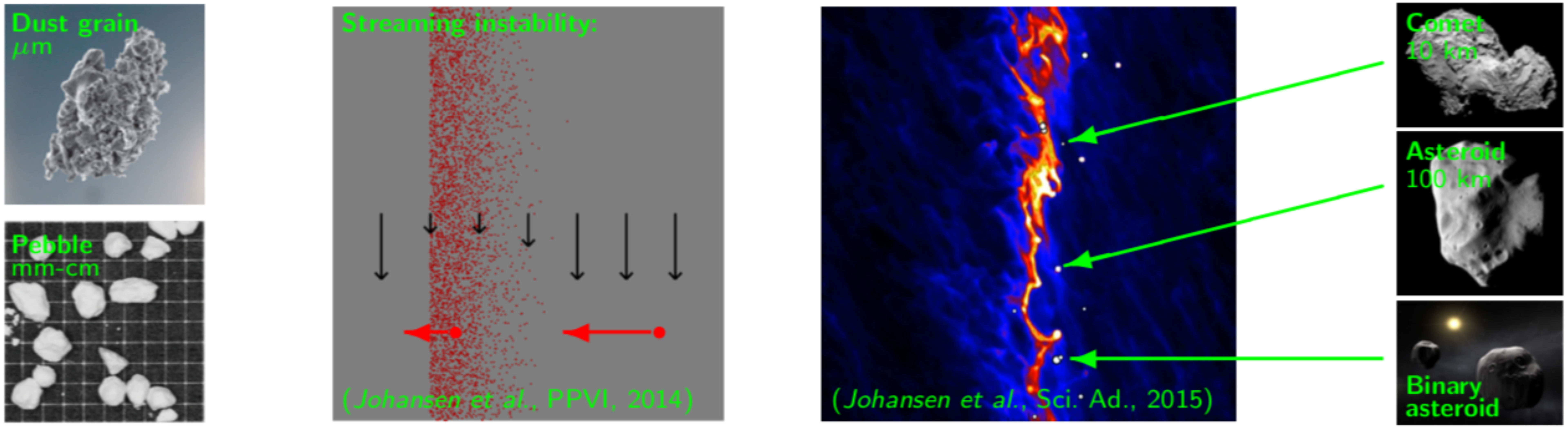
Planetesimal formation in protoplanetary discs

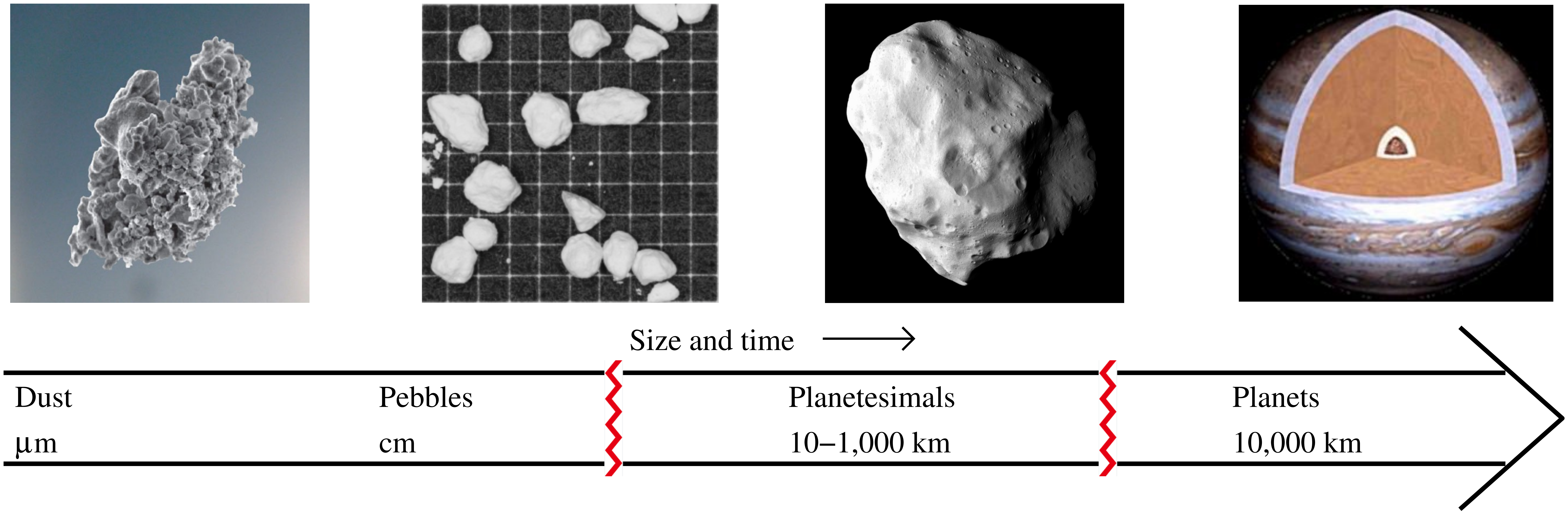


Perspectives of Planet and Star Formation

Heidelberg, June 2026

Anders Johansen, Globe Institute, University of Copenhagen // Lund University

Barriers in planet formation



- Planets form in protoplanetary discs around young stars consisting of gas and dust
- Dust and ice grains stick to form pebbles of millimeter-centimeter sizes
- **How do pebbles come together to form planetesimals?**
- How do the cores of giant planets form before disc dissipation?

Pebbles in protoplanetary discs

- I started my PhD with Hubert and Thomas in 2004 (with support from Kees also!)
- A handful of papers had begun reporting the detection of cm-sized pebbles in discs
- MPIA had the perfect scientific environment to use these observations to develop new planet formation theory based on *stalled growth at pebble sizes*

Large grains in the disk of CQ Tau

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Abstract. We present 7 mm observations of the dusty disk surrounding the 10 Myr old 1.5 $M_\odot$ pre-main-sequence star CQ Tauri obtained at the Very Large Array with 0.8 arcsec resolution and 0.1 mJy rms sensitivity. These observations resolve the 7 mm emission in approximately the north-south direction, confirming previous results obtained with lower resolution. We use a two-layer flared disk model to interpret the observed fluxes from 7 mm to 1.3 mm together with the resolved 7 mm structure. We find that the disk radius is constrained to the range 100 to 300 AU, depending on the steepness of the disk surface density distribution. The power law index of the dust opacity coefficient, β, is constrained to be 0.5 to 0.7. Since the models indicate that the disk is optically thin at millimeter wavelengths for radii greater than 8 AU, the contribution of an optically thick region to the emission is less than 10%. This implies that high optical depth or complex disk geometry cannot be the cause of the observed shallow millimeter spectral index. Instead, the new analysis supports the earlier suggestion that dust particles in the disk have grown to sizes as large as a few centimeters. The dust in the CQ Tauri system appears to be evolved much like that in the TW Hydra system, a well-studied pre-main-sequence star of similar age and lower mass. The survival of gas-rich disks with incomplete grain evolution at such old ages deserves further investigations.

TOWARD PLANETESIMALS IN THE DISK AROUND TW HYDRAE: 3.5 CENTIMETER DUST EMISSION

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ABSTRACT

We present Very Large Array observations at $\lambda = 3.5$ cm of the nearby young star TW Hya that show the emission is constant in time over weeks, months, and years, and spatially resolved with peak brightness temperature ~10 K at ~0″.25 (15 AU) resolution. These features are naturally explained if the emission mechanism at this wavelength is thermal emission from dust particles in the disk surrounding the star. To account quantitatively for the observations, we construct a self-consistent accretion disk model that incorporates a population of centmeter-size particles that matches the long-wavelength spectrum and spatial distribution. A substantal mass fraction of orbiting particles in the TW Hya disk must have agglomerated to centmeter size. These data provide the first clear indication that dust emission from protoplanetary disks may be observed at centmeter wavelengths, and that changes in the spectral slope of the dust emission may be detected, providing constraints on dust evolution and the planet formation process.

Large dust particles in disks around T Tauri stars

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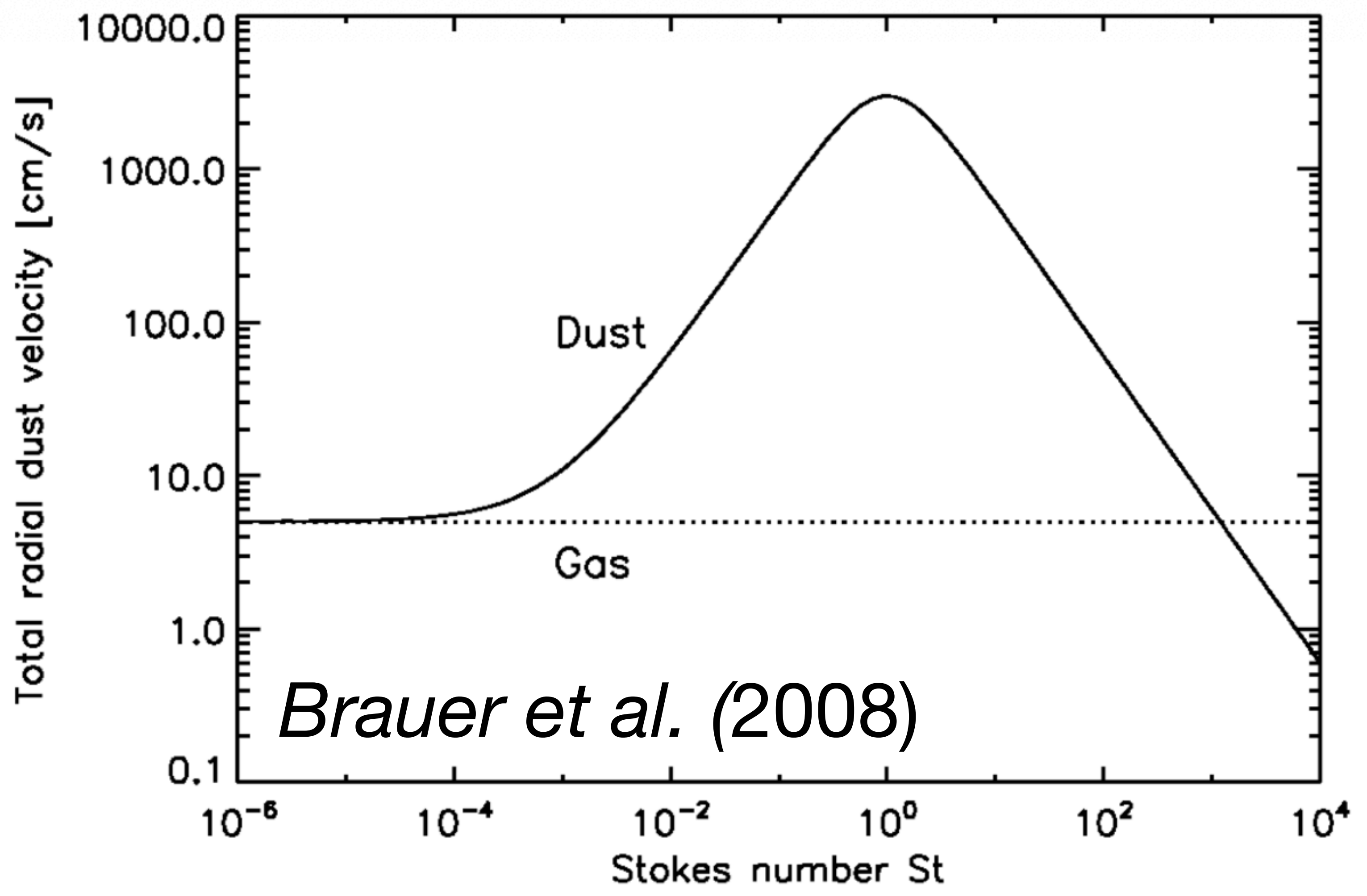
ABSTRACT

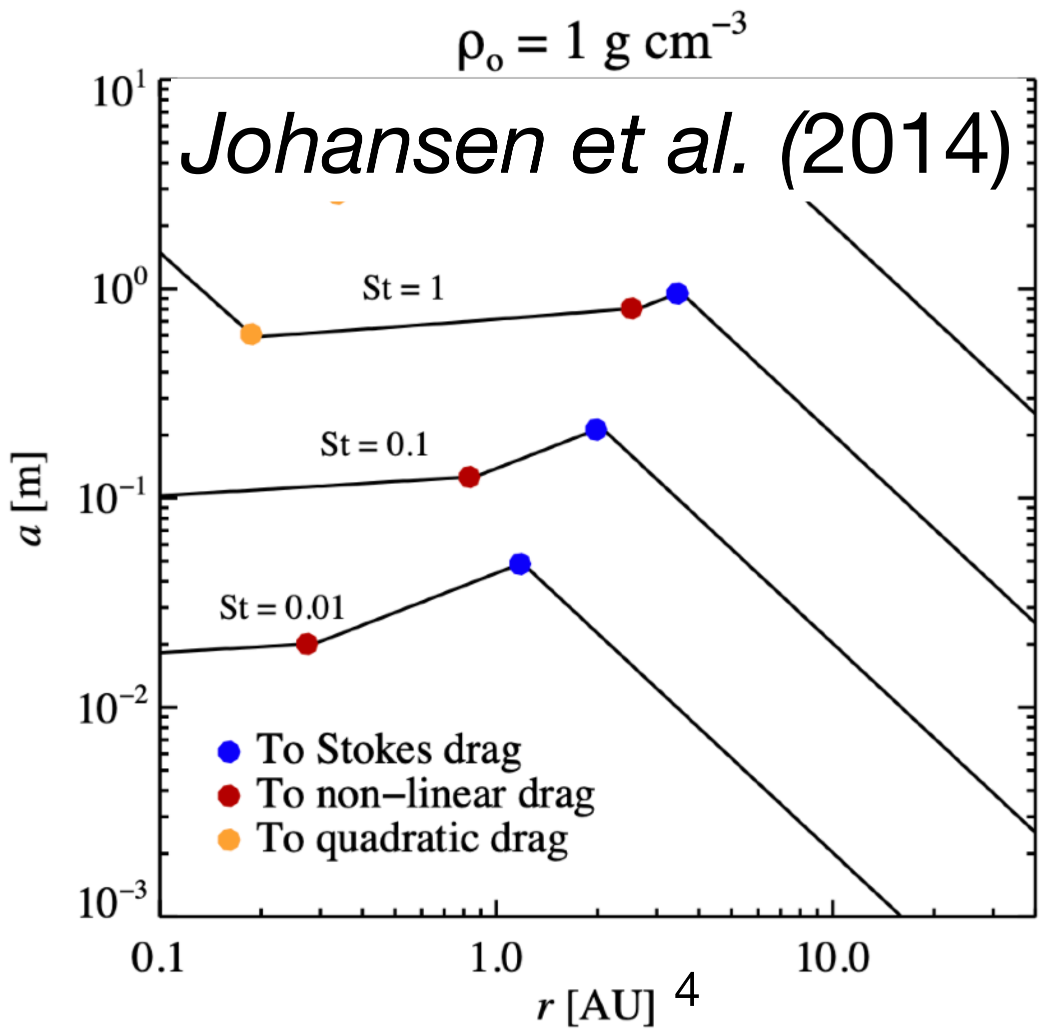
We present 7-mm continuum observations of 14 low-mass pre-main-sequence stars in the Taurus-Auriga star-forming region obtained with the Very Large Array with ~1″.5 resolution and ~0.3 mJy rms sensitivity. For 10 objects, the circumstellar emission has been spatially resolved. The large outer disk radii derived suggest that the emission at this wavelength is mostly optically thin. The millimetre spectral energy distributions are characterised by spectral indices $\alpha_{\rm mm} = 2.3$ to 3.2. After accounting for contributions from free-free emission and corrections for optical depth, we determine dust opacity indices β in the range 0.5 to 1.6, which suggest that millimetre-sized dust aggregates are present in the circumstellar disks. Four of the sources with $\beta > 1$ may be consistent with submicron-sized dust as found in the interstellar medium. Our findings indicate that dust grain growth to millimetre-sized particles is completed within less than 1 Myr for the majority of circumstellar disks.

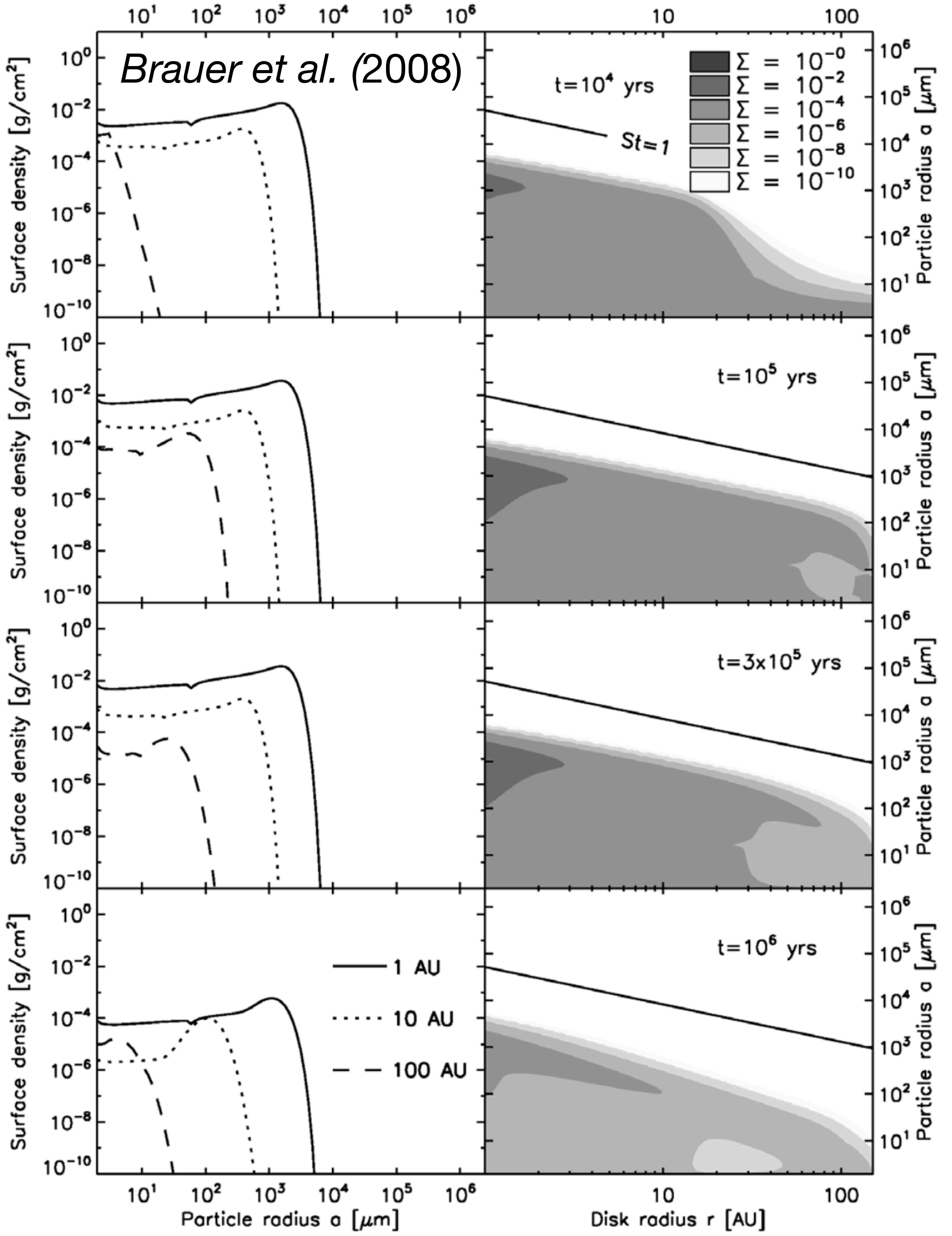
Stalled pebble growth

- <u>Drift barrier:</u> boulders of Stokes number unity drift towards the star at 20 — 30 m/s, corresponding to several thousand AU per Myr (*Weidenschilling*, 1977)
- <u>Fragmentation barrier:</u> Collisions faster than 1-10 m/s lead to fragmentation (*Blum & Wurm*, 2000; *Güttler et al.*, 2010)
- Approximate expression for fragmentation-limited growth (*Birnstiel et al.*, 2011; *Jiang et al.*, 2024; *Luo et al.*, 2026)

$$\mathrm{St} = \frac{1}{3}\frac{1}{\alpha}\left(\frac{v_\mathrm{f}}{c_\mathrm{s}}\right)^2 = 9.5\times10^{-3}\left(\frac{\alpha}{10^{-4}}\right)^{-1}\left(\frac{v_\mathrm{f}}{1\,\mathrm{m\,s^{-1}}}\right)^2\left(\frac{T}{100\,\mathrm{K}}\right)^{-1}$$

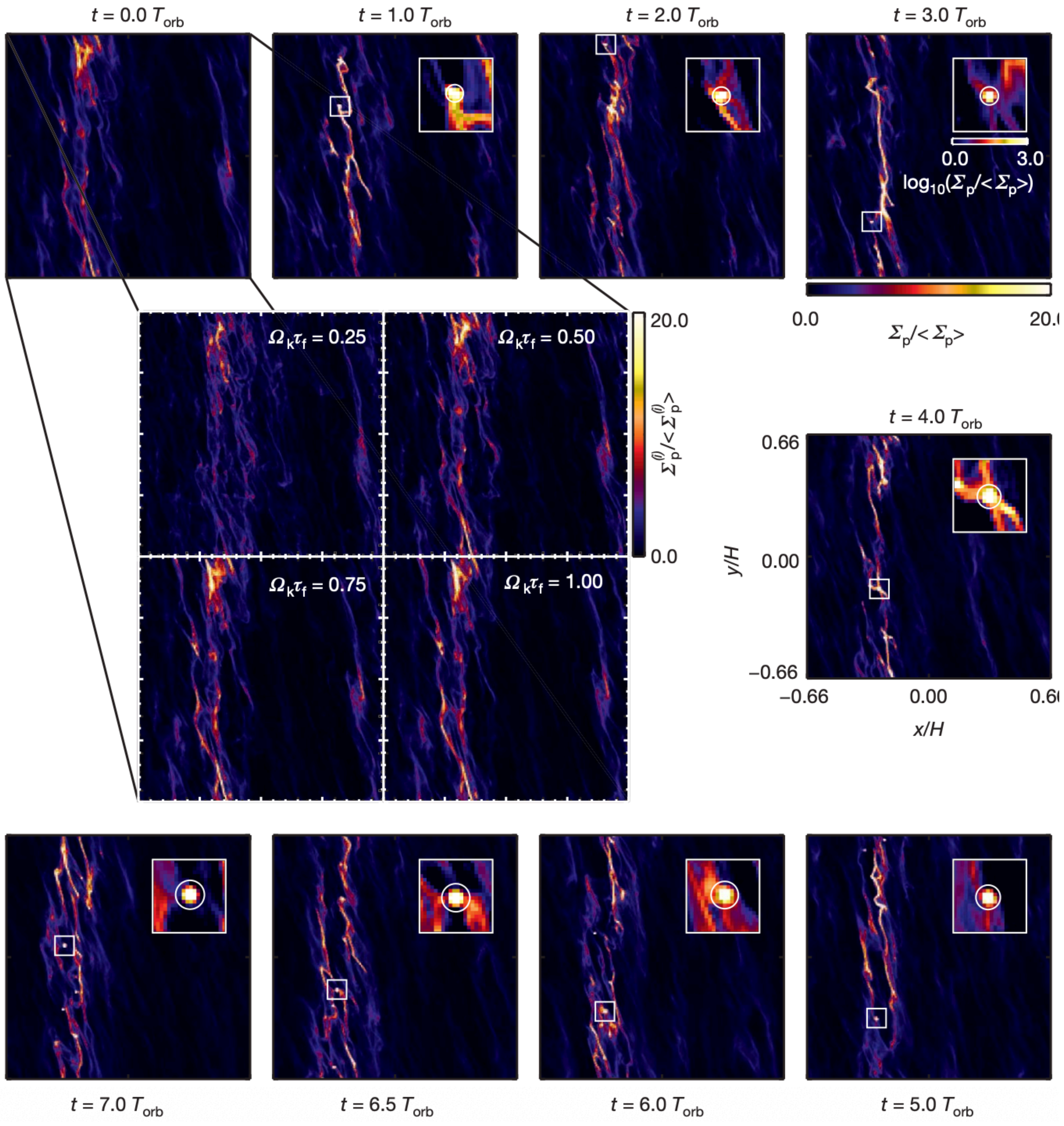


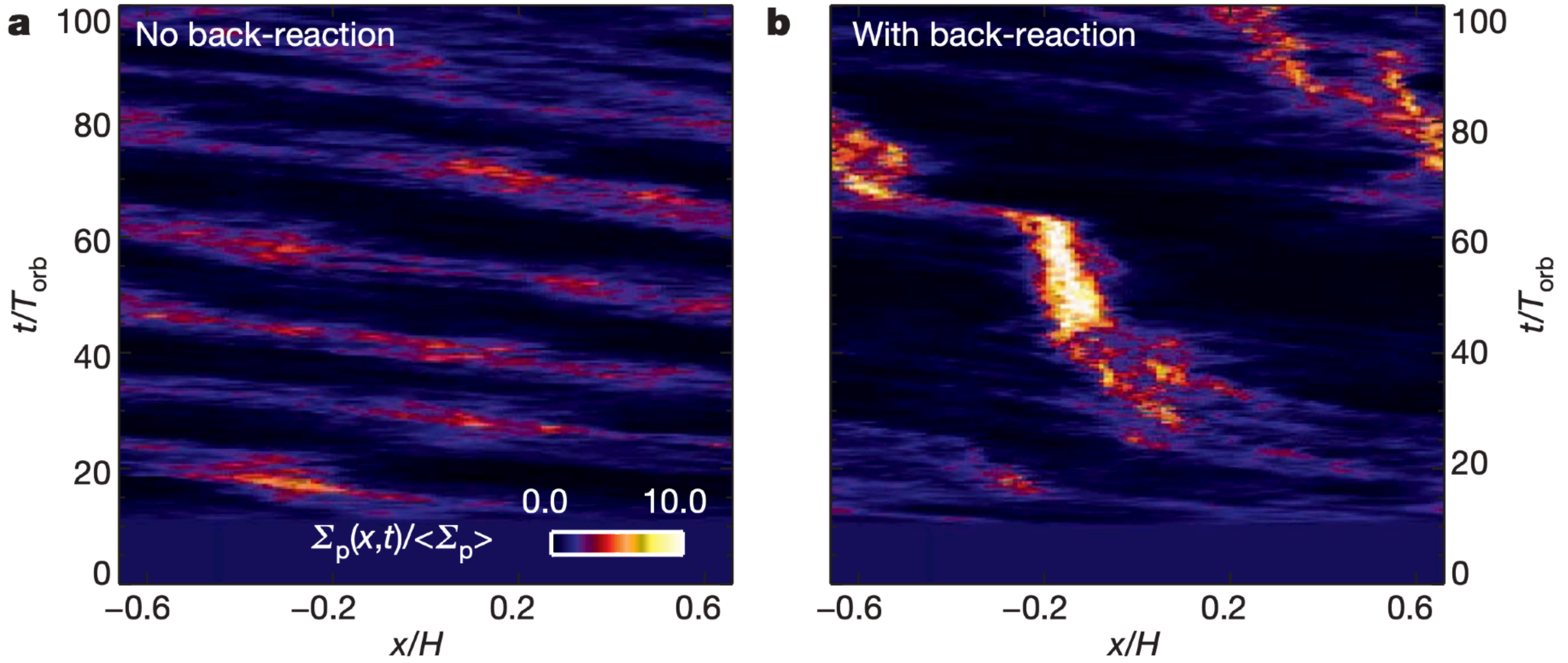




Planetesimal formation in turbulence

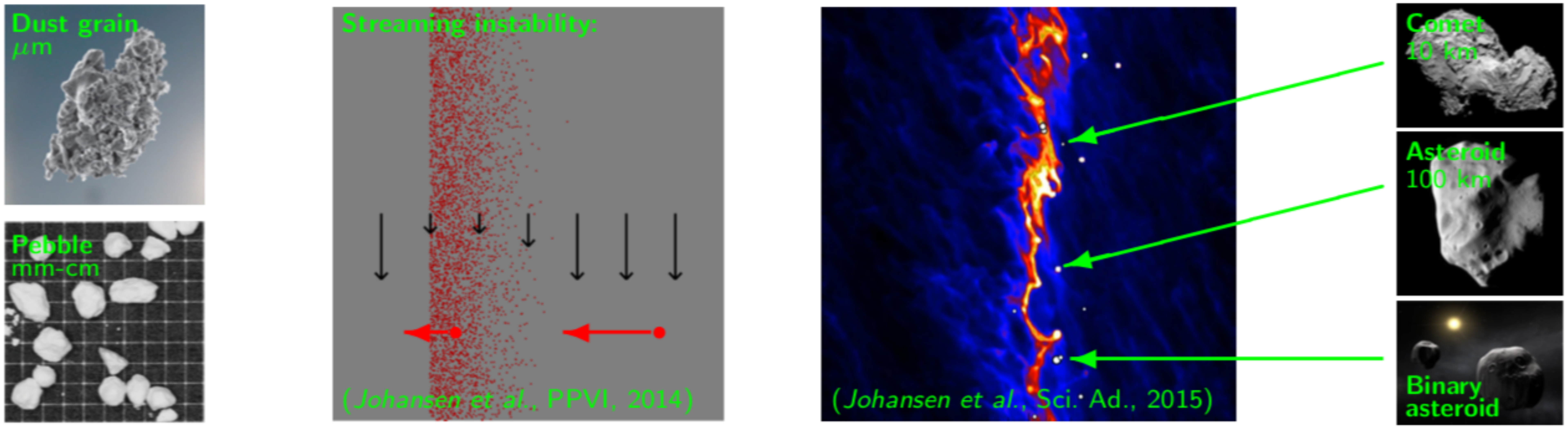
- Important aspect of my PhD work was to simulate dust and pebble dynamics in turbulence and measure concentration
- We found strong concentration of “boulders” in MHD turbulence (*Johansen, Klahr, & Henning*, 2006)
- The concentration was much stronger including back-reaction onto the gas — first numerical discovery of the streaming instability





Johansen et al. (2007)

The streaming instability

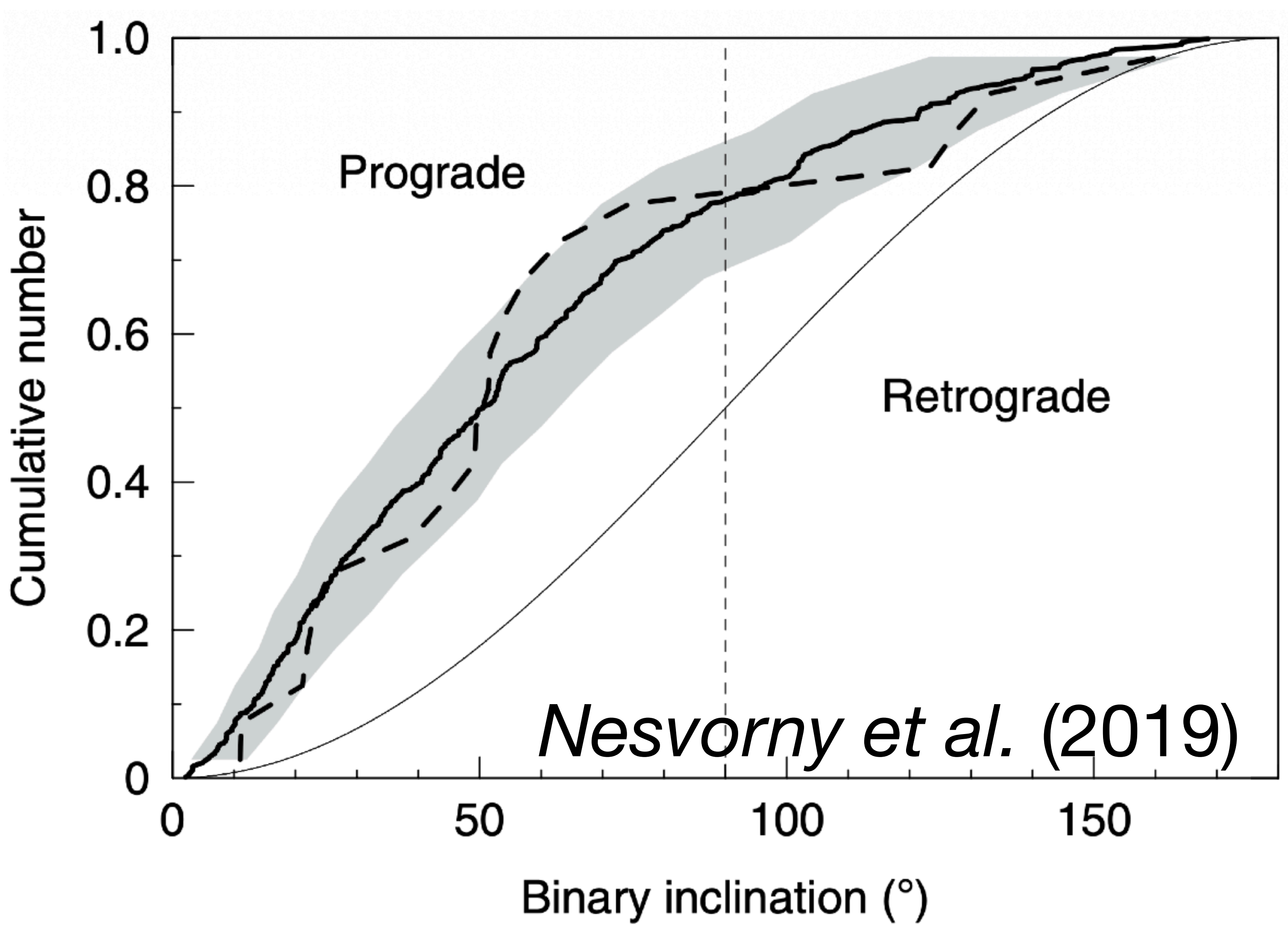


- Dense pebble filaments emerge through the streaming instability (*Youdin & Goodman*, 2005; *Johansen et al.*, 2007; *Johansen & Youdin*, 2007; *Bai & Stone*, 2010)
- Filaments collapse by gravity to form planetesimals with sizes from 10 km to several 100 km (*Johansen et al.*, 2015; *Simon et al.*, 2016)
- Most mass in 100-km-scale planetesimals, similar to asteroids in the asteroid belt
- Small bodies like comet 67P/Churyumov-Gerasimenko are piles of primordial pebbles, as observed for the comet 67P/Churyumov-Gerasimenko (*Blum et al.*, 2017)
- Many planetesimals form as binaries, similar to those observed in the Kuiper belt beyond Neptune (*Noll et al.*, 2008)

The streaming instability as a research area

- Reaching the metallicity and pebble size to trigger the streaming instability
  (*Carrera et al.*, 2015; *Drazkowska & Alibert*, 2017; *Yang et al.*, 2017; *Li & Youdin*, 2021; *Dominik & Dullemond*, 2024)
- Triggering the streaming instability by photoevaporation or streamer infall
  (Carrera et al., 2017; Ercolano et al., 2017; *Zhao et al.*, 2025; *Lau et al.*, 2025; Li & Chiang, 2025; 2026; *Ying et al.*, 2026)
- Collapse from streaming instability filament to planetesimals
  (*Nesvorny et al.*, 2010; *Johansen et al., 2015*; *Nesvorny et al.*, 2019; *Gerbig et al.*, 2020; *Polak & Klahr*, 2023)
- Measuring the initial mass function (IMF) of planetesimals
  (*Johansen et al.*, 2015; *Simon et al.*, 2016, 2017; *Schäfer et al.*, 2017; *Li et al.*, 2019; *Liu et al.*, 2020; *Schäfer et al.*, 2024)
- Interaction of streaming instability with other sources of turbulence and pressure bumps
  (*Johansen et al.*, 2007; *Yang et al.*, 2018; *Schäfer et al.*, 2020, 2025; Huang & Bai, 2025; *Eriksson et al.*, 2026)
- How the pebble size distribution affects the growth rate and saturation
  (*Krapp et al.*, 2019; *Zhu & Yang*, 2021; *Yang & Zhu*, 2021; *Schaffer et al.*, 2021; *Paardekooper et al.*, 2021, 2022)
- Coagulation in streaming instability filaments (*Carrera et al.*, 2025; *Vallucci-Goy et al.*, 2025; *Pierens et al.*, 2026)
- Observational consequences of the streaming instability (*Godines et al.*, 2026; *Lin et al.*, 2026)
- Coupling the streaming instability to pebble accretion
  (*Liu et al.*, 2019; *Lorek & Johansen*, 2022; *Kaufmann et al.*, 2025; *Johansen & Lyra*, 2026)

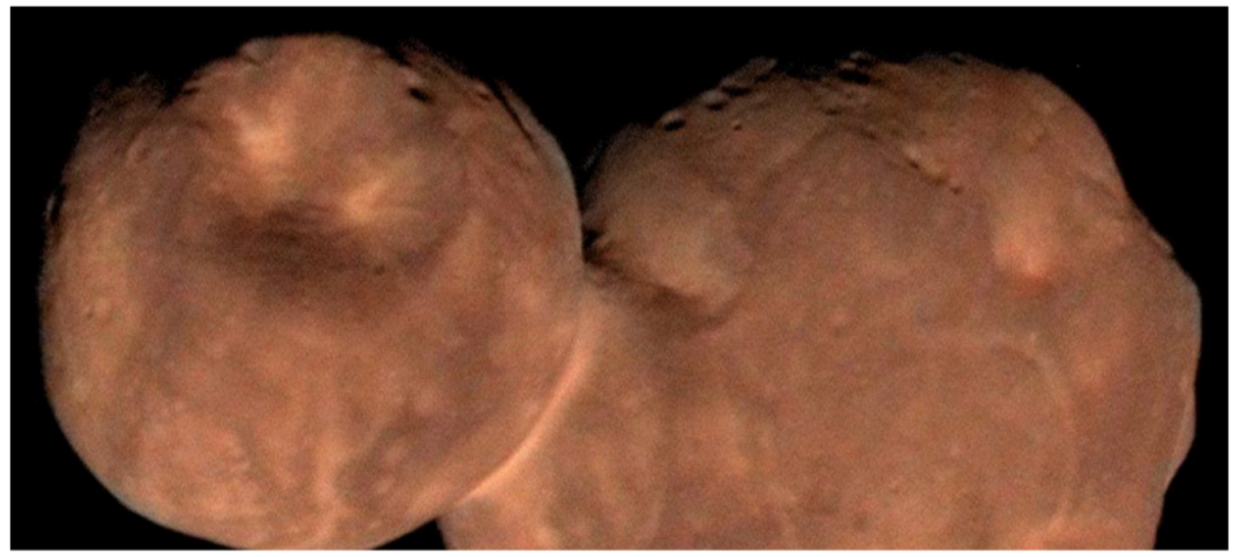
Arrokoth “alters theory of planet formation”



New Horizons spacecraft 'alters theory of planet formation'

By Pallab Ghosh
Science correspondent, BBC News, Seattle

13 February 2020 | Comments



The moment Alan Stern (L) had confirmation that New Horizons had flown by the Kuiper Belt object

Anders Johansen marks the confirmation of his theory with his daughter Laura

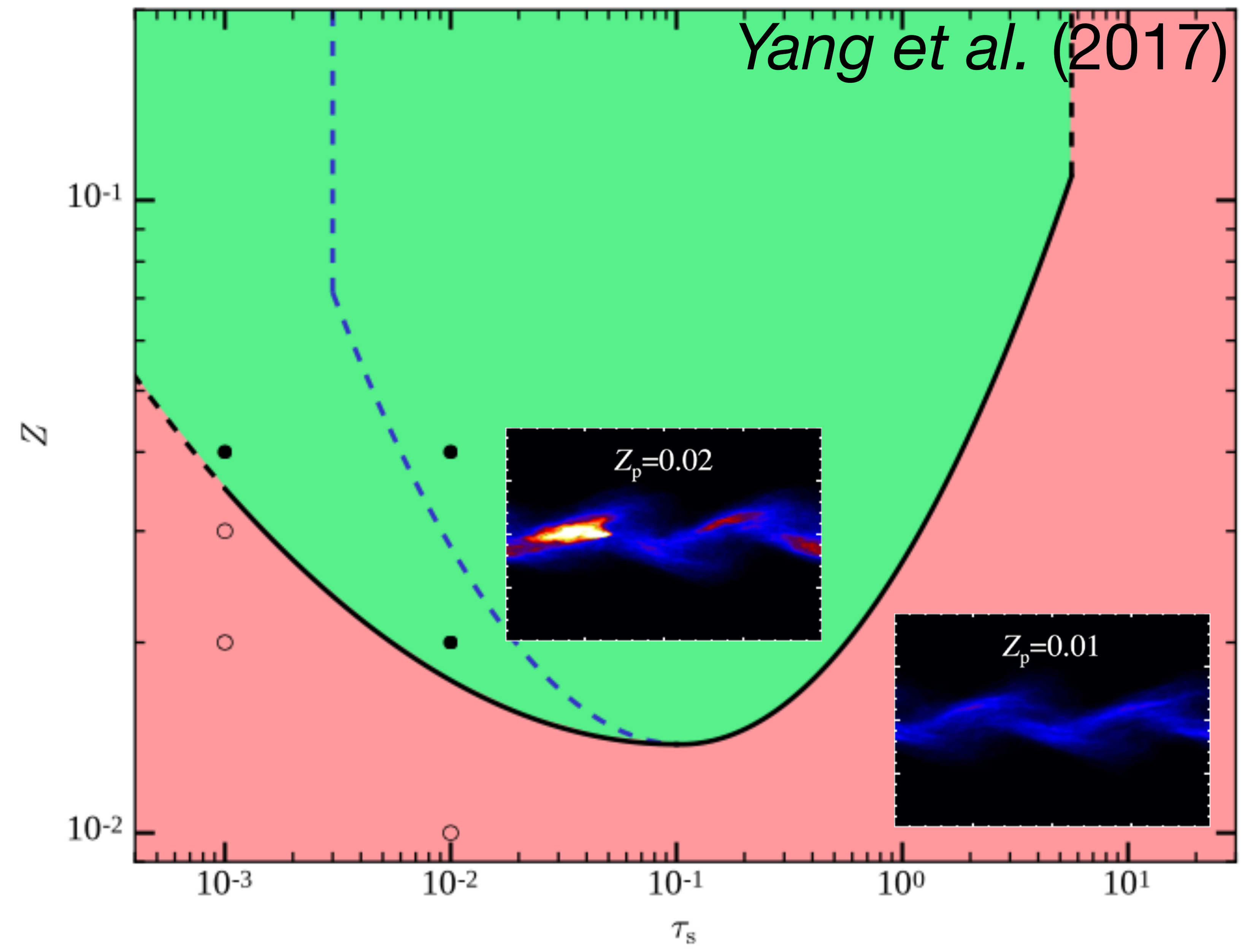
- At least 30% of low-inclination cold Kuiper Belt objects are binary (*Noll et al.*, 2008)
- At least 20% are contact binaries (*Sheppard & Jewitt*, 2004; *Lacerda & Jewitt*, 2007)
- Kuiper belt binary inclinations are very similar to those formed by the streaming instability (*Nesvorny et al.*, 2019)
- New Horizons flew by Arrokoth on 1 January 2019
- Concluded that the two components of Arrokoth formed as a binary that collapsed at a speed of less than 3 meters per second (*McKinnon et al.*, 2020; *Grundy et al.*, 2020; *Spencer et al.*, 2020)
- Support for the “gentle accumulation” model (streaming instability) in contrast to the “violent collisions” (hierarchical growth)

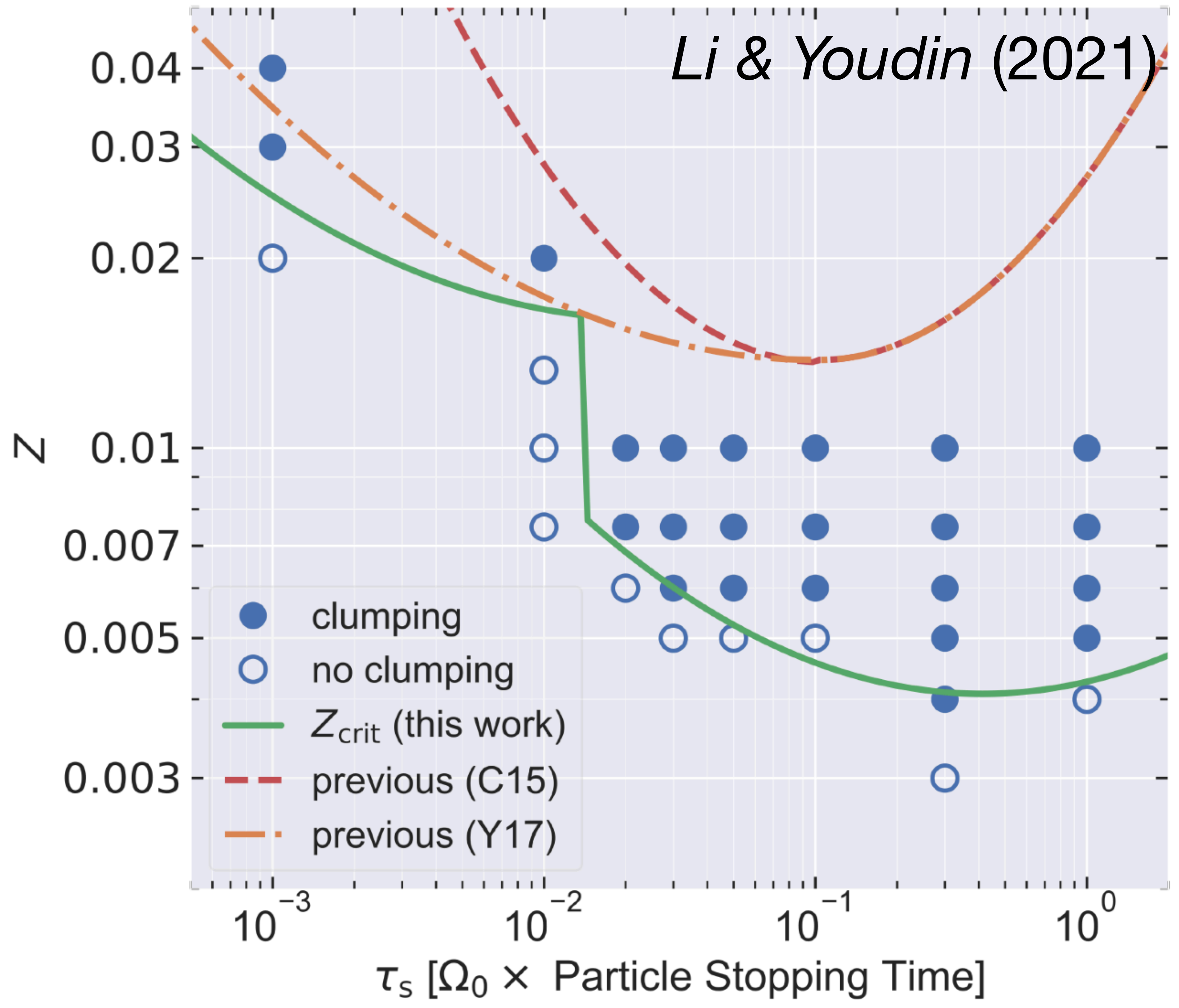
Metallicity threshold

- The streaming instability makes filaments only above threshold metallicity $Z = \Sigma_{\rm p}/\Sigma_{\rm g}$
- *Carrera et al.* (2015), *Yang et al.* (2017), *Li & Youdin* (2021) mapped metallicity threshold as a function of St
- Lowest around a sweetspot at $\mathrm{St} \sim 0.1$
- Jumps to high values for $\mathrm{St} \lesssim 0.01$
- The metallicity threshold can be reached at ice lines, by photoevaporation or in pressure bumps
(*Drazkowska & Alibert*, 2017; *Ros et al.*, 2019; *Zhao et al.*, 2025)
- The characteristic mass of planetesimals formed by the streaming instability scales with stellar mass:

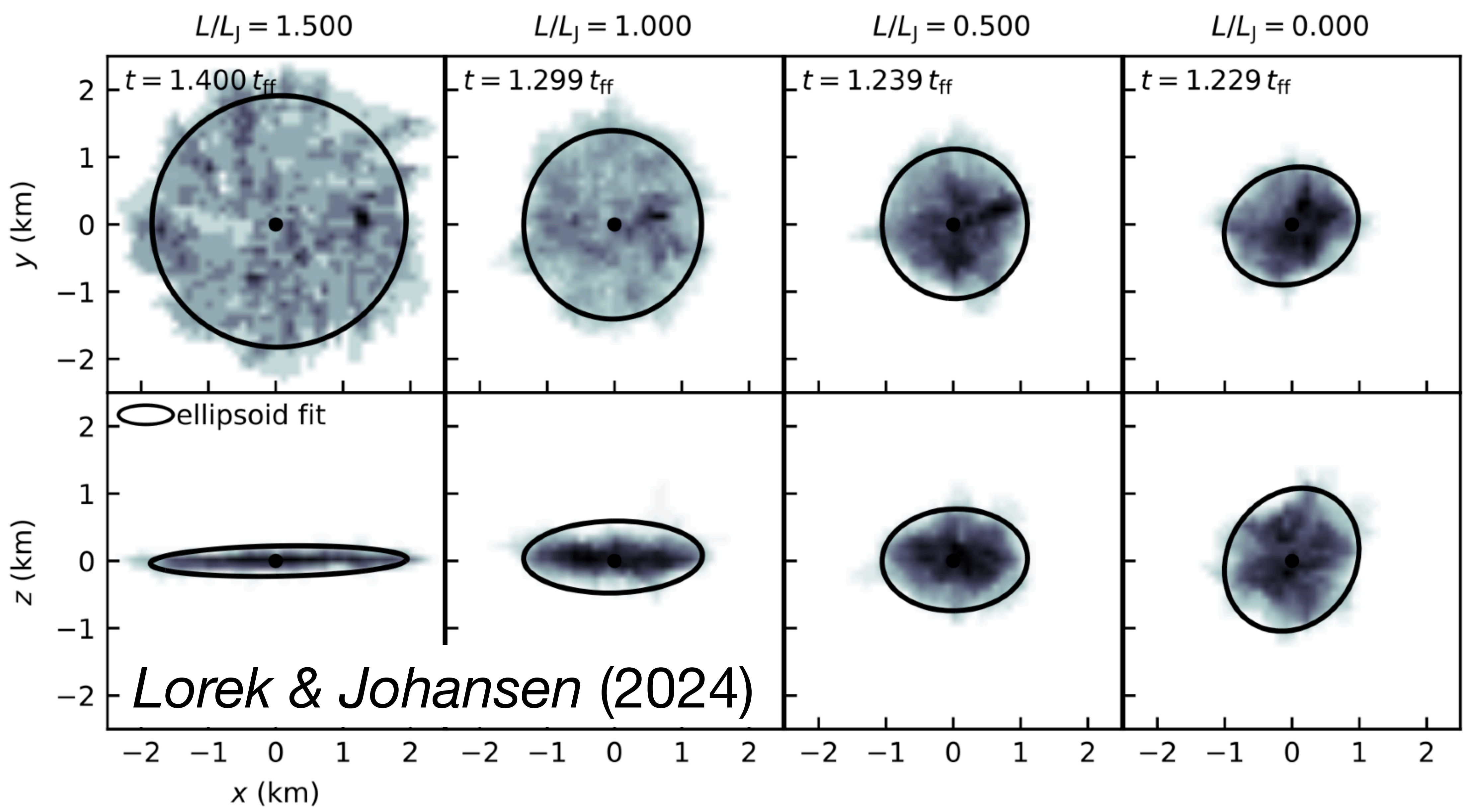
$$M_{\rm SI} = 5 \times 10^{-5} M_{\rm E} \left(\frac{\Gamma}{\pi^{-1}}\right)^{1.5} \left(\frac{H/r}{0.05}\right)^{3} \left(\frac{M_\star}{M_\odot}\right)$$

(Liu et al. incl AJ and TH, 2020; Klahr & Schreiber, 2021; Johansen & Lyra, 2026)

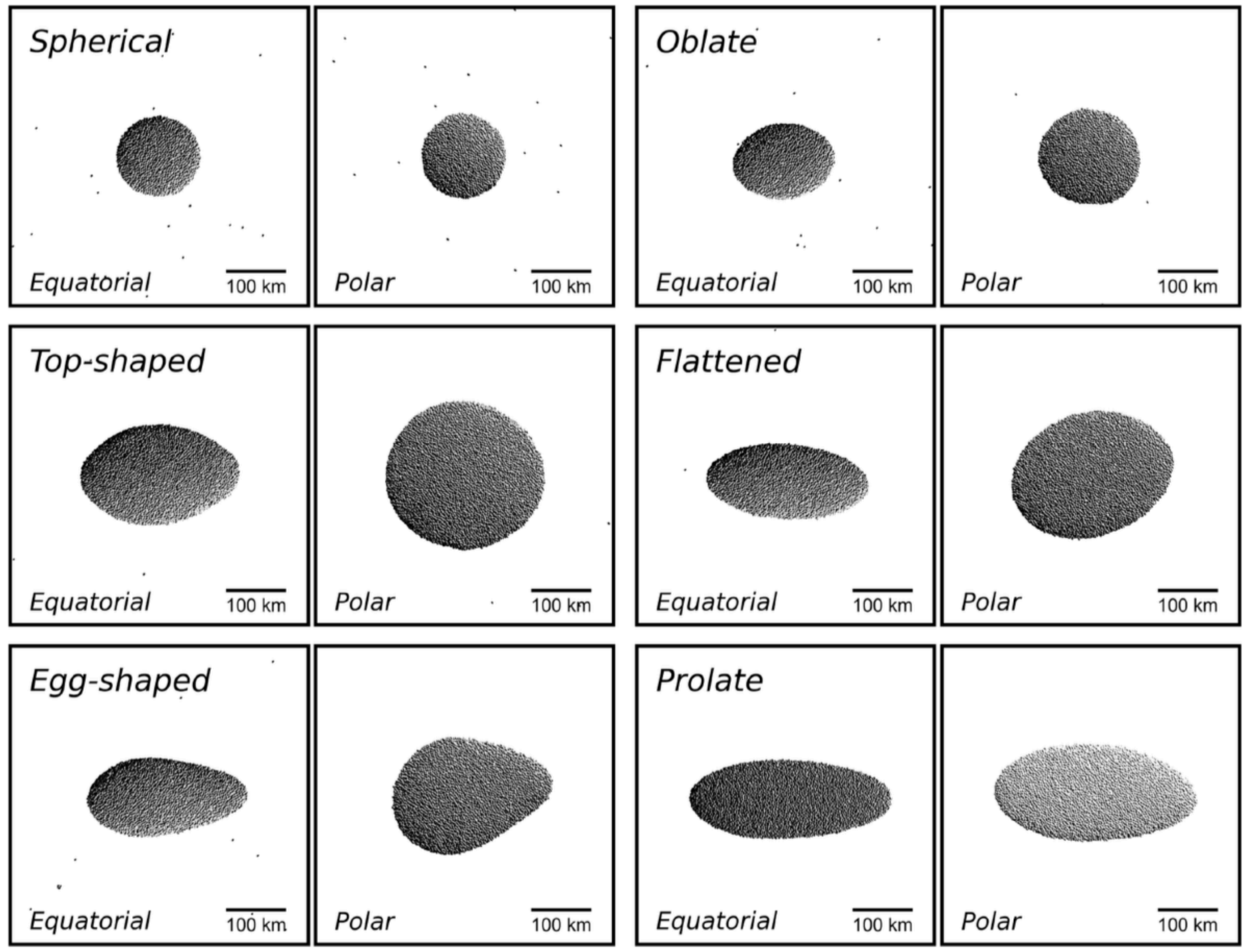




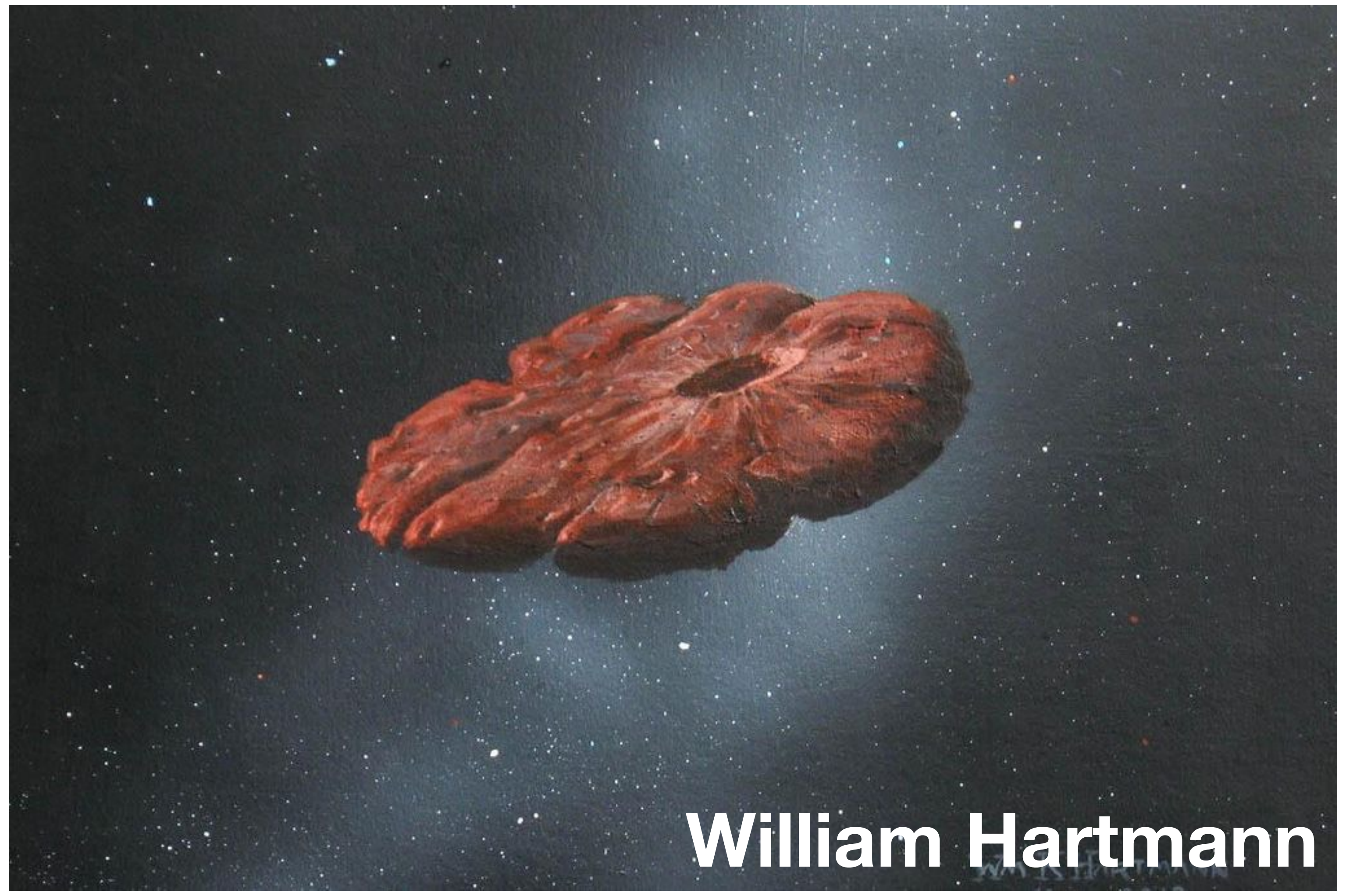
Forming flattened planetesimals



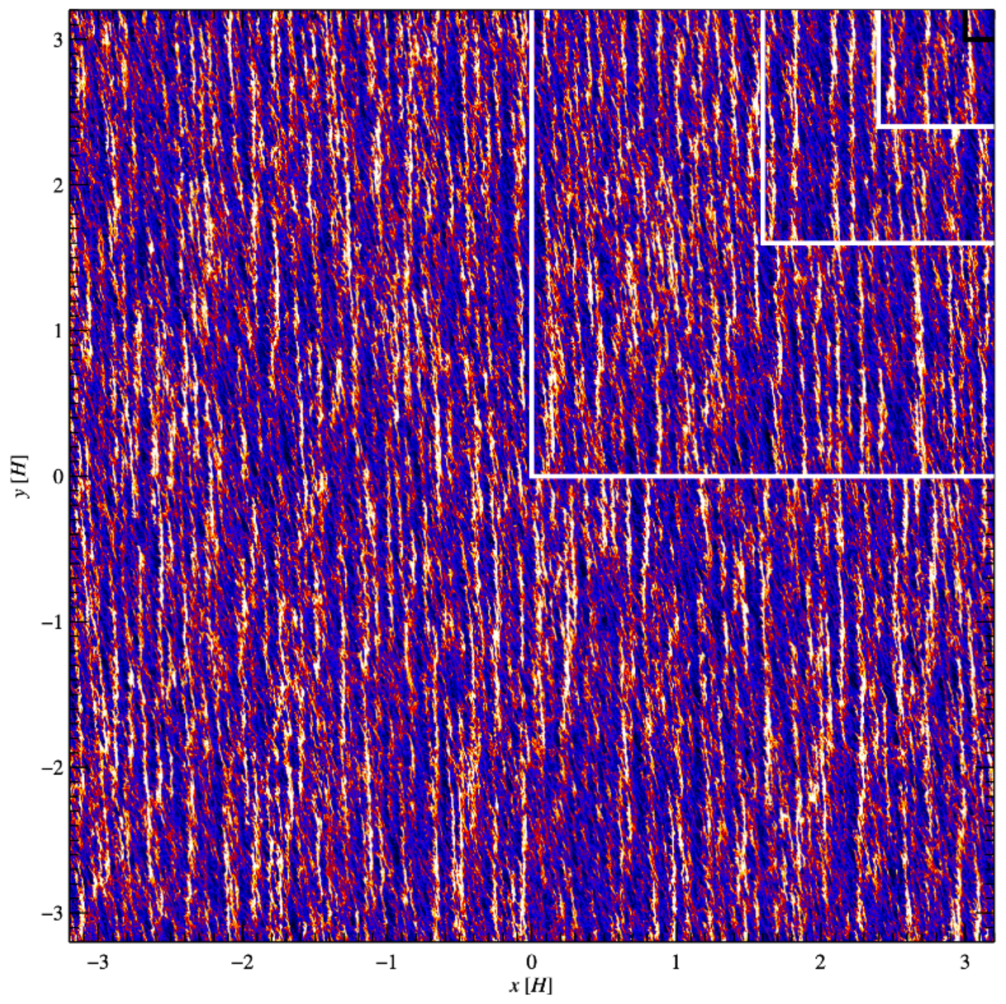
Barnes et al. (2025)

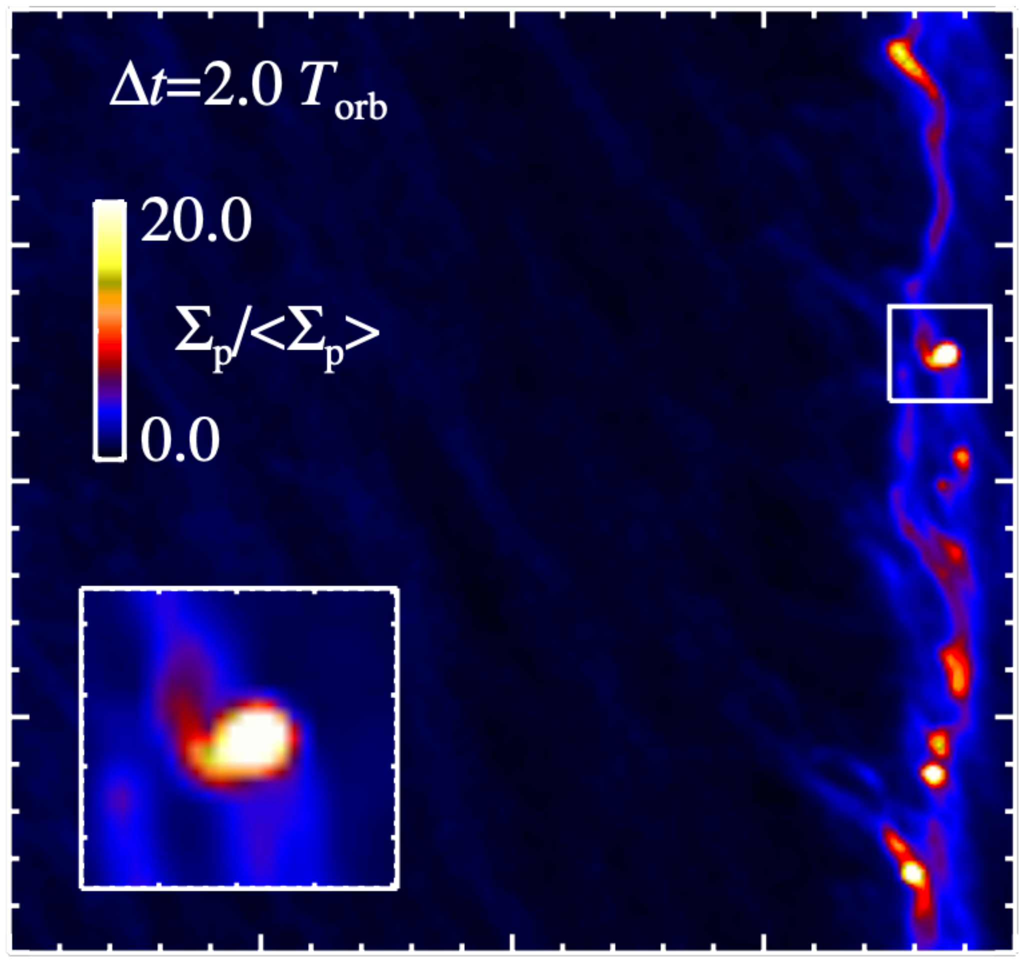


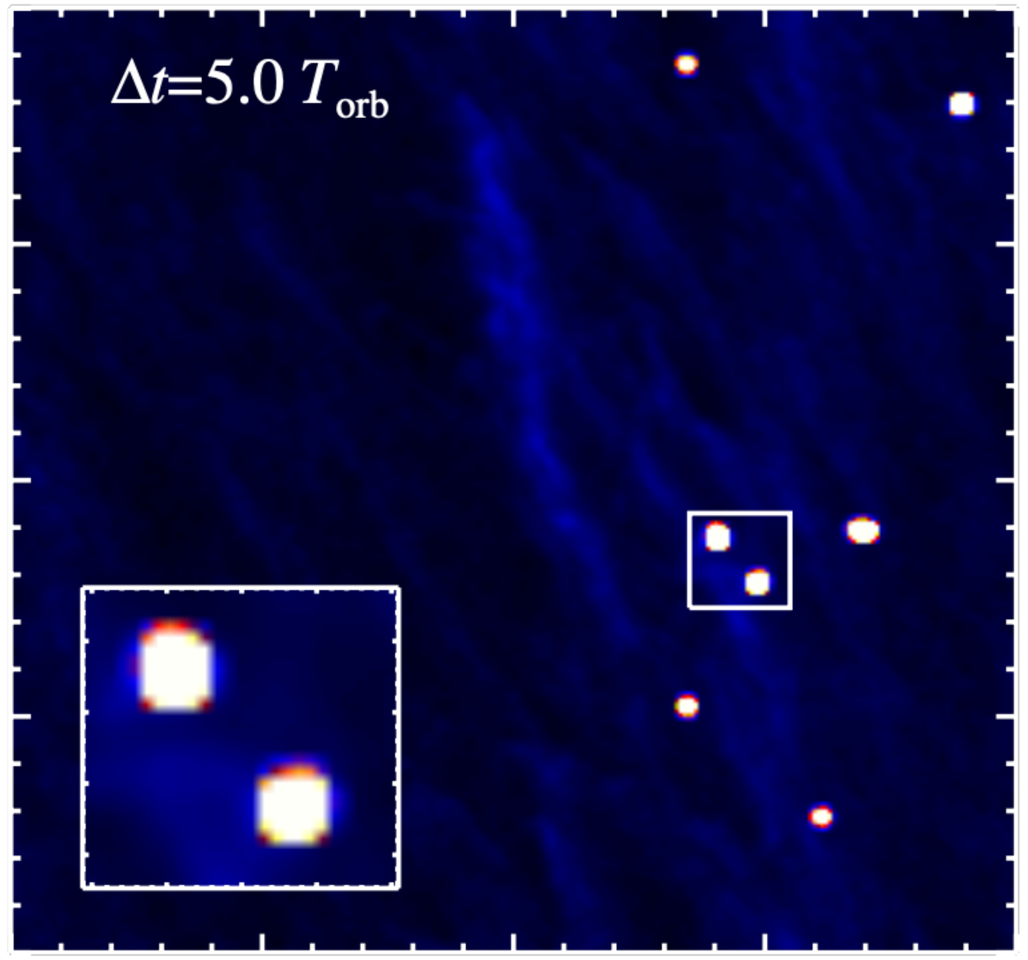
- The angular momentum of the pebble cloud determines whether a planetesimal becomes spherical or oblate (*Lorek & Johansen*, 2024)
- The collapse can lead to a range of other shapes (*Barnes et al.*, 2025)
- The highest angular momentum budgets lead to the formation of pancake-shaped planetesimals akin to interstellar comet 1I/‘Oumuamua (*Maschenko*, 2019)

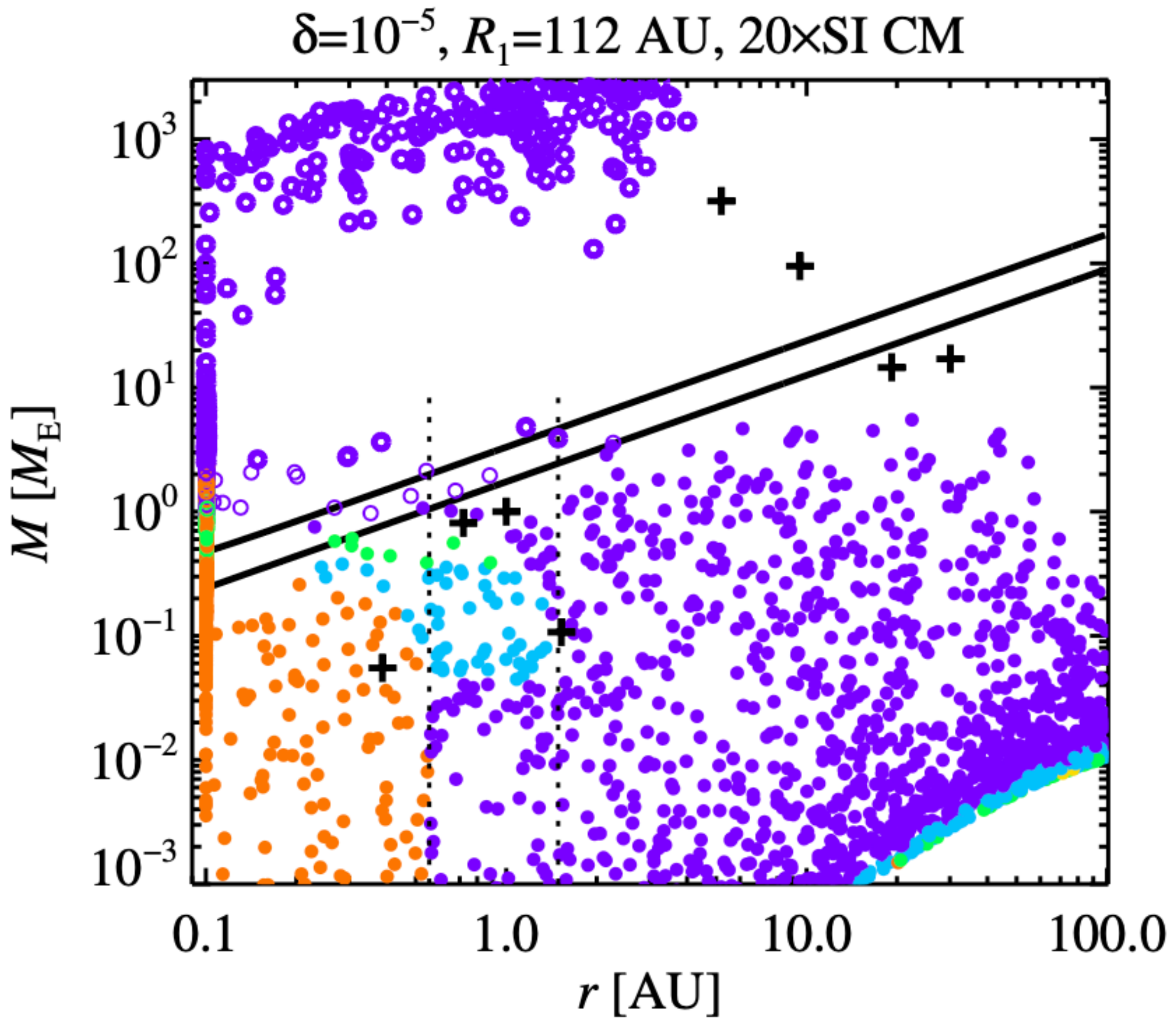


Conclusions









- The streaming instability could only be discovered and explored due to observations of pebbles in protoplanetary discs and dust collision experiments showing poor sticking of pebbles: MPIA was the perfect environment for this

- The streaming instability also led to the development of the pebble accretion theory
(*Ormel & Klahr*, 2010; *Johansen & Lacerda*, 2010; *Lambrechts & Johansen*, 2012)

- Under what conditions is the streaming instability triggered? What are its consequences for planetesimal formation and observations of protoplanetary discs? Those questions continue to inspire a large body of publications concerning the streaming instability.