Origin and Evolution of the Giant Planets from Comparative Planetology and In Situ Exploration

Sushil Atreya

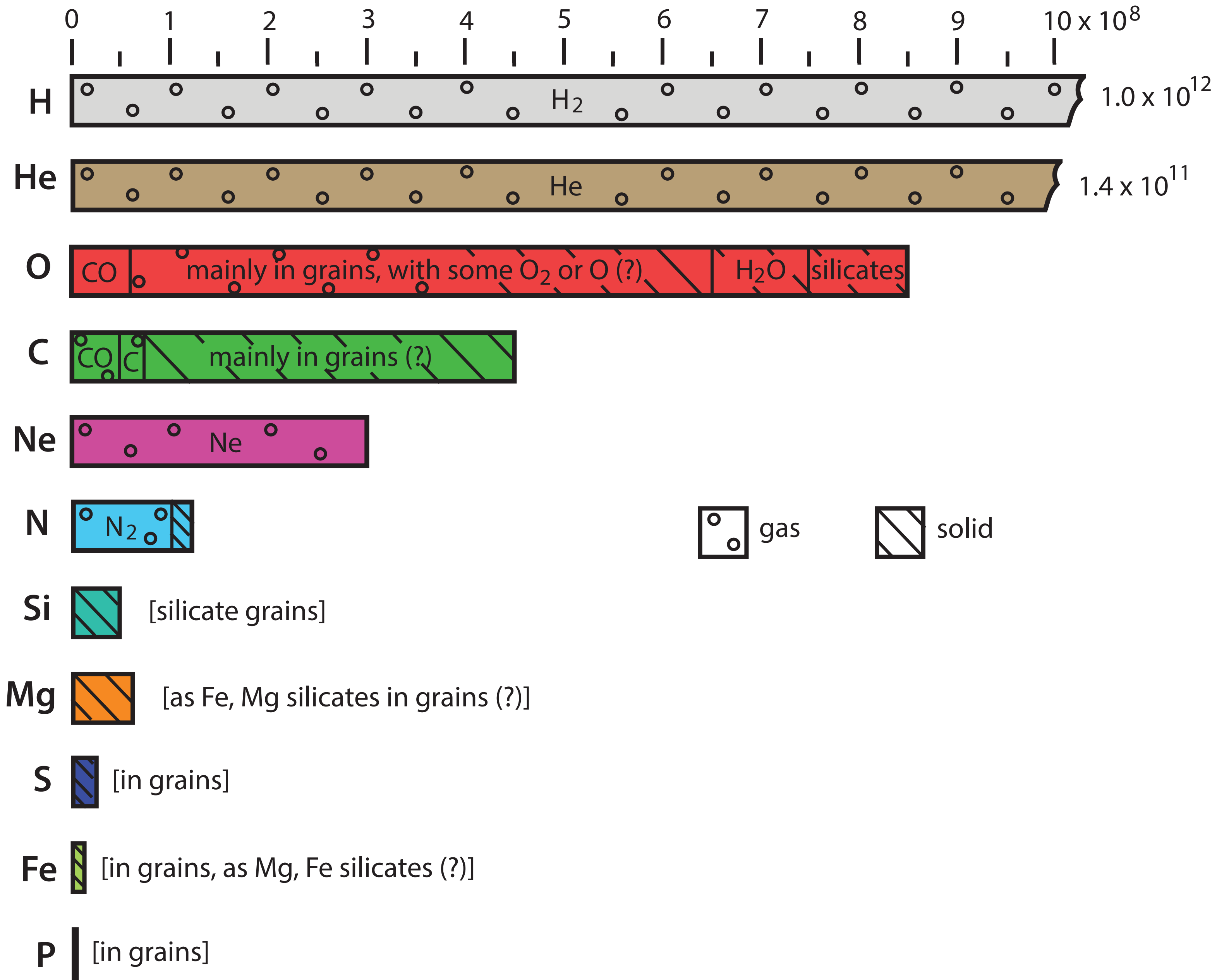
IPPW2019 SC

6 July 2019 Oxford

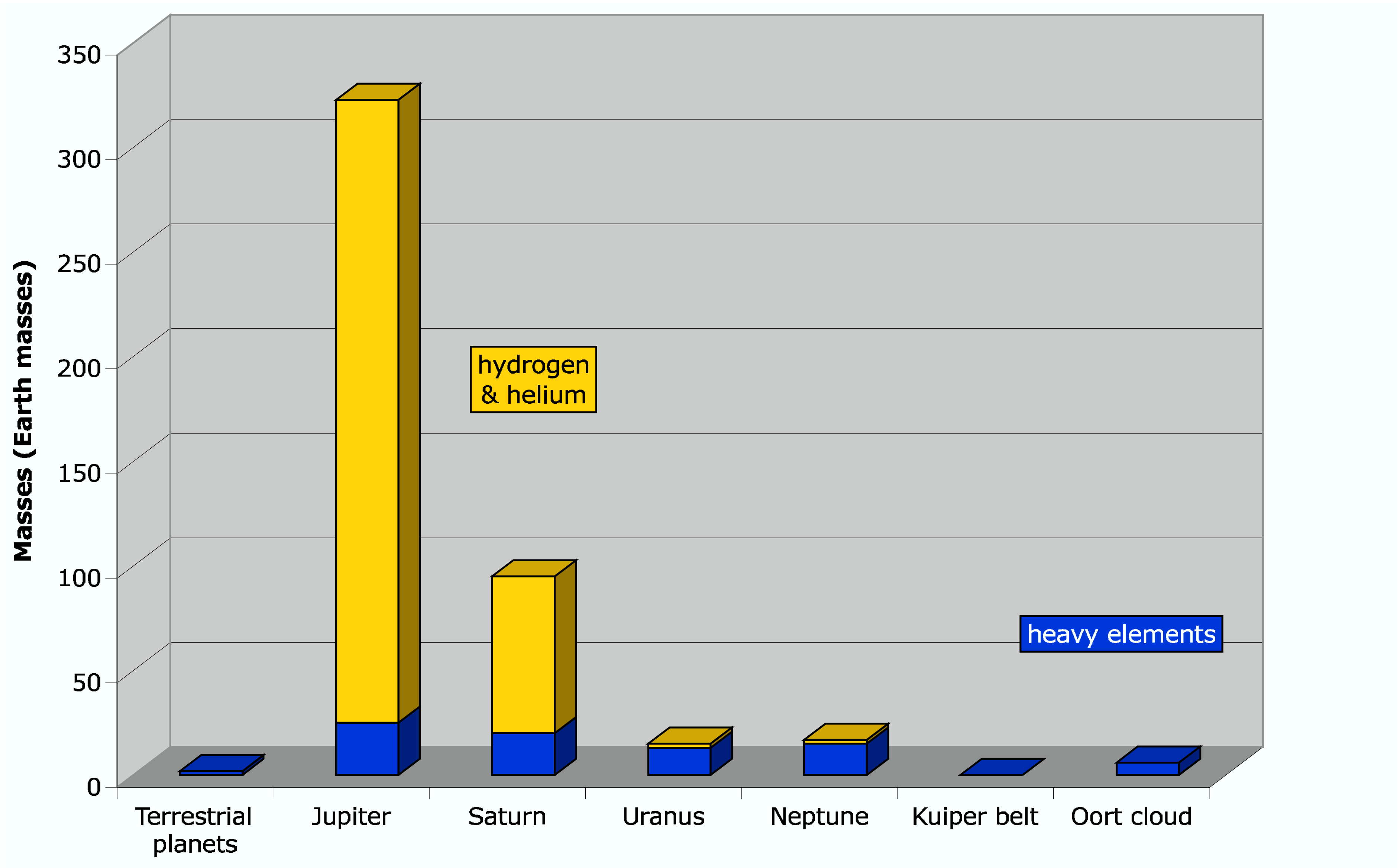
Formation:

how it all started and evolved

elemental distribution in typical interstellar cloud



Hydrogen, helium and the heavy elements



[Guillot and Gautier, 2014]

Core Accretion
(Mizuno ‘80; Pollack ’84)

- Dust grains (refractory, metals, ices) accrete into planetesimals
➔planetary embryos
➔10-15M_E core forms
➔core captures gas

Pros:

- Chondrules in meteorites and asteroids clear evidence of solid material accumulation from very early on
- Greater frequency of Exoplanets around higher metallicity stars
- All GP’s have similar (common) core masses
- Explains greater metallicity of J&S than Sun

Cons:

- Gas disk may dissipate before GP formation is completed

TWO PLANET FORMATION SCENARIOS

Accretion model

Orbiting dust grains accrete into "planetesimals" through nongravitational forces.

Planetesimals grow, moving in near-coplanar orbits, to form "planetary embryos."

Gas-giant planets accrete gas envelopes before disk gas disappears.

Gas-giant planets scatter or accrete remaining planetesimals and embryos.

Gas-collapse model

A protoplanetary disk of gas and dust forms around a young star.

Gravitational disk instabilities form a clump of gas that becomes a self-gravitating planet.

Dust grains coagulate and sediment to the center of the protoplanet, forming a core.

The planet sweeps out a wide gap as it continues to feed on gas in the disk.

Gravitational Instability Model
(Boss, 1997)

- GP’s form *directly* from clumps

Protoplanetary disk of gas and dust forms around juvenile star
➔gravitational disk Instabilities
➔clumps ➔planet
➔dust grains settle to center and form Core

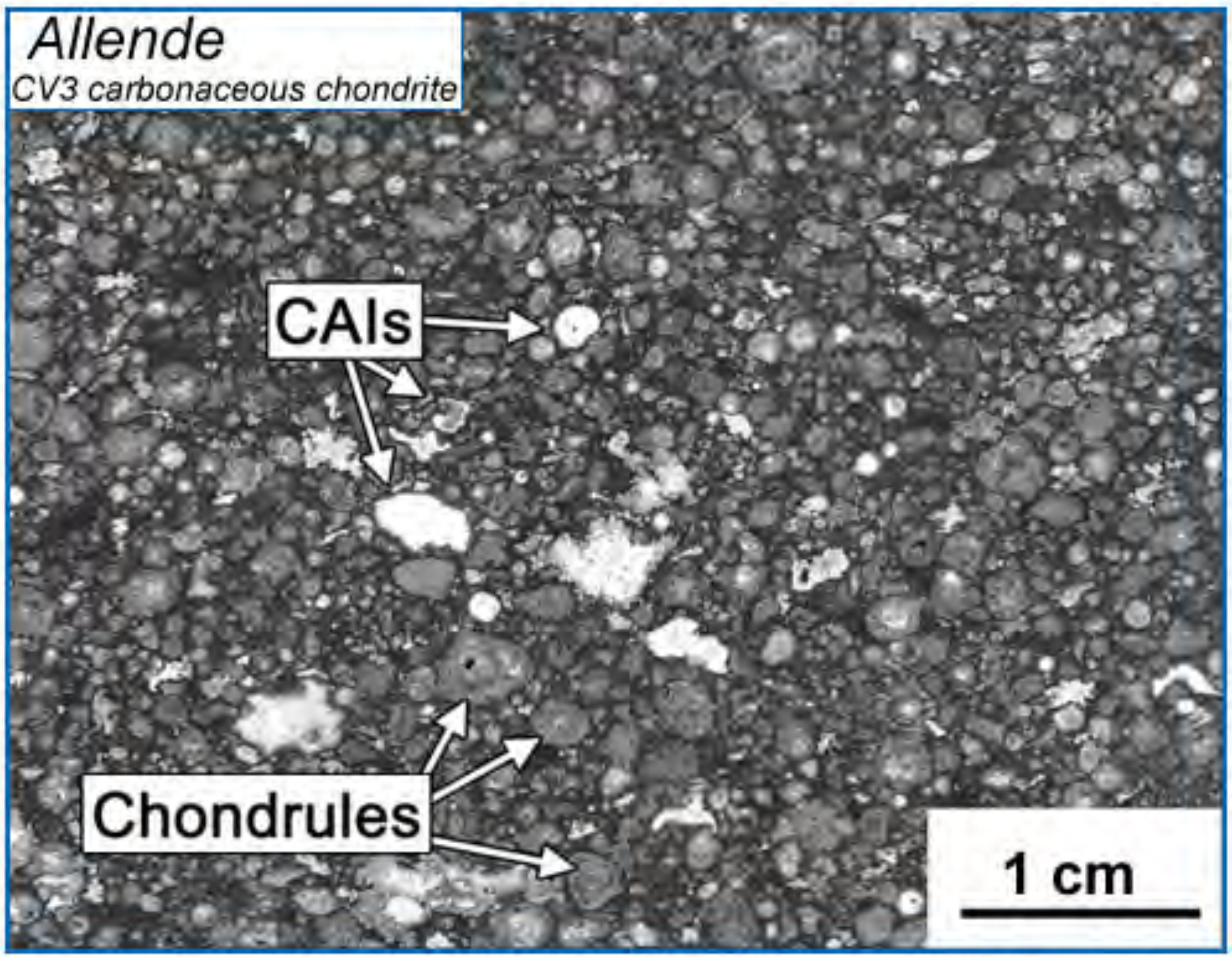
Pros:

- Formation time short
- Could form >1M_J GP’s

Cons:

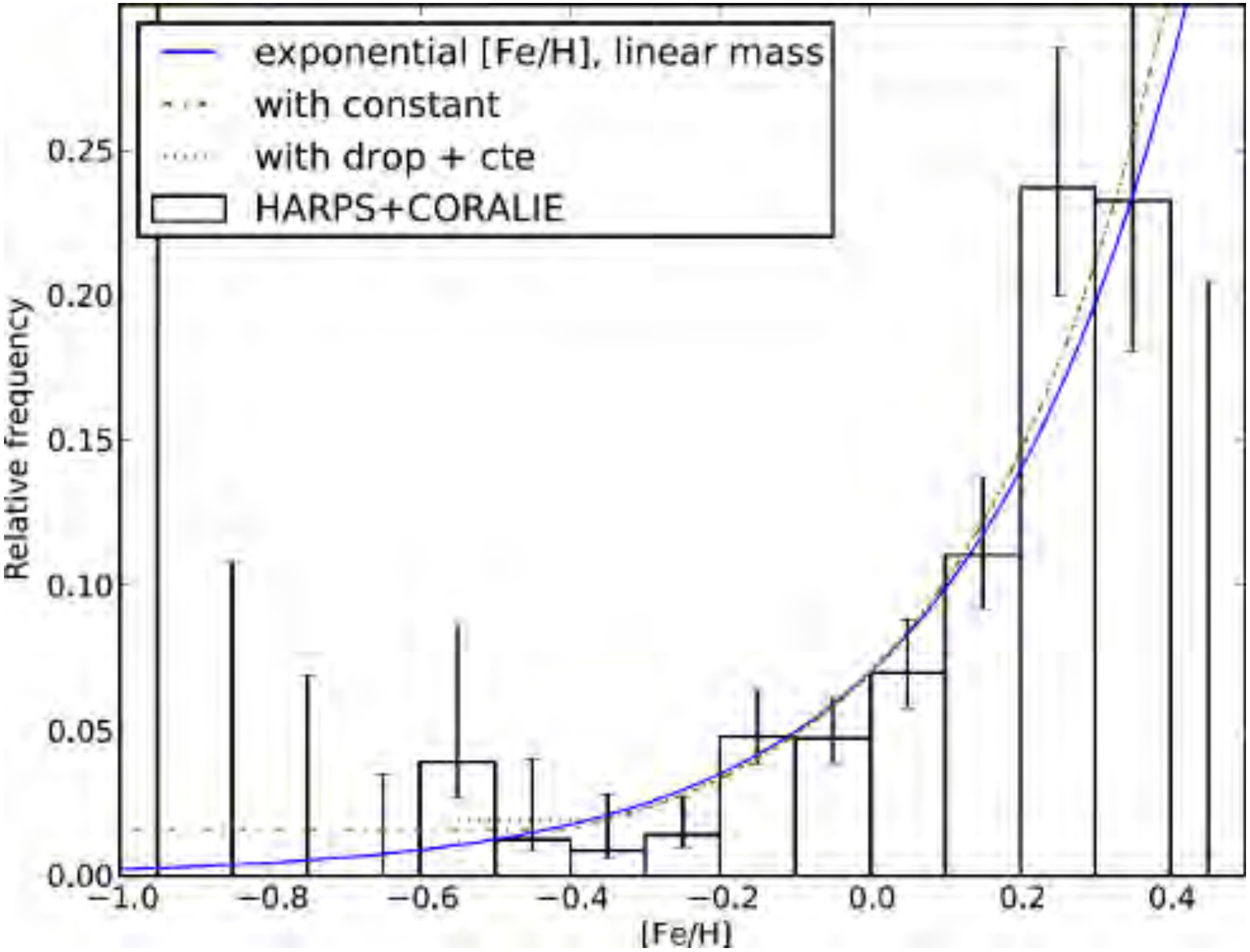
- Difficult to sustain stable clumps for long
- Fails to explain high metallicity of Jupiter & Saturn; chondrules, and exoplanet frequency

4.567 Gy old mm-size CAI’s and chondrules – evidence of core accretion



(From MacPherson, G. J. and Boss, A. (2011) Cosmochemical evidence for astrophysical processes during the formation of our solar system, *PNAS*, v. 108(48), p. 19152-19158, doi: 10.1073/pnas.1110051108.)

Greater frequency of giant exoplanets around higher metallicity stars



[Mortier et al. 2013]

Heavy elements are key constraints to Formation and Migration Models

i.e. abundances and isotopic ratios of the heavy elements*

determined from the

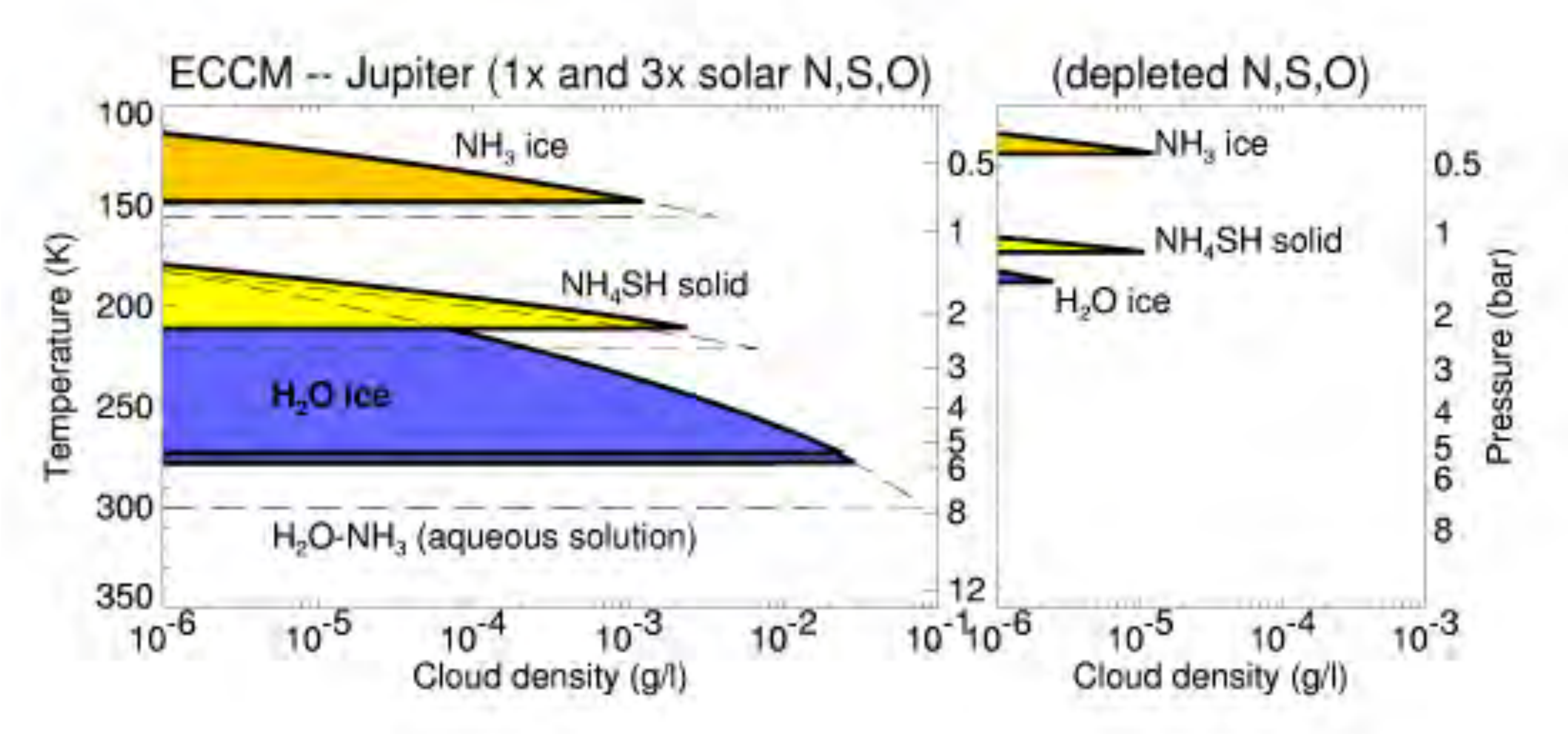
Bulk Composition

(*m/z > ^{4}He)

Test:
What did Galileo probe find?

Galileo Probe enters Jupiter, 7 Dec 1995

Galileo probe finds only thin haze layers



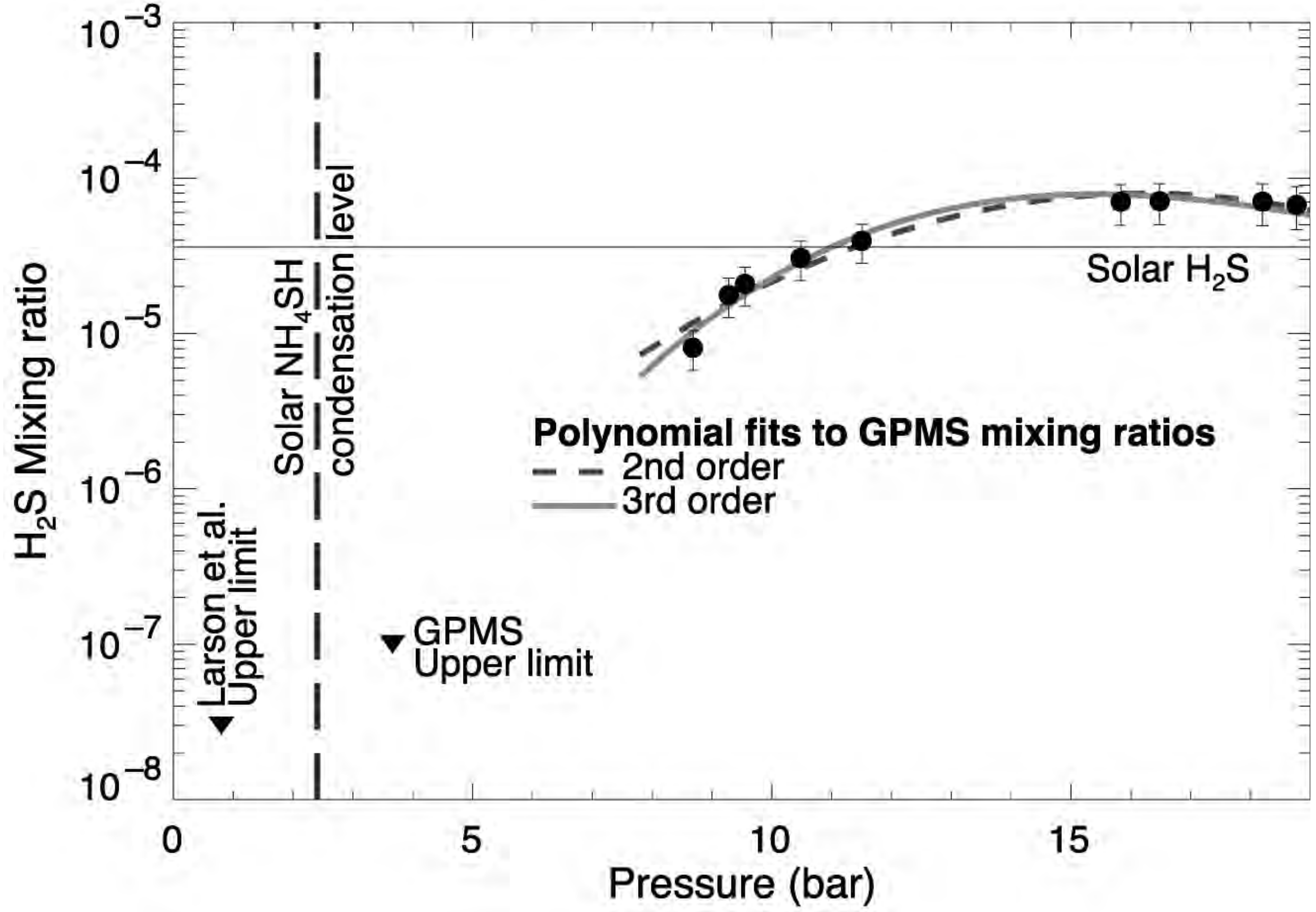
Equilibrium Thermodynamics

Galileo probe Entry Site

cloud densities are upper limits
cloud bases are robust, however

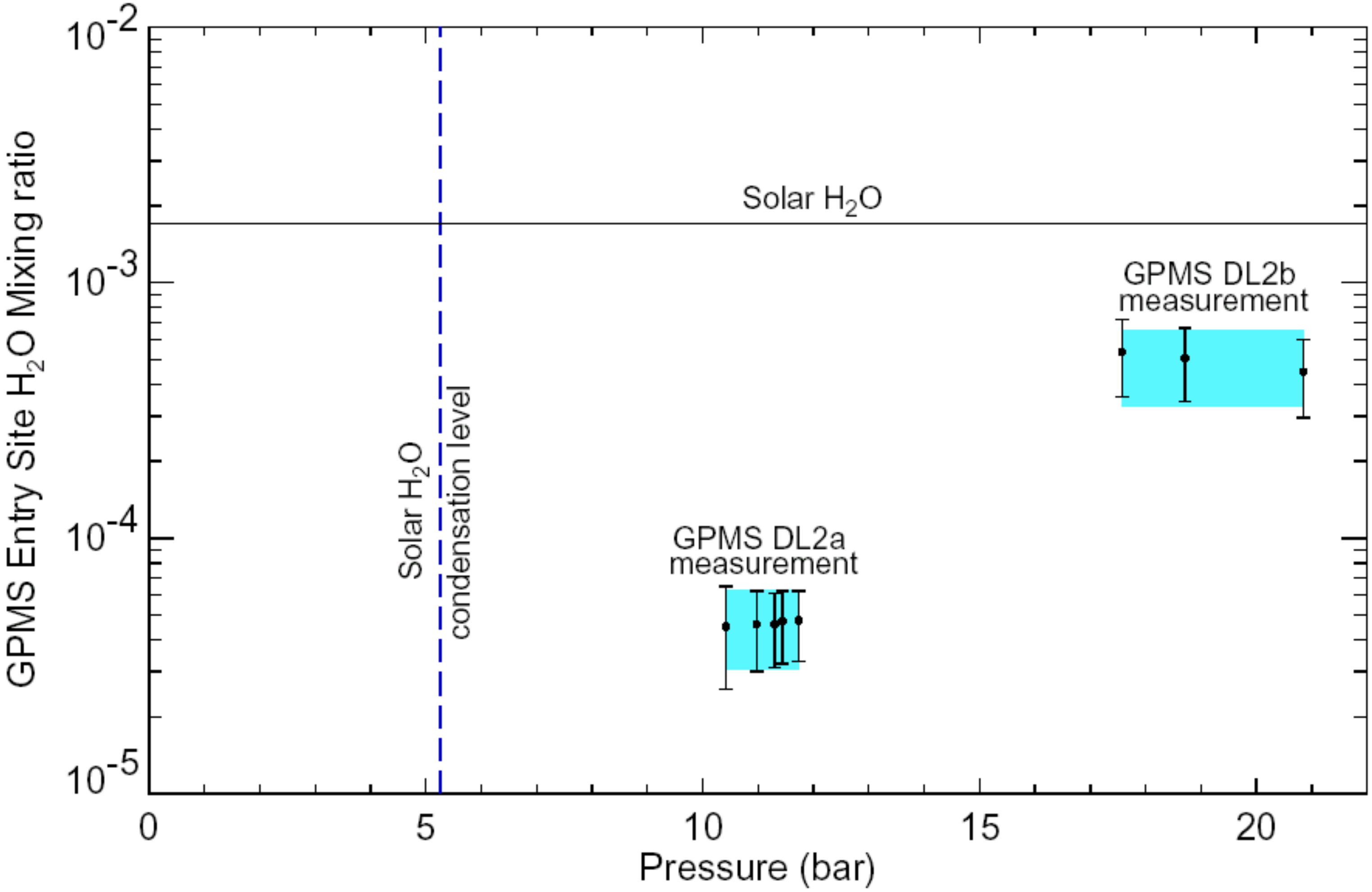
[Atreya et al. 1999]

Little volatiles: little clouds
H_2S recovered at 15 bars



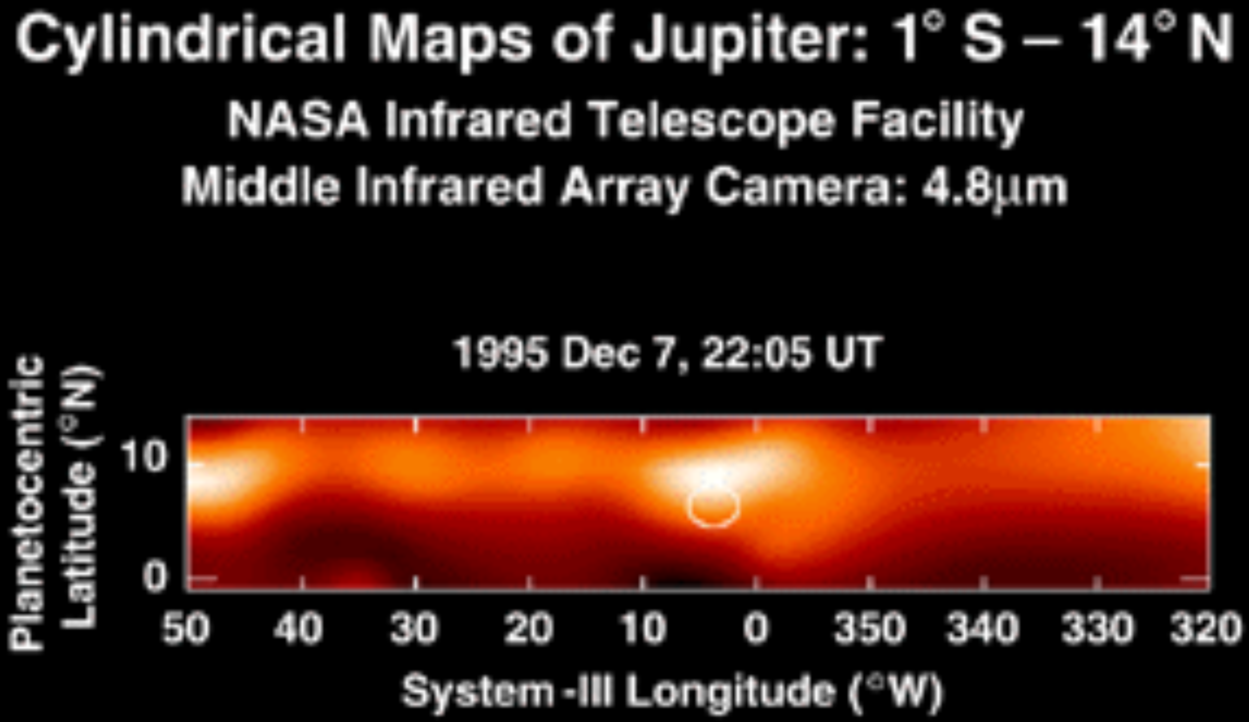
[Atreya et al. 1999]

Little volatiles: little clouds
H_2O depleted even at 22 bars



[Wong et al. 2004]

Galileo probe entry site: 5-µm hotspot



Cylindrical Maps of Jupiter: 1° S – 14° N

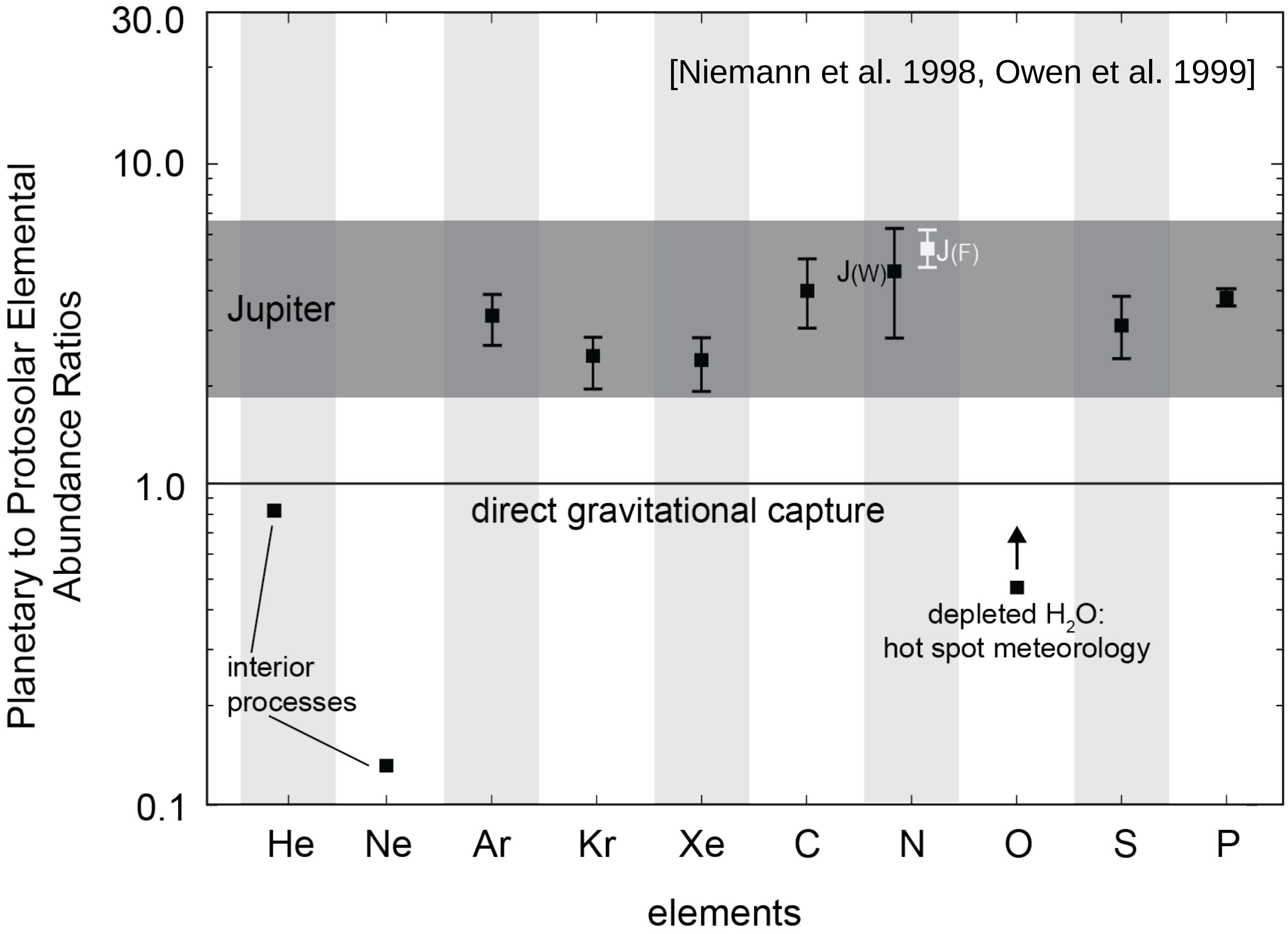
NASA Infrared Telescope Facility

Middle Infrared Array Camera: 4.8µm

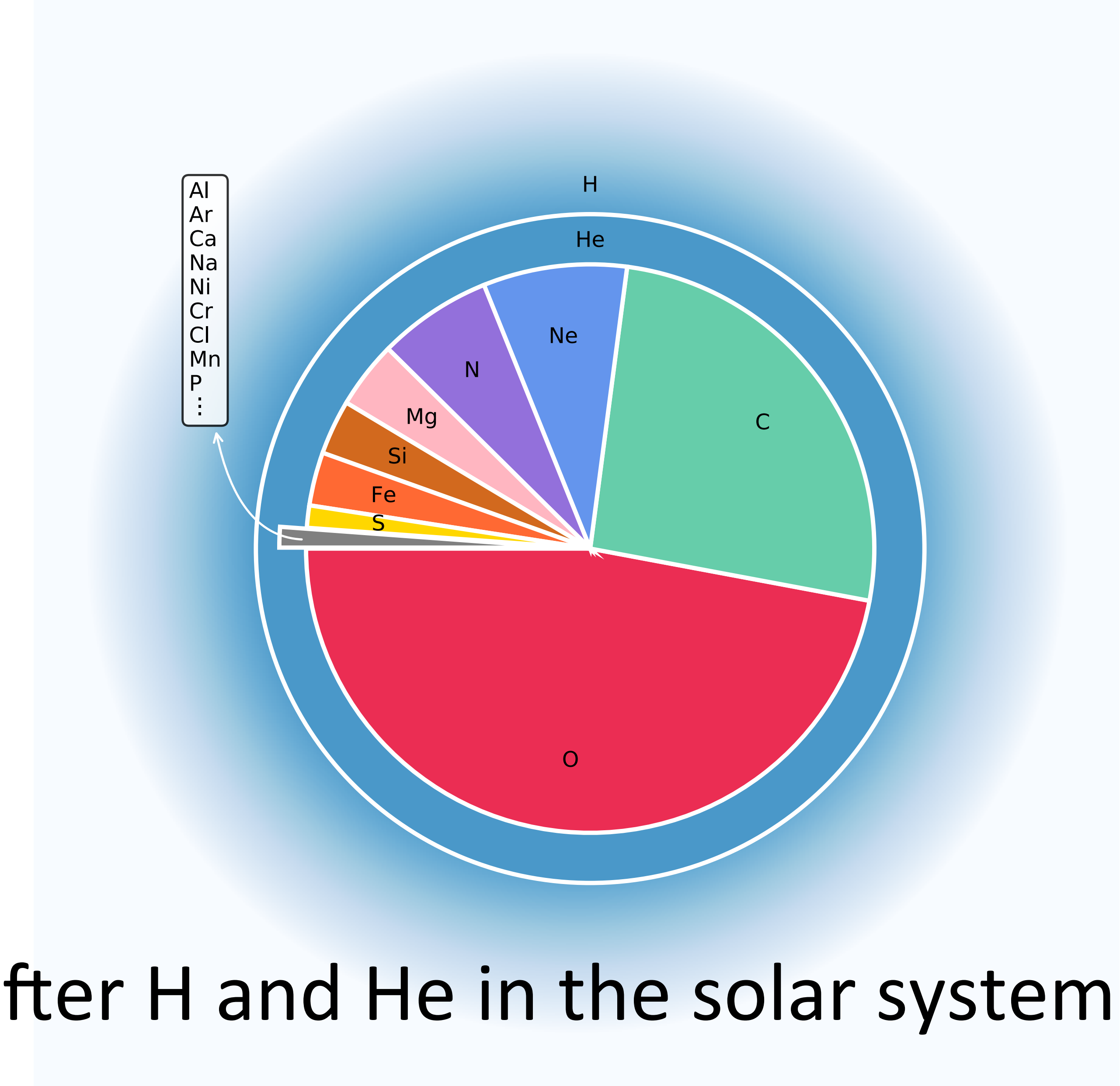
1995 Dec 7, 22:05 UT

[Orton et al. 1996]

Game changer:
Heavy elements are enriched in Jupiter!



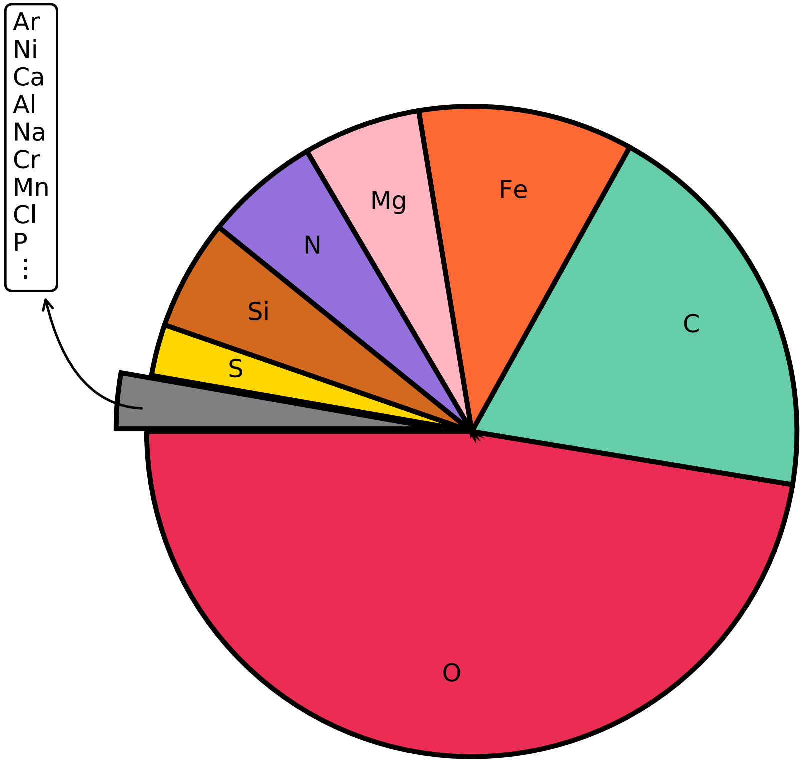
Oxygen is the most abundant element



after H and He in the solar system

[Atreya et al. 2018]

Water was presumably the original carrier of heavy elements in Jupiter



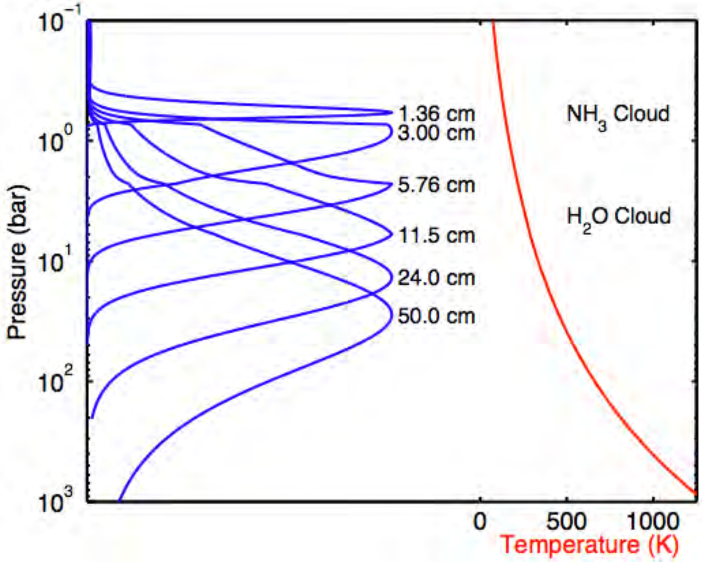
and may have been half of the core mass

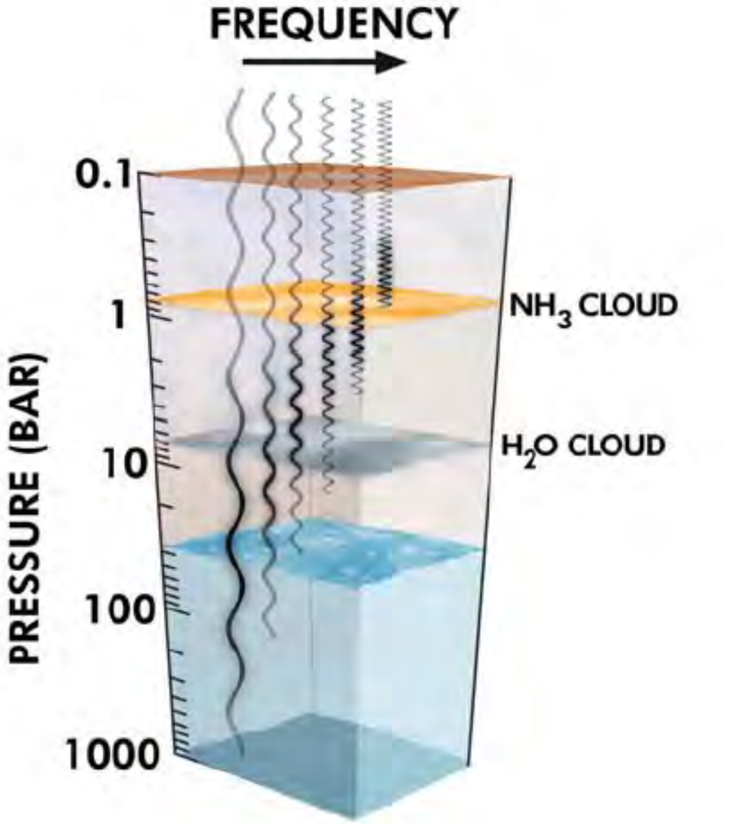
[Atreya et al. 2018]

Juno:
Surprise!

Juno Microwave Radiometry maps Jupiter's water and ammonia

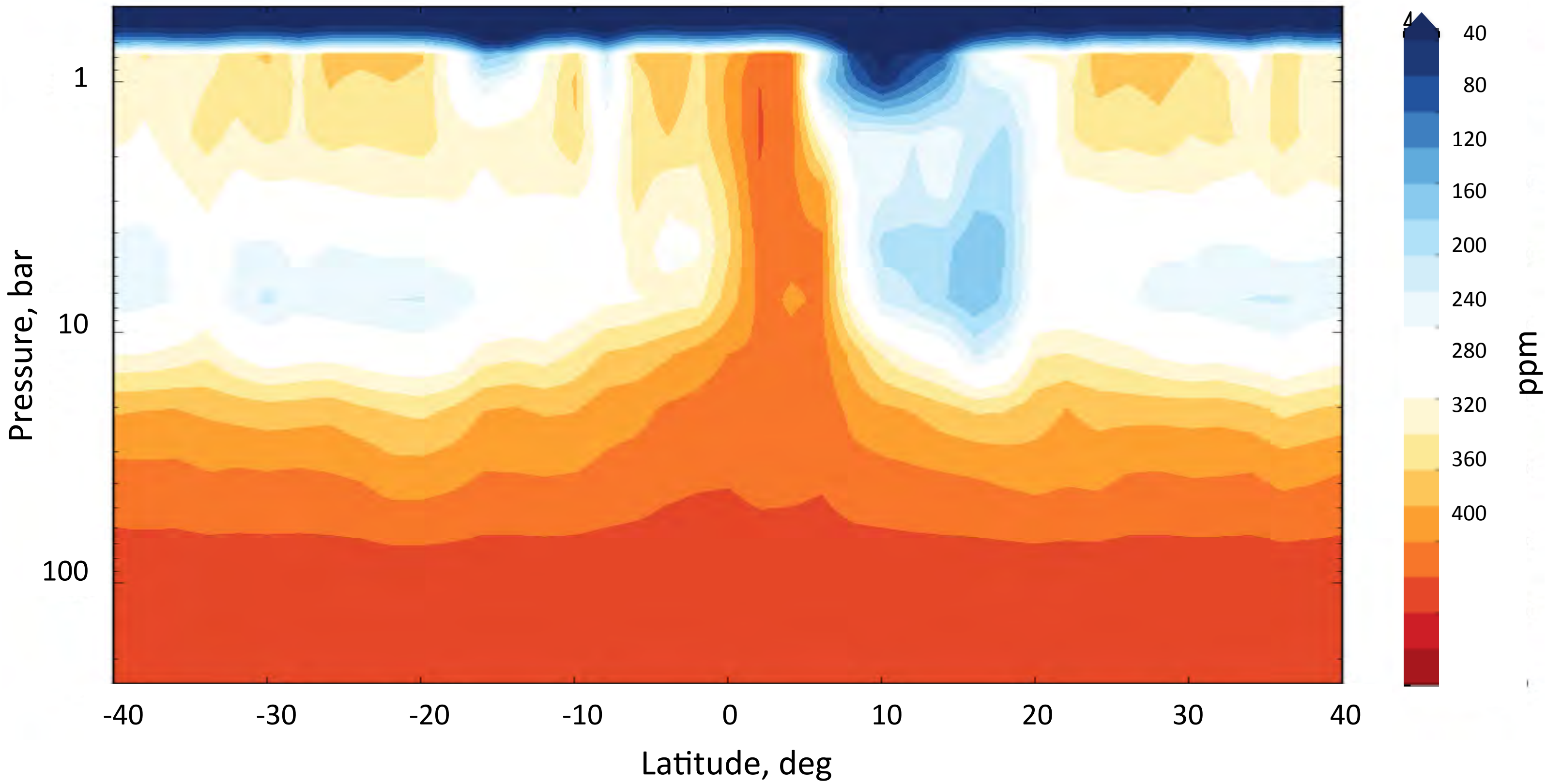
- Radiometry sounds the deep atmosphere
- Six wavelengths: 1- 50 cm
- Determines and *maps* H_2O and NH_3 abundances to ≥100 bars globally





[Janssen et al. 2018]

Ammonia from Juno:
most of Jupiter is like what Galileo probe saw

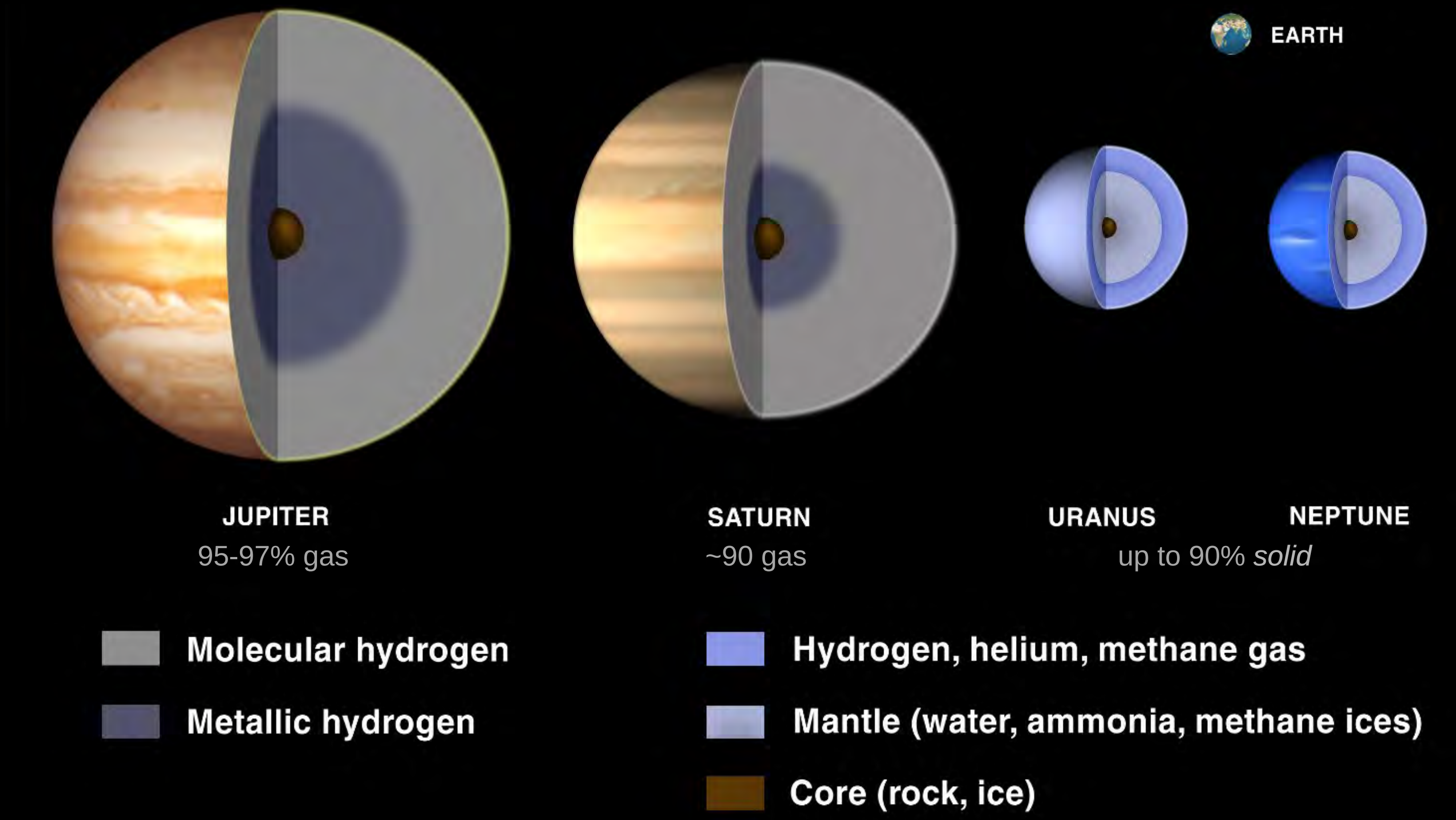


NH_3 cloud base 0.7 bars, but well-mixed NH_3 may be at 10's of bars!

[Bolton et al. 2007]

Fast forward to the Icy Giants: *looking to the future!*

Uranus and Neptune are the missing pieces of the outer solar system formation puzzle

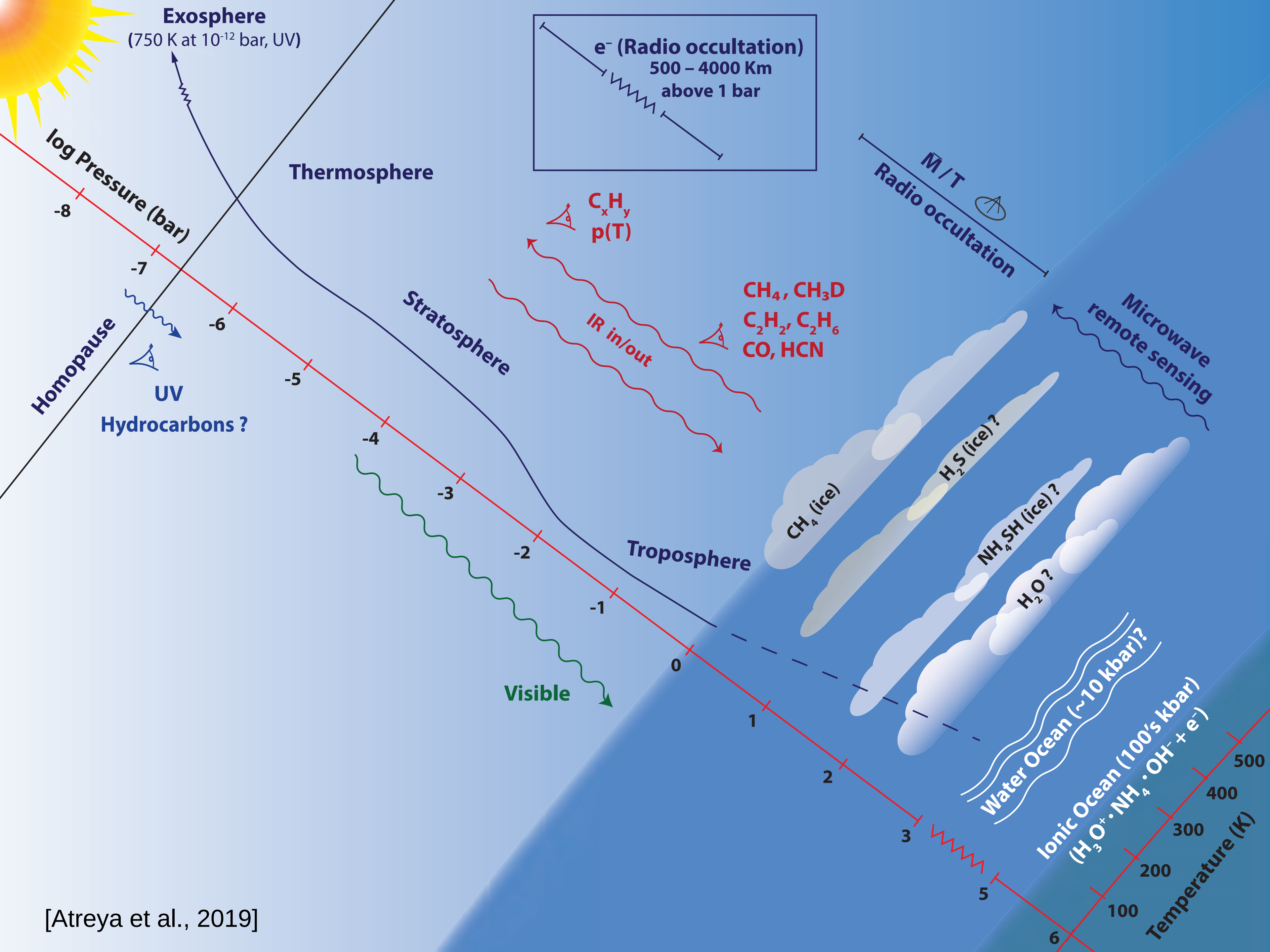


95-97% gas

~90 gas

up to 90% *solid*

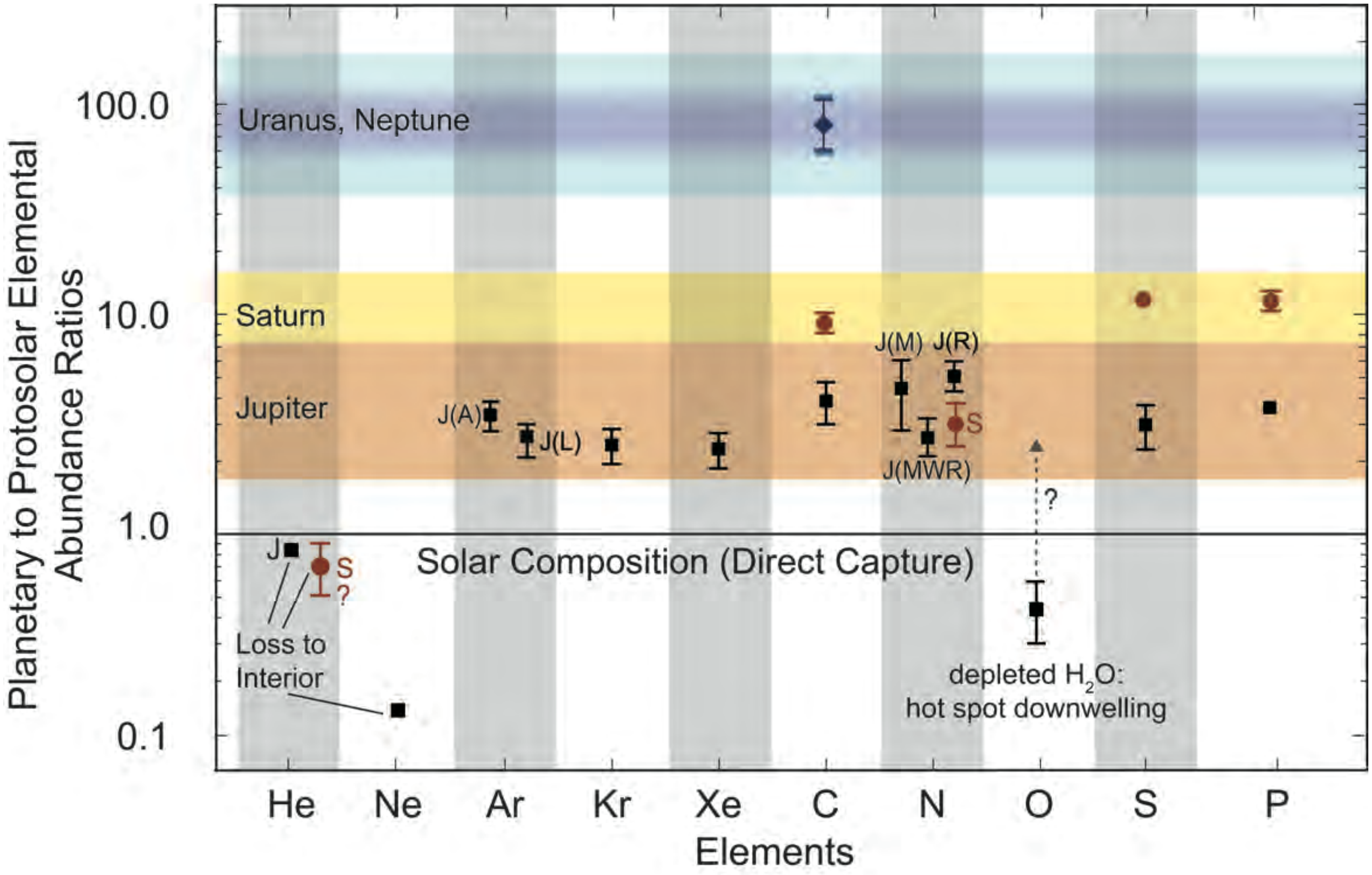
[Image: Tristan Guillot]



[Atreya et al., 2019]

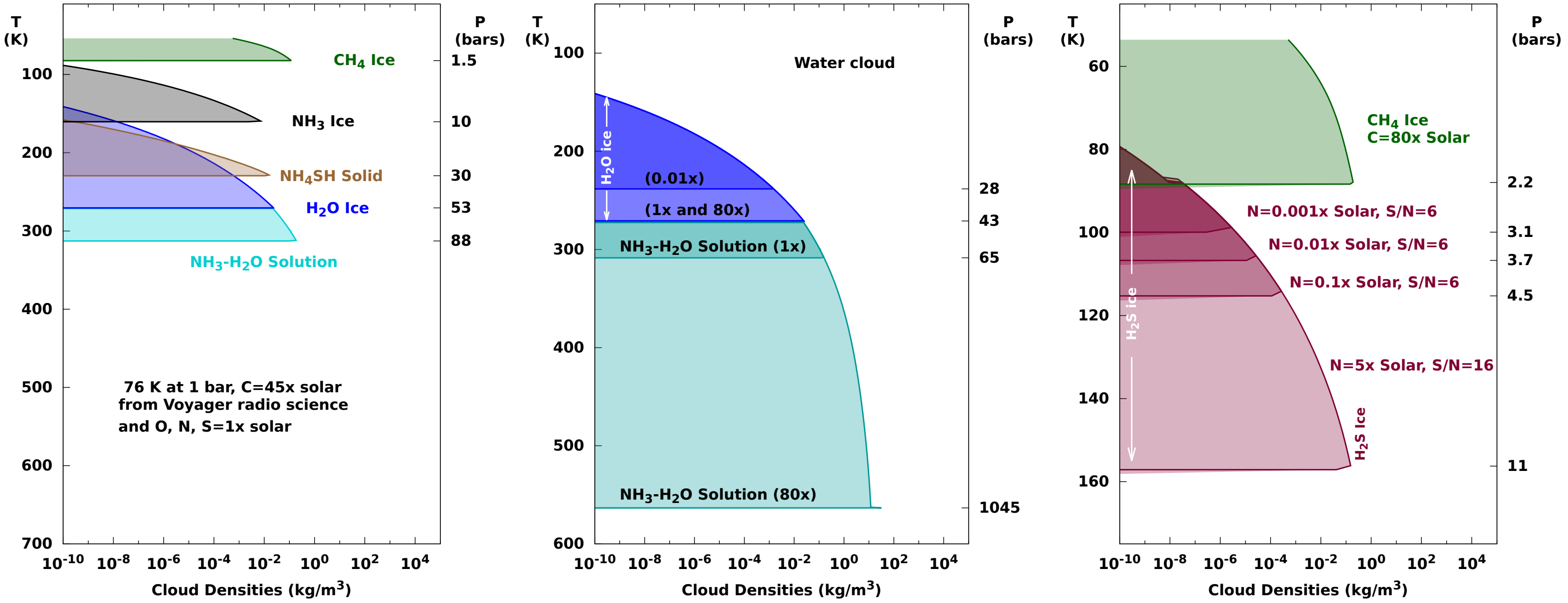
Only C/H known in the Icy Giants

[Jupiter 3±1x solar (Galileo Probe); Saturn C, S (?) 10x solar]



[Atreya et al., 2019]

Water (and most other condensibles) too deep for entry probes at Icy GP’s

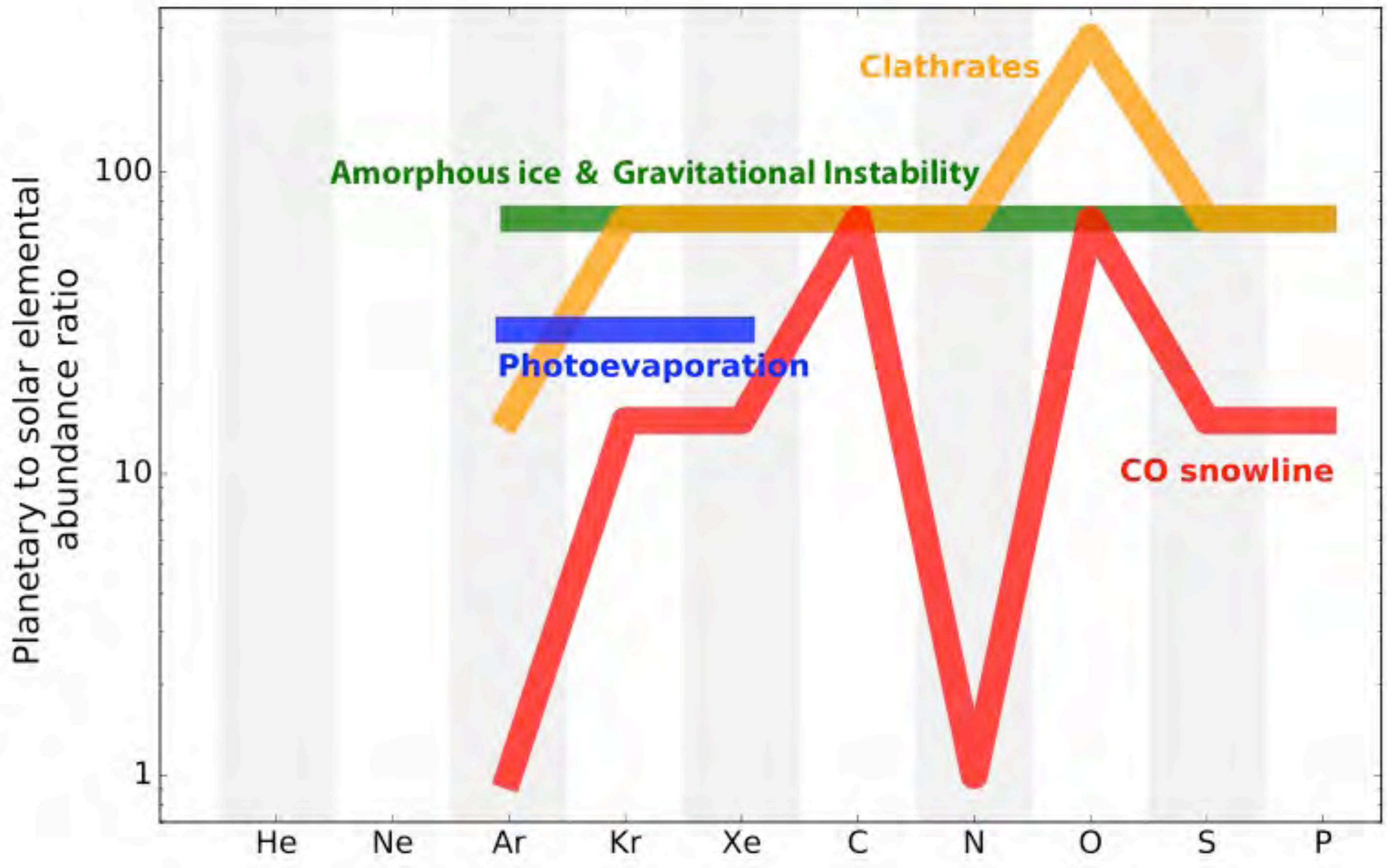


Equilibrium Thermodynamics

cloud densities are upper limits
cloud bases are robust, however

[Atreya et al. 2019]

IGP formation: Noble gases are key, and accessible at shallow depths (1-5 bars)



[Mousis et al. 2019]

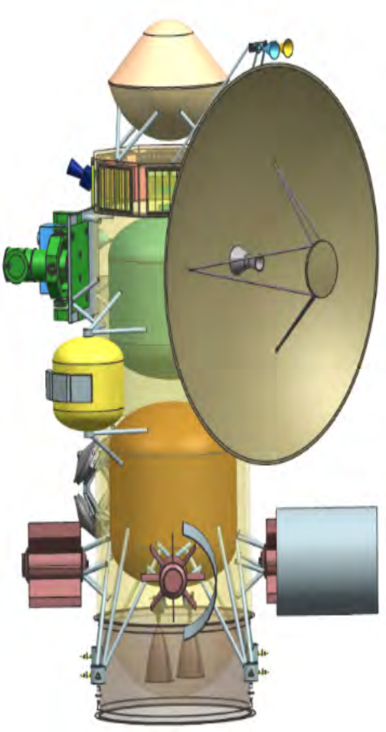
Recent Mission Studies and Future

NASA (with ESA participation) completed a broad survey of possible missions.

- Full report available at http://www.lpi.usra.edu/icegiants/mission_study/, or just google “ice giant mission planning” and click on the LPI link
- Recommends an orbiter plus atmospheric probe, instrumented to study the entire system
- Emphasizes the value of studying both Uranus and Neptune
- Optimal launch dates 2029-2031 (Neptune), 2030-2035 (Uranus)
- IGP’s make up a number of NASA’s Pre-Decadal proposals
- US National Academy begins Planetary Decadal Survey in 2020 for the decade beginning in 2023

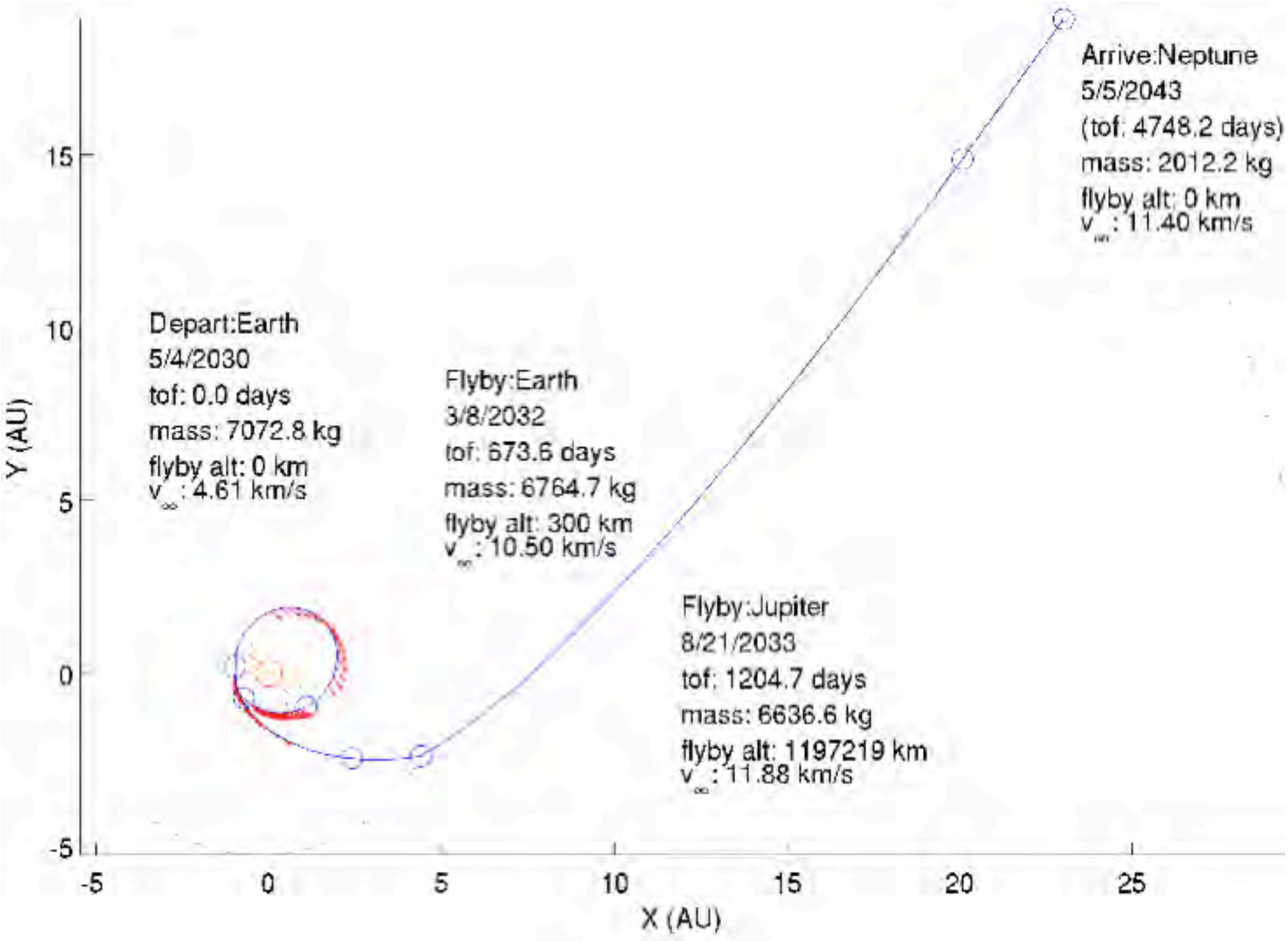
ESA (with NASA participation) has just completed its own study

- It explored providing either an atmospheric probe, a Triton lander, or a separate spacecraft to enable studying both Uranus and Neptune
- Request for increase in ESA’s budget will be made to the European Council of Ministers that will meet in Nov 2019



Notional Uranus mission design from the above referenced NASA study

Mission-Enabling Technology Exists Today to do a Uranus or Neptune Mission



[Credit: JPL-ID-100520, 2017]

Take Aways

- *Comparative planetology* of the gas ice giants and the icy giants is essential for understanding the formation and evolution the outer solar system

- *Only entry probes* can measure the noble gases and certain other heavy elements, but complementary data from orbiter are essential

- *Core accretion* is favored, but *disk instability* also has merits, to be re-assessed after measurements of heavy elements and isotopes at IGP's