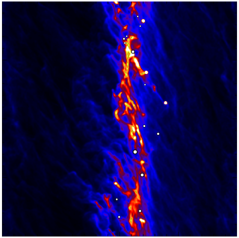
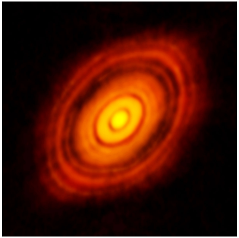
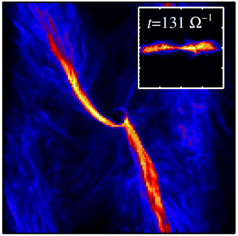
The formation of planets by pebble accretion



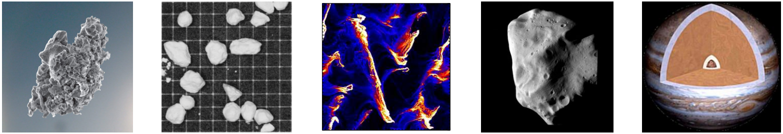




Anders Johansen
Lund University

The 7th annual Nordita Winter School on Theoretical Physics
"The Physics of Planets"

Planet formation in protoplanetary discs

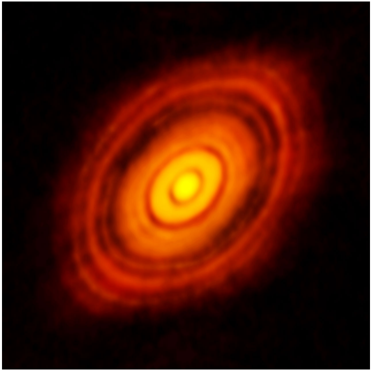


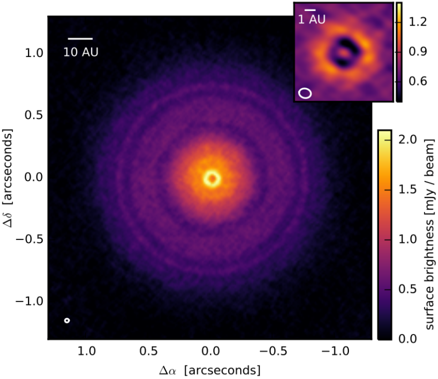
Size and time ⟶

Dust	Pebbles	Planetesimals	Planets
µm	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 as dust grains stick in collisions
- Pebbles spontaneously form dense clumps and clumps contract to form *planetesimals* – the building blocks of planets
- Planets grow by accretion of planetesimals and pebbles
- Gas giants like Jupiter form by contraction of gas from the protoplanetary disc onto a solid core of 10 Earth masses

Protoplanetary discs

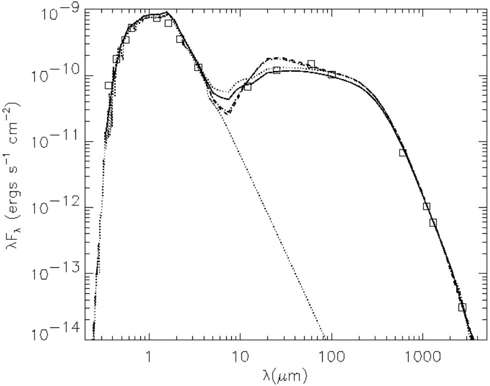




- Two ALMA images of protoplanetary discs
  (*ALMA partnership*, 2015; *Andrews et al.*, 2016)
- HL Tau is 140 pc away, 1 million years old
- TW Hya is 54 pc away, 10 million years old
- Emission comes mainly from mm-sized pebbles
- Dark rings are debated but may trace young planets

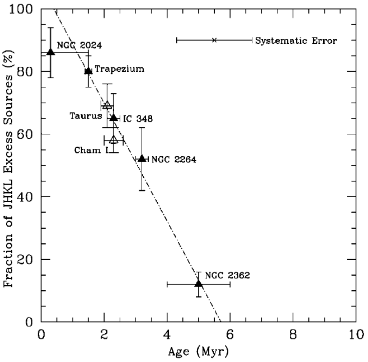
Spectral energy distribution of young stars

- The spectral energy distribution of young stars reveals two components: the stellar black body at short wavelengths and emission from warm circumstellar dust at long wavelengths

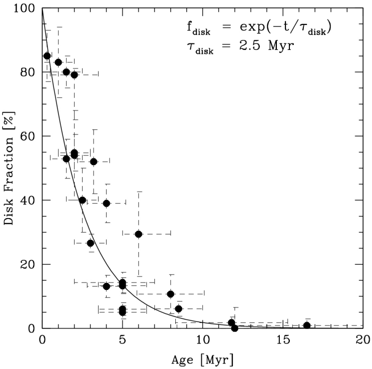


Life-times of protoplanetary discs

- Stars in same star-forming region are pretty much the same age
- Compare instead *disc fraction* between regions of different age



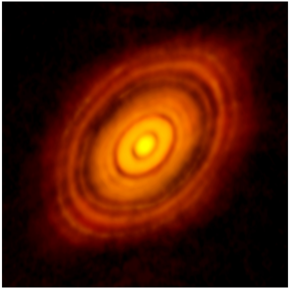
Haisch et al. (2001)



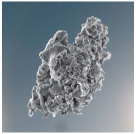
Mamajek (2009)

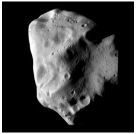
$\Rightarrow$ Protoplanetary discs live for 1–5 Myr

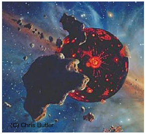
Conditions for planet formation

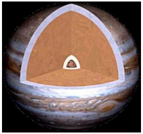


- Young stars are orbited by accreting protoplanetary discs
- Disc masses of 10^{-4}–10^{-1} $M_\odot$
- Disc life-times of 1–5 million years

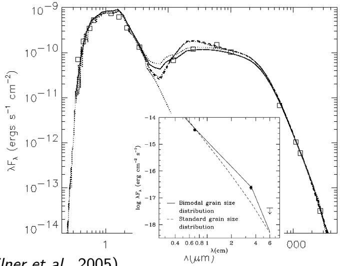




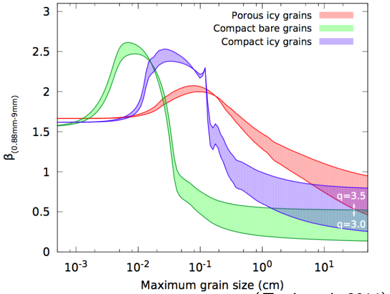




Observed dust growth in protoplanetary discs



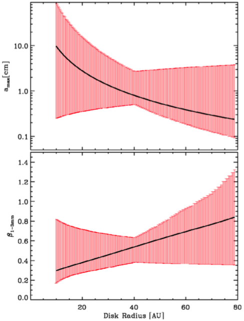
(*Wilner et al.*, 2005)



(*Testi et al.*, 2014)

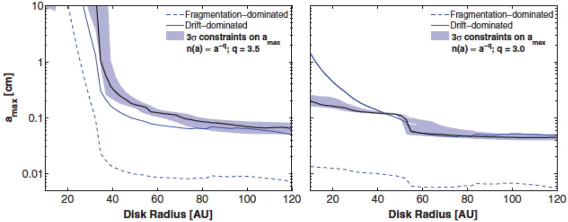
- Dust opacity as a function of frequency $\nu = c/\lambda$:
  - $\kappa_\nu \propto \nu^2$ for $\lambda \gg a$
  - $\kappa_\nu \propto \nu^0$ for $\lambda \ll a$
- $F_\nu \propto \nu^\alpha \propto \kappa_\nu B_\nu \propto \kappa_\nu \nu^2 \propto \nu^\beta \nu^2$
- By measuring α from SED, one can determine β from $\beta = \alpha - 2$
- Knowledge of β gives knowledge of dust size

Pebbles in protoplanetary disks



(*Trotta et al.*, 2013)

(*Perez et al.*, 2012)



- Many nearby protoplanetary disks observed in mm-cm wavelengths show opacity indices below $\beta = 2$ ($\kappa_\nu \propto \nu^\beta$)
- Typical pebble sizes of mm in outer disk and cm in inner disk
- *Protoplanetary disks are filled with pebbles*

Drag force

Gas accelerates solid particles through drag force:

(*Whipple*, 1972; *Weidenschilling*, 1977)

$$\frac{\partial \boldsymbol{v}}{\partial t} = \ldots - \frac{1}{\tau_{\mathrm{f}}}(\boldsymbol{v} - \boldsymbol{u})$$

Particle velocity

Gas velocity

In the Epstein drag force regime, when the particle is much smaller than the mean free path of the gas molecules, the friction time is

$$\tau_{\mathrm{f}} = \frac{R\rho_{\bullet}}{c_{\mathrm{s}}\rho_{\mathrm{g}}}$$

R: Particle radius

$\rho_{\bullet}$: Material density

c_{s}: Sound speed

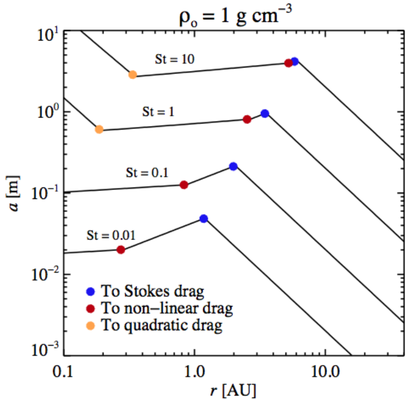
ρ_{g}: Gas density

Important nondimensional parameter in protoplanetary discs:

$$\mathrm{St} = \Omega\tau_{\mathrm{f}} \ (\textit{Stokes number})$$

Ω is the Keplerian frequency

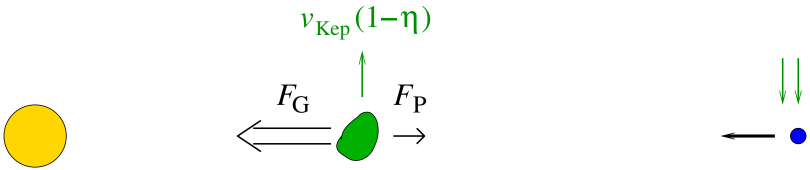
Particle sizes



(*Johansen et al.*, 2014, Protostars & Planets VI)

- In the Epstein regime $\mathrm{St} = \dfrac{\sqrt{2\pi} R \rho_\bullet}{\Sigma_\mathrm{g}}$
- Other drag force regimes close to the star yield different scalings with the gas temperature and density (*Whipple*, 1972)

Radial drift



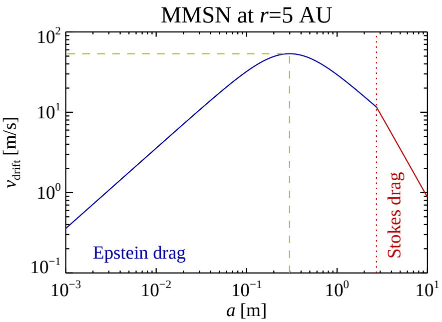
- Disc is hotter and denser close to the star
- Radial pressure gradient force mimics decreased gravity $\Rightarrow$ gas orbits slower than Keplerian
- Particles do not feel the pressure gradient force and would orbit at Keplerian speed in absence of gas
- Headwind from sub-Keplerian gas drains angular momentum from particles, so they spiral in through the disc

Radial drift speed

Balance between drag force and head wind gives radial drift speed
(Adachi et al. 1976; Weidenschilling 1977)

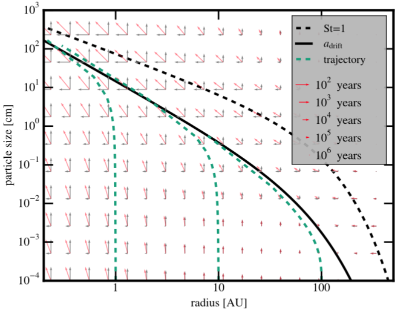
$$v_{\mathrm{drift}} = -\frac{2\Delta v}{\Omega_{\mathrm{K}}\tau_{\mathrm{f}} + (\Omega_{\mathrm{K}}\tau_{\mathrm{f}})^{-1}}$$

for Epstein drag law $\tau_{\mathrm{f}} = a\rho_\bullet/(c_{\mathrm{s}}\rho_{\mathrm{g}})$

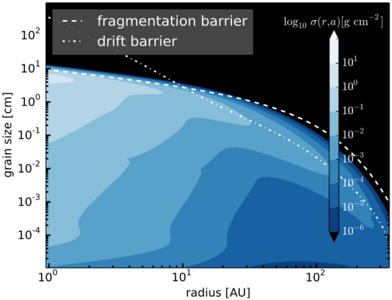


- MMSN $\Delta v \sim 50 \ldots 100$ m/s
- Drift time-scale of 100 years for particles of 30 cm in radius at 5 AU

Drift-limited pebble growth



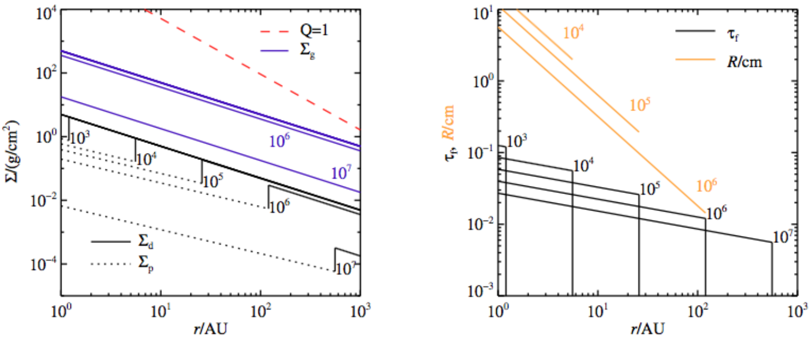
(*Birnstiel et al.*, 2015)



(*Testi et al.*, 2014)

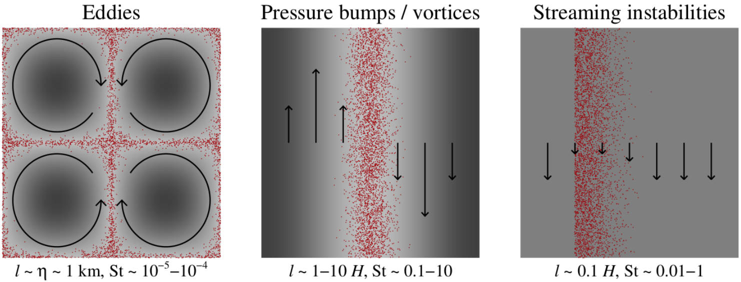
- Particles in the outer disc grow to a characteristic size where the growth time-scale equals the radial drift time-scale (*Birnstiel et al.*, 2012)
- Growth time-scale $t_{\rm gr} = R/\dot{R}$, drift time-scale $t_{\rm dr} = r/\dot{r}$
- Yields dominant particle size that increases as pebble drifts inwards
- The pebble column density can be obtained from the pebble mass flux through $\dot{M}_{\rm p} = 2\pi r v_r \Sigma_{\rm p}$

Radial pebble flux



- The pebble mass flux can be calculated from the pebble formation front that moves outwards with time (*Lambrechts & Johansen*, 2014)
- The Stokes number is ∼0.1 inside 10 AU and ∼0.02 outside of 10 AU
- The drift-limited solution shows a fundamental limit to particle growth
- Pebble sizes agree well with observations
- Bouncing and fragmentation would result in even smaller particle sizes

Particle concentration mechanisms



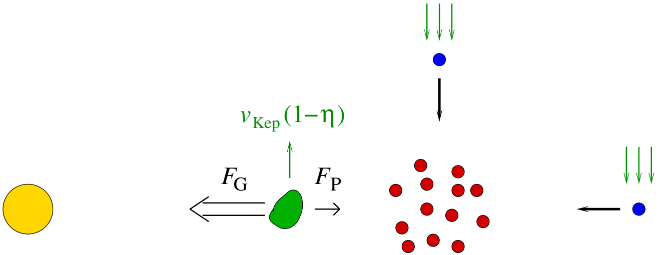
(*Johansen et al.*, Protostars and Planets VI, 2014)

Three mechanisms for concentrating particles:

- Between small-scale low-pressure eddies
  (*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)

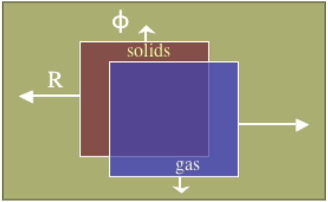
Streaming instability

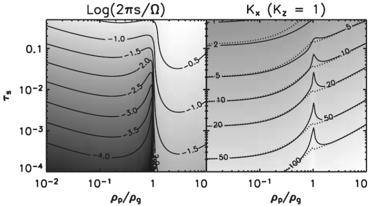
- Gas orbits slightly slower than Keplerian
- Particles lose angular momentum due to headwind
- Particle clumps locally reduce headwind and are fed by isolated particles



$\Rightarrow$ Youdin & Goodman (2005): **“Streaming instability”**

Linear analysis



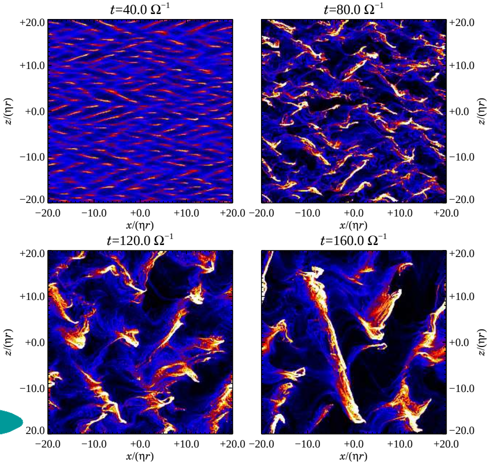


(*Youdin & Goodman*, 2005)

- The streaming feeds off the velocity difference between gas and particles
- Particles move faster than the gas and drift inwards, pushing the gas outwards
- In total there are 8 linear modes (density waves modified by drag)
- *One* of the modes is unstable (*Youdin & Goodman*, 2005; *Jacquet, Balbus, & Latter*, 2011)
- Requires both radial and vertical displacements
- Fastest growth for large particles and local dust-to-gas ratio above unity

Streaming instability

Evolution of the flow of cm-sized pebbles embedded in gas:

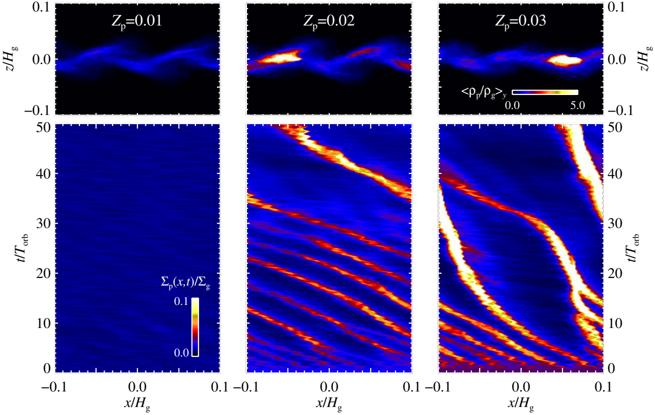


High particle concentrations driven by the streaming instability

(*Youdin & Johansen*, 2007; *Johansen & Youdin*, 2007; *Johansen et al.*, 2007; 2009; 2012; *Bai & Stone*, 2010a,b,c)

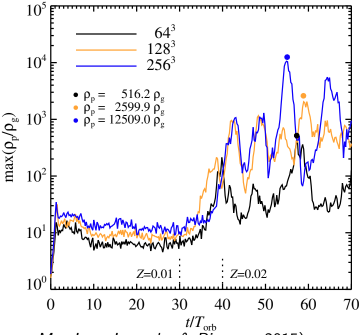
Stratified simulations

- *Johansen, Youdin, & Mac Low* (2009) presented stratified simulations of streaming instabilities
- Pebble sizes $\Omega\tau_{\rm f} = 0.1, 0.2, 0.3, 0.4$ (3–12 cm at 5 AU, 1–4 cm at 10 AU)
- Metallicity $Z = \Sigma_{\rm p}/\Sigma_{\rm g}$ is a free parameter

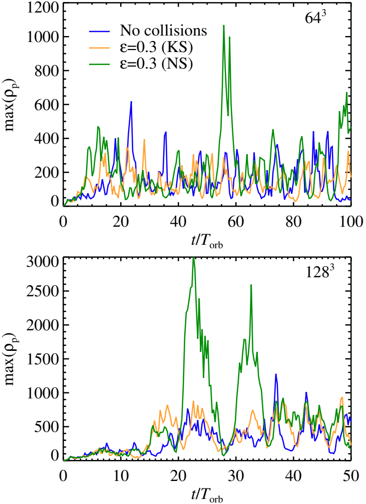


Convergence tests

- Criterion for gravitational collapse: $\rho_\mathrm{p} \gtrsim \Omega^2/G \sim 100\rho_\mathrm{g}$
- Maximum density increases with increasing resolution
- Particle density up to 10,000 times local gas density

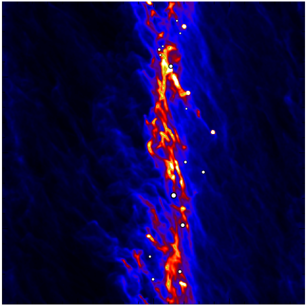


(*Johansen, Mac Low, Lacerda, & Bizzarro*, 2015)



(*Johansen, Youdin, & Lithwick*, 2012)

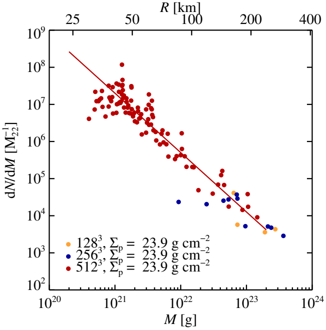
Gravitational collapse



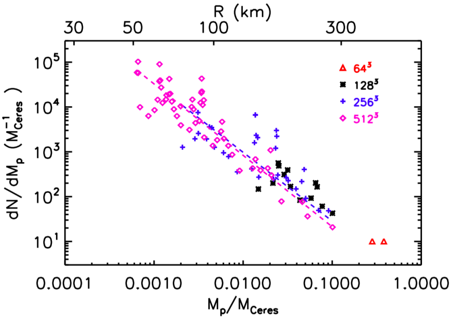
- Particle concentration by streaming instabilities reach at least 10,000 times the gas density
- Filaments fragment to planetesimals with contracted radii 25-200 km (*Johansen, Mac Low, Lacerda, & Bizzarro*, 2015)

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

Planetesimal birth sizes



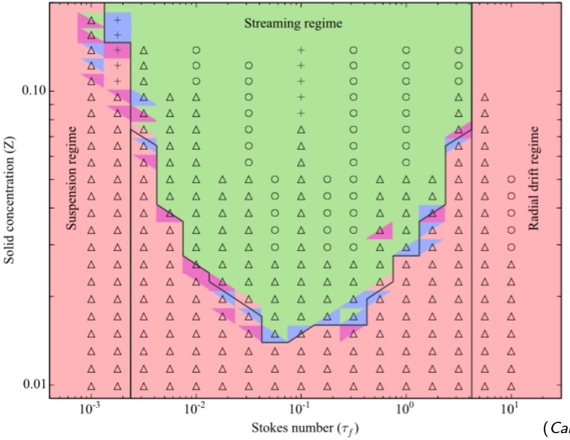
(*Johansen et al.*, 2015)



(*Simon et al.*, 2016)

- Differential size 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 code are very similar
- Most of the mass resides in the largest planetesimals
- Small planetesimals dominate in number
- Size of largest planetesimal decreases with decreasing particle column density, down to 100 km at MMSN-like density at 2.5 AU

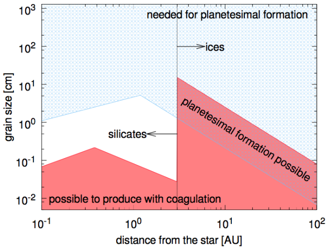
Metallicity threshold



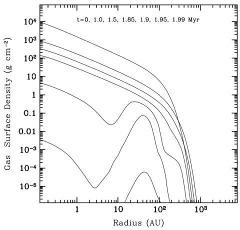
(*Carrera et al.*, 2015)

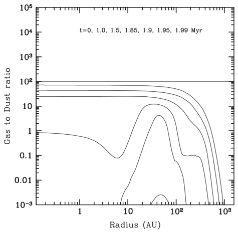
- The streaming instability makes dense filaments above a threshold metallicity (*Carrera et al.*, 2015)
- Lowest around a sweetspot at St $\sim$ 0.1 (1 mm at 30 AU)
- Increases to smaller and larger St
- The threshold also depends on the radial pressure support (*Bai & Stone*, 2010)

Achieving the conditions for the streaming instability



(*Drazkowska & Dullemond*, 2014)

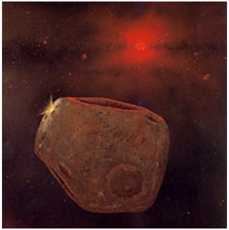


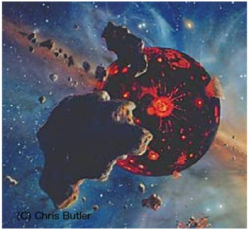


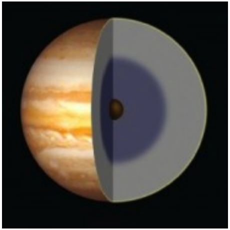
(*Gorti et al.*, 2015)

- Possible to form pebble sizes needed for streaming instability outside of the ice line (*Drazkowska & Dullemond*, 2014)
- But bouncing stalls silicate particles at mm sizes inside of the ice line
- About half of the solid mass remains in tiny grains unable to participate in the streaming instability
- Photoevaporation can increase the dust-to-gas ratio towards the end of the disc life-time (*Gorti et al.*, 2015; *Carrera, Gorti, & Johansen*, submitted)
- Raising the metallicity to trigger the streaming instability is a very active research area (e.g., *Drazkowska et al.*, 2016; *Gonzalez et al.*, 2017)

Classical core accretion scenario







1. Dust grains and ice particles collide to form km-scale planetesimals
2. Large protoplanet grows by run-away accretion of planetesimals
3. Protoplanet attracts hydrostatic gas envelope
4. Run-away gas accretion as $M_{\mathrm{env}} \approx M_{\mathrm{core}}$
5. Form gas giant with $M_{\mathrm{core}} \approx 10 M_{\oplus}$ and $M_{\mathrm{atm}} \sim M_{\mathrm{Jup}}$

(*Safronov*, 1969; *Mizuno*, 1980; *Pollack et al.*, 1996)

All steps must happen within 1–3 Myr while there is gas orbiting the star

Core formation time-scales

- The size of the protoplanet relative to the Hill sphere:

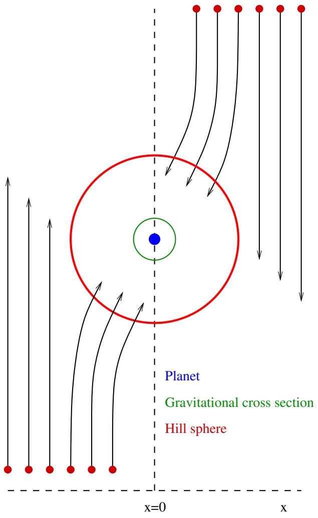
$$\frac{R_{\rm p}}{R_{\rm H}} \equiv \alpha \approx 0.001 \left(\frac{r}{5\,{\rm AU}}\right)^{-1}$$

- Maximal growth rate by gravitational focussing

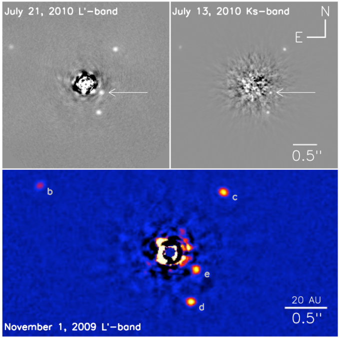
$$\begin{aligned} \dot{M} &= \pi R_{\rm p}^2 v \rho_{\rm s} \alpha^{-1} \\ &= \alpha R_{\rm H}^2 F_{\rm H} \end{aligned}$$

⇒ Only 0.1% (0.01%) of planetesimals entering the Hill sphere are accreted at 5 AU (50 AU)

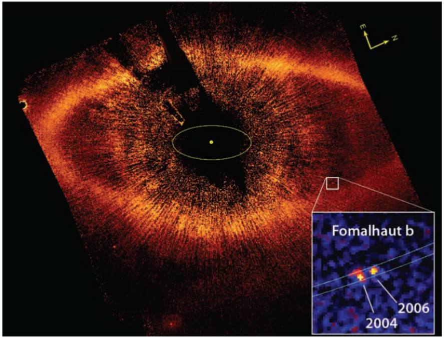
⇒ Time to grow to 10 $M_\oplus$ is
 ∼10 Myr at 5 AU
 ∼50 Myr at 10 AU
 ∼5,000 Myr at 50 AU



Directly imaged exoplanets



(*Marois et al.*, 2008; 2010)

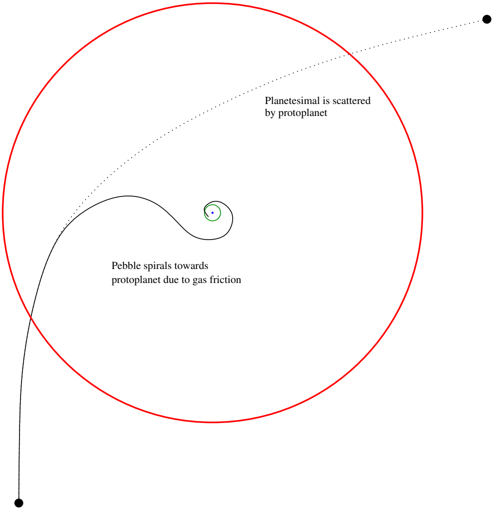


(*Kalas et al.*, 2008)

- HR 8799 (4 planets at 14.5, 24, 38, 68 AU)
- Fomalhaut (1 controversial planet at 113 AU)

⇒ No way to form the cores of these planets within the life-time of the protoplanetary gas disc *by standard core accretion*

Pebble accretion



- Most planetesimals are simply scattered by the protoplanet
- Pebbles spiral in towards the protoplanet due to gas friction

$\Rightarrow$ Pebbles are accreted from the entire Hill sphere

- Growth rate by planetesimal accretion is

$$\dot{M} = \alpha R_{\mathrm{H}}^2 F_{\mathrm{H}}$$

- Growth rate by pebble accretion is

$$\dot{M} = R_{\mathrm{H}}^2 F_{\mathrm{H}}$$

Relevant parameters for pebble accretion

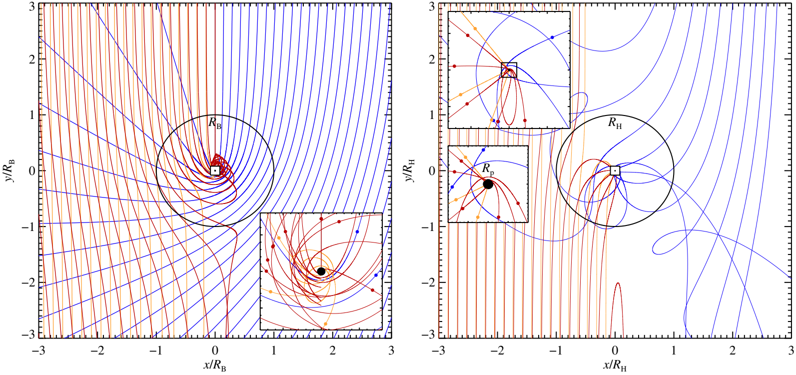
- Hill radius $R_{\rm H} = [GM_{\rm p}/(3\Omega^2)]^{1/3}$
  Distance over which the gravity of the protoplanet dominates over the the tidal force of the central star

- Bondi radius $R_{\rm B} = GM/(\Delta v)^2$
  Distance over which a particle with approach speed Δv is significantly deflected by the protoplanet (in absence of drag)

- Sub-Keplerian speed Δv
  Orbital speed of gas and pebbles relative to Keplerian speed

- Hill speed $v_{\rm H} = \Omega R_{\rm H}$
  Approach speed of gas and pebbles at the edge of the Hill sphere

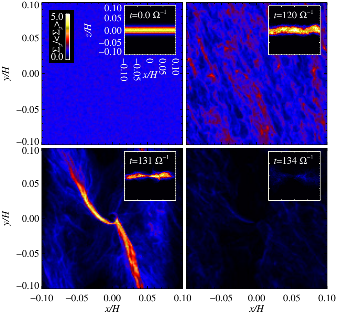
Pebble accretion regimes

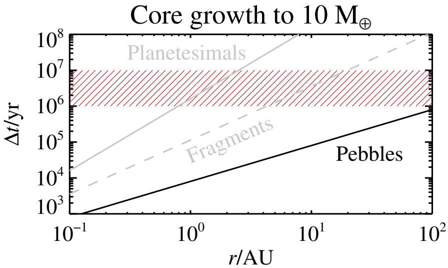


Two main pebble accretion regimes: (*Lambrechts & Johansen*, 2012)

1. Bondi regime (when $\Delta v \gg v_{\rm H}$)
   Particles pass the protoplanet with speed Δv, so $\dot{M} \propto R_{\rm B}^2 \propto M^2$
2. Hill regime (when $\Delta v \ll v_{\rm H}$)
   Particles enter protoplanet's Hill sphere with speed $v_{\rm H} \approx \Omega R_{\rm H}$, so $\dot{M} \propto R_{\rm H}^2 \propto M^{2/3}$

Time-scale of pebble accretion



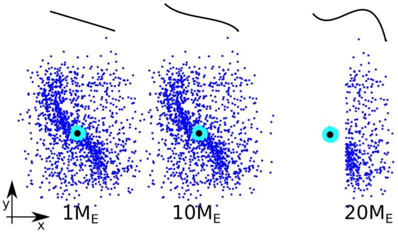


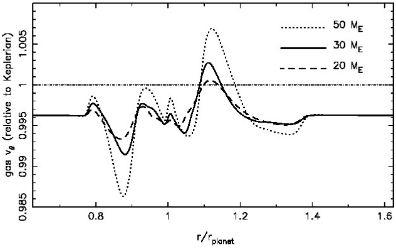
⇒ Pebble accretion speeds up core formation by a factor 1,000 at 5 AU and a factor 10,000 at 50 AU
(*Ormel & Klahr*, 2010; *Lambrechts & Johansen*, 2012; *Nesvorny & Morbidelli*, 2012)

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

- Requires large planetesimal seeds to accrete in Hill regime, consistent with planetesimal formation by gravitational collapse

Halting pebble accretion



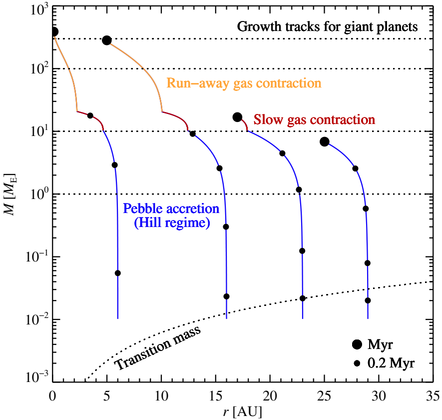


- Pebble accretion is stopped when the protoplanet grows massive enough to carve a gap in the pebble distribution
- Gap formation known for Jupiter-mass planets (*Paardekooper & Mellema*, 2006)
- *Lambrechts et al.* (2014) demonstrate that pebble accretion is stopped already at 20 $M_\oplus$ at 5 AU, with isolation mass scaling as

$$M_{\rm iso} = 20 \left(\frac{r}{5\mathrm{AU}}\right)^{3/4} M_\oplus$$

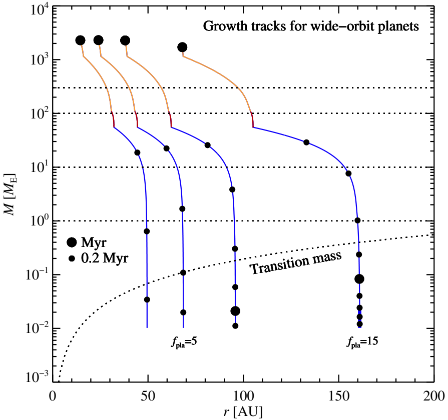
$\Rightarrow$ Collapse of the gas envelope

Growth tracks of giant planets



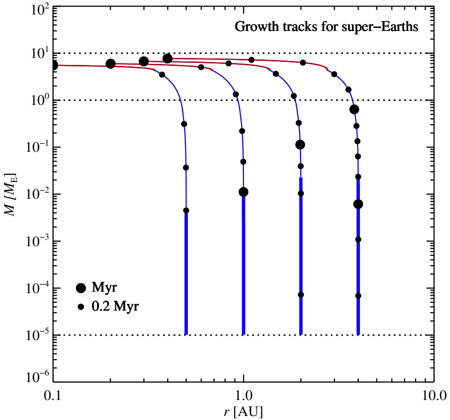
- Pebble accretion combined with planetary migration
  (*Johansen & Lambrechts*, 2017, Annual Review of Earth and Planetary Sciences)
- Giant planets undergo substantial migration
- Embryo at 6 AU forms hot Jupiter; Jupiter-analogue starts at 16 AU
- Ice giants are stranded by photoevaporation

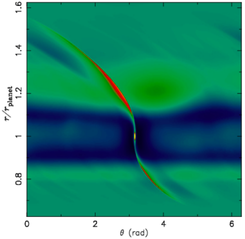
Growth tracks of wide-orbit planets



- Many wide-orbit exoplanet systems now, including HR 8799 (*Marois et al.*, 2008; 2010)
- Migration is very severe in wide orbits
- Three inner planets start at 50 – 100 AU
- The outer planet is challenging, even for pebble accretion

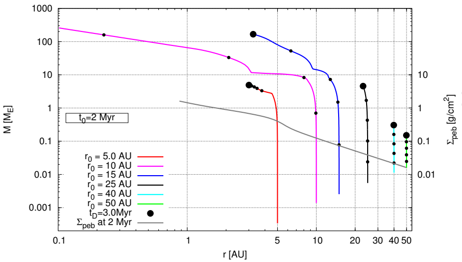
Growth tracks of super-Earths

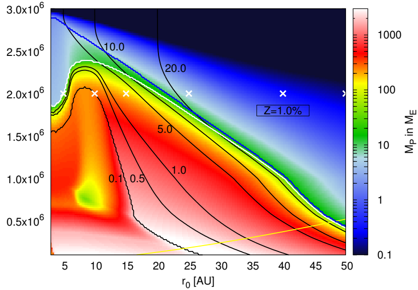




- The pebble isolation mass is around 5 M_{E} in the inner disc (*Lambrechts et al.*, 2014)
- Gas contraction is slow on small cores (*Piso & Youdin*, 2014; *Lee et al.*, 2014)
- Super-Earths are stuck in the slow gas contraction phase (*Ikoma & Hori*, 2012)
- Planetesimal accretion dominates growth to embryo sizes, then pebble accretion takes over

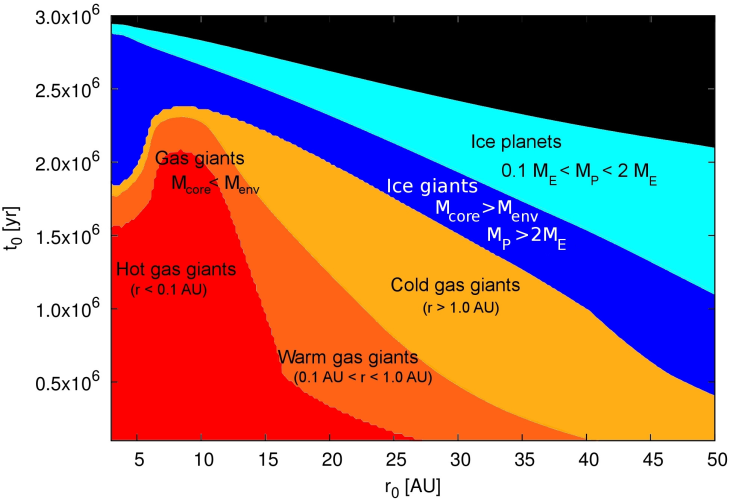
Planet formation in evolving protoplanetary disc





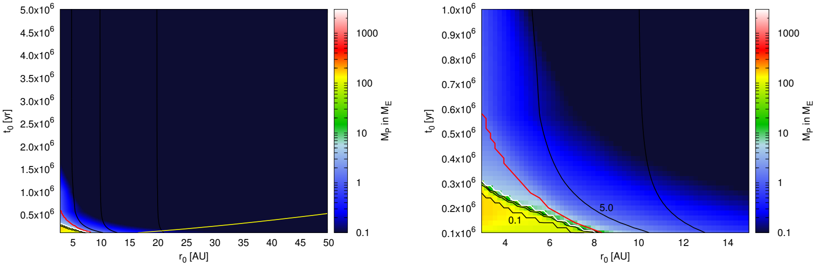
- Pebble accretion combined with protoplanetary disc evolution and planetary migration (*Bitsch, Lambrechts, & Johansen*, 2015)
- Jupiter analogue forms late (after 2 Myr) and far out (beyond 15 AU)
- Migrates into 3 AU orbit while growing to 300 M_{E}
- Growth tracks can be bundled into a growth map
- Early formed planets migrate to become hot and warm Jupiters
- Formation after 2 Myr yields a range of planetary classes

Emergence regions of planetary classes



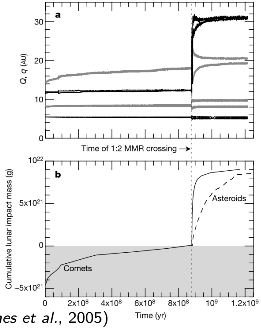
(*Bitsch et al.*, 2015)

Growth map with planetesimal accretion

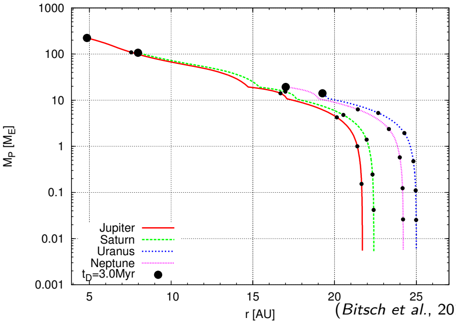


- Accretion of planetesimals can not form cores within 5 Myr, even if planetesimal surface density enhanced by factor 8
- Hard to form Jupiter at 5 AU due to the slow accretion rate and the high migration rate

Forming the Solar System



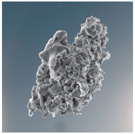
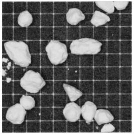
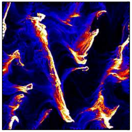
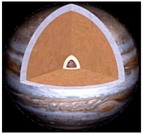
(*Gomes et al.*, 2005)



(*Bitsch et al.*, 2015)

- In the Nice model the giant planets orbit initially in a compact configuration
- Natural consequence of planetary migration combined with rapid pebble accretion
- Orbital architecture of the Nice model can be explained if the planetary embryos emerge after 1.5–2 Myr in initial orbits between 20 and 25 AU
- What happened to the embryos that formed closer to the Sun?

Summary

- Protoplanetary discs are really good pebble factories
- Rapid pebble accretion leads to the formation a wide range of planetary classes despite planetary migration
- Details depend on protoplanetary disc structure, pebble sizes, planetesimal birth masses, ...
- *N*-body approach important to form self-consistent planetary systems (*Levison et al.*, 2015, Nature)
- Some plots from "Forming Planets via Pebble Accretion" (*Johansen & Lambrechts*, Annual Review of Earth and Planetary Sciences, 2017)