Kuiper belt binaries: Evidence for streaming instability and pebble accretion in their mass distribution and size-density relationship

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NH Science Plenary Meeting - Jun 12th, 2025

The PFITS+ Collaboration
(Planet Formation in the Southwest)

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Wladimir Lyra – *New Mexico State University*
Andrew Youdin – *University of Arizona*
Jake Simon – *Iowa State University*
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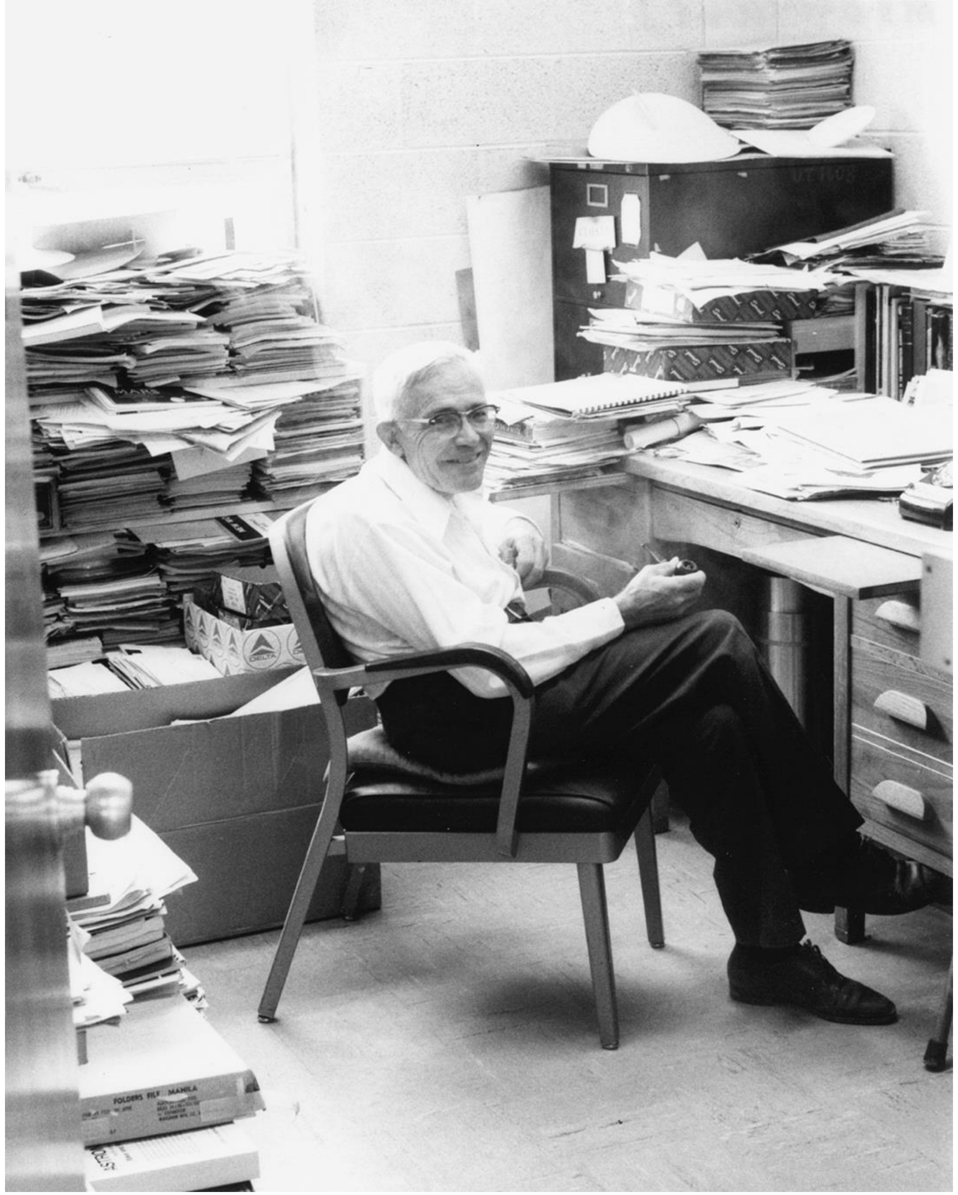
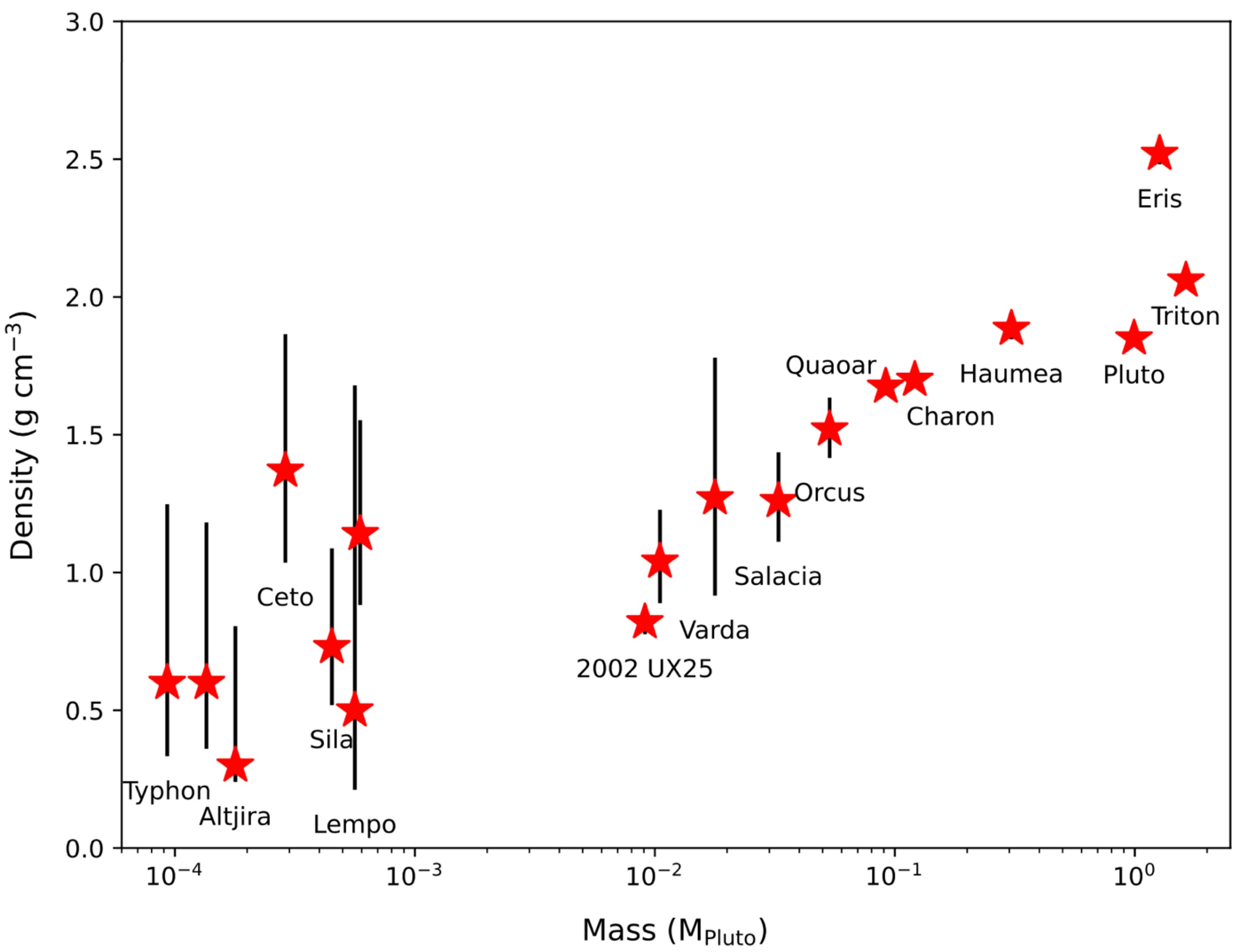


NMSU professor awarded NASA grant, research may show how Pluto was formed

Release Date: 24 Aug 2022

The size-density relationship of Kuiper Belt objects



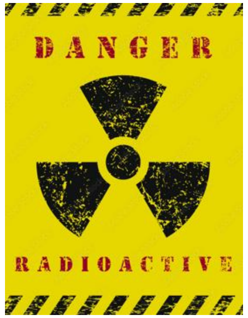
Cañas+Lyra et al. (2024)

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).*

Previous best bet:
Porosity removal by gravitational compaction

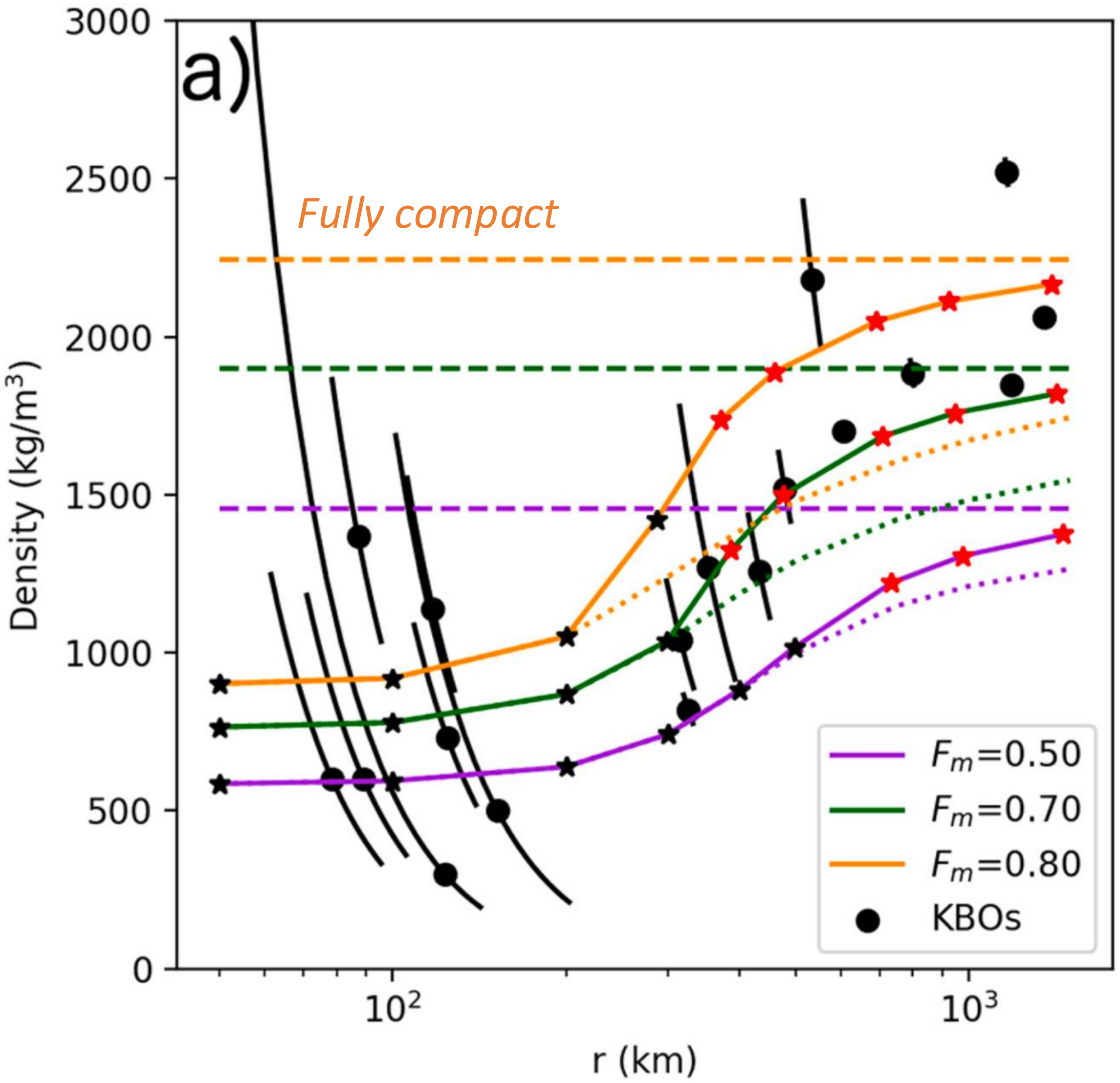
Problem

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



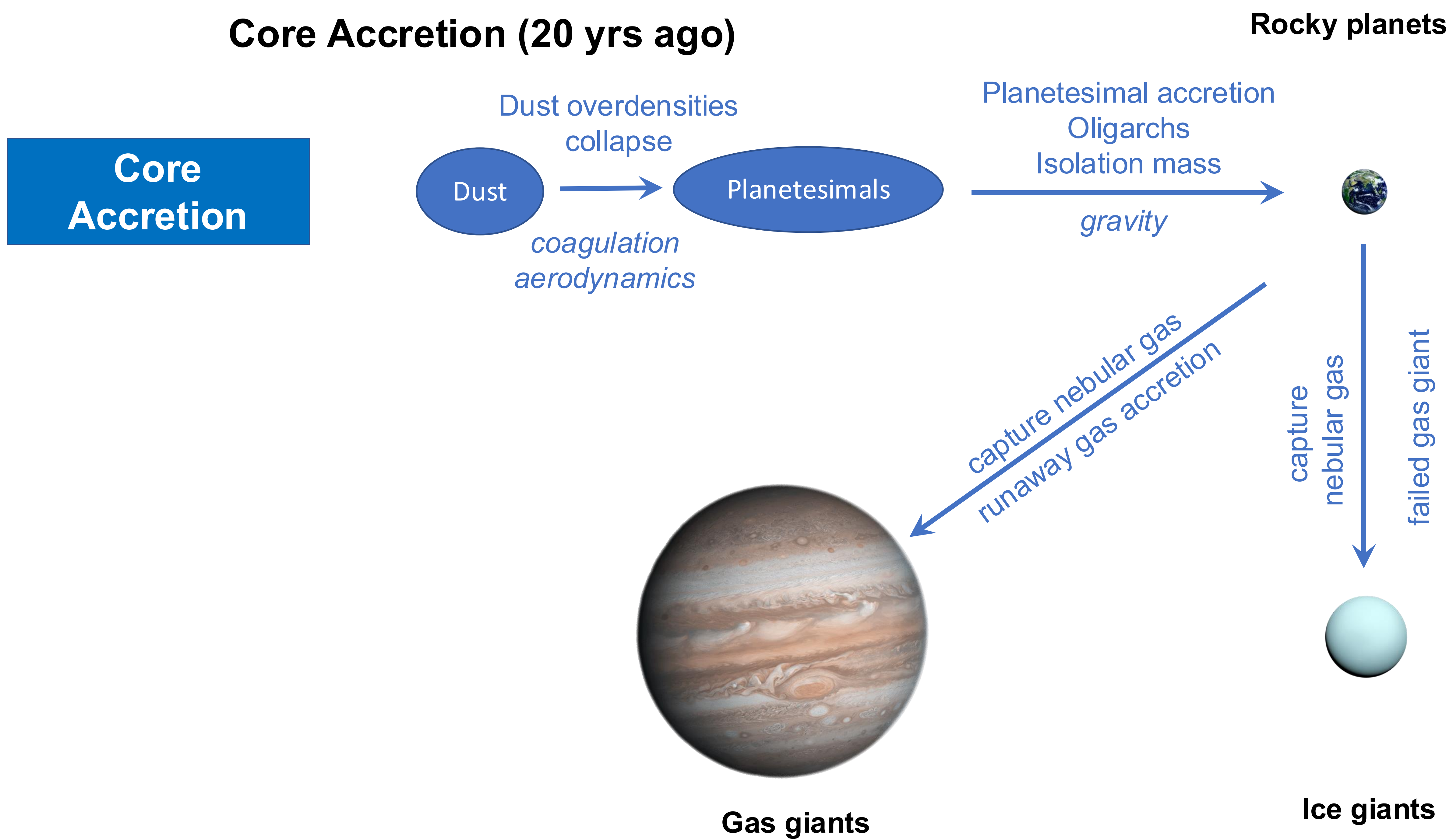
Assumptions

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



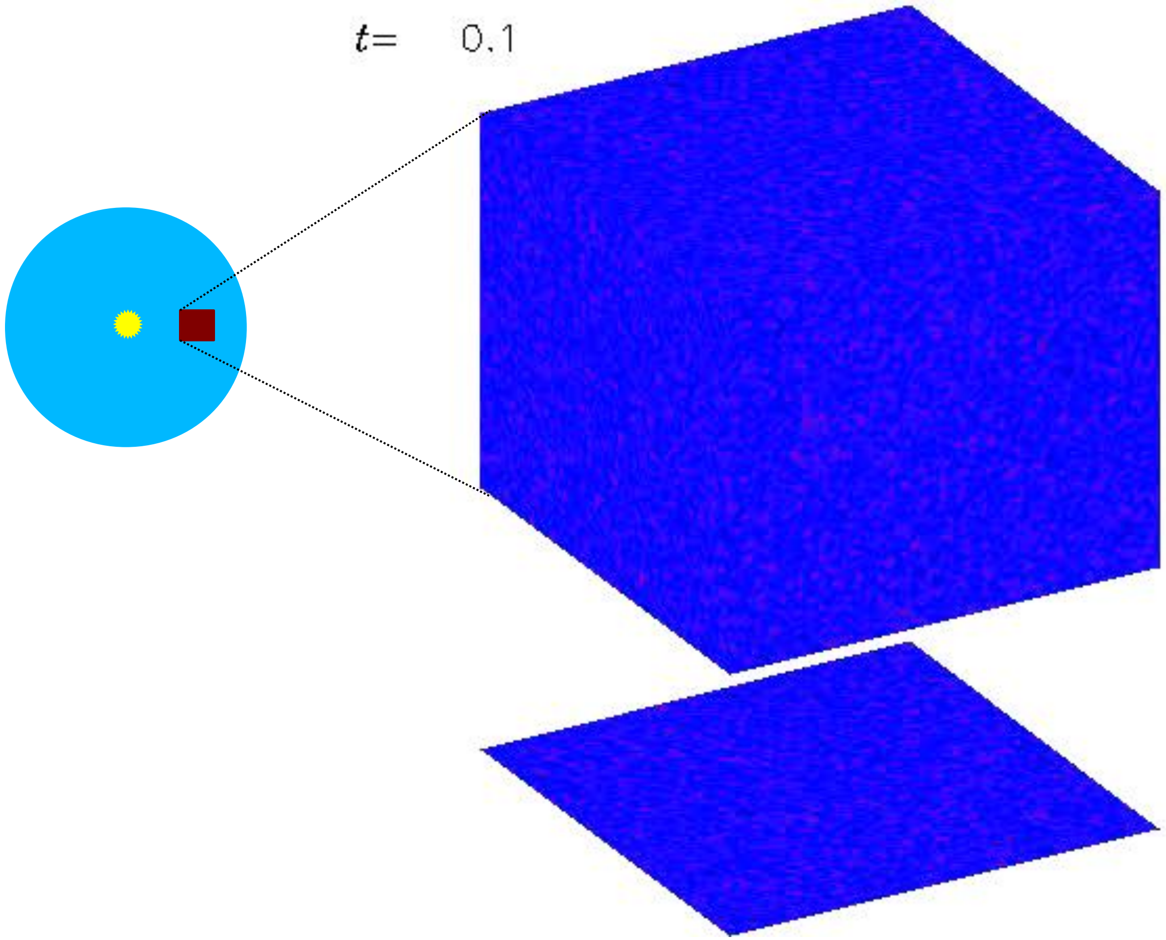
F_m = rock mass fraction

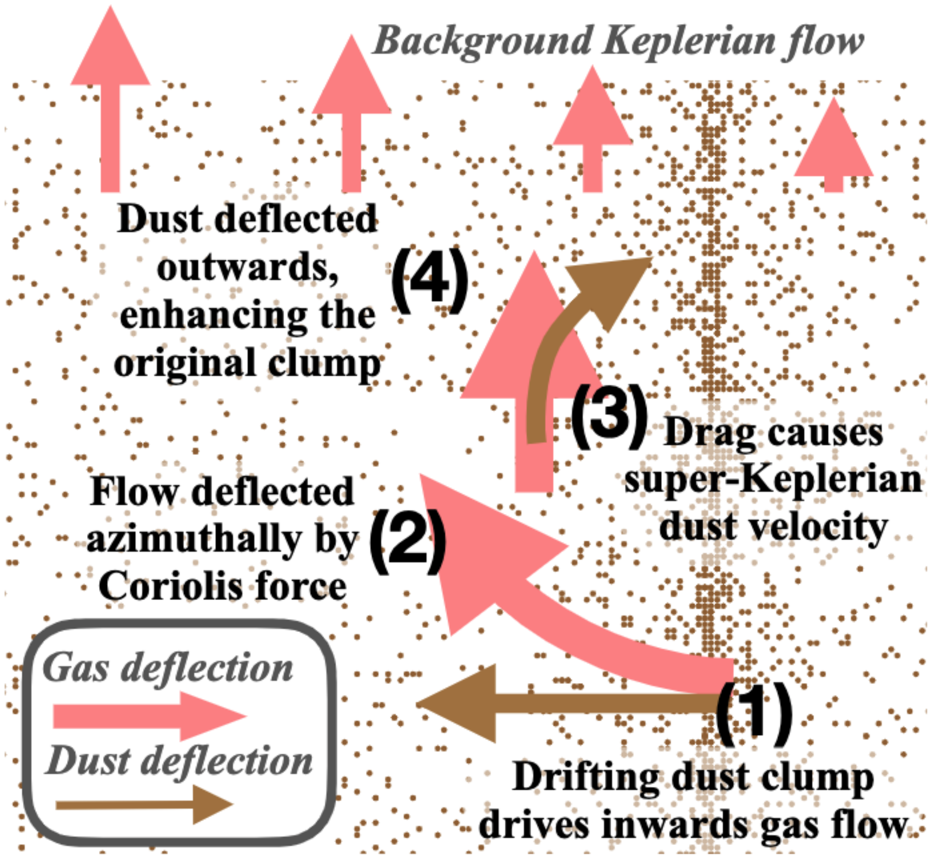
Bierson & Nimmo (2019)


Core Accretion (20 yrs ago)
Rocky planets
Core Accretion
Dust overdensities
collapse
Dust
Planetesimals
coagulation
aerodynamics
Planetesimal accretion
Oligarchs
Isolation mass
gravity
capture nebular gas
runaway gas accretion
capture
nebular gas
failed gas giant
Gas giants
Ice giants

Streaming Instability

The dust drift is hydrodynamically unstable





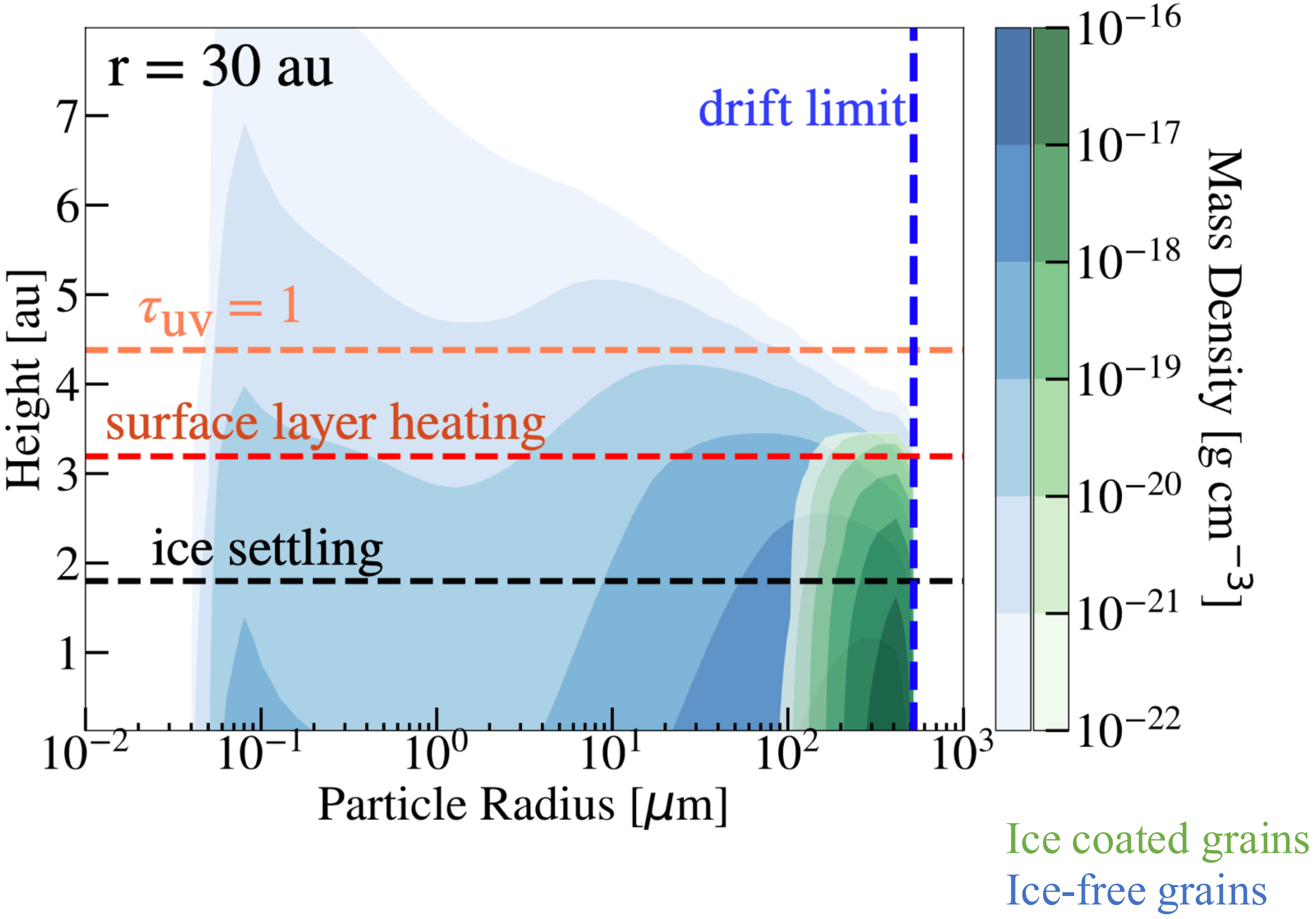
Lesur et al. (2022)

Youdin & Goodman ‘05, Johansen & Youdin ‘07, Youdin & Johansen+ ‘07, Kowalik+ ’13, Lyra & Kuchner ‘13, Schreiber+ ‘18, Klahr & Schreiber ’20, Simon+ ‘16, ‘17, Carrera+ ‘15, ‘17, ‘20, Gole+ ’20, Li+ ‘18, ‘19, Abod+ ’19, Nesvorny+ ’19

Abandoning Constant Composition

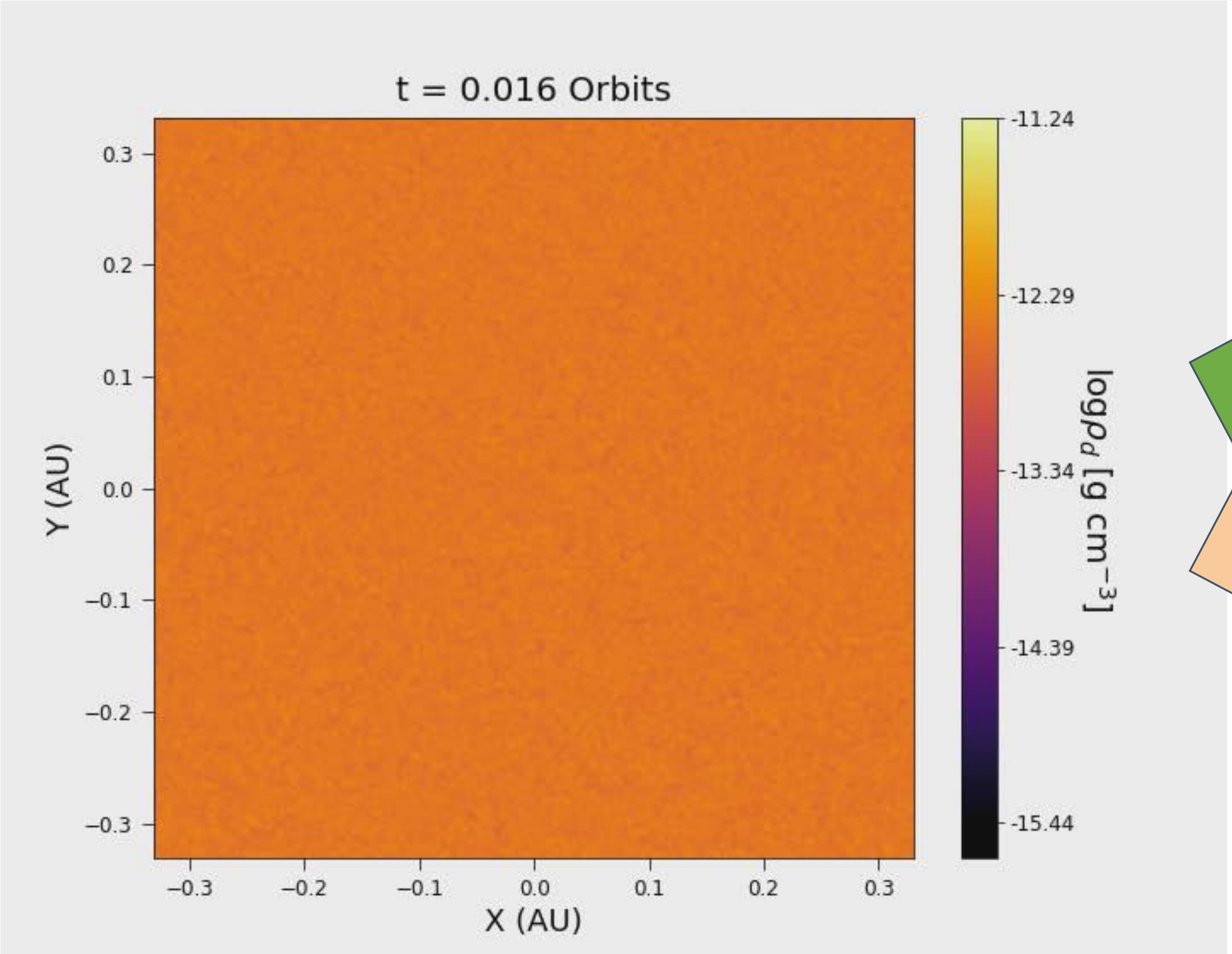
Heating and UV irradiation remove ice on Myr timescales (Harrison & Schoen 1967)

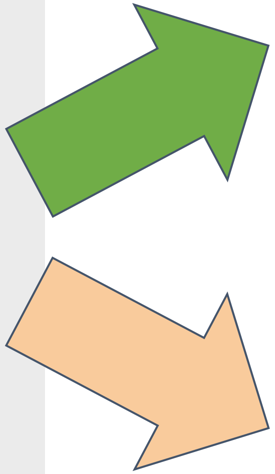
- Small grains lofted in the atmosphere lose ice
- Big grains are shielded and remain icy.

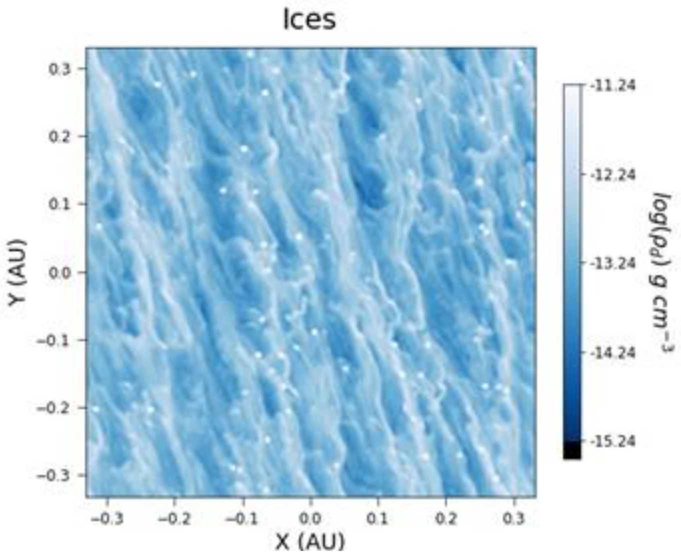


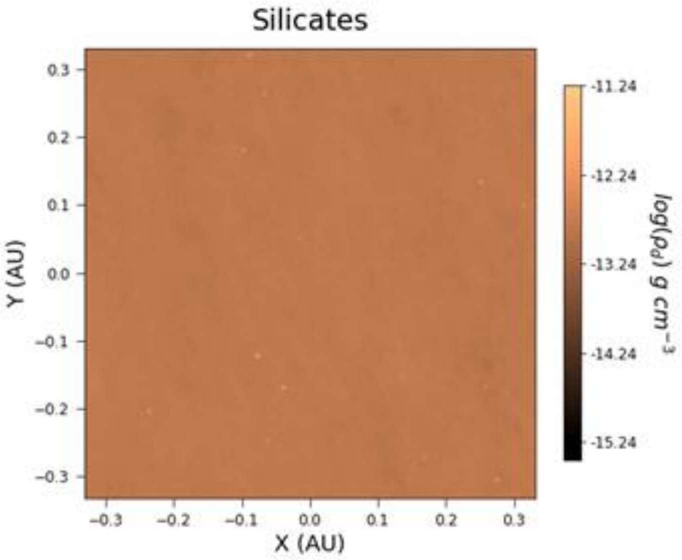
Powell et al. 2022

Split into icy and silicate pebbles



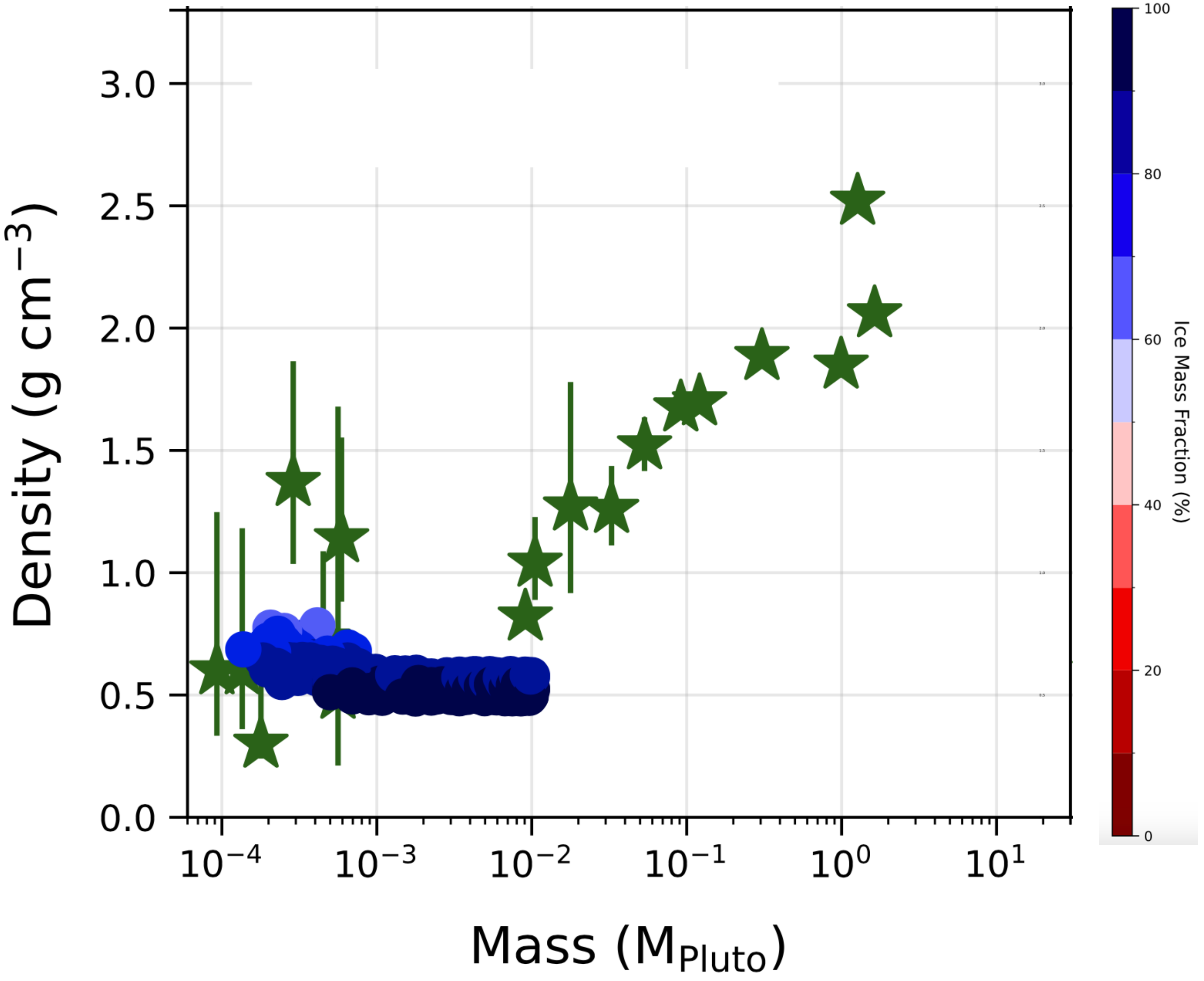






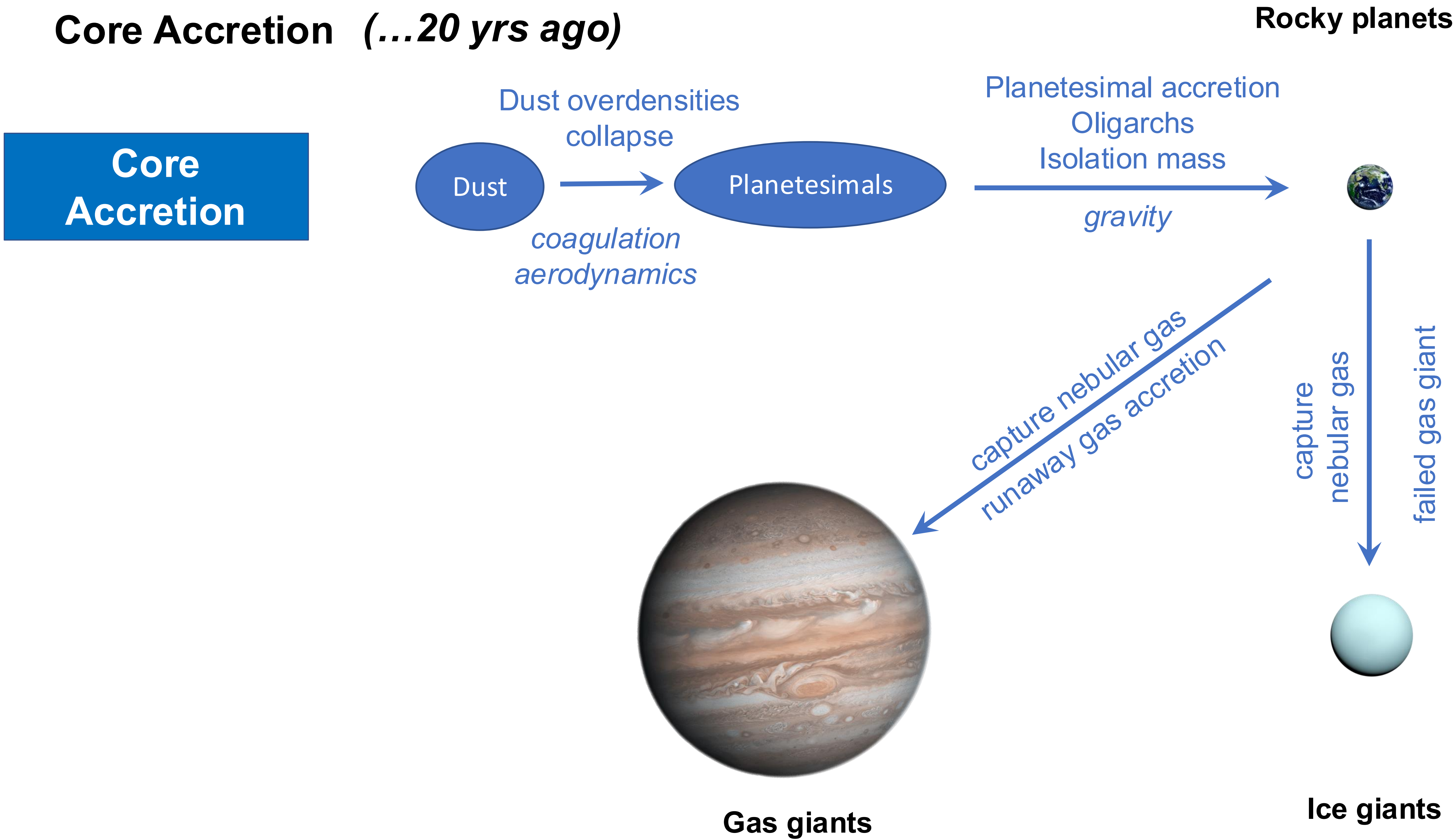
Canas+Lyra et al. 2024

The first planetesimals are icy

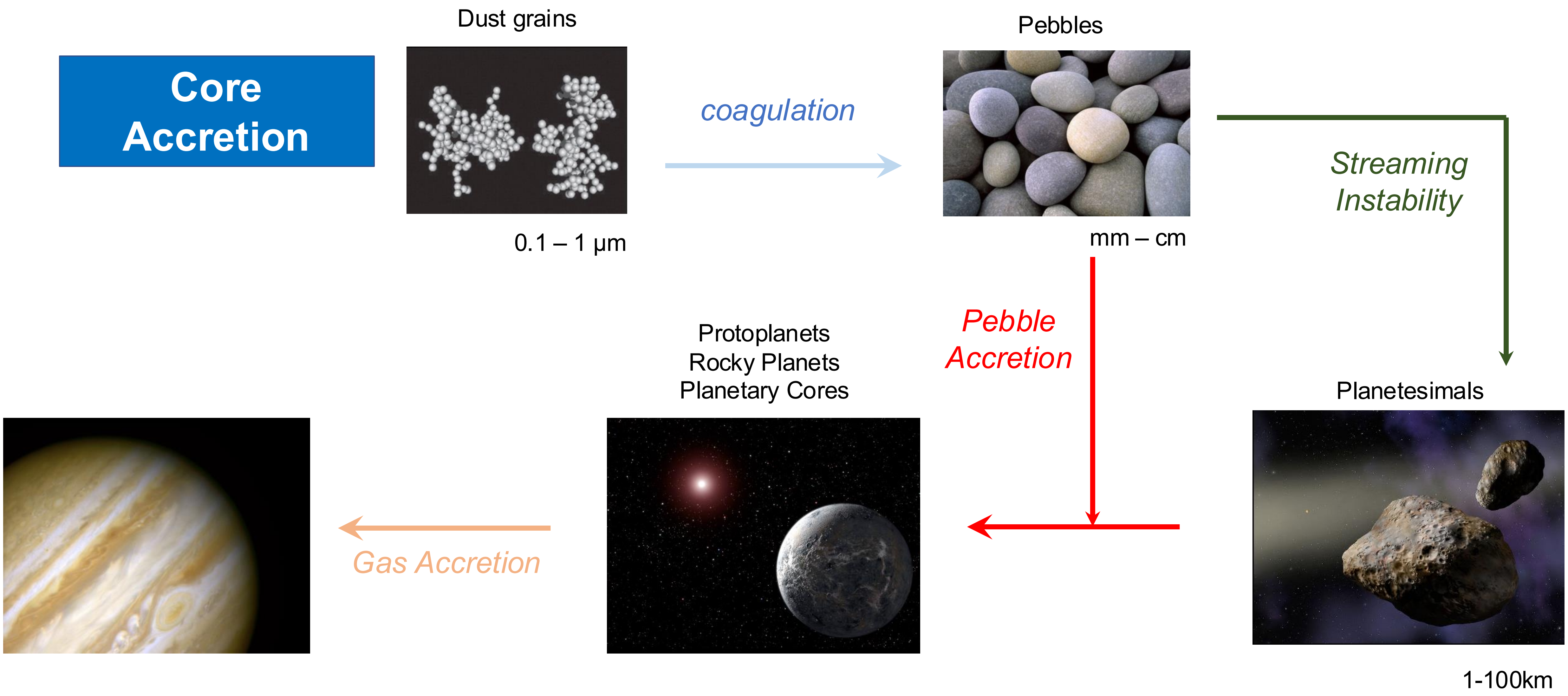


Canas+Lyra et al. 2024

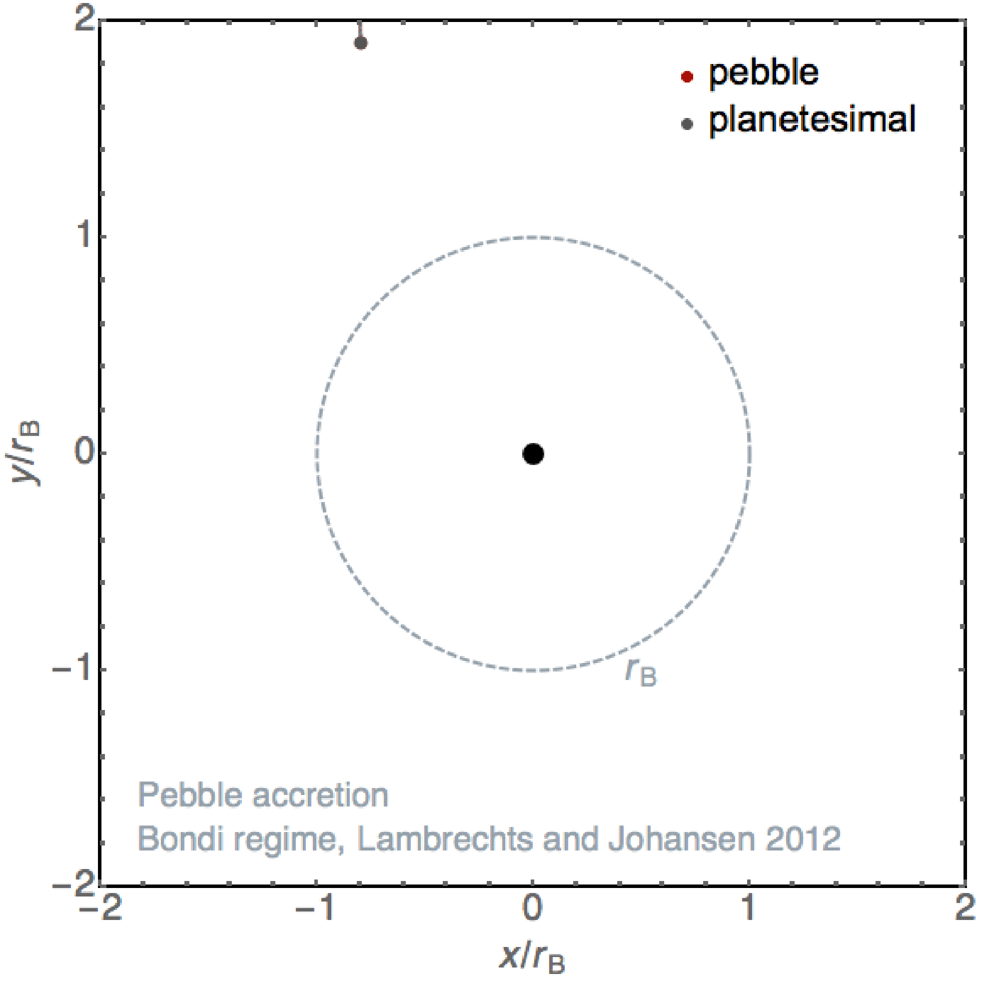
Core Accretion (…20 yrs ago)

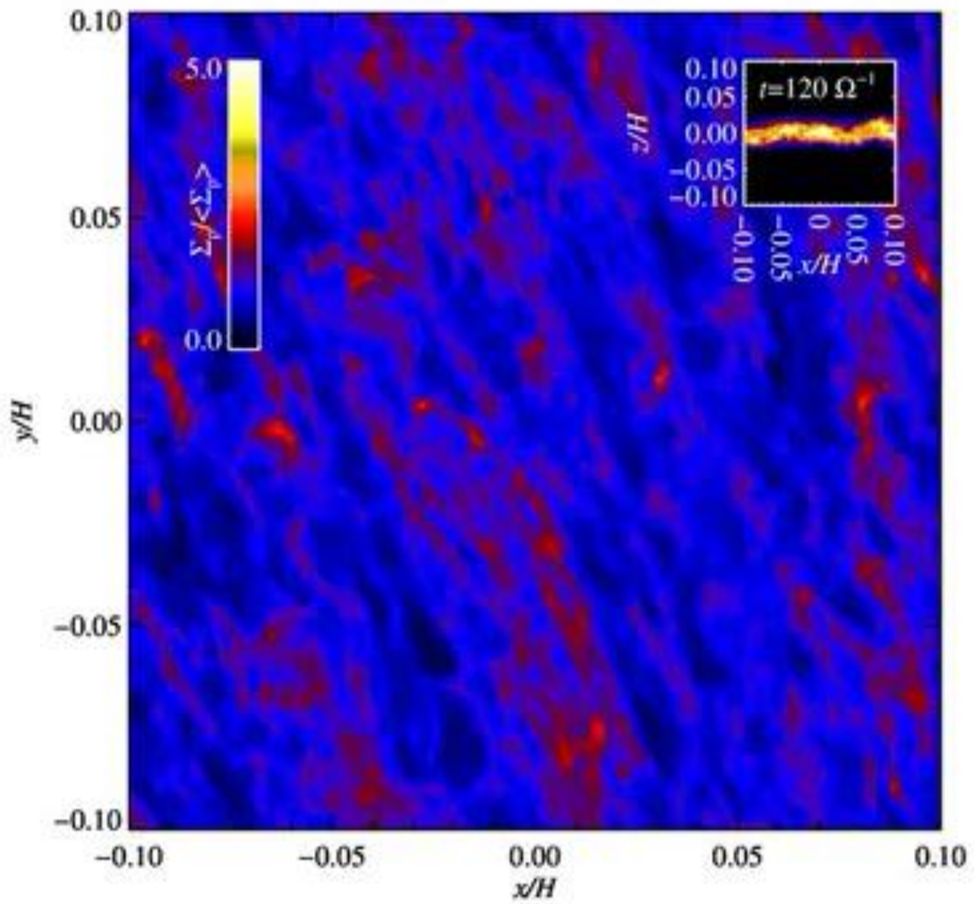


Core Accretion



Pebble Accretion

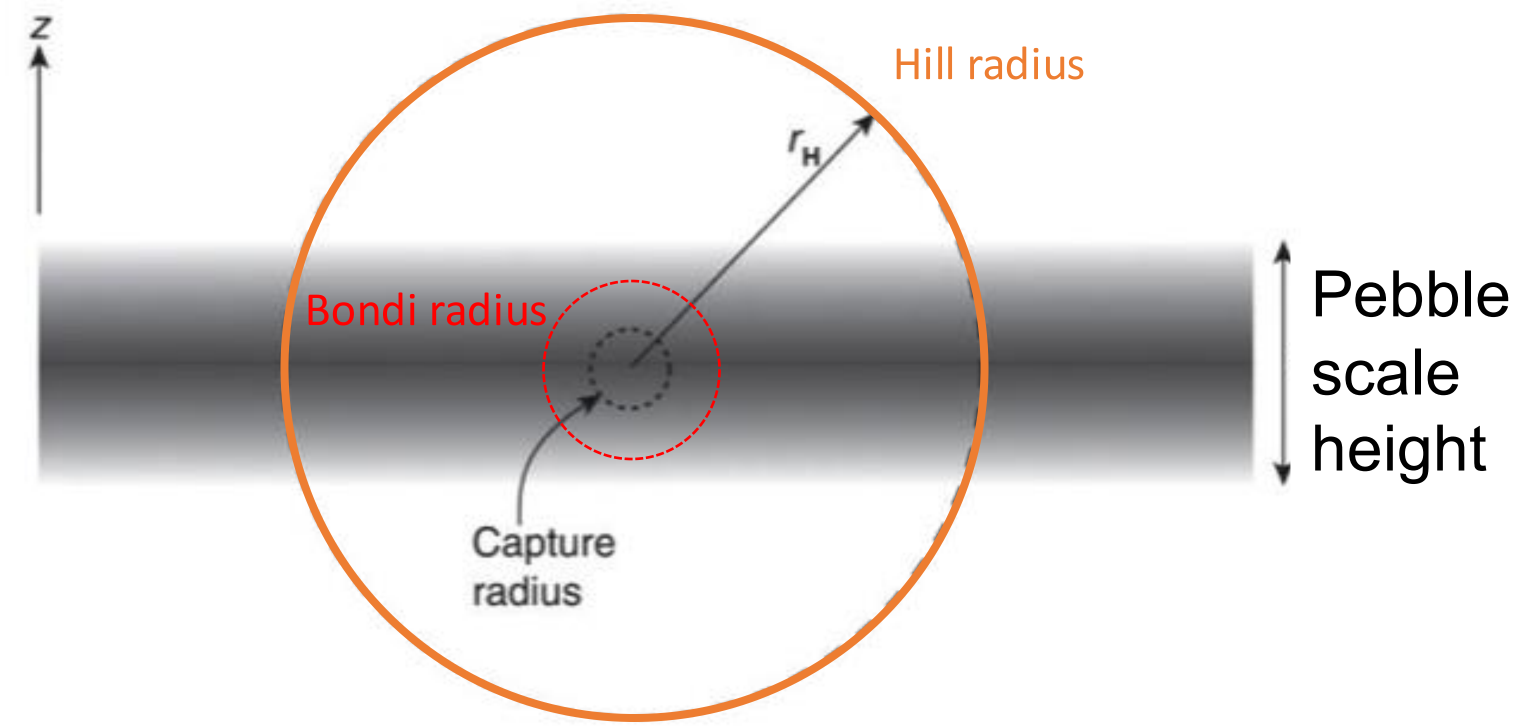


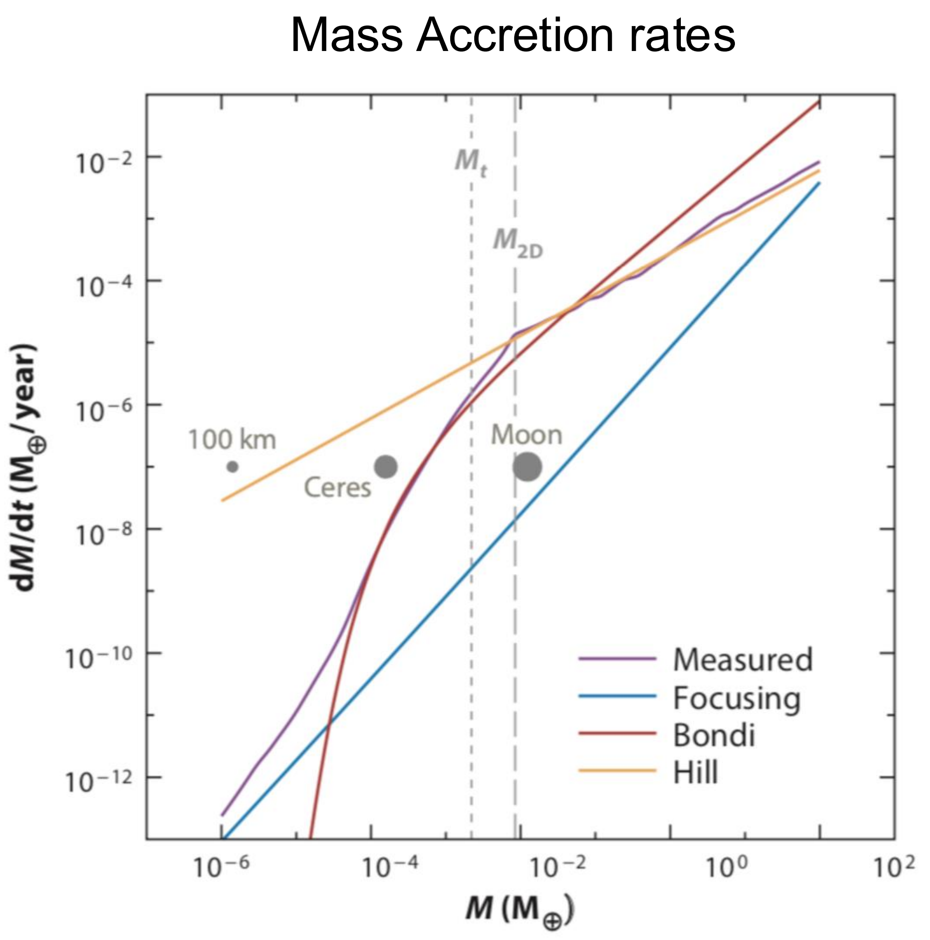


Lyra+ ‘08, ’09, ’23, Ormel & Klahr ‘10, Lambrechts & Johansen ’12
See Johansen & Lambrechts ‘17 for a review

Pebble Accretion: Geometric, Bondi, and Hill regime

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





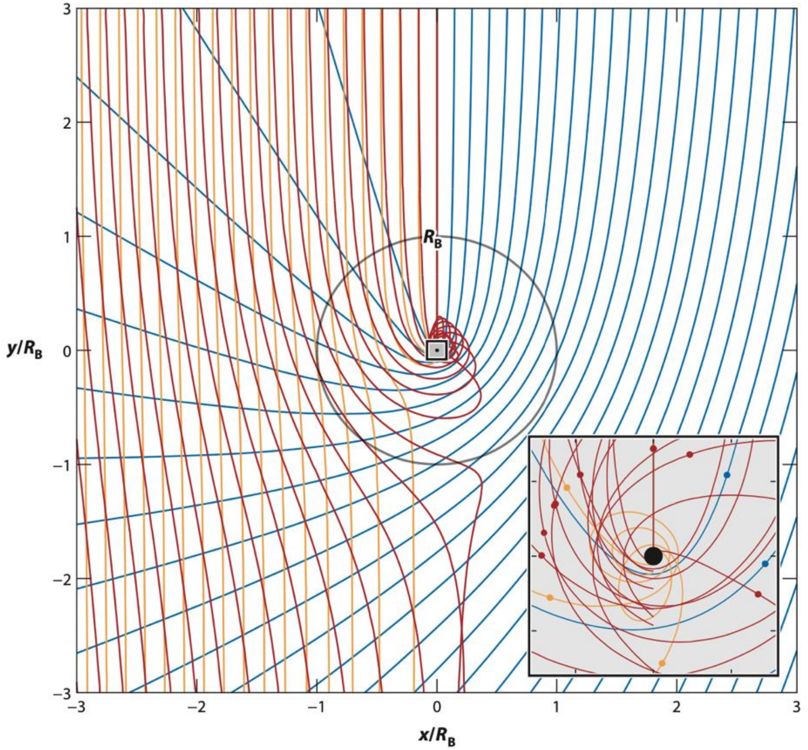
Johansen & Lambrechts (2017); Lyra et al (2023)

Pebble Accretion: Pebbles of different size accrete differently

Large
Medium
Small

”Goldilocks effect” in the Bondi regime

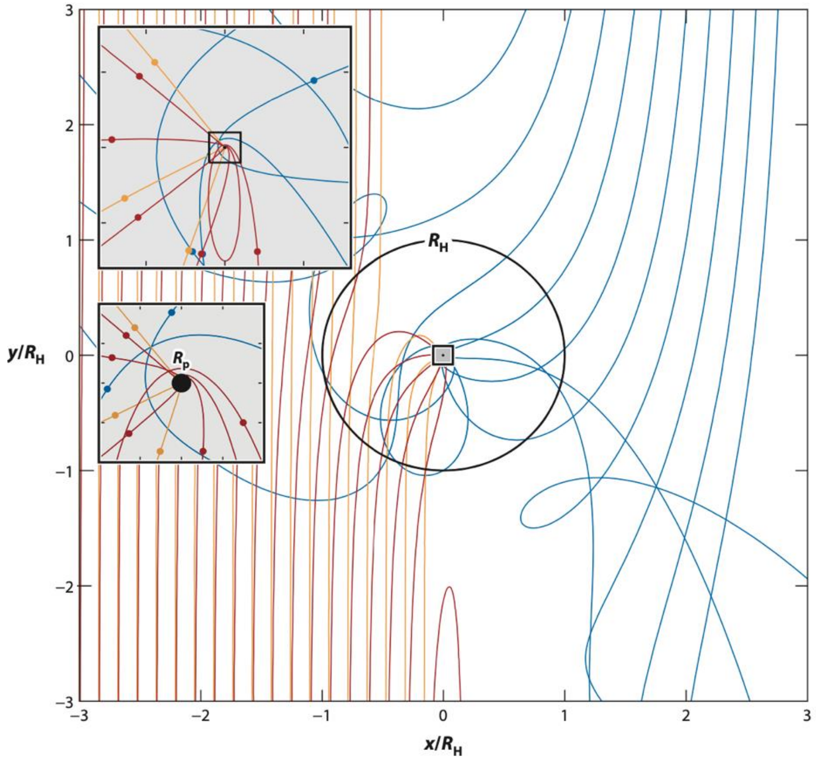
Bondi Regime



Best accreted pebble

Drag time ~ Bondi Time

Hill Regime

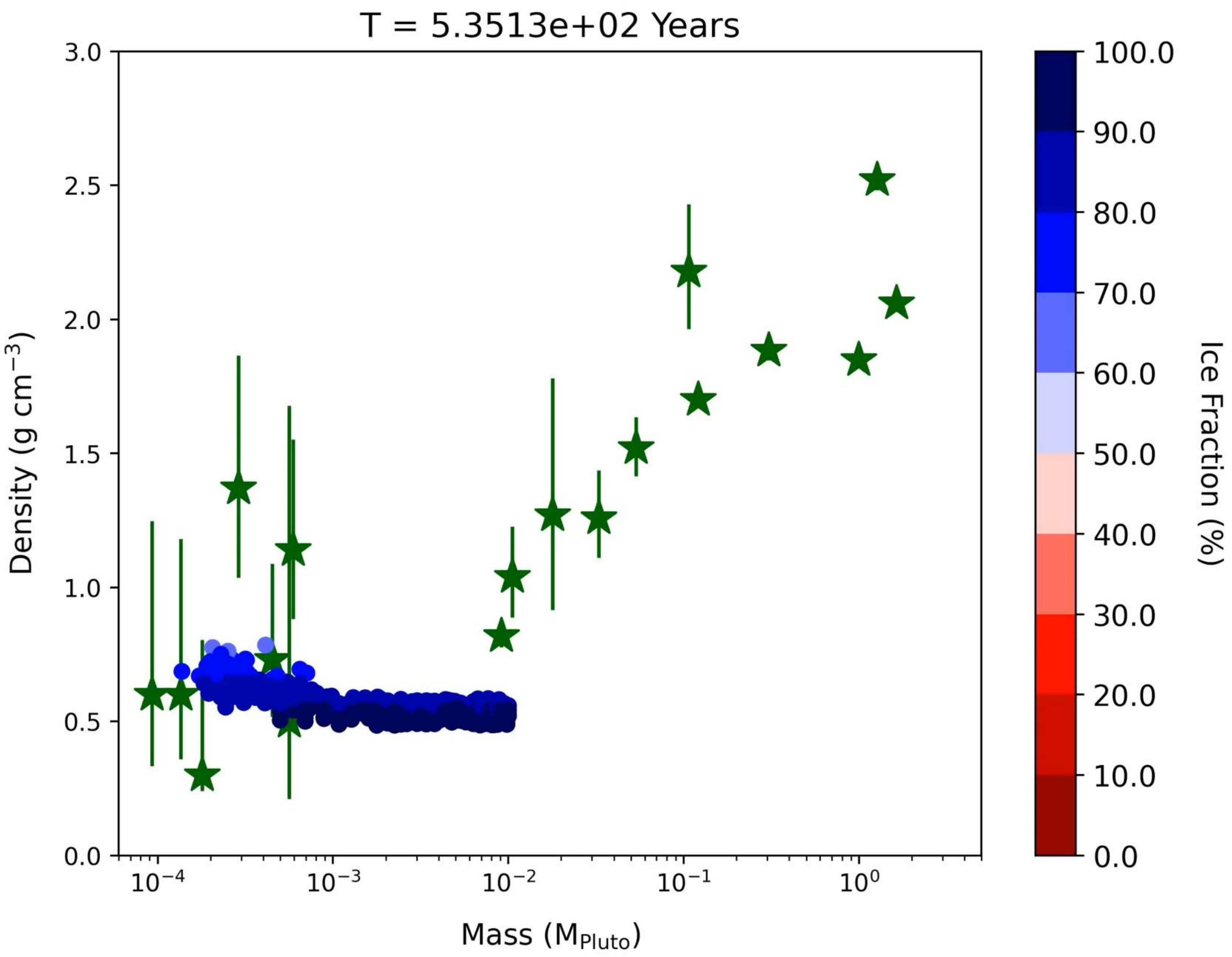


Best accreted pebble

Drag time ~ Orbital Time

Johansen & Lambrechts (2017); Lyra et al (2023)

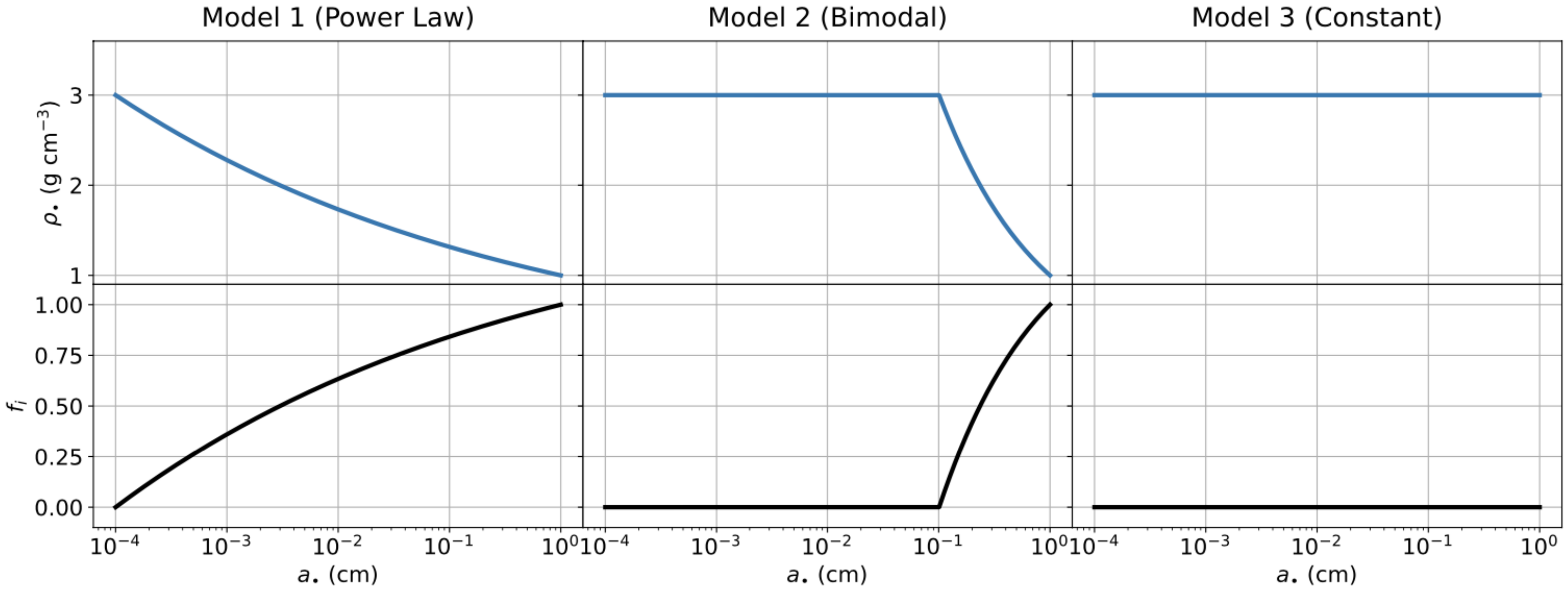
Growing Pluto by silicate pebble accretion



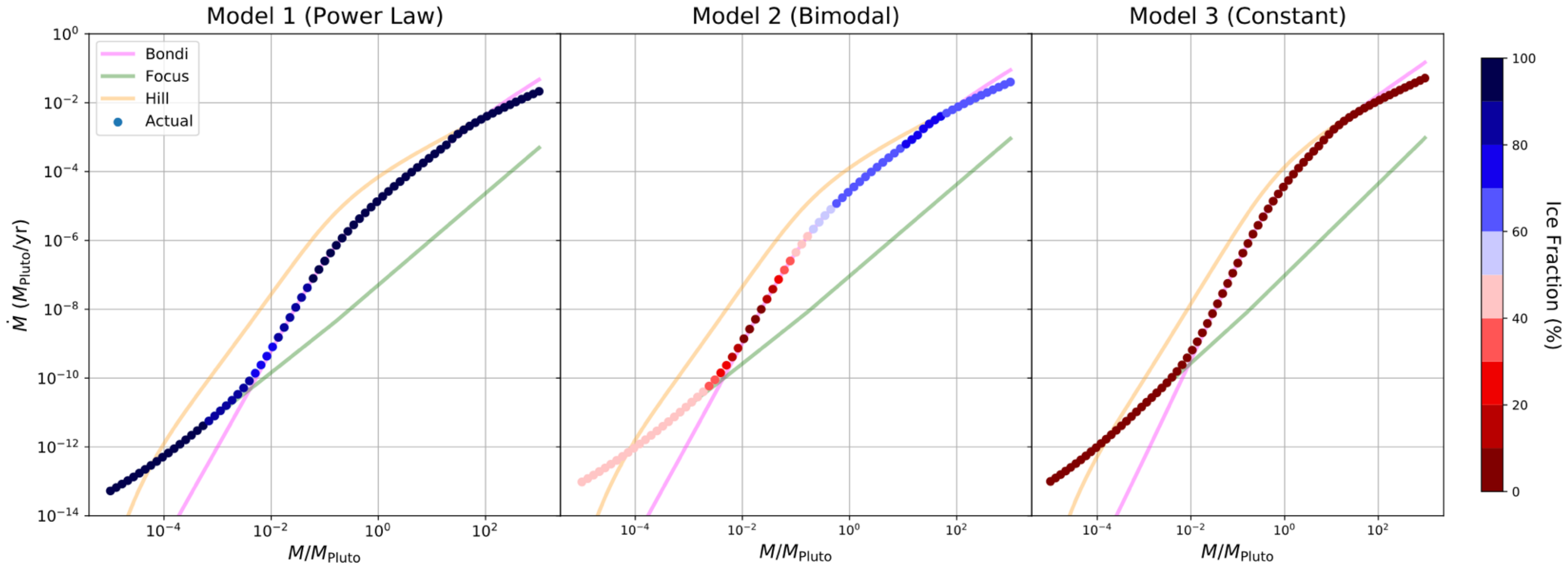
Canas+Lyra et al. 2024

Pebble Internal Density

Ice Volume Fraction

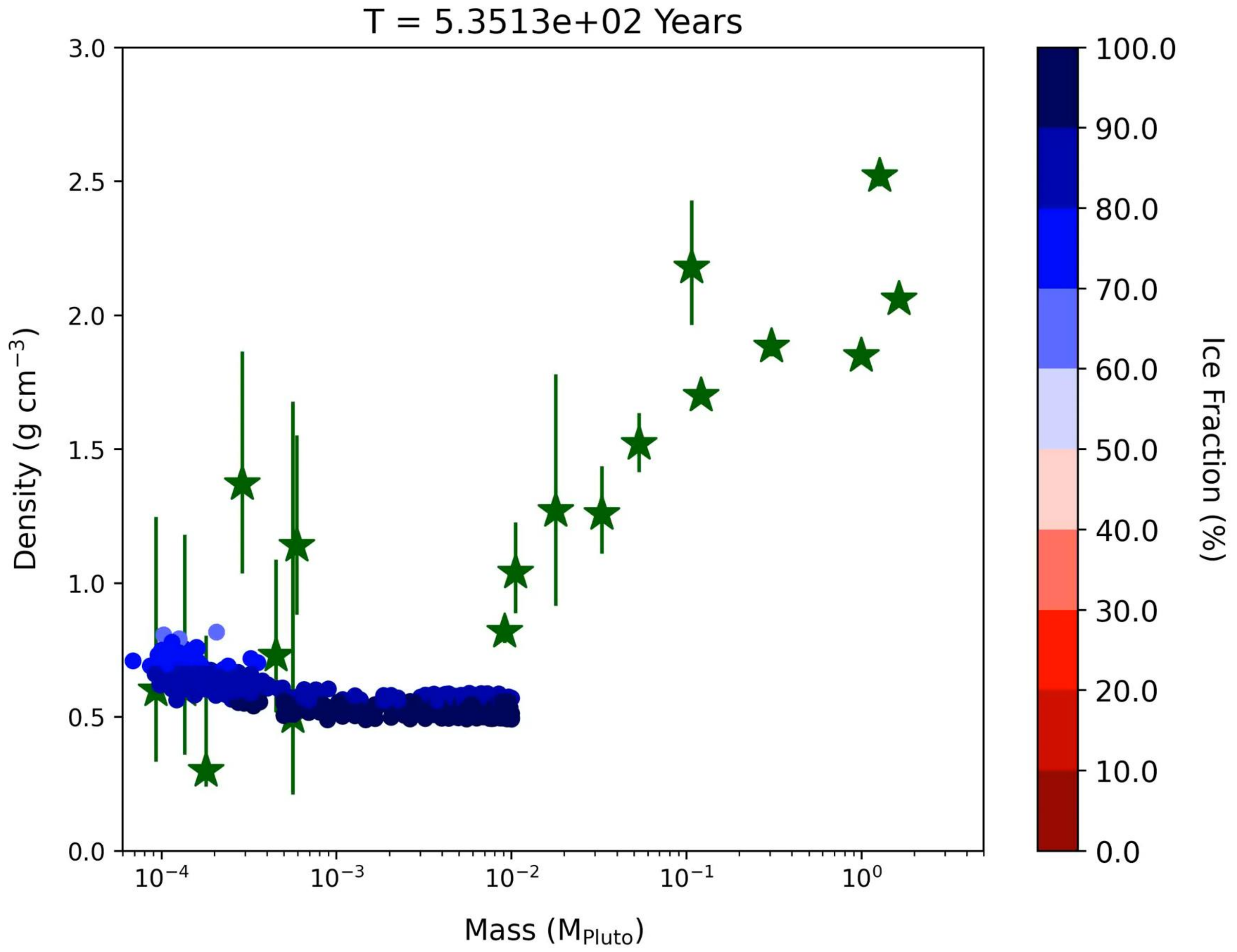


Mass Accretion rate



Canas+Lyra et al. 2024

Growing Pluto by silicate pebble accretion

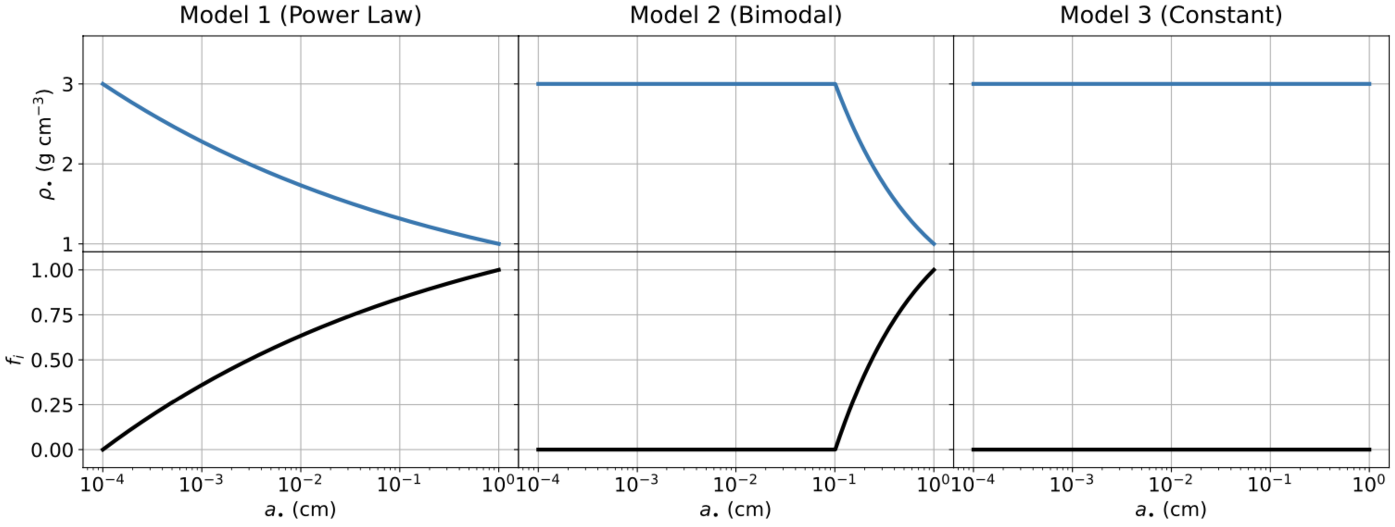


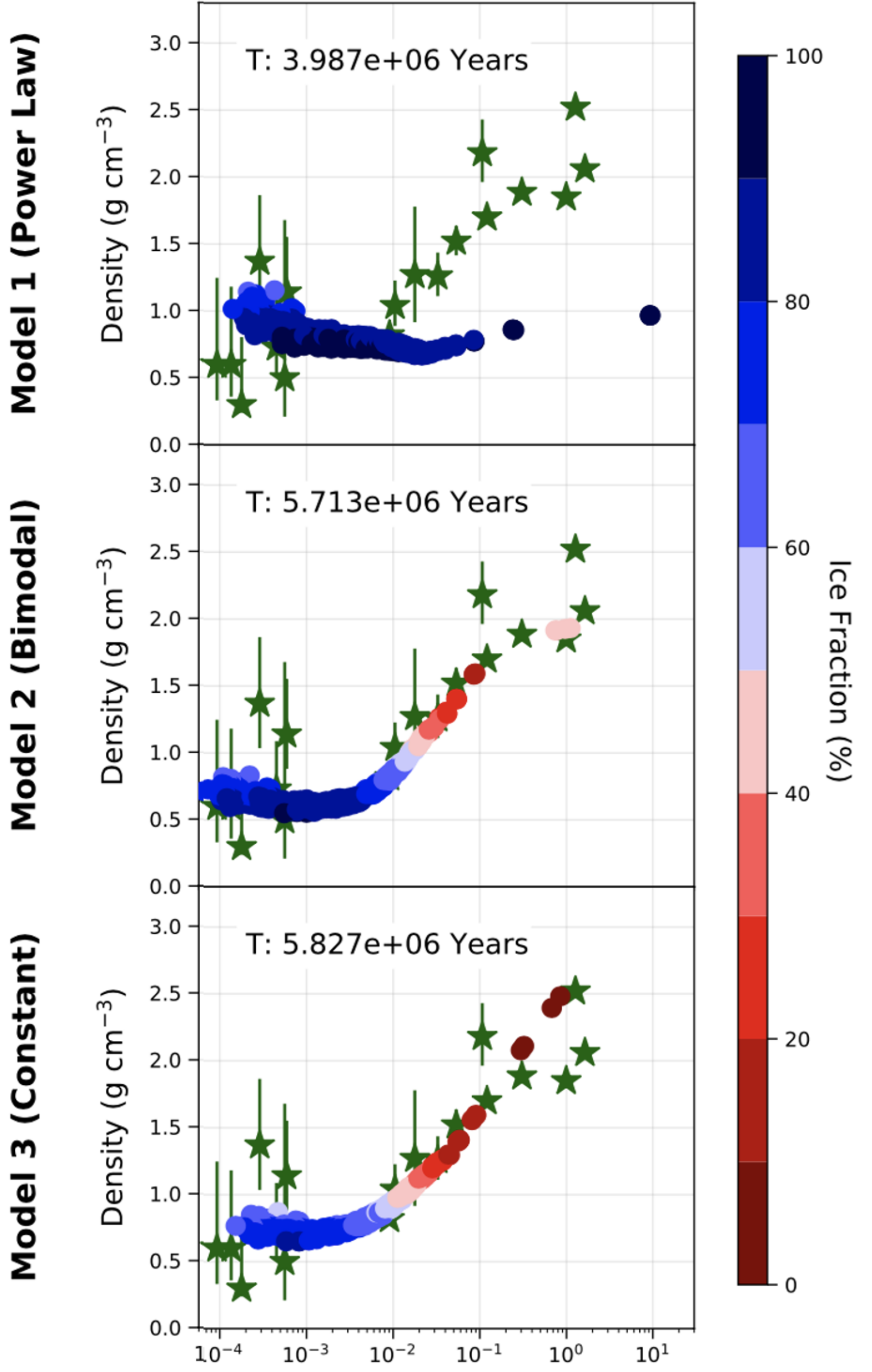
Canas+Lyra et al. 2024

Resulting Densities vs Mass relations

Pebble Internal Density

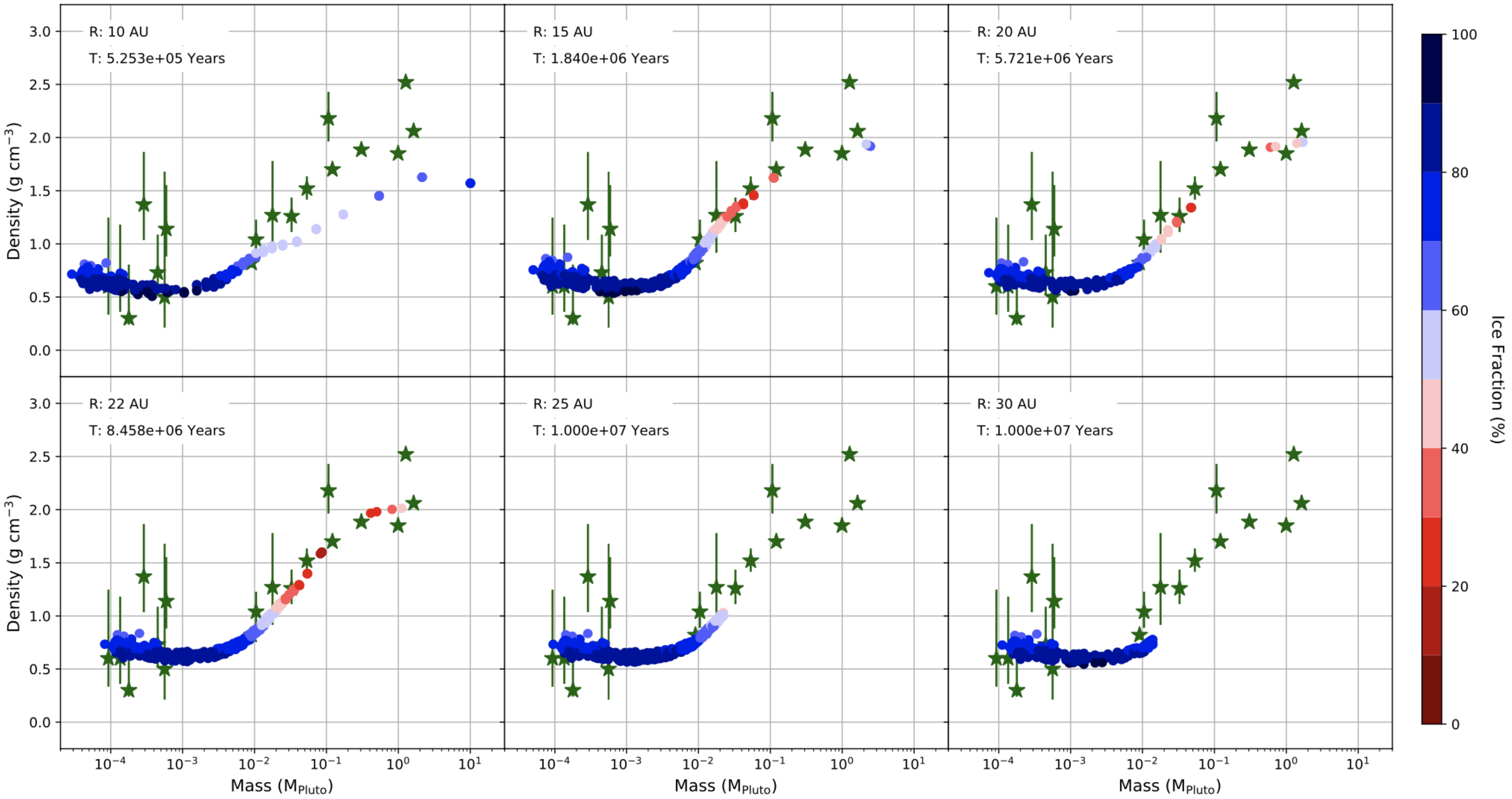
Ice Volume Fraction





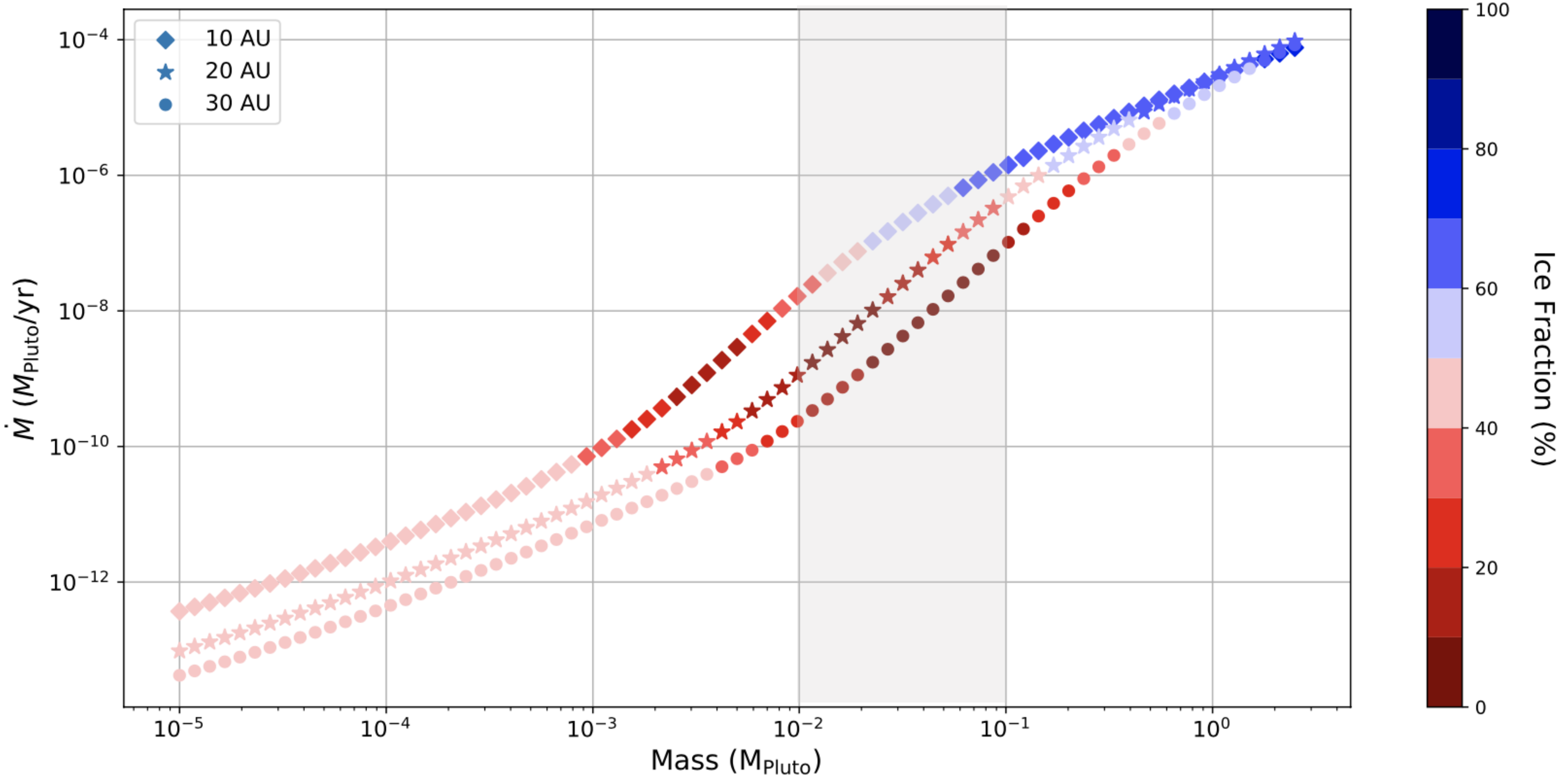
Canas+Lyra et al. 2024

Distance Range
15 - 25AU



Canas+Lyra et al. 2024

The window of silicate accretion



Canas+Lyra et al. 2024

Where are the missing Kuiper Belt binaries?

Where are the missing Kuiper Belt binaries?

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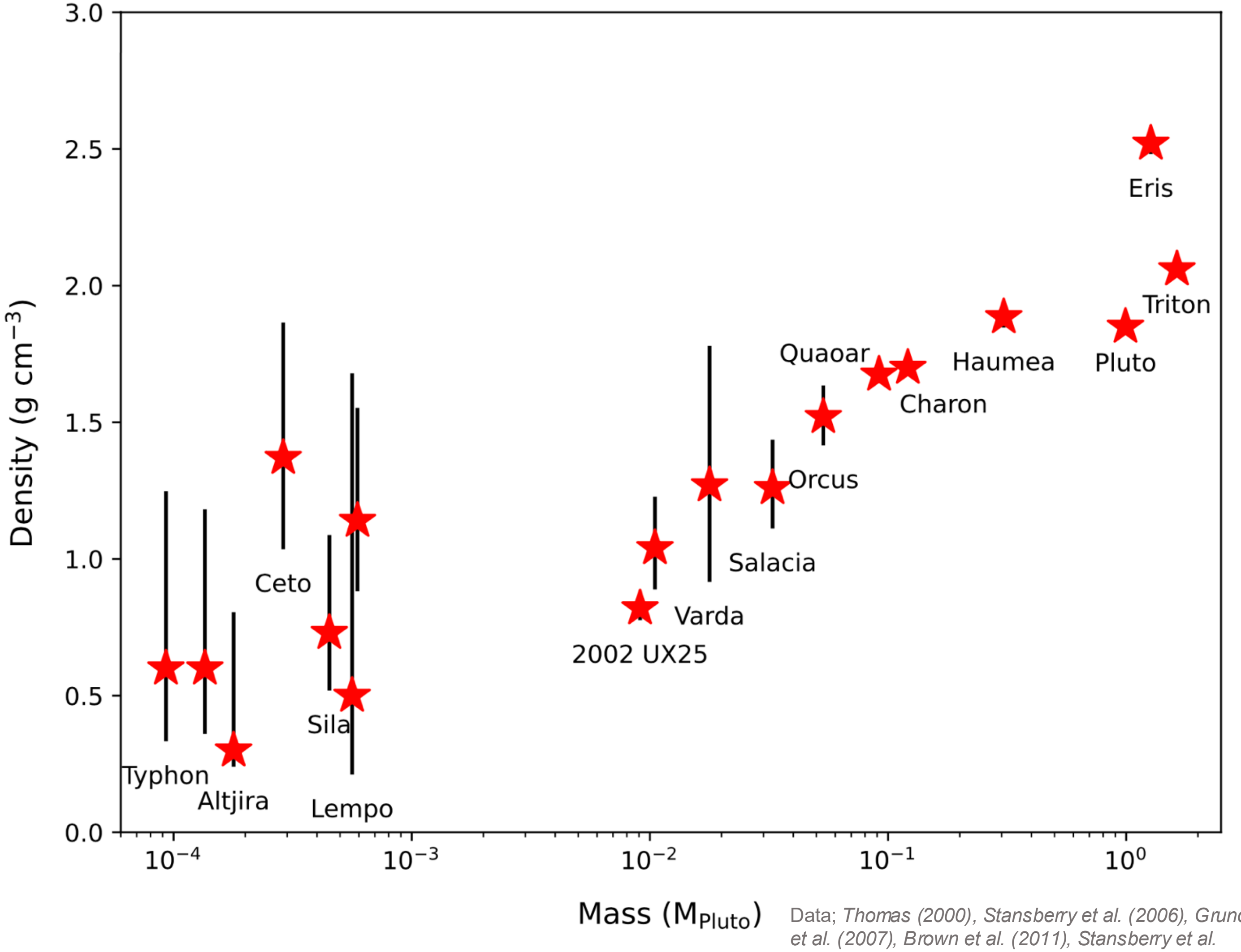
ARTICLE INFO

Keywords:
Kuiper belt
Planetesimals
Binaries
Origin, solar system
Planetary formation

ABSTRACT

In this letter, we call attention to a gap in binaries in the Kuiper belt in the mass range between 10^{-3} and 10^{-2} Pluto masses ($\approx 10^{19}$-10^{20} kg), with a corresponding dearth in binaries between 4th and 5th absolute magnitude H. The low-mass end of the gap is consistent with the truncation of the cold classical population at 400 km, as suggested by the OSSOS survey, and predicted by simulations of planetesimal formation by streaming instability. The distribution of magnitudes for all KBOs is continuous, which means that many objects exist in the gap, but the binaries in this range have either been disrupted, or the companions are too close to the primary and/or too dim to be detected with the current generation of observational instruments. At the high-mass side of the gap, the objects have small satellites at small separations, and we find a trend that as mass decreases, the ratio of primary radius to secondary semimajor increases. If this trend continues into the gap, non-Keplerian effects should make mass determination more challenging.



Cañas+Lyra et al. (2024)

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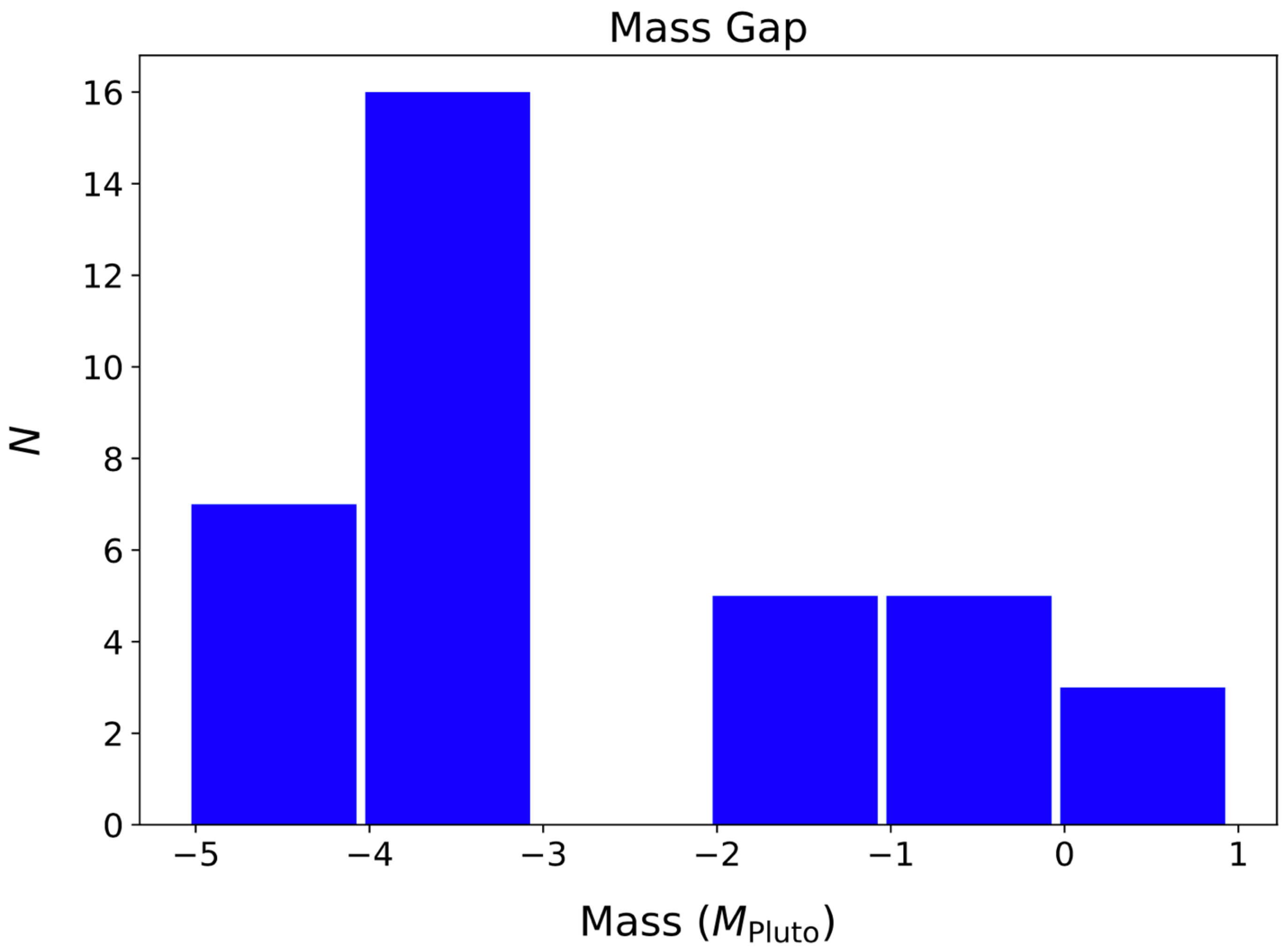
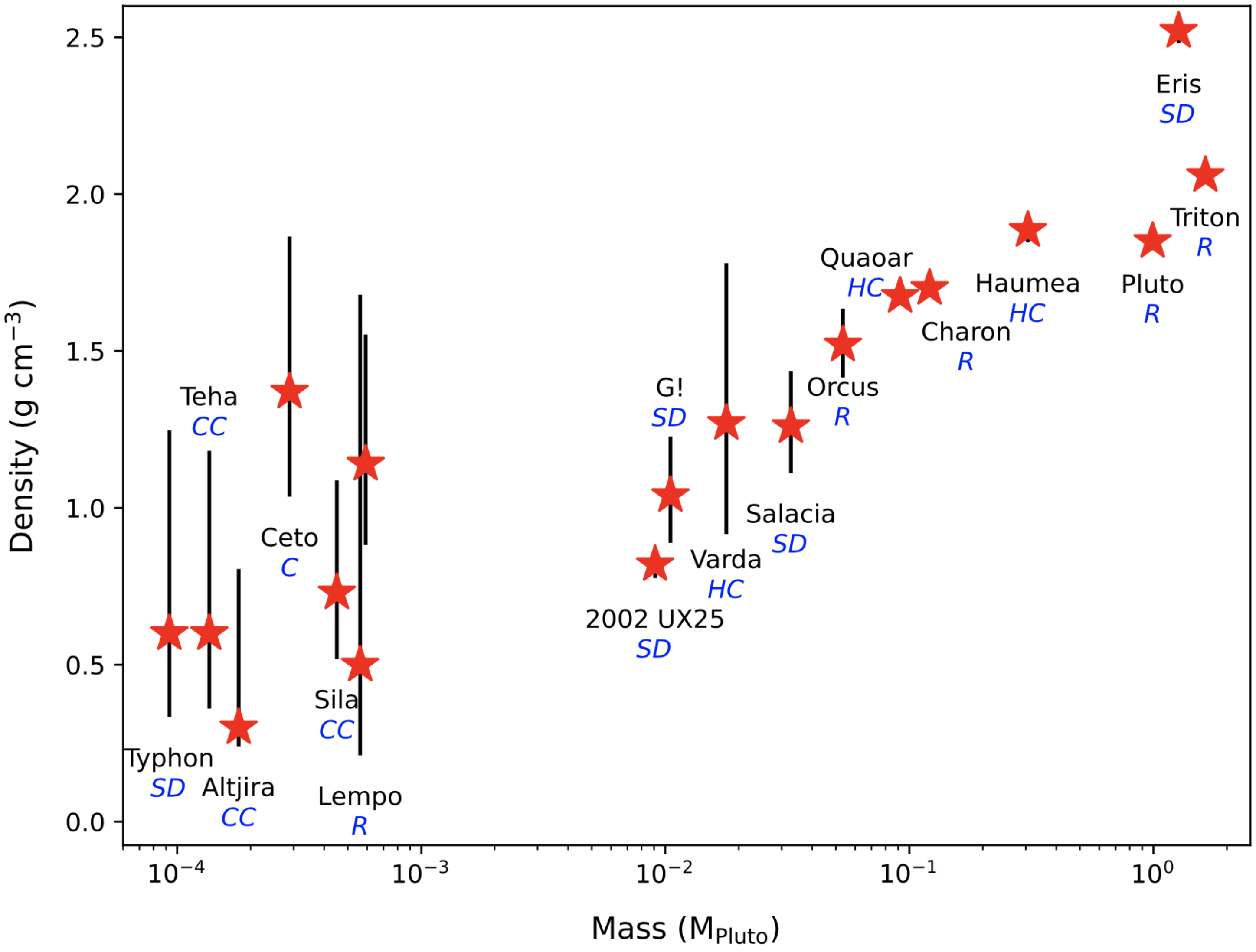
Where are the missing Kuiper Belt binaries?



Lyra (2025, submitted)

Two Populations



CC – Cold Classicals

C – Centaurs

SD – Scattered Disk

R – Resonant

HC – Hot Classicals

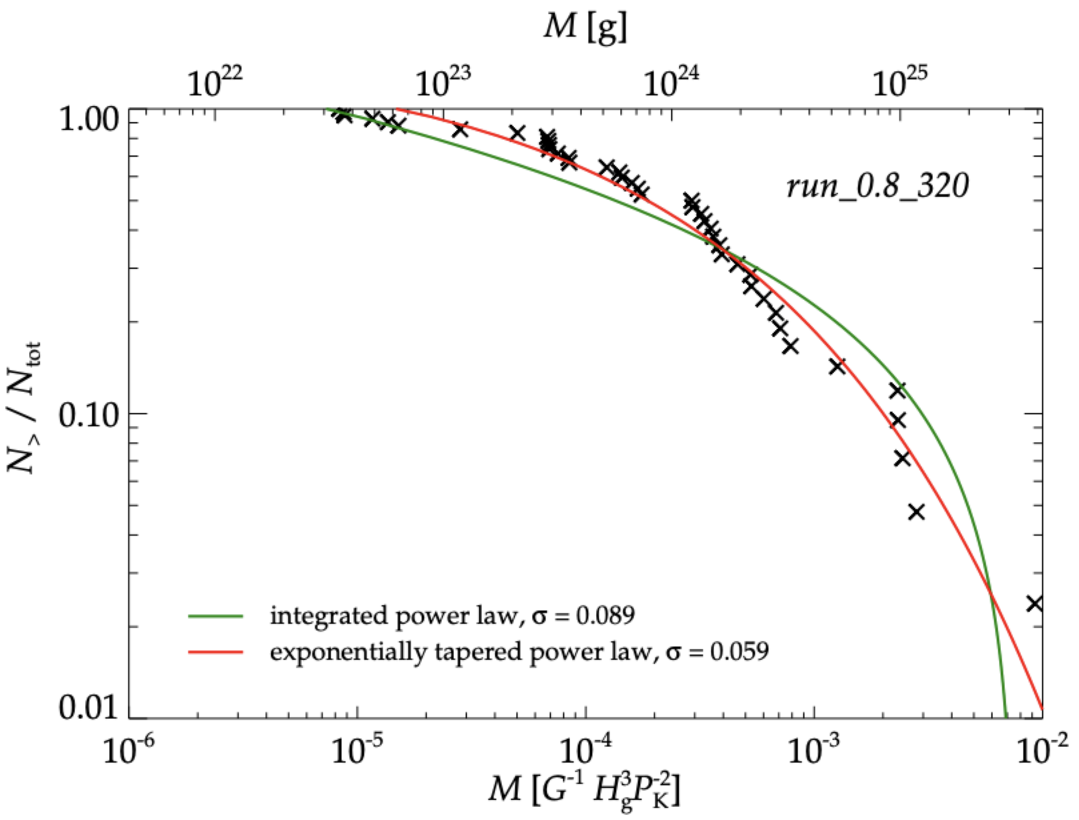
Lyra (2025, submitted)

A&A 597, A69 (2017)
DOI: 10.1051/0004-6361/201629561

Astronomy & Astrophysics

Initial mass function of planetesimals formed by the streaming instability

Urs Schäfer[1,2], Chao-Chin Yang[2], and Anders Johansen[2]



Schafer et al. (2017)

The Astrophysical Journal Letters, 920:L28 (7pp), 2021 October 20
https://doi.org/10.3847/2041-8213/ac2c72

CrossMark

OSSOS Finds an Exponential Cutoff in the Size Distribution of the Cold Classical Kuiper Belt

J. J. Kavelaars[1,2,3], Jean-Marc Petit[4], Brett Gladman[3], Michele T. Bannister[5], Mike Alexandersen[6], Ying-Tung Chen[7], Stephen D. J. Gwyn[1], and Kathryn Volk[8]

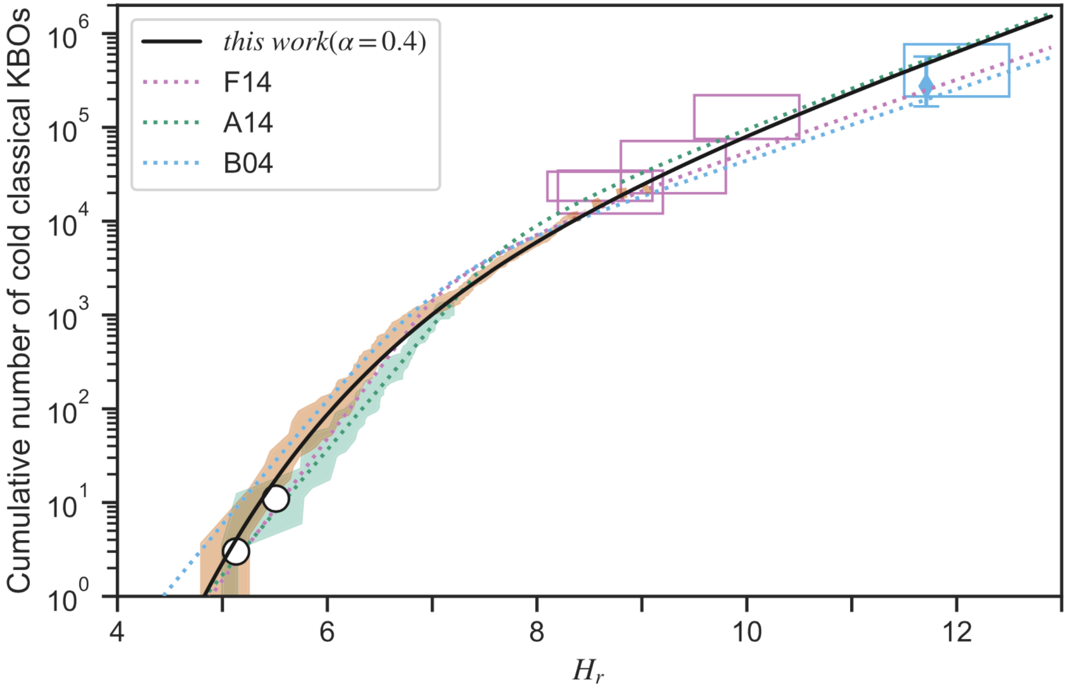
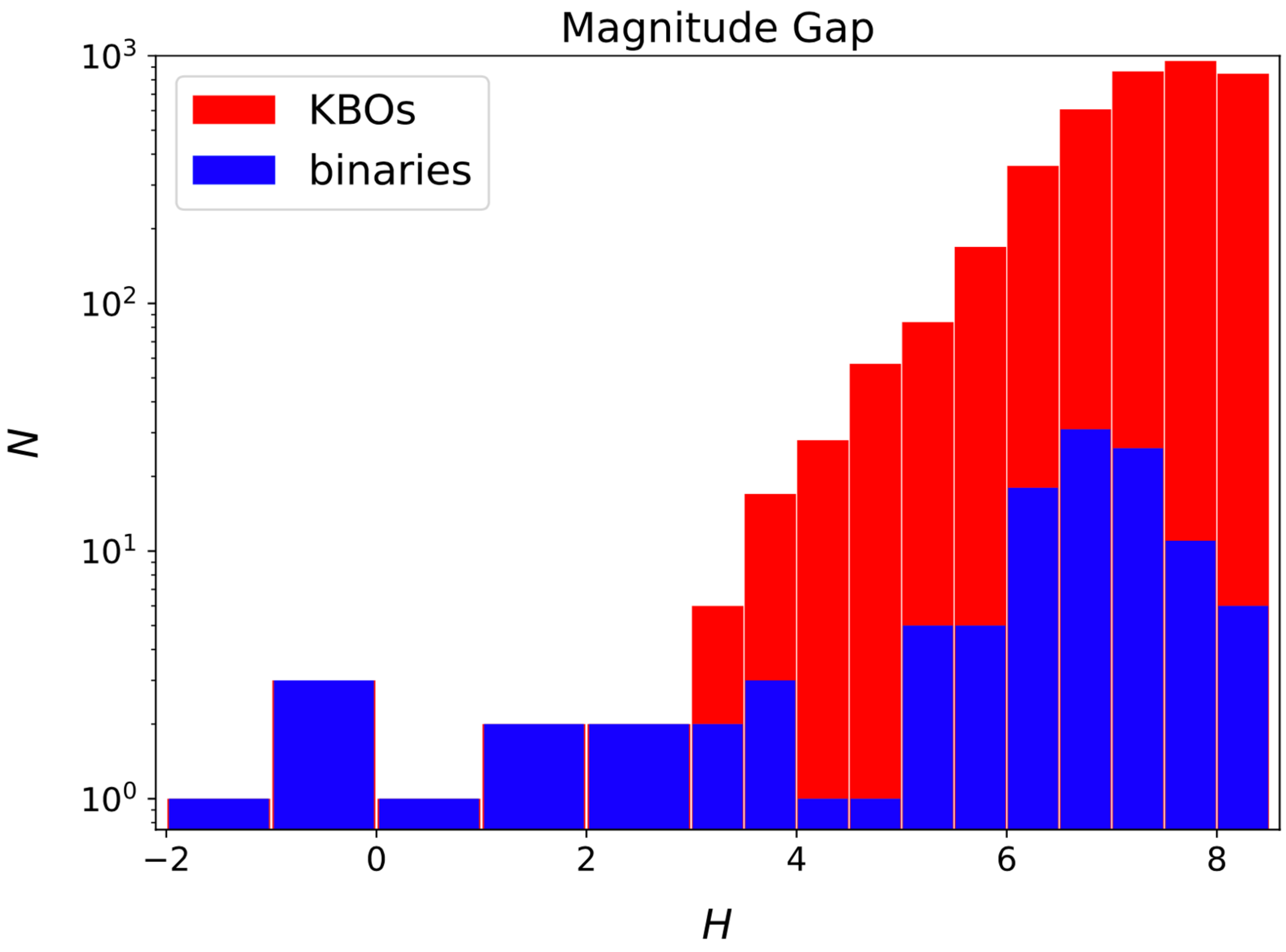


Figure 2. As in Figure 1, the orange region represents the debiased OSSOS++ sample. The green shaded area represents the debiased detections from the Deep Ecliptic Survey (Adams et al. 2014), with the green dotted line indicating the best-fit double exponential. Also shown are the best fits from Bernstein et al. (2004; cyan dotted line) and Fraser et al. (2014; magenta dotted line). The curves have been scaled to reflect the difference in survey filters and for differences in selection function for cold classical KBOs. In particular, we use $(r - R) = 0.25$ (Jordi et al. 2006) for $(V - R) = 0.6$ cold classical KBOs, and we scale the apparent magnitude distribution given in B04 using a fixed distance of 42 au to transform from r to H_r. The A14 total population is slightly low compared to the OSSOS++ sample; this may be due to tracking losses reported in A14. The F14 fit has been scaled to match the OSSOS++ sample at $H_r = 8$, as we were uncertain of the scaling from the surface density reported in F14 and the absolute total numbers reported here.

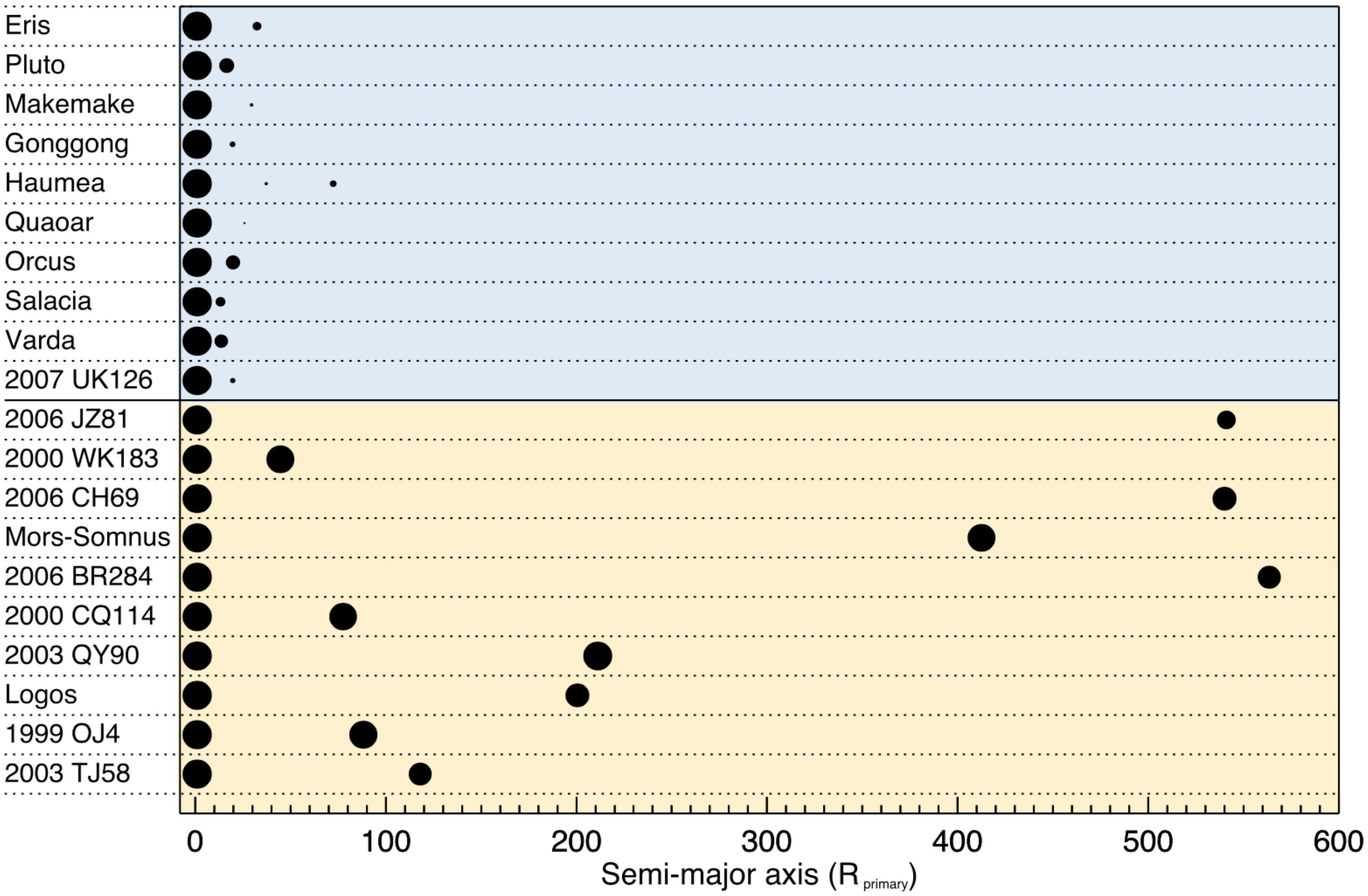
Kavelaars et al (2021)

Observational bias?



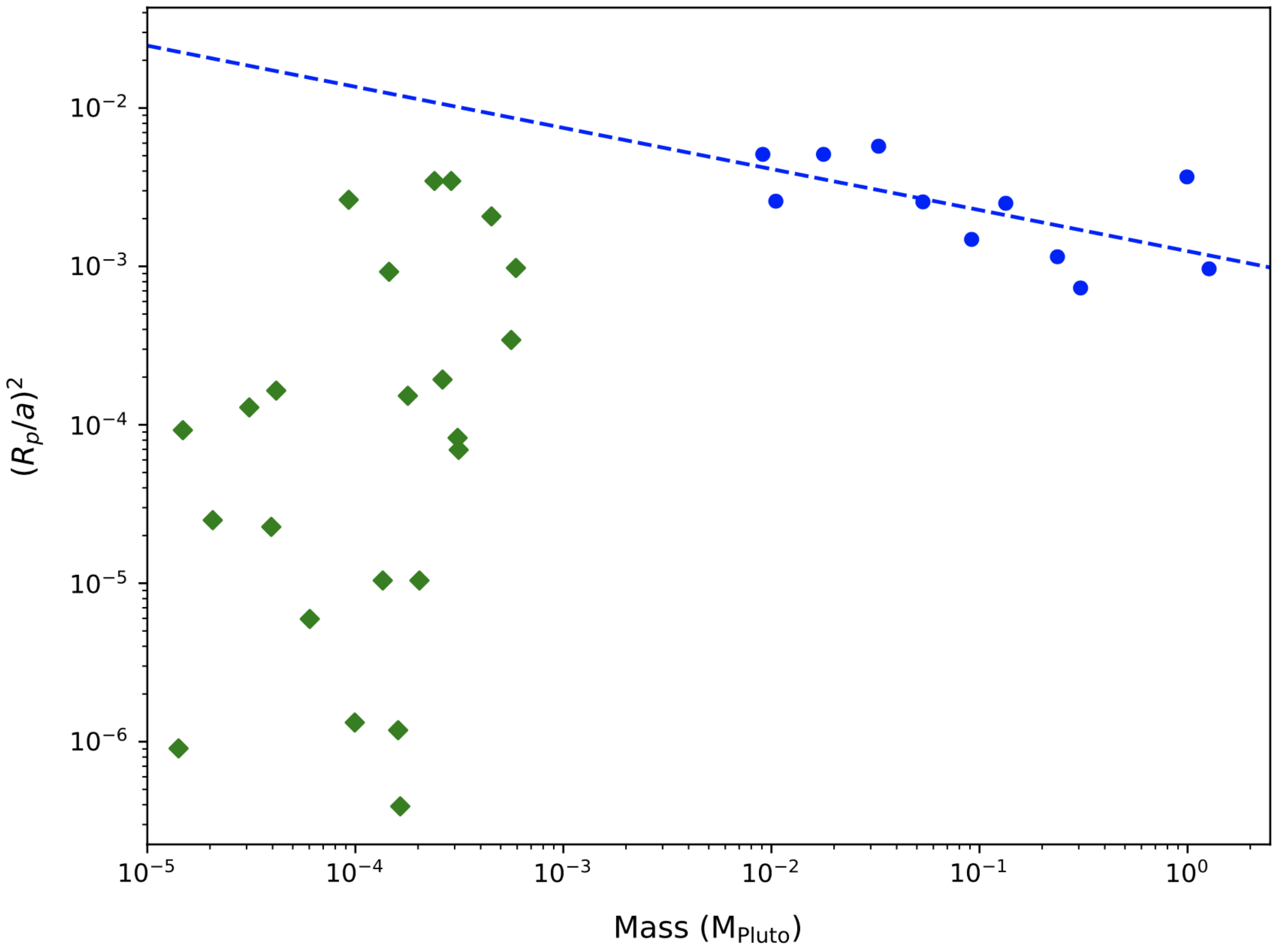
Lyra (2025, submitted)

Different system architecture

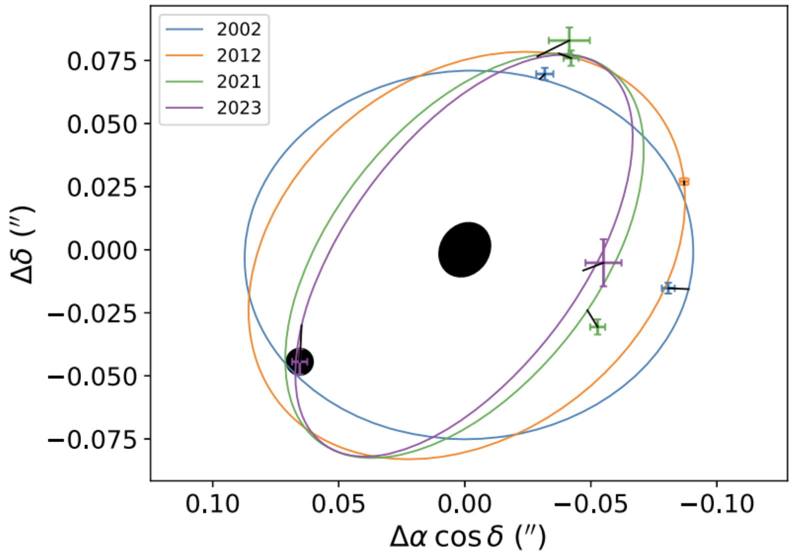


Bernstein et al (2023)

Non-Keplerian orbits?



Lyra (2025, submitted)



Rommel et al. (2025)

Conclusions

- KBO density problem:
  - Two different pebble populations, maintained by ice desorption off small grains
  - Streaming instability: icy-rich small objects; nearly uniform composition
  - 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
- Missing Binaries
  - Cold classicals capped at 10^{-3} Pluto masses
  - Gap between 10^{-3} and 10^{-2} Pluto masses for non-cold classicals
    - Formation imprint?
    - Dynamical loss?
    - Observation bias?