

Planetesimal Formation and Pebble Accretion in the Kuiper Belt

**NM
STATE**



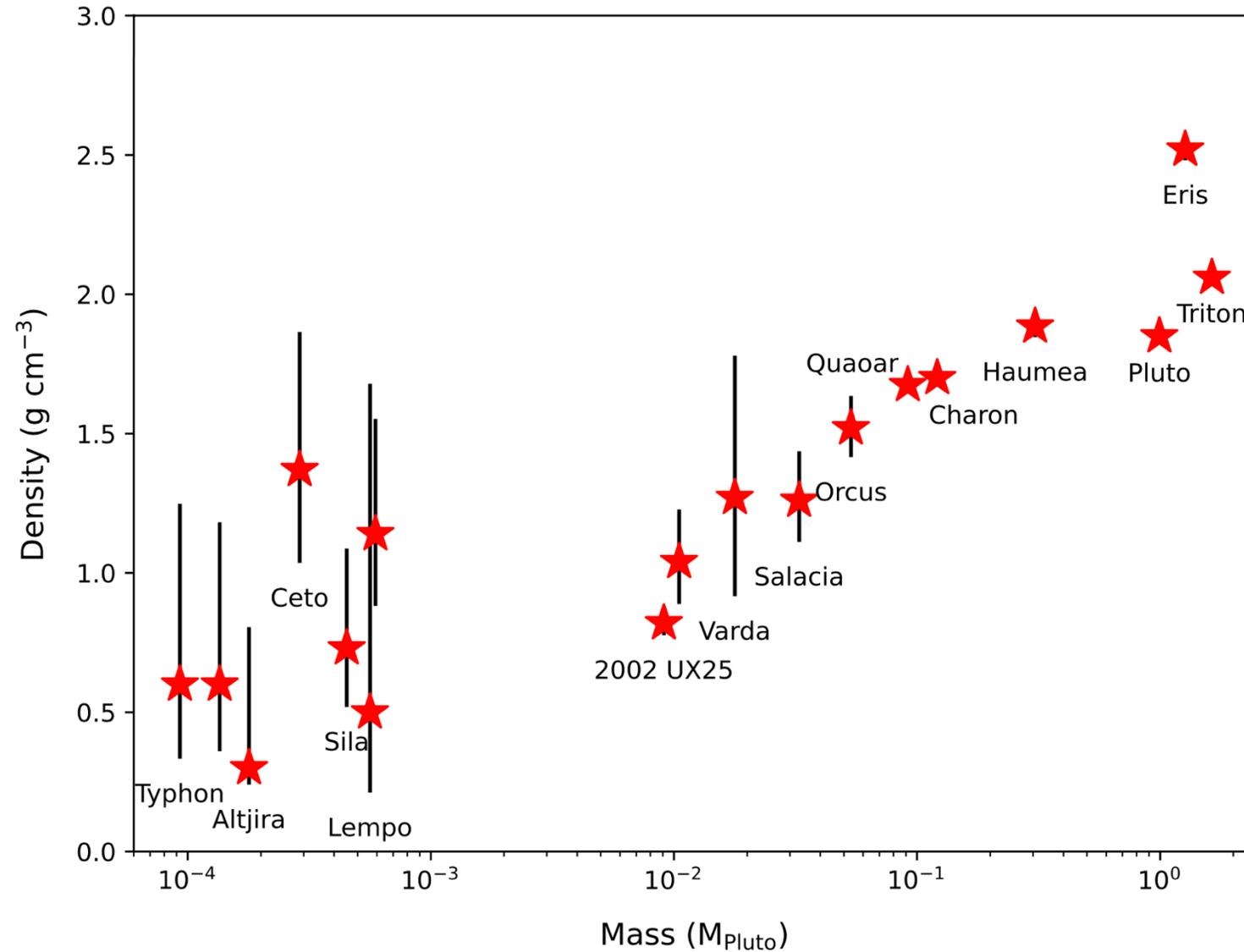
Wladimir Lyra
New Mexico State University
Las Cruces NM, USA



New Horizons Open Science Team Meeting #59
APL - Laurel MD - Jan 21-Jan22, 2026



The size-density relationship of Kuiper Belt objects



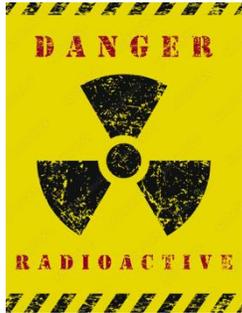
Cañas+Lyra et al. (2024)

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

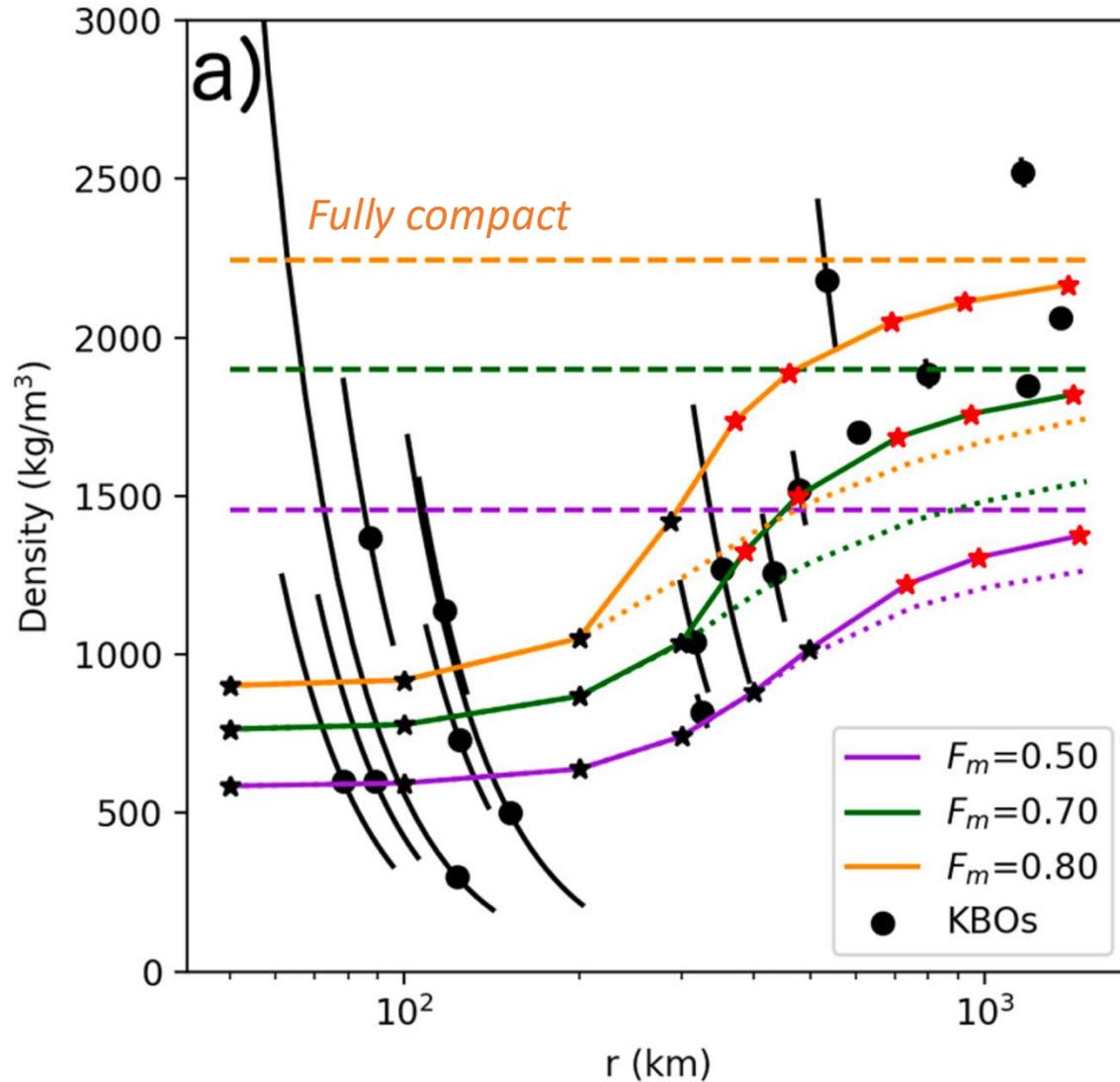
Problem

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



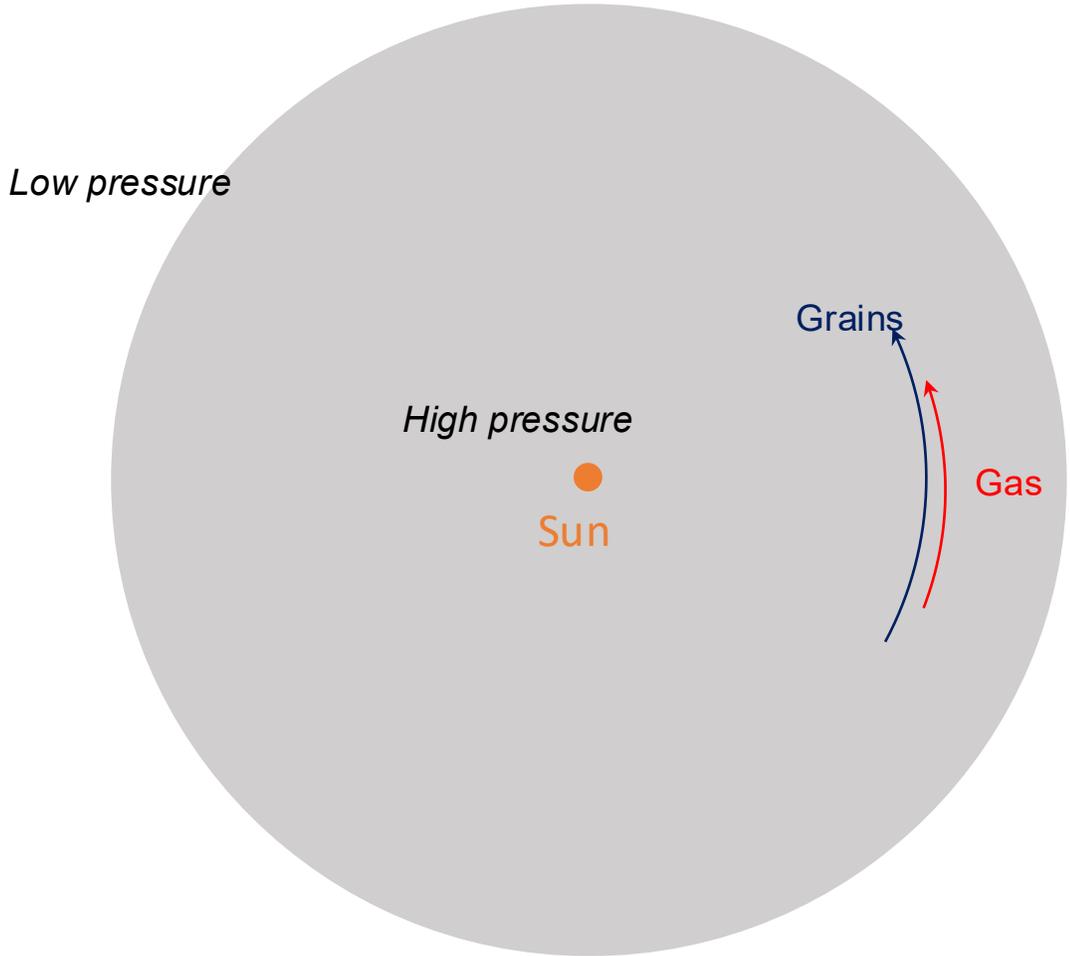
Assumptions

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



F_m = rock mass fraction

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

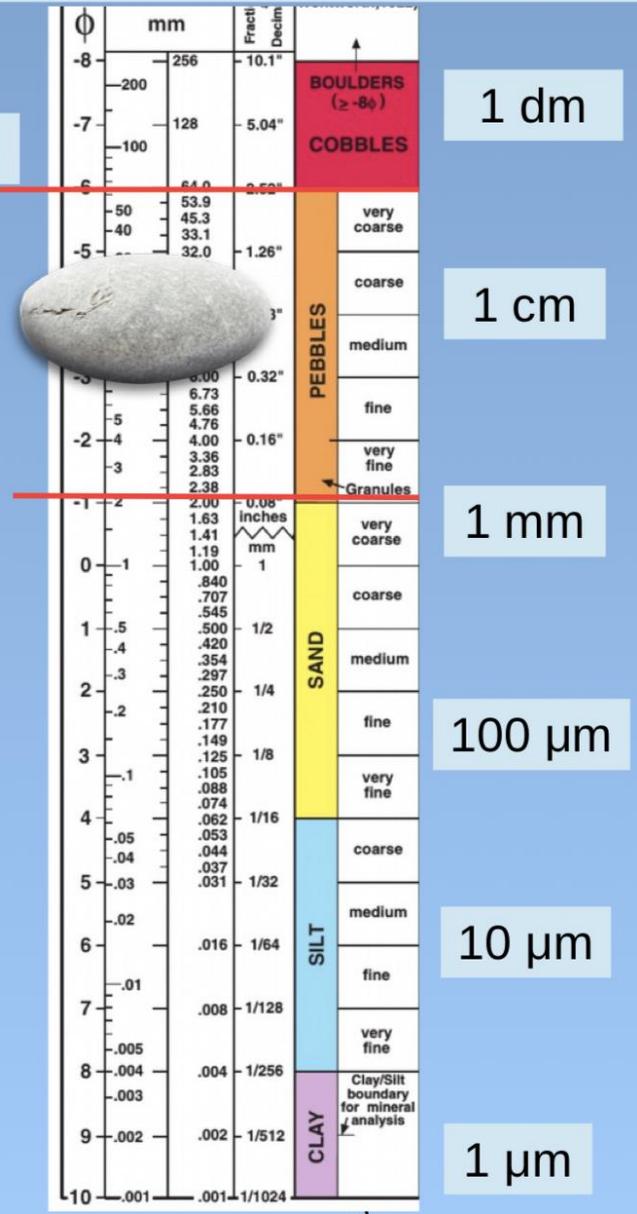
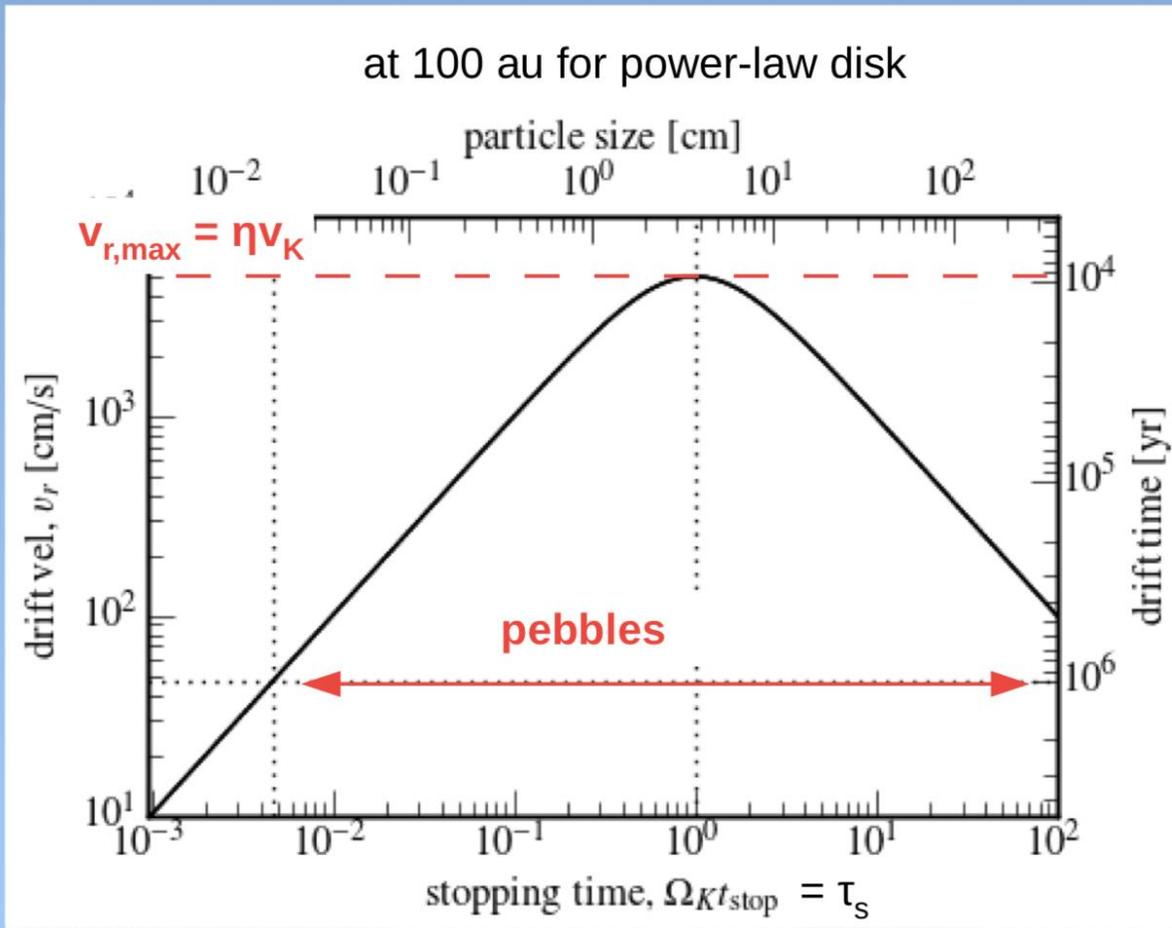
F. Brauer, C.P. Dullemond
Th. Henning

Pebble definition

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

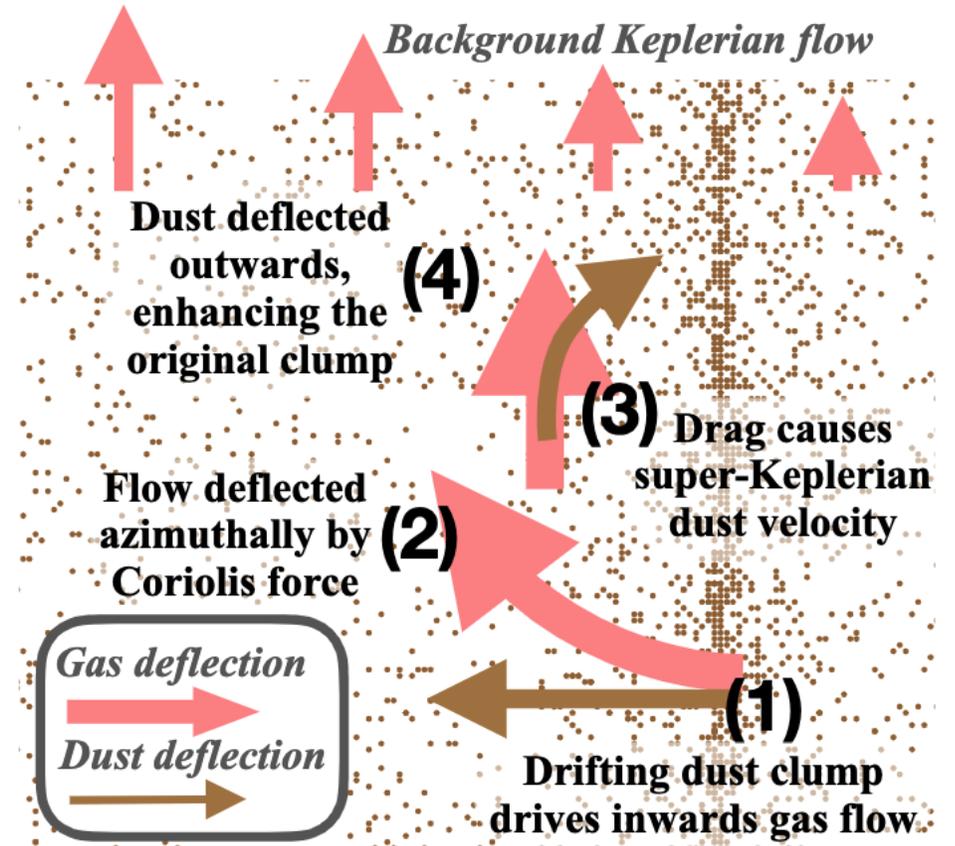
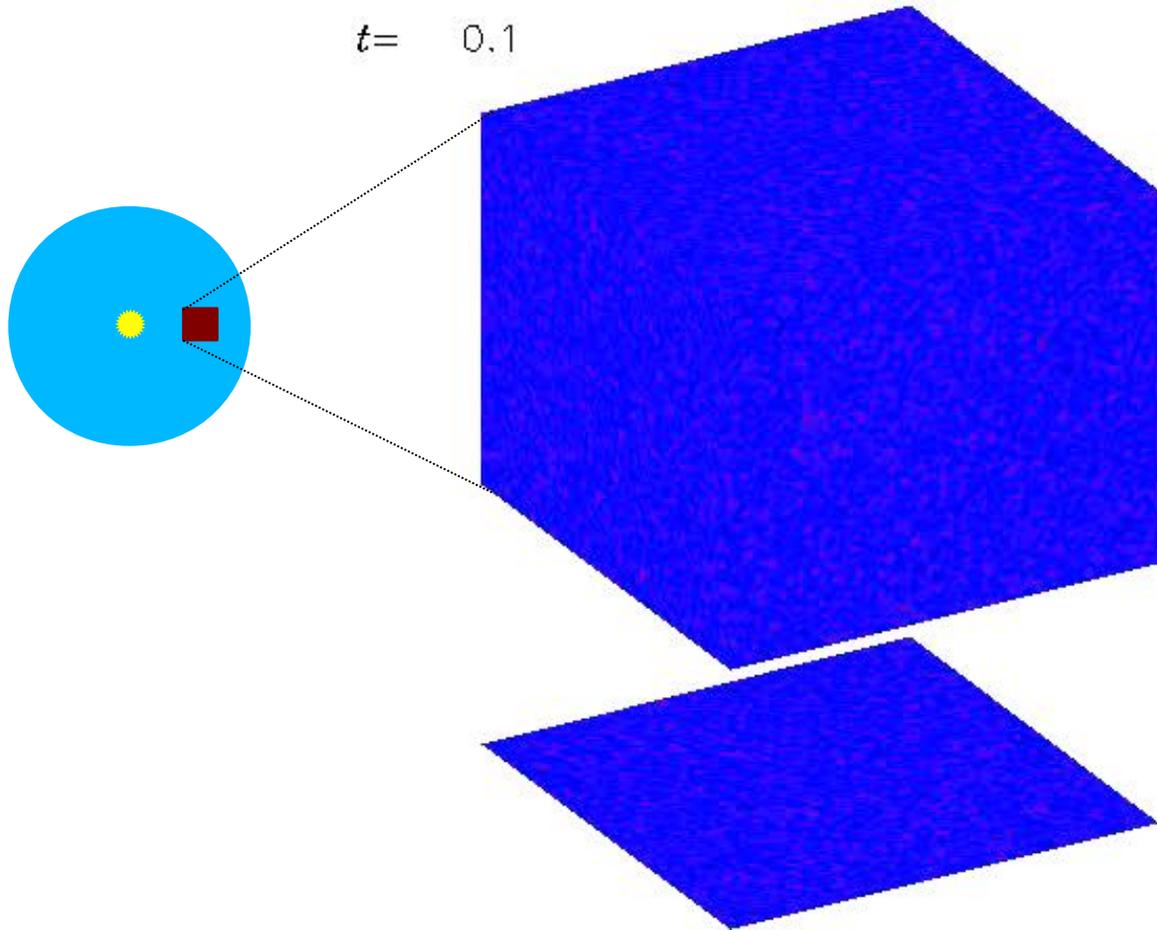
Astrophysical: particles that drift

6.4 cm



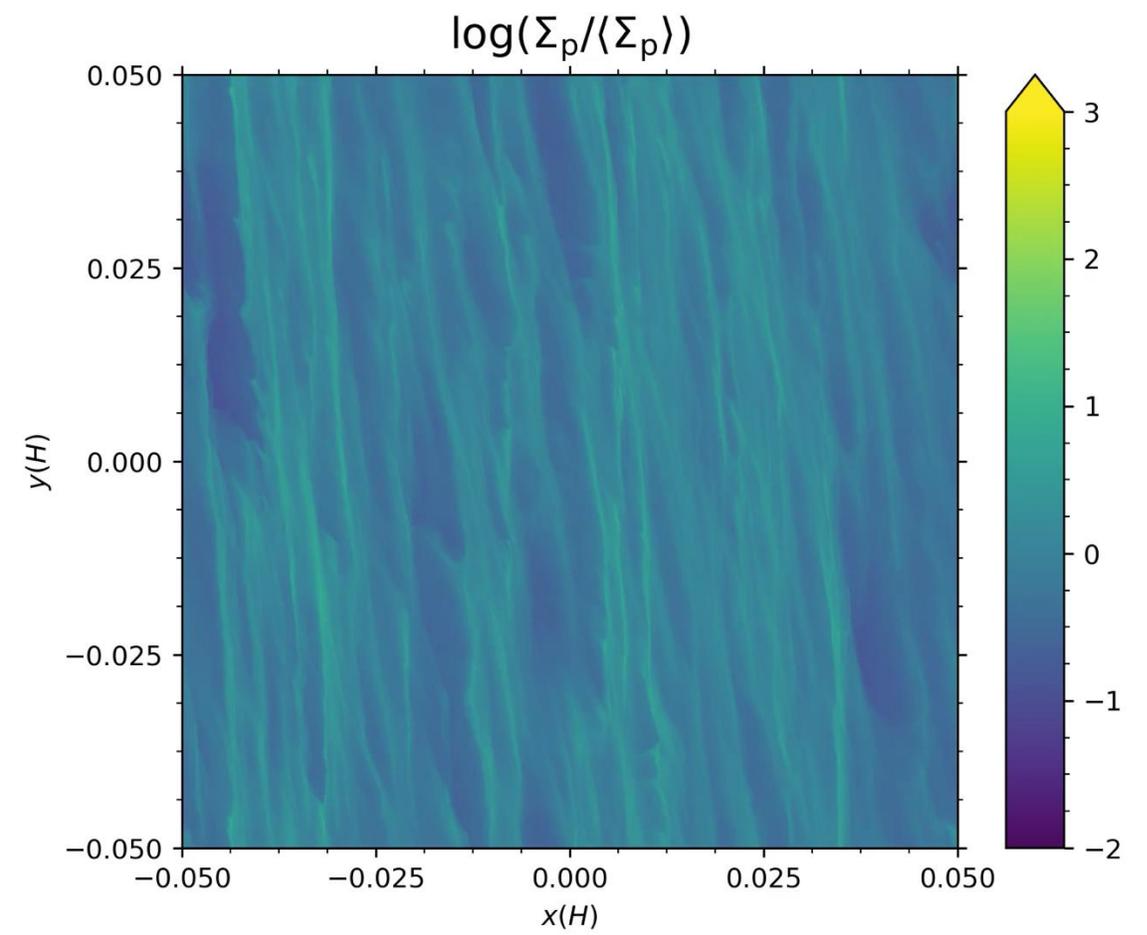
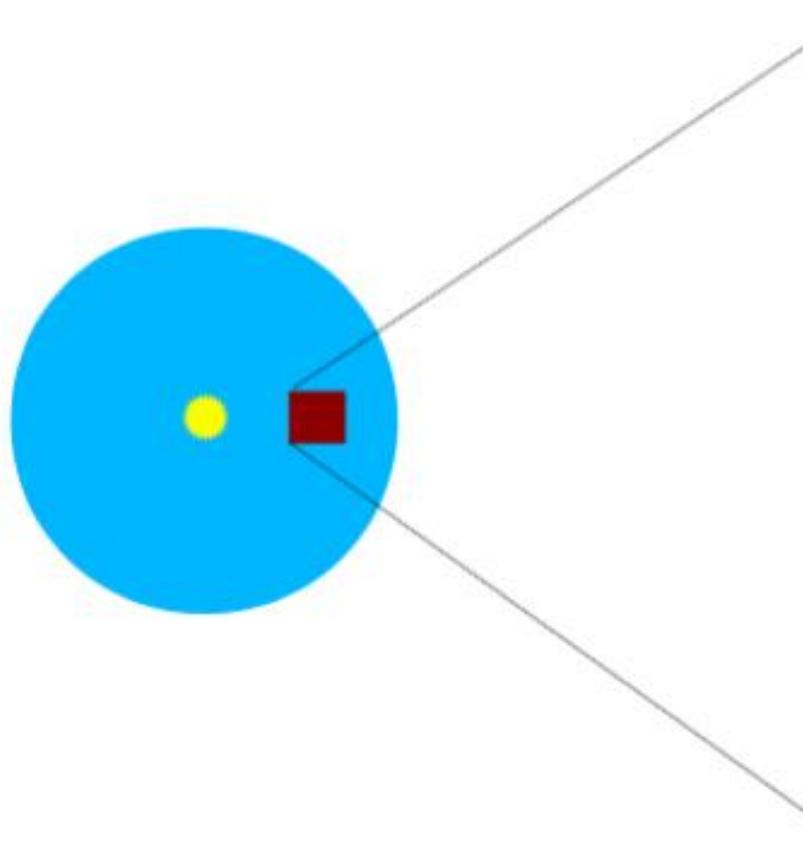
Streaming Instability

The pebble drift is hydrodynamically unstable



Lesur et al. (2022)

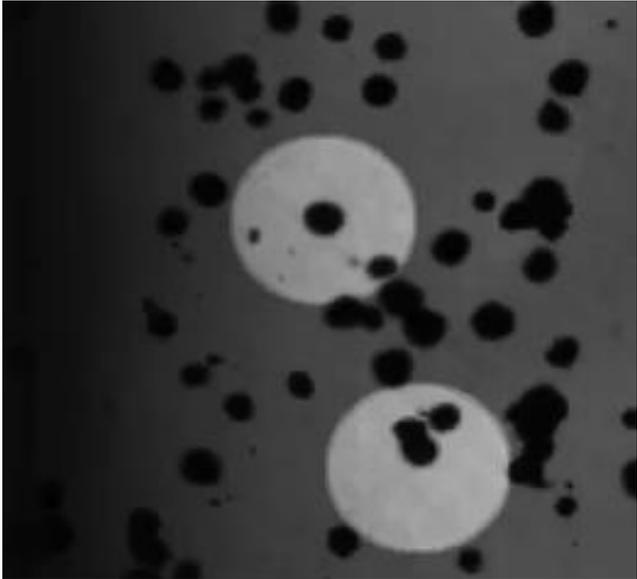
Gravitational collapse into planetesimals



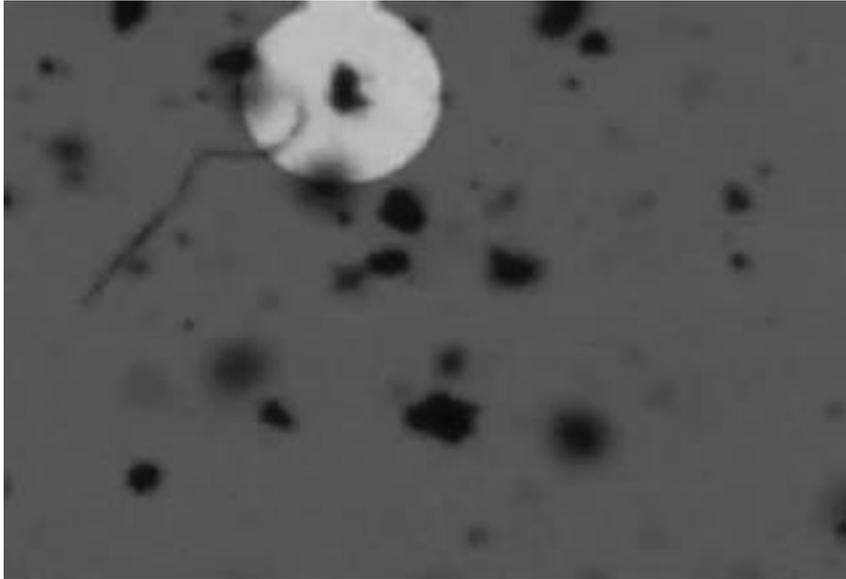
Animation by: Rixin Li

Grain collision outcomes

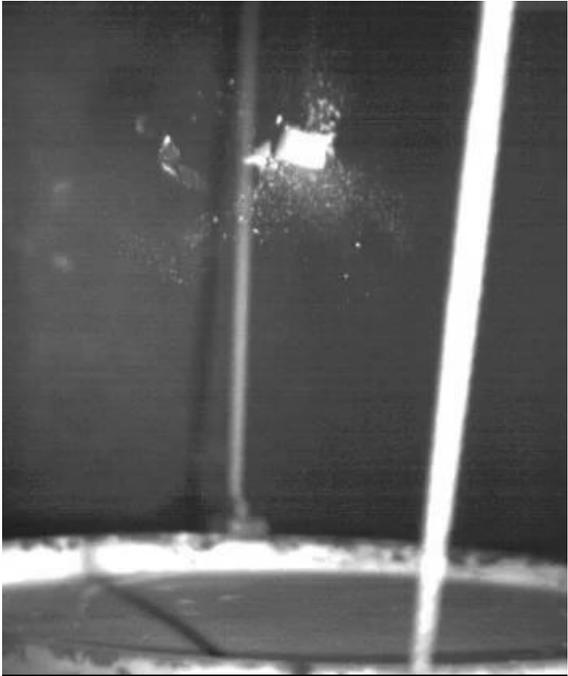
Bouncing



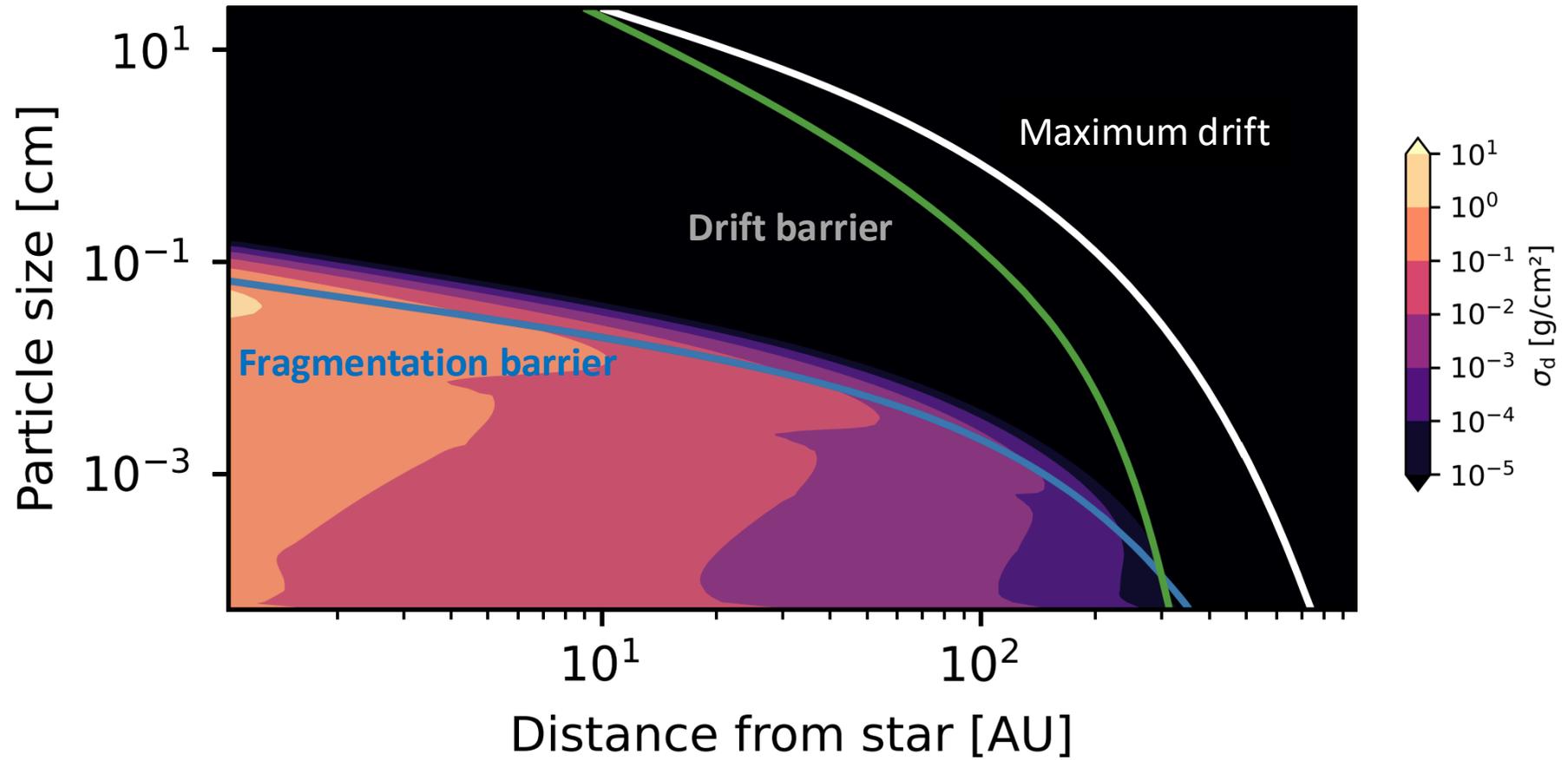
Sticking



Fragmentation

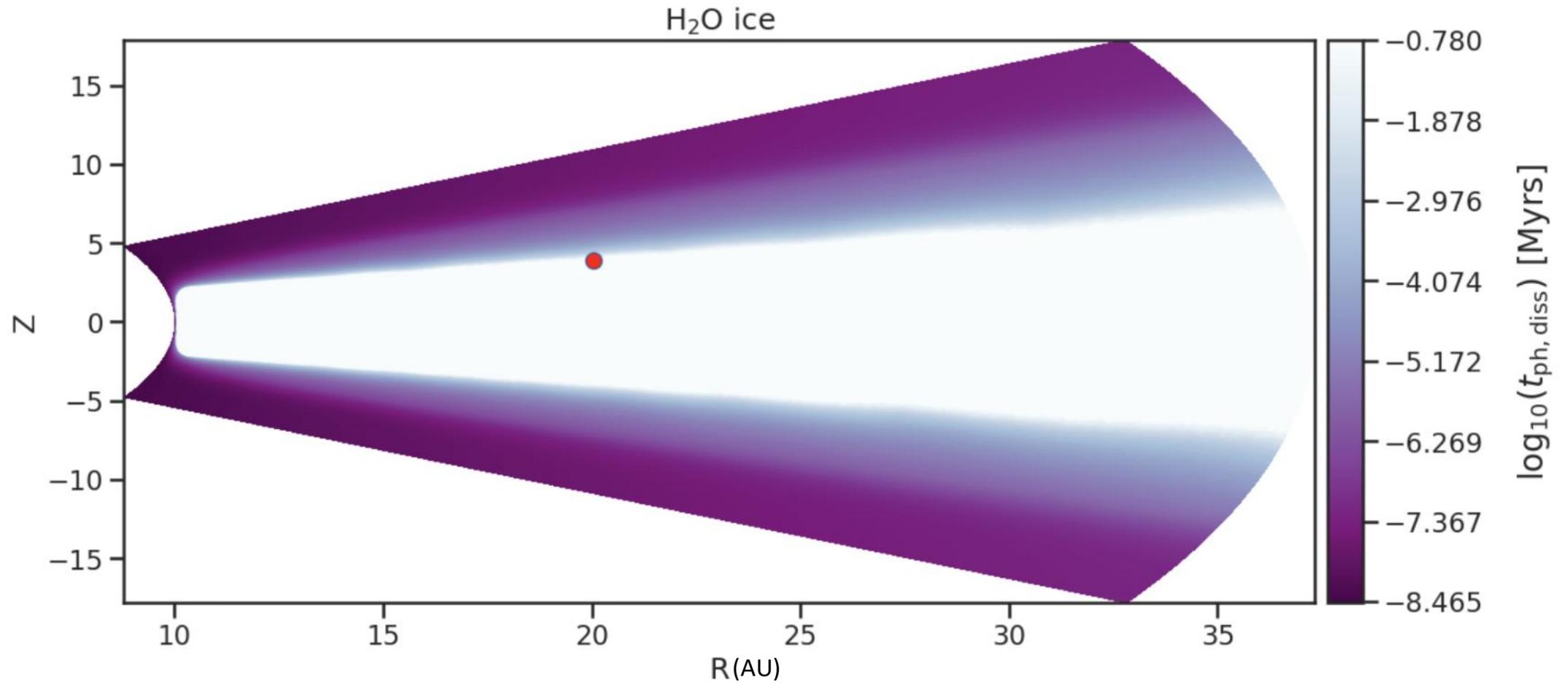


Fragmentation Barrier



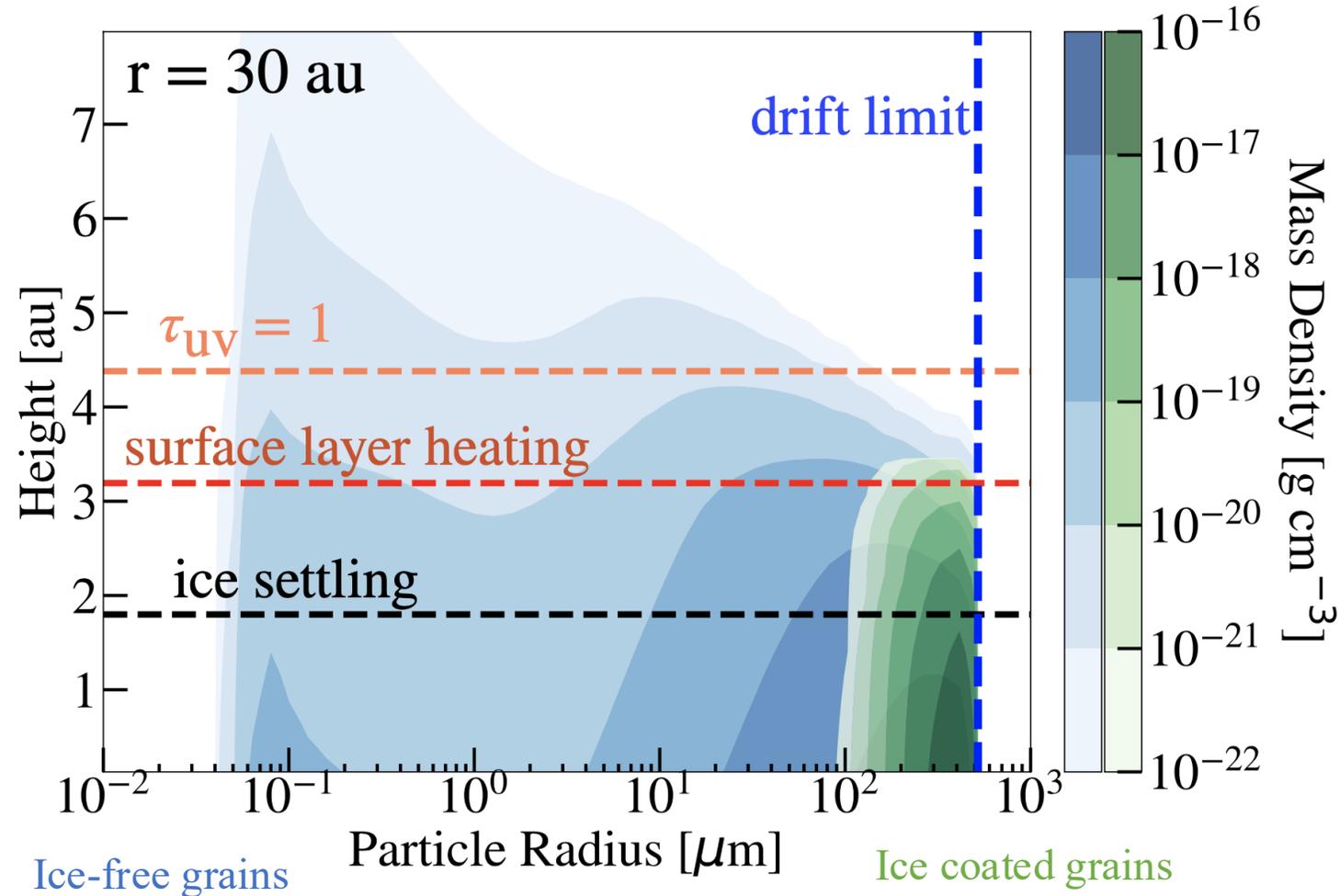
Thermal and photo-desorption, photodissociation

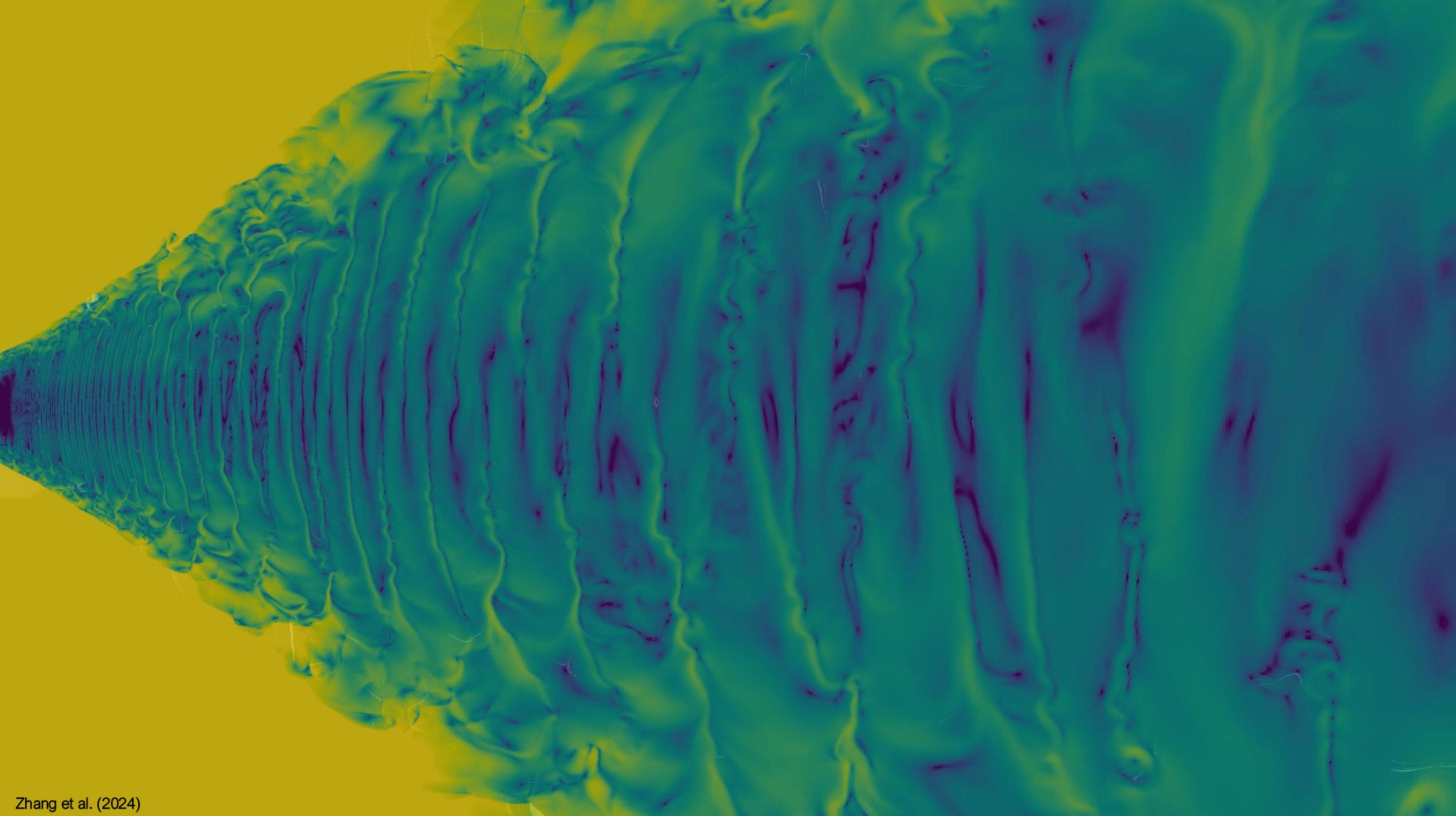
Heating and UV irradiation remove ice
on Myr timescales (Harrison & Schoen 1967).



Thermal and photo-desorption

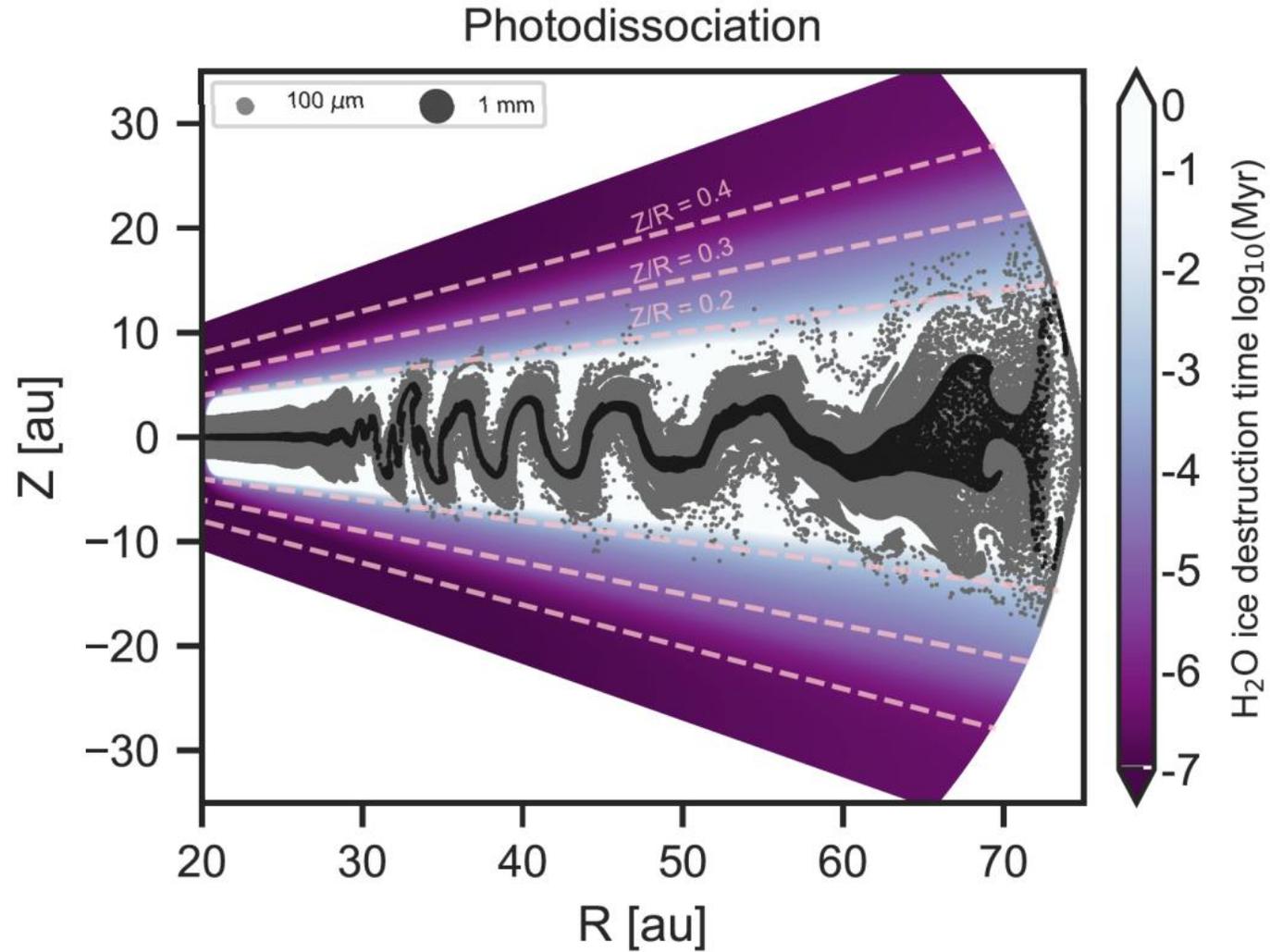
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Thermal and photo-desorption

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Thermal and photo-desorption

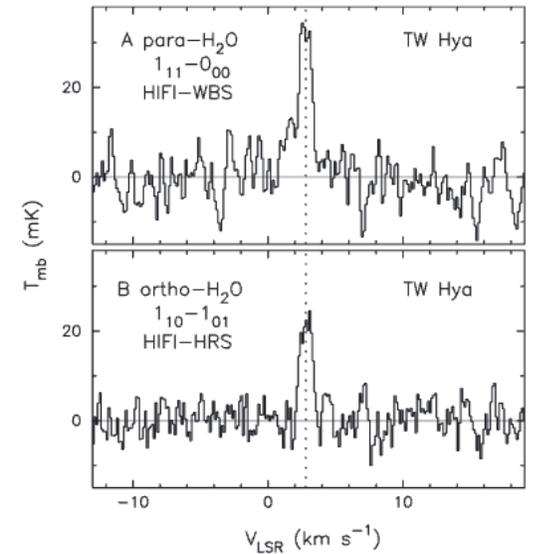
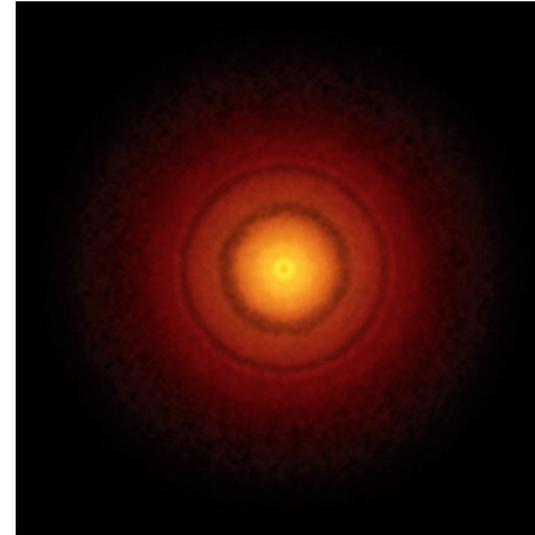
Evidence in disks

Debris disks



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

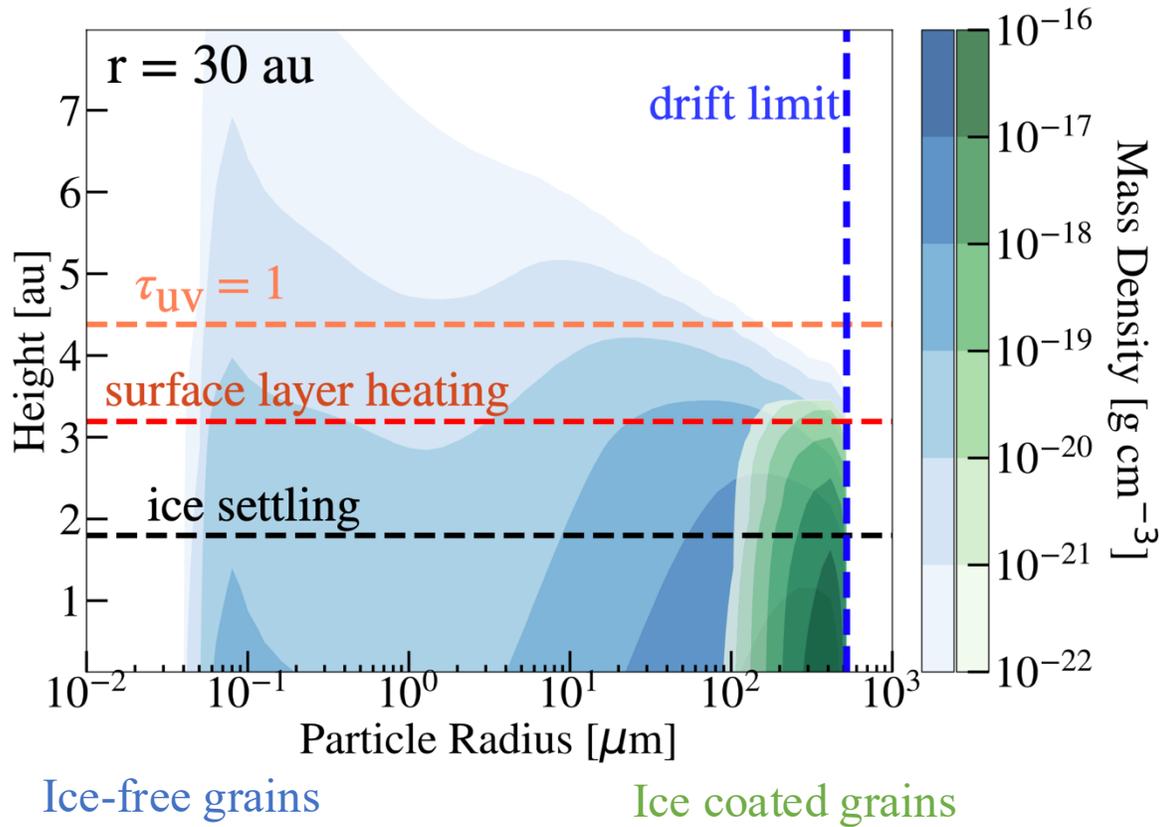
Primordial disks



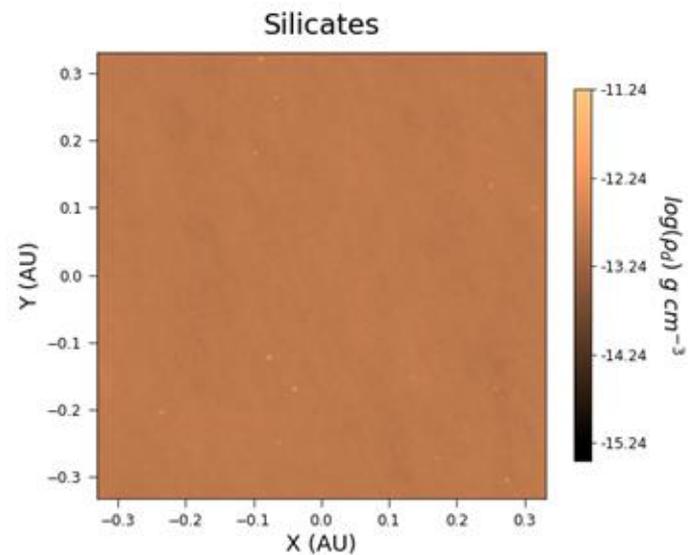
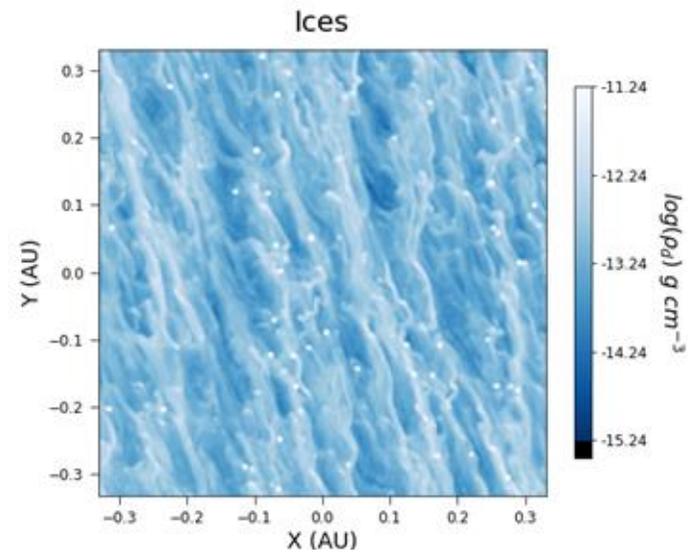
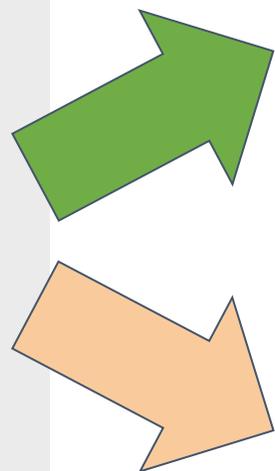
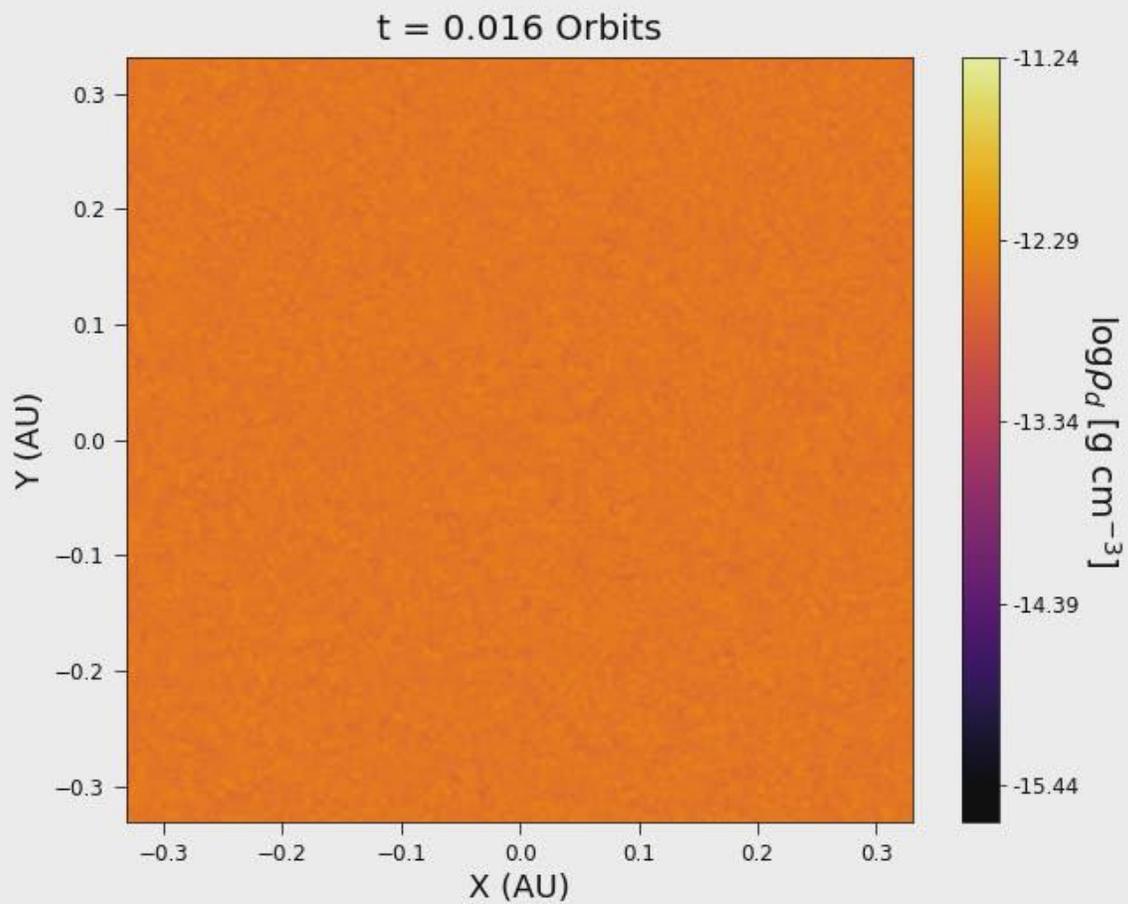
Water vapor observed at large distances for TW Hya
(Hogerheijde et al. 2011, 2012)

Proof-of-concept model

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



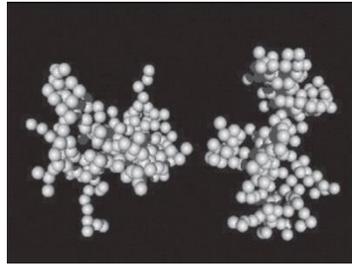
Split into icy and silicate pebbles



Core Accretion

**Core
Accretion**

Dust grains



0.1 – 1 μm

coagulation



Pebbles



mm – cm

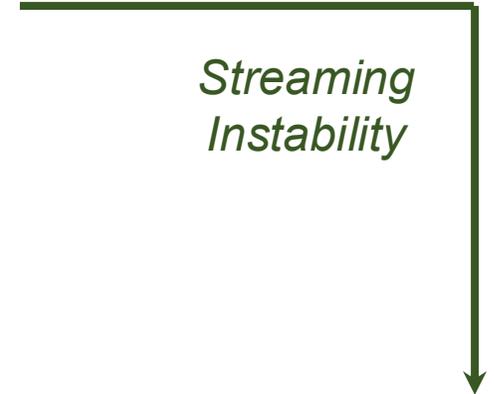
*Pebble
Accretion*



Protoplanets
Rocky Planets
Planetary Cores



*Streaming
Instability*



Planetesimals



1-100km

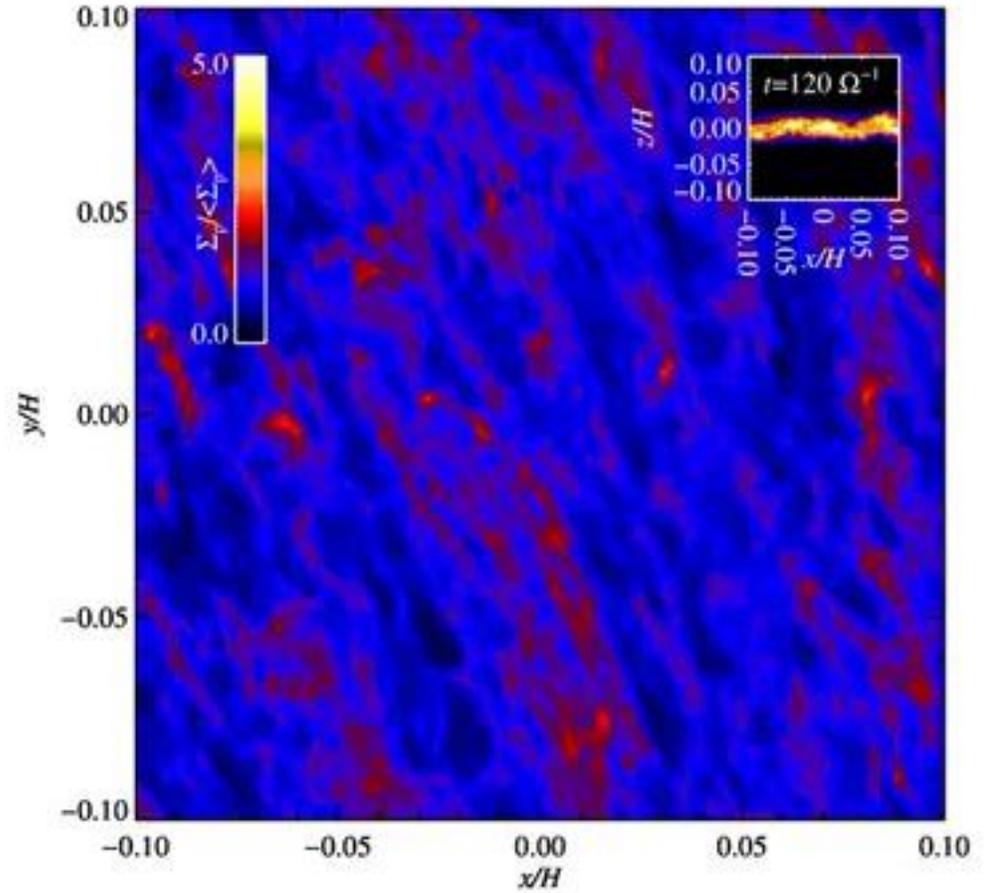
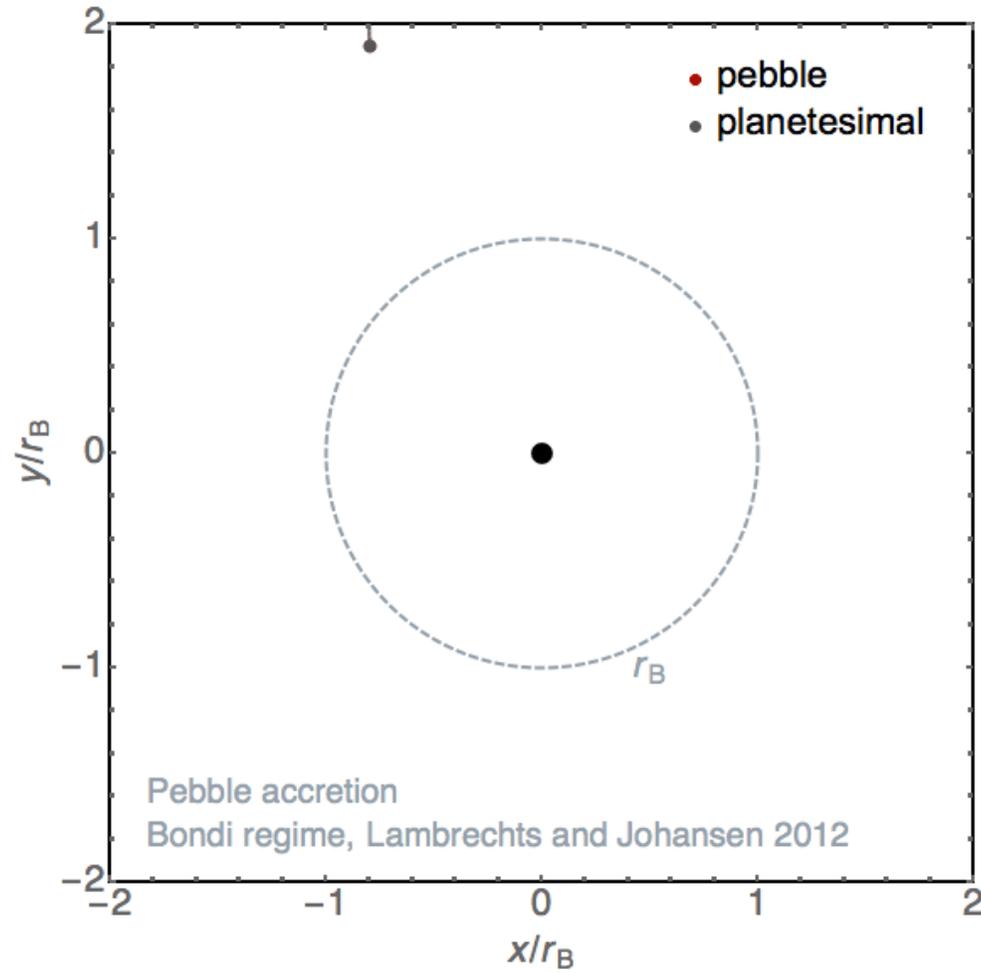


*Stops pebble accretion
Gas Accretion*

*Does not stop
pebble accretion*



Pebble Accretion

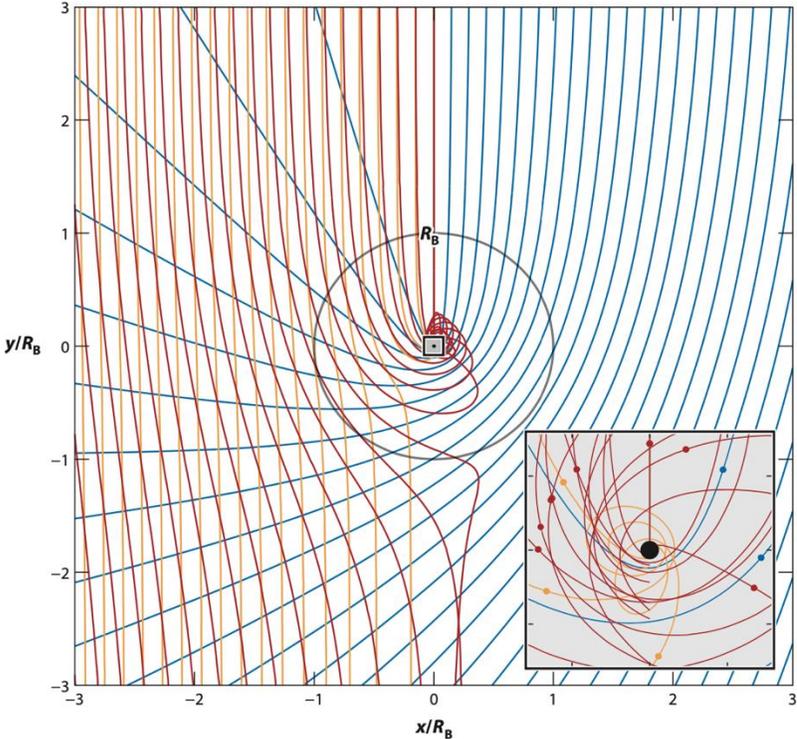


Lyra+ '08, '09, '23, Ormel & Klahr '10, Lambrechts & Johansen '12
See Johansen & Lambrechts '17 for a review

Pebble Accretion: Pebbles of different size accrete differently

”Goldilocks effect”

- Large ($t_s \gg t_b$)
- Medium ($t_s \sim t_b$)
- Small ($t_s \ll t_b$)

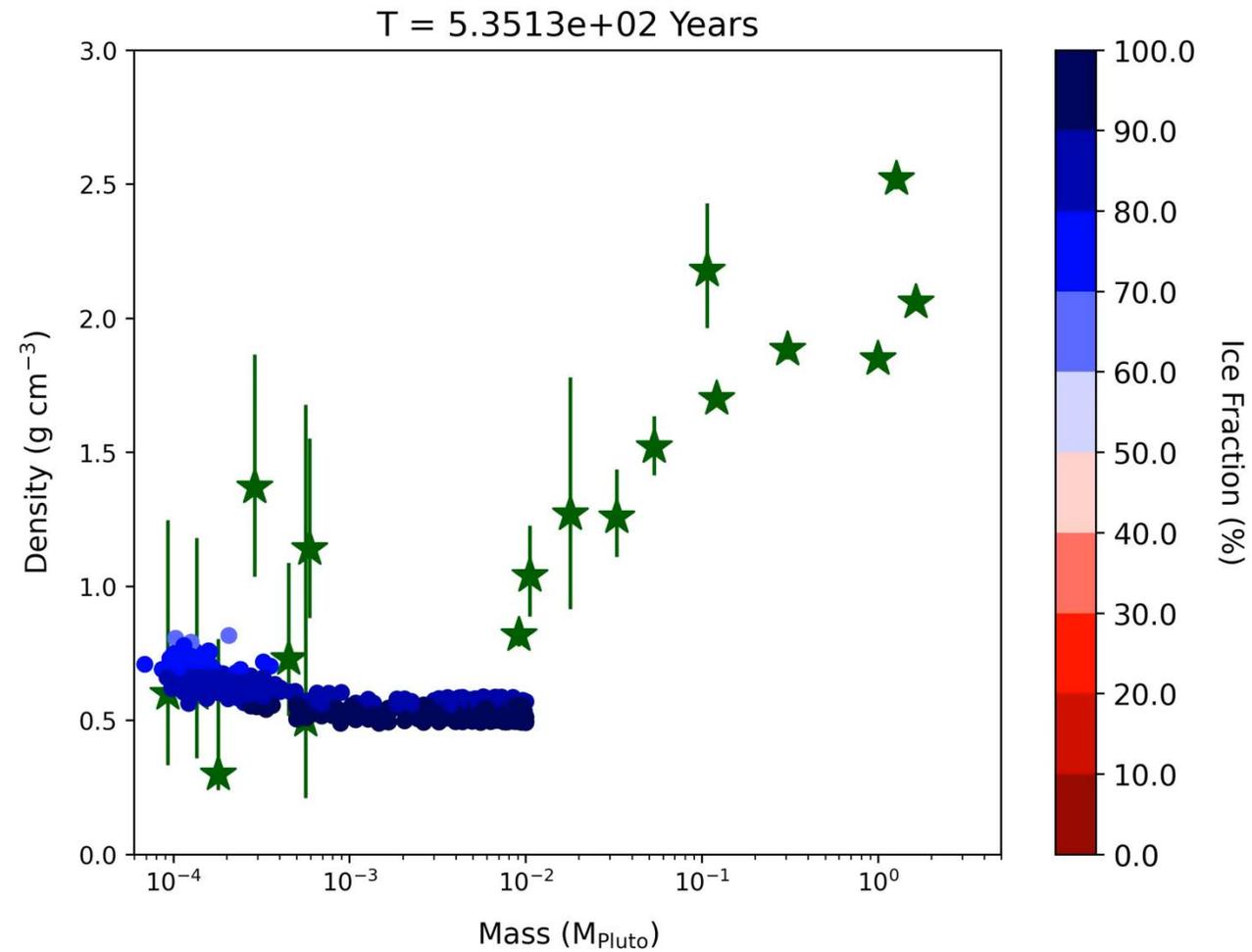
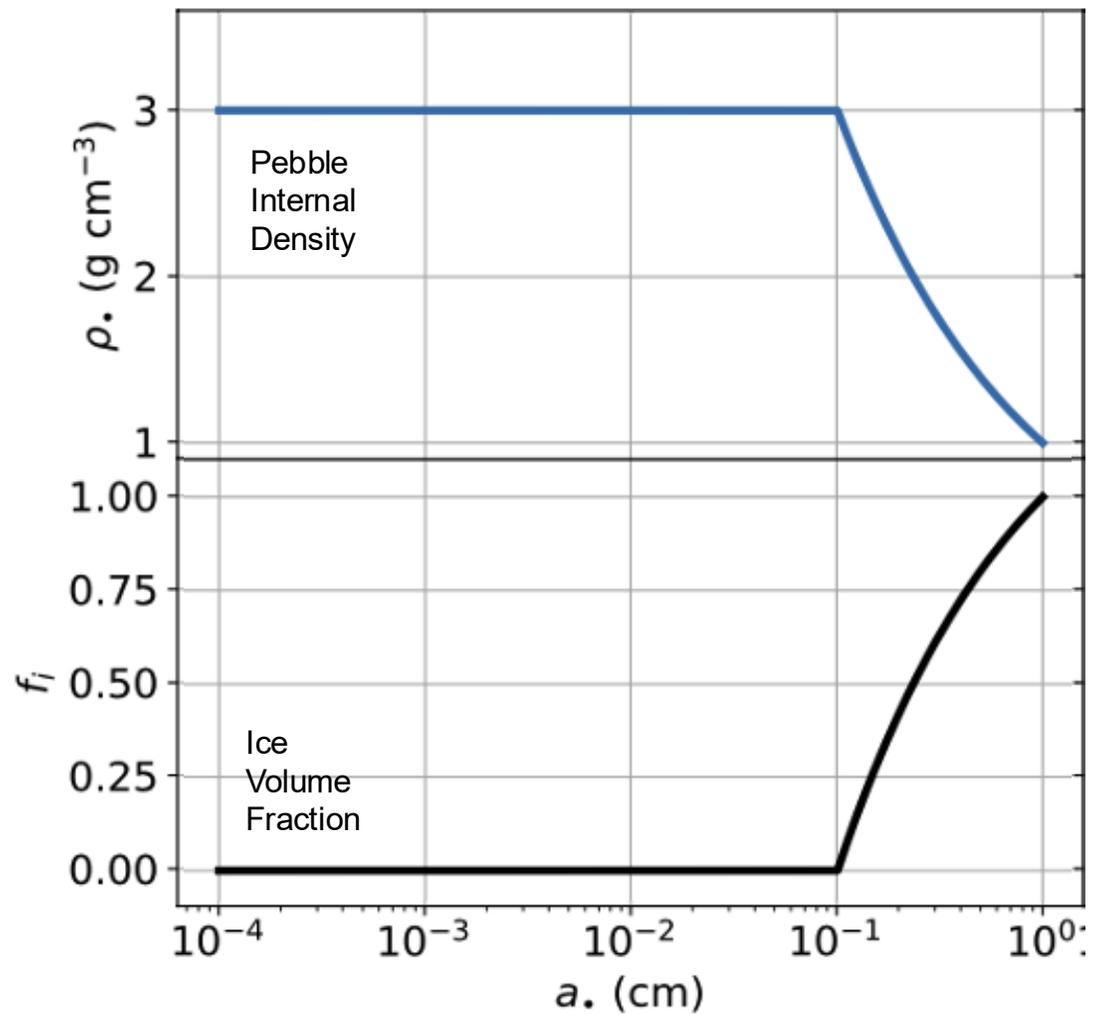


Pebble size that accretes optimally

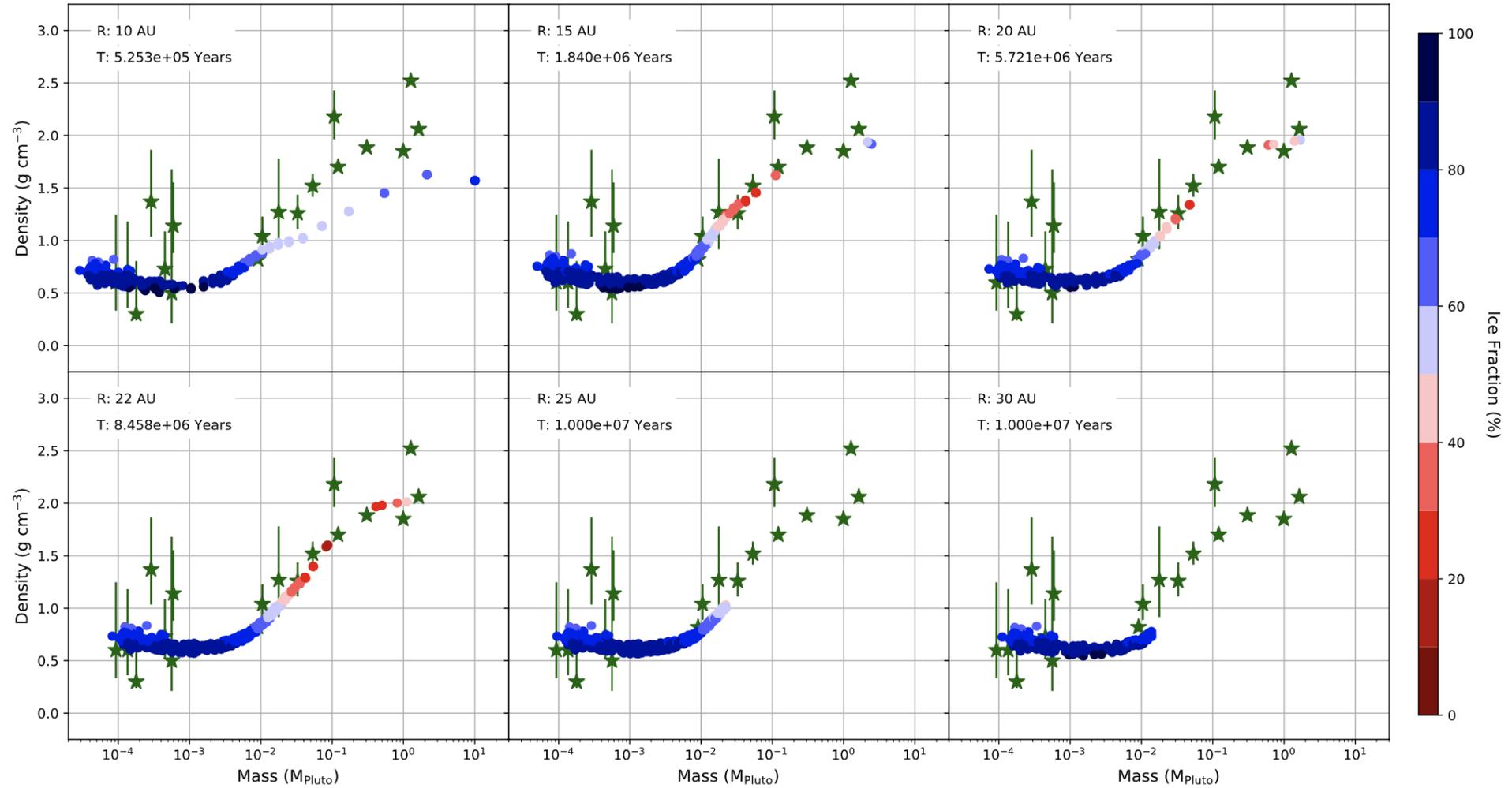
Drag time $t_s \sim$ Time to cross Bondi sphere t_b

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

Growing Pluto by silicate pebble accretion

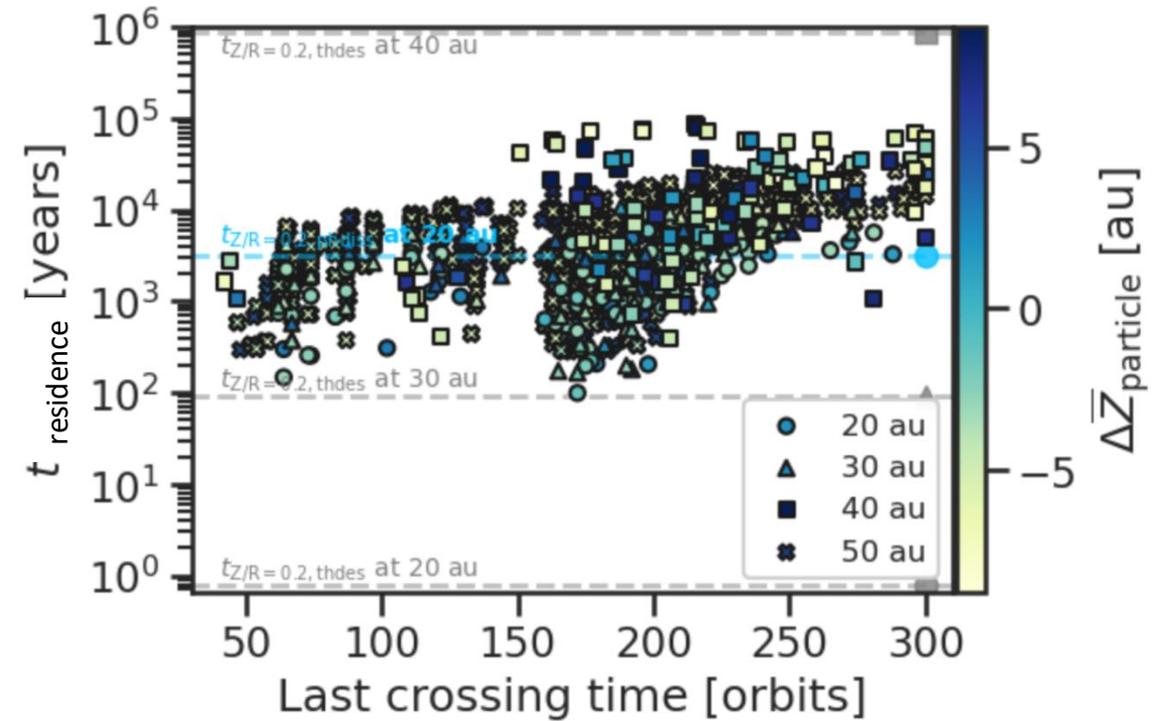
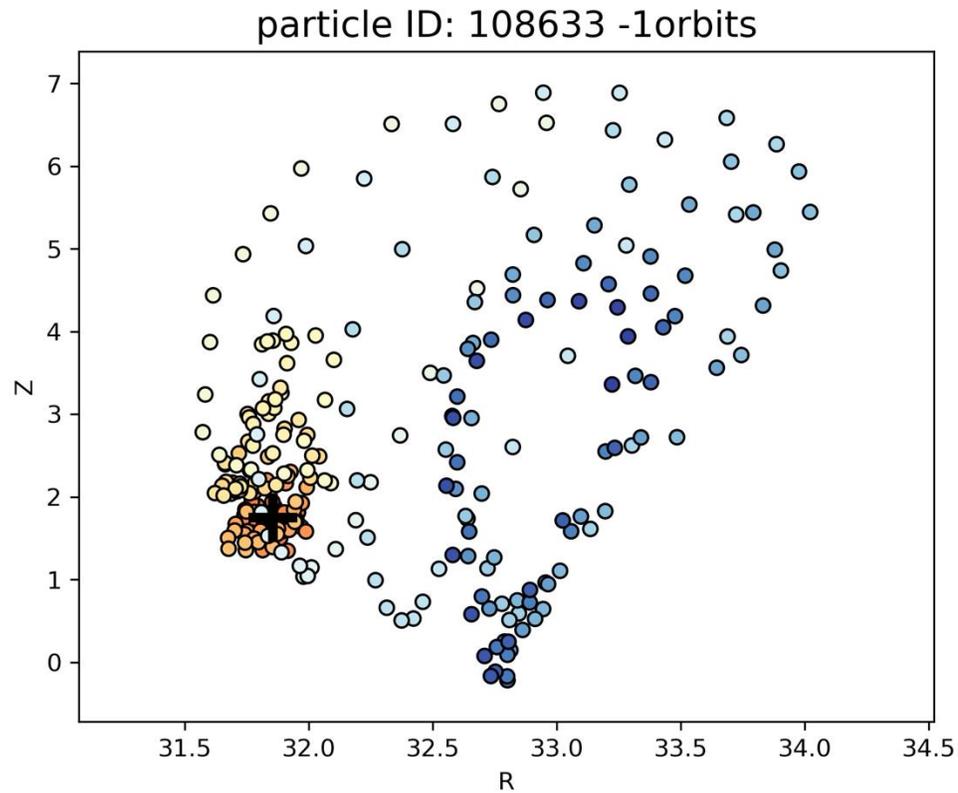


Distance Range 15 - 25AU



Pebble composition

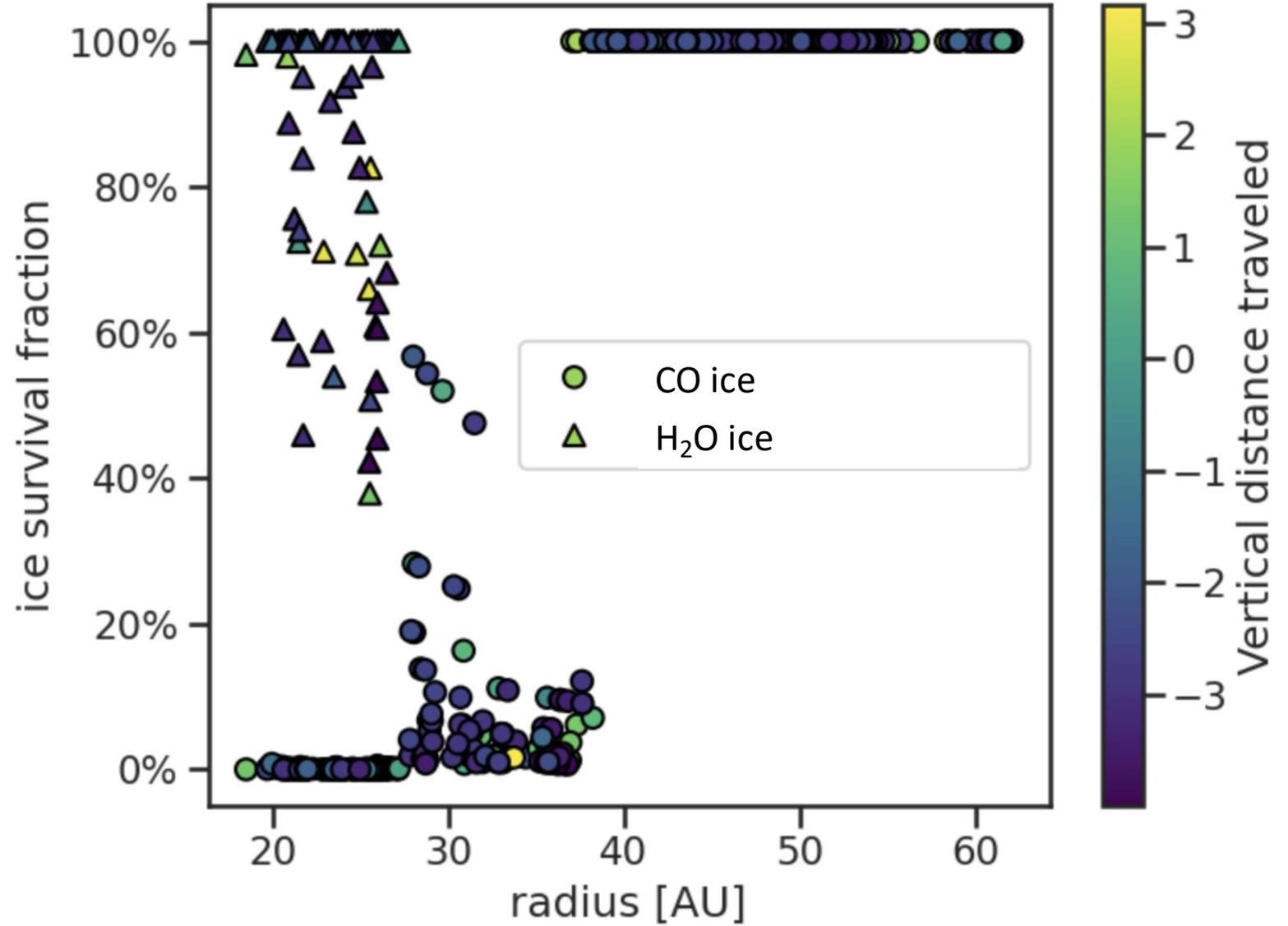
Turbulence + grains (100 μm and 1mm) + photodissociation



Ice survival Fraction

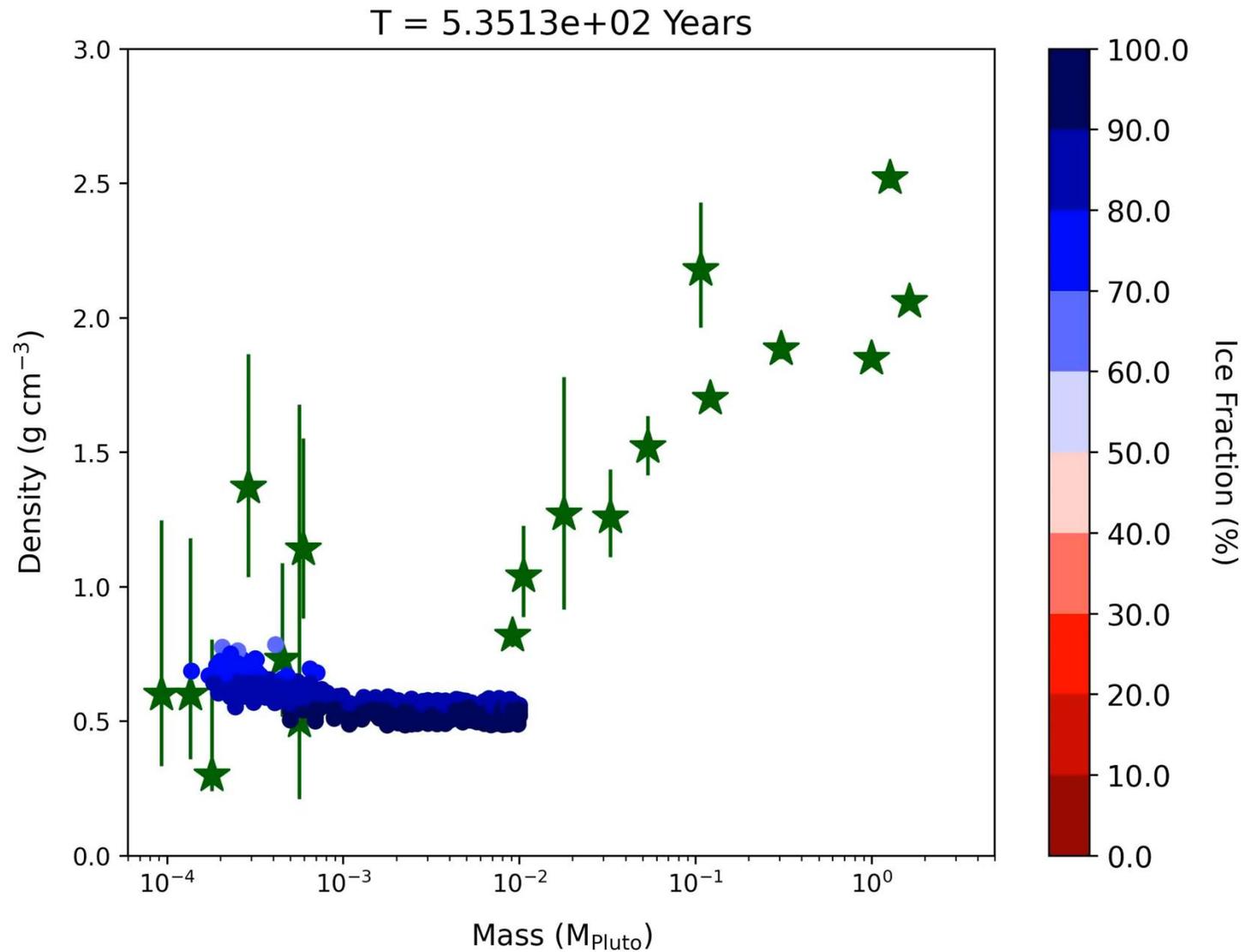
1mm - unprocessed

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

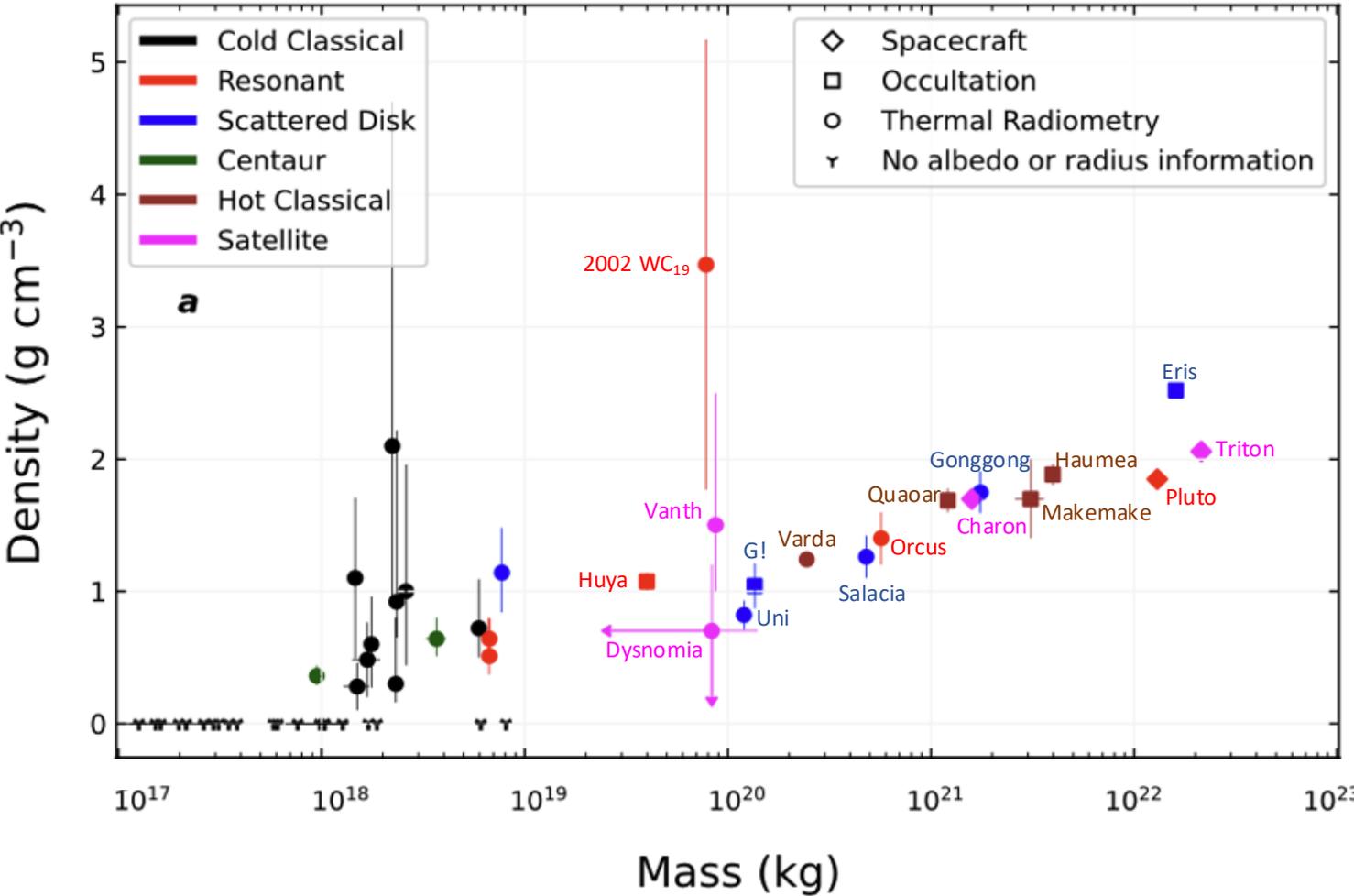


Growing Eris by silicate pebble accretion

Requires ~100% silicate composition



Eris as an outlier



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 ($>\text{Myr}$) phase of silicate accretion
- KBOs best reproduced between 15-25 AU
- 1mm ice grains preserved; 100 micron grains processed
- Eris is an outlier: possible collision removing ice mantle (which also formed Dysnomia from the icy debris)

