A comparative study of Uranus and Neptune with Herschel

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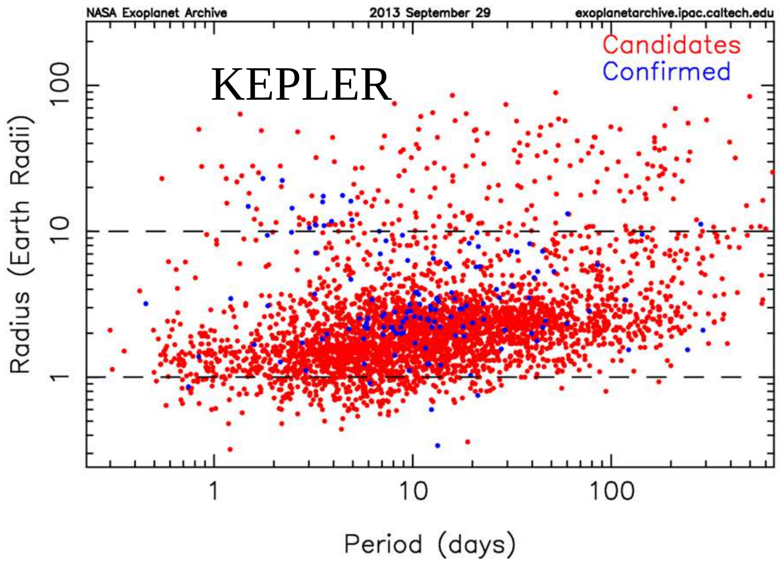
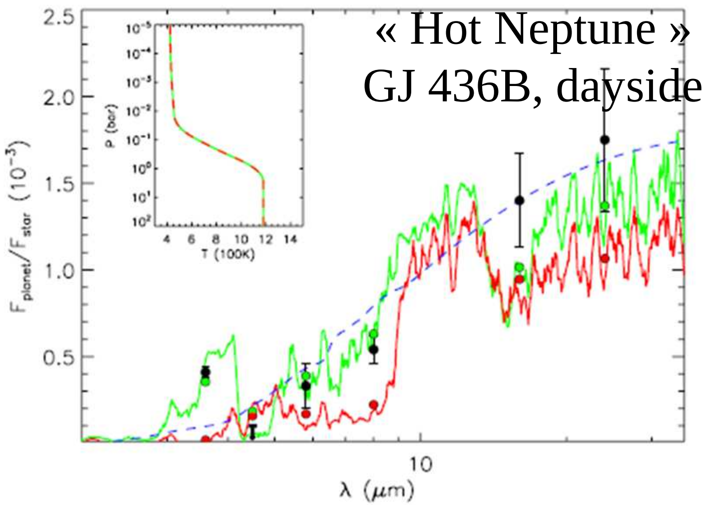
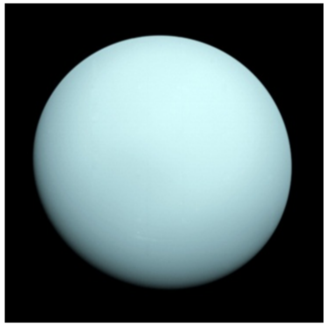
Why study Uranus and Neptune ?

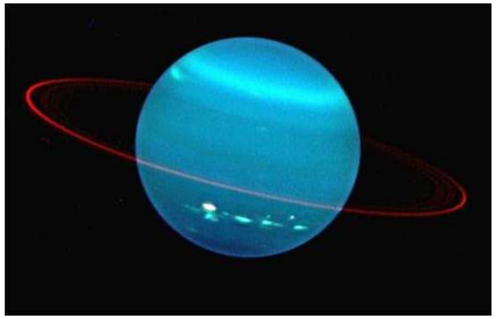
- Uranus and Neptune are “twins” in the outer Solar System : similar masses (~15 M_E), radii (4 M_E), rotation rates (~17 h)
- They are representative of the “icy giant” family, where most of the mass is in solid phase
- The majority of exoplanets / exoplanet candidates are in the Uranus/Neptune size/mass regime



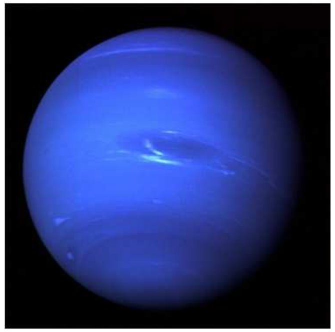




Uranus 1986



Uranus 2004



Neptune

Why study Uranus and Neptune ?

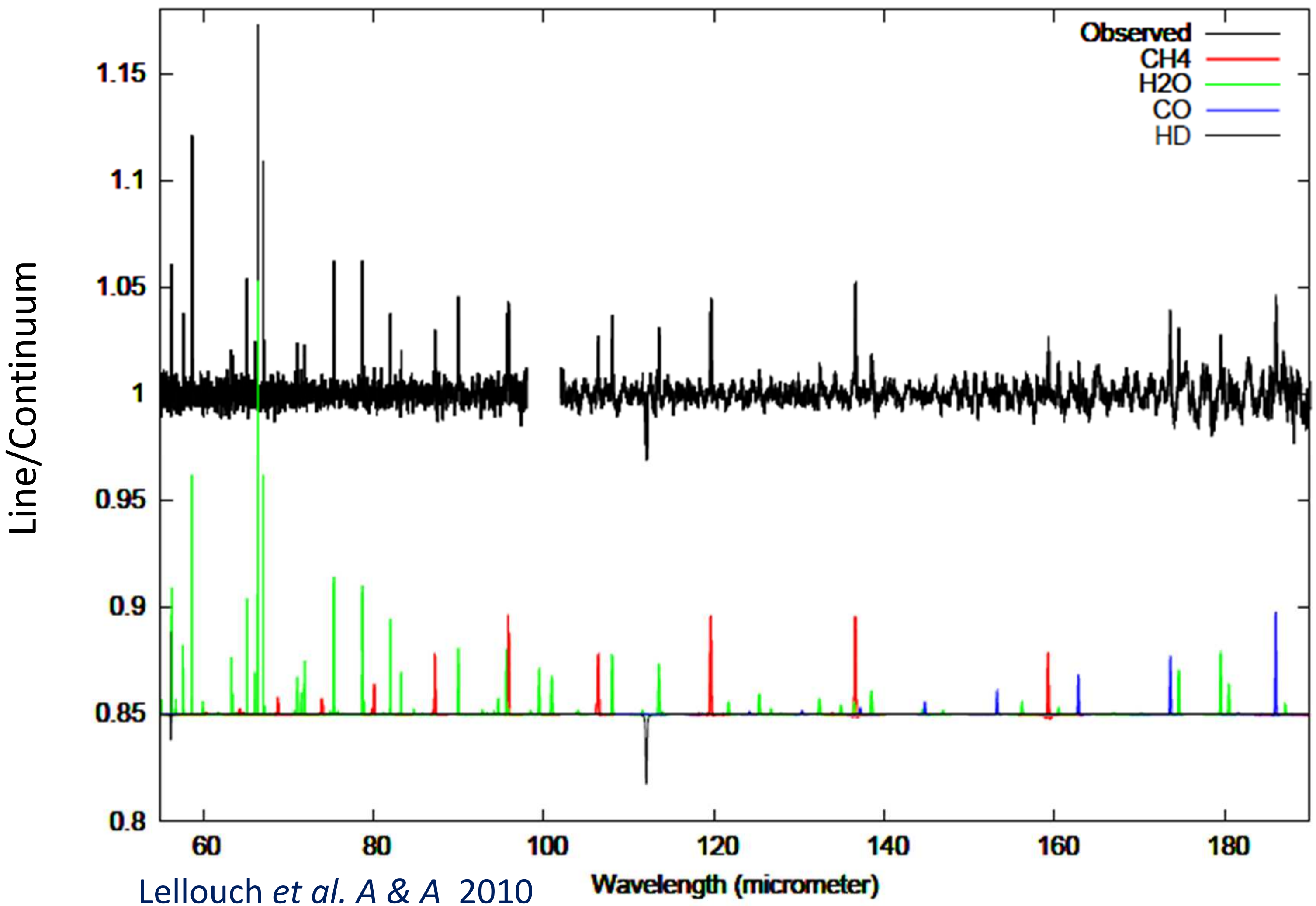
- But they are “fraternal twins”, exhibiting large differences
  - Uranus has large tilt of polar axis, hence large seasonal variations
  - Uranus has virtually no internal heat source, while Neptune has the largest of all Giant Planets → difference in internal structure
  - Winds are x 2 stronger in Neptune’s atmosphere, despite larger distance to Sun
  - Vertical transport is more sluggish in Uranus, indicating a less well mixed atmosphere
  - All this implies also differences in atmospheric composition

Goals and approach of the Herschel observations

- Observe the sub-millimeter spectrum of Uranus and Neptune to measure expected species in this range:
  - H_2O, CO → nature of external/internal source of oxygen
  - CH_4 → meteorology and vertical mixing
  - HD → D/H → composition of original icy grains
- Search for new species (e.g. PH_3, diagnostic of convection): none found
- Probed region: upper troposphere and stratosphere (~500 mbar – 0.1 mbar)
- Improve atmospheric models for calibration purposes

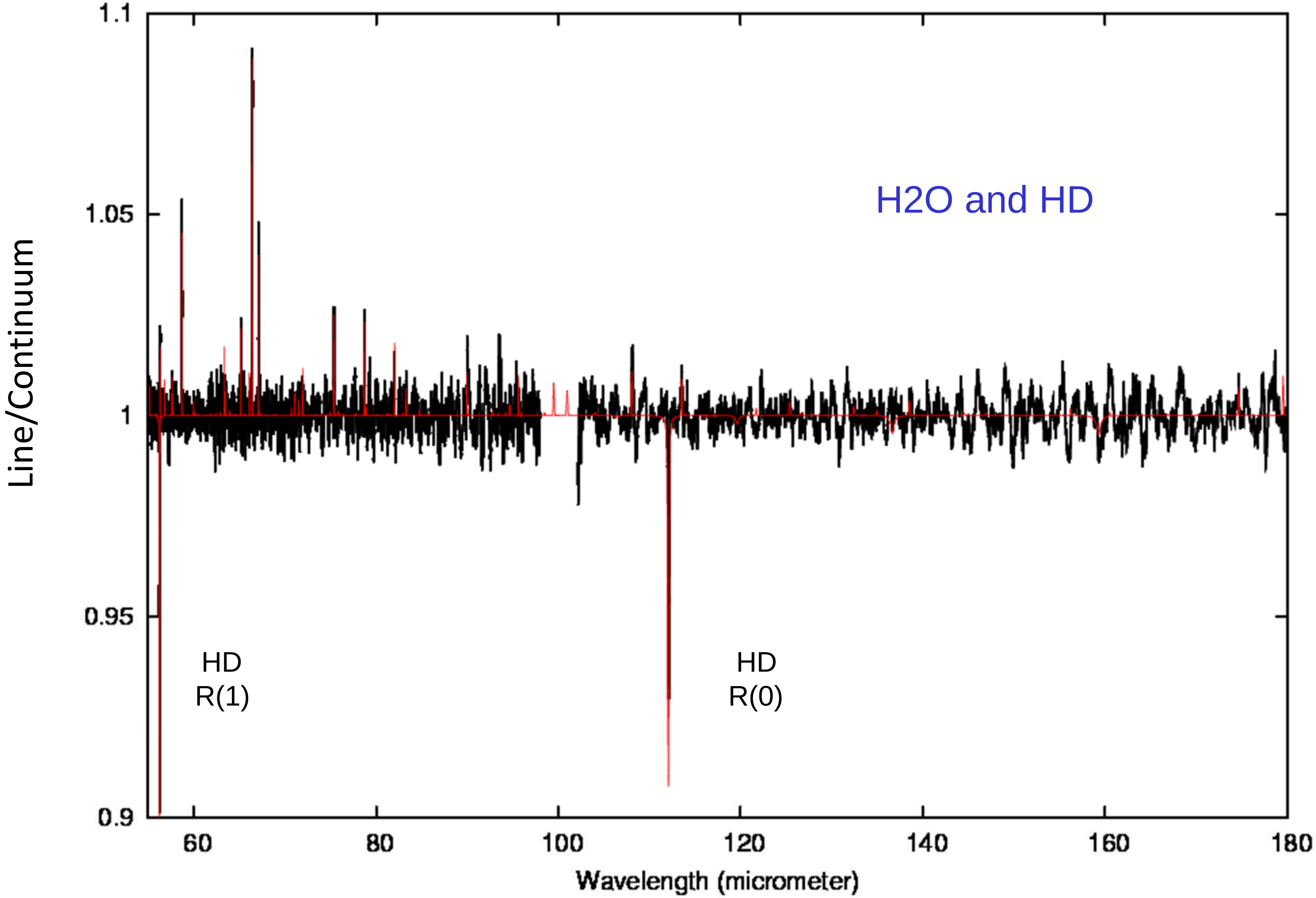
- Approach: combination of PACS and SPIRE full range spectra with dedicated line observations (PACS, HIFI)

PACS spectrum: Neptune (line/continuum)

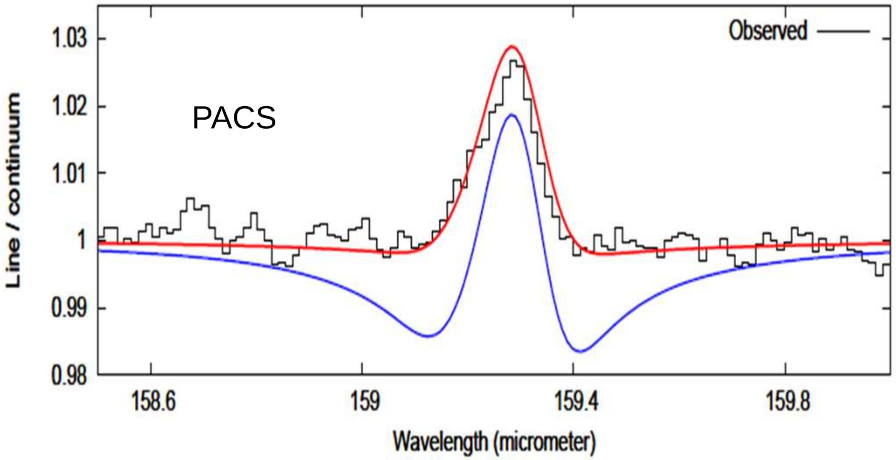


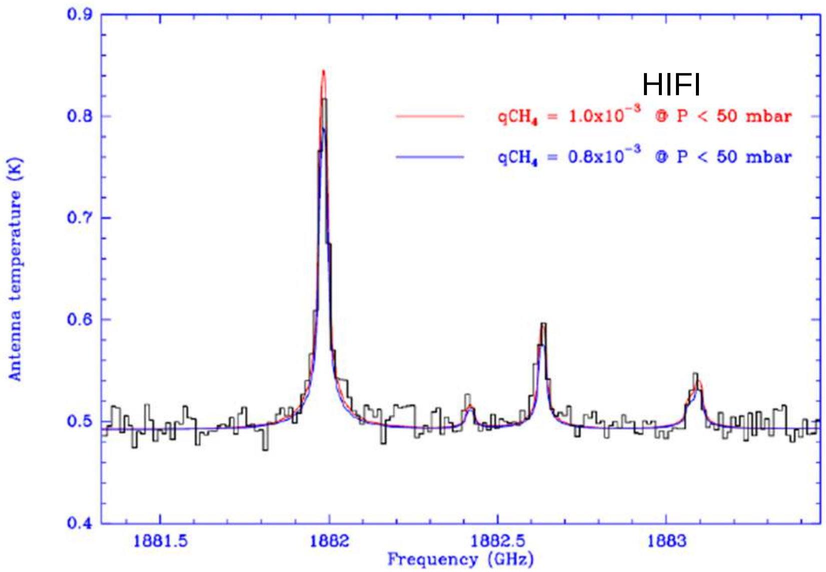
Lellouch *et al. A & A* 2010

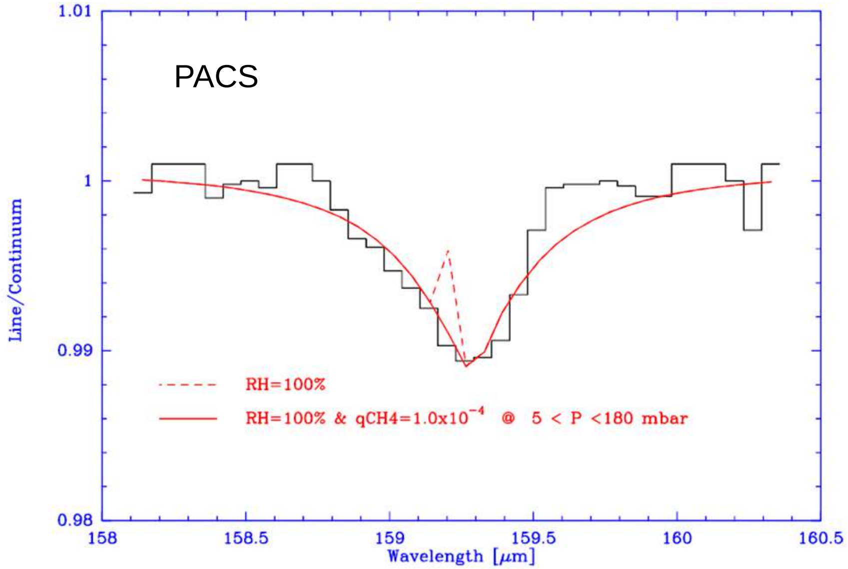
PACS spectrum: Uranus (line/continuum)



Methane







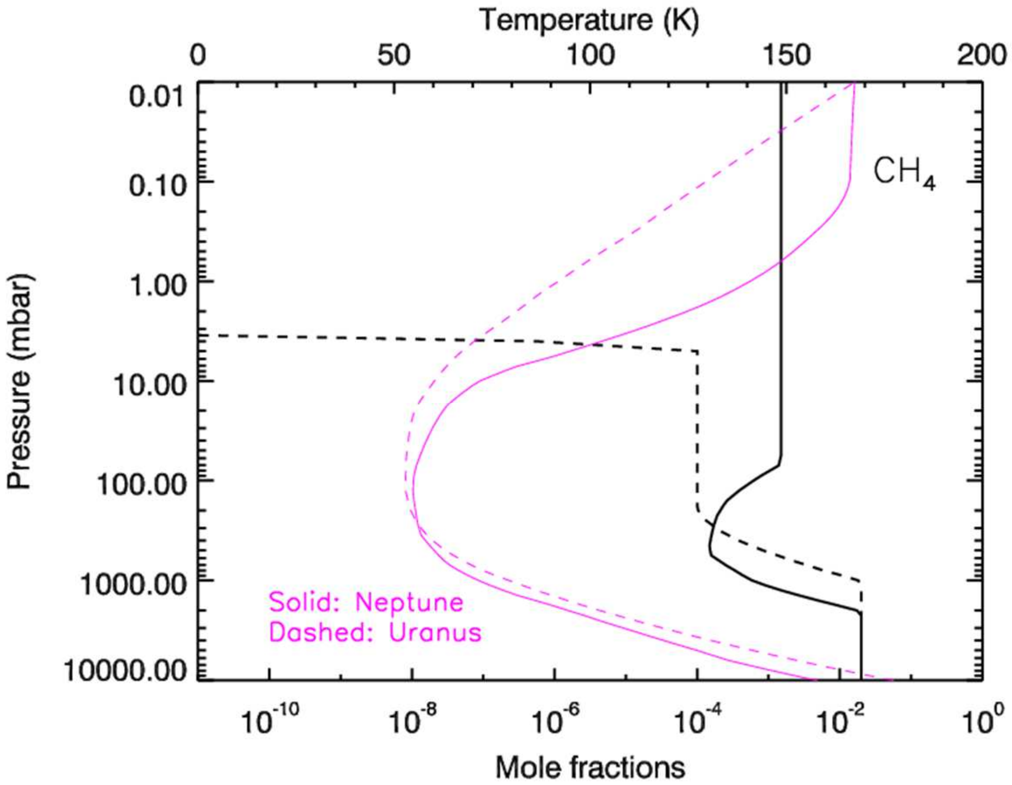
Abundance and vertical profile determination

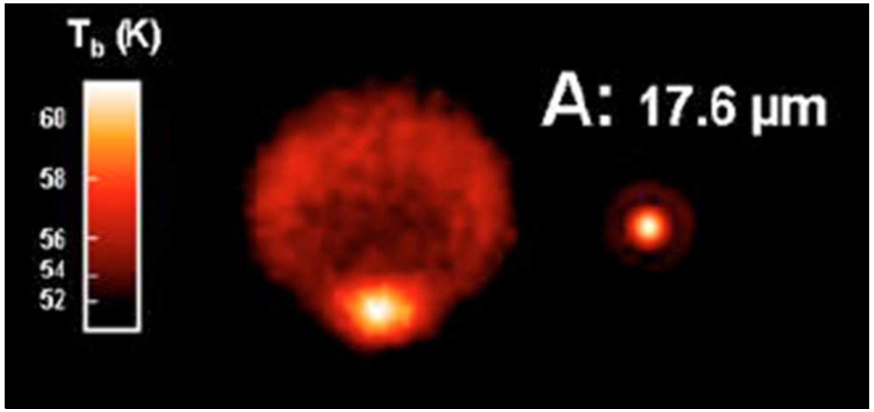
NEPTUNE

URANUS

Lellouch et al. 2010, Moreno et al DPS 2012

Methane in Neptune

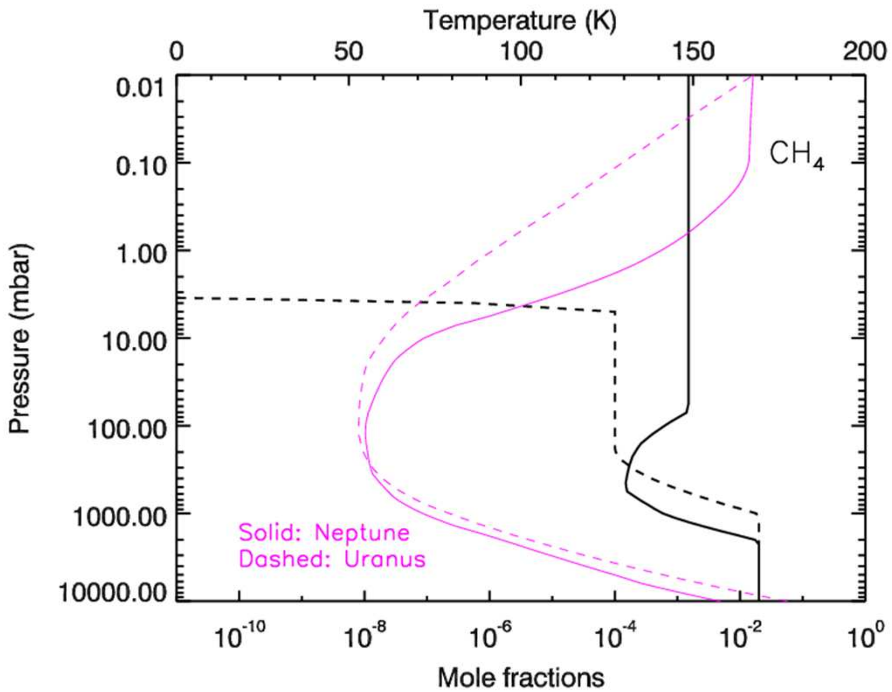


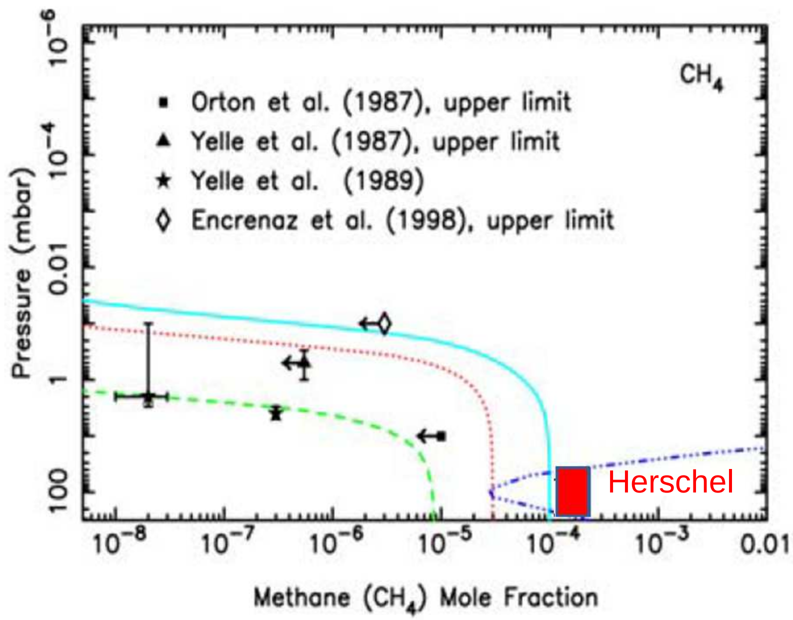


VLT/VISIR (Orton et al. 2007)

- Large stratospheric abundance (CH_4 = 0.1-0.15 %) at 10 mbar, decreasing downwards
- Supersaturated by factor 10 compared to value « allowed » by 56 K tropopause → **injection from warm polar region**

Methane in Uranus: seasonal changes

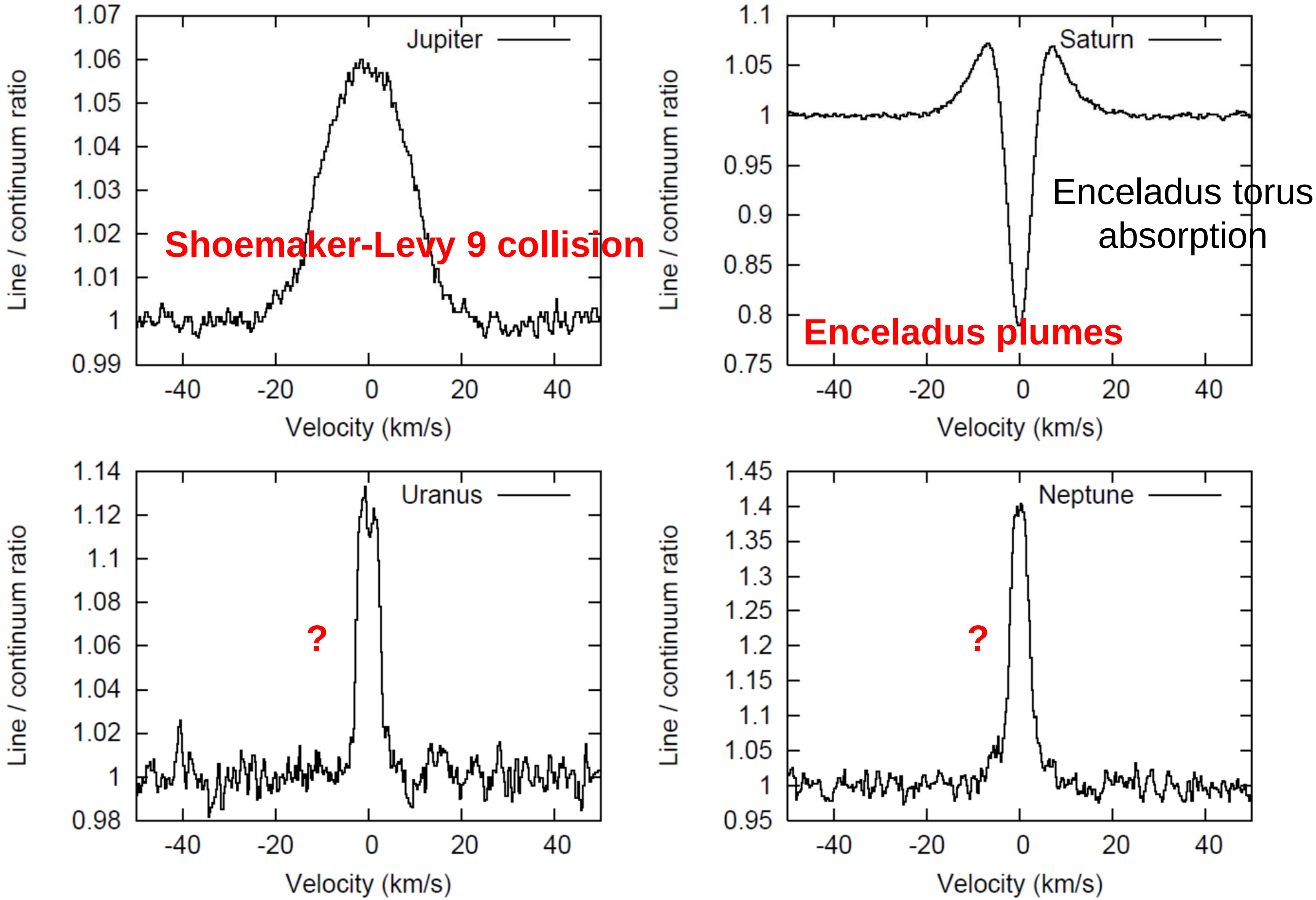




- In upper trosposphere, methane close to saturation (100 % relative humidity)
- Strong depletion in middle stratosphere (~3 mbar) due to low homopause (i.e. poor mixing)
- Still, methane much more abundant in Herschel observations (Equinox) compared to Solstice conditions (Voyager, ISO): seasonal/latitudinal variability

H_2O: the origin of external oxygen in outer planets

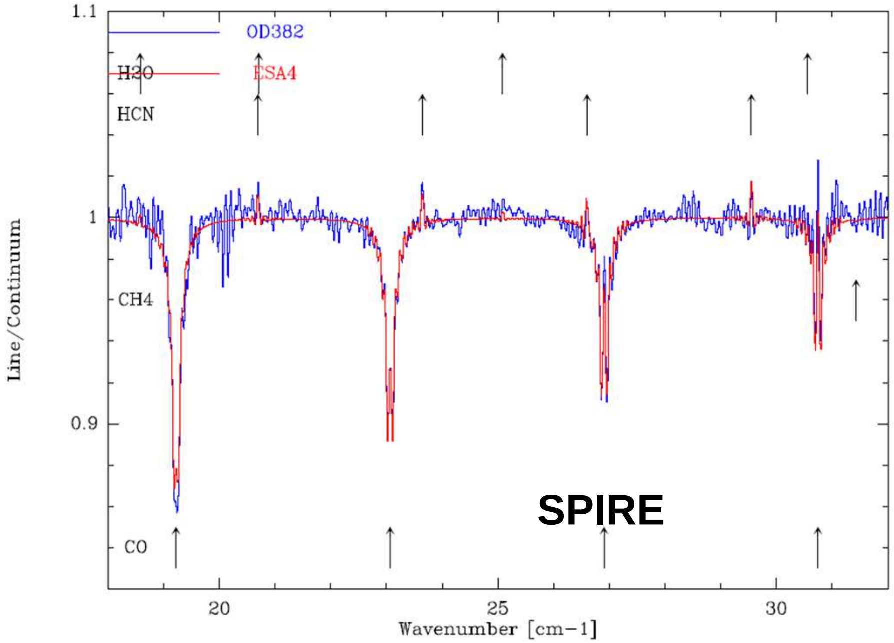
H_2O 557 GHz line spectrally resolved by HIFI



External water in Uranus and Neptune

- Vertical profile difficult to retrieve (less information in HIFI line-resolved profiles) → source of water still unknown
- Data still confirm ISO-derived result that amount of external H_2O is ~2.5 times higher at Neptune than at Uranus
- Input fluxes (ISO-based)
  - (0.5-1.5) x 10^5 $cm^{-2}s^{-1}$ at Uranus
  - ~ 10^5 - 10^7 $cm^{-2}s^{-1}$ at Neptune, depending on eddy diffusion coefficient profile

Carbon monoxide

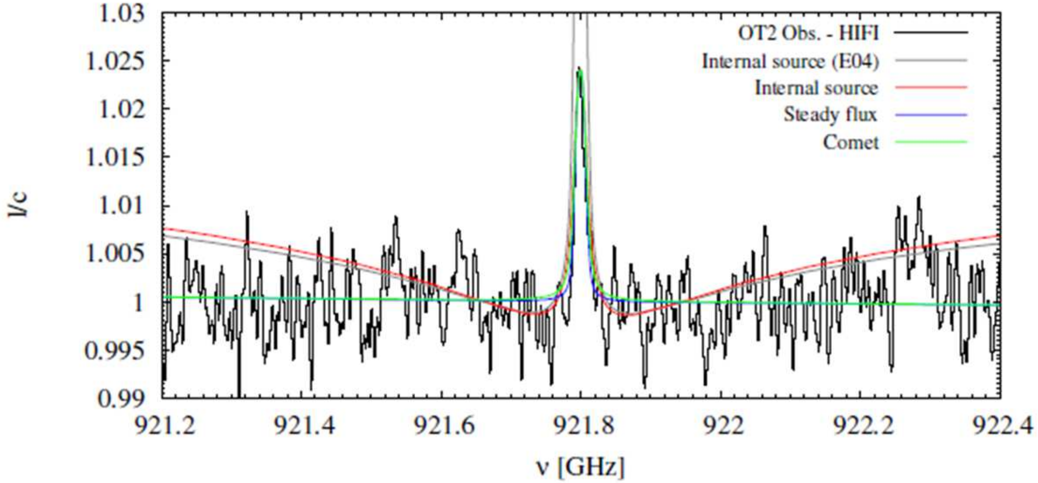


Moreno et al. in prep.

NEPTUNE

First observation of CO at submillimeter wavelengths in Uranus (HIFI @ 922 GHz)

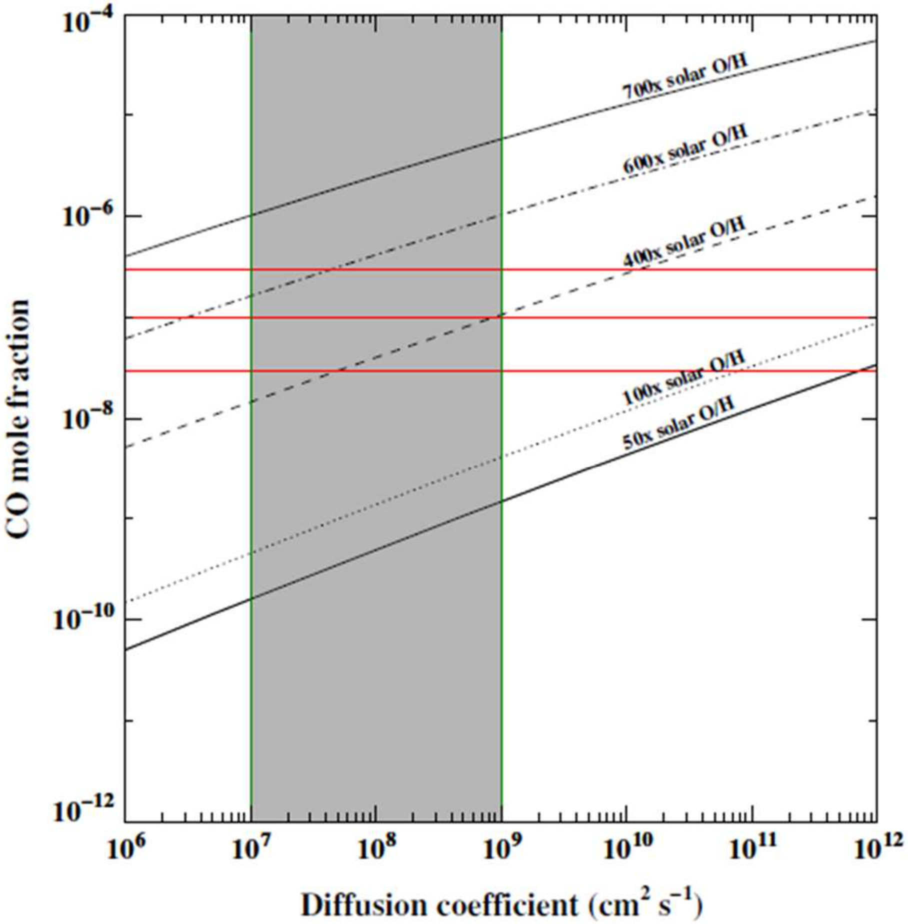
Cavalié et al., submitted



A dual origin of carbon monoxide

- An *external* source in both planets, producing a stratospheric mixing ratio of $\sim10^{-6}$ at Neptune and $\sim10^{-8}$ at Uranus
  - A permanent influx of interplanetary CO-rich grains
  - Cometary impact (or a distribution of); favored at Neptune (large CO/H_2O flux ratio)
- An *internal* source, producing a tropospheric mixing ratio smaller than the stratospheric by ~1 order of magnitude at Neptune . Source not visible at Uranus
  - Disequilibrium thermochemistry: CO produced from H_2O ($H_2O + CH_4 = CO + 3H_2$) and transported upwards
  - Permits to estimate deep H_2O, i.e. O/H ratio

O/H ratio in Neptune



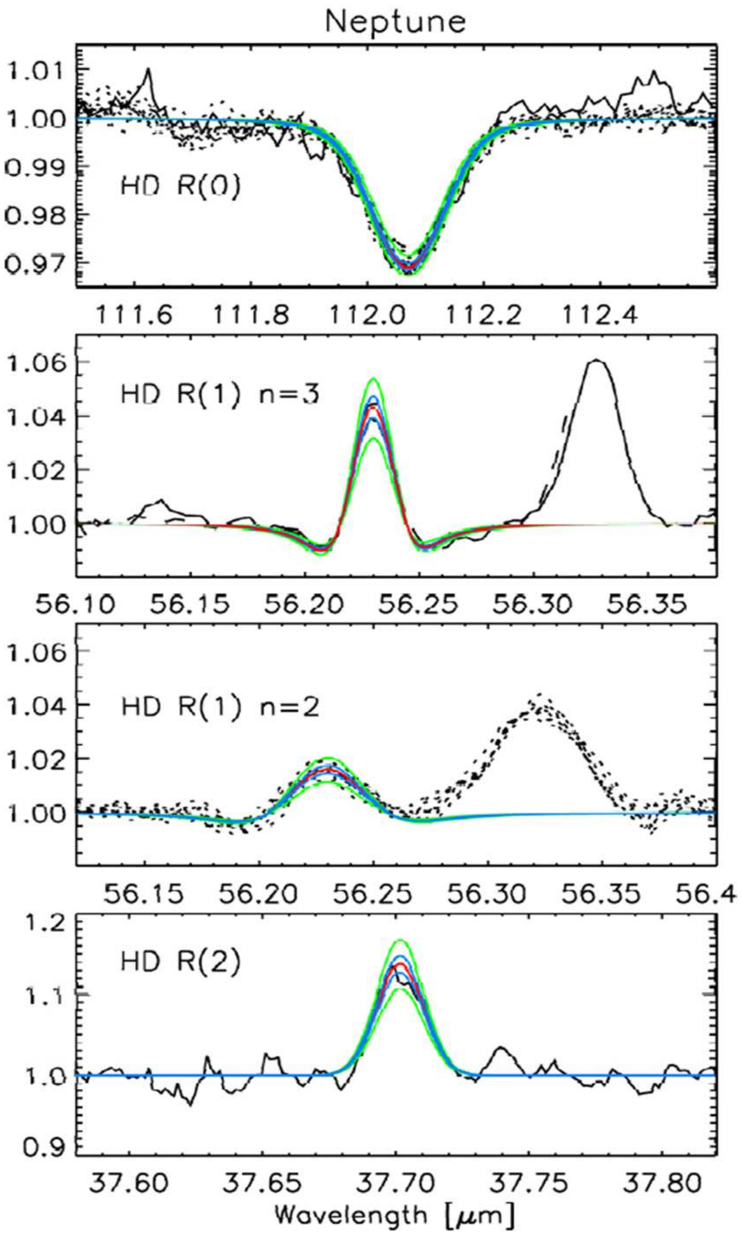
For « reasonable » vertical transport (eddy K_{zz} = 10^7 -10^9 cm^2 s^{-1}), internal CO = 0.2 ppm implies **500-700 solar O/H ratio !**
(i.e. O/H ~ 60 % by volume in Neptune's gaseous envelope)

Problems:
- C/H is only 30-50 solar !
- Current internal structure models are inconsistent with O/H > 200 solar

Much larger diffusion coefficient ?

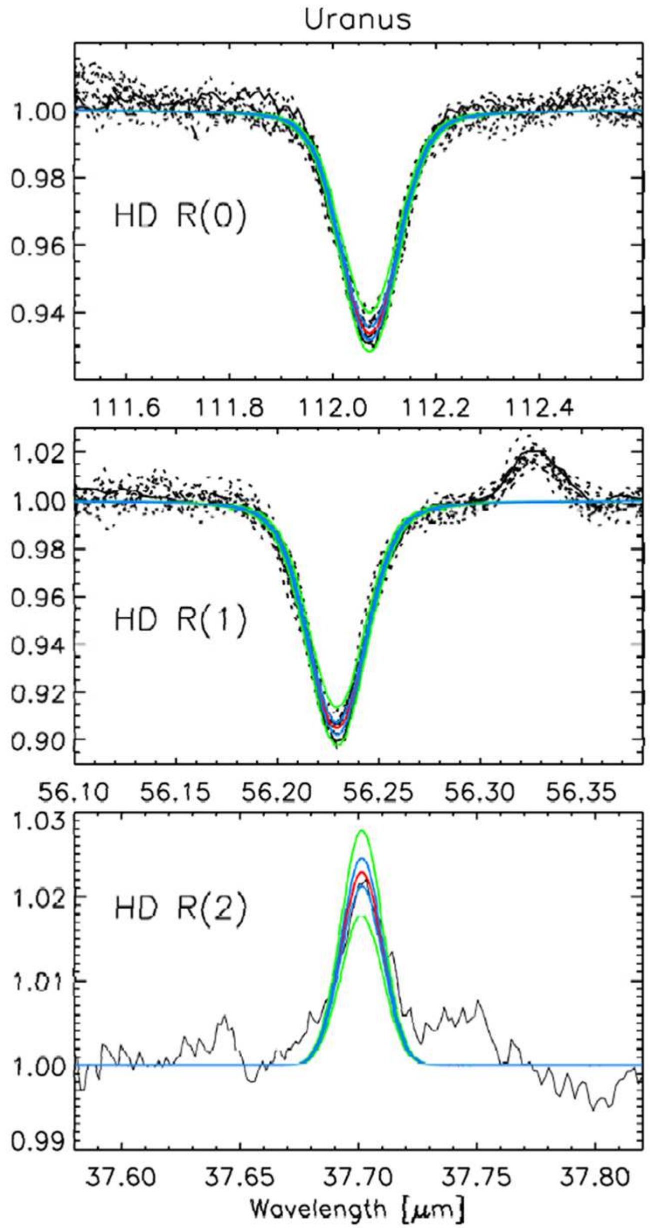
Luszcz-Cook and de Pater 2013

D/H ratio



HD

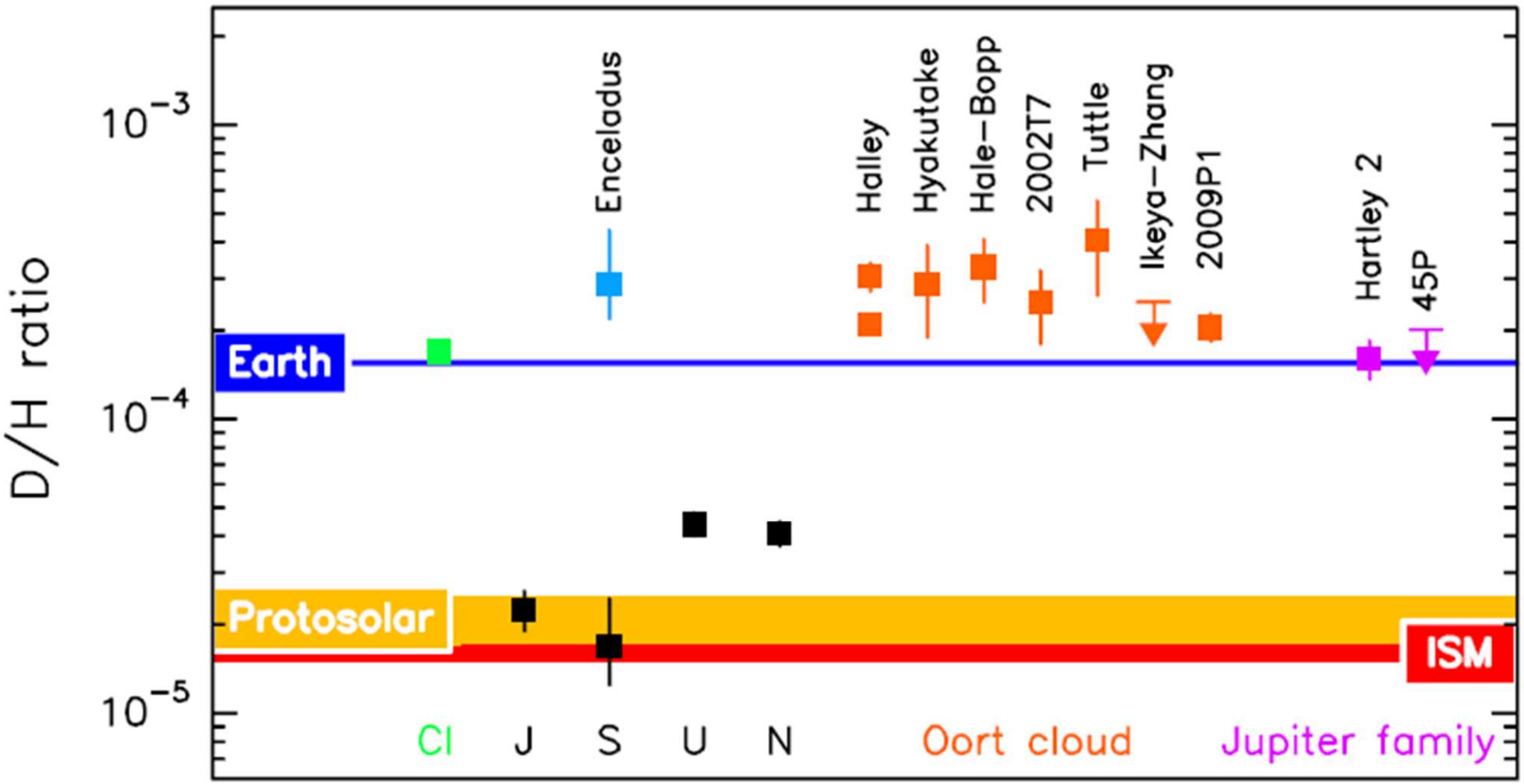
Herschel
+
ISO



NEPTUNE
D/H = (4.1+/-0.4) x 10^{-5}

Feuchtgruber et al. 2013

URANUS :
D/H = (4.4+/-0.4) x 10^{-5}



D/H ratio
10^{-3}
10^{-4}
10^{-5}
Earth
Protosolar
ISM
Enceladus
Halley
Hyakutake
Hale-Bopp
2002T7
Tuttle
Ikeya-Zhang
2009P1
Hartley 2
45P
CI
J
S
U
N
Oort cloud
Jupiter family

D/H: interpretation

- D/H higher in U & N than in J & N due to mixing of their atmosphere with D-rich icy grains
- Can be used to constrain D/H in proto-planetary grains

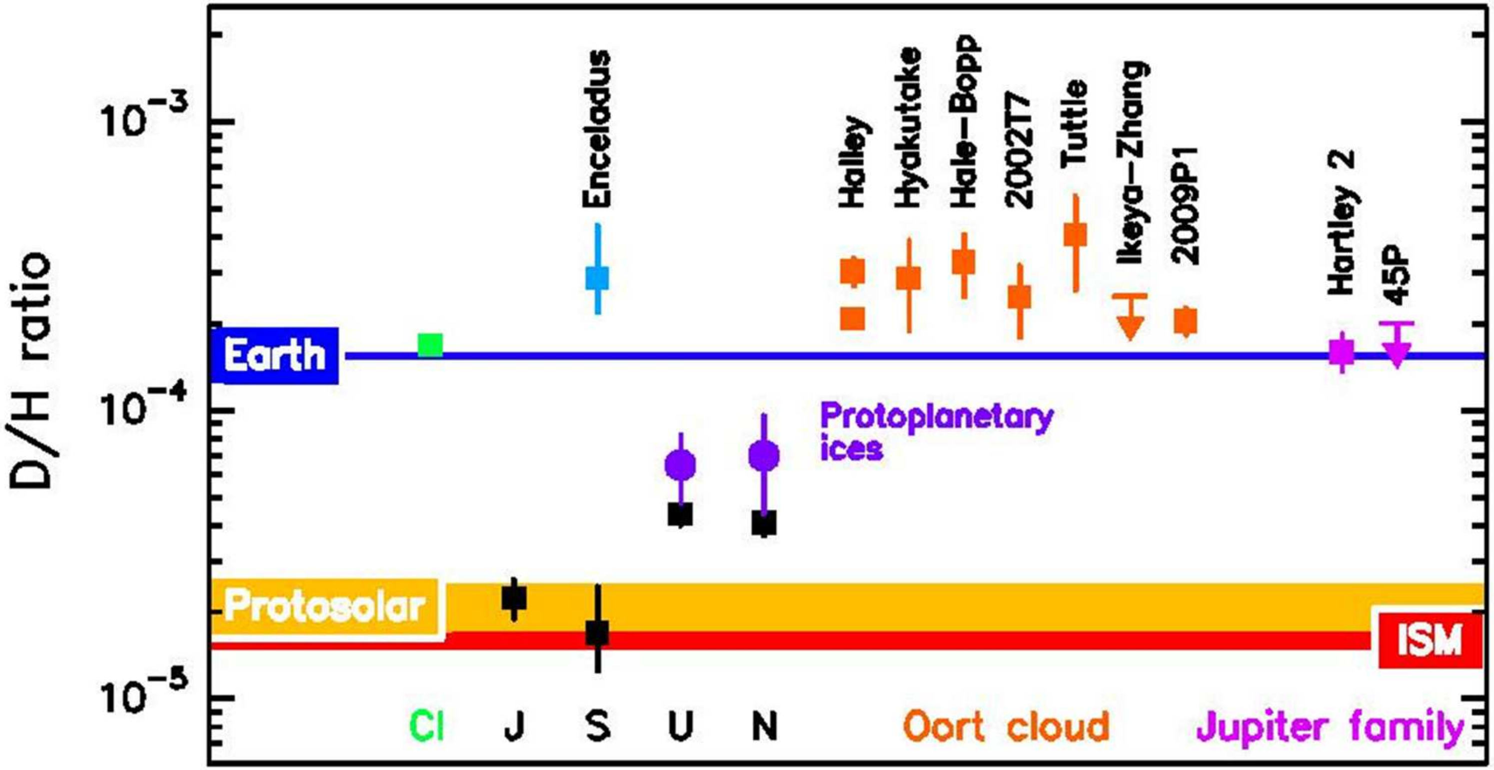
$$(D/H)_{ices} = \frac{(D/H)_{planet} - x_{H_2}(D/H)_{proto}}{(1 - x_{H_2})}$$

where $D/H_{(planet)} = (D/H)_{H2}$

$$x_{H_2} = n_{H_2}/(n_{H_2}+n_{H_2O})$$

- Requires an internal structure model, incl. n_{H_2}, ice/rock fraction
- Fundamental assumption: the planets have been fully mixed during their history, i.e. equilibration of deuterium between H_2 and ices has occurred

Implication



- Proto-uranian and -neptunian ices are less D-rich than comets!

Alternatives

- May be the D/H in protoplanetary ices do not have to be equal to that in cometary ices?
  - Alexander et al. (2012) find evidence for low D/H ($<10 \times 10^{-5}$) component in formation region of comets
- U & N are less ice (H_2O)-rich than internal structure models say
  - “Inverting” the problem indicates rock-rich planets (14-32 % ice fraction) !
- The planets were never fully mixed during their history
  - Formation models suggest the gas envelopes of the early planets were well mixed, but not necessarily the cores

Conclusions

- Even from the mere “observable atmosphere’ point of view, and just from a limited spectral range, Uranus and Neptune appear rather different
- There remains fundamental unresolved questions related to

the “large abundance” of CO in Neptune and the “low” D/H ratio in both planets

- We do not have a good “reference” Uranus or Neptune

for comparison with exoplanets.