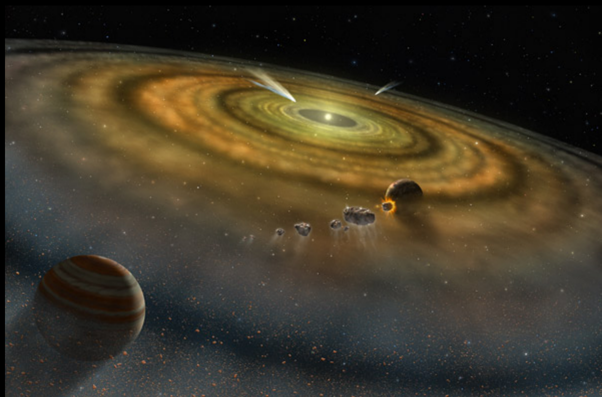

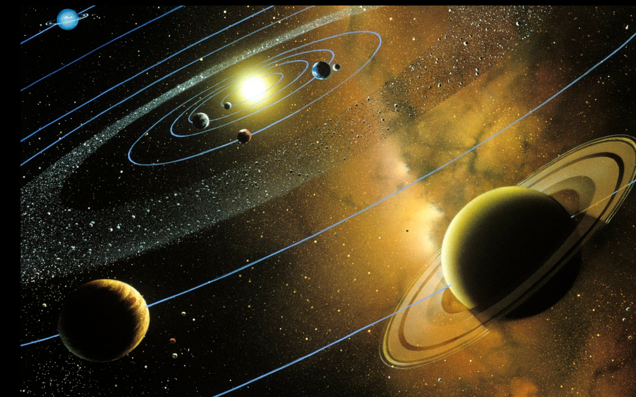

Exploring the role of planetesimals stirred by forming giant planets in shaping the characteristics of protoplanetary disks

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Protoplanetary Disks Workshop – INAF-OAR, 25-28 June 2018

The Lifetime of Circumstellar Disks

The observations of circumstellar disks suggest an **upper limit of ~10 Ma** to the lifetime of disks (see e.g. Meyer 2009, Fedele et al. 2010).

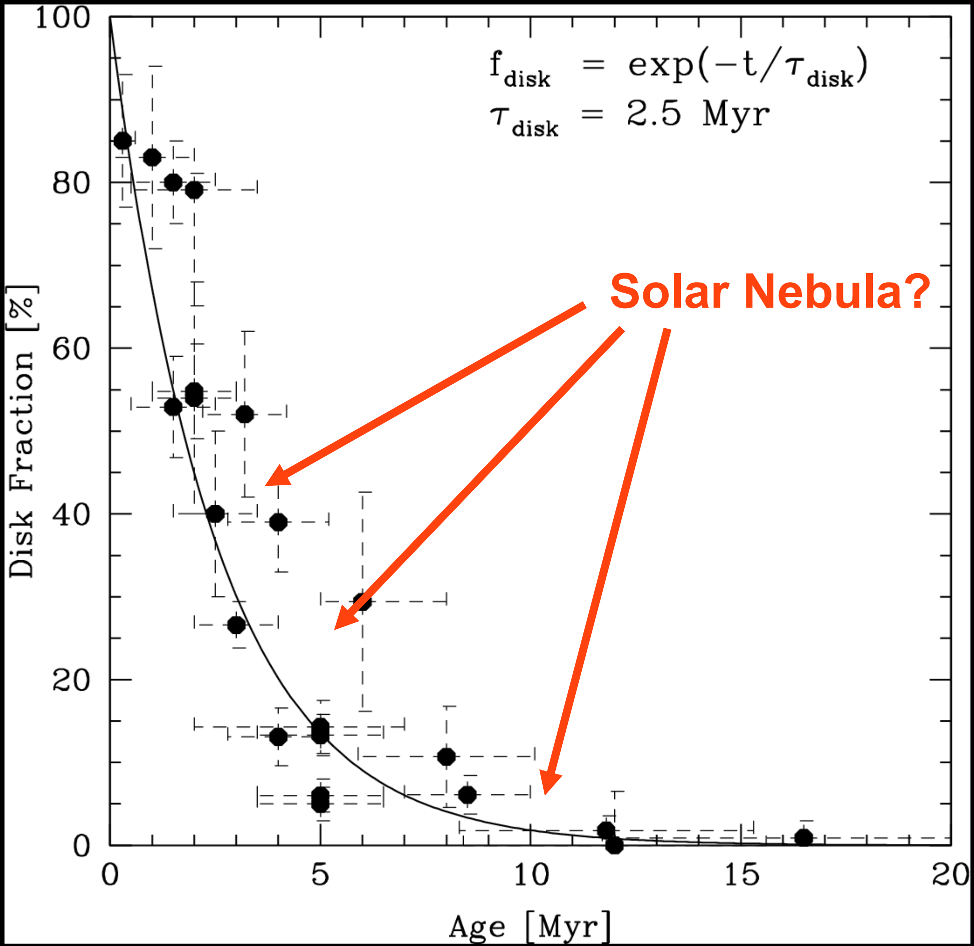
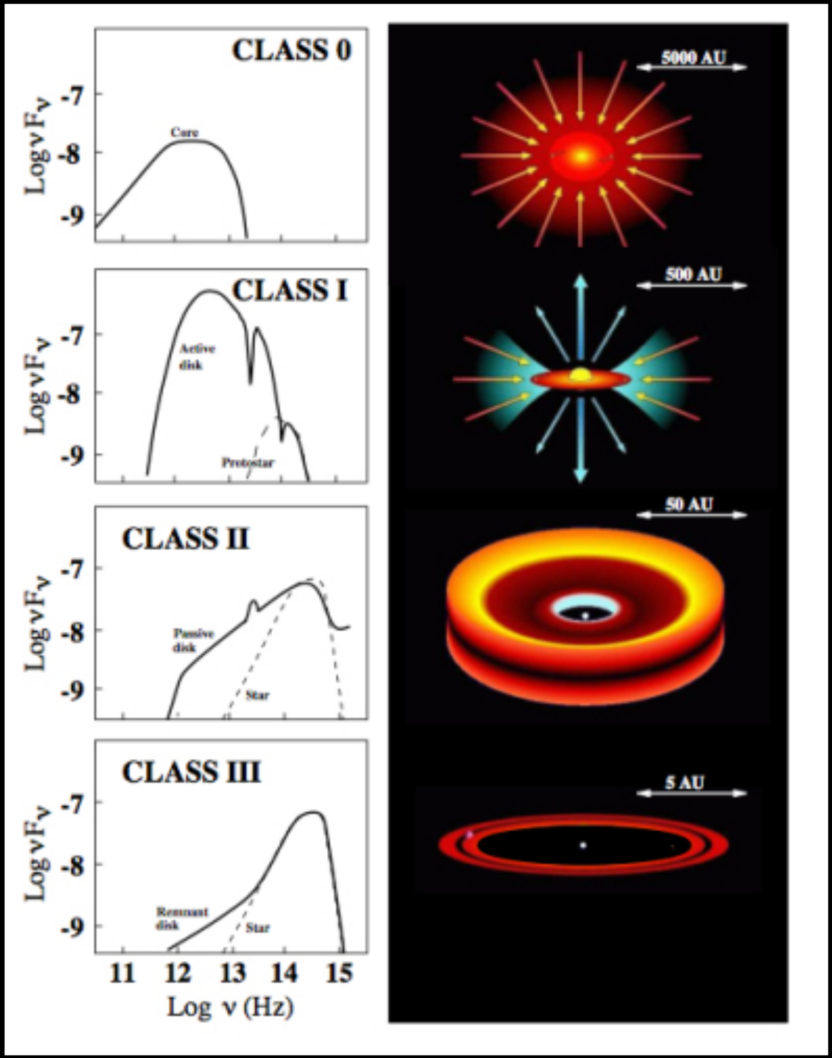
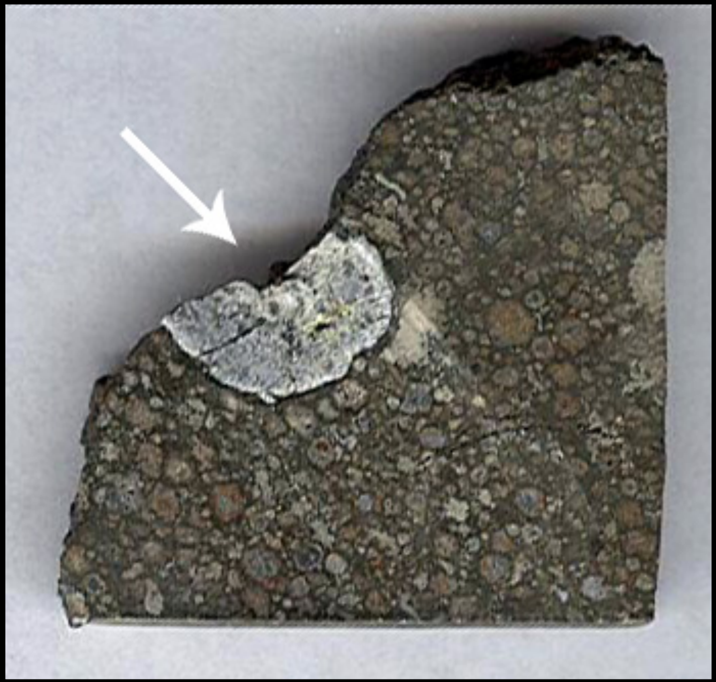


Image credits: Mamajek (2009).

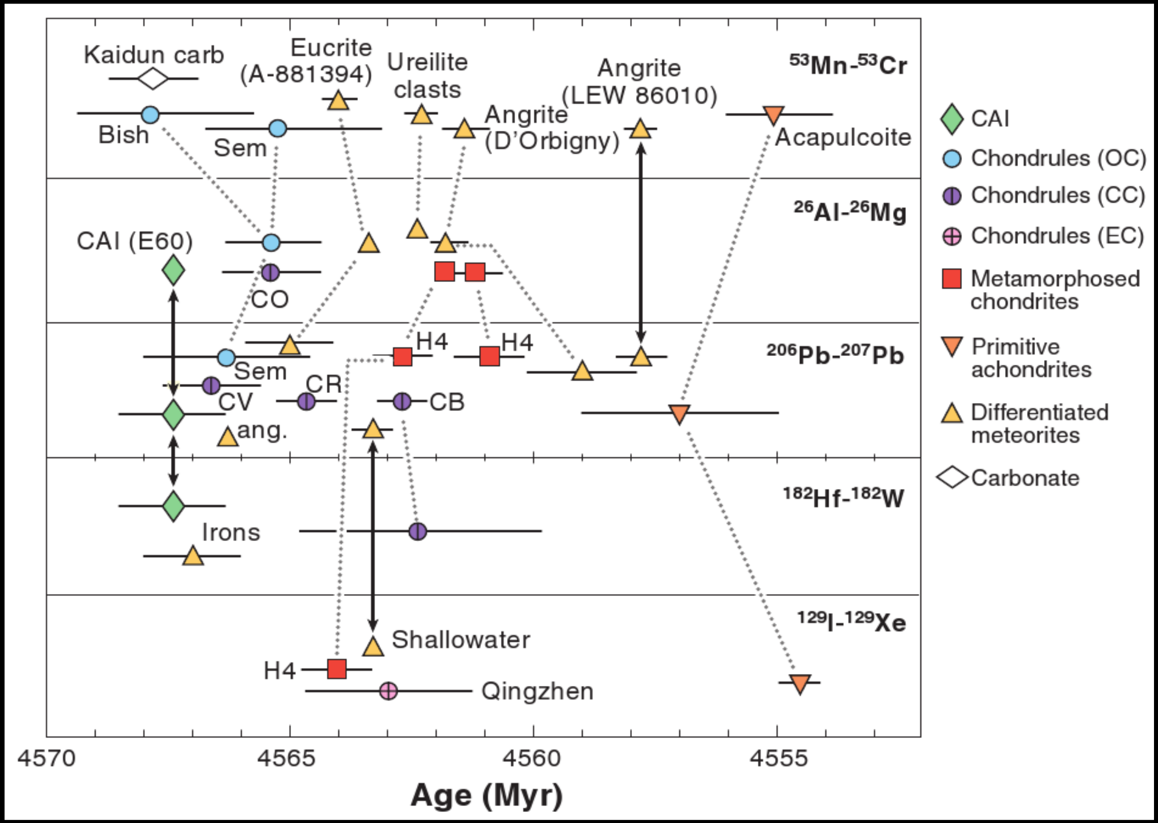


Meteorites as Cosmic Clocks

Thanks to different radiometric clocks, meteorites provide us with a temporally-resolved record of the formation and evolution processes of planetesimals in the Solar Nebula.



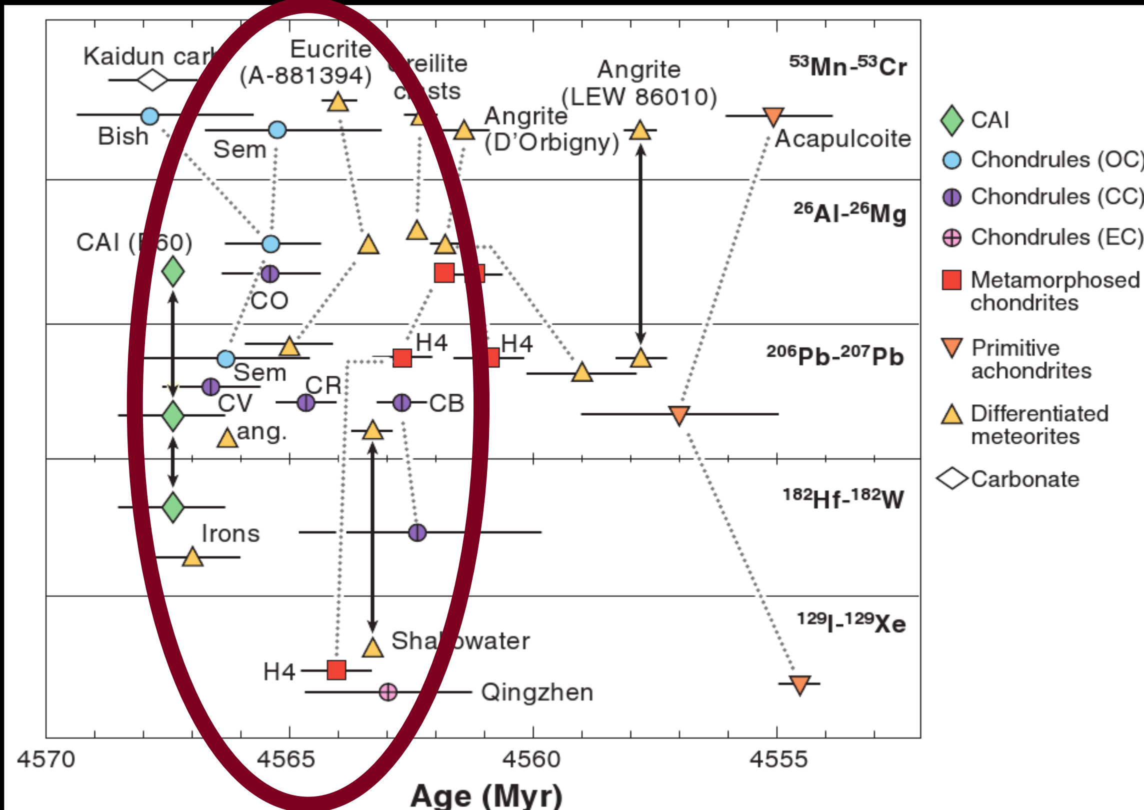
NWA-2364 carbonaceous chondrite: the 14 mm wide CAI (white arrow) is the oldest known solid in the Solar System. Image source: Northern Arizona Meteorite Laboratory



Chronology of the early Solar System from the radiometric ages of meteorites (Scott, 2007).

Meteorites and the Solar Nebula

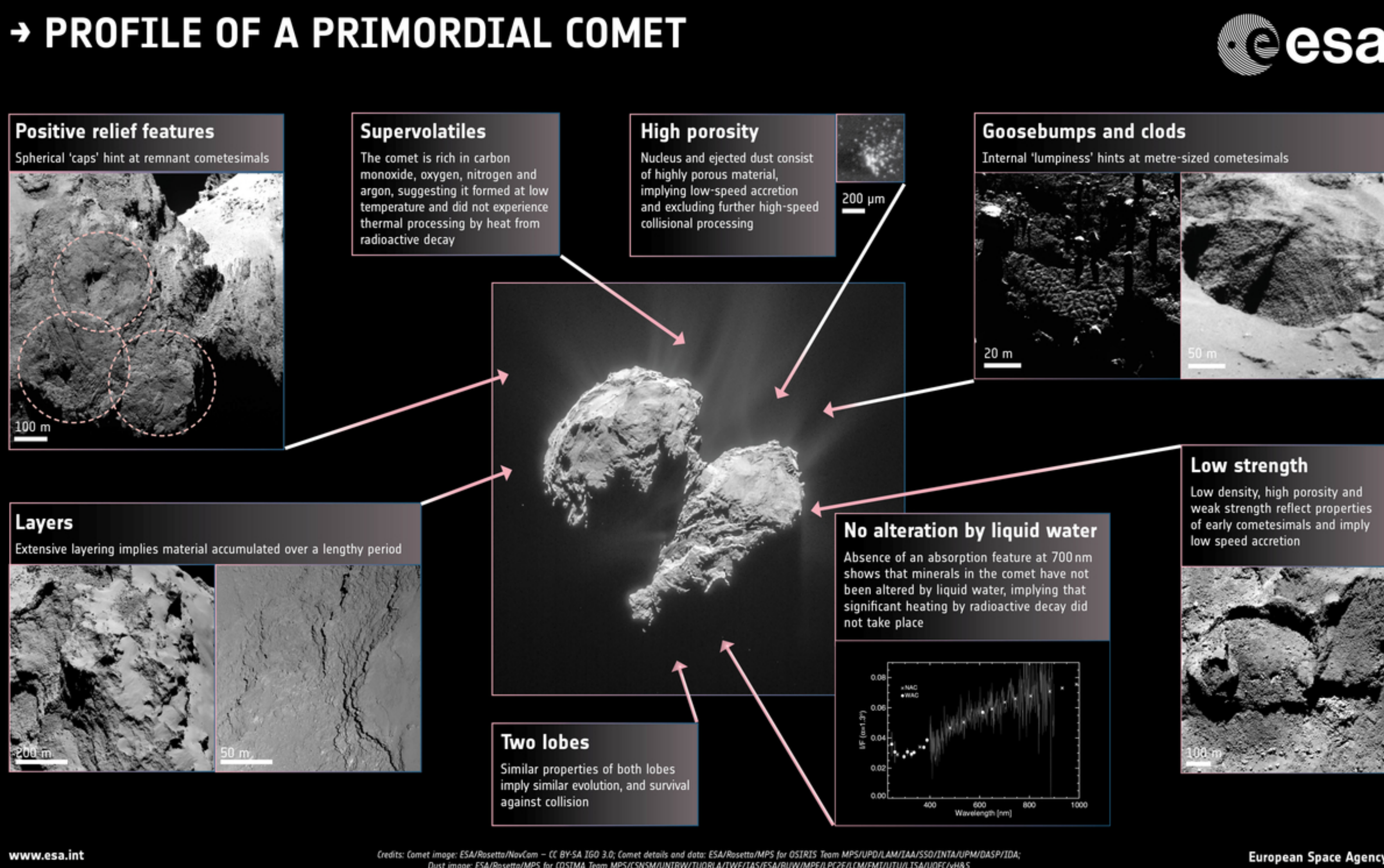
Meteoritic data tell us that the ***first generation of planetesimals***, including bodies of several ***tens of km in diameter***, could appear in less than ***1 Ma***. Over ***3 Ma multiple generations*** of planetesimals appear in the disk, ***decreasing*** its original ***dust*** content (first-generation dust).



Chronology of the early Solar System from the radiometric ages of meteorites (Scott, 2007).

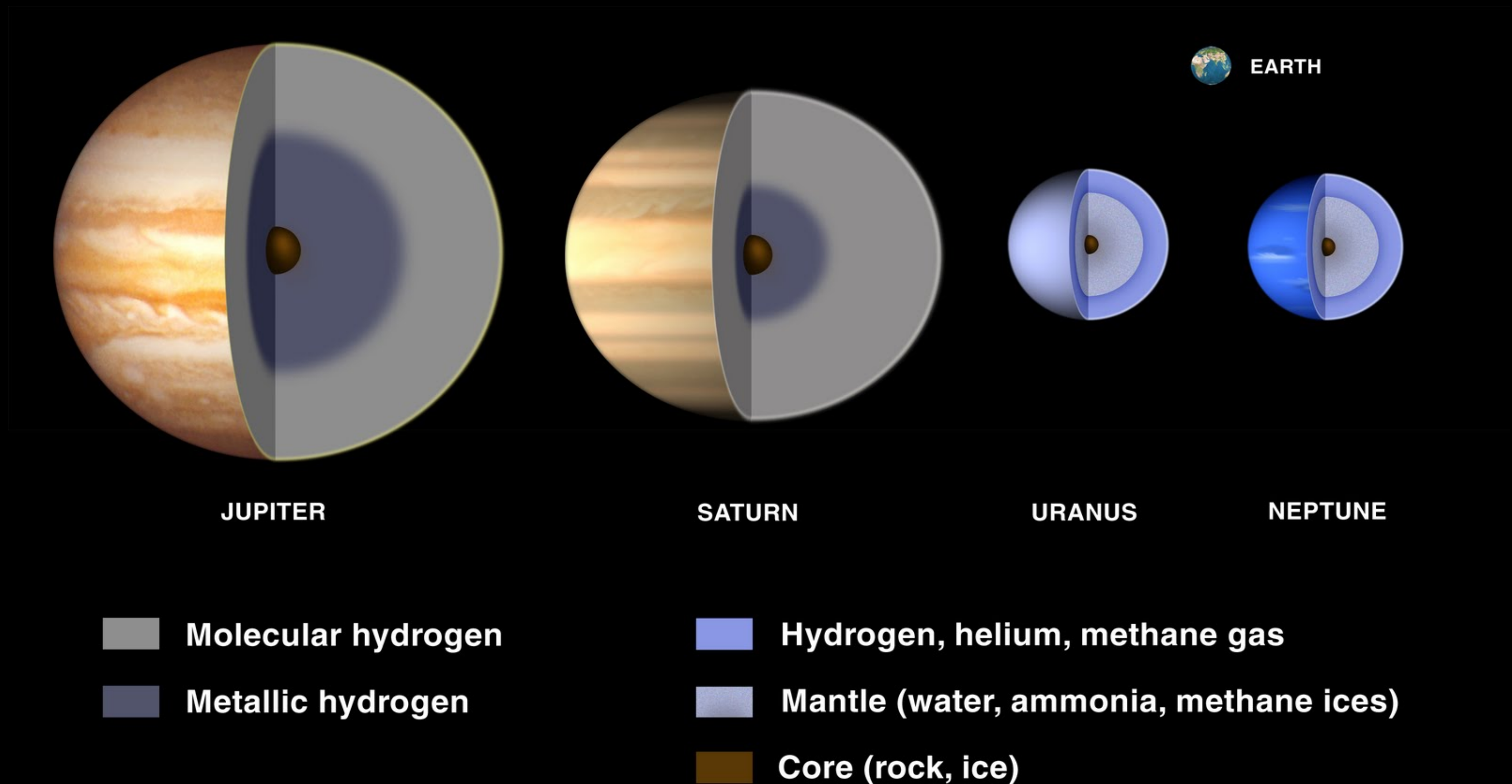
This, at least, is valid for ***rock-dominated planetesimals*** sampling the region within the H_2O snow line.

Rosetta and Comet 67P/C-G



Giant Planets and the Solar System

While planetesimals were forming in the inner Solar System, the **outer Solar System** (*a > 3-4 AU*) saw the birth of four **giant planets**, the two gas giants Jupiter and Saturn and the two ice giants Uranus and Neptune.



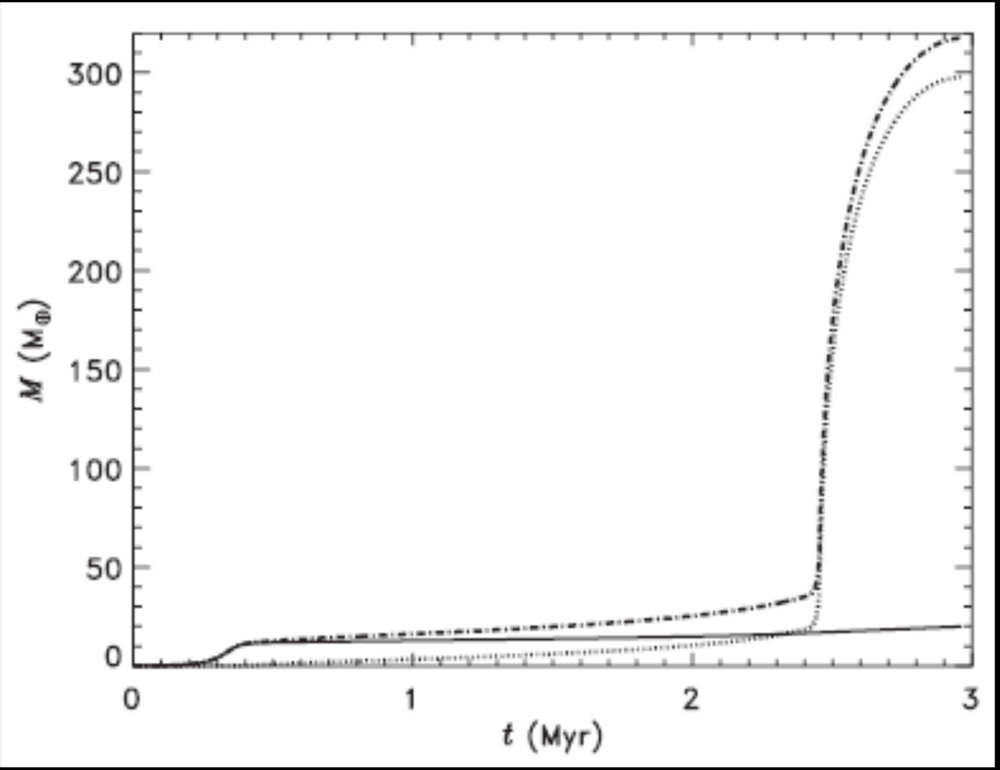
Giant Planet Formation and Core Accretion

We know that giant planets should have formed in the Solar Nebula, since **molecular H and He exist only in gaseous form in** the conditions typical of **circumstellar disks** and therefore the **nebular gas** represents the **only available source material**.

Nucleated Instability Scenario

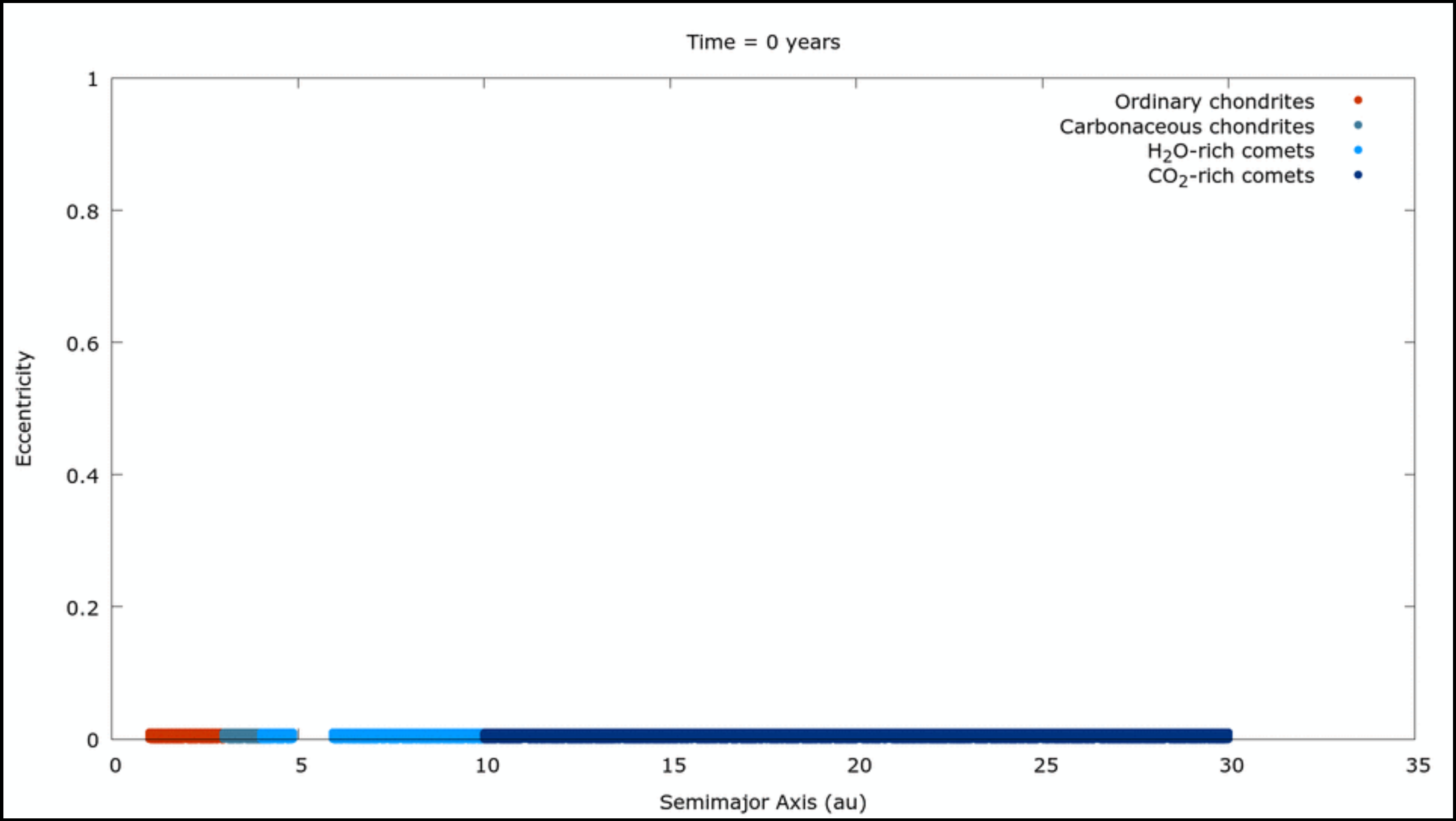
First, a **planetary core with mass of ~10 $M_\oplus$** should form with the same process as planetary embryos and terrestrial planets
(τ_C= a few 10^6 years)

Once the critical mass is reached, nebular **gas** will start to be rapidly **accreted in runaway process** (τ_G= 10^5 years)



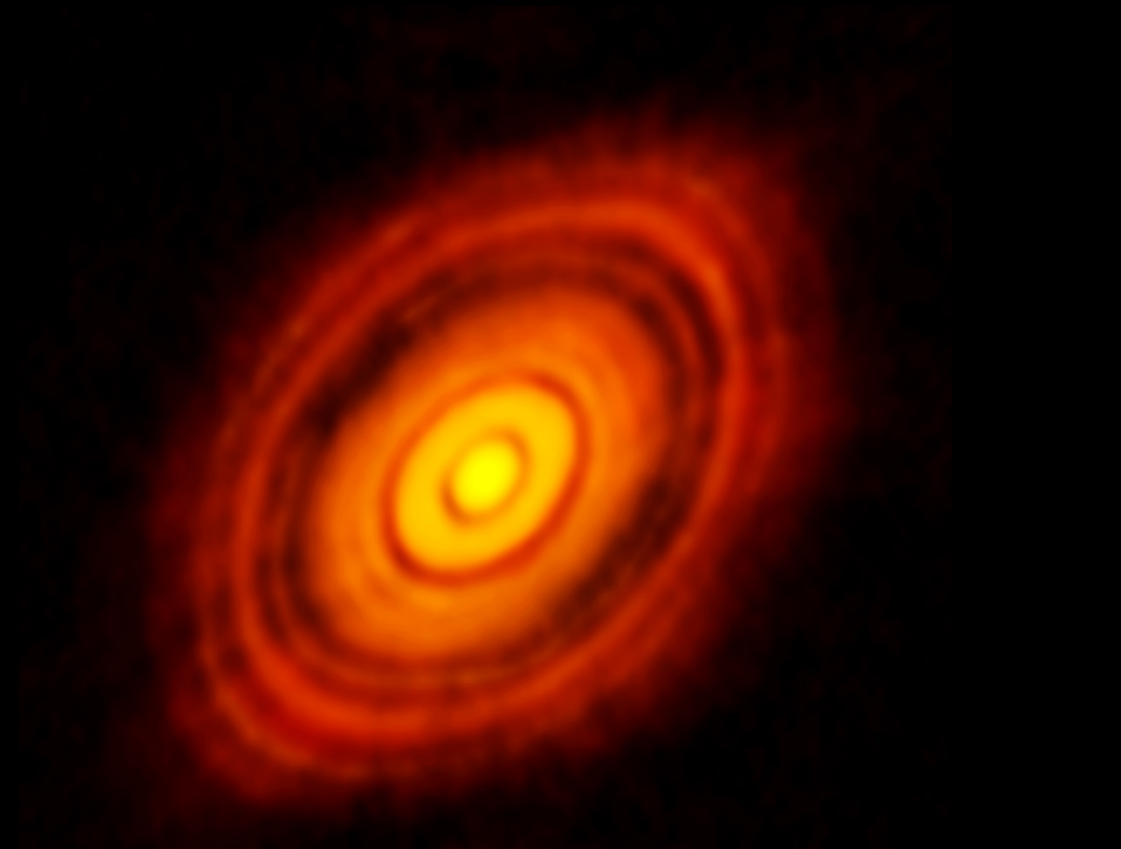
Mass growth of Jupiter from Lissauer et al. (2009).

Jovian Early Bombardment – Static Jupiter

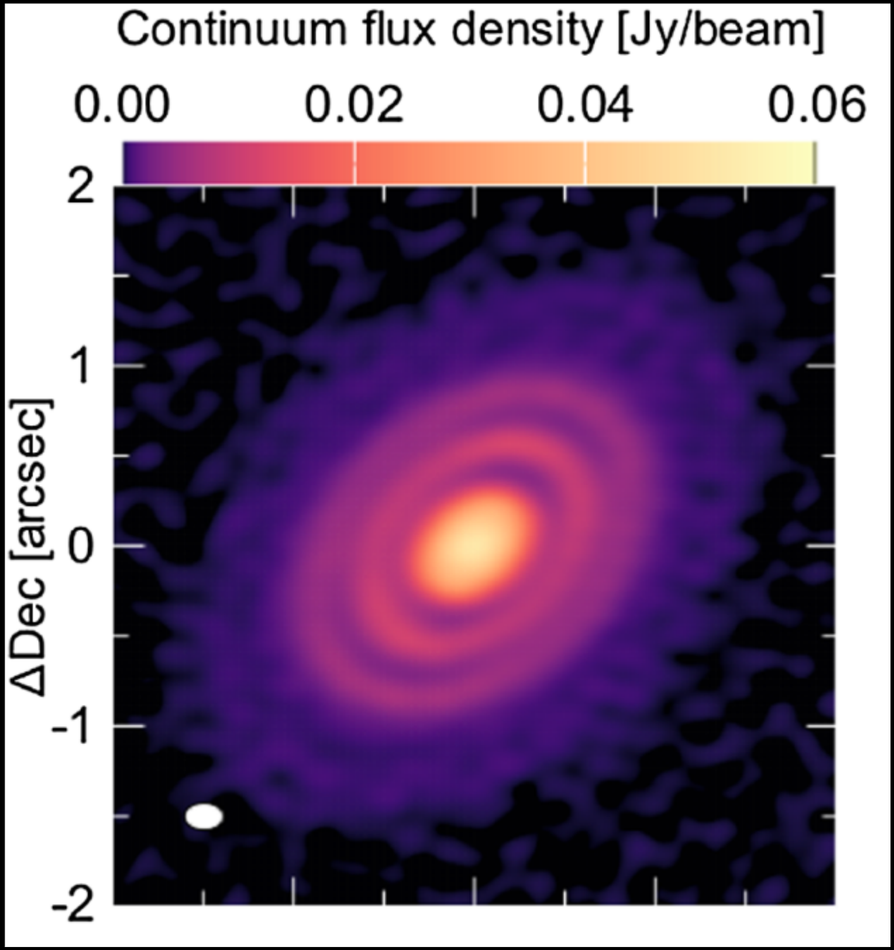


*Turrini, Magni & Coradini (2011); **Turrini, Coradini & Magni (2012)**; Turrini (2014); Turrini & Svetsov (2014); Turrini, Nelson & Barbieri (2015); Turrini et al. (2018).*

Circumstellar Discs & Formation Regions

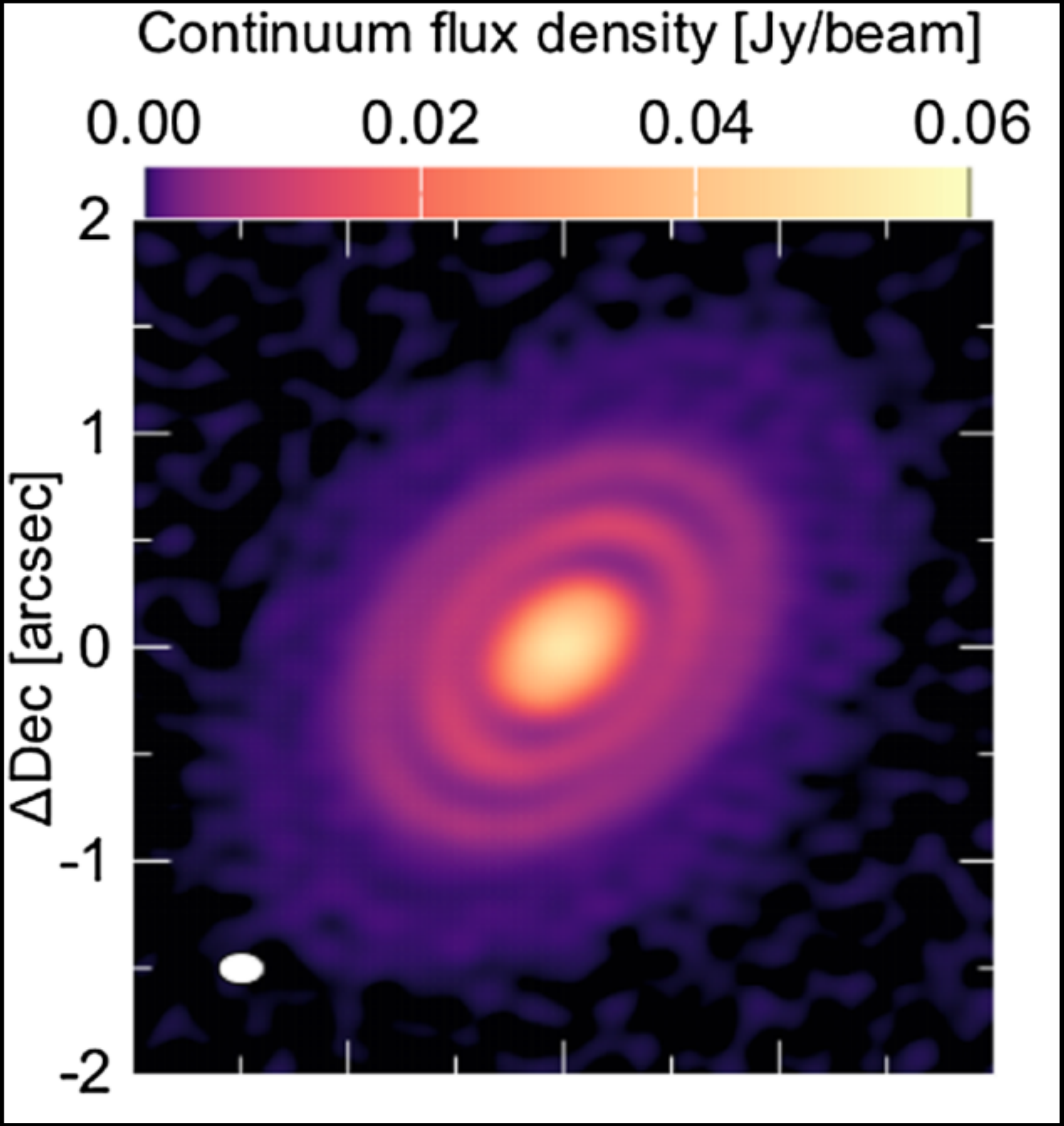


The first resolved observations of circumstellar discs with ALMA revealed signatures of giant planets forming *earlier and further out* than expected.



Top: *the 1 Myr-old circumstellar disc of HL Tau, where three giant planets are possibly residing at ~10, ~30 and ~70 au (Dipierro et al. 2015).* Left: *the 5 Myr-old circumstellar disc of HD163296, where three giant planets are possibly residing at ~60, ~100 and ~160 au (Isella et al. 2016)*

HD163296: A Case Study for Late Disks

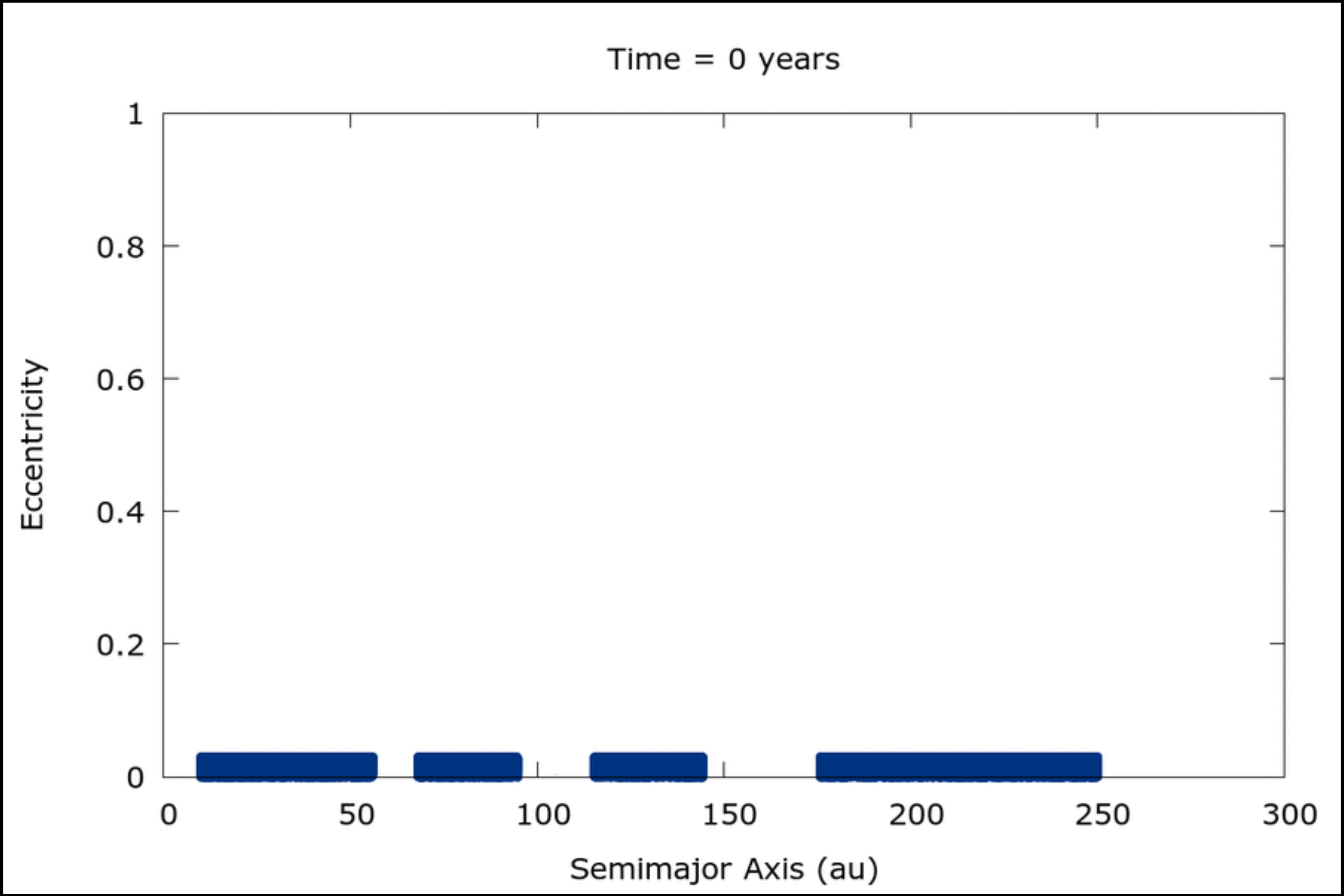


5 Ma old circumstellar disk around a star of 2.3 solar masses. ***Three*** identified ***gaps in the dust, two in the gas*** (Isella et al. 2016).

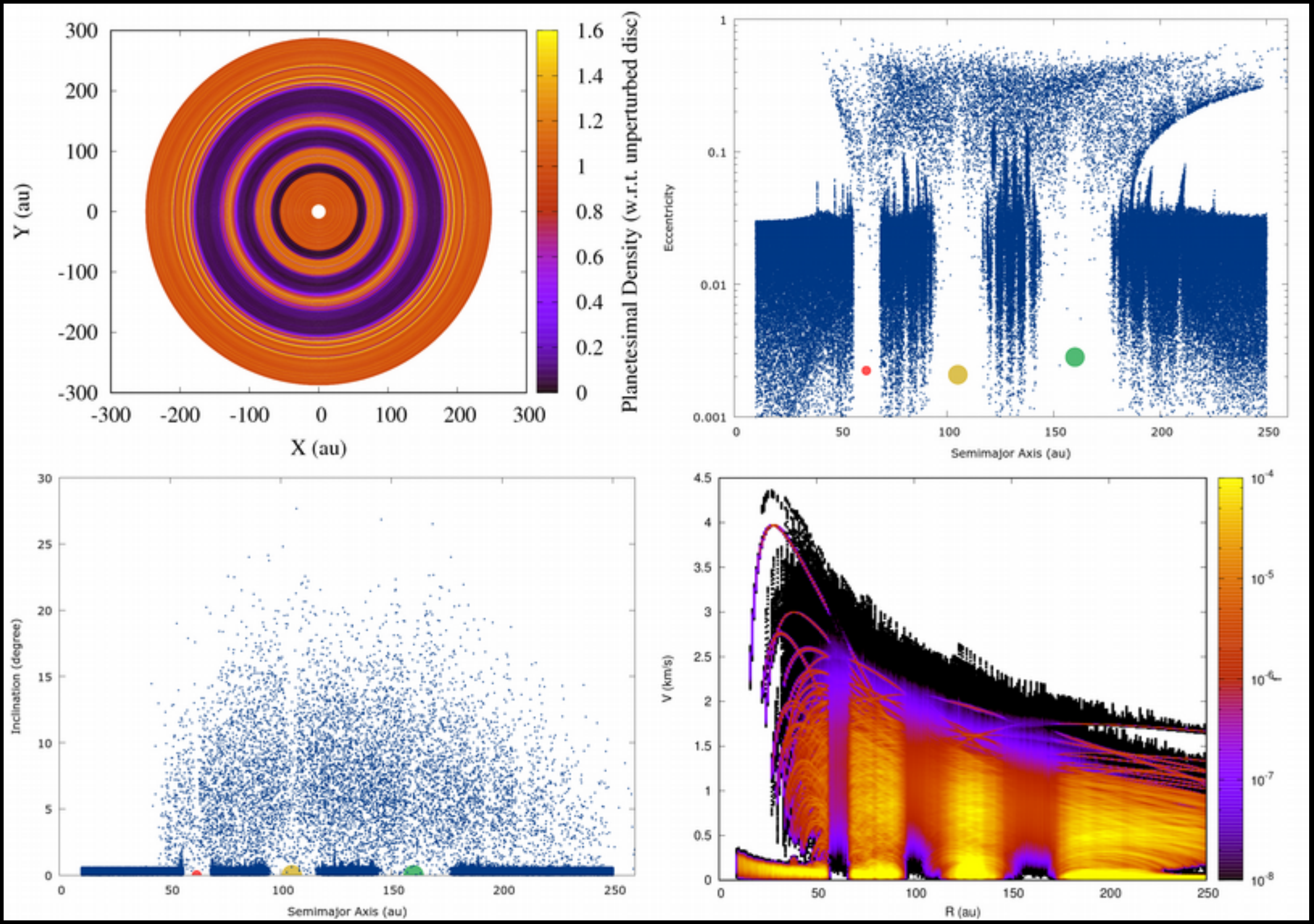
Proposed cause: ***3 giant planets*** of 0.1, 0.3, 0.3 Jovian masses at 60, 105 and 160 au (Isella et al. 2016). **Mass estimates now revised upward** to at least 0.46, 0.46, 0.58 Jovian masses (Liu et al. 2018, Teague et al. 2018).

Dust gaps in the circumstellar disc of HD163296 imaged with ALMA (Isella et al. 2016)

Jovian Early Bombardment in HD163296

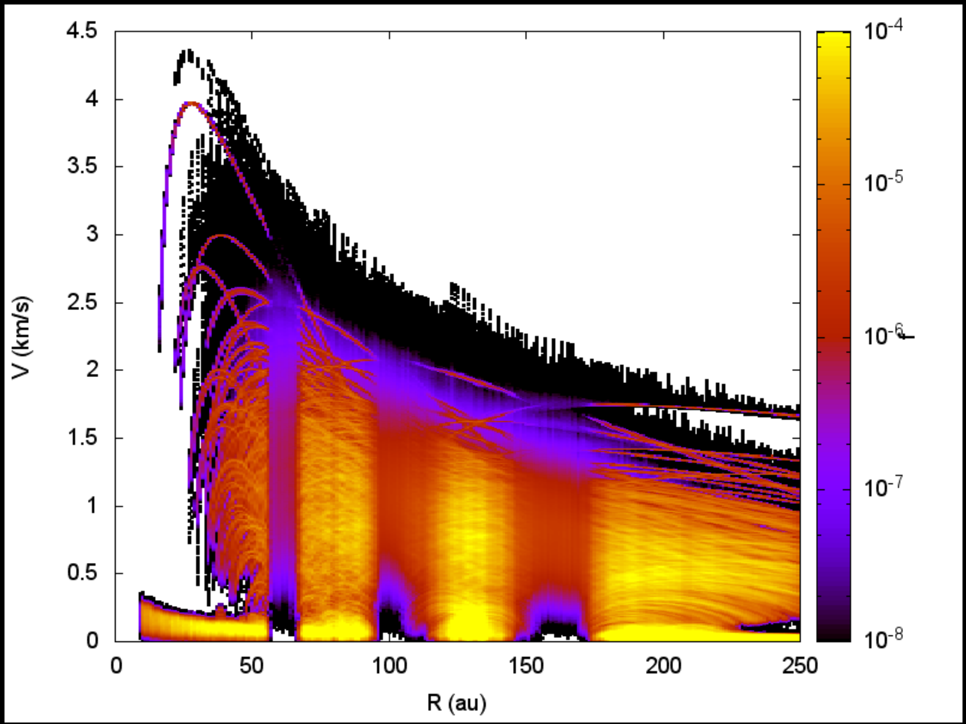


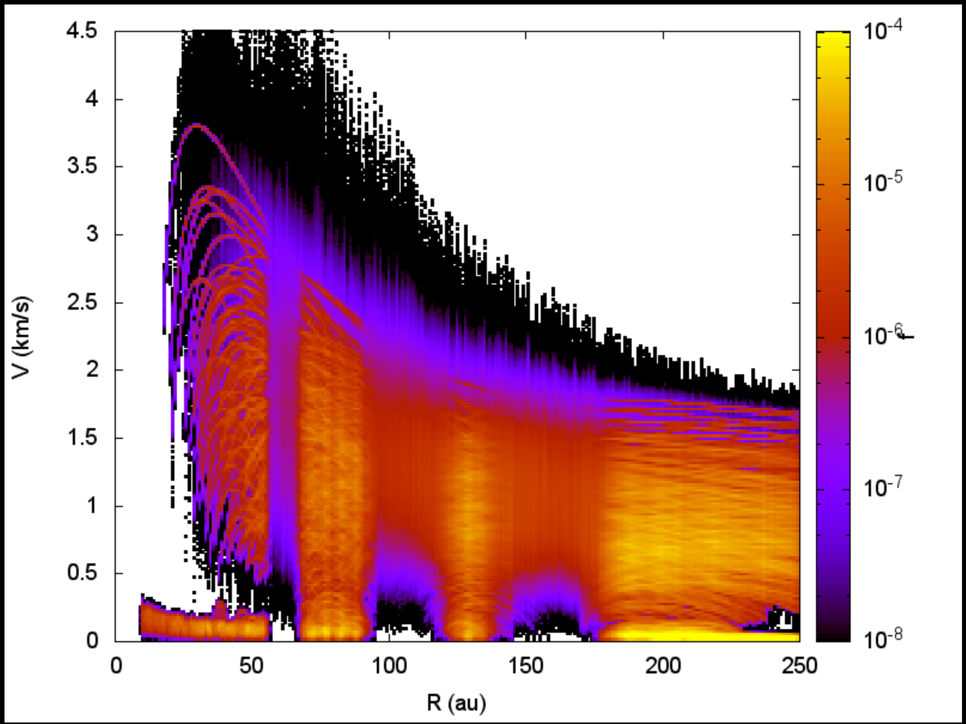
HD163296: Current State?

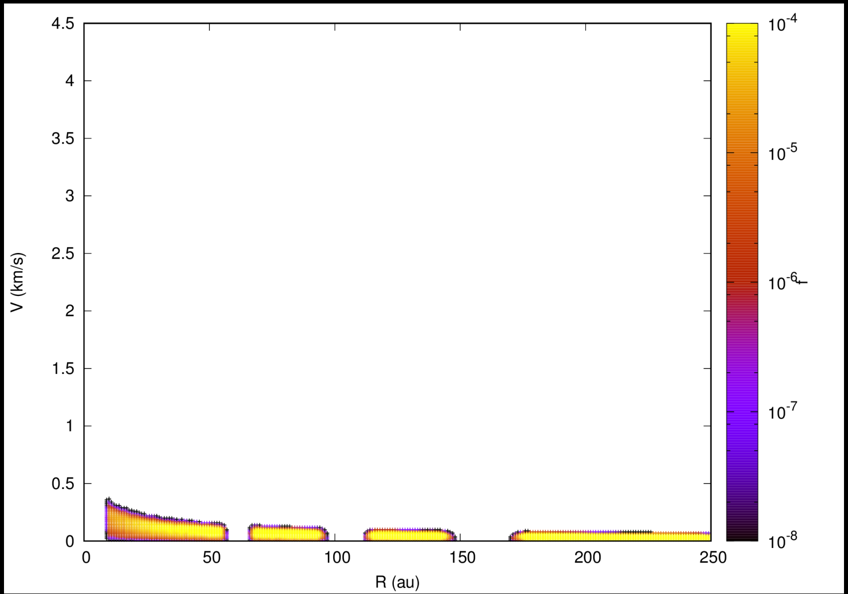


__Dynamical excitation of the planetesimal disk__ of HD 163296 caused by the formation of its three giant planets and __enhancement of the planetesimal impact velocities__, resulting in __collisional regeneration of the dust__ population (Turrini et al., submitted)

Dynamical Excitation and Planetary Masses





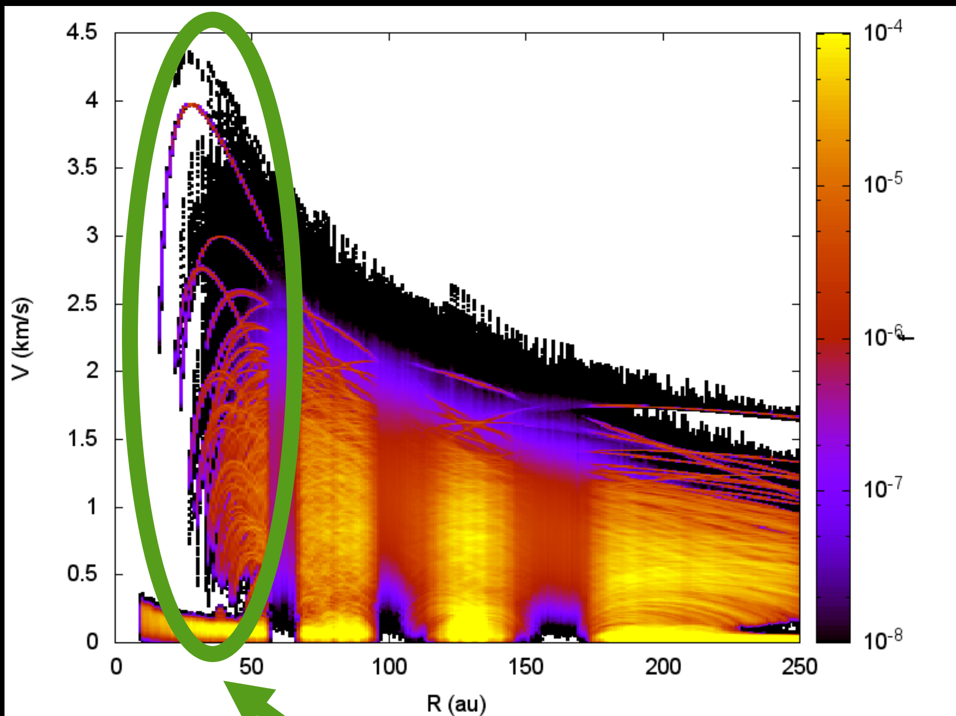


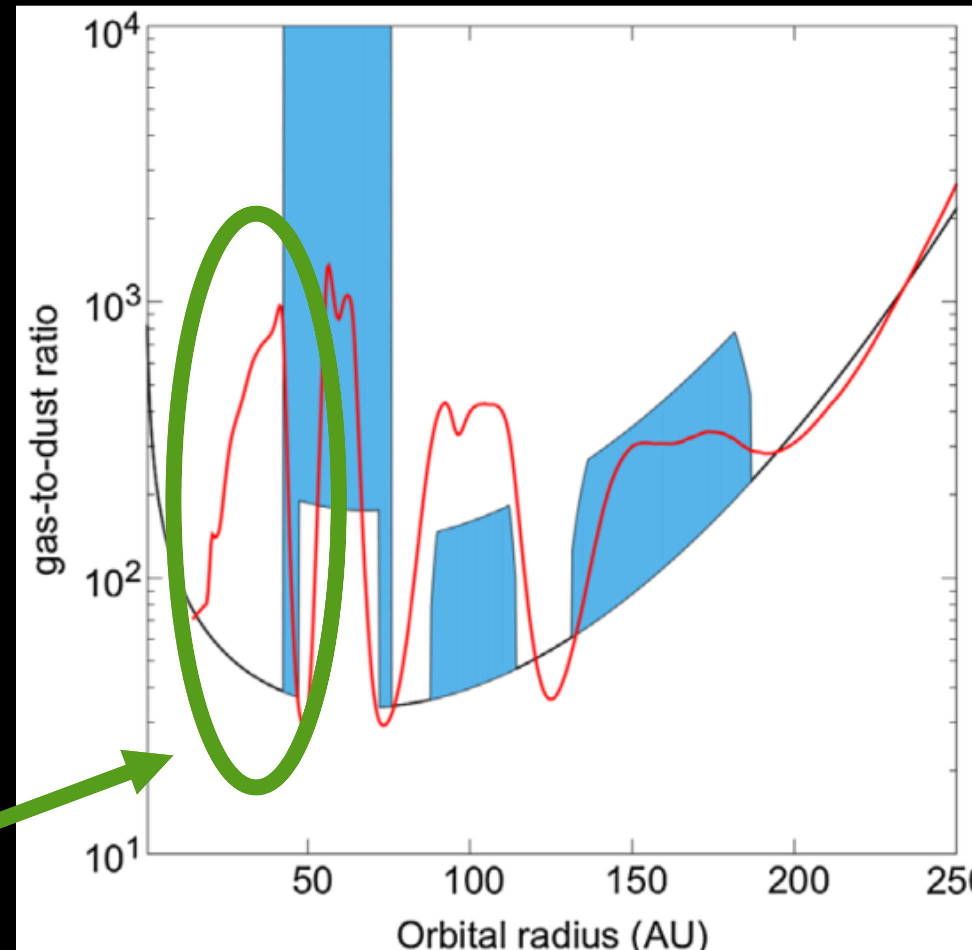
Top Left: dynamical excitation in the reference case (fiducial planetary masses)

Top Right: dynamical excitation in the massive case (2x fiducial planetary masses)

Bottom: initial dynamical state of the planetesimal disk

Dynamical Excitation and Planetary Masses





Qualitative match between the ***position and size of the region of peak dust production*** due to the excited impact velocities and a ***estimated overabundance of dust*** in HD163296 (Turrini et al. submitted)

Reconstructed gas-to-dust ratio in HD163296 and comparison with theoretical expectations (Isella et al. 2016)

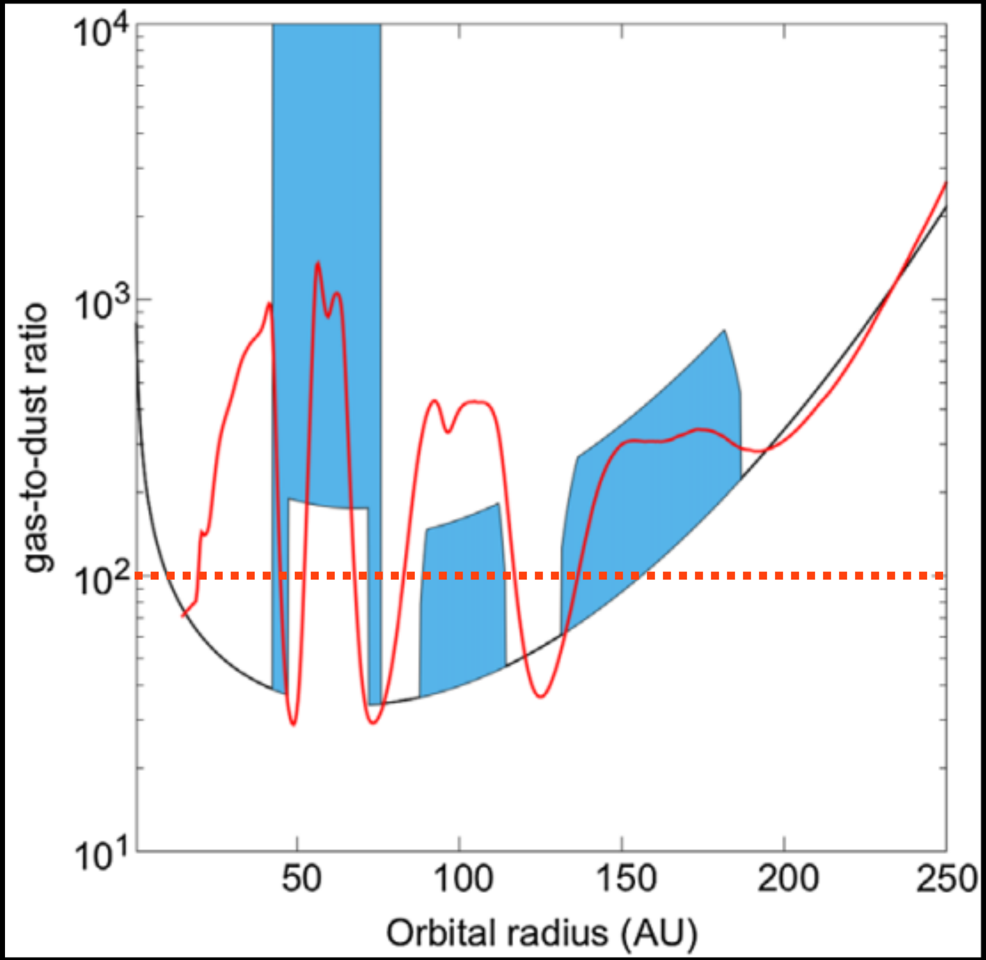
Collisional Dust Production: Viable Path?

Integrating the **dust profile** one obtains **~420 Earth masses** of dust in HD163296. Integrating and scaling the **gas profile** one would expect **~280 Earth masses** of dust.

The additional **~140 Earth masses** arise from the region populated by the giant planets.

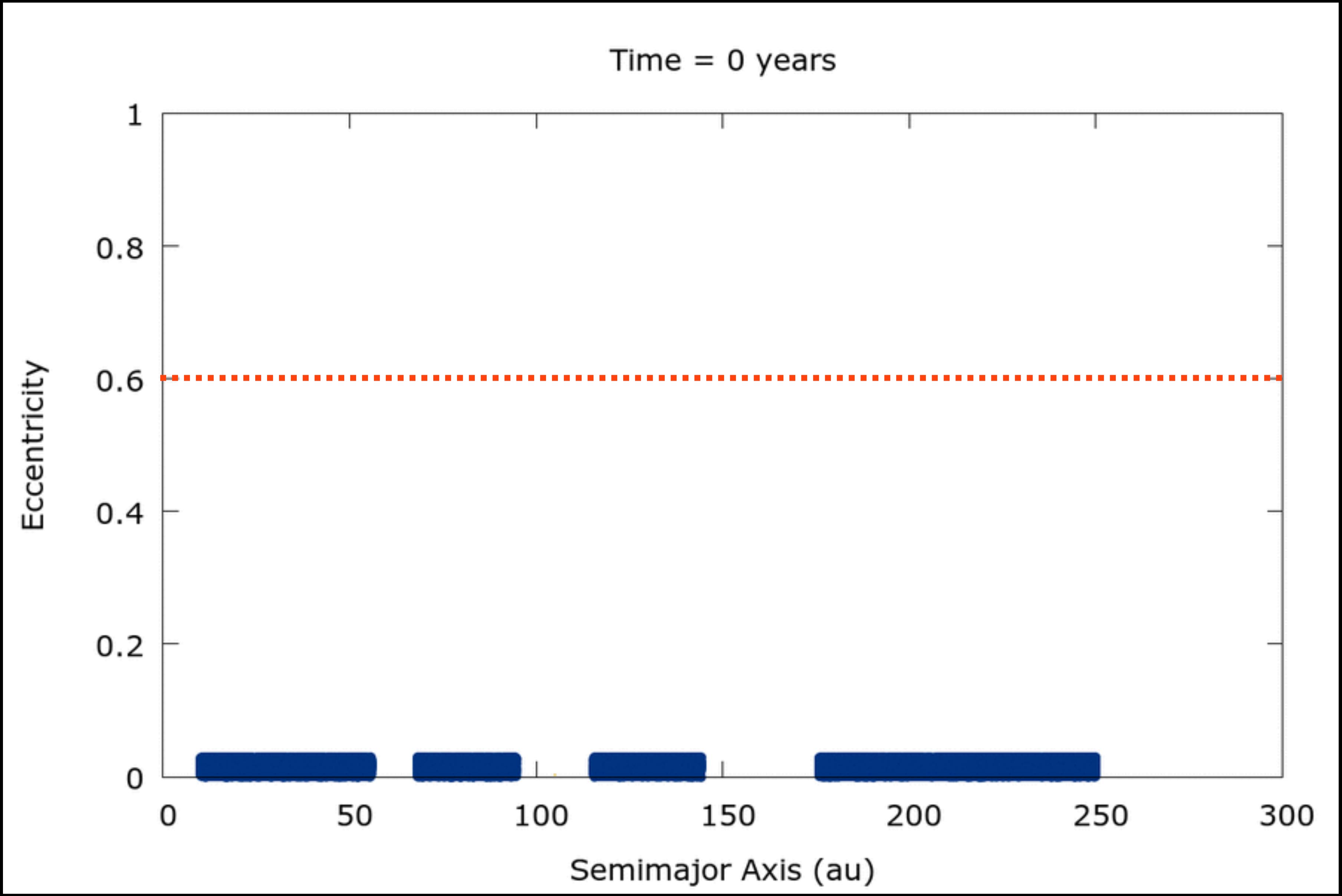
Collisions produce dust through two processes:
- **catastrophic destruction** (stochastic process due to high-energy impacts)
- **cratering erosion** (continuous process due to low-energy impacts).

In presence of a sufficiently massive excited planetesimal disk (~1000 Earth masses), even **cratering erosion is enough** to generate the required 140 Earth masses of dust (Turrini et al., submitted).



Reconstructed gas-to-dust ratio in HD163296 and comparison with theoretical expectations (Isella et al. 2016)

HD163296 with Gas Drag & New Masses



Take Home Messages

1. ***Planetesimals appear early*** and several generations can form through the life of protoplanetary disks, supplying the ***building blocks for the cores of giant planets***.

2. ***Forming giant planets*** disrupt the dynamical equilibrium of the planetesimal disk and ***initiate a phase of dynamical and collisional excitation***.

3. ***Planetesimals are invisible but not inconsequential***: their dynamical and collisional excitation can ***inject hundreds of Earth masses of dust*** in protoplanetary disks.

4. The ***dust population in planet-forming disks can vary non-linearly over time*** depending on the number and masses of embedded giant planets.

5. Leonardo Testi is probably evolving into a non-physical life form… or has a very, very, very, very small collisional cross section.