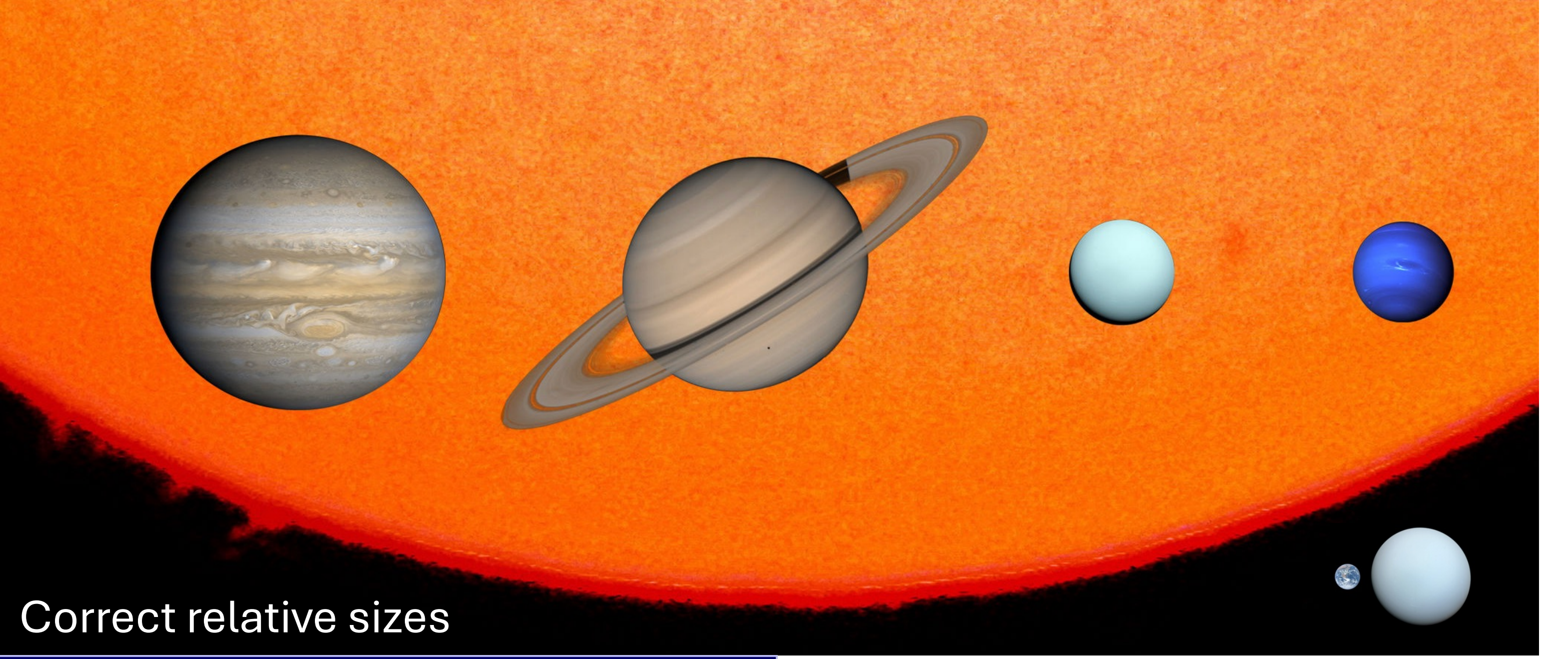
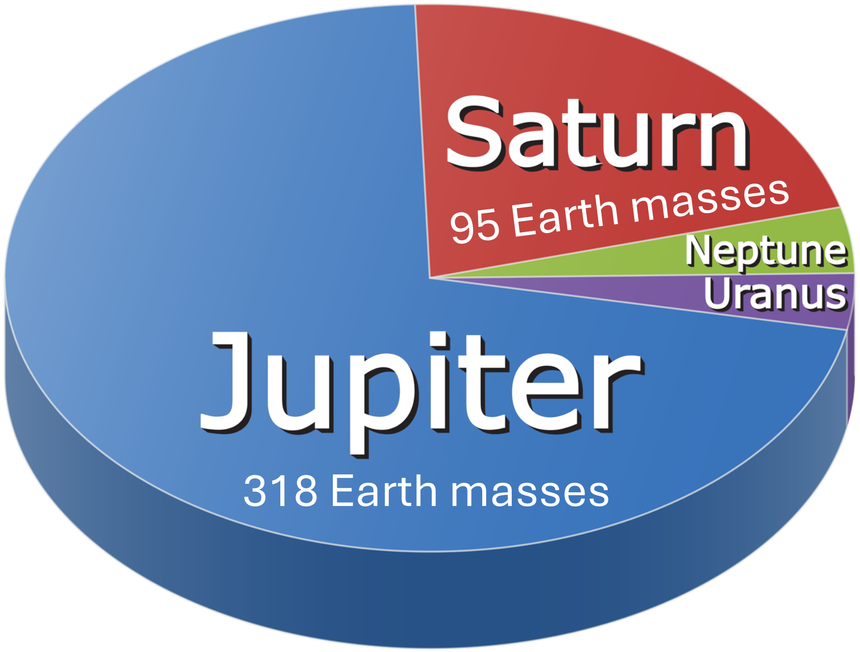
Giant Planet Formation: Reservoirs and Processes

Jonathan I. Lunine
Cornell University

- What types of material were available and what were their locations?
- What processes brought the material together and modified it?
- What markers exist today to identify reservoirs and processes?

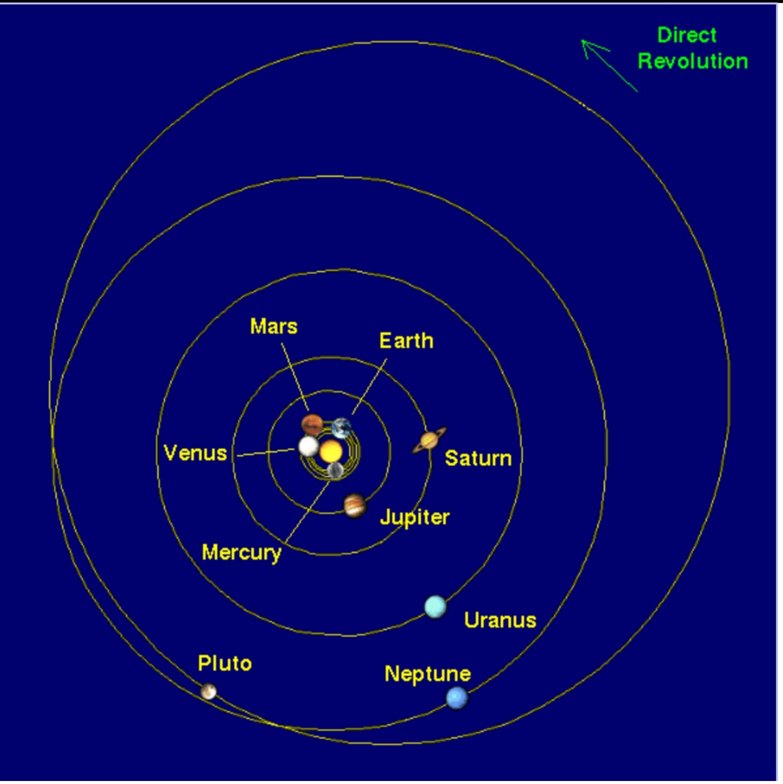




Uranus mass: 14.5 Earth masses

Density of Uranus ~ density of Jupiter, 1.3 (water = 1)

Mass of hydrogen/helium ~ 1 Earth mass



Scale: 1 Astronomical Unit (AU) = 149,000,000 km.

Earth is at 1 AU

Jupiter 5.2 AU

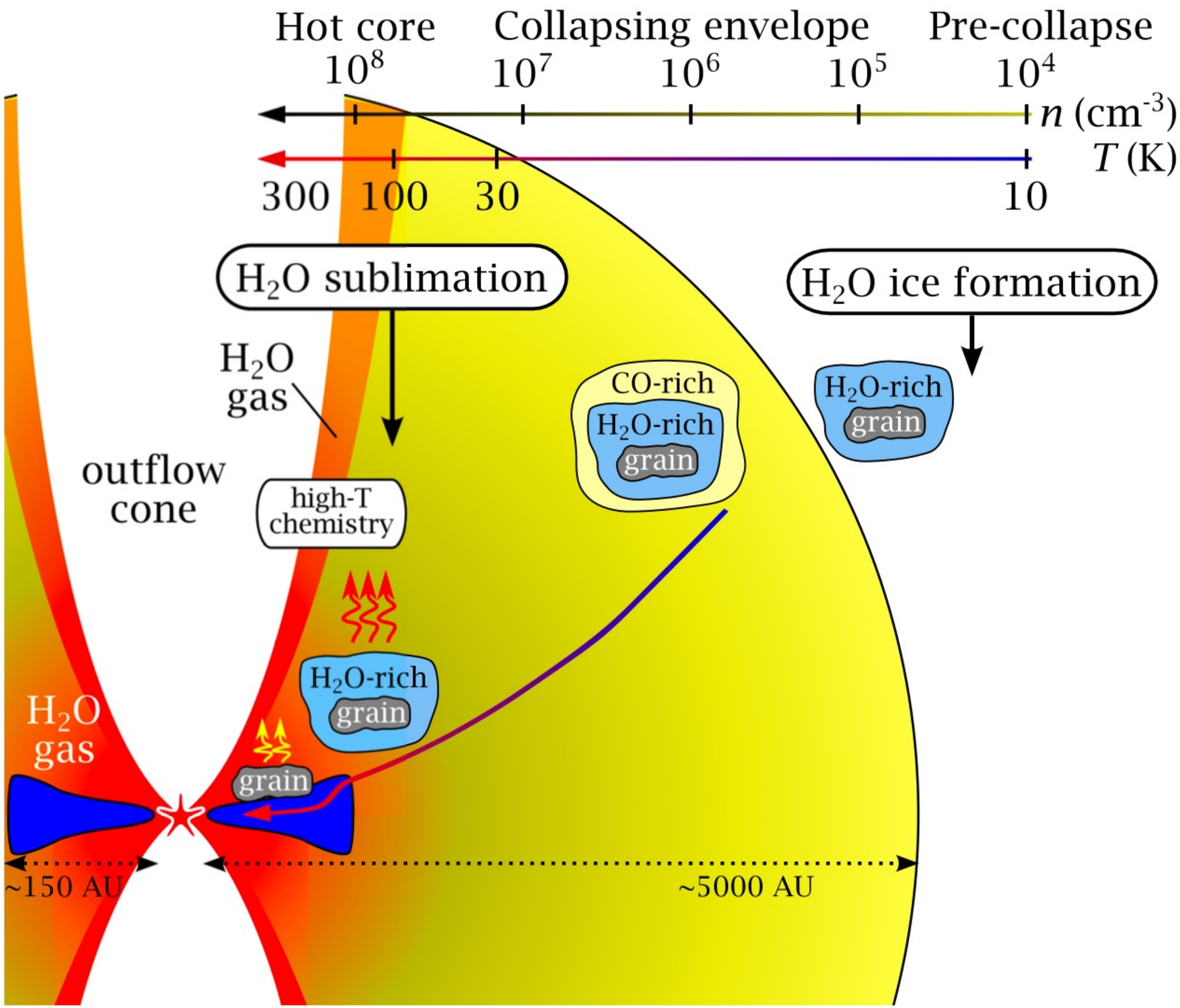
Saturn 9.5 AU

Uranus 19 AU, T_{eff} = 78 K

Neptune 30 AU, T_{eff} = 73 K

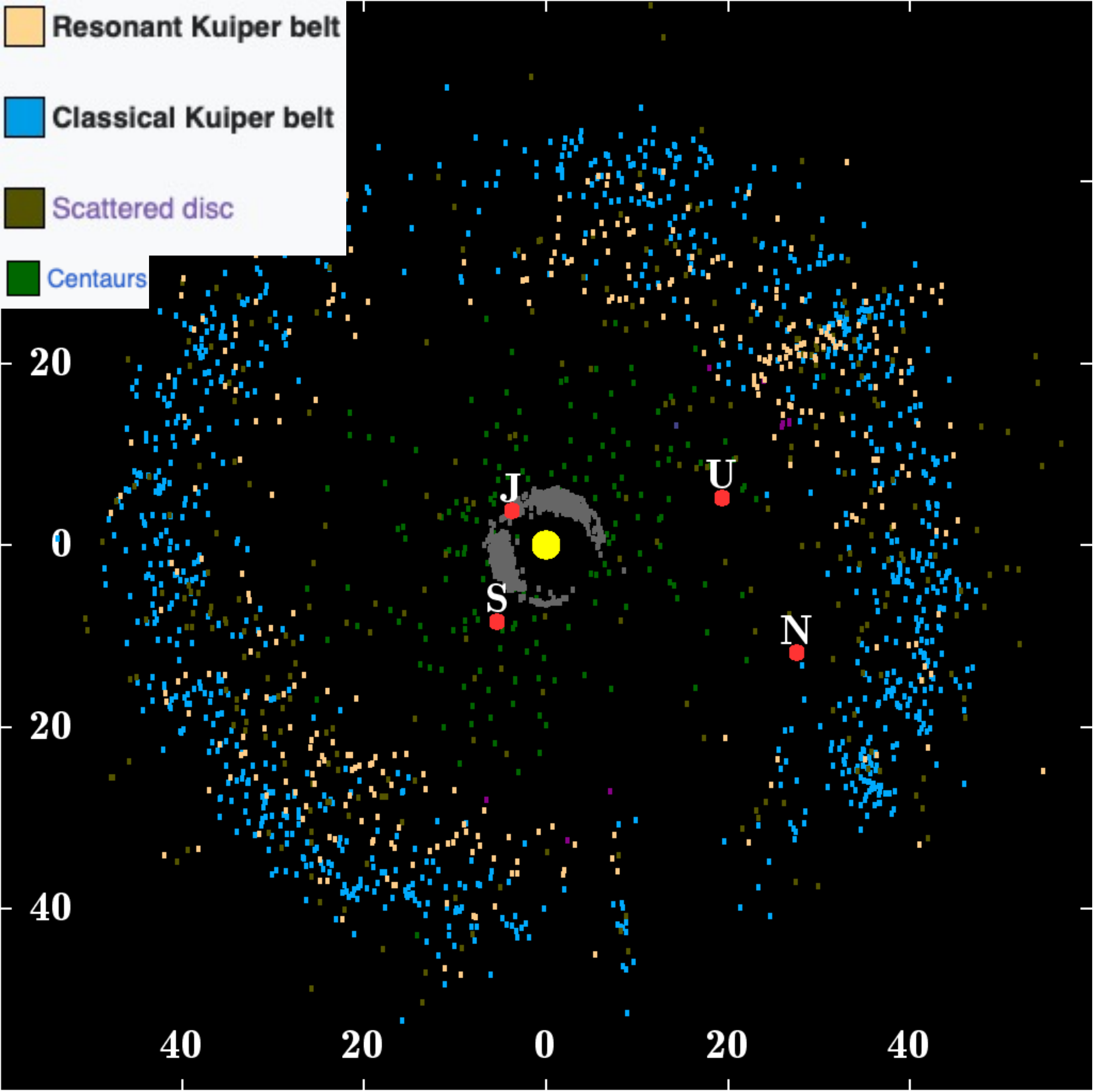
What types of material were available, and what were their locations?

- The solar system likely formed from the collapse of a molecular cloud core within a cluster of perhaps ~1000 stars, forming a disk, and chemistry (ion, neutral, gas, gas-grains) occurred as new environments appeared.
- The outer solar system was a mixture of gas and grains with varying degrees of processing.
- Comets may be the most pristine known bodies in the solar system, but are not in their original formation location.
  - Jupiter family comets (with orbital periods less than 20 years) are thought to have originated in the Kuiper Belt. The Kuiper Belt is a disk of material beyond the orbit of Neptune including bodies scattered from the giant planet region.
  - During giant plant formation, the orbits were more compact (< 20 AU) and the Kuiper Belt more massive. Jupiter and Saturn scattered away material. As Uranus and Neptune evolved outward, they pushed some Kuiper Belt objects into resonances.



The material from which the planets formed was processed in a variety of environments from the ISM to the protoplanetary disk.

Van Dishoeck et al, PPVI.

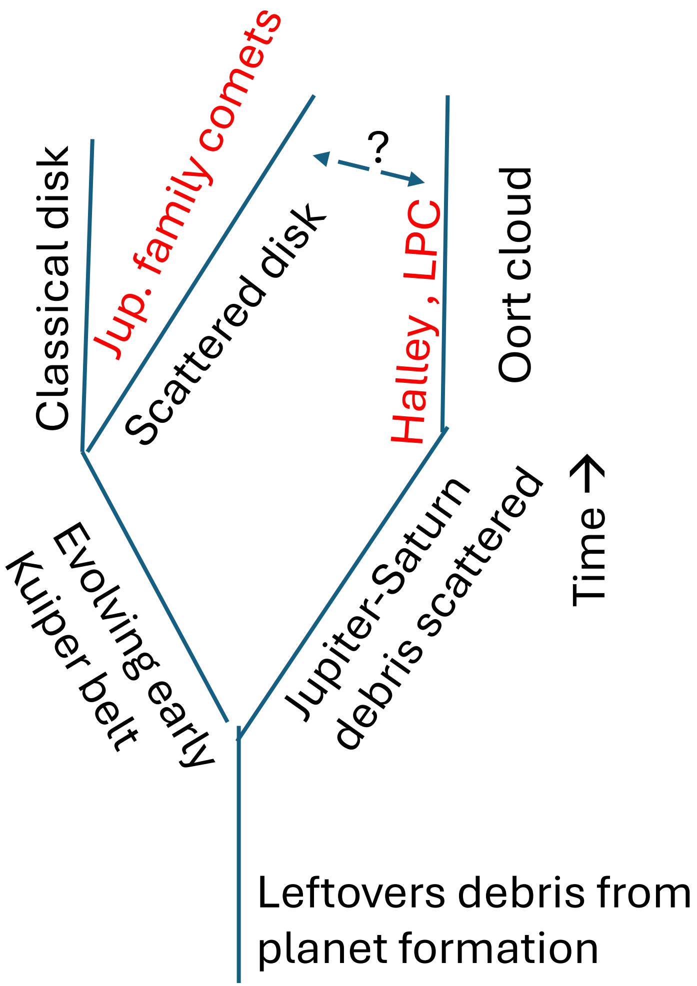


The Kuiper Belt (“classical disk”) is where material leftover from giant planet formation, and mostly external to it, resides today. The scattered disk includes material from within the giant planet system that was gravitationally scattered outward by Neptune.

Oort cloud is a much larger scale (10^3-10^5 AU) cloud of debris ejected by Jupiter

WilyD at English Wikipedia

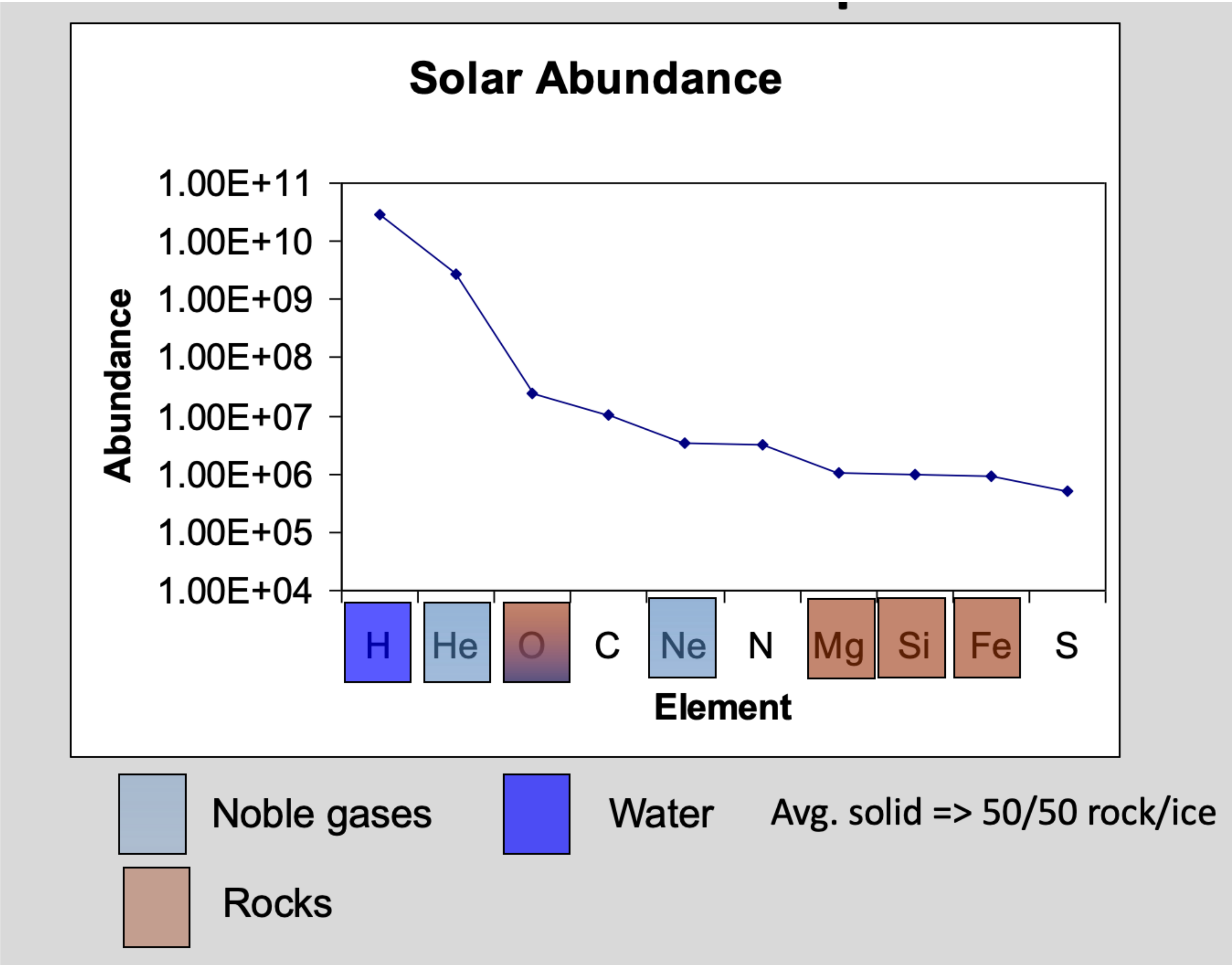
Oort cloud and Kuiper Belt are the reservoirs of comets



LPC = long period comets
Halley= Halley family comets

- Some ~ 4 billion ago, the orbits of the giant planets—Jupiter, Saturn, Uranus and Neptune—were more compact and the solar system contained a lot more planetary debris in the form of asteroids and comets.
- That debris was gradually cleared by the collective gravitational perturbations of the planets, but this process had a back-reaction on the planets: it caused a spreading out and re-arrangement of the giant planets' orbits and eventually led to a more stable solar system that we enjoy now.
- The interaction can be described by adiabatic invariants that relate the current eccentricities of objects trapped in resonances with Neptune to the original semi-major axis of Neptune's orbit: 18 AU!
- For the migration to have occurred, 10-50 Earth masses of small bodies were cleared out: the populations of minor planets were decimated.
- The small fraction that survived in proximity to their formation locations are predominantly beyond Neptune.

R. Malhotra, 2019, Geosci Letters



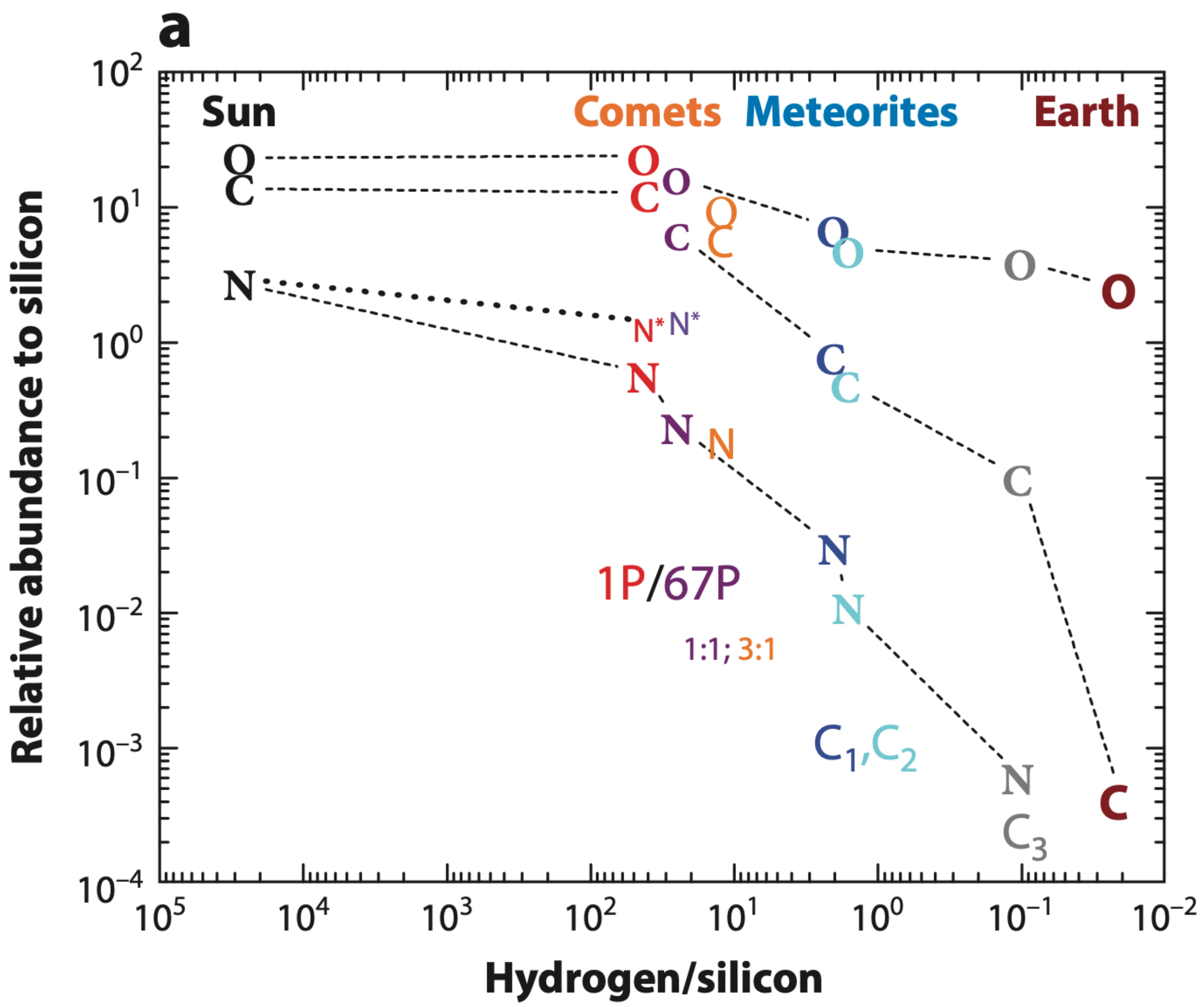
Solar abundance by number:

$O/H_2 = 0.001$

$C/O = 0.5\text{-}0.6$

$N/O = 0.13$

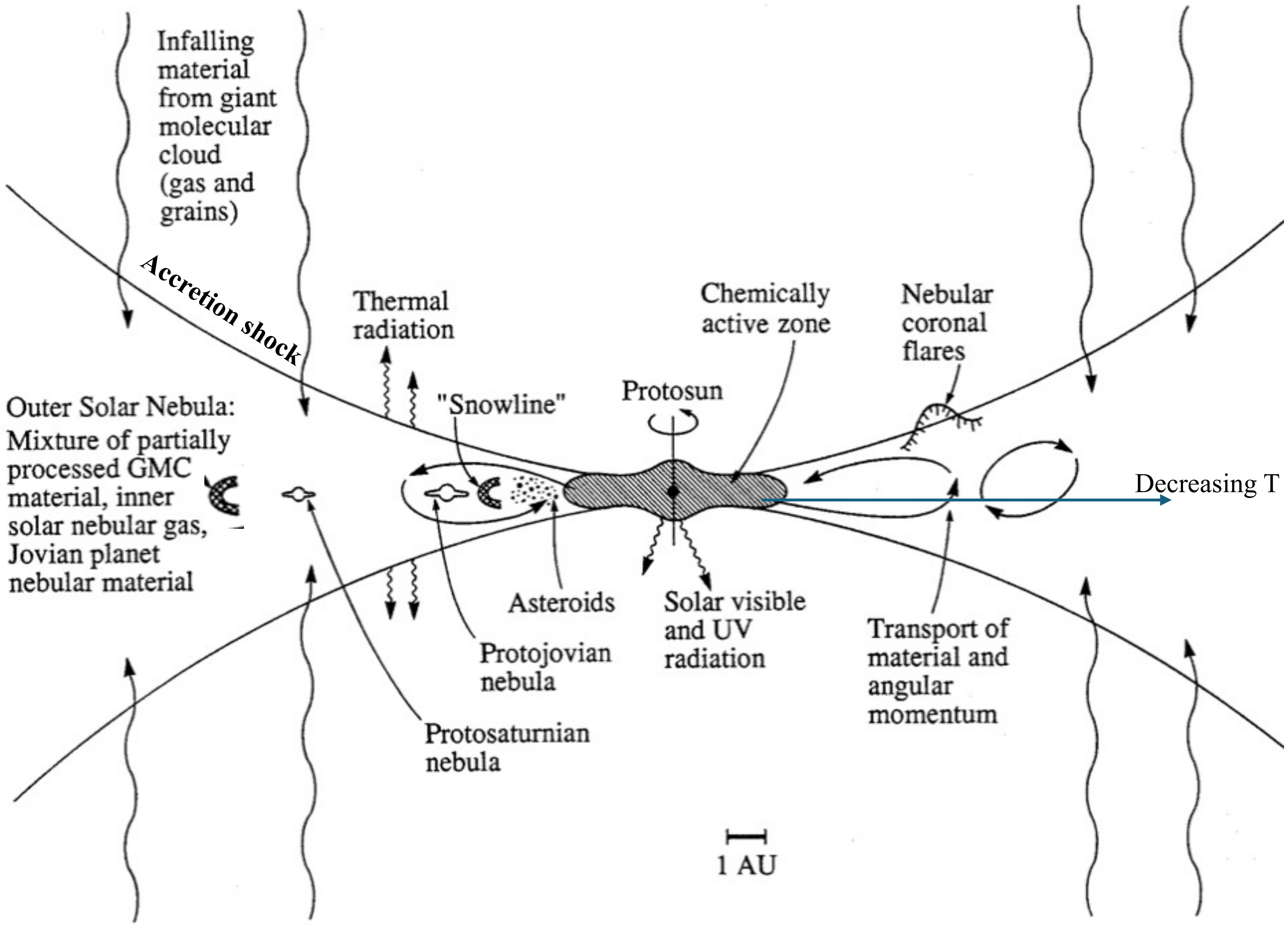
Comets most closely resemble solar composition, for the key volatiles



Altwegg, et al 2019, ARAA

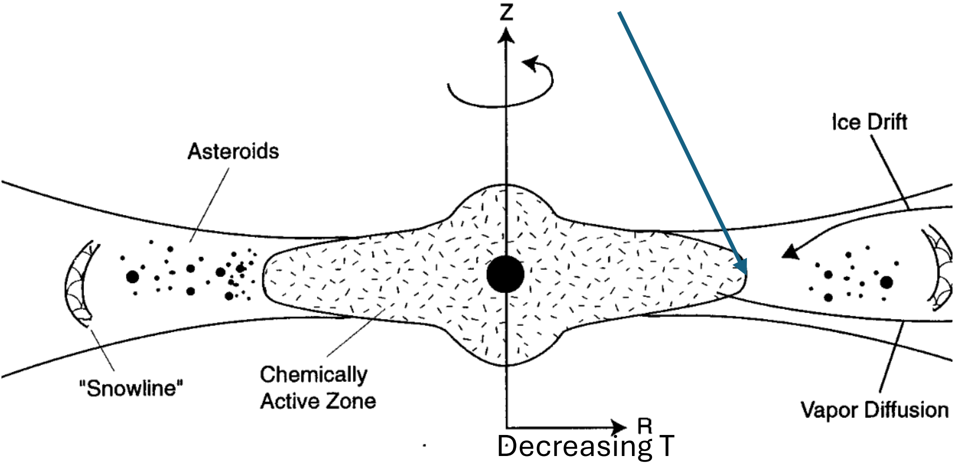
What processes brought the material together and modified it?

- The composition of gases and solids in our protoplanetary disk (a.k.a. solar nebula) was affected by many chemical and condensation processes.
- Over time, gas composition in the disk evolved as ices of varying volatility condensed at snowlines, changed phase, and trapped some amount of even more volatile species.
- Solids partly decouple from the gas at mm to cm scales and begin to move inwards in the disk.
- After a few million years the gaseous hydrogen and helium (and perhaps neon) in the disk were driven off under the influence of protosolar ionizing ultraviolet radiation
- Material was added to the giant planets in the gas phase, and as solids, and possibly in a late veneer outer envelope not related to the interior.

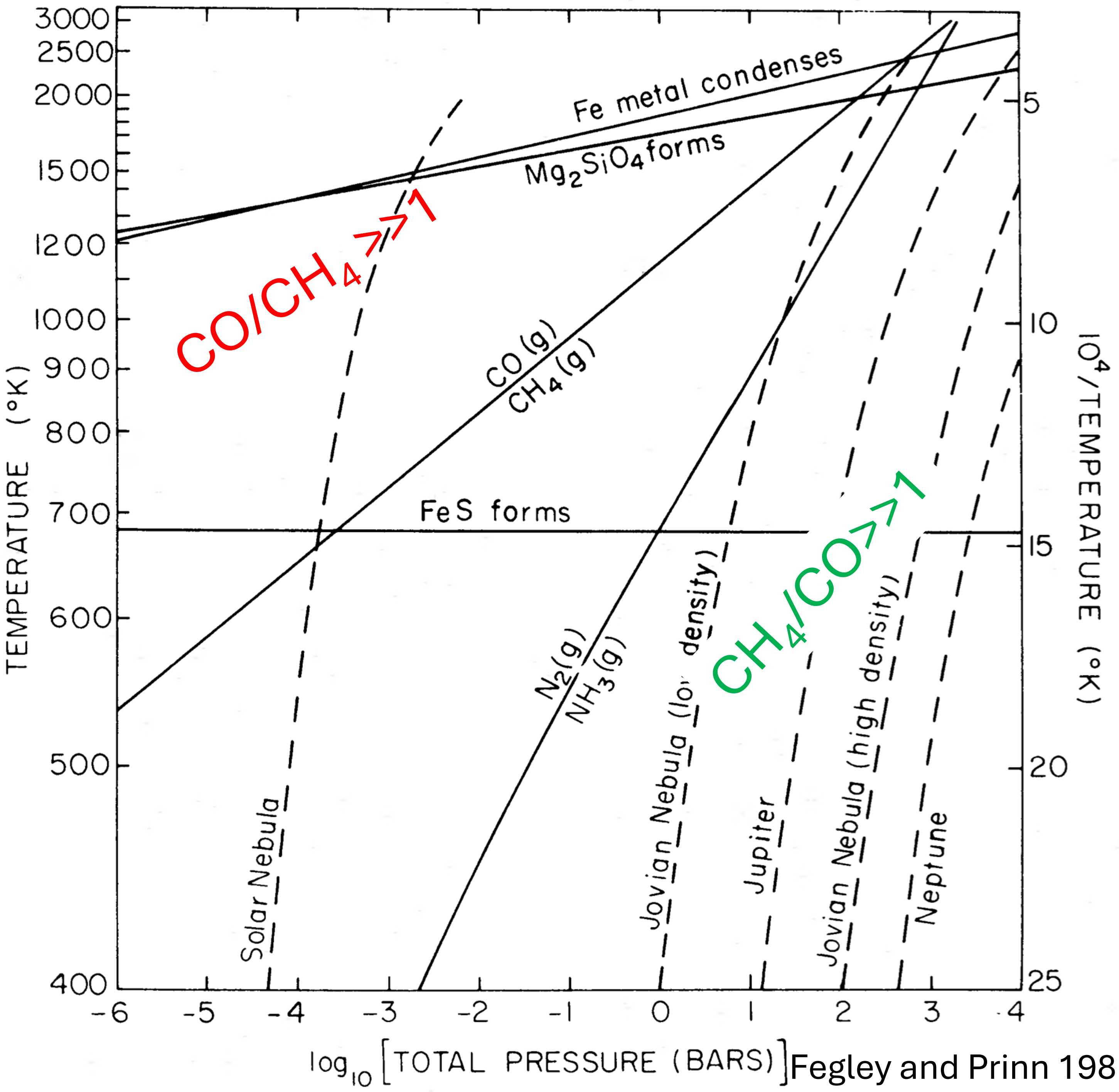


"A protoplanetary disk is intrinsically heterogeneous, with large radial gradients in temperature, pressure and chemical compositions due to the presence of a growing central protostar, cold interstellar medium at its edges, and nearby massive, luminous stars" OWL, 2023

Where gas phase chemistry in the disk is dominated by kinetics, *not* thermodynamics, defines the outer edge of the chemically active zone



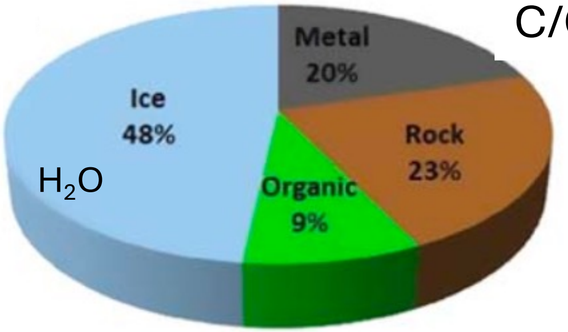
$CO + 3H_2 \leftrightarrow CH_4 + H_2O$
$N_2 + 3H_2 \leftrightarrow 2NH_3$



Fegley and Prinn 1981

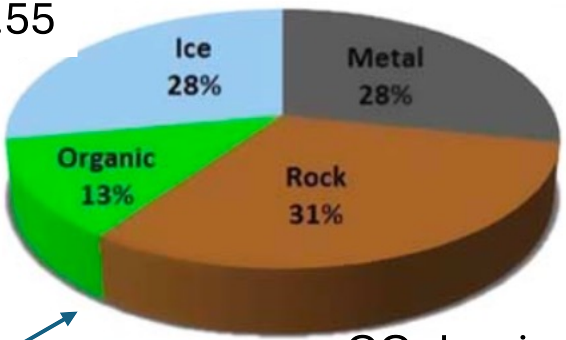
The abundance of water in planetesimals is strongly dependent on the C to O ratio and the oxidation state of the carbon in the coexisting gas

This corresponds best to Pluto, from models in McKinnon et al 2016



CH_4 dominates
Bulk density 1.5 g/cm^3

C/O ~ 0.55

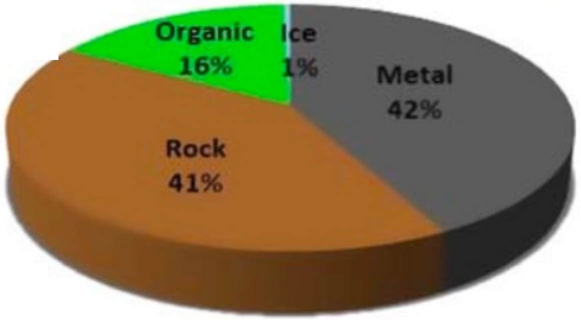


CO dominates
Bulk density 1.9 g/cm^3

C/O ~ 0.81

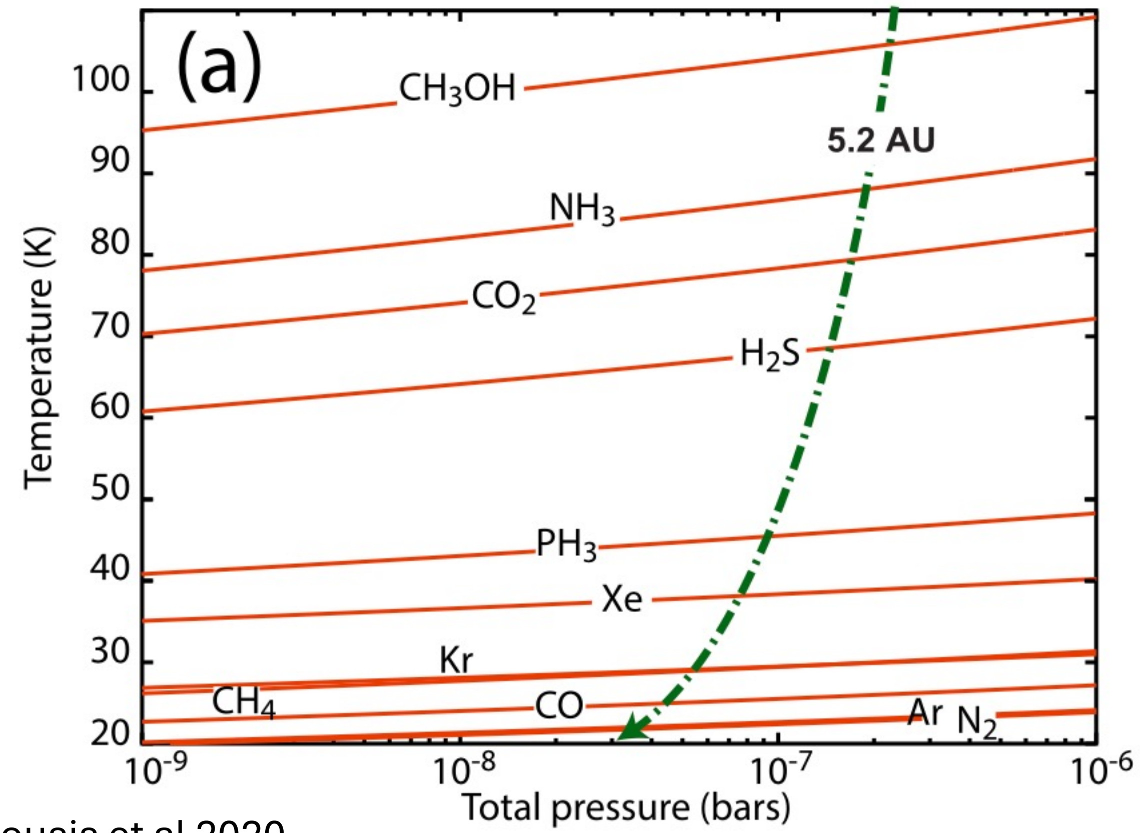
CO dominates

Bulk density
3.1 g/cm^3



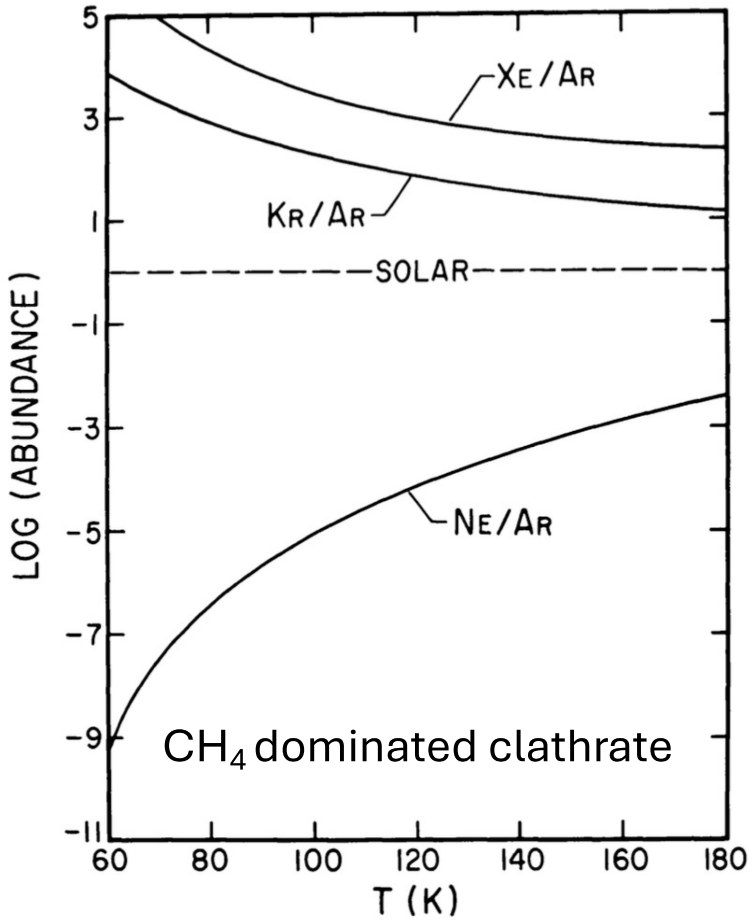
Pekmezci et al., 2019

Condensation occurred at “snowlines” where the partial pressure of a given molecule or atom exceeds its saturation vapor pressure at the local temperature

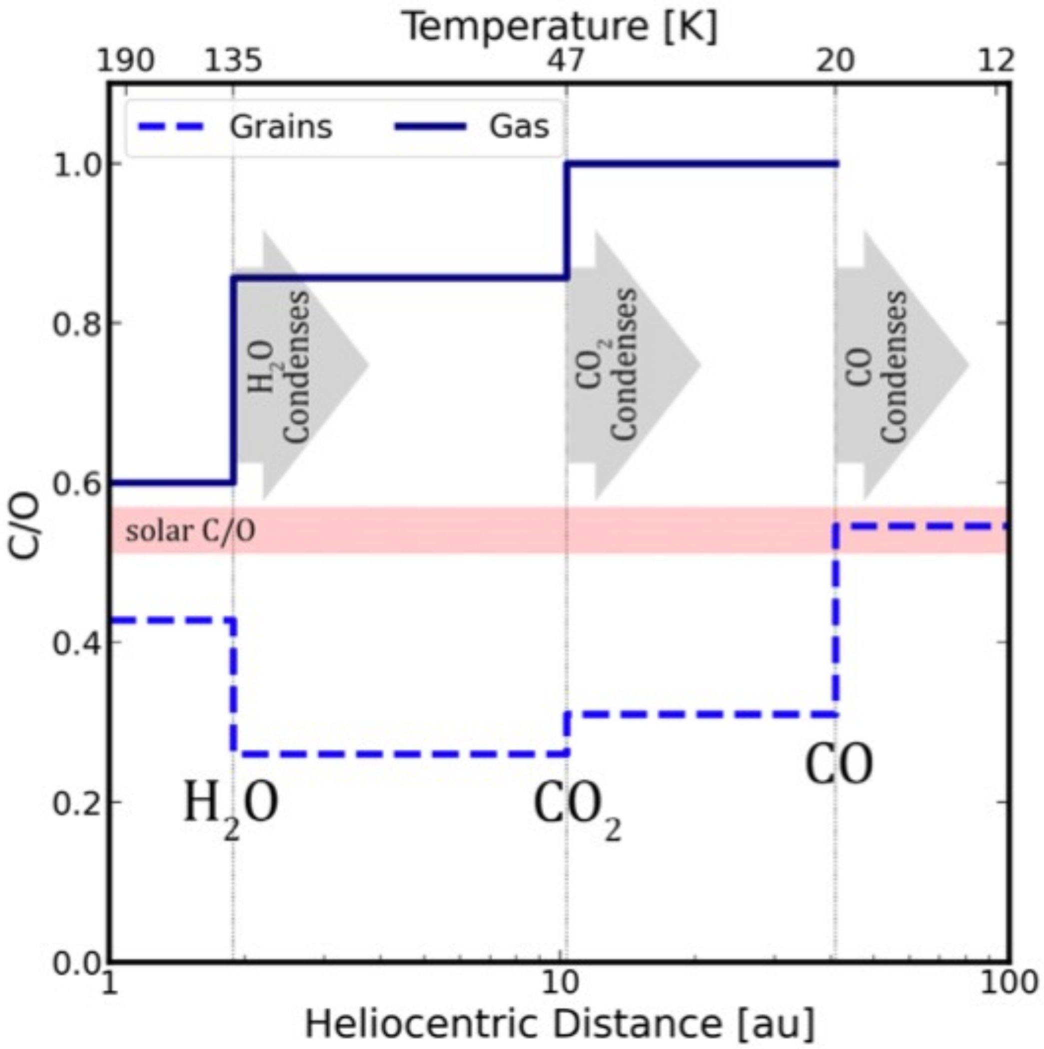


Mousis et al 2020

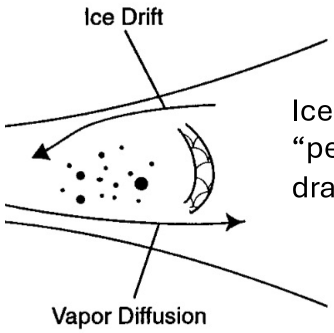
However, species will also be trapped by adsorption in water ice, or even clathration (volumetric trapping), affecting the volatile composition of the solids



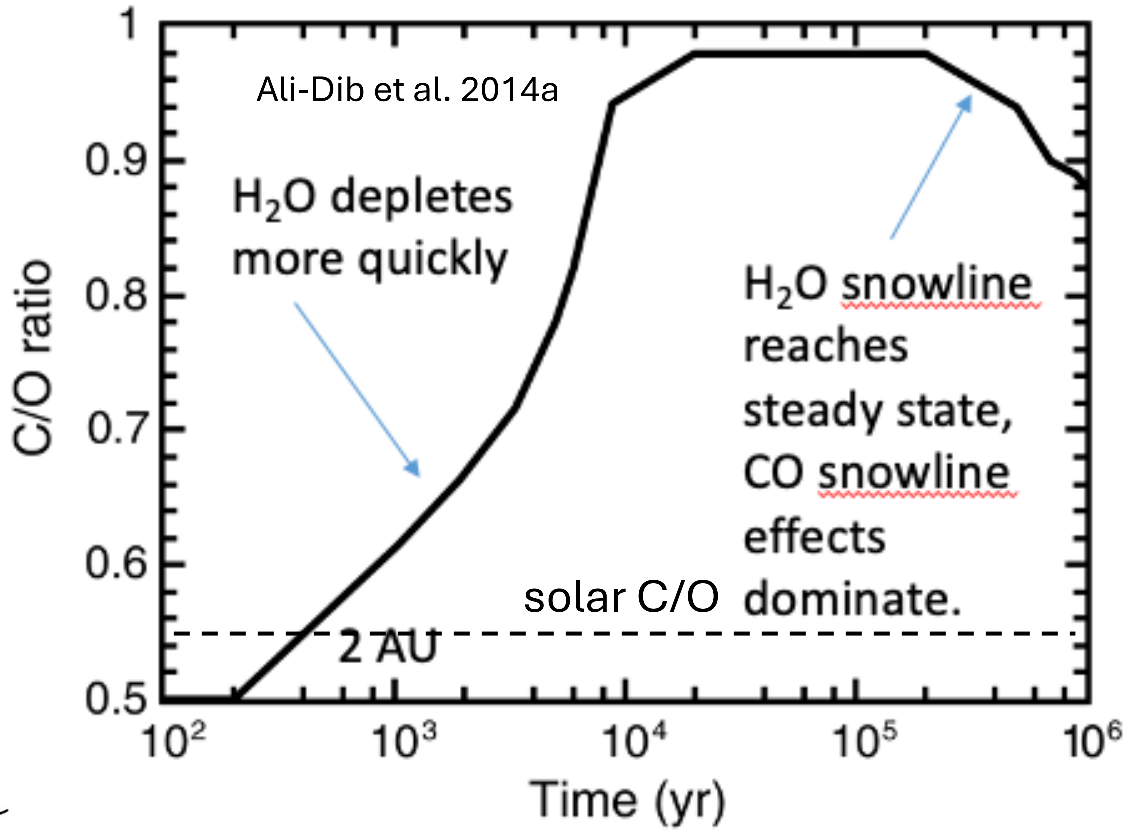
Multiple snowlines cause C/O to vary in space and time



Seligman et al 2022 after Oberg et al 2011

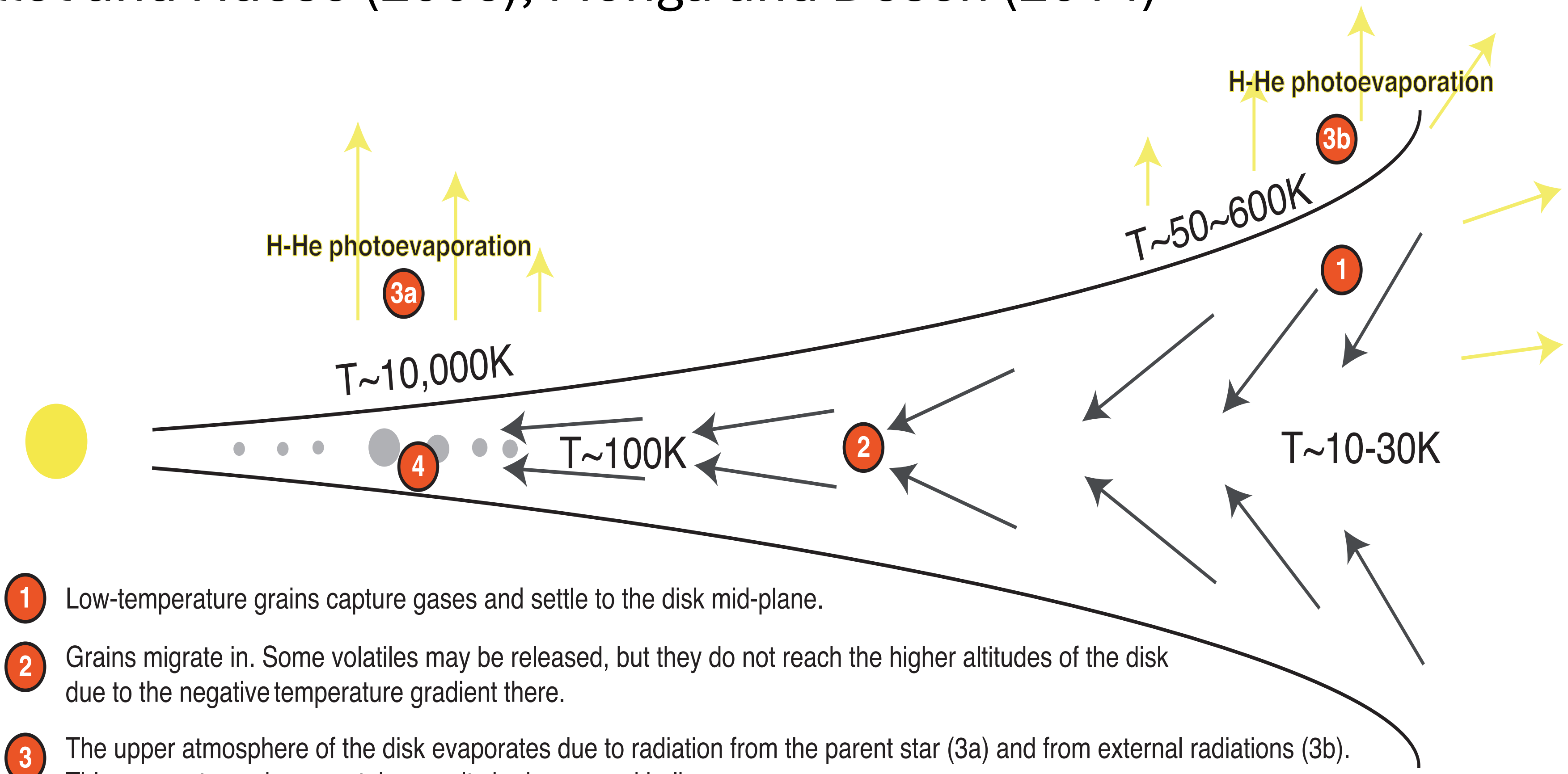


Ice grows to "pebble"-size, dragged inward



Disk photoevaporation also enriches heavy elements

Guillot and Hueso (2006); Monga and Desch (2014)



1 Low-temperature grains capture gases and settle to the disk mid-plane.

2 Grains migrate in. Some volatiles may be released, but they do not reach the higher altitudes of the disk due to the negative temperature gradient there.

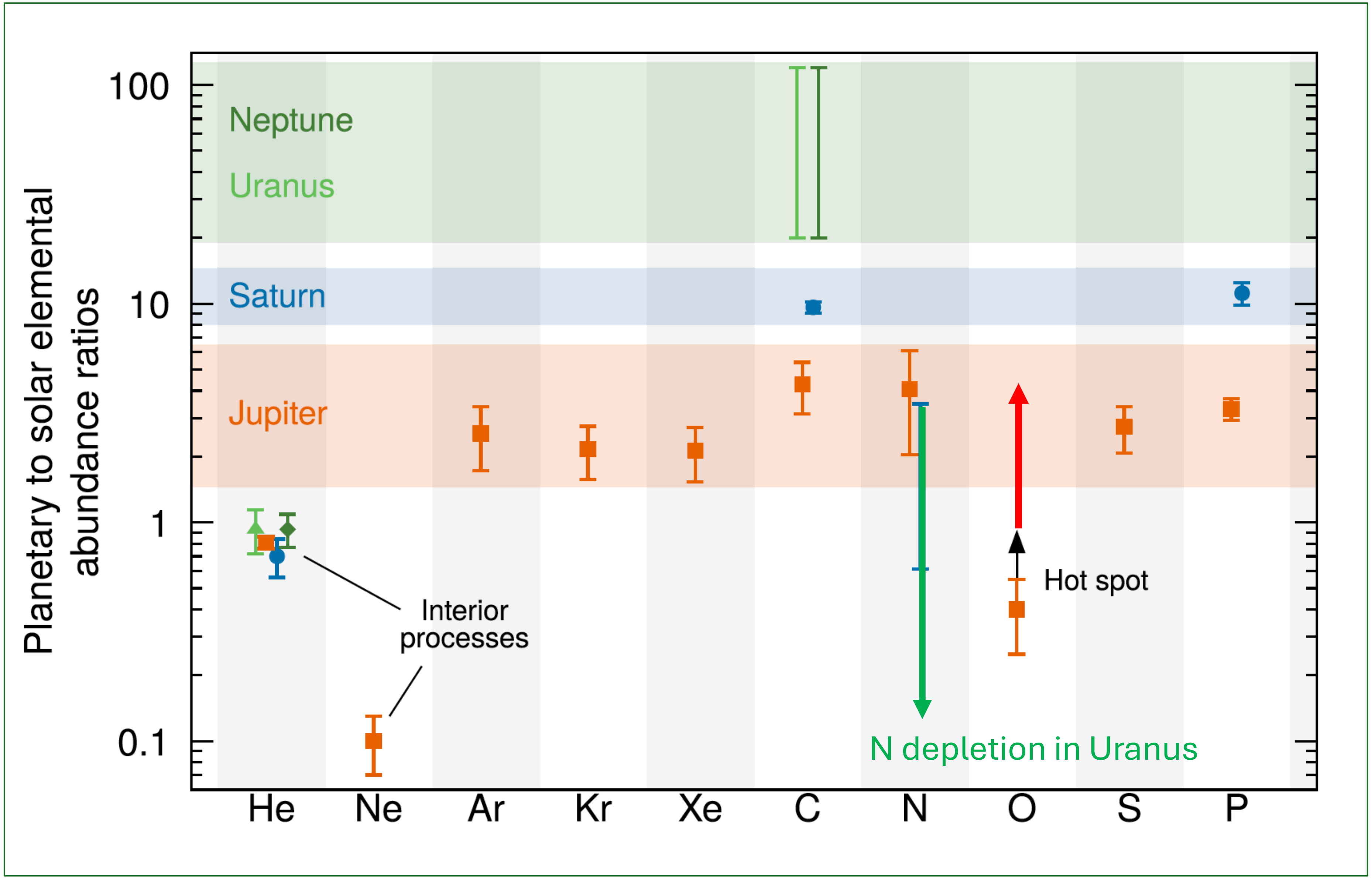
3 The upper atmosphere of the disk evaporates due to radiation from the parent star (3a) and from external radiations (3b). This upper atmosphere contains moslty hydrogen and helium.

4 Giant protoplanets gradually capture a disk gas which is enriched in non-hydrogen-helium species.

What markers exist today to identify reservoirs and processes?

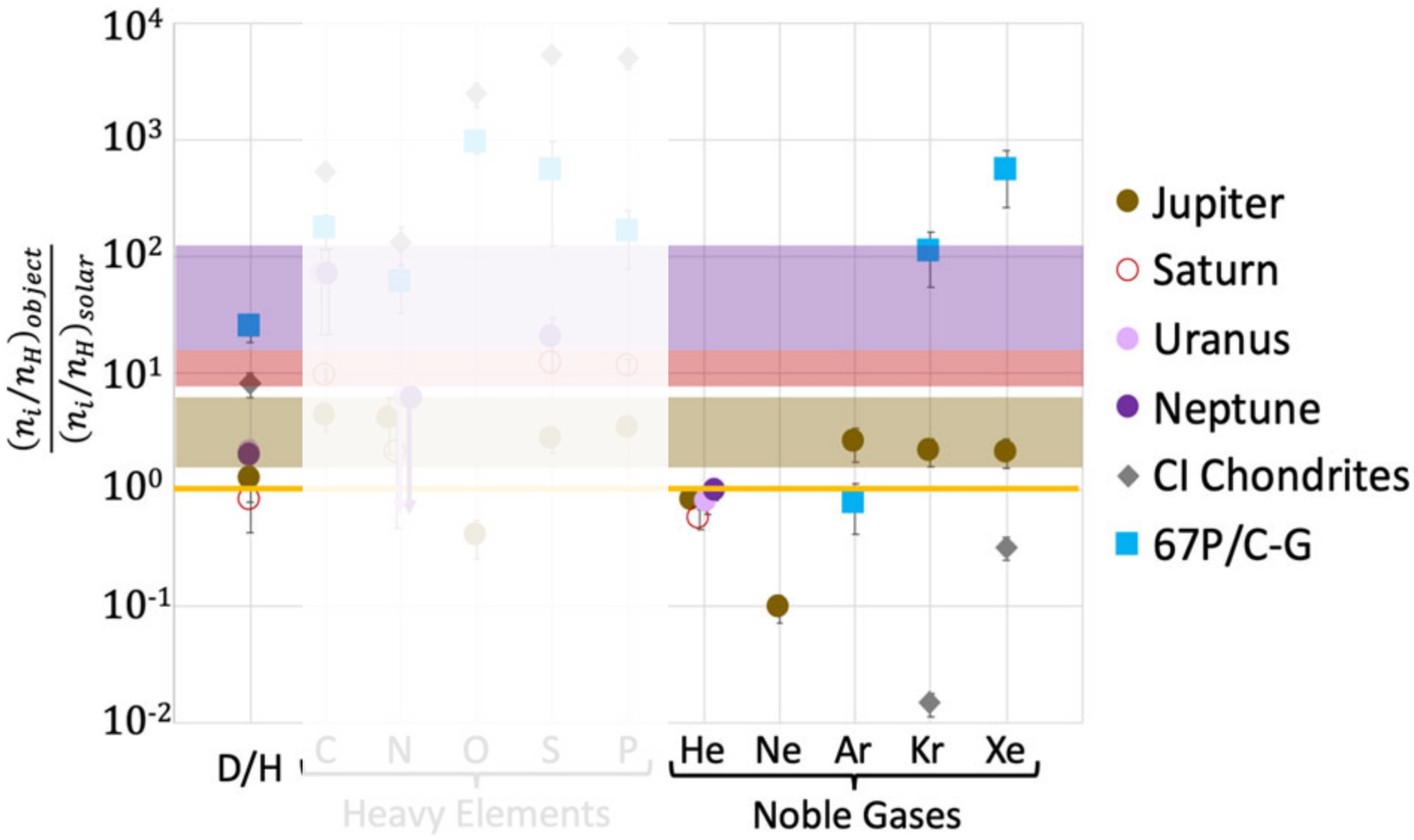
- The abundances of CHNOPS and noble gases (He, Ne, Ar, Kr, Xe) and their isotopes are potential tracers of the origin of material accreted into the giant planets
- For accreted solids, relative abundances of the elements *potentially can* distinguish
  - source regions and extant "primitive bodies" as examples of source material
  - whether the bulk of the heavy elements came from gas vs solids
  - something about the way volatiles were trapped (pure ices, amorphous water ice, clathrates)
- Interpreting these tracers in terms of giant planet formation requires making assumptions about mixing in the interiors, stability of a late veneer outer layer, selective dissolution of species in layers, etc.
- Useful measurements that a future shallow atmospheric probe can make in Uranus include noble gases and isotopic ratios

Known abundances in the giant planets



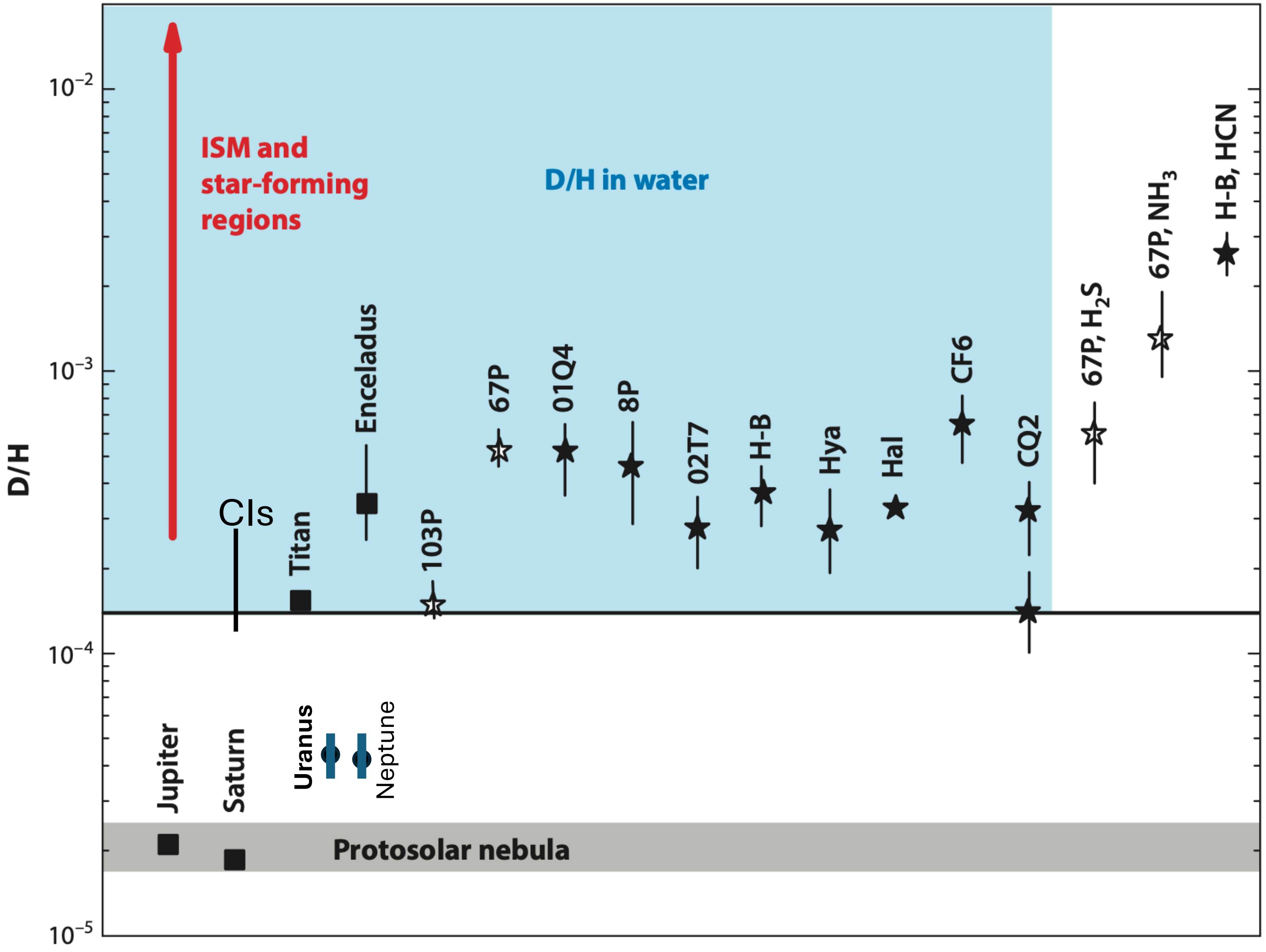
Note: Mandt et al 2020: N/H < 6 and S/H 10-30 for Uranus and Neptune. Atreya (2020) has lower values

Noble gas ratios in Jupiter do not resemble those in comets



Mandt et al 2020

D/H suggests something surprising about Uranus and Neptune source material



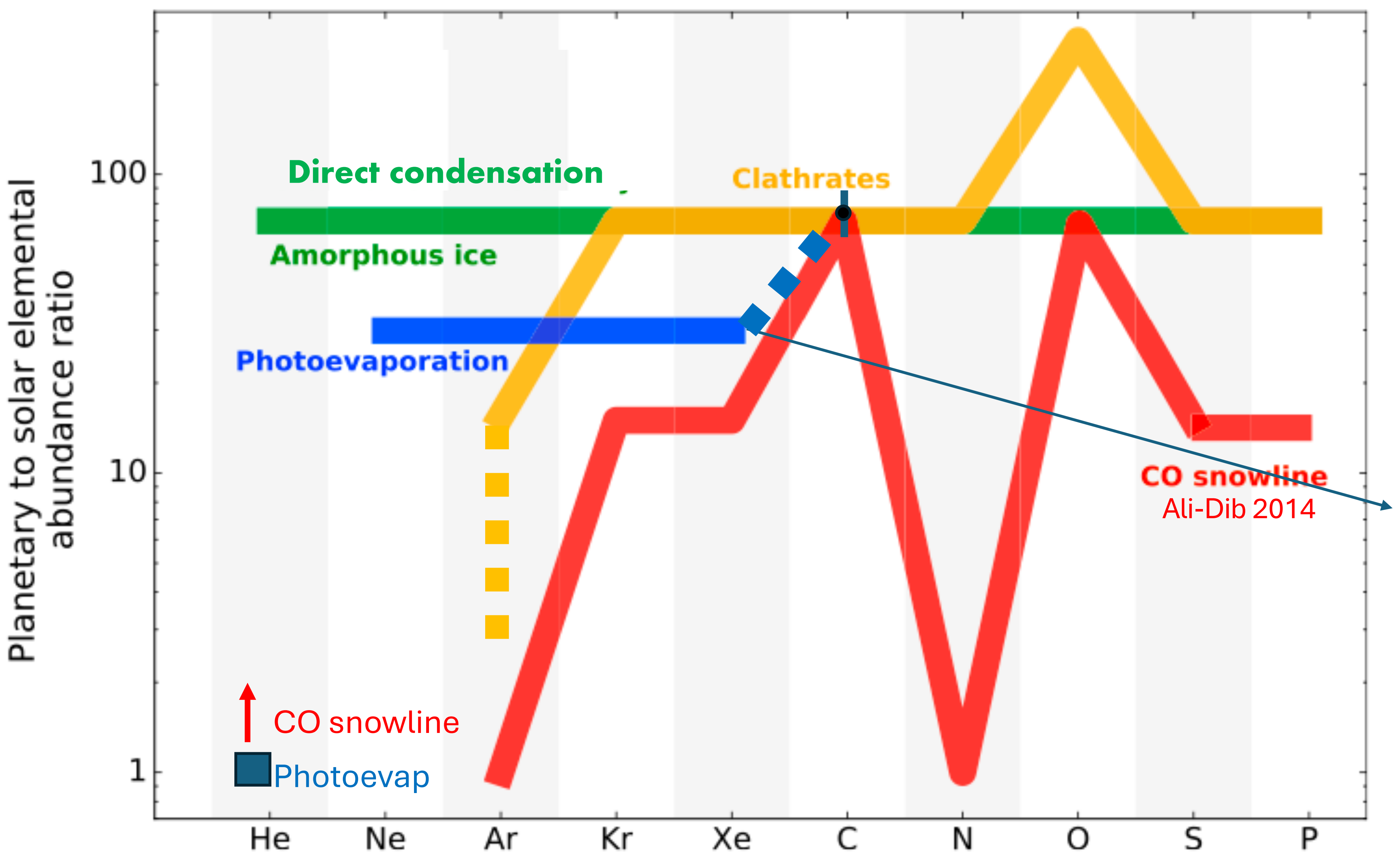
Altwegg + Feuchtgruber et al

From measured D/H in Uranus, can work out fraction of heavy element component in Uranus that is ice. (Feuchtgruber et al., 2013, A&A)

$$x_{H2}(D/H)_{protosolar} + (1\text{-}x_{H2})\ (D/H)_{primitive\ ices} = (D/H)_{measured,\ envelope}$$

- Uranus D/H = 4.4 $\pm$ 0.4 x 10^{-5} from far-IR HD lines (Herschel mission)
- Cometary D/H ~15-30 x 10^{-5} ; protosolar gas D/H ~ 2 x 10^{-5}
- Assume ice in Uranus is primarily H_2O; ignore D/H in the rock phase.
- Assume D-H equilibration between H_2O and H in Uranus and *fully mixed*
- Use interior models to determine amount of H_2 relative to total (rock+ice)
- *Result:*
  - *An ice mass fraction for Uranus between ~15-30% of total rock+ice. → Uranus and Neptune are mostly rock +H,He. Chondritic meteorites have a lower D/H value consistent with Uranus*
  - *A mostly rocky composition → condensing near the CO snowline (Ali-Dib, et al 2014b)*
  - *Alternatively, assuming Uranus is mostly ice, requires that the bodies supplying the ice were deuterium-poor by a factor of 2-6 compared to comets.*
  - *Noble gases, including He, will help us, because we know their abundances in meteorites and one comet (67P).*

Qualitative differences between the enrichments in volatiles in Uranus. Modified from Mousis et al 2006.

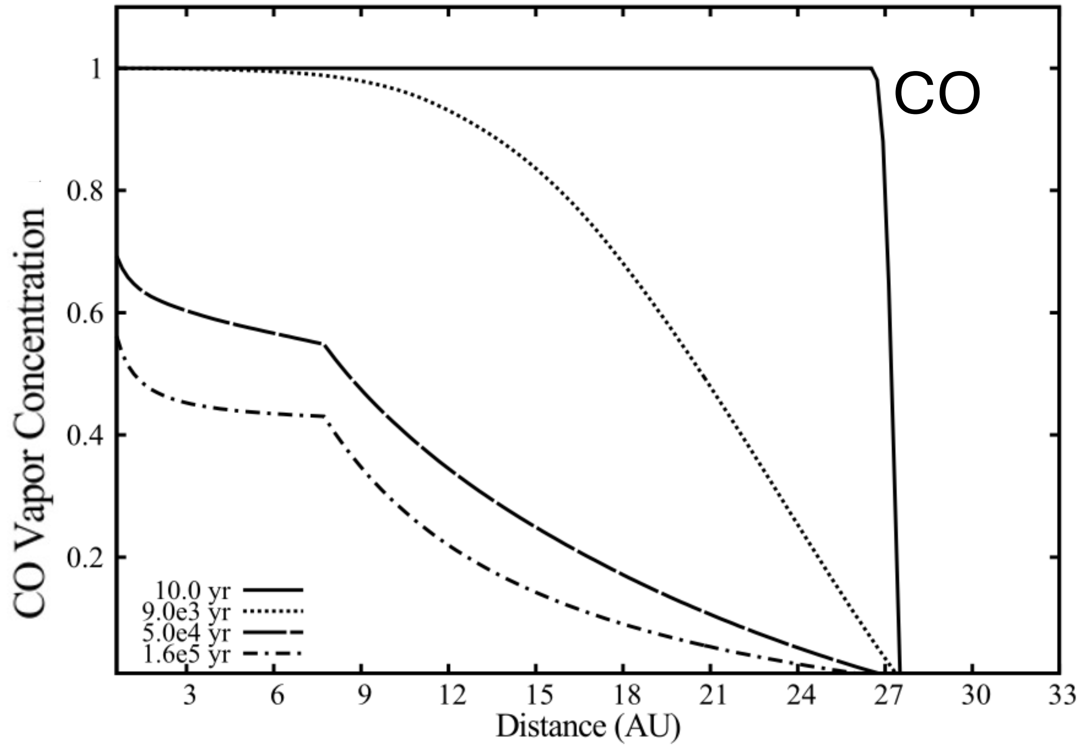


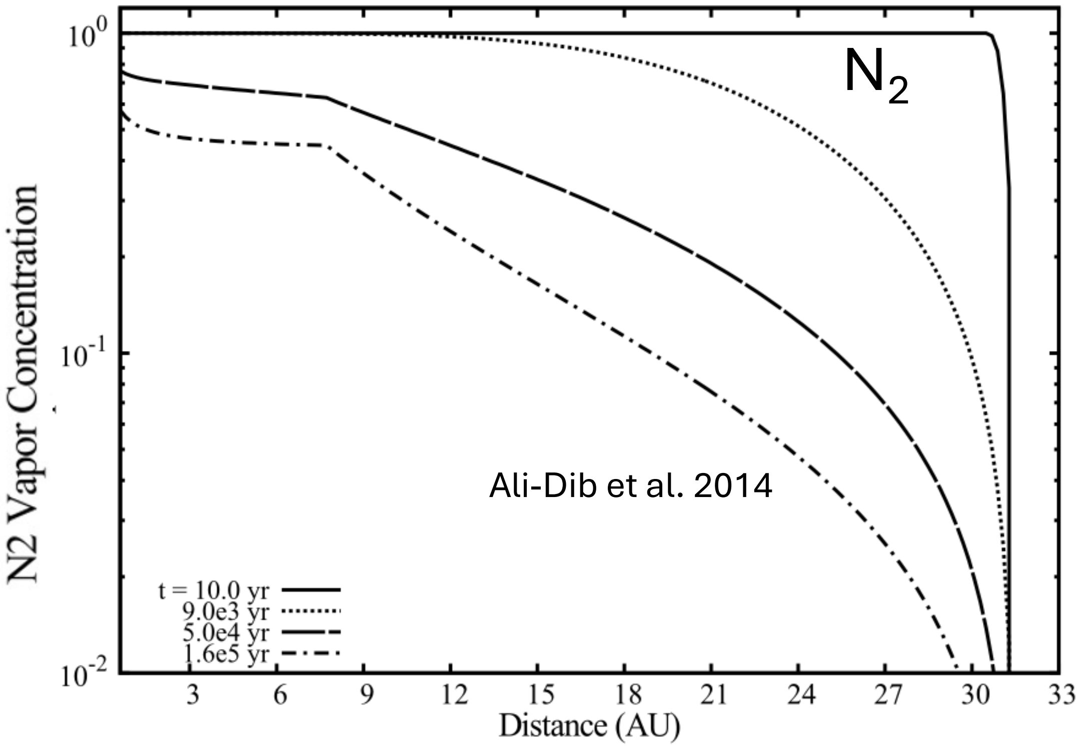
Photoevap: Guillot and Hueso (2006) assume C,N,O,S,P follow clathrate or amorphous

Conclusions

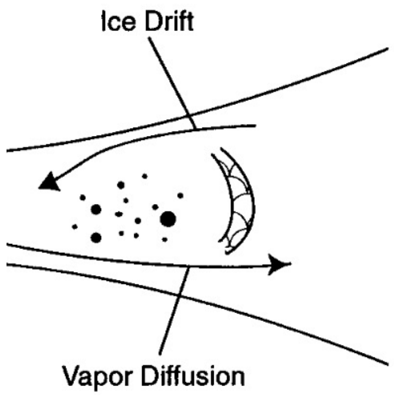
- We really know very little about the actual source regions of Uranus (and Neptune)
- Both could have formed from CO-rich, water-poor solids, or from more ice-rich solids with a different D/H than comets. In either case, comets seem to be a poor match for the heavy element phases.
- Getting noble gases is important, but especially helpful would be:
- As precise a value as possible for the atmospheric helium abundance
- Gravity mapping + interior models that could determine how much rock vs ice
- B-field measurements that might point to the presence of electrically conducting water phases in the interior
- Behavior of water and other materials at the pressures and temperatures of Uranus:
  - Is nitrogen depleted in Uranus or dissolved in a deep ocean? Do we understand the thermodynamics of water oceans at megabar pressure?
  - What about a He-NH_3 stable phase at 1 megabar? (Shi et al 2020). If that is stable, do the other noble gases incorporate in ammonia as well?

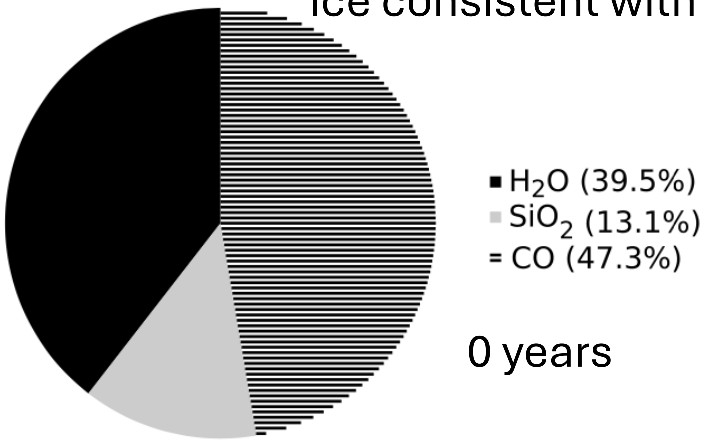
Ali-Dib et al. (2014b) proposed that Uranus formed near the CO snowline....



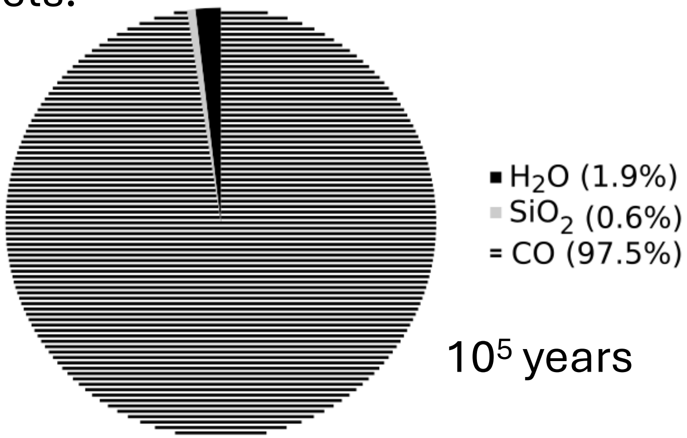


...leading to high CO enrichment, low N, D/H in the small amount of primordial ice consistent with comets.





0 years



10^5 years