Planet formation review

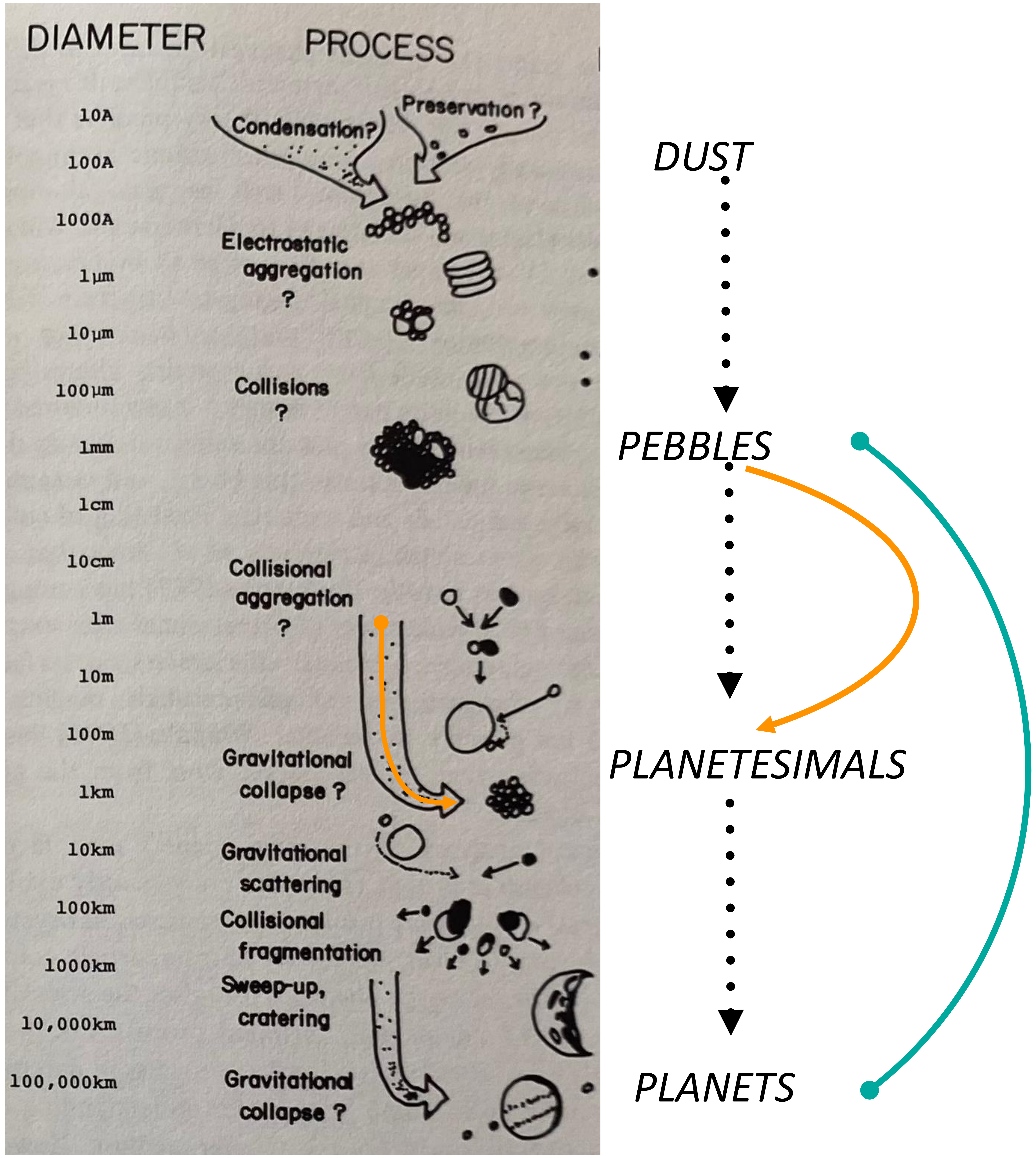
Michiel Lambrechts (StarPlan — University of Copenhagen)

Starting Grant

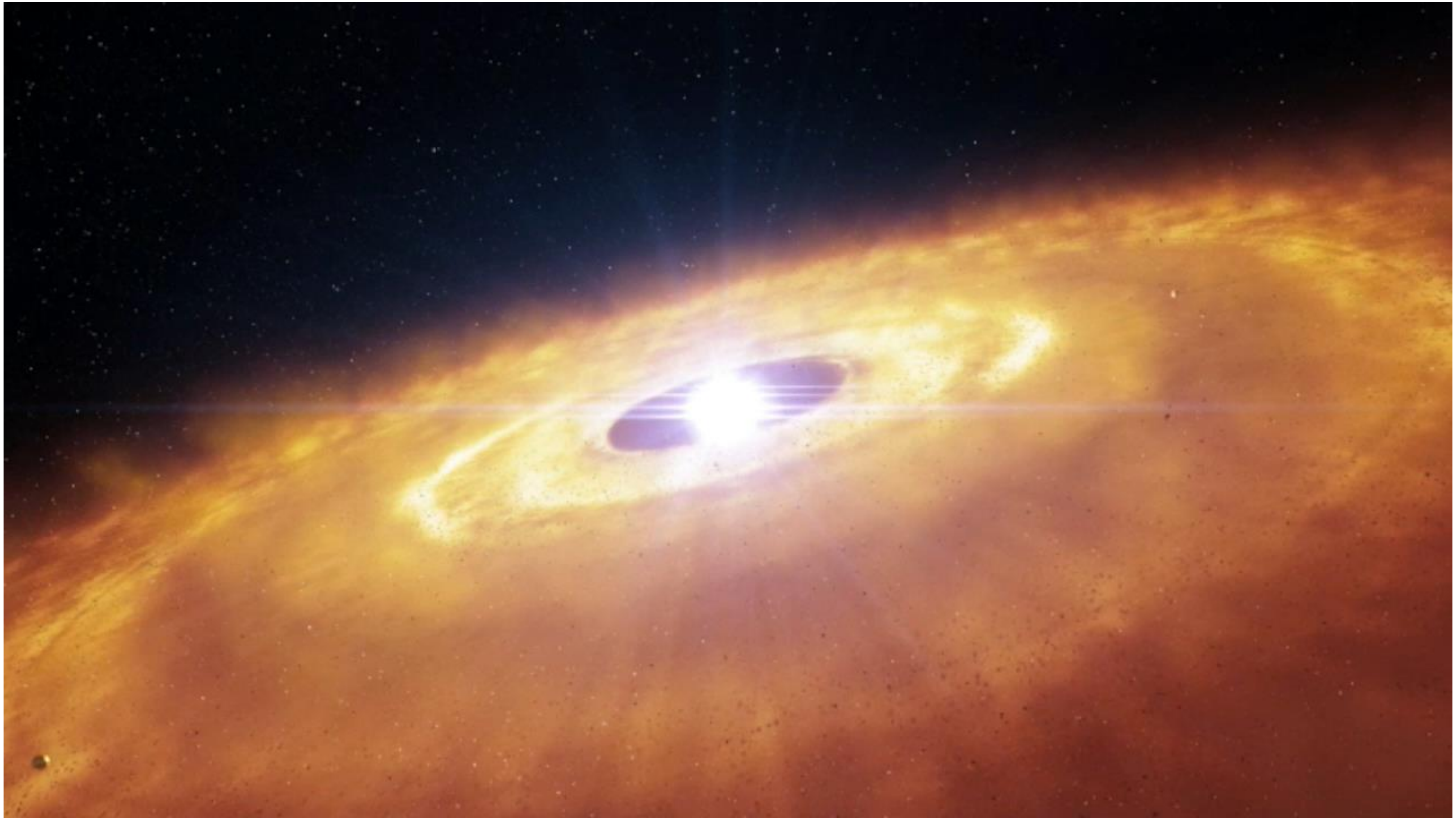
V883 Orionis - artist impression (ESO)

Planet formation length scales

Hartmann 1978, Protostars and Planets 1



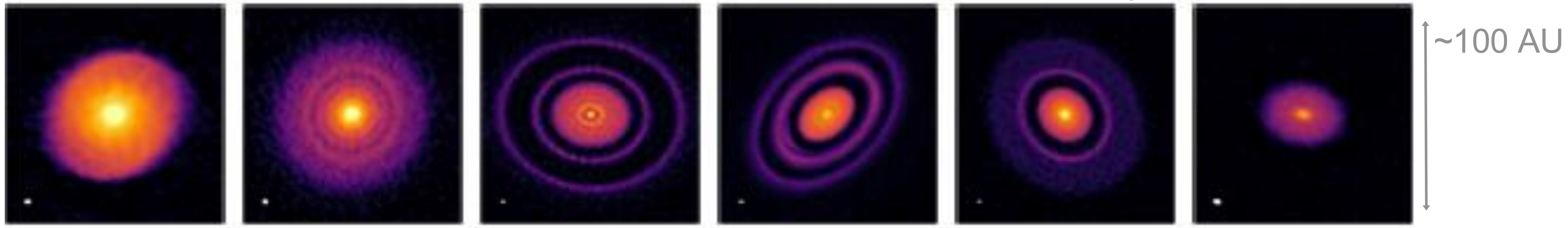
Pebbles in protoplanetary discs



ESO

Pebbles as planetary building blocks

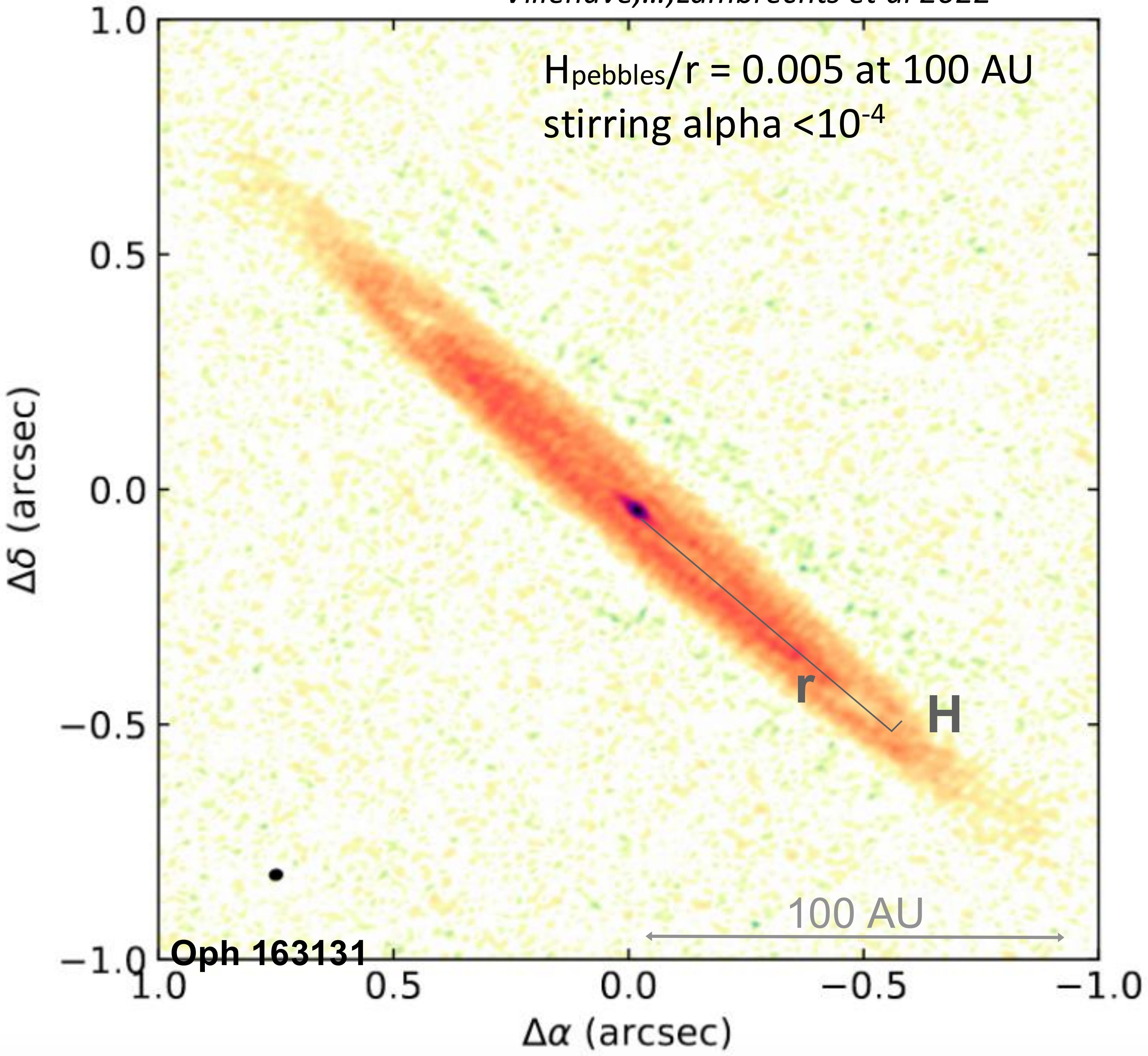
Disc observed with the DSHARP survey *Andrews et al 2018*



- ALMA surveys of discs around young stars (< 3 Myr) show discs with tens to hundreds of Earth masses of ~mm-sized solids
  Ansdell et al 2017, Tychoniec et al 2020, see also Zhu et al 2019, Liu 2019

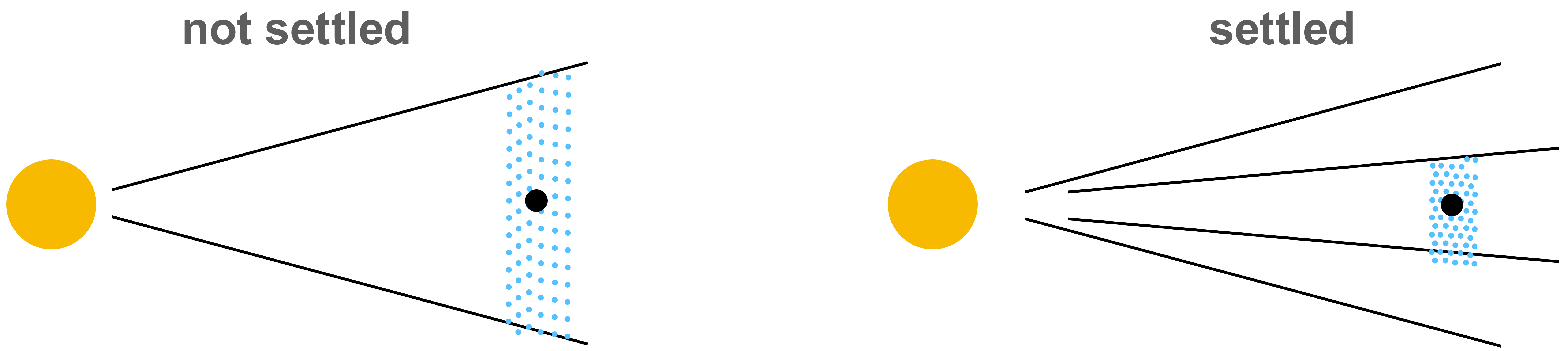
- Pebbles are located in a thin midplane layer
  Pinte et al 2016, Villenave et al 2022

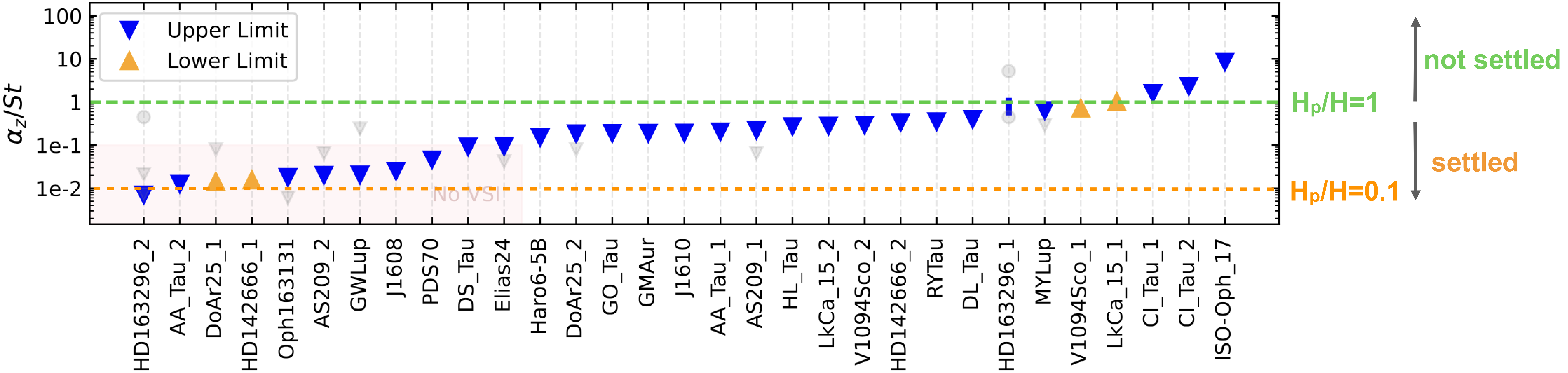
Villenave,…,Lambrechts et al 2022



Most protoplanetary discs are consistent with low levels of vertical stirring

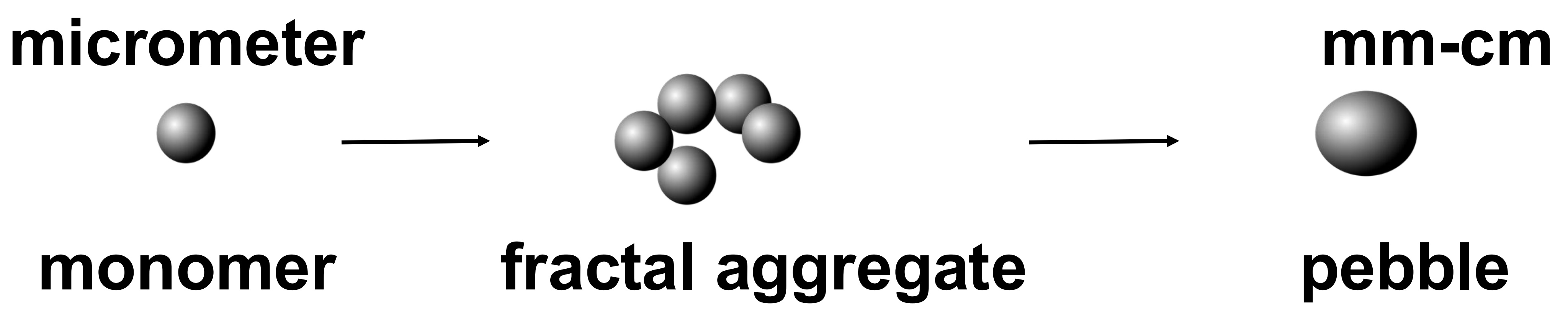
Villenave, Rosotti, Lambrechts, Ziampras et al 2025





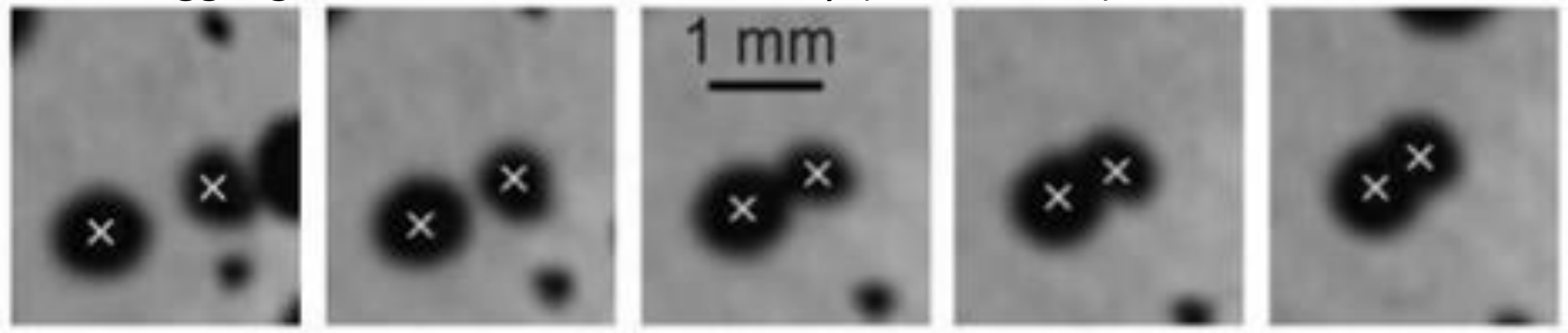
Pebbles: fragmentation limit

- Collisional particle growth stalls when fragmentation starts dominating, resulting in a characteristic pebble size
  Blum & Wurm 2008 annu. rev.



- For small particles, ~sticking collisions are expected
  Dominik & Tielens 1997

1mm aggregate, 0.004m/s rel. velocity (Blum 2010)



- If large particles (>cm) form, characteristic relative velocities (~1 to 10 m/s) lead to fragmentation
  for both silicates and ices, Güttler et al 2010, Musiolik and Wurm 2019

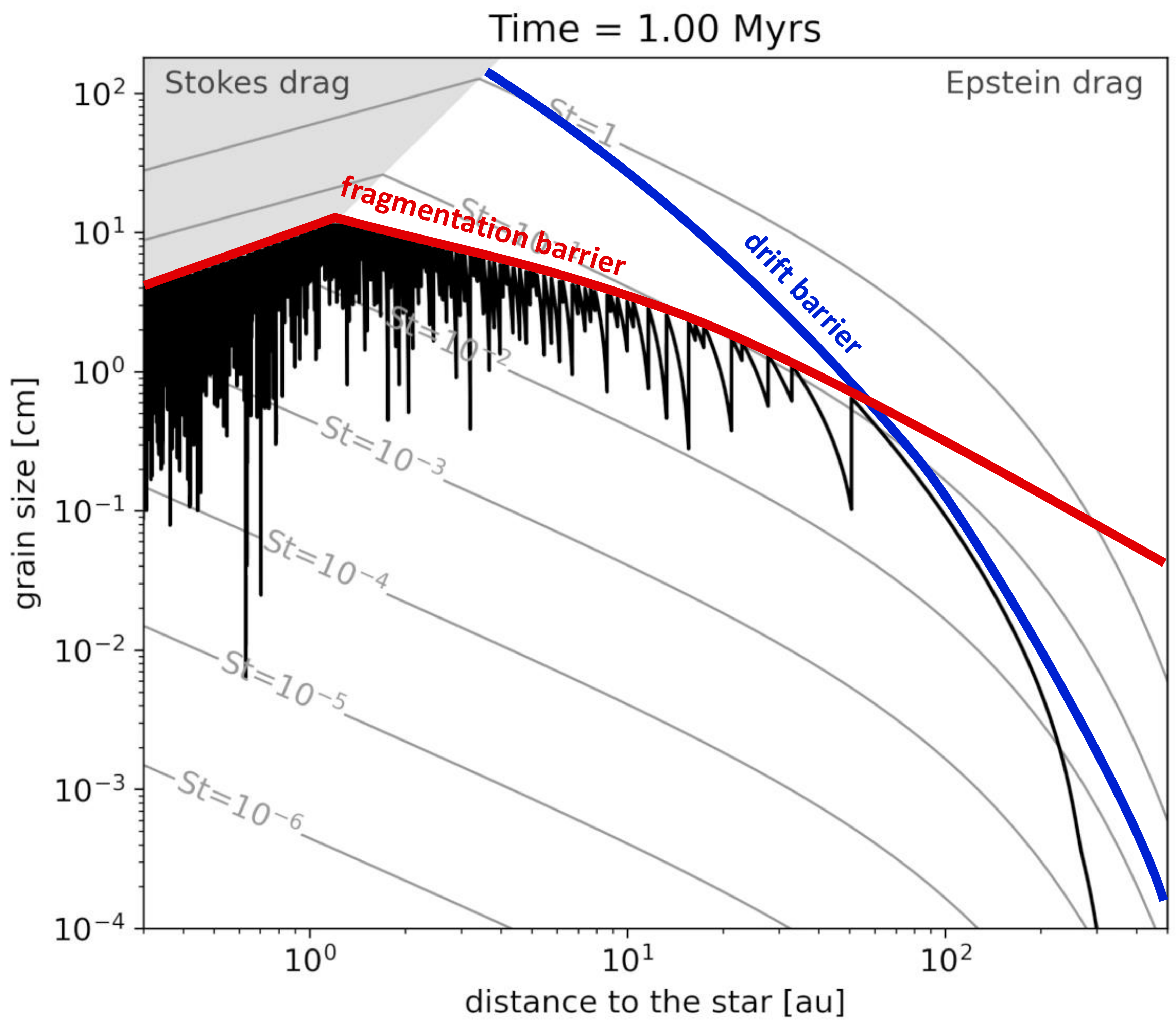
Silicate
2 cm dust aggregates
7.4 m/s relative velocity
complete fragmentation

(drop tower, Jürgen Blum lab)

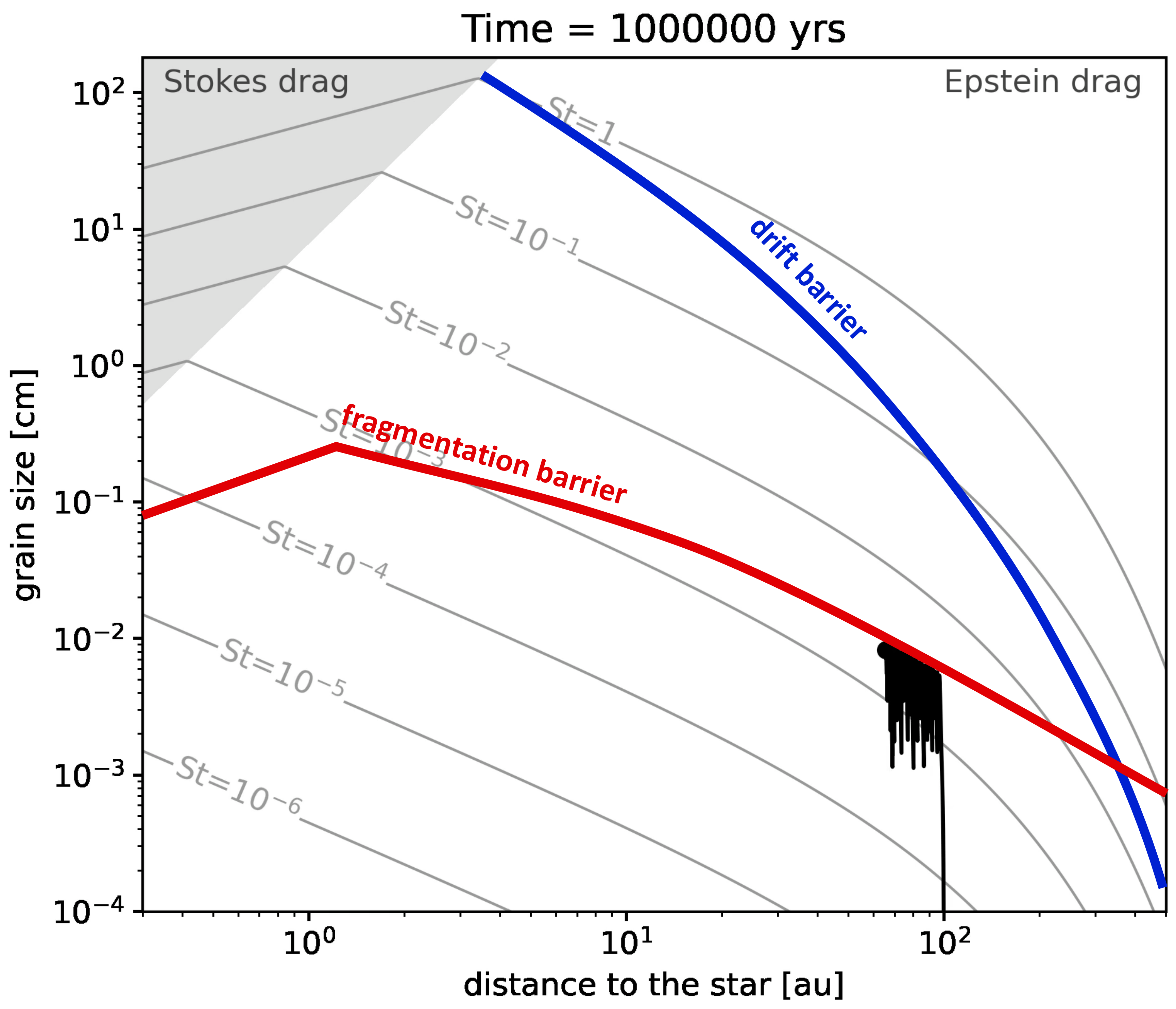
Pebble growth, drift and fragmentation

Drazkowska, …, Lambrechts et al PPVII

Fragmentation barrier: 10 m/s



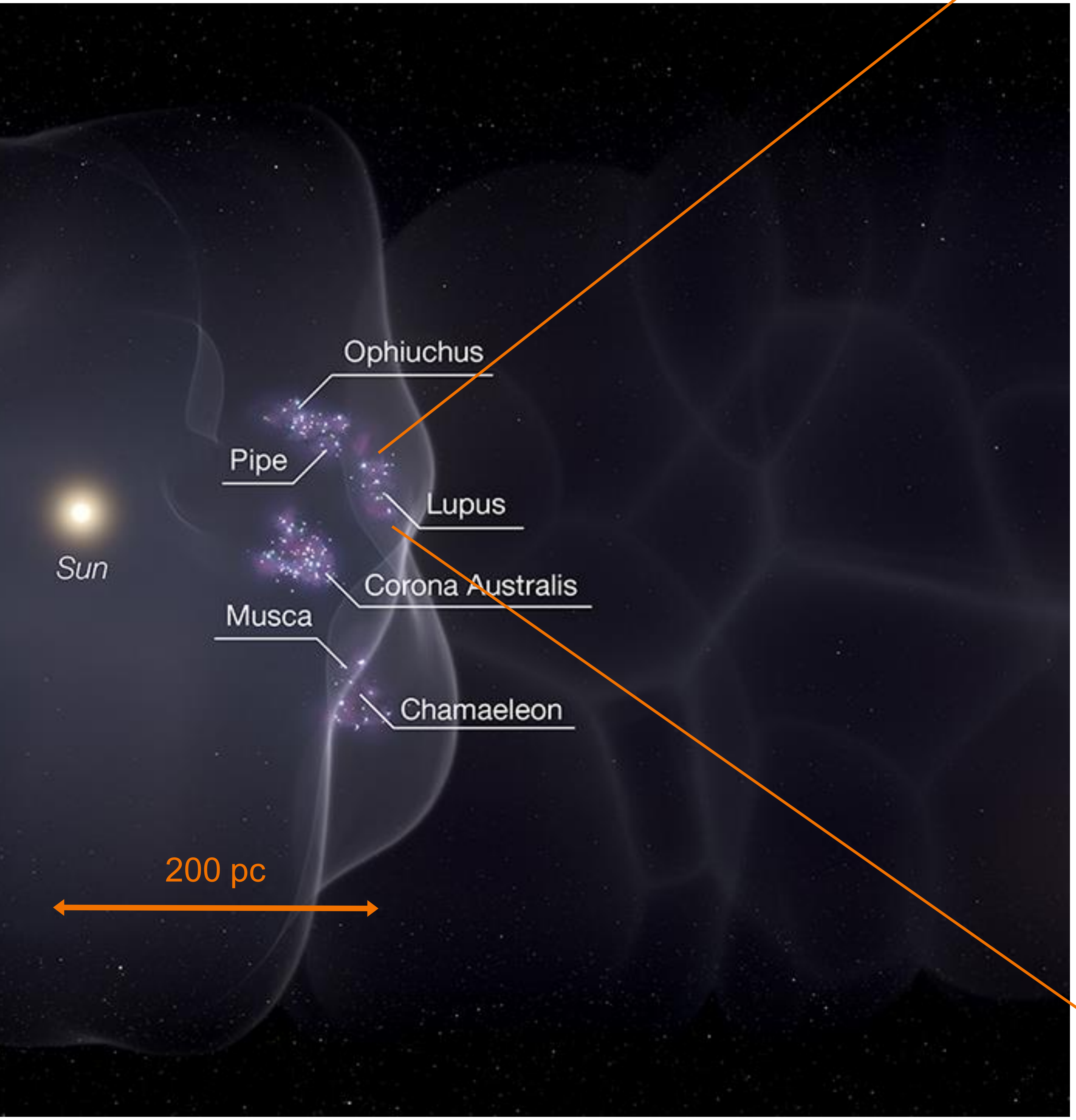
Fragmentation barrier: 1 m/s

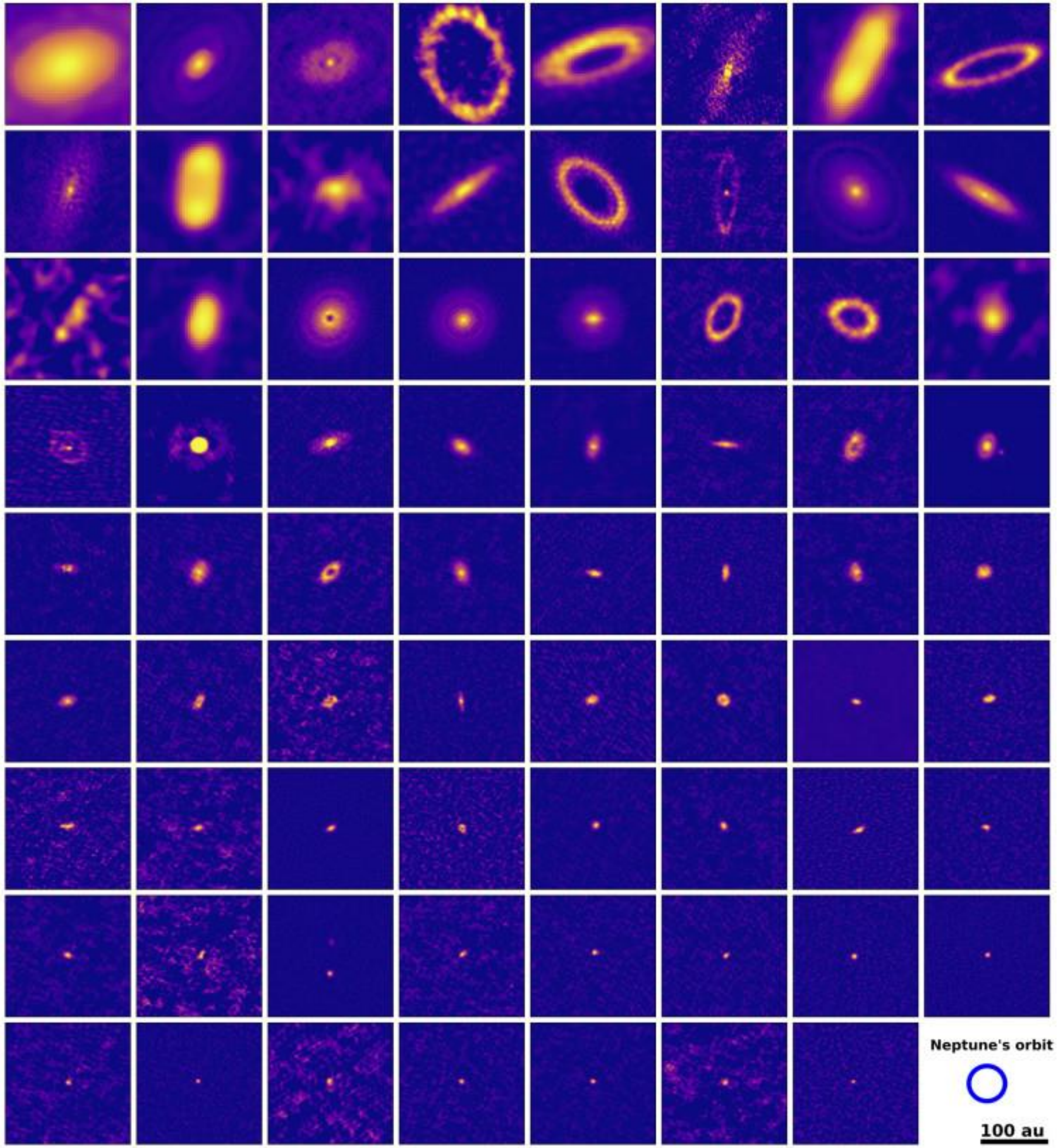


Compact growth: Brauer et al 2007, Zsom et al 2010, Birnstiel et al 2012, Estrada et al 2016, Booth et al 2018
Porous growth: Ormel et al 2007, Okuzumi et al 2012, Krijt et al 2015, Tatsuuma and Kataoka 2021, Kobayashi & Tanaka 2021

Lupus disc statistics (3 Myr)

Guerra-Alvarado,..Lambrechts.. 2025





Lupus disc statistics

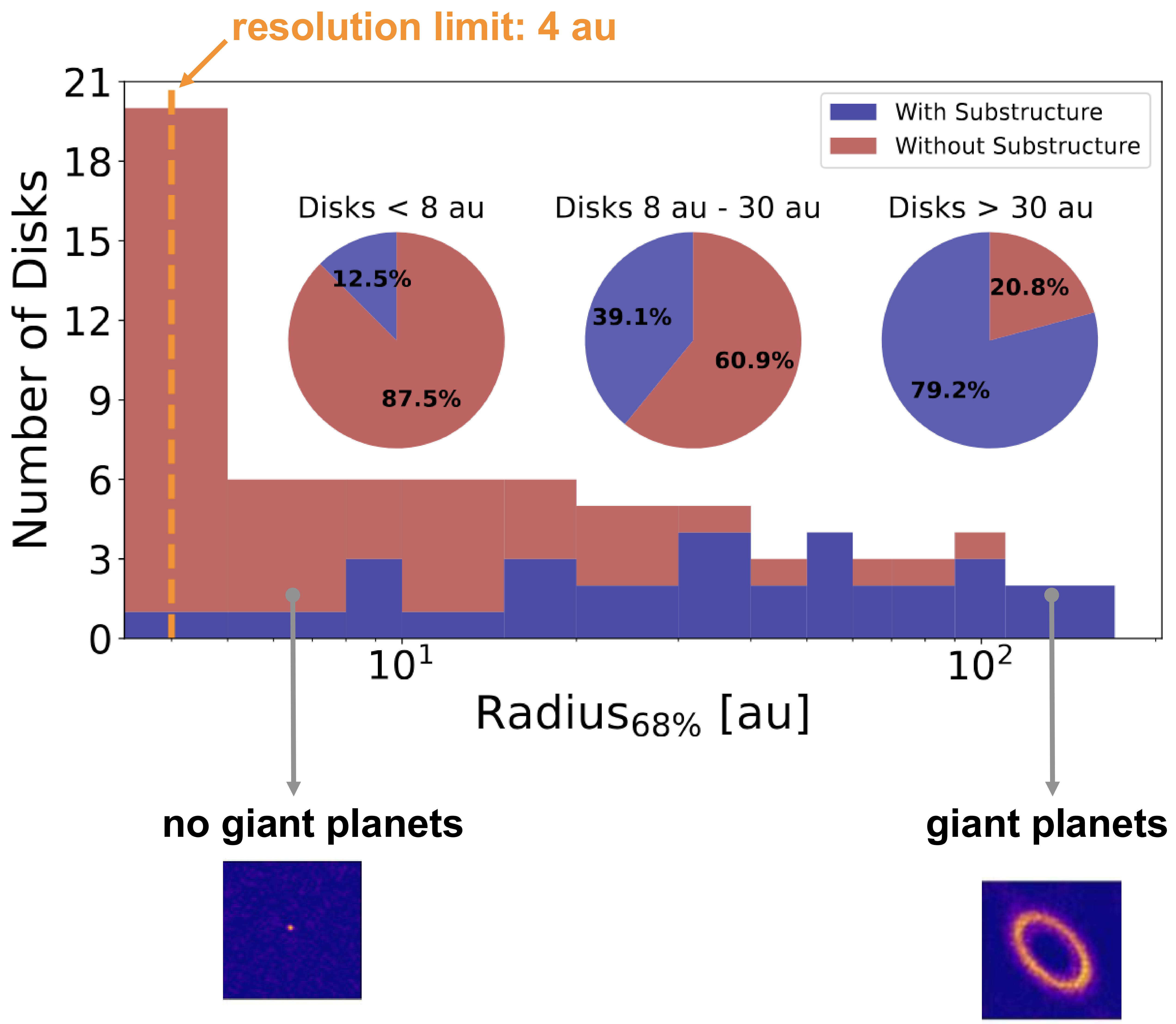
Guerra-Alvarado,..Lambrechts.. 2025

- Interpretation:
  - most discs are drift-dominated
  - large discs (100 au) are prone to giant planet formation
  - gap formation show up as rings and possibly delay of pebble drift

- Caveat:
  - resolution 4 au
  - mainly sub-solar mass stars

  [terming compact discs as drift-dominated is problematic as we do not know the initial disc radius distribution around (low-mass) stars]

- Implication:
  - cold giant planet formation rare (10%, agrees with exoplanet surveys)
  - Solar System originates from a rare large disc



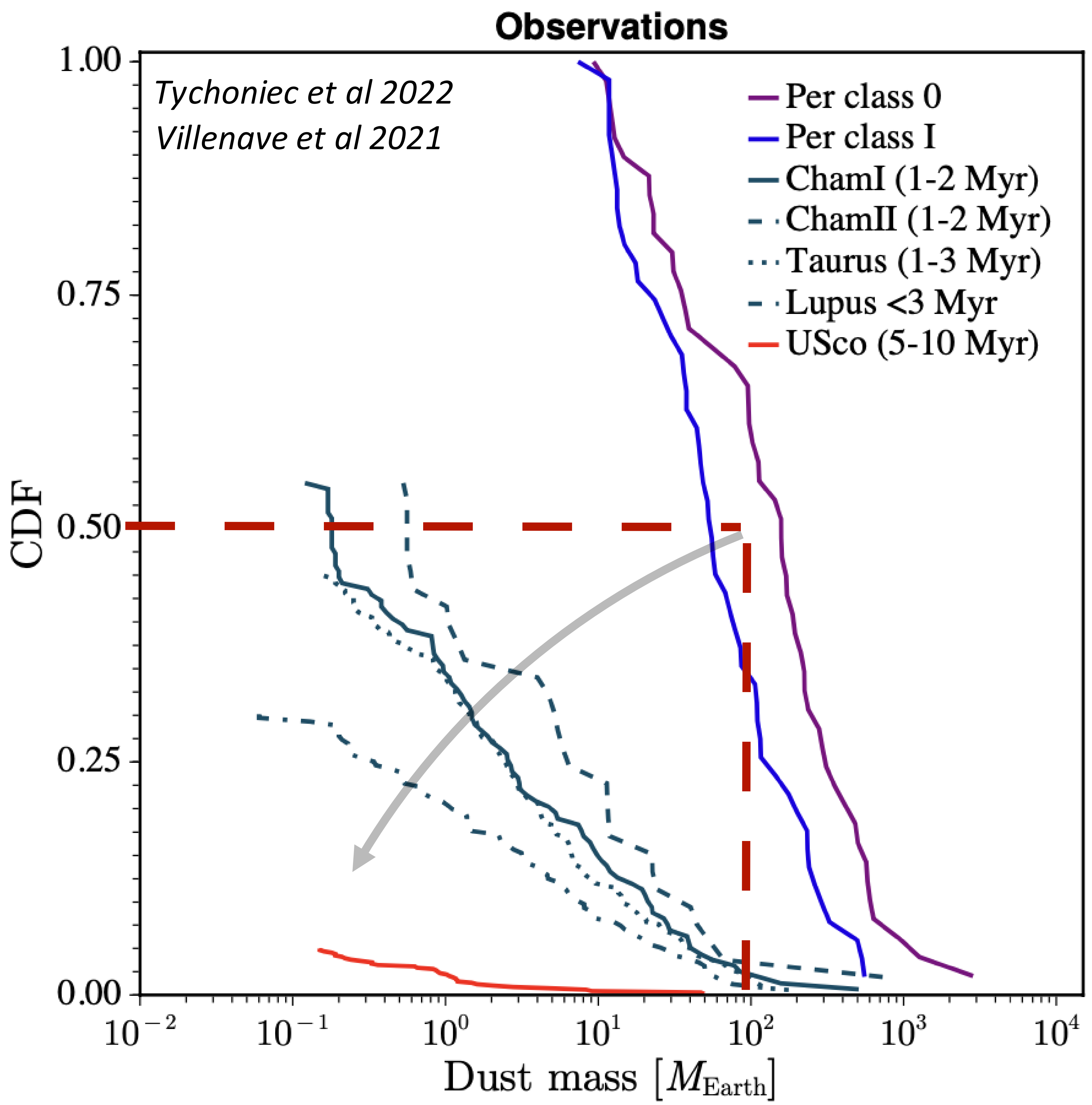
Disc population synthesis

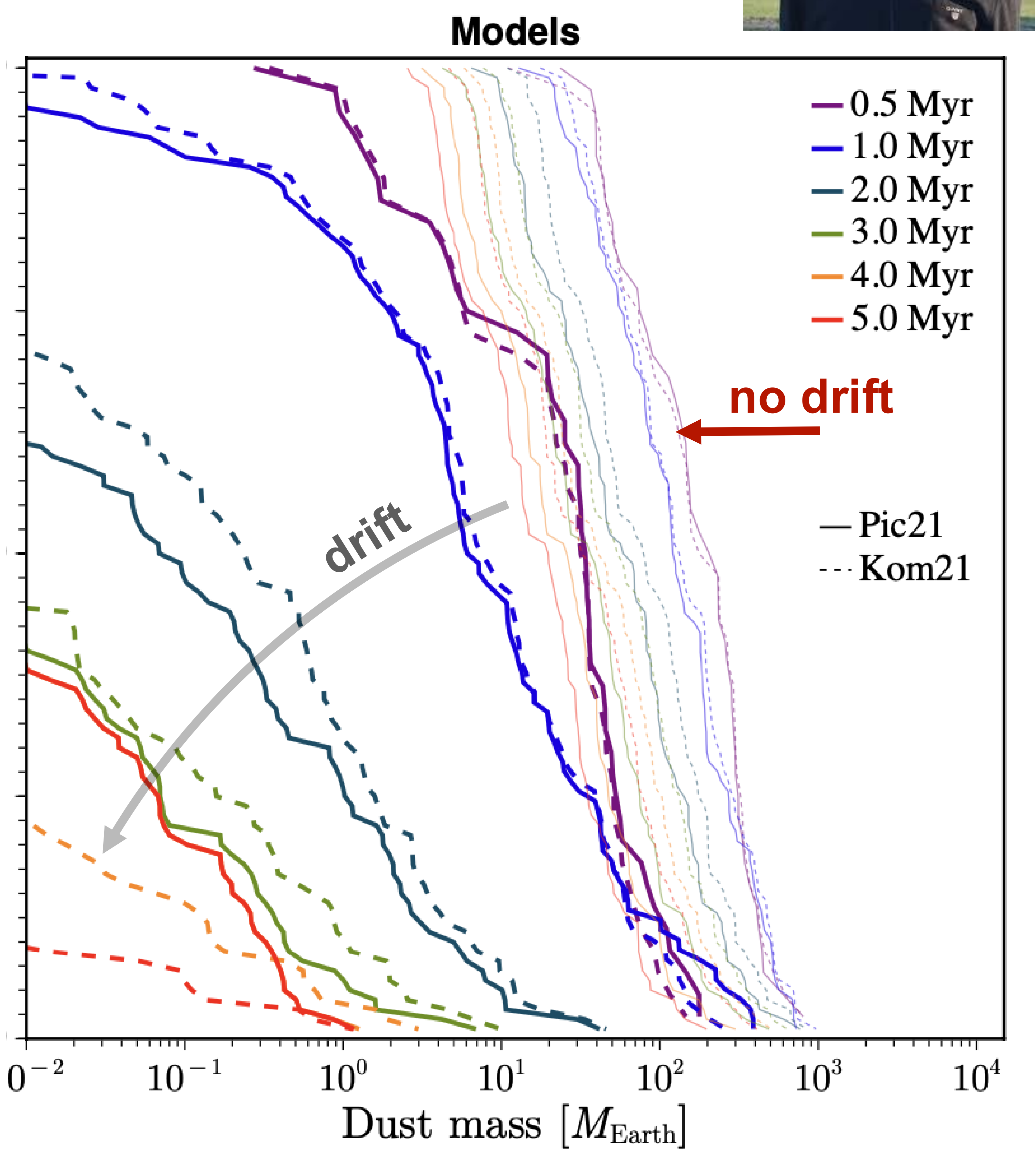
Appelgren, Lambrechts and van der Marel 2023

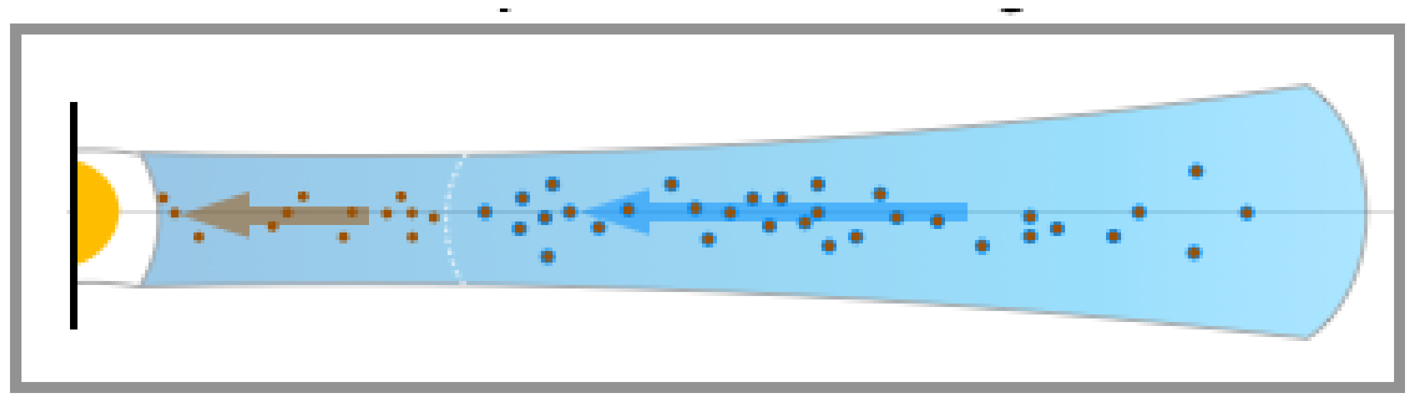
- Disc synthesis shows that the observed dust depletion with time is consistent with the inwards drift of pebbles limited in size by fragmentation
  Appelgren et al 2023

- Pebbles sizes are observed to be below the drift limit, consistent with fragmentation limit
  Jiang et al 2023

- Pebbles are drifting inwards on a Myr timescale, resulting in a radial pebble flux of ~10–100 M_E/Myr for Sun-like stars



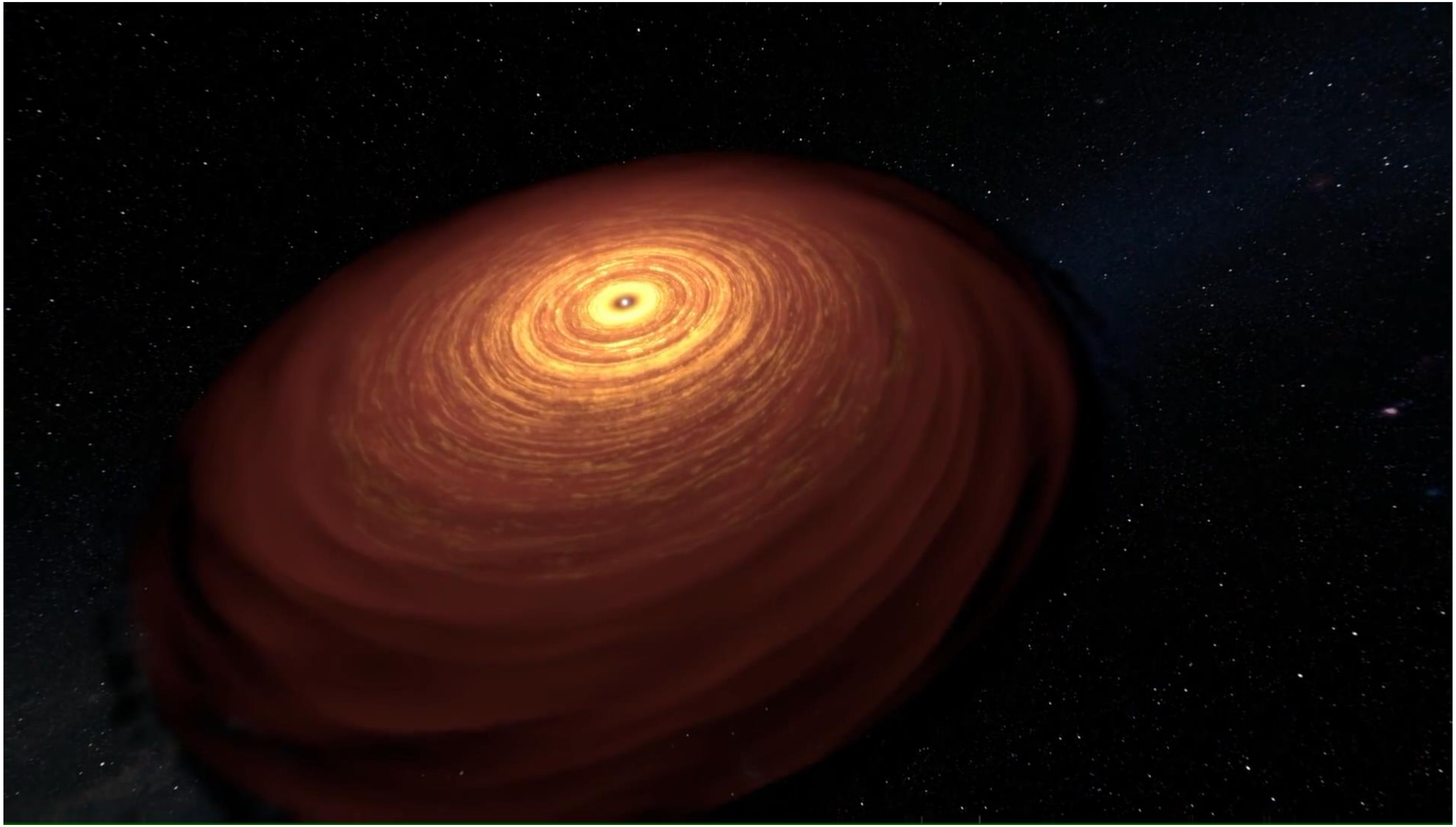




Forward model the evolution of a discs in a star-forming region

stellar initial mass function / observed angular momentum protostellar clouds / viscous disc evolution / photo-evaporation (Sellek et al 2020)/ fragmentation-limited pebbles / pebble drift

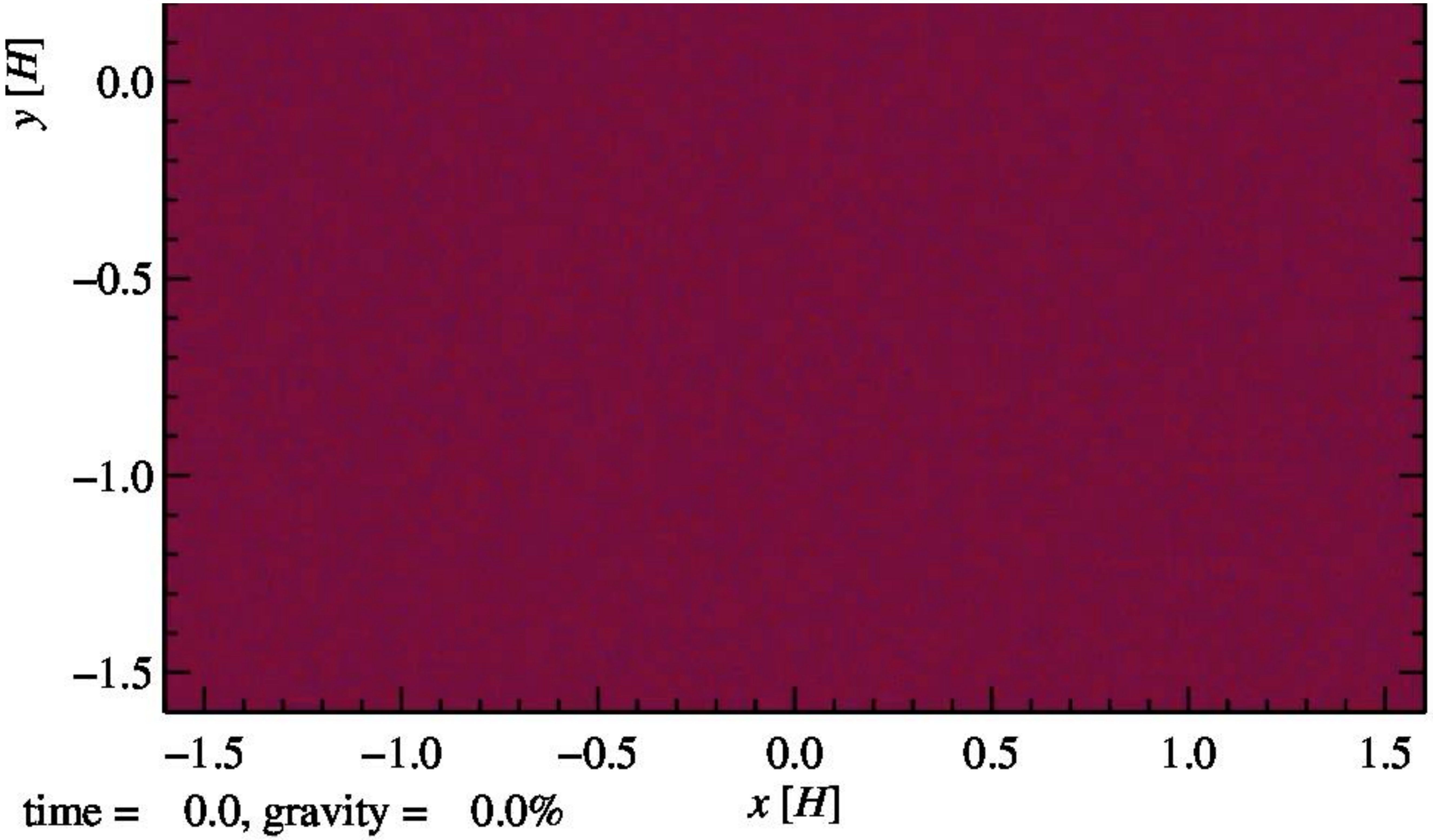
Planetesimal formation



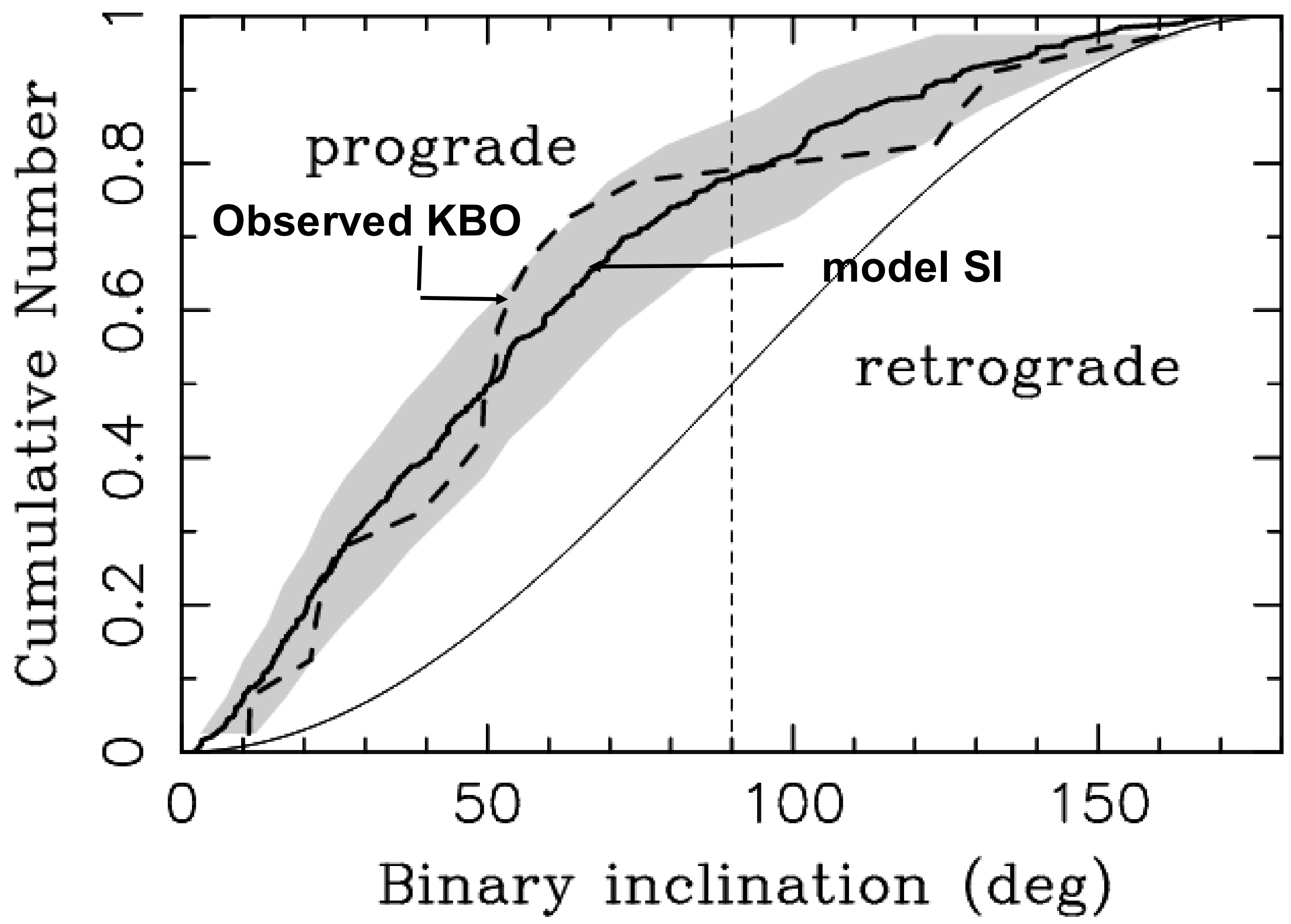
CAS / Zhaohuan Zhu /Jake Simon

Streaming instability

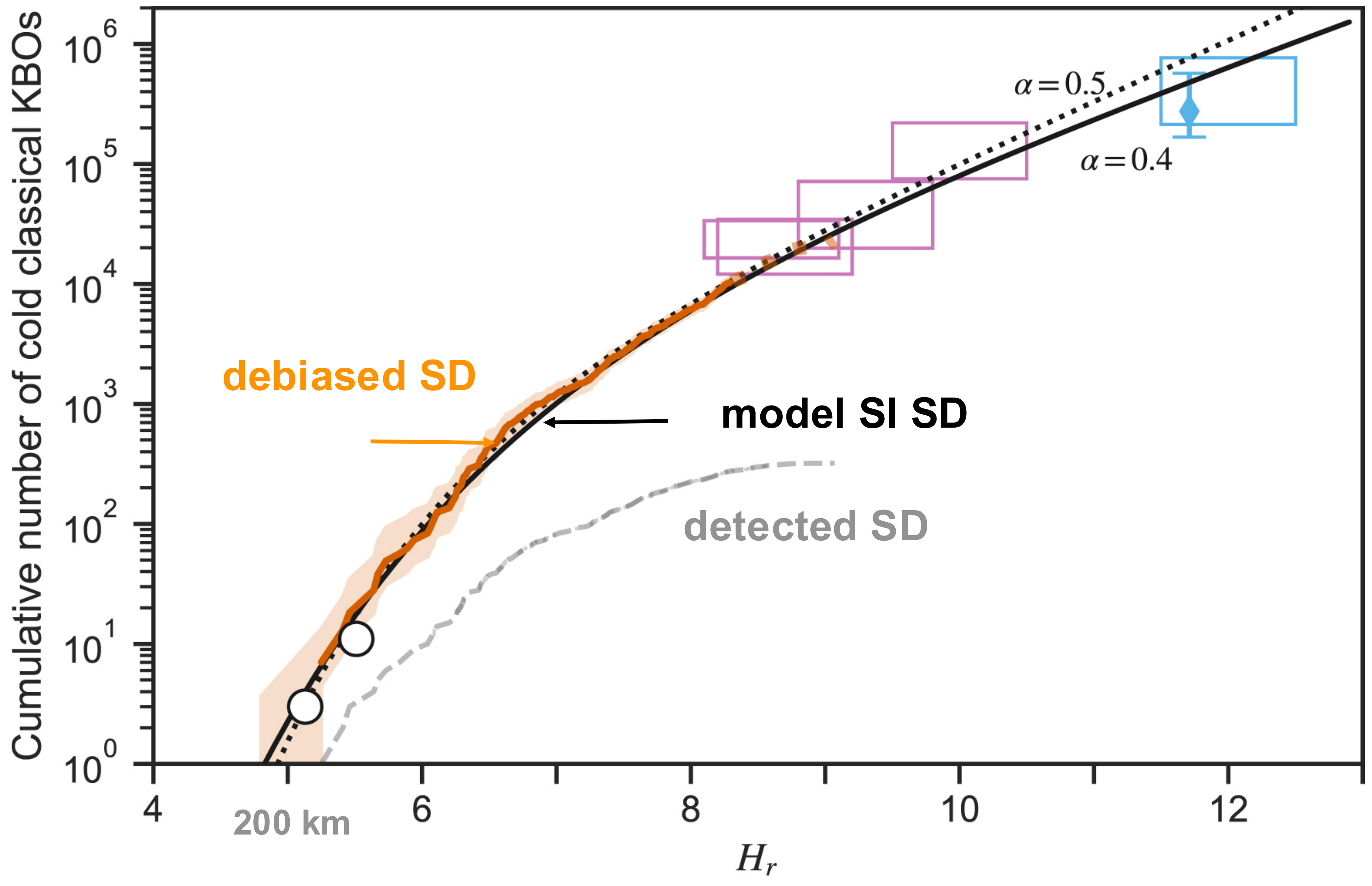
Schäfer et al 2025



Nesvorny et al 2019

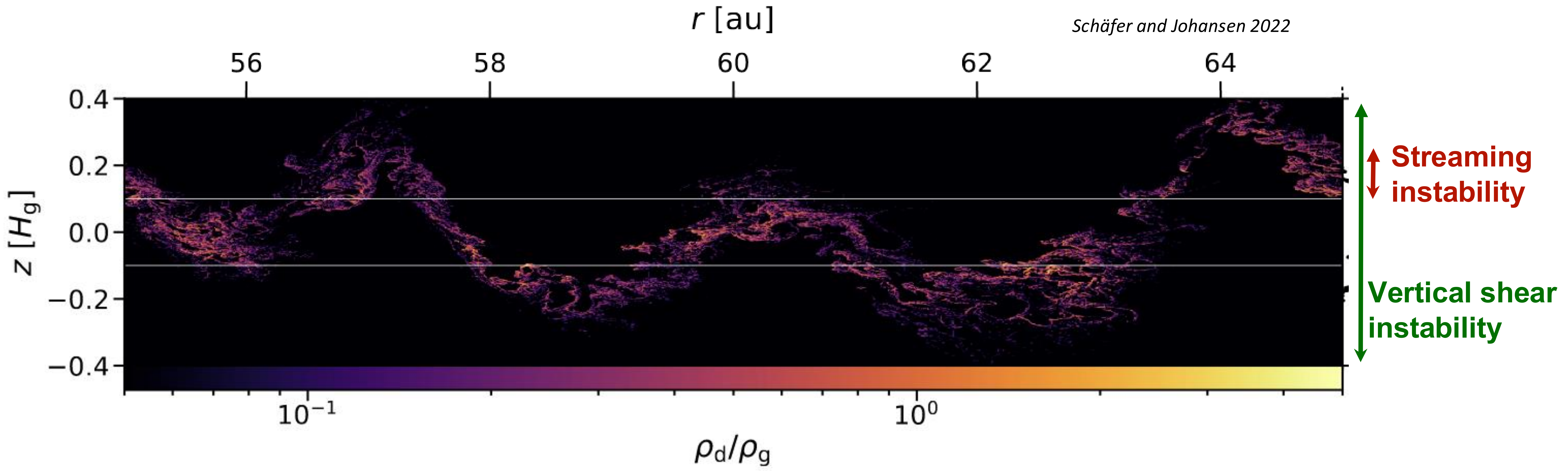


OSSOS survey cold KBOs, Kavelaars et al 2021



- Gravitational collapse of streaming-instability-pebble swarms (*Johansen et al 2015, Simon et al 2016, Schafer et al 2017, Li et al 2019*) reproduce:
  - the preferred prograde KBO binaries
  - the Asteroid and KBO minor body size distribution

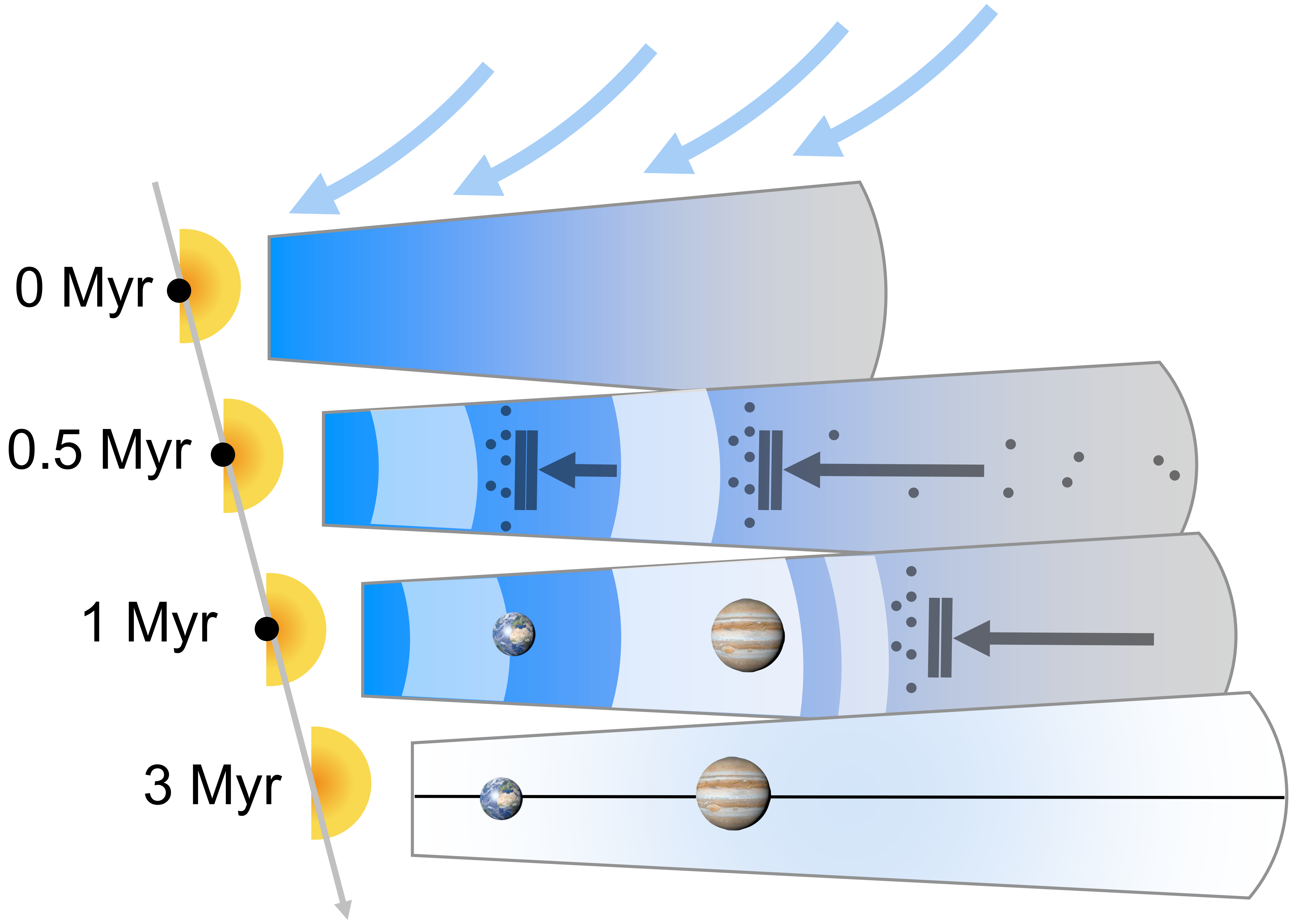
Conditions for planetesimal formation remain poorly understood



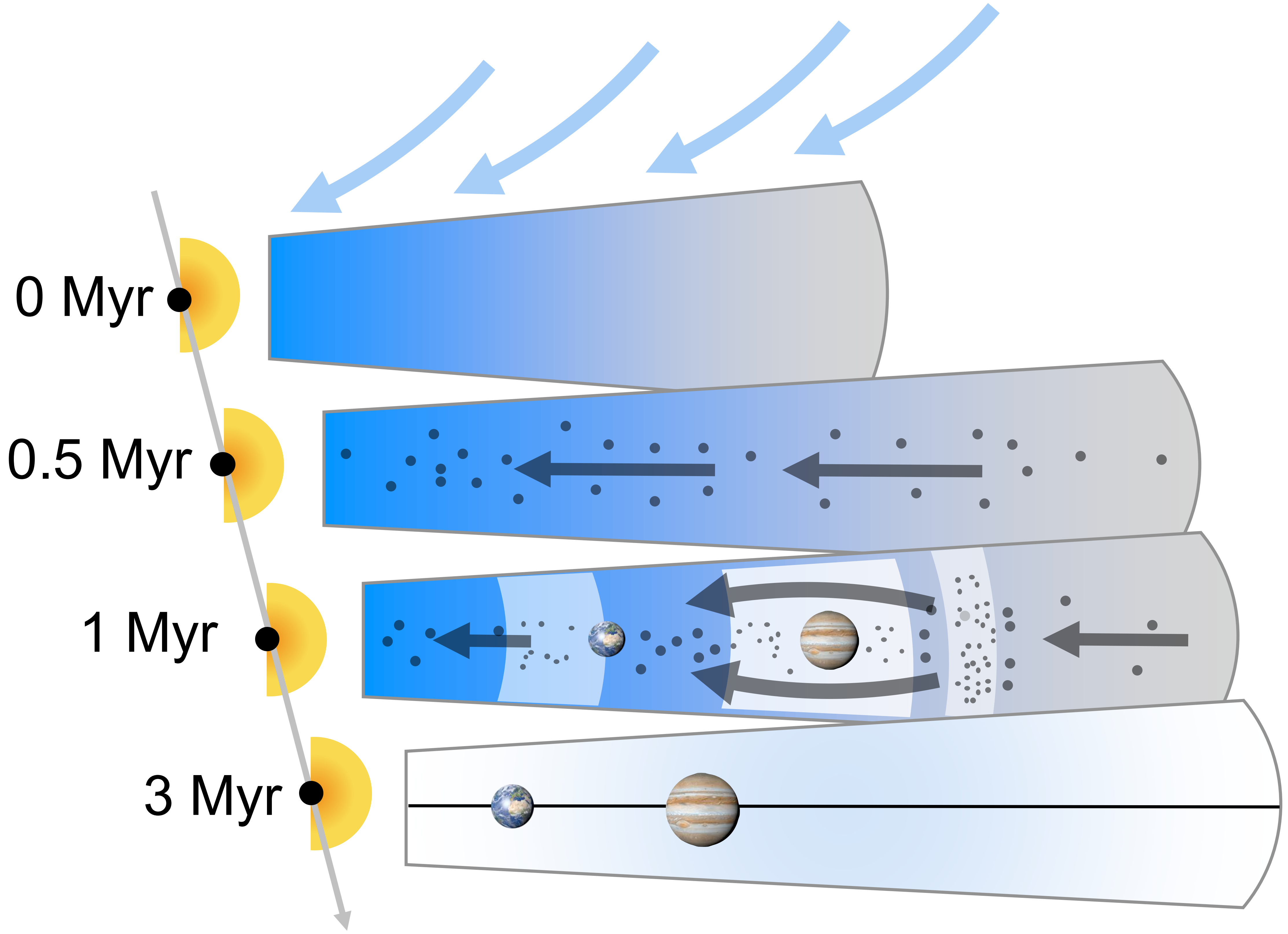
- Where, when, and with which efficiency planetesimals form remains unsolved
- Planetesimal formation requires: pebbles (St>10^{-3}) and some form of pre-clumping on small scales (<H) towards unity dust-to-gas ratio *Carrera et al 2015*
- Does not strictly require strong settling and/or radial concentration in pressure bumps (dust rings)

Two developing views on planet formation

View 1: efficient planetesimal formation
pebble drift inhibited by early-formed pressure bumps



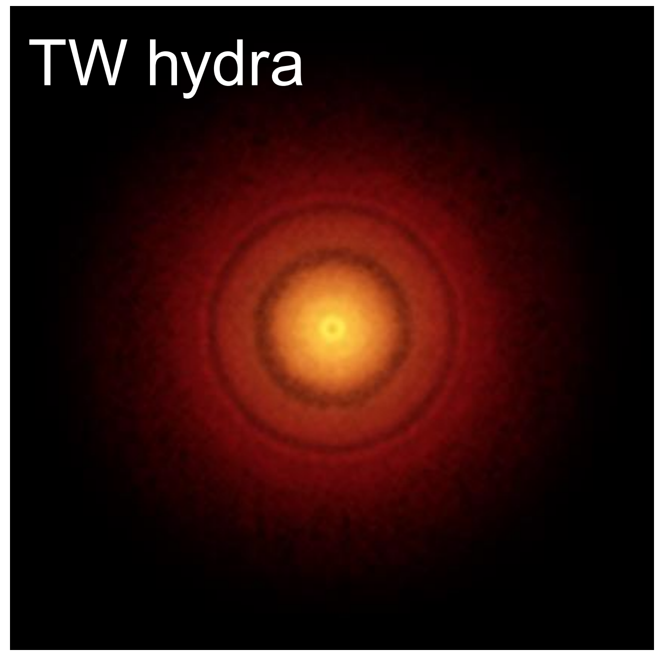
View 2: inefficient planetesimal formation
pebble drift throughout the disc



Growth of planetary embryos

1. Dust growth until fragmentation-limited pebbles

~100 AU

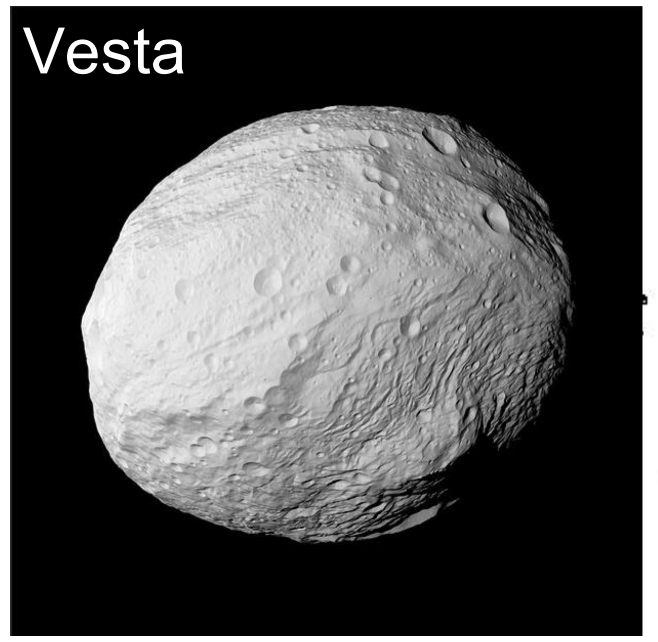


Andrews et al 2016

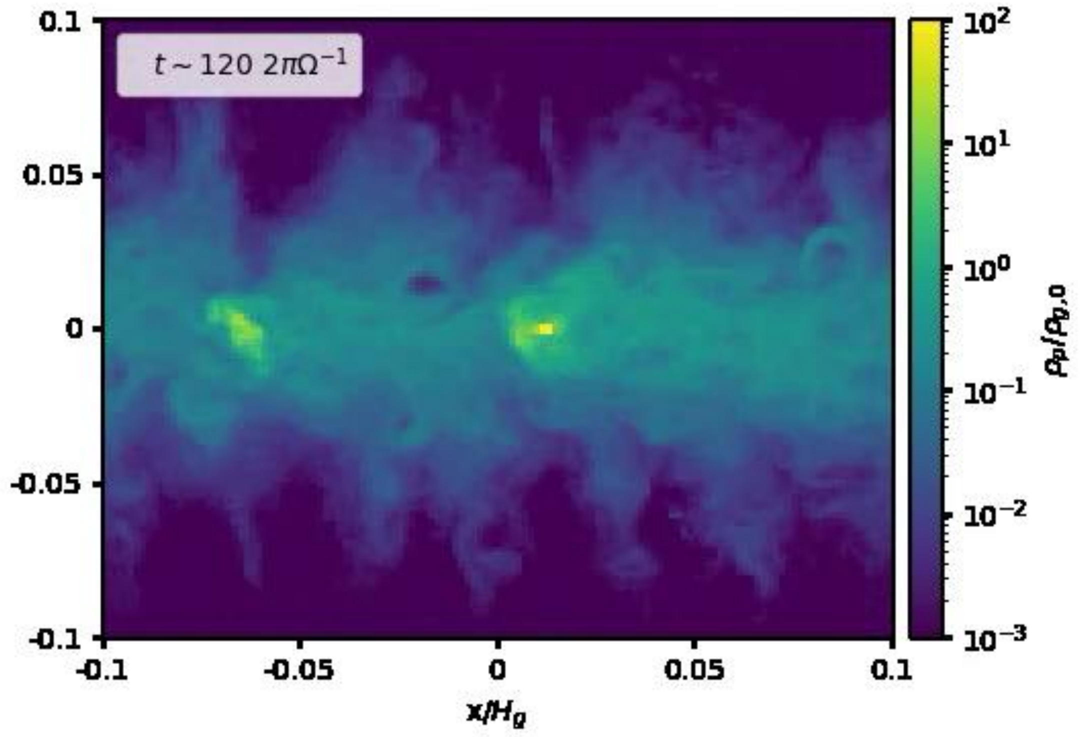
ESO animation

2. Pebbles can self-concentrate to form planetesimals via streaming instabilities

~100 km



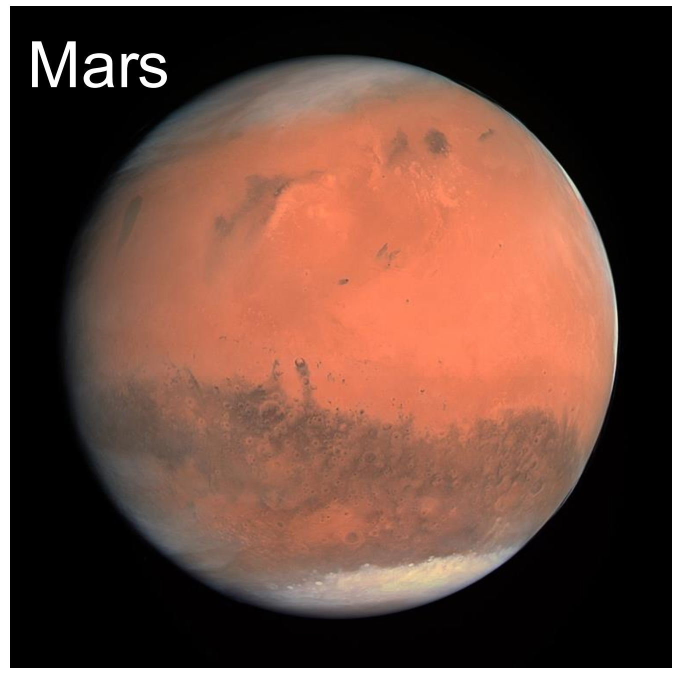
ESO



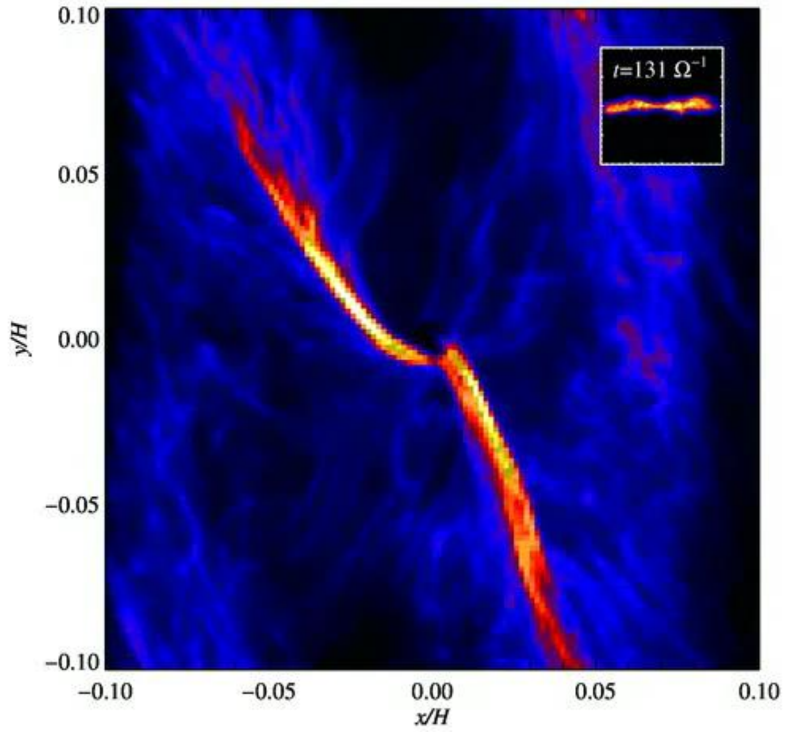
Schaffer, Johansen, Lambrechts 2021

3. Planetesimals and protoplanets continue to grow by collisions and by sweeping up pebbles

~1000 km



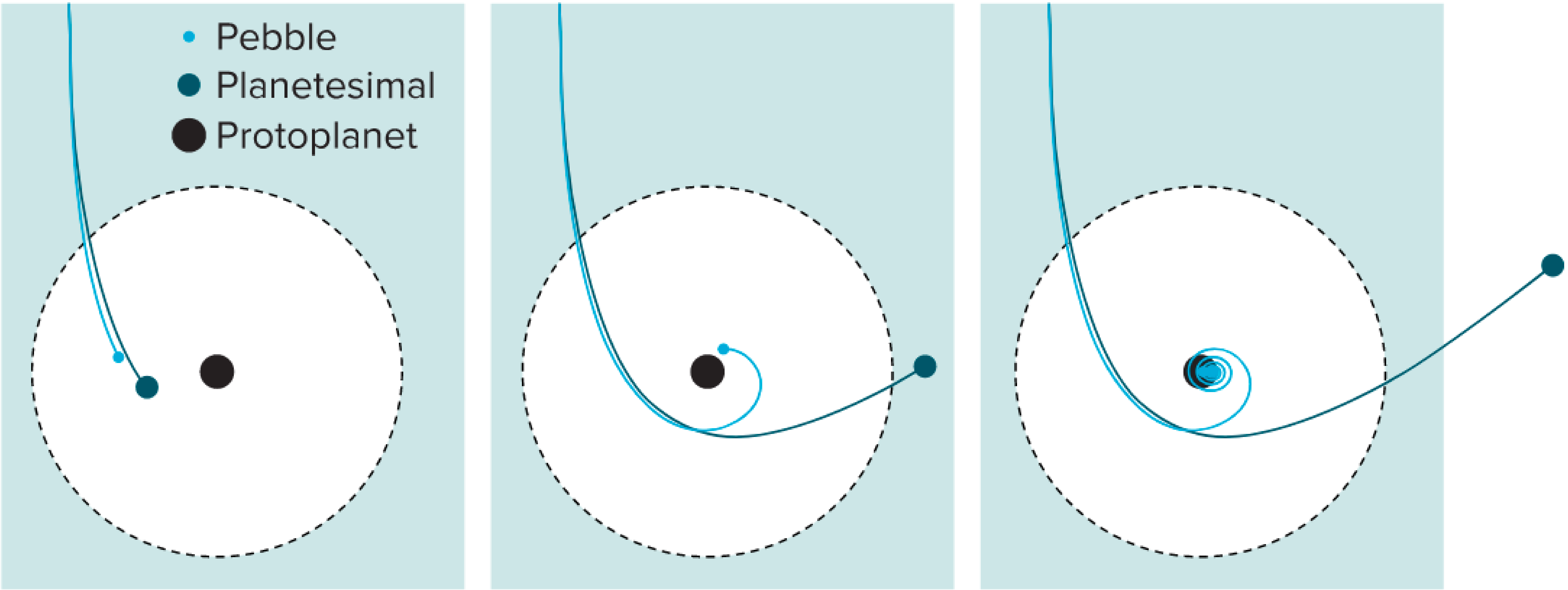
ESA



Lambrechts and Johansen 2012

Pebble accretion

Adapted by Knowable magazine from Lambrechts and Johansen 2012



- Pebbles are accreted with a large cross section because of gas drag

Pebble accretion and planetesimal accretion

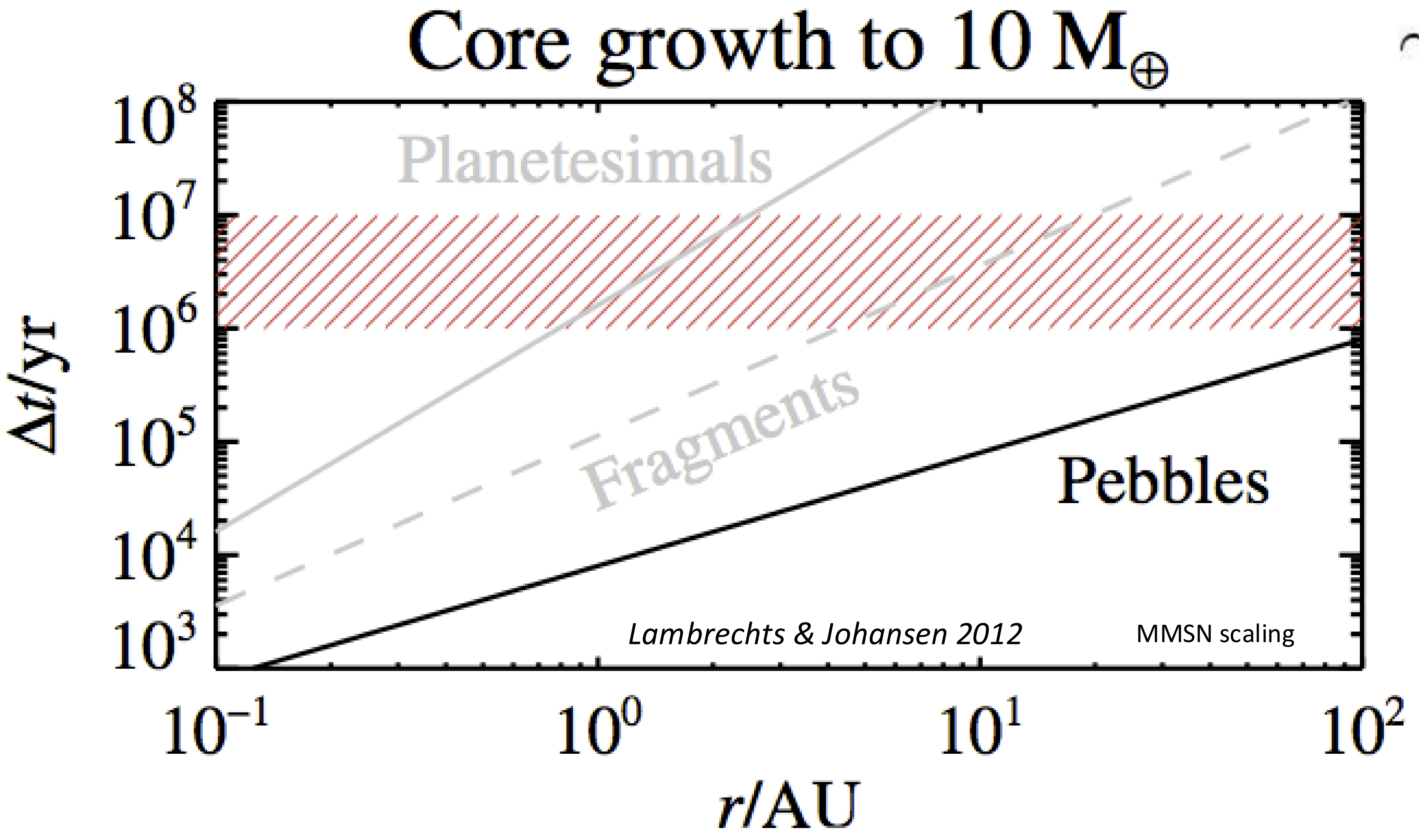
pebbles

$$\dot{M}_{\rm peb} \sim r_{\rm H} v_{\rm H} \Sigma_{\rm peb}$$

planetesimals

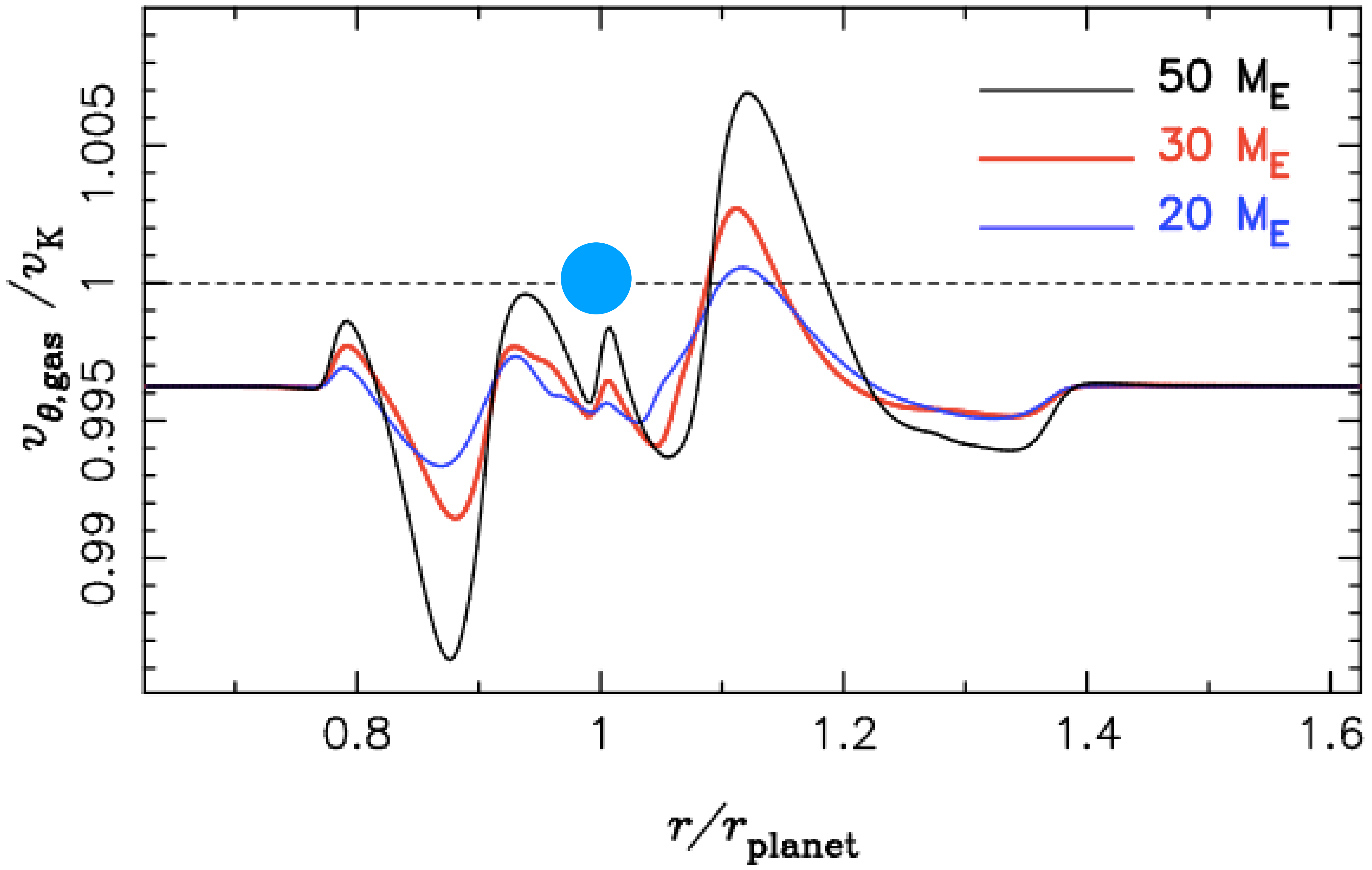
$$\dot{M}_{\rm plan} \sim \alpha^2 r_{\rm H} v_{\rm H} \Sigma_{\rm plan}$$

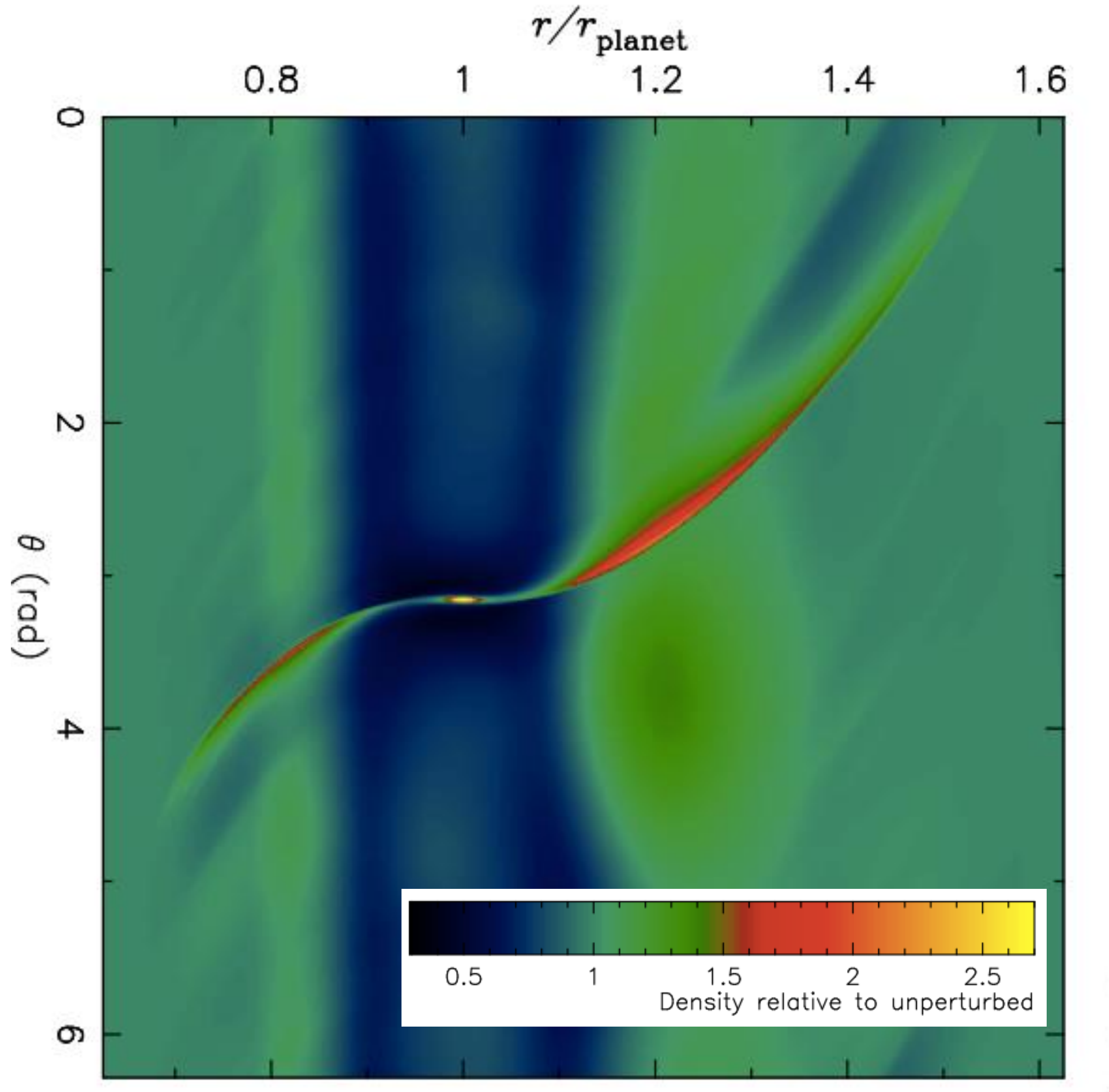
$$\alpha = r_{\rm acc}/r_H \sim 10^{-2}(r/5{\rm AU})^{-1/2}$$



Pebble isolation mass

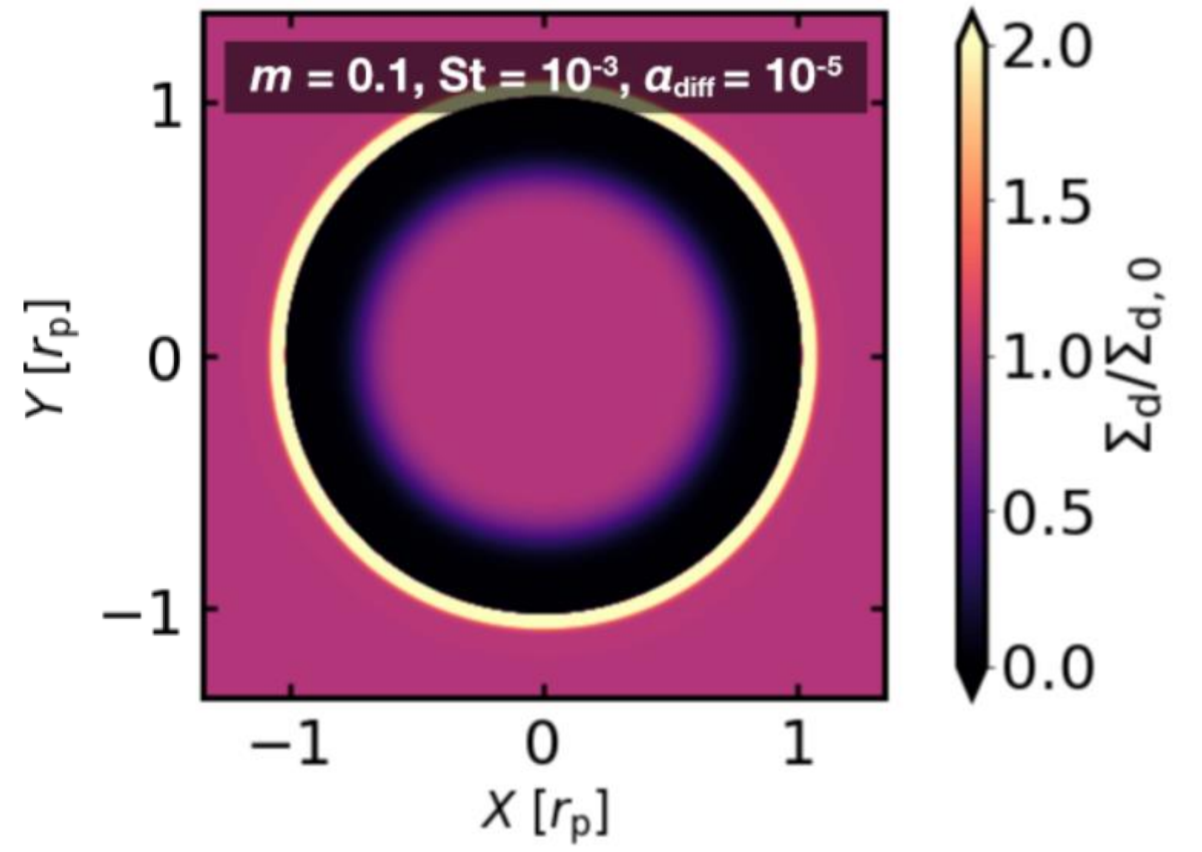
Lambrechts et al 2014





~minimal mass to make dust ring

Kuwahara et al 2024

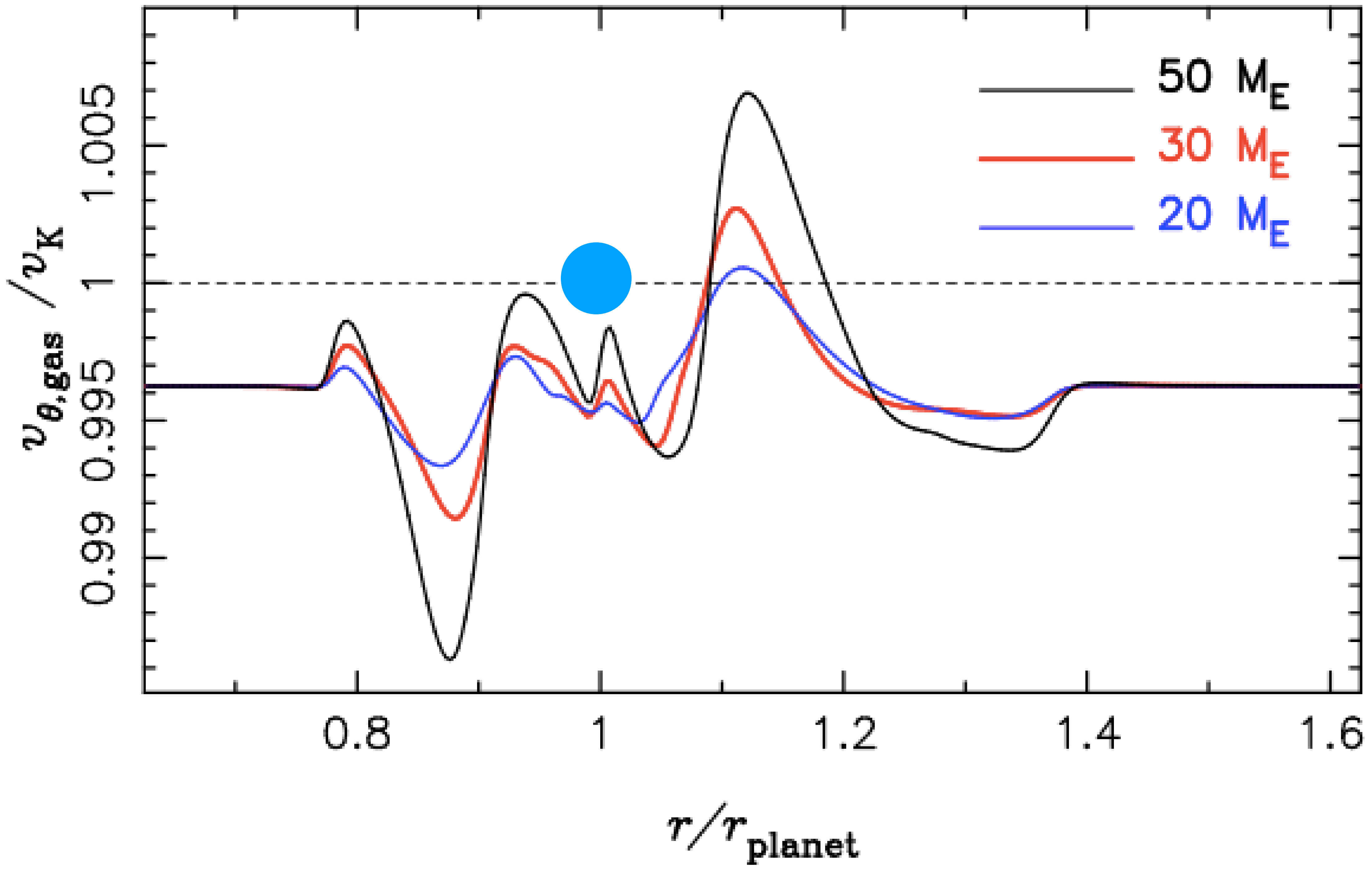


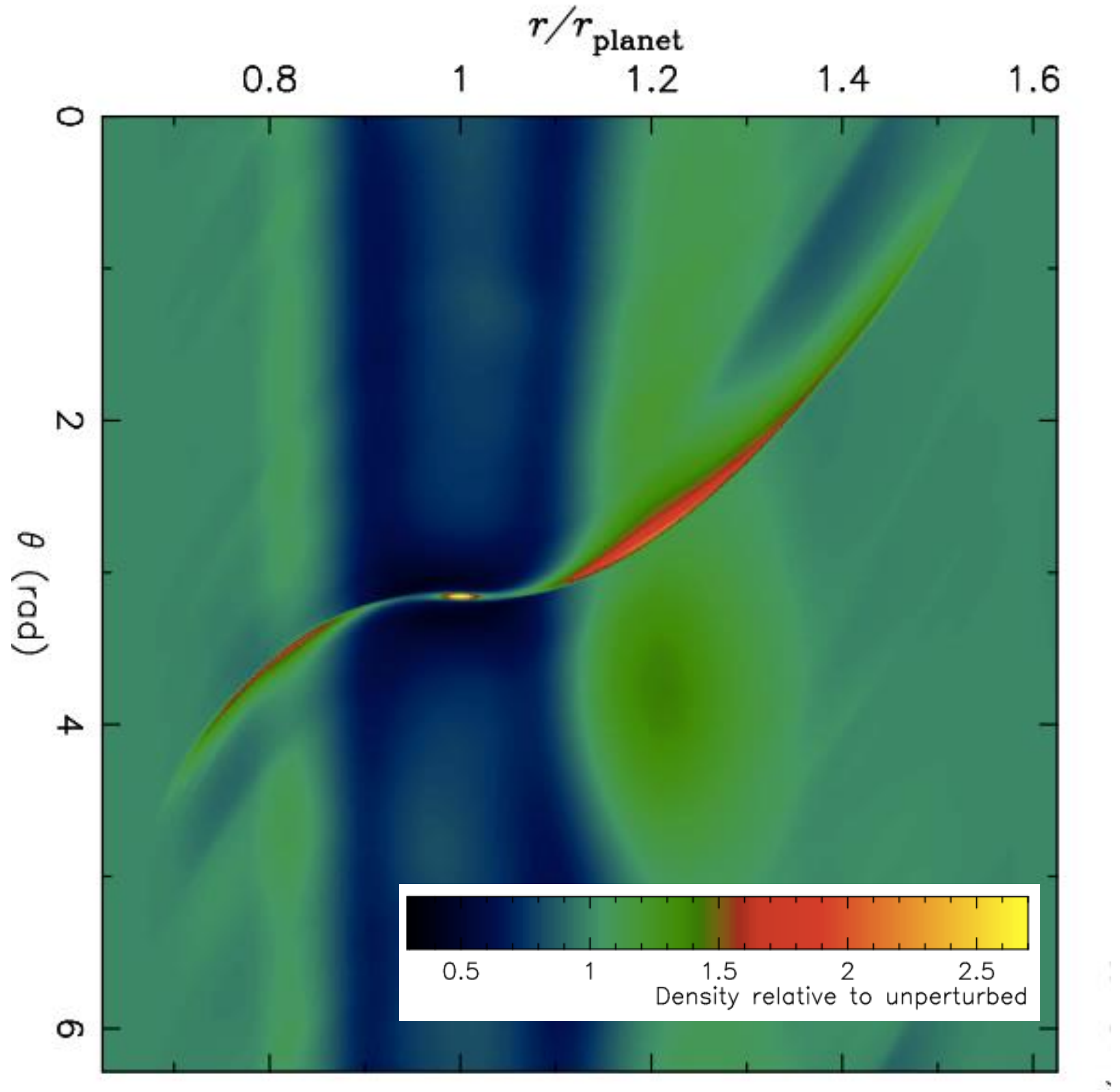
- Gravity of a sufficiently large core perturbs gas disc
- Creates a pressure bump (shallow gap) that traps particles outside the accretion radius, thereby halting solid accretion

Lambrechts et al 2014, Bitsch et al 2018, Ataiee et al 2018, Zormpas et al. 2020, …

Pebble isolation mass

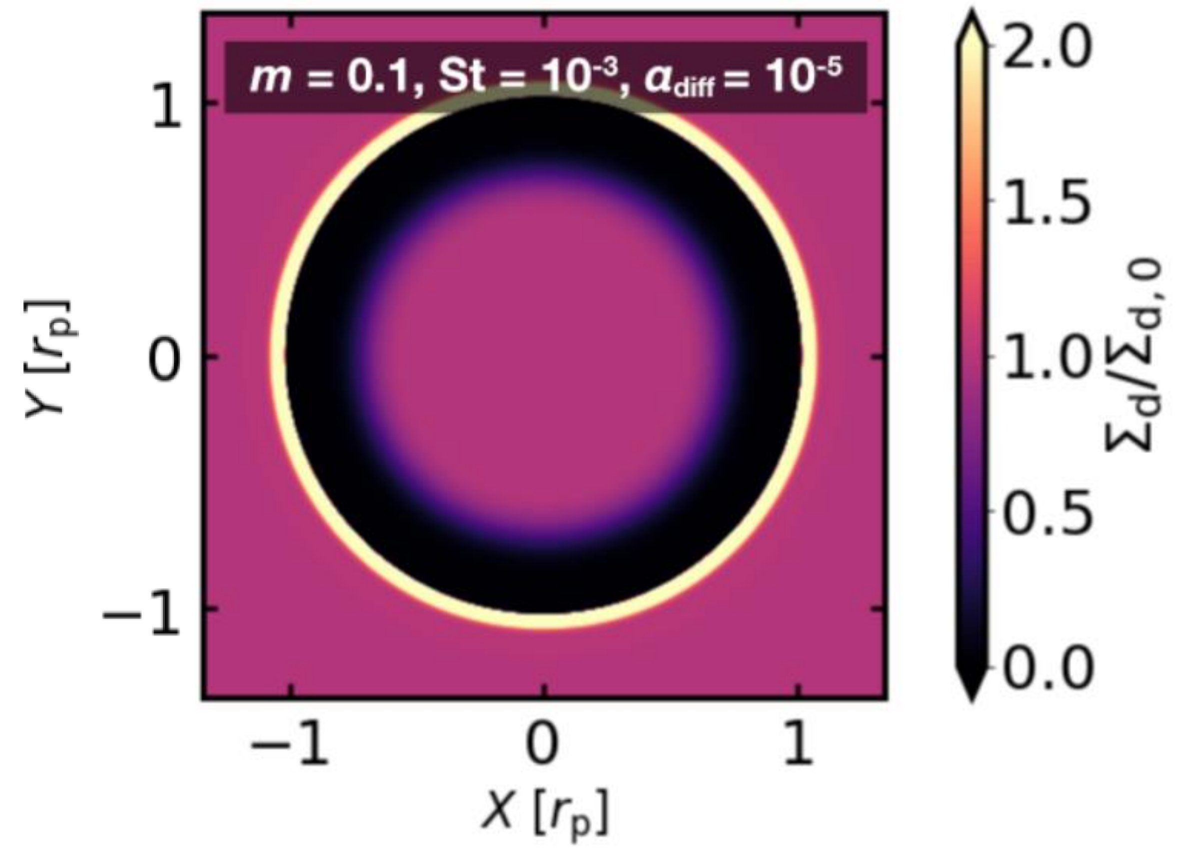
Lambrechts et al 2014





~minimal mass to make dust ring

Kuwahara et al 2024

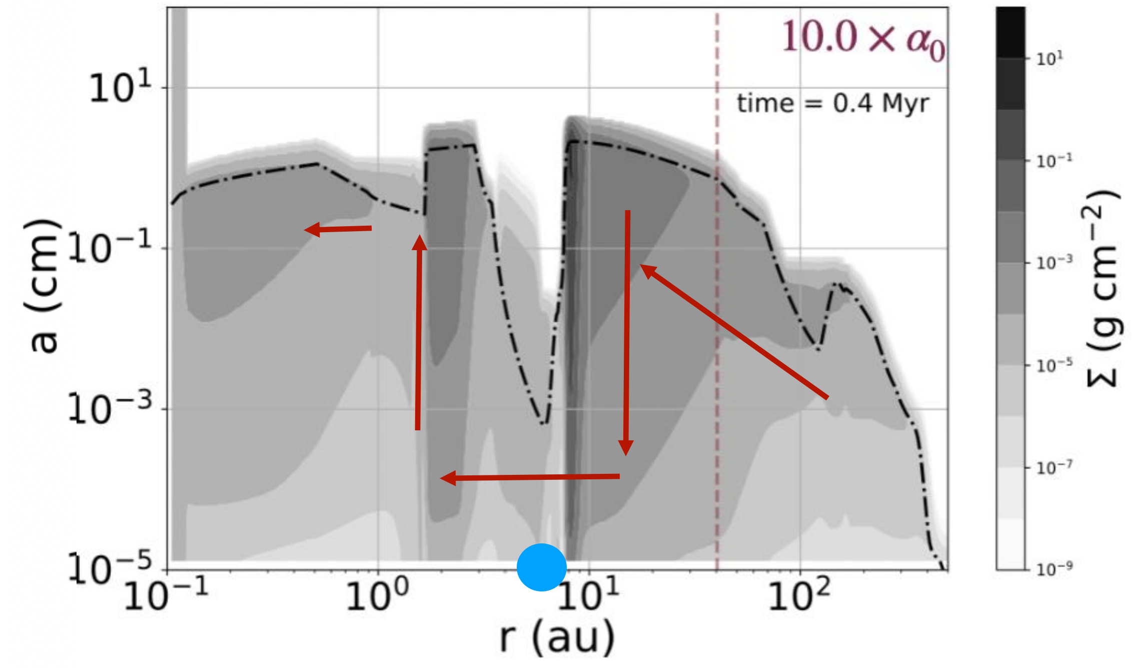


Two implications:

(1) Isolation mass triggers gas accretion

(2) Halts/ reduces the flow of pebbles to inner embryos

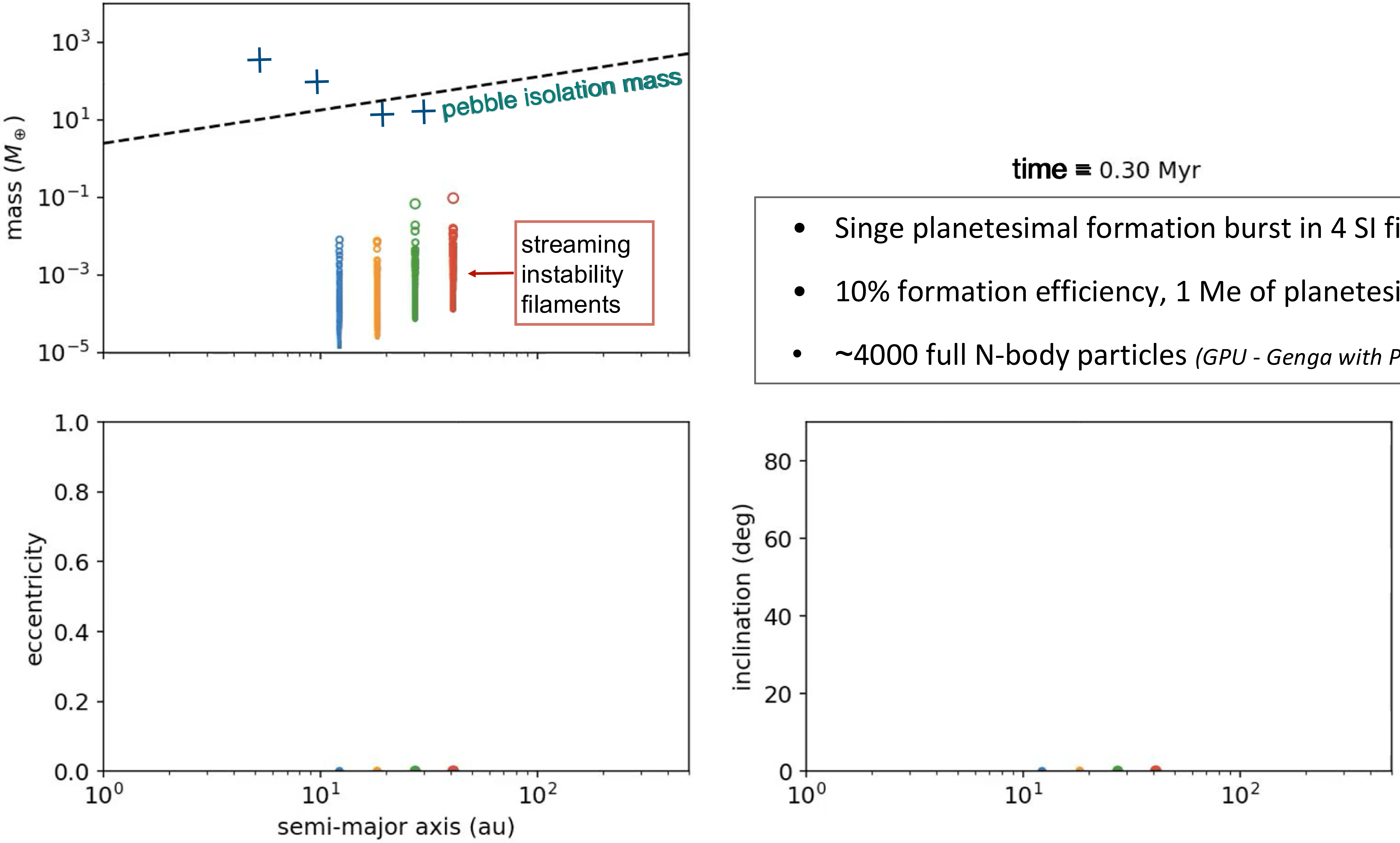
Kalyaan et al 2023



- Blocking pebble flow requires:
  - no fragmentation (no bouncing)
  - no diffusion
  - no *in*wards gas midplane flow
- Jupiter is no barrier for pebbles
  1D: *Pinilla+12,Liu+22, Stammler +23, Kalyaan+23, …*
  Hydro: Zhu+12, +14, Weber+18, Drążkowska et al 2019, Bi+ 21, Binkert+21, Huang+25, …

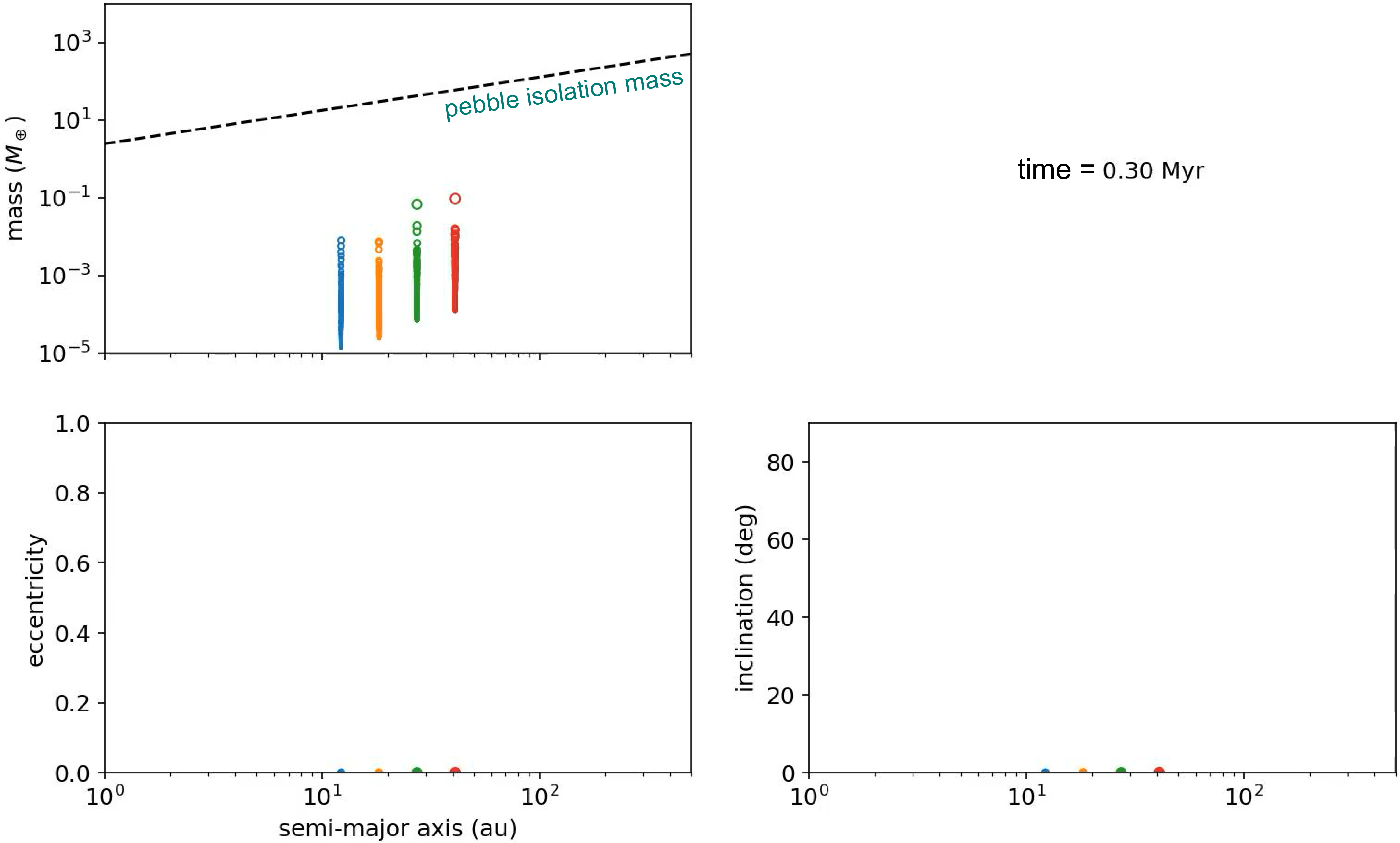
Giant planet formation - from planetesimal to planet

Sebastian Lorek

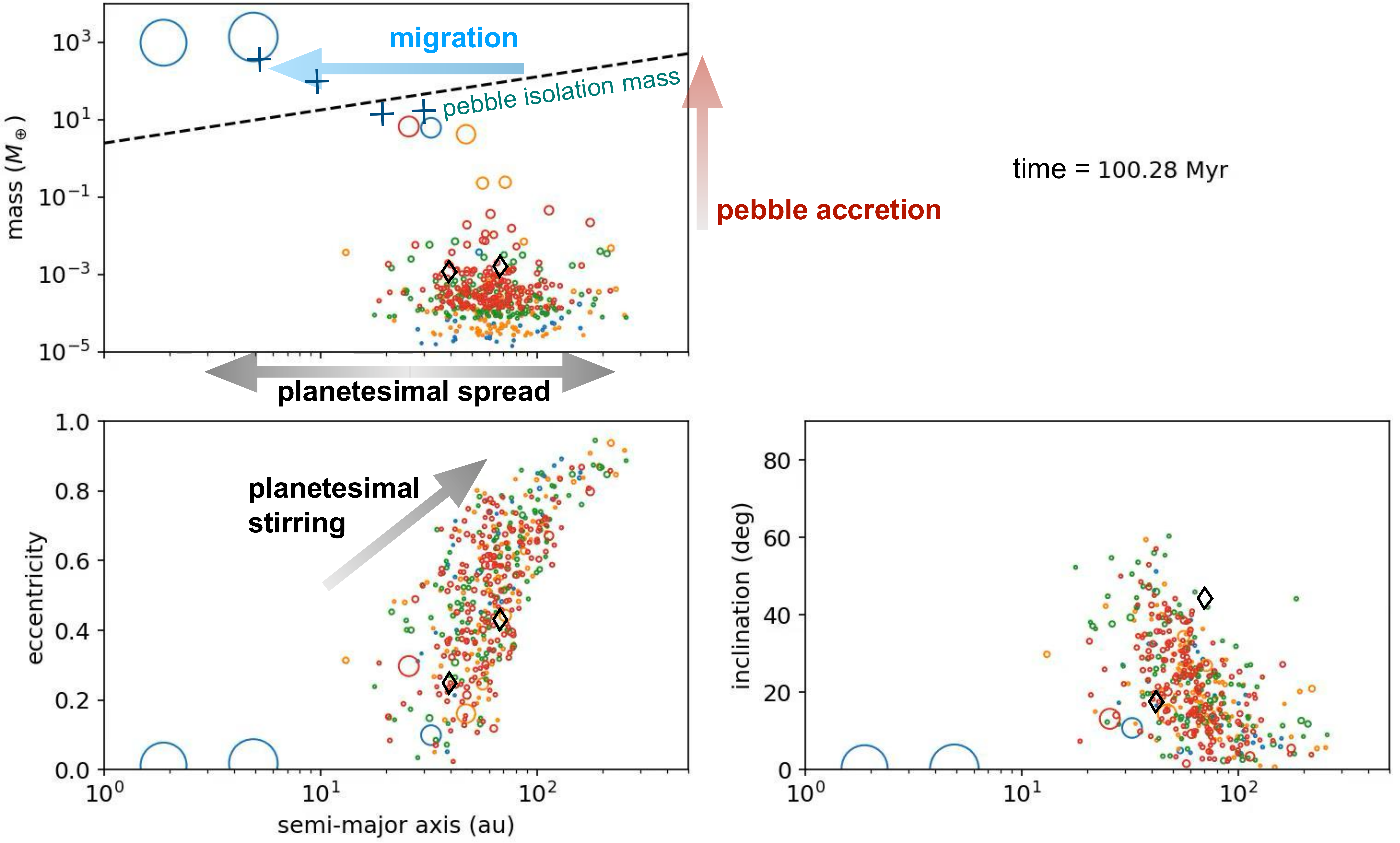


- Singe planetesimal formation burst in 4 SI filaments
- 10% formation efficiency, 1 Me of planetesimals
- ~4000 full N-body particles *(GPU - Genga with PA module)*

Giant planet formation - from planetesimal to planet

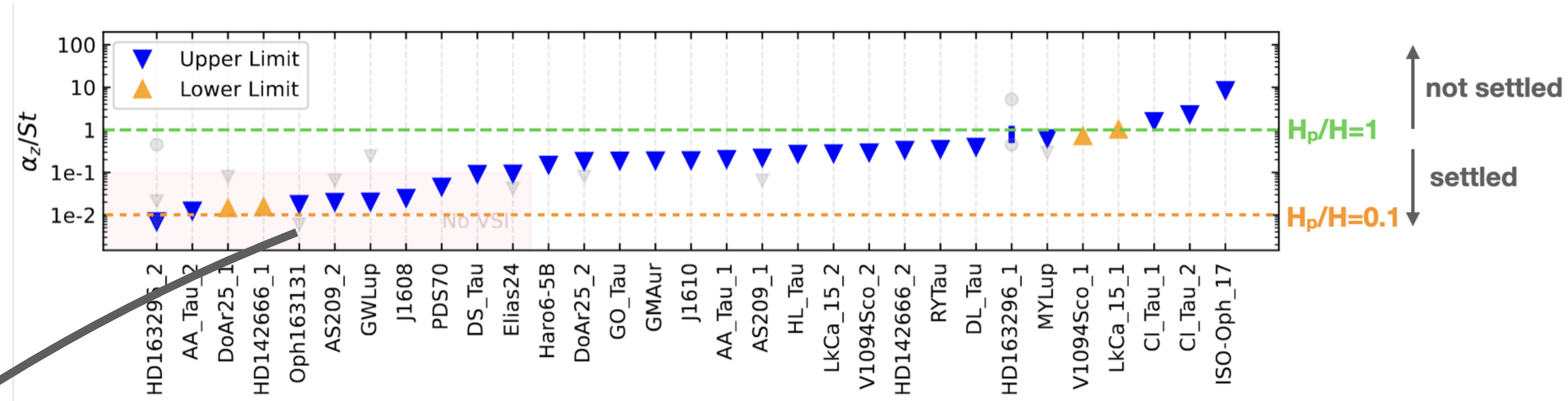


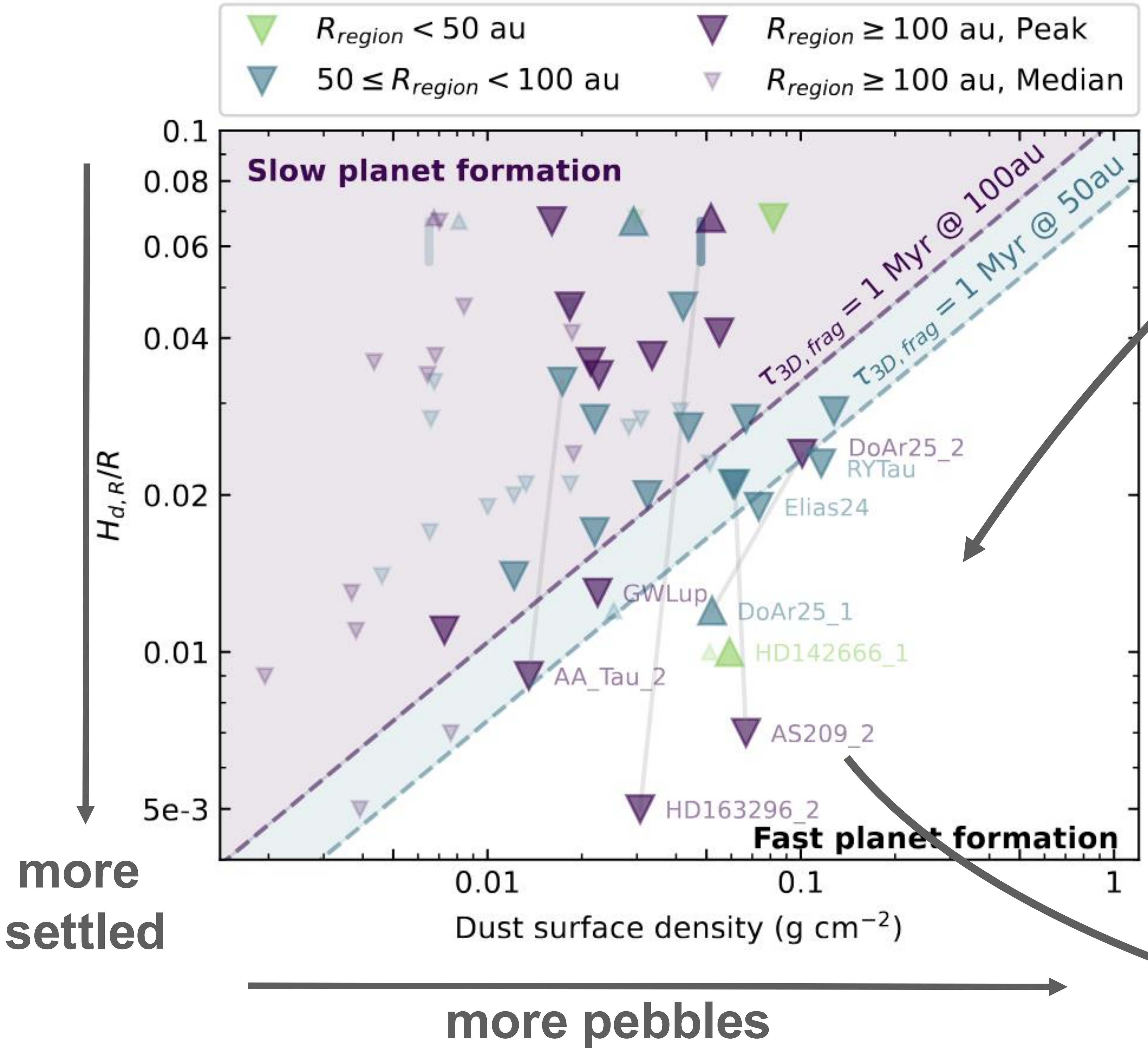
Giant planet formation - from planetesimal to planet



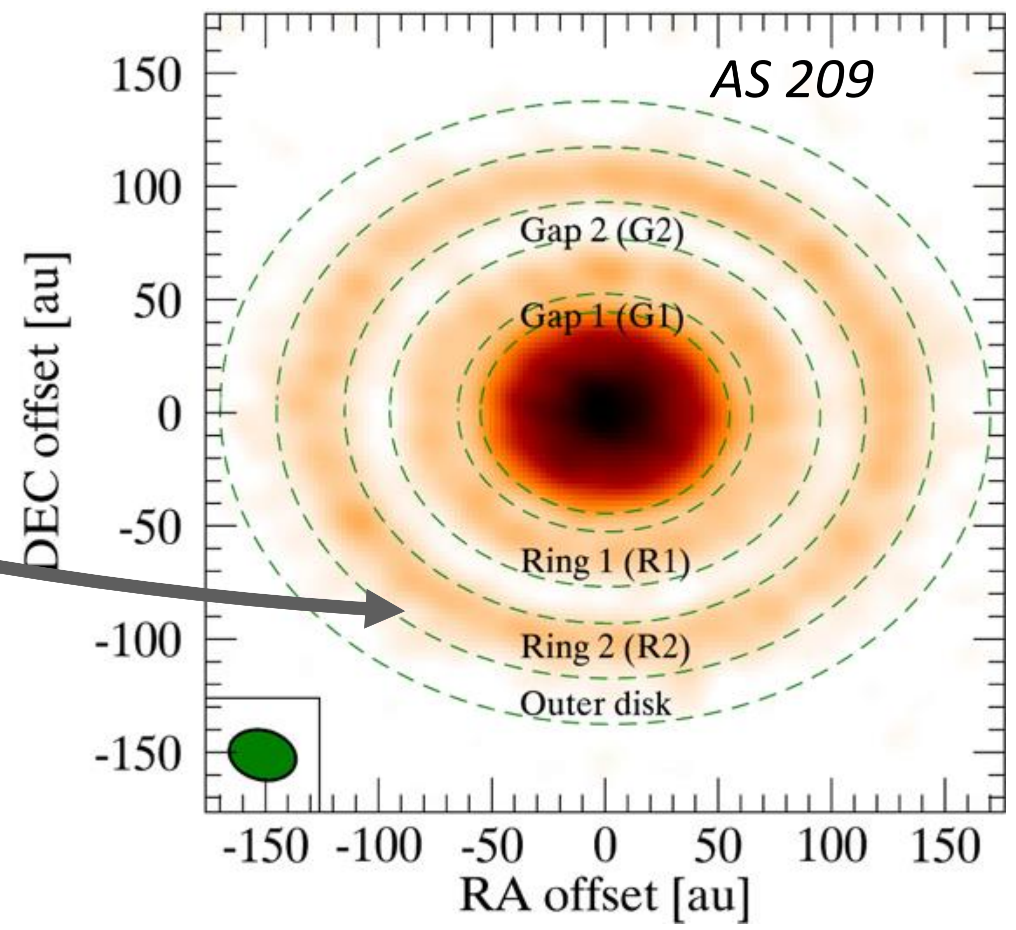
Rings as planet factories

Villenave, Rosotti, Lambrechts, Ziampras et al 2025





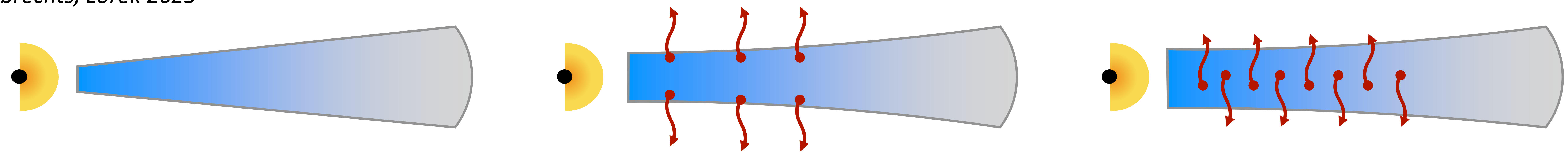
- Wide-orbit planet formation with pebble accretion in discs with both
  — low pebble scale height (pebbles in disc mid-lane)
  — high pebble surface density (high abundance of pebbles)



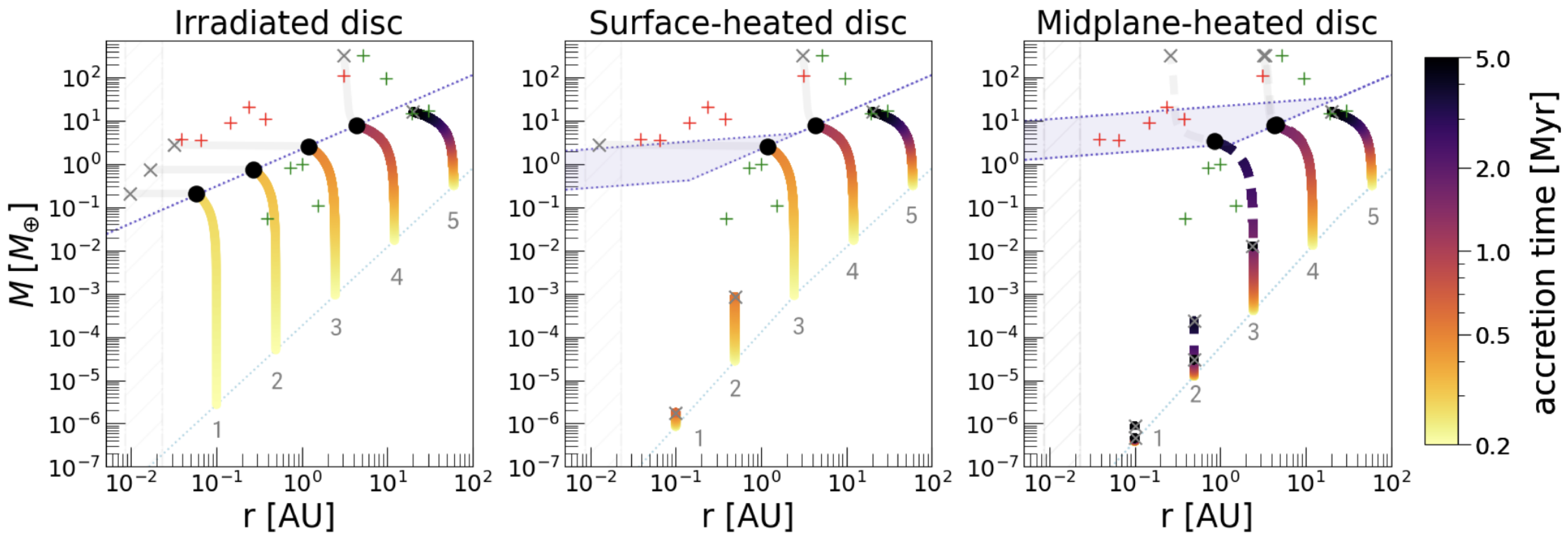
- Rings as birth sites of cores that carve inner gaps
  Morbidelli 2022, Jiang and Ormel 2022

Giant planets do not suppress inner disc growth (model dependent)

Danti, Lambrechts, Lorek 2025

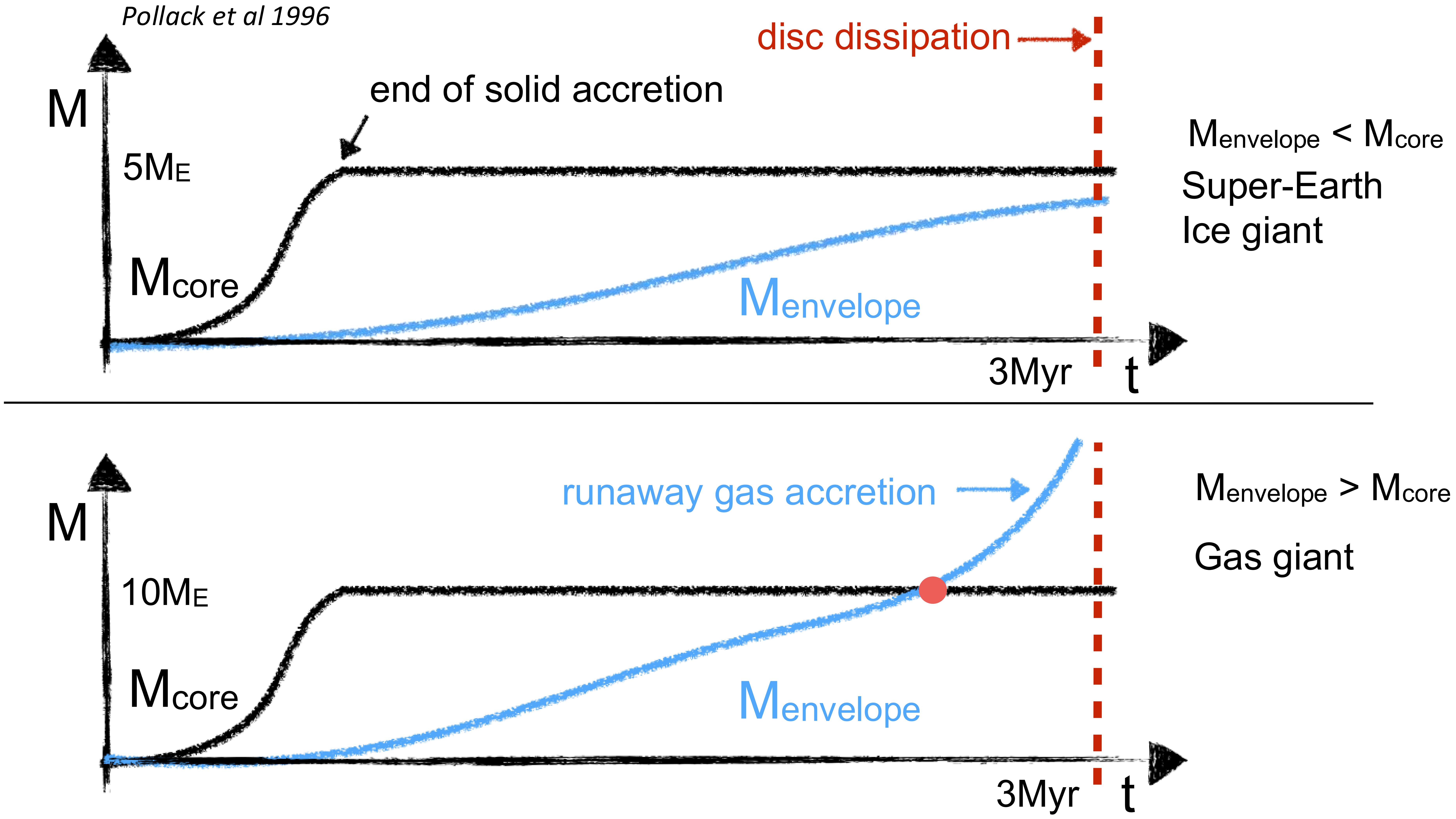


Claudia Danti



- Irradiated inner discs preserves inside-out growth
- Very strong midplane viscous heating breaks this trend (only weakly flaring inner disc aspect ratio)
- Non-ideal MHD simulations argue for intermediate surface heating *Mori et al 2022*
- Consistent with no suppression of super-Earth occurrence in systems with cold giants *Bonomo et al 2023*

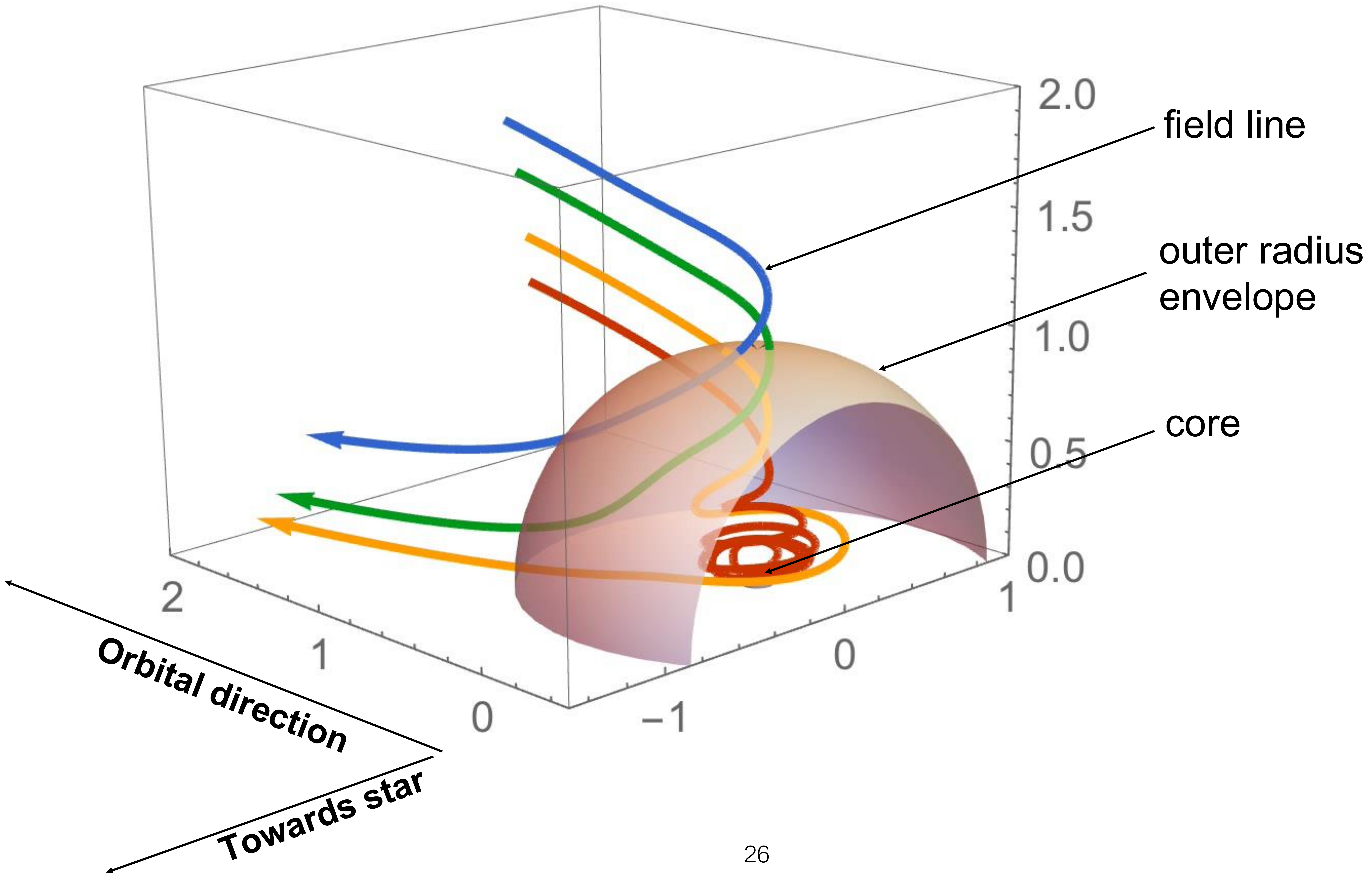
Core accretion scenario: attracting a gaseous envelope



- Maintaining $M_{envelope} < M_{core}$ is possible for low mass (5 M_E cores) in high opacity environments, but unlikely for higher mass cores (e.g. Lambrechts & Lega 2017)

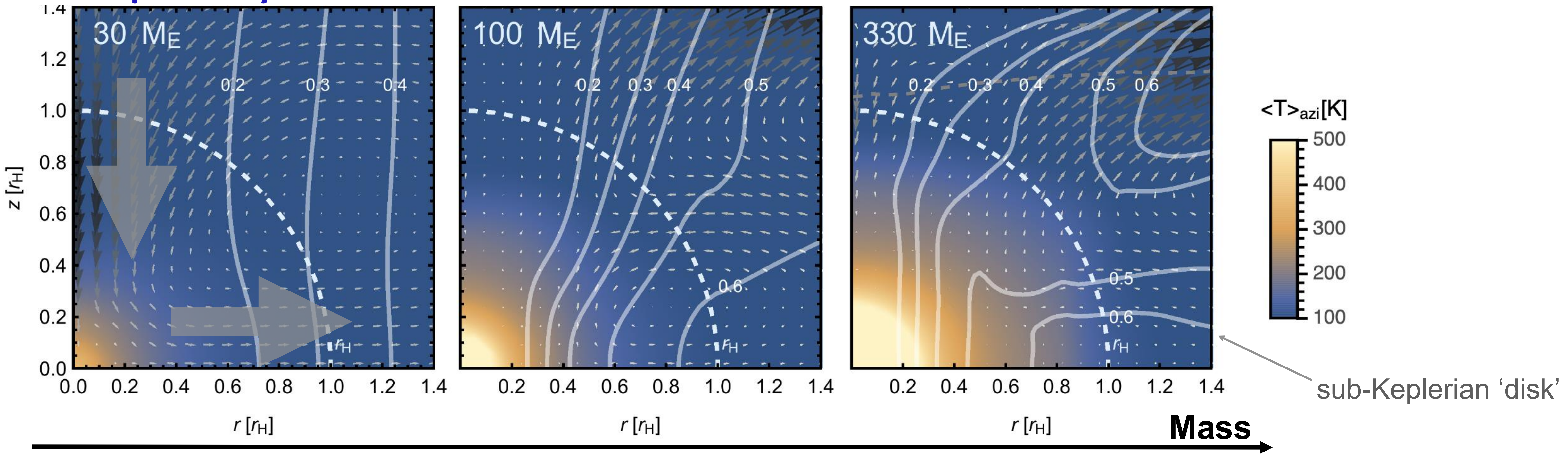
Avection of gas through the Hill radius

Ormel et al 2015, Cimerman 2017, Lambrechts & Lega 2017, Kurokawa et al 2018, …



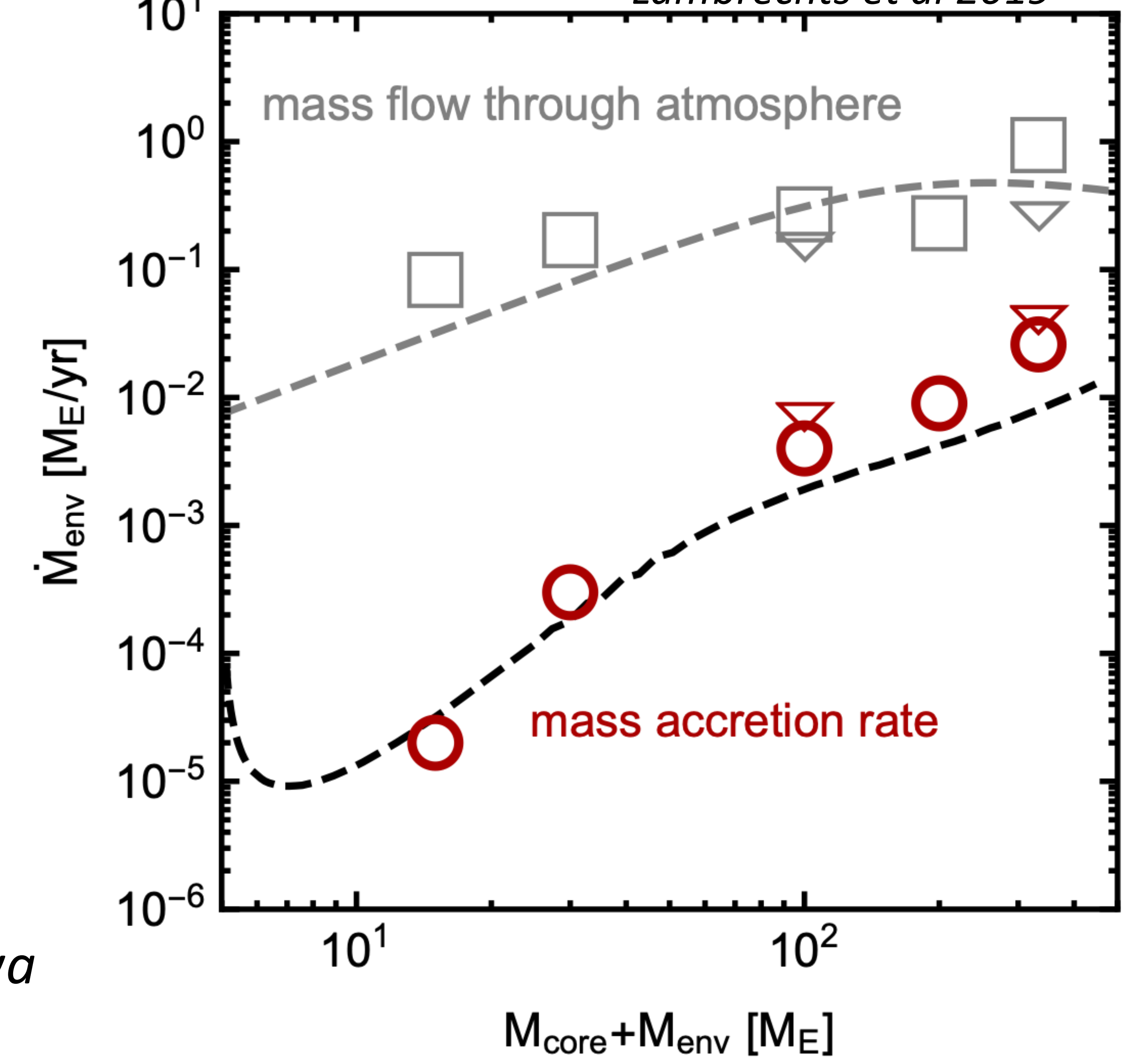
Envelopes as open systems

Lambrechts et al 2019



- There is a complex interplay between gas accretion and advection: the accretion rates can be 10 to 10^3 times smaller compared to the flow through the Hill sphere of approximately 0.1 M_E/yr
- Nevertheless, gas accretion rates remain high and imply gas giants grew to completion late in the disc lifetime

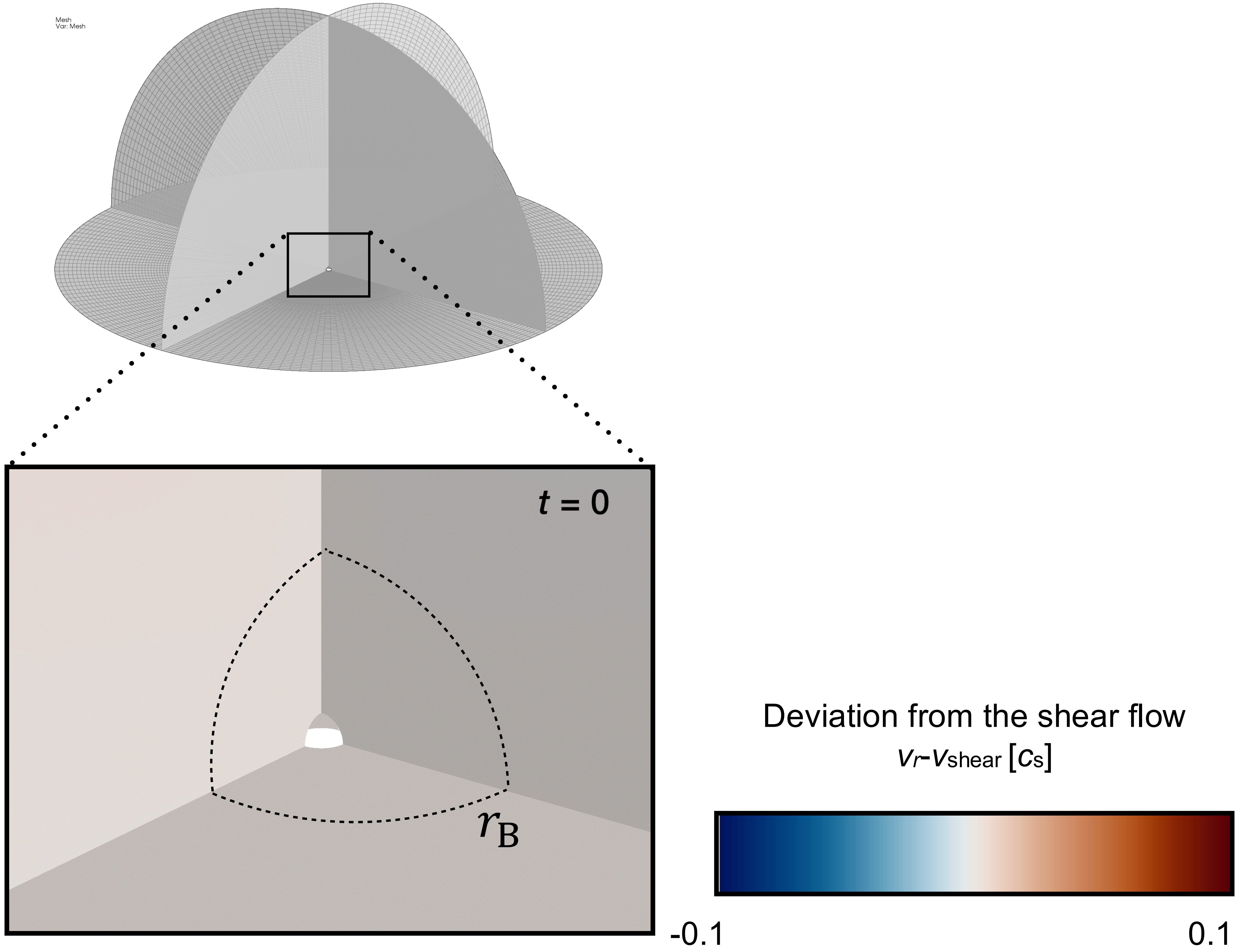
Lambrechts et al 2019



Ormel et al. (2015), Fung et al. (2015), Cimerman et al. 2017, Lambrechts and Lega 2017, Kurokawa and Tanigawa 2018, Popovas et al 2018; Béthune and Rafikov 2019, Nelson et al 2023

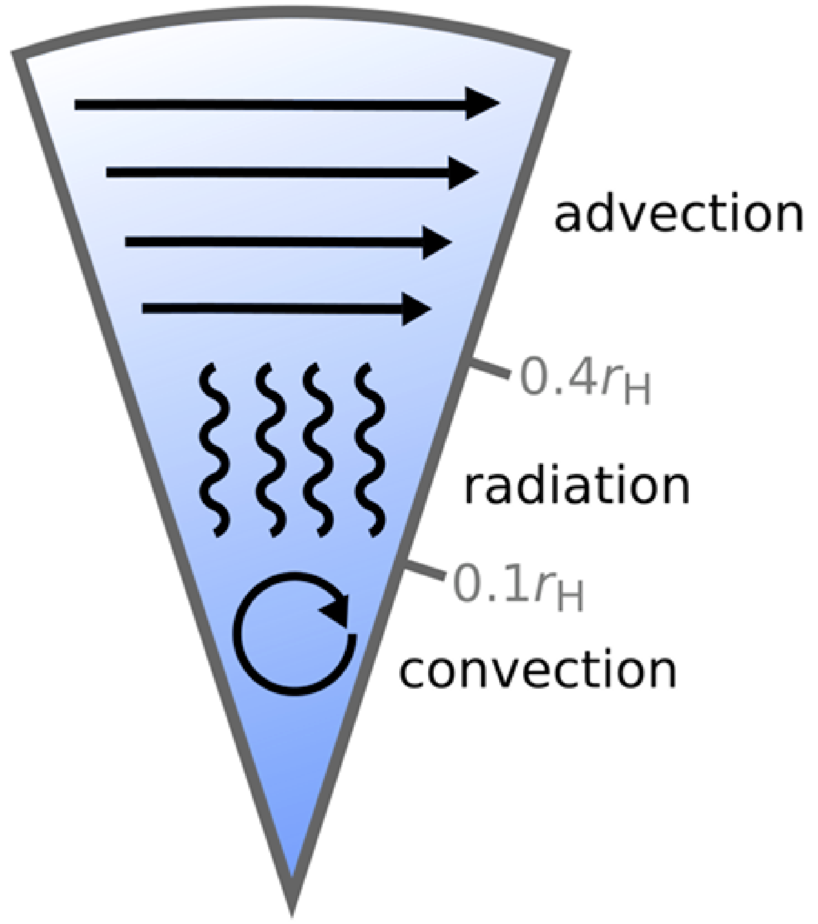
Inner convective envelope

Kuwahara & Lambrechts submitted



1 au, 1 M_E, $\beta = 10^2$

Ayumu Kuwahara



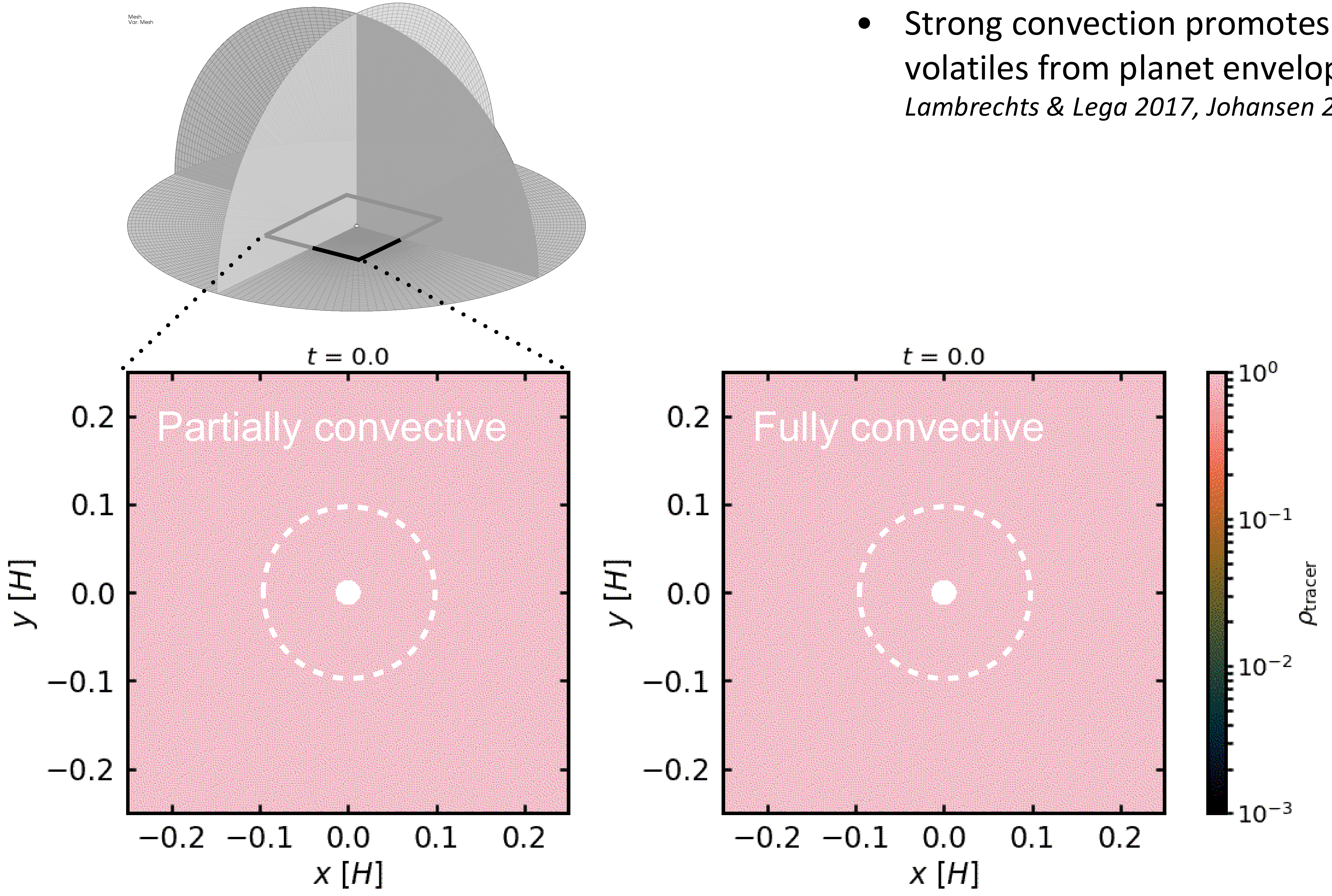
Lambrechts & Lega 2017

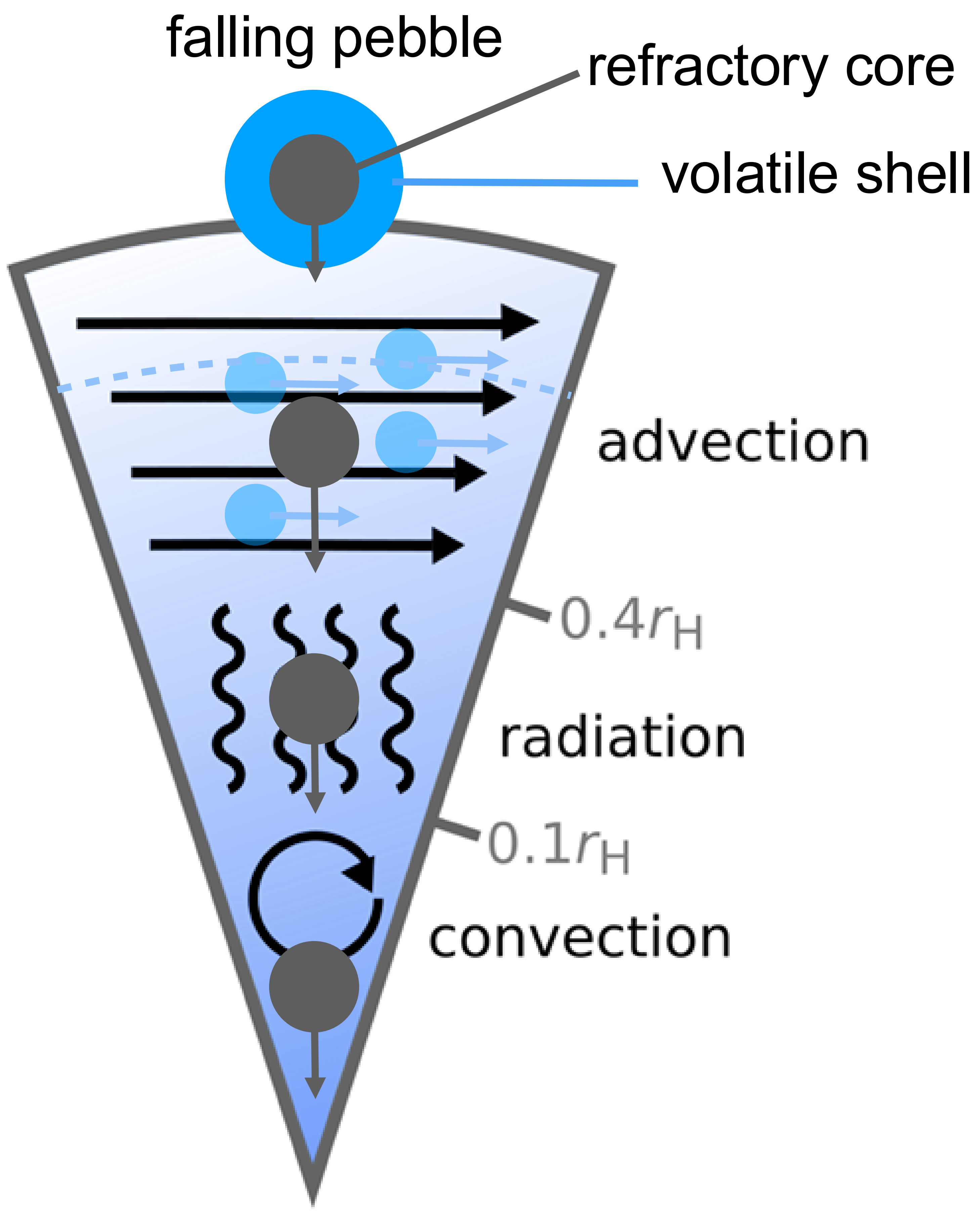
- Inner envelope is convective for nominal opacity and accretion rate regimes

Inner convective envelope

Kuwahara & Lambrechts submitted

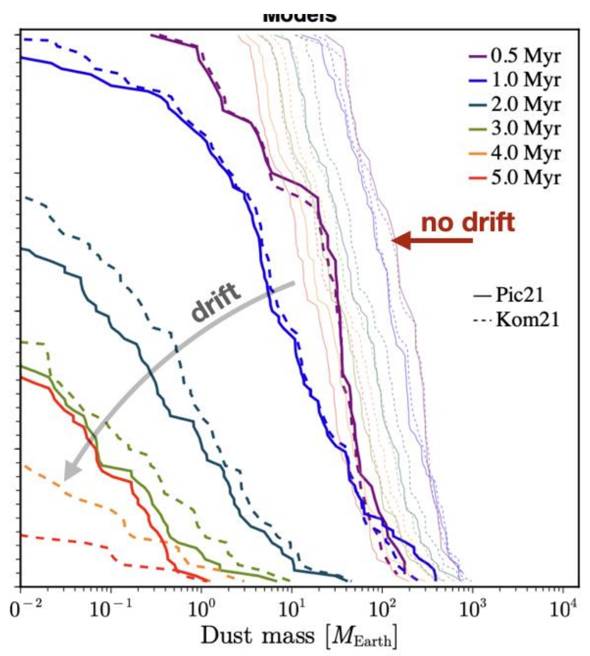
- Strong convection promotes the loss of sublimated volatiles from planet envelope to disc
  Lambrechts & Lega 2017, Johansen 2019, Wang et al 2023,…

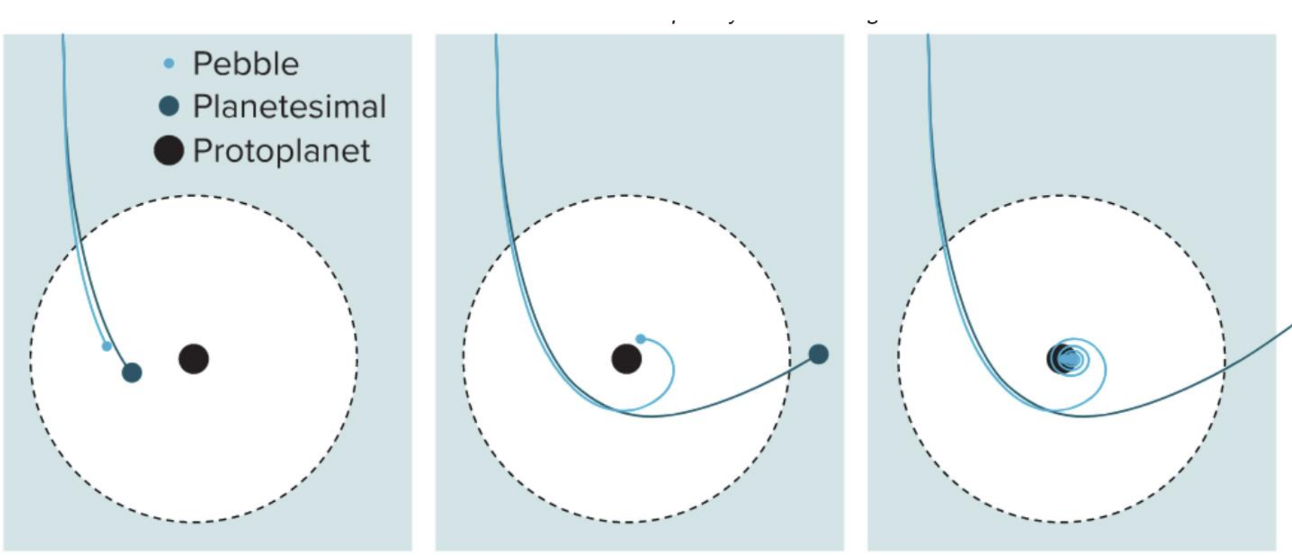


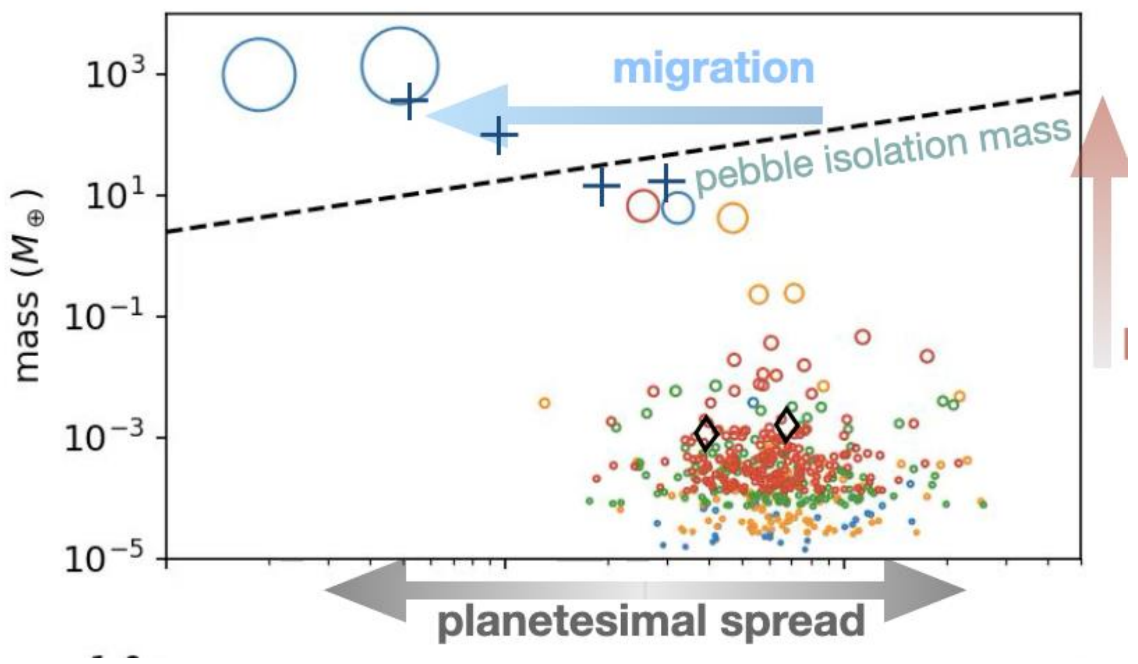


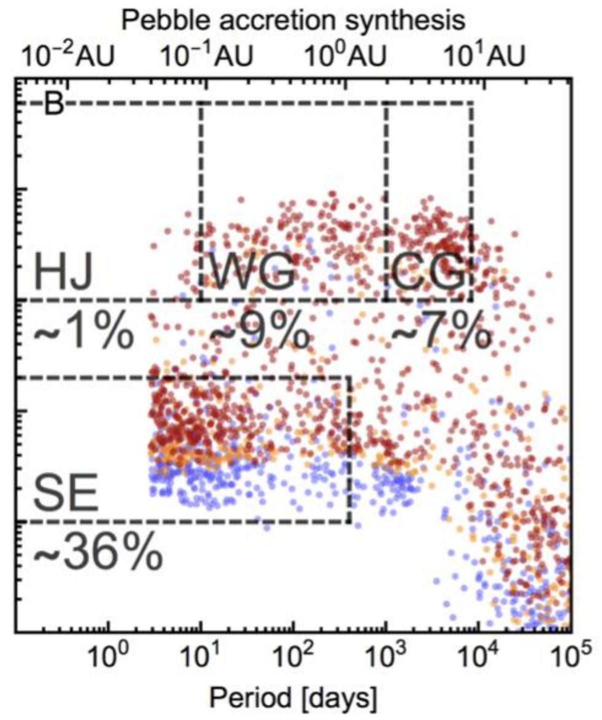
High accretion rate and opacity, towards inner disc

Summary





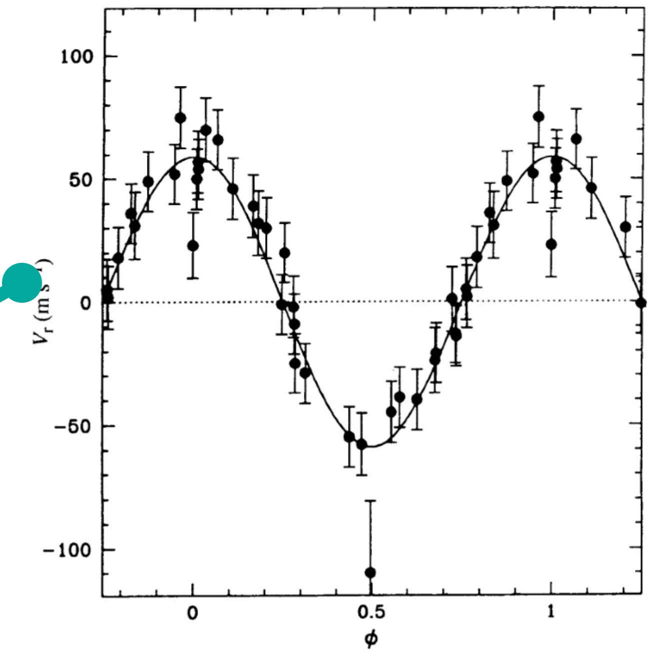


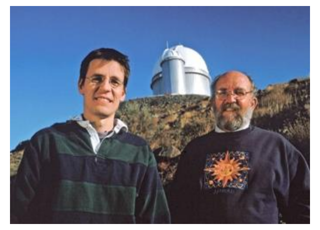


- Planetesimal formation (via streaming instability), followed by pebble accretion leads to wide-orbit planet formation (<50 au), in discs with a pebble flux of 10-100 Me/Myr

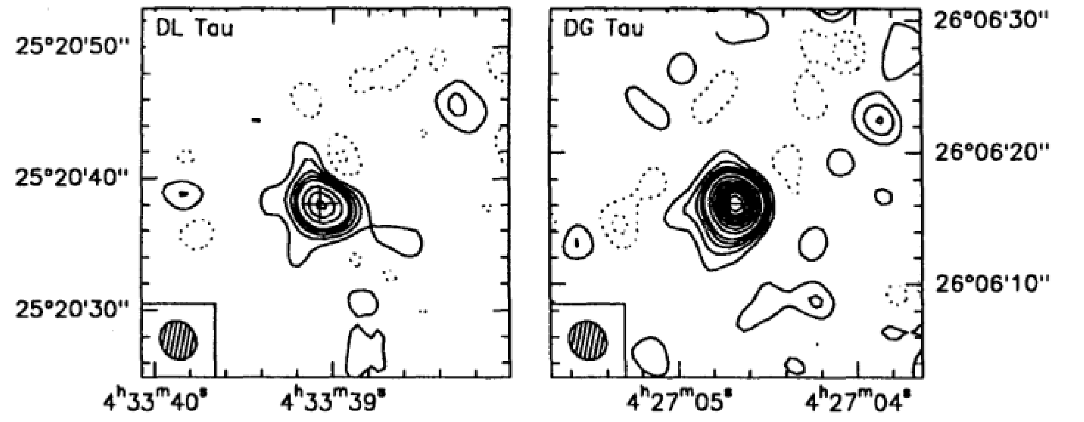
- A key research objective is to link protoplanetary disc properties to resulting planetary system architectures: a project with clear roots in the major discoveries of the mid-nineties.

- Observed dust rings could be signposts of primordial planetesimal/planet formation sites (interpretation hampered by our lack of understanding of planetesimal formation conditions). Gaps are consistent with being signposts of planets post pebble isolation mass.





Mayor & Queloz 1995, 55 Peg b

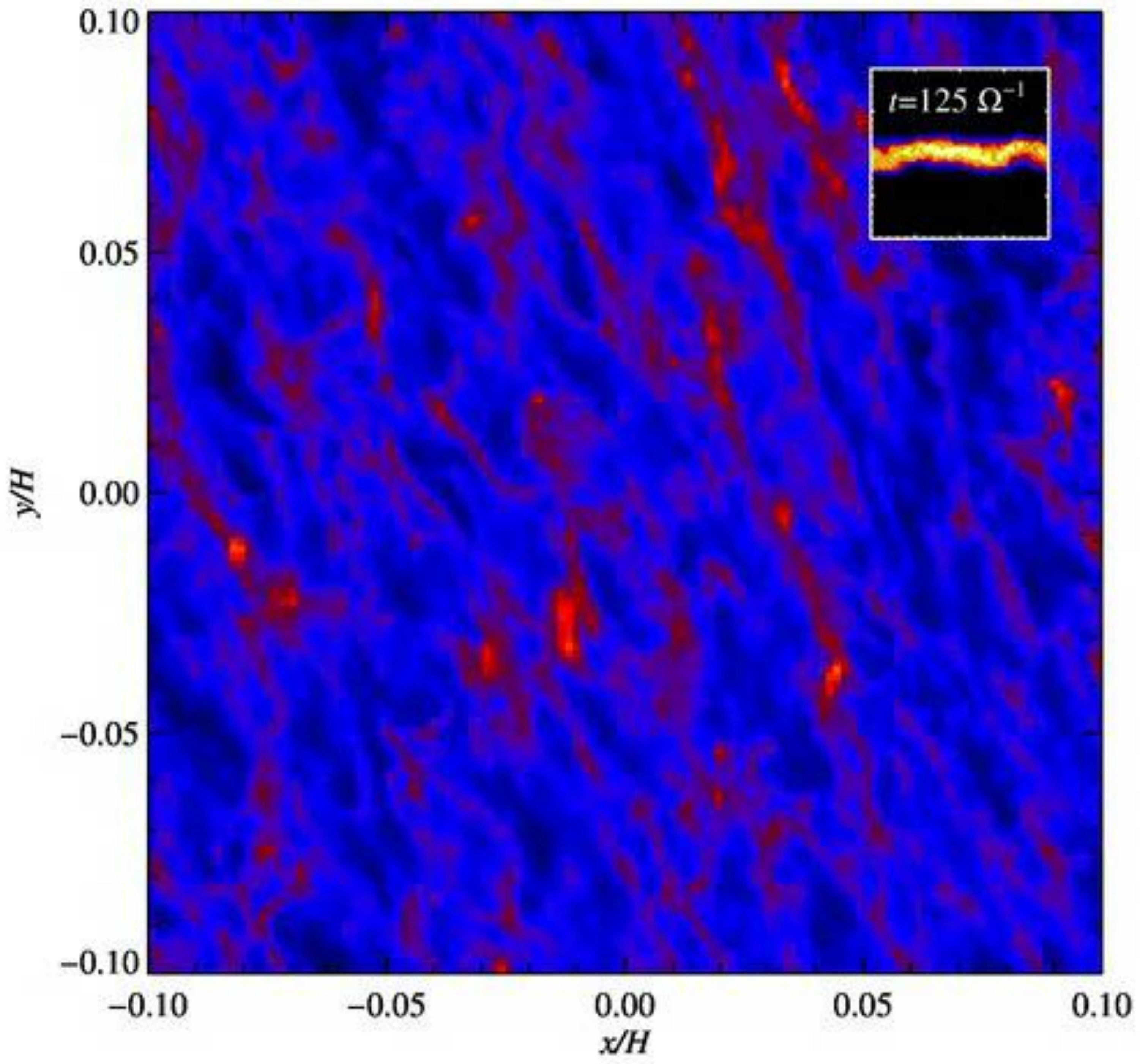


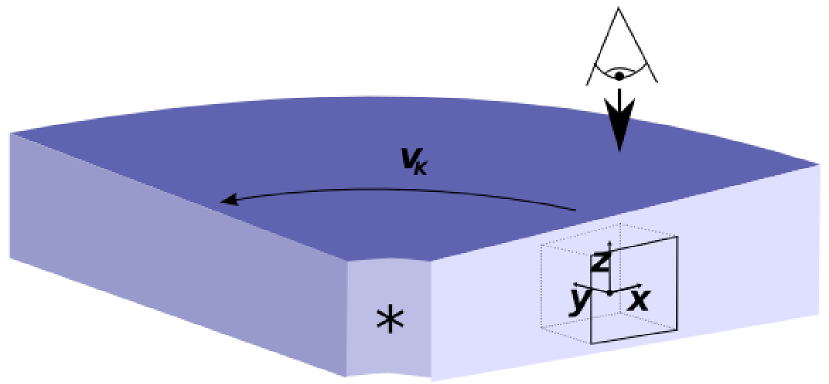
Dutrey et al 1996, DL tau, DG tau

Extra slides

Pebble accretion: Hill regime

Lambrechts and Johansen 2012





Pebble accretion ("Hill regime"):

- Hill regime starts above a transition mass:

$$M_t \approx 3 \times 10^{-3} \left(\frac{r}{5\mathrm{AU}}\right)^{3/4} \mathrm{M}_\oplus$$

- Accretion occurs from the full Hill radius when

$$t_{\mathrm{cross,Hill}} \sim \Omega_{\mathrm{K}}^{-1} \sim t_{\mathrm{drag}}$$

- Relative velocities are set by the Keplerian shear (independent of $\dot{M}_c$

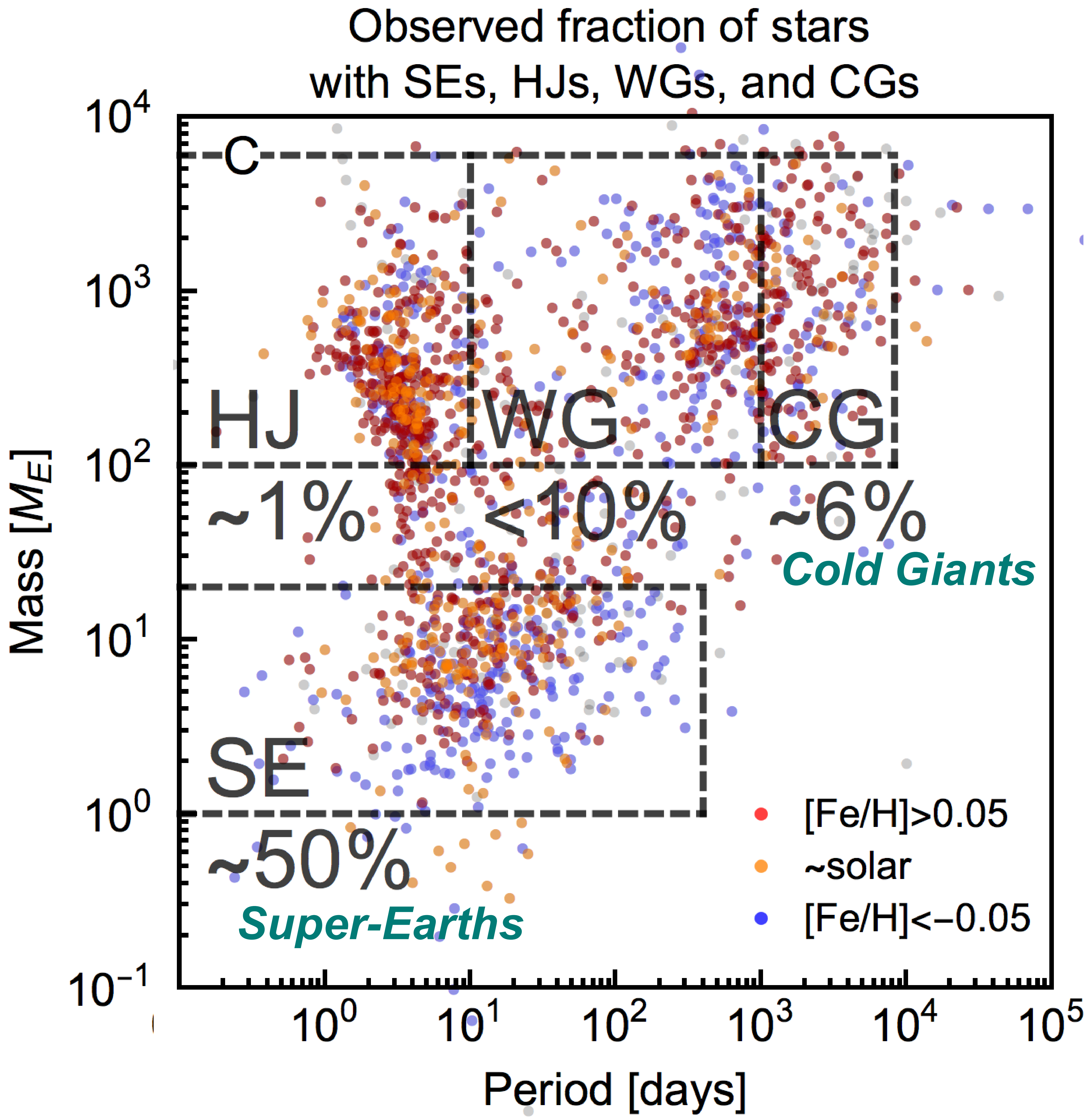
- Accretion rate is independent of radius of embryo, only mass

PART 4: Planet population synthesis

PPVII chapter, Drazkowska, Bitsch, Lambrechts et al 2022

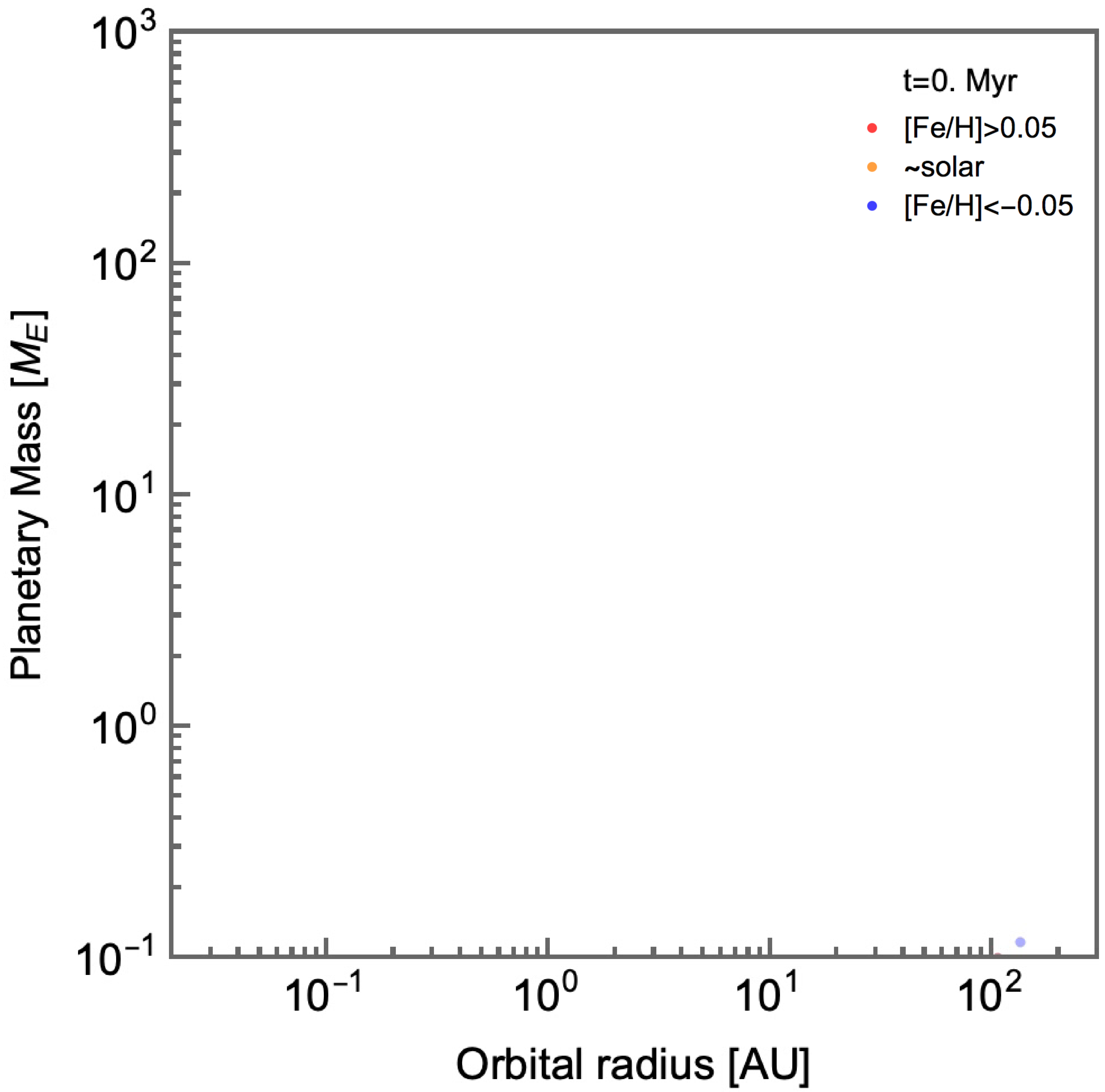
- 30-50% of solar-like stars host super-Earth-like planets
  (Mulders et al 2018, Zhu et al 2018, He et al 2021, Lissauer et al PPVII)

- Hot Jupiters are rare, less than 10% of stars hots warm giants and 5-10% of stars host a cold giants (>100Me)
  (Fernandes et al 2019, Fulton et al 2021)



Pebble accretion synthesis model

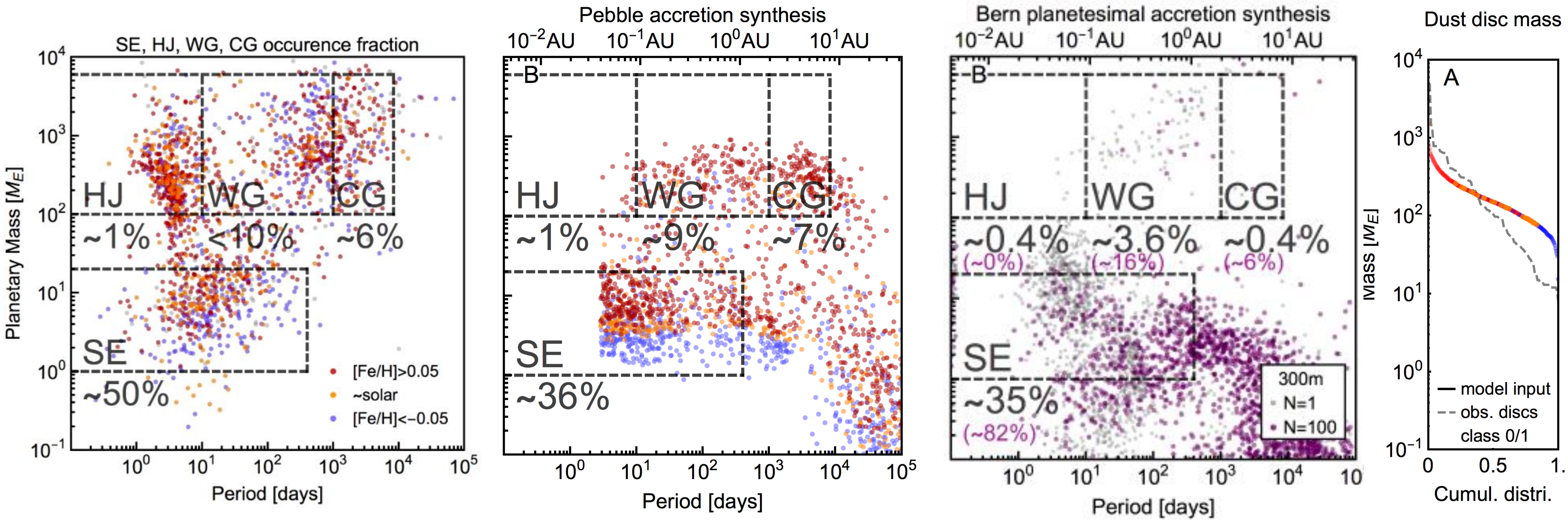
Drazkowska et al PPVII



- Key ingredients: pebble accretion, type I/II planet migration *(Paardekooper 2010, Kanagawa 2018)*, and gas accretion *(Bitsch et al 2015, Ndugu et al 2018, 2021)*
- Key input: initial disc mass distribution and disc lifetimes
- Parameter choices for: pebble/gas disc evolution, pebble and gas accretion, migration, …

Pebble vs planetesimal accretion exoplanet synthesis

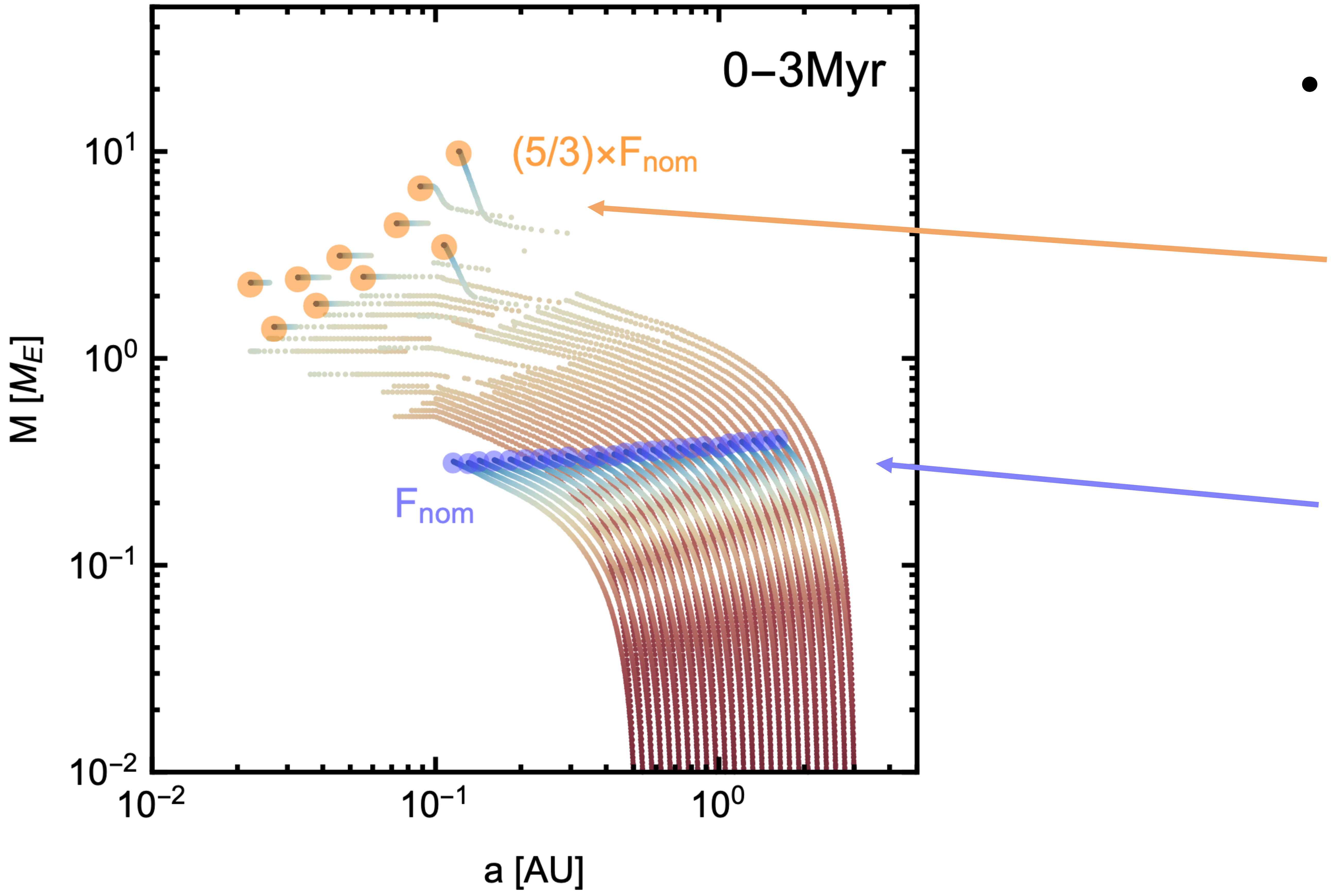
PPVII chapter, Drazkowska, Bitsch, Lambrechts et al 2022



- Fast ☑ planet formation within disc lifetimes (2.5 Myr)
- Efficient ☑ planetary growth starting with average dust disc mass of ~100 Me for solar like stars
- Diverse ☑ outcomes: occurrence fractions of different planetary classes are approximately reproduced
- Parametrised physics here remains poorly understood, but key qualities are now observed (in the outer disc): pebble size, surface density and scale height

Inner-disc planet formation is strongly disc model dependent

Lambrechts et al 2019



- The amount of available pebbles is a disc property that regulates the type of planetary system that forms:
  - A high pebble flux (190 M_E integrated) leads to substantial migration and the formation of a super-Earth/mini-Neptune system near the disc edge
  - A lower pebble flux (110 M_E integrated) leads to Mars-mass embryos and little migration: the initial conditions for classical terrestrial planet formation

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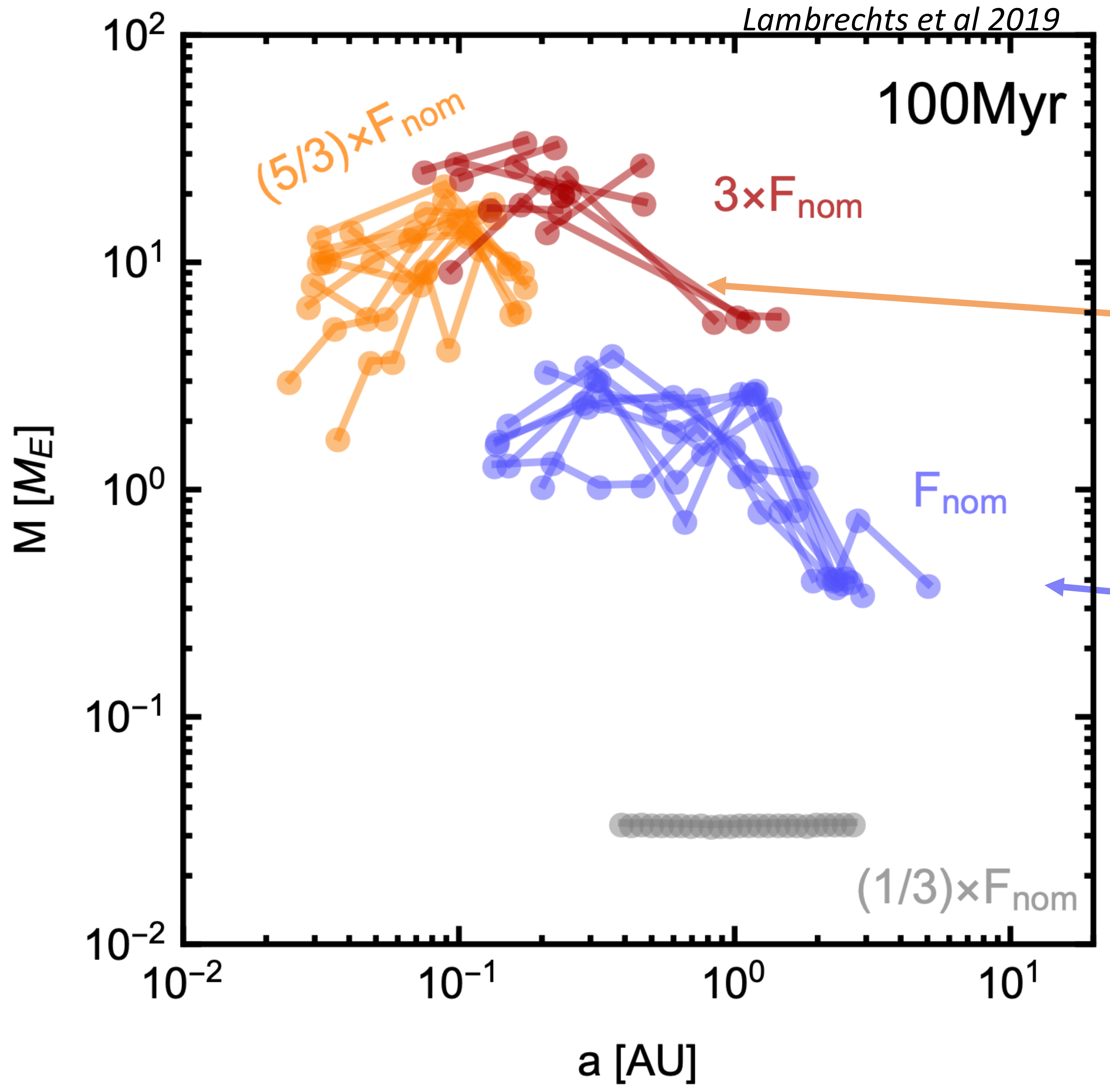

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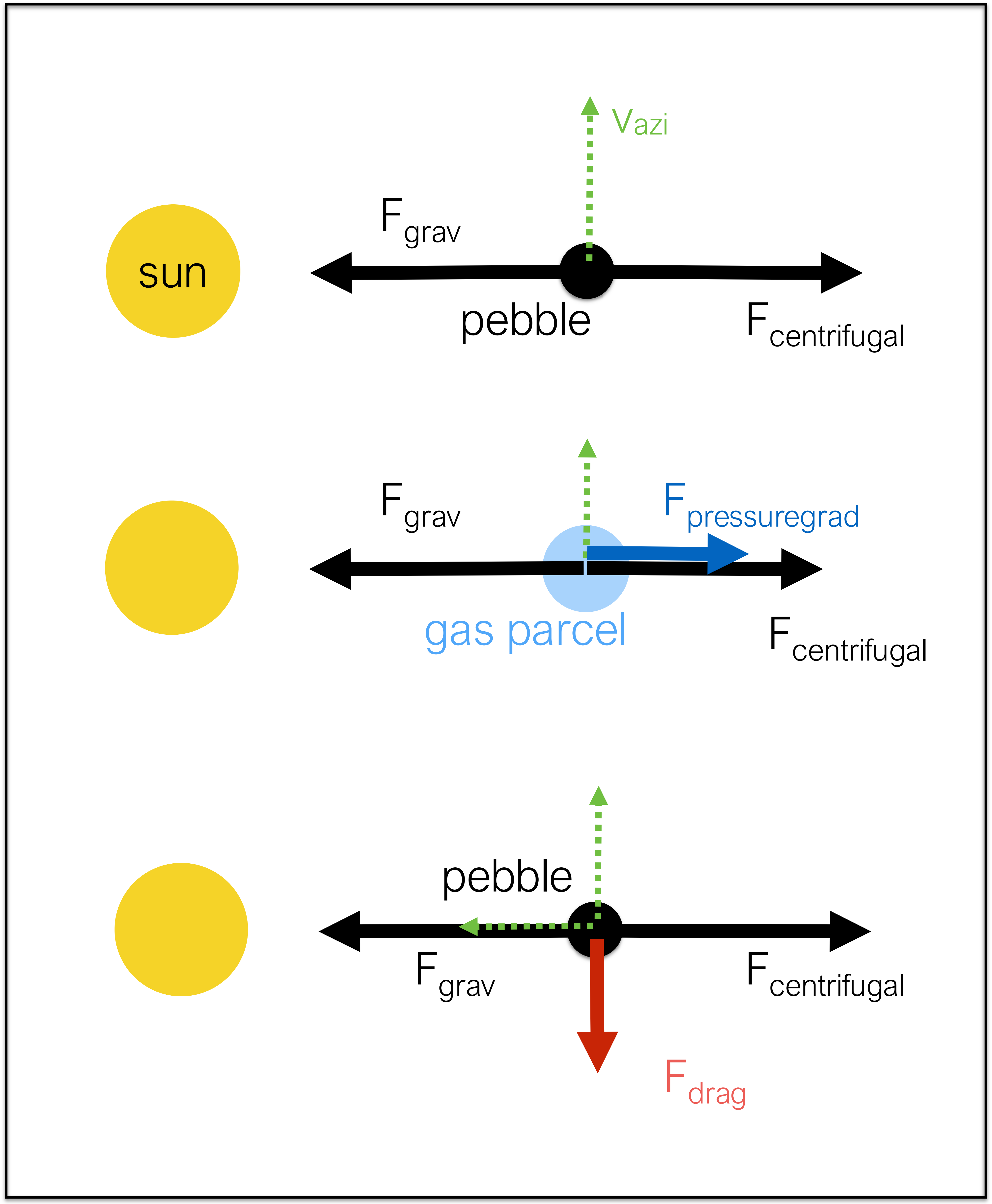
Pebble drift

- Pressure support on the gas reduces the orbital velocity of the gas
- Particles feel a headwind
- Gas drag forces the particles to drift inwards



Is pebble drift consistent with observed dust disc radii?

- During pebble drift the mm-flux decreases by orders of magnitude while the R68% radius only changes moderately

- 1 m/s fragmentation pebbles are broadly consistent with constraints

  - caveat: the opacity index arguing for slightly larger pebbles
  Pinilla et al 2012, 2021 & Delussu et al 2024

  - but challenge to determine opacity
  size distribution Zhu et al 2019, porosity Zhang et al 2023

- *Pressure bumps?*

Appelgren et al 2025