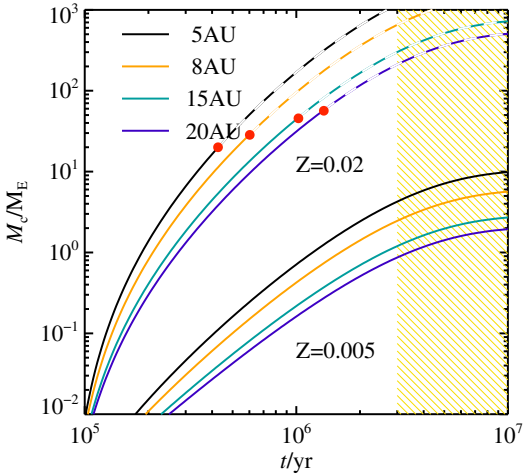
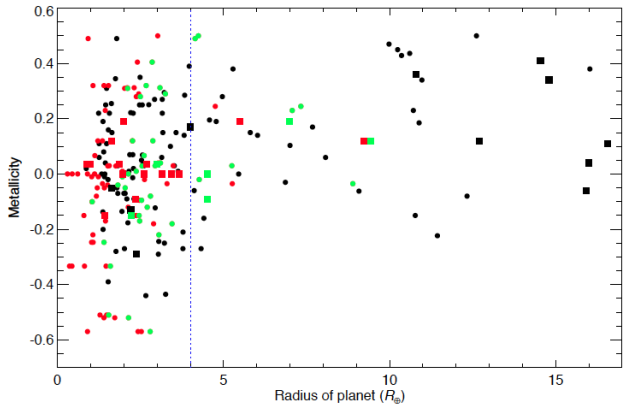
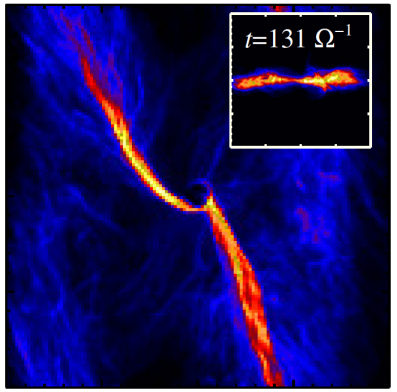
Planet formation with Gaia







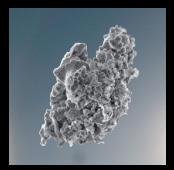
Anders Johansen

Lund University

"The Milky Way Unravelled by Gaia", Barcelona, December 2014

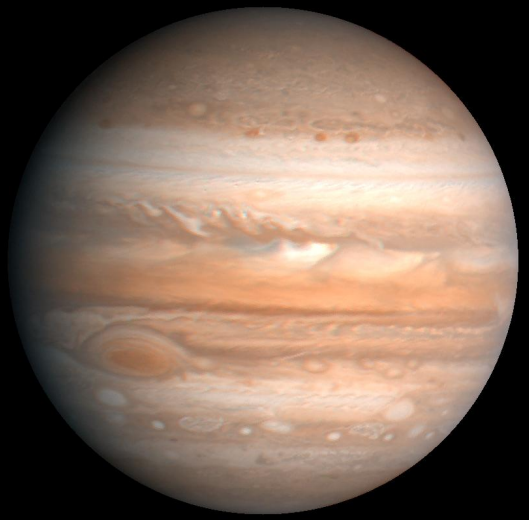
Observational view of planet formation

Protoplanetary discs

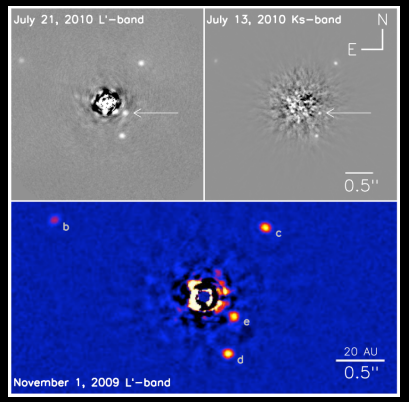


Dust grains

Pebbles



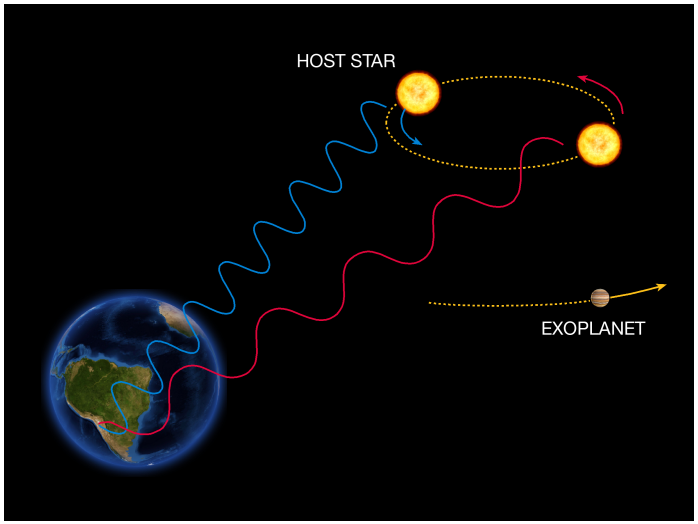
Gas giants and ice giants

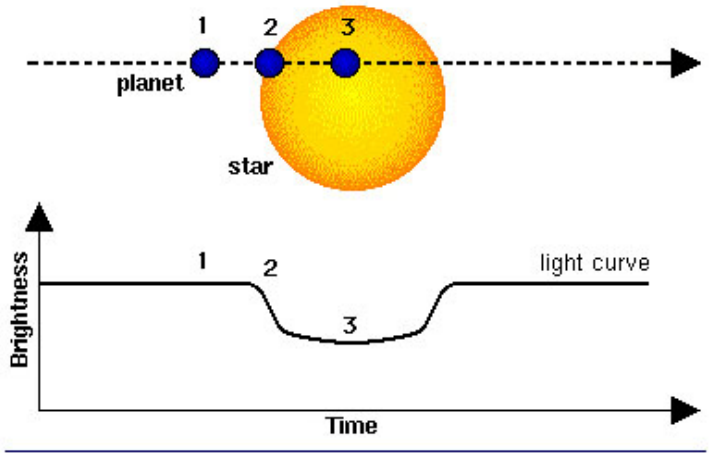


Terrestrial planets

Minor bodies

Detection of exoplanets

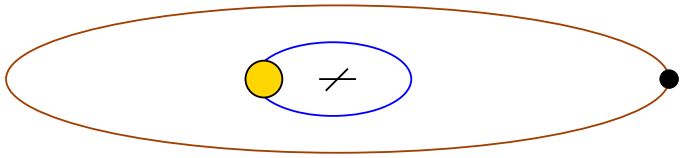




Exoplanets are mainly found via indirect methods where the presence of the planet is inferred from its effect on the host star:

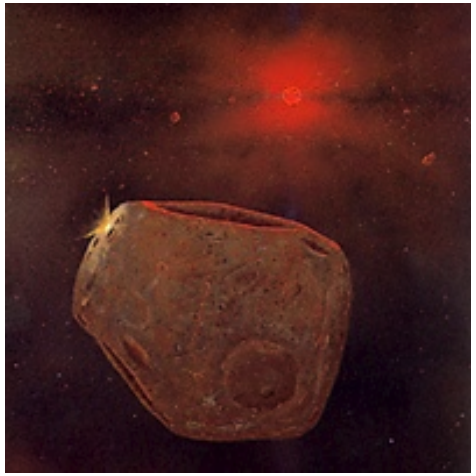
1. *Radial velocity method* (gives minimum mass)
2. *Transit method* (gives radius)

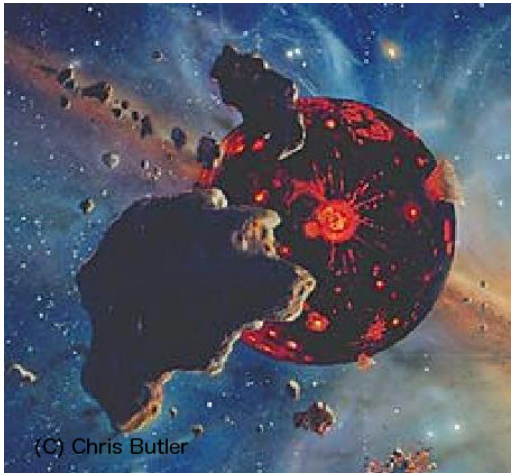
⇒ Today we know of several thousand exoplanets

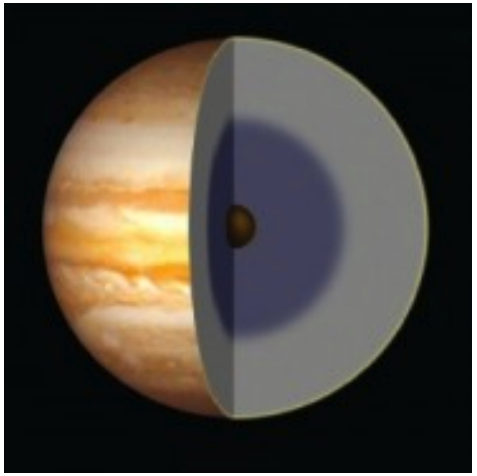


- *Gaia* will detect 10,000s of Jupiter-mass planets by *astrometry*
  (*Casertano et al.*, 2008; *Perryman et al.*, 2014)
- Sensitive out to 3 AU orbits in nominal 5-year mission

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 $M_{\rm env} \approx M_{\rm core}$
5. Form gas giant with $M_{\rm core} \approx 10 M_\oplus$ and $M_{\rm atm} \sim M_{\rm Jup}$

(*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:

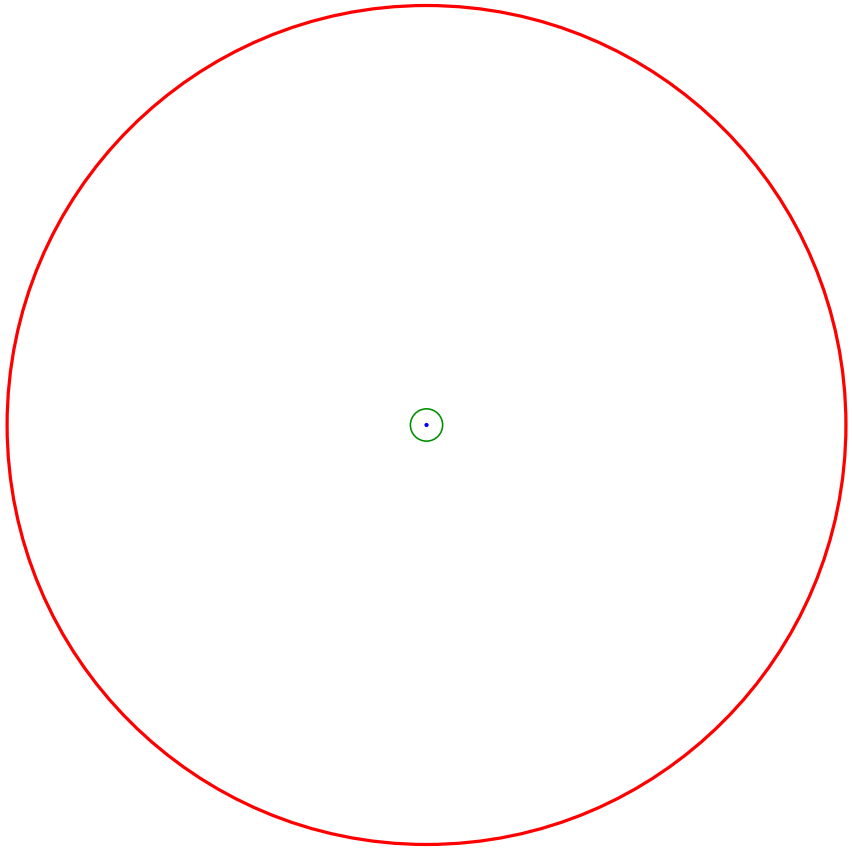
$$\frac{R_{\rm p}}{R_{\rm H}} \equiv \alpha \approx 0.001 \left(\frac{r}{5\,{\rm AU}}\right)^{-1}$$

- Maximal growth rate

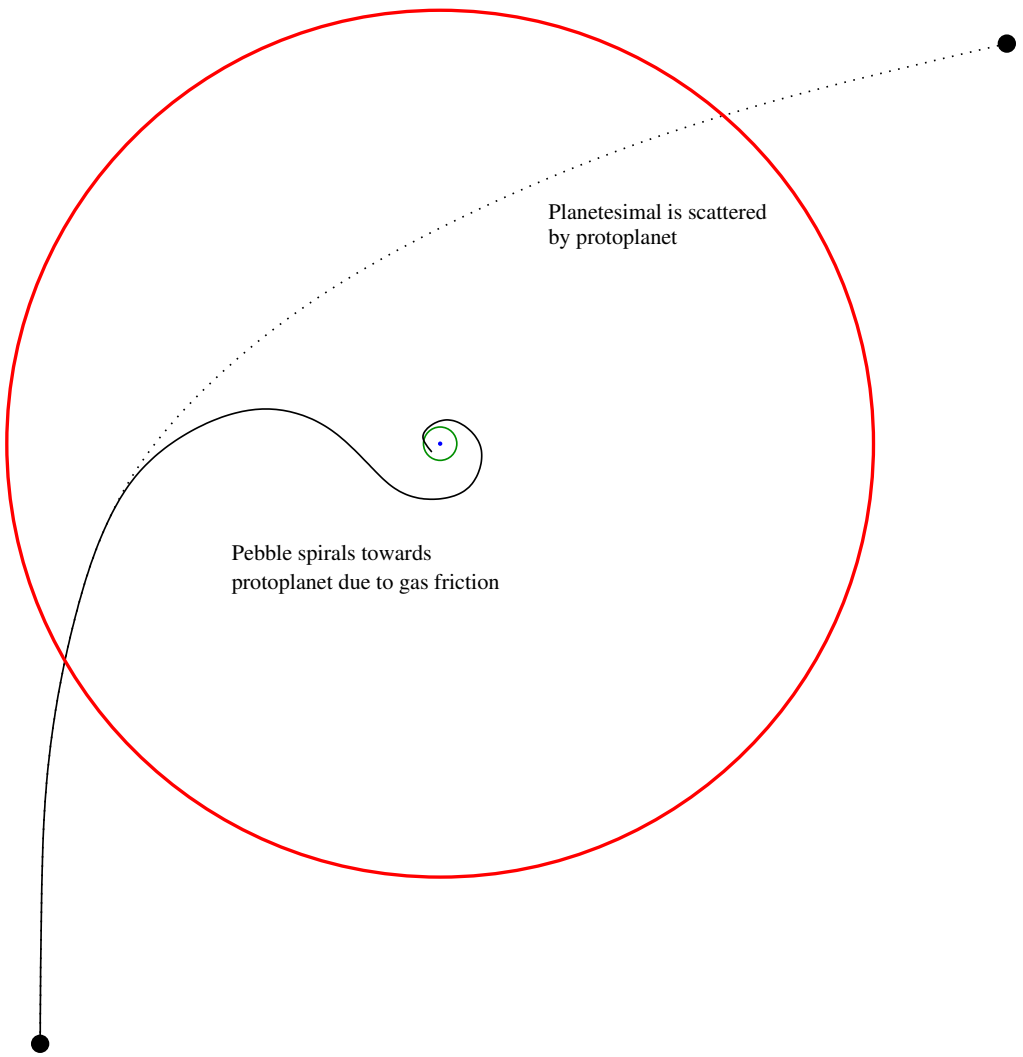
$$\dot{M} = \alpha R_{\rm H}^2 \mathcal{F}_{\rm H}$$

⇒ 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



Planetesimal accretion versus 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

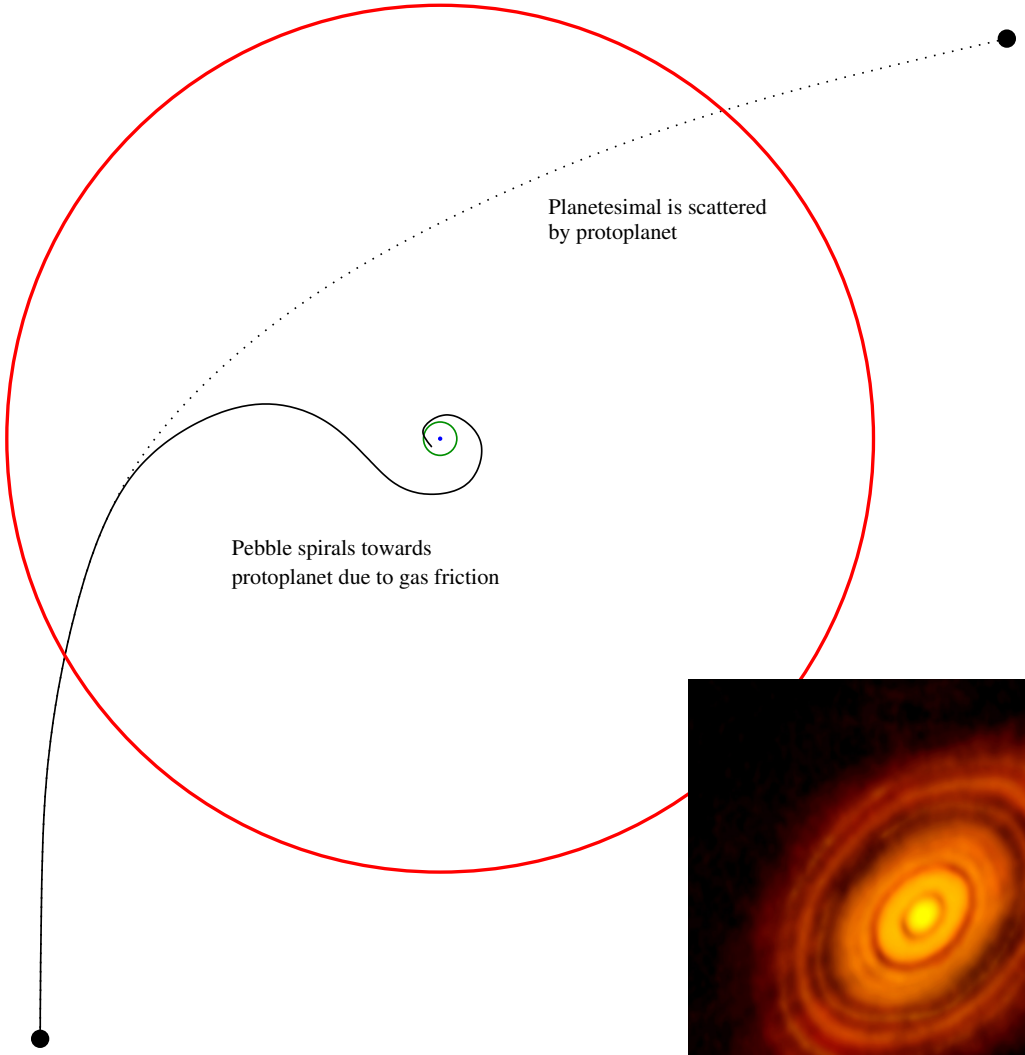
- Growth rate by planetesimal accretion is

$$\dot{M} = \alpha R_{\mathrm{H}}^2 \mathcal{F}_{\mathrm{H}}$$

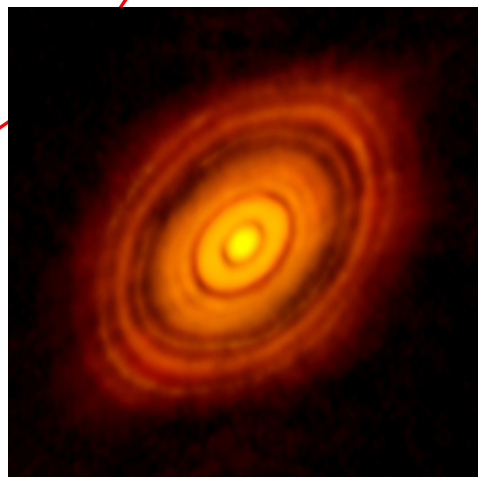
- Growth rate by pebble accretion is

$$\dot{M} = R_{\mathrm{H}}^2 \mathcal{F}_{\mathrm{H}}$$

Planetesimal accretion versus pebble accretion



Protoplanetary disks (like HL Tau) are pebble factories →



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⇒ Pebbles are accreted from the entire Hill sphere

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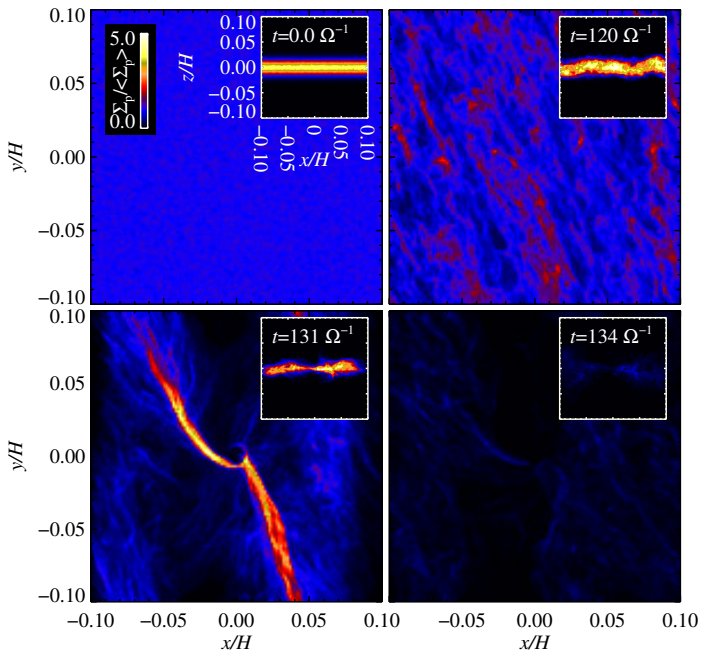
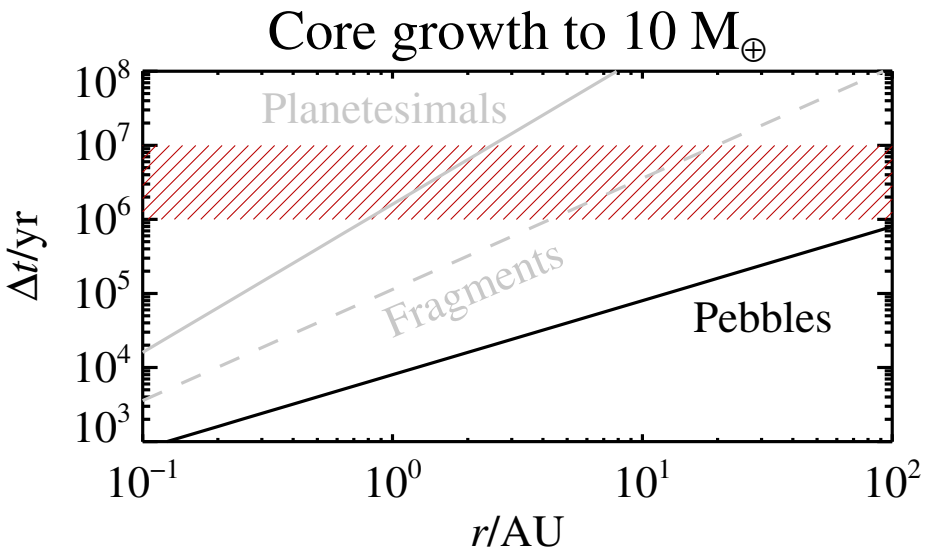
- Growth rate by pebble accretion is

$$\dot{M} = R_{\rm H}^2 \mathcal{F}_{\rm H}$$

Time-scale of pebble accretion



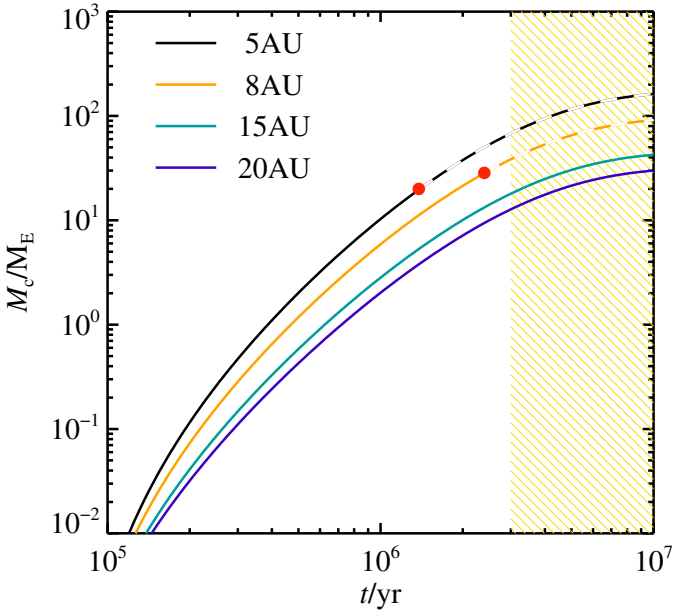


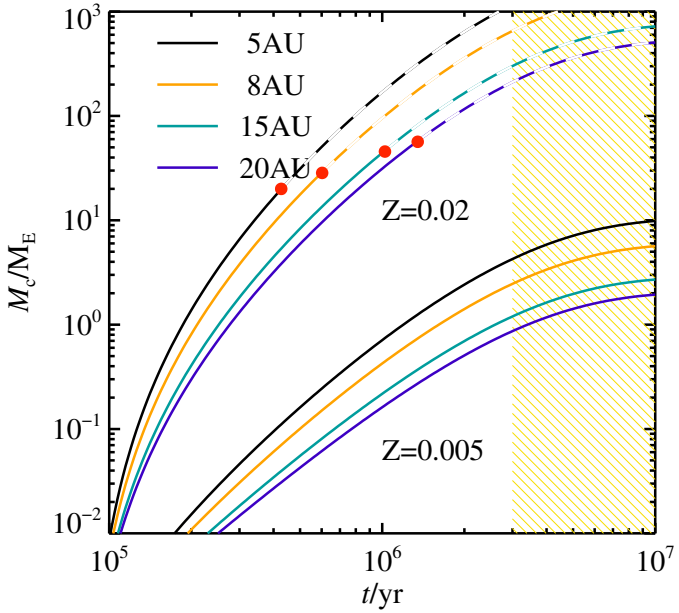
⇒ Pebble accretion speeds up core formation by a factor 1,000 at 5 AU and a factor 10,000 at 50 AU
(*Lambrechts & Johansen*, 2012; also *Ormel & Klahr*, 2010; *Morbidelli & Nesvorny*, 2012)

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

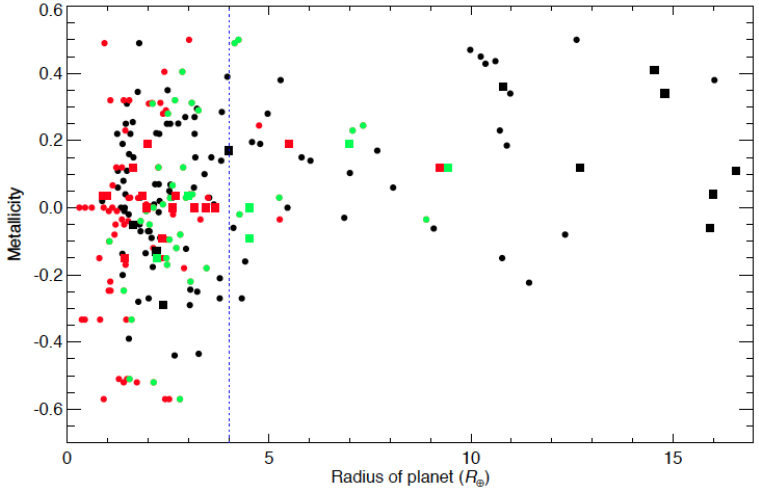
⇒ Population synthesis with pebble accretion

Planetary systems



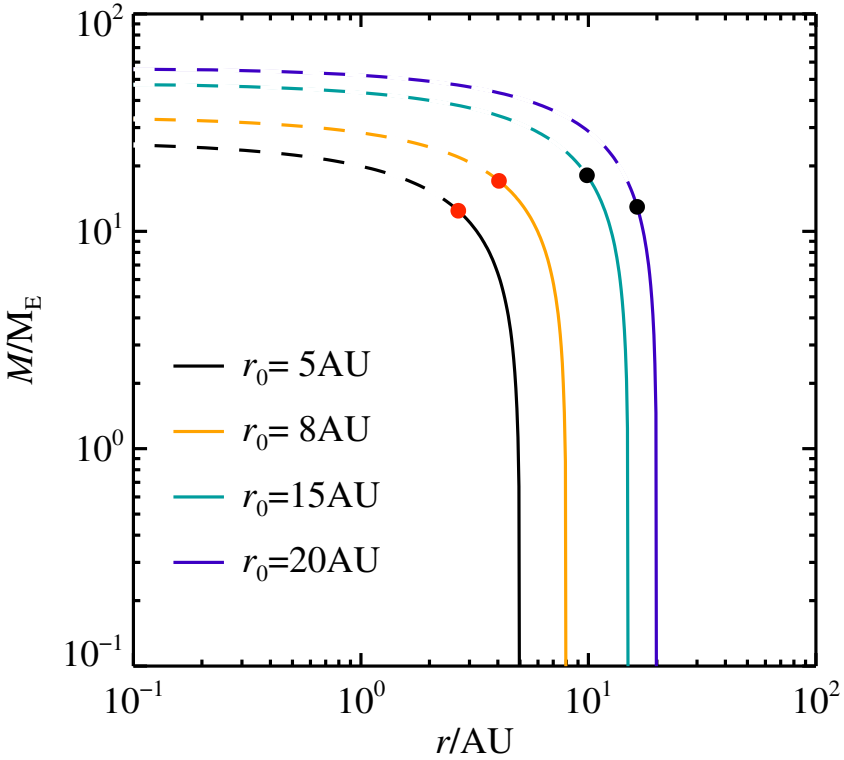


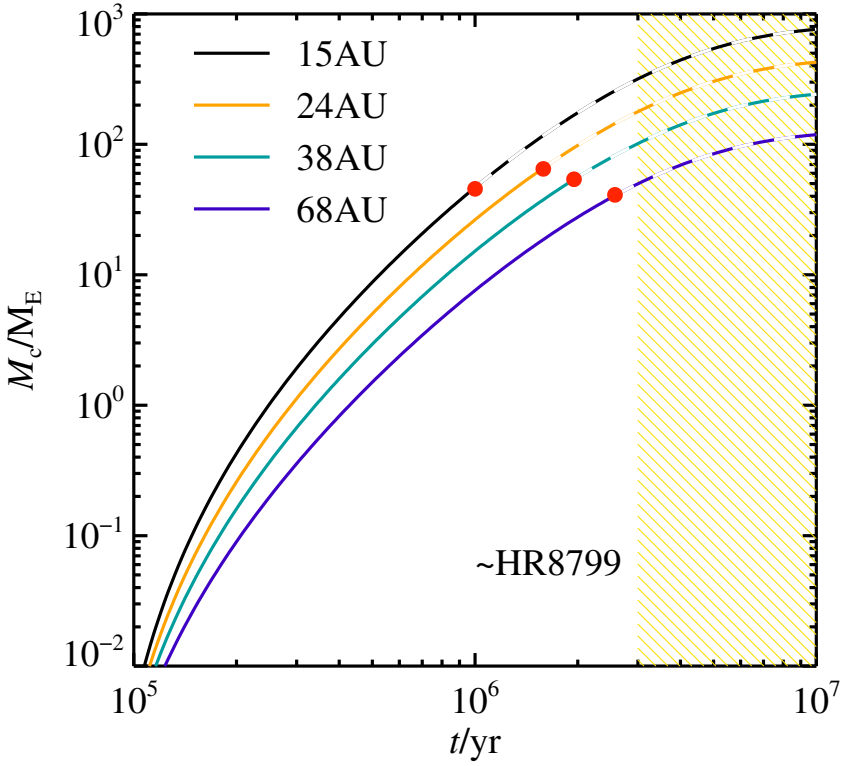
- Protoplanets grow to planets by pebble accretion over 1–3 Myr (*Lambrechts & Johansen*, 2012; *Ormel & Klahr*, 2010; *Lambrechts, Johansen, & Morbidelli*, 2014)
- Growth depends strongly on the amount of heavy elements in the protoplanetary disc ($Z = 0.01$ in the Sun's photosphere) (*Lambrechts & Johansen*, 2014)
- Gas-giant planets like Jupiter form if Z is high, in agreement with exoplanet surveys



(*Buchhave, Latham, Johansen, et al.*, 2012, *Nature*)

Migration and wide-orbit planets



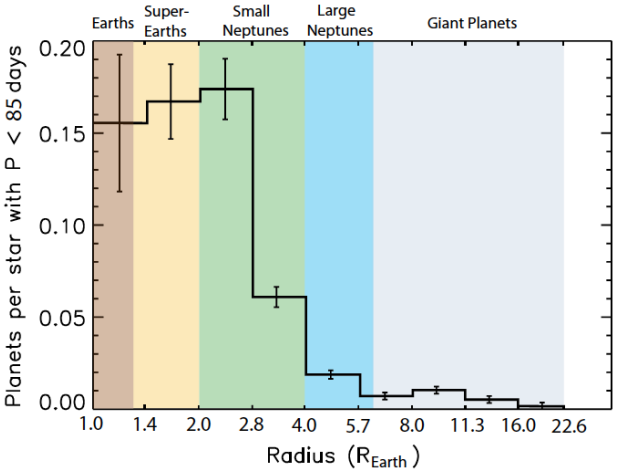


- Planets migrate towards the star due to gravitational torques from gas disc
- Type I migration becomes much less severe if growth rate is high

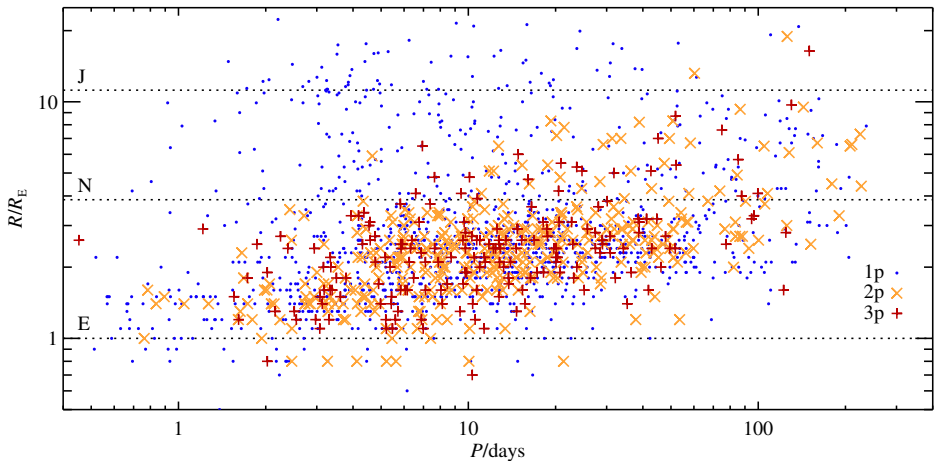
⇒ Cores starting at 5 and 8 AU grow to gas giants at 2 and 3 AU

- Direct imaging has revealed several wide-orbit planetary companions to young stars
- HR 8799 has gas-giant planets at 15, 24, 38 and 68 AU
- The critical core mass is 50 M_E at large orbital distances

Results from *Kepler* satellite

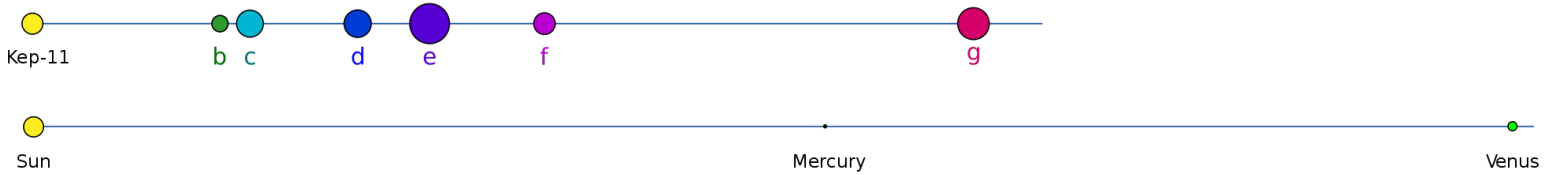


(*Fressin et al.*, 2013)



(*Johansen et al.*, 2012)

- Results from *Kepler* satellite show that solar-type stars are very often orbited by super-Earths in close orbits



- Systems of super-Earths are flat to within a few degrees
  (*Lissauer et al.*, 2011; *Tremaine & Dong*, 2012; *Johansen et al.*, 2012)
- Super-Earths are rarely accompanied by giant planets

How do gas giants affect the formation of super-Earths?

- Super-Earths in close orbits are rarely accompanied by giant planets
- Possible that the formation or migration of the gas giant prevents the accumulation of further planets

⇒ Formation of small planets and large planets is coupled

⇒ Knowing 10,000 gas-giant planets in 1-3 AU orbits from *Gaia* could tell lots about the conditions for forming smaller planets