

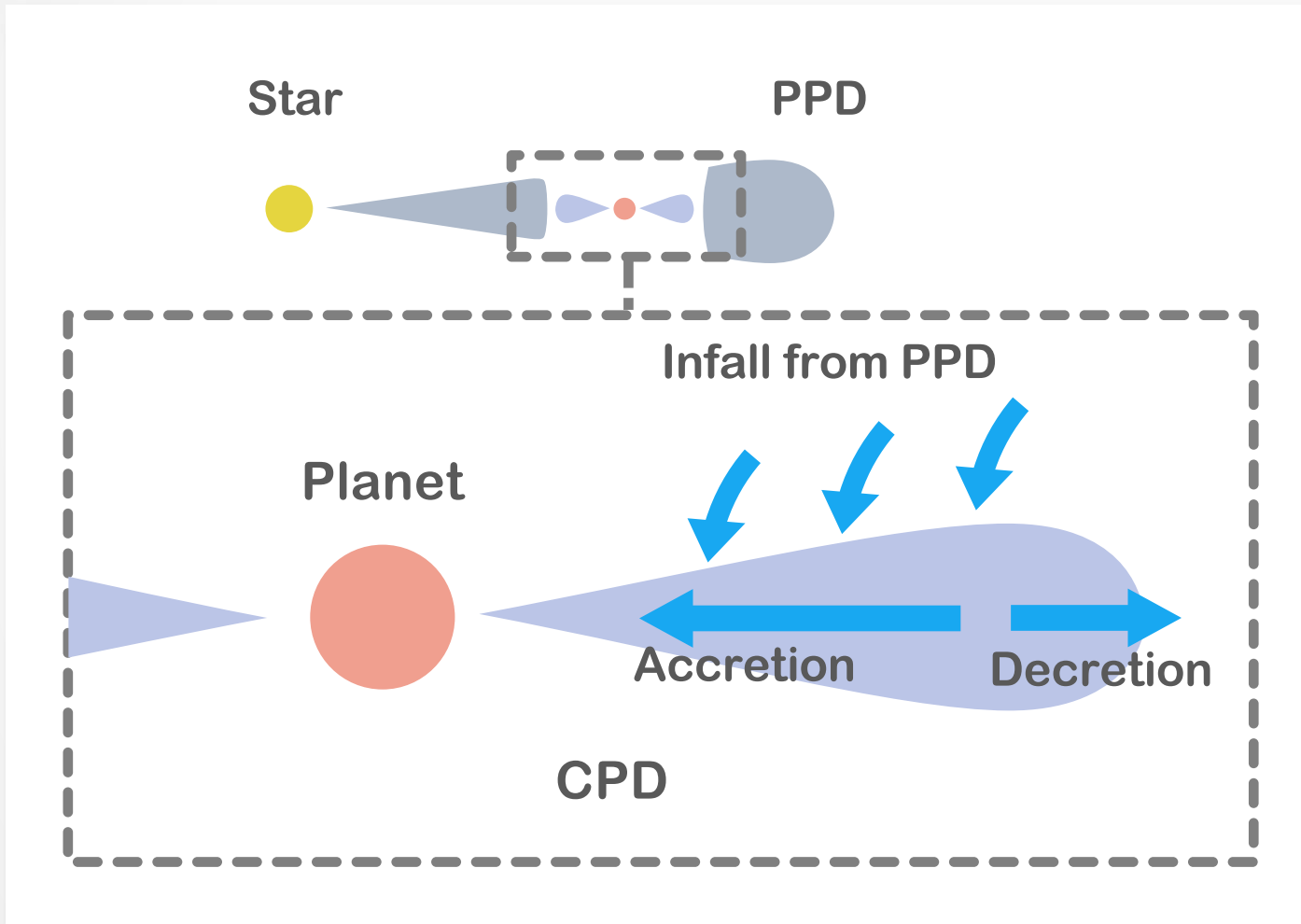
Magnetically Driven Accretion and Satellitesimal Formation in CPDs

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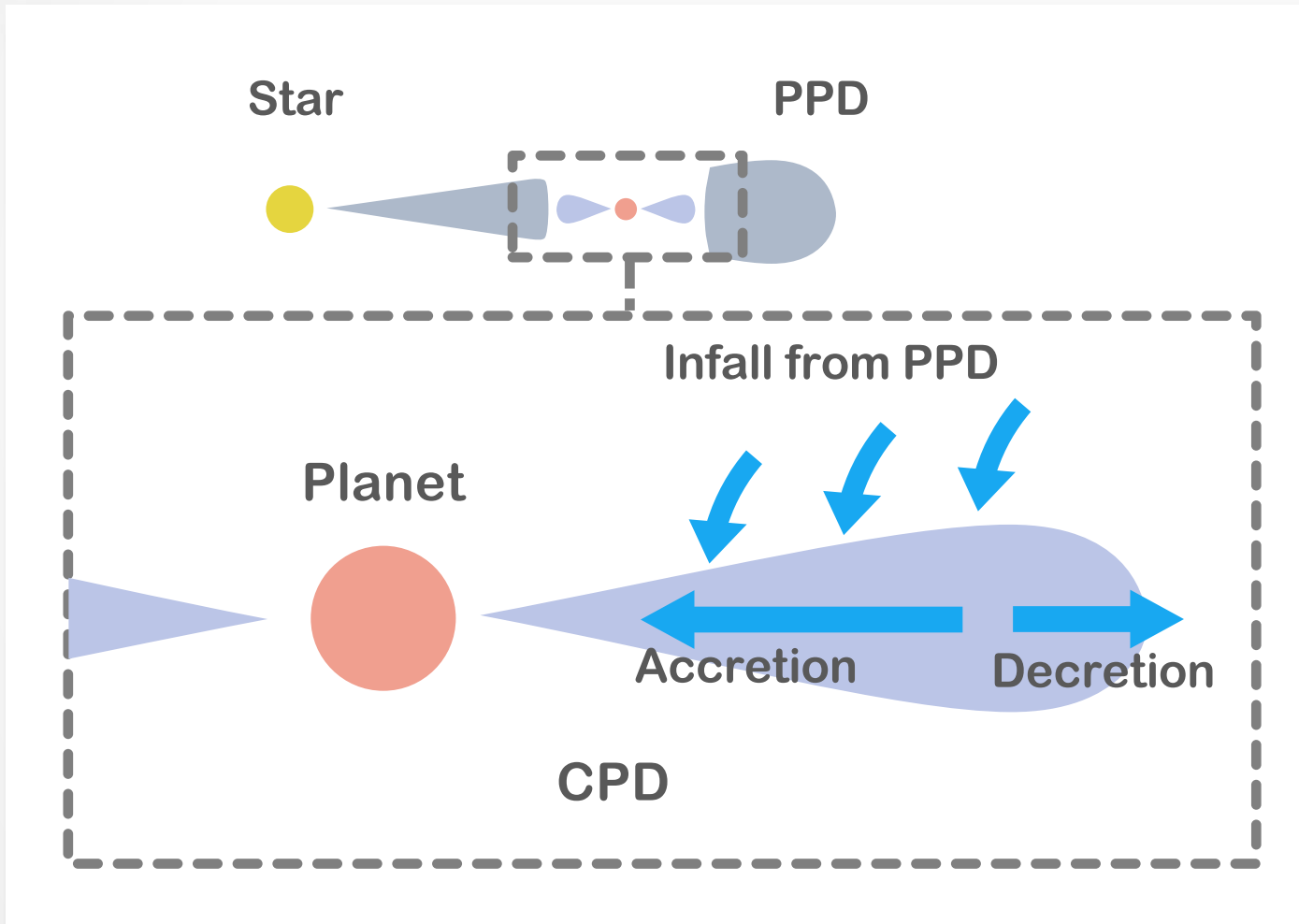
Toward understanding of CPD structures

How does gas accrete?



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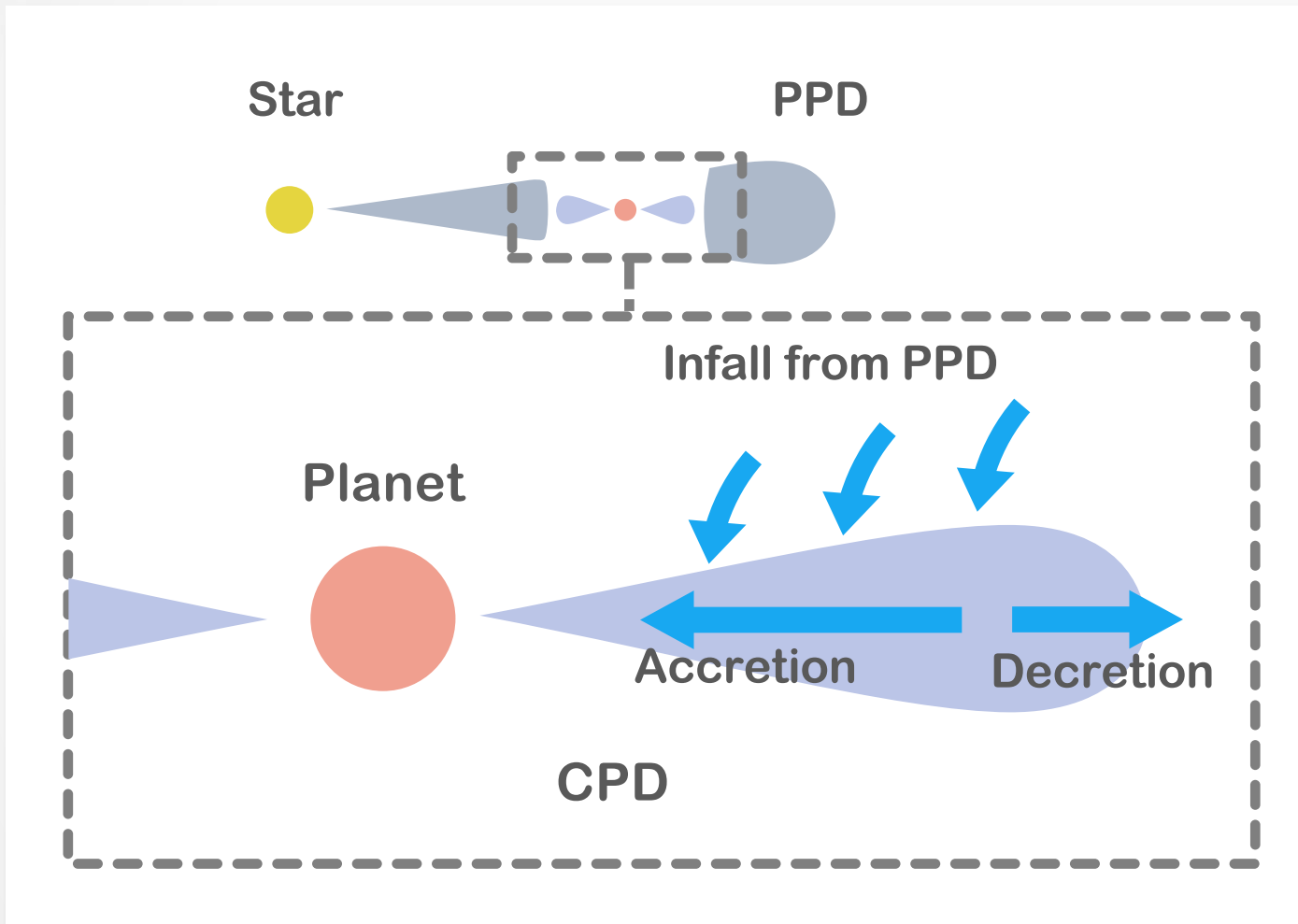
Accretion rate

$$\dot{M} = 3\pi\Sigma\nu$$

→ Viscosity controls Σ

Toward understanding of CPD structures

How does gas accrete?



- MRI is dead
(e.g., Fujii+14; Keith&Wardle+14)
Weakly ionized + small scaleheight
- Hydrodynamic instability?
(Ward&Canup2010)
- Spiral shocks? (Zhu+2016)

Accretion in PPDs can be driven by large-scale magnetic fields

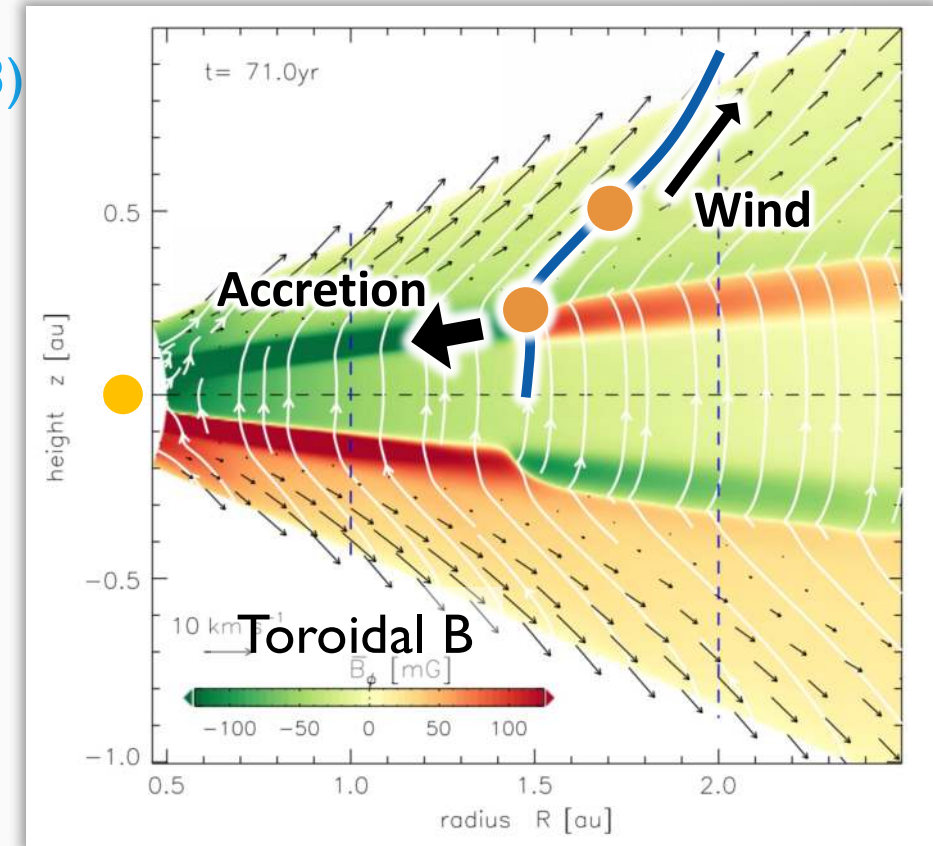
Even if MRI is quenched by nonideal MHD effects,
(e.g. Fleming et al. 2000; Turner & Sano 2008; Bai & Stone 2013)

accretion can be driven by magnetic fields
(e.g. Gressel et al. 2015; Suzuki et al. 2016; Bai 2017)

Does this work in CPDs?

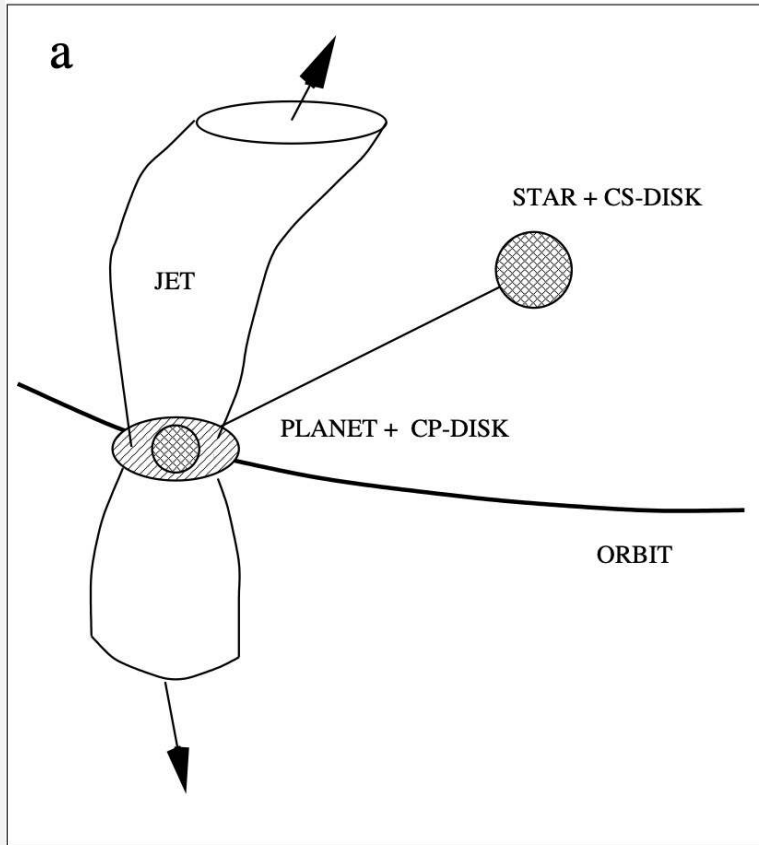
Observations might suggest outflows from CPDs
(Recall Yoshida-san's talk;
HD 169142: Law+23; TW Hya: Yoshida et al. 2024)

Nonideal MHD simulation in PPD
(Ohmic + Ambipolar diffusion)

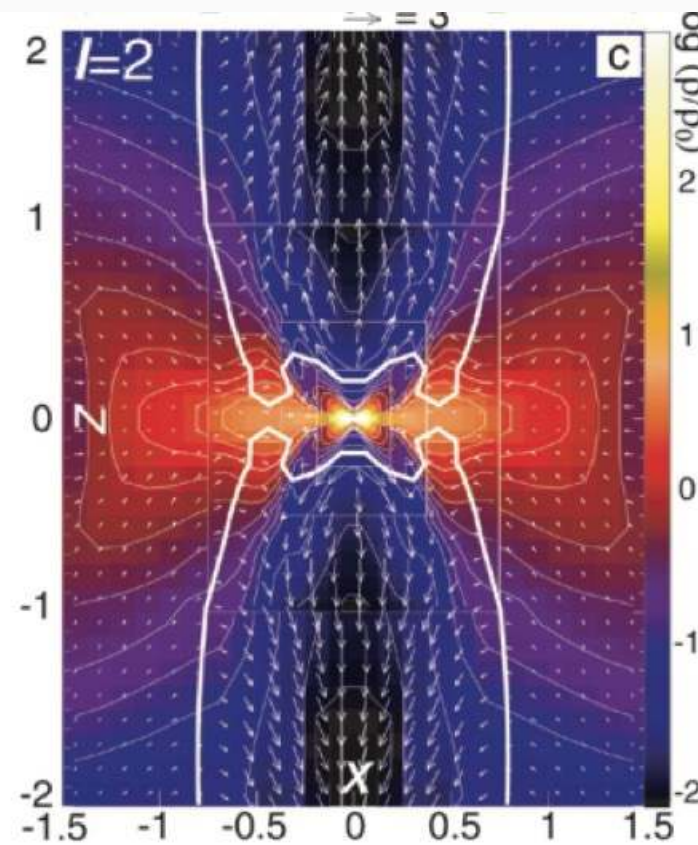


Gressel et al. (2015)

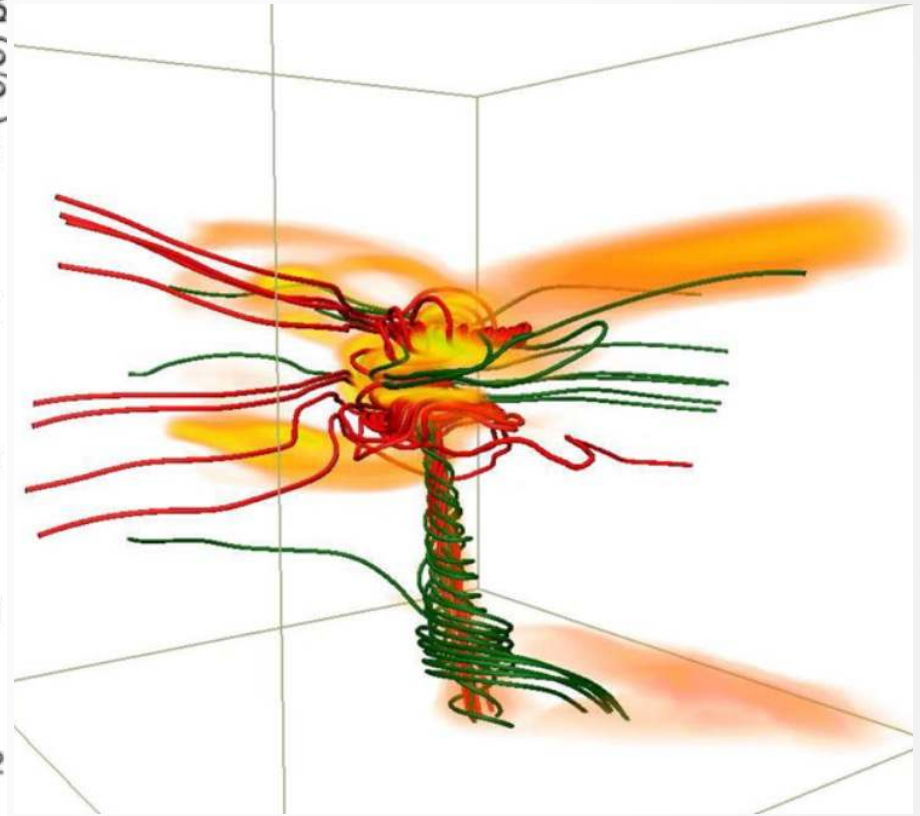
Theoretical studies on winds from CPDs



Quillen & Trilling 98; Fendt 03



Machida+06



Gressel+13

Satellite-forming region ($R \sim 10 R_p \ll R_{\text{Hill}}$) is not investigated

What we need to think

1. Well ionized?
2. Well magnetized?
3. Winds survive inflows?

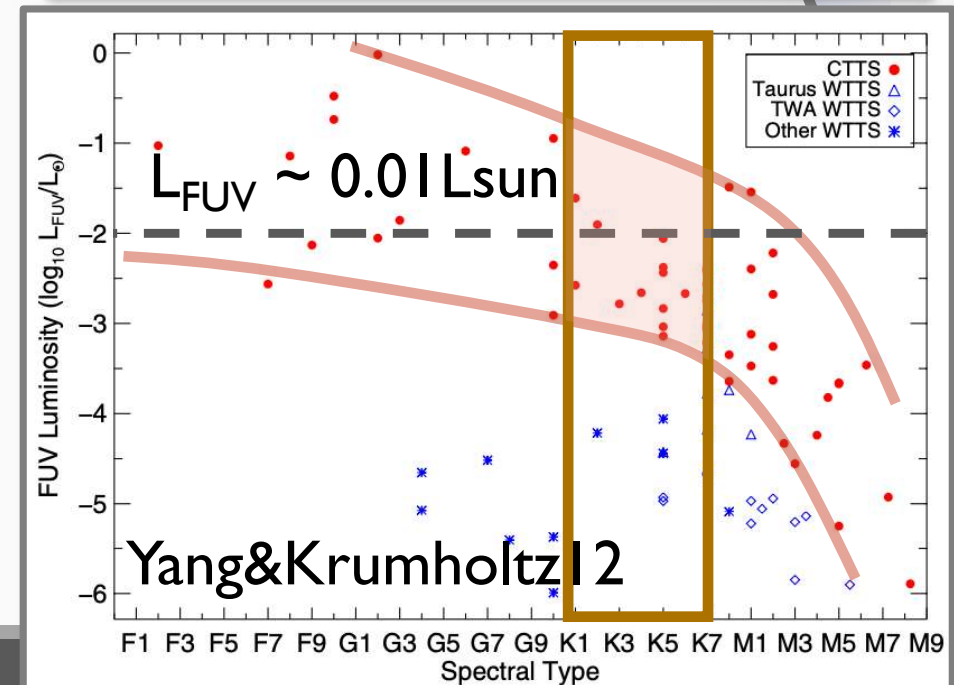
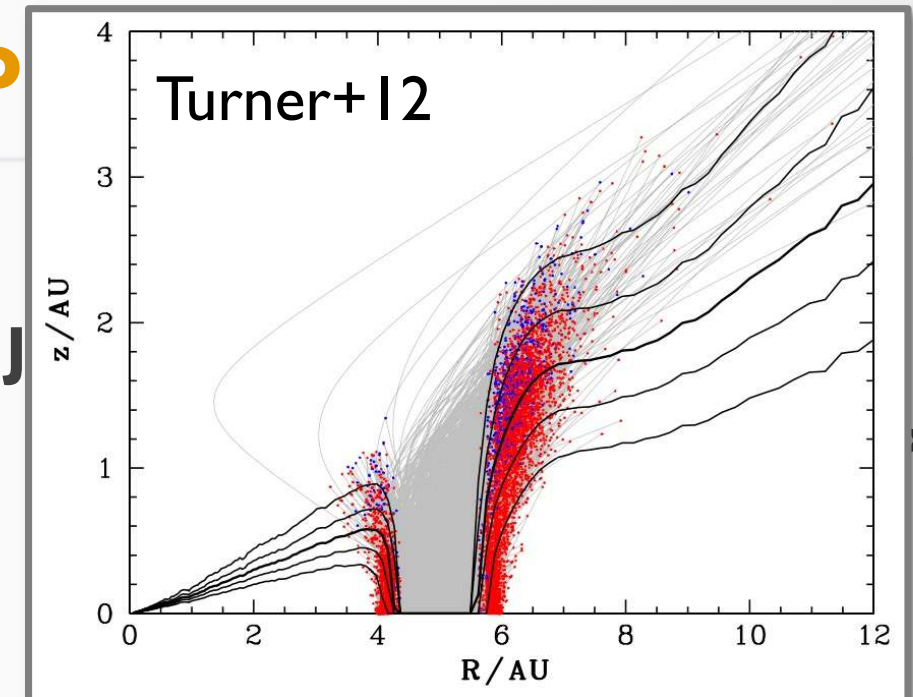
Estimate of ionization rate in CP

- Xray : direct comp + indirect comp.

$L_x = 1e30 \text{ erg/s}$ (Gamire+00)

$$\zeta_X = 2 \cdot 10^{-14} \text{ s}^{-1} \times \exp \left[- \left(\frac{\Sigma_{\text{col}}}{2.3 \text{ g cm}^{-2}} \right)^{0.7} \right] \left(\frac{r}{1 \text{ au}} \right)^{-2.2}$$

- FUV : Lyman alpha may be scattered
 - $L_{\text{scatter}} / L_{\text{direct}} = 0.4\%$ (Turner+12)
 - stellar $L_{\text{FUV}} = 0.01 L_{\text{sun}}$ (Yang&Krumholtz12)
 - $L_{\text{scatter}} = 1.5e29 \text{ erg/s}$ (x0.1 smaller)
 - $\Sigma_{\text{depth}} \sim 0.01 \text{ g/cm}^2$;
 - $x_e \sim 1e-5$ (Perez-Becker&Chiang11)



What we need to think

1. Well ionized?
 - CPD surface can be somewhat ionized
2. Well magnetized?
3. Winds survive inflows?

Estimate of magnetic fields brought into CPDs

Mass conservation

$$(Rv_R \Sigma)_{\text{CPD}} = (f_{\text{acc}} Rv_R \Sigma)_{\text{PPD}} \quad f_{\text{acc}} = \dot{M}_{\text{acc,PPD}} / \dot{M}_{\text{CPD}}$$

Assume: Magnetic field frozen accreting gas onto CPD

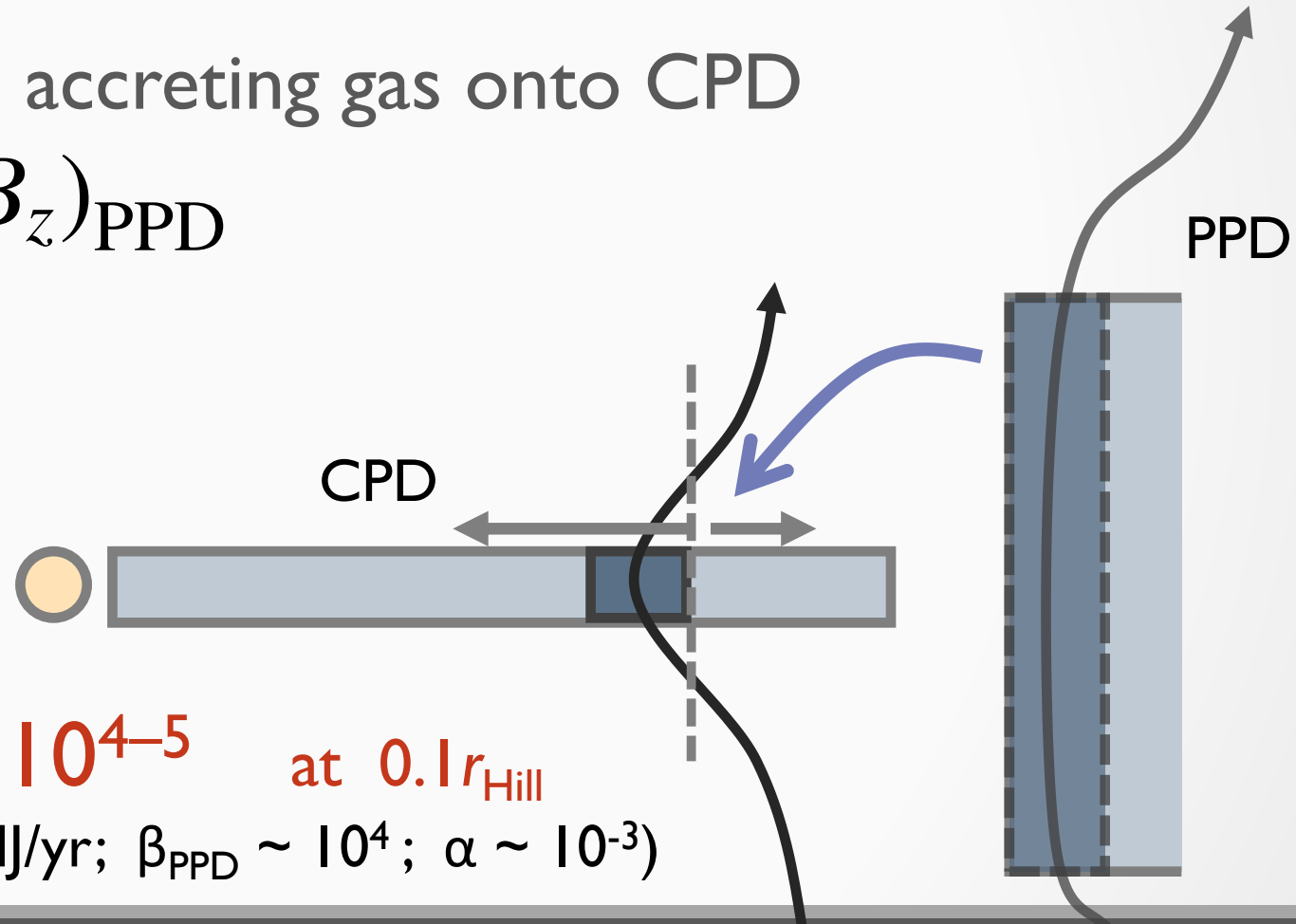
$$(Rv_R B_z)_{\text{CPD}} = (f_{\text{acc}} Rv_R B_z)_{\text{PPD}}$$

$$\left(\frac{\Sigma}{B_z} \right)_{\text{CPD}} = \left(\frac{\Sigma}{B_z} \right)_{\text{PPD}}$$

For example:

$$B_z \sim 0.1 - 0.01 \text{ G}, \quad \beta_z \sim 10^{4-5} \quad \text{at } 0.1 r_{\text{Hill}}$$

$$(\text{Macc}_{\text{PPD}} \sim 10^{-8} \text{ Ms/yr}; \text{Macc}_{\text{CPD}} \sim 10^{-7} \text{ MJ/yr}; \beta_{\text{PPD}} \sim 10^4; \alpha \sim 10^{-3})$$



What we need to think

1. Well ionized?
 - CPD surface can be somewhat ionized
2. Well magnetized?
 - Not too weak
3. Winds survive inflows?

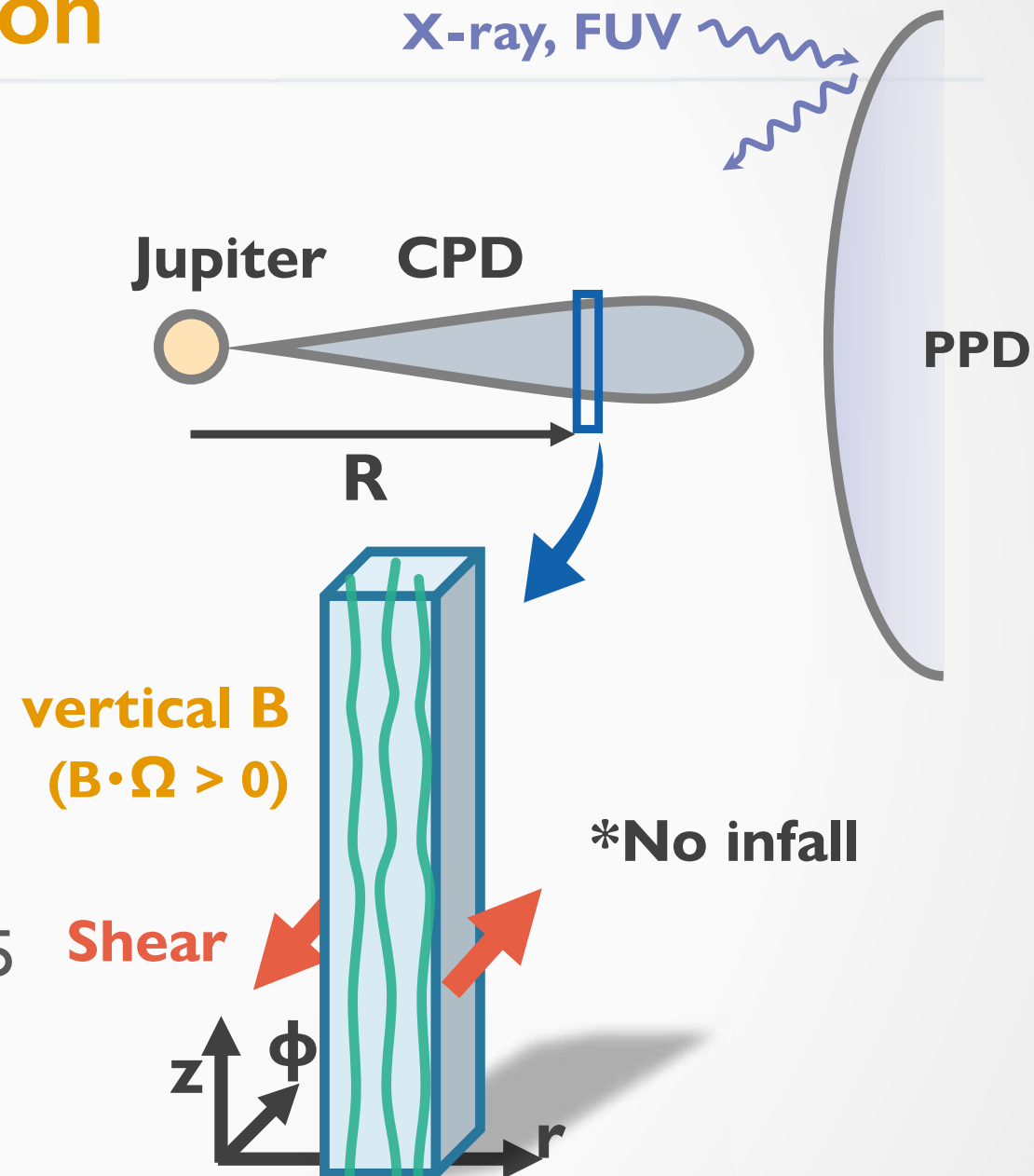
Local nonideal MHD simulation

Simulation

- Athena (Stone et al. 2008)
- Ohmic + ambipolar diffusion, Hall effect

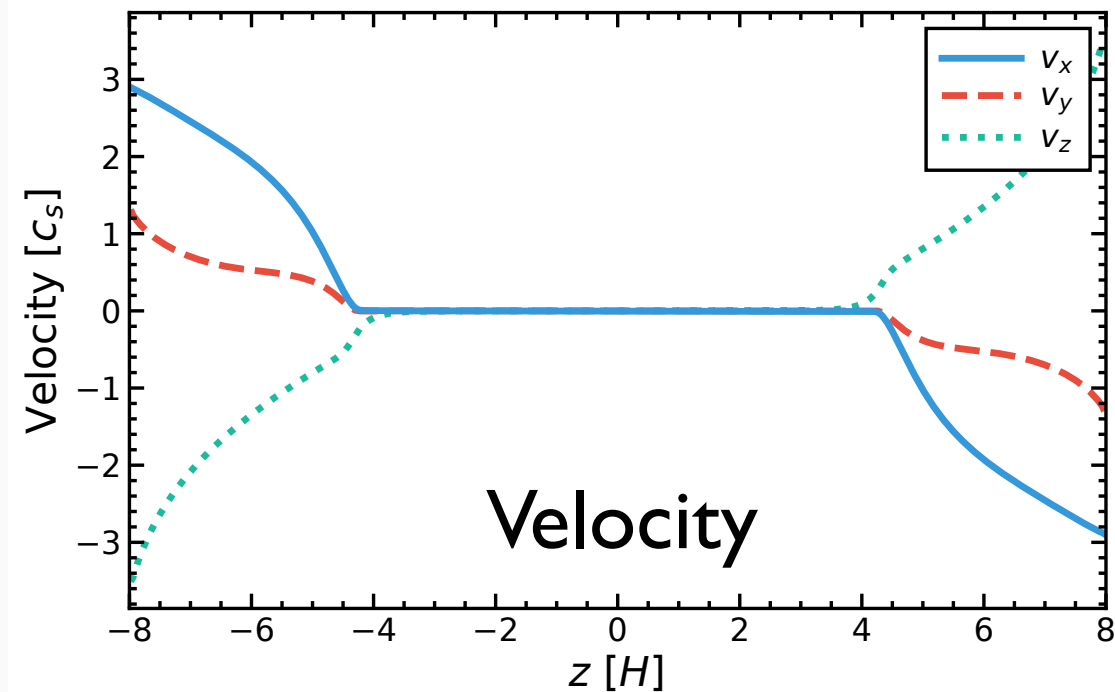
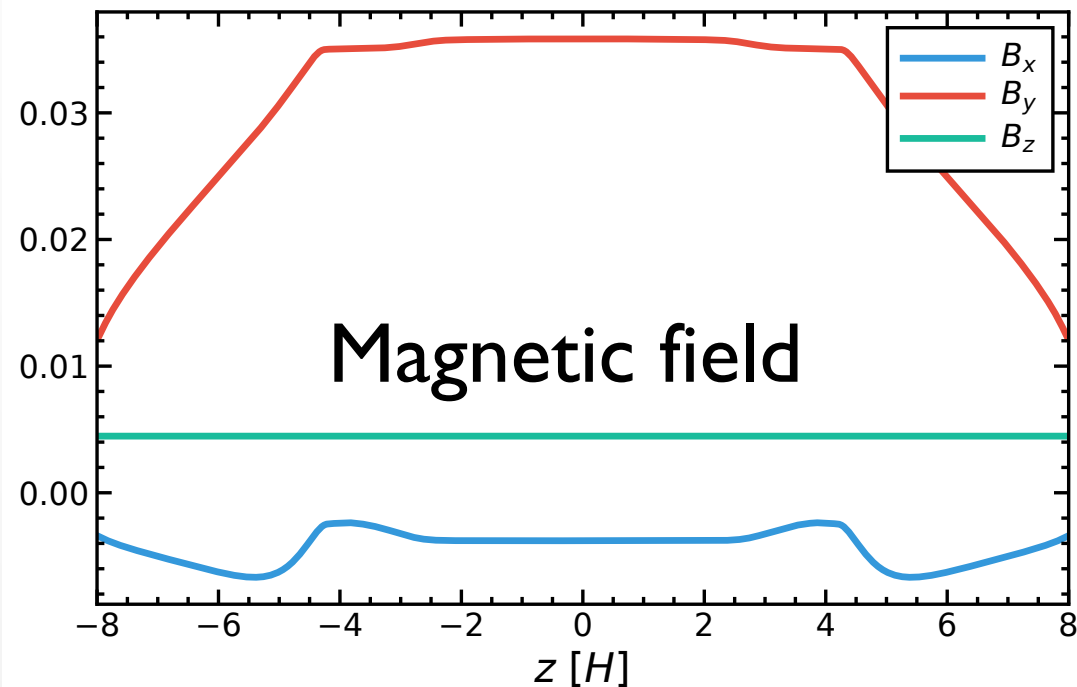
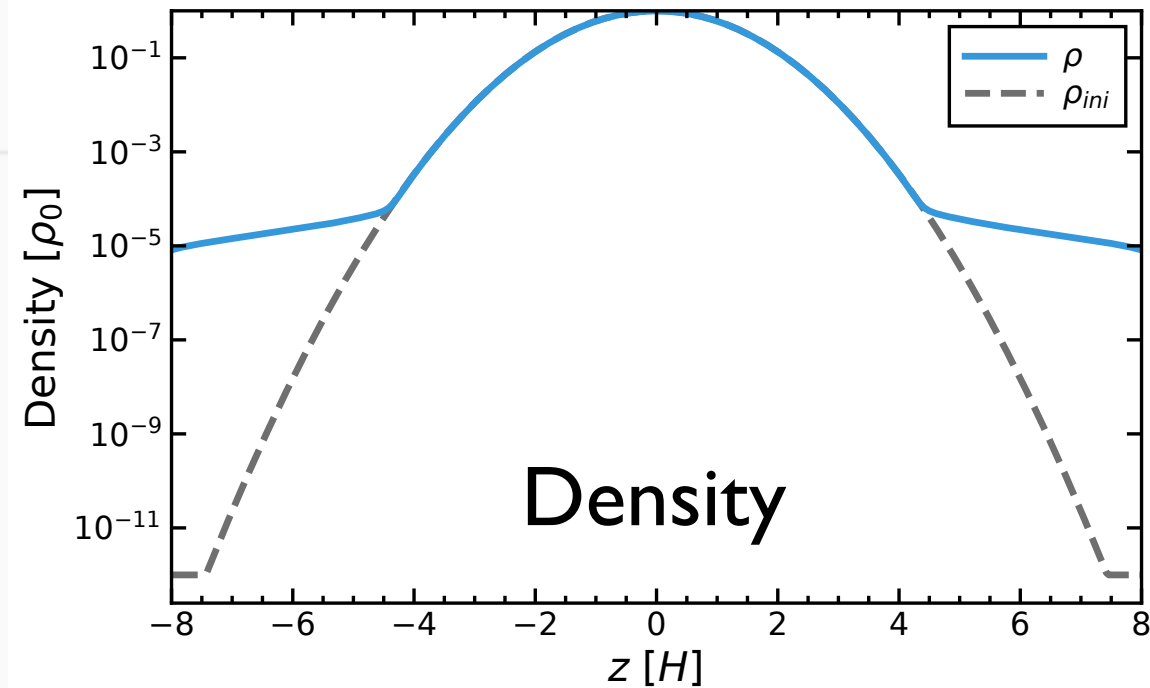
Disk model

- $R \sim 10 R_j$
- $\Sigma = 1000 (R/R_j)^{-0.75} \text{ g/cm}^2$
- $T_0 = 160 (R/R_j)^{-0.75} \text{ K}$
- Dust: $d/g = 1e-6$; $a = 0.1 \mu\text{m}$
- Ionization rate (cosmic rays, X rays, FUV)
 - Xray: $L_x = 1e30 \text{ erg/s}$, indirect comp. only
 - FUV: $\Sigma_{\text{depth}} \sim 0.01 \text{ g/cm}^2$; $x_e \sim 1e-5$
- $\beta_0(P_{\text{gas}}/P_{\text{mag}}) = 10^5$



MHD winds from CPD

- $z > 4H$:
 - density structure deviates from hydrostatic equilibrium
- Magnetic-pressure driven wind (similar to PPD cases; Bai 2014; 2015)



Potential wind-launching Region

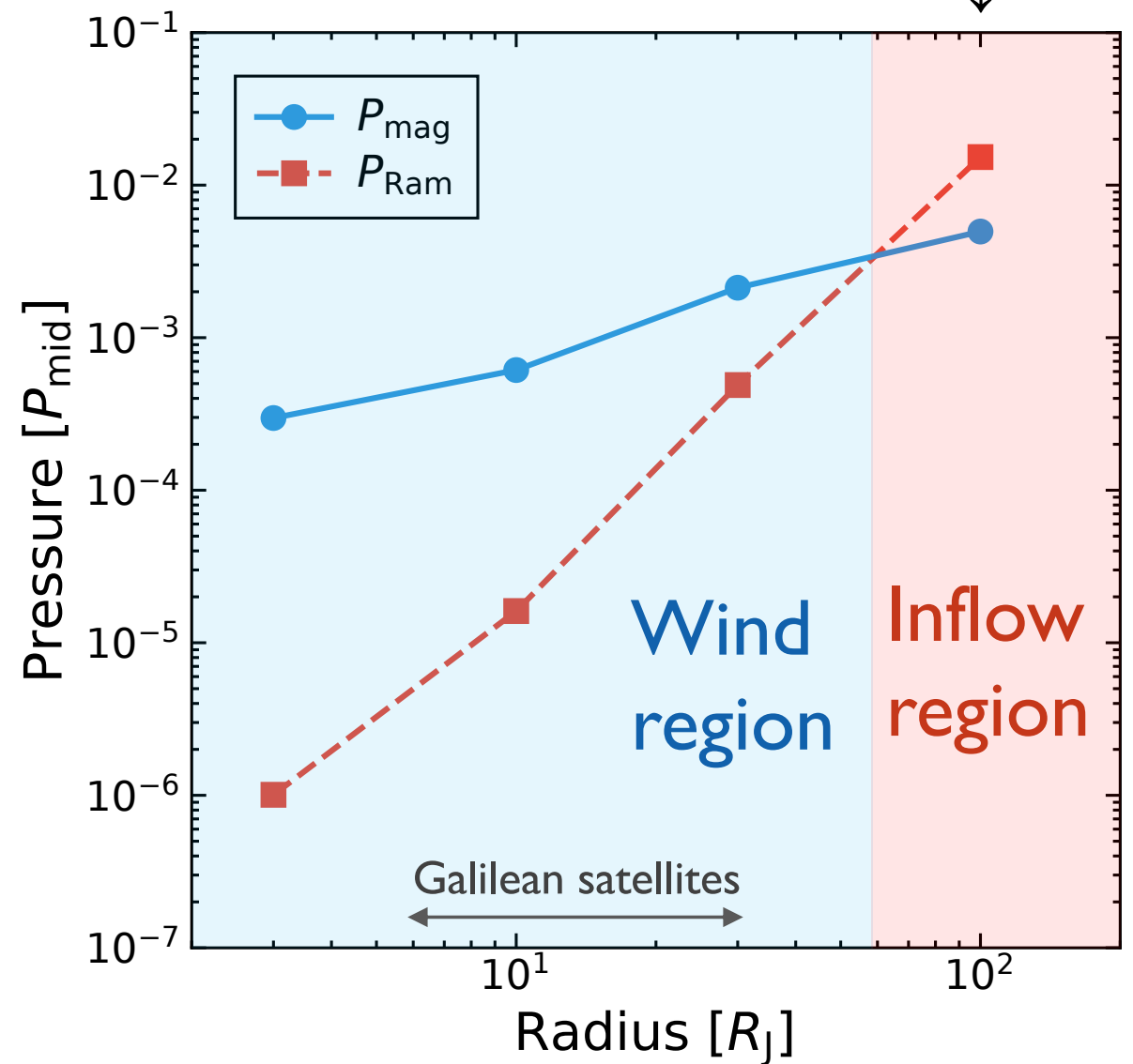
~ 0.1 Hill radius

Winds survive inflow?

- A condition of launching winds:
inflow $P_{\text{Ram}} < \text{wind } P_{\text{mag}}$
 - Assume: Steady state;
Inflow rate ~ Accretion rate

$$\frac{P_{\text{Ram}}}{P_{\text{mid}}} = \frac{3 \sqrt{\pi} \alpha_{\text{acc}} H R \dot{M}_{\text{in}}}{R_{\text{in}}^2 \dot{M}_{\text{acc}}}$$

At $R \lesssim 30 R_{\text{Jup}}$, accretion may be driven by magnetic field



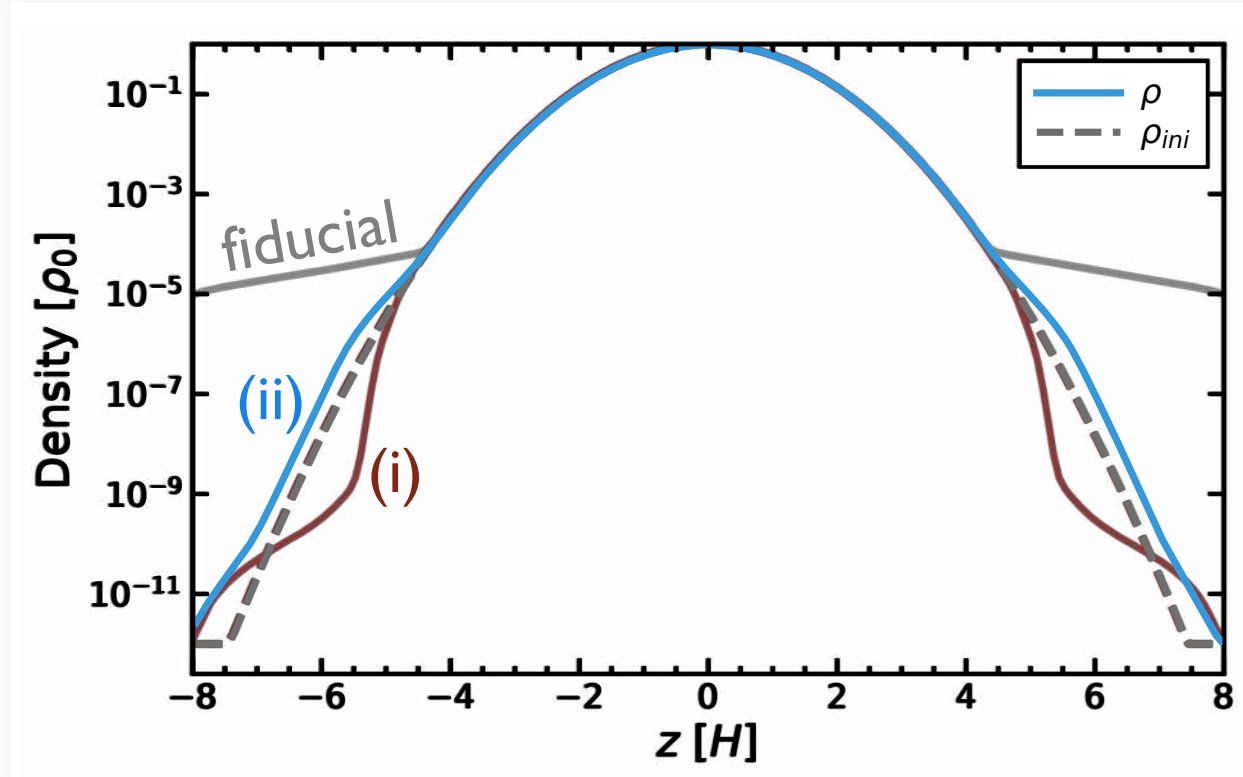
What we need to think

1. Well ionized?
 - CPD surface can be somewhat ionized
2. Well magnetized?
 - Not too weak
3. Winds survive inflows?
 - Inner region is dominated by winds

MHD winds are not always

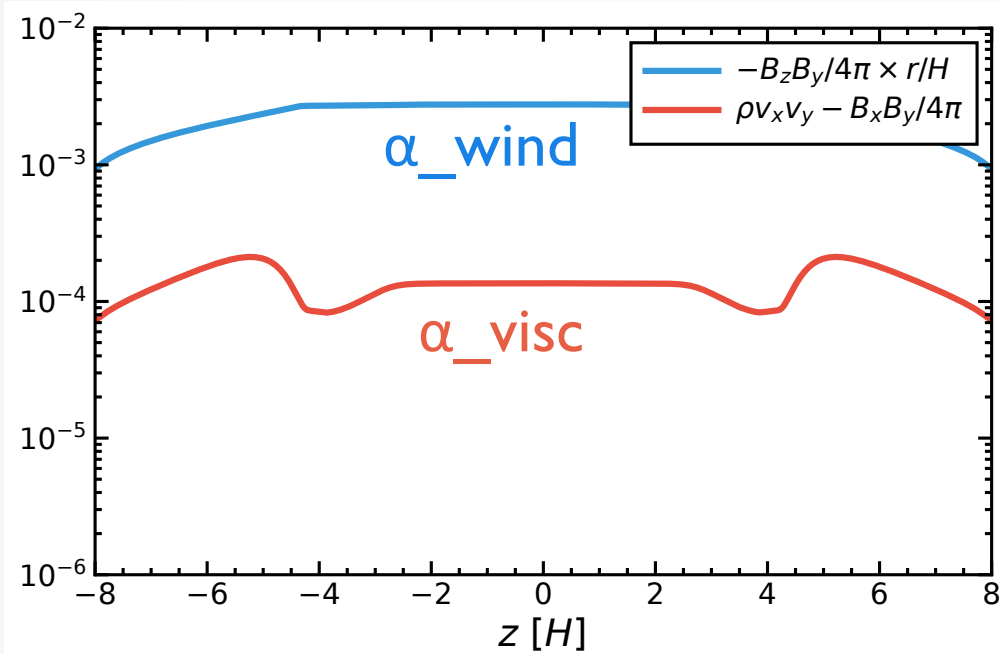
(i) Strong B ($\beta = 10^3$)

(ii) Weak B & Low ionization frac ($\beta = 10^7$, $x_{\text{FUV}} = 0.01$)



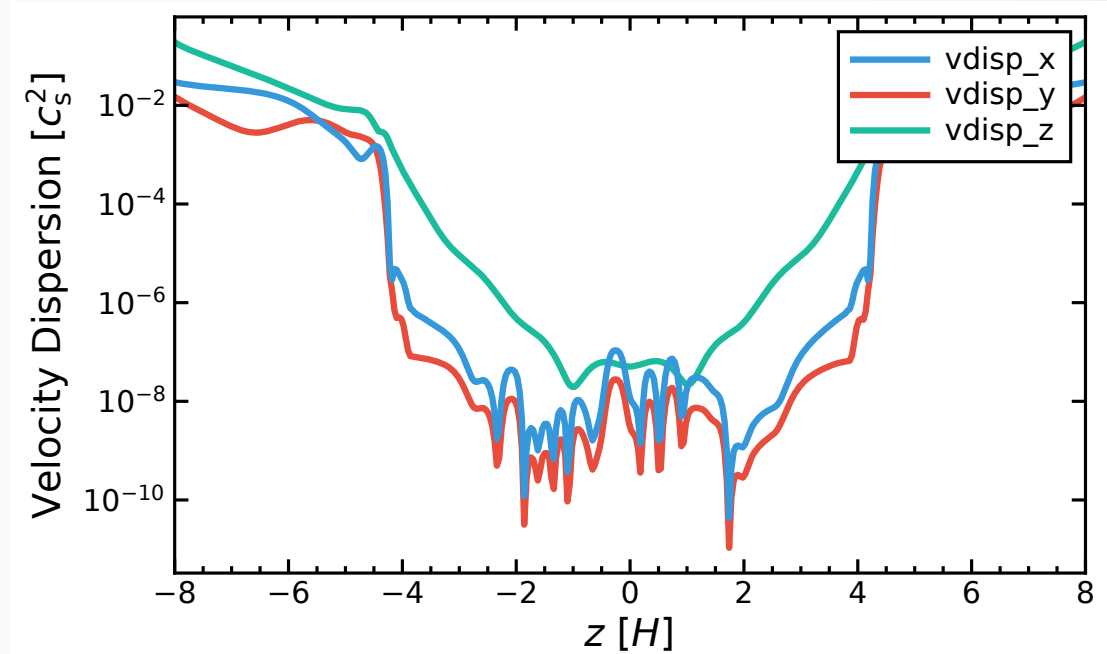
Obtained parameters

- Stress



$$\alpha_{\text{wind}} \sim 3 \times 10^{-3}$$

- Turbulent velocity

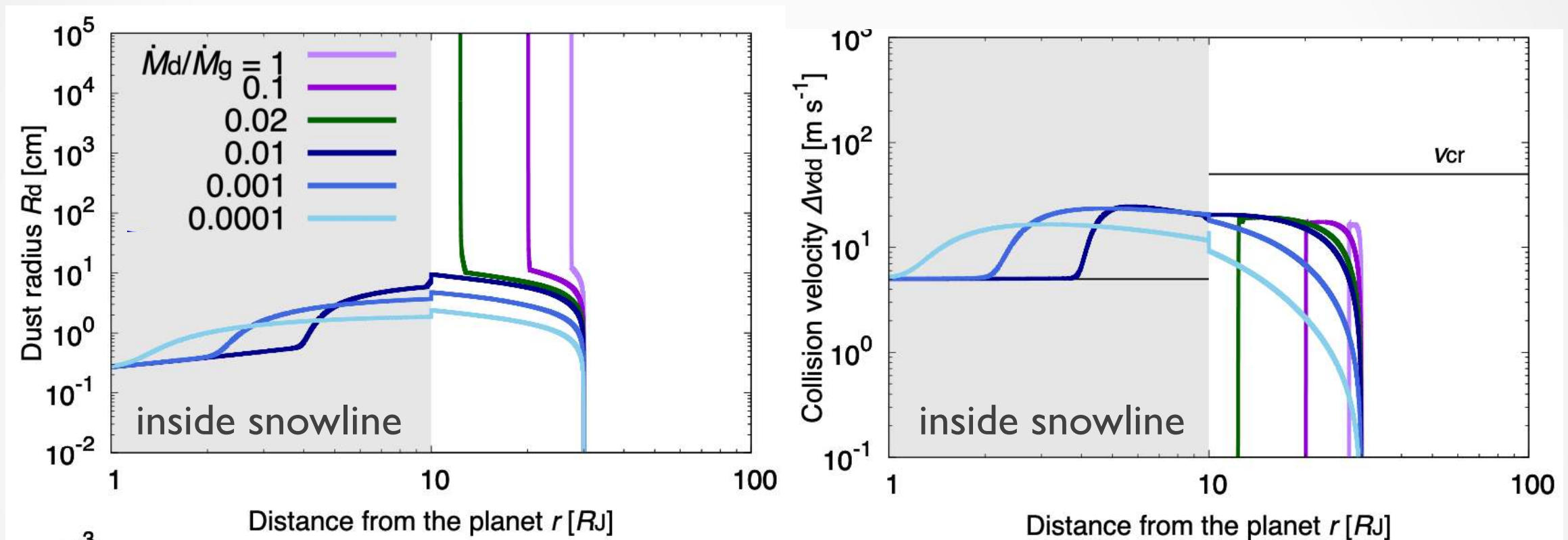


$$\alpha_{\text{diff}} (= \delta v^2 / c_s^2) \sim 10^{-7}$$

→ **Laminar wind-driven accretion**

Satellitesimal formation

Shibaike & Mori 2023

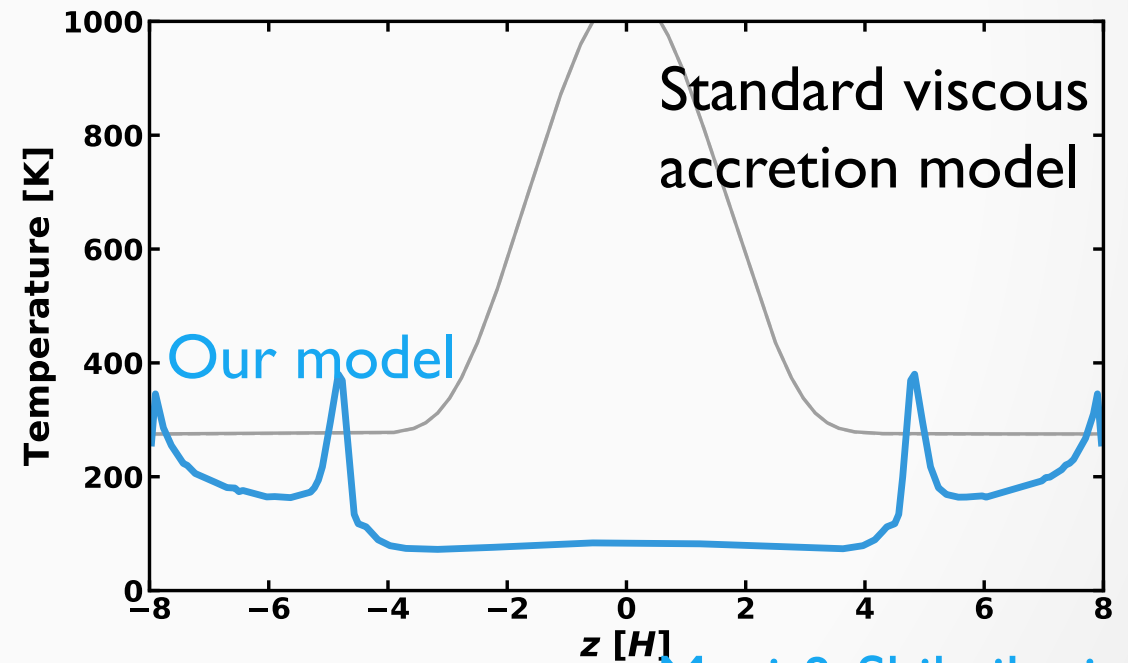
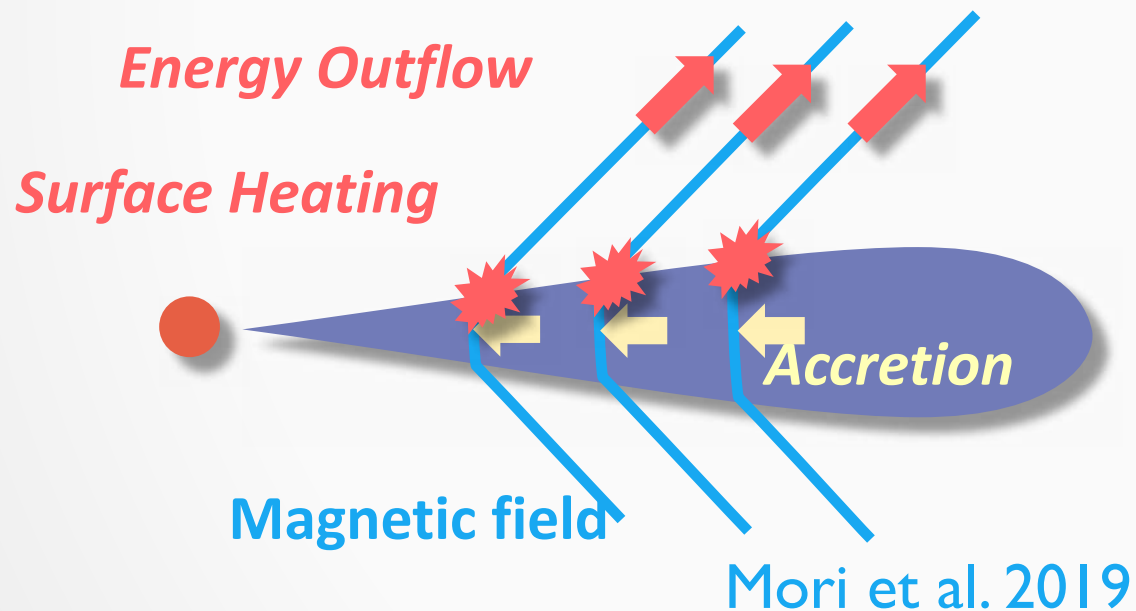


Low α_{diff} \rightarrow sedimentation & no fragmentation

High α_{acc} \rightarrow low density \rightarrow drag to dust: slow drift

CPDs can be cold

- Accretion heating in windy PPDs is **inefficient** (Mori et al. 2019)
→ Good for **formation of icy satellites**



Take Aways

Accretion in CPDs can be driven by magnetic fields

Disk surface may be ionized by scattered ionization sources

Favorable environment for satellitesimal growth

laminar, but not too dense

