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

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Las Cruces NM, USA

Uppsala, Oct 30th, 2025

NMSU Planet Formation Group

Postdoctoral Scholars

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(2022-)
Dust growth, meteoritics, accretion.

Daniel Carrera
(2024-)
Planetesimal formation, pebble accretion

Alumni

Ali Hyder
(2019-2022)
Jupiter's atmosphere and geochemistry.

Manuel Cañas
(2019-2023)
Kuiper belt objects.

Graduate Students

Harrison Cook
(2019-)
Black hole mergers
Transients in AGN

Daniel Godines
(2021-)
Observational signatures of streaming instability

Eleanor Serviss
(2024-)
Gravitational Instability

Leopold Hutnik
(2024-)
Pebble Accretion

Olivia Brouillette
(2024-)
Streaming Instability

The PFITS+ Collaboration
(Planet Formation in the Southwest – and beyond)

Co-PIs

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Andrew Youdin – *University of Arizona*
Jake Simon – *Iowa State University*
Chao-Chin Yang –*University of Alabama*
Orkan Umurhan – *NASA Ames*

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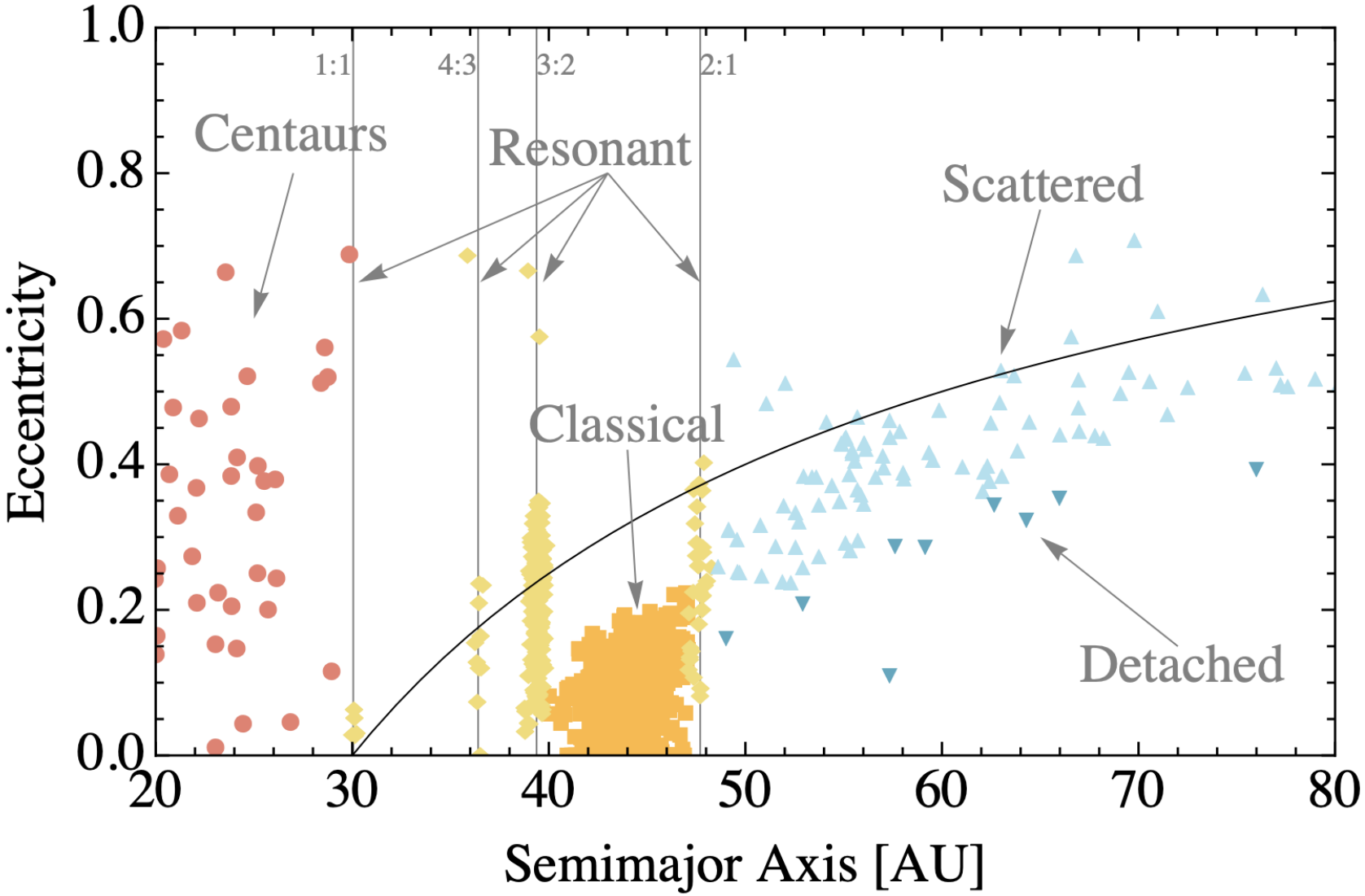
Eleanor Serviss, Leopold Hutnik
ISU – Jeonghoon (Jay) Lim, David Rea, Weston Hall
UNLV – Stanley Baronett
U Az – Eonho Chang

Alumni

Manny Cañas (NMSU), Aleksey Mohov (MSc UNLV),
Leonardo Krapp (UAz -> Chile),

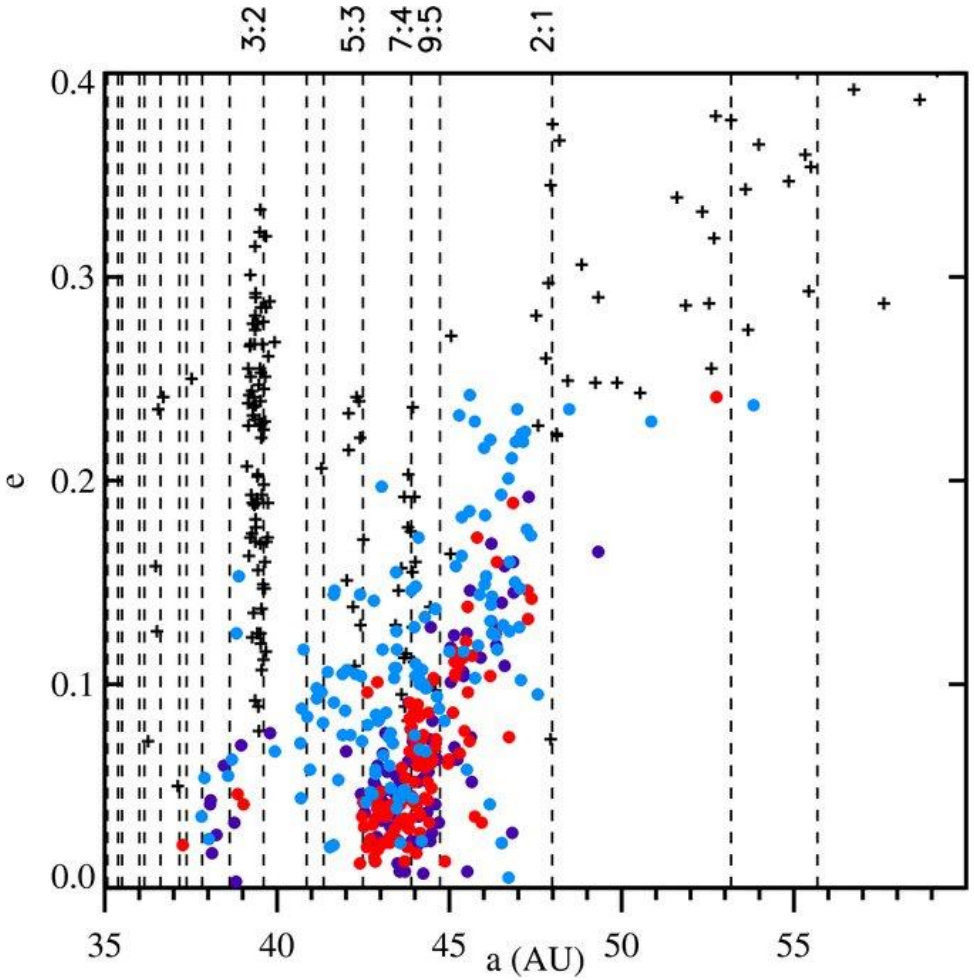
Structure of the Kuiper Belt



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

Cold Classicals

Presumably pristine planetesimals

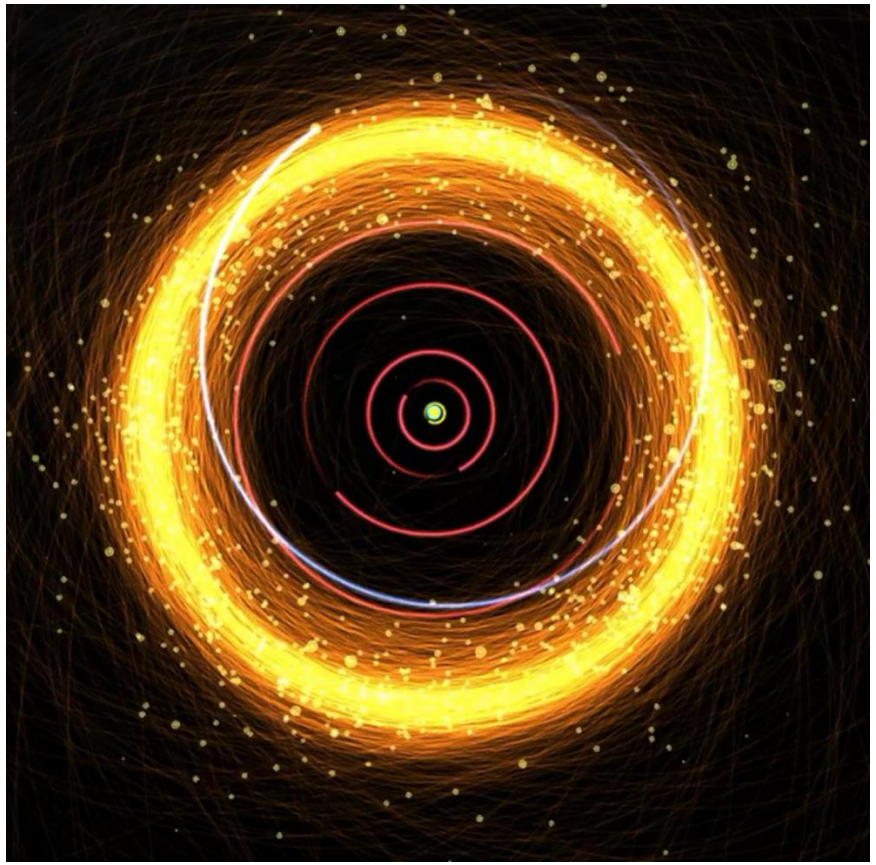


+ Resonant and Scattered

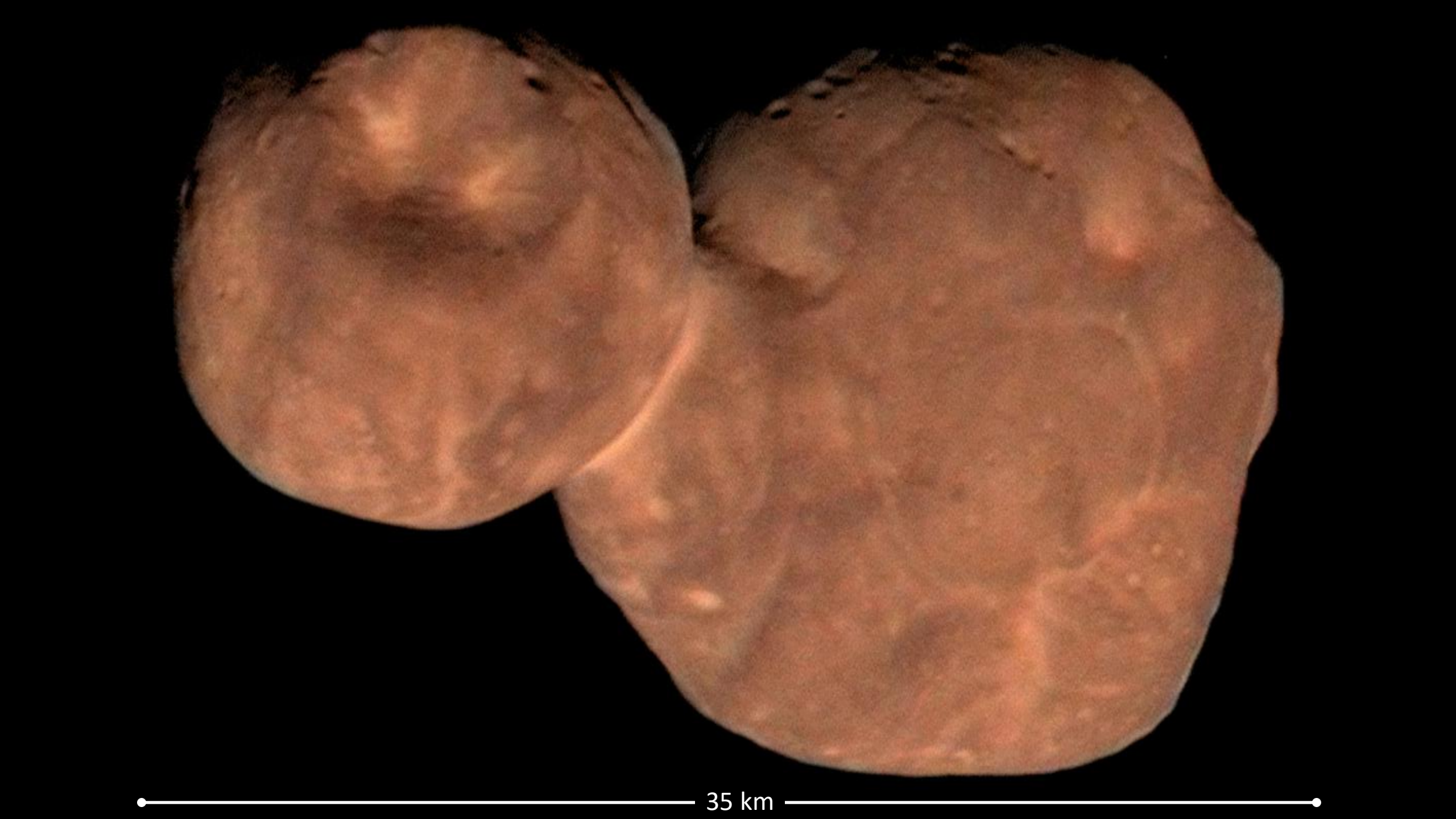
Cold Classical $i<2^o$

"Ambiguous" $2^o<i<6^o$

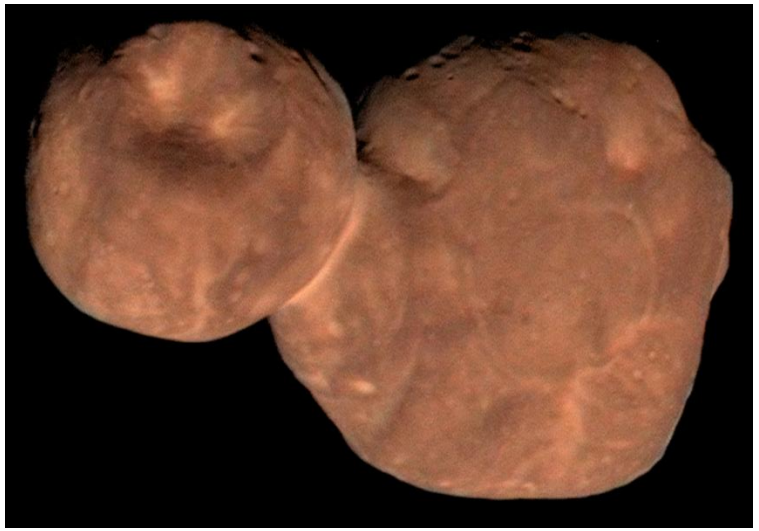
Hot Classicals $i>6^o$

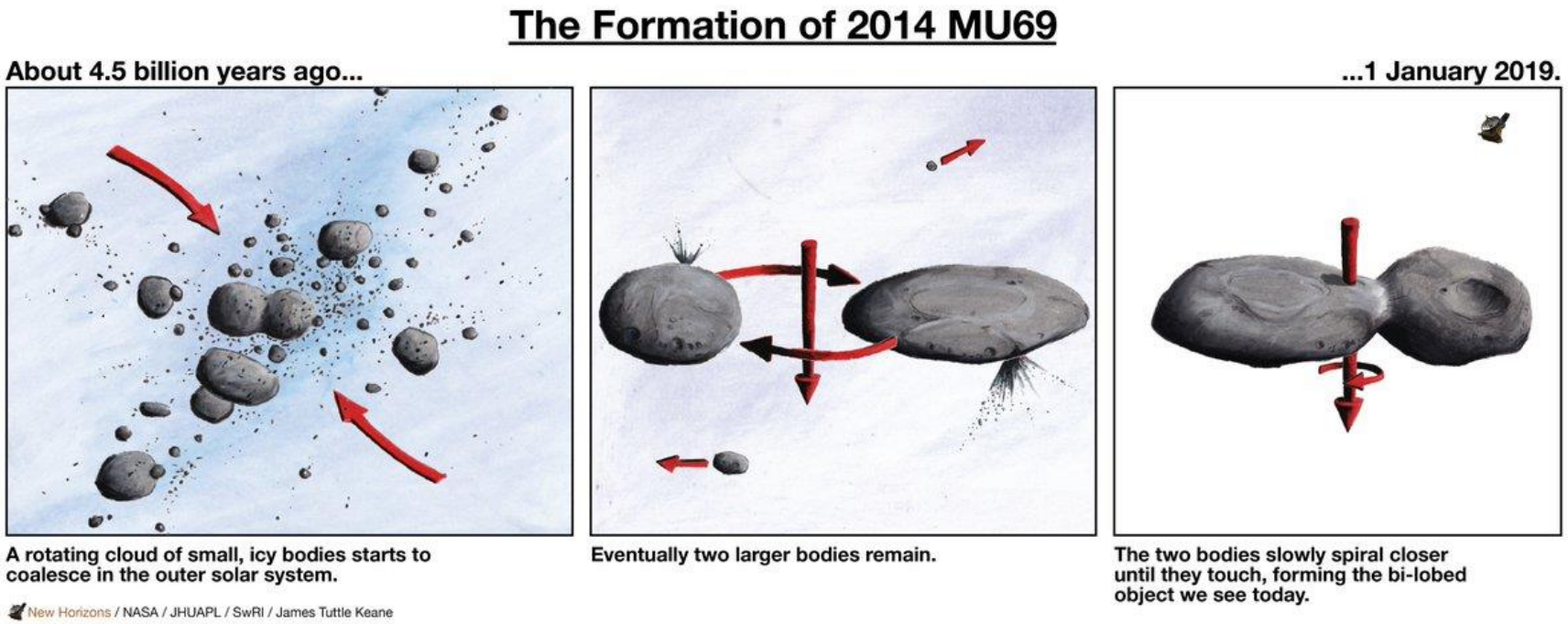


Gladman+ '08, Lacerda '09, Batygin+ '10, Dawson & Murray-Clay '12


35 km

Arrokoth (MU_{69})



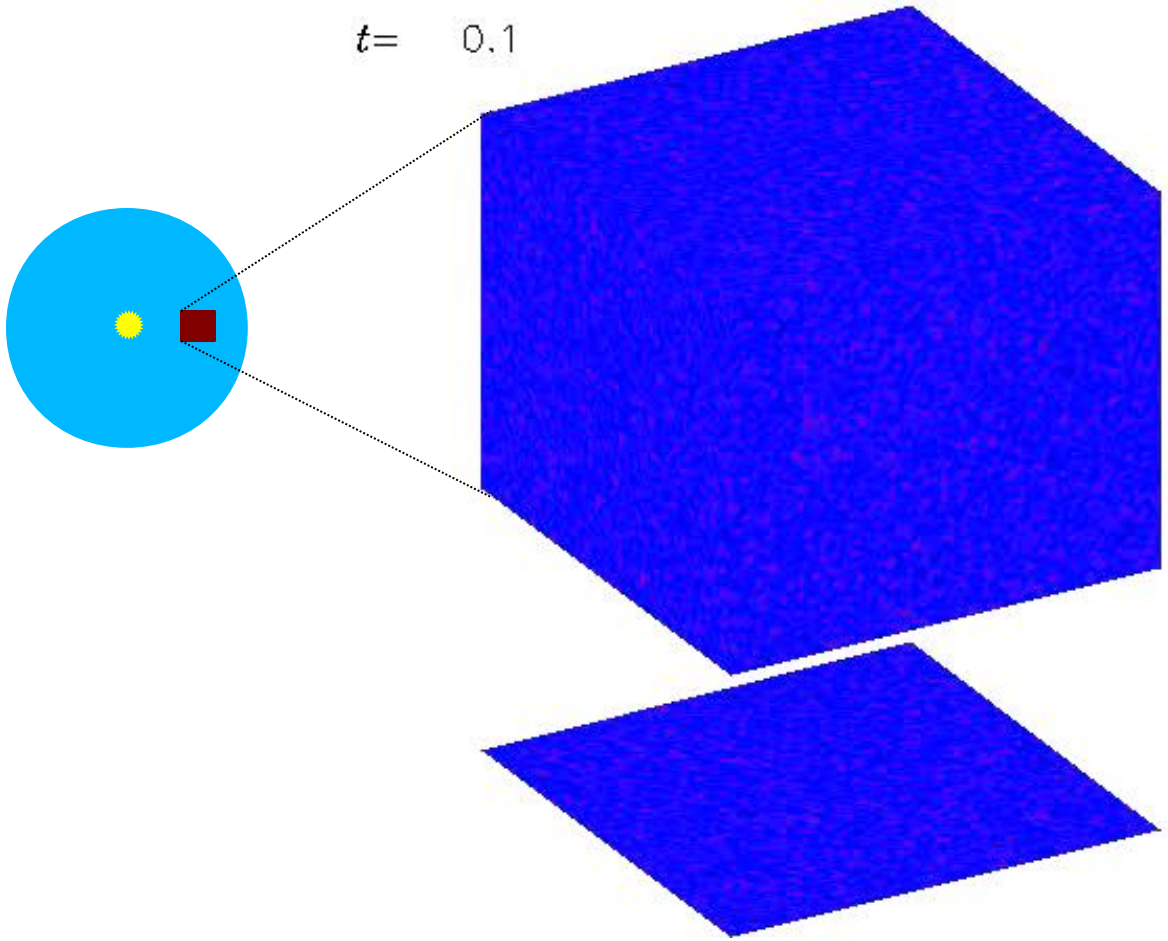


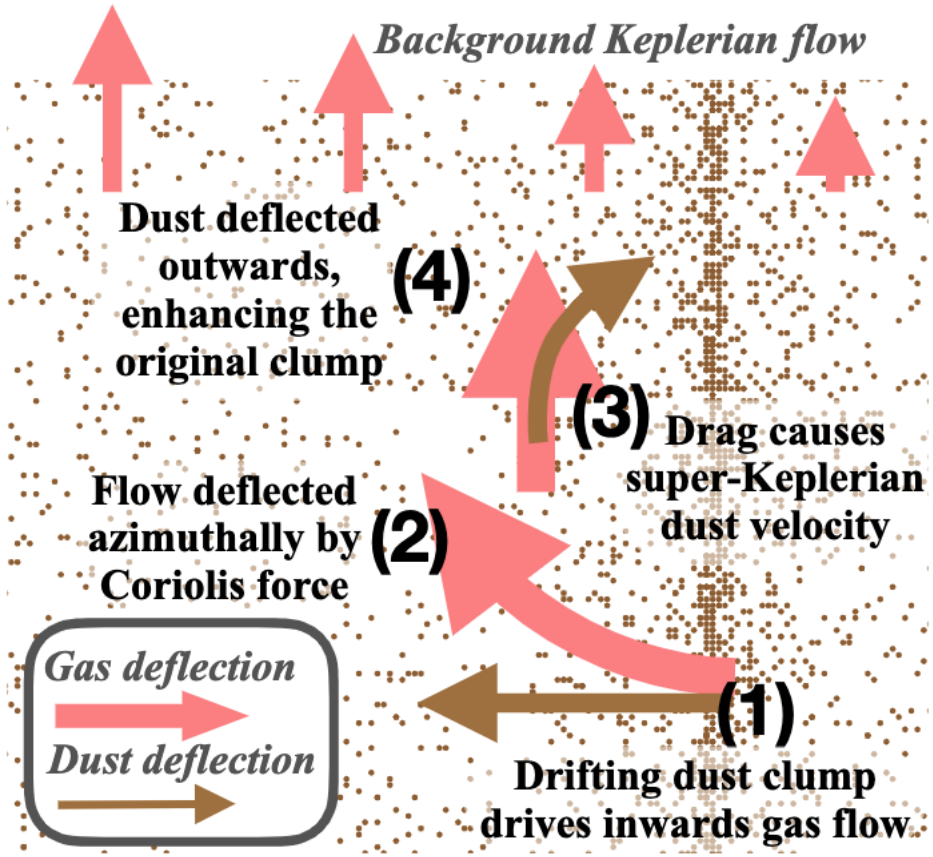
New Horizons Flyby, Jan 2019

Sketch by J.T. Keane

Streaming Instability

The dust drift is hydrodynamically unstable

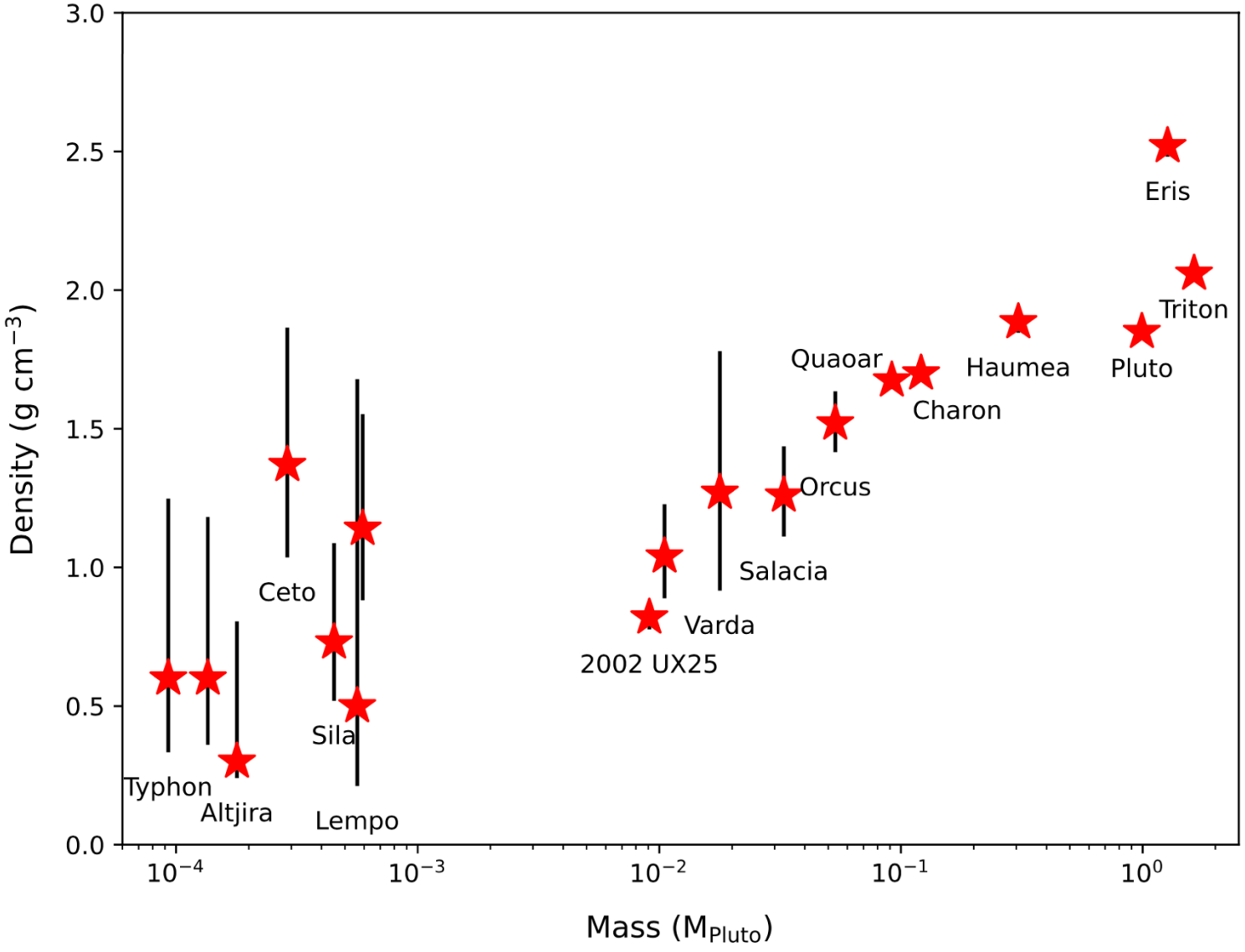




Lesur et al. (2022)

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

The size-density relationship of Kuiper Belt objects



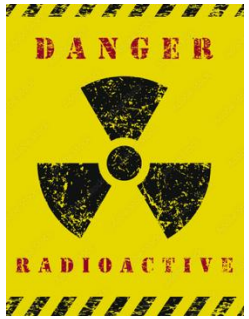
Brown (2013), McKinnon et al. (2017), Noll et al. (2020), Cañas & Lyra + (2024)

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

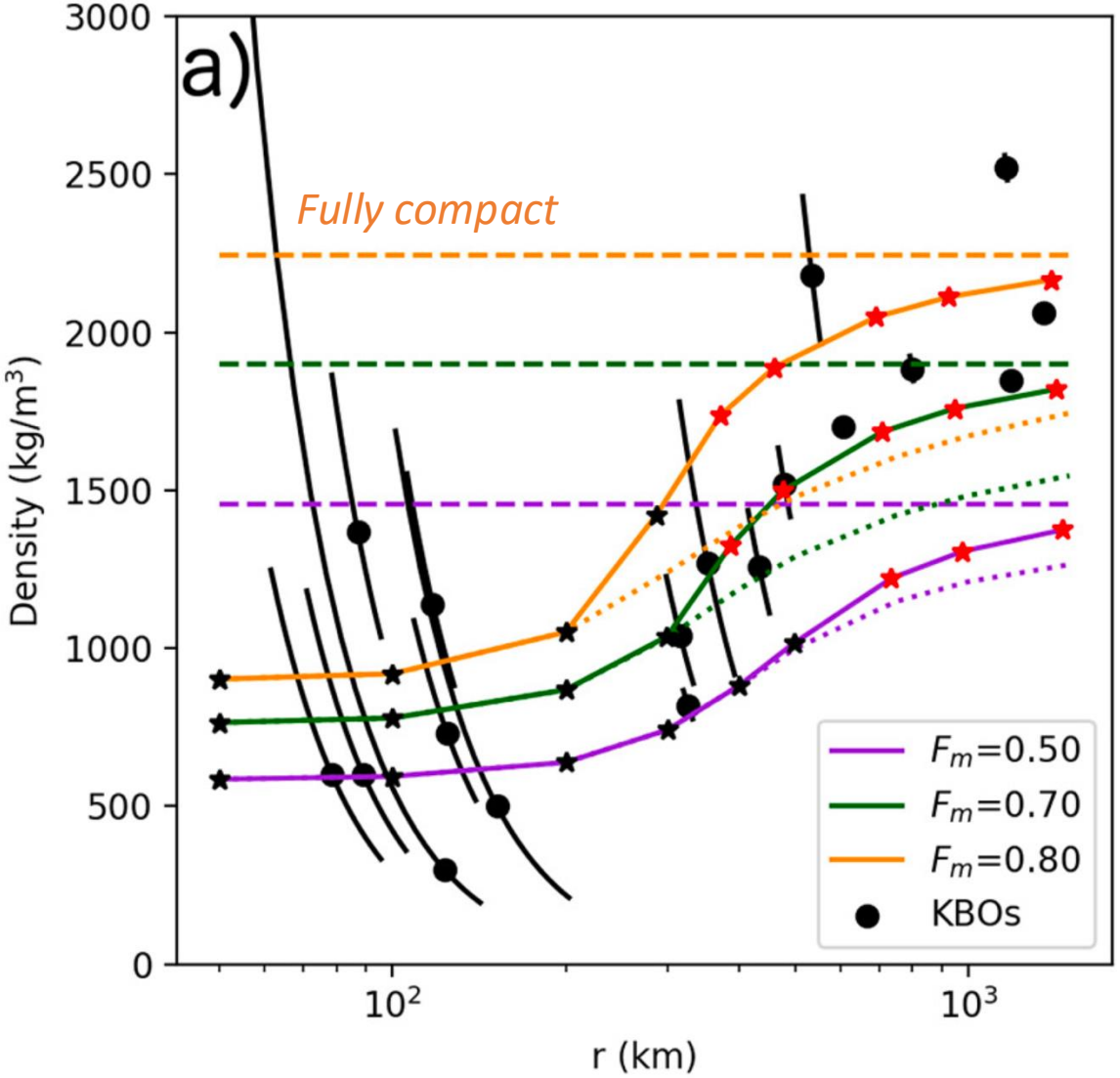
Problem

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



Assumptions

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

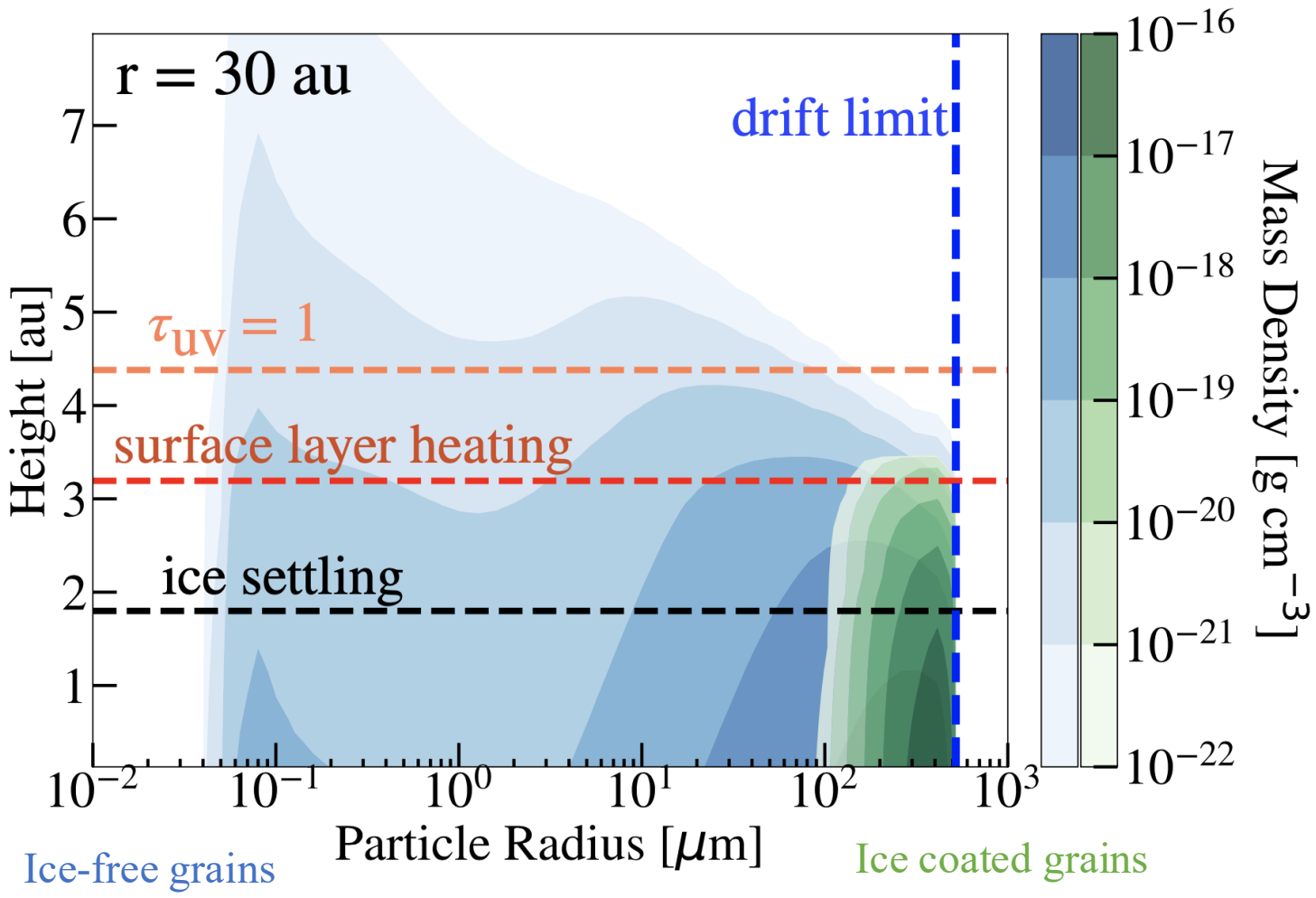


F_m = rock mass fraction

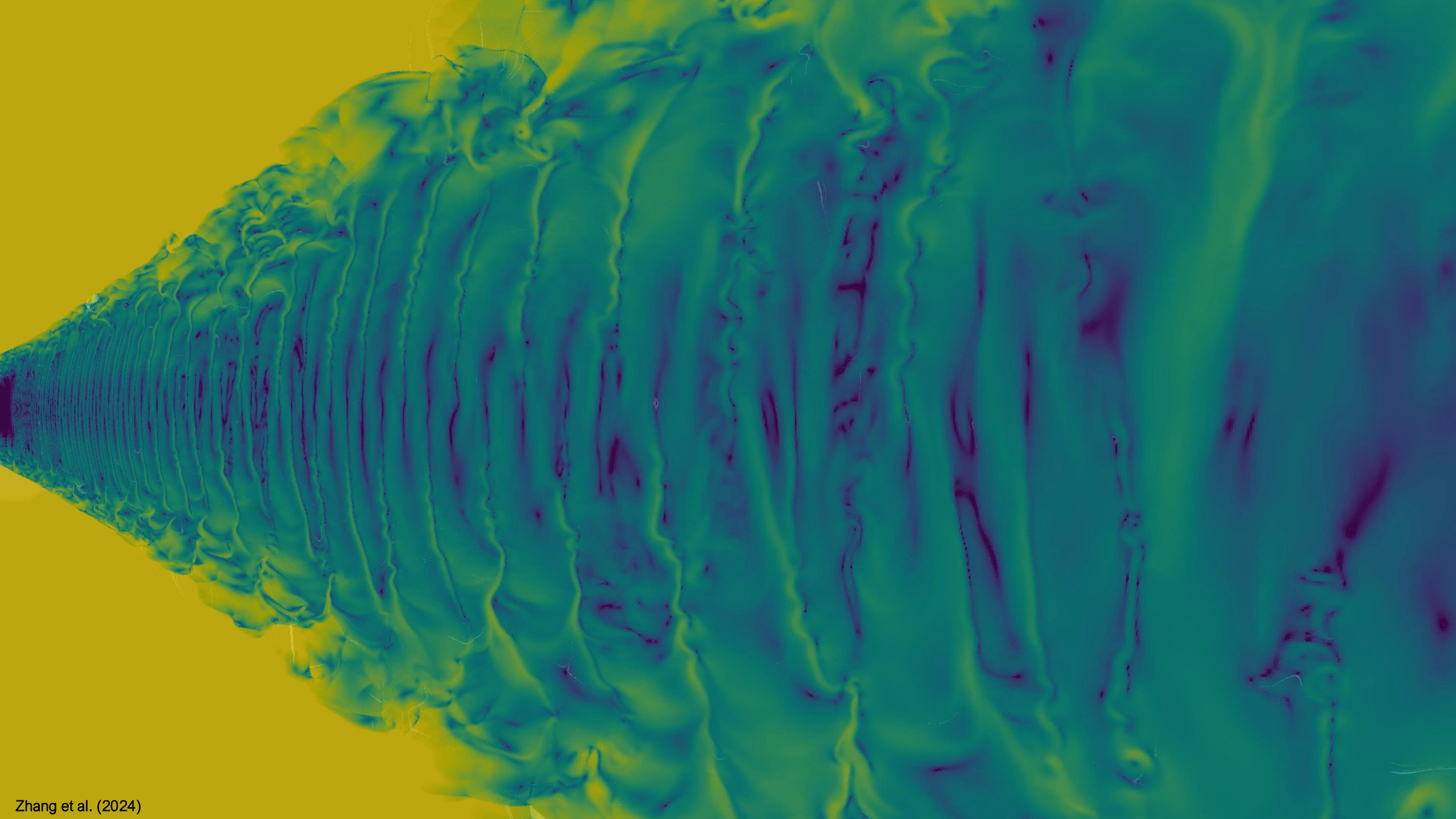
Bierson & Nimmo (2019)

Thermal and photo-desorption

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



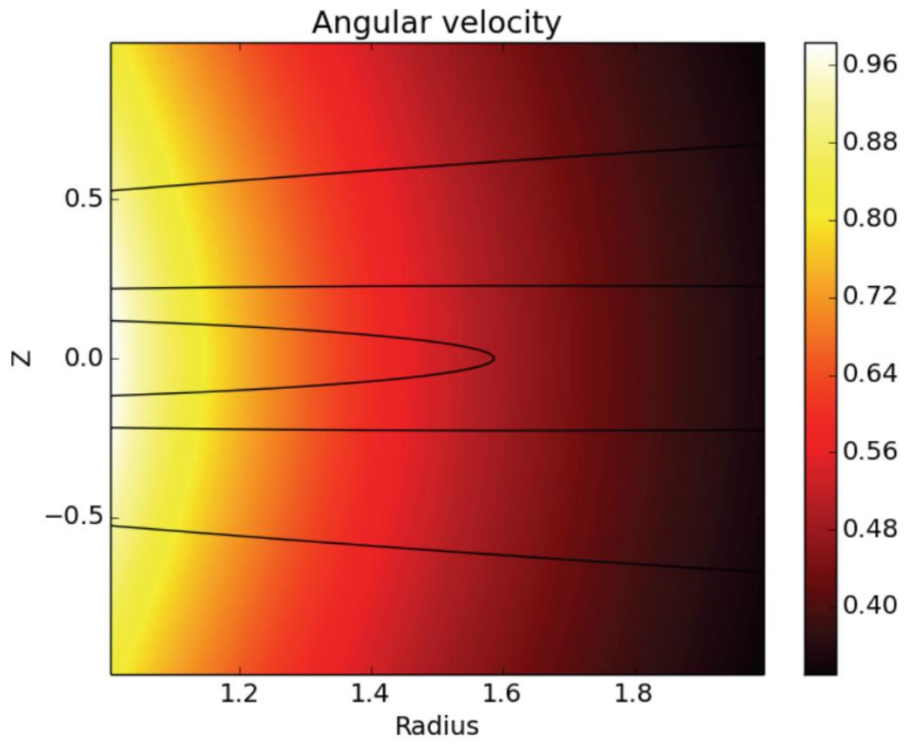
Powell et al. (2022)

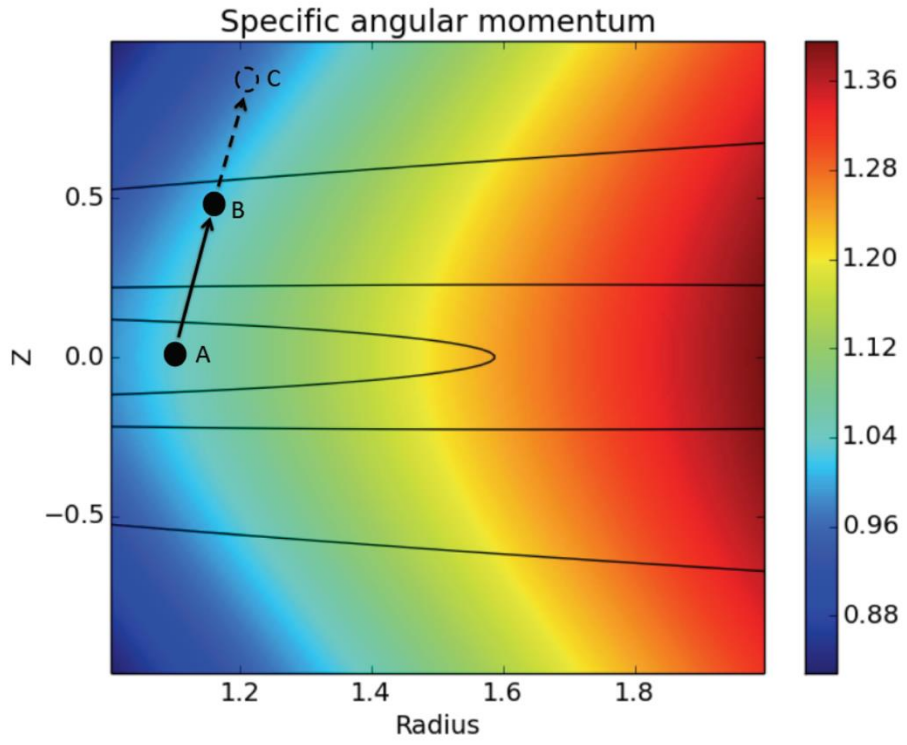


Zhang et al. (2024)

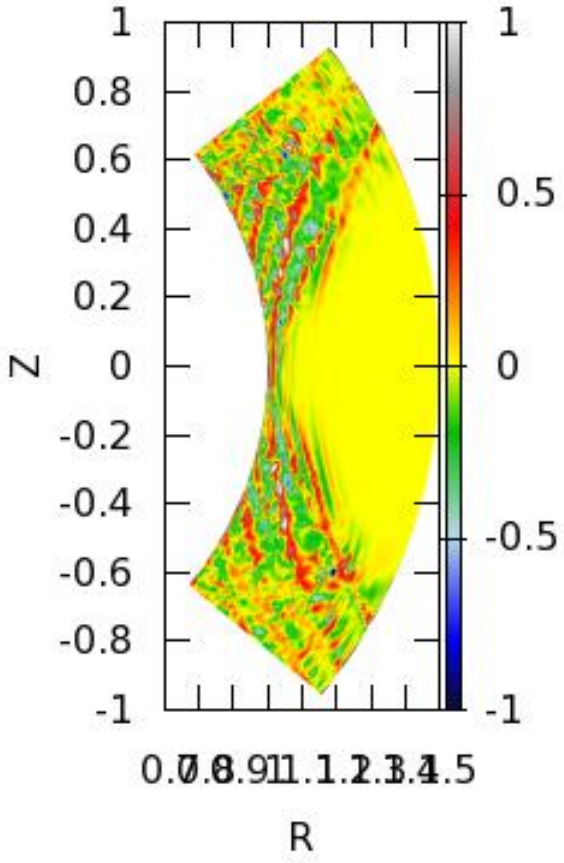
Vertical shear instability

Angular momentum decreases vertically: unstable





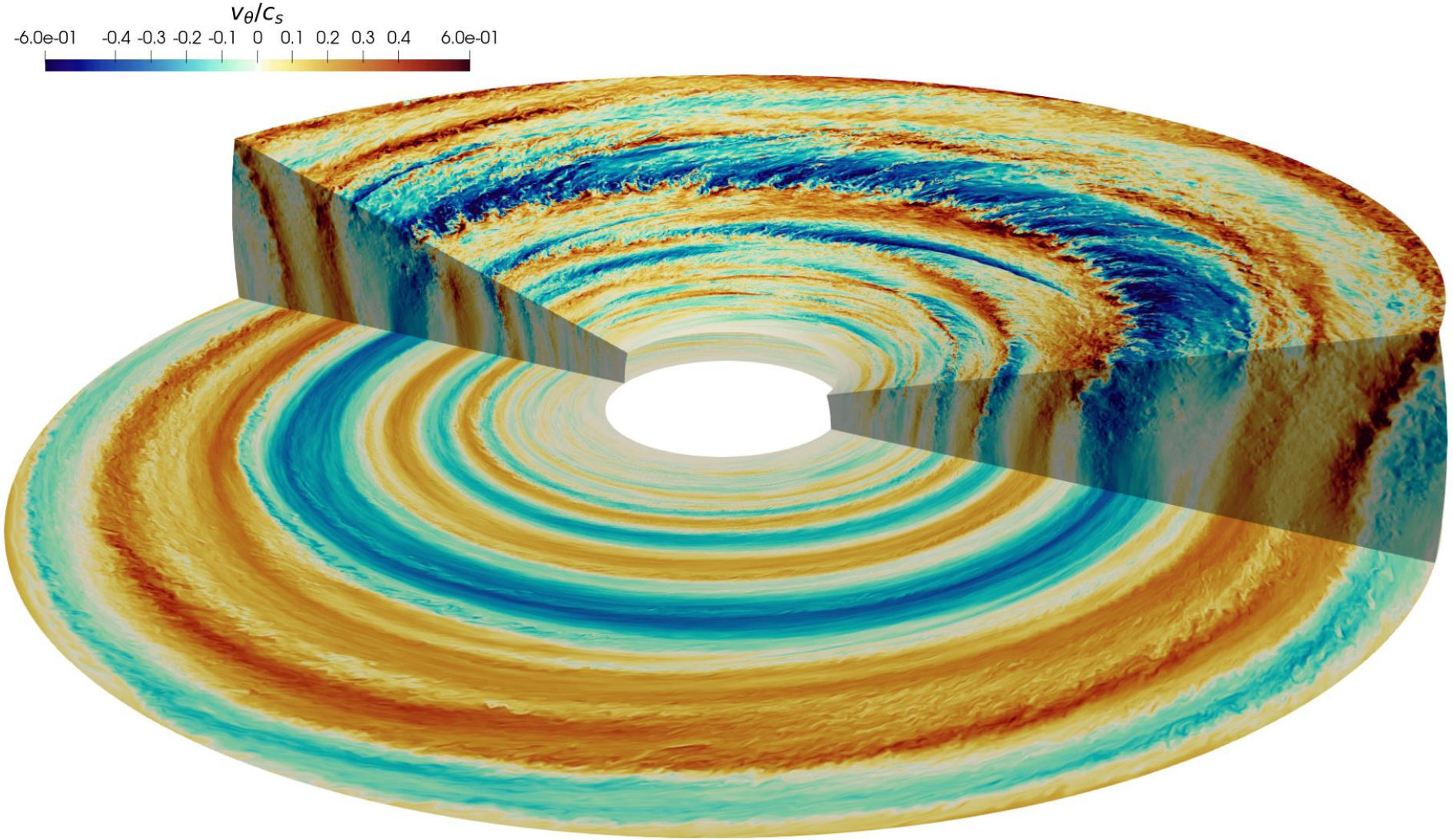
Fromang & Lesur (2017)



Nelson et al. (2013)

Urpin & Brandenburg (1998), Urpin (2003), Nelson et al. (2013),
Barker & Latter (2015), Fromang & Lesur (2017), Flock et al. (2020), Zhang et al. (2024)

Vertical shear instability

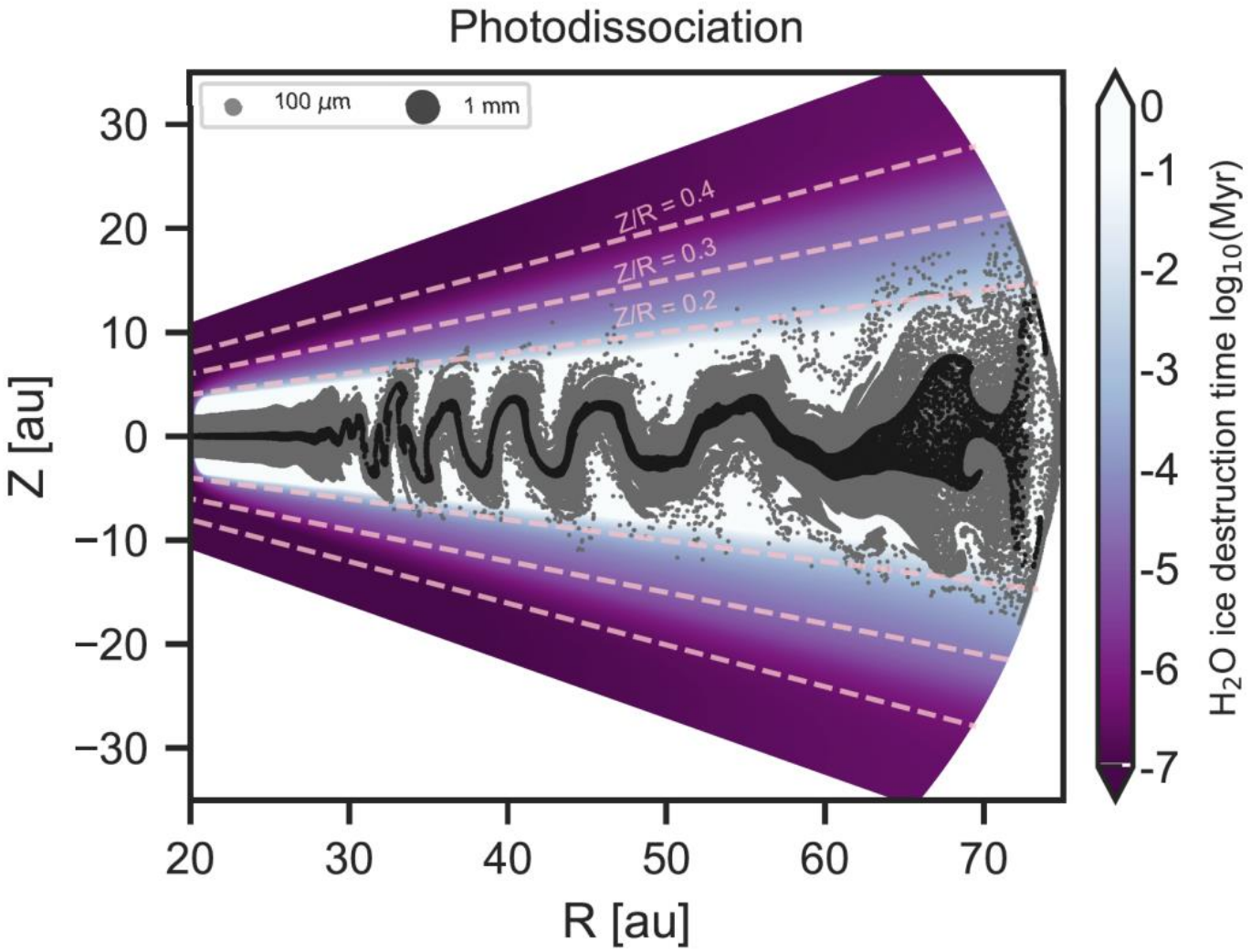


Resolution 3872 x 2000 x 12544
Run on 4096 GPUs

Lesur et al (2025)

Thermal and photo-desorption

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

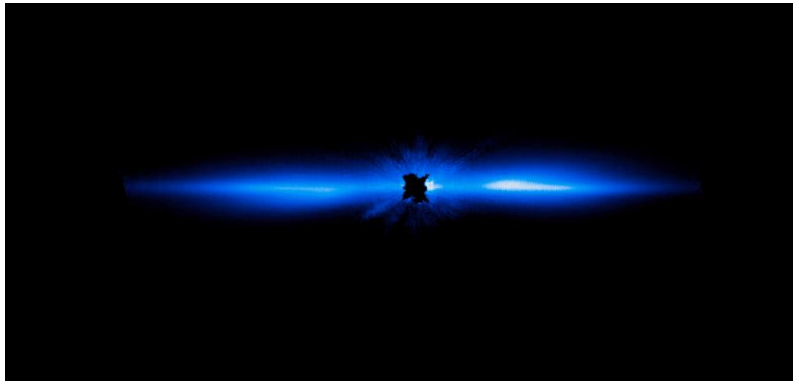


Flores-Rivera et al. (2025)

Thermal and photo-desorption

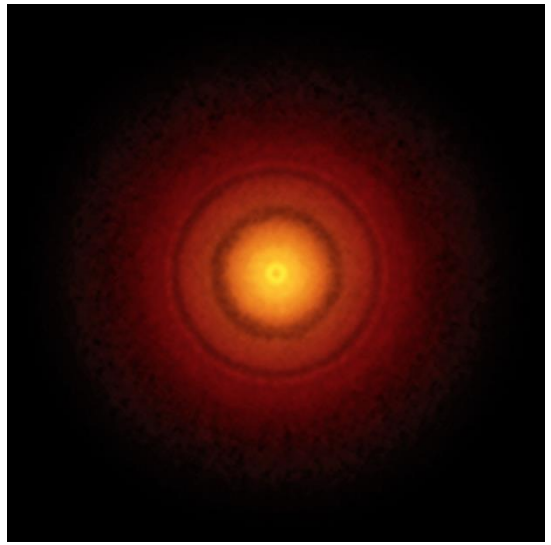
Evidence in disks

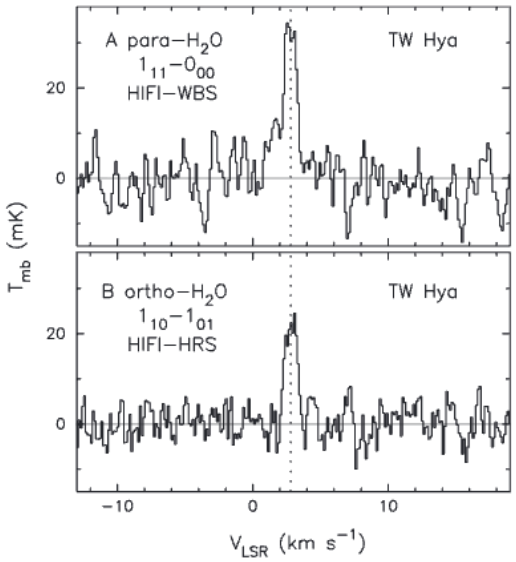
Debris disks



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

Primordial disks

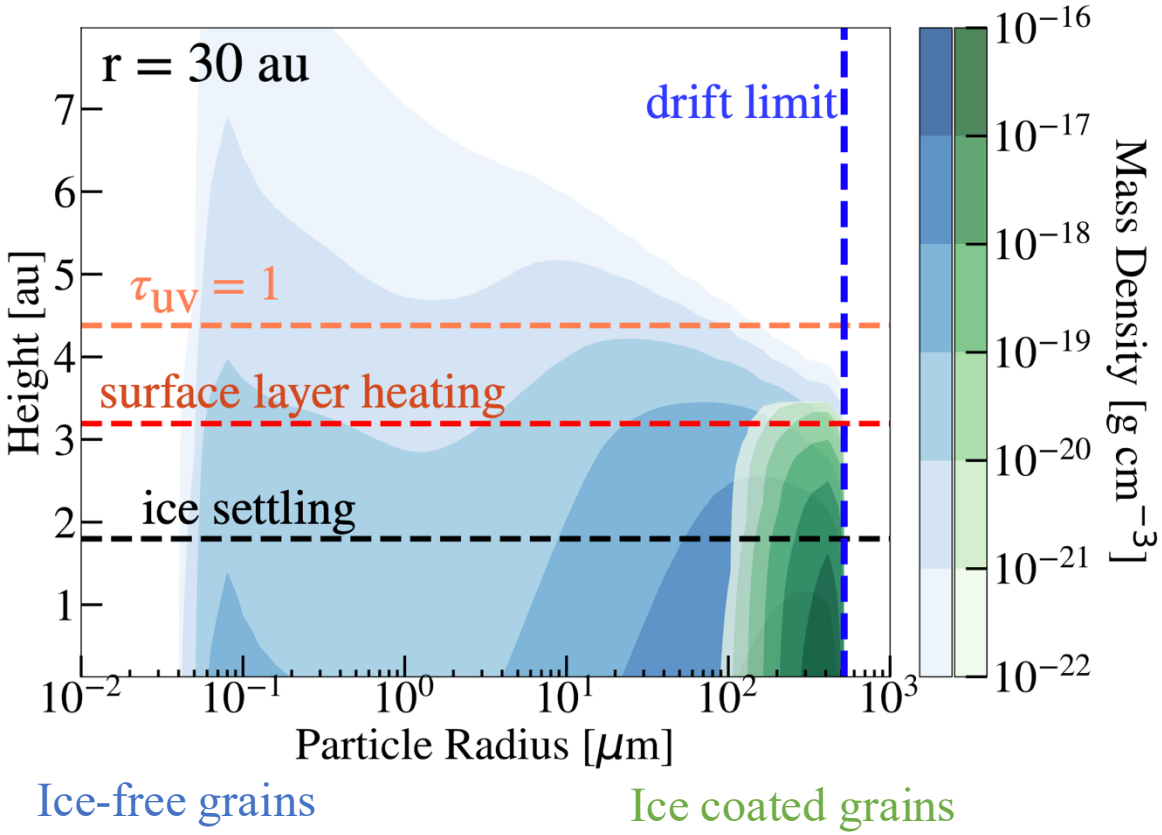




Water vapor observed at large distances for TW Hya
(Hogerheijde et al. 2011, 2012)

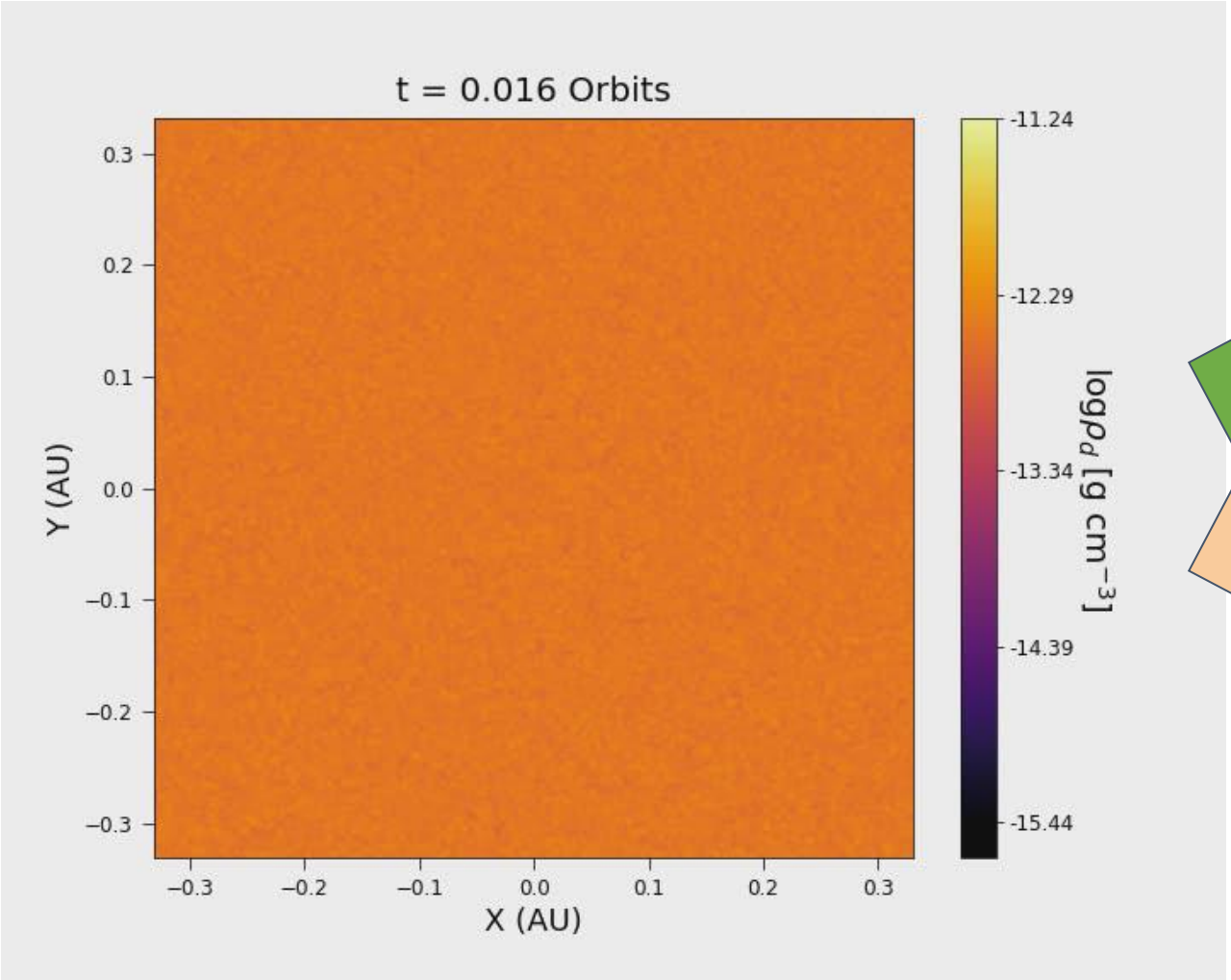
Proof-of-concept model

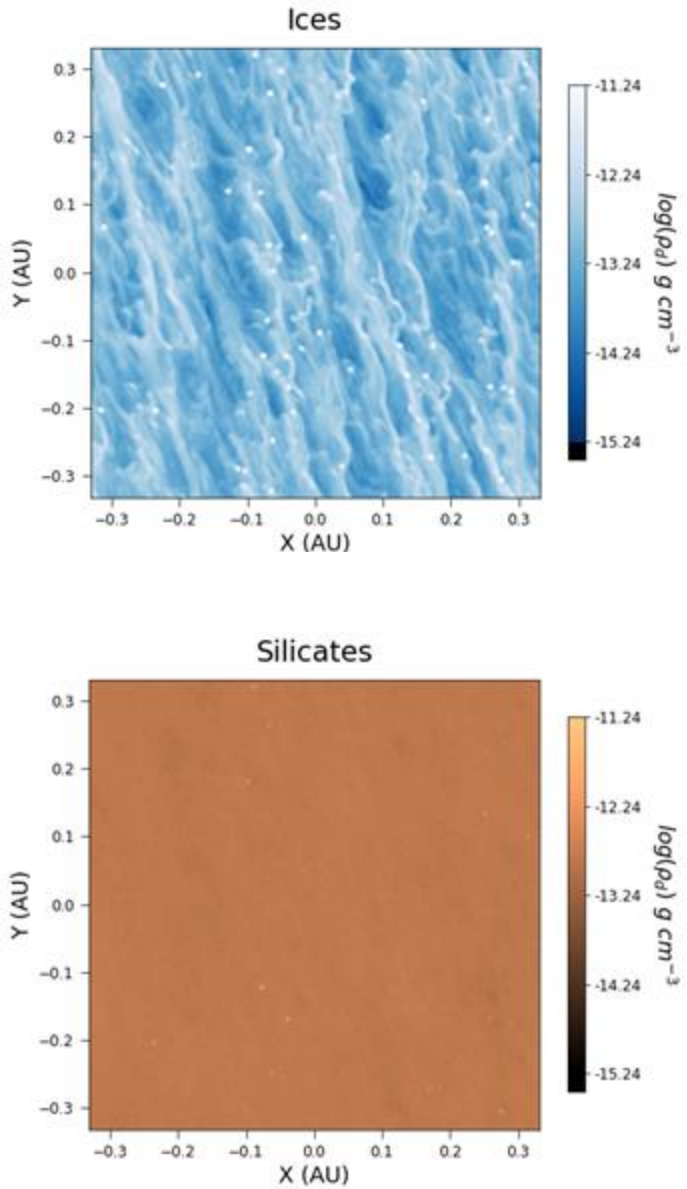
Small grains lofted in the atmosphere lose ice
Big grains are shielded and remain icy.



Powell et al. (2022)

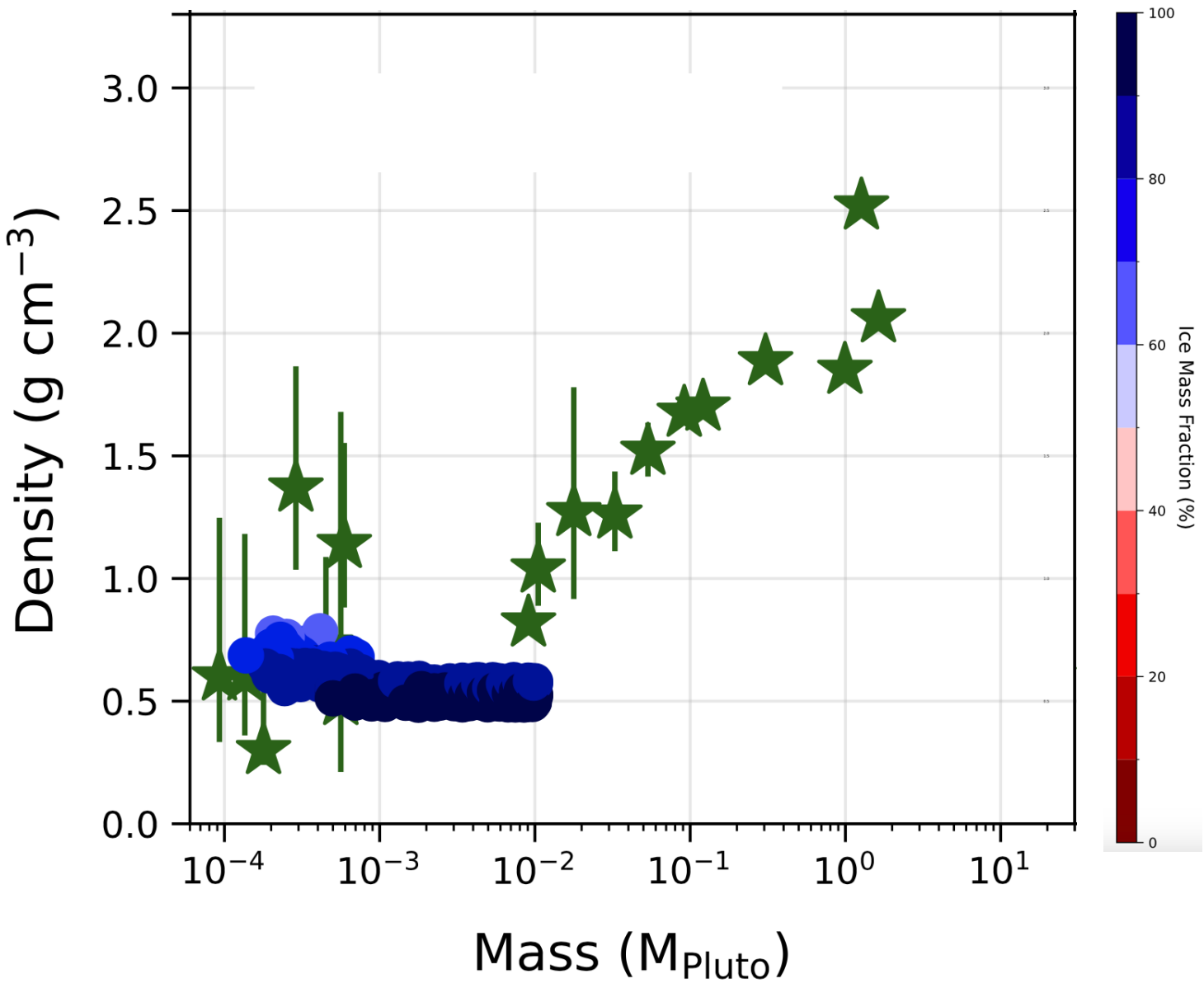
Split into icy and silicate pebbles





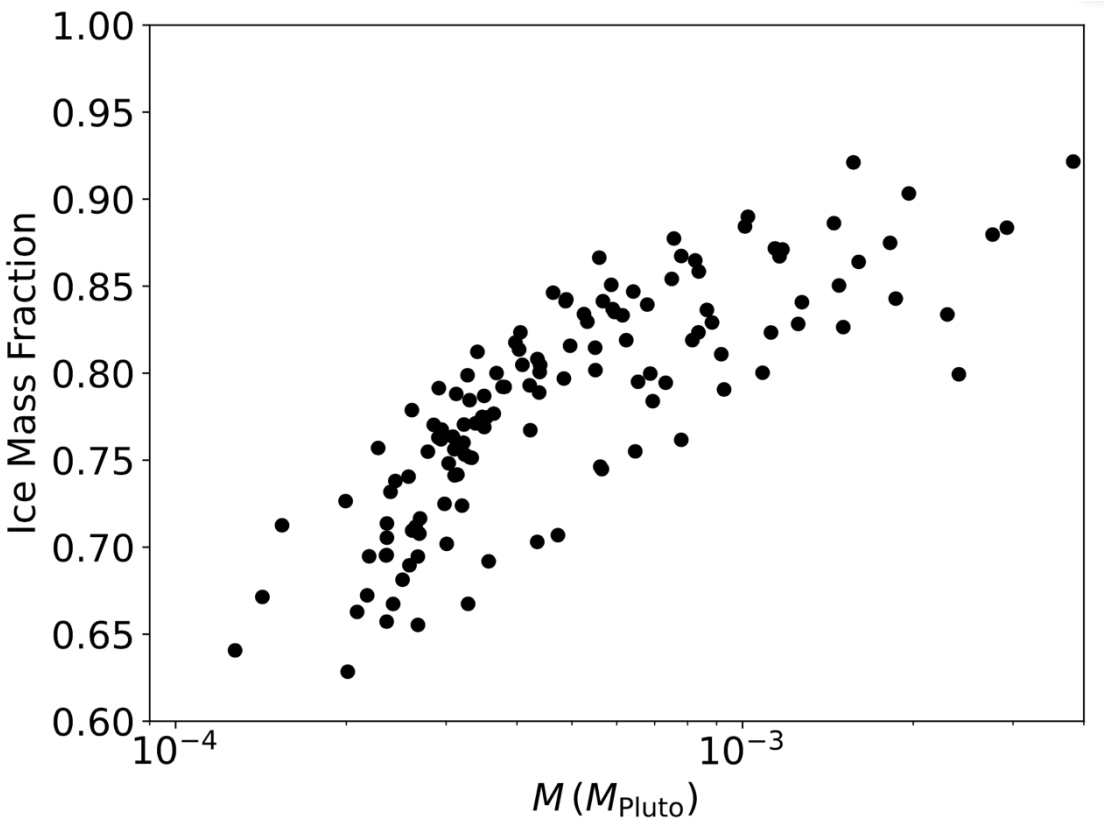
Canas & Lyra + (2024)

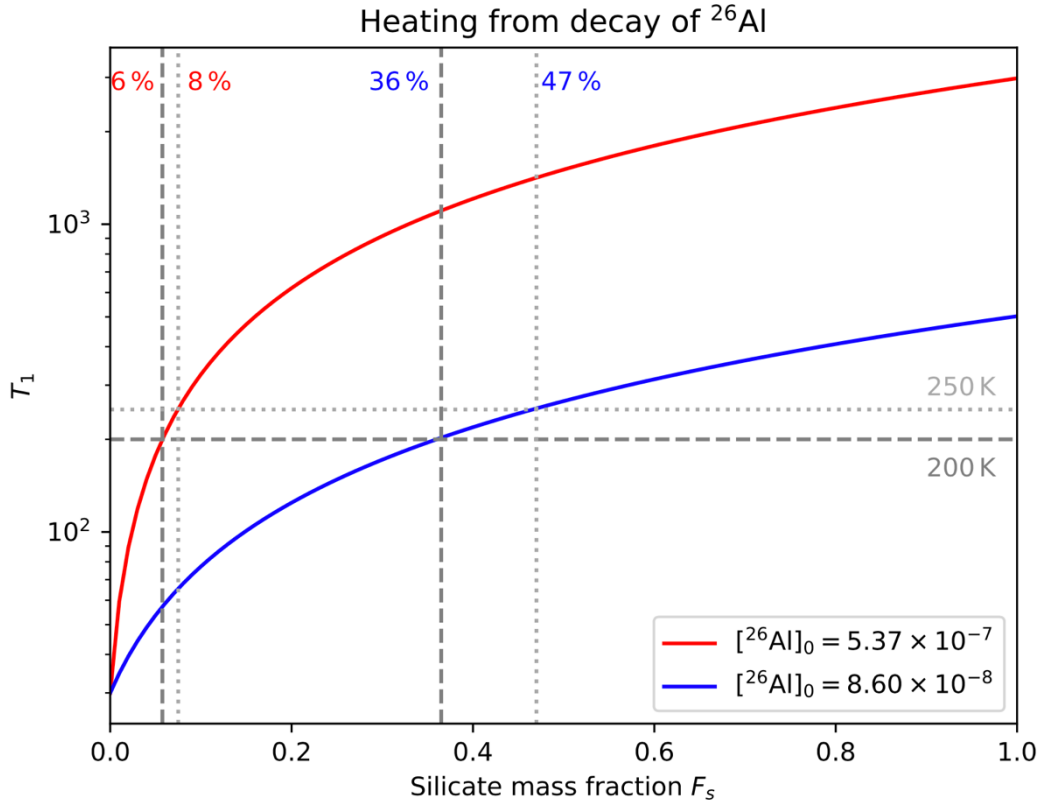
The first planetesimals are icy



Canas & Lyra + (2024)

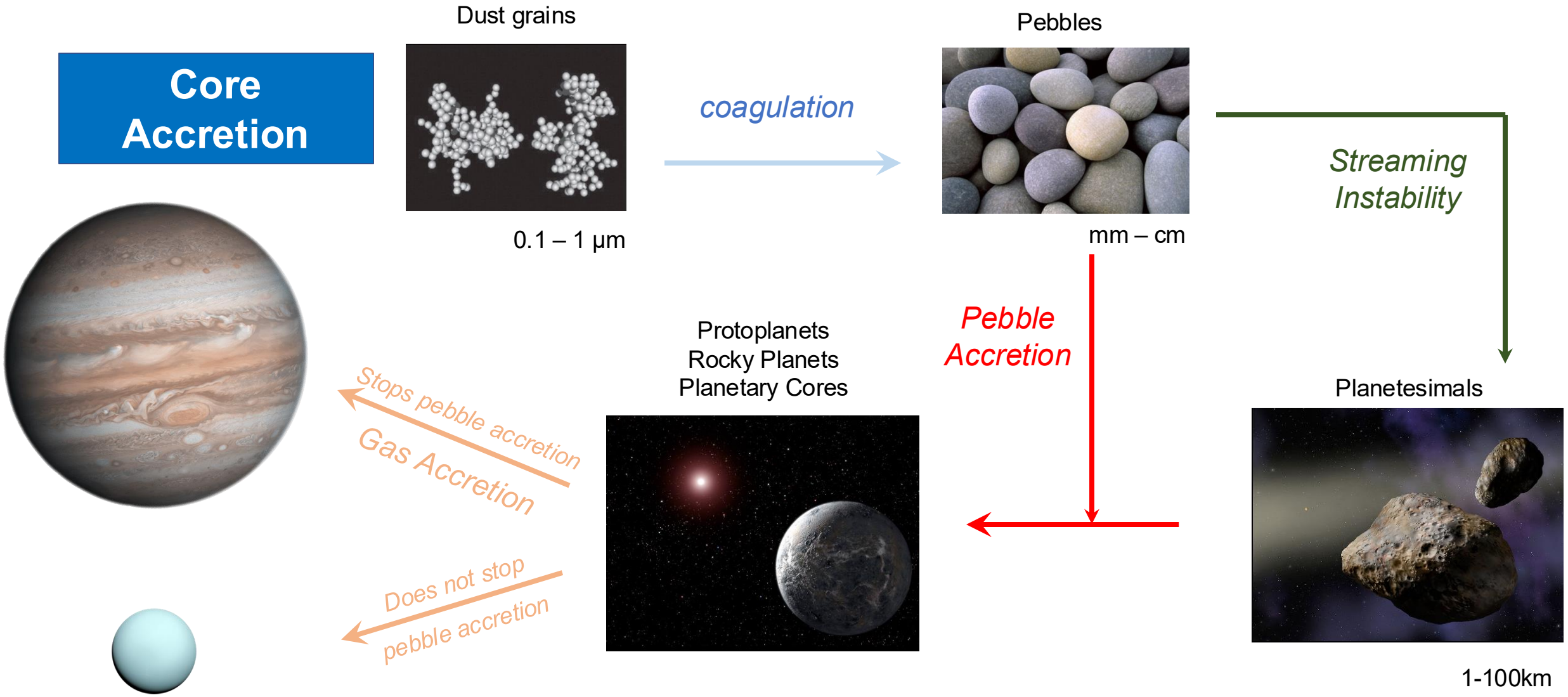
^{26}Al binds to silicates: the first planetesimals won't melt



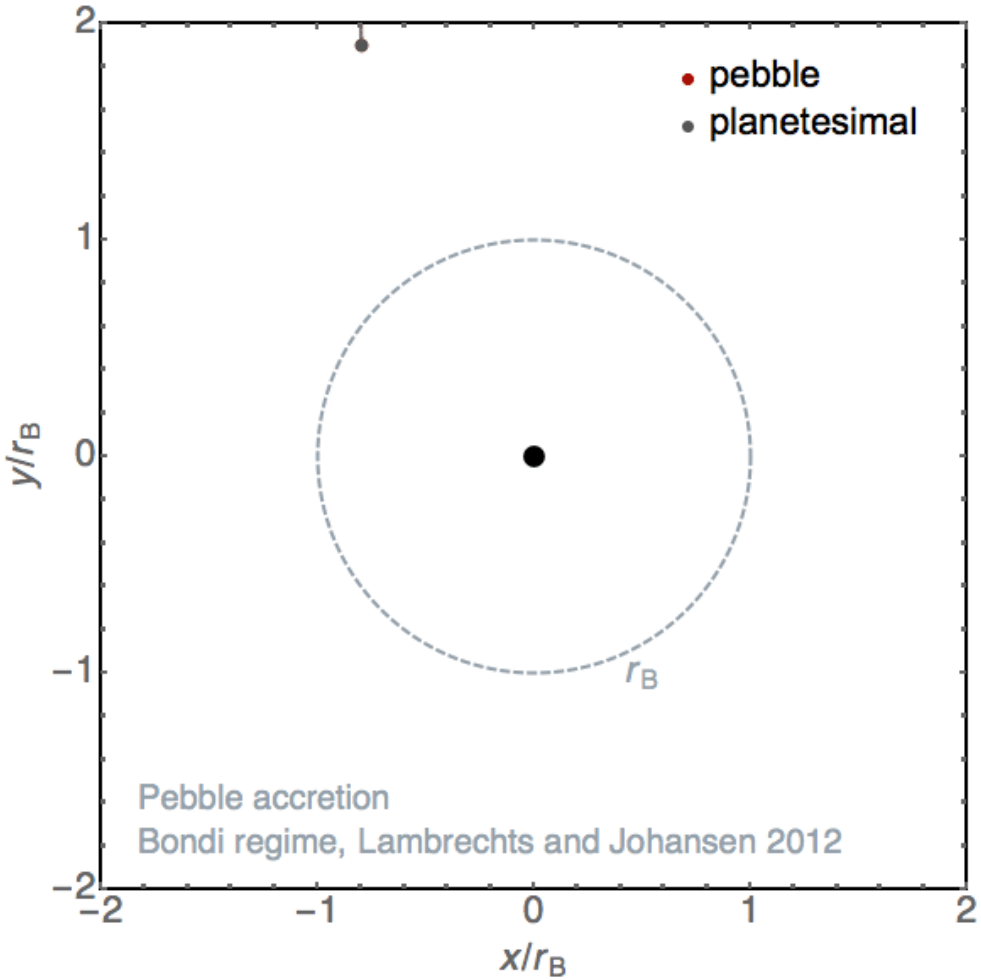


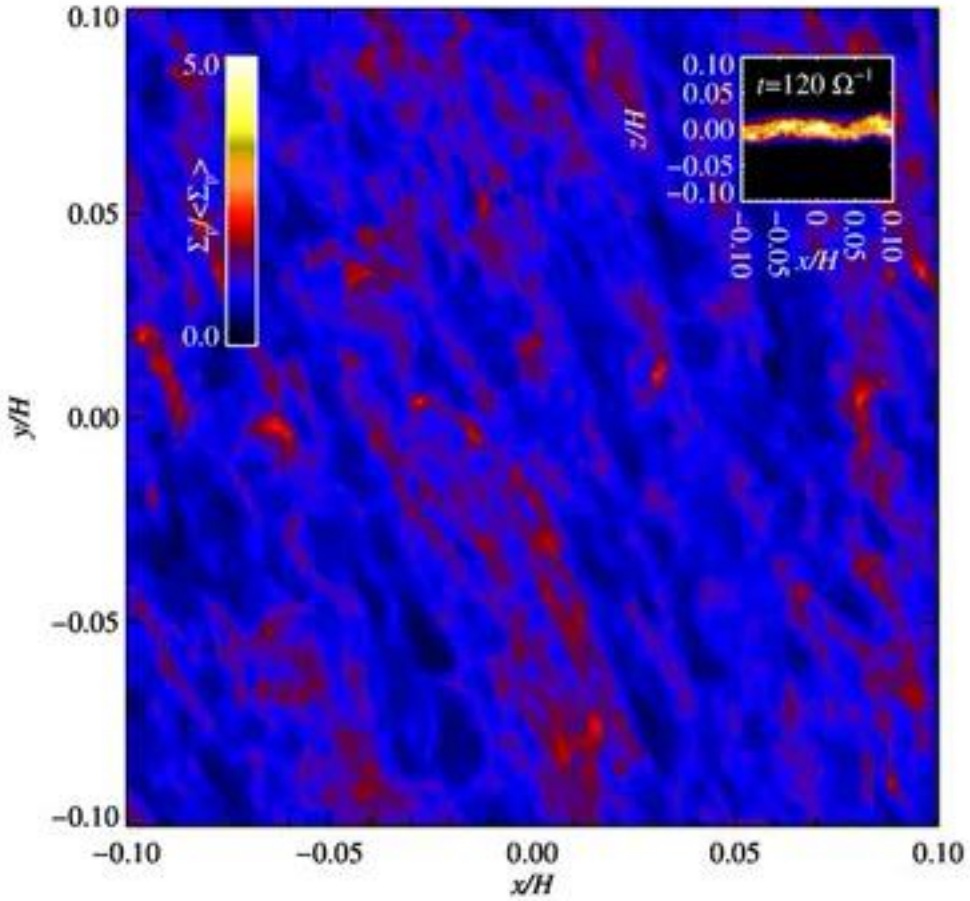
Canas & Lyra + (2024)

Core Accretion



Pebble Accretion

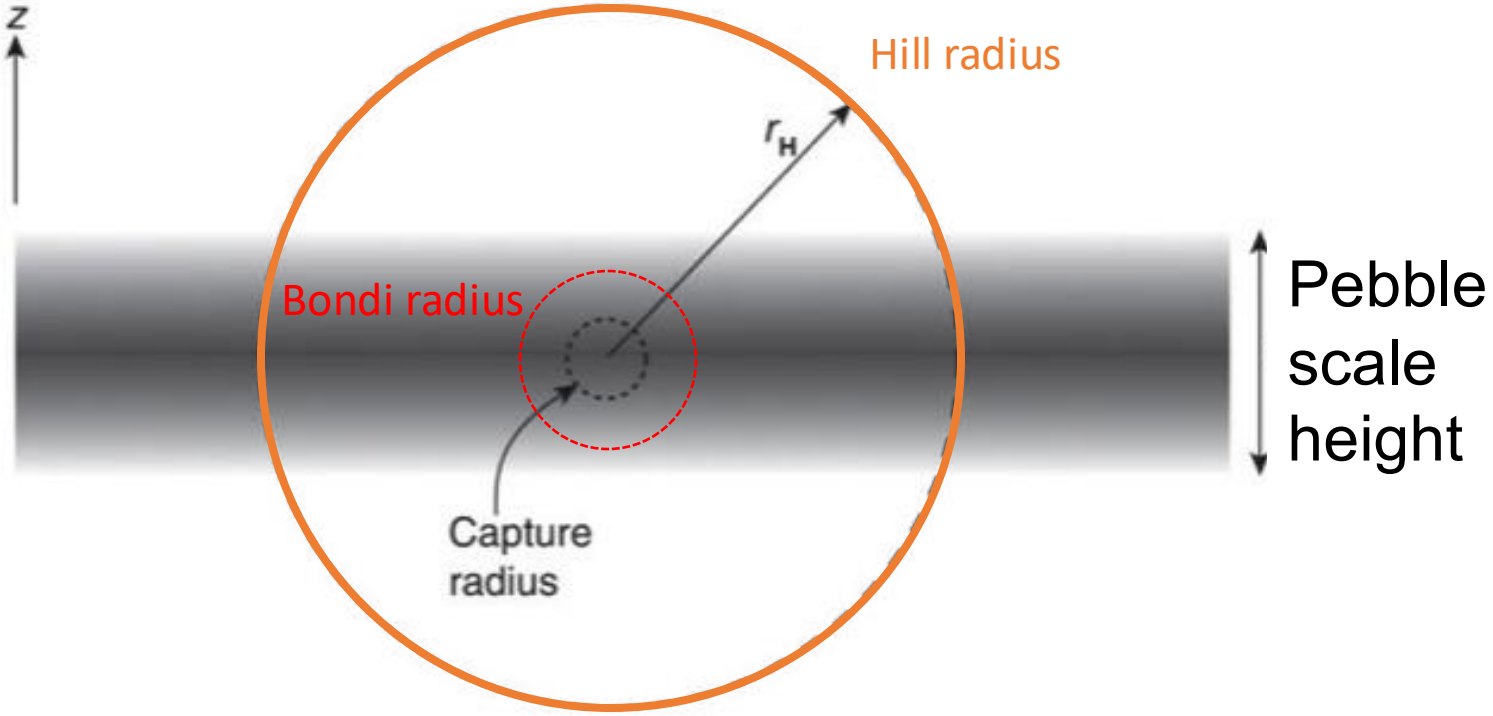




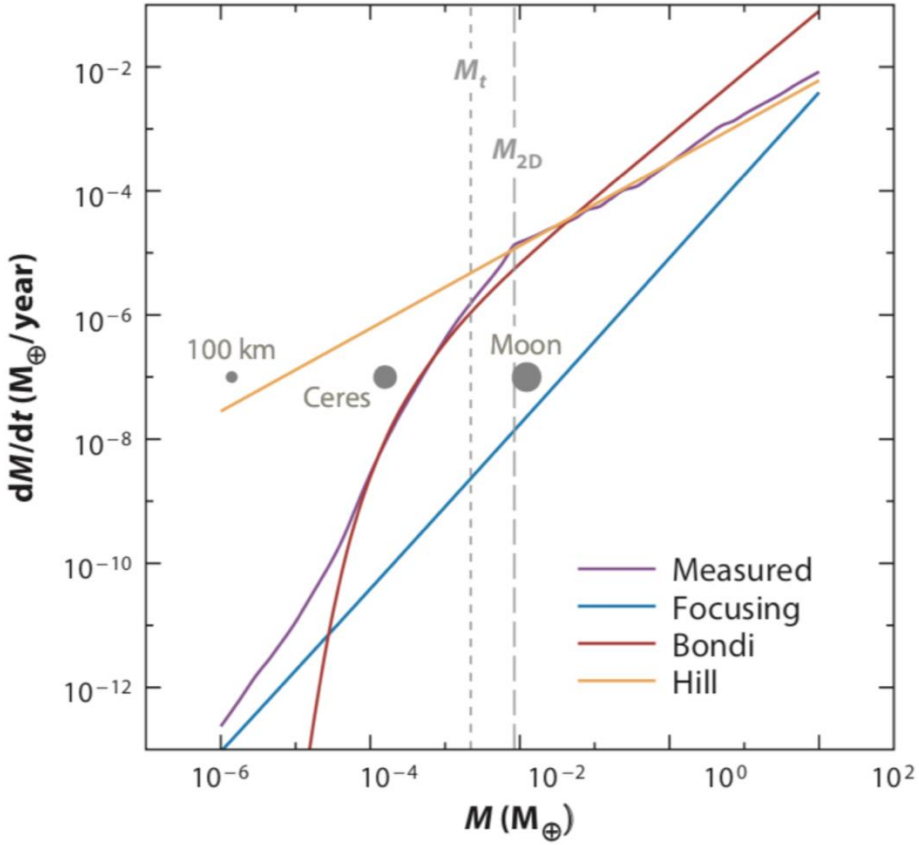
Ormel & Klahr ‘10, Lambrechts & Johansen ’12
See Johansen & Lambrechts ‘17 for a review

Pebble Accretion: Geometric, Bondi, and Hill regime

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

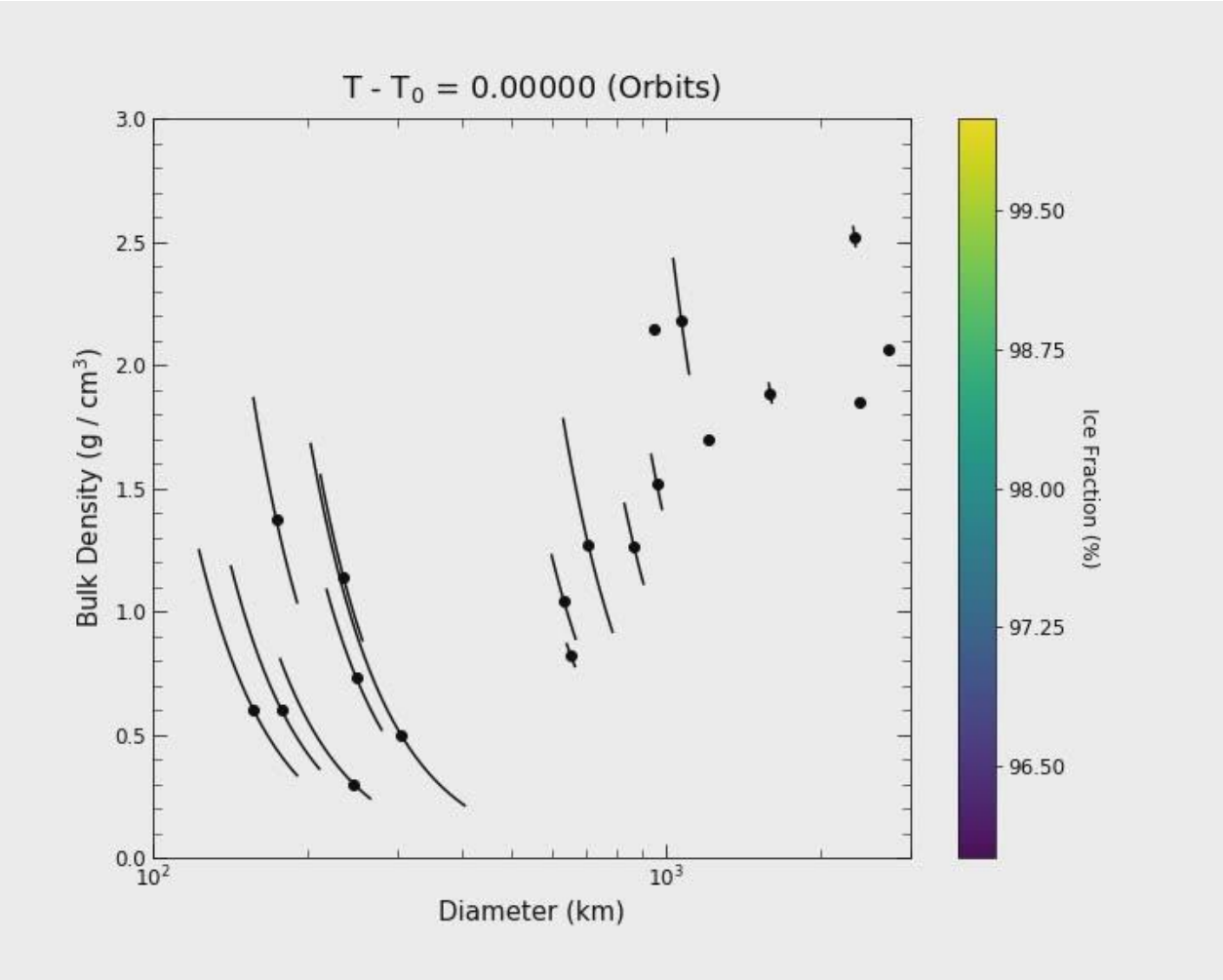


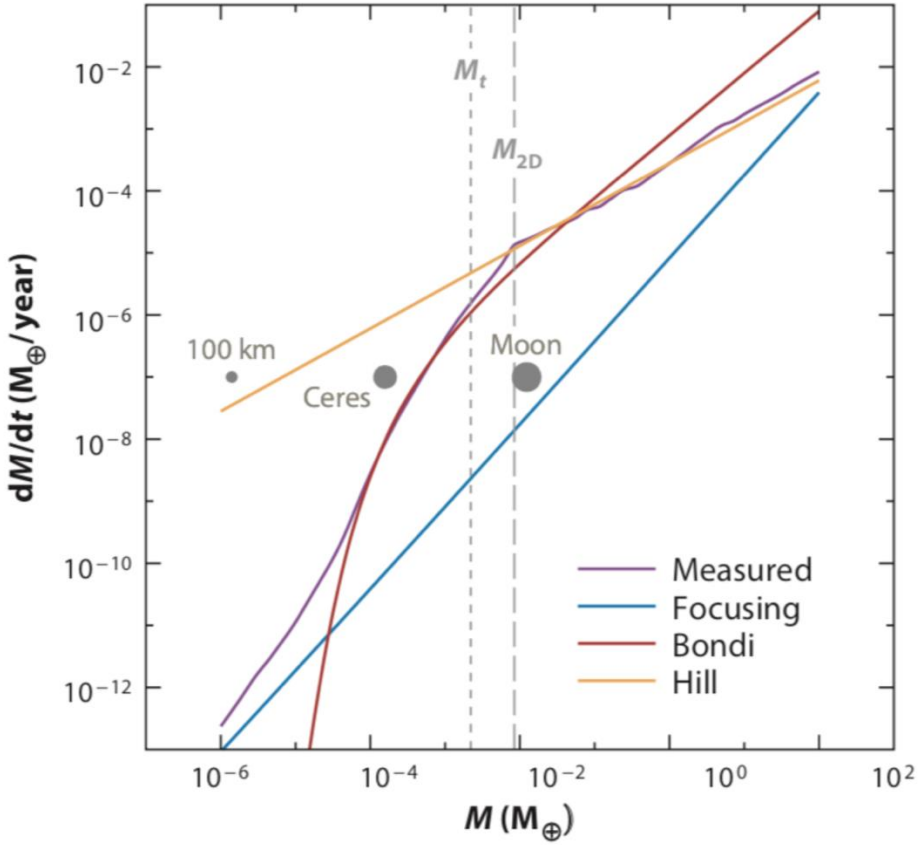
Mass Accretion rates



Ormel & Klahr (2010), Lambrechts & Johansen (2012)

Integrate pebble accretion





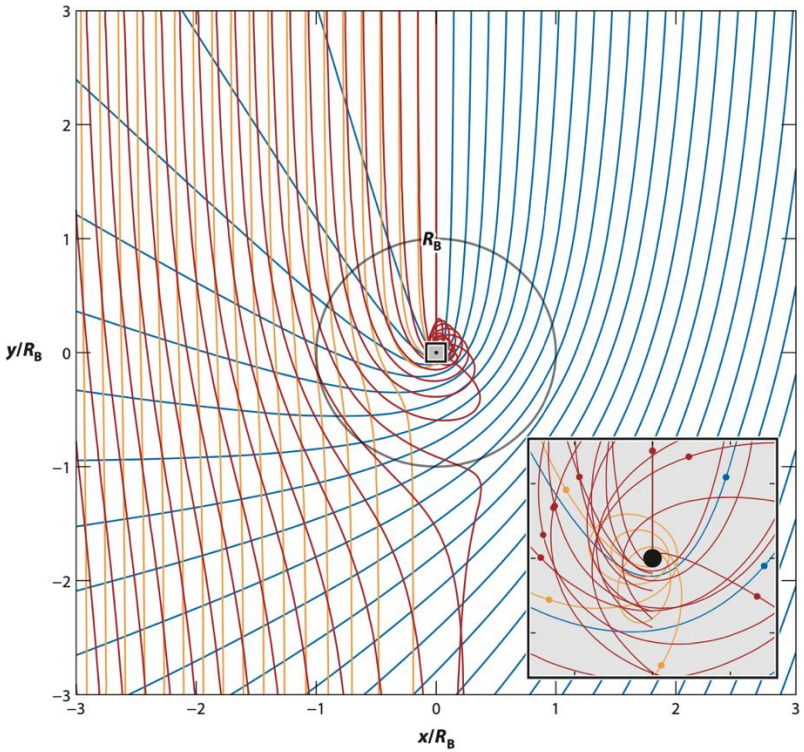
Johansen & Lambrechts (2017)

Pebble Accretion: Pebbles of different size accrete differently

Large
Medium
Small

"Goldilocks effect" in the Bondi regime

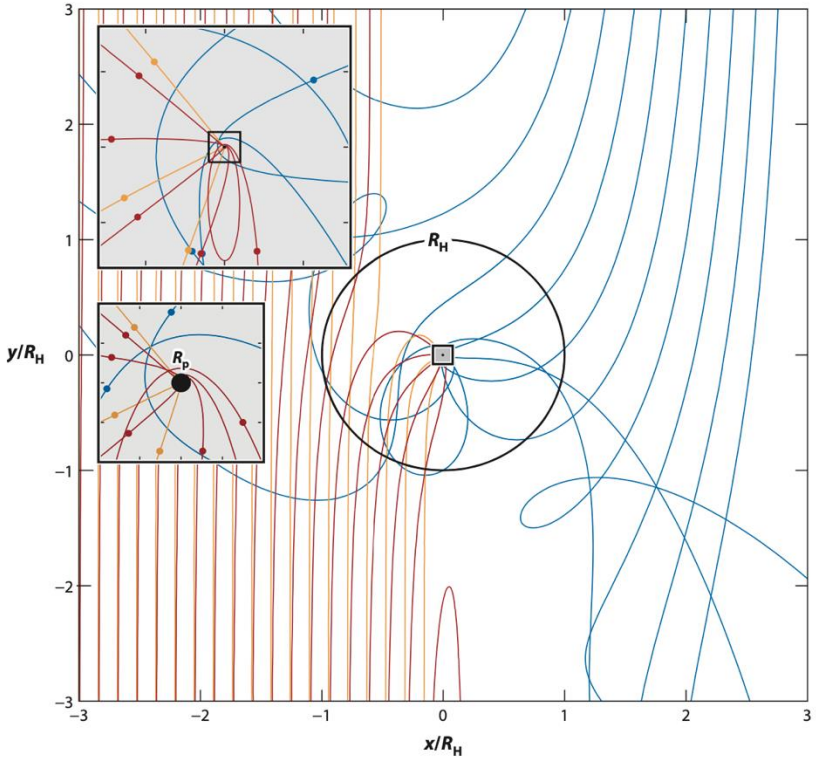
Bondi Regime



Best accreted pebble

Drag time ~ Bondi Time

Hill Regime

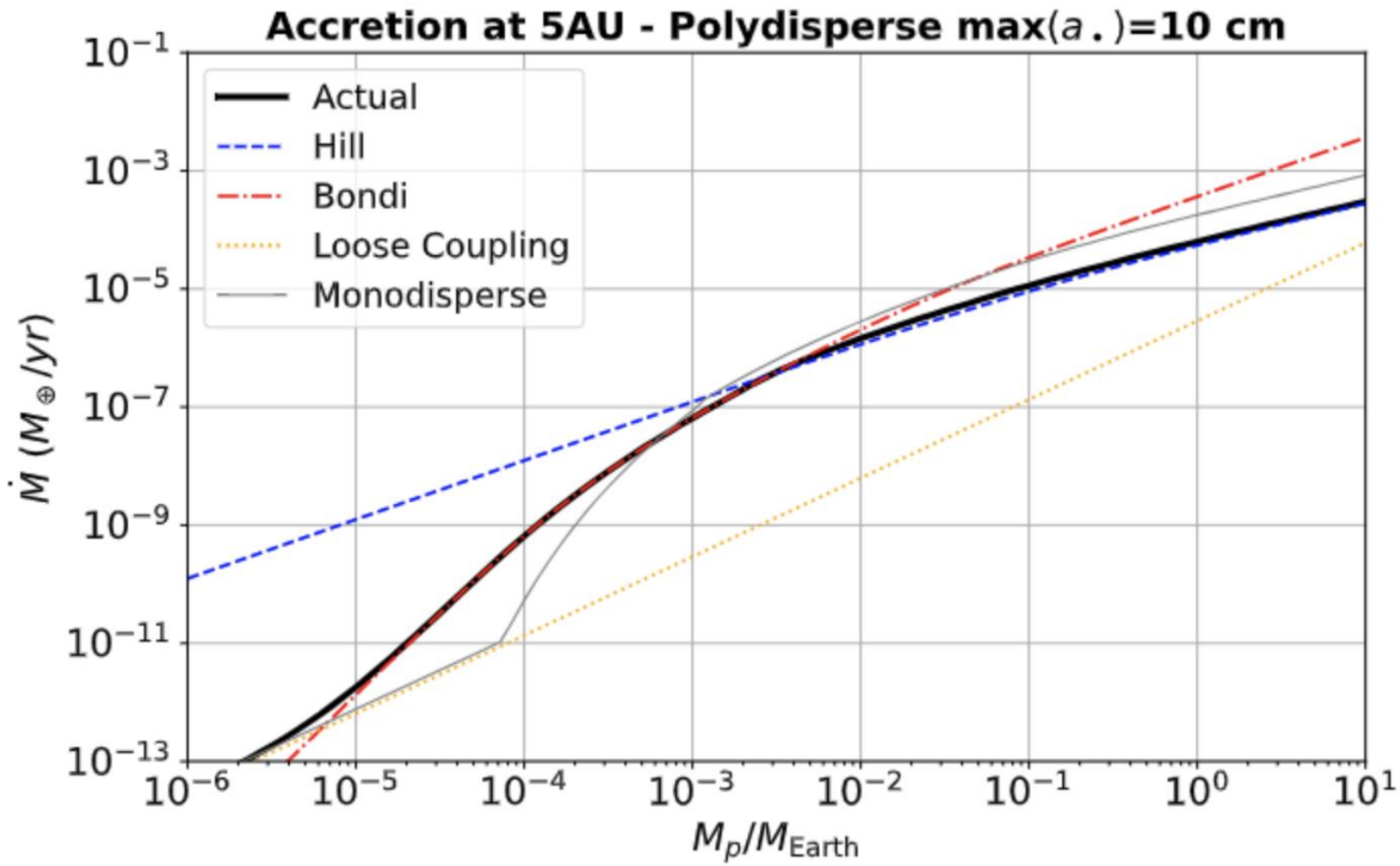


Best accreted pebble

Drag time ~ Orbital Time

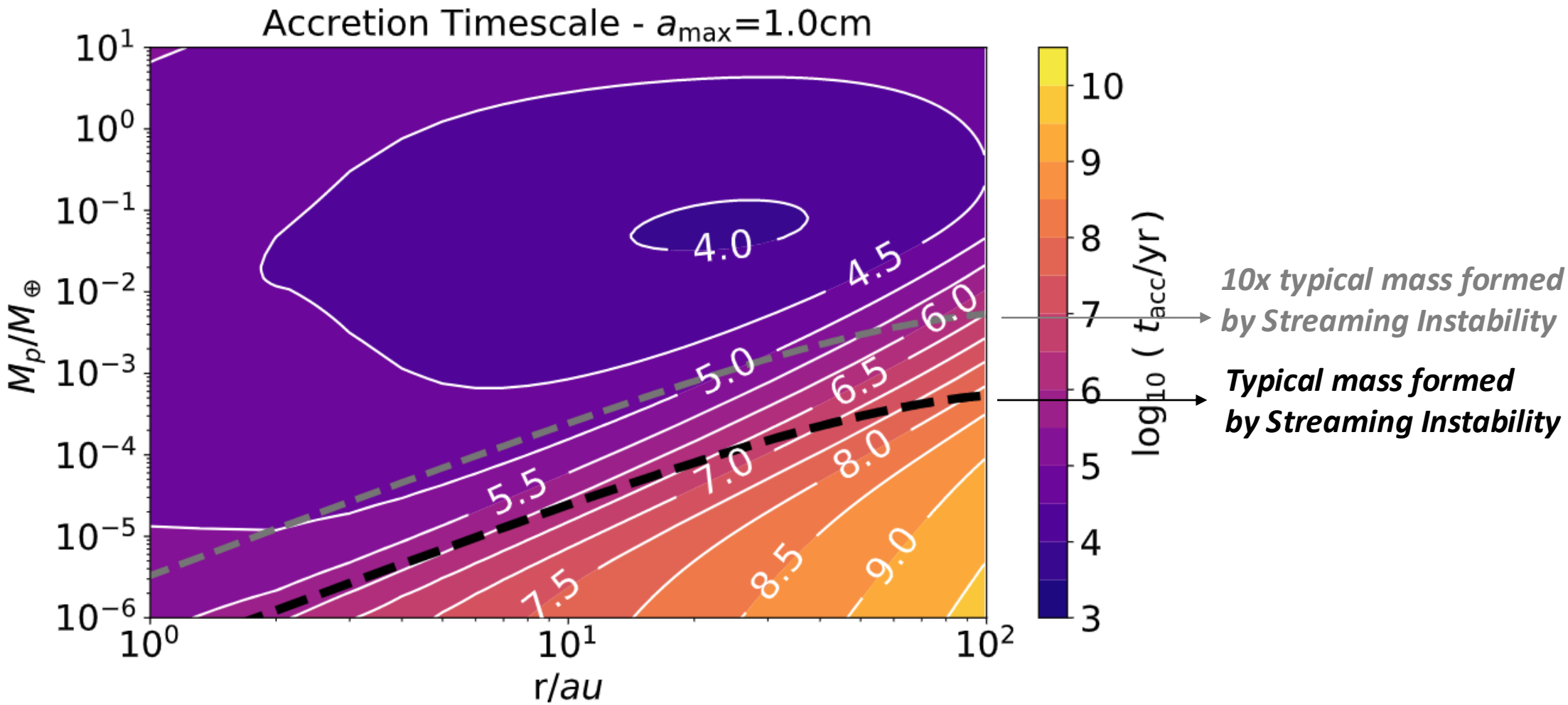
Johansen & Lambrechts (2017)

Accretion Rates



Lyra & Johansen + (2023)

Accretion Timescales



Lyra & Johansen + (2023)

Polydisperse (Multi-Species) Pebble Accretion

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Lyra & Johansen + (2023)

Analytical theory of polydisperse (multi-species) pebble accretion

Monodisperse (single species)

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

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

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

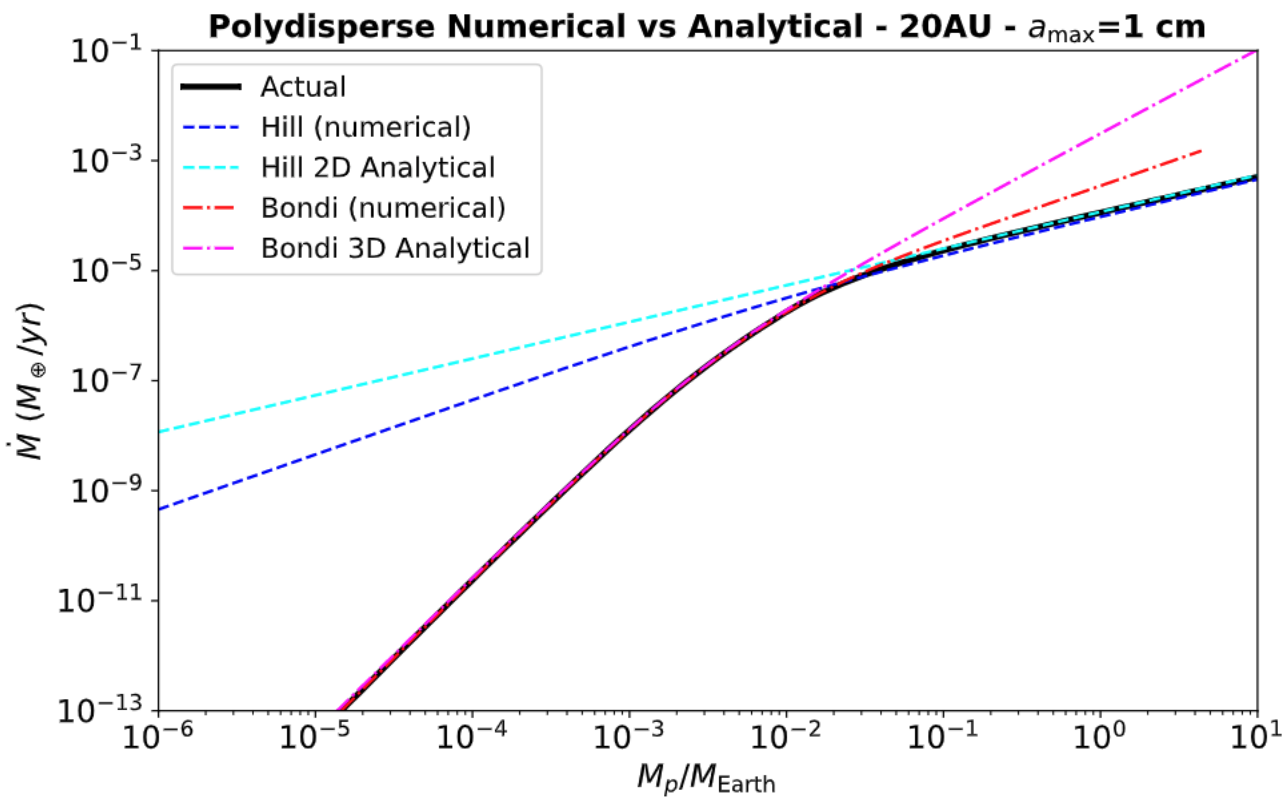
Lambrechts & Johansen (2012)

Polydisperse (multiple species)

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

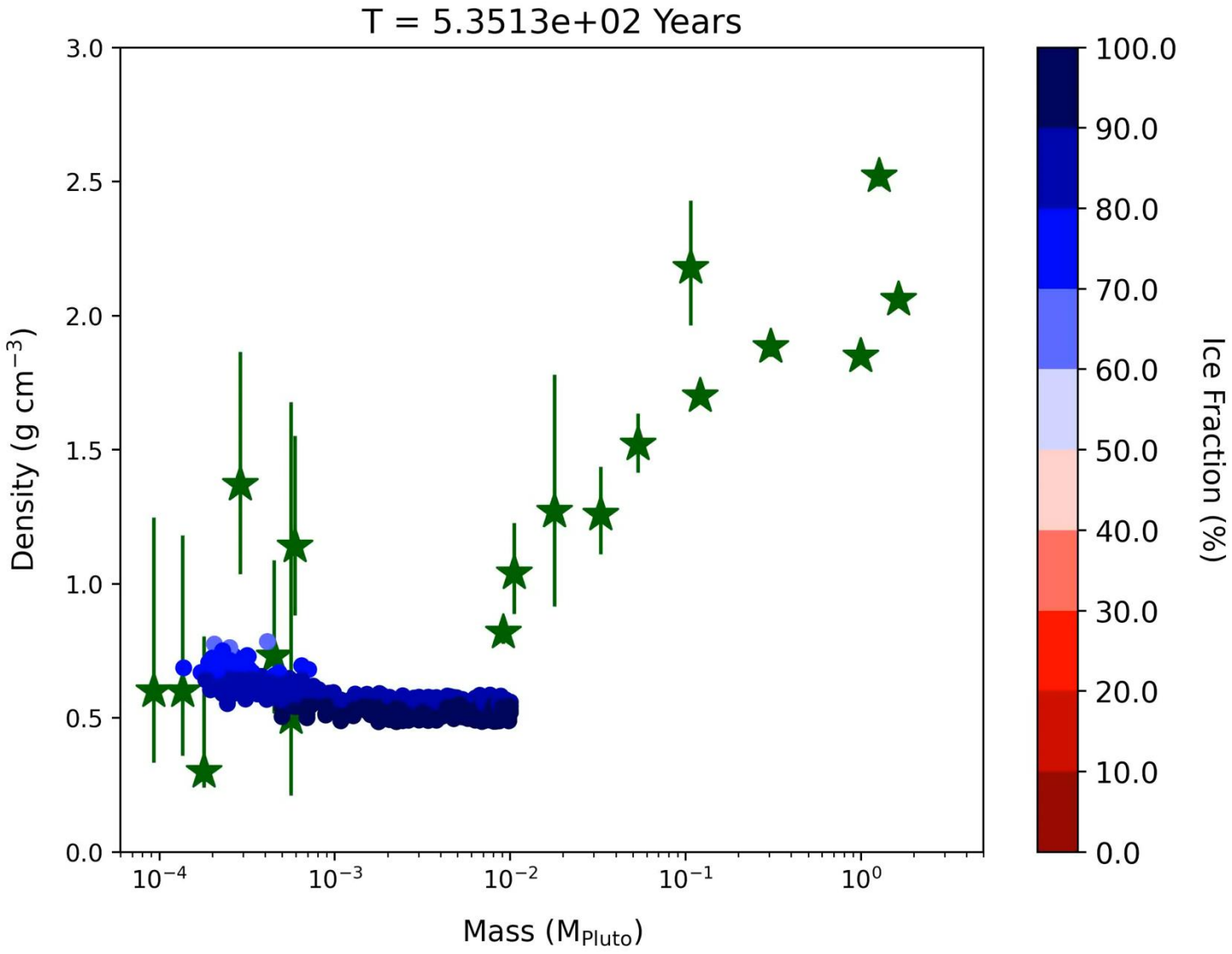
$$\dot{M}_{\rm 3D,Bondi} \approx C_1 \frac{\gamma_l\left(\frac{b_1+1}{s}, j_1 a_{\rm max}^s\right)}{s j_1^{(b_1+1)/s}} + C_2 \frac{\gamma_l\left(\frac{b_2+1}{s}, j_2 a_{\rm max}^s\right)}{s j_2^{(b_2+1)/s}} + C_3 \frac{\gamma_l\left(\frac{b_3+1}{s}, j_3 a_{\rm max}^s\right)}{s j_3^{(b_3+1)/s}} + C_4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

Lyra et al. (2023)



Lyra & Johansen + (2023)

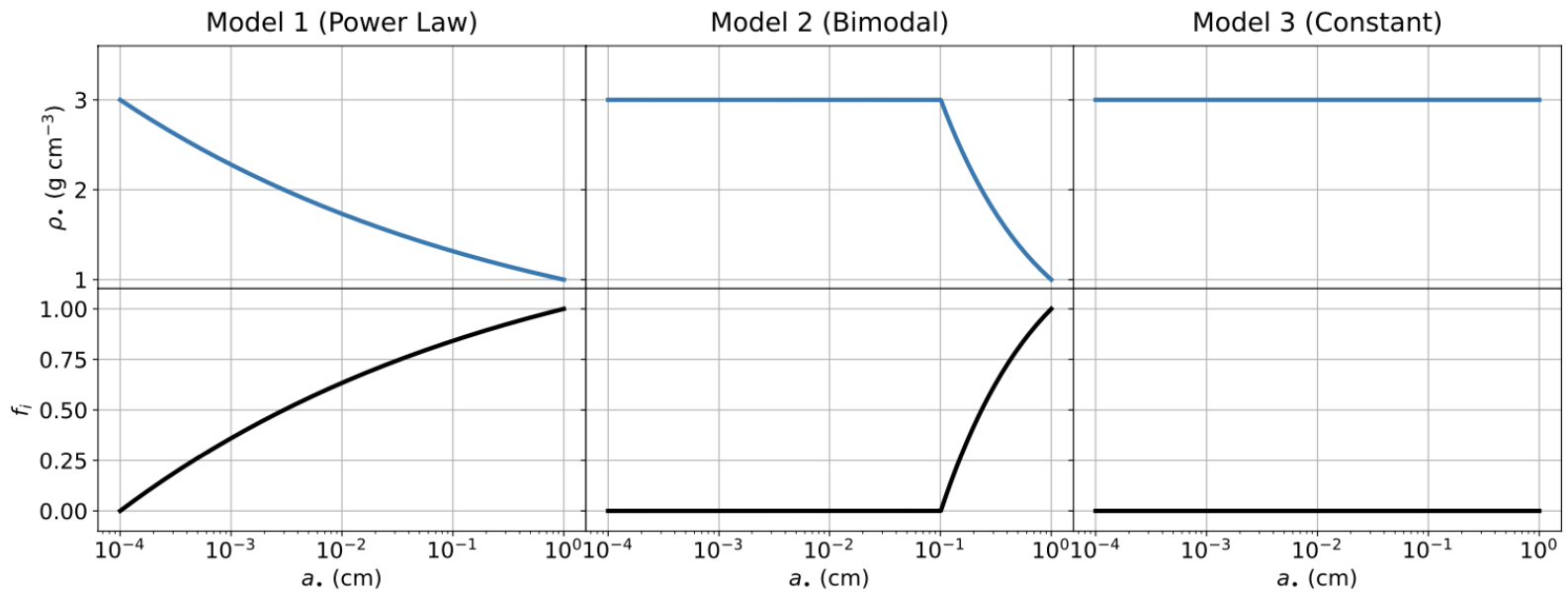
Growing Pluto by silicate pebble accretion



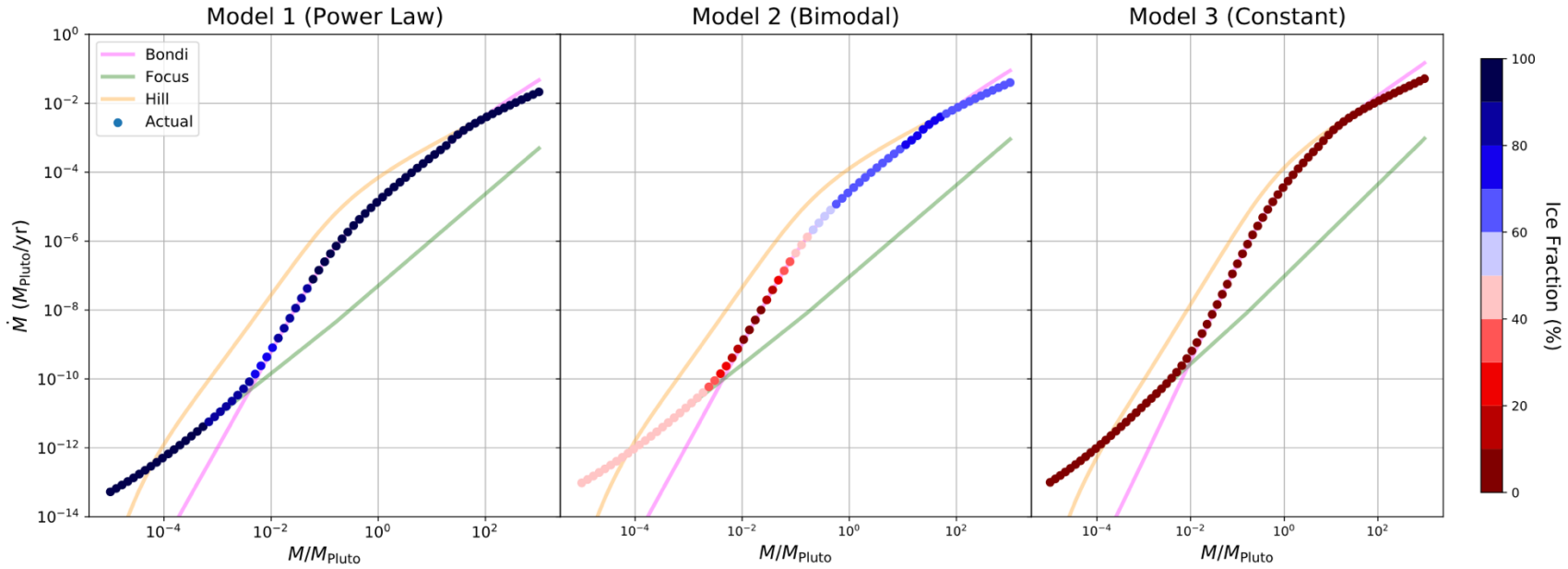
Canas & Lyra + (2024)

Pebble Internal Density

Ice Volume Fraction

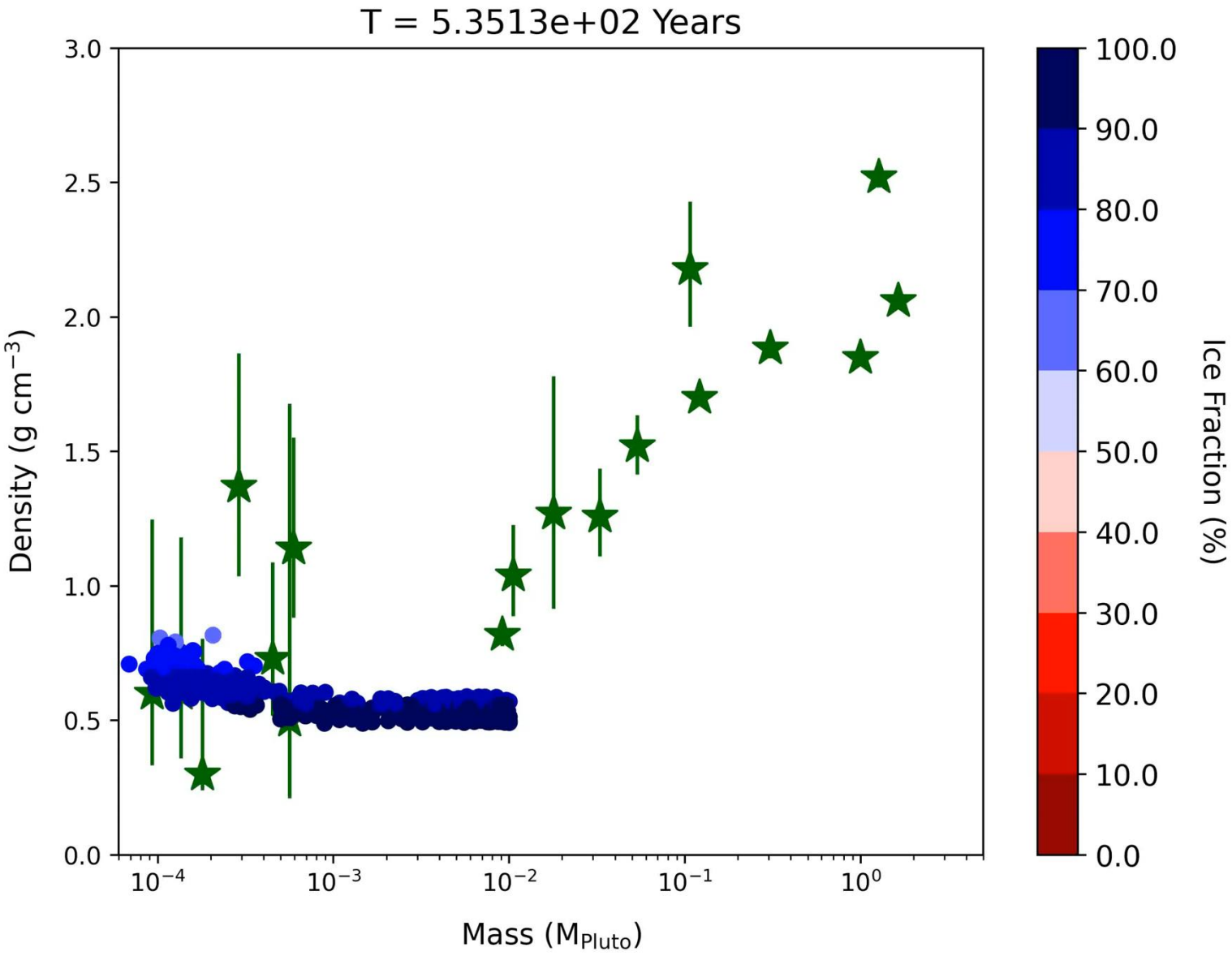


Mass Accretion rate



Canas & Lyra + (2024)

Growing Pluto by silicate pebble accretion

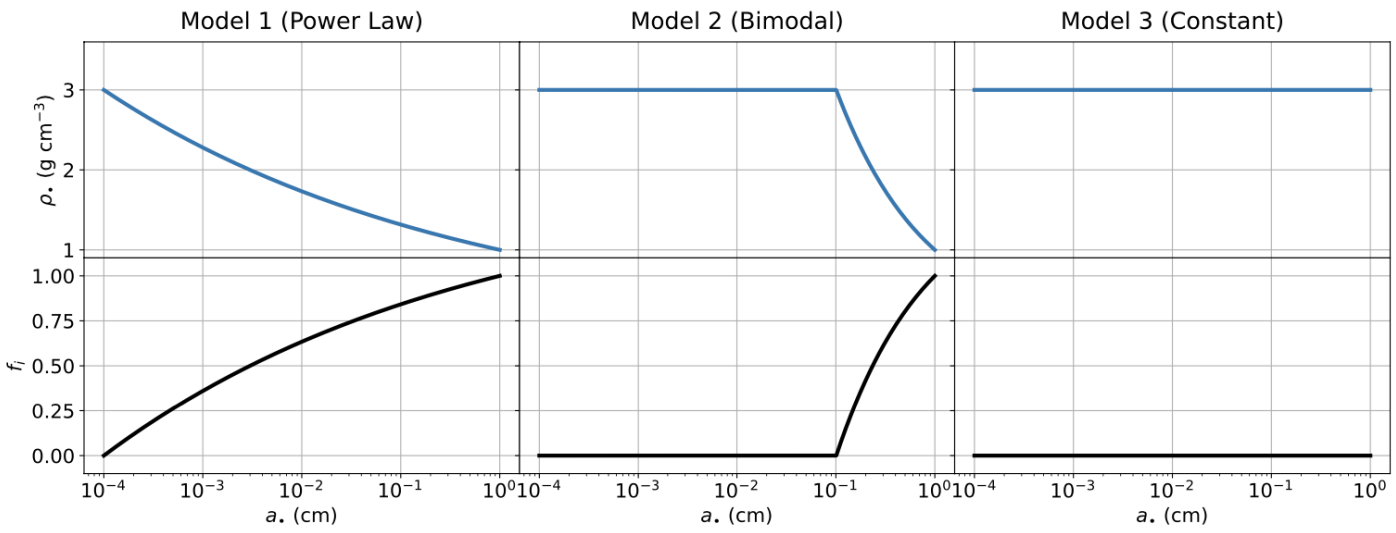


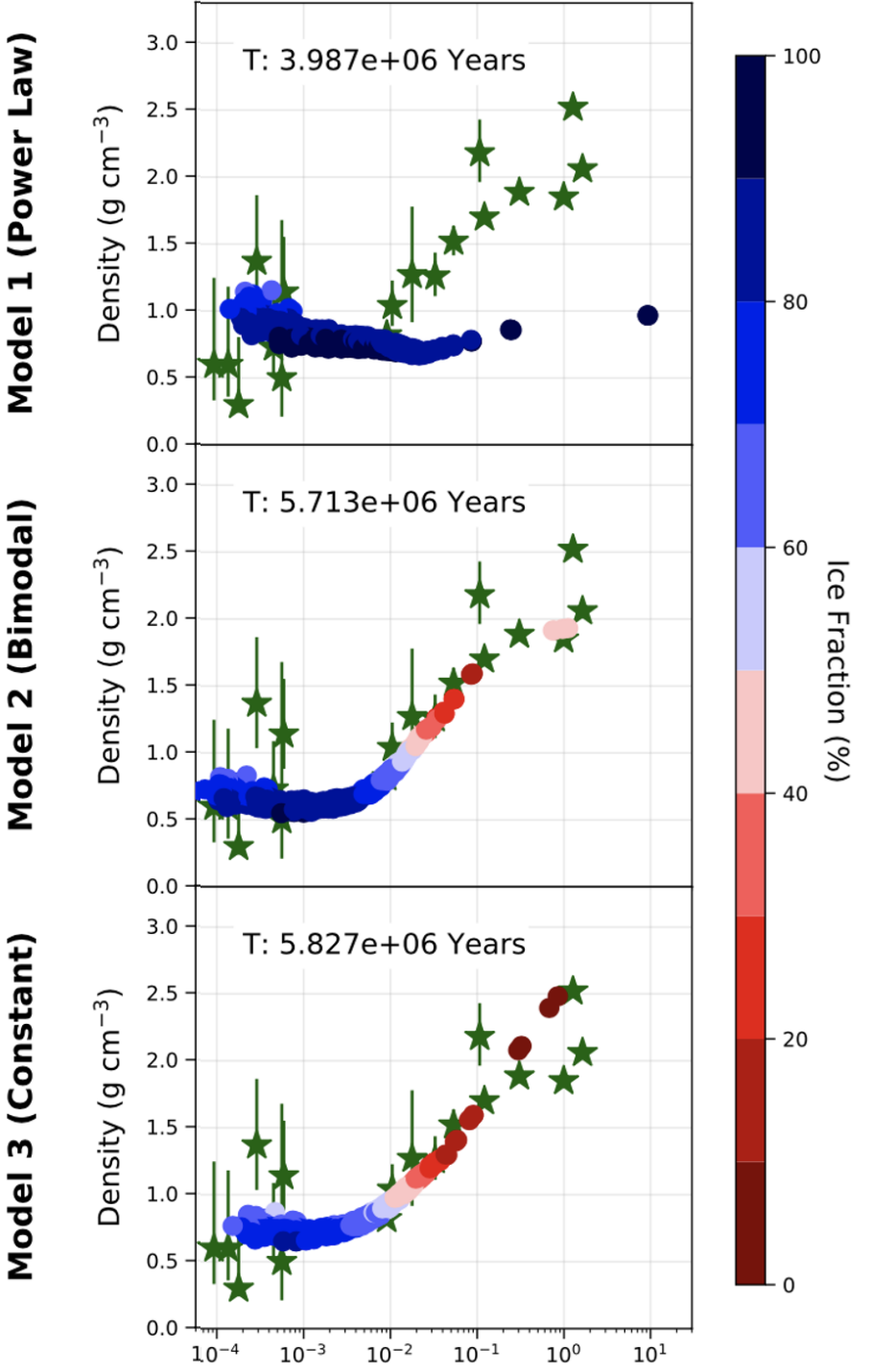
Canas & Lyra + (2024)

Resulting Densities vs Mass relations

Pebble Internal Density

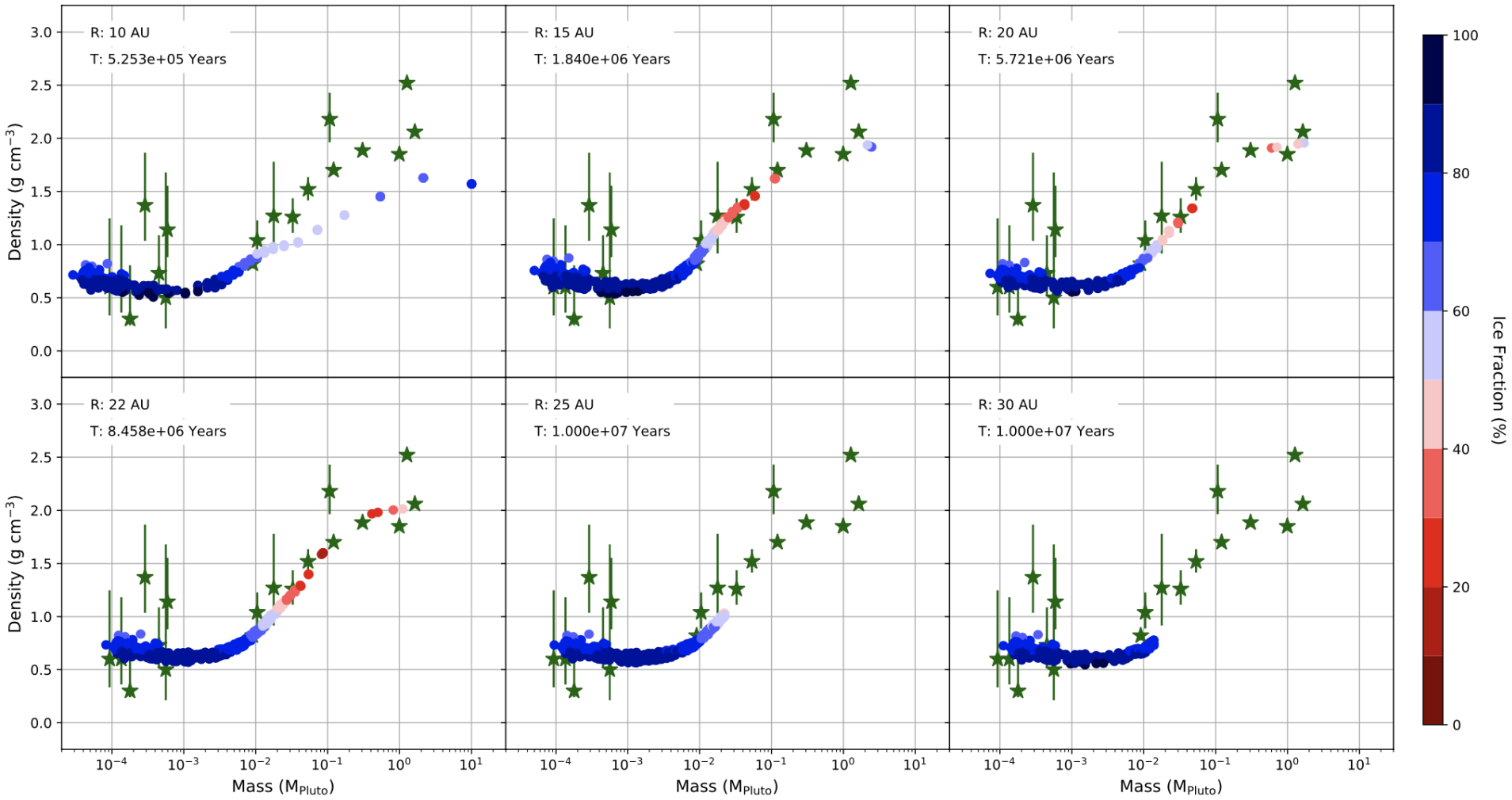
Ice Volume Fraction





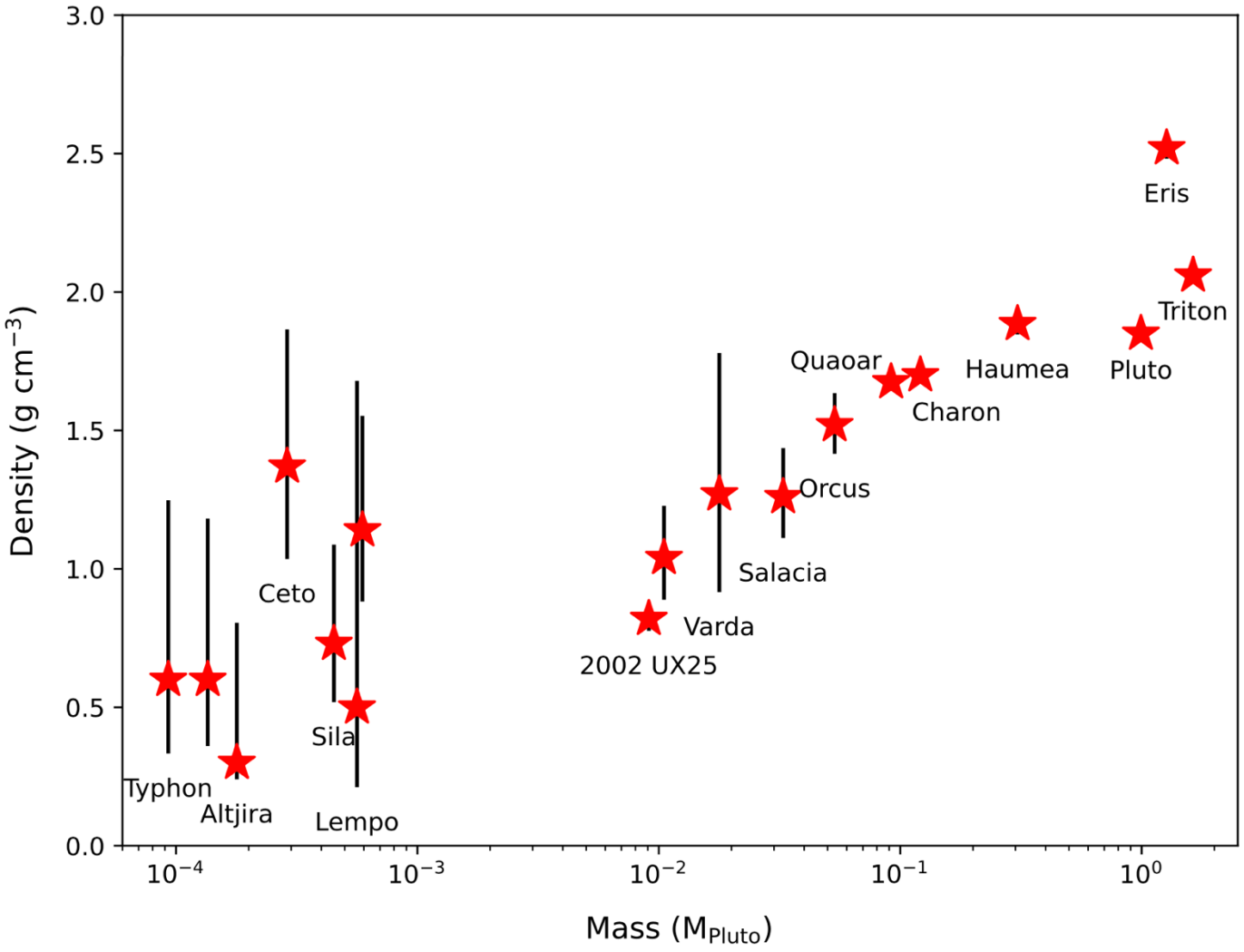
Canas & Lyra + (2024)

Distance Range
15 - 25AU



Canas & Lyra + (2024)

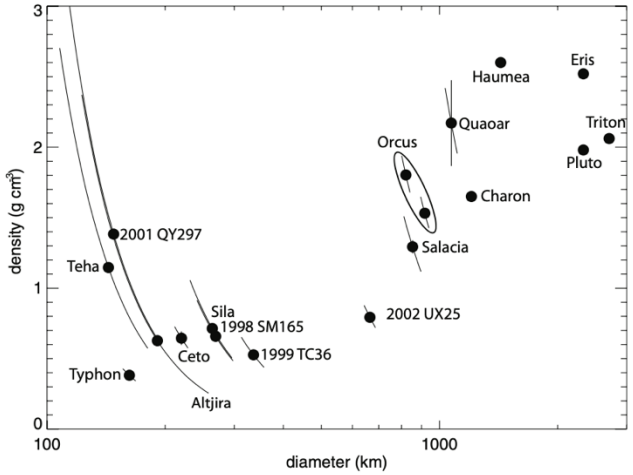
Where are the missing Kuiper Belt binaries?



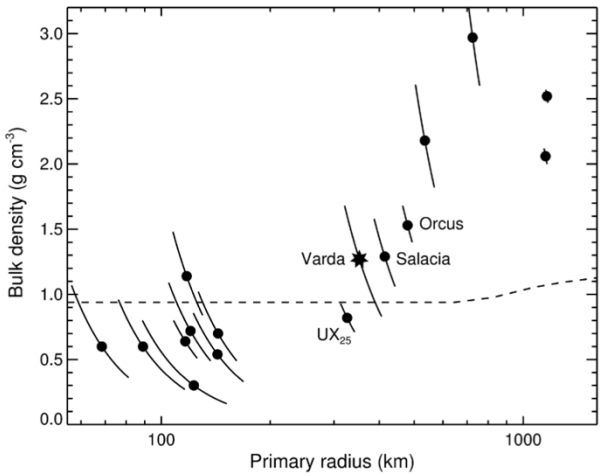
Lyra (2025)

Mass gap

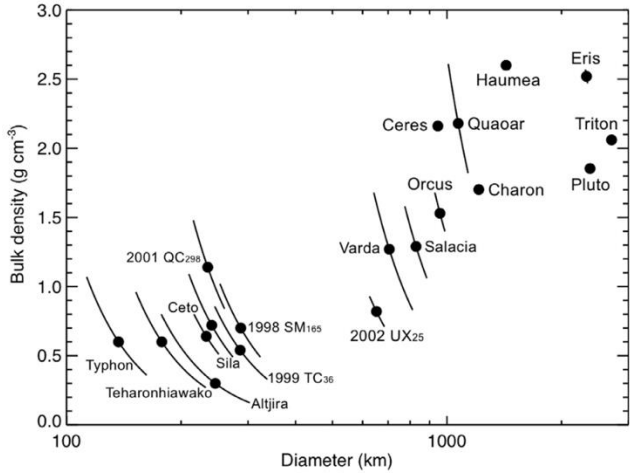
Brown 2013



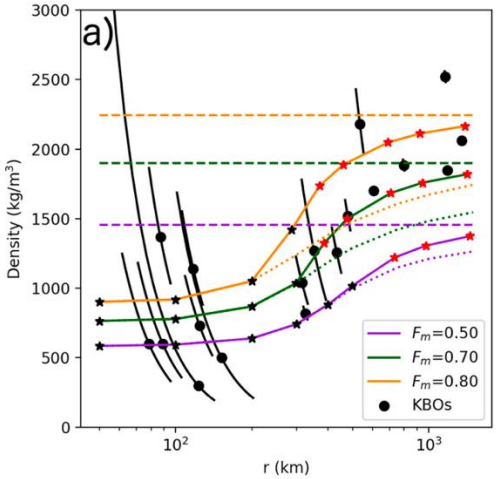
Grundy et al. 2015



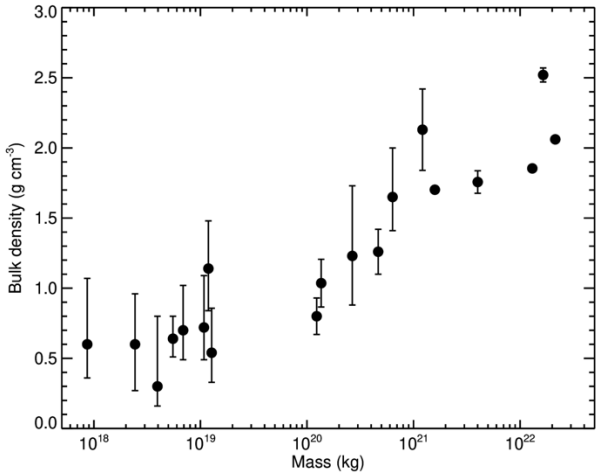
McKinnon et al. 2017



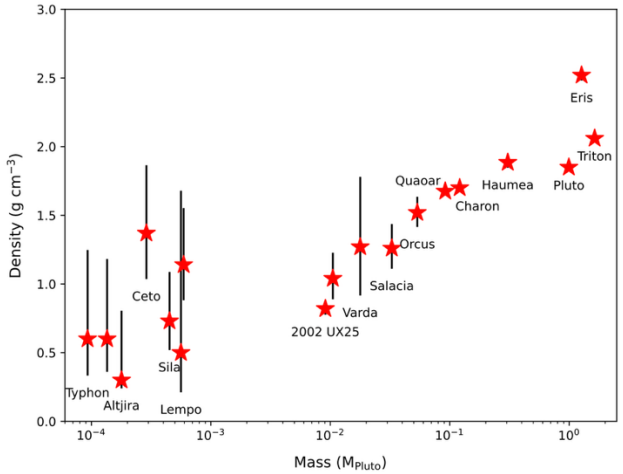
Bierson & Nimmo 2019



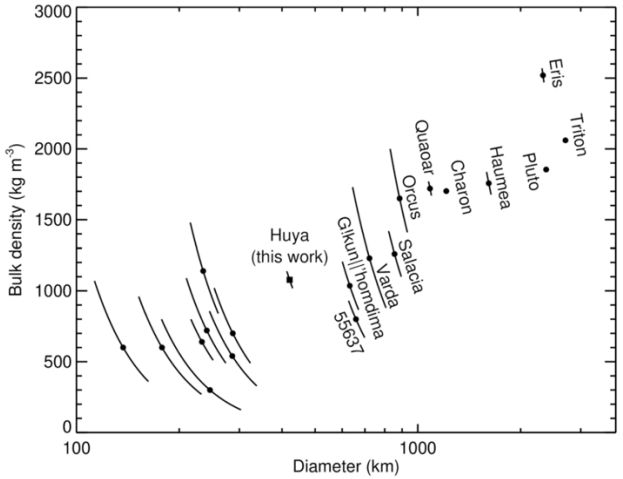
Noll et al. 2020

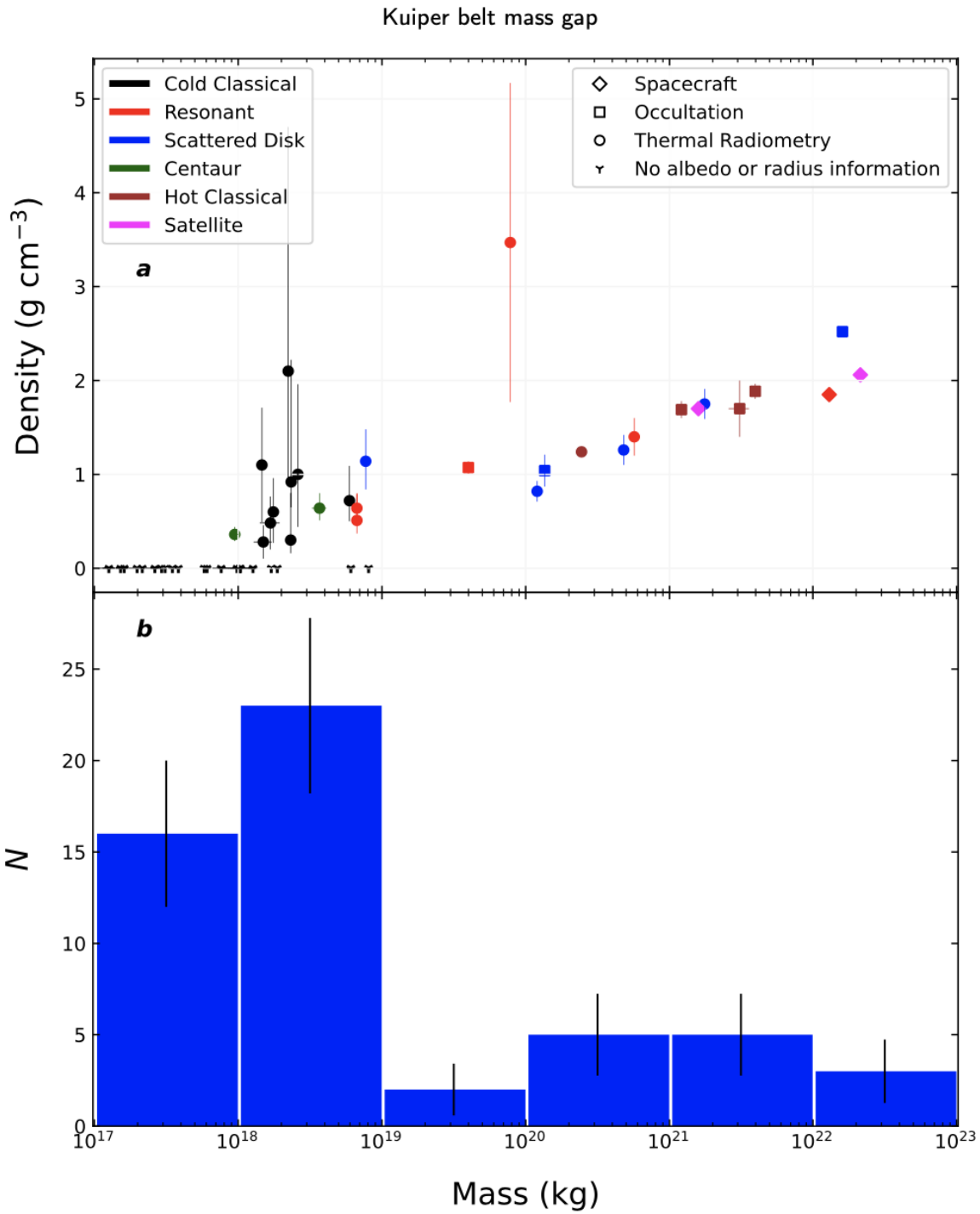


Canas et al. 2024



Rommel et al. 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 Classicals 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.*

Lyra (2025)

Low-mass end: consistent with high-mass end of Streaming Instability

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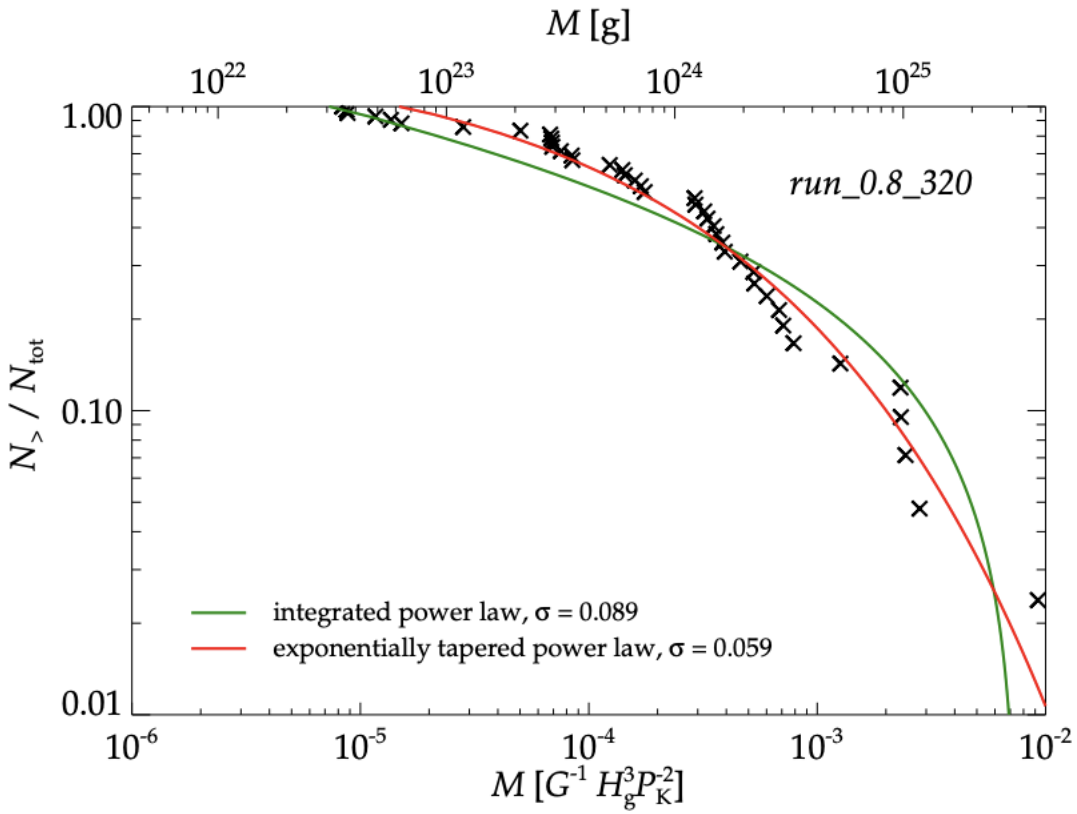
Astronomy & Astrophysics

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 Planetary Science Journal, 5:50 (18pp), 2024 February
https://doi.org/10.3847/PSJ/ad1528
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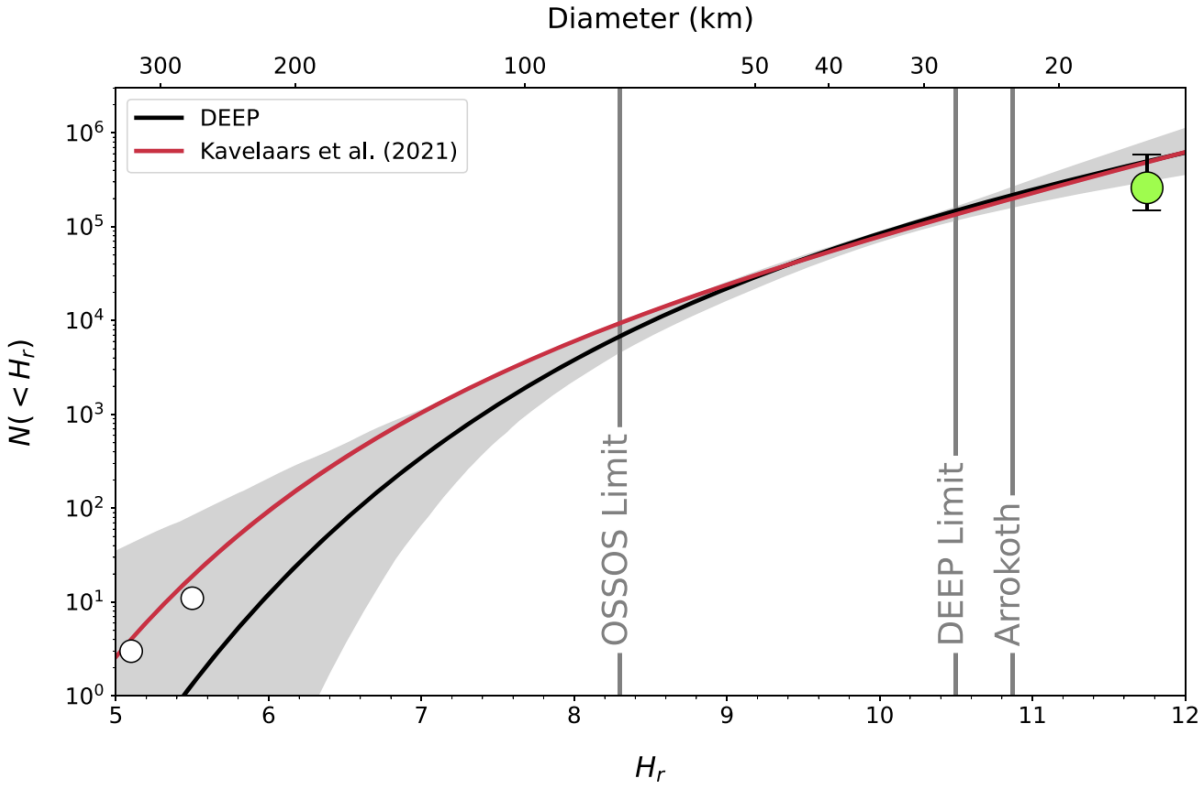
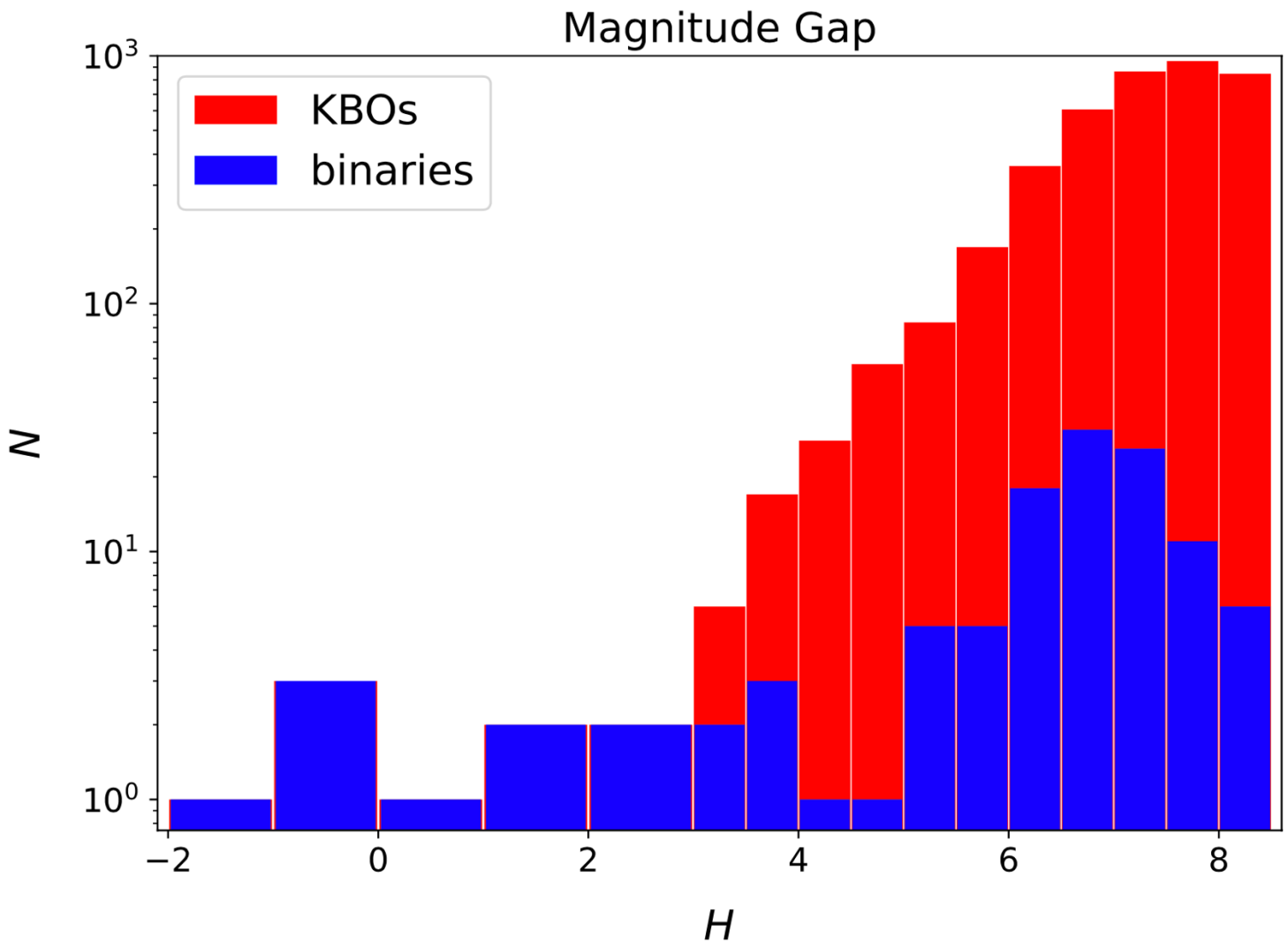
The DECam Ecliptic Exploration Project (DEEP). V. The Absolute Magnitude Distribution of the Cold Classical Kuiper Belt

Kevin J. Napier[1], Hsing Wen Lin (林省文)[1], David W. Gerdes[1,2], Fred C. Adams[1,2], Anna M. Simpson[1,2], Matthew W. Porter[1], Katherine G. Weber[3], Larissa Markwardt[2], Gabriel Gowman[1,2], Hayden Smotherman[4], Pedro H. Bernardinelli[4], Mario Jurić[4], Andrew J. Connolly[4], J. Bryce Kalmbach[4], Stephen K. N. Portillo[4], David E. Trilling[5], Ryder Strauss[5], William J. Oldroyd[5], Chadwick A. Trujillo[5], Colin Orion Chandler[4,5,6], Matthew J. Holman[7], Hilke E. Schlichting[8], and Andrew McNeill[9,10]

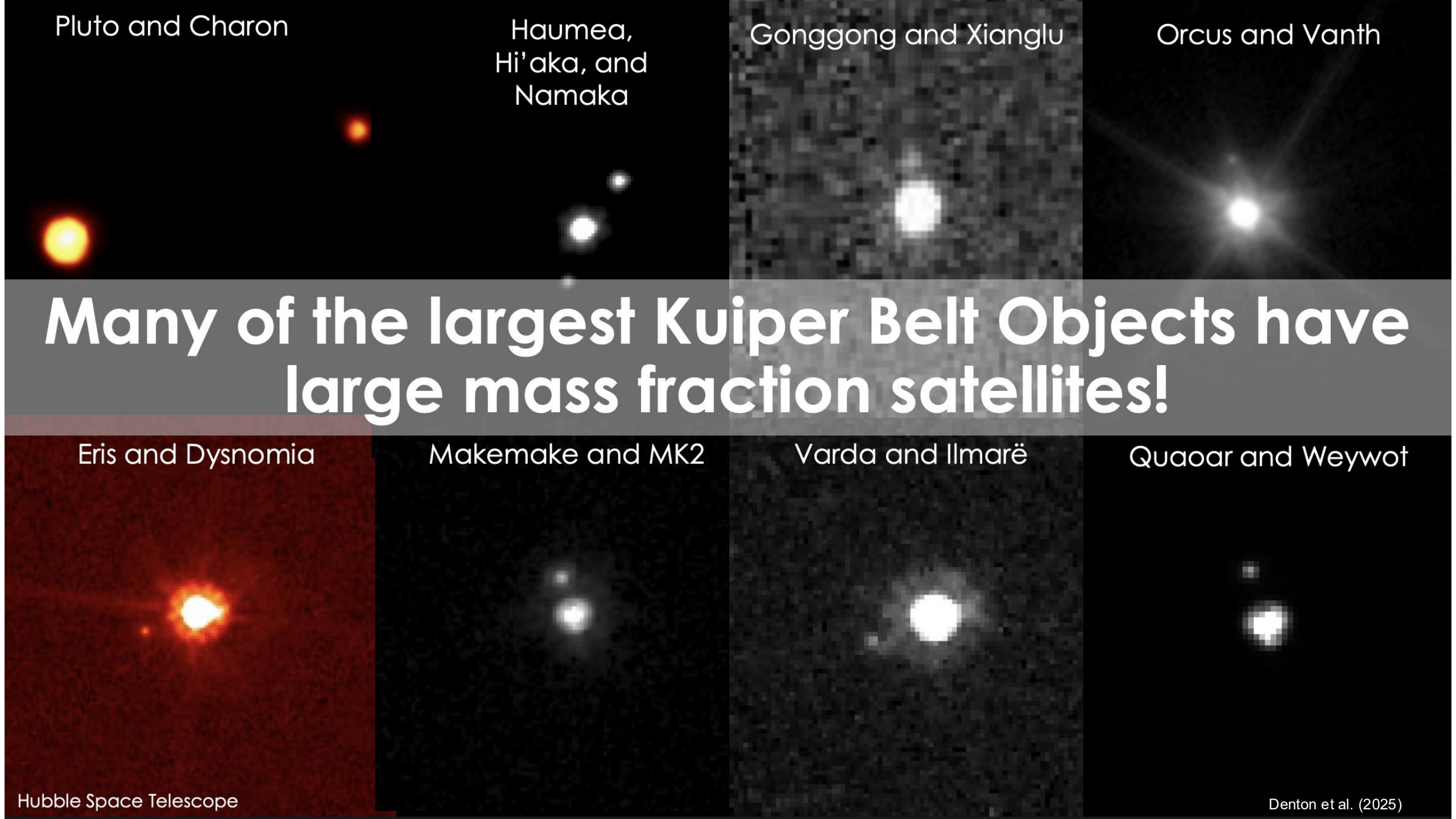


Kavelaars et al (2021); Napier et al. (2024)

High-mass side. Observational bias?



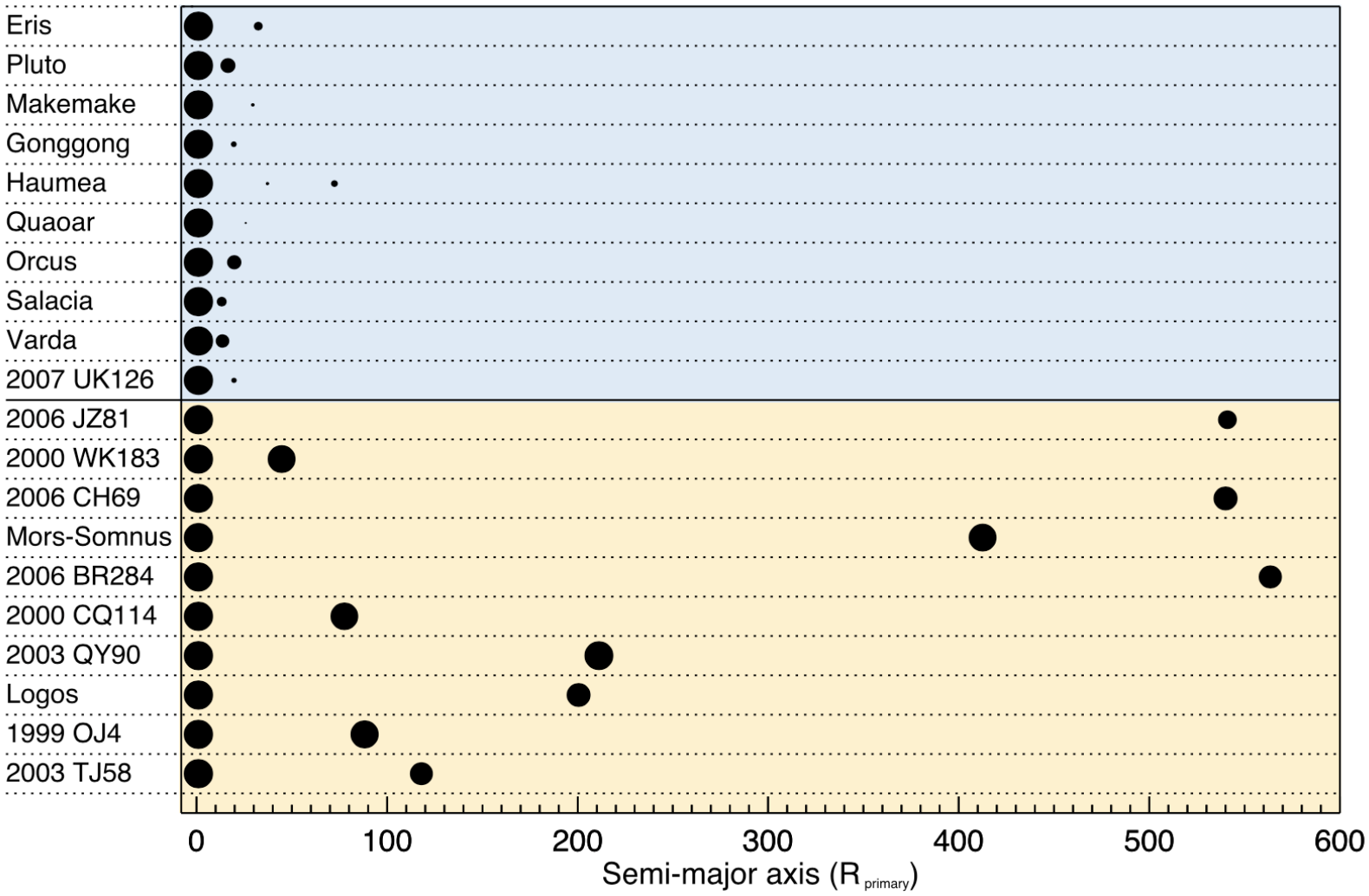
Lyra (2025)



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

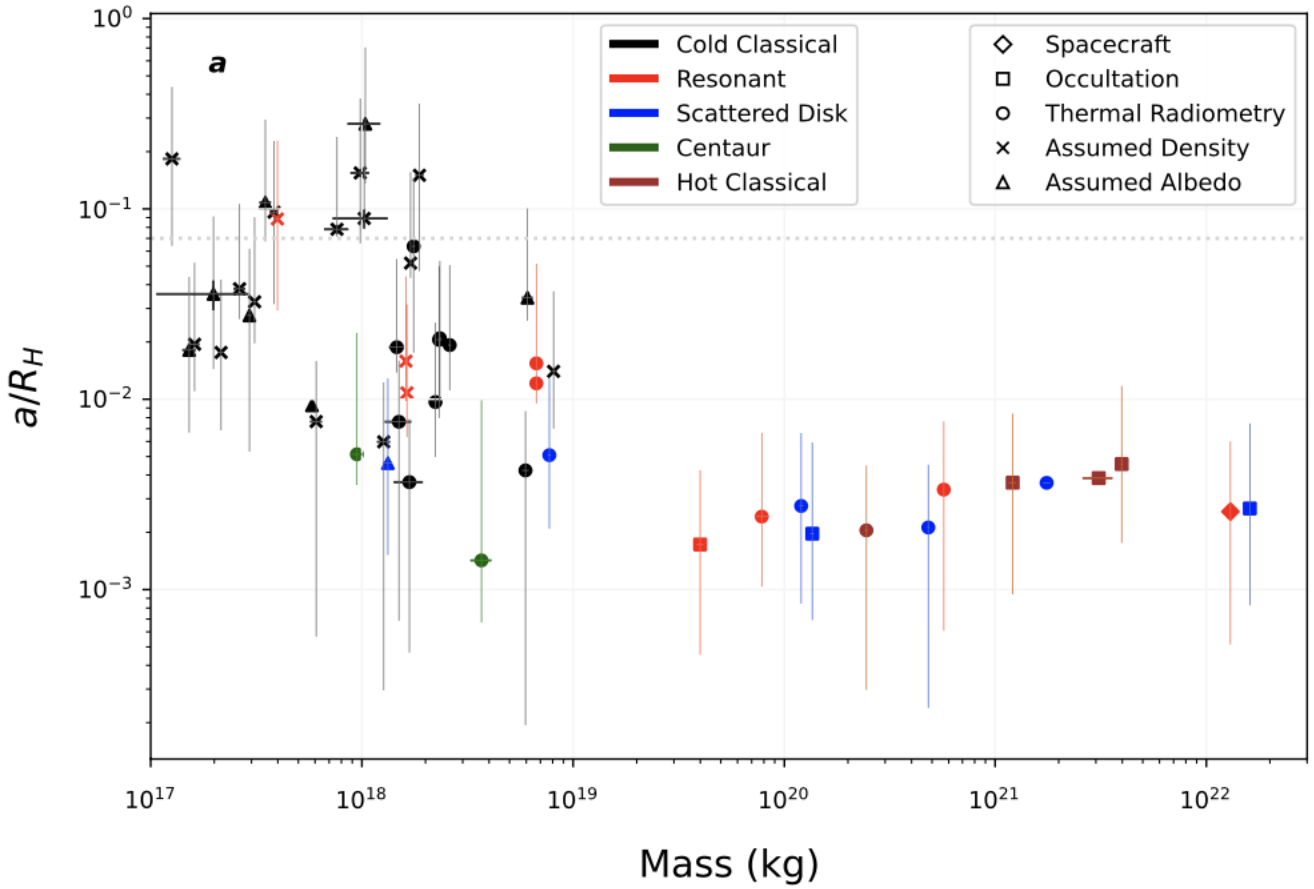
Denton et al. (2025)

Different system architecture



Bernstein et al (2023)

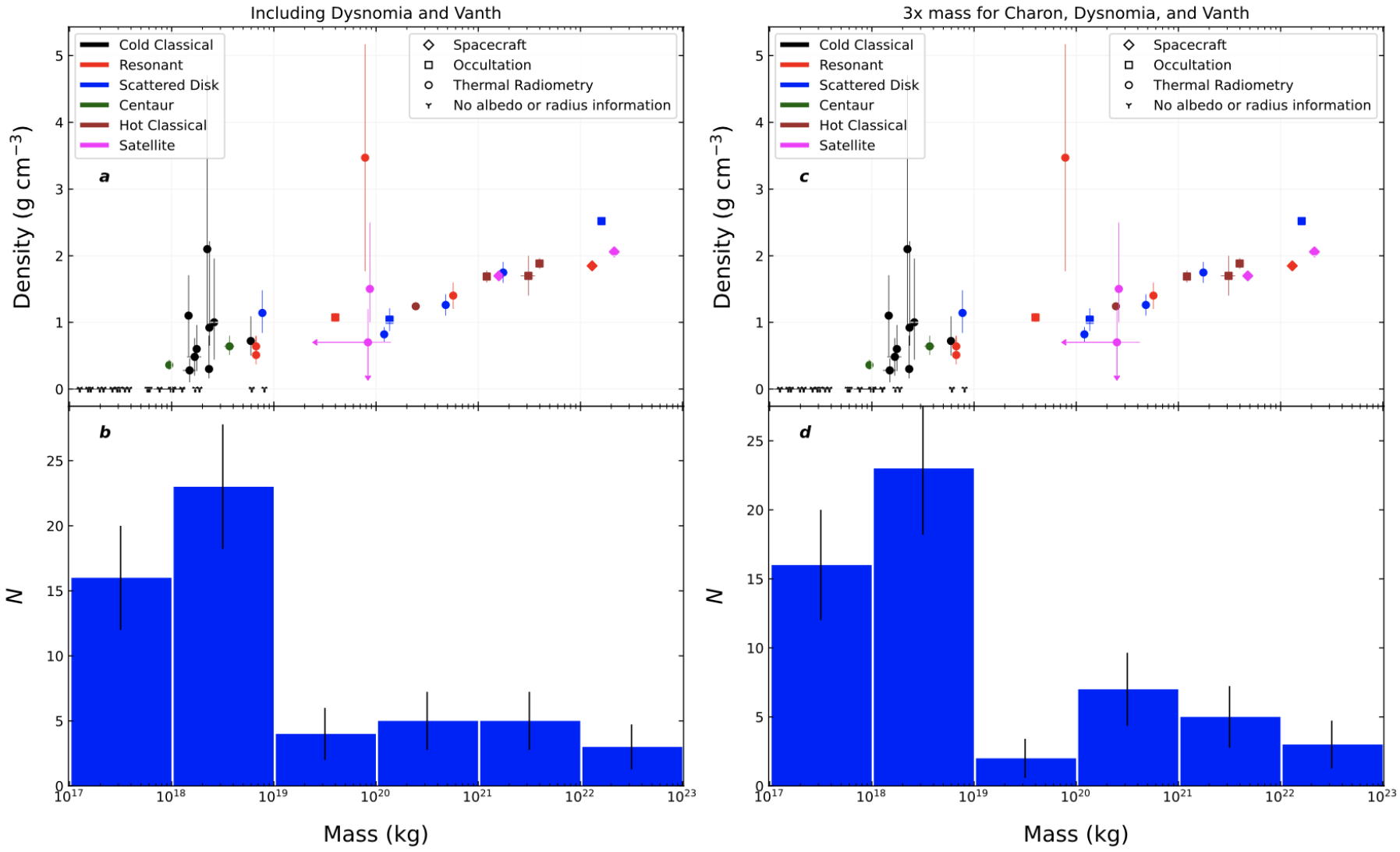
Did the high-mass objects lose their primordial satellites?



UWBs

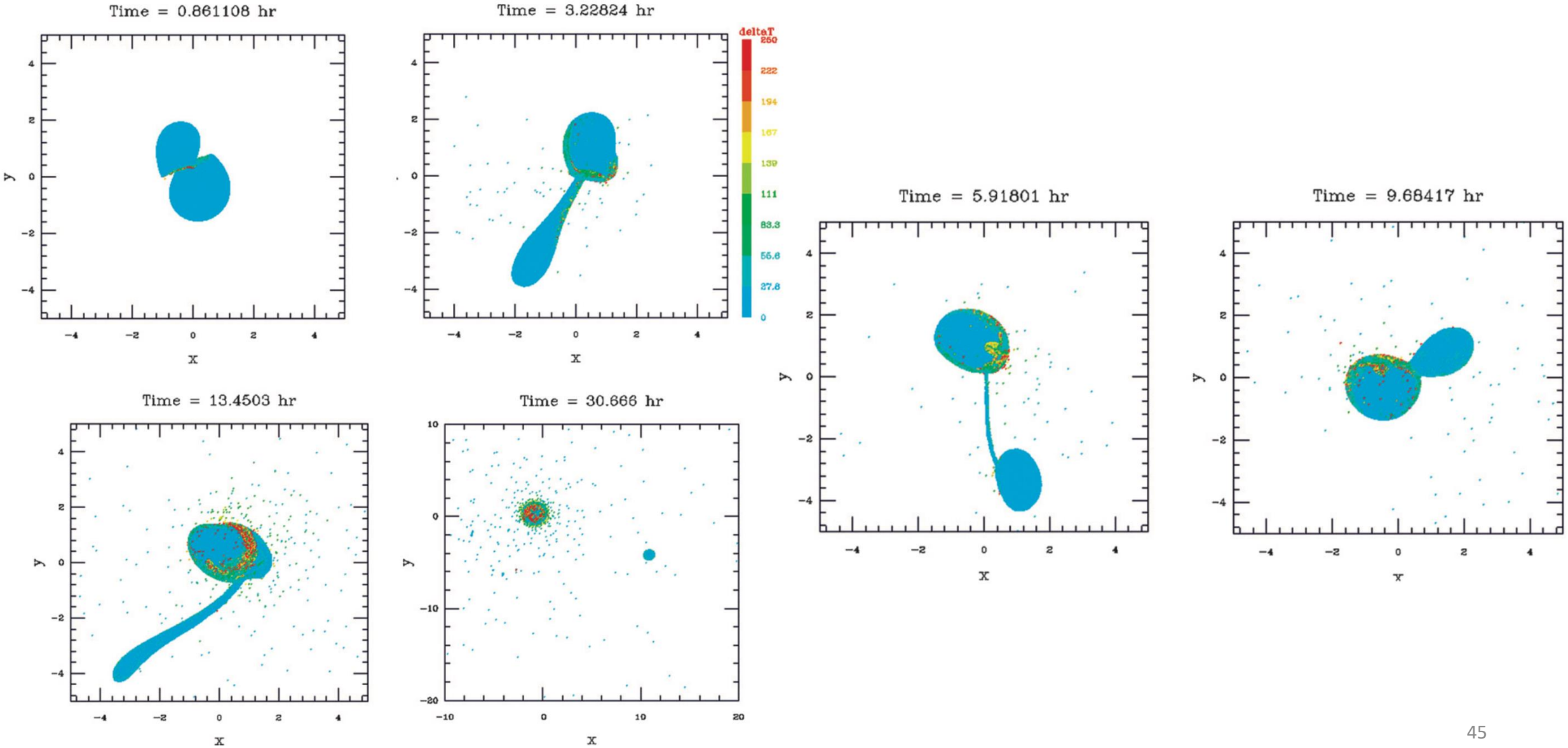
Lyra (2025)

Satellites



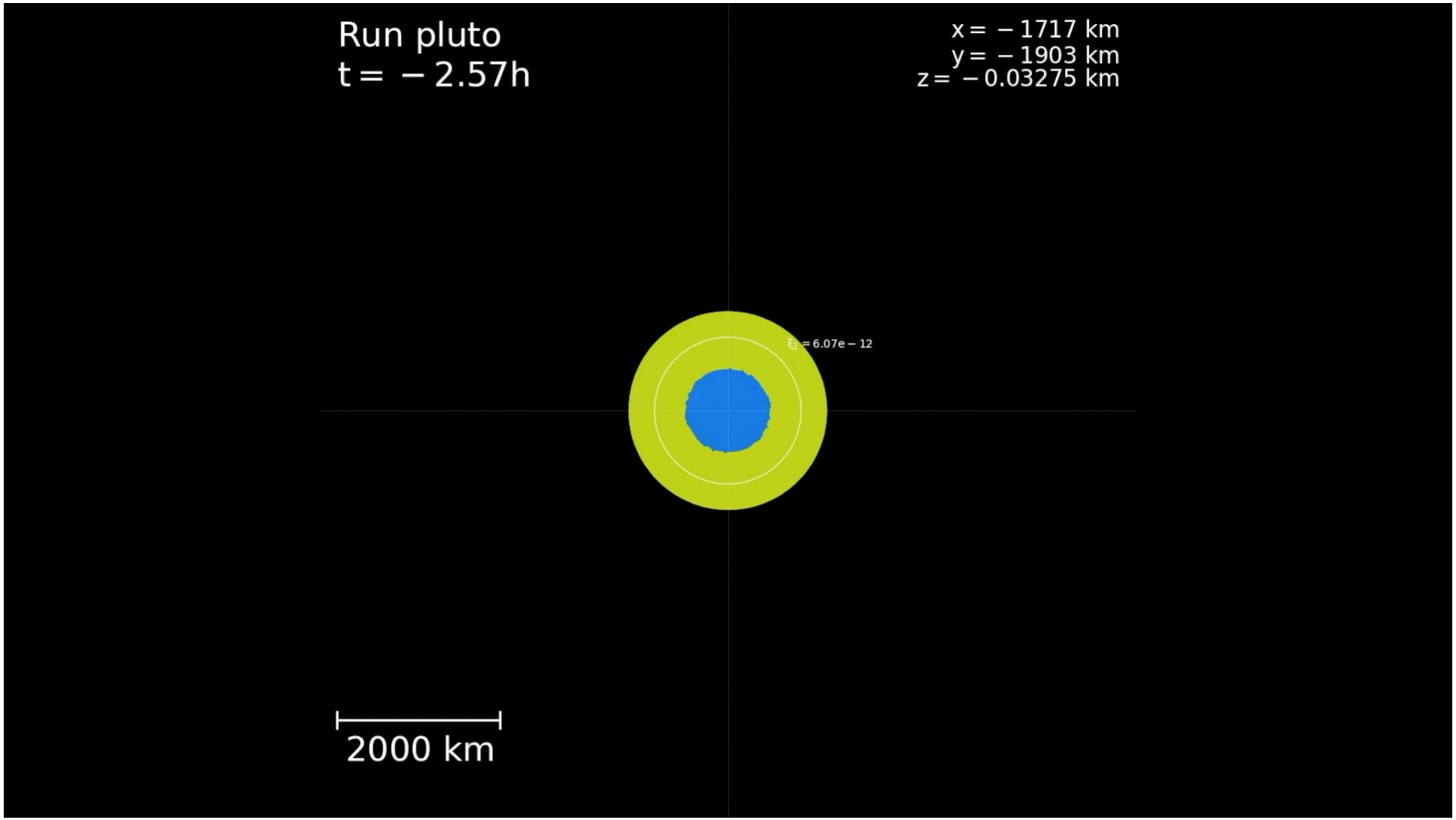
Lyra (2025, but see Denton et al. 2025 for lower mass ratios)

Pluto-Charon without strength high loss of mass scenario



Canup (2011)

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

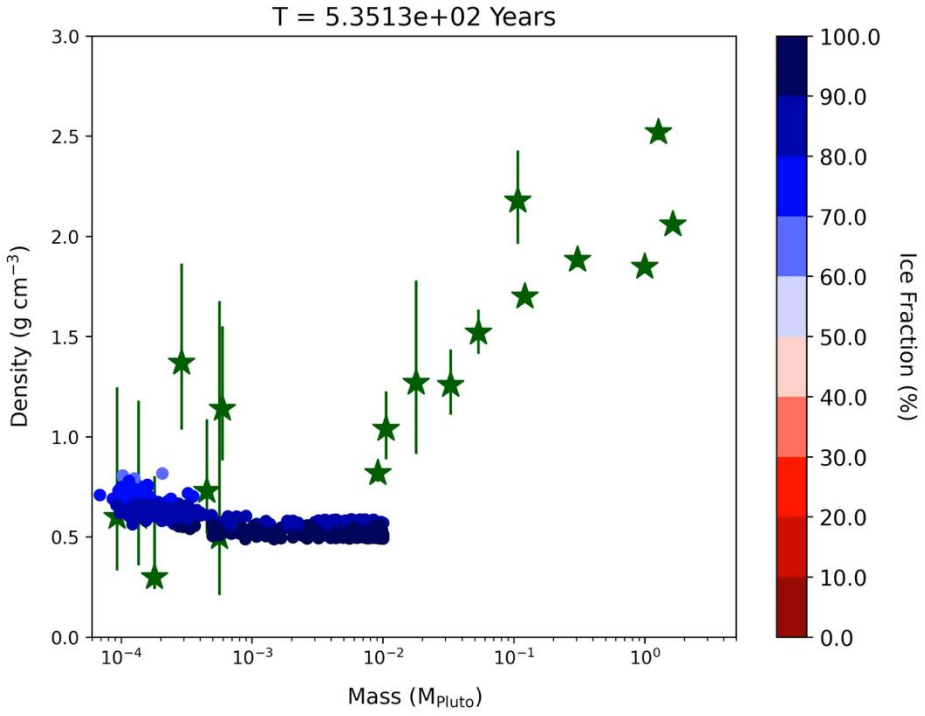


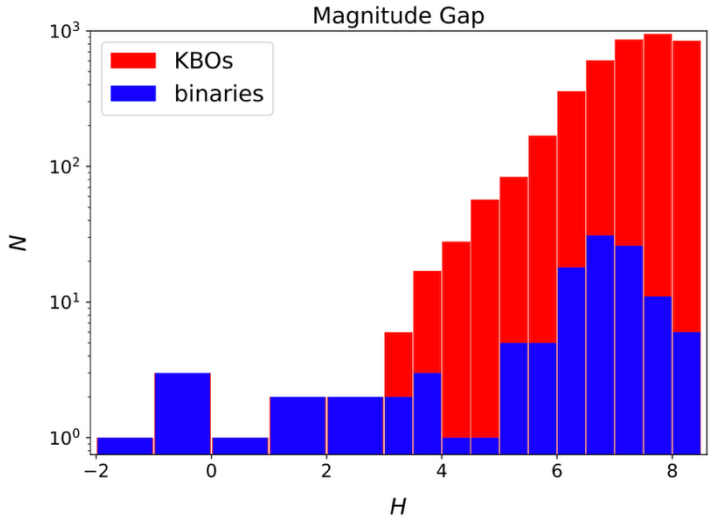
Denton et al. (2025)

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



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?