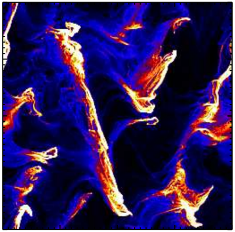
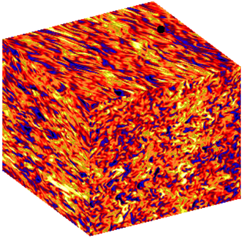
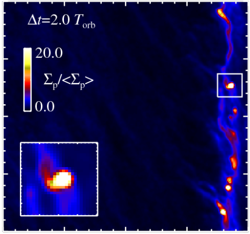
Particle concentration in protoplanetary discs





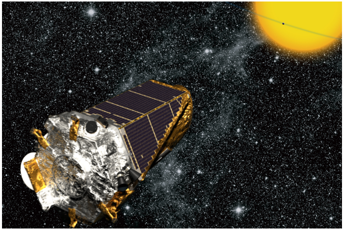


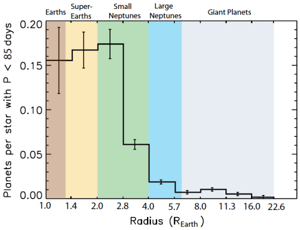
Anders Johansen (Lund University)

"Conference on Dynamics of Particles in Flows"

Stockholm, June 2014

Exoplanets





In the first 16 months the *Kepler* satellite detected 2321 planet candidates

- 253 Earth-sized ($R \leq 1.25 R_\oplus$)
- 712 Super-Earth-sized ($1.25 R_\oplus < R \leq 2 R_\oplus$)
- 1078 Neptune-sized ($2 R_\oplus < R \leq 6 R_\oplus$)
- 207 Jupiter-sized ($6 R_\oplus < R \leq 15 R_\oplus$)
- 71 Super-Jupiter-sized ($15 R_\oplus < R$)

- 245 double systems
- 84 triple systems
- 27 quadruple systems
- 8 quintuple systems
- 1 sextuple system

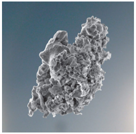
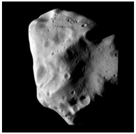
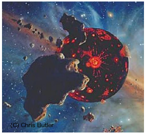
$\Rightarrow$ Nature is *very* efficient at converting dust to planets

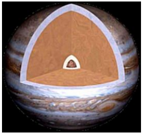
Classical picture of planet formation

Planetesimal hypothesis of *Safronov* (1969):

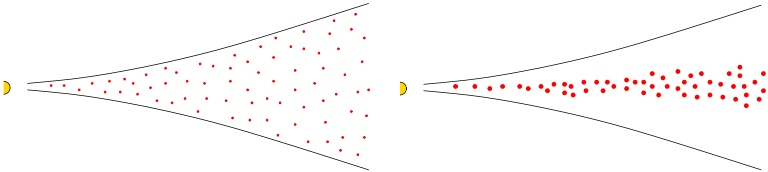
Planets form in protoplanetary discs around young stars from dust and ice grains that stick together to form ever larger bodies

1. Dust to planetesimals
   μm $\rightarrow$ cm: contact forces during collision lead to sticking
   cm $\rightarrow$ km : ???
2. Planetesimals to protoplanets
   km $\rightarrow$ 1,000 km: gravity (run-away accretion)
3. Protoplanets to planets
   Terrestrial planets: protoplanets collide (10^7–10^8 years)
   Gas giants: 10 $M_\oplus$ core accretes gas ($< 10^7$ years)

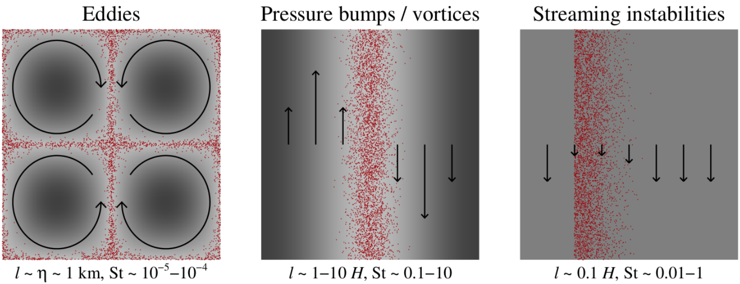
Sedimentation



- Pebbles and rocks *sediment* to the mid-plane of the disc
- Further growth frustrated by high-speed collisions ($>$1–10 m/s) which lead to erosion and bouncing
- Layer not dense enough for gravitational instability

$\Rightarrow$ **Need some way for particle layer to get dense enough to initiate gravitational collapse**

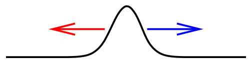
Particle concentration

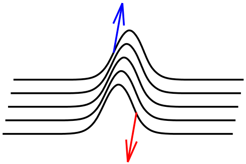


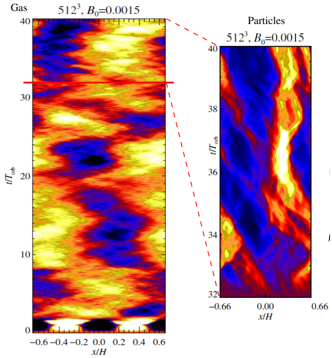
Three ways to concentrate particles: (*Johansen et al.*, 2014, arXiv:1402.1344)

- 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)

Pressure bumps and zonal flows



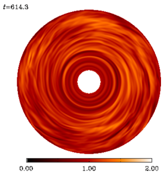




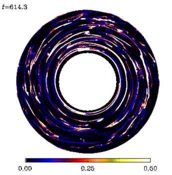
- Large-scale variation in turbulent viscosity of magnetorotational turbulence launches zonal flows
  (*Johansen et al.*, 2006, 2009a; *Lyra et al.*, 2008; *Simon et al.*, 2012; *Dittrich et al.*, 2013)

- Particles are trapped in pressure bumps surrounded by zonal flow envelope

- Ionisation of protoplanetary discs may be insufficient to sustain MHD turbulence



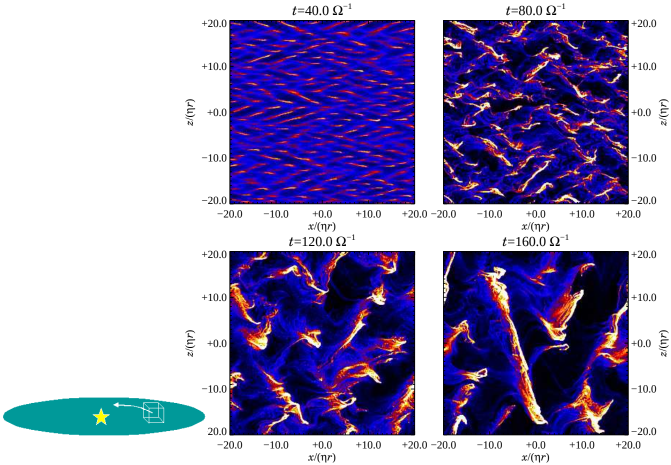
Gas density ($320 \times 320 \times 32$)



Particle density (10^6 particles)

Streaming instability

Linear and non-linear evolution of radial drift flow of meter-sized boulders:



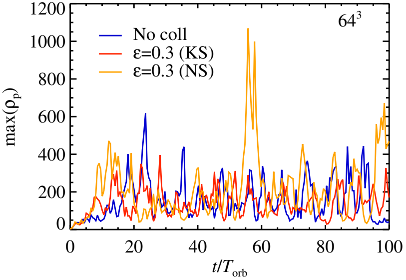
Strong clumping in non-linear state of the streaming instability

(Johansen & Youdin 2007; Johansen, Youdin, & Mac Low 2009)

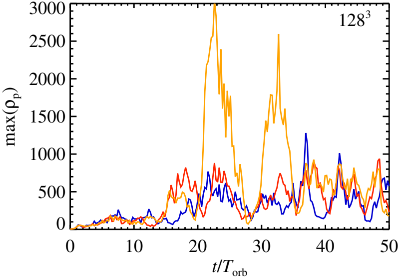
Particle density

- Particle density up to 3000 times local gas density
- Criterion for gravitational collapse: $\rho_\mathrm{p} \gtrsim 100\rho_\mathrm{g}$

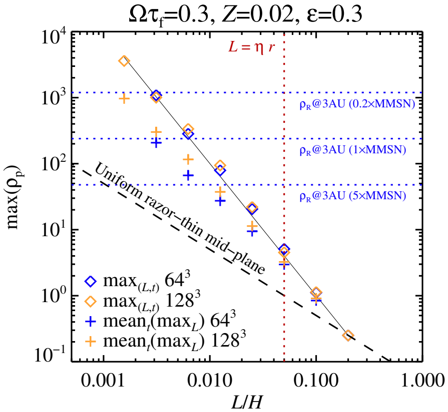
$\Rightarrow$ Gravitational contraction to form planetesimals

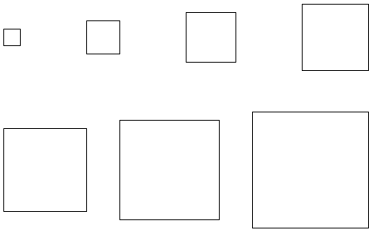


- Maximum density increases with increasing resolution $\rightarrow$ *(Johansen, Lithwick, & Youdin 2012)*



Scale-by-scale convergence



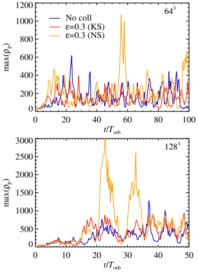


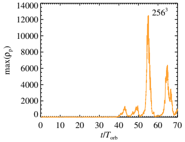
- Plot shows maximum density over a given scale (averaged over time)
- Points for 64^3 and 128^3 almost on top of each other

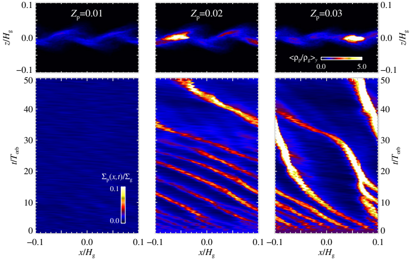
$\Rightarrow$ Streaming instability clumping converges scale-by-scale

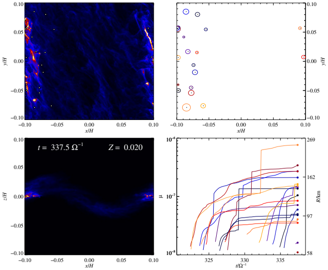
- Increasing the resolution increases the maximum density because density at grid-cell level gains structure at increased resolution

Gravitational collapse



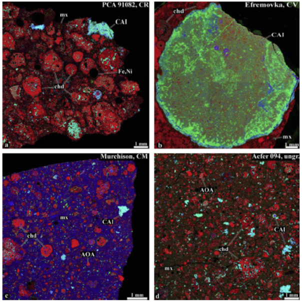


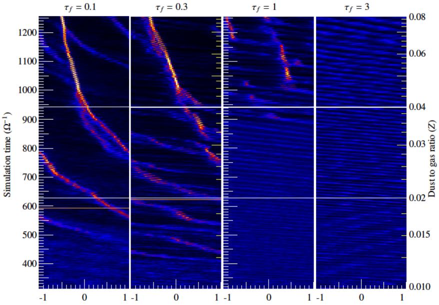




- Particle concentration by streaming instabilities reach at least 10,000 times the gas density
  (*Johansen, Youdin, & Lithwick*, 2012;
  Johansen, Mac Low, & Lacerda, in preparation)
- Filaments fragment to bound pebble clumps, with contracted radii from 50 to 200 km
- Talk by Chao-Chin Yang

Concentrating chondrules





- Meteorites contain up to 80% mass in *chondrules* of sizes 0.1–1 mm (e.g. *Krot et al.*, 2009)
- Typical particle sizes considered for the streaming instability are of size 10 cm (when scaled to the asteroid belt)

⇒ Smaller particles can be concentrated at higher metallicity (*Carrera, Johansen, & Davies*, in preparation)

- Metallicity increase by photoevaporation or drifting particles? (*Alexander et al.*, 2006; *Alexander & Armitage*, 2007)

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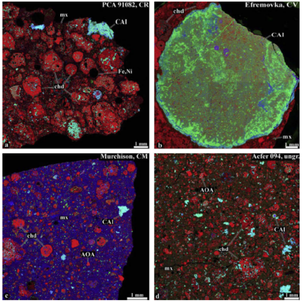

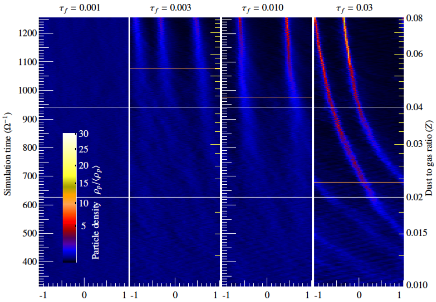

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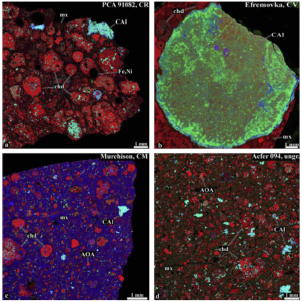

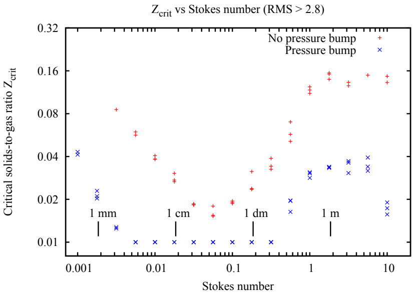

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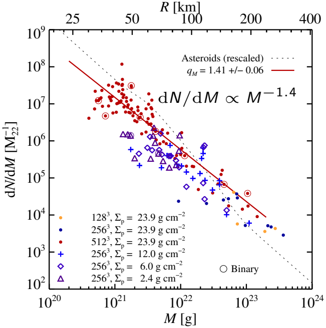
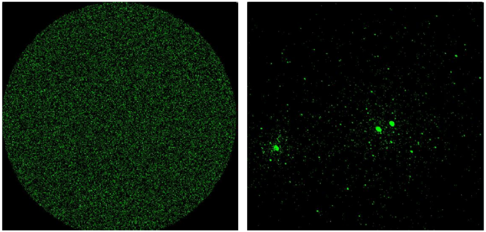
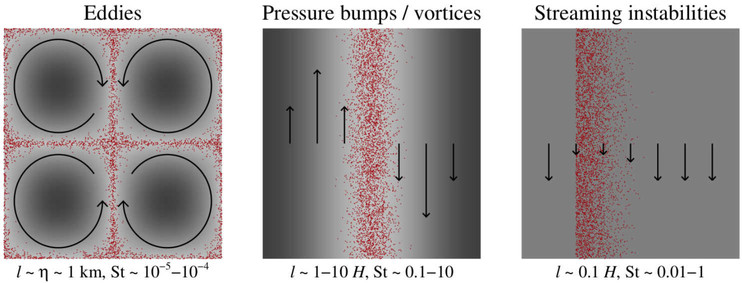
Initial Mass Function of planetesimals





- Very-high-resolution simulations of particle concentration and gravitational collapse yield the Initial Mass Function of *pebble clumps* at the grid scale
- *Nesvorny et al.* (2010) assumed pure sticking and found typical outcome to be a dominant binary with smaller lumps of material around
- Processes of sticking/bouncing/erosion/fragmentation will determine the further collapse to planetesimals of a range of sizes
- Unexplored venue for collision physics (*Jansson & Johansen*, submitted)

Conclusions



- Several particle concentration mechanisms operating in protoplanetary discs have been identified in the last decades
- The streaming instability is very efficient in absence of strong global turbulence
- Planetesimals form by gravitational collapse and continue to grow by accreting pebbles