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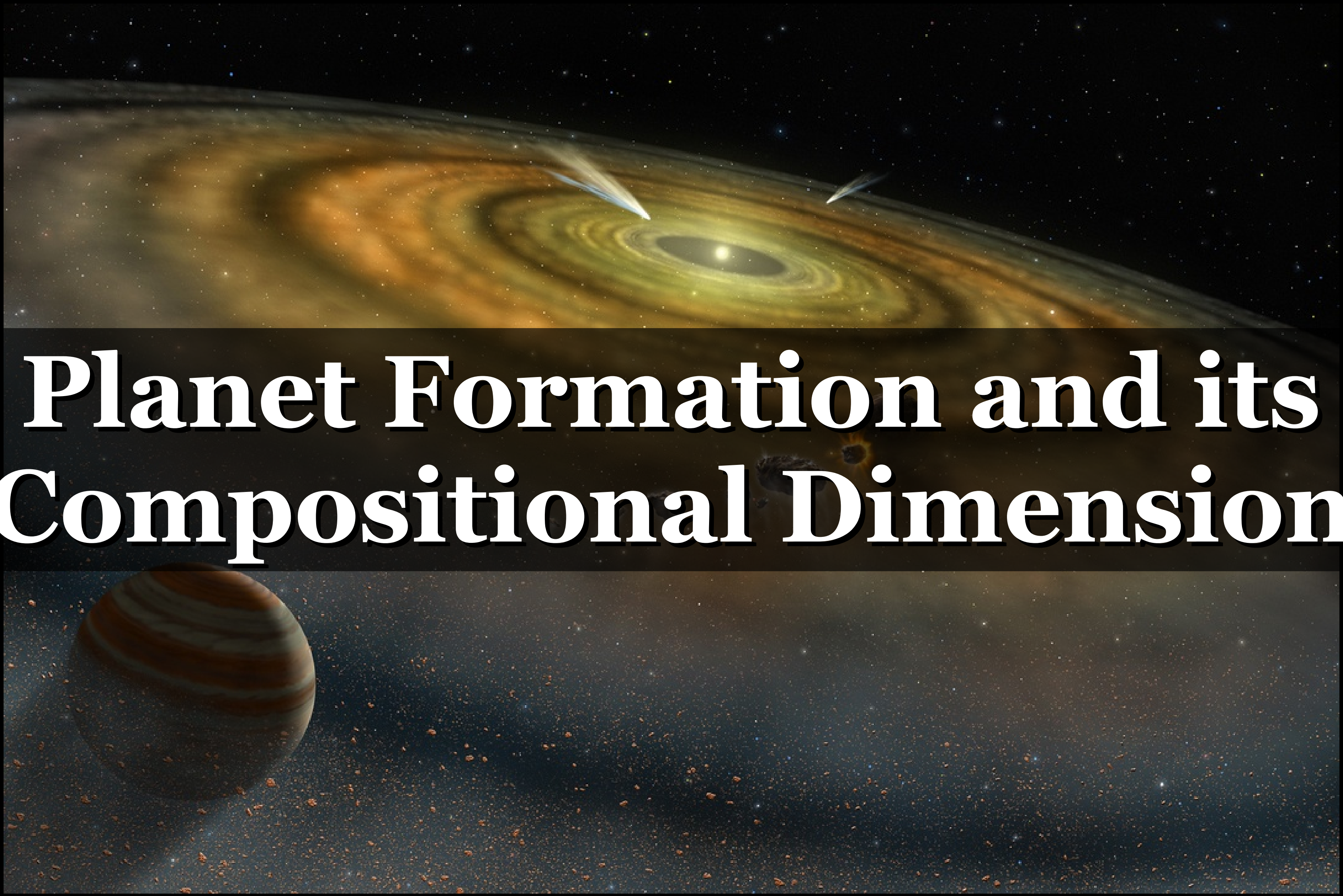
Planet Formation and its Compositional Dimension

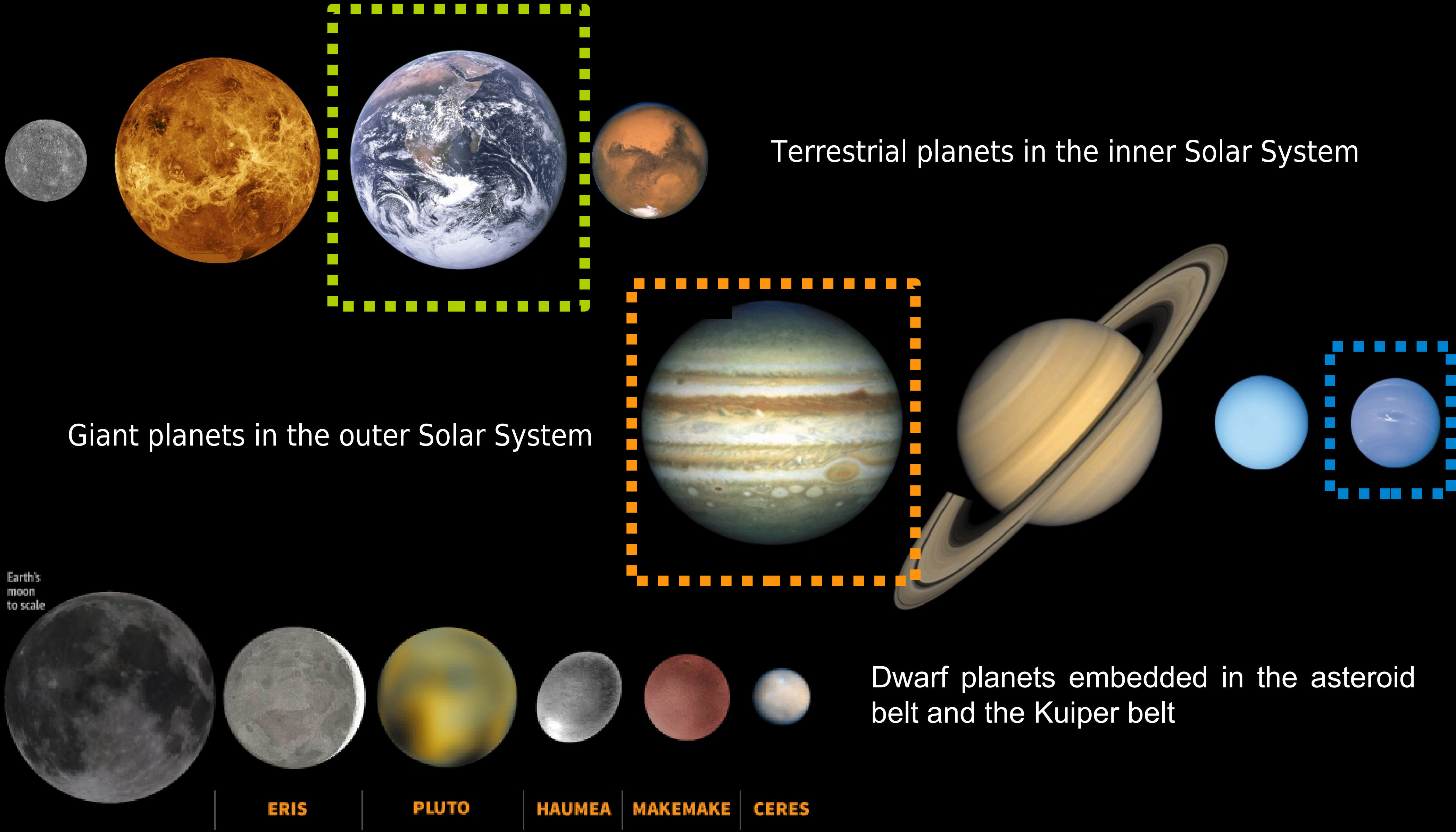


ARES III School - Biarritz, 11-16 September 2023

Part I

Planet Formation and Planetary Diversity

Planet Formation and the Solar System



Terrestrial planets in the inner Solar System

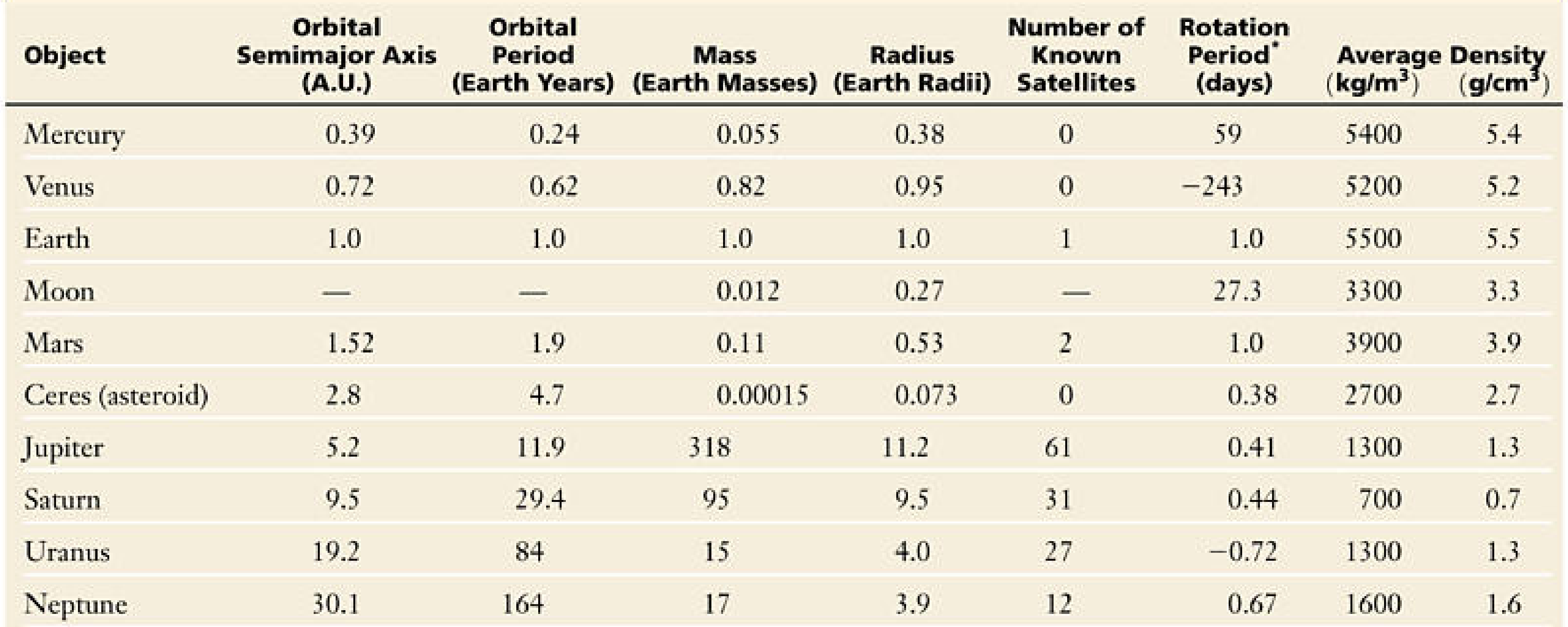
Giant planets in the outer Solar System

Dwarf planets embedded in the asteroid belt and the Kuiper belt

Planets in the Solar System: Physical Properties

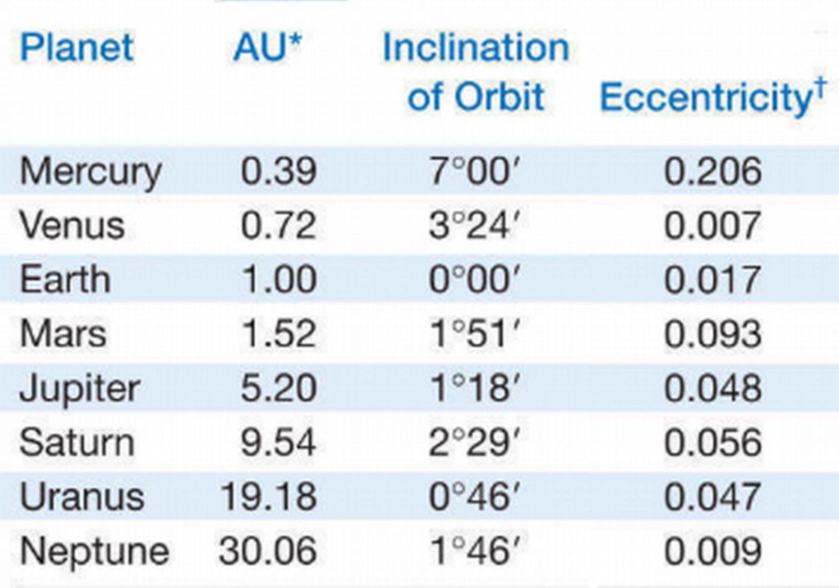
Terrestrial and giant planets in the Solar System have well distinct characteristics:

- **Terrestrial planets** have radii < 10000 km, **giant planets** have radii > 10000 km or, alternatively, ≤ 1 Earth radii and > 3 Earth radii respectively)
- Terrestrial planets have masses ≤ 1 Earth mass, giant planets > 10 Earth masses
- Terrestrial planets have densities ≥ 3 g/cm^3, giant planets < 2 g/cm^3
- Terrestrial planets have few satellites, giant planets have > 10 satellites

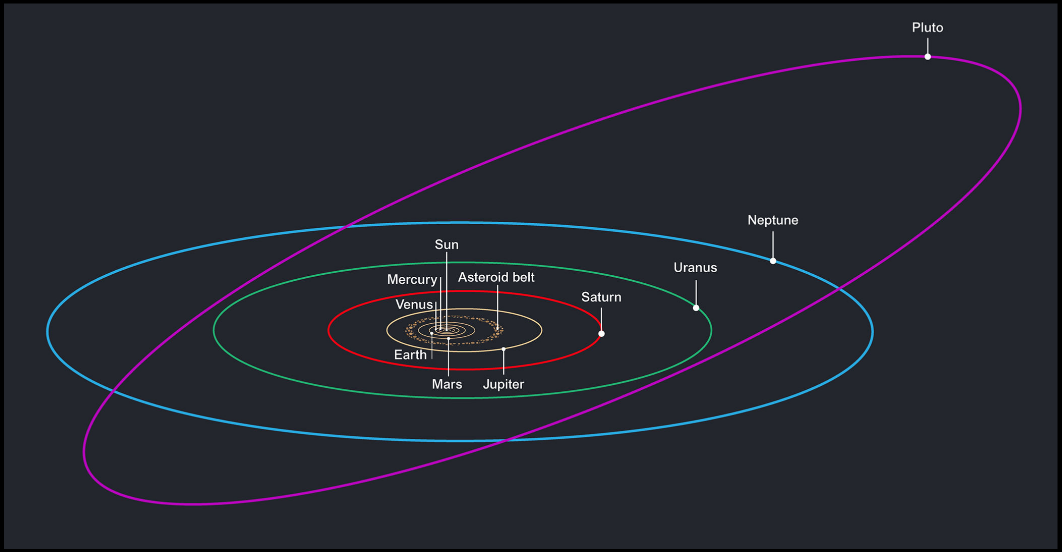


Object	Orbital Semimajor Axis (A.U.)	Orbital Period (Earth Years)	Mass (Earth Masses)	Radius (Earth Radii)	Number of Known Satellites	Rotation Period* (days)	Average Density (kg/m^3)	(g/cm^3)
Mercury	0.39	0.24	0.055	0.38	0	59	5400	5.4
Venus	0.72	0.62	0.82	0.95	0	−243	5200	5.2
Earth	1.0	1.0	1.0	1.0	1	1.0	5500	5.5
Moon	—	—	0.012	0.27	—	27.3	3300	3.3
Mars	1.52	1.9	0.11	0.53	2	1.0	3900	3.9
Ceres (asteroid)	2.8	4.7	0.00015	0.073	0	0.38	2700	2.7
Jupiter	5.2	11.9	318	11.2	61	0.41	1300	1.3
Saturn	9.5	29.4	95	9.5	31	0.44	700	0.7
Uranus	19.2	84	15	4.0	27	−0.72	1300	1.3
Neptune	30.1	164	17	3.9	12	0.67	1600	1.6

Planets in the Solar System: Orbital Properties



Planet	AU*	Inclination of Orbit	Eccentricity[†]
Mercury	0.39	7°00′	0.206
Venus	0.72	3°24′	0.007
Earth	1.00	0°00′	0.017
Mars	1.52	1°51′	0.093
Jupiter	5.20	1°18′	0.048
Saturn	9.54	2°29′	0.056
Uranus	19.18	0°46′	0.047
Neptune	30.06	1°46′	0.009

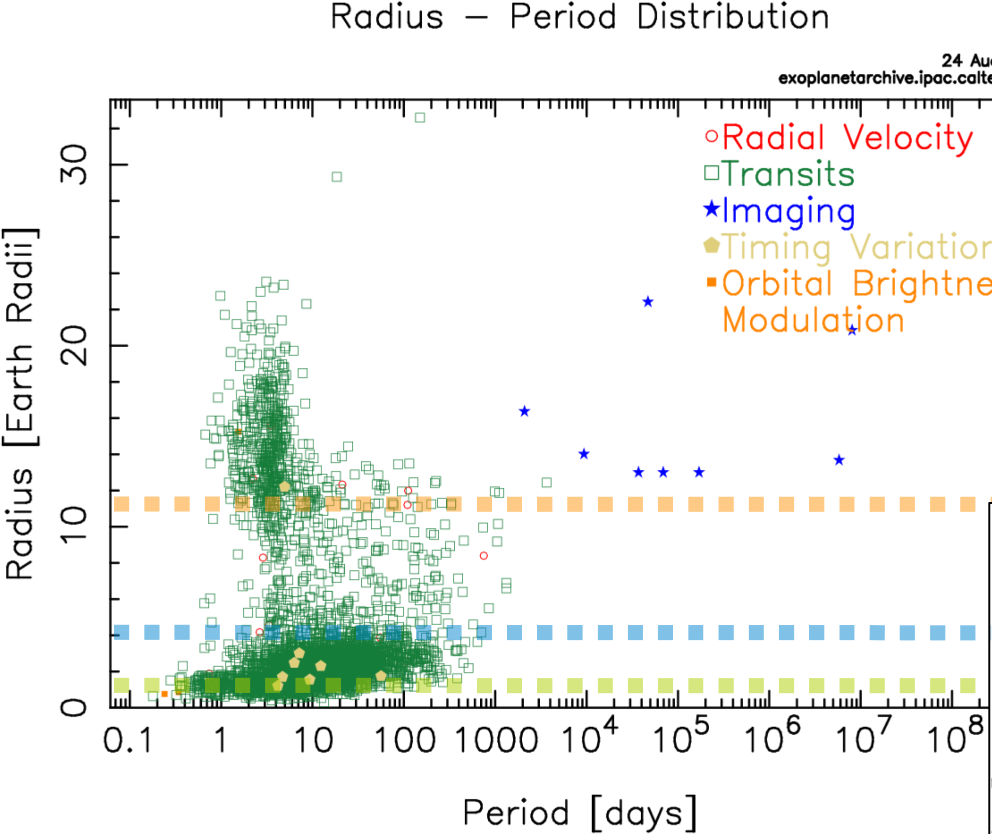


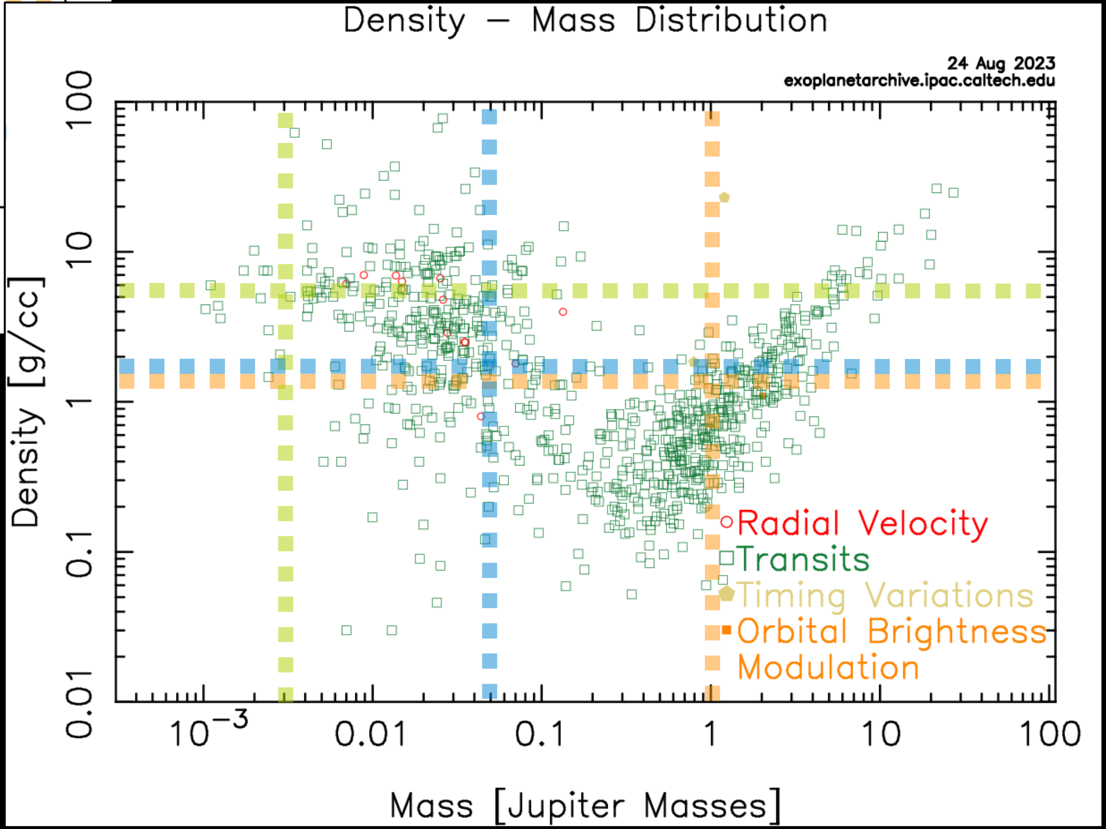
Their orbital characteristics have similarities but also divide them into two well-separated categories:

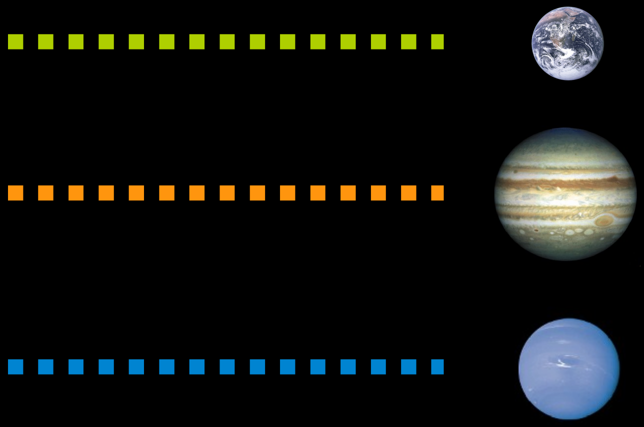
- Terrestrial planets have orbital radii **< 2 au**, giant planets have orbital radii **> 5 au**
- All planets have orbital inclinations of few degrees from the mean orbital plane of the Earth-Moon system (ecliptic plane)
- All planets, with the exception of Mercury, have orbital eccentricities of a few 10^{-2}

Exoplanets: Physical Properties

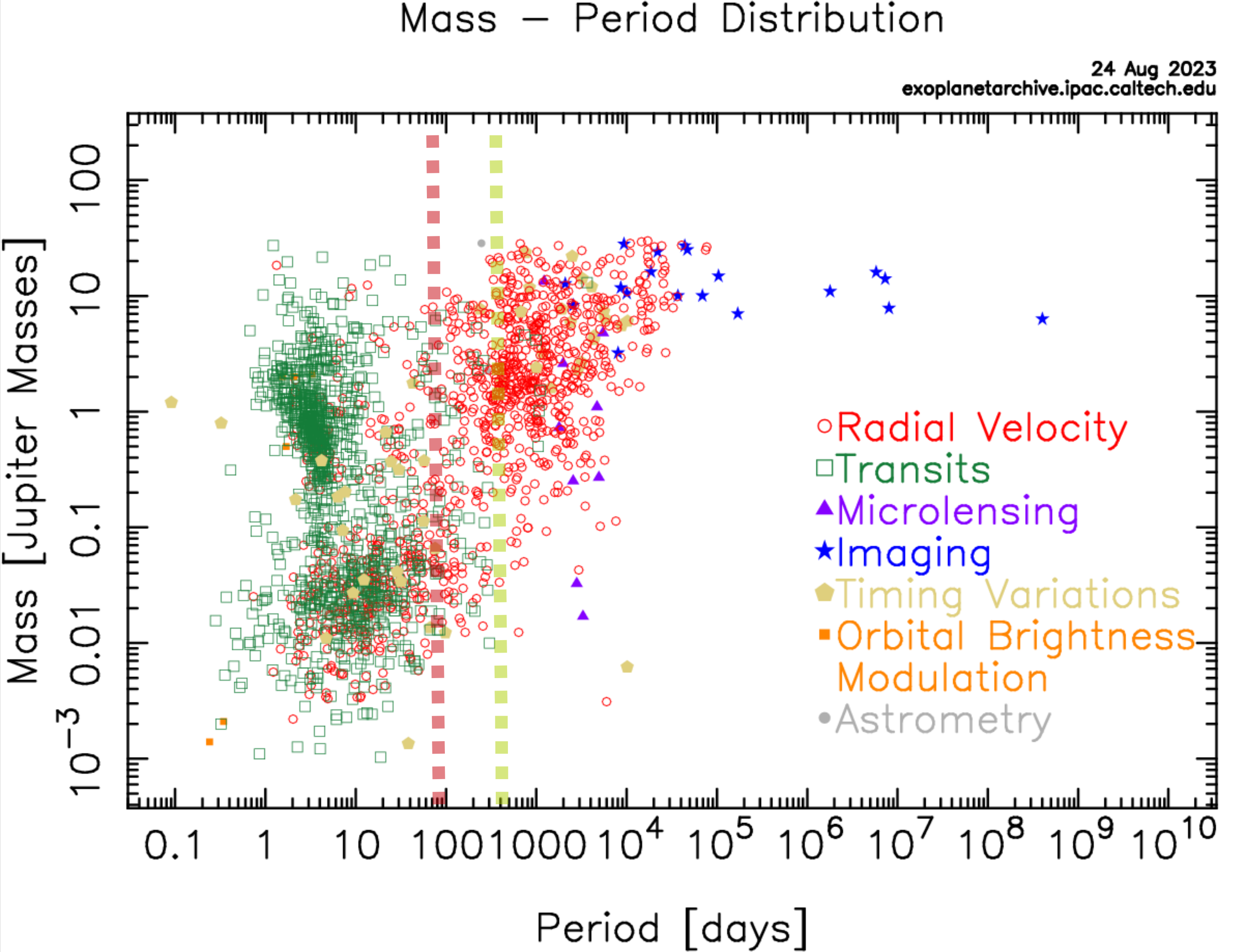
When we look at the physical properties of **exoplanets**, we immediately see that there are **classes of planets that are not represented in the Solar System**



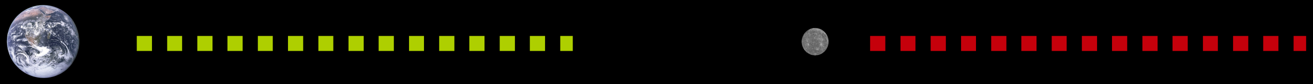




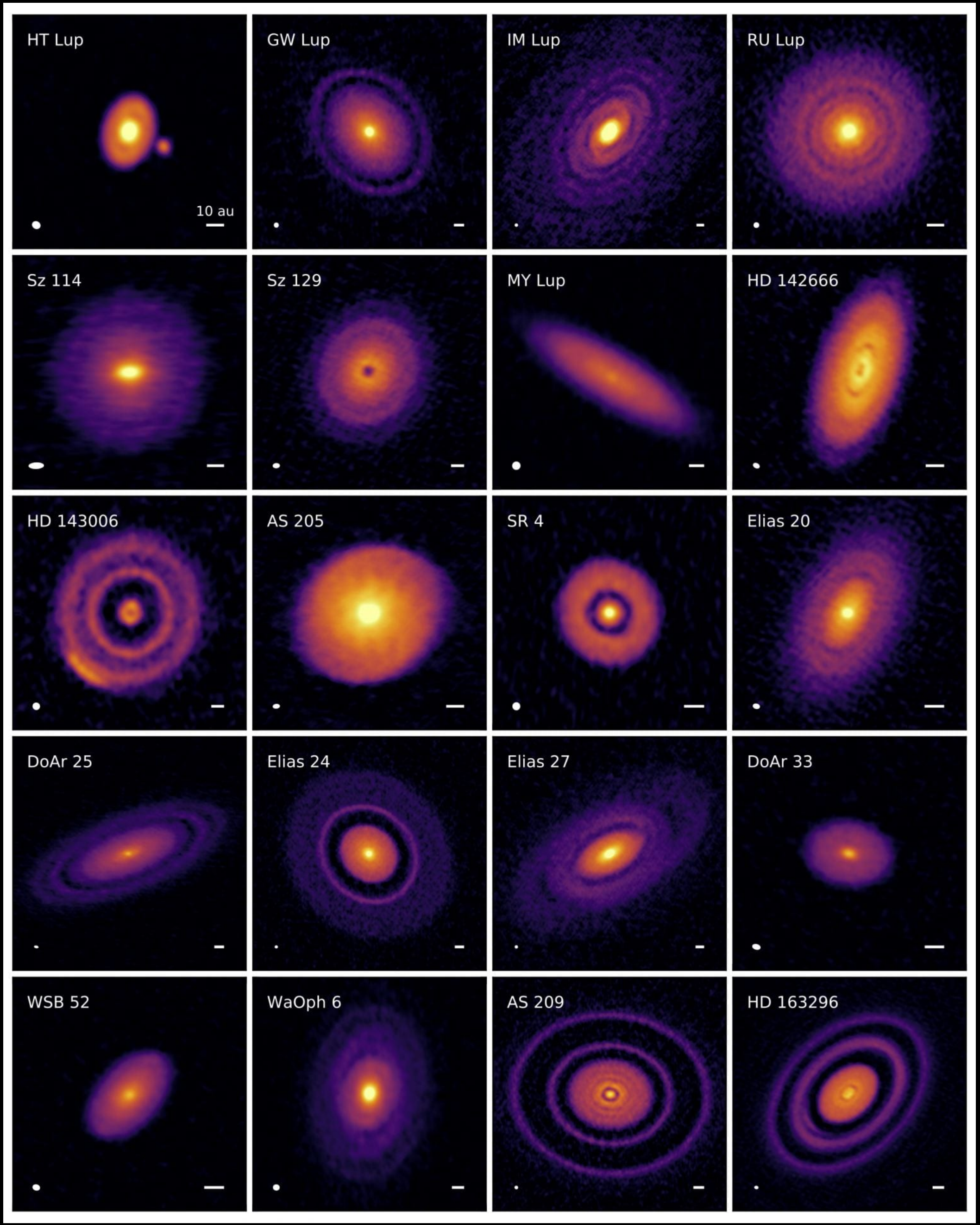
Exoplanets: Orbital Properties



75% of currently known **exoplanets** have orbital periods **P < 100 days** (source: exoplanet.eu).



Exoplanets in Circumstellar Disks



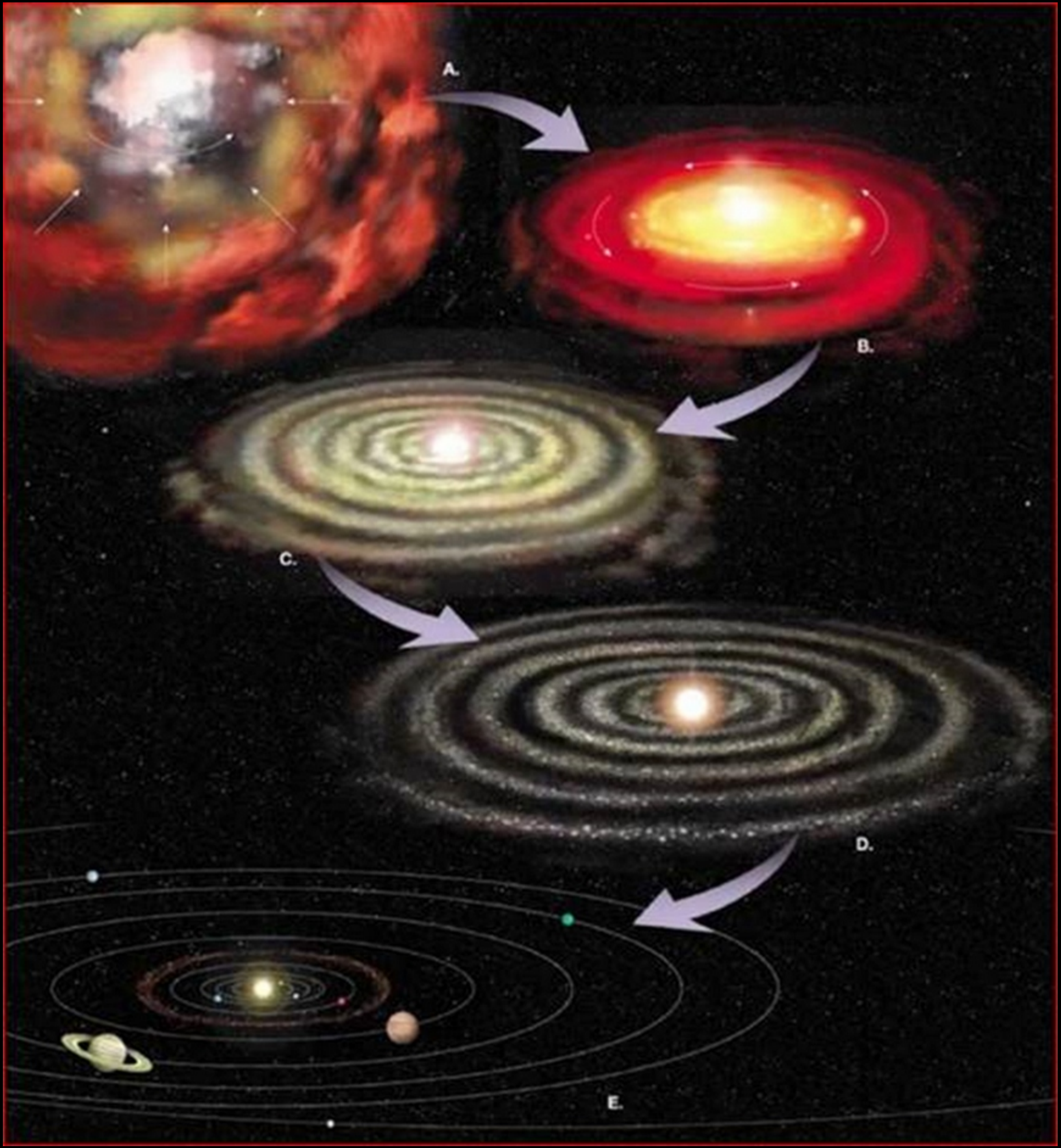
Since 2014, new high-resolution observations of circumstellar discs with ALMA have provided likely evidences of the signatures of giant planets formation.

The signatures we observe reveal that the majority of these potential **giant planets orbit from several 10s of au to 100s of au**.

These distances are significantly larger than the planet-forming region generally assumed for the Solar System and exoplanets.

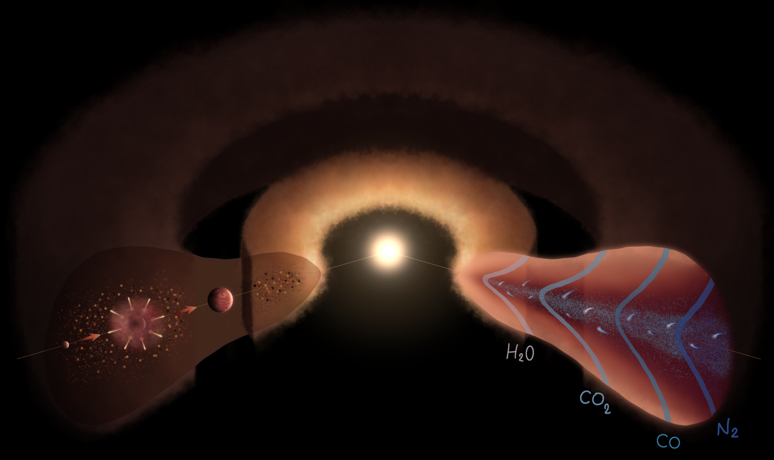
Left: example of a protoplanetary disk as seen in mid-90s with Hubble (credits: MPIA/Rice University/NASA)
Right: Dust morphology in the circumstellar disks observed by the ALMA Large Program DSHARP (Andrews et al. 2018)

Star and Planet Formation



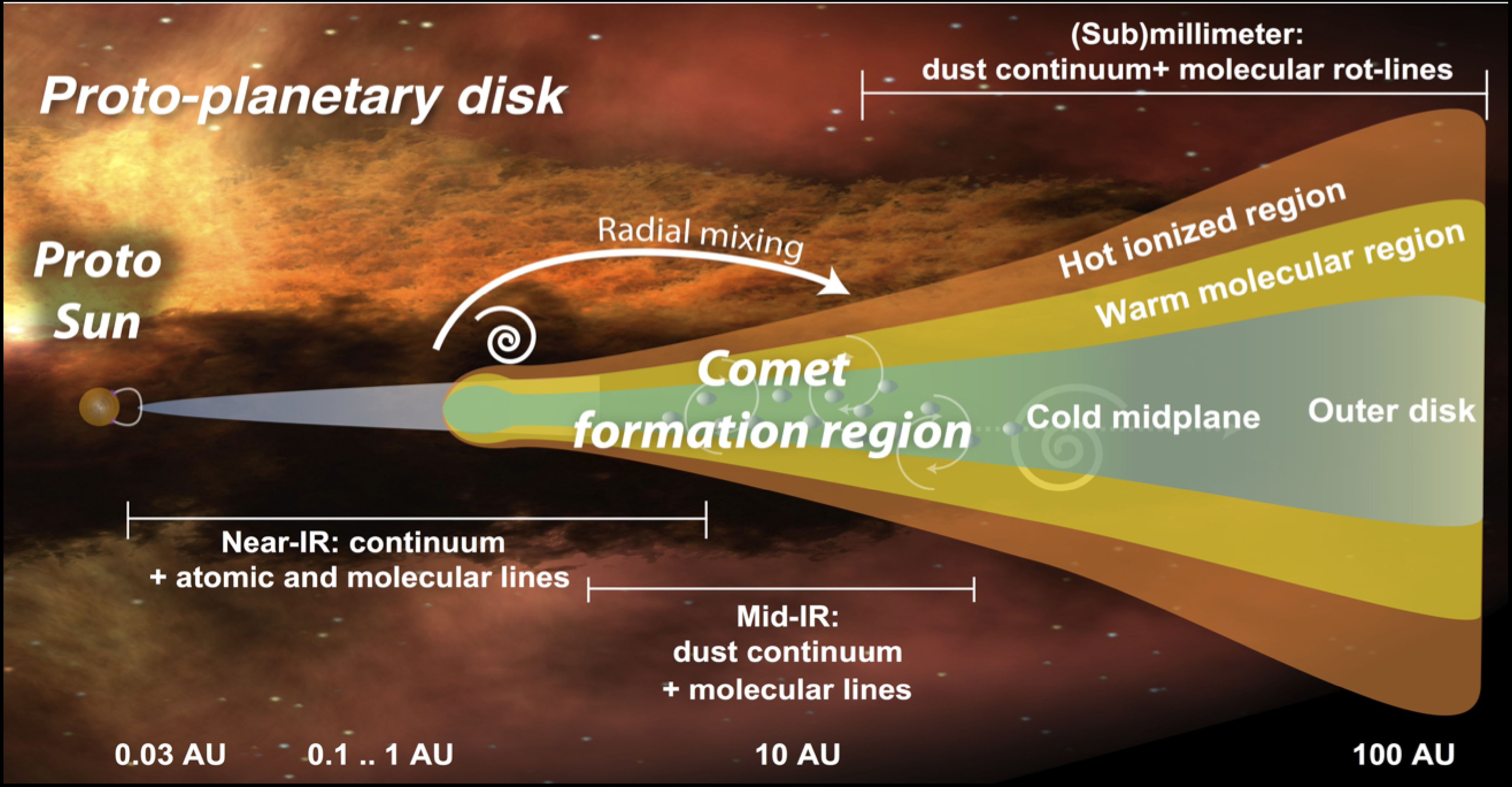
Planetary systems are formed during the late stages of the star formation process. Stars are born in molecular clouds from the gravitational collapse of large regions of gas, which gives rise to protostars surrounded by circumstellar disks.

The circumstellar disks are made of gas and dust originating from the molecular cloud and thermally processed by the radiation of the protostar. **The global composition of circumstellar disks matches that of the central star.**



The Protoplanetary Disks

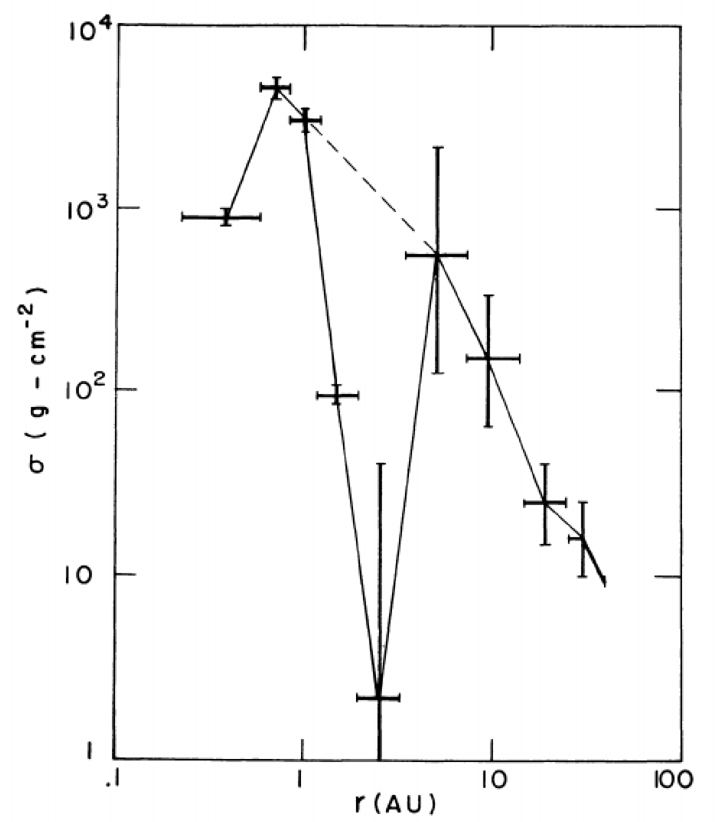
Circumstellar disks are not homogeneous nor flat structures: they possess **vertical and radial density and temperature gradients**, set by their interactions with the stellar radiation, that determine their local composition.



Schematic representation of protoplanetary disks and their planet-forming midplane. Figure from Gibb et al. (2015), credits Goddard Visualization Center, A. Mandell, G. Villanueva.

The Minimum Mass Solar Nebula

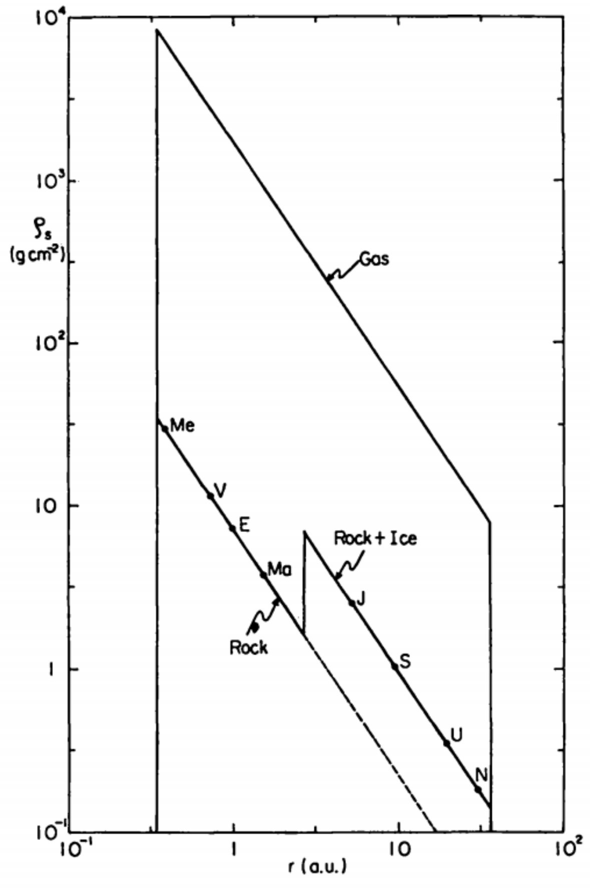
Between the ‘70 and the ‘80 of the previous century, attempts were made to constrain the structure and mass of the **Solar Nebula**. Assuming that the *planets formed near their present orbits* and adding to their composition enough hydrogen (H) and helium (He) to *match the solar composition*, we obtain the **smallest disk capable of forming the Solar System** (i.e. assuming 100% efficiency).



This **Minimum Mass Solar Nebula** (MMSN) has the following reconstructed surface density and thermal profiles:

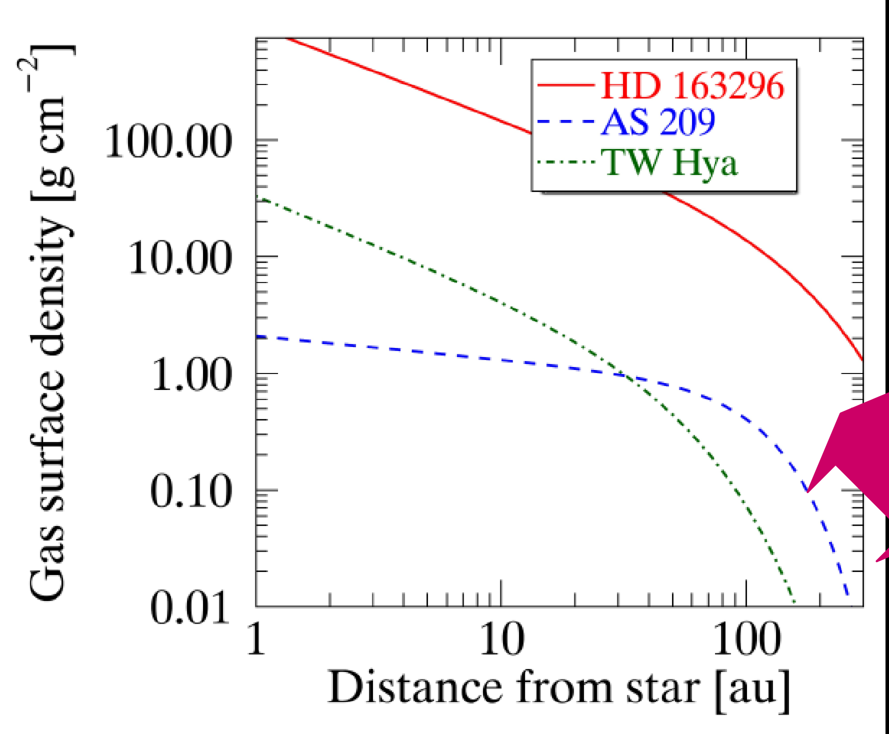
$$\rho_s\,(\text{gas}) = 1.7 \times 10^{3} r^{-1.5}\ \text{g cm}^{-2}$$

$$T = 280 r^{-1/2} (L/L_{\odot})^{1/4}\ ^{\circ}\text{K}$$

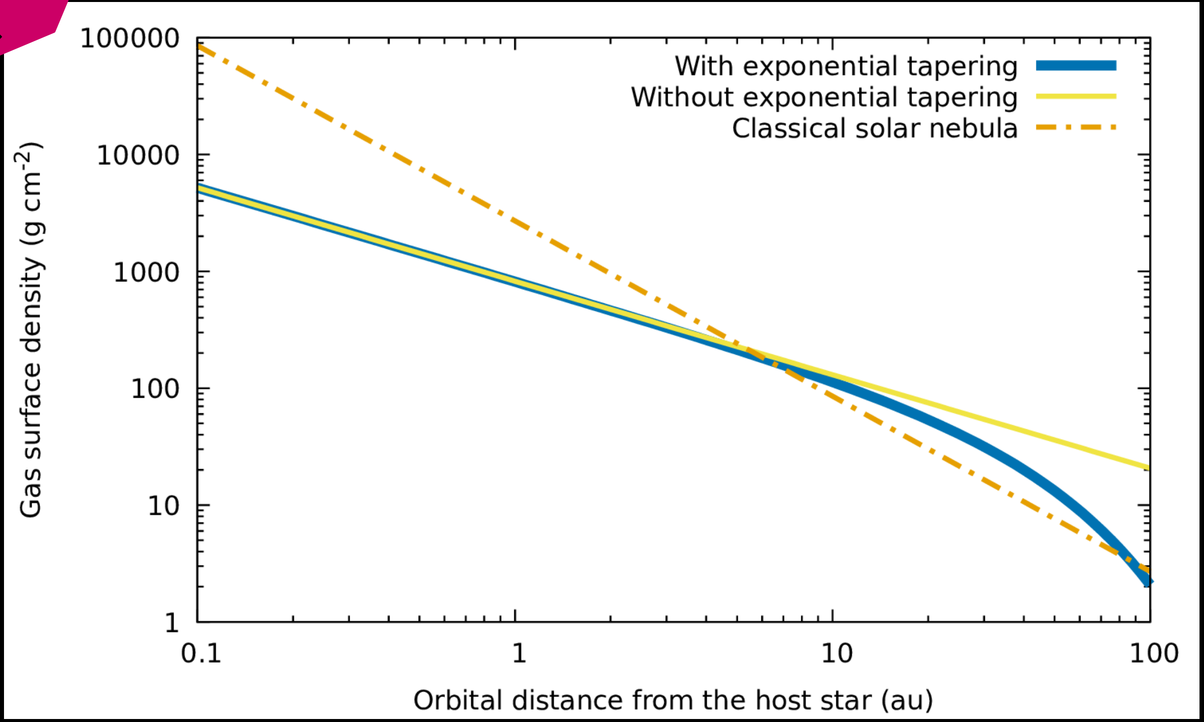


Left: radial density profile of the solar nebula based on the current Solar System planets (Weidenschilling 1977)
Right: reconstructed gas and solids density profiles of the minimum mass solar nebula (Hayashi et al. 1981)

The Mass Distribution in Protoplanetary Disks



Circumstellar disks are more radially extended and their **gas distribution is much less centrally concentrated** than that what hypothesized for the (Minimum Mass) Solar Nebula.



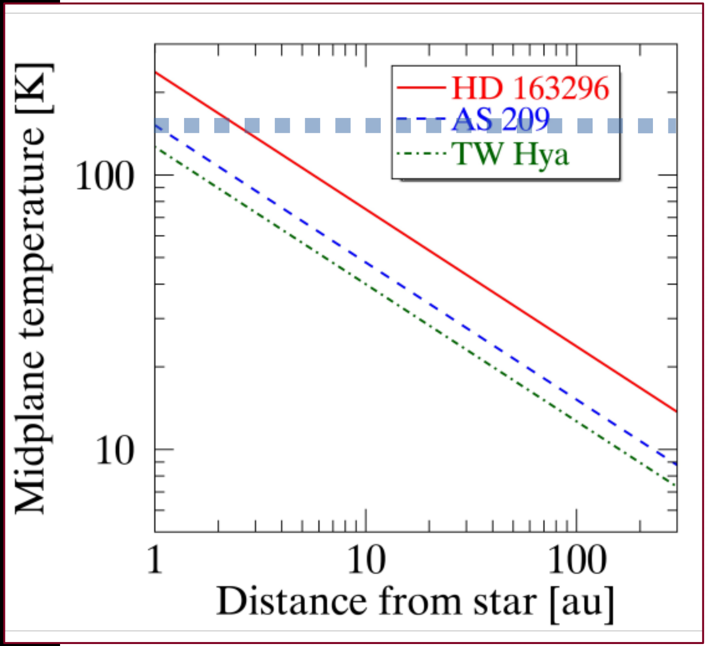
Only the initial distribution of dust inside circumstellar disks can be obtained by the gas distribution scaling it by the dust-to-gas ratio. **Dust undergoes aerodynamic drag and moves with differential motion with respect to the gas**.

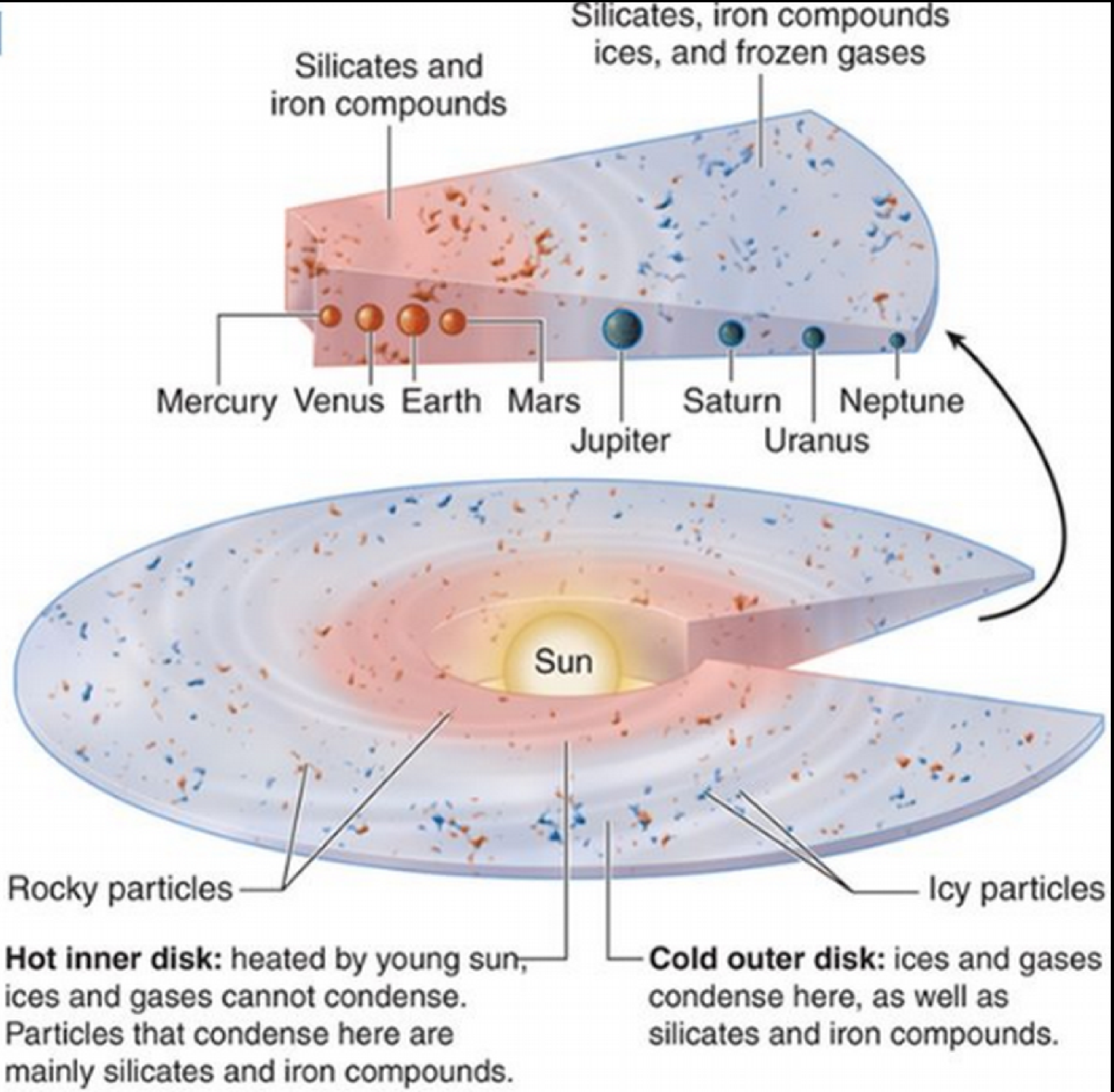
Disk Temperature and the Water Snow Line

- ☐ Condensation Sequence

Classical MMSN Thermal Profile:

$$T = 280 r^{-1/2} (L/L_{\odot})^{1/4} \text{ °K}$$





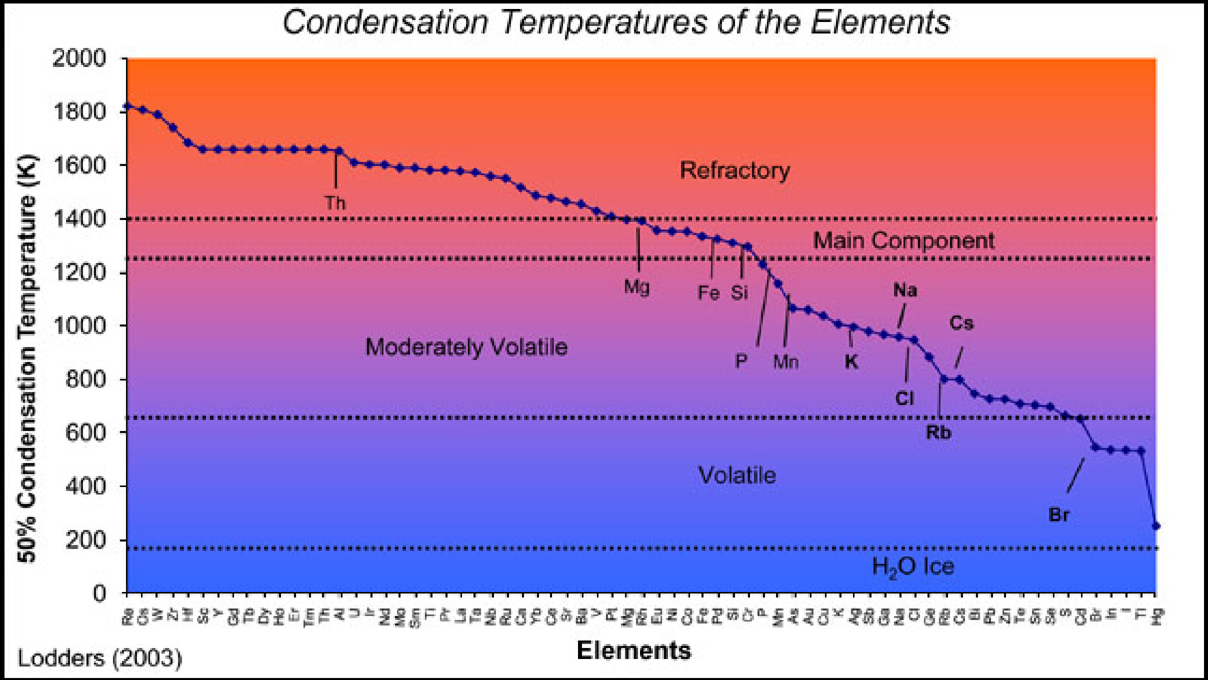
Hot inner disk: heated by young sun, ices and gases cannot condense. Particles that condense here are mainly silicates and iron compounds.

Cold outer disk: ices and gases condense here, as well as silicates and iron compounds.

Part II

Cosmochemistry and Astrochemistry

Condensation Fronts across Elements



Each element is distributed among different molecules and materials that condense at different temperature.

The **condensation front** is defined by the disk radius where the **half of a given element/molecule is in solid form**.

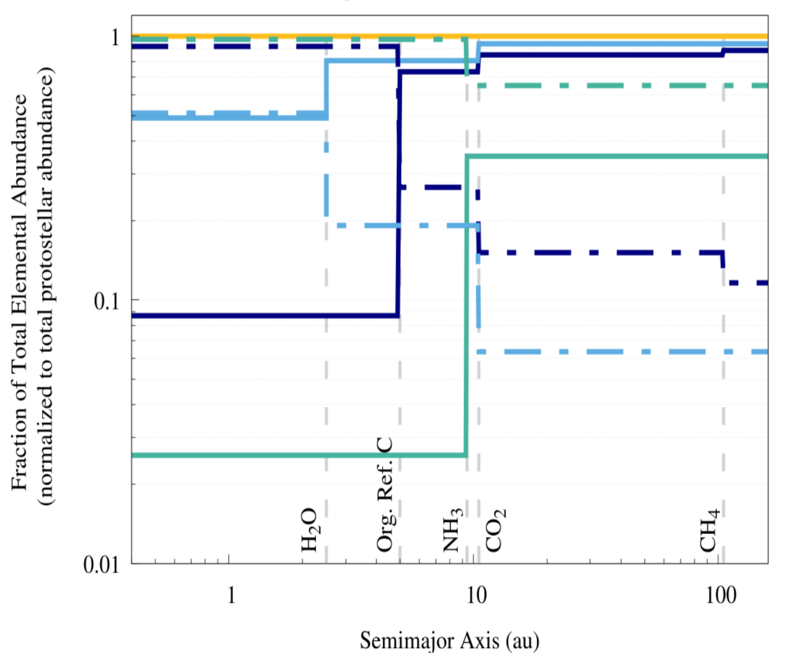
Species	T_{cond} [K]
H_2O	130 - 150
HCN	100 - 120
CH_3OH	95 - 110
NH_3	75 - 85
CO_2	60 - 70
H_2S	45 - 50
CH_4	26 - 32
CO	22 - 28
N_2	12 - 15

We can divide the elements in cosmochemical classes based on their chemical behaviour (Fegley & Scheafer 2010):

- **Refractory elements** (high-temp. condensates, e.g. Ca, Al, Ti)
- **Main rock-forming elements** (Fe, Mg and Si)
- **Moderately volatile and volatile elements** (e.g lower temperature condensate like K, Na & Cl; separated by S)
- **Atmophile elements/ices** (C, N, O, condensing as H_2O, CO_2, CO, NH_3, CH_4, N_2 at temperatures below 150 K)

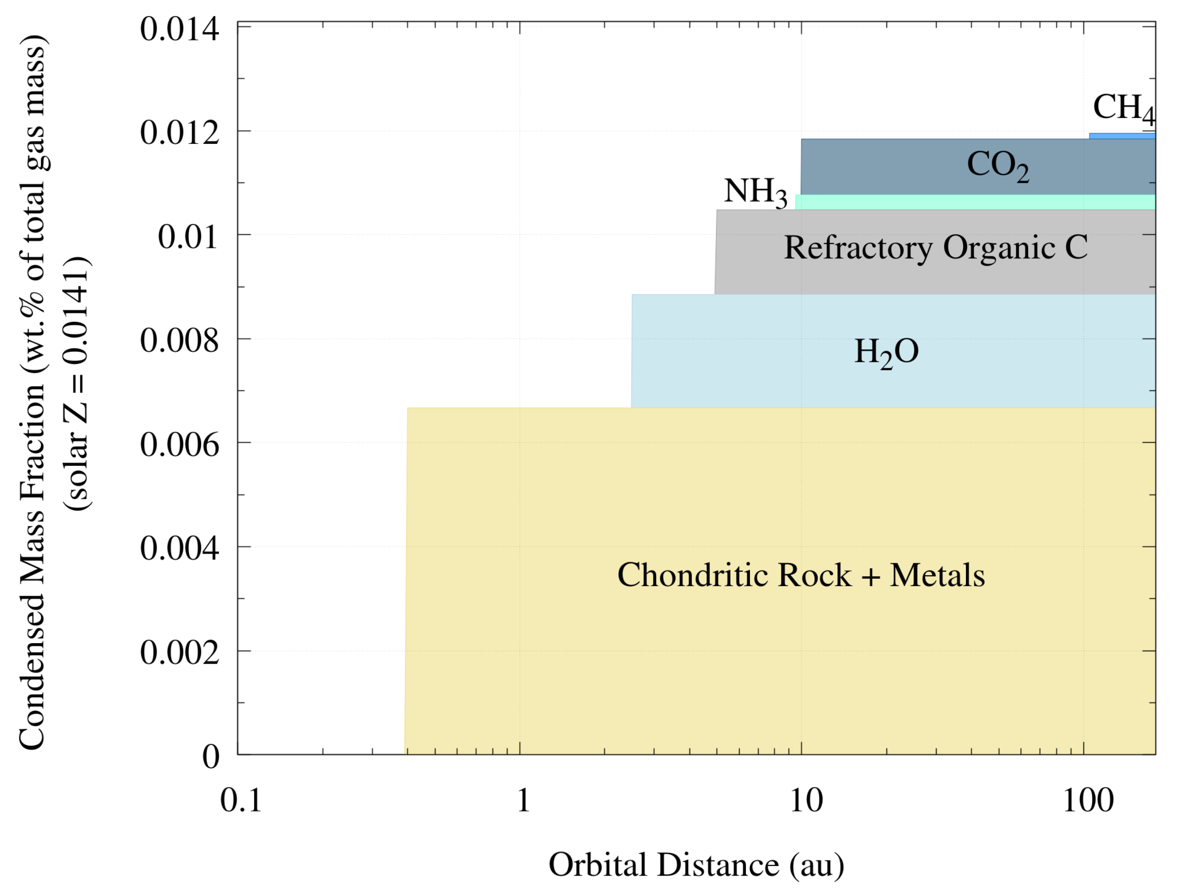
Top: condensation temperatures of non-atmophile elements (figure credits: Jeffrey Taylor; data from Lodders 2003).

Condensation Fronts & Solids Abundance in Disks



The diffent volatility of the chemical elements means that there are multiple condensation fronts across disks.

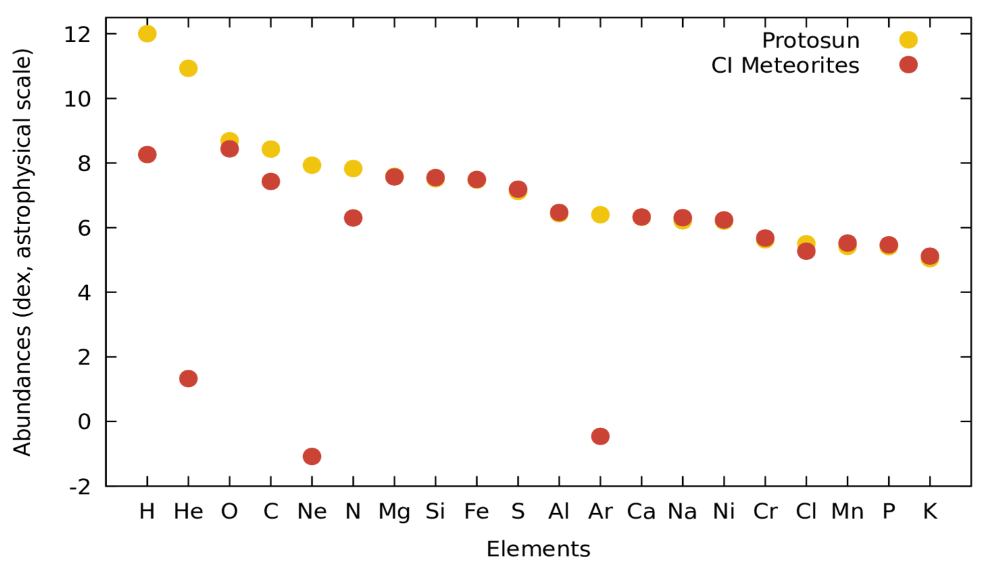
As a result, the **abundance of solids** available to form planets **increases with the distance from the star**.



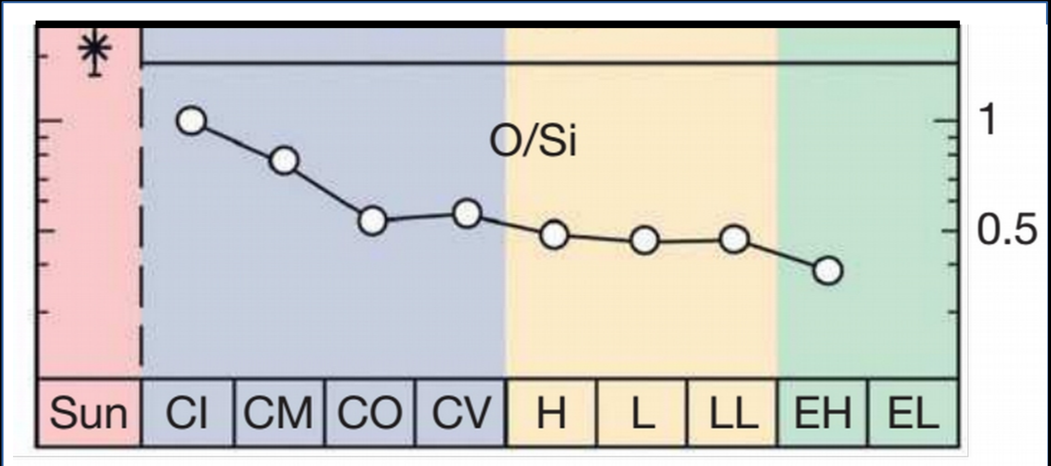
In disks around stars with solar composition, **rocks and metals represent about half the total amount of solids** and are condensed already at a fraction of au.

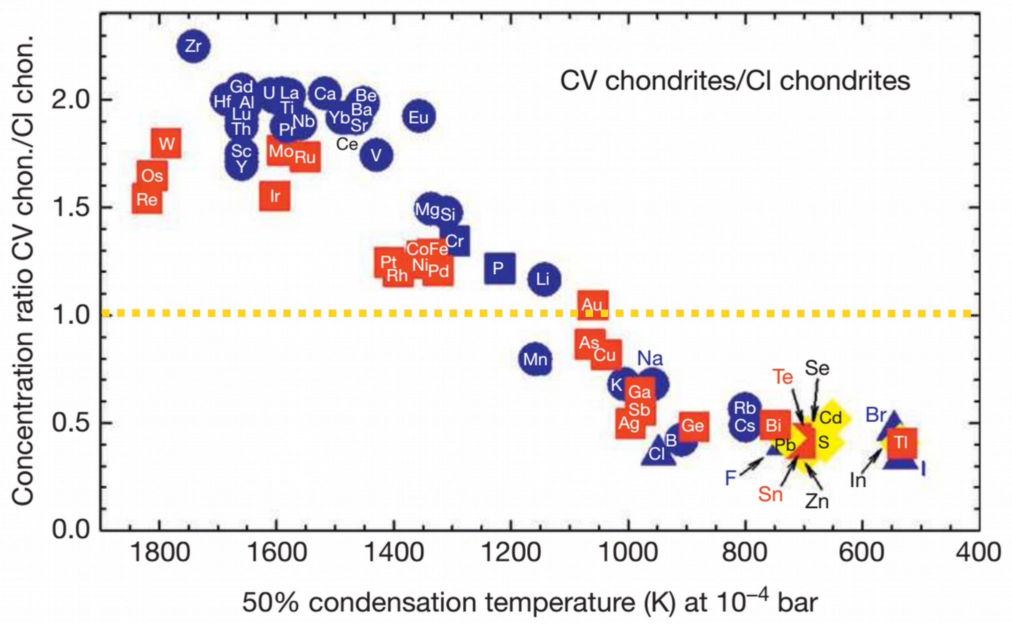
Water, ices and organics condense across a large range of distances. Water generally condense between 1 and 3 au.

Condensation Fronts Recorded in Meteorites



CI meteorites are the class of meteorites whose composition most closely matches the **solar composition** except H, the atmophile elements C, O, N and the noble gases (Lodders 2010, Palme et al. 2014, Palme & Zipfel 2017).

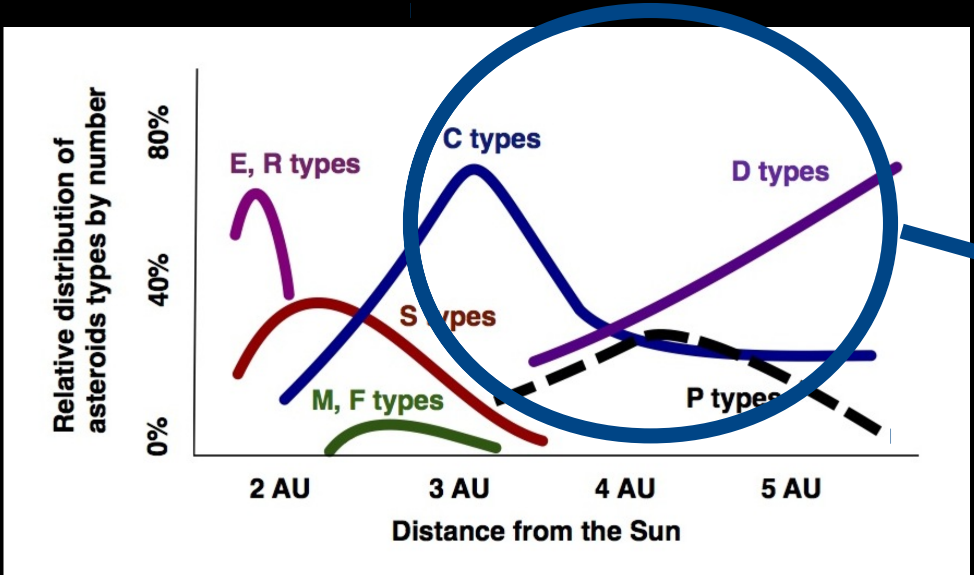




The other classes of chondritic meteorites are increasingly deprived of elements according to their volatility (Lodders 2010, Palme et al. 2014, Palme & Zipfel 2017).

Top: elemental abundances of Sun and CI meteorites (figure from Turrini 2023). Center: O/Si abundances of the Sun and the chondrites (Palme et al. 2014). Bottom: abundance vs. volatility of elements between CI and CV meteorites (Palme et al. 2014).

Condensation Fronts Recorded by Asteroids



Asteroids show a rough compositional gradient with their heliocentric distance.

Carbonaceous asteroids: rocky, increasingly rich in carbon/organics and hydrated materials, similar to cometary nuclei (without the ice).

Silicate asteroids, rocky, rich in magnesium iron silicates, no carbon/organics nor hydrated materials

Metallic asteroids, dominated by Fe-Ni, no silicon, no carbon/organics nor hydrated materials

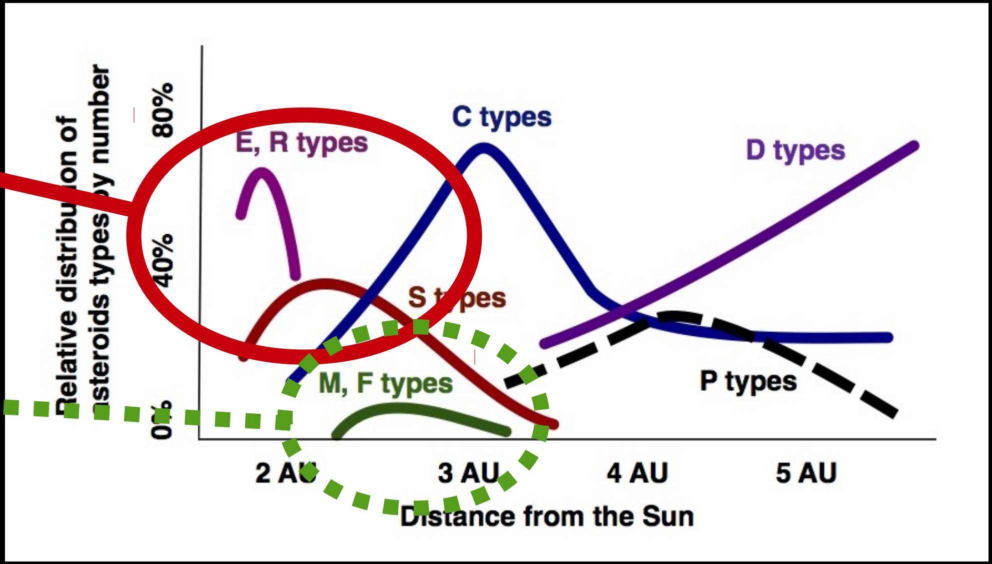
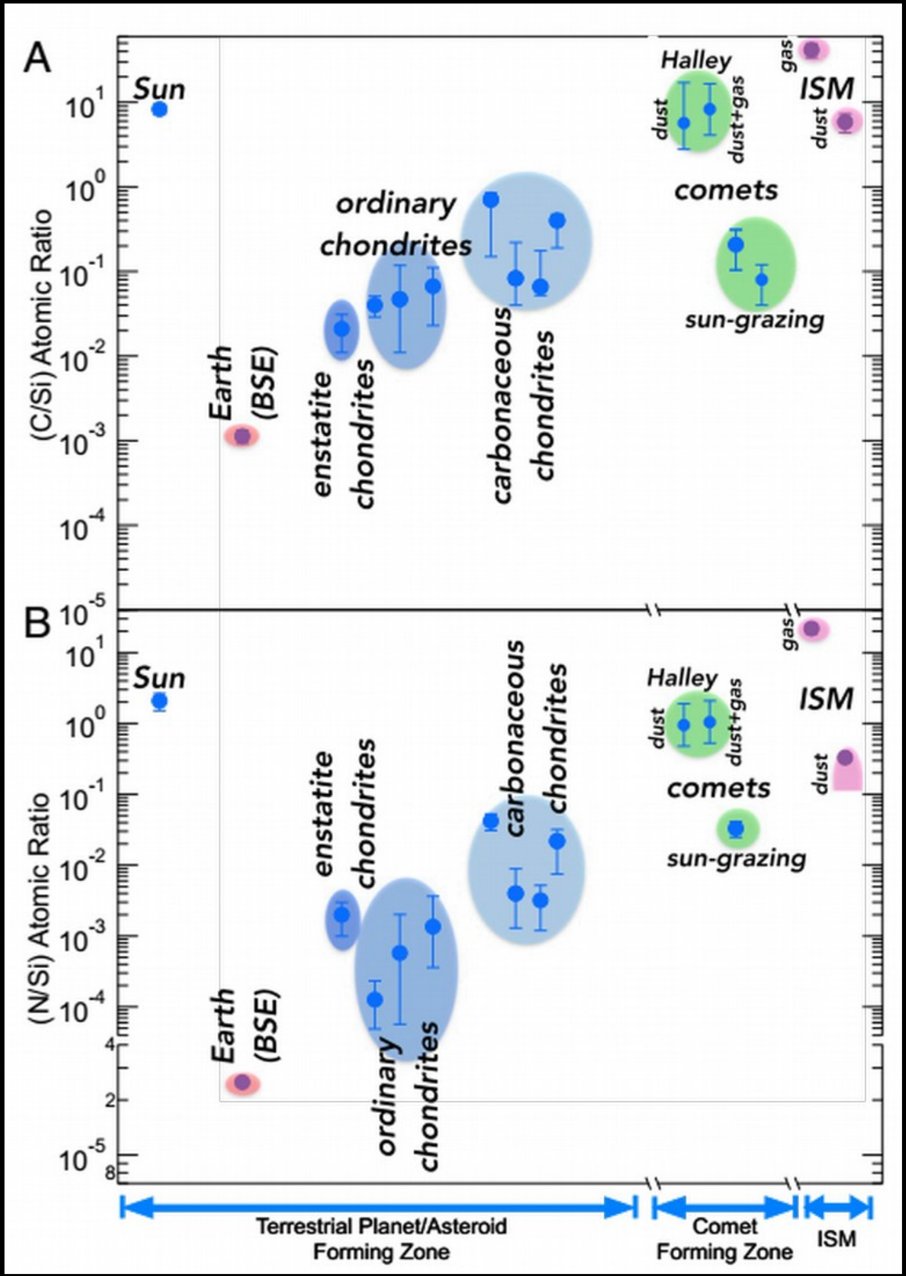


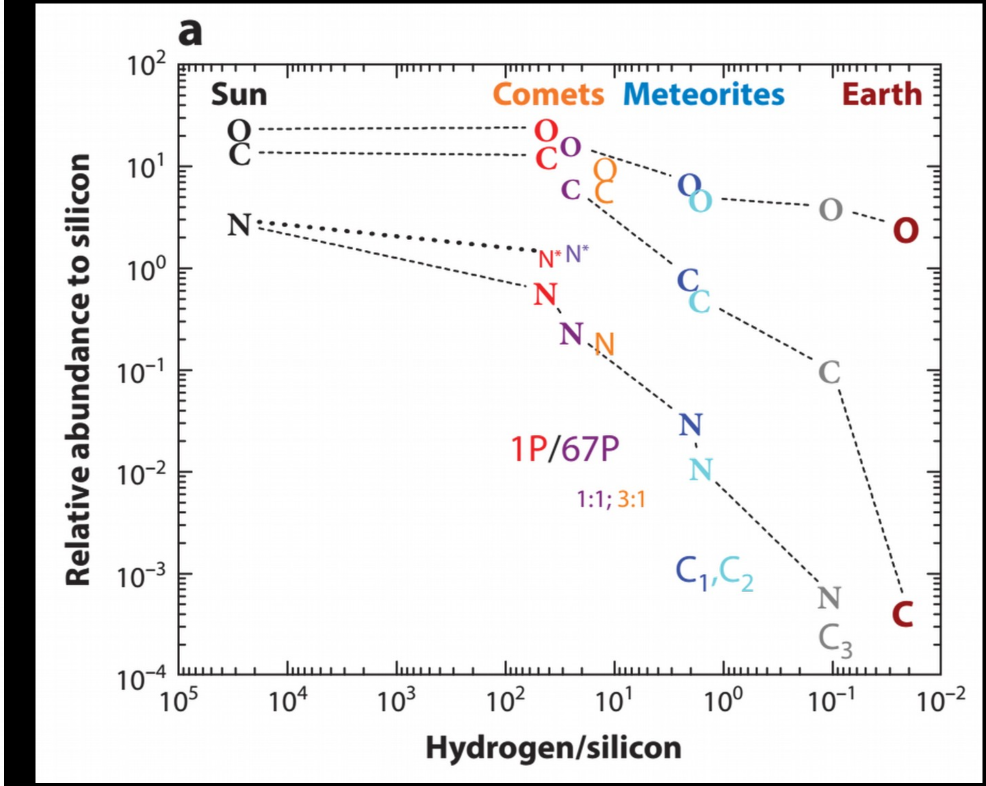
Figure: compositional mapping in spectral classes of the asteroid belt (De Meo & Carry 2014).

Condensation Fronts Recorded in Comets



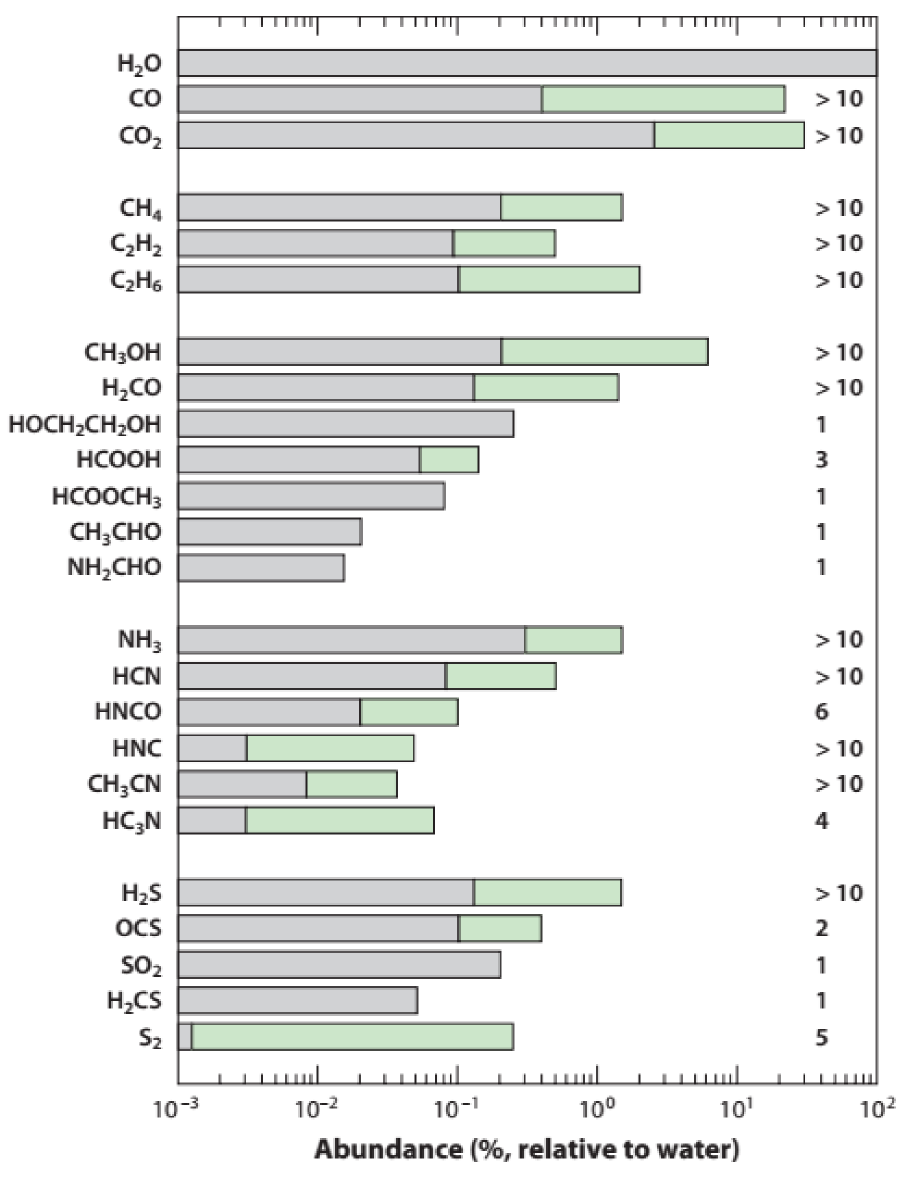
About **25-50%** of solar **O is trapped by rocks** (Palme et al. 2014, Palme & Zipfel 2017).

Only **9% of C** and **3% of N** are contained in rocks, the rest is supplied by increasingly volatile molecules (e.g. Bergin et al. 2015; Eistrup et al. 2016, 2018; Altwegg et al. 2020; Turrini et al. 2021).



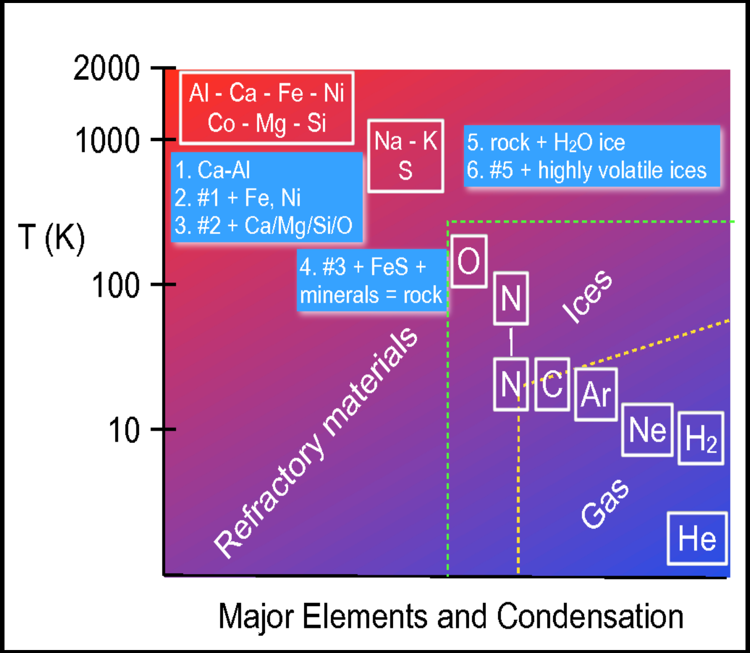
Left: C and N abundances (w.r.t. Si) in Sun, Earth, meteorites, comets and interstellar medium (Bergin et al. 2015).
Right: similar O, C, N trends with comparison between comets 1P and 67P (Altwegg et al. 2020).

The Diversity of Comets



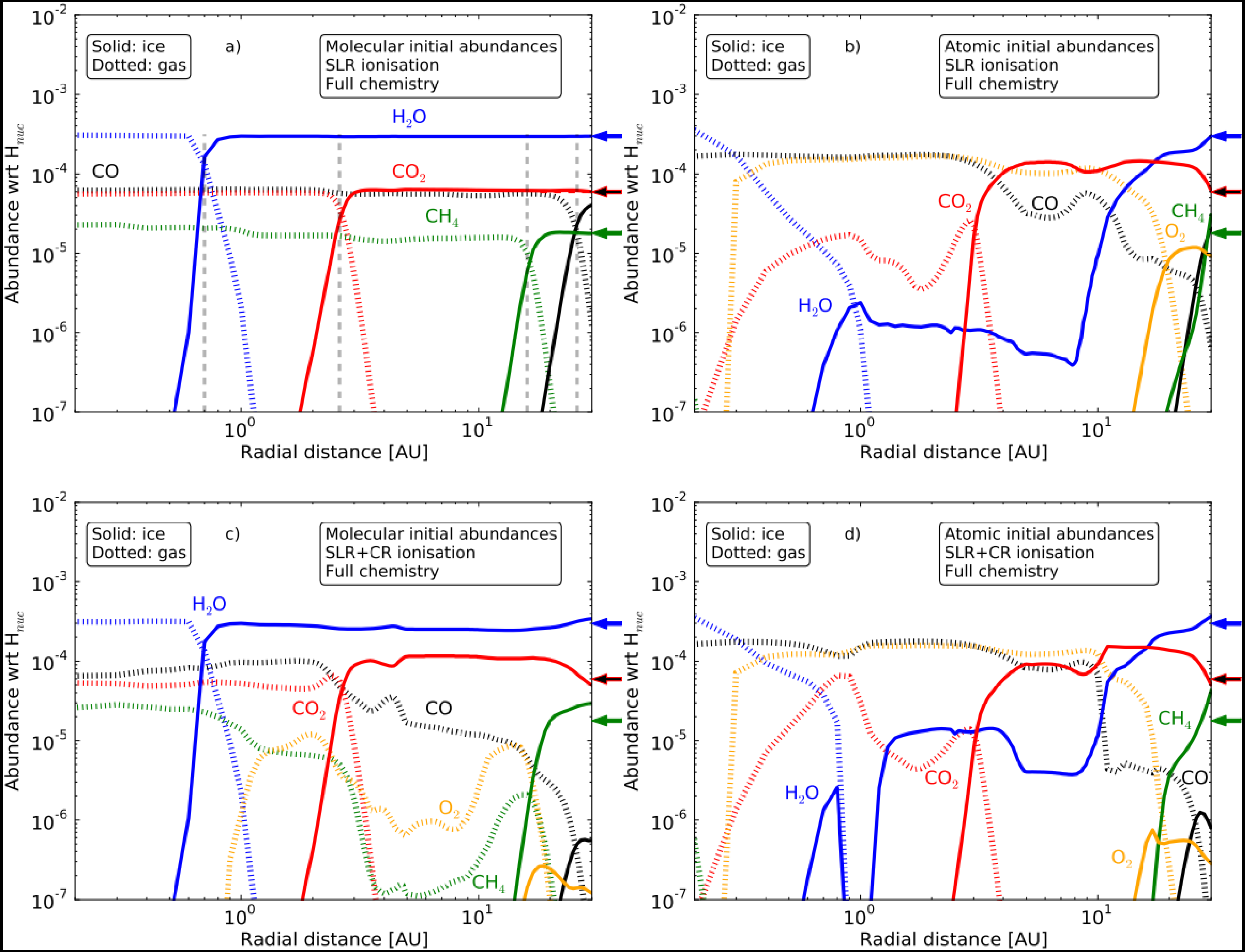
Comets exhibit a variety of compositions, but they all show evidences of volatile ices (H_2O, CO_2, CO, NH_3, CH_4) and organic molecules in the gas and dust they emit.

The presence of highly volatile molecules as CH_4, CO and N_2 testifies their genetic link to the coldest, outermost disk regions (Mumma & Charnley 2011; Altwegg et al. 2020).



Left: abundances of volatile molecules in comets measured with respect to the abundance of water. Figure from Mumma & Charnley (2011).

Circumstellar Disks and the Stellar Environment

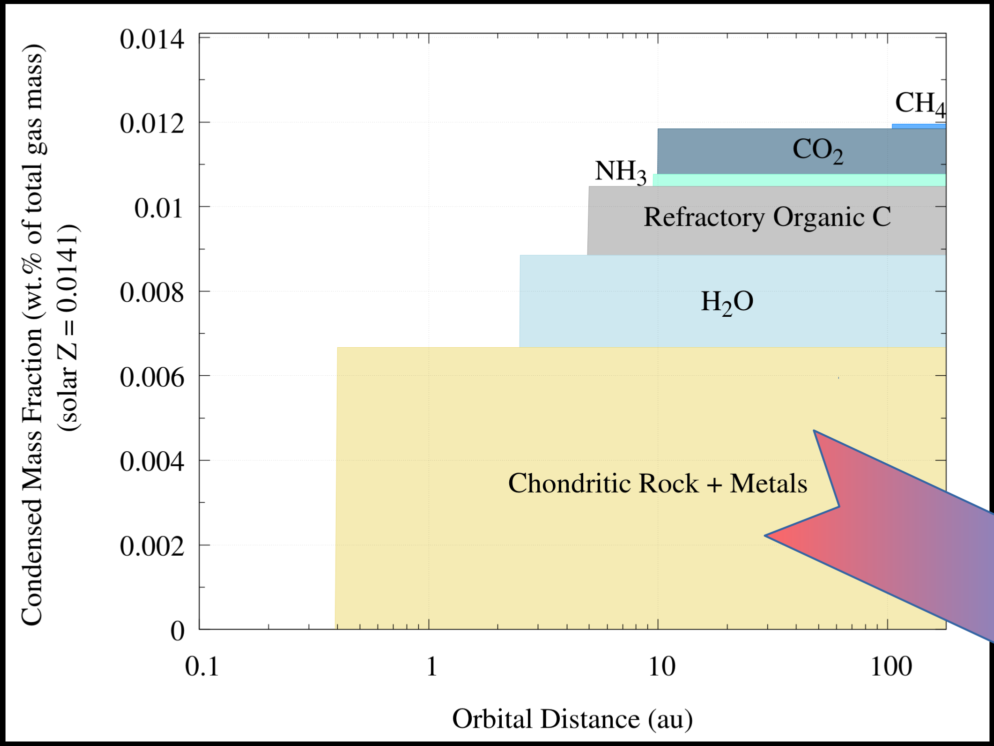


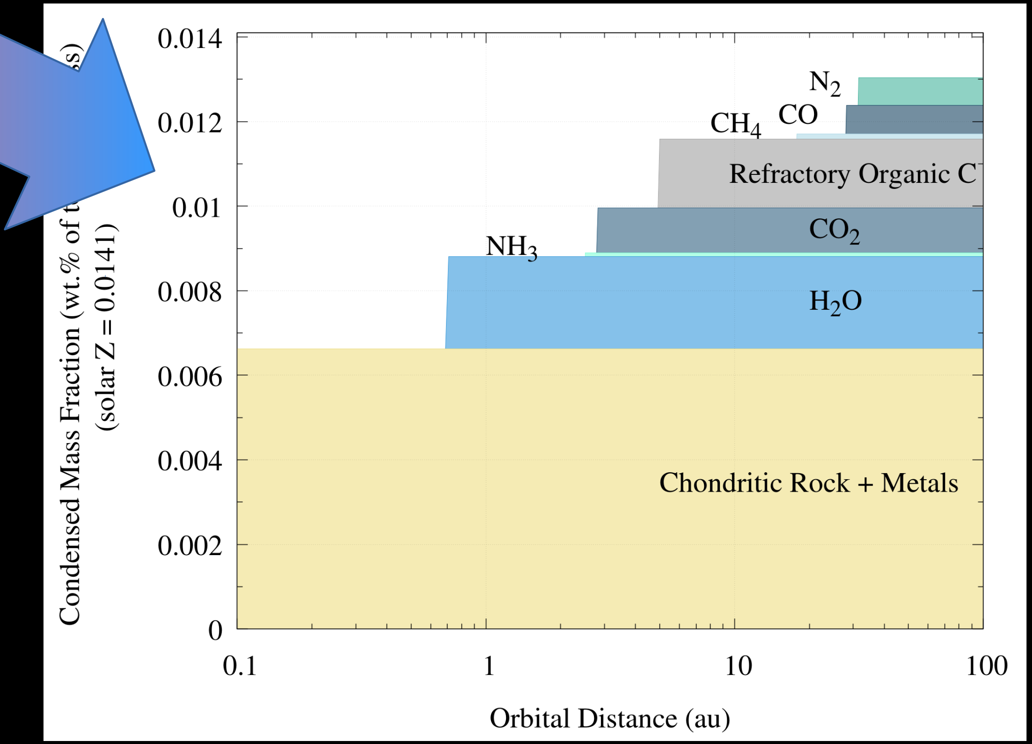
Disk chemistal structures in response to the stellar environment from Eistrup+16. Left: the disk inherits its volalile molecules from the interstellar medium. Right: the disk is heated up by stellar flares that reset its volatile molecules. Top: the disk orbit an isolated star. Bottom: the disk is embedded in a stellar cluster

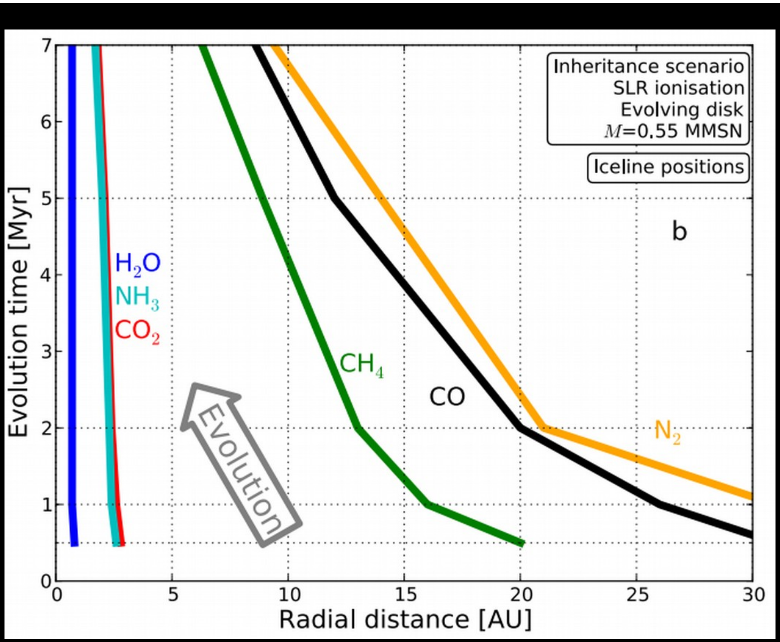
Circumstellar Disk Cooling and Drifting Snowlines

The temperature profile of individual disks is set by the balance between the luminosity of their host stars and the opacity of the gas and dust.

As the star-disk pair evolves over time, **the disk cools down and the position of the snowlines drift inward**.







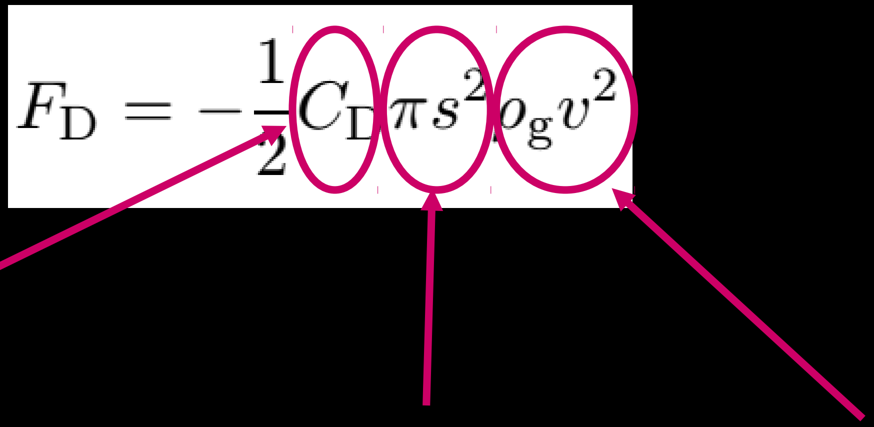
Left: inward drift of the snowlines over time while the disk cools down (Eistrup et al. 2018).

Part III

Planet Formation: Dust and Circumstellar Disks

Aerodynamic Drag Force

Gas and solids move differently in circumstellar disks: a local blob of gas is more affected by the pressure of the surrounding gas than solids (particularly above a certain size, see later), so they "feel" a different net gravity and have different orbital velocities. This differential motion results in a force acting on the solids, the **gas drag force F_D**.



$$F_\mathrm{D} = -\frac{1}{2}C_\mathrm{D}\pi s^2\rho_\mathrm{g}v^2$$

Drag coefficient: it defines how strong is the coupling between the solid body and the gas

Cross-sectional area of the solid body: it accounts the amount of solid surface affected by the force of the gas

Ram-pressure of gas: it accounts for the "headwind" felt by the body due to its motion relative to gas

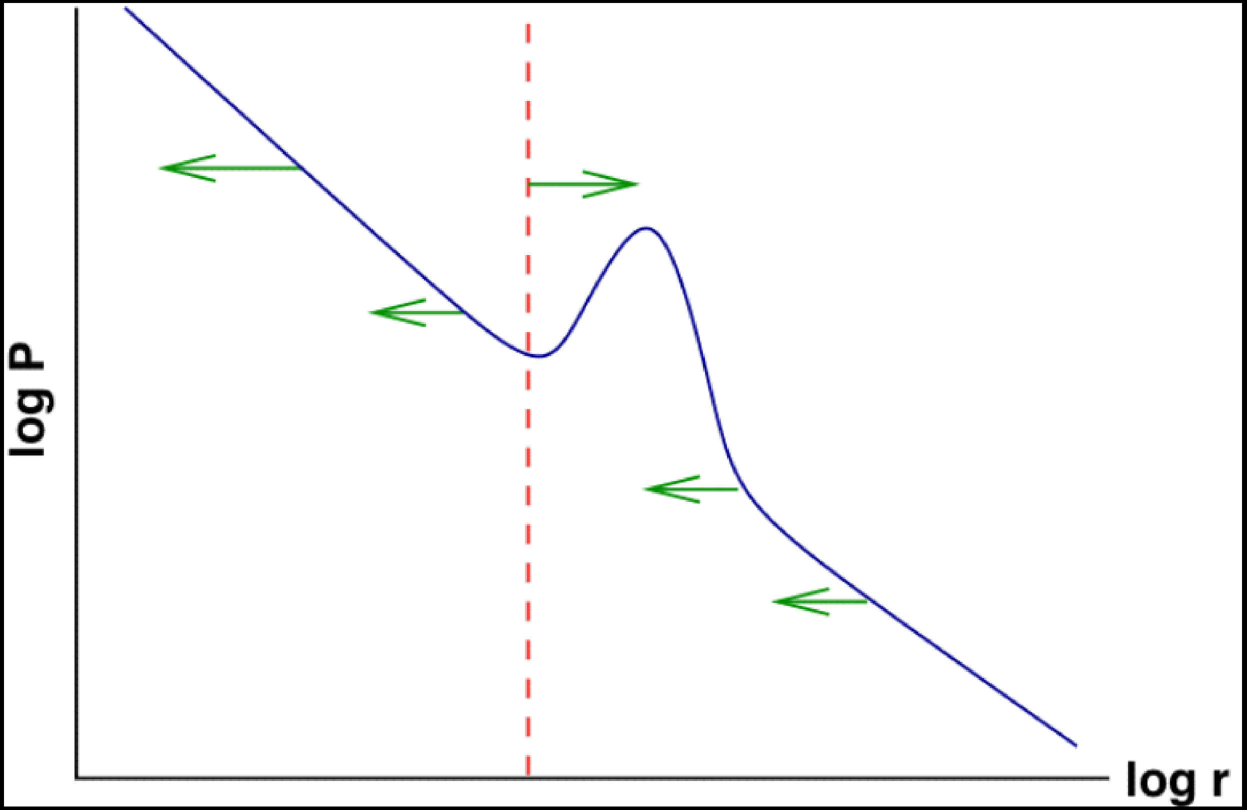
Dust Concentration in Dust Traps

If we consider a local radial pressure maximum at radius R_0, the gas is sub-Keplerian for $R > R_0$ but super-Keplerian for $R < R_0$. Dust particles feel **headwind** at $R > R_0$, and **tailwind** if $R < R_0$. The headwind removes angular momentum and causes inward drift, the tailwind adds angular momentum and drives outward drift. **Dust will concentrate at local pressure maxima**.

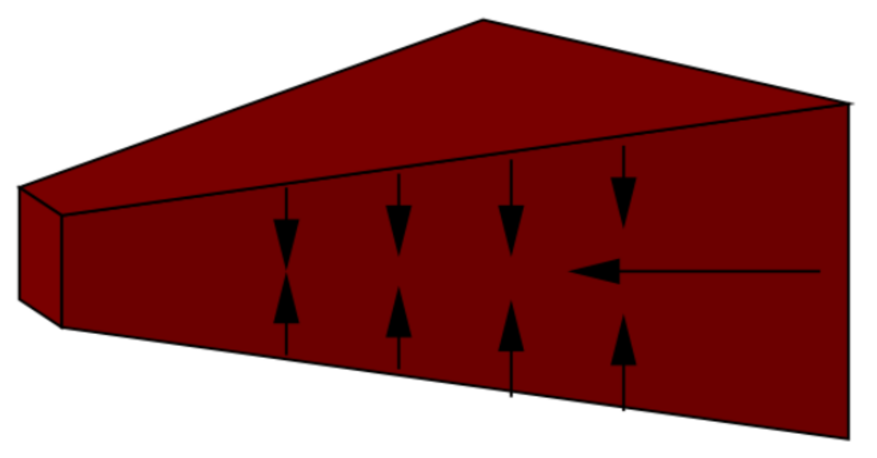
From the ratio between the linear momentum of the dust relative to gas and the drag force, we can derive a **friction timescale**:

$$t_{\mathrm{fric}} = \frac{mv}{|F_D|} = \frac{\rho_d}{\rho}\frac{a}{\bar{v}}$$

The coupling between dust and gas scales with the dust size: for small grains (e.g. $a < 1$ mm), t_{fric} will be short and the dust motion will be set by the gas motion.

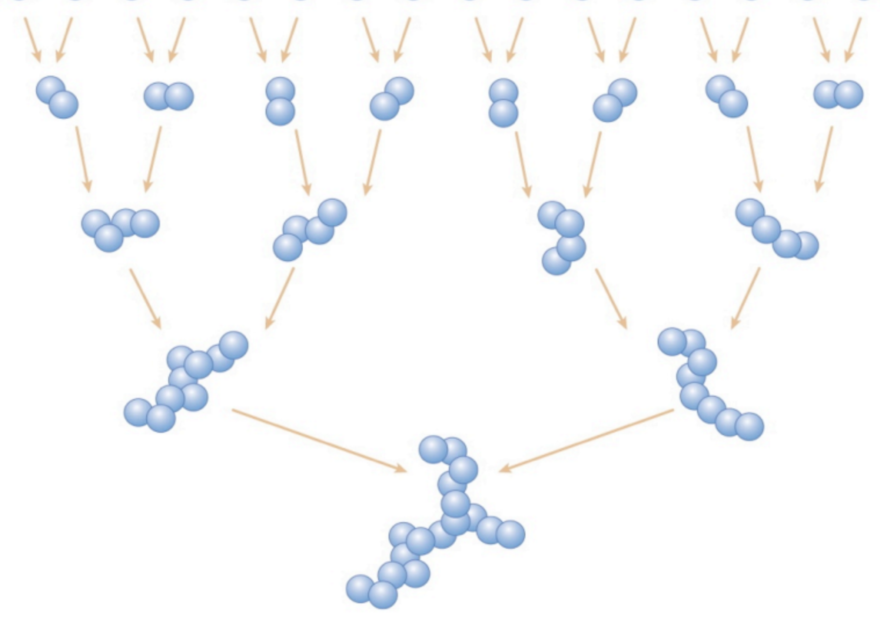


Dust Motion in the Gas: Dust Settling and Growth



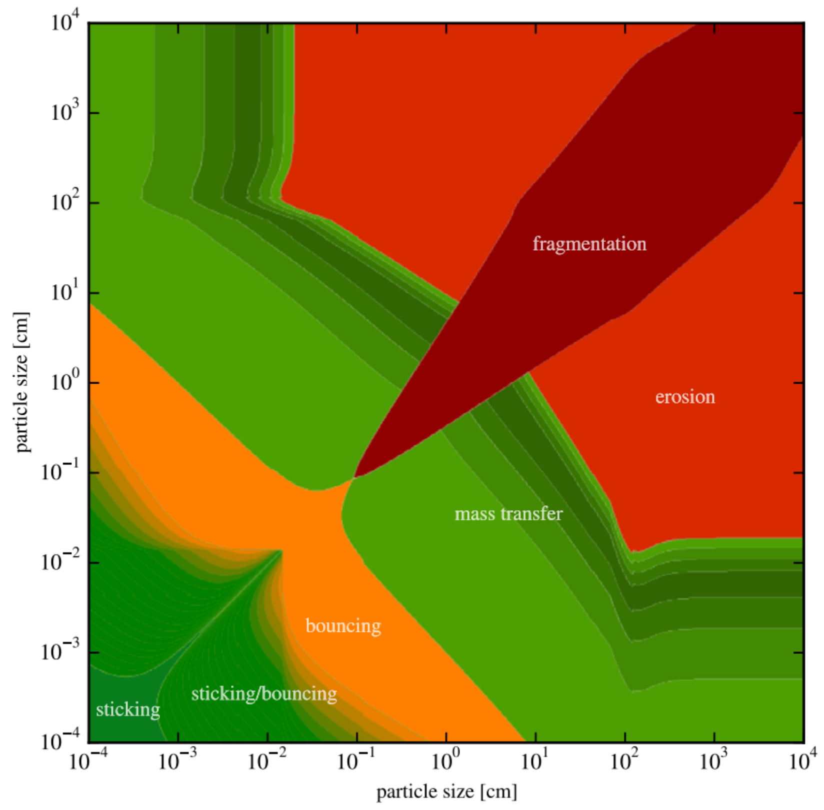
The combination of gravity, gas drag and turbulence in the gas cause **dust grains to collide and to merge** (initially due to electrostatic forces).

This collisional process allows dust grains to grow to cm-size from micron-size. Once dust grains reach dm-size collisions rapidly become destructive.



Right: outcome of collisions between dust grains (figure from Birnstiel+2016).

The initial growth of the dust by electrostatic sticking during collisions produces large porous and fractal aggregates, which beyond a certain size become very fragile.



Gas-Solids Coupling: Epstein and Stokes Regimes

Dust and larger solid bodies “see” the gas in different ways:
- **dust** “sees” the gas as a number of impacting individual molecules (***Epstein* regime**)
- **larger bodies** (e.g. asteroids) “see” the gas a fluid (***Stokes* regime**)

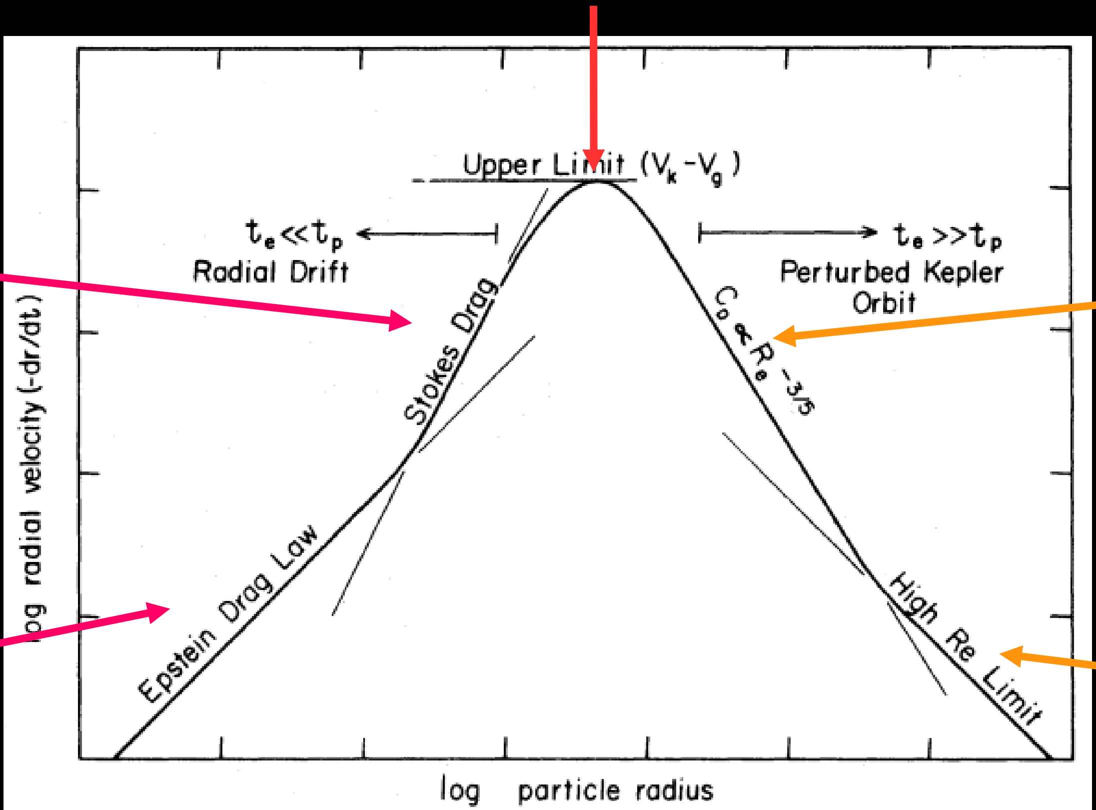
“Meter Barrier”

Pebbles (mm to cm)

Small Planetesimals (sub-km to km)

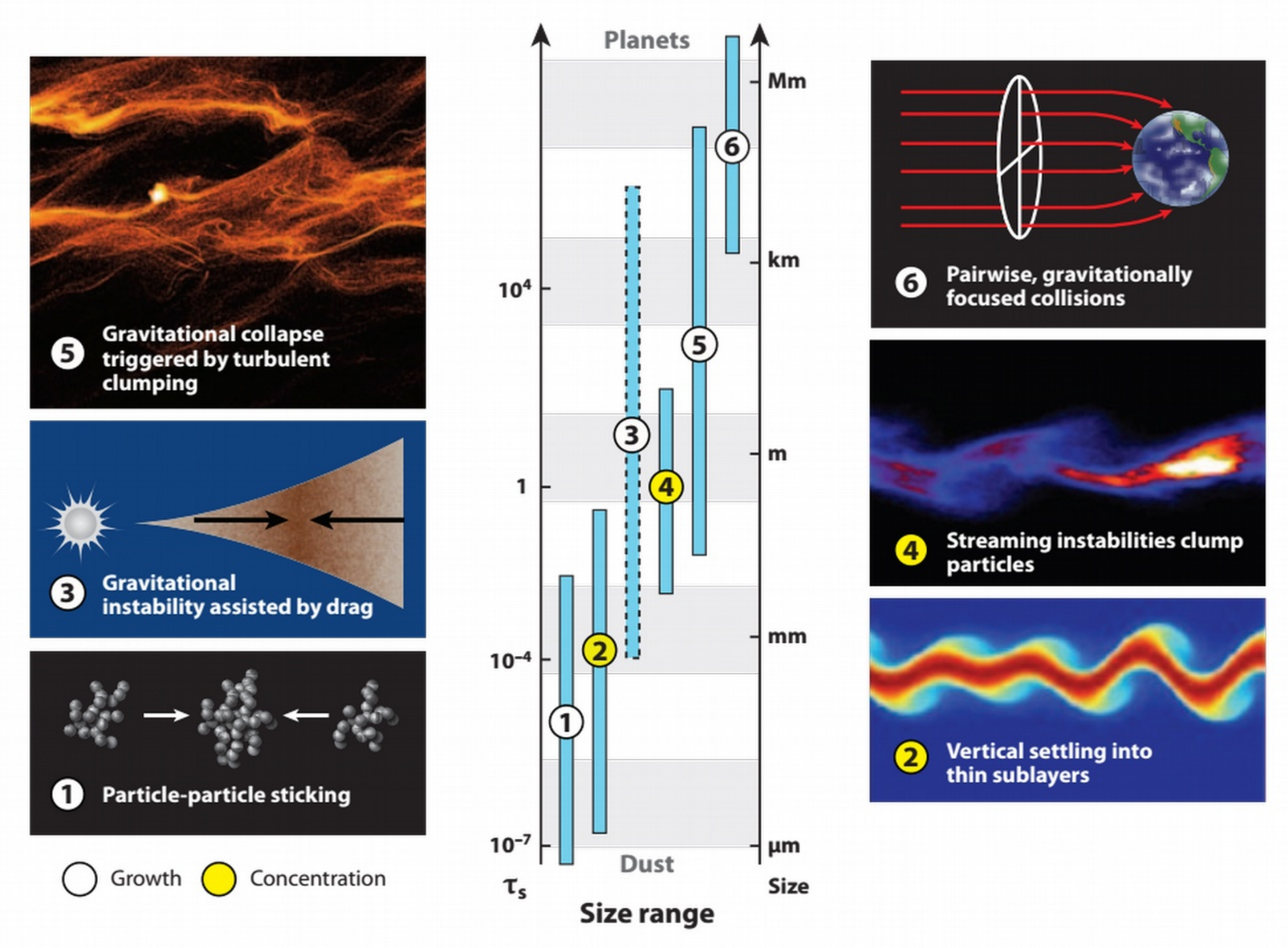
Large Planetesimals (10 – 100 km)

Primordial disk dust (micron to sub-mm)

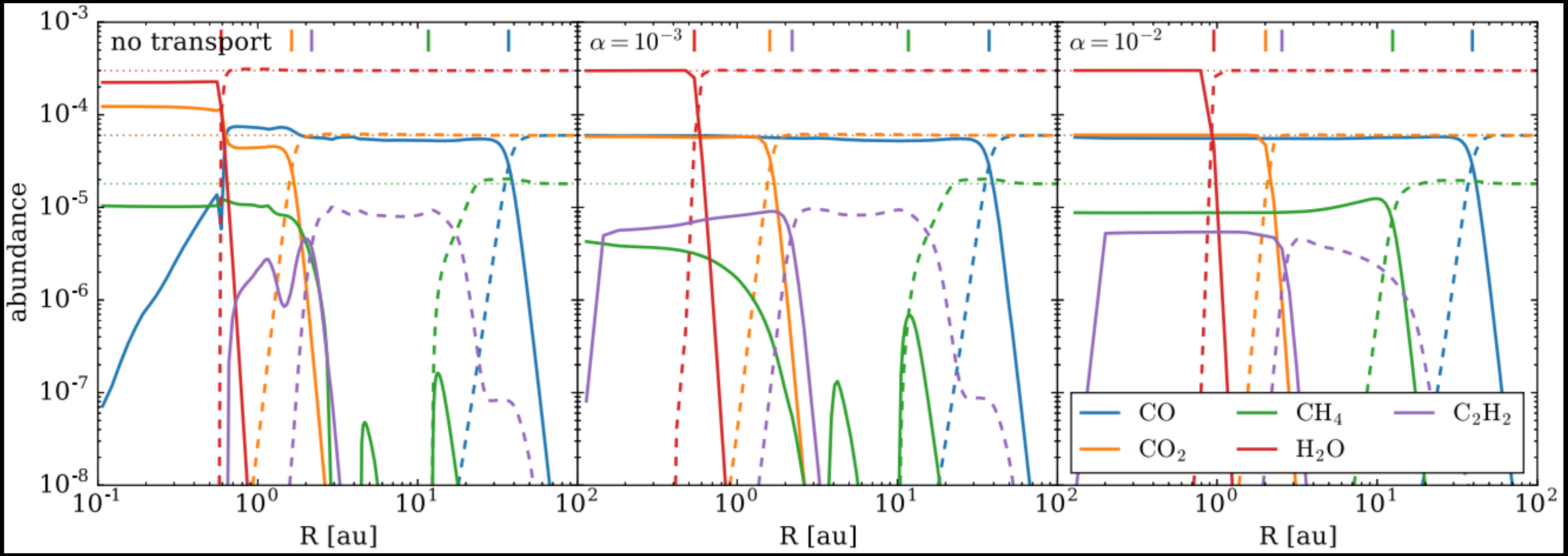


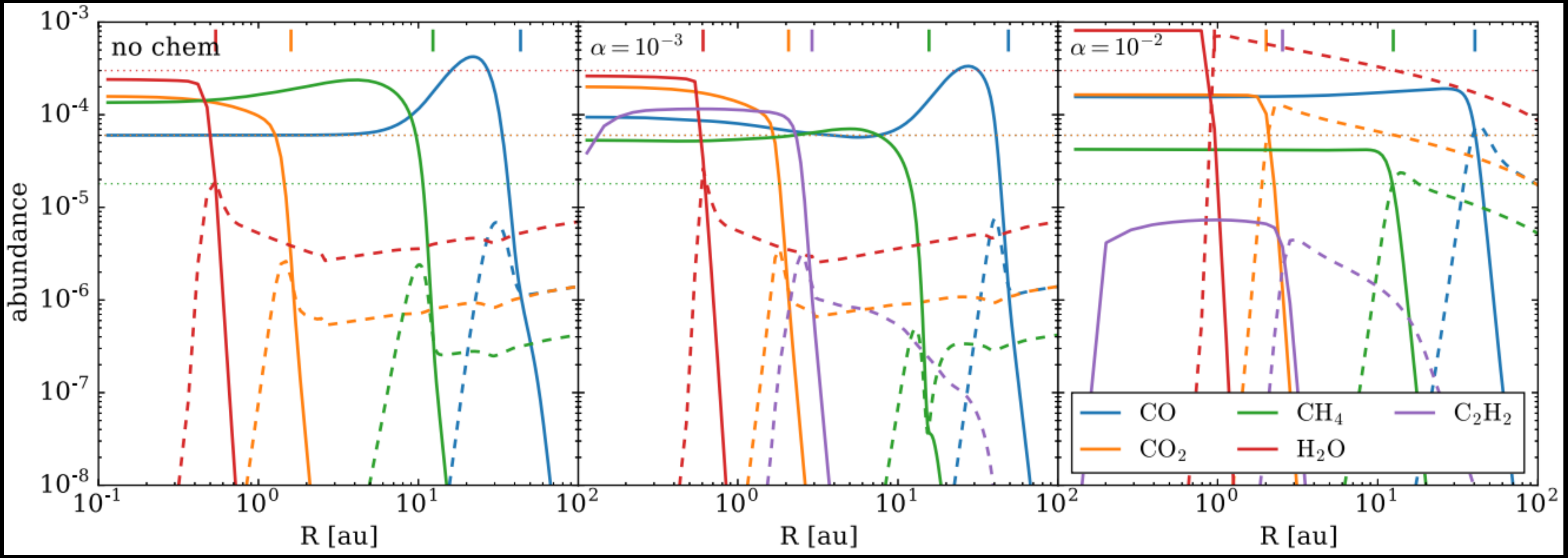
Radial drift velocity of solids embedded in the disk gas as a function of their size (figure from Weidenschilling 1977)

From Dust to Planetesimals: Physical Processes



Dust and Gas Drift and Disk Chemical Composition



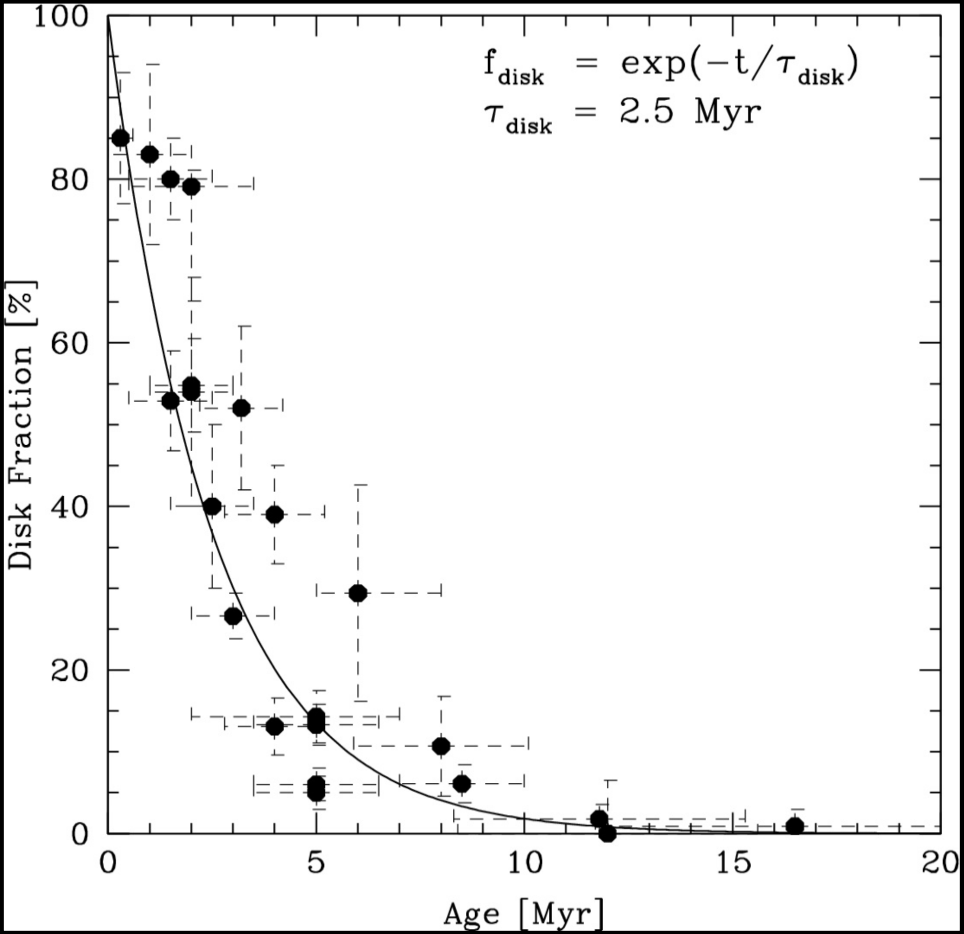


Effects of gas and dust transport on the molecular composition of circumstellar disks from Booth & Ilee (2019).

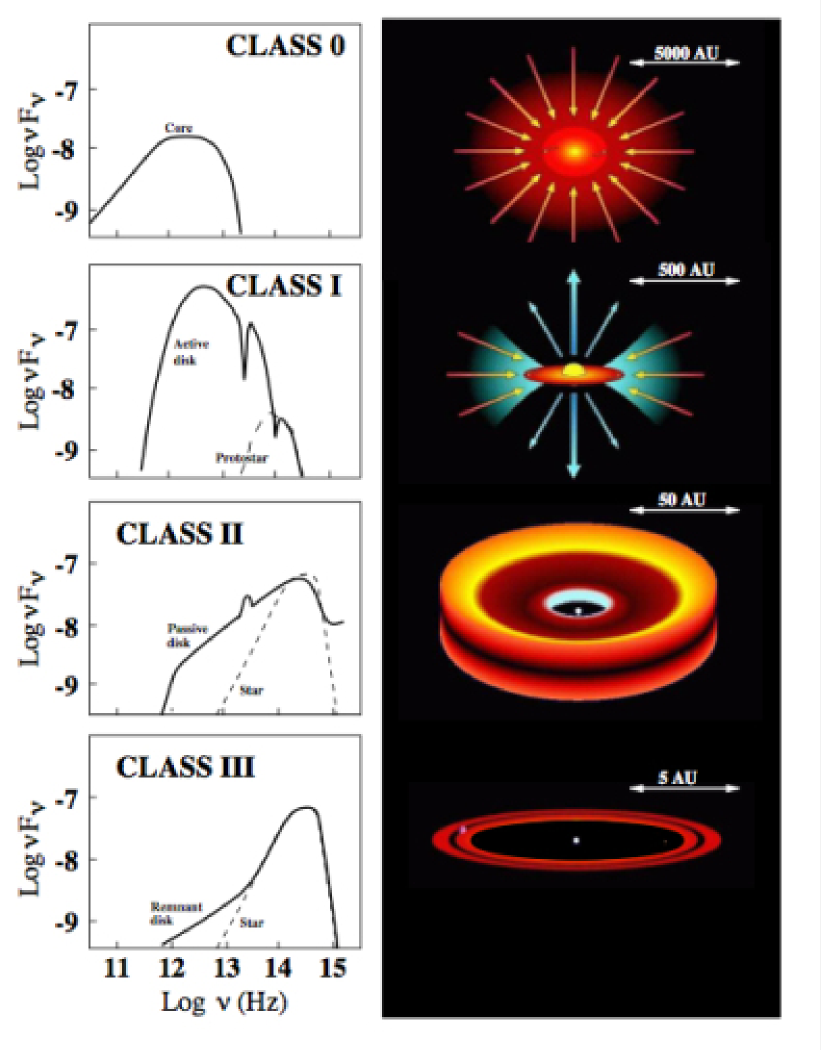
Top: dust moves together with gas and gas transport changes. Bottom: dust drift with respect to the gas.

The Lifetime of Circumstellar Disks

The observations of circumstellar disks reveal an **upper limit of ~10 Ma** to the lifetime of their gaseous component.



Fraction of circumstellar disks as a function of time (Mamajek et al. 2009)

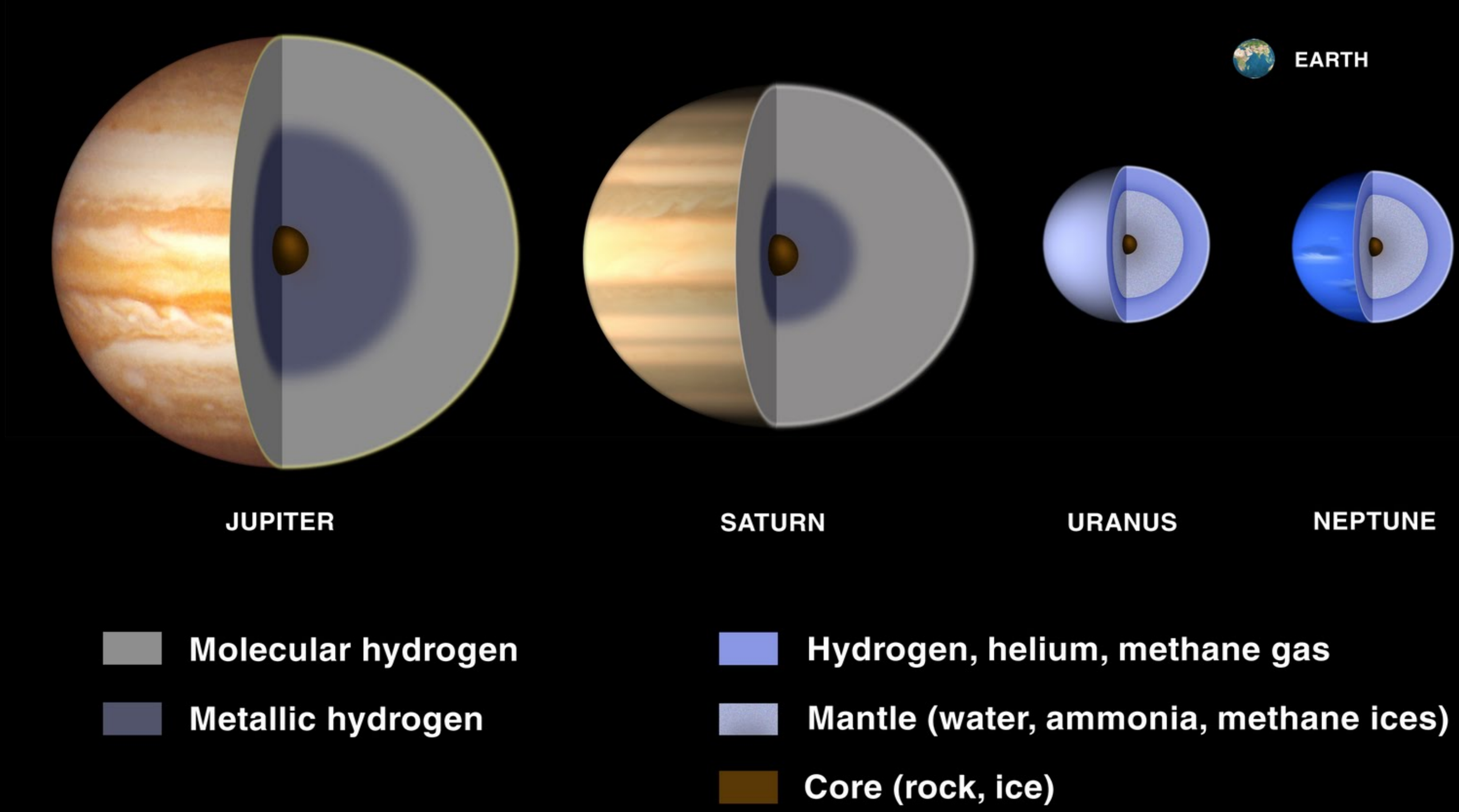


Part IV

Planet Formation: From Dust and Gas to Planets

Giant Planets and Circumstellar Disks

Differently from the terrestrial planets, most (>90%) of the mass of Jupiter and Saturn and a significant fraction (15-30%) of the mass of Uranus and Neptune is due to the two lightest elements, hydrogen (H) and helium (He).



Pebble Accretion and Giant Planets

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**.

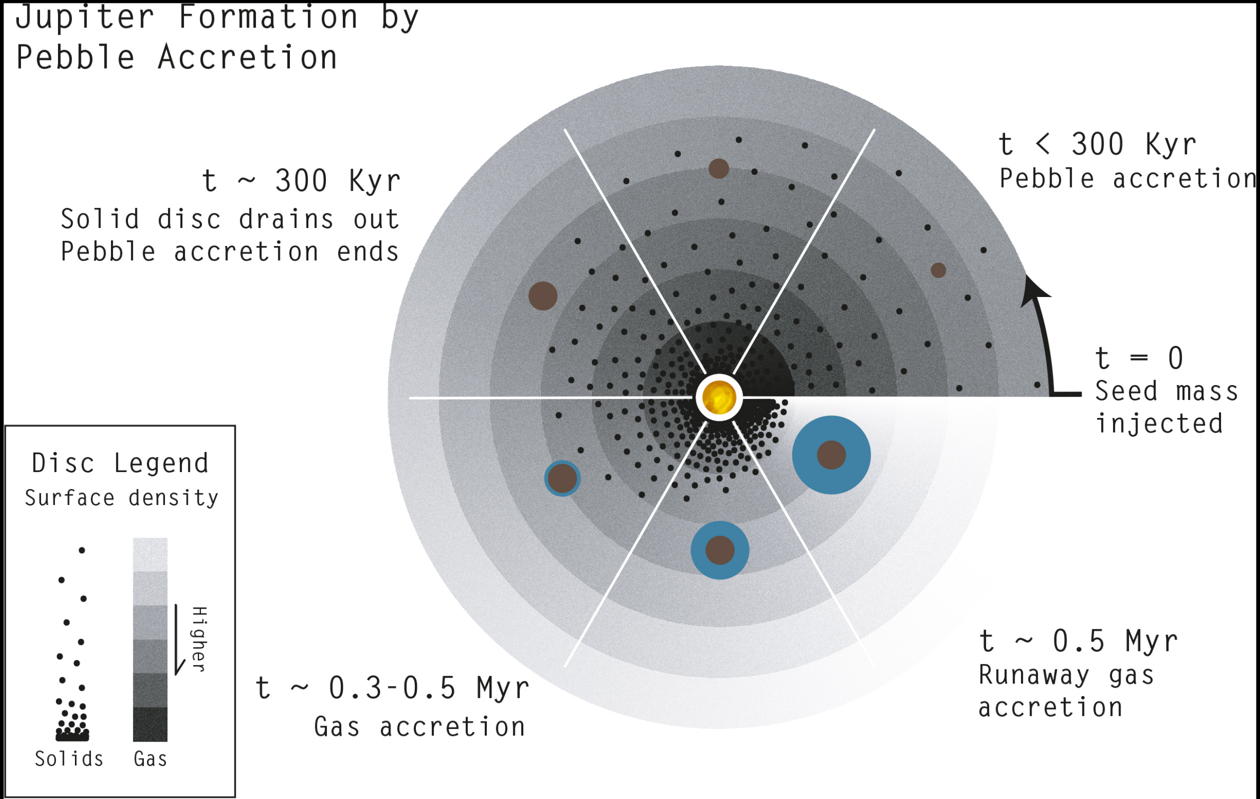
Nucleated Instability Scenario

↓

First, a **planetary core with mass of ~10 $M_\oplus$** should form with the same process as planetary embryos and terrestrial planets

↓

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

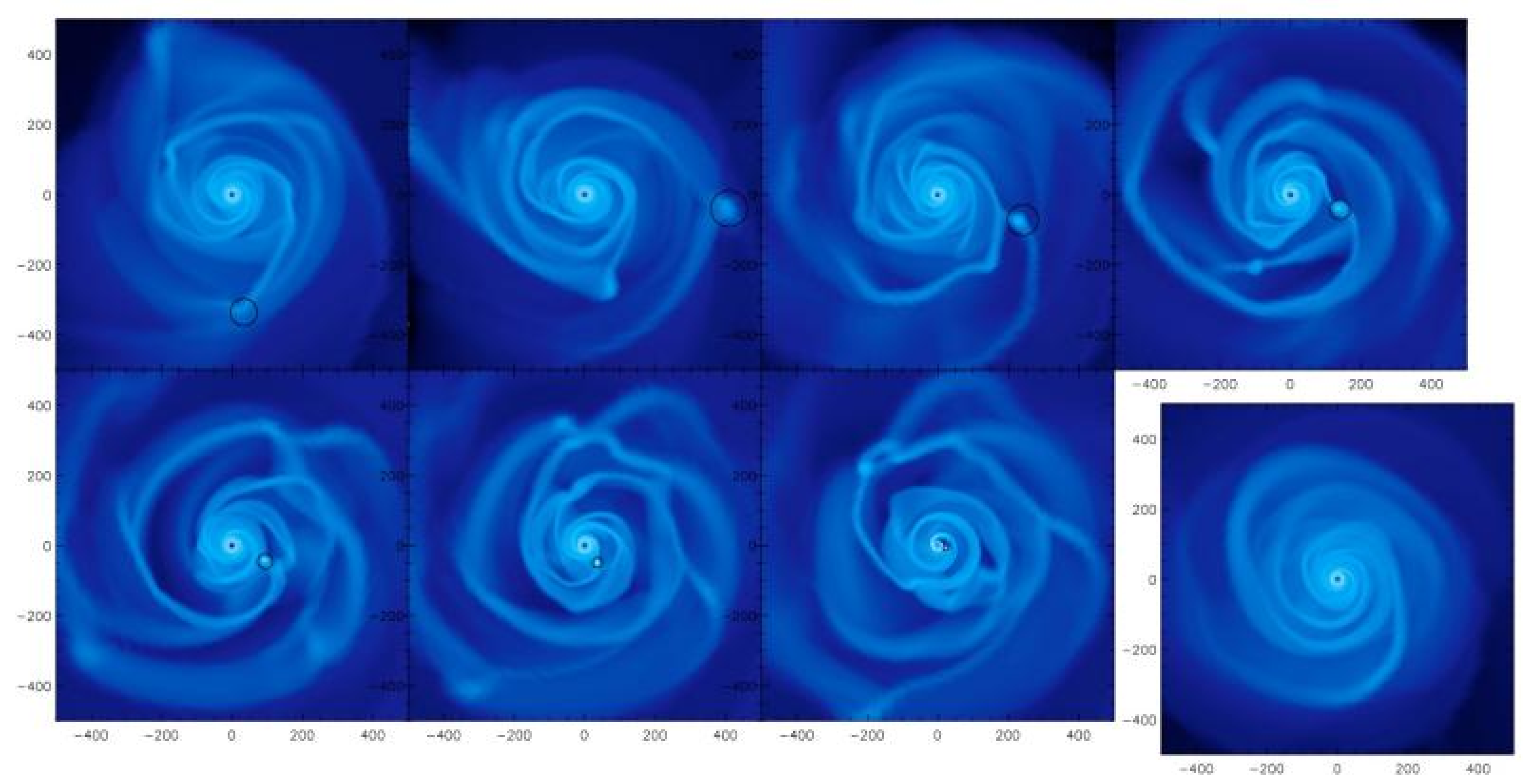


Sketch of the formation process of giant planets by pebble accretion (Lin, Lee & Chiang 2018).

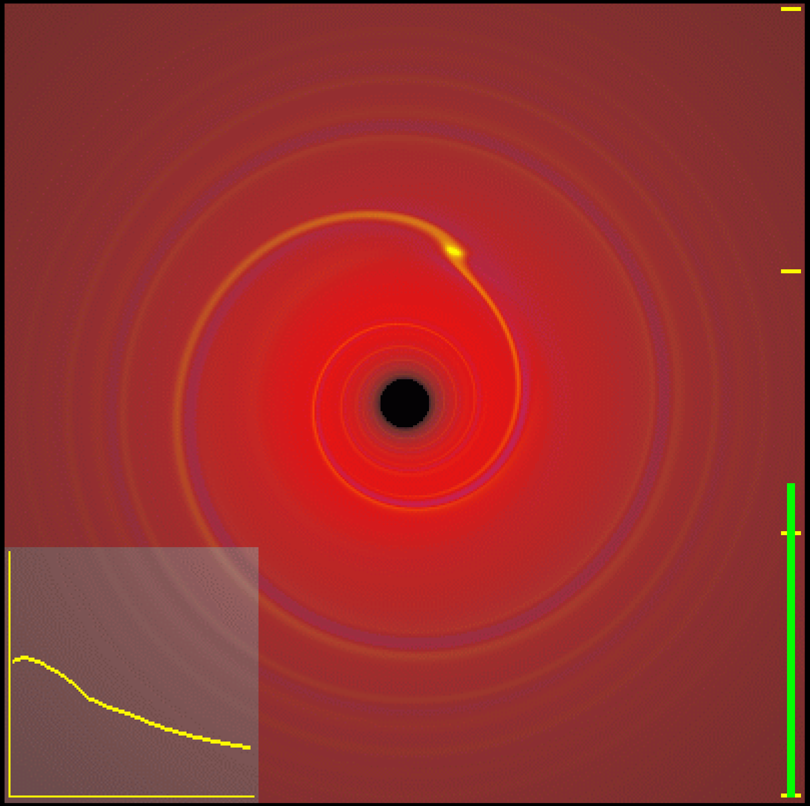
Giant Planet Formation by Disk Instability

Giant planets at such large distances (> 50-100 au) can also have formed by **disk gravitational instability**, i.e. by direct gravitational collapse of a blob of gas in the circumstellar disk.

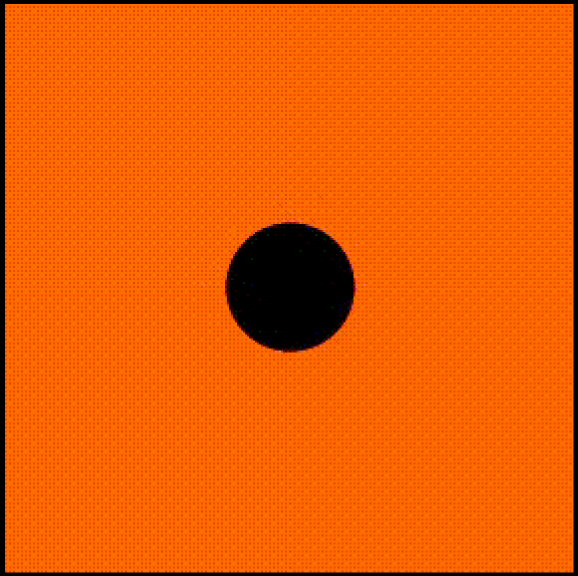
This model requires **low temperatures** (thermal pressure contrasts the collapse) and **high masses** of gas, but if the conditions are satisfied it can form in < 1 Myr giant planets of Jovian mass or larger.



Planets and Disk Gas: Type I Migration

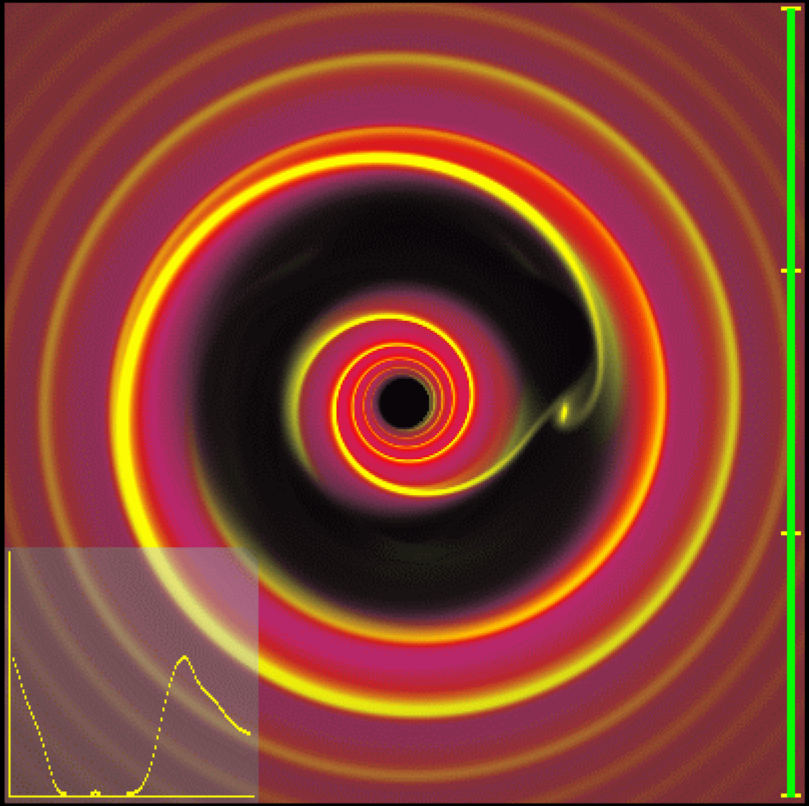


If the mass of a planet is no larger than 30-40 Earth masses, the planet perturbs the disk creating **spiral density waves**: its interaction with the regions of enhanced gas density results in **inward migration**.

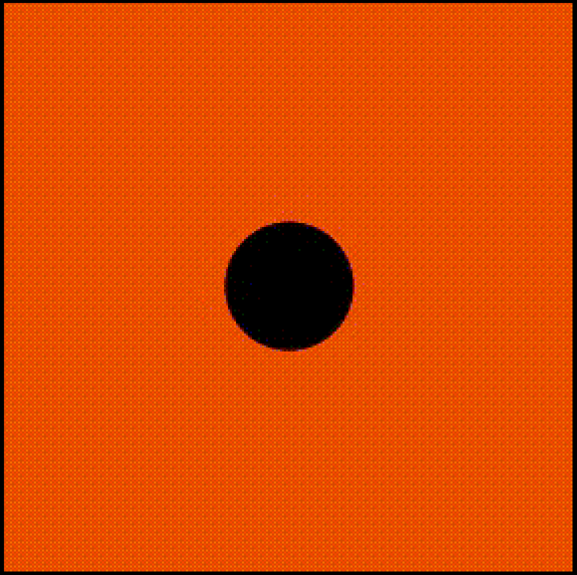


Type I migration can be quite fast and destructive (planets can fall into the star on a timescale of **10^4-10^5 years**). In certain disk conditions, however, it can be suppressed or reversed for planets below 30 Earth masses.

Planets and Disk Gas: Type II Migration

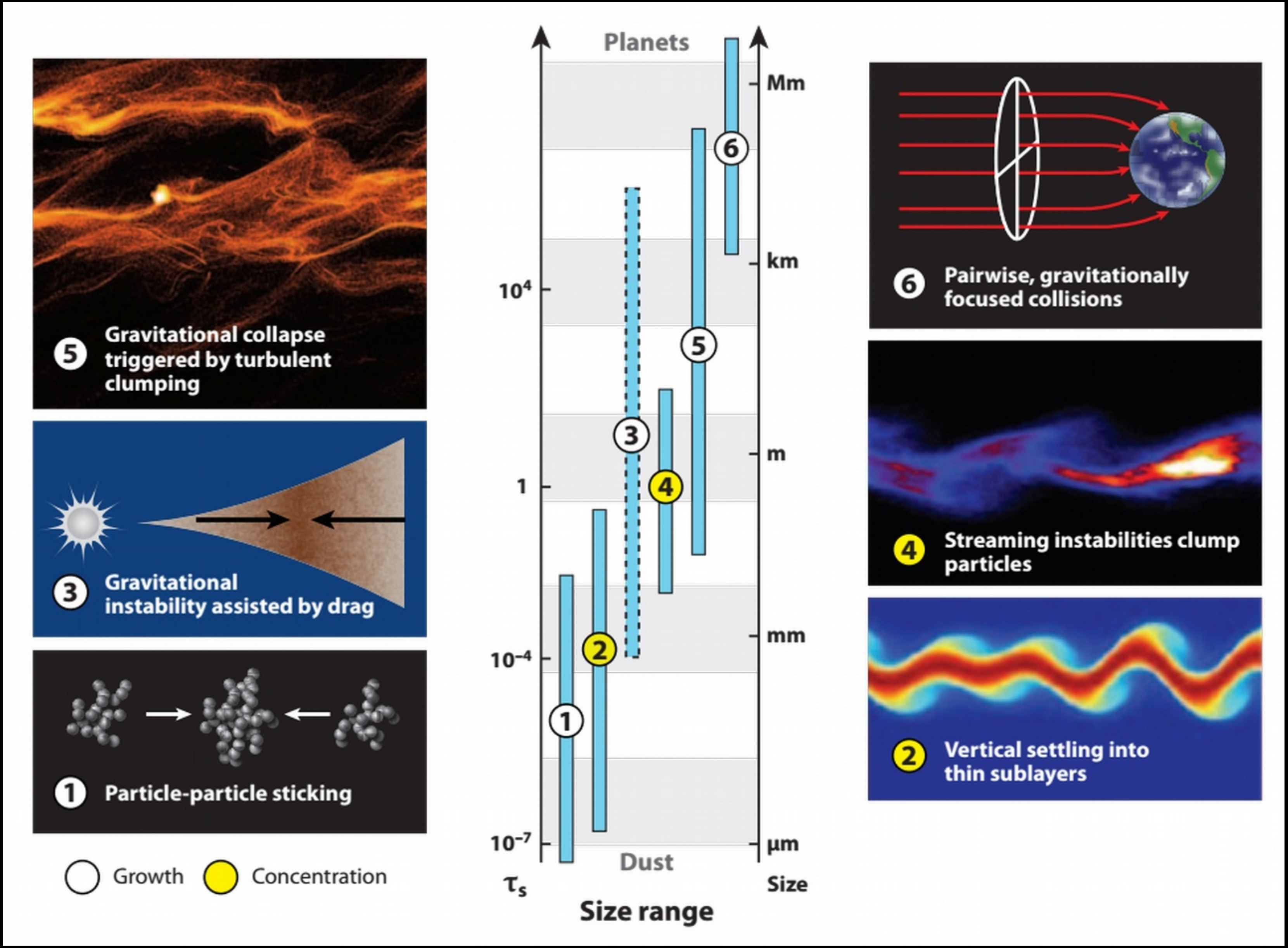


If the planet is large enough to open a **gap in the gas** of the disk (in the Solar System this happens between Saturn's and Jupiter's masses), migration transition from Type I to Type II.

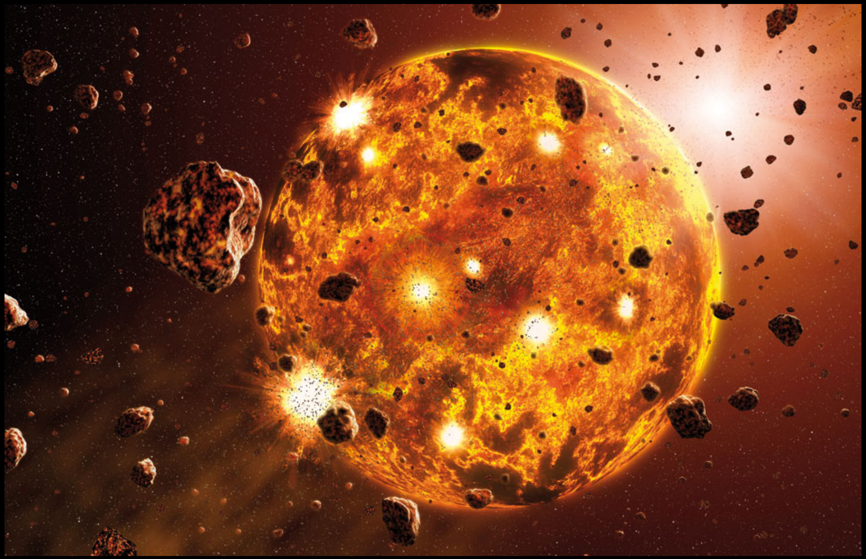


In the **Type II migration**, giant planets the size of Jupiter and Saturn migrate toward their central star (from 5.2 au) with a characteristic time of **10^5-10^6 years**.

From Dust to Planetesimals: Physical Processes



Collisional Growth and Gravitational Focusing



Once planetesimals become larger than ~1000 km in diameter, their gravity is strong enough to affect the orbits of nearby planetesimals by bending them during close encounters.

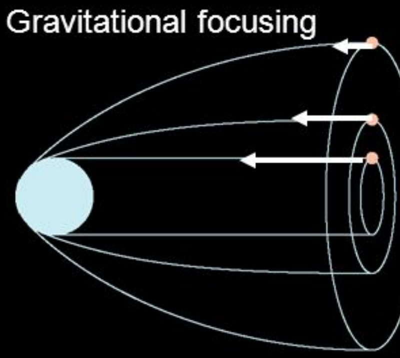
Their gravity act as a lens, effectively increasing the collisional cross-section by a factor called ***gravitational focusing factor***.

Since the gravitational focusing factor is proportional to the escape velocity, the more massive a planetesimal the more effective it is in capturing other planetesimals.

This causes a **positive feedback process** that results in a few larger planetesimals growing faster than the other ones (*oligarchic growth* phase).

Collision cross section

$$\sigma = \underbrace{\pi R^2}_{\text{Geometrical cross section}} \underbrace{\left(1 + \frac{v_{\rm esc}^2}{v^2}\right)}_{\text{Gravitational focusing factor}}$$



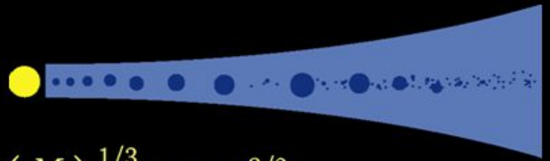
Growth rate of planets

$$\frac{dM}{dt} \simeq \rho \sigma v \simeq \Sigma_{\rm d} \pi R^2 \left(1 + \frac{v_{\rm esc}^2}{v^2}\right) \Omega_{\rm K}$$

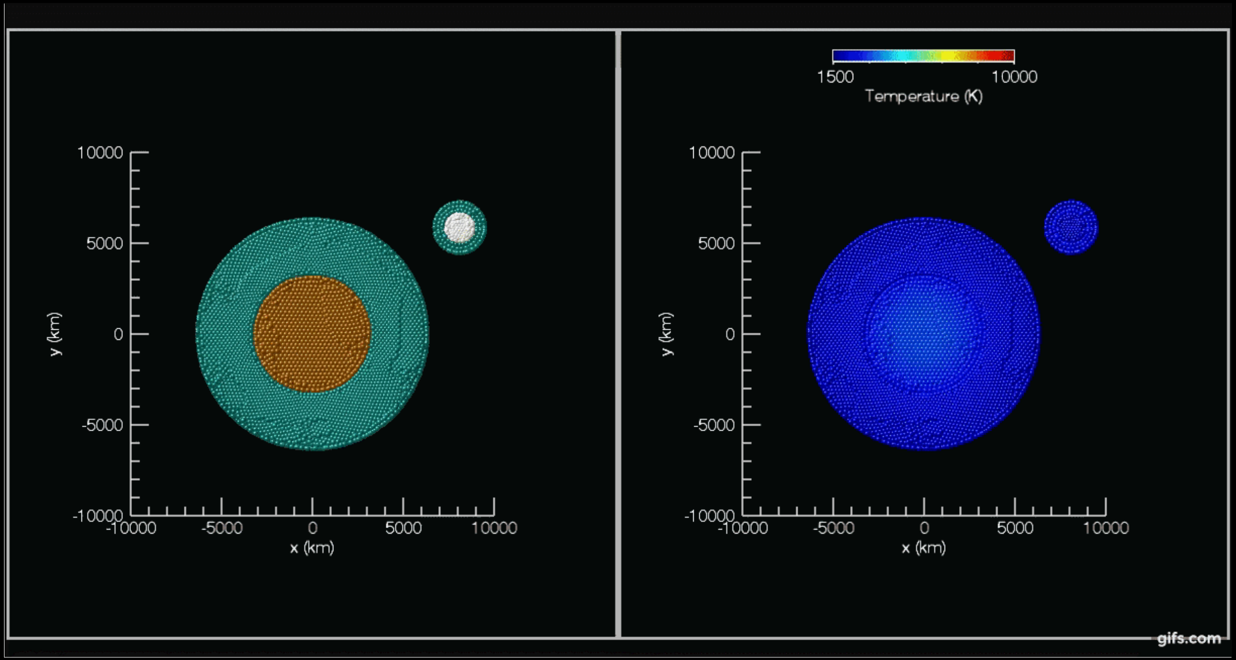
Growth time scale

$$t_{\rm grow} \equiv \left(\frac{1}{M}\frac{dM}{dt}\right)^{-1}$$

$$\simeq \; 4\times10^7 \left(\frac{\Sigma_{\rm d}}{\Sigma_{\rm d}^{\rm H}}\right)^{-1} \left(\frac{\rho_{\rm mat}}{3\,{\rm g\,cm^{-3}}}\right)^{2/3} \left(\frac{M}{M_{\rm E}}\right)^{1/3} \left(\frac{a}{1{\rm AU}}\right)^{3/2} \; \text{yr}$$



The Final Growth Phase: Giant Impacts

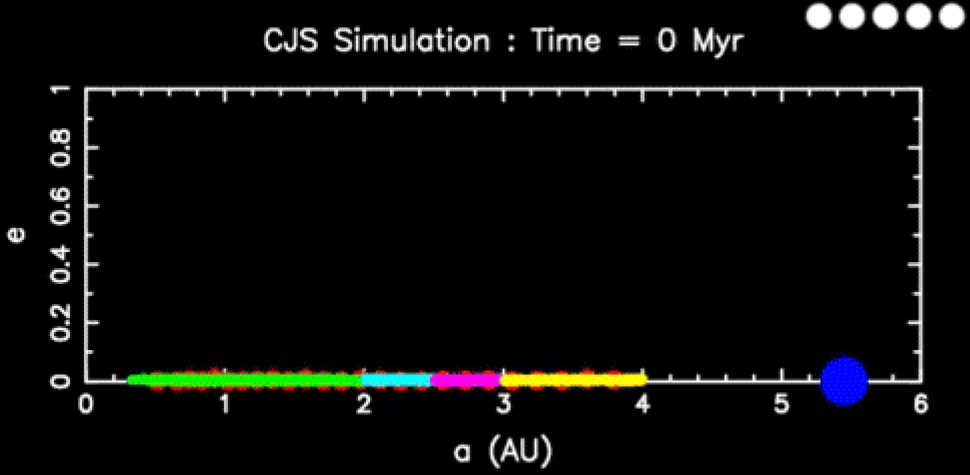


Once planetesimals grow to a size comprised between those of the Moon and of Mars (1500-3000 km in radius), they become *planetary embryos.*

At this stage, they have cleared their surrounding regions by the smaller planetesimals and their growth slows down.

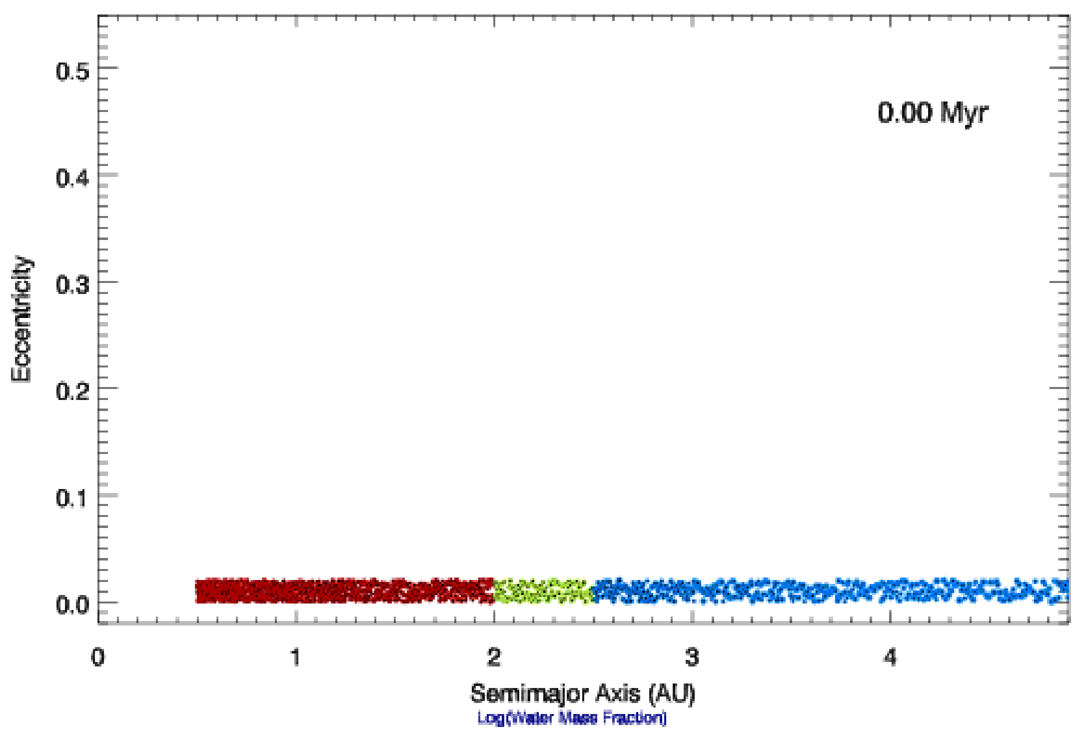
Planetary embryos main mode of growth is by colliding with other planetary embryos, since in their mass range collisions always result in mass gain.

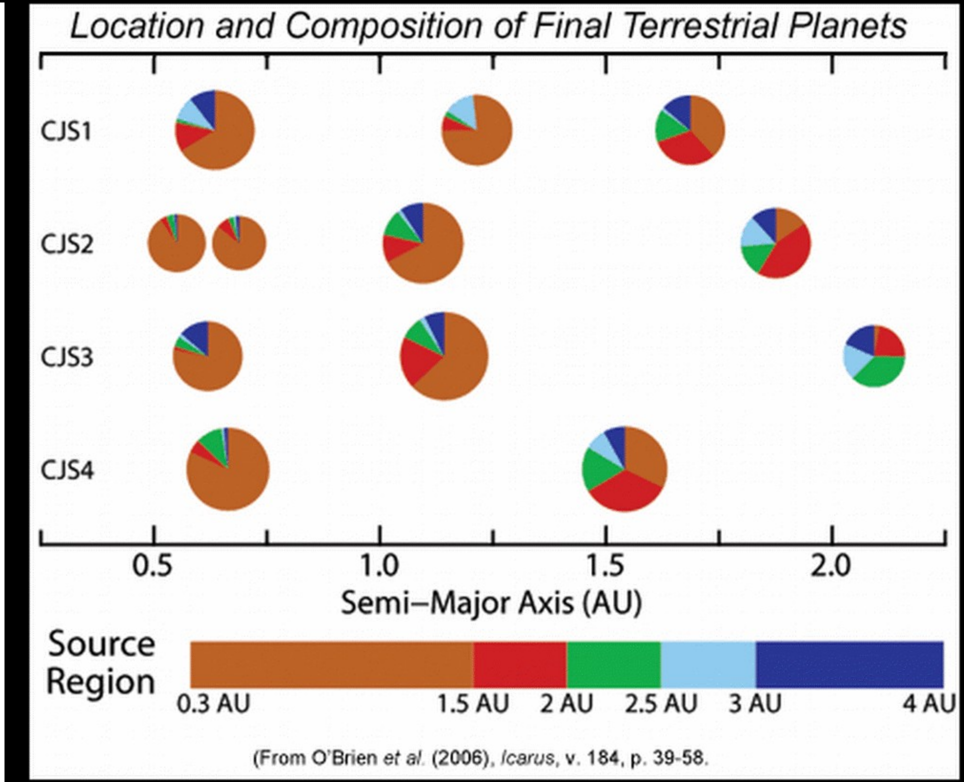
Their mass growth is not continuous but becomes step-like. This process takes 100s of Myr, but the presence of large perturbers (e.g. the giant planets) can speed it up.



Top: simulation of a giant impact on the young Earth (credits: Southwest Research Institute/Simone Marchi). Bottom: formation of the terrestrial planets in the inner Solar System (credits: David P. O'Brien/Planetary Science Institute)

Compositional Remixing due to Gravitational Scattering





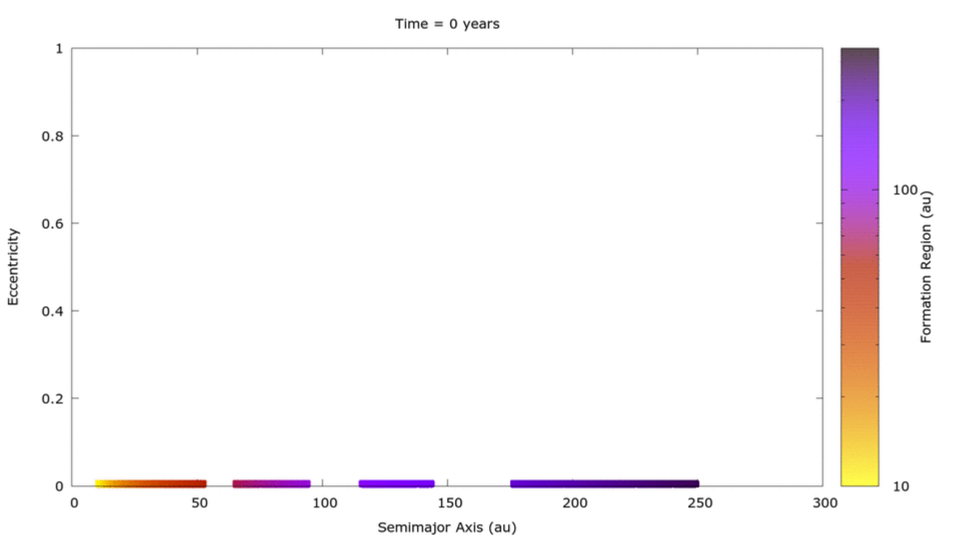
(From O'Brien *et al.* (2006), *Icarus*, v. 184, p. 39-58.

The interactions between planetary embryos and planetesimals cause a **remixing of the planetesimals and the accretion of materials that did not condense *in situ*.** The magnitude of the remixing depends on their masses and their number.

This remixing and accretion process is stochastic but is in-built in the planetary formation process.

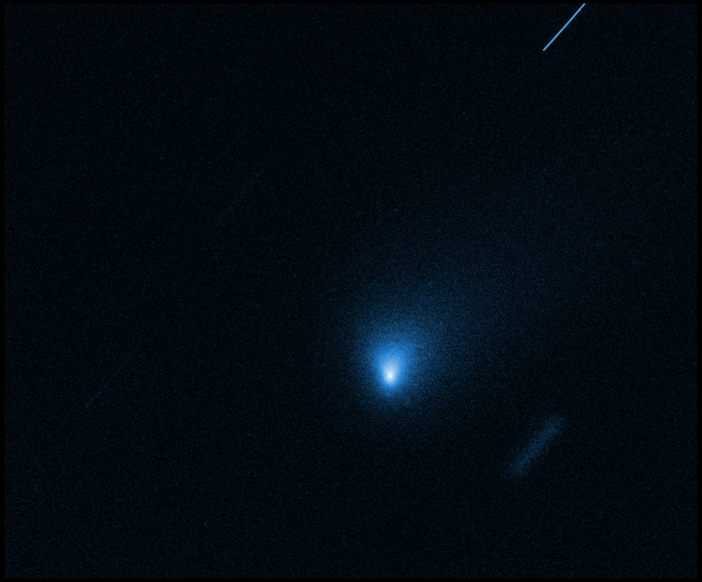
Left: simulation of the formation of the terrestrial planets in the inner Solar System tracing water diffusion and accretion (credits Sean Raymond).
Right: composition of terrestrial planets as a result of the stochastic diffusion and accretion process in different simulations (O'Brien et al. 2006).

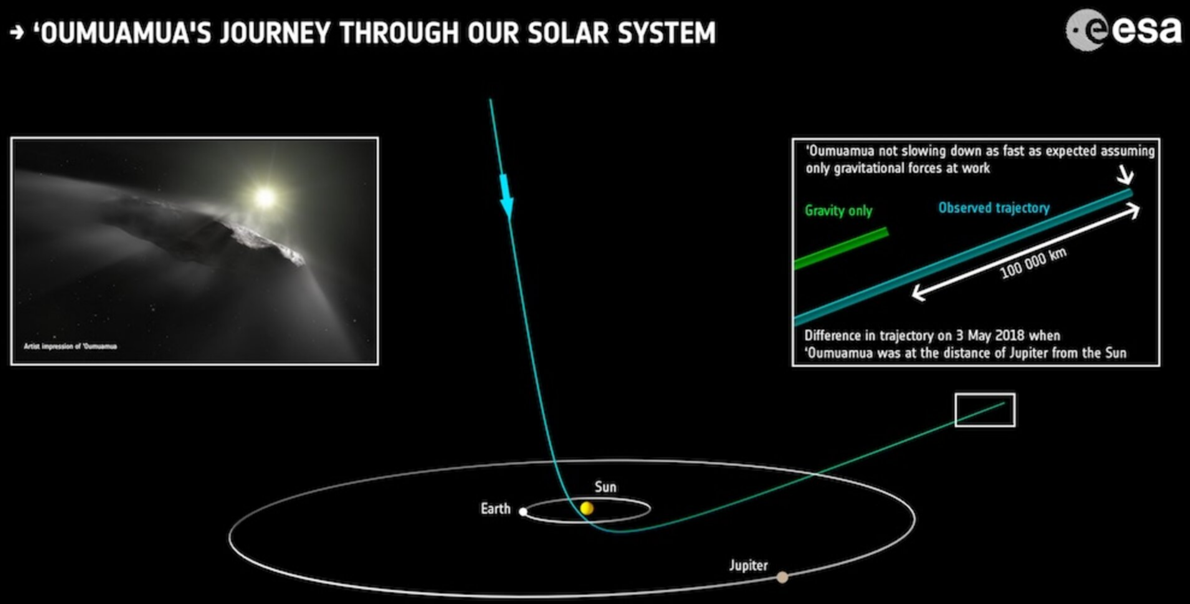
Excitation, Remixing and Interstellar Objects



Once giant planets appear in circumstellar disks, the drastically change the dynamical equilibrium of the surrounding planetesimals.

Ejection of dynamically-excited exocomets from the outer regions of protoplanetary disks is one of the most likely sources of interstellar objects like 1I/Oumuamua (2017) and 2I/Borisov (2019).



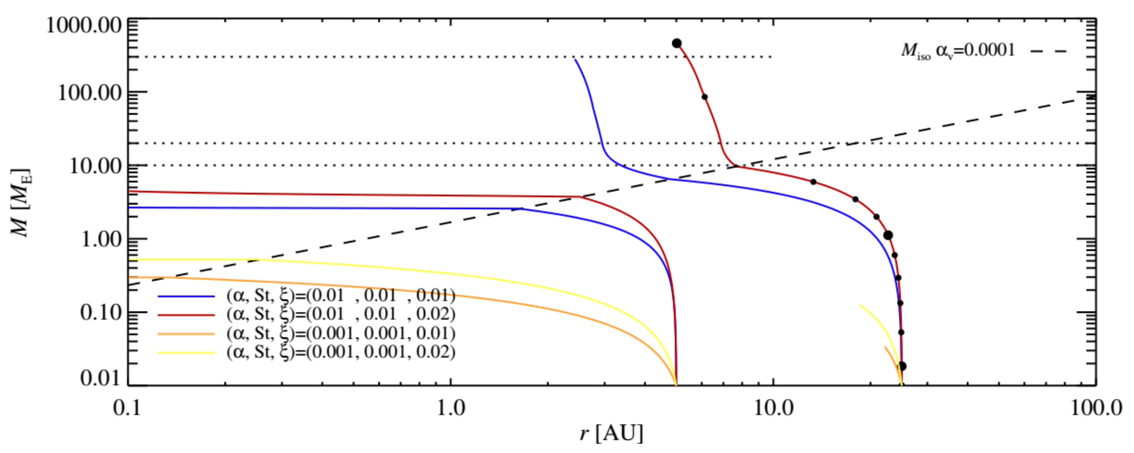


Top: simulation of the dynamical excitation of HD163296's planetesimal disk (from Polychroni et al., in prep.).

Part V

Planet Formation and Planetary Composition

Growth, Migration and Accretion of Gas and Solids



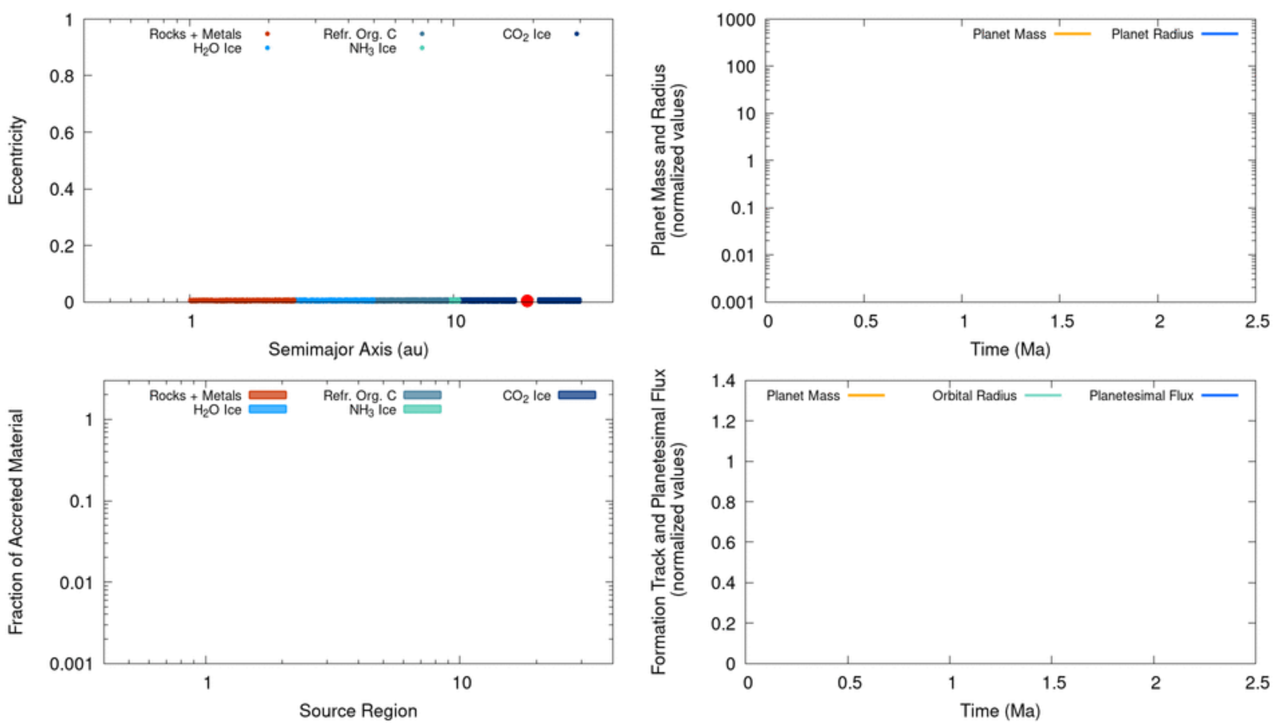
Planetary growth and migration occur at the same time, so their effect on the surrounding planetesimal disk **combine**.

A single migrating planet can completely break the original compositional gradient of solids in the crossed orbital regions.

Examples of growth and migration tracks due to pebble and gas accretion from Johansen+19.

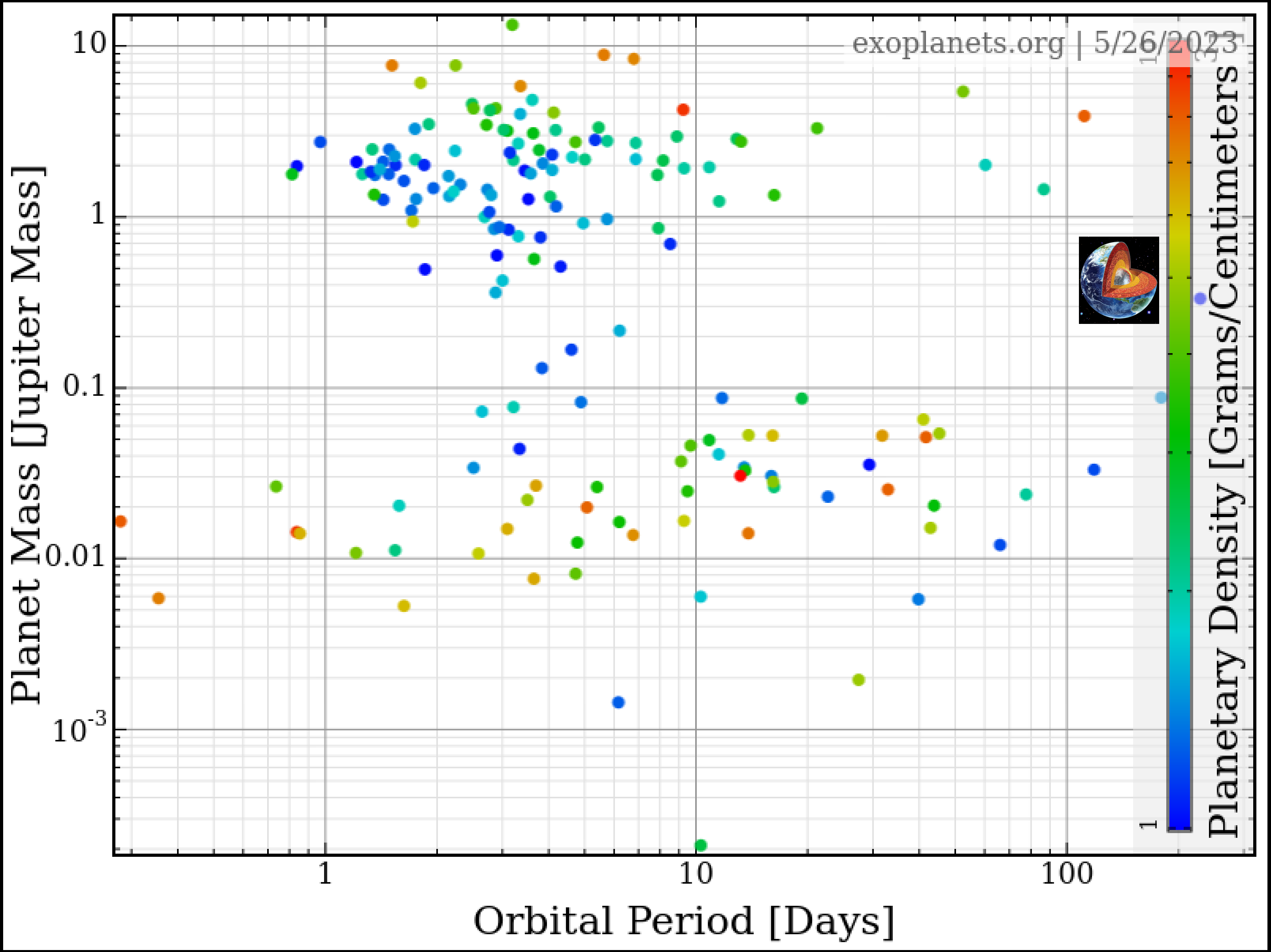
The planetesimal capture efficiency changes during migration due to the shifting balance between planet and stellar gravity and gas drag.

Each formation and migration history results in a unique balance of gas and solids accretion and in a **non-stellar composition**.

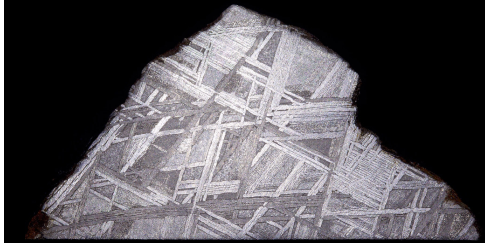


Example of the planetesimal accretion by a growing and migrating giant planet from Turrini+21

Exoplanets: Planetary Density vs Final Orbit

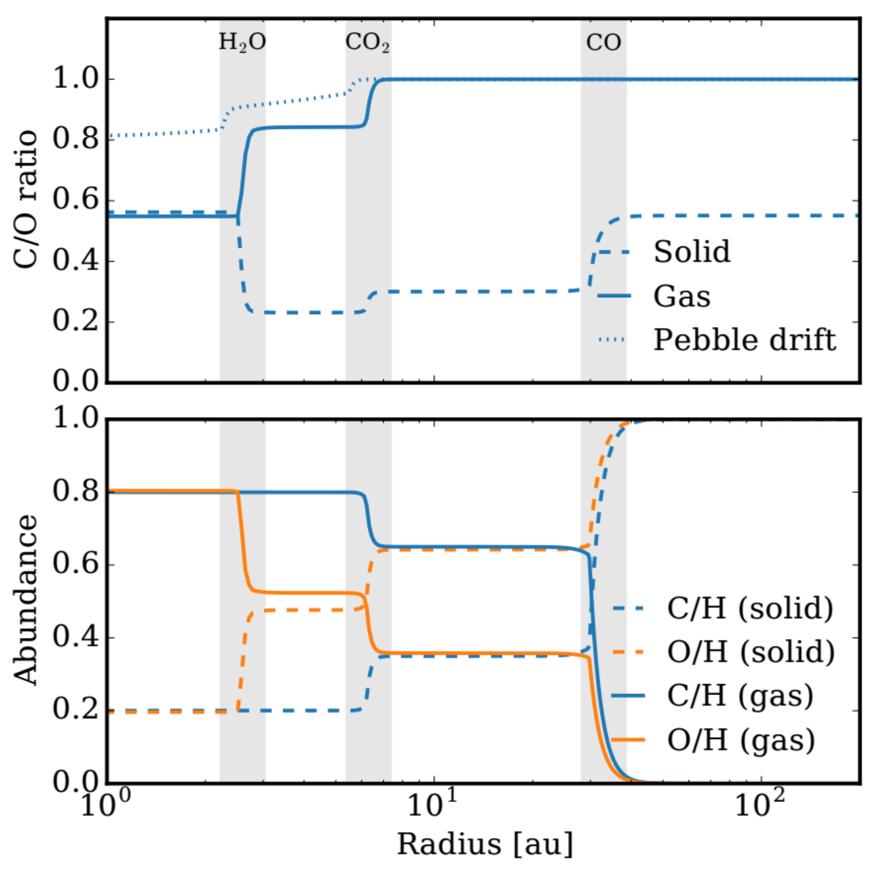


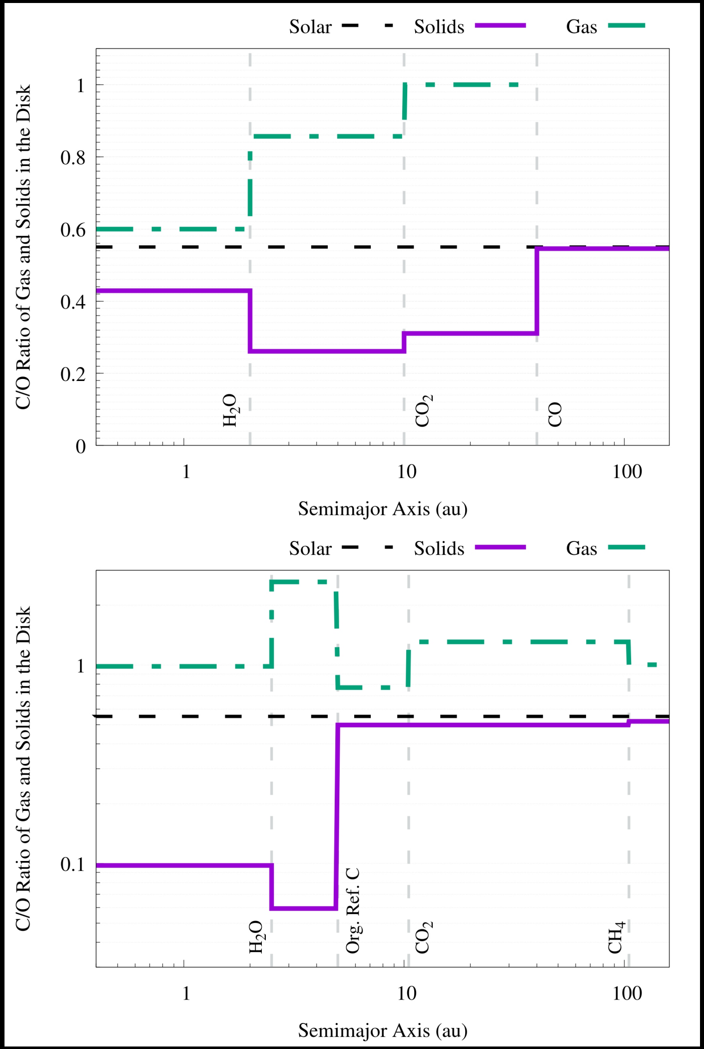
If we look at planets with densities comprised between 1 (H_2O) e 8 g/cm^3 (Fe-Ni), we see no correlations between density and orbital distance.



Elemental Ratios as a Window into Planet Formation

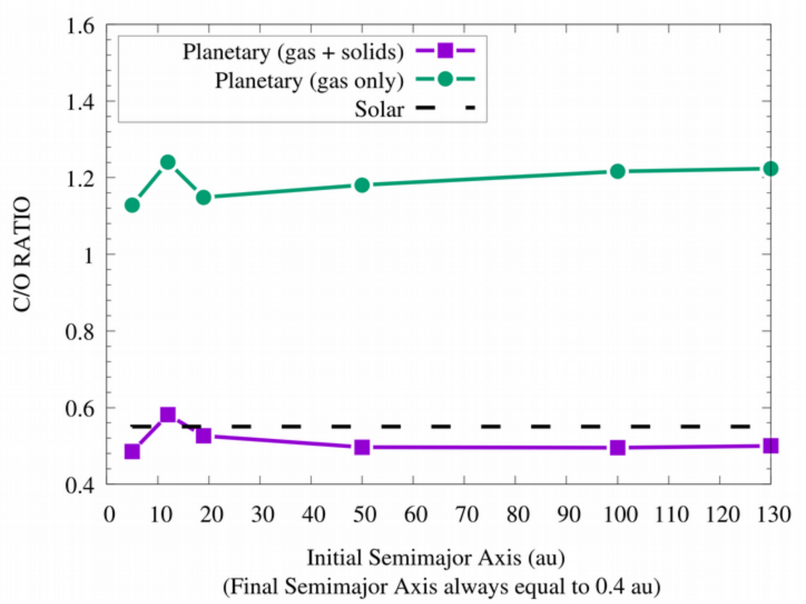
The **relative abundance of elements with different volatility** can provide us indications on how far the planet formed from its star and, for giant planets, on the main source of heavy elements (gas or solids)… but this is not as straightforward as it seems.





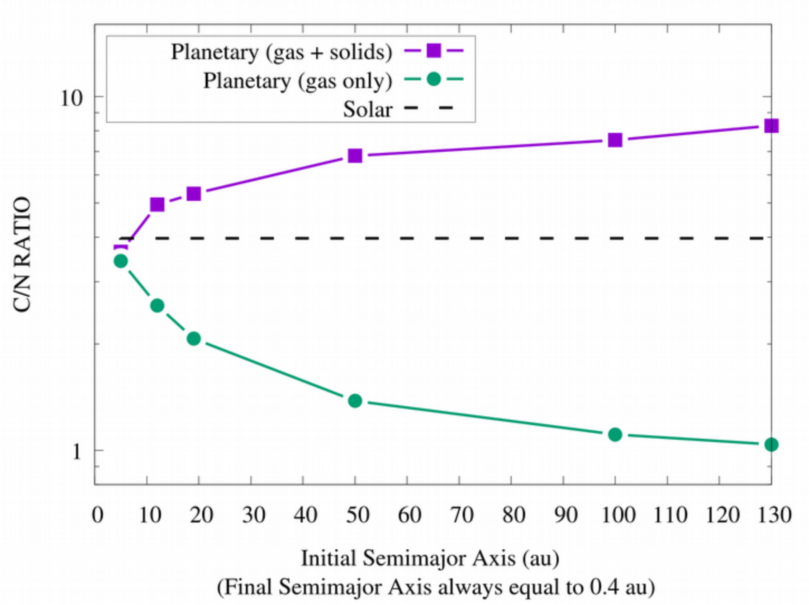
Left: C/O ratio of gas and solids in disks updated from the original structure proposed by Oberg+11 to include dust drift (figure from Madhusudhan 2019).
Right: comparison between the Oberg's suggested partition of C and O (top) and the updated one accounting for meteoritic and cometary data (Turrini 2023).

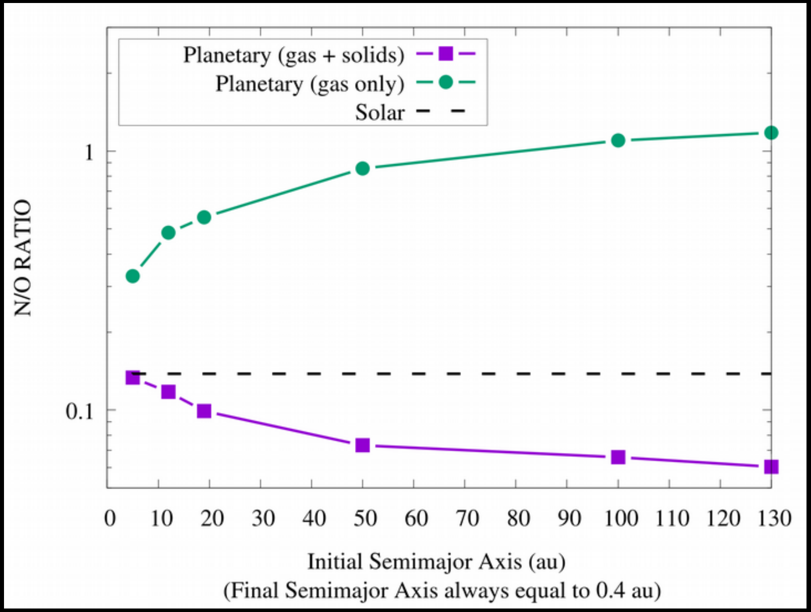
Elemental Ratios: Expanding the Suite of Elements



The **C/O ratio** of giant planets can provide **limited information** on the formation region, particularly in case of extensive migration.

Elemental **ratios involving N**, an element with higher volatility than C and O, **break the degeneracy**.

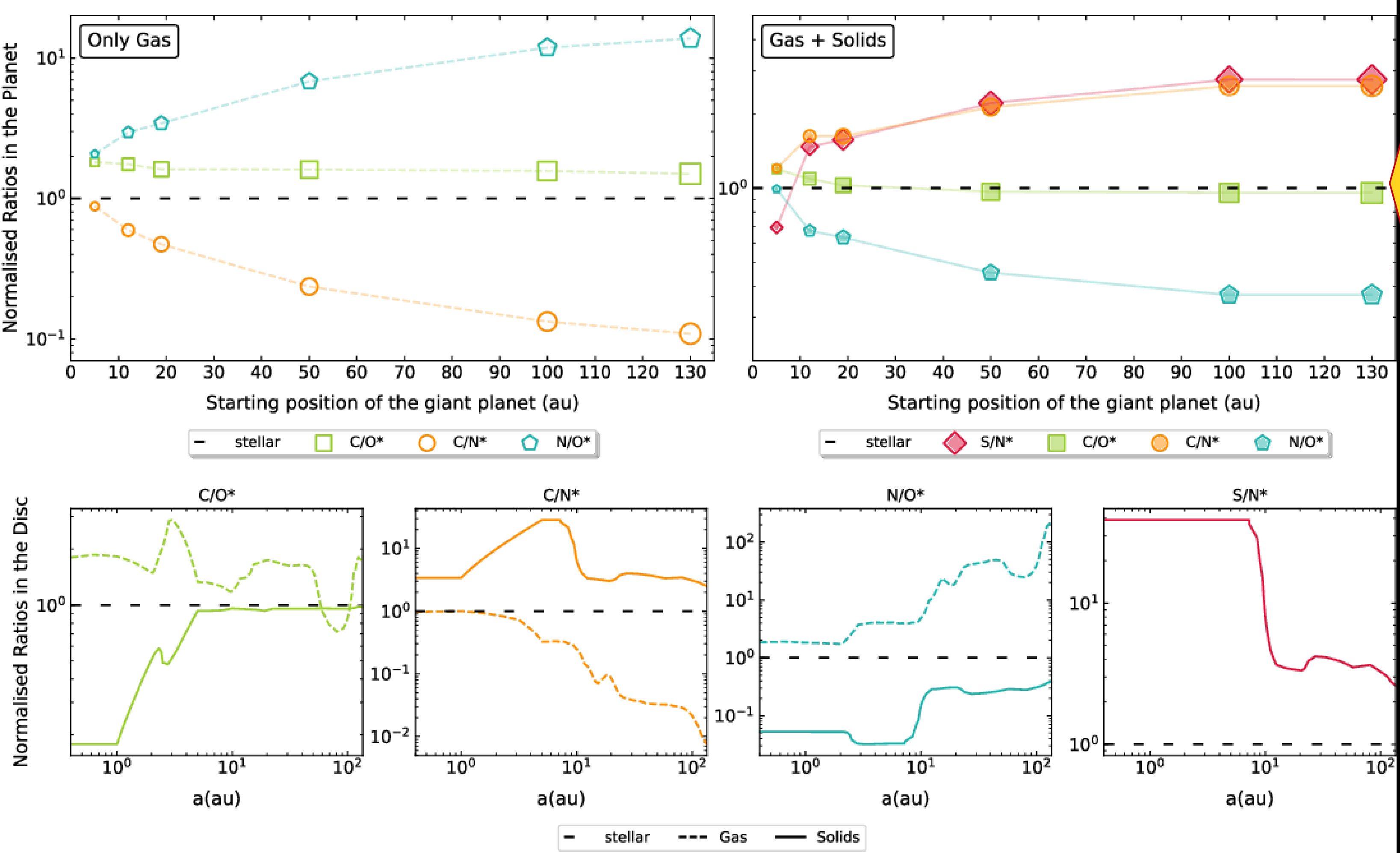




From left to right: C/O, C/N and N/O ratios of high (purple) and low (green) metallicity giant planets (Turrini et al. 2021).

Disks vs Planets: Non-Stellar Planetary Compositions

Expressing the planetary and disk abundances in units of the stellar abundances allows to define **normalized elemental ratios** where all elements share a **common scale** (Turrini+2021; Pacetti+2022)



The **planetary elemental ratios do not match the disk ones** but are shaped by migration and the concurrent accretion of gas and solids (Turrini+2021; Pacetti+2022)

Comparison of the elemental ratios in giant planets starting their formation at different distances from the star and those of the native circumstellar disk (Pacetti+2022)

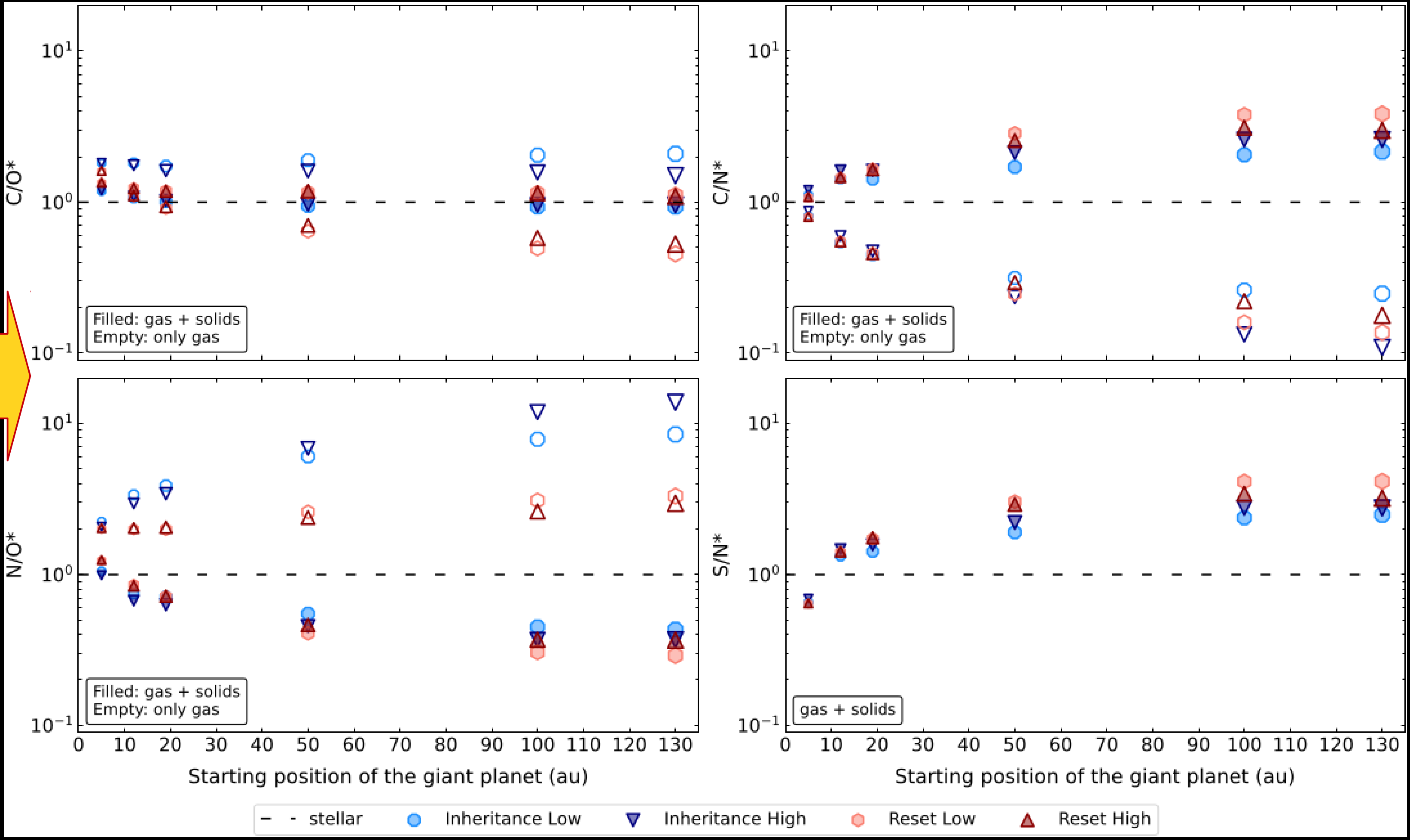
Disks vs Planets: O and the Stellar Environment

Elemental ratios not involving O are mostly **unaffected** by the disc chemical setup (inheritance vs reset; Pacetti+2022)

O-based elemental ratios are **affected** by the disc chemical setup

The widely studied **C/O** is the **most affected** (Pacetti+2022)

The C/O dependence can **costrain the natal disk environment** (see Pacetti+2022, Biazzo+2022 & Guilluy+2022 for observational validation)

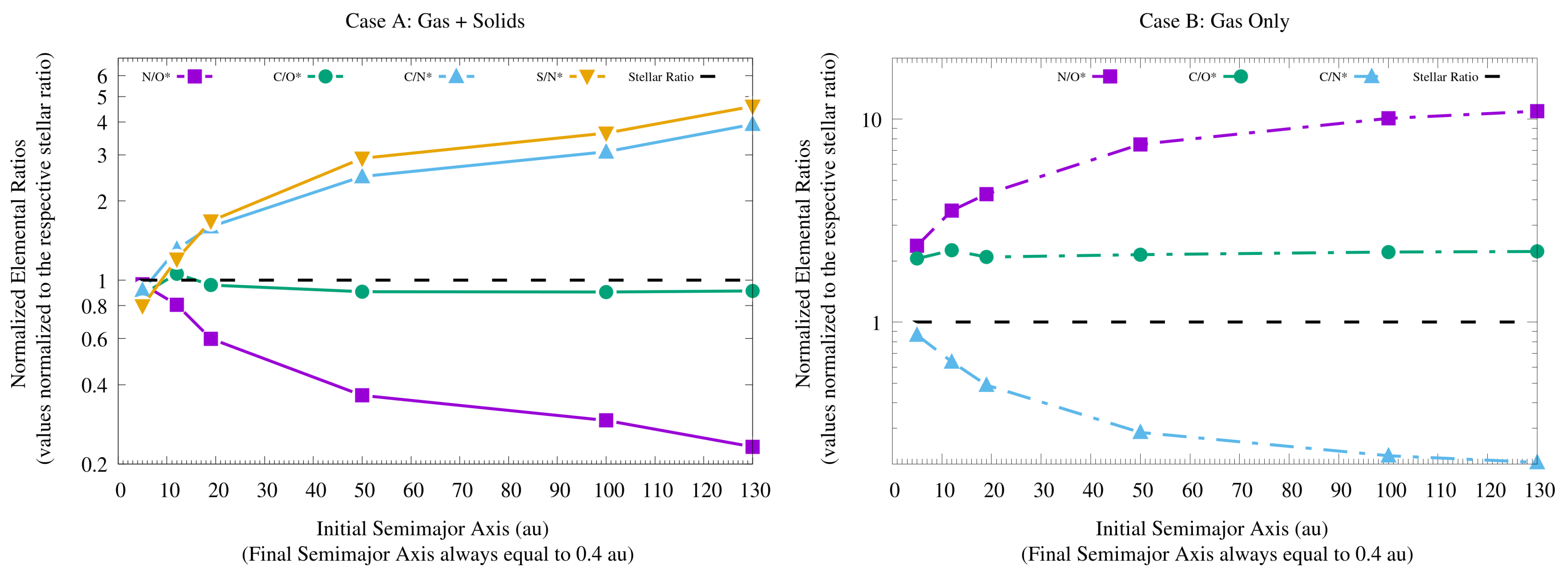


Comparison of the planetary elemental ratios in the four disk chemical scenarios considered by Pacetti+2022

Normalized Elemental Ratios and Global Trends

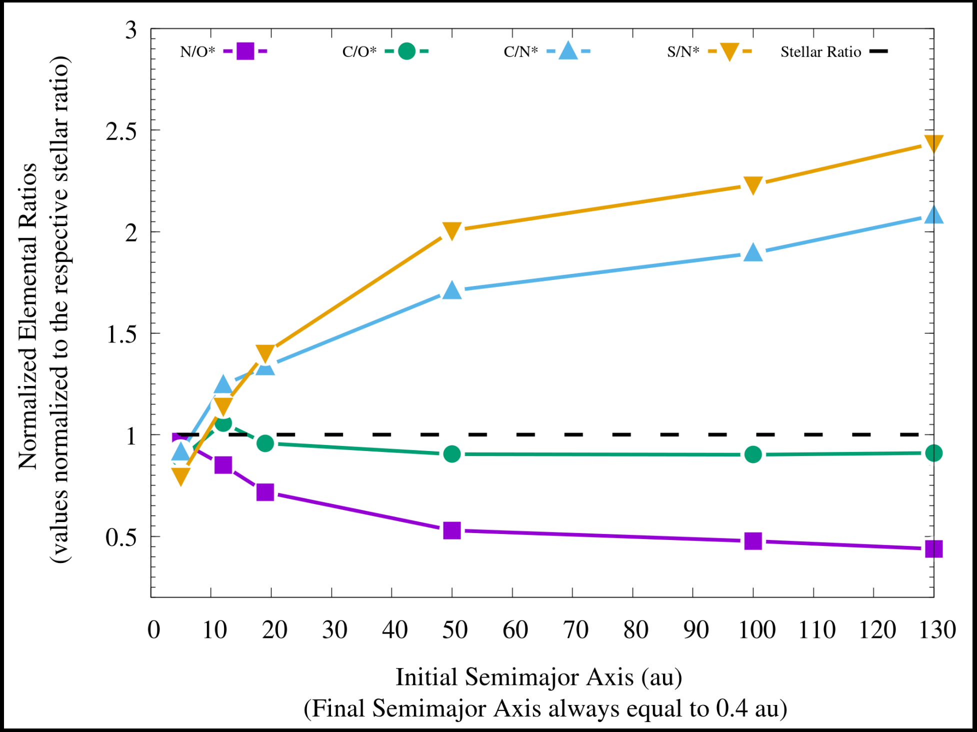
Comparing the normalized elemental ratios reveals that (Turrini+2021, Pacetti+2022):

- **Gas-dominated giant planets** have **N/O* > C/O* > C/N*** (S/N* should be absent or highly substellar)
- **Solid-enriched giant planets** have **C/N* (S/N*) > C/O* > N/O***
- Patterns **observationally validated** by Biazzo+2022 and, independently, Kolecki & Wang (2022)
- Note, moreover, that **C/N*** and **S/N*** cross paths along their tracks...



Normalized elemental ratios in giant planets formed withi chemically inheritend disks for high (left) and low (right) metallicity planets (Turrini+2021).

S, C and N: Comparing the Role of Gas and Solids

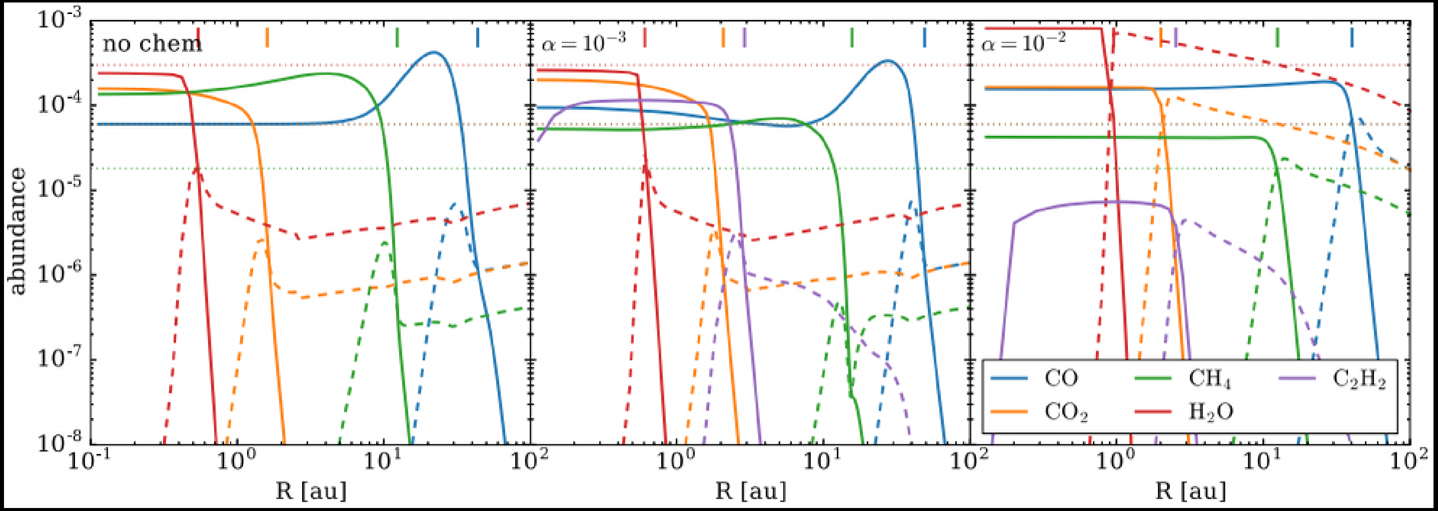


S is supplied to the giant planets by solids, while C is supplied by both gas and solids as a result of its higher volatility.

When **planetesimal accretion** dominates, the giant planet will have **S/N* > C/N***

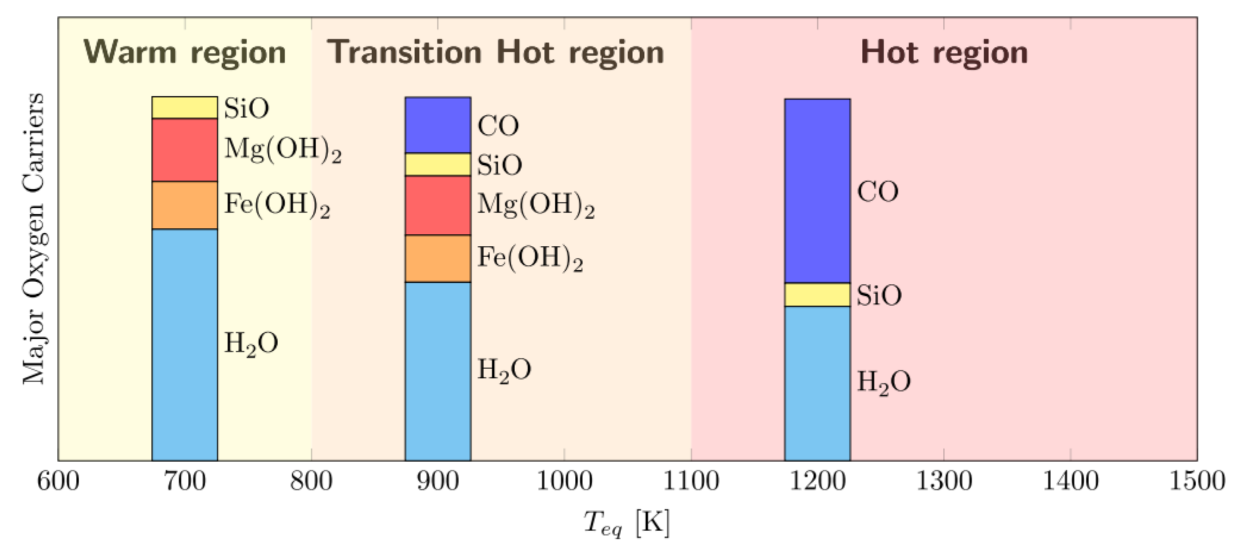
When **both gas and planetesimal accretion** contribute to the planetary metallicity **C/N* > S/N***

Comparing of C/N* and S/N* allows to identify when giant planets accreted **gas enriched by pebble sublimation** (Turrini+2021; Pacetti+2022)



Top: normalized elemental ratios for planetesimal-enriched giant planets in linear scale (data from Turrini+2021).
Bottom: gas enrichment in heavy elements due to dust/pebbles drift in circumstellar disks (Booth & Ilee 2019)

Refractories, O Sequestration and C/O ratio

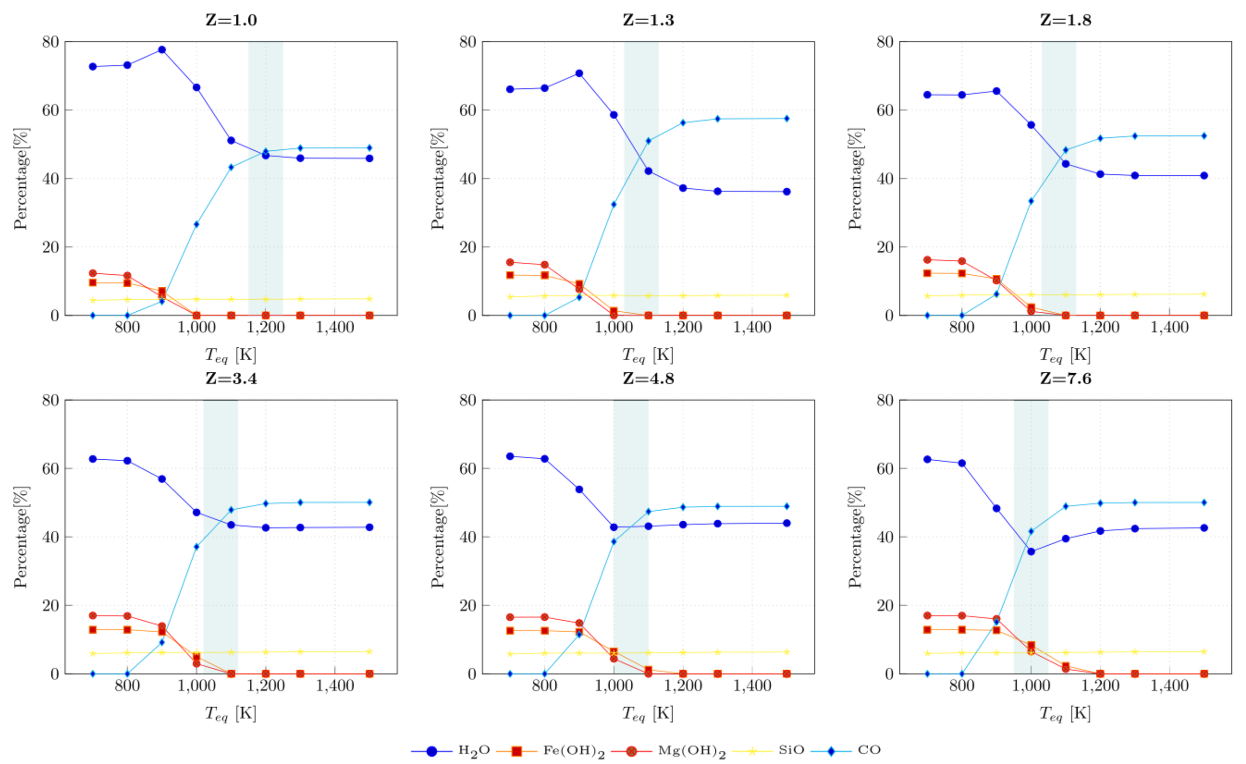


The **role of refractory oxides in sequestering O** from the atmosphere is well studied for brown dwarfs (e.g. Burrows & Sharp 1999) and disks (e.g. Fegley & Schaefer 2010), but it is generally neglected for exoplanets.

Due to the non-stellar compositions of exoplanets, O sequestration can be much larger than in brown dwarfs and disks.

O sequestration makes the **C/O ratio appear higher** than it really is if only CO, CH$_4$ and H$_2$O are observed (Fonte+2023).

Another effects is that it makes CO the major carrier of O at lower temperatures.



Top: schematic illustration of the evolution of the main O-carriers with temperature (Fonte+2023)
Bottom: CO-H$_2$O crossing as a result of O sequestration by refractories (Fonte+2023)

QUESTION TIME

For offline questions, my email is diego.turrini@inaf.it!

Futher details on the subjects where the slides don't provide references can be found in:

- Armitage P., *Astrophysics of Planet Formation*, Cambridge University Press, 2020
- Lissauer J. J., De Pater I., *Fundamental Planetary Science*, Cambridge University Press, 2019
- Turrini D., *The Compositional Dimension of Planet Formation,* in *Planetary Systems Now,* World Scientific Publishing, Eds. Luisa Lara & David Jewitt, 2023.