Ice Giants
Motivations and Science Objectives for in situ exploration

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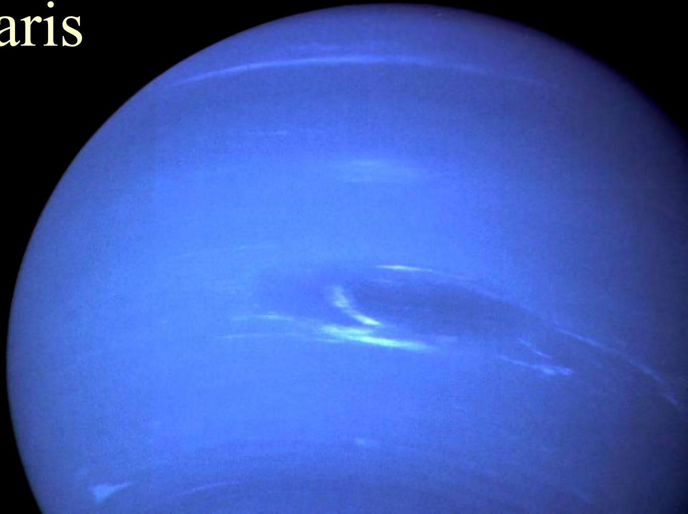
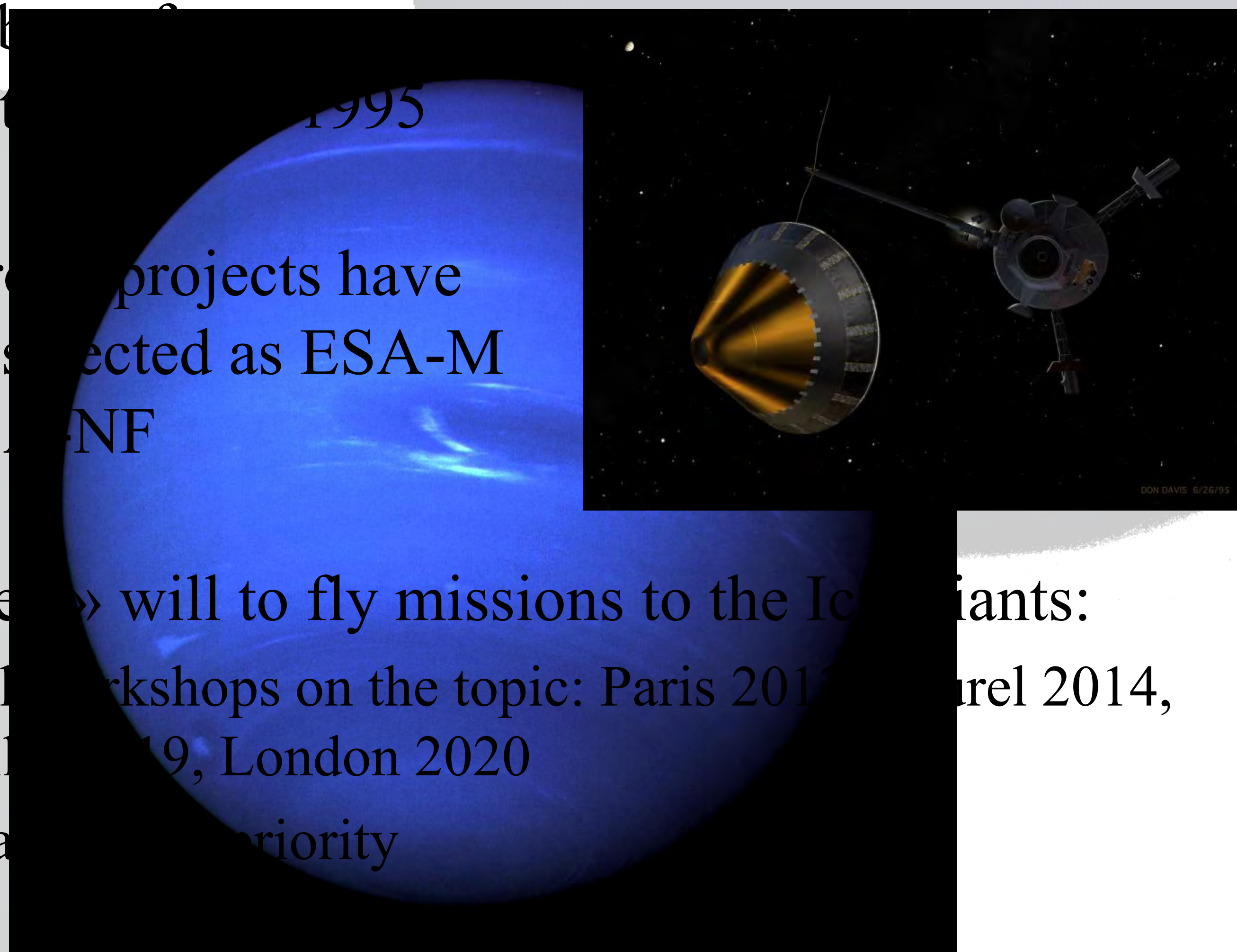


Context

- Neptune visited 30 years ago by Voyager 2
- Only prob ... Galileo a ... 1995
- Saturn pr ... projects have not been s ... ected as ESA-M and NAS ... NF
- « Renewe ... » will to fly missions to the Ic ... iants:
  - Several ... kshops on the topic: Paris 201 ... urel 2014, Marsei ... 19, London 2020
  - Decada ... riority
  - NASA



Some outstanding questions regarding Ice Giants

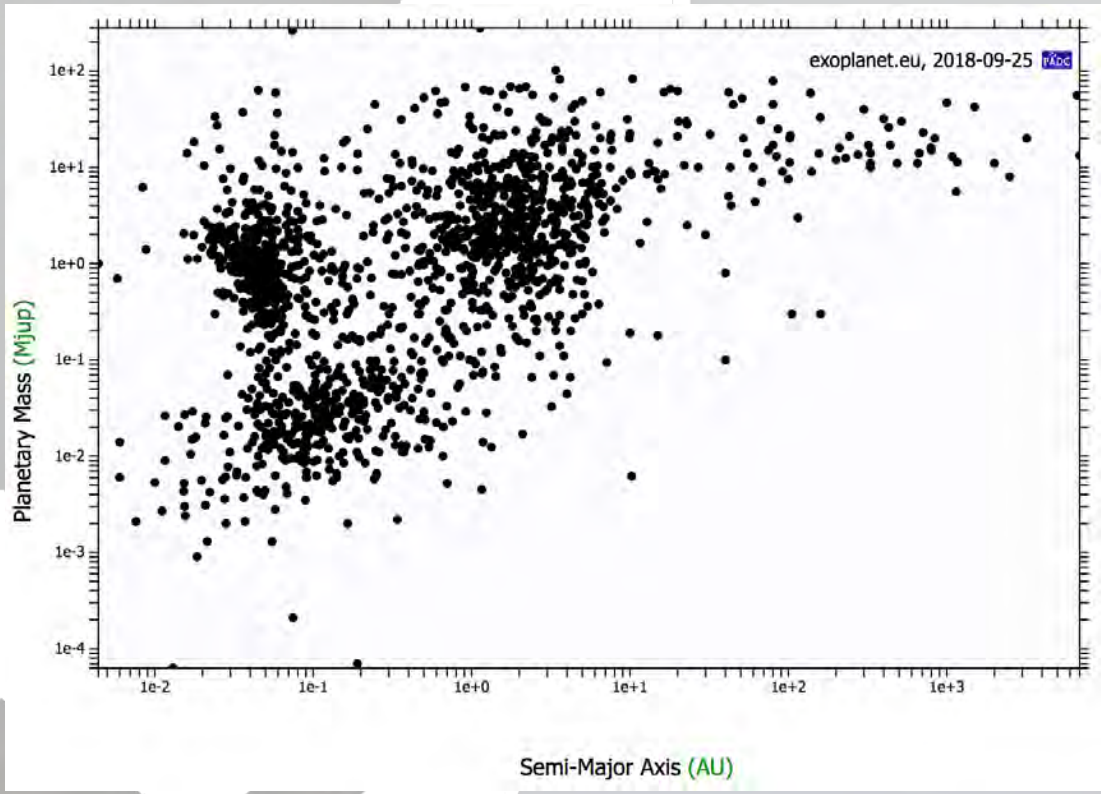
- How did the Ice Giants form?
- What constraints can be placed on the mechanisms for planetary accretion?
- What is the role of giant impacts in explaining the differences between Uranus and Neptune?
- What is the bulk composition and internal structure of Uranus and Neptune?
- What physical and chemical processes during the planetary formation and evolution shape the magnetic field, thermal profile, and other observable quantities?

→ ***Broader exoplanet context***

Context

- ~ 4000 exoplanets detected

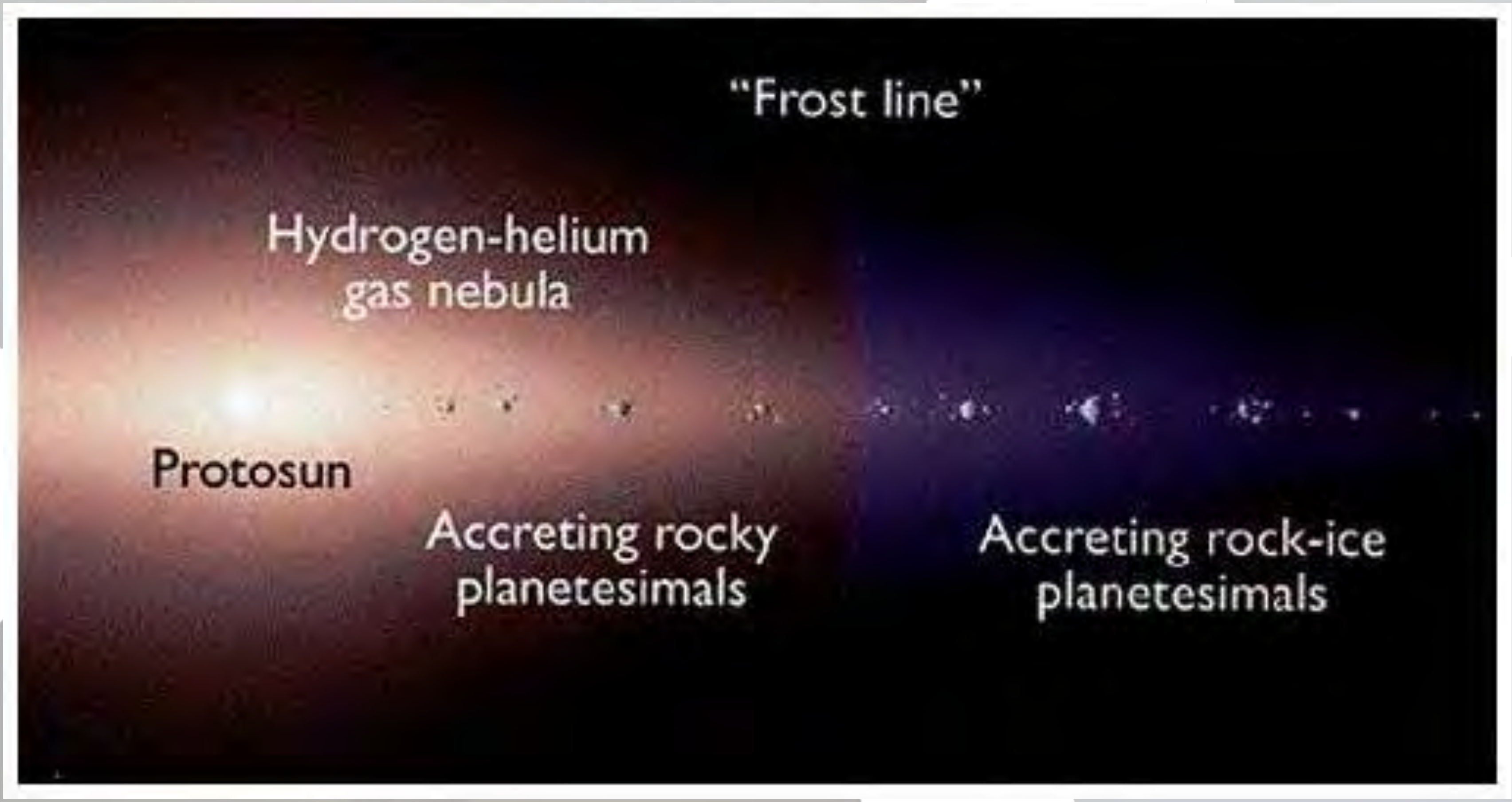
- Great variety
  - Hot Jupiters
  - Hot Neptunes
  - Super Earths
  - More common giants



- How do these systems form?
  And how do they evolve?

Giant planet formation

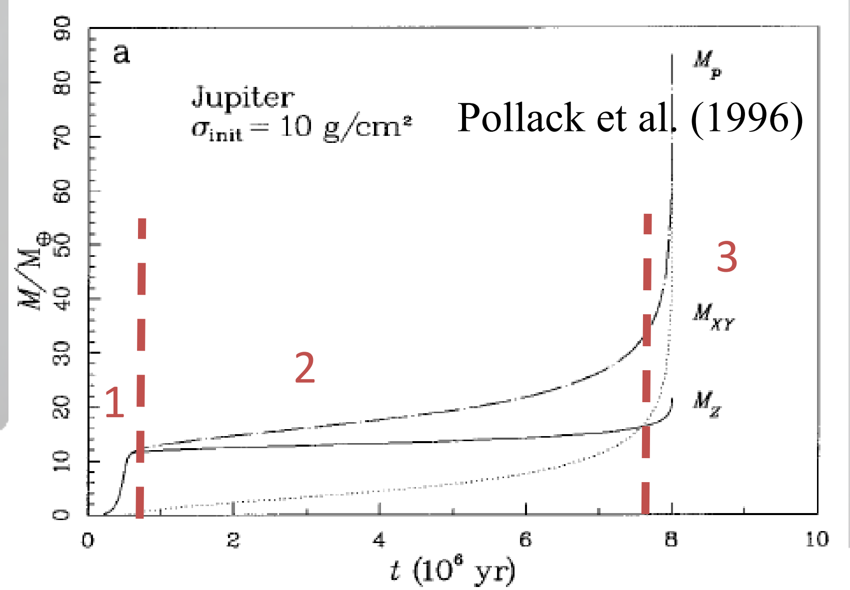
- Giant planets have formed in the protoplanetary disk, beyond the snow line ⟶ large amounts of material available !

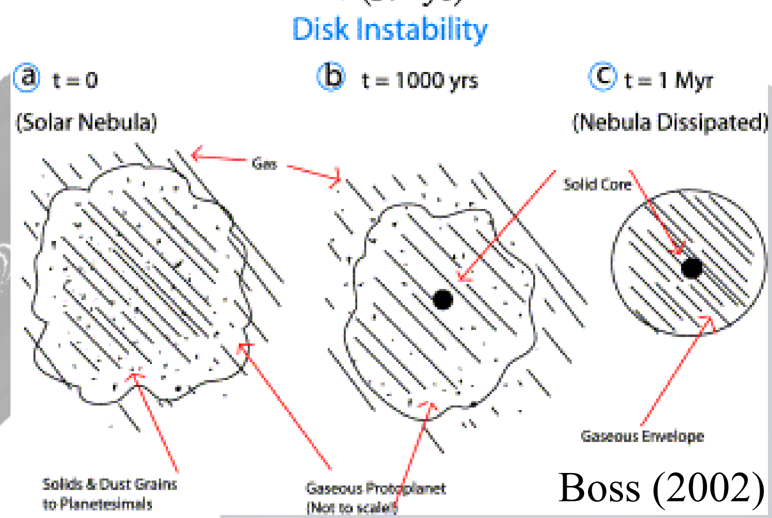


Giant planet formation

- Core accretion model (Pollack et al. 1996)
  ~1 to few Myr

- Disk instability model (Boss 1997, 2002)
  ~1 Myr





Composition provides constraints on the conditions in the solar nebula, the planetary formation location and formation timescale

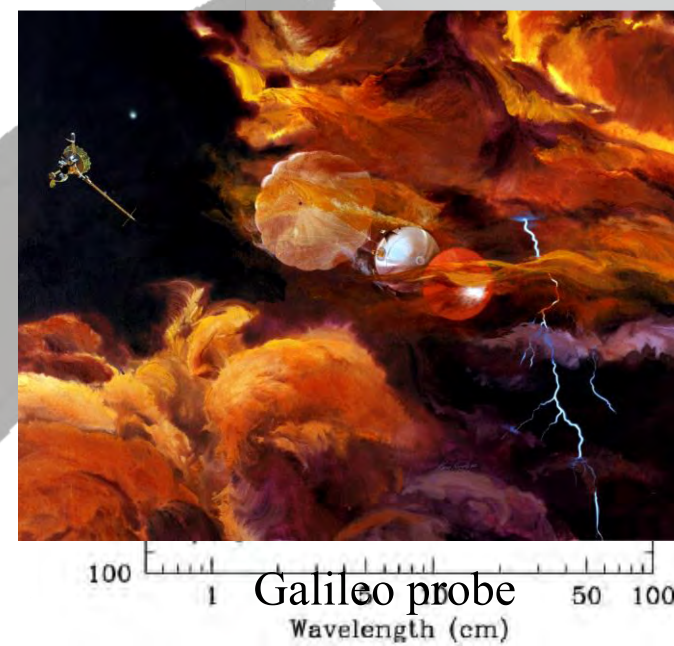
Deep composition

- Understanding the fomation of GP requires measuring their deep composition

- How can we measure deep composition?
  - *Remote sensing (+ models)*
  - *In situ*

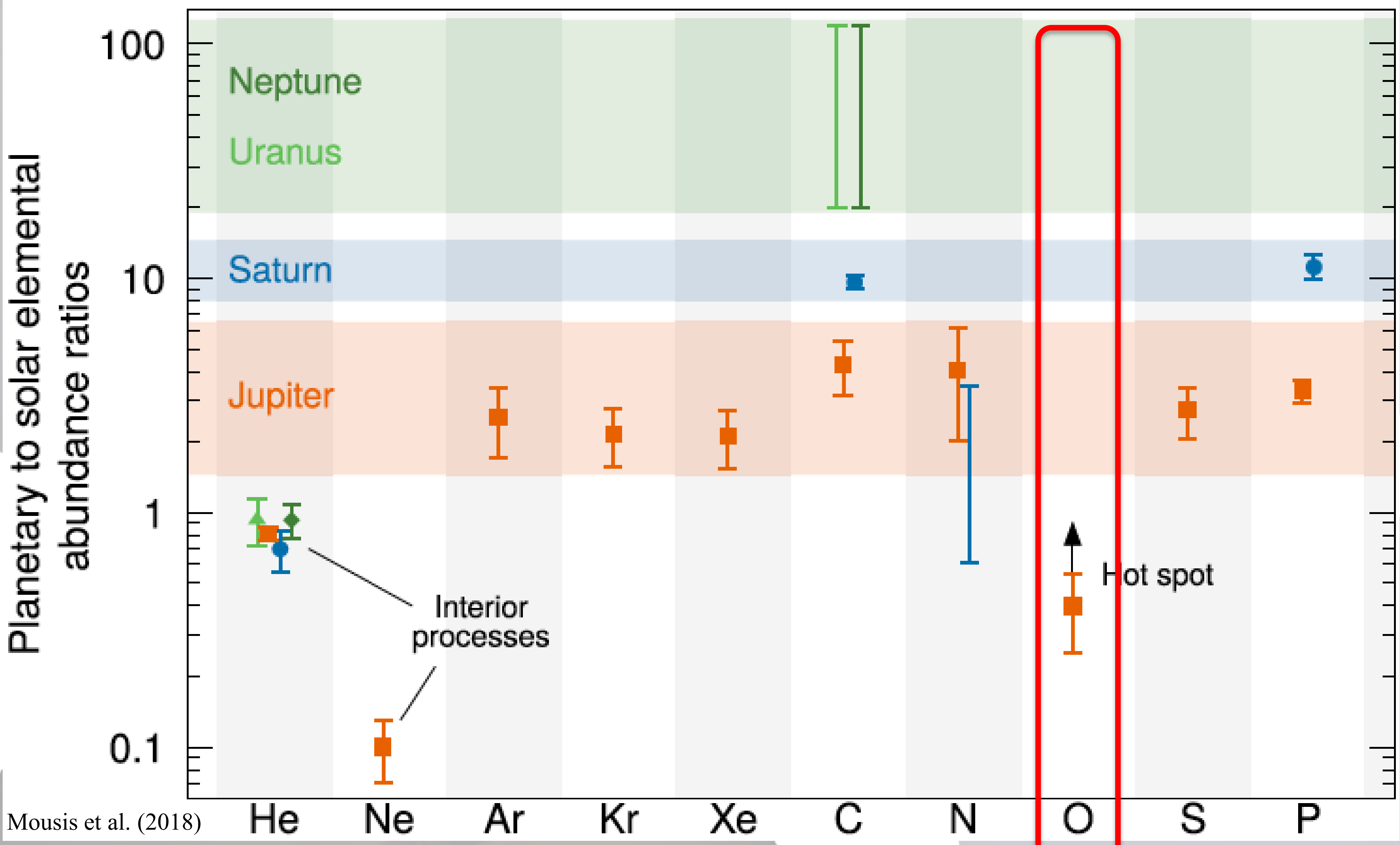
ALMA

Juno/MWR



Galileo probe

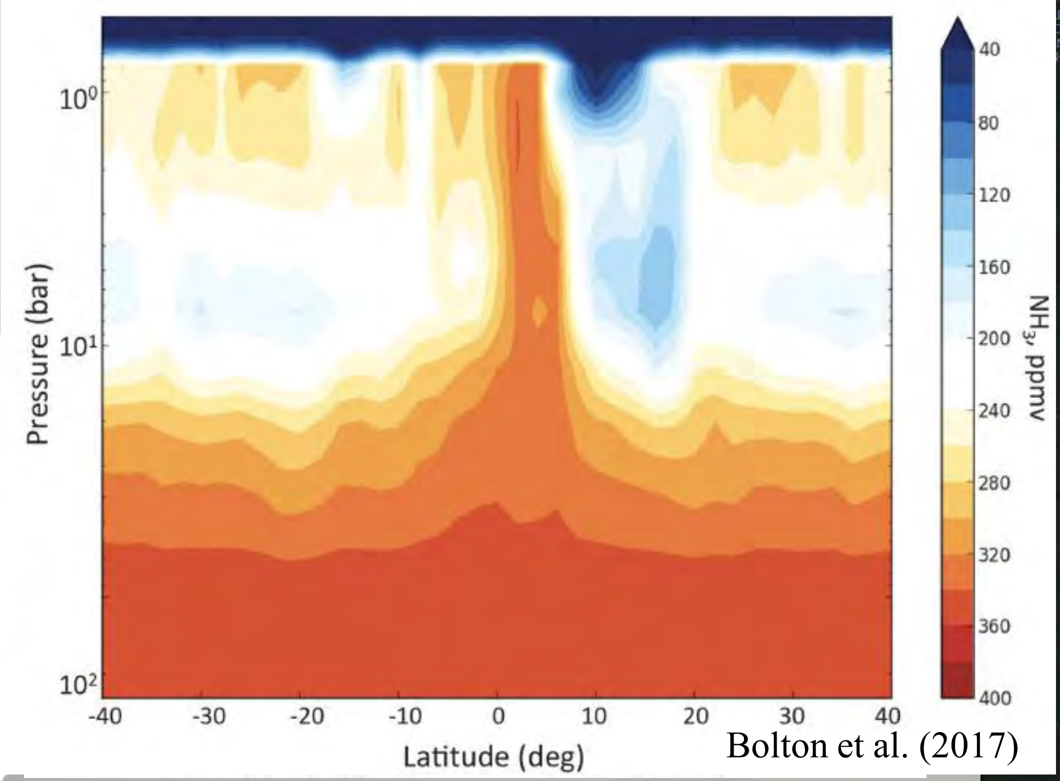
Deep composition



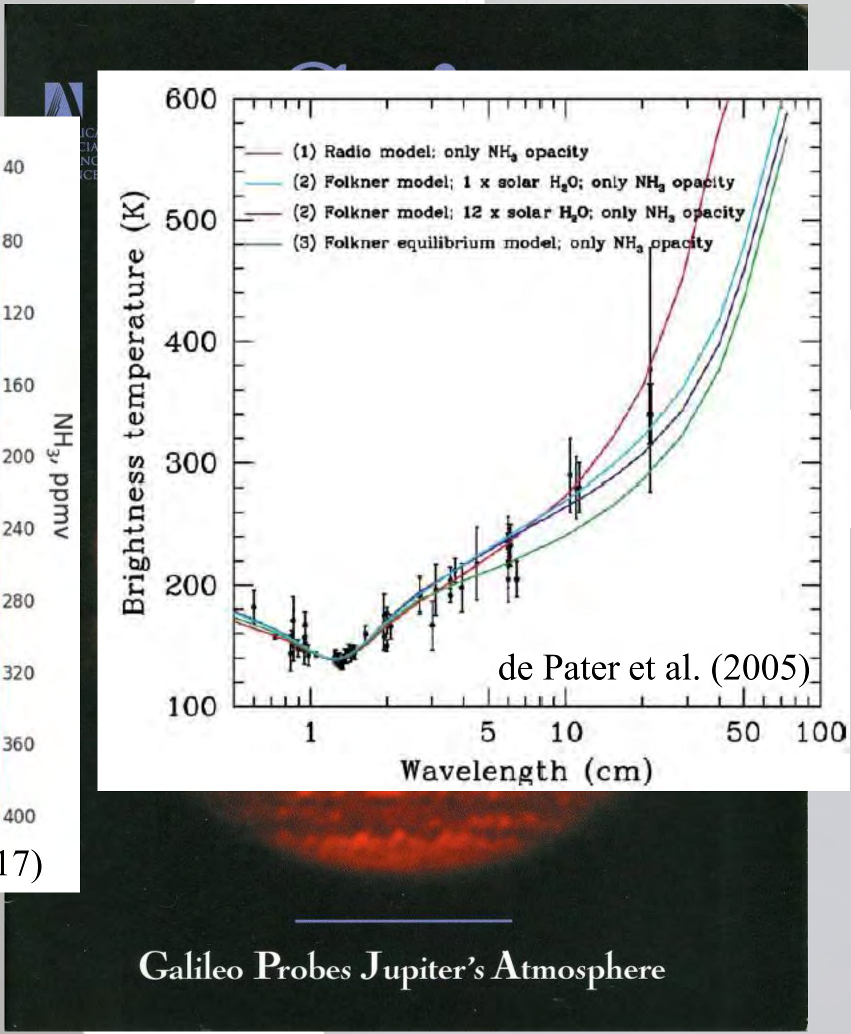
Mousis et al. (2018)

Deep composition

- Has Galileo failed at measuring O/H?
  - ⇨ Goal for Juno



Bolton et al. (2017)

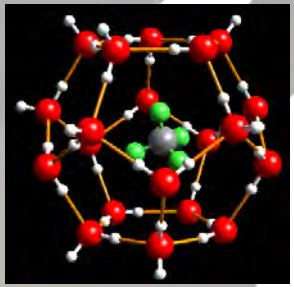


de Pater et al. (2005)

Deep composition

- Galileo failed at measuring O/H
  - ⇨ Goal for Juno
- Why is O so important?
  The oxygen abundance constrains the condensation processes of planetesimal ices

- Amorphous ices (Owen et al. 1999)
  - Heavy elements, including O, should be uniformly enriched
- Cristalline ices (clathrate) (Gautier et al. 2000, 2005)
  - Heavy elements trapped as a function of clathration temperature
  - High O abundance required

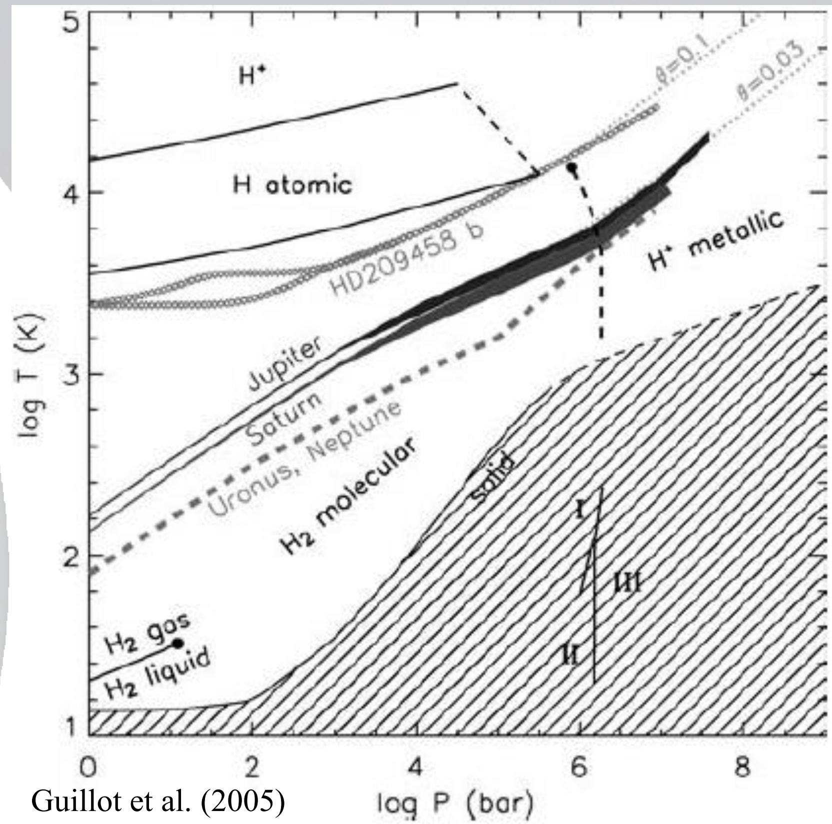


Key Science objectives for an Ice Giant probe

- Tier 1 goals: ***deep composition***
  - What is the abundance of He relative to H_2?
  - What is the abundance of noble gases?
  - What are the abundance profiles of key cosmogenic species?
- Tier 2 goals: ***deep composition and atmospheric structure***
  - What are the most important reservoirs for main isotopes of H, He, N, C, O, Ne and heavy noble gases?
  - What is the vertical structure of atmospheric temperature?

Deep composition and interior models

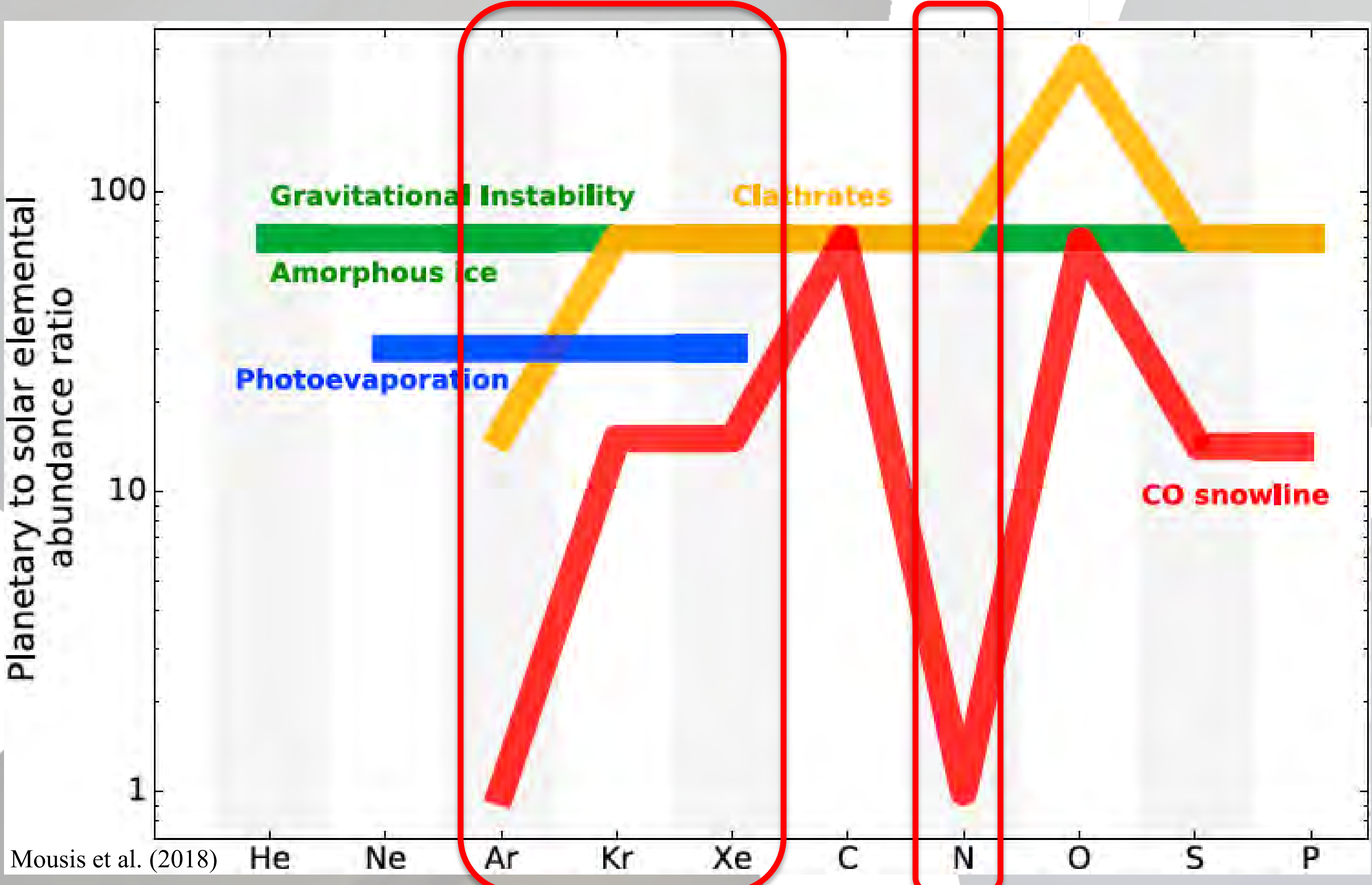
- Helium is the one of the main keys to better understand giant planet interiors
  - Fundamental to compute the equation-of-state
  - Internal structure
  - Luminosity, cooling history
  - Mass/radius relationship



Guillot et al. (2005)

Go talk to Ravit Helled and Tristan Guillot
They are the experts 🙂

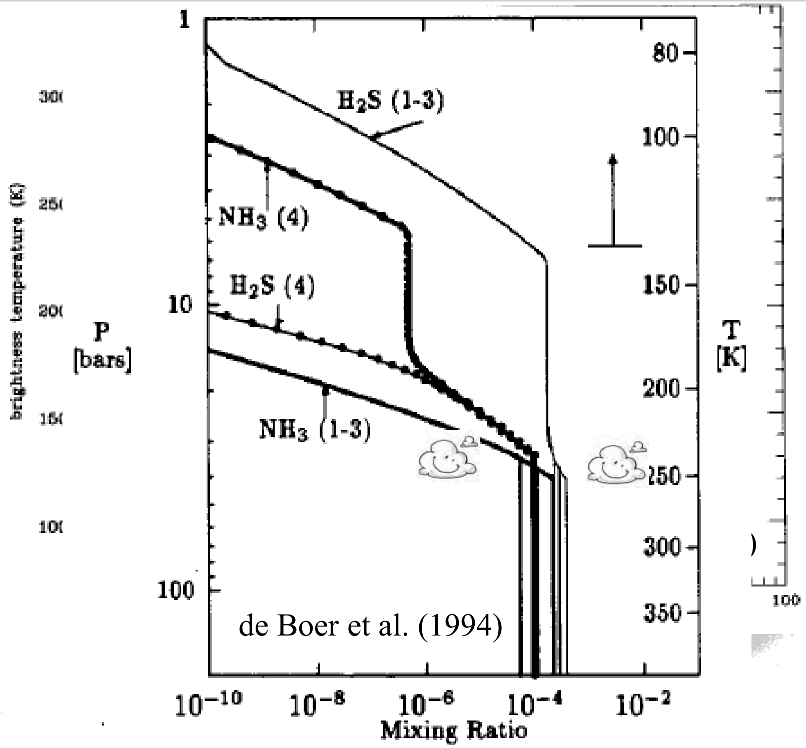
Deep composition and formation models



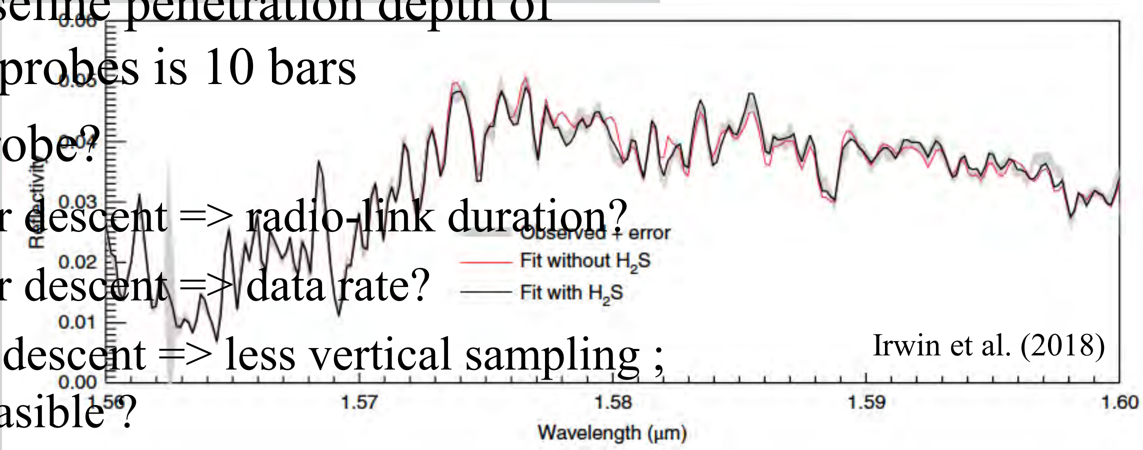
Mousis et al. (2018)

N/S abundances: The question of depth

- Absorber in the cm-range
  - NH_3 or H_2S?
  - NH_4SH cloud at 30-40 bar
  - "depleted" NH_3 or H_2S above (and until condensation)
  - Recent detection of H_2S in Uranus => S/N > 4.4-5 ⊙



- To measure independently N and S, one needs to go below the NH_4SH cloud…
- … but baseline penetration depth of proposed probes is 10 bars
- Deeper probe?
  - Longer descent => radio-link duration?
  - Deeper descent => data rate?
  - Faster descent => less vertical sampling ; is it feasible?

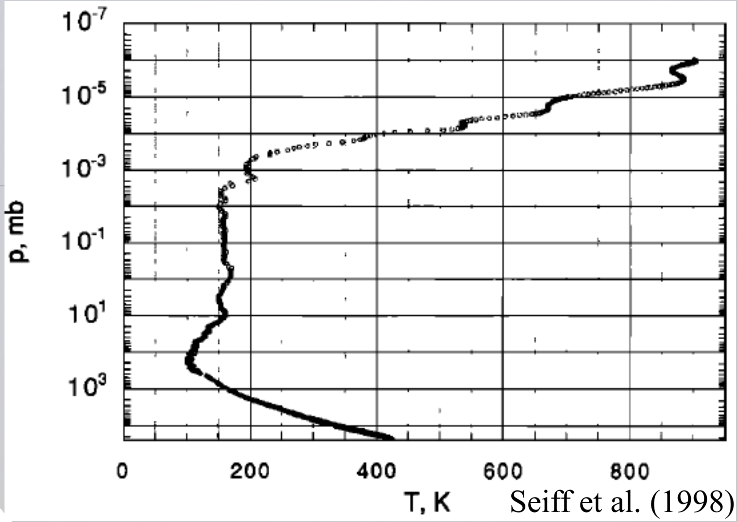


Isotopic ratios

- Isotopic ratio constrain main reservoir of heavy elements
- D/H
  - Measured in the stratosphere (Feuchtrgruber et al. 2013)
  - Mix between protosolar H_2 and cometary H_2O ices
  - A deep measurement would help unveil any fractionation with depth
- $^{14}N/^{15}N$
  - Jupiter and Saturn value consistent with solar value
    ⇨ N_2 main reservoir of NH_3
  - Uranus and Neptune probably more icy/rocky (cometary origin)
    ⇨ cometary value seen in NH_3 and HCN expected

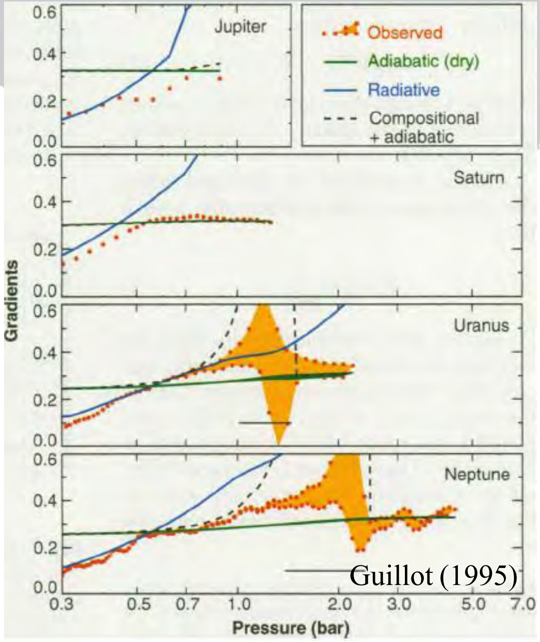
Temperature/pressure profile

- Ground-truth for remote sensing observations
  - Look at the citation count of Seiff et al. (1998) (jovian temperature profile from Galileo)



Seiff et al. (1998)

- Ortho-para H_2 effect on temperature gradient around the tropopause in Ice Giants
- Dry/wet adiabat vs. Inhibited convection (Guillot et al. 1995, Leconte et al. 2017, Cavalié et al. 2017)



Guillot (1995)

Conclusion

- Motivations
  - Giant planet formation & evolution
  - Broader exoplanet context

- Science objectives
  - Measurement priority 1:
    - He abundance
    - Noble gas abundances
    - Key cosmogenic species (C, N, S)

    Formation and evolution
  - Measurement priority 2:
    - Isotopic ratios
    - Temperature and pressure profile

    Formation and evolution

    State of the atmosphere

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Thank you for your attention !