Accretion Discs and Planet Formation

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Overview of the lectures

- Lecture 1
  - (Exo)planets
  - Protoplanetary discs
  - Protoplanetary discs as accretion discs
  - Evolution of dust in protoplanetary discs
- Lecture 2
  - Dust growth
  - Planetesimal formation
  - Formation of planet cores
  - Accretion of planet envelopes
  - How do (exo)planets form?

Recap of Lecture 1

- Planets around other stars are numerous and diverse
- Planets form in discs of gas and dust surrounding newly-born stars
- These protoplanetary discs last a few million years, and during that time they accrete onto the star
- Protoplanetary discs are likely turbulent, which may or may not be driving accretion onto the star
- Evolution of dust is driven by gas drag
- Dust grains settle vertically and migrate radially in the disc

Planet formation

Stages of planet formation

sub-µm-sized dust grains inherited from ISM → cm-sized dust grains → km-sized planetesimals → 1000 km-sized protoplanets → planet cores → fully-grown planets with atmospheres

Dust growth

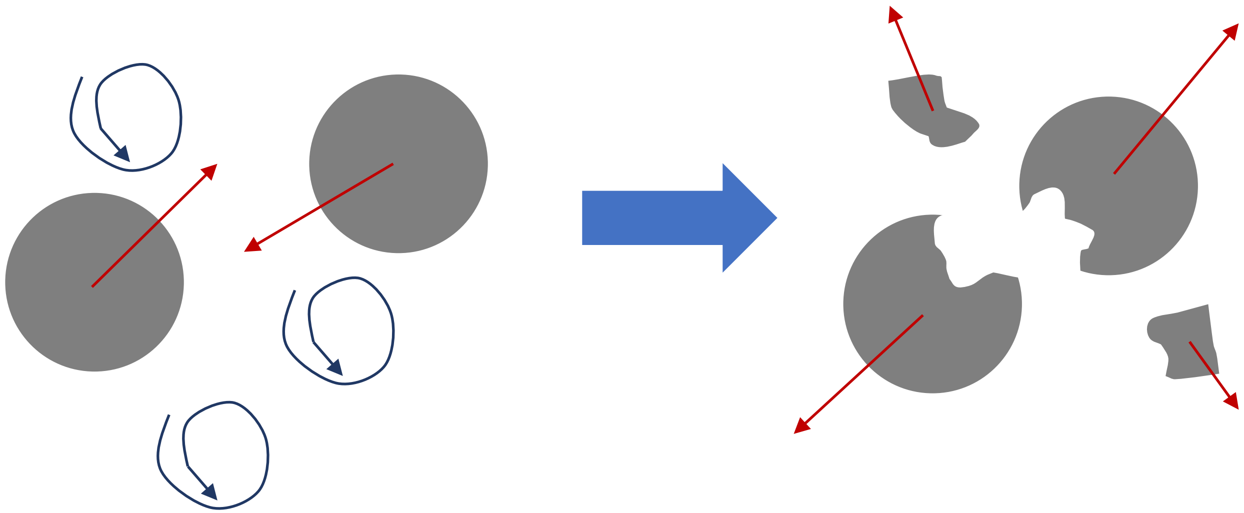
- Collision velocities due to: Brownian motion, turbulence, difference in settling & radial drift velocities

- Collision outcomes: sticking, bouncing, fragmentation

- Mathematically described by the coagulation equation

$$\frac{dn_k}{dt} = \frac{1}{2}\sum_{ij} A_{ij} n_i n_j - n_k \sum_i A_{ik} n_i$$

Fragmentation limits growth beyond cm-sizes



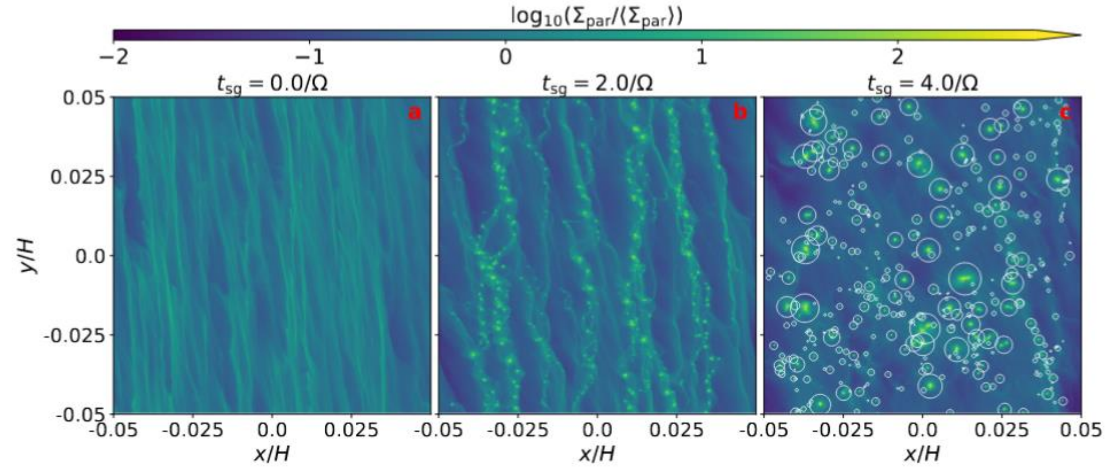
So how do cm-sized dust grains grow into larger bodies?

Planetesimal formation

- When dust becomes dynamically important, under certain conditions…

Planetesimal formation

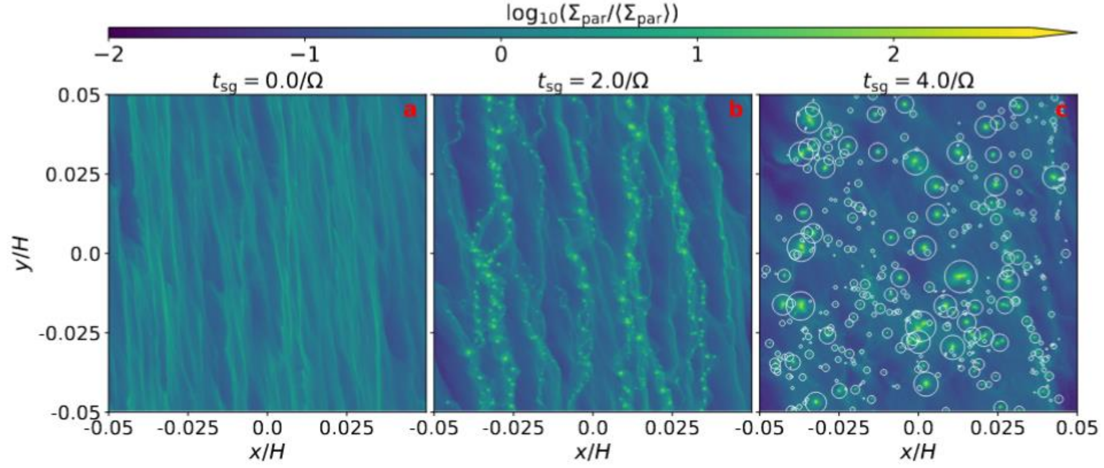
- When dust becomes dynamically important, under certain conditions…
- Streaming instabilities produce dust clumps



Nesvorny et al. (2019)

Planetesimal formation

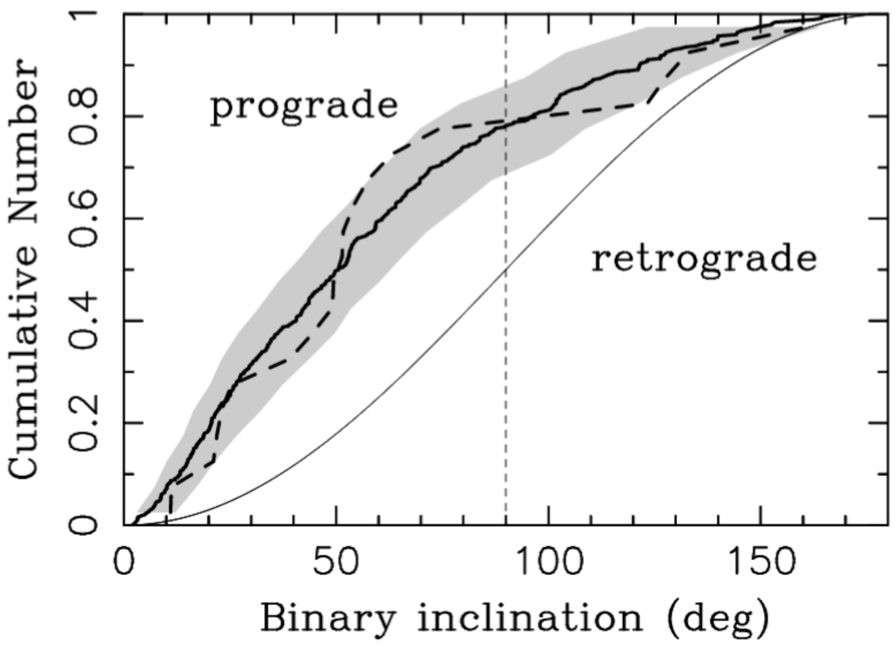
- When dust becomes dynamically important, under certain conditions…
- Streaming instabilities produce dust clumps
- Gravitational collapse if clumps dense enough



Nesvorny et al. (2019)

Planetesimal formation

- There is evidence for the SI + GI planetesimal formation in the Solar system.



Nesvorny et al. (2019)

Formation of planet cores: planetesimal-driven growth

- Once km-sized planetesimals are formed, things get easier
  - Objects held together by gravity - material strength unimportant
  - Mutual gravitational interactions become important

Formation of planet cores: planetesimal-driven growth

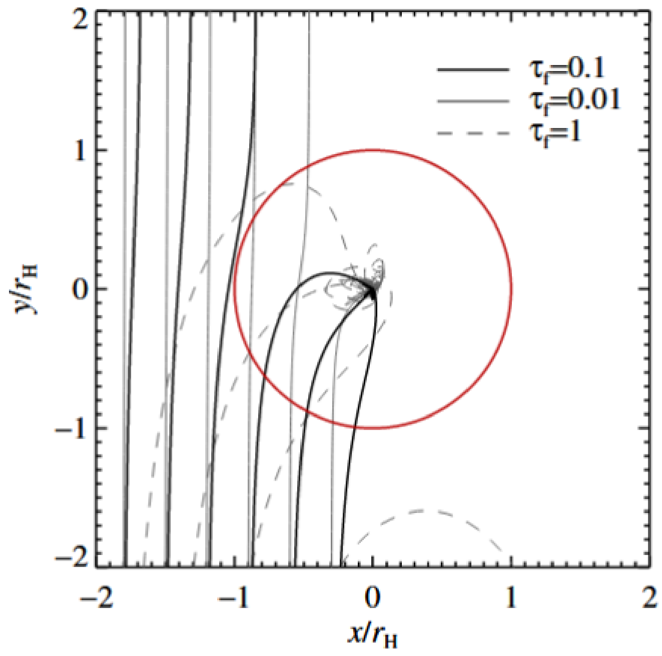
- Size evolution and velocity evolution are coupled
  - Collision cross-sections depend on velocities
  - Velocity evolution depends on mass distribution

$$\frac{dn_k}{dt} = \frac{1}{2}\sum_{ij} A_{ij} n_i n_j - n_k \sum_i A_{ik} n_i$$

$$\frac{dv_k}{dt} = B_{vs} + B_{df} + B_{ic} + B_{gd}$$

Formation of planet cores: pebble accretion

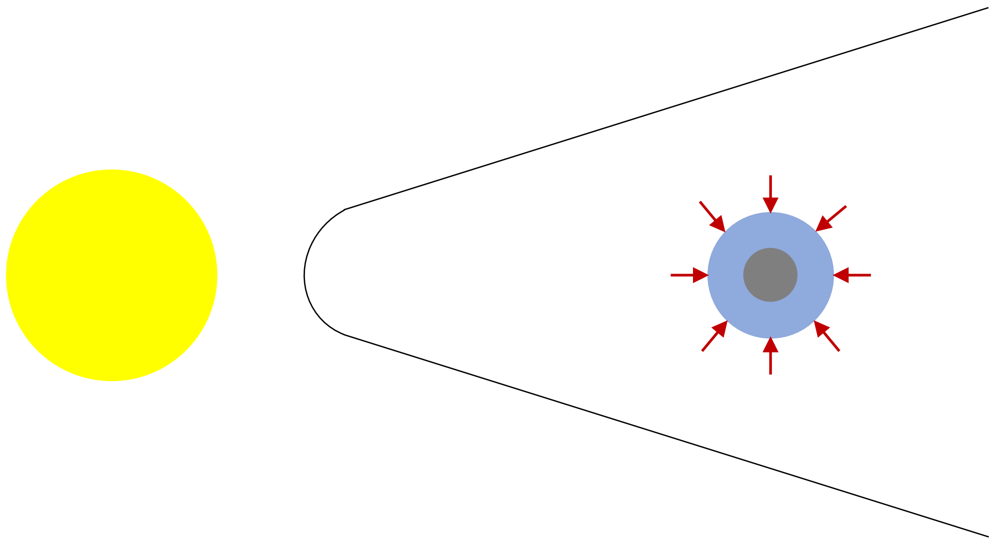
- Pebble accretion is assisted by gas drag, and under some conditions more mass can be accreted through accretion of pebbles than through accretion of planetesimals.



Lambrechts & Johansen (2012)

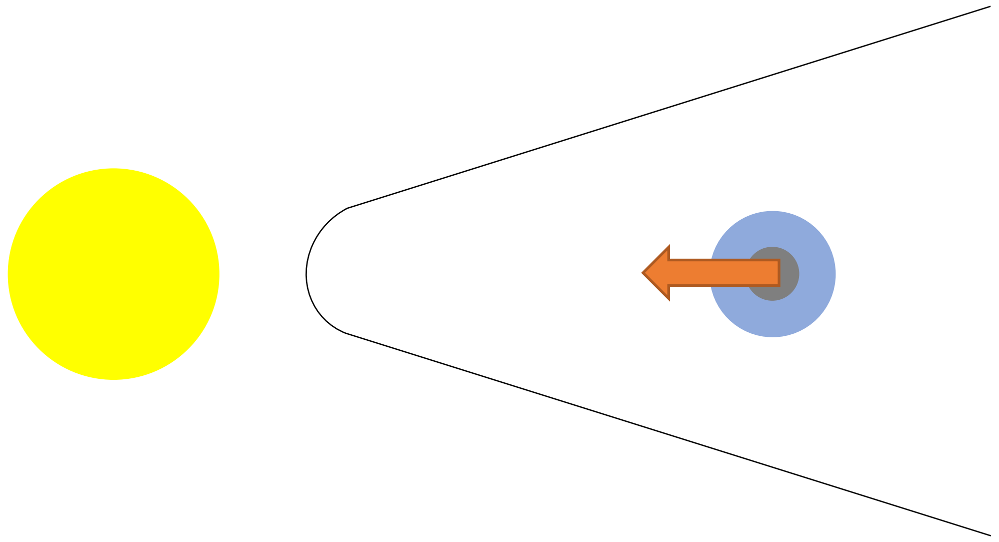
Accretion of gaseous envelopes

- Solid planet cores accrete gas from the protoplanetary disc, while continuing to accrete planetesimals and pebbles
- *Hydrostatic growth*
- *Runaway growth*
- Accretion ends when surrounding gas disperses

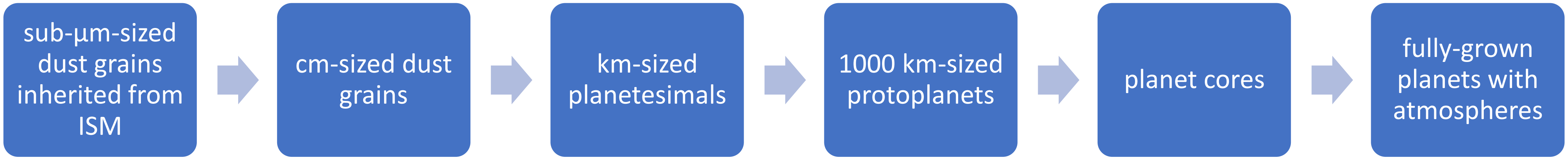


Planets move in discs

- and may also open gaps in the disc
- This is due to gravitational interaction between a planet and the disc

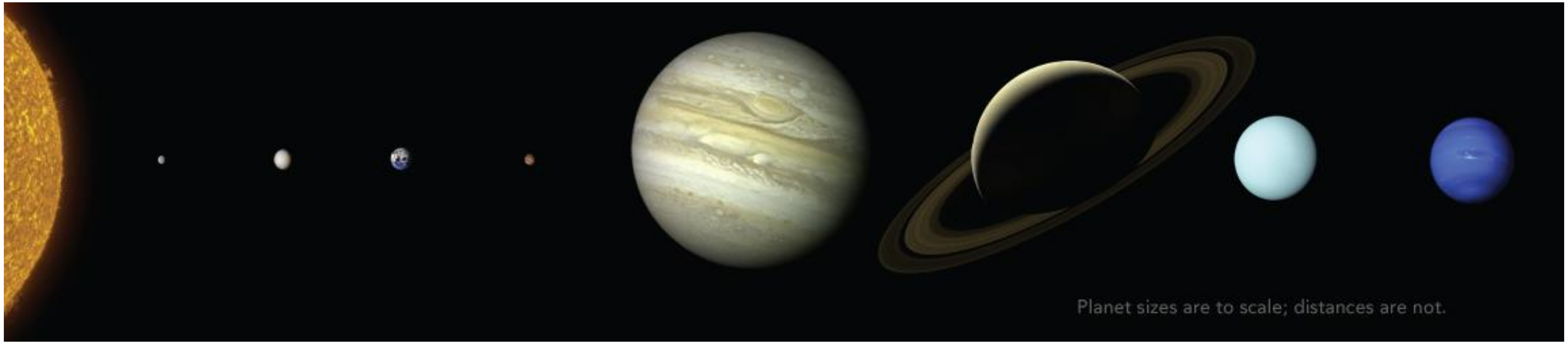


Stages of planet formation

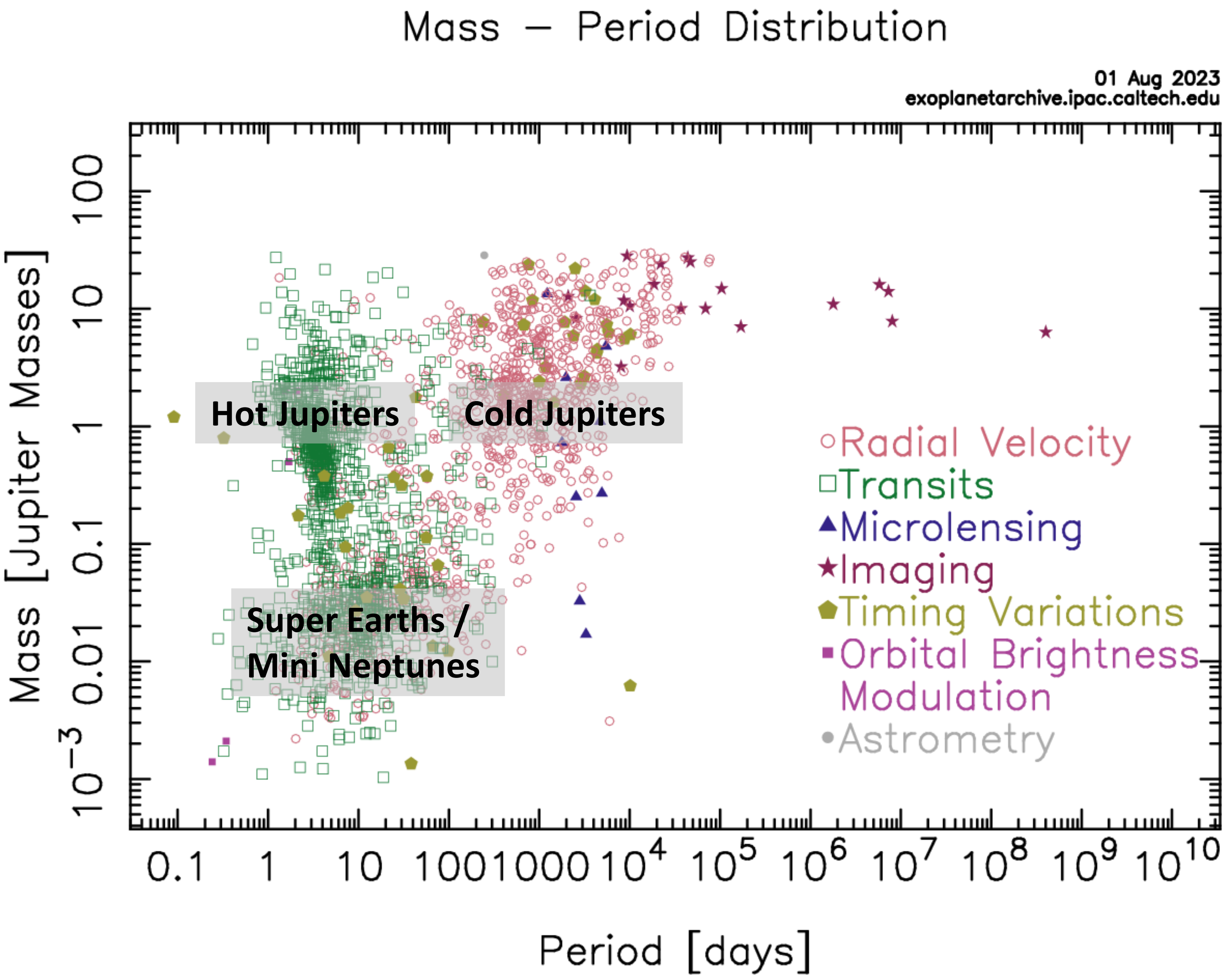


So how did planets we observe form?

Solar system

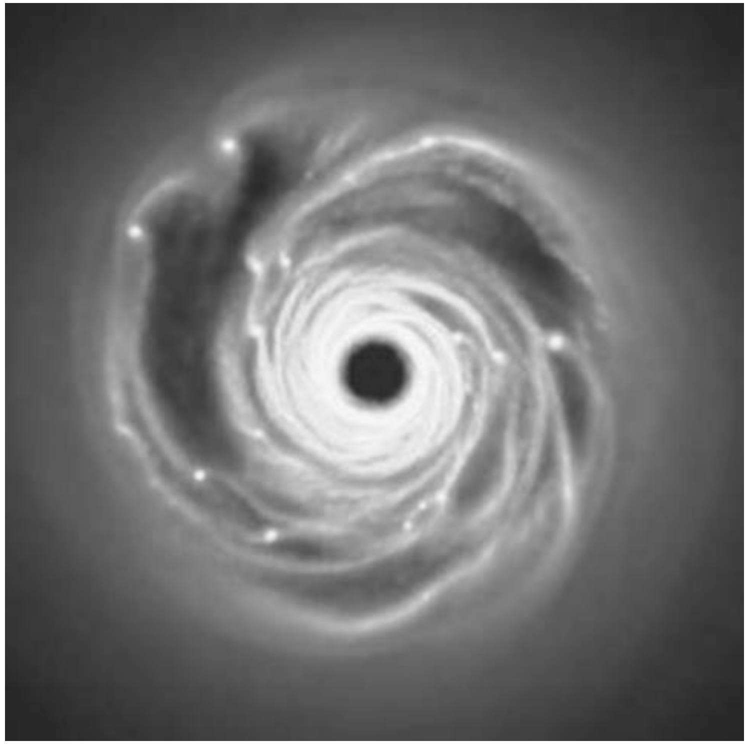


Credits: NASA/Ames Research Center/Wendy Stenzel



Mass – Period Distribution
01 Aug 2023
exoplanetarchive.ipac.caltech.edu
Mass [Jupiter Masses]
100
10
1
0.1
0.01
10^{-3}
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
Period [days]
Hot Jupiters
Cold Jupiters
Super Earths /
Mini Neptunes
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry

Giant planets on wide orbits: formation through gravitational instability



Rice et al. (2003)

Resources

- Philip J . Armitage, *Astrophysics Of Planet Formation* (textbook)
- Philip J. Armitage, *Lecture notes on the formation and early evolution of planetary systems* (available on arxiv)
- Philip J. Armitage, *Physical Processes in Protoplanetary Disks* (available on arxiv)
- Juhan Frank, Andrew King, Derek Raine, *Accretion Power in Astrophysics* (textbook)

End of Lecture 2