3D MHD simulations of star-disk interaction

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Collaborators:
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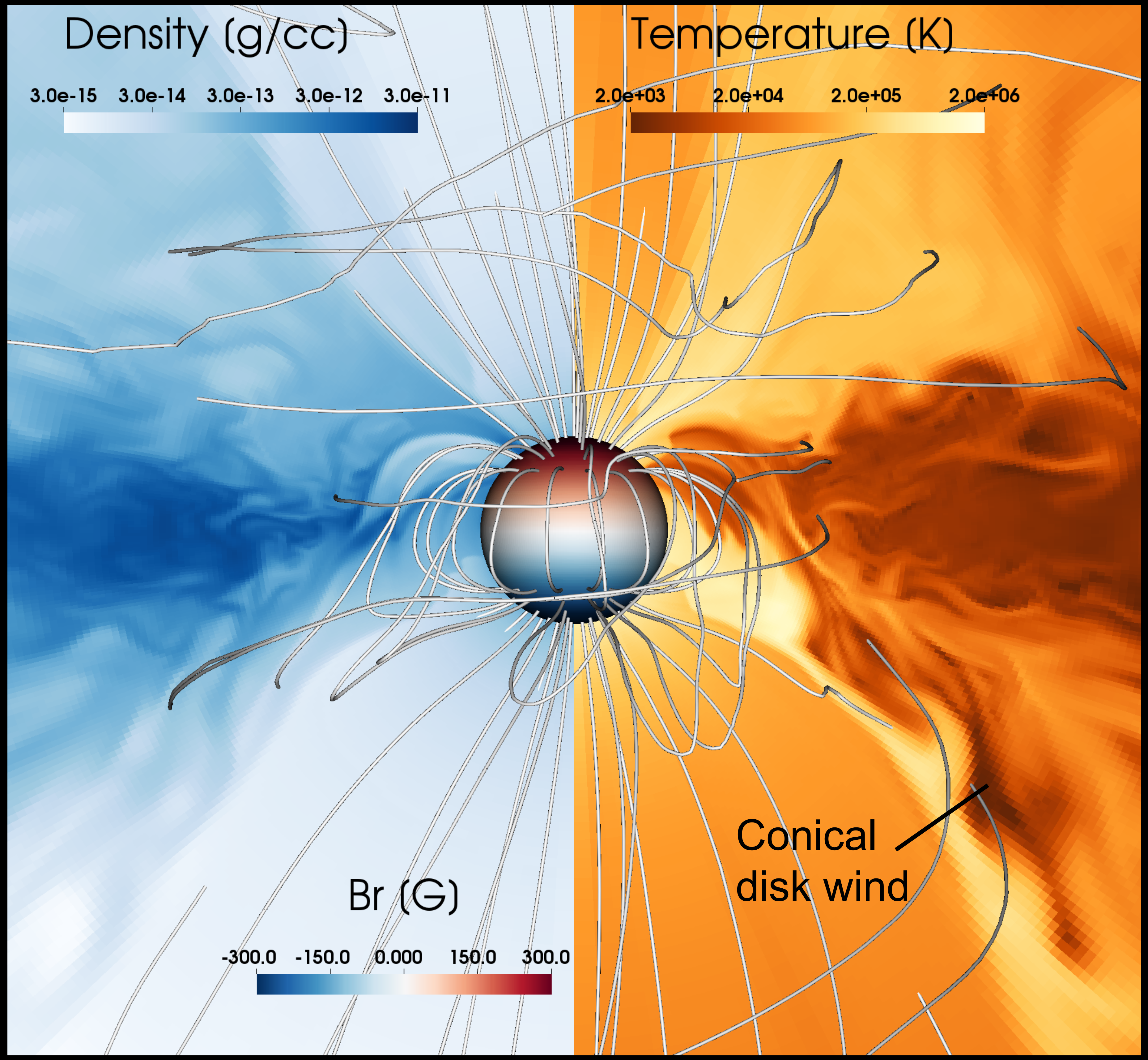
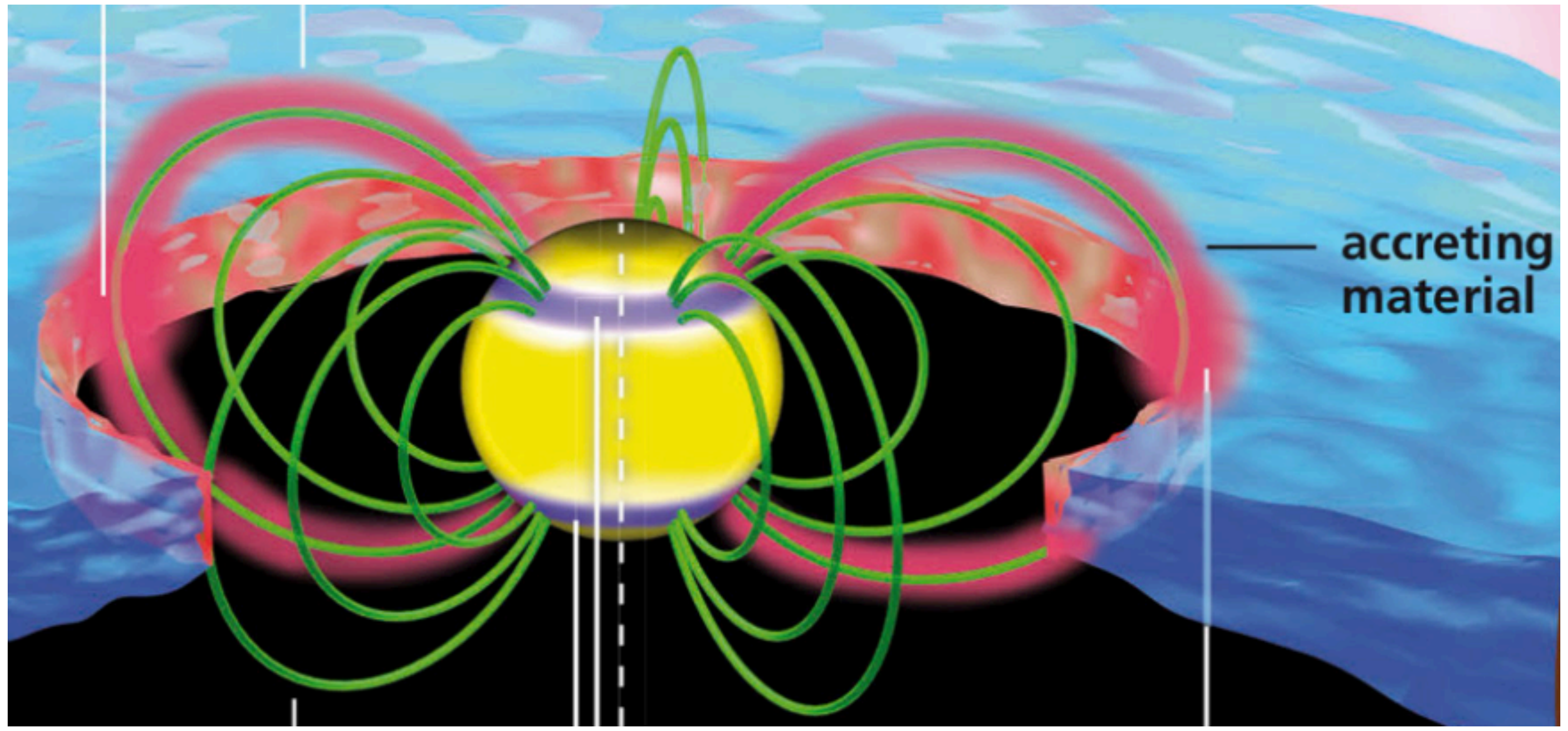
Ref. Takasao et al. 2022 ApJ

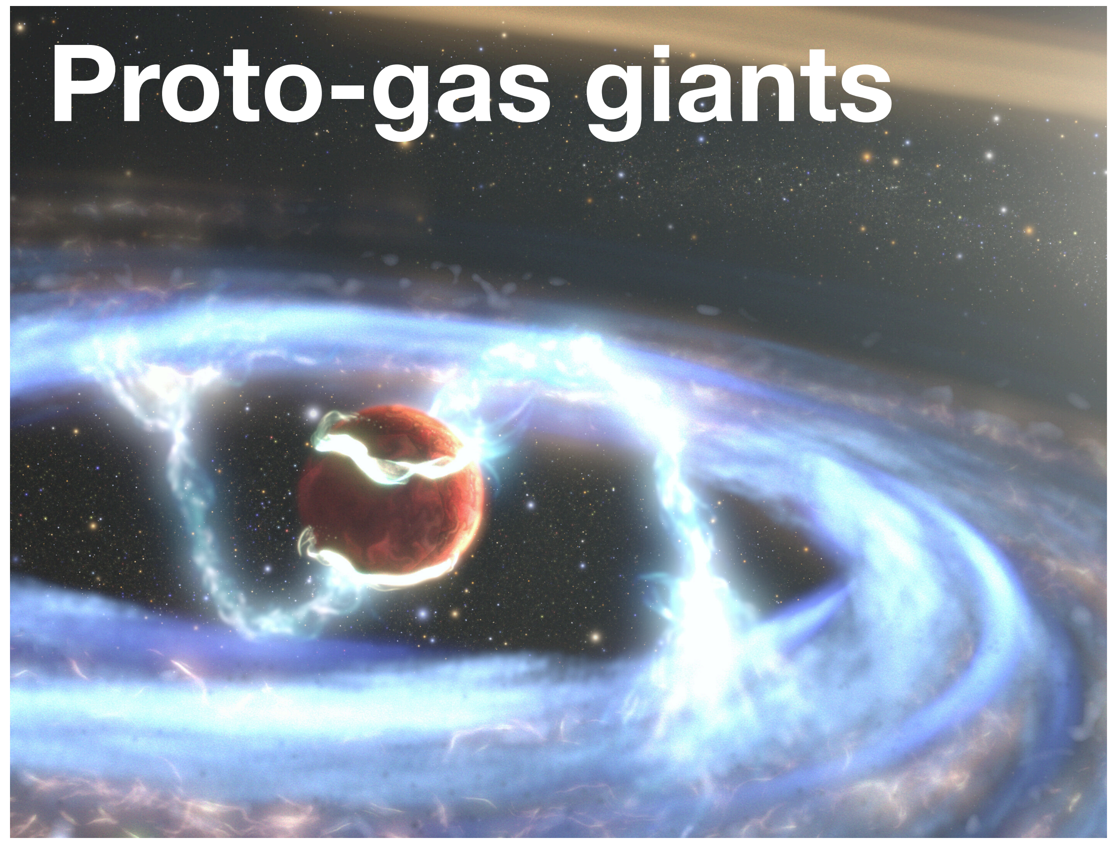


Magnetospheric accretion

T Tauri stars (pre-main-seq. stars)



Schematic picture of TW Hya (GRAVITY collaboration 2021)



General accretion mode in strongly magnetized objects

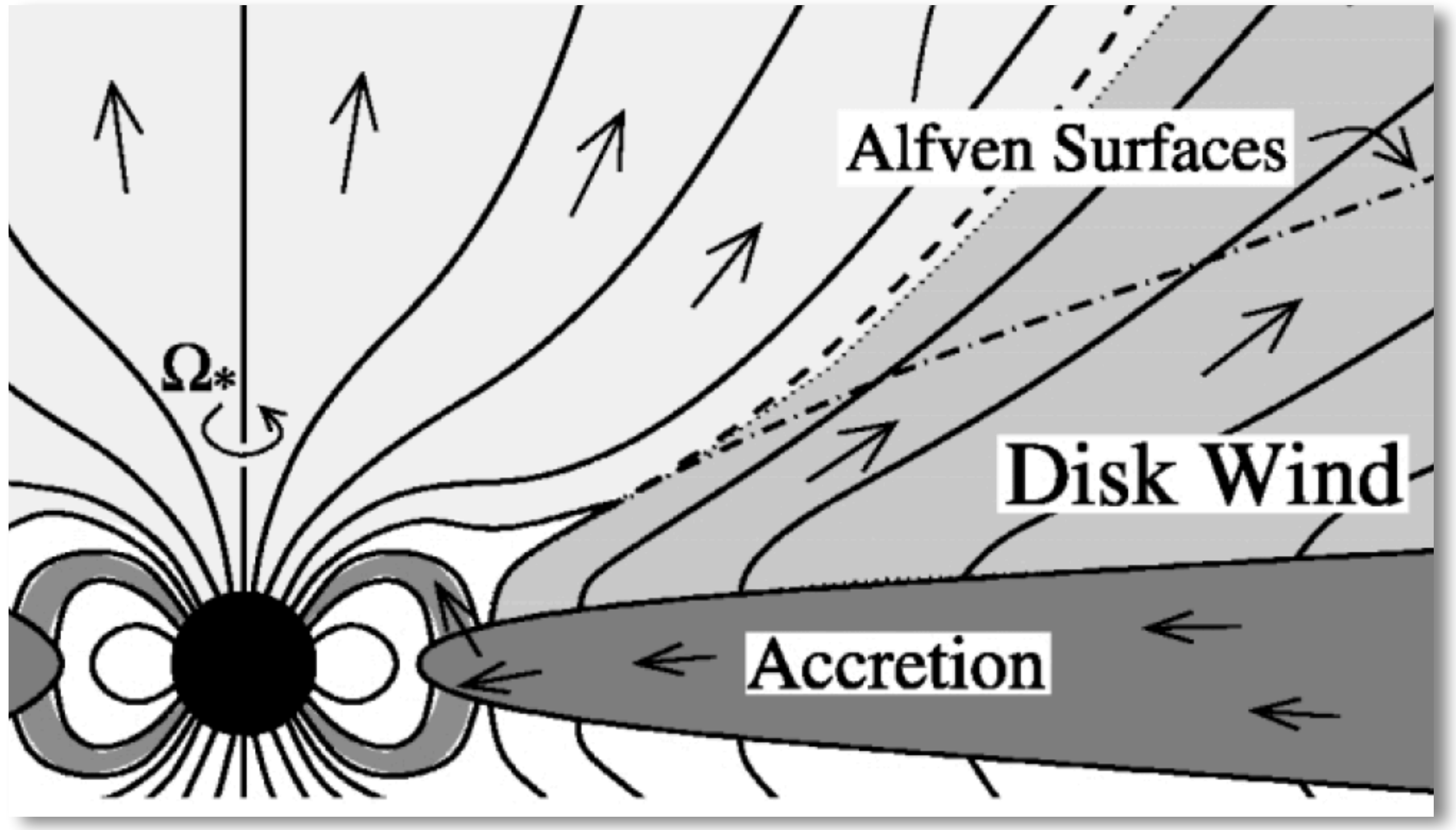
See a review by e.g. Romanova & Owocki 2015

Classical T Tauri stars are typical examples.

Today's topic: Importance of 3D effects

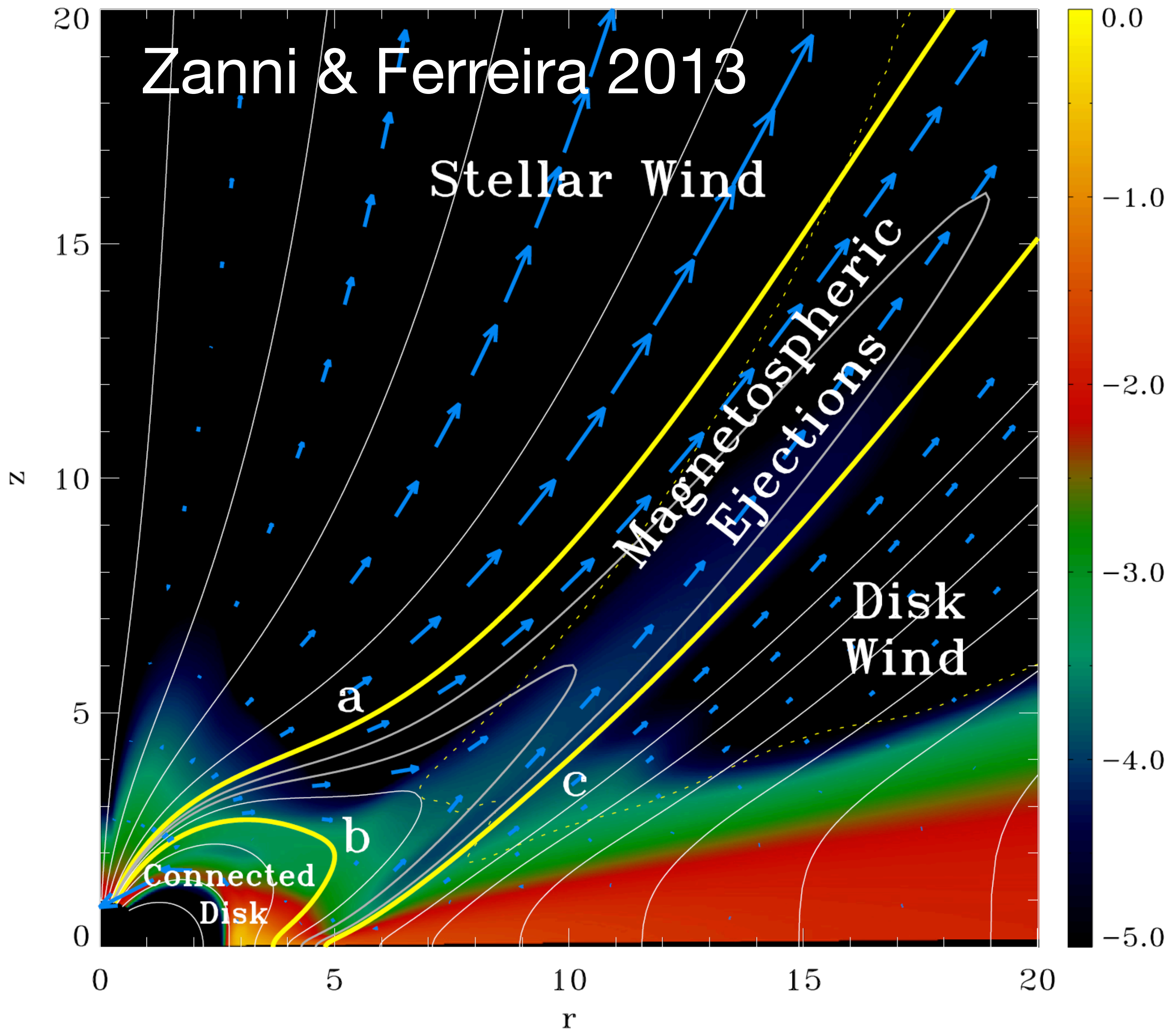
Previous 2D axisymmetric models

General accretion and outflow structures



Matt & Pudritz 2005
See also Ghosh & Lamb 79, Fendt 09

coronal mass ejections/flares

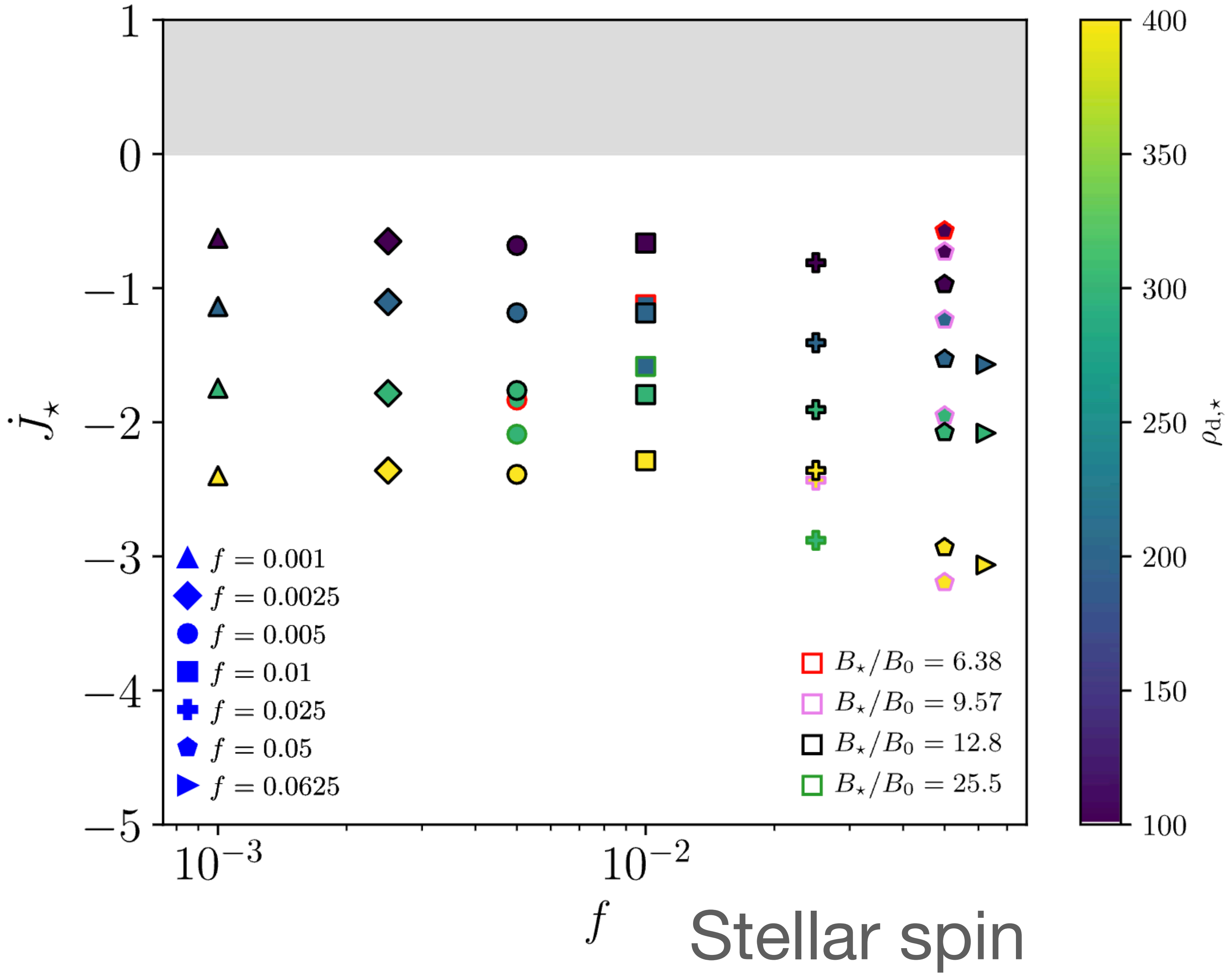


See also Shu+94, Hayashi+ 96, Ireland+12

spin-up/down torques

Ireland+20

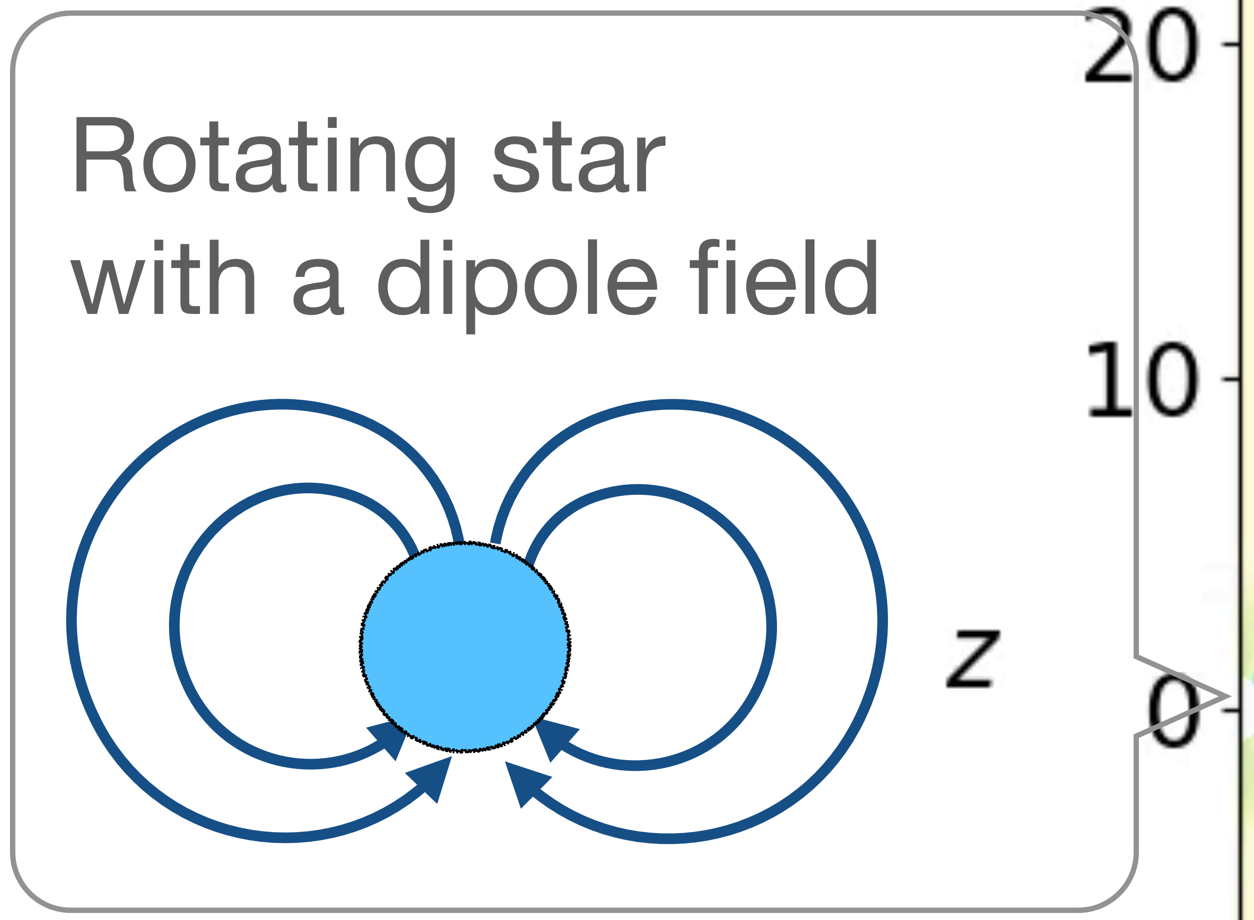
See also Pantolmos+20

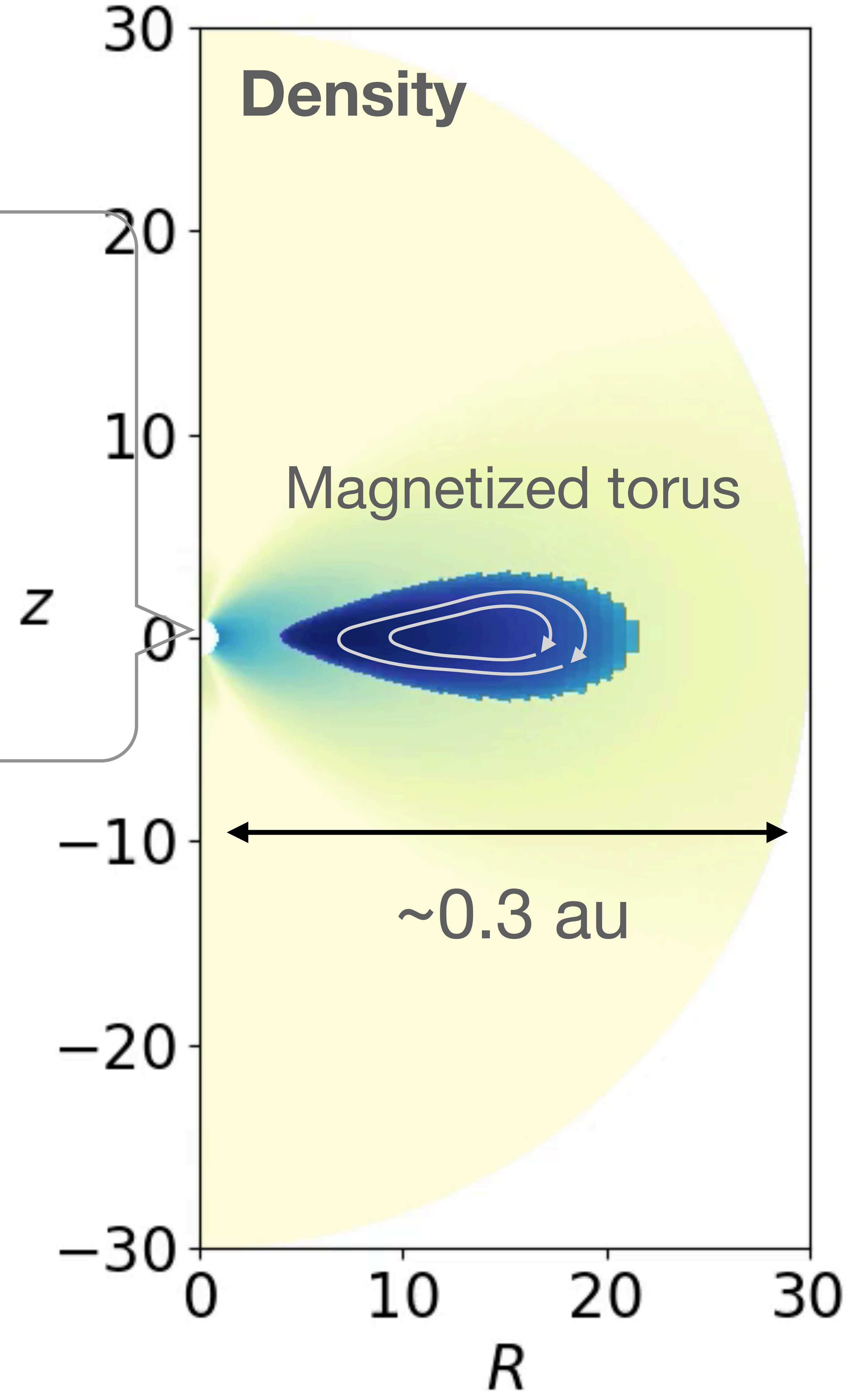


Stellar spin

2D models have established a “standard picture”
and enabled a wide range of parameter investigations.

Model setup of our 3D models

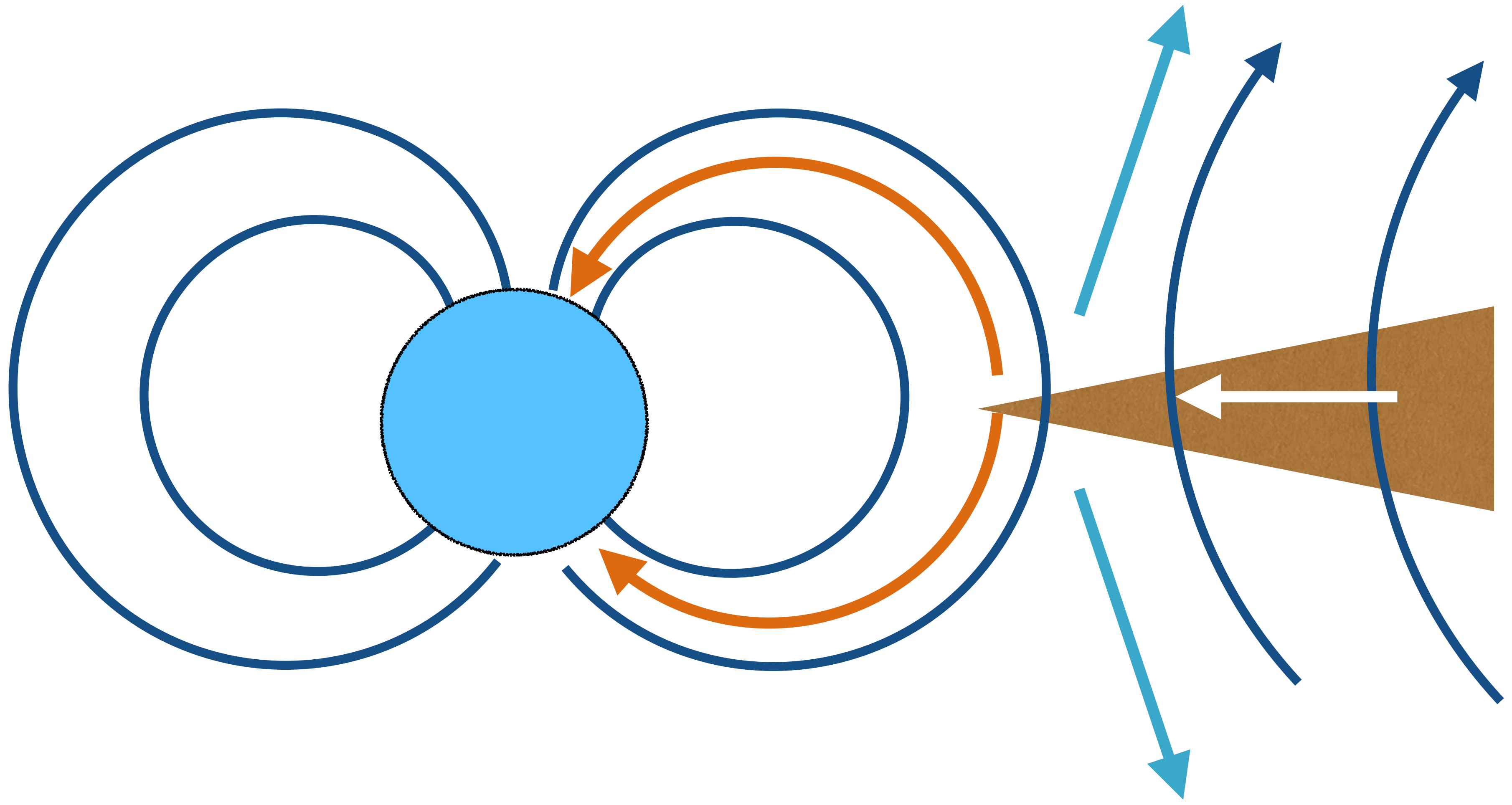




- Spherical coordinates
- Resistive MHD simulations
- Radiation transfer is not solved.
  Locally isothermal in the disk.
- Stellar wind included.

2D vs 3D

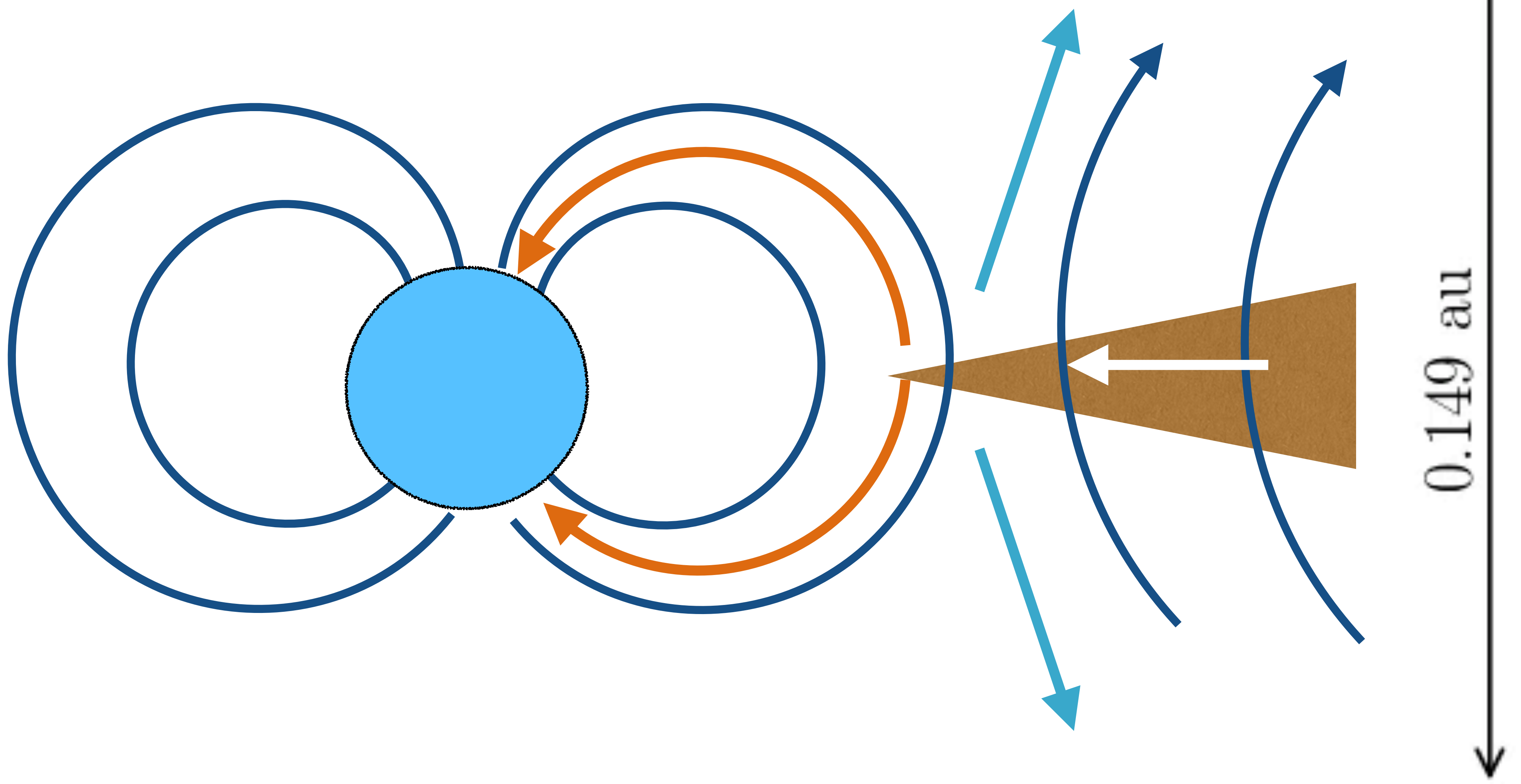
2D models



- Laminar flow structure
- Transition from midplane accretion to polar accretion
- Magnetosphere-disk interaction occurs via some effective resistivity.

2D vs 3D

2D models



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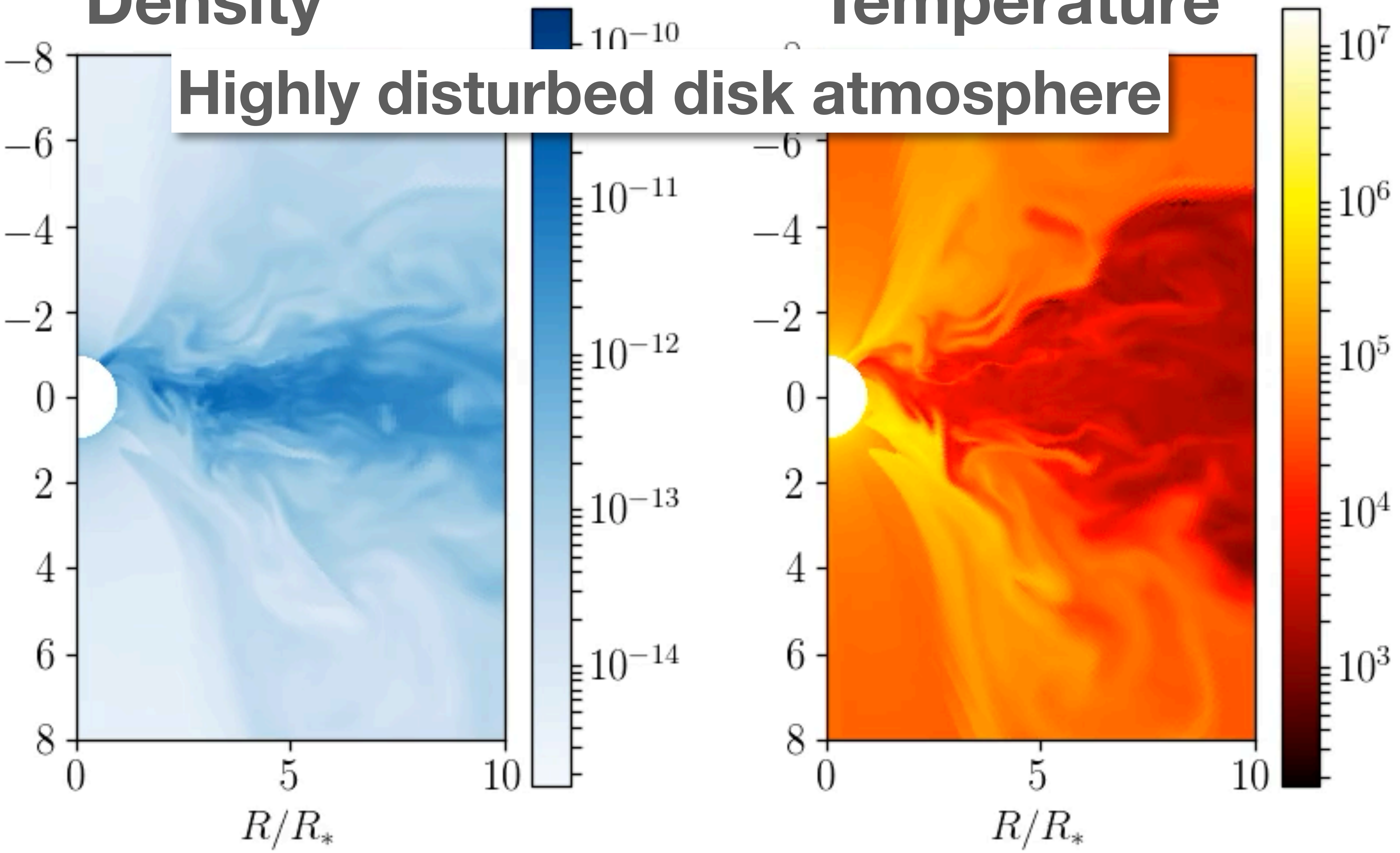
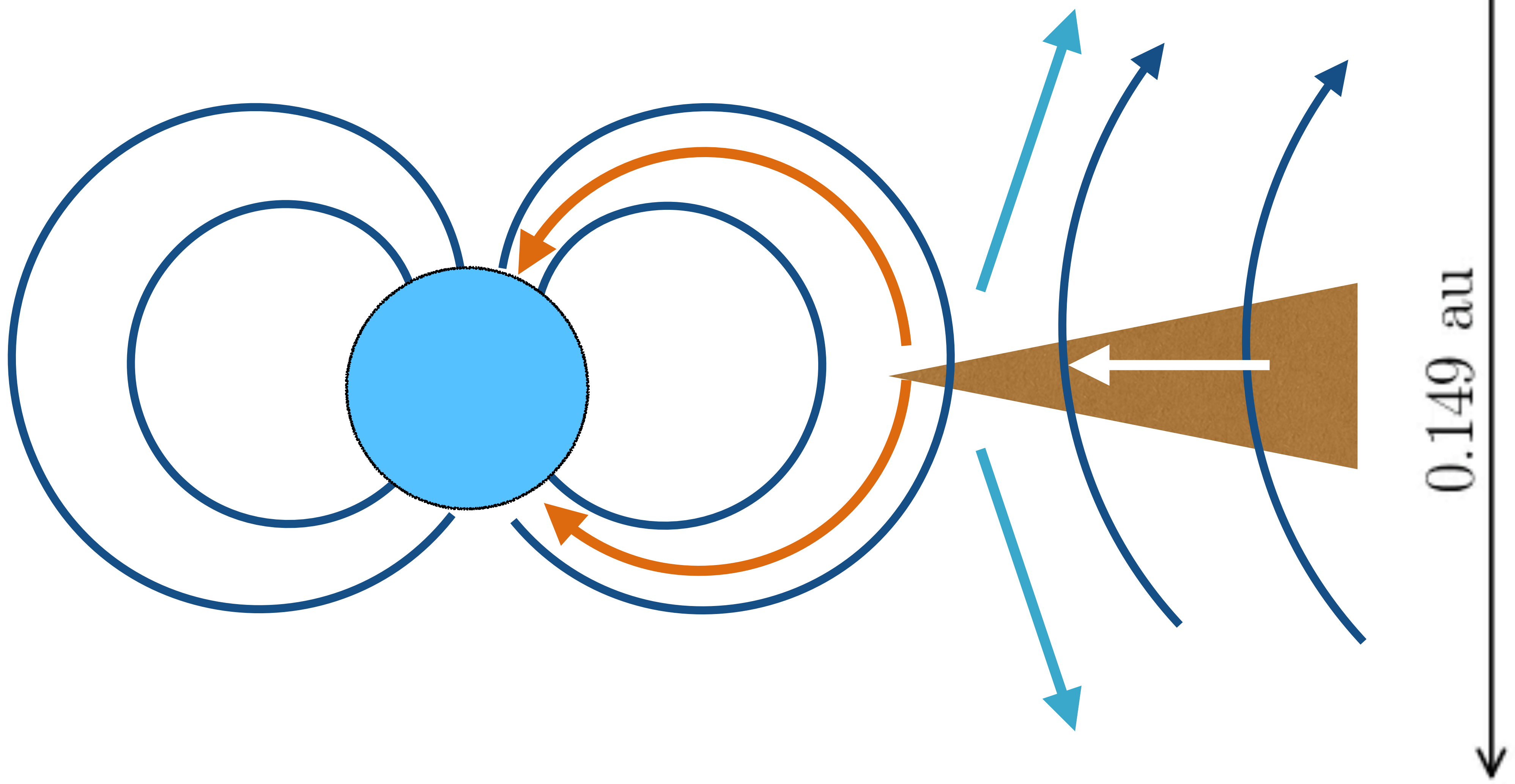
3D model (ST+22)

Density **Temperature**



2D vs 3D

2D models



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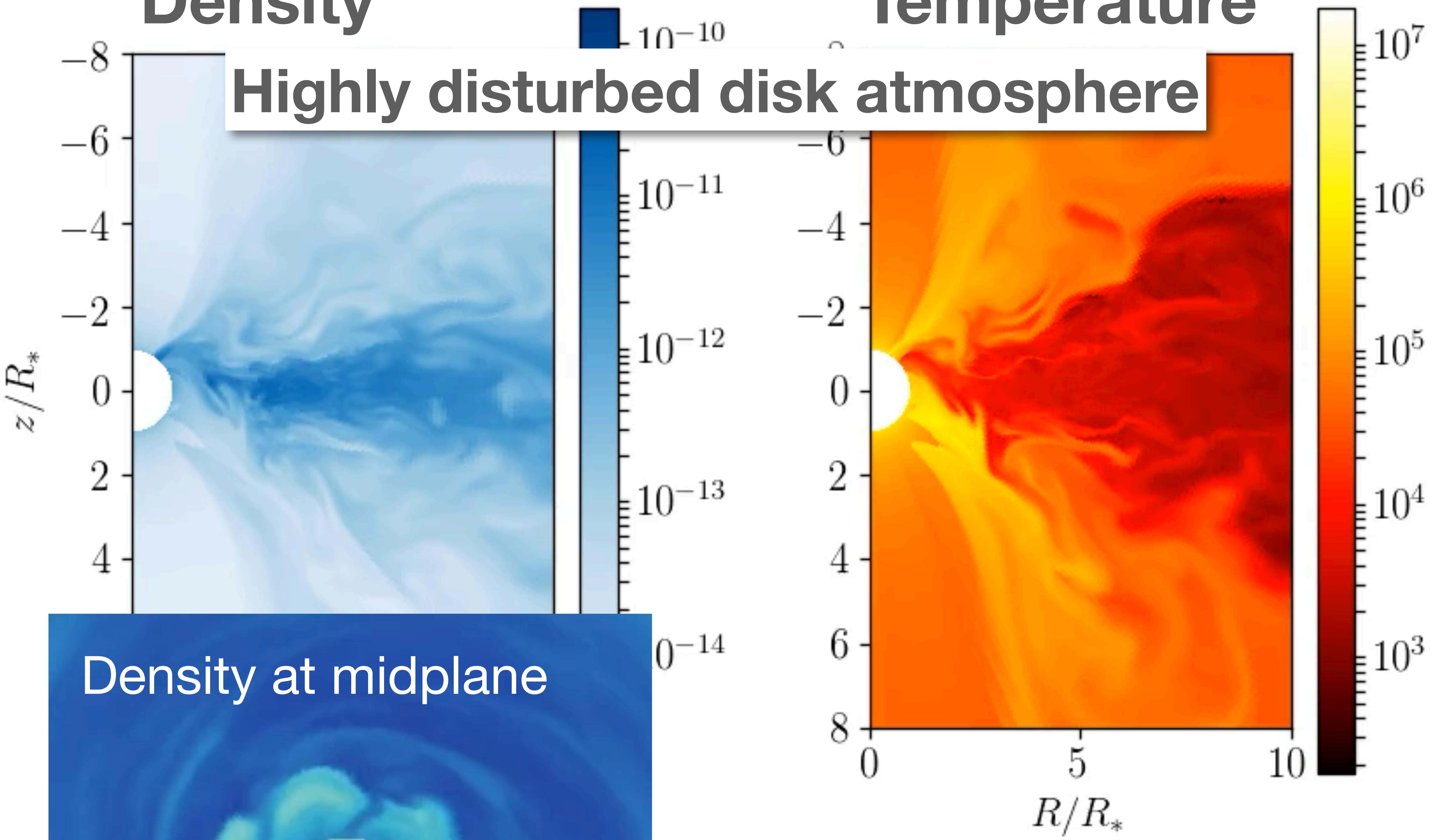
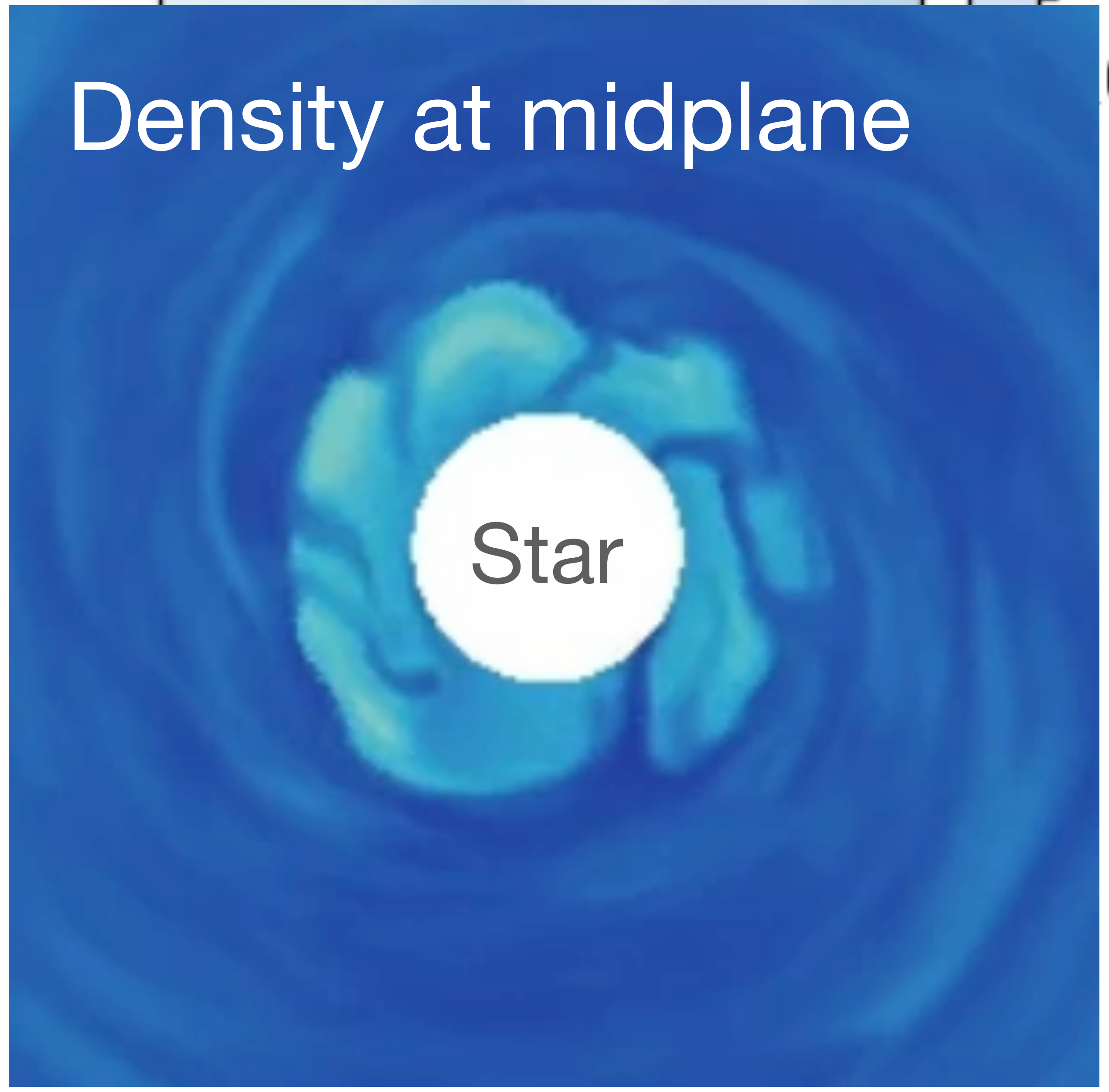
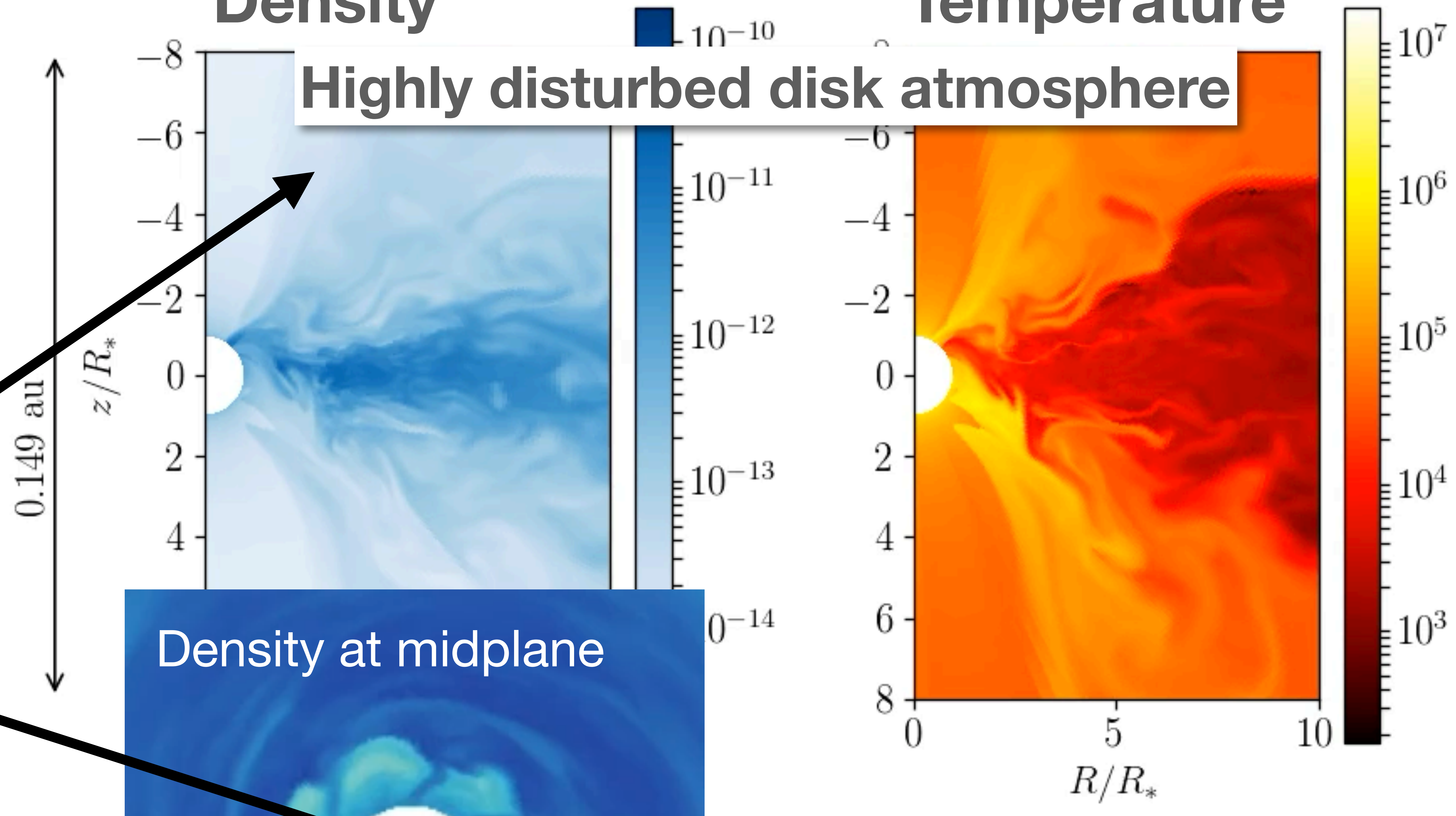




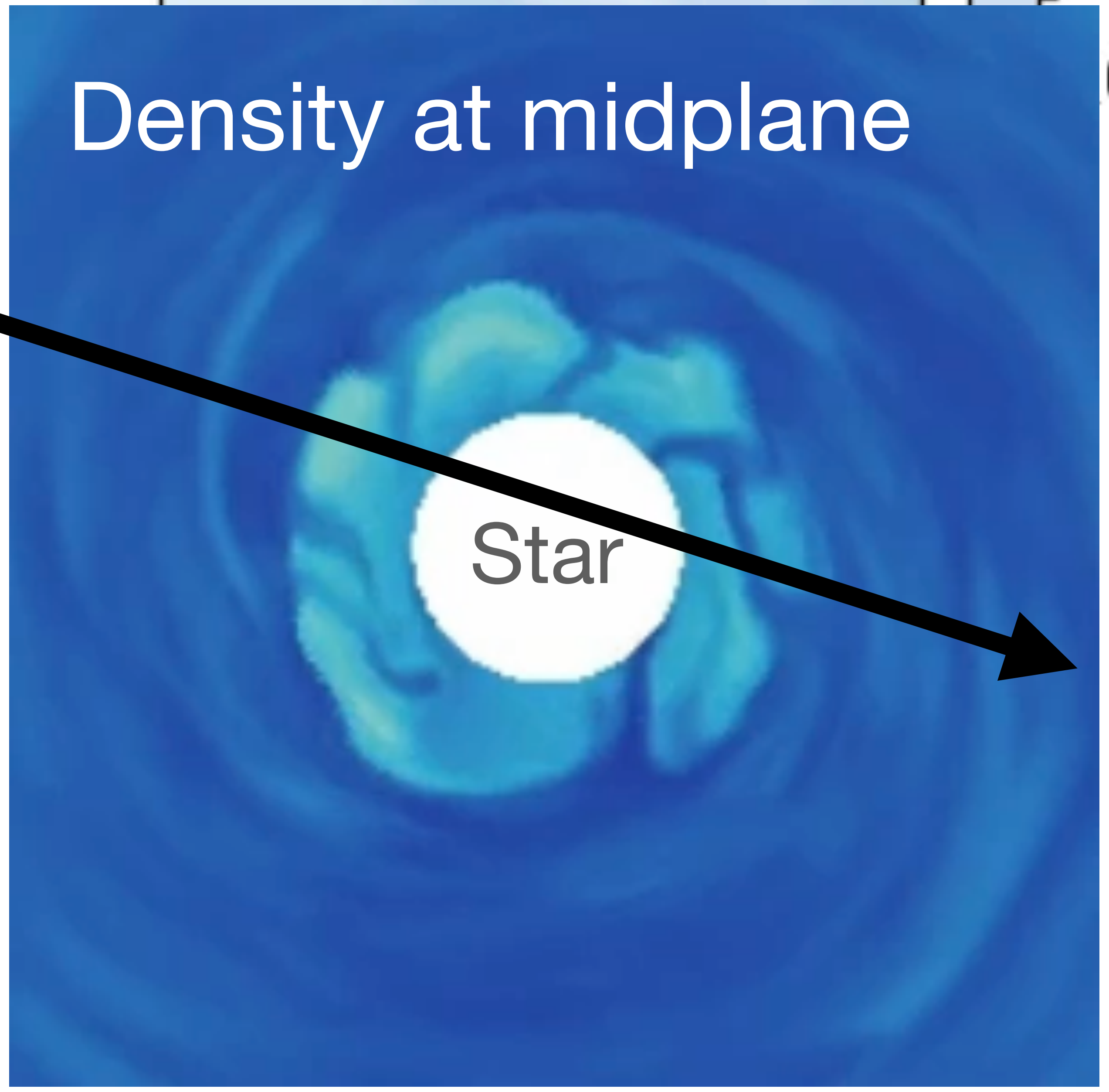
Penetrating flows in the magnetosphere

Stehle & Spruit 01, Blinova+16

3D model (ST+22)



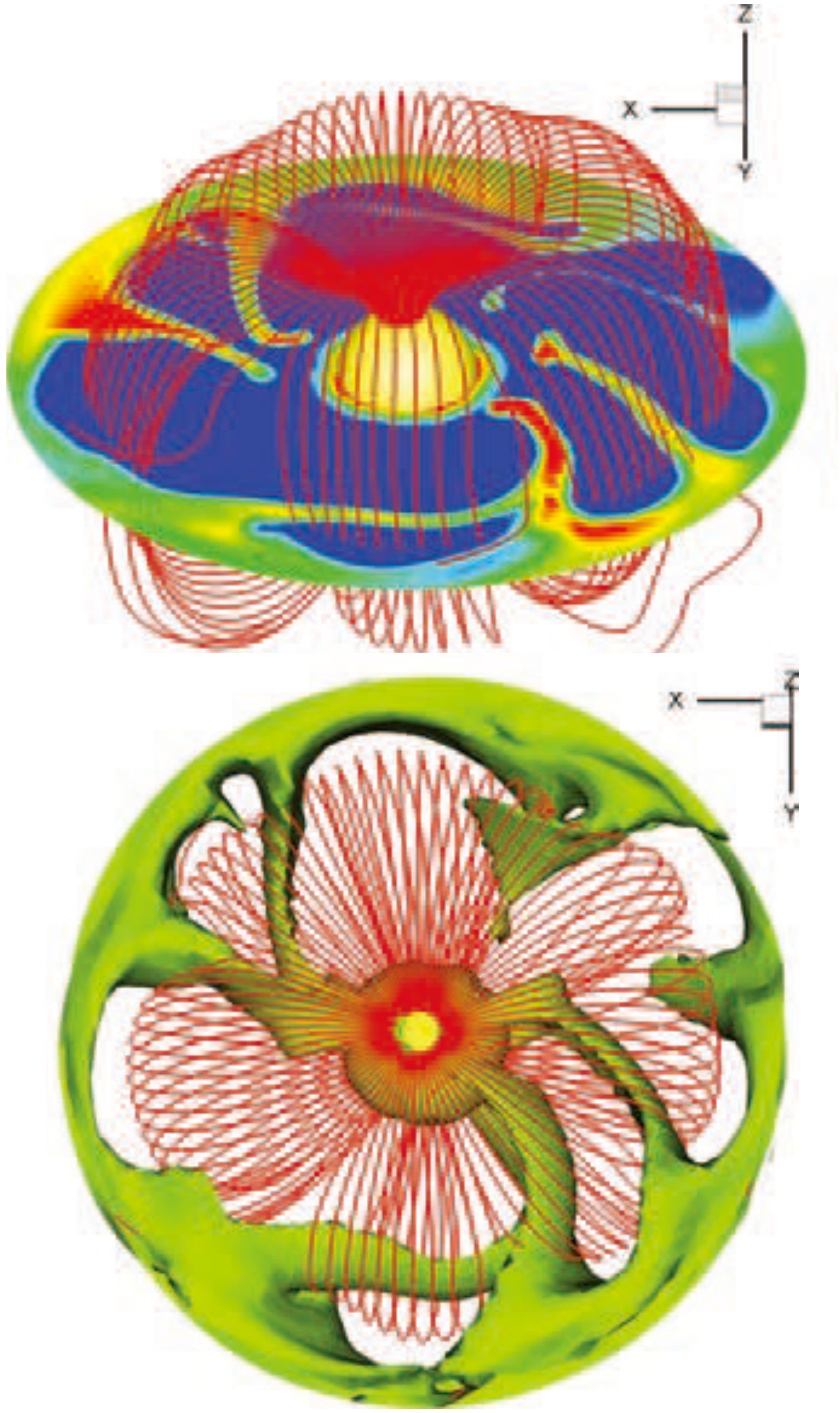
Importance of these 3D structures?



Penetrating flows in the magnetosphere

Stehle & Spruit 01, Blinova+16

Magnetic Rayleigh-Taylor instability



Kulkarni & Romanova 08
See also Romanova+12, Blinova+13

Criterion for the development of the instability (Spruit et al. 95)

$$\gamma_{B\Sigma}^2 \equiv -g_{\rm eff}\frac{d}{dr}\ln\frac{\Sigma}{B_z} > 2\left(r\frac{d\Omega}{dr}\right)^2 \equiv \gamma_\Omega^2,$$

Destabilizing by gravity & magnetic field

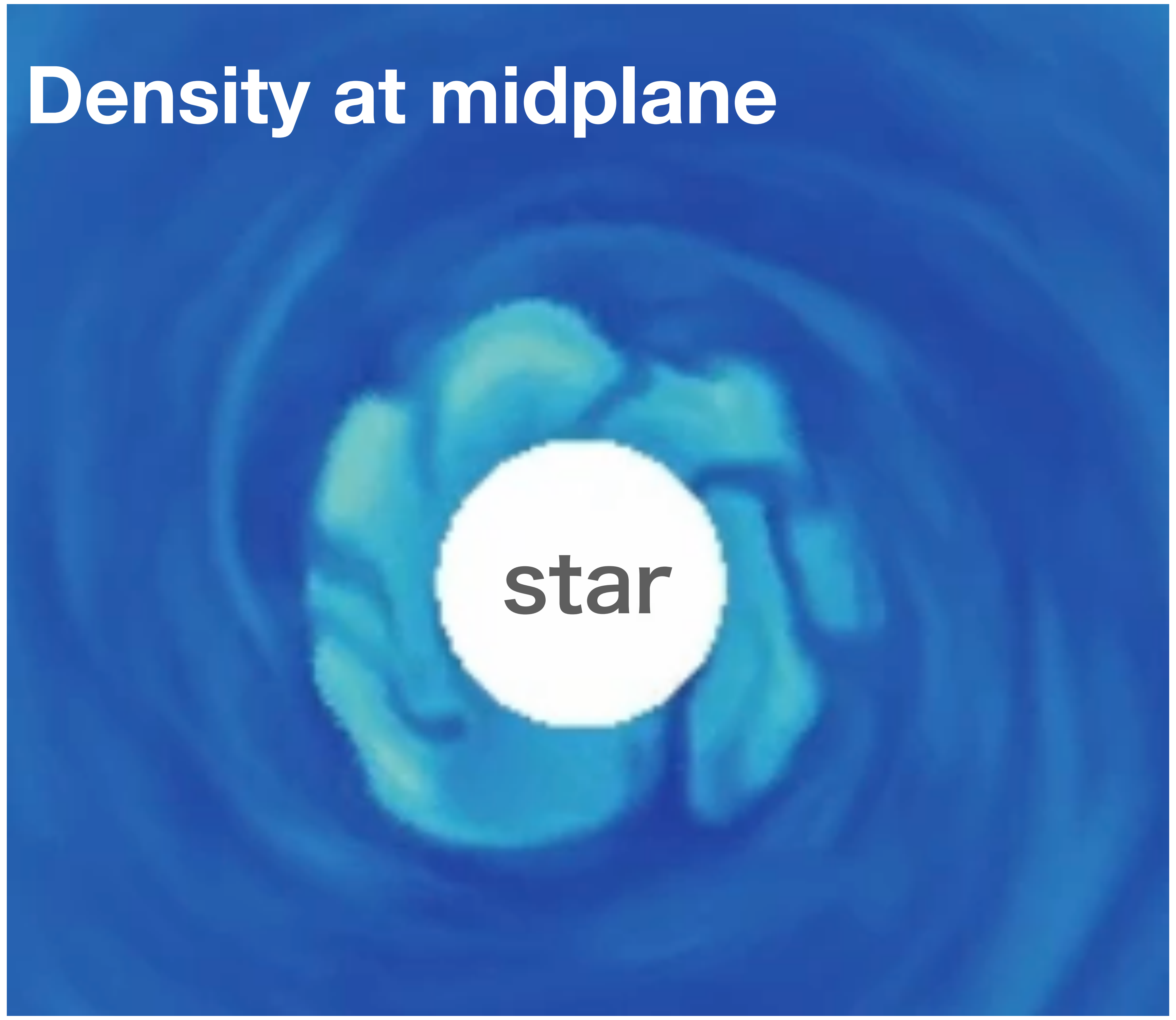
Stabilizing by the velocity shear

$$g_{\rm eff} \equiv -\left[\Omega_{\rm K}(r)^2 - \langle\Omega(r)\rangle^2\right] r$$

Effective gravitational acceleration

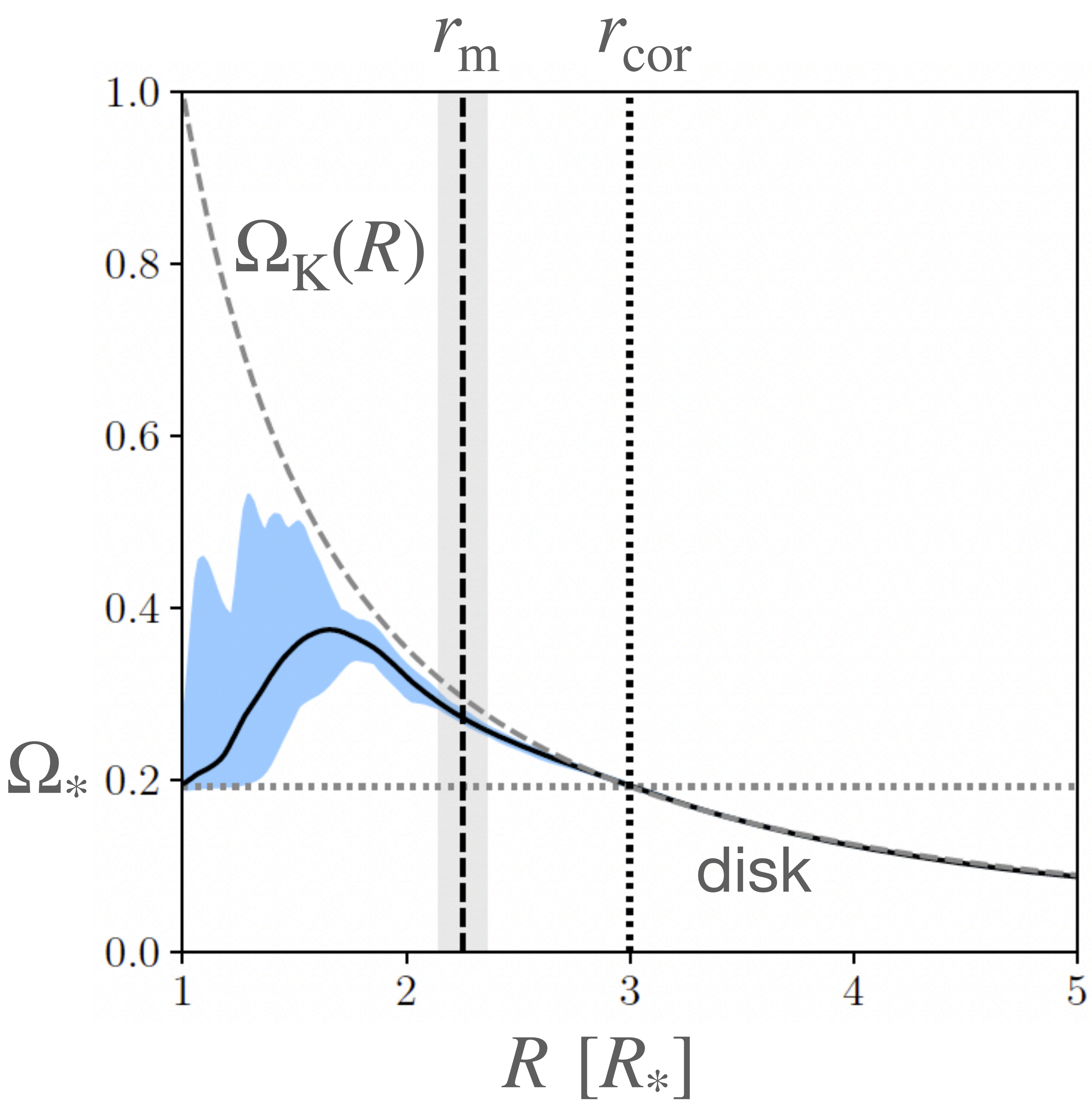
The finger structures are more prominent in more slowly rotating stars.

Penetrating flows and rotation profile



Penetrating flows continue to rotate at ~Keplerian speed until they lose angular momenta

—> They force to rotate the surrounding magnetic field together.

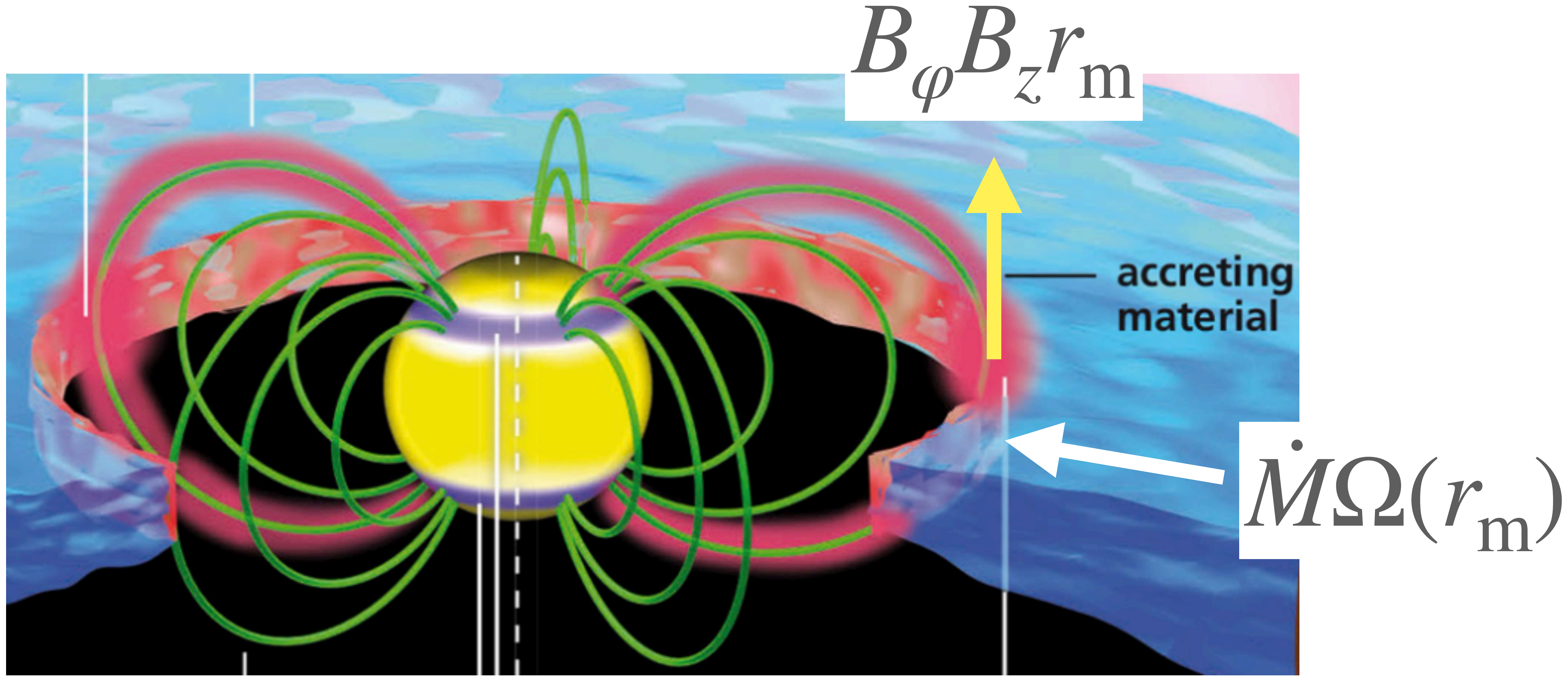


See also Kluzniak & Rappaport 2007

Magnetospheric radius

The steady angular momentum transfer eq:

$$\dot{M}\Omega(r_\mathrm{m}) \approx B_\varphi B_z r_\mathrm{m}$$



3D sim: $\Omega(r_\mathrm{m}) = \Omega_\mathrm{K}(r_\mathrm{m})$ (Kepler rot.)

$$r_\mathrm{m} \approx \eta'^{2/7} \left(\frac{\mu_*^4}{GM_*\dot{M}^2} \right)^{1/7}$$

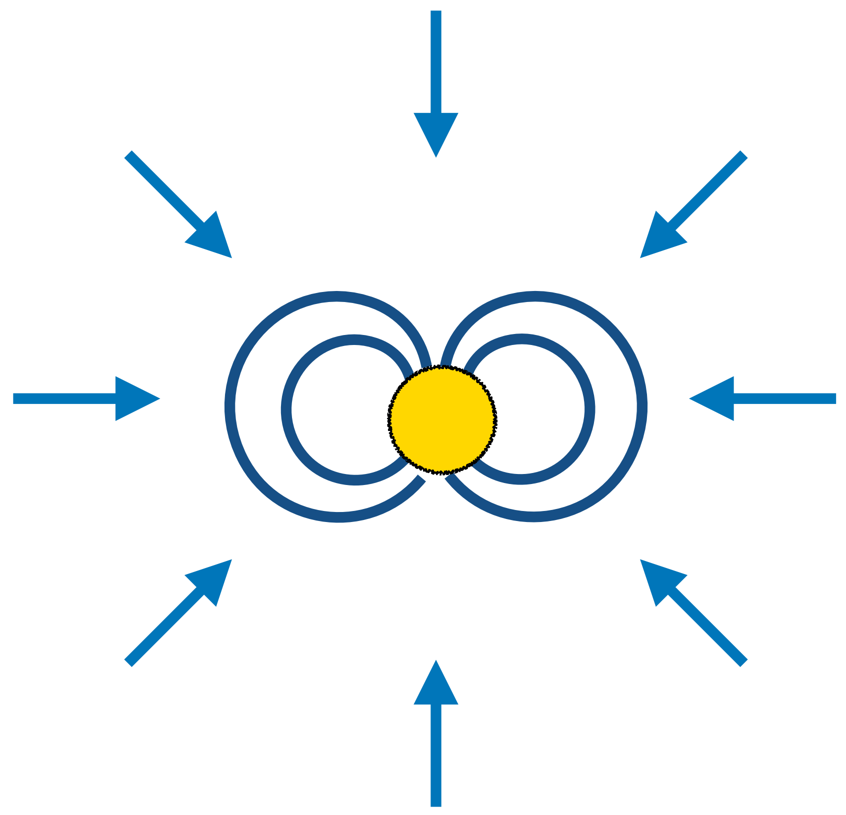
$$\mu_* \equiv B_* R_*^3, \;\; \eta' = |B_\varphi / B_z|$$

For other formulae based on 2D models, see e.g. Bessolaz+08, D'Angelo & Spruit 10

Magnetospheric radius

Commonly used formula

Ghosh & Lamb 1978, 1979, Königl 1991



$$\rho v_r^2 \approx \frac{B^2}{8\pi}$$

in the spherical accretion flows

$$r_{\mathrm{m,GL}} \approx \left(\frac{\mu_*^4}{2GM_*\dot{M}^2}\right)^{1/7}$$

Observations suggest that this relation works well even for disk accretion (e.g. Gravity collab. 20). Why?

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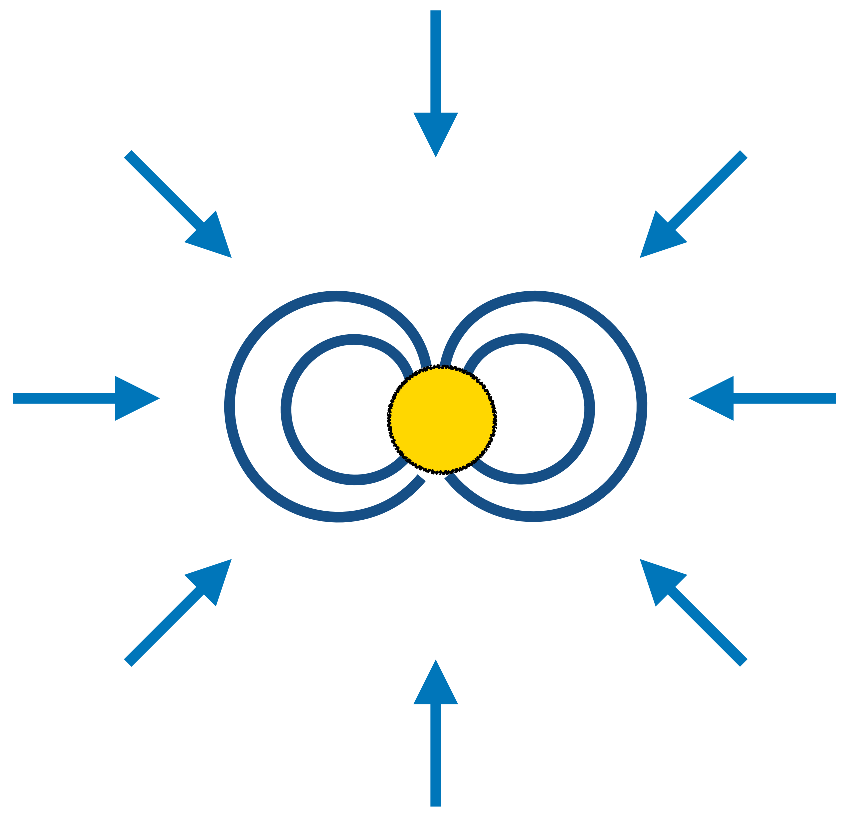

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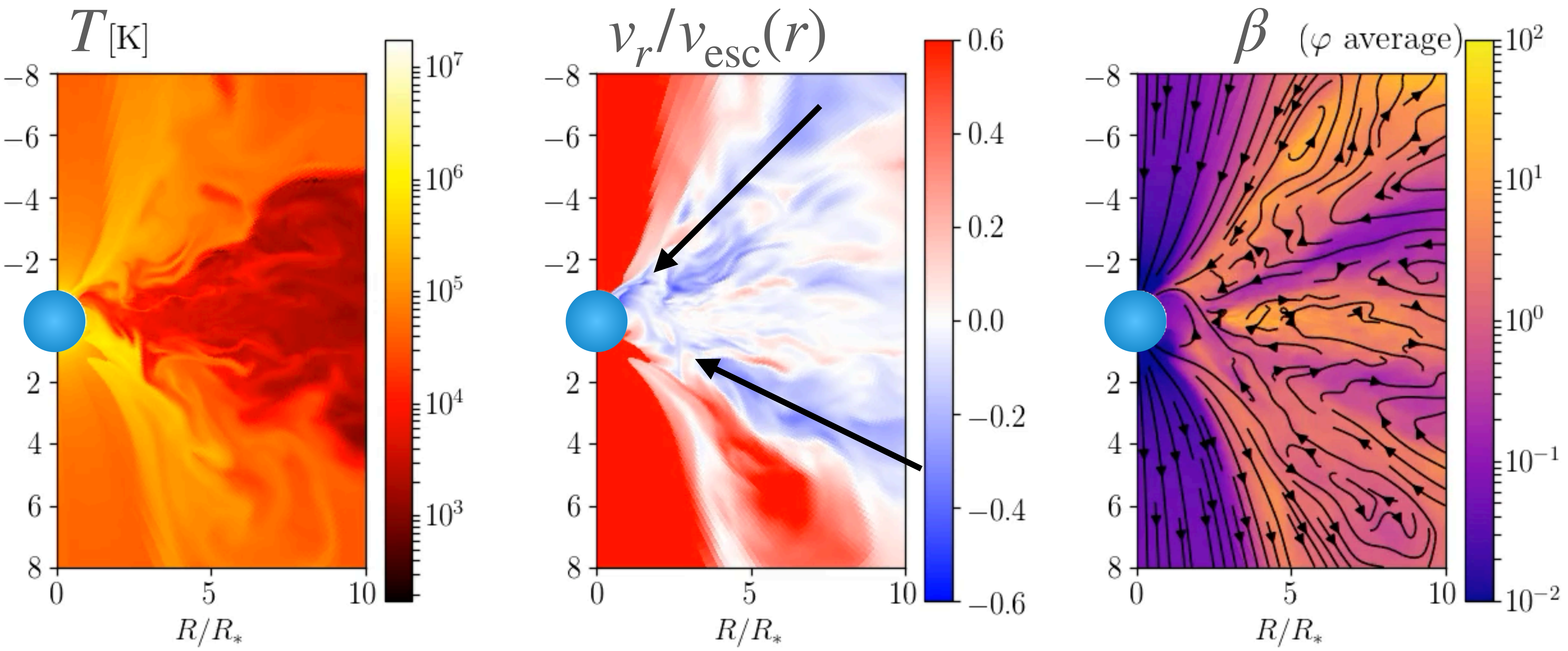
Ghosh-Lamb-like relation can be derived from the angular momentum transfer eq. for disk accretion (ST+22)

Penetrating flows are important for determining the magnetospheric radius.

Fluctuating atmosphere above MRI-turbulent disk

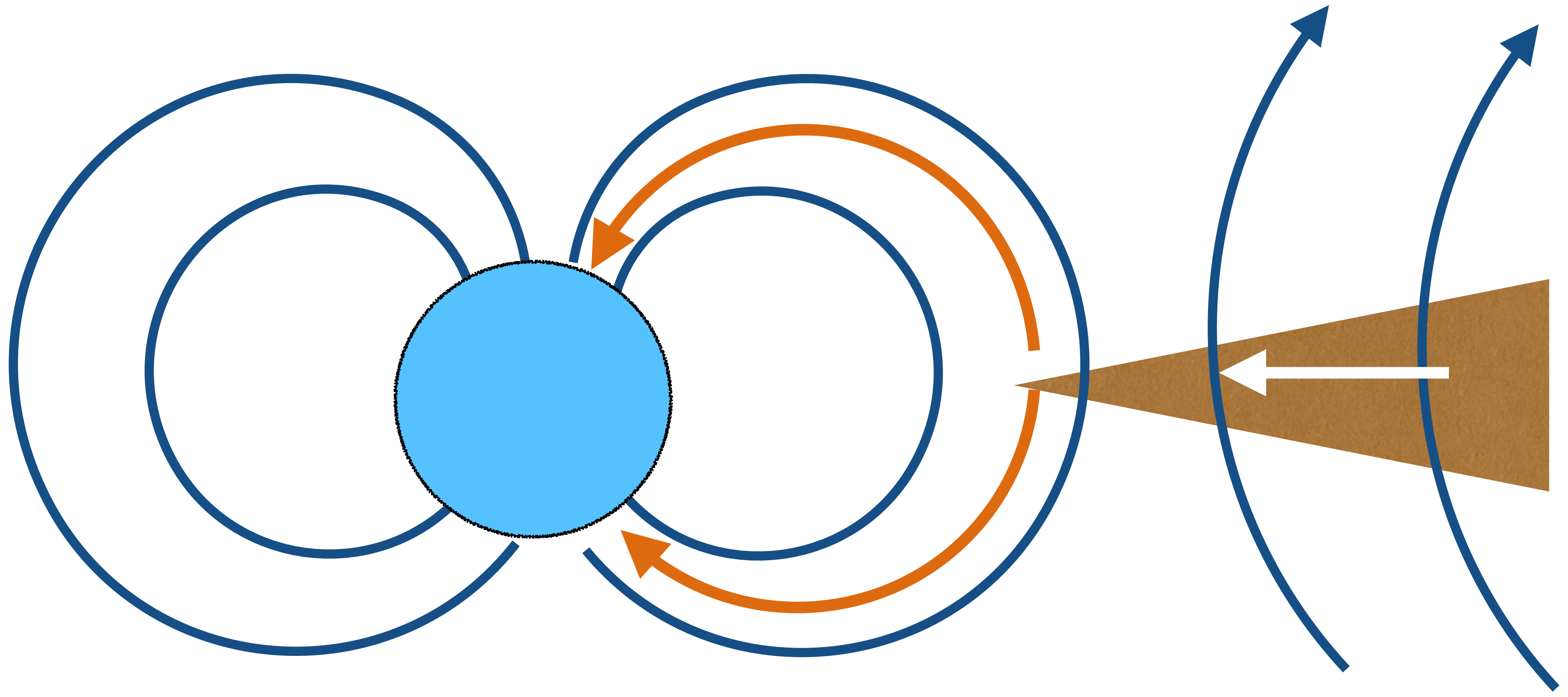
MRI-turbulent disks produce failed disk wind (disk surface acc).
(e.g. ST+18, Zhu & Stone 18, Jacquemin-Ide+21)

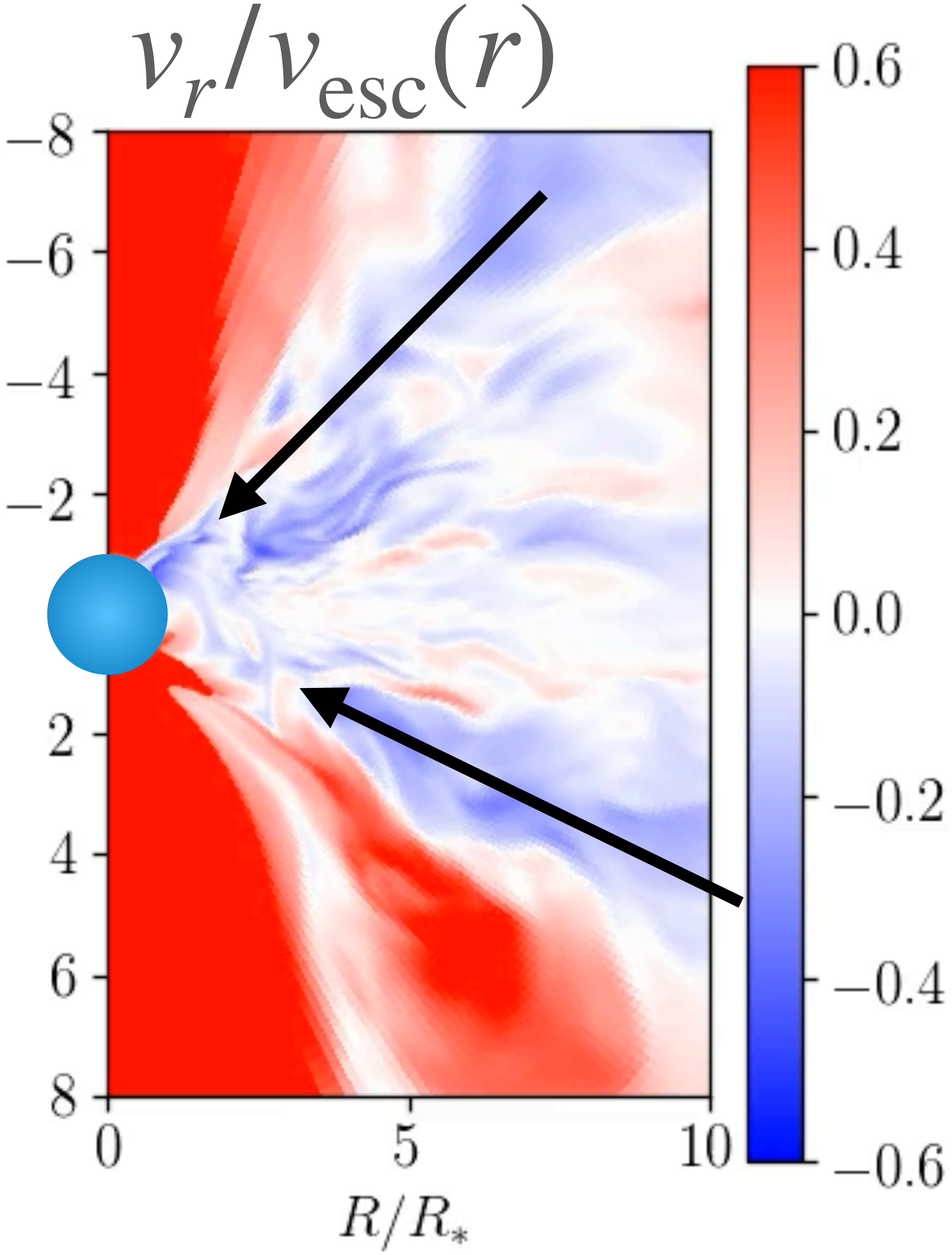


Comparison: accretion flow structure

Polar accretion = classical magnetospheric acc. + failed disk wind (disk surface acc)

Classical magnetospheric accretion





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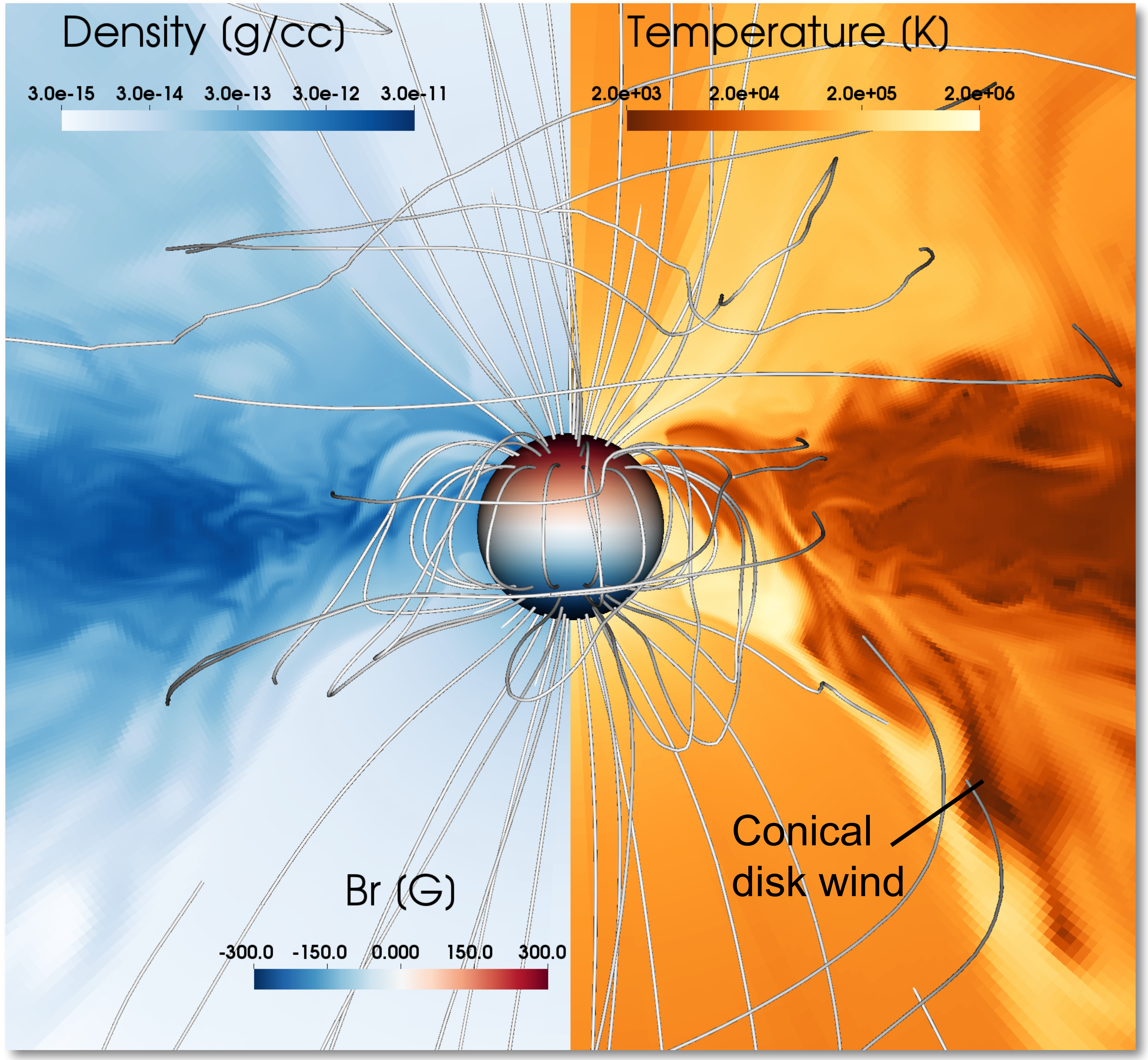
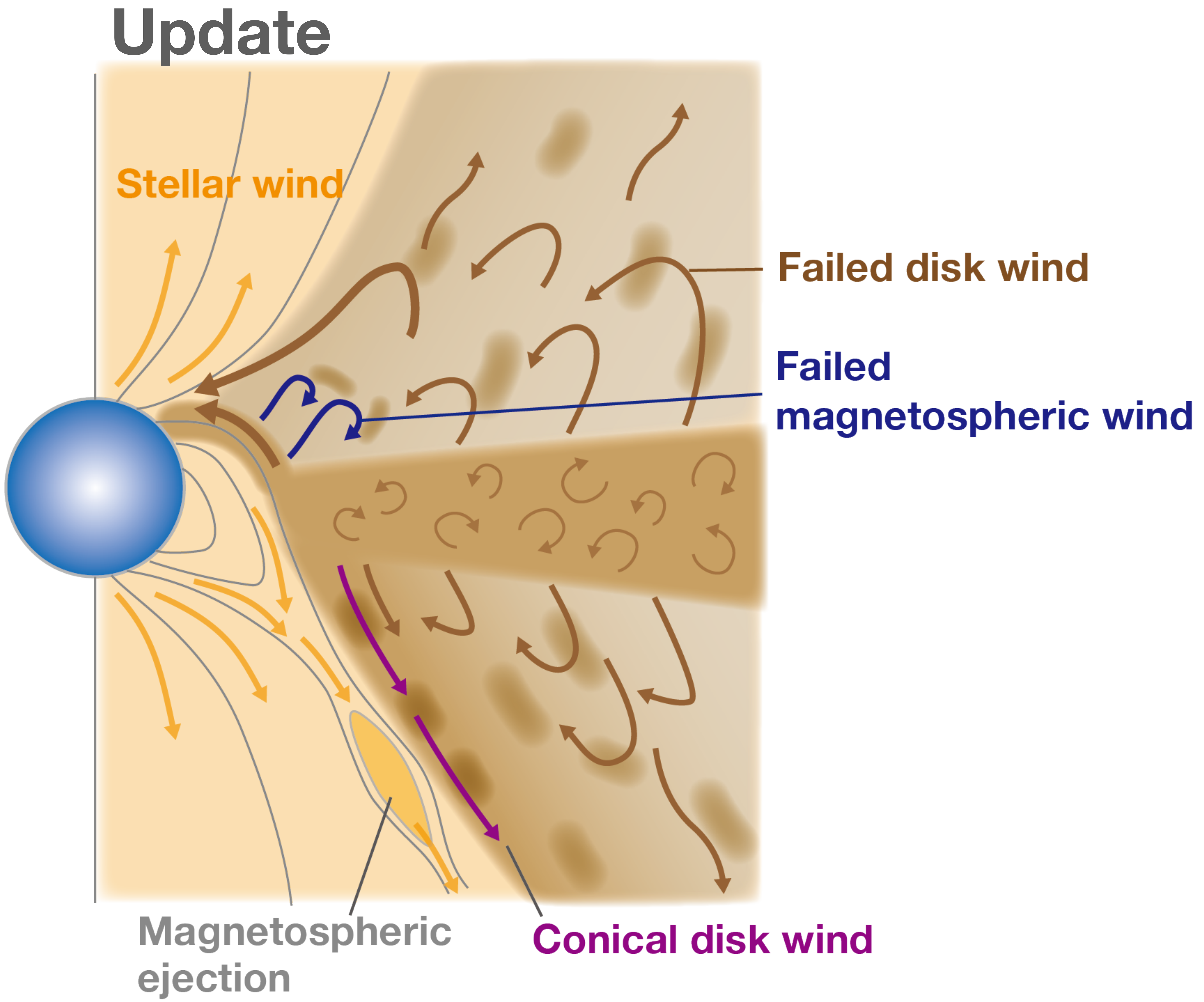
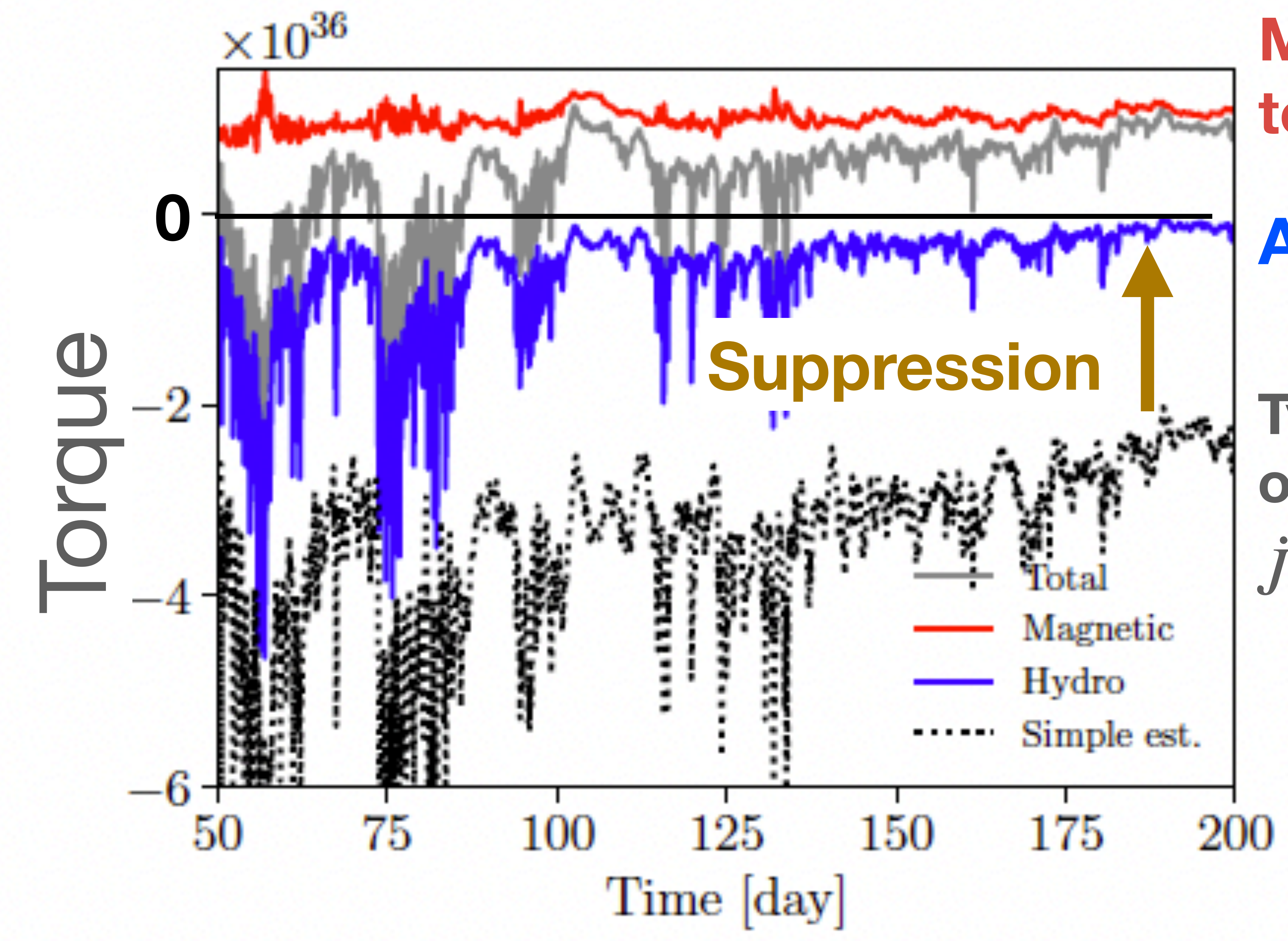




Comments on accretion torque

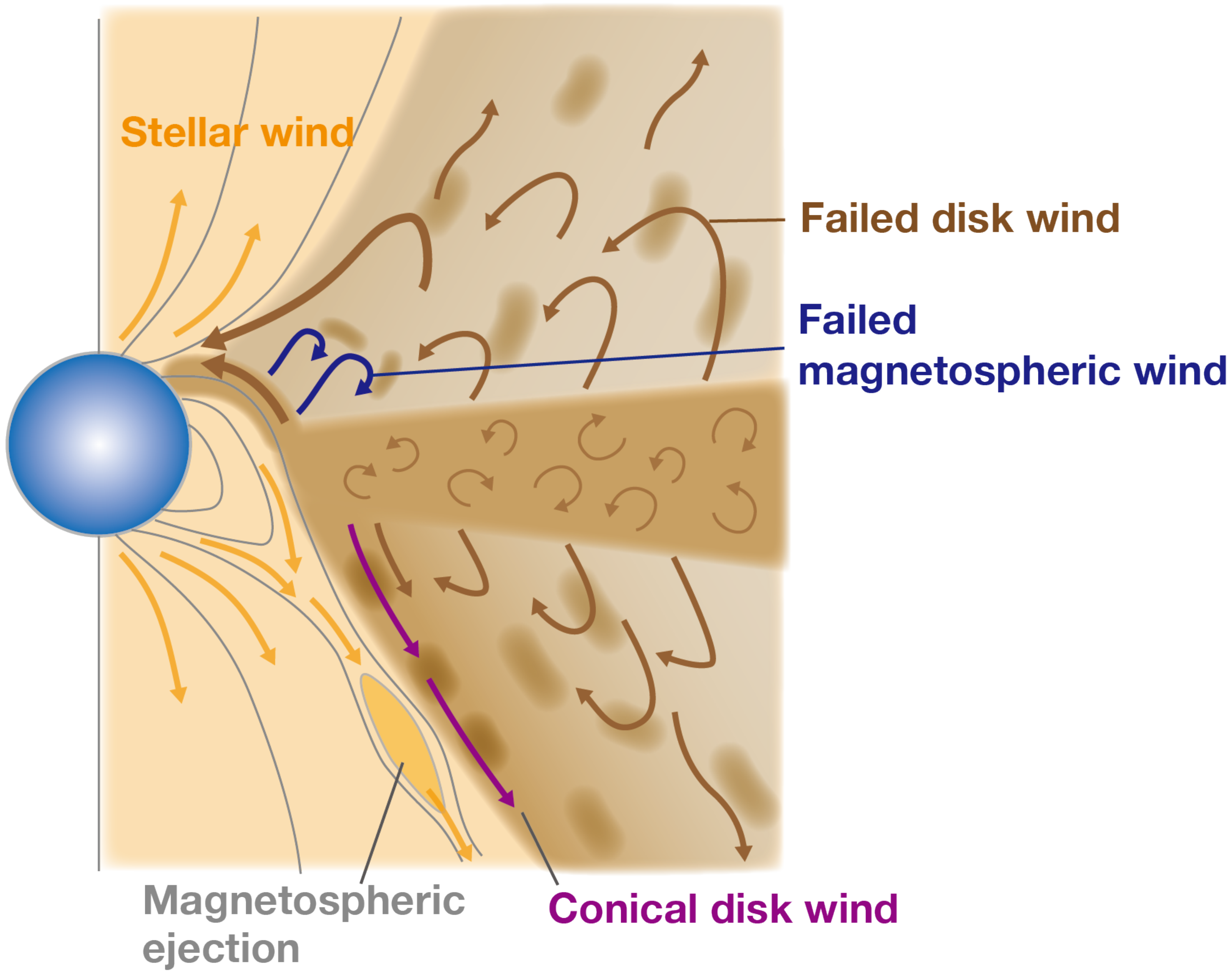


Magnetic spin-down torque

Accretion torque

Typical estimation of accretion torque

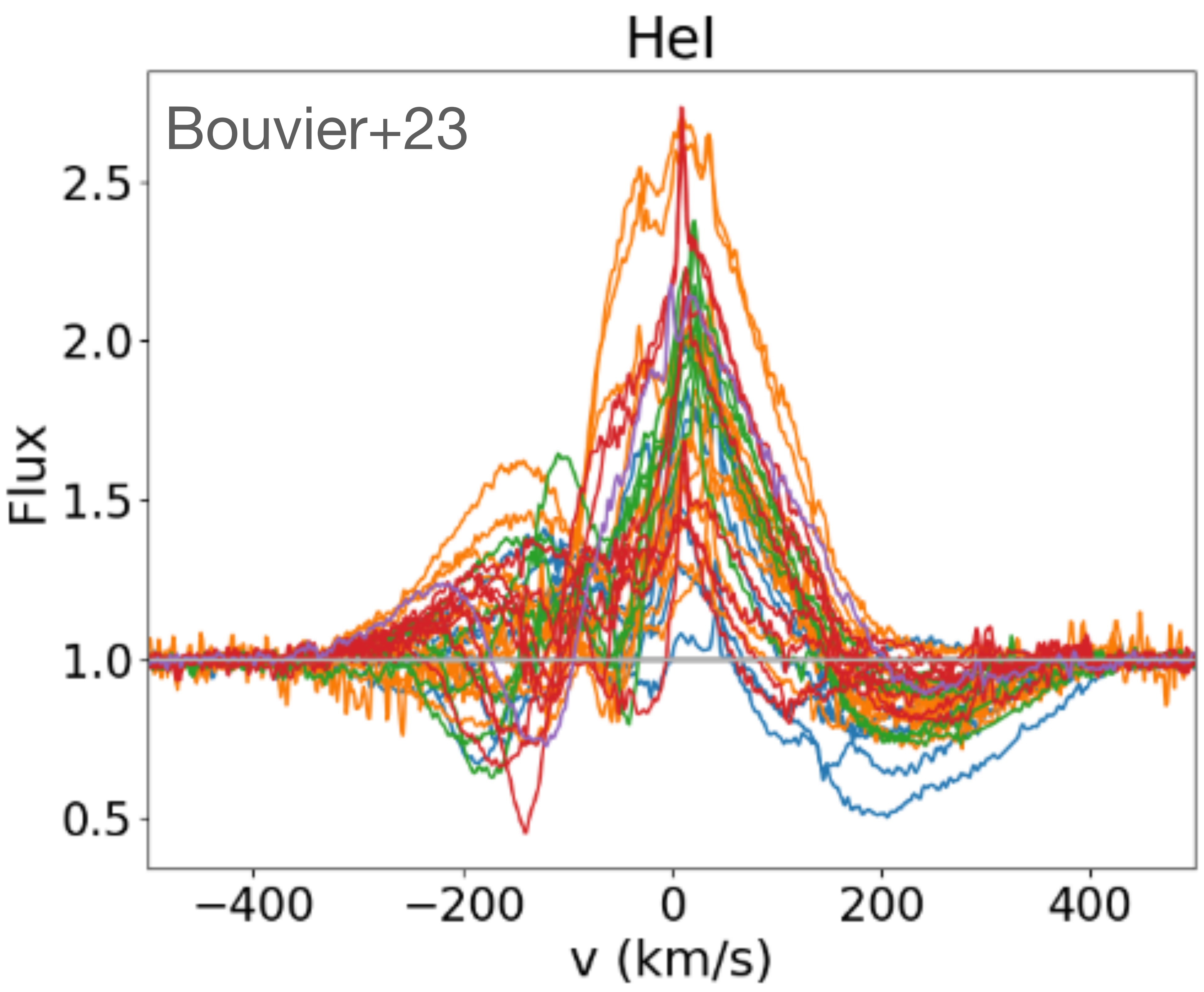
$$\dot{J}' = \dot{M}_{\rm acc}\sqrt{GM_* r_{\rm mag}}$$



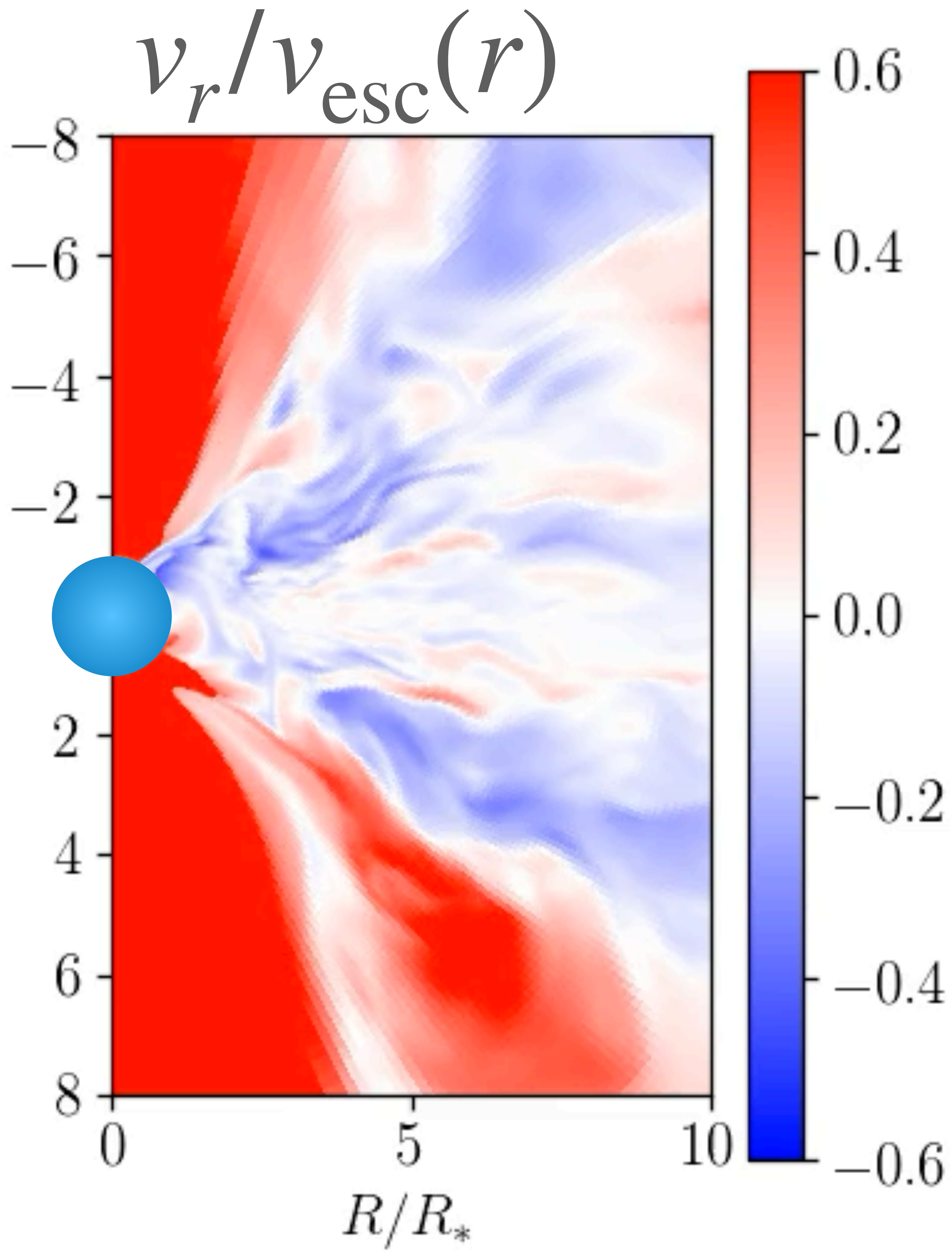
Slow, turbulent winds seem to extract angular momentum from accreting flows.
A possible key to solving the stellar spin-down problem.

Fluctuating atmosphere observed?

Variable red and blue components in He I line (timescale ~ day)



An indication of mixture of accretion and outflow?



Explosive aspect of young stars

Chandra X-ray movie of Orion

Flickering lights = Flares on protostars and pre-main-seq. stars

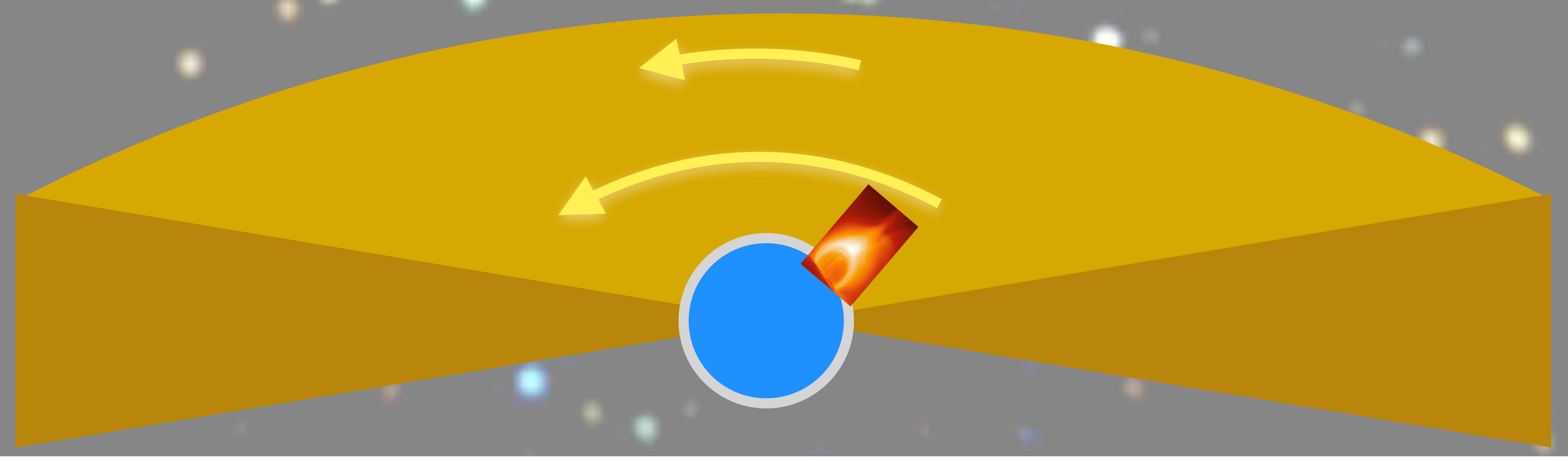
Chandra X-ray movie of Orion

Flickering lights = Flares on protostars and pre-main-seq. stars

10^{34} - 10^{37} erg only in X-ray

>> flare energy of the largest solar flare ($\sim 10^{32}$ erg)

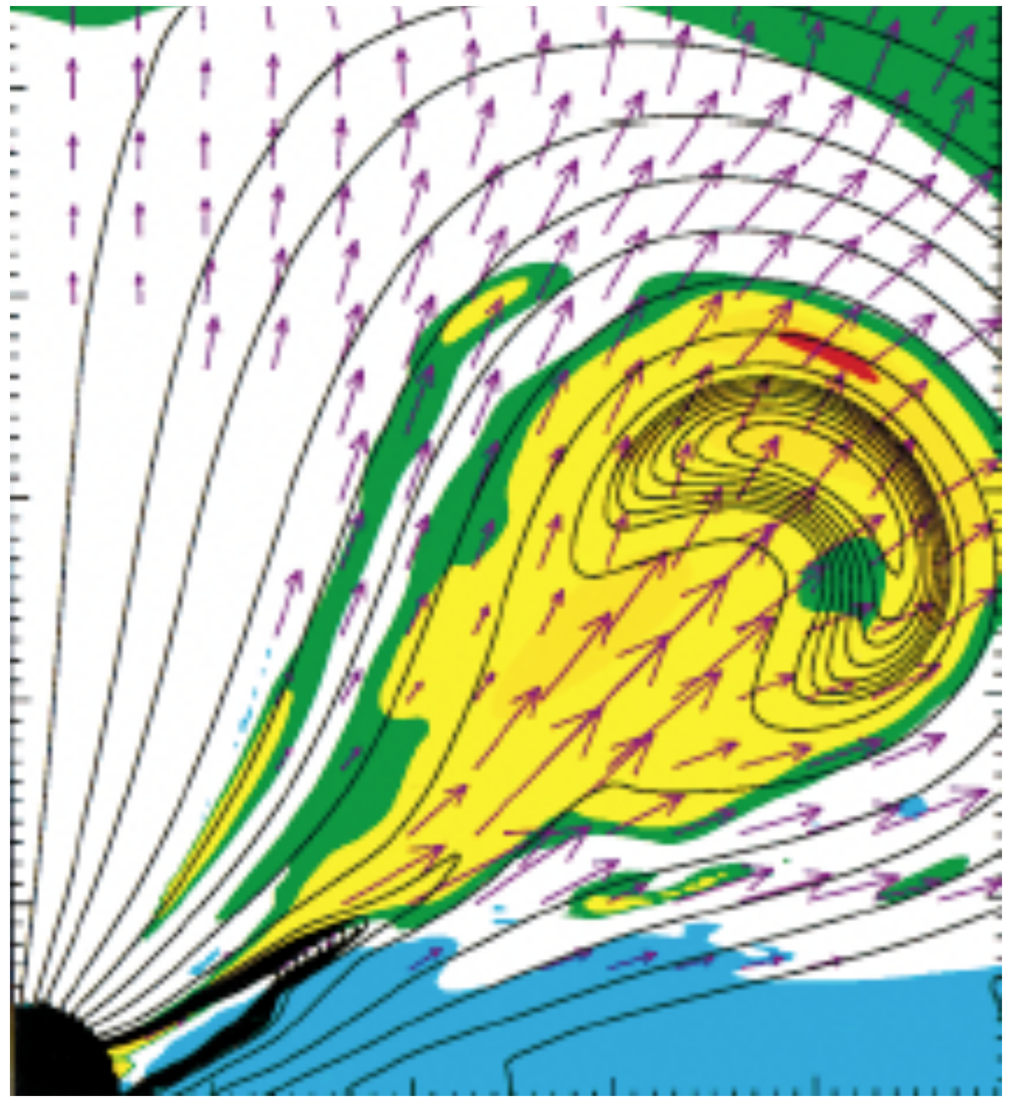
Disk



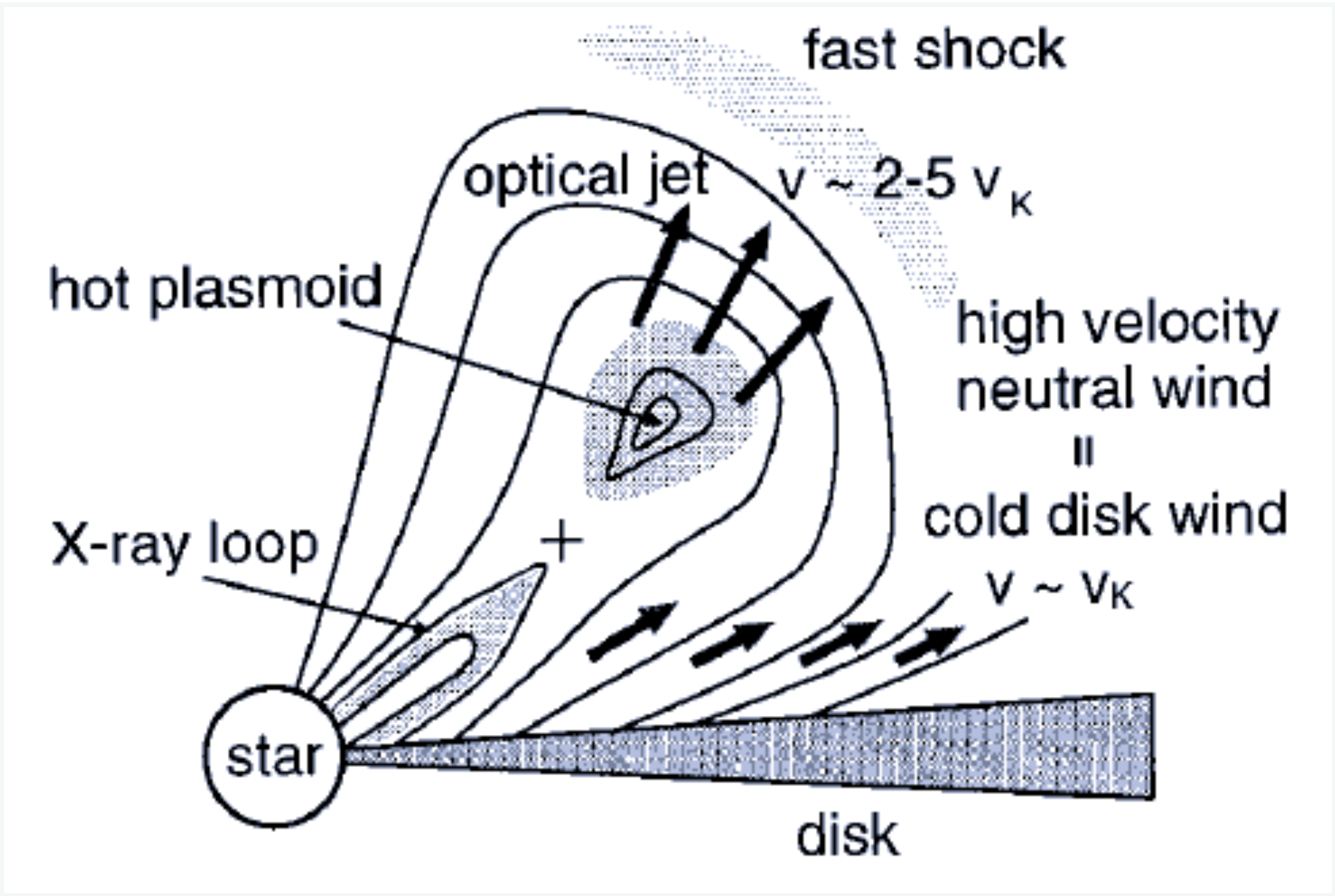
Mechanisms related to the accretion disk?

Magnetospheric ejection model

Hayashi+96



magnetospheric ejections



Twisting the stellar field by the rotating disk (release of grav. energy)

—> Eruption

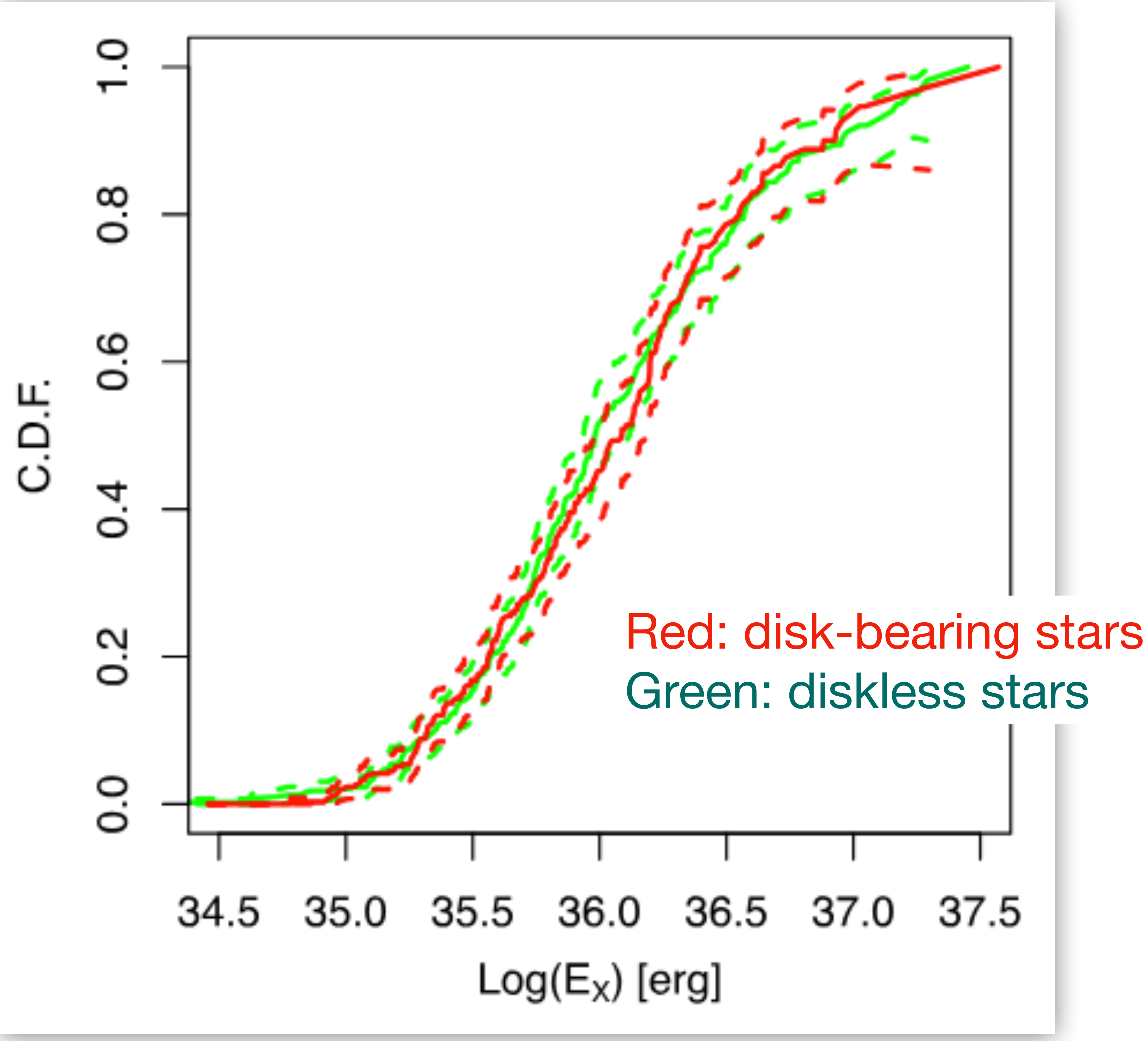
See also, e.g., Shu+94, Hirose+97, Zanni+13, Čemeljić+13, Ireland+20

Predictions:

- High-accretors will produce stronger flares.
- Correlation between flare occurrence and stellar/disk rotation.
  - quasi-periodic production of flares
  - non-power-law flare occurrence rate
    <=> power law for solar/stellar flares, $\mathrm{Freq.}\,[\mathrm{erg}^{-1}\mathrm{yr}^{-1}] \propto E_{\mathrm{flare}}^{-1.8}$ (Shibata+13)

Observations

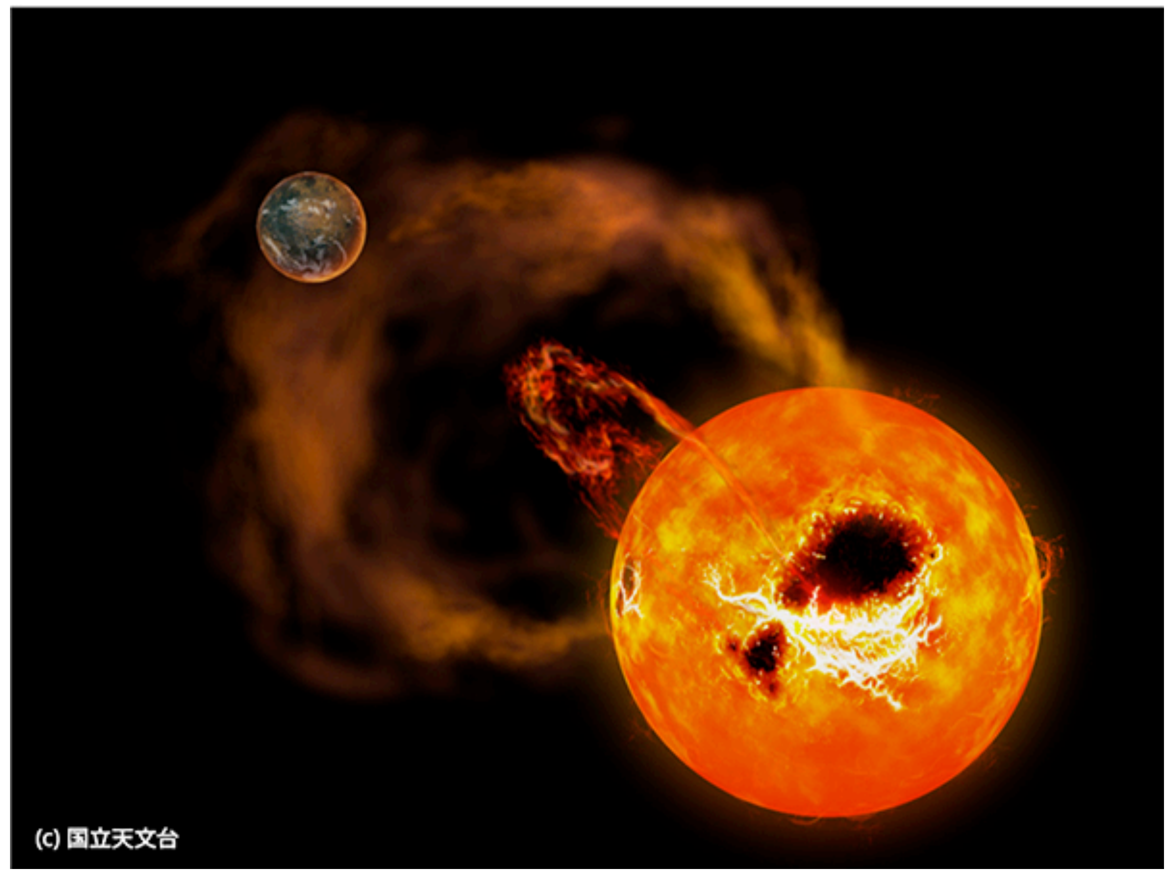
Getman & Feigelson 21



“no evidence for a distinct flaring mechanism involving the circumstellar disk”

See also Getman+08b

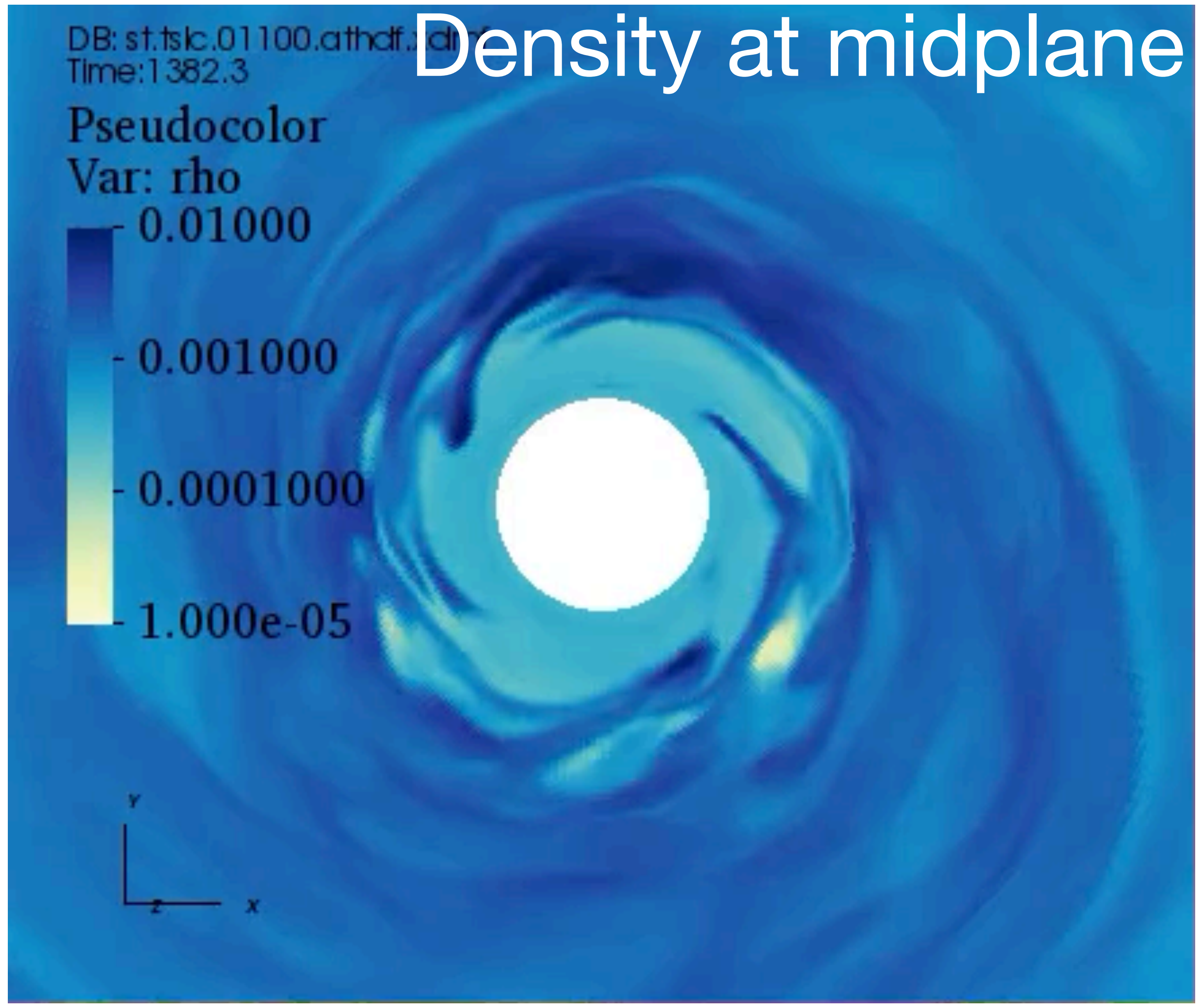
So flares on pre-MS stars should occur in the same way as MS stars.



Why star-disk interaction cannot produce huge flares efficiently?

3D effects on magnetospheric ejections

Eruptions occur in 3D models. But producing huge & hot flares is difficult!!



1. Fragmentation of accretion flow
—> inefficient twisting (energy build-up)

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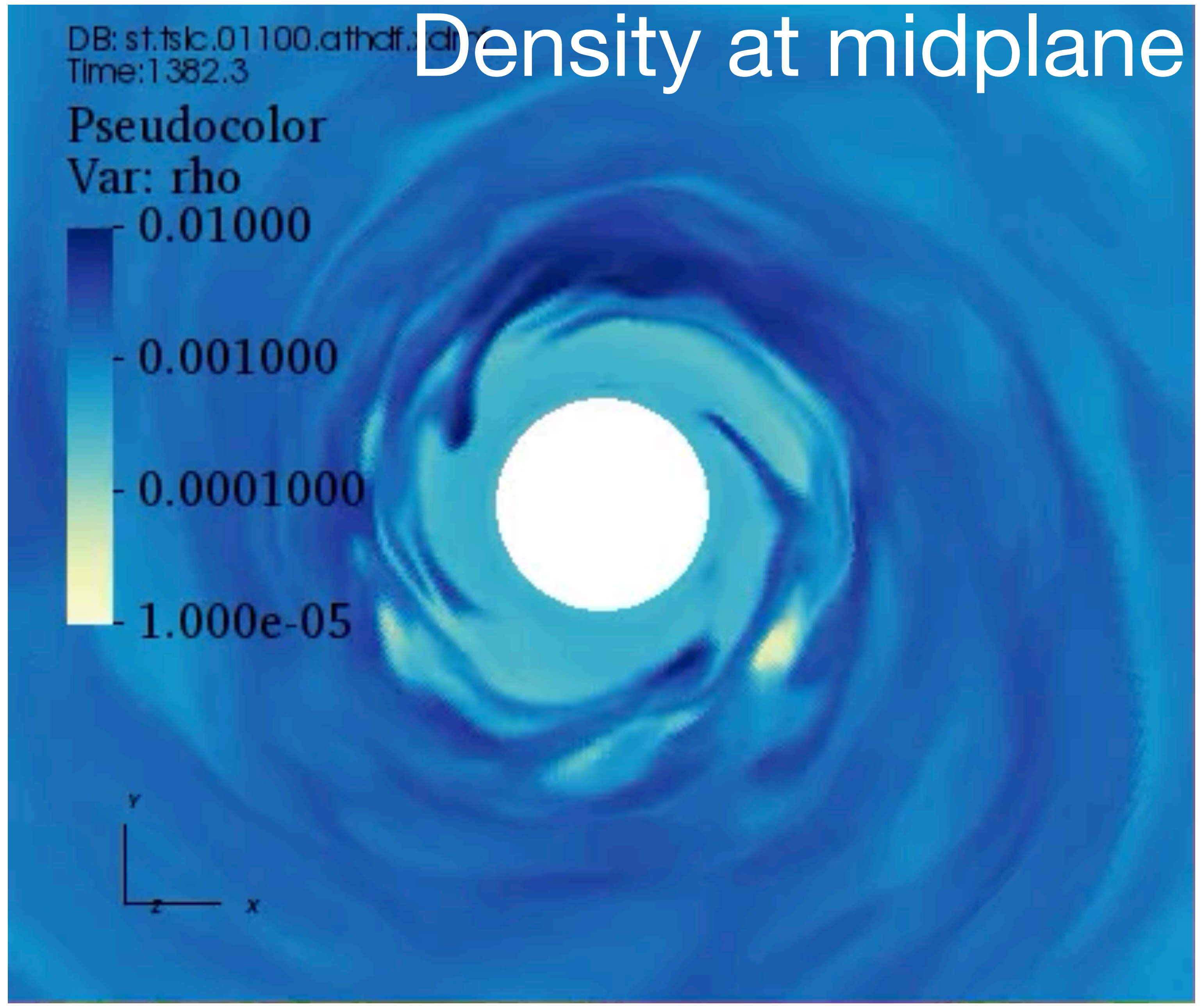
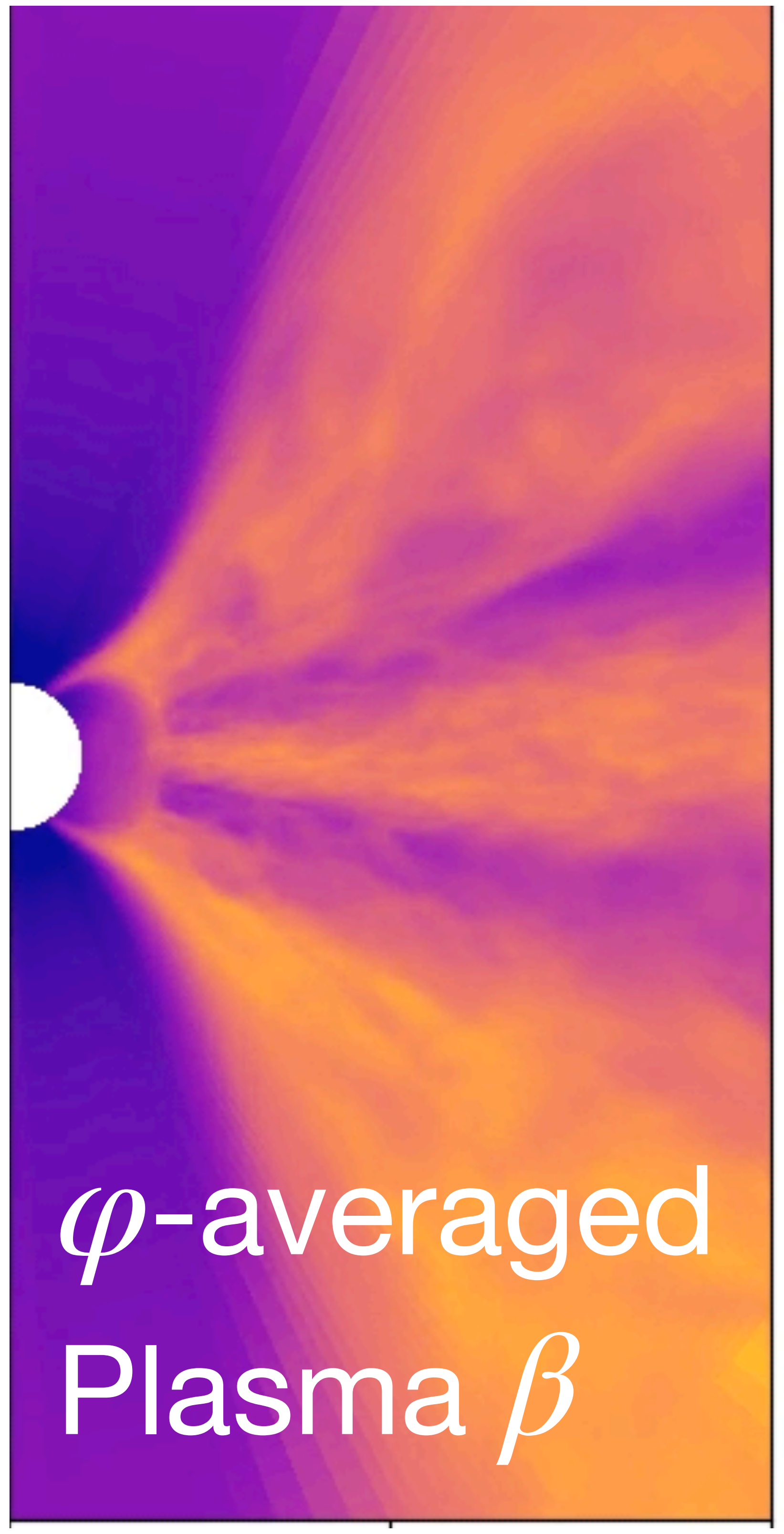
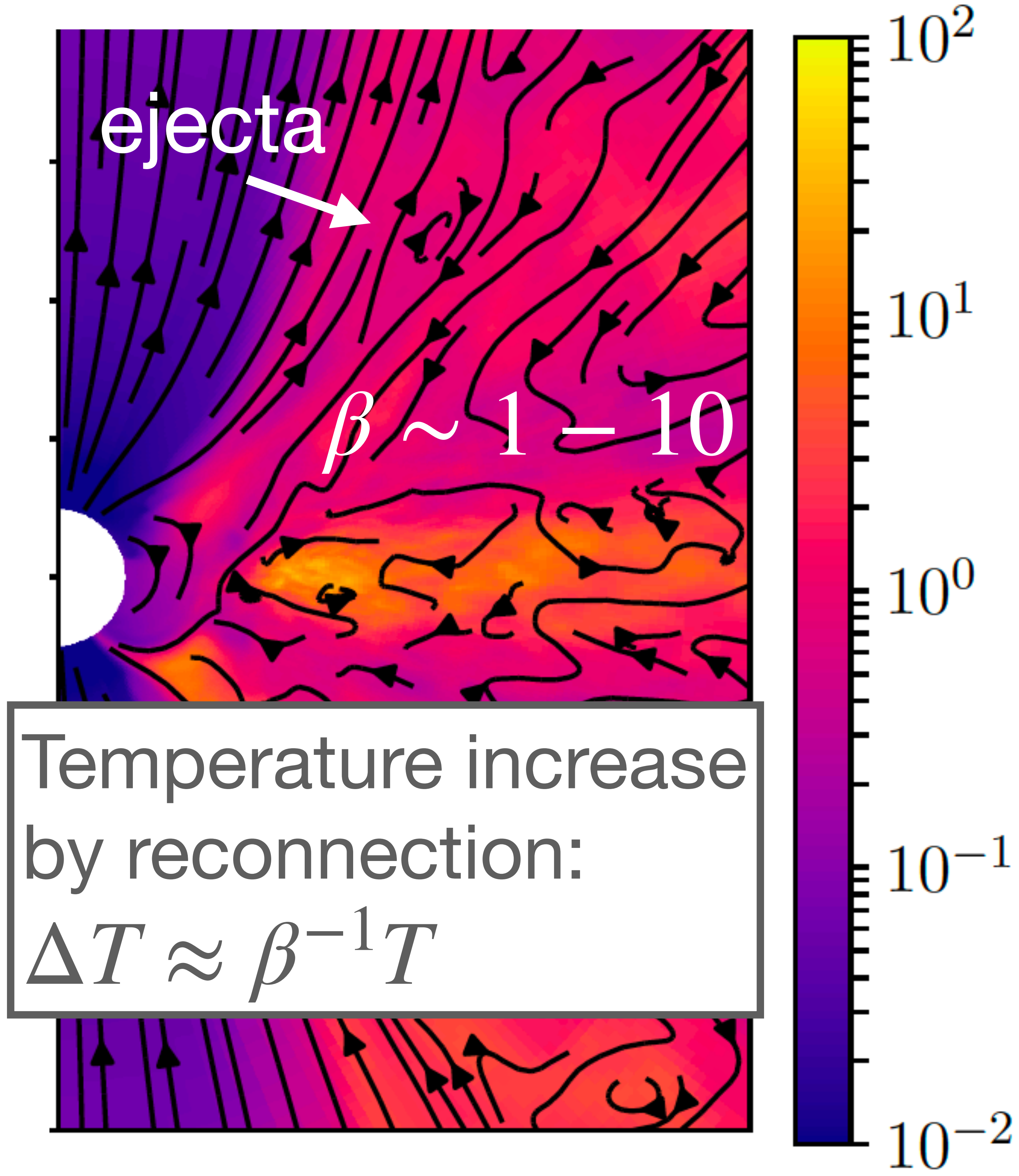




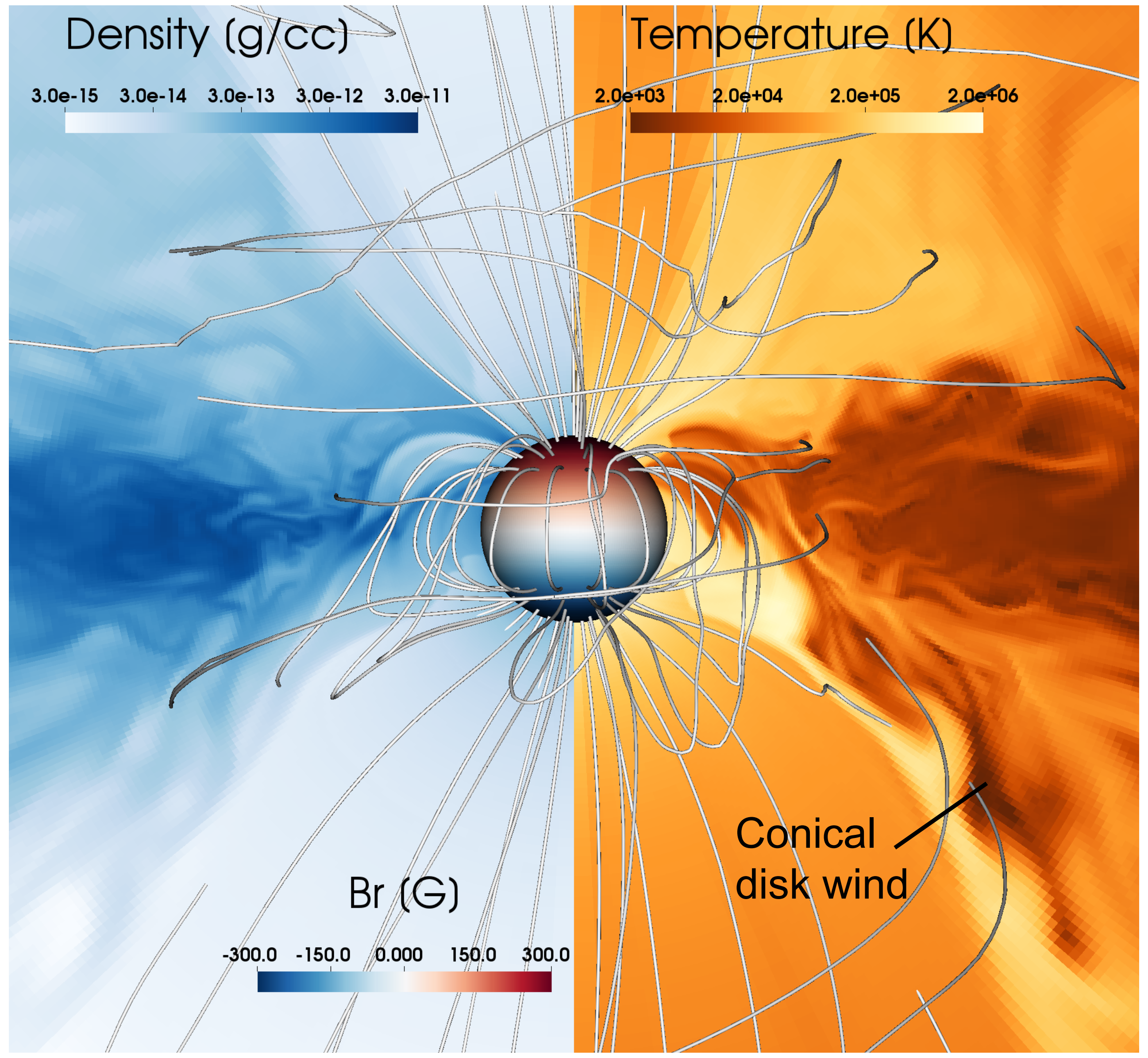


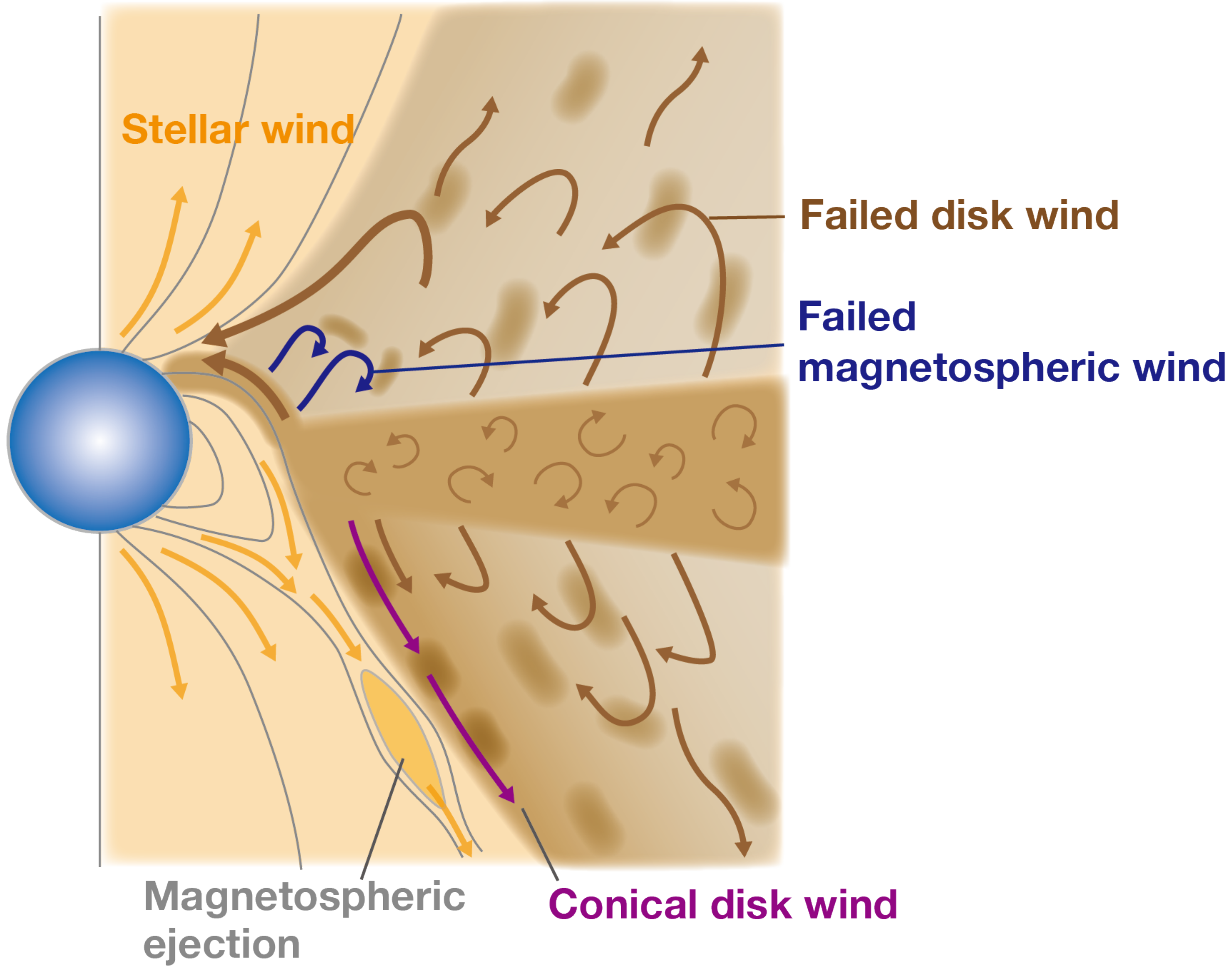
1. Fragmentation of accretion flow
—> inefficient twisting (energy build-up)

2. Reconnection cannot produce hot plasma because of mass loading by the disk wind

Summary

We suggest an **updated picture of magnetospheric accretion** based on our 3D MHD simulations (Takasao et al. 2022)





Impacts of 3D effects:

- determination of magnetospheric radius
- origin of polar accretion flows (classical MA + failed disk wind)
- Suppression of spin-up torque
- Possible source of time variable line profiles
- Suppression of flaring activities driven by star-disk interaction