The big and the small: how giant planets shape their smaller neighbours

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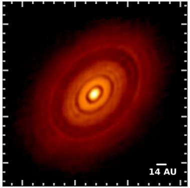
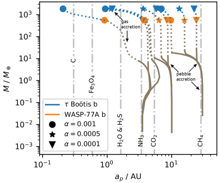
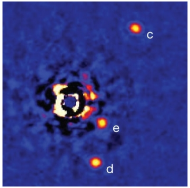
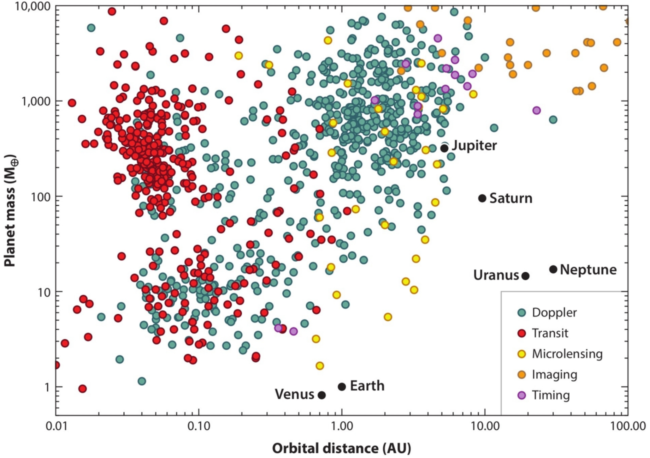






Observations of planets



(*Winn & Fabrycky 2015*)

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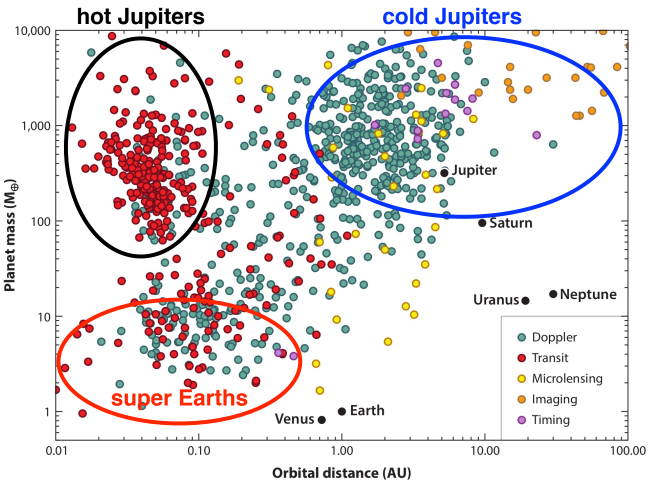
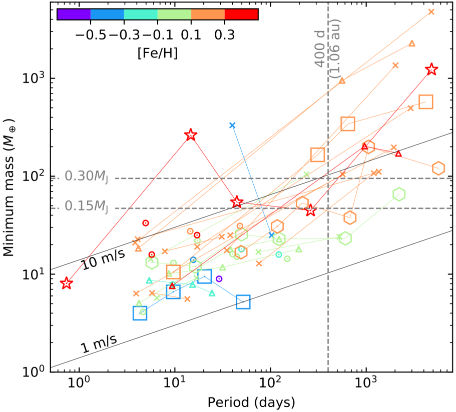


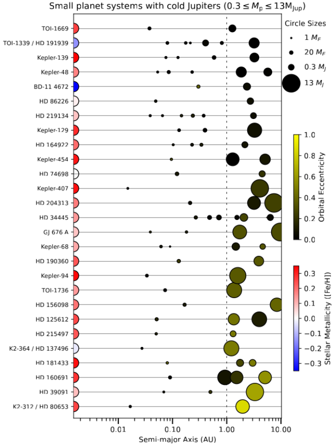
(*Winn & Fabrycky 2015*)

⇒ What is the connection between super-Earths and outer giants?

Inner super-Earths and outer gas giants?



(*Zhu & Wu 2018*)



(*Bonomo et al. 2025*)

⇒ Observations indicate a correlation between inner super-Earths and outer giant planets

⇒ Exact correlation is still subject to debate and depends on the observational (?) biases

(e.g. *Barbato et al. 2018*, *Bryan et al. 2019*, *Weiss et al. 2024*, *Bryan & Lee 2024*, *Bonomo et al. 2025*, *Li & Zhu 2026*)

Planet formation: Core accretion

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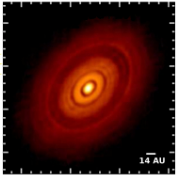

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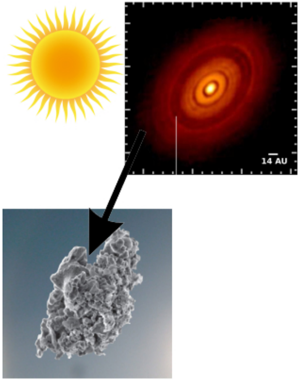

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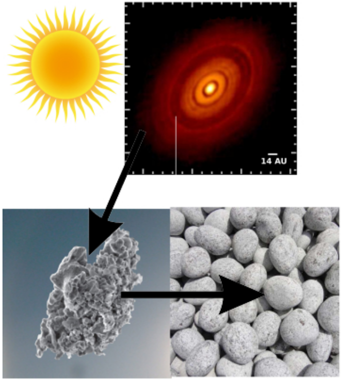

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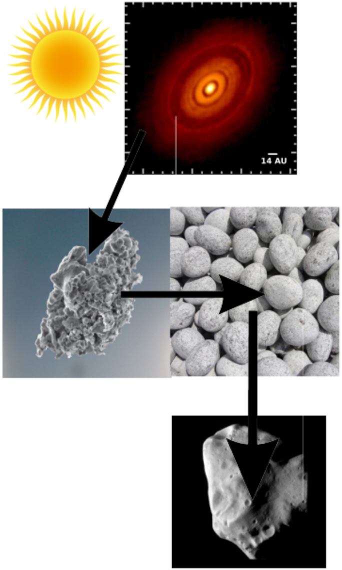

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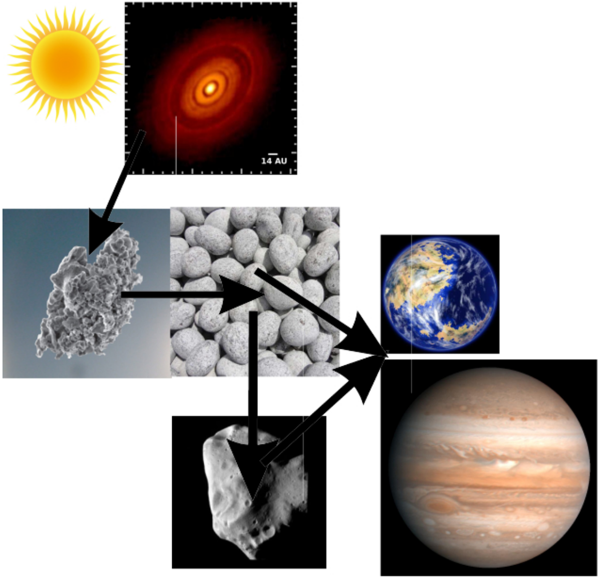

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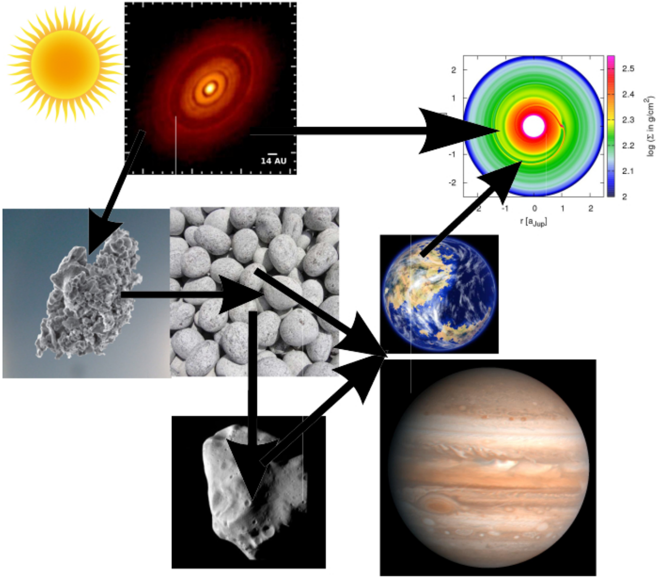

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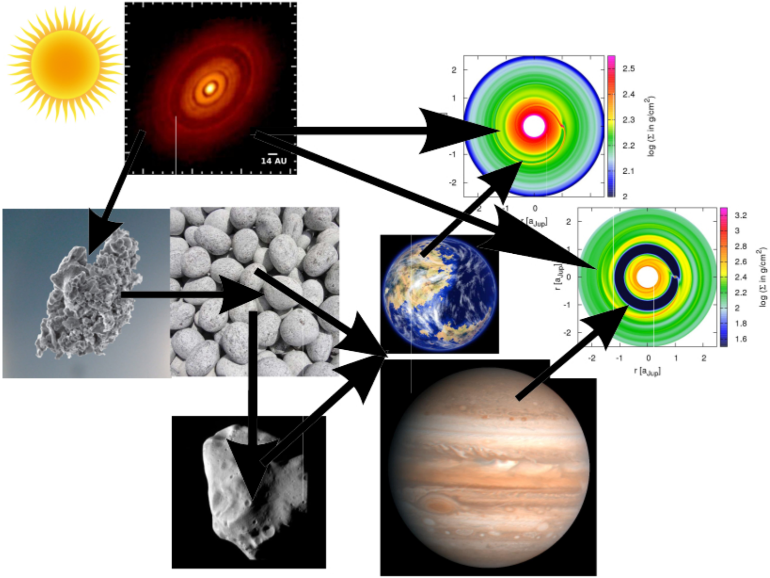

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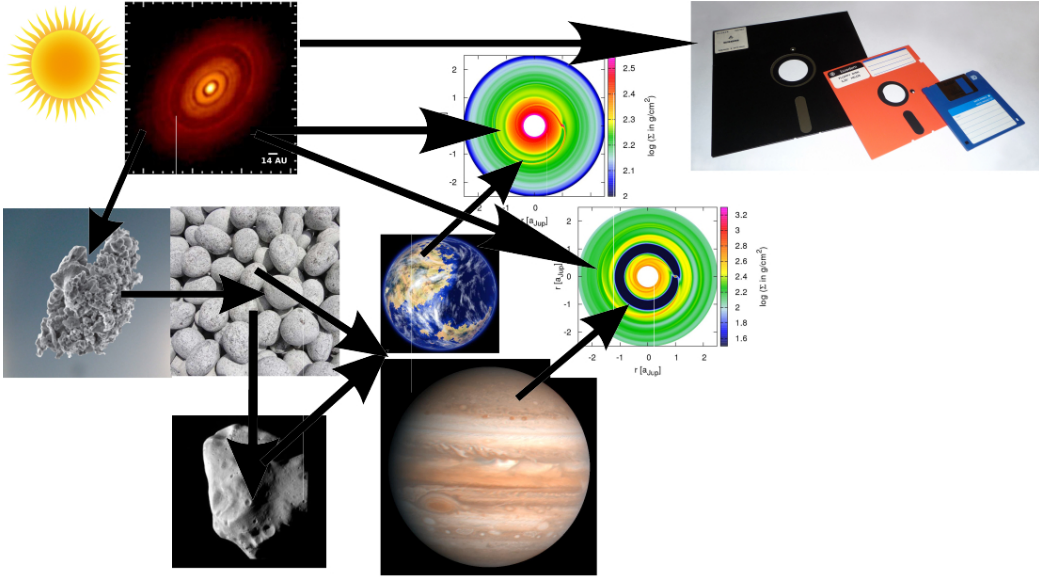

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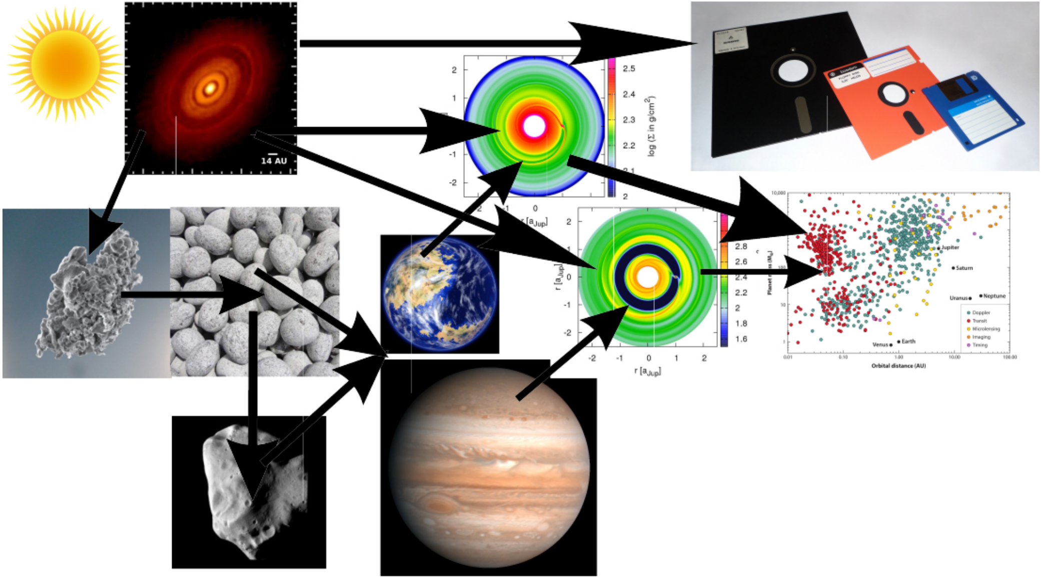

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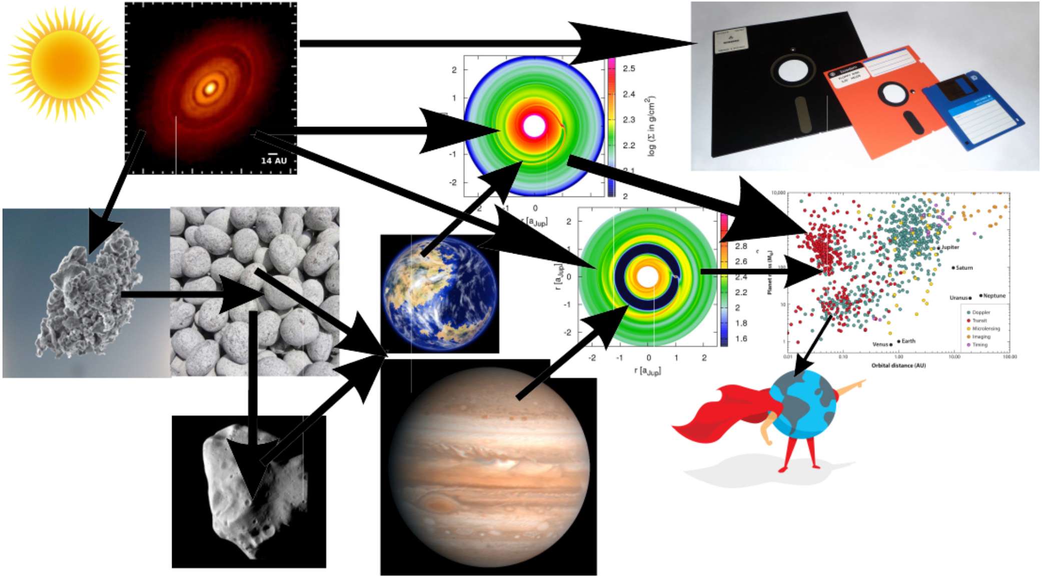

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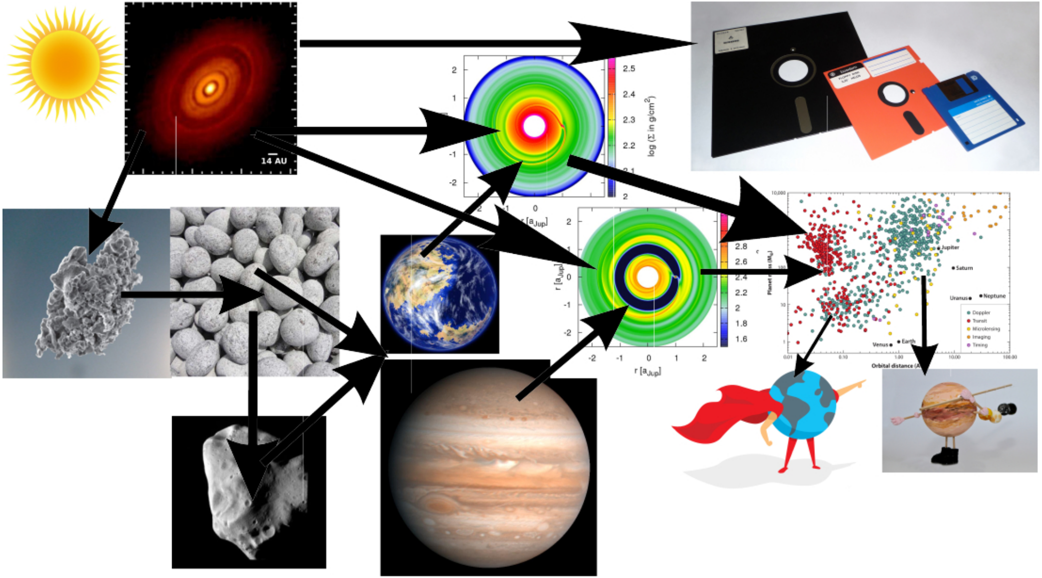

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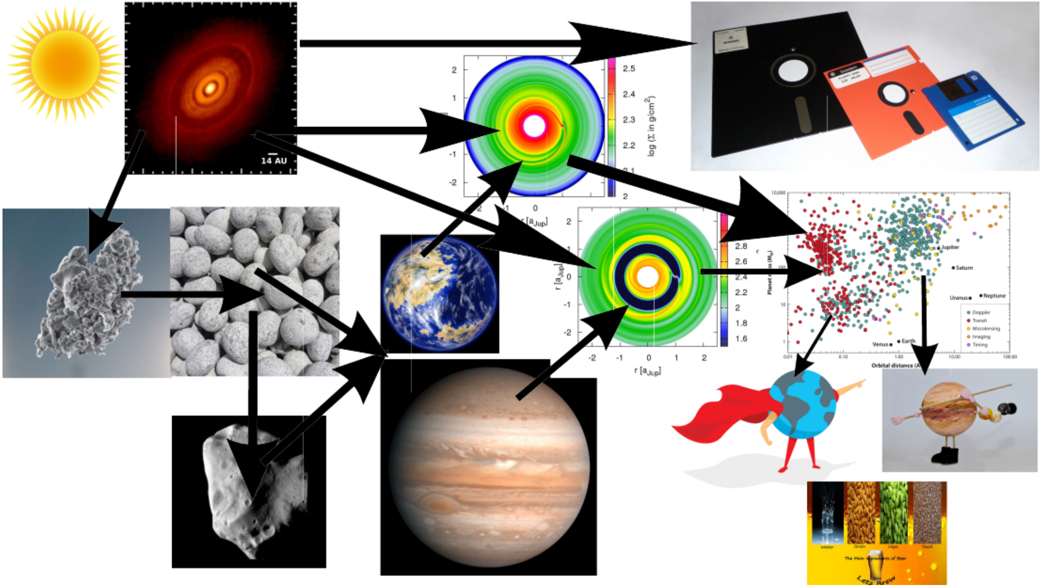

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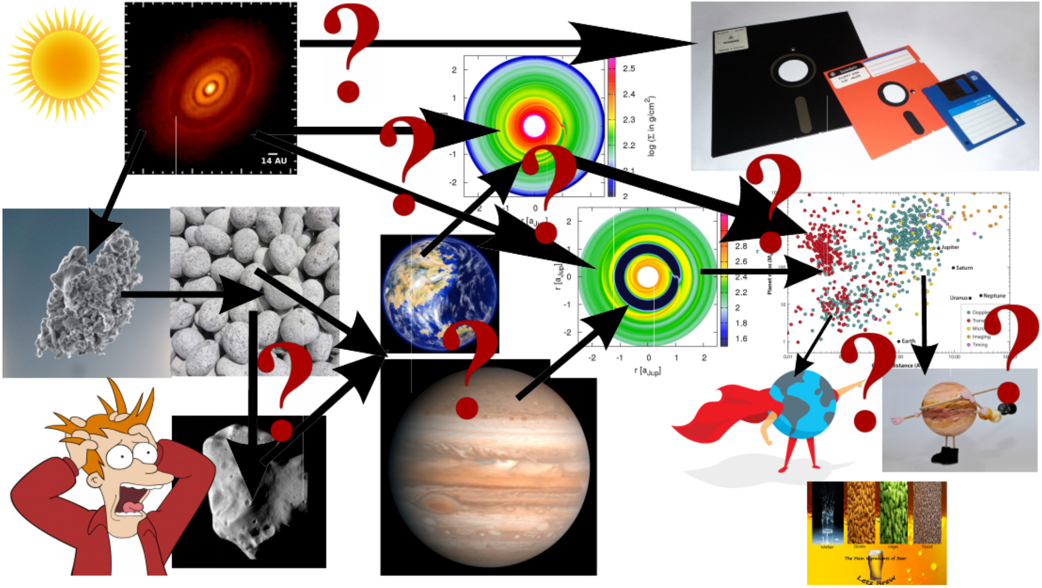
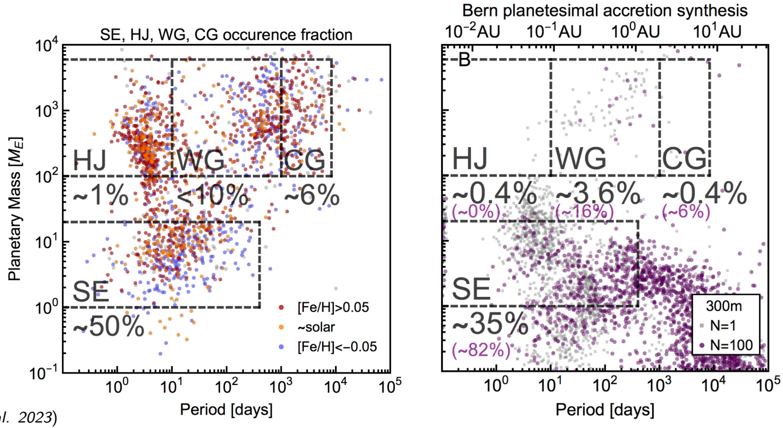


Planetesimal accretion



(*Drążkowska, Bitsch, et al. 2023*)

⇒ Planetesimal accretion could explain the formation of inner super-Earths in various models, **but** planetesimal sizes too small!

(e.g. *Emsenhuber et al. 2021, Batygin & Morbidelli 2023, Ogihara et al. 2024*)

⇒ Planetesimal accretion has problems to explain the outer giant planet populations!

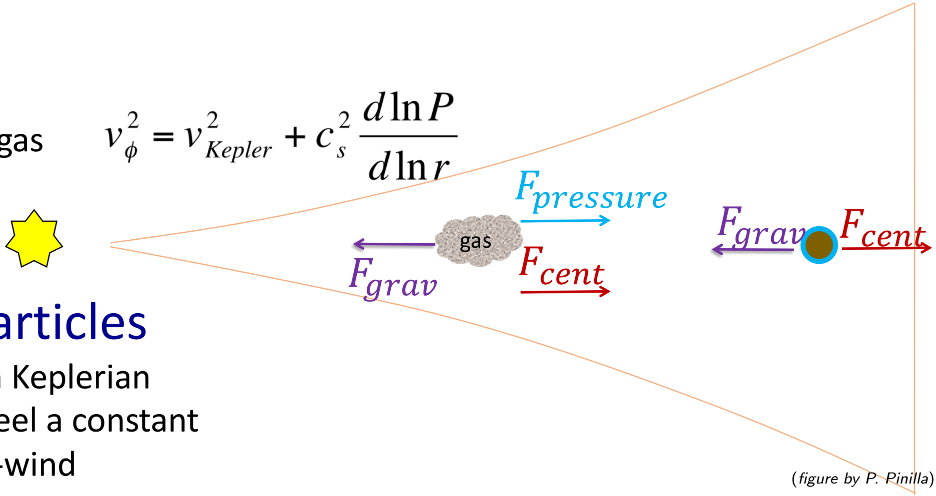
(e.g. *Levison et al. 2010, Johansen & Bitsch 2019*)

Dust motion

GAS

Supported by gas pressure

$$v_\phi^2 = v_{Kepler}^2 + c_s^2 \frac{d \ln P}{d \ln r}$$



(*figure by P. Pinilla*)

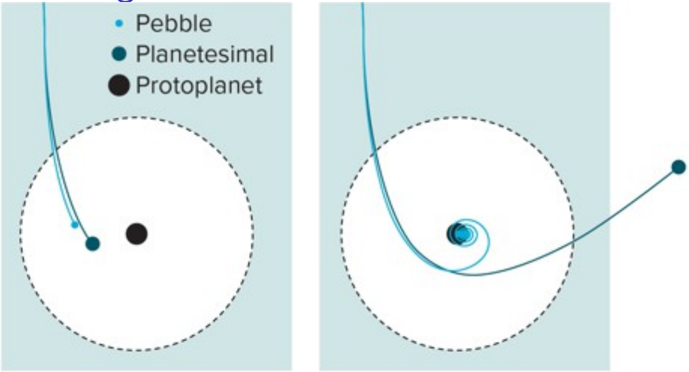
Dust Particles

Move with Keplerian velocity and feel a constant head-wind

⇒ Dust orbits on the Keplerian velocity, while the gas orbits sub-Keplerian

⇒ Dust moves inwards much faster than the gas!

Planet growth: Pebble accretion



(e.g *Johansen & Lambrechts 2017*)

⇒ Planetesimal accretion inefficient, especially in the outer disc (*e.g. Johansen & Bitsch 2019*)

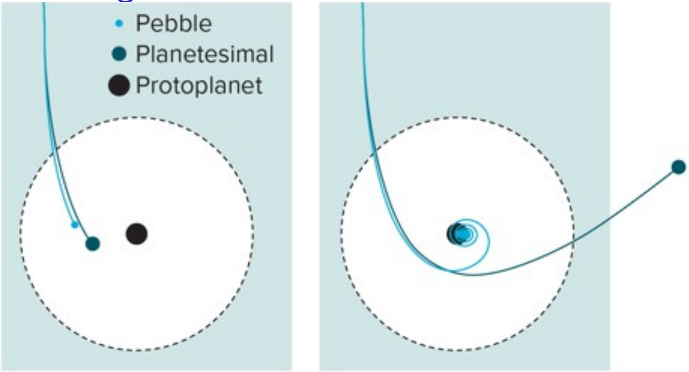
- Pebbles spiral on to the planet due to gas friction

⇒ Pebbles are accreted efficiently

- Accretion rate $\dot{M}_c$ by pebble accretion:

$$\dot{M}_c = 2\left(\frac{\tau_f}{0.1}\right)^{2/3} r_H^2 \Omega_K \Sigma_{Peb}$$

Planet growth: Pebble accretion



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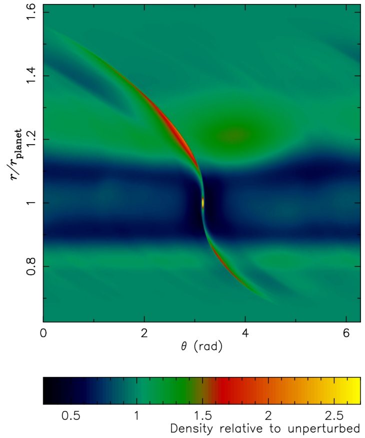
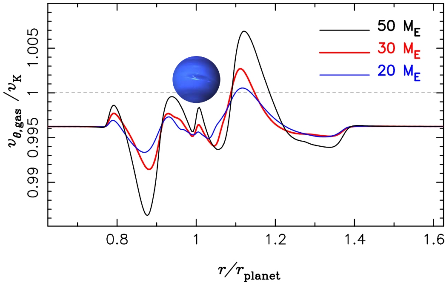
⇒ Pebble accretion becomes efficient once the embryo is ≈0.01 $\mathrm{M_E}$

⇒ Initial collisions might be needed, before pebble accretion finishes the job!
(but see *Lorek & Johansen 2022, Lyra et al. 2023*)

⇒ Pebble accretion is efficient, because a single planet could have access to the full mass reservoir of the disc!

Gaps in discs: Pebble isolation mass





$\Rightarrow$ Pebble accretion self-terminates: no accretion of solids any more!

(*Lambrechts et al., 2014; Bitsch et al., 2018a, Ataiee et al. 2018*)

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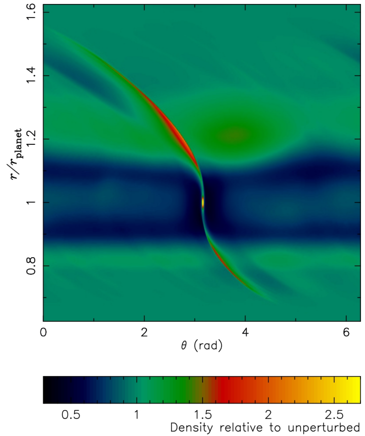

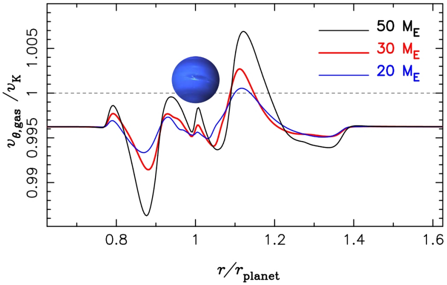

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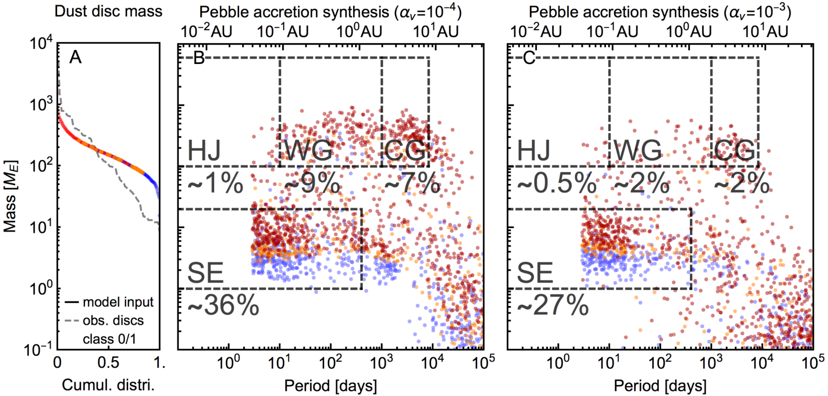
(*Lambrechts et al., 2014; Bitsch et al., 2018a, Ataiee et al. 2018*)

⇒ The pebble isolation mass depends strongly on the disc properties (e.g. H/r, ν, α) and the particle size as well as on the stellar mass!

⇒ Still in dicussion how "leaky" these gaps are

(e.g. *Weber et al. 2018, Stammler et al. 2023*)

Pebble accretion population synthesis



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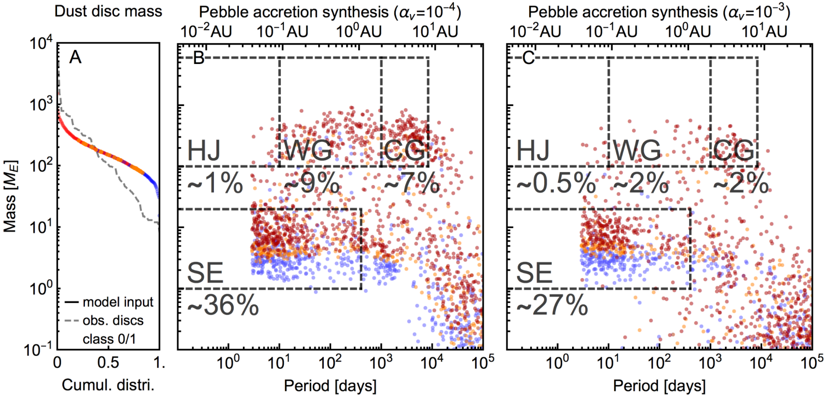
⇒ Wide orbit giants can be formed at high metallicity!

⇒ Vertical stirring can have important consequences for pebble accretion!

Pebble accretion population synthesis



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⇒ Wide orbit giants can be formed at high metallicity!

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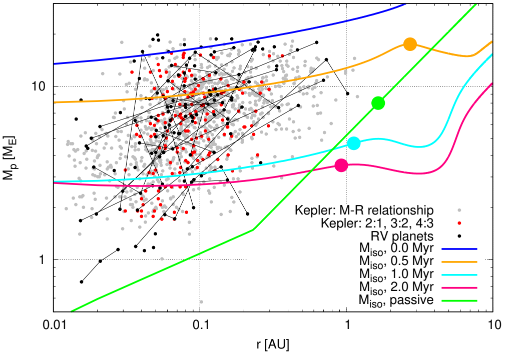
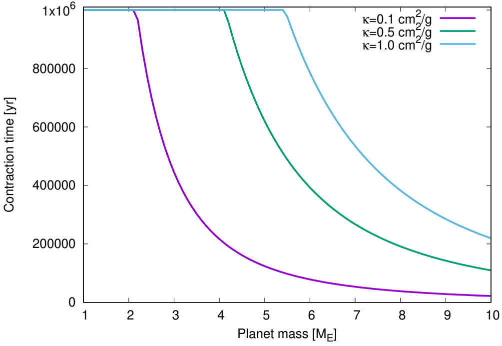
⇒ What sets the formation of different planetary types for pebble accretion?

What parameters influence the growth of planets?



(*Bitsch 2019*)



(*Bitsch et al. 2019, Bitsch & Izidoro 2023*)

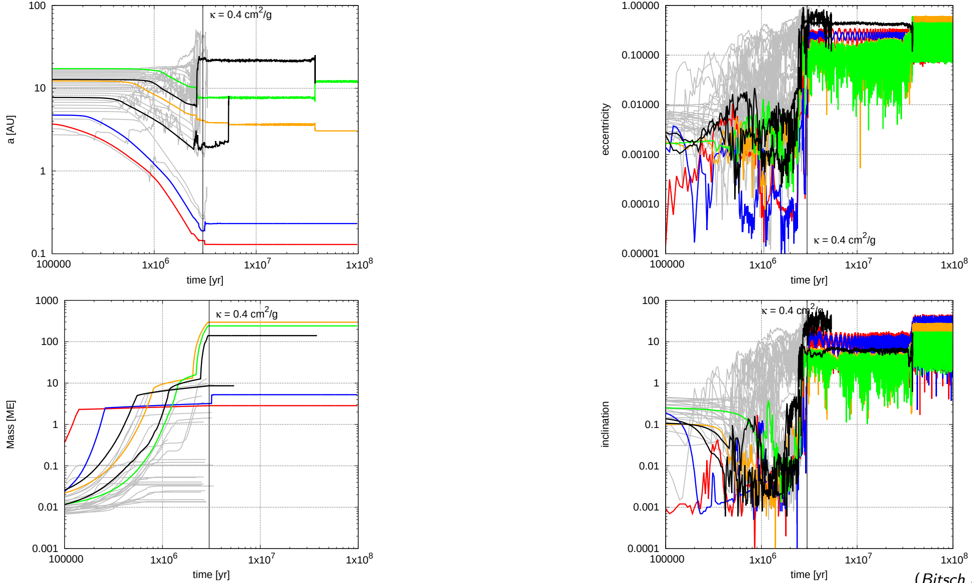
⇒ Pebble isolation mass can explain the masses of inner super-Earths!

⇒ Pebble flux determines when envelope contraction can start!

⇒ Pebble isolation mass and envelope opacity determine the envelope contraction time!

⇒ Planets growing in the inner disc region are too small to reach runaway gas accretion!

System evolution



(*Bitsch & Izidoro 2023*)

Planet statistics

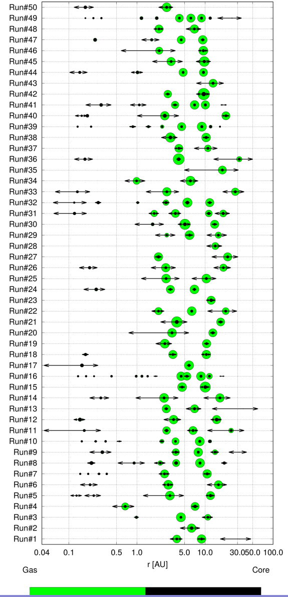
κ [cm^2/g]	SN, stable	SN, unstable	SN with Giants
0.05	0%	6%	6%
0.1	0%	14%	14%
0.2	6%	10%	16%
0.3	8%	14%	22%
0.4	12%	38%	50%
0.4, $S_{\rm peb}$=10.0	25%	19%	44%

- Inner planet formation possible: if pebble flux is large enough to make giants, it is large enough to make super-Earths!

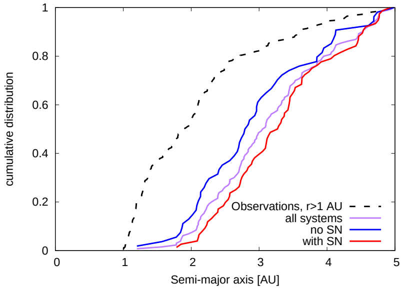
⇒ Lower κ: larger planet masses: more extreme instabilities: less surviving inner super-Earths

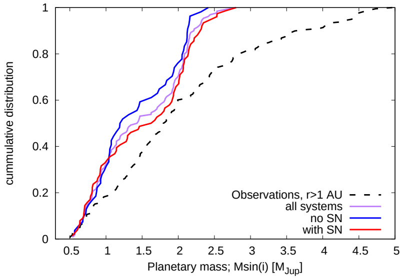
⇒ No anti-correlation between inner super-Earths and outer giants!

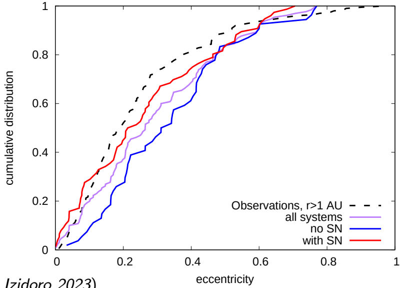
⇒ What does that imply for the properties of the giant planets?



Distribution of giant planets





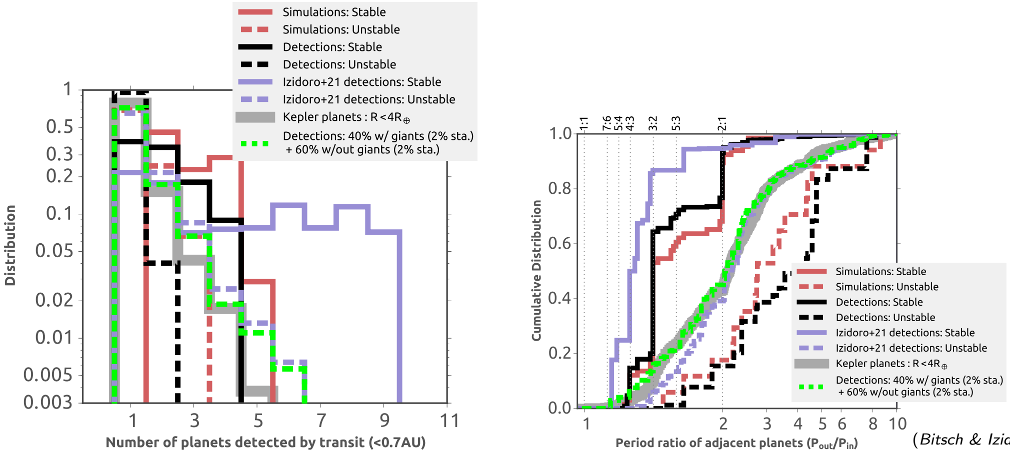


(*Bitsch & Izidoro 2023*)

- Giants with inner super-Earths have:
  - slightly larger distances
  - slightly lower eccentricities
  - no difference in mass

⇒ Results depend on the number of outer embryos that grow to become giants!

Breaking the inner chains with giants

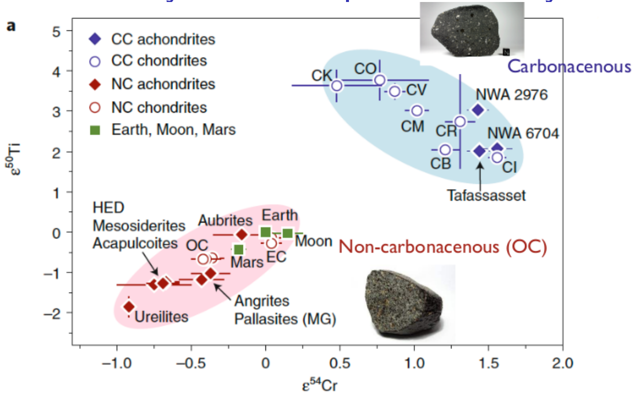


(*Bitsch & Izidoro 2023*)

- Multiple outer giant planets cause instabilities in inner systems
  (e.g. *Mustill et al. 2015*, *Bitsch & Izidoro 2023*, *2024*)

⇒ The breaking the chains scenario remains valid also with outer giant planets

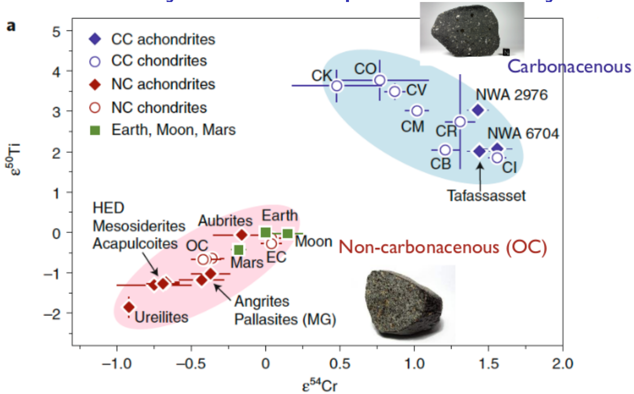
The solar system isotopic dichotomy

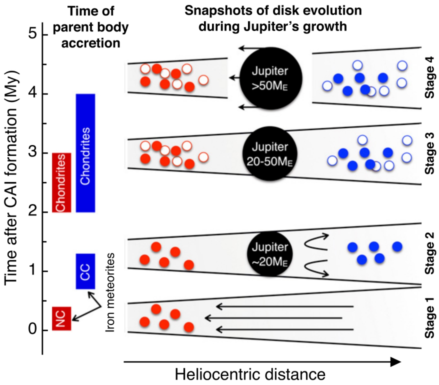


(*Warren et al. 2011, Brasser et al. 2017, Kruijer et al. 2017;2020*)

$\Rightarrow$ Clear isotopic dichotomy between inner and outer solar system material!

The solar system isotopic dichotomy



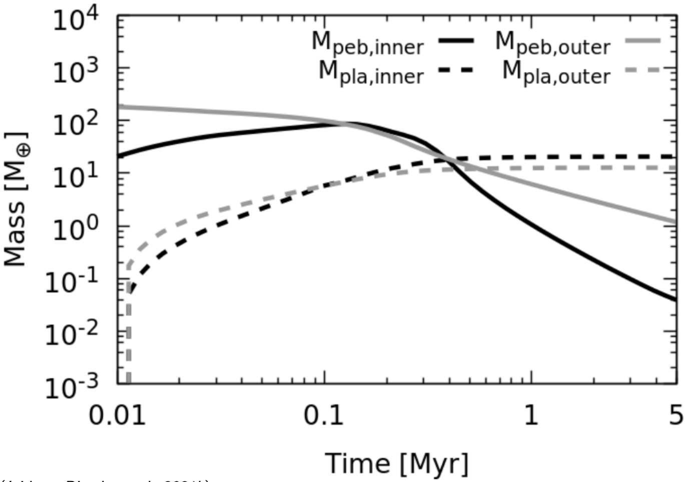


(*Warren et al. 2011, Brasser et al. 2017, Kruijer et al. 2017;2020*)

⇒ Clear isotopic dichotomy between inner and outer solar system material!

⇒ Jupiter's formation could help to seperate the reservoirs by blocking the inward flowing pebbles (?)

Influence of pebble drift and planetesimal formation



(*Izidoro, Bitsch, et al. 2021b*)

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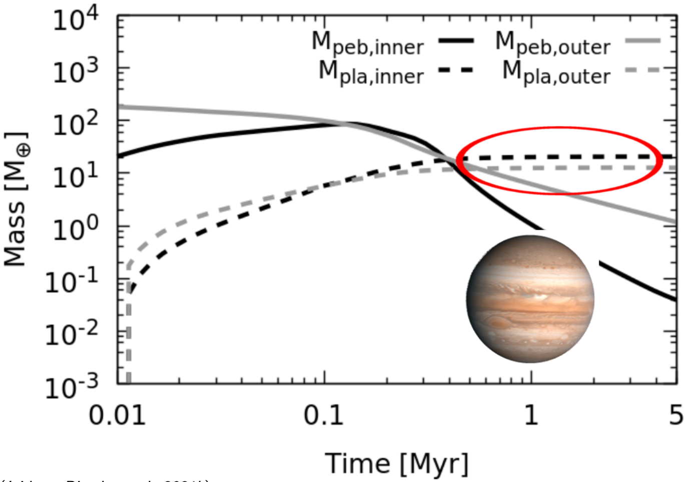


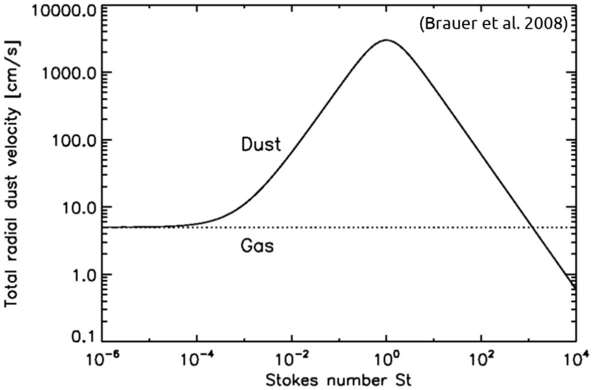
(*Izidoro, Bitsch, et al. 2021b*)

⇒ Too many planetesimals to make the terrestrial planets have been formed if the pebble flux is just cut at 1 Myr of disc evolution!

⇒ Probably some original pressure perturbations needed to explain the solar system formation!
(*Izidoro et al. 2022, Morbidelli et al. 2022*)

⇒ What does that imply for the formation of super-Earth systems?

Effects of pebble drift and evolution



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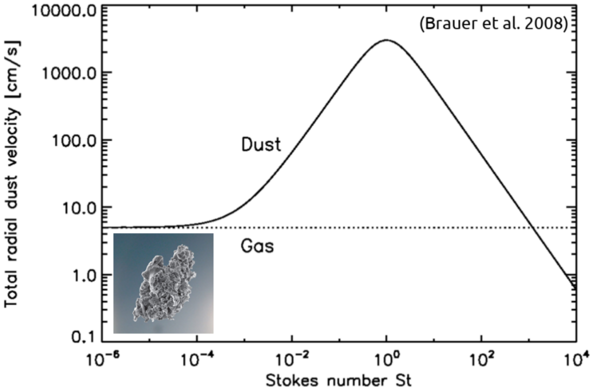

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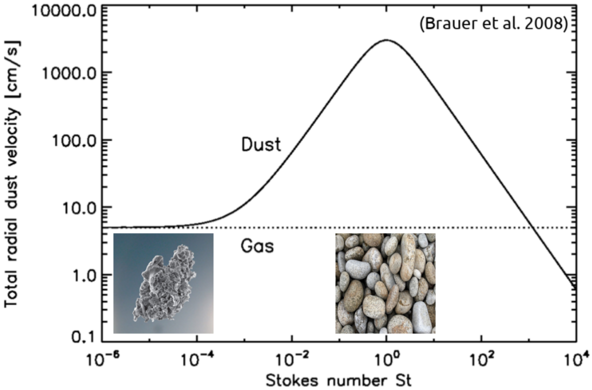

- Pebbles drift inwards faster than the gas moves!

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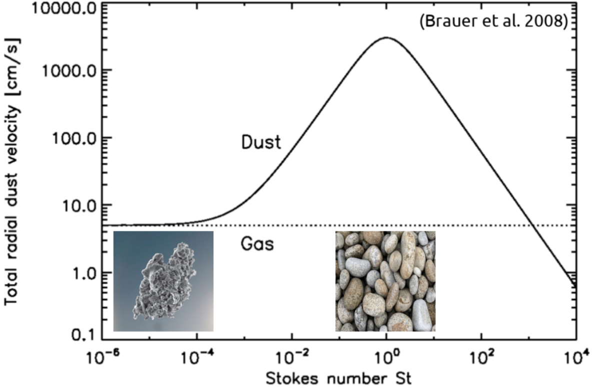

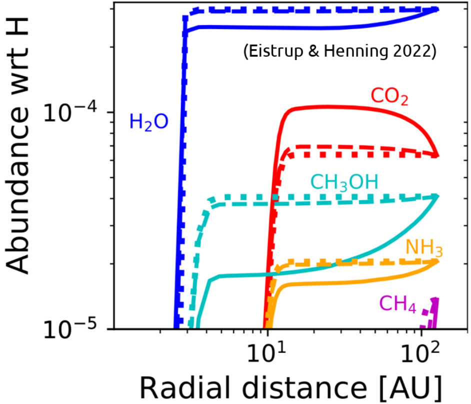

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⇒ Pebble composition is probably unaltered during drift
(e.g. *Booth & Ilee 2019, Eistrup & Henning 2022*)

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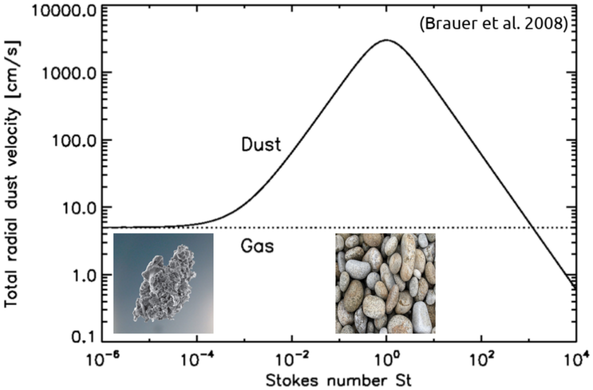

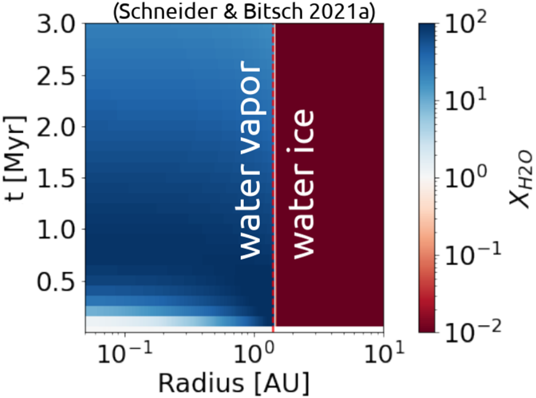

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⇒ Pebble drift and evaporation can lead to a pile-up of volatile vapor!
(e.g. *Booth et al. 2017, Aguichine et al. 2020, Schneider & Bitsch 2021a,b, Kalyaan et al. 2023, , Mah et al. 2023, 2024*)

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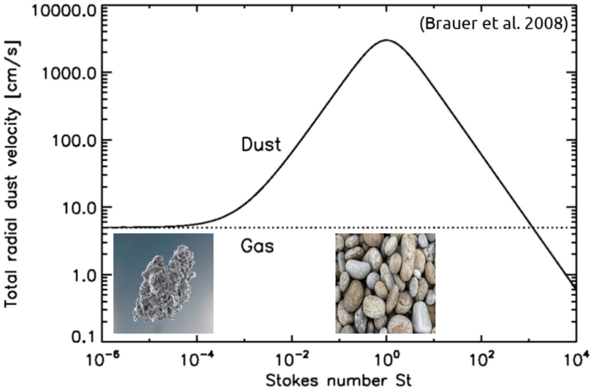

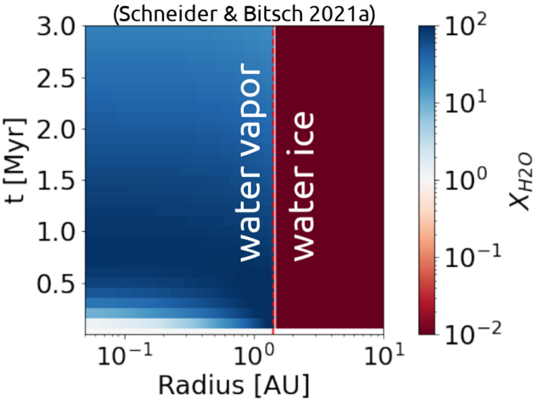

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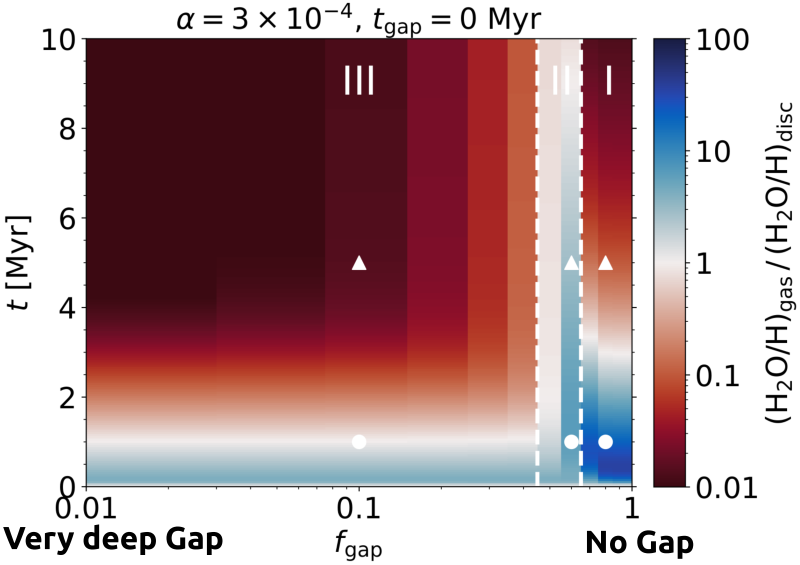
⇒ Disc composition evolves with time!

Water evolution in discs



(*Mah et al. 2024*)

The 3 regimes of disc structures and their implications

No bumps:

- Pebbles drift inward fast
- Initial water content increases in inner disc
- Pebble flux $\dot{M}_{\rm peb}$ ceases

$\Rightarrow$ Water content becomes sub-solar after 2-3 Myr

The 3 regimes of disc structures and their implications

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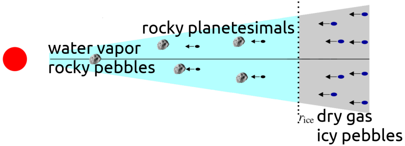
⇒ Viscosity regulates at which gap depth the transitions occurs!

⇒ Time of gap opening determines (initial) water content of inner disc!

(*Mah, Savvidou & Bitsch 2024*, see also *Kalyaan et al.2023*, *Houge et al. 2025*)

Implication for exoplanets: sub-Neptune formation



(*Bitsch et al., 2021*)

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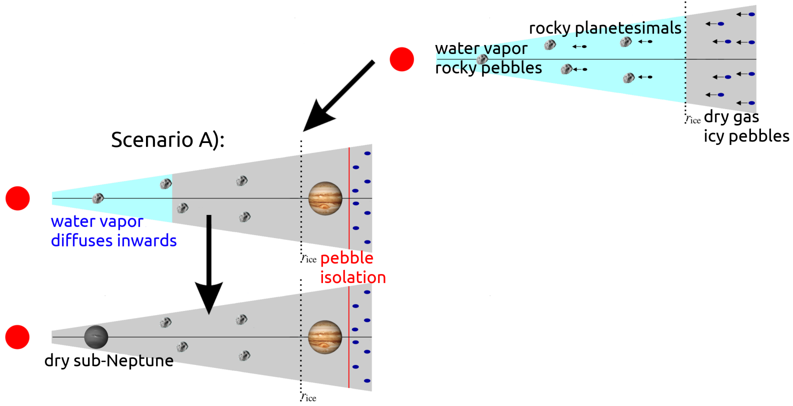

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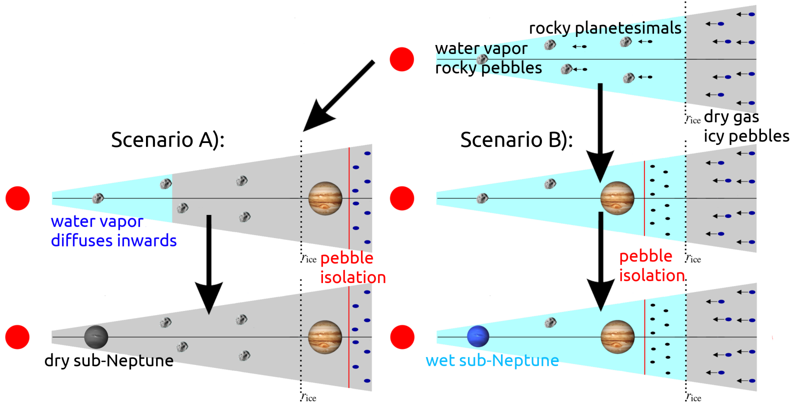

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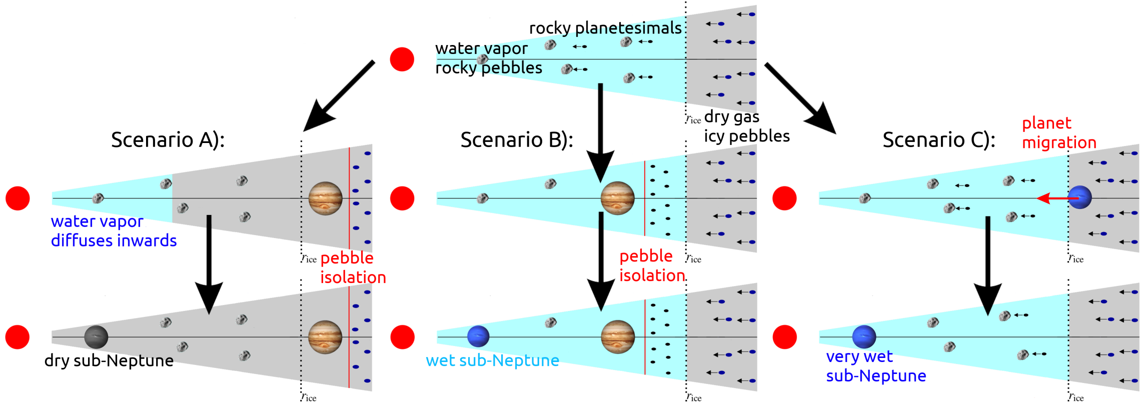

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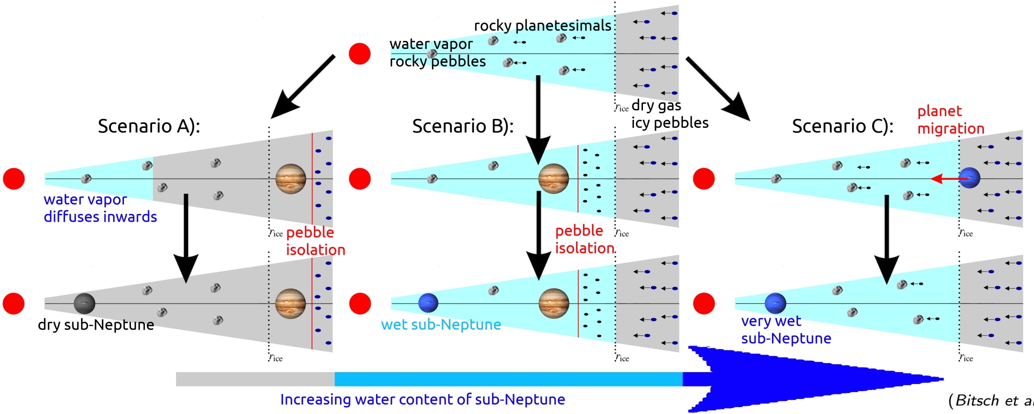

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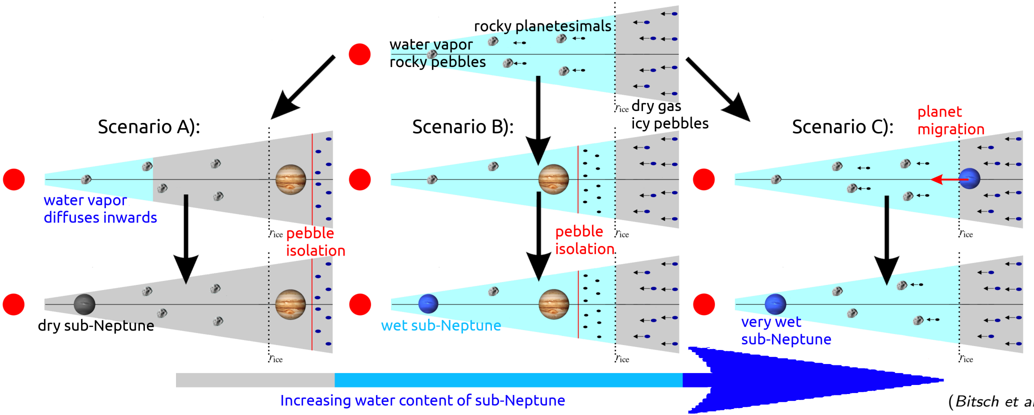

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$\Rightarrow$ Giant planet formation time and position relative to the ice line is key!

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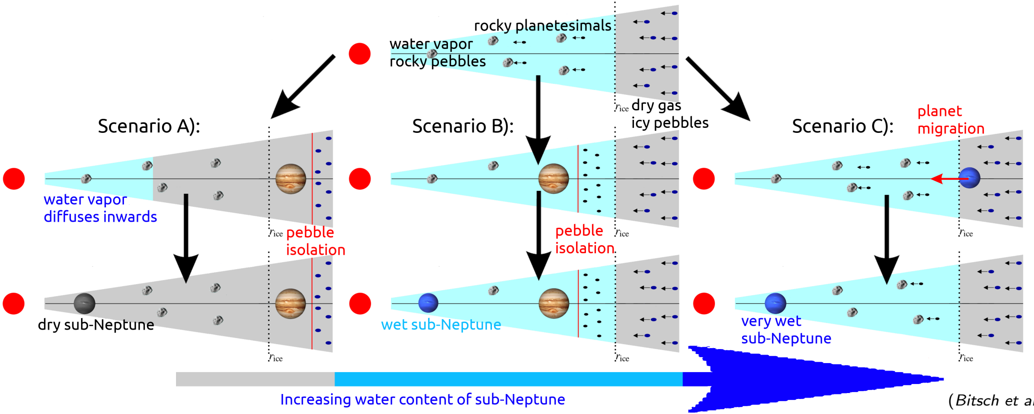

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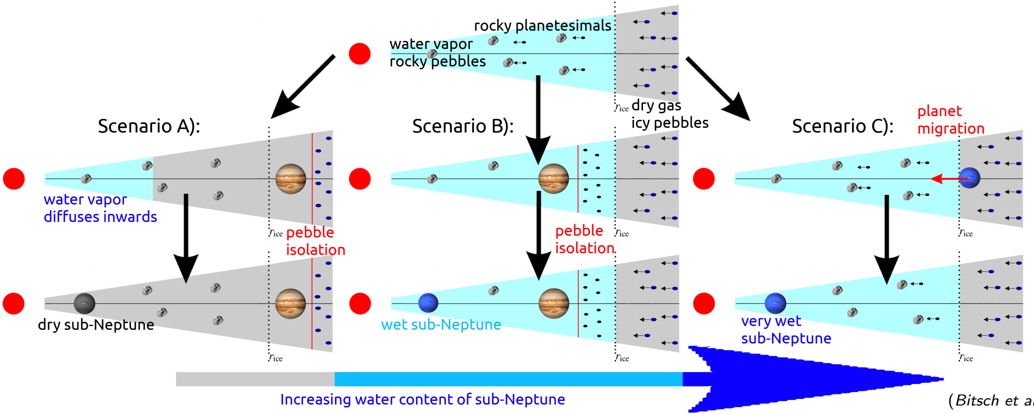
Implication for exoplanets: sub-Neptune formation



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⇒ Giant planet formation time and position relative to the ice line is key!

⇒ Water content of sub-Neptunes could help to constrain if Jupiter formed early?

⇒ Hat-P-11b's sub-solar water content implies an early formation of its outer Jovian companion!
(*Chatziastros et al. 2024*)

Summary

⇒ Everything in the disc moves (gas, dust, pebbles, planets)
(e.g. *Brauer et al. 2008, Lambrechts & Johansen 2014, Paardekooper et al. 2022*)

- Inward drifting pebbles evaporate and enrich the disc and atmospheres of growing planets
(e.g. *Booth et al. 2017, Banzatti et al. 2020, Aguichine et al. 2020, Schneider & Bitsch 2021a,b, Bitsch et al. 2022*)
- Pressure traps (e.g. caused by giant planets) influence the composition of inner discs
(e.g. *Schneider & Bitsch 2021a, Bitsch et al. 2021, Kalyaan et al. 2023, Banzatti et al. 2023, Mah et al. 2024*)
- Planetsimal accretion can not explain the cold Jupiter population
(e.g. *Levison et al. 2010, Johansen & Bitsch 2019, Emsenhuber et al. 2021*)
- Pebble accretion can allow the formation of wide orbit planets
(e.g. *Lambrechts & Johansen 2014, Bitsch et al. 2015, Savvidou & Bitsch 2023*)

⇒ There is no anti-correlation (from a formation perspective) between inner super-Earths and outer giant planets!
(e.g. *Bitsch et al. 2019, 2020, Schlecker et al. 2021, Bitsch & Izidoro 2023*)

⇒ Constraints of atmospheric abundances could help to solve the puzzle!

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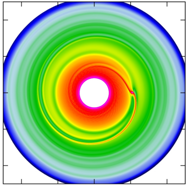

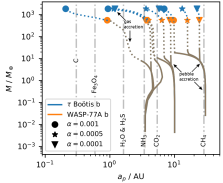

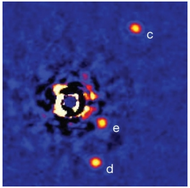

PLANETS

Acknowledgements

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- General Webpage: `www.cost.eu`