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

Wladimir Lyra

New Mexico State University

Planet Formation in the Southwest (PFITS+) Collaboration

National Institute of Science Education and Research – Jatni, India
Oct 15th, 2025

The PFITS+ Collaboration
(Planet Formation in the Southwest +)

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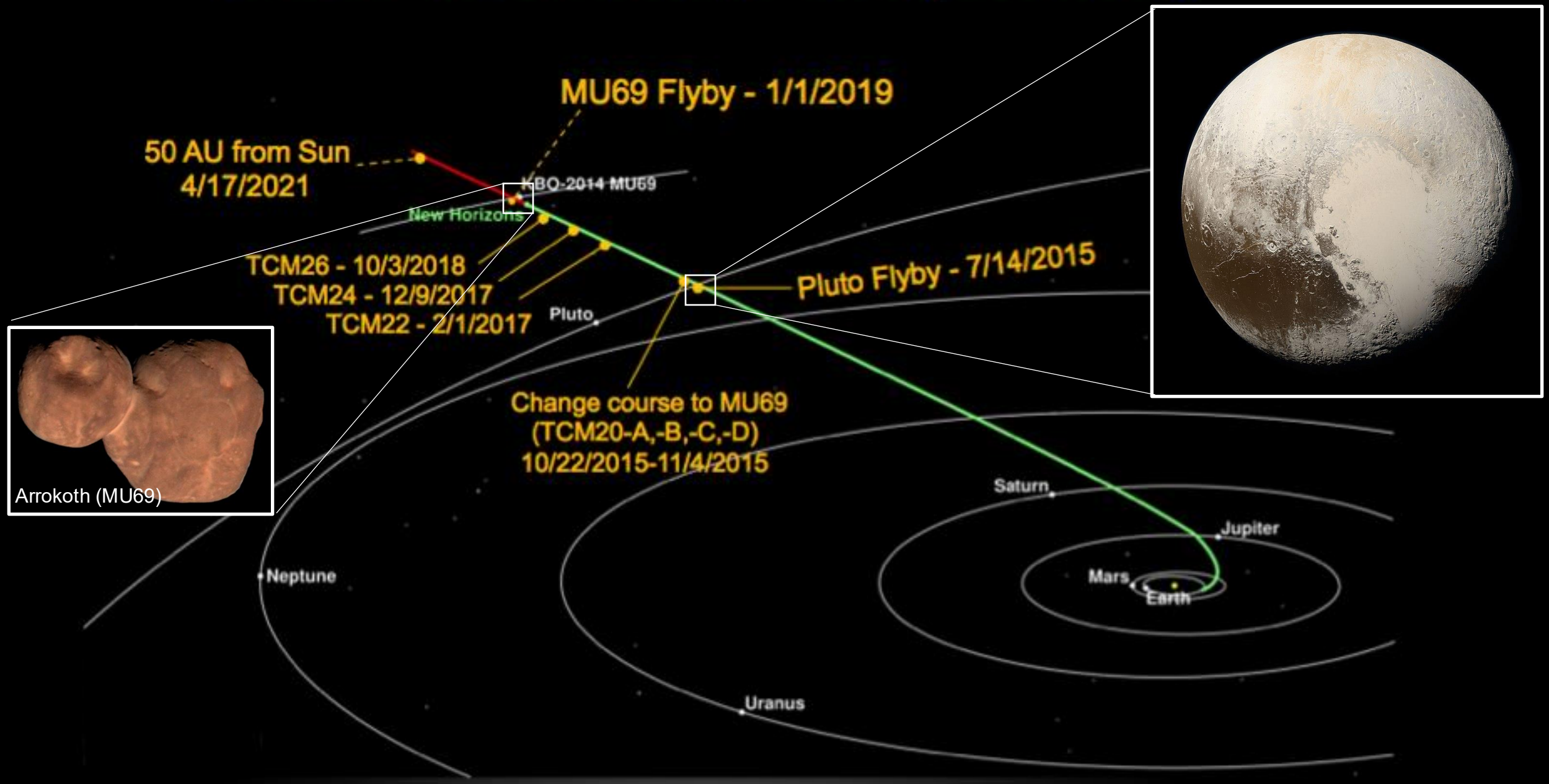
Leonardo Krapp (UAz -> Chile),

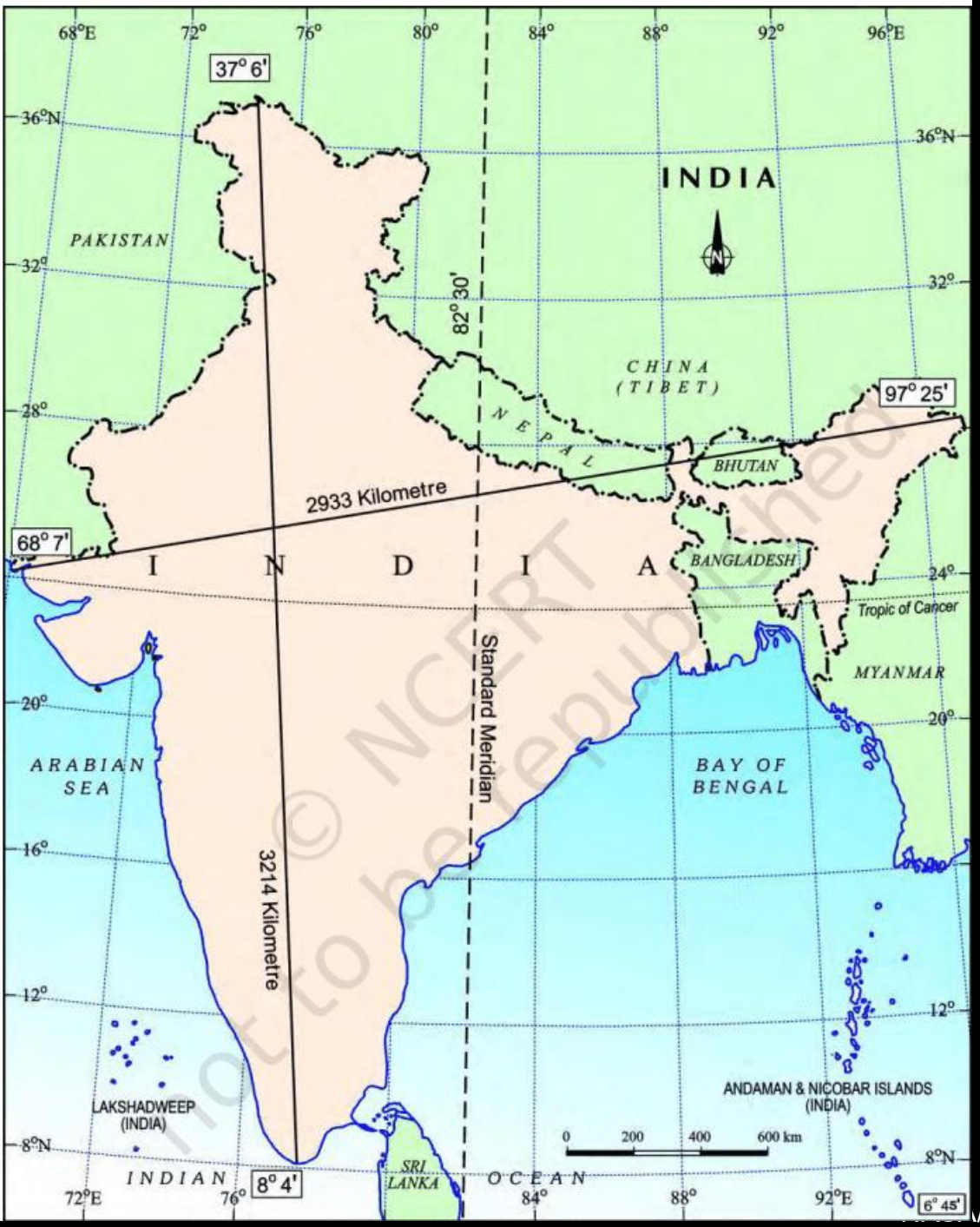
New Horizons Trajectory



Arrokoth
~20km

2400km

NASA/JHUAPL/SwRI/Jason Major

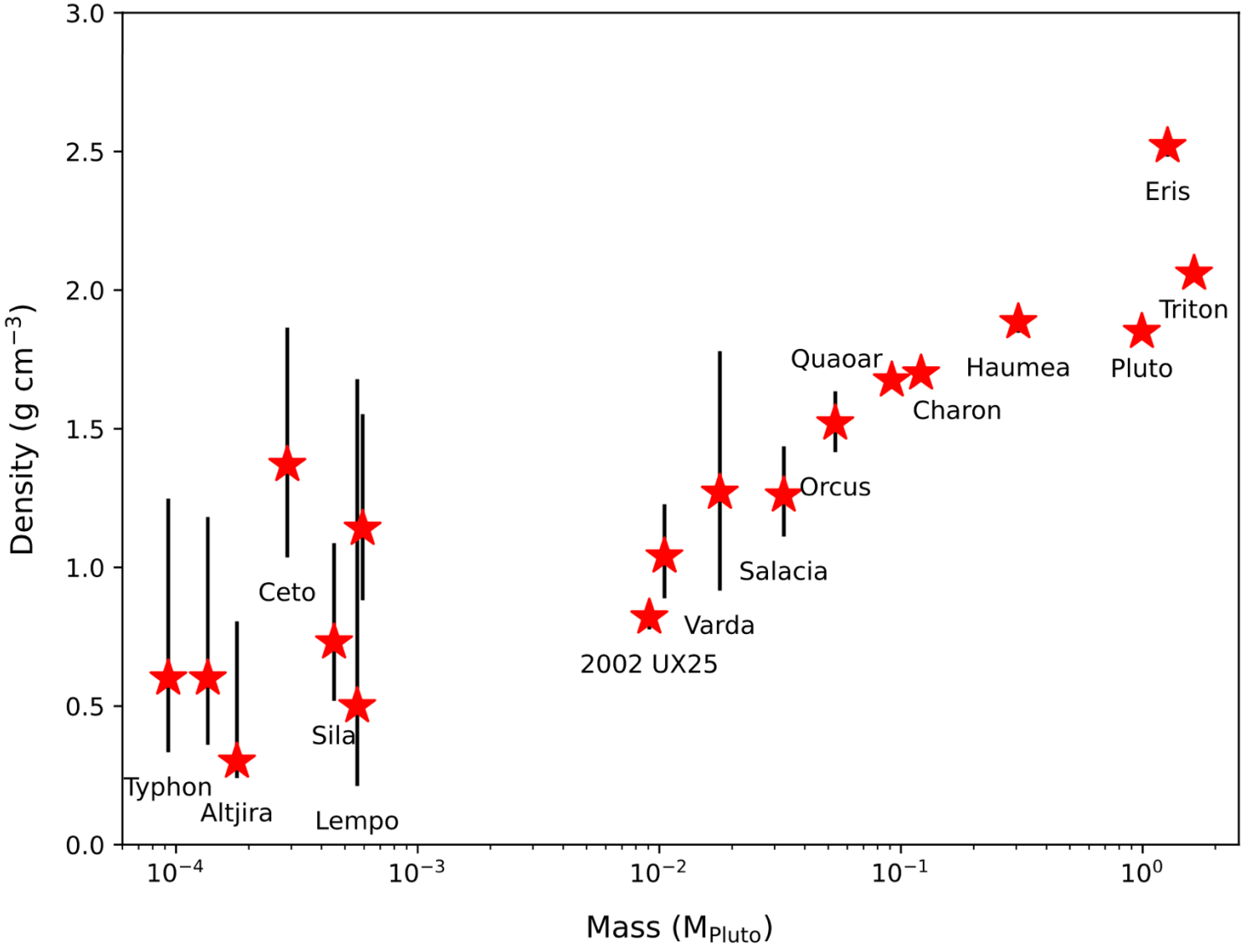


Arrokoth
~20km

2400km

/JHUAPL/SwRI/Jason Major

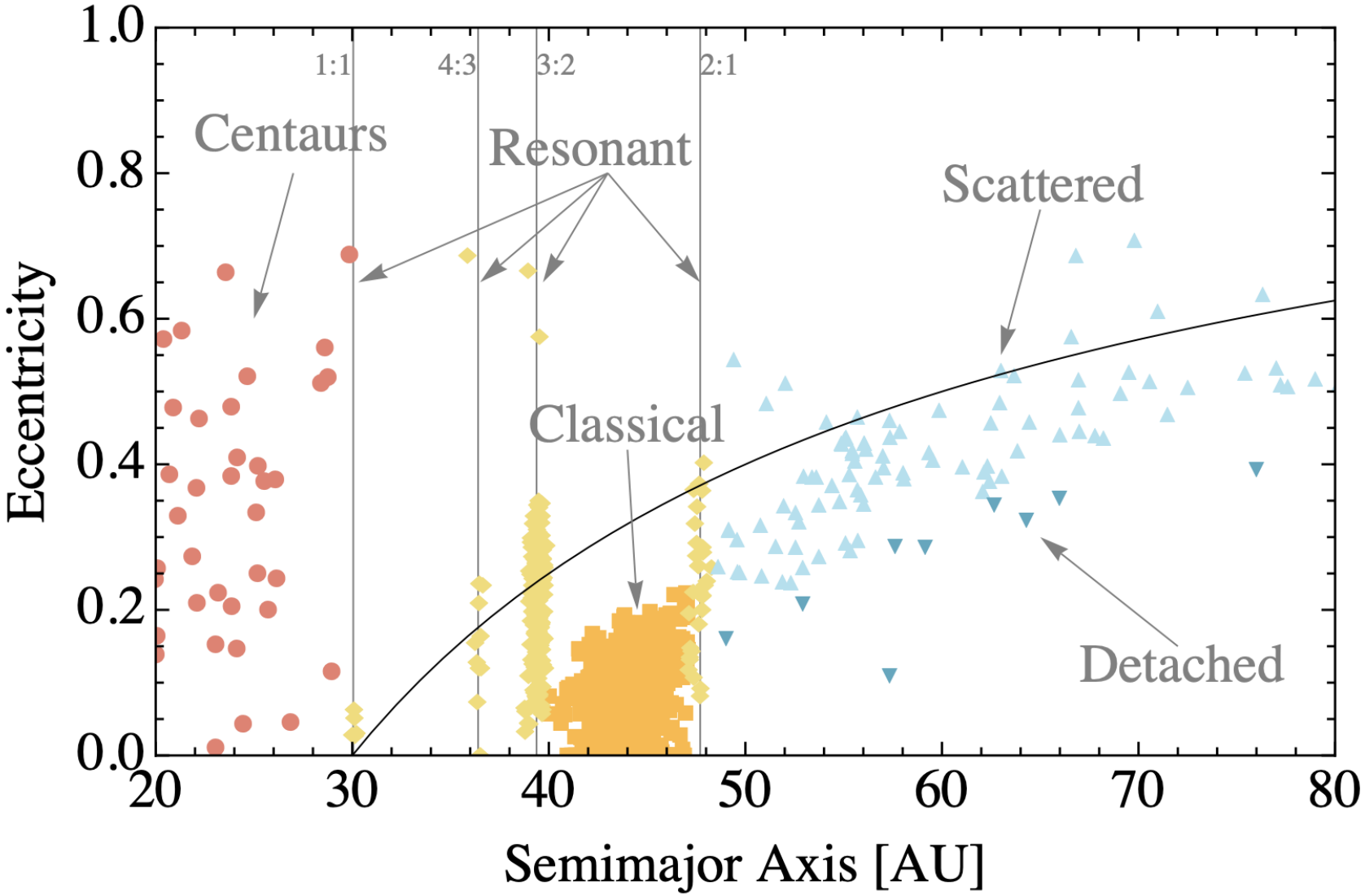
The size-density relationship of Kuiper Belt objects



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).*

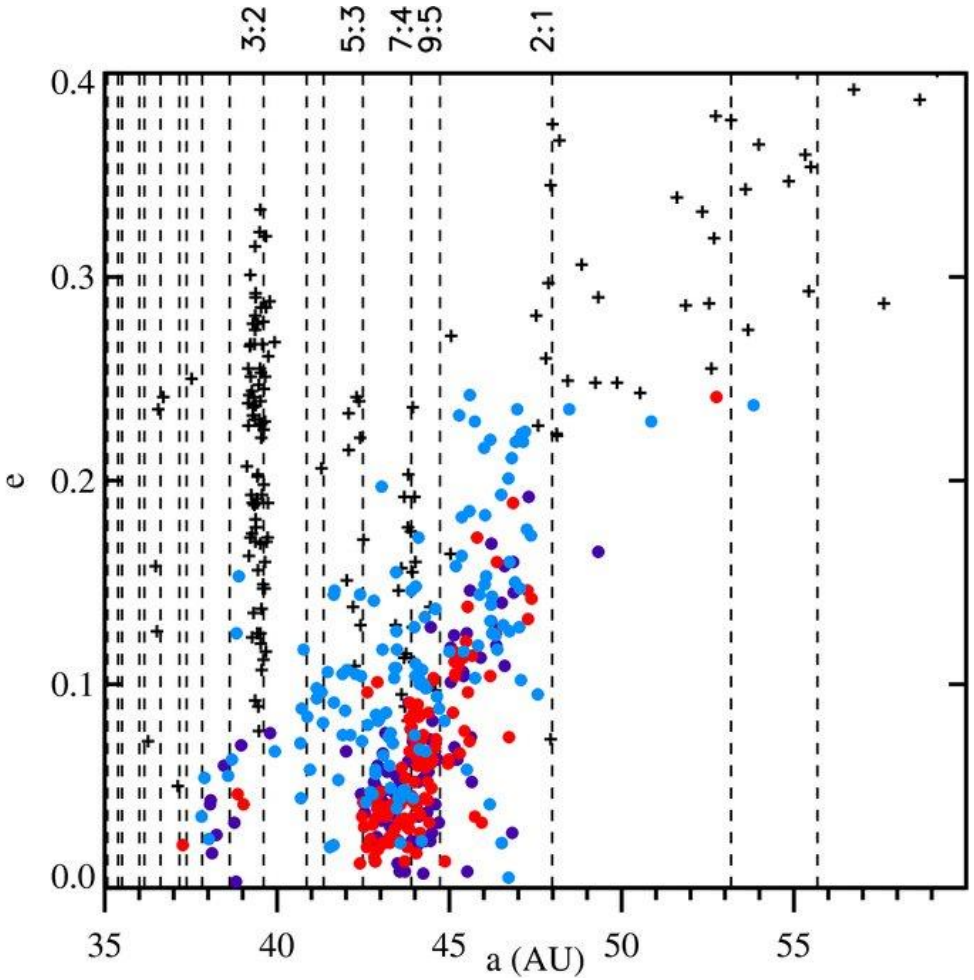
Structure of the Kuiper Belt



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

Cold Classicals

Presumably pristine planetesimals

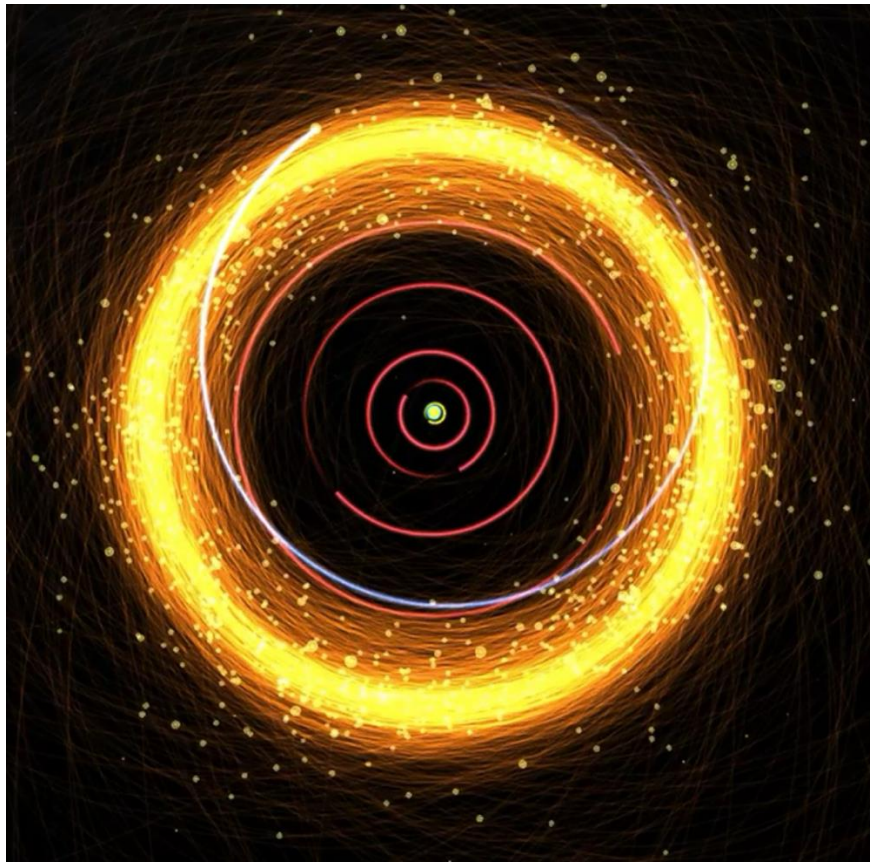


+ Resonant and Scattered

Cold Classical $i<2^o$

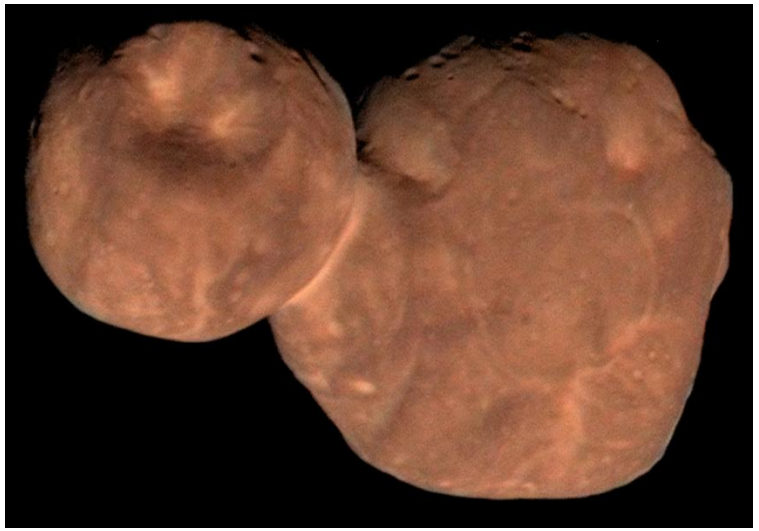
"Ambiguous" $2^o<i<6^o$

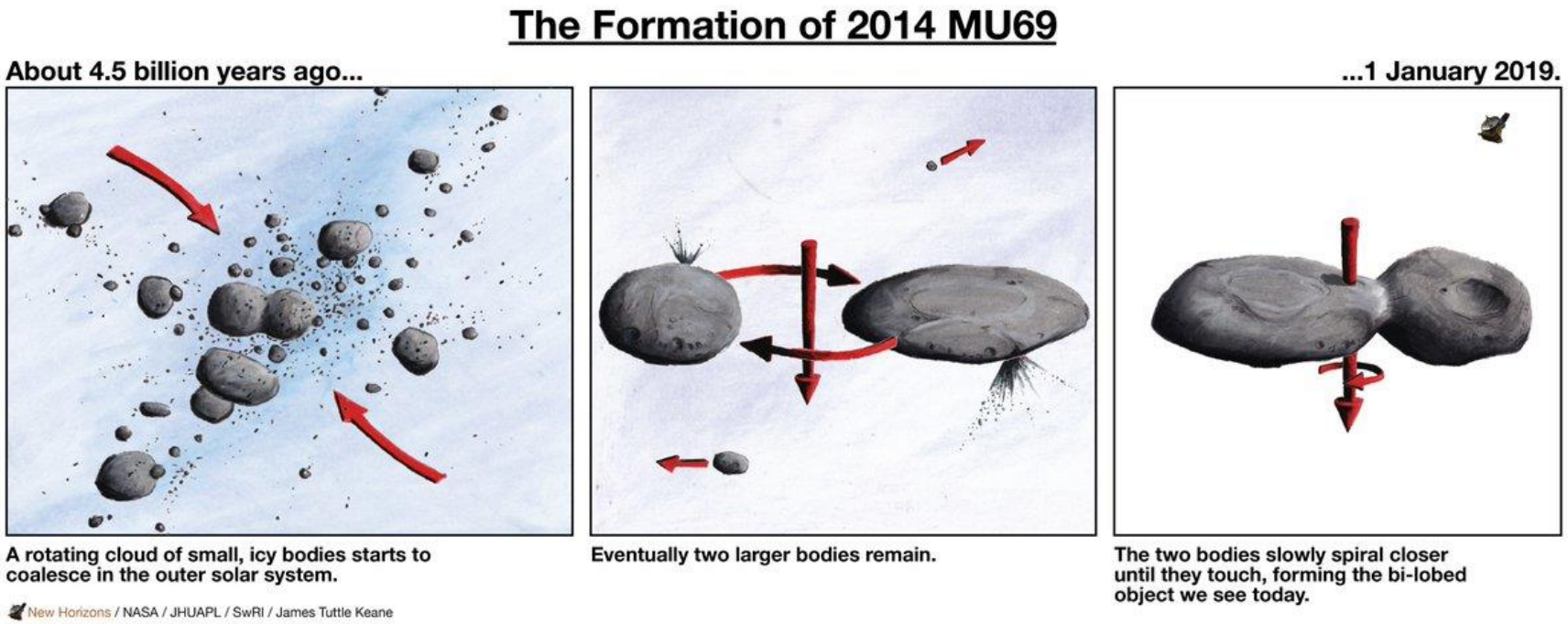
Hot Classicals $i>6^o$



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

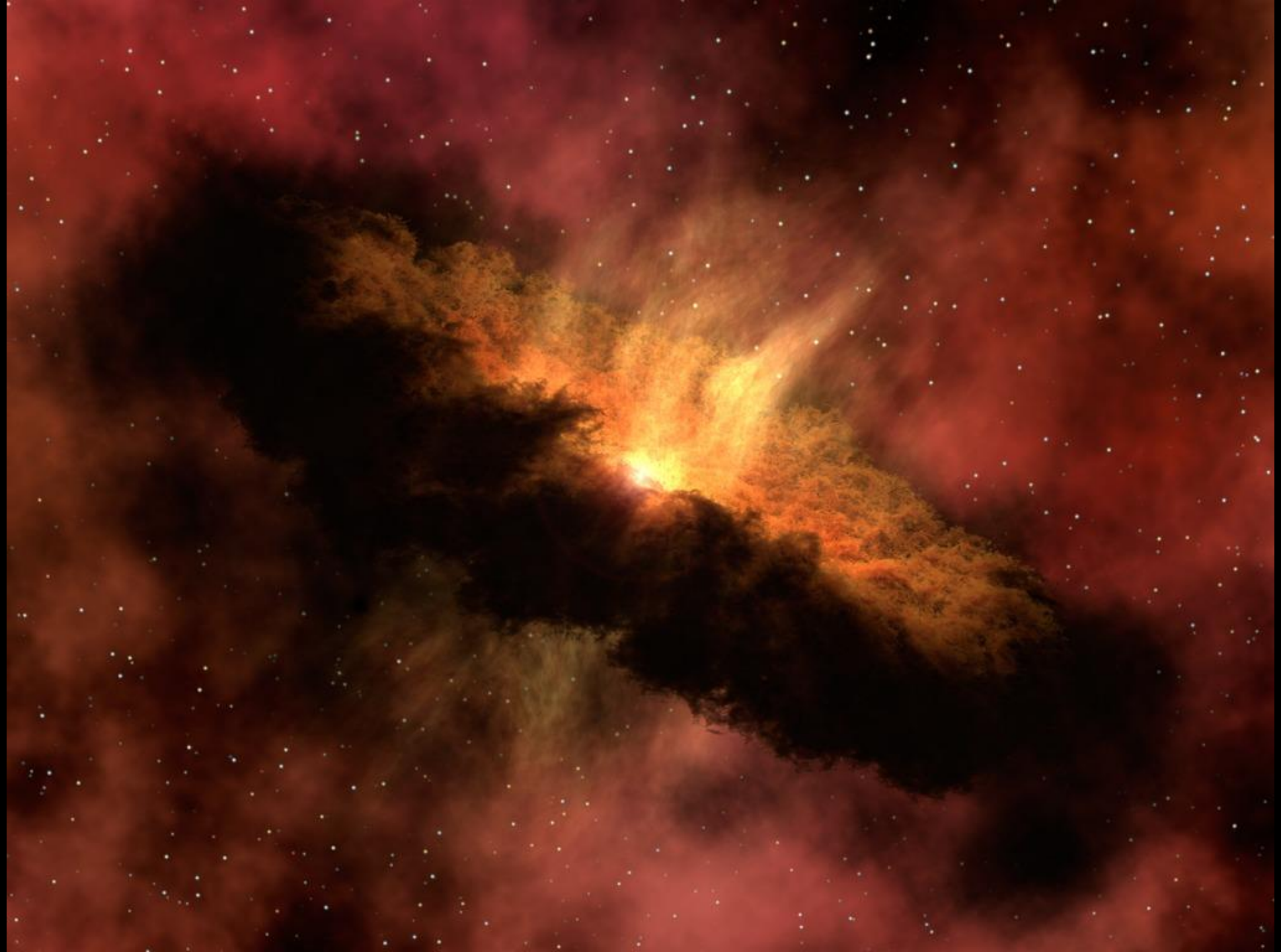
Arrokoth (MU_{69})





New Horizons Flyby, Jan 2019

Sketch by J.T. Keane



Circumstellar/Protoplanetary Disks

PP disk fact sheet

Density: 10^{13} – 10^{15} cm^{-3}
(Air: 10^{19} cm^{-3})

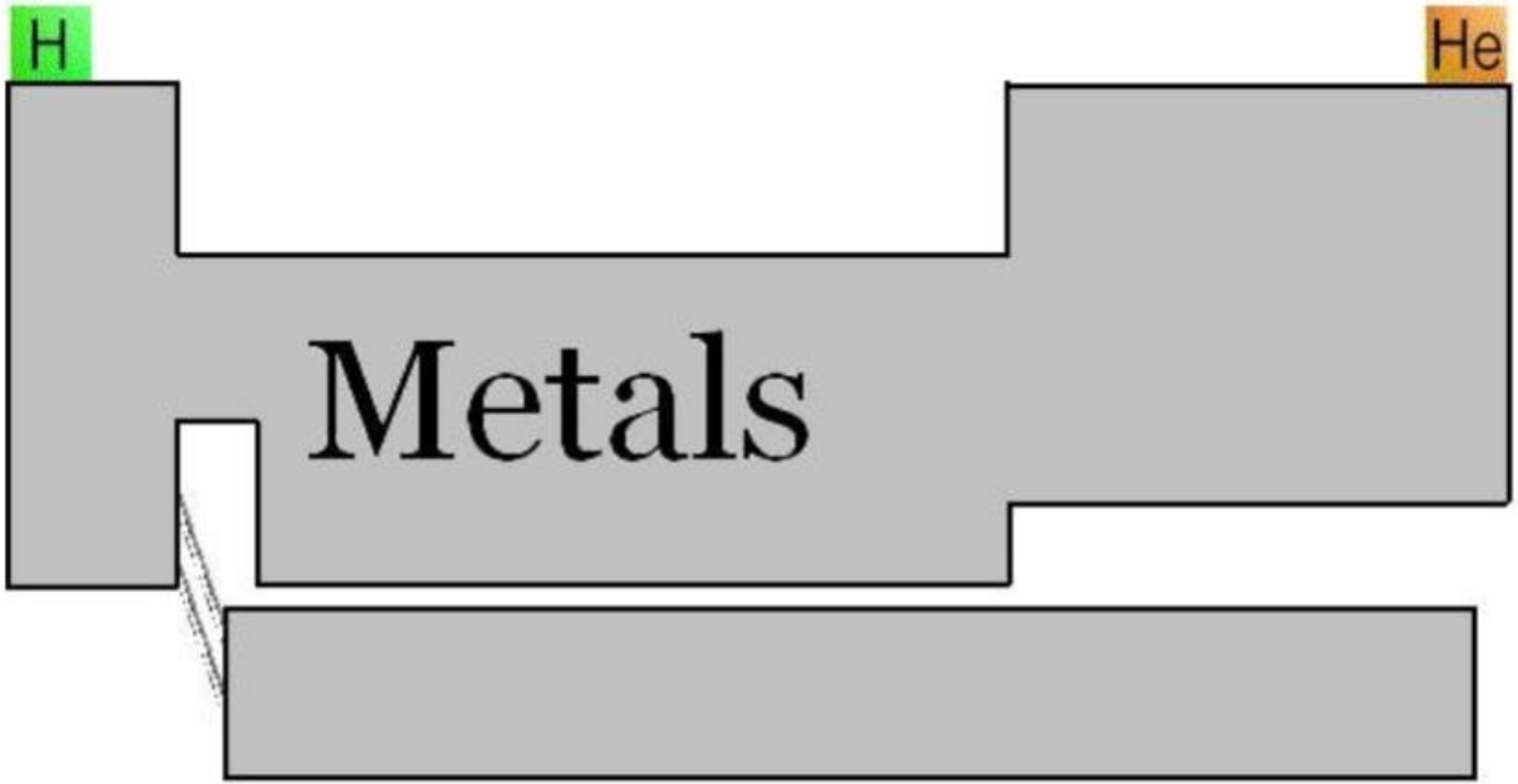
Temperature: 10-1000 K

Scale: 0.1-100AU

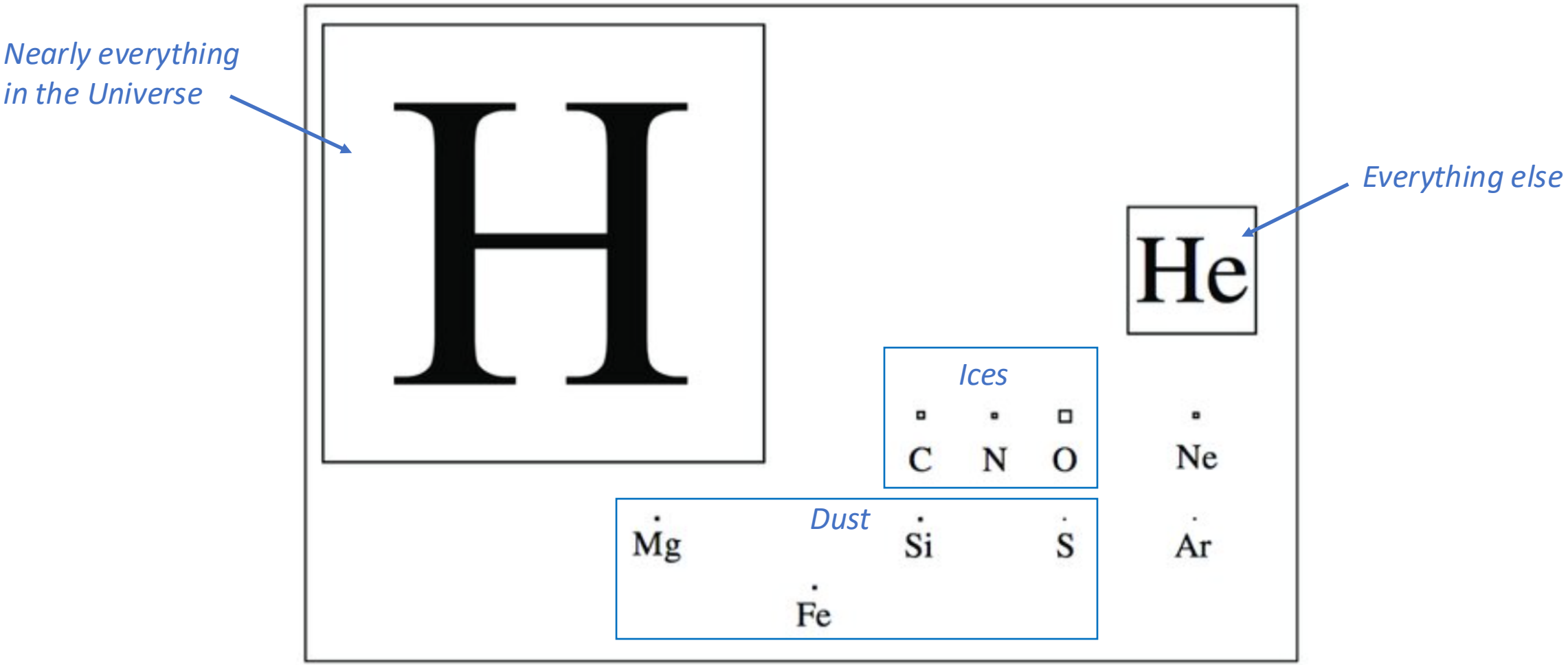
Mass: 10^{-3} – 10^{-1} M_{sun}

Composition:
5:2 H_2-He mixture.
1% “metals”

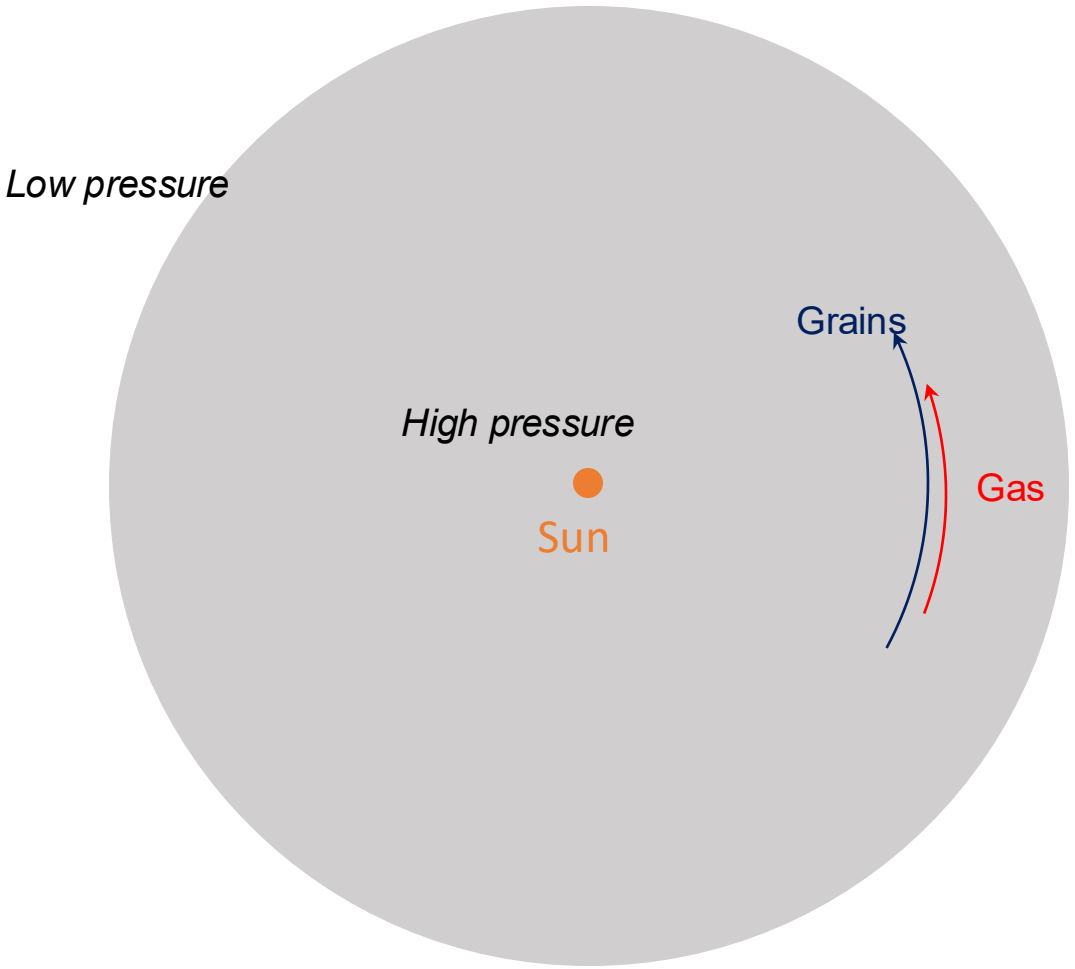
The Astronomer's Periodic Table



The Astronomer's Periodic Table



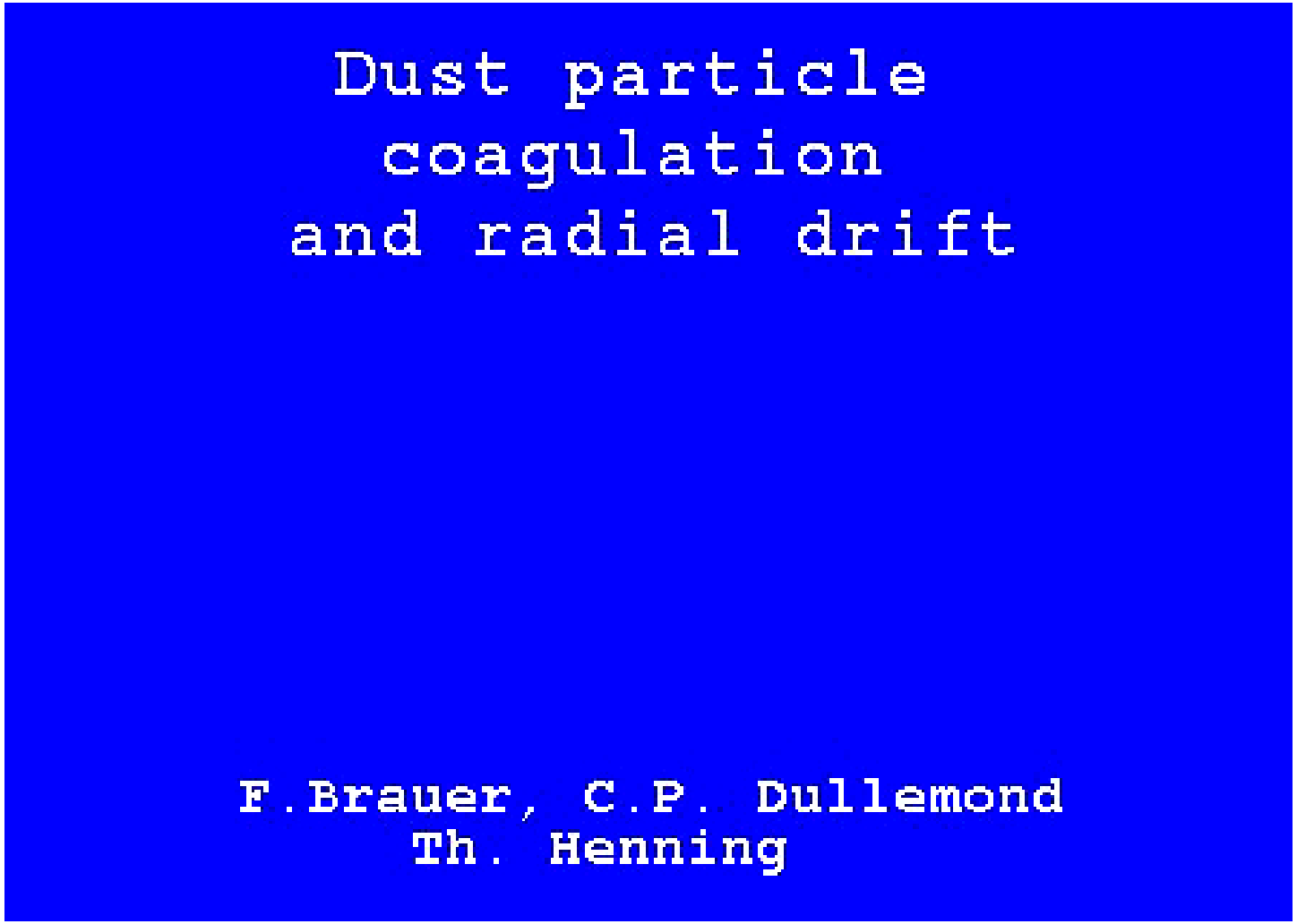
Headwind and Grain Drift



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

The grains have none (Keplerian).

Dust coagulation and drift

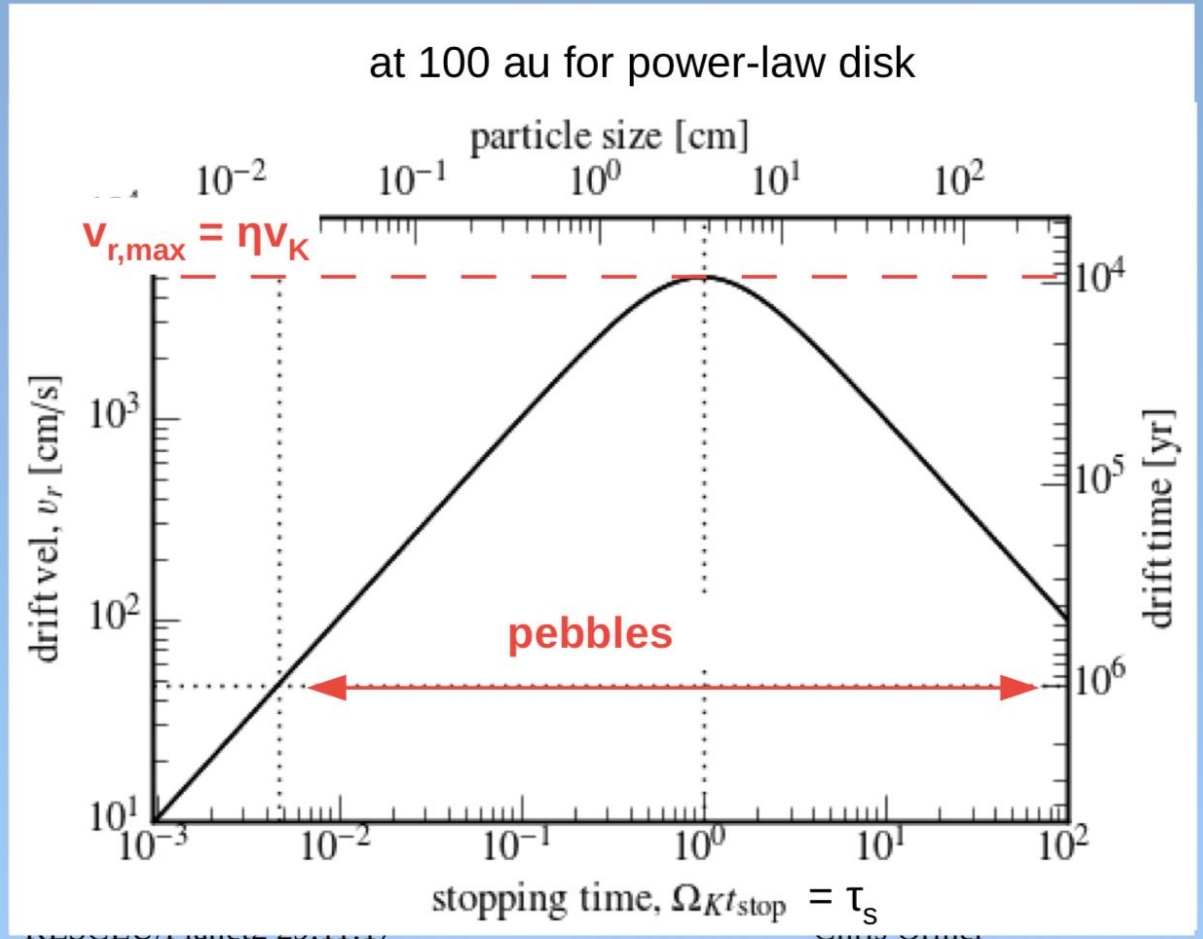


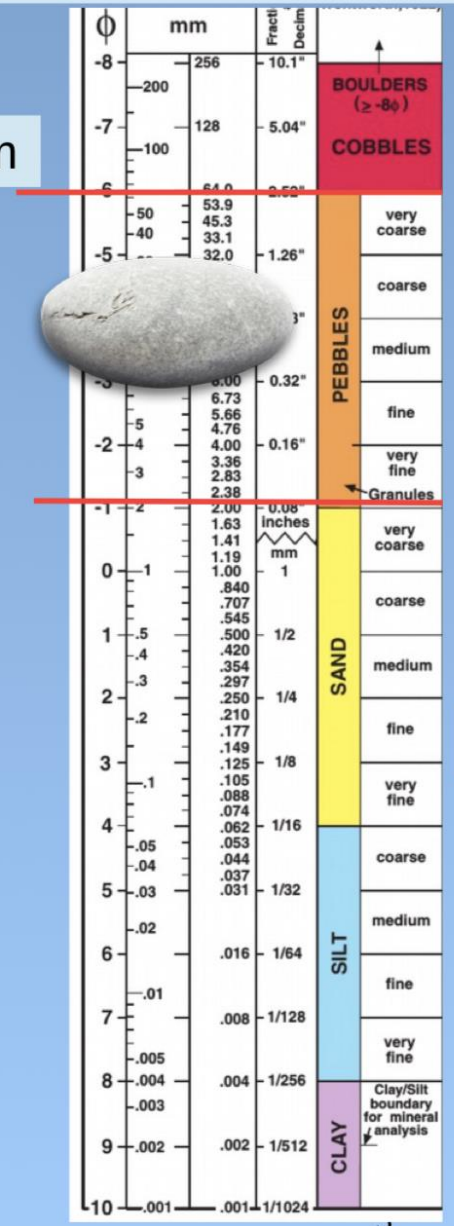
Brauer et al. (2008)

Pebble definition

Geologist: *particles 2 mm < d < 6.4 cm*

Astrophysical: *particles that drift*





6.4 cm

1 dm

1 cm

1 mm

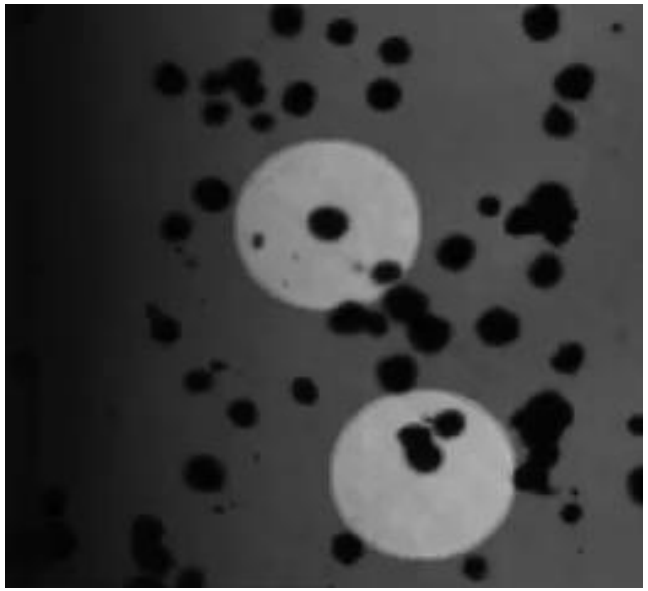
100 μm

10 μm

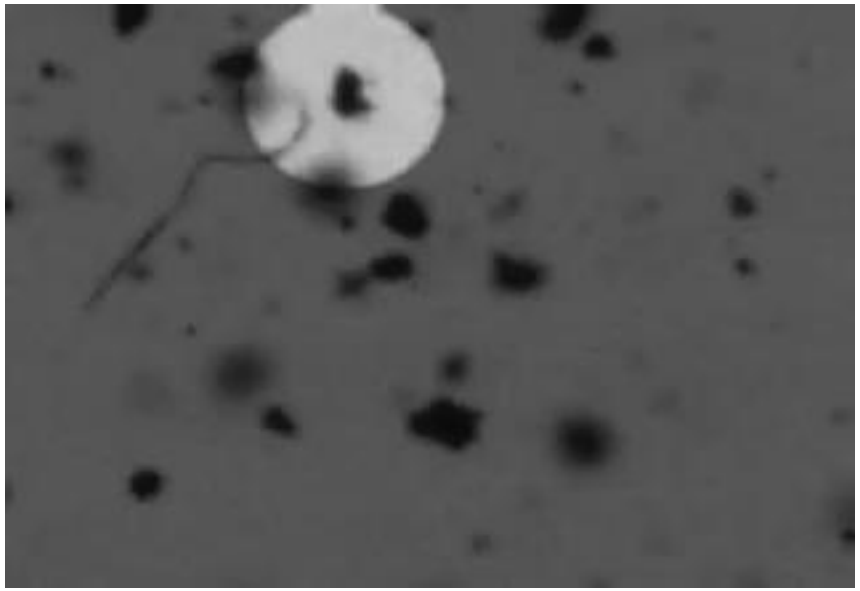
1 μm

Grain collision outcomes

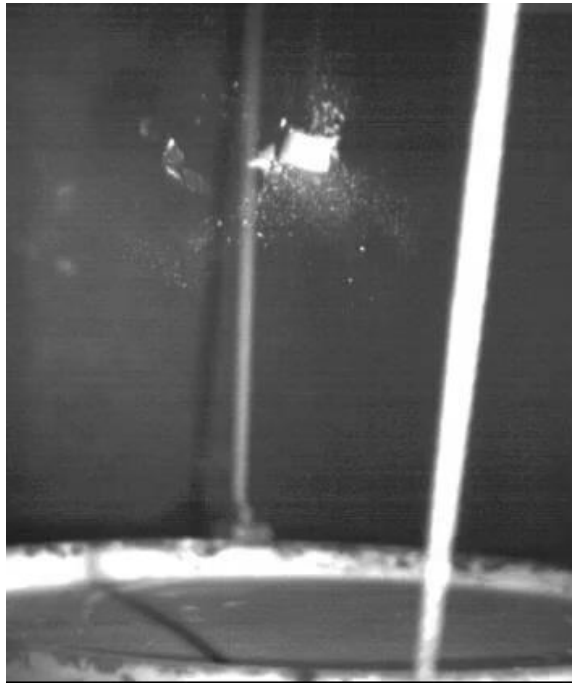
Bouncing



Sticking

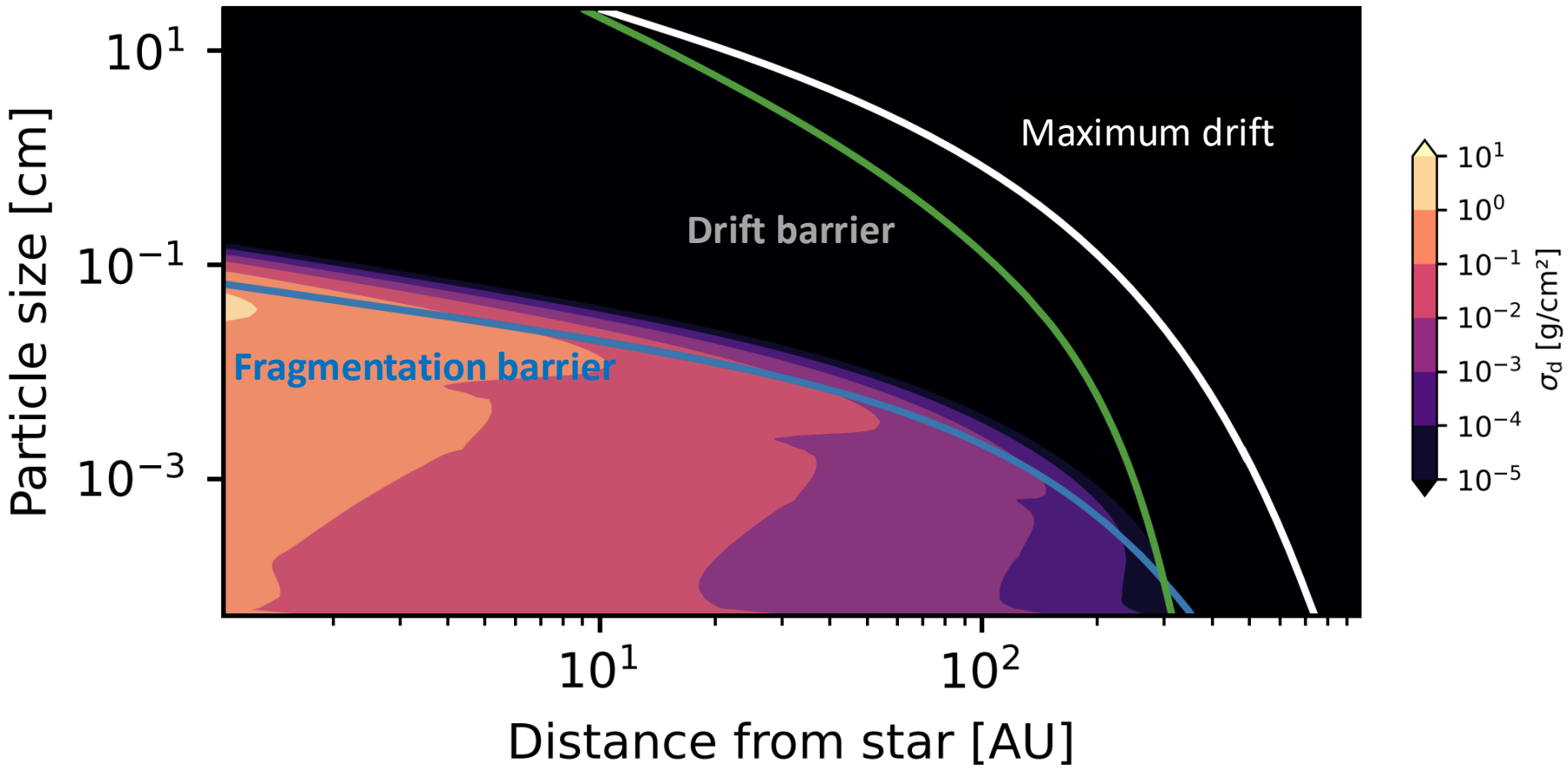


Fragmentation



Wurm (2018)

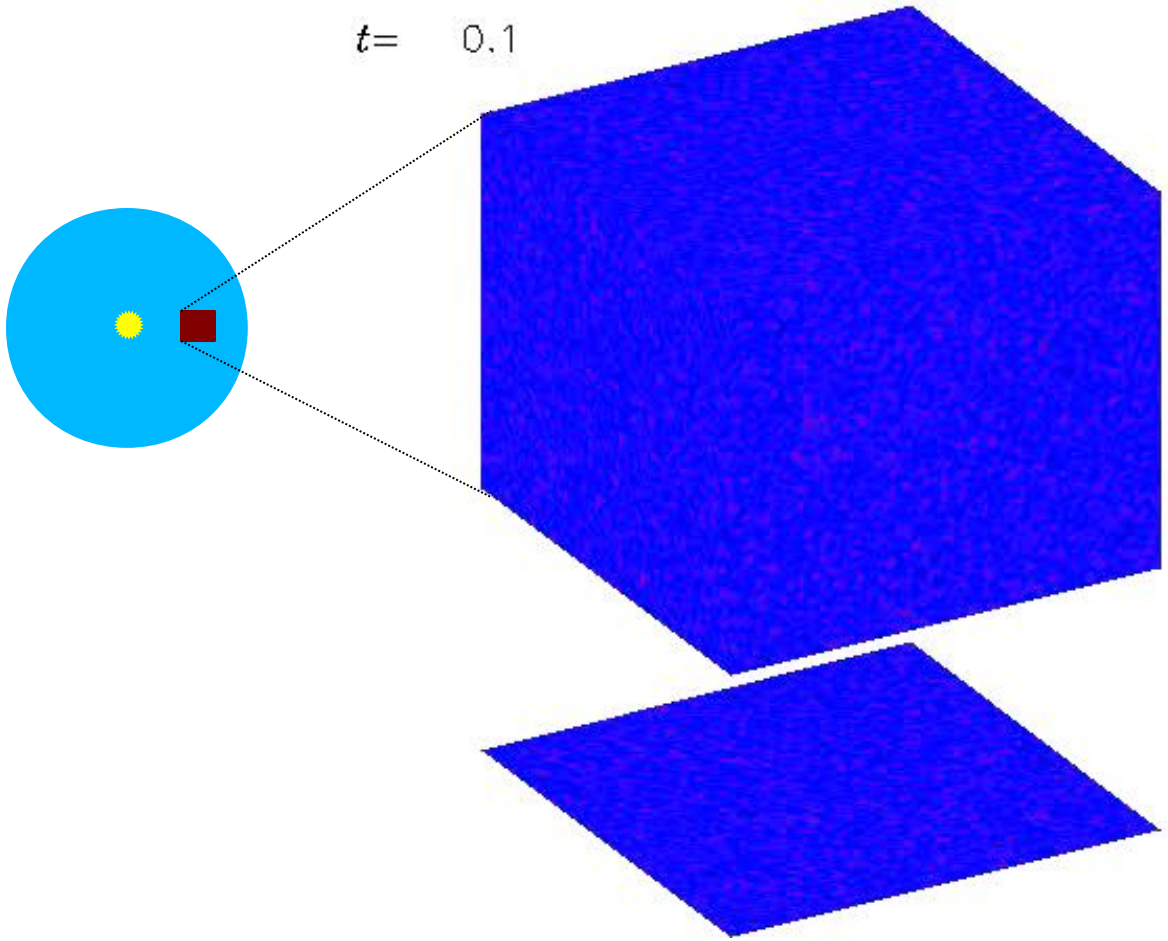
Fragmentation Barrier

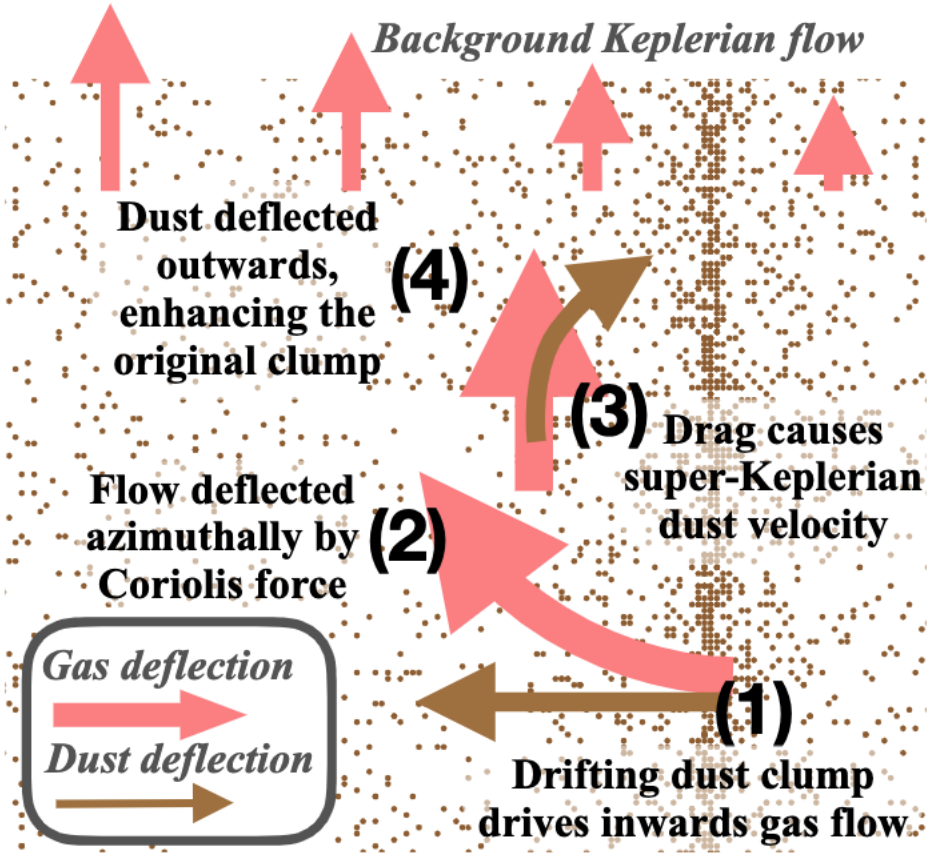


Brauer et al (2008), Zsom et al. (2009, 2010), Stammler & Birnstiel (2022)

Streaming Instability

The pebble drift is hydrodynamically unstable

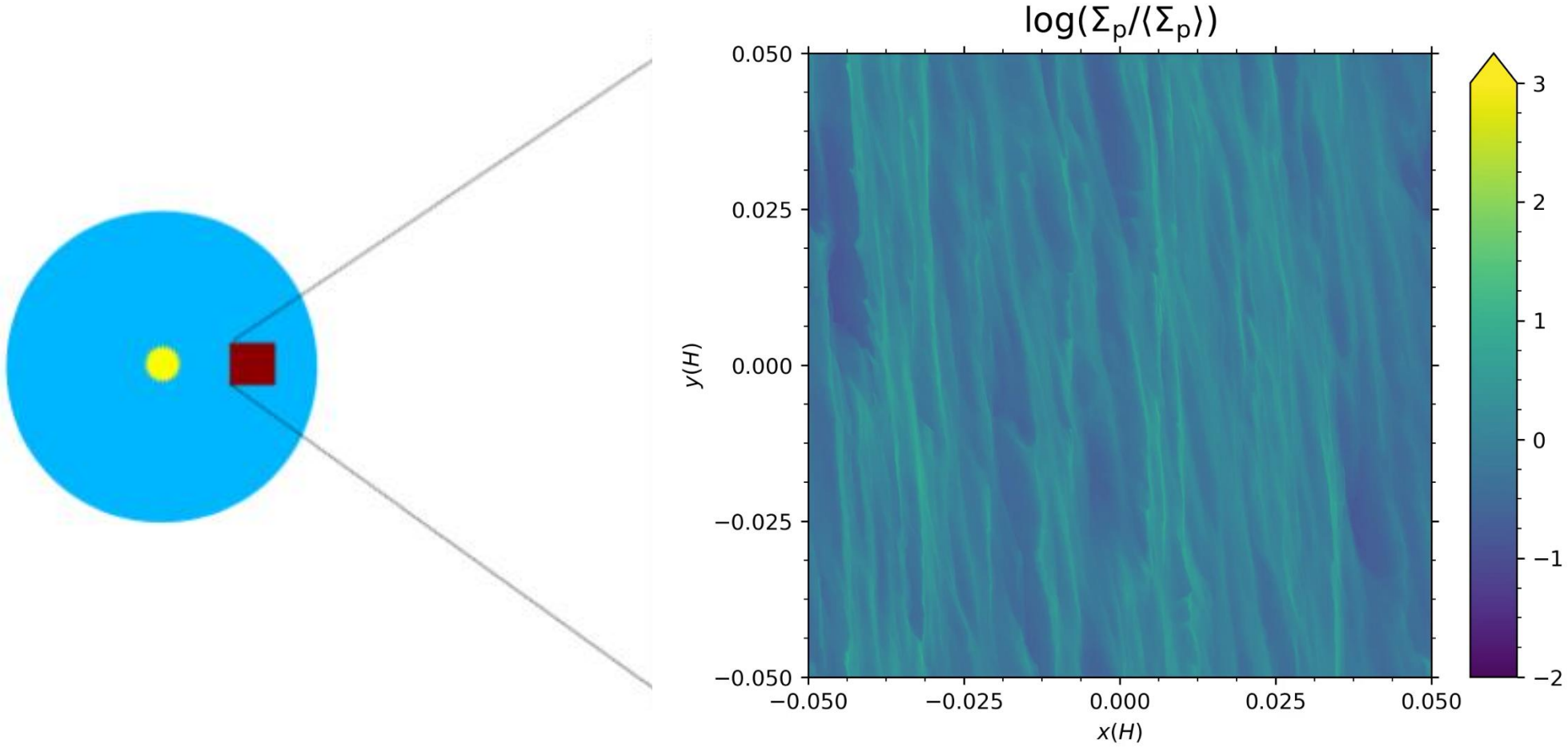




Lesur et al. (2022)

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, Nesvorny+ '19

Gravitational collapse into planetesimals



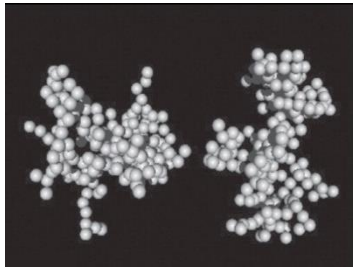
Animation by: Rixin Li

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, Nesvorny+ ’19

Core Accretion

Core Accretion

Dust grains



0.1 – 1 μm

coagulation

Pebbles

mm – cm

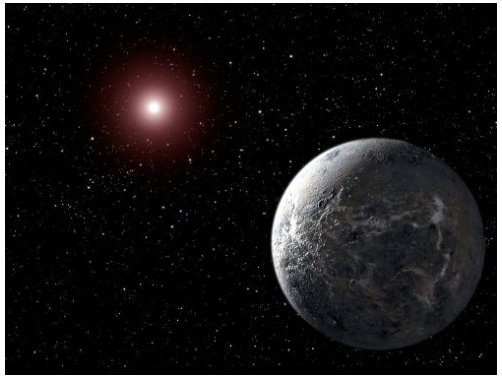
Streaming Instability

Planetesimals

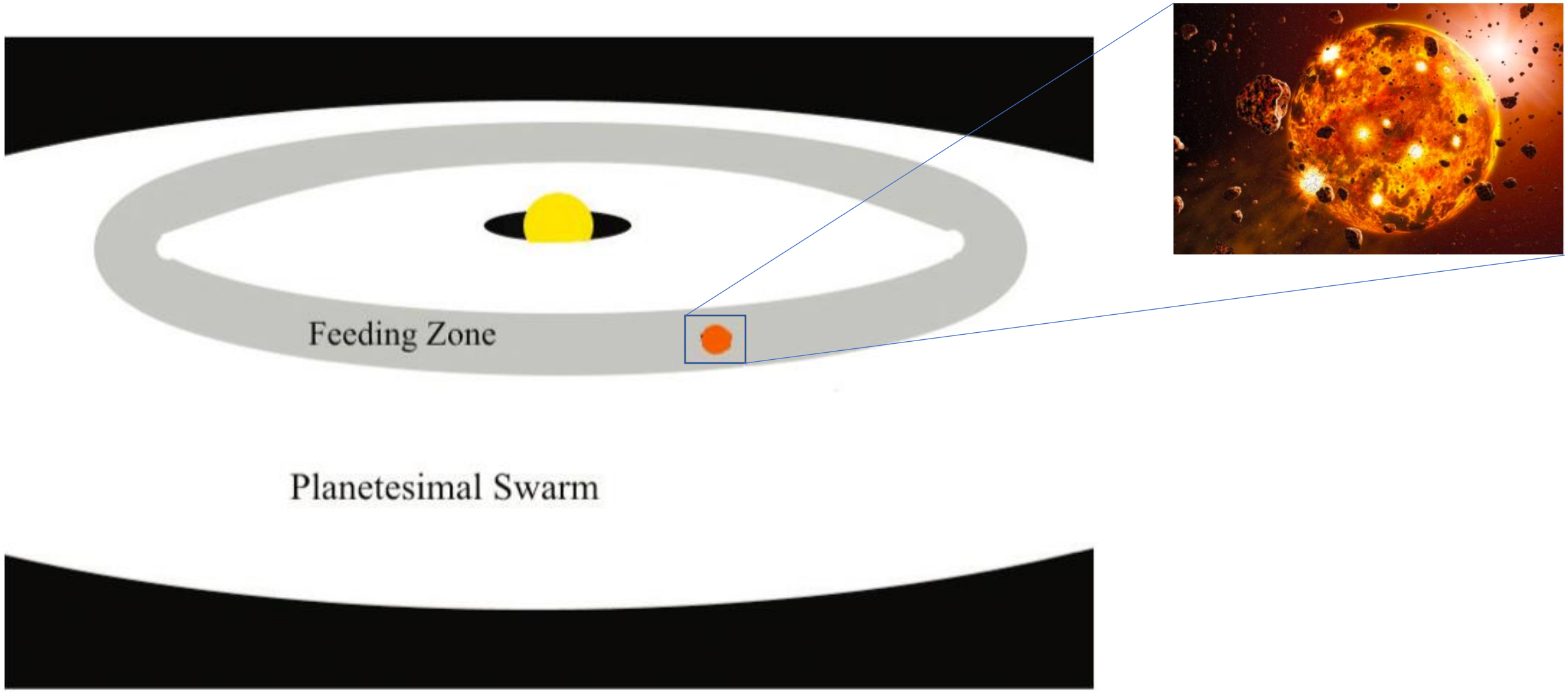
1-100km

Planetesimal collisions

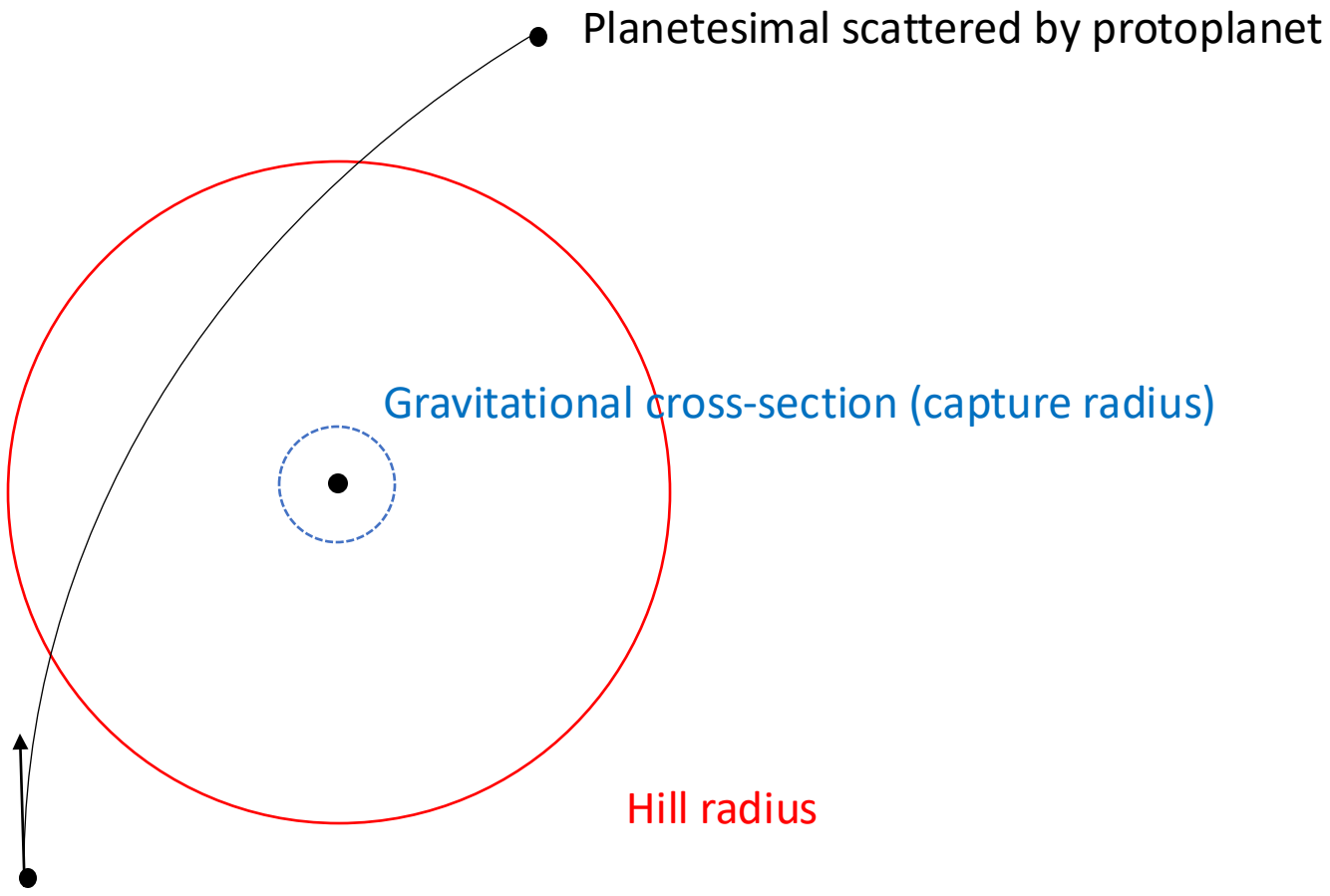
Protoplanets
Rocky Planets
Planetary Cores



Collisional Growth (Planetesimal Accretion)

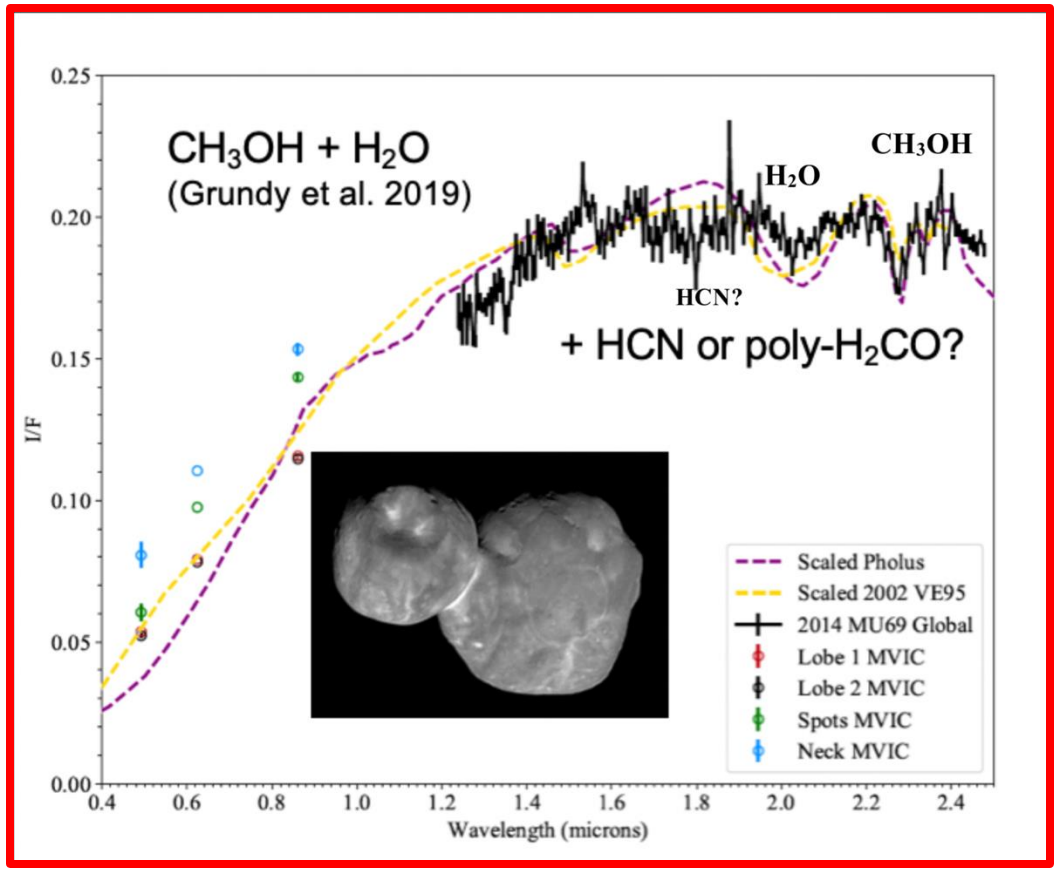


Planetesimal Accretion is inefficient

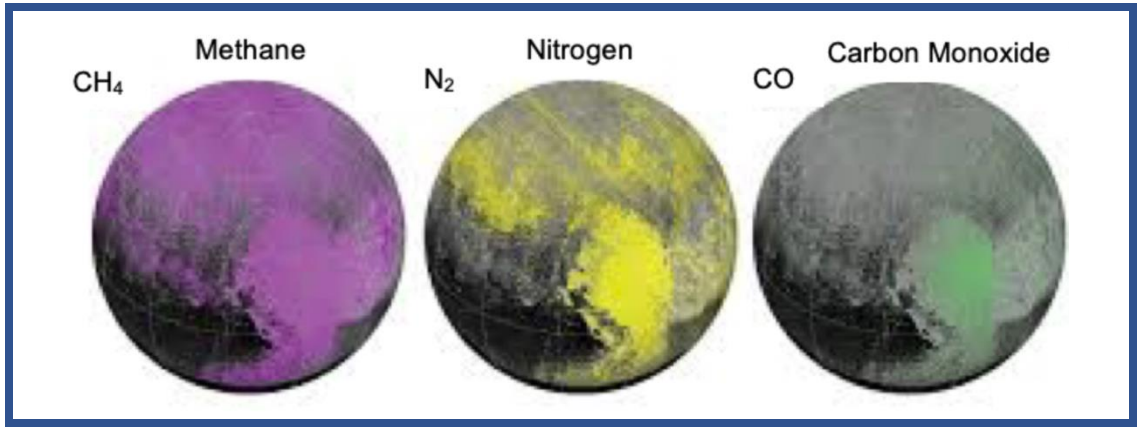


Arrokoth and Pluto ices are different

Arrokoth : Methanol, H_2O, HCN



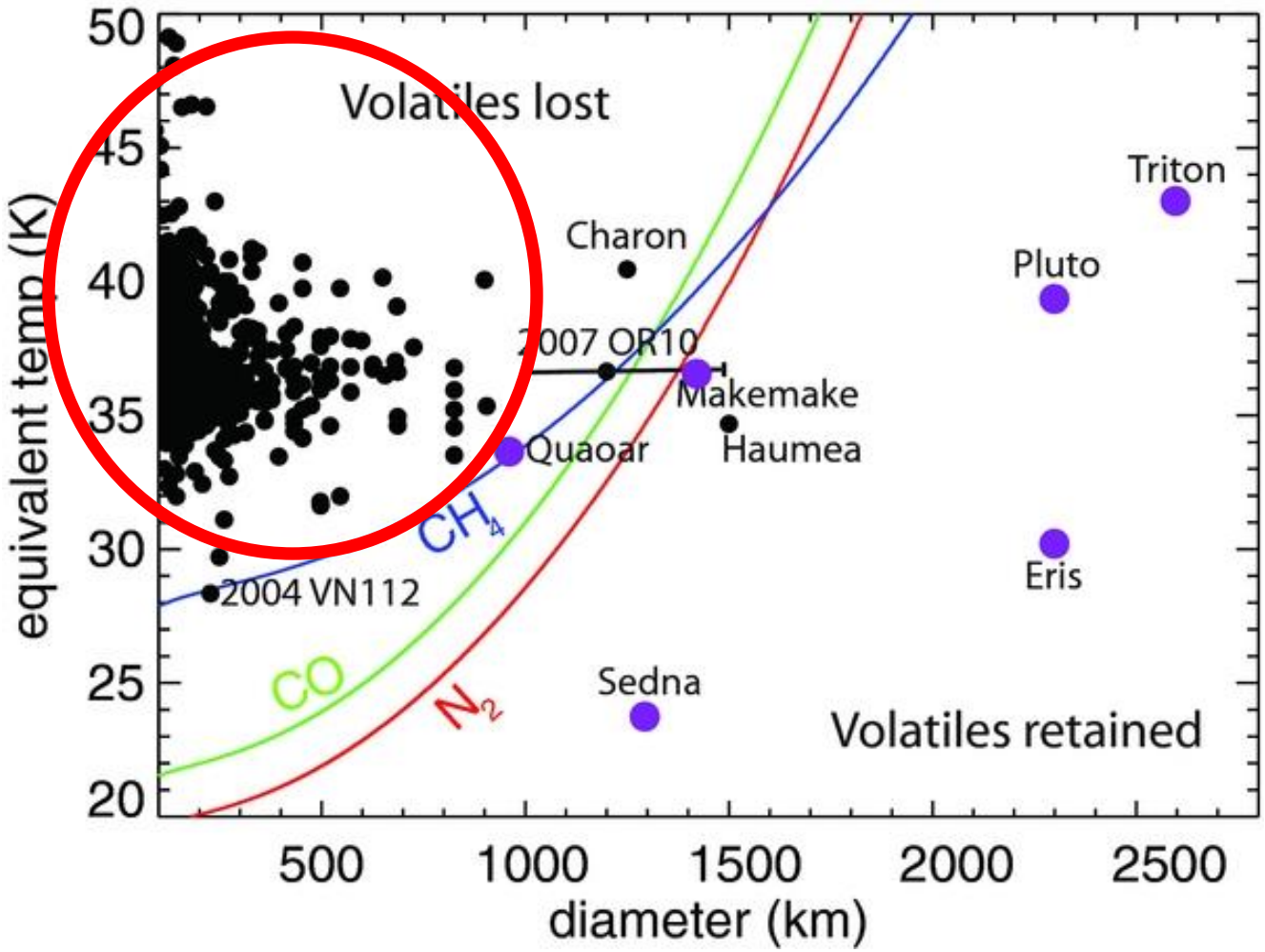
Pluto : CH_4, N_2, CO



Grundy+ '16, Lisse+ '20

Retention of volatiles

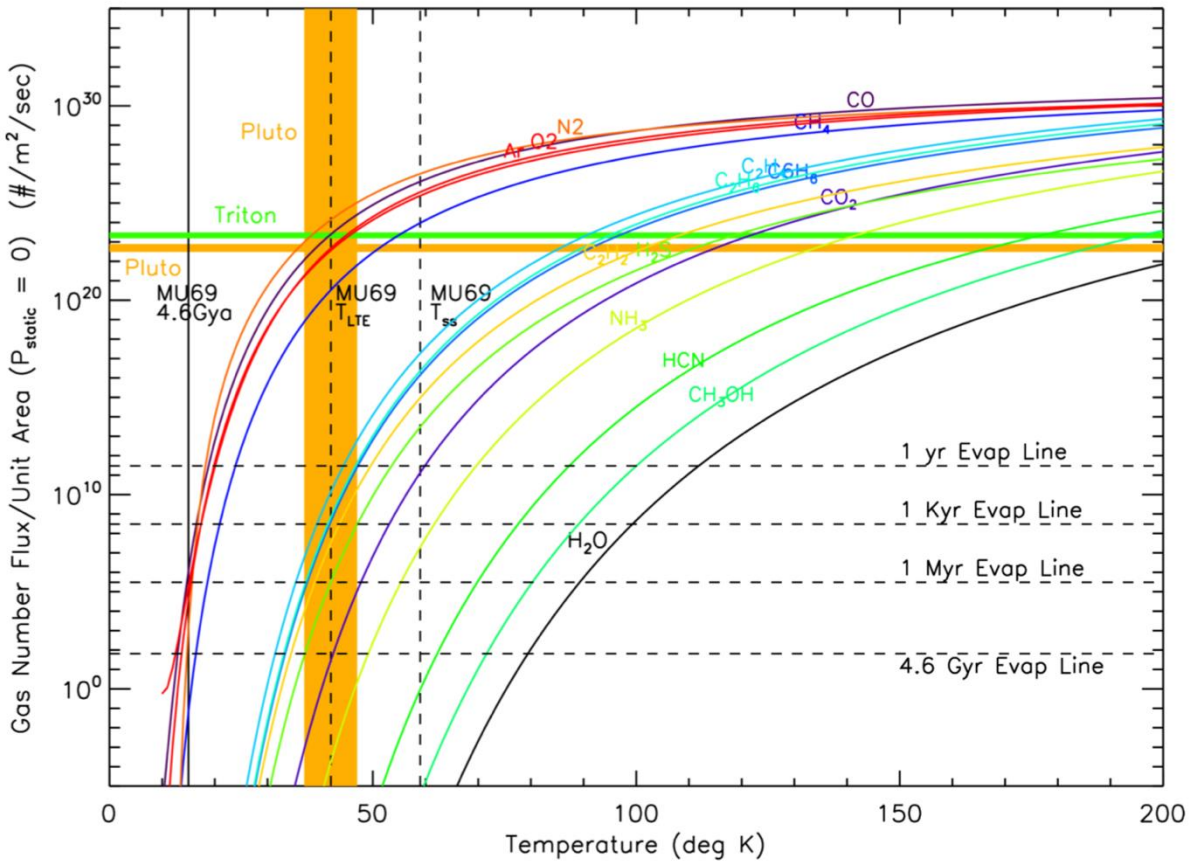
Arrokoth formed with volatiles but lost them



Brown et al. (2011); Lisse et al. (2020)

Retention of volatiles

Pluto cannot have been formed by accumulation of bodies like Arrokoth



Hypervolatiles (CH_4 / CO / N_2)

Lost under vacuum pressure and microgravity in ~1 Myr for 40 K

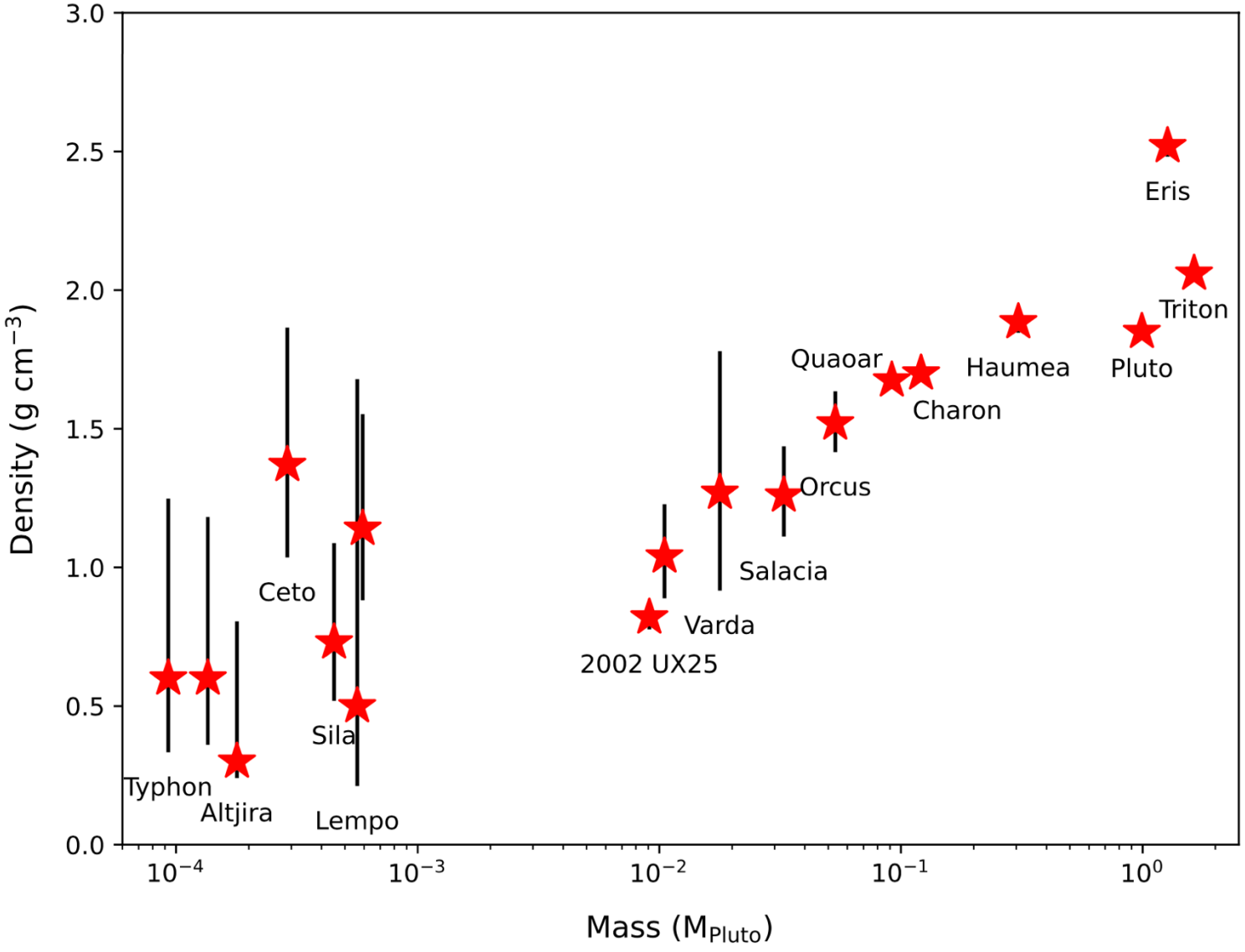
Retained for long times only for T < 20K

Arrokoth hypervolatiles lost when disk dissipates and temperature rises to 40K.

Hypervolatile-rich **Pluto cannot form via planetesimal accretion**

Lisse et al. (2020)

The size-density relationship of Kuiper Belt objects



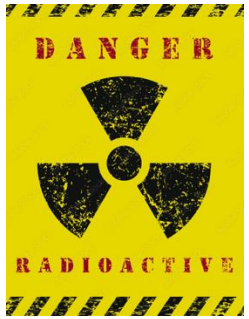
Brown (2013), McKinnon et al. (2017), Noll et al. (2020), Cañas & Lyra + (2024)

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

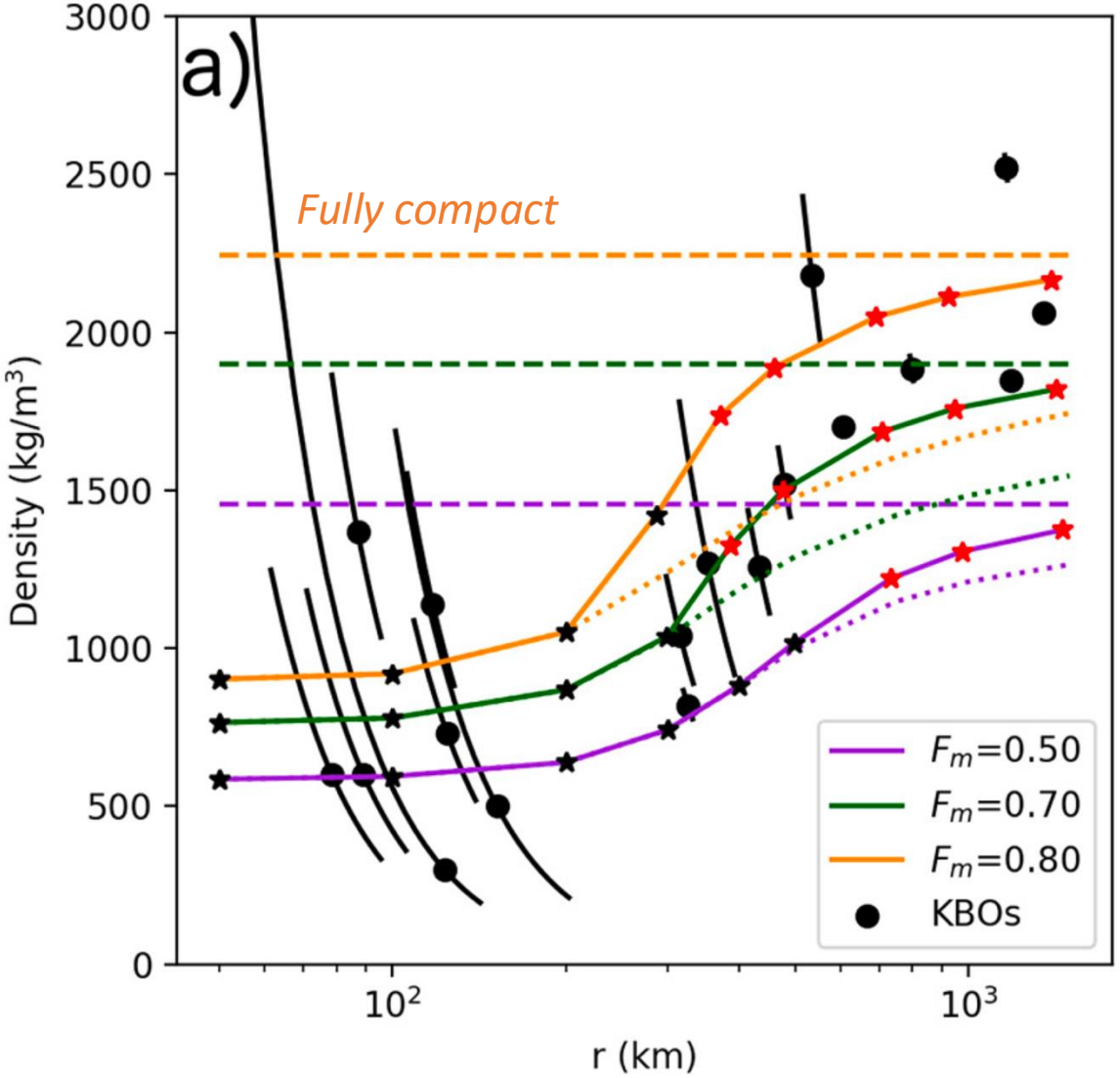
Problem

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



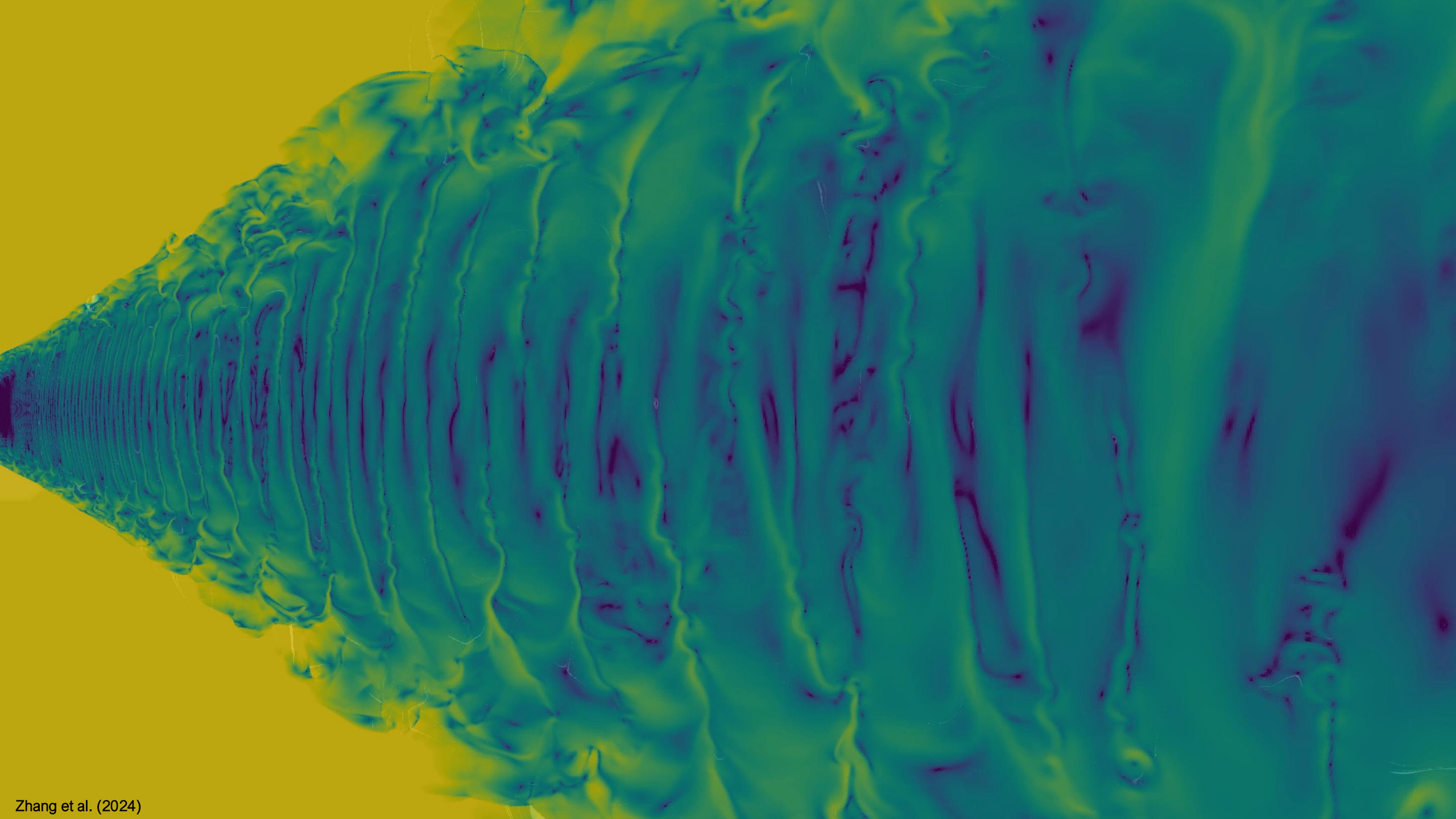
Assumptions

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



F_m = rock mass fraction

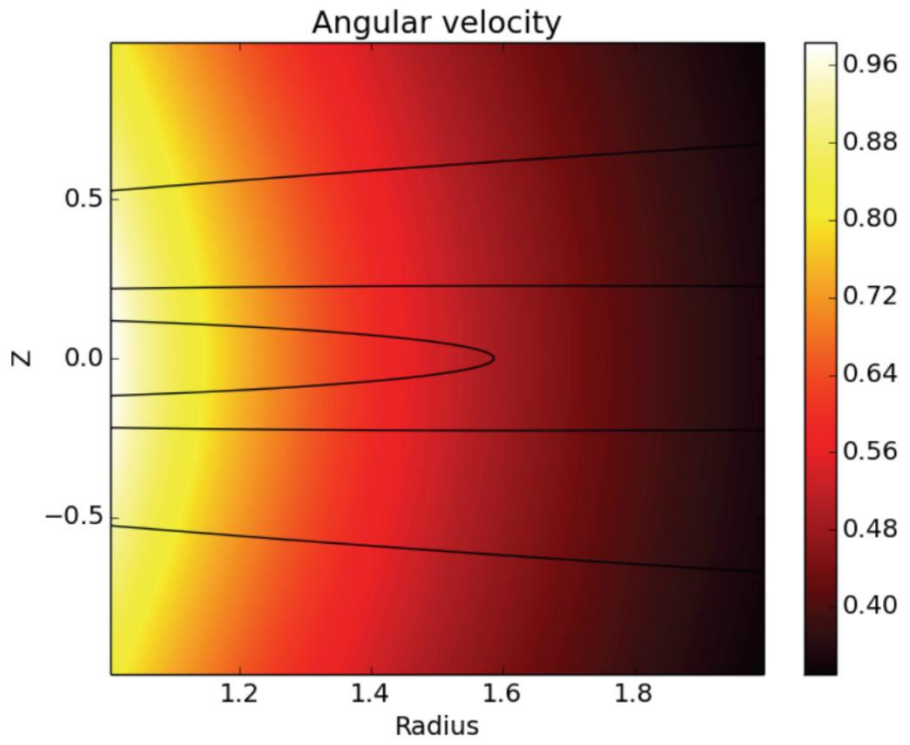
Bierson & Nimmo (2019)

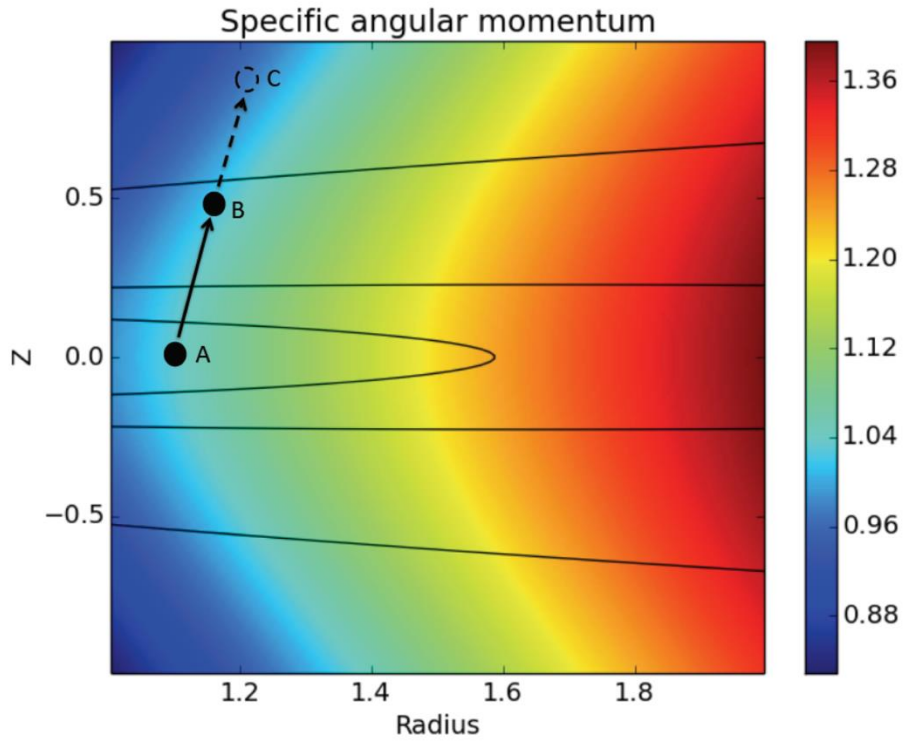


Zhang et al. (2024)

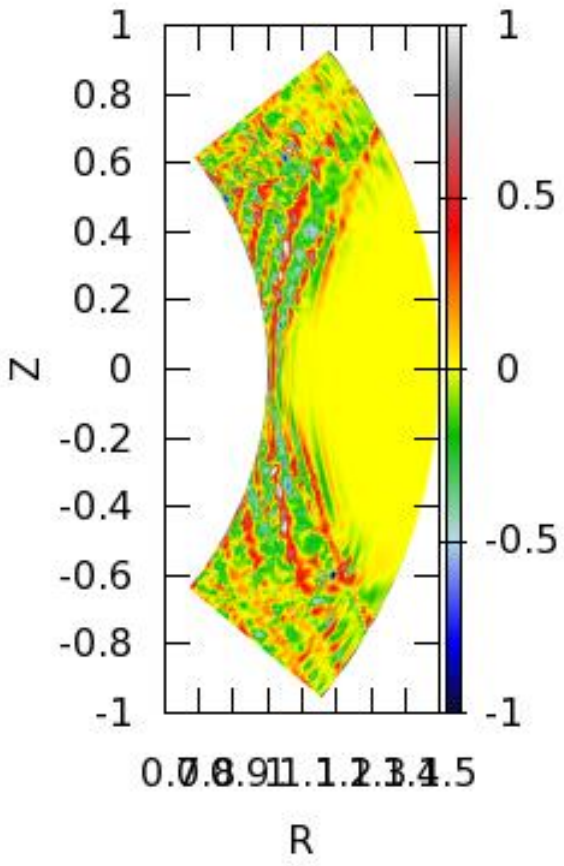
Vertical shear instability

Angular velocity not constant in cylinders: unstable





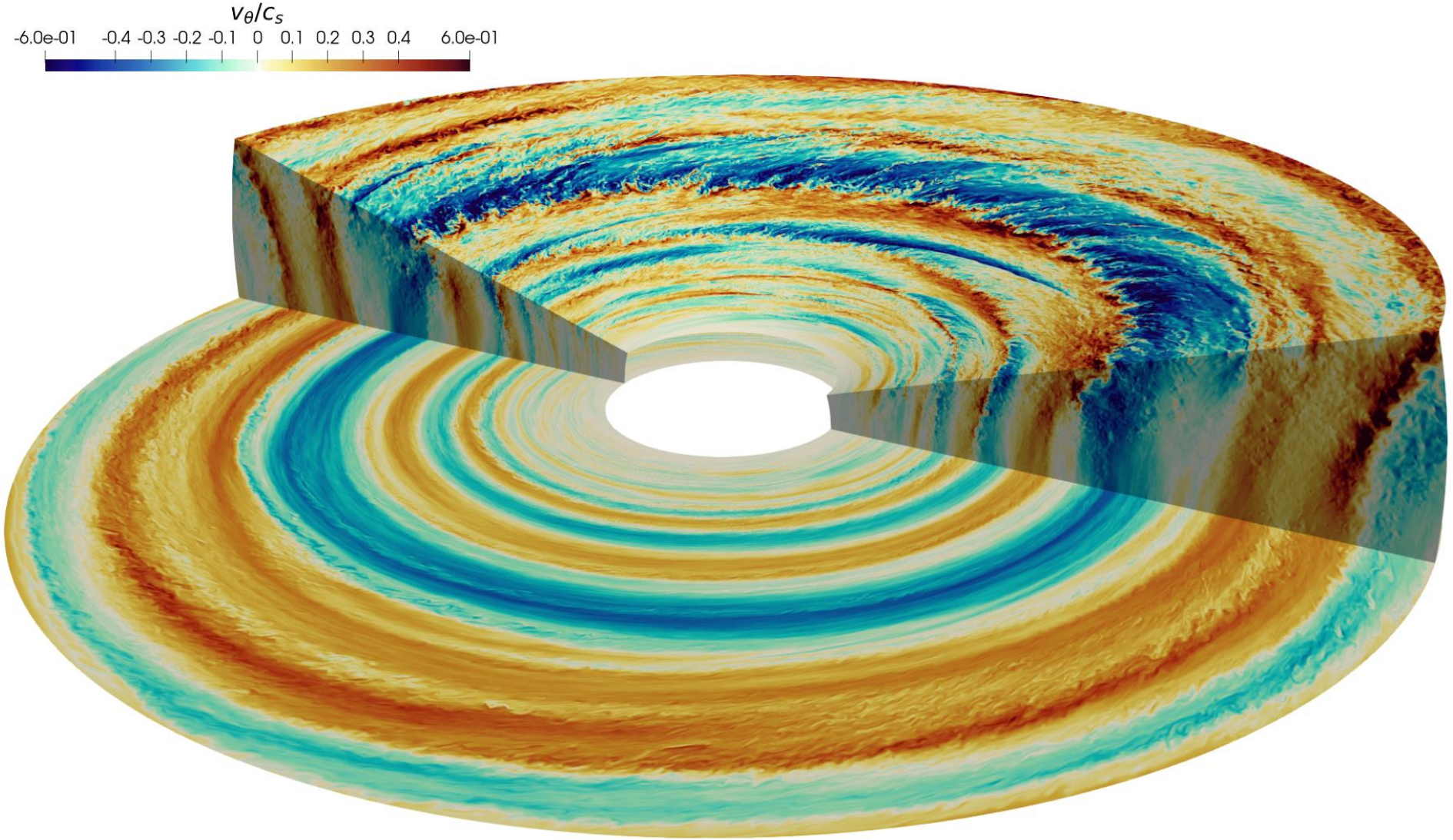
Fromang & Lesur (2017)



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

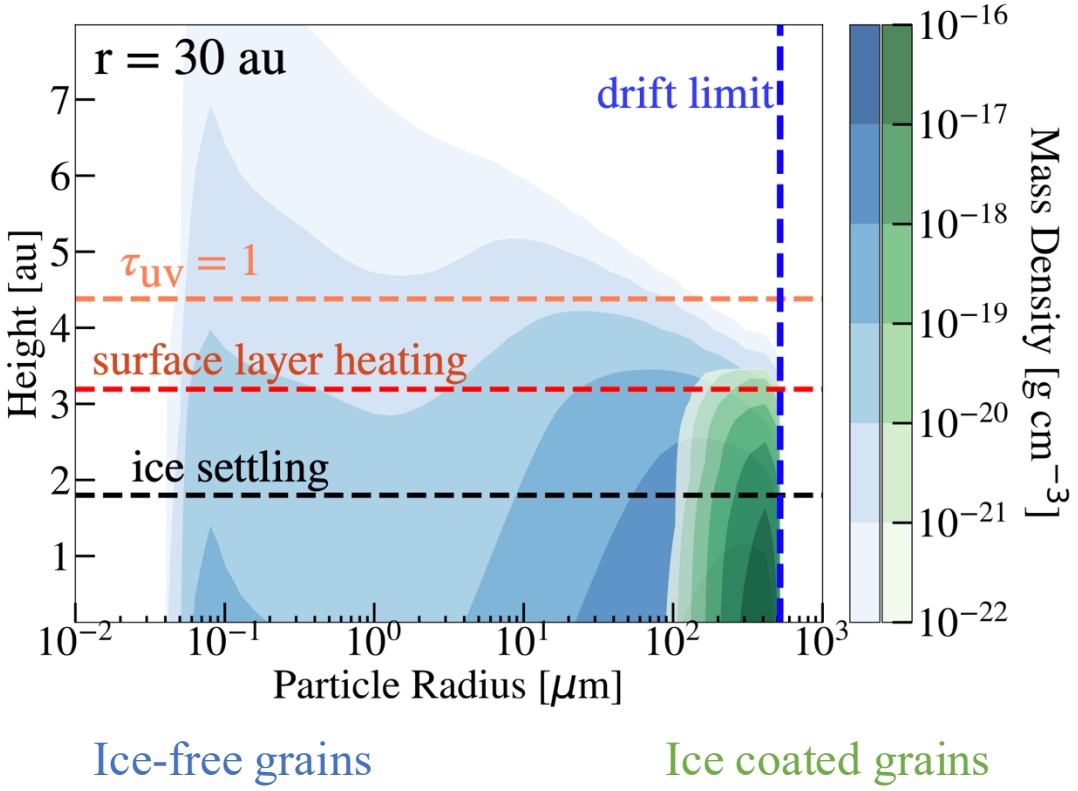


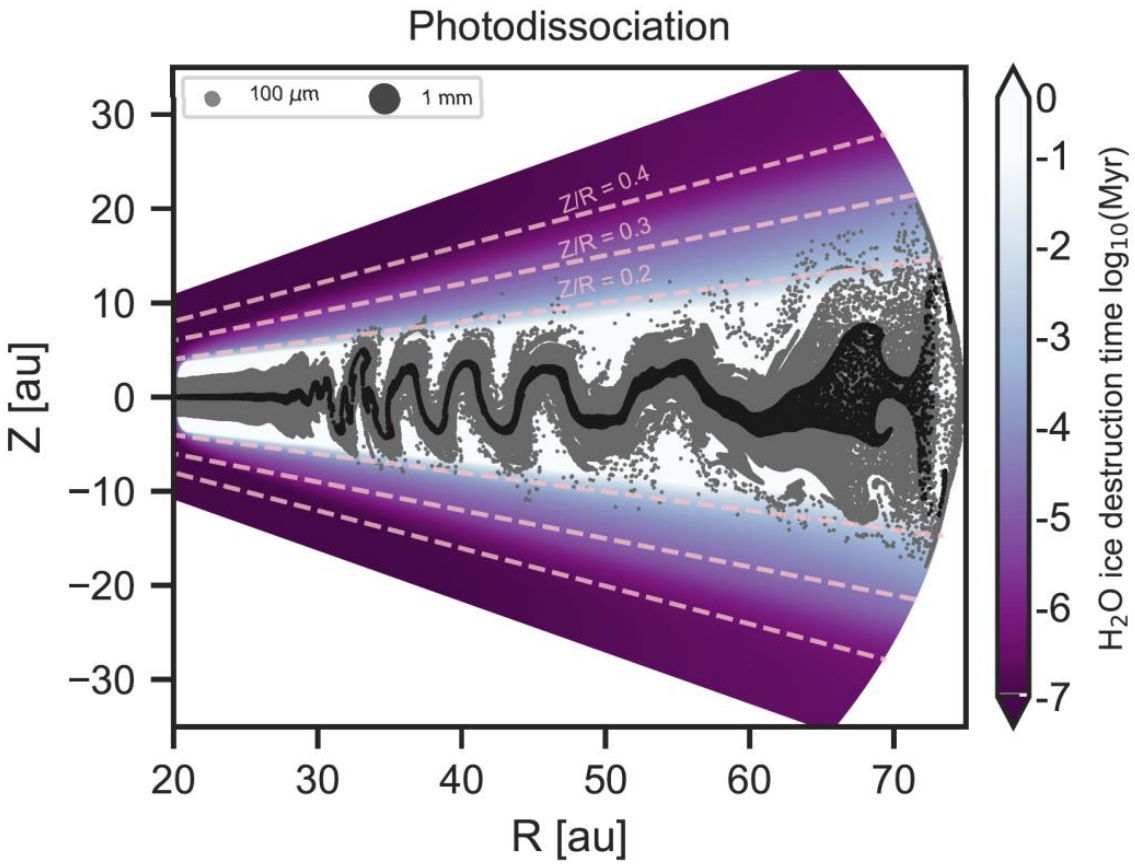
Resolution 3872 x 2000 x 12544
Run on 4096 GPUs

Lesur et al (2025)

Thermal and photo-desorption

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





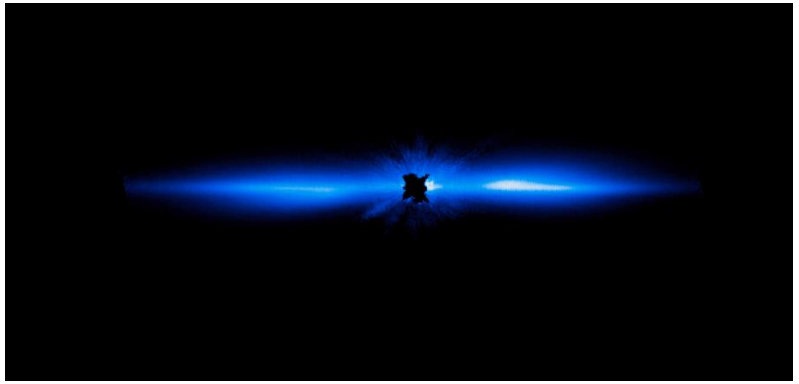
Powell et al. (2022)

Flores-Rivera et al. (2025)

Thermal and photo-desorption

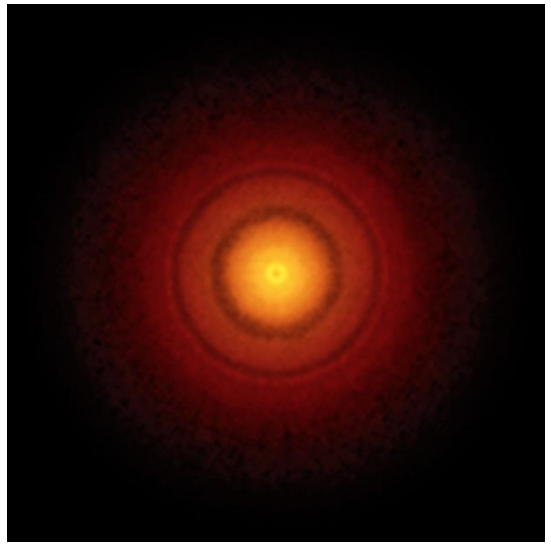
Evidence in disks

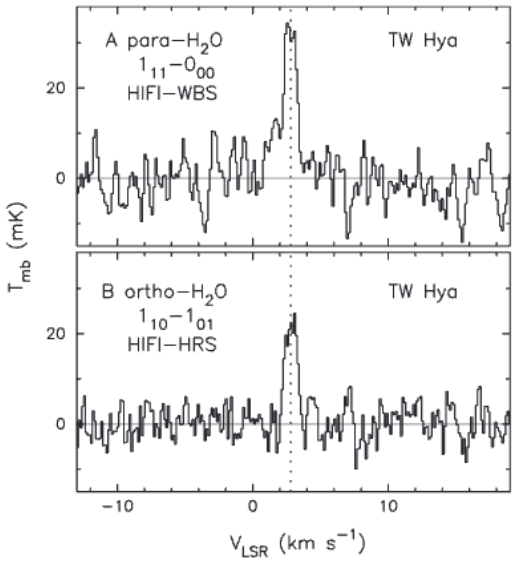
Debris disks



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

Primordial disks

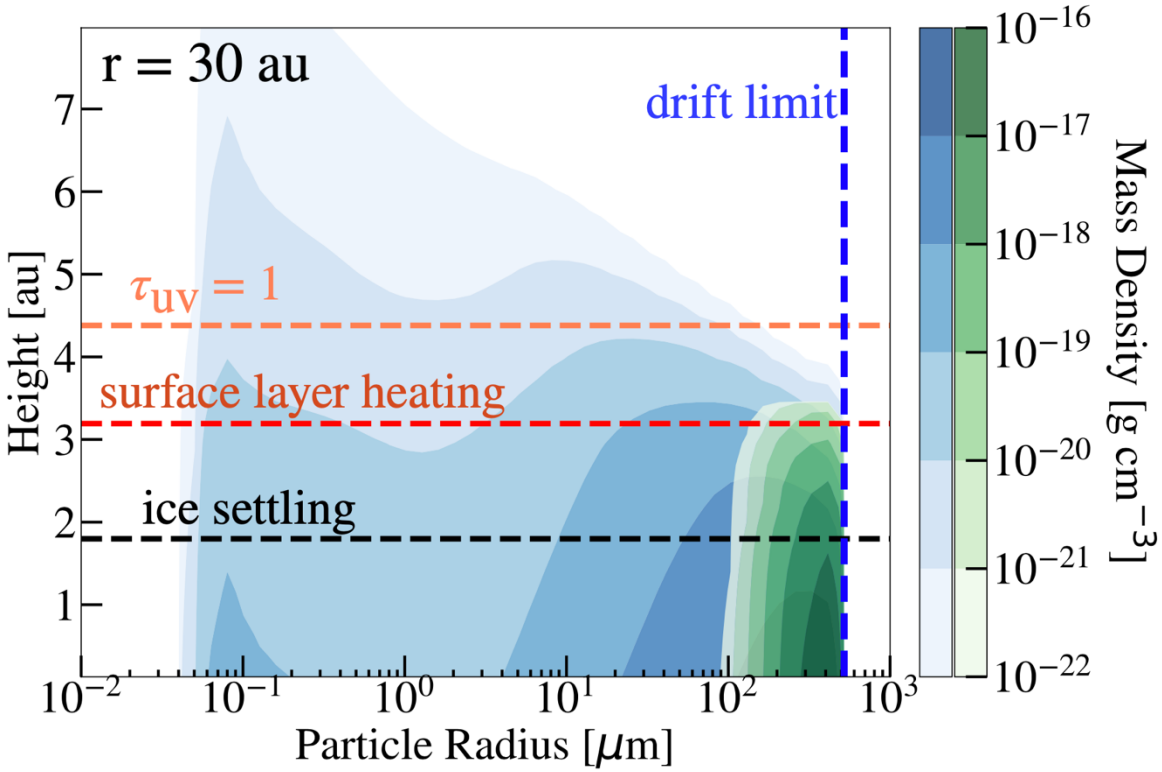




Water vapor observed at large distances for TW Hya
(Hogerheijde et al. 2011, 2012)

Proof-of-concept model

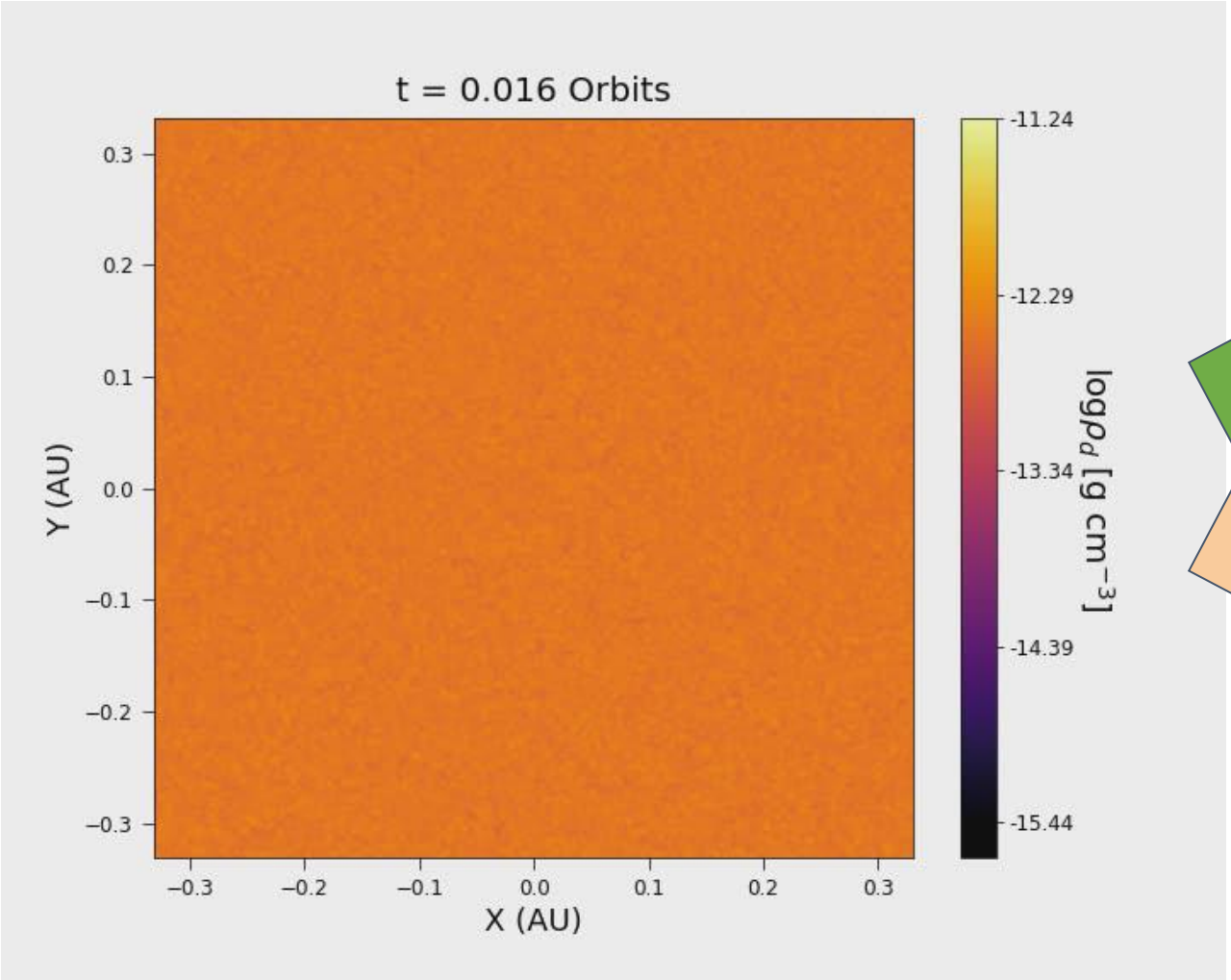
Small grains lofted in the atmosphere lose ice
Big grains are shielded and remain icy.

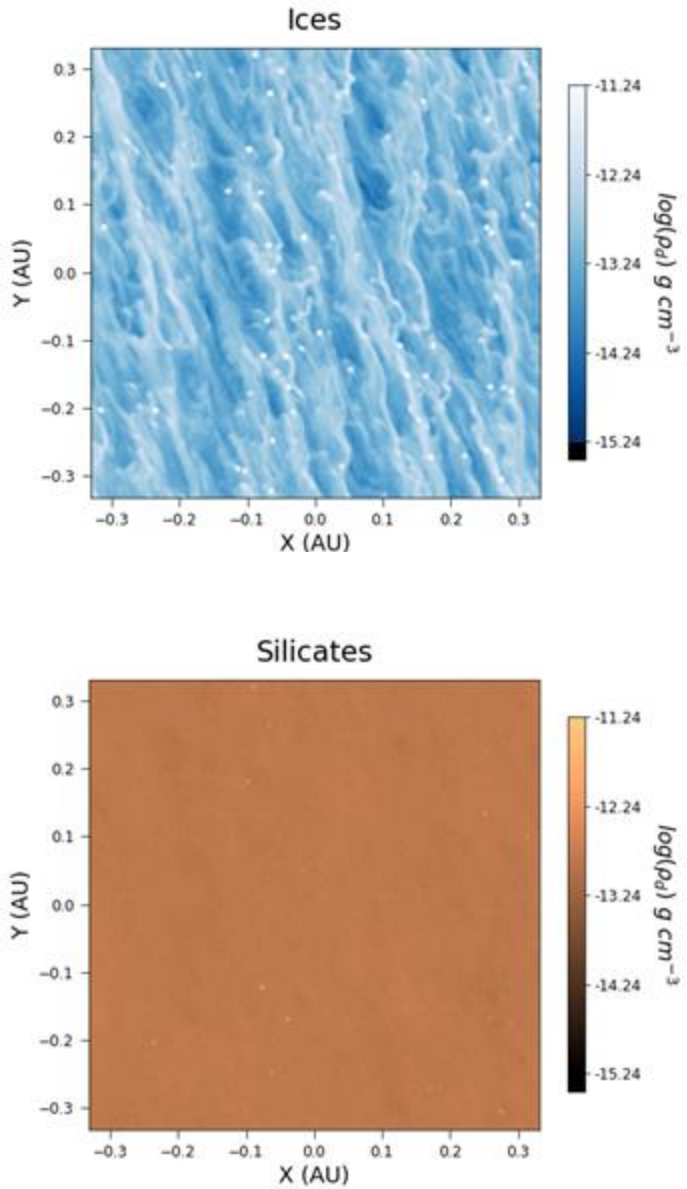


Ice coated grains
Ice-free grains

Powell et al. (2022)

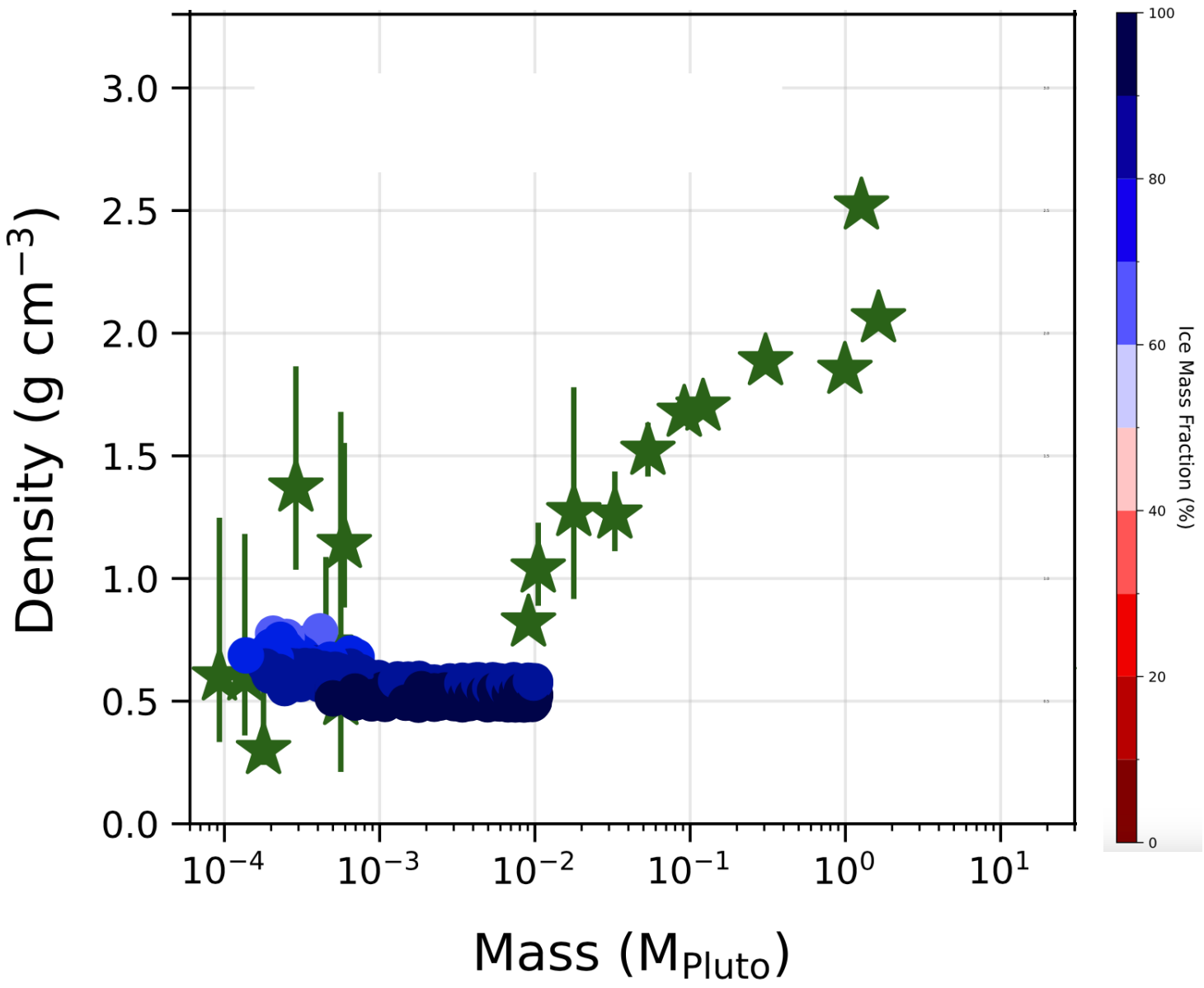
Split into icy and silicate pebbles





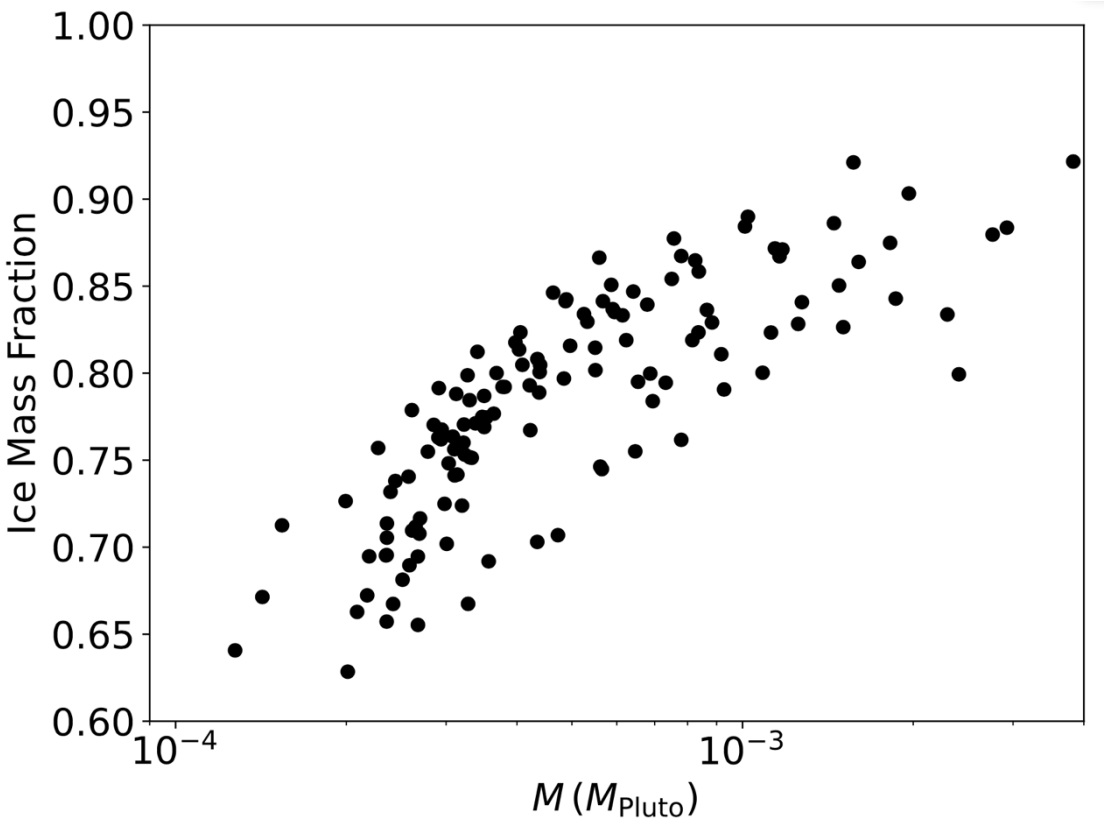
Canas & Lyra + (2024)

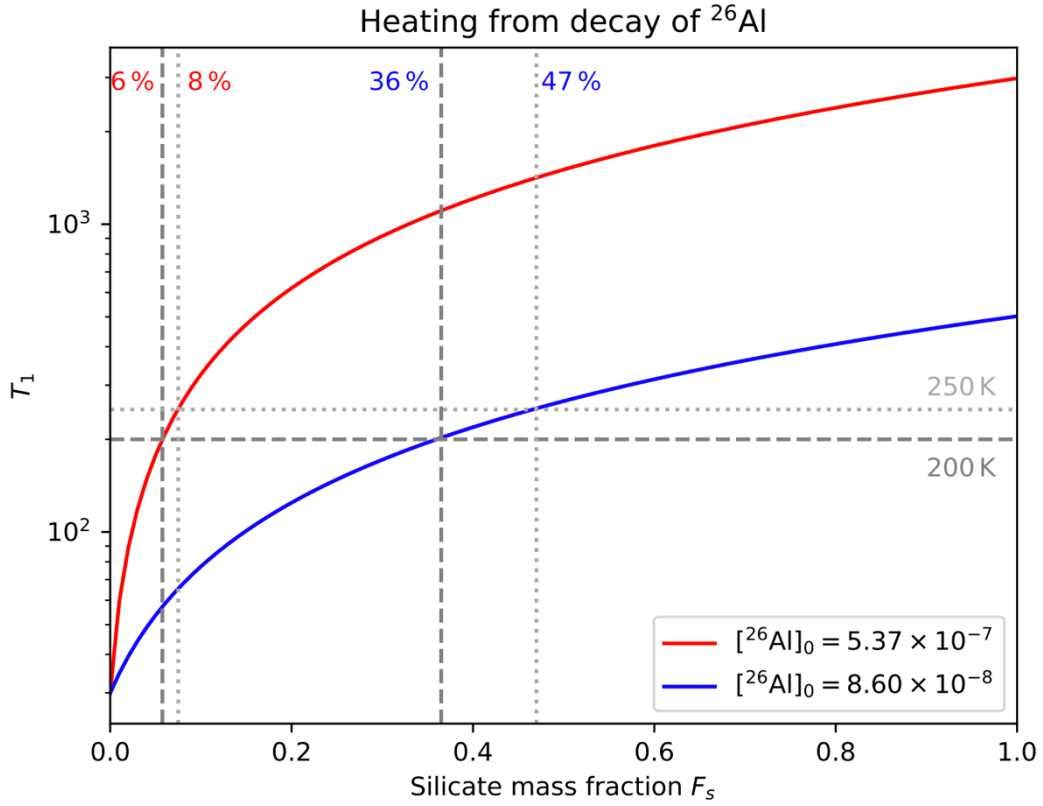
The first planetesimals are icy



Canas & Lyra + (2024)

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



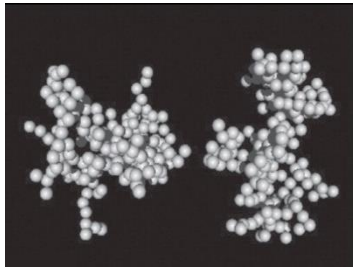


Canas & Lyra + (2024)

Core Accretion

Core Accretion

Dust grains



0.1 – 1 μm

coagulation

Pebbles

mm – cm

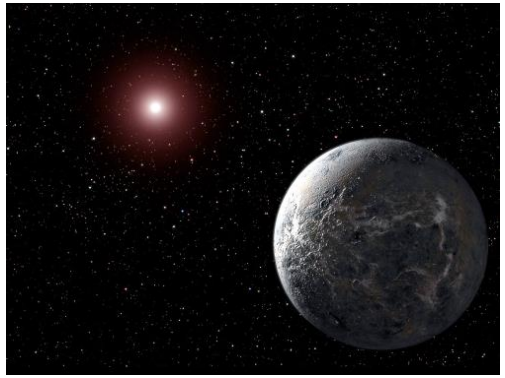
Streaming Instability

Planetesimals

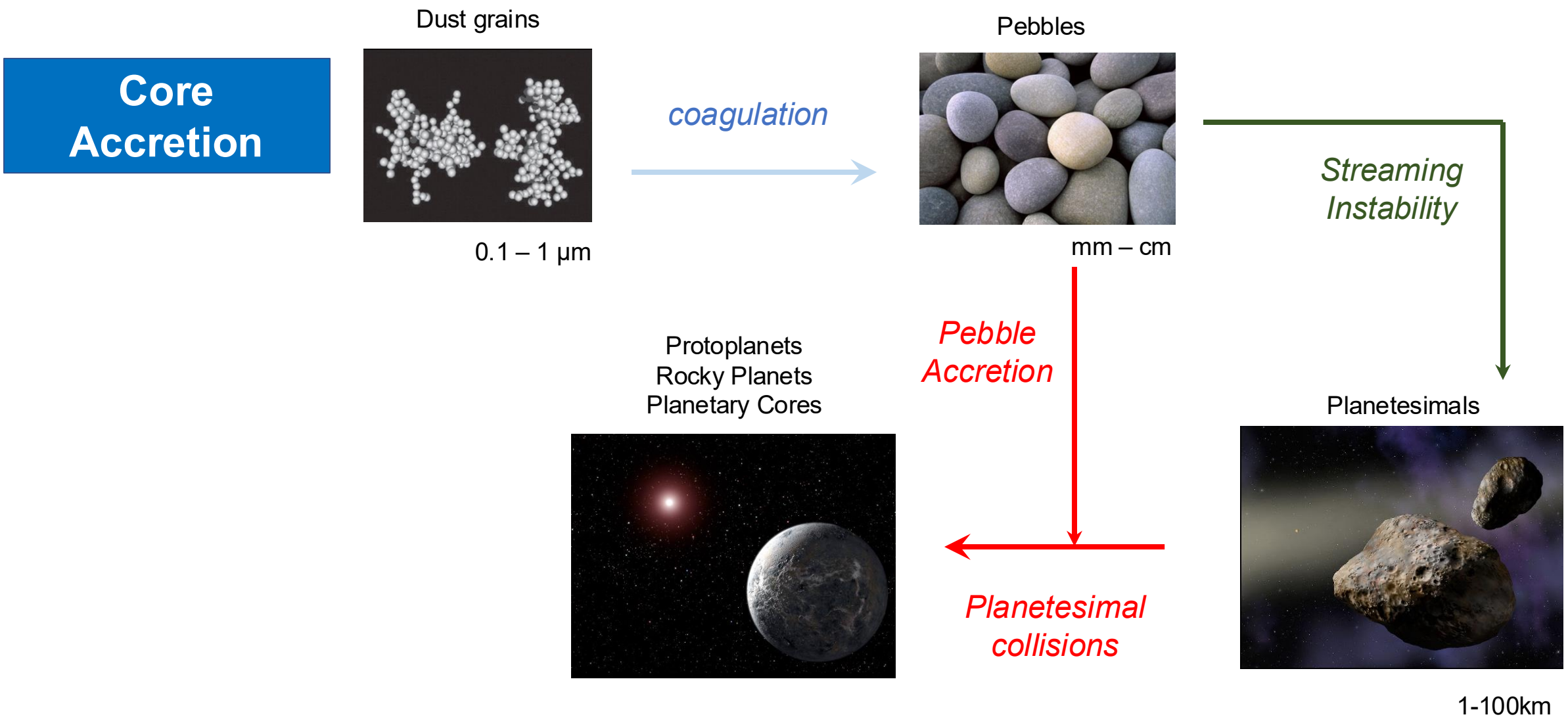
1-100km

Planetesimal collisions

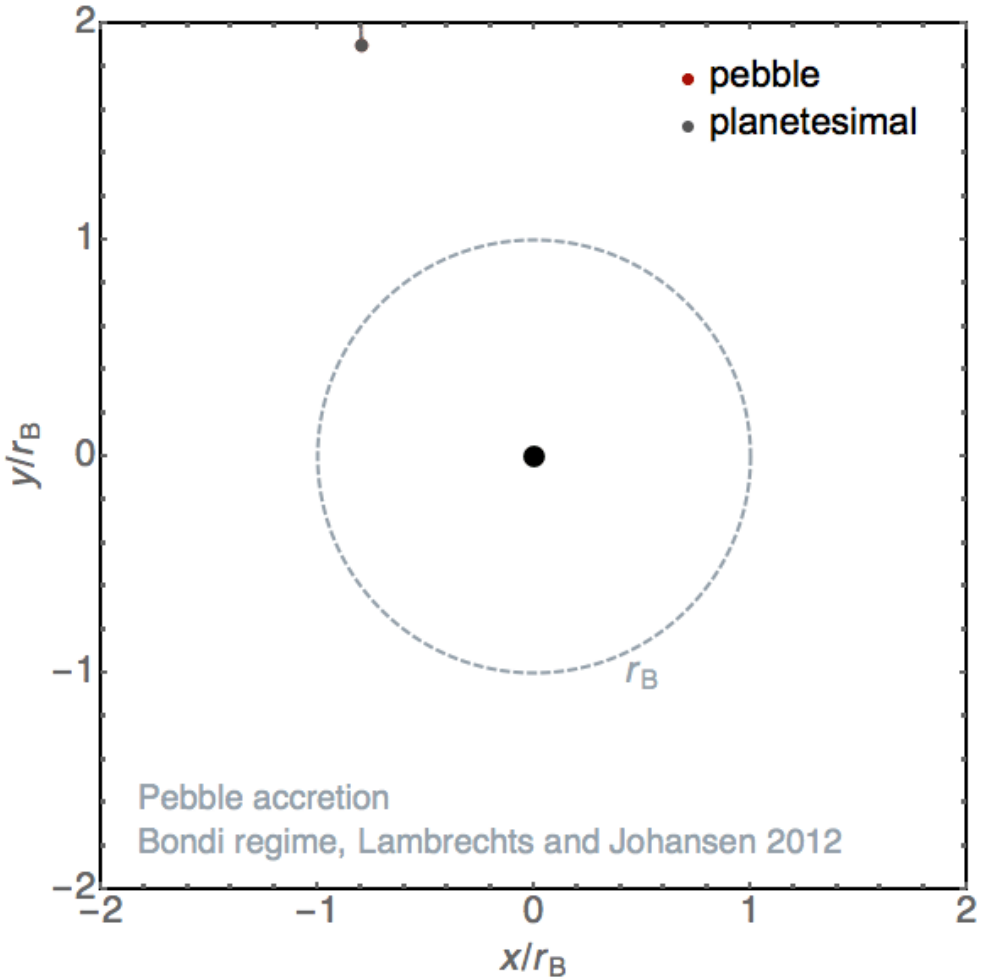
Protoplanets
Rocky Planets
Planetary Cores

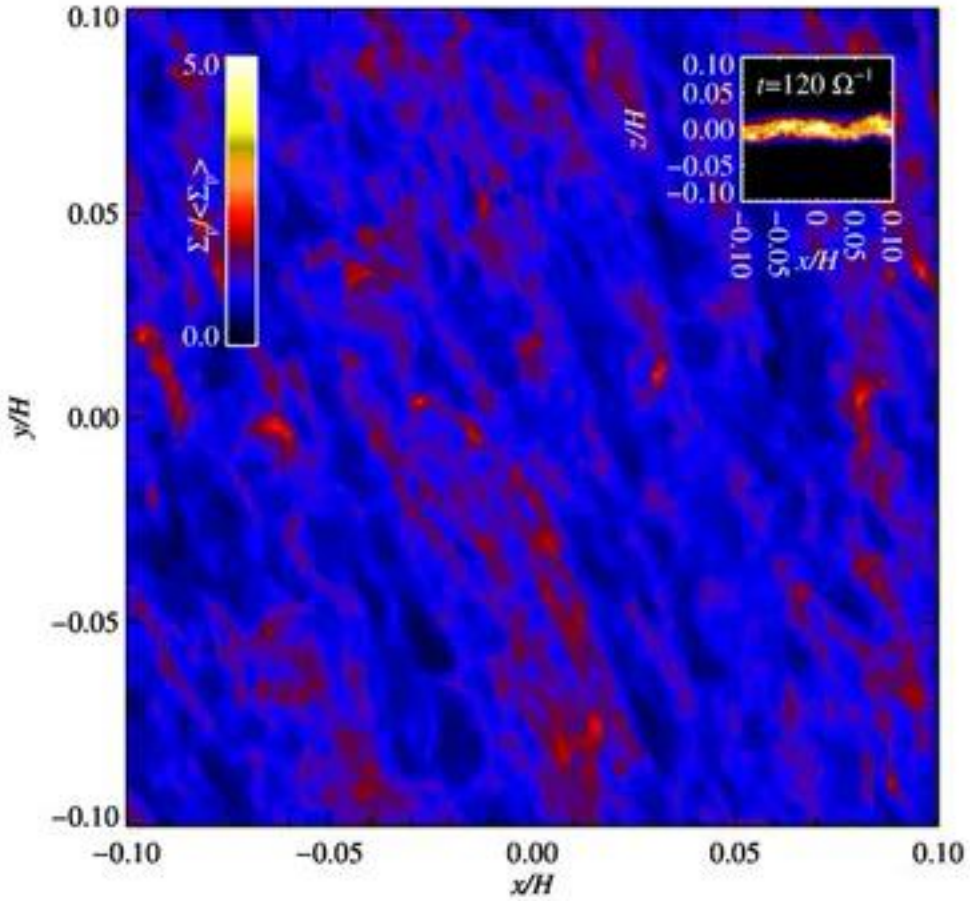


Core Accretion



Pebble Accretion

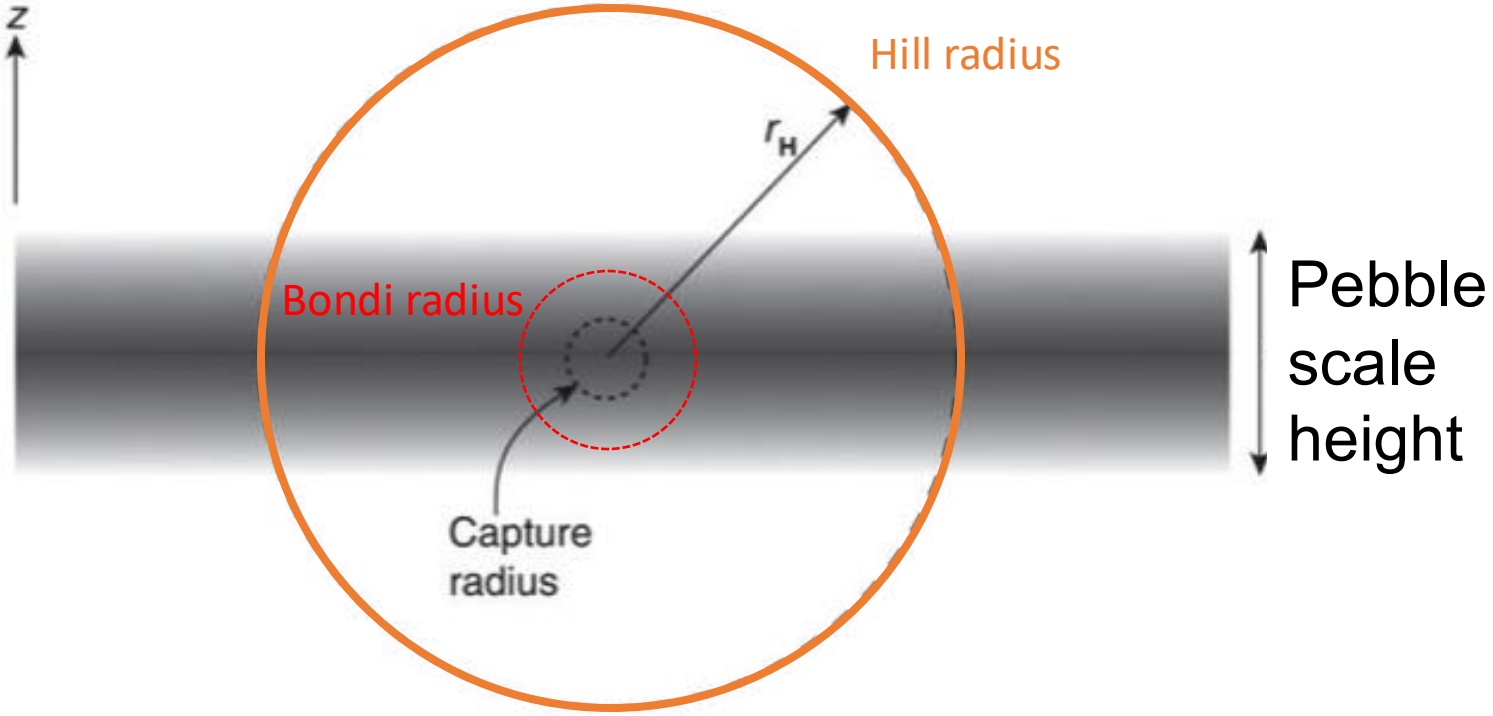




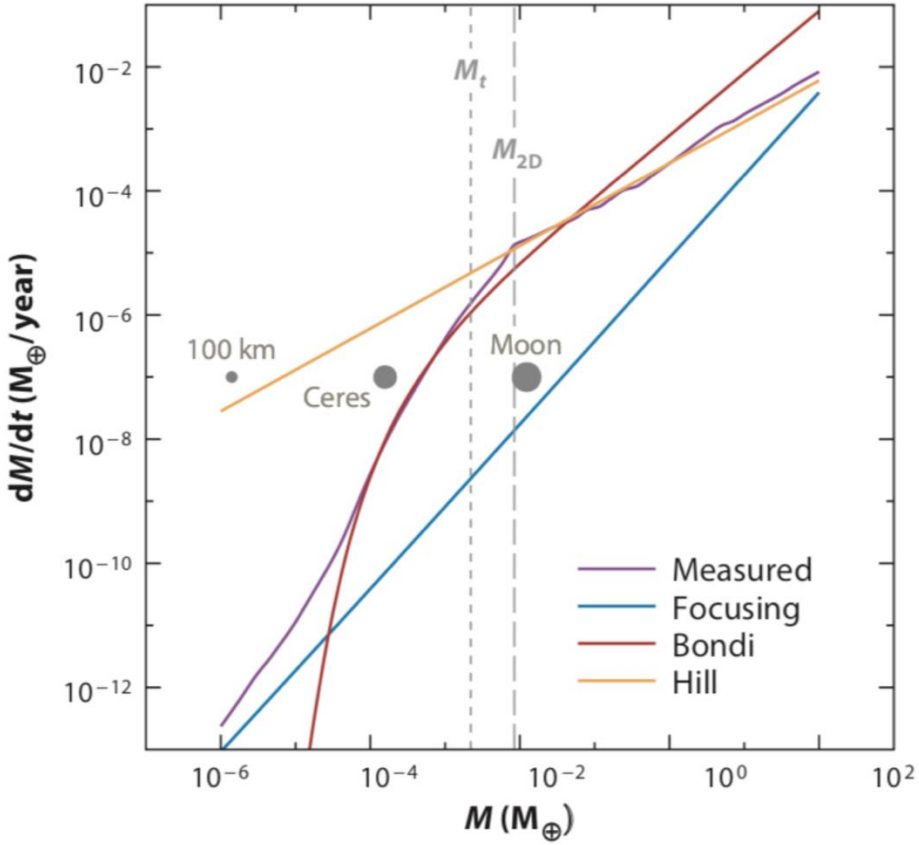
Lyra+ ‘08, ’09, ’23, Ormel & Klahr ‘10, Lambrechts & Johansen ’12
See Johansen & Lambrechts ‘17 for a review

Pebble Accretion: Geometric, Bondi, and Hill regime

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

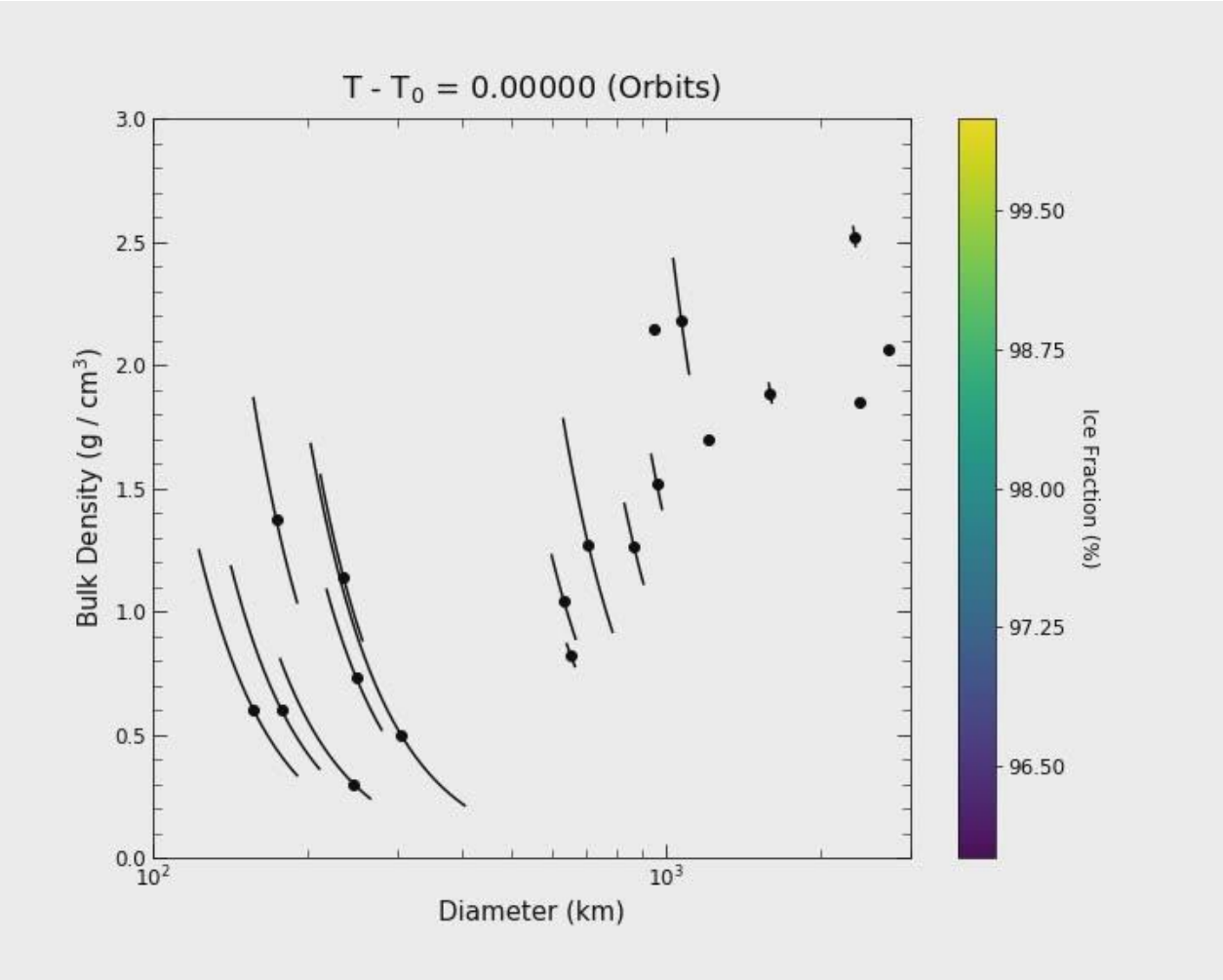


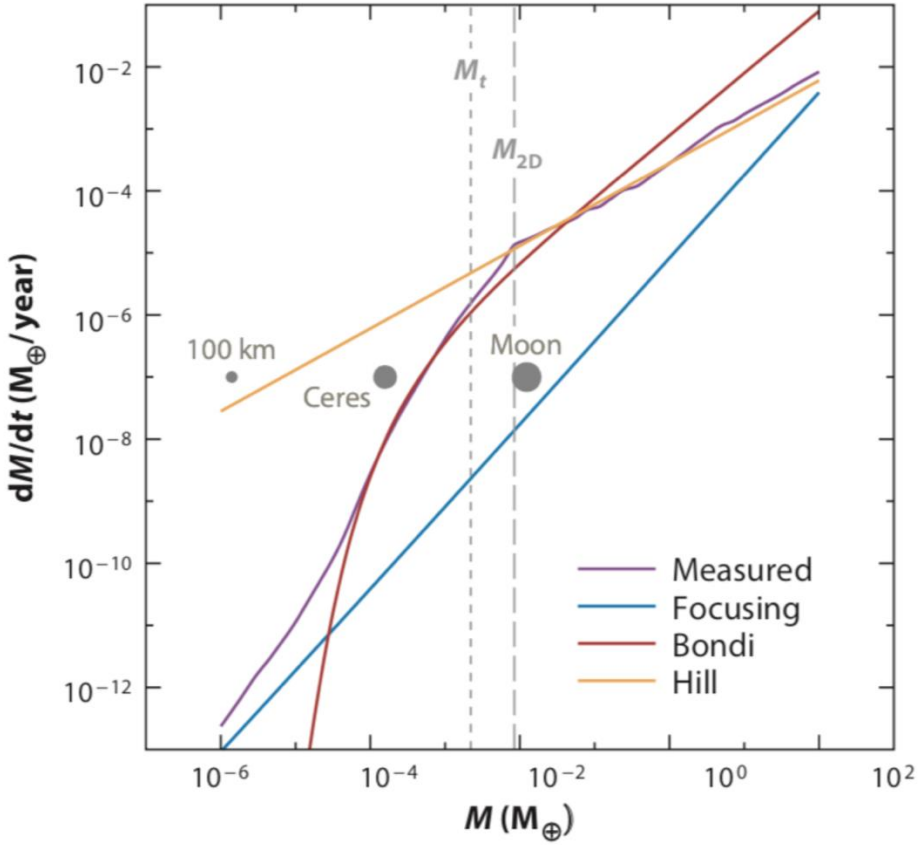
Mass Accretion rates



Ormel & Klahr (2010), Lambrechts & Johansen (2012), Johansen & Lambrechts (2017)

Integrate pebble accretion





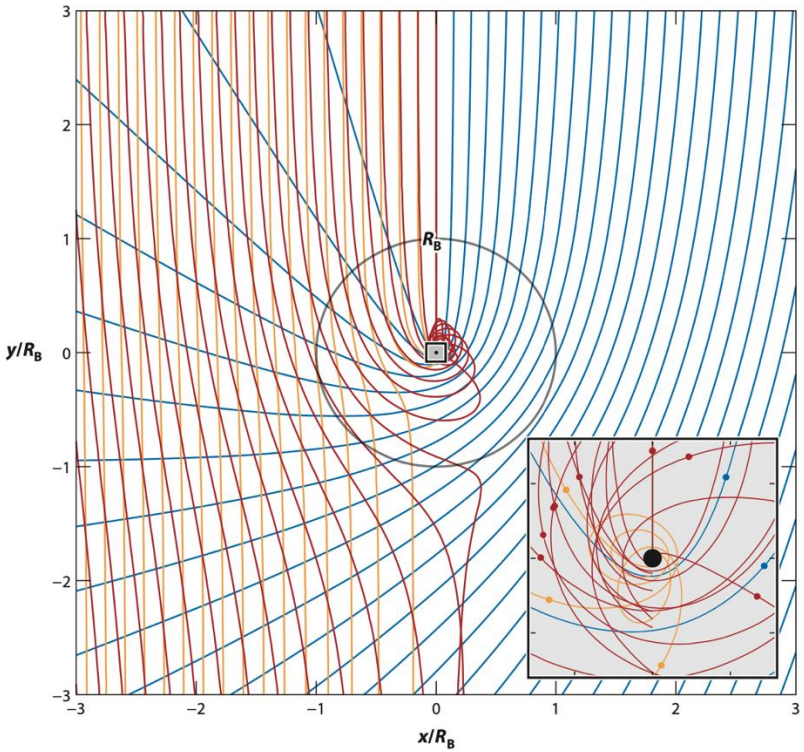
Johansen & Lambrechts (2017)

Pebble Accretion: Pebbles of different size accrete differently

Large
Medium
Small

”Goldilocks effect” in the Bondi regime

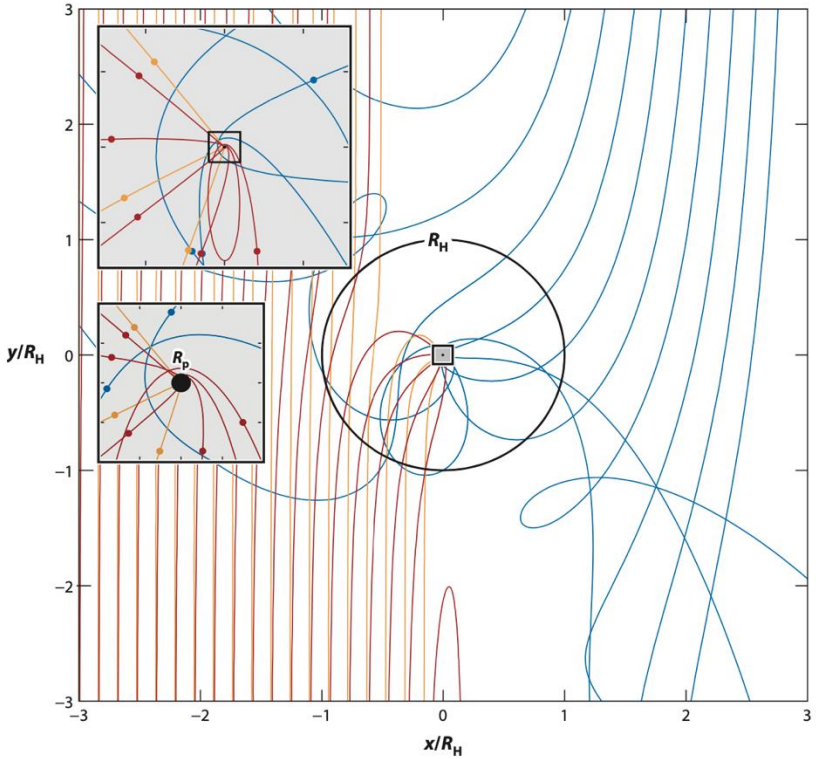
Bondi Regime



Best accreted pebble

Drag time ~ Bondi Time

Hill Regime

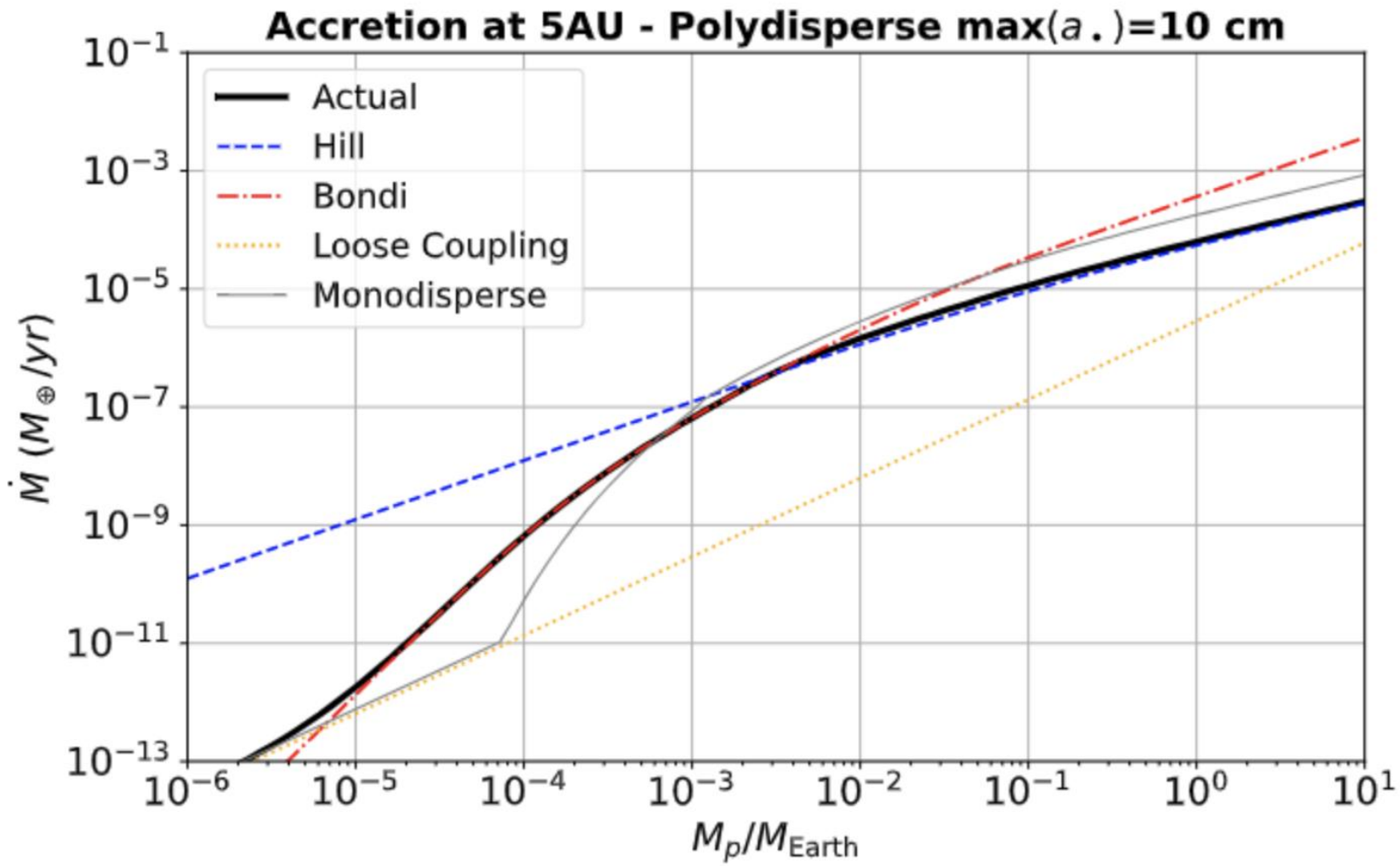


Best accreted pebble

Drag time ~ Orbital Time

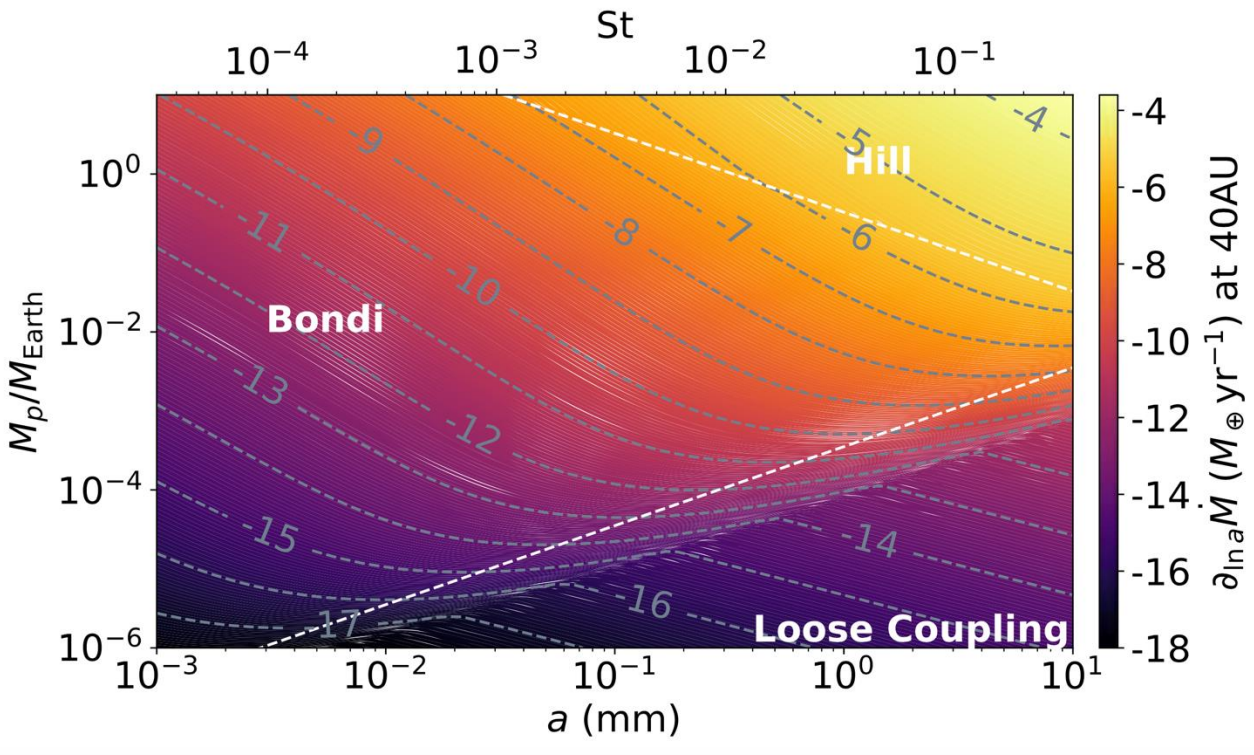
Johansen & Lambrechts (2017); Lyra & Johansen + (2023)

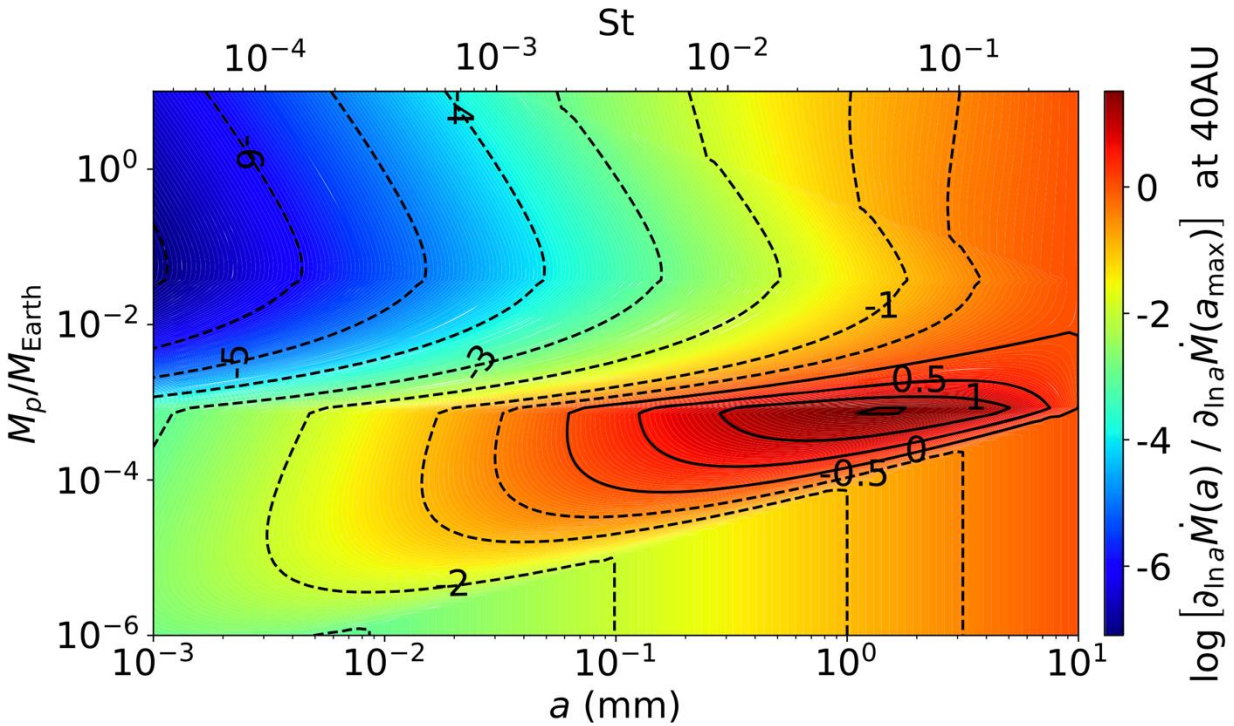
Accretion Rates



Lyra & Johansen + 2023

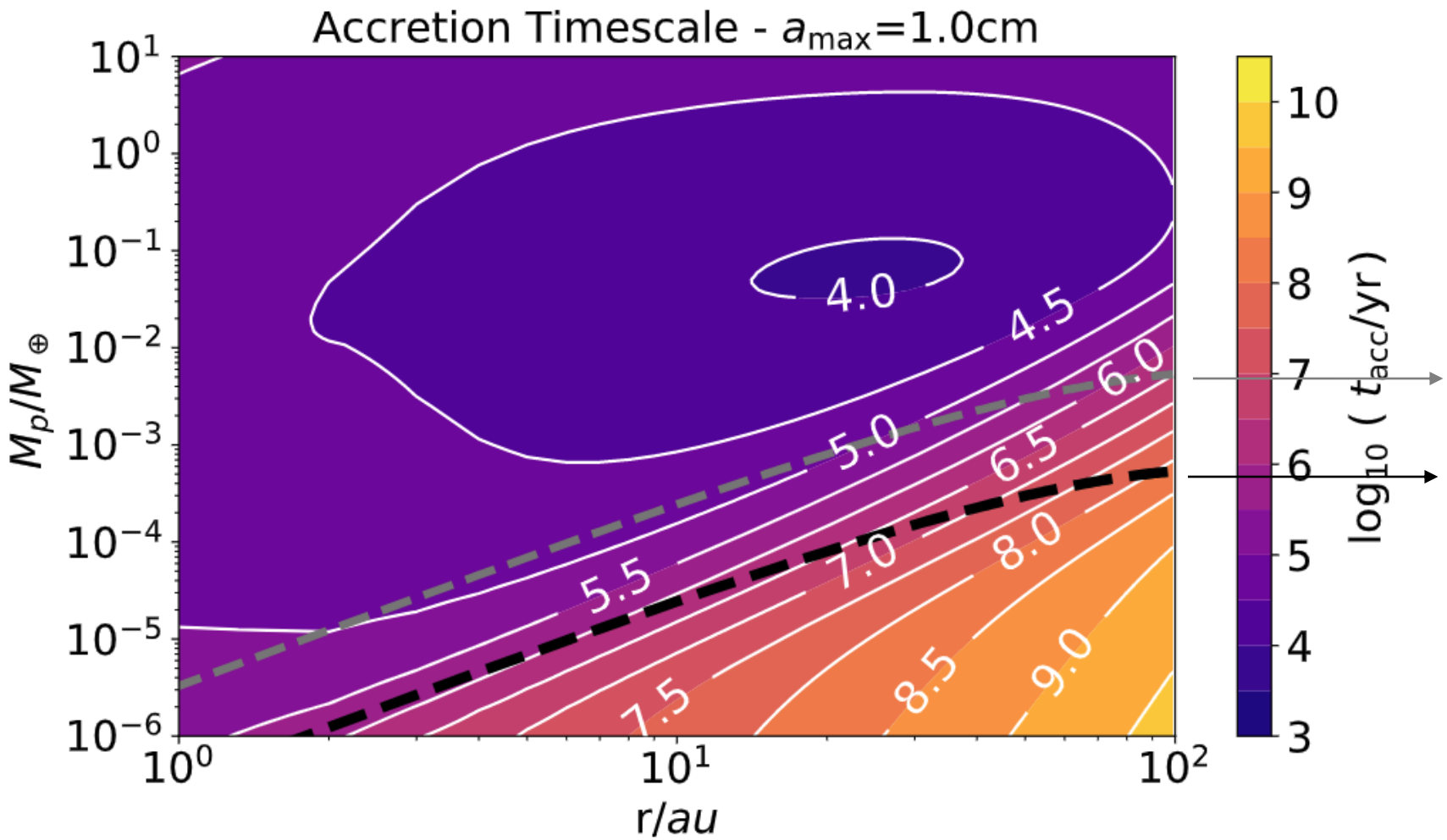
Differential Accretion Rates





Lyra & Johansen + 2023

Accretion Timescales



10x typical mass formed by Streaming Instability

Typical mass formed by Streaming Instability

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)

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

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

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

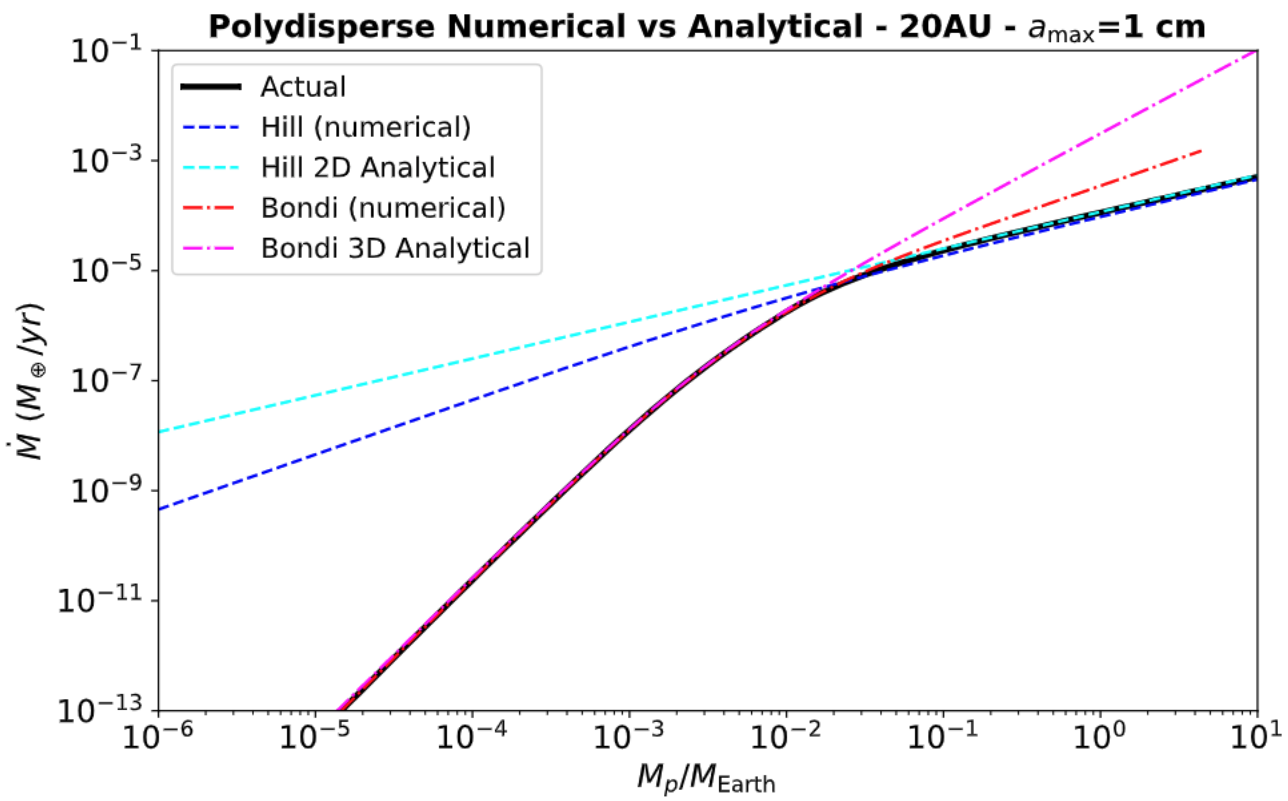
Lambrechts & Johansen (2012)

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)



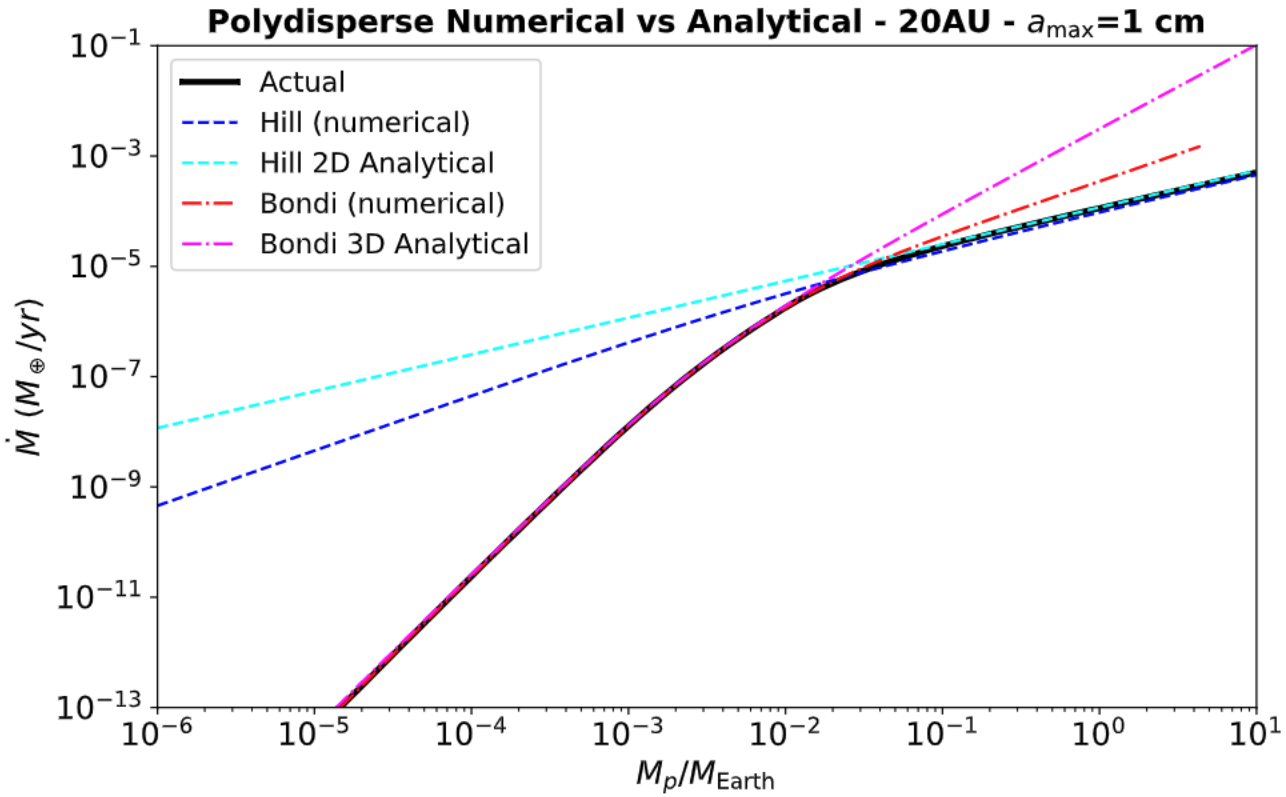
Lyra & Johansen + 2023

Analytical Solutions

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

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

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

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

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



Lyra et al. 2023

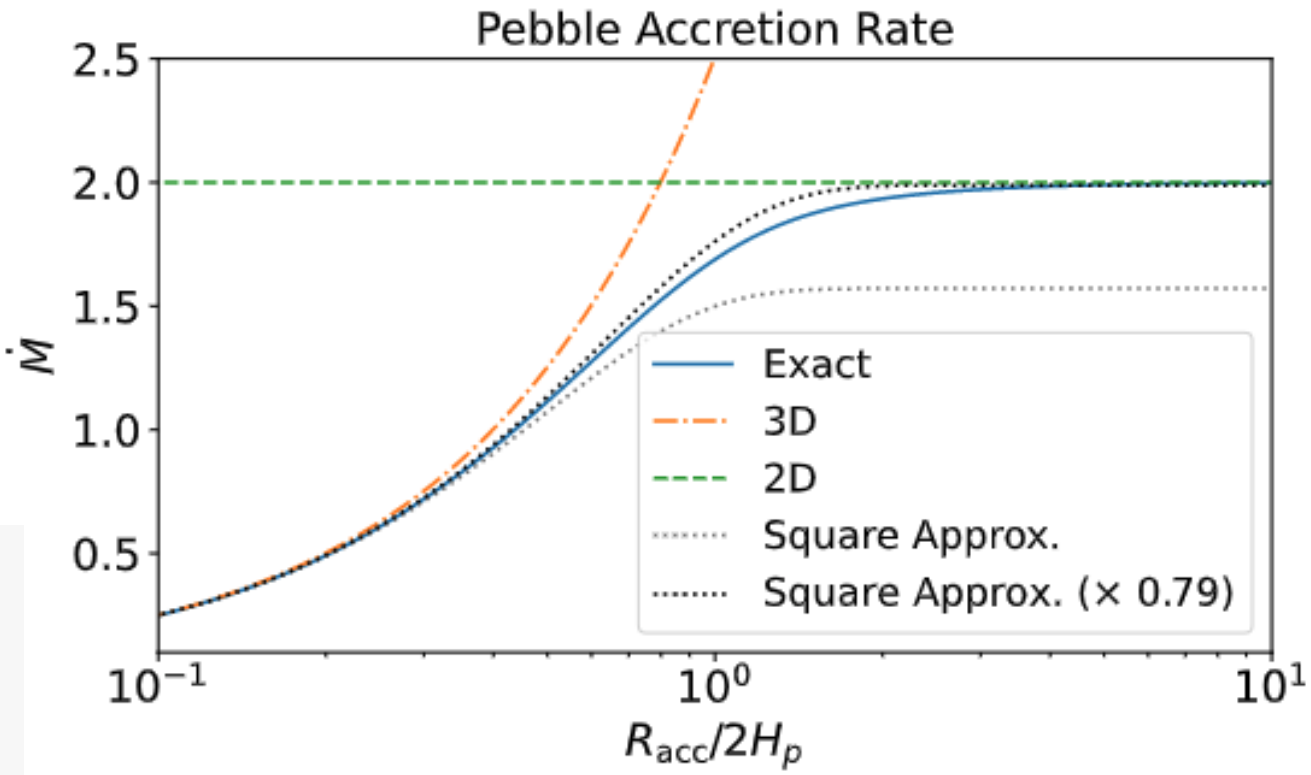
Analytical Solutions

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

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

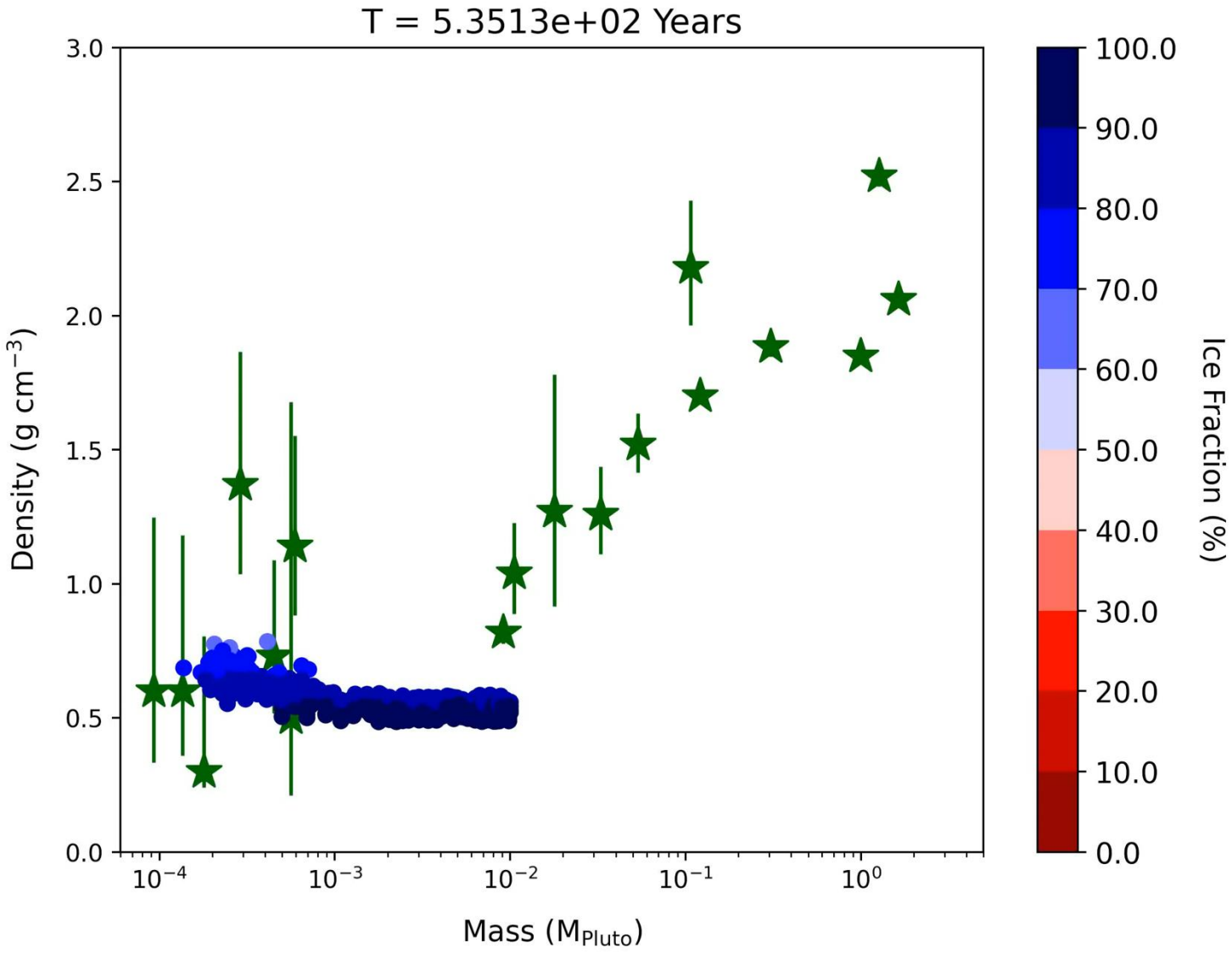
$$S = e^{-\xi}\,[I_0(\xi) + I_1(\xi)], \qquad \xi \equiv \left(\frac{R_{\rm acc}}{2H_d}\right)^2$$

```
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

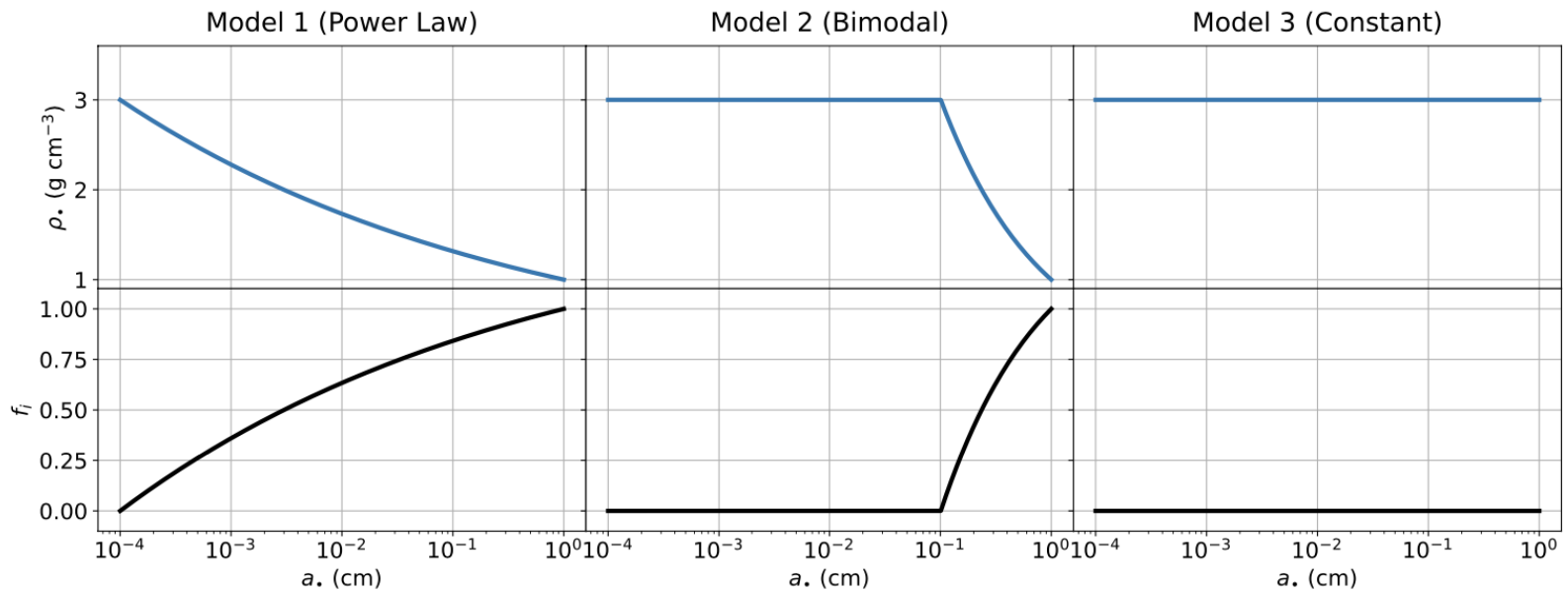
Growing Pluto by silicate pebble accretion



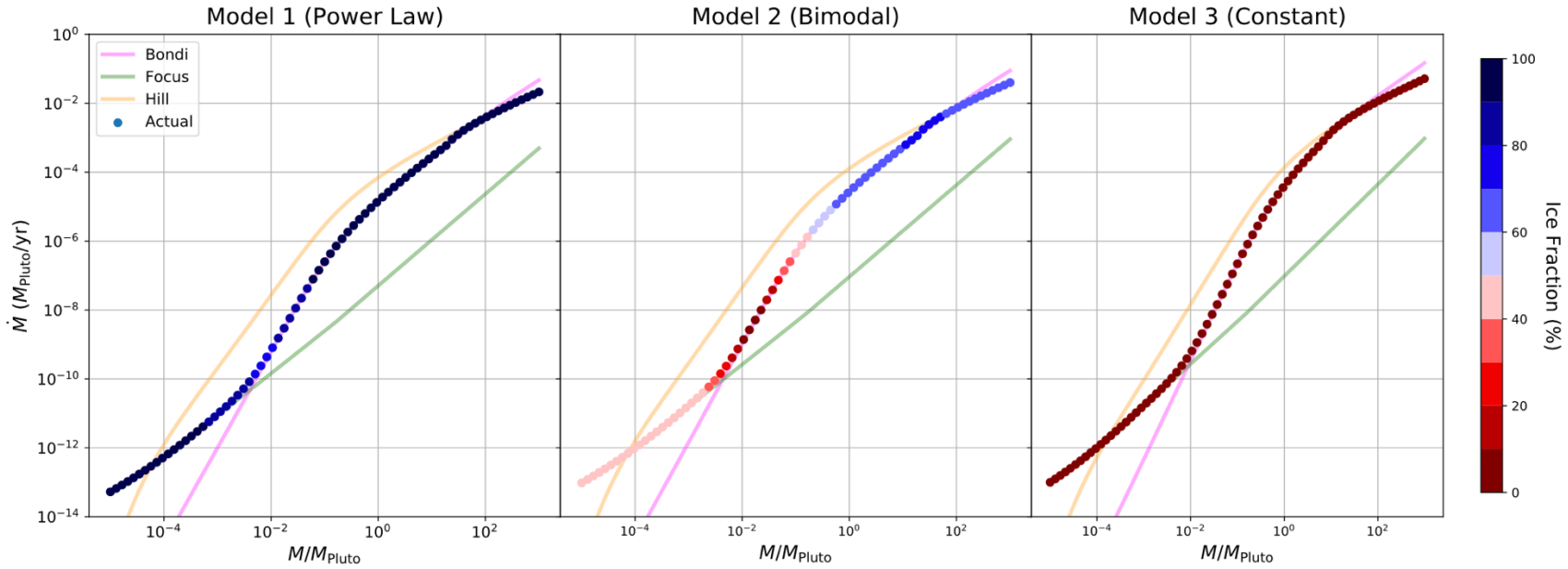
Canas & Lyra + (2024)

Pebble Internal Density

Ice Volume Fraction

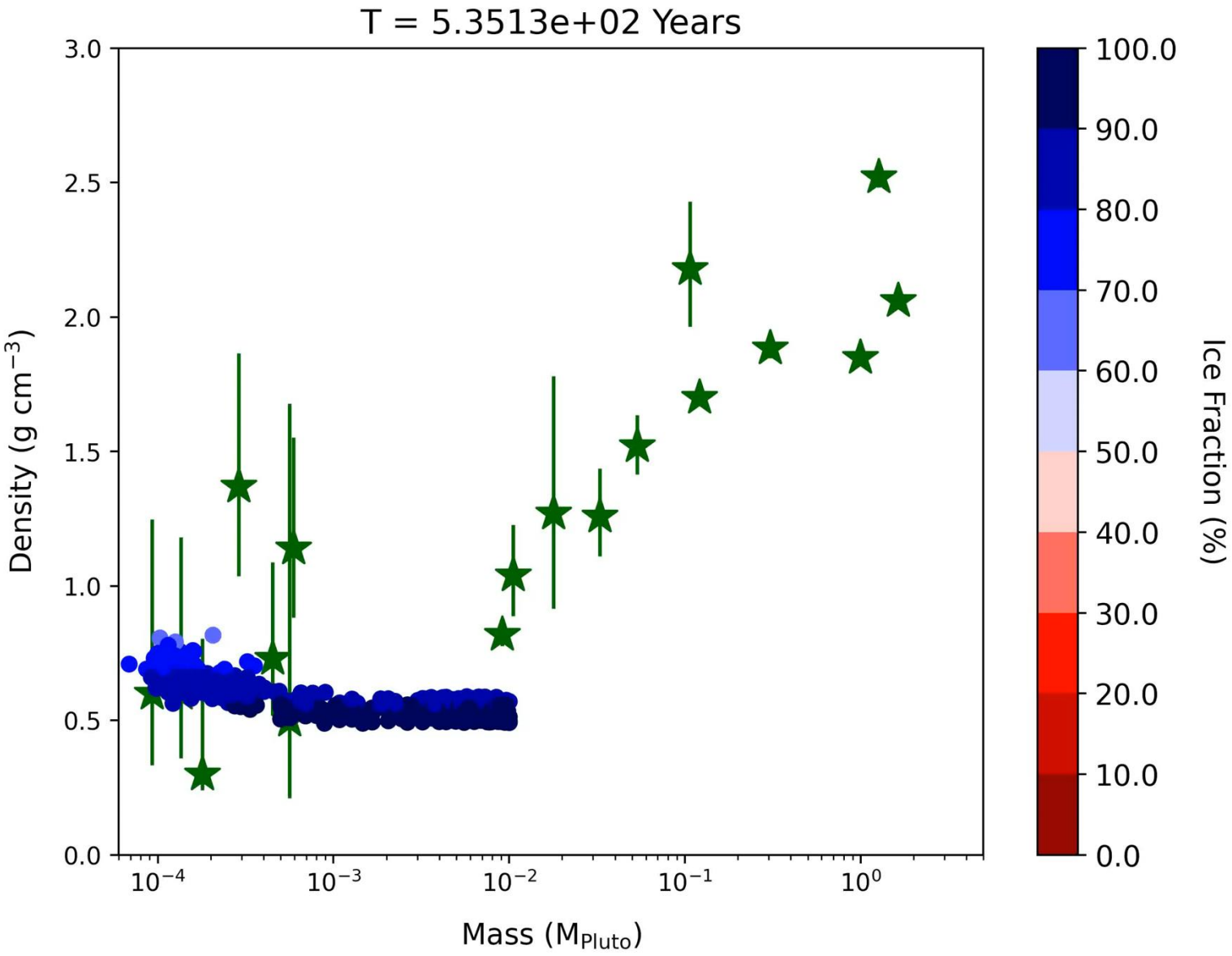


Mass Accretion rate



Canas & Lyra + (2024)

Growing Pluto by silicate pebble accretion

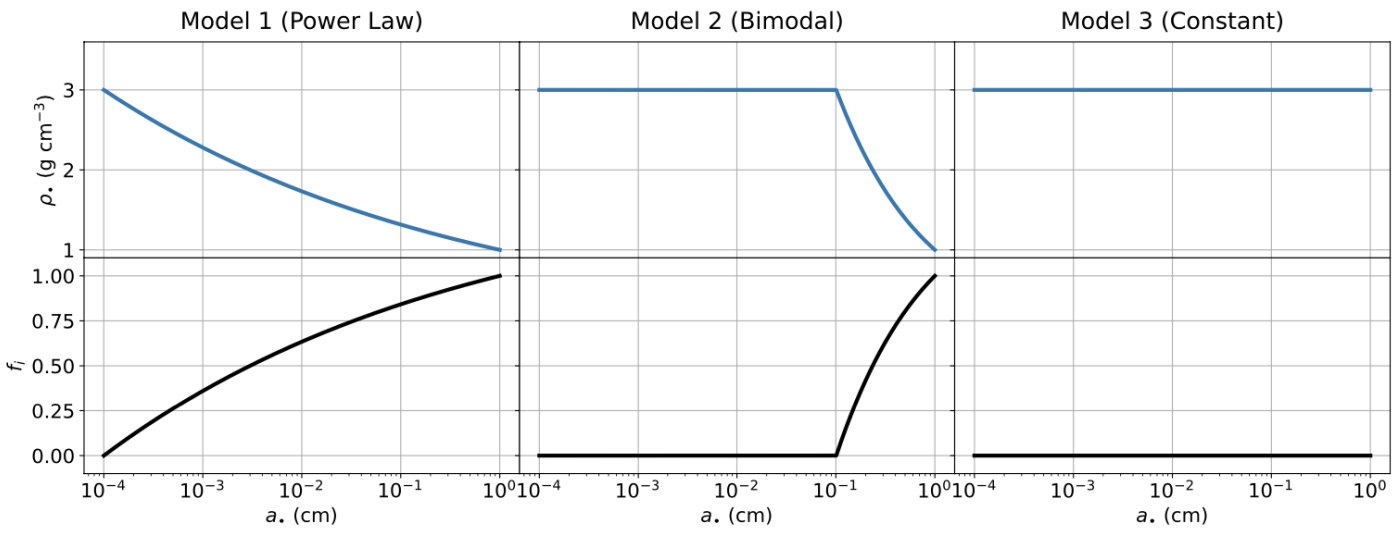


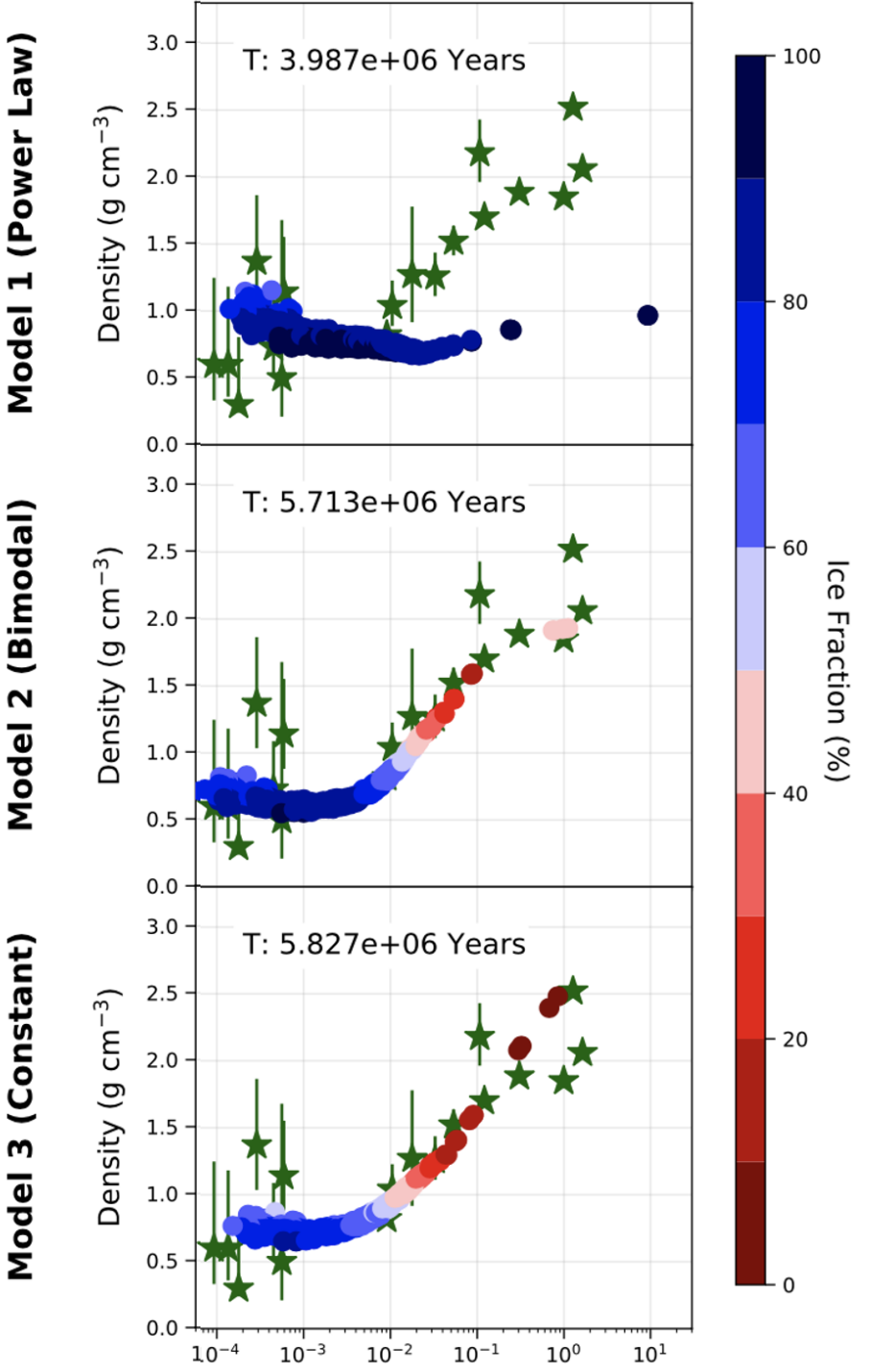
Canas & Lyra + (2024)

Resulting Densities vs Mass relations

Pebble Internal Density

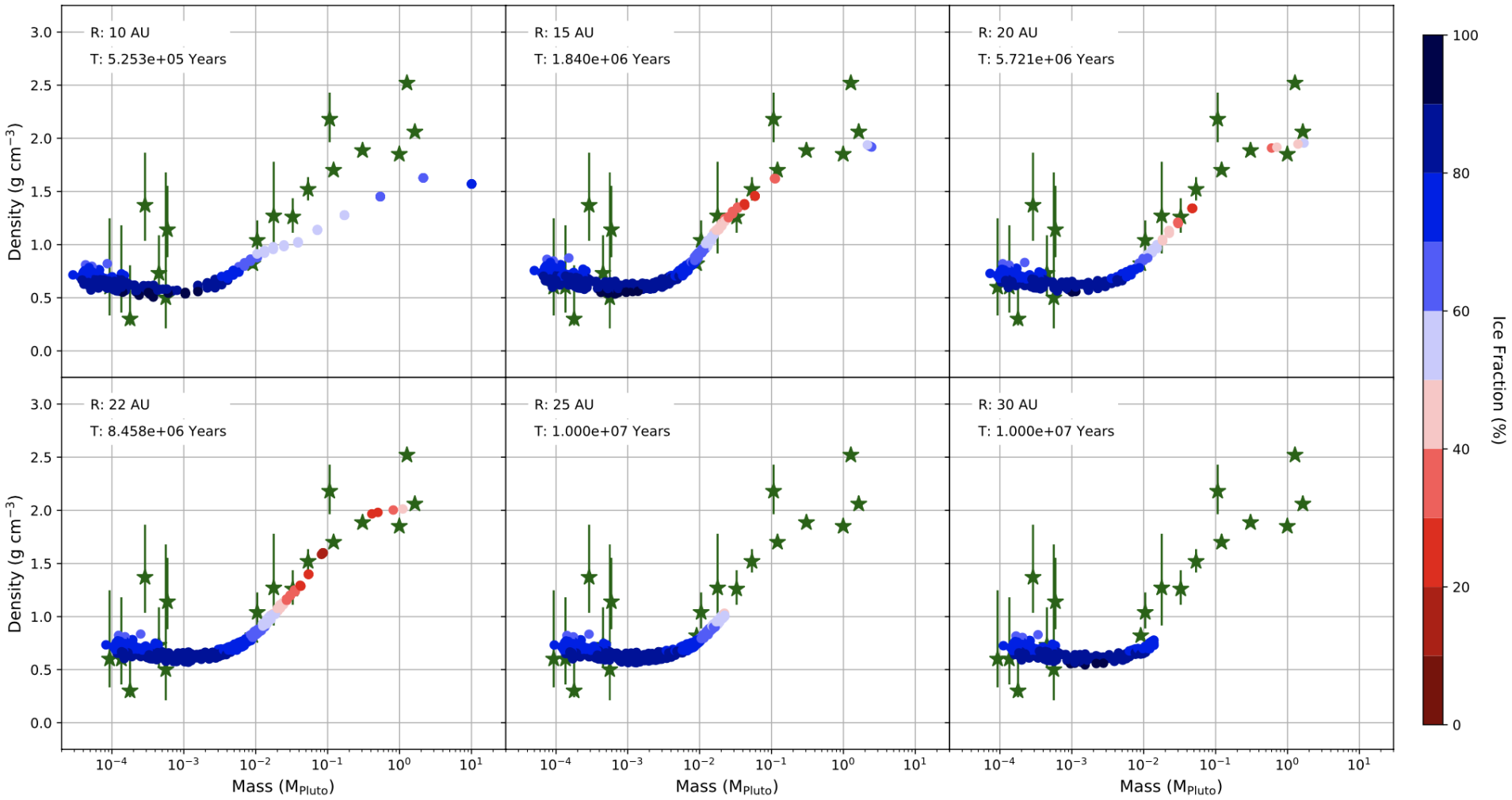
Ice Volume Fraction





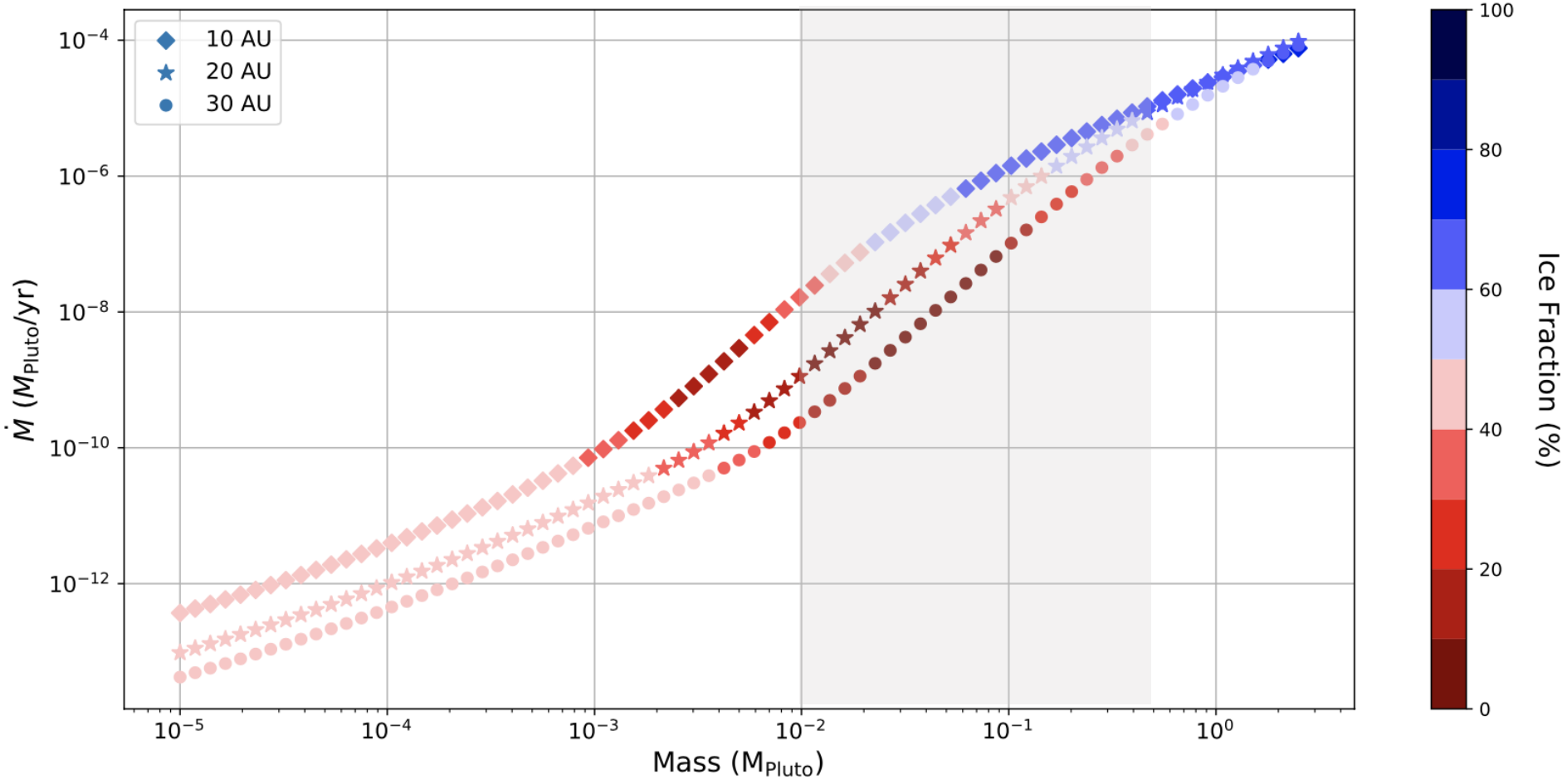
Canas & Lyra + (2024)

Distance Range
15 - 25AU

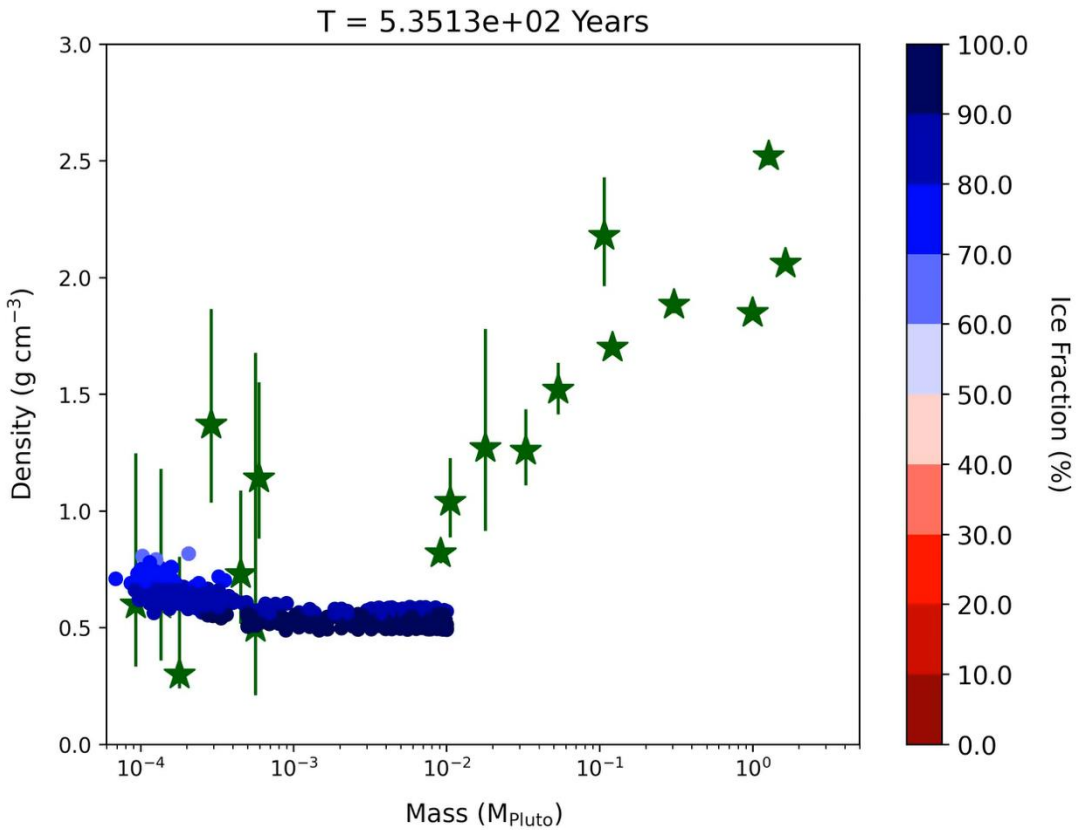


Canas & Lyra + (2024)

The window of silicate accretion



Canas & Lyra + (2024)

Conclusions

- 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