Molecules and planets in the outer Galaxy: is there a boundary of the Galactic Habitable Zone?
Florence, Fuligno Cenacle – 12-14 November 2024

The Genetic Link between Planet Formation and the Host Star

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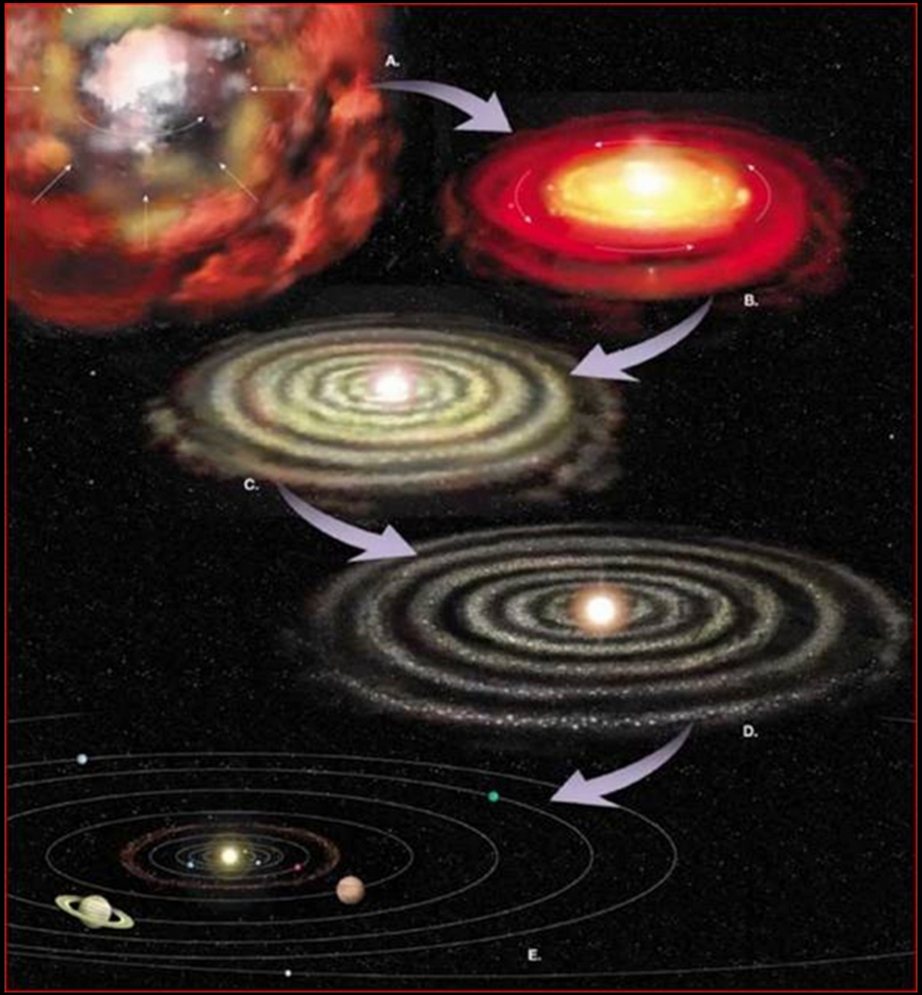
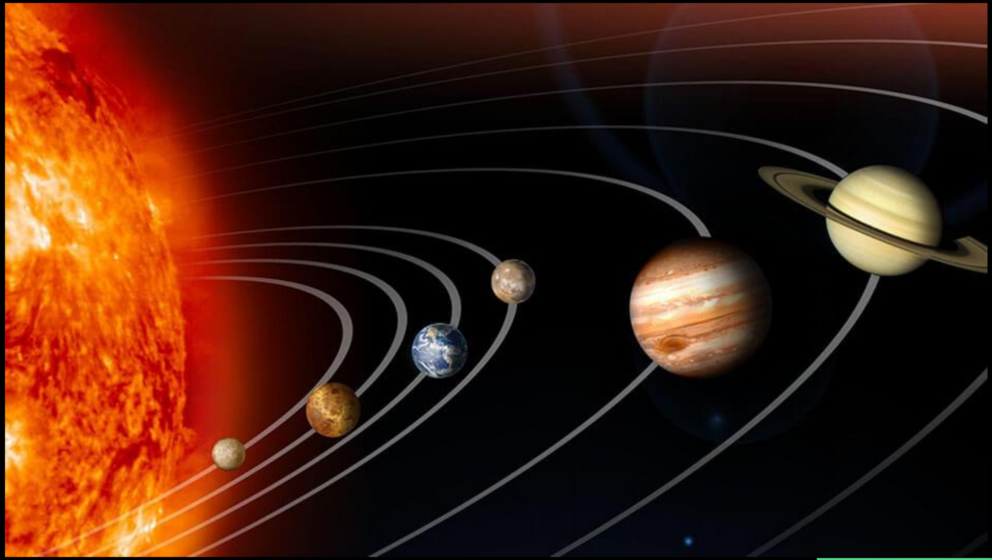
A Problem with a Pedigree

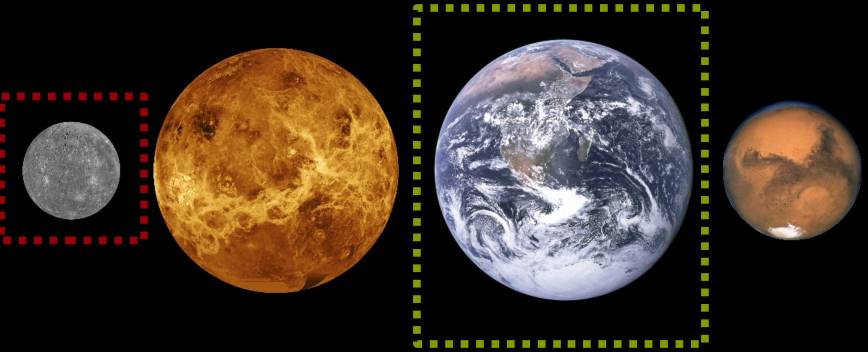


The idea of a genetic connection between star and planet formation dates back to the 18th Century with the solar nebula hypothesis and, in its modern formulation, to the early work of Safronov (1969).

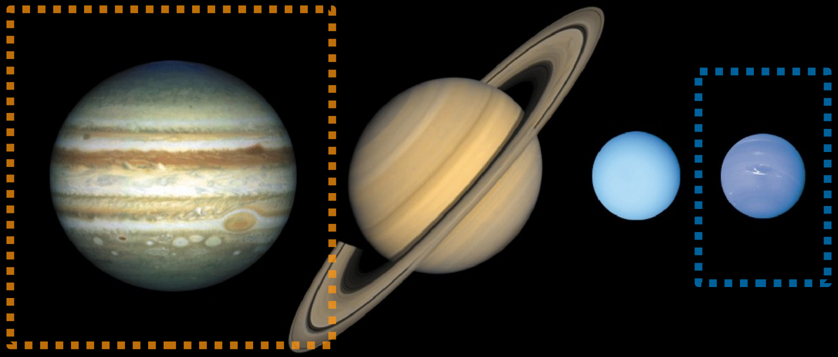
Until the last two decades, however, our view of this connection was shaped solely on the characteristics of the Solar System.



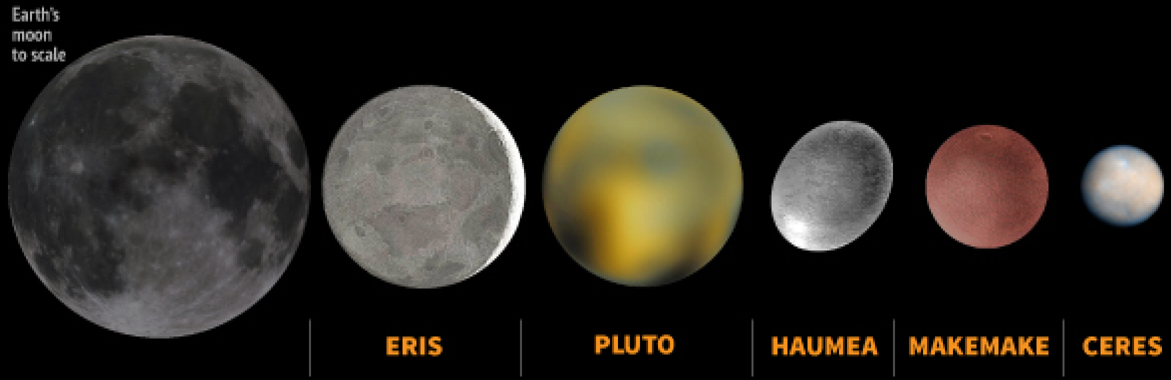
The Diversity of Planets in the Solar System



Terrestrial planets on inner orbits...

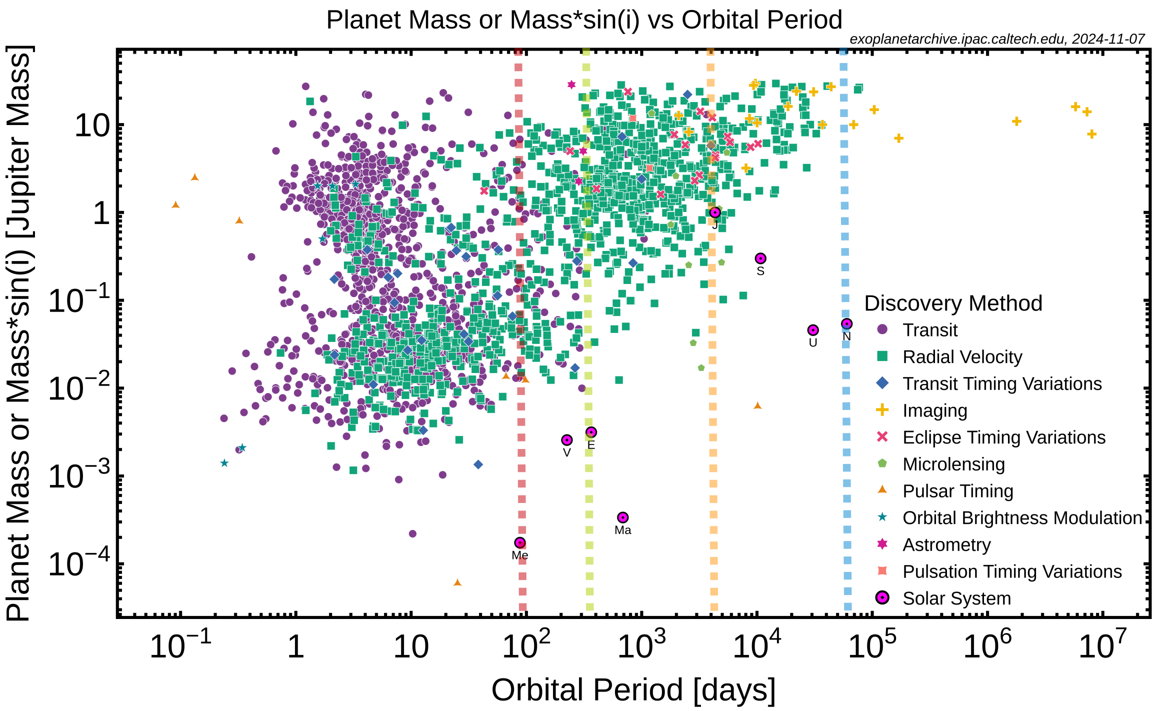


...and giant planets on outer wide orbits



Dwarf planets and minor bodies across most of its extension

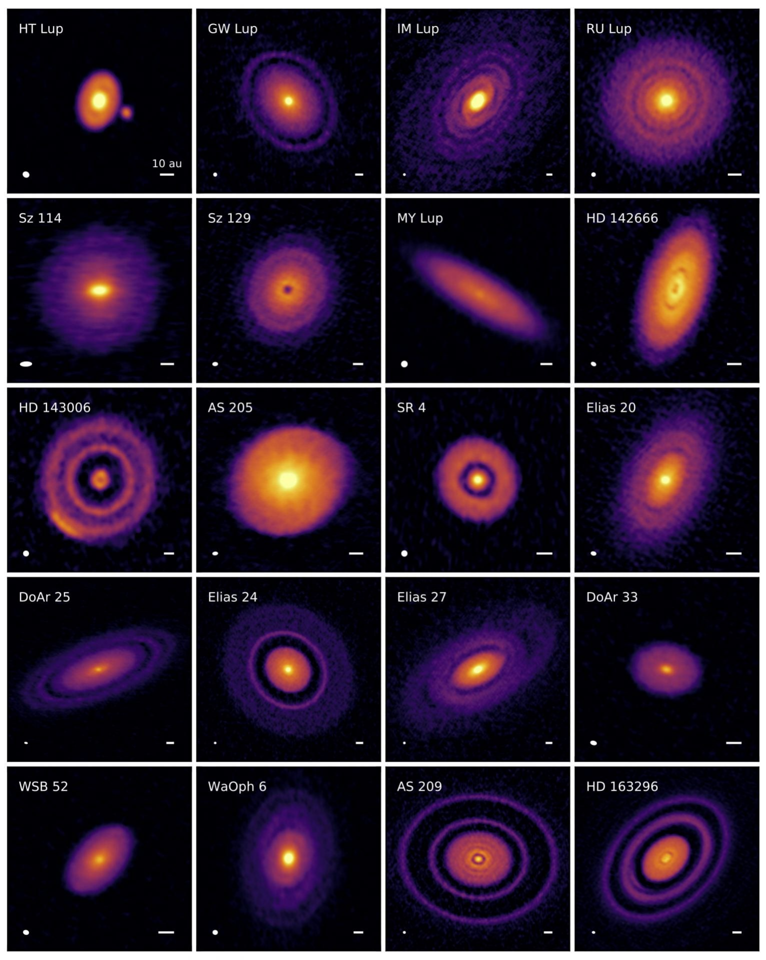
The Diversity of Planets around Other Stars



Exoplanets show a large population of systems with more massive and more compact architectures than the Solar System.

Signature of migration or incomplete understanding of formation process?

The Diversity of Planets in Circumstellar Disks

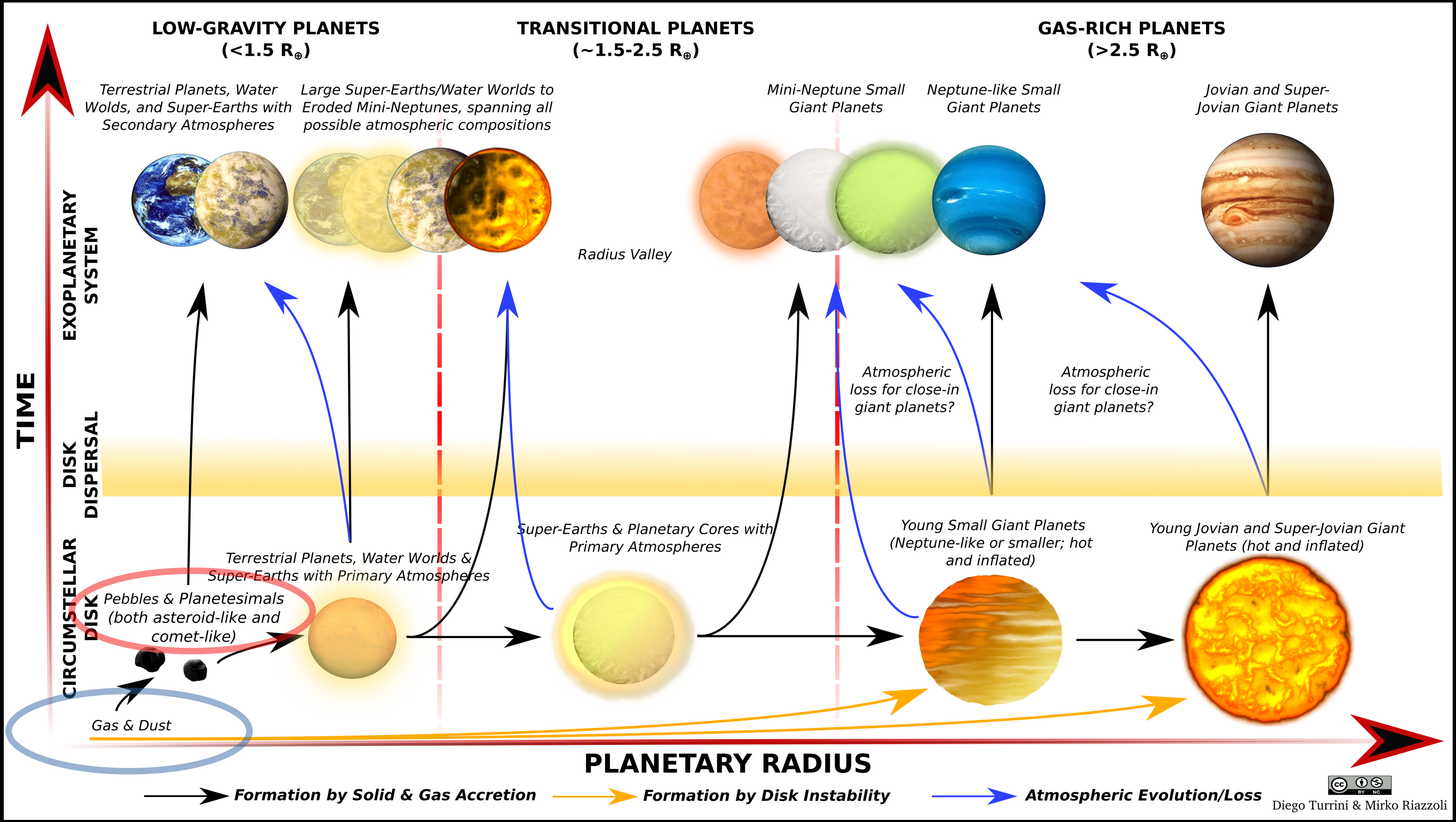


Circumstellar disks observed by the DSHARP Alma Program (Andrews+2018)

The signatures in the dust of circumstellar disks suggest potential young giant planets orbiting from several 10s of au to 100s of au.

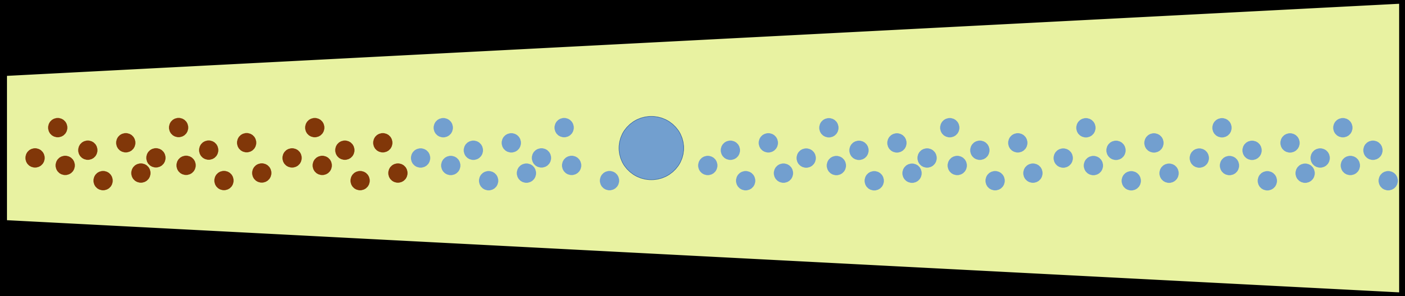
Different formation mechanism or incomplete understanding of migration?

Forming the Family of Planets

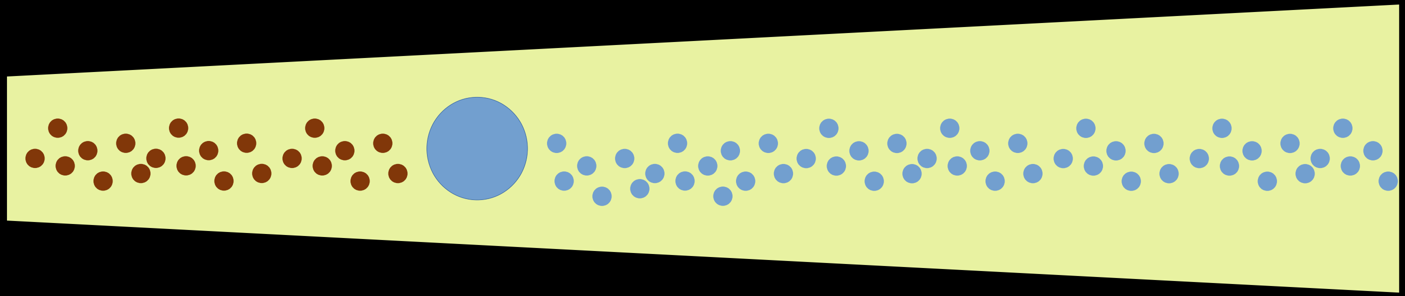


Pebble Accretion - Fundamentals

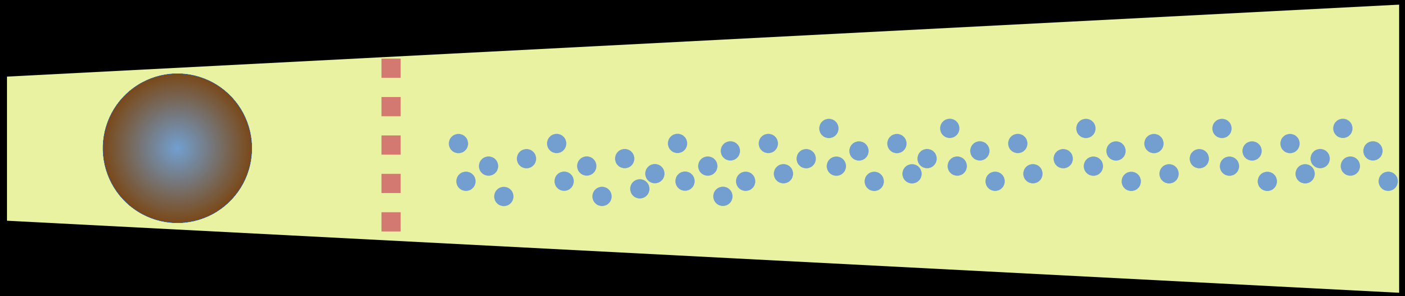
Early-formed planetesimals are embedded into a continuous flux of dust and grow by its capture.



Planets that grow beyond the Earth mass start migrating across the disk while growing.



Massive planets create pressure bumps in the disk gas that halt the dust flux and stop growth.



Beyond the Pebble Isolation Mass

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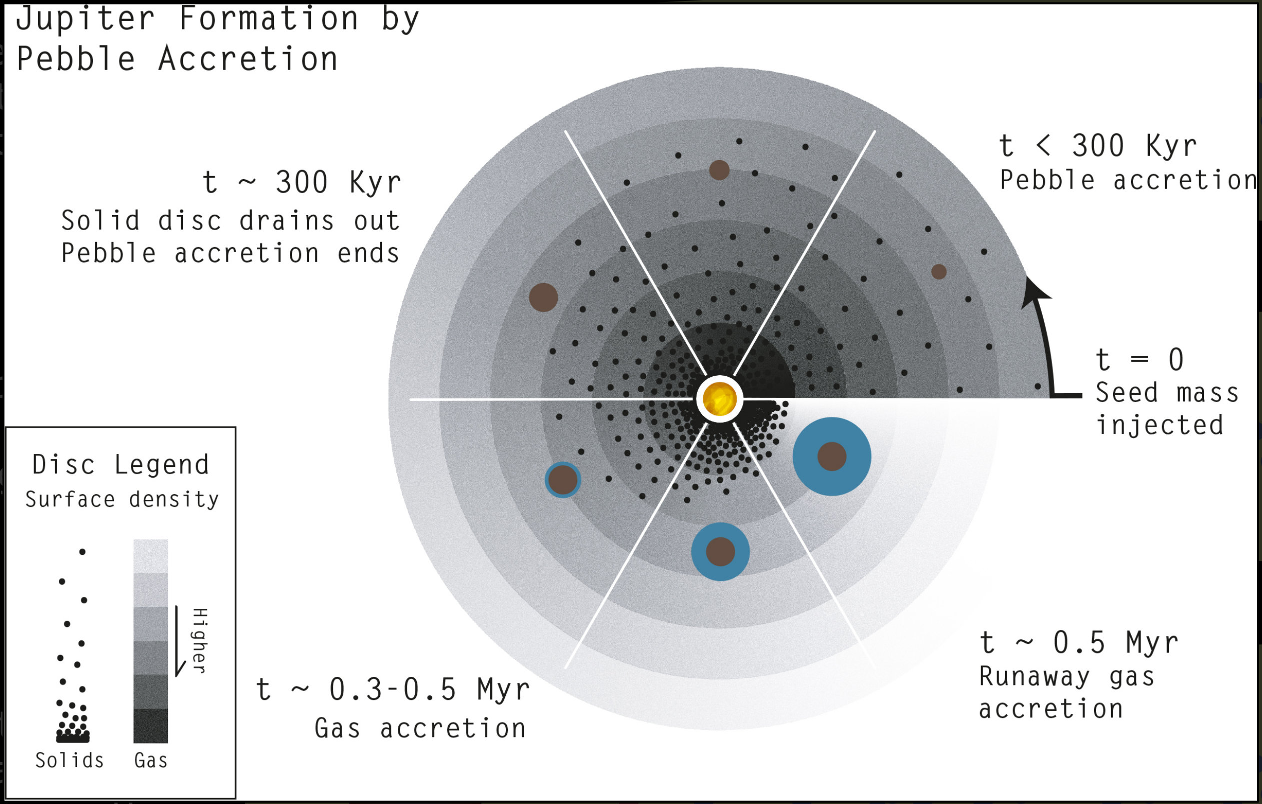
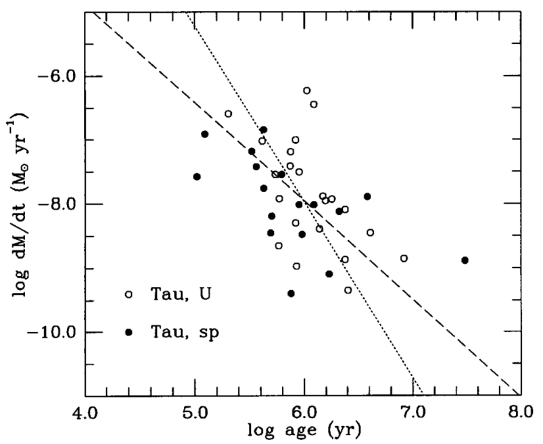


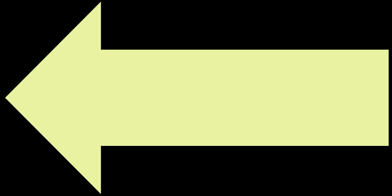
Sketch of the formation process of giant planets by pebble accretion (Lin+2018).

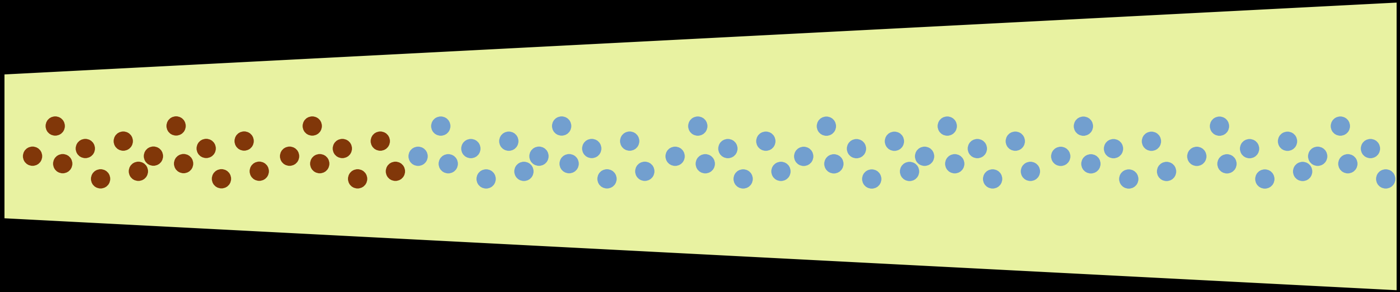
Pebble Flux - Fundamentals

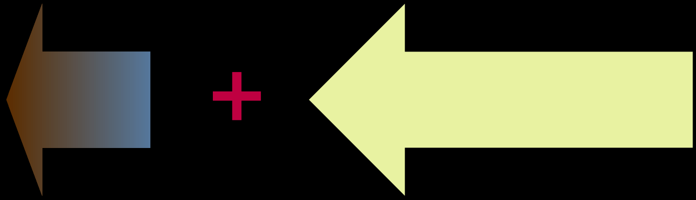


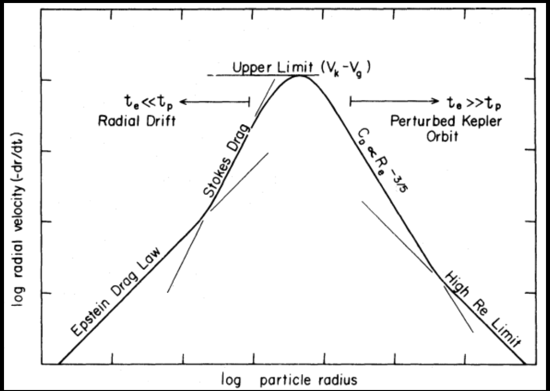
Mass accretion rate evolution over time (Hartmann+1998)

The gas accretion rate of the disk onto the star sets the inward drift of the gas









Radial drift from aerodynamic drag (Weidenschilling 1977)

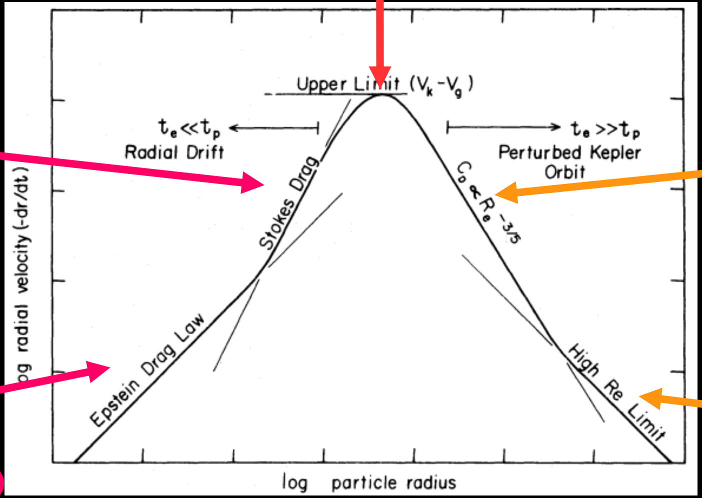
The dust drift rate is set by the combination of the inward drift of the gas and the relative drift of the dust w.r.t. the gas due to aerodynamic drag.

Aerodynamic Drag: Dust vs Pebbles vs Planetesimals

"Meter Barrier"

Pebbles
(mm to cm)

Small Planetesimals
(sub-km to km)

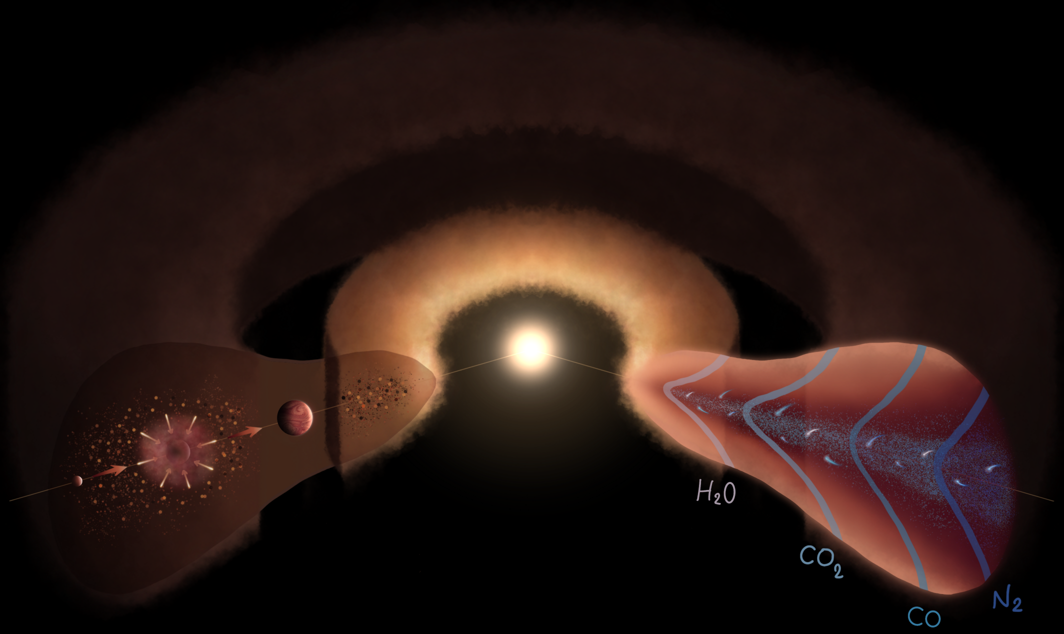


Primordial dust
(micron to sub-mm)

Large Planetesimals
(10 – 100 km)

Radial drift velocity of solids embedded in the disk gas as a function of their size (figure from Weidenschilling 1977)

Pebble Accretion and Solids Abundance

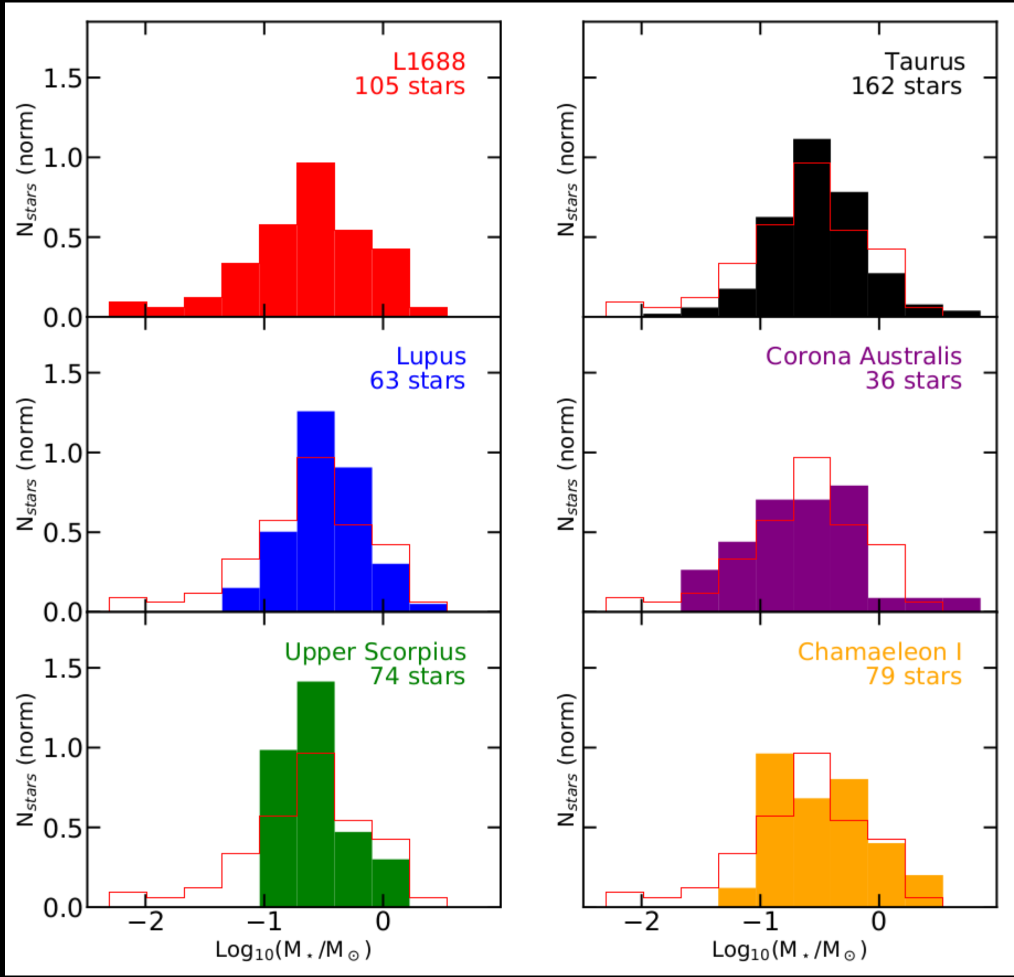


Illustrative sketch of the physical and chemical processed shaping disk evolution and planet formation (credits: Elenia Pacetti).

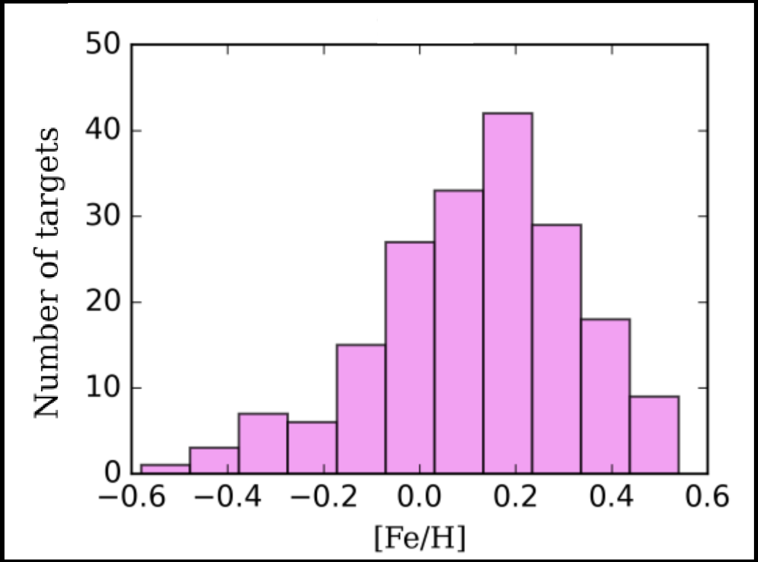
The key factor in shaping the growth of planets by pebble accretion is the pebble flux across the circumstellar disks (e.g. Johansen & Lambrechts 2017 and references therein)

Most studies focus on the roles of the stellar metallicity and the disk condensation sequence in controlling the amount of pebbles available to form planets (e.g. Bitsch+2018; Johansen+2019; Schneider & Bitsch 2021a,b; Drazkovska+2023).

The Diversity of Stars



Distribution of stellar masses in different star forming regions (Testi+2022)

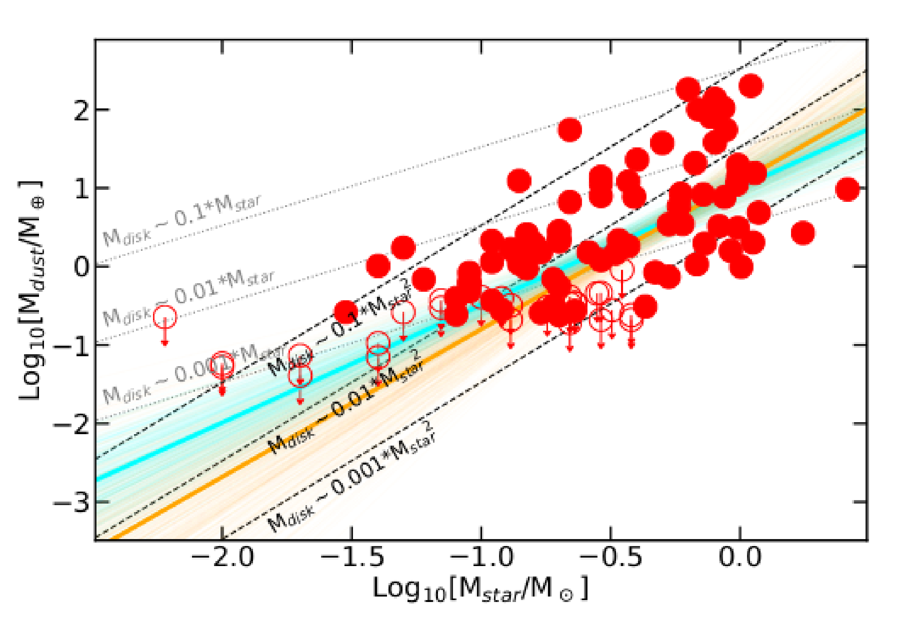


Distribution of stellar metallicities for planet-host stars from the Ariel mission sample (Magrini+2022)

The spread in stellar metallicity impact the abundance of solid material.

The spread of stellar masses impacts the characteristics of the circumstellar disks.

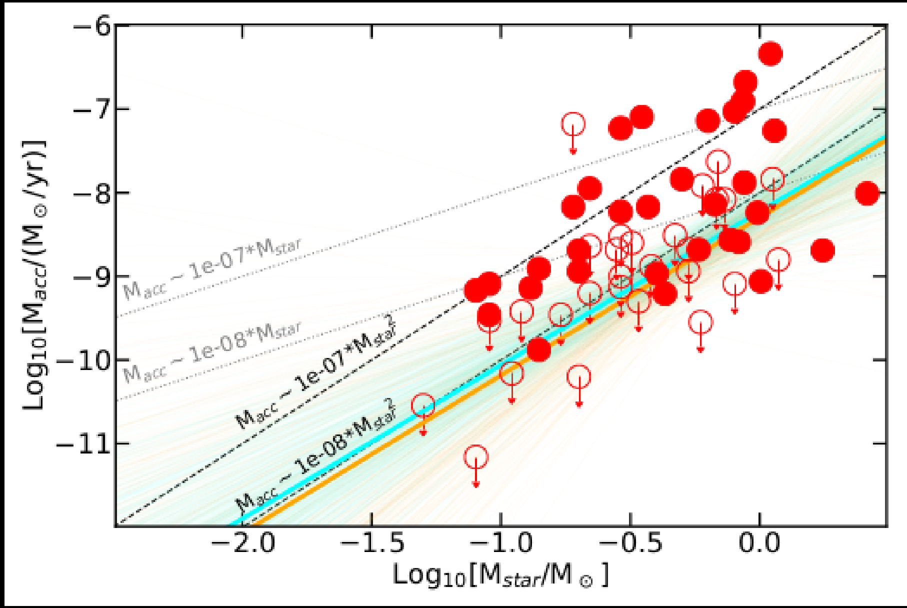
The Star-Disk Genetic Link



Correlation between stellar mass and disk mass (Testi+2022)

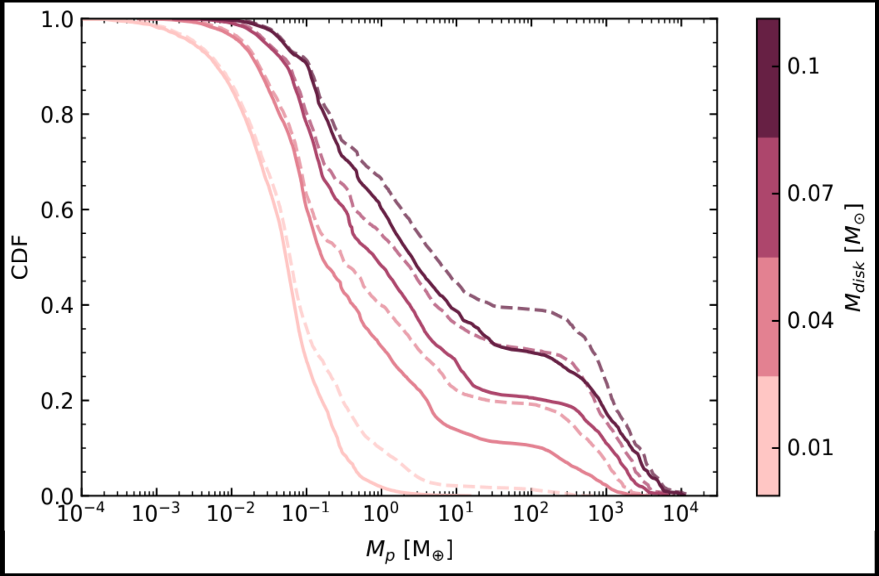
Disk mass and gas accretion rate are proportional to the stellar mass (e.g. Pascucci+2016; Testi+2022; Manara+2023 and references therein).

Disks with different masses and accretion rates translate into different pebble accretion efficiencies around stars with the same mass.

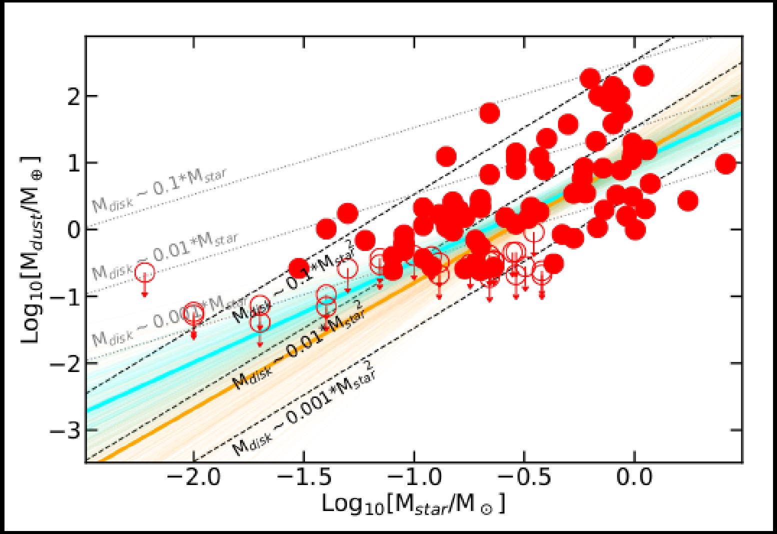


Correlation between stellar mass and disk mass accretion rate (Testi+2022)

Disk Mass and Planet Formation Efficiency



Cumulative distributions of planetary masses as a function of the disk mass and stellar metallicity (Savvidou & Bitsch 2023)

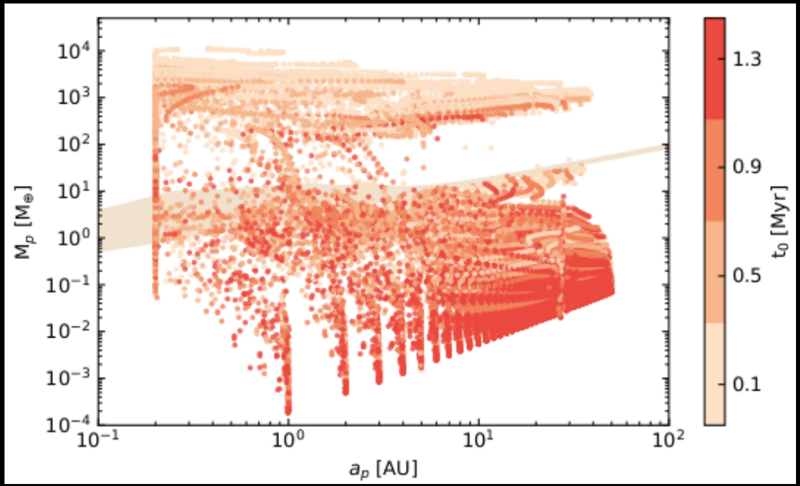


Correlation between stellar mass and disk mass (Testi+2022)

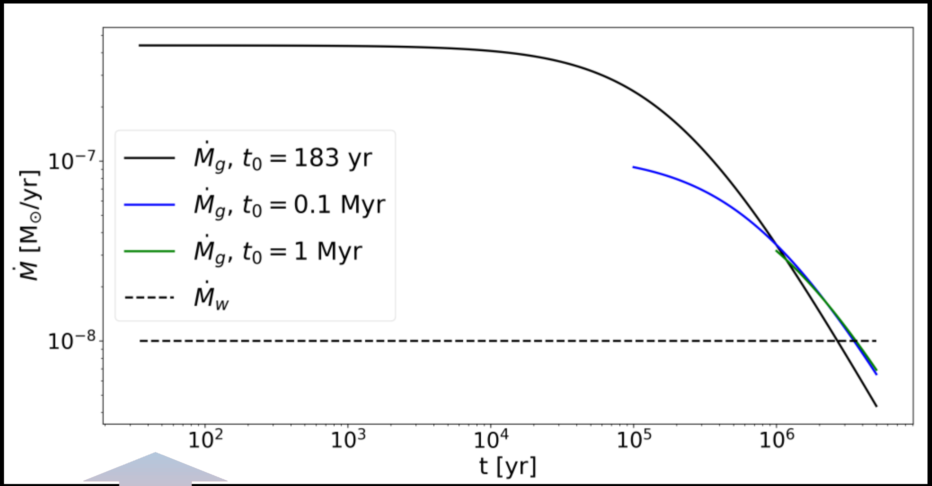
The spread in disk masses impacts the efficiency in forming planets more massive than the Earth and giant planets (e.g. Savvidou & Bitsch 2023). This effect stack with that due to the spread of stellar metallicities (e.g. Savvidou & Bitsch 2023).

We can only constrain the average disk mass from the knowledge of the star, implying a degeneracy in reconstructing the formation history of its planets.

Mass Accretion Rate and Planet Formation Timescale



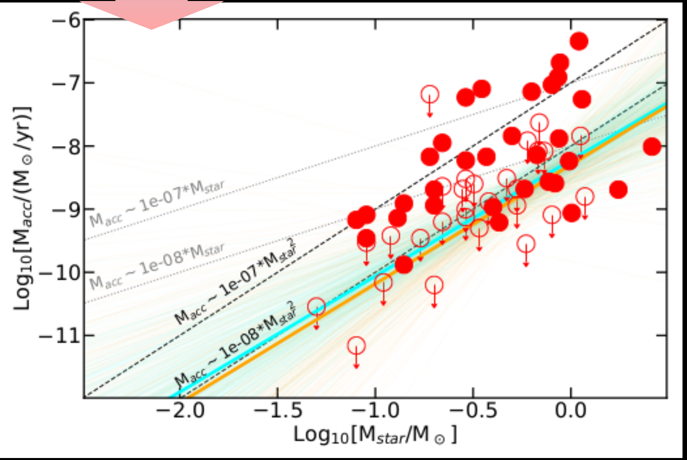
Planetary population for different starting times of pebble accretion in the disk lifetime (Savvidou & Bitsch 2023)



Evolution of the disk mass accretion rate over time (Ledda+2023)

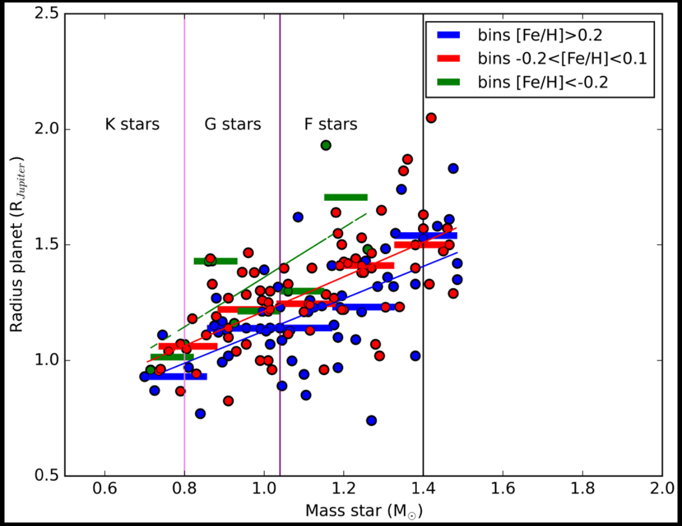
The gas accretion rate of circumstellar disks decays over time.

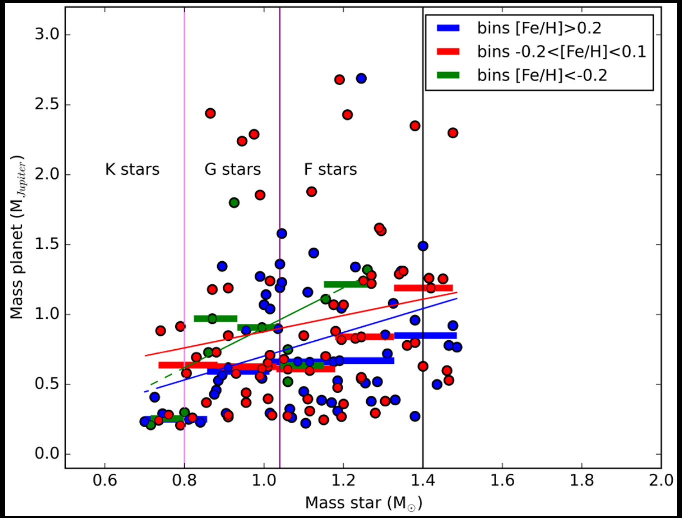
The time at which planet formation starts controls the kind of planets that can be formed.



Right: correlation between stellar mass and disk mass accretion rate (Testi+2022)

Temporal Dimension in Star-Planet Correlations



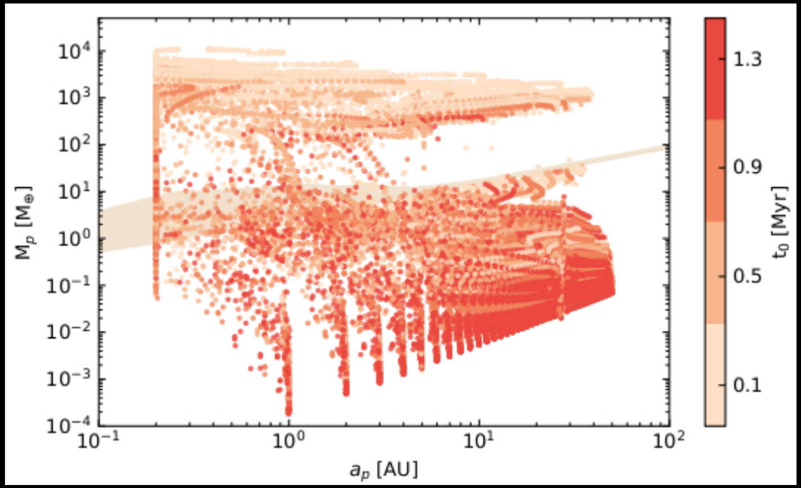


Young disks have higher gas accretion rates that support the formation of giant planets even in low-metallicity environments. (Magrini+2022; Tsantaki+submitted).

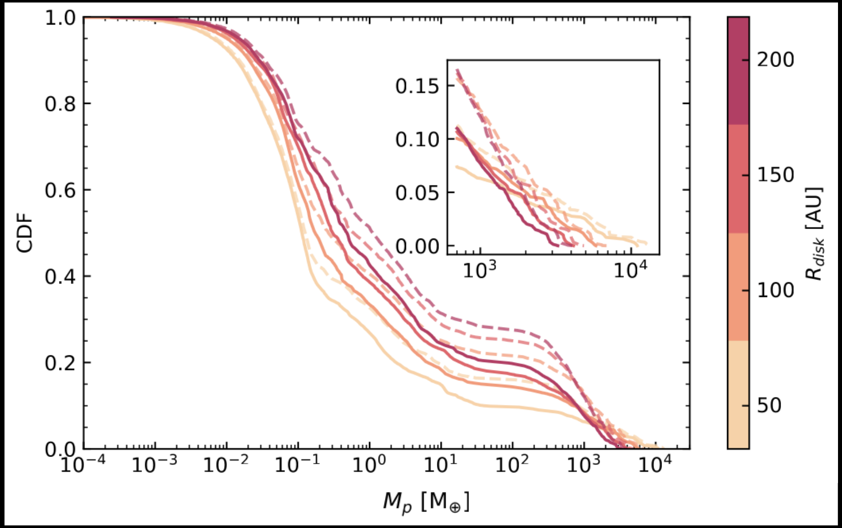
Late disks can continue forming giant planets in higher-metallicity environments, but with comparatively lower final masses than younger disks.

Left: planetary radius (top) and mass (bottom) as a function of stellar mass for different stellar metallicities (Magrini+2022)

Right: planetary population for different starting times of pebble accretion (Savvidou & Bitsch 2023)



Disk Parameters and Planet Formation

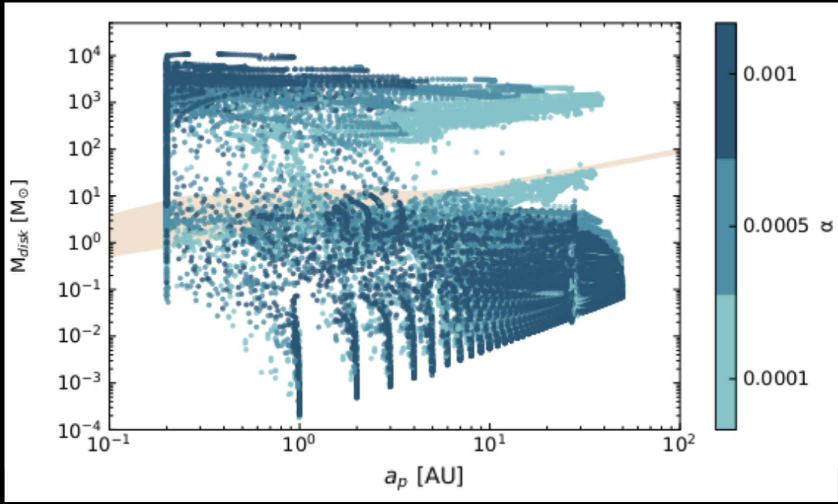


Cumulative distributions of planetary masses as a function of disk radius and stellar metallicity (Savvidou & Bitsch 2023)

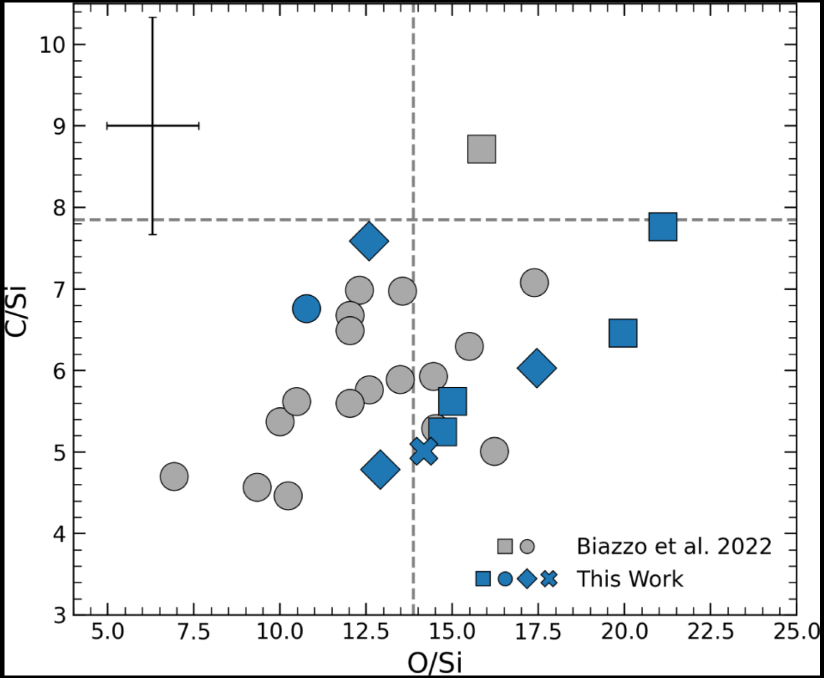
The disk extension controls the density of the dust and the time available for pebble accretion during migration.

The disk turbulent viscosity controls the vertical extension of the pebble layer and the pebble accretion rate.

Right: planetary population for different disk turbulent viscosity values (Savvidou & Bitsch 2023)



Stellar Composition and Pebble Accretion



O/Si ratio for high mass giant planets (circles), low mass giant planets (squares) and mixed systems (diamonds) from Filomeno+2024.

Pebble accretion is controlled by the flux of condensed heavy elements, which is controlled by Z and not by [Fe/H].

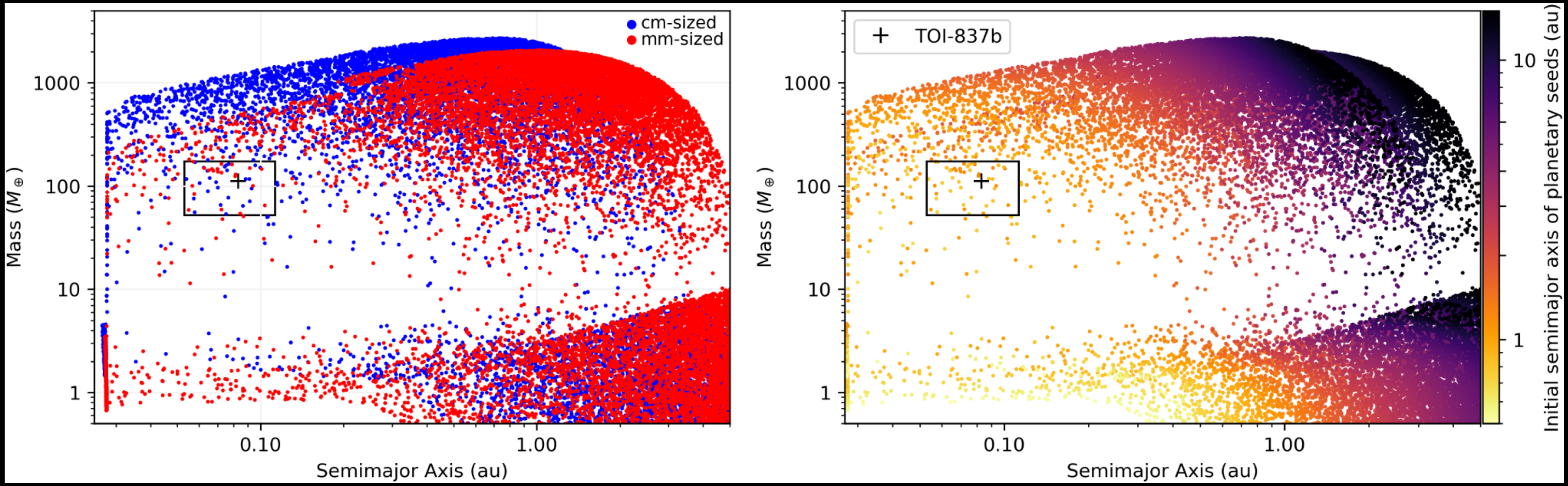
Low-mass giant planets favour more O-rich stars with respect to their more massive counterparts (Biazzo+2022; Filomeno+2024).

Increasing the O abundance increase temporal window where pebble accretion is effective and allow for the late formation of low-mass giant planets (Biazzo+2022; Filomeno+2024).

	Type of Planet	O-Enriched disk	Solar disk
N° of planets formed	5–30 M_E	5931	2413
	30–954 M_E	10 974	7604
Relative abundance	5–30 M_E	35%	24%
	30–954 M_E	65%	76%
5–30 M_E	< 1 Myr	70%	76%
	> 1 Myr	30%	24%
30–954 M_E	< 1 Myr	56%	60%
	> 1 Myr	44%	40%

Statistics for population synthesis simulations with solar composition and O-enriched disks (Filomeno+2024)

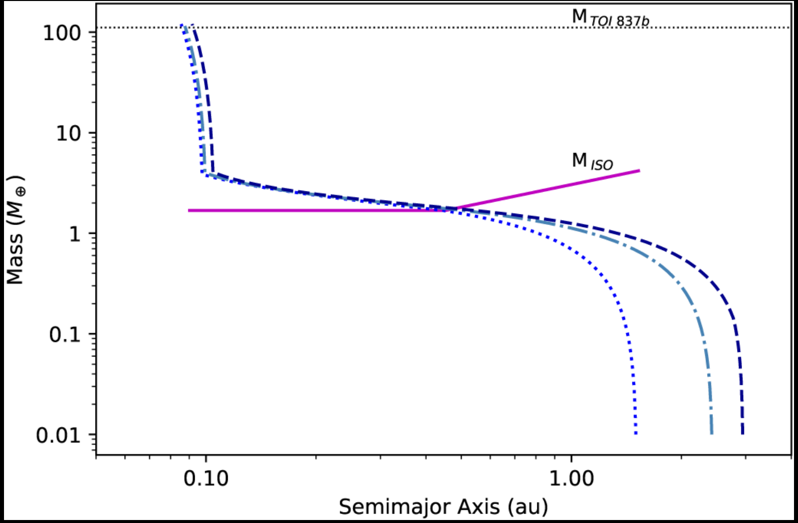
Retrieving Planet Formation Histories



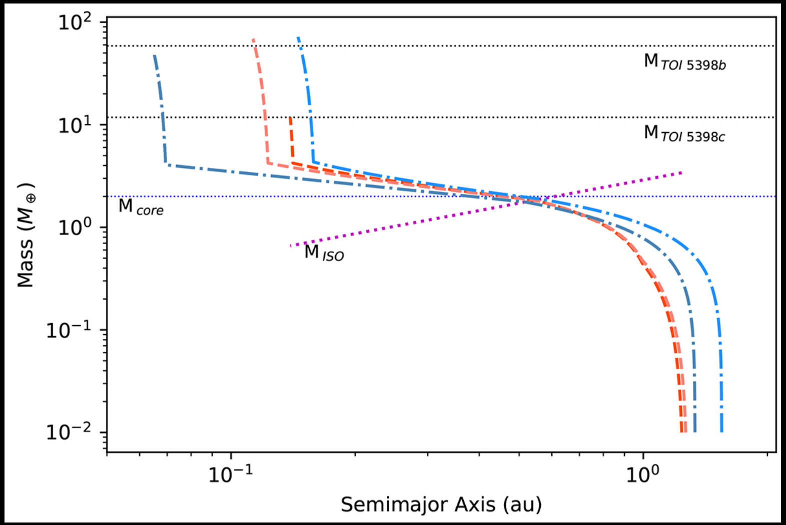
Planetary population synthesis simulations for different pebbles sizes (left) and initial formation region (right) and comparison with the present characteristics of the young Saturn TOI-837b (Damasso+2024)

The genetic link between star and planet formation in pebble accretion allows to use population synthesis models to *retrieve* the range of possible formation histories, although it is a high-dimensionality problem.

Informing Atmospheric Observations



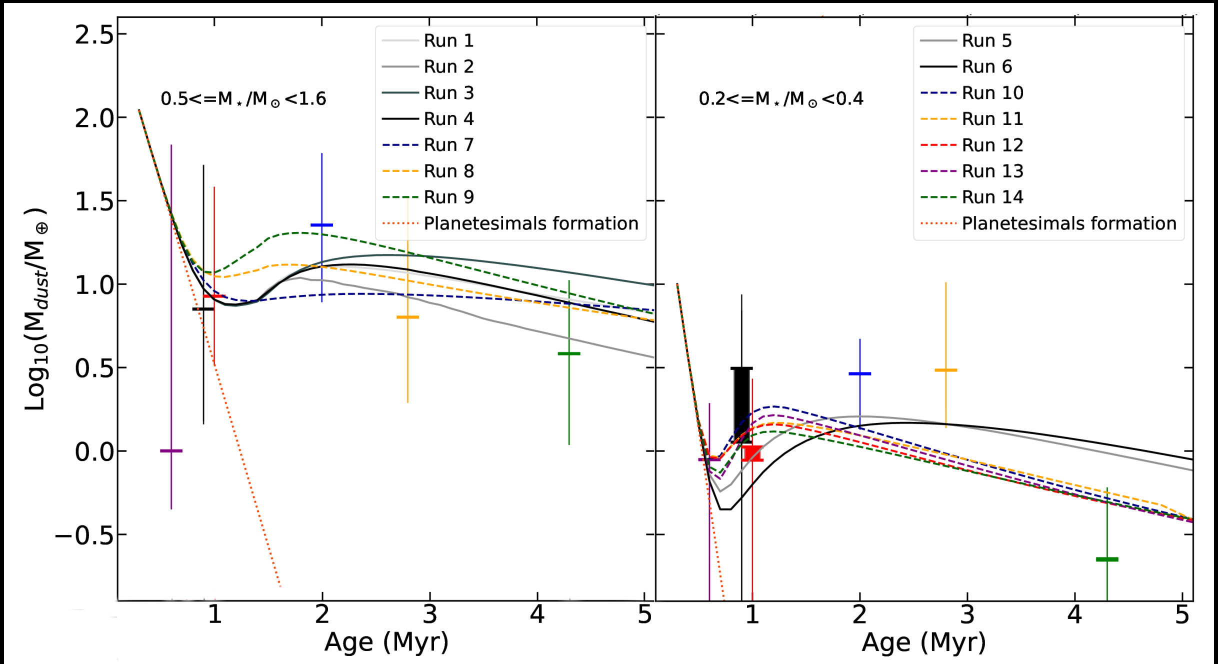
Possible planet formation tracks and core masses for the young Saturn TOI-837b (Damasso+2024)



Possible planet formation tracks and core masses for the two planets around TOI-5398 (Mantovan+2024)

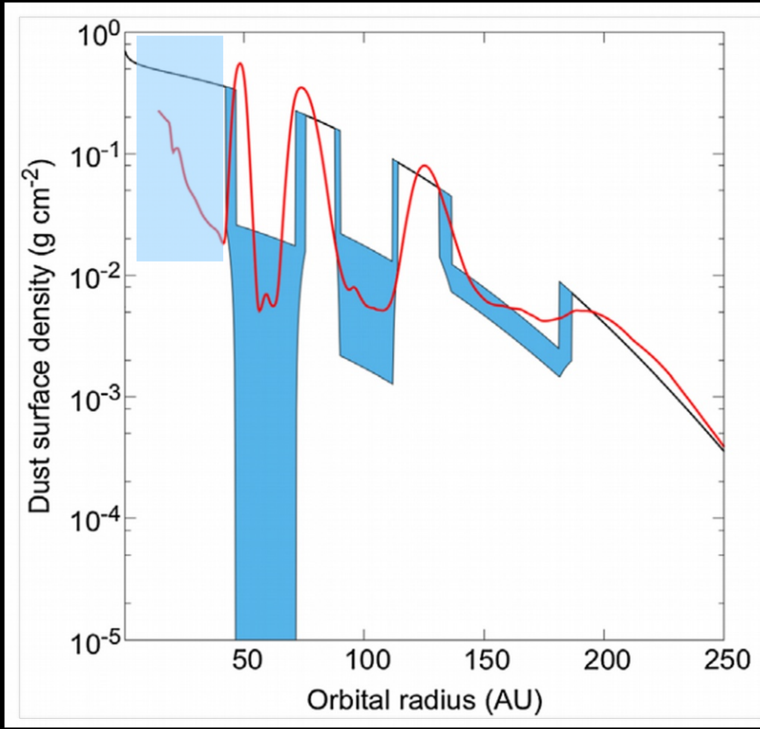
The retrieved formation histories can be used for differential predictions to guide atmospheric characterization studies and in support of comparative planetology studies of multi-planet systems (e.g. Mantovan+2024; Damasso+2024; Naponiello+in press).

Not Only Pebbles…



Temporal evolution of the median dust abundances of disks in star forming regions of different ages (Testi+2022; Bernabò+2022)

Observed (grey) and expected (red) dust surface density for the disk around HD 163296 (Isella+2016)



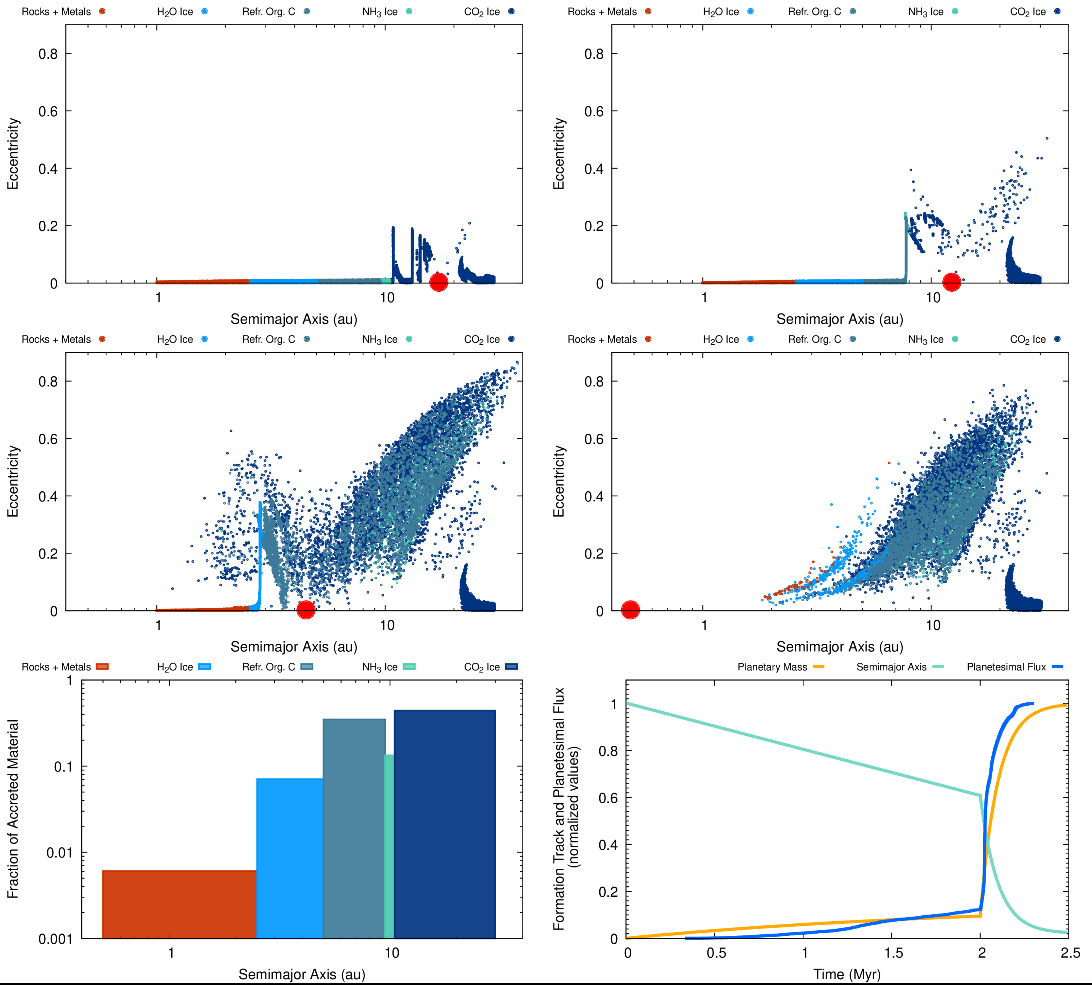
Population studies of disks show unexpected increases of the dust abundances in mature disks (e.g. Isella+2016; Testi+2022).

Planetesimal collisions can explain this behaviour while pebble-dominated disks cannot (Turrini+2019; Bernabò+2022).

Planetesimal Disks and Migrating Giant Planets

The accretion of planetesimals is the source of elements more refractory than O and C in the envelopes of giant planets (Turrini+2021; Schneider & Bitsch 2021; Pacetti+2022; Crossfield 2023).

Migrating planets cause the compositional remixing of the planetesimal disk. Later-formed planets are born in compositionally-altered environments.

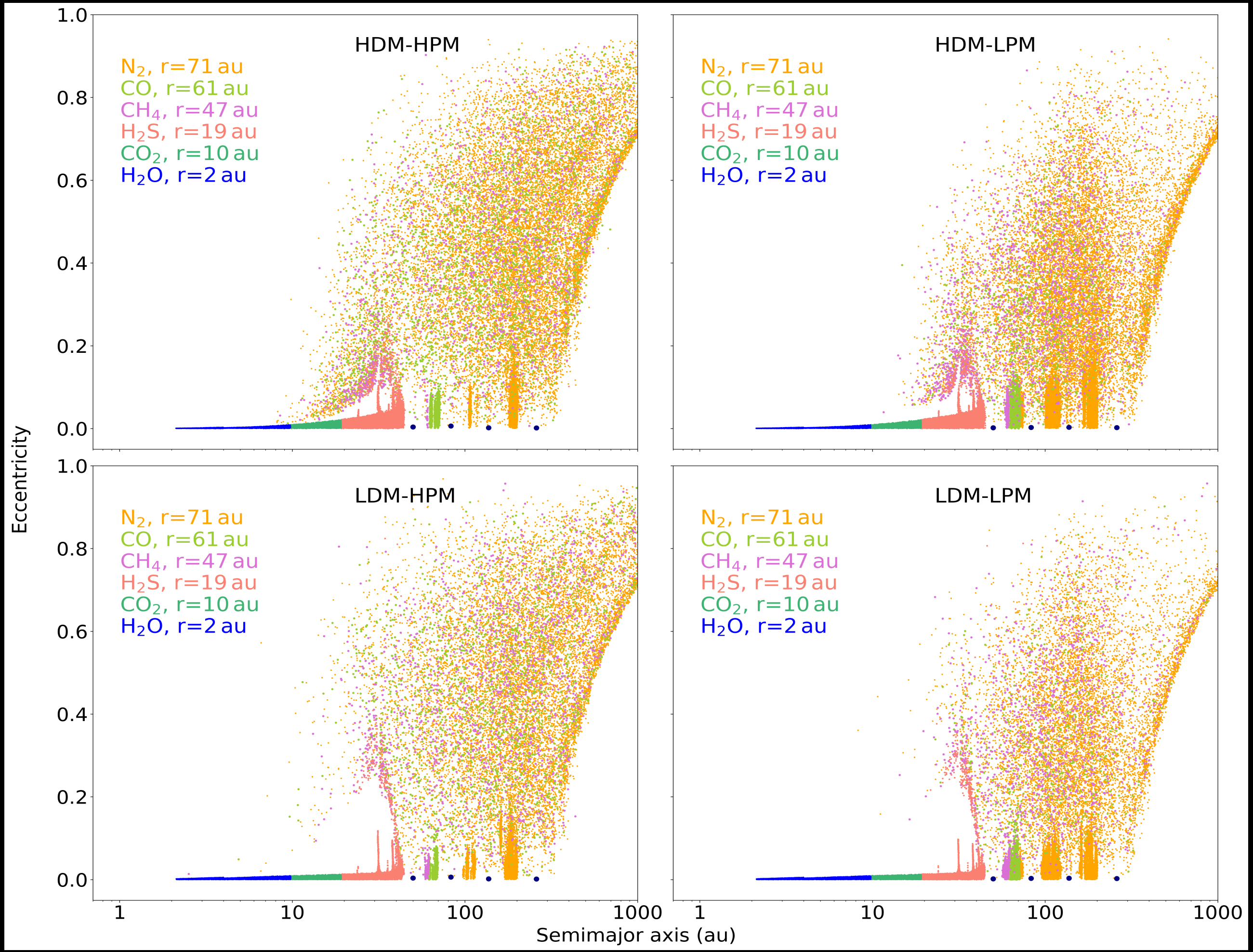


Growth, migration and accretion of planetesimals by a forming hot Jupiter (Pacetti+2022 based on the planet formation simulations from Turrini+2021).

Planetesimal Disks and Multi-Planet Systems

Around the Sun: Jupiter's formation compositionally remixed the nebula and delivered water to the inner Solar System (Turrini+2014; Raymond+2017; Ronnet+2018; Pirani+2019).

In circumstellar disks: giant planets in outer disk regions scatter planetesimals and alter the composition of inner disk regions (Turrini+2019; Polychroni+in prep.).



Dynamical excitation and compositional remixing of planetesimals in HD163296's circumstellar disk (Polychroni+in preparation).

Take Home Messages

Planet formation is shaped by the characteristics of the native circumstellar disk and host star

Star-disk correlations help us constrain the initial conditions and their uncertainty

Star-planet correlations encode information on the planet formation process

The *outcome of planet formation* is a matter of both *when* and *where*

Planet formation alters the disk environment

The *first planets* to form affect the formation of later planets

Fascinating interdisciplinary topic, sure, but… dear god if it is bloody complex!