星周円盤から星へのガス降着に関する
３次元磁気流体シミュレーション

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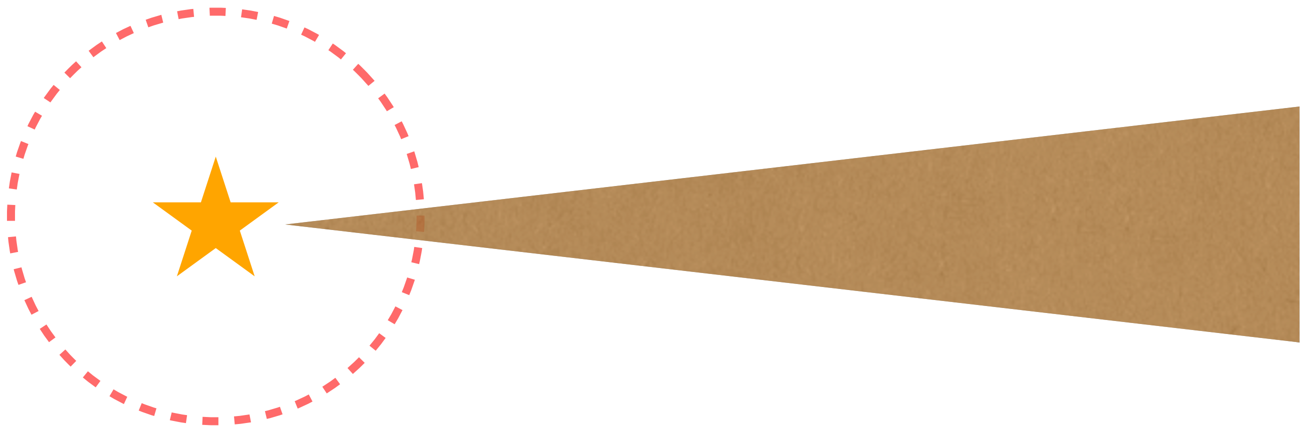
Accretion onto protostars/pre-main-seq. stars

- Mass/ang. mom. evolution of stars
- Similarity with other accreting systems
  (e.g. neutron stars)
- Influence on the global protoplanetary disk evolution via
  occultation of the stellar radiation (shadowing effect)

Structure of the inner region?



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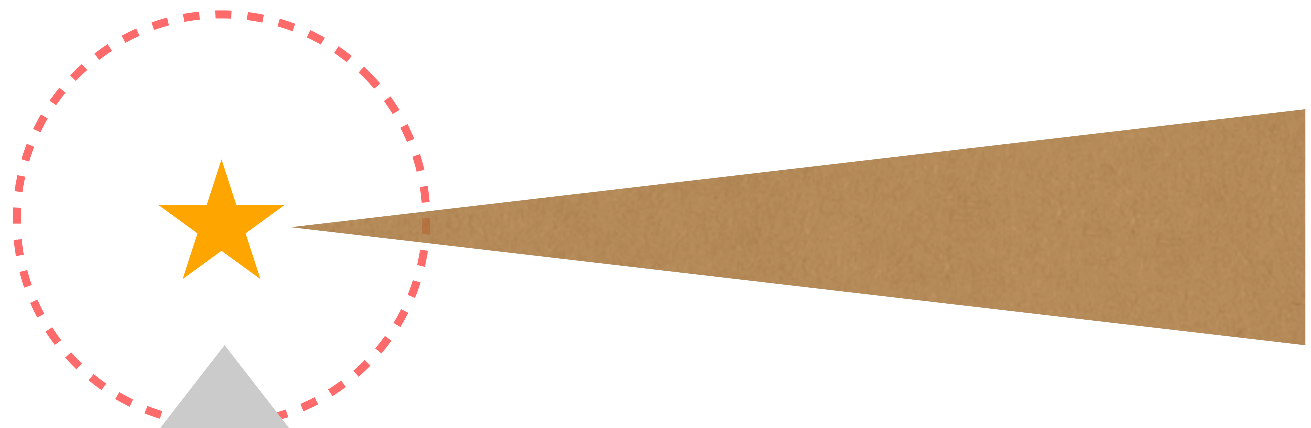


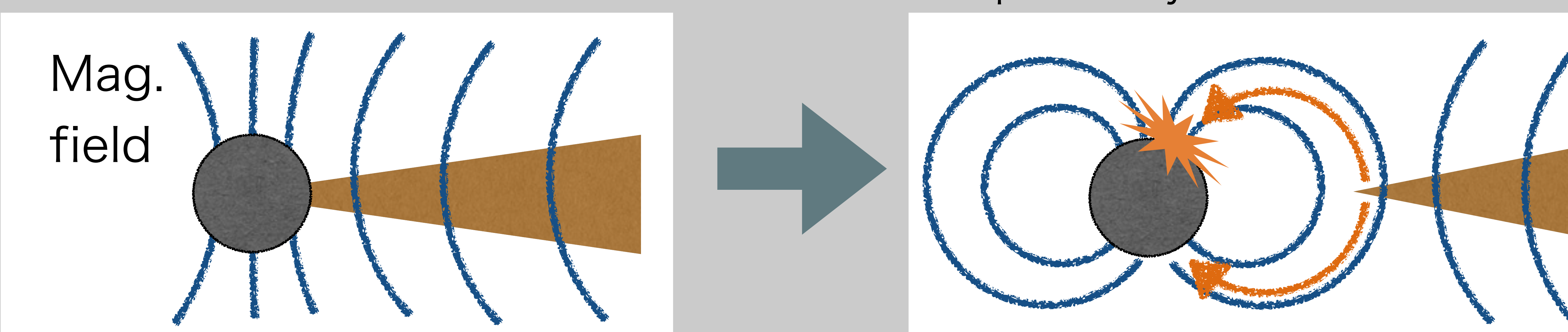
Classical picture

- ➤ UV excess compared to the stellar emission
- ➤ Hot spots at high latitudes

quiet **disk accretion**

Magnetospheric Accretion

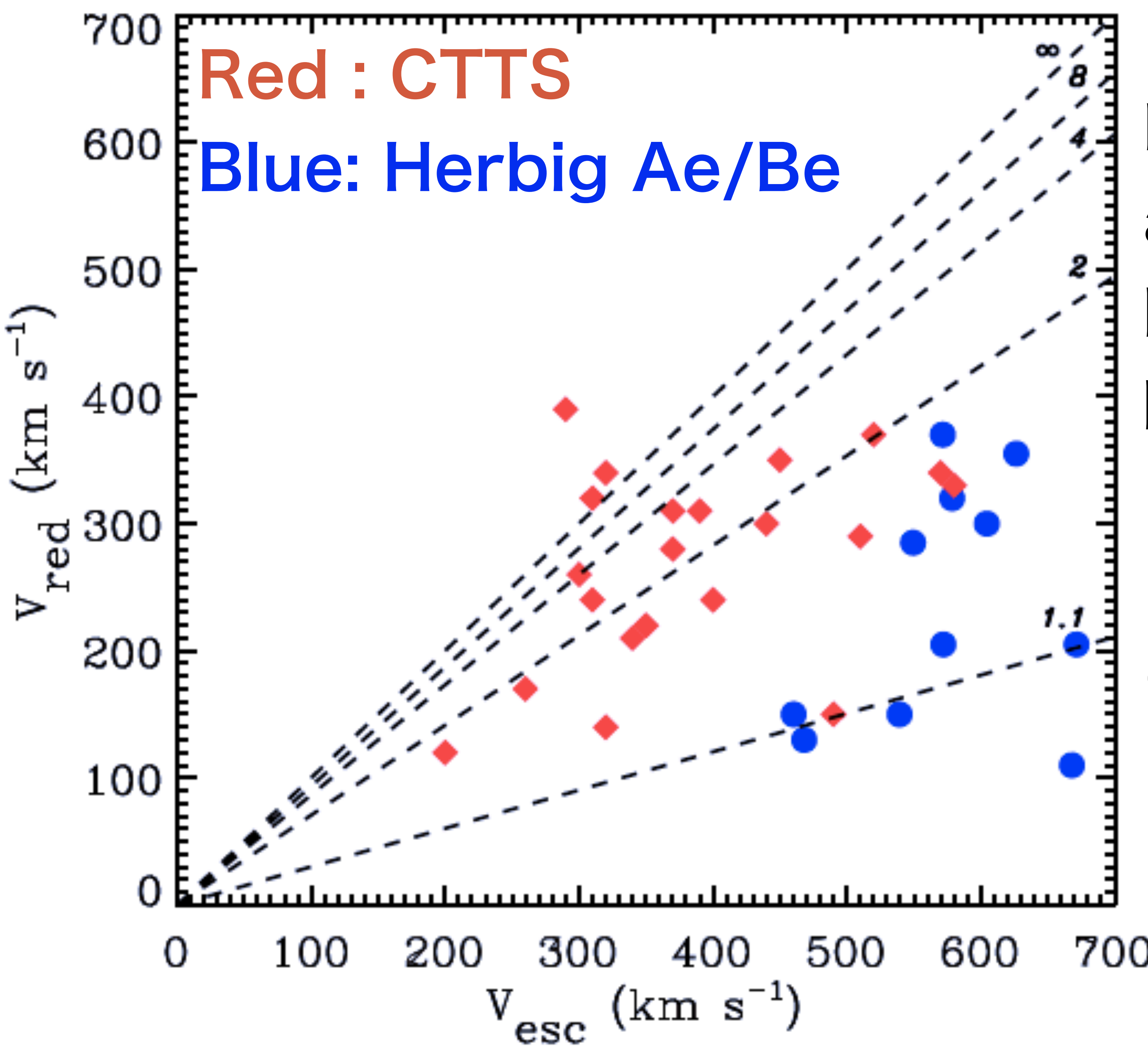
accompanied by **the accretion shock**



e.g. Konigl 1991

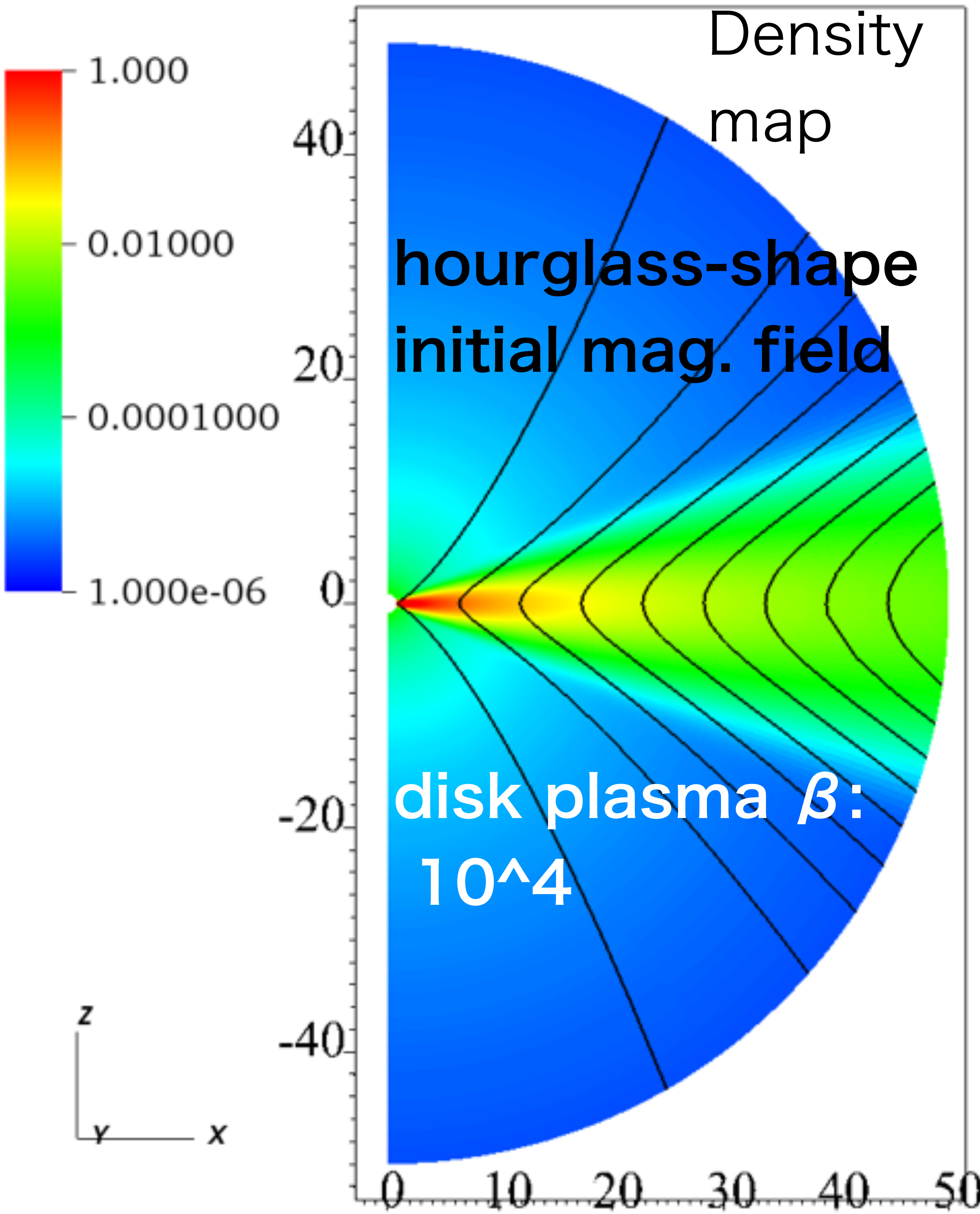
Magnetospheric accretion even in weak B-field stars?

Herbig Ae/Be: intermediate mass stars at the PMS stage. **The fraction of magnetic (> ~100 G) stars is only ~10% (Wade+2007)**
—> **too weak B-field for magnetospheric acc.**



Magnetospheric acc.:
accretion speed ~ free fall velocity
Herbig Ae stars also have a large accretion speed
(although it's smaller than
that of CTTS).
(Cauley & Johns-Krull 14)

Setting of 3D MHD simulation: Accretion onto a star without a magnetosphere



Code : Athena++

(Stone, Tomida, White in prep)

- ideal MHD (OK for this region)
- Spherical coordinate (4π covered)

A self-similar atmospheric structure is adopted:

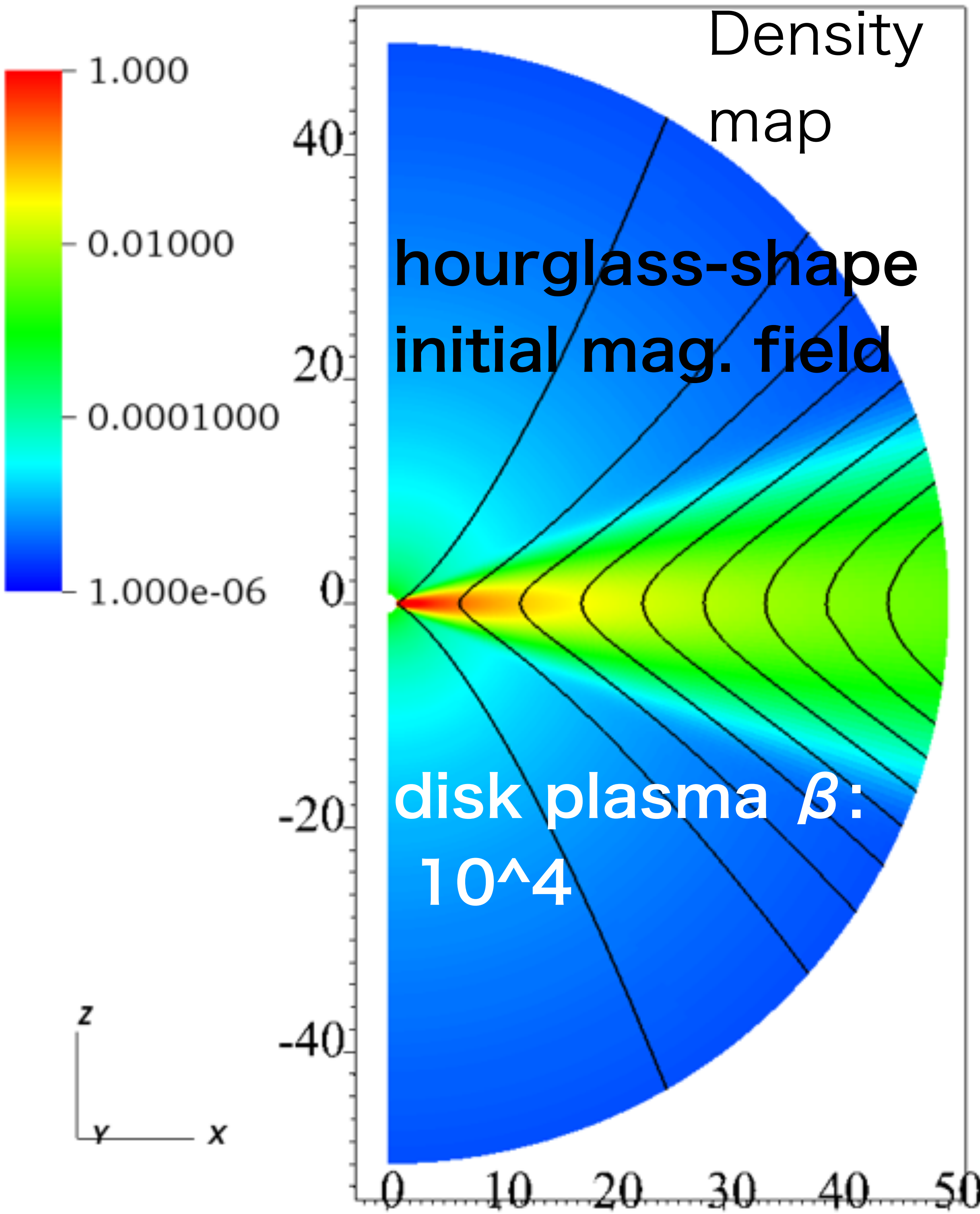
$$V_K, C_s, V_A \propto r^{-1/2}$$

$$H/r = 0.14 \text{ (thin disk)}$$

in the midplane

stellar rotation included (corotation radius = 3 Rstar)

Setting of 3D MHD simulation: Accretion onto a star without a magnetosphere



Code : Athena++

(Stone, Tomida, White in prep)

- ideal MHD (OK for this region)
- Spherical coordinate (4π covered)
- Modelled stellar surface

↓

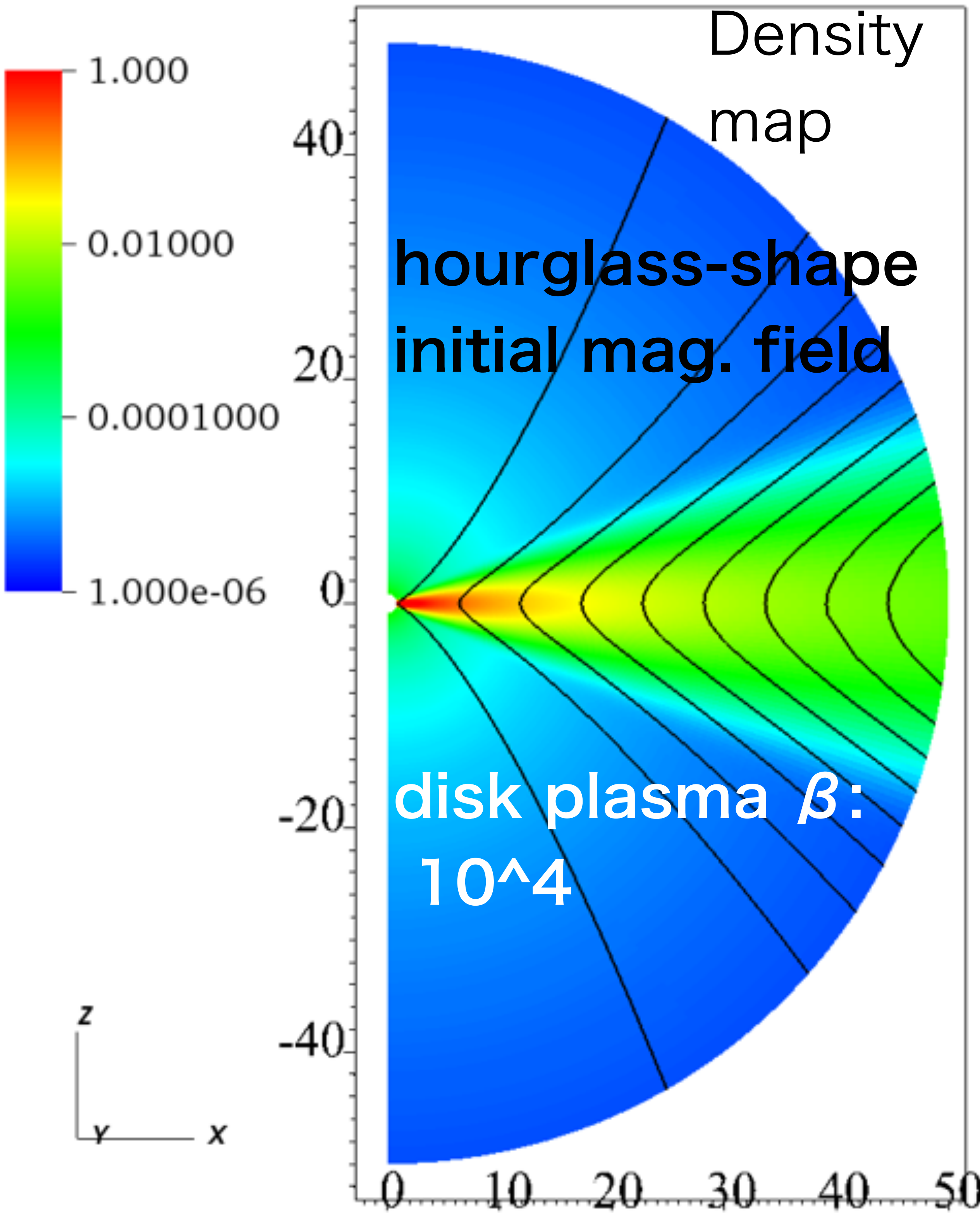
- Stellar surface behaves as a “wall”
- Star absorbs the accreting matter
- Stellar wind blows from the corona

Solve $$\frac{\partial q}{\partial t} = -\frac{q - q_0}{\tau}$$ in a thin shell around the star

q: density, velocity, pressure

so-called **damping layer**

Setting of 3D MHD simulation: Accretion onto a star without a magnetosphere



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- ideal MHD (OK for this region)
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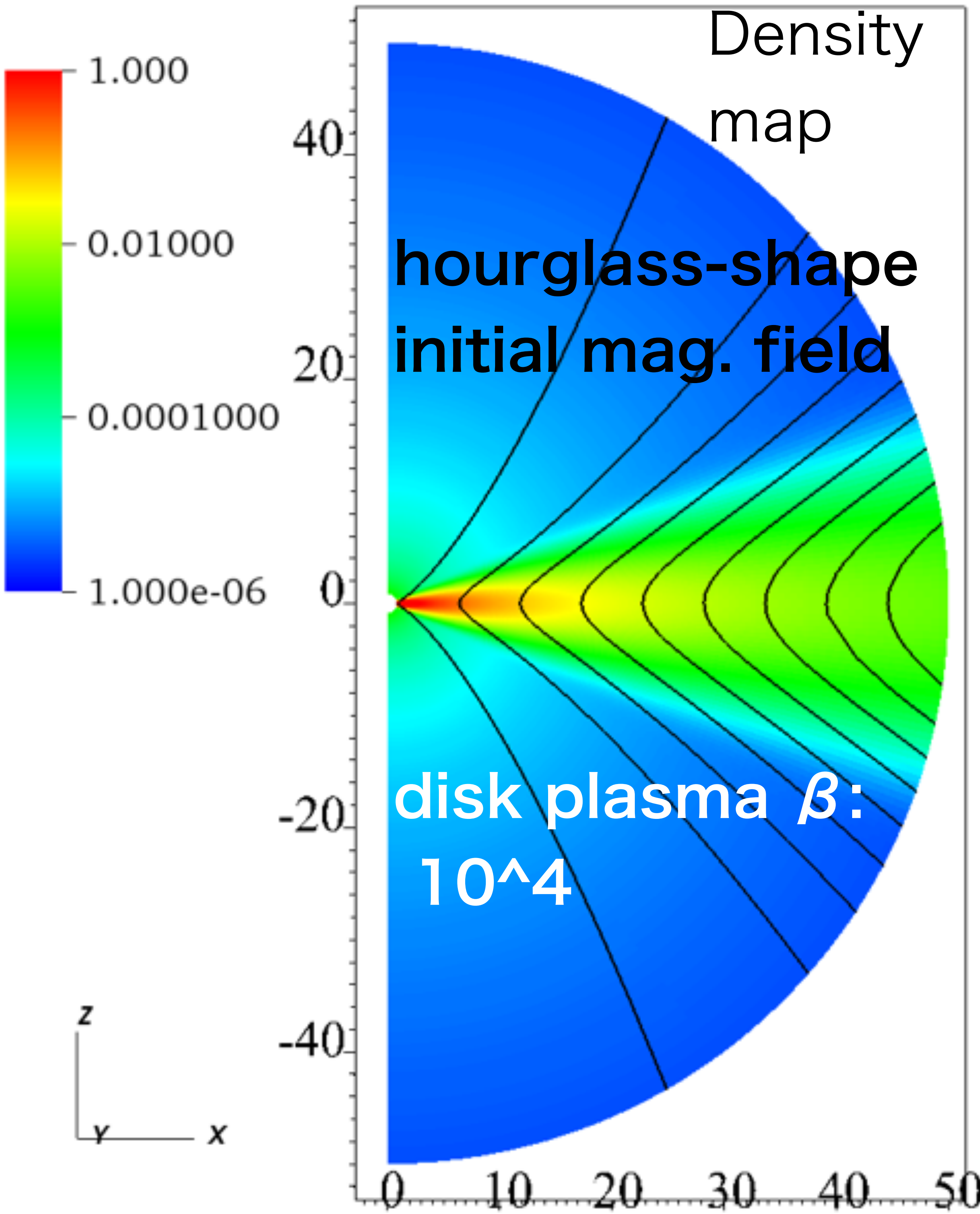
- Simplified rad. cooling in the disk

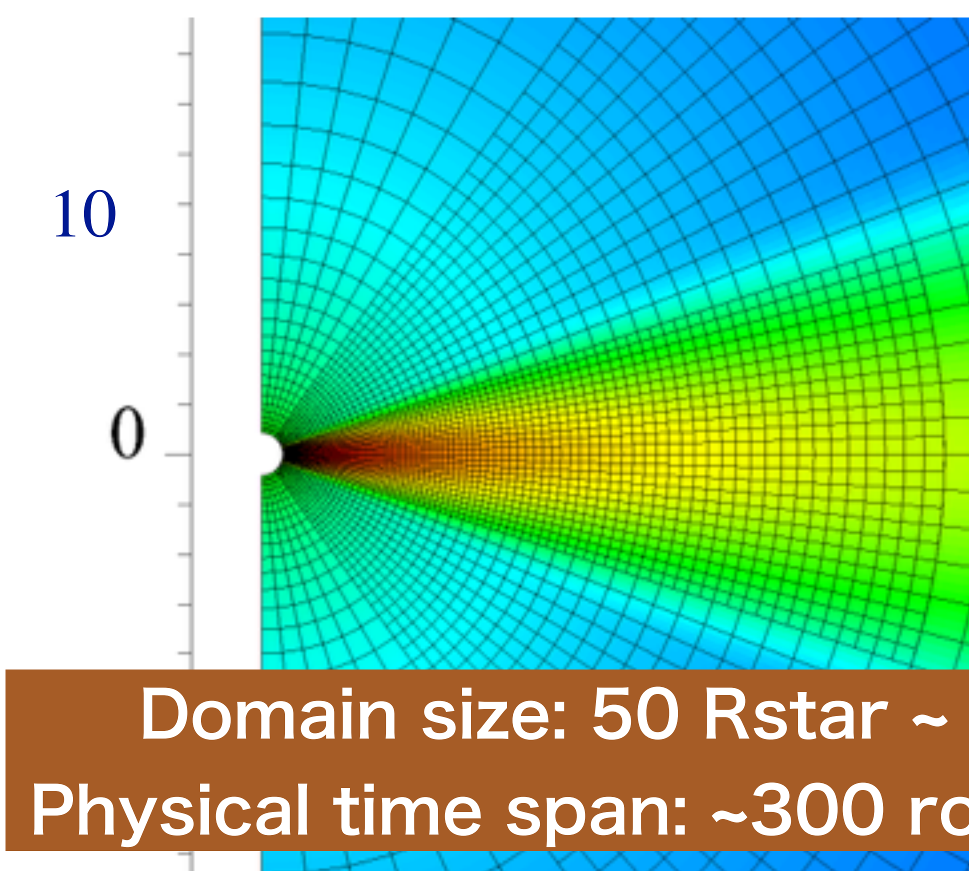
Setting of 3D MHD simulation: Accretion onto a star without a magnetosphere



Code : Athena++

(Stone, Tomida, White in prep)

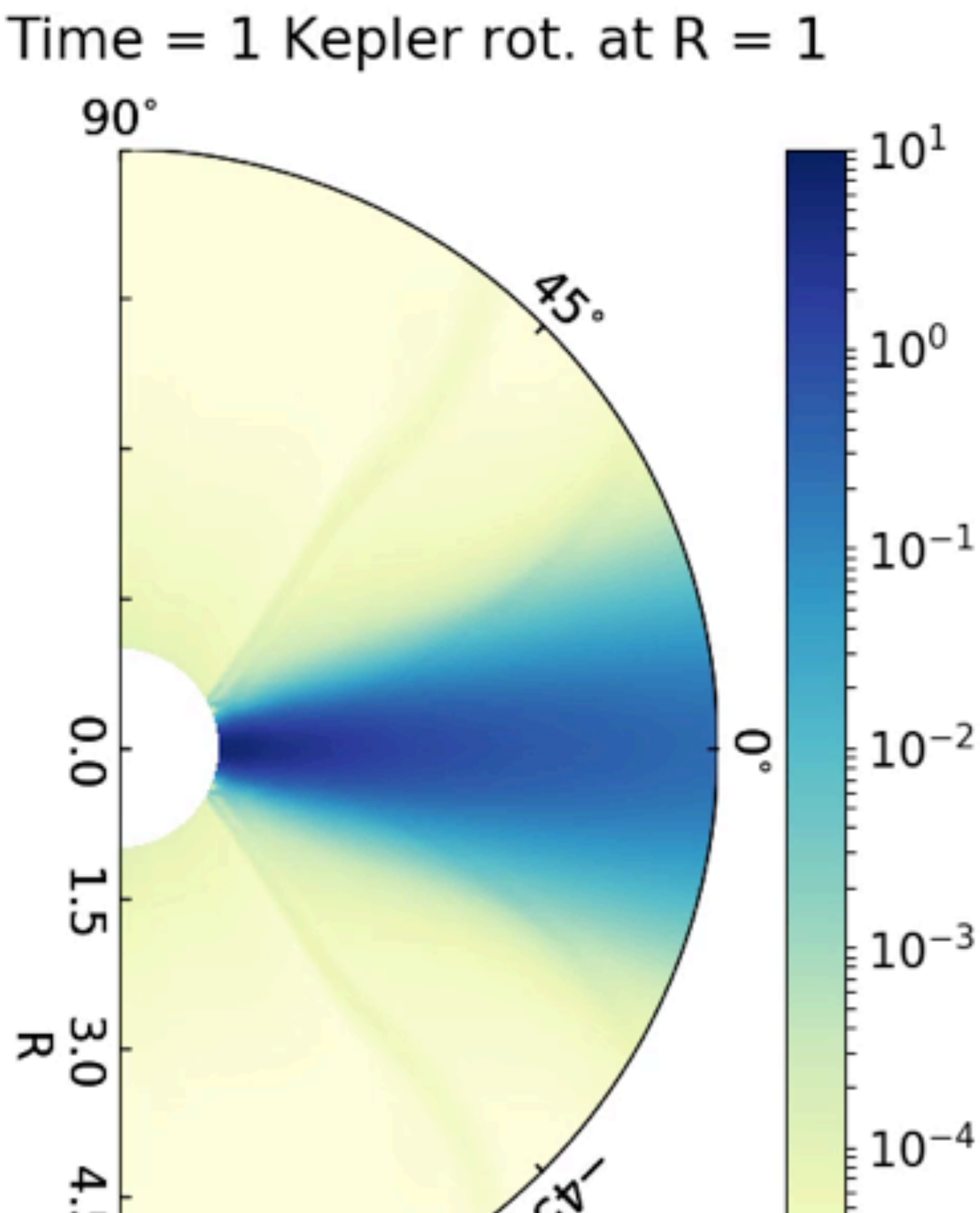
- ideal MHD (OK for this region)
- Spherical coordinate (4π covered)
- Modelled stellar surface
- Simplified rad. cooling in the disk
- MRI resolved with the nested grid



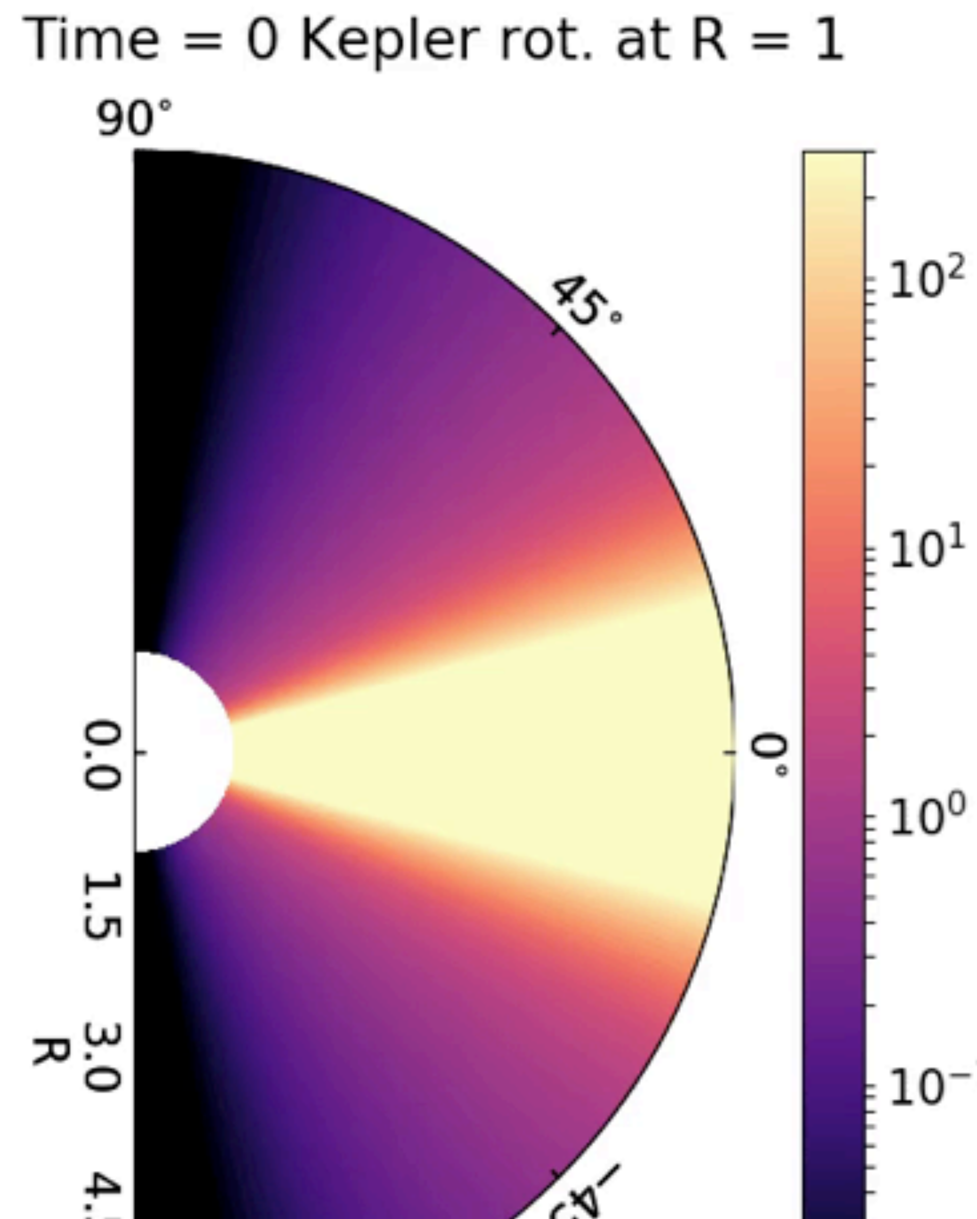
Domain size: 50 Rstar ~ 0.5 au
Physical time span: ~300 rot ~ 0.4 yr

Gas map around the star

Density

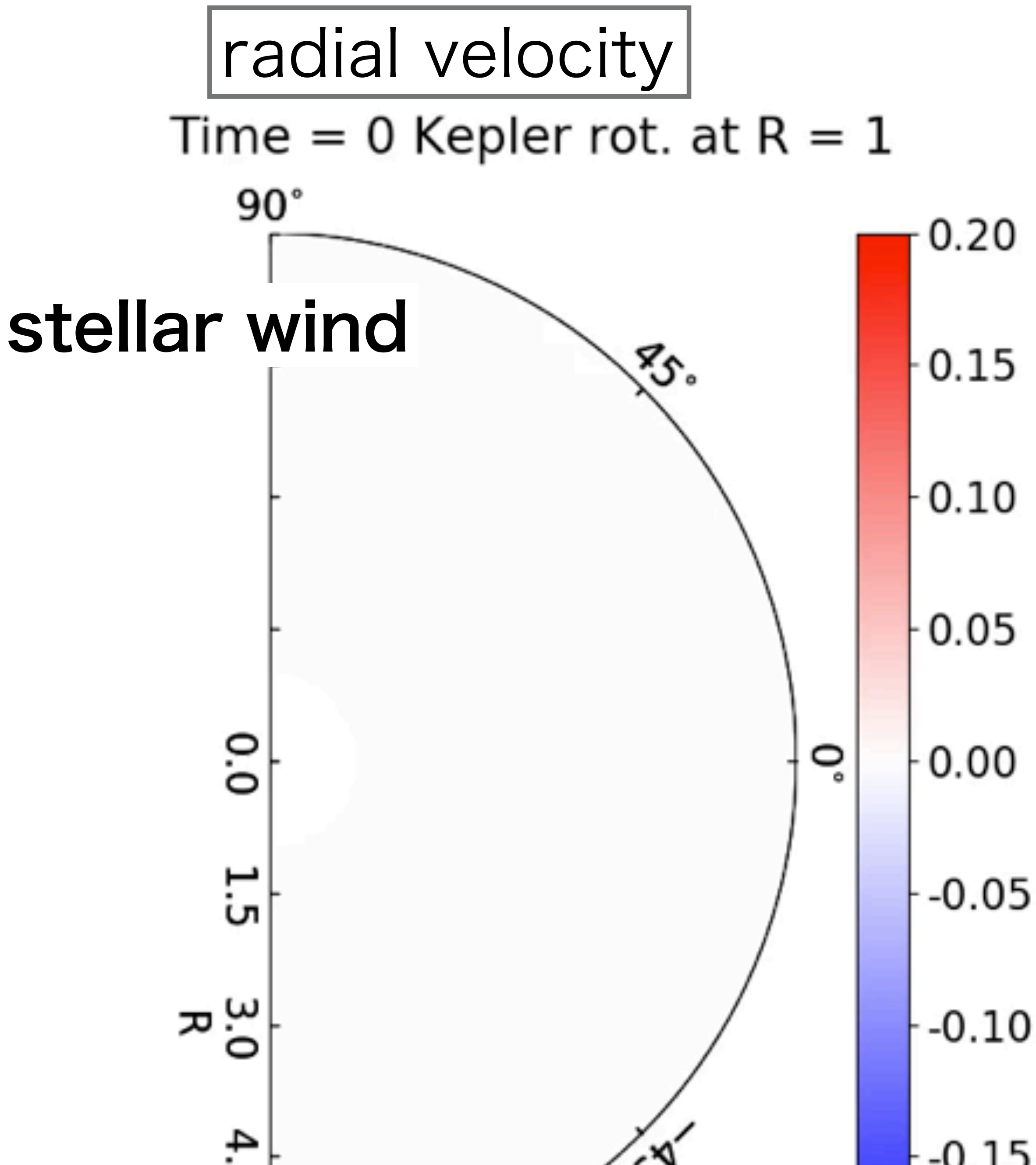


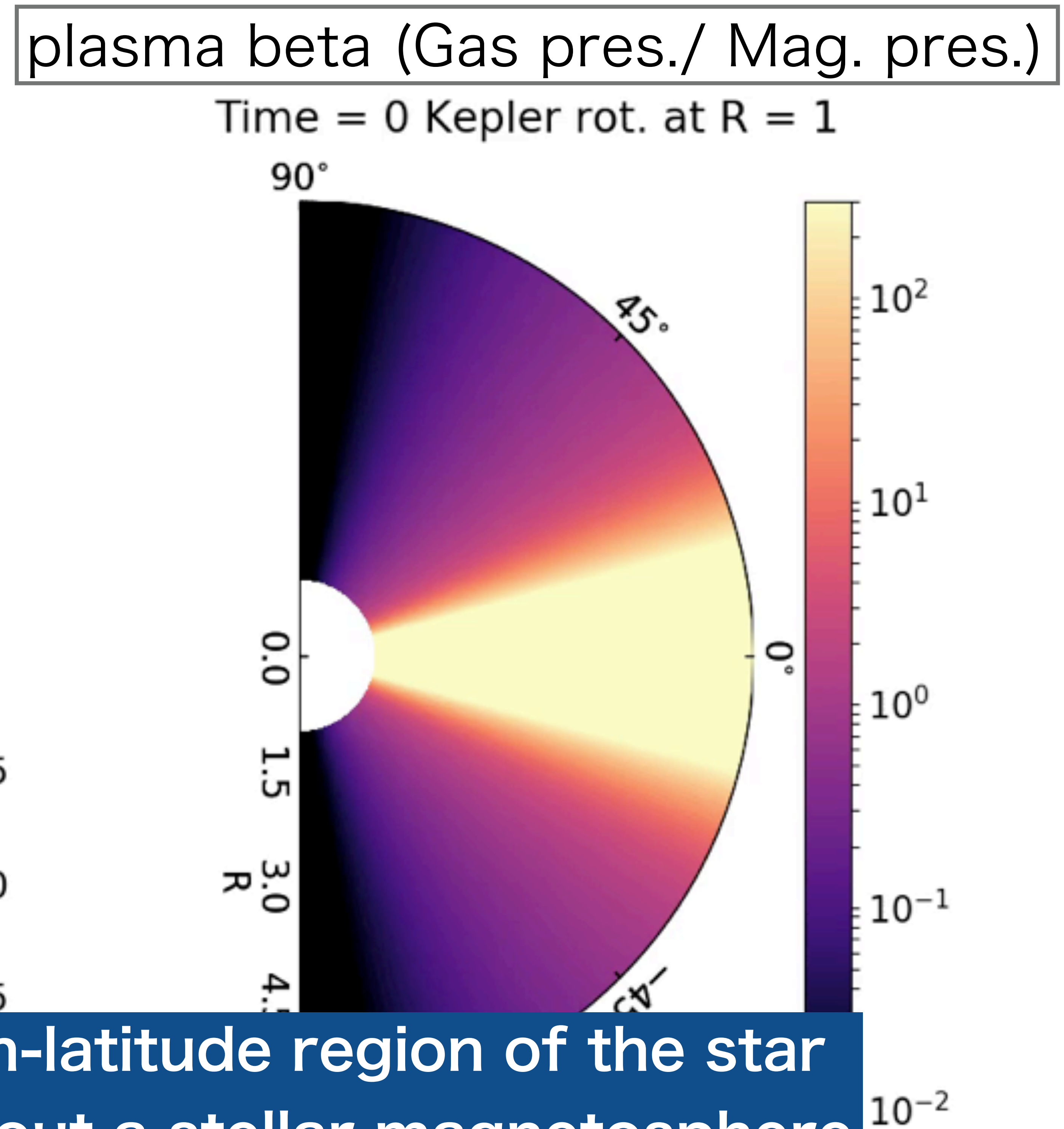
plasma beta (Gas pres./ Mag. pres.)



Highly fluctuating/turbulent disk atmosphere
(source of turbulence: MagnetoRotational Instability, MRI)

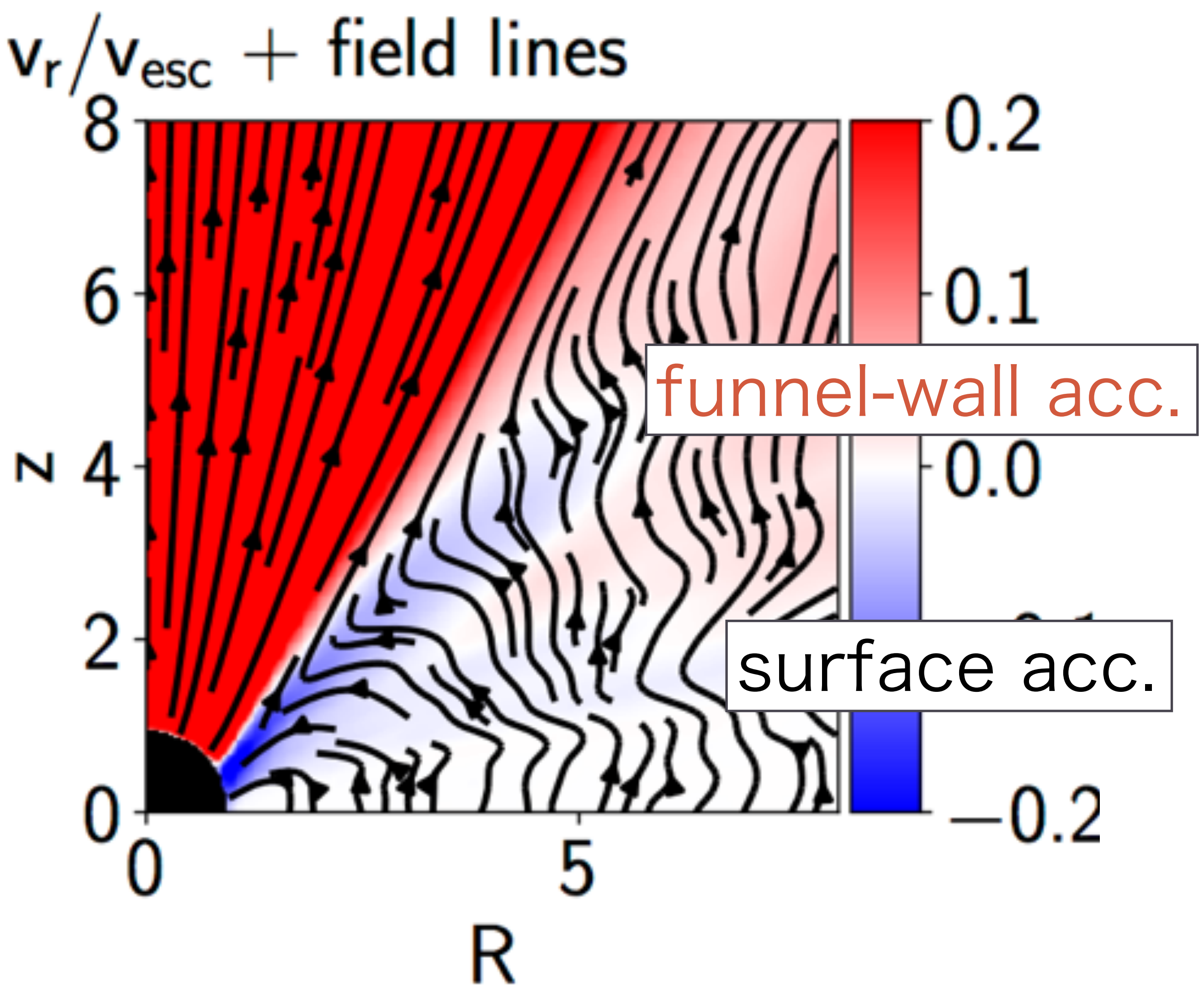
Gas map around the star

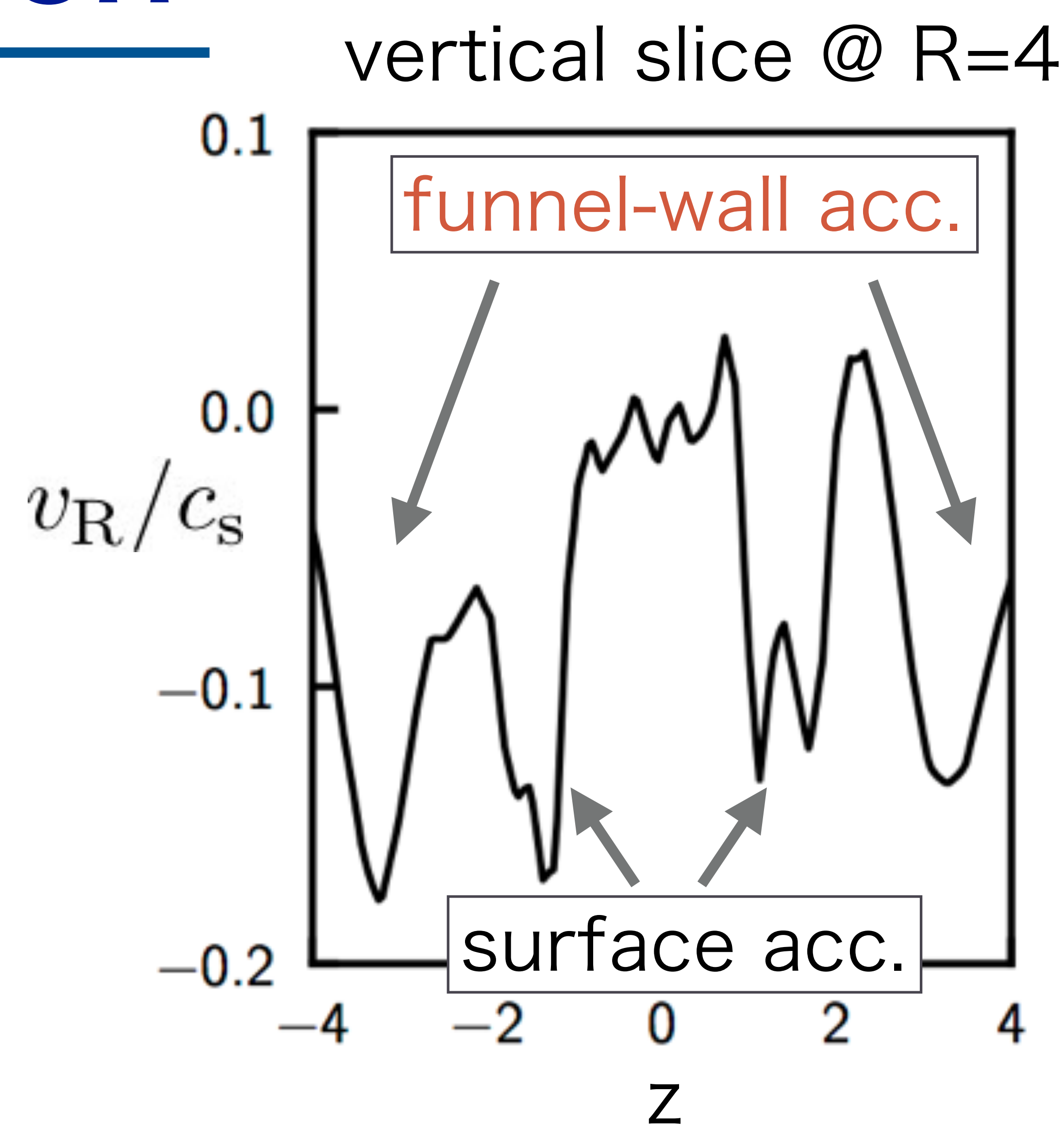




Fast accretion to a high-latitude region of the star is established even without a stellar magnetosphere

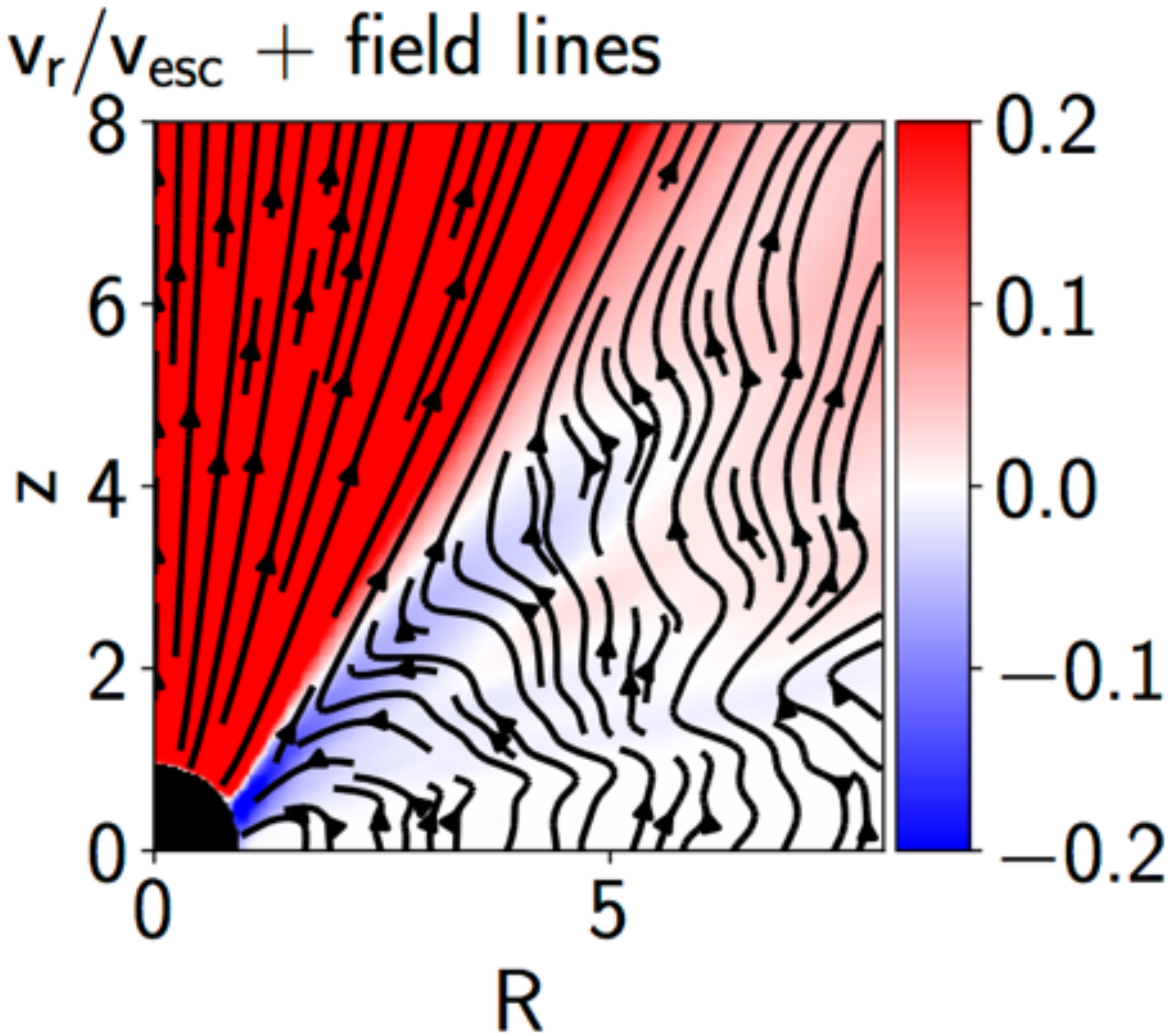
Funnel-wall accretion

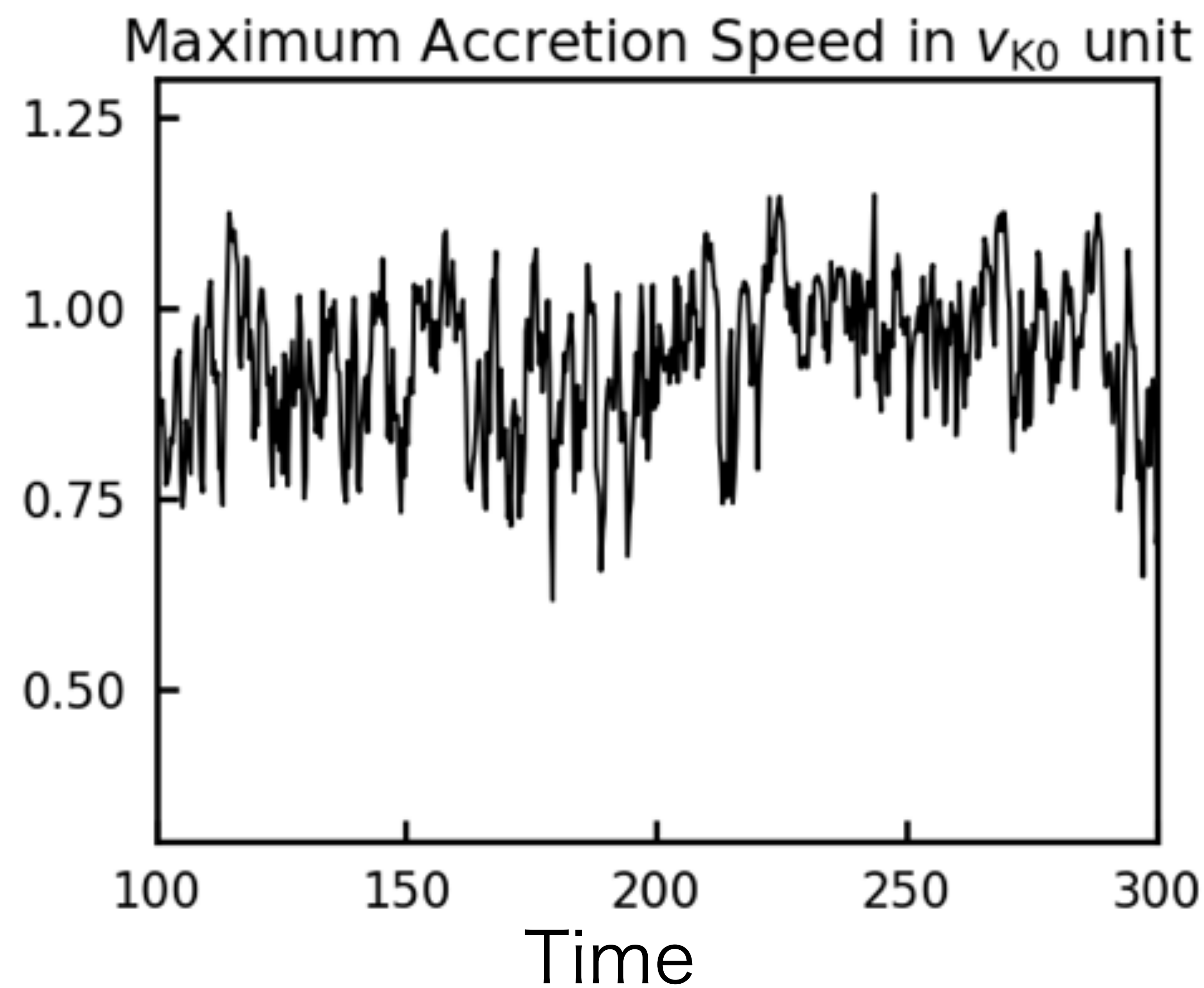




- Similarity with funnel-wall jets seen in BH disk simulations (e.g. Hawley & Balbus 2002), we call it funnel-wall accretion.
- Accretion streams do not fall along a magnetic field line

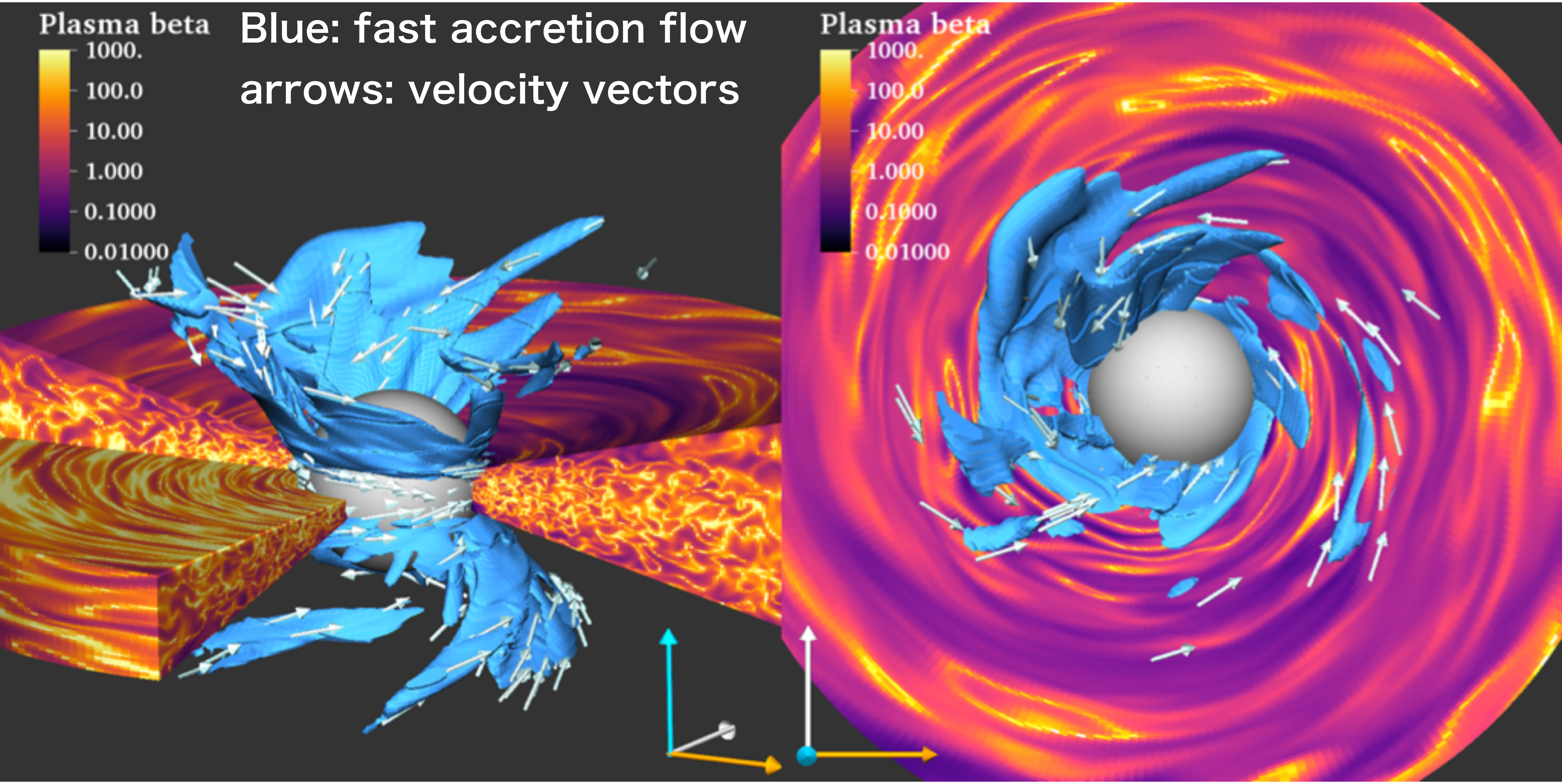
Funnel-wall accretion





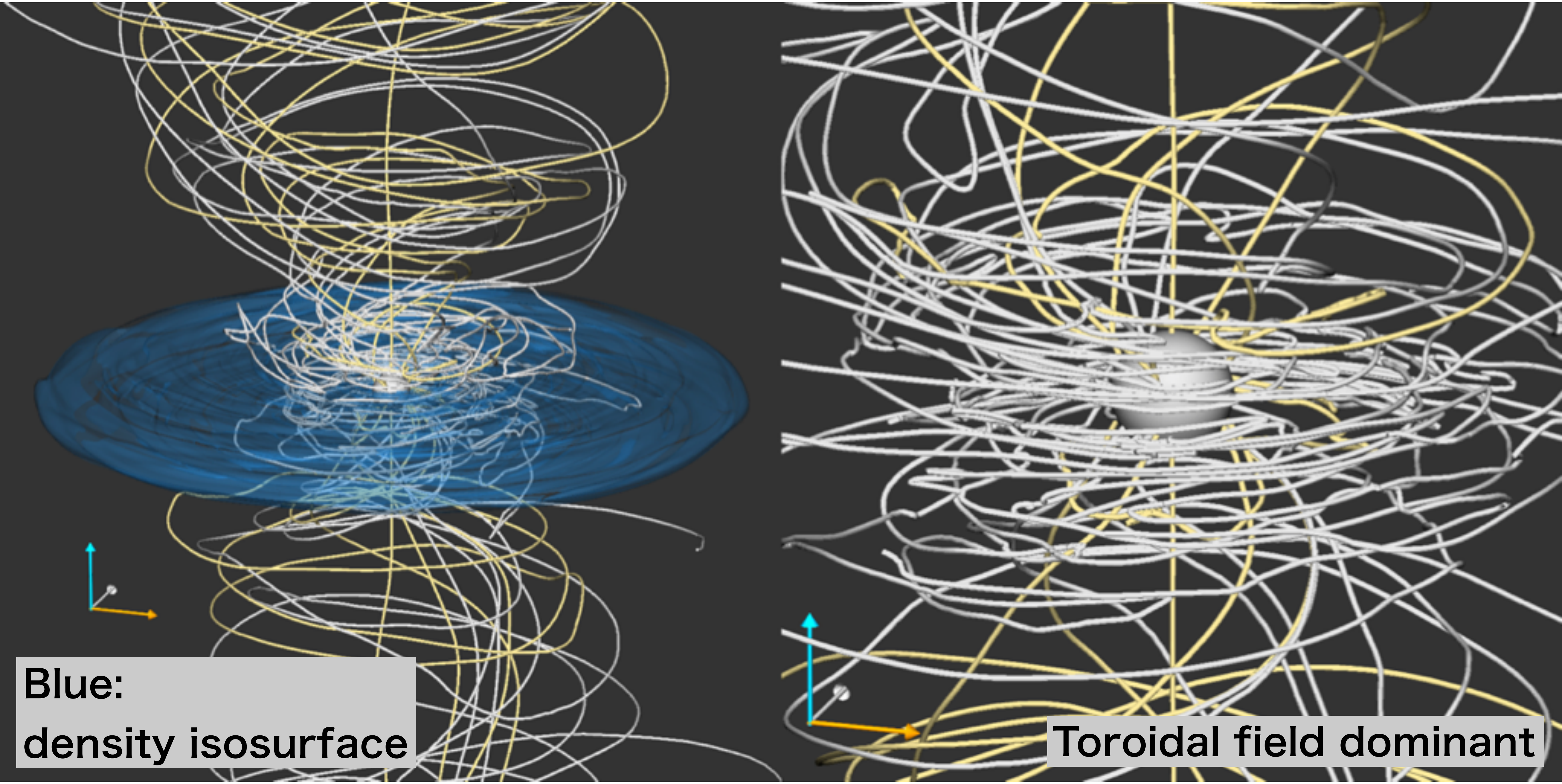
- Similarity with funnel-wall jets seen in BH disk simulations (e.g. Hawley & Balbus 2002), we call it funnel-wall accretion.
- Accretion streams do not fall along a magnetic field line
- Maximum accretion speed at the stellar surface ~ Kepler velocity

3D accretion flow structure



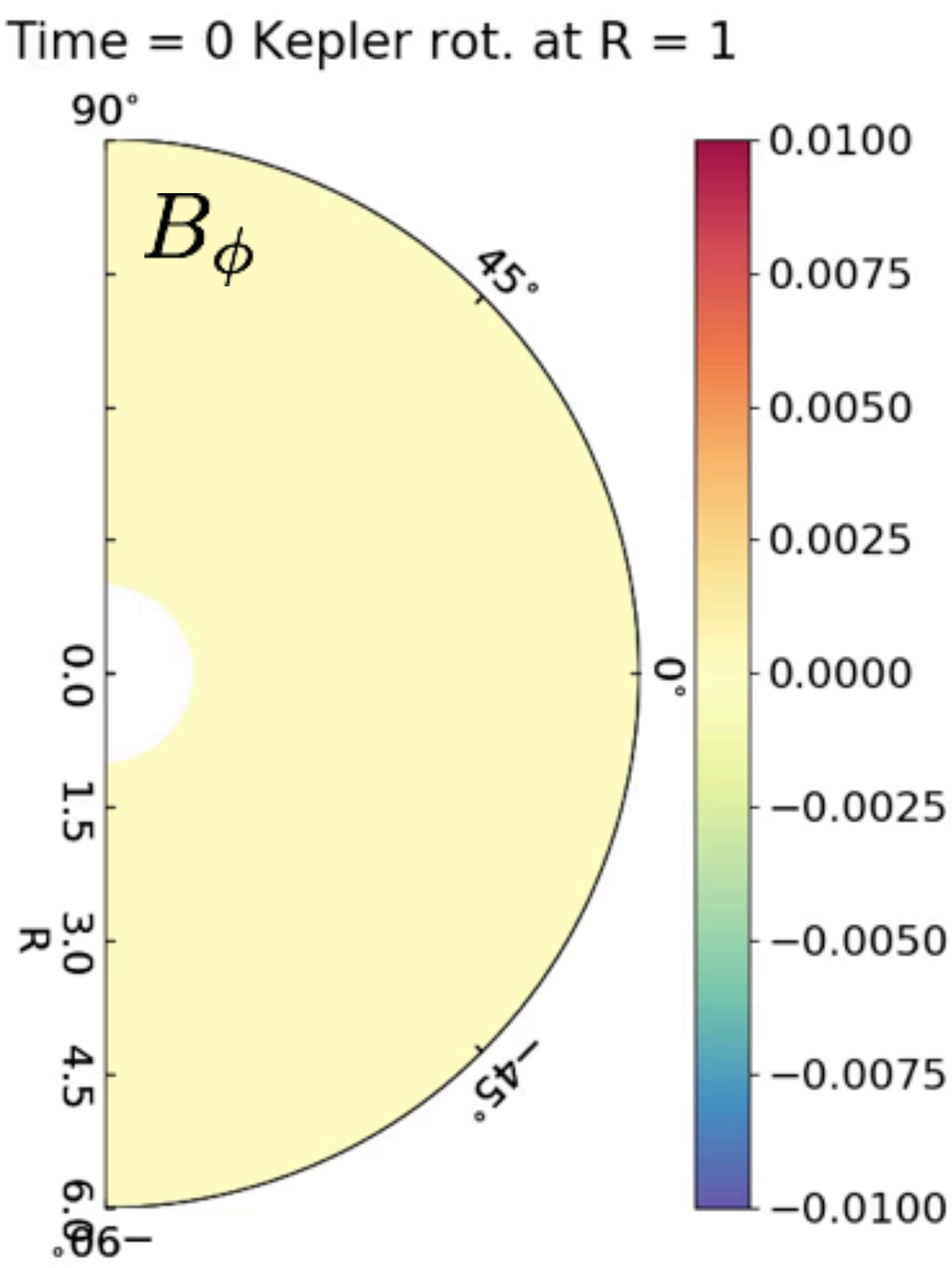
- ➤ Patchy accretion streams flowing to high-latitudes
- ➤ Coexistence of the disk accretion and funnel-wall accretion (but acc. rate in the mid plane >> acc. rate by funnel-wall acc.)

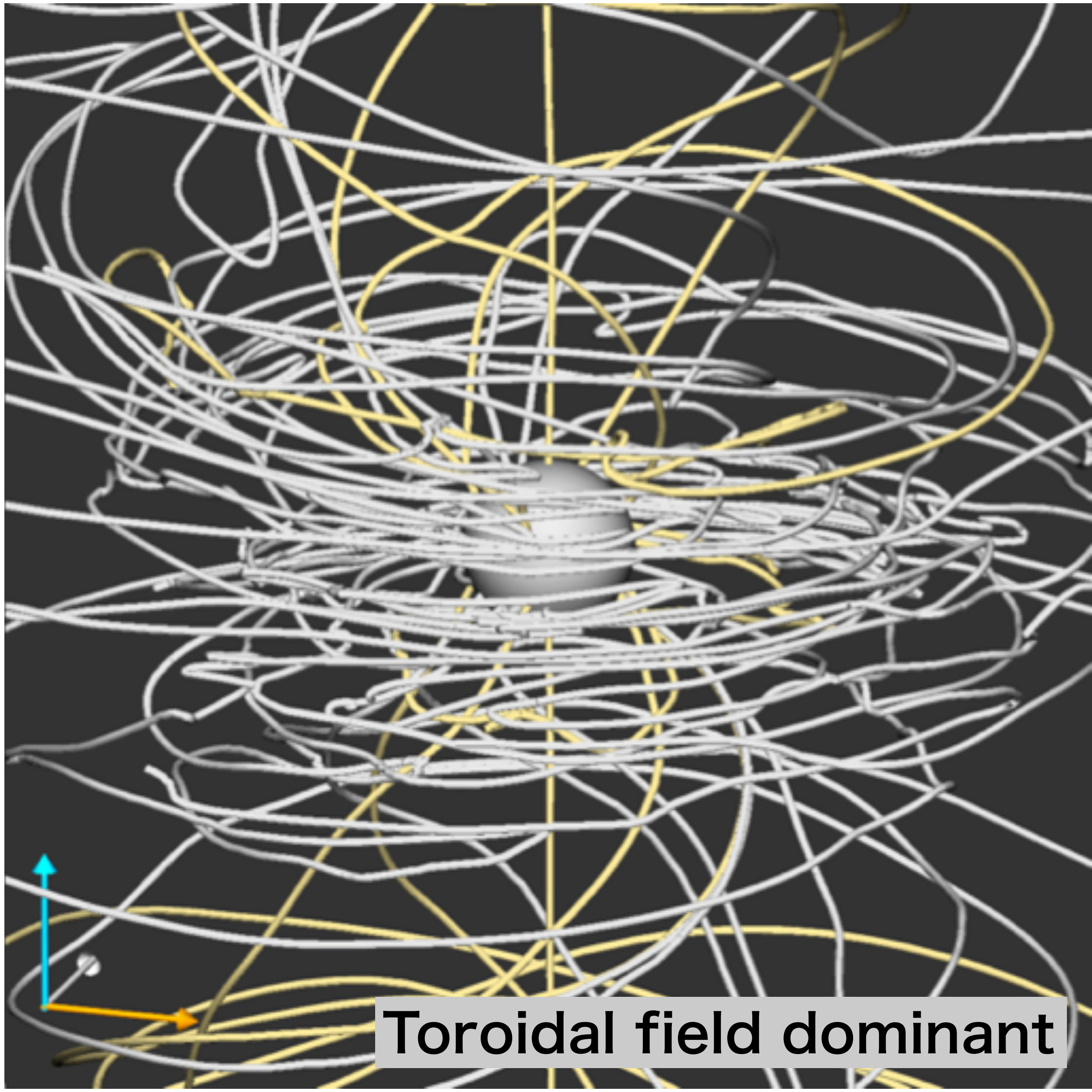
3D magnetic field structure



Contrast to the magnetospheric accretion model, accretion streams do not move along a field line in this case

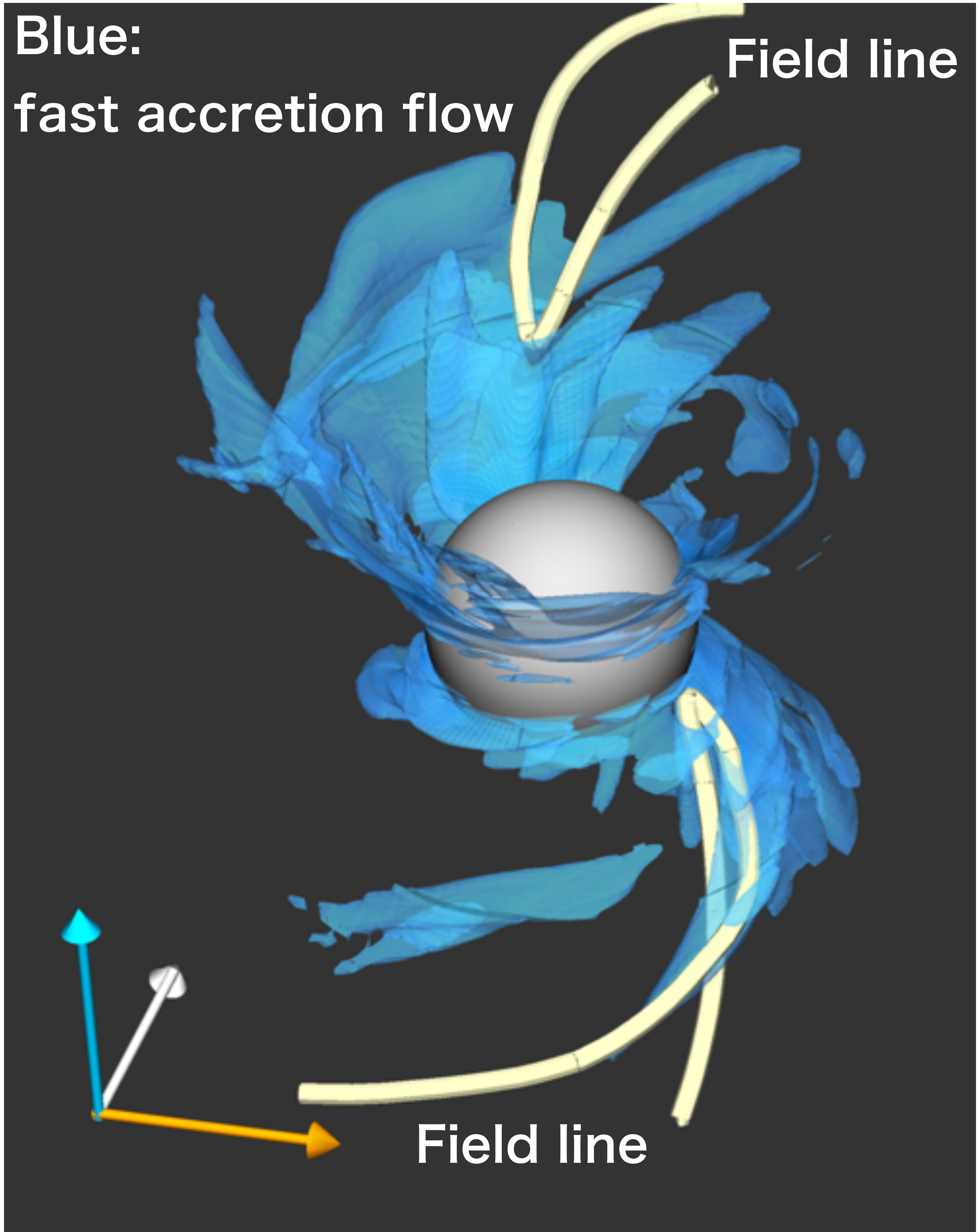
3D magnetic field structure



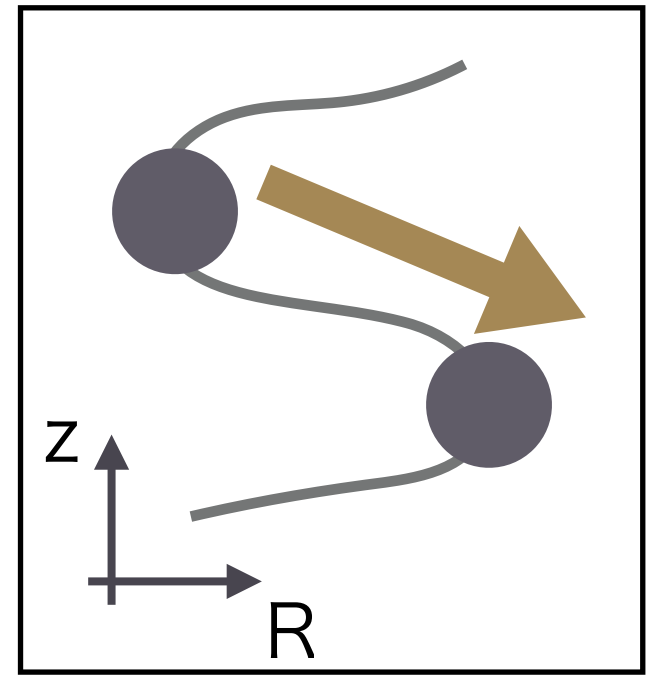


Toroidal field is amplified by the disk dynamo and is ejected by magnetic buoyancy

Angular momentum exchange mechanism



MRI-like ang. mom. exchange



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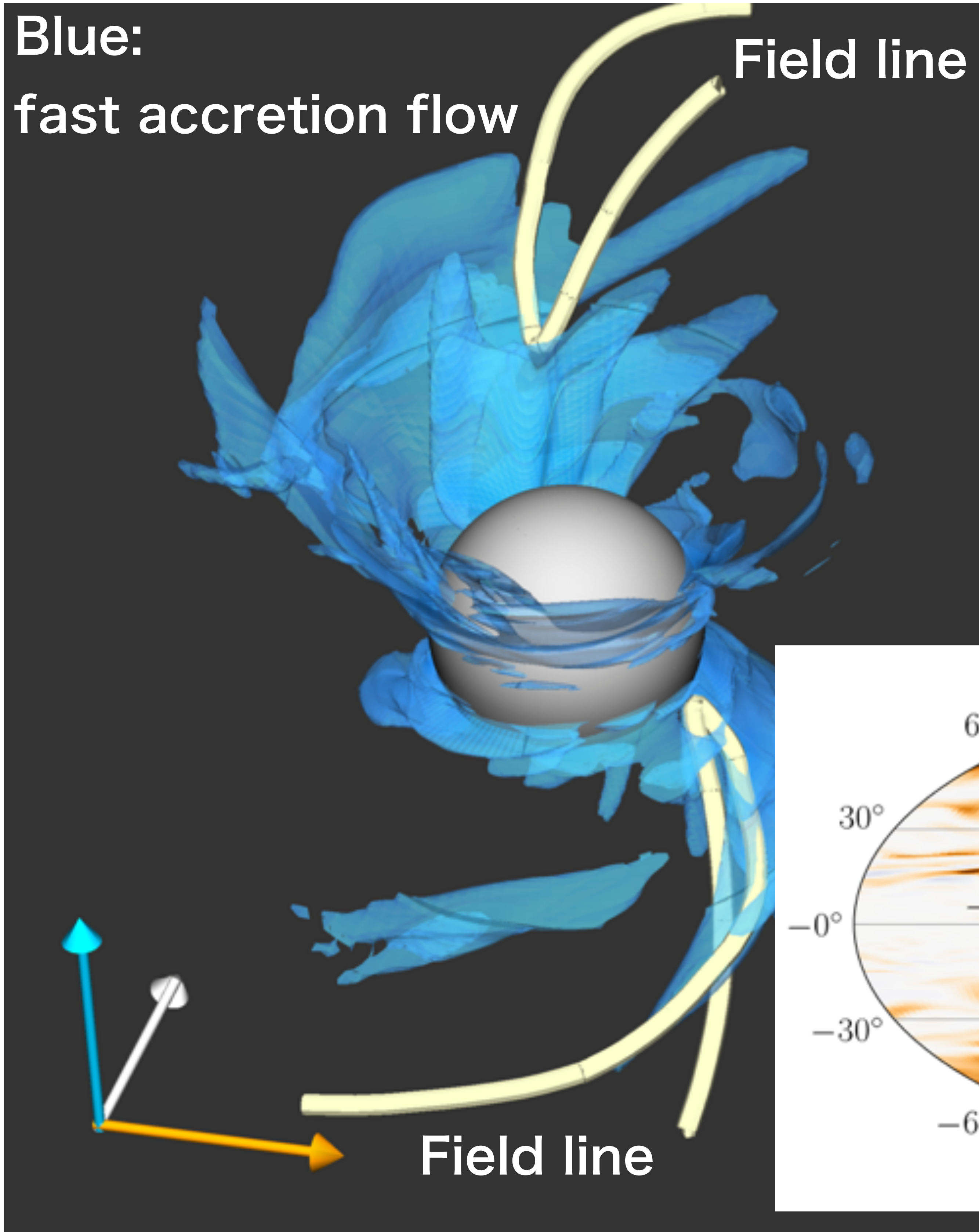

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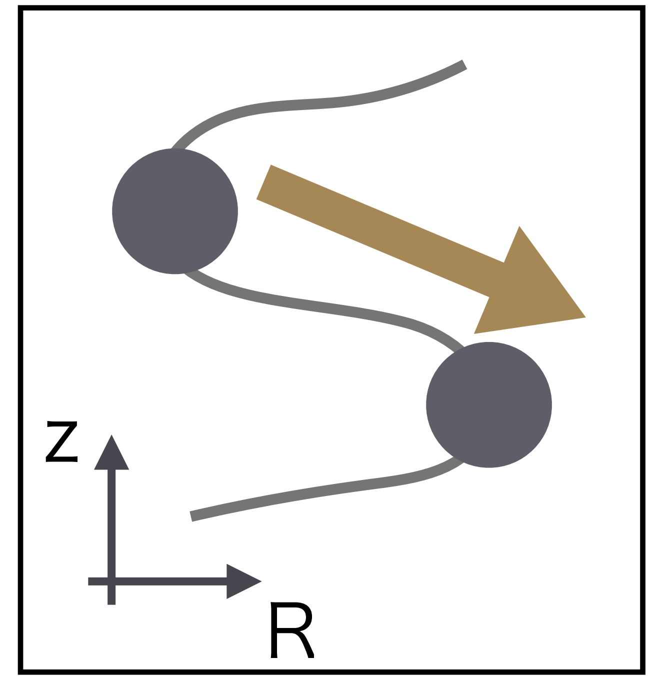
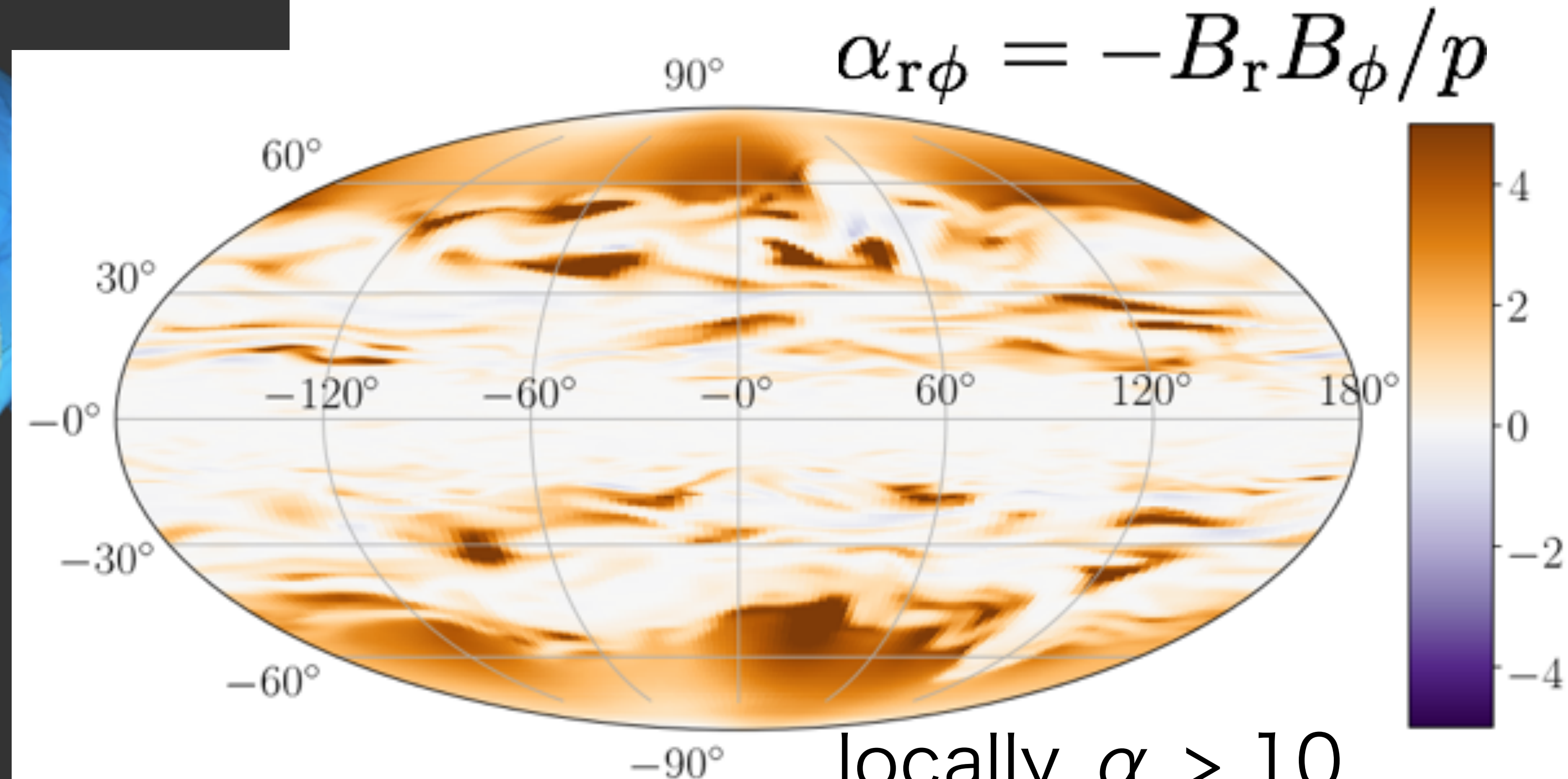
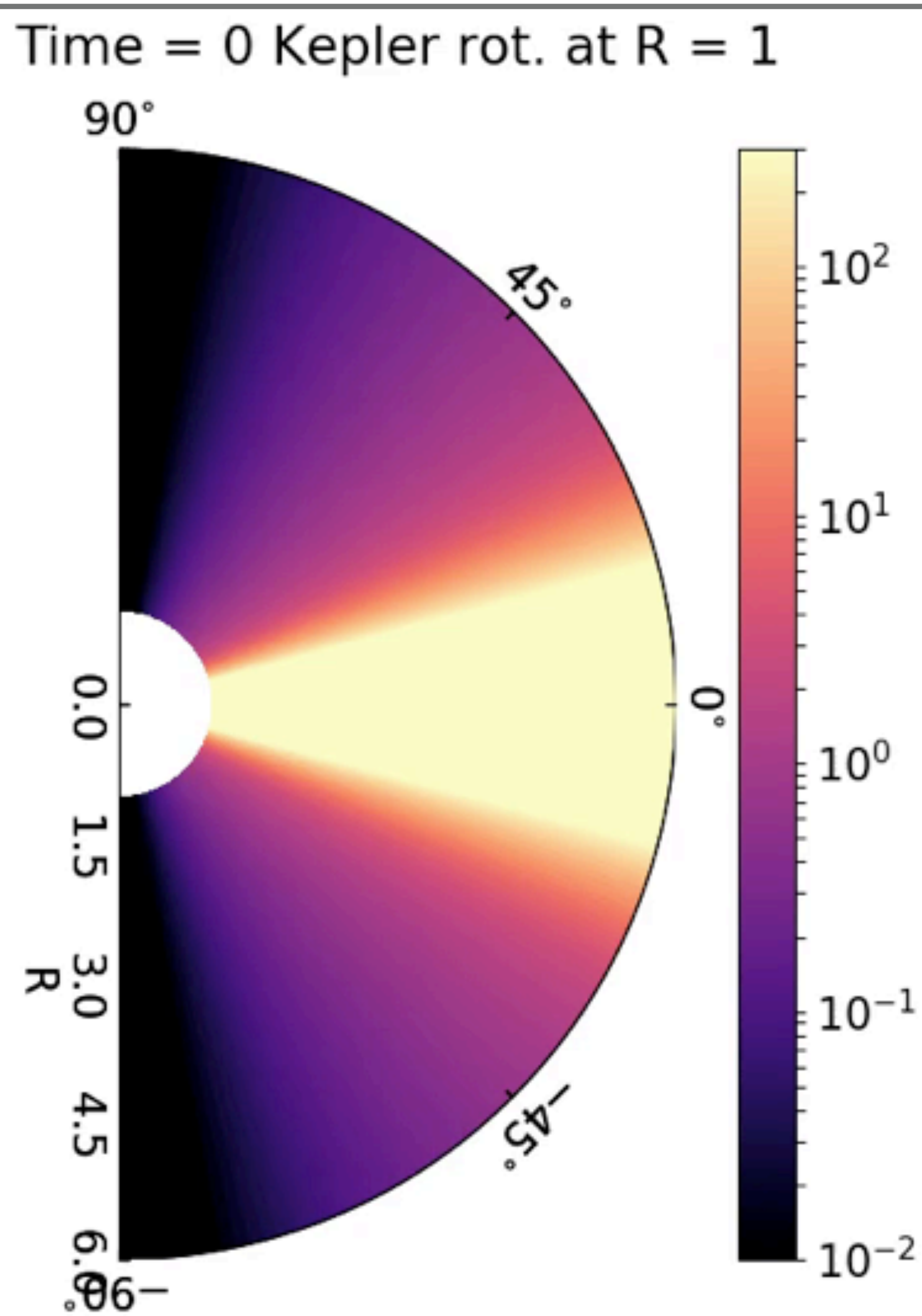




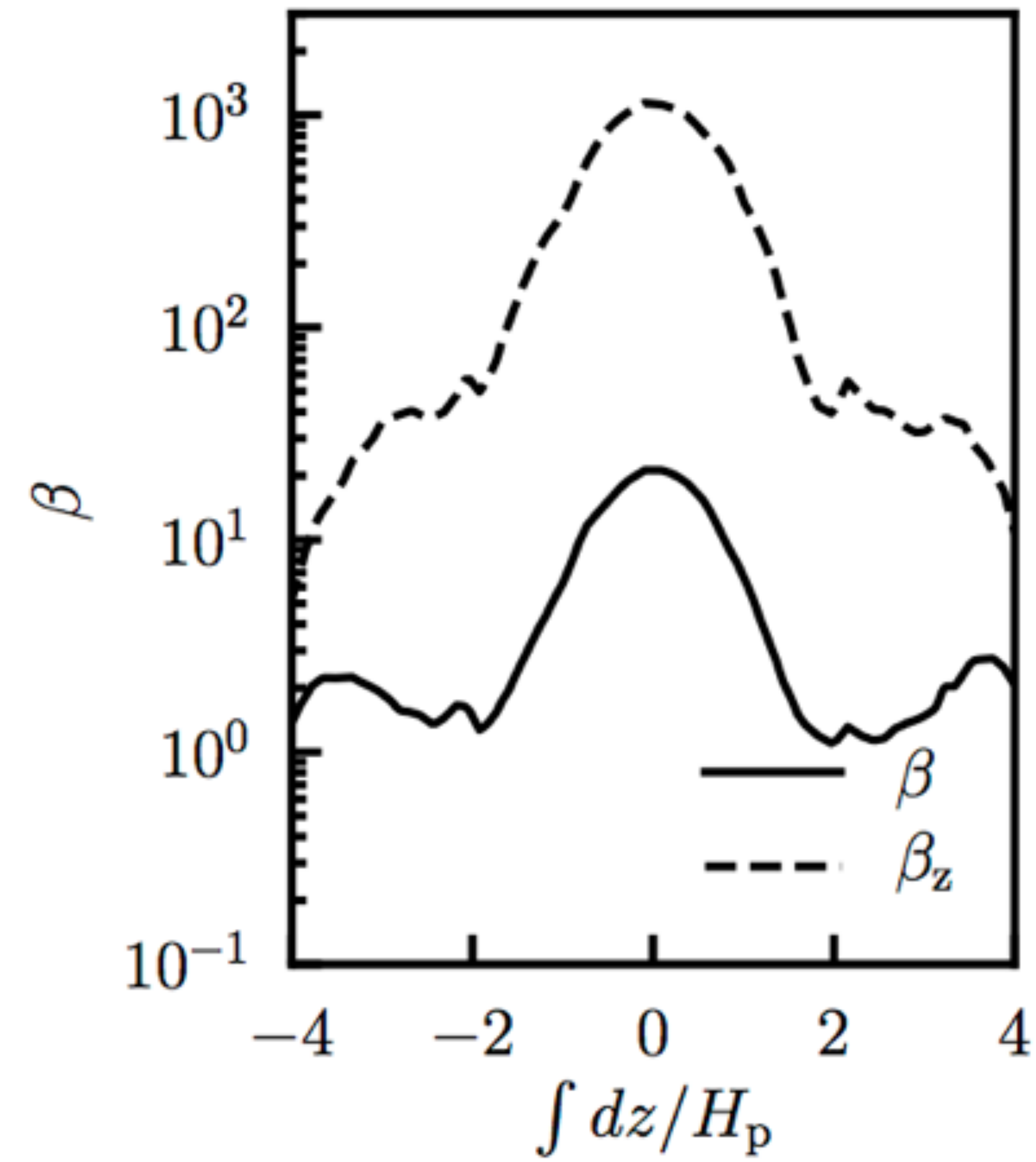
locally α > 10

Why MRI-like ang. mom. exchange occurs well above the disk?

plasma beta (Gas pres./ Mag. pres.)



vertical plot at R = 3 Rstar



e.g. for MRI, $\beta_z > (2\pi)^2$

Mass supply from MRI-turbulent disk —> increase of β above the disk

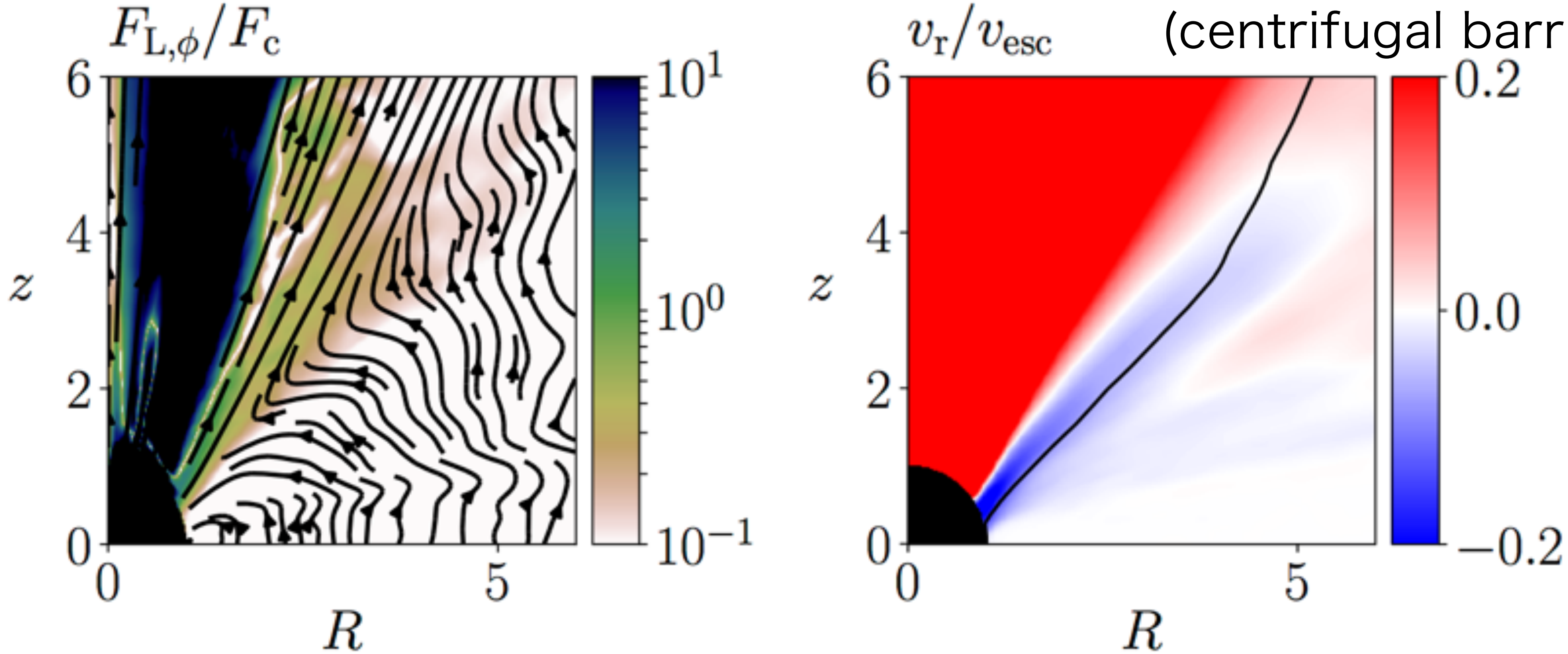
(e.g. Suzuki et al. 2009, Fromang et al. 2013) —> easy to obtain bent mag field

Why funnel-wall accretion is so fast (~free-fall)?

Efficient ang. mom. loss near the centrifugal barrier

Lorentz force/centrifugal force

iso specific ang. mom. line (centrifugal barrier)



The deceleration by mag. torque becomes important when

$$F_{\mathrm{L},\phi} \approx F_{\mathrm{cen}}$$ (e.g. Matsumoto+1996)

magnetic tension　　centrifugal force

$$\beta \gtrsim v_{\phi}/c_{\mathrm{s}}$$: necessary condition for the funnel-wall acc.

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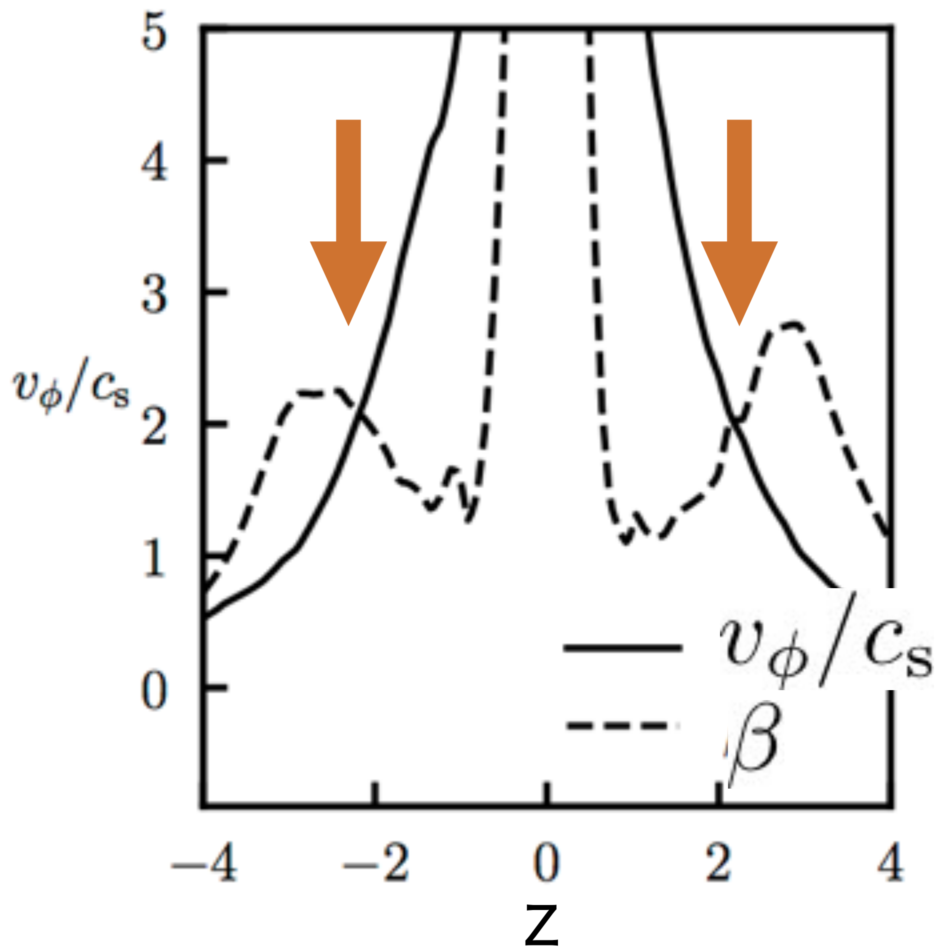

iso specific ang. mom. line
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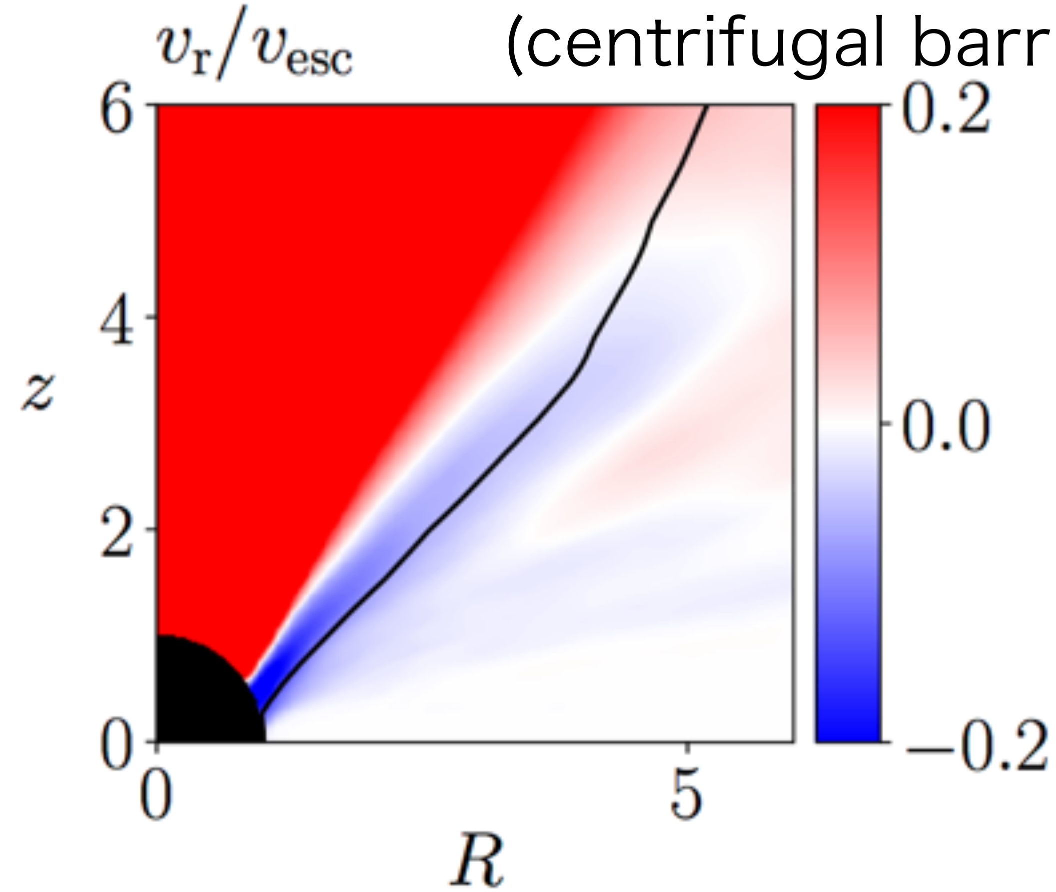

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magnetic tension centrifugal force

$$\beta \gtrsim v_\phi/c_s$$

: necessary condition
for the funnel-wall acc.

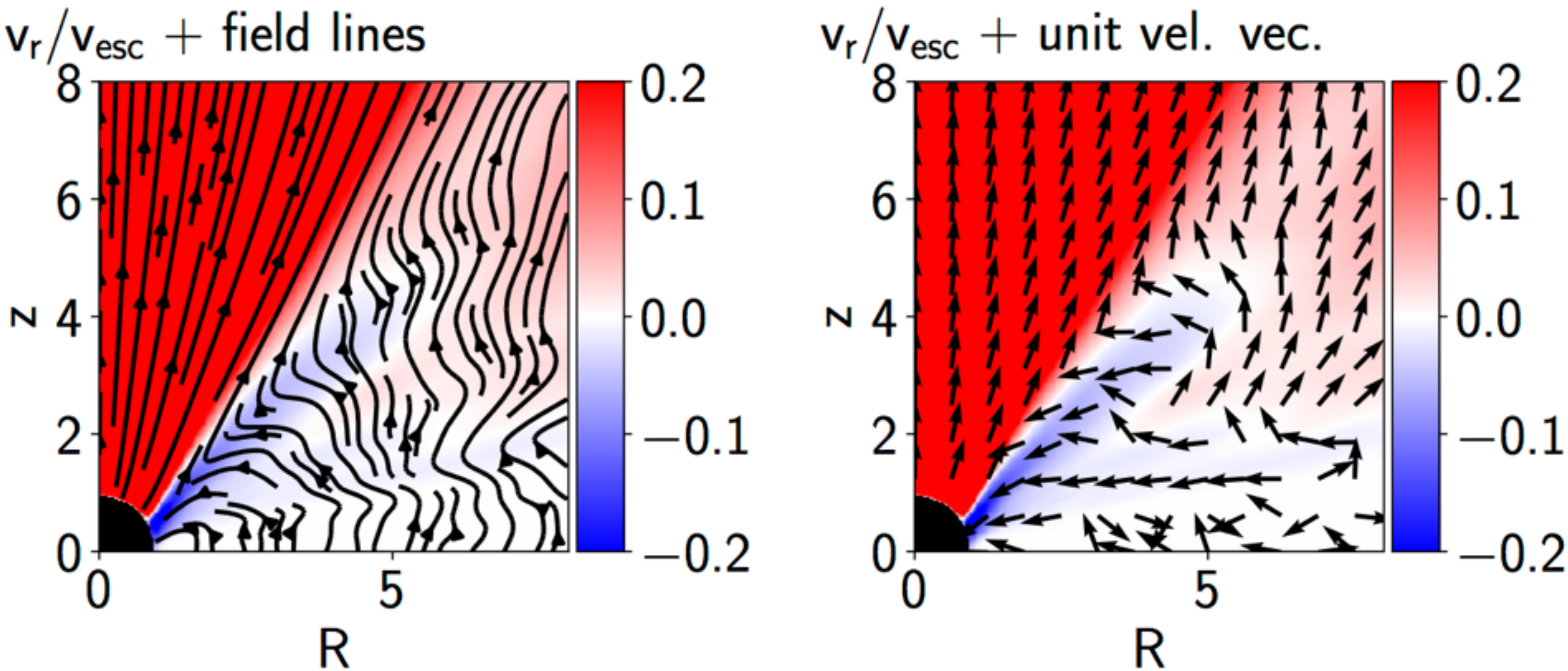
Required Computational Resource

- For a case with a moderate magnetic field strength (initial beta = 10^4)
    - **474 cores, ~1 month**
- For a case with a strong magnetic field strength (initial beta = 10^3)
    - 474 cores, ~2 month

Summary

- We develop a physically-motivated, numerically stable boundary condition for the stellar surface.
- We find that a fast, high-latitude accretion is possible even without a stellar magnetosphere.
- The accretion (funnel-wall accretion) is driven by MRI-like angular momentum exchange well above the disk surface.
- We need more computational resource to conduct
  - a parameter survey with the current model
  - simulations including a stellar magnetosphere

B-field and gas flow structures: centeral region



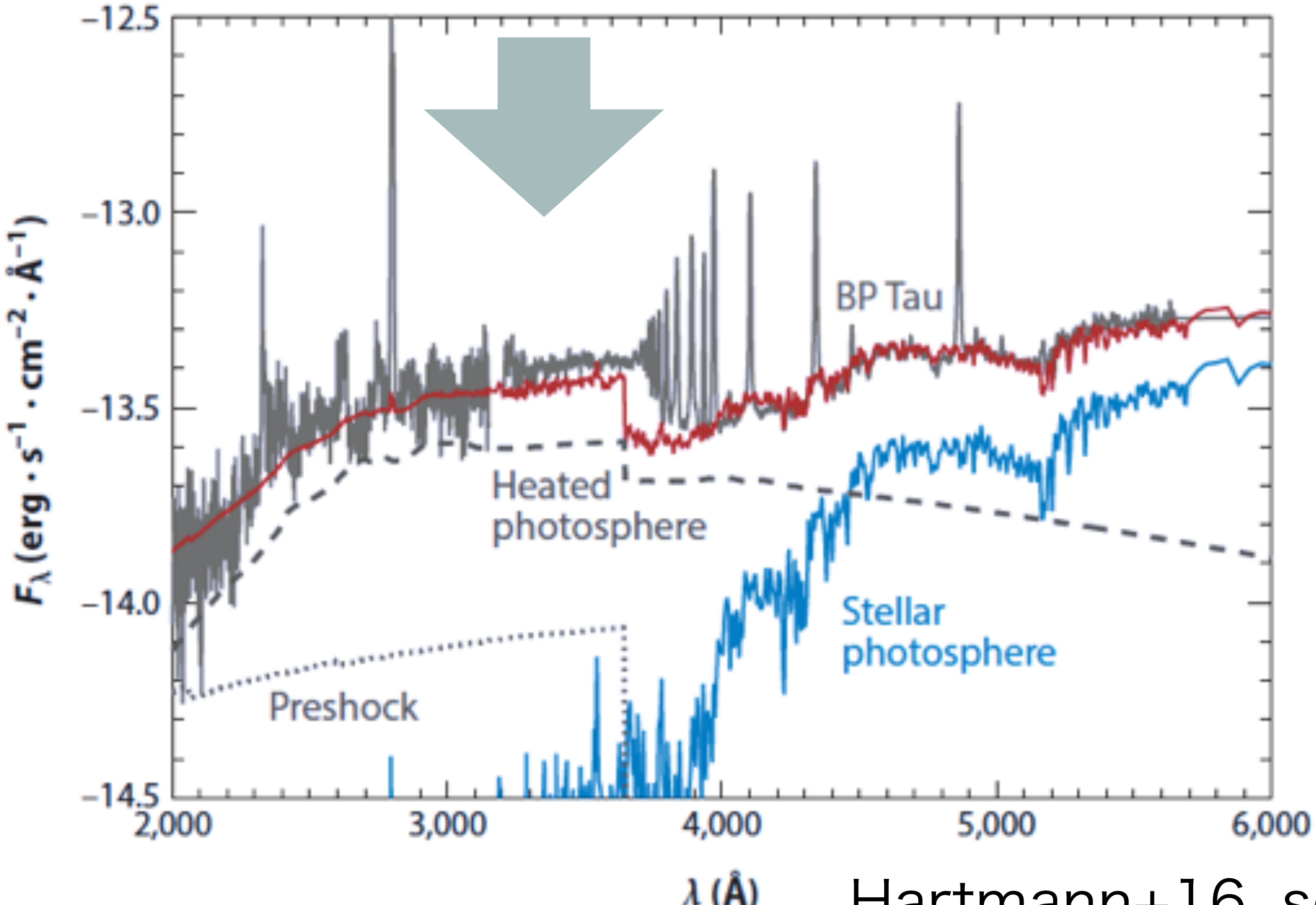
Outer region: wind is blowing outward

Inner region: wind is flowing to the star ("failed" wind)

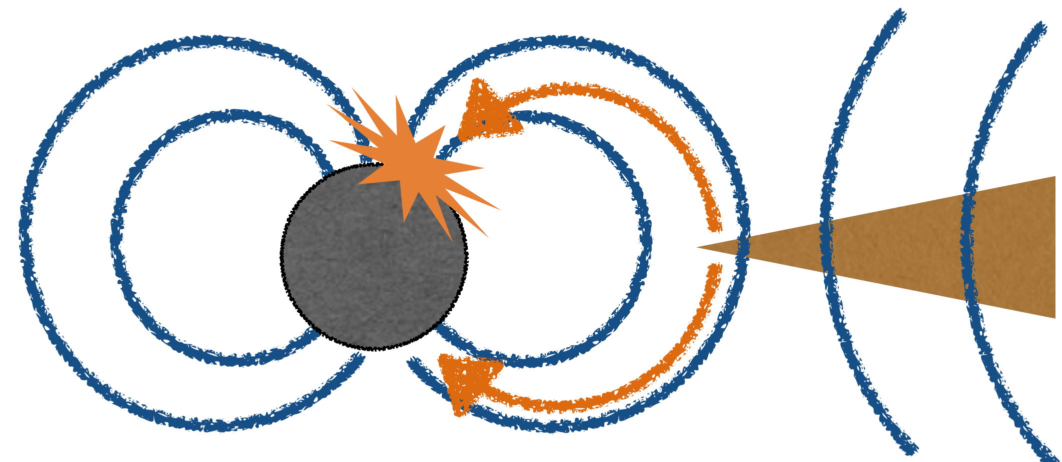
Magnetic field is more vertical or inclined to the star
as a result of the vertical variation of accretion speed.

Magnetospheric accretion is successful?

UV excess due to the shock heating



Accretion shock



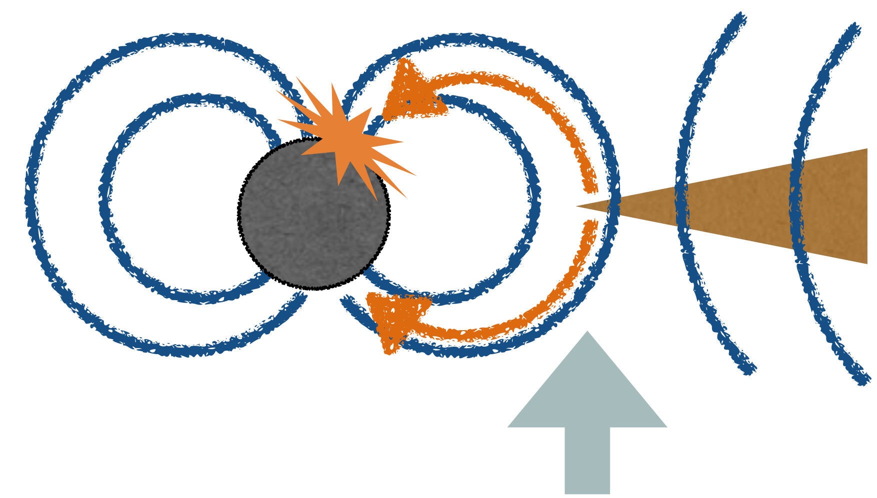
Hartmann+16, see also Calvet & Gullbring 1998

- UV excess (Valenti+93), accretion at high latitudes (Donati+08)
    - **Indicating that fast accretion streams flow to high latitudes**

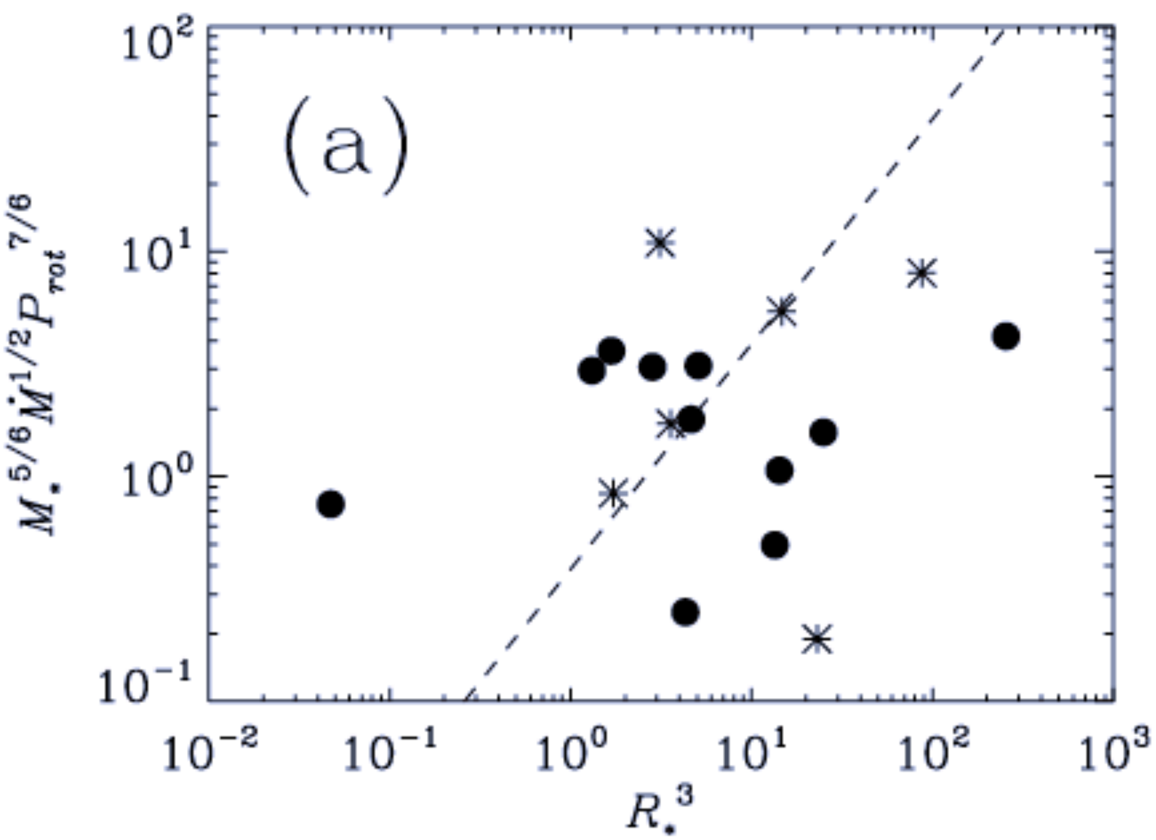
Magnetospheric accretion scenario looks OK?

Magnetospheric accretion is successful?

Assume that
the inner disk is truncated at a radius
where Emag ~ Ekin
(i.e. magnetic field is strong enough to
stop rotating material by magnetic tension)



$\Rightarrow$ $R_*^3 \propto M_*^{5/6} \dot{M}^{1/2} P_{\rm rot}^{7/6}$ (Ghosh & Lamb 1978, Konigl 1991)



Johns-Krull & Gafford 2002

No clear correlation found from observations,,,

$\boxed{\text{Not clear if magnetospheric accretion is successful or not.}}$