

What are the Kuiper Belt objects telling us about planet formation?

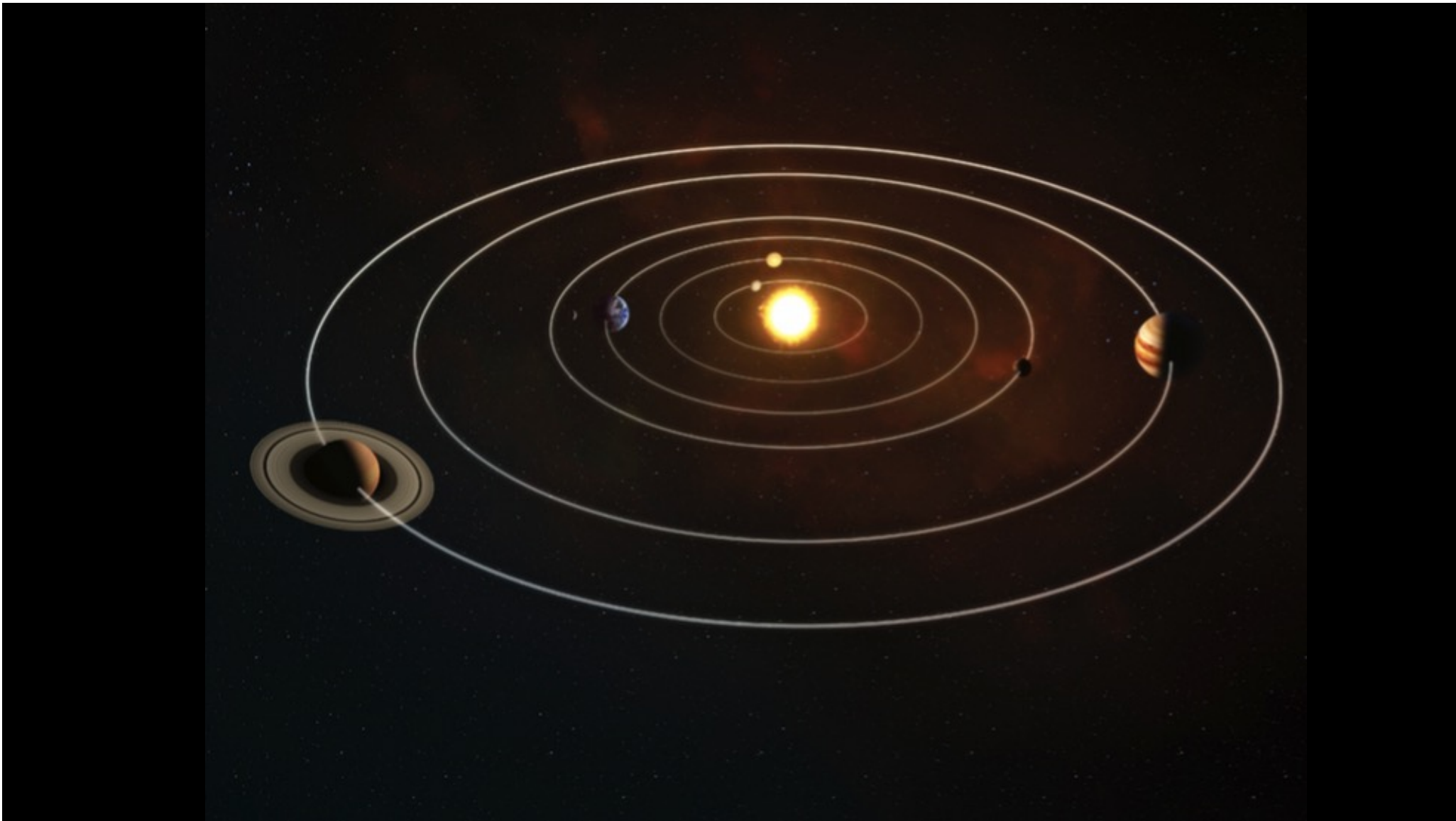
**NM
STATE**



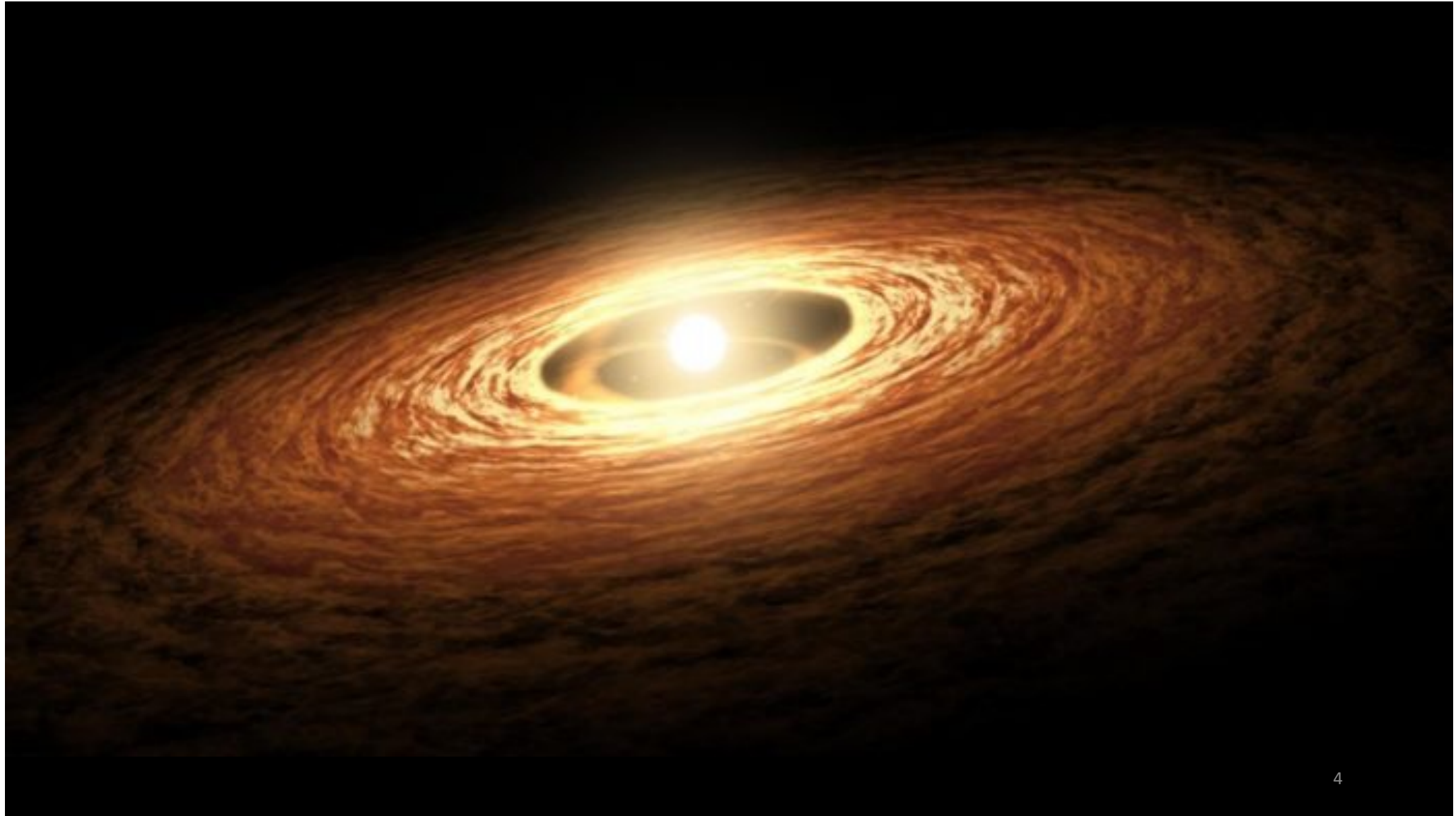
Wladimir Lyra
New Mexico State University
Las Cruces NM, USA



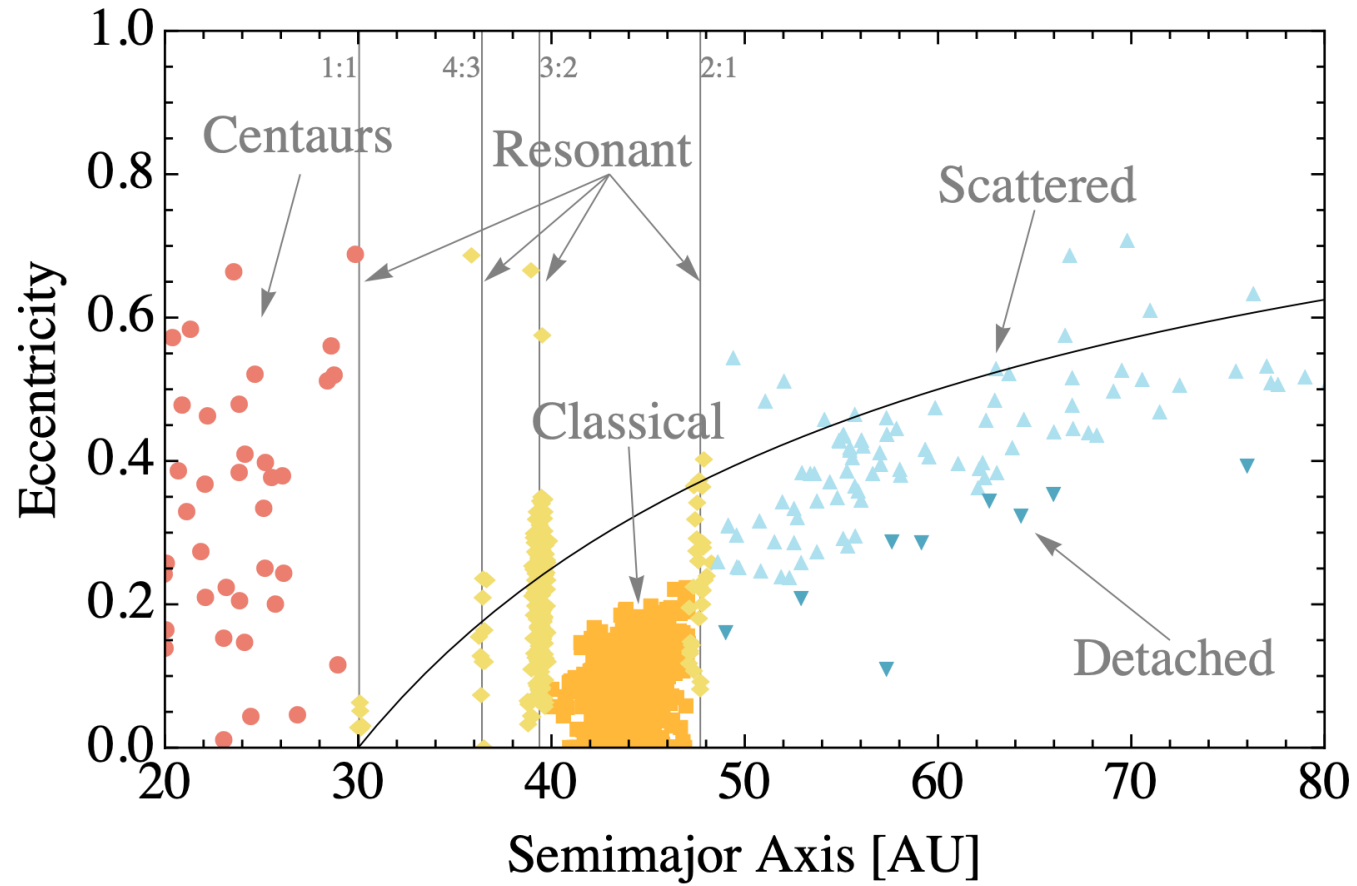
TU Delft, March 31st, 2026







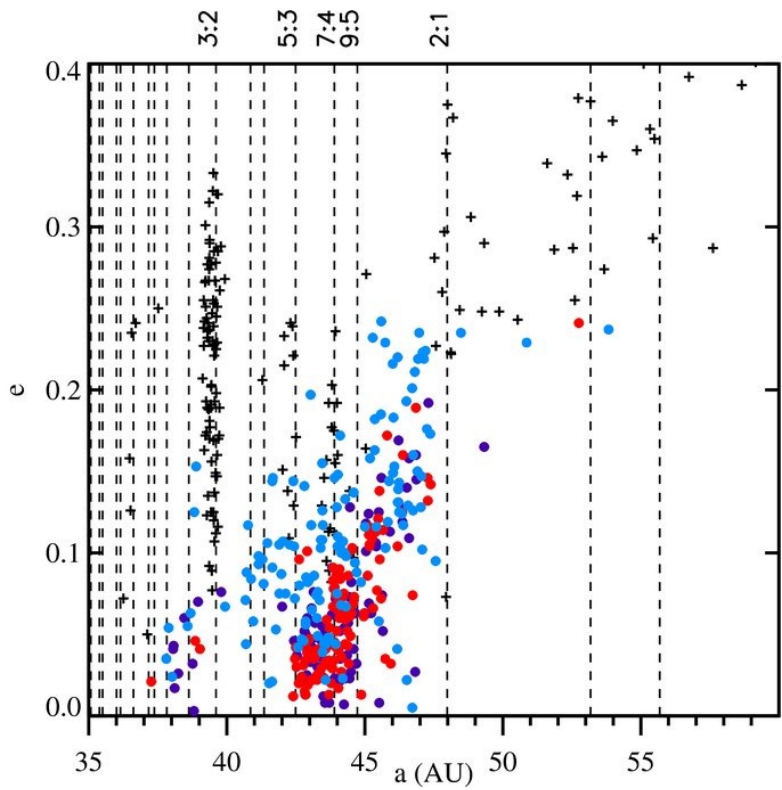
Structure of the Kuiper Belt



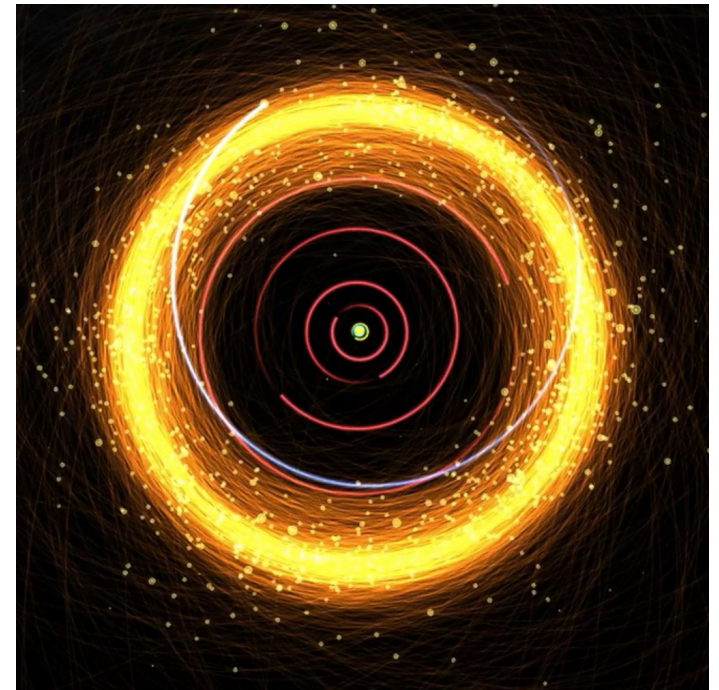
Gladman+ '08, Lacerda '09, Batygin+ '10, Dawson & Murray-Clay '12

Cold Classicals

Presumably pristine planetesimals

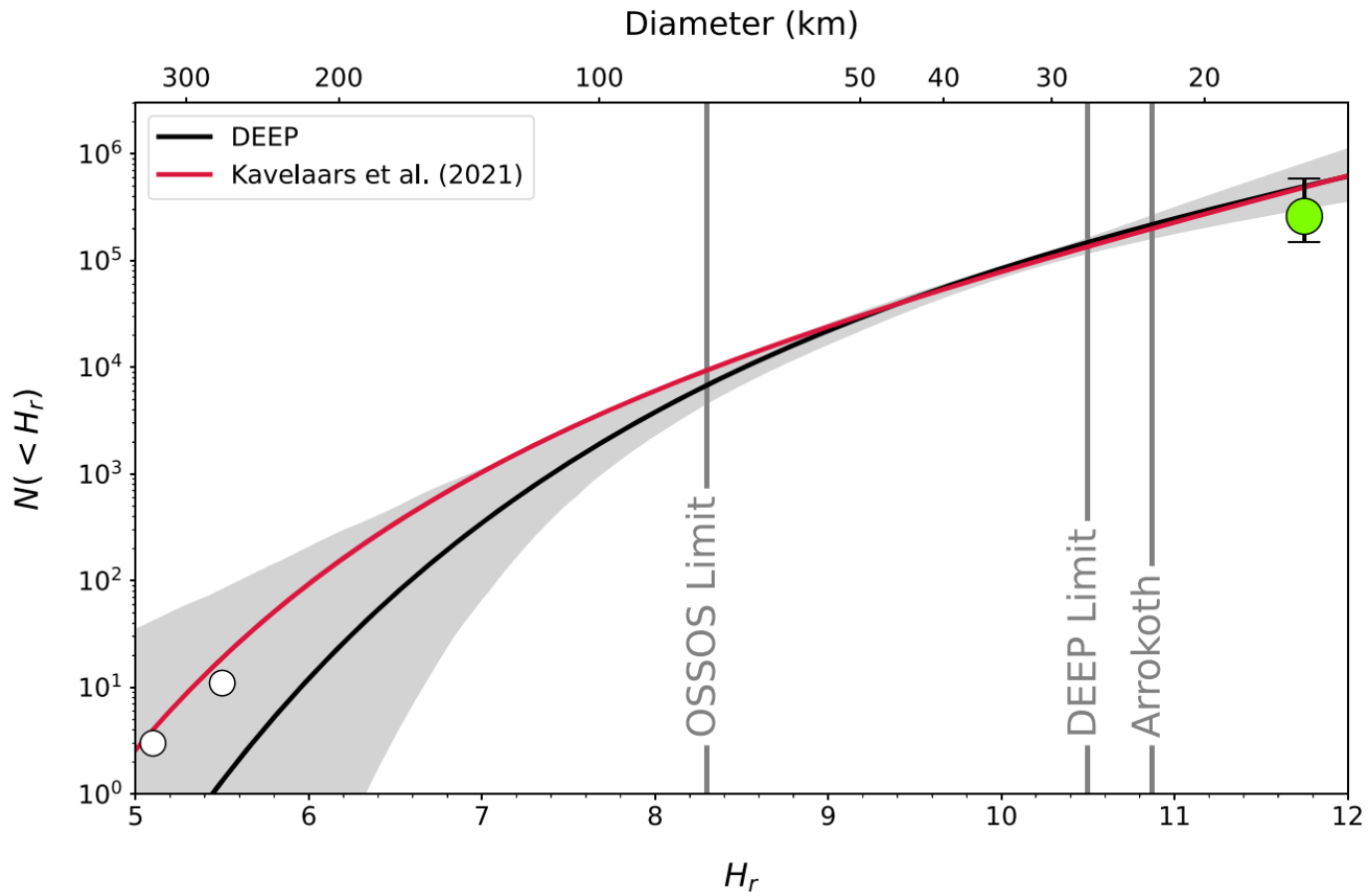


+ Resonant and Scattered
Cold Classical $i < 2^\circ$
"Ambiguous" $2^\circ < i < 6^\circ$
Hot Classicals $i > 6^\circ$



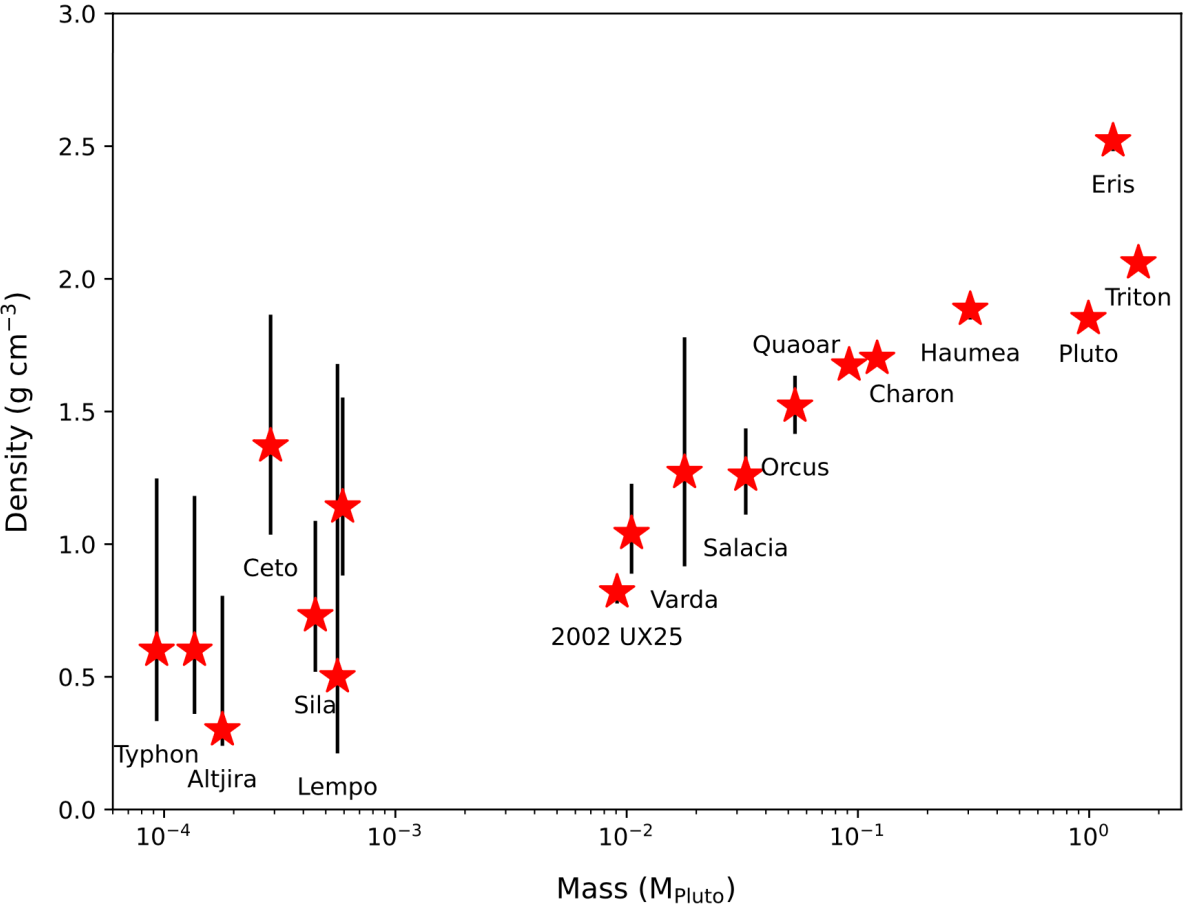


Cold Classicals: Mass Function



Kavelaars et al (2021); Napier et al. (2024)

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

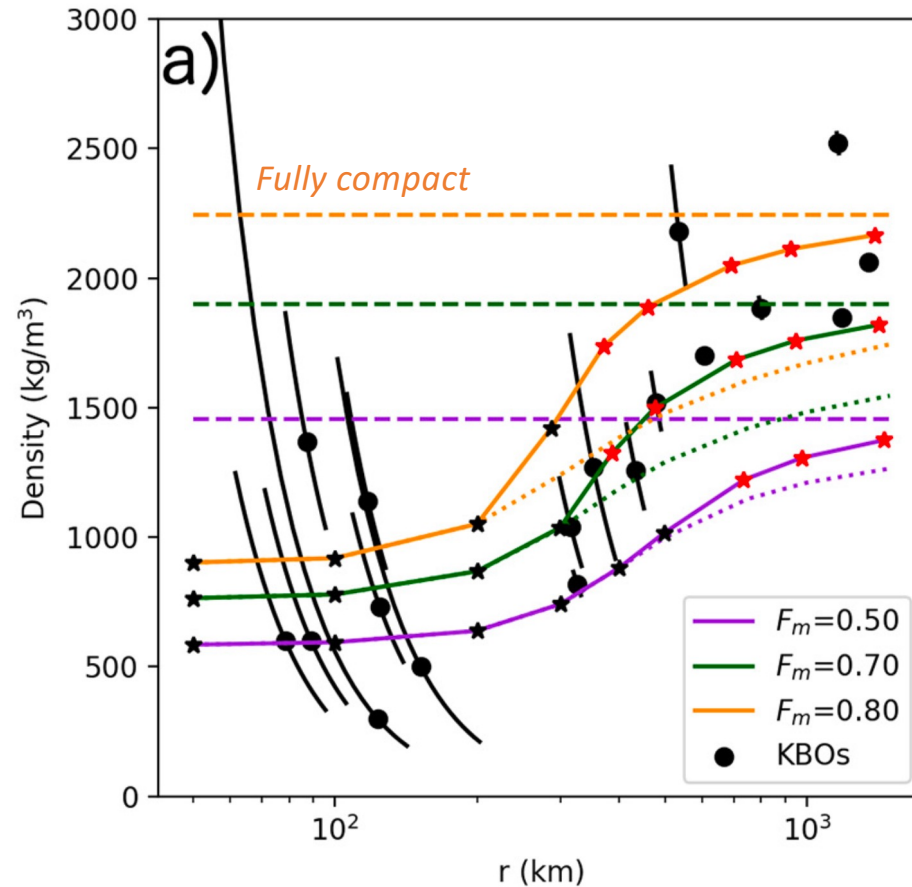
Problem

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



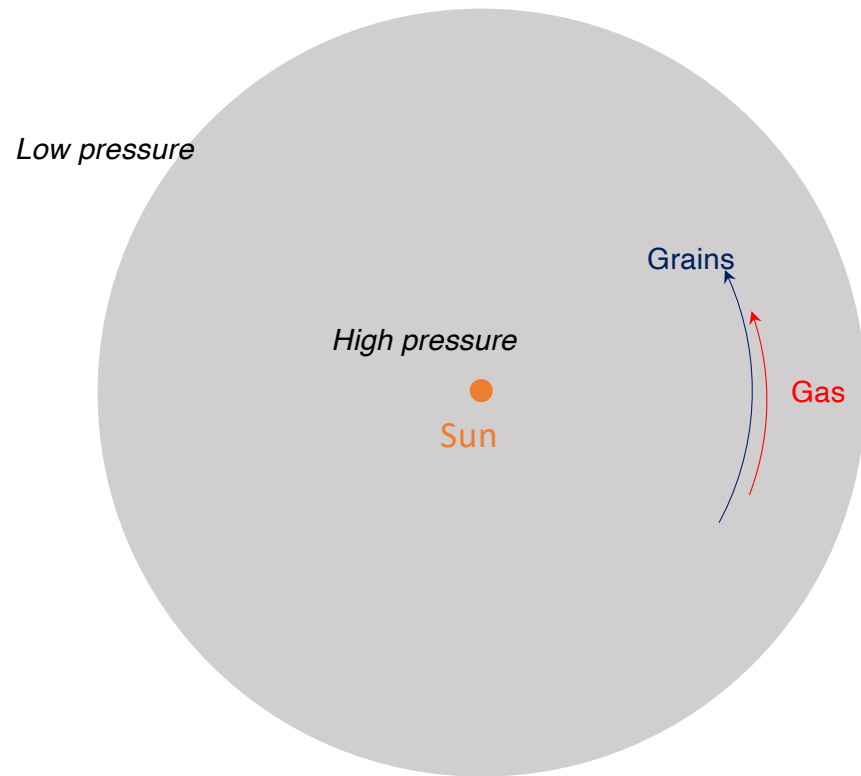
Assumptions

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



Bierson & Nimmo (2019)

Headwind and Grain Drift



The **gas** has some pressure support (sub-Keplerian).

The **grains** have none (Keplerian).

Dust coagulation and drift

Dust particle
coagulation
and radial drift

F. Brauer, C.P. Dullemond
Th. Henning

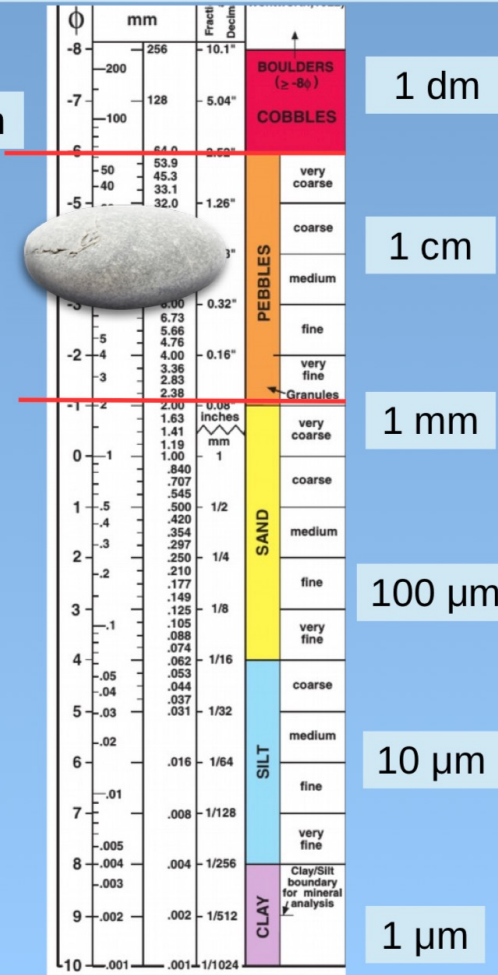
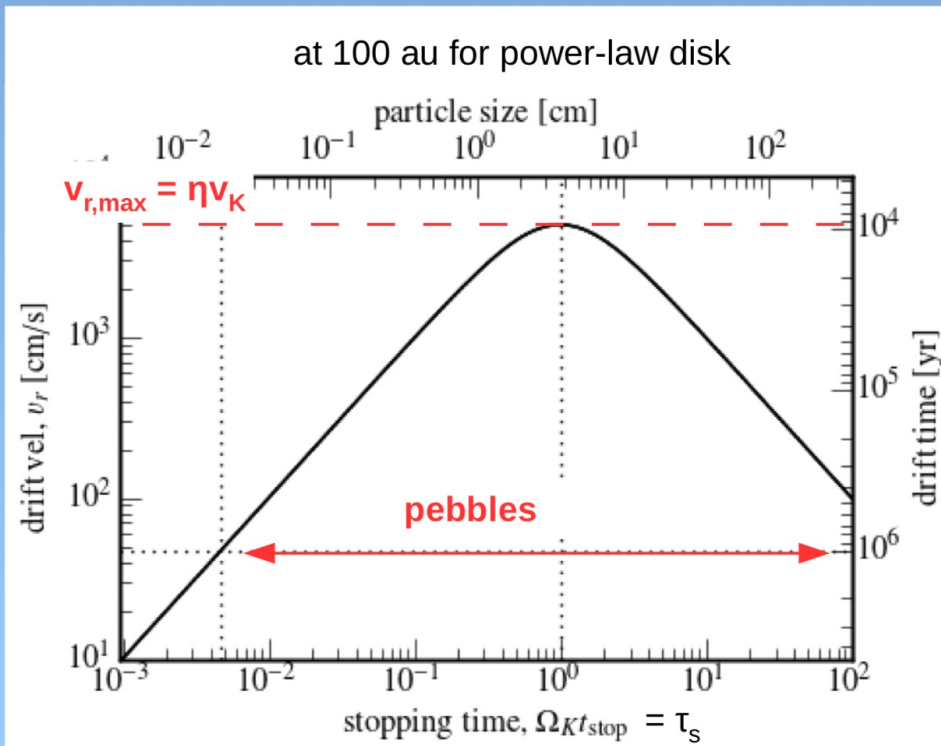
Brauer et al. (2008)

Pebble definition

Geologist: particles $2 \text{ mm} < d < 6.4 \text{ cm}$

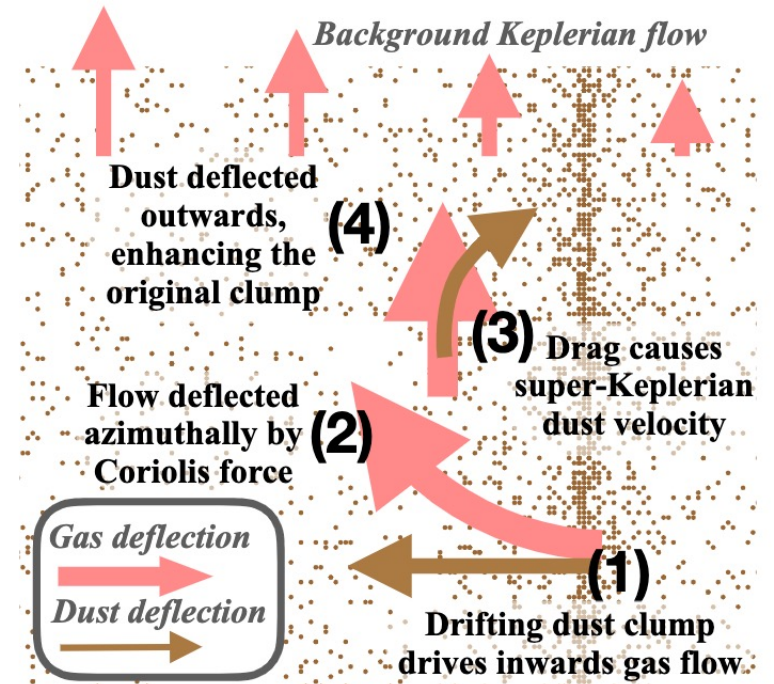
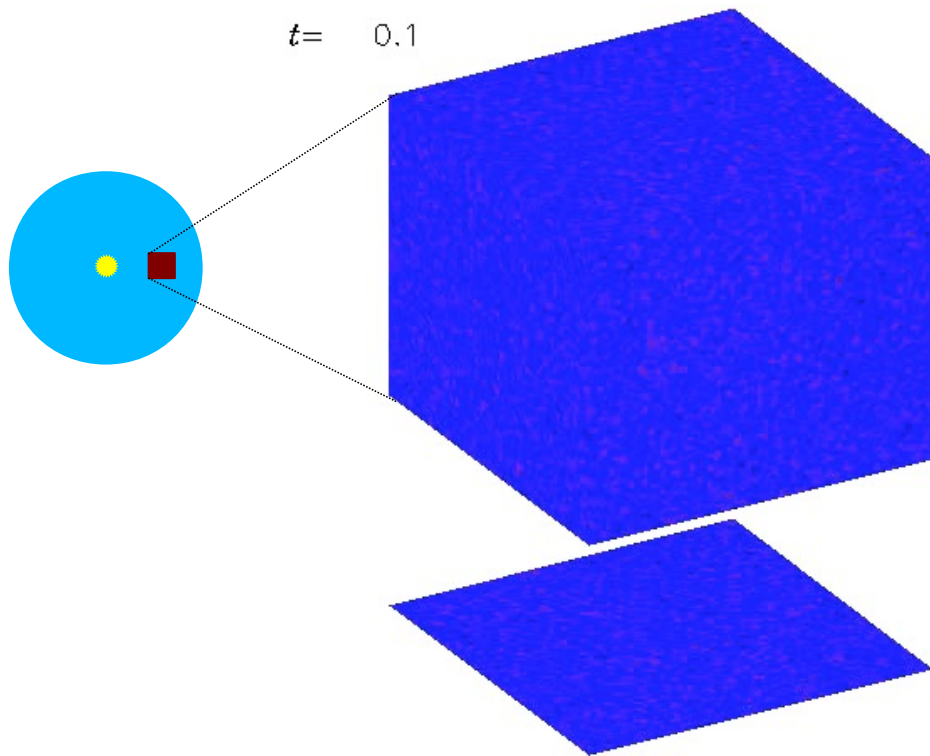
Astrophysical: particles that drift

6.4 cm



Streaming Instability

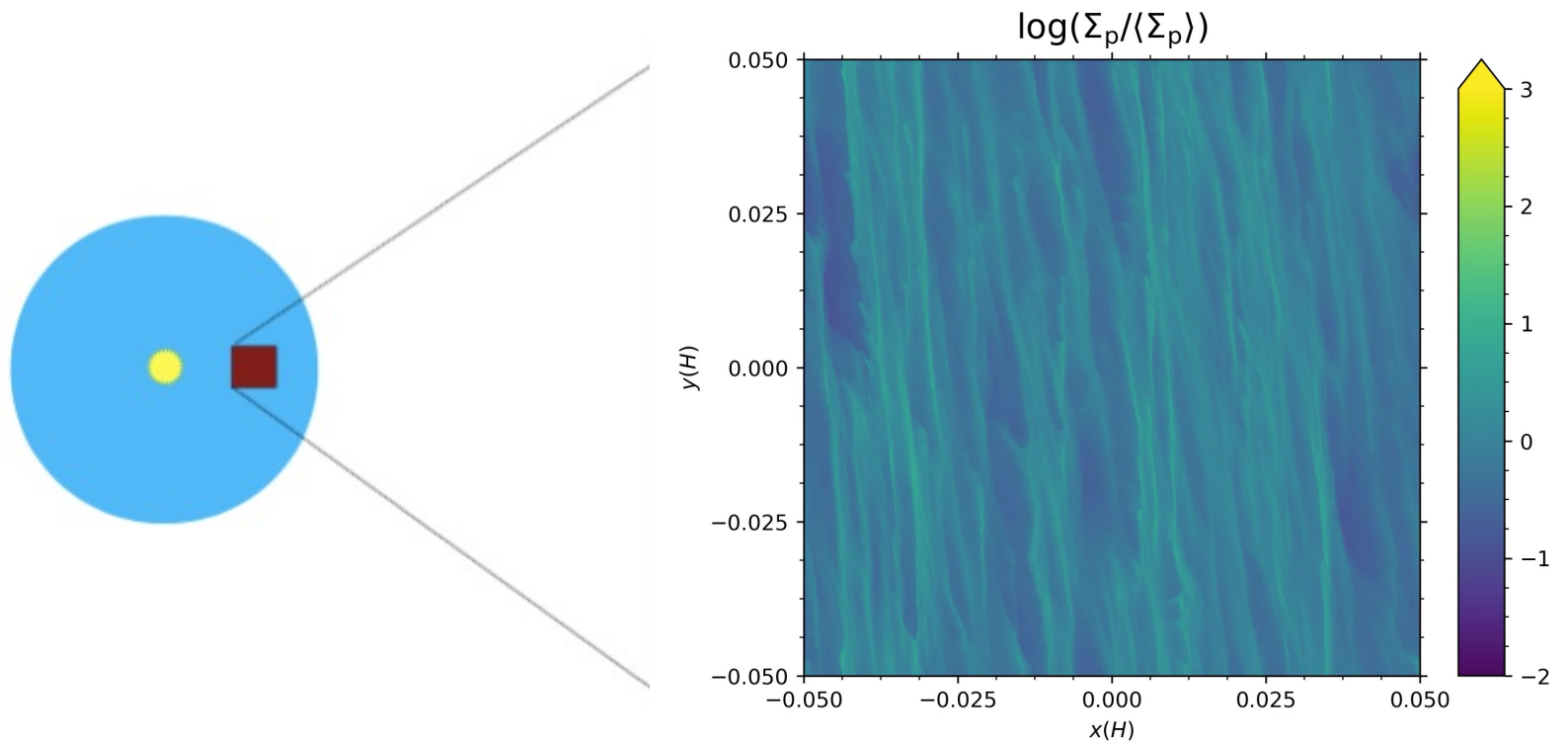
The pebble drift is hydrodynamically unstable



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, Nesvornyy+ '19

Gravitational collapse into planetesimals



Animation by: Rixin Li

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, Nesvornyy+ '19

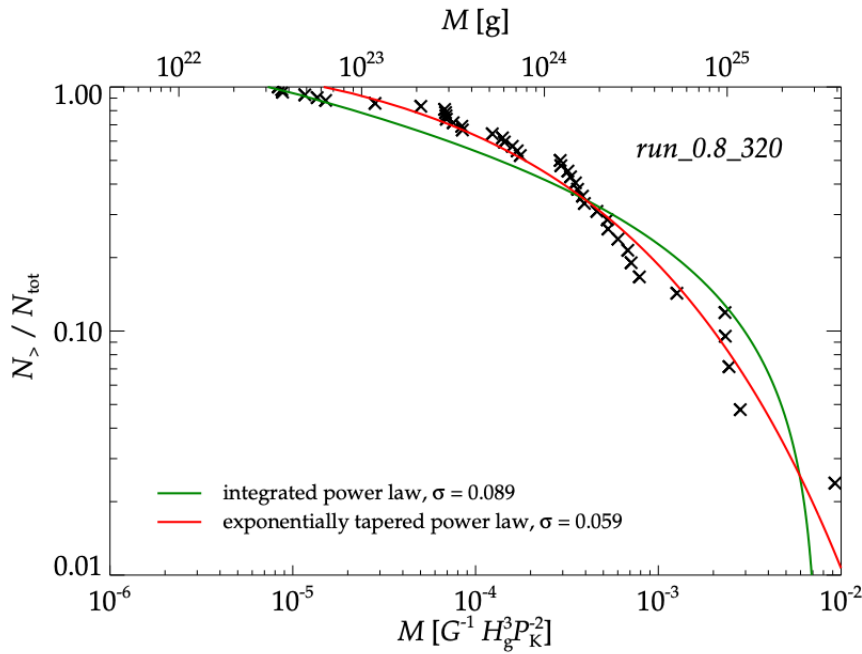
Streaming Instability consistent with Cold Classicals

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

Astronomy
 Astrophysics

Initial mass function of planetesimals formed by the streaming instability

Urs Schäfer^{1,2}, Chao-Chin Yang², and Anders Johansen²



Schafer et al. (2017)

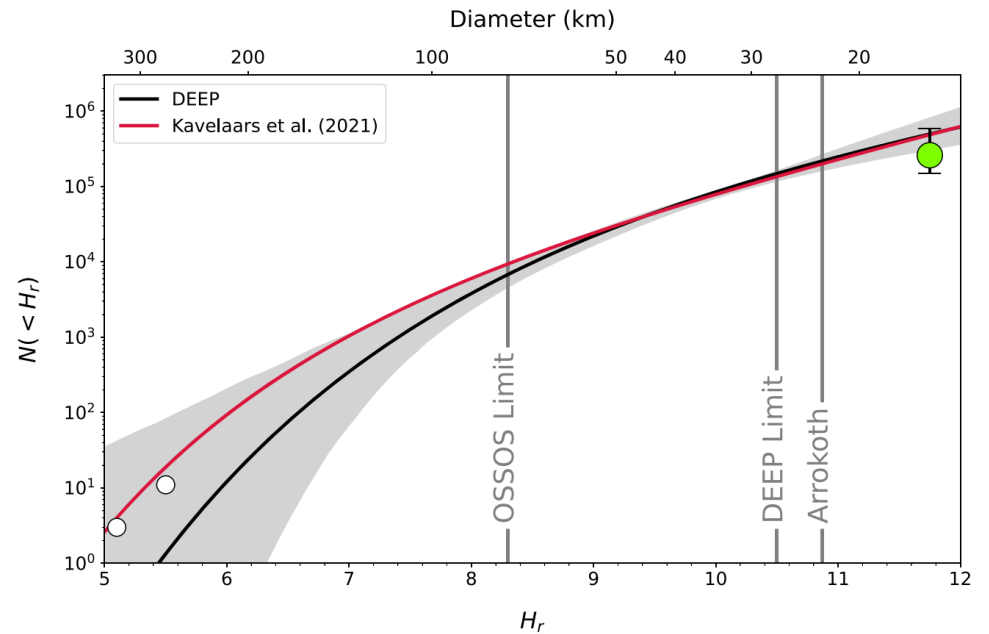
THE PLANETARY SCIENCE JOURNAL, 5:50 (18pp), 2024 February
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 OPEN ACCESS

<https://doi.org/10.3847/PJ/1528>



The DECam Ecliptic Exploration Project (DEEP). V. The Absolute Magnitude Distribution of the Cold Classical Kuiper Belt

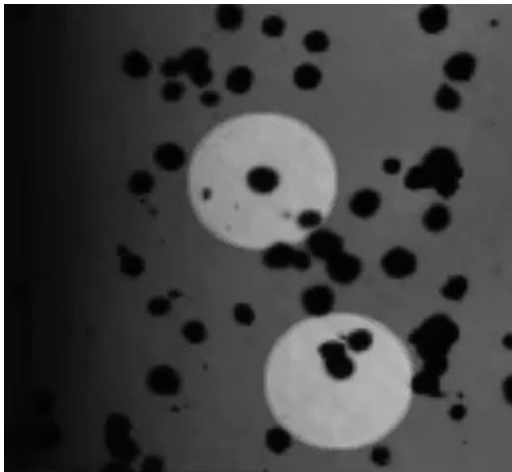
Kevin J. Napier¹, Hsing Wen Lin (林省文)¹, David W. Gerdes^{1,2}, Fred C. Adams^{1,2}, Anna M. Simpson^{1,2}, Matthew W. Porter¹, Katherine G. Weber¹, Larissa Markwardt², Gabriel Goman^{1,2}, Hayden Smotherman¹, Pedro H. Bernardinelli¹, Mario Juric¹, Andrew J. Connolly¹, J. Bryce Kalmbach¹, Stephen K. N. Portillo¹, David E. Trilling¹, Ryder Strauss¹, William J. Oldroyd¹, Chadwick A. Trujillo¹, Colin Orion Chandler^{4,5,6}, Matthew J. Holman⁷, Hilke E. Schlichting⁸, and Andrew McNeill^{9,10}



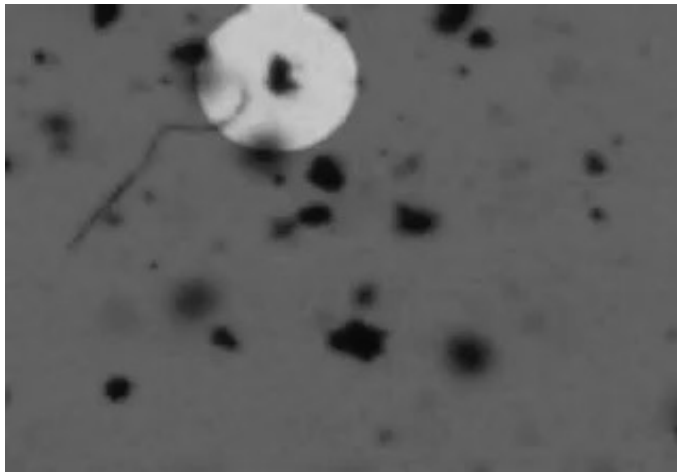
Kavelaars et al (2021); Napier et al. (2024)

Grain collision outcomes

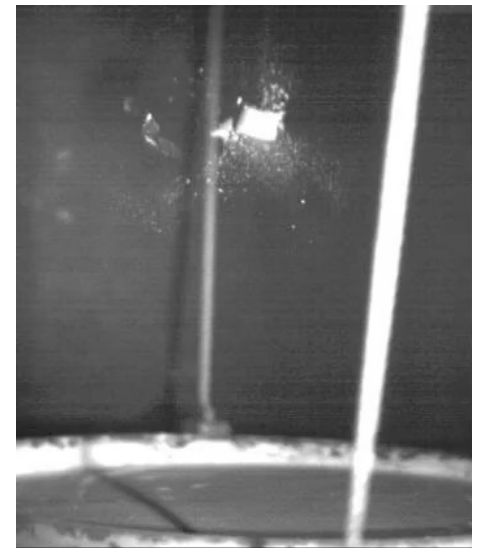
Bouncing



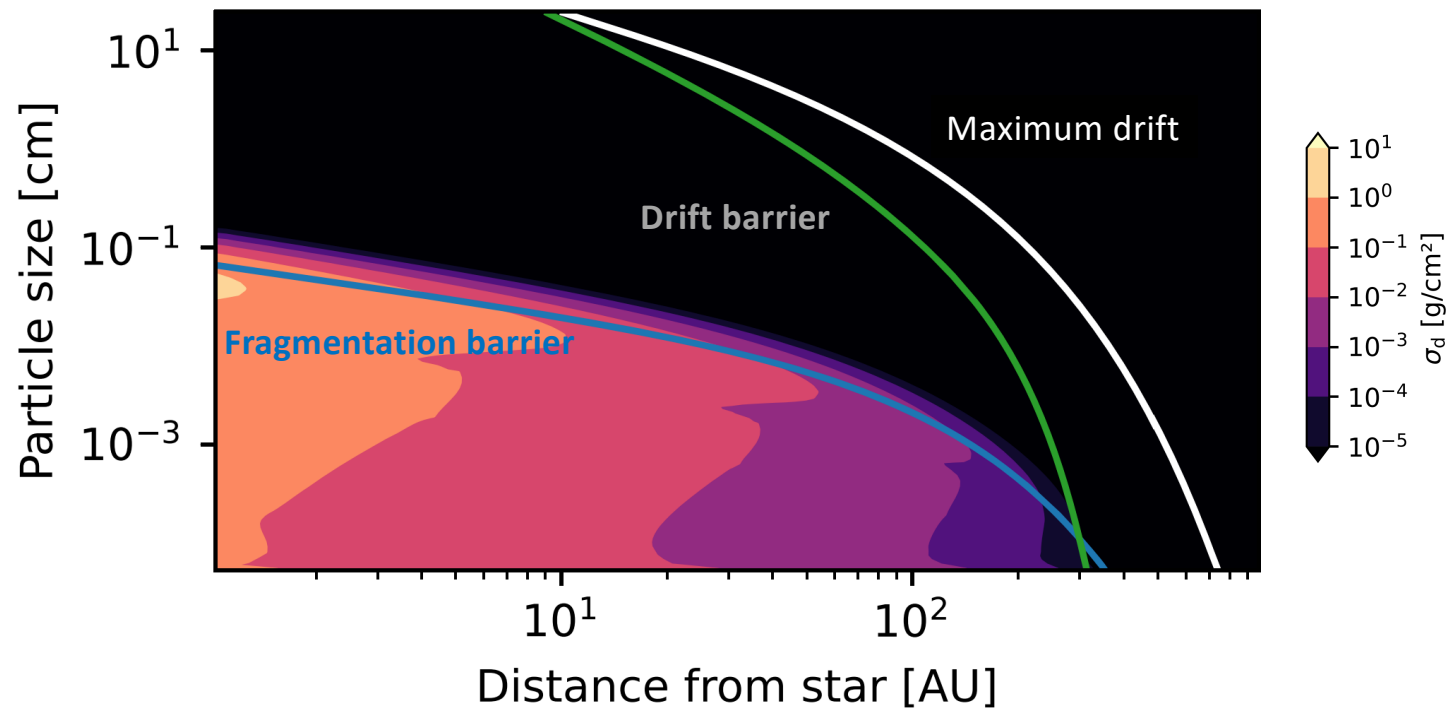
Sticking



Fragmentation



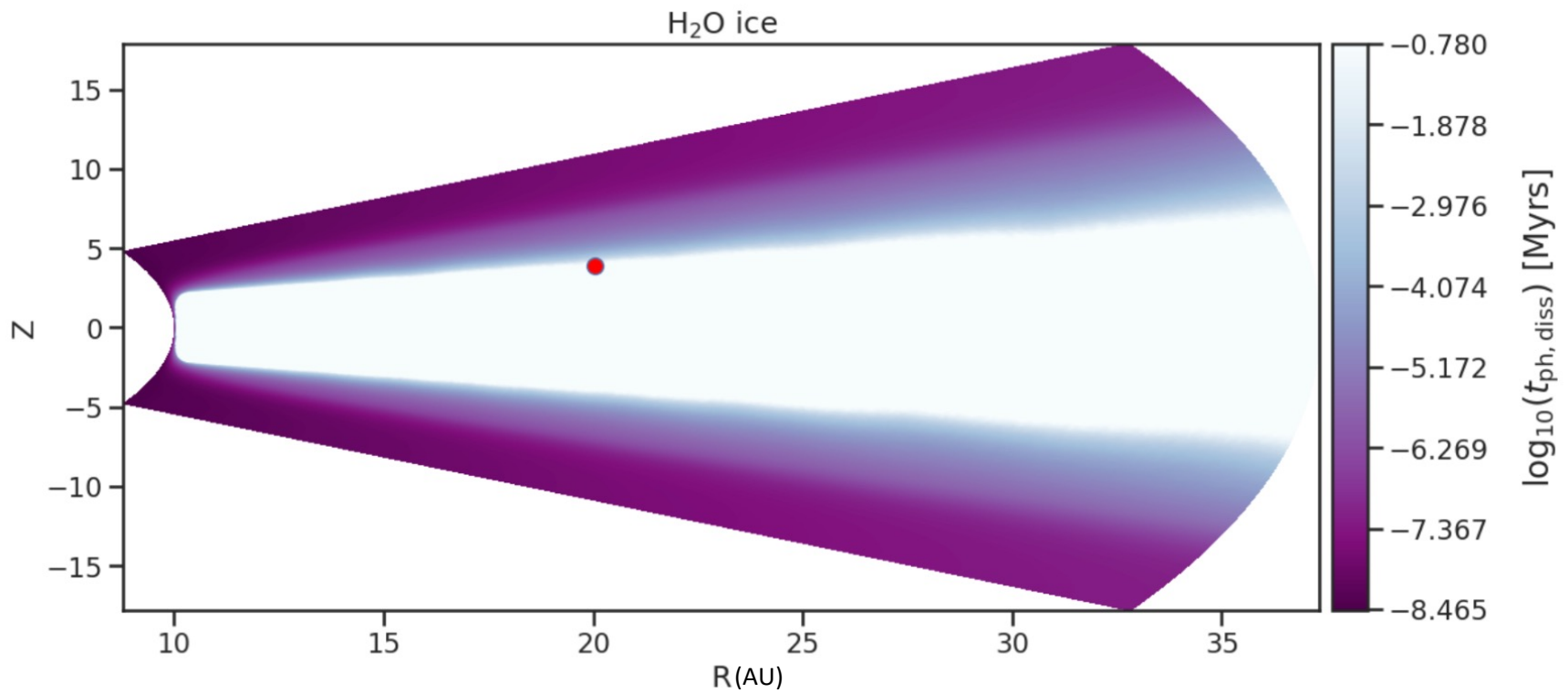
Fragmentation Barrier



Brauer et al (2008), Zsom et al. (2009, 2010), Stammler & Birnstiel (2022)

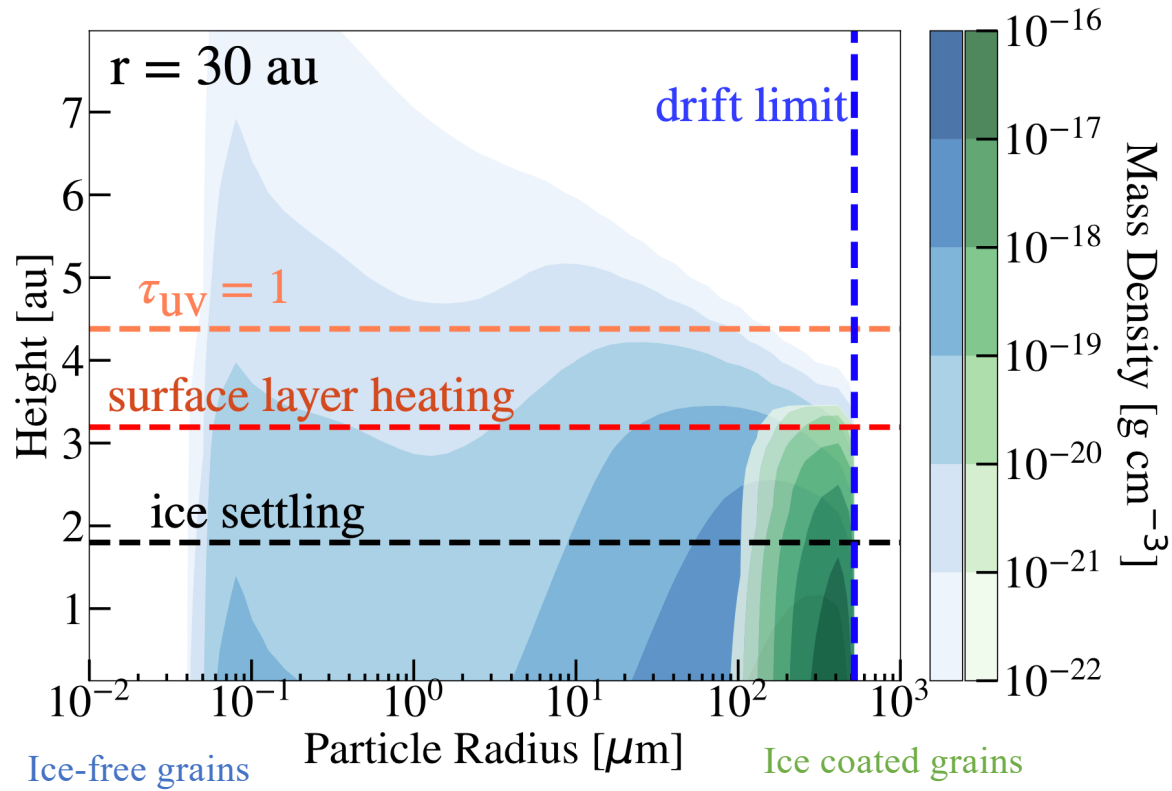
Thermal and photo-desorption, photodissociation

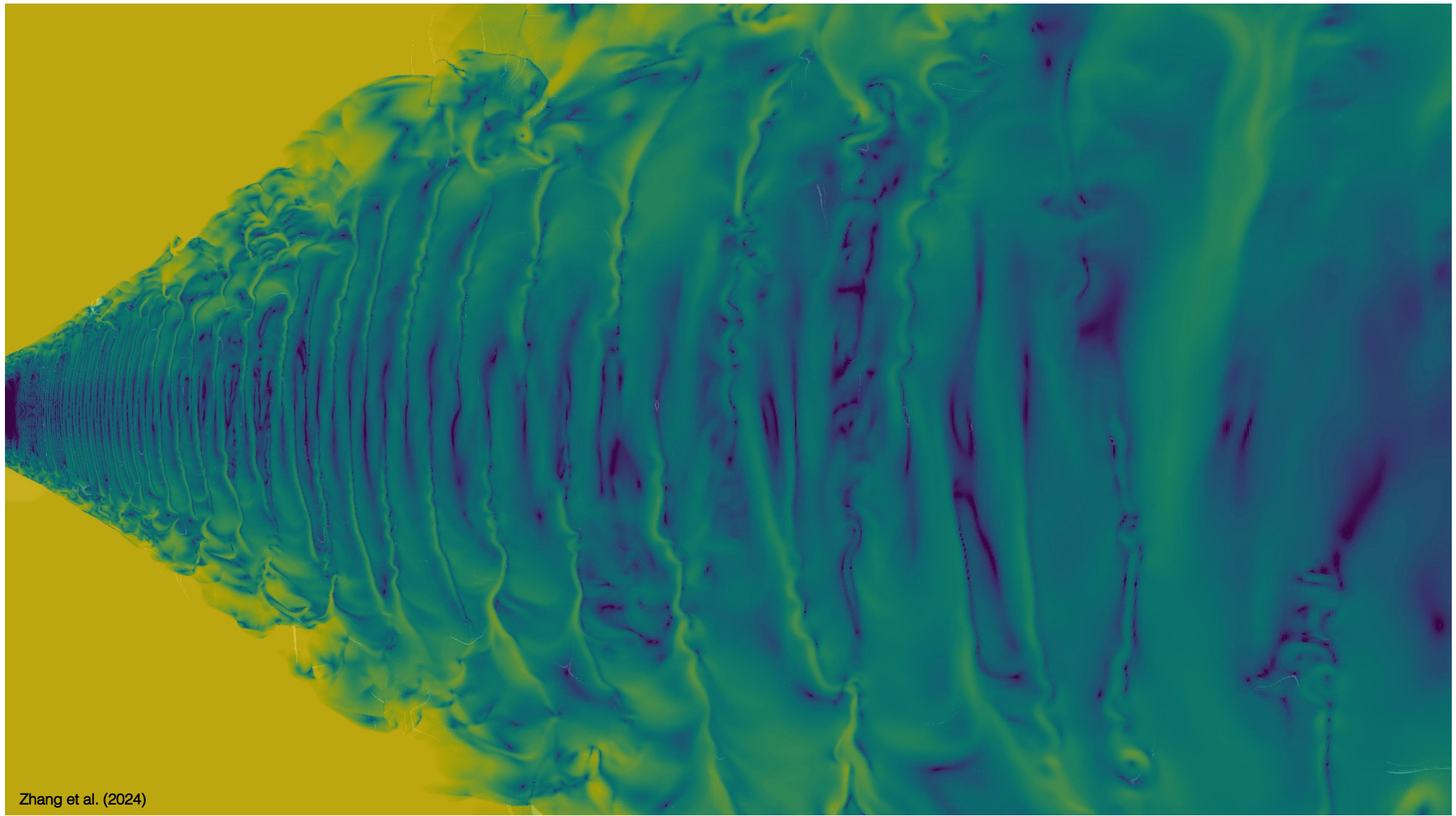
Heating and UV irradiation remove ice
on Myr timescales (Harrison & Schoen 1967).



Thermal and photo-desorption

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



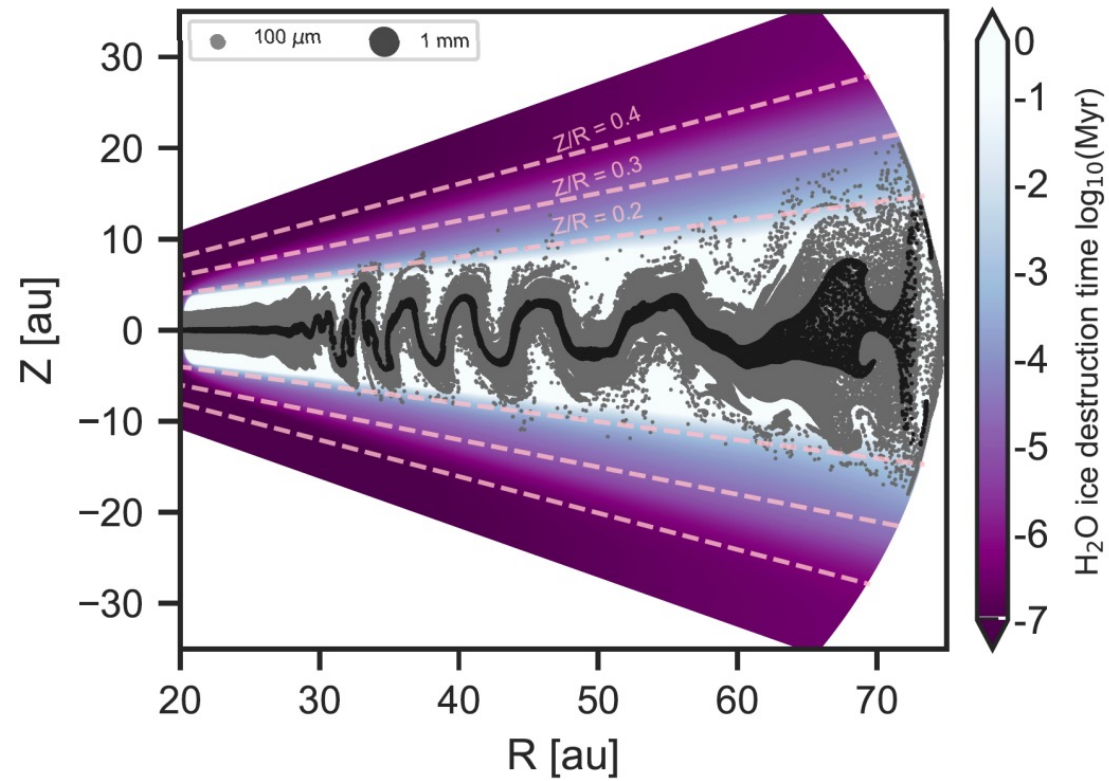


Zhang et al. (2024)

Thermal and photo-desorption

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

Photodissociation



Flores-Rivera et al. (2025)

Thermal and photo-desorption

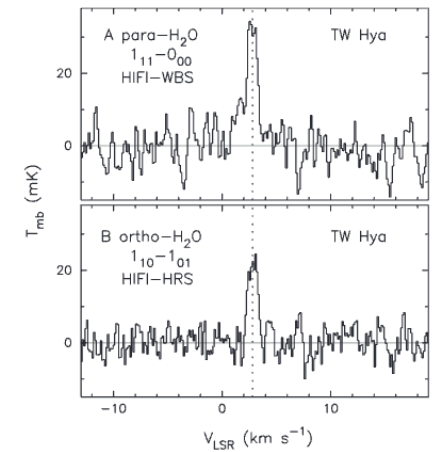
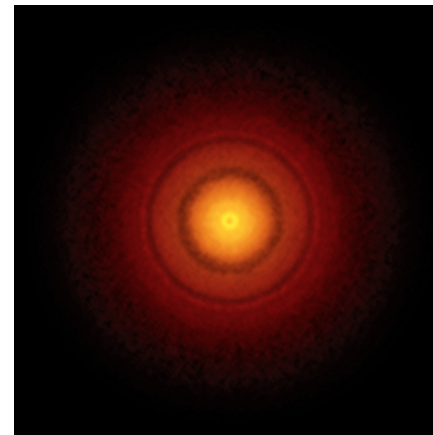
Evidence in disks

Debris disks



Only upper limits for ice in β Pic
(Ballering et al. 2016, Cavallius et al 2019)

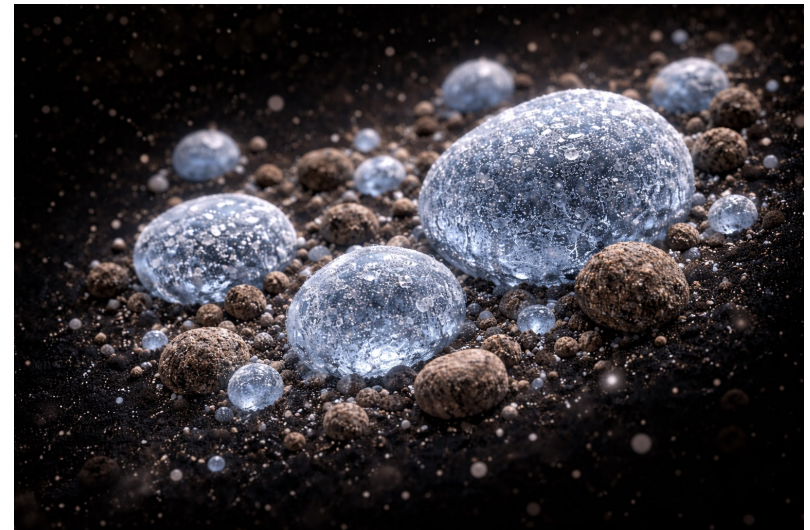
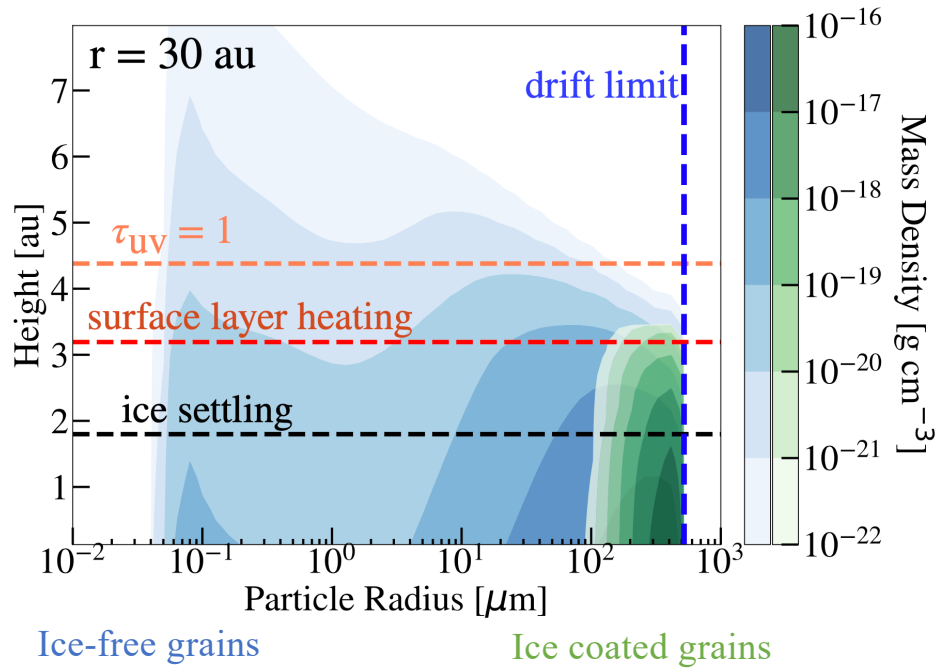
Primordial disks



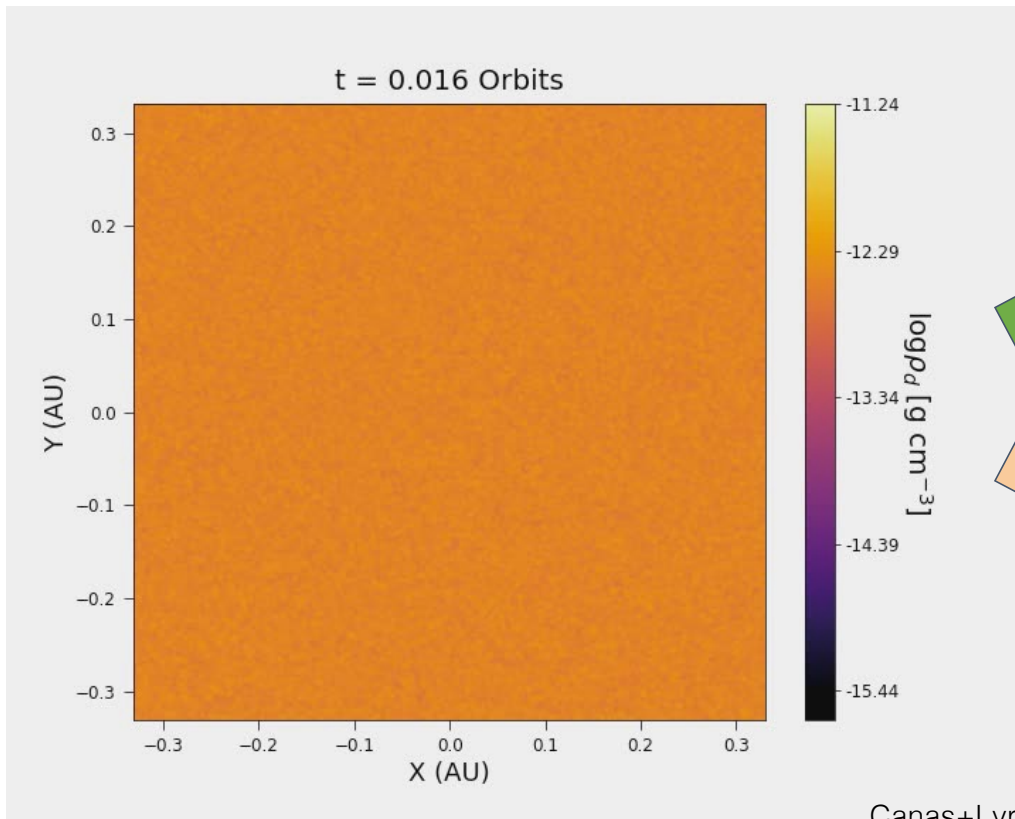
Water vapor observed at large distances for TW Hya
(Hogerheijde et al. 2011, 2012)

Proof-of-concept model

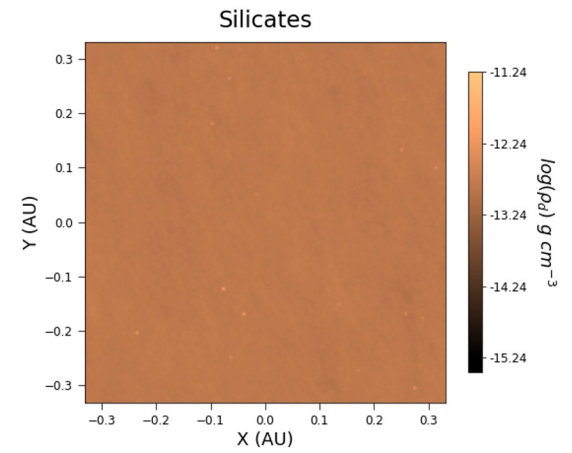
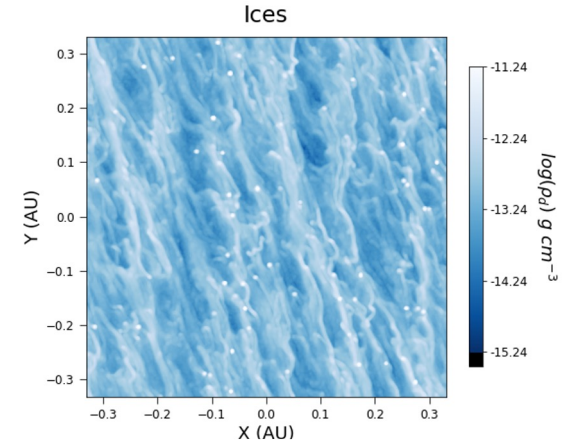
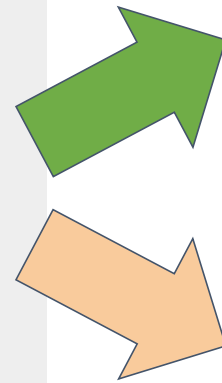
Small grains lofted in the atmosphere lose ice
Big grains are shielded and remain icy.



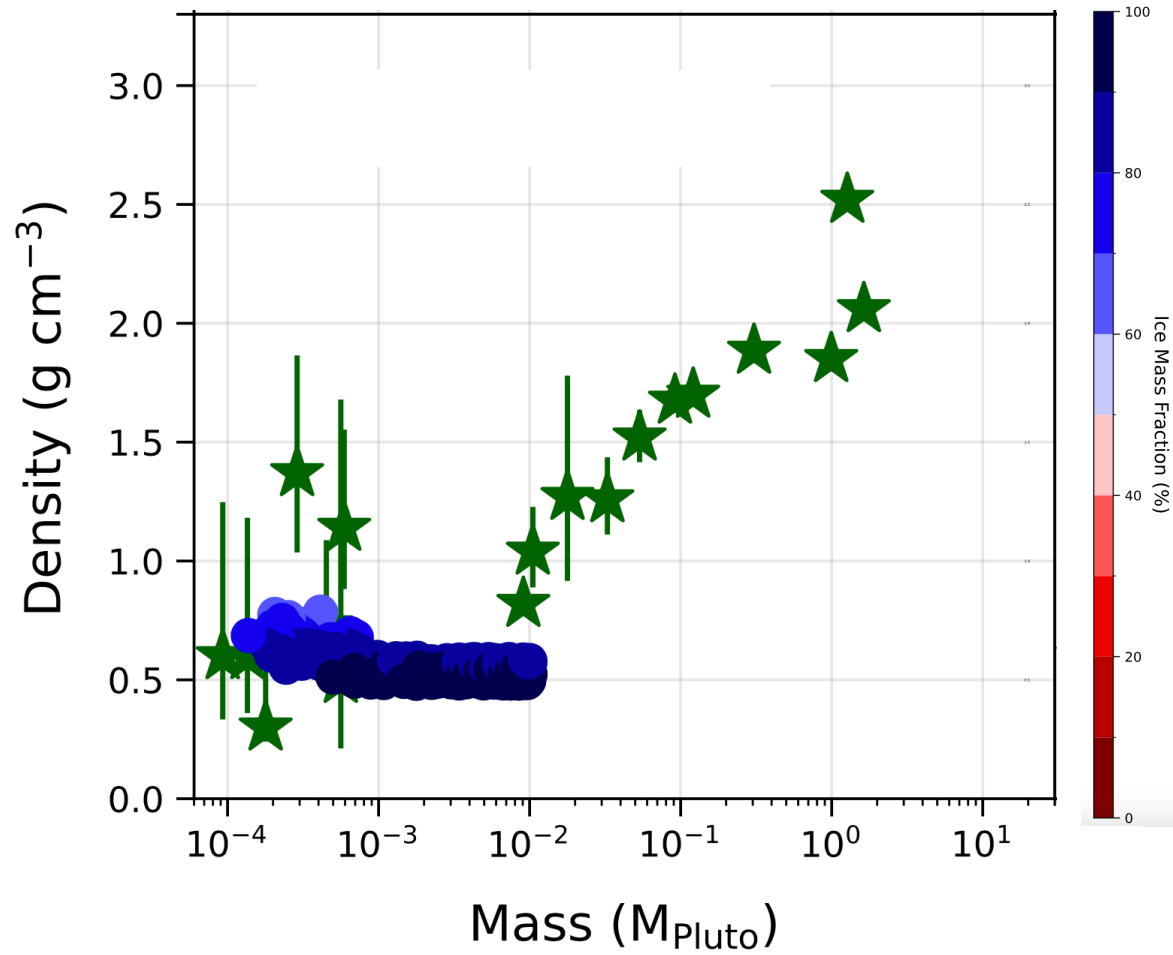
Split into icy and silicate pebbles



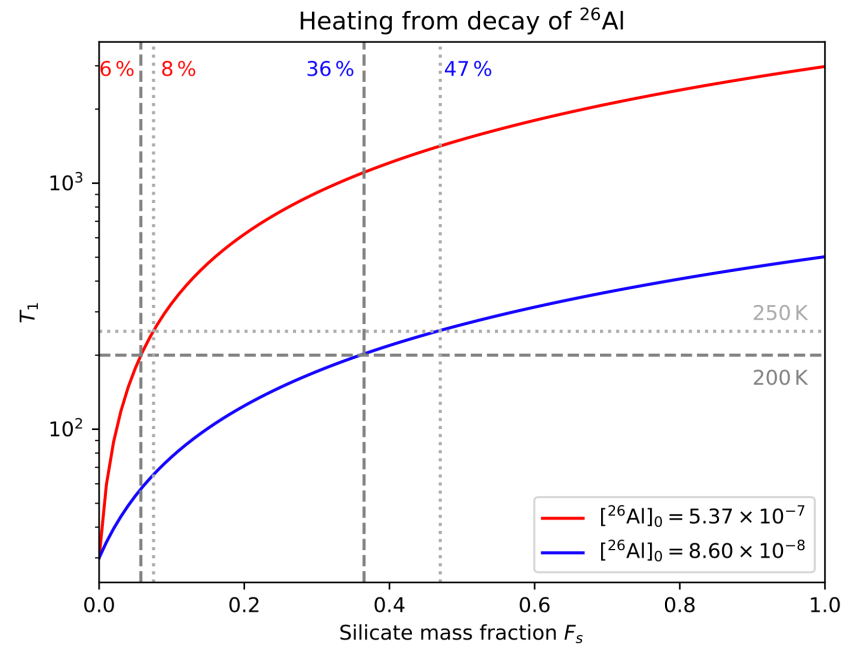
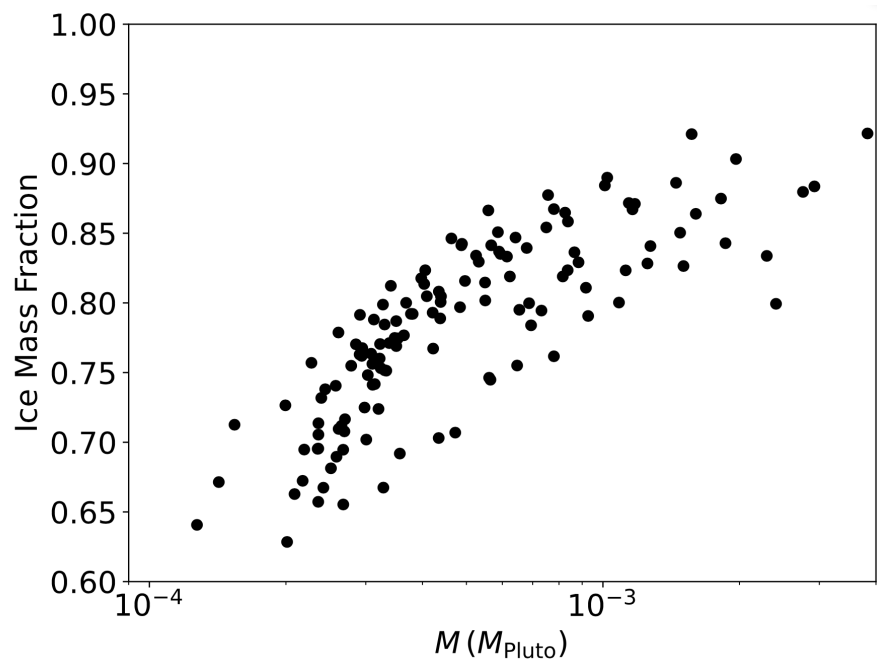
Canas+Lyra et al. 2024



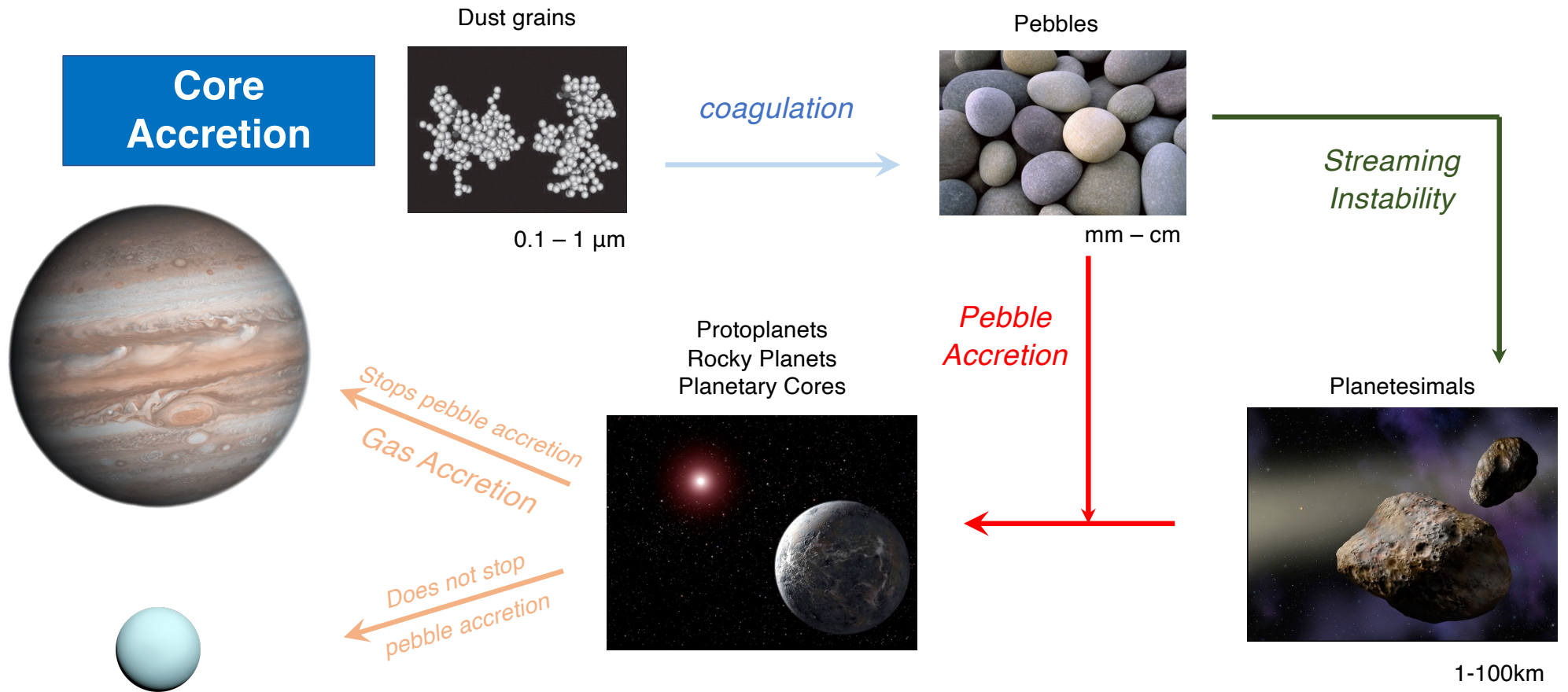
The first planetesimals are icy



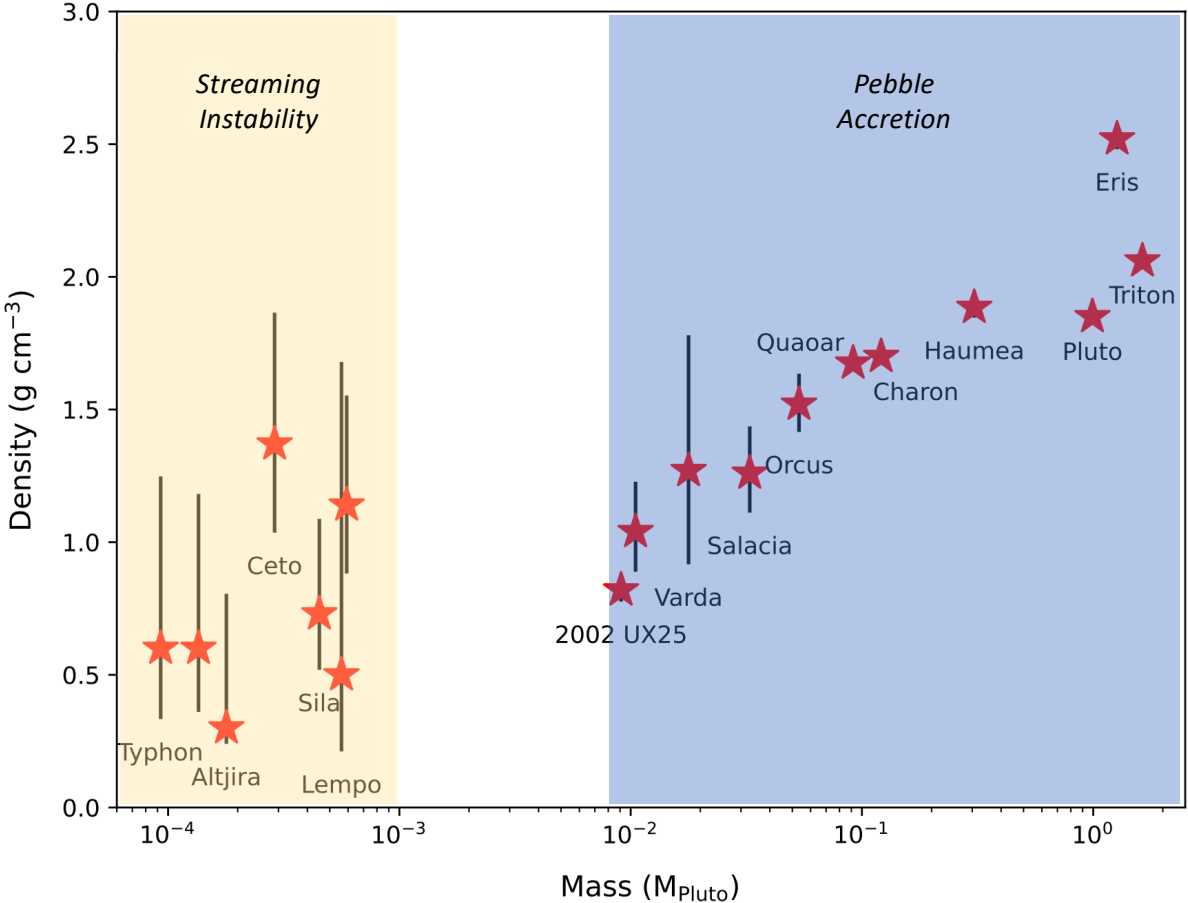
^{26}Al binds to silicates: the first planetesimals won't melt



Core Accretion

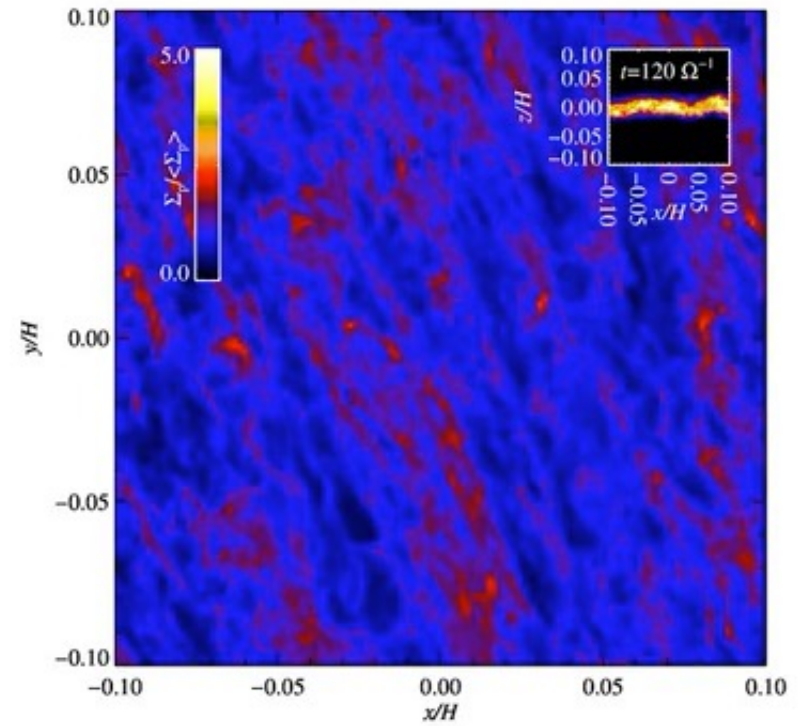
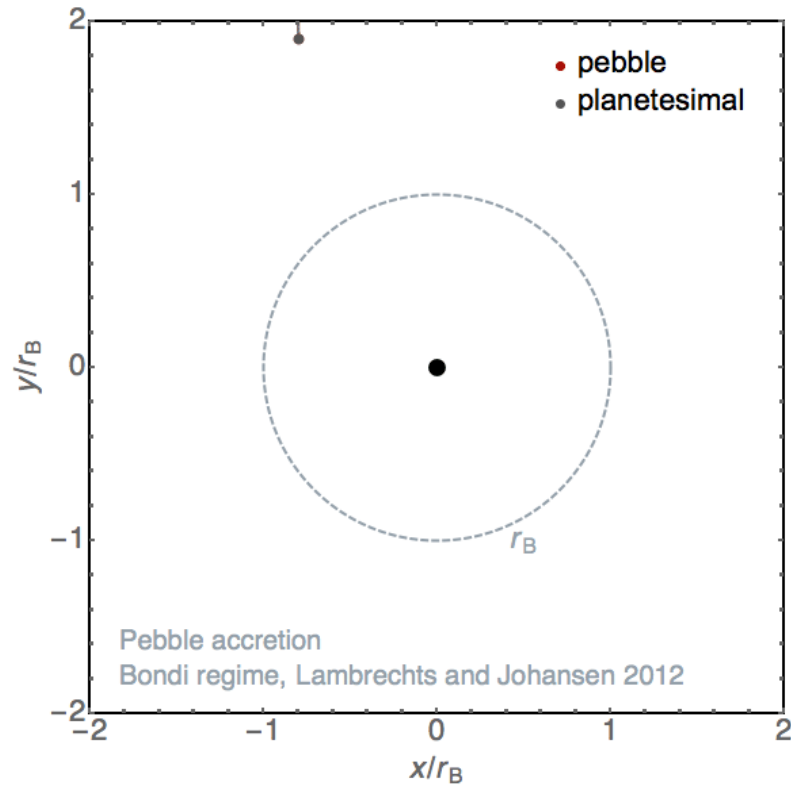


The size-density relationship of Kuiper Belt objects



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).

Pebble Accretion

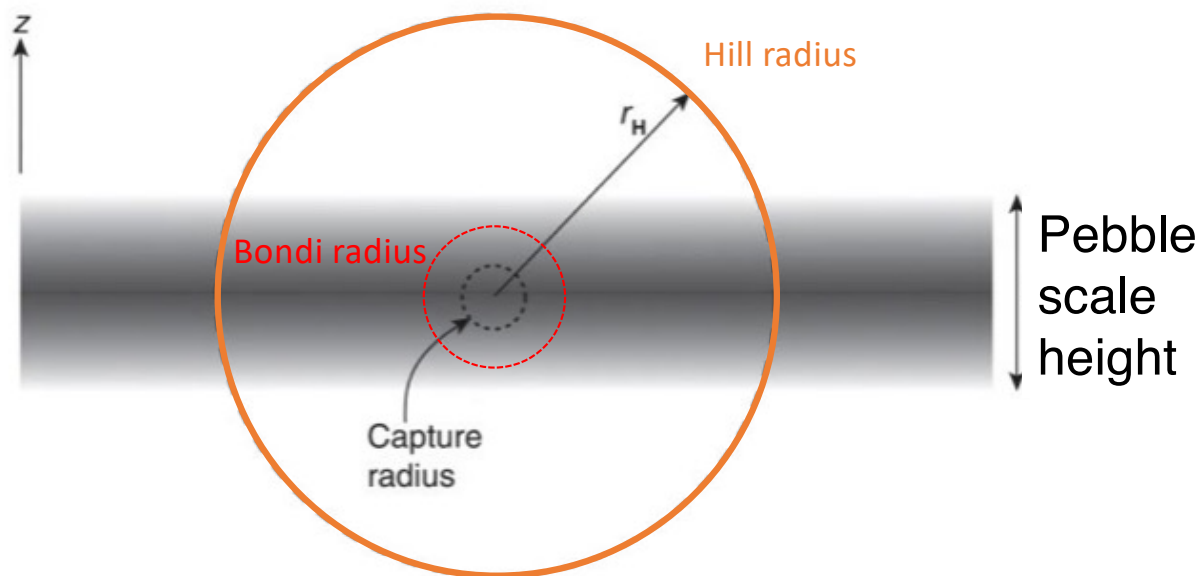


Lyra+ '08, '09, '23, Ormel & Klahr '10, Lambrechts & Johansen '12
See Johansen & Lambrechts '17 for a review

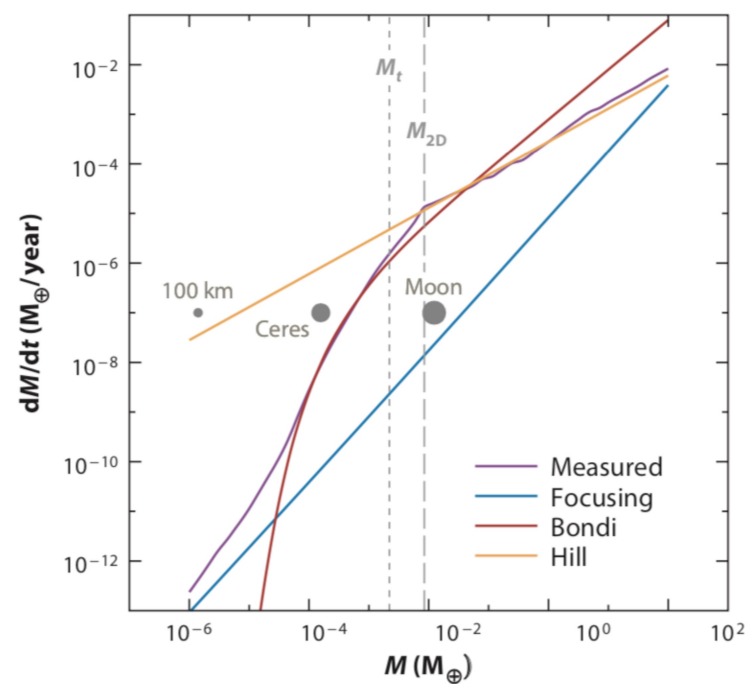
Pebble Accretion: Geometric, Bondi, and Hill regime

Bondi accretion - Bound against **headwind**

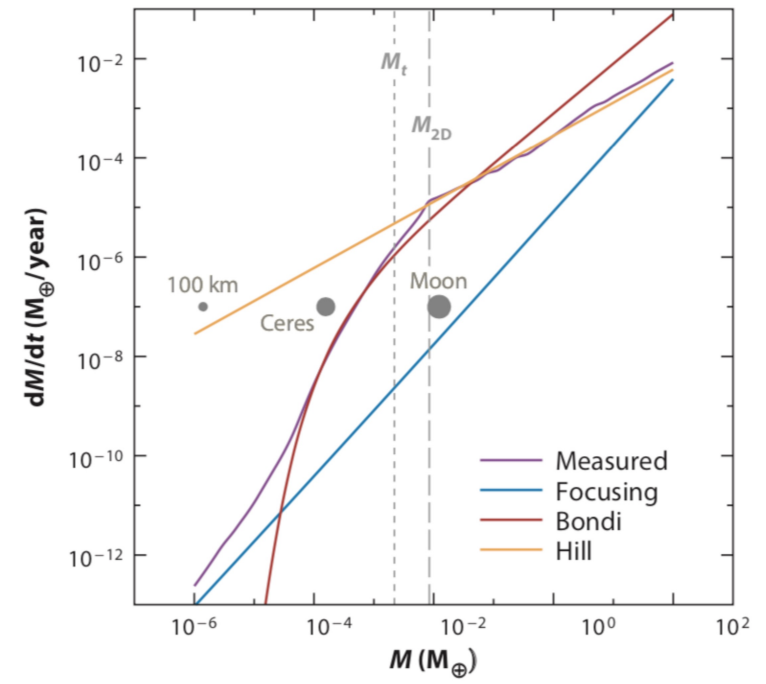
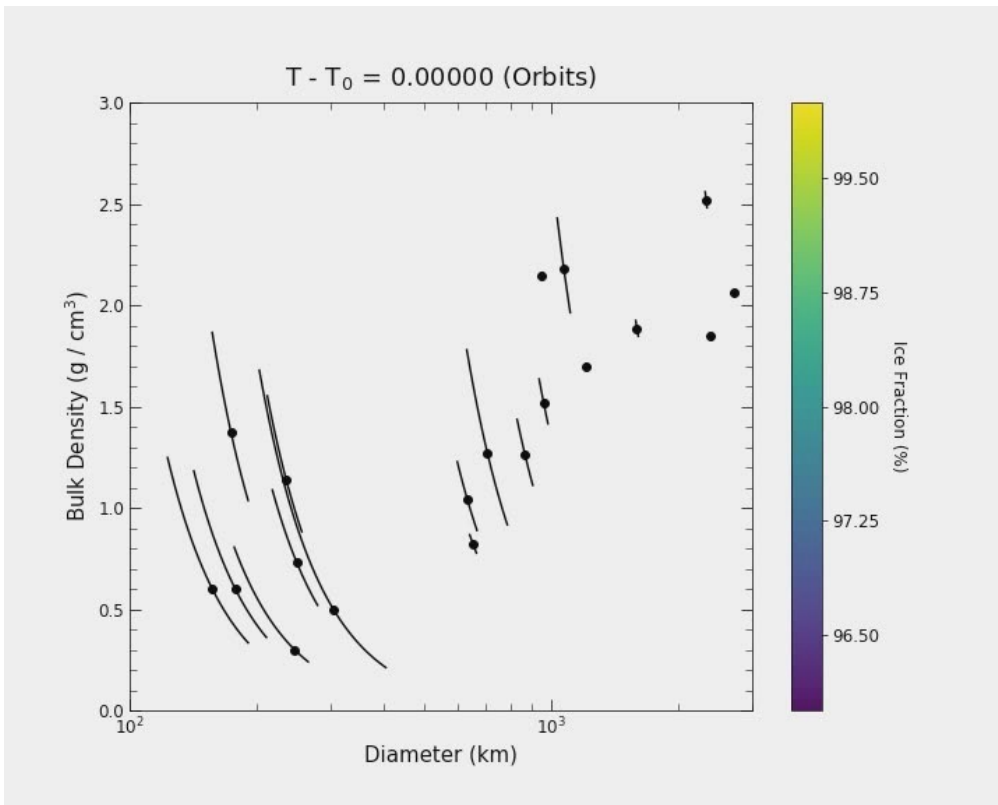
Hill accretion - Bound against **stellar tide**



Mass Accretion rates

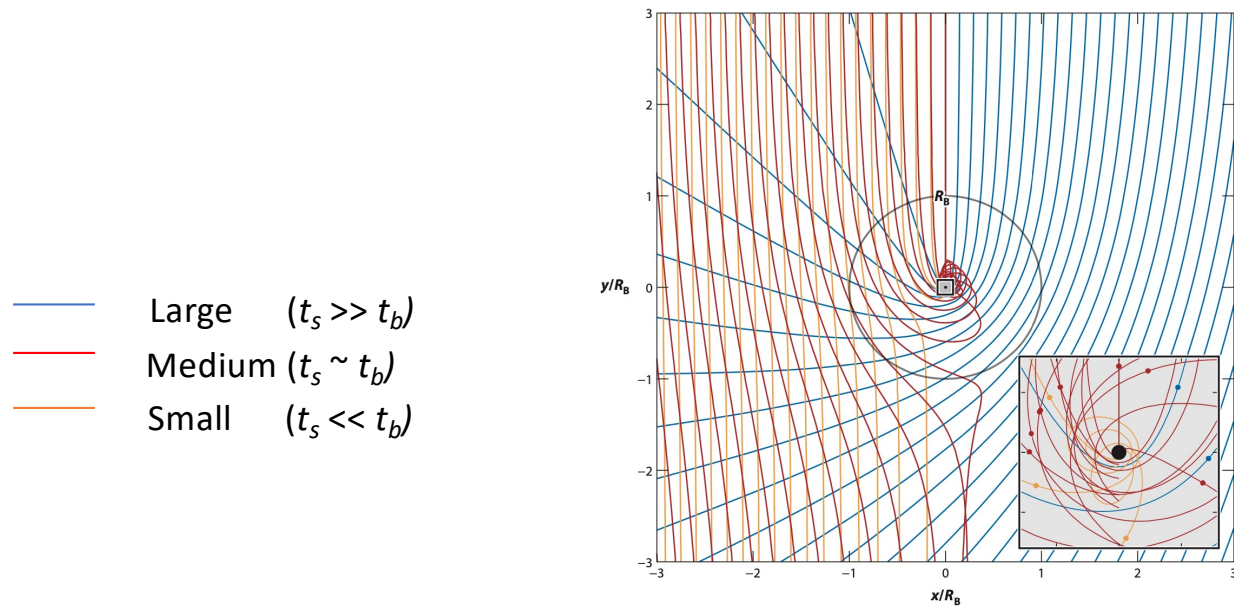


Integrate pebble accretion



Pebble Accretion: Pebbles of different size accrete differently

“Goldilocks effect”



Pebble size that accretes optimally

Drag time $t_s \sim$ Time to cross Bondi sphere t_b

$$t_b = GM/\Delta v^3$$

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

Polydisperse (Multi-Species) Pebble Accretion

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

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

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

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

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

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

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

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

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

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

$$\rho_\bullet \propto a^{-q}; \quad t_p \equiv \frac{GM_p}{(\Delta v + \Omega R_H)^3}$$

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

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

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

$$\begin{aligned} \dot{M}_{3D, \text{Bondi}} &= \frac{4\pi R_B \Delta v^2}{\Omega} \\ &\times \int_0^{a_{\max}} \text{St} e^{-2\psi} m(a) f(a) \\ &\times \left[1 + 2 \left(\text{St} \frac{\Omega R_B}{\Delta v} \right)^{1/2} e^{-\psi} \right] da, \quad \psi \equiv \chi [\text{St}/(\Omega t_p)]^\gamma. \end{aligned}$$

Analytical theory of polydisperse (multi-species) pebble accretion

Monodisperse (single species)

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

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

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

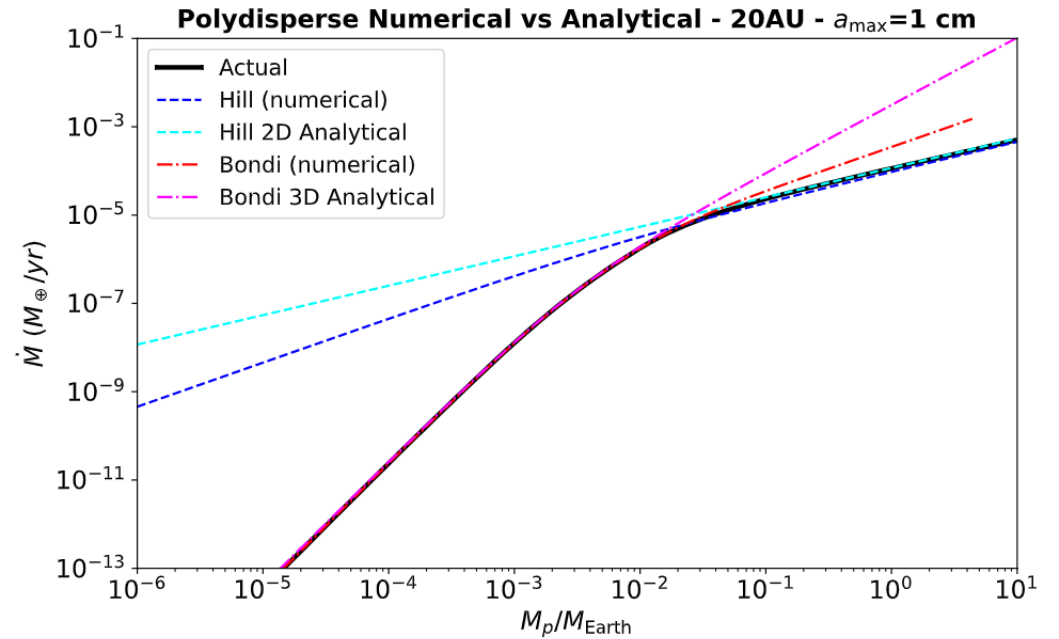
Lambrechts & Johansen (2012)

Polydisperse (multiple species)

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

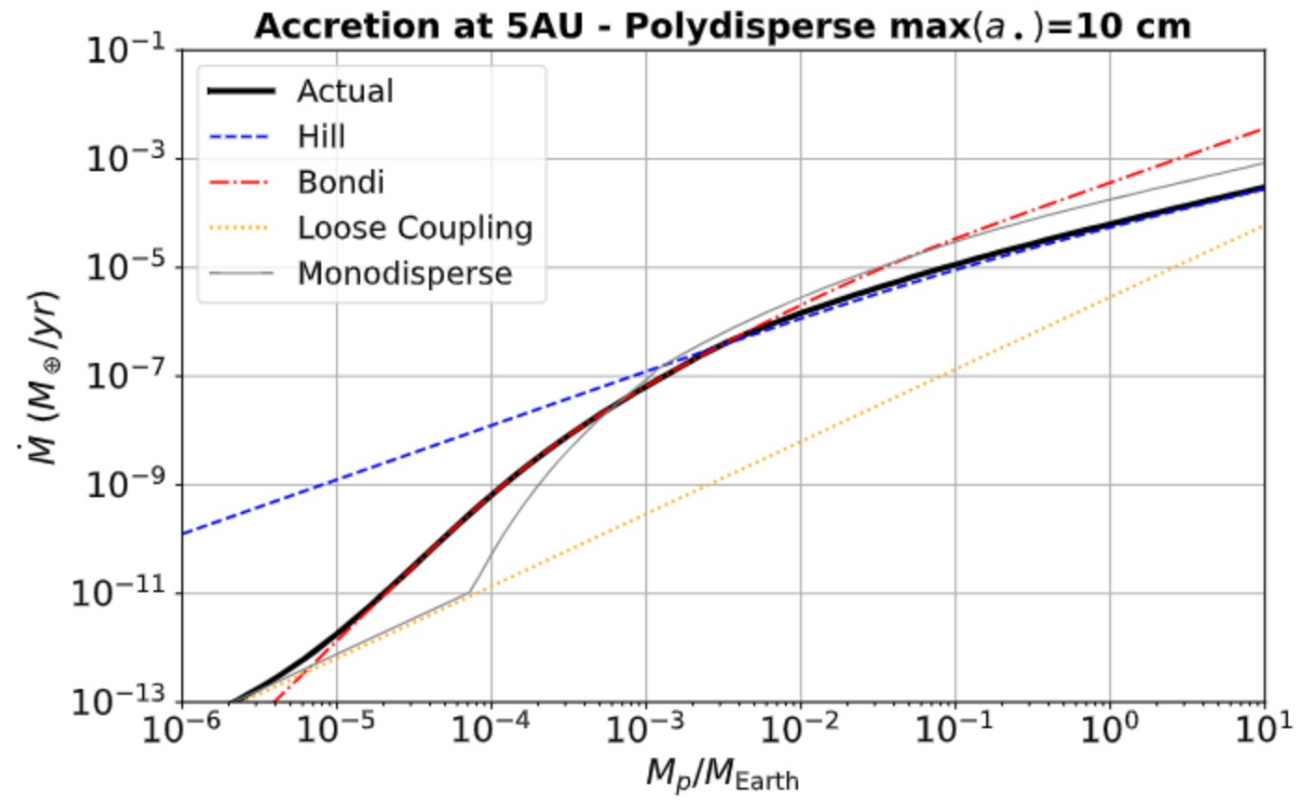
$$\dot{M}_{3D,\text{Bondi}} \approx C_1 \frac{\gamma_l \left(\frac{b_1+1}{s}, j_1 a_{\text{max}}^s\right)}{s J_1^{(b_1+1)/s}} + C_2 \frac{\gamma_l \left(\frac{b_2+1}{s}, j_2 a_{\text{max}}^s\right)}{s J_2^{(b_2+1)/s}} + C_3 \frac{\gamma_l \left(\frac{b_3+1}{s}, j_3 a_{\text{max}}^s\right)}{s J_3^{(b_3+1)/s}} + C_4 \frac{\gamma_l \left(\frac{b_4+1}{s}, j_4 a_{\text{max}}^s\right)}{s J_4^{(b_4+1)/s}},$$

Lyra et al. (2023)

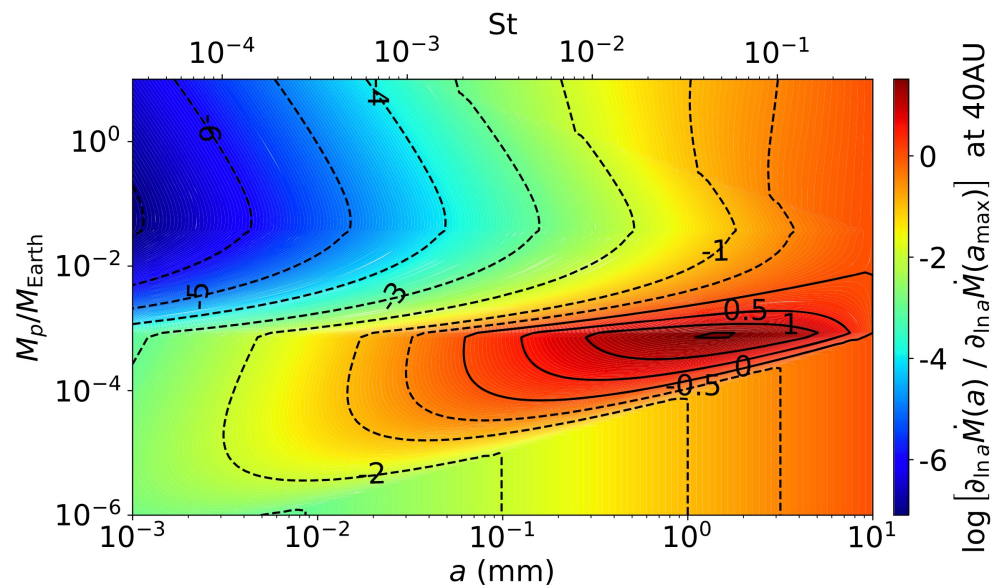
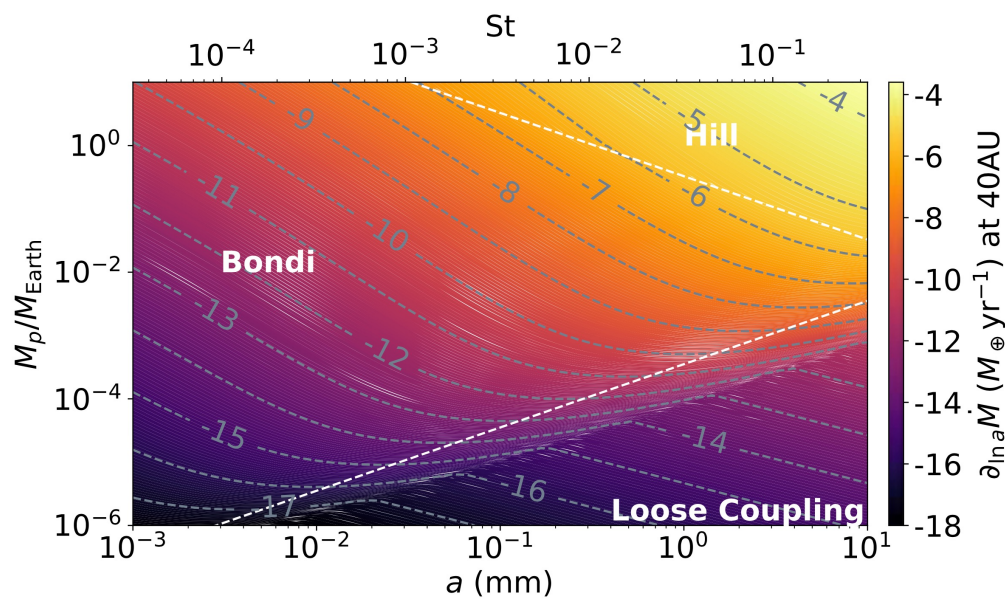


Lyra & Johansen + 2023

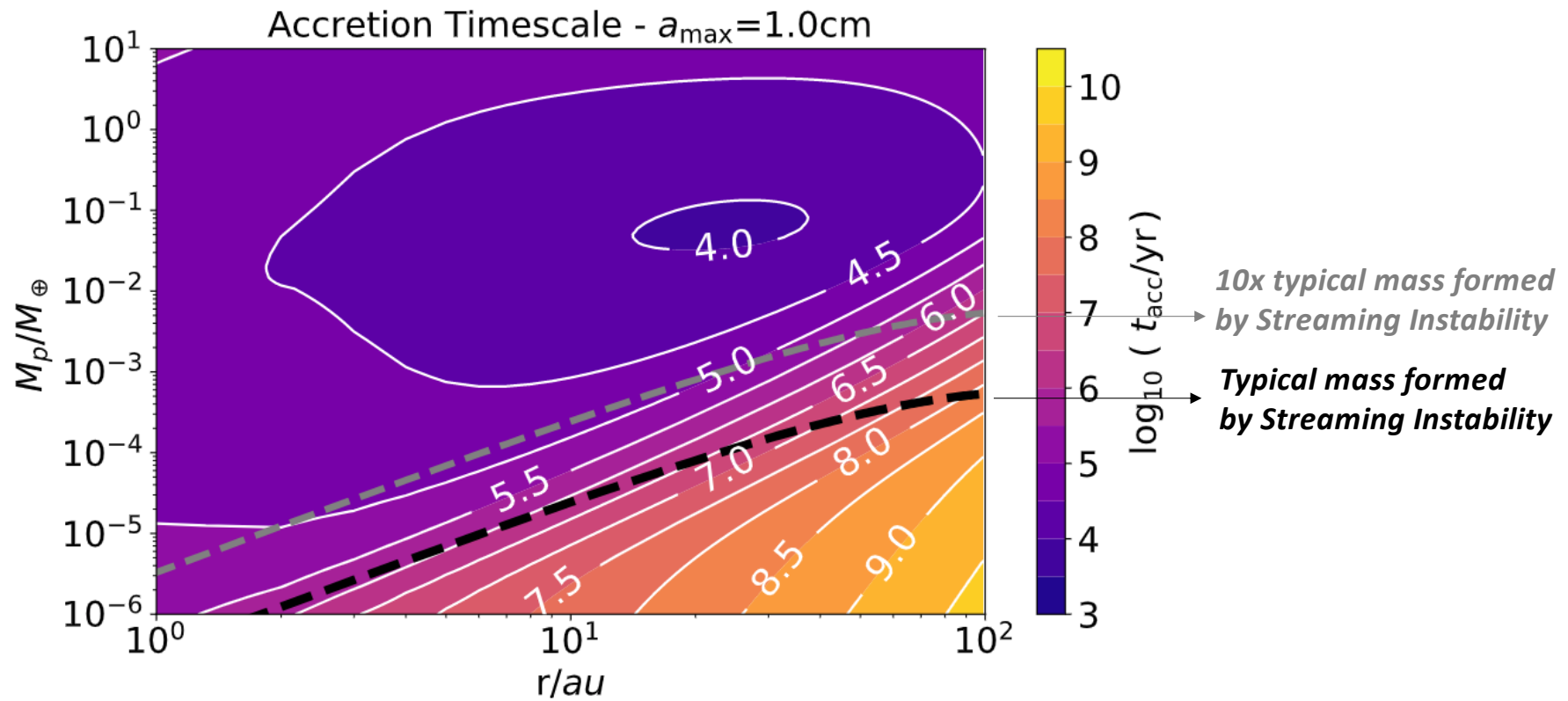
Accretion Rates



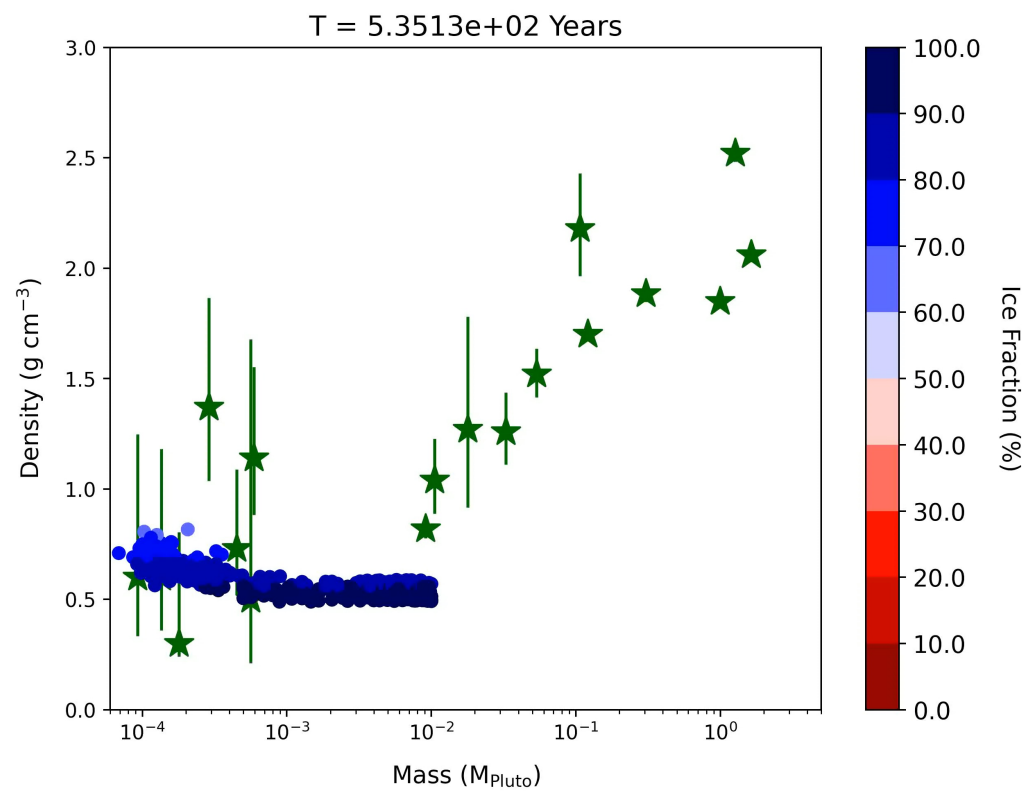
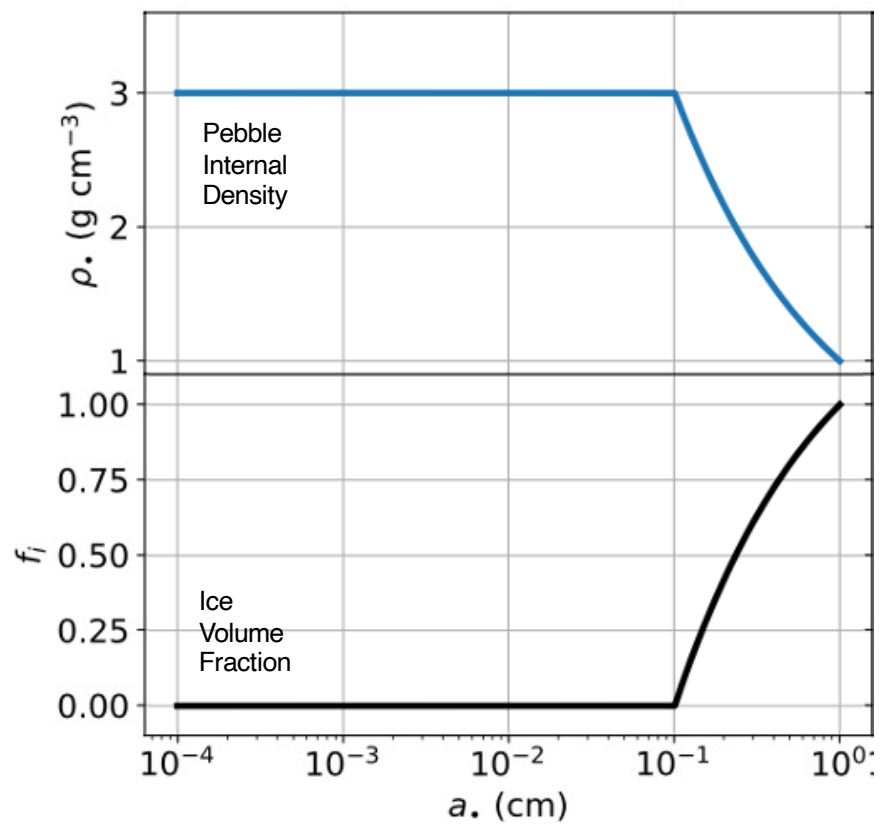
Differential Accretion Rates



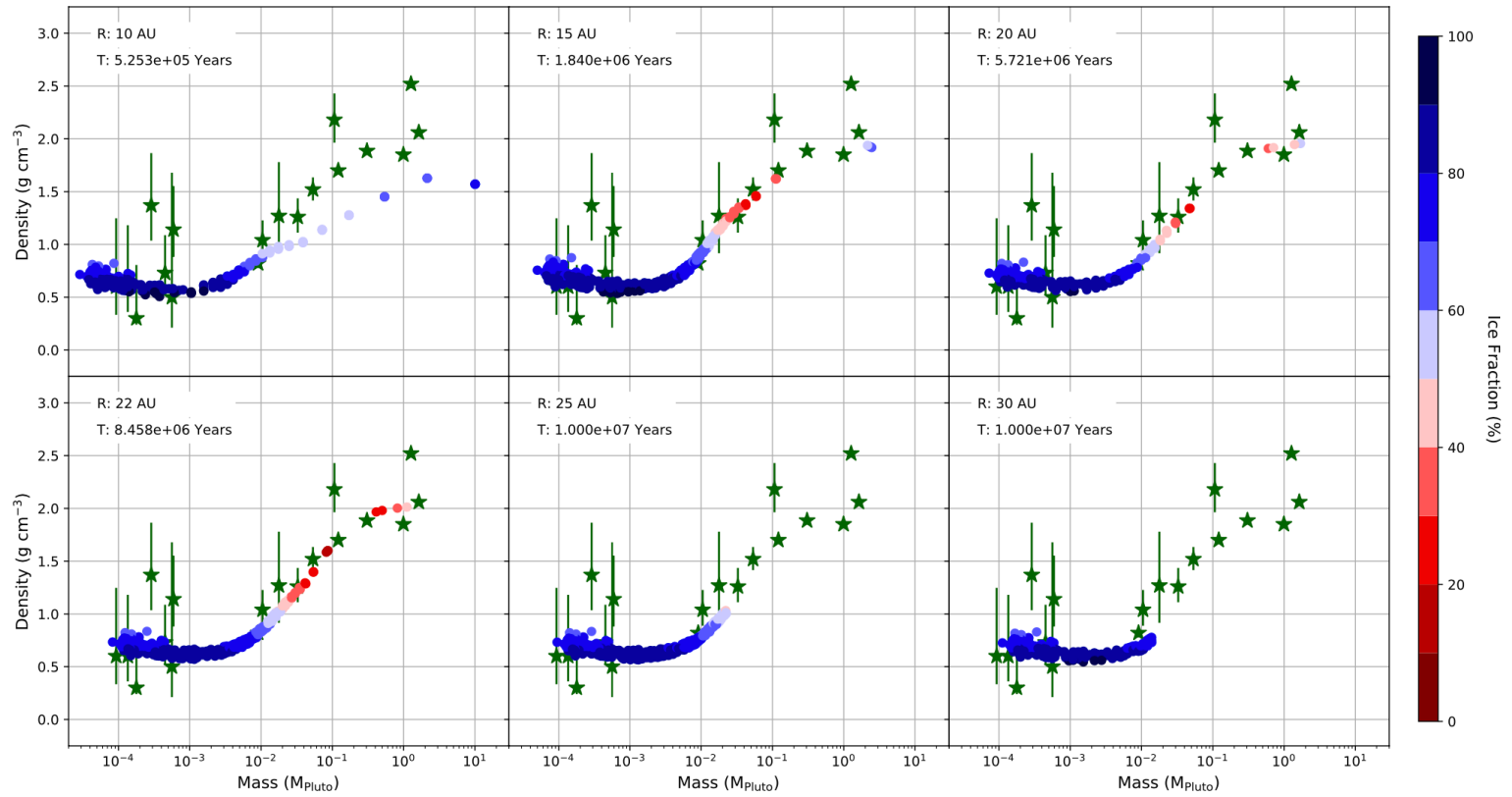
Accretion Timescales



Growing Pluto by silicate pebble accretion

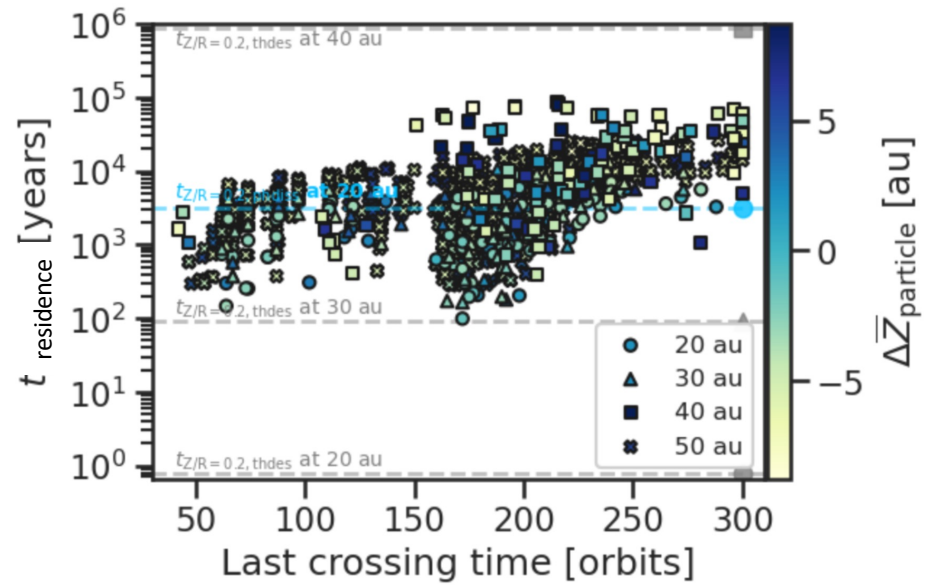
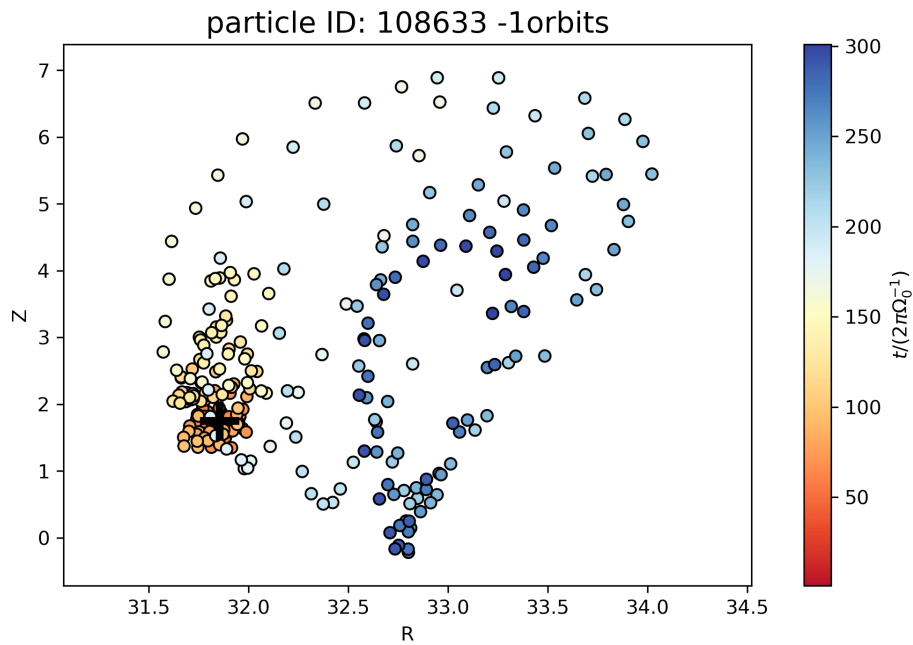


Distance Range 15 - 25AU



Pebble composition

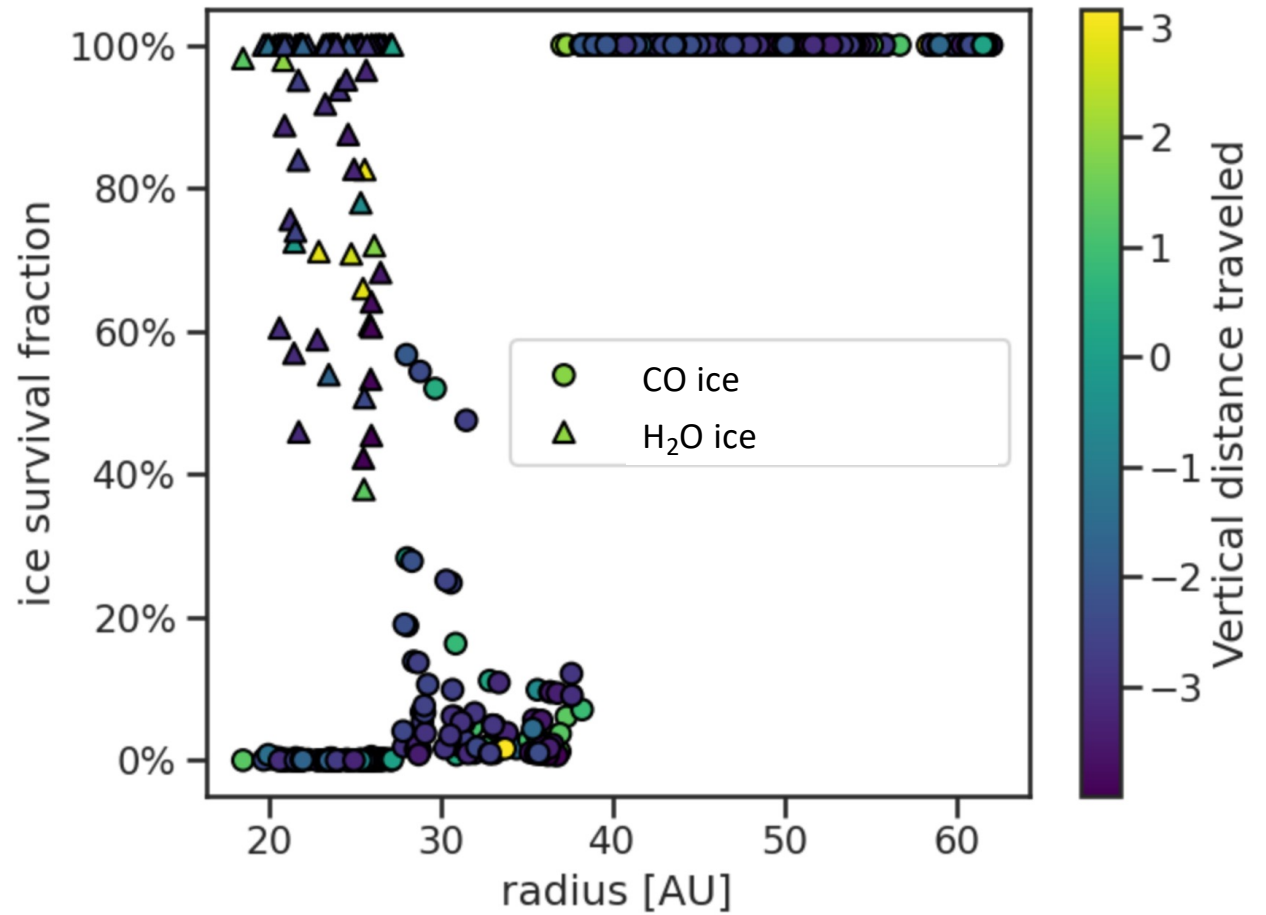
Turbulence + grains (100 μm and 1mm) + photodissociation



1 mm - unprocessed

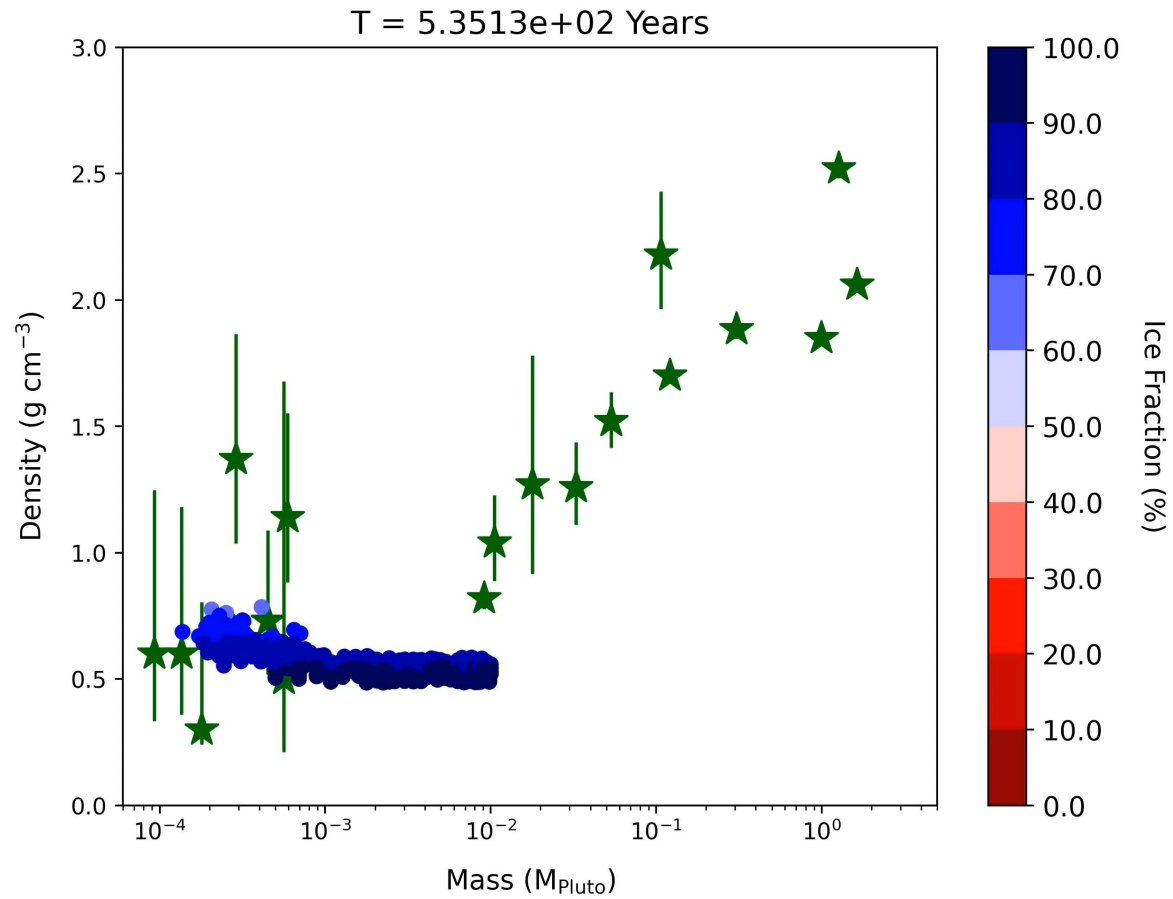
100 μm - *processed*
(some pebbles keep only 40% of the original ice)

Ice survival Fraction



Growing Eris by silicate pebble accretion

Requires ~100% silicate composition



Analysis of the *Gaia* DR3 photometry of the dwarf planet Eris

J. L. Ortiz ,  N. Morales  and P. J. Gutiérrez 

Instituto de Astrofísica de Andalucía, Consejo Superior de Investigaciones Científicas (IAA-CSIC), Glorieta de la Astronomía S/N, E-18008 Granada, Spain

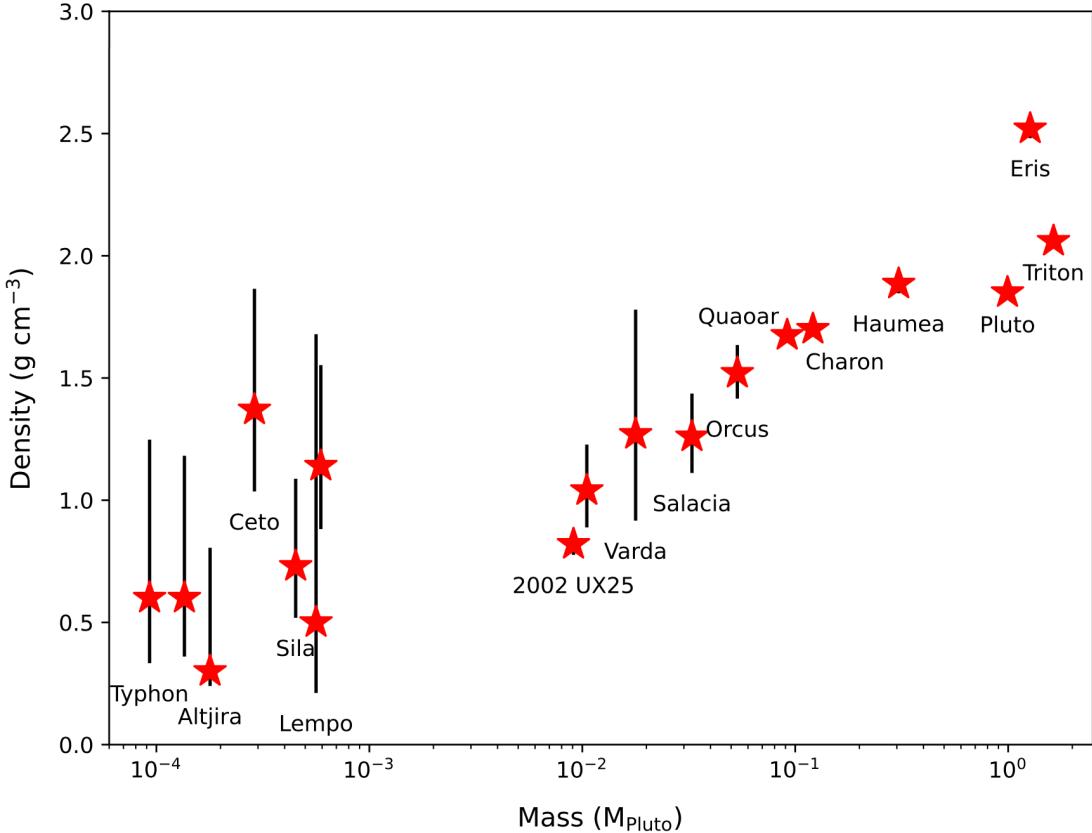
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ABSTRACT

Eris, one of the five official dwarf planets, is slightly smaller than Pluto and notable for its high geometric albedo and homogeneous surface, which has hindered a clear determination of its rotation period. Recently, it was shown that Eris is tidally locked to the 15.786-d orbit of its satellite, Dysnomia. Our analysis of Eris' *Gaia* DR3 photometry reveals a strong periodicity peak at 18.852 ± 0.003 h, which is the most prominent in the Lomb–Scargle periodogram, with a slightly stronger signal than the 15.77 ± 0.02 -d period also present in the data. We analysed whether the newly identified period could be an artefact, but found no reason other than a phenomenon in Eris. Since Dysnomia is too faint to account for the photometric variability, a potential explanation for either of the periodicities could be the presence of an unknown close-in satellite. An additional satellite, undetectable so far by the *Hubble Space Telescope* (*HST*), could also explain Dysnomias non-Keplerian orbit and could lower Eris's density to ~ 2000 kg m⁻³, consistent with other similar-sized Trans-Neptunian Objects (TNOs) and Triton. It would also decrease Eris's albedo by ~ 10 per cent, aligning it more closely with expected values. However, this possibility also has considerable problems, and other scenarios are explored.

Key words: minor planets – Kuiper belt objects: individual: (136199) Eris – techniques: photometric.

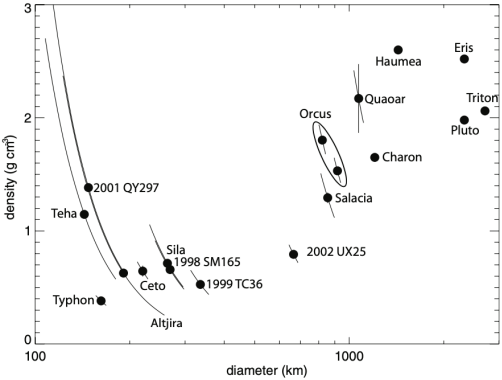
Where are the missing Kuiper Belt binaries?



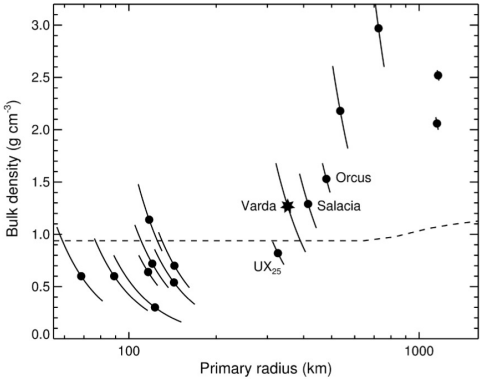
Lyra (2025)

Mass gap

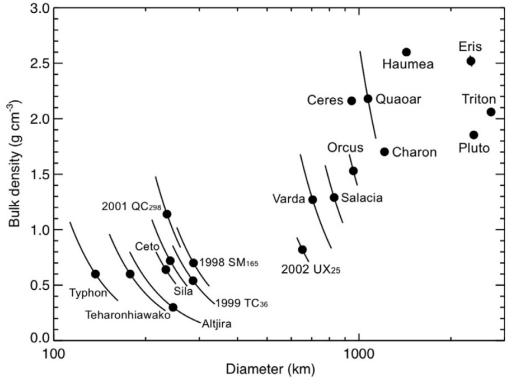
Brown 2013



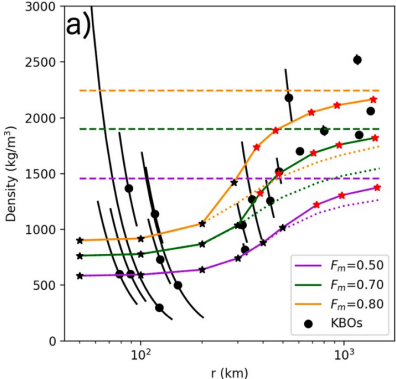
Grundy et al. 2015



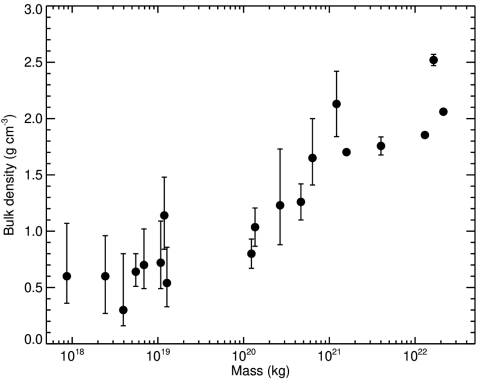
McKinnon et al. 2017



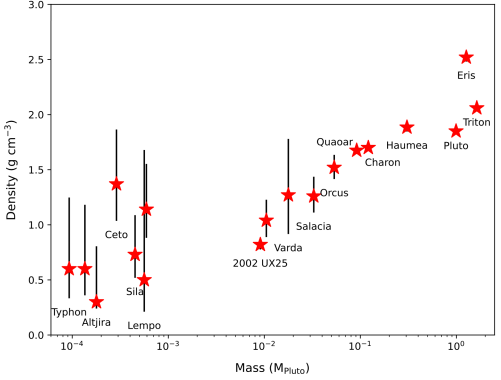
Biersson & Nimmo 2019



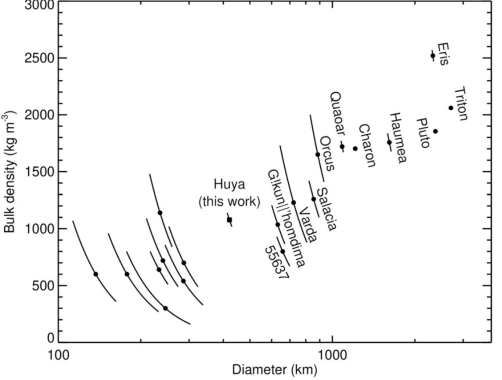
Noll et al. 2020



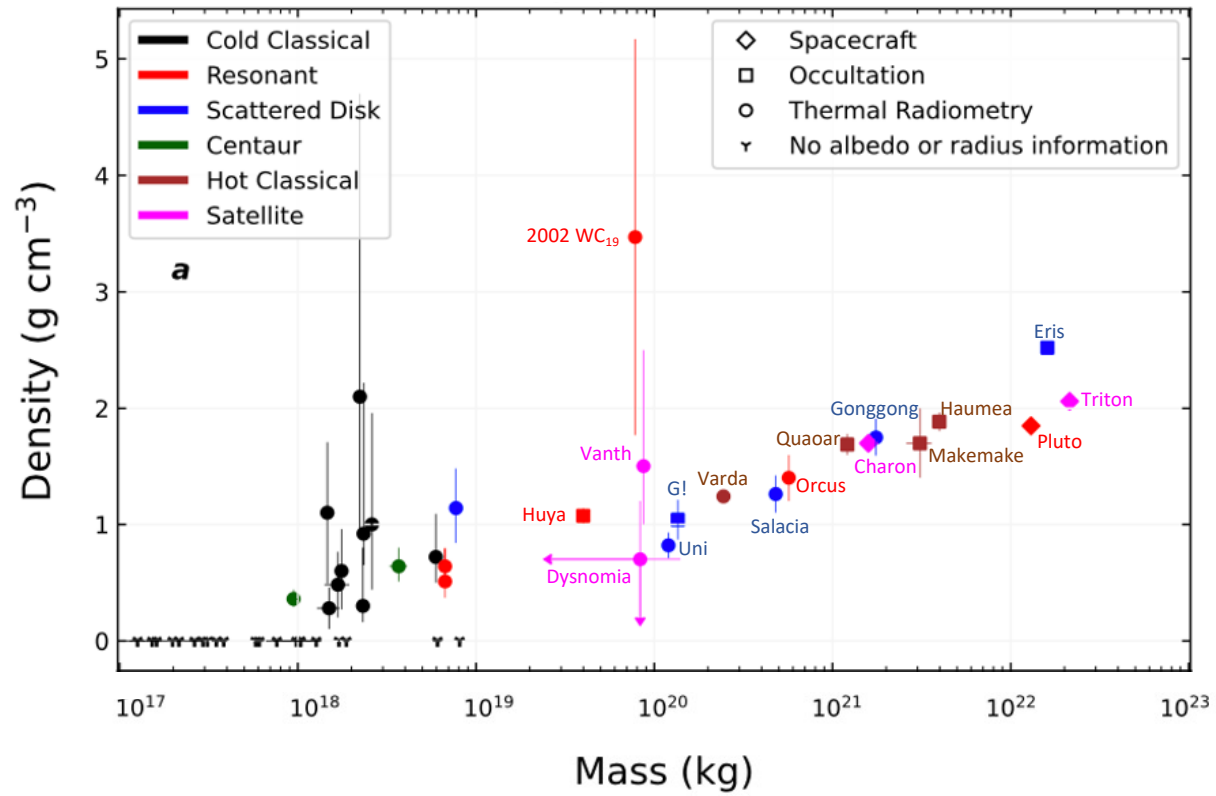
Canas et al. 2024



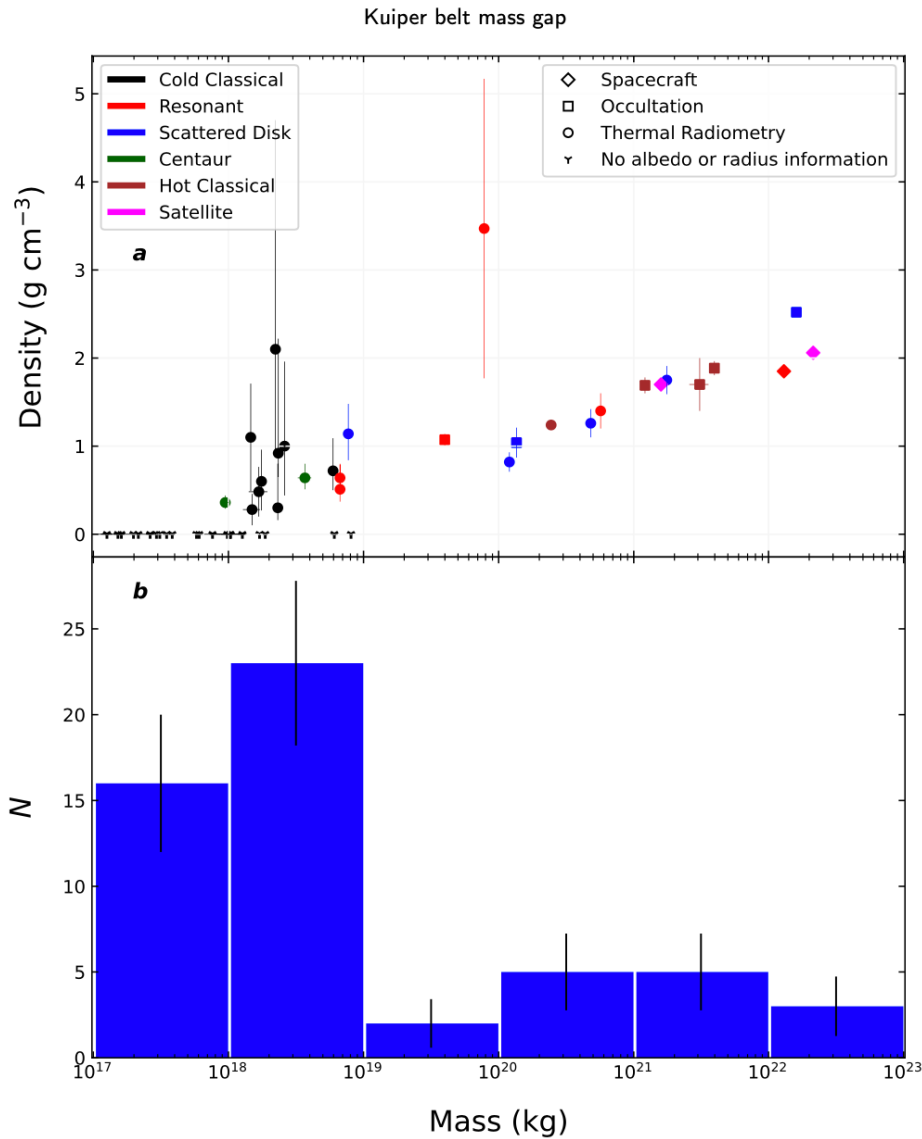
Rommel et al. 2025



Objects in the gap



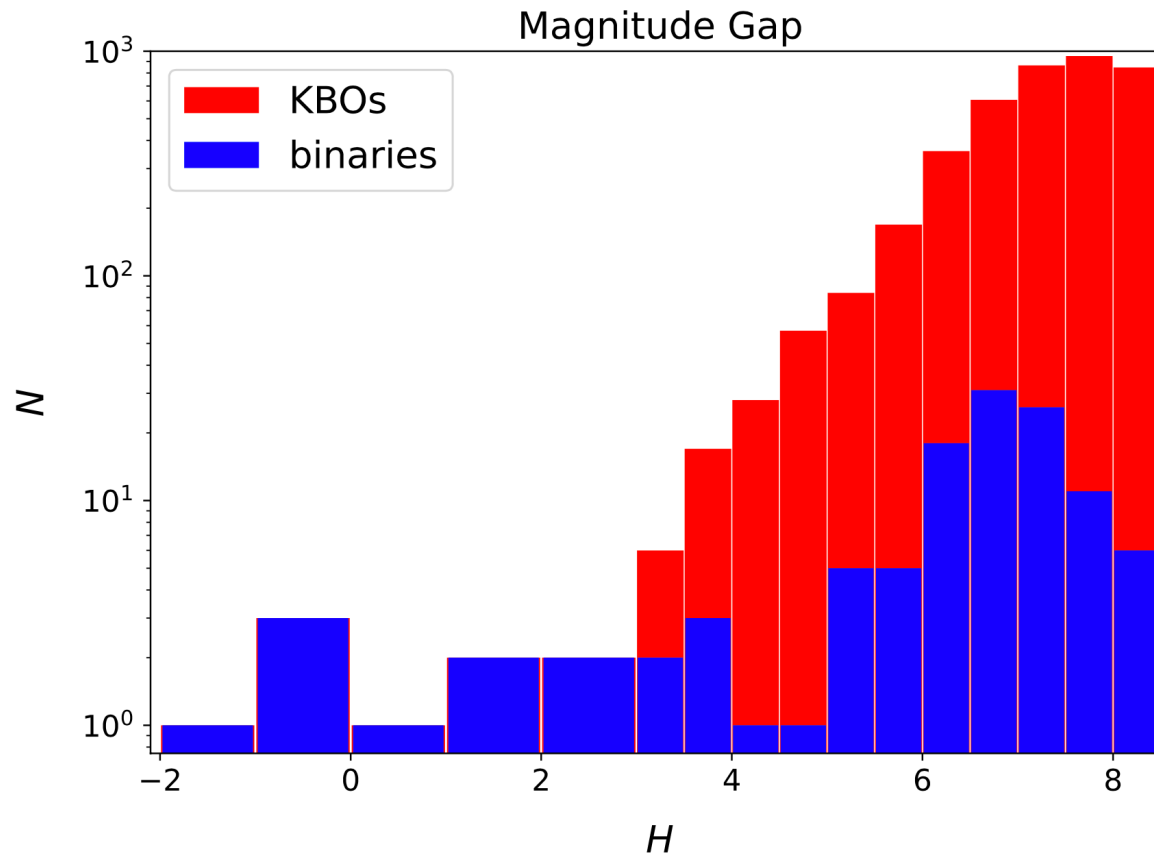
Lyra (2025)



Where are the missing Kuiper Belt binaries?

- Gap between 10^{19} and 10^{20} kg (10^{-3} and 10^{-2} Pluto masses)
- Population difference
 - Cold Classics are on low-mass side of the gap
- Likely not small number statistics
- *Low mass side is the high-mass end of the planetesimal initial mass function.*

High-mass side. Observational bias?



Pluto and Charon

Haumea,
Hi'aka, and
Namaka

Gonggong and Xianglu

Orcus and Vanth

Many of the largest Kuiper Belt Objects have large mass fraction satellites!

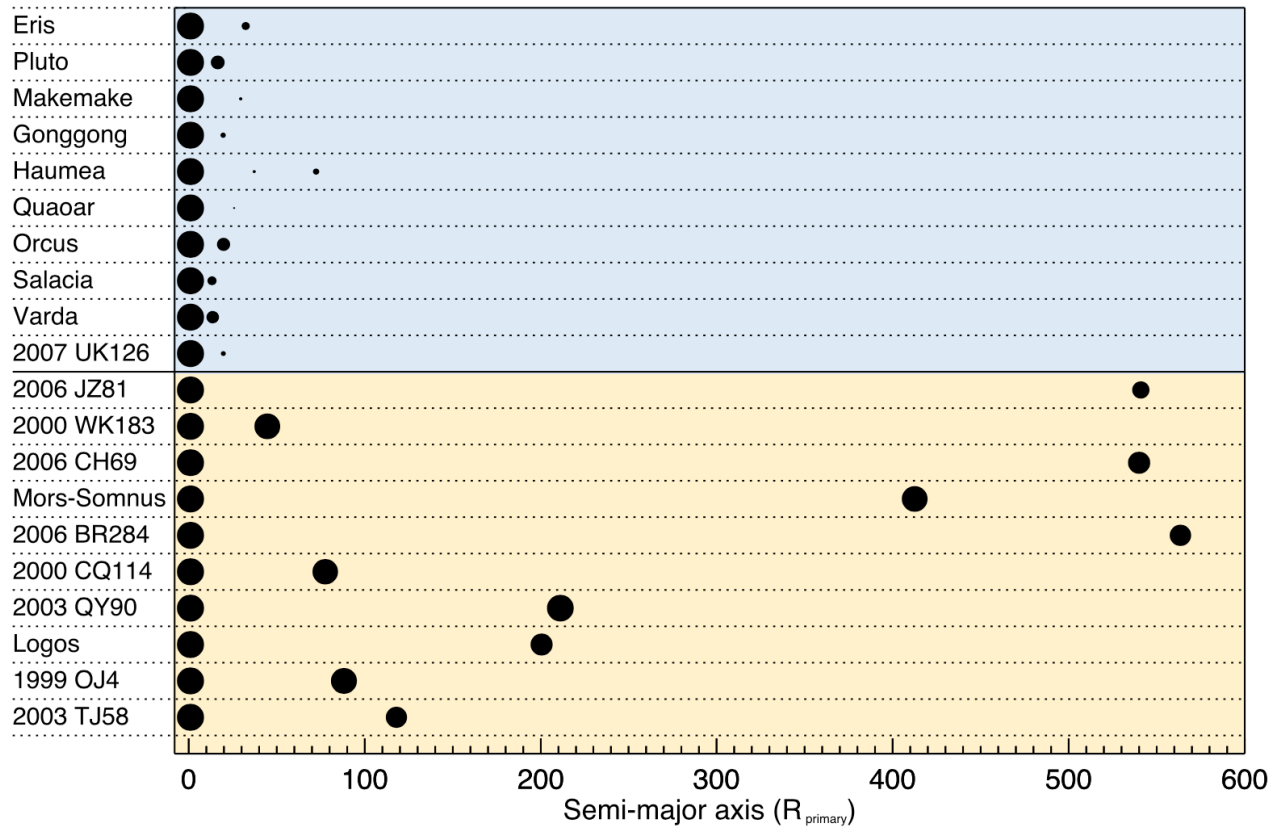
Eris and Dysnomia

Makemake and MK2

Varda and Ilmarë

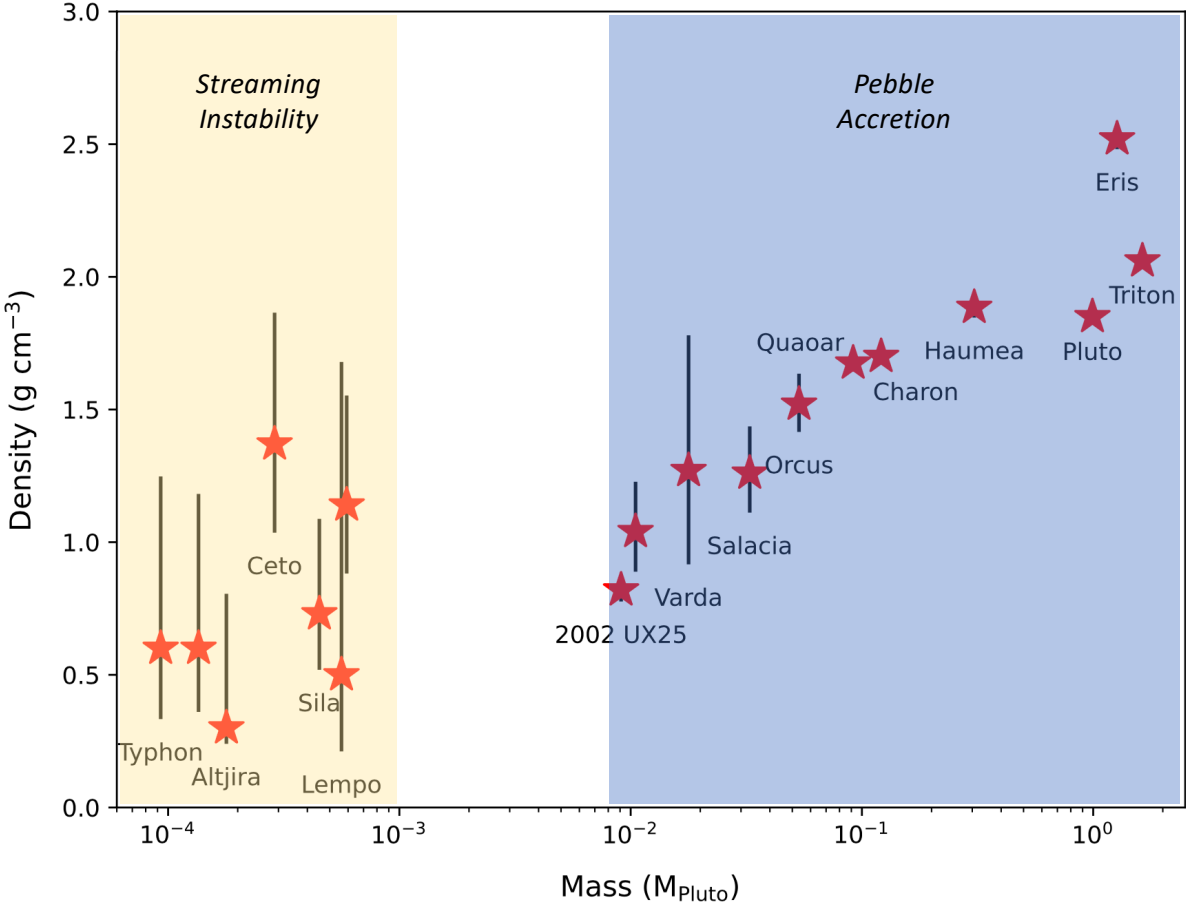
Quaoar and Weywot

Different system architecture



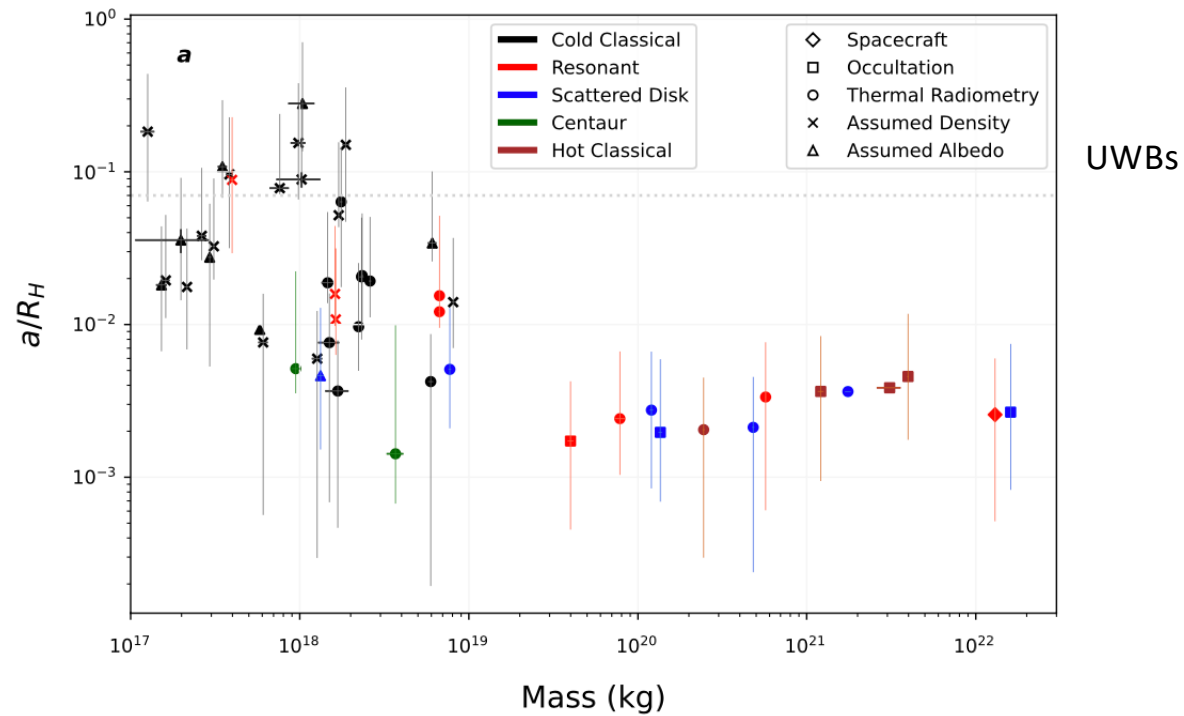
Bernstein et al (2023)

The size-density relationship of Kuiper Belt objects

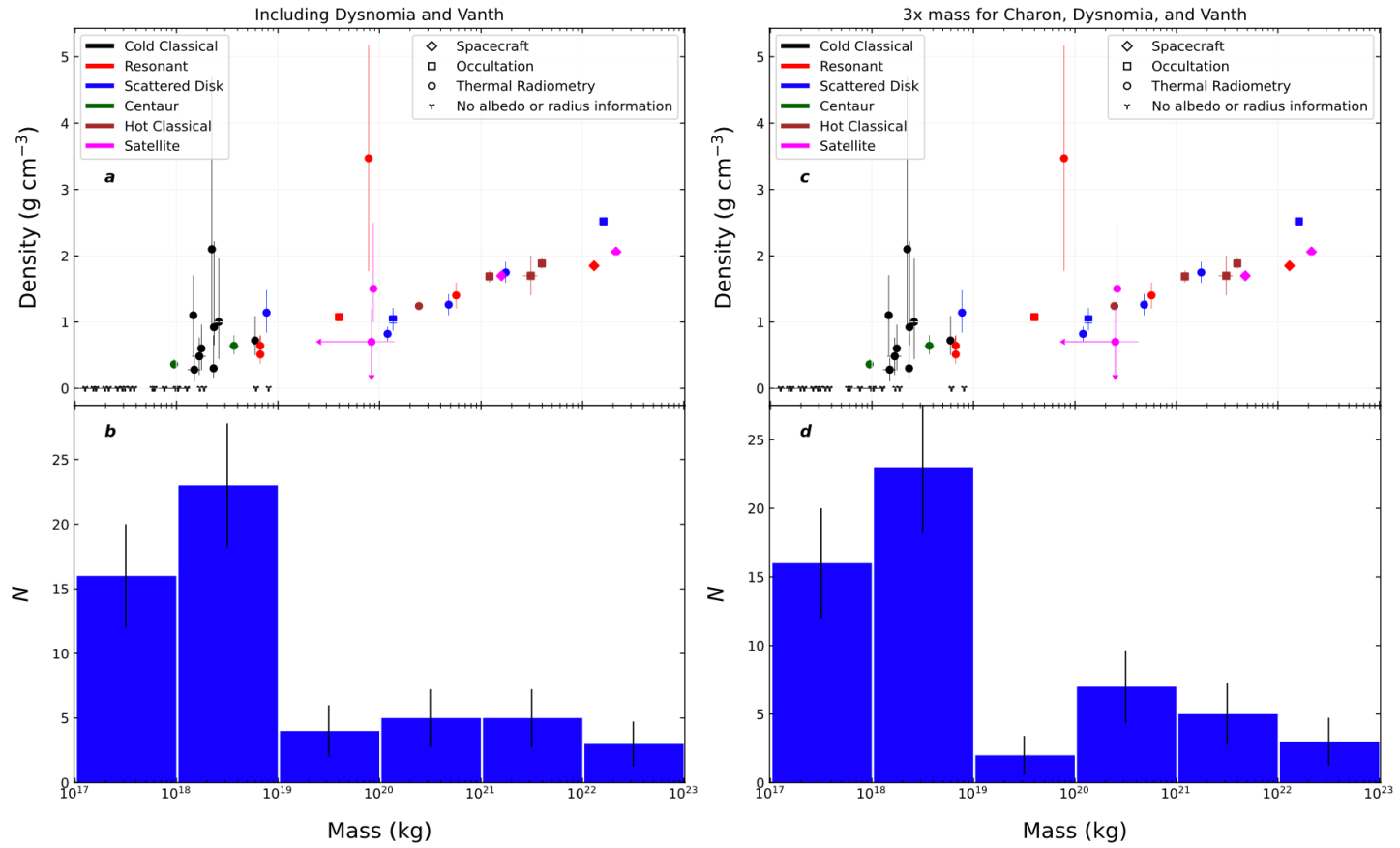


Data; Thomas (2000), Stansberry et al. (2006), Grundy et al. (2007), Brown et al. (2011), Stansberry et al. (2012), Brown (2013), Fornasier et al. (2013), Vilenius, et al. (2014), Nimmo et al. (2016), Ortiz et al. (2017), Brown and Butler (2017), Grundy et al. (2019), Morgado et al. (2023), Pereira et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

Did the high-mass objects lose their primordial satellites?

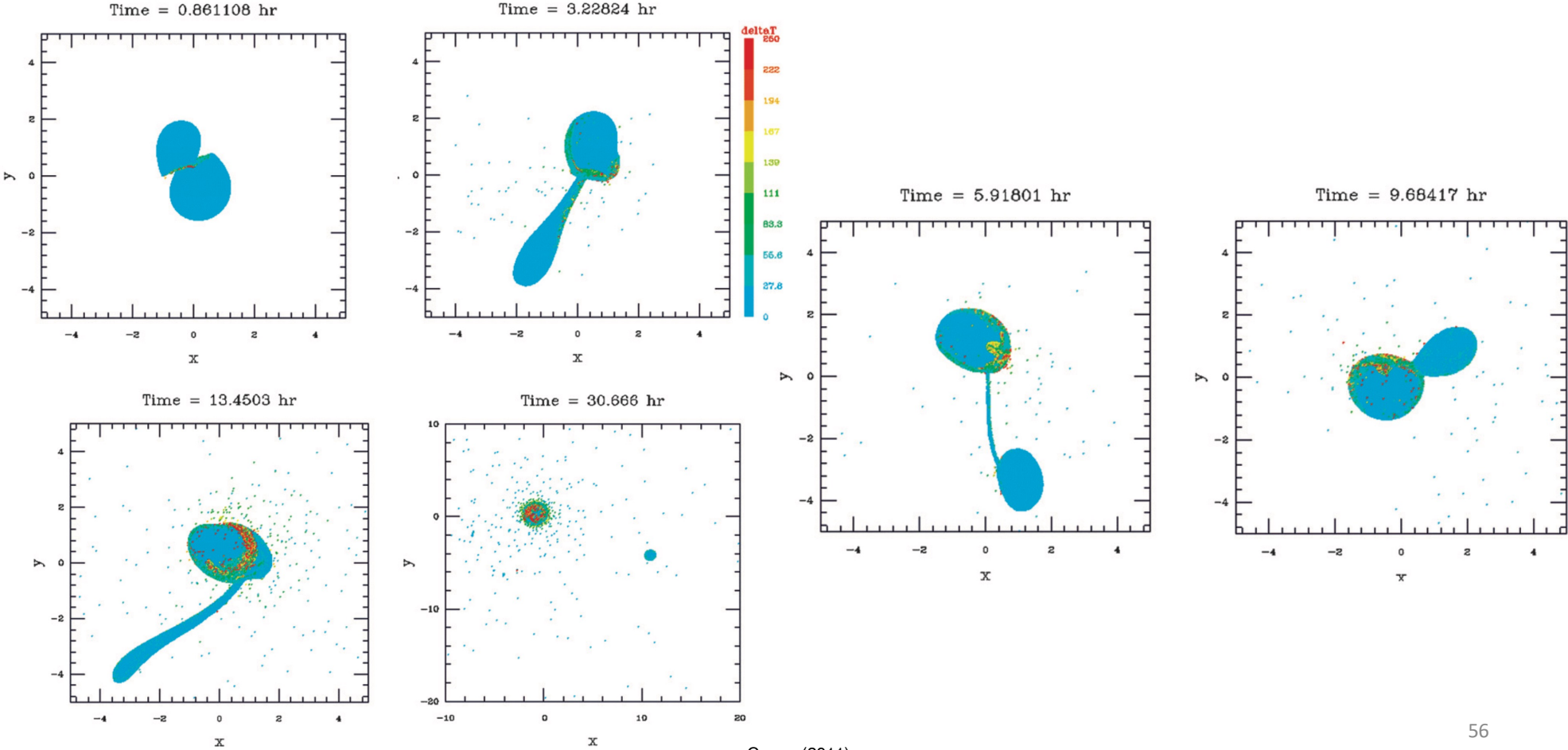


Satellites



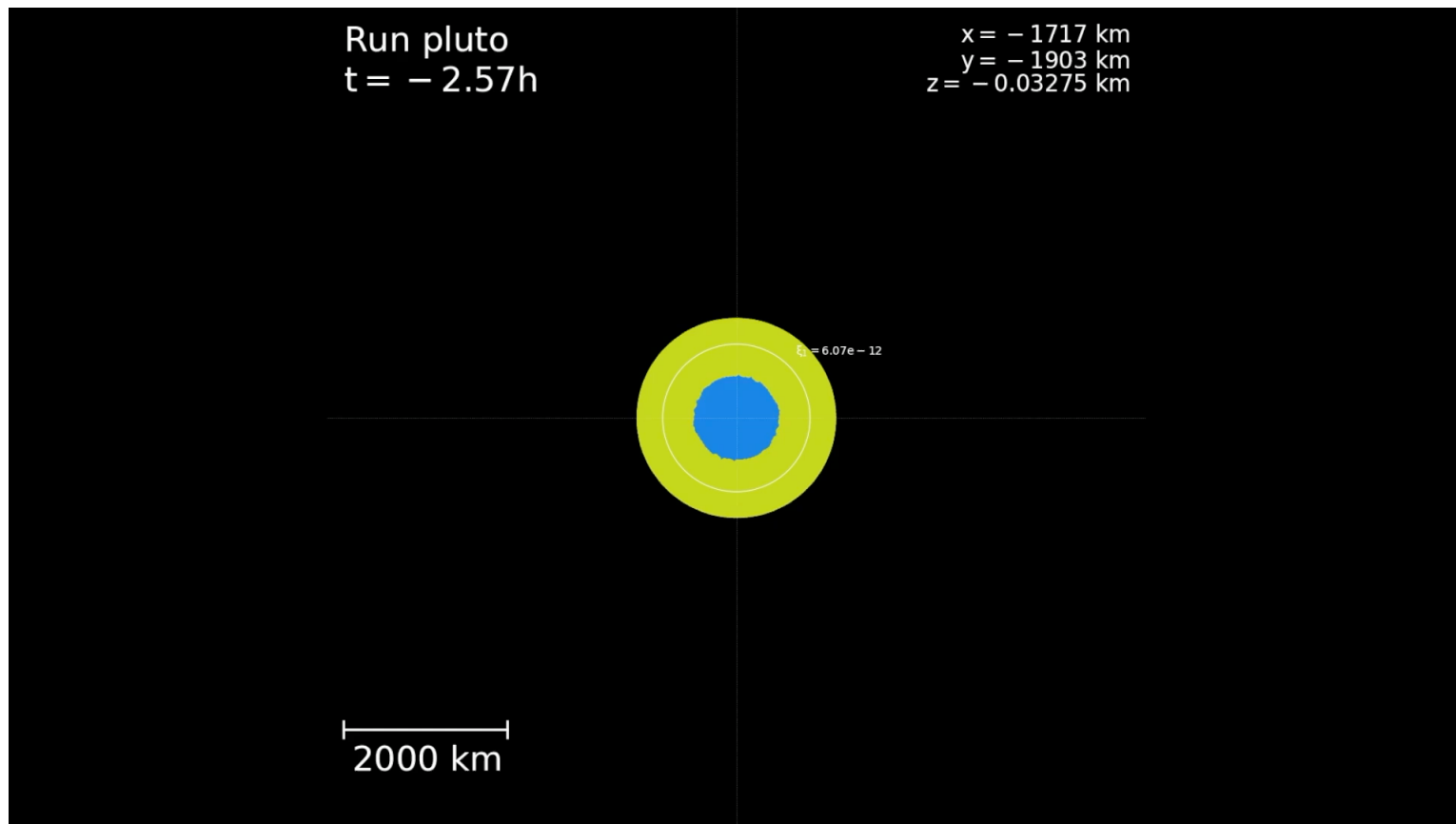
Lyra (2025, but see Denton et al. 2025 for lower mass ratios)

Pluto-Charon without strength high loss of mass scenario



Canup (2011)

Pluto-Charon with strength “kiss and capture” low loss of mass scenario



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
- 1mm ice grains preserved; 100 micron grains processed

A gap in KBO 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?
 - Eris is an outlier: wrong albedo? Collision removing ice mantle? (which also formed Dysnomia from the icy debris);

