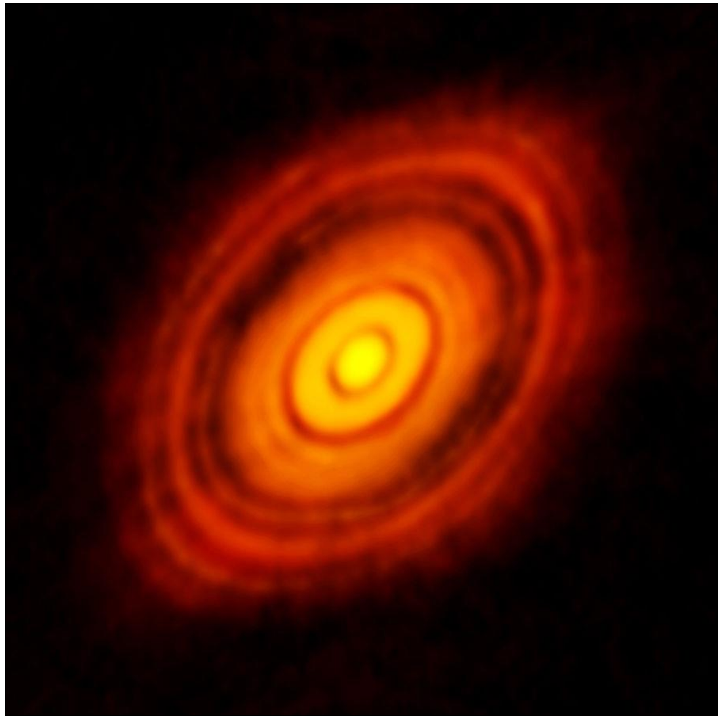
Observational Cosmology Journal Club

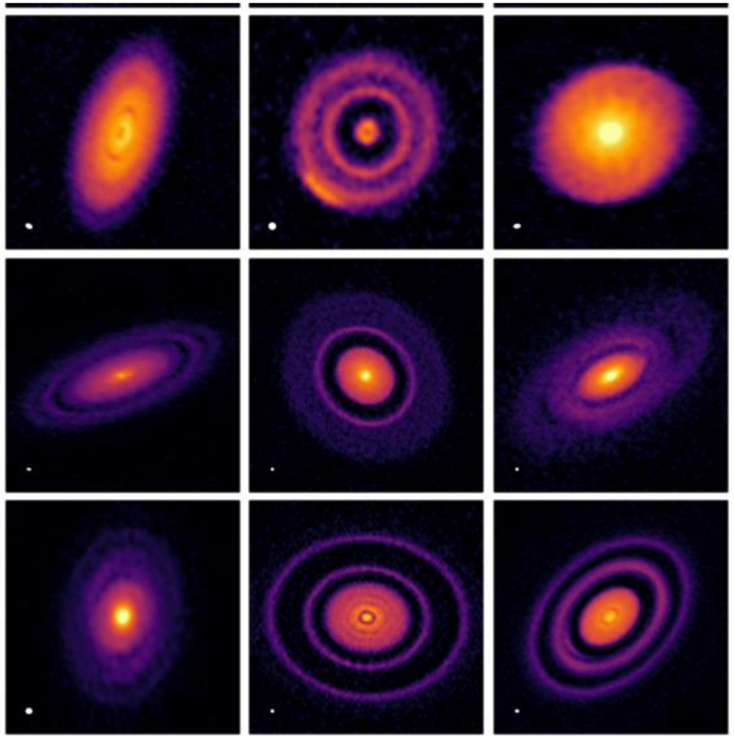
July 8th, 2019 | Shijie Wang

1. R.Miranda and R.Rafikov. **On the Planetary Interpretation of Multiple Gaps and Rings in Protoplanetary Disks Seen By ALMA.** 2019 *ApJL* 878 L9.
2. N.Nelson, B.Bitsch and E.Jurua. **Are the observed gaps in protoplanetary discs caused by growing planets?** arXiv:1906.11491

Common Background

ALMA observation on HL Tau, followed by DSHARP survey of protoplanetary disks → Rings/Gaps





Left: HL Tau[ALMA (ESO/NAOJ/NRAO)]. **Right**: Disk continuum images with rings/gaps[DSHARP]

Interpretation and verification

Multiple Interpretations

- Snow Lines(Zhang & Jin 2015), Instability(Takahashi & Inutsuka 2016), Sintering(Okuzumi et al. 2016), MHD effect(e.g. Flock et al. 2015, Hu et al. 2019), and
- **The most popular: Planet(s)**

Verification: different approaches

- **Miranda and Rafikow[P1]:** hydrodynamical simulations → compare with ALMA observation and other models
- **Ndugu et al.[P2]:** Planet population synthesis → compare with observed exoplanetary population

[P1]Motivation

- Previous studies
  - A **low-mass** (sub-M_{th}) planet can produce multiple rings

$$M_{\rm th} = \left(\frac{H_{\rm p}}{r_{\rm p}}\right)^3 M_* = 1\ M_{\rm J}\left(\frac{H_{\rm p}/r_{\rm p}}{0.1}\right)^3 \frac{M_*}{M_\odot}$$

  - Assume**: locally isothermal model**→ short cooling time → only works well at outer part, not poorly-cooled inner part
- This work
  - Re-examine the case use both **isothermal** and **adiabatic model**
  - Compare the simulation results & show the difference.
  - ‘Urge caution regarding the isothermal model’

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Numerical Setup

Disk Model

- A planet of mass M_p with a radius r_p
- Sound speed given by

$$c_s(r) = h_p r_p \Omega_p \left(\frac{r}{r_p}\right)^{-q/2}$$

- Initial gas surface density

$$\Sigma_g(r) = \Sigma_{g,p}(r/r_p)^{-1}$$

Equation of state

- Isothermal: $P = c_s^2(r)\Sigma_g$
  - No need solving energy equation.
- Adiabatic: $P = (\gamma - 1)e\Sigma_g$
  - **e:** specific internal energy
  - $c_s^2 = \gamma(\gamma - 1)e$ determined by energy equation
  - $\gamma = 1.001$ close to unity to show difference

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Simulations

- 2D inviscid hydrodynamical simulations using FARGO3D
- Two sets of simulations:
  - high spatial resolution (Nr × Nf = 3004 × 4096)
  - lower spatial resolution (Nr × Nf = 1128 × 1536)
- Dust evolution
  - 1D simulation(axial-symmetric)
  - Assume low dust-to-gas ratio → no dust feedback
  - Dust radial velocity(Takeuchi & Lin 2002)

$$u_{r,\mathrm{d}} = \frac{1}{1+\mathrm{St}^2}\left(\bar{u}_{r,\mathrm{g}} + \frac{\mathrm{St}}{\langle\Sigma_\mathrm{g}\rangle\Omega_\mathrm{K}}\frac{d\langle P\rangle}{dr}\right)$$

St: Stokes number
$\bar{u}$: Effective gas radial velocity

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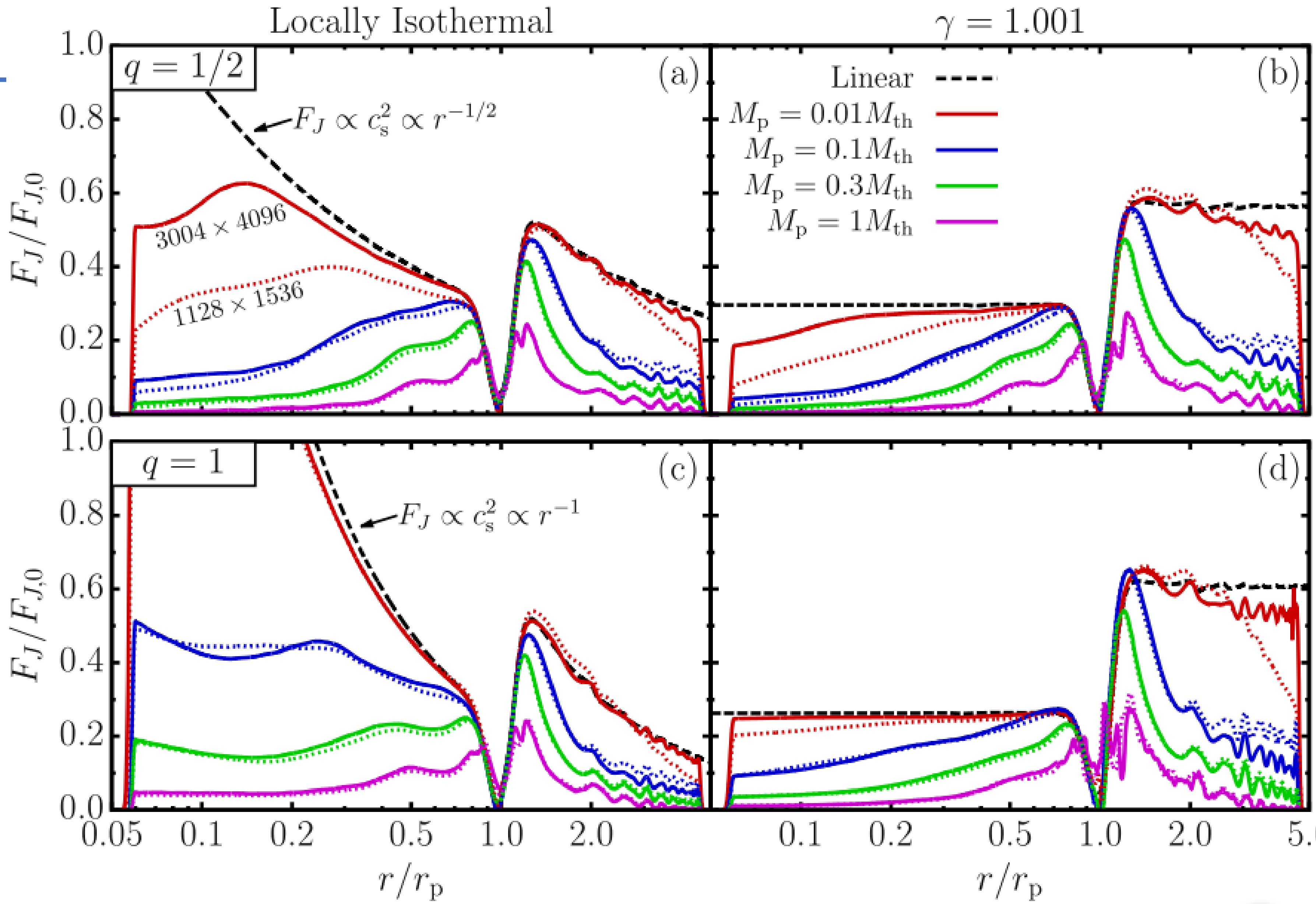
Results

- Angular momentum flux(AMF)
  - Conserved if no dissipation
  - Larger AMF→higher wave amplitude
- $F_j \propto r^{-1}$ (iso) v.s. F_j flat
- Larger mass → more disspation → smaller F_j
- Increase resolution → larger diff. in ISO case→ ISO AD diff. not due to resolution



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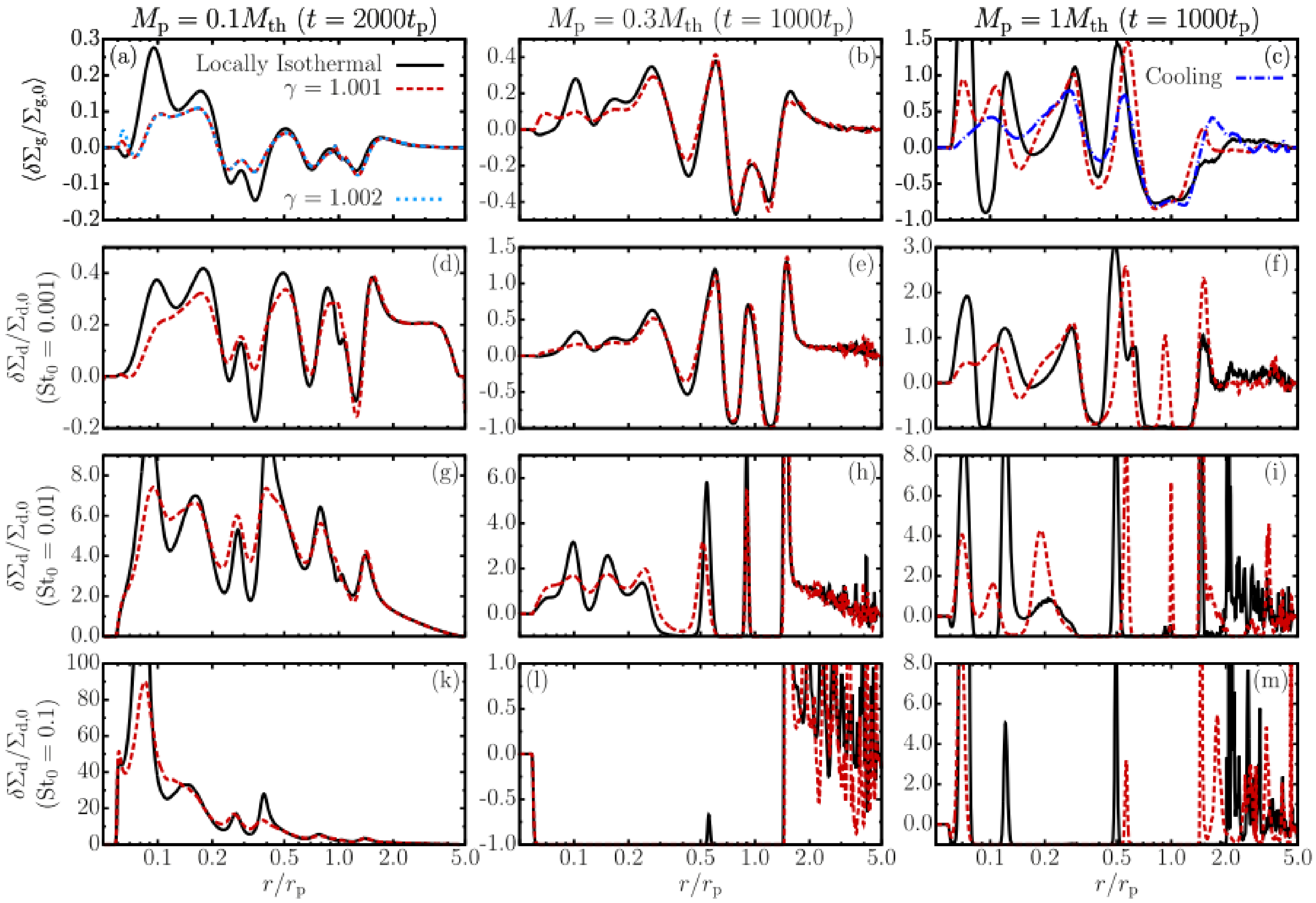
Results: Averaged Gas perturbation

- Results is time-dependent.
- Main difference between ISO and Adb is rate of change.(not shown: ISO higher)
- Four to six rings and some gaps formed
- Gap/ring position diff. increases when:
  - Mass ↑
  - St.#(Dust size) ↑



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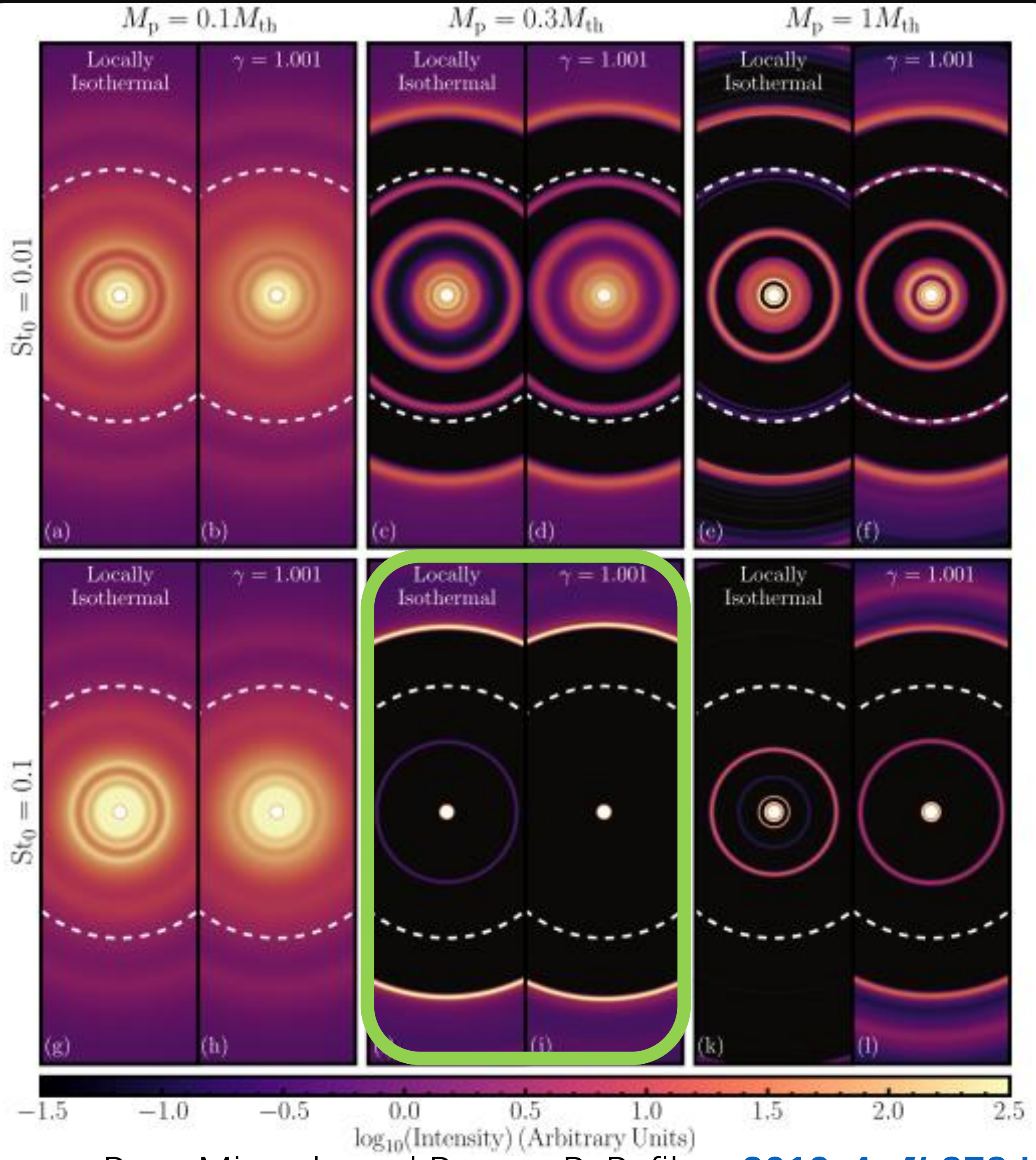
Emission Maps

- Same feature as Fig 2.
- Gaps are more pronounced at $r \leq 0.5 r_p$ when :
  - Small M_P
  - Small Dust size
  - Isothermal case
- $M = 0.3 M_{th}, St = 0.1 \rightarrow$ a faint ring is absent!



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Discussions

- Anomalous behavior of the locally isothermal EoS in numerical applications: qualitative difference
  - A more realistic treatment requires $\gamma = 7/5$, cooling/radiative transfer, and 3D treatment.
  - Deviations arise mainly when waves travel far from the planet, absorbing a significant amount of AMF from the disk flow
- Consideration of additional physics such as migration requires attention to Isothermal treatment
- AMF is useful in showing nonlinear evolution & subtle effects

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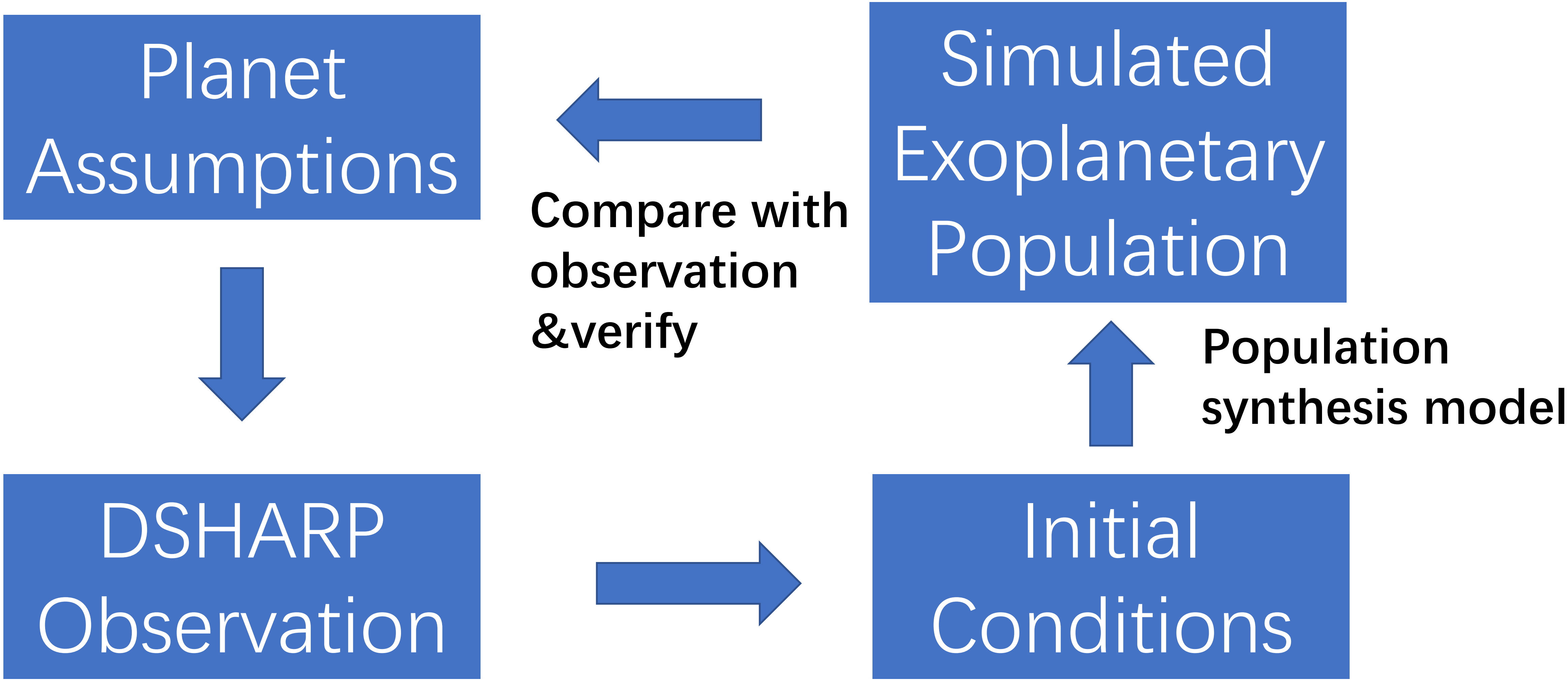
[P2]Motivation



N.Ndugu, B.Bitsch, E.Jurua 2019 arXiv:1906.11491

Model

- Disk Model
  - Based on 2D Hyd-dyn simulations of Bitsch+15
  - Viscosity $\alpha = 5.4 \times 10^{-3}$
- Formation & Migration
  - Pebble accretion rate:

$$\dot{M}_{\rm peb} = 2S_{\rm peb}\pi r_{\rm g}\frac{dr_{\rm g}}{dt}\left(Z_{\rm peb}\Sigma_{\rm g(r_g)}\right)$$

  - Gas accretion rate(Bitsch+15a):

$$\dot{M}_{\rm gas} = 0.000175 f^{-2}\left(\frac{\kappa_{\rm env}}{1{\rm cm}^2/{\rm g}}\right)^{-1}\left(\frac{\rho_{\rm C}}{5.5{\rm g/cm}^3}\right)^{-\frac{1}{6}}\left(\frac{M_{\rm c}}{\rm M_E}\right)^{\frac{11}{3}}\left(\frac{M_{\rm env}}{1{\rm M_E}}\right)^{-1}\left(\frac{T}{81{\rm K}}\right)^{-0.5}\frac{\rm M_E}{\rm My},$$

  - Migration(Paardekooper+11): Γ_L and Γ_C

Randomised Initial Conds

- Disc metallicity and lifetime → disc structure
  - Power-law disk profile: $\Sigma_g \propto R^{-\frac{14}{15}}$, $H \propto R^{2/7}$
- Implantation time and position → growth and migration trajectories of cores
- Full simulations performed until 10 Myr

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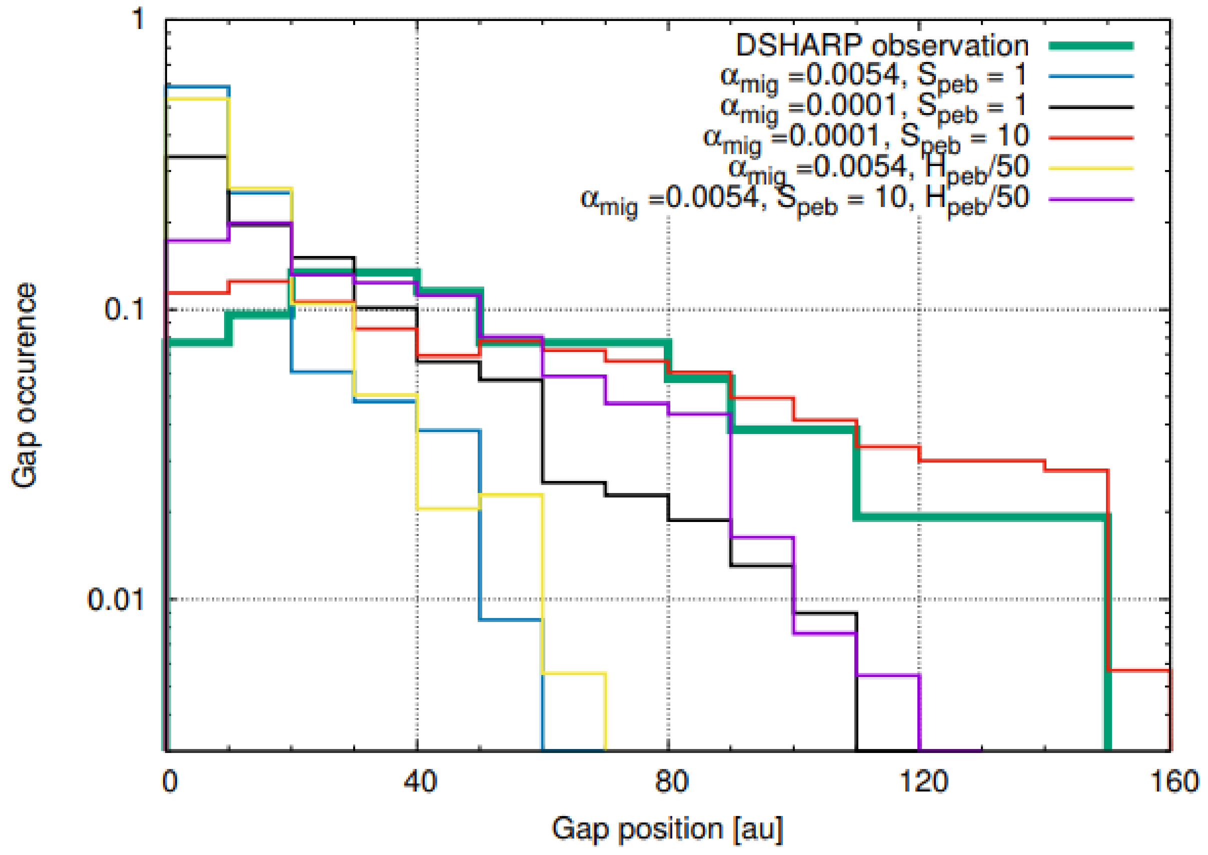
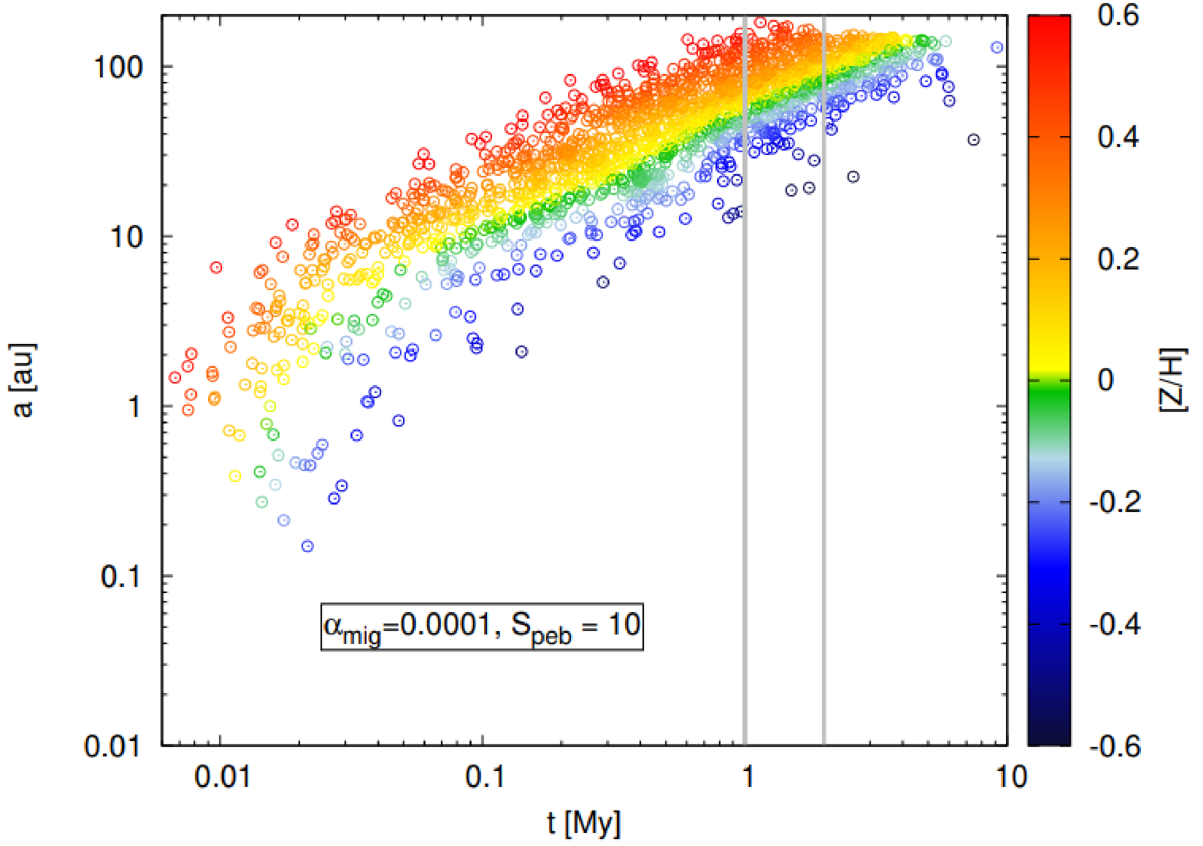
Match to DSHARP



Comparison of gap occurrence rate (embryos reach M_{iso} per disk)



Position and time when $M_p = M_{iso}$

M_{iso}: pebble isolation mass; S: pebble scaling factor

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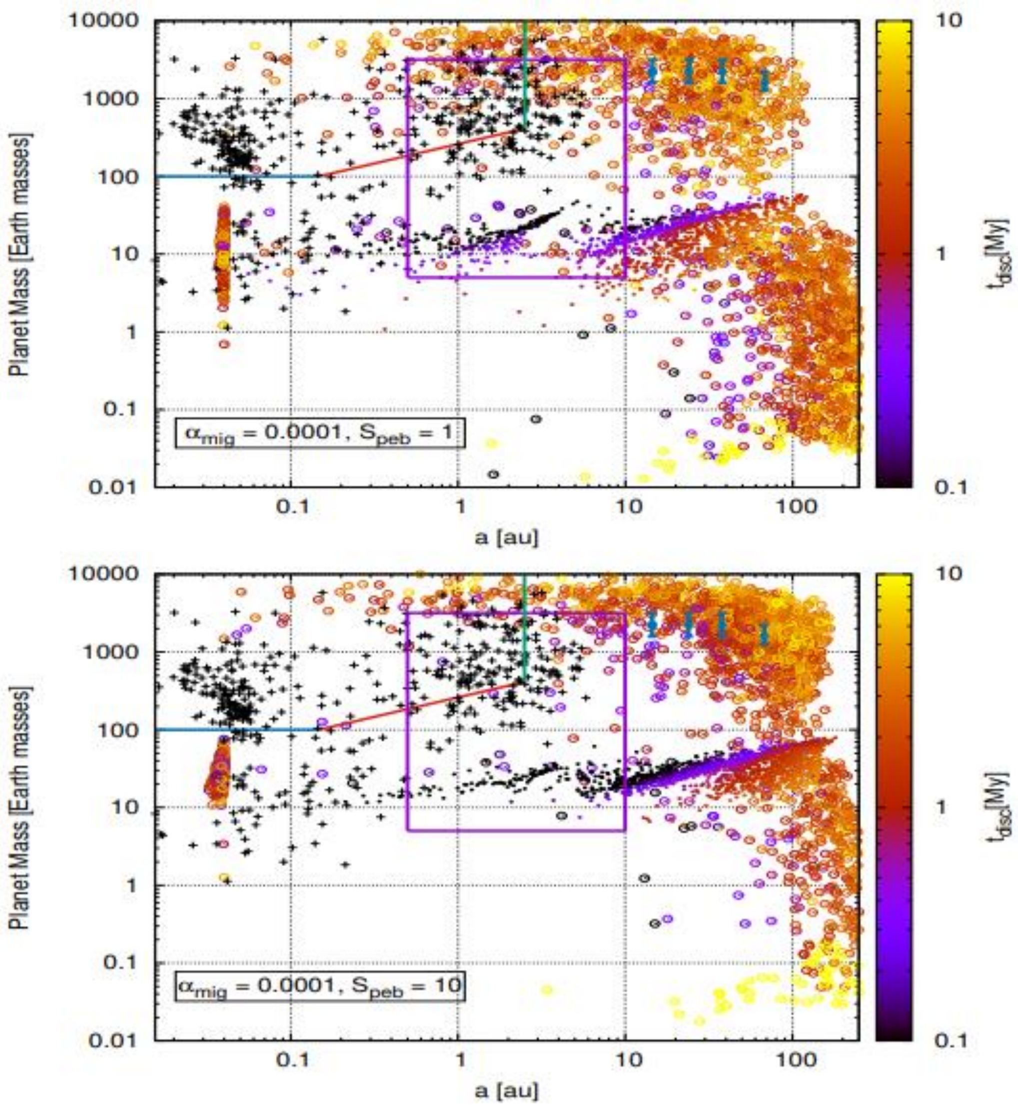
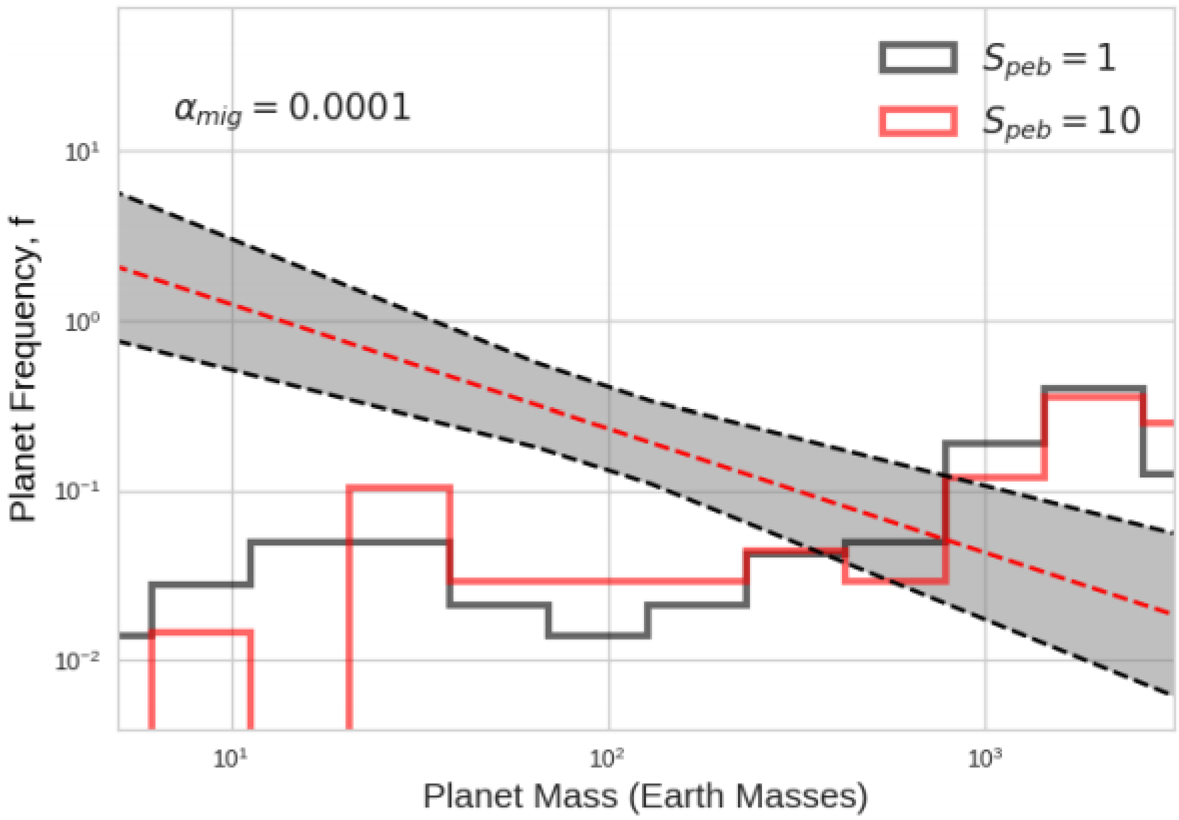
Match to Exoplanet data(RV & Microlensing)





↑ Gas giants are overestimated and super-earths underestimated(with Microlensing)

↑ black '+' : RV data, open circle: full simulation

N.Ndugu, B.Bitsch, E.Jurua 2019 arXiv:1906.11491

Takeaway

- A large amount of pebbles are required to explain the observed rings.
  - Not all rings are caused by planets, or
  - Planet formation simulation missed important ingredients of gas accretion
- Planetary formation timescale required is close or longer than disk lifetime
- Pebble production line at around 300 au required → larger than observation
- DSHARP can be biased and not representative

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