Preservation of hot Super Earths & cold Gas Giants after Pebble Isolation

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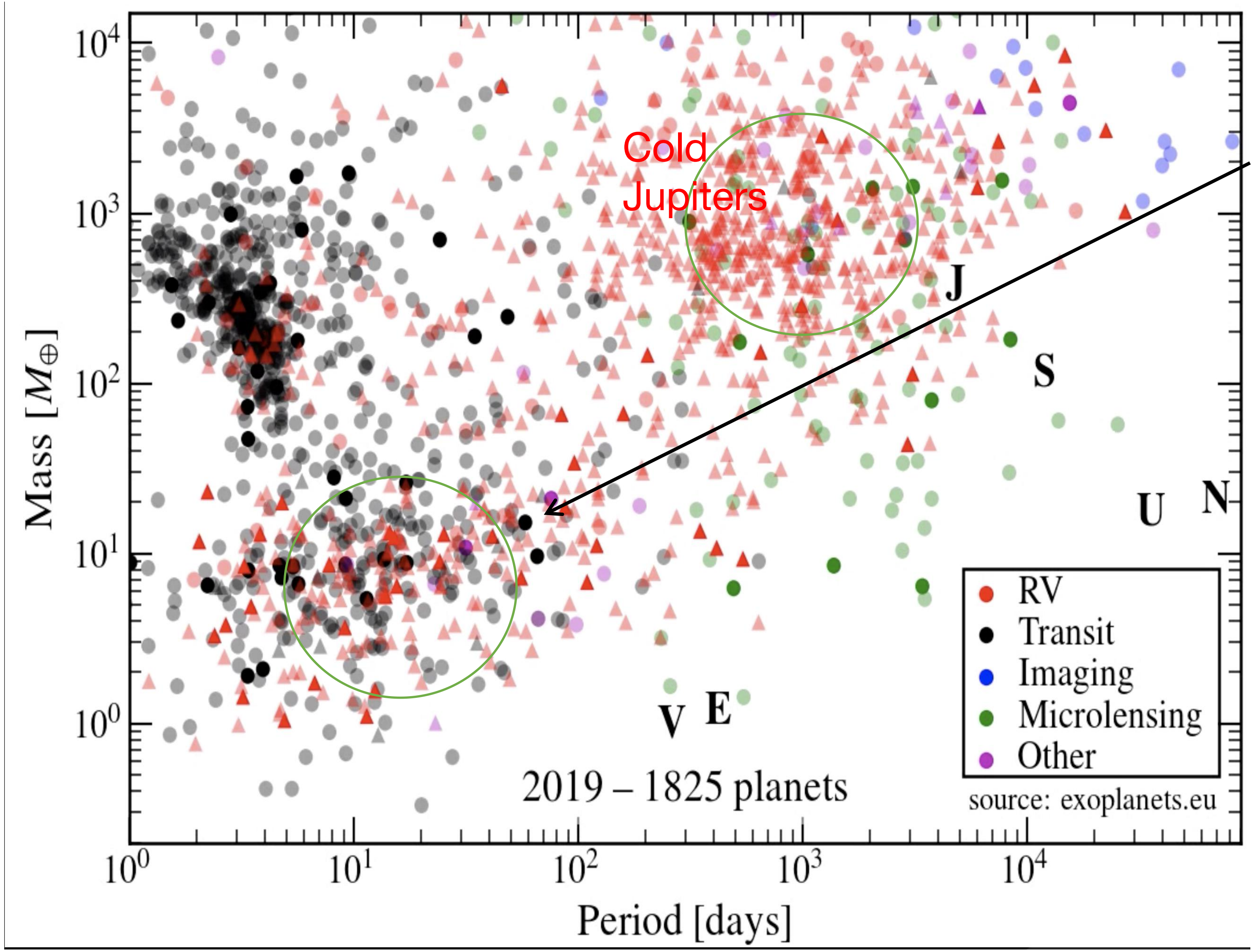
Super Earths and Gas Giants



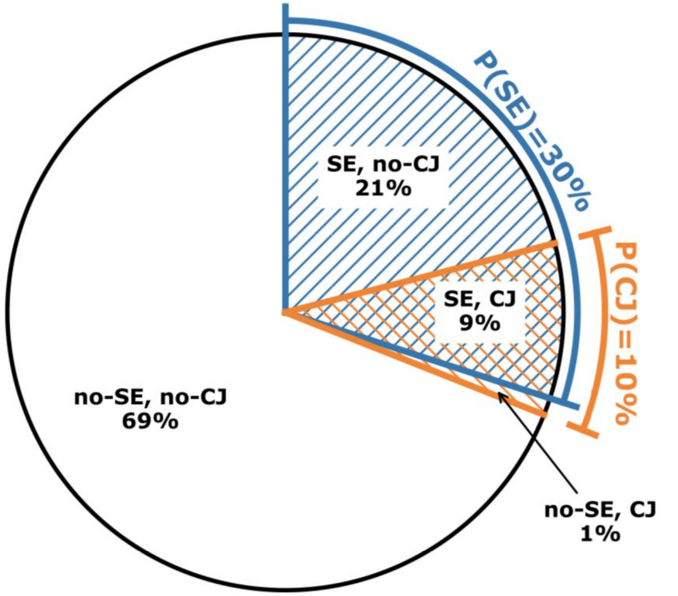
Super Earths / Sub-Neptunes

2-10 M_e; Rock core with 1-10% atmosphere

(Earth: 1e-4%)

But **0.03-0.5 AU** close in and very common inferred to be in 30% of systems

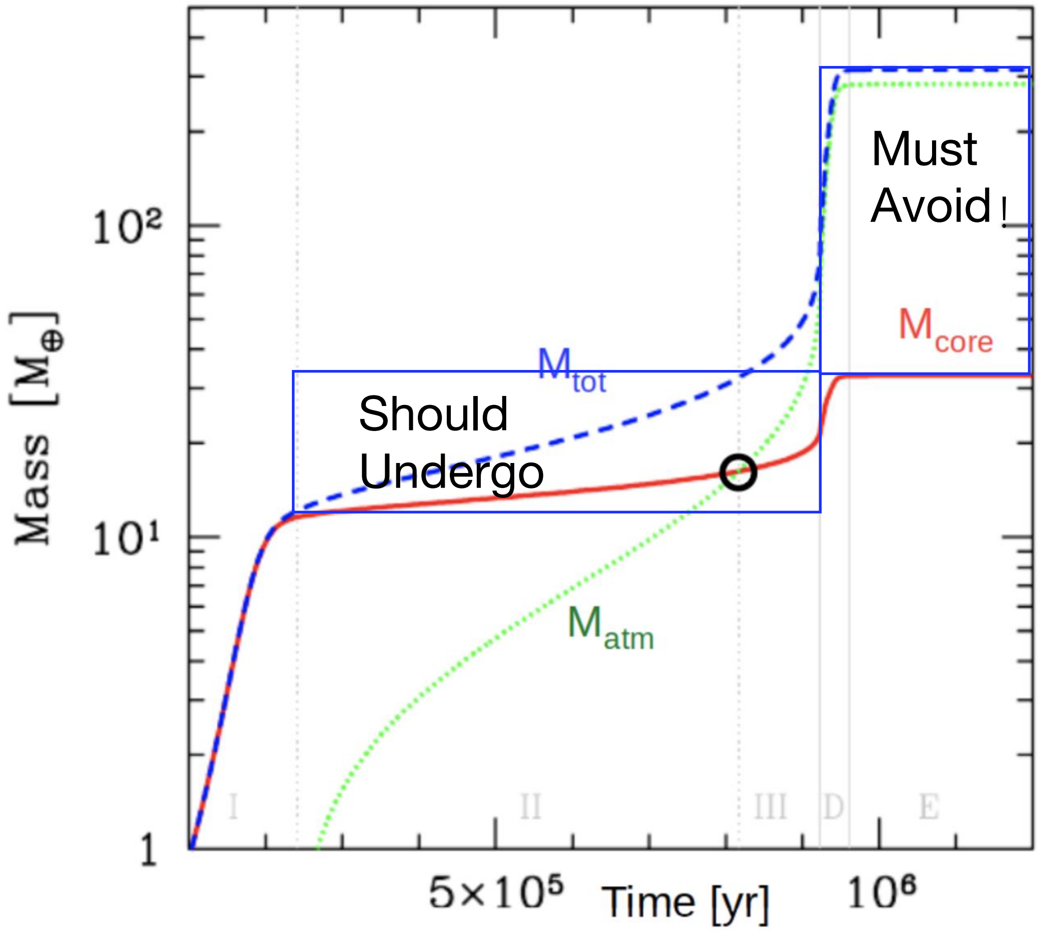
(E.g. Howard+. 2010)



Zhu & Wu 2018: systems with cold Jupiters almost certainly have super Earths, suggesting similar origin

Super Earth Retention Problem

Recall the core-accretion model: After formation of core, a ~10 M_e planet core undergoes slow accretion till Gas to Core mass ratio ~1 then explode into a gas giant



Mordasini et al. (2012)

Typical Disk Lifetime ~10 Myrs

The retention problem: cores might accrete massive envelopes and explode into gas giants after GCR~1

Gas Accretion by KH Contraction (Piso & Youdin 2014)

After the planet reaches a stable core-mass, gas starts to accrete onto it

1D atmospheric Core Accretion Model

$$\text{Mass Distribution: } \frac{dM(<R)}{dR} = 4\pi R^2 \rho_g$$

$$\text{Hydrostatic Equilibrium: } \frac{dP}{dR} = -\frac{GM(<R)}{R^2}\rho_g$$

$$\text{Heat Transfer: } \frac{dT}{dR} = \frac{T}{P}\frac{dP}{dR}\nabla$$

$$\text{Ideal Gas EOS: } P = \frac{\rho_g}{\mu}\mathcal{R}T,$$

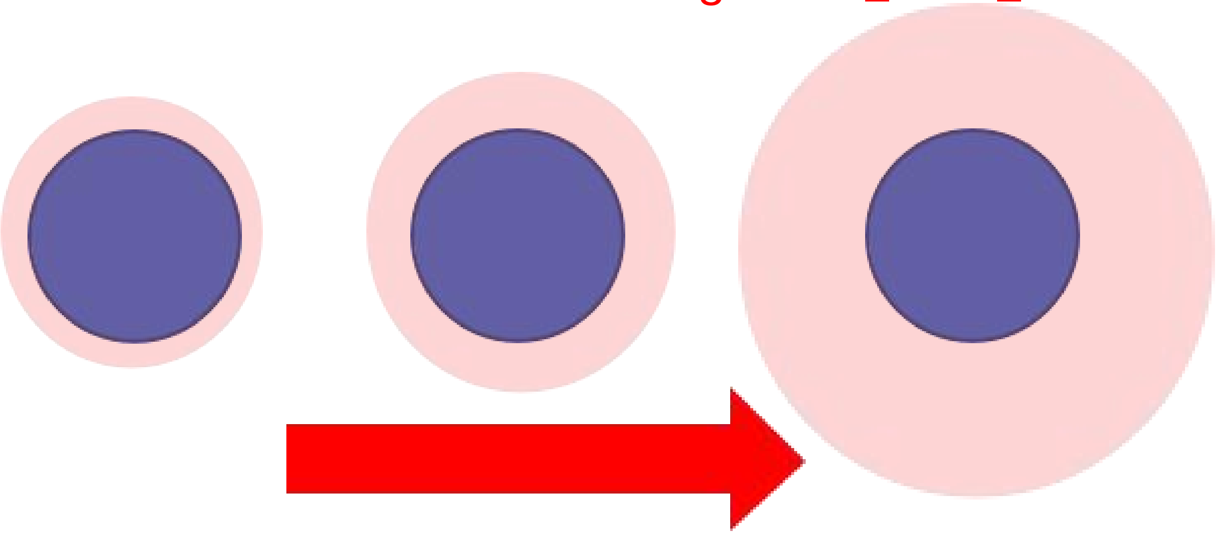
$$\nabla = \min(\nabla_{ad}, \nabla_{rad}),$$

$$\nabla_{ad} = \frac{\gamma - 1}{\gamma},$$

$$\nabla_{rad} = \frac{3\kappa P}{64\pi G M \sigma T^4} L.$$

Construct a series of solutions with different envelope mass

Integrate from Rout (the smaller of Bondi and Hill radius)
To Rin: (core radius)
Known: M_out, T_out, P_out
Iterate out the correct L that gives M_in=M_core



$$\Delta t = \frac{-\Delta E + \langle e_M \rangle \Delta M - \langle P \rangle \Delta V_{\langle M \rangle}}{\langle L \rangle}$$

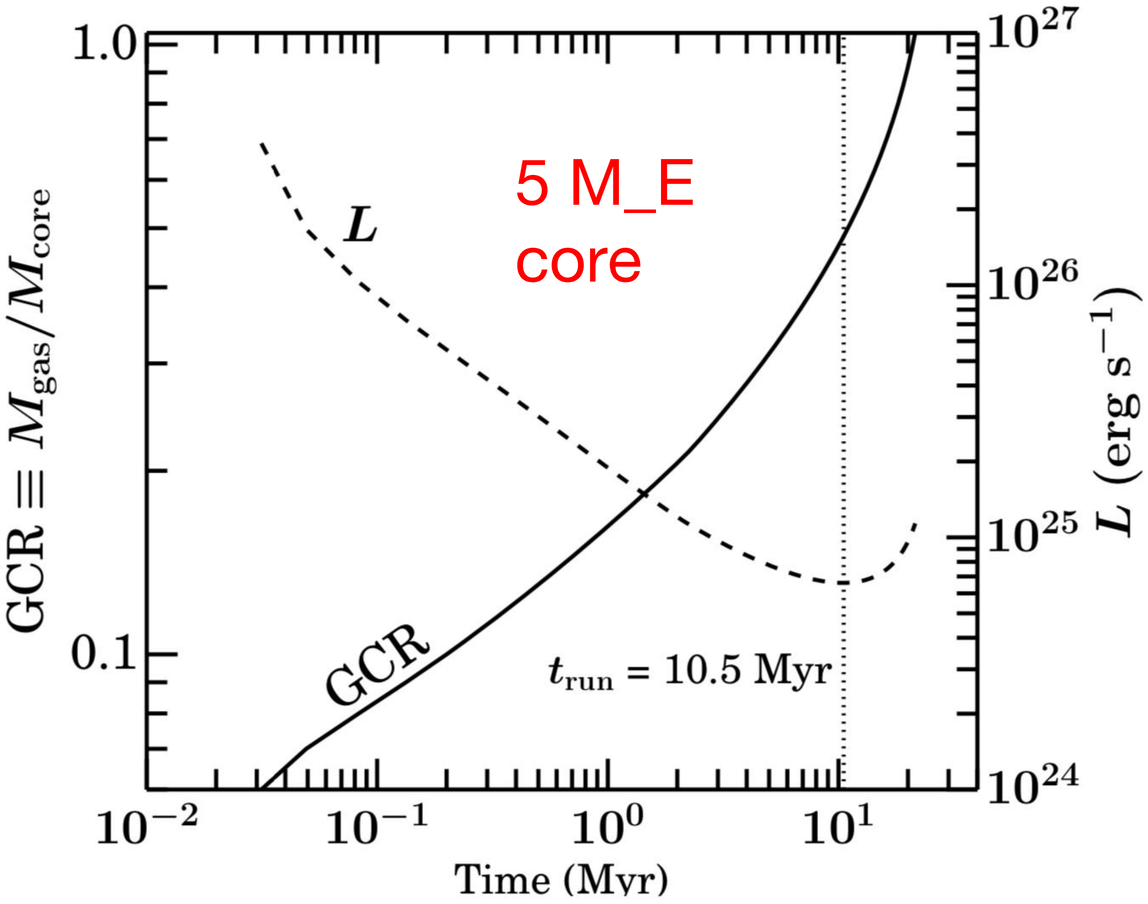
Time elapsed

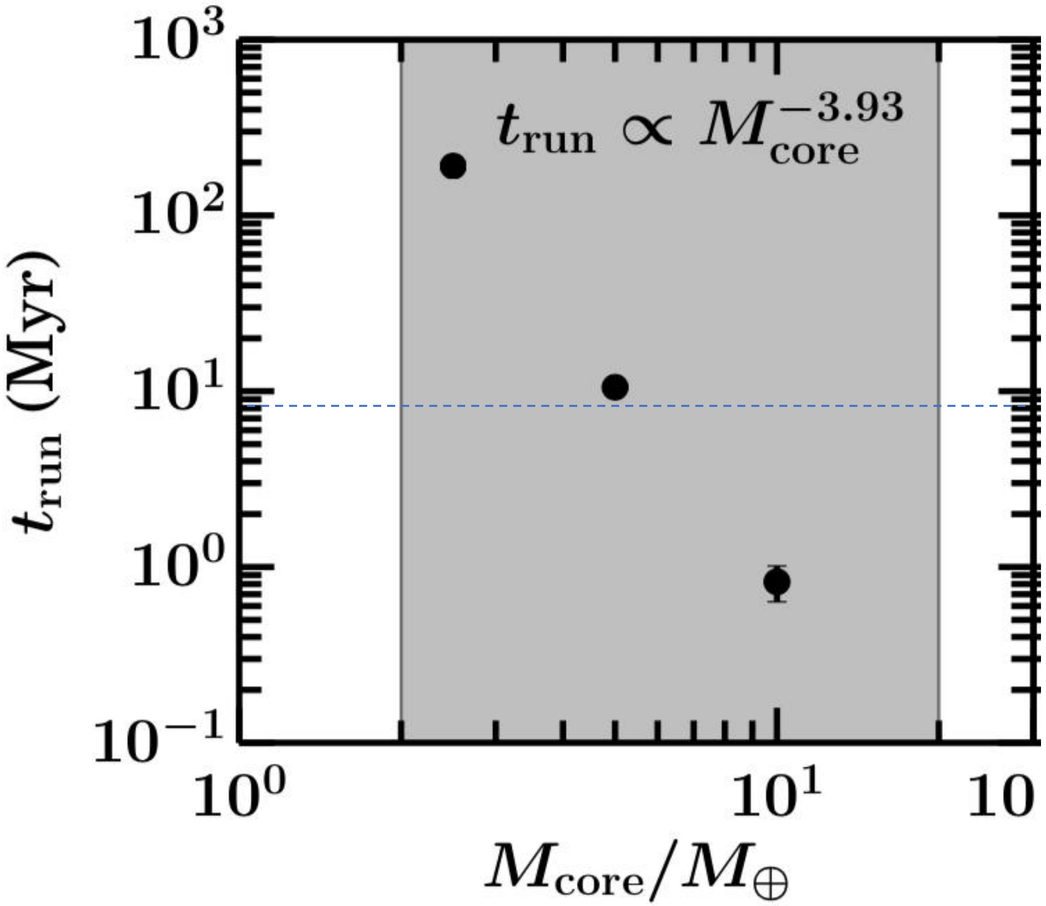
Super Earths forming in-situ at 0.1AU

Lee, Chiang & Ormel (2014): Boundary condition MMEN
A more sophisticated opacity table
Adiabatic gradient obtained from solving ionization fraction
to be ~1.25 inside the convective zone instead of a fixed 1.4

$$\rho_{\rm MMEN} = 6 \times 10^{-6} \left(\frac{a}{0.1\,\rm AU}\right)^{-2.9}\ \rm g/cm^3$$

$$T_{\rm MMEN} = 1000 \left(\frac{a}{0.1\,\rm AU}\right)^{-3/7}\ \rm K$$





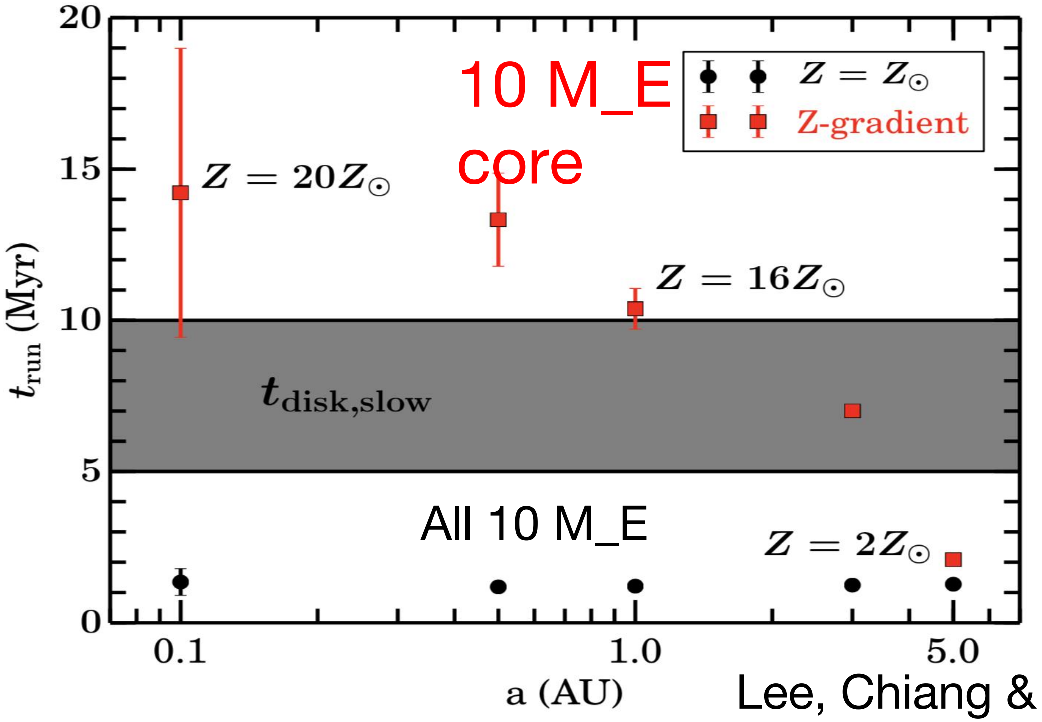
Remedy: Opacity

$$\nabla_{rad} = \frac{3\kappa P}{64\pi G M \sigma T^4} L.$$

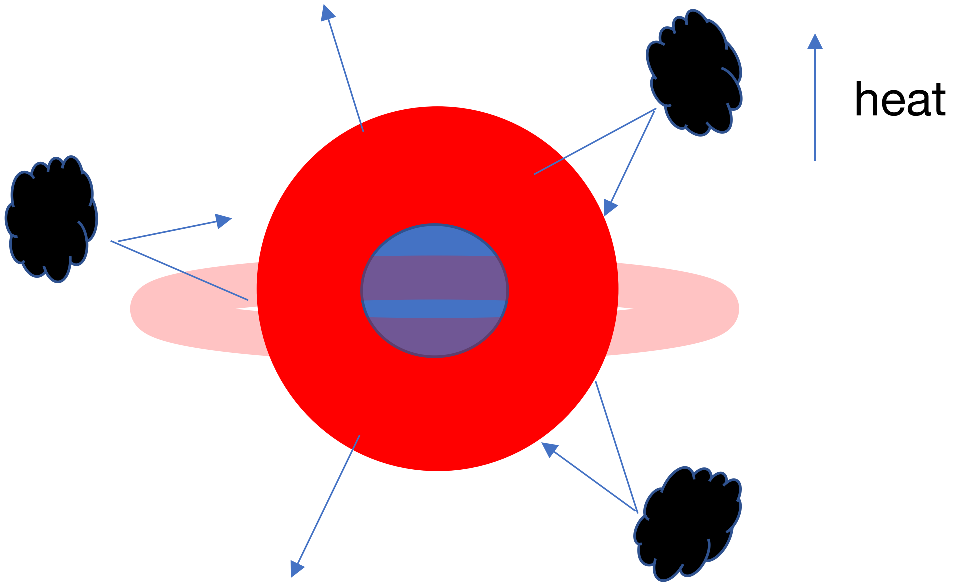
Contributed by dust grains <2000 K (usually since radiative zone is near outer boundary)
or gas >2000K

- Grain Contaminant ↑
- Opacity ↑
- Cooling ↓
- Accretion Rate↓ (Ikoma+2001: t_run ~ opacity)

"To Cool is to Accrete!"
— —Lee & Chiang 2015



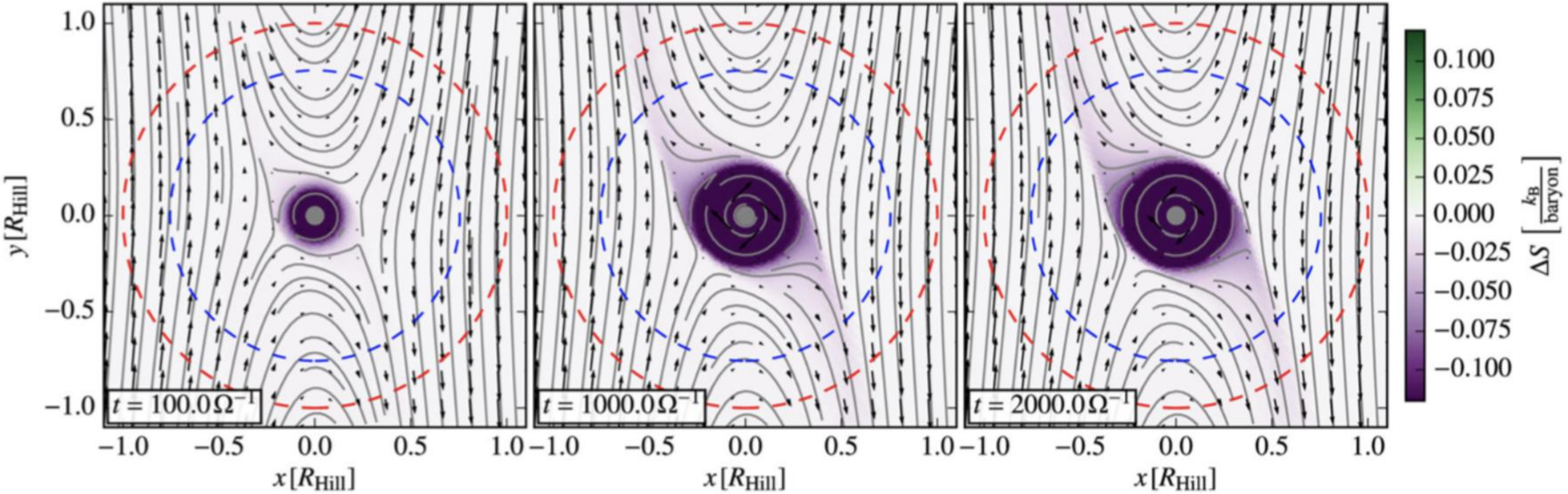
Lee, Chiang & Ormel (2014)



Remedy: Entropy Advection

Ormel+ 2015, Cimerman, Ormel+ 2017

Time



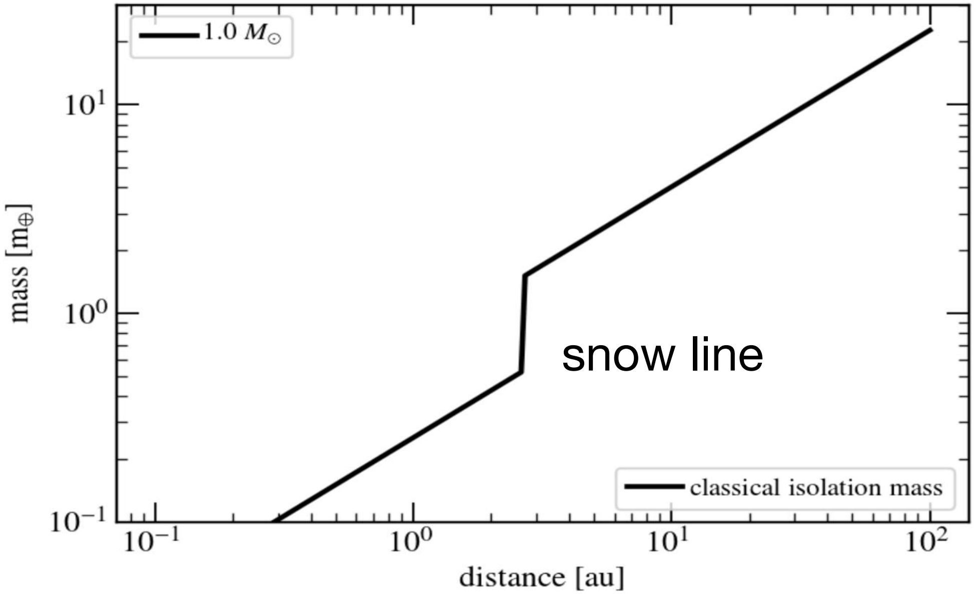
In 3D simulations, gas continually RECYCLES between the cores atmosphere and the back-ground disk

A considerable part of the Hill/Bondi radius maintains same ENTROPY with environment and is not bounded to the core. <~0.3 R_H we finally see trace of entropy transition (radiative zone), and an inner equi-entropy zone (REAL bounded convective zone)

Ali-Dib+2020: effective at 0.1AU, less effective at ~1-5AU

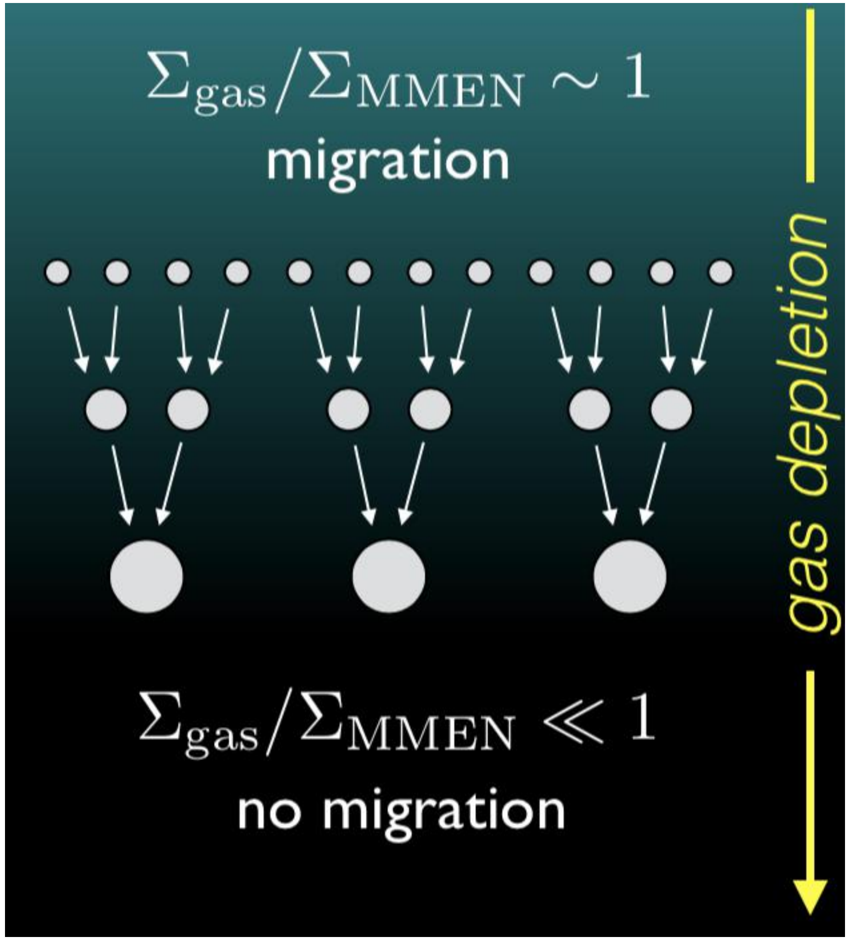
Late Formation of Cores

- the planet **isolation mass** is reached when
  $$M_{\mathrm{iso,pl}} = 2\pi r \cdot \Sigma \cdot \Delta(M_{\mathrm{iso,pl}})$$
  with:
  - –Δ the spacing between embryos
  - –Σ the surface density (solids)
- the mutual spacing is usually expressed in terms of Hill radii:
  $$\Delta = bR_{\mathrm{Hill}} \text{ where } b \approx 10.$$



Classical isolation mass with b=10 and MMSN Σ (2x enhancement outside iceline)

Lee & Chiang 2016: the final 10M_E masses can only form through giant impacts and mergers of small mars-size embryo isolating cores at late stages with ~two order of magnitude lower gas density to quench the accretion rate



Then is there no possibility for larger cores to form early?

Pebble Accretion

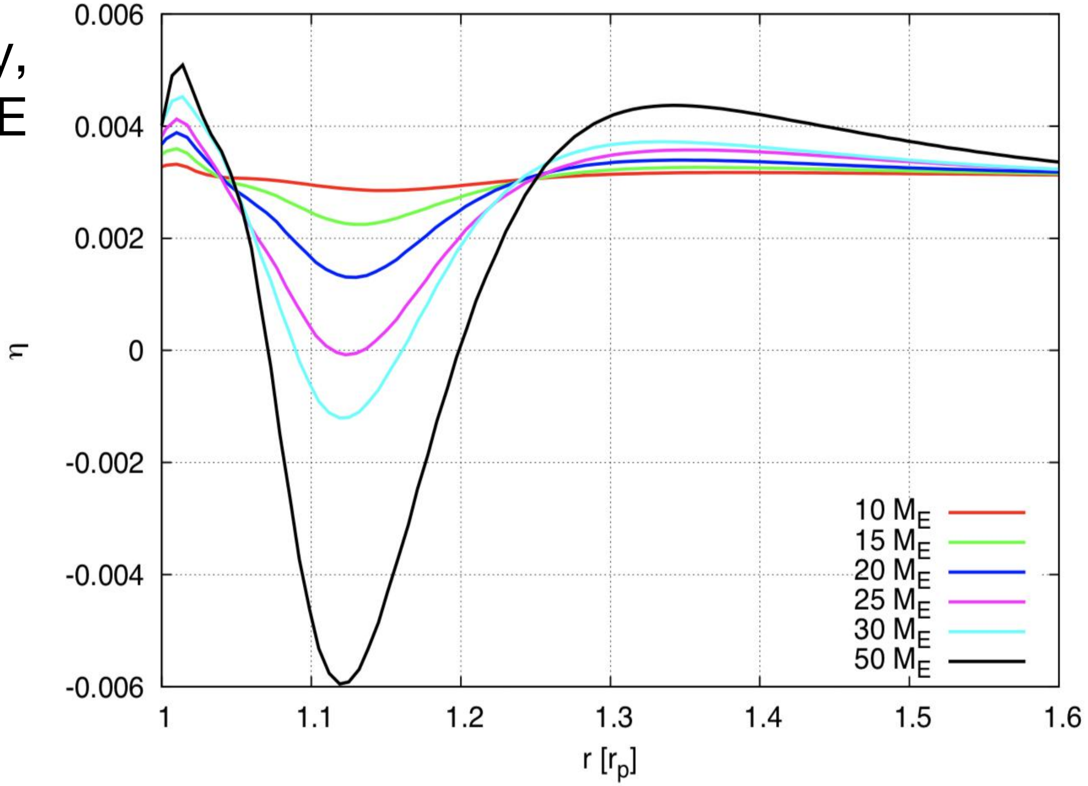
1. Small embryo-isolation cores emerge very quickly, but can subsequently grow up to masses of 5-10M_E via pebble accretion (since pebbles constantly drift past the planet orbit)

$$M_{\rm Iso} \approx 20\,(h/0.05)^3\, m_* M_\oplus$$

$$m_* = M_*/M_\odot$$

passive disks:
increase with r
active disks:
nearly constant

Lambrecht+ 2014

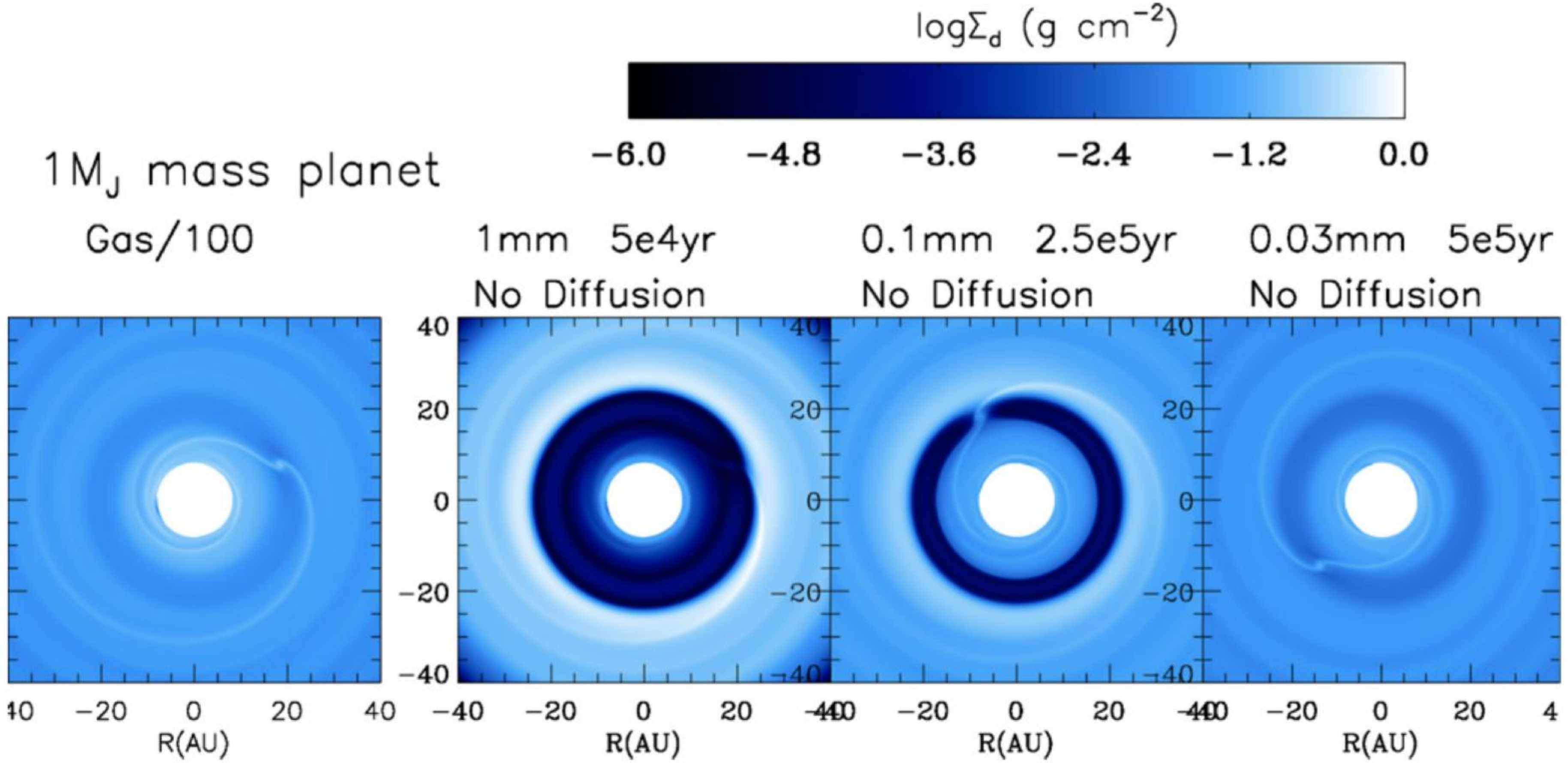


E.G. pressure gradient parameter around a planet for different mass Bitsch+. 2018

2. Pebble isolation: tidal interaction of Gas & Planet creates a pressure maxima that traps in-drifting pebbles
-Start of quasi-steady gas accretion

Self-limiting Opacity Enhancement

Pebble isolation -> Pebble accumulation at the boundary
-> fraction of abundant pebble fragment into dust -> filtered through to enhance dust around planet vicinity ->growth of opacity



Filtering effect of pressure maxima (Zhu+ 2012, jupiter mass)

Super Earth has smaller magnitude, but similar

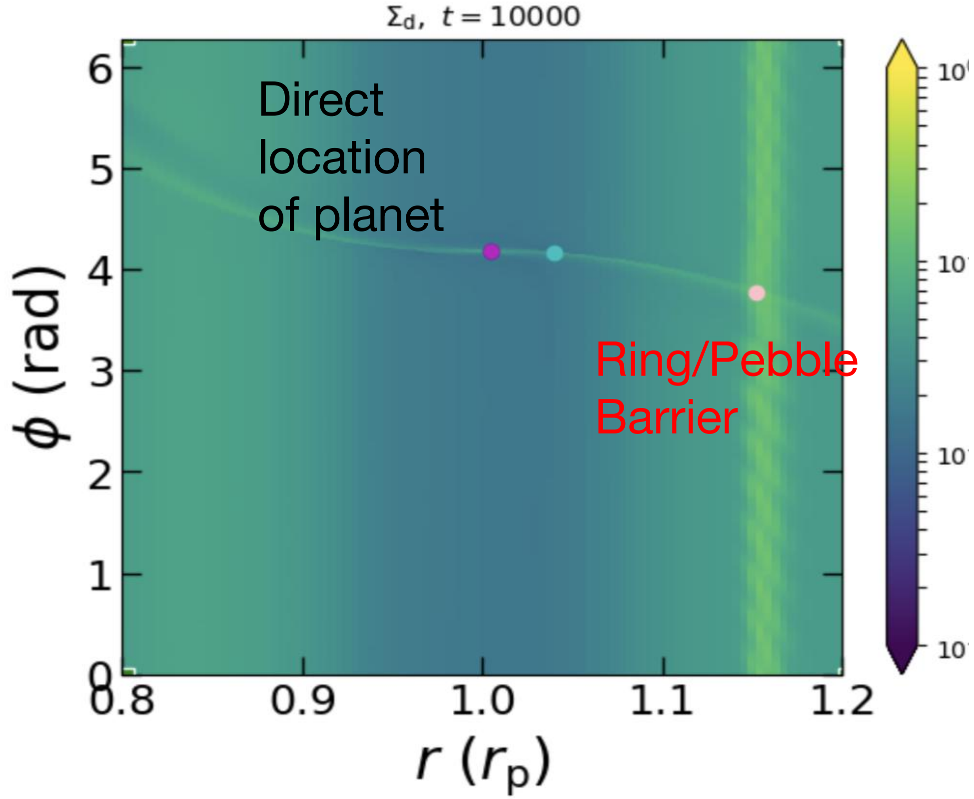
What happens at Pebble Isolation (10 M_E core)

- Initial Dust: total d2g=0.01, MRN distribution from 10^-4-10^2cm, divided into 151 species (152 fluids)

- Run full coagulation model (Li Y-P et al 2019) with LA-COMPASS, provided constant flux from outer boundary

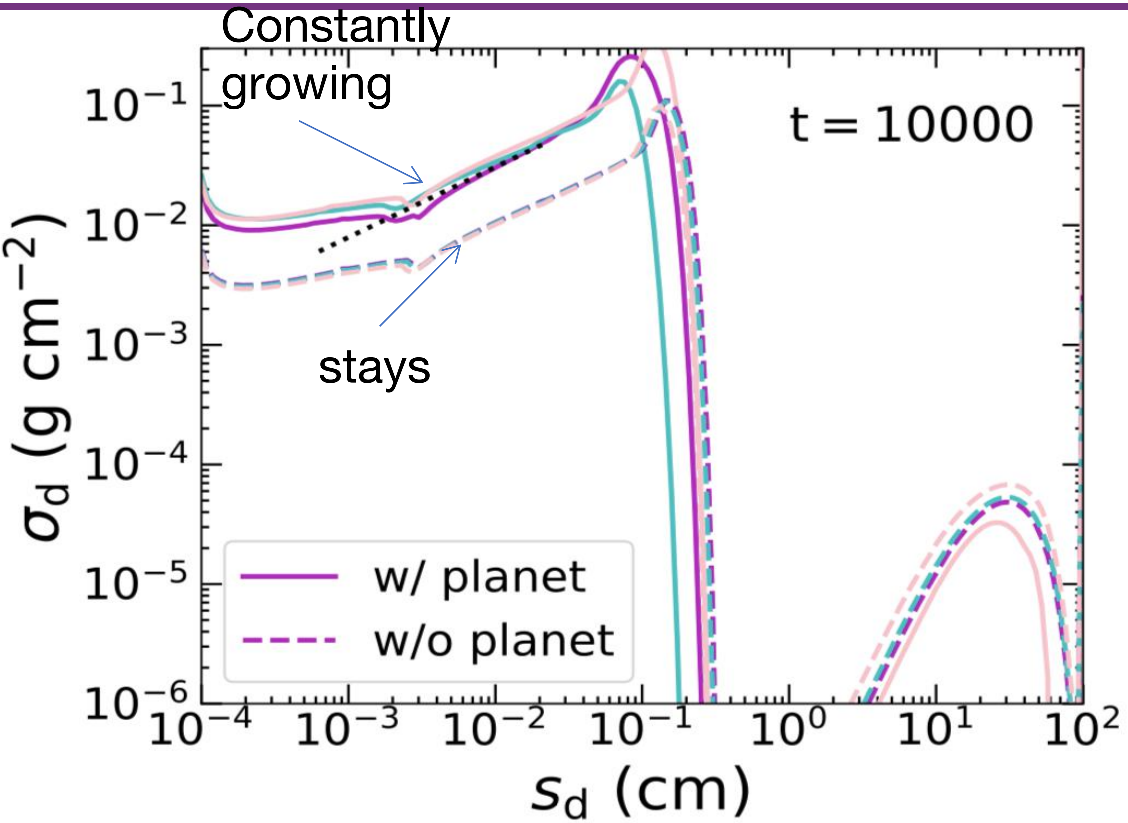
- Coagulation Scheme based on Birnstiel (2010), fragmentation if collision velocity > v_f=10m/s
  fragmentation result: ~MRN distribution

What happens at Pebble Isolation (10 M_E core)



Direct location of planet

Ring/Pebble Barrier



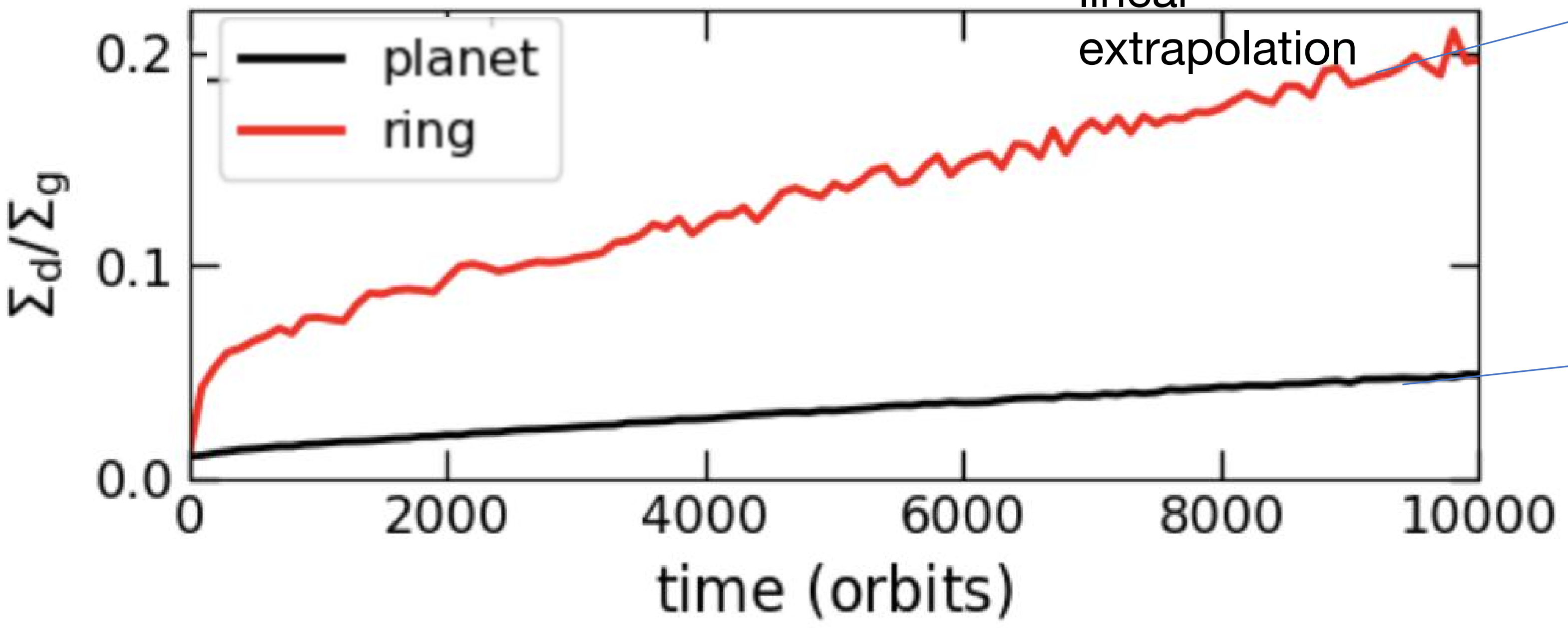
Constantly growing

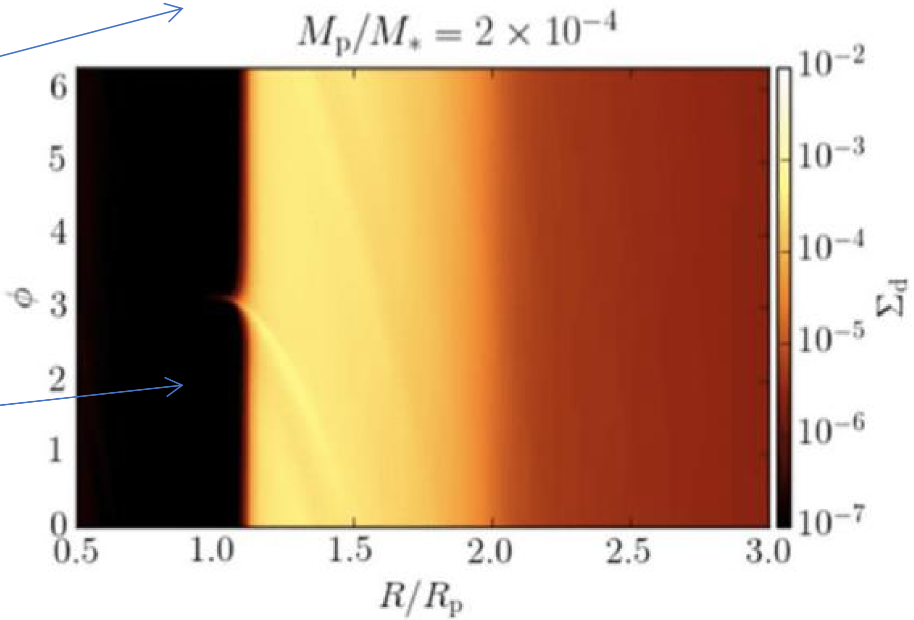
stays

1. no planet case: three locations have little difference and the total d2g settles at ~0.02
2. planet case: pebbles (St>=1) population is blocked at the ring and does not enter to planet radius
3. comparing two cases, one is stalled and other one is growing

only growing in magnitude, but the shape of size distribution fixed

What happens at Pebble Isolation (10 M_E core)



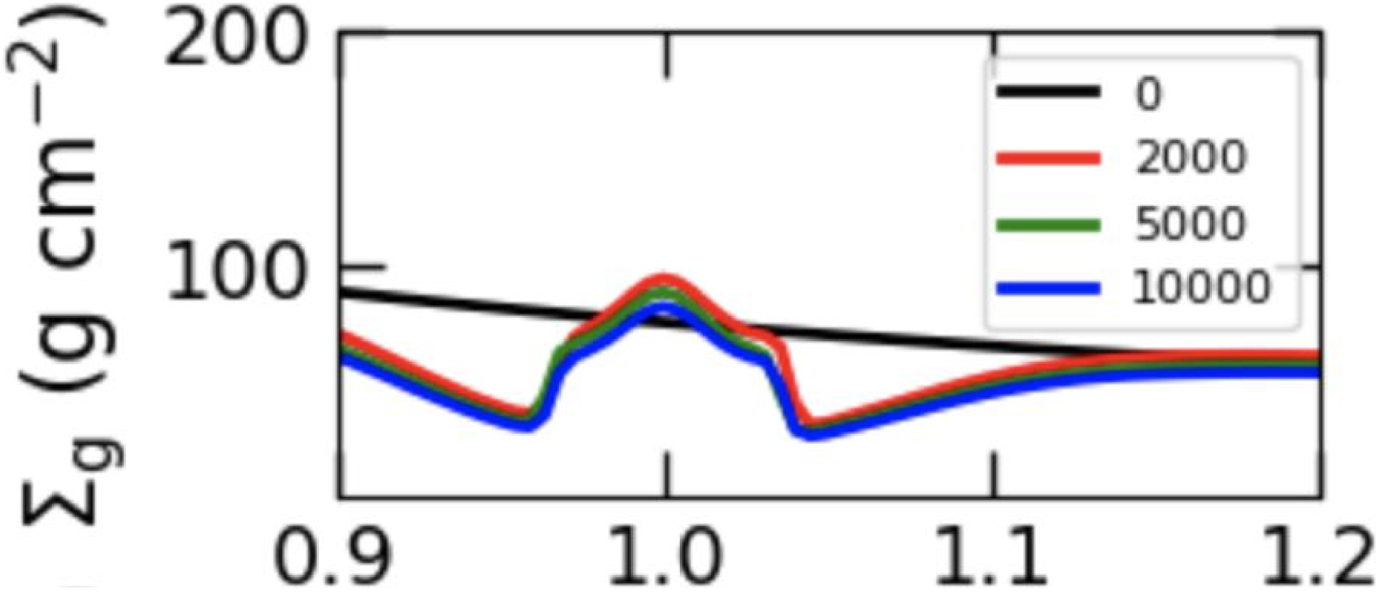


Dust density flattens out after d2g~1, Kanagawa+. 2018

- Linear extrapolation to get a “final” dust size distribution around vicinity of planet when the ring d2g reaches ~1
- Compared to no planet stable case, dust density is higher by ~10 and concentrated more towards the <mm size (because no pebbles)

similar at closer-in distance

Does the Boundary Gas Density Change?



At the exact planet azimuth, the Density wave cancels out the small reduction of gas density. Therefore boundary gas density is nearly unchanged

Used a small gas density to save computational expenses
Pebble isolation is generic-> the change in dust distribution for MMEN, different radii will be similar, scaling with a higher gas density

Dust Distribution -> Perturbed Opacity

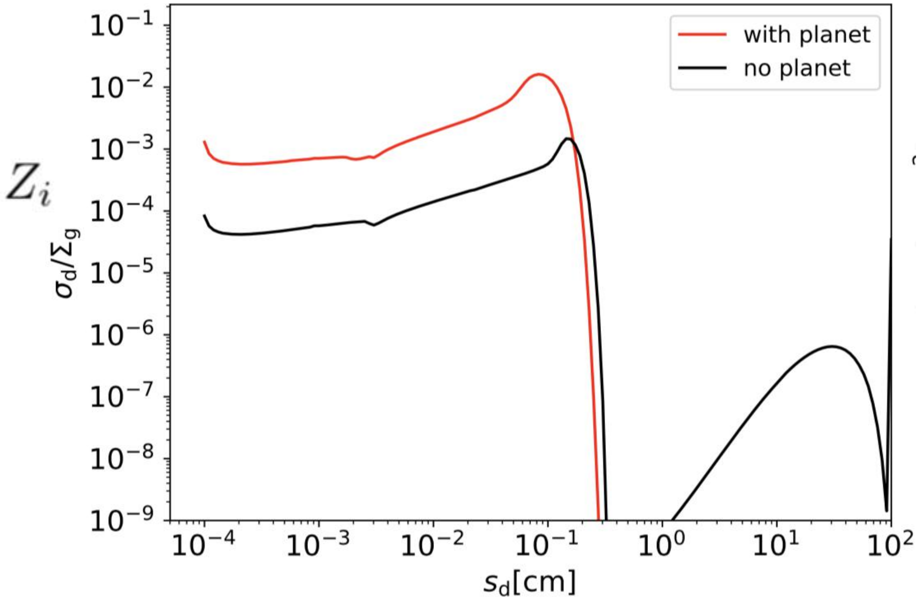
$$\nabla_{rad} = \frac{3\kappa P}{64\pi G M \sigma T^4} L.$$

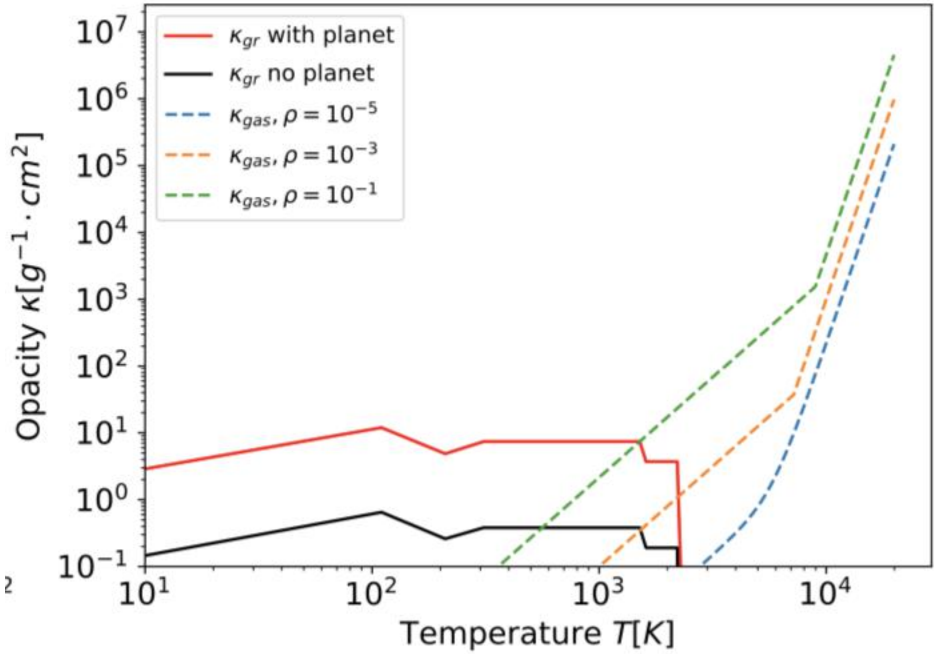
$$\kappa = \kappa_{\rm gas} + \kappa_{\rm gr} = \kappa_{\rm gas} + \sum_i \kappa_{\rm geom}(s_i) Q_e(s_i)$$

Formula from Ormel 2014
Gas opacity from Bell & Lin 1994

$$\kappa_{\rm geom}(s_i) = \frac{3}{4\rho_\bullet s_i} Z_i, Q_e(s_i) = \min(0.3x_i, 2) \qquad x_i = 2\pi s_i/\lambda_{\rm max}(T)$$

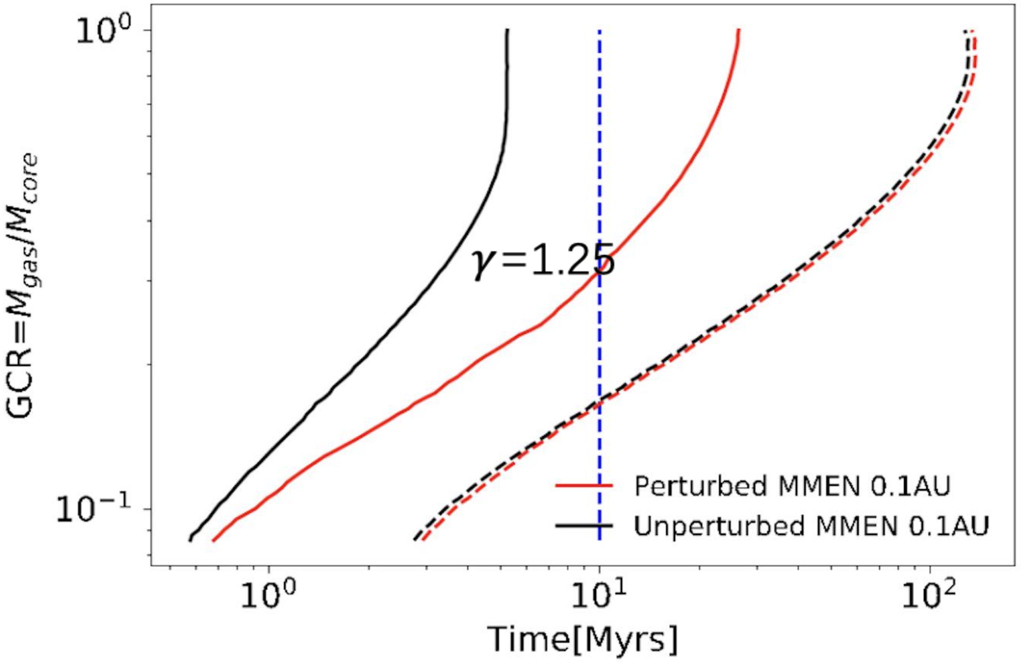
Abundance(d2g ratio)





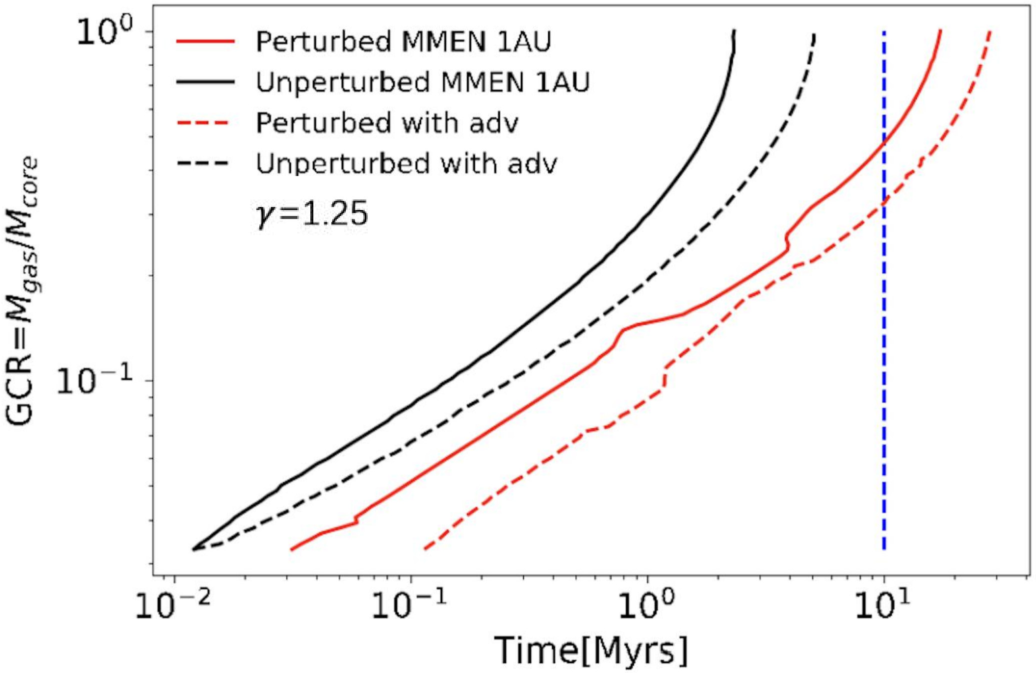
Slowing Down of Runaway - Passive disk (10M_E)

Method to model adv: impose adiabatic temperature gradient at Rout>R>0.4Rout (Ali-Dib+ 2020)



0.1AU
No adv: opacity enhancement is enough to avoid runaway within 10Myrs

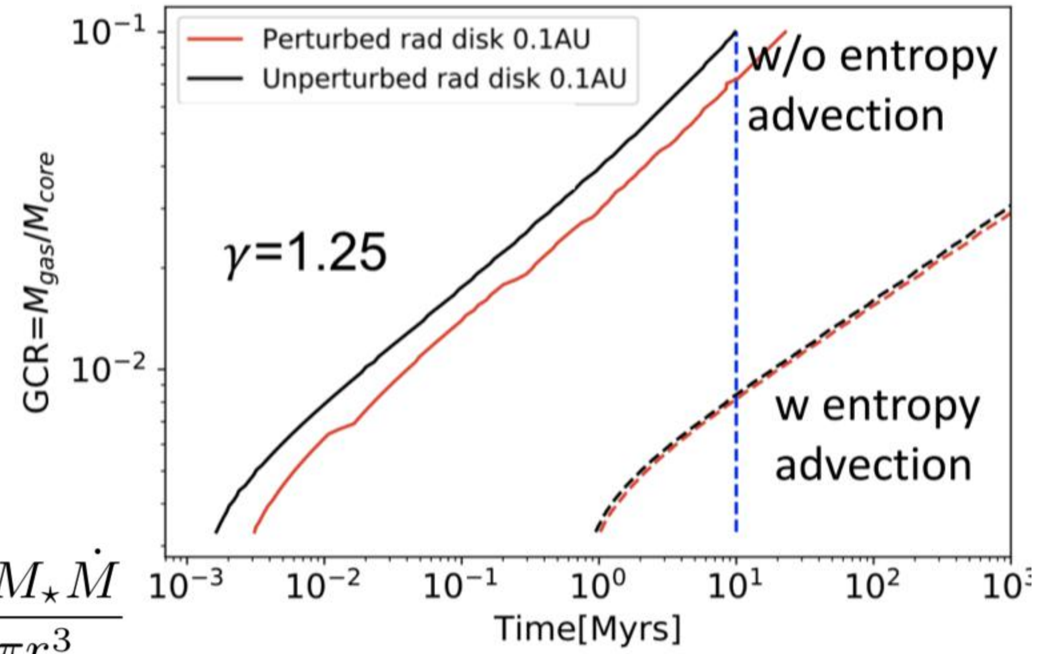
With adv: alone is enough to quench runaway, and since RCB>~2000K, changing dust opacity has little influence on luminosity



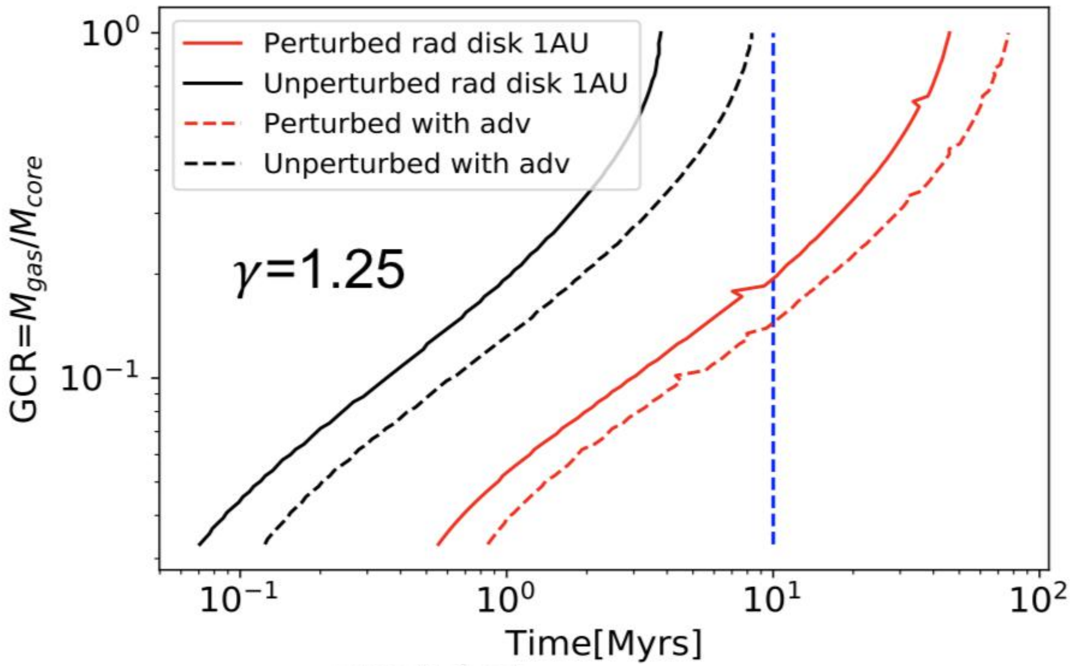
1AU:
Hill radius is larger, adv effect is smaller

Opacity effect dominates in delaying the cooling of atmosphere

Slowing Down of Runaway - Active disk (10M_E)



$$\sigma T_s^4 = \frac{3GM_\star \dot{M}}{8\pi r^3}$$



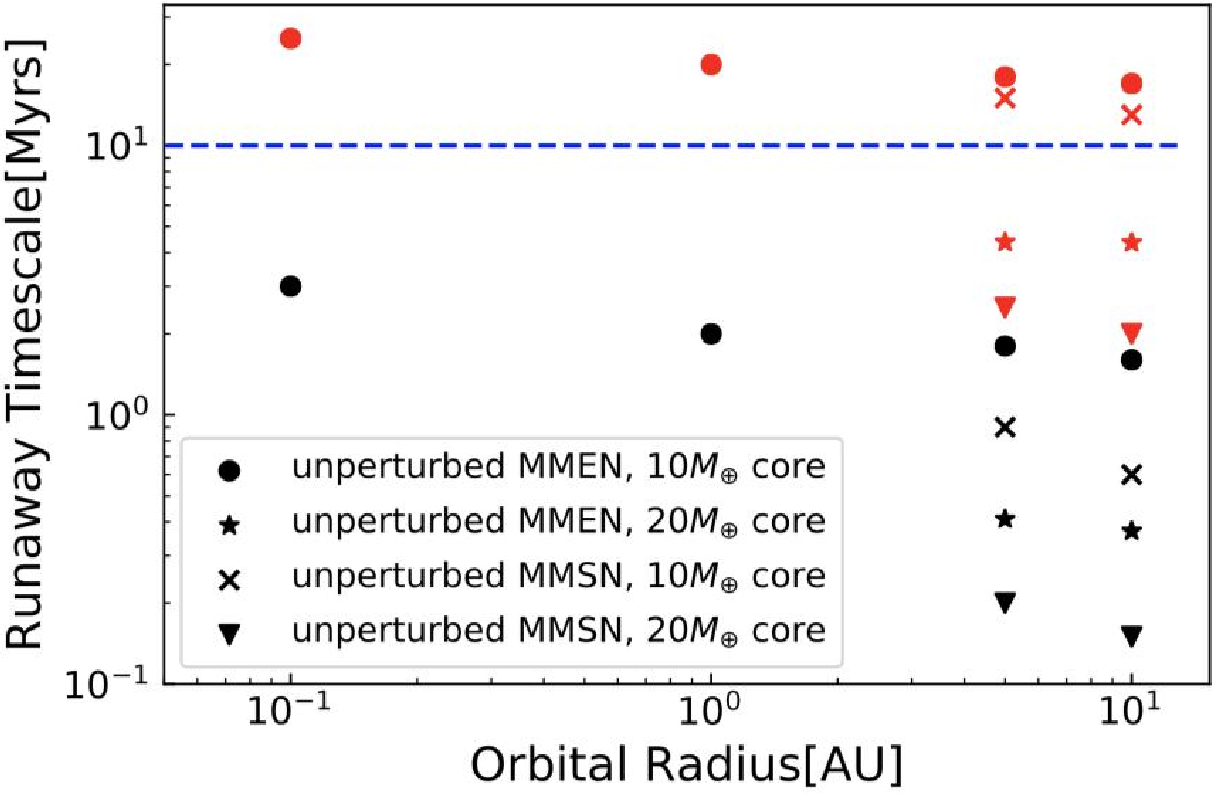
The inner disk <1AU for solar-type stars is more likely to be heated by viscous heating

Result: the effect is similar for active disks with heat transported by radiation or convection

- Can robustly retain super Earths at 0.1AU-1AU
- whether the core mass changes through merger or migrates in the process does not affect conclusion
- Future prospect: How would formation of second planet in the pressure bump (like Inside out formation) affect the opacity environment?

Emergence of Gas Giants

$$M_{\rm Iso} \approx 20\,(h/0.05)^3\, m_* M_\oplus$$



Outer regions, adv does not matter as Hill radius quite large.

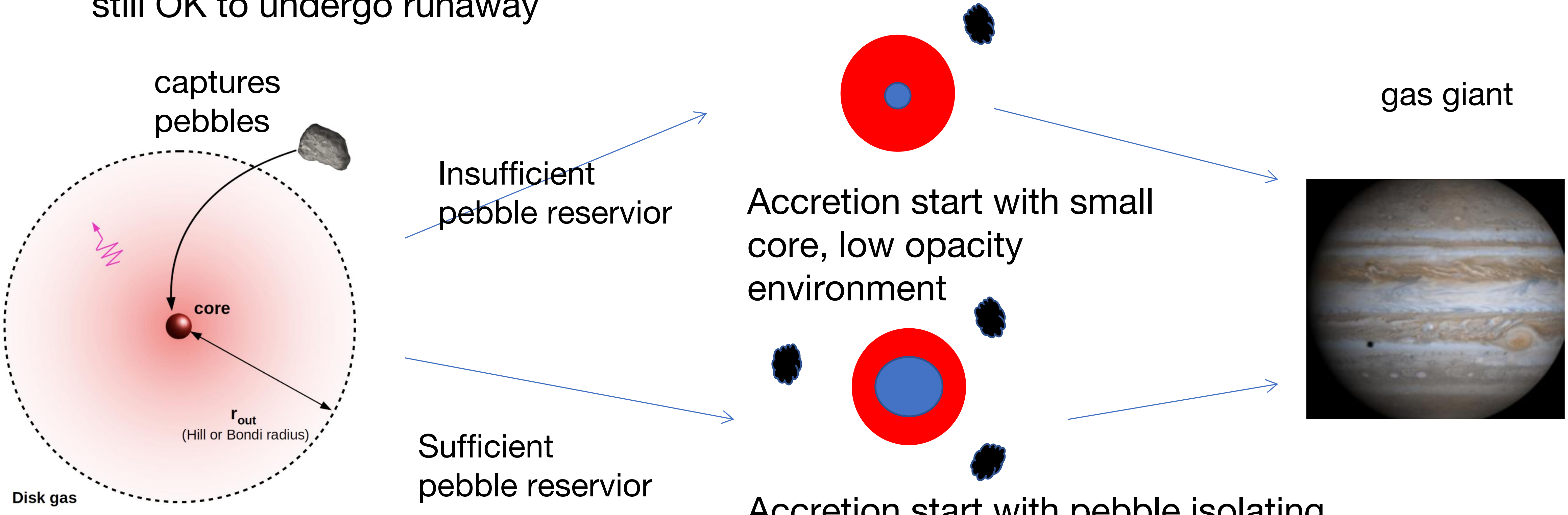
However, opacity is also very effective and can quench runaway in MMEN/MMSN at 5-10 AU (red circle and crosses).

For the mostly passive outer disk regions (MMEN, MMSN) 5-10AU M_iso can reach >20M_E isolation mass->runaway! (red star and wedges)

active disks: 20M_E may come from mergers

Emergence of Gas Giants

So either one of these scenarios happen
1. pebbles run out very quickly, and <20M_E goes on to accrete with unperturbed opacity
2. reach pebble isolation (>20M_E) and go with large opacity, but since more massive still OK to undergo runaway



captures pebbles

Insufficient pebble reservior

Accretion start with small core, low opacity environment

gas giant

Sufficient pebble reservior

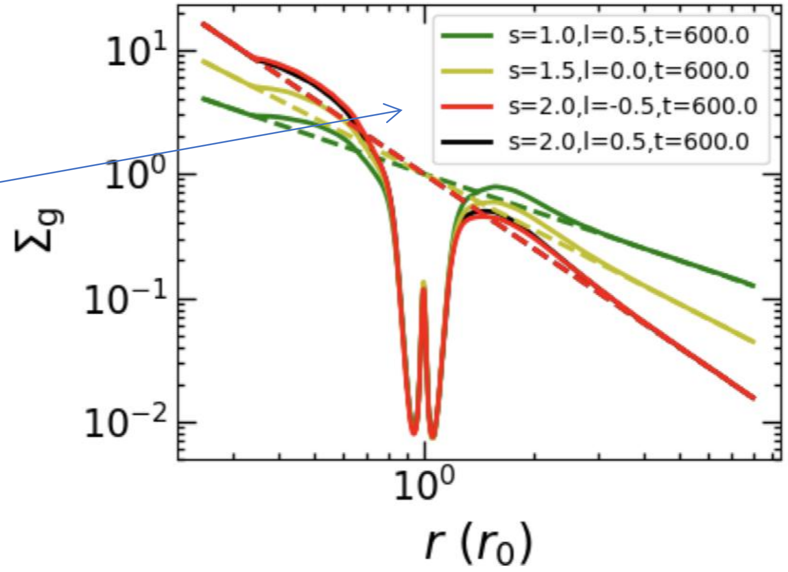
Accretion start with pebble isolating MASSIVE cores, high opacity environment

Saving Cold Giants From Rapid Migration

(A recently submitted paper)

Classical Type II migration: opens extremely deep gap
migration speed coupled with viscosity
(Lin & Papaloizou 1986)

$$\Sigma(r) = \Sigma_p \left(\frac{r}{r_p}\right)^{-s}$$



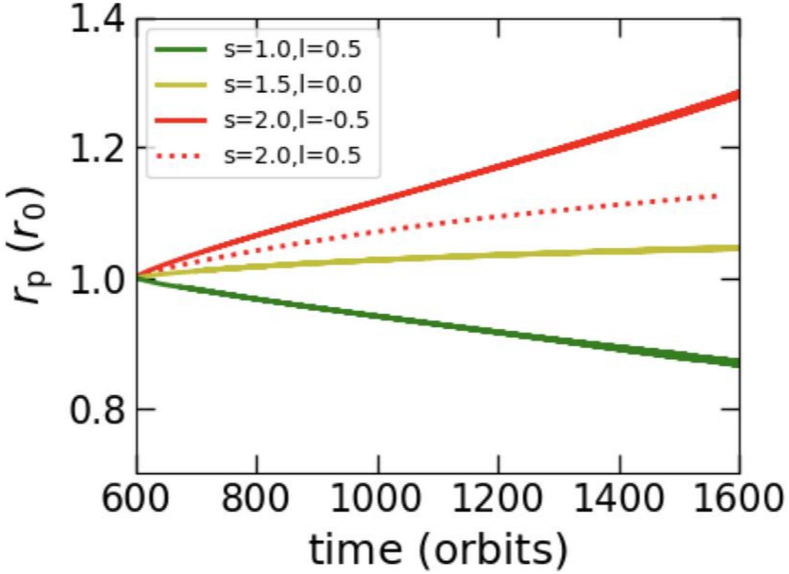
Recent Paradigm: a finitely deep gap
assuming planetary torque from bottom (Kanagawa+2015)

$$\frac{\Sigma_{min}}{\Sigma_p} \approx \frac{1}{1+0.04K} \qquad \text{where} \qquad K \equiv q^2 h_p^{-5} \alpha^{-1}.$$

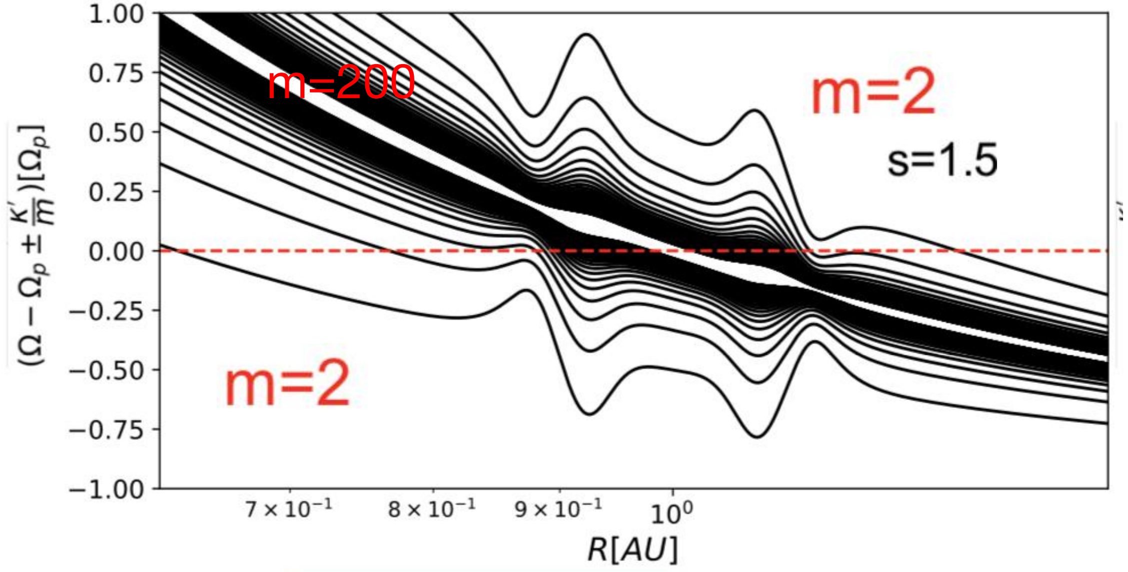
Kanagawa+ 2018: Type II torque should be analogous
to Type I migration Linblad torque, scales as

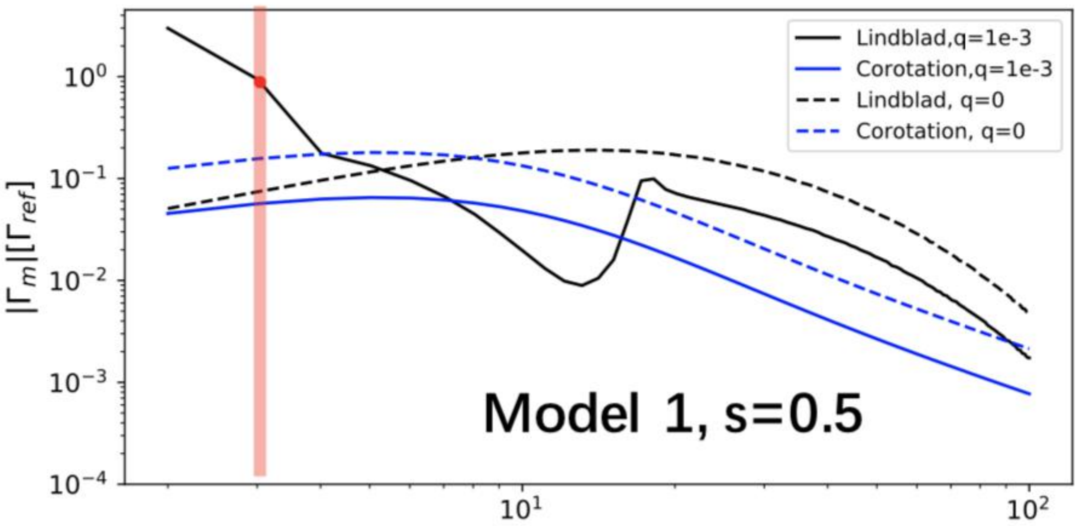
$$\Gamma_{ref} = \left(\frac{q}{h_p}\right)^2 \Sigma_{min} \Omega_p^2 r_p^4 = \Gamma_0 \frac{\Sigma_{min}}{\Sigma_p}$$

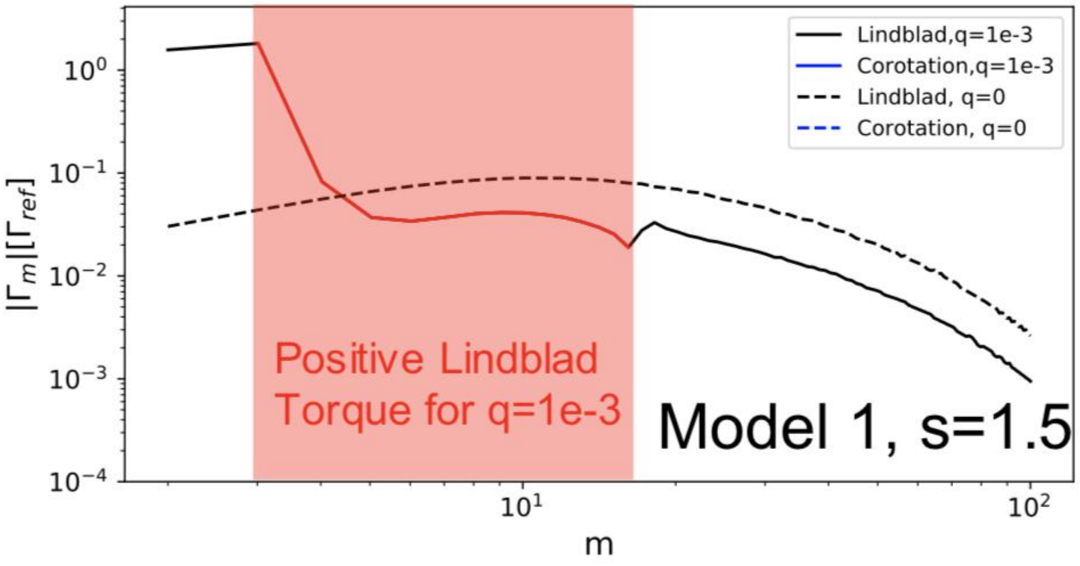
Why does it have such a negative dependence on s?
(Paardekooper+2010, Type I inner torque should have
positive dependence on s)



Saving Cold Giants From Rapid Migration







The linear corotation torque is not the dominating factor of torque deviation from the Kanagawa scaling

The low-order Lindblad torques at gap edges dominates
inner torque farther->but gas density larger
stronger for large s

Summary

- It is meaningful to examine the transition to runaway for large cores that formed early (e.g. out of pebble accretion)
- Pebble isolation, as a local process, naturally enhances the opacity around the vicinity of the planet
- Entropy advection dominates in quenching super Earth accretion at 0.1AU, but opacity is more effective at larger radii
- Pebble isolating cores of 20M_E in outer regions can reach runaway to become gas giants even in enhanced opacity
- (a separate project) Migration for gap-opening planets depends delicately on the balancing of low-order Lindblad torques, and for some initial density slope migration can be significantly stalled or reversed