The saga of planetesimal formation at planetary gap edges

Linn Eriksson

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From January:
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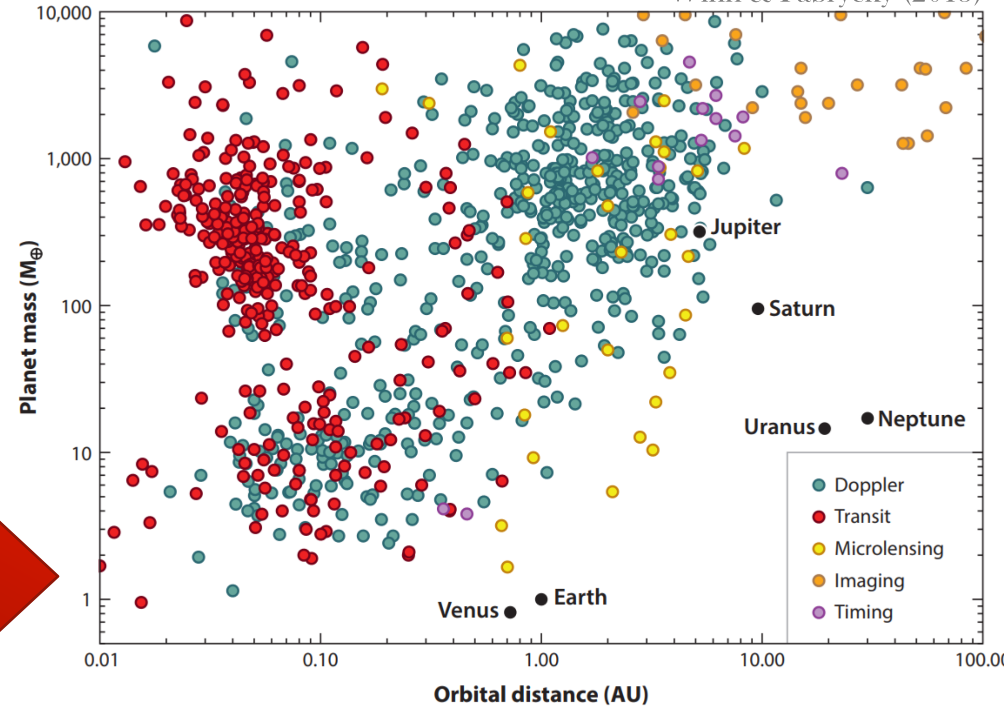
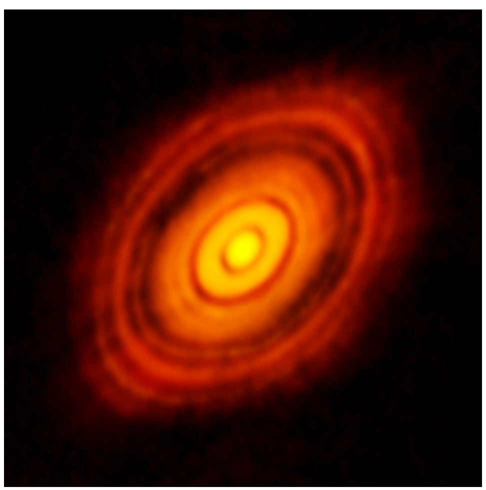
Stony Brook University, NY

Credit: ESO/L. Calçada

From disks→ planets
The big picture

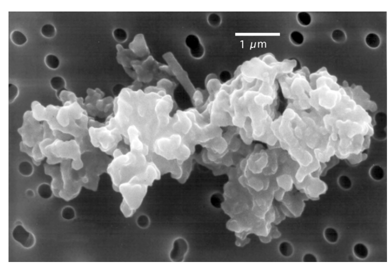
Winn & Fabrycky (2015)





ALMA partnership et al. (2015)

Dust ~ 10^{-6} m

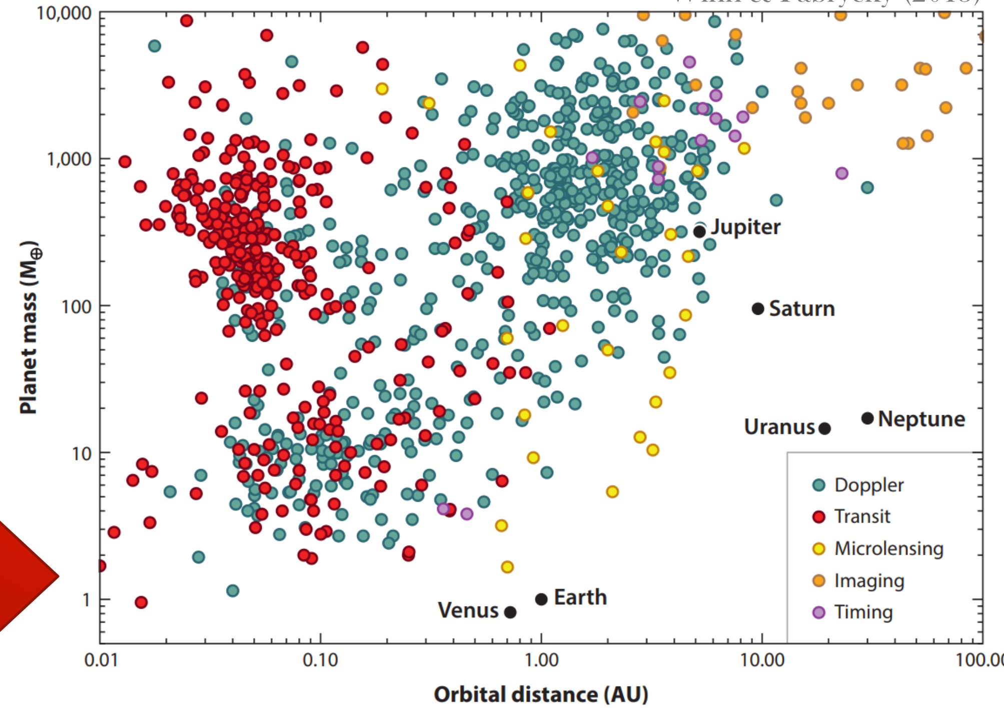


Source: Brownlee & Jessberger

→ … →

Planets ~ 10^{8} m

From disks→ planets
The big picture



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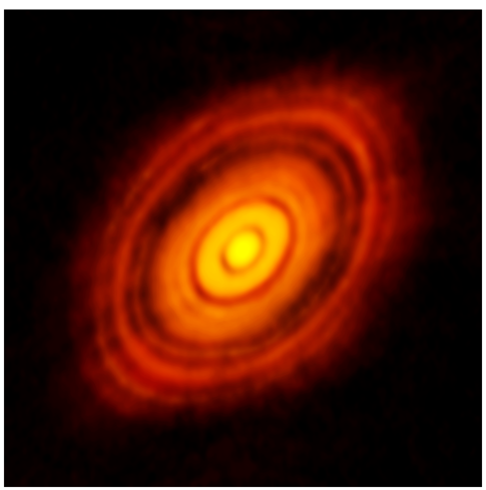

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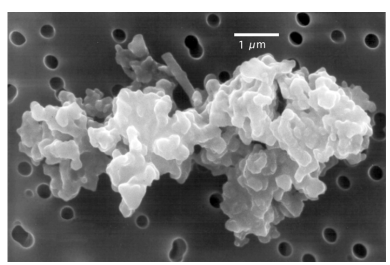
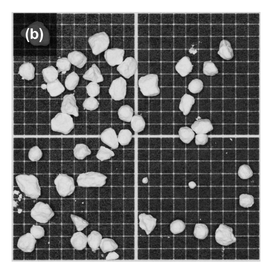


Source: Brownlee & Jessberger

→

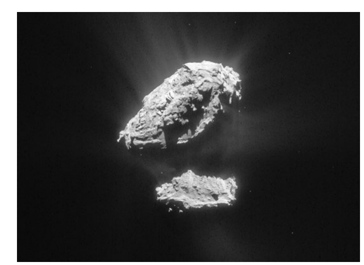
Pebbles ~ 10^{-3} m



Blum et al.(2014)

→

Planetesimals ~ 10^{5} m

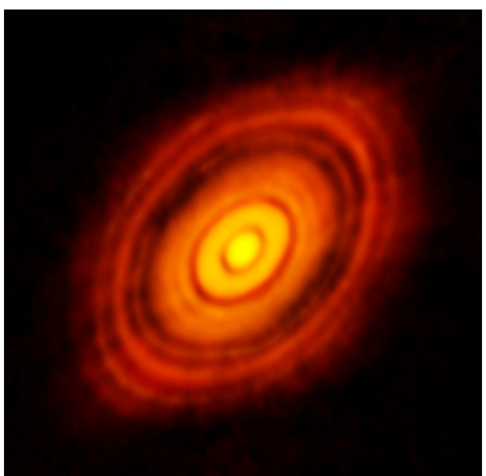


Source: ESA/Rosetta/NavCam

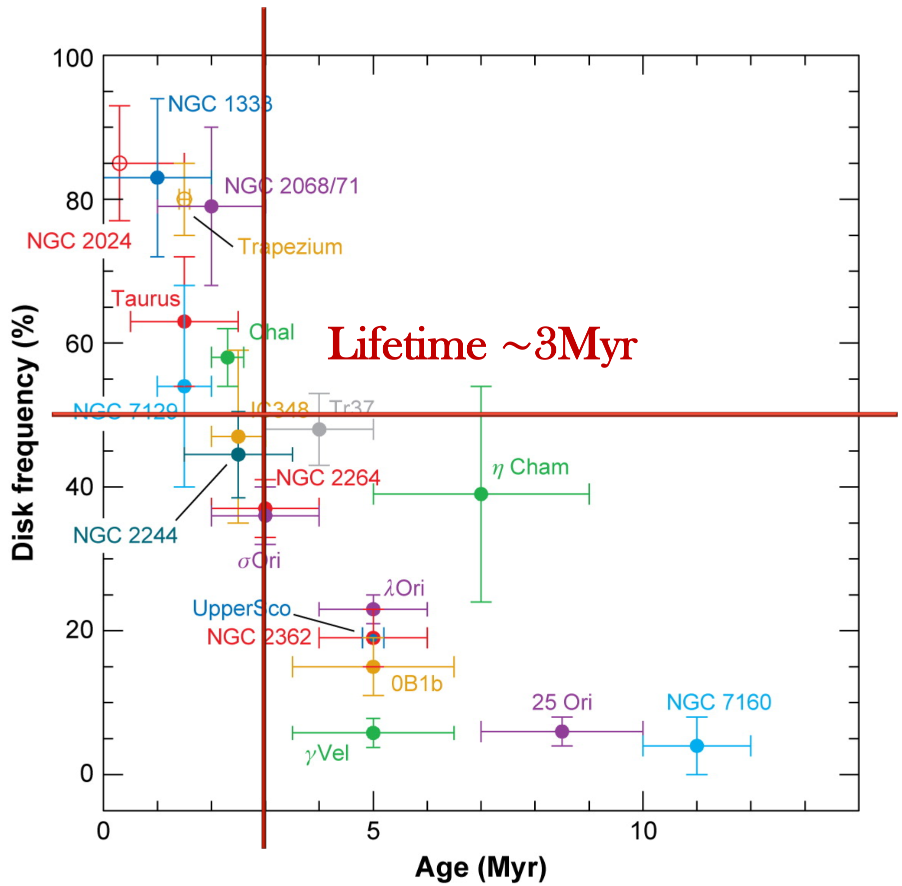
→…

Protoplanetary disk evolution

- 99% gas – 1% solids
- Accrete onto the star



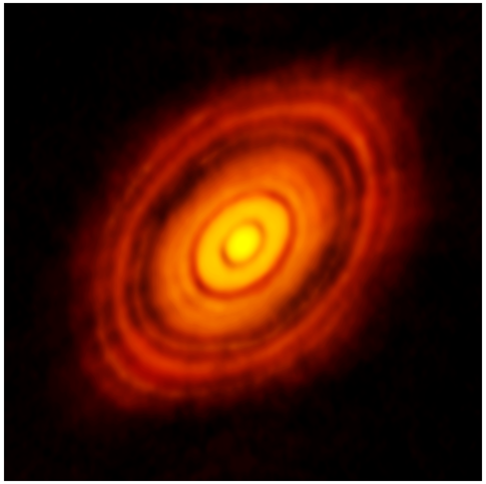
ALMA partnership et al. (2015)



Wyatt MC. 2008.
Annu. Rev. Astron. Astrophys. 46:339–83

Protoplanetary disk evolution

- 99% gas – 1% solids
- Accrete onto the star
- Viscous accretion disk



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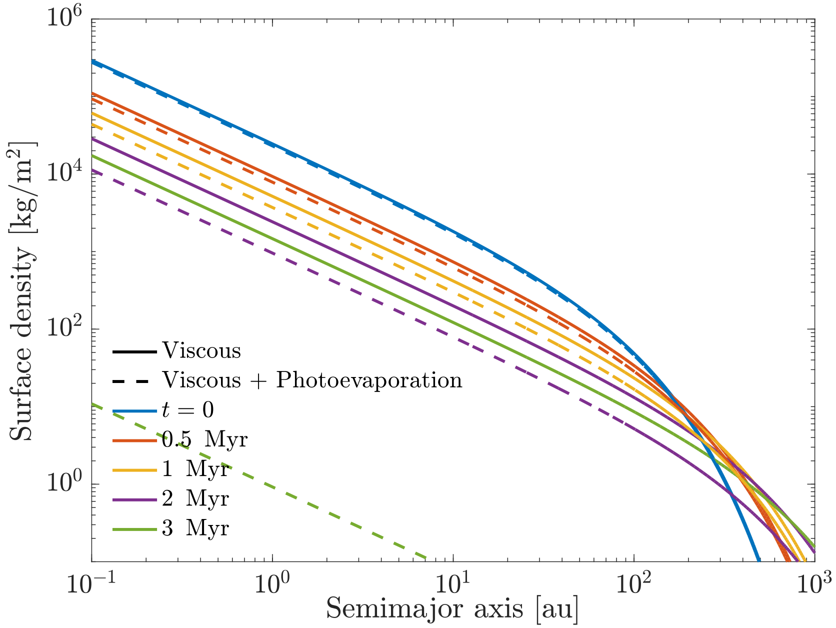
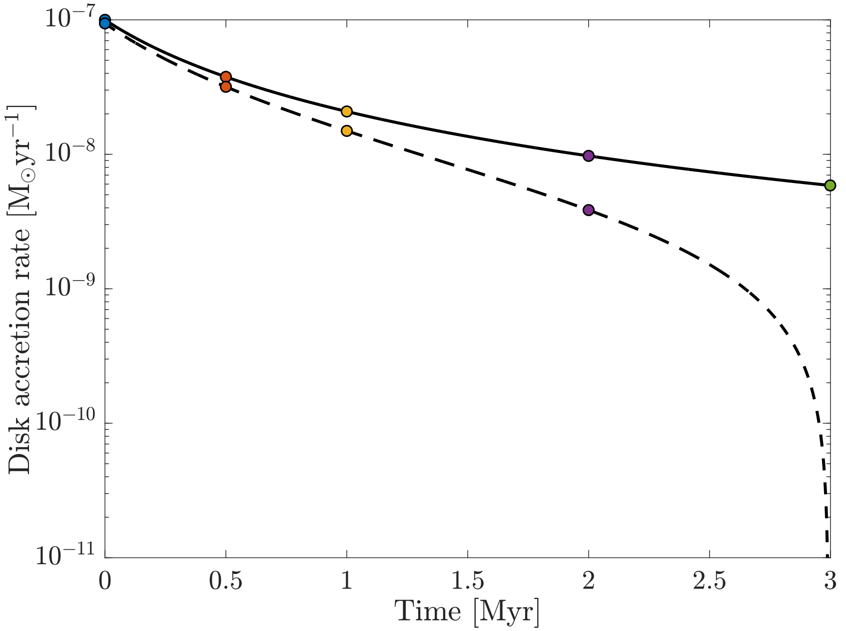
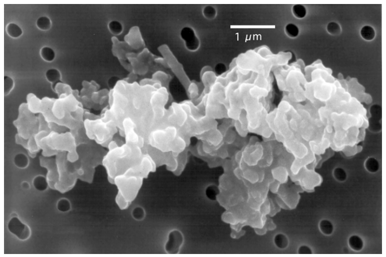




From dust to pebbles

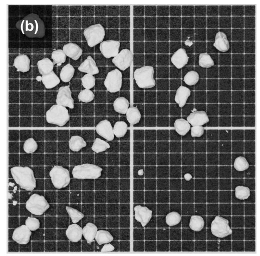
Dust ~ 10^{-6} m



Source: Brownlee & Jessberger

→

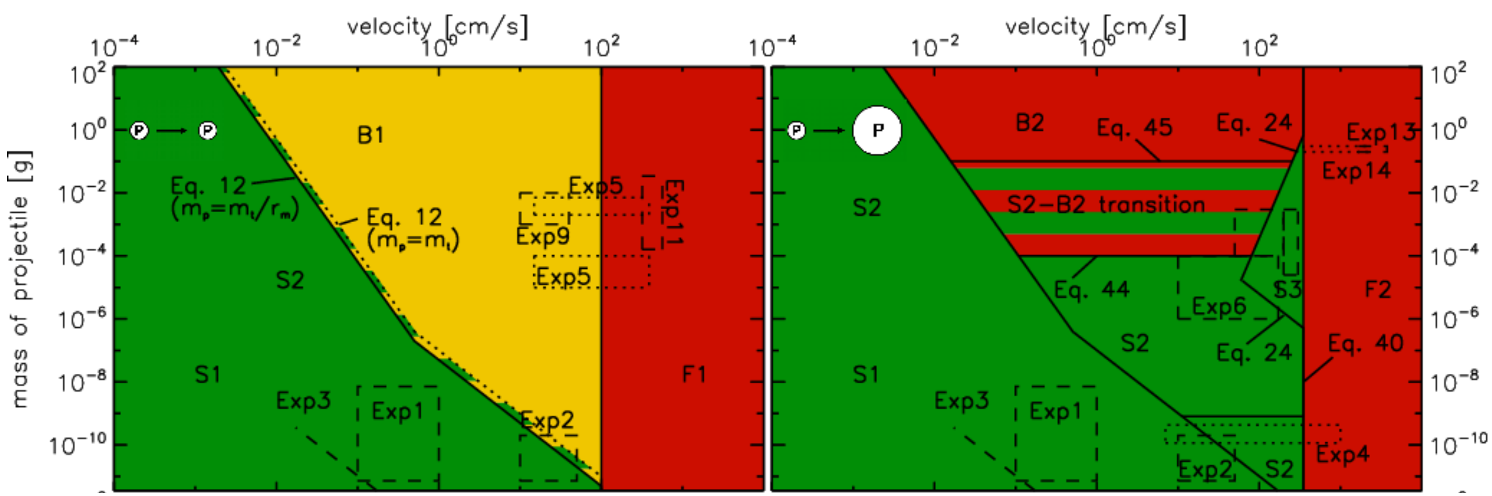
Pebbles ~ 10^{-3} m



Blum et al.(2014)

Collisions between dust →

- Sticking
- Bouncing
- Fragmentation



Güttler et al. (2010)

From dust to pebbles

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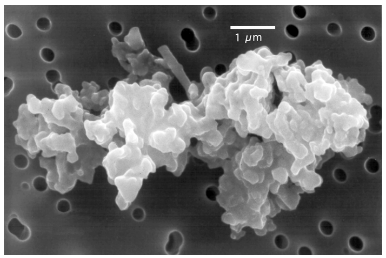
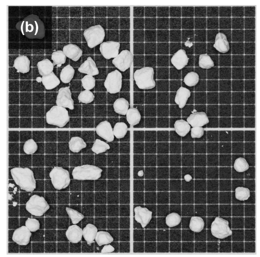


Source: Brownlee & Jessberger

Pebbles ~ 10^{-3} m



Blum et al.(2014)

Collisions between dust →

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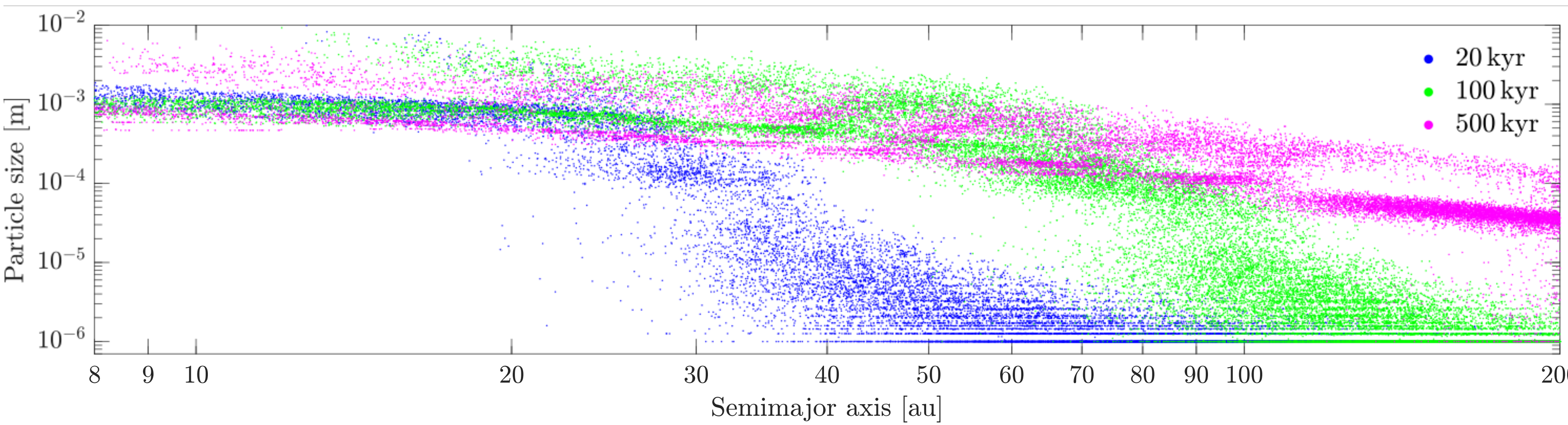
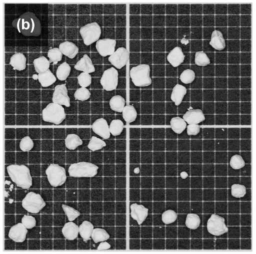


Eriksson et al. (2020)

From pebbles to planetesimals

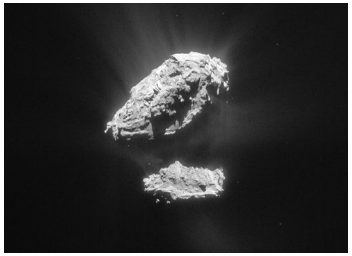
Pebbles $\sim 10^{-3}$ m



Blum et al.(2014)

→

Planetesimals $\sim 10^{5}$ m



Source: ESA/Rosetta/NavCam

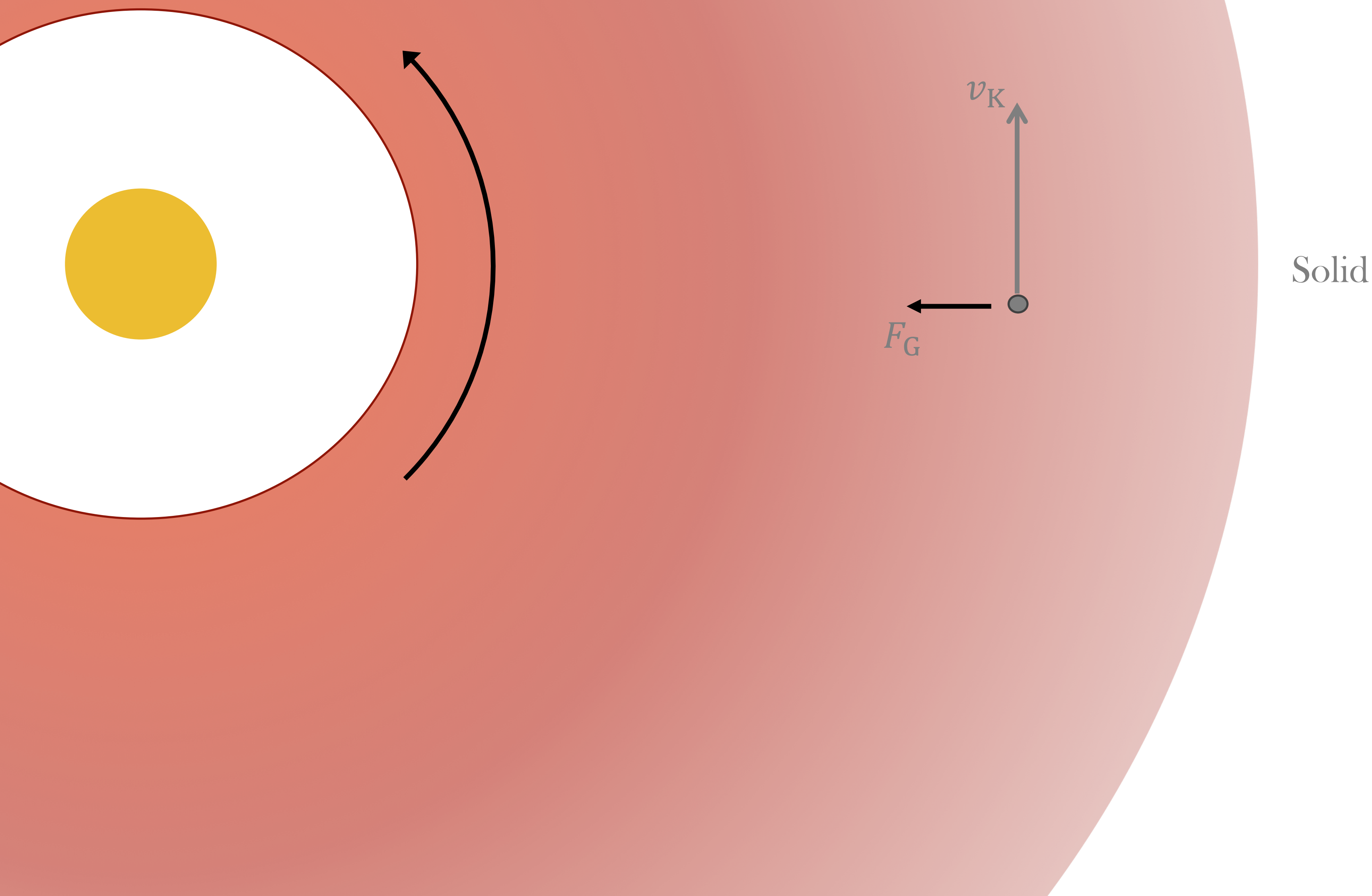
Collisional growth stops at ~mm-sizes

Gravitational collapse of particle clumps

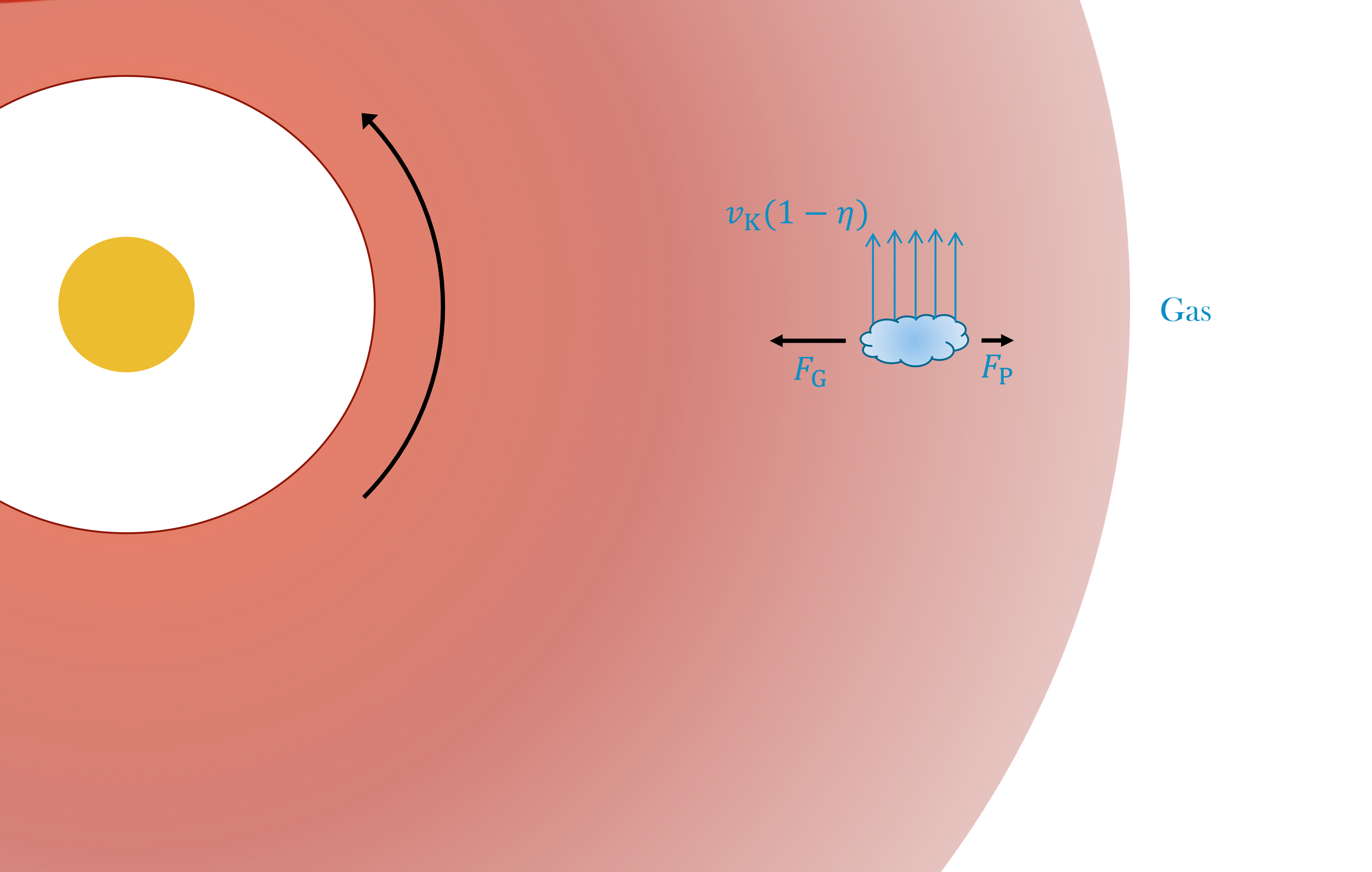
Need to concentrate particles

→ Streaming instability

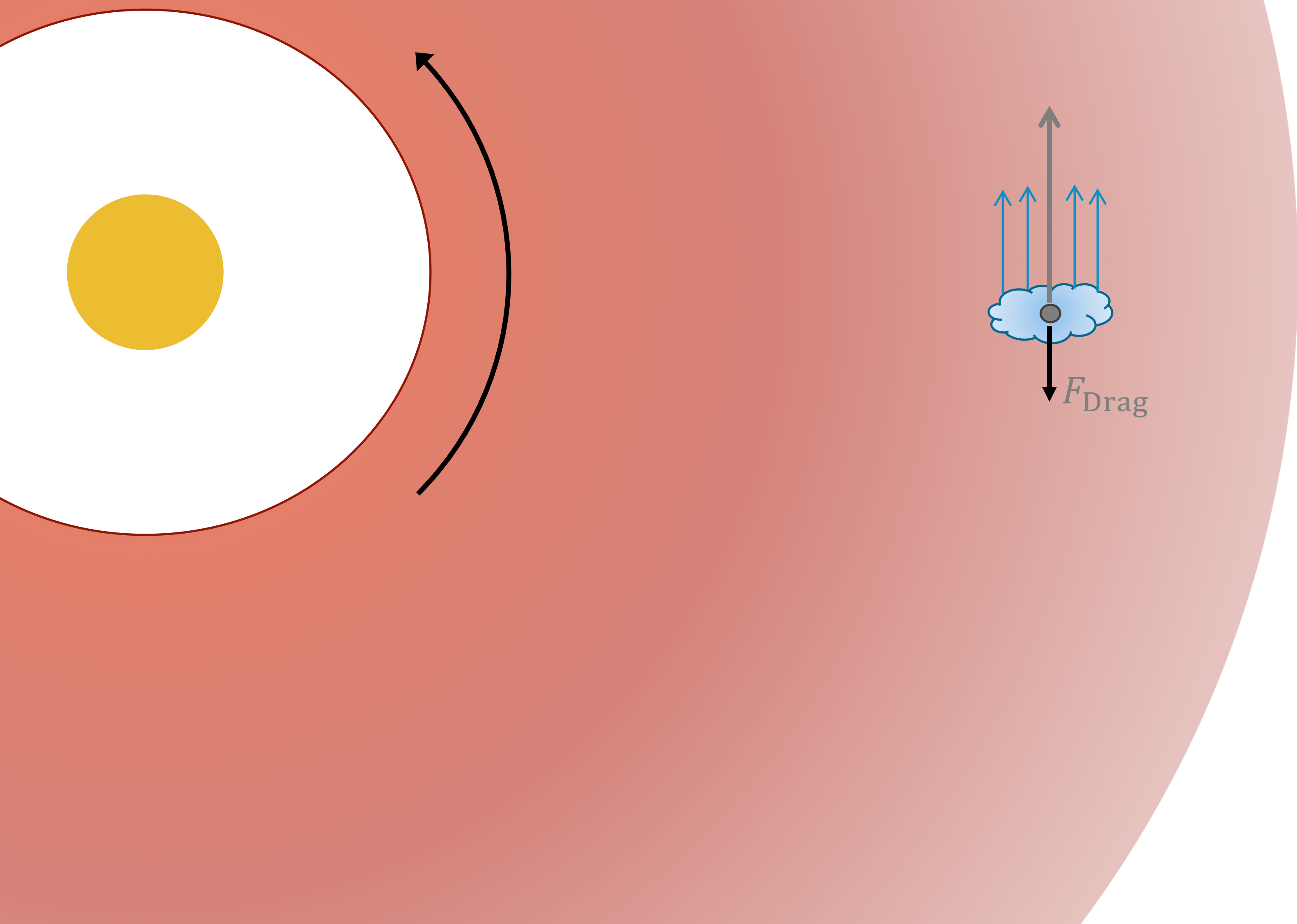
The streaming instability



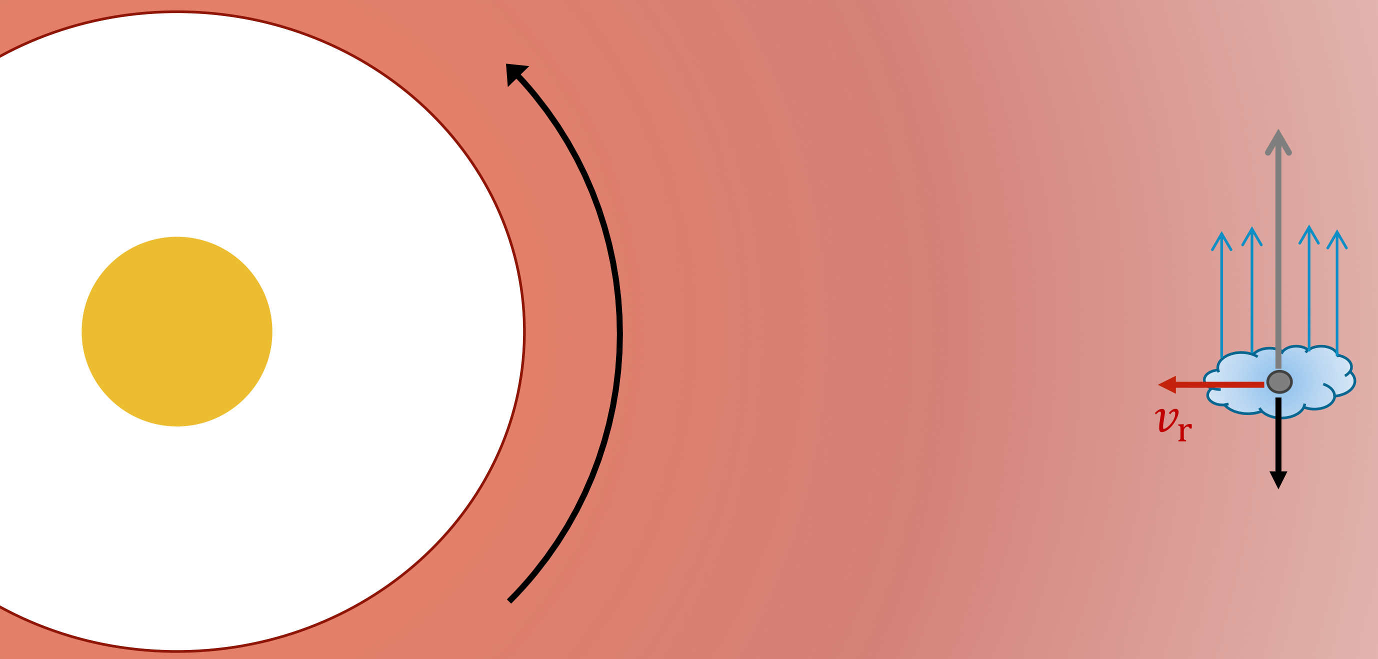
The streaming instability



The streaming instability

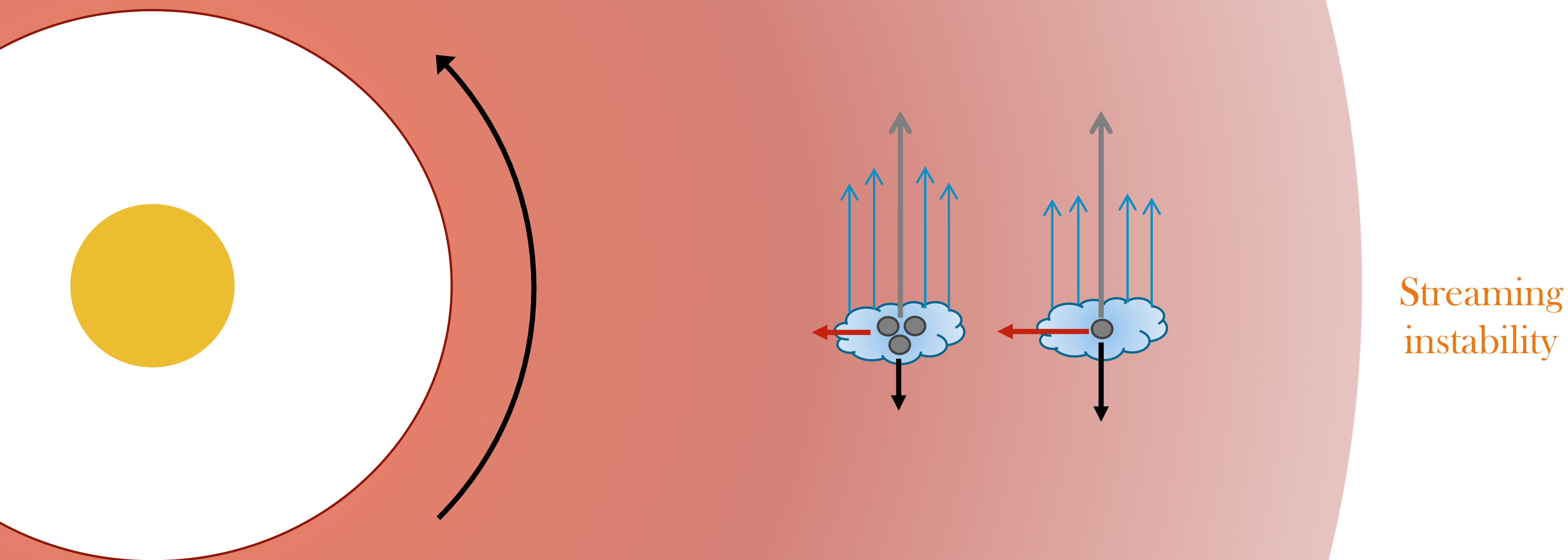


The streaming instability

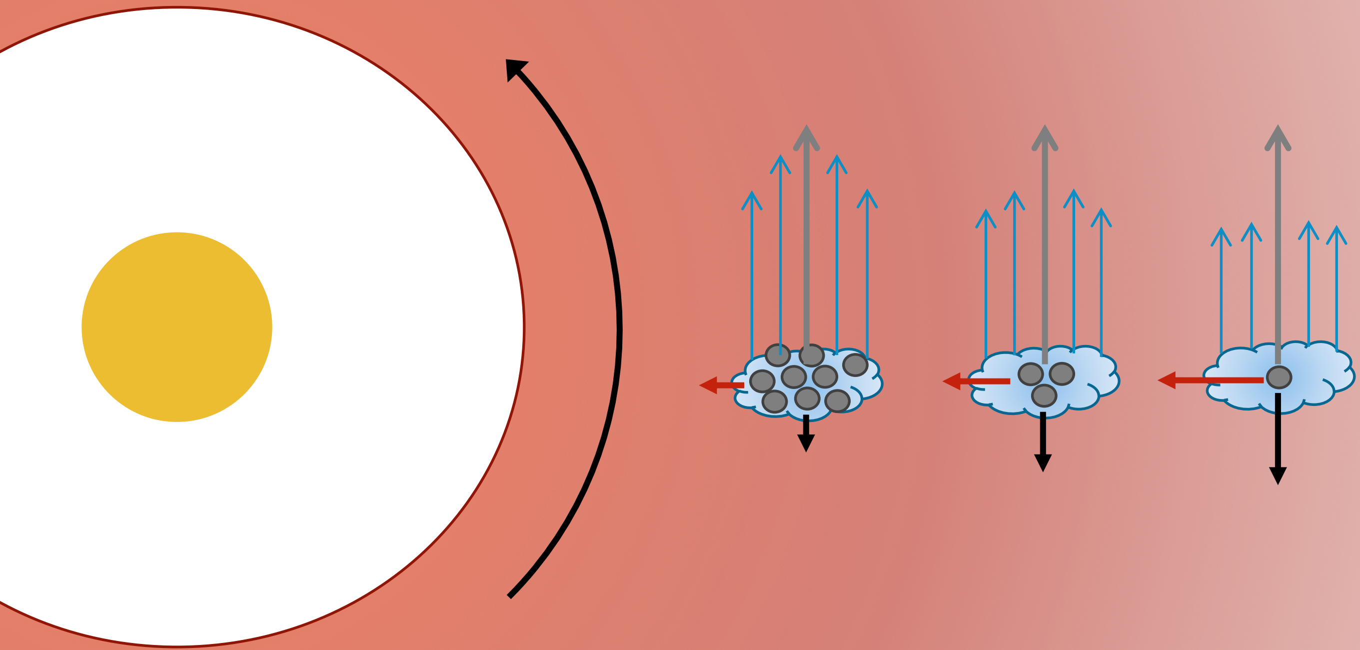


Radial drift

The streaming instability

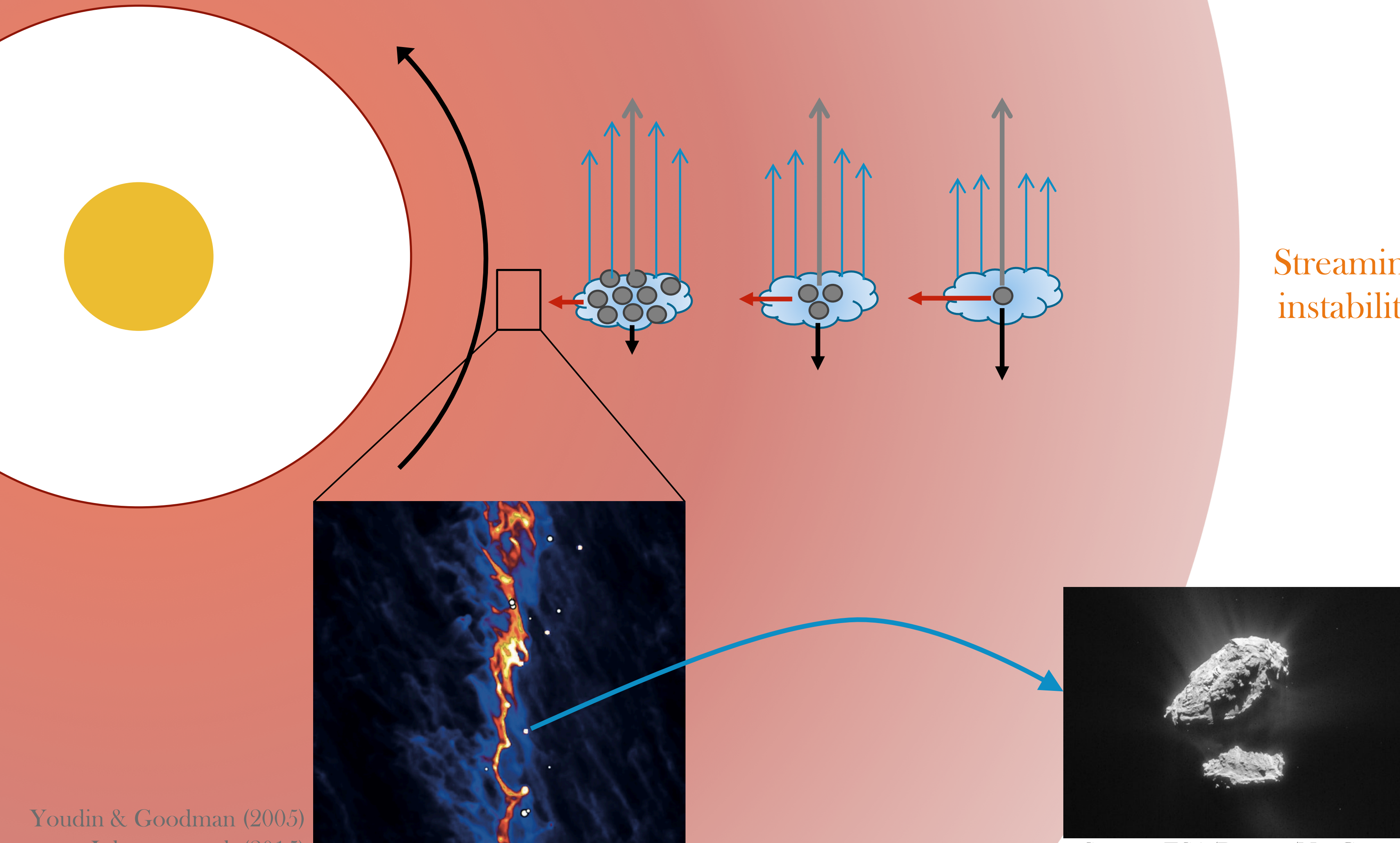


The streaming instability



Streaming instability

The streaming instability

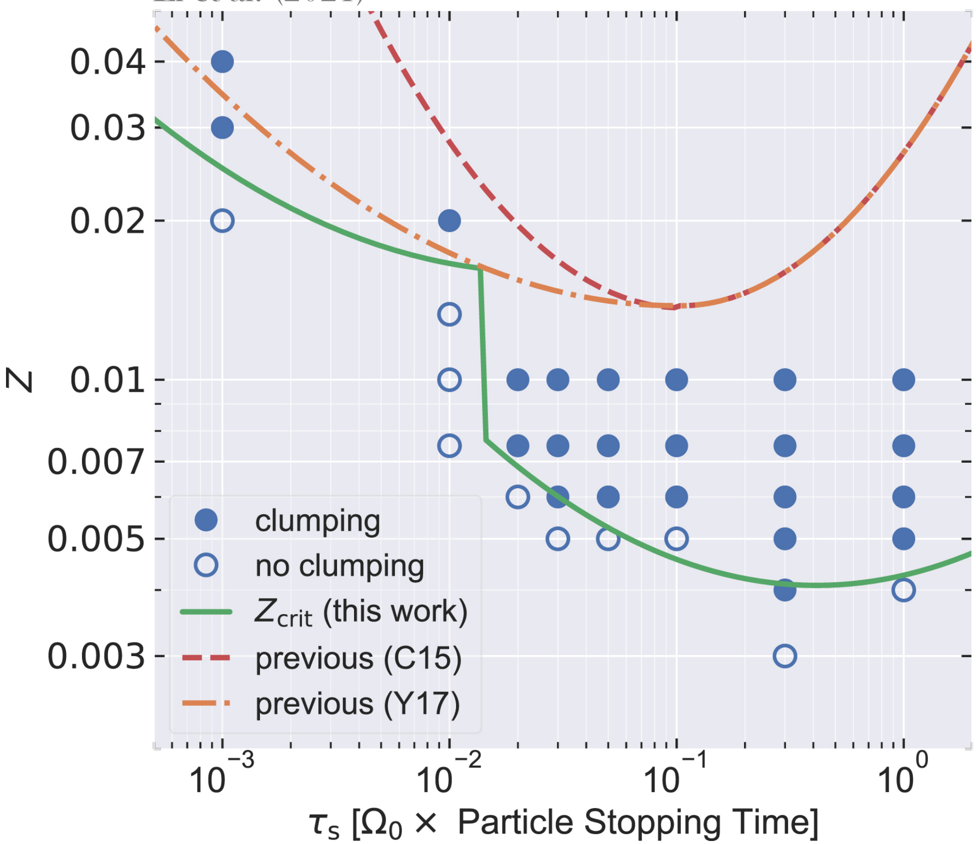


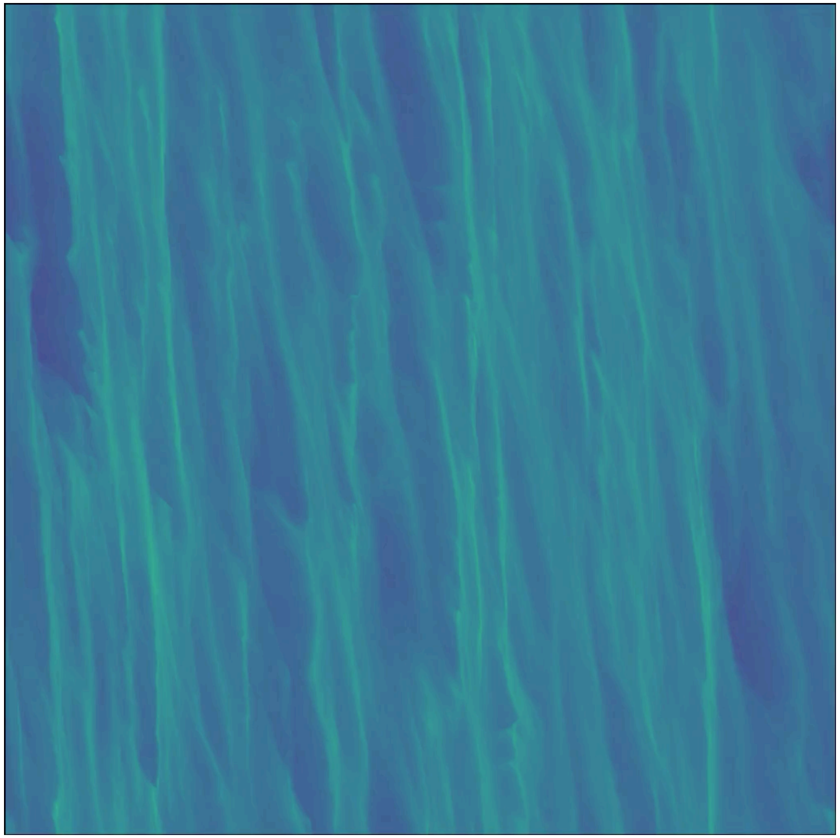
Youdin & Goodman (2005)
Johansen et al. (2015)

Source: ESA/Rosetta/NavCam

The streaming instability

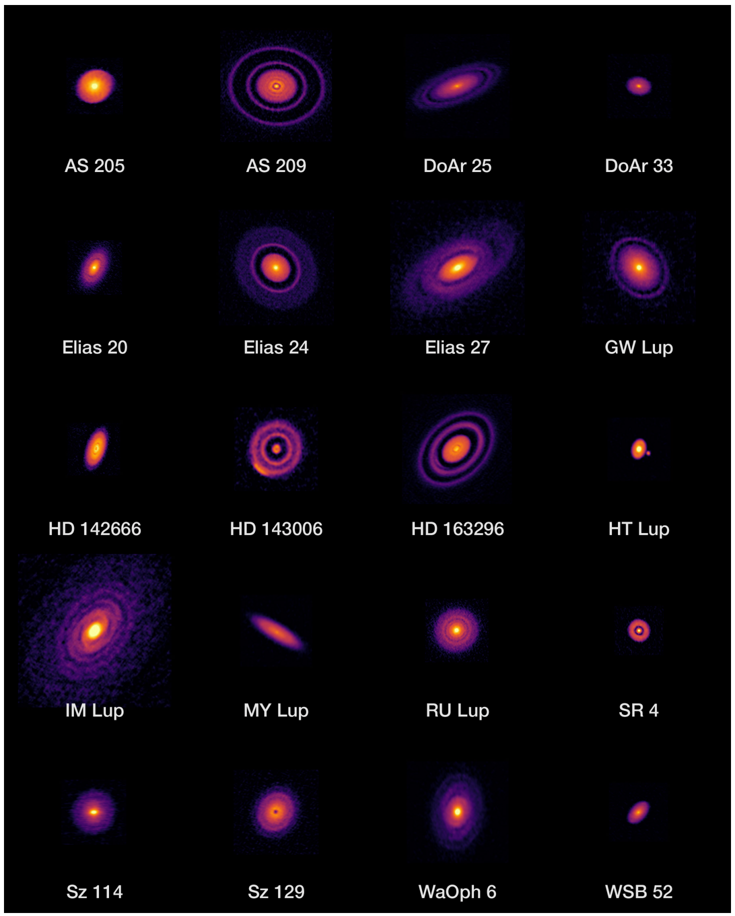
Li et al. (2021)





Source: Rixin Li

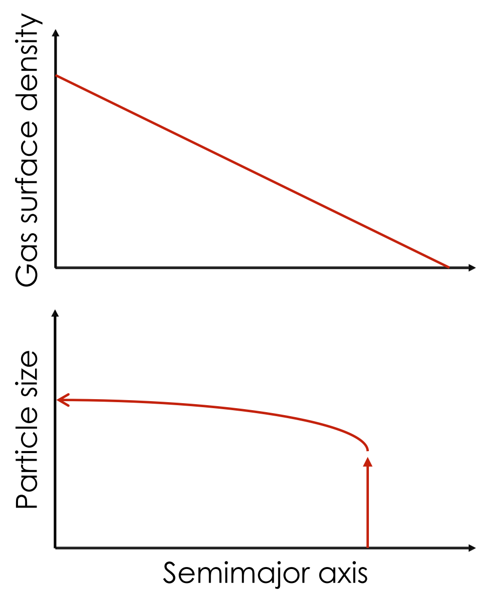
The saga of planetesimal formation at planetary gap edges

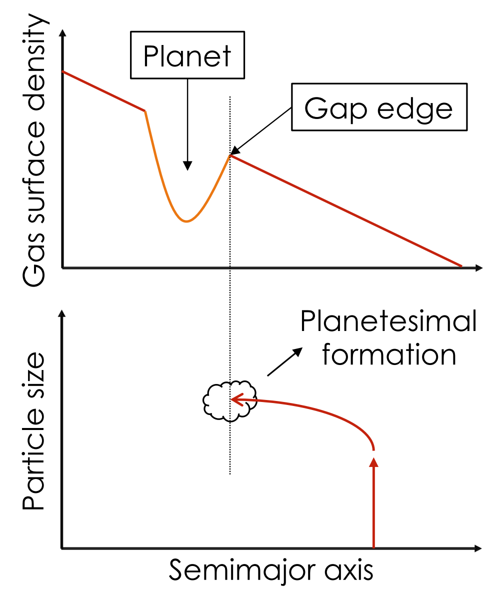


Andrews et al. (2018)

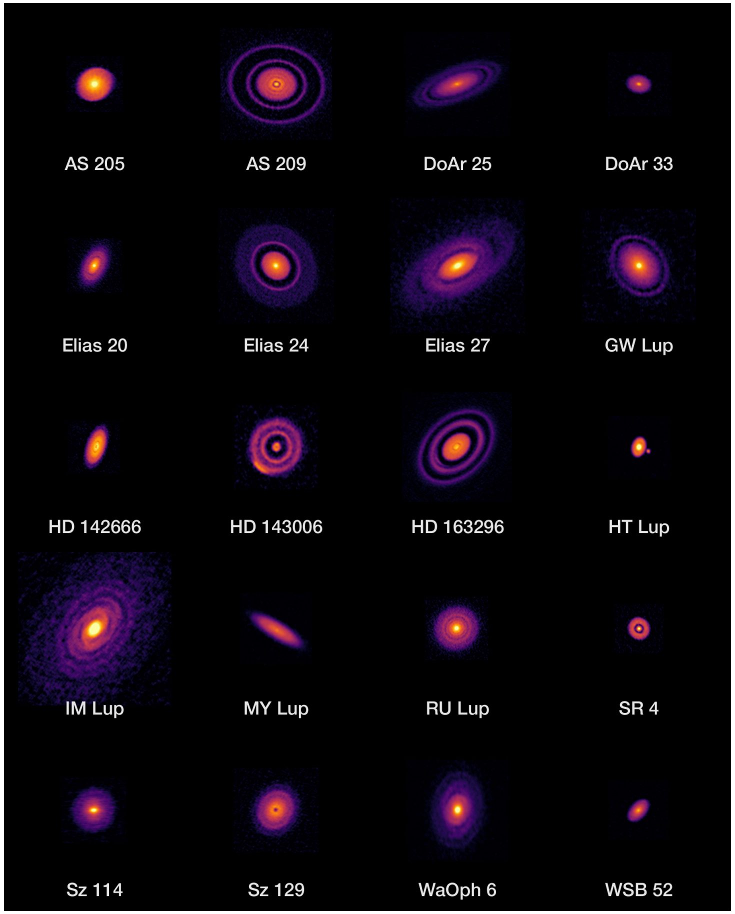
The planet interpretation:

- Growing planets open gaps in the gas disk
- Drifting pebbles become trapped at the gap edges
- Favourable location for planetesimal formation via the streaming instability



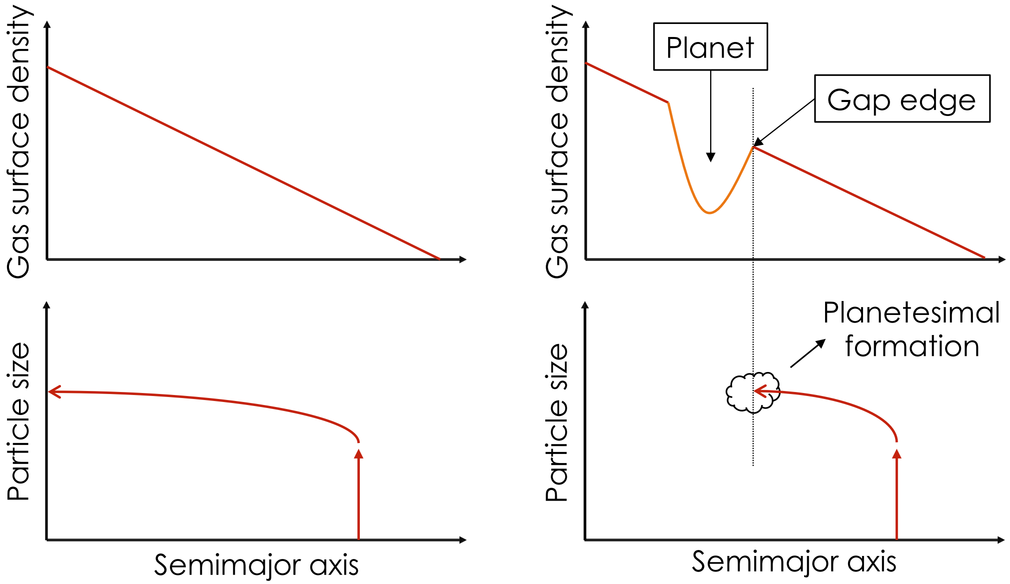


The saga of planetesimal formation at planetary gap edges



Andrews et al. (2018)

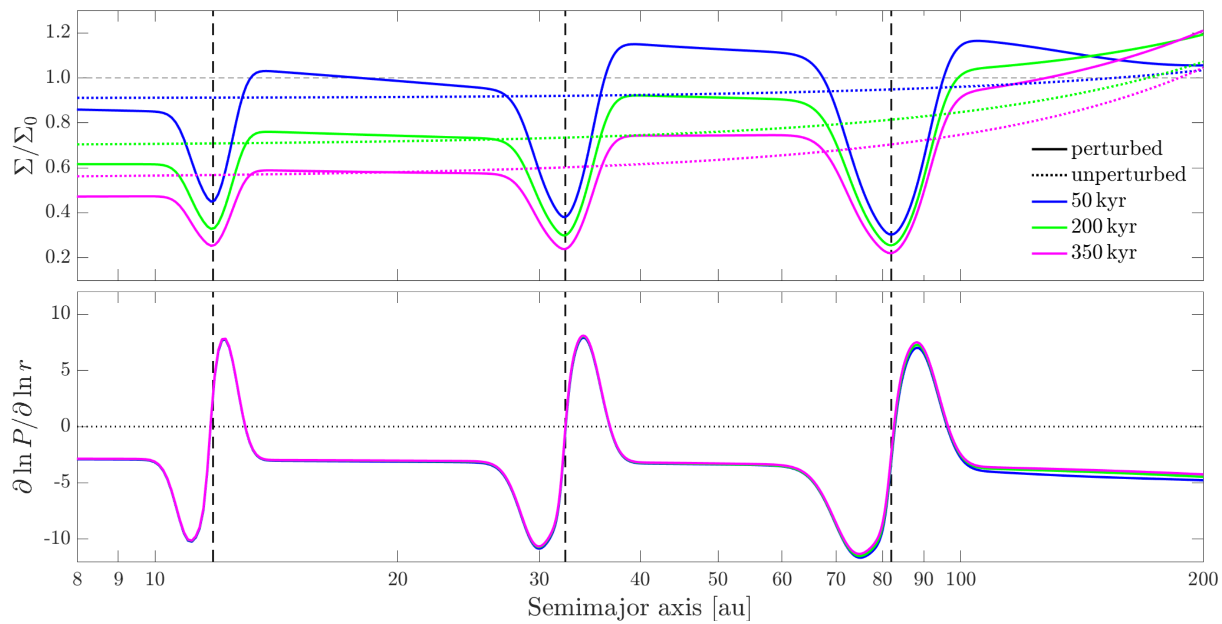
1. Do planetesimals form at planetary gap edges?
2. What is the effect on disk evolution?
3. What is the fate of these planetesimals?
   - Where do they end up?
   - Accretion onto planets?

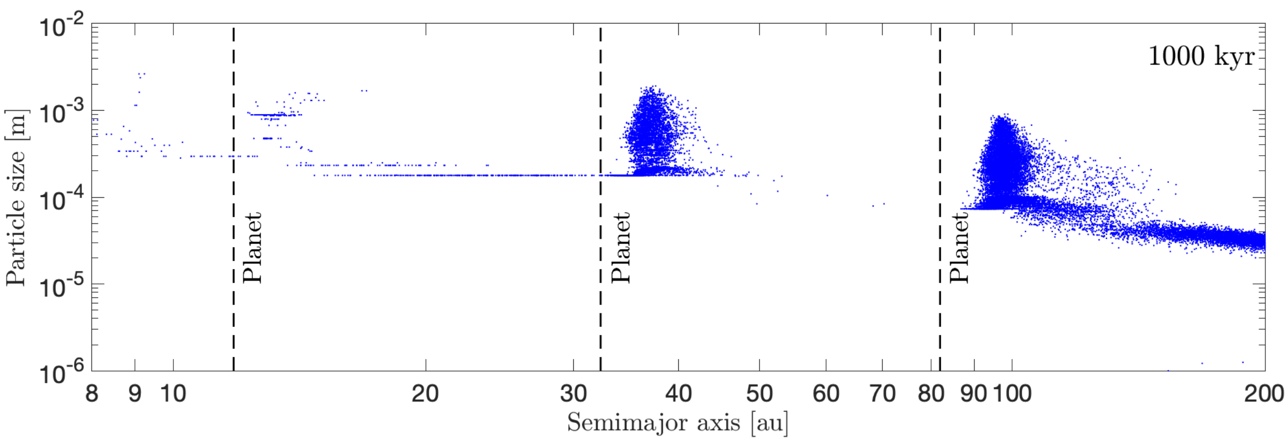


Global 1D models with particles
Eriksson et al. (2020)

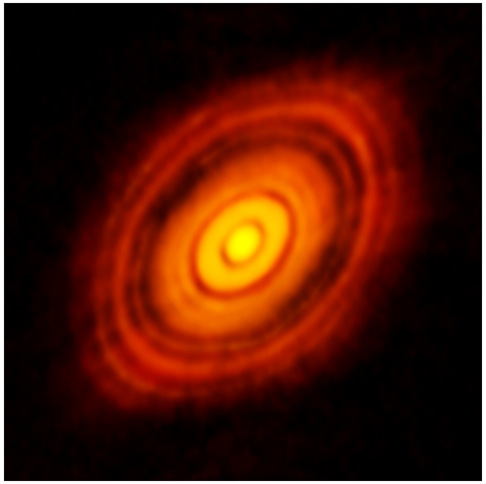
Planetesimal formation at gap edges

Nominal case without planetesimal formation





- Viscous evolution disk
- 3 planets – location: major gaps in HL Tau
- 100,000 particles
  - Drag
  - Stirring via turbulent diffusion
  - Coagulation (Güttler et al. 2010)



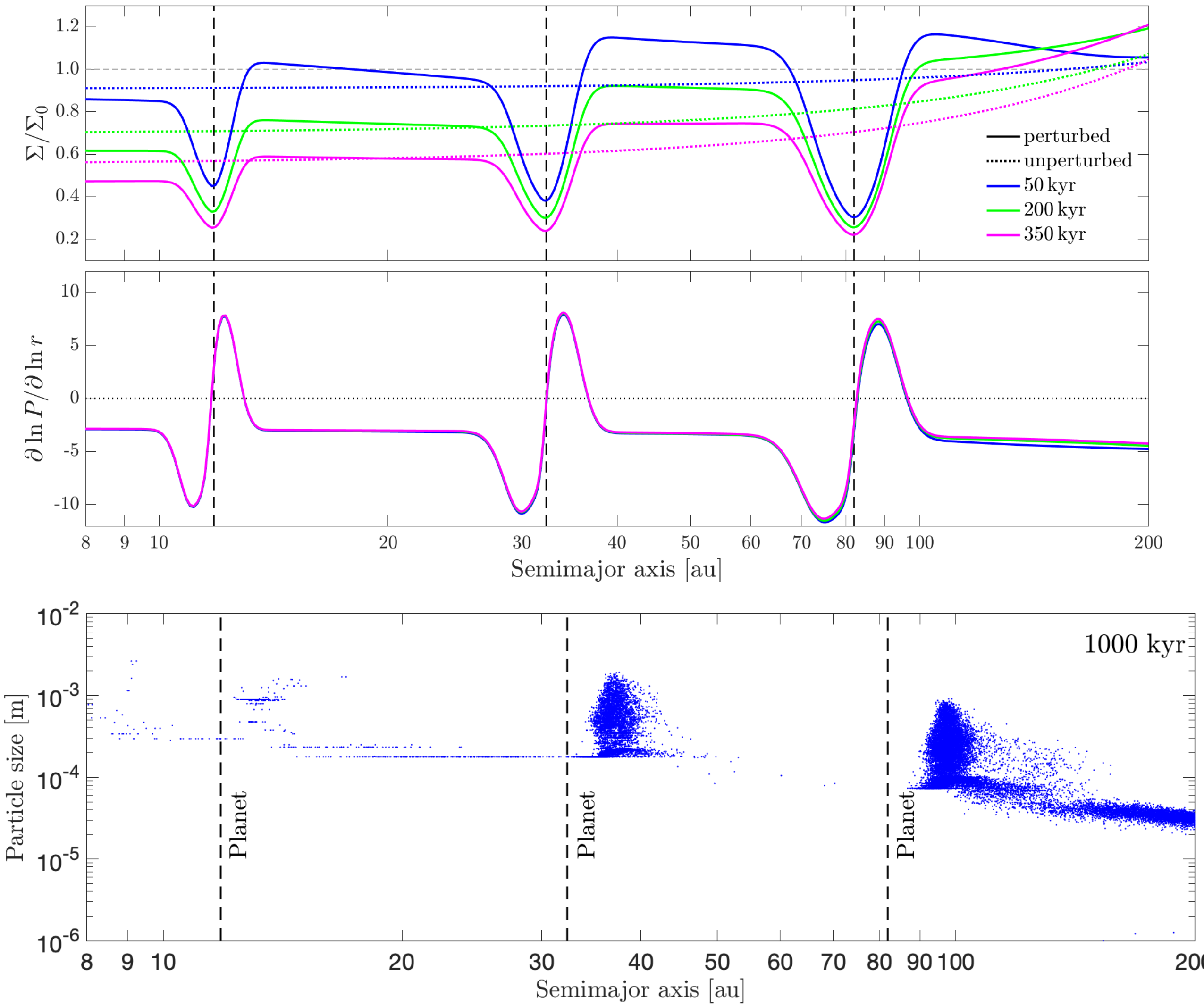
ALMA partnership et al. (2015)

Global 1D models with particles

Eriksson et al. (2020)

Planetesimal formation at gap edges

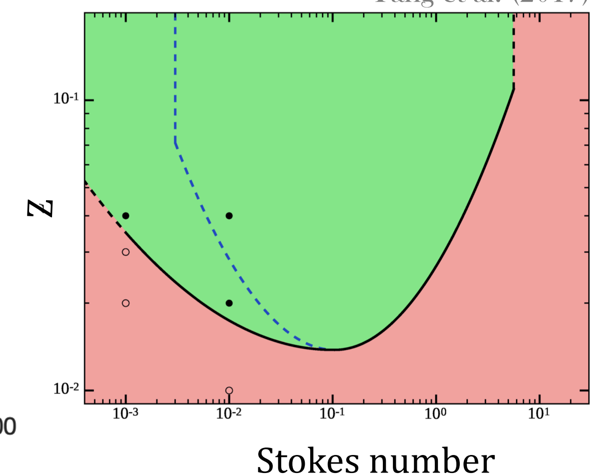
Nominal case with planetesimal formation



- Planetesimal formation via the streaming instability (Yang et al. 2017)
- Linear pressure scaling (Bai & Stone 2010)

➢ Upper limit on amount of planetesimal formation

Yang et al. (2017)



Global 1D models with particles

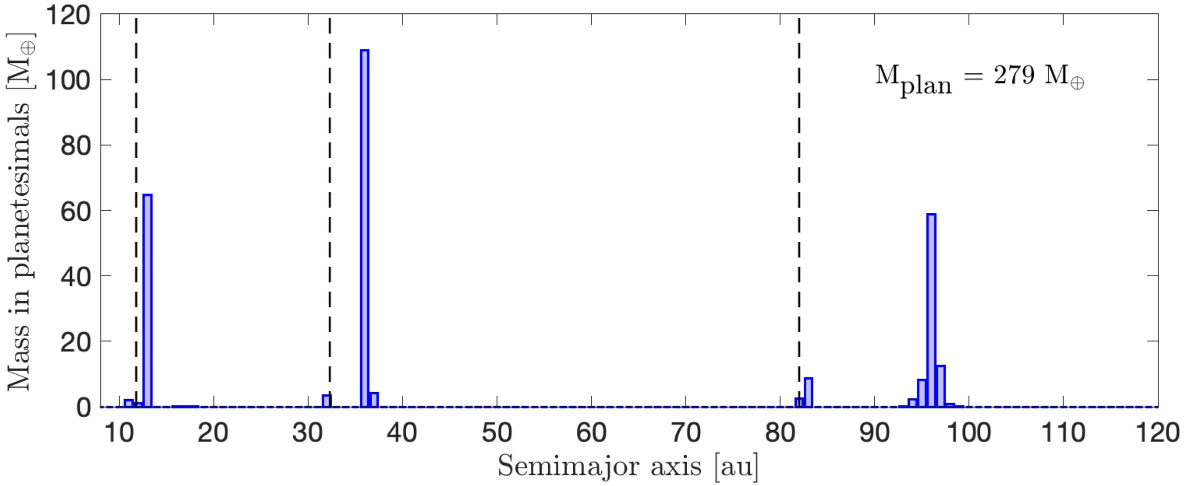
Eriksson et al. (2020)

Planetesimal formation at gap edges

Nominal case with planetesimal formation

Significant planetesimal formation at planetary gap edges

(e.g. Stammler et al. 2019; Carrera et al. 2021)



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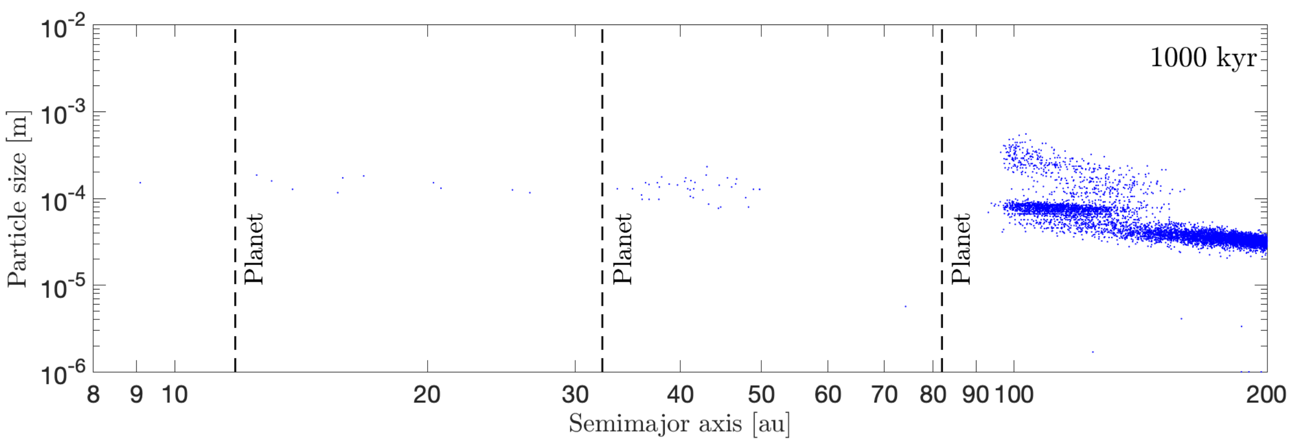
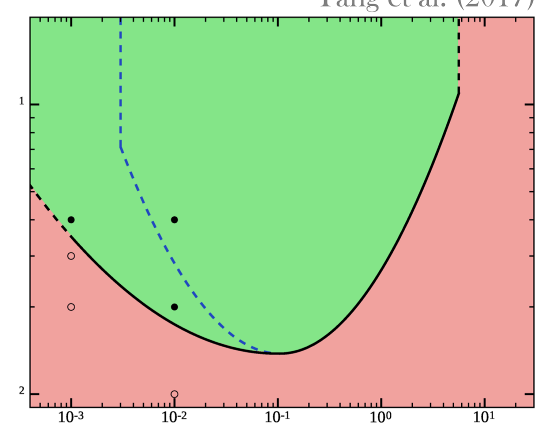


Yang et al. (2017)

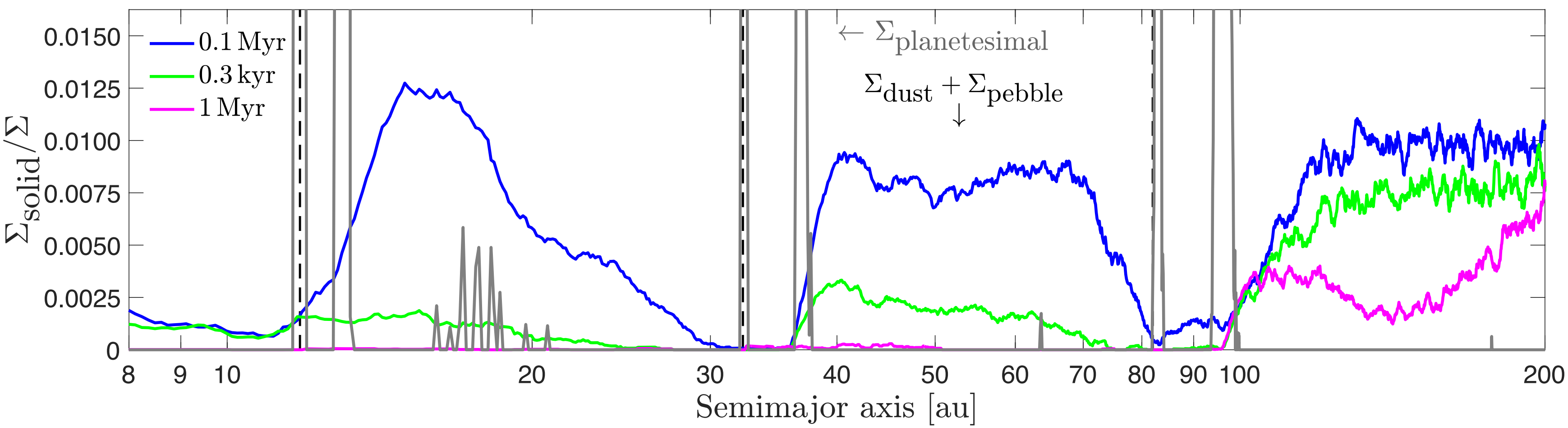


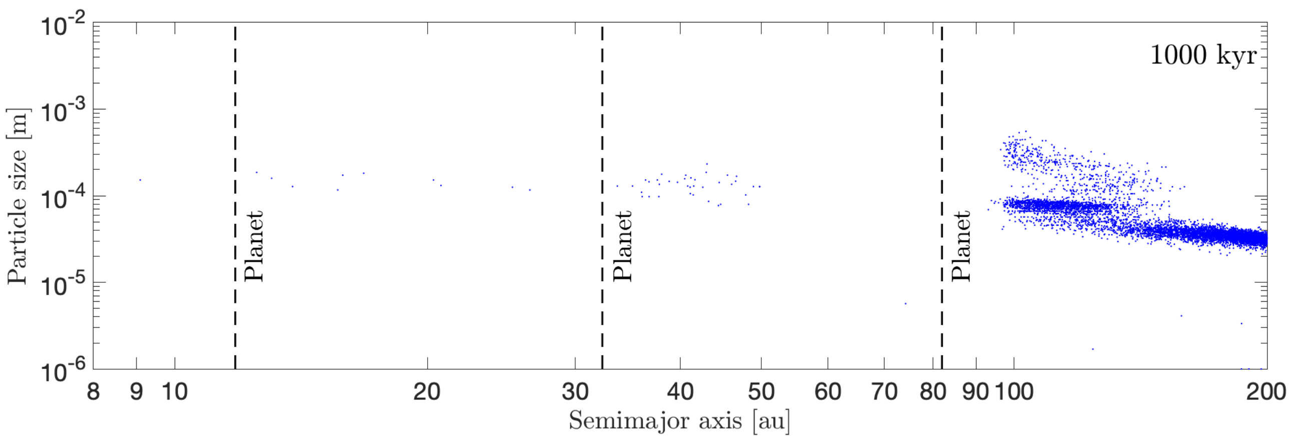
Global 1D models with particles

Eriksson et al. (2020)

Planetesimal formation at gap edges

Effect on disk evolution



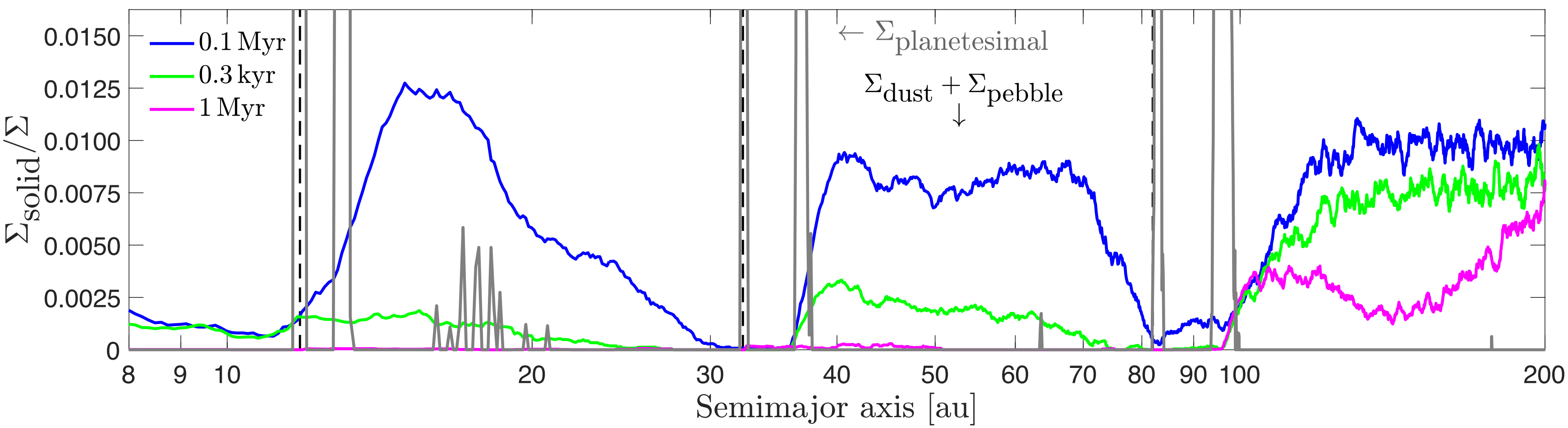


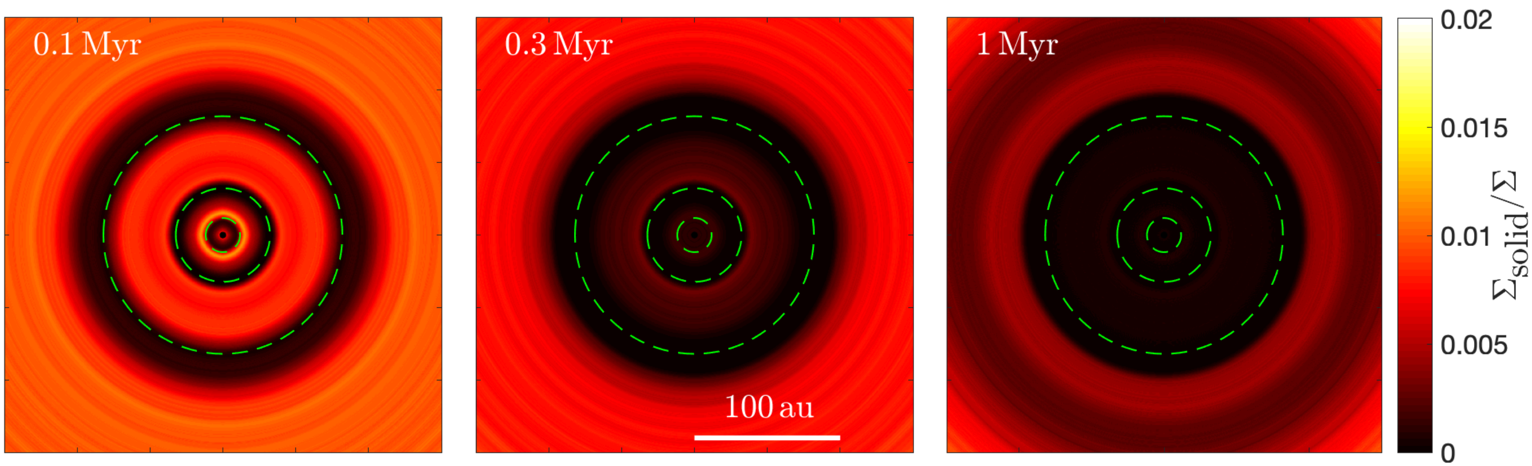
Global 1D models with particles

Eriksson et al. (2020)

Planetesimal formation at gap edges

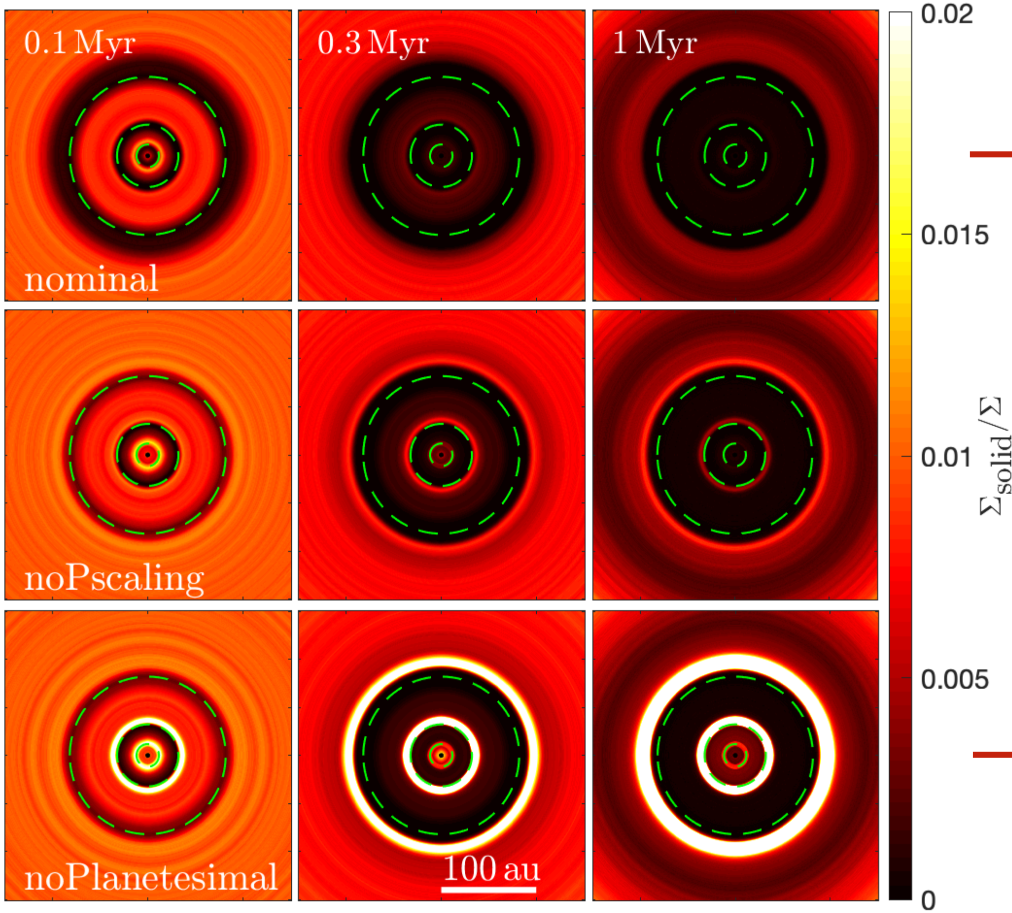
Effect on disk evolution





Global 1D models with particles
Eriksson et al. (2020)

Planetesimal formation at gap edges
Effect on disk evolution



$M \geq M_{iso}$ & very efficient planetesimal formation:
Depletion of solids interior of planets

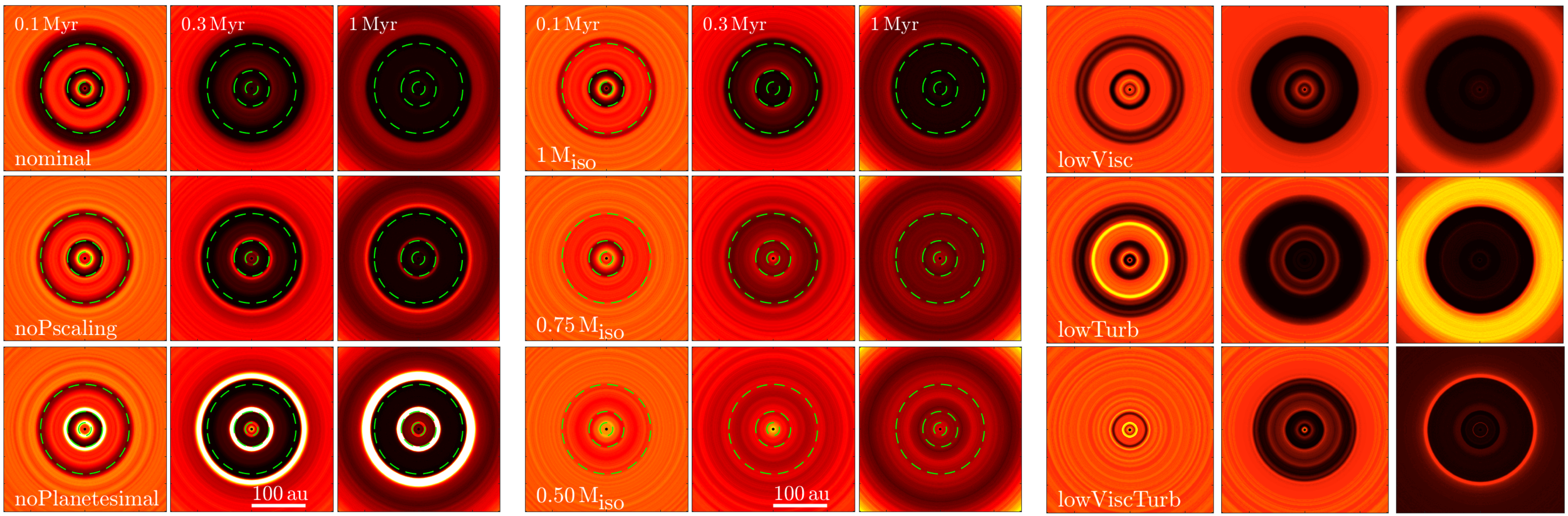
In between case

$M \geq M_{iso}$ & no planetesimal formation:
Most solids concentrate in narrow rings

Global 1D models with particles
Eriksson e t al. (2020)

Planetesimal formation at gap edges

Effect on disk evolution



What is the fate of planetesimals formed at planetary gap edges?

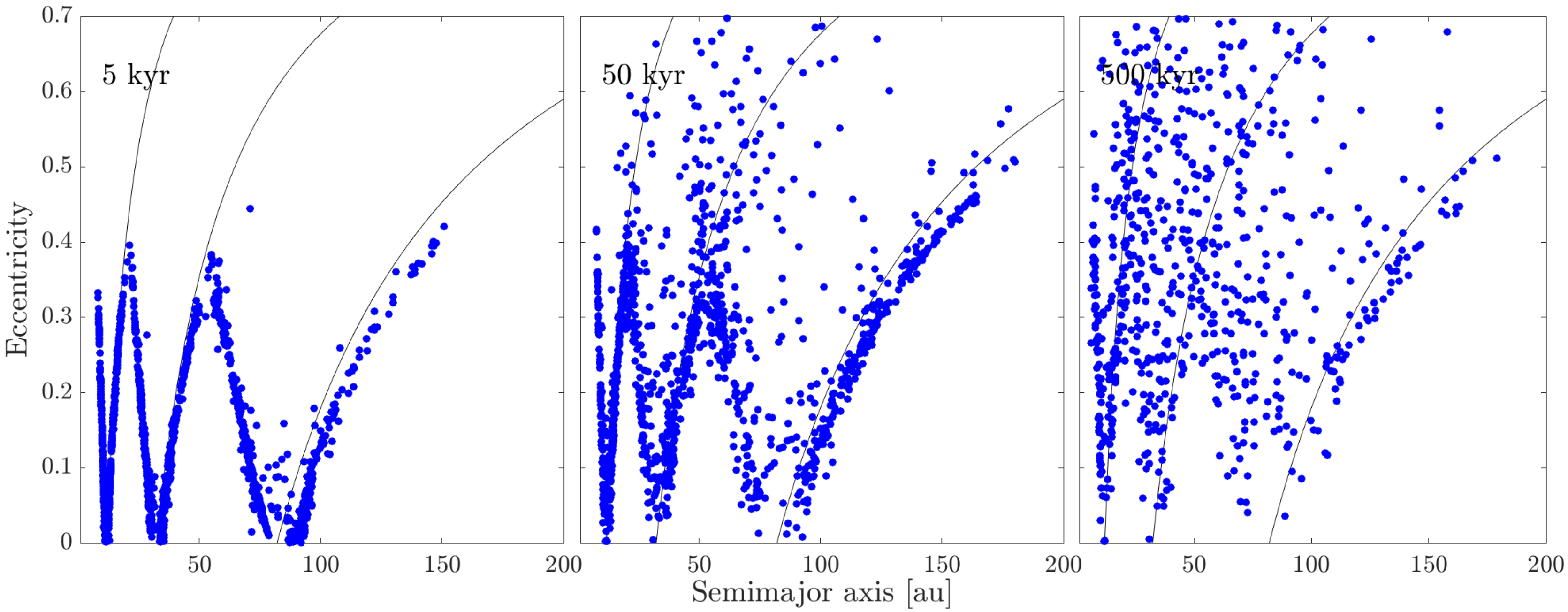
N-body

Eriksson et al. (2021)

The fate of planetesimals formed at gap edges
Where do they end up?

Start simple

- No disk evolution
- Planets with constant mass & no migration
- Form all planetesimals at the gap edges at $t = 0$ with $e \sim 0$



➢ Planetesimals formed at planetary gap edges do not remain at their birth locations

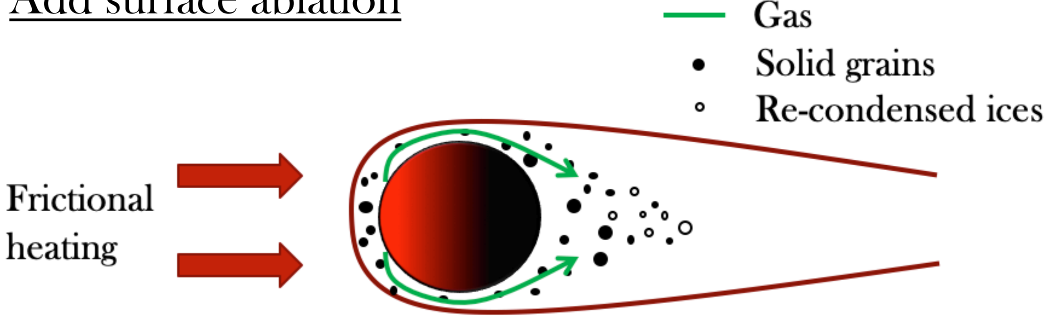
N-body

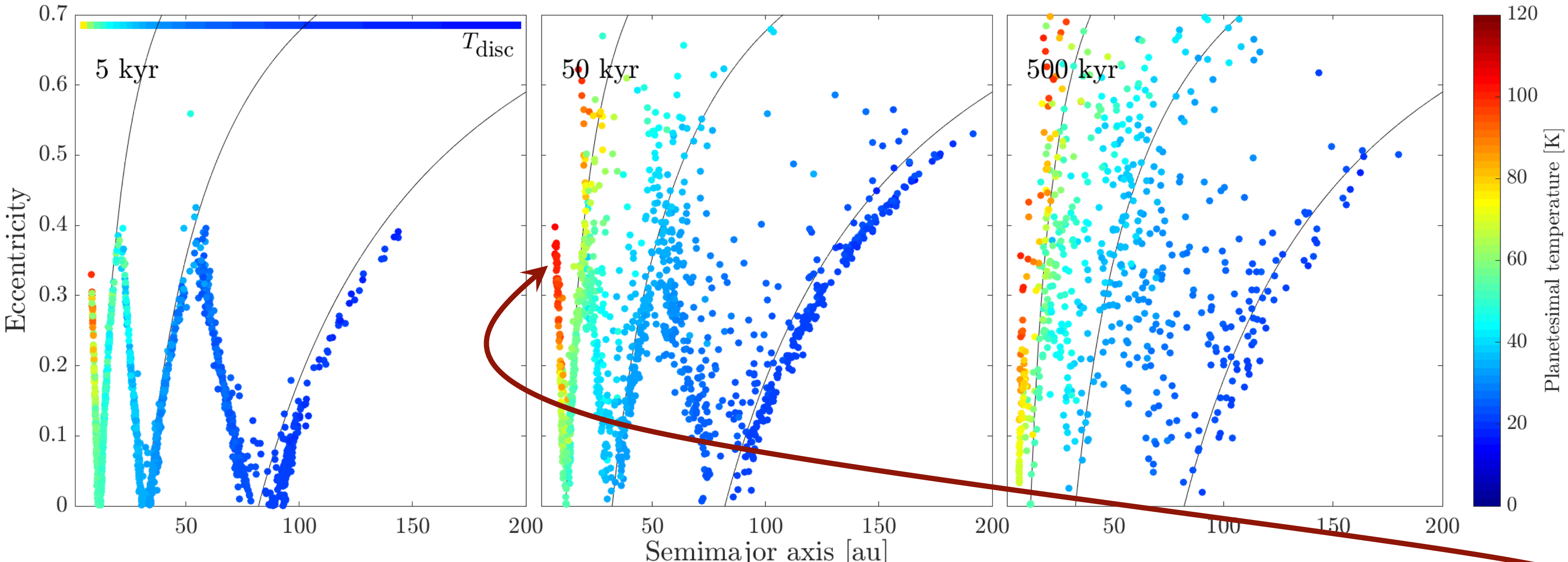
Eriksson e t al. (2021)

The fate of planetesimals formed at gap edges

Where do they end up?

Add surface ablation





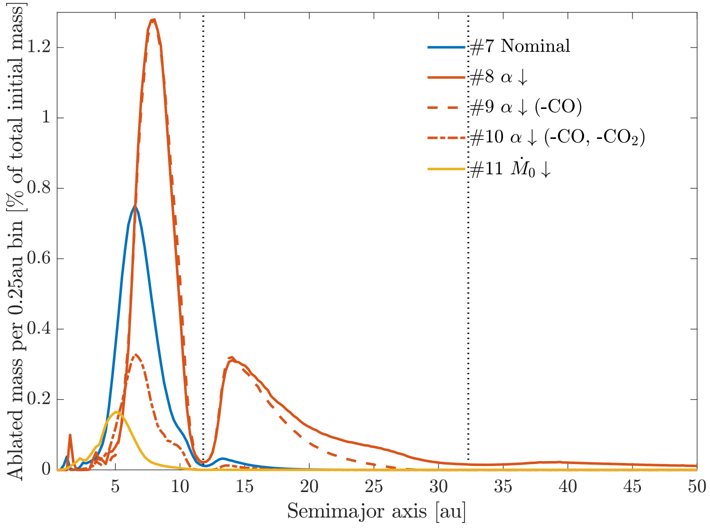
➢ Planetesimals scattered into the inner parts of young/massive disks suffer efficient ablation

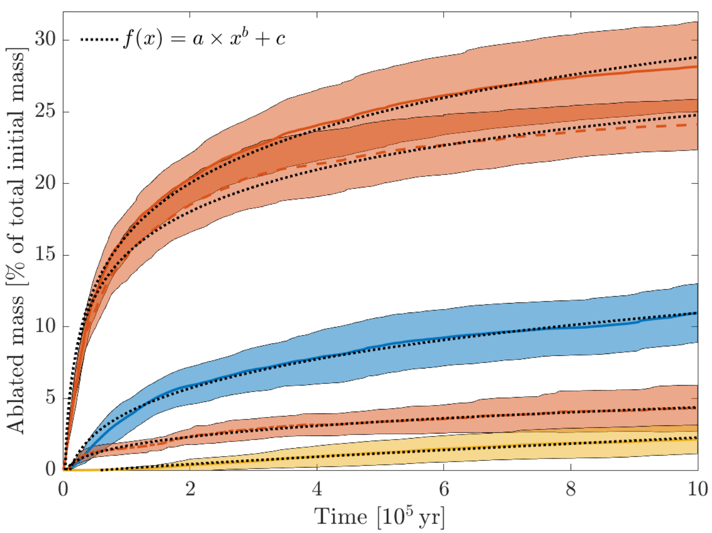
N-body

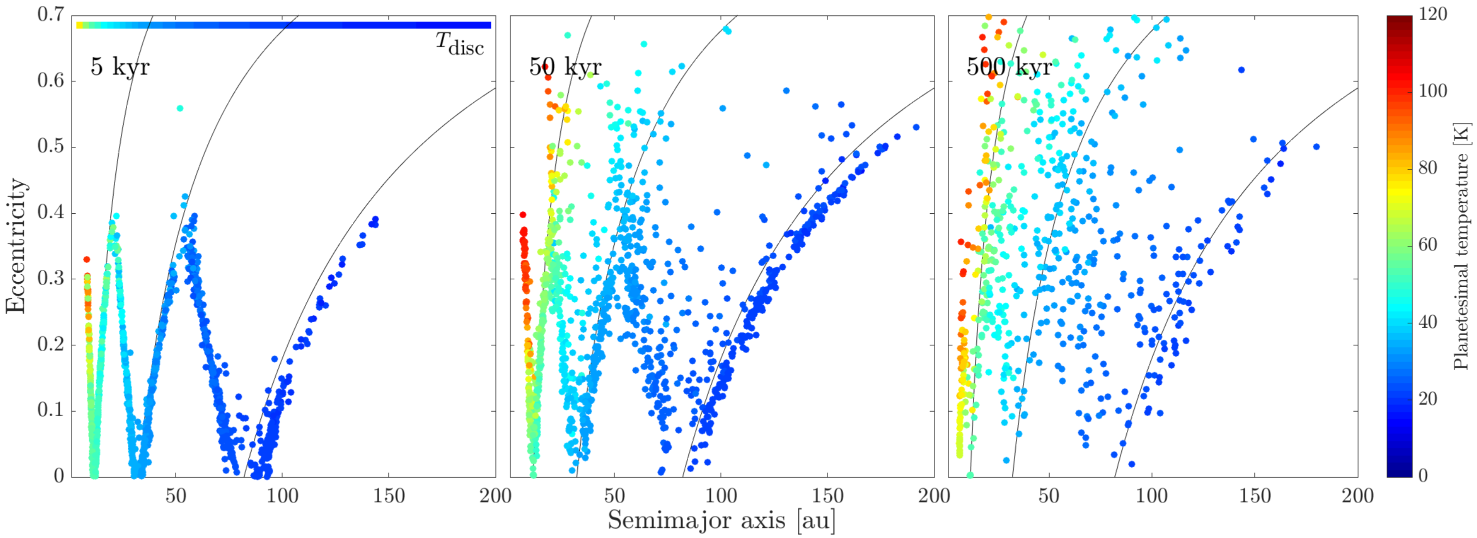
Eriksson et al. (2021)

The fate of planetesimals formed at gap edges

Where do they end up?





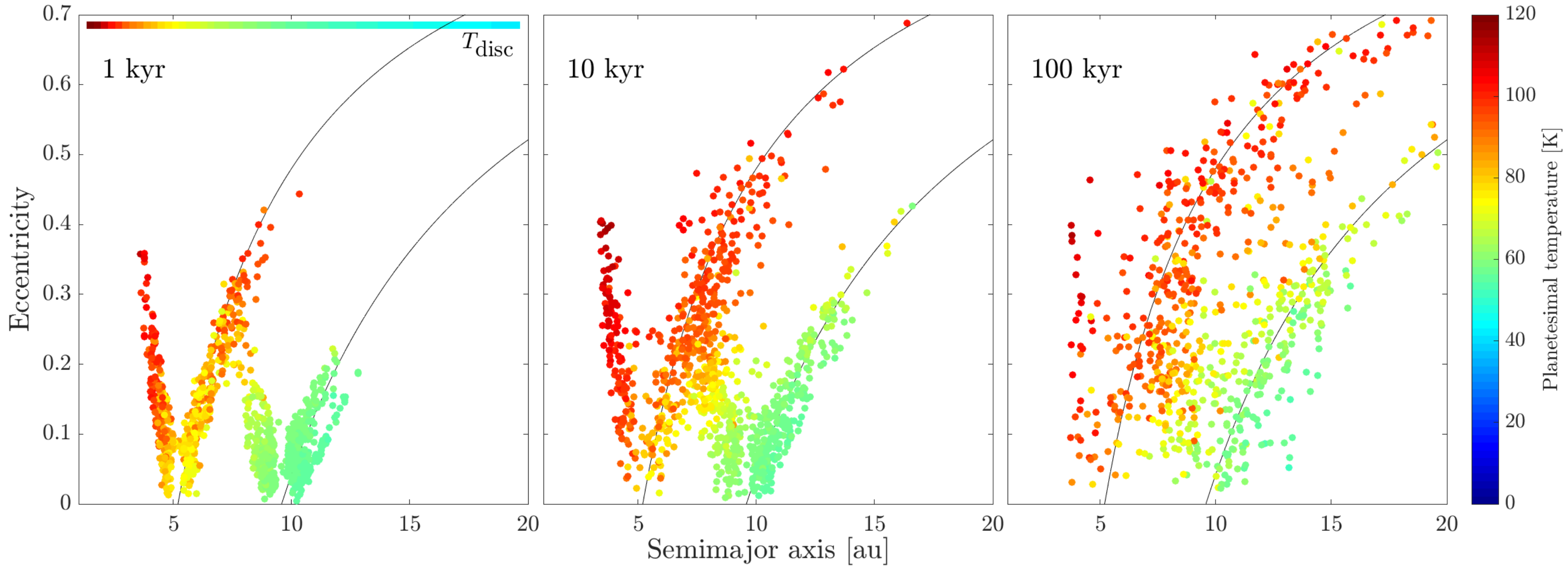


N-body
Eriksson e t al. (2021)

The fate of planetesimals formed at gap edges
Where do they end up?

Planetesimal formation at gap edges of Jupiter & Saturn

Planetesimals form closer to star → higher disk density → higher surface temperatures → more ablation

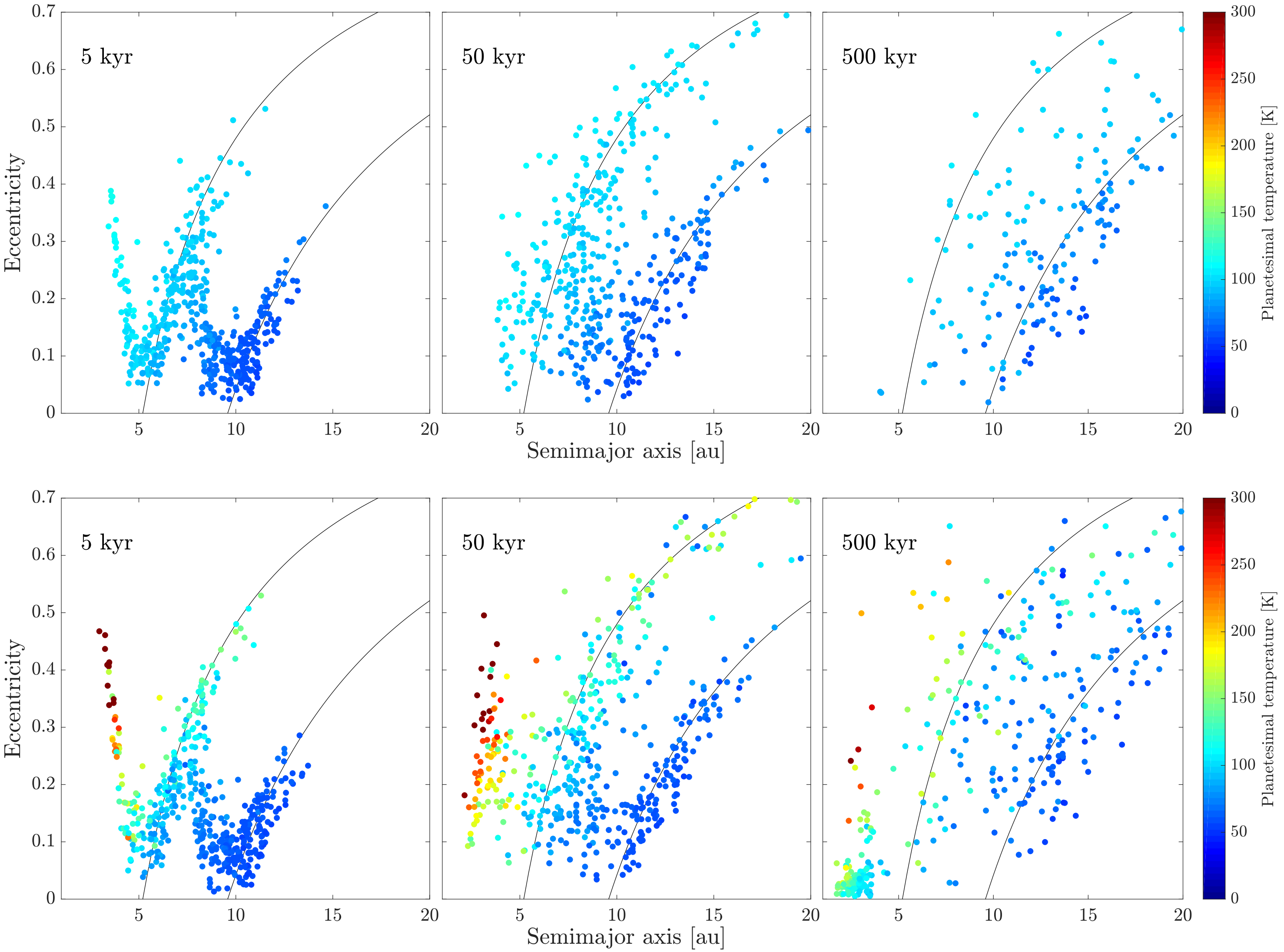


N-body

Eriksson e t al. (2021)

The fate of planetesimals formed at gap edges

Consequences of ablation?



With ablation

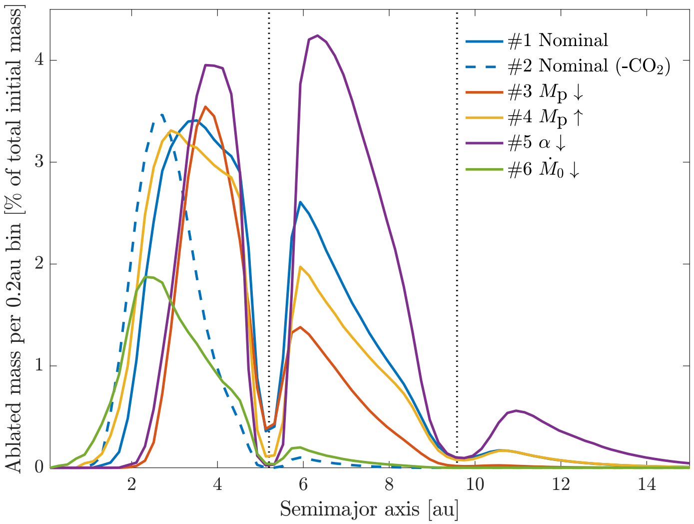
No ablation

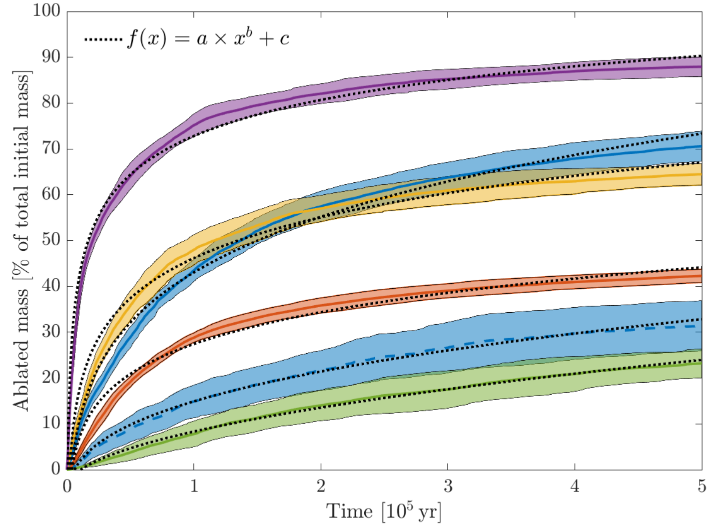
N-body

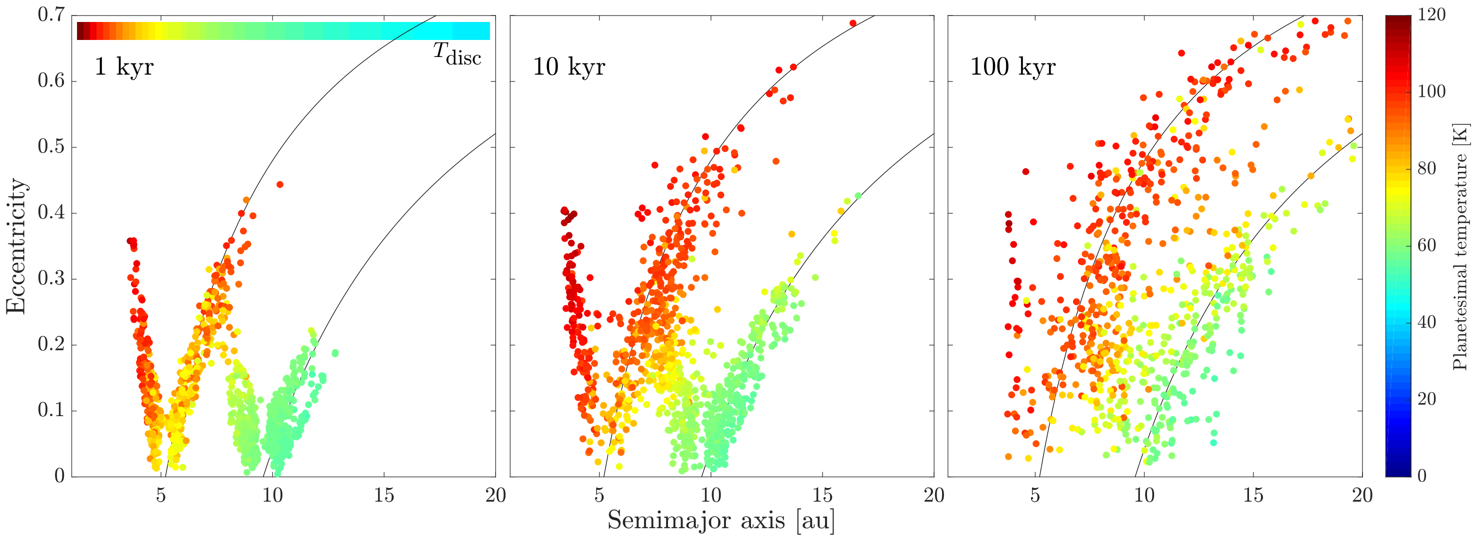
Eriksson et al. (2021)

The fate of planetesimals formed at gap edges

Where do they end up?





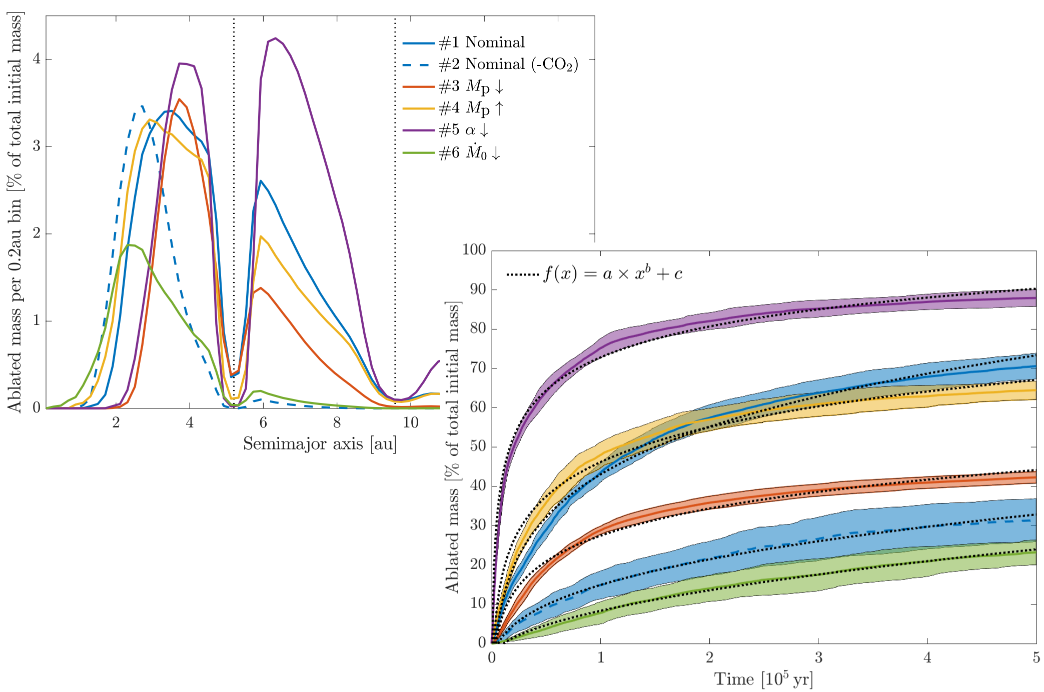


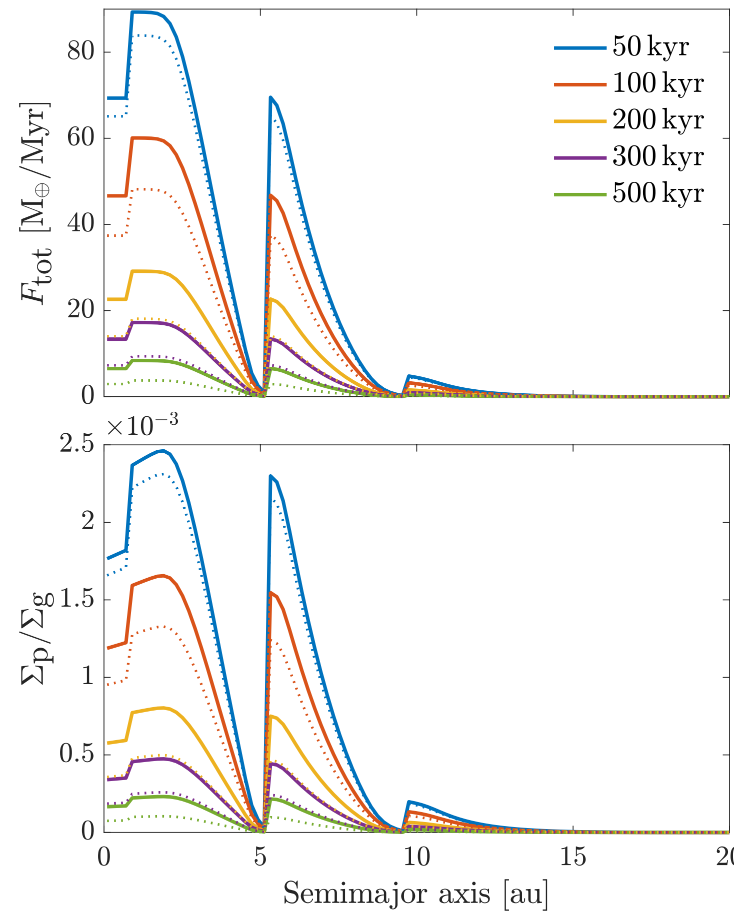
The fate of planetesimals formed at gap edges

Consequences of ablation?

A large fraction of the vaporized ices re-condense to form solid ice → re-coagulate to form new pebbles → flux of pebbles interior of the planets

→ Transport of pebbles across planetary gaps





N-body
Eriksson et al. (2022)

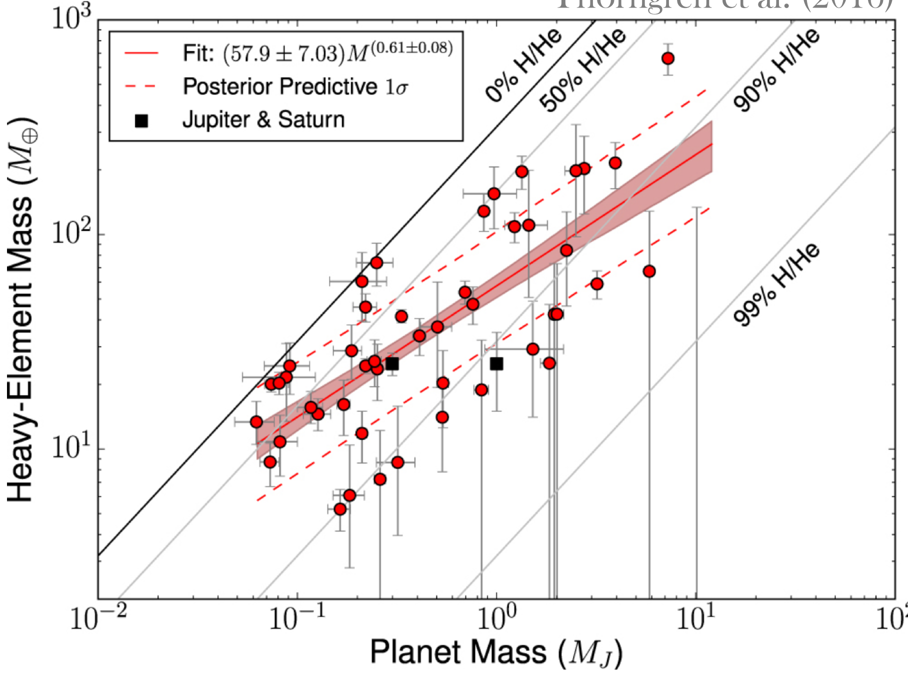
The fate of planetesimals formed at gap edges
Accretion onto planets?

Why do we care?

- Total heavy-element mass in Jupiter & Saturn estimated to $M_z \gtrsim 20\ M_\oplus$
  (Wahl et al. 2017; Helled & Guillot 2013)
- Total heavy-element mass in exogiants estimated to $M_z \sim 10-100\ M_\oplus$
  (Guillot et al. 2006; Miller & Fortney 2011; Thorngren et al. 2016)

→ Giant planets typically have atmospheres enriched in heavy-elements

Thorngren et al. (2016)



- Common explanation: accretion of planetesimals during the gas-accretion phase
  (Alibert et al. 2018; Venturini & Helled 2020; Shibata et al. 2020, 2022)
- Studies typically assume a massive wide-stretched disk of planetesimals
- How efficient is the accretion of planetesimals formed at planetary gap edges?

N-body
Eriksson et al. (2022)

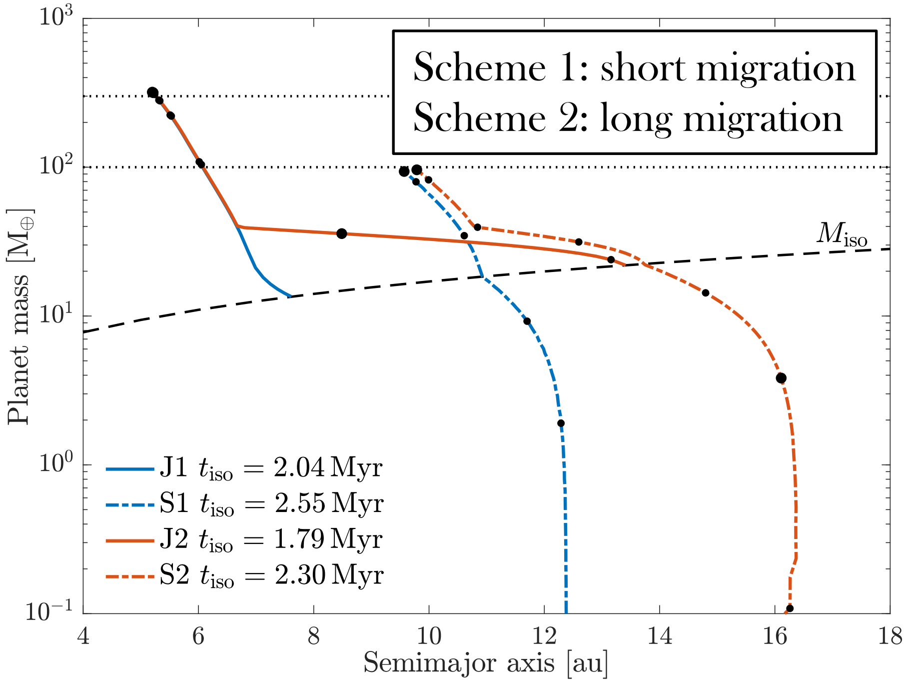
The fate of planetesimals formed at gap edges
Accretion onto planets?

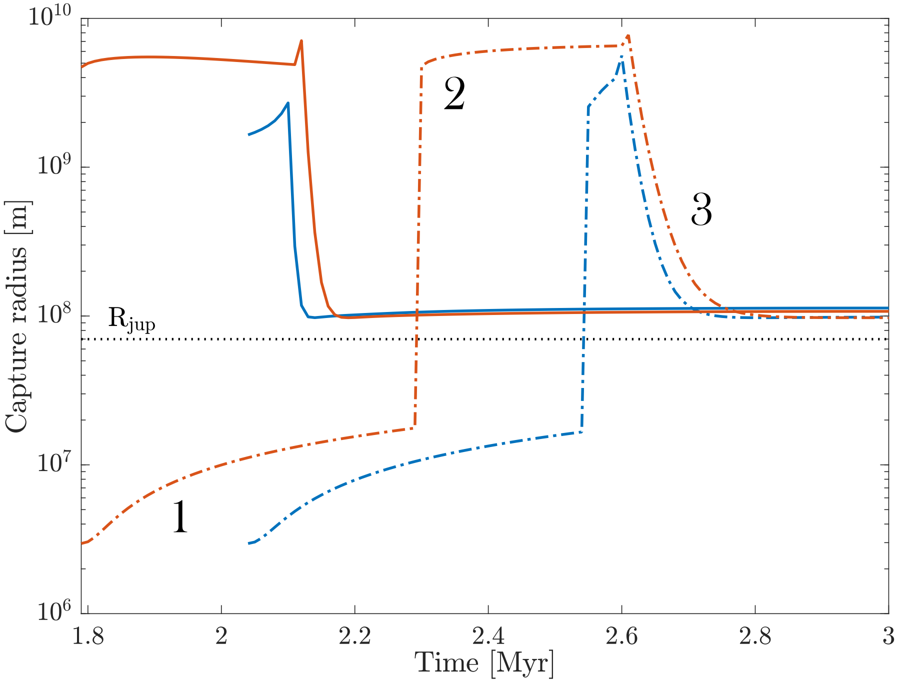
<u>More advanced model</u>

+ Disk evolution
+ Gas-accretion (2 schemes)
+ Migration
+ Add core formation for Saturn
+ Capture radius prescription
+ Continuous planetesimal formation
− Ablation

Valletta & Helled (2021)

1. Core formation ($M_p < M_{iso}$)
2. Attached phase ($M_{env} < M_{core}$)
3. Detached phase ($M_{core} < M_{env}$)



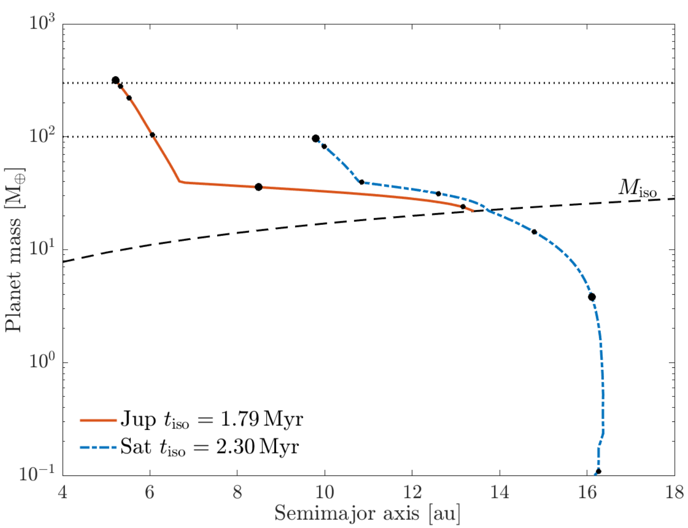


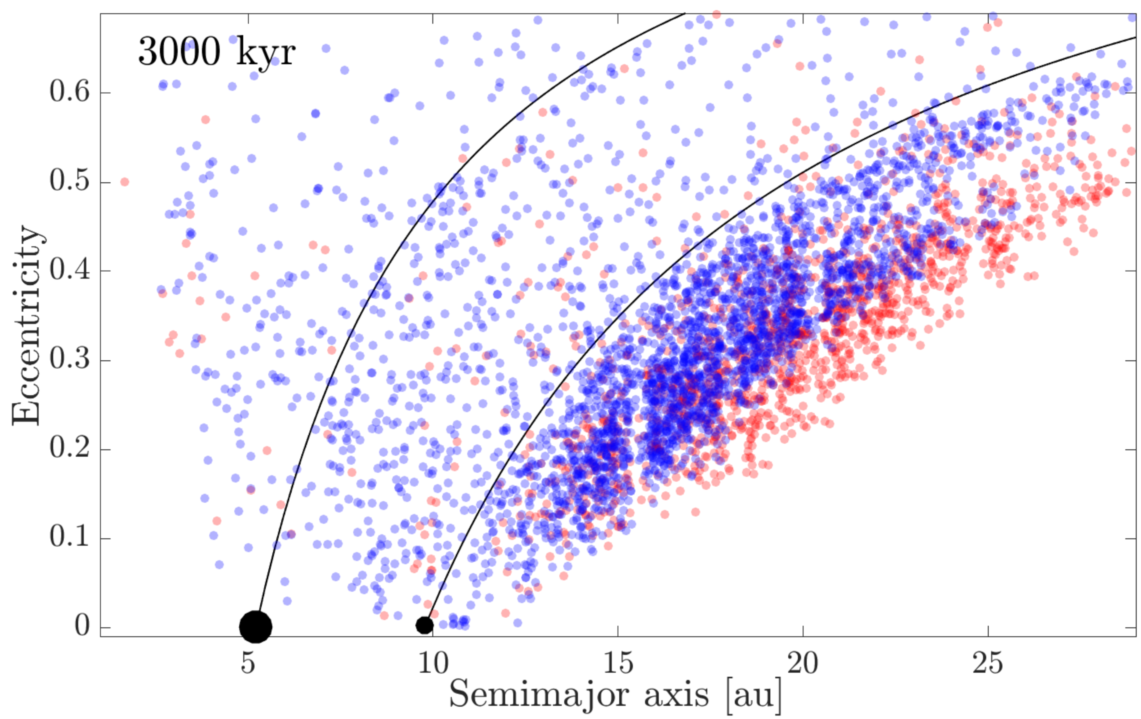
The fate of planetesimals formed at gap edges

Accretion onto planets?

<u>Planetesimals</u>

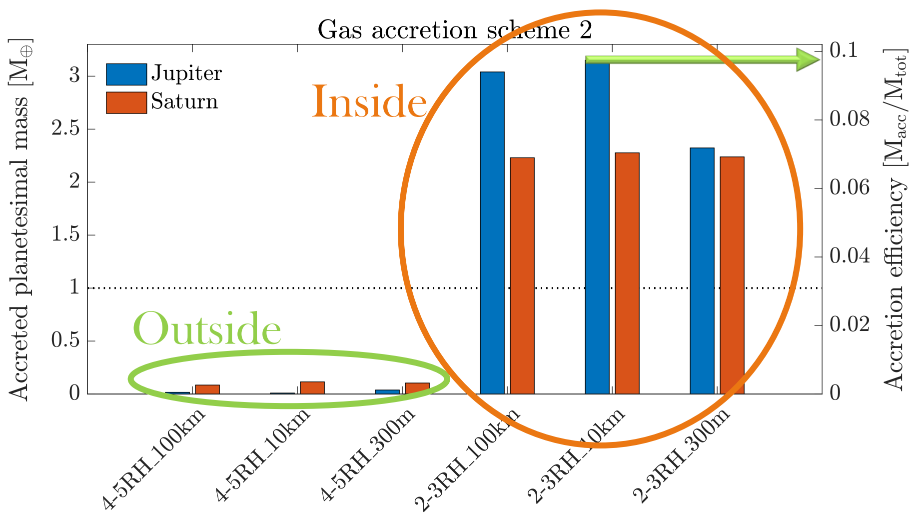
Assumption 1: no planetesimal formation before the end of core formation (M_{iso})
Assumption 2: all pebbles reaching the gap edge are turned into planetesimals
→Upper limit on planetesimal mass
→Once Saturn reaches M_{iso} → pebble flux towards Jupiter halted → no more planetesimal formation at Jupiter's gap edge





The fate of planetesimals formed at gap edges
Accretion onto planets?

- Total formed planetesimal mass at the gap edges is: $\sim 20 - 30 M_{\oplus}$



- Maximum accretion efficiency:
  <10%
- Maximum accreted mass onto Jupiter:
  $3.1\ M_{\oplus}$
- Maximum accreted mass onto Saturn:
  $2.2\ M_{\oplus}$

Very inefficient process

<u>Vary formation location</u>

- Outside the feeding zone:
  Very few collisions
- Inside feeding zone:
  Many more collisions

<u>Vary planetesimal size</u>

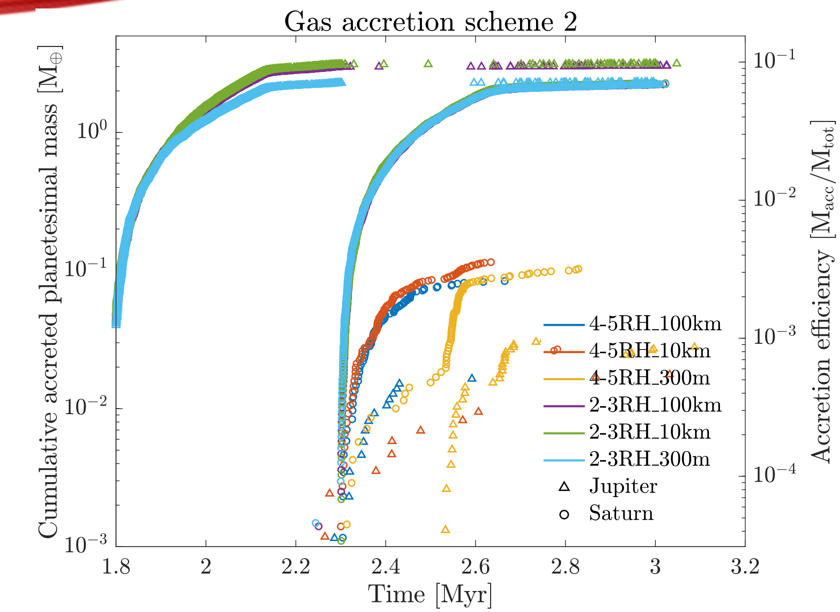
- No significant effect

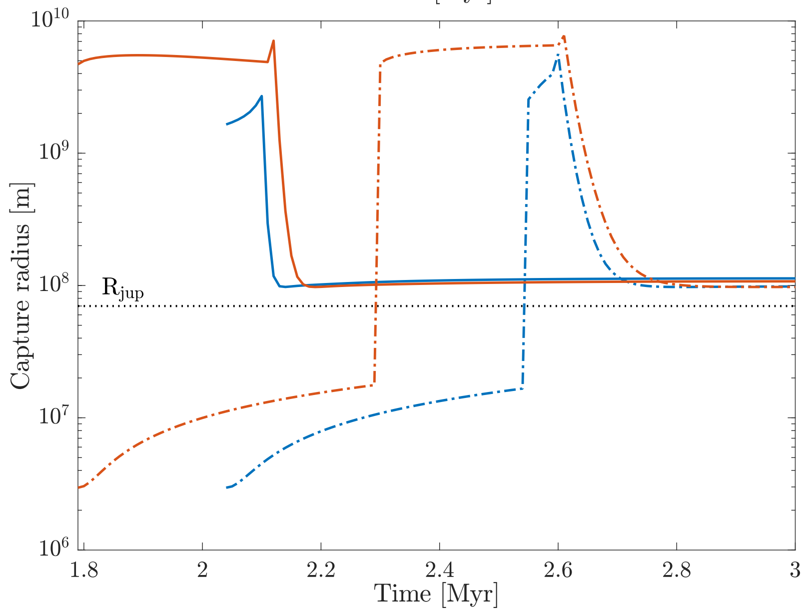
<u>Vary gas-accretion scheme</u>

- Longer migration → more accretion

The fate of planetesimals formed at gap edges

Accretion onto planets?





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The fate of planetesimals formed at gap edges

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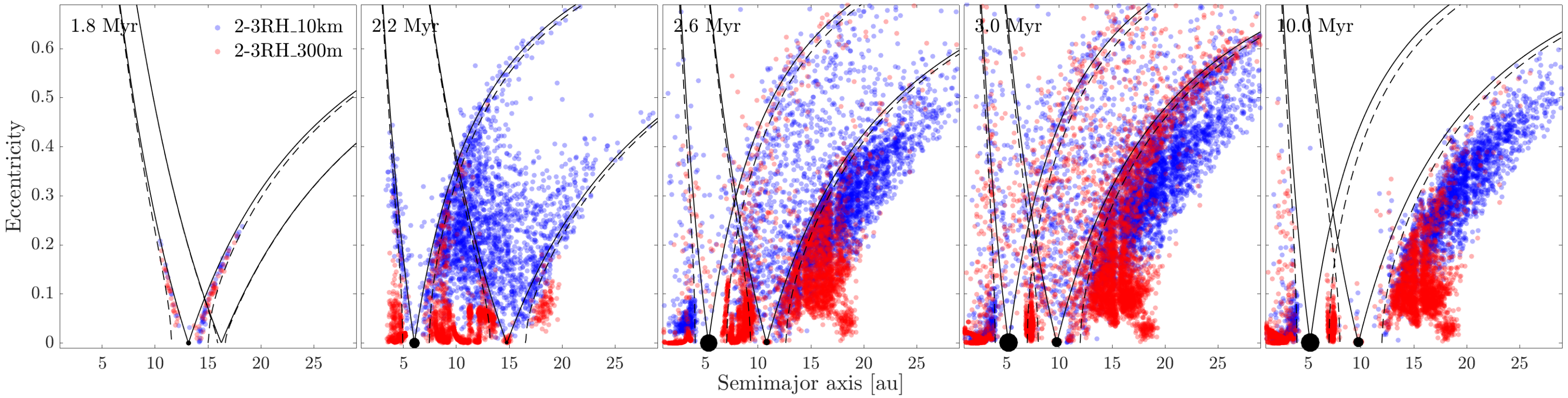

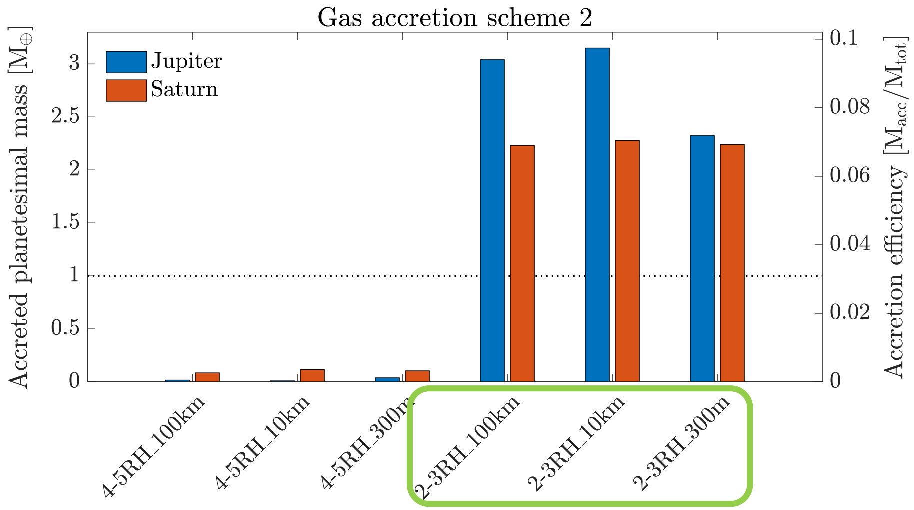

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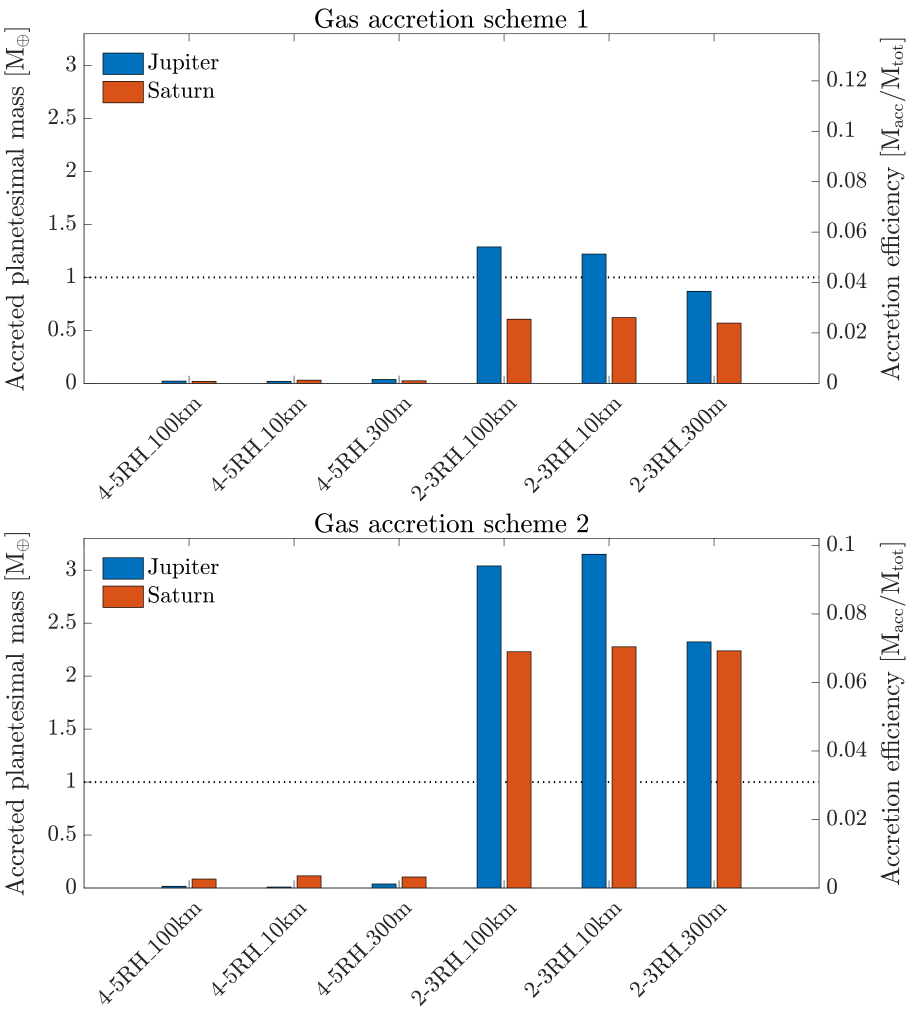
Accretion onto planets?



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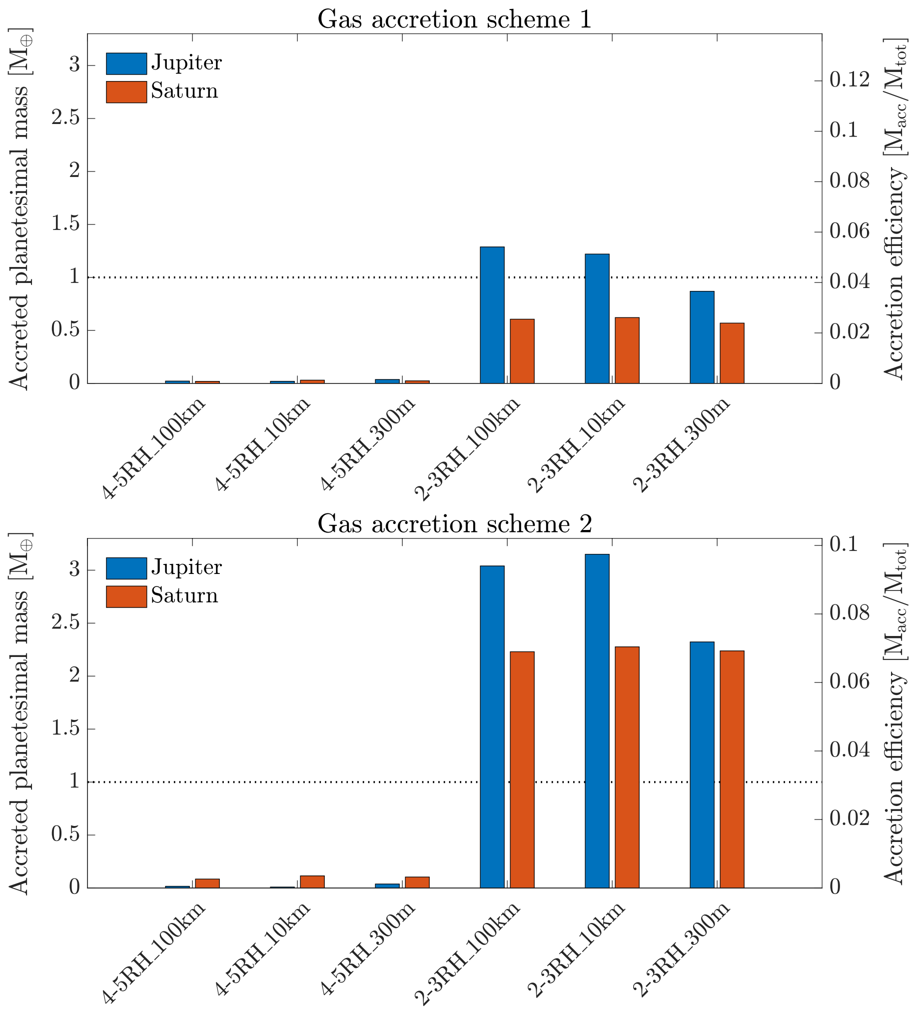

Conclusion

- ➢ Hard to explain high heavy element content of giant planets with this process

Solutions:

- Long migration through a wide-stretched disk of planetesimals (Shibata et al. 2022)
- Accretion of enriched gas from inwards drifting and evaporating pebbles (Booth et al. 2017, Schneider & Bitsch 2021a,b)
- Giant impacts and mergers (Li et al. 2010, Liu et al. 2019)

The saga of planetesimal formation at planetary gap edges

Summary so far

1. Significant planetesimal formation at planetary gap edges
   ➢ Major implications for distribution of pebbles & thus how disk appear in observations

2. Planetesimals formed at planetary gap edges do not remain at their birth locations
   ➢ Efficient ablation in inner parts of young disks

3. The accretion efficiency of planetesimals formed at planetary gap edges is very low
   ➢ Hard to explain enriched atmospheres of giant planets via this process