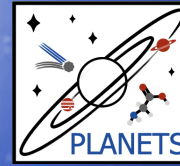
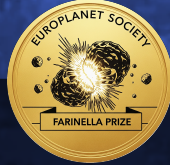
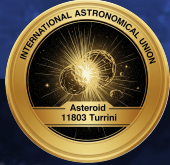


# On the Shoulders of Giants

Turin, 25-27 March 2026



Agenzia Spaziale Italiana



## Giants in the cradle - Part 1

# Exploring how Jupiter's birth shaped the compositional evolution of the inner Solar System

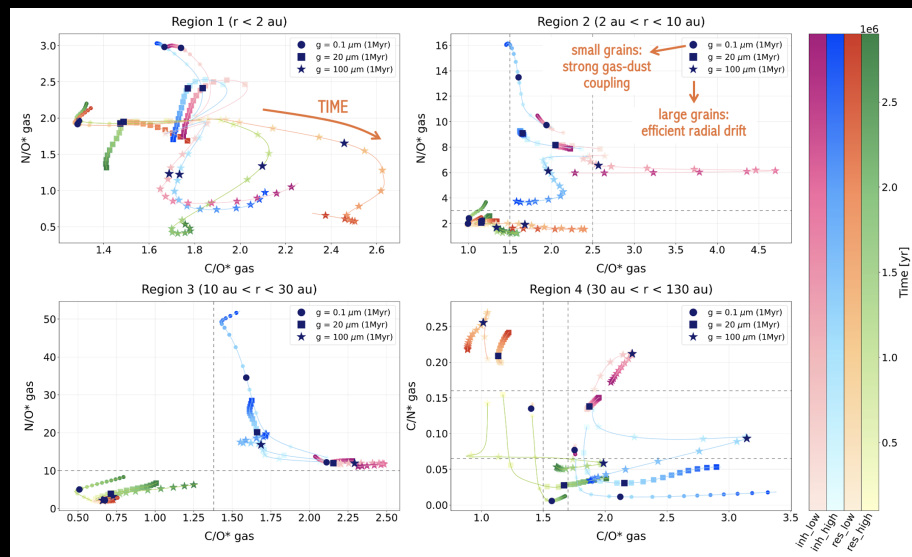
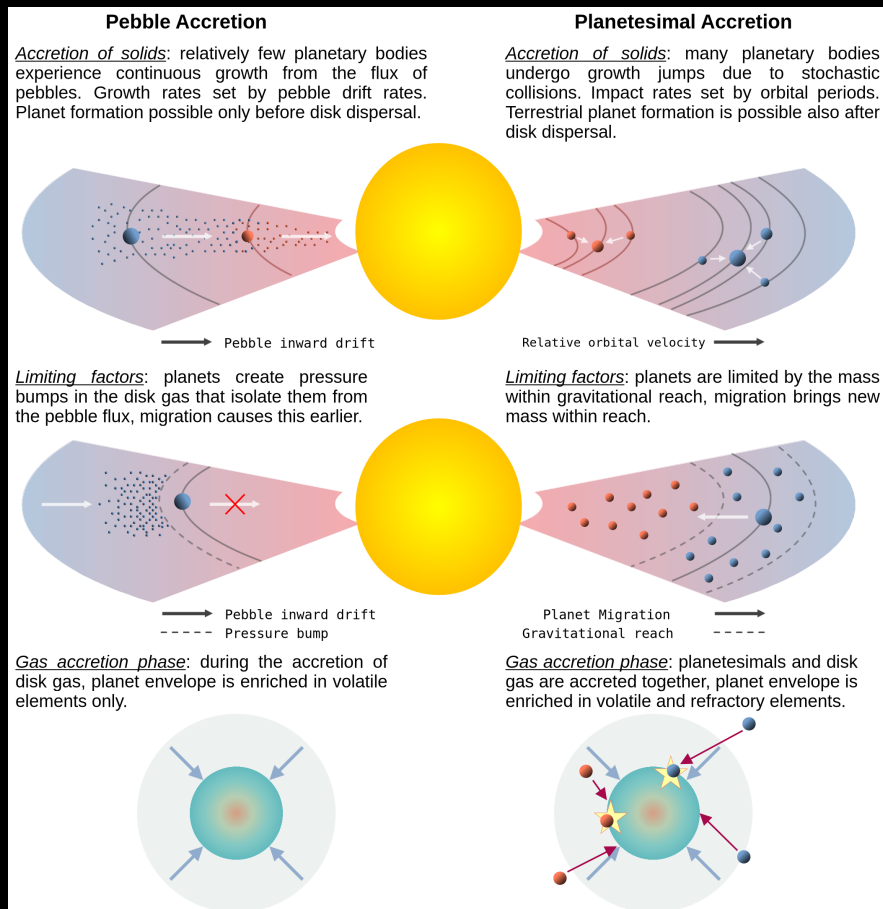


**Diego Turrini<sup>1,2</sup>**

<sup>1</sup> INAF - Turin Astrophysical Observatory <sup>2</sup> ICSC - National Research Centre for High Performance Computing, Big Data and Quantum Computing

# The "Formation Timescale" and "Formation Environment" problems

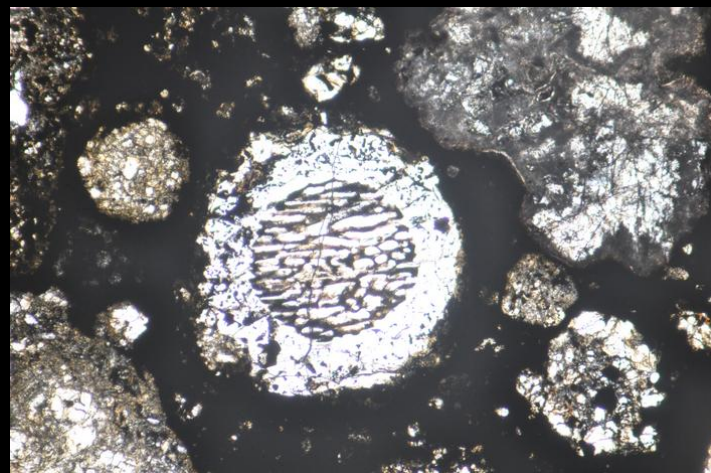
Different giant planet formation mechanisms point to **different formation timescales**, implying that the giant planets also form in **different astrochemical environments** in protoplanetary disks.



Elemental ratios normalized to the stellar values in an evolving disc across 4 key regions delimited by the snowlines of H<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub>. Results are shown for 3 different sizes of dust grains and 4 chemical scenarios (Pacetti+2025).

Schematic representation of the key features of the pebble accretion and planetesimal accretion scenarios for giant planet formation. Credit: Diego Turrini

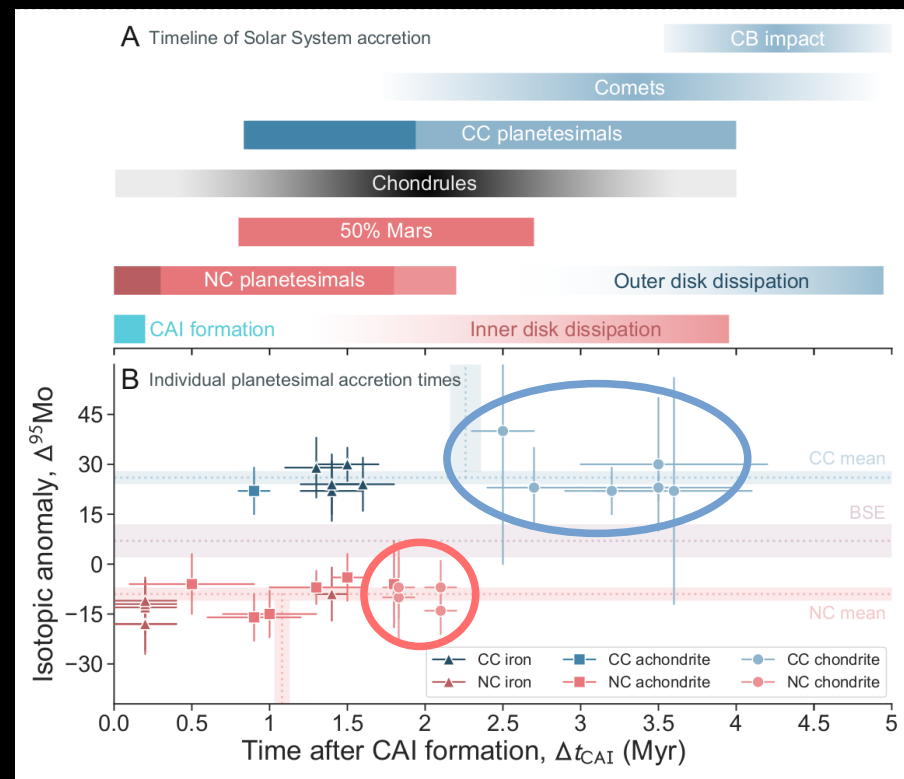
# Chondrules as precision clocks of the Solar Nebula



Round chondrules visible in a thin section of the Allende meteorite under microscopic view. Credit: Akira Miyake, Kyoto University.

**Chondrules** are mm-sized spherical particles of crystallized liquid silicates that constitute large-volume fractions of most chondritic meteorites.

Emerging consensus, based also on their ages, is that they are **products of collisions between planetary bodies**, not primary building blocks (i.e. they are not pebbles).



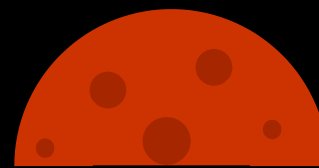
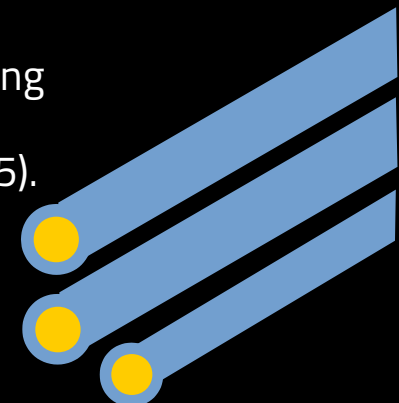
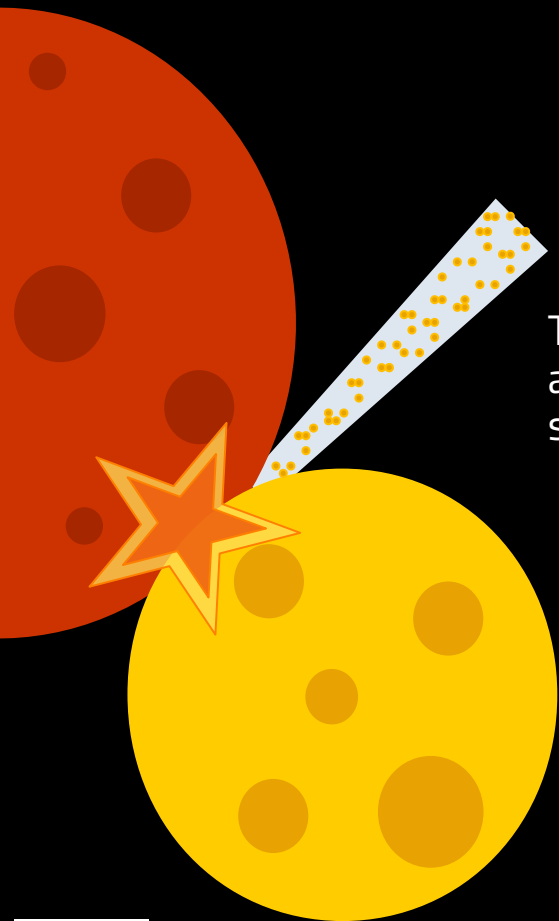
Chronology of solar nebula from radiometric data of meteorites (Lichtenberg+2023)

# Planetary impacts and chondrule production

The current explanation for the origins of chondrules is the **ejection and fragmentation into droplets of molten rocks** by impacting planetary bodies.

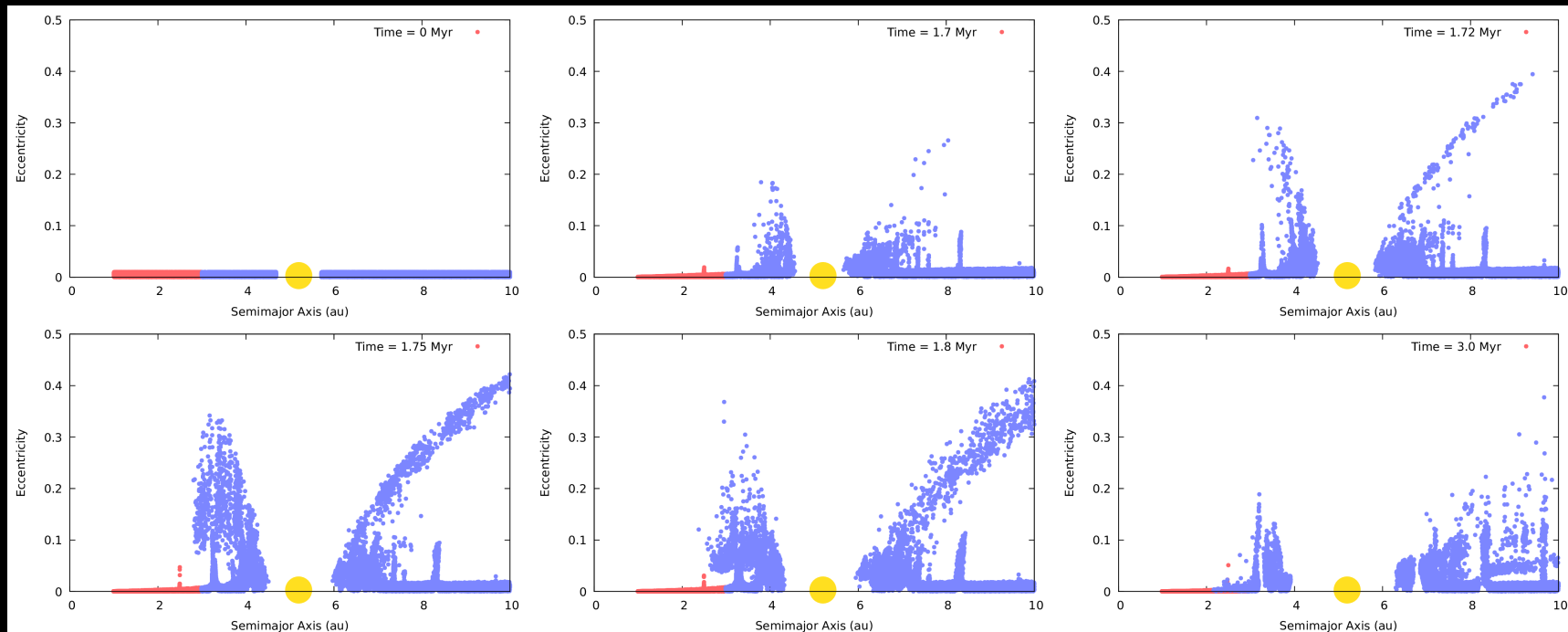
This process has low efficiency and requires high impact velocities: current models address these shortcomings by invoking the fast and extensive formation of Moon-sized planetary embryos (e.g. Johnson+2015, Hasegawa+2016, Cashion+2025).

The more natural scenario is linked to their formation during the **cometary bombardment triggered by Jupiter's formation** in the inner Solar System (Sirono & Turrini 2025).



# Jupiter's formation and the first cometary bombardment

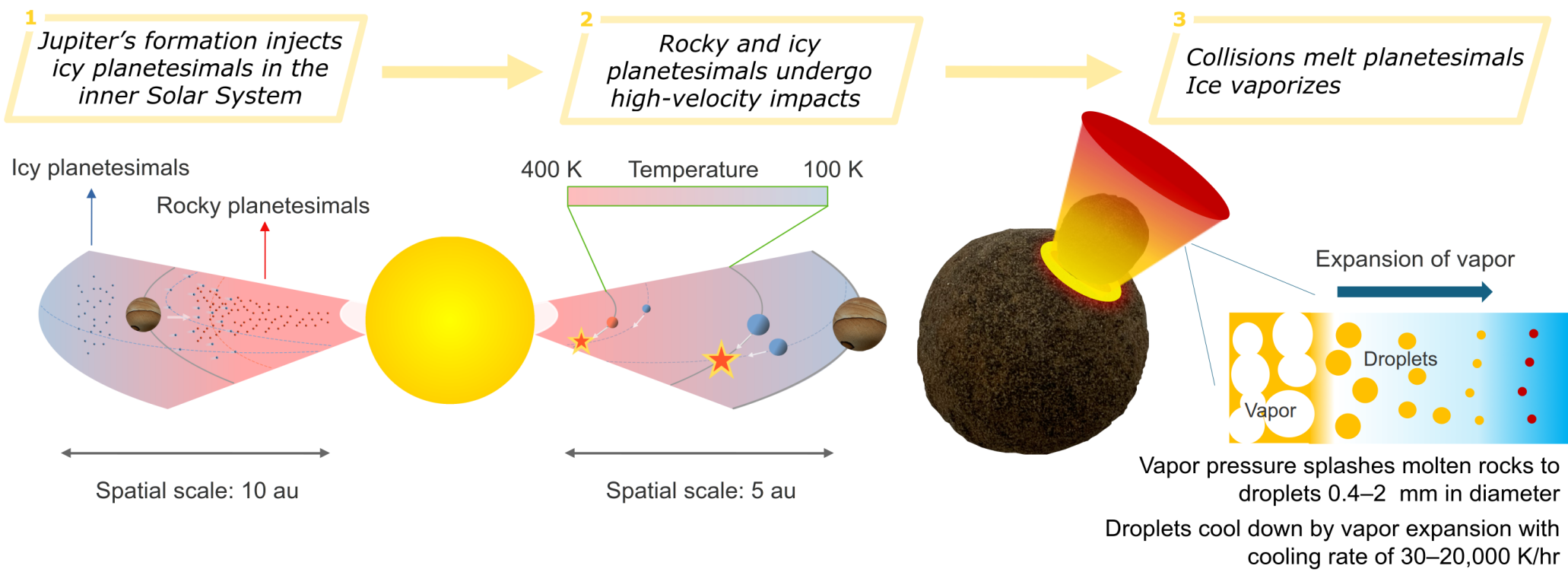
Jupiter's formation alters the dynamical equilibrium of the Solar System, scattering **cometary planetesimals into the inner Solar System** (*Turrini+2011; Turrini & Svetsov 2014; Raymond & Izidoro 2017; Pirani+2019*).



Scattered cometary planetesimals initiate **high-velocity collisional cascades** with planetesimals in the inner Solar System (*Turrini+2012; Turrini & Svetsov 2014; Turrini+2018; Carter & Stewart 2020; Sirono & Turrini 2025*).

# Genetic link between chondrules, cometary impacts and Jupiter's formation

The volatile elements present in the **cometary planetesimals create vapor plumes** that are critical to **break up and cool down the silicate melt** to the size and cooling ranges observed in chondrules (Sirono & Turrini 2025).



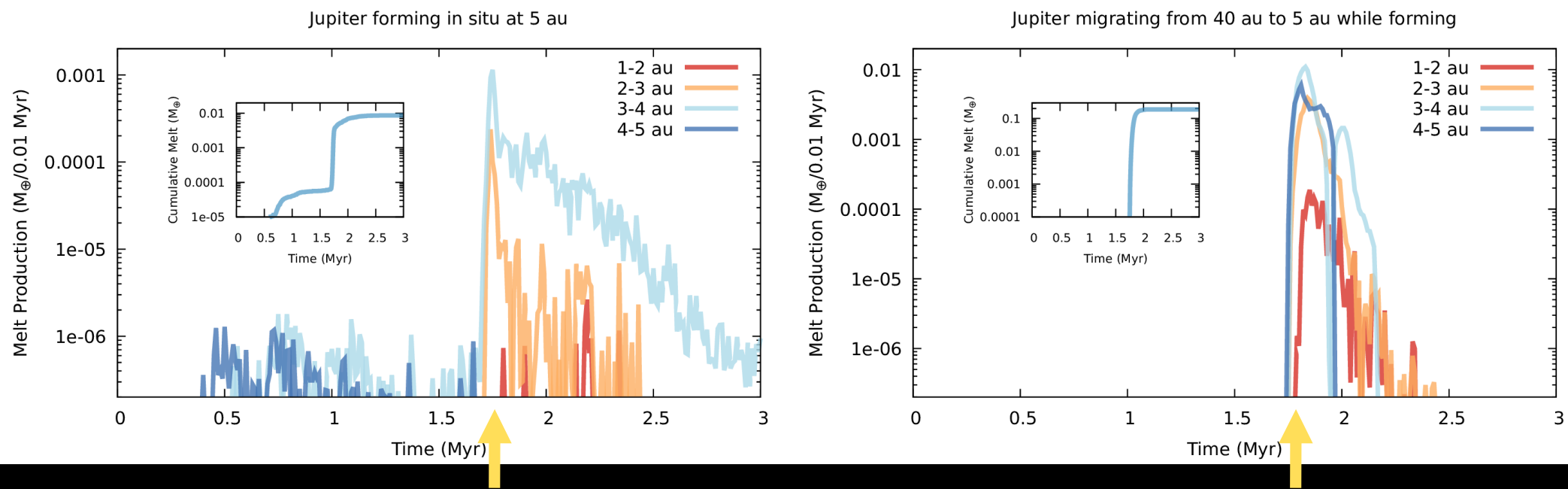
Vapor pressure splashes molten rocks to droplets 0.4–2 mm in diameter  
Droplets cool down by vapor expansion with cooling rate of 30–20,000 K/hr



Schematic illustration of the link between Jupiter's formation and chondrule production by planetesimal impacts.  
Credit: Diego Turrini & Sin-iti Sirono.

# Jupiter's formation and the onset of chondrule production

The chondrule-producing region spans the orbital region between the Earth and Jupiter (1-5 au), with **peak production occurring across the asteroid belt (2-4 au)**.

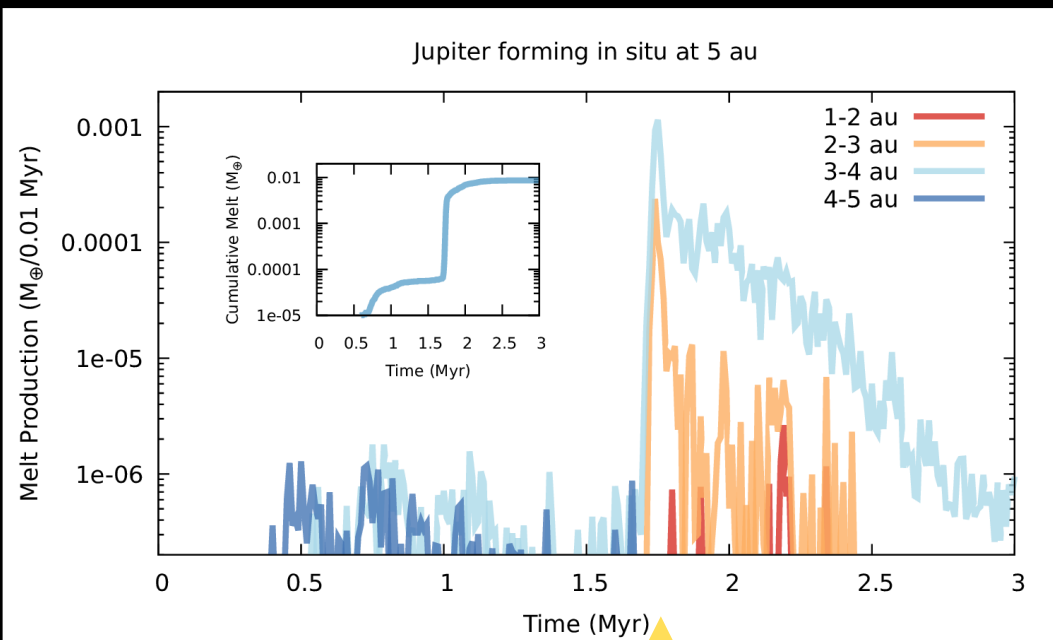


The spike in the chondrule production matches the **onset of the runaway gas accretion by Jupiter**, independently on whether if formed in situ or migrated from the trans-neptunian region.

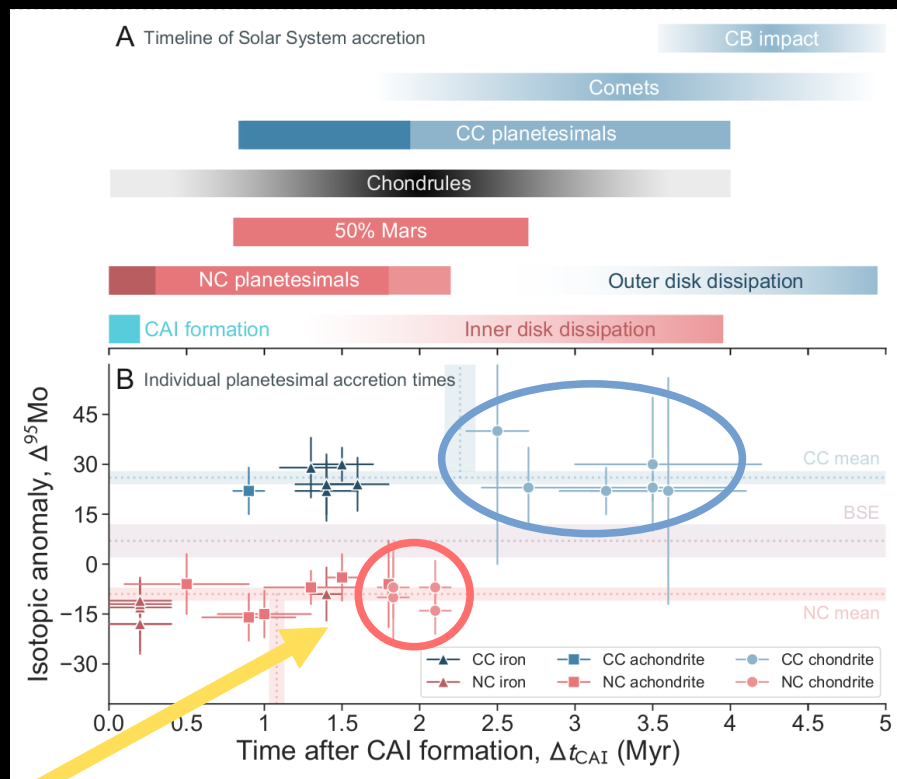


Temporal evolution of chondrule production across the inner Solar System (Sirono & Turrini 2025). Left: Jupiter's in situ formation scenario. Right: Jupiter's extensive migration scenario.

# Timing Jupiter's runaway gas accretion with non-carbonaceous chondrites



Temporal evolution of chondrule production across the inner Solar System in Jupiter's in situ formation scenario (Sirono & Turrini 2025).

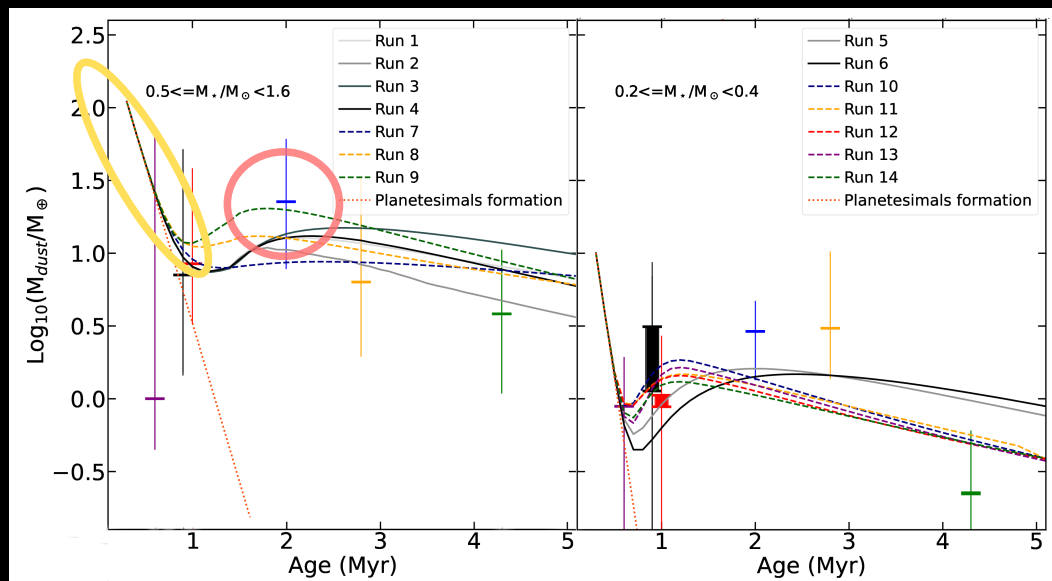


Chronology of solar nebula from radiometric data of meteorites (Lichtenberg+2023)

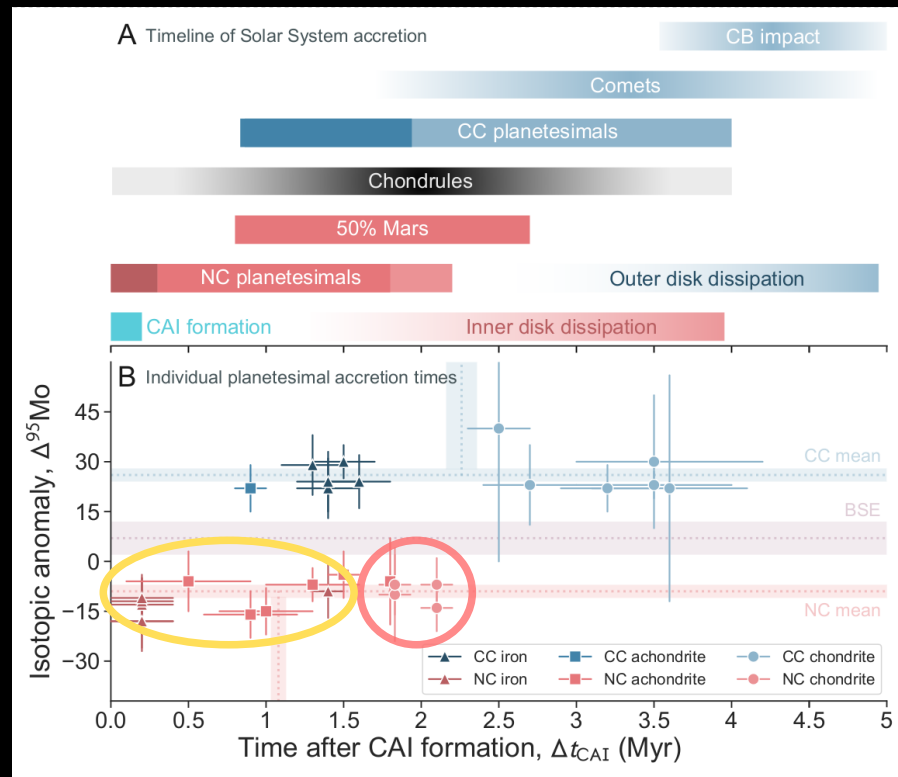
The causal link between Jupiter's formation and chondrule-forming collisions with volatile-rich planetesimals dates Jupiter's formation to **1.8 Myr after CAIs** (Sirono & Turrini 2025 based on chondrule ages from Pape+2018).

# Matching timescales of giant planet formation

Observational evidence of the **early formation of massive planetesimal disks** comes from the **dust evolution** in protoplanetary disks (Turrini+2019; Testi+2022; Bernabò+2022) and from the **formation ages of chondrules** in the Solar System (Sirono & Turrini 2025).

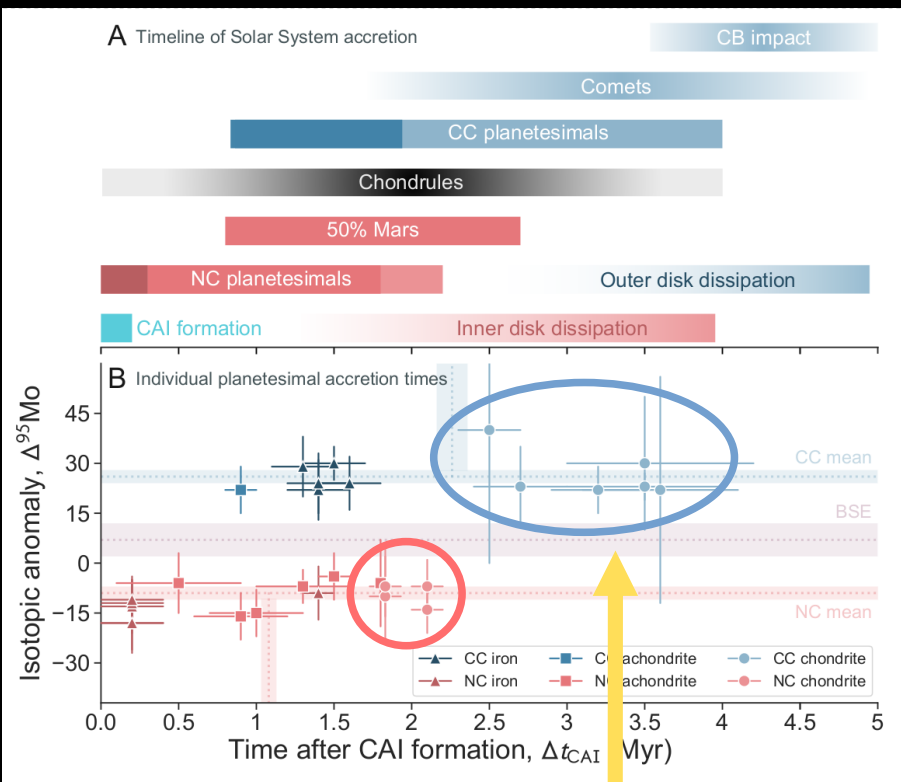


Temporal evolution of the median dust abundances of disks in star forming regions of different ages (Testi+2022) and collisional dust production curves (Bernabò+2022).



Chronology of planetesimal formation in the solar nebula from radiometric data of meteorites (Lichtenberg+2023)

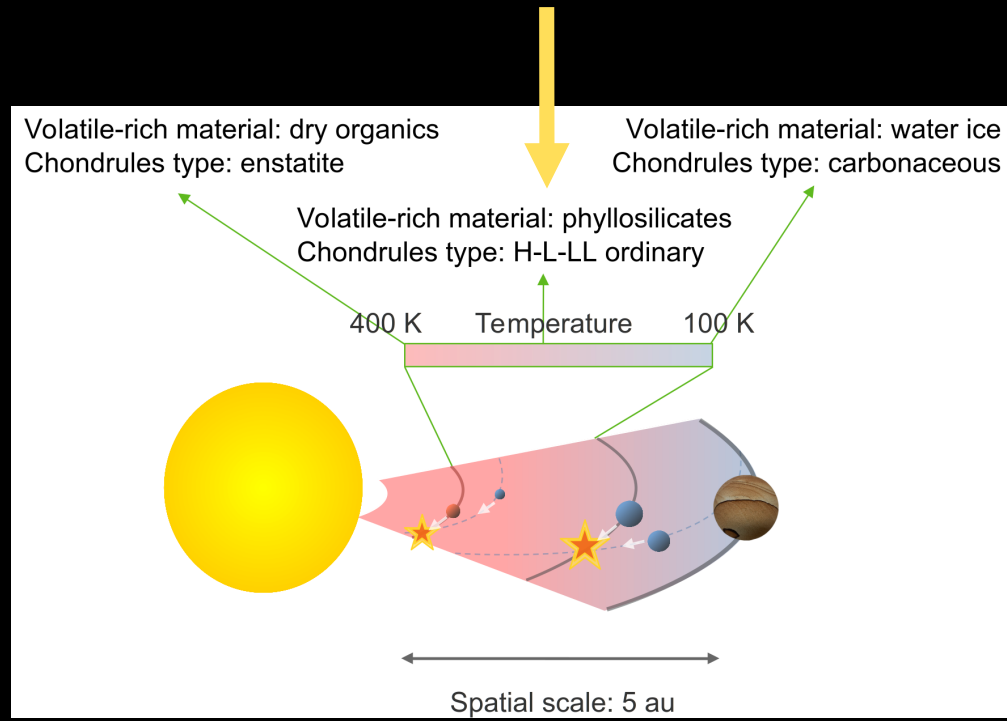
# Temporal and compositional constraints from different chondrule types



Chronology of solar nebula from radiometric data of meteorites (Lichtenberg+2023)

**Carbonaceous chondrules** are produced later and over a wider temporal interval → signature of Saturn's formation?

The different compositional classes of chondrules are explained by their formation in different **astrochemical environments** across the inner Solar System.

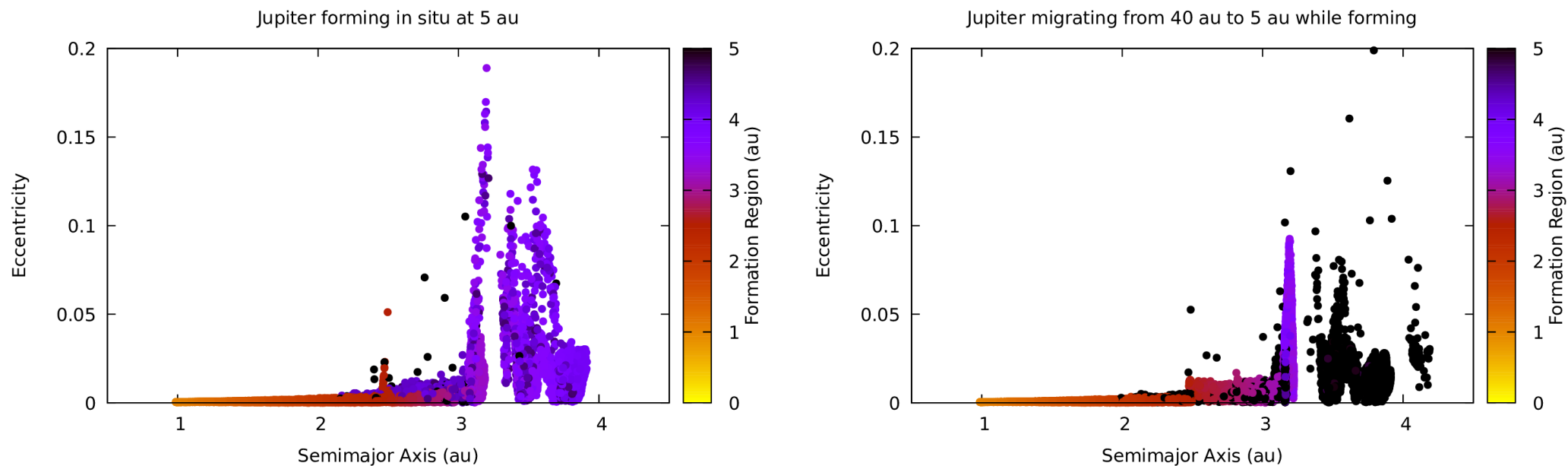


Sketch of the production of the different classes of chondrules across the astrochemical regions of the inner Solar System. Credit: Diego Turrini.



# Asteroid belt compositional structure in the aftermath of Jupiter's formation

The nature of the **volatile-rich planetesimals implanted in the asteroid belt** is different depending on whether Jupiter migrated or not. The presence of ammoniated minerals among asteroids (De Sanctis+2015; Kurokawa+2022) may indicate that Jupiter underwent migration.

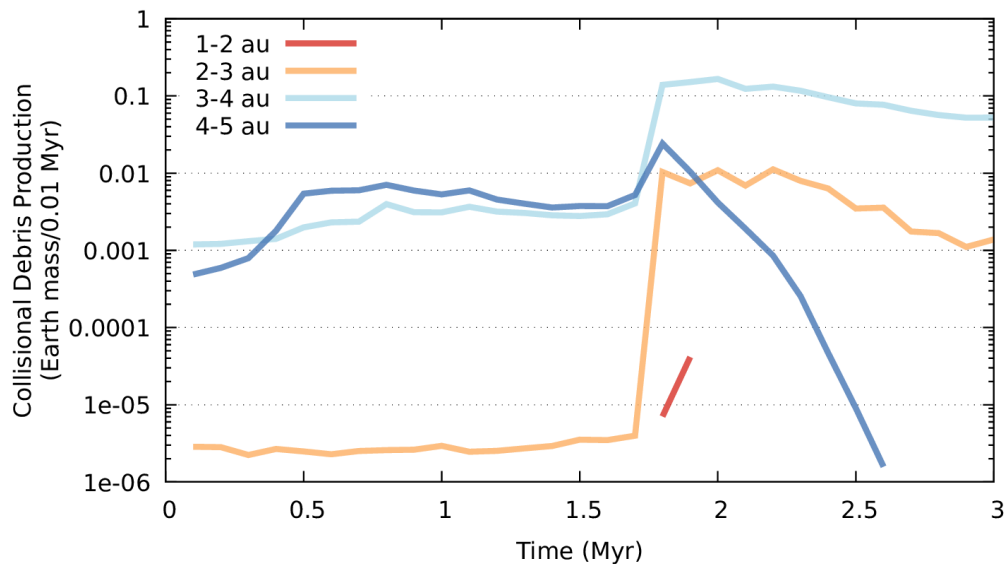


Final compositional structure of the asteroid belt after Jupiter's formation (Sirono & Turrini, 2025, Supplementary Information). Left: Jupiter's in situ formation scenario. Right: Jupiter's extensive migration scenario (in this case, the black color in the color scale marks planetesimals formed beyond 5 au)

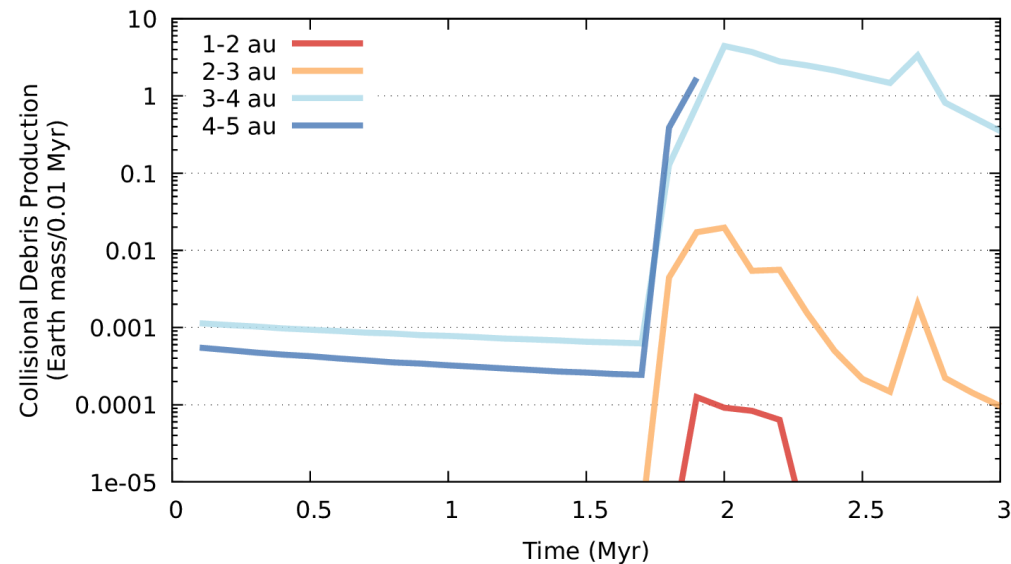
# Sustaining pebble accretion in the inner Solar System

Planetesimal collisions are orders of magnitude more efficient in generating collisional debris than melt. Part of the debris will be in the form of **pebble-sized collisional dust** (Turrini+2019; Wada+2021; Polychroni+2025) capable of **sustaining pebble accretion** after the formation of Jupiter (Turrini+2023; Sirono & Turrini 2025).

Jupiter forming in situ at 5 au



Jupiter migrating from 40 au to 5 au while forming



Collisional debris production from the simulations of Sirono & Turrini, 2025. Left: Jupiter's in situ formation scenario. Right: Jupiter's extensive migration scenario

# Conclusions and take-home messages

1. Jupiter's formation triggered the **production of chondrules** by planetesimal impacts in the Solar Nebula.
2. The Jupiter-chondrule link dates **Jupiter's formation** to **1.8 Myr after CAIs**, predating it by 1-3 Myr with respect to previous attempts (Johnson+2016, Kruijer+2017).
3. Temporal constraints on Jupiter's formation match those on massive planets from **dust resurgence in protoplanetary disks**.
4. Both lines of evidence point to the existence of **massive planetesimal populations** across the extension of the Solar Nebula and protoplanetary disks
5. Ordinary and carbonaceous chondrites provide a window into the **thermal and compositional structure of the Solar Nebula** at 2 Myr.
6. The collisional environment necessary to produce chondrules generates the conditions to **sustain pebble accretion** in the inner Solar System

# Thanks!

For further details:

**Bernabò L.M., Turrini D., Testi L., Marzari F., Polychroni D.,** *Dust Resurgence in Protoplanetary Disks Due to Planetesimal–Planet Interactions.* *ApJL* 927, L22 (2022). <https://doi.org/10.3847/2041-8213/ac574e>

**Sirono, S., Turrini, D.** *Chondrule formation by collisions of planetesimals containing volatiles triggered by Jupiter's formation.* ***Scientific Reports*** 15, 30919 (2025). <https://doi.org/10.1038/s41598-025-12643-x>