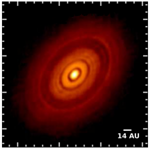
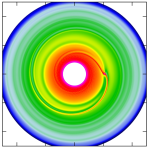
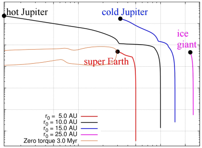
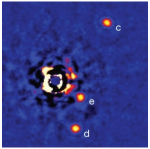
Planet formation modeling

Bertram Bitsch

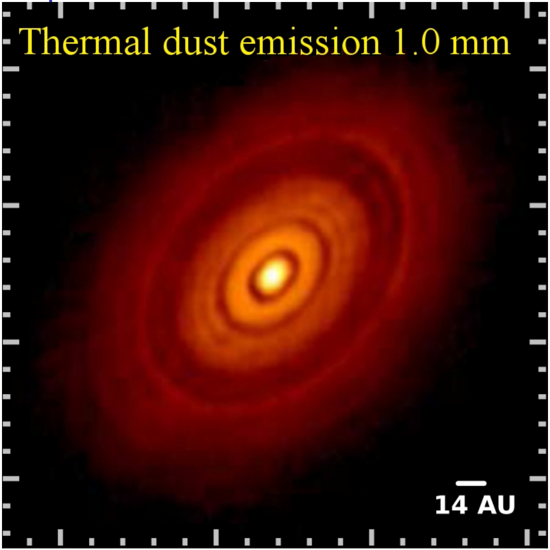








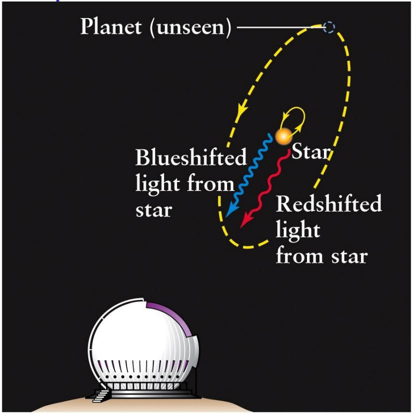
Planetary birthplaces



(*ALMA Partnership et al. 2015*)

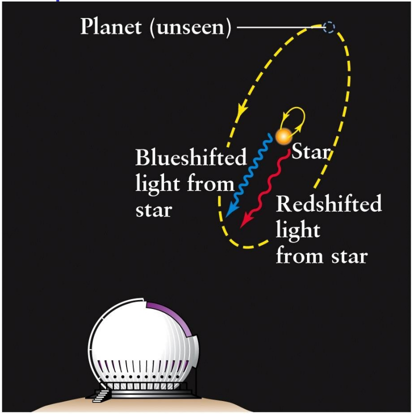
$\Rightarrow$ Protoplanetary discs: consist of gas and dust ($\sim 1\%$)

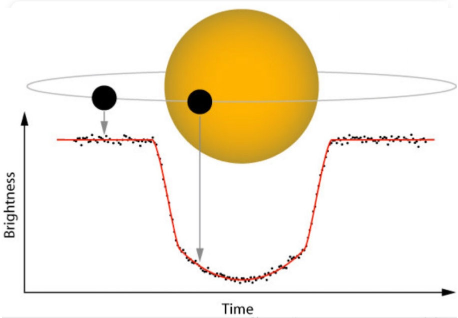
Exoplanet detections: main methods



- Radial velocity (RV) method determines planetary mass
- First exoplanet detected around main sequence star with RV
  (*Mayor & Queloz 1995*)

Exoplanet detections: main methods





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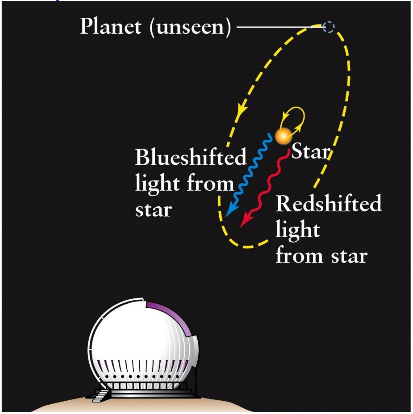

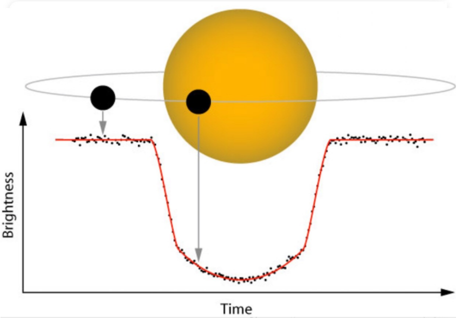

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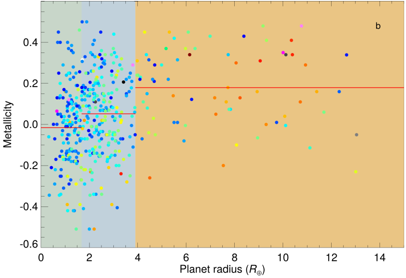
⇒ Both together can constrain the planetary density and composition!

Planetary systems



(*Buchhave et al. 2014*)

- Larger (more massive) planets occur around more metal rich stars (e.g. *Santos et al. 2004, Fischer & Valentin 2005, Buchhave et al. 2014, Narang et al. 2018, Petigura et al. 2018*)

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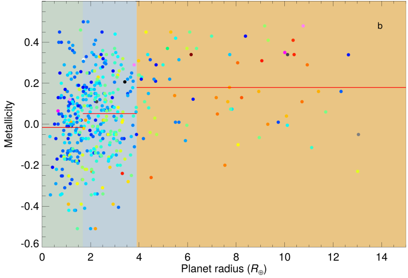

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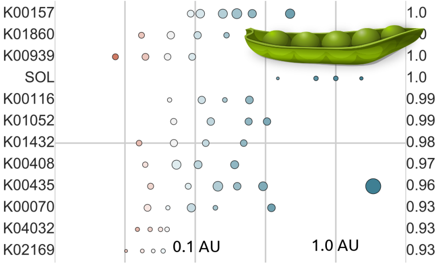

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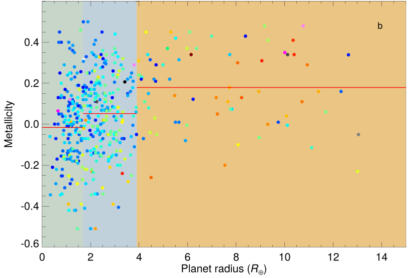
- Planets in super-Earth systems have similar sizes and masses (e.g. *Millholland et al. 2017, Weiss et al. 2018, Millholland & Winn 2021*)

Planetary systems



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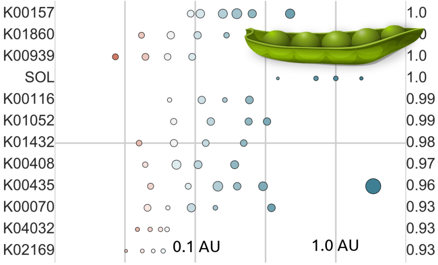

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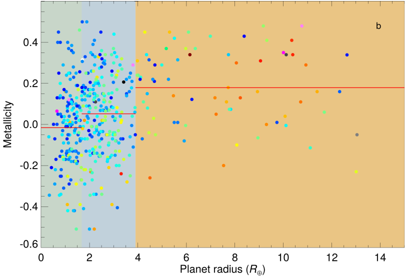

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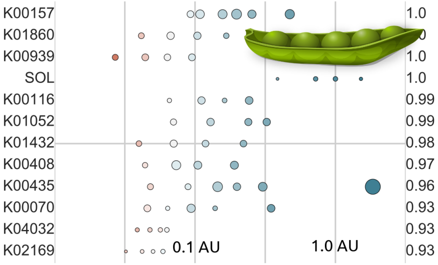

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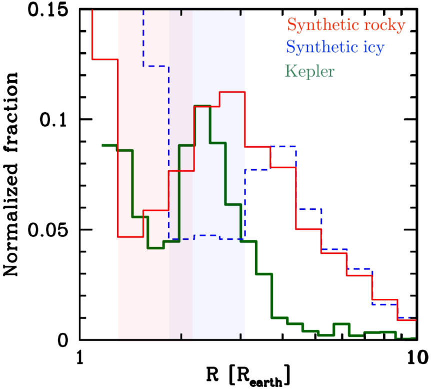
⇒ How can we explain the diversity of planets and planetary systems?

Rocky vs. Waterworld

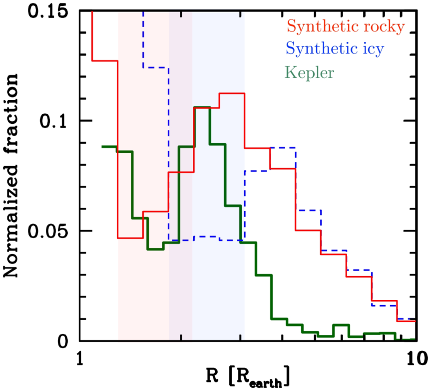


(*Jin & Mordasini, 2018*; see also *Owen & Wu, 2013, 2017, Lopez & Fortney, 2014*; Observations: *Fulton et al. 2017*)

- Small planets loose their atmosphere and are bare cores
- Valley consistent with mostly rocky composition

⇒ Statistical result for planets with period less than 100 days (0.3 AU)

Rocky vs. Waterworld



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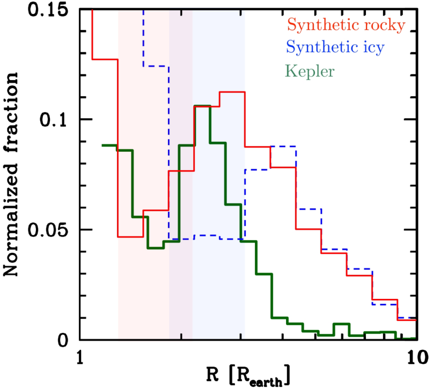
⇒ Radius valley caused by planet's own cooling and super-Earths have up to 20% water ice

(*Gupta & Schlichting, 2018*)

Rocky vs. Waterworld



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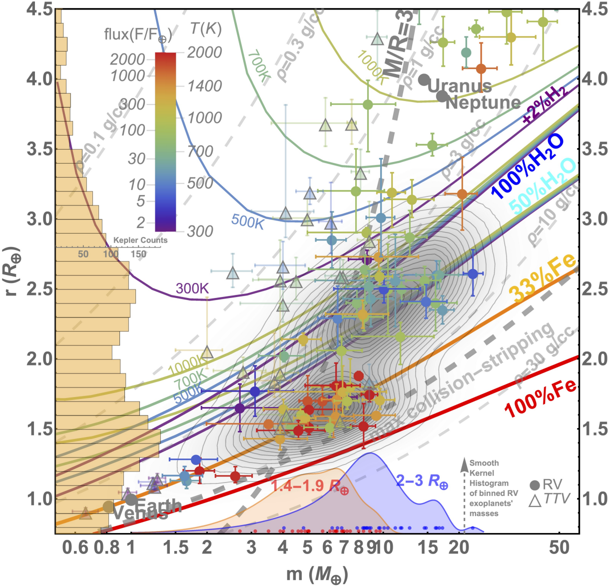
(*Gupta & Schlichting, 2018*)

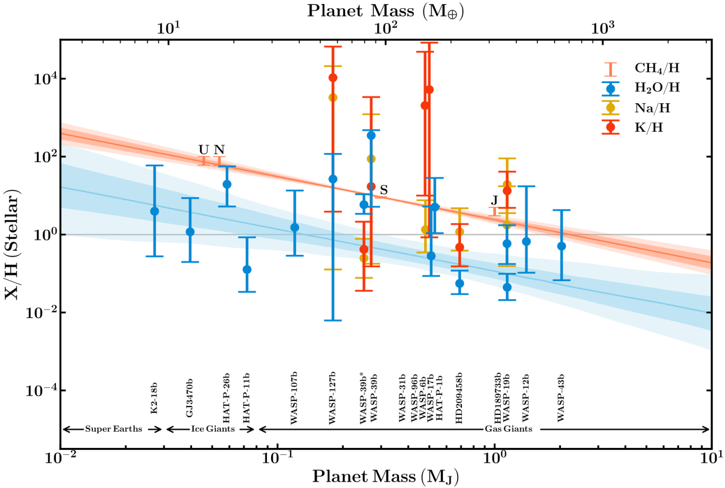
⇒ Assuming all super-Earths are rocky or all super-Earths are icy: naive!

Exoplanet observations



(*Zeng et al. 2019*)

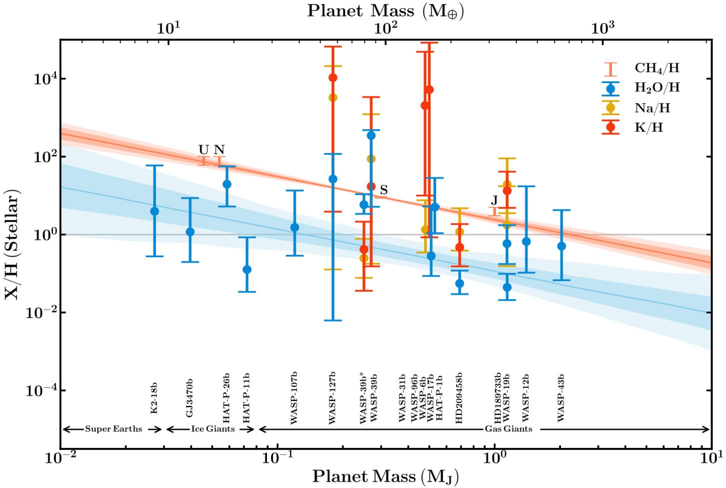
Water content of giant planets



(*Welbanks et al. 2019*)

- Low atmospheric water content of giant planets observed

Water content of giant planets

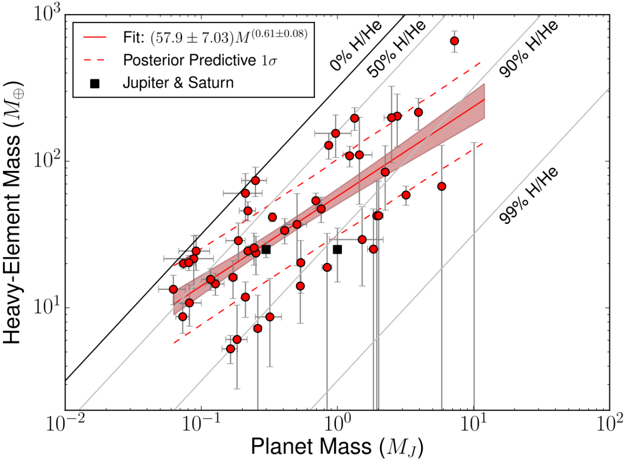


(*Welbanks et al. 2019*)

- Low atmospheric water content of giant planets observed

⇒ How can we explain this diversity in atmospheric compositions?

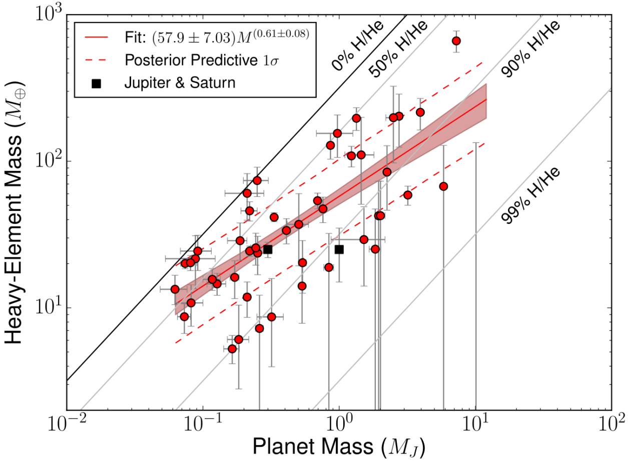
Heavy element content of giant planets



(*Thorngren et al. 2016*)

- Heavy element content of giants increases with planetary mass

Heavy element content of giant planets

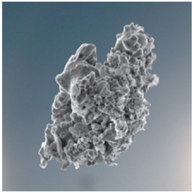


(*Thorngren et al. 2016*)

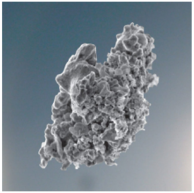
- Heavy element content of giants increases with planetary mass

⇒ How can we explain these large heavy element contents?

The challenge of planet formation

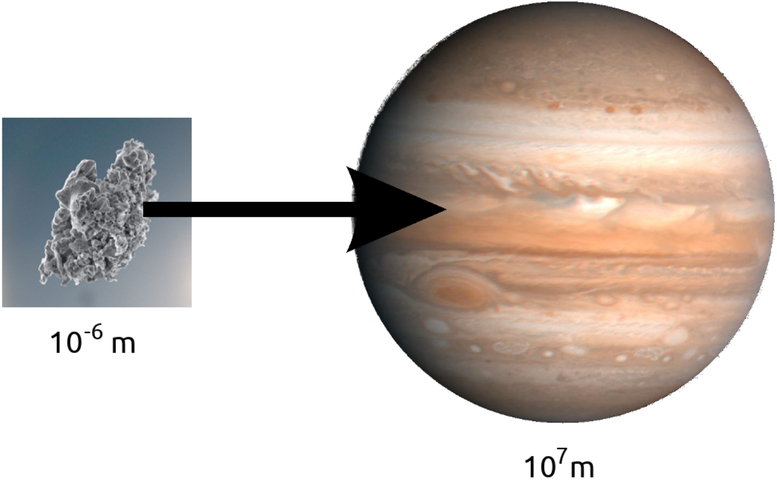


The challenge of planet formation



10^{-6} m

The challenge of planet formation



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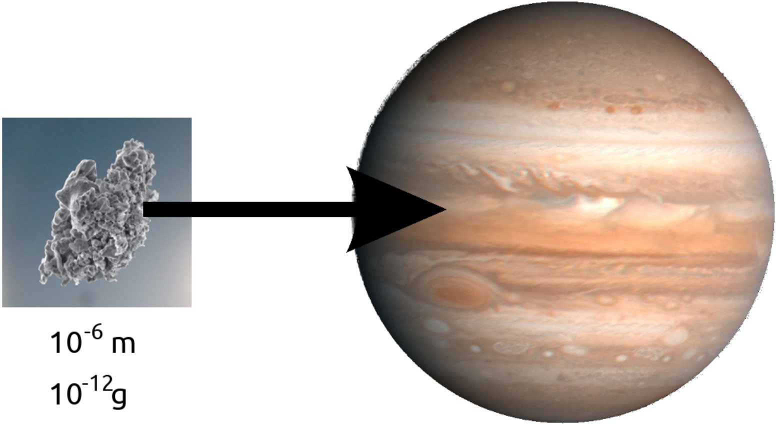

10^{-6} m

10^{-12}g

10^{7}m

10^{30}g

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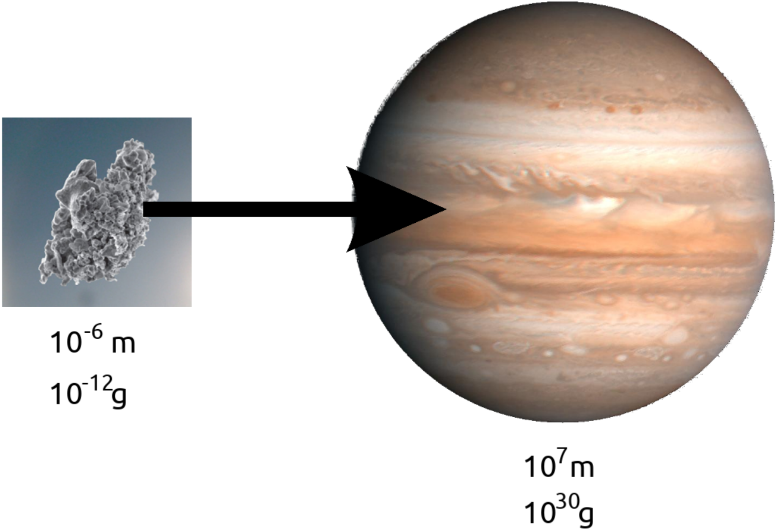

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10^{-12}g

10^{7}m

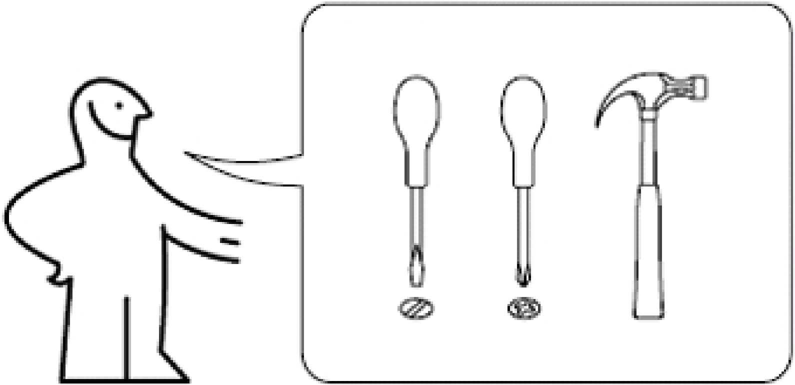
10^{30}g

⇒ This growth has to happen during the few Myrs of disc lifetime!

Outline

- How to model planet formation?
- How do drifting and evaporating pebbles influence planets?
- What does the star tell about the planet?

How to model planet formation?



Planet formation: Core accretion

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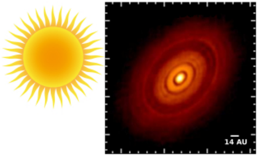

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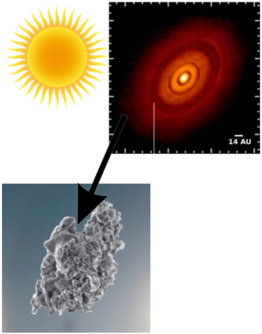

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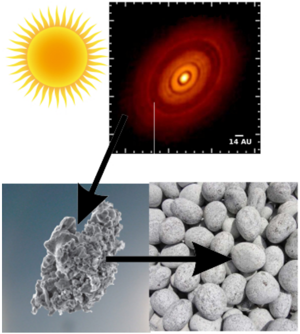

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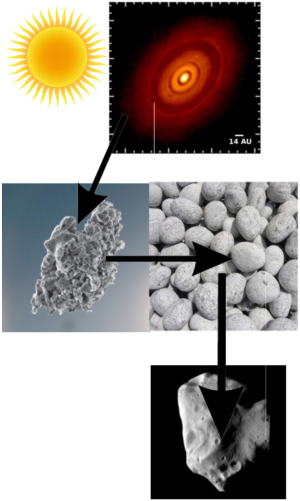

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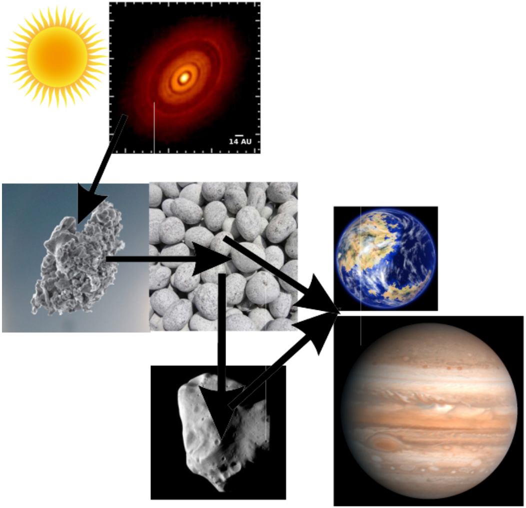

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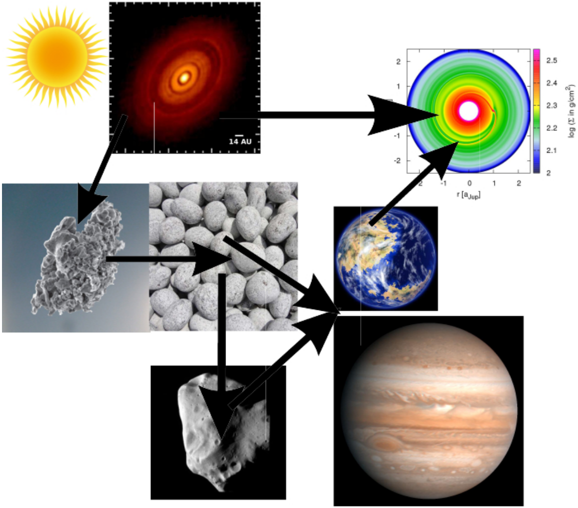

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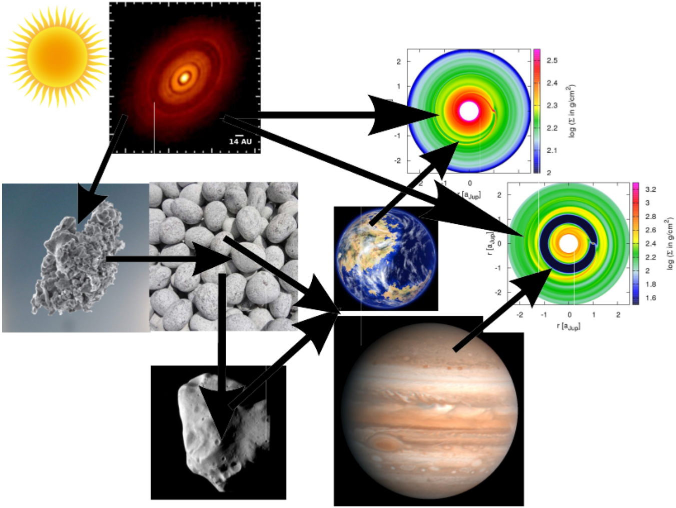

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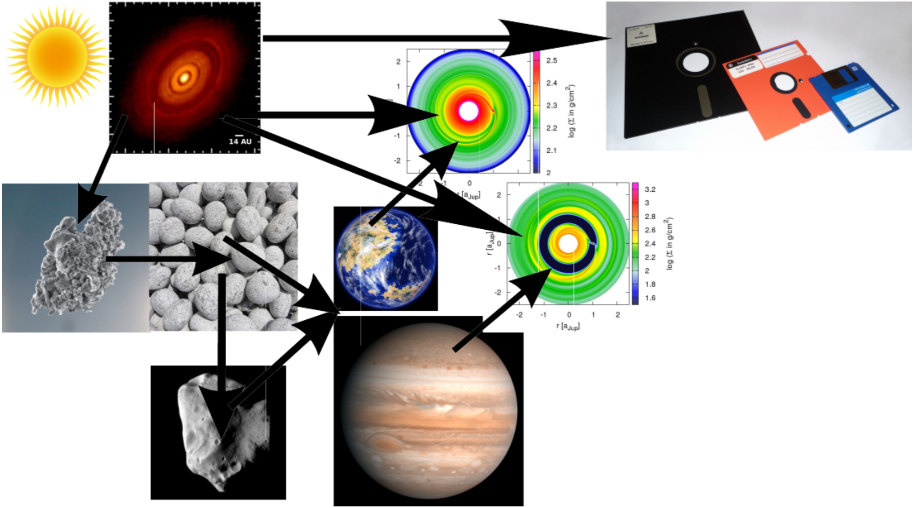

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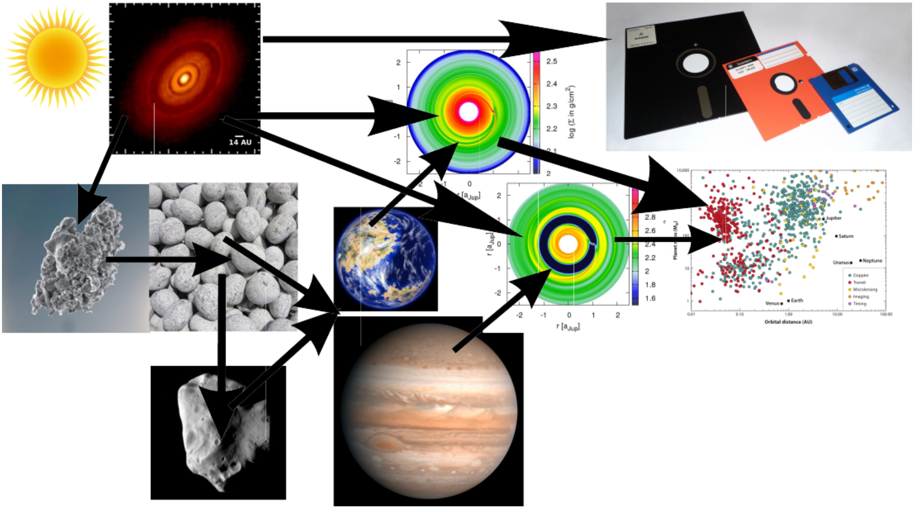

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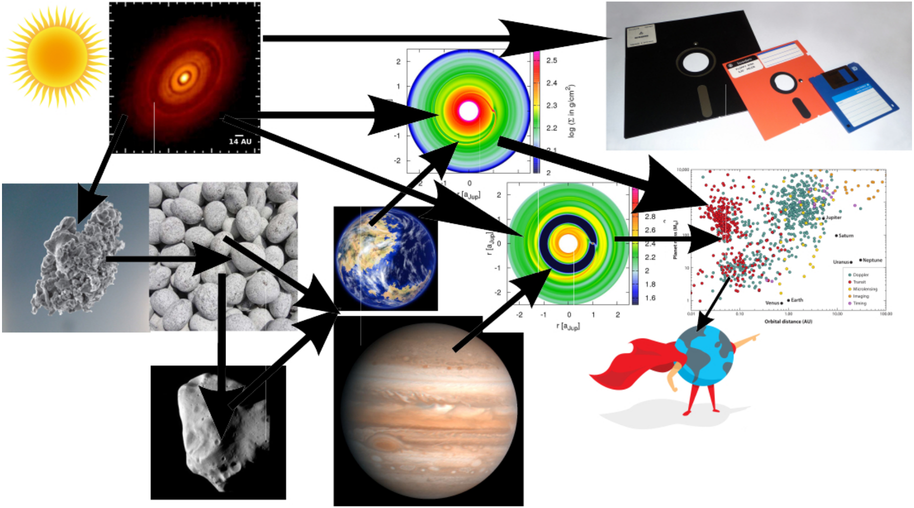

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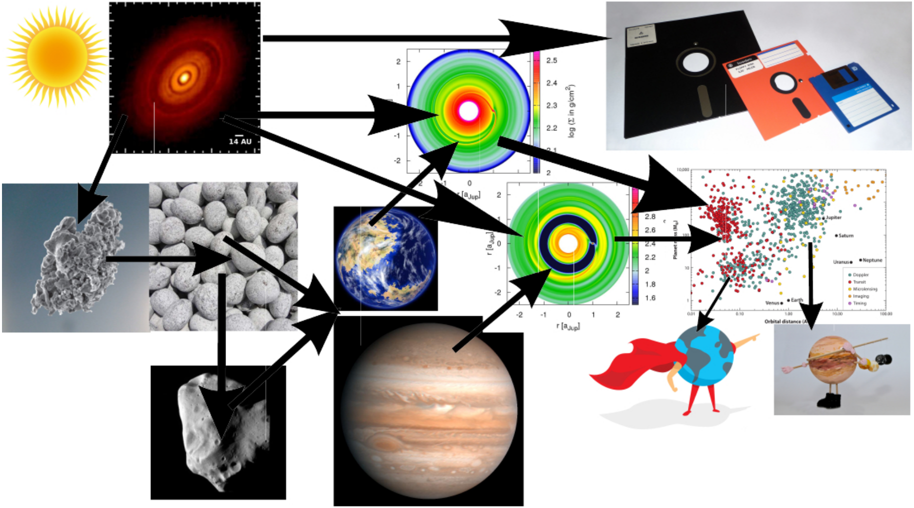

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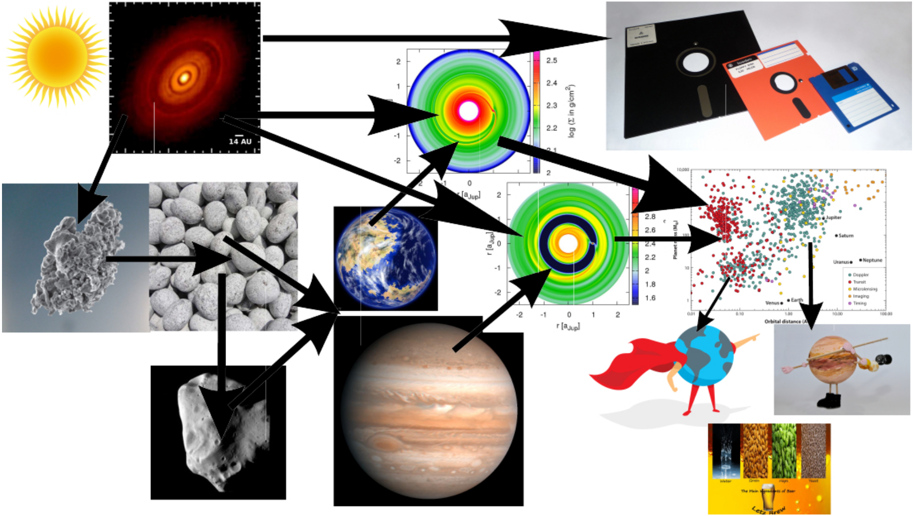

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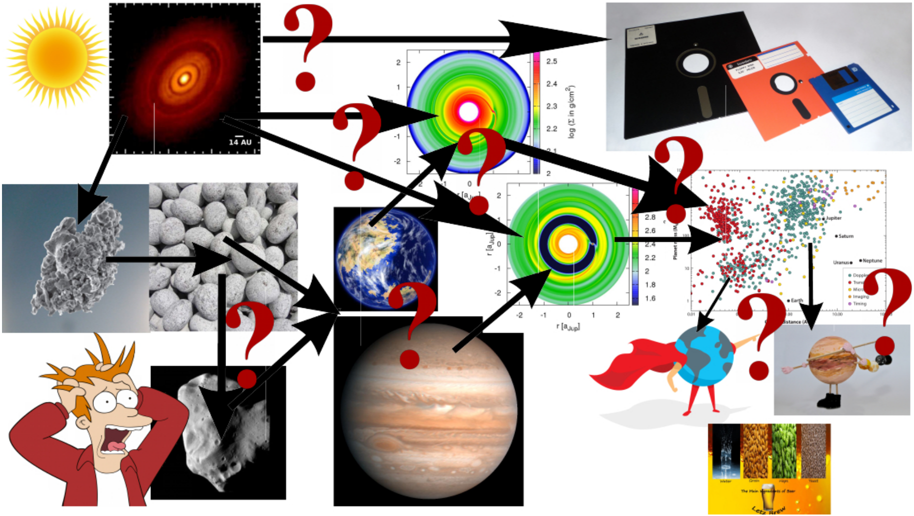
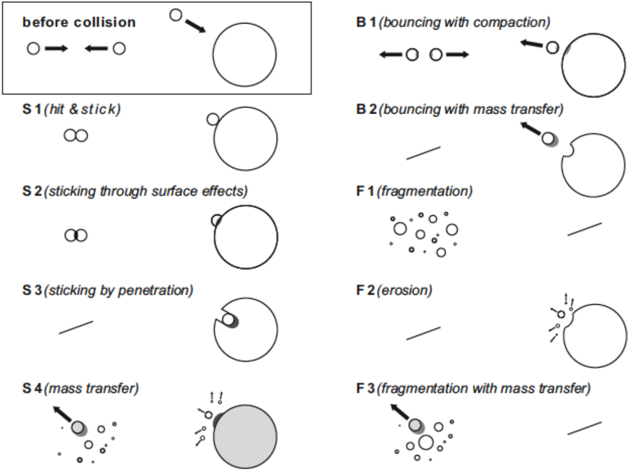
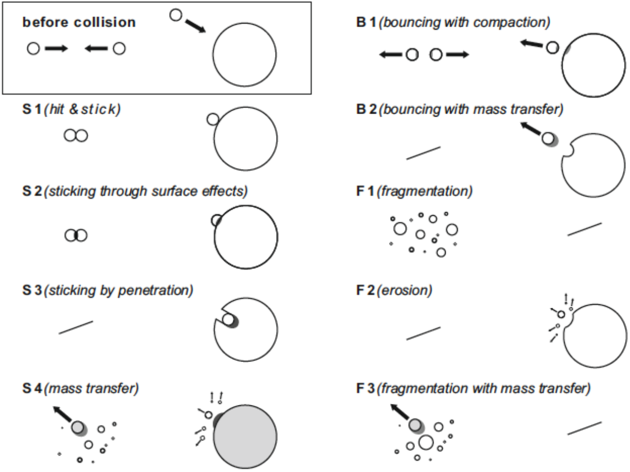


Grain growth



(*Güttler et al. 2010*)

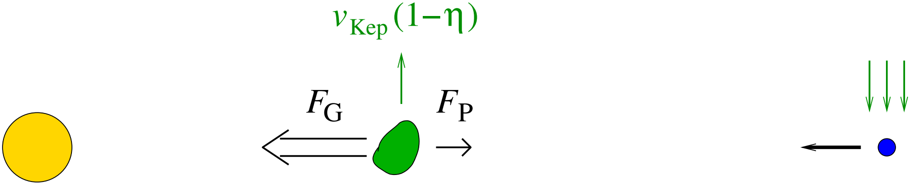
Grain growth



(*Güttler et al. 2010*)

- ⇒ Speed between the particles determines collisional outcomes!
- ⇒ Large particles have larger speeds, preventing growth above cm-dm!

Radial drift of small pebbles



- Disc is hotter and denser close to the star: radial pressure gradient
- Radial pressure gradient force mimics decreased gravity
  ⇒ gas orbits slower than Keplerian:

$$v_{\mathrm{gas}} = v_{\mathrm{Kep}} - \Delta v = v_{\mathrm{Kep}} - \eta v_{\mathrm{Kep}}, \quad \eta = -\frac{1}{2}\left(\frac{H}{r}\right)^2 \frac{\partial \ln(P)}{\partial \ln(r)}$$

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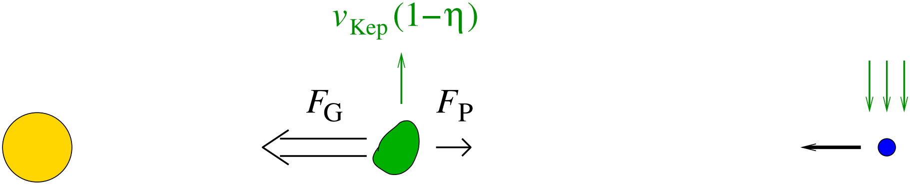

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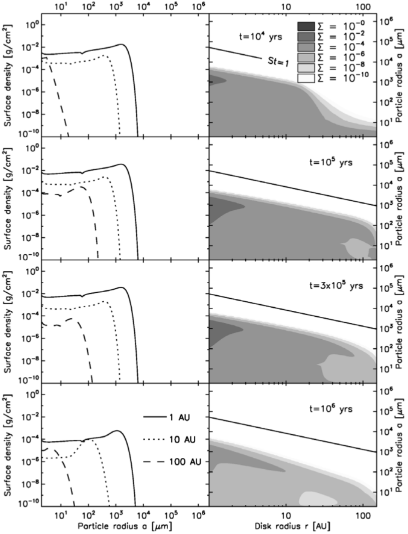
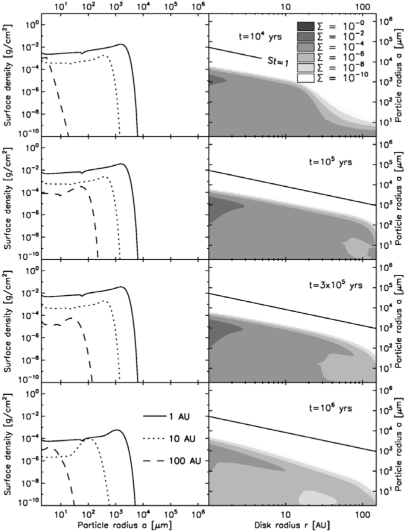
- Particles do not feel the pressure gradient force and want to orbit Keplerian
- Headwind from sub-Keplerian gas drains angular momentum from particles, so they spiral in through the disc faster than the gas!

Dust evolution



(*Brauer et al. 2008*)

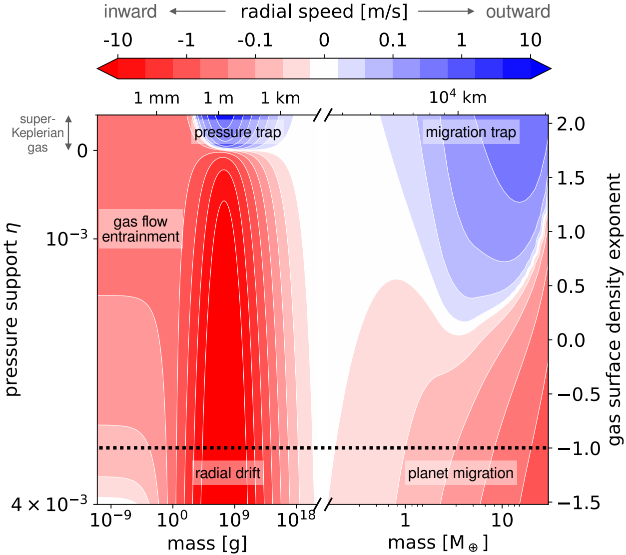
Dust evolution



(*Brauer et al. 2008*)

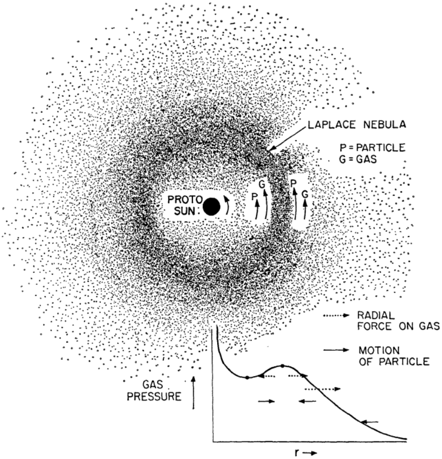
⇒ Smooth discs loose their material too fast compared to observed disc lifetimes!

Motion of particles



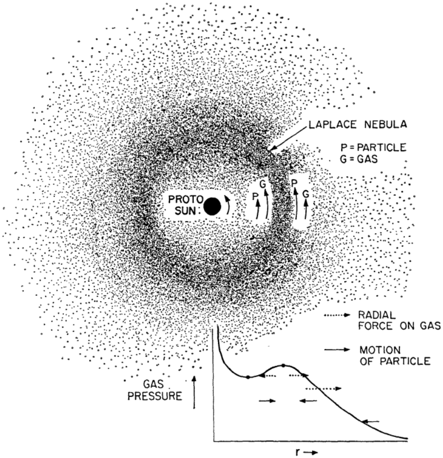
(*Drążkowska, Bitsch, et al. 2022*)

Trapping particles



(*Whipple 1972*)

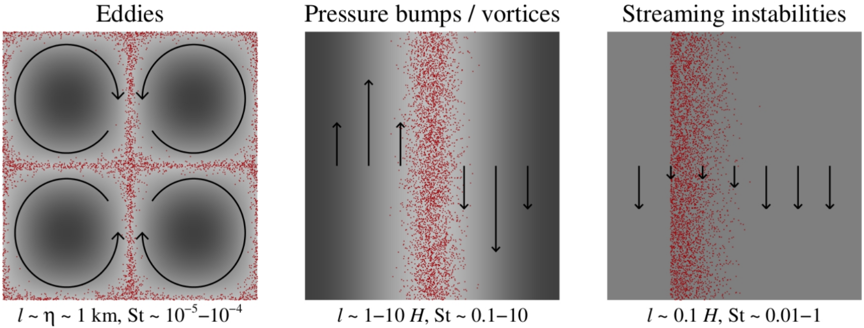
Trapping particles



(*Whipple 1972*)

- Sources to generate pressure bumps:
  - Planets, zonal flows, ice lines, ...

Particle concentrations

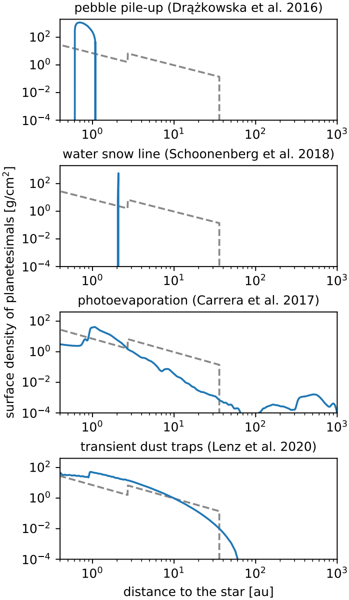


Three ways to concentrate particles: (Johansen et al., 2014, arXiv:1402.1344)

- Between small-scale low-pressure eddies
  (Squires & Eaton, 1991; Fessler et al., 1994; Cuzzi et al., 2001, 2008; Pan et al., 2011)
- In pressure bumps and vortices
  (Whipple, 1972; Barge & Sommeria, 1995; Klahr & Bodenheimer, 2003; Johansen et al., 2009a)
- By streaming instabilities
  (Youdin & Goodman, 2005; Johansen & Youdin, 2007; Johansen et al., 2009b; Bai & Stone, 2010a,b,c)

⇒ Characteristic size of planetesimals: ∼100km
(Morbidelli et al. 2005, Schreiber & Klahr, 2018)

Planetesimal formation recipes

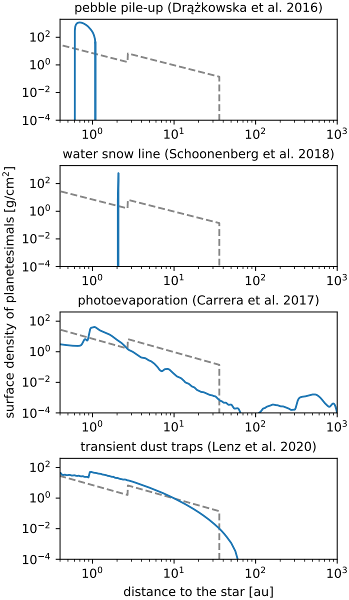


(*Drążkowska, Bitsch, et al. 2022*)

- Different recipes for planetsimal formation

⇒ Wide variety of distributions!

Planetesimal formation recipes



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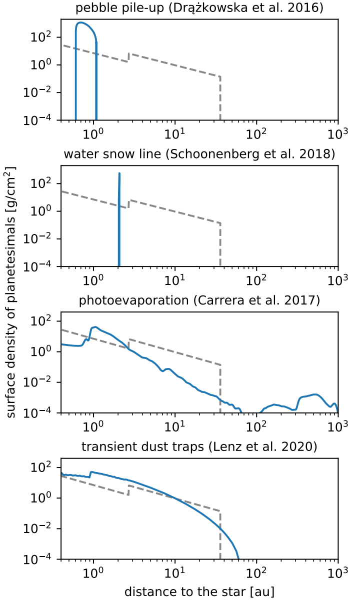
Planetesimal formation recipes



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⇒ It is thus key to know where and when planetesimals and planetary embryos form!
(*Völkel et al. 2021, 2022*)

Constraints from the Solar Sytem and protoplanetary discs

1) Terrestrial planet formation, the asteroid belt, the scattered disc and the Oort cloud are consistent with a primordial planetesimal population in the Solar System of $\approx$ 2-3 Earth masses per astronomical unit
(*Raymond et al. 2009; Brasser 2008; Raymond & Izidoro 2017*)

2) The characteristic planetesimal size in the Solar System was $\approx$ 100 km
(*Morbidelli et al. 2009; Johansen et al. 2015; Singer et al. 2019*)

3) Protoplanetary discs are weakly turbulent; this turbulence stirs up the planetesimal inclinations
(*Ida et al. 2008; Pinte et al. 2016; Nelson et al. 2013;*)

Constraints from the Solar Sytem and protoplanetary discs

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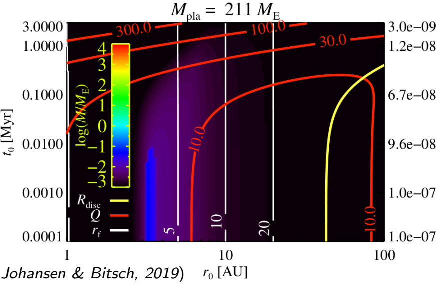
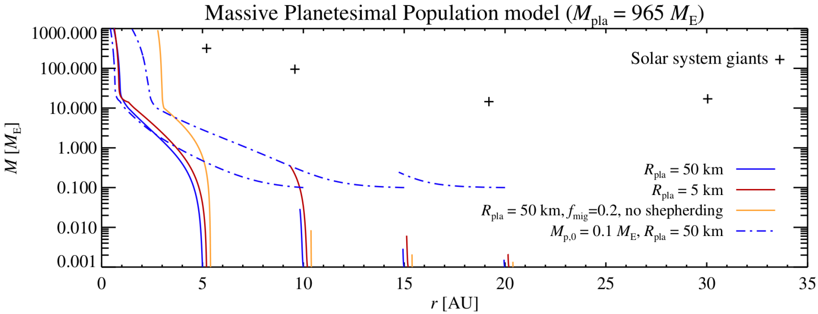


(*Johansen & Bitsch, 2019*)

- We integrate growth and migration of single protoplanets accreting planetesimals and gas
- Planetesimal accretion rate based on *Tanaka & Ida* (1999)

⇒ Models satisfying all three above constraints yield maximum planet mass of 0.1 Earth masses

Violating the constraints of the solar system

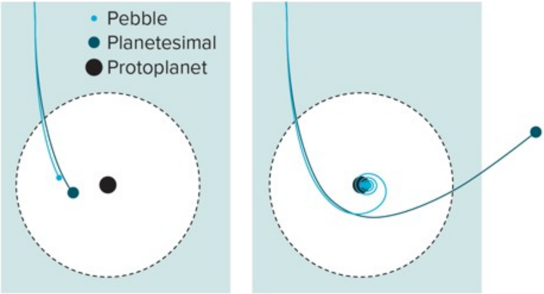


(*Johansen & Bitsch, 2019*)

- Even a population of 1000 Earth masses of planetesimals does not reproduce the solar system
- Smaller planetesimals do not help!
- Reducing the migration does not help!

⇒ Must reduce the turbulent stirring and the planetesimal size as well to form the giants, violating all three constraints!!!

Planet growth: Pebble accretion



(e.g *Johansen & Lambrechts 2017*)

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

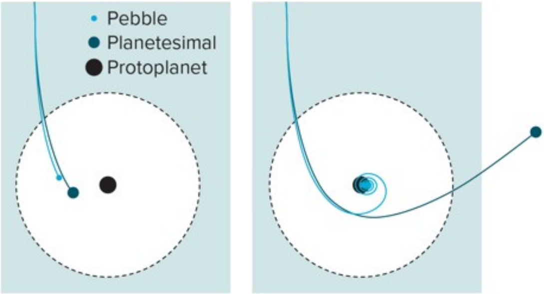
- Pebbles spiral in to the planet due to gas friction

⇒ Pebbles are accreted efficiently

- Accretion rate $\dot{M}_{\rm c}$ by pebble accretion:

$$\dot{M}_{\rm c} = 2 \left(\frac{\tau_{\rm f}}{0.1} \right)^{2/3} r_{\rm H}^2 \Omega_{\rm K} \Sigma_{\rm Peb}$$

Planet growth: Pebble accretion



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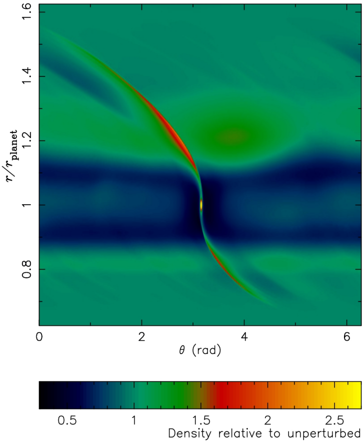
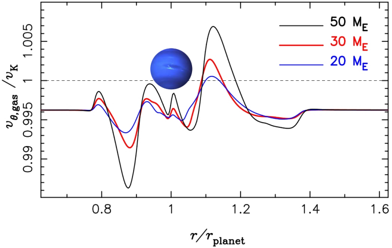
⇒ Pebble accretion becomes efficient once the embryo is ≈0.01 $\mathrm{M_E}$

⇒ Initial collisions needed, before pebble accretion finishes the job!

Gaps in discs: Pebble isolation mass





⇒ 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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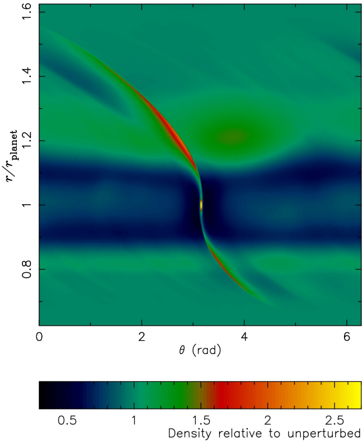

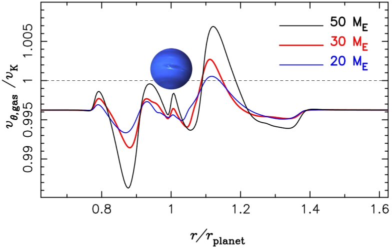

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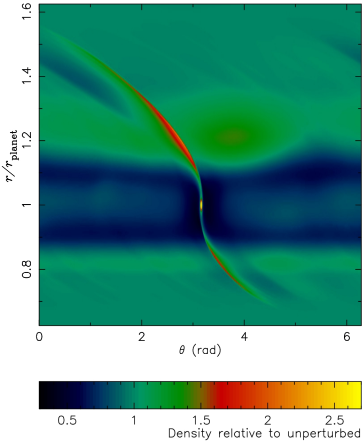

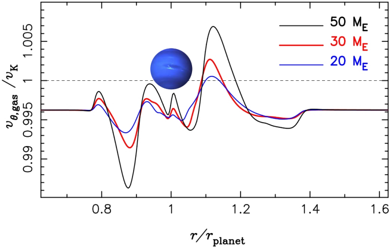

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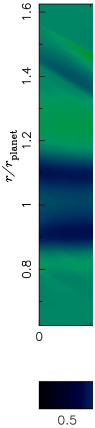
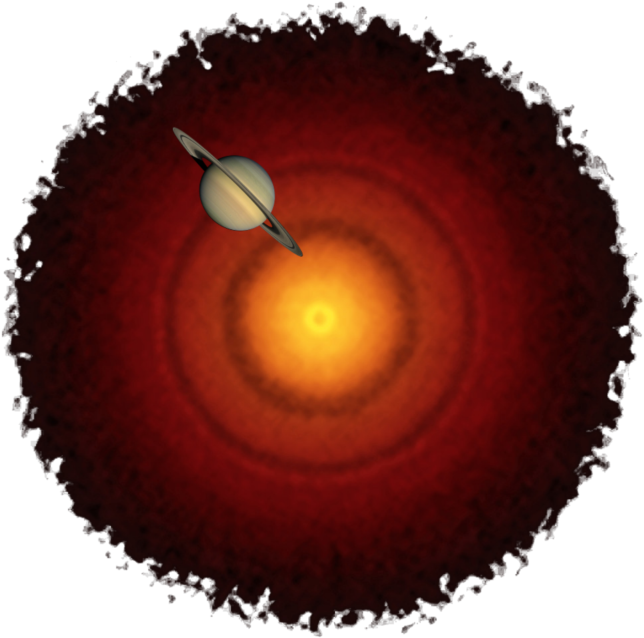
⇒ Knowing the disc is knowing the planet!

Gaps in d





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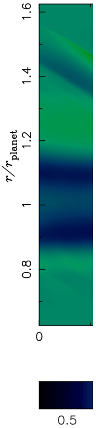

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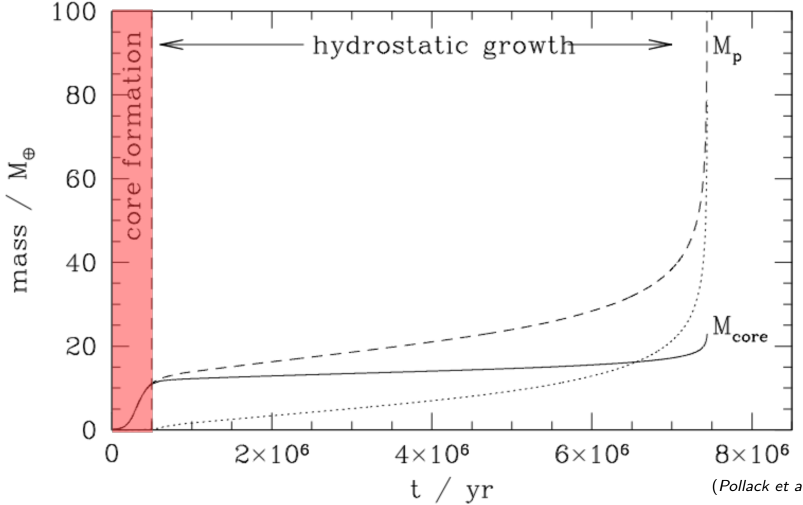
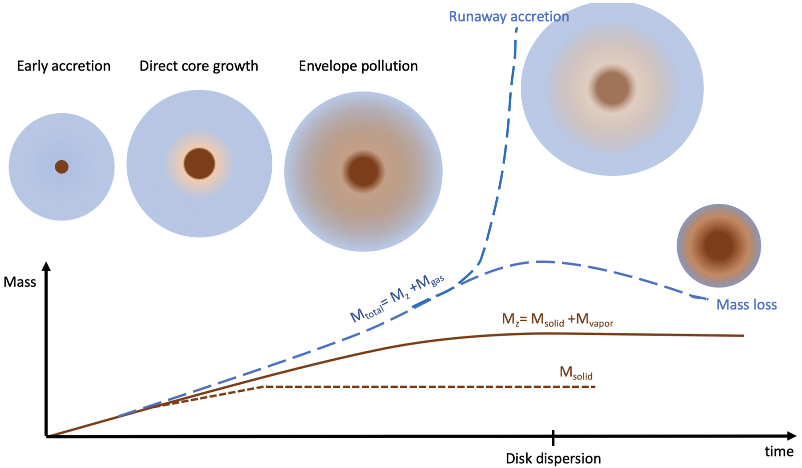
Gas accretion



(*Pollack et al. 1996*)

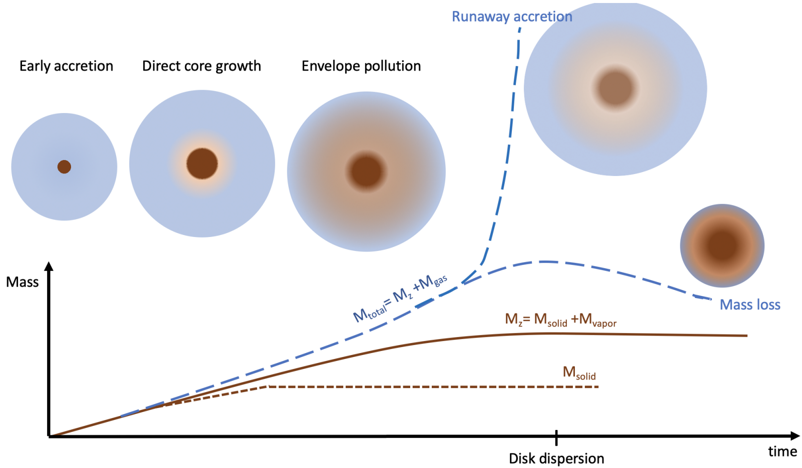
- After the core is formed, envelope contraction can start
- Contraction depends on core mass and opacity
  (*Ikoma et al. 2000; Piso & Youdin, 2014; Lambrechts & Lega, 2017; Cimerman et al. 2017, Bitsch & Savvidou 2021*)

Interior structure during planet formation



(*Drążkowska, Bitsch, et al. 2022*)

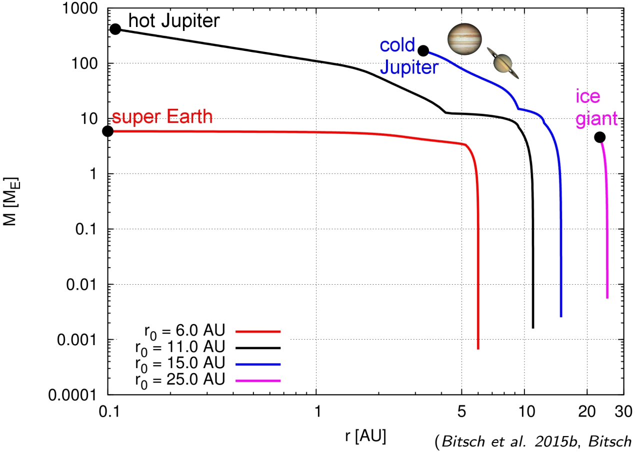
Interior structure during planet formation



(*Drążkowska, Bitsch, et al. 2022*)

⇒ The classical two layer model (core + envelope) should be expanded, as also supported by the results of JUNO!

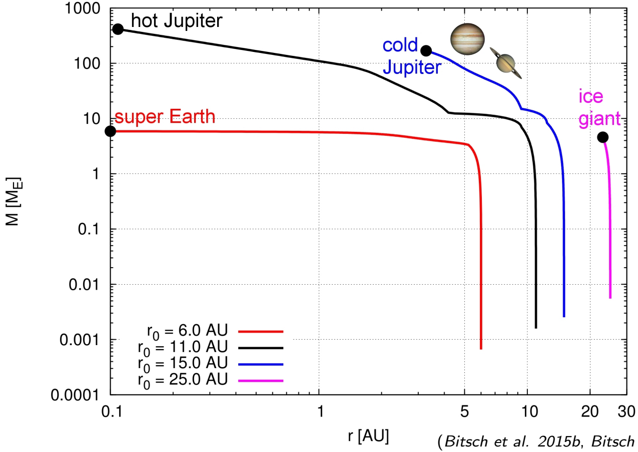
Formation of different planetary types



(*Bitsch et al. 2015b*, *Bitsch & Johansen, 2016*)

⇒ Formation of different planetary types possible!

Formation of different planetary types



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⇒ Formation of different planetary types possible!

⇒ But N-body interactions needed to explain the formation of full systems!
(*Bitsch et al. 2019b; 2020, Lambrechts et al. 2019, Izidoro et al. 2021, Matsumuara et al. 2021*)

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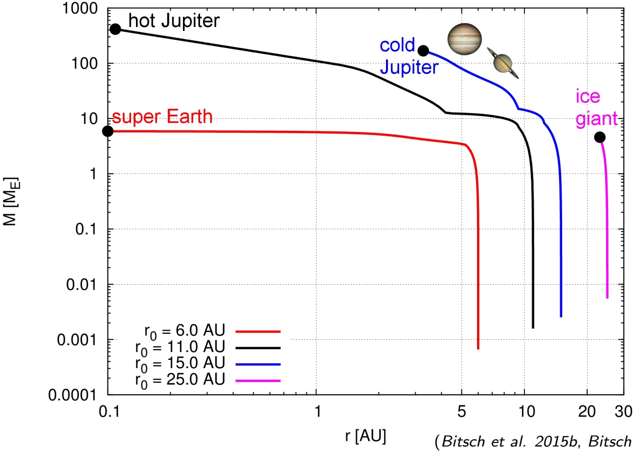

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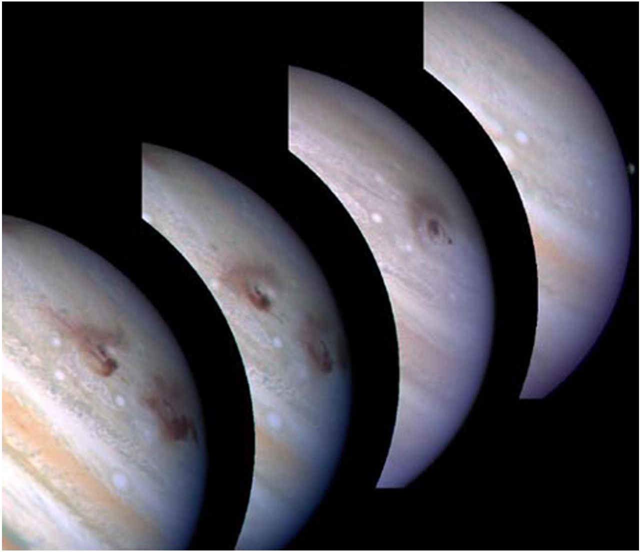
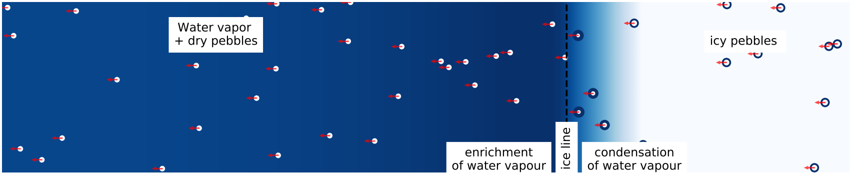
⇒ We will investigate the different parameters relevant for planet formation in the hands-on session!

How do drifting and evaporating pebbles influence planets?



Pebble evaporation



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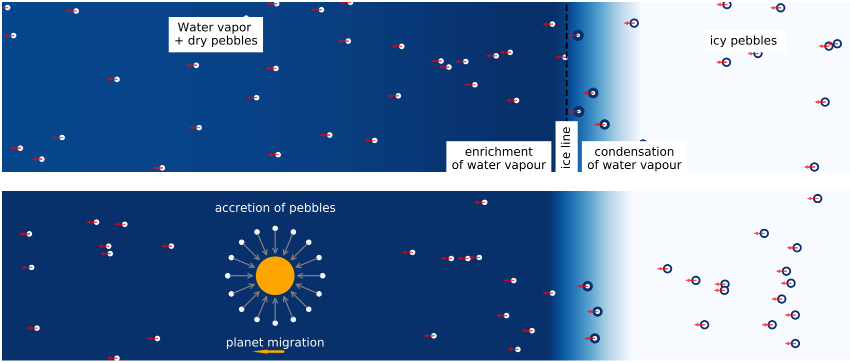

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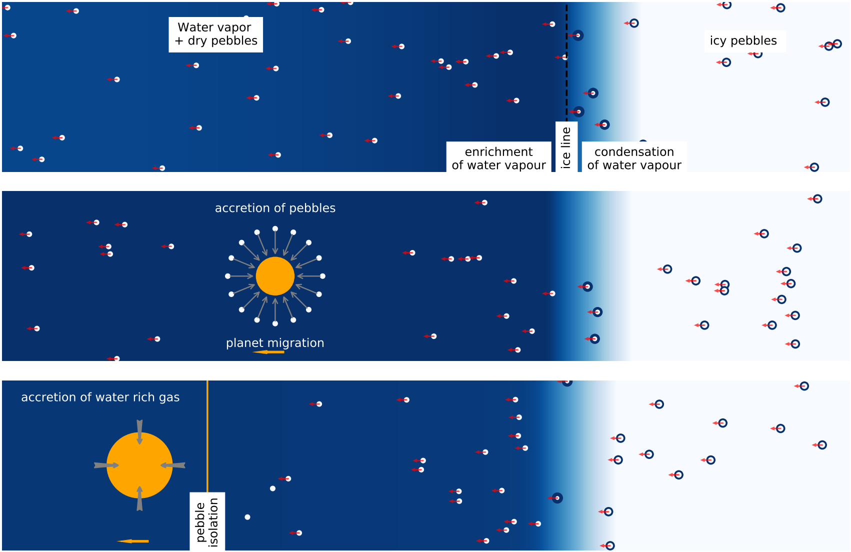
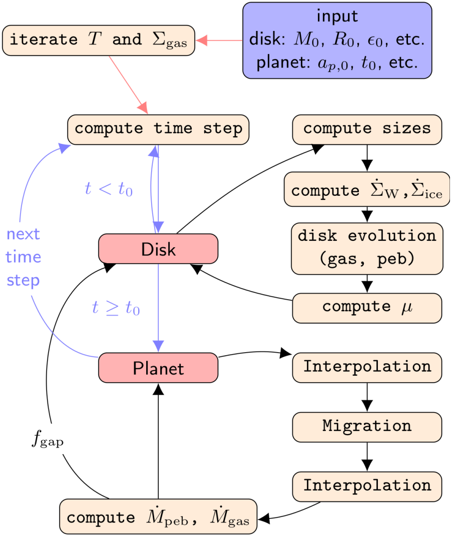


(*Schneider & Bitsch, 2021a*)

Model: chemcomp

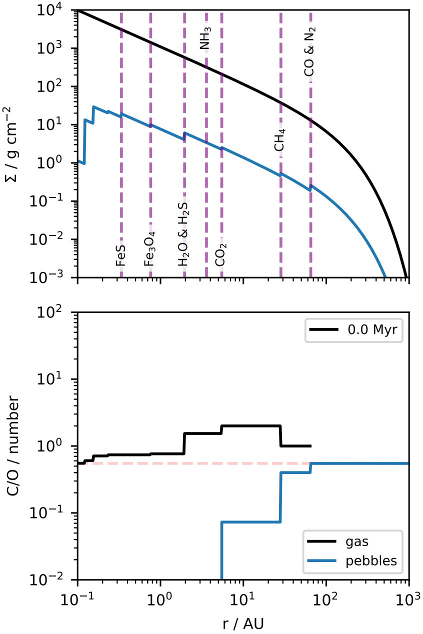
- Viscous disc evolution
- Pebble growth and drift
  (*Birnstiel et al. 2012*)
- Pebble evaporation and recondensation at ice lines
- Pebble accretion
  (*Johansen & Lambrechts 2017*)
- Gas accretion, limited by $\dot{M}_{\rm disc}$
  (*Ndugu et al. 2021*)
- Type-I migration
  (*Paardekooper et al. 2011*)
- Type-II migration
  (*Ndugu et al. 2021*)



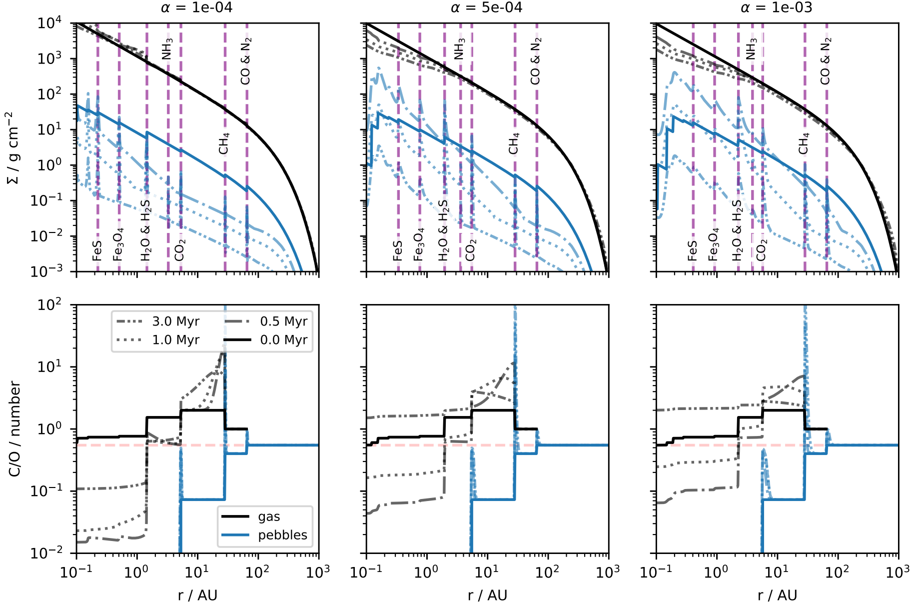
(*Schneider & Bitsch, 2021a*)

Initial disc model

- Solar composition of the different species
  (*Asplund et al. 2019*)
- Chemical intial conditions with step functions
  (*Öberg et al. 2011*)
- No chemical evolution included!
  (*Booth & Ilee 2019*)
- $M_{\rm disc} = 0.128\ M_\odot,\ R = 137$ AU

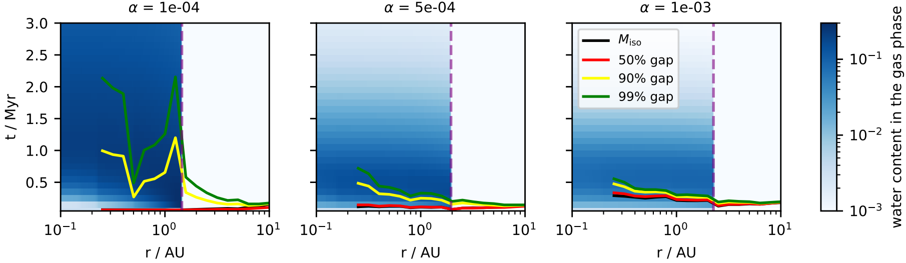


Disc evolution



(*Schneider & Bitsch, 2021a*)

Evolution of the water content in the gas phase



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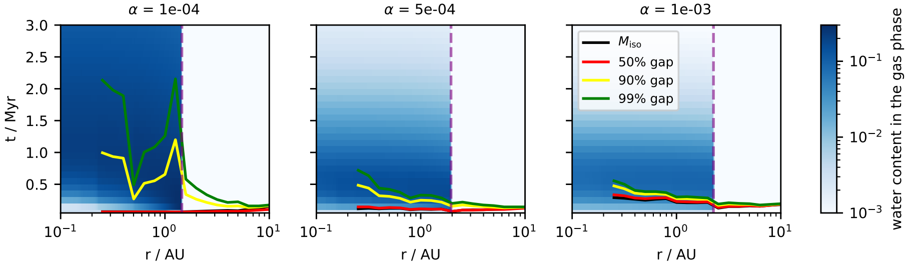

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- Water vapor enriches the inner disc
- Lower/higher viscosity allows larger/smaller particle sizes
- Lower/higher viscosity leads to slower/faster water vapor motion

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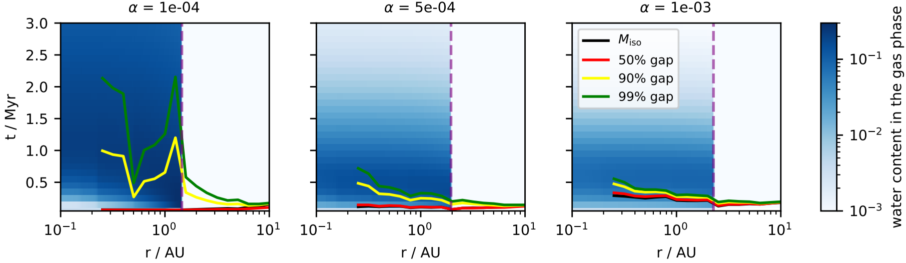

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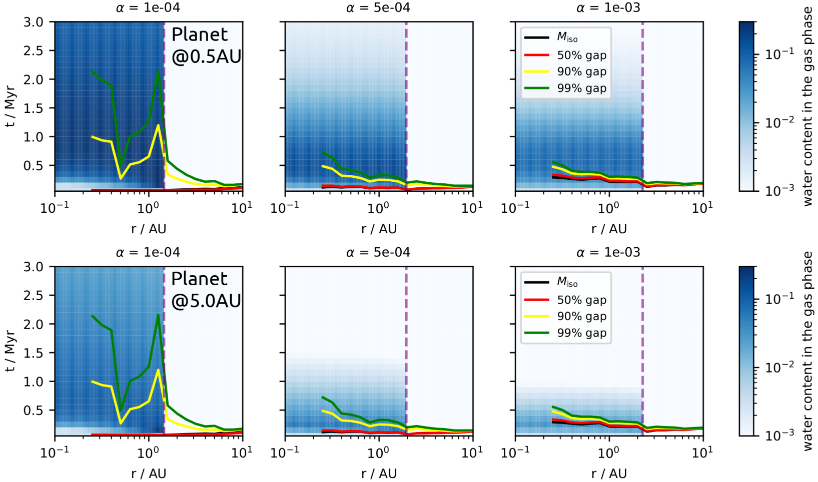
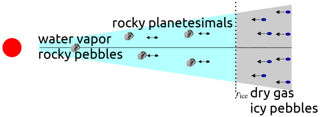


(*Schneider & Bitsch, 2021a*)

⇒ Planet interior/exterior (top/bottom) to the water ice line is inefficient/efficient in blocking water to the inner system (*Bitsch et al. 2021*)

Sub-Neptune formation



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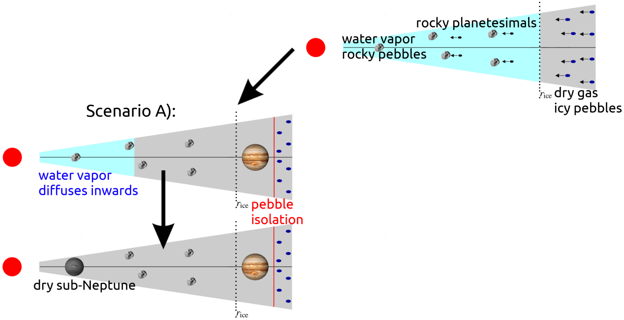

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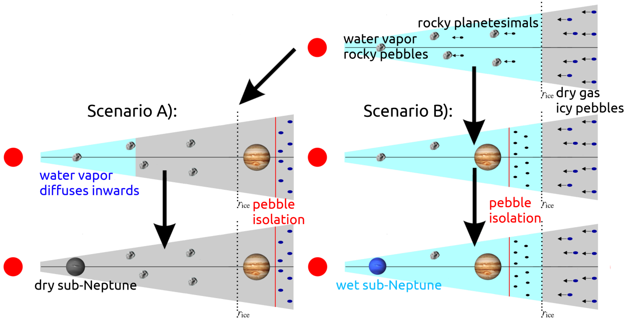

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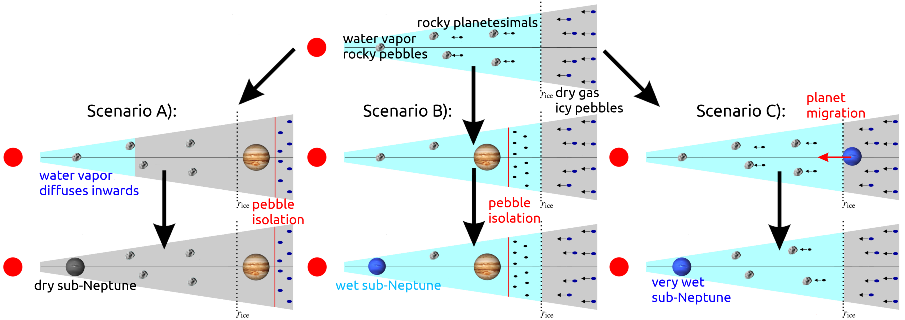

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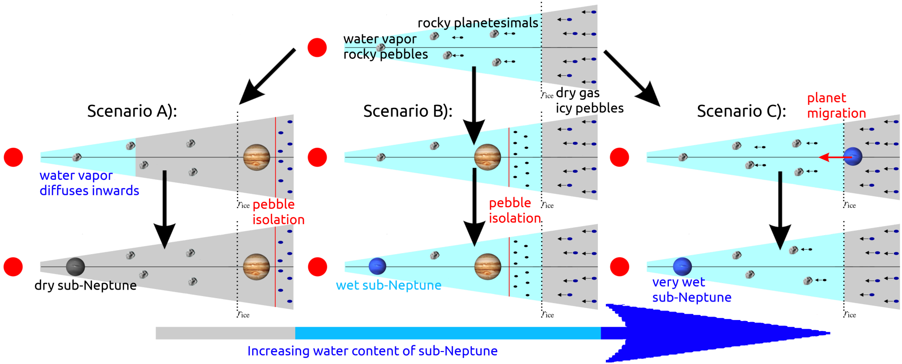

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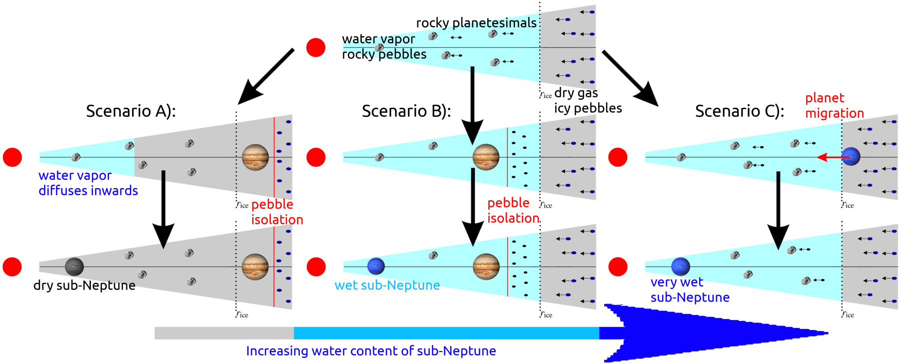

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⇒ Giant planet formation time and position relative to the ice line is key!

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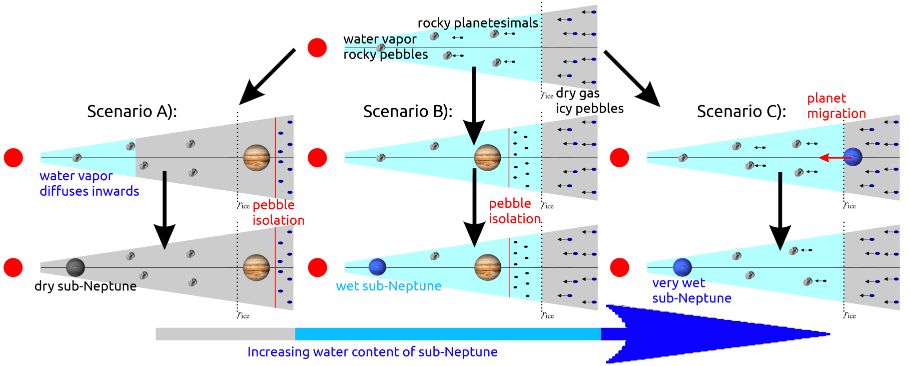

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⇒ Water content of sub-Neptune can help to constrain Jupiter's formation time!

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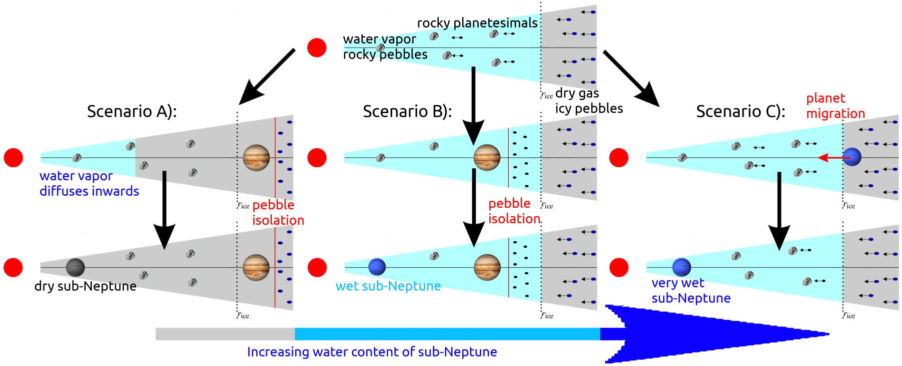

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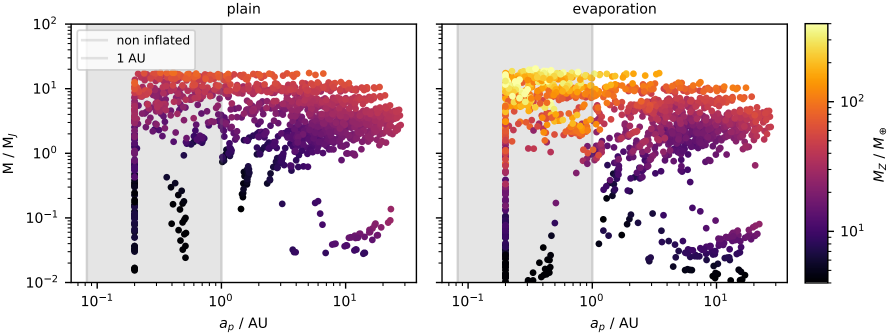
⇒ Hat-P-11b's sub-solar water content implies an early formation of its outer Jovian mass companion!

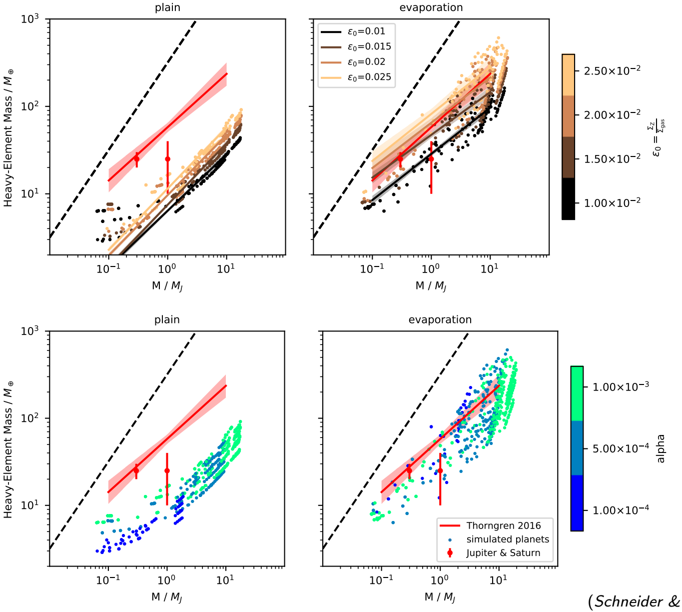
Heavy element content of giant planets



(*Schneider & Bitsch, 2021a*)

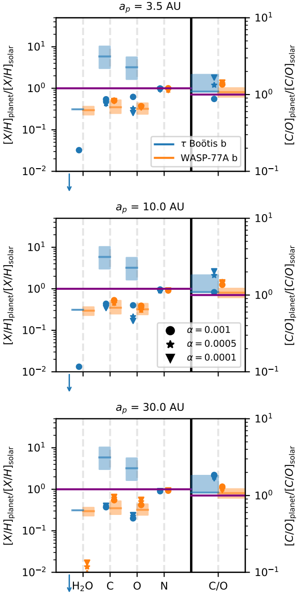
- ⇒ Pebble evaporation increases the heavy element content of giants
- ⇒ Closer-in planets have a larger heavy element content, because the inner disc is more enriched with vapor, especially water!

Heavy element content of giant planets



(*Schneider & Bitsch, 2021a*)

Planetary compositions: **no pebble evaporation**



(*Bitsch et al., submitted*)

- No super-solar C/H and O/H possible!

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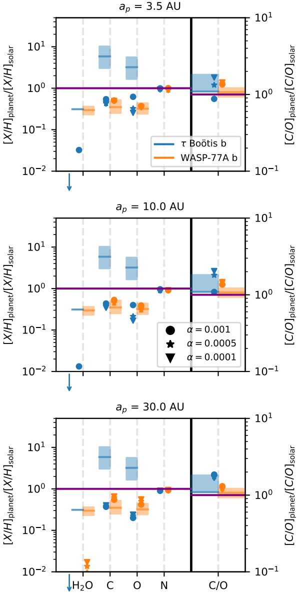

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- No super-solar C/H and O/H possible!
- No infuence of viscosity!

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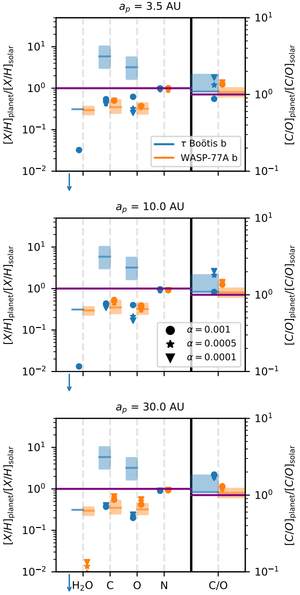

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- WASP77-A b's composition could be matched...

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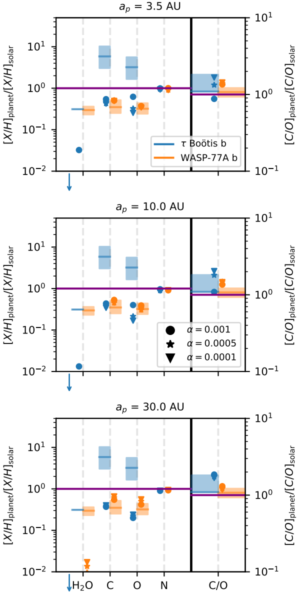
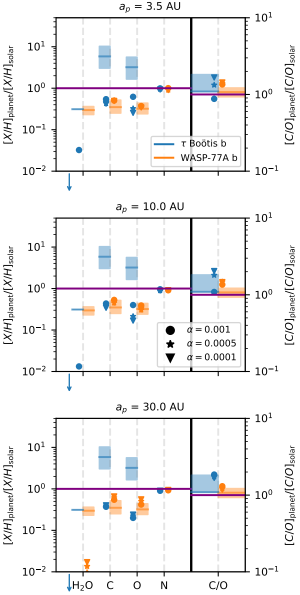


(*Bitsch et al., submitted*)

- No super-solar C/H and O/H possible!
- No infuence of viscosity!
- WASP77-A b's composition could be matched...
- tau Boötis b's composition can only be matched if additional solids are accreted!

Planetary compositions: **no pebble evaporation**

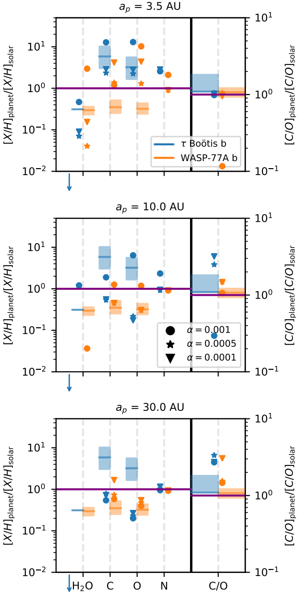


(*Bitsch et al., submitted*)

- No super-solar C/H and O/H possible!
- No infuence of viscosity!
- WASP77-A b's composition could be matched...
- tau Boötis b's composition can only be matched if additional solids are accreted!

⇒ But why only sometimes planetesimal accretion???

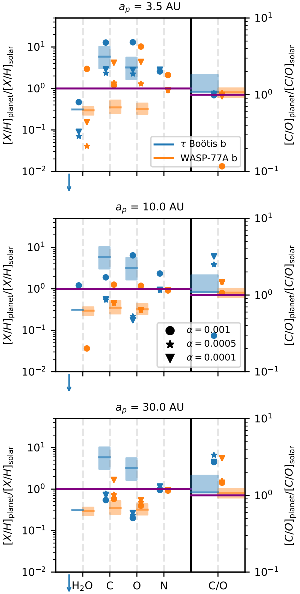
Planetary compositions: with pebble evaporation



(*Bitsch et al., submitted*)

- Pebble evaporation allows super-solar C/H and O/H

Planetary compositions: with pebble evaporation



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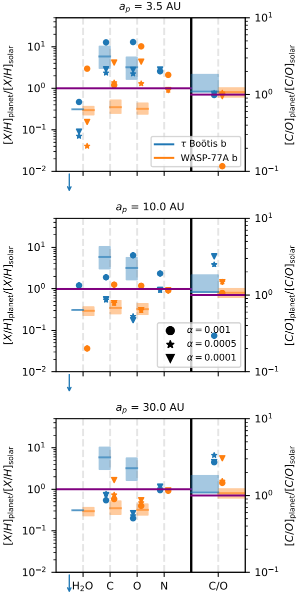

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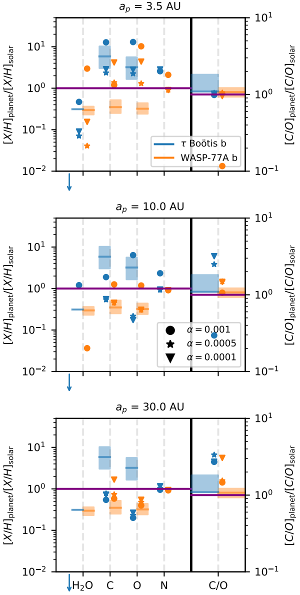

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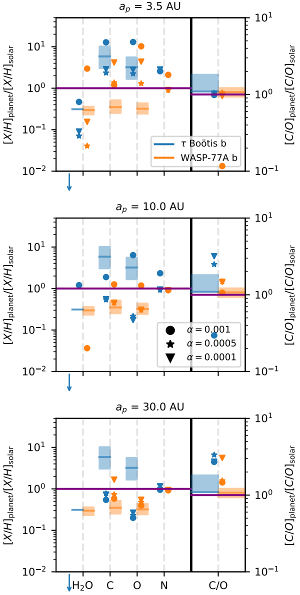

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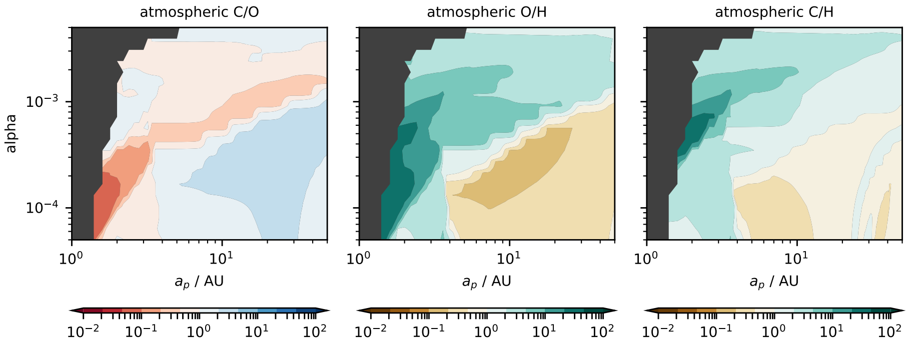
⇒ No additional accretion of solids needed!

Importance of viscosity



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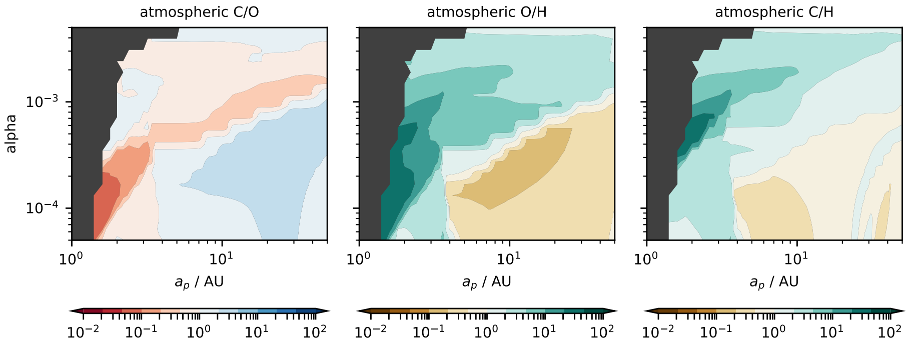
- Viscosity sets the pebble sizes and diffusion timescale

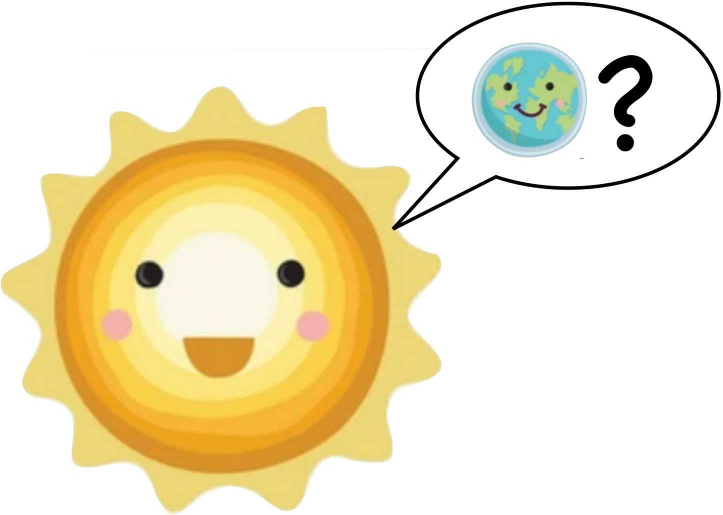
Importance of viscosity



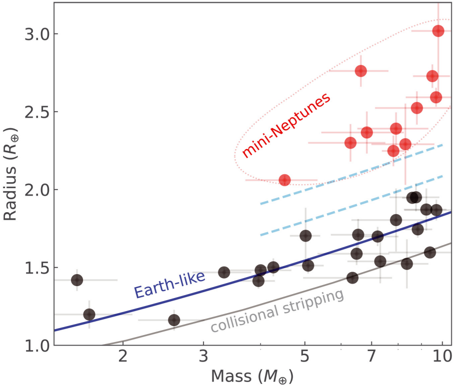
(*Bitsch et al., submitted*)

- Viscosity sets the pebble sizes and diffusion timescale
- Larger viscosity results in smaller pebbles and faster diffusion, leading to less extreme C/H, O/H and C/O ratios

What does the star tell about the planet?



The chemical link between stars and their rocky planets



(*Adibekyan et al. 2021*)

- Compositional link between **rocky** exoplanets and host stars

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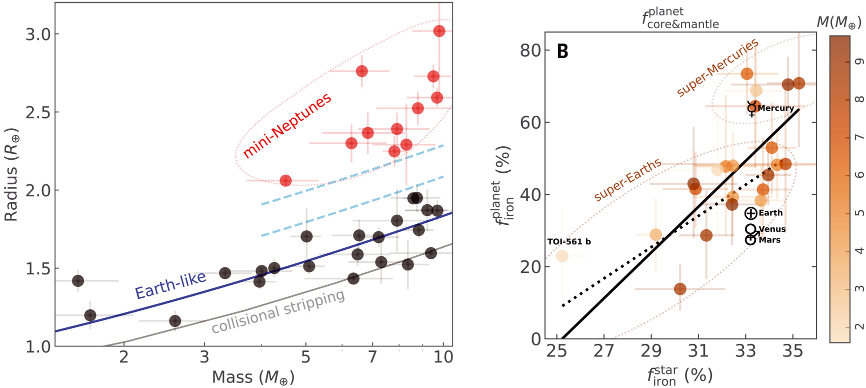
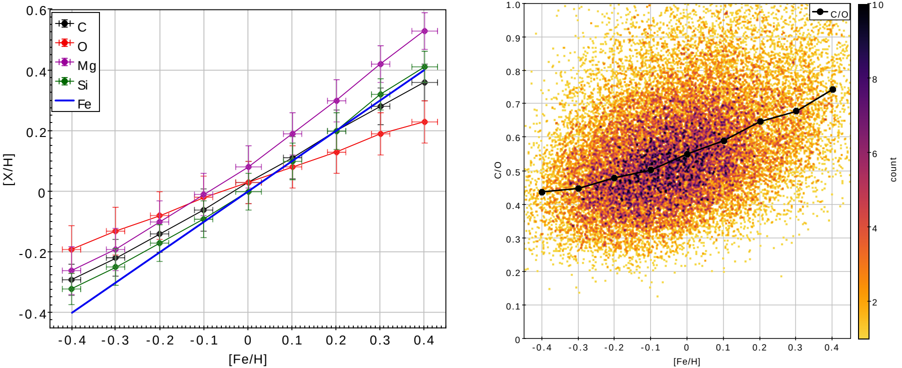


(*Adibekyan et al. 2021*)

- Compositional link between **rocky** exoplanets and host stars
- Estimates of the planetary iron mass fractions correlate with stellar [Fe/H]
- Super-Mercuries appear to be distinct, implying a different formation channel

Stellar abundances



(*Bitsch & Battistini, 2020*)

- Different elements scale differently with [Fe/H] due to galactic chemical evolution (*Burbidge et al. 1957*)
- C/O ratio in different stars varies a lot

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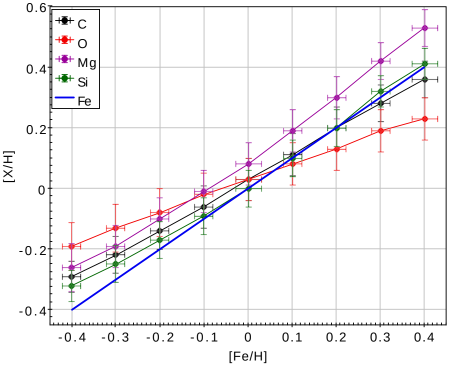

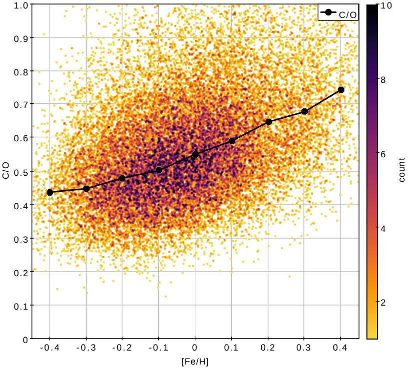

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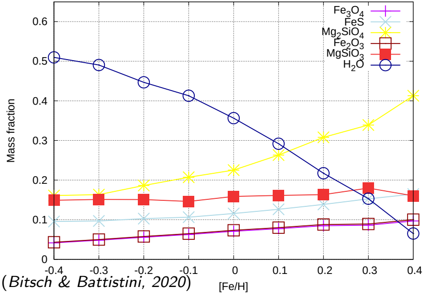
⇒ What does this mean for the chemical composition in discs?

Influence on planet formation

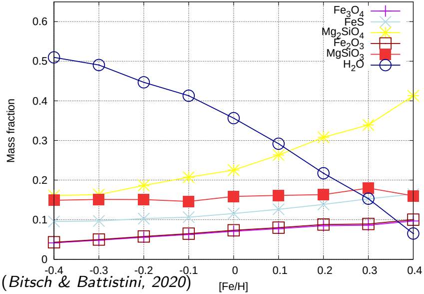


(*Bitsch & Battistini, 2020*)

- Significant reduction in H_2O content with increasing [Fe/H]

⇒ Reduction in H_2O mainly caused by increase in C/O, because C binds O in CO and CO_2!

Influence on planet formation



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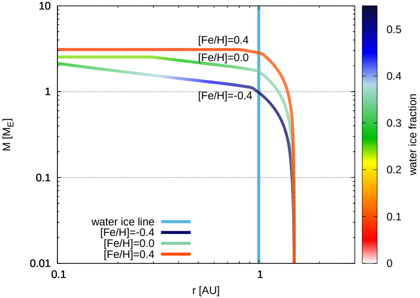

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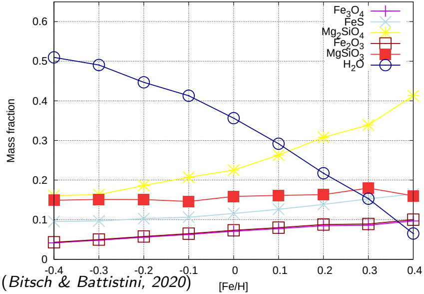
Influence on planet formation



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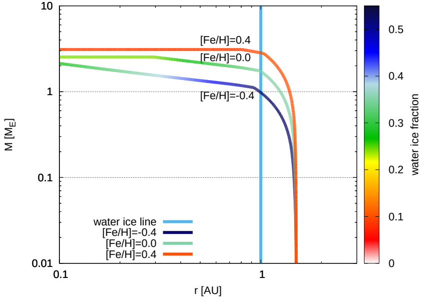

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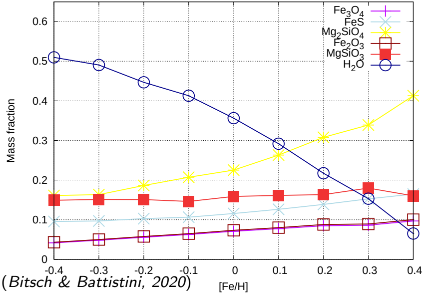

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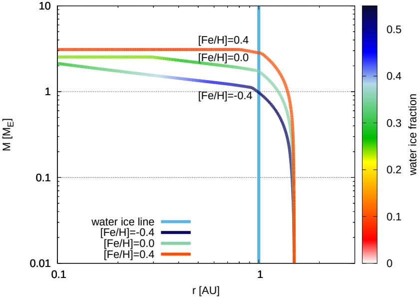

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⇒ Super important when determining if planetary atmosperes have super/sub solar water!

Summary

- Pebbles grow and drift through the disc, but can be trapped at pressure maxima
  (e.g. *Whipple 1972, Brauer et al. 2008, Birnstiel et al. 2012, Drążkowska et al. 2022*)
- Planetesimal accretion is inefficient in the outer regions, while pebble accretion can explain the formation of wide orbit giants
  (e.g. *Lambrechts & Johansen 2012, Bitsch et al. 2015b, Johansen & Bitsch 2019*)
- Pebble drift and evaporation is a crucial ingredient for planet formation and can explain the heavy element content of giant planets!
  (e.g. *Booth et al. 2017, Schneider & Bitsch 2021a,b*)
- Planetary atmospheres could help to constrain planet formation, but more work to relate atmospheric to bulk compositions is needed!
  (*Schneider & Bitsch 2021b, Bitsch et al. submitted, Helled et al. 2021, Guillot et al. 2022*)
- Each star is individual and the different elemental abundances may be key to understand planet formation!
  (*Bitsch & Battistini 2020, Adibekyan et al. 2021*)