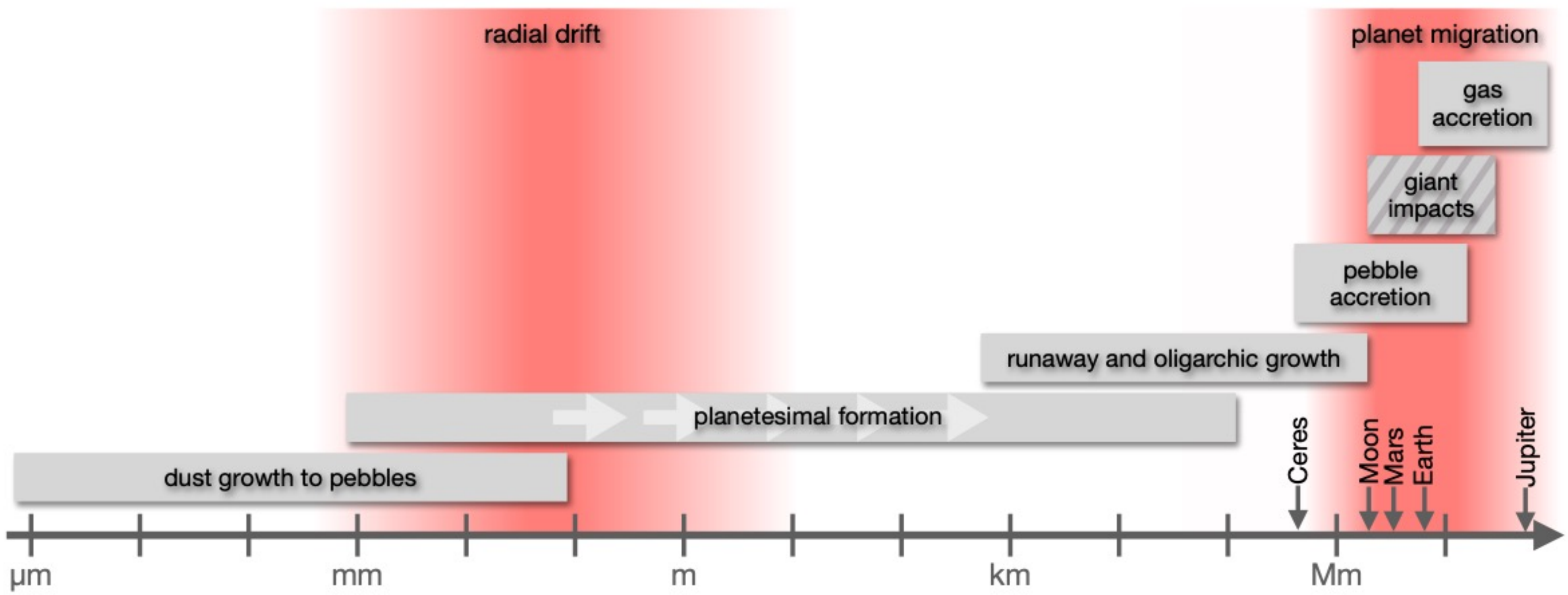
Overview of Planet Formation



Drazkowska et al. 2023

Suggested Reading

ANNUAL REVIEWS

Annual Review of Earth and Planetary Sciences

Forming Planets via Pebble Accretion

Anders Johansen[1] and Michiel Lambrechts[2]

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[2]Laboratoire Lagrange, Observatoire de la Côte d'Azur, Université Côte d'Azur, 06304 Nice Cedex 4, France; email: michiel.lambrechts@oca.eu

Planet Formation Theory in the Era of ALMA and Kepler: from Pebbles to Exoplanets

Joanna Drążkowska[1,2], **Bertram Bitsch**[3], **Michiel Lambrechts**[4,5], **Gijs D. Mulders**[6,7], **Daniel Harsono**[8,9], **Allona Vazan**[10], **Beibei Liu**[11], **Chris W. Ormel**[12], **Katherine Kretke**[13] and **Alessandro Morbidelli**[14]

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[5]*Center for Star and Planet Formation, GLOBE Institute, University of Copenhagen, Øster Voldgade 5-7, 1350 Copenhagen, Denmark*
[6]*Facultad de Ingeniería y Ciencias, Universidad Adolfo Ibáñez, Av. Diagonal las Torres 2640, Peñalolén, Santiago, Chile*
[7]*Millennium Institute for Astrophysics, Chile*
[8]*Institute of Astronomy, Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
[9]*Academia Sinica Institute of Astronomy and Astrophysics, No.1, Sec. 4., Roosevelt Road, Taipei 10617, Taiwan*
[10]*Astrophysics Research Center of the Open University (ARCO), Department of Natural Sciences, The Open University of Israel, 4353701 Raanana, Israel*
[11]*Zhejiang Institute of Modern Physics, Department of Physics & Zhejiang University-Purple Mountain Observatory Joint Research Center for Astronomy, Zhejiang University, 38 Zheda Road, Hangzhou 310027, China*
[12]*Department of Astronomy, Tsinghua University, Beijing 100084, China*
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Abstract

Our understanding of the planet formation has been rapidly evolving in recent years. The classical planet formation theory, developed when the only known planetary system was our own Solar System, has been revised to account for the observed diversity of the exoplanetary systems. At the same time, the increasing observational capabilities of the young stars and their surrounding disks bring new constraints on the planet formation process. In this chapter, we summarize the new information derived from the exoplanets population and the circumstellar disks observations. We describe the new developments in planet formation theory, from dust evolution to the growth of planetary cores by accretion of planetesimals, pebbles, and gas. We review the state-of-the-art models for the formation of diverse planetary systems, including the population synthesis approach which is necessary to compare theoretical model outcomes to the exoplanet population. We emphasize that the planet formation process may not be spatially uniform in the

The emerging paradigm of pebble accretion

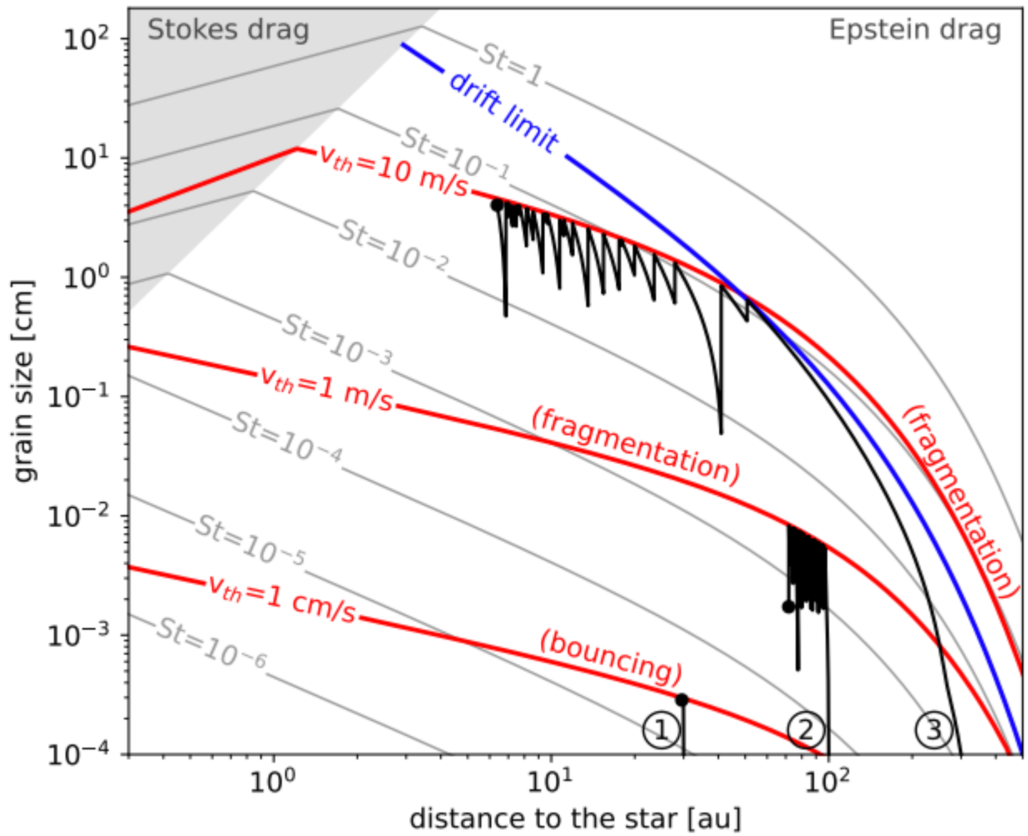
Chris W. Ormel

Abstract Pebble accretion is the mechanism in which small particles ('pebbles') accrete onto big bodies (planetesimals or planetary embryos) in gas-rich environments. In pebble accretion, accretion occurs by settling and depends only on the mass of the gravitating body, not its radius. I give the conditions under which pebble accretion operates and show that the collisional cross section can become much larger than in the gas-free, ballistic, limit. In particular, pebble accretion requires the pre-existence of a massive planetesimal seed. When pebbles experience strong orbital decay by drift motions or are stirred by turbulence, the accretion efficiency is low and a great number of pebbles are needed to form Earth-mass cores. Pebble accretion is in many ways a more natural and versatile process than the classical, planetesimal-driven paradigm, opening up avenues to understand planet formation in solar and exoplanetary systems.

1 Introduction

Ormel 2017, Johansen & Lambrechts 2017, Drazkowska et al. 2023

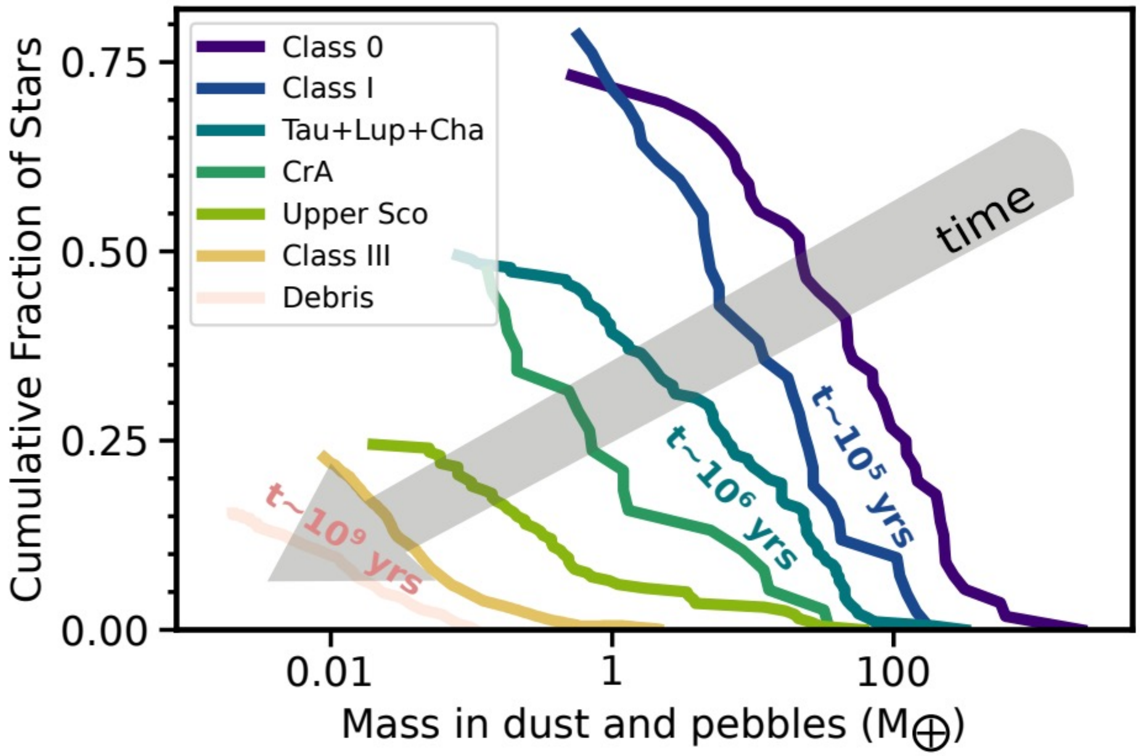
Drift and Fragmentation Limits



Drazkowska et al. 2023

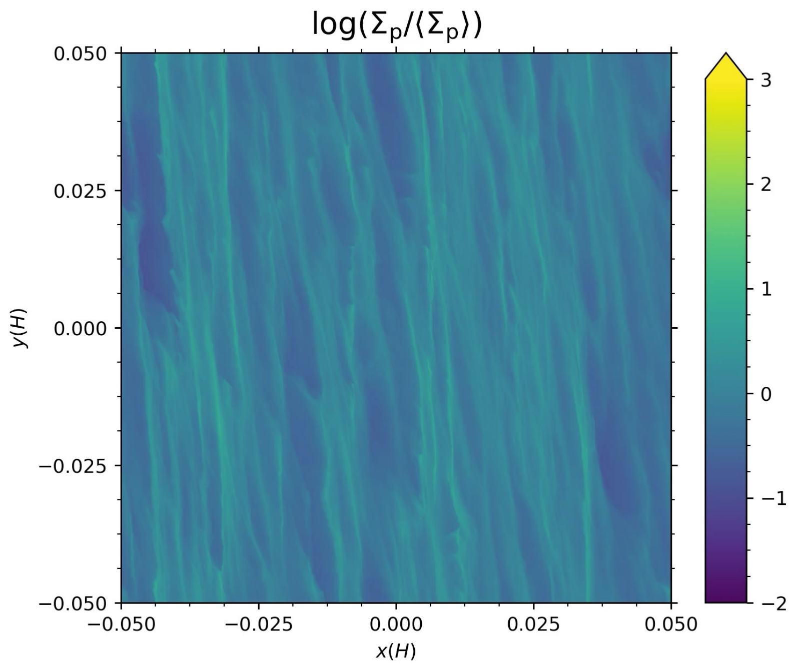
Pebble Flux

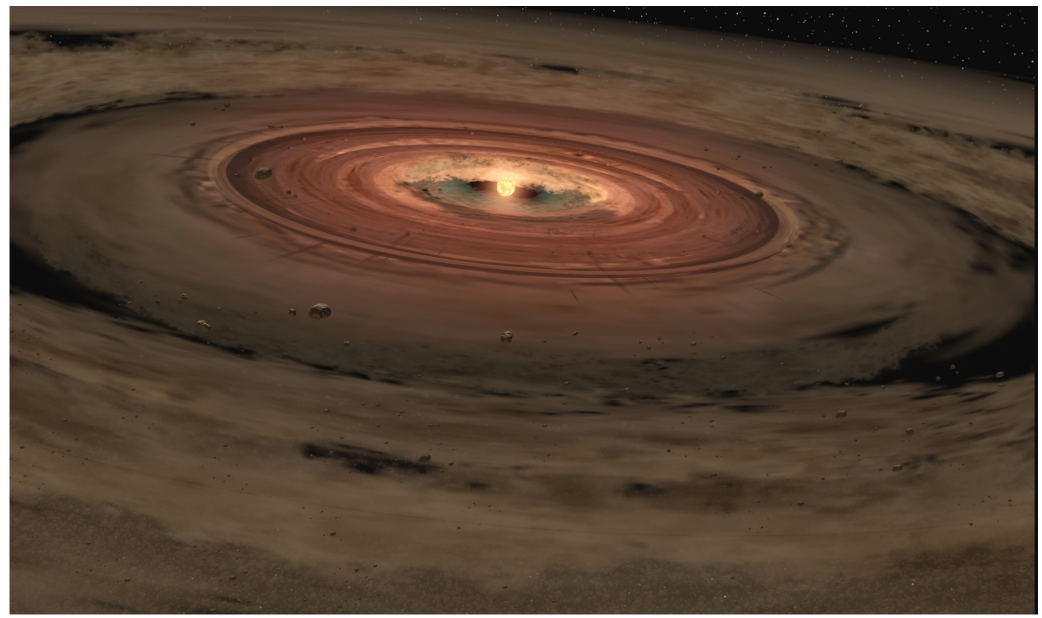
The dust mass evolution in disk is consistent with a pebble flux of 100 Mearth/Myr



Drazkowska et al. 2023

Terrestrial Planet Formation
From Pebbles and Planetesimals to Planets





Core Accretion: From Planetesimals to Planets

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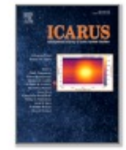
ELSEVIER

Icarus
Volume 124, Issue 1, November 1996, Pages 62-85



Regular Article

Formation of the Giant Planets by Concurrent Accretion of Solids and Gas ☆

James B. Pollack [a][2], Olenka Hubickyj [b][3], Peter Bodenheimer [b], Jack J. Lissauer [c], Morris Podolak [d], Yuval Greenzweig [d]

⊞ Show more

https://doi.org/10.1006/icar.1996.0190

Abstract

New numerical simulations of the formation of the giant planets are presented, in which for the first time both the gas and planetesimal accretion rates are calculated in a self-consistent, interactive fashion. The simulations combine three elements: (1) three-body accretion cross sections of solids onto an isolated planetary embryo, (2) a stellar evolution code for the planet's gaseous envelope, and (3) a planetesimal dissolution code within the envelope, used to evaluate the planet's effective capture radius and the energy deposition profile of accreted material. Major assumptions

☆ UCO/Lick Observatory Bulletin No. 1341.

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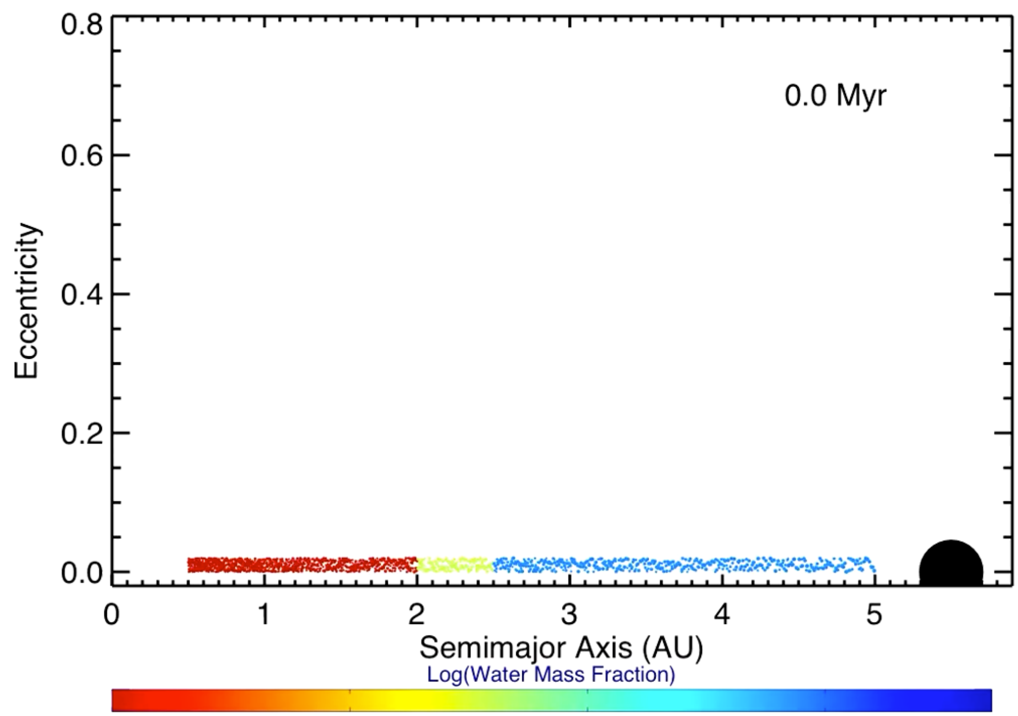
2 Deceased.

3 Present address: SETI Institute, 2035 Landings Dr., Mountain View, CA 94043.

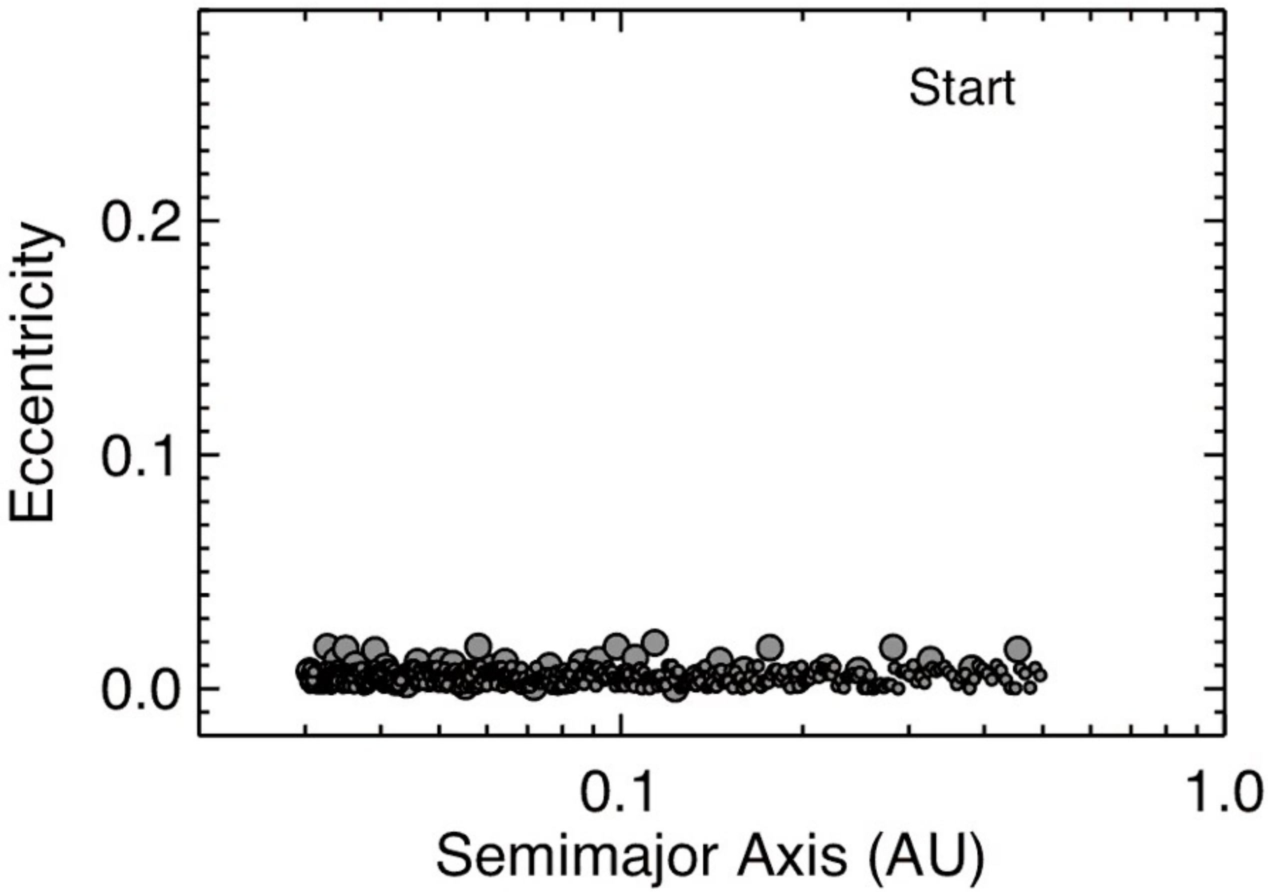
Terrestrial Planet Formation

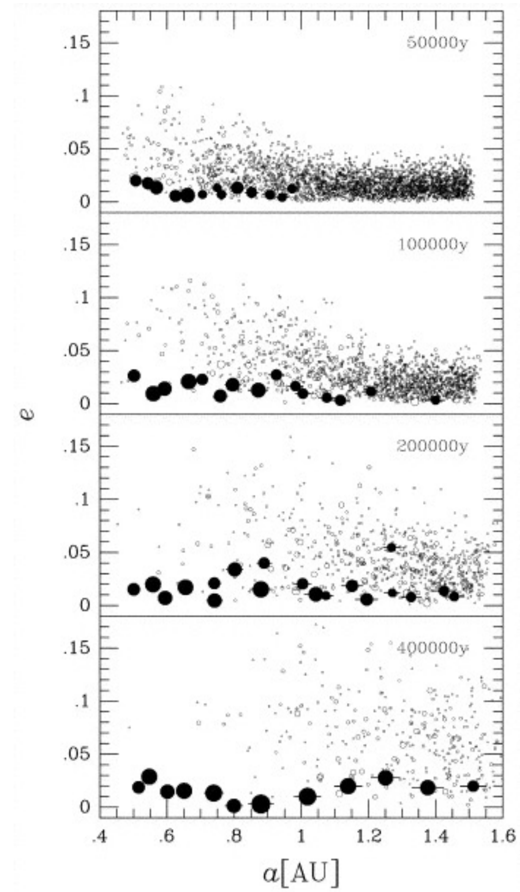
Core Accretion: From Planetesimals to Planets



Terrestrial Planet Formation

Core Accretion: From Planetesimals to Planets





Terrestrial Planet Formation

Core Accretion: From Planetesimals to Planets

- Hill Dynamics (how cores grow)
- Growth rates (how fast cores grow)
- Isolation mass (how massive cores grow)

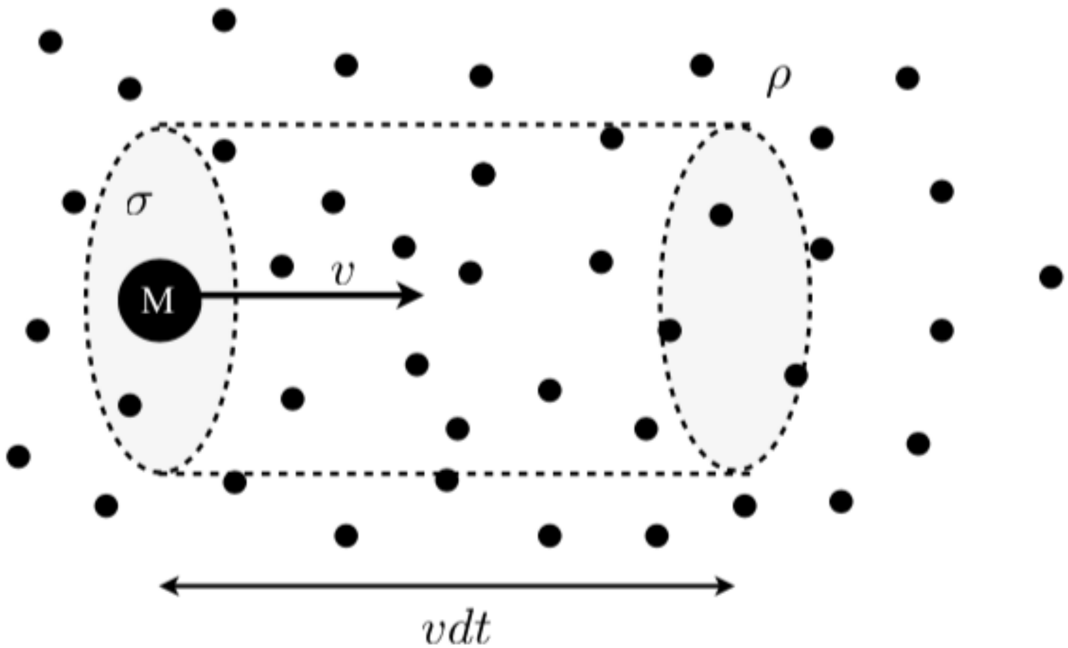
Problem

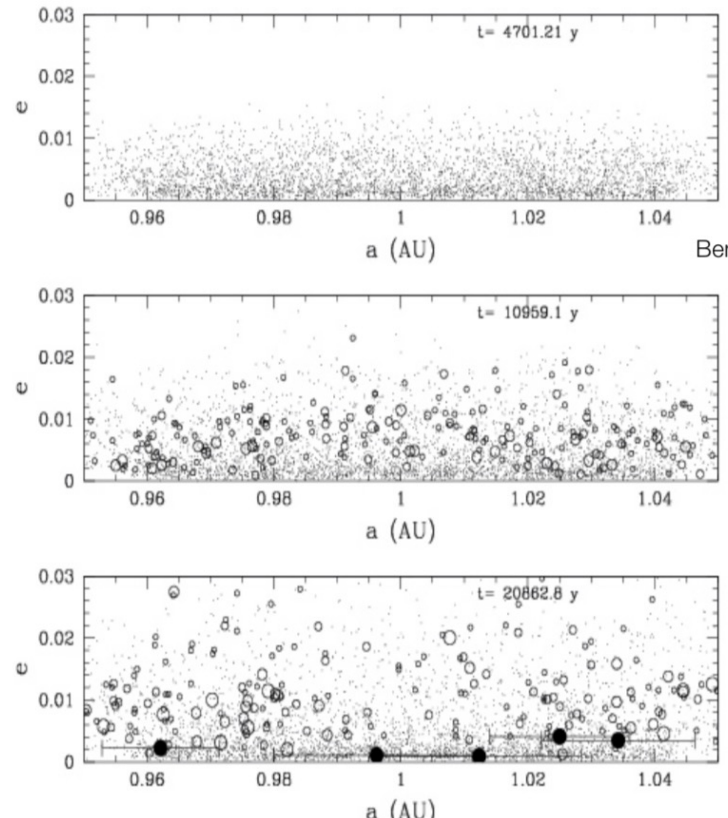
- Growing planets by planetesimal collisions.
  - There are a trillion planetesimals.
    - Statistical treatment needed

Aims

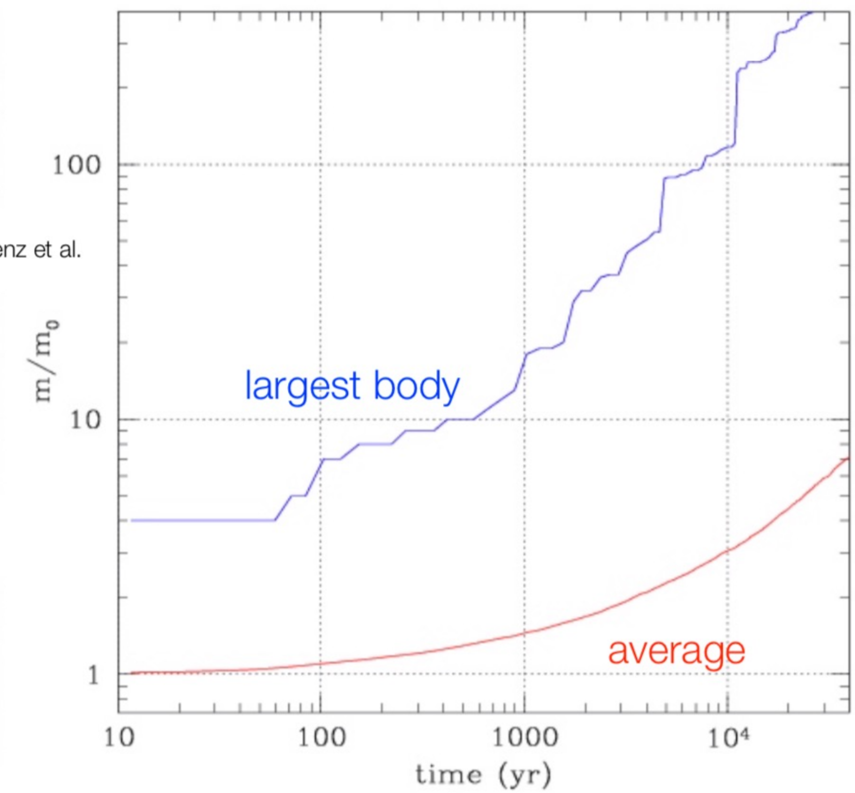
- Find collision rate for planetesimal distribution
- Determine outcome of collisions
- Put it all together in a model

Growth rate





Benz et al.



Formation of a few large bodies well separated (~ 5 R_{hills}). Note their low eccentricity

The largest body is growing faster than the average body. It decouples from the background planetesimals.

From runaway growth to oligarchic growth

$$\frac{dm}{dt} = \frac{\sqrt{3}}{2}\Sigma\Omega\pi R^2 f \qquad f = 1 + \frac{{v_{esc}}^2}{{v_{rms}}^2}$$

The growing embryo "heats" the planetesimal disk.

Low v_{rms} ($f >> 1$)

$$\frac{1}{m}\frac{dm}{dt} \propto m^{1/3}$$

Largest body grows fastest

Runaway growth

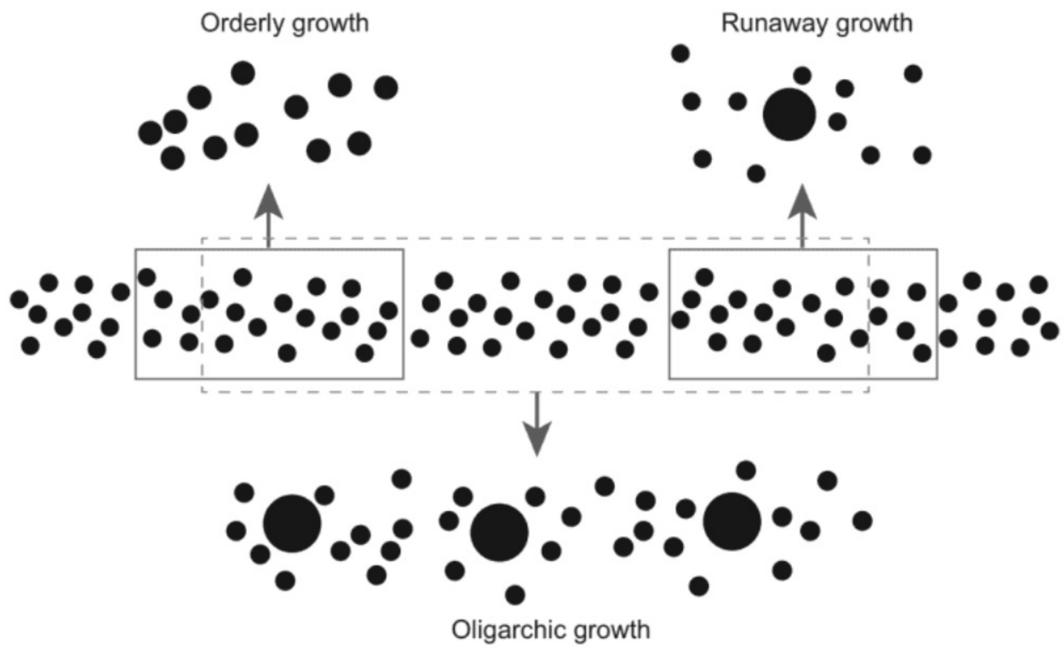
High v_{rms} ($f \sim 1$)

$$\frac{1}{m}\frac{dm}{dt} \propto m^{-1/3}$$

Largest body grows slowest

Oligarchic growth

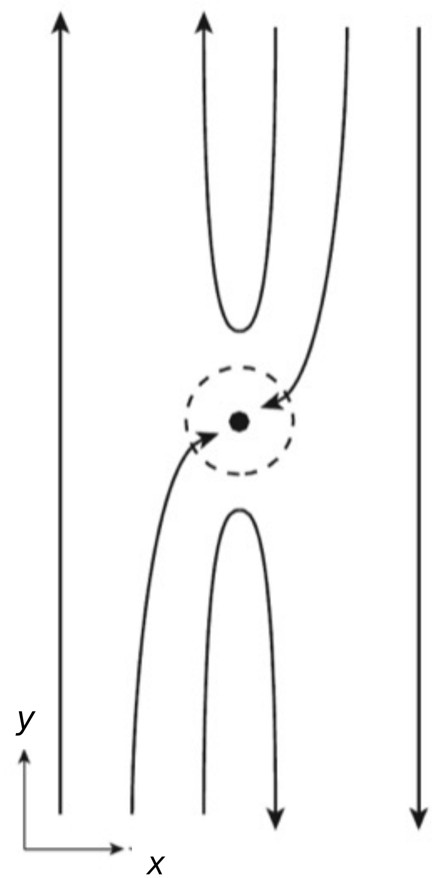
Growth regimes



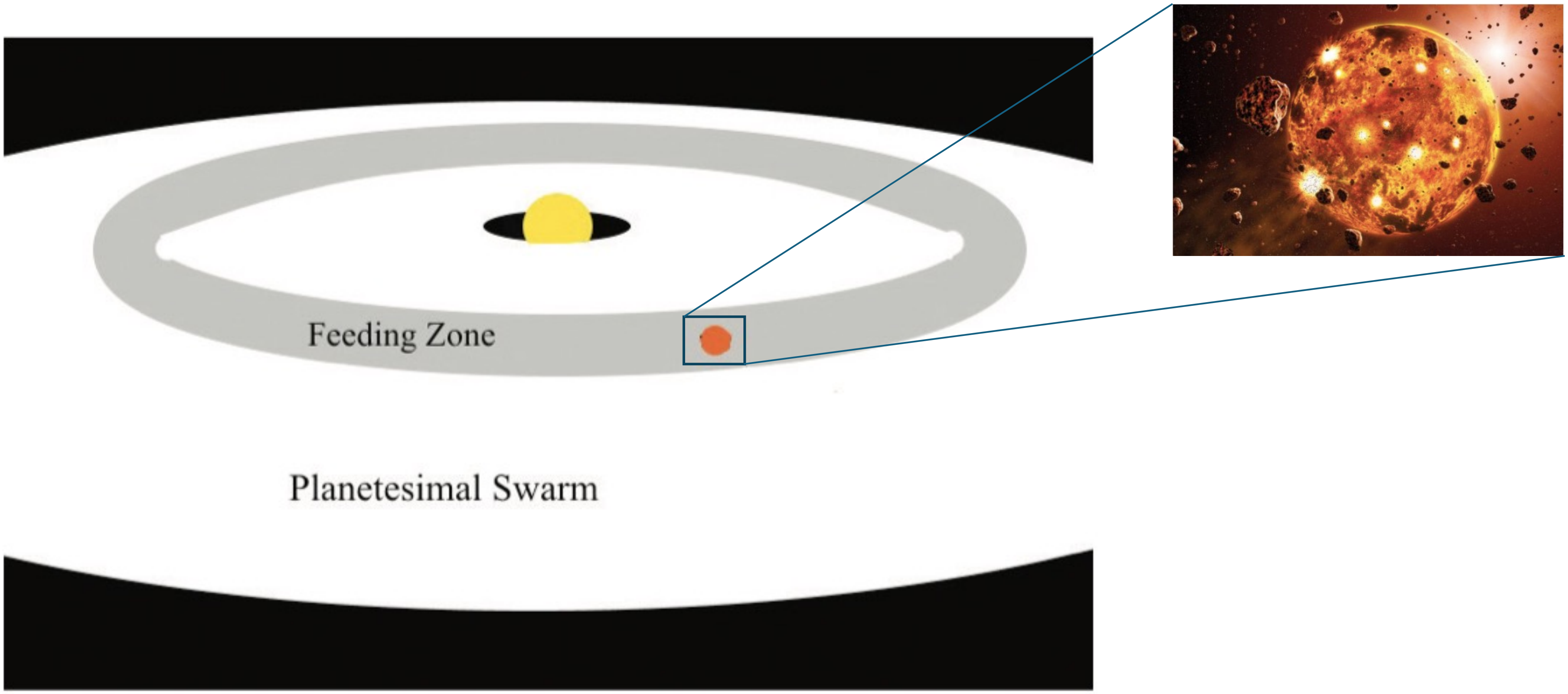
Hill (local) approximation

Hill Radius

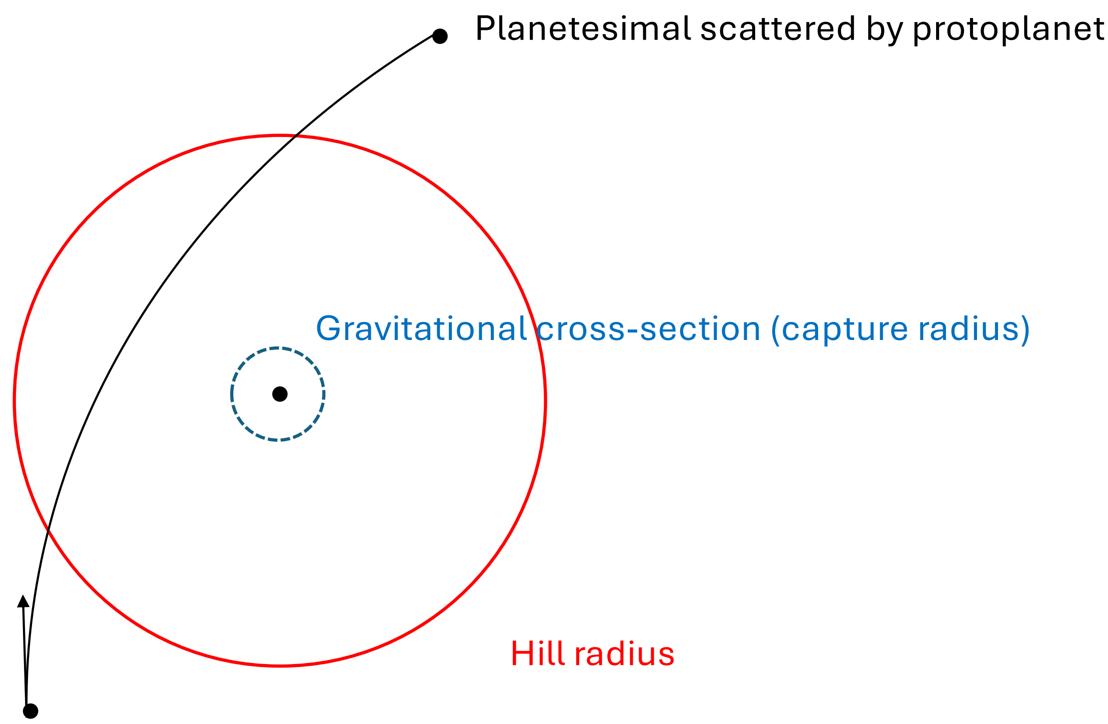
$R_H = a\ [M_{planet} / (3M_{star})]^{1/3}$



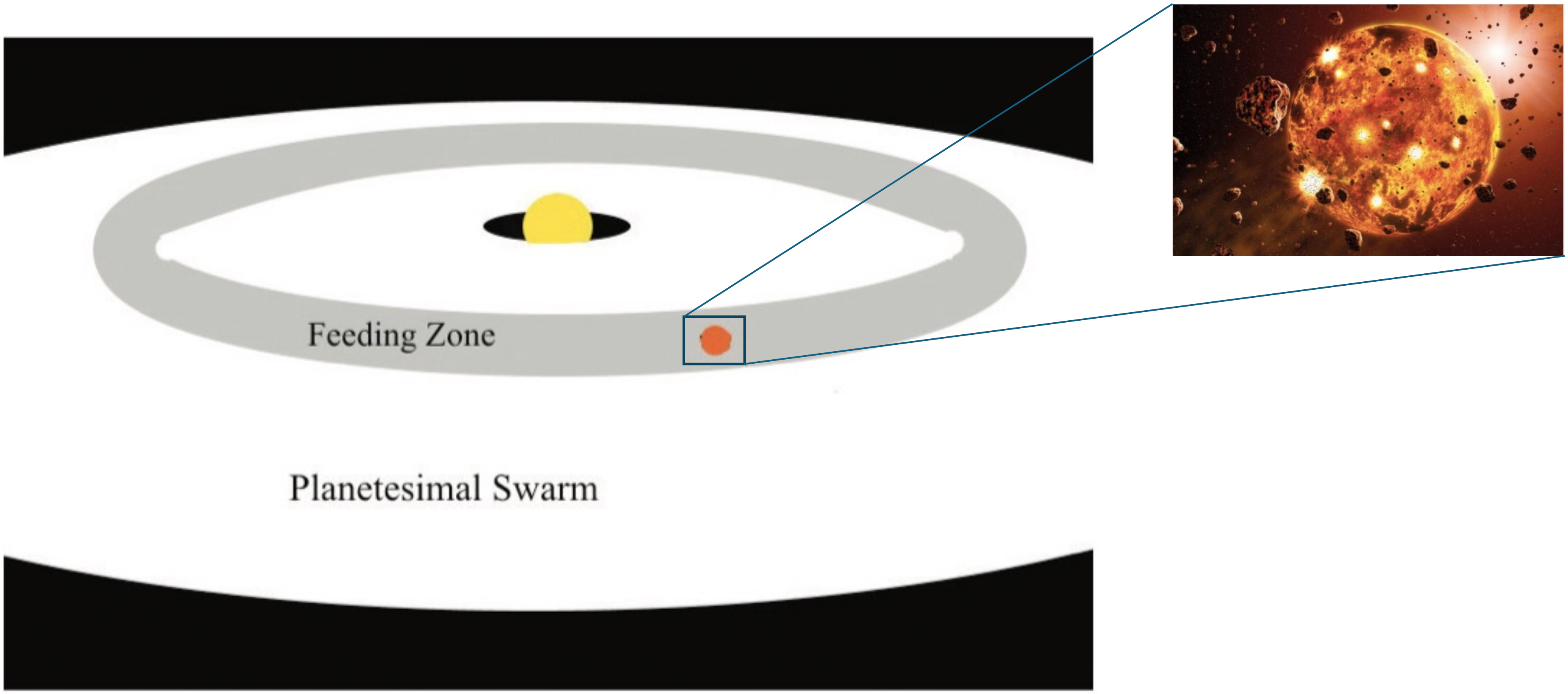
Planetesimal Accretion

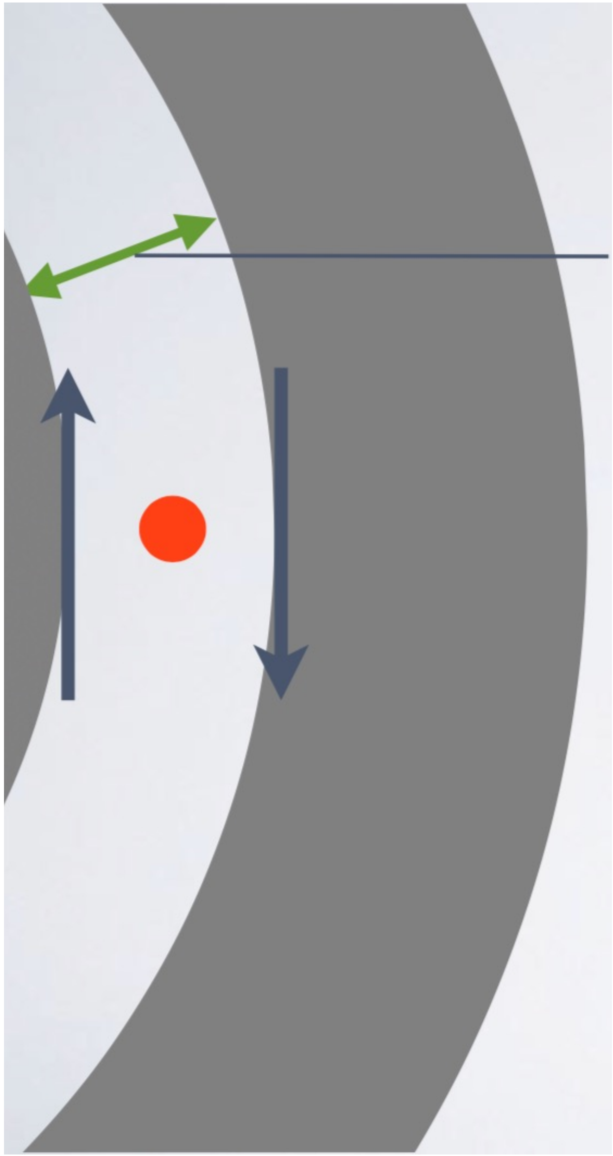


Planetesimal Accretion is inefficient



Isolation Mass

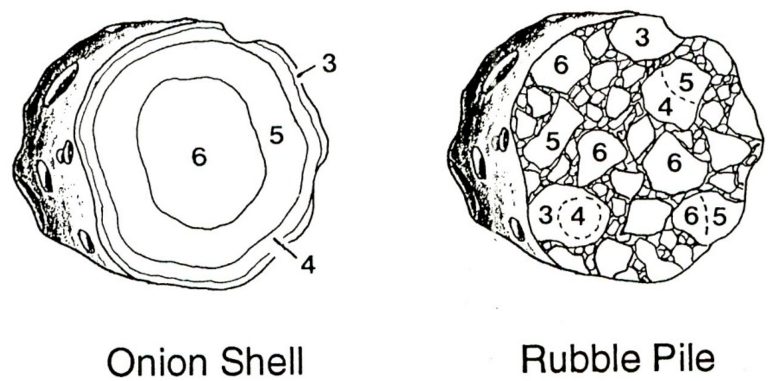




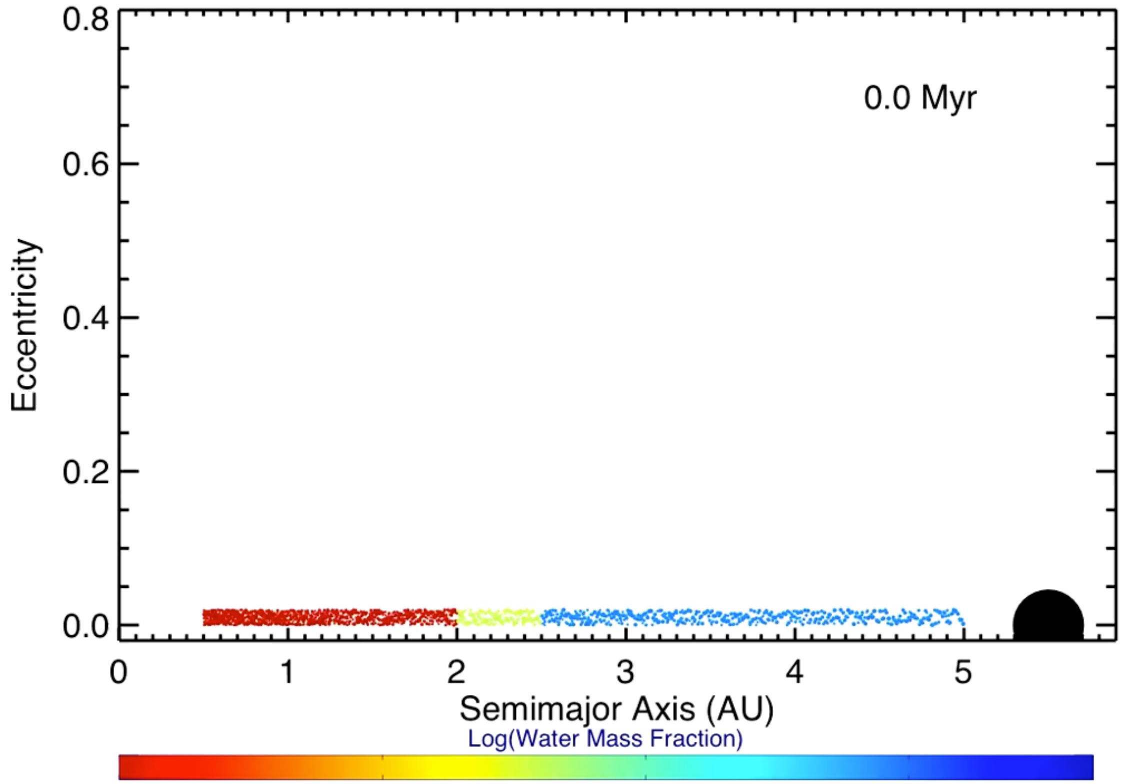
Isolation Mass

Of the order of the Hill radius

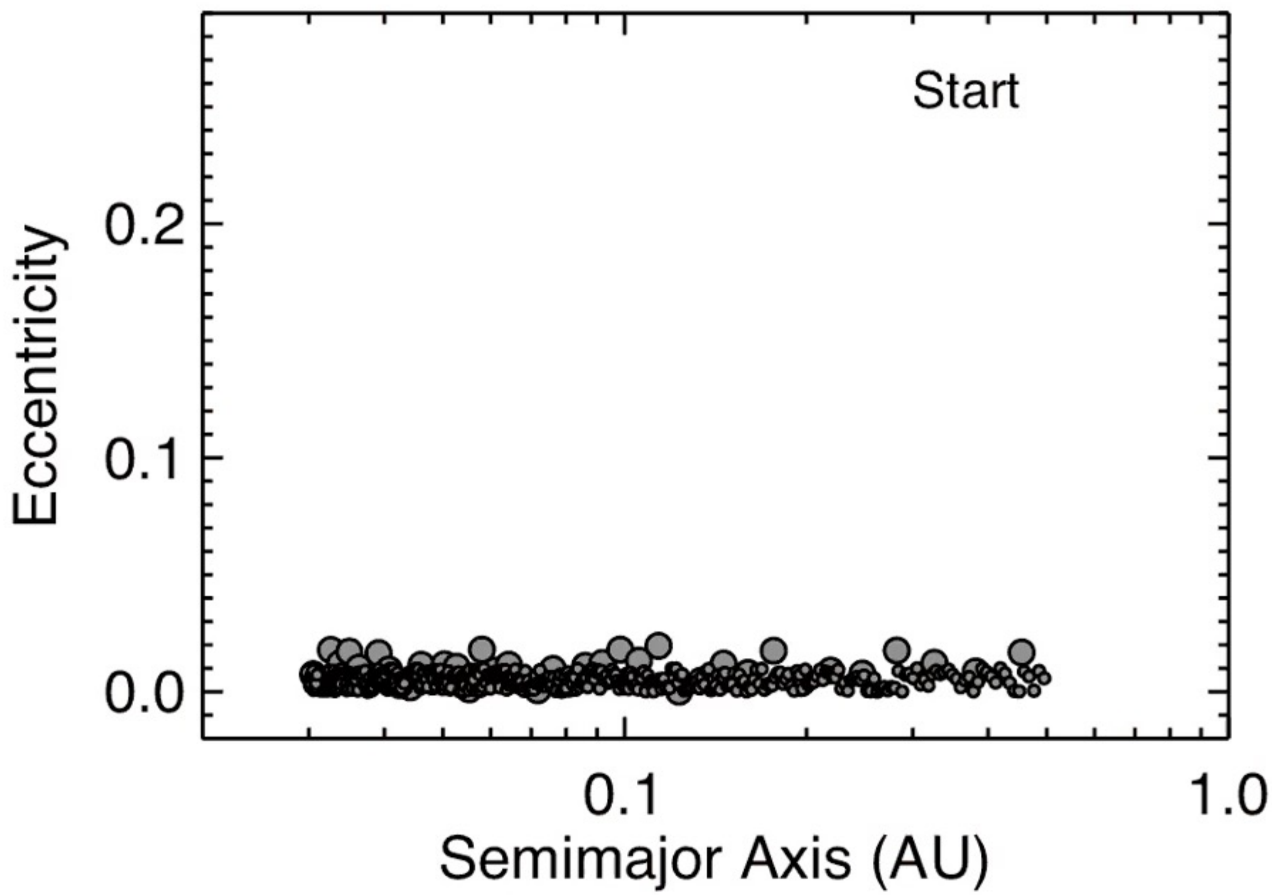
Protoplanet accretes all planetesimals in its feeding zone
(even is collisions happen, the amount of gravitational binding energy is such that the fragments reaccumulate)



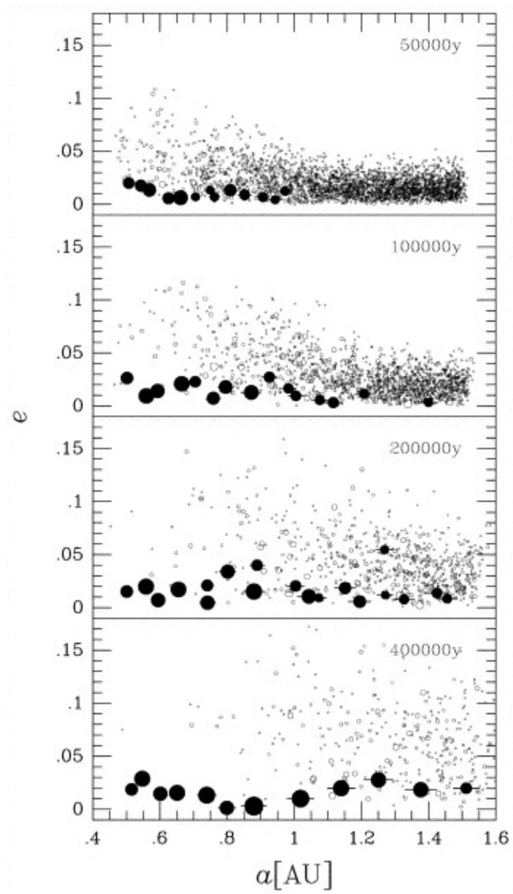
Core Accretion and Oligarchic Growth



Core Accretion and Oligarchic Growth



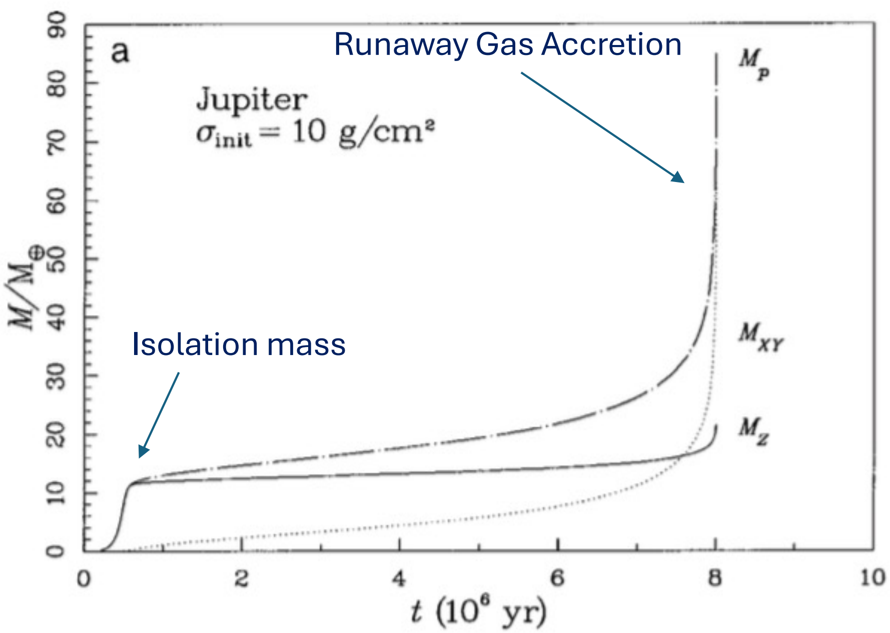
Core Accretion and Oligarchic Growth

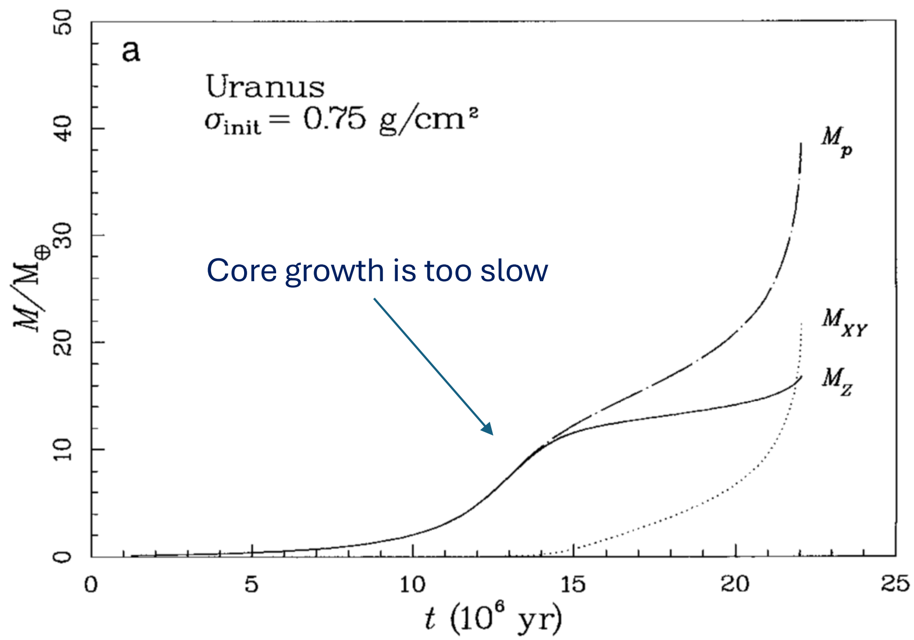


Problem

Planetesimal accretion is TOO SLOW in the outer solar system

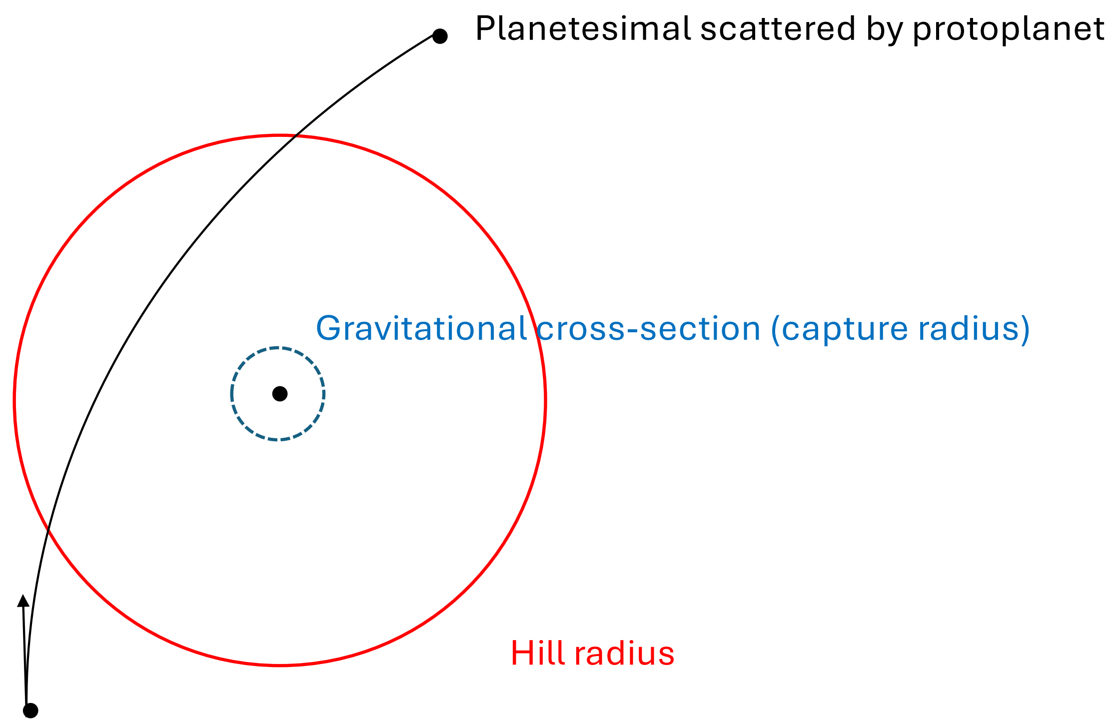
Low growth rates for Uranus and Neptune

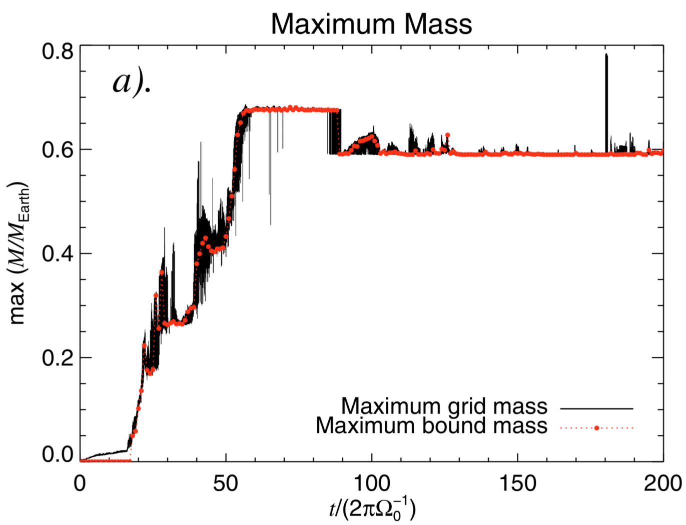




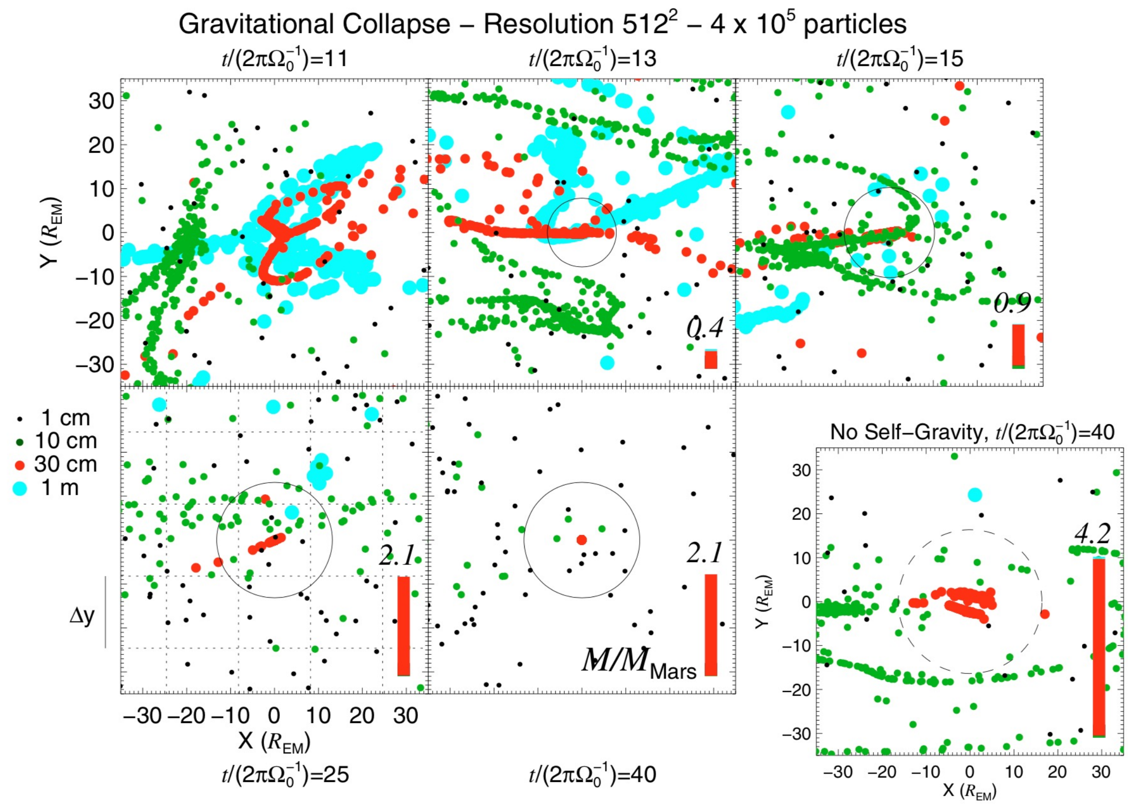
Pollack+ '96

Planetesimal Accretion is inefficient



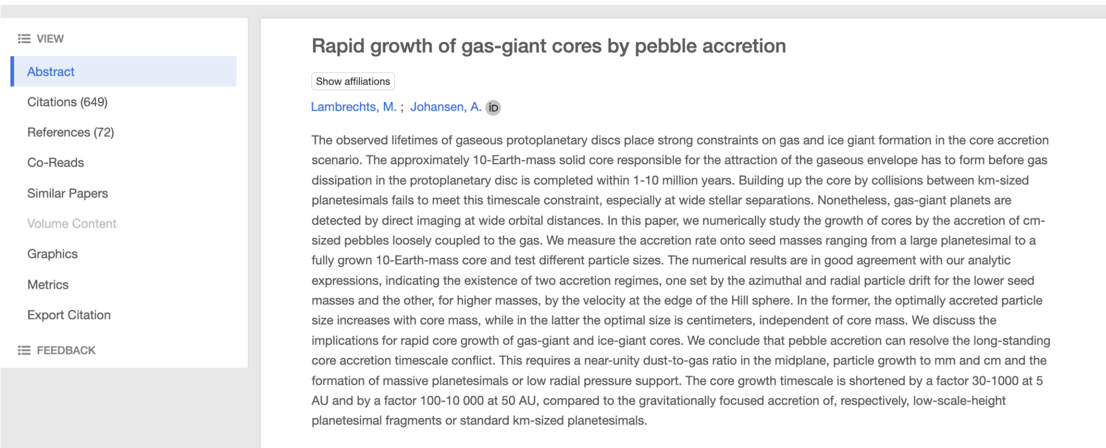


Maximum Mass
a).
max (M/M_{Earth})
$t/(2\pi\Omega_0^{-1})$
Maximum grid mass
Maximum bound mass



Gravitational Collapse – Resolution 512^2 – 4 x 10^5 particles
$t/(2\pi\Omega_0^{-1})$=11
$t/(2\pi\Omega_0^{-1})$=13
$t/(2\pi\Omega_0^{-1})$=15
Y (R_{EM})
0.4
0.9
1 cm
10 cm
30 cm
1 m
Δy
2.1
2.1
M/M_{Mars}
X (R_{EM})
$t/(2\pi\Omega_0^{-1})$=25
$t/(2\pi\Omega_0^{-1})$=40
No Self–Gravity, $t/(2\pi\Omega_0^{-1})$=40
4.2
Y (R_{EM})
X (R_{EM})

Pebble Accretion



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Abstract

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FEEDBACK

Rapid growth of gas-giant cores by pebble accretion

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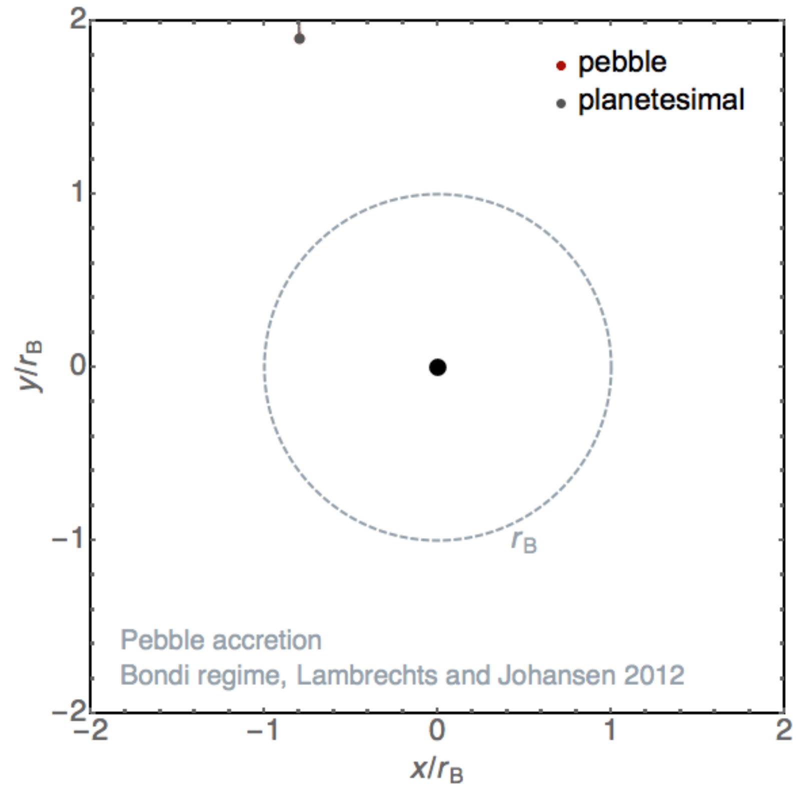
Lambrechts, M. ; Johansen, A.

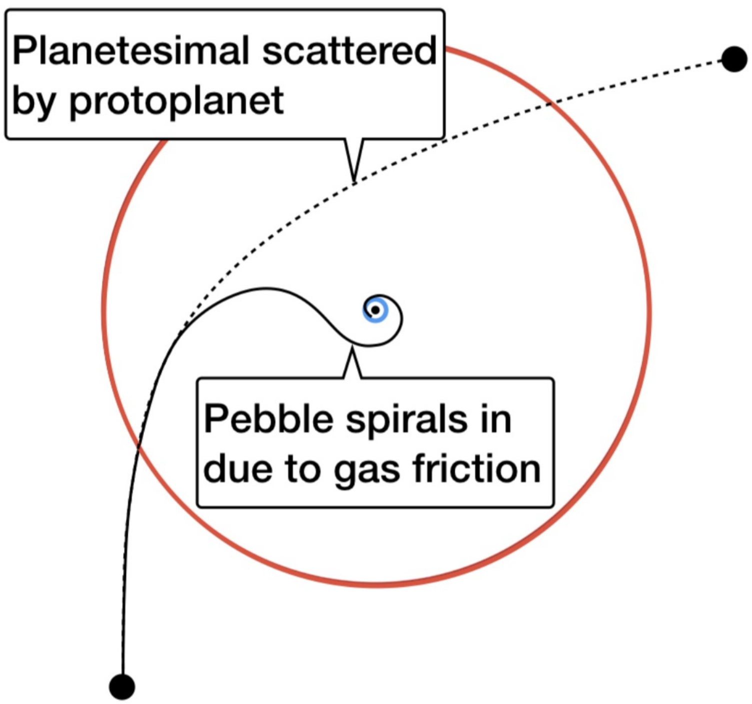
The observed lifetimes of gaseous protoplanetary discs place strong constraints on gas and ice giant formation in the core accretion scenario. The approximately 10-Earth-mass solid core responsible for the attraction of the gaseous envelope has to form before gas dissipation in the protoplanetary disc is completed within 1-10 million years. Building up the core by collisions between km-sized planetesimals fails to meet this timescale constraint, especially at wide stellar separations. Nonetheless, gas-giant planets are detected by direct imaging at wide orbital distances. In this paper, we numerically study the growth of cores by the accretion of cm-sized pebbles loosely coupled to the gas. We measure the accretion rate onto seed masses ranging from a large planetesimal to a fully grown 10-Earth-mass core and test different particle sizes. The numerical results are in good agreement with our analytic expressions, indicating the existence of two accretion regimes, one set by the azimuthal and radial particle drift for the lower seed masses and the other, for higher masses, by the velocity at the edge of the Hill sphere. In the former, the optimally accreted particle size increases with core mass, while in the latter the optimal size is centimeters, independent of core mass. We discuss the implications for rapid core growth of gas-giant and ice-giant cores. We conclude that pebble accretion can resolve the long-standing core accretion timescale conflict. This requires a near-unity dust-to-gas ratio in the midplane, particle growth to mm and cm and the formation of massive planetesimals or low radial pressure support. The core growth timescale is shortened by a factor 30-1000 at 5 AU and by a factor 100-10 000 at 50 AU, compared to the gravitationally focused accretion of, respectively, low-scale-height planetesimal fragments or standard km-sized planetesimals.

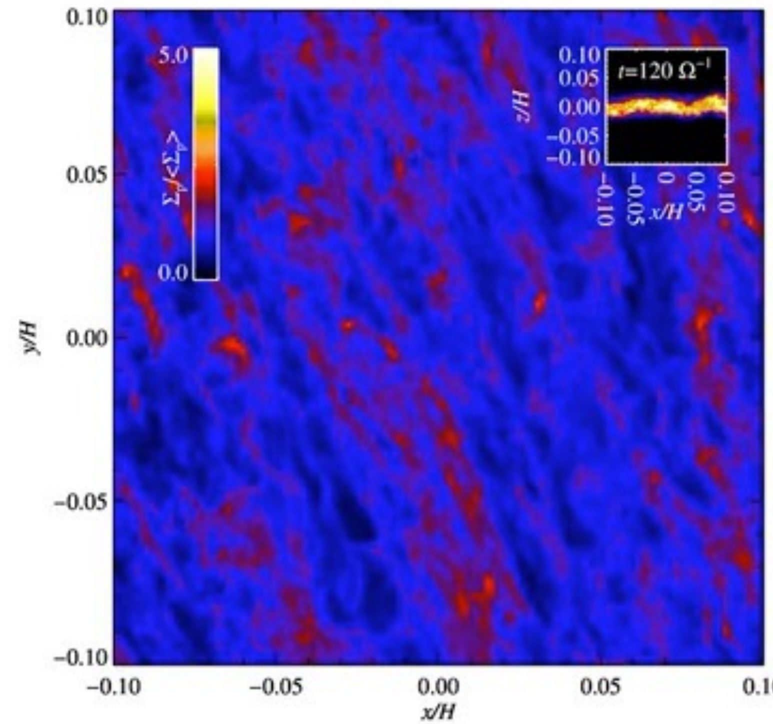


Klahr & Henning ’97, Klahr ‘06, Inaba & Barge ‘08, Lyra+ ‘08, ’09ab
Ormel & Klahr ‘10, **Lambrechts & Johansen ’12,**

See Johansen & Lambrechts ‘17 for a review

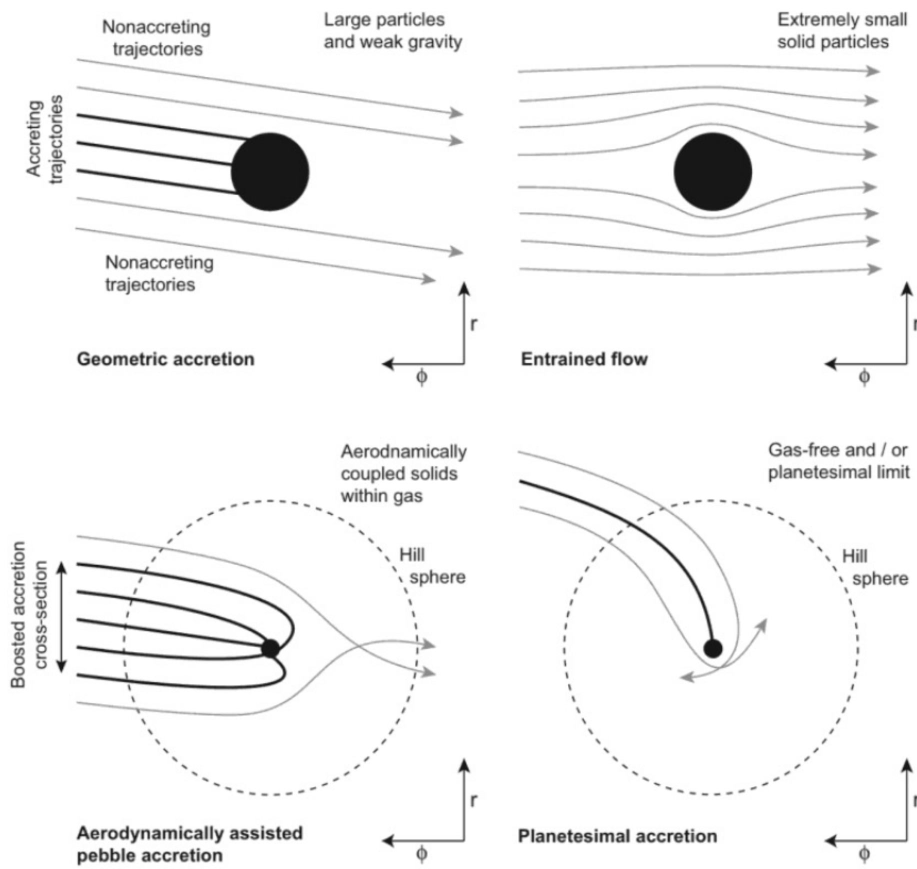
Pebble Accretion



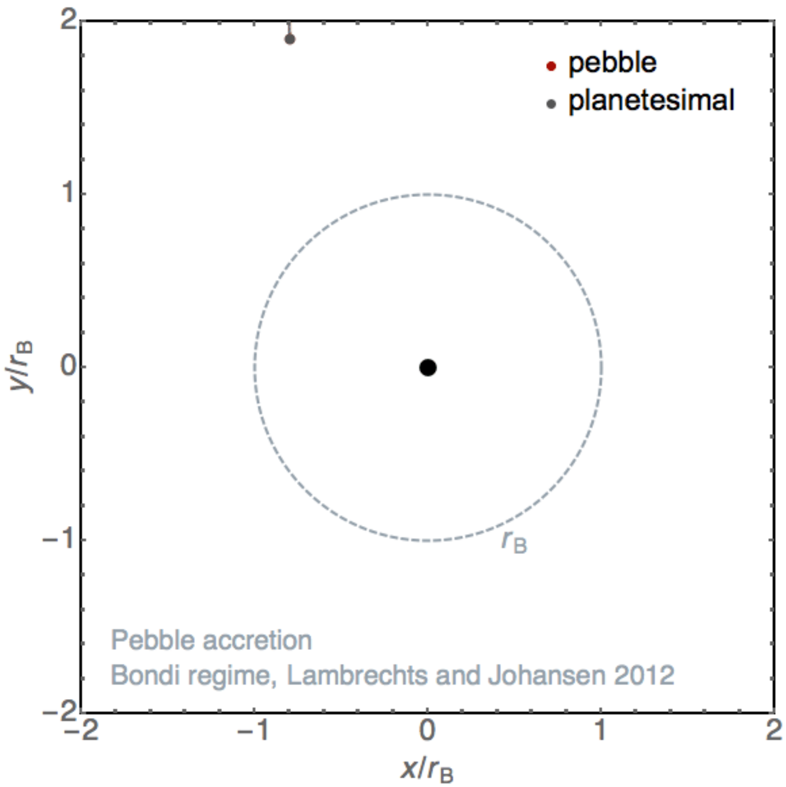


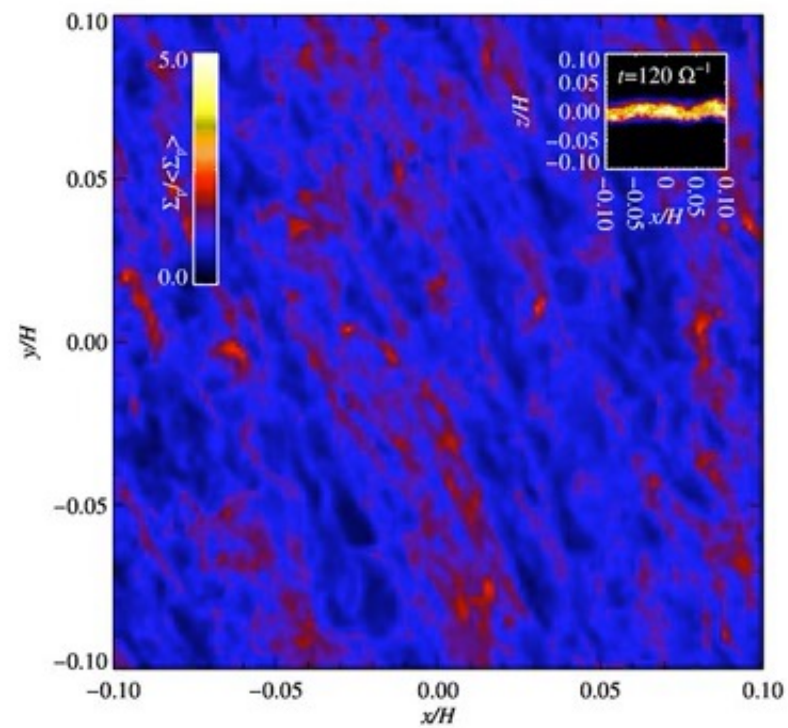
Klahr & Henning '97, Klahr '06, Inaba & Barge '08, Lyra+ '08, '09ab
Ormel & Klahr '10, **Lambrechts & Johansen '12,**

See Johansen & Lambrechts '17 for a review


Nonaccreting trajectories
Large particles and weak gravity
Accreting trajectories
Nonaccreting trajectories
r
ϕ
Geometric accretion
Extremely small solid particles
r
ϕ
Entrained flow
Aerodnamically coupled solids within gas
Hill sphere
Boosted accretion cross-section
r
ϕ
Aerodynamically assisted pebble accretion
Gas-free and / or planetesimal limit
Hill sphere
r
ϕ
Planetesimal accretion

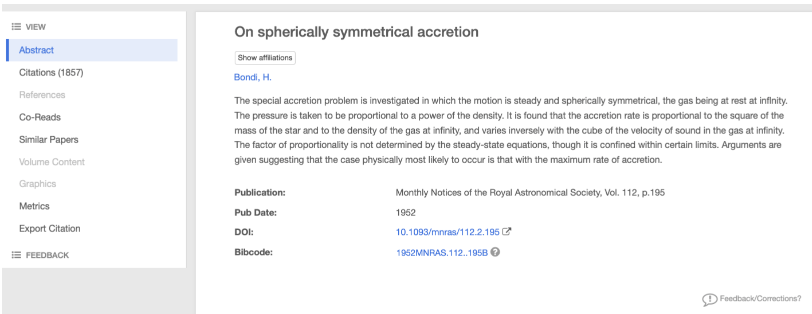
Pebble Accretion





Lyra+ '08, '09, '23, Ormel & Klahr '10, Lambrechts & Johansen '12
See Johansen & Lambrechts '17 for a review

Bondi Accretion



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Abstract

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On spherically symmetrical accretion

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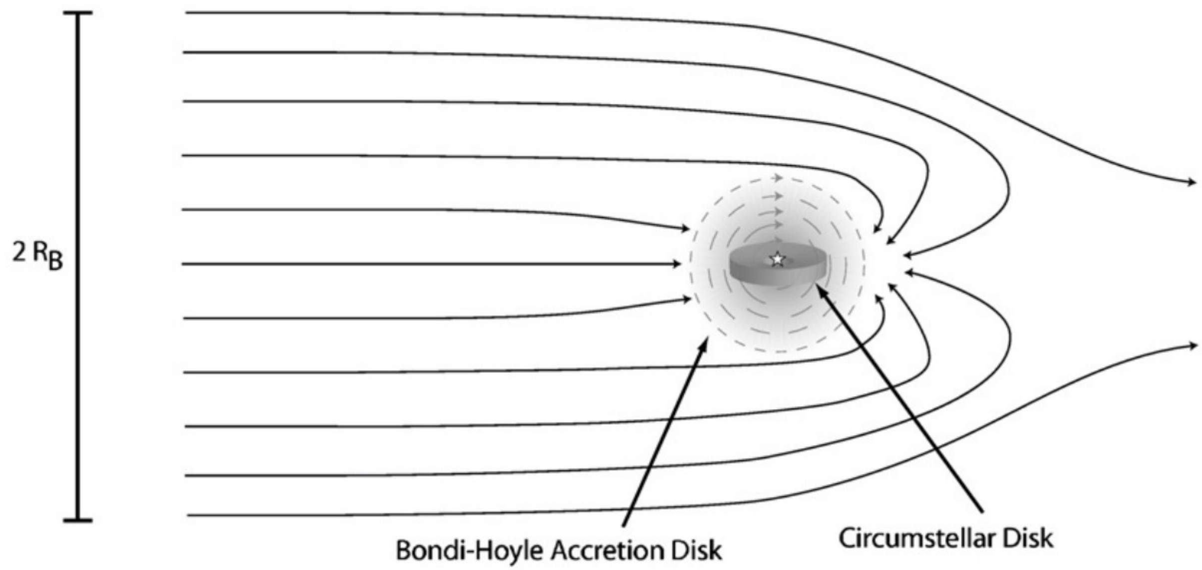
Bondi, H.

The special accretion problem is investigated in which the motion is steady and spherically symmetrical, the gas being at rest at infinity. The pressure is taken to be proportional to a power of the density. It is found that the accretion rate is proportional to the square of the mass of the star and to the density of the gas at infinity, and varies inversely with the cube of the velocity of sound in the gas at infinity. The factor of proportionality is not determined by the steady-state equations, though it is confined within certain limits. Arguments are given suggesting that the case physically most likely to occur is that with the maximum rate of accretion.

Publication:	Monthly Notices of the Royal Astronomical Society, Vol. 112, p.195
Pub Date:	1952
DOI:	10.1093/mnras/112.2.195
Bibcode:	1952MNRAS.112..195B

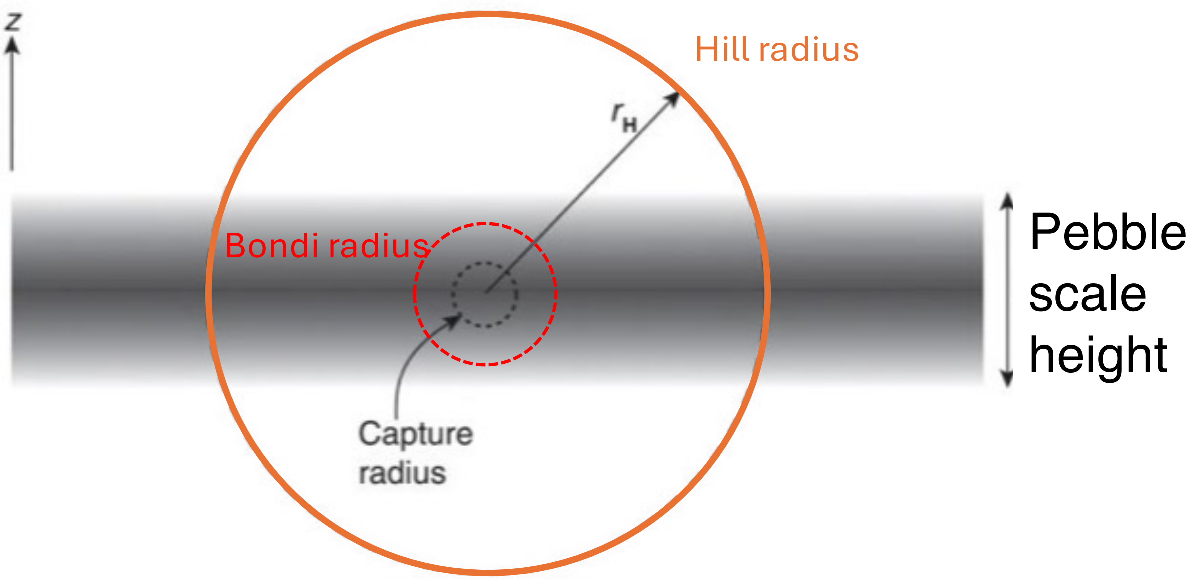
Feedback/Corrections?



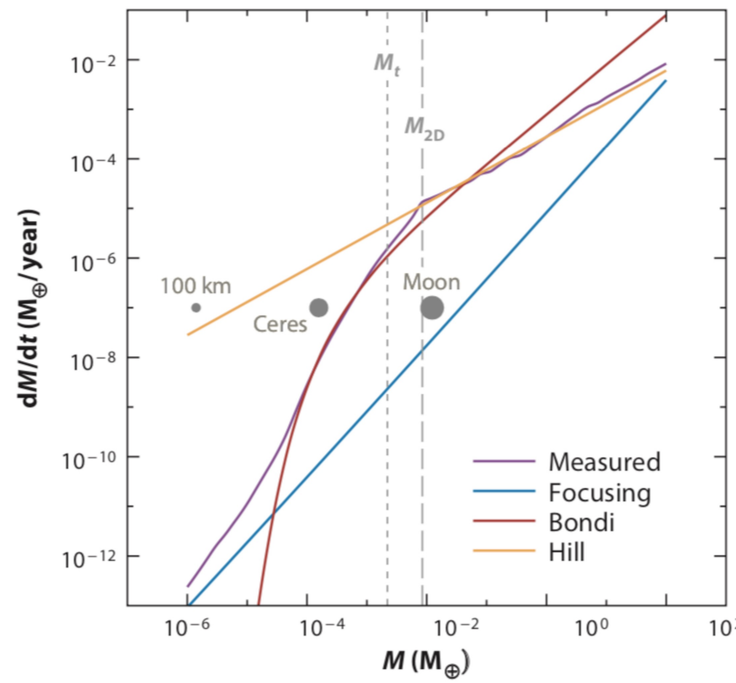
Pebble Accretion: Geometric, Bondi, and Hill regime

$$\xi \equiv \left(\frac{R_{acc}}{2H_d}\right)^2 \qquad \dot{M}_{3D} = \lim_{\xi\to 0} \dot{M} = \pi R_{acc}^2 \rho_{d0} \delta v, \qquad \dot{M}_{2D} = \lim_{\xi\to\infty} \dot{M} = 2R_{acc}\Sigma_d \delta v,$$

Bondi accretion - Bound against headwind
Hill accretion - Bound against stellar tide

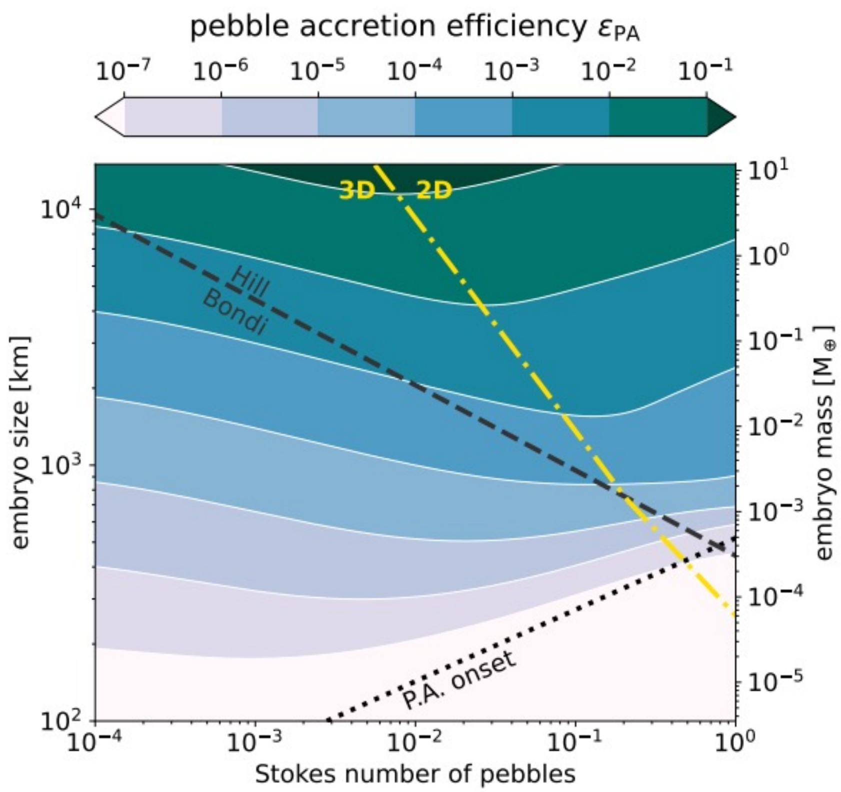


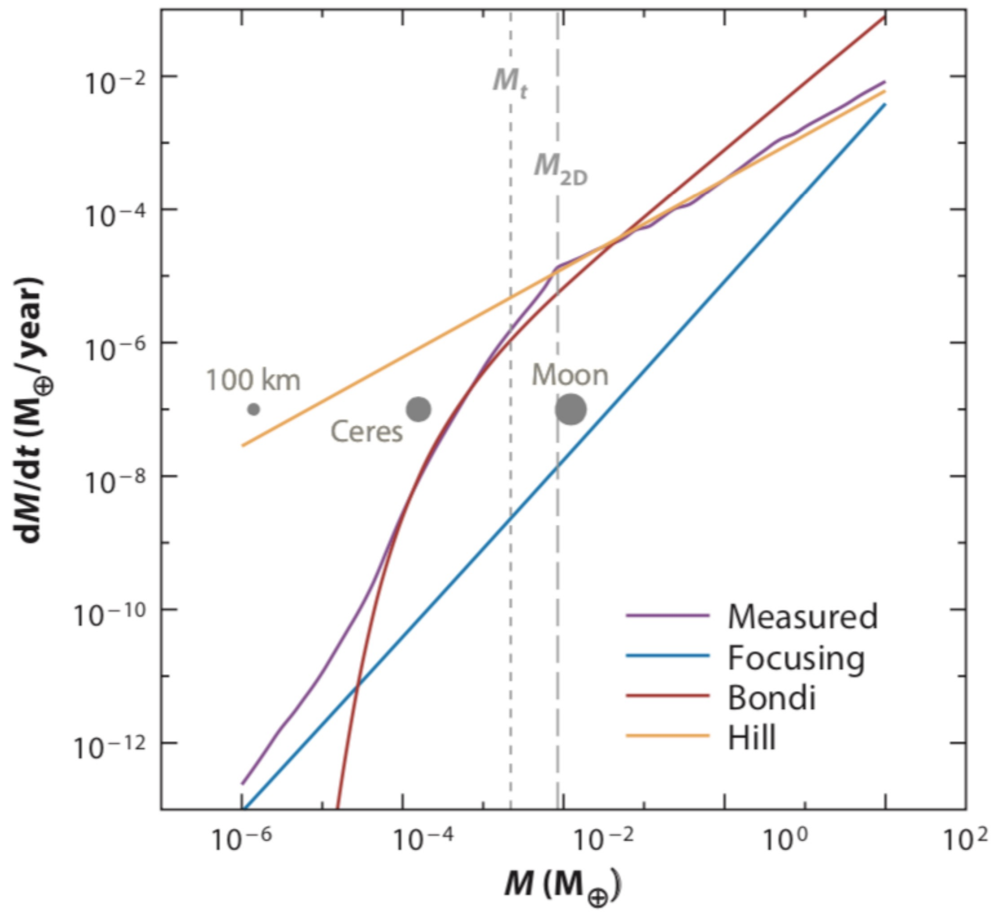
Mass accretion rates



Johansen & Lambrechts (2017)

Accretion Rates





The size-density relationship of Kuiper Belt objects

THE ASTROPHYSICAL JOURNAL LETTERS, 778:L34 (

THE DENSITY OF MID-SIZED KUIPER BELT OBJECT 2002 UX25
AND THE FORMATION OF THE DWARF PLANETS

M. E. BROWN
Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA; mbrown@caltech.edu
Received 2013 July 10; accepted 2013 October 28; published 2013 November 13

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 ∼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 g cm^{-3} rather than the 2.5 g cm^{-3} density of Eris (Sicardy et al. 2011).

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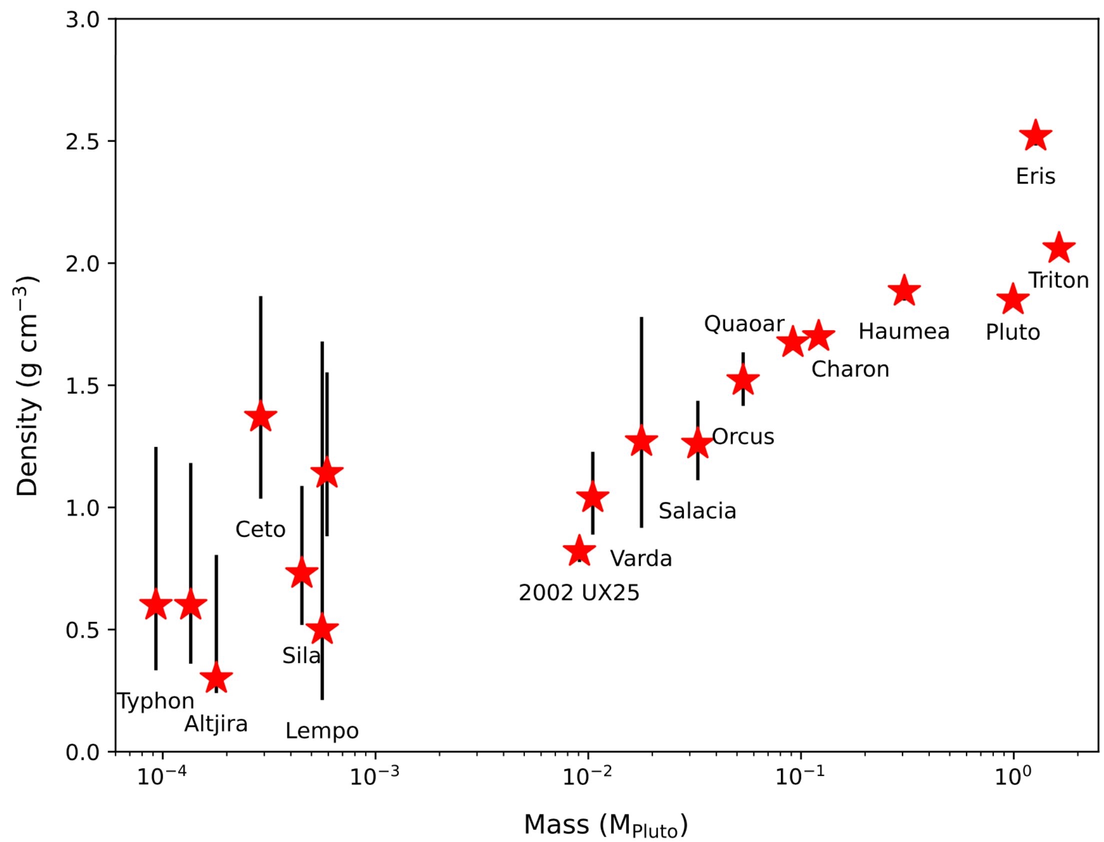
- Extremely low porosity;
- Biased sample;
- Compaction through giant impacts

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.

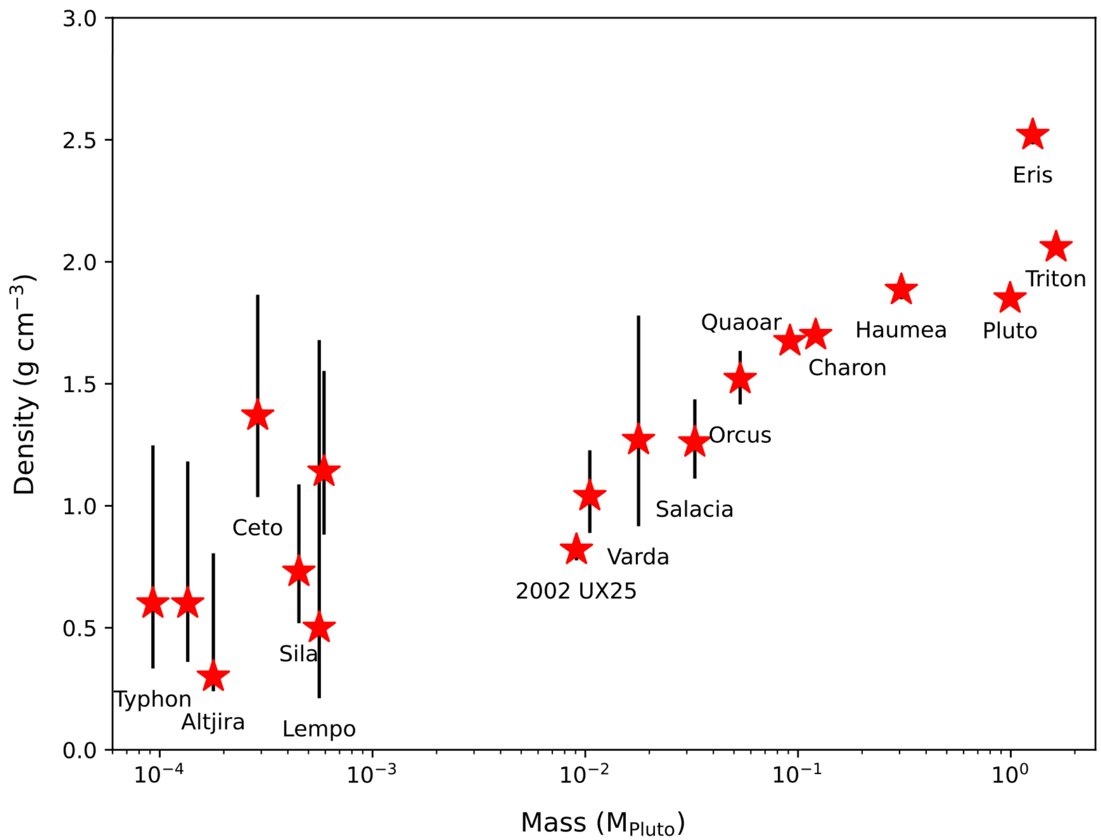


Data; *Thomas (2000), Stansberry et al. (2006), Grundy et al. (2007), Brown et al. (2011), Stansberry et al. (2012), Brown (2013), Fornasier et al. (2013), Vilenius, et al. (2014), Nimmo et al. (2016), Ortiz et al. (2017), Brown and Butler (2017), Grundy et al. (2019), Morgado et al. (2023), Pereira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

Cañas+Lyra et al. (2024)

The size-density relationship of Kuiper Belt objects

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



Cañas+Lyra et al. (2024)

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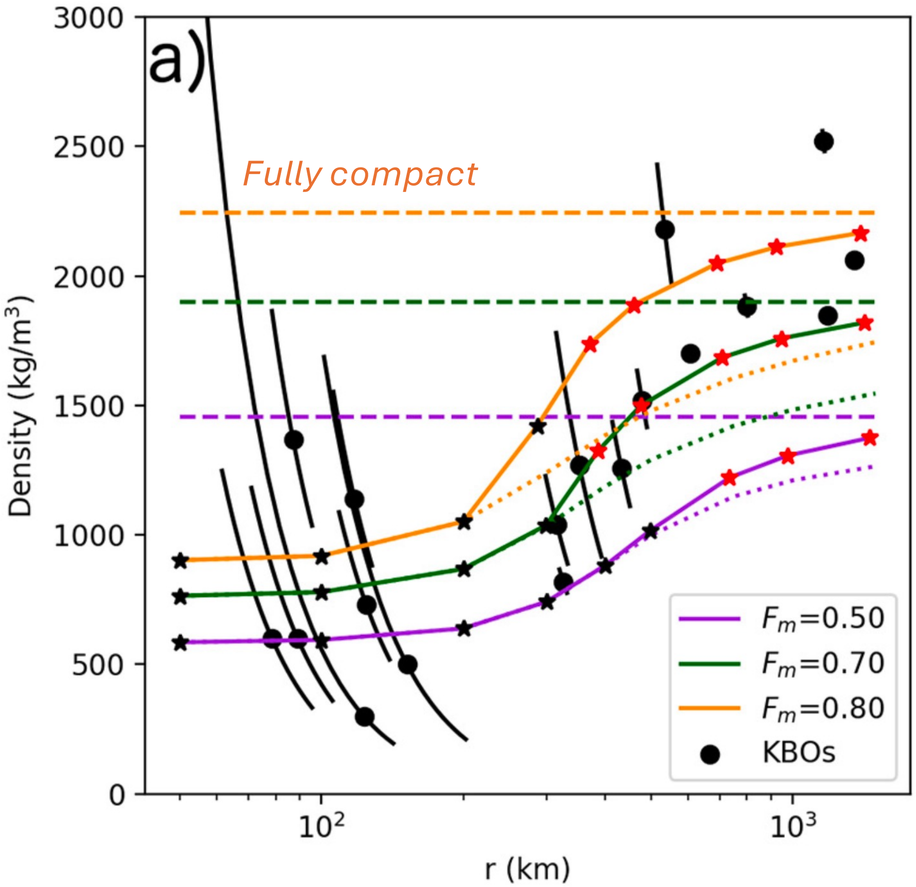
Current best bet:
Porosity removal by gravitational compaction

Problem

- Timing! ^{26}Al would melt if formed within 4 Myr

Assumptions

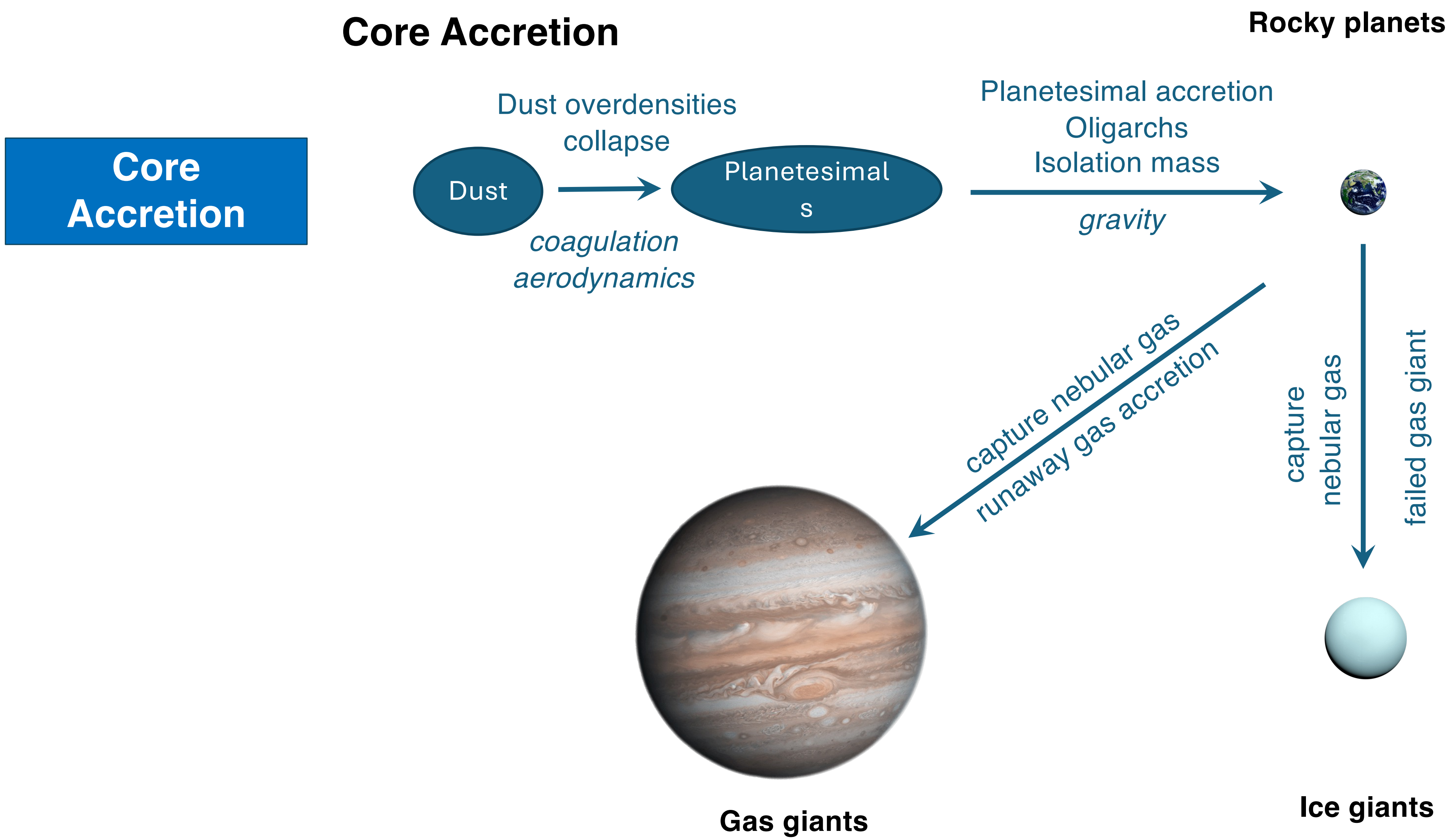
- ~~Constant composition at birth and growth~~
- ~~Growth by planetesimal accretion~~



Bierson & Nimmo (2019)

F_m = rock mass fraction

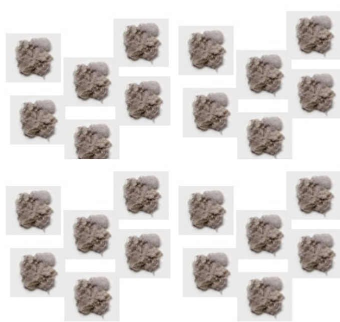
Core Accretion

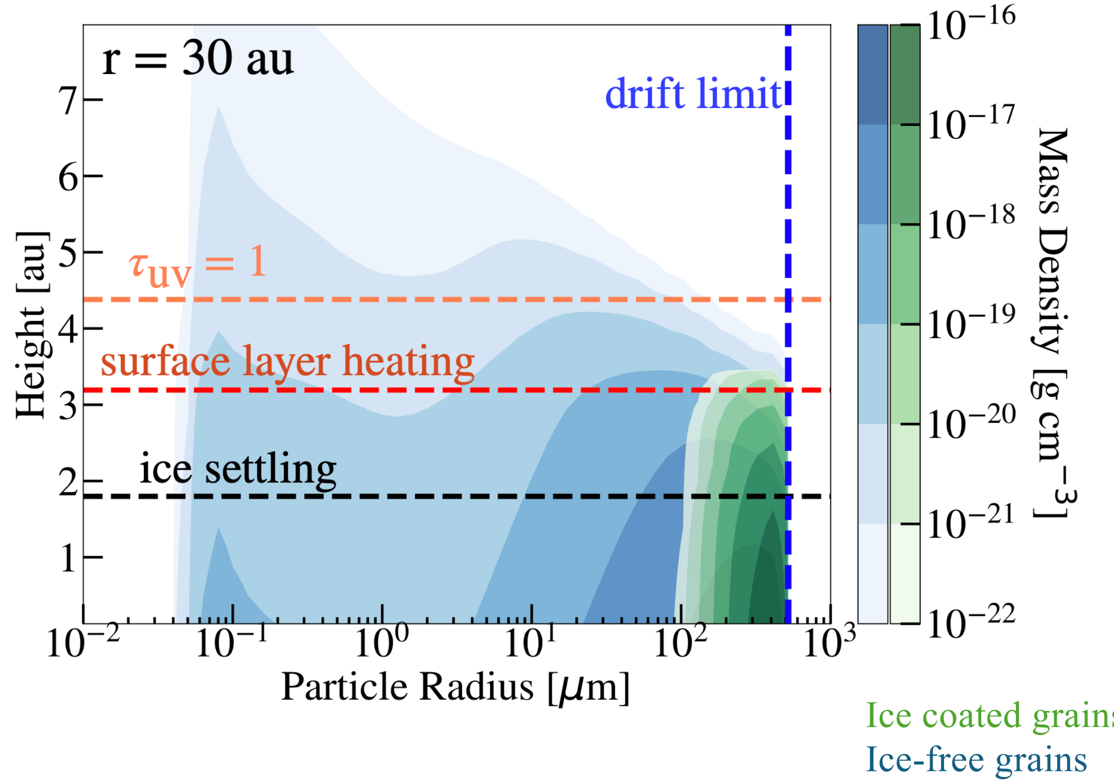


Abandoning Constant Composition

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

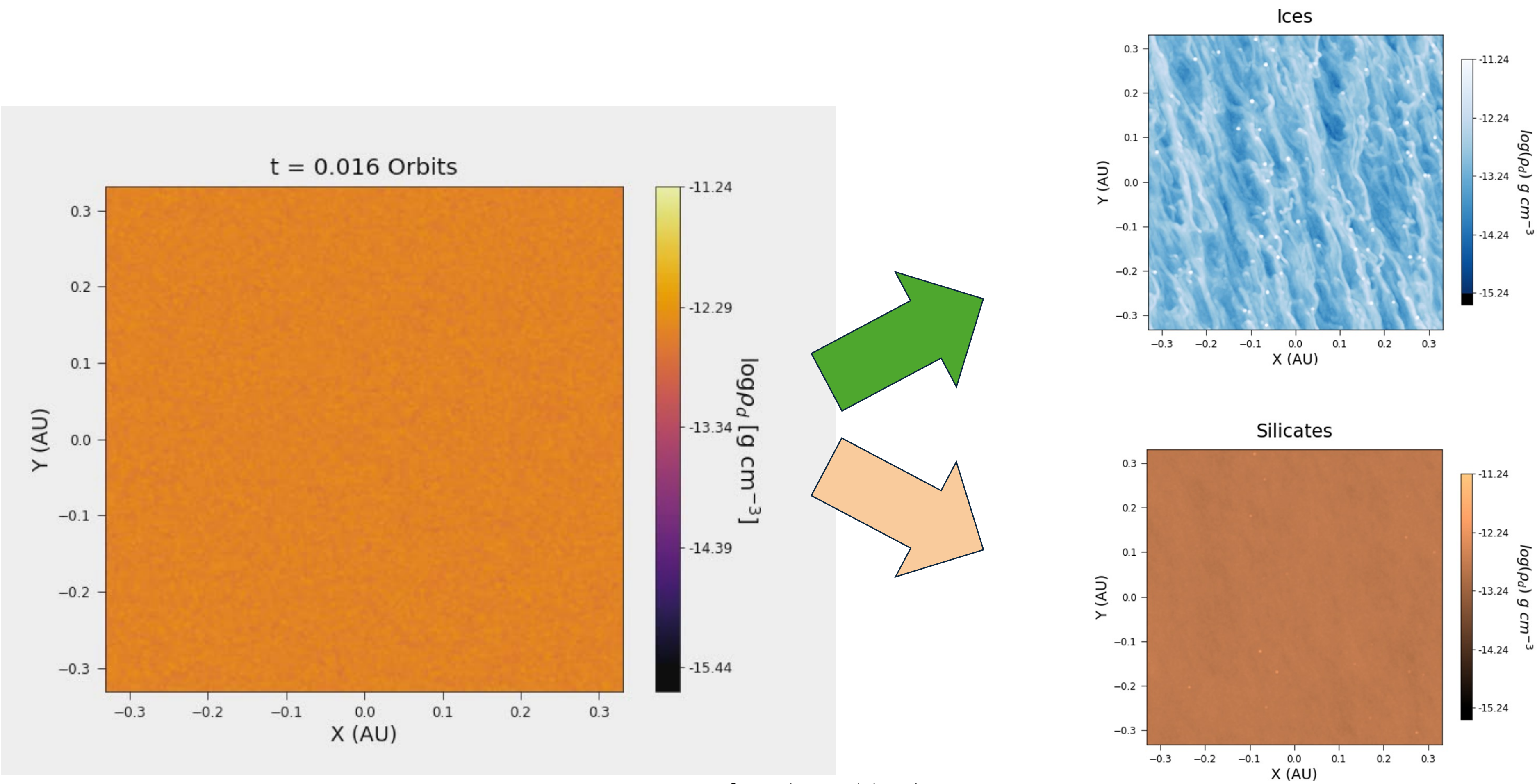
- Small grains lofted in the atmosphere lose ice
- Big grains are shielded and remain icy.





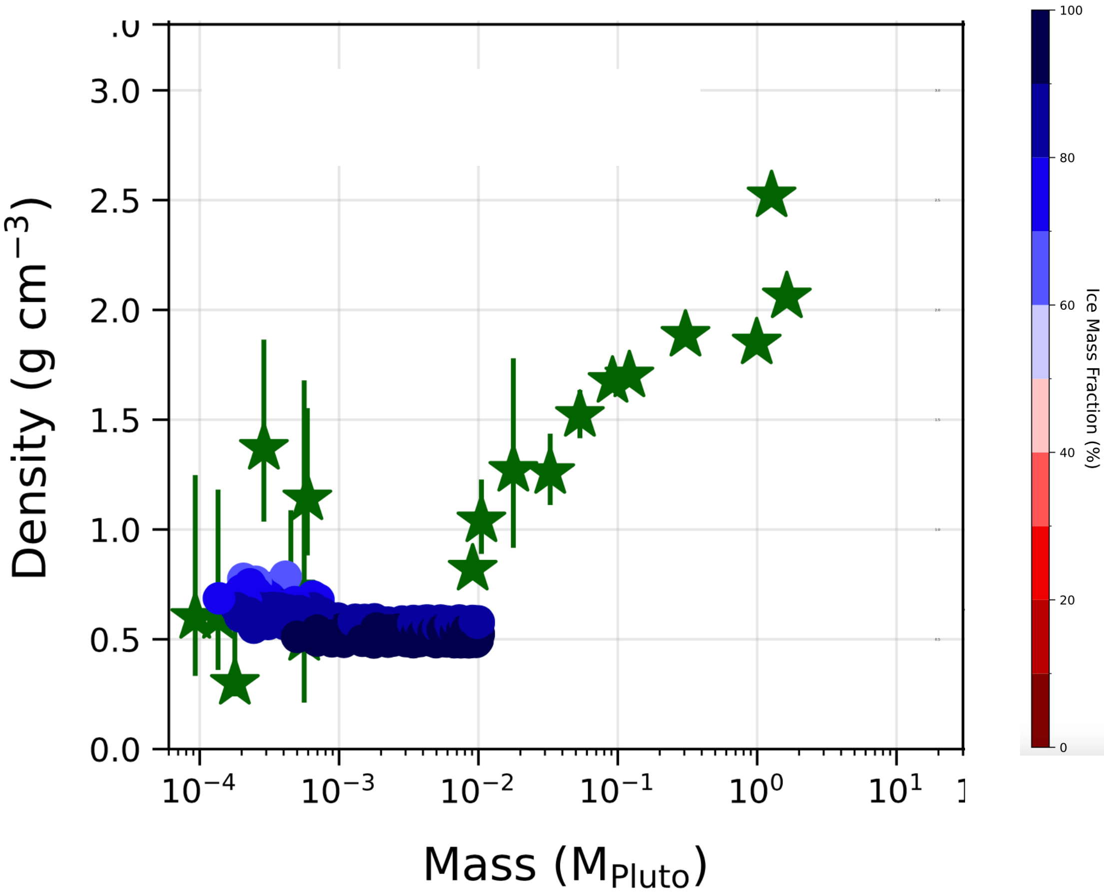
Powell et al. (2022)

Split into icy and silicate pebbles



Cañas+Lyra et al. (2024)

The first planetesimals are icy



Cañas+Lyra et al. (2024)

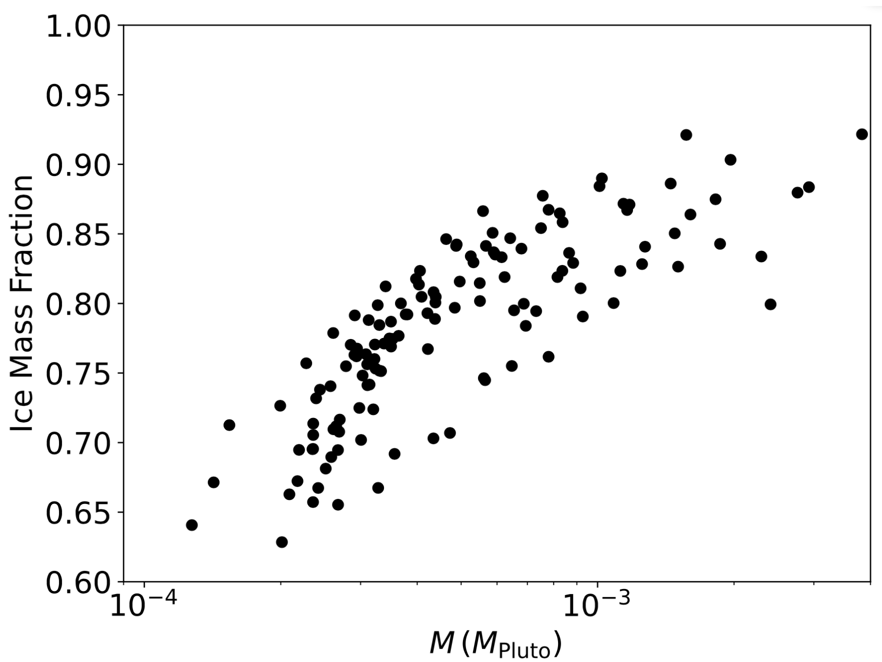
The first planetesimals won't melt

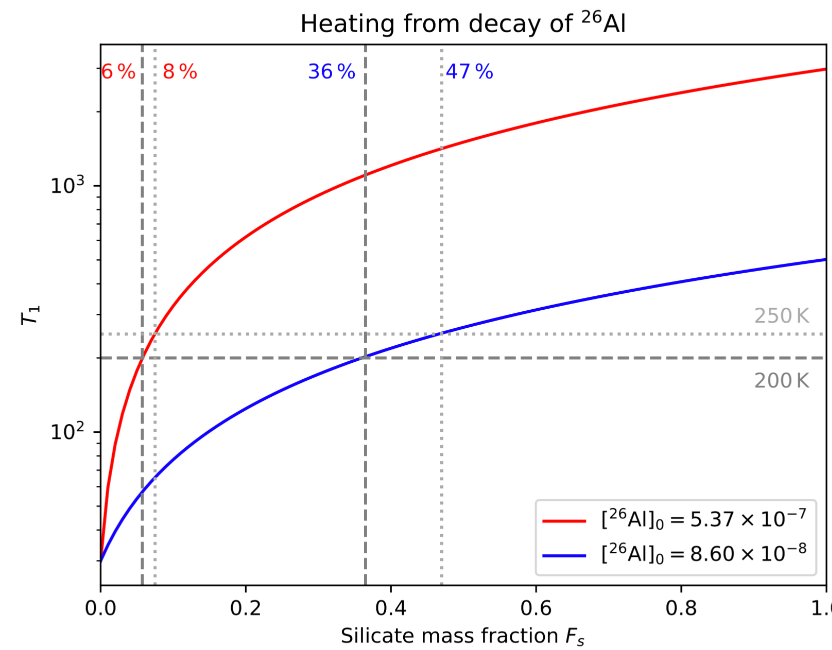
$$\mathcal{H} = \rho\, F_s\, [^{26}\mathrm{Al}]_0\, \mathcal{H}_0\, e^{-\lambda t}$$

$$Q(t) = V \int_0^t \mathcal{H}(t')dt'$$
$$= M_p\, F_s\, [^{26}\mathrm{Al}]_0\, \mathcal{H}_0\, \lambda^{-1} \left(1 - e^{-\lambda t}\right)$$

$$Q = M_p\, c_p\, \Delta T$$

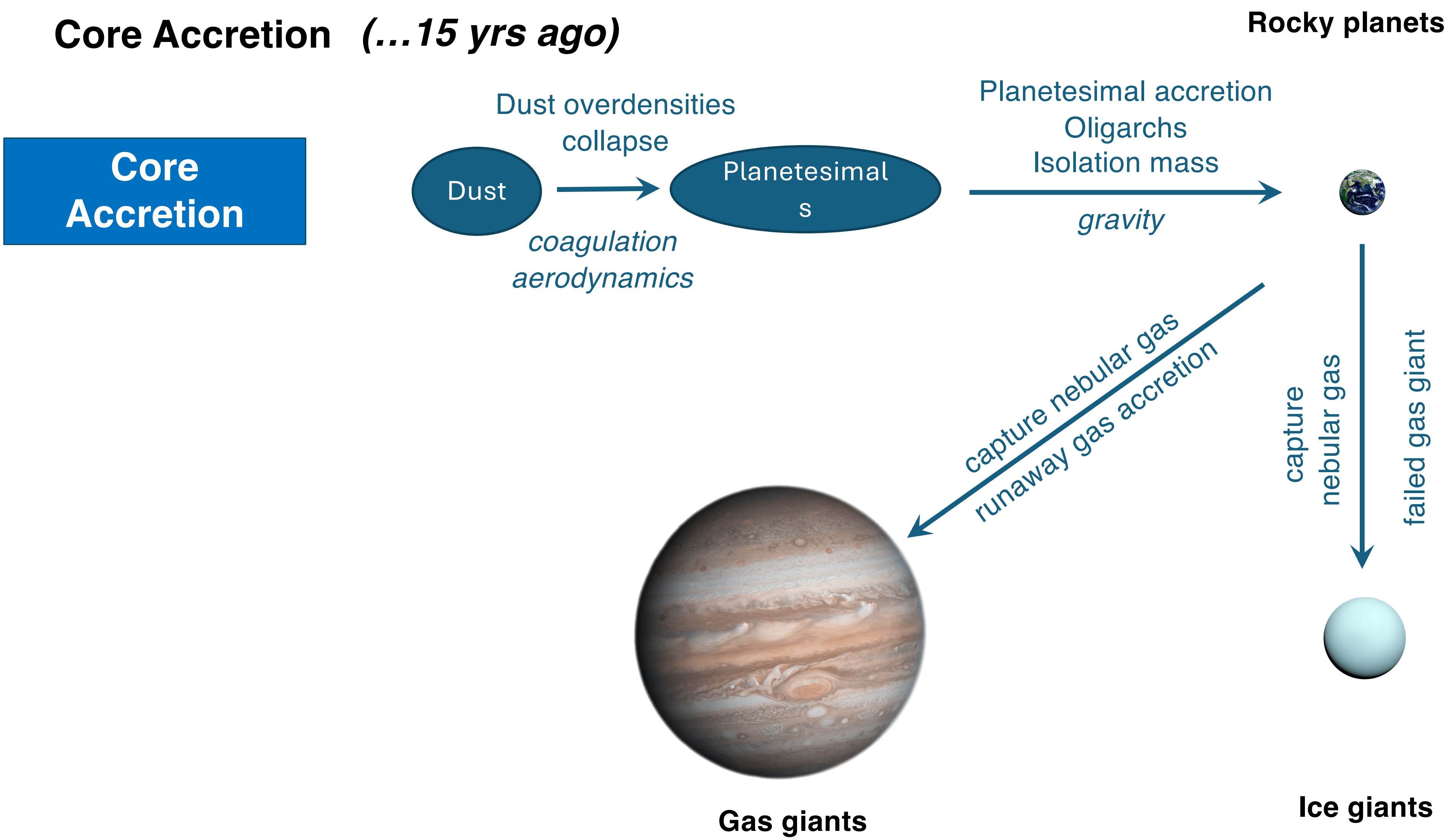
$$\Delta T = F_s\, [^{26}\mathrm{Al}]_0\, \mathcal{H}_0\, \lambda^{-1}\, c_p^{-1}$$



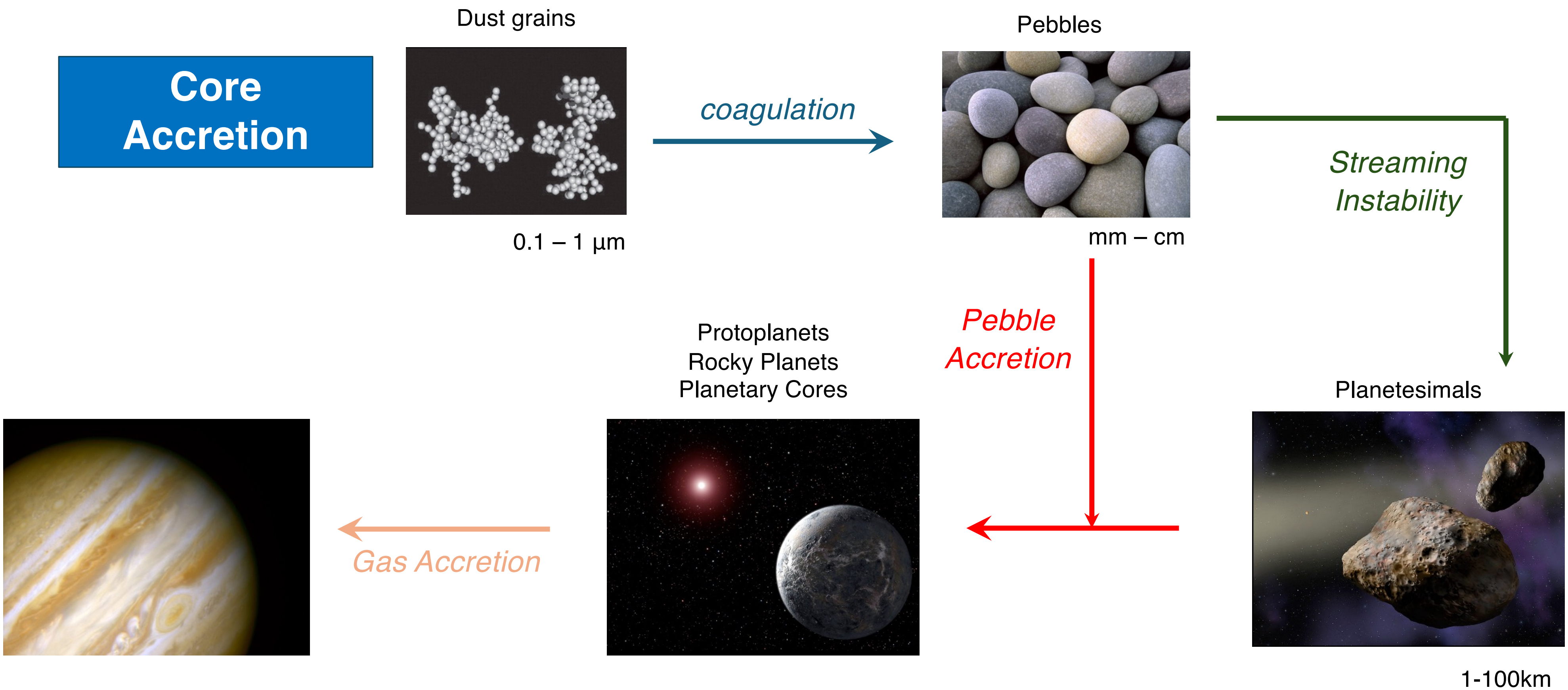


Cañas+Lyra et al. (2024)

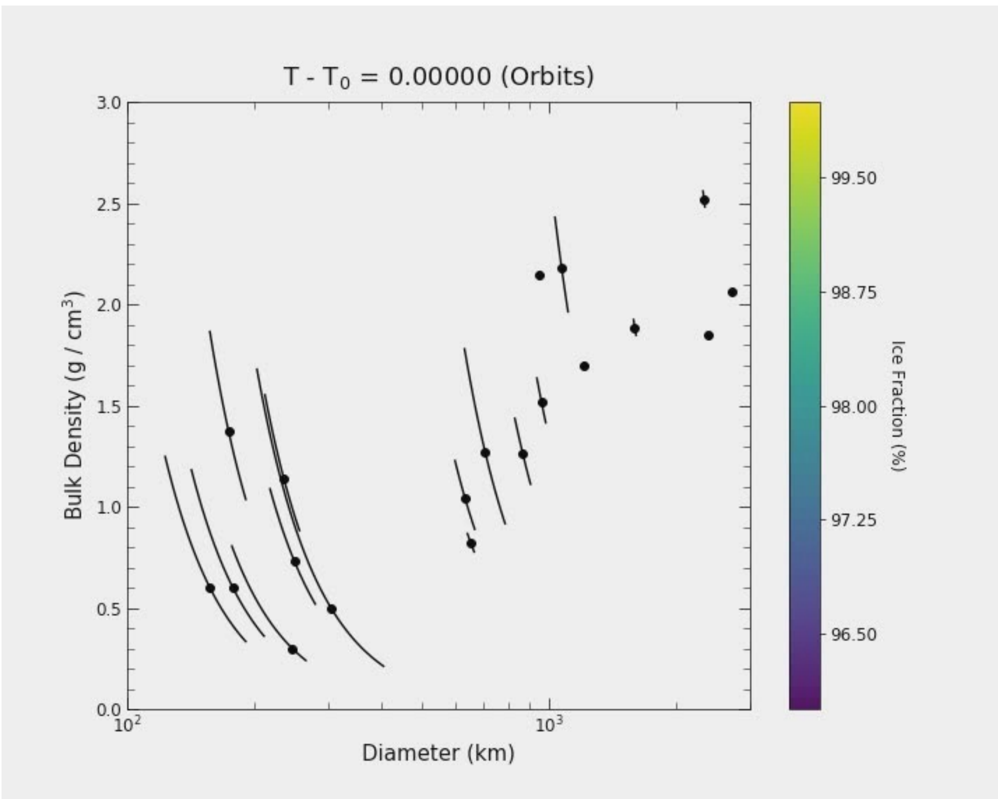
Core Accretion *(…15 yrs ago)*

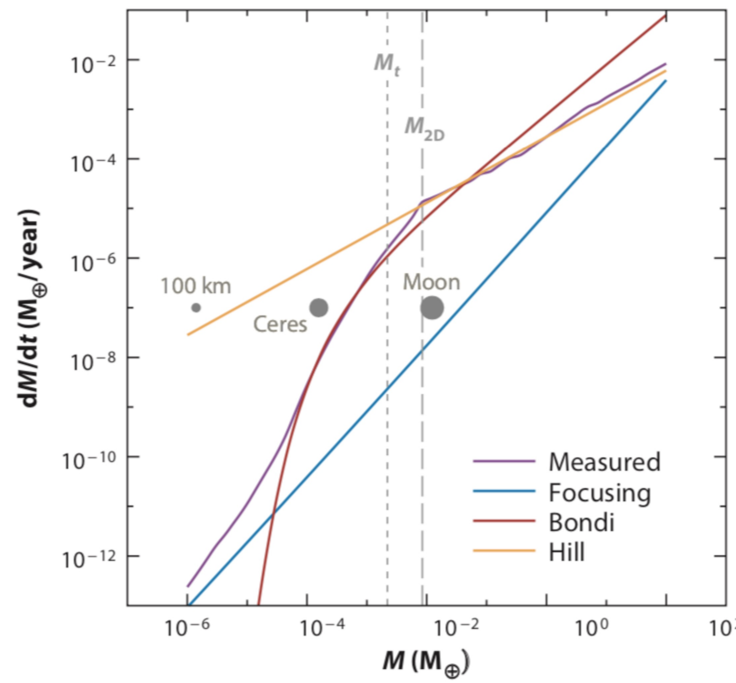


Core Accretion



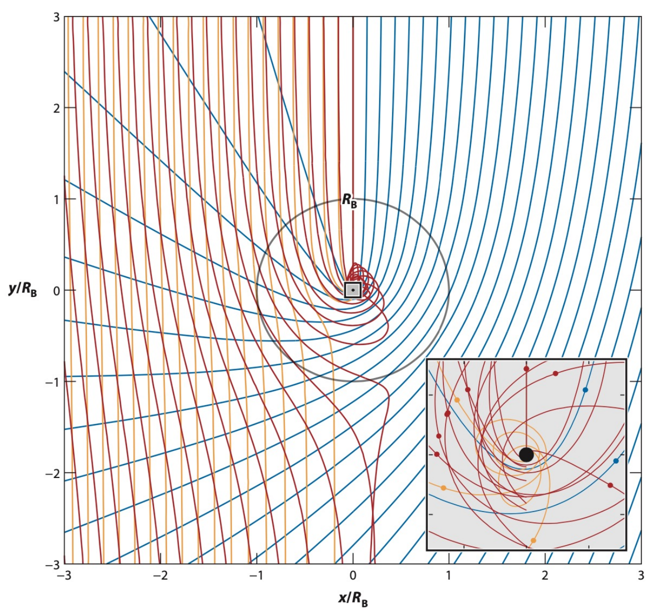
Integrate pebble accretion





Pebble Accretion: Pebbles of different size accrete differently

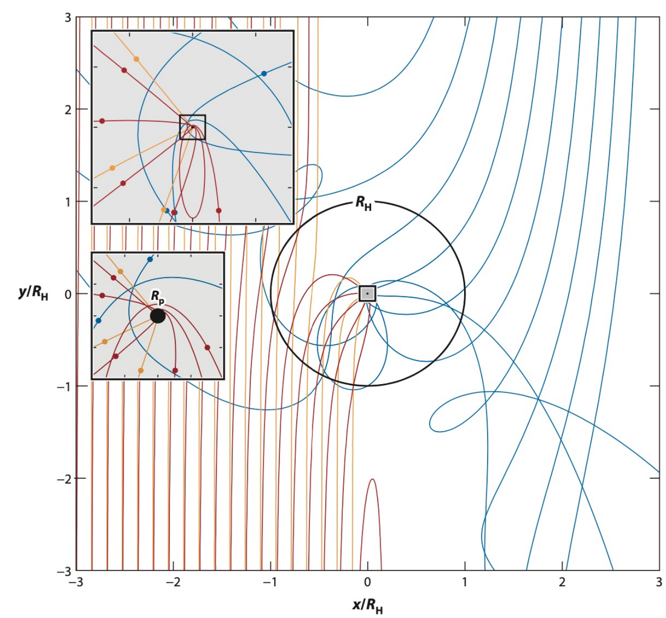
Bondi Regime



Best accreted pebble

Drag time ~ Bondi Time

Hill Regime



Best accreted pebble

Drag time ~ Orbital Time

Polydisperse (Multi-Species) Pebble Accretion

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

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

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

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

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

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

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

$$\hat{R}_{\rm acc}^{\rm (Bondi)} = \left(\frac{4\tau_f}{t_{\rm B}}\right)^{1/2} R_{\rm B},$$

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

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

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

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

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

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

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

$$\dot{M}_{\rm 3D,\ Bondi} = \frac{4\pi R_{\rm B}\Delta v^2}{\Omega} \times \int_0^{a_{\max}} {\rm St}\, e^{-2\psi} m(a) f(a)\left[1 + 2\left({\rm St}\frac{\Omega R_{\rm B}}{\Delta v}\right)^{1/2} e^{-\psi}\right] da,$$

$$\psi \equiv \chi[{\rm St}/(\Omega t_p)]^\gamma.$$

Lyra et al. (2023)

Analytical theory of polydisperse (multi-species) pebble accretion

Monodisperse (single species)

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

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

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

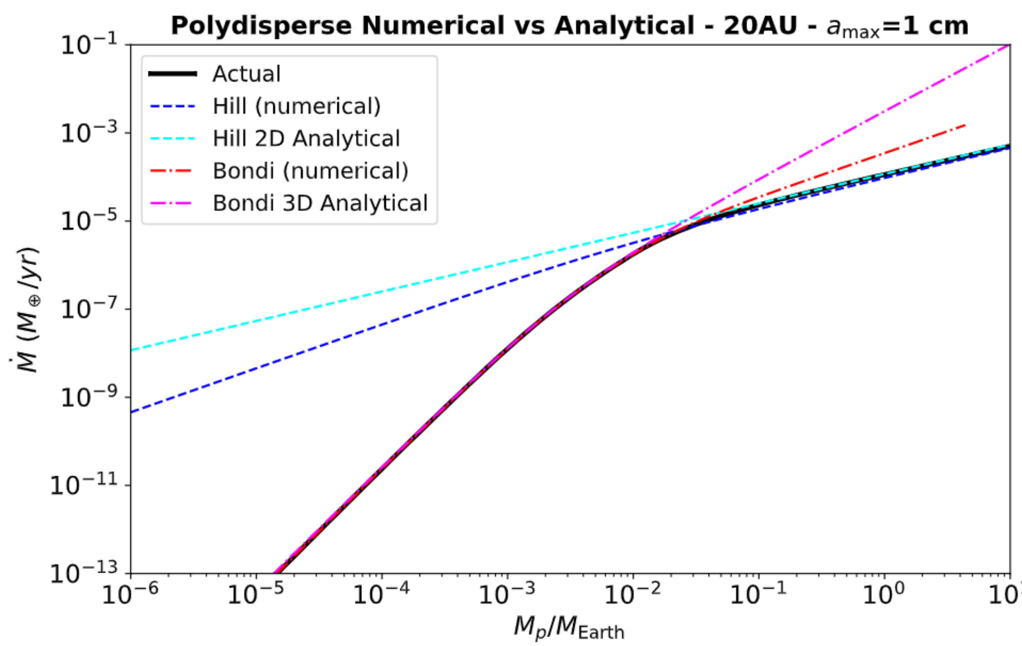
Lambrechts & Johansen (2012)

Polydisperse (multiple species)

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

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

Lyra et al. (2023)



Lyra et al. (2023)

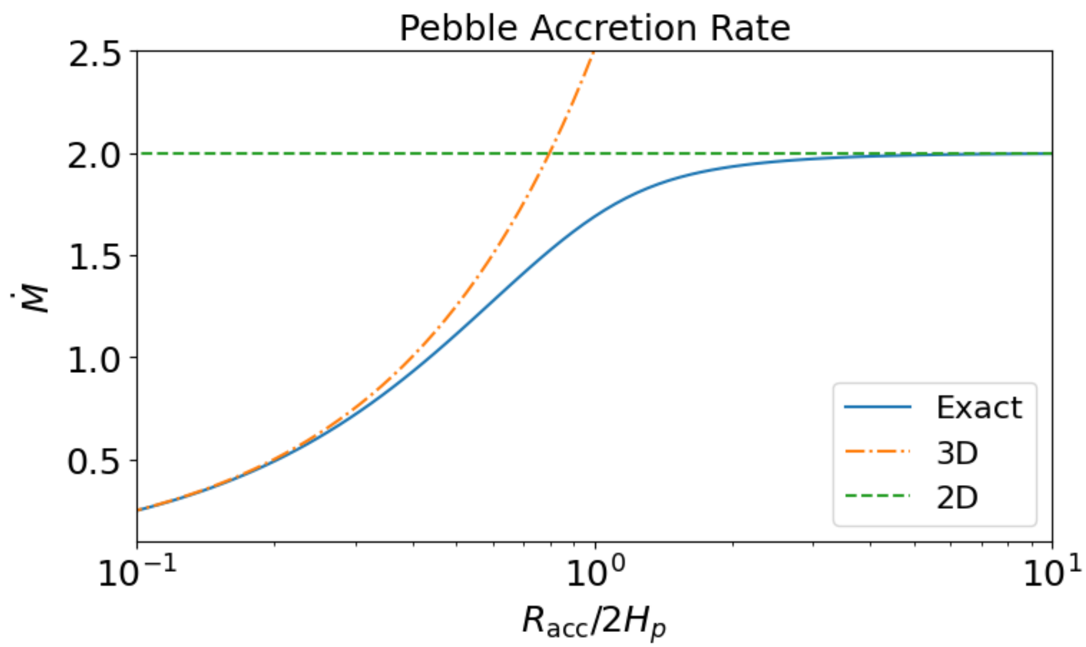
Analytical Solution for
General Monodisperse (single species) Pebble Accretion

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

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

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

```
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
```



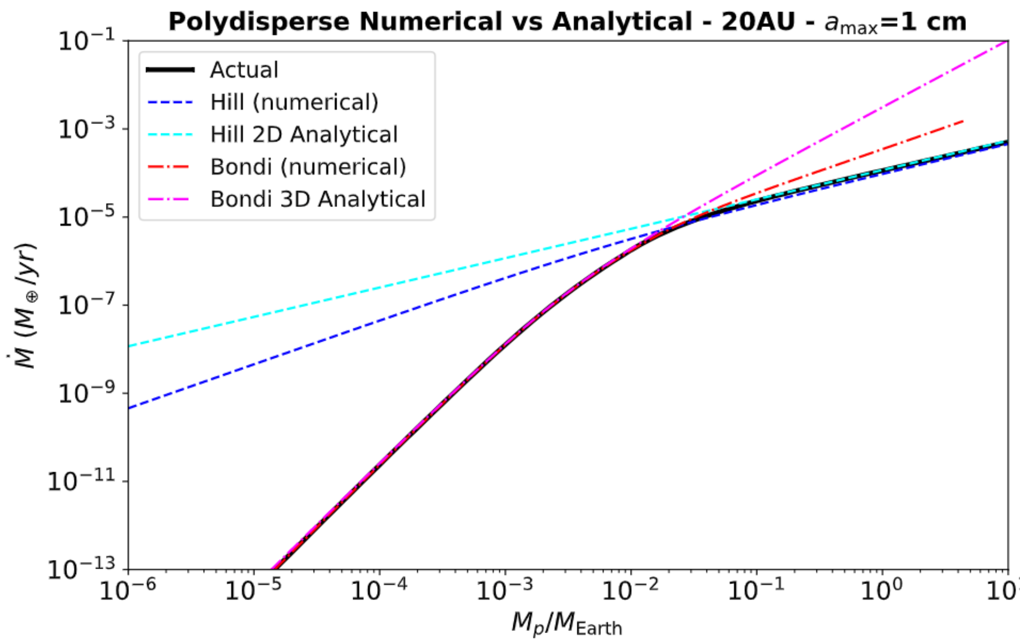
Lyra et al. (2023)

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

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

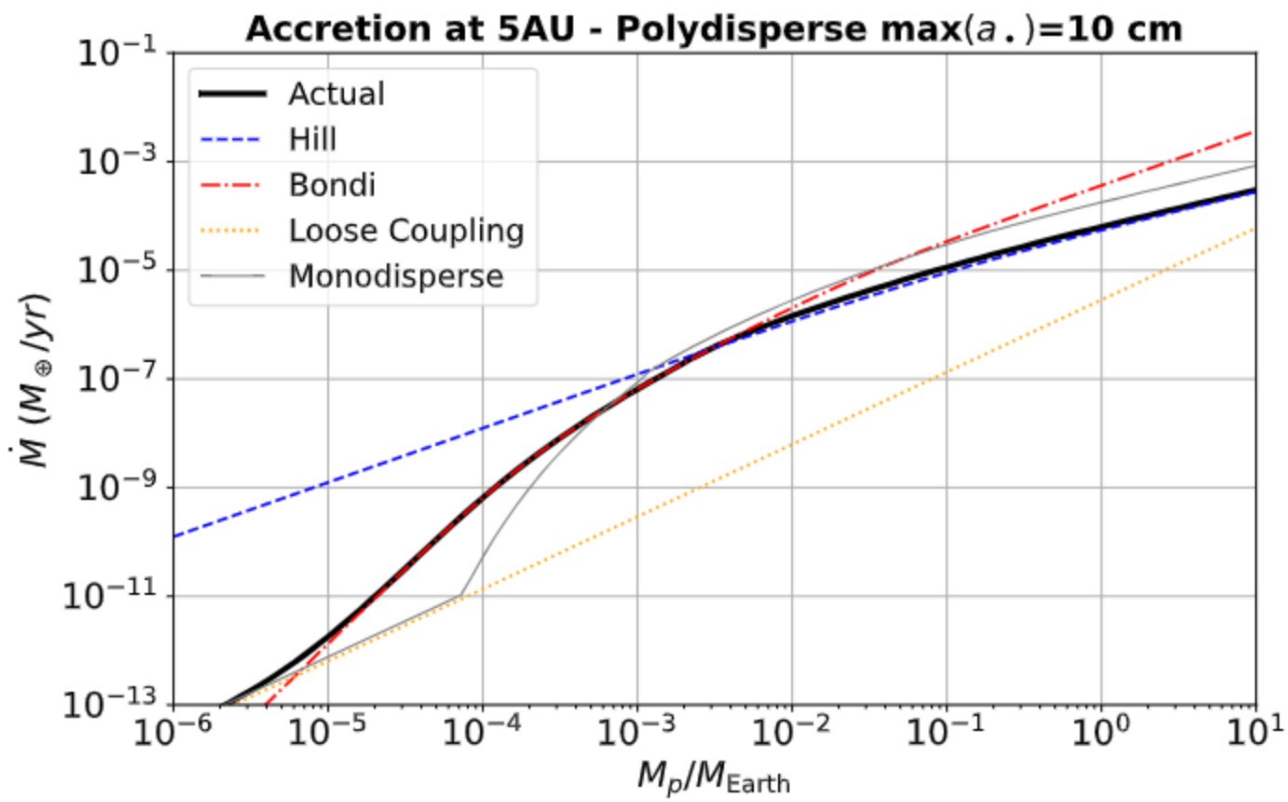
$$\dot{M}_{3D,\mathrm{Bondi}} \approx C_1\frac{\gamma_l\left(\frac{b_1+1}{s}, j_1 a_{\max}^s\right)}{s j_1^{(b_1+1)/s}} + C_2\frac{\gamma_l\left(\frac{b_2+1}{s}, j_2 a_{\max}^s\right)}{s j_2^{(b_2+1)/s}} + C_3\frac{\gamma_l\left(\frac{b_3+1}{s}, j_3 a_{\max}^s\right)}{s j_3^{(b_3+1)/s}} + C_4\frac{\gamma_l\left(\frac{b_4+1}{s},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

```
gammal1 = sp.special.gammainc((b1+1)/s,j1*a**s)*sp.special.gamma((b1+1)/s)
gammal2 = sp.special.gammainc((b2+1)/s,j2*a**s)*sp.special.gamma((b2+1)/s)
gammal3 = sp.special.gammainc((b3+1)/s,j3*a**s)*sp.special.gamma((b3+1)/s)
gammal4 = sp.special.gammainc((b4+1)/s,j4*a**s)*sp.special.gamma((b4+1)/s)

G1 = C1*gammal1/s/j1**((b1+1)/s)
G2 = C2*gammal2/s/j2**((b2+1)/s)
G3 = C3*gammal3/s/j3**((b3+1)/s)
G4 = C4*gammal4/s/j4**((b4+1)/s)

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



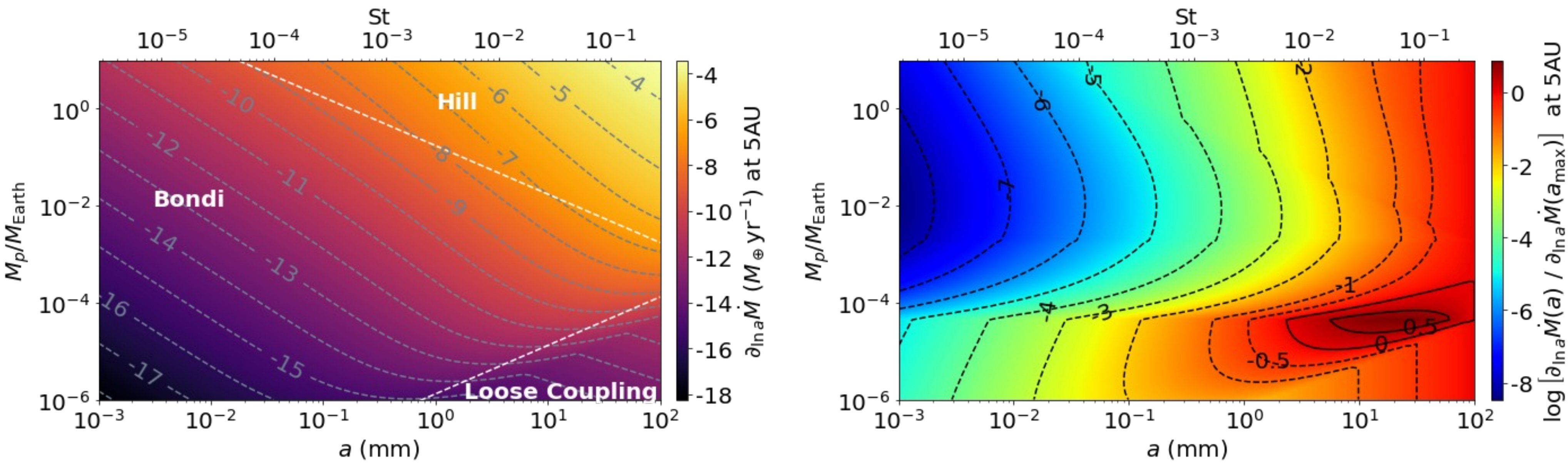
Lyra et al. (2023)

Accretion Rates



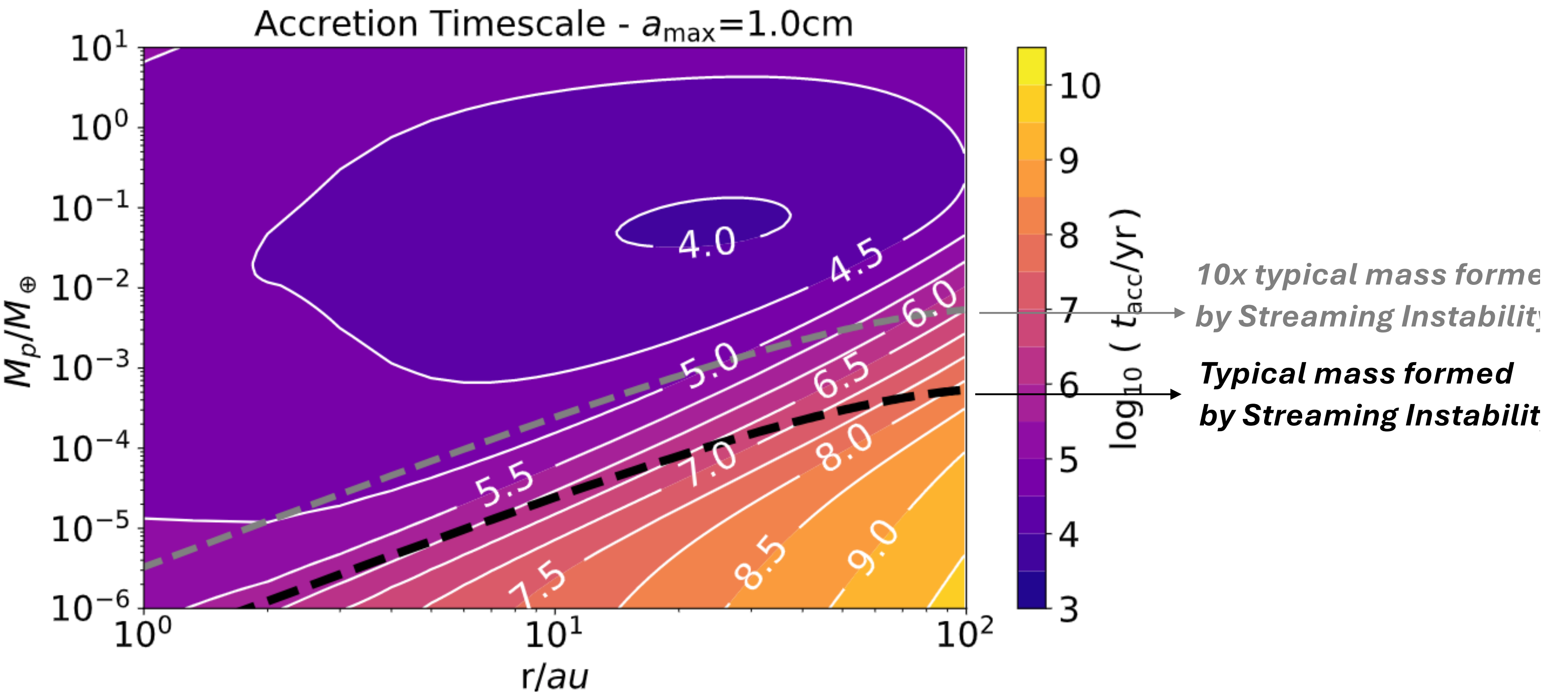
Lyra et al. (2023)

Accretion Rates



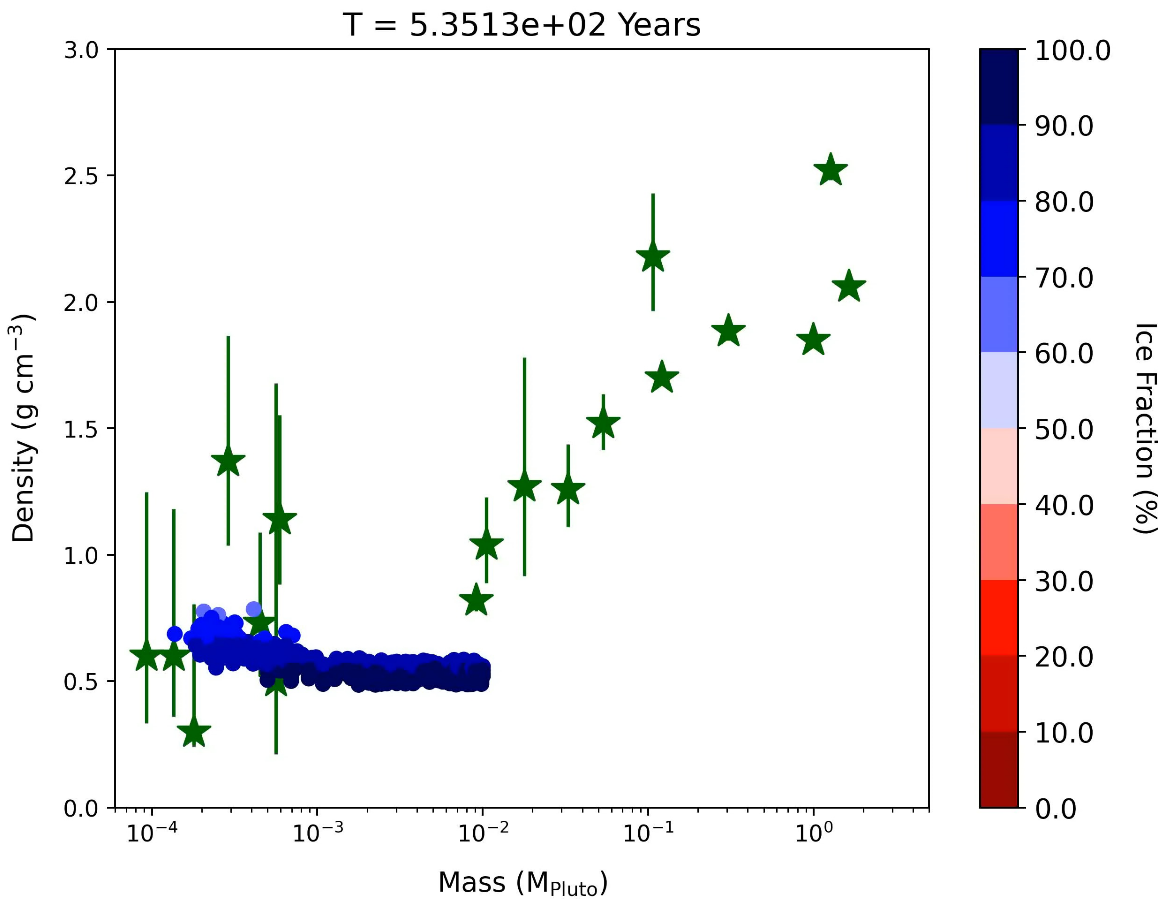
Lyra et al. (2023)

Accretion Timescales



Lyra et al. (2023)

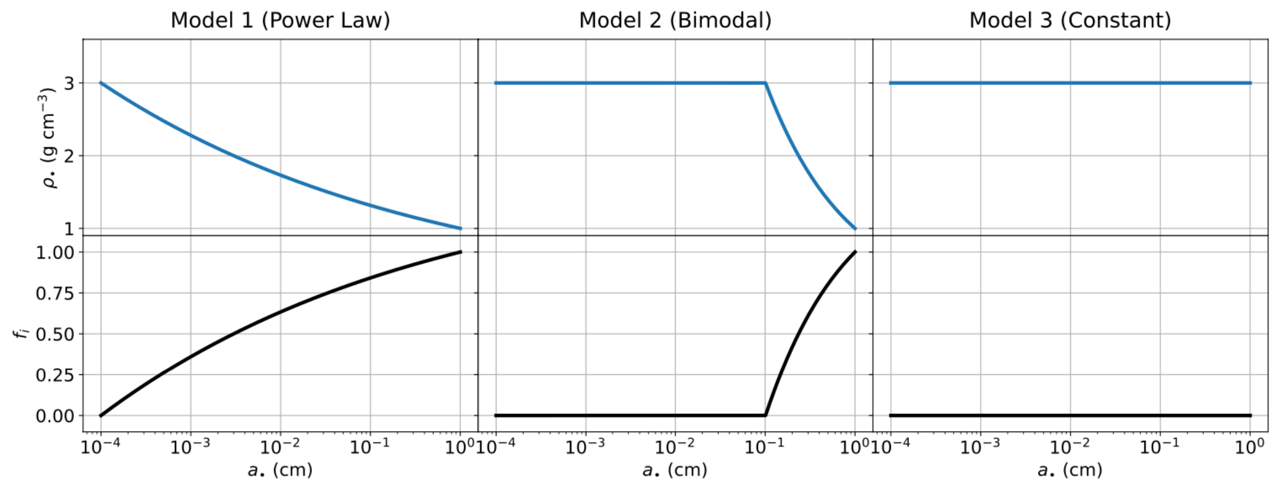
Growing Pluto by silicate pebble accretion



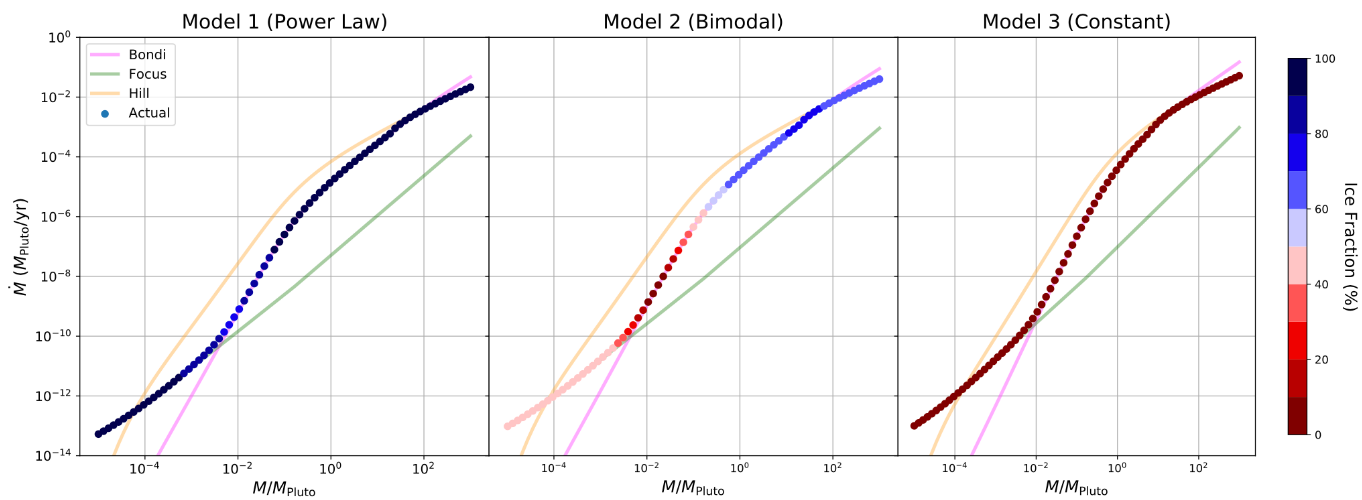
Cañas+Lyra et al. (2024)

Pebble Internal Density

Ice Volume Fraction

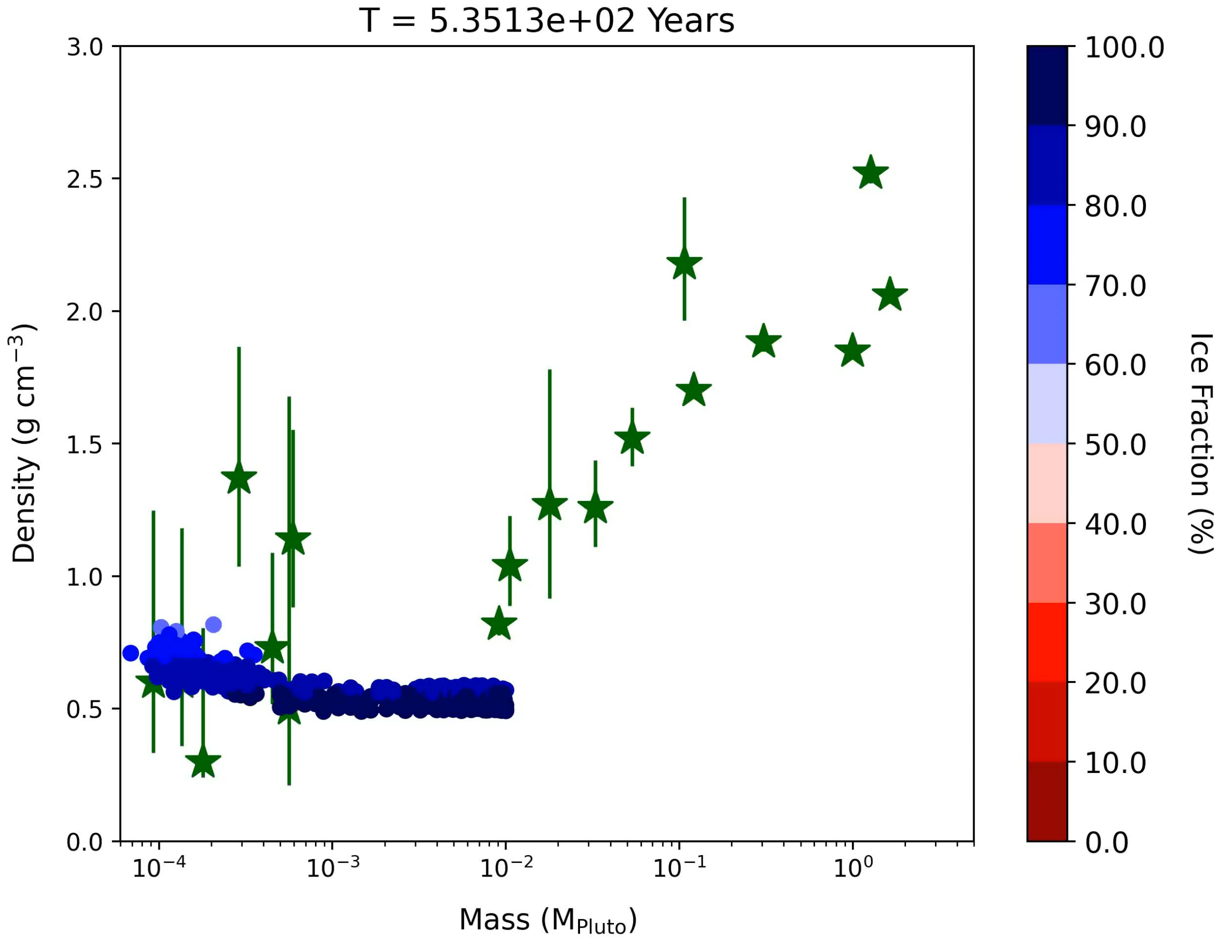


Mass Accretion rate



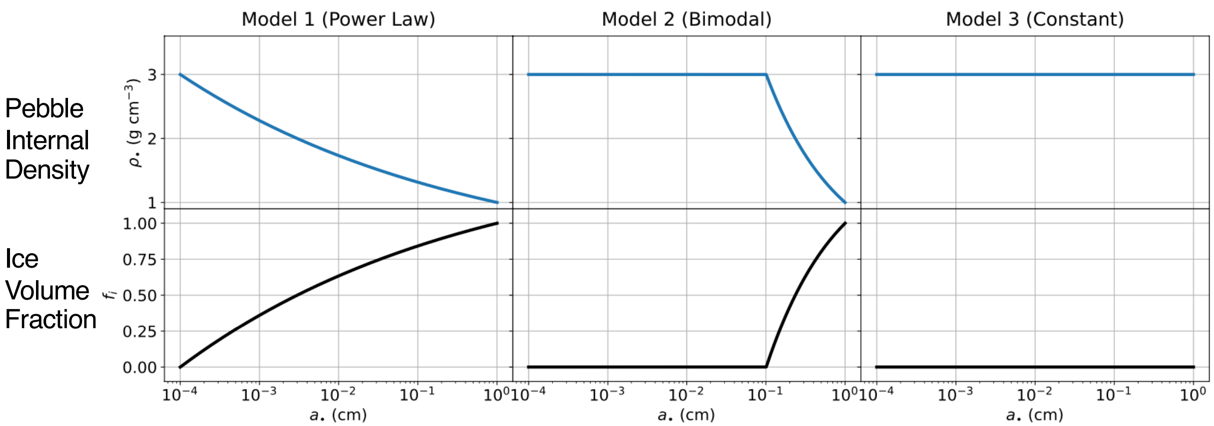
Cañas+Lyra et al. (2024)

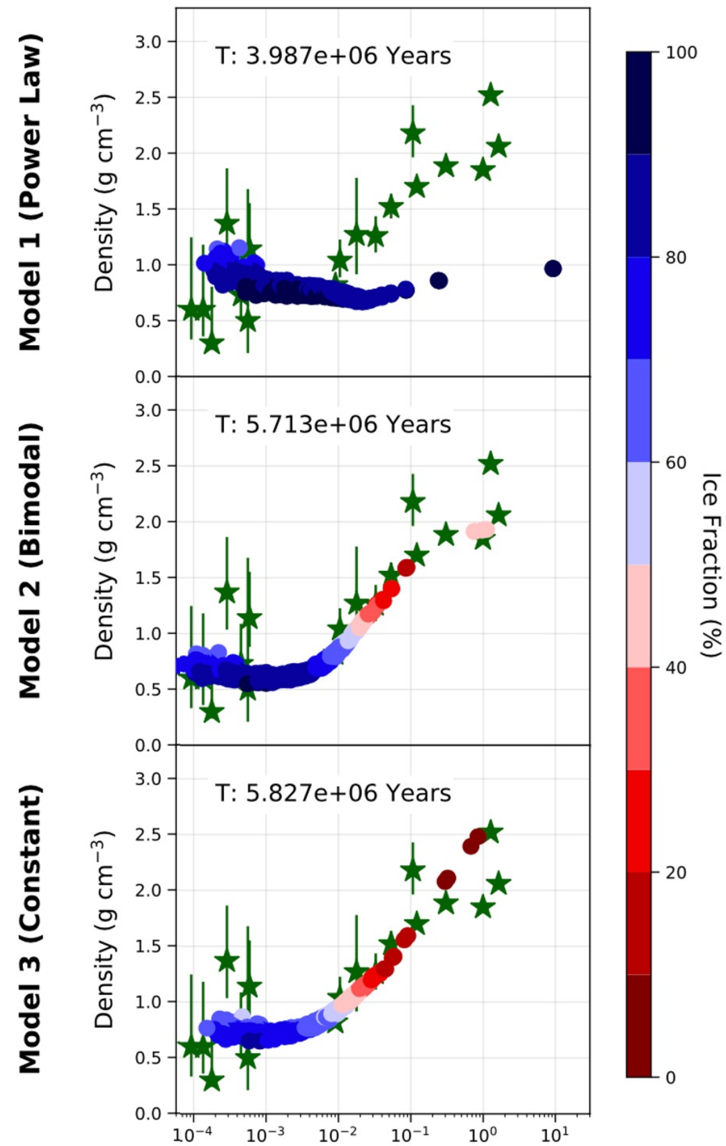
Growing Pluto by silicate pebble accretion



Cañas+Lyra et al. (2024)

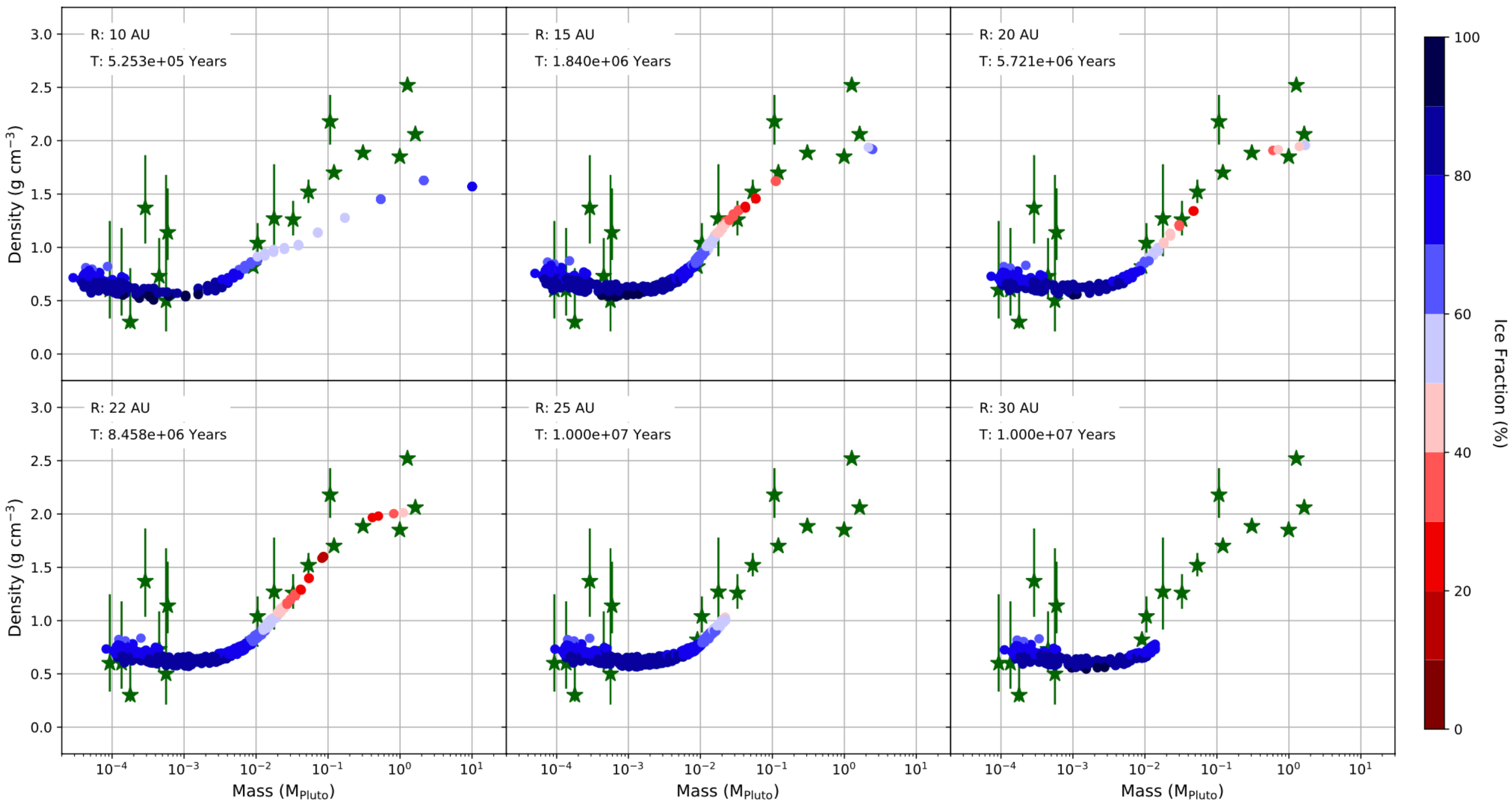
Resulting Densities vs Mass relations





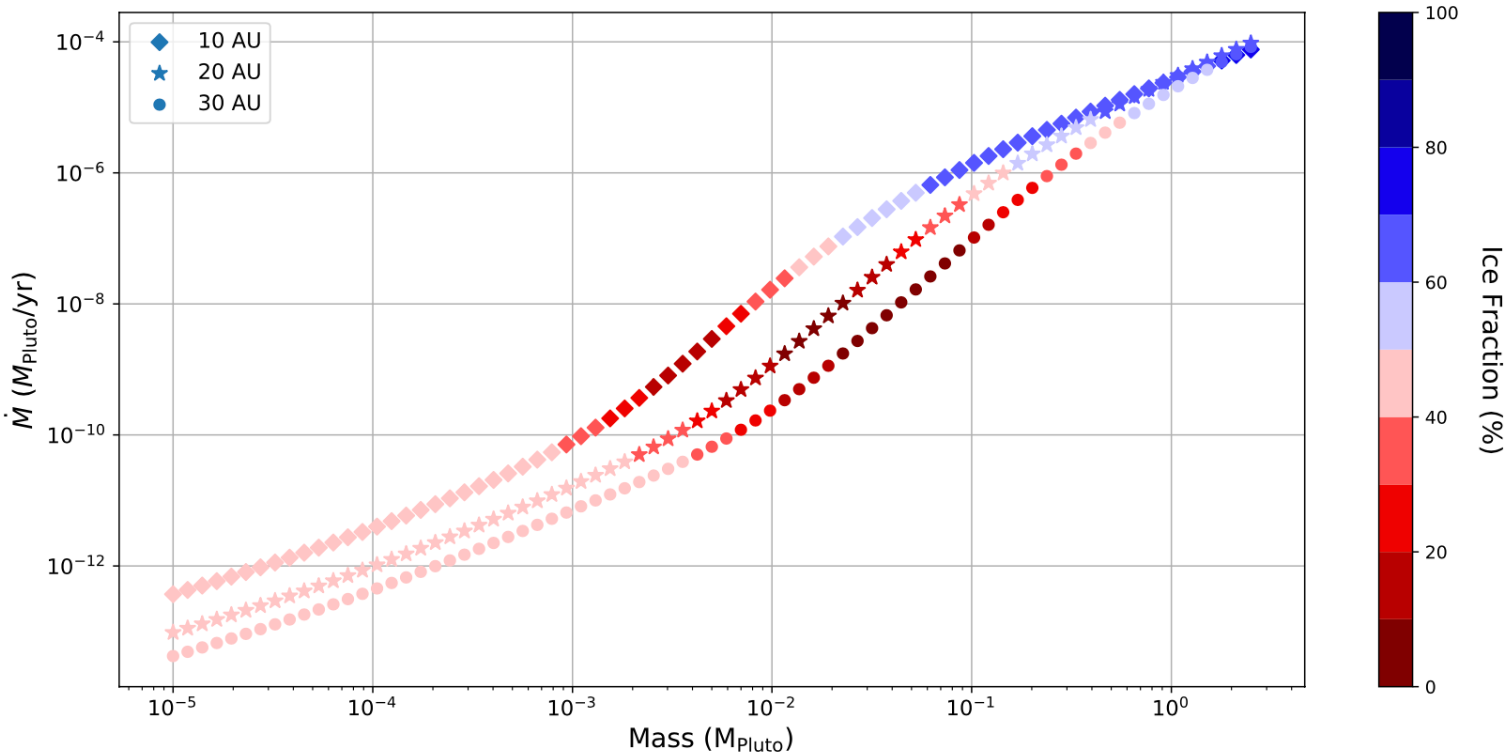
Cañas+Lyra et al. (2024)

Distance Range
15 - 25AU



Cañas+Lyra et al. (2024)

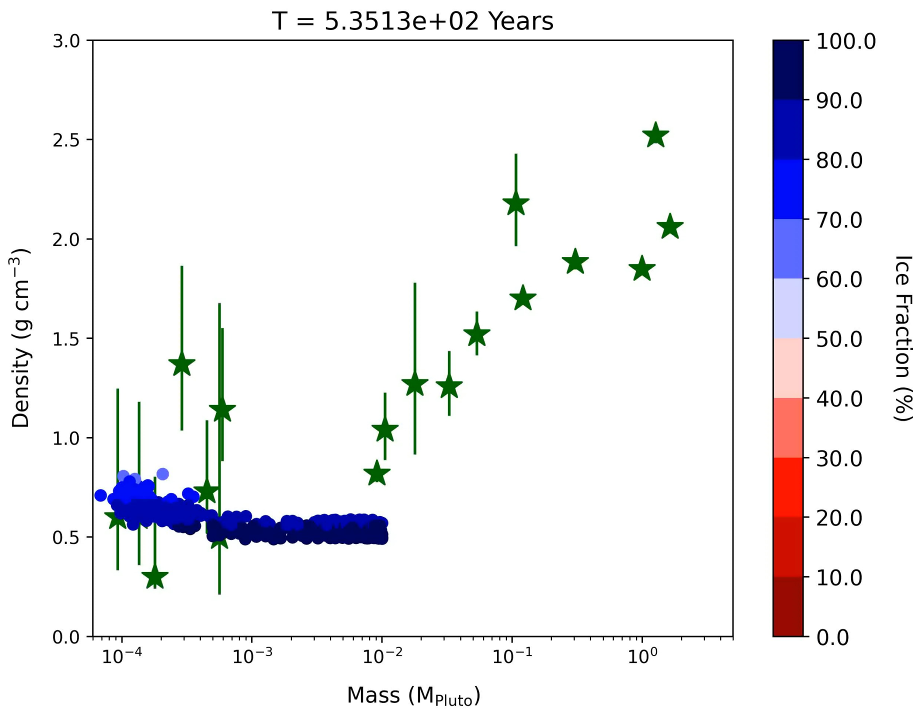
The window of silicate accretion



Cañas+Lyra et al. (2024)

Conclusions

- Polydisperse Bondi accretion 1-2 orders of magnitude more efficient than monodisperse
    - Best accreted pebbles are those of drag time ~ 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}Al incorporated mostly in long (>Myr) phase of silicate accretion
    - KBOs best reproduced between 15-25 AU



Lyra et al. (2023), Cañas et al. (2024)