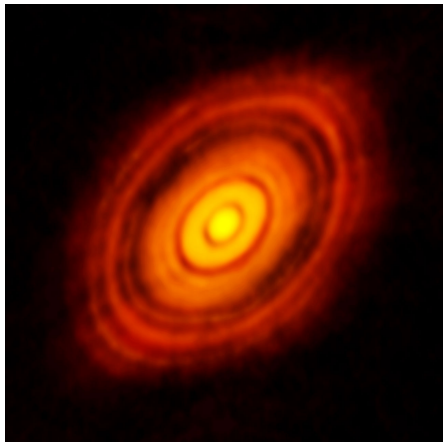
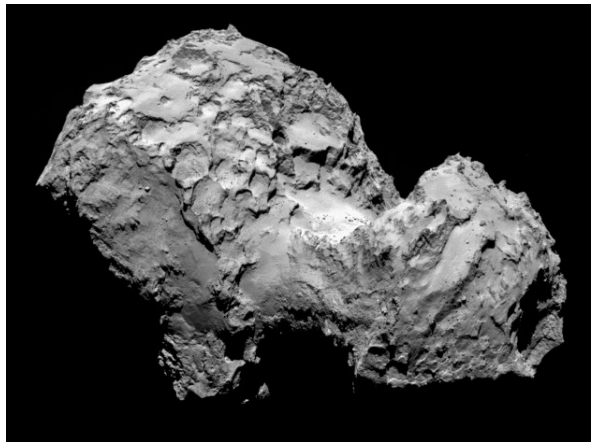
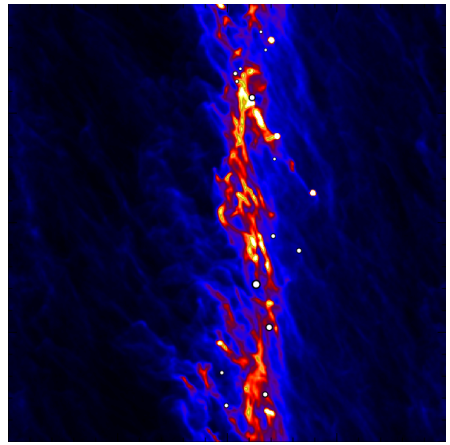
Forming volatile-rich planetesimals

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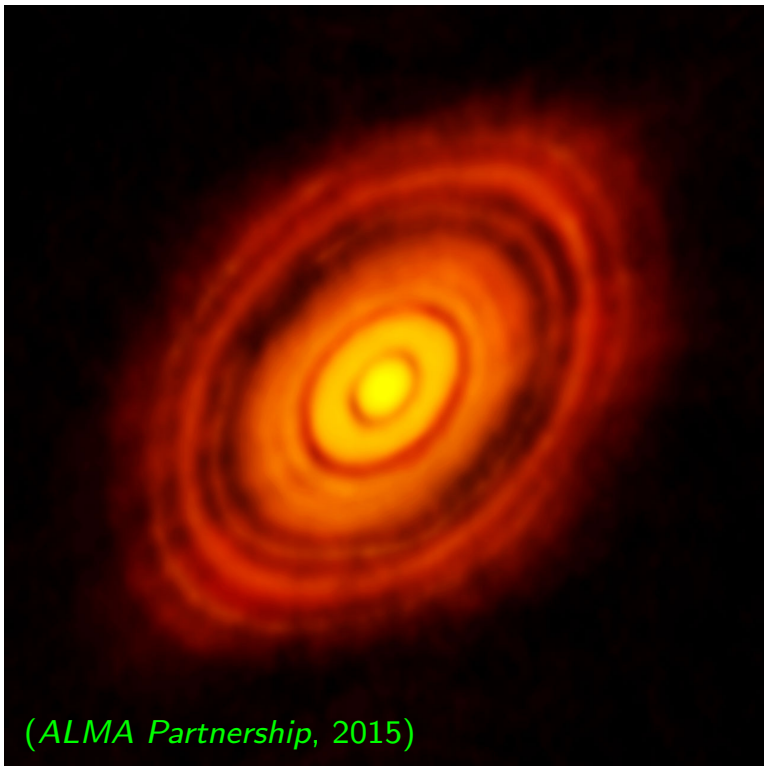
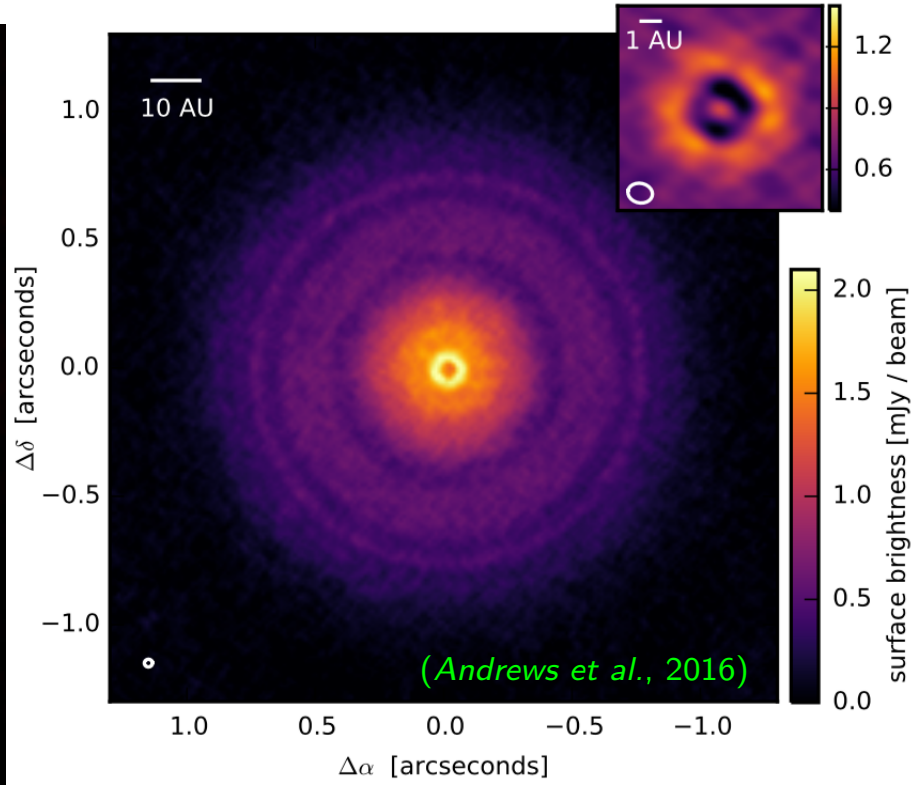
Lund Observatory, Lund University

51st ESLAB Symposium "Extreme Habitable Worlds"
Noordwijk, December 2017

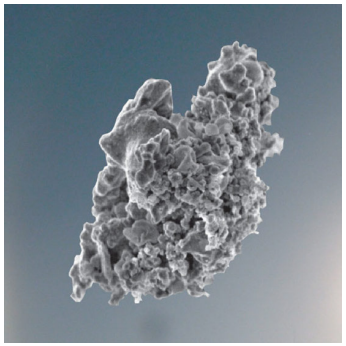
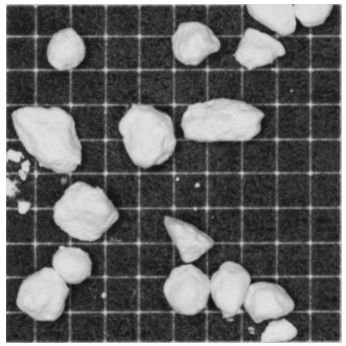
Two protoplanetary discs

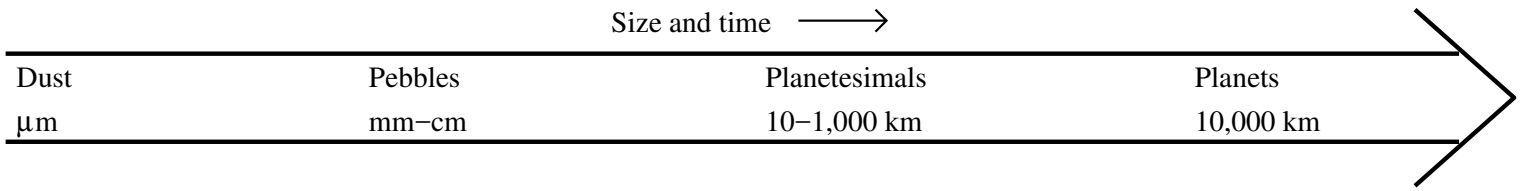




- Two ALMA images of protoplanetary discs
- HL Tau is 140 pc away, $\sim$1 million years old
- TW Hydrae is 54 pc away, $\sim$10 million years old
- Emission comes mainly from its the 1% mass in mm-sized pebbles
- Pebbles are formed by collisions between micron-sized dust grains
- Protoplanetary discs live for a few million years

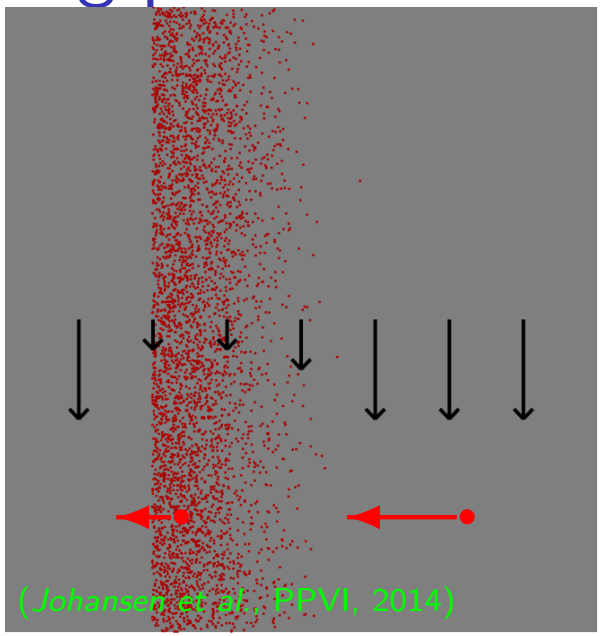
From dust to habitable planet

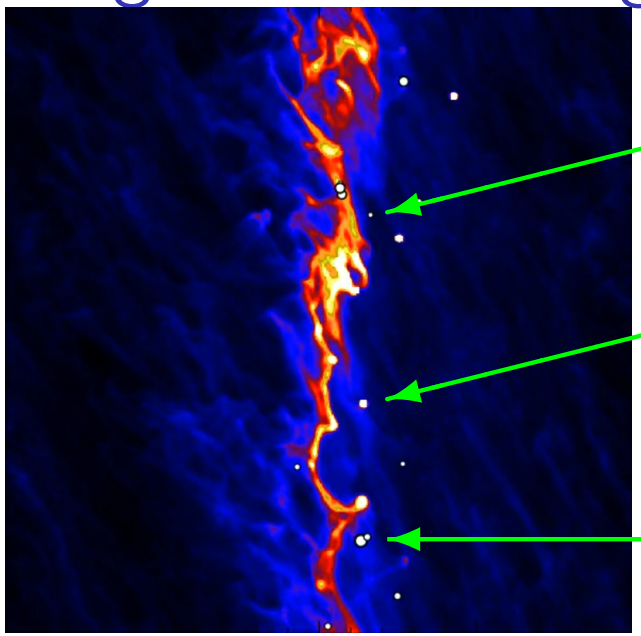



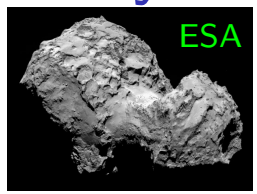


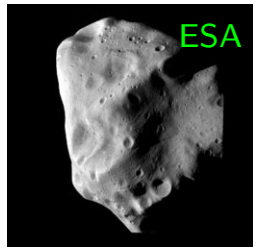
- Dust and ice in protoplanetary discs coagulate to form mm-cm-sized pebbles
- Pebbles gather to form km-scale planetesimals
- The cores of giant planets accrete rapidly by accretion of pebbles and planetesimals
- Terrestrial planets form by slow accumulation of dry planetesimals
- Life-essential molecules are delivered by planetesimals from the cold regions beyond the water ice line

Forming planetesimals through the streaming instability









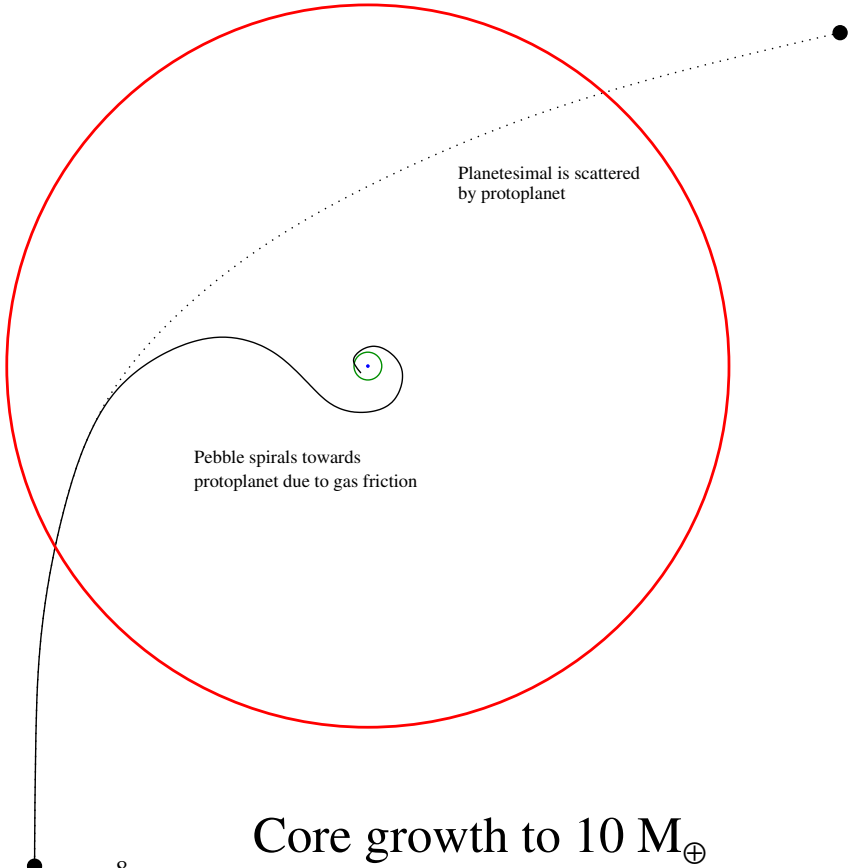
- Dense pebble filaments emerge through the streaming instability
  (*Youdin & Goodman*, ApJ, 2005; *Johansen et al.*, 2007; *Bai & Stone*, ApJ, 2010)
- Filaments collapse by gravity to form planetesimals with sizes from 10 km to several 100 km (*Johansen et al.*, 2015; *Simon et al.*, ApJ, 2016)
- Most mass in 100-km-scale planetesimals, as in asteroid belt
- Small bodies like comet 67P/Churyumov-Gerasimenko are piles of primordial pebbles, as observed for 67P
  (*Wahlberg Jansson & Johansen*, 2014; *Poulet et al.*, MNRAS, 2016)
- Many planetesimals form as binaries, similar to those observed in the Kuiper belt beyond Neptune (*Noll et al.*, Icarus, 2008) – perhaps also MU69

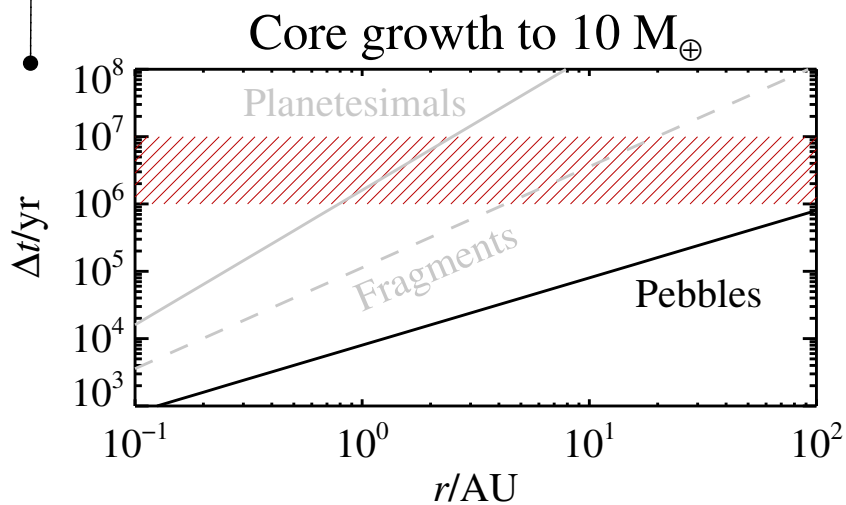
Pebble accretion

- Hill radius marks the region of gravitational influence of a growing protoplanet
- Most planetesimals that enter the Hill sphere of a protoplanet are simply scattered – less than 0.1% are accreted
- Pebbles spiral in towards the protoplanet due to gas friction

$\Rightarrow$ Very high pebble accretion rates

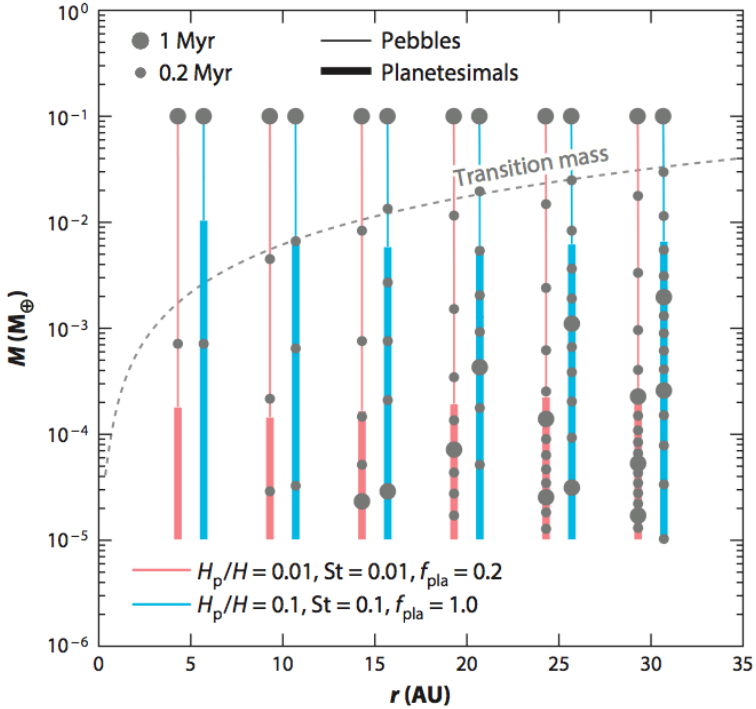
$\Rightarrow$ Possible to form solid cores of 10 Earth masses before the gaseous protoplanetary disc is accreted after a few million years

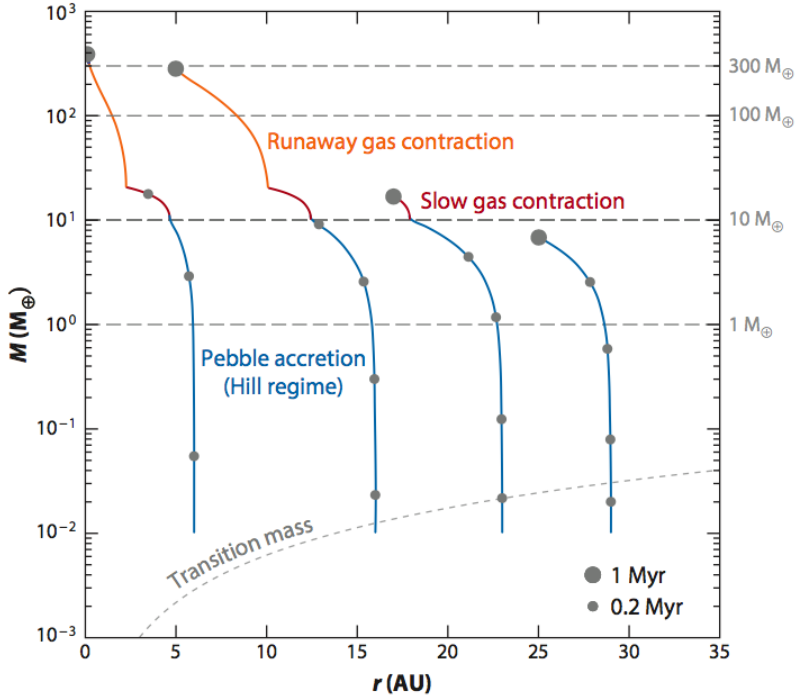




(*Johansen & Lacerda*, MNRAS, 2010; *Ormel & Klahr*, A&A, 2010; *Lambrechts & Johansen*, A&A, 2012)

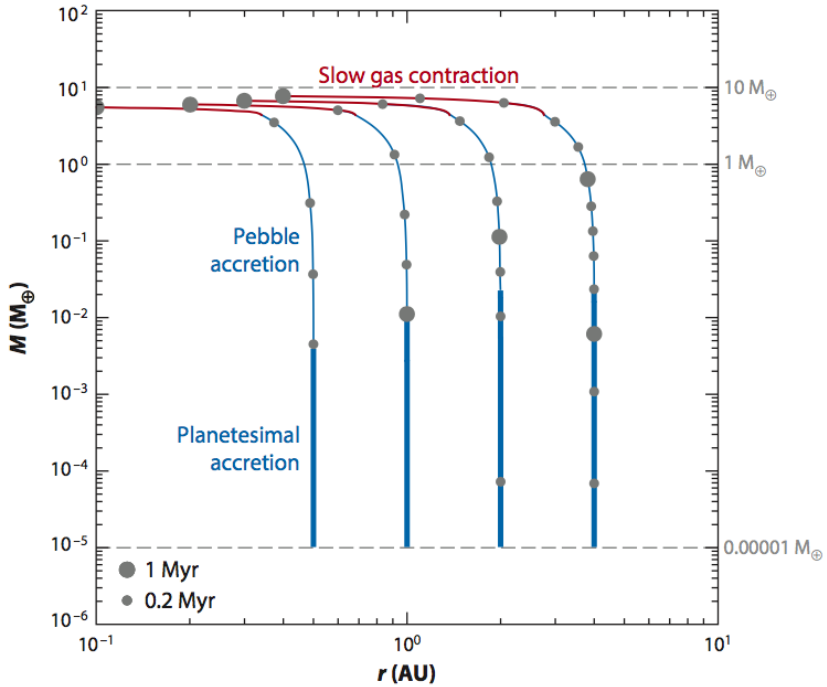
Planetary growth tracks





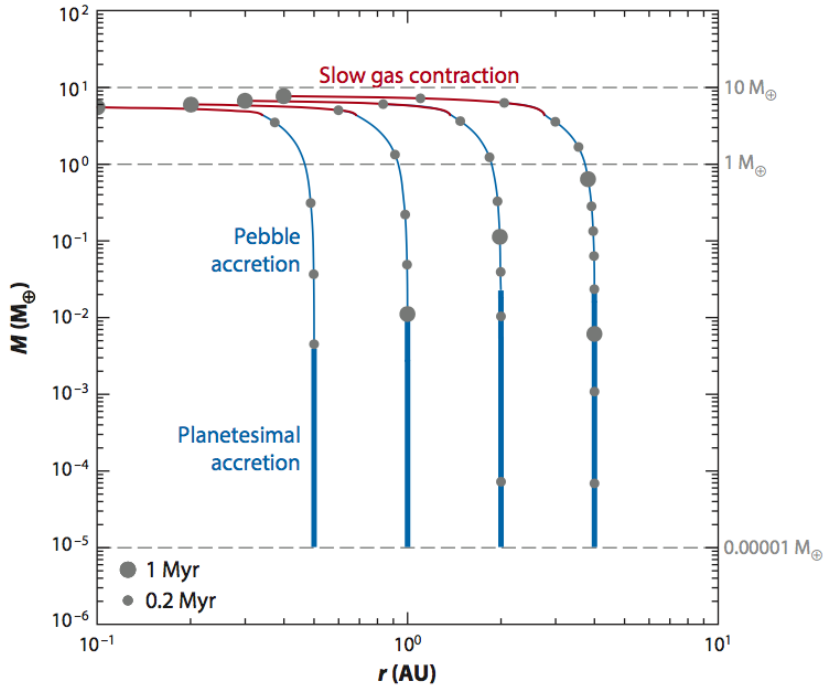
- Rapid pebble accretion can explain how planets remain in the protoplanetary disc despite planetary migration
  (*Bitsch, Lambrechts, & Johansen*, 2015; *Bitsch & Johansen*, 2016; *Johansen & Lambrechts*, 2017)
- Initial growth driven by accretion of planetesimals and pebbles, but pebble accretion dominant 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

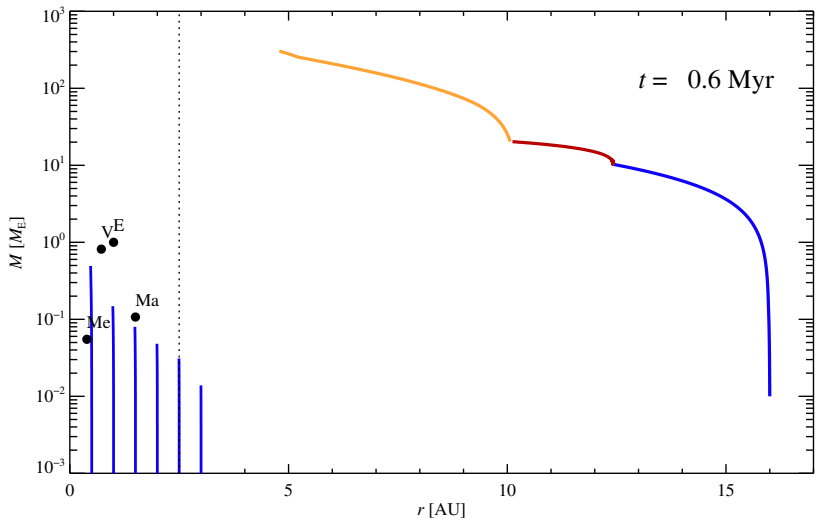
Forming terrestrial planets or super-Earths



- Growth tracks of planets in the inner disc (*Bitsch & Johansen*, 2016)
- Planetesimal accretion dominates until Moon-mass protoplanets
- Protoplanets grow to form super-Earths with gaseous envelopes
- Did the formation of Jupiter block the infall of pebbles? (*Morbidelli et al.*, 2016)
- A single giant impact with an icy protoplanet could have delivered all the Earth's budget of water, carbon and nitrogen (*Marty*, 2012)

Forming terrestrial planets or super-Earths





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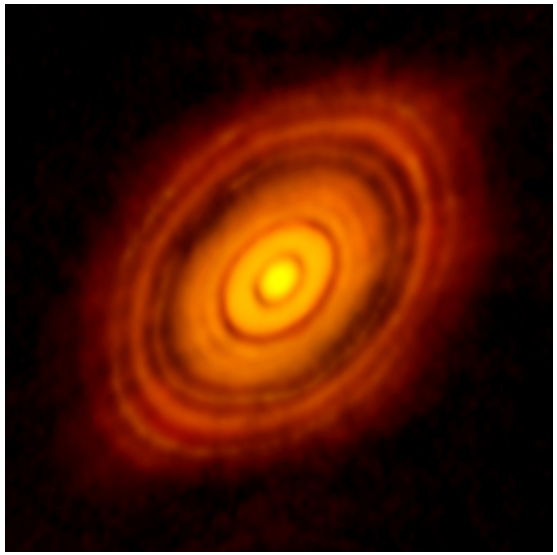
Forming habitable planets



- Physical mechanisms relevant for planet formation in protoplanetary discs are understood better and better
- Solid planets and planetary cores grow by accretion of planetesimals and pebbles
- Super-Earths, ice giants and gas giants accrete gas from the protoplanetary disc
- The formation of *planetary systems* is still poorly understood
- Perhaps the formation of a gas giant planet determines whether the inner planetary system forms super-Earths or terrestrial planets
- How does volatile delivery occur in different planetary system architectures?