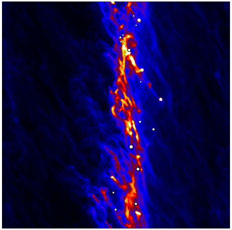
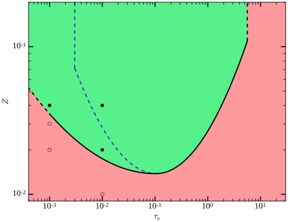
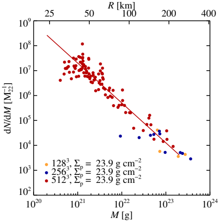
Simulating the early stages of planet formation







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Lund University

"Stars, planets and galaxies", Berlin, April 2018

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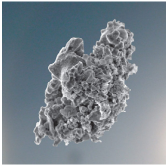
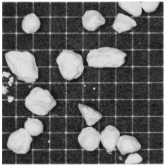
Planet formation

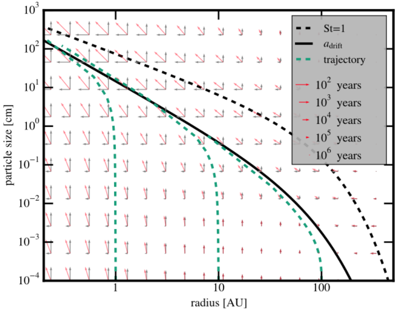
   

Size and time $\longrightarrow$

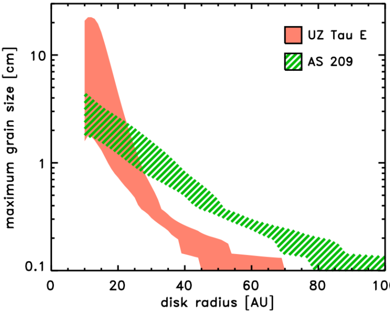
Dust	Pebbles	Planetesimals	Planets
µm	mm–cm	10–1,000 km	10,000 km

- Planets form in protoplanetary discs around young stars as dust grains collide and grow to ever larger bodies
- Pebbles form by collisional sticking
- Pebbles have poor sticking properties and drift rapidly towards the star
- Planetesimals likely form by gravitational collapse of dense pebble filaments
- Protoplanets grow to planets by accreting planetesimals, pebbles and gas

Limits to pebble growth



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

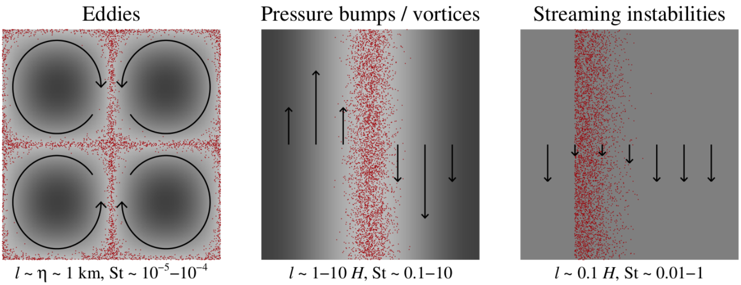


(*Testi et al.*, 2014)

- Dust growth rate $\gamma_{\rm gr} = \dot{R}/R$, drift rate $\gamma_{\rm dr} = \dot{r}/r$
- Pebbles grow maximally to a size where the growth time-scale equals the radial drift time-scale (*Birnstiel et al.*, 2012; *Lambrechts & Johansen*, 2014)
- Yields cm-sized pebbles in inner disc and mm-sized pebbles in outer disc, in good agreement with observations
- Bouncing and fragmentation result in even smaller pebble sizes

$\Rightarrow$ Protoplanetary discs are good pebble factories

Particle concentration mechanisms

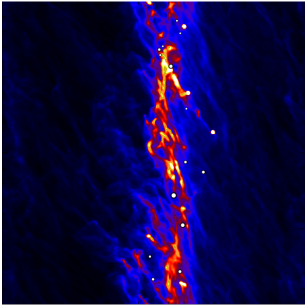


(*Johansen et al.*, Protostars and Planets VI, 2014 arXiv:1402.1344)

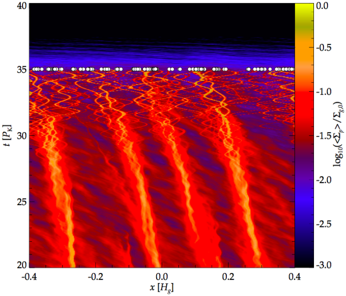
Three categories of particle concentration:

- Between small-scale low-pressure eddies
  (*Maxey*, 1987; *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)

Gravitational collapse



(*Johansen, Mac Low, Lacerda, & Bizzarro*, 2015)

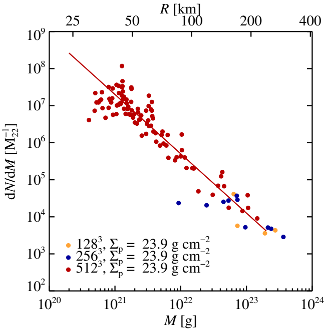


(*Schäfer, Yang, & Johansen*, 2017)

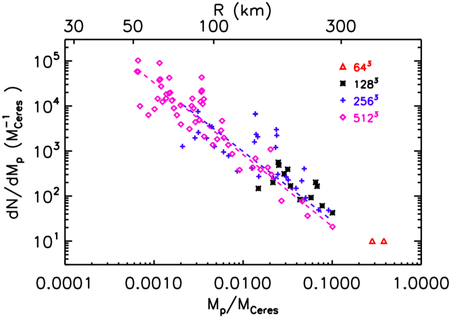
- Initial Mass Function of planetesimals at up to 512^3 resolution (through European PRACE supercomputing grant)

$\Rightarrow$ Filaments fragment to planetesimals with contracted radii 25-200 km

Initial Mass Function of planetesimals



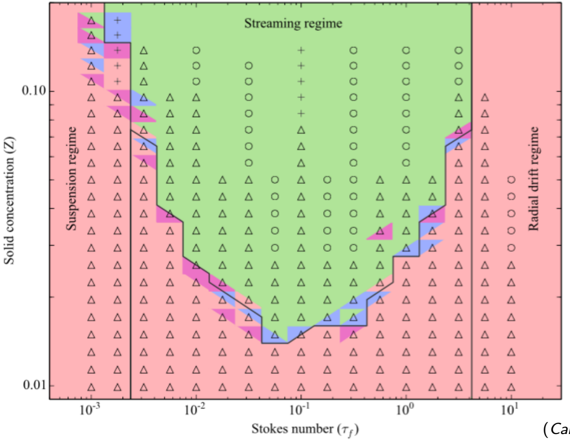
(*Johansen et al.*, 2015)



(*Simon et al.*, 2016)

- Differential mass distribution is well fitted by a power law with $\mathrm{d}N/\mathrm{d}M \propto M^{-1.6}$
- Results with Pencil Code and Athena are very similar
- Most of the mass resides in the largest planetesimals
- Characteristic planetesimal size of $\sim$100 km
- Small planetesimals dominate in number
- Power law concatenated by exponential at high masses (*Schäfer et al.*, 2017)

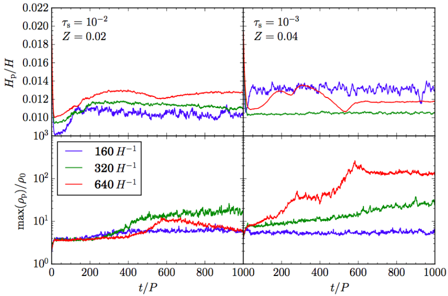
Metallicity threshold

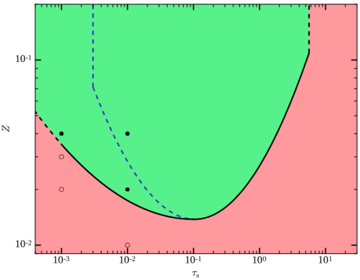


(*Carrera et al.*, 2015)

- 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)
- Such pebbles can form by sticking outside ice line (*Drazkowska & Dullemond*, 2014)
- The threshold also depends on the radial pressure support (*Bai & Stone*, 2010)

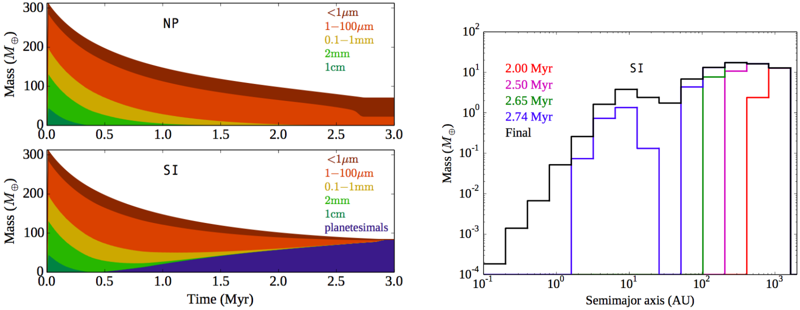
Concentrating small particles in 3-D





- With new drag force scheme of *Yang & Johansen* (2016) we run 3-D simulations of small particles to 1000 orbits (*Yang, Johansen, & Carrera*, 2017)
- Small particles concentrate at much lower metallicities than previously thought
- Opens up the possibility to concentrate chondrule-sized particles to form asteroids

Forming planetesimals by photoevaporation



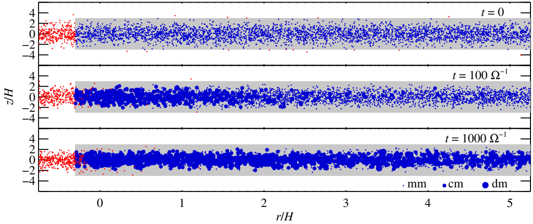
(*Carrera, Gorti, Johansen, & Davies*, 2017)

- Photoevaporation models including X-rays, EUV and FUV show evolution in gas-to-dust 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 terrestrial planet formation and to debris phase

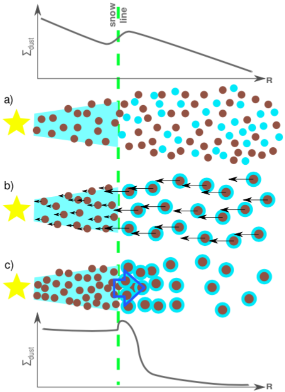
? How to form planetesimals that grow to gas-giant cores?

Achieving the conditions for the streaming instability early

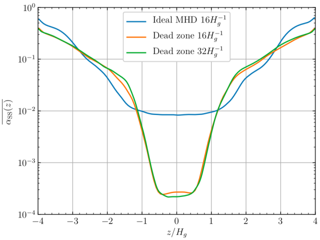


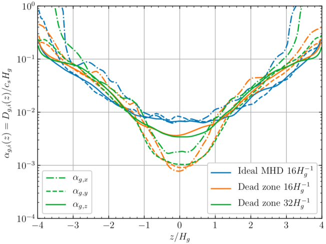
- Lots of ongoing work on early planetesimal formation at ice lines
- Pebbles may grow large by condensation outside ice lines (*Ros & Johansen*, 2013)
- Pile up of ice outside ice line to trigger streaming instability (*Schoonenberg & Ormel*, 2017; *Drazkowska & Alibert*, 2017)
- Also dust pile up inside ice line (*Ida & Guillot*, 2016)

? Do planetesimals form in an early and a late generation?



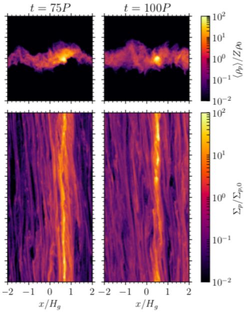
The effect of background turbulence



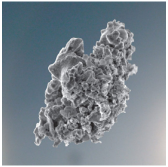


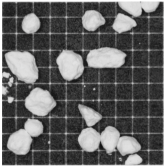
(*Yang, Mac Low, & Johansen*, submitted)

- Protoplanetary discs may accrete in magnetised surface layers (*Gammie*, 1996)
- The mid-plane has low α-viscosity, but high diffusion (*Okuzumi & Hirose*, 2011)
- Pebbles can not sediment below $H_{\rm p}/H_{\rm g} \sim 0.1$
- Filaments still form by the streaming instability above $Z = 0.02$, helped by the weak radial diffusion (*Yang, Mac Low, & Johansen*, submitted)
- Are these models consistent with observed stirring? (e.g. $\alpha \sim 10^{-4}$ in HL Tau, *Pinte et al.*, 2016)



Summary





- Many particle concentration mechanisms are known
- Streaming instability is very powerful because it can lead to very high particle concentration
- Simulations of the streaming instability are converged on the resolved scales, but higher resolution gives stronger particle concentration as the filamentary structure is resolved better
- The initial mass function of planetesimals follows a shallow power $\mathrm{d}N/\mathrm{d}M \propto M^{-q}$ with index $q \approx 1.6$
- The streaming instability can concentrate particles down to mm sizes, but role of realistic turbulence needs to be explored better