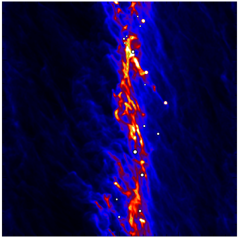
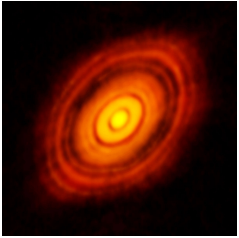
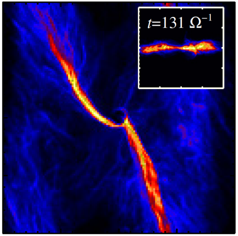
The growth of pebbles and protoplanets near ice lines







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"Planet Formation around Snowline" University of Tokyo, November 2017

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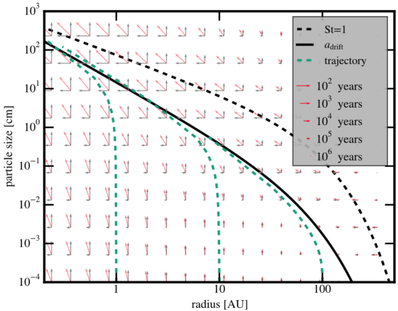
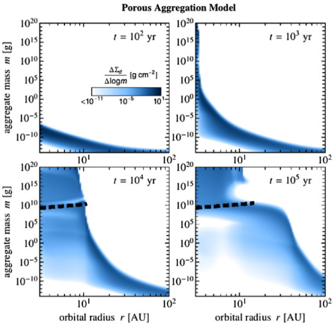
The main challenge for planetesimal formation: radial drift



(*Birnstiel, Fang, & Johansen*, 2016)



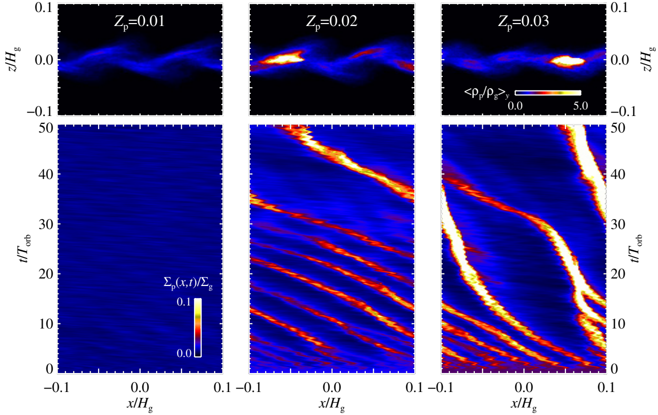
(*Okuzumi et al.*, 2012)

- Pebbles grow to a characteristic size where the growth time-scale equals the radial drift time-scale (*Birnstiel et al.*, 2012; *Lambrechts & Johansen*, 2014)
- Growth time-scale $t_{\rm gr} = R/\dot{R}$, drift time-scale $t_{\rm dr} = r/\dot{r}$
- Yields cm-sized pebbles in inner disc and mm-sized pebbles in outer disc, in good agreement with observations
- Bouncing and fragmentation would result in even smaller pebble sizes
- Planetesimals can only form by direct sticking in pressure bumps (*Drazkowska et al.*, 2013) or if pebbles are extremely fluffy (*Okuzumi et al.*, 2012)

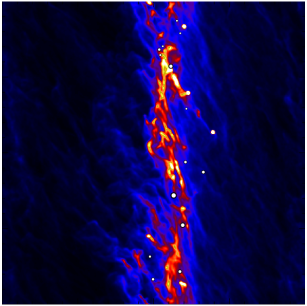
Streaming instability

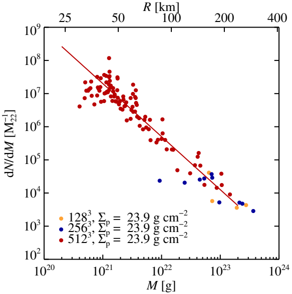
- The streaming instability arises in the streaming motion of particles through the gas (*Youdin & Goodman*, 2005)
- Metallicity $Z = \Sigma_\mathrm{p}/\Sigma_\mathrm{g}$ determines filament formation
- Filaments reach high densities well above the Roche density (*Johansen et al.*, 2007; 2009; *Bai & Stone*, 2010; *Johansen et al.*, 2015)

⇒ Collapse to form planetesimals



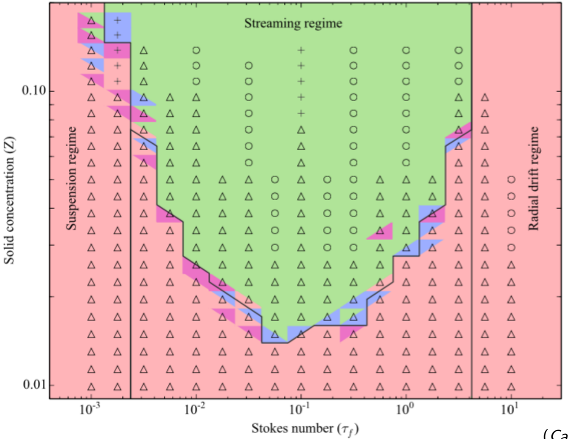
Gravitational collapse





- Initial Mass Function of planetesimals at up to 512^3 resolution
- Differential mass distribution is well fitted by a power law with $\mathrm{d}N/\mathrm{d}M \propto M^{-1.6}$ (*Johansen et al.*, 2015)
- Results with Pencil Code and Athena are very similar (*Simon et al.*, 2016)
- Most of the mass resides in the largest planetesimals
- Characteristic planetesimal size of ∼100 km
- Small planetesimals dominate in number

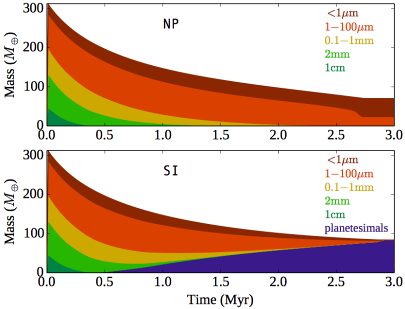
Metallicity threshold

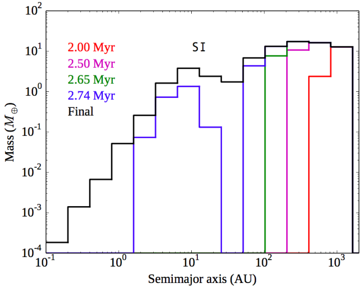


(*Carrera et al.*, 2015)

- The streaming instability makes filaments above threshold metallicity
- *Carrera, Johansen, & Davies* (2015) mapped the metallicity threshold as a function of St in 2-D simulations
- Lowest around a sweetspot at St $\sim$ 0.1 (1 cm at 10 AU)
- The threshold also depends on the radial pressure support (*Bai & Stone*, 2010)

Forming planetesimals by photoevaporation





(*Carrera, Gorti, Johansen, & Davies*, 2017)

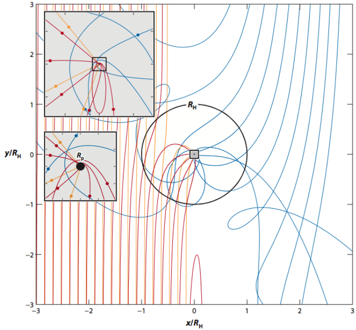
- ▶ Photoevaporation models including X-rays, EUV and FUV show increase in dust-to-gas ratio (*Gorti et al.*, 2015)
- ▶ Typically 50–100 M_E of pebbles remain after gas disc gone
- ▶ Pebbles turn into planetesimals when including prescription for streaming instability (*Carrera et al.*, 2017)

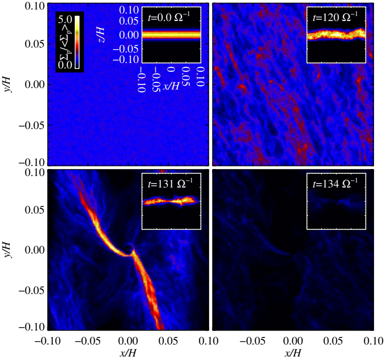
⇒ Efficient delivery of planetesimals to debris disc phase

? How do we form the cores of gas giants and super-Earths early?

Pebble accretion

(*Johansen & Lambrechts*, 2017, AREPS)



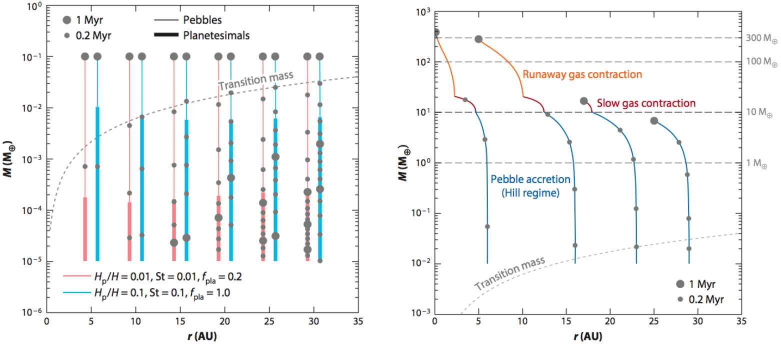


(*Lambrechts & Johansen*, 2012)

- Pebbles can be accreted from the entire Hill radius of a protoplanet
- Pebble accretion speeds up core formation significantly relative to planetesimal accretion
  (*Johansen & Lacerda*, 2010; *Ormel & Klahr*, 2010; *Lambrechts & Johansen*, 2012)

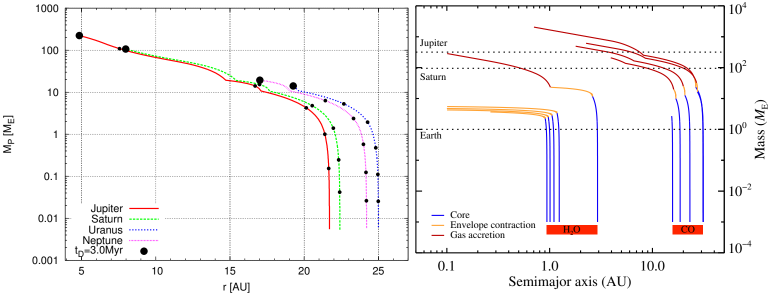
⇒ Cores can form well within the life-time of the protoplanetary gas disc, even at large orbital distances

Planetary growth tracks



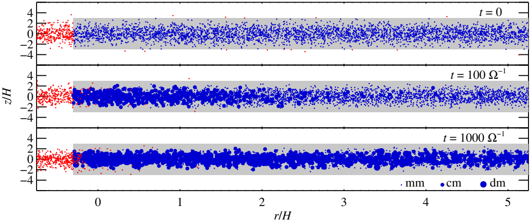
- Rapid pebble accretion can explain how planets remain in the protoplanetary disc despite planetary migration
  (*Bitsch, Lambrechts, & Johansen*, 2015; *Bitsch & Johansen*, 2016)
- Initial growth driven by accretion of planetesimals and pebbles, but pebble accretion dominant beyond $\sim 0.01 M_{\mathrm{E}}$
- Cores emerging within 10 AU migrate to become hot Jupiters
- Giant planets ending in cold orbits must start beyond 15 AU in the disc

Forming the giant planets of the Solar System

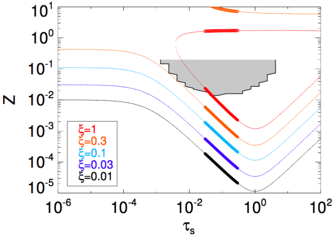


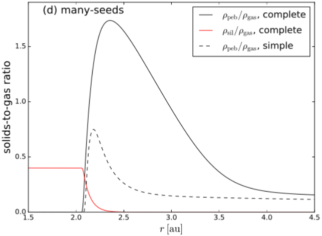
- Giant planets undergo substantial migration
- All four giant planets of the Solar System are consistent with formation near the CO ice line
- The water ice line is efficient at creating super-Earths (*Ormel et al.*, 2017)

Achieving the conditions for the streaming instability early

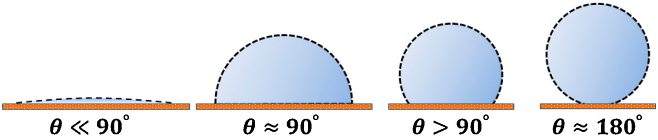


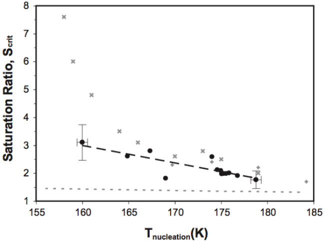
- Lots of ongoing work on early planetesimal formation at ice lines
- Pebbles may grow large by condensation outside ice lines (*Ros & Johansen*, 2013)
- Dust pile up inside ice line to trigger streaming instability (*Ida & Guillot*, 2016)
- Pile up of ice outside ice line (*Schoonenberg & Ormel*, 2017)
- ? Do planetesimals form in an early and a late generation?

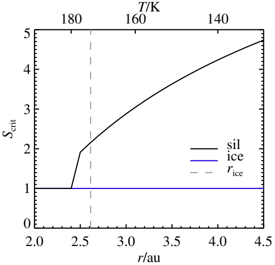




Nucleation versus condensation



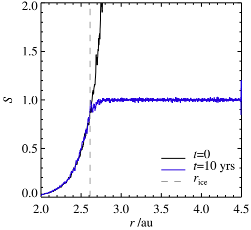


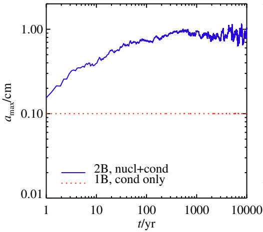


- *Heterogeneous nucleation* describes the formation of first ice layer on silicate substrate
- Ice clusters are unstable due to contact angle $\theta > 0$
- Requires substantial super-saturation to nucleate ice (*Iraci et al.*, 2010)
- Experimental data: $S_{\rm crit} = -0.0626T + 13$

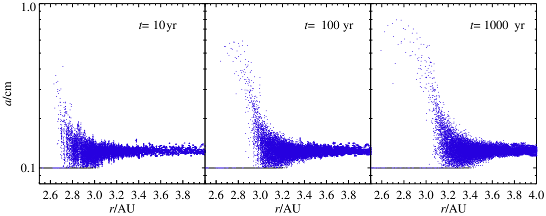
$\Rightarrow$ Silicate grains can not nucleate ice at the ice line

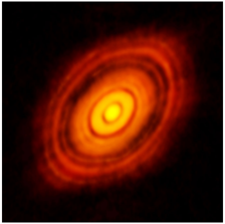
The effect of nucleation on icy pebble growth





(*Ros et al.*, in preparation)





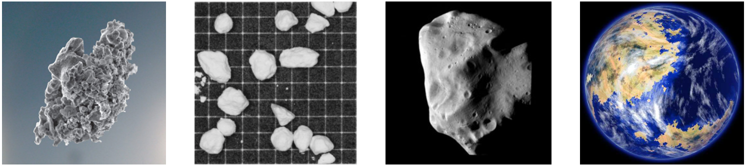
- The saturation ratio is near one outside ice line

⇒ Silicate grains can not nucleate ice anywhere in the disc

- Penetrating pebbles grow to centimeter sizes by condensation
- CO_2 requires $S > 1$ to nucleate on Si and H_2O substrates (*Glandorf et al.*, 2002)

⇒ Could explain dark rings of protoplanetary discs (*Zhang et al.*, 2015)

Summary



- The streaming instability produces an IMF that is very top-heavy
- Photoevaporation of gas triggers the formation of planetesimals
- Accretion of the pebbles is very rapid and can explain how gas giants can form before gas dissipation
- Rapid pebble accretion leads to the formation a wide range of planetary classes despite planetary migration
- Ice lines may act as sites for early pebble and planetary growth, thus defining the final architecture of the planetary system