Planet Formation at Cosmic Dawn

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The Formation of Stars and Planets in the Evolving Galaxy
Okinawa – Aug 3-7, 2026

Planets and planetesimals at cosmic dawn: vortices as planetary nurseries

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Accepted 2025 July 26. Received 2025 July 14; in original form 2025 March 14

The Astrophysical Journal Letters, 970:L19 (7pp), 2024 July 20 https://doi.org/10.3847/2041-8213/ad5af6
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Rapid Protoplanet Formation in Vortices: Three-dimensional Local Simulations with Self-gravity

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Received 2024 February 22; revised 2024 June 11; accepted 2024 June 24; published 2024 July 19

Letter to the Editor

Positive feedback

II. How dust coagulation inside vortices can form planetesimals at low metallicity

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Received 4 April 2025 / Accepted 5 July 2025



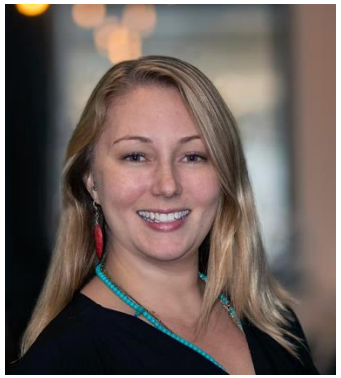
Linn Eriksson



Shyam Menon



Daniel Carrera



Blakesley Burkhart

W. Lyra

Lyra et al. (2024), Carrera et al. (2025), Eriksson et al. (2025)

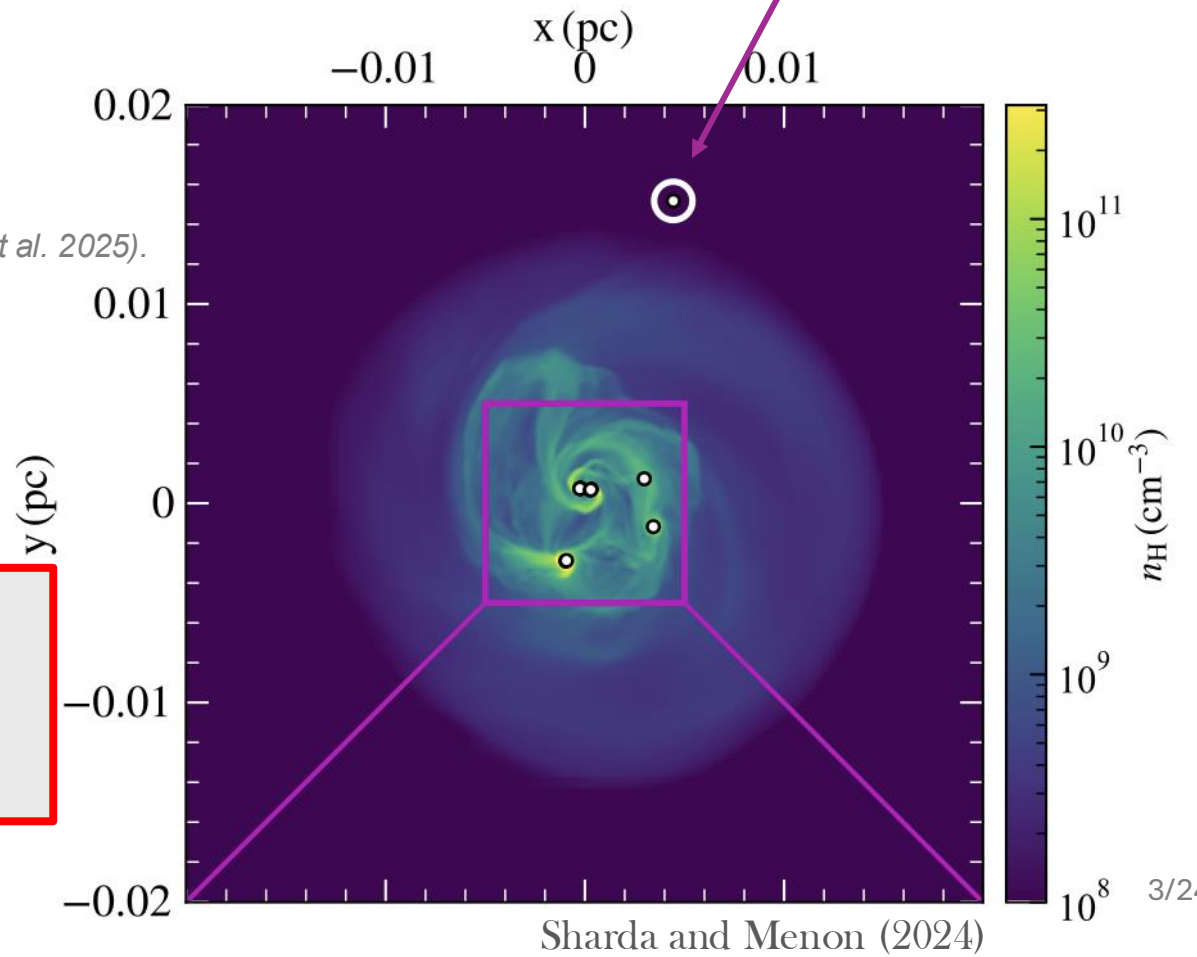
Can star-disk systems suitable for planet formation form at cosmic dawn?

- **Stellar mass**
  Low-mass and solar-mass stars can form at all metallicities *(e.g. Stacy & Broom 2014, Sharda, Federrath & Krumholtz 2020, Prole et al. 2022)*.
  Low mass star formation at zero metallicity *(Sharda & Menon 2024)*.

- **Metallicity/Solid-mass**
  - On average metal enrichment is slow
  - Localized regions may have higher metallicity

Examples: A disk with $Z = 0.04 Z_{\odot}$ forms in pair-instability SN explosion simulation at redshift $z \sim 20$ *(Whalen et al. 2025, Vorobyov et al. 2025).*

Star: $0.45\ M_{\odot}$
Disk: $0.007\ M_{\odot}$



Sharda and Menon (2024)

When did the first planet form?
When did the Universe start getting populated with planets?

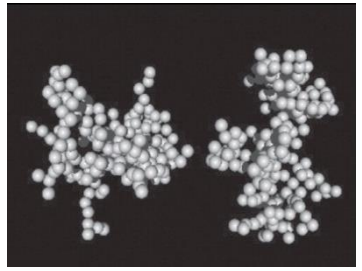
What metallicity do we need to form planets?

Slide by L. Eriksson

Planet Formation 101

Core Accretion

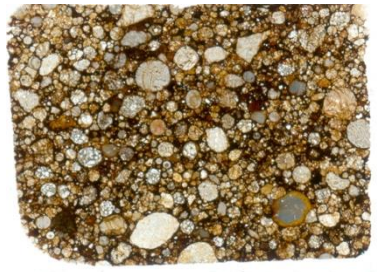
Dust grains



0.1 – 1 μm

coagulation

Pebbles



mm – cm

Streaming Instability

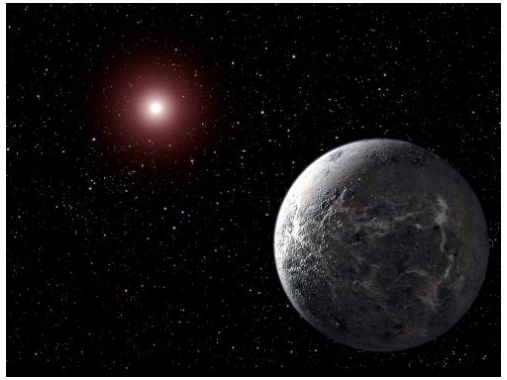
Planetesimals



1-100km

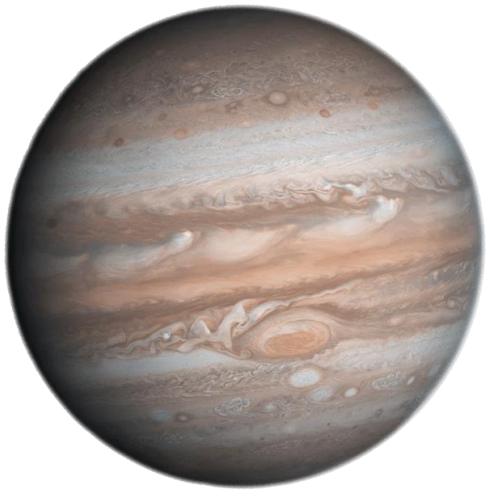
Pebble Accretion

Protoplanets
Rocky Planets
Planetary Cores



Significant Gas Accretion

Little gas accretion



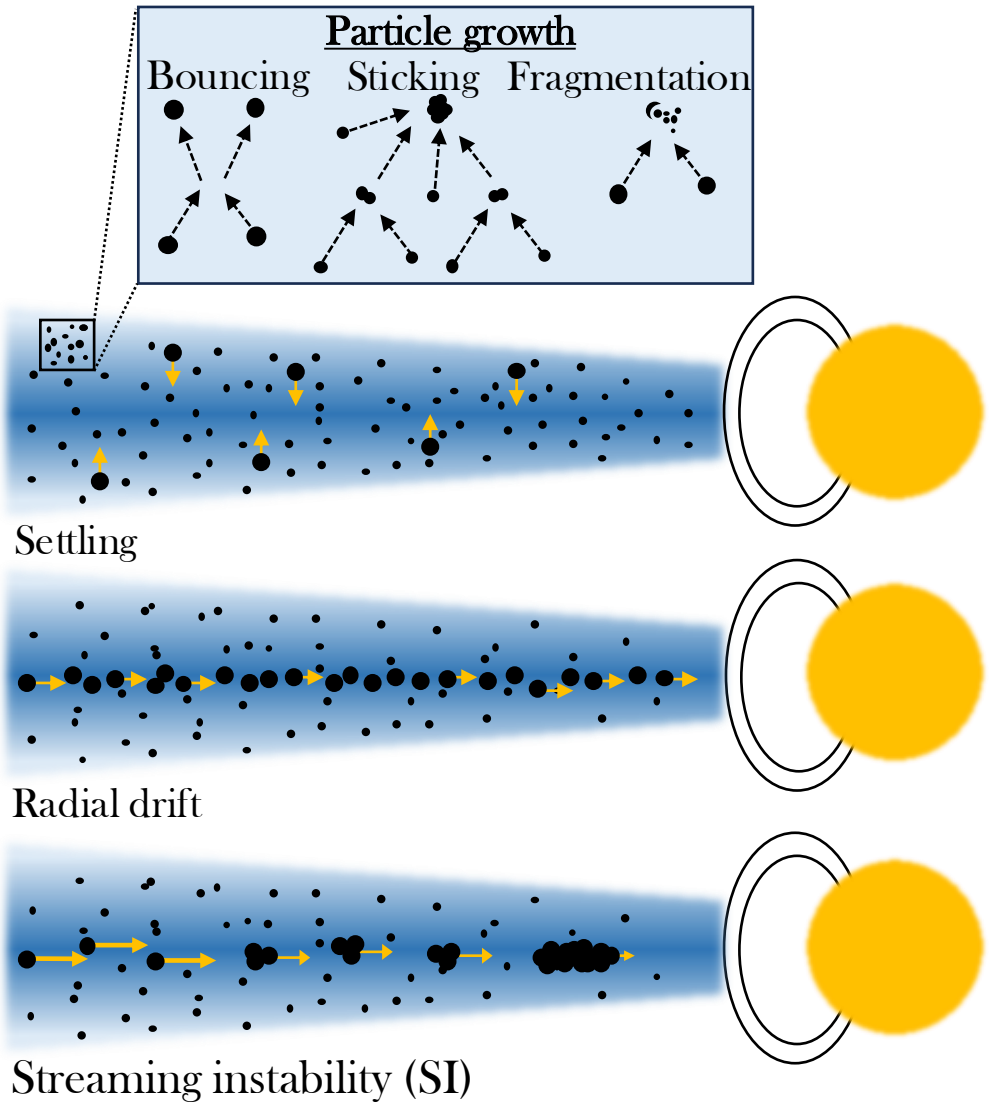


Collisional dust growth

- DustPy *(Stammler & Birnstiel 2022)*
- 1D viscous accretion disk *(Lynden-Bell & Pringle 1974)*
- $\tau_{\mathrm{disk}} = 3\mathrm{Myr}$
- $\mathrm{M_{star}} = 0.45\ \mathrm{M_\odot}$
- $\mathrm{M_{disk}} = 0.007\ \mathrm{M_\odot}$
- $\alpha_{\mathrm{Shakura-Sunyaev}} = 5{\times}10^{-3}$

Parameter study:

- $Z = \frac{\Sigma_{\mathrm{solid}}}{\Sigma_{\mathrm{gas}}} = [10^{-4} - 1.6{\times}10^{-3}]$
- $\alpha_{\mathrm{t}} = [10^{-5} - 10^{-3}]$
- $v_{\mathrm{frag}} = [1\mathrm{ms}^{-1} - 10\mathrm{ms}^{-1}]$

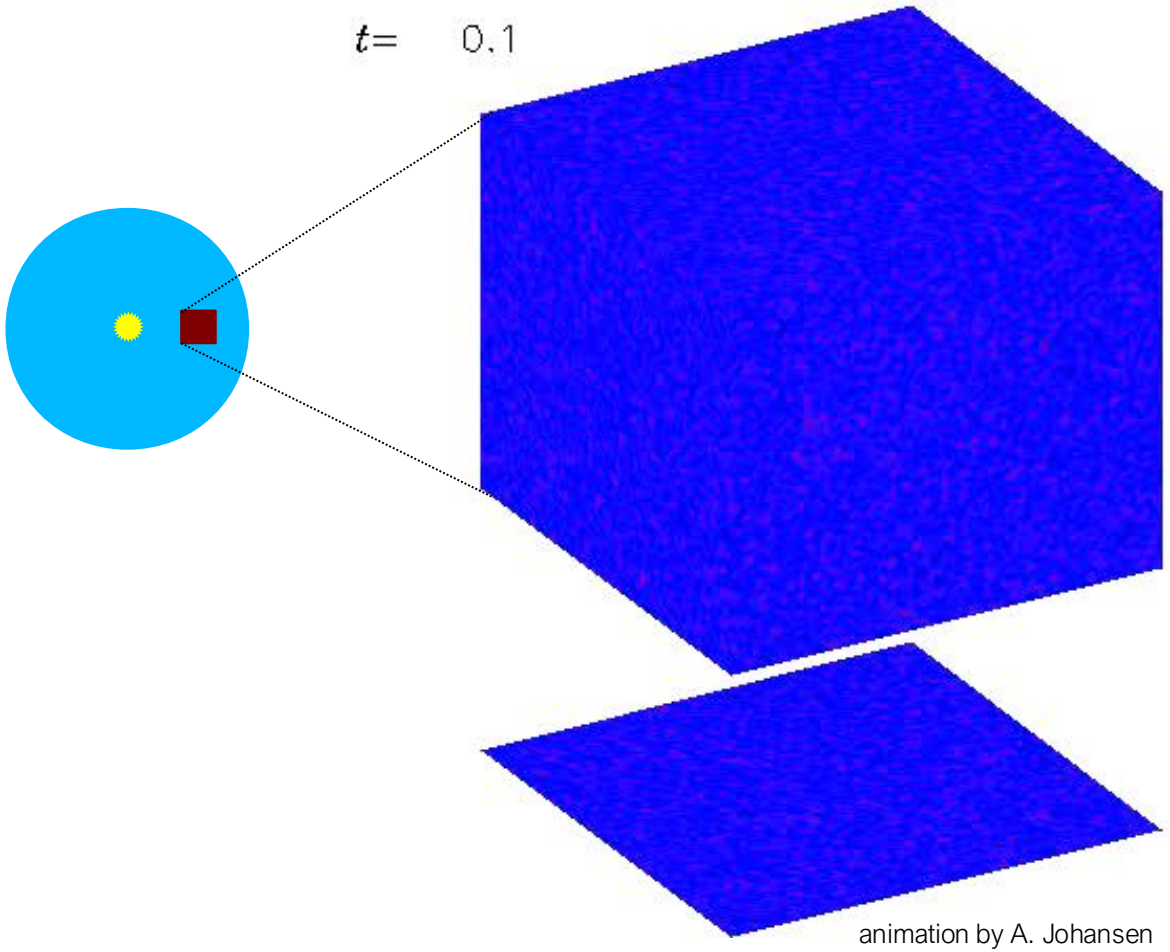


Slide by L. Eriksson

Planetesimal Formation

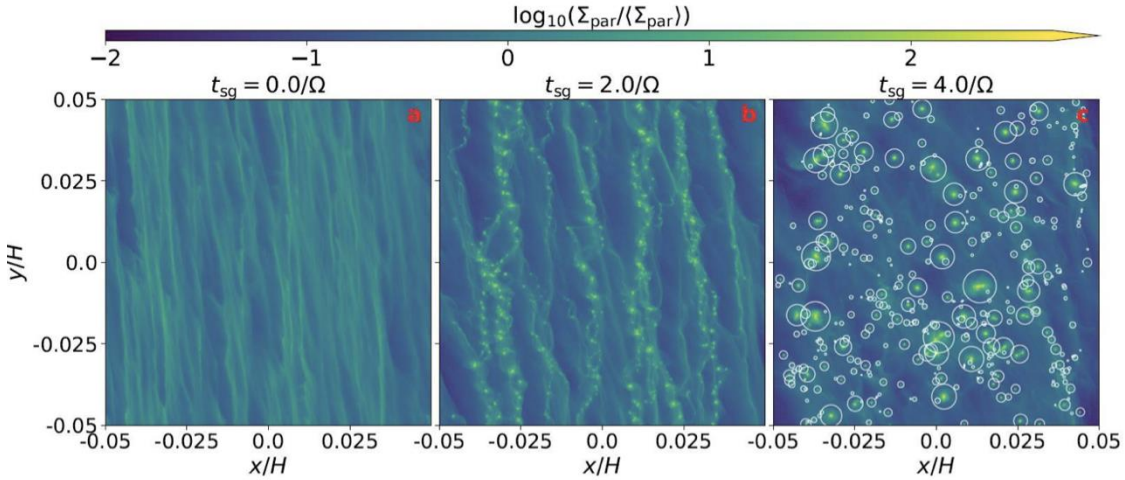
Streaming Instability: The dust drift is hydrodynamically unstable

(see also Tominaga's talk)



animation by A. Johansen

Filaments form and fragment into gravitationally bound clumps

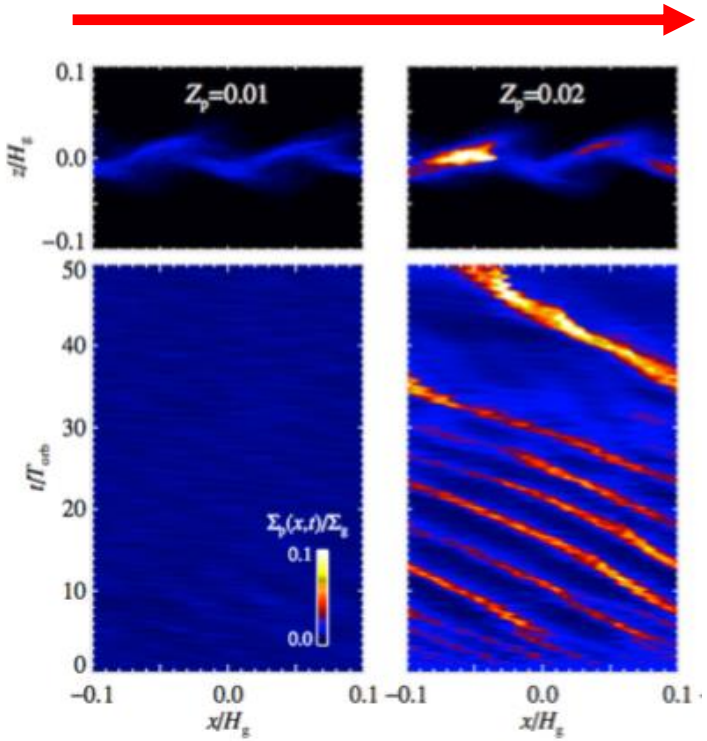


Nesvorny+'19; model by Rixin Li

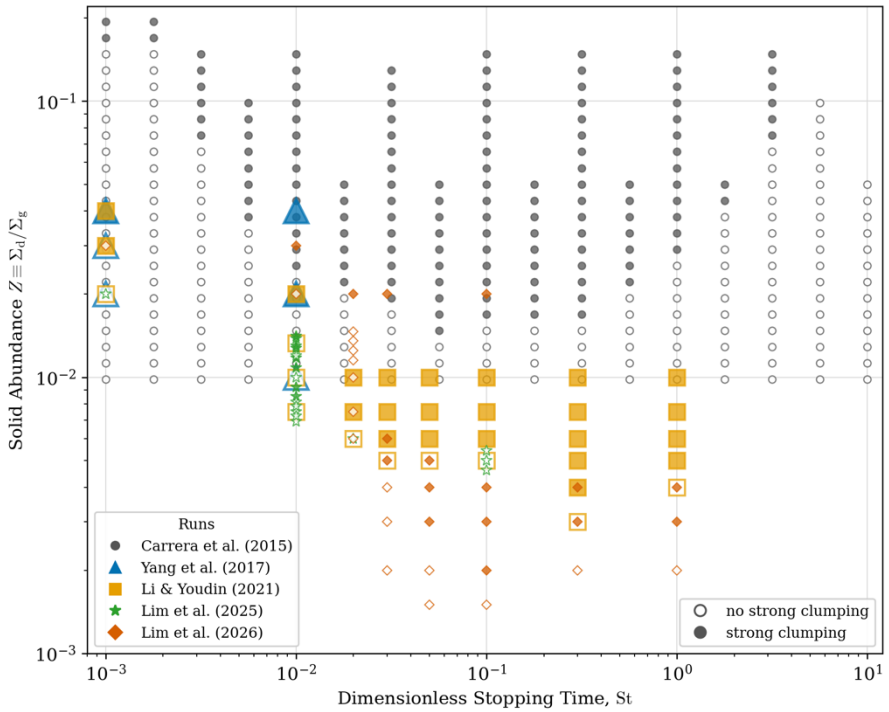
Youdin & Goodman 2005, Johansen & Youdin 2007, Youdin & Johansen 2007, Kowalik+ 2013, Lyra & Kuchner 2013, Schreiber+ 2018, Klahr & Schreiber 2020, Simon+ 2016, 2017, Carrera+ 2015, 2017, 2020, Gole+ 2020, Li+ 2018, 2019, Abod+ 2019, Nesvorny+ 2019, Li & Youdin 2021, Carrera & Simon 2022, Canas+Lyra 2024, Lim+ Lyra 2024, 2025, 2026, Godines+Lyra 2026, Baronett+Lyra 2026.

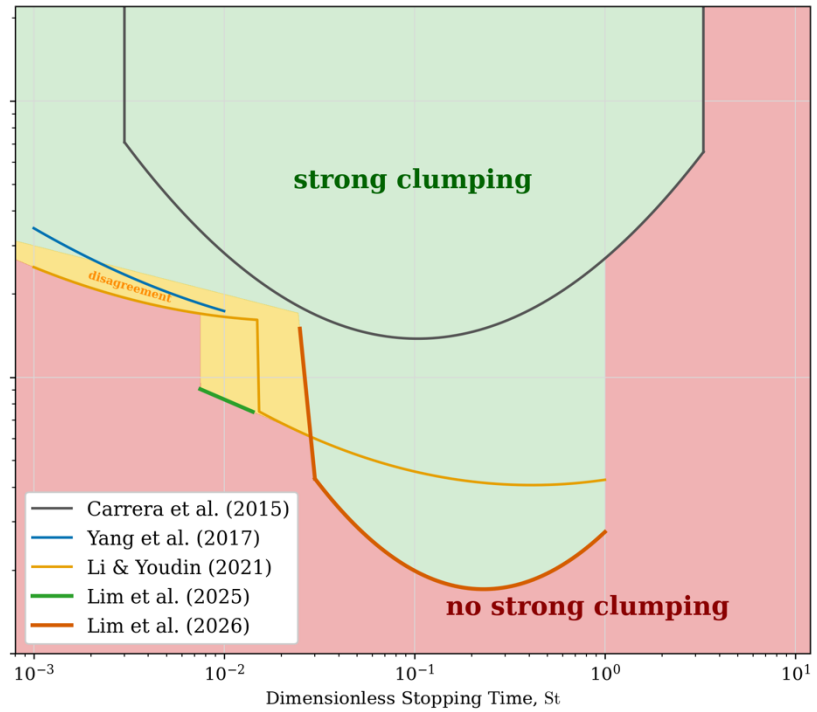
Metallicity and Stokes number dependency for strong clumping

Metallicity



Johansen et al. (2011)

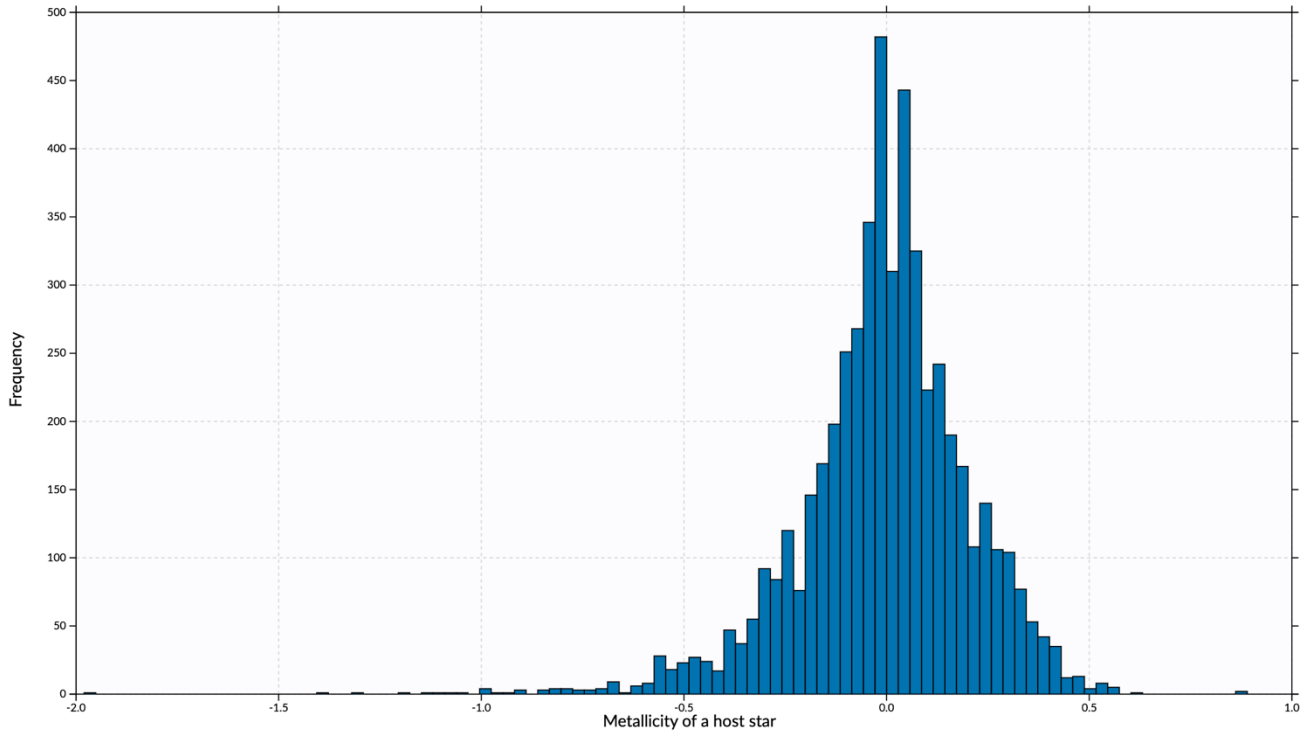




Lyra, Johansen, Youdin & Ida (in prep)

see also Tominaga's talk

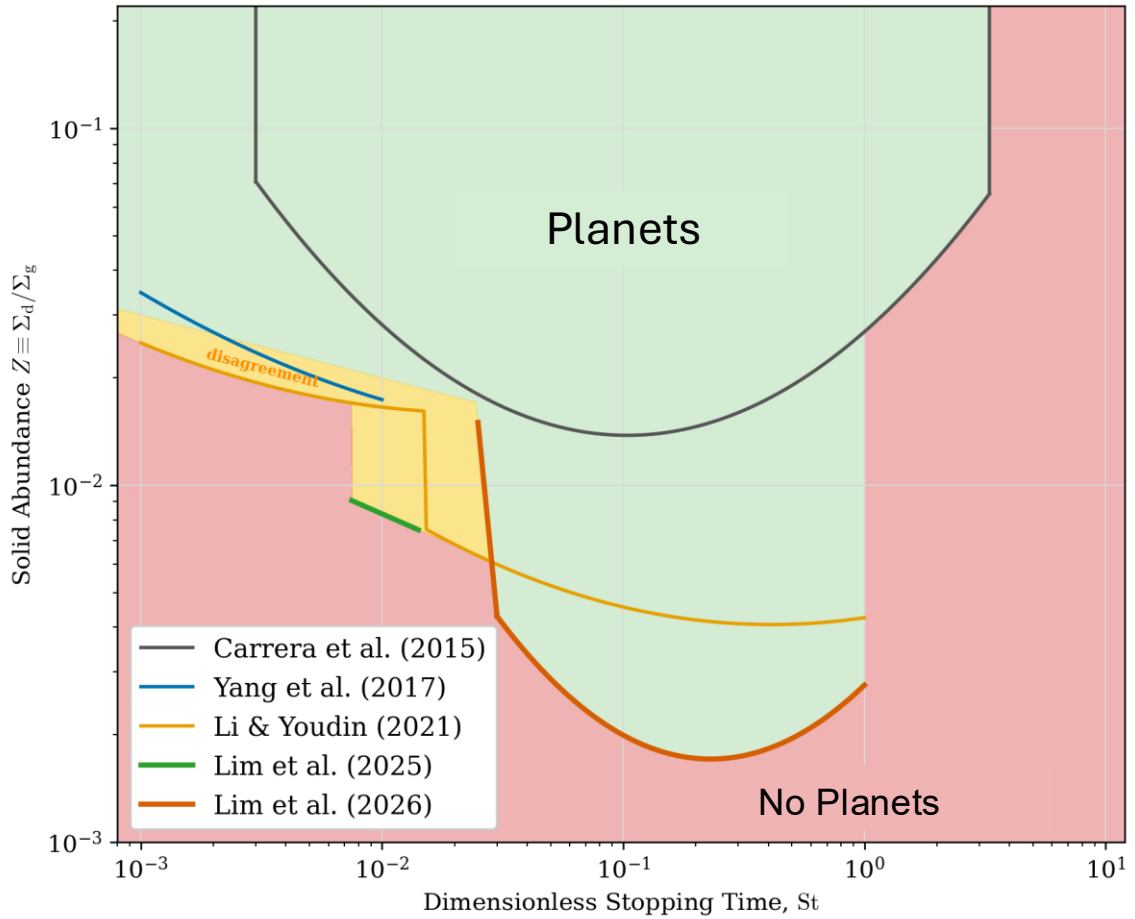
Metallicity threshold?



[Fe/H]

From exoplanet encyclopedia

$Z = Z_\odot \, 10^{[Fe/H]}$



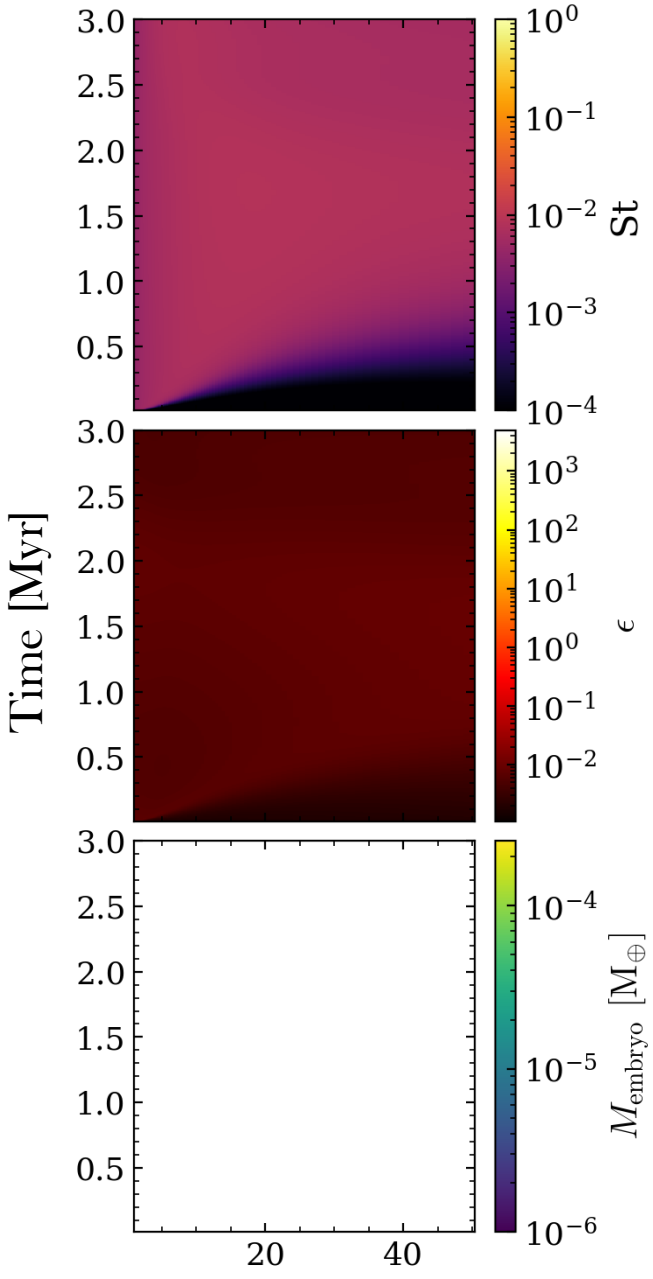
Lyra, Johansen, Youdin & Ida (in prep)

see also Stamatellos's talk

Dust growth + Planetesimal formation

- No planetesimal formation in smooth, low-metallicity disks
- Can we locally increase the solid-to-gas ratio?

This simulation: $Z = 1.6\times10^{-3}, \alpha_t = 5\times10^{-5}, v_{frag} = 1 ms^{-1}$



Density-weighted average Stokes number

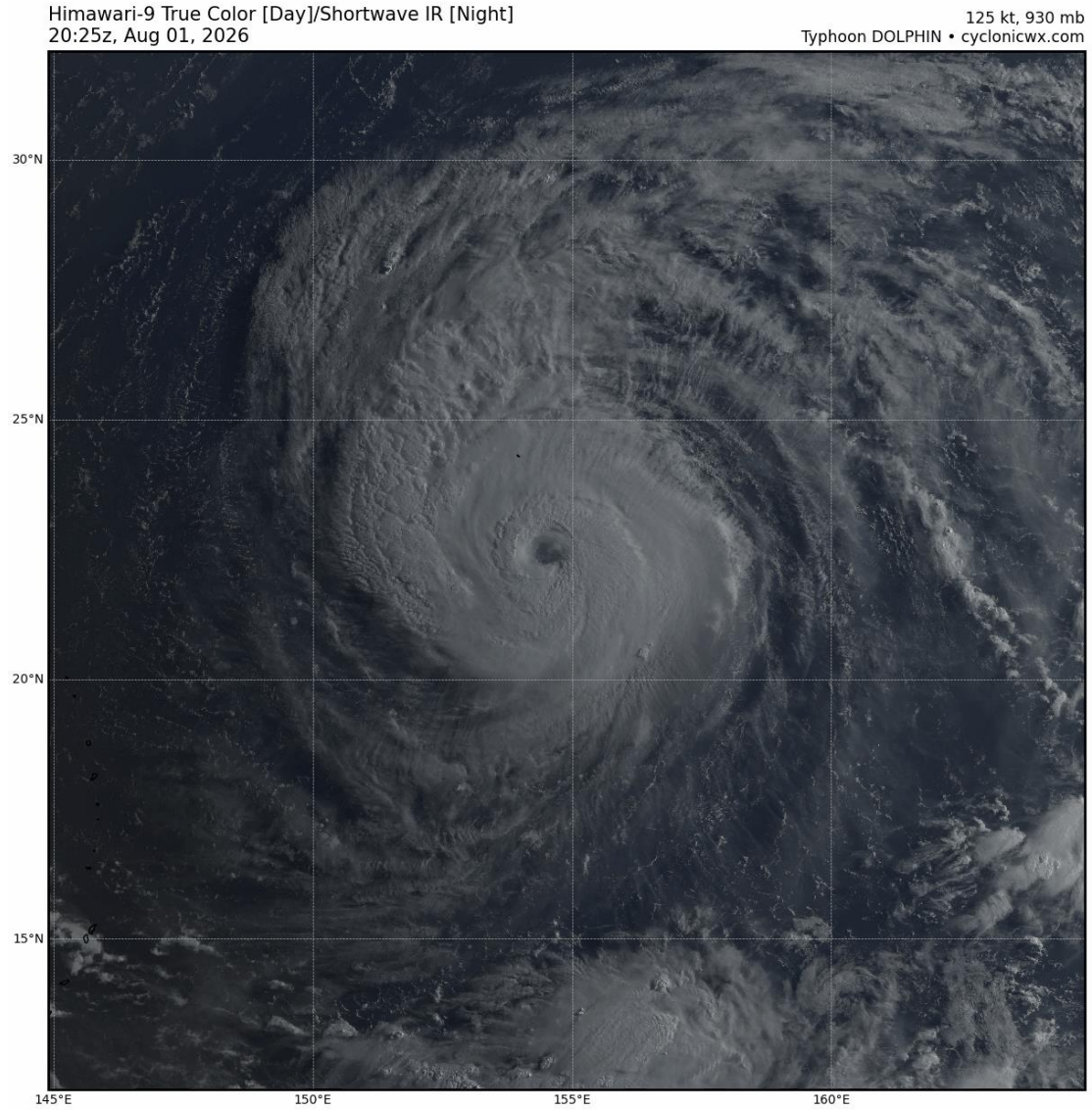
Solid-to-gas midplane density ratio

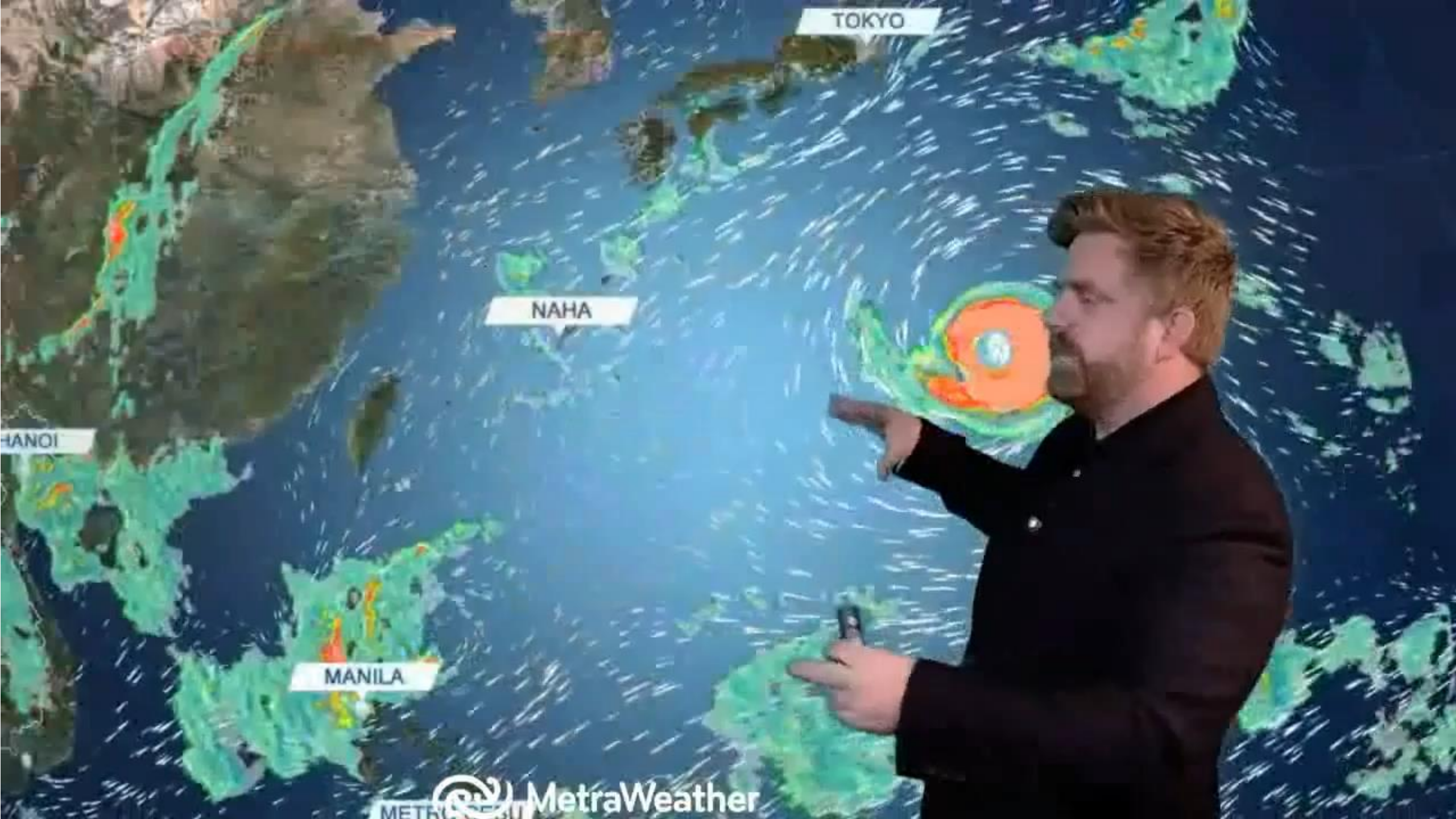
When and where planetesimals can form

Slide by L. Eriksson

Eriksson et al. (2025)

How to increase the solids-to-gas ratio locally?
A vortex!




TOKYO
NAHA
HANOI
MANILA
MetraWeather

Disk structure

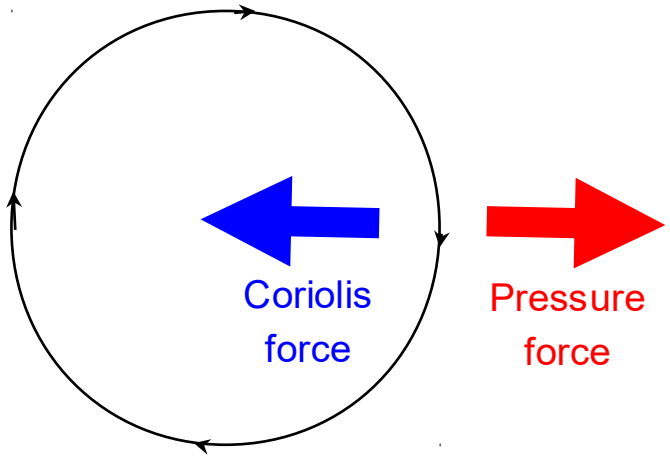
- Vortices are the end state of many hydrodynamical instabilities
- Dust gets concentrated towards the center
  (Barge & Sommeria 1995, Klahr & Henning 1997)

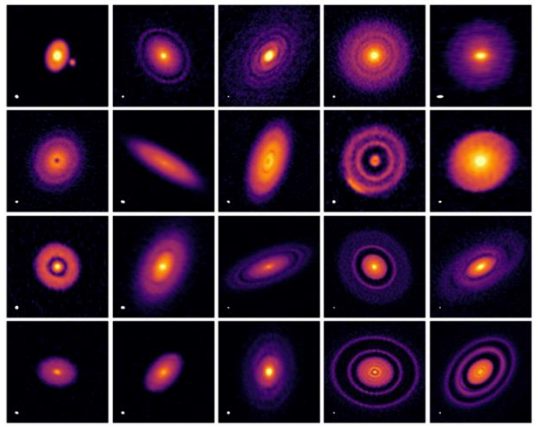
$$\varepsilon = \varepsilon_0 (1+ St/\alpha_t)^{3/2}$$

(Lyra & Lin 2013)

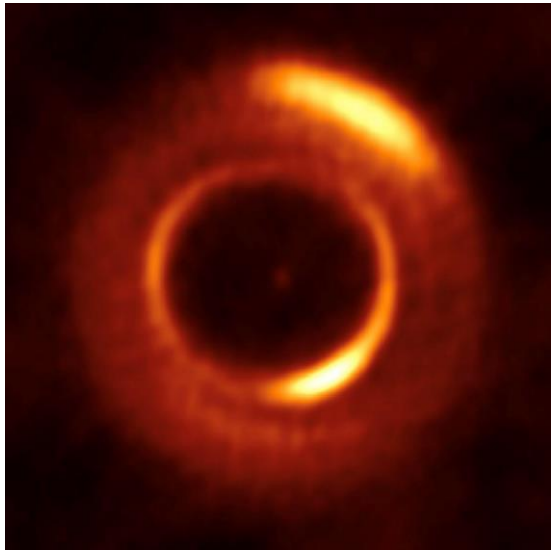
$$\alpha_t = v_{rms}^2/c_s^2$$

- Easily reaches dust-to-gas ratio 1 even for sub-solar metallicities
- Prime sites for planet formation
  (Klahr 2006, Lyra et al. 2008, 2009, 2024, Raettig et al. 2021)

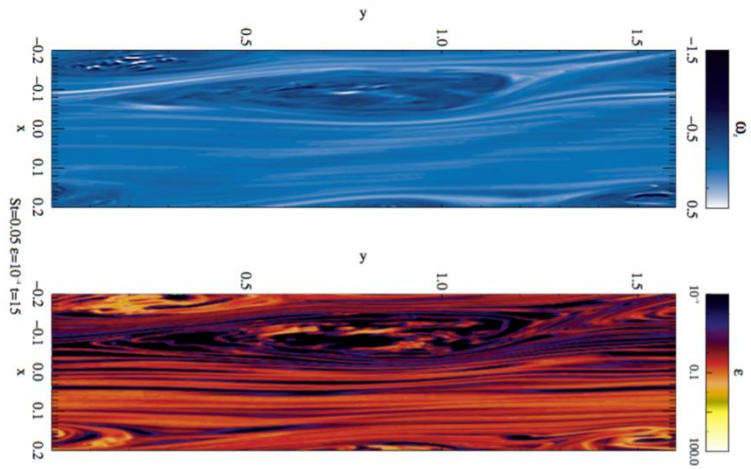


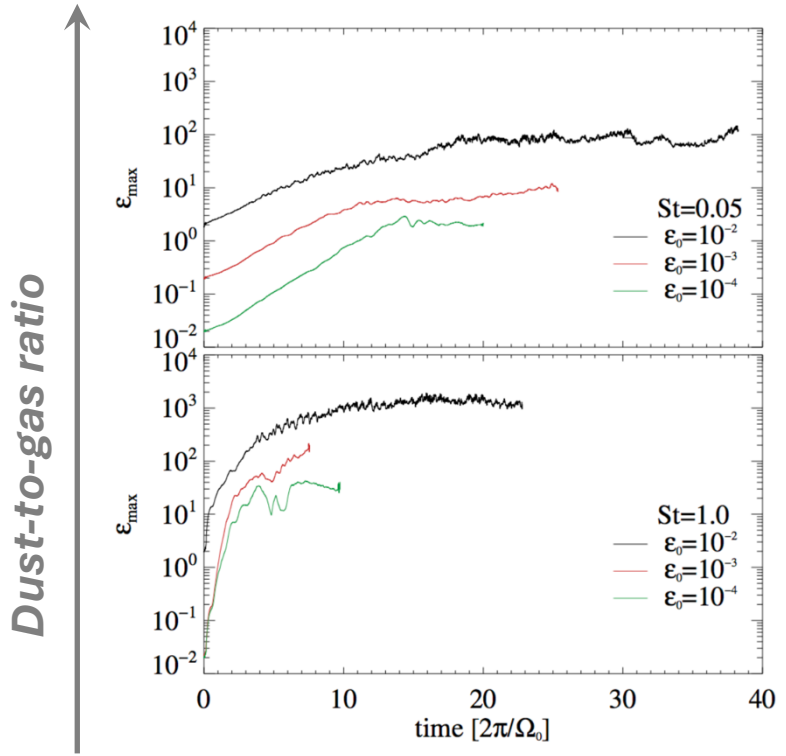


DSHARP, Andrews et al. (2018)



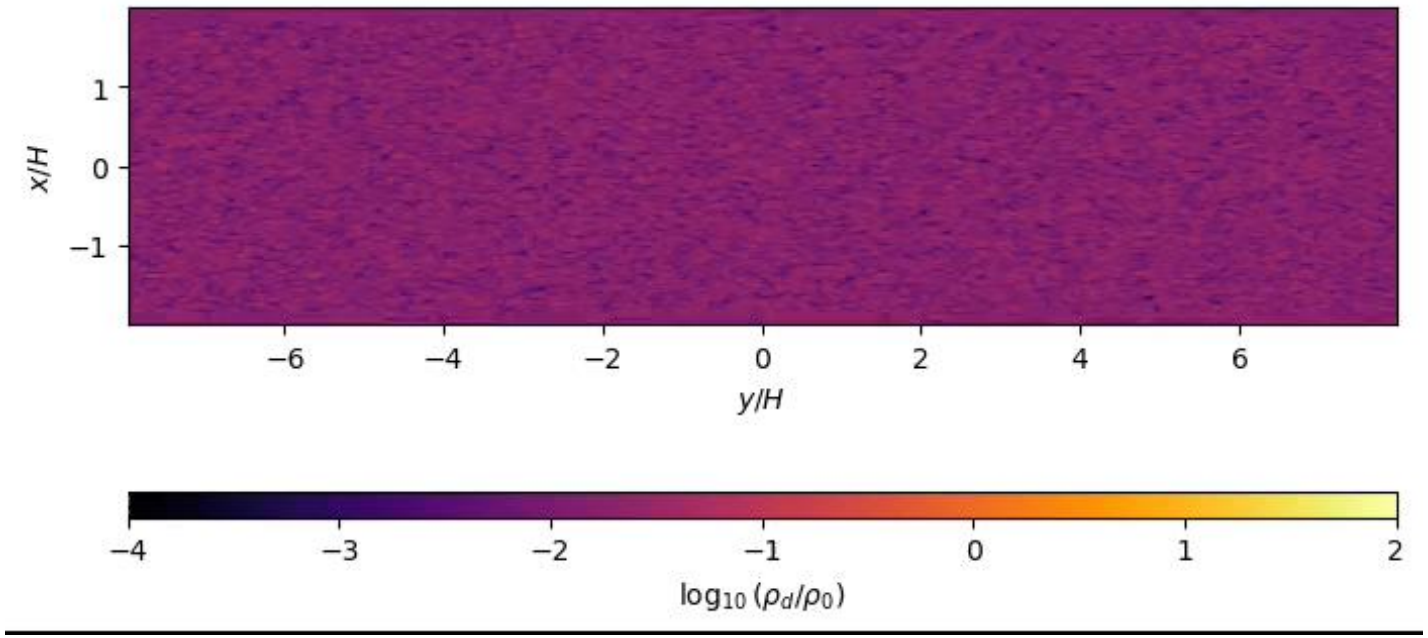
Dong et al. (2018), Cassasus+Lyra (2019)

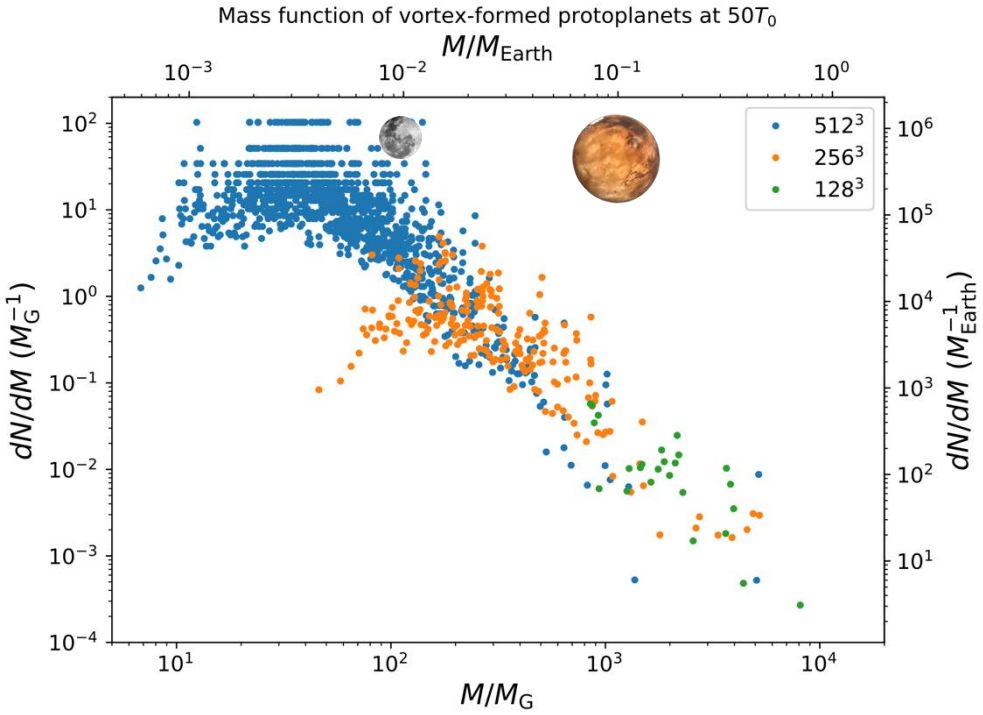




Raettig, Lyra, & Klahr (2021)

Gravitational Collapse





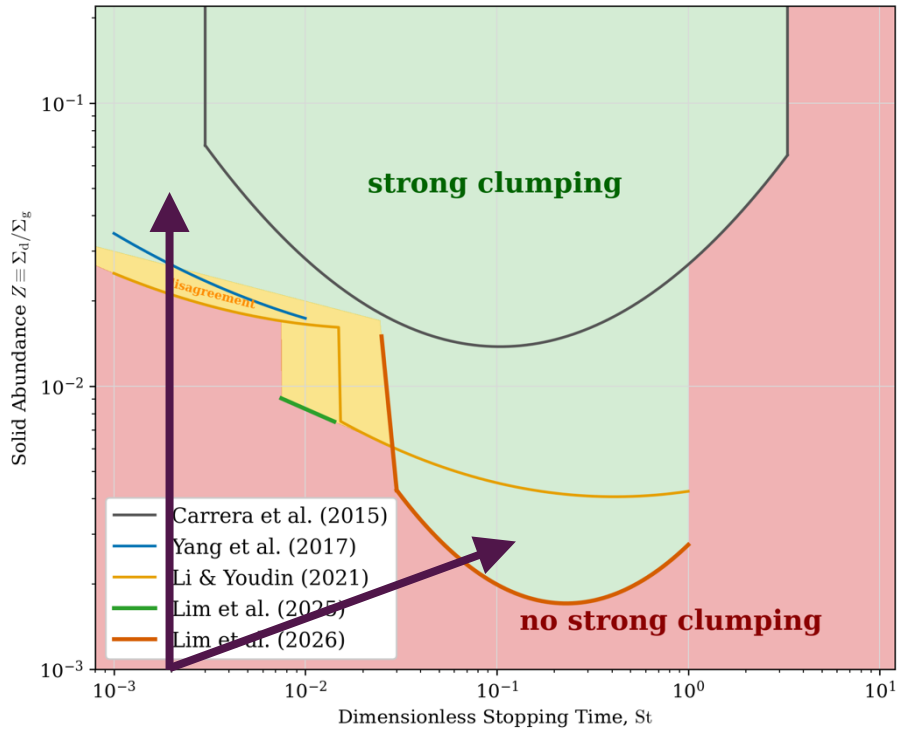
Lyra et al. (2024)

Vortex "Boost" $Z = Z_0 (1 + St/\alpha_t)$
For Population II and III stars

Z (pop II): $10^{-4}\, Z_\odot \leq Z < 10^{-1}\, Z_\odot$
Z (pop III) $\approx< 10^{-4}\, Z_\odot$

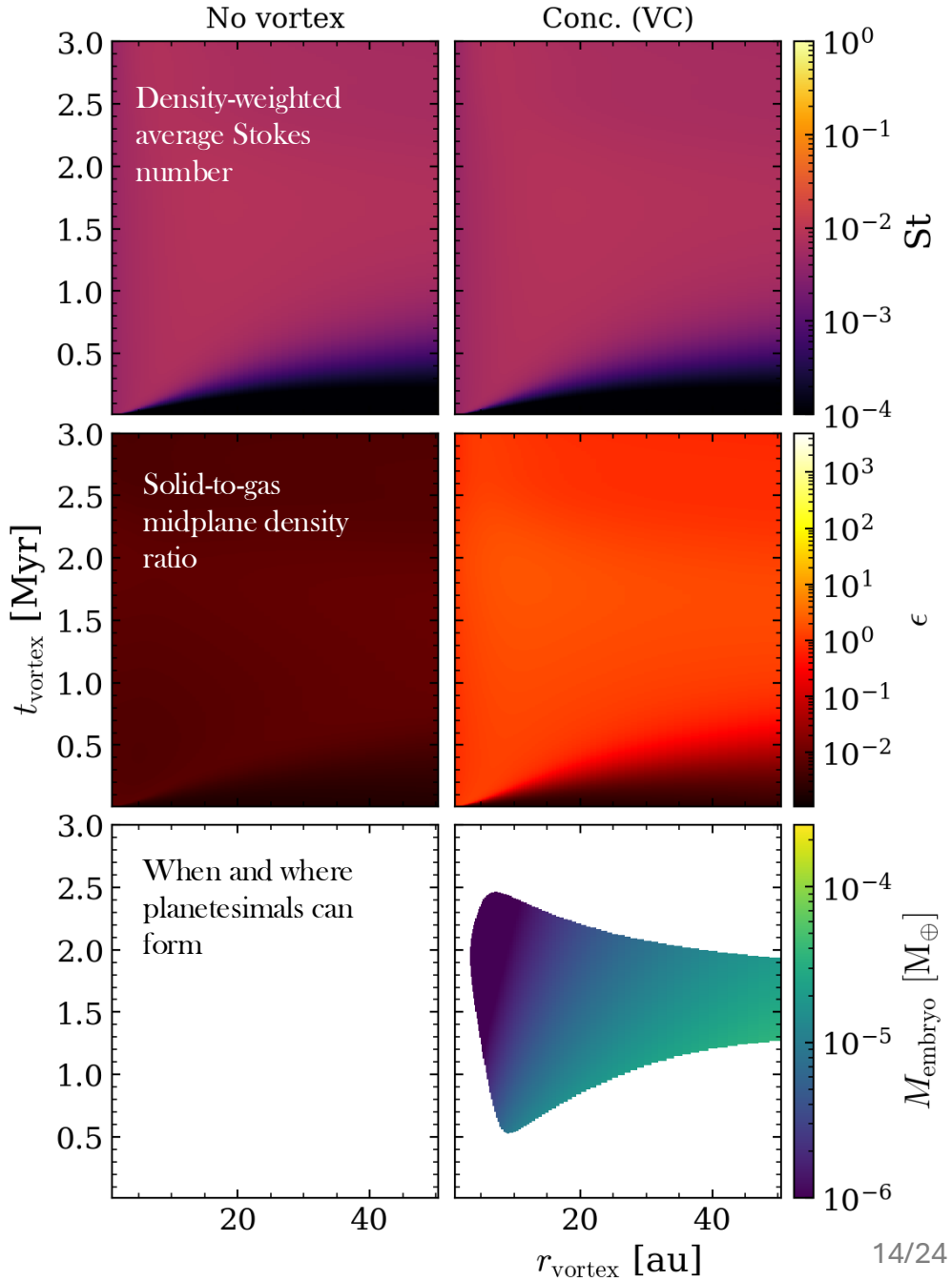
The boost in dust-to-gas ratio might be able to get the grains into the strong clumping regime

$Z = Z_\odot\, 10^{[Fe/H]}$



- Post-process DustPy data to find solid-to-gas ratio for all possible vortex formation times and locations
- Is the solid-to-gas ratio high enough for planetesimal formation inside the vortex? Yes!

This simulation: $Z = 1.6\times10^{-3}, \alpha_t = 5\times10^{-5}, v_{frag} = 1 ms^{-1}$



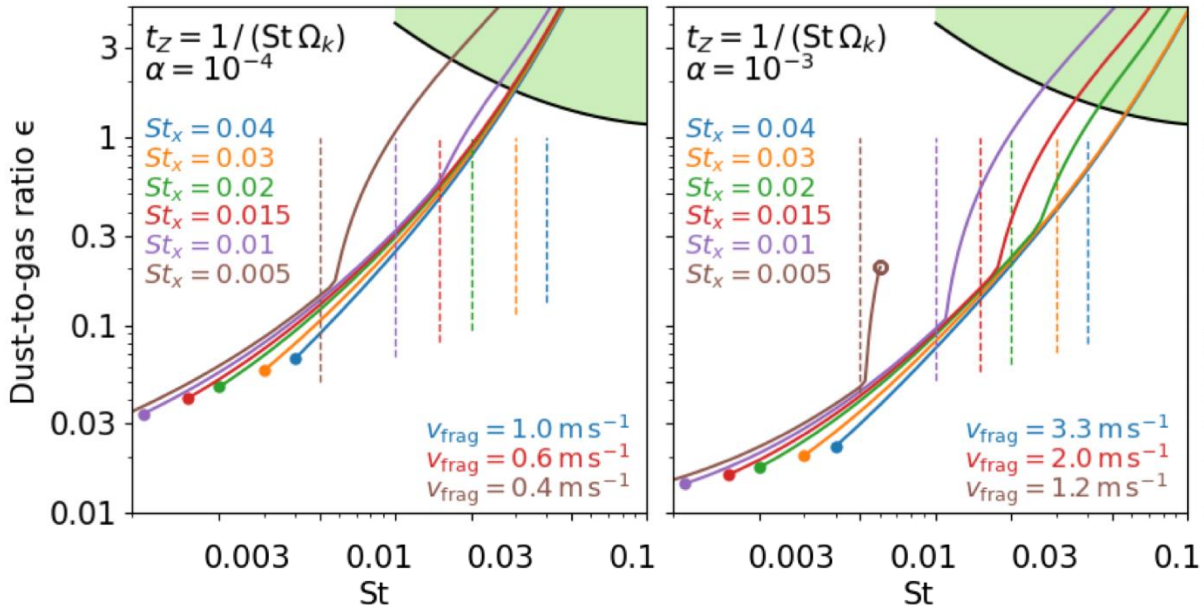
W. Lyra

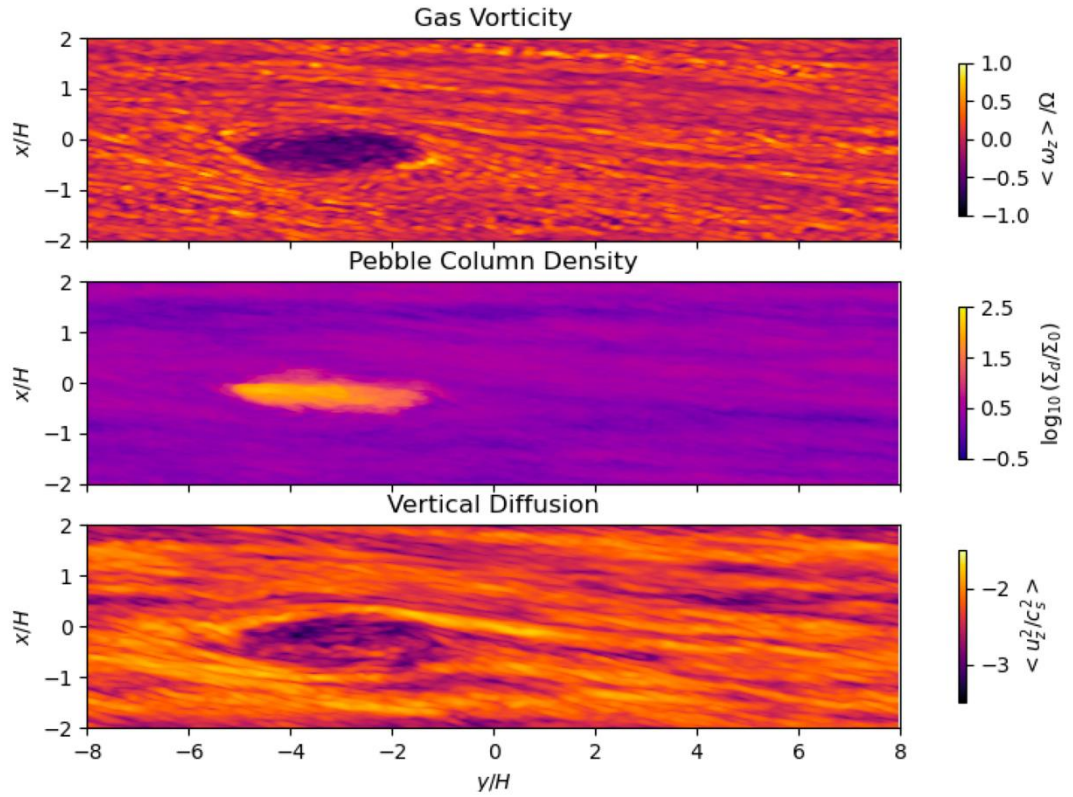
Eriksson et al. (2025)

Vortex boost + Dynamical Dust Loading + Coagulation
Positive Feeback

- The positive loop (*Tominaga et al. 2021, 2022ab, Tominaga & Tanaka 2025, Carrera+Lyra 2025a)*
  - Higher dust density promotes coagulation $t_{coag} \propto {}^{1}/_{Z}$
  - Larger grains concentrate better
- Dust loading dampens the turbulence *(Lyra et al. 2024)*
  - also leads to positive loop *(Carrera+Lyra 2025b)*
- Both Stokes number St (↑) and diffusion parameter α_t (↓) are functions of Z (↑)

$$Z = Z_0\,[1 + \mathrm{St}(Z) / \alpha_t(Z)]$$

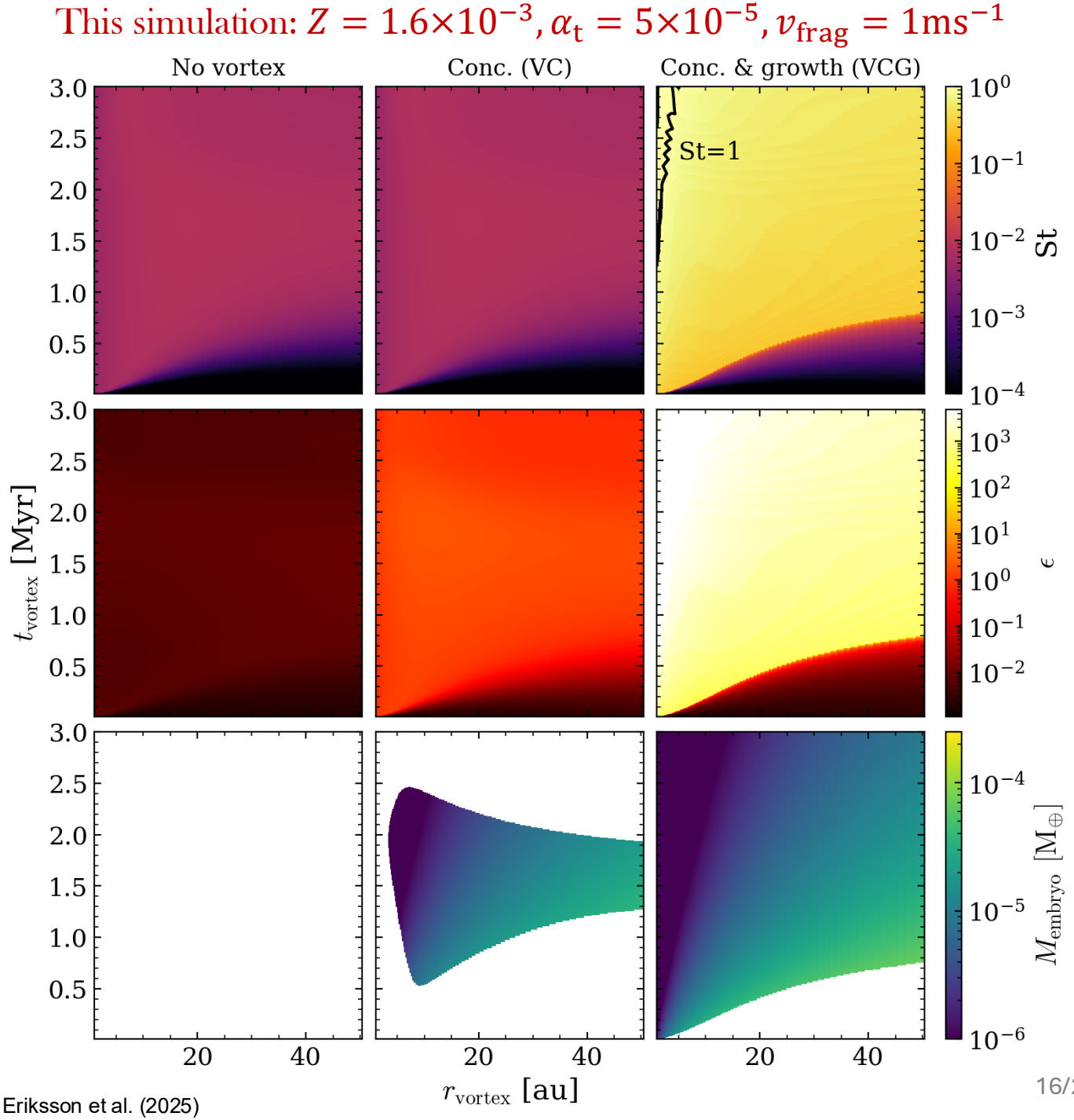




Lyra et al. (2024), Carrera et al. (2025)

Dust growth + Vortices + Planetesimal formation

- Post-process DustPy data using the new feedback loop
- Planetesimals can form in vortices almost everywhere!



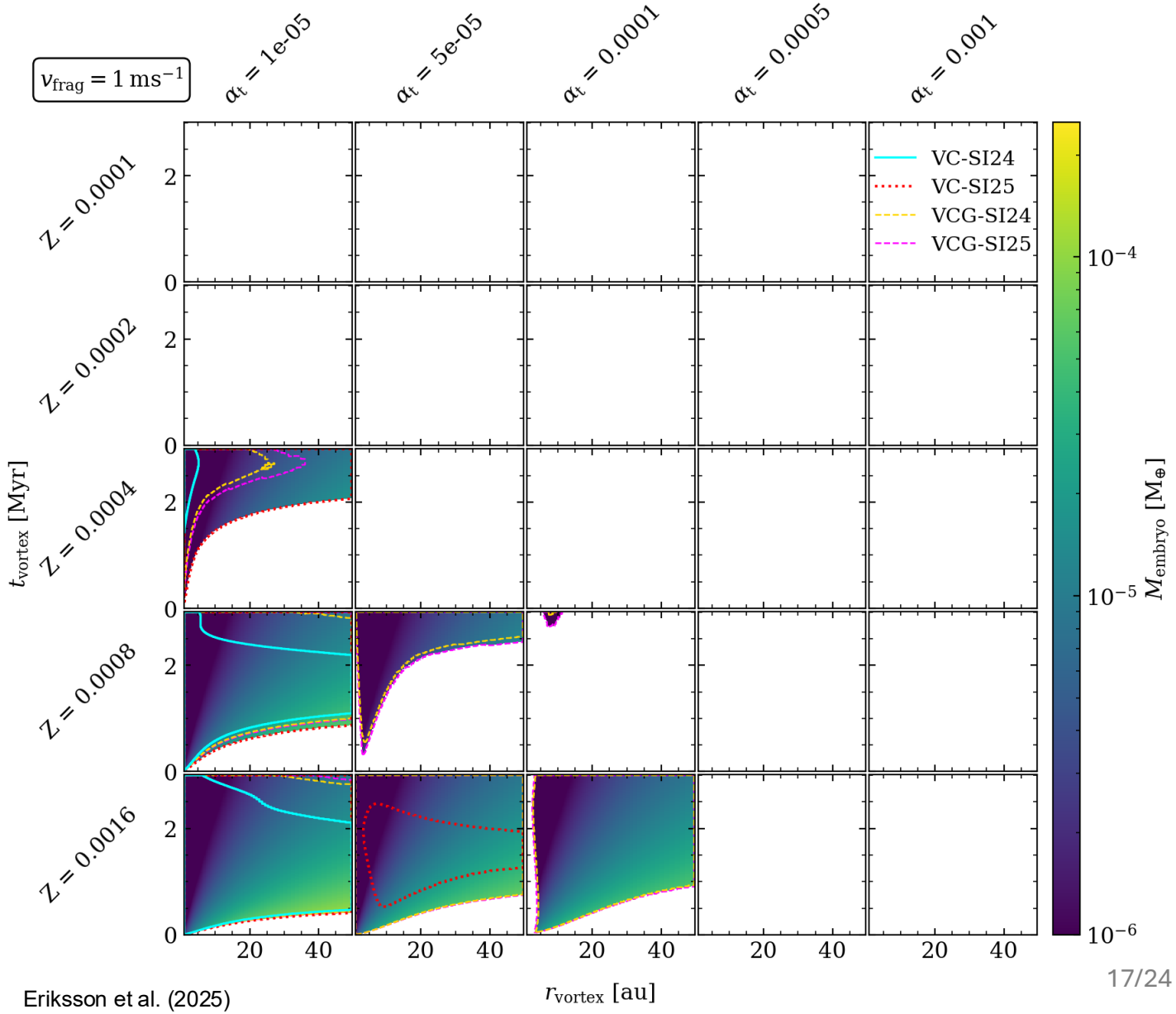
Slide by L. Eriksson

Eriksson et al. (2025)

What solid-to-gas ratio is required for planetesimal formation inside vortices?

- Parameter study
  - Turbulence α_t
  - Solid-to-gas ratio Z
  - Fragmentation velocity v_{frag}

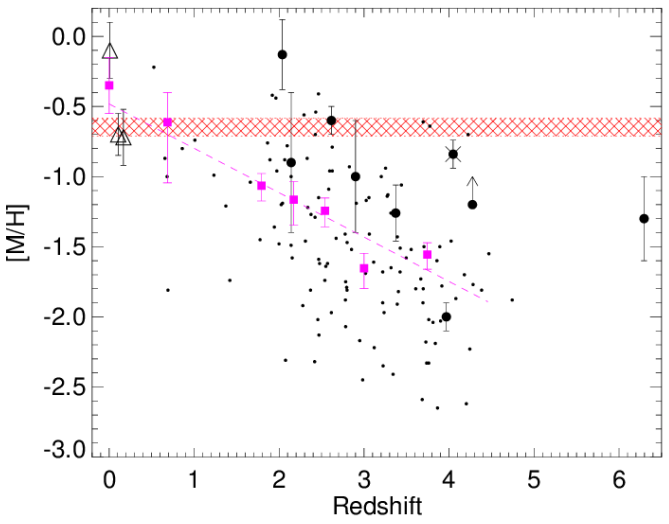
- Planetesimal formation at $Z = 4{\times}10^{-4}$ if $\alpha_t = 10^{-5}$



Eriksson et al. (2025)

Slide by L. Eriksson

Metallicity vs Redshift



Metallicity as a function of redshift for different classes of objects. The black circles are the measurements for GRBs from Table 2 (GRB 060206 is also marked with ×). The open triangles show the metallicity of three low-z GRB host galaxies (Sollerman et al. 2005). The squares and the dashed line represent the column density weighted metallicity evolution derived by Zwaan et al. (2005, their Fig. 22). The small dots with no error-bars are measurements for 121 DLAs from Prochaska et al. (2003). The hatched region indicates the metallicity above which GRBs cannot form in the collapsar models.

Fynbo et al. (2006)

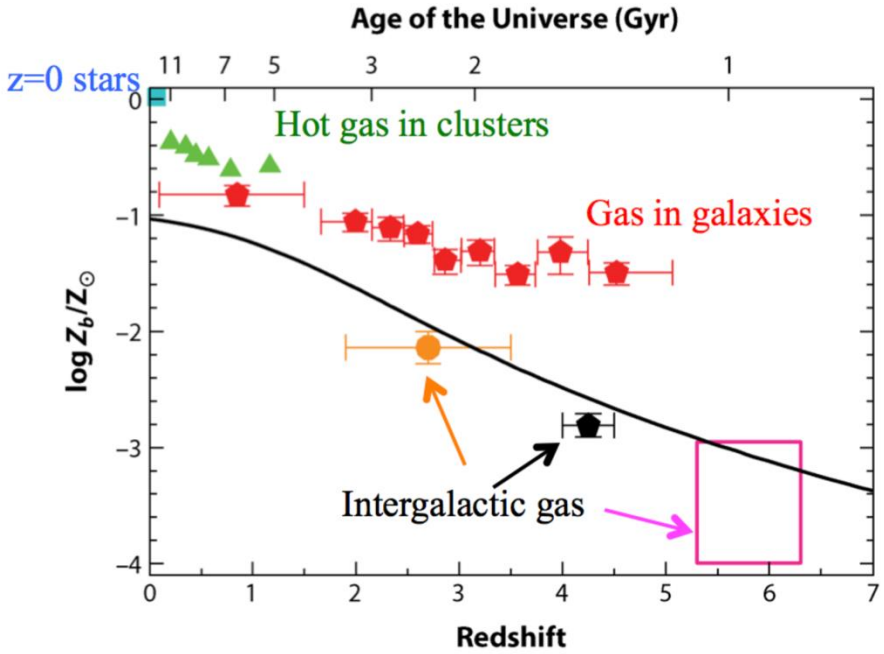
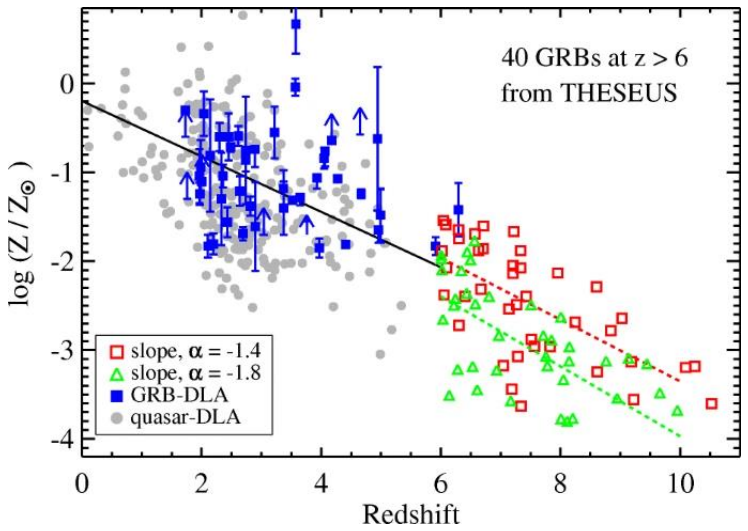


Figure 14: Mean metallicity of the Universe (in solar units): (*solid curve*) mass of heavy elements ever produced per cosmic baryon from our model SFH, for an assumed IMF-averaged yield of $y = 0.02$; (*turquoise square*) mass-weighted stellar metallicity in the nearby Universe from the SDSS (Gallazzi et al. 2008); (*green triangles*) mean iron abundances in the central regions of galaxy clusters (Balestra et al. 2007); (*red pentagons*) column density-weighted metallicities of the damped Lyα absorption systems (Rafelski et al. 2012); (*orange dot*) metallicity of the IGM as probed by O VI absorption in the Lyα forest (Aguirre et al. 2008); (*black pentagon*) metallicity of the IGM as probed by C IV absorption (Simcoe 2011); (*magenta rectangle*) metallicity of the IGM as probed by C IV and C II absorption (Ryan-Weber et al. 2009, Simcoe et al. 2011, Becker et al. 2011).

Madau & Dickinson (2014)



Absorption-line based metallicities relative to solar, corrected for dust depletion as a function of redshift for Quasar Damped Ly α absorbers (DLAs, grey symbols) and GRB-DLAs (blue symbols) (adapted from [97], [98]). Open square symbols show representative expectations for THESEUS, assuming continued evolution of the mass-metallicity relationship, and a dominant population of low mass galaxies at $z > 6$ (green triangles and red squares assume faint-end slopes of -1.8 and -1.4 for the galaxy luminosity function, respectively). GRBs represent the unique way for probing evolution of ISM absorption–based metallicities in the first billion years of cosmic history

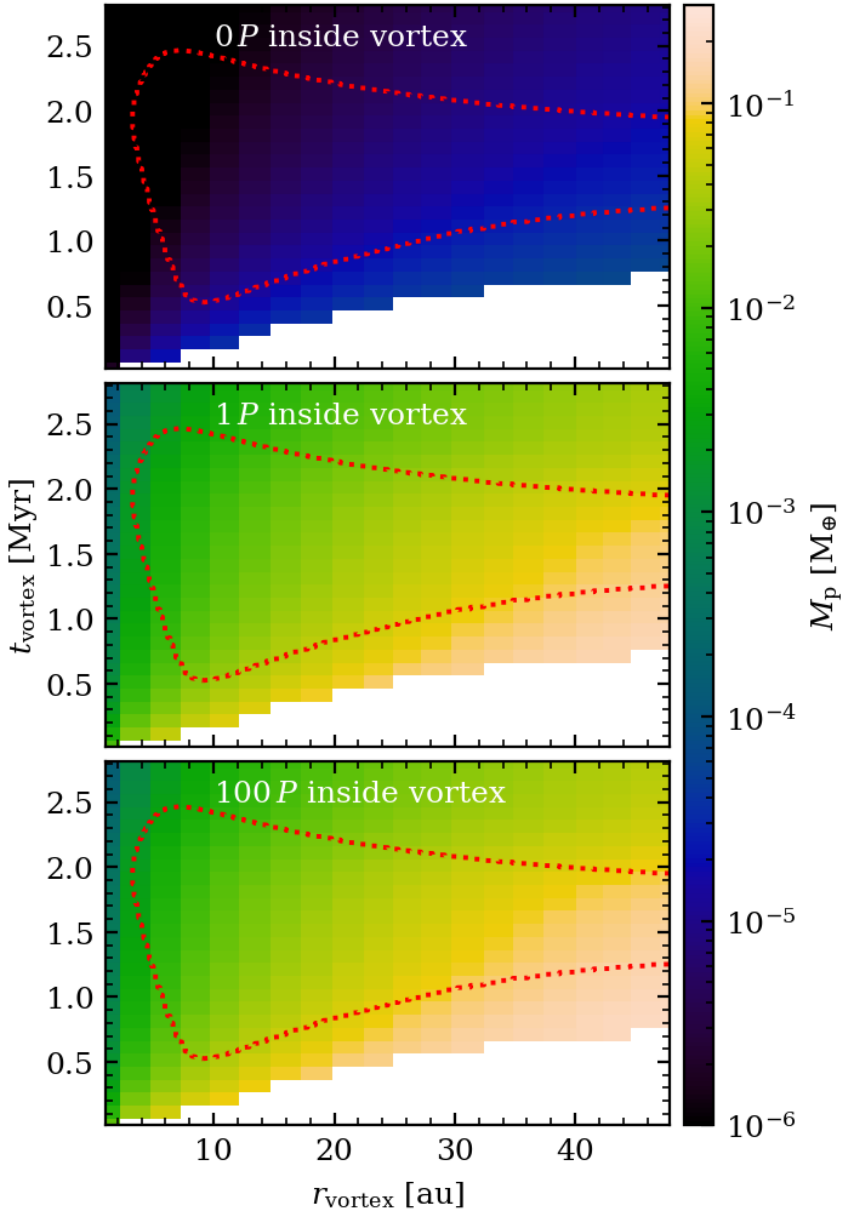
Tanvir et al. (2021)

Further growth: Pebble Accretion

- Polydisperse pebble accretion *(Lyra & Johansen+ 2023)*
- If planetesimal immediately leave the vortex:
  → No significant growth
- If planetesimal remains inside the vortex for a while:

  → Vortex-boosted pebble accretion:

  - Very high accretion rates of the trapped pebbles
    - Significant growth!
  - Most of the final mass attained within one (!) orbit

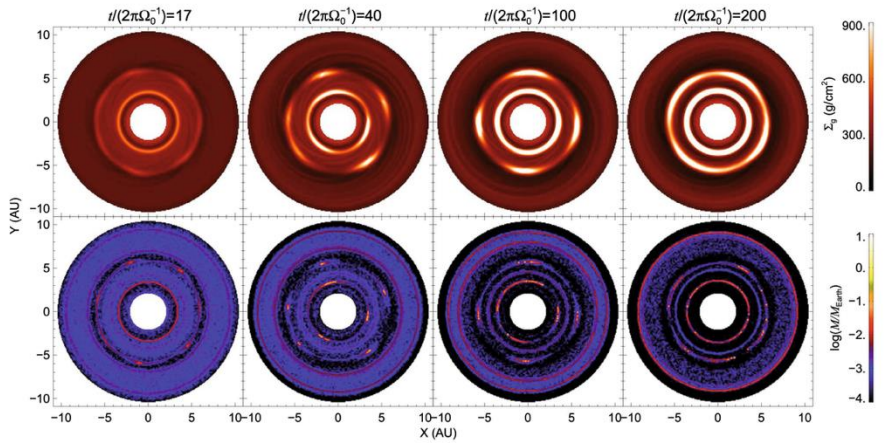


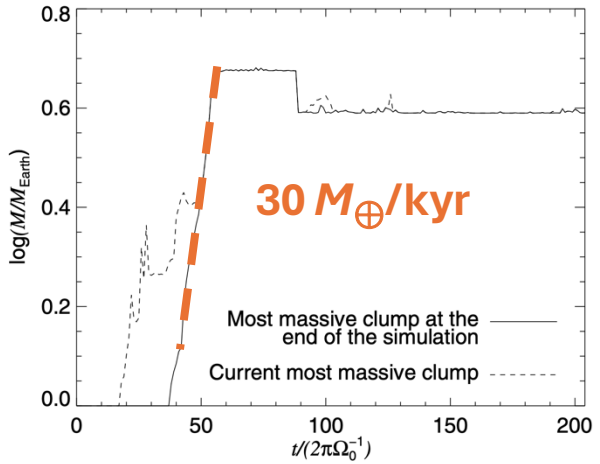
Slide by L. Eriksson

Eriksson et al. (2025)

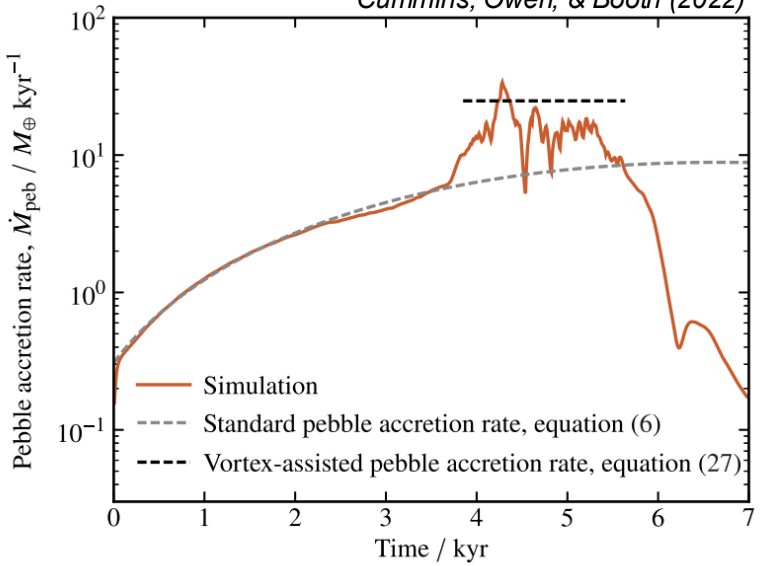
Pebble accretion in vortices

Lyra & Johansen (et al 2008, 2009)





Cummins, Owen, & Booth (2022)



Pebble Accretion

$\dot{M}_{2D} = \lambda\, \Sigma_d\, \delta v$

Cross section (line segment)
Column density
Approach velocity

Lambrechts & Johansen (2012)

For **Hill accretion**, $\lambda = 2R_H$, $\delta v = \Omega R_H$

$\dot{M}_{2D,Hill} = 2\Omega R_H^2\, \Sigma_d$ ***Capture-limited***

Lyra & Johansen (et al 2008, 2009), Cummins, Owen, & Booth (2022)

For a **vortex**, $\lambda = 4H/3$, $\delta v = \Omega H$

$\dot{M}_{2D,vortex} = {}^4/_3 \Omega H^2\, \Sigma_d$ ***Transport-limited***

(Independent of mass)

$\dot{M} = 2\pi\, r\, v_r\, \Sigma_d\, \varepsilon$

(mass flux scaled by efficiency)

For St=1, $v_r = \eta\Omega r$

$\dot{M} \sim 30\ M_\oplus\ \mathrm{kyr}^{-1}\ \times\ \varepsilon$

Efficiency ε = 1 (!)

The whole pebble flux accreted!

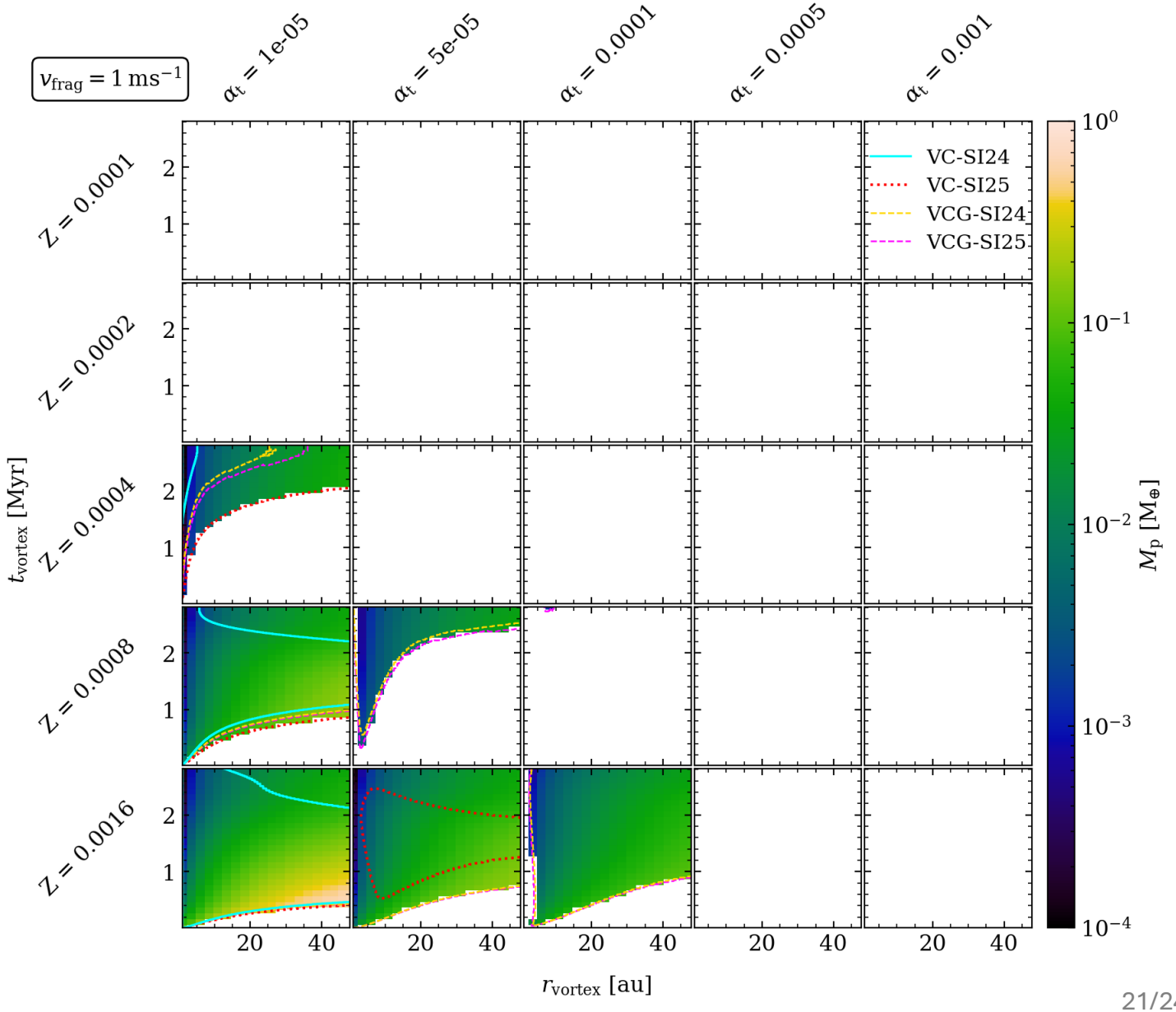
Transport-limited Pebble Accretion

- Parameter study
  - Turbulence α_t
  - Solid-to-gas ratio Z
  - Fragmentation velocity v_{frag}

- Assume planetesimals stay inside the vortex for 10 orbital periods

- Mercury-mass planets at $Z = 0.0004$
- Mars-mass planets at $Z \gtrsim 0.001$

- In general, higher metallicity and low turbulence favor planet growth.
  - A threshold seems to exist around $Z = 4\text{x}10^{-4}$ ($0.04\ Z_\odot$)

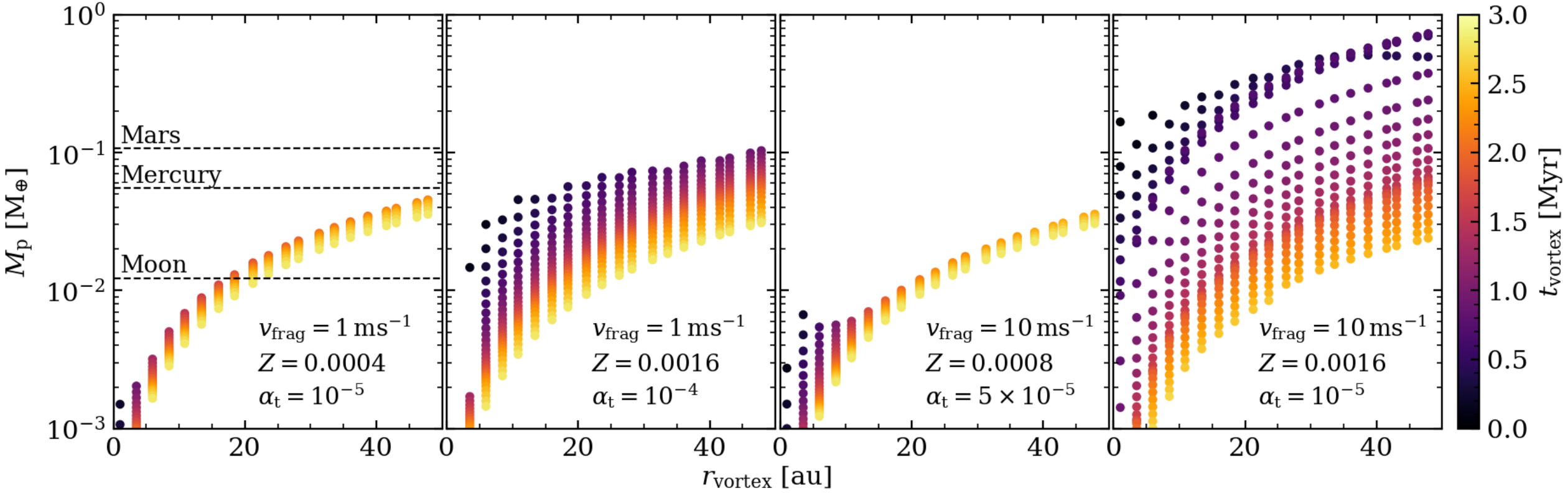


Eriksson et al. (2025)

Slide by L. Eriksson

Final Planet Masses vs Distance and Timing

- Significant growth by pebble accretion for early formation
- Growth stalled at
  - Mercury mass for pessimistic conditions
  - Earth mass for optimistic conditions
- Planet mass increases with distance
  - Opposite as expected for capture-limited pebble accretion
  - Due to scaling with vortex volume $M_{\rm trapped} = (2\pi)^{3/2}\,\rho_{\rm d}\,\chi\,H^3$, $M\dot{}\propto H^2$



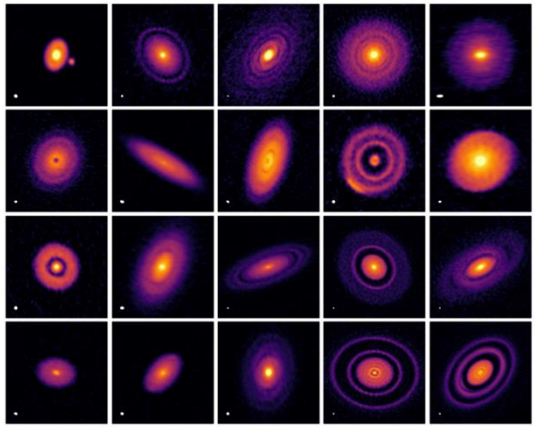
Eriksson et al. (2025)

Conclusions

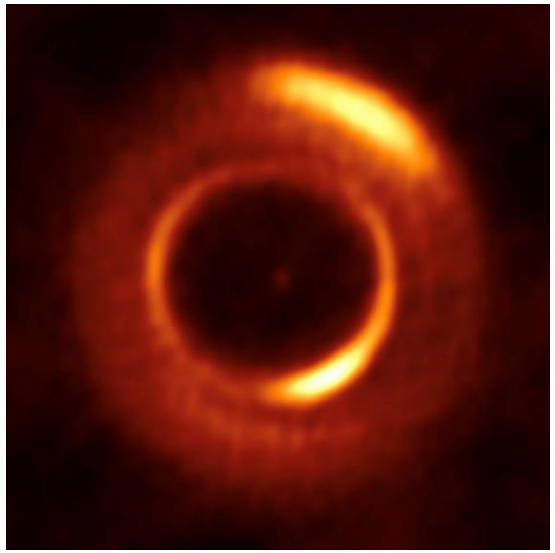
- **Can planets be formed at cosmic dawn?**
  - If there are vortices (or traps, in general) in the disk: Yes!

- **Planet population is of planetary embryo mass**
  - Moon to Mars mass objects
  - Mercury-mass planets can form at $Z \sim 4\times10^{-4}$

- **Limitations**
  - Streaming Instability not resolved
  - Coagulation/Fragmentation not modeled
  - Semi-analytic model
    - Growth-Concentration feedback loop in vortices not tested numerically
  - How common are vortices in low-metallicity disks?



Andrews et al. (2018)



Dong et al. (2018)