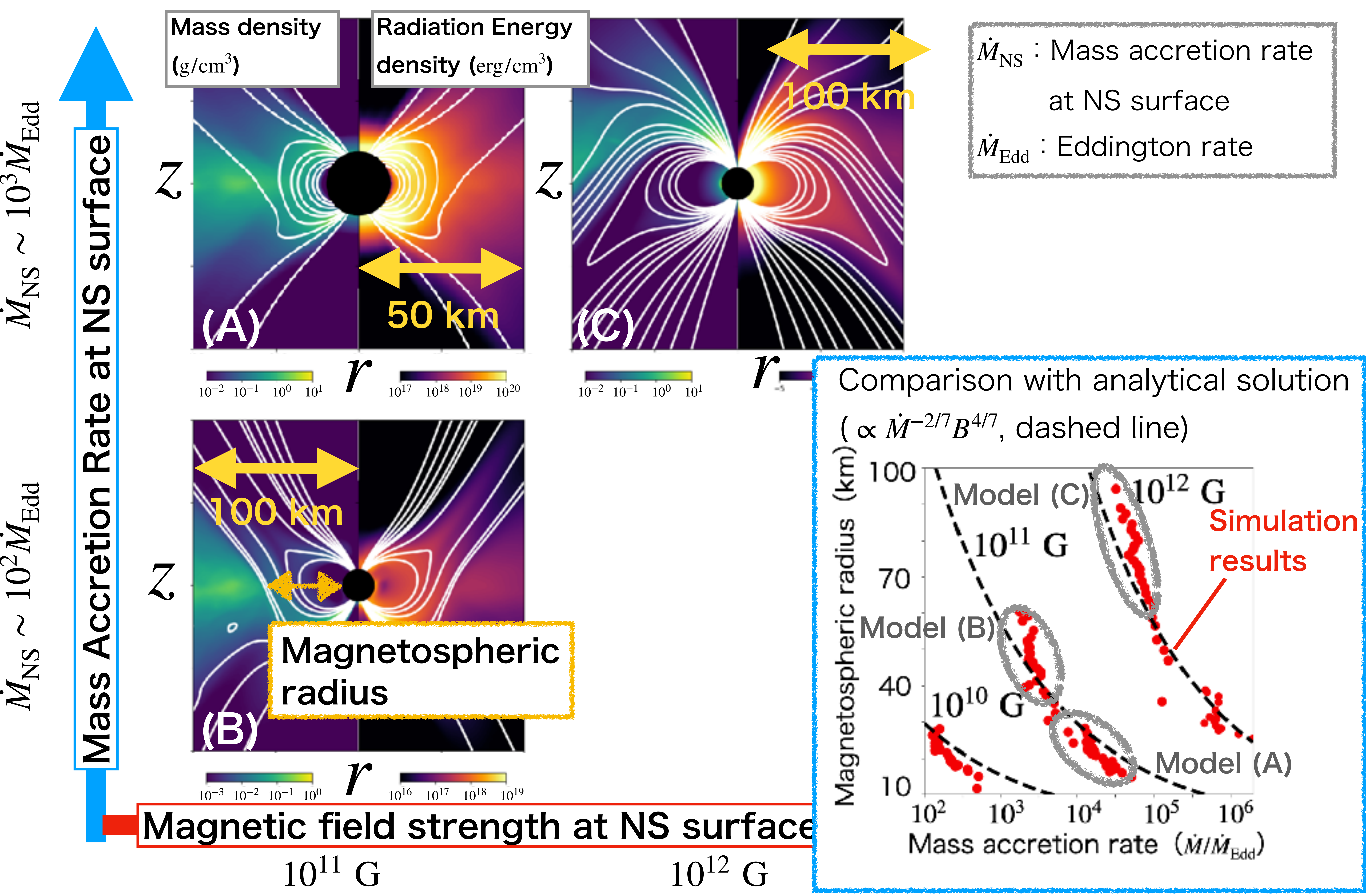
-assume keplerian angular momentum at r_M is transported to NS

spin up rate

$$\dot{P} = -\frac{\dot{M} l_\mathrm{K}(r = r_\mathrm{M})}{I\Omega}P$$
$$= -2 \times 10^{-11}\ \mathrm{s\ s^{-1}}\left(\frac{\dot{M}}{10^2 L_\mathrm{Edd}/c^2}\right)^{6/7}\left(\frac{B_*}{10^{10}\ \mathrm{G}}\right)^{2/7}\left(\frac{M_*}{1.4M_\odot}\right)^{2/7}\left(\frac{R_*}{10\ \mathrm{km}}\right)^{-8/7}\left(\frac{P}{1\ \mathrm{s}}\right)^{2}$$

These analytic solutions are consistent with numerical results.
But we only check the case for $B_0 = 10^{10}$ G, and $\dot{M} = 100\dot{M}_\mathrm{crit}$.

See Poster by Inoue : Dependence of B



Summary of my talk

GR-RMHD simulations has been well developed by authors.

We can perform realistic simulations of accretion flow onto BH / NS.

Q: How the jet is accelerated in supercritical accretion disks?

A: The jet is accelerated by the radiation pressure force v~0.3c

Q: Which is more powerful, BH, or NS ?

rapidly rotating BH > NS > non-rotating BH

But we only study a case for $\dot{M} \sim 100\dot{M}_{\rm crit}$.

<- It depends on the mass accretion rate ? -> future work

Q: Supercritical Accretion is possible to weakly magnetized NS?

Yes. radiation force is not strong sufficient to blow the gas away.

Q: Supercritical Accretion is possible to magnetized NS?

Yes. Accretion column forms near the magnetic pole.

Angular momentum is efficiently transferred to NS -> spin up.

Brief Summary 3: Neutron Star

We performed 2-dimensional GRRMHD simulations to study gas accretion onto the NS.

- For NS, the gas and energy is accumulated on the NS surface.

- Since the energy is swallowed by central star like BH, the energy is transported outward, and it forms stronger outflows than BH.

- When the central object is rotating, the black hole is more powerful than NS due to the BZ effects

-> The total power is

rotating BH > non rotating NS > non rotating BH

(Poynting) (Kinetic) (Radiative)

Summary of my talk

Q: How the jet is accelerated in supercritical accretion disks?

A: The jet is accelerated by the radiation pressure force v~0.3c

Q: How the hot corona is formed near the black hole?

A: Dynamical (infalling) time becomes shorter than the cooling time.

Size of the hot corona depends on the mass accretion rate.

Q: Which is more powerful, BH, or NS ?

A: Rapidly rotating BH is the most powerful source

← BH spin energy is available

NS is powerful following to rapidly rotating BH

← energy is not swallowed by NS

Non-rotating BH is the least powerful source.

← energy is swallowed by BH