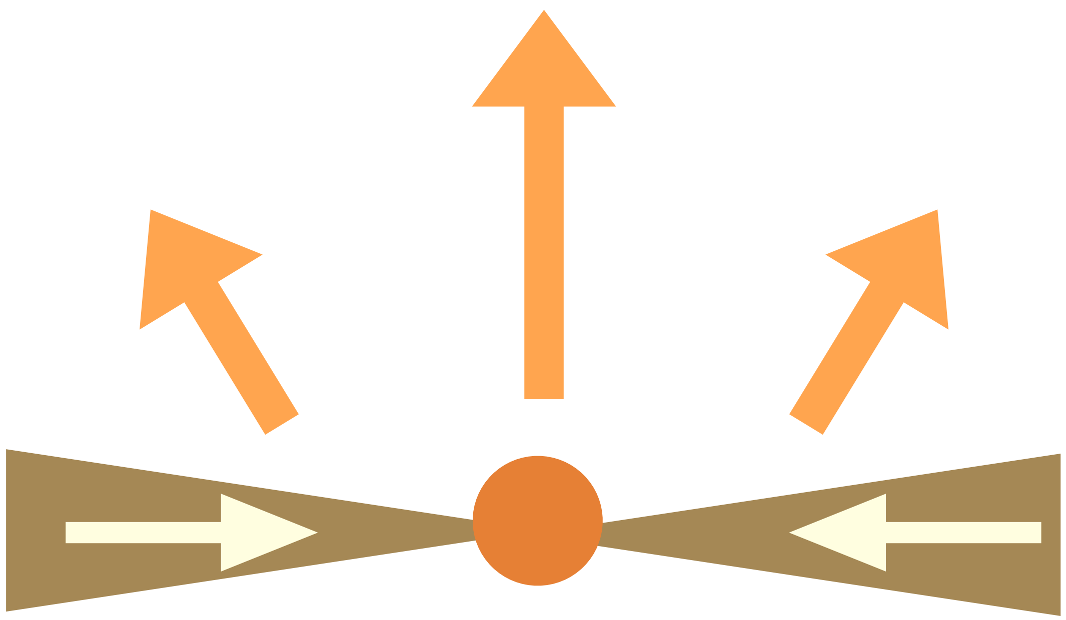
Magnetic Field & Accretion Structures around Young Stars

Shinsuke Takasao (Nagoya Univ.)

Collaborators:
Kengo Tomida, Kazunari Iwasaki (Osaka Univ.),
Takeru K. Suzuki (Univ. of Tokyo)

Importance of investigating accretion processes onto young stars



Accretion structure onto stars

- ang. mom. evolution of stars
- estimation of mass accretion rate
- occultation of the star
  (—> impact on the disk evolution)

Angular momentum/mass extraction from disks & stars

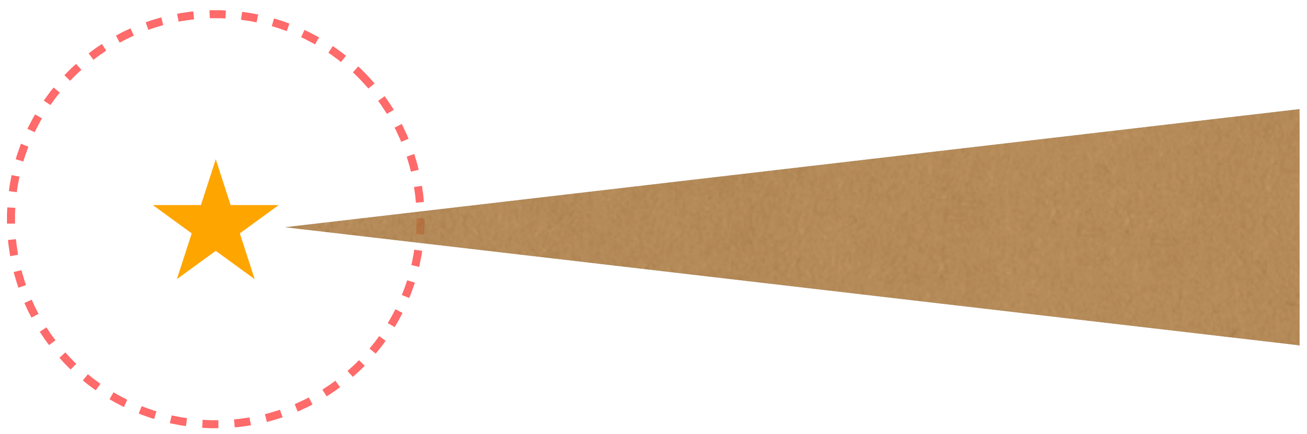
- Jet, outflow, wind

Understanding the roles of a magnetic field around the star is crucial

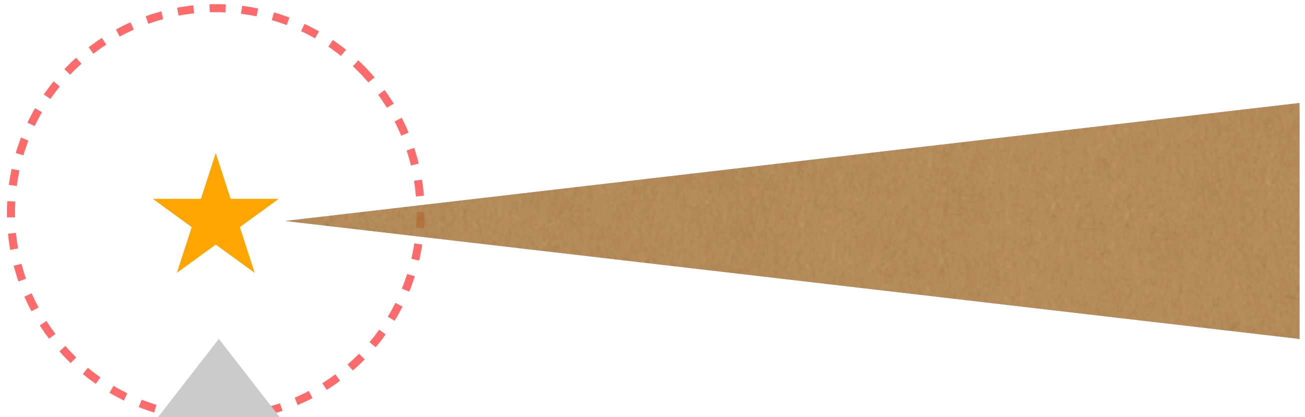
Note: In this talk,

- **<< 1au scale is focused**
- **late protostars ~ early pre-main seq. stars considered**

Structure of the inner region?



Structure of the inner region?



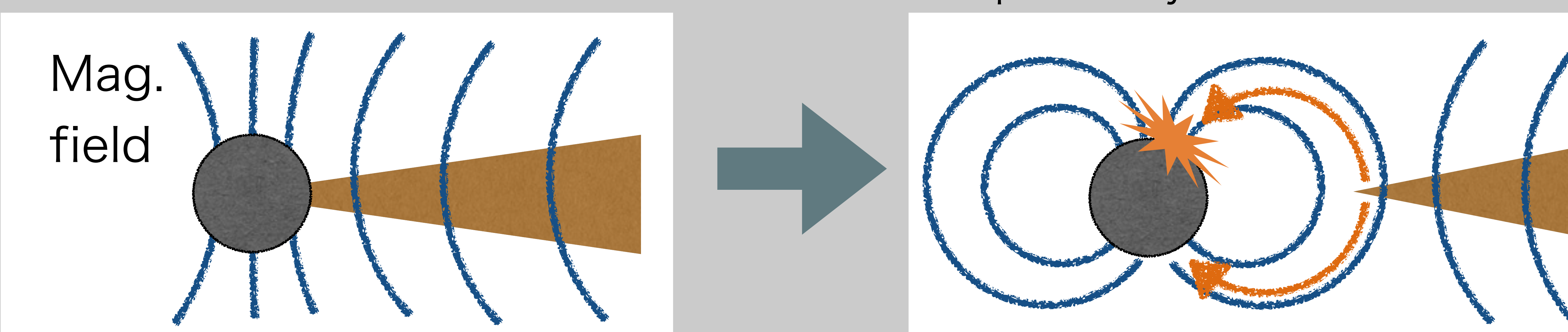
Classical picture

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

quiet **disk accretion**

Magnetospheric Accretion

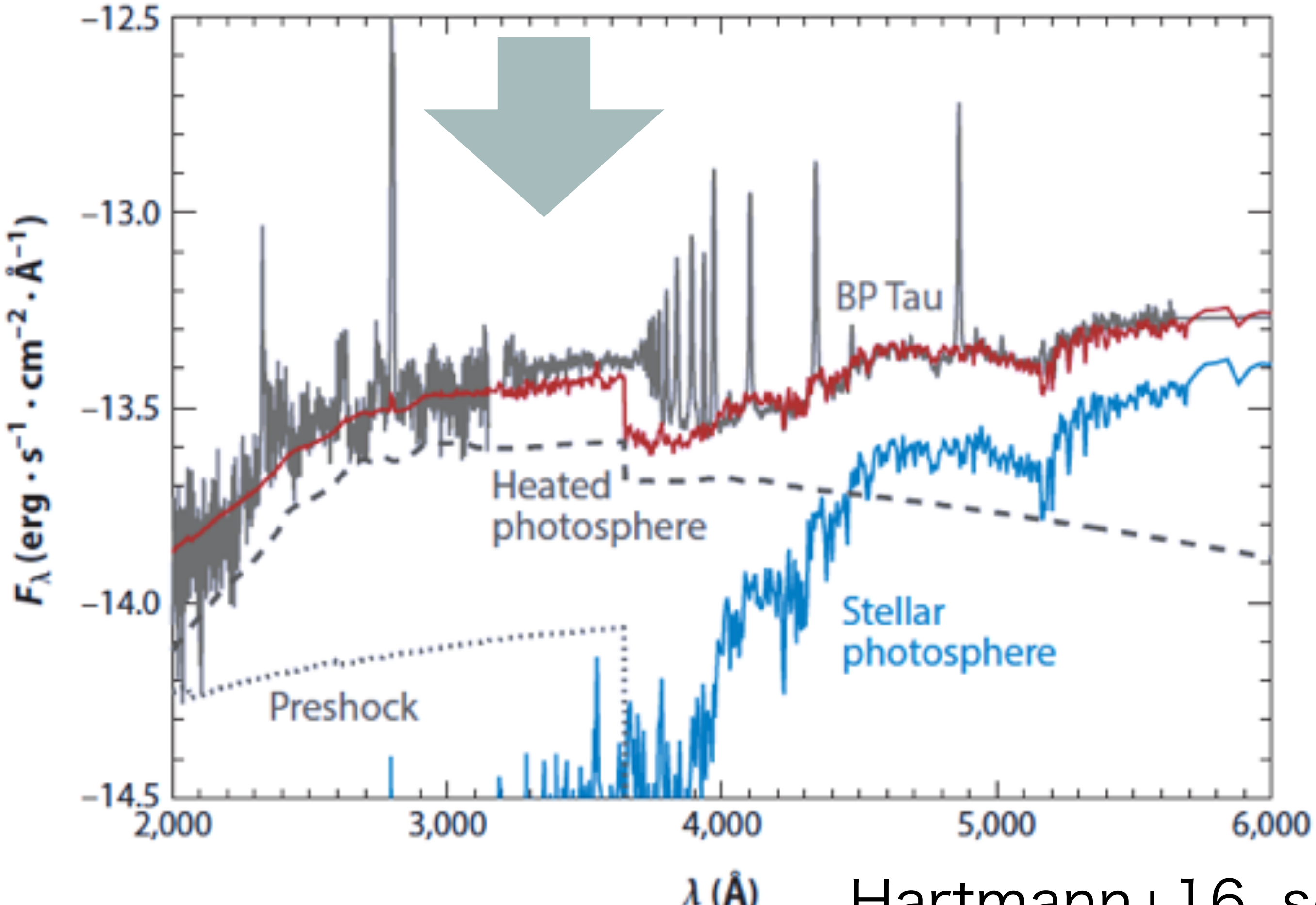
accompanied by **the accretion shock**



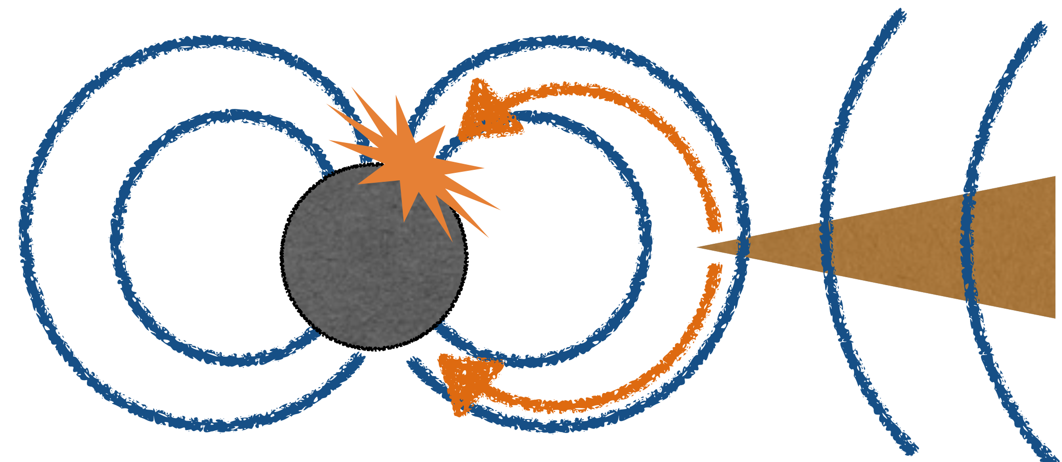
e.g. Konigl 1991

Magnetospheric accretion is successful?

UV excess due to the shock heating



Accretion shock



Hartmann+16, see also Calvet & Gullbring 1998

- **UV excess** (Valenti+93), **hot spots at high-latitudes** (Donati+11)
  - Indicating a fast accretion at high-latitudes
  - opt./UV excess — [fitting by the shock model] —> Estimation of $\dot{M}$

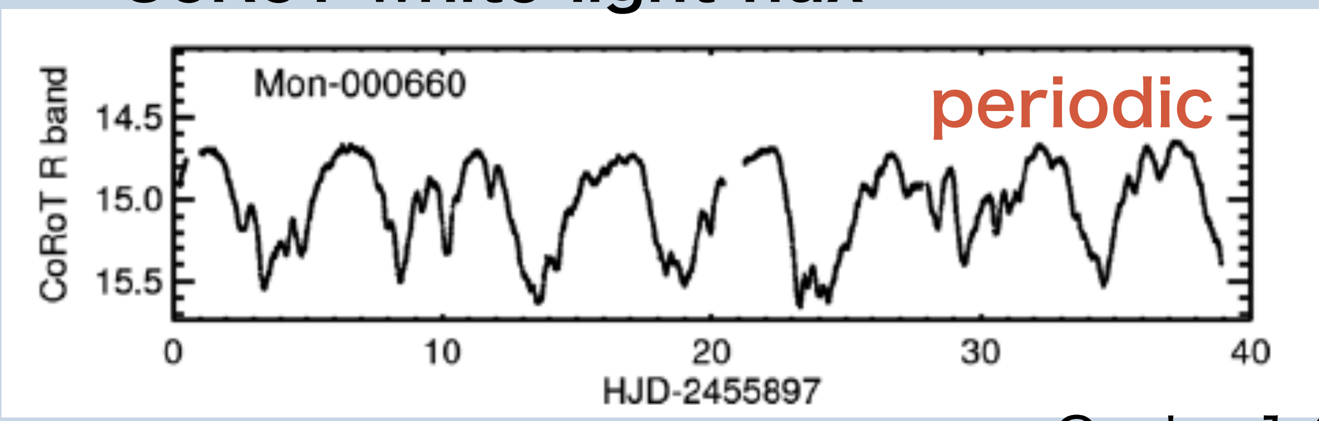
Magnetospheric accretion scenario looks OK?

Occultation of the star

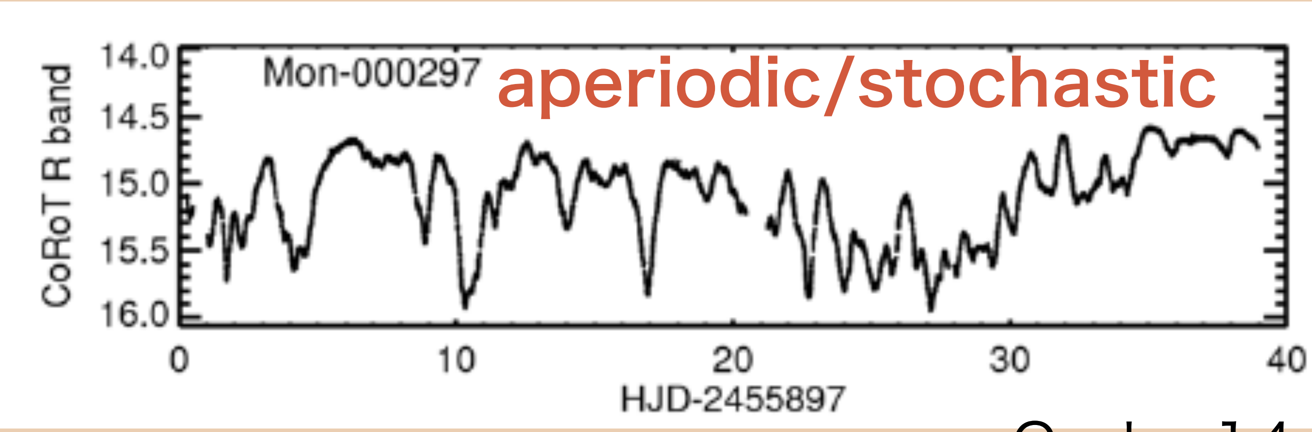
Bouvier + 1999 and many

Changing stellar radiation to the disk: Important for the disk evolution

CoRoT white-light flux

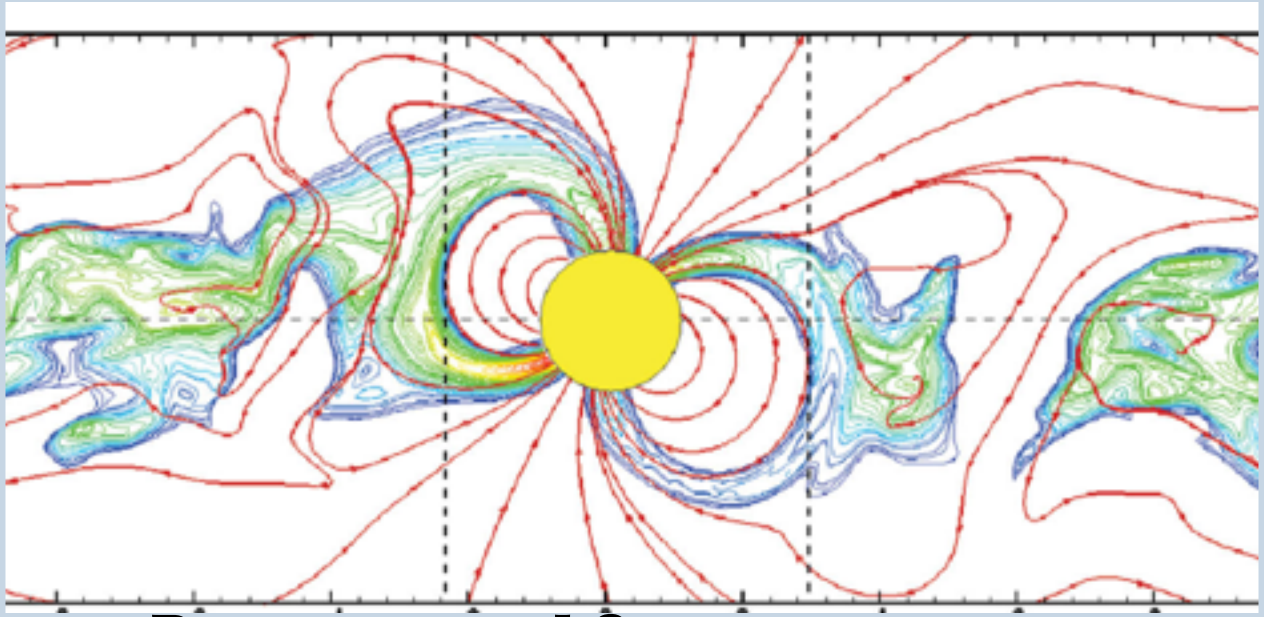


Cody+14



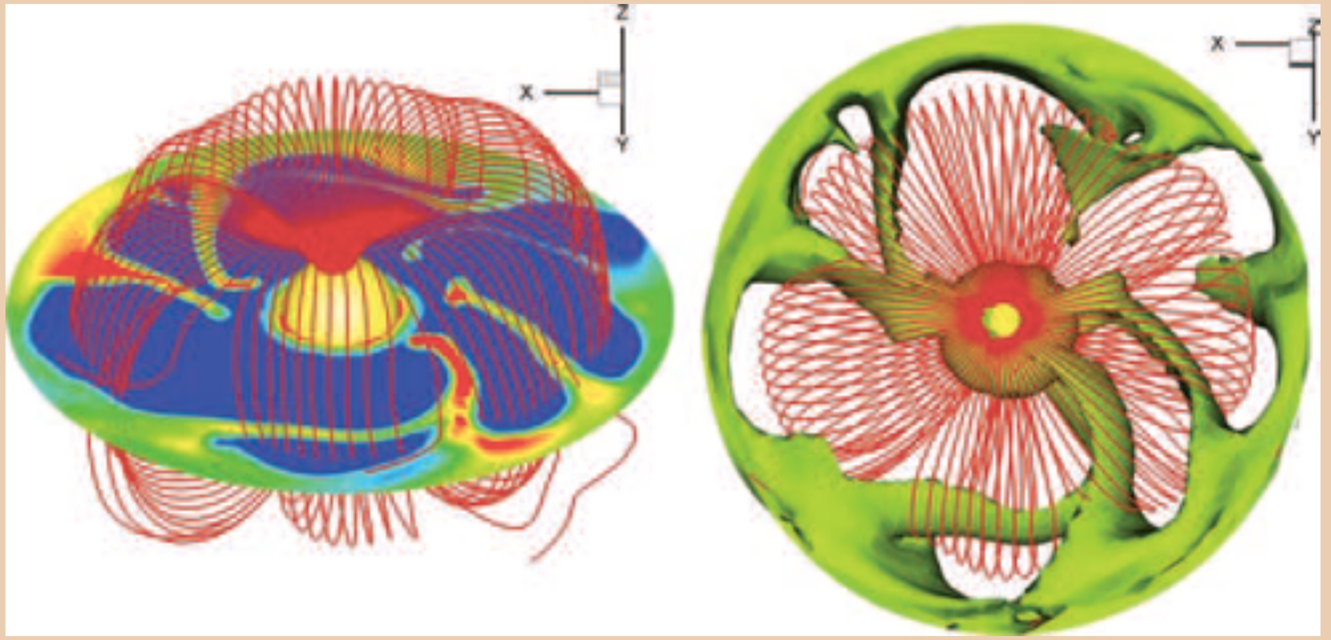
Cody+14

Occultation by a warped disk caused by the magnetosphere



Romanova+13

Rayleigh-Taylor instability in the magnetosphere



Kulkarni & Romanova08

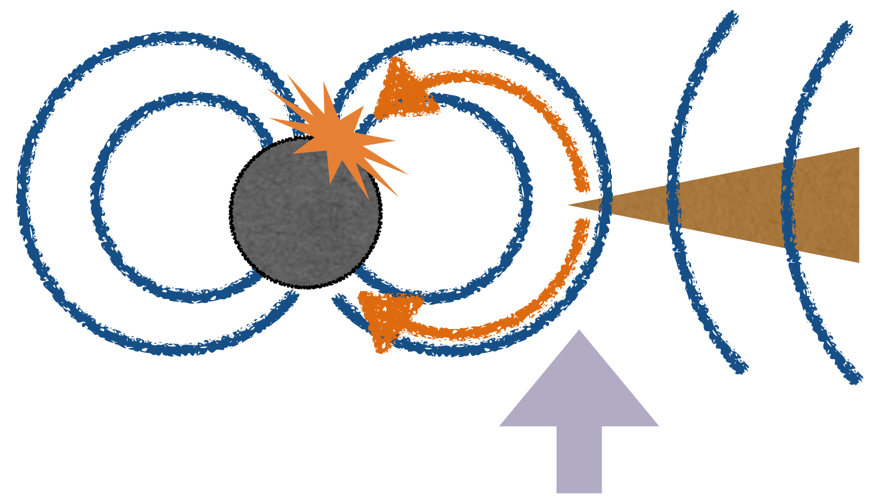
Magnetospheric accretion is successful?

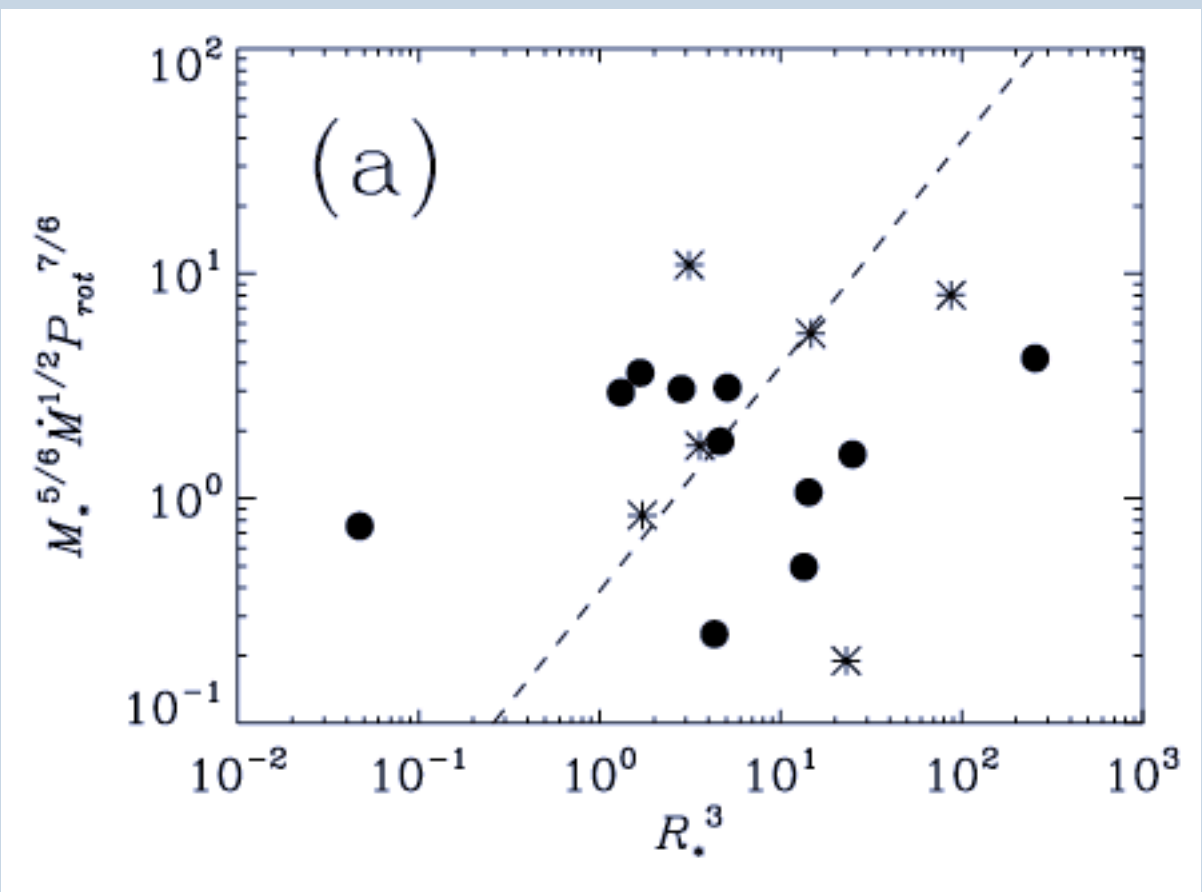
Assume that

the inner disk is truncated at a radius where Emag ~ Ekin

$$\Rightarrow R_*^3 \propto M_*^{5/6} \dot{M}^{1/2} P_{\rm rot}^{7/6}$$

(Ghosh & Lamb 1978, Konigl 1991)





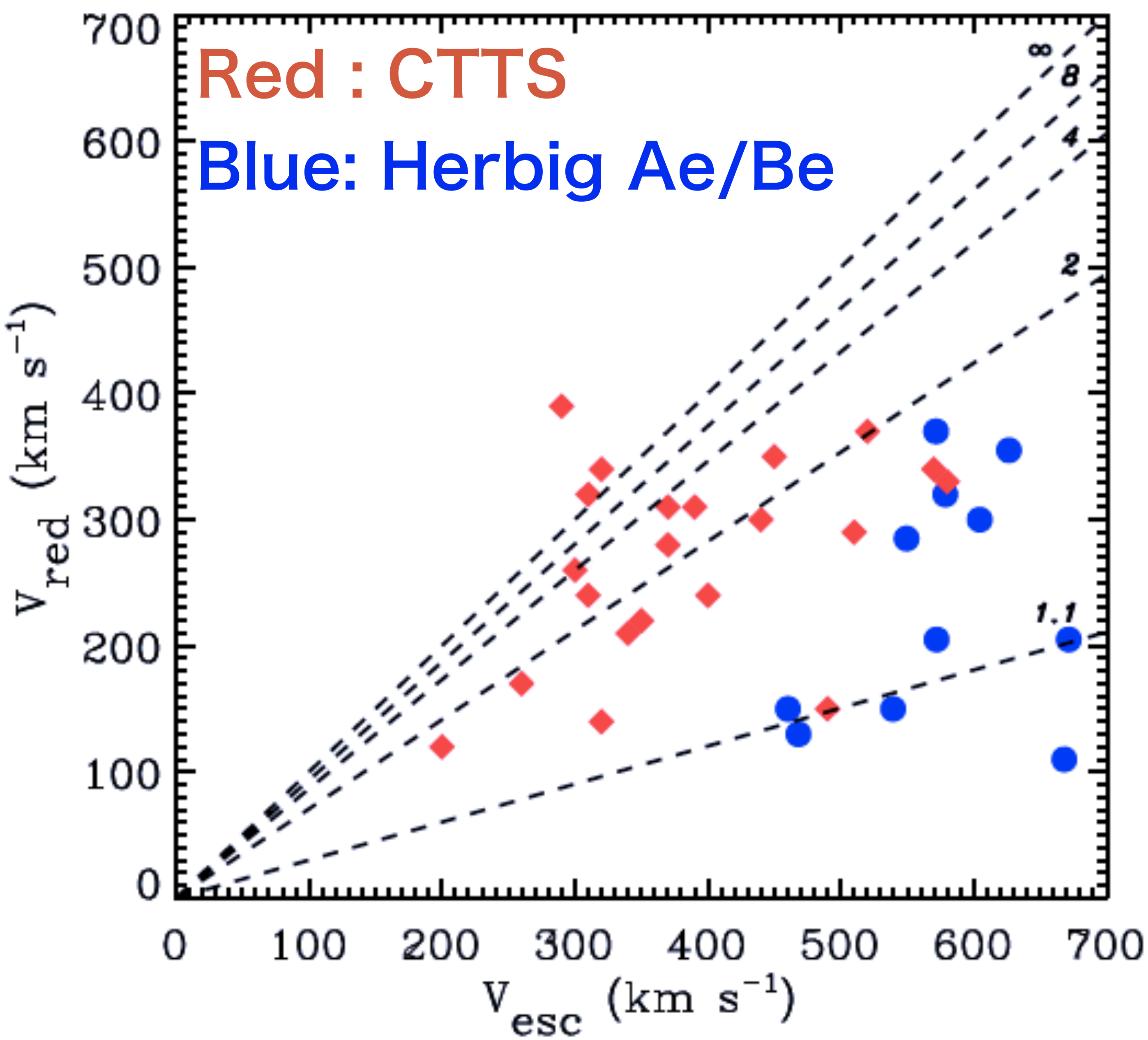
Johns-Krull & Gafford 2002

No clear correlation found from observations,,,

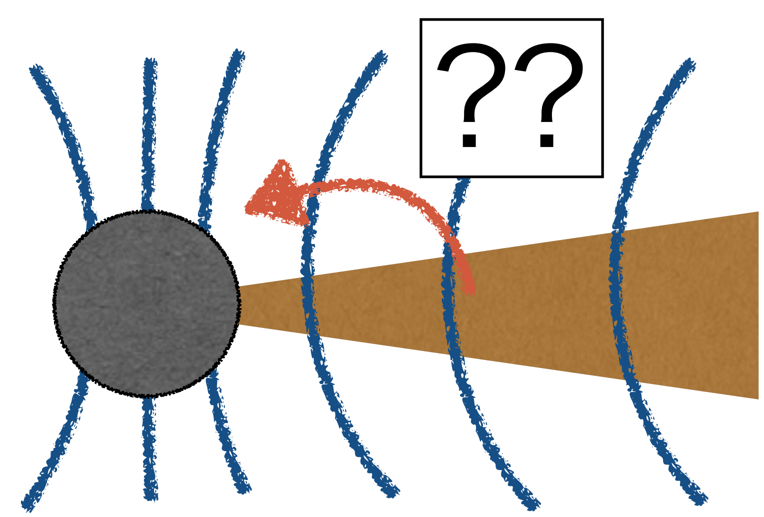
Not clear if magnetospheric accretion is successful or not.

Magnetospheric accretion even in weak B-field stars?

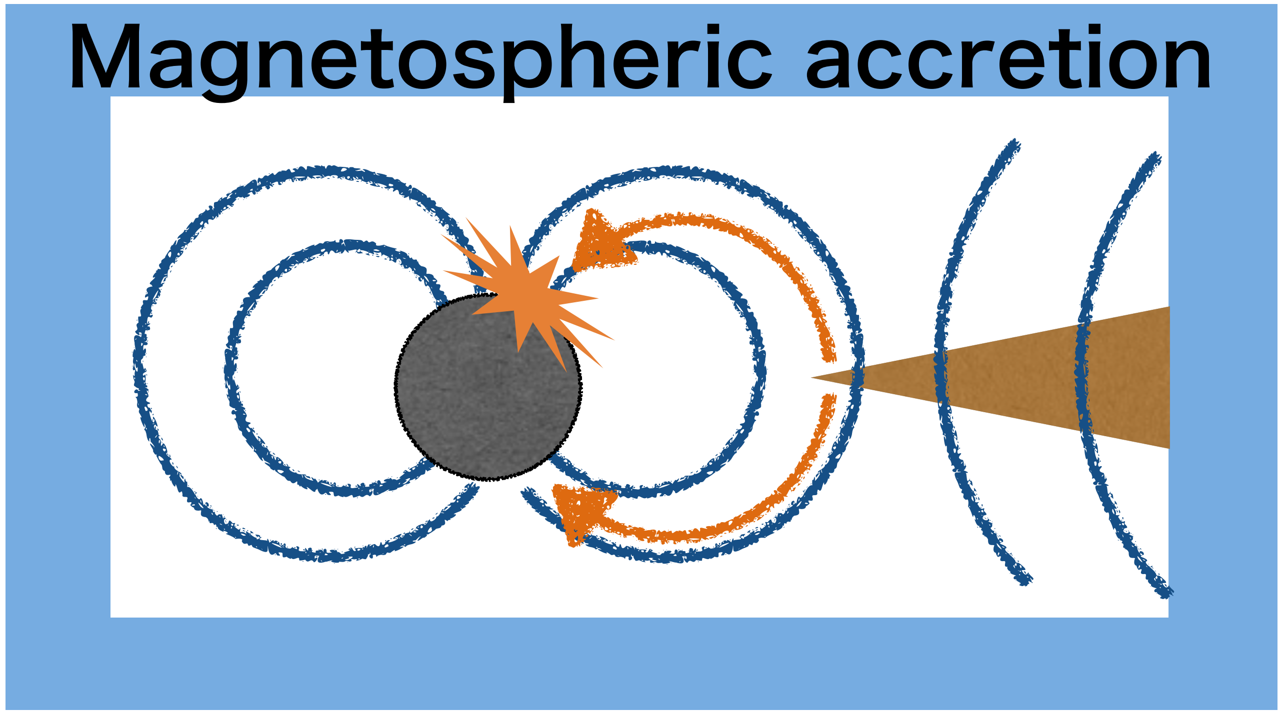
Herbig Ae/Be: intermediate mass stars at the PMS stage. **The fraction of magnetic (> ~100 G) stars is only ~10% (Wade+2007)**
—> too weak B-field for magnetospheric acc.

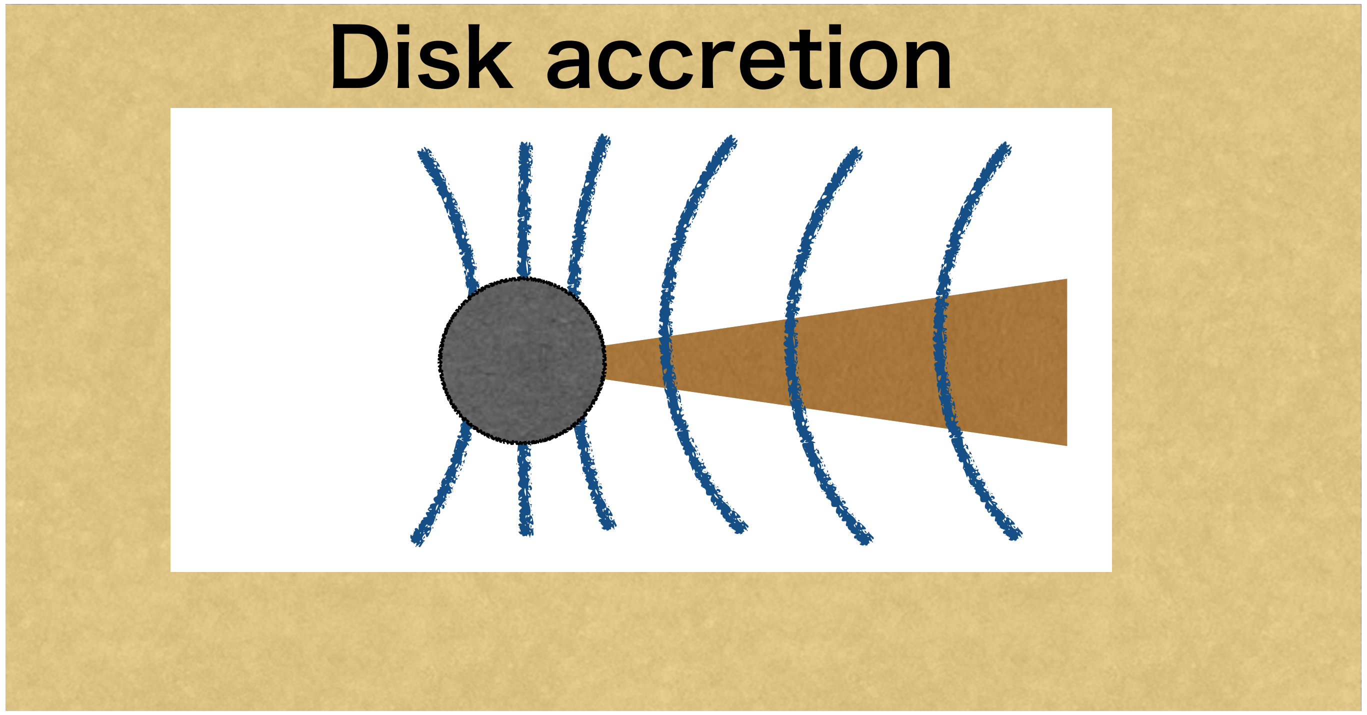


Herbig Ae stars also have a large accretion speed
(Cauley & Johns-Krull 14)



Re-examine disk accretion process





Existence of magnetosphere is unclear

—> Re-examine the disk accretion process

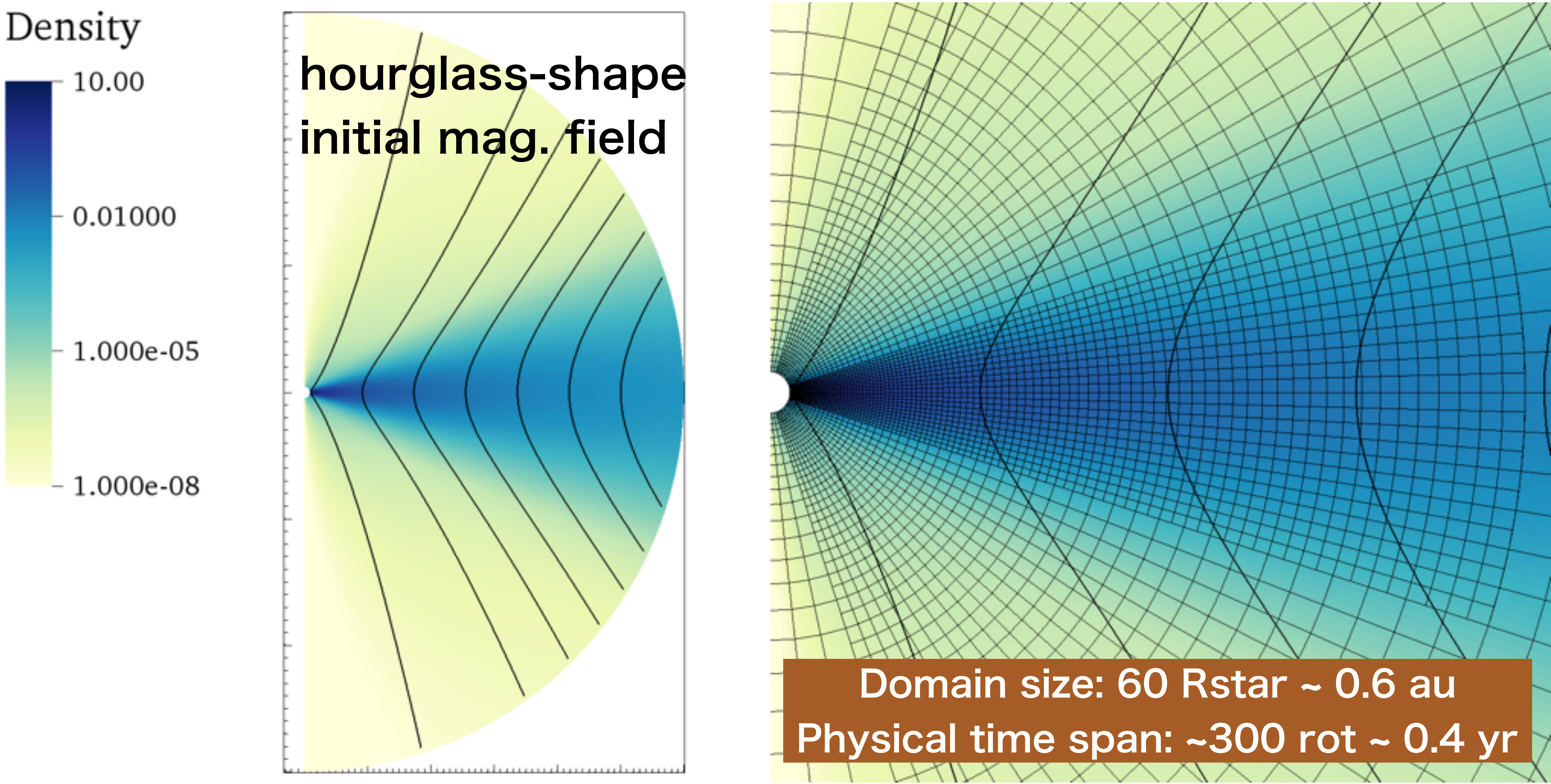
using 3D magnetohydrodynamic (MHD) simulations

- Is fast accretion possible without the magnetosphere?
- Occultation process?
- Does a fast, magnetically-driven jet blow ?

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

Code : Athena++ (Stone, Tomida, White in prep)

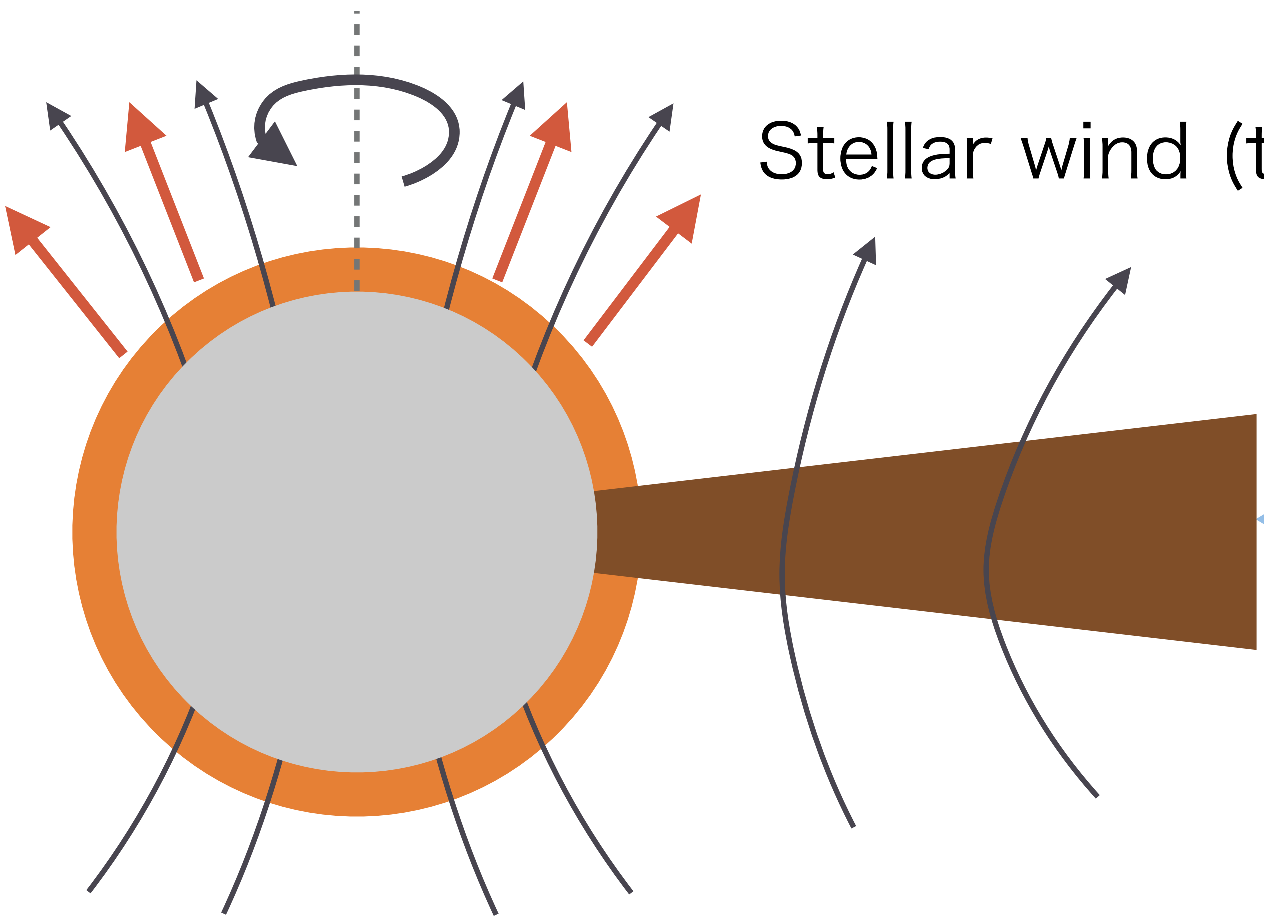
Basic eqs: ideal MHD (OK for this inner region)



Model setting: Stellar surface & disk

Slowly rotating (r_corot = 3 Rstar)

Stellar wind (thermally driven)

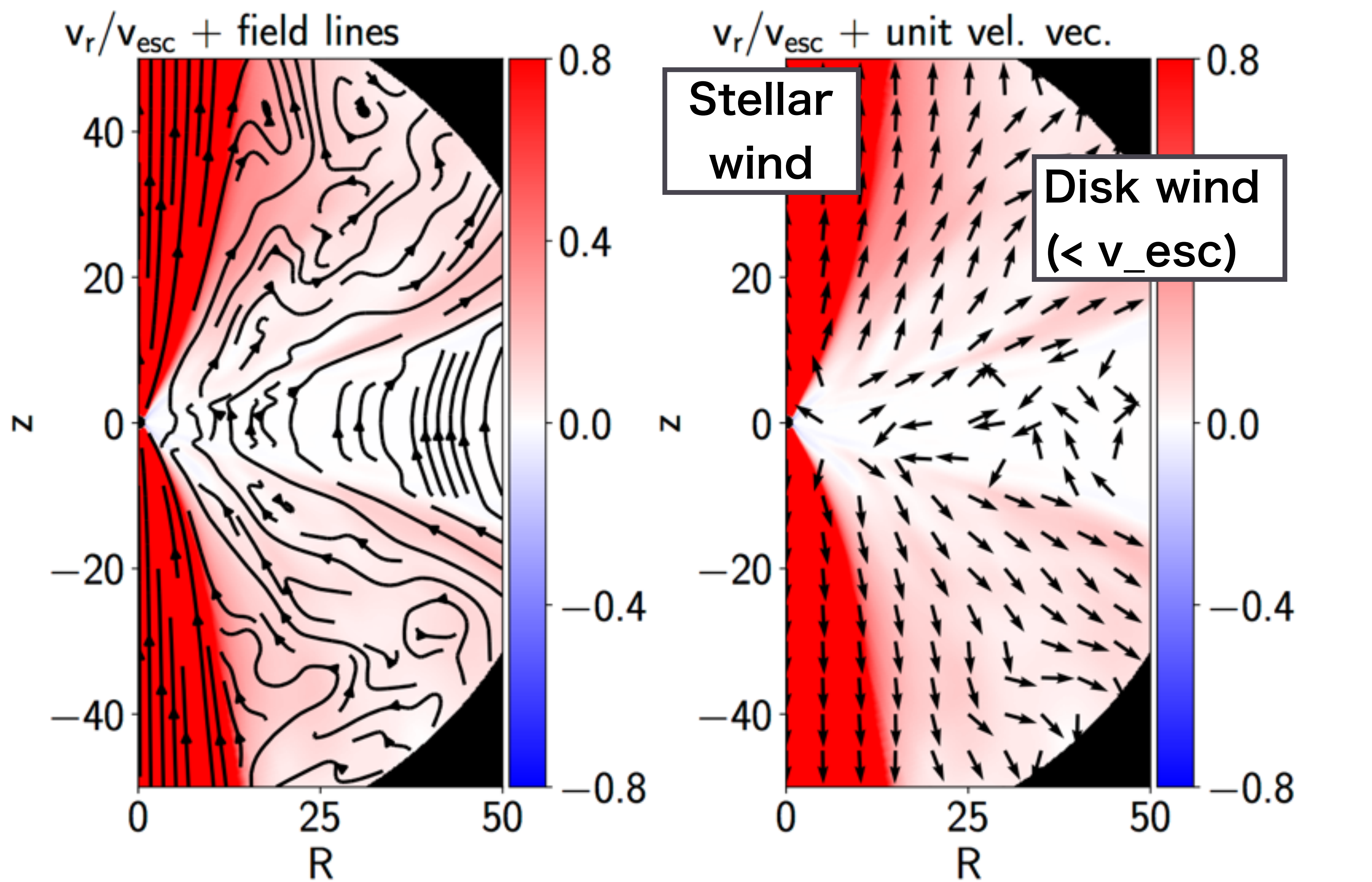


- ➤ Cold (thin) disk: Hp/R = 0.14
- ➤ Weakly magnetized: β=10^4
- ➤ A simplified radiation cooling is adopted to maintain the initial disk temperature profile

weakly magnetized

a damping layer method used:
The disturbed stellar surface reverts to a certain coronal state gradually.

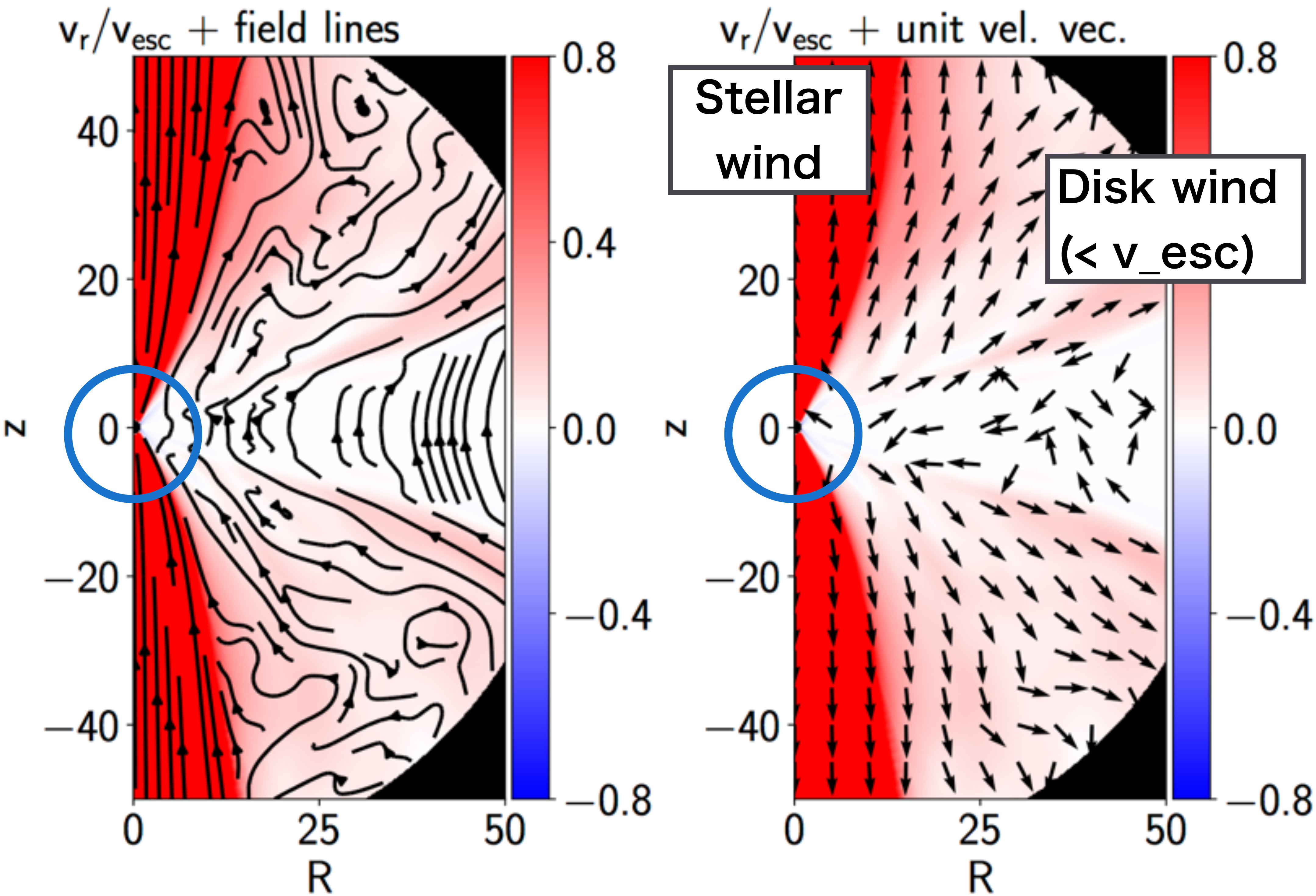
B-field and gas flow structures: large view



No magnetically-driven jets with v ~ v_esc from the MRI disk found

(consistent with previous simulations of disks with non-rotating BH, e.g. Beckwith+09)

B-field and gas flow structures: large view



No magnetically-driven jets with v ~ v_esc from the MRI disk found

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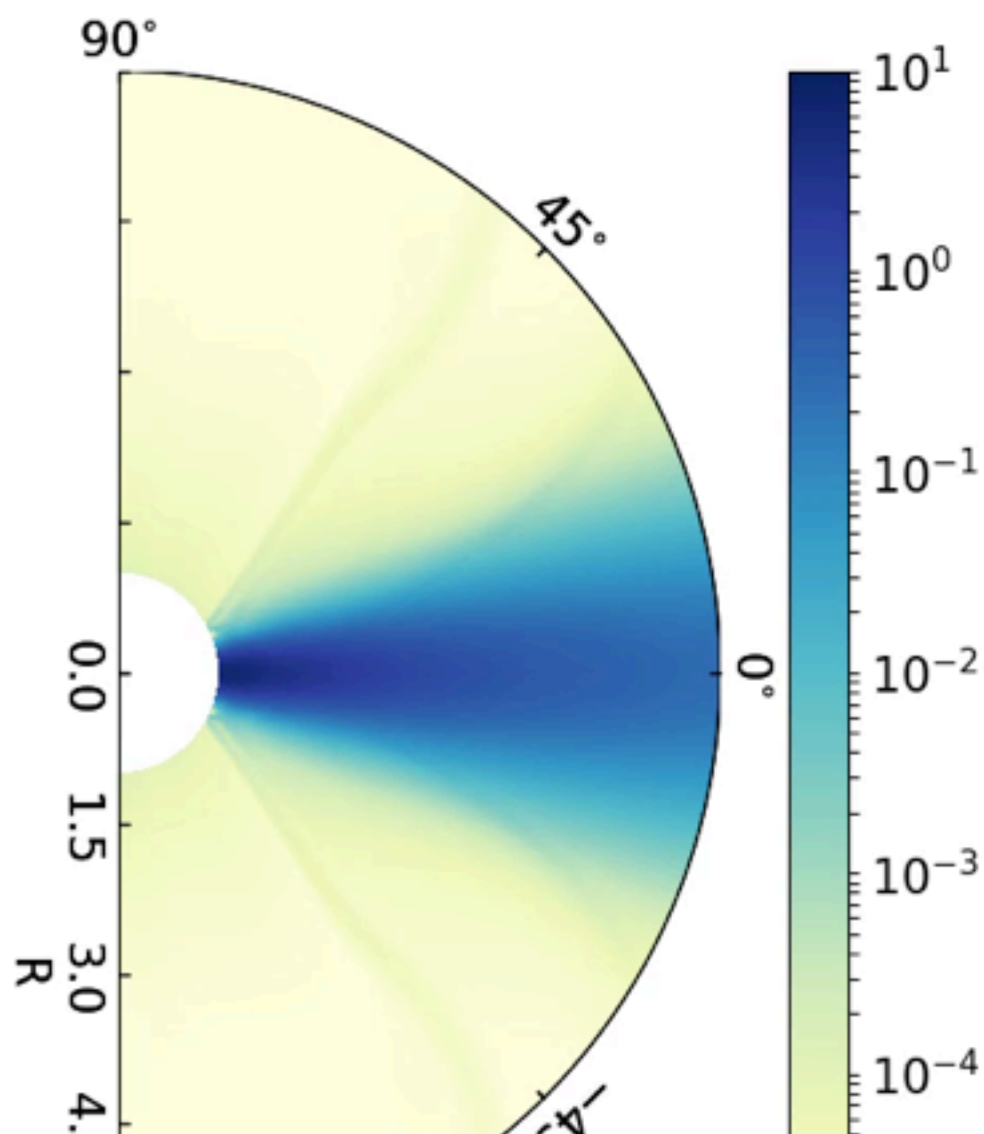
Gas map around the star

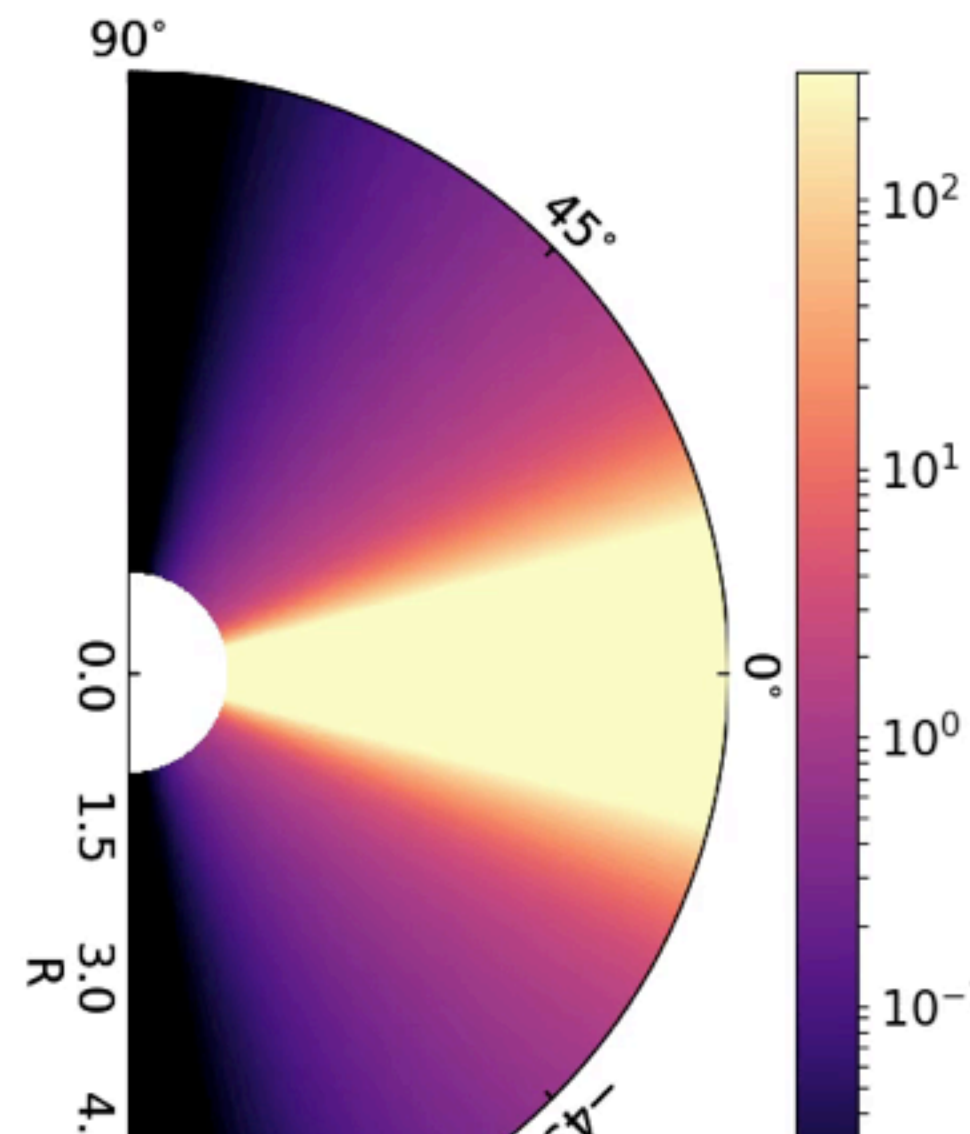
Density

Time = 1 Kepler rot. at R = 1



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

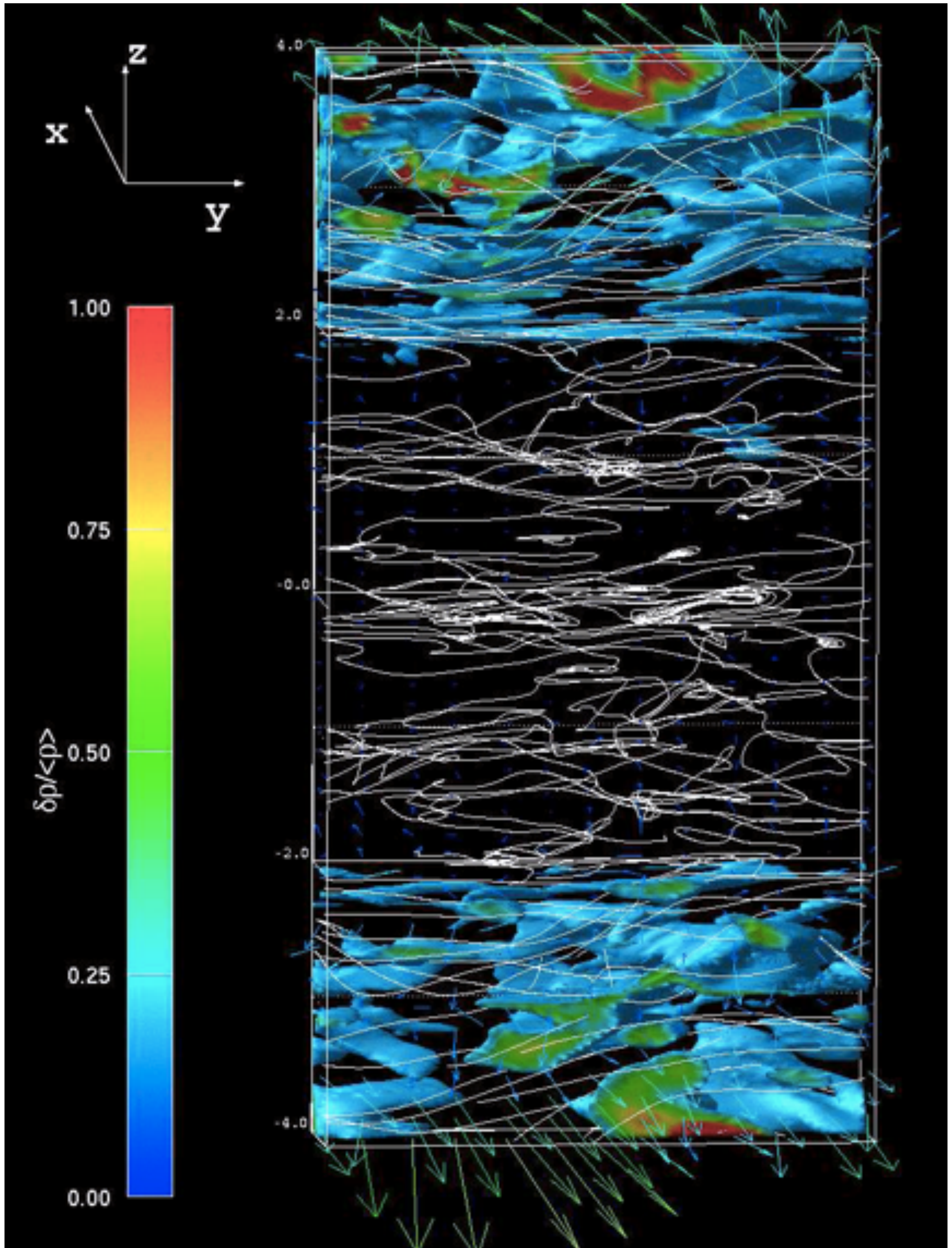
Time = 0 Kepler rot. at R = 1



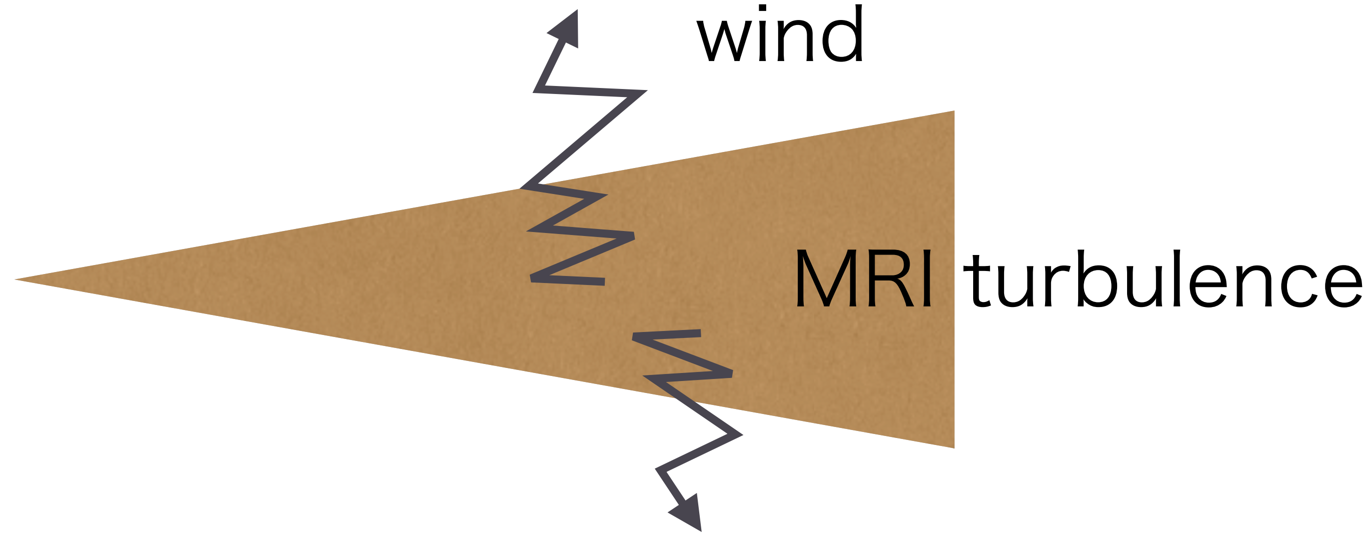
- The density above the disk increases
- Highly fluctuating/turbulent disk atmosphere

(source of turbulence: MagnetoRotational Instability, MRI)

MRI-driven wind



Suzuki & Inutsuka 2009



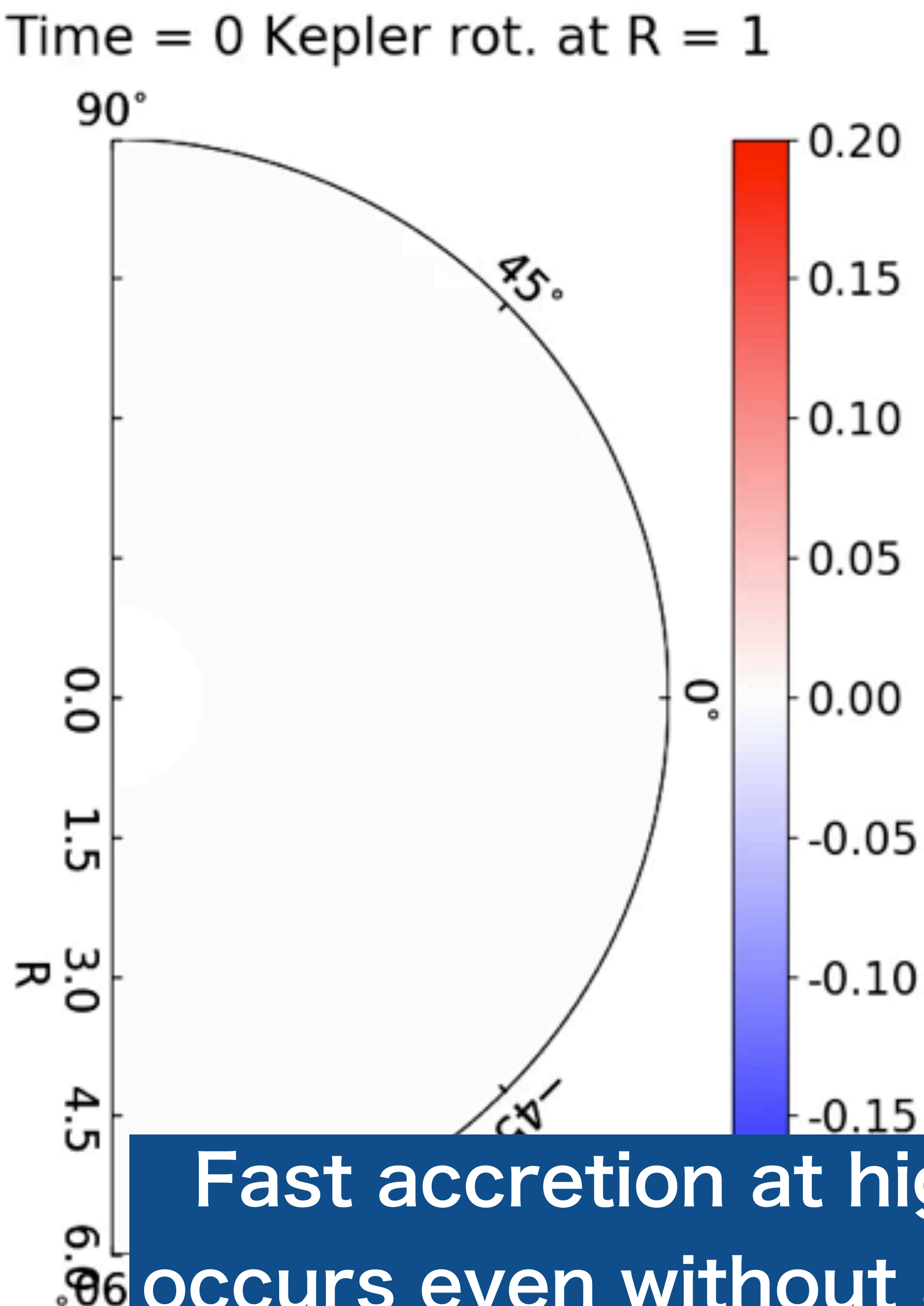
Suzuki & Inutsuka 2009, 2014

Fromang et al. 2013, Bai & Stone 2013

- **The wind supplies a large amount of mass to the upper atmosphere**
- Slow (<< escape velocity)
- The wind is expected to become magnetically-driven outflows (but unclear)

Gas map around the star

radial velocity



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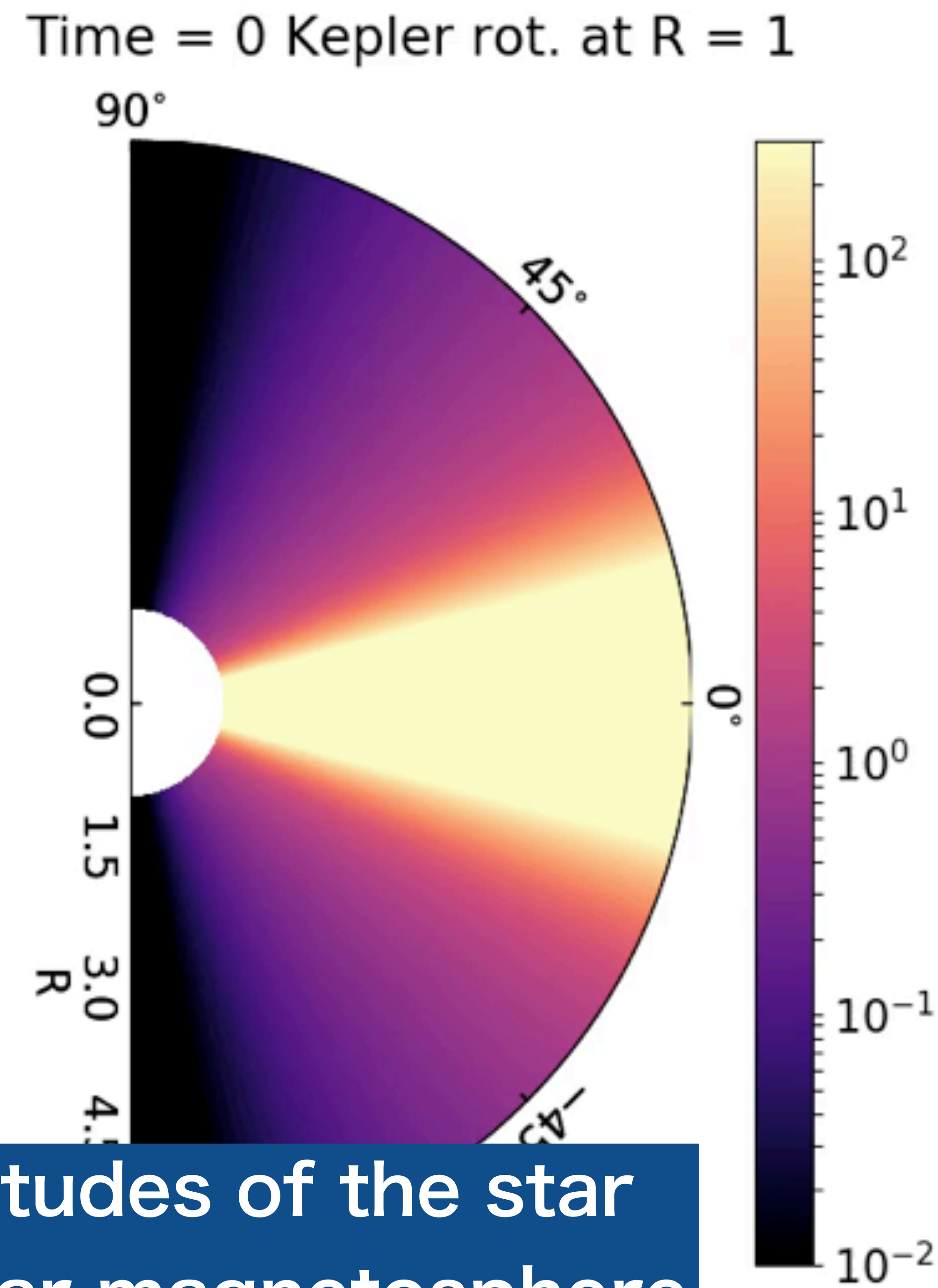
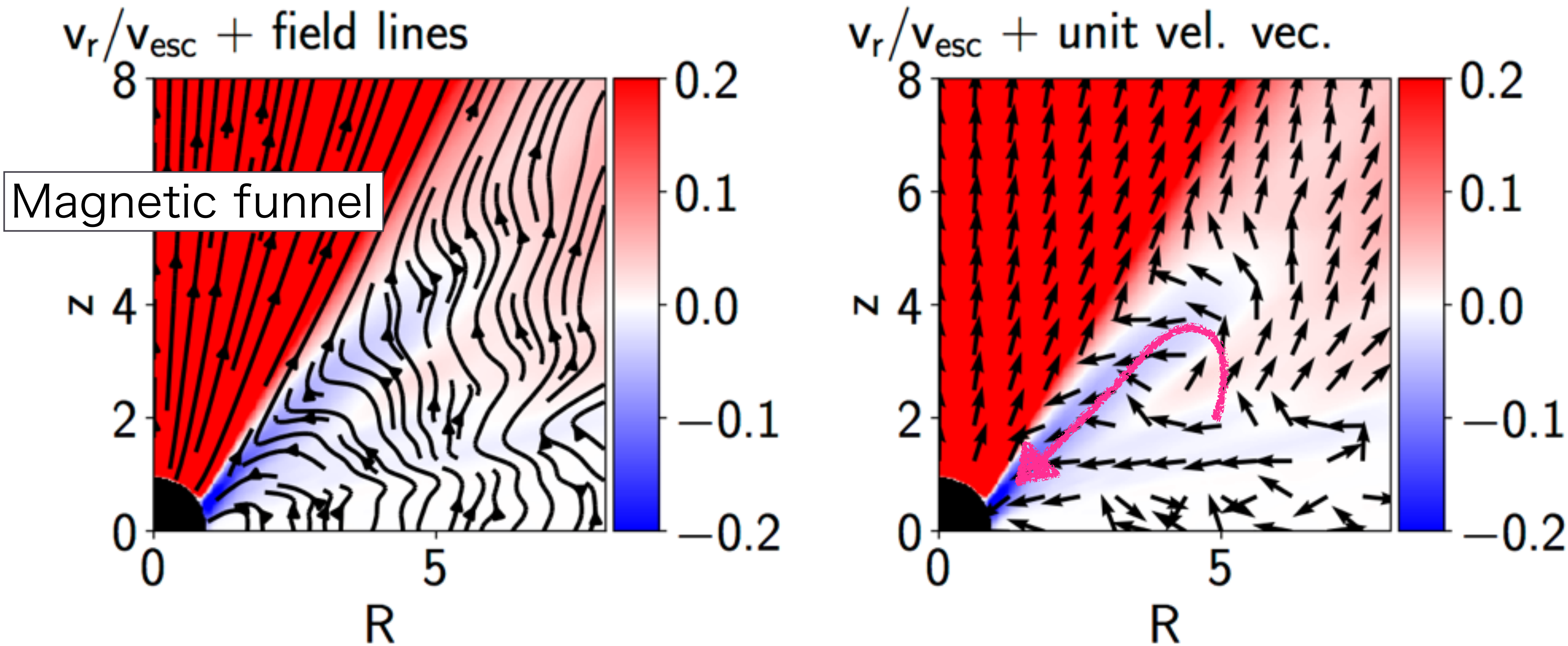


Fast accretion at high-latitudes of the star occurs even without a stellar magnetosphere

B-field and gas flow structures: centeral region

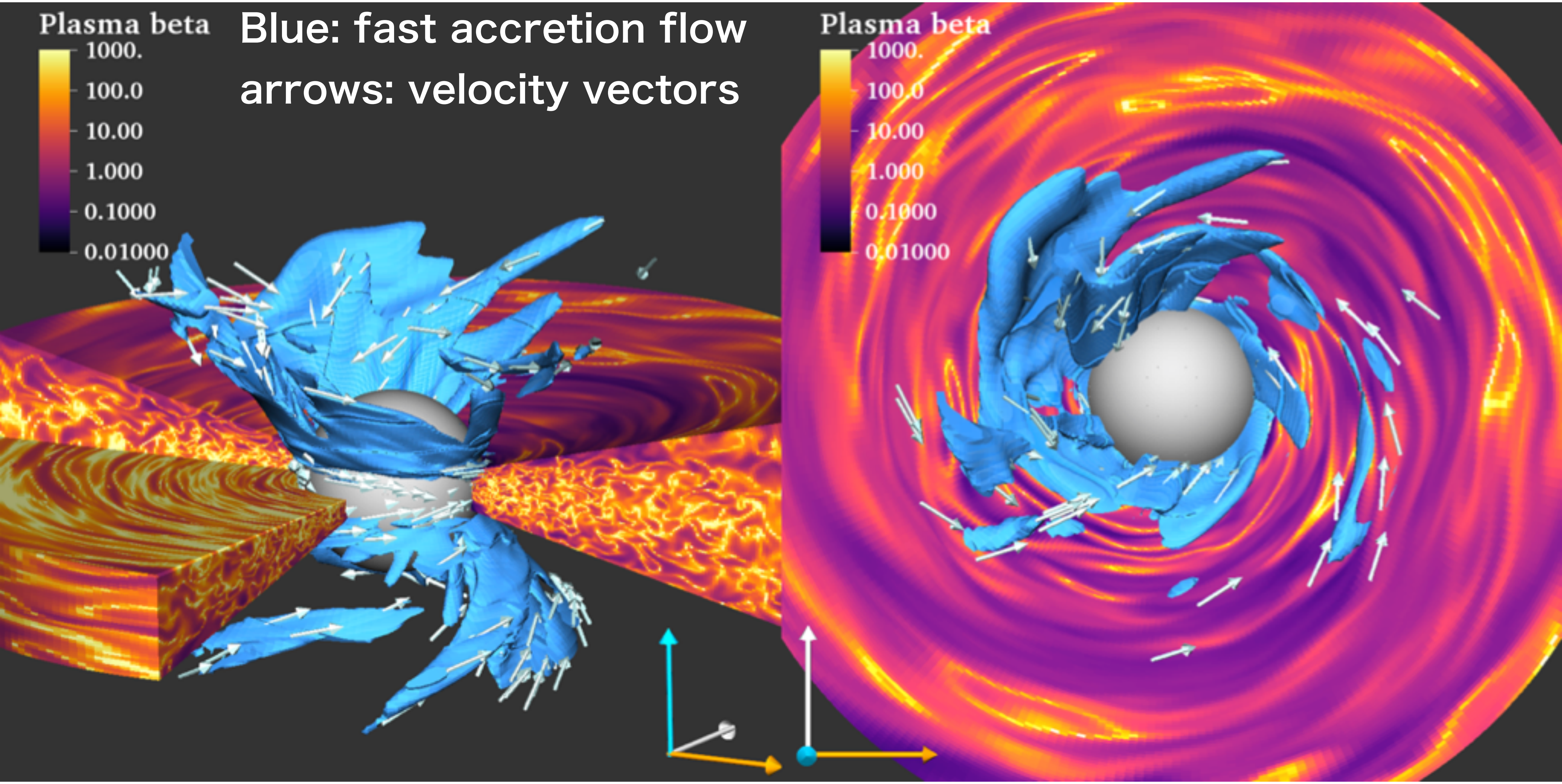


Outer region: wind is blowing outward (but slowly)

Inner region: MRI-driven wind is flowing to the star
("failed" wind) along the magnetic funnel

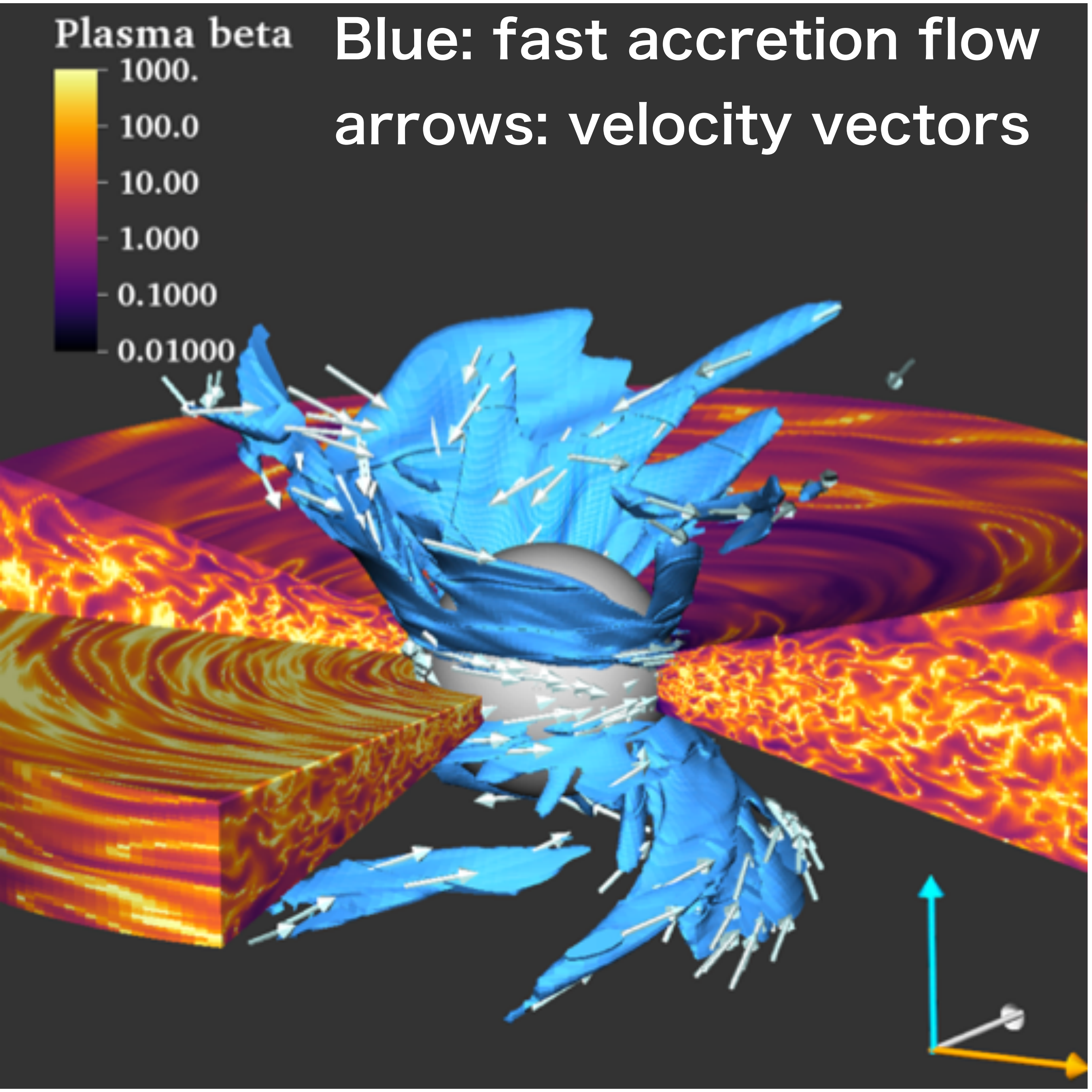
Funnel-wall accretion

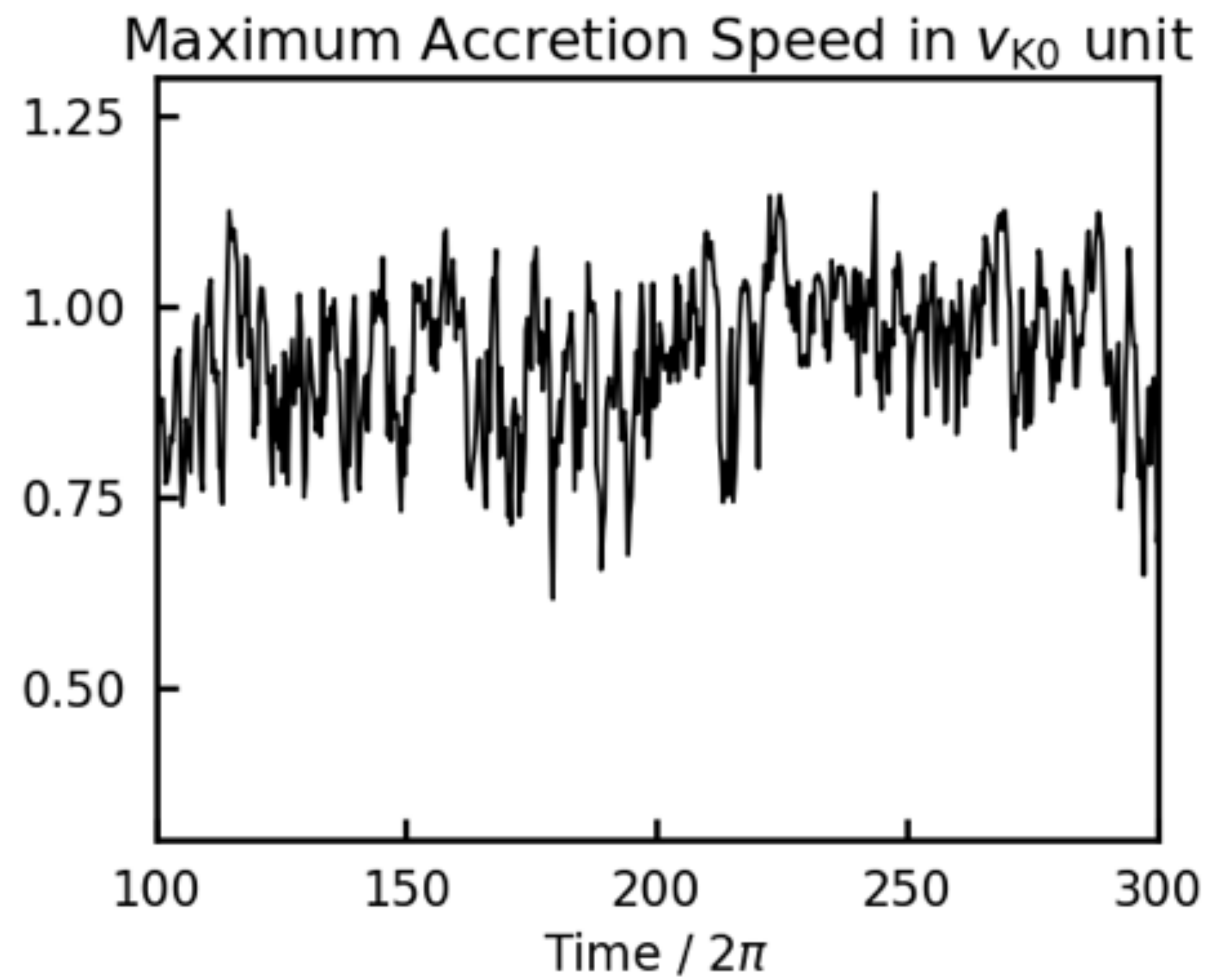
3D structure of funnel-wall accretion



- Patchy accretion streams flowing to high-latitudes
- Coexistence of the disk accretion and funnel-wall accretion

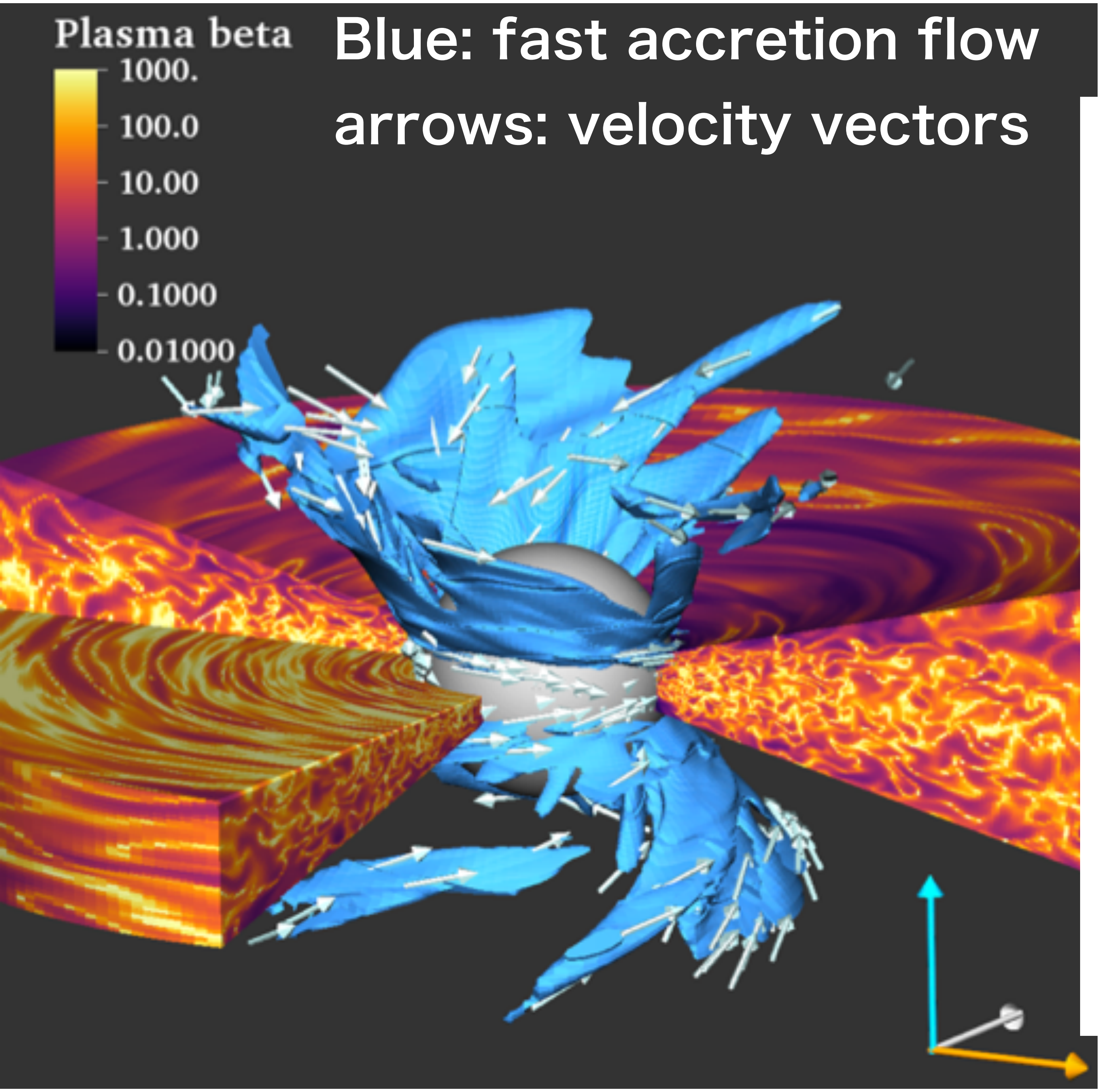
Maximum accretion speed



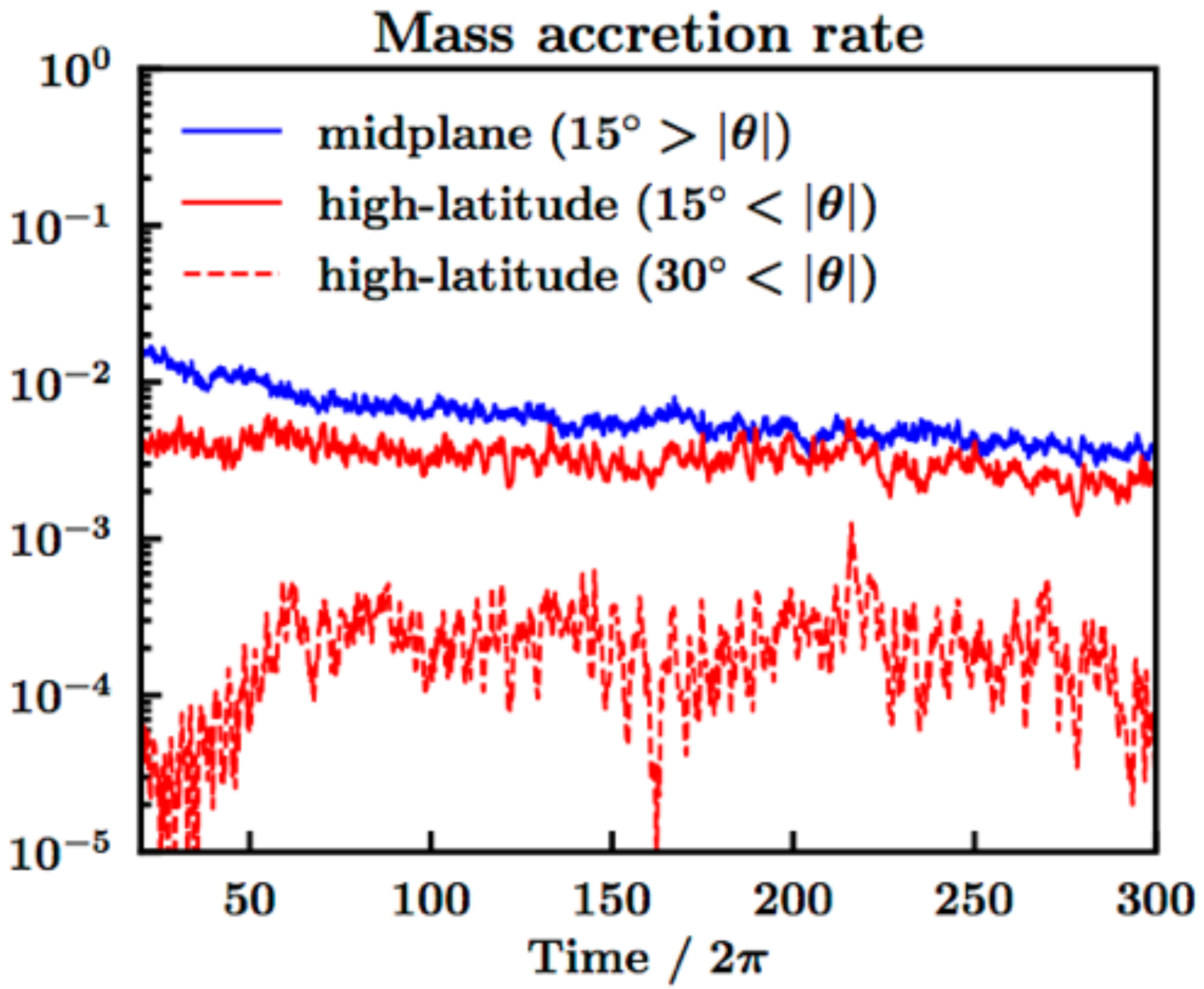


Even without a magnetosphere,
accretion with a speed of $v_K \sim 0.7 v_{esc}$ (>100 km/s) is possible
(observed soft X-ray emission can be produced at acc. shocks)

Accretion rate



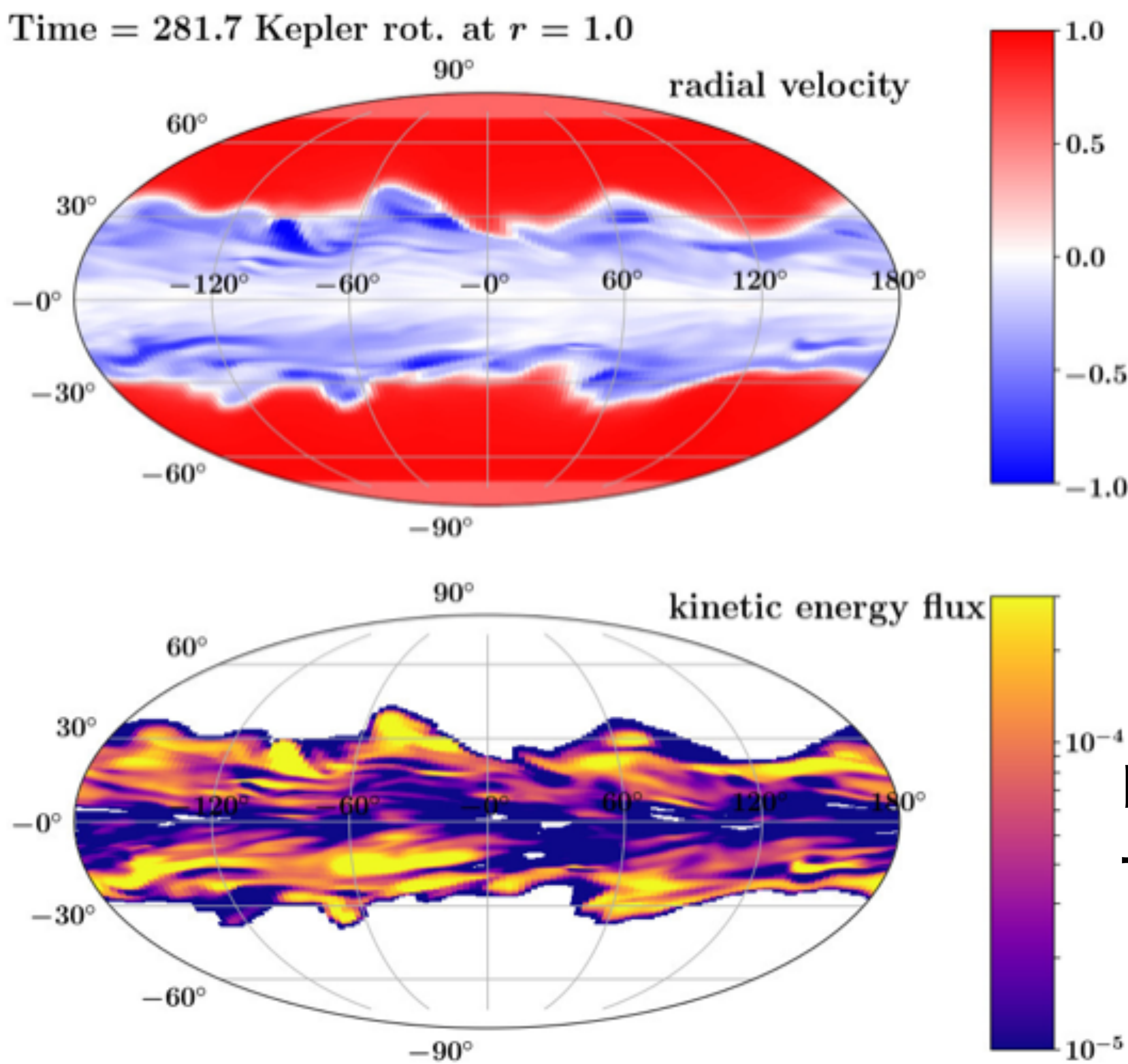
The disk opening angle: ~15°



Mid plane accretion is dominant:

Rate of the funnel-wall acc. ~ 0.01-0.5 x rate of mid plane acc.

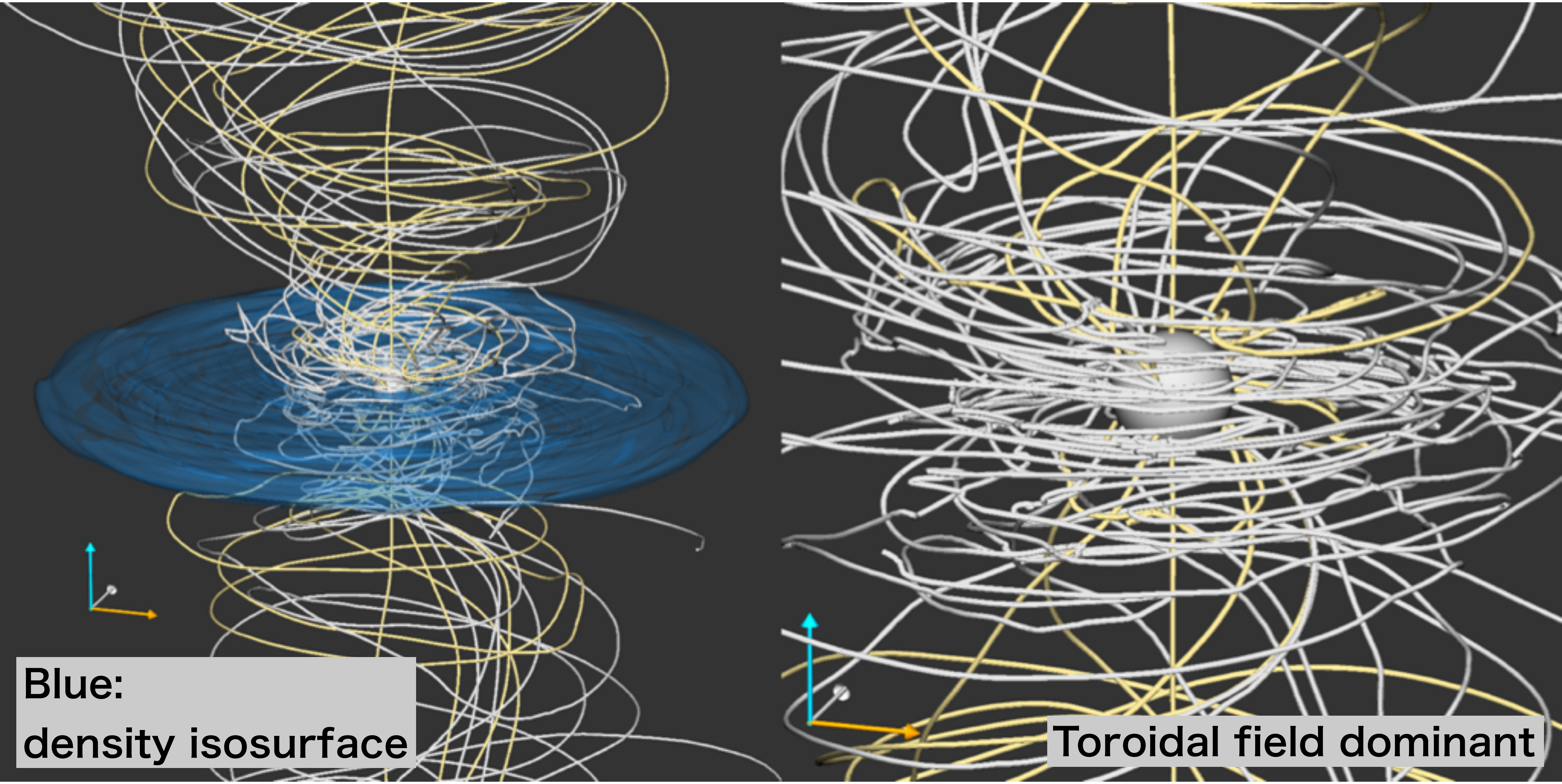
Accretion structure on the stellar surface (r=1)



Many localized accretion spots

Large kinetic energy flux regions ~ hot spots

3D magnetic field structure

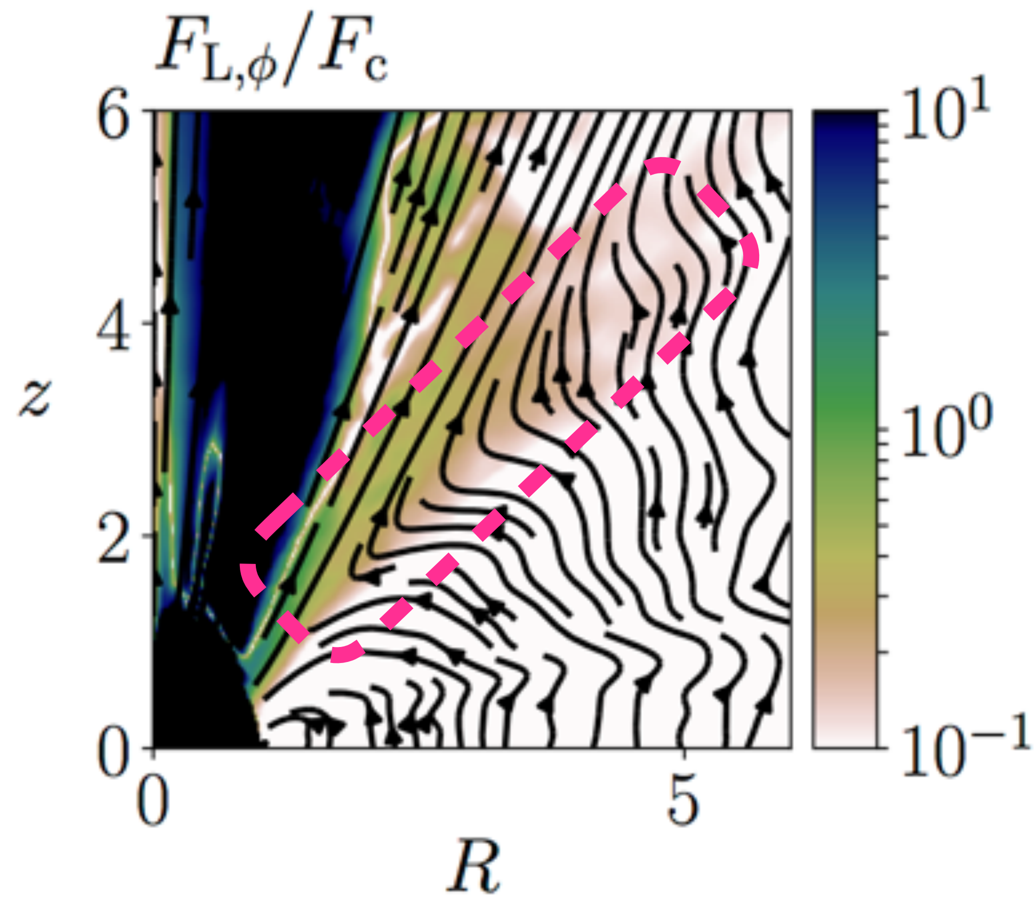


Contrast to the magnetospheric accretion model,
accretion streams do not move along a field line in this case

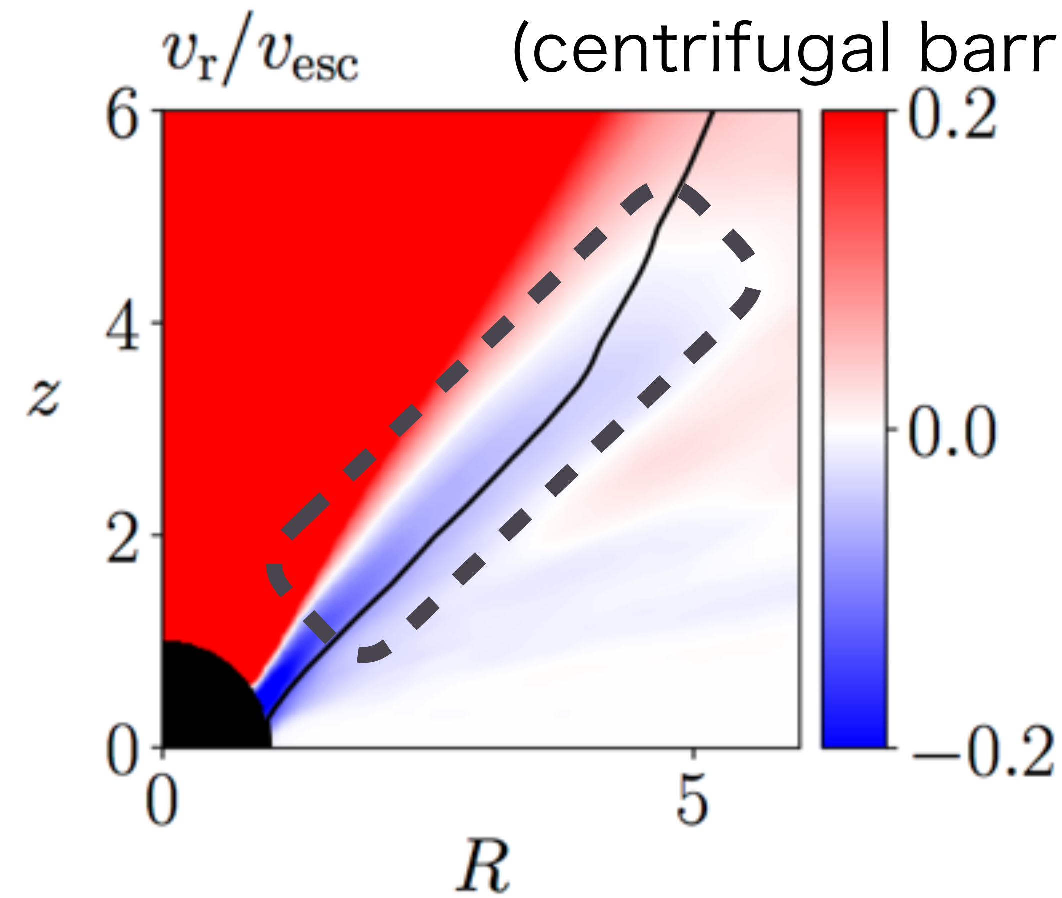
Why funnel-wall accretion is so fast (~free-fall)?

Significant ang. mom. loss by the Lorentz force

Lorentz force/centrifugal force



iso specific ang. mom. line
(centrifugal barrier)



The deceleration by mag. torque becomes important when

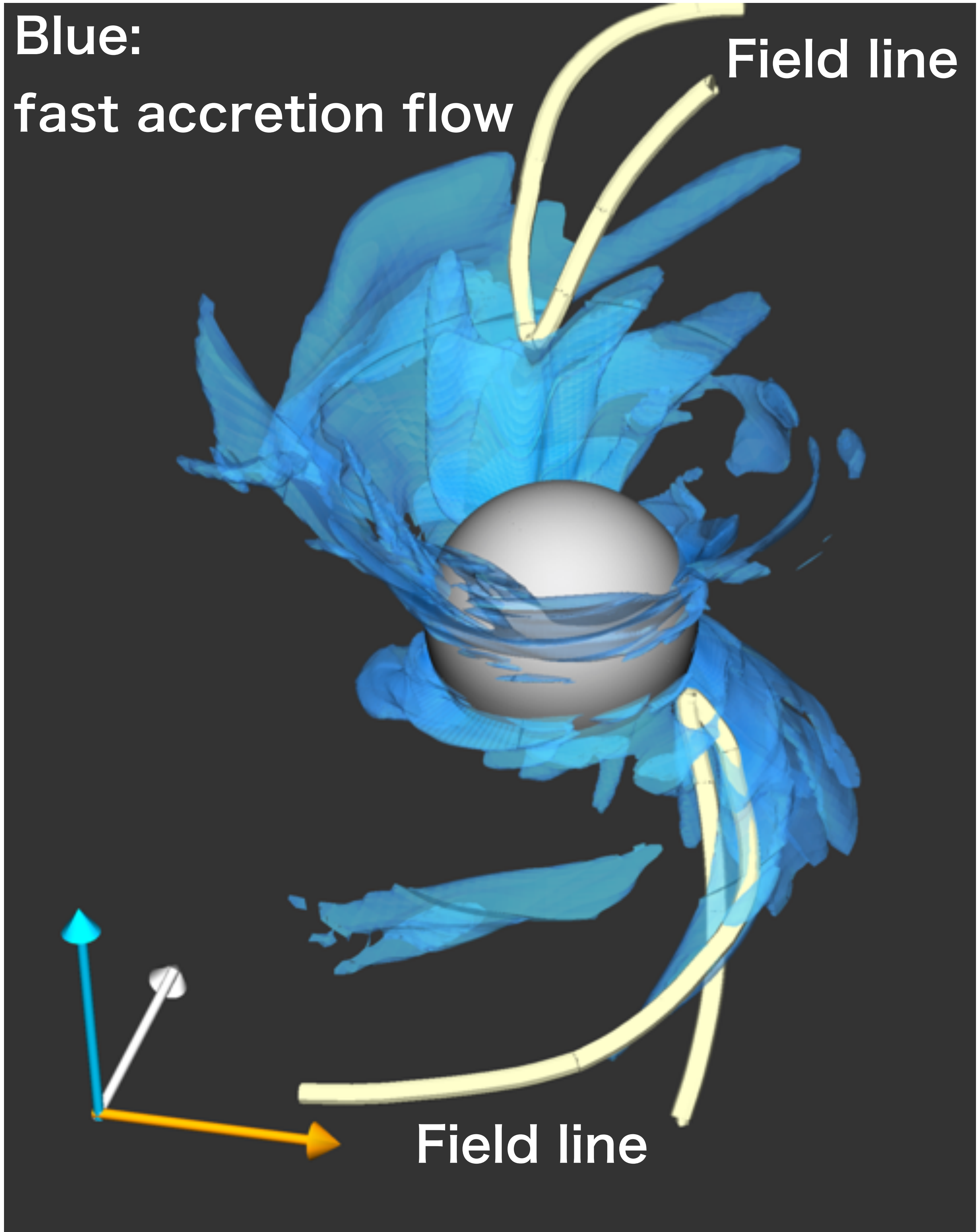
$$F_{\mathrm{L},\phi} \approx F_\mathrm{cen}$$

Lorentz force centrifugal force

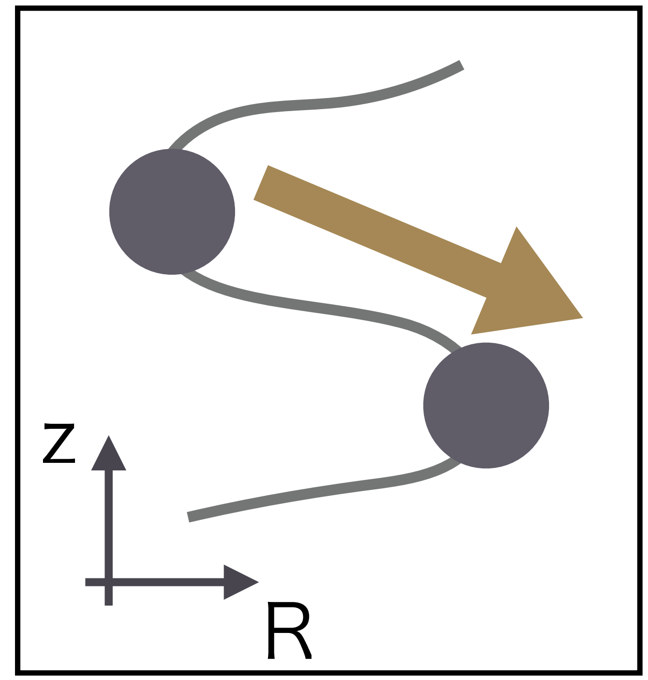
So-called <u>avalanche flow</u> (Matsumoto+ 1996)

but it occurs well above the disk surface

Angular momentum exchange mechanism



MRI-like ang. mom. exchange



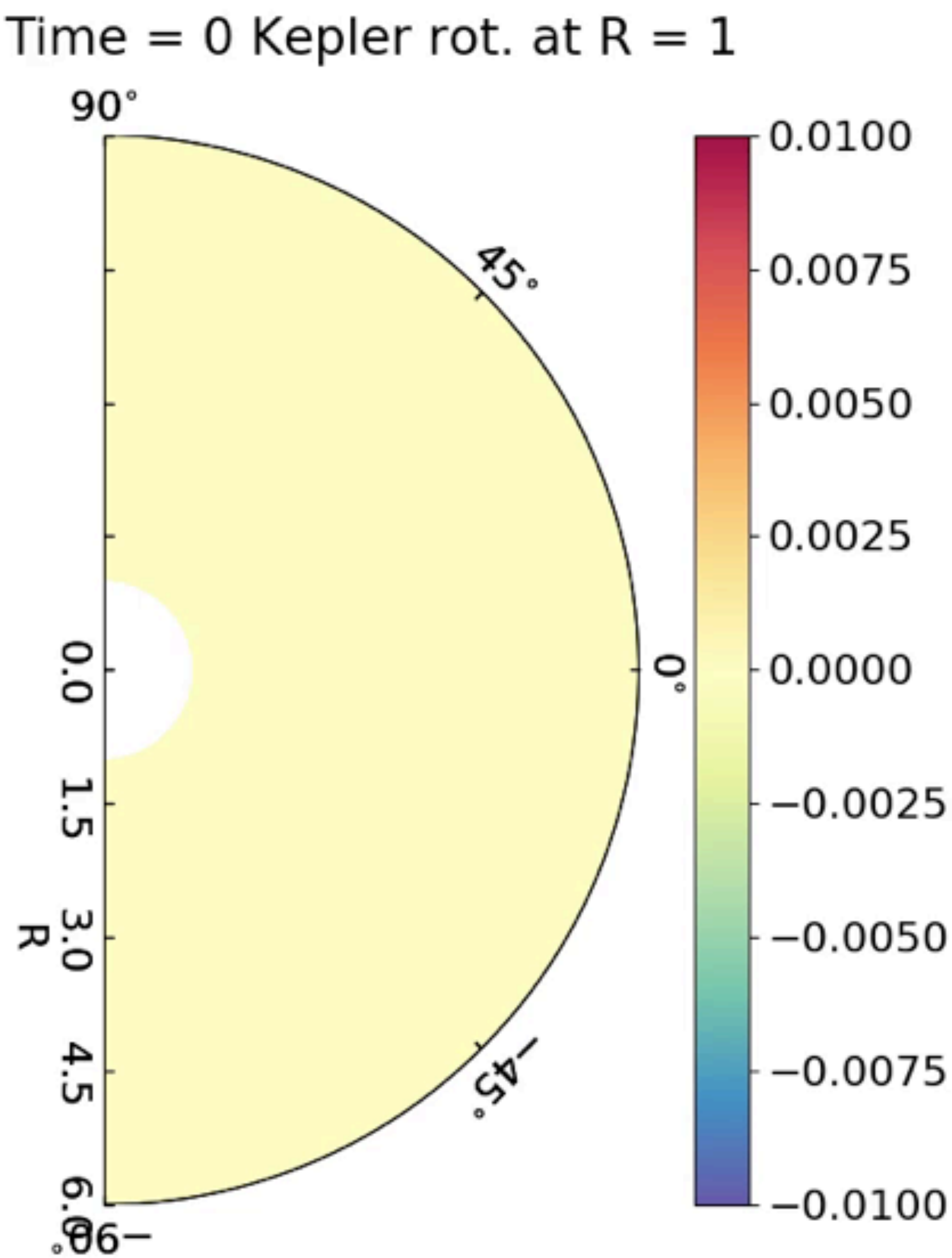
$$\lambda_{\rm MRI} \approx H$$

$$F_{\rm L,\phi} \approx F_{\rm cen}$$

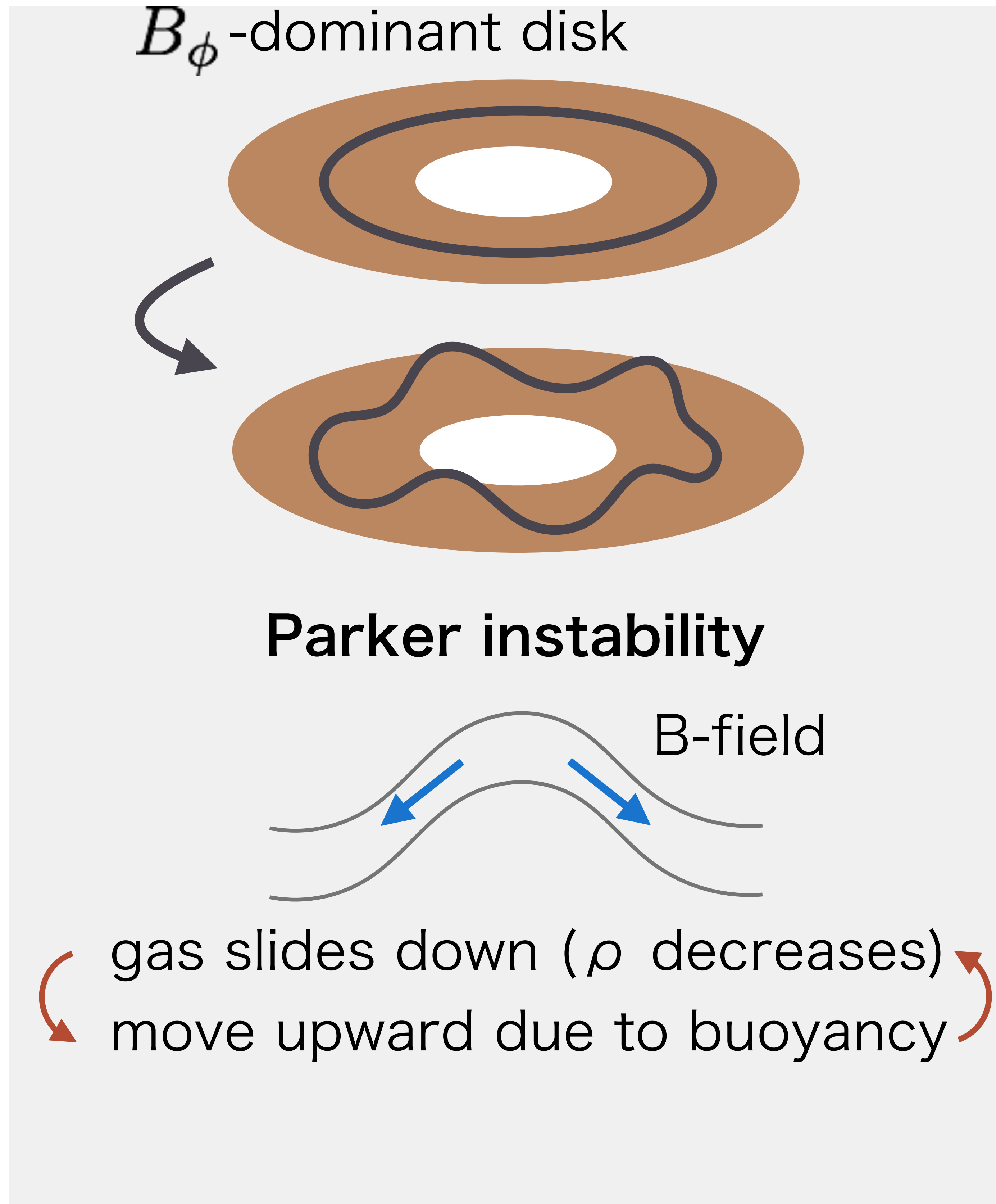
$$\rightarrow \frac{B^2}{4\pi H} \approx \rho \frac{v_\phi^2}{R}$$

This is confirmed in our sim.

Origin of funnel-wall accretion: Relation to the disk dynamo



As for reversal of the sign of Bphi, see e.g. Machida et al. 2013



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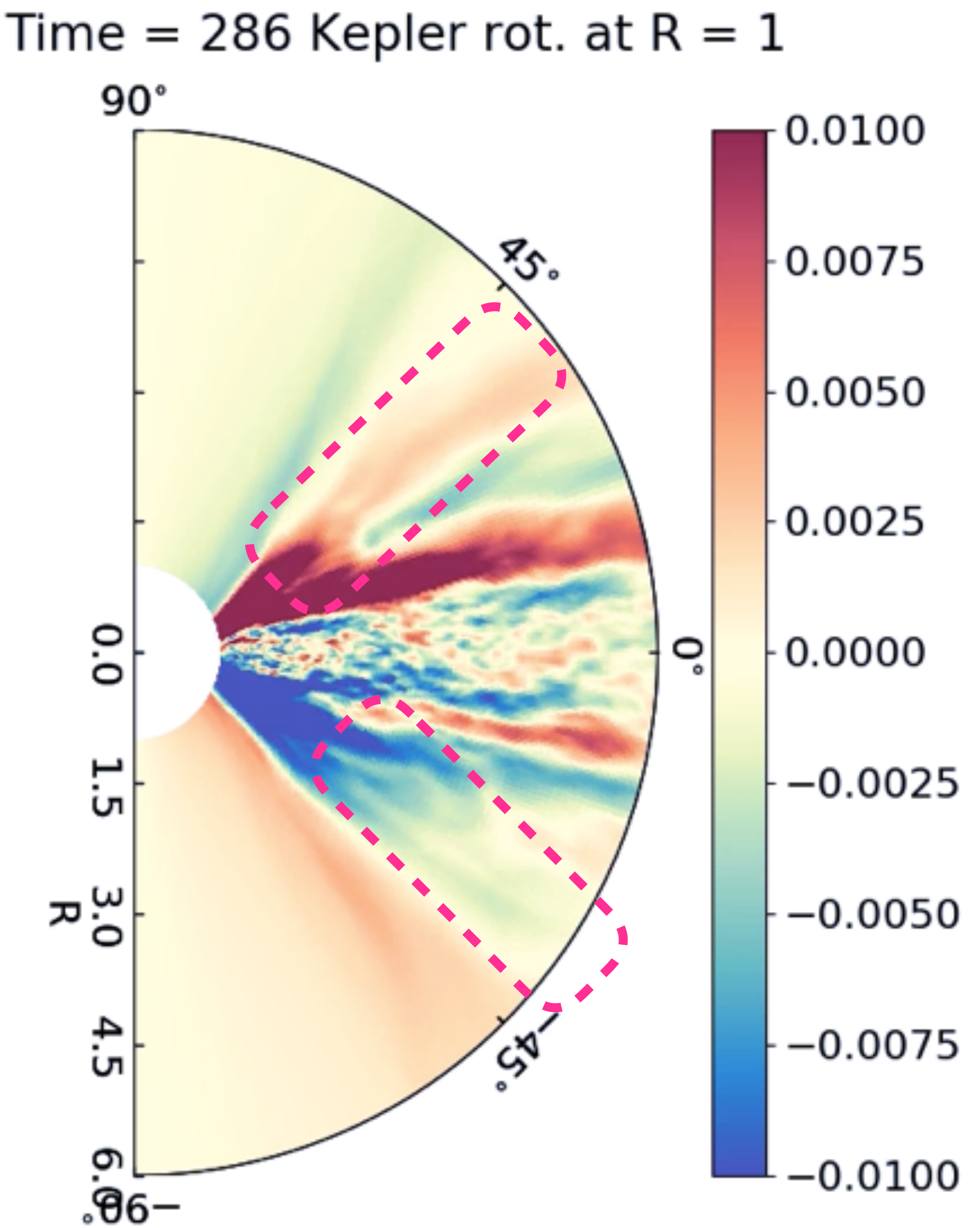
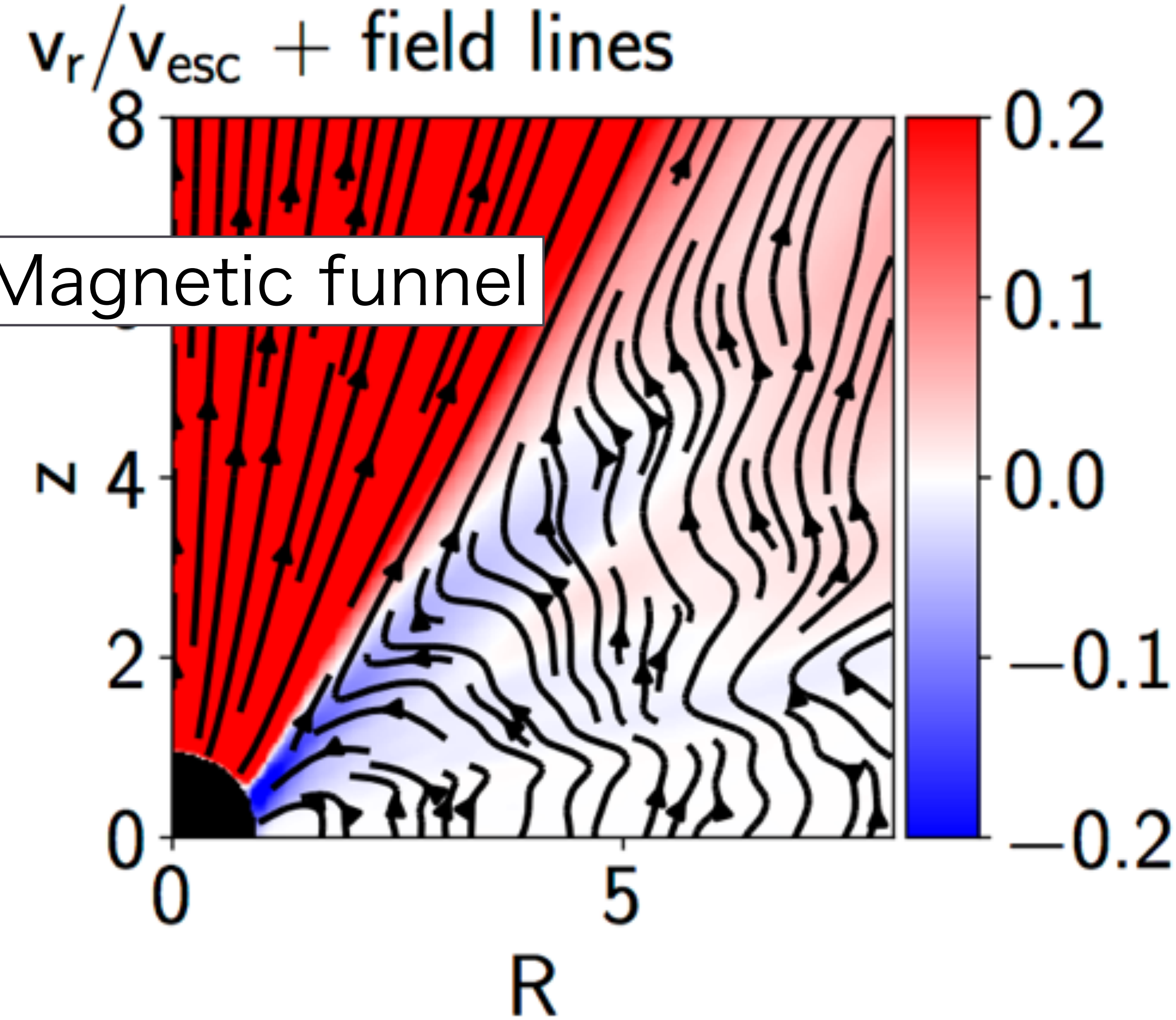




As for reversal of the sign of Bphi, see e.g. Machida et al. 2013

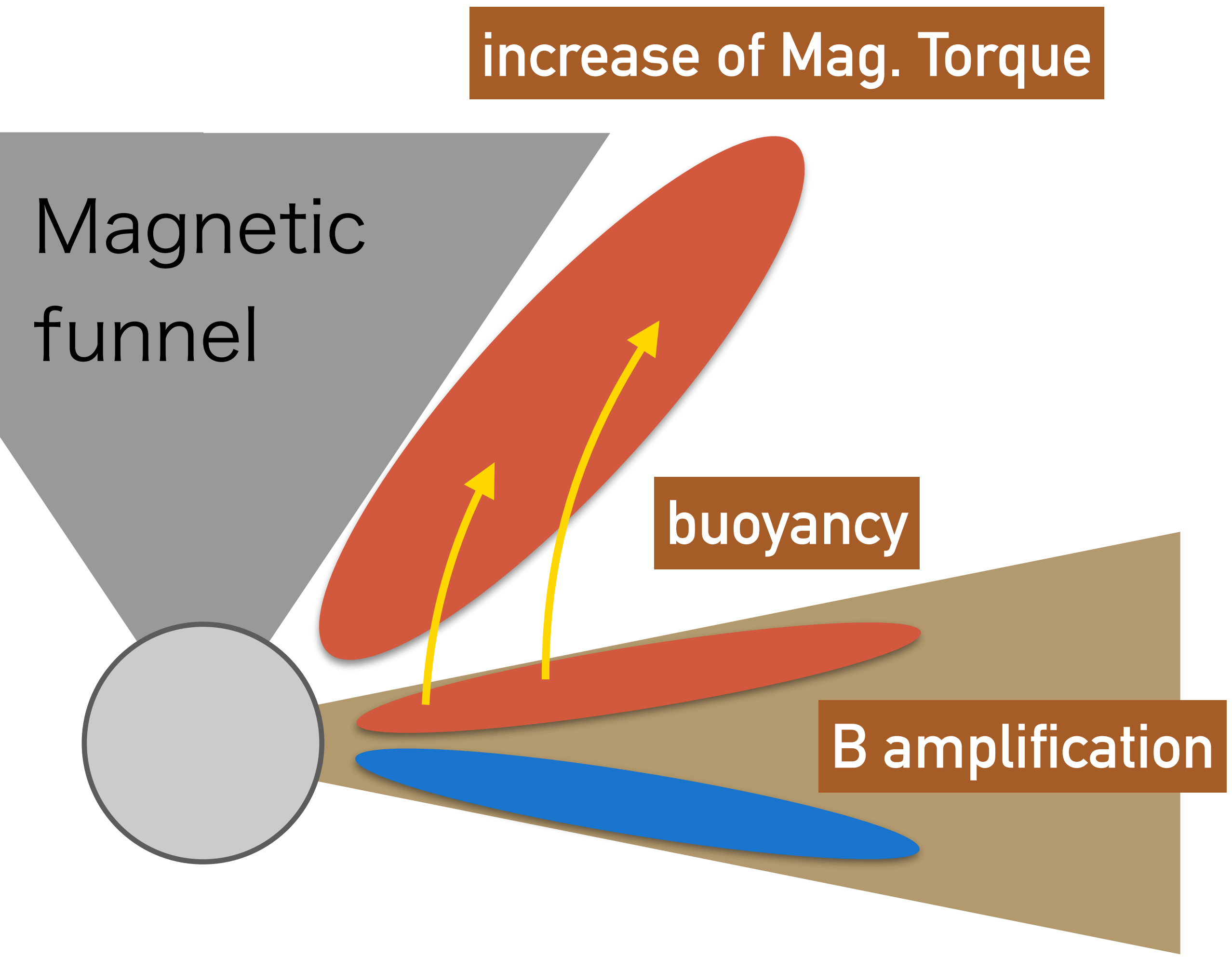
Rising magnetic field cannot penetrate the magnetic funnel.

—> move along the funnel

—> **supply B-field along the funnel**

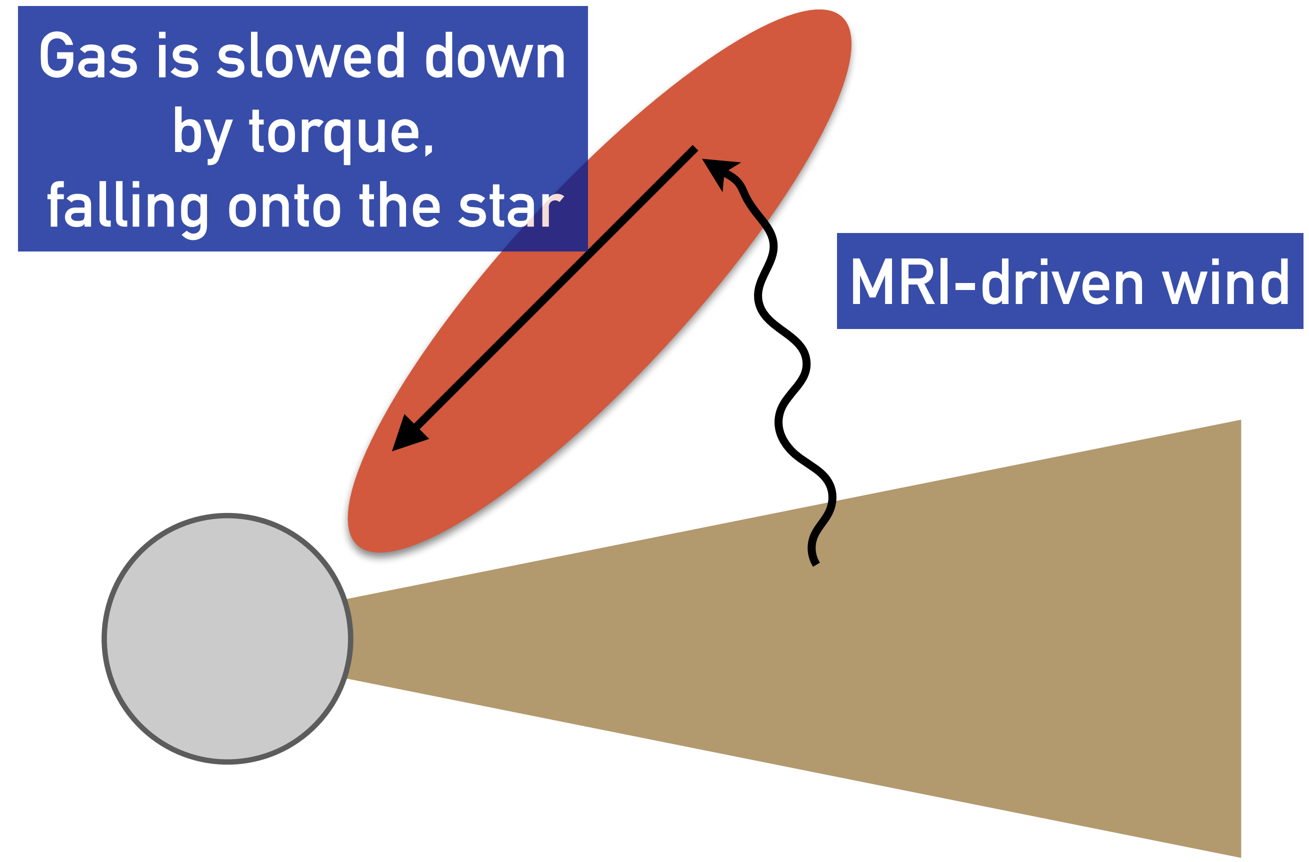
Movement of B-fields & accreting materials

Movement of magnetic fields



Disk dynamo
—> strong B above the disk

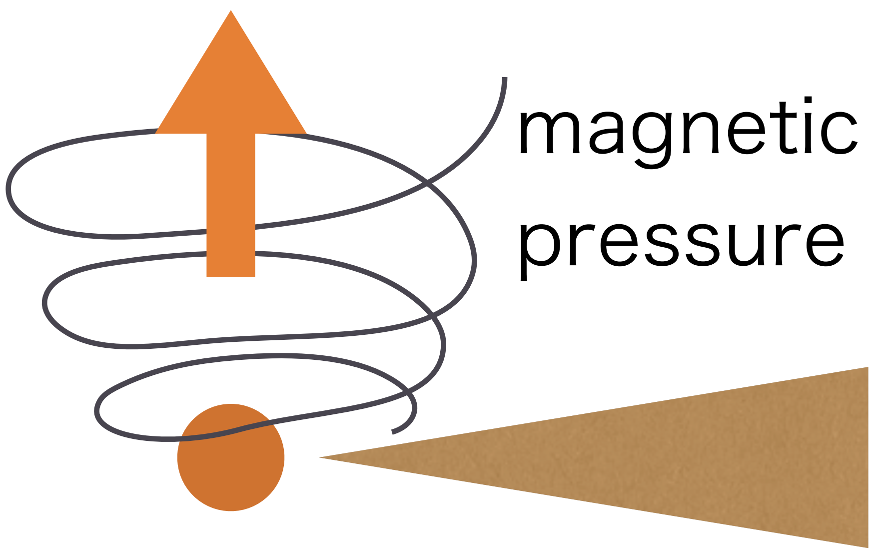
Movement of accreting materials



MRI-driven wind
—> Rapid ang. mom. loss around the funnel
—> funnel-wall accretion

Note: B-field and materials move in the opposite direction (decoupled)

Why a fast jet does not blow?



Prediction (Kudoh & Shibata 1995, 1998):
Magnetically-driven jets can form
even when the disk B-field is weak

Our result:
No jet from a 3D weakly magnetized (β=10^4),
cold (Hp/R ~ 0.1, Eth << Eg) disk

Prediction

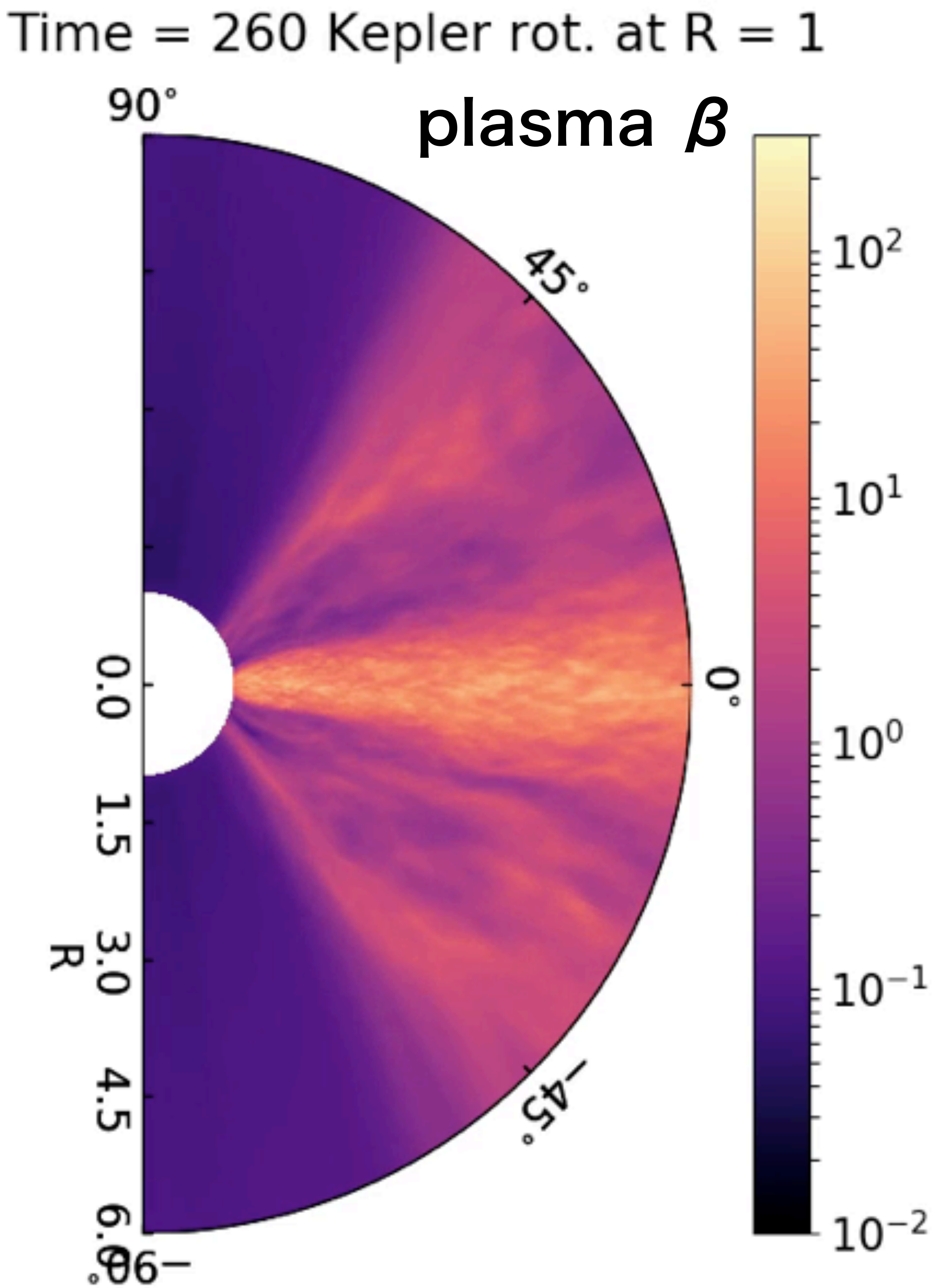
Amplify B-field → Emag ~ Eg → Jet (probably OK for thick/hot disks)

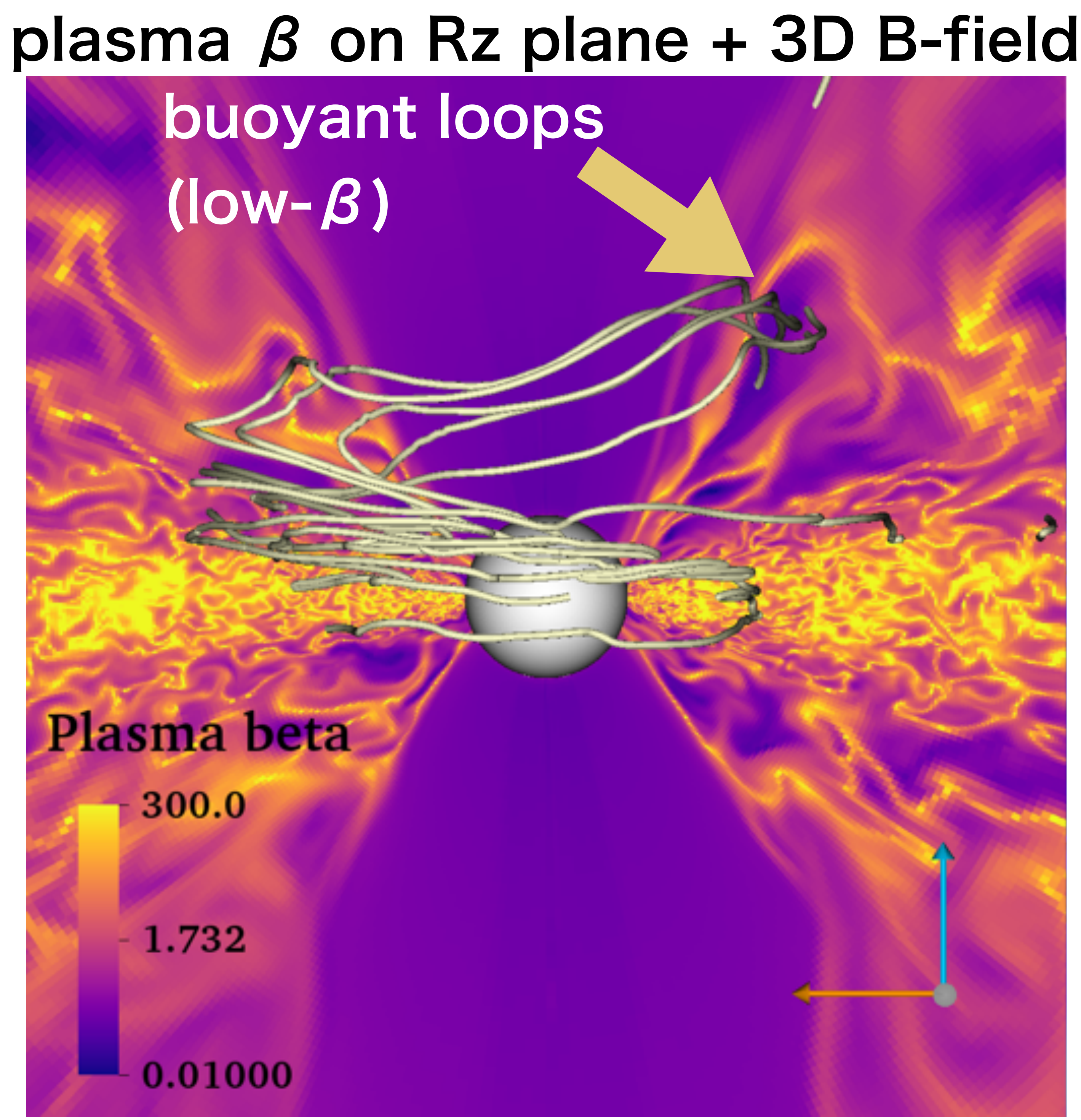
Our result ↘ **Emag ~ Eth << Eg** (β ~ 1) → **Parker instability**
Growth time ~ Amp. time

Note: Emag << Eg even well above the disk **because the density is enhanced by the MRI-driven wind**

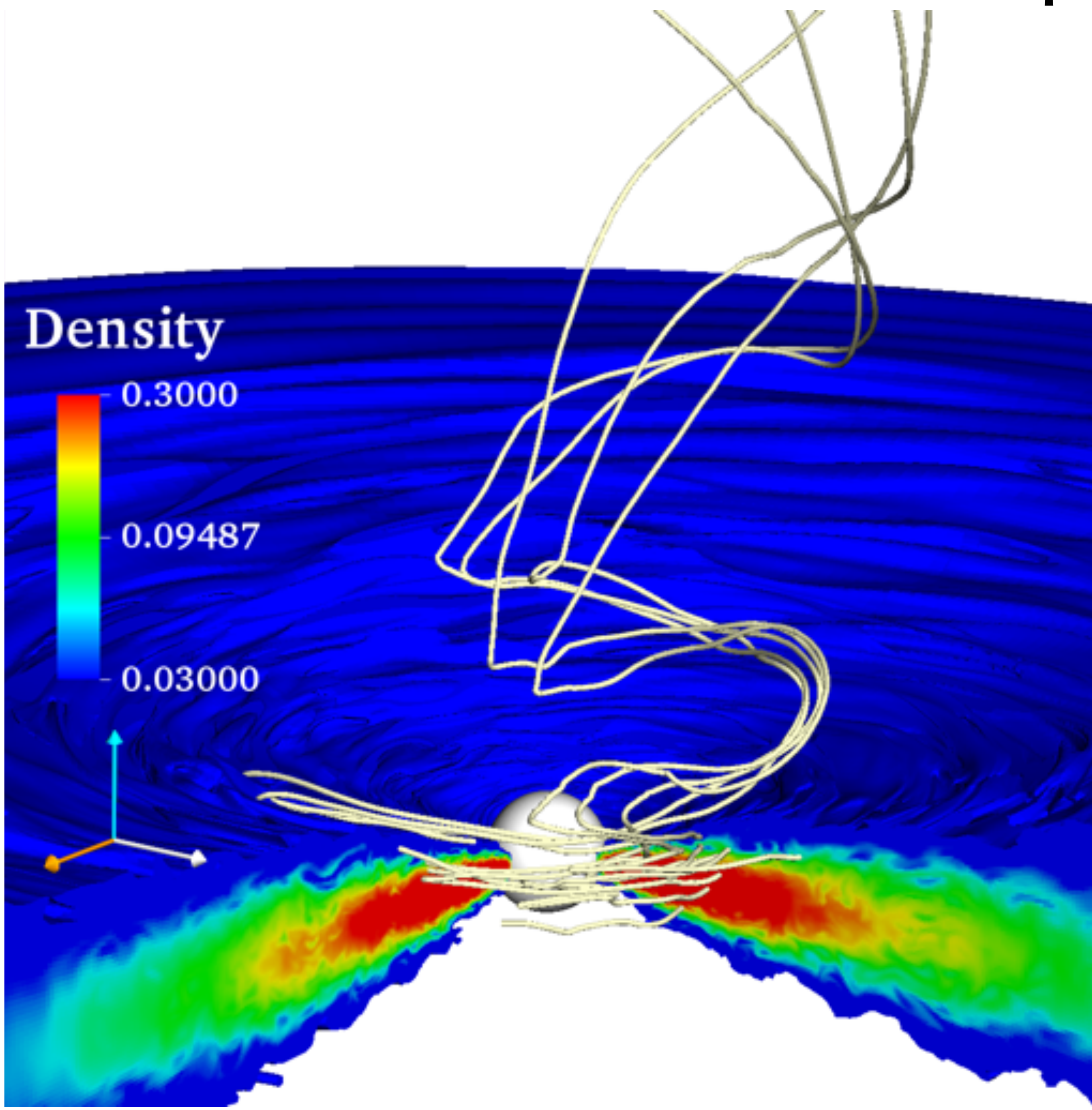
Parker instability

low-β (dark purple) = strong B

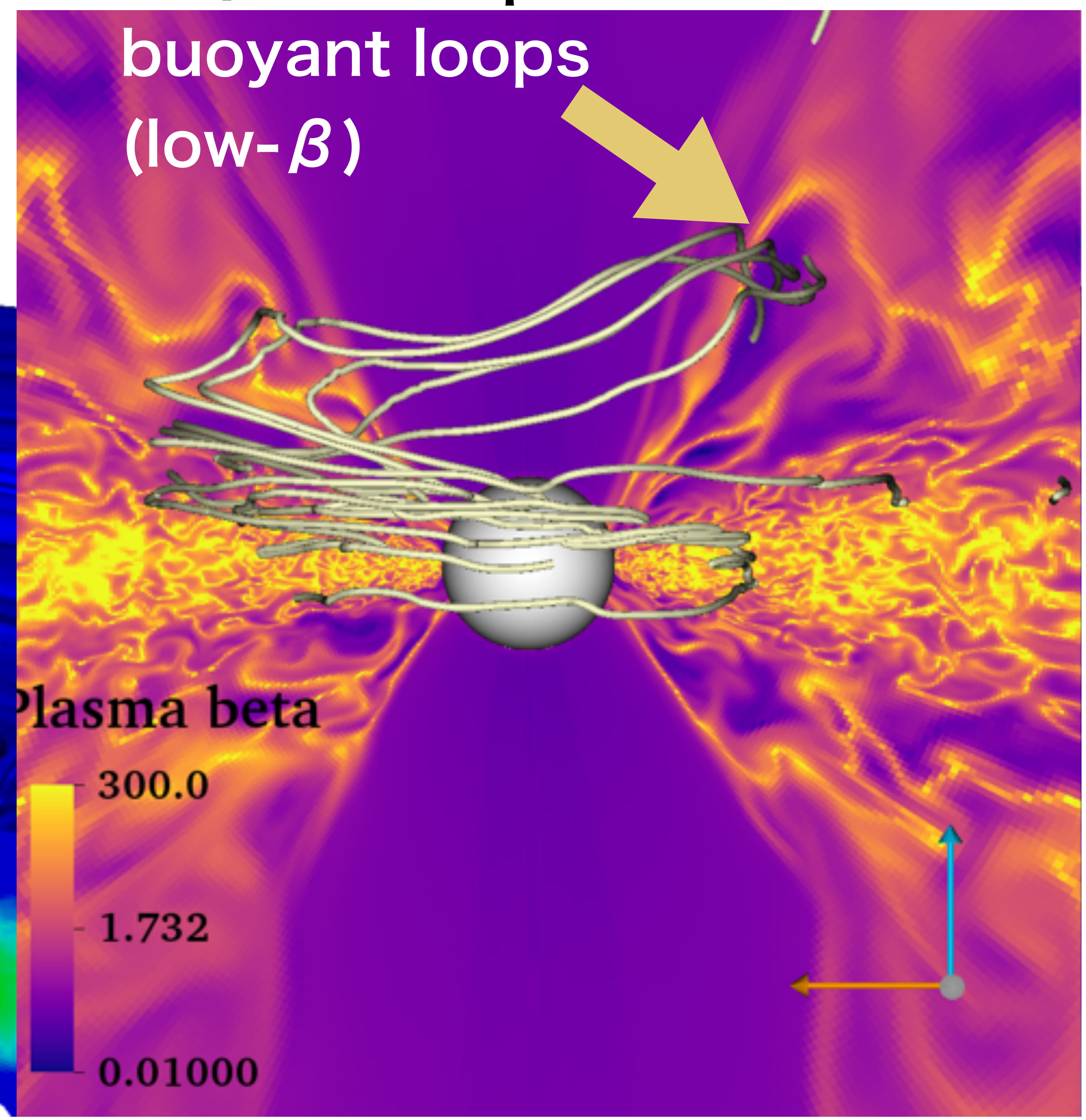




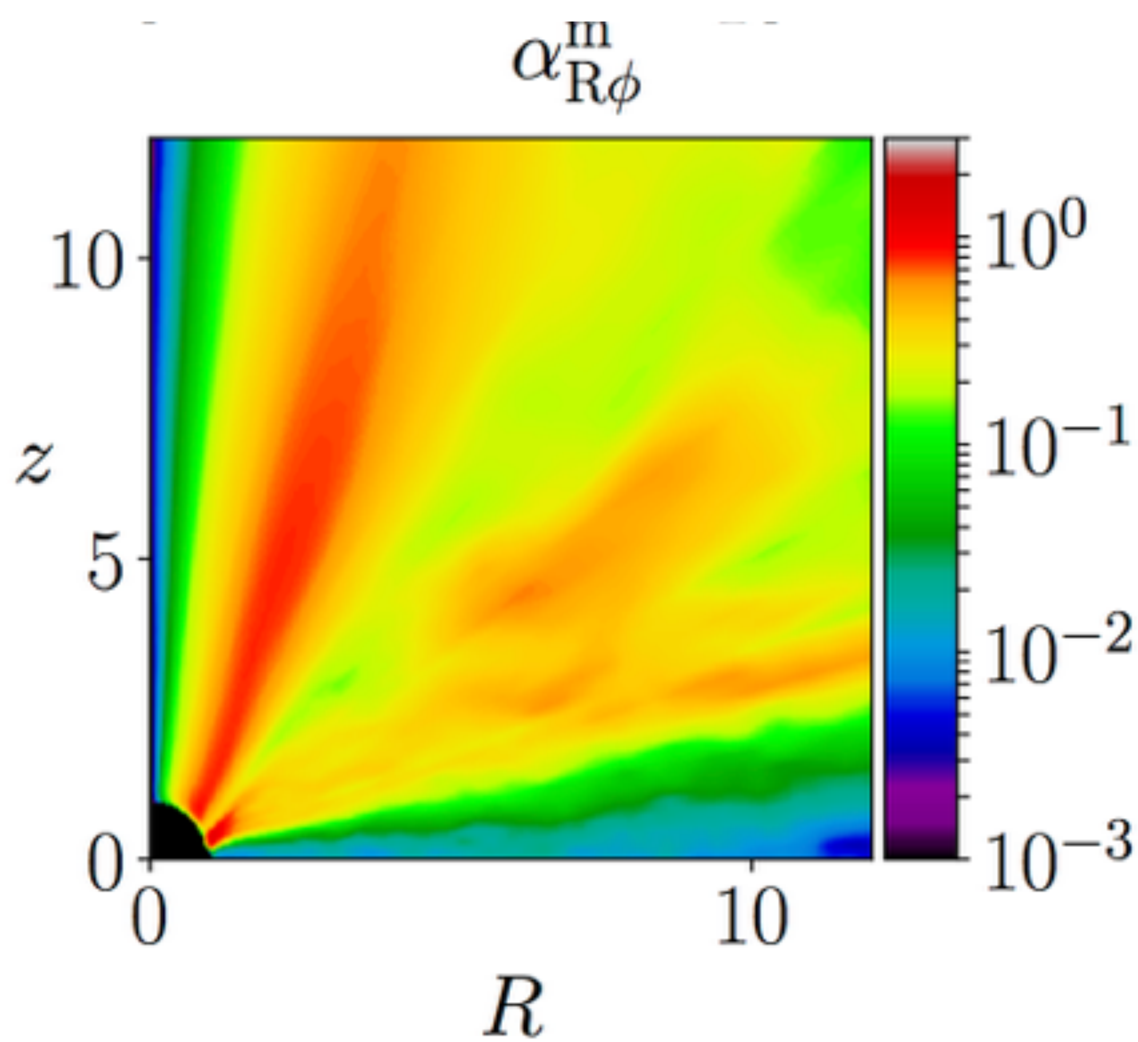
Parker instability

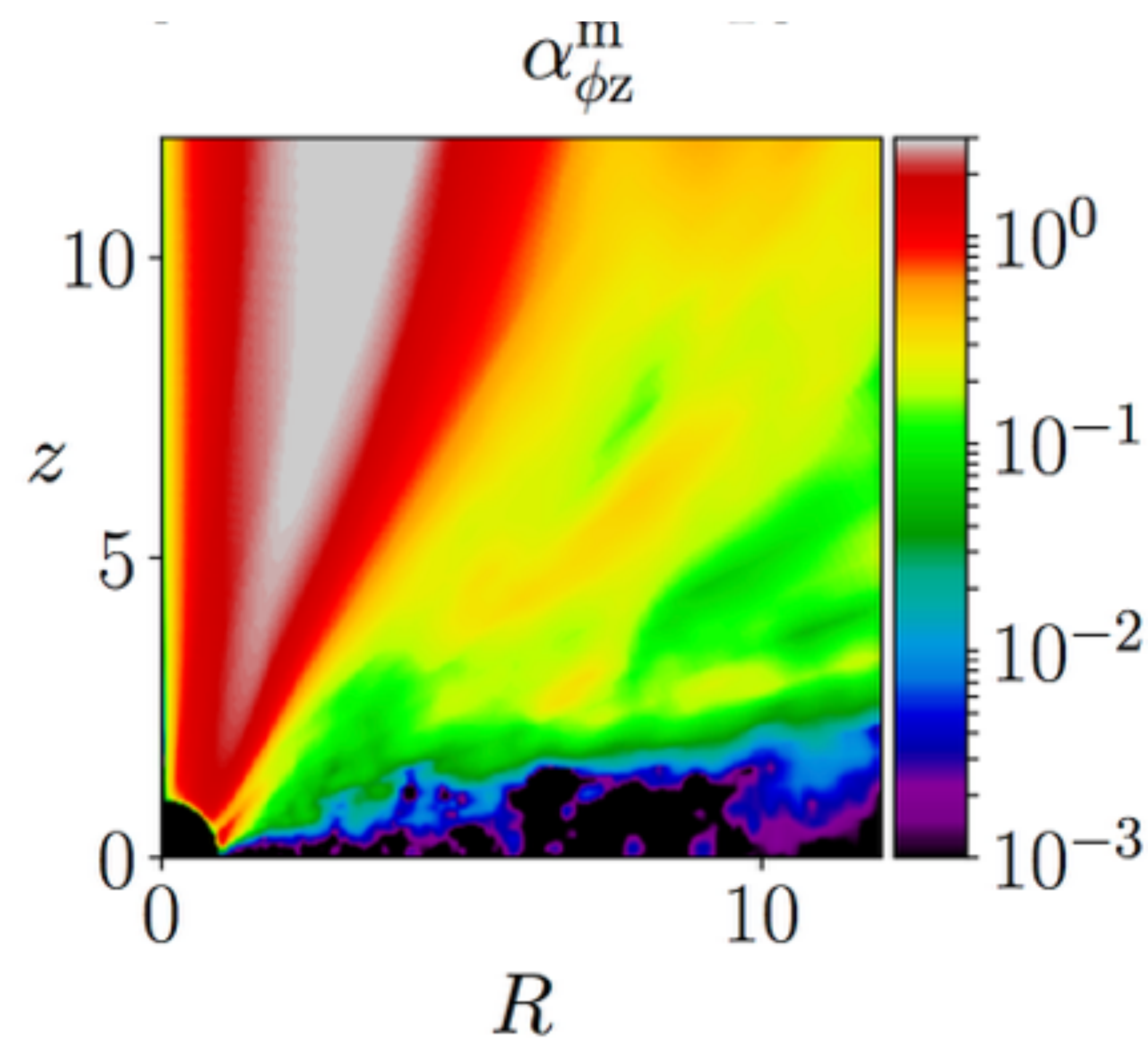


plasma β on Rz plane + 3D B-field



Angular momentum transport





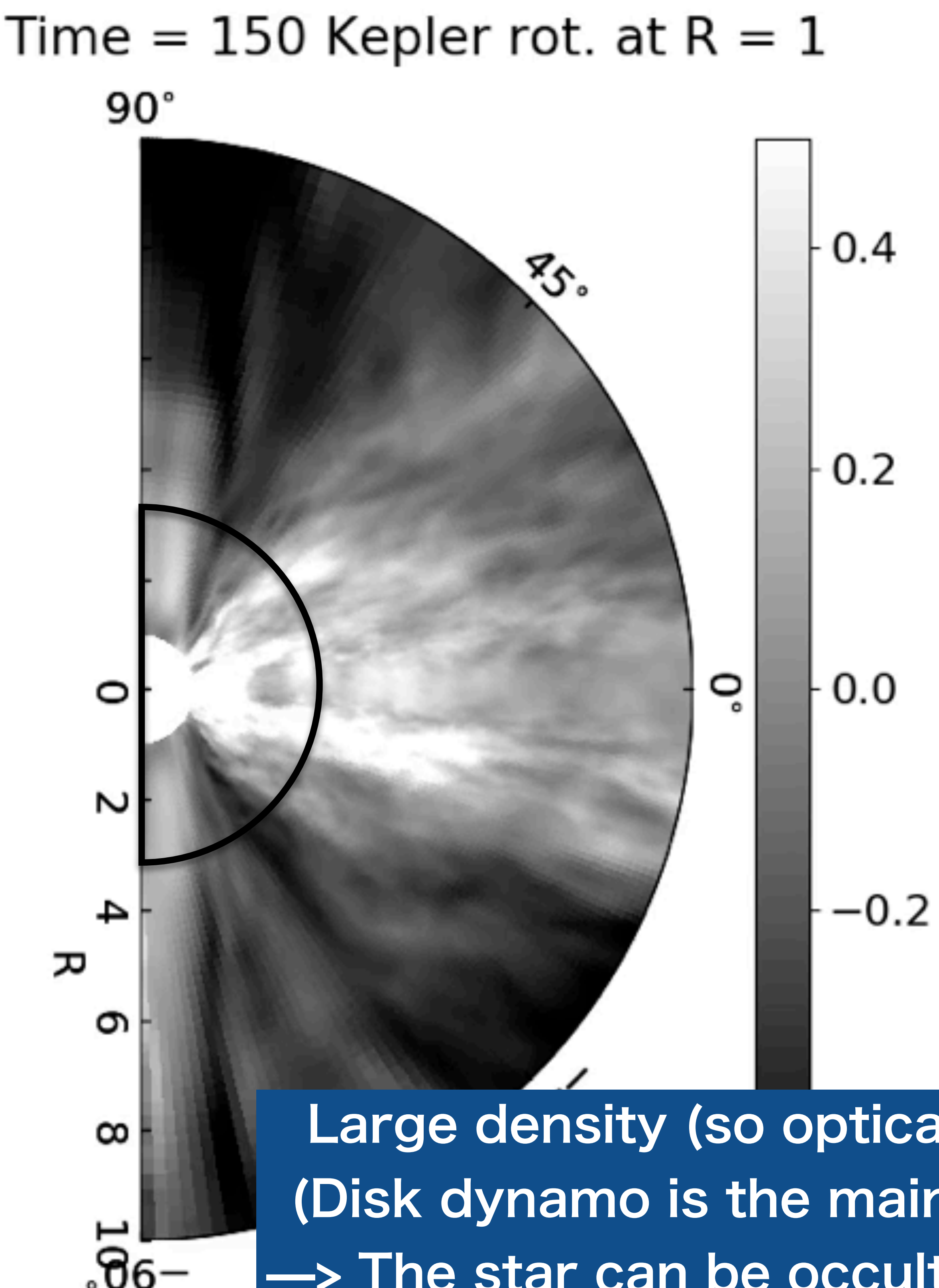
$$\alpha_{\mathrm{R}\phi} = -\frac{B_{\mathrm{R}} B_{\phi}}{4\pi p} \qquad \alpha_{\phi\mathrm{z}} = -\frac{B_{\phi} B_{\mathrm{z}}}{4\pi p}$$

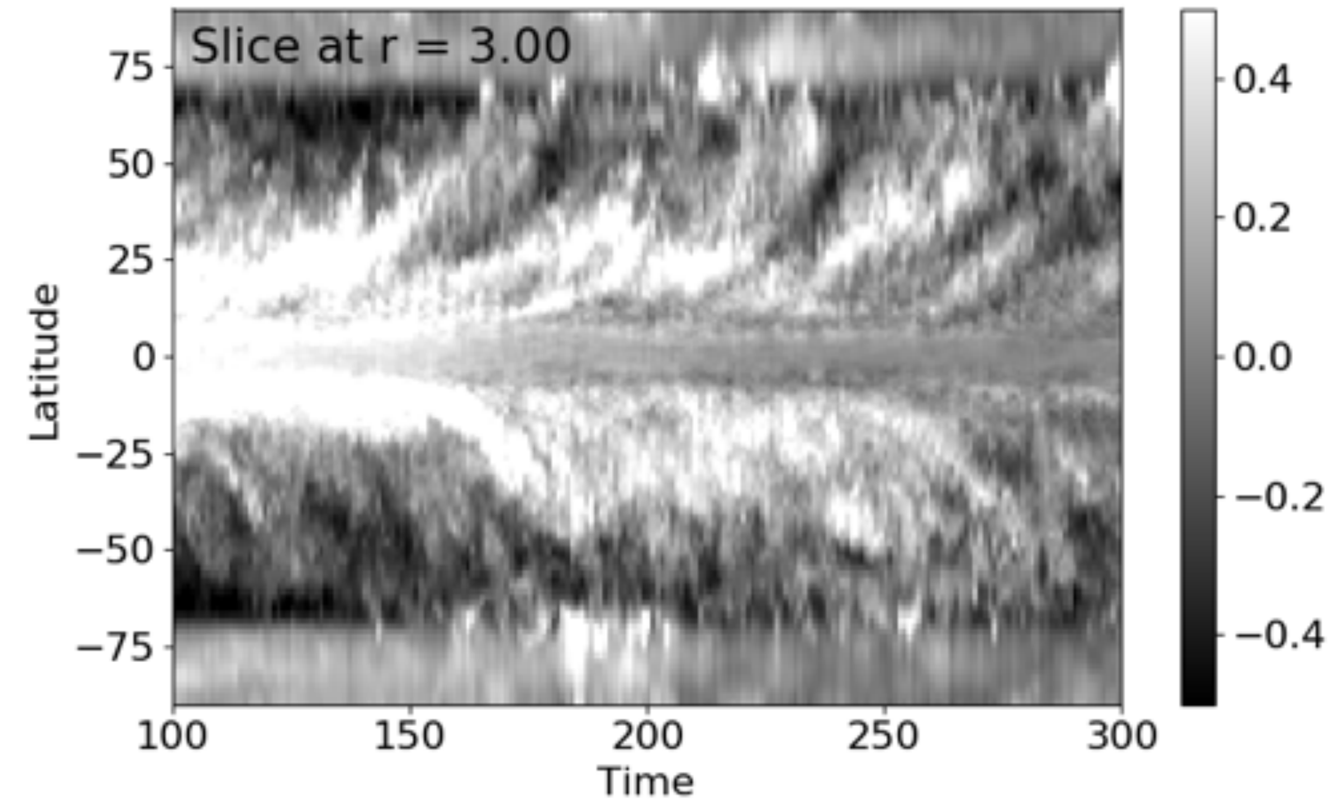
Transport in R-direction >> Transport in z-direction
(MRI) (outflow, wind)

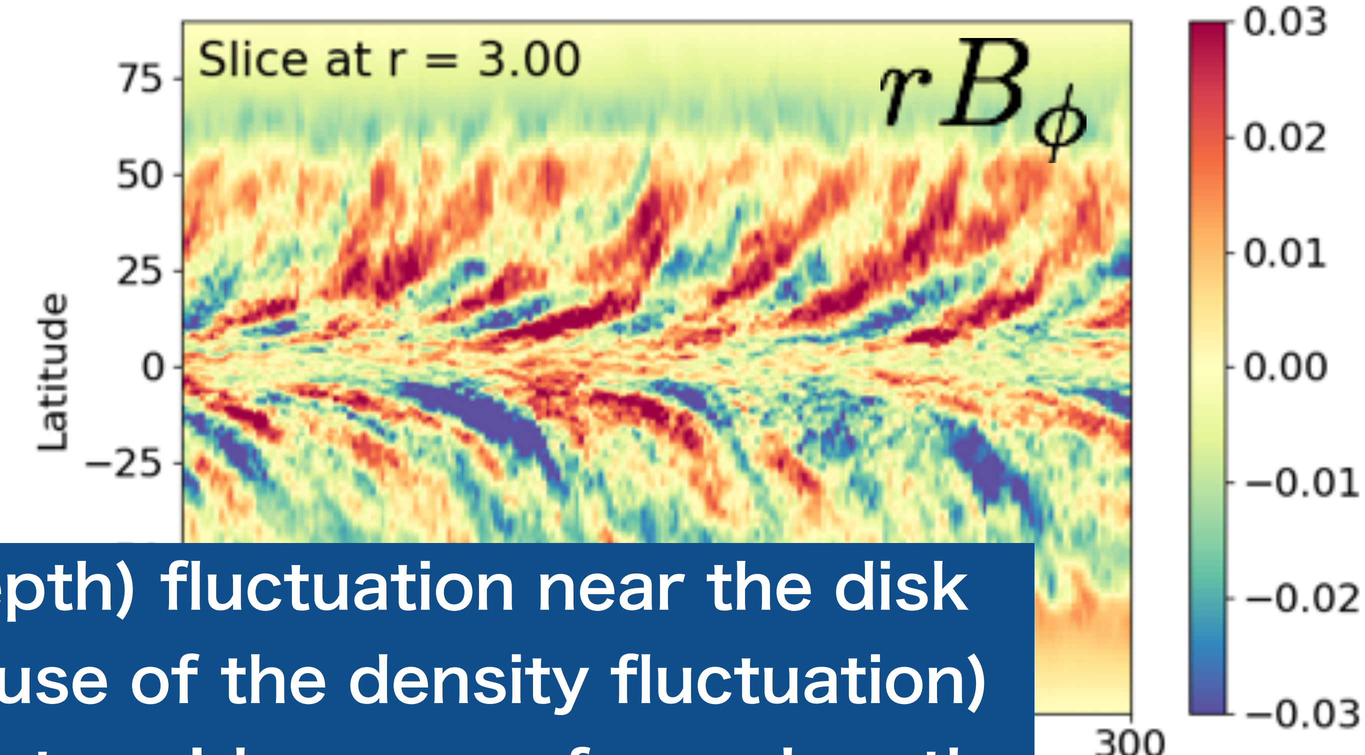
(consistent with other MRI disk sims.: Beckwith+09, Zhu & Stone 17)

Occultation due to dynamo

$$\frac{\Delta\rho(t)}{\rho_{\rm av}} = \frac{\rho(t) - \rho_{\rm av}}{\rho_{\rm av}}$$



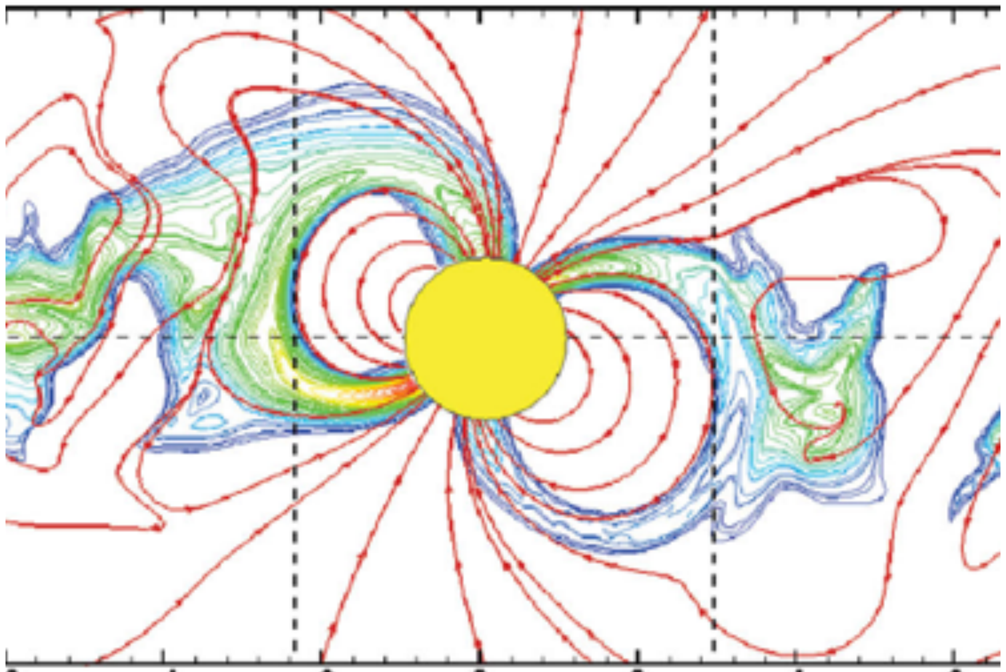




Large density (so optical depth) fluctuation near the disk
(Disk dynamo is the main cause of the density fluctuation)
—> The star can be occulted at a wide range of wavelengths

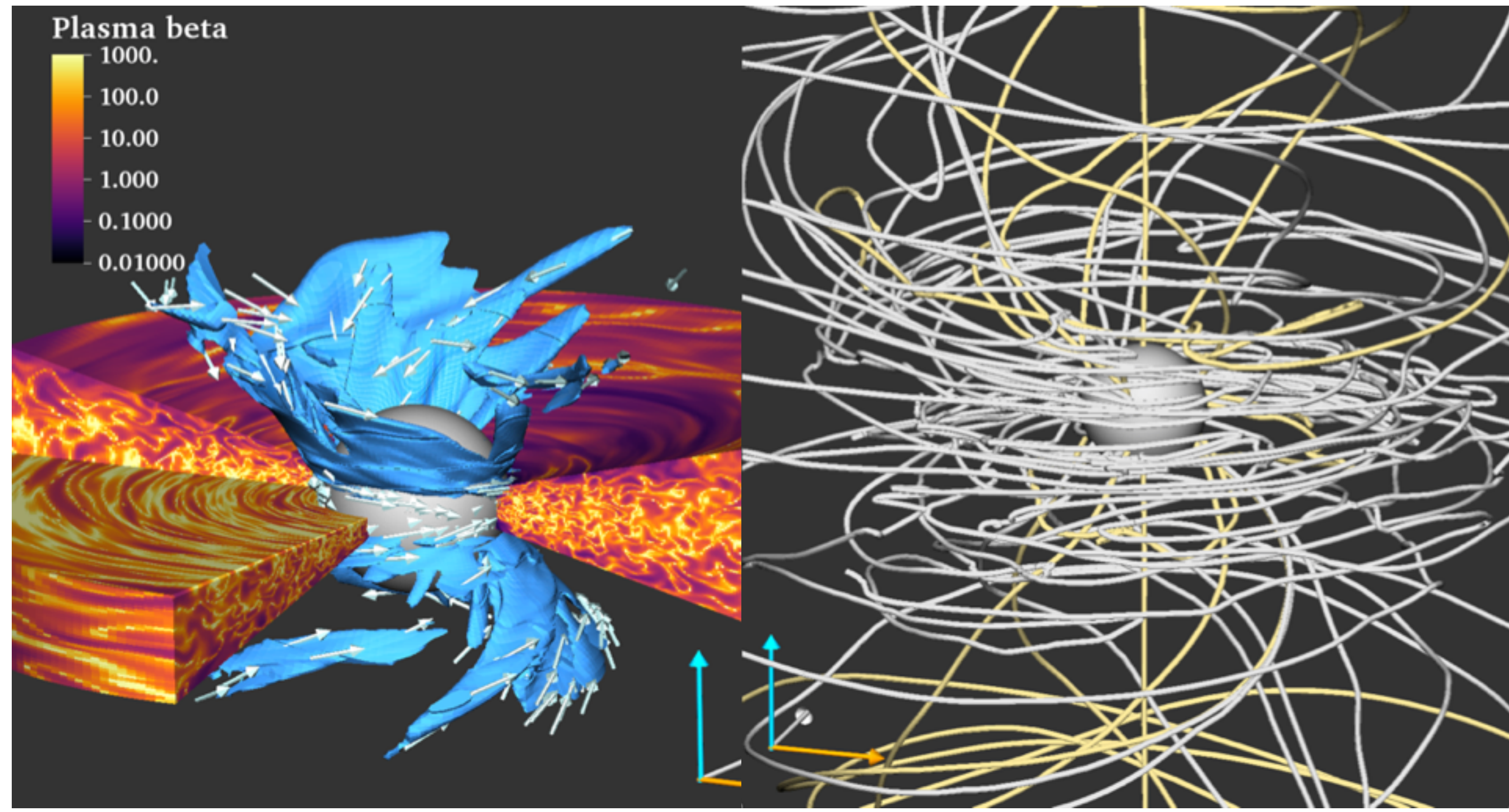
Comparison with magnetospheric acc. model

Magnetospheric Accretion (MA) model



Romanova+12

Our model



	MA model	our model
Strong stellar B necesary?	yes	no
fast accretion?	yes	yes
flow along field lines?	yes	no
aperiodic accretion?	not clear	yes
occultation	disk warp	dynamo

Summary

- Fast accretion at high-latitudes of the star (funnel-wall accretion) is found to occur even without magnetosphere.

- Failed MRI-driven wind = Funnel-wall accretion

- Funnel-wall accretion is a result of a complex coupling among the disk wind, dynamo, and ang. mom. transport. (not a local process!!)

- A fast jet does not blow from our cold, MRI-turbulent disk.