

# Evidence for streaming instability and pebble accretion in the densities of Kuiper belt objects

*Happy birthday, Steve and Doug!*



**Wladimir Lyra**

New Mexico State University

**Manuel Cañas** (NMSU), **Daniel Carrera** (Iowa State University),  
**Anders Johansen** (University of Copenhagen), **Leonardo Krapp** (University of Arizona),  
**Debanjan Sengupta** (NMSU), **Jake Simon** (ISU), **Orkan Umurhan** (NASA Ames),  
**Chao-Chin Yang** (University of Alabama), **Andrew Youdin** (University of Arizona).

# AI will be able to summarize works



You

Did Steve Lubow work on Kuiper Belt objects?



ChatGPT

Yes, Steve Lubow is an astronomer who has worked on Kuiper Belt objects. He has been involved in research related to the outer solar system, including studying objects within the Kuiper Belt. The Kuiper Belt is a region of the solar system beyond the orbit of Neptune that is populated with small icy bodies, including dwarf planets like Pluto, as well as comets and other objects.



You

Give me a summary of Steve Lubow's work on Kuiper Belt objects.



ChatGPT

Steve Lubow has made significant contributions to the study of Kuiper Belt objects (KBOs). His work in this field often revolves around understanding the dynamics, characteristics, and formation processes of these distant icy bodies. Some key aspects of his research on Kuiper Belt objects include:

- 1. Dynamical Studies:** Lubow **has likely conducted research** to understand the orbital dynamics of KBOs, including their interactions with other objects in the Kuiper Belt and the influence of Neptune's gravitational effects on their orbits. This research helps elucidate the stability of KBOs' orbits over long timescales.
- 2. Formation and Evolution:** Lubow **may have investigated** the formation mechanisms of Kuiper Belt objects and their evolutionary history. This could involve theoretical modeling and simulations to explore how these objects formed from the primordial solar nebula and how they have evolved since then.
- 3. Physical Properties:** Lubow **might have studied** the physical characteristics of KBOs, such as their size, shape, composition, and surface properties. Understanding these properties provides insights into the nature of these distant bodies and their similarities or differences with other solar system objects.
- 4. Occultations and Surveys:** Lubow **may have been involved** in observational campaigns aimed at studying KBOs through techniques such as stellar occultations or large-scale surveys. These efforts help identify and characterize KBOs, contributing to our overall understanding of the Kuiper Belt population.

Overall, Lubow's work on Kuiper Belt objects **likely spans** theoretical modeling, numerical simulations, observational studies, and data analysis, all aimed at advancing our knowledge of these intriguing remnants of the early solar system.

# AI will replace ADS, Google scholar, etc



**You**

Who are Steve Lubow's most frequent co-authors?



**ChatGPT**

To provide accurate and up-to-date information on Steve Lubow's most frequent co-authors, I would need access to a recent database of his publications or academic profiles. Unfortunately, I don't have real-time access to such data. However, you can find this information by searching academic databases like Google Scholar, NASA Astrophysics Data System (ADS), or university research portals using Steve Lubow's name as the primary author. These databases often list co-authors along with their frequency of collaboration, which can give you insight into his most frequent collaborators.





## A Solution for the Density Dichotomy Problem of Kuiper Belt Objects with Multispecies Streaming Instability and Pebble Accretion

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<sup>7</sup> Received 2023 August 25; revised 2023 December 27; accepted 2024 January 5; published 2024 February 28

### Abstract

Kuiper Belt objects (KBOs) show an unexpected trend, whereby large bodies have increasingly higher densities, up to five times greater than their smaller counterparts. Current explanations for this trend assume formation at constant composition, with the increasing density resulting from gravitational compaction. However, this scenario poses a timing problem to avoid early melting by decay of <sup>26</sup>Al. We aim to explain the density trend in the context of streaming instability and pebble accretion. Small pebbles experience lofting into the atmosphere of the disk, being exposed to UV and partially losing their ice via desorption. Conversely, larger pebbles are shielded and remain icier. We use a shearing box model including gas and solids, the latter split into ices and silicate pebbles. Self-gravity is included, allowing dense clumps to collapse into planetesimals. We find that the streaming instability leads to the formation of mostly icy planetesimals, albeit with an unexpected trend that the lighter ones are more silicate-rich than the heavier ones. We feed the resulting planetesimals into a pebble accretion integrator with a continuous size distribution, finding that they undergo drastic changes in composition as they preferentially accrete silicate pebbles. The density and masses of large KBOs are best reproduced if they form between 15 and 22 au. Our solution avoids the timing problem because the first planetesimals are primarily icy and <sup>26</sup>Al is mostly incorporated in the slow phase of silicate pebble accretion. Our results lend further credibility to the streaming instability and pebble accretion as formation and growth mechanisms.

*Unified Astronomy Thesaurus concepts:* Dwarf planets (419); Kuiper Belt (893); Pluto (1267); Hydrodynamics (1963); Planet formation (1241)



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Daniel Carrera  
ISU -> NMSU



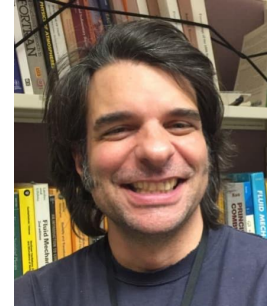
Leo Krapp  
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## An Analytical Theory for the Growth from Planetesimals to Planets by Polydisperse Pebble Accretion

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### Abstract

Pebble accretion is recognized as a significant accelerator of planet formation. Yet only formulae for single-sized (monodisperse) distribution have been derived in the literature. These can lead to significant underestimates for Bondi accretion, for which the best accreted pebble size may not be the one that dominates the mass distribution. We derive in this paper the polydisperse theory of pebble accretion. We consider a power-law distribution in pebble radius, and we find the resulting surface and volume number density distribution functions. We derive also the exact monodisperse analytical pebble accretion rate for which 3D accretion and 2D accretion are limits. In addition, we find analytical solutions to the polydisperse 2D Hill and 3D Bondi limits. We integrate the polydisperse pebble accretion numerically for the MRN distribution, finding a slight decrease (by an exact factor 3/7) in the Hill regime compared to the monodisperse case. In contrast, in the Bondi regime, we find accretion rates 1–2 orders of magnitude higher compared to monodisperse, also extending the onset of pebble accretion to 1–2 orders of magnitude lower in mass. We find megayear timescales, within the disk lifetime, for Bondi accretion on top of planetary seeds of masses  $10^{-6}$  to  $10^{-4} M_{\oplus}$ , over a significant range of the parameter space. This mass range overlaps with the high-mass end of the planetesimal initial mass function, and thus pebble accretion is possible directly following formation by streaming instability. This alleviates the need for mutual planetesimal collisions as a major contribution to planetary growth.

*Unified Astronomy Thesaurus concepts:* Planet formation (1241); Planetary system formation (1257)



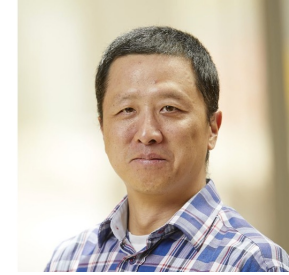
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Wladimir Lyra – *New Mexico State University*

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# The density dichotomy of Kuiper Belt objects

THE ASTROPHYSICAL JOURNAL LETTERS, 778:L34 (  
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## THE DENSITY OF MID-SIZED KUIPER BELT OBJECT 2002 UX25 AND THE FORMATION OF THE DWARF PLANETS

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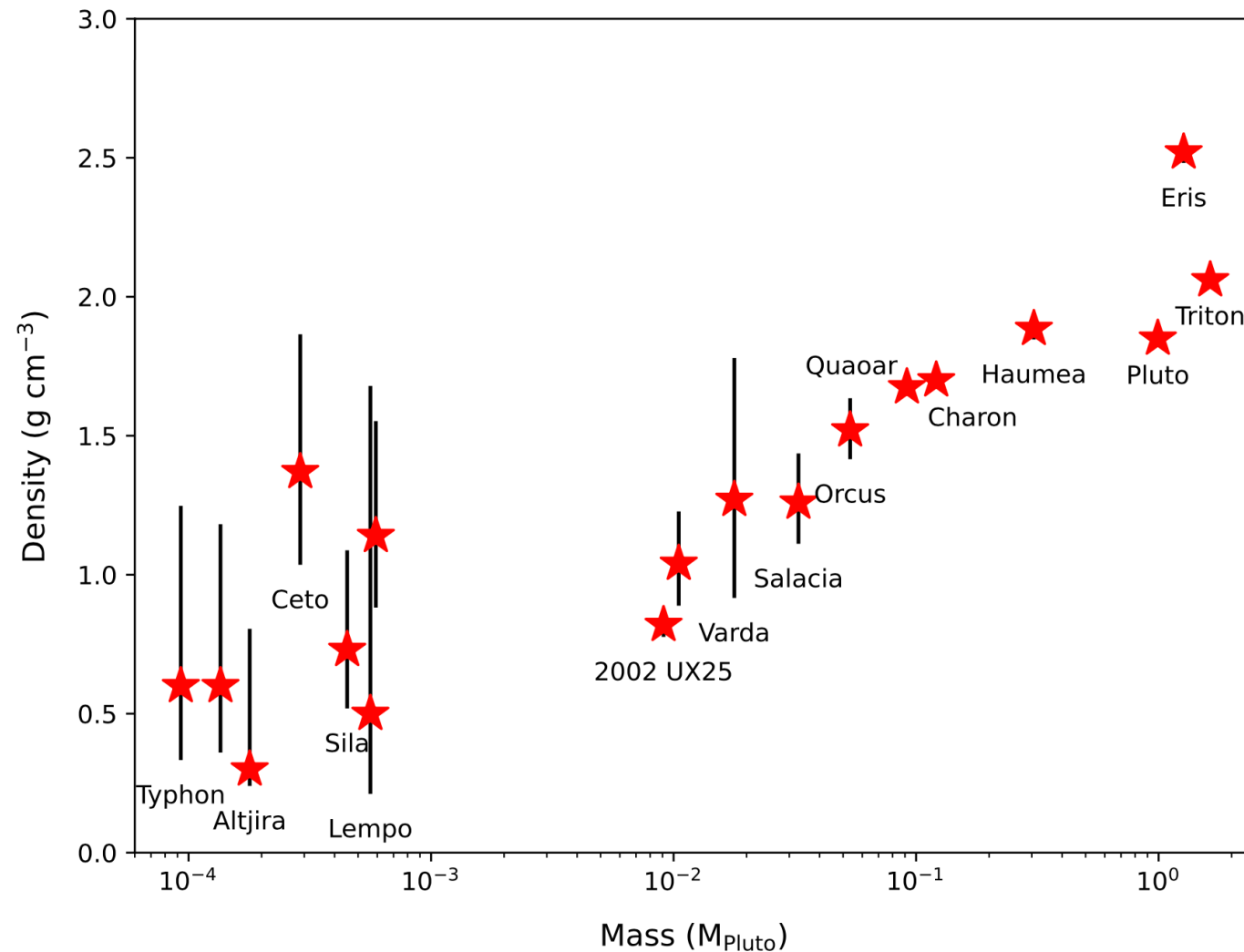
### ABSTRACT

The inferred low rock fraction of the 2002 UX25 system makes the formation of rock-rich larger objects difficult to explain in any standard coagulation scenario. For example, to create an object with the volume of Eris would require assembling  $\sim 40$  objects of the size of 2002 UX25. Yet the assembled object, even with the additional compression, would still have a density close to  $1 \text{ g cm}^{-3}$  rather than the  $2.5 \text{ g cm}^{-3}$  density of Eris (Sicardy et al. 2011).

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out invoking  
in to increase  
on occurs for  
en  $\sim 350 \text{ km}$   
ould provide  
acterization,  
a diameter of  
solar system  
unlikely to be  
presentation  
higher from  
ss: formation

- Extremely low porosity;
- Biased sample;
- Compaction through giant impacts

None of these alternatives appears likely. We are left in the uncomfortable state of having no satisfying mechanism to explain the formation of the icy dwarf planets. While objects up to the size of 2002 UX25 can easily be formed through standard coagulation scenarios, the rock-rich larger bodies may require a formation mechanism separate from the rest of the Kuiper belt.



Data; Thomas (2000), Stansberry et al. (2006), Grundy et al. (2007), Brown et al. (2011), Stansberry et al. (2012), Brown (2013), Fornasier et al. (2013), Vilenius, et al. (2014), Nimmo et al. (2016), Ortiz et al. (2017), Brown and Butler (2017), Grundy et al. (2019), Morgado et al. (2023), Pereira et al. (2023).

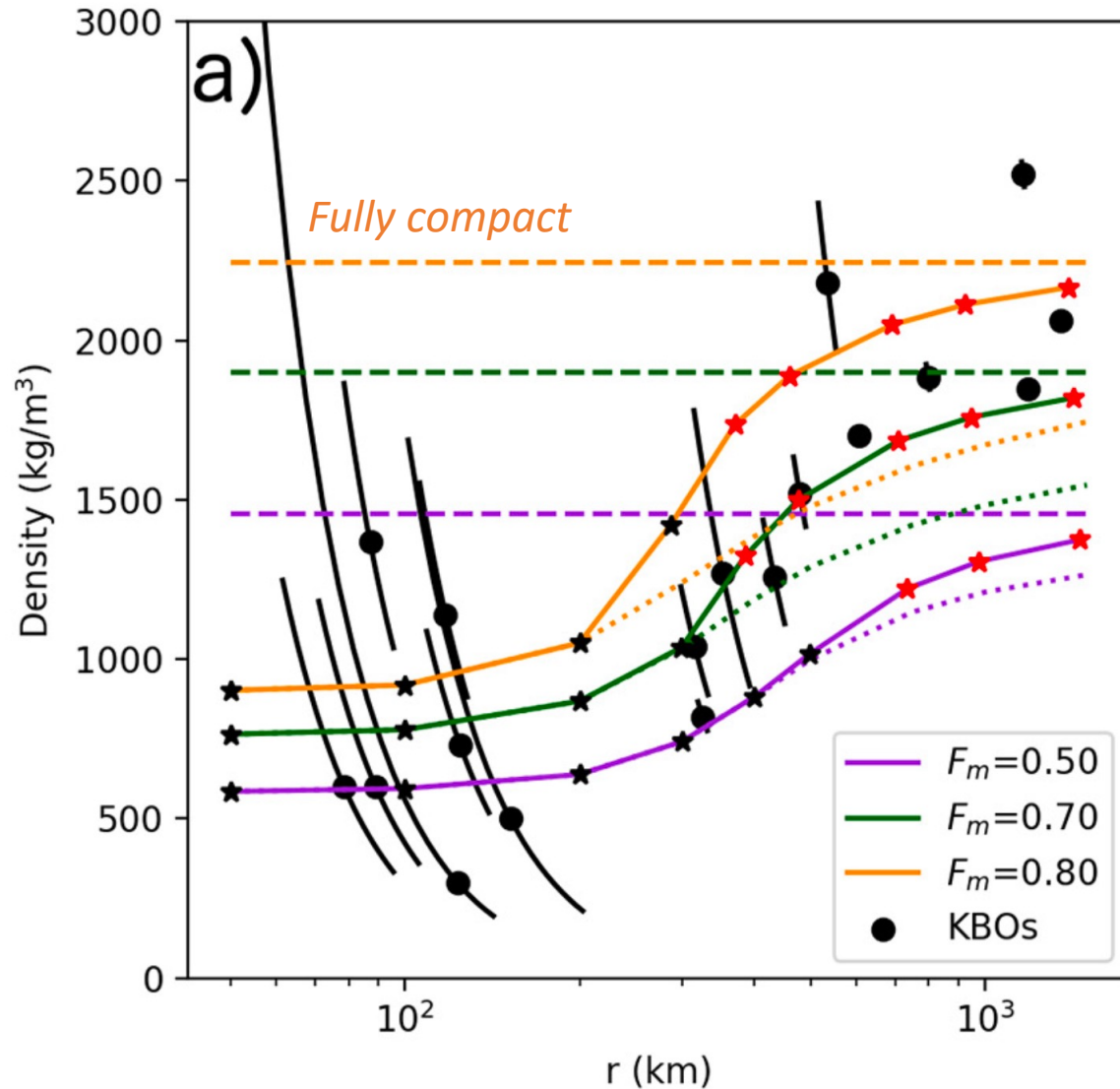
# Current best bet: Porosity removal by gravitational compaction

## Problems

- Low-mass objects need to be unreasonably porous
- Timing!  $^{26}\text{Al}$  would melt if formed within 4 Myr

## Assumptions

- ~~• Constant composition at birth and growth~~

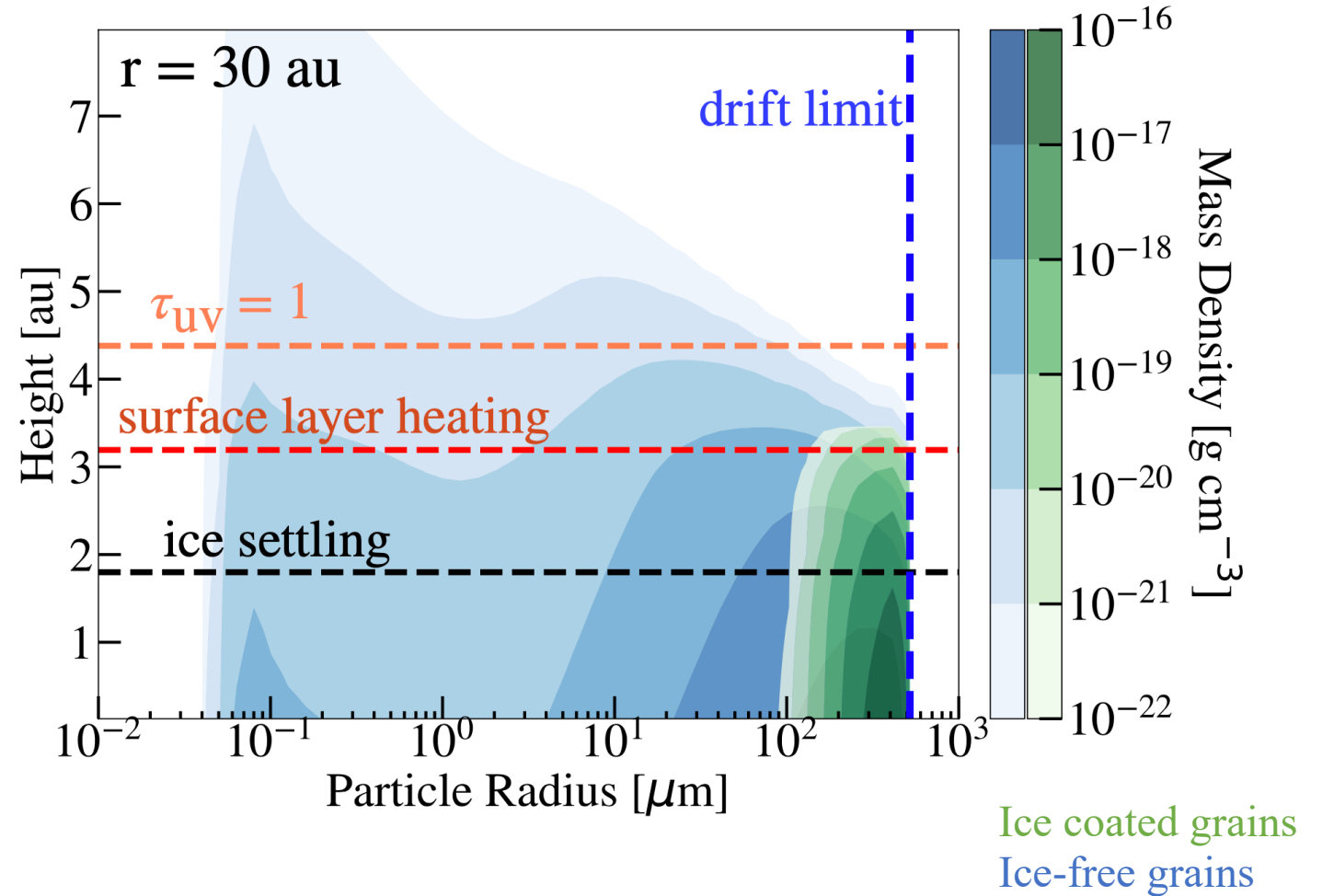


$F_m$  = rock mass fraction

# Abandoning Constant Composition

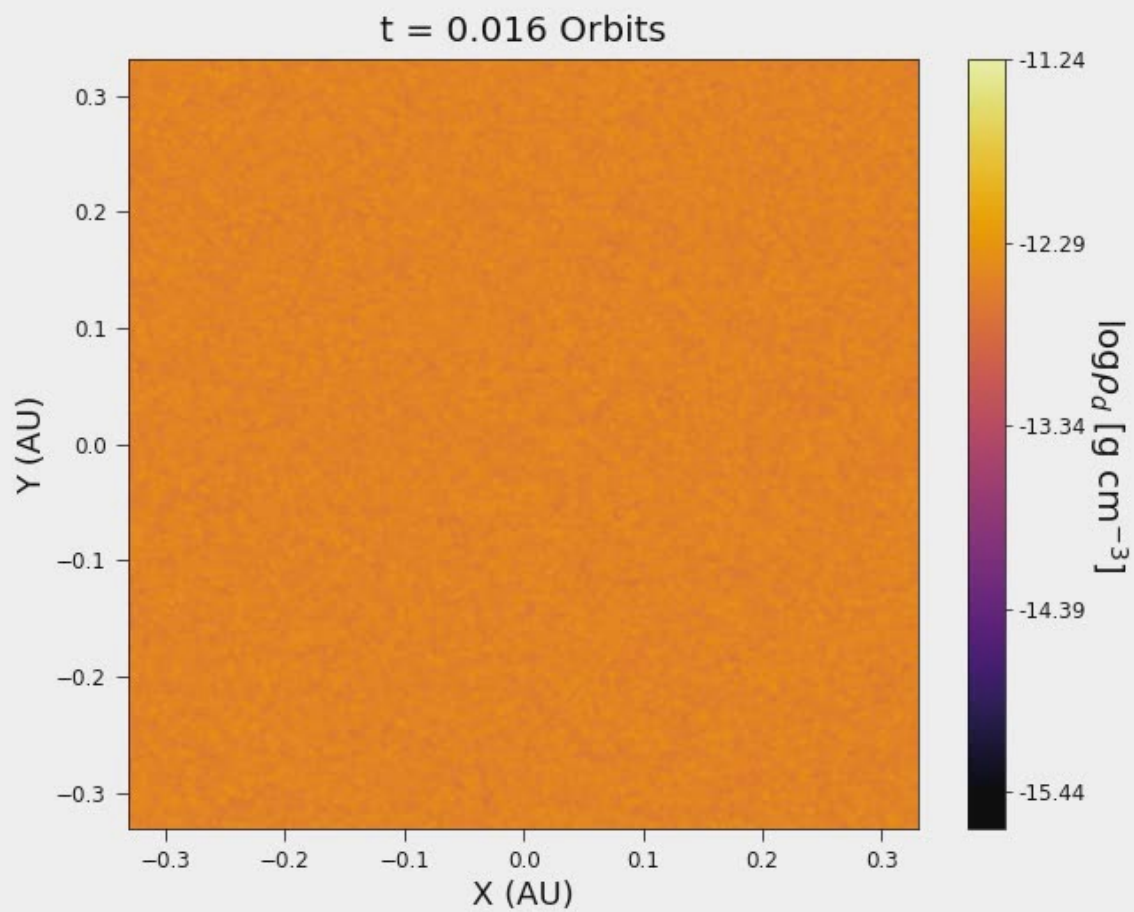
Heating and UV irradiation remove ice on Myr timescales (Harrison & Schoen 1967)

- Small grains lofted in the atmosphere lose ice
- Big grains are shielded and remain icy.

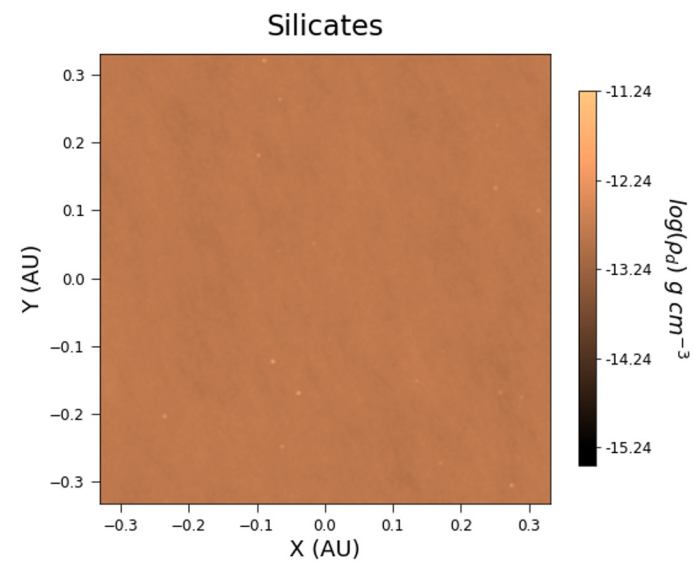
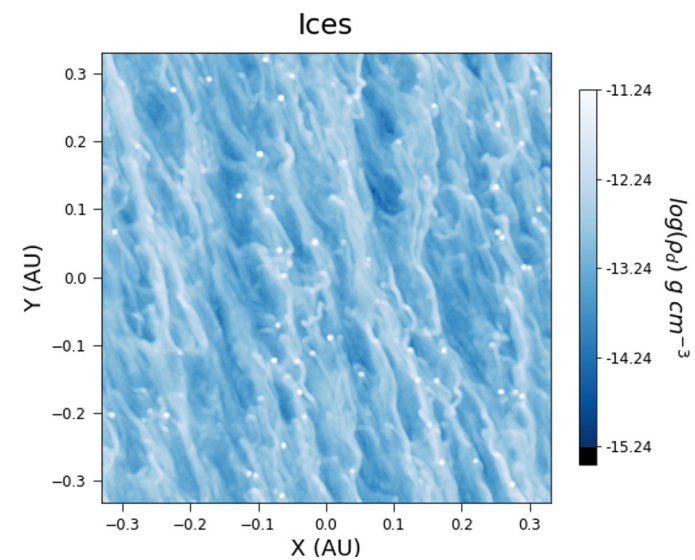




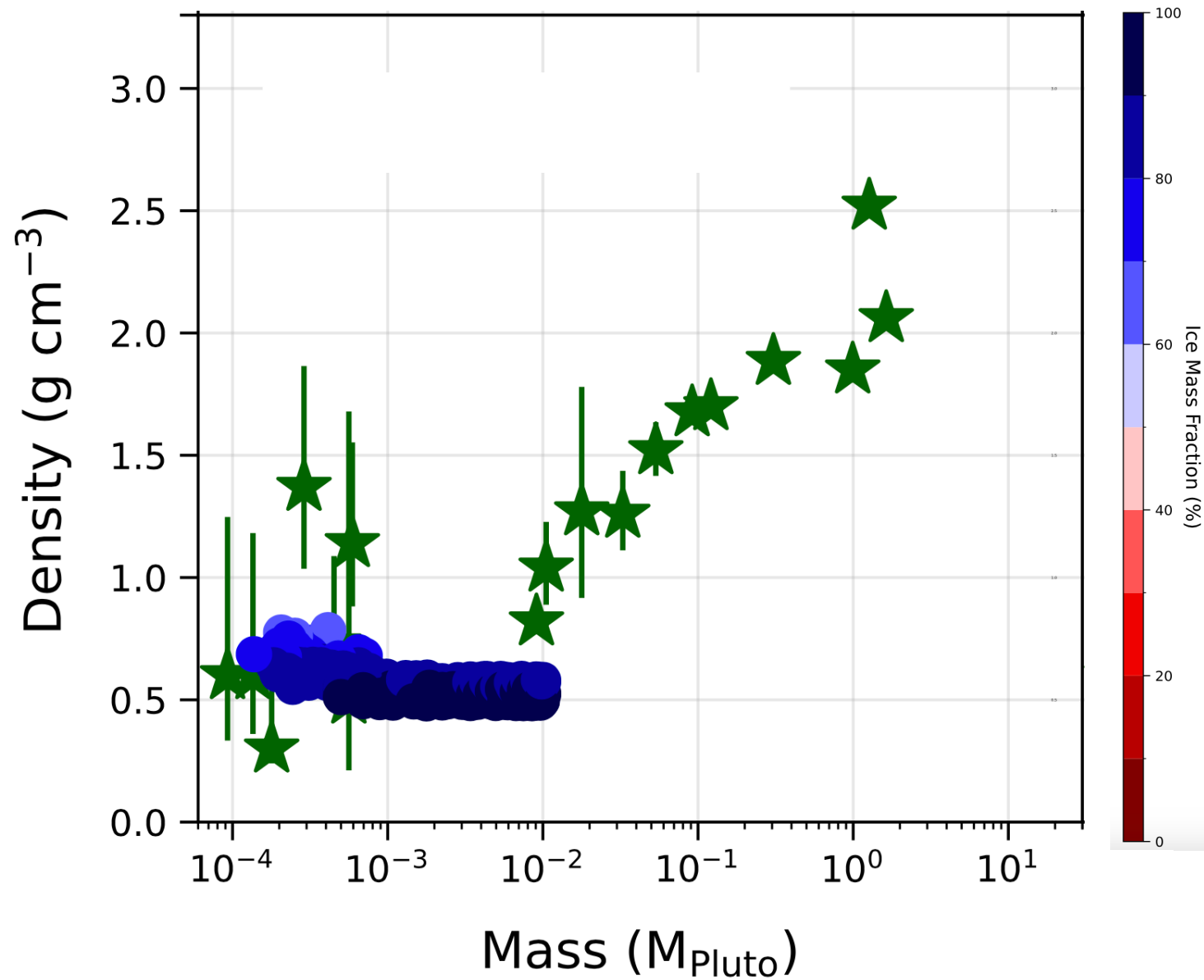
# Split into icy and silicate pebbles



Canas+Lyra et al. 2024



# The first planetesimals are icy



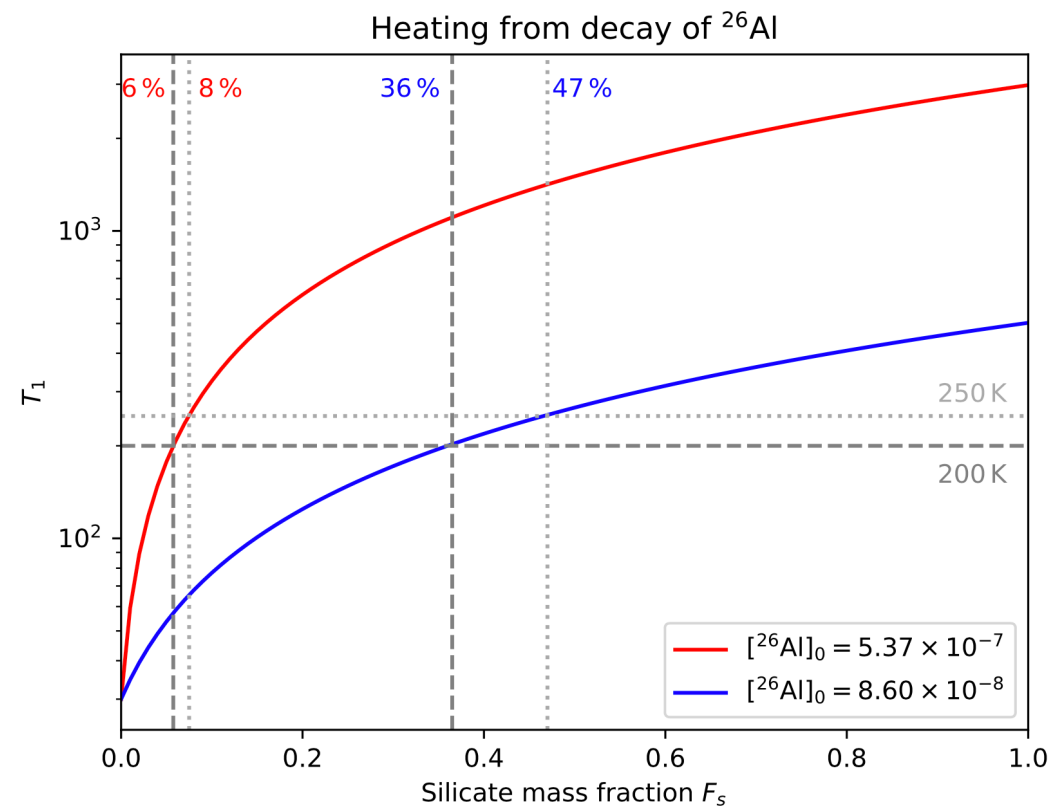
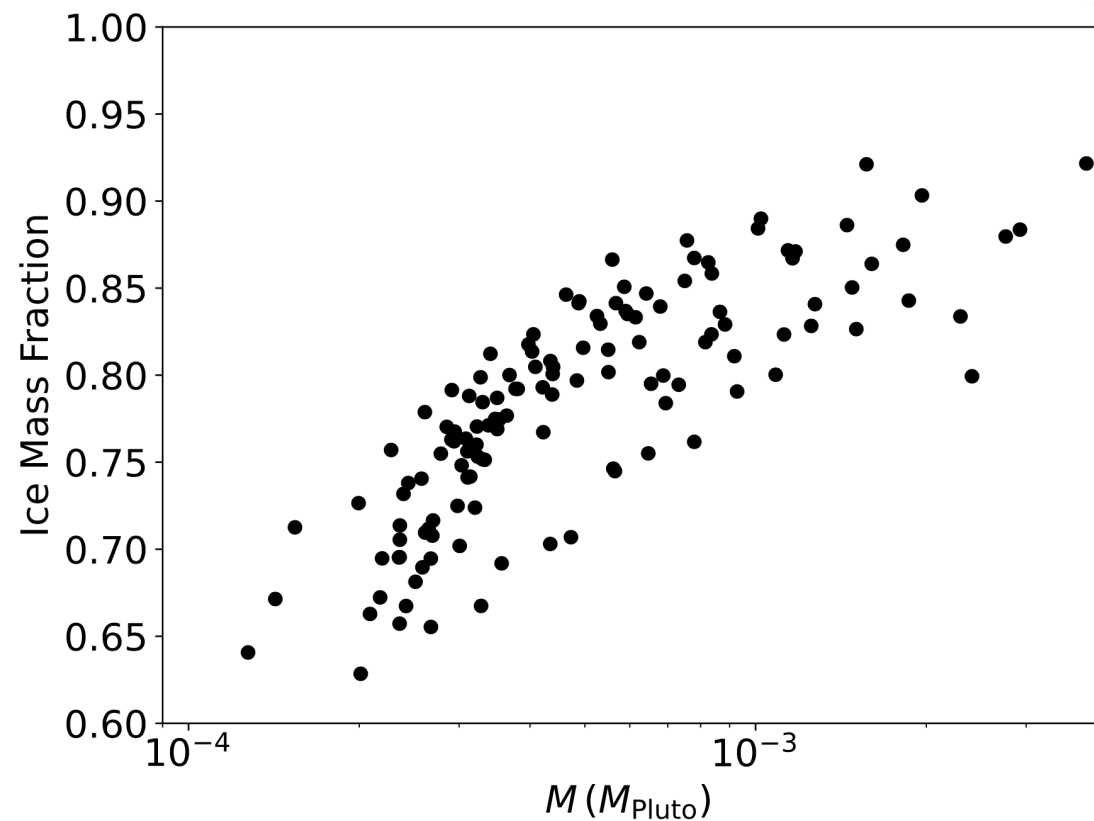
# The first planetesimals won't melt

$$\mathcal{H} = \rho F_s [^{26}\text{Al}]_0 \mathcal{H}_0 e^{-\lambda t}$$

$$\begin{aligned} Q(t) &= V \int_0^t \mathcal{H}(t') dt' \\ &= M_p F_s [^{26}\text{Al}]_0 \mathcal{H}_0 \lambda^{-1} (1 - e^{-\lambda t}) \end{aligned}$$

$$Q = M_p c_p \Delta T$$

$$\Delta T = F_s [^{26}\text{Al}]_0 \mathcal{H}_0 \lambda^{-1} c_p^{-1}$$

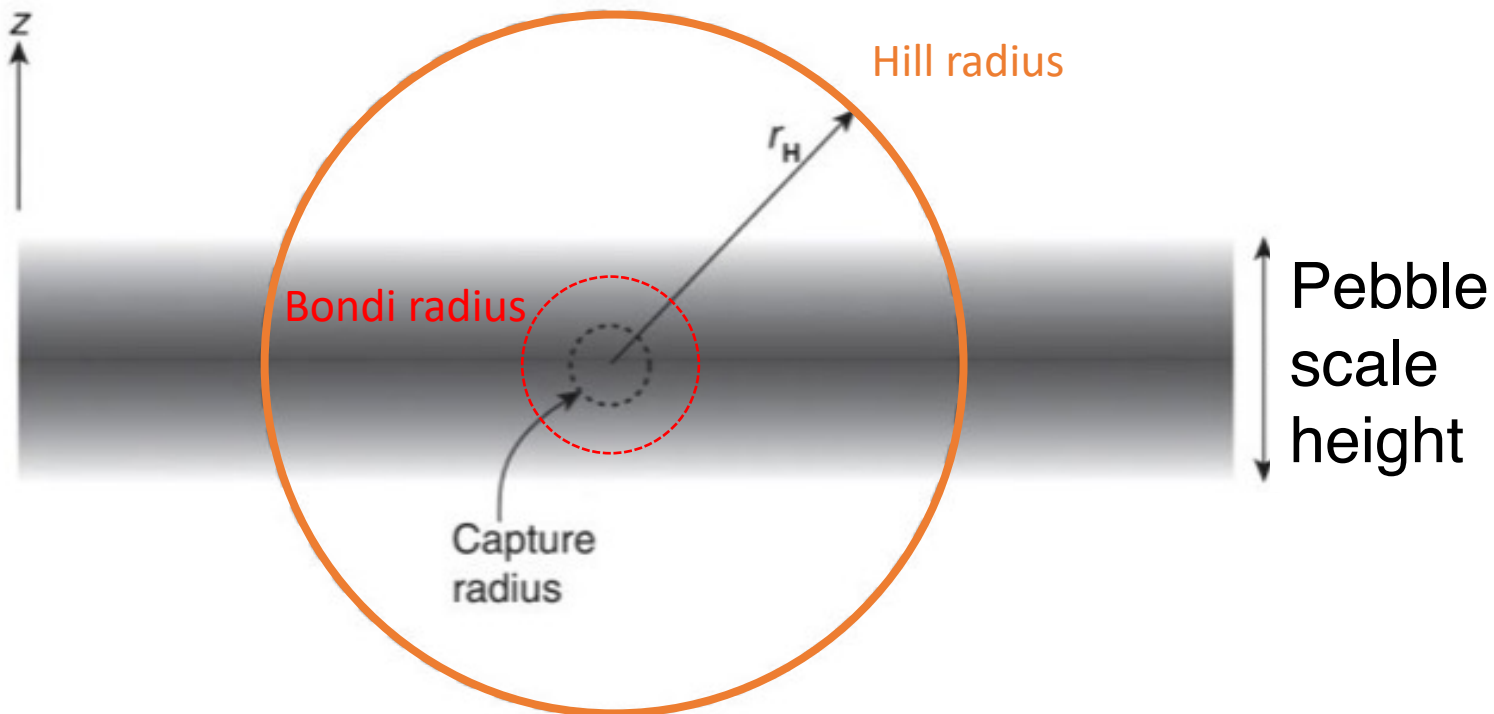


# Pebble Accretion: Geometric, Bondi, and Hill regime

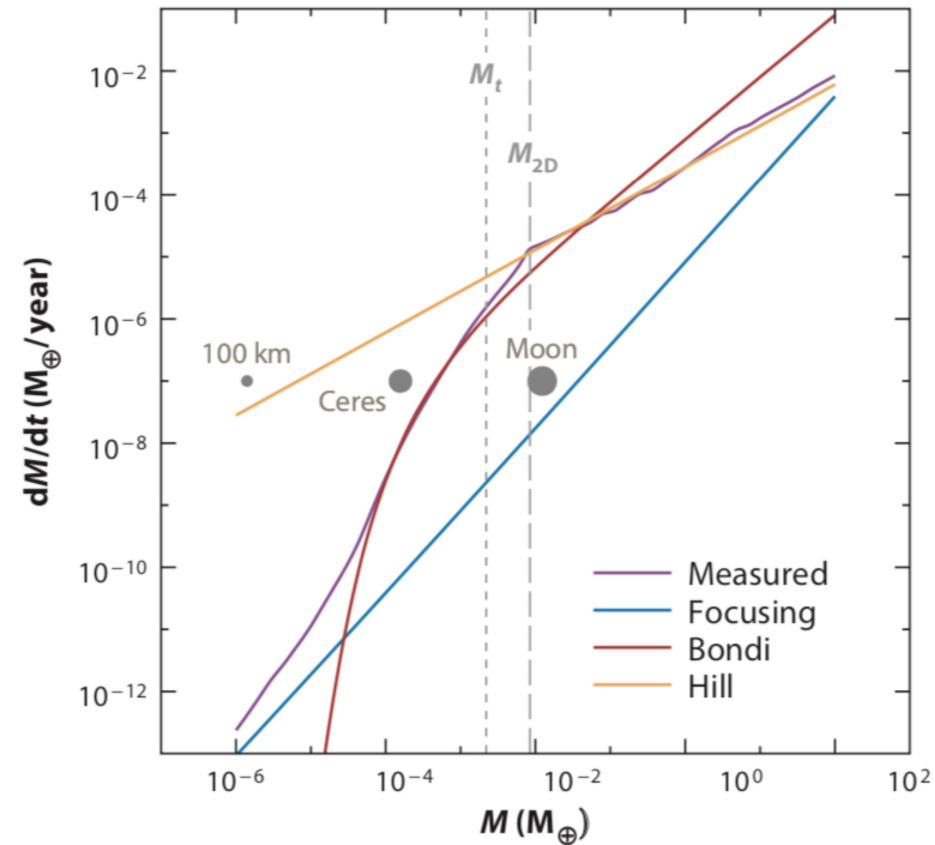
**Bondi** accretion - Bound against **headwind**

**Hill** accretion - Bound against **stellar tide**

$$\xi \equiv \left( \frac{R_{\text{acc}}}{2H_d} \right)^2 \quad \begin{aligned} \dot{M}_{3D} &= \lim_{\xi \rightarrow 0} \dot{M} = \pi R_{\text{acc}}^2 \rho_{d0} \delta v, \\ \dot{M}_{2D} &= \lim_{\xi \rightarrow \infty} \dot{M} = 2R_{\text{acc}} \Sigma_d \delta v, \end{aligned}$$

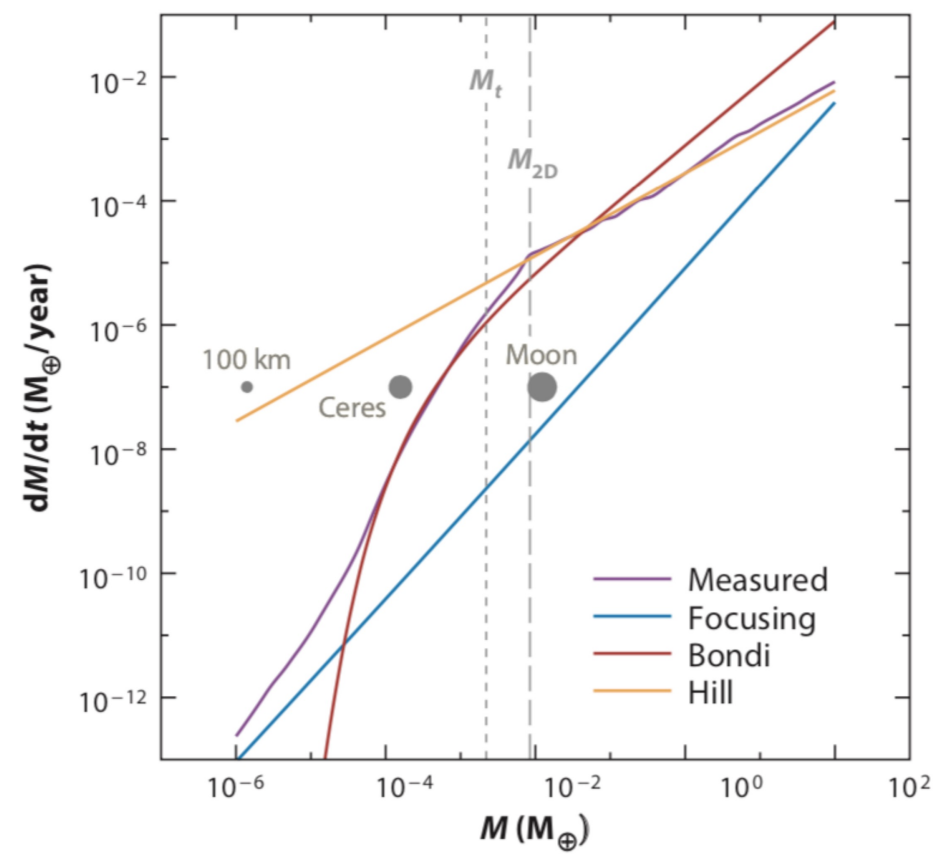
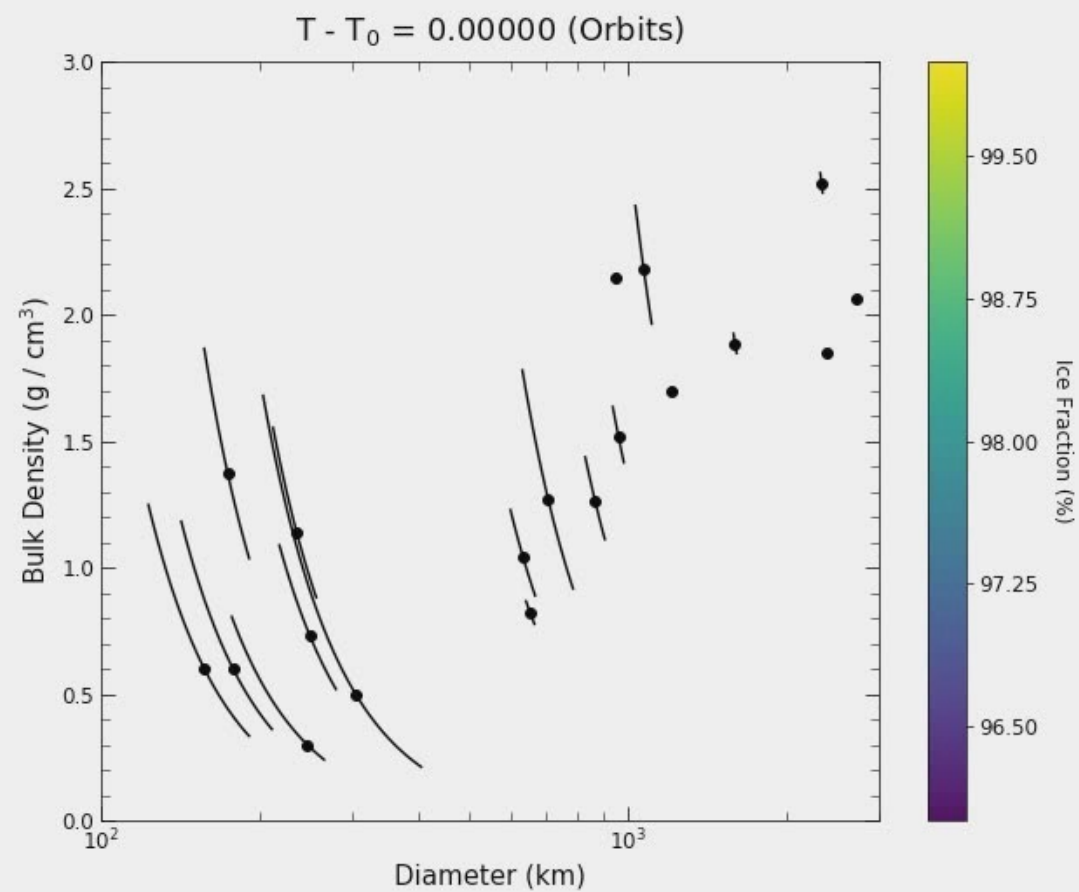


## Mass Accretion rates



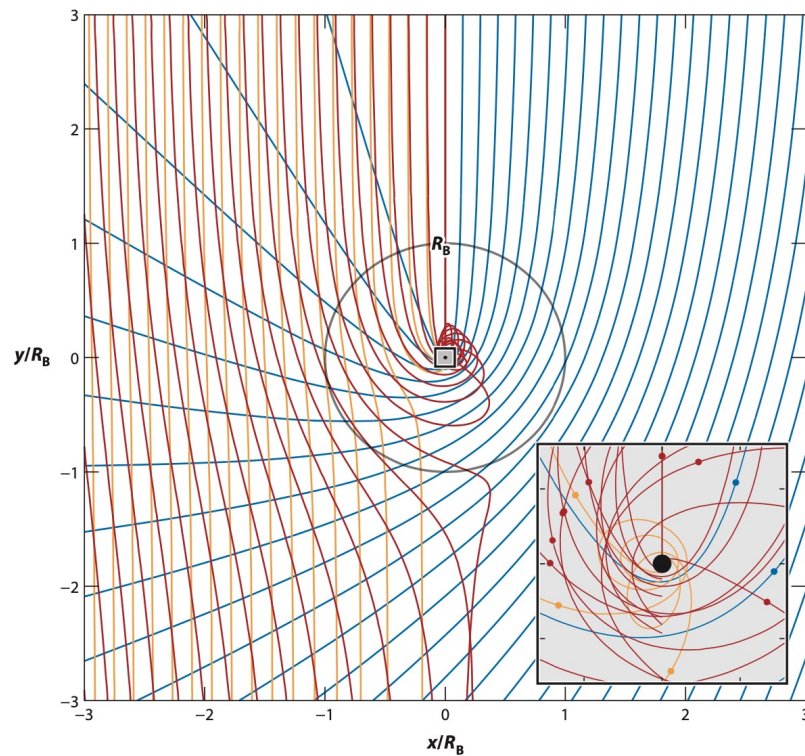


## Integrate pebble accretion



## Pebble Accretion: Pebbles of different size accrete differently

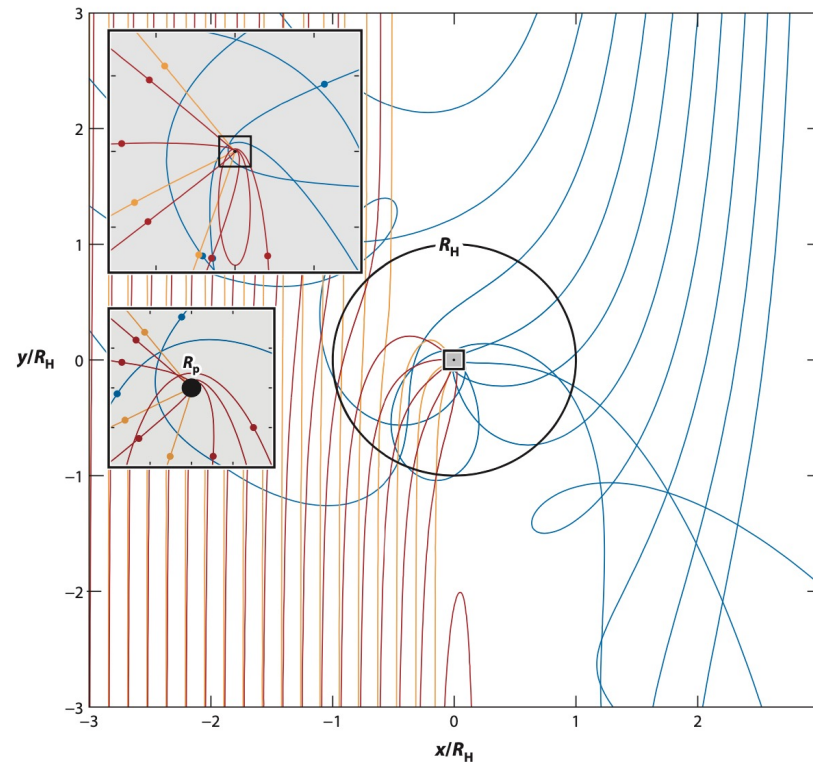
Bondi Regime



Best accreted pebble

*Drag time  $\sim$  Bondi Time*

Hill Regime



Best accreted pebble

*Drag time  $\sim$  Orbital Time*

## Polydisperse (Multi-Species) Pebble Accretion

$$\rho_d(a, z) = \int_0^a m(a') F(a', z) da'.$$

$$F(a, z) \equiv f(a) e^{-z^2/2H_d^2},$$

$$f(a) = \frac{3(1-p)Z\Sigma_g}{2^{5/2}\pi^{3/2}H_g\rho_\bullet^{(0)}a_{\max}^{4-k}} \sqrt{1 + a\frac{\pi}{2}\frac{\rho_\bullet(a)}{\Sigma_g\alpha}} a^{-k}.$$

$$S \equiv \frac{1}{\pi R_{\text{acc}}^2} \int_{-R_{\text{acc}}}^{R_{\text{acc}}} 2\sqrt{R_{\text{acc}}^2 - z^2} \exp\left(-\frac{z^2}{2H_d^2}\right) dz,$$

$$W(a) = \frac{3(1-p)Z\Sigma_g}{4\pi\rho_\bullet^{(0)}a_{\max}^{4-k}} a^{-k},$$

$$\delta v \equiv \Delta v + \Omega R_{\text{acc}},$$

$$R_{\text{acc}} \equiv \hat{R}_{\text{acc}} \exp[-\chi(\tau_f/t_p)^\gamma],$$

$$\hat{R}_{\text{acc}}^{(\text{Bondi})} = \left(\frac{4\tau_f}{t_B}\right)^{1/2} R_B,$$

$$\hat{R}_{\text{acc}}^{(\text{Hill})} = \left(\frac{\text{St}}{0.1}\right)^{1/3} R_H,$$

$$\frac{\partial \Sigma_d(a)}{\partial a} \propto a^{-p};$$

$$\rho_\bullet \propto a^{-q};$$

$$t_p \equiv \frac{GM_p}{(\Delta v + \Omega R_H)^3}$$

$$\dot{M}(a) = \int_0^a \frac{\partial \dot{M}(a')}{\partial a'} da',$$

$$\frac{\partial \dot{M}(a)}{\partial a} = \pi R_{\text{acc}}^2(a) \delta v(a) S(a) m(a) f(a).$$

$$\dot{M}_{\text{2D, Hill}} = 2 \times 10^{2/3} \Omega R_H^2 \int_0^{a_{\max}} \text{St}(a)^{2/3} m(a) W(a) da.$$

$$\dot{M}_{\text{3D, Bondi}} = \frac{4\pi R_B \Delta v^2}{\Omega}$$

$$\times \int_0^{a_{\max}} \text{St} e^{-2\psi} m(a) f(a)$$

$$\times \left[ 1 + 2 \left( \text{St} \frac{\Omega R_B}{\Delta v} \right)^{1/2} e^{-\psi} \right] da, \quad \psi \equiv \chi [\text{St}/(\Omega t_p)]^\gamma.$$

# Analytical theory of polydisperse (multi-species) pebble accretion

## Monodisperse (single species)

$$\xi \equiv \left( \frac{R_{\text{acc}}}{2H_d} \right)^2$$

$$\dot{M}_{3D} = \lim_{\xi \rightarrow 0} \dot{M} = \pi R_{\text{acc}}^2 \rho_{d0} \delta v,$$

$$\dot{M}_{2D} = \lim_{\xi \rightarrow \infty} \dot{M} = 2R_{\text{acc}} \Sigma_d \delta v,$$

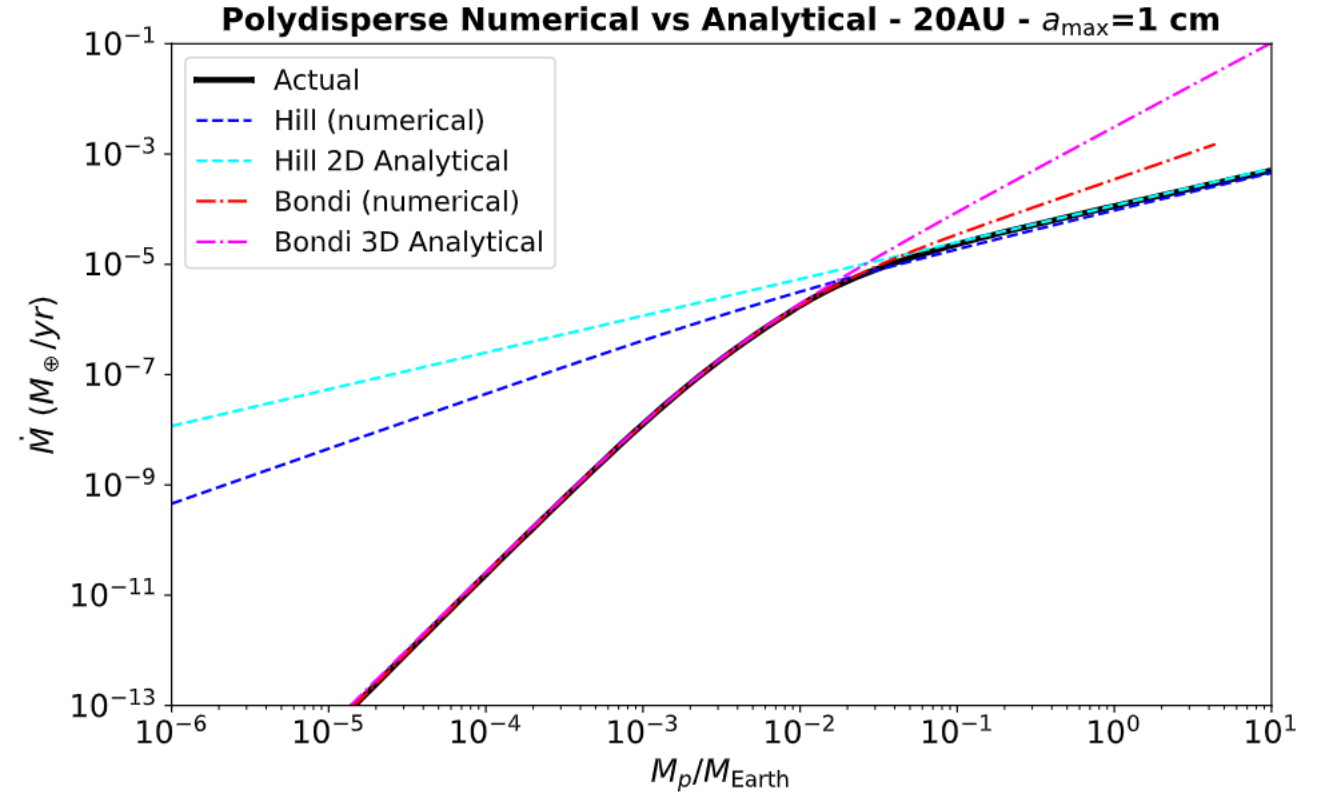
Lambrechts & Johansen (2012)

## Polydisperse (multiple species)

$$\dot{M}_{2D,\text{Hill}} = \frac{6(1-p)}{14-5q-3k} \left( \frac{\text{St}_{\text{max}}}{0.1} \right)^{2/3} \Omega R_H^2 Z \Sigma_g.$$

$$\dot{M}_{3D,\text{Bondi}} \approx C_1 \frac{\gamma_l \left( \frac{b_1+1}{s}, j_1 a_{\text{max}}^s \right)}{s j_1^{(b_1+1)/s}} + C_2 \frac{\gamma_l \left( \frac{b_2+1}{s}, j_2 a_{\text{max}}^s \right)}{s j_2^{(b_2+1)/s}} + C_3 \frac{\gamma_l \left( \frac{b_3+1}{s}, j_3 a_{\text{max}}^s \right)}{s j_3^{(b_3+1)/s}} + C_4 \frac{\gamma_l \left( \frac{b_4+1}{s}, j_4 a_{\text{max}}^s \right)}{s j_4^{(b_4+1)/s}},$$

Lyra et al. (2023)



Lyra et al. 2023



# Analytical Solution for General Monodisperse (single species) Pebble Accretion

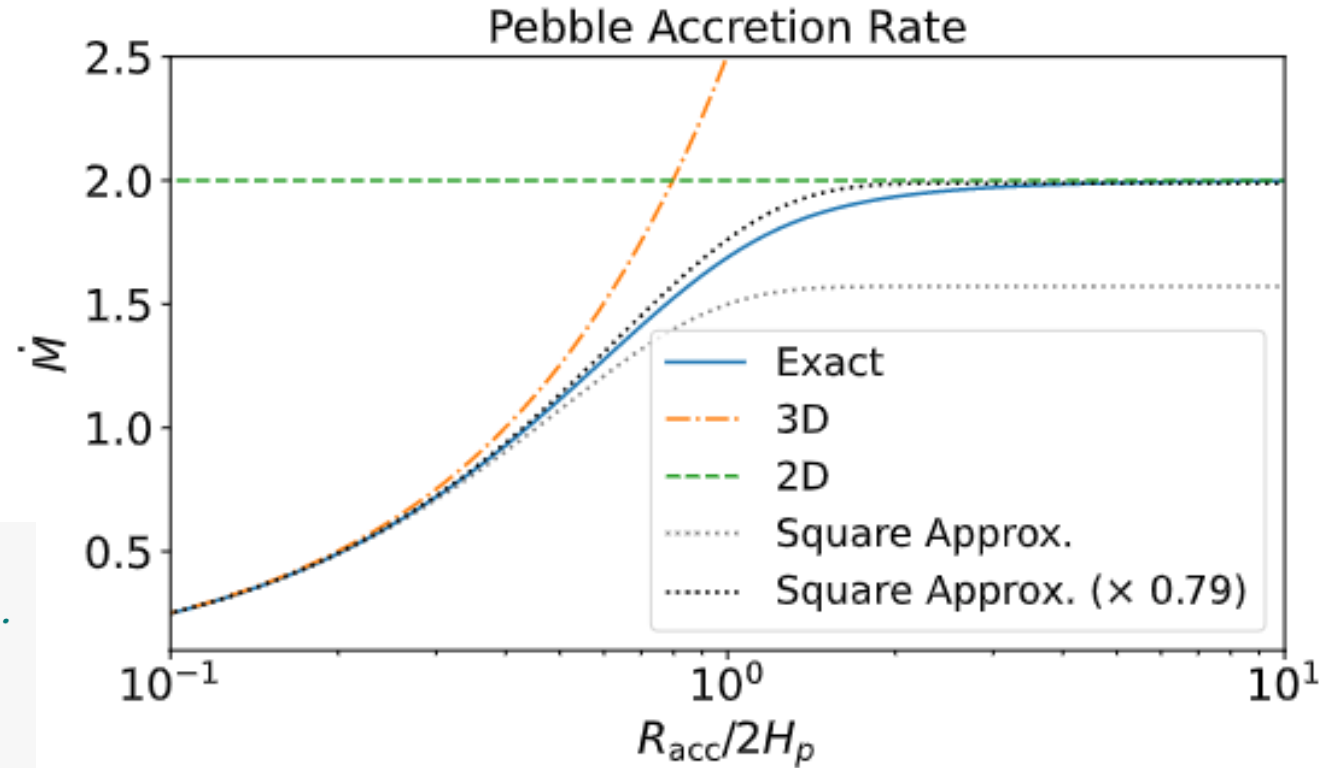
$$\dot{M} = \pi R_{\text{acc}}^2 \rho_{d0} S \delta v.$$

$$S \equiv \frac{1}{\pi R_{\text{acc}}^2} \int_{-R_{\text{acc}}}^{R_{\text{acc}}} 2 \sqrt{R_{\text{acc}}^2 - z^2} \exp\left(-\frac{z^2}{2H_d^2}\right) dz,$$

$$S = e^{-\xi} [I_0(\xi) + I_1(\xi)], \quad \xi \equiv \left(\frac{R_{\text{acc}}}{2H_d}\right)^2$$

```
y = (x/2)**2
# Modified Bessel function of the first kind of real order.
I0 = sp.special.iv(0, y)
I1 = sp.special.iv(1, y)

Sint = np.exp(-y) * (I0 + I1)
rho_int = rhop * Sint
Mdot = pi*r**2 * rho_int * deltav
```



# Analytical Solutions for 2D and 3D Polydisperse (multi-species) Pebble Accretion

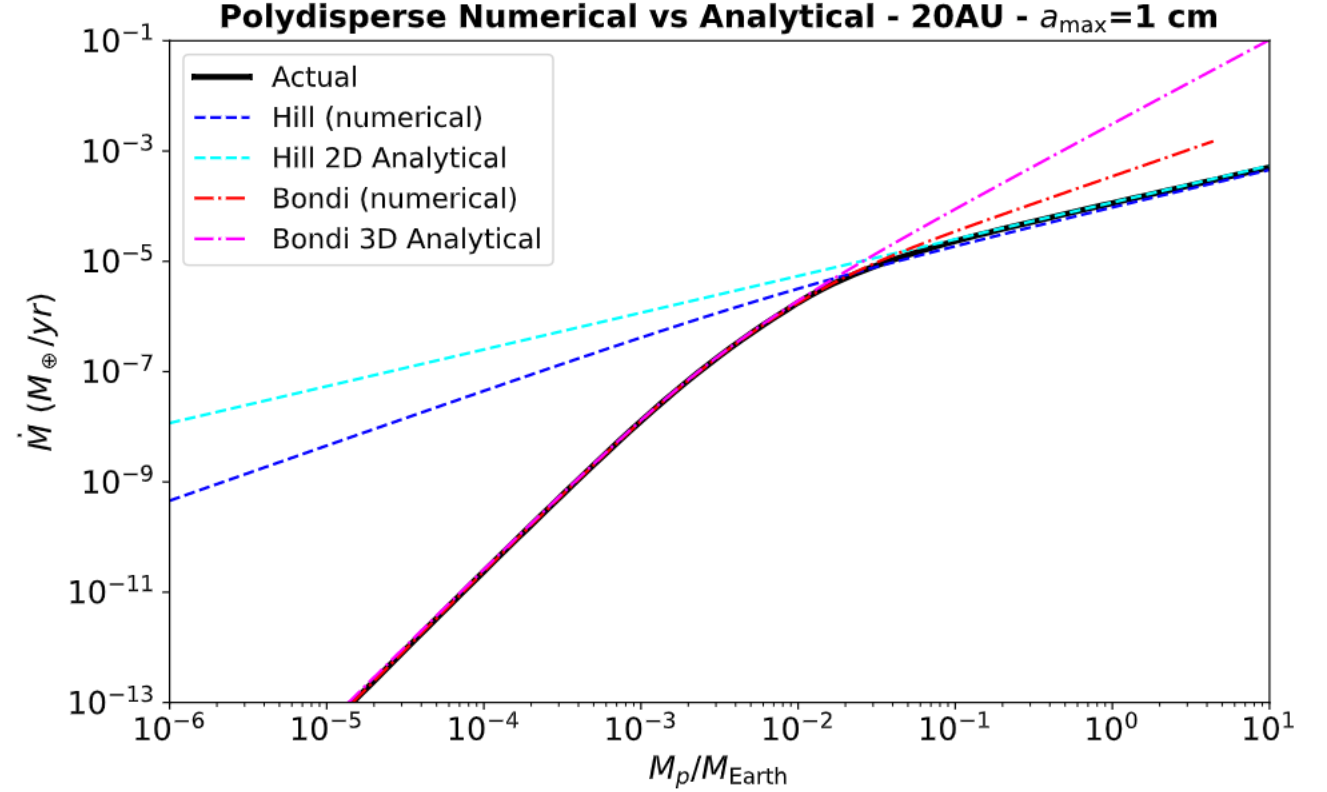
$$\dot{M}_{2D,Hill} = \frac{6(1-p)}{14-5q-3k} \left( \frac{St_{\max}}{0.1} \right)^{2/3} \Omega R_H^2 Z \Sigma_g.$$

$$\dot{M}_{3D,Bondi} \approx C_1 \frac{\gamma_l \left( \frac{b_1+1}{s}, j_1 a_{\max}^s \right)}{s j_1^{(b_1+1)/s}} + C_2 \frac{\gamma_l \left( \frac{b_2+1}{s}, j_2 a_{\max}^s \right)}{s j_2^{(b_2+1)/s}} + C_3 \frac{\gamma_l \left( \frac{b_3+1}{s}, j_3 a_{\max}^s \right)}{s j_3^{(b_3+1)/s}} + C_4 \frac{\gamma_l \left( \frac{b_4+1}{s}, j_4 a_{\max}^s \right)}{s j_4^{(b_4+1)/s}}.$$

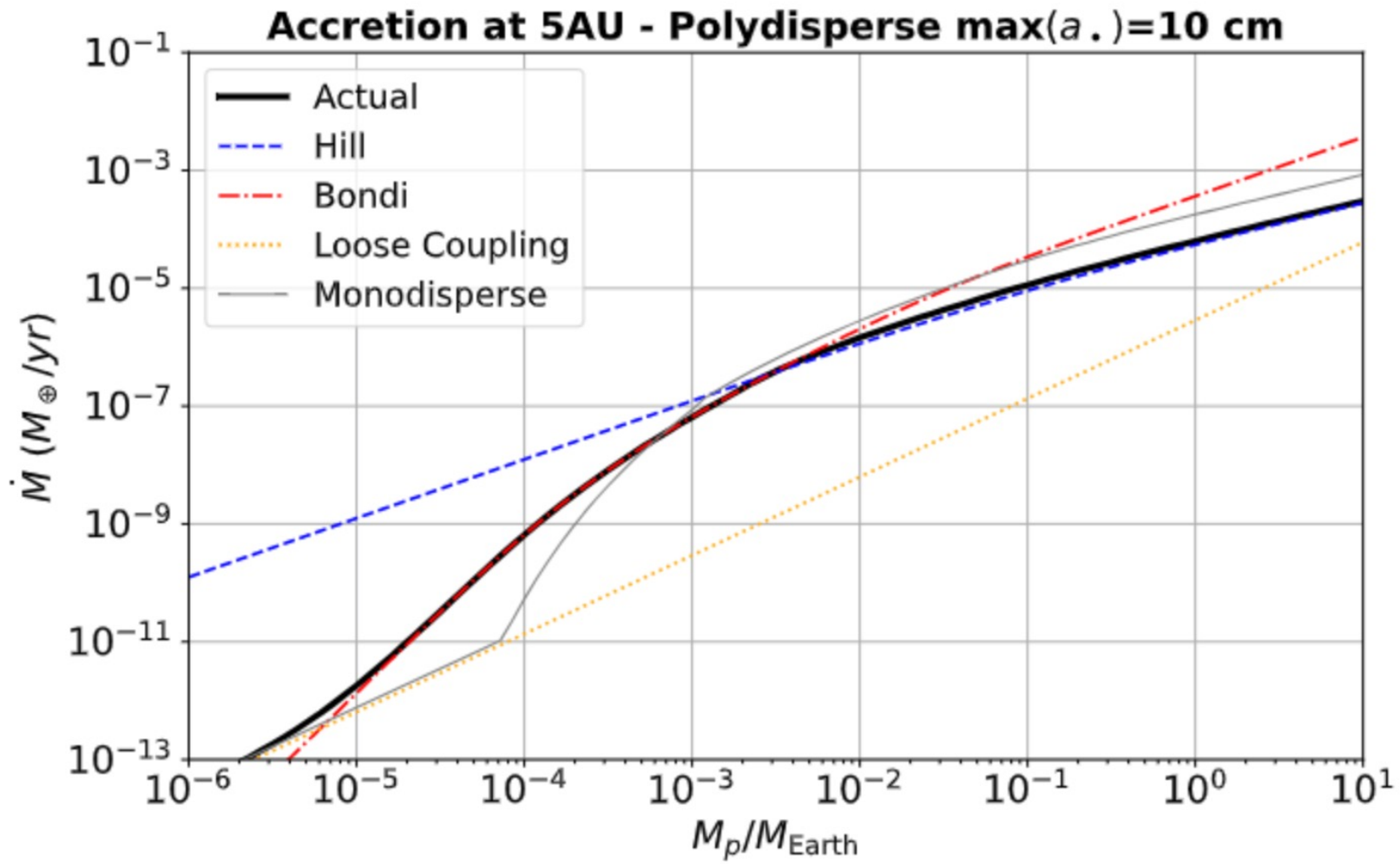
```
gamma1 = sp.special.gammainc((b1+1)/s, j1*a**s)*sp.special.gamma((b1+1)/s)
gamma2 = sp.special.gammainc((b2+1)/s, j2*a**s)*sp.special.gamma((b2+1)/s)
gamma3 = sp.special.gammainc((b3+1)/s, j3*a**s)*sp.special.gamma((b3+1)/s)
gamma4 = sp.special.gammainc((b4+1)/s, j4*a**s)*sp.special.gamma((b4+1)/s)
```

```
G1 = C1*gamma1/s/j1**((b1+1)/s)
G2 = C2*gamma2/s/j2**((b2+1)/s)
G3 = C3*gamma3/s/j3**((b3+1)/s)
G4 = C4*gamma4/s/j4**((b4+1)/s)
```

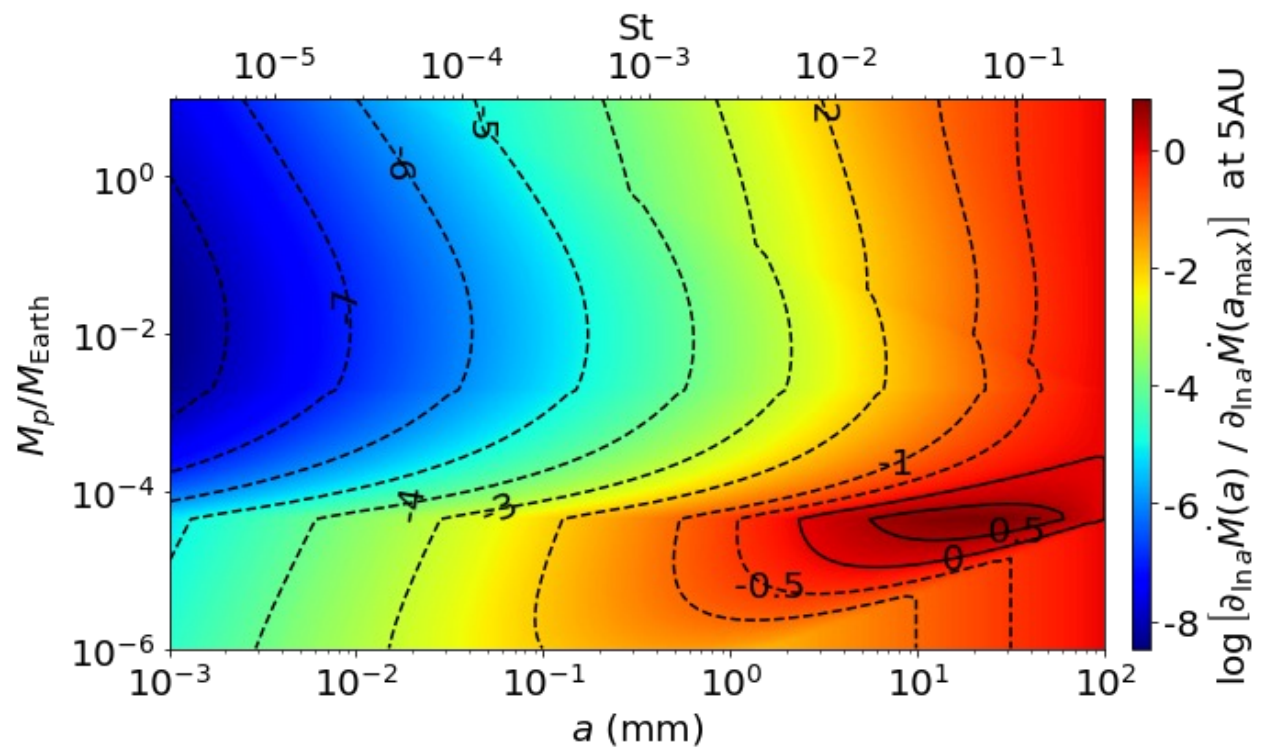
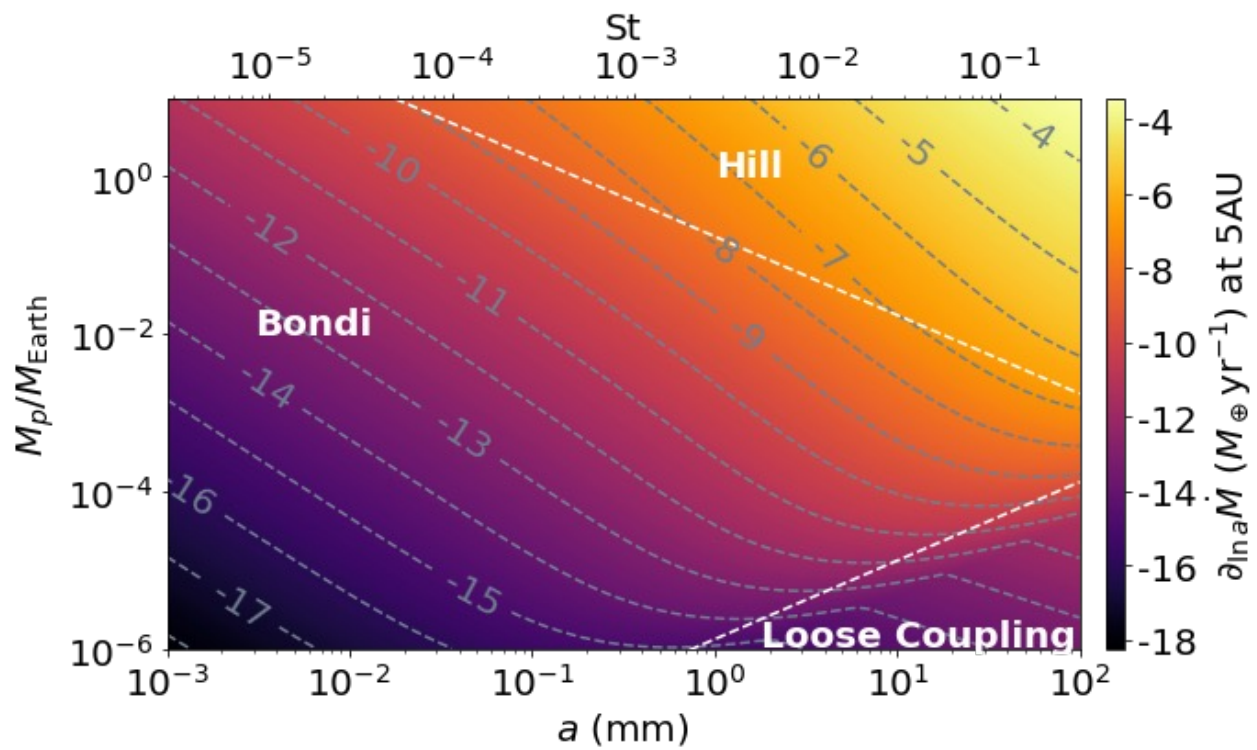
```
Mbondi3d = G1 + G2 + G3 + G4
```



## Accretion Rates

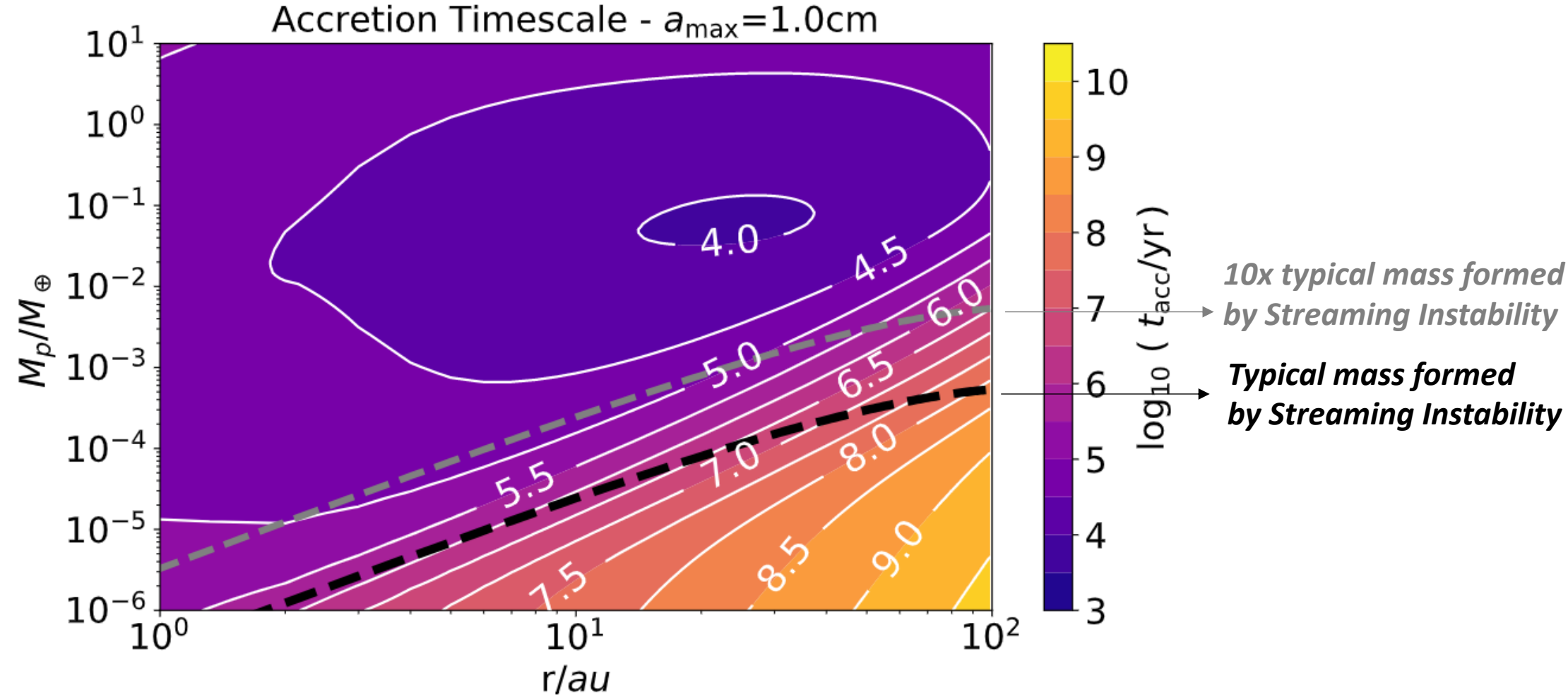


# Accretion Rates

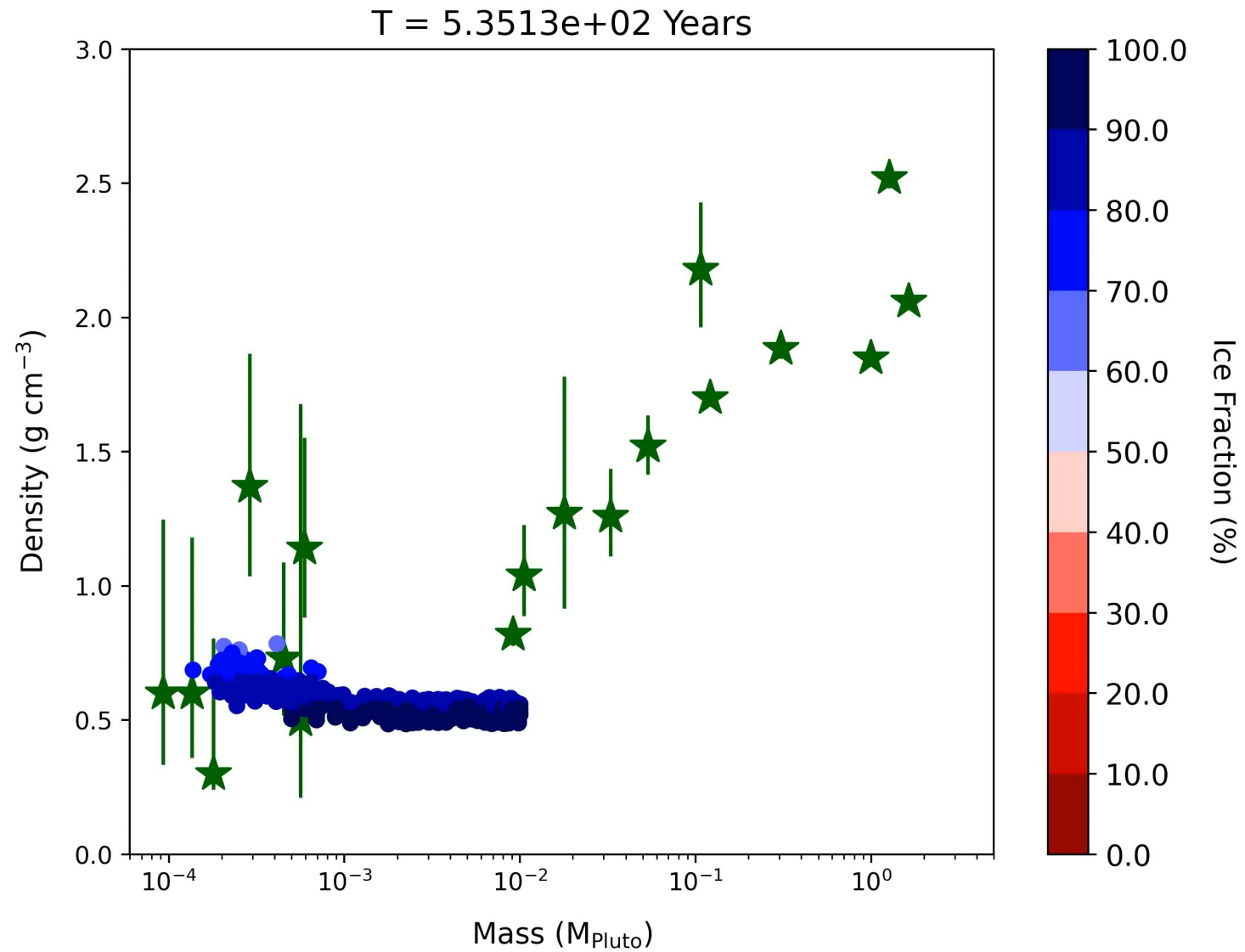




# Accretion Timescales

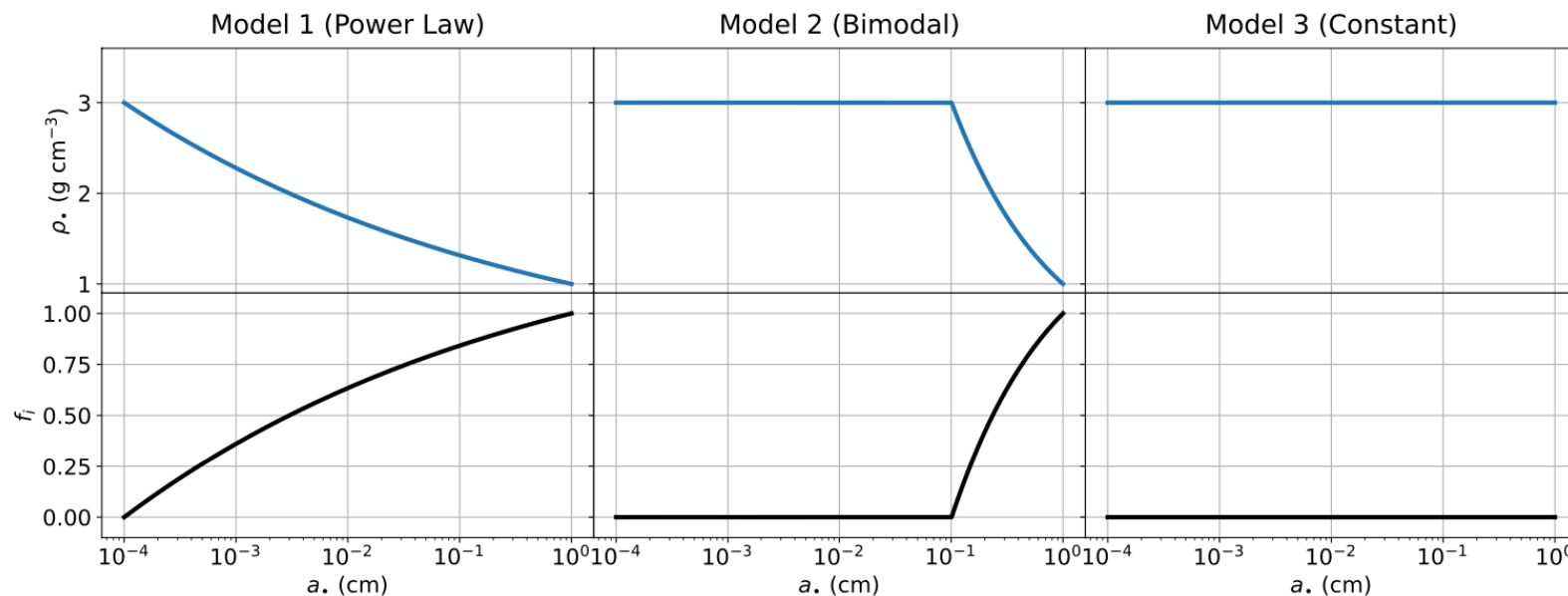


# Growing Pluto by silicate pebble accretion

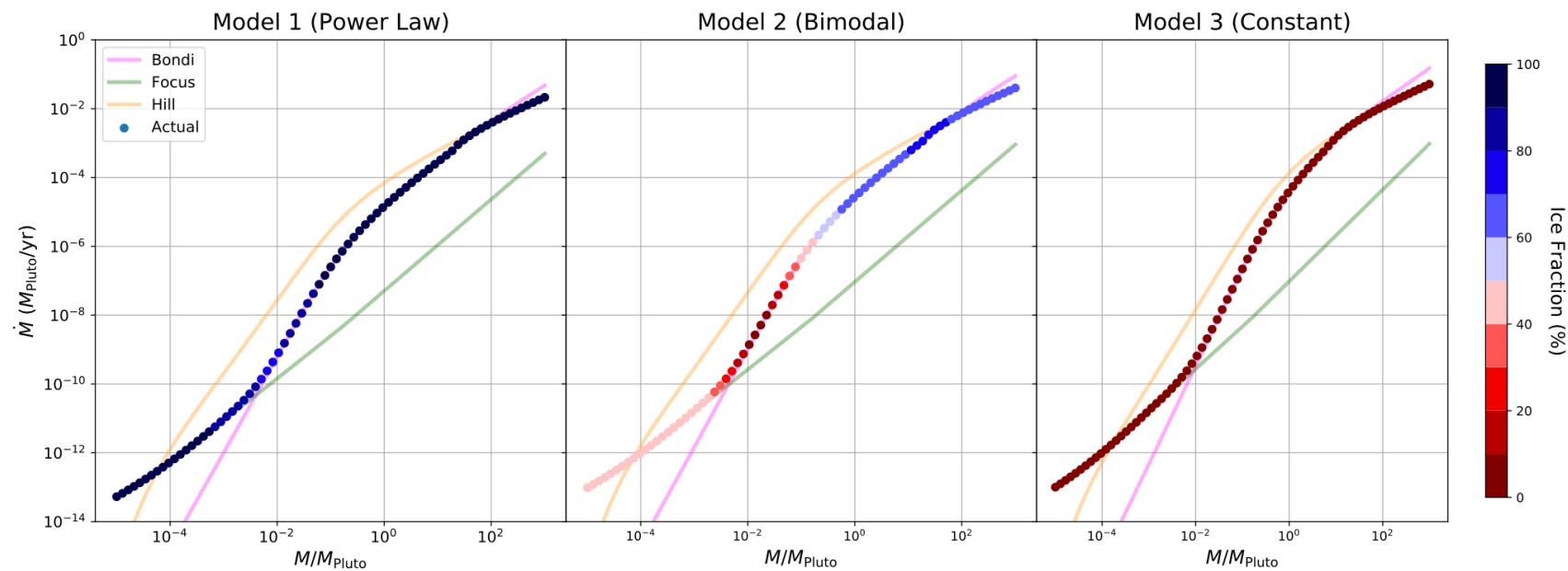


**Pebble Internal Density**

**Ice Volume Fraction**

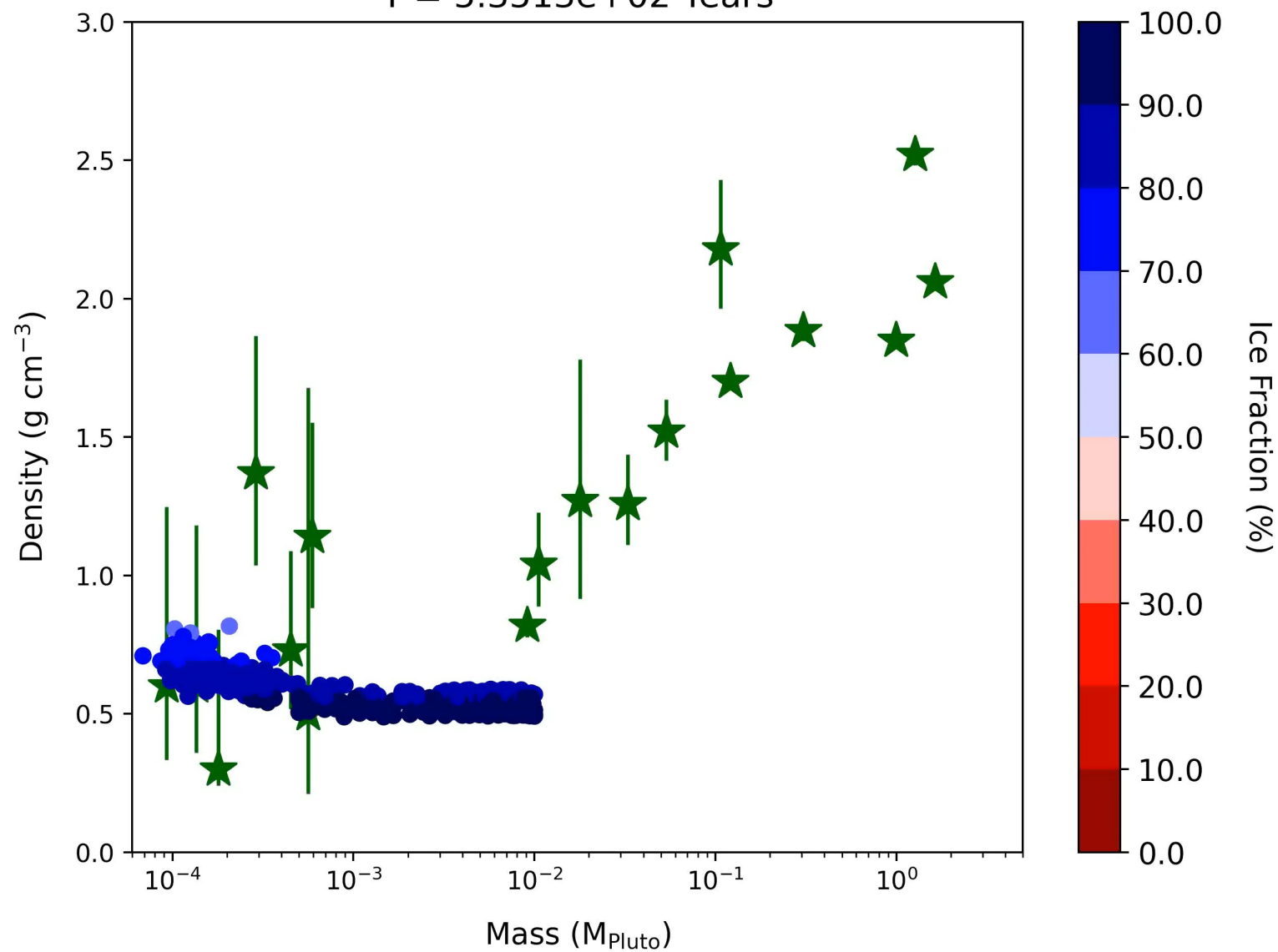


**Mass Accretion rate**

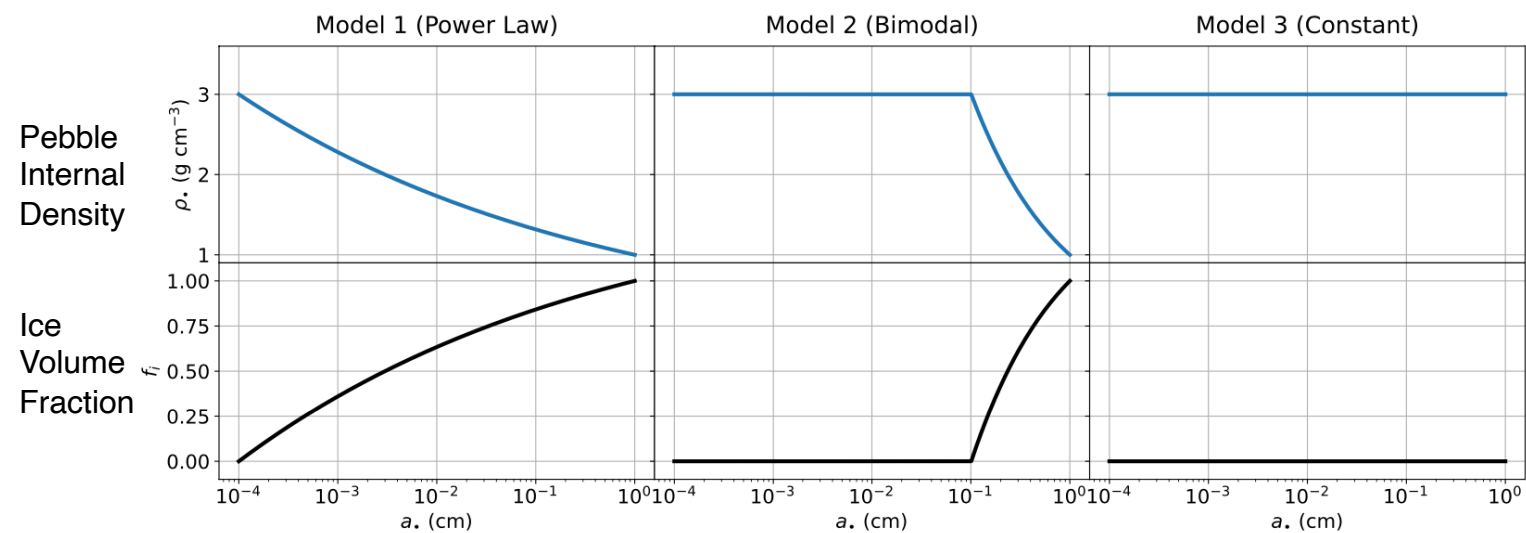


# Growing Pluto by silicate pebble accretion

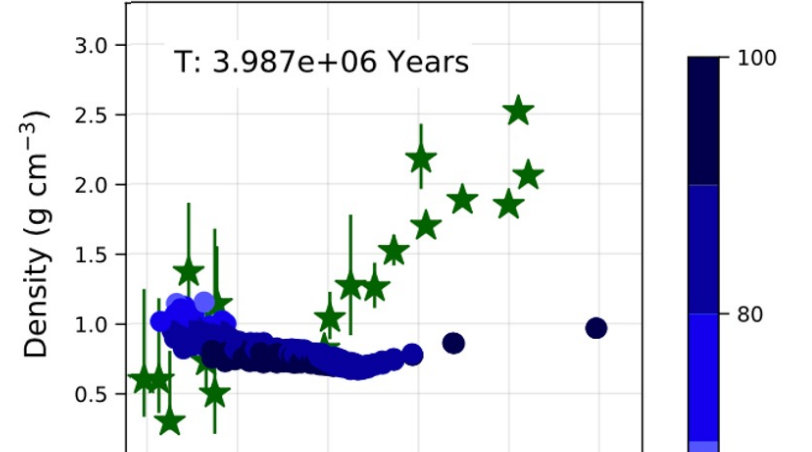
T = 5.3513e+02 Years



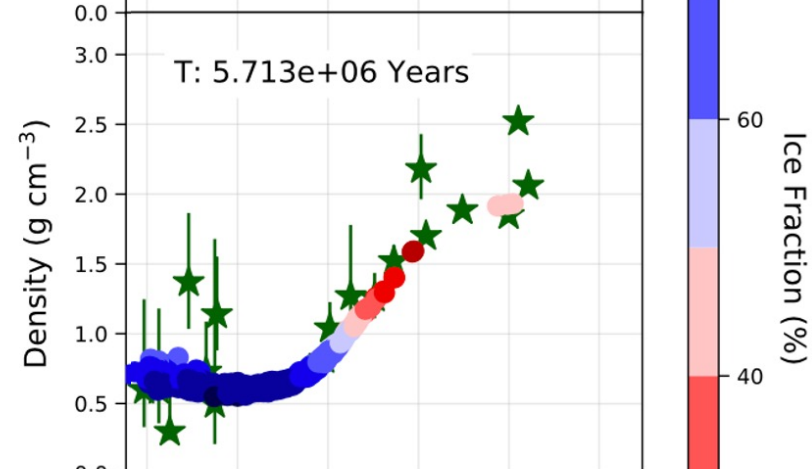
# Resulting Densities vs Mass relations



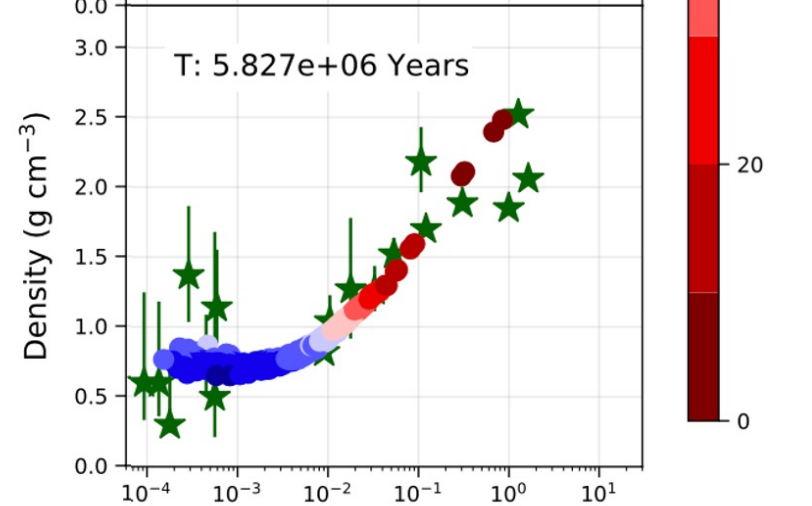
**Model 1 (Power Law)**



**Model 2 (Bimodal)**

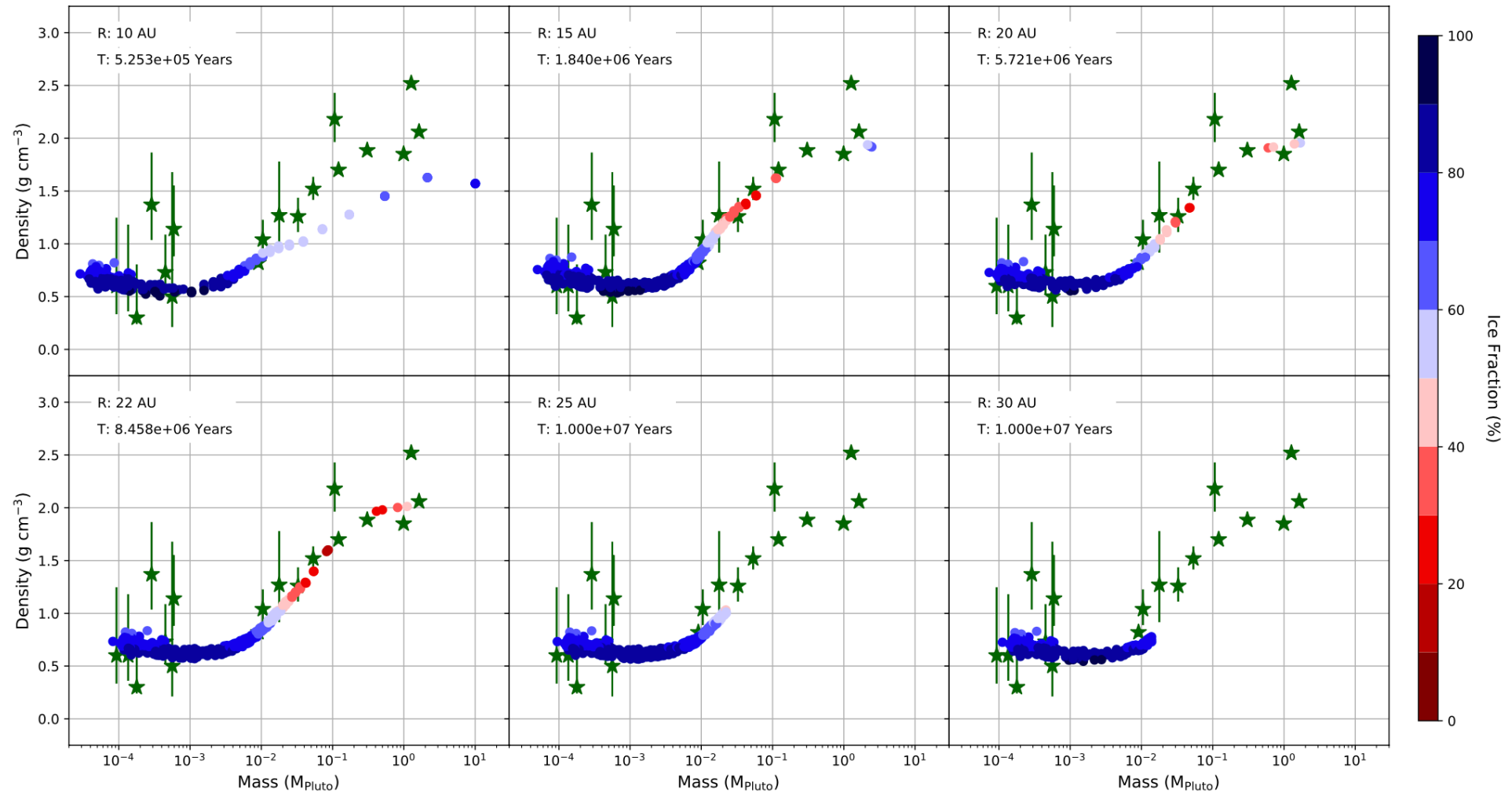


**Model 3 (Constant)**

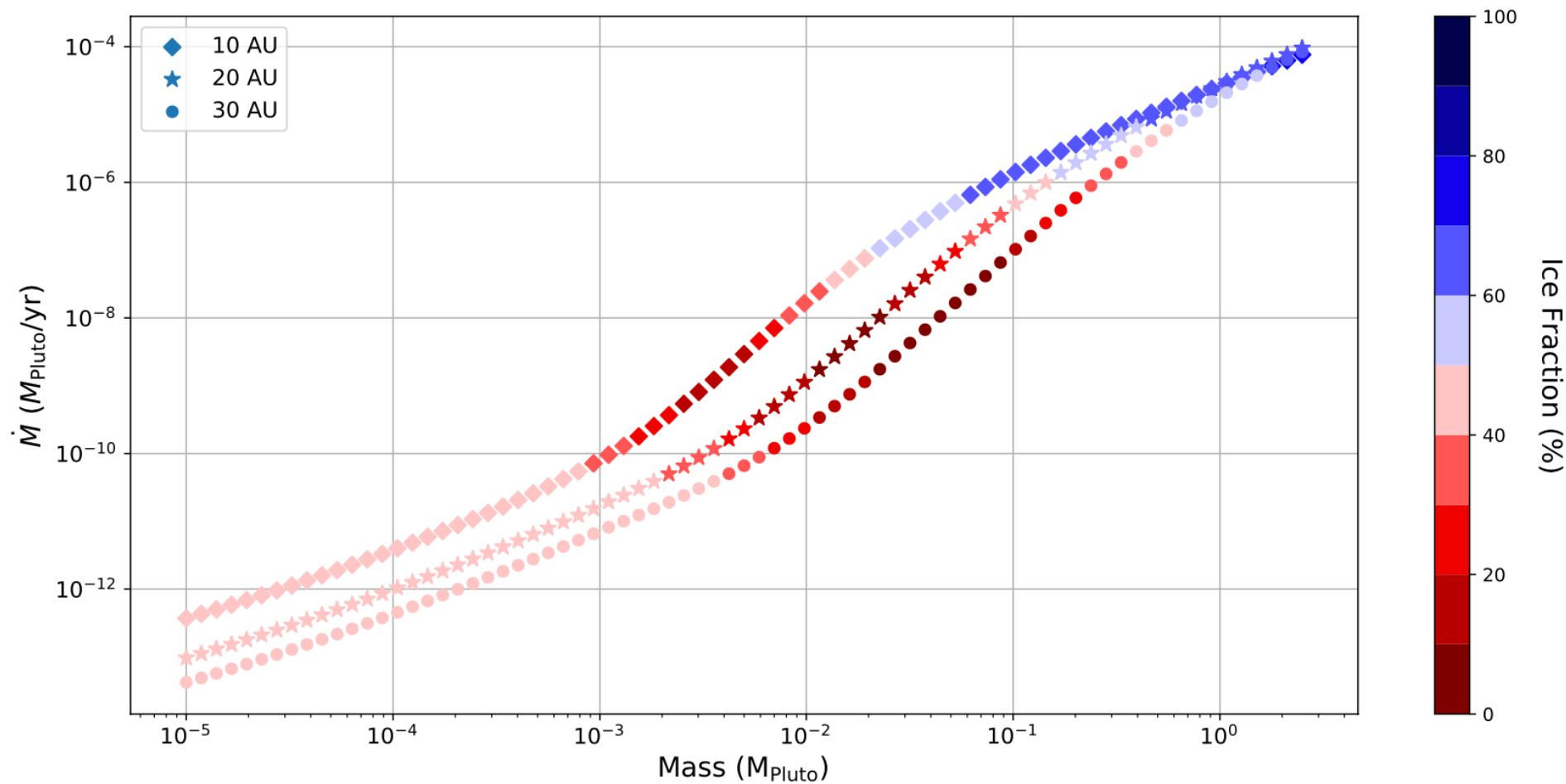




# Distance Range 15 - 25AU



# The window of silicate accretion



# Conclusions

- Polydisperse Bondi accretion 1-2 orders of magnitude more efficient than monodisperse
  - Best accreted pebbles are those of drag time  $\sim$  Bondi time, not the largest ones
  - The largest ones dominate the mass budget, but accrete poorly
- Onset of Bondi accretion 1-2 orders of magnitude lower in mass compared to monodisperse
  - Bondi accretion possible on top of Streaming Instability planetary embryos within disk lifetime
  - Reaches 100-350km objects within Myr timescales
- Analytical solution to
  - Monodisperse general case
  - Polydisperse 2D Hill and 3D Bondi
- KBO density dichotomy problem:
  - Two different pebble populations, maintained by ice desorption off small grains
  - Streaming instability: icy-rich small objects; nearly uniform composition
  - Polydisperse pebble accretion: silicate-rich larger objects; varied composition
  - Melting avoided by
    - ice-rich formation
    - $^{26}\text{Al}$  incorporated mostly in long ( $>$ Myr) phase of silicate accretion
  - KBOs best reproduced between 15-25 AU

