Temperature Structure of Magnetized Protoplanetary Disks

Abstract

Understanding the thermal structure of protoplanetary disks (PPDs) is crucial for elucidating the formation of rocky planets. We present 2D global radiative magnetohydrodynamic (MHD) simulations of the inner region of PPDs, taking into account all three non-ideal MHD effects, irradiation and Joule heating due to the global magnetic structure. The thermal structure consistent with the disk dynamics is calculated using a simplified radiative transfer method that is computationally efficient. Our simulations show that strong Joule heating occurs primarily in the strong current layer at the disk surface, where the global magnetic fields bend, which does not significantly heat the disk midplane. This is the case whether the poloidal magnetic field is aligned or anti-aligned. As a result, the temperature structure of PPDs, even at a few au, is mainly determined by irradiation heating. In addition, the structure of the irradiated surface is affected by the high-density disk wind, and the intensity of irradiation heating depends on the MHD disk wind structure. This suggests the need to construct a disk temperature model that considers the MHD behavior of the disk.

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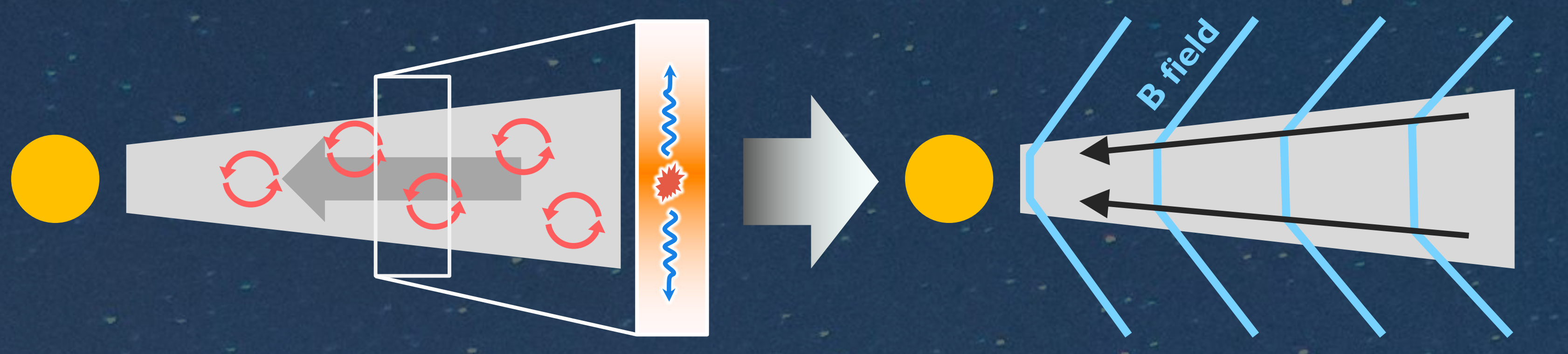
1 Thermal structure of PPDs

- Temperature in inner region (~ au) impacts planet formation processes
  - Snowlines, streaming instability, pebble isolation mass, planet migration …
- Heating: Irradiation heating + Accretion heating
- Viscous heating efficiently warms disk
  - Viscosity due to MRI turbulence
  - Blanketing effect : released around midplane and accumulated
- MRI is suppressed by nonideal MHD effects (Bai & Stone13; Gressel+15)
- Global magnetic field drives the accretion on disk surface



Turbulent viscous accretion

Laminar magnetic accretion

2 Radiative nonideal MHD simulation

to investigate thermal structure in Magnetized PPDs

- Global 2D, *Athena++* (Bai17, Stone+21)
- Full nonideal MHD effects
  (Ohm diffusion, Hall effect, ambipolar diffusion)
  - calculating column density(by ray-tracing), ionization rate, and ionization fractions
- Radiative transfer model

Energy eq — Optically thin term — Optically thick term

$$\frac{\partial \rho u}{\partial t} = \quad \dots \quad + \boxed{\exp(-\tau_\theta) Q_{\rm thin}} \; \boxed{- \nabla \cdot \left[\exp\left(-1/\tau_\theta\right) \boldsymbol{F}_{\rm thick}\right]}$$

Relaxing to target temperature

$$Q_{\rm thin} = -4\rho\kappa_{\rm P}\sigma\left(T^4 - T^4_{\rm thin}\right)$$

$$T^4_{\rm thin} = \left(T_{\rm opt}(r)\exp(-\tau_r)\right)^4 + T^4_{\rm re}$$

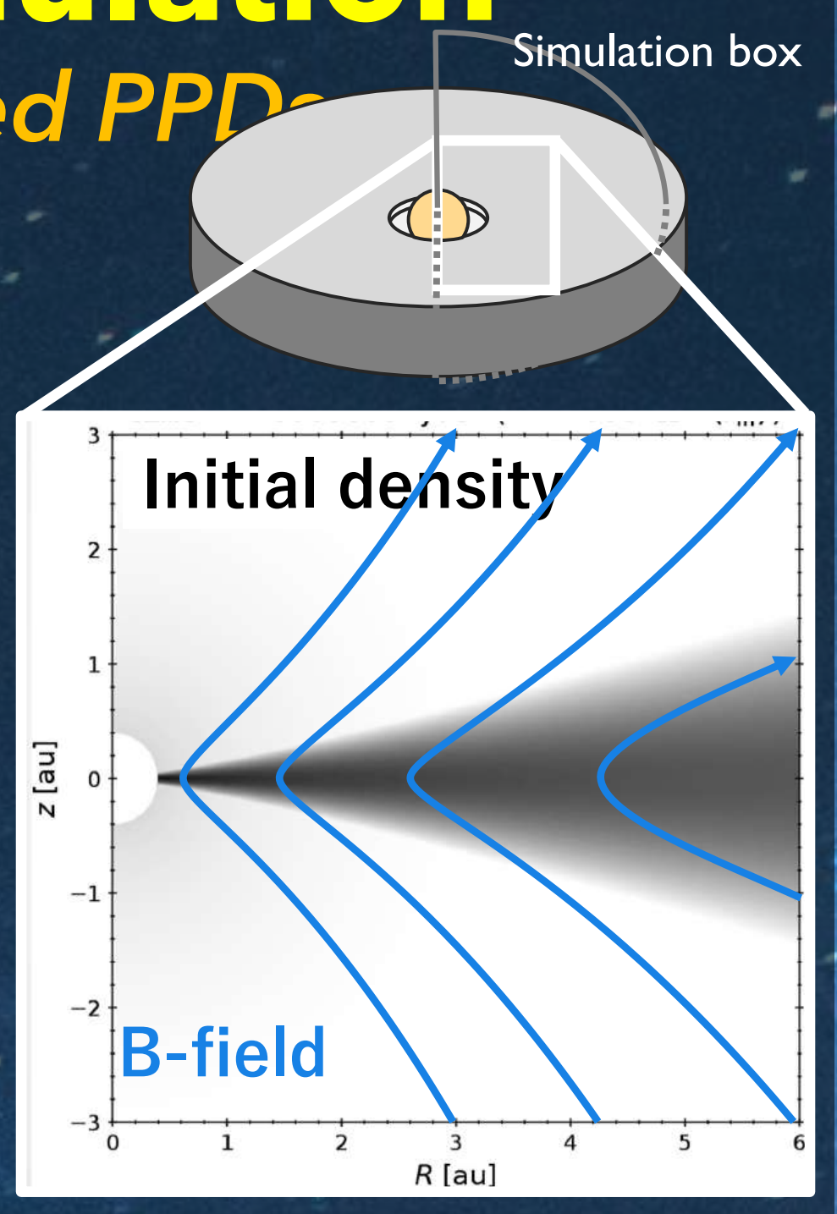
$T^4_{\rm re}$: reemitted radiation T, $\sigma T^4_{\rm re} \equiv J$
given by θ-integration of RT eq:

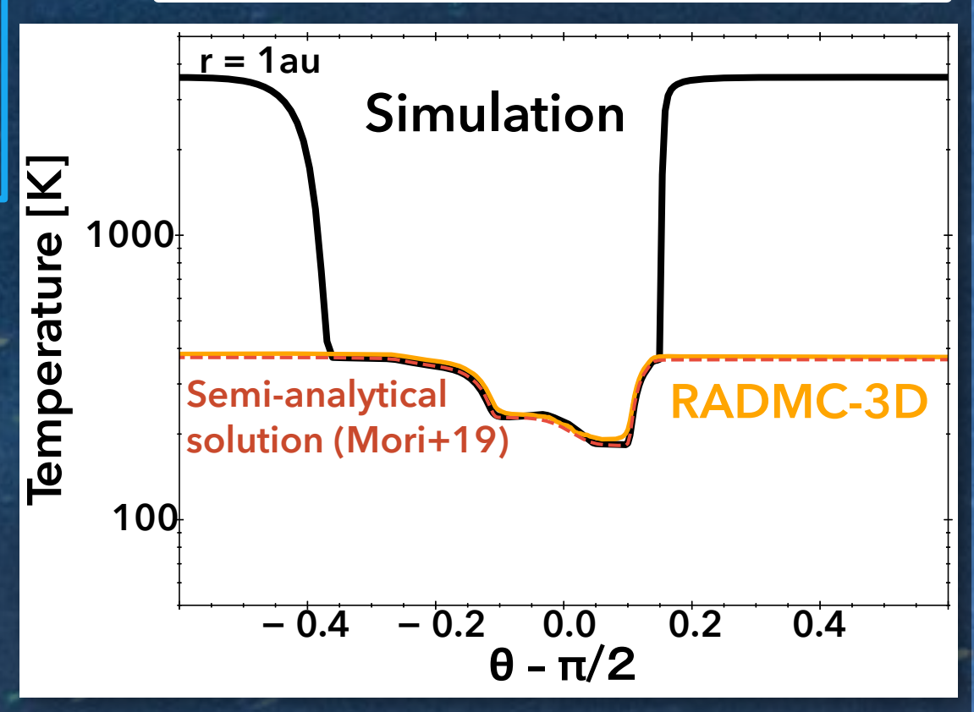
$$\mu \frac{\partial I(\tau,\mu)}{\partial \tau} = I(\tau,\mu) - S(\tau)$$

with two-stream approximation

Diffusion approximation

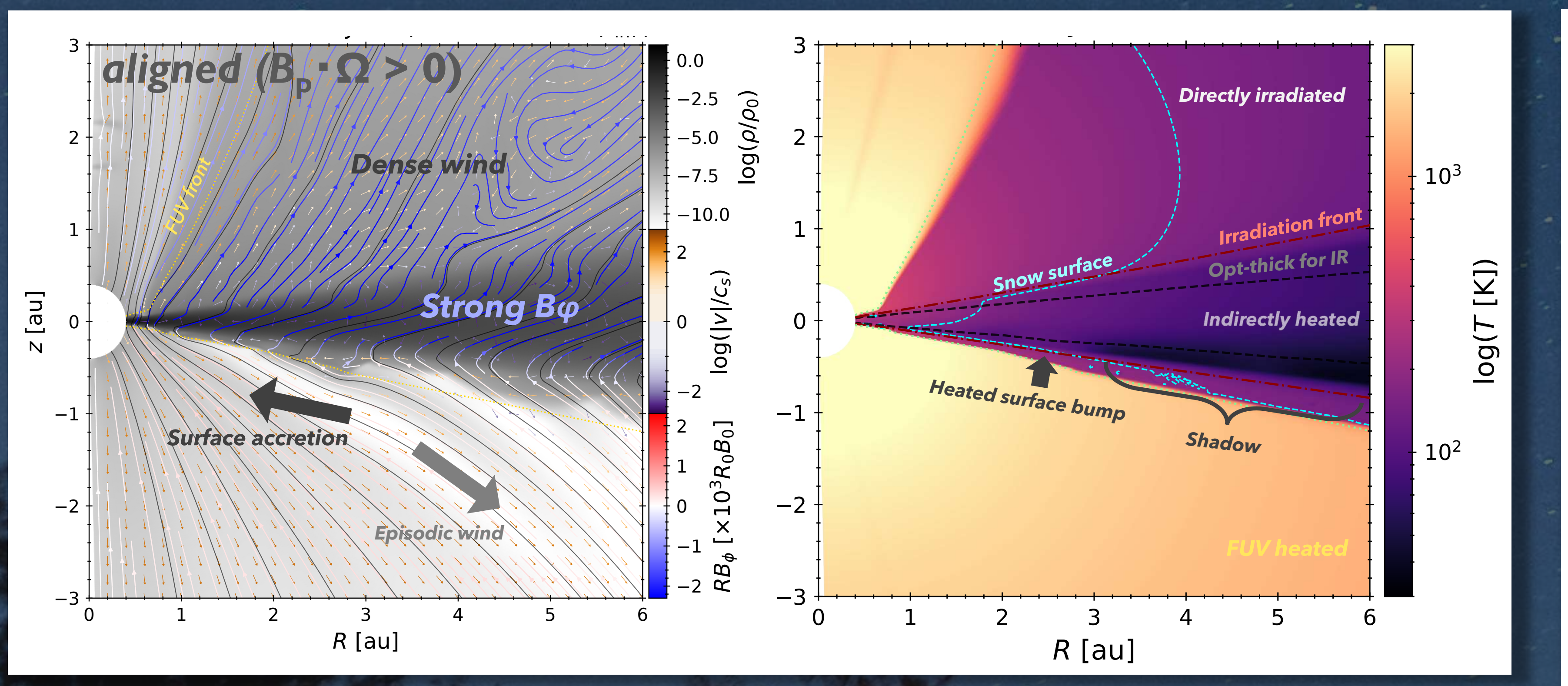
$$\boldsymbol{F}_{\rm thick} = -\frac{4\sigma}{3\rho\kappa}\nabla T^4$$





3 Results

Physical Structures

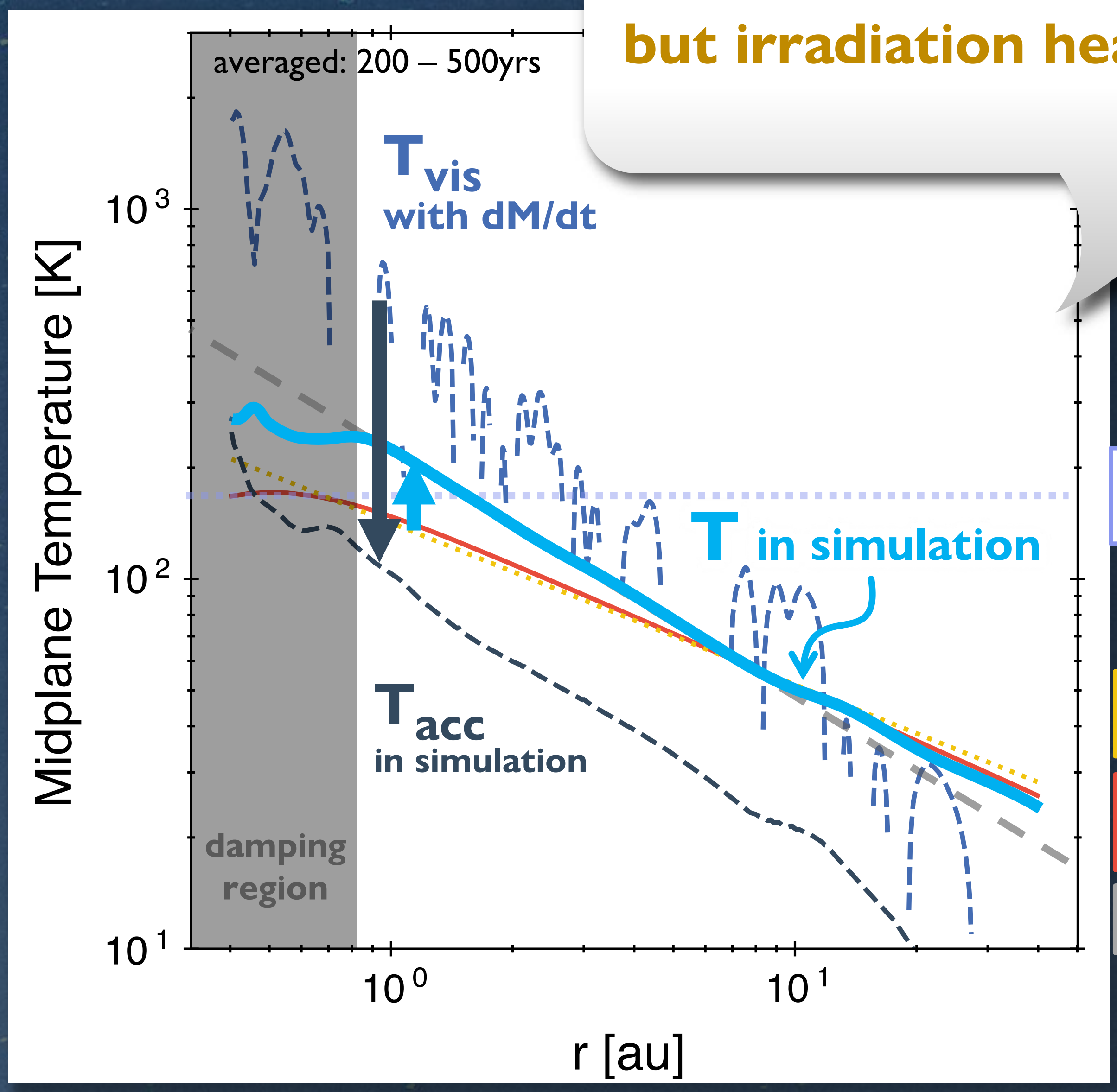


- Strong toroidal field (Bai17)
  Hall effect amplifies *B*
- Asymmetric disk wind
  Monopolar outflow? (e.g. HH30, Louvet+18)
- Clumpy accretion surface
  Casting shadows
- Episodic accretion & wind

- Σ = 500 g/cm² (R/au)⁻¹
- $\beta_{\rm ini}$ = 10000 (*Bz*>0)
- $f_{\rm dg}$ = 0.01
- $\kappa_{\rm disk}$ = 1 cm²/g (const.)
- $\kappa_{\rm star}$ = 1 cm²/g
- $\kappa_{\rm FUV}$ = 100 cm²/g
- $L = 2.7\,L_\odot$

Temperature Profile

Accretion heating is weaker but irradiation heating is stronger



Water evaporation T = 170 K

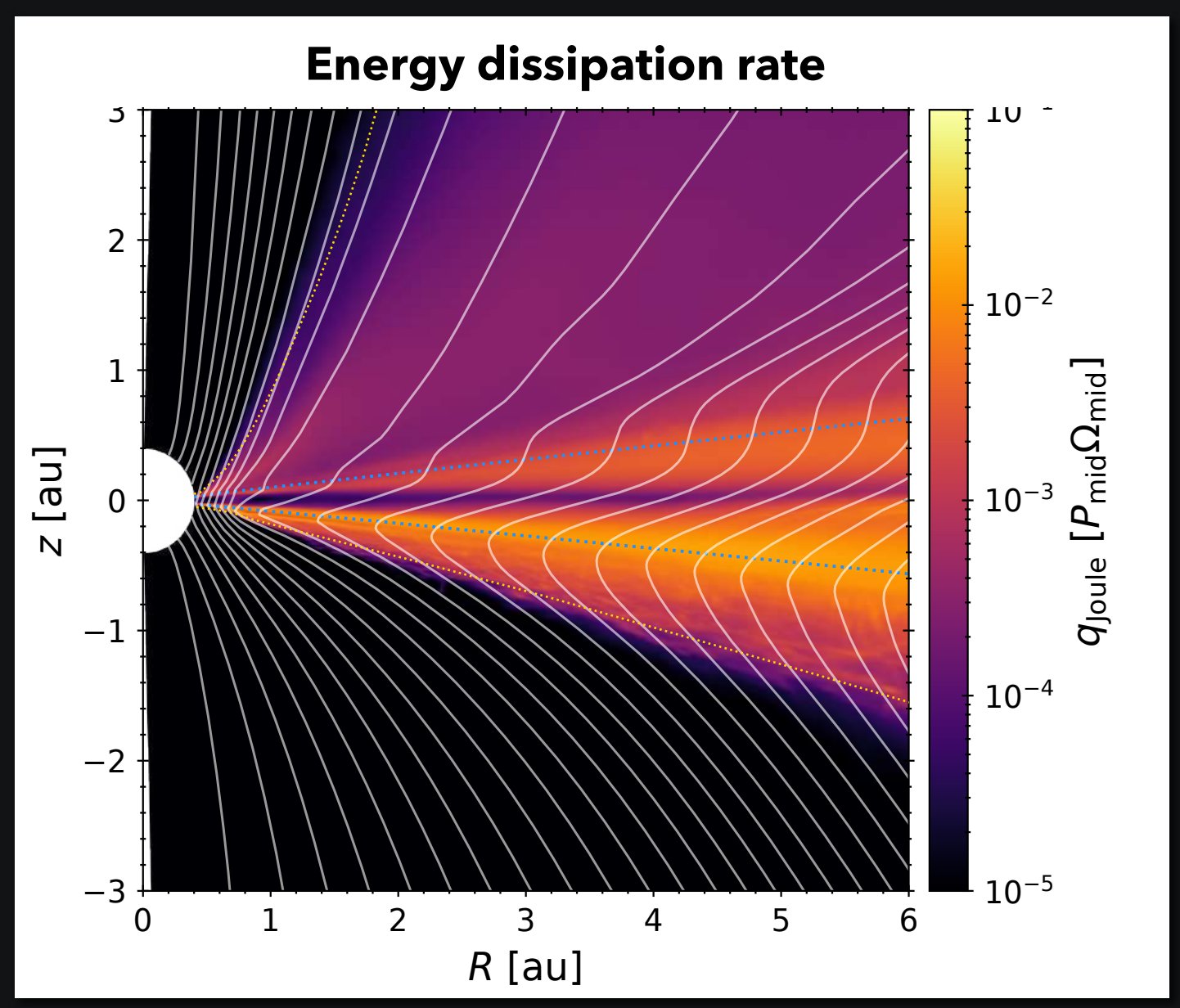
Analytic $T_{\rm irr}$ (Chiang & Goldreich 97)

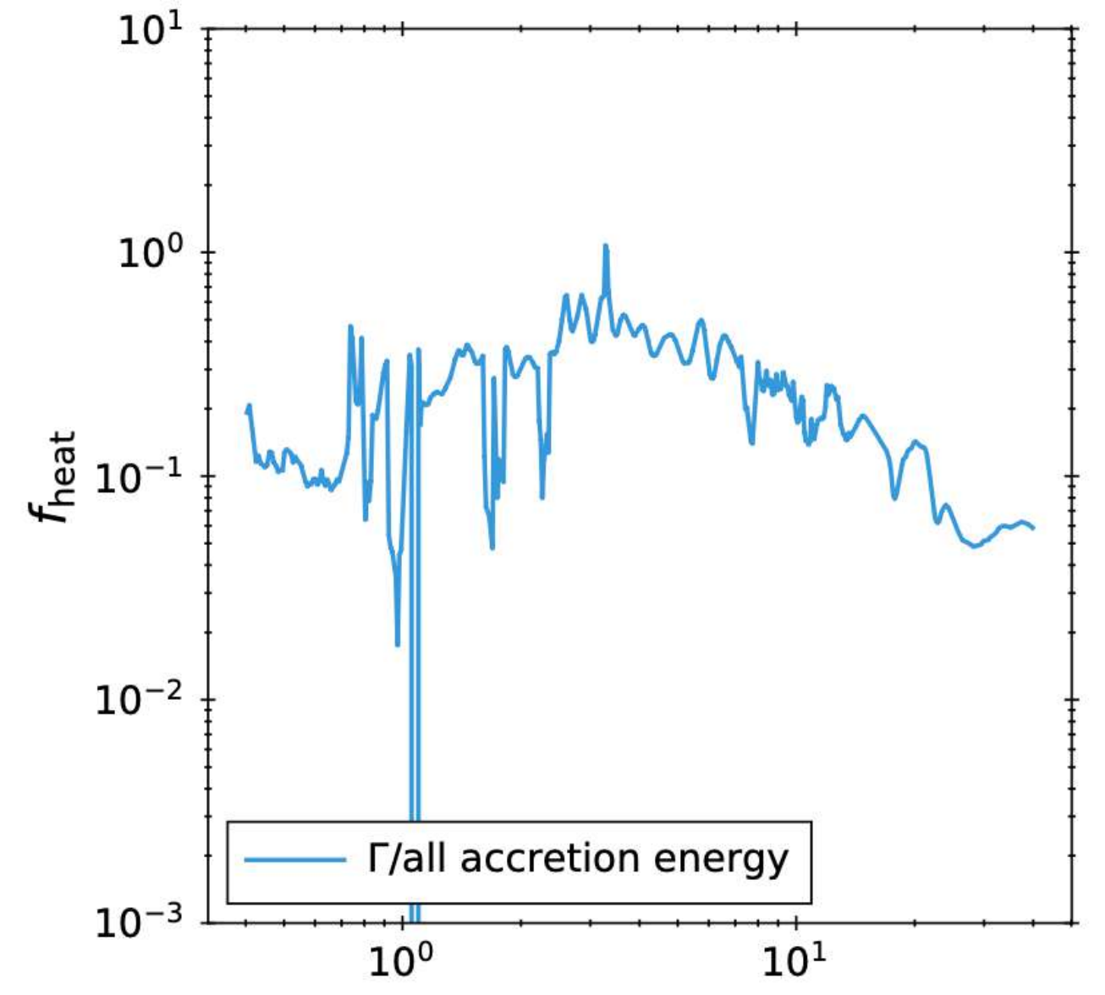
$T_{\rm irr}$ with hydrostatic structure

$T \simeq 224\ {\rm K} \times r_{\rm au}^{-0.66}$

Why accretion heating is weaker

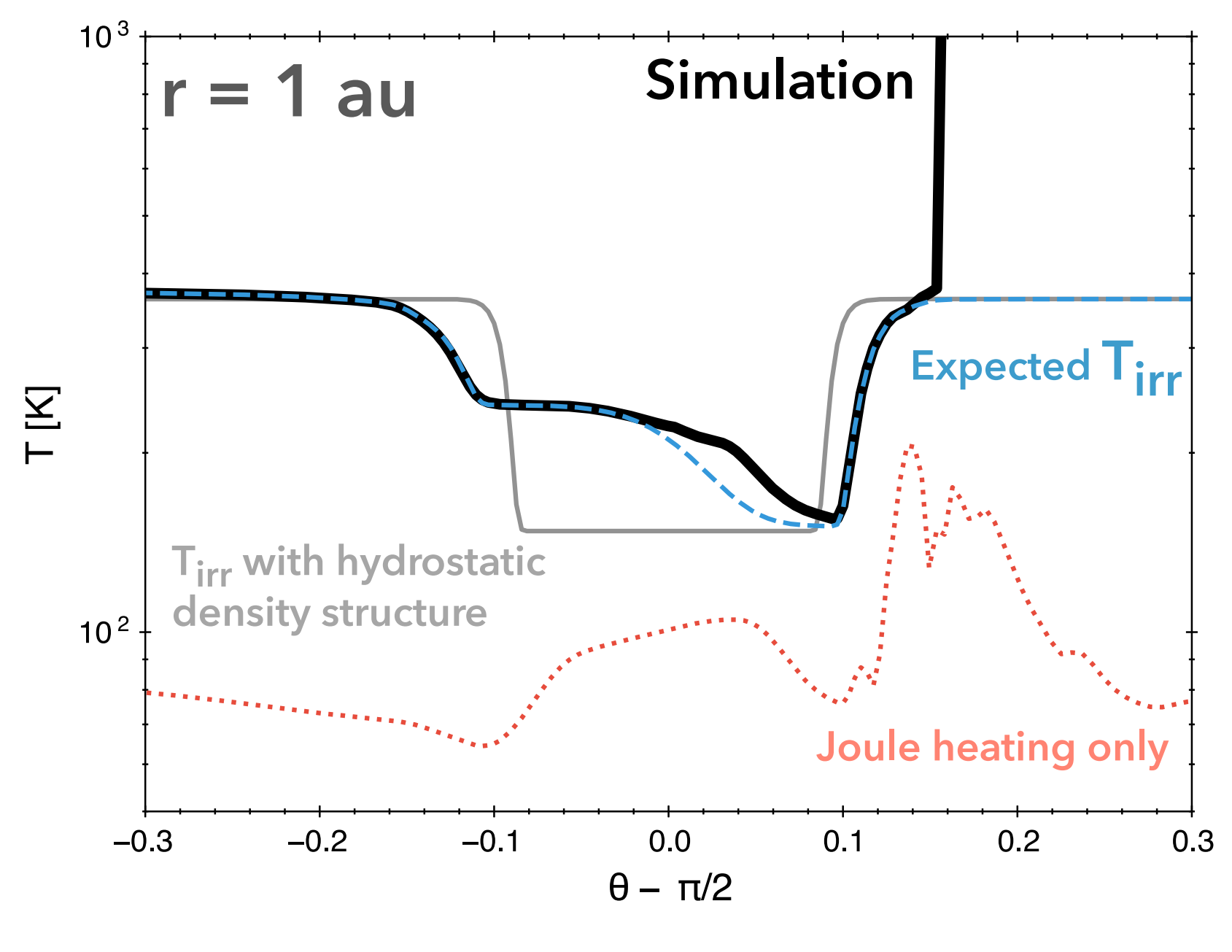
- Heating due to dragged magnetic field occurs in high altitude
  → Efficient cooling (weak blanketing effect)
- Disk winds remove accretion energy (~10-50% dissipated in disk)

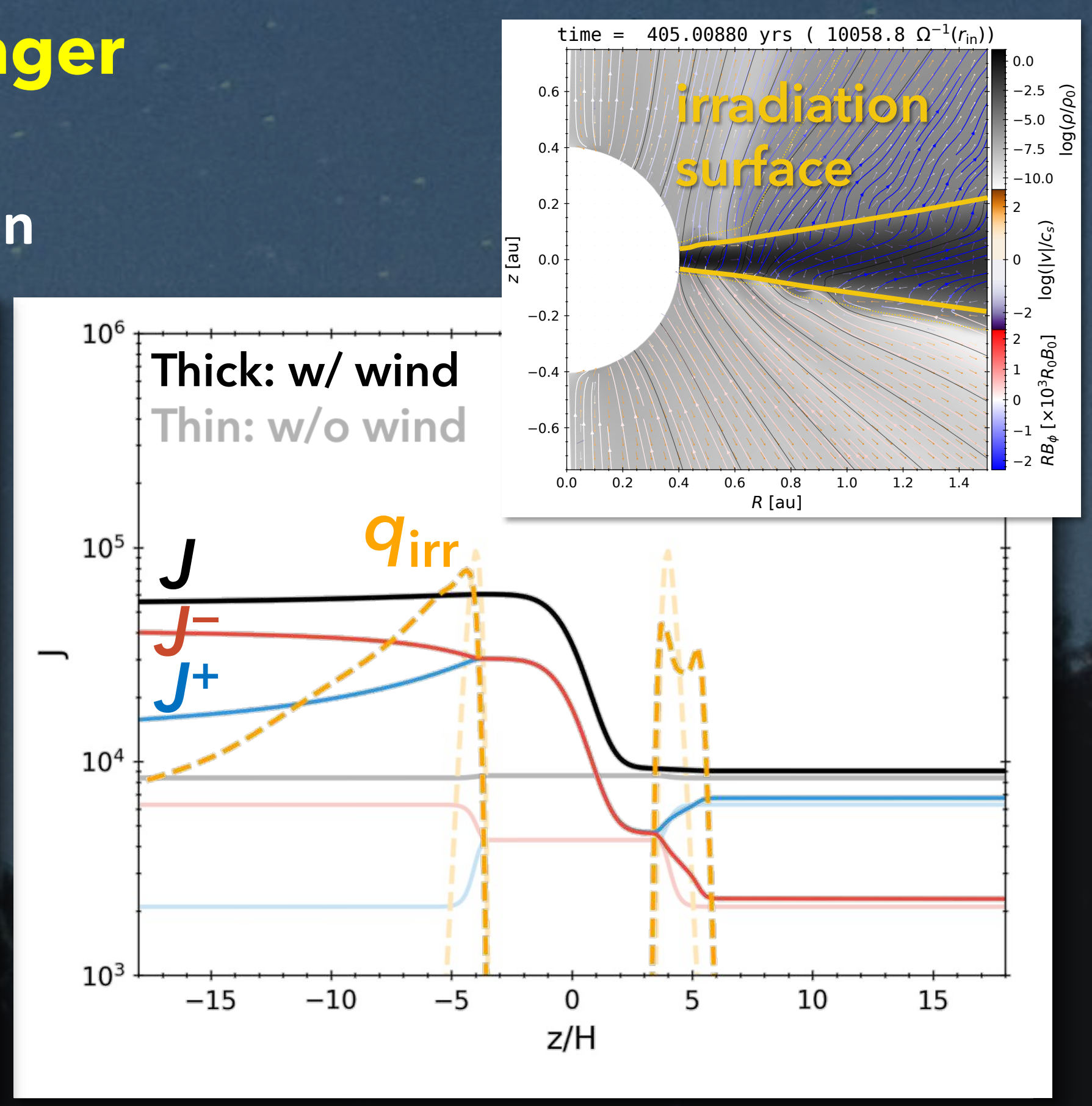




Why irradiation heating is stronger

Disk winds arise irradiation surface
➔ disk surface gets more stellar radiation





Summary

We have conducted 2D global radiative nonideal MHD simulations of the inner region of PPDs. Our simulations show that strong Joule heating primarily takes place at the strong current layer at the disk surface. As a result, the temperature structure of PPDs, even at a few au, is mainly determined by irradiation heating. We also found that the irradiation heating can become efficient by disk winds.