

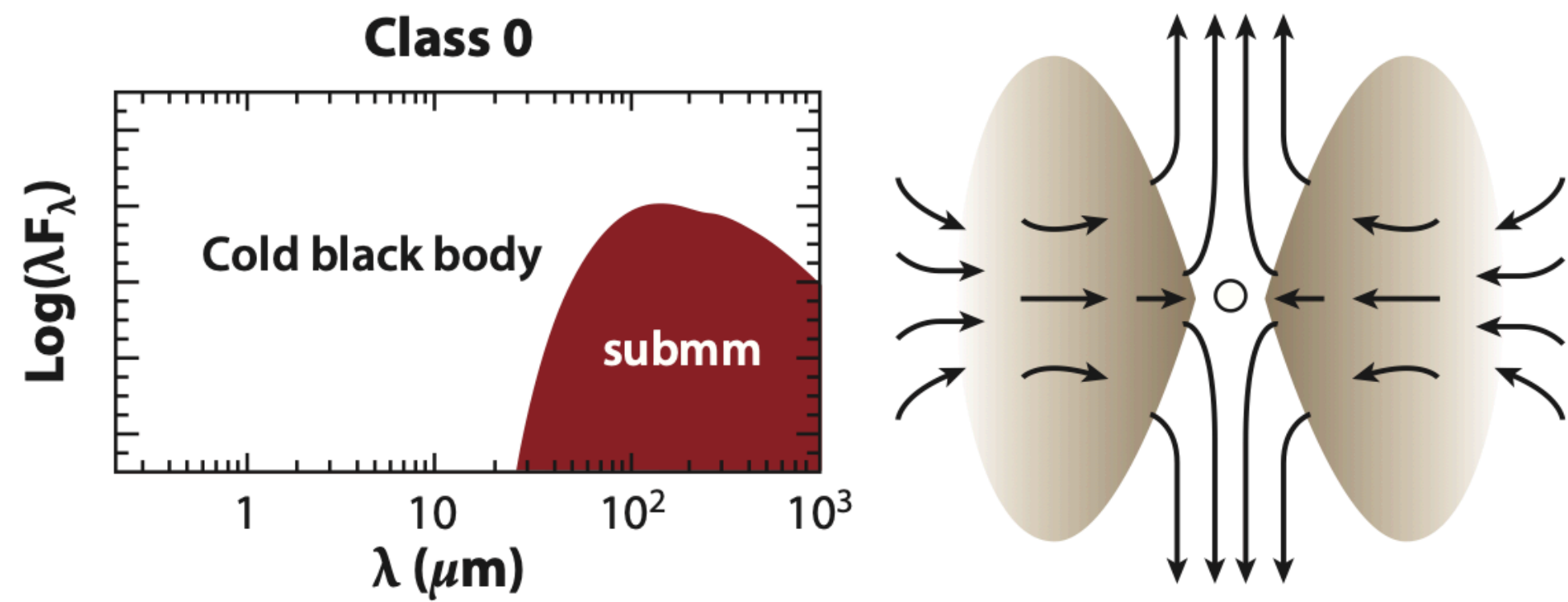
Direct Formation of Gas Giants via Disk Fragmentation in 3D Radiation Hydrodynamic Simulations

Yang Ni 倪阳 (Tsinghua)

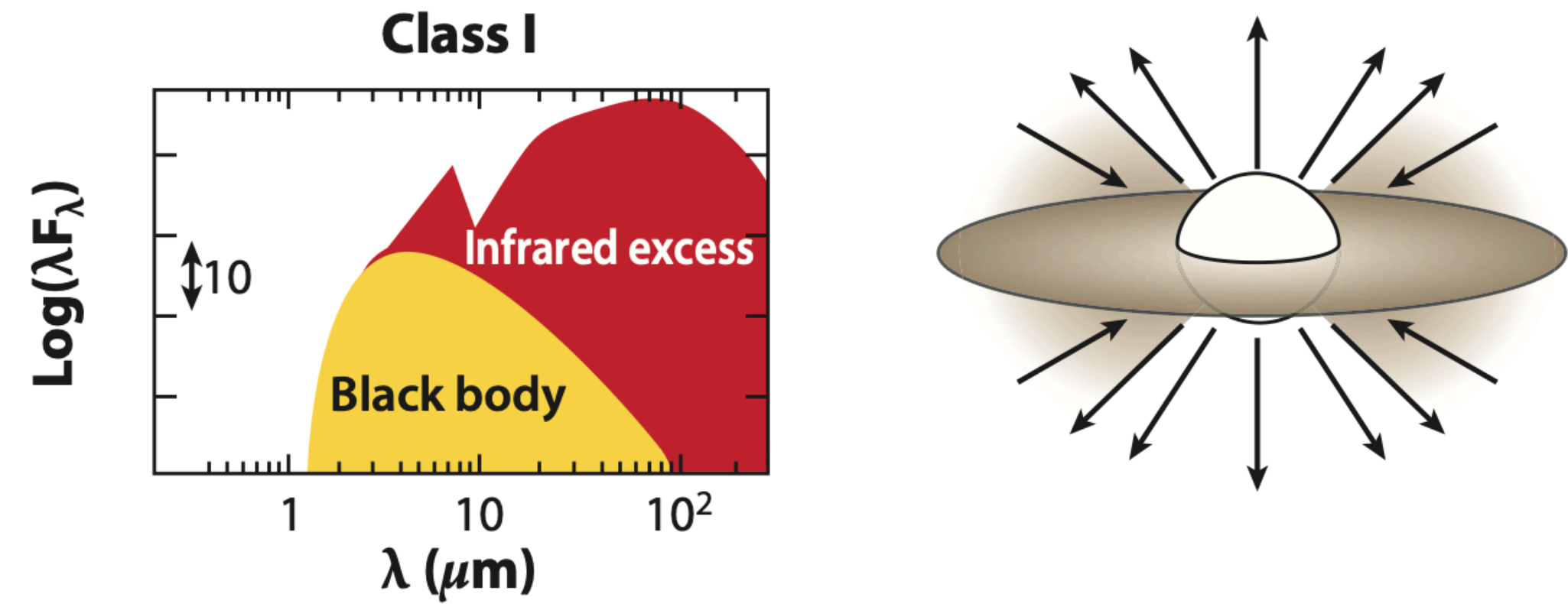
Collabrators: Hongping Deng (SHAO), Xue-Ning Bai (Tsinghua)

EANAM10, 2025

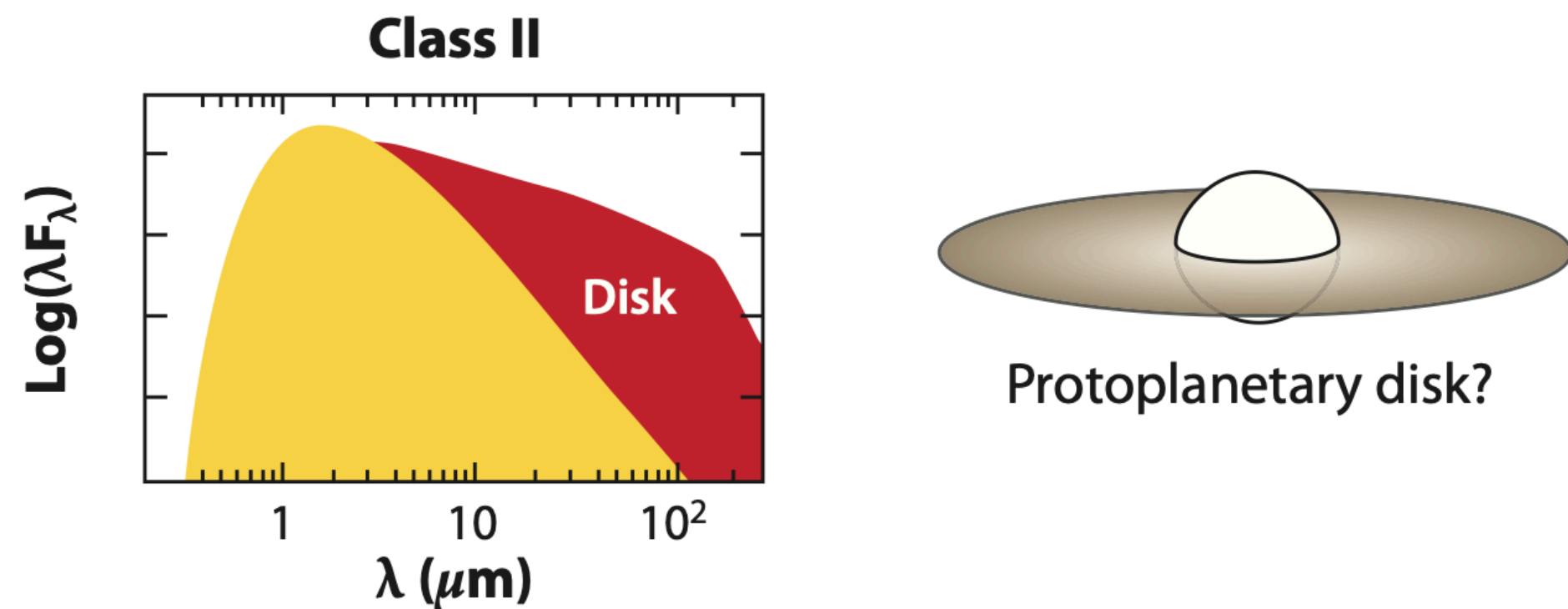
Different stages during PPD formation and evolution



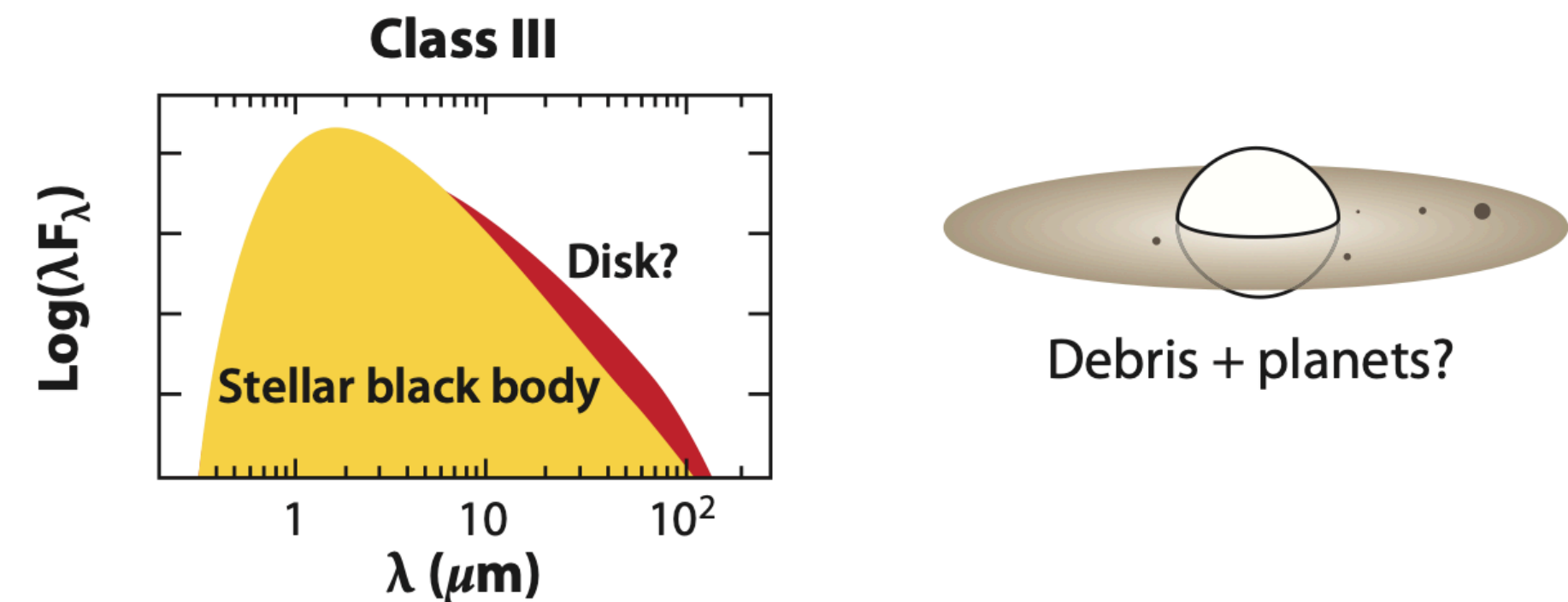
dense core + envelope



protostar + envelope/infall & disk



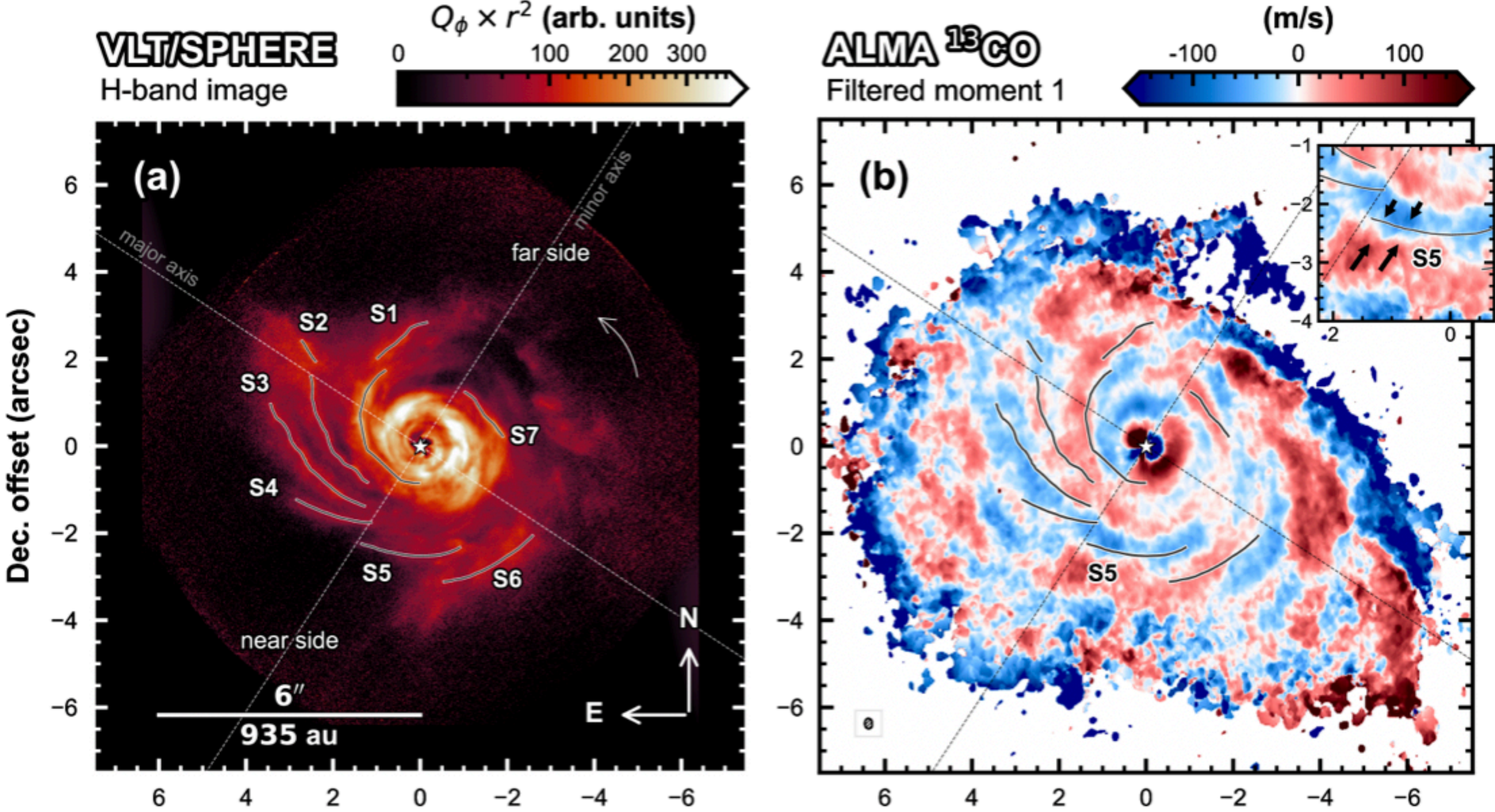
pre-main-sequence star + disk



zero-age-main-sequence star
+ debris disk & planets

(Early) PPDs can be massive and gravitationally unstable

- Massive ($\sim 10^{-1} - 10^0 M_{\star}$)
- Expect Toomre $Q = \frac{c_s \Omega}{\pi G \Sigma} \sim 1$, subject to **Gravitational Instability (GI)**



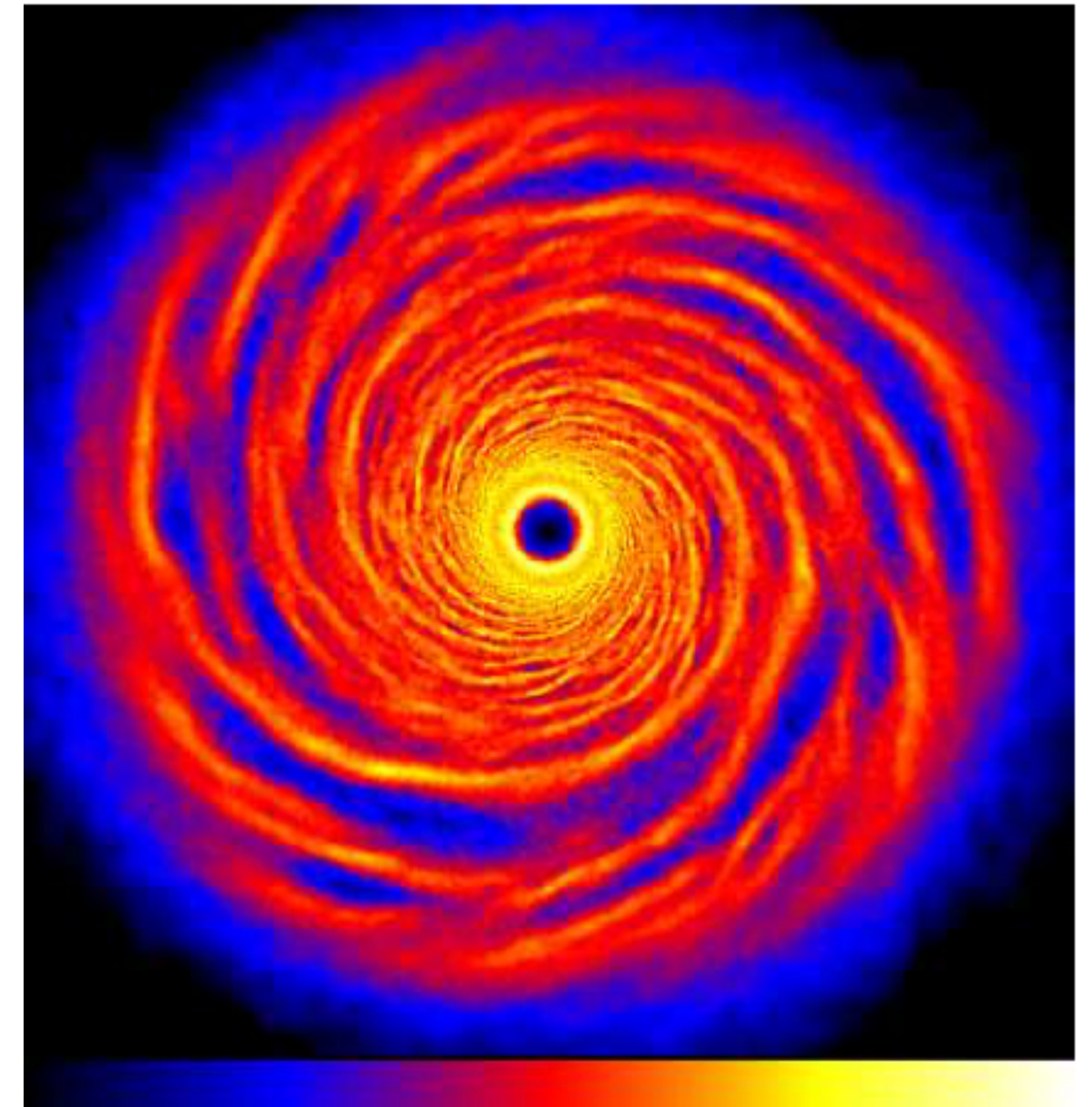
AB Aur, Class II; Speedie et al. 2024

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generate turbulence, drive accretion



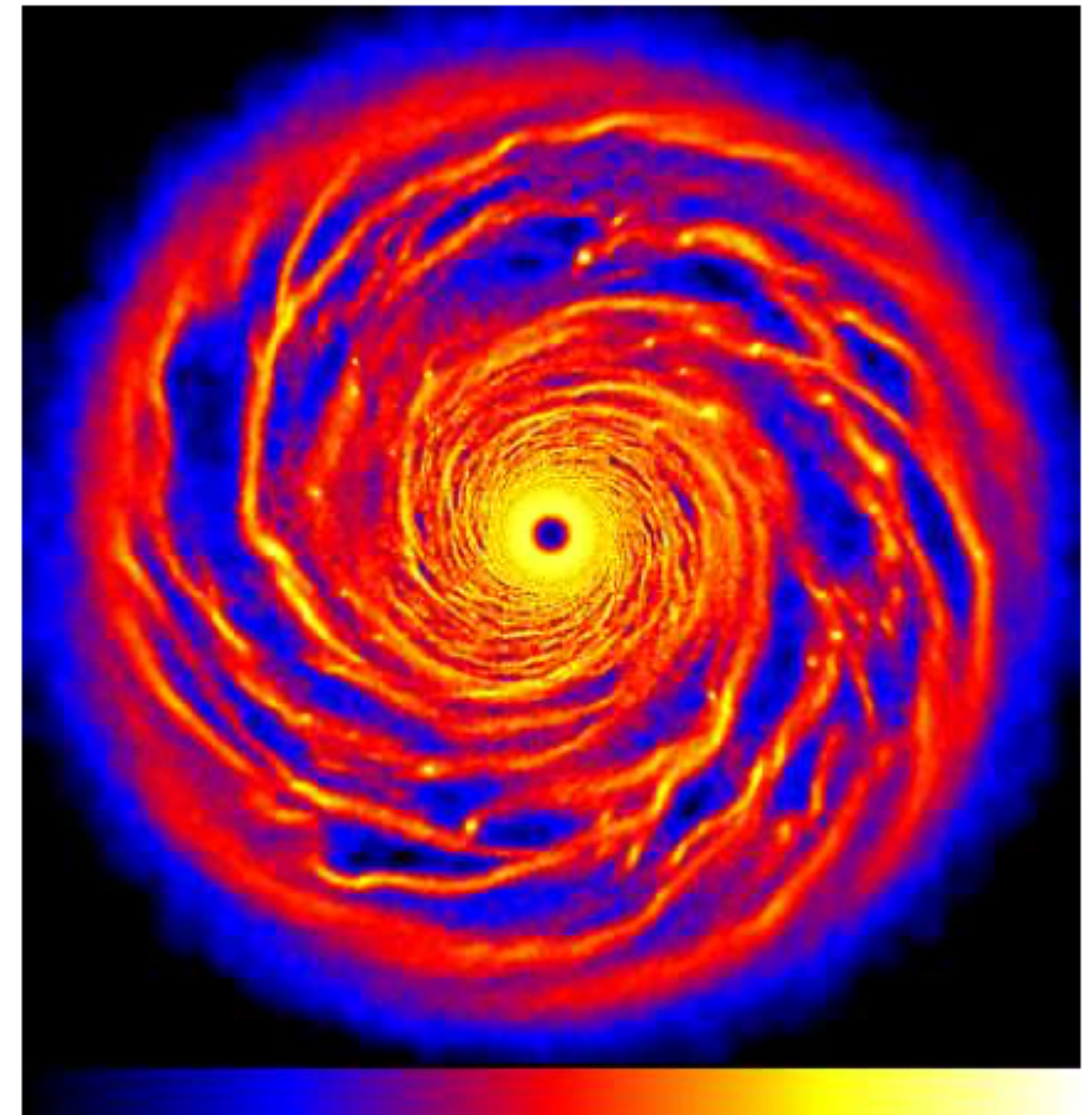
Rice et al. 2005

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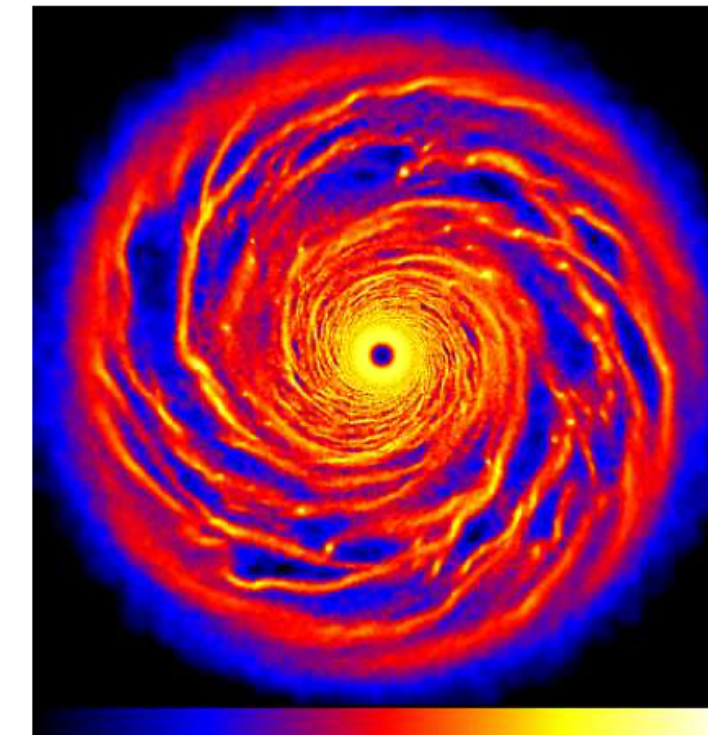
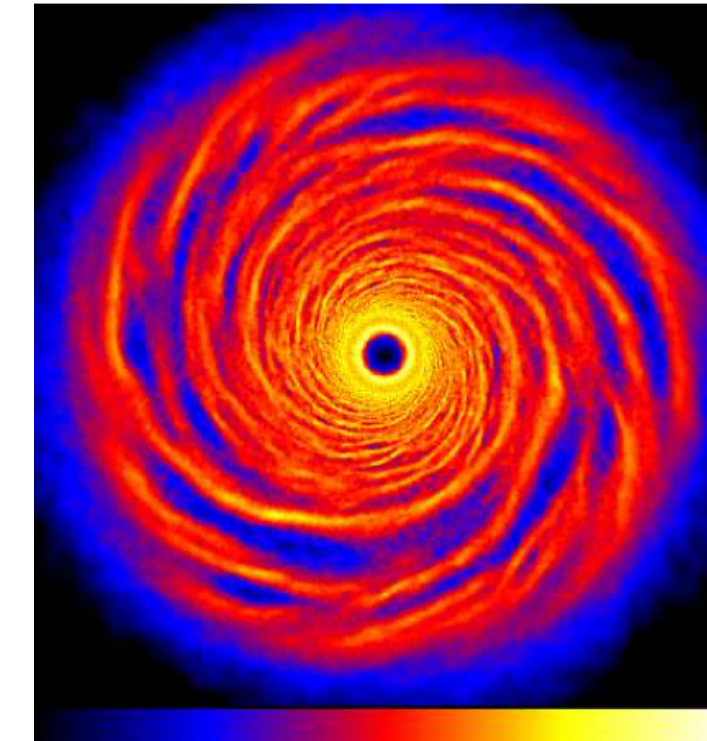
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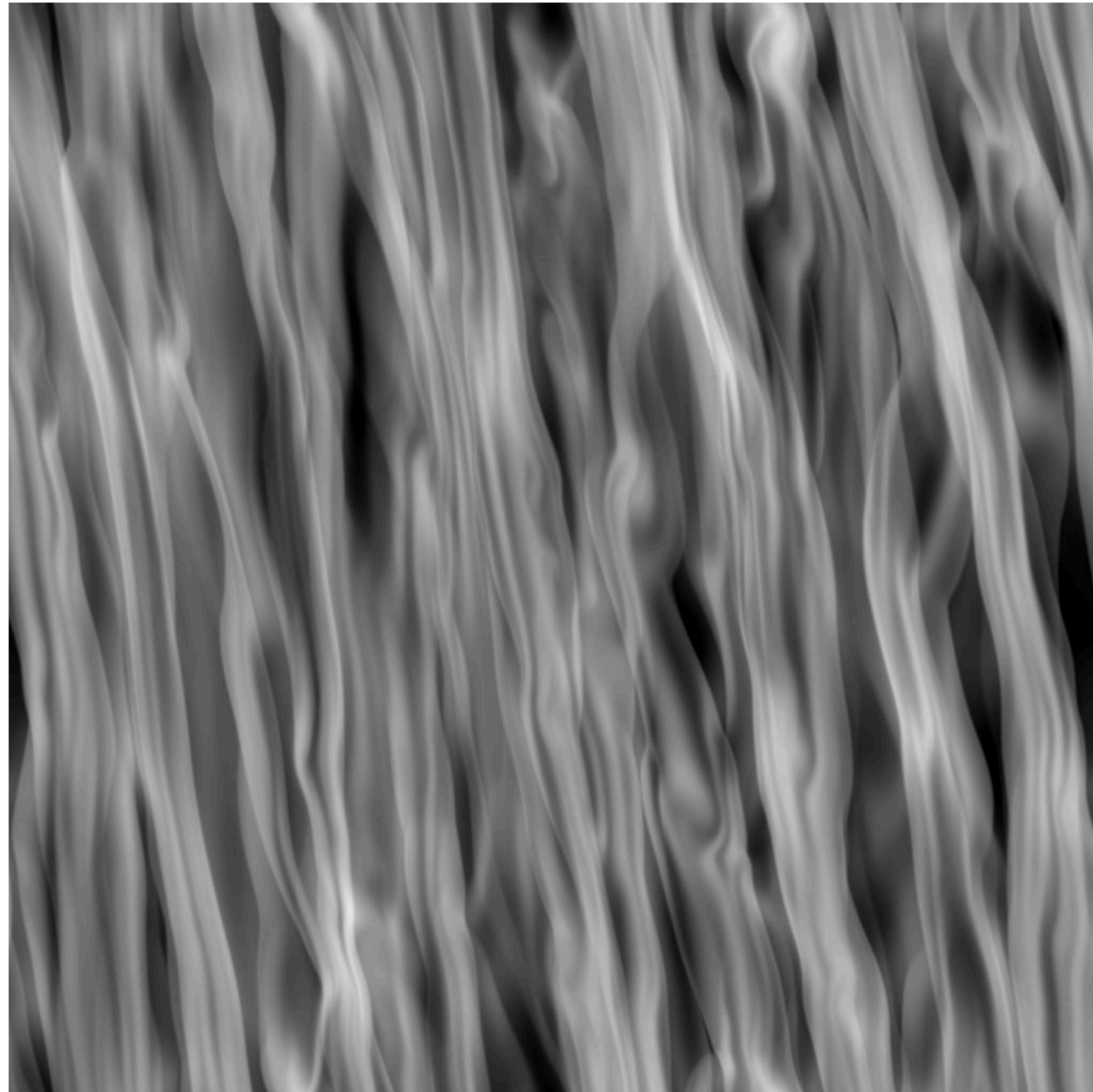
Rice et al. 2005 (see also Gammie 2001, Paardekooper et al. 2011, Meru et al. 2012, Baehr et al. 2017, Deng et al. 2017, Brucy et al. 2021, Xu et al. 2024)

Questions:

- Q1. In PPDs, does GI saturate into a quasi-steady state or lead to fragmentation?
- Q2. If fragments form in PPDs, what are their masses, and how do they evolve?

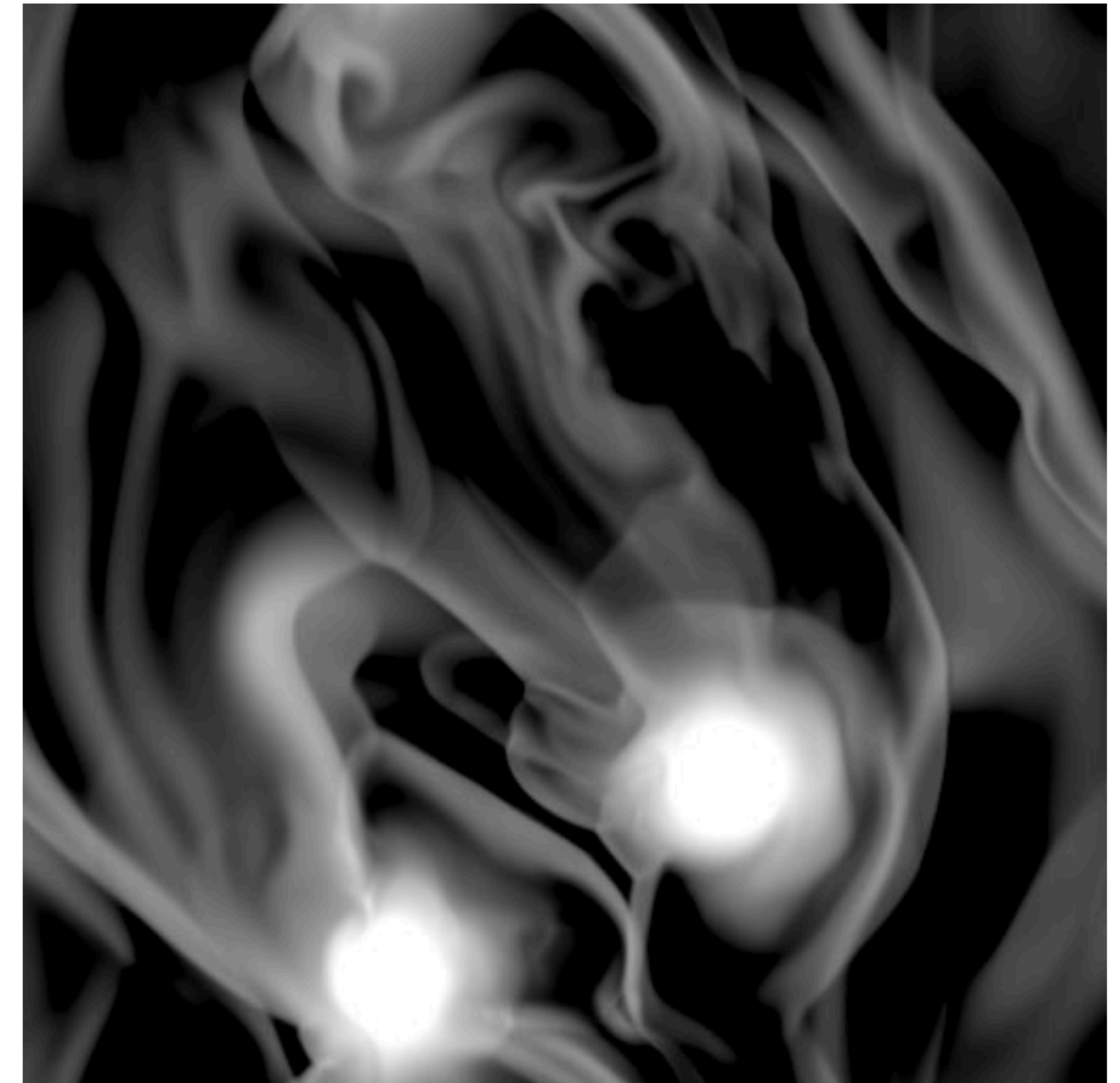
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- ▶ *quasi-steady turbulence vs. fragmentation depends on cooling efficiency* (Define $\beta_{\text{cool}} = \Omega t_{\text{cool}}$)



$$\beta_{\text{cool}} = 10 \quad (> 3)$$

turbulence heating balances
cooling \rightarrow viscosity $\alpha \sim \beta_{\text{cool}}^{-1}$

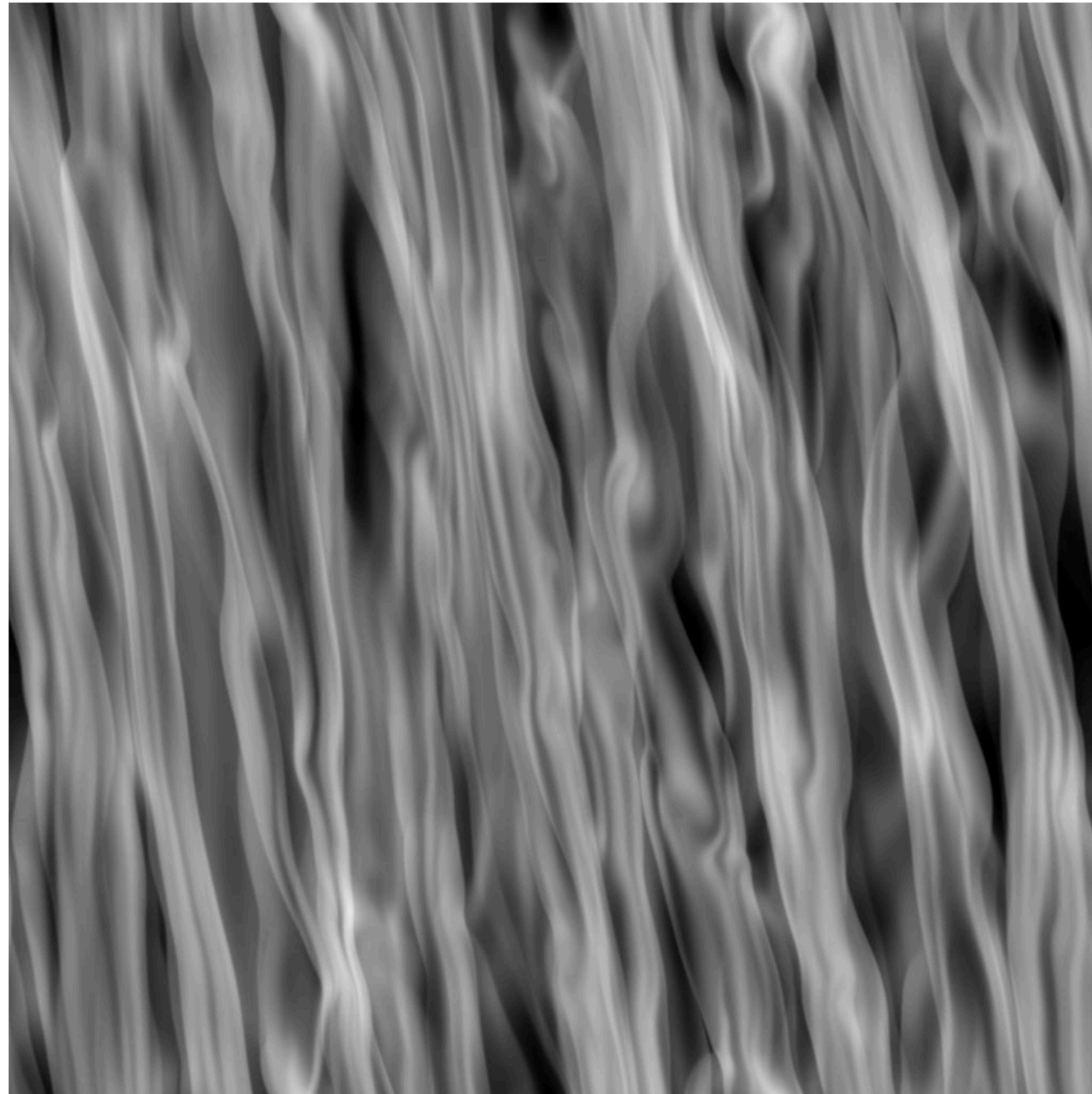


$$\beta_{\text{cool}} = 2 \quad (< 3)$$

disk fragments

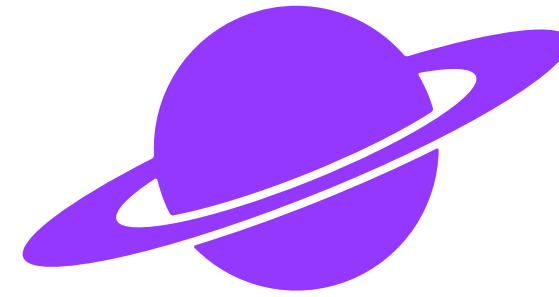
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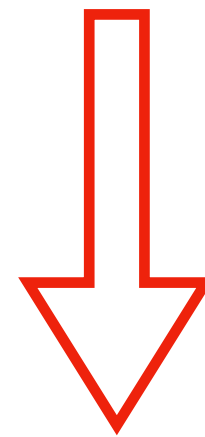


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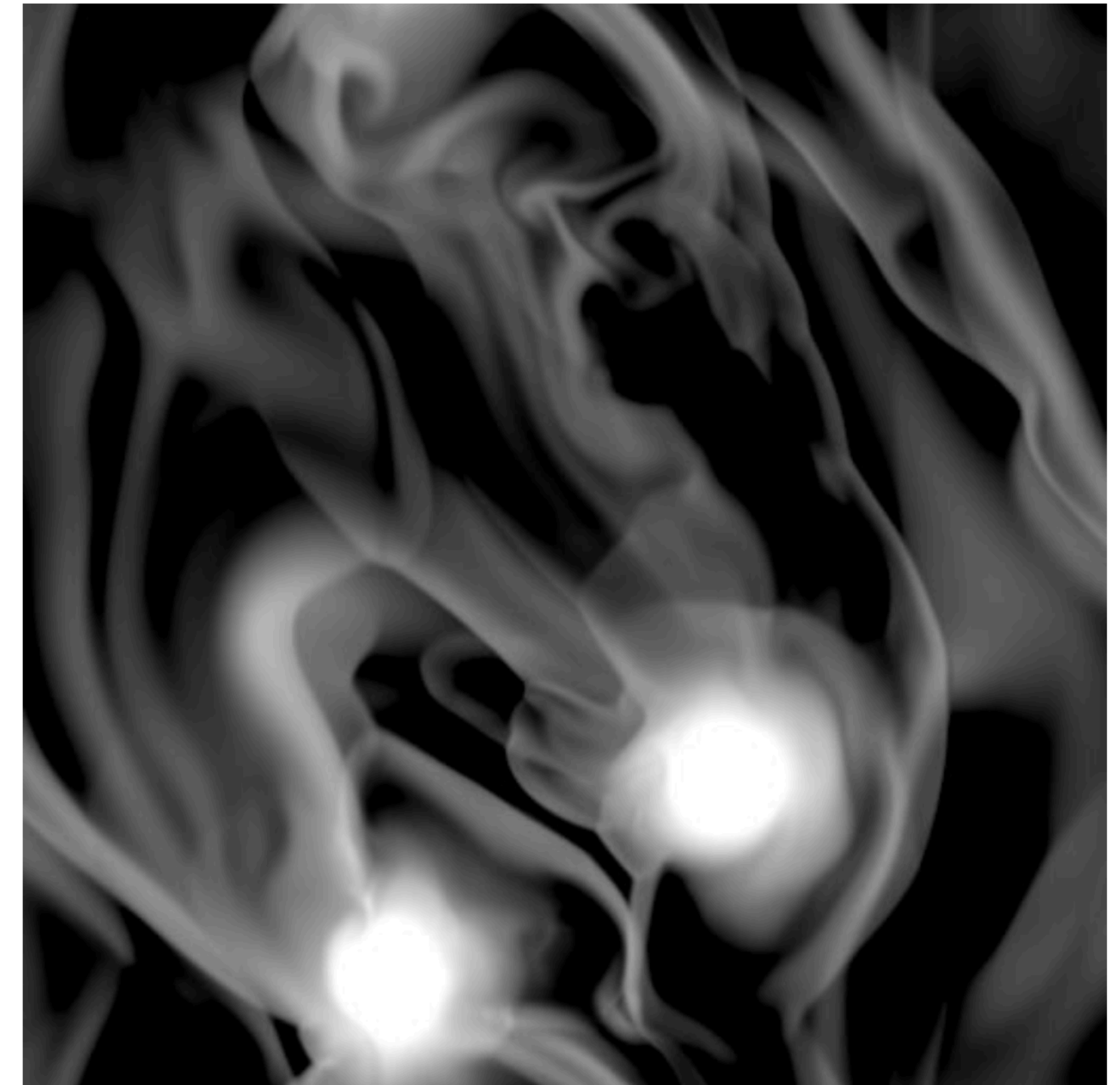
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What about β_{cool} in PPDs?



We need radiation hydro simulations



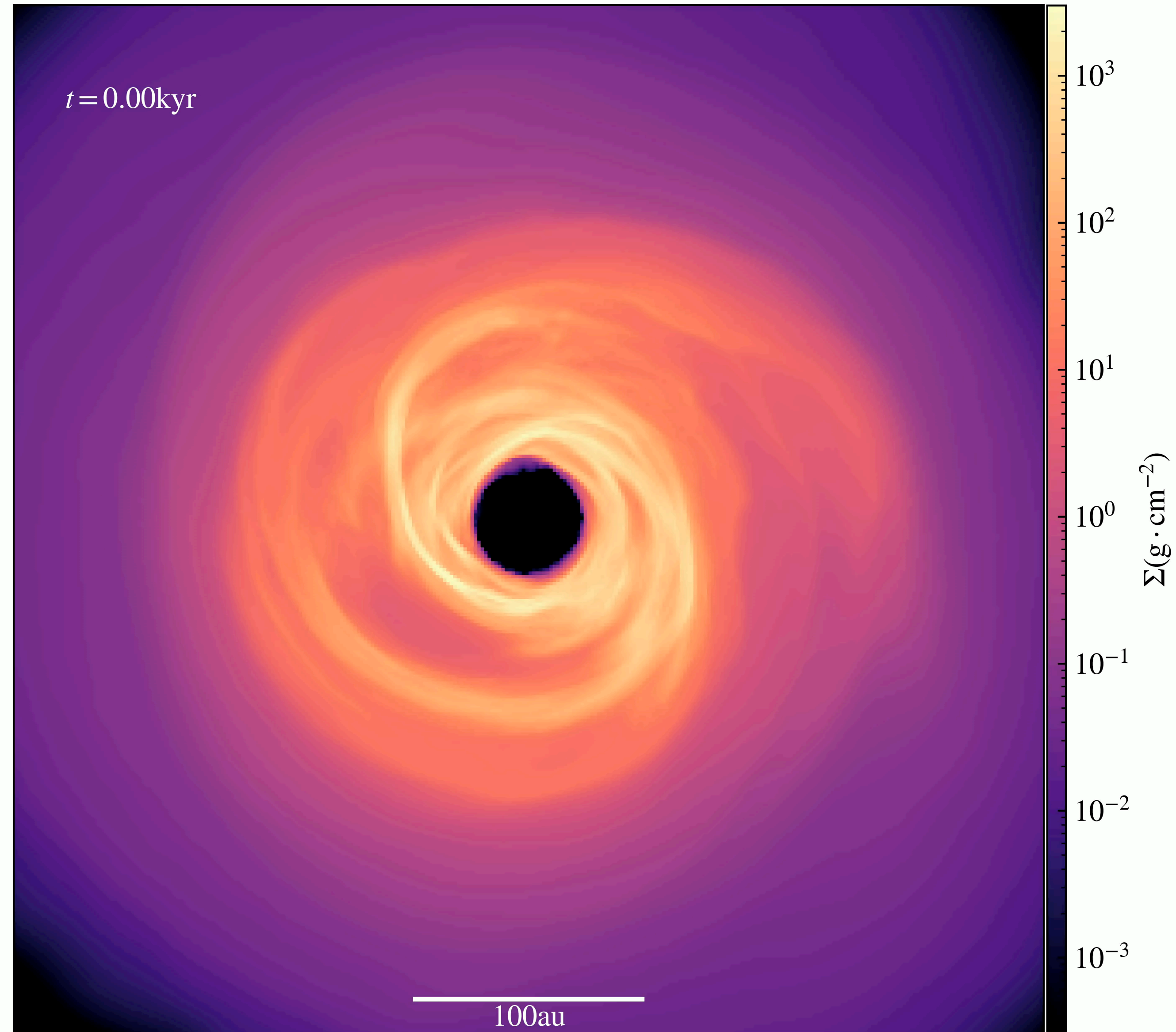
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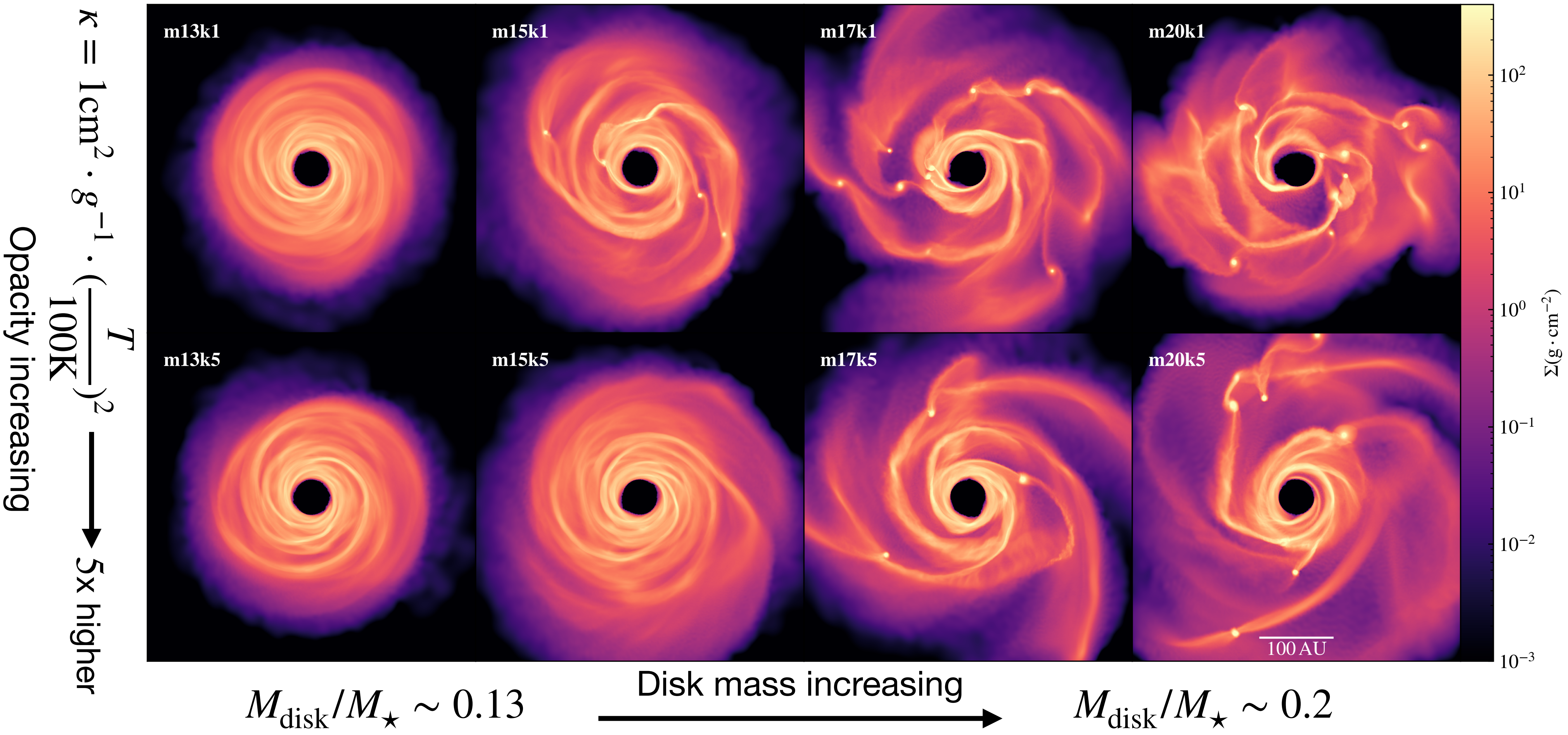
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Radiation Hydrodynamic Simulations using GIZMO (Meshless Finite Mass, quasi-Lagrangian)

- ▶ Start from gravito-turbulent disks extending ~ 20 AU to > 100 AU
- ▶ Assume no irradiation i.e., self-shadowing
- ▶ Adopt **M1 radiation transport** scheme (better treatment in optically thin regions than flux limited diffusion)
- ▶ $\sim 10^{-5} M_{\text{Jup}}$ mass resolution

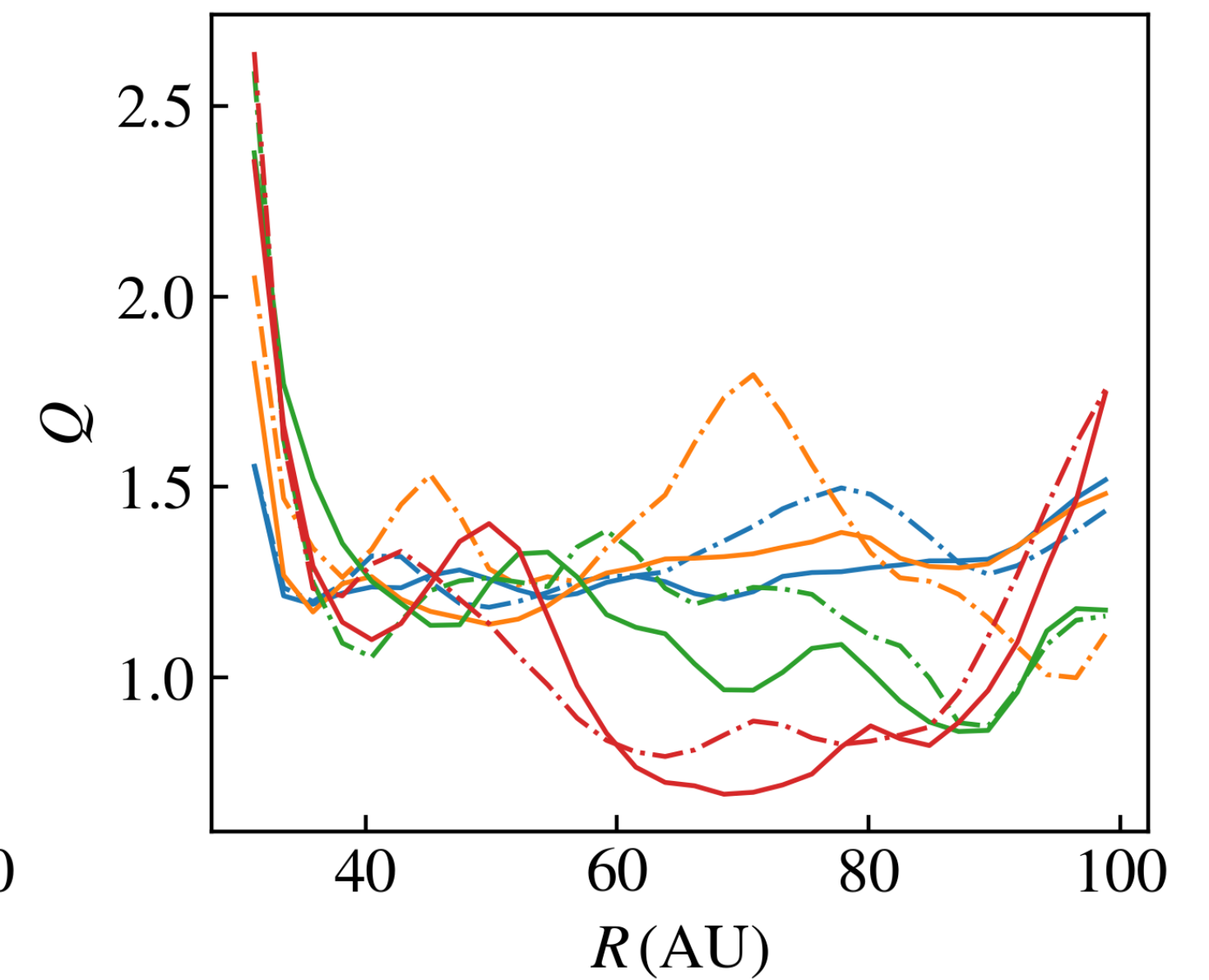
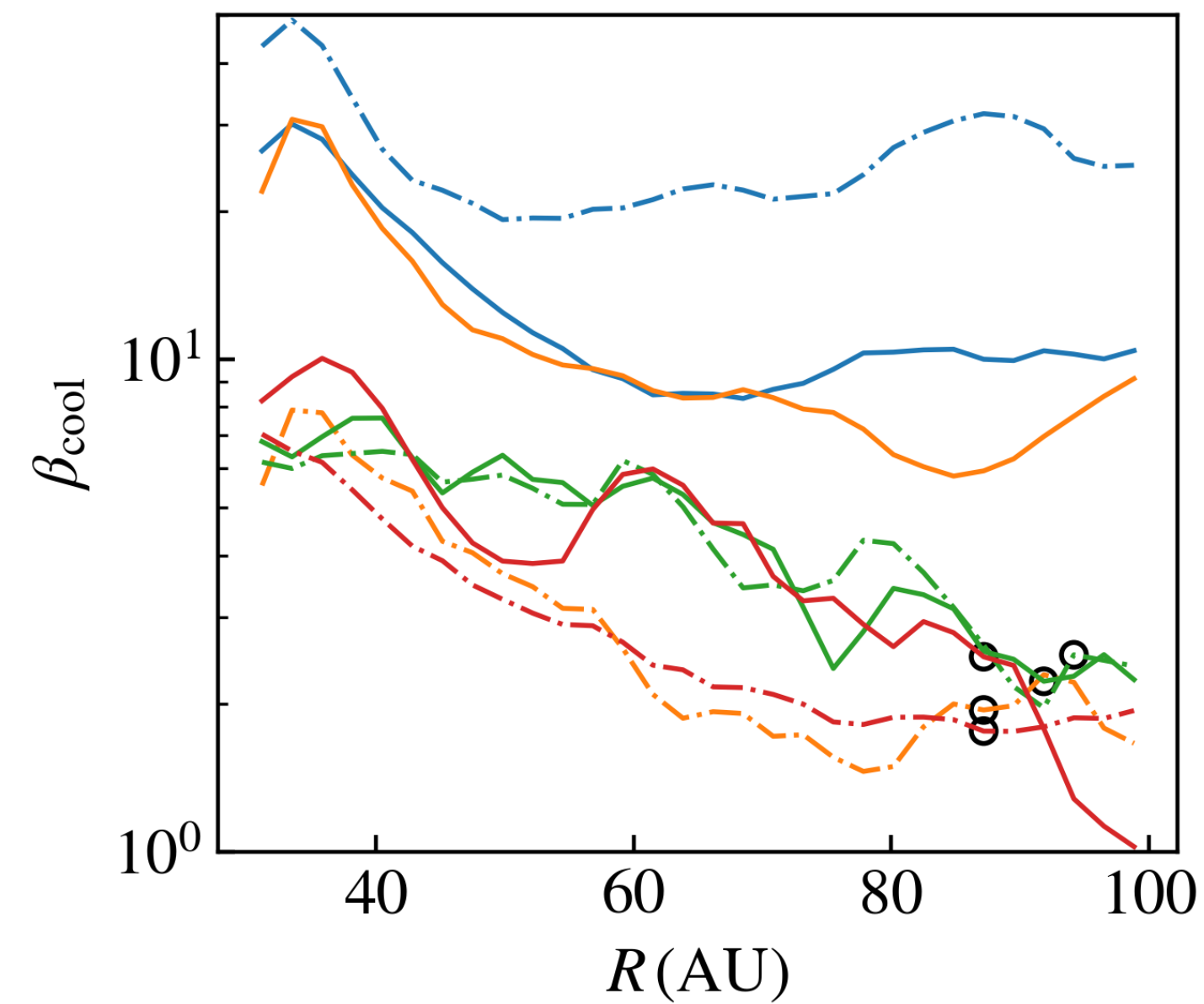
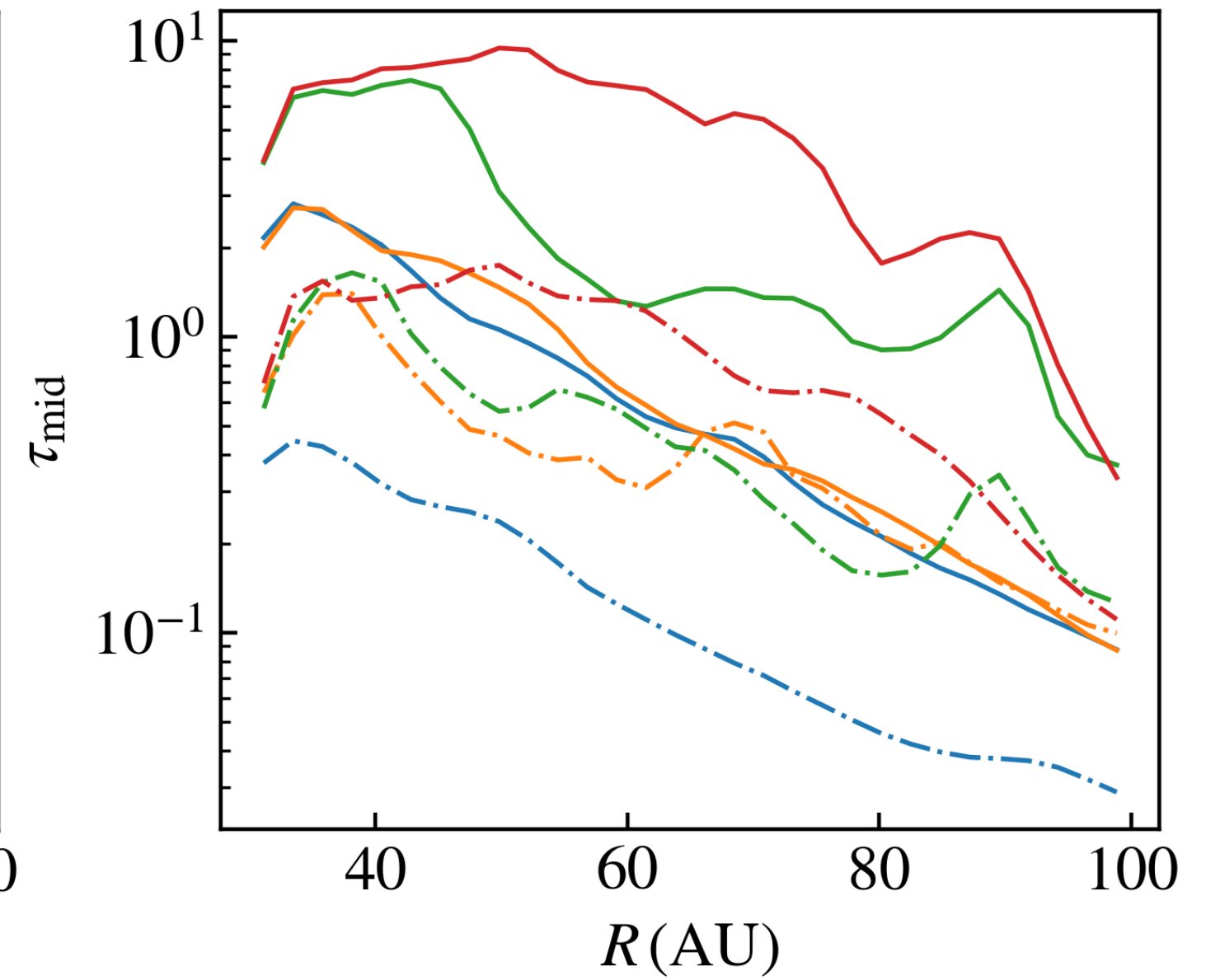
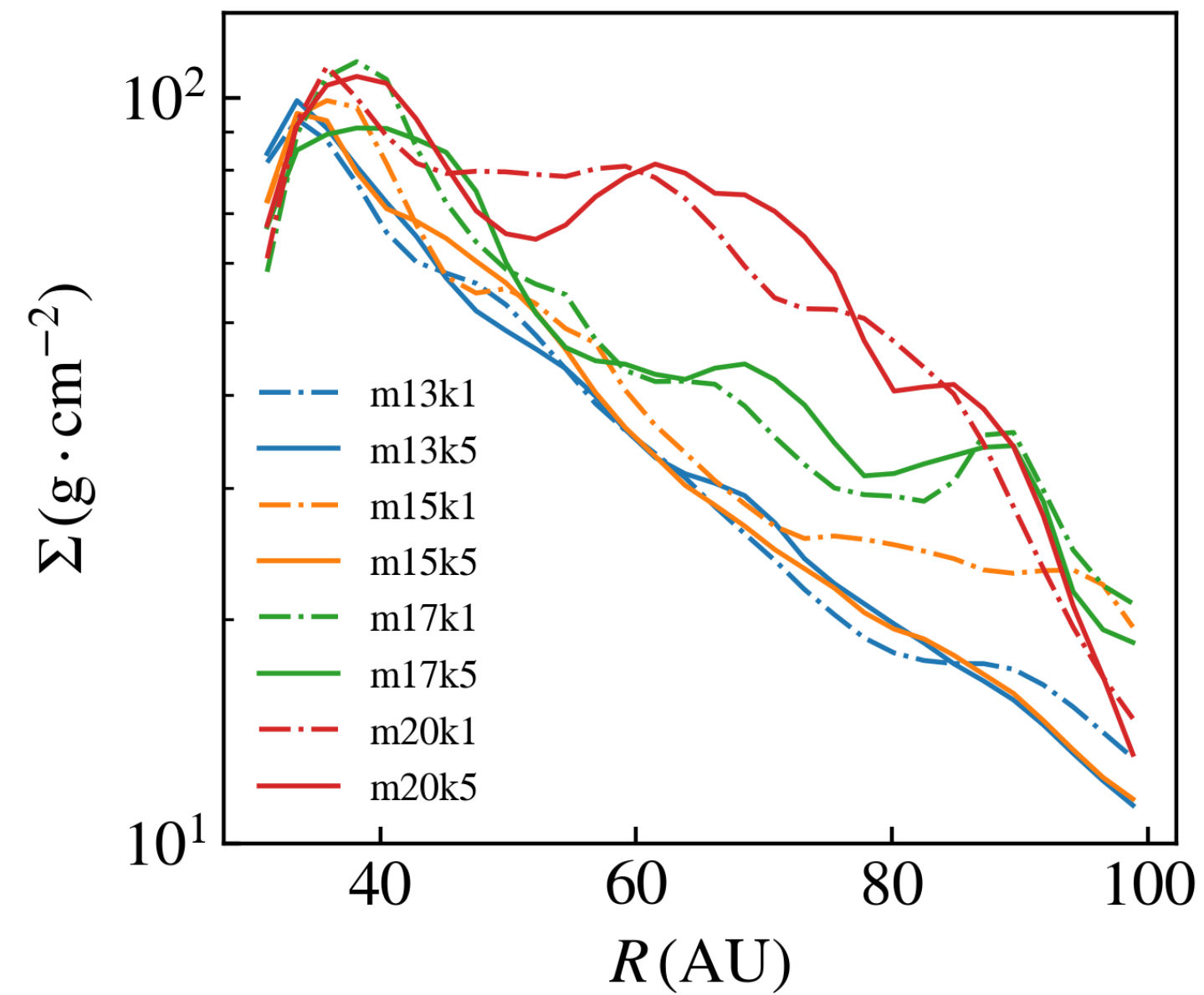


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Ni, Deng, Bai to be submitted

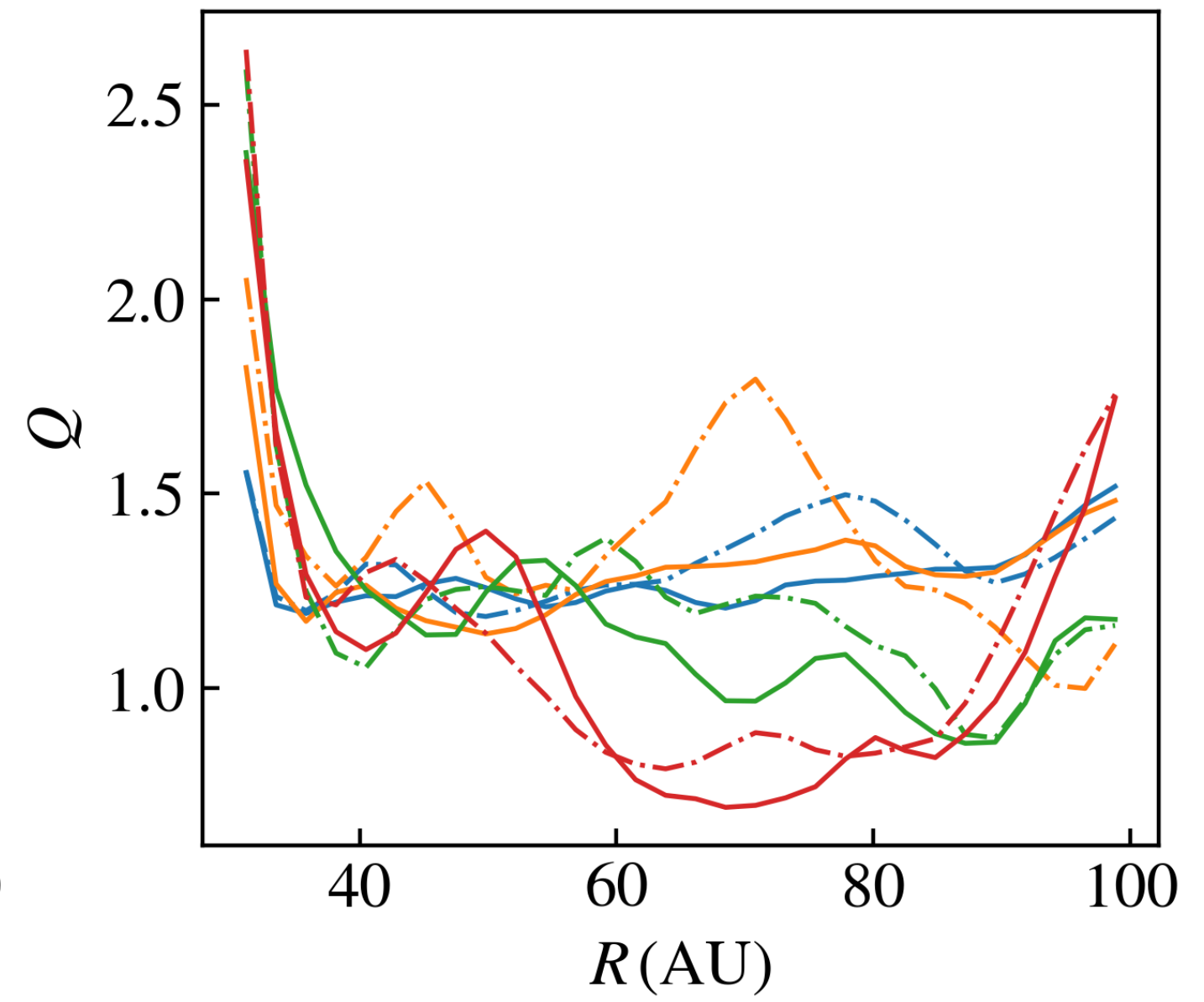
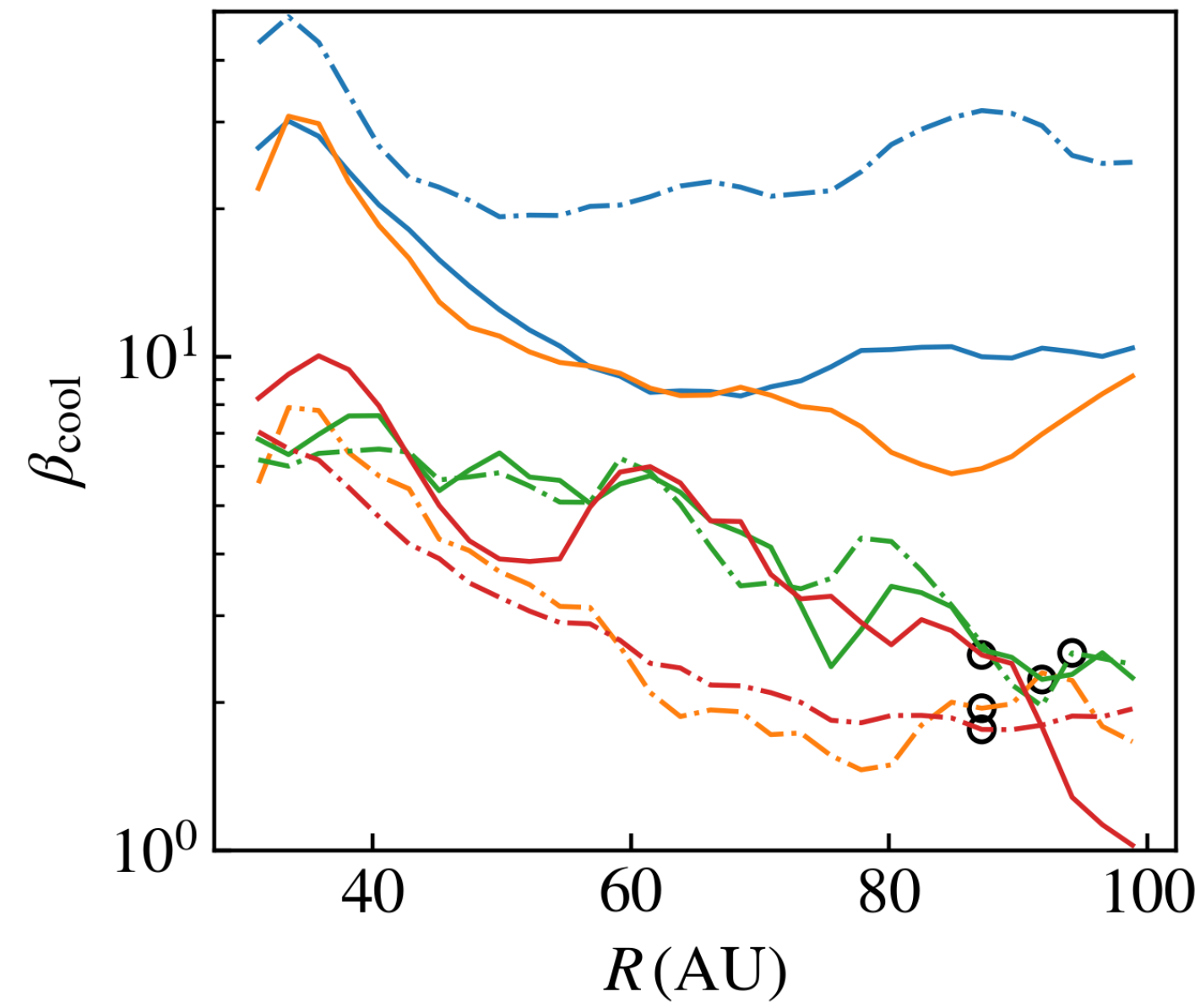
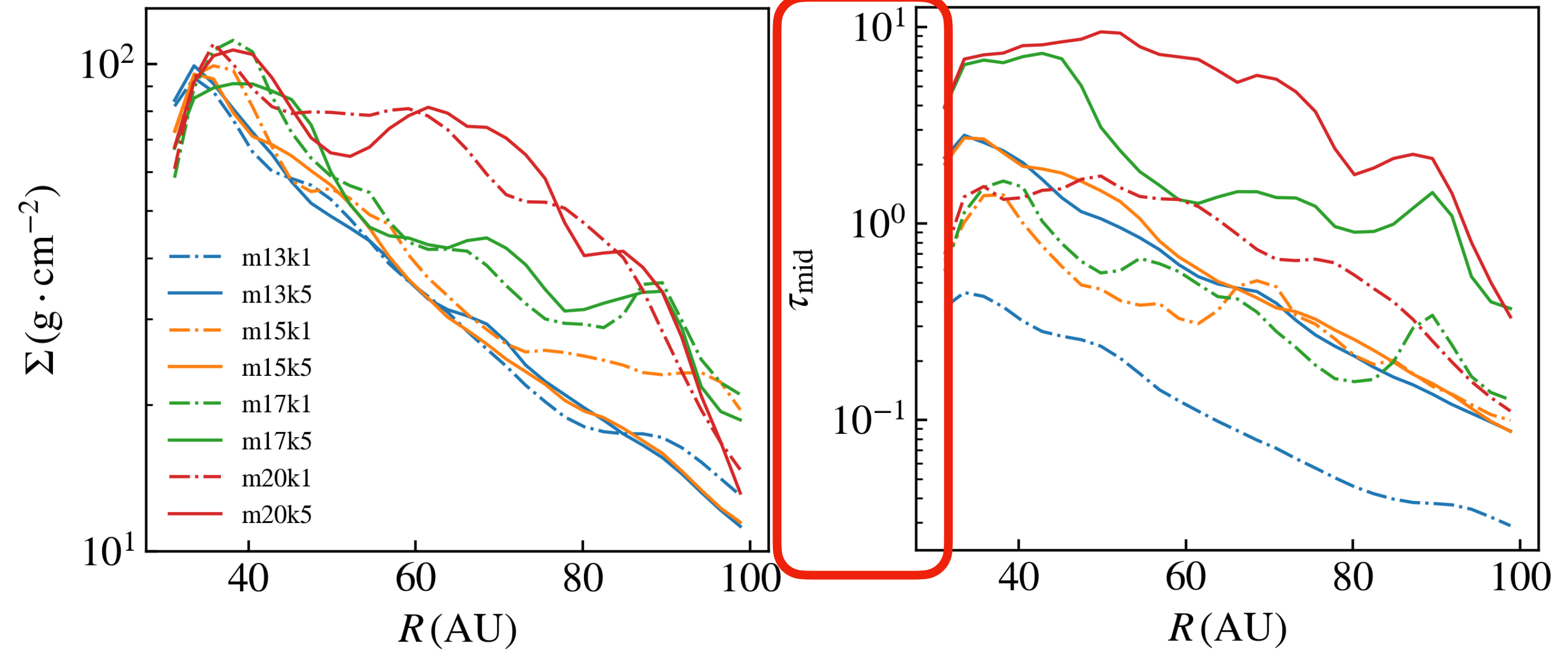
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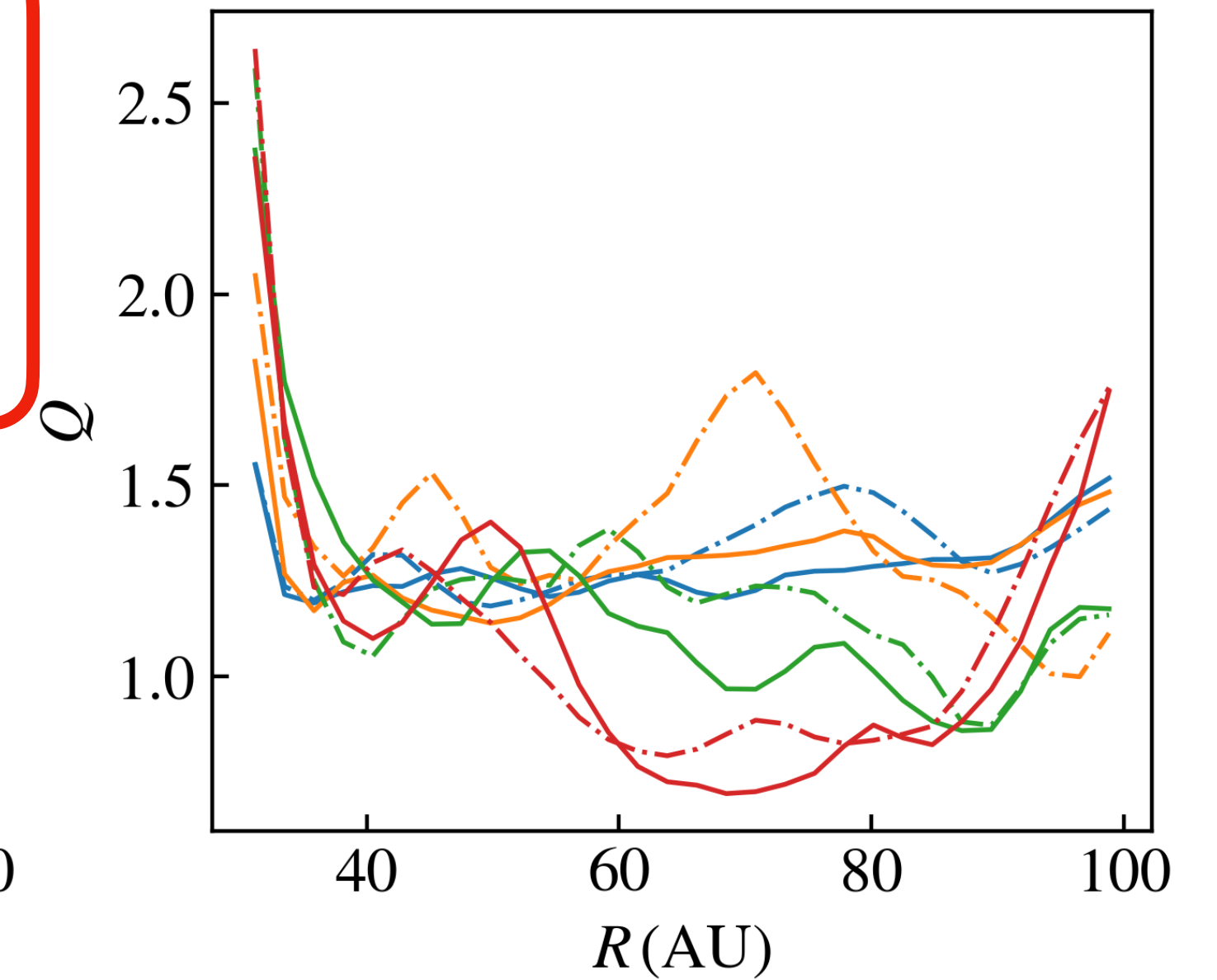
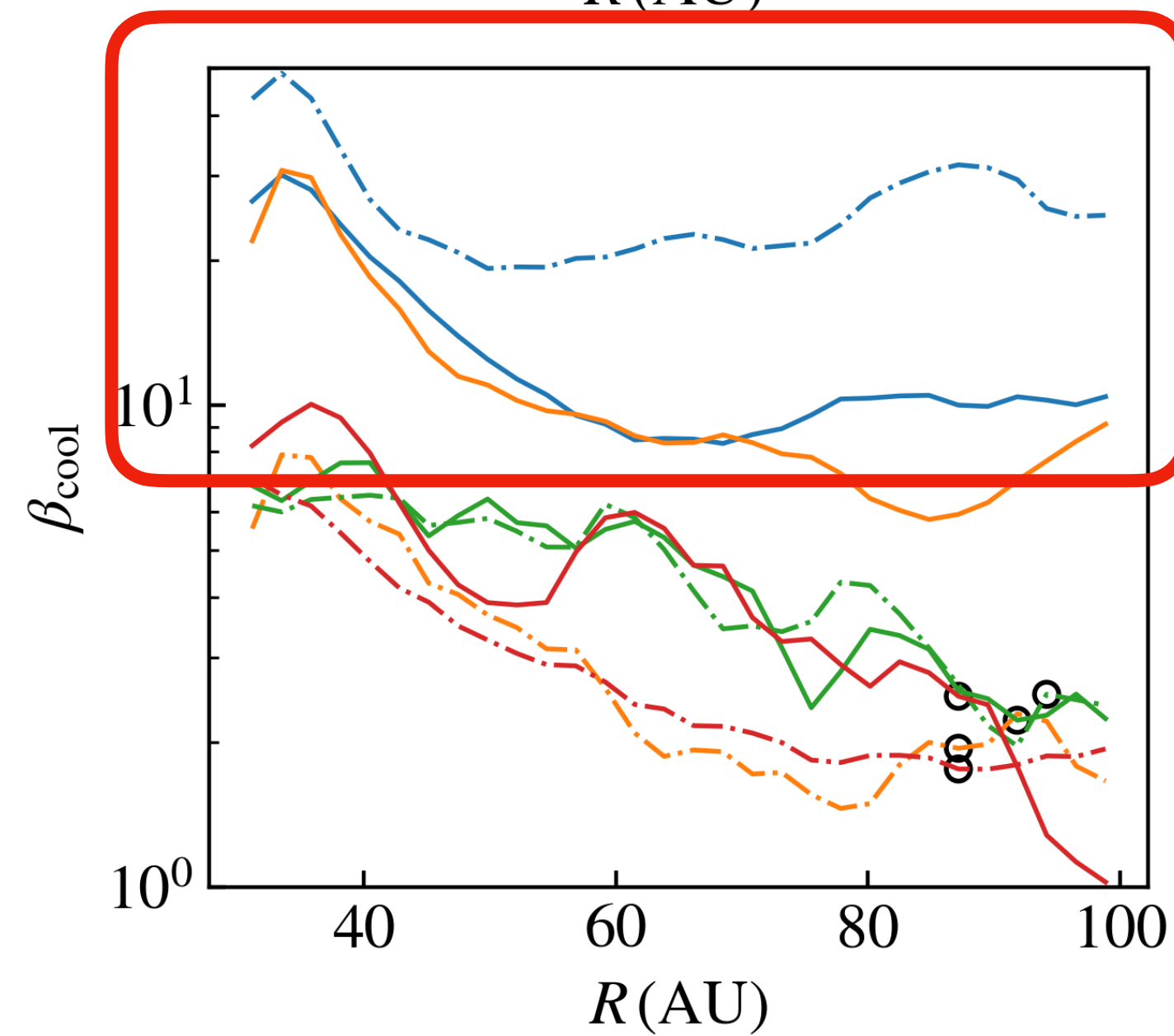
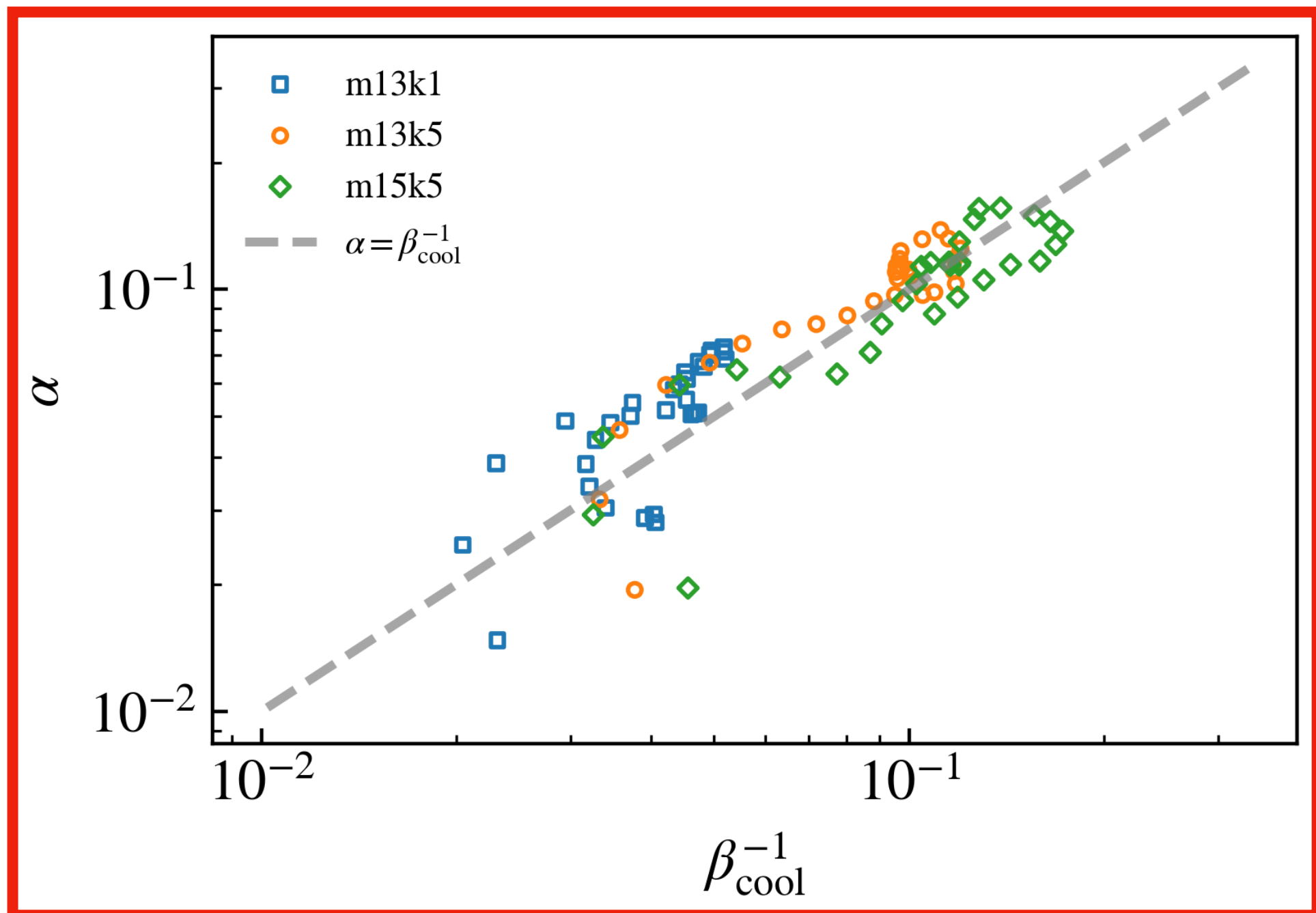
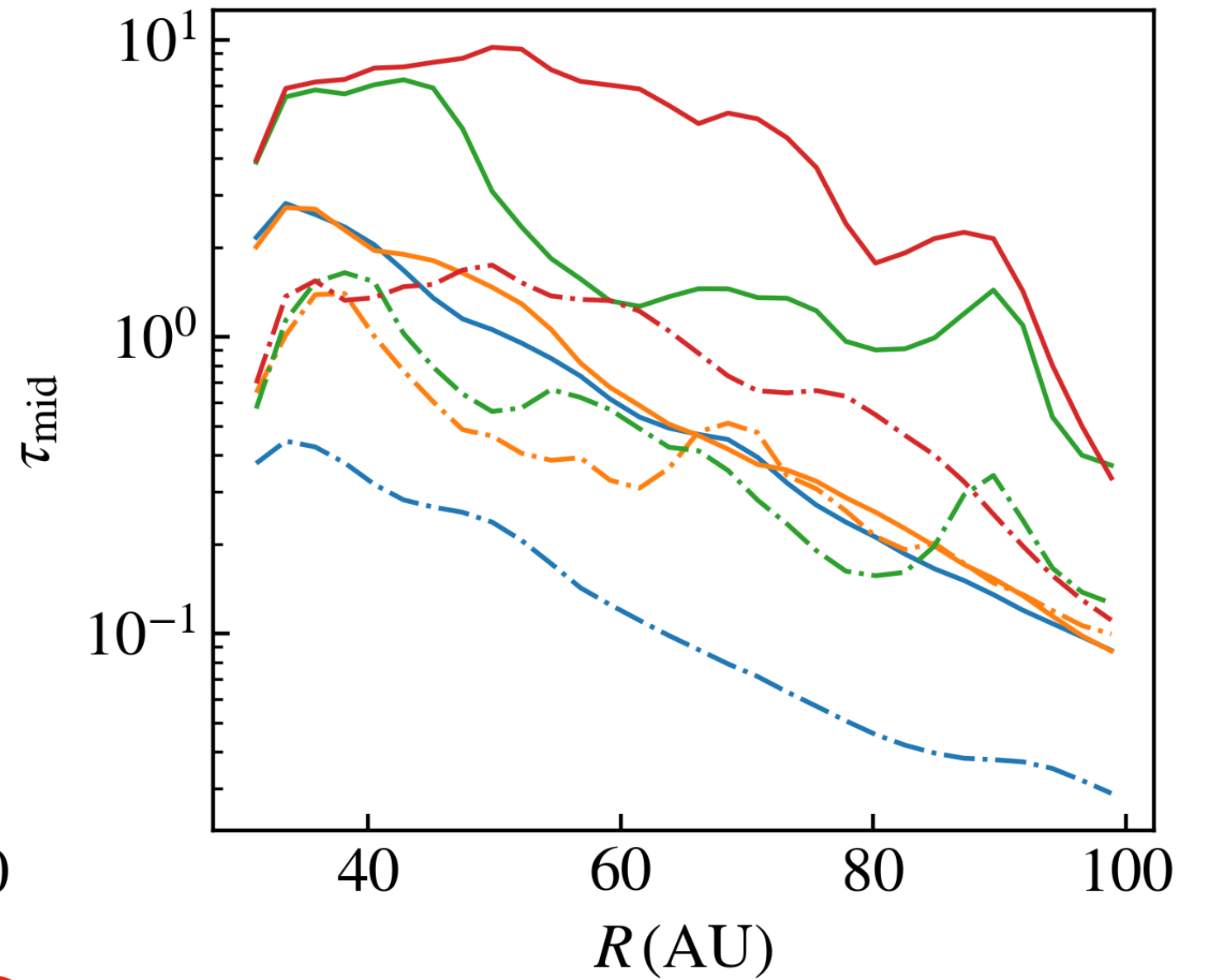
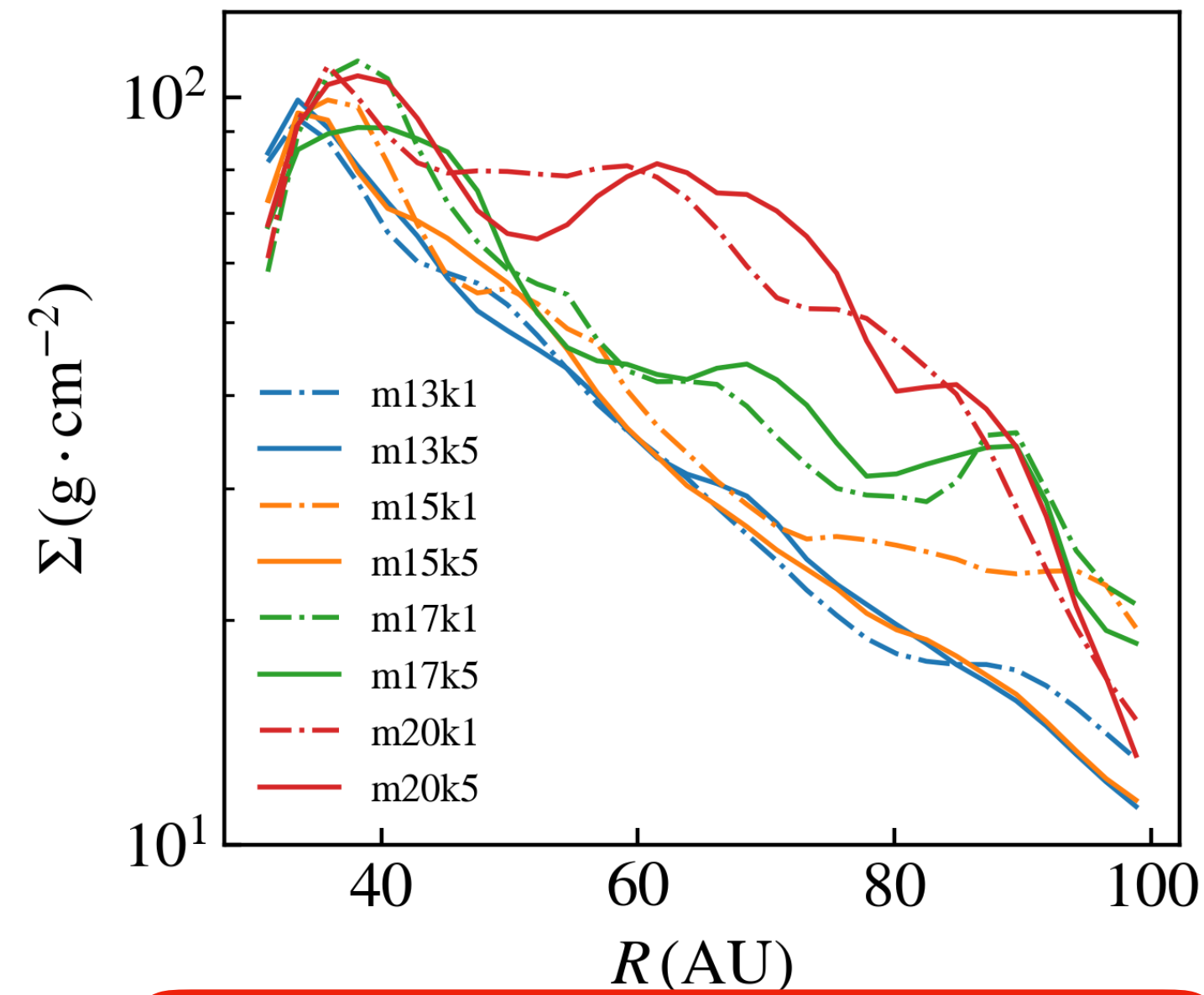
► Parameter space:
 $\tau_{\text{mid}} \sim 10^{-1} - 10^1$



Ni, Deng, Bai to be submitted

Q1. In PPDs, does GI saturate into a quasi-steady state or lead to fragmentation?

► Quasi-steady state
($\beta_{\text{cool}} \sim 10$): consistent with previous theoretical studies (e.g. Gammie 2001, Xu et al. 2025)



Ni, Deng, Bai to be submitted

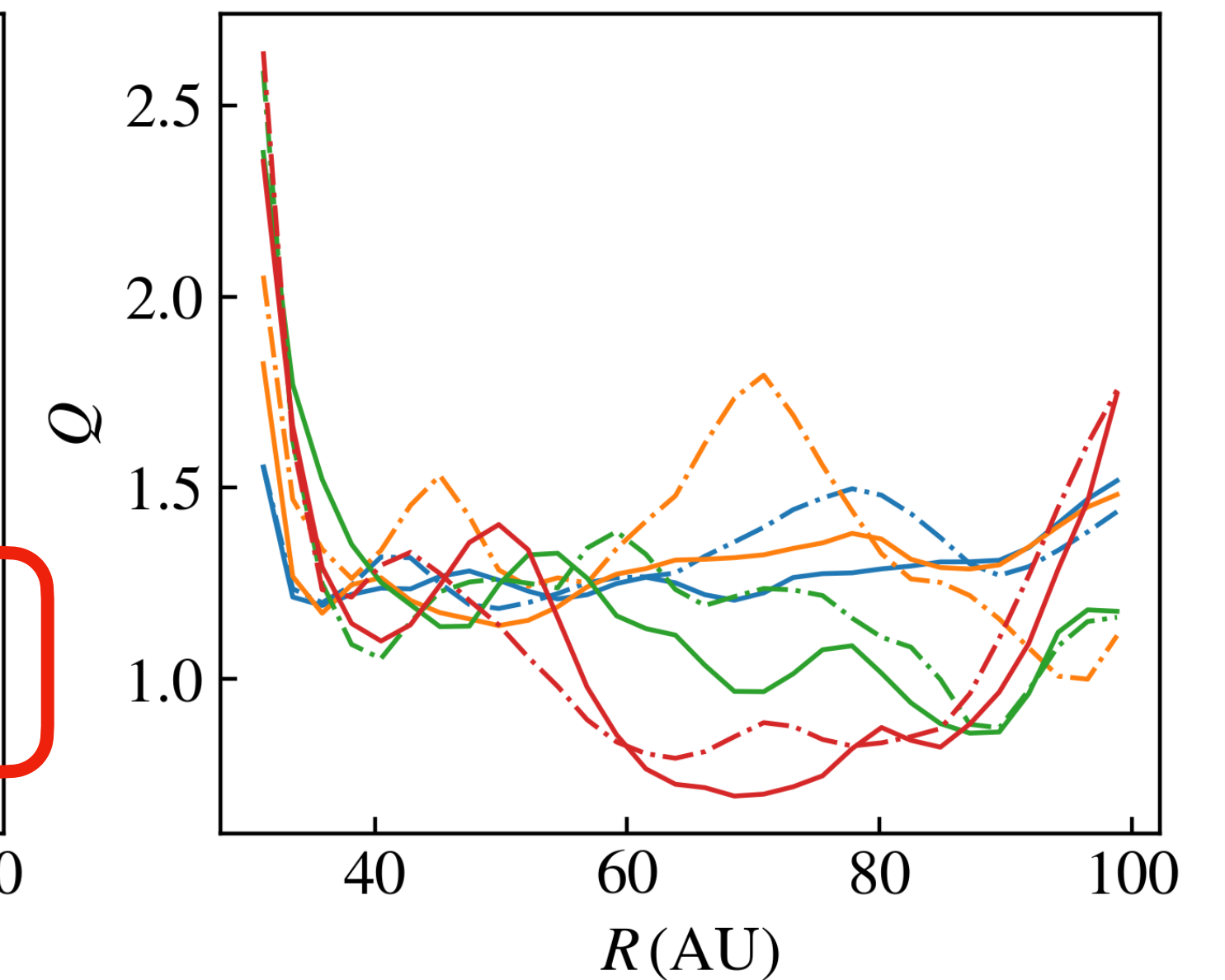
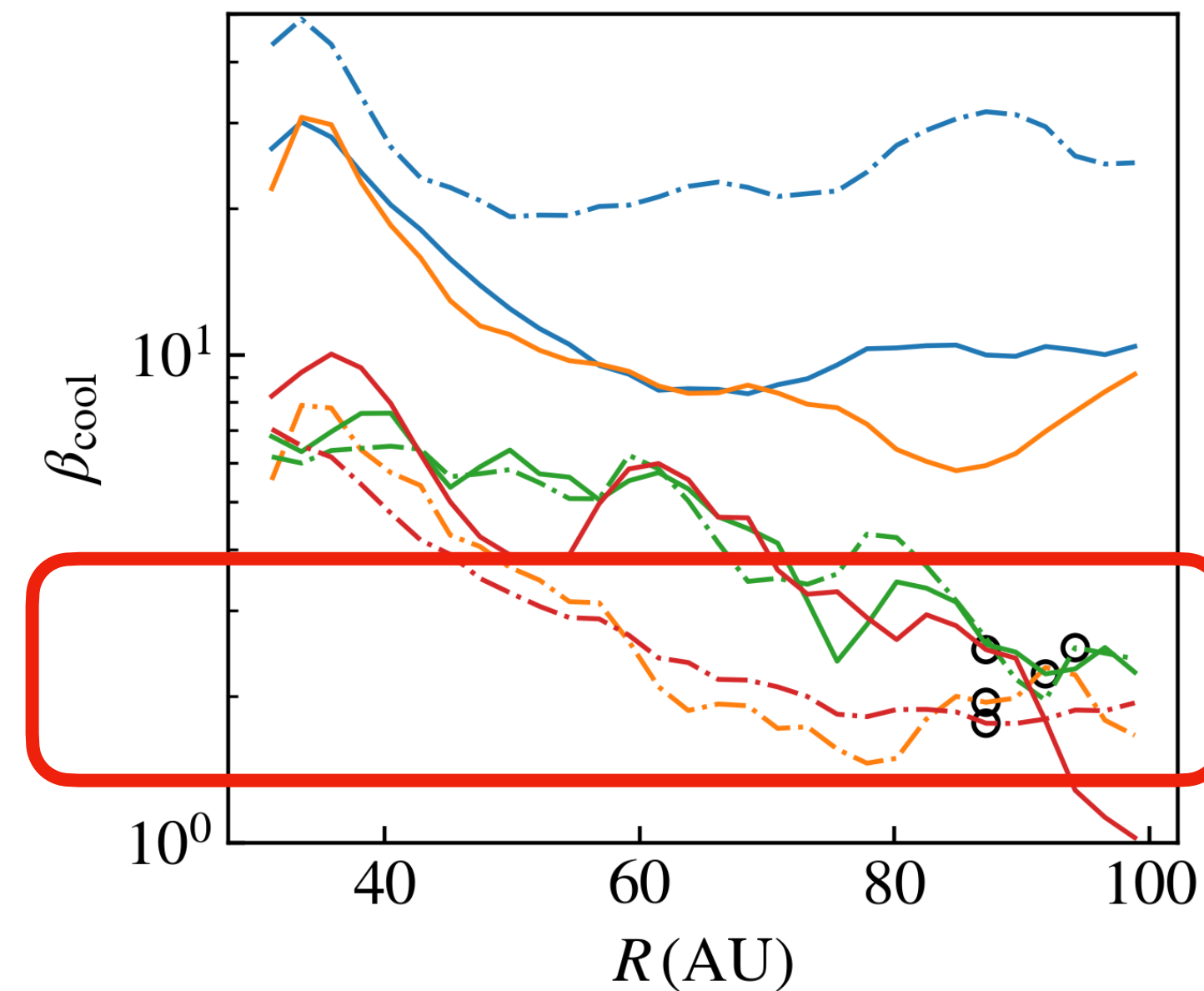
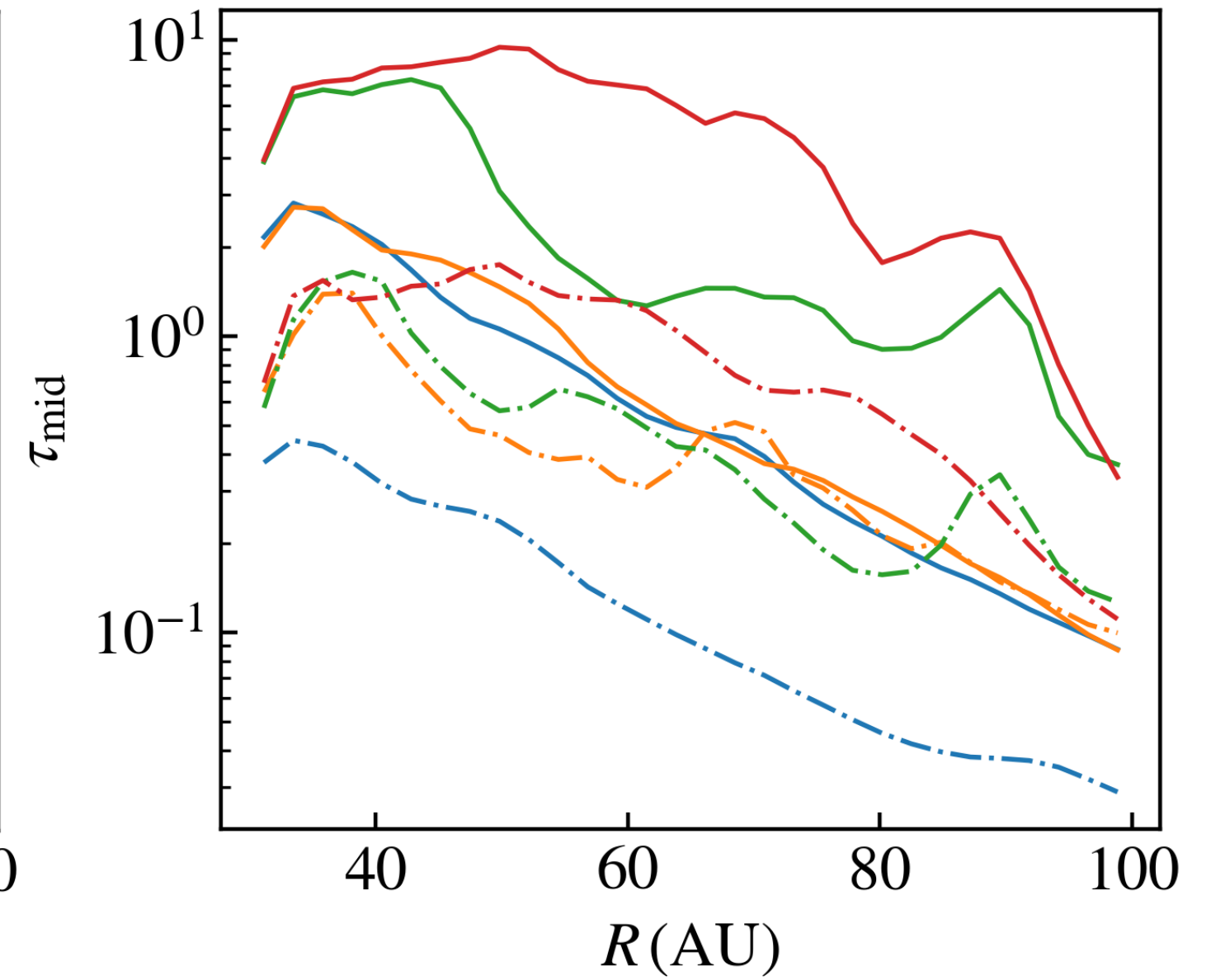
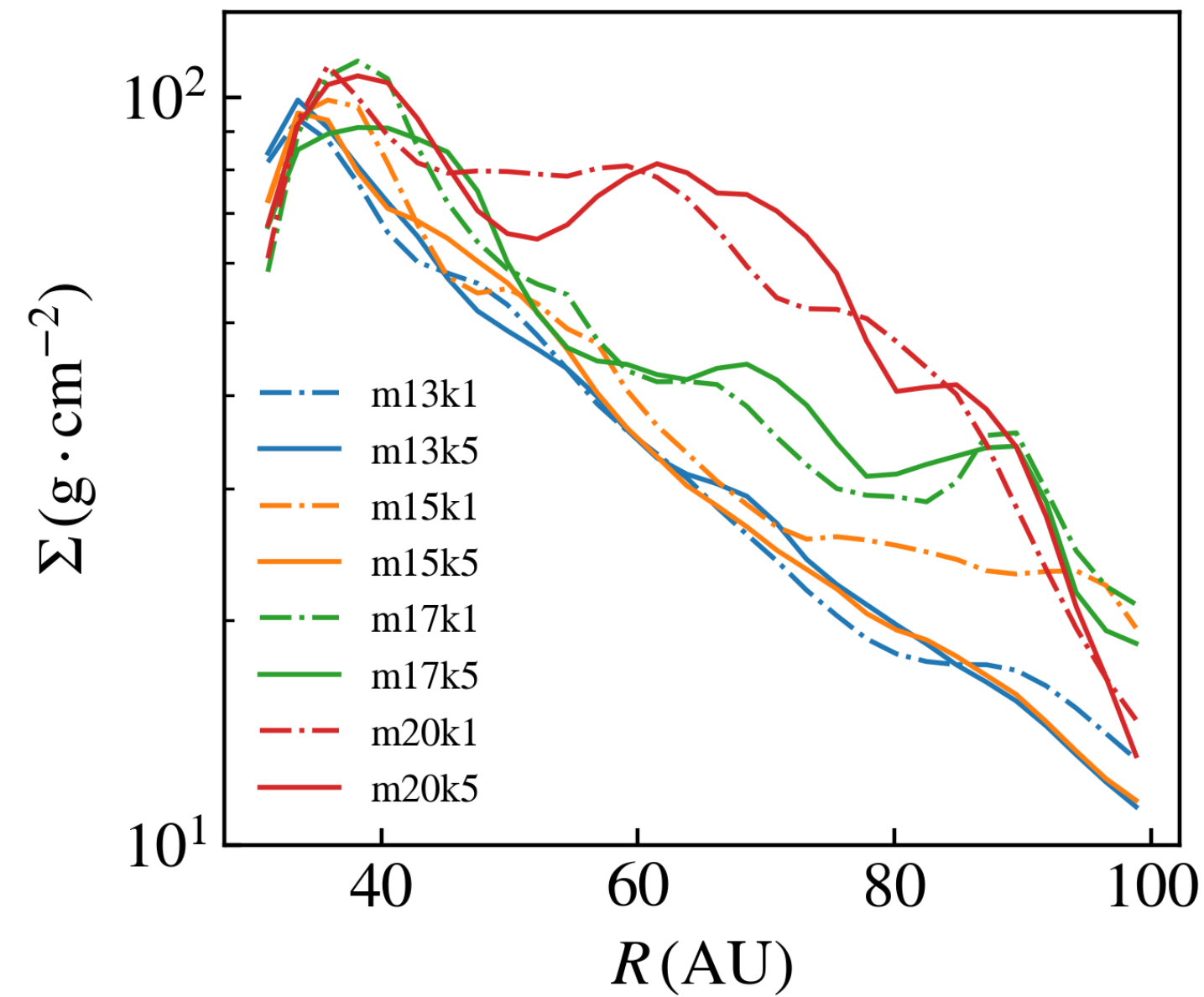
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► Fragmenting disk:

black circles: mark first fragments

We do find $\beta_{\text{cool}} < 3$ regions where fragmentation happens

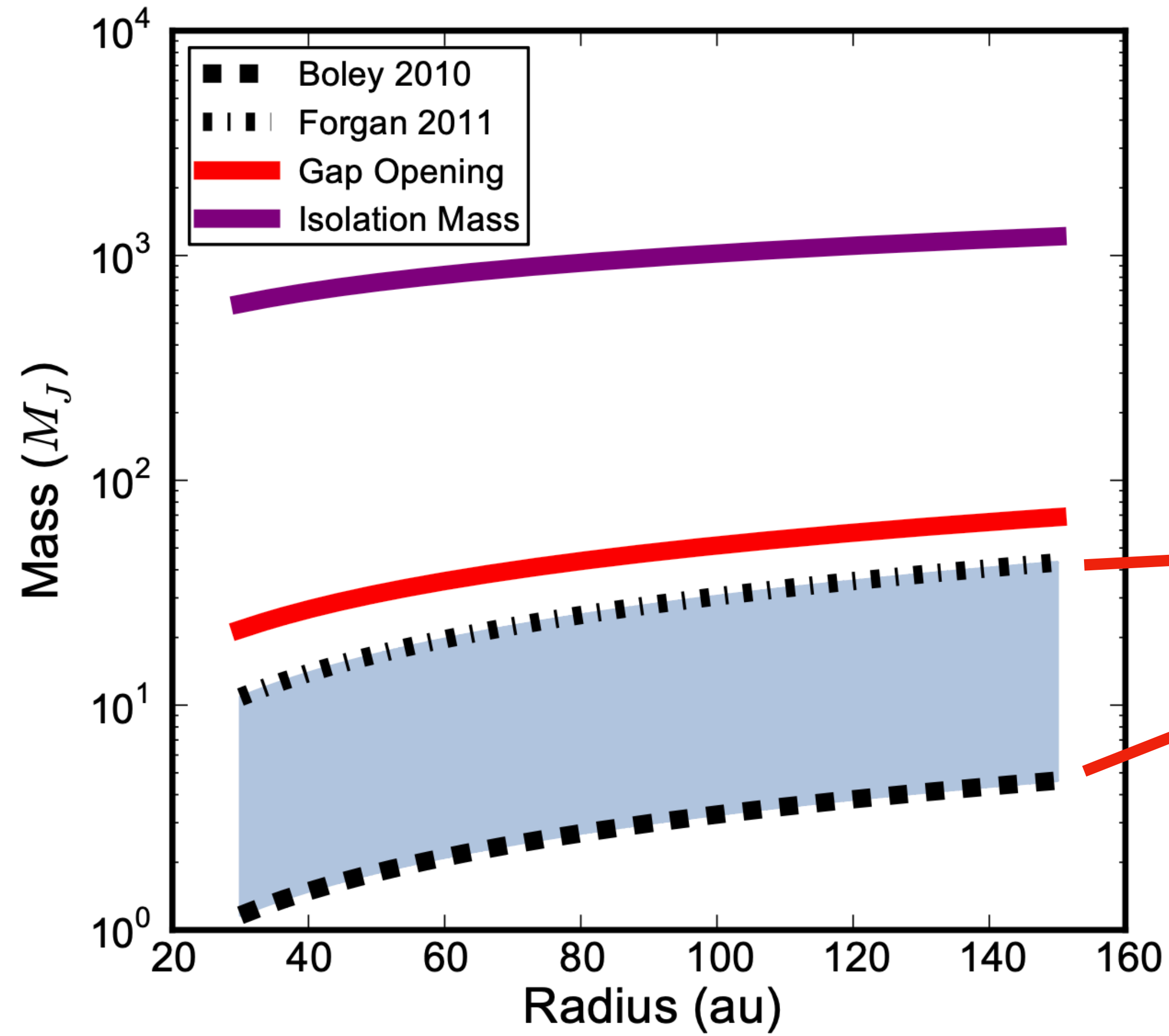
(e.g. Gammie 2001, Baehr et al. 2017, Deng et al. 2017)



Ni, Deng, Bai to be submitted

Q2. If fragments form in PPDs, what are their masses, and how do they evolve?

- Gas giants or brown dwarfs? ▶ debating



Different analytical predictions differ by a factor of 10

(Non-linear regime)

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	Hydro Method	Thermodynamics	MHD Effect	Fragmentation
Xu et al., 2024, 2025	3D static mesh	Full Radiation transport	X	dissolved shortly by numerical artifact, ~ brown dwarf mass
Béthune et al., 2022	3D static mesh	Beta cooling	Ideal + ohmic resistivity	Not intended (slow cooling)
Deng et al., 2020, 2021	Meshless finite mass (MFM)	Beta cooling	Ideal + ohmic resistivity	resolved, ~ Neptune mass
Brucy et al., 2021	3D mesh with AMR	Beta cooling	X	resolved, not measured
Forgan et al., 2017	SPH	Beta cooling	purely hydro / Ideal MHD	resolved, ~ Jupiter mass (both hydro & MHD)

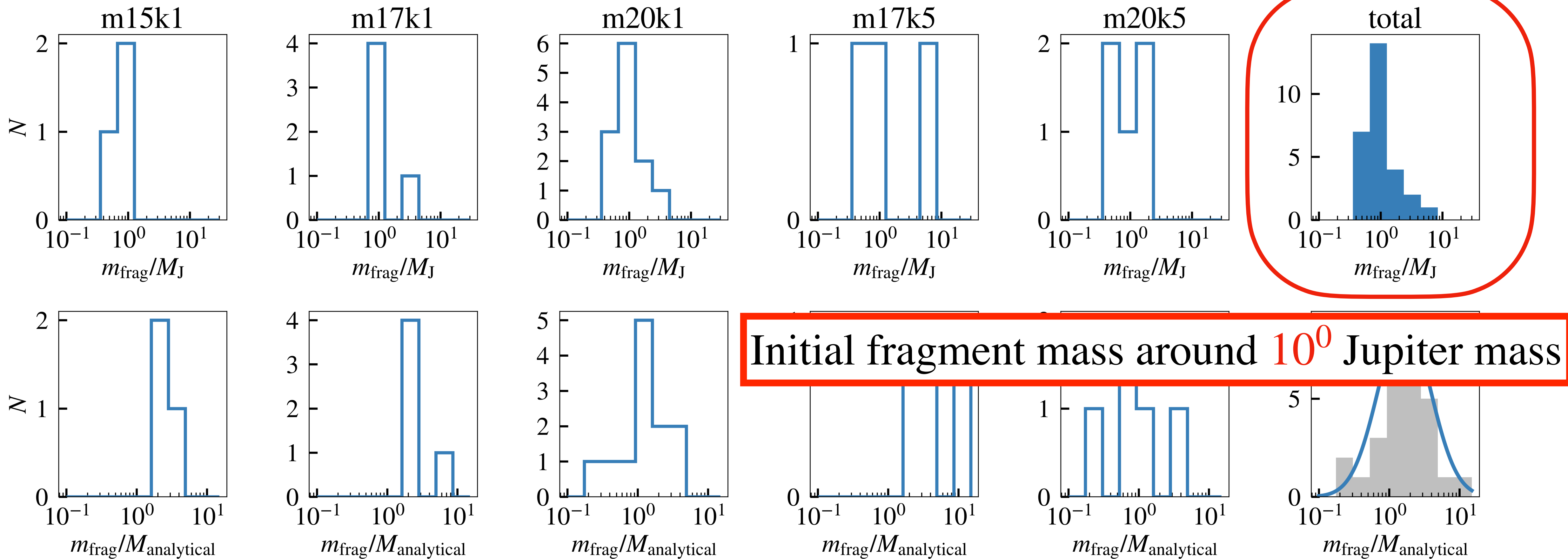
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► Hydro: need to **resolve fragments**

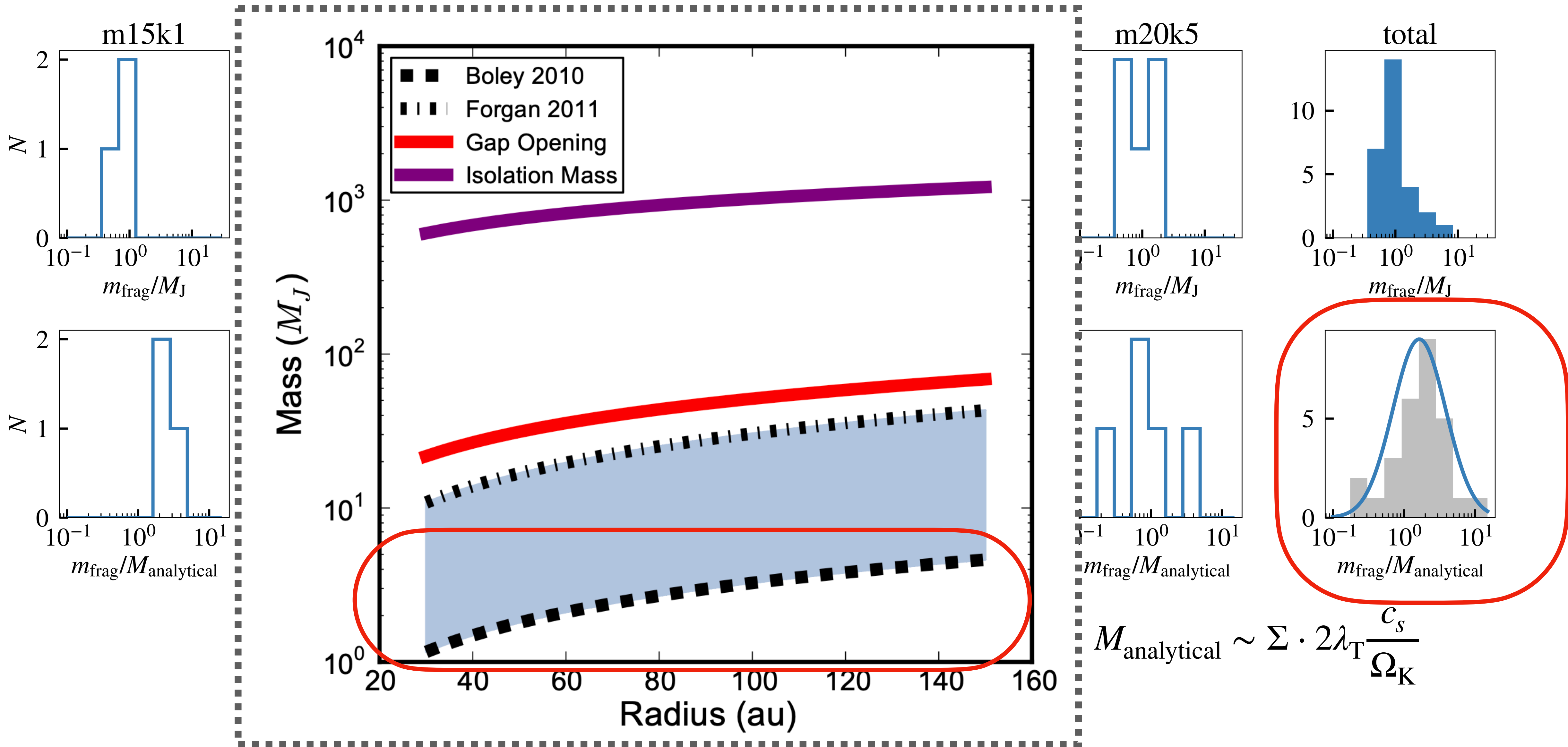
► Thermodynamics: need **self-consistent cooling**

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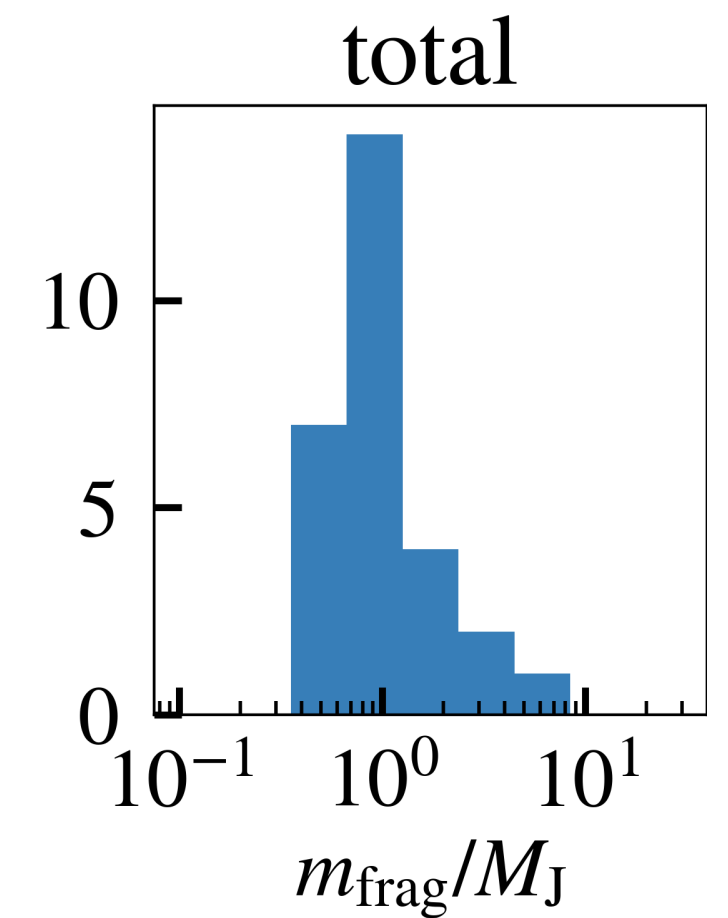
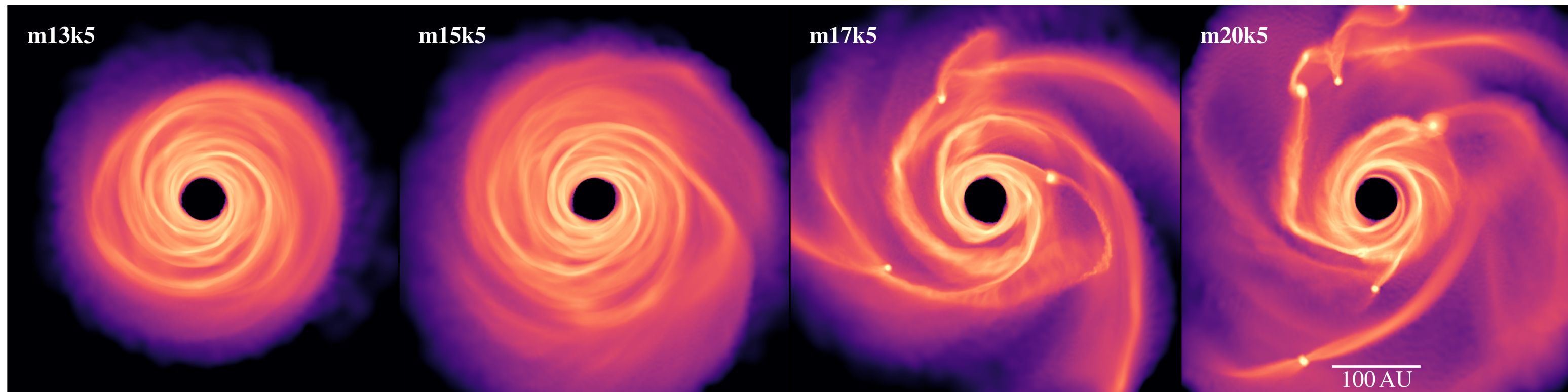
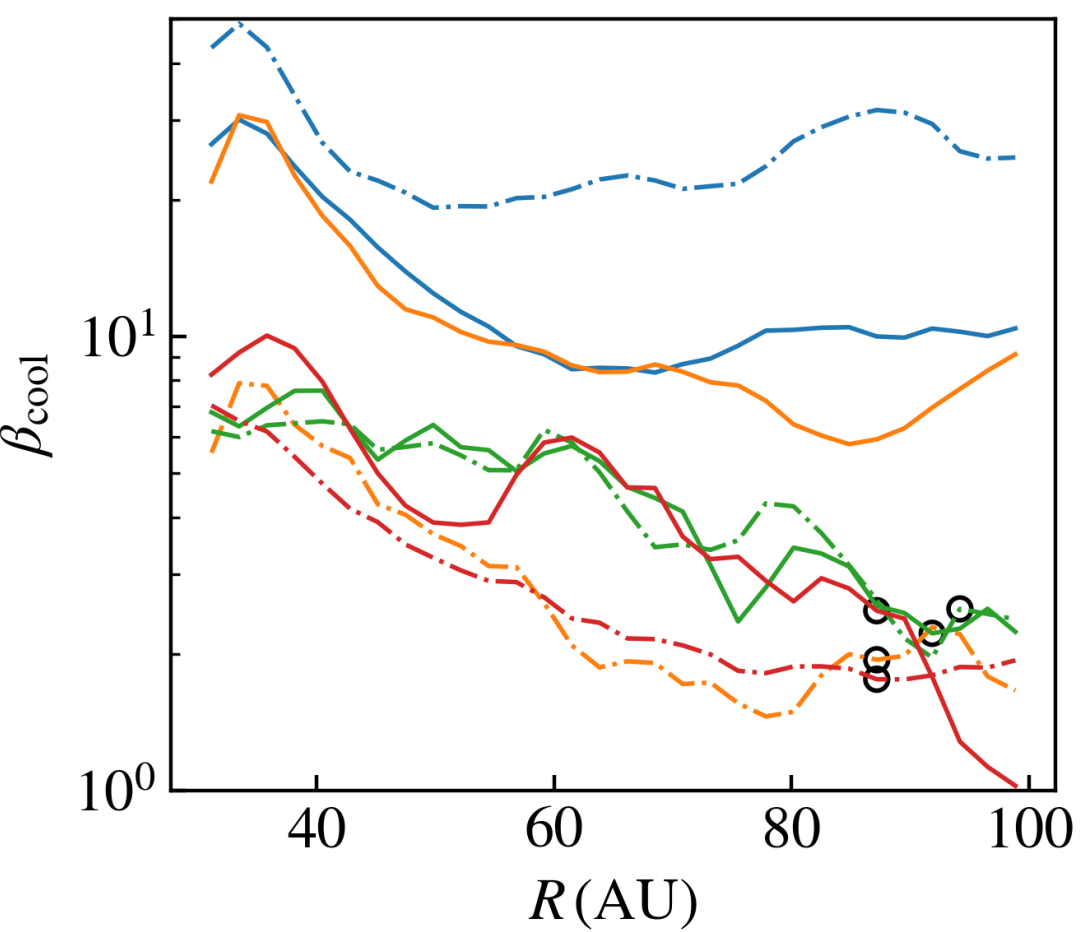


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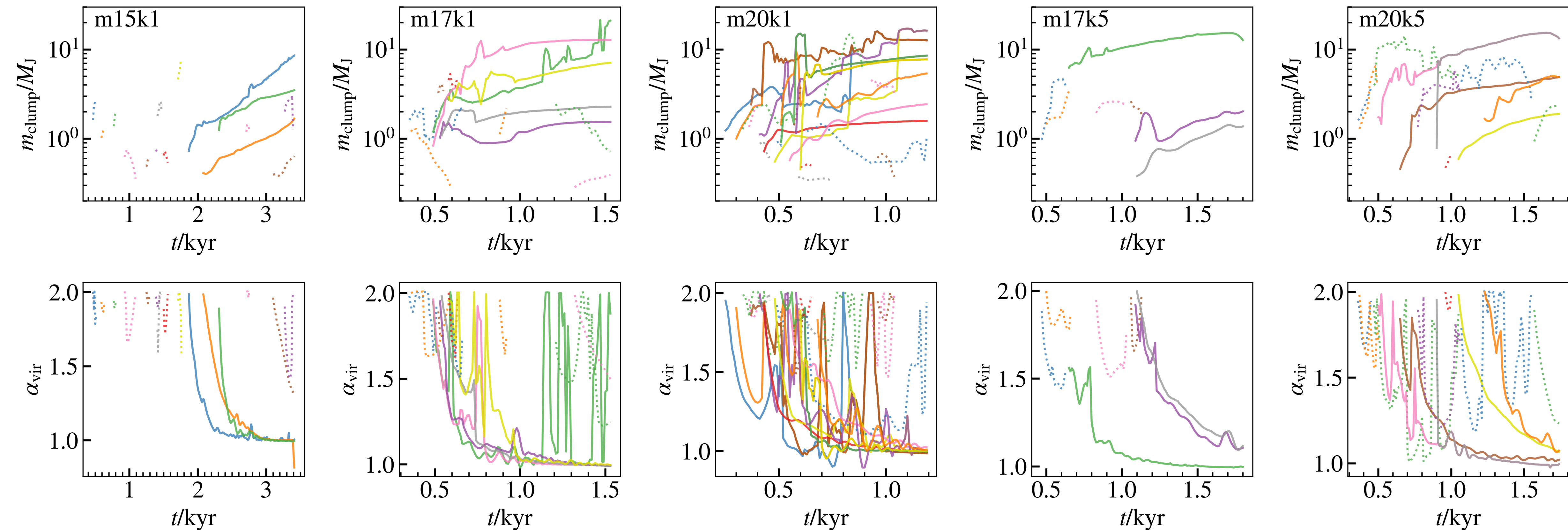
Summary

- Performed 3D radiation hydro simulations varying disk mass and opacity;
- Reproduced quasi-steady gravito-turbulence seen in theoretical studies;
- Found fragmentation in outer disks ($\sim 100\text{AU}$) for $M_{\text{disk}} \gtrsim 0.15M_{\star}$ with $\beta_{\text{cool}} < 3$;
- The initial fragment mass $\sim 10^0$ Jupiter mass (long-term fragment evolution remains an open question)



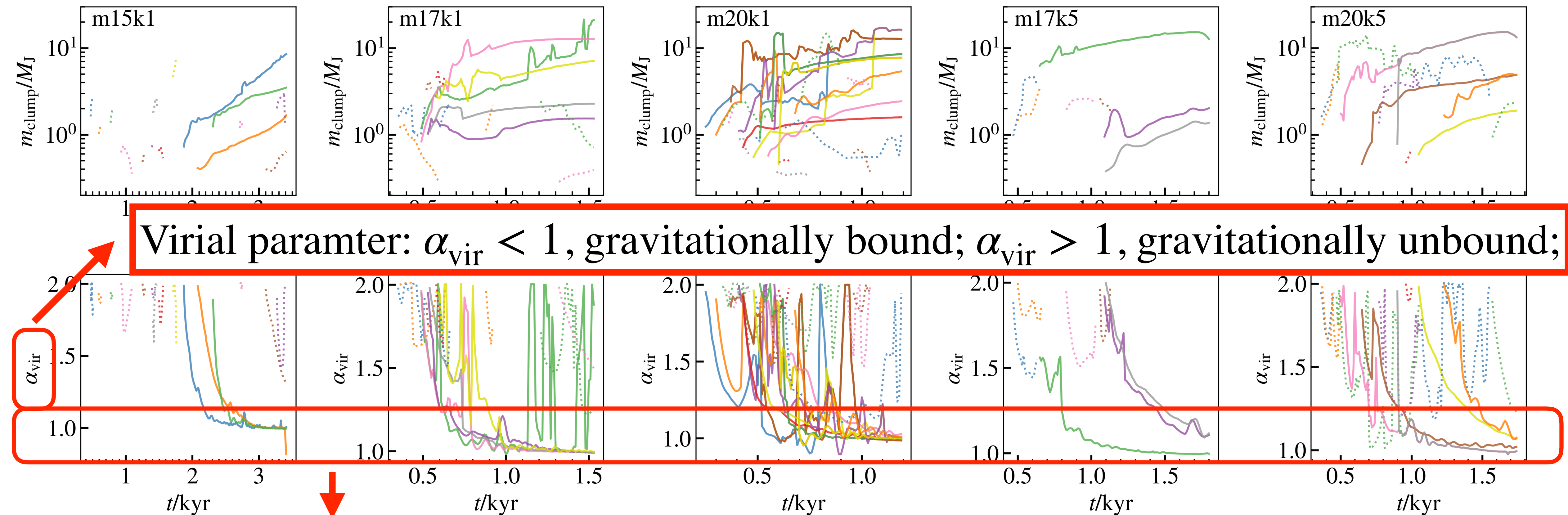
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dissolved clumps: dashed lines; bound clumps: solid lines



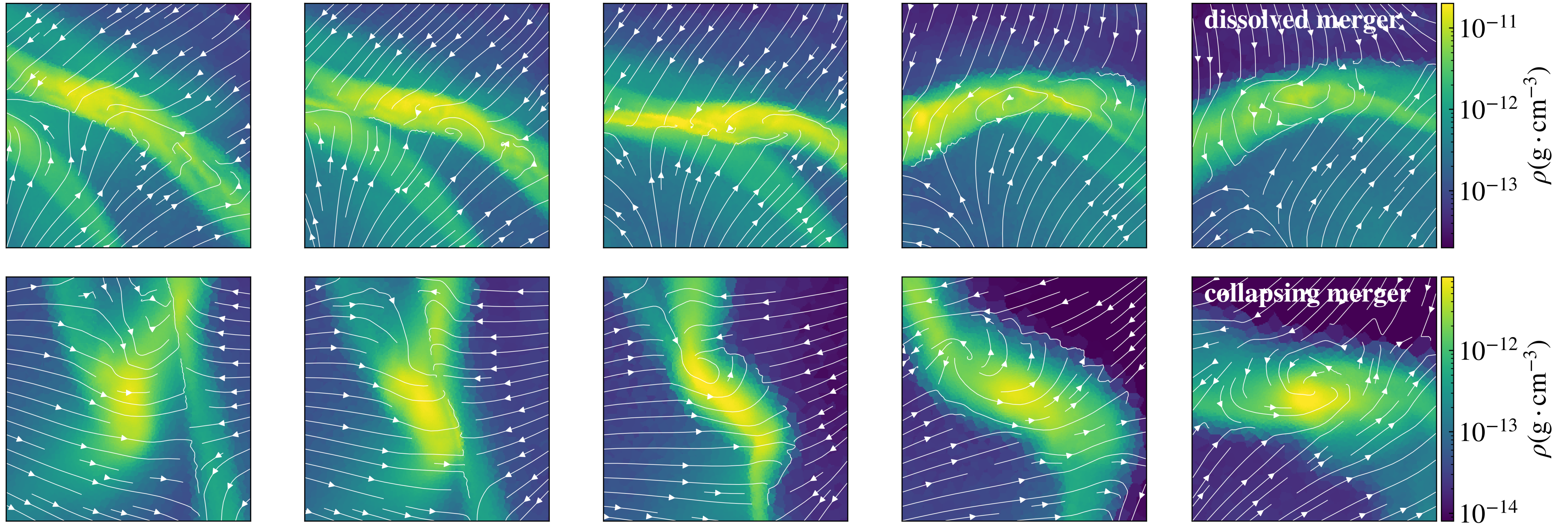
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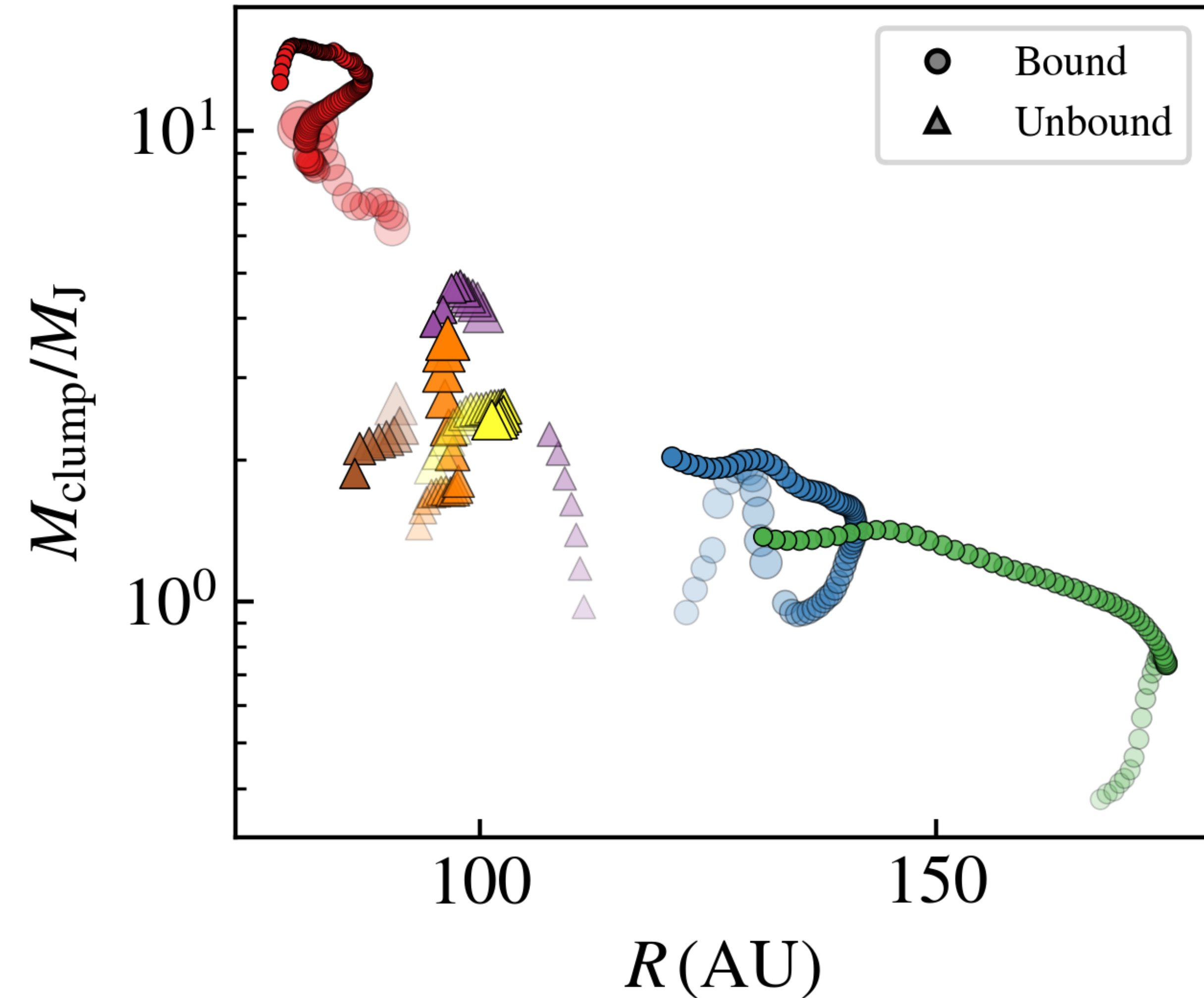
We focus on the initial masses of these gravitationally bound fragments

Q2. If fragments form, what happens to them (mass, survival, migration)?



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Migration & Accretion after fragmentation @m17k5 (fiducial run)



Marker Size: radius

Transparency: time

(early = transparent, late = solid)

Marker shape: triangle = unbound,
circle = bound

Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (1)$$

$$\begin{aligned} \frac{\partial(\rho \mathbf{v})}{\partial t} + \rho \mathbf{v} \cdot \nabla \mathbf{v} = & -\nabla P - \rho \nabla \Phi + \frac{\rho \kappa_F}{c} \mathbf{F}_r \\ & + (\rho \kappa_E E_r \frac{\tilde{c}}{c} - S_r) \frac{\mathbf{v}}{c} - \rho \kappa_E \frac{\tilde{c} \mathbf{v}}{c^2} \cdot (E_r \mathbb{I} + \mathbb{P}_r), \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial(\rho e)}{\partial t} + \nabla \cdot [(\rho e + P) \mathbf{v}] = & -\rho \mathbf{v} \cdot \nabla \Phi - c S_r + \rho \kappa_E \tilde{c} E_r \\ & + \rho (\kappa_F - 2\kappa_E) \frac{\mathbf{v}}{c} \cdot \mathbf{F}_r, \end{aligned} \quad (3)$$

$$\frac{\partial E_r}{\partial t} + \nabla \cdot \mathbf{F}_r = -\rho \kappa_E \tilde{c} E_r + c S_r + \rho (2\kappa_E - \kappa_F) \frac{\mathbf{v}}{c} \cdot \mathbf{F}_r, \quad (4)$$

$$\begin{aligned} \frac{\partial \mathbf{F}_r}{\partial t} + \tilde{c}^2 \nabla \cdot \mathbb{P}_r = & -\rho \kappa_F \tilde{c} \mathbf{F}_r - (\rho \kappa_E E_r \frac{\tilde{c}}{c} - S_r) \tilde{c} \mathbf{v} \\ & + \rho \kappa_E \frac{\tilde{c}^2}{c} \mathbf{v} \cdot (E_r \mathbb{I} + \mathbb{P}_r), \end{aligned} \quad (5)$$

$$\kappa_P = \kappa_E = \kappa_F = \kappa,$$