Herschel observations of water in the solar system

Paul Hartogh (and HssO team)

MPS Göttingen

Outline

- **Mars**
- **Asteroid belt**
- **Jupiter**
- **Enceladus torus**
- **Comets**

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3

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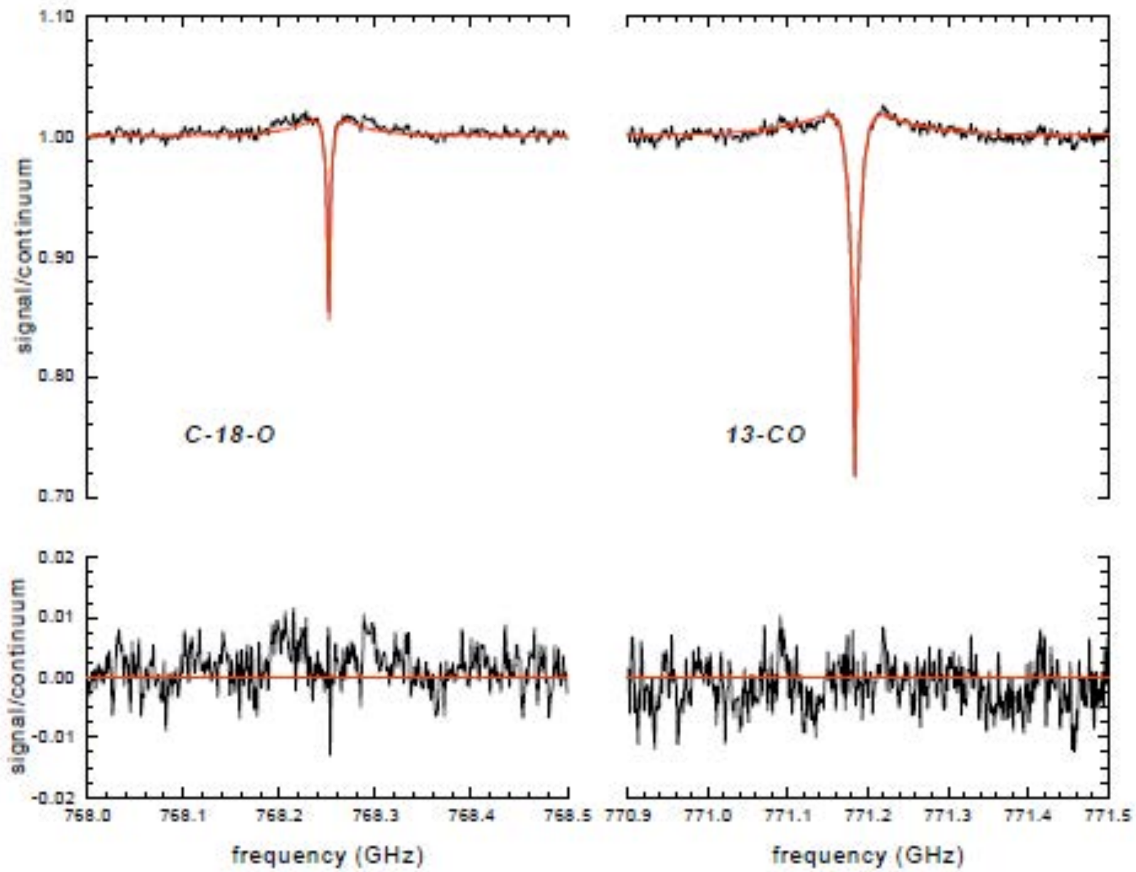
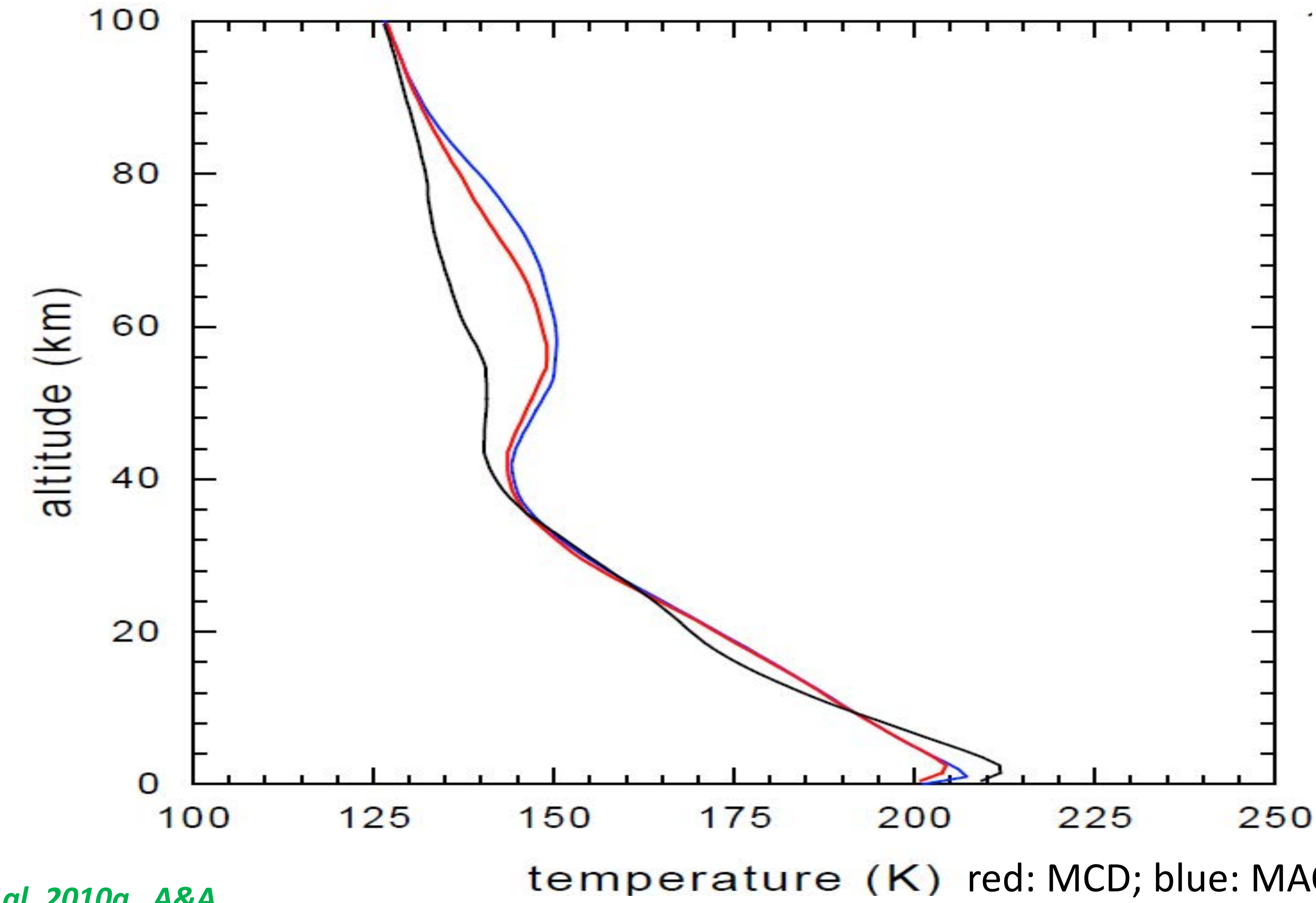
- *26 Bluesky Spectroscopy, Lethbridge – Canada*

HIFI Mars CO observations

- Observations done during Ls = 78° (2010)
- Dedicated CO isotopic line observations
- Strong emission feature from morning side

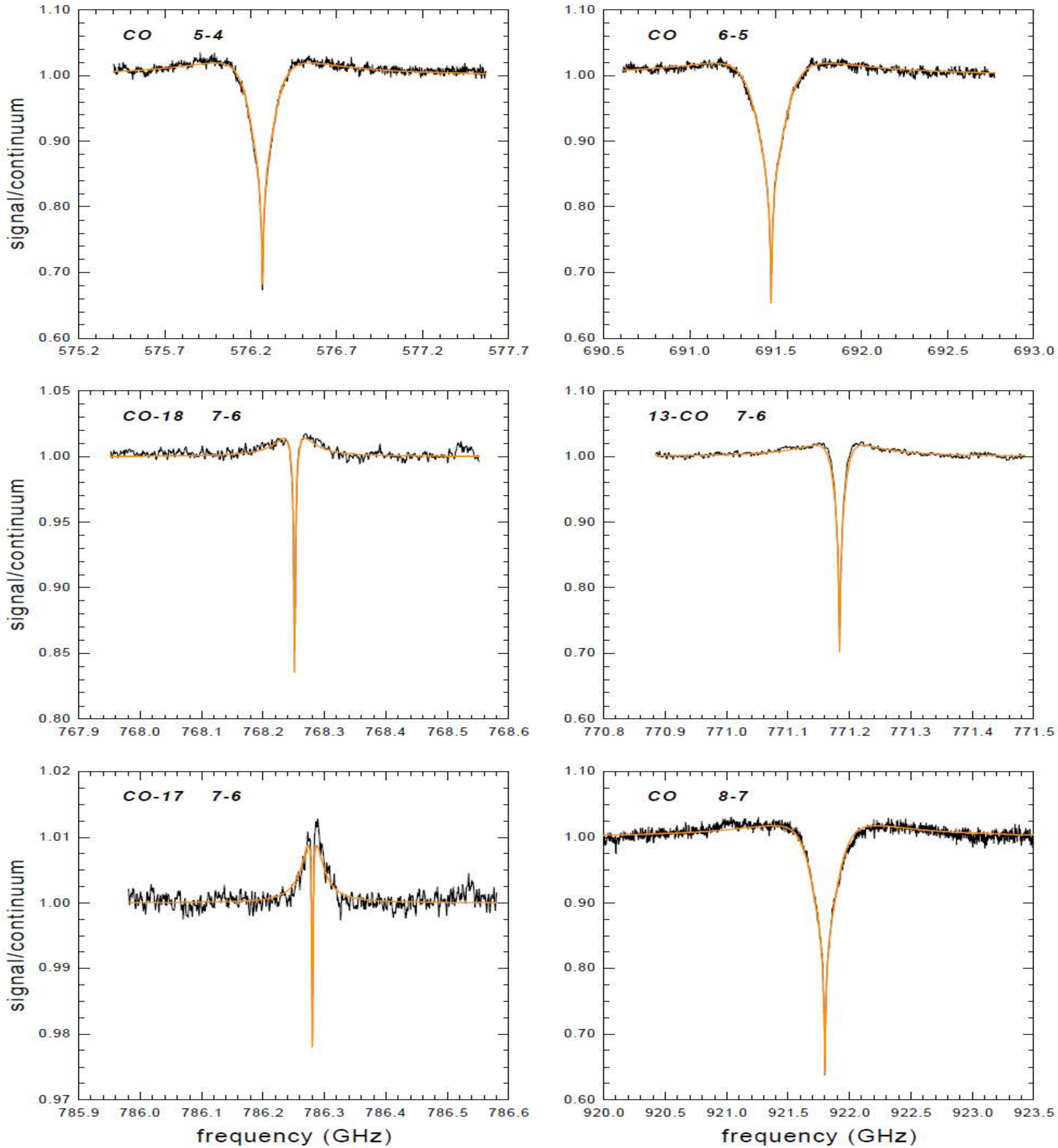


etrieved temperature profile and 980 ppm constant with altitude CO volume mixing ratio



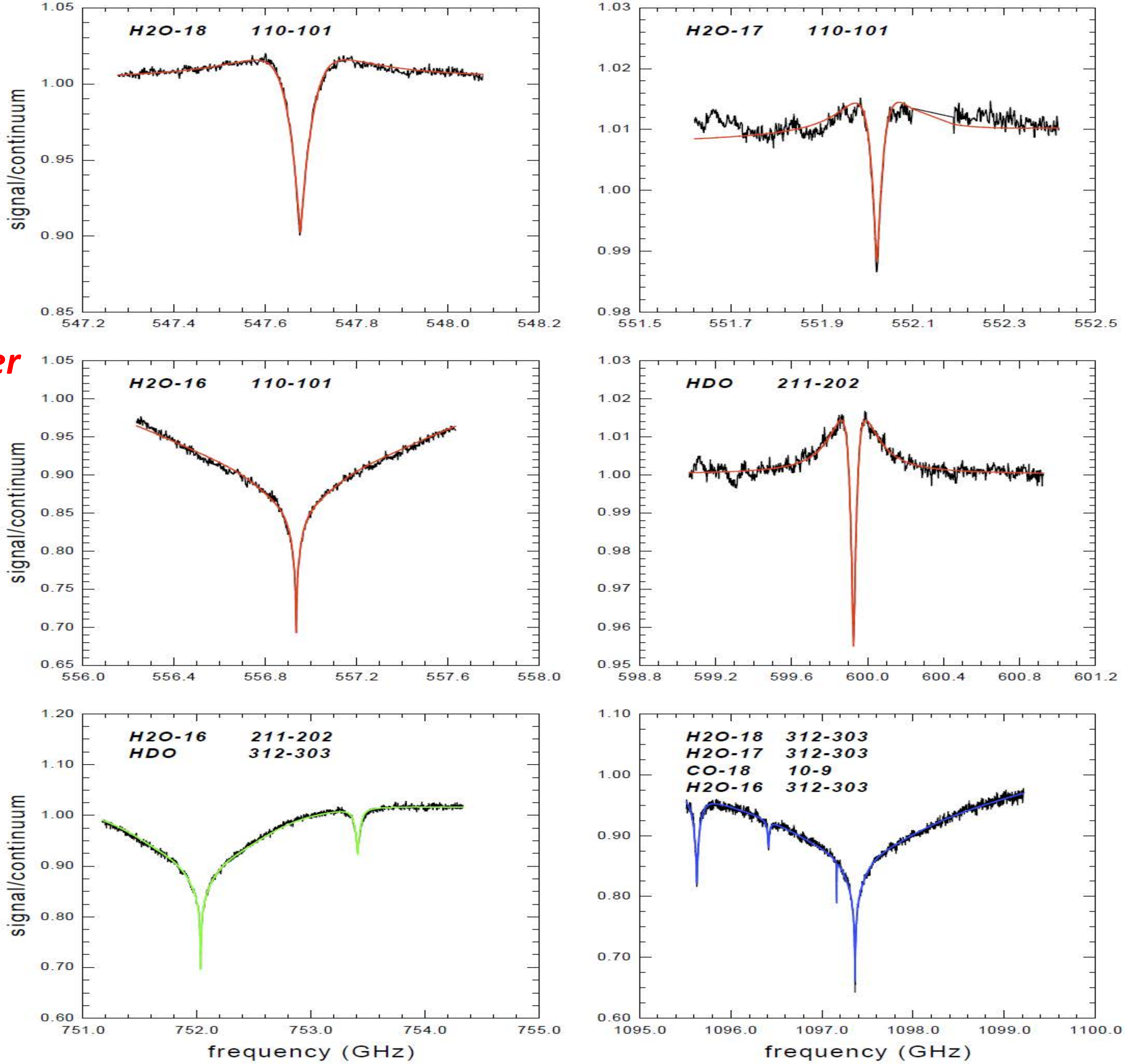
red: MCD; blue: MAOAM; black: observation

Hartogh et al. 2010a, A&A
Hartogh et al., 2005, JGR planets



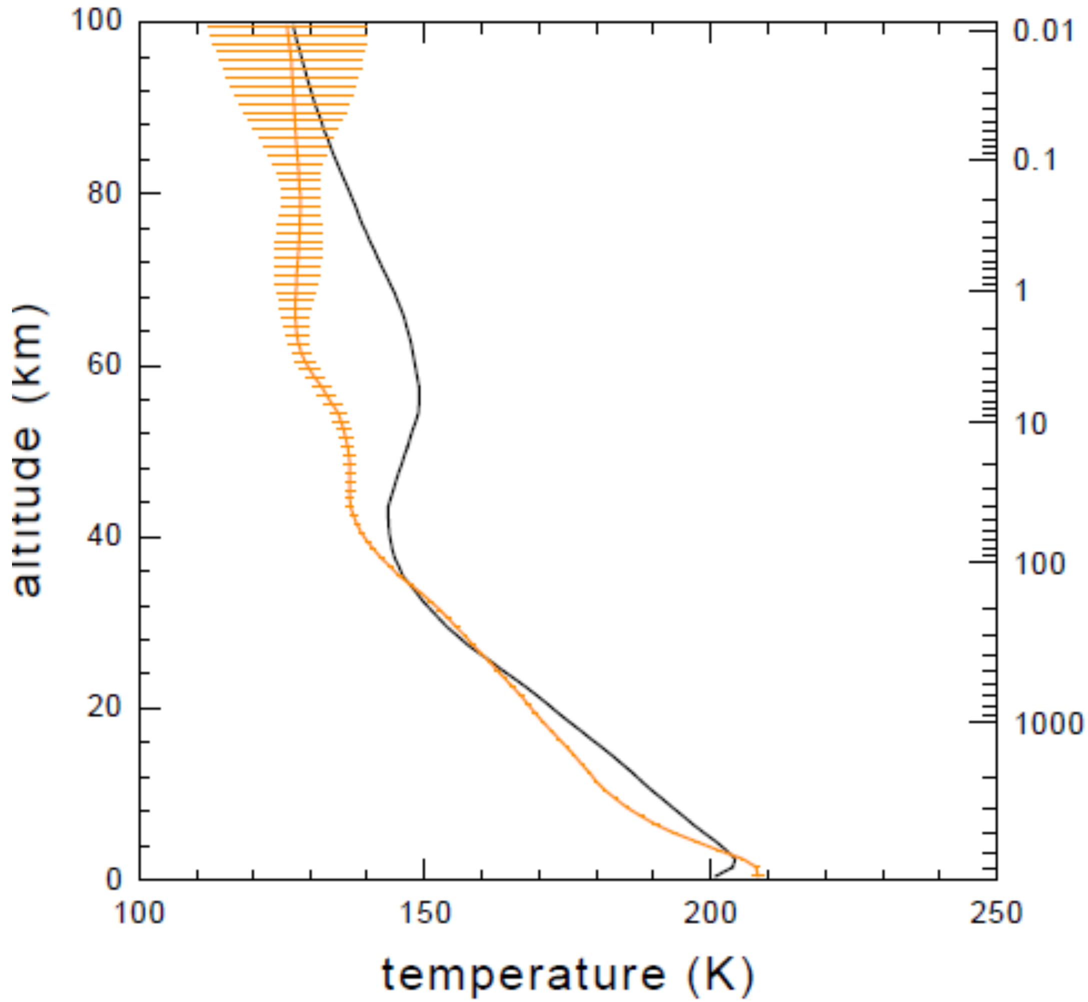
Isotopic ratios derived from CO isotopologues are telluric! Deviations are < 5%.

Isotopic ratios derived from water isotopologues are telluric, too! Deviations are < 5%.

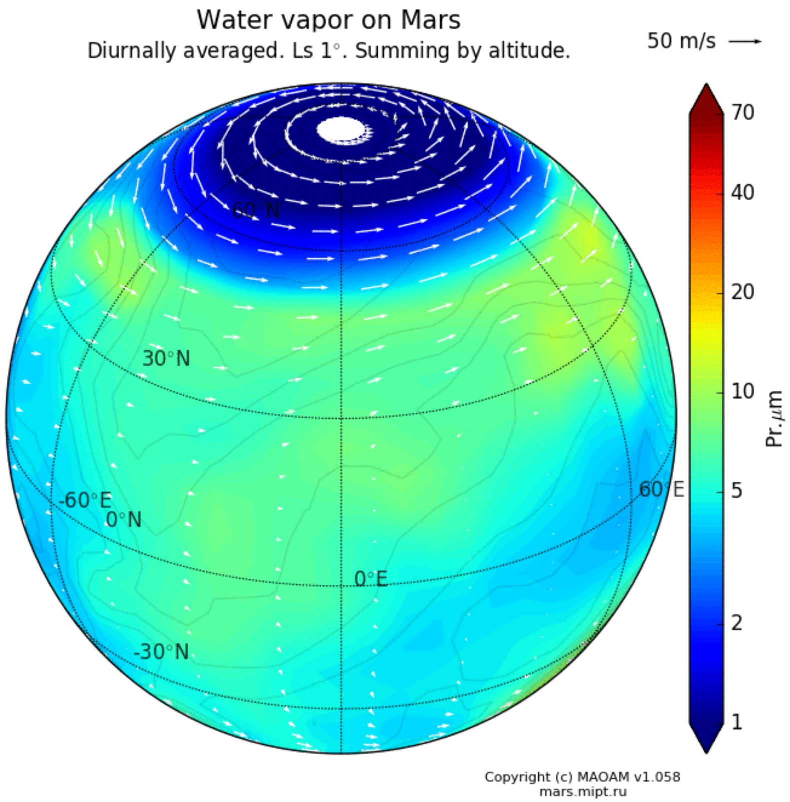


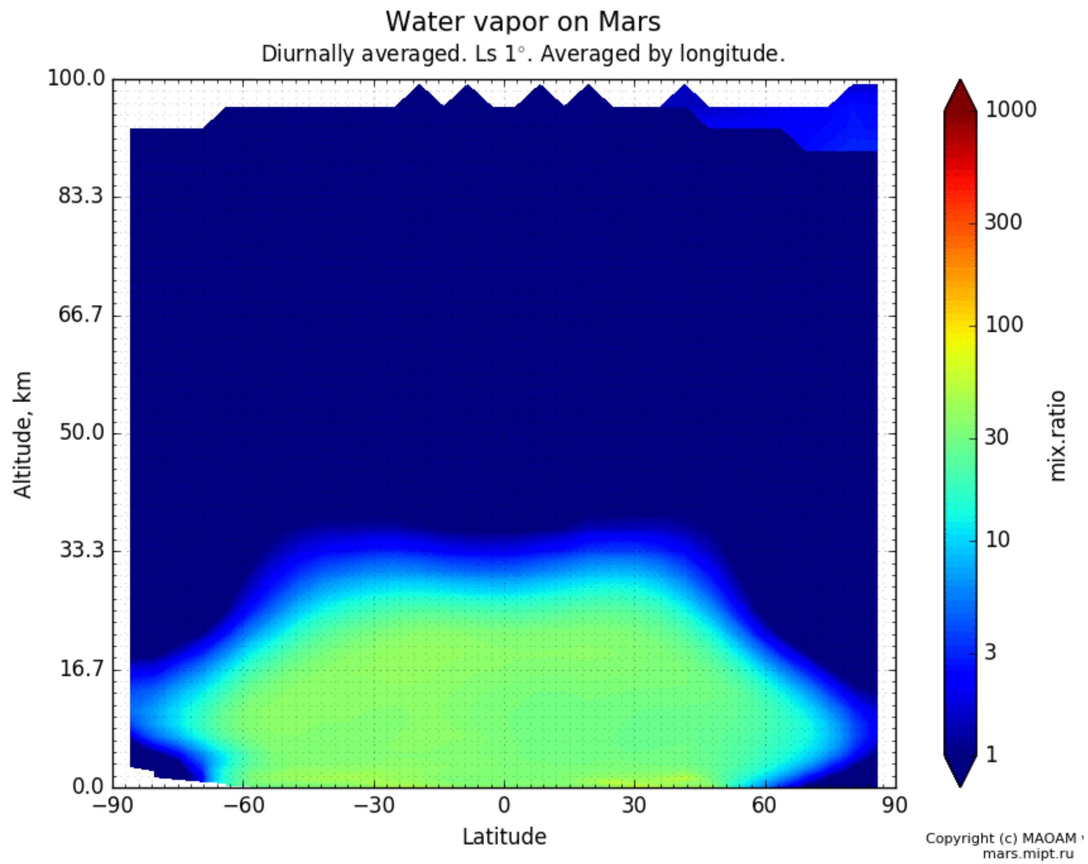
Optimum fit using VSMOW for oxygen. Deviations < 5 %.

Temperature profile retrieved with all CO and water lines confirms the one derived before



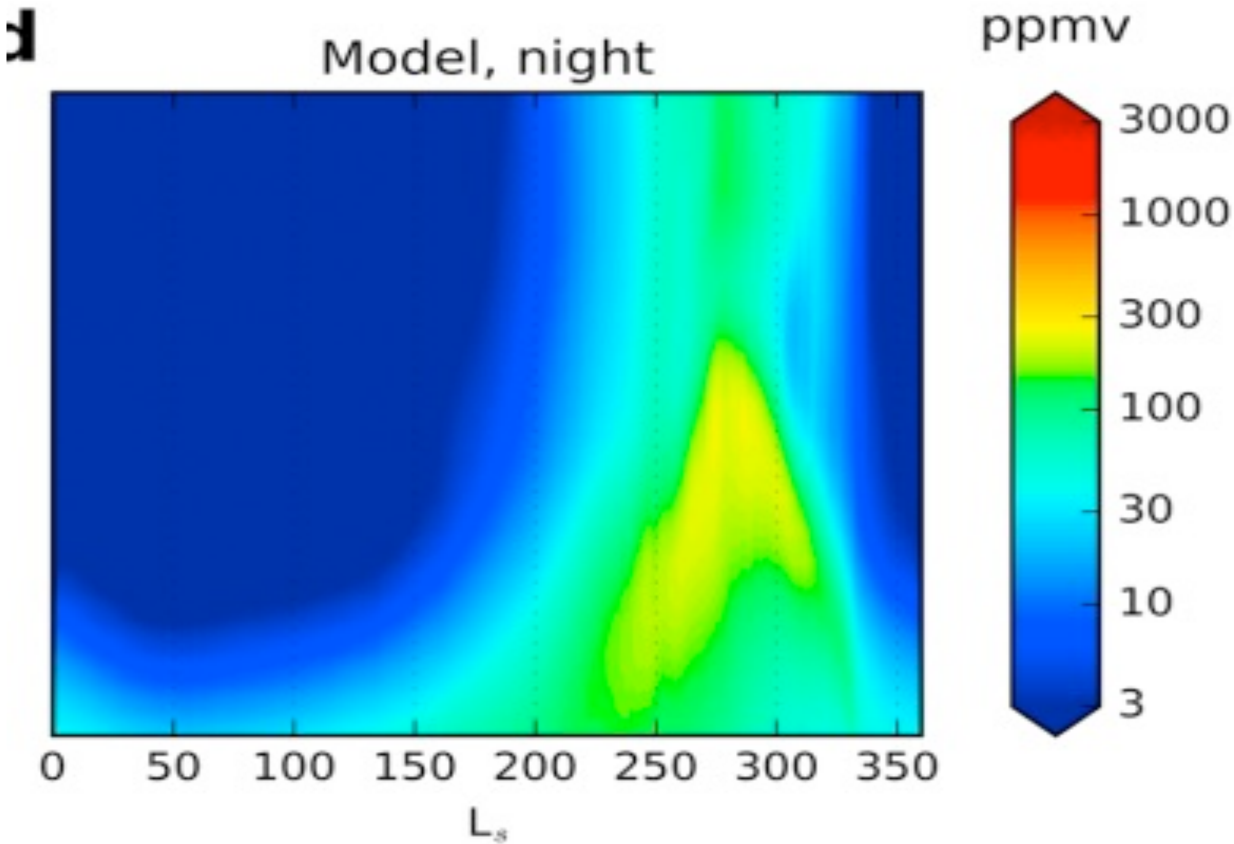
MPI-MGCM simulation of water cycle





Shaposhnikov et al., JGR 2017
Hartogh et al., JGR 2005

New mechanism transporting H2O through cold trap into the thermosphere during southern summer

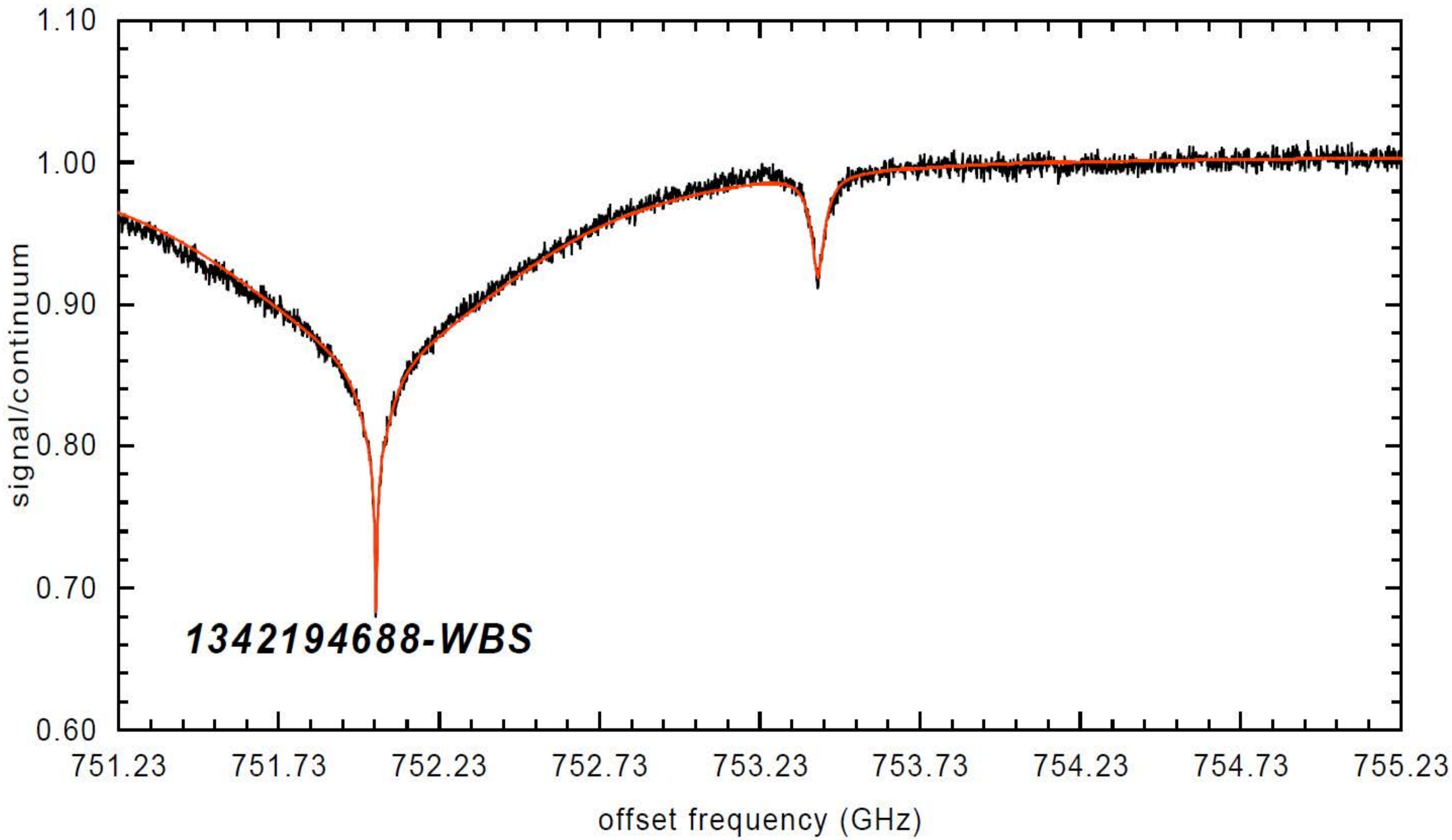


Shaposhnikov et al. JGR, 2019

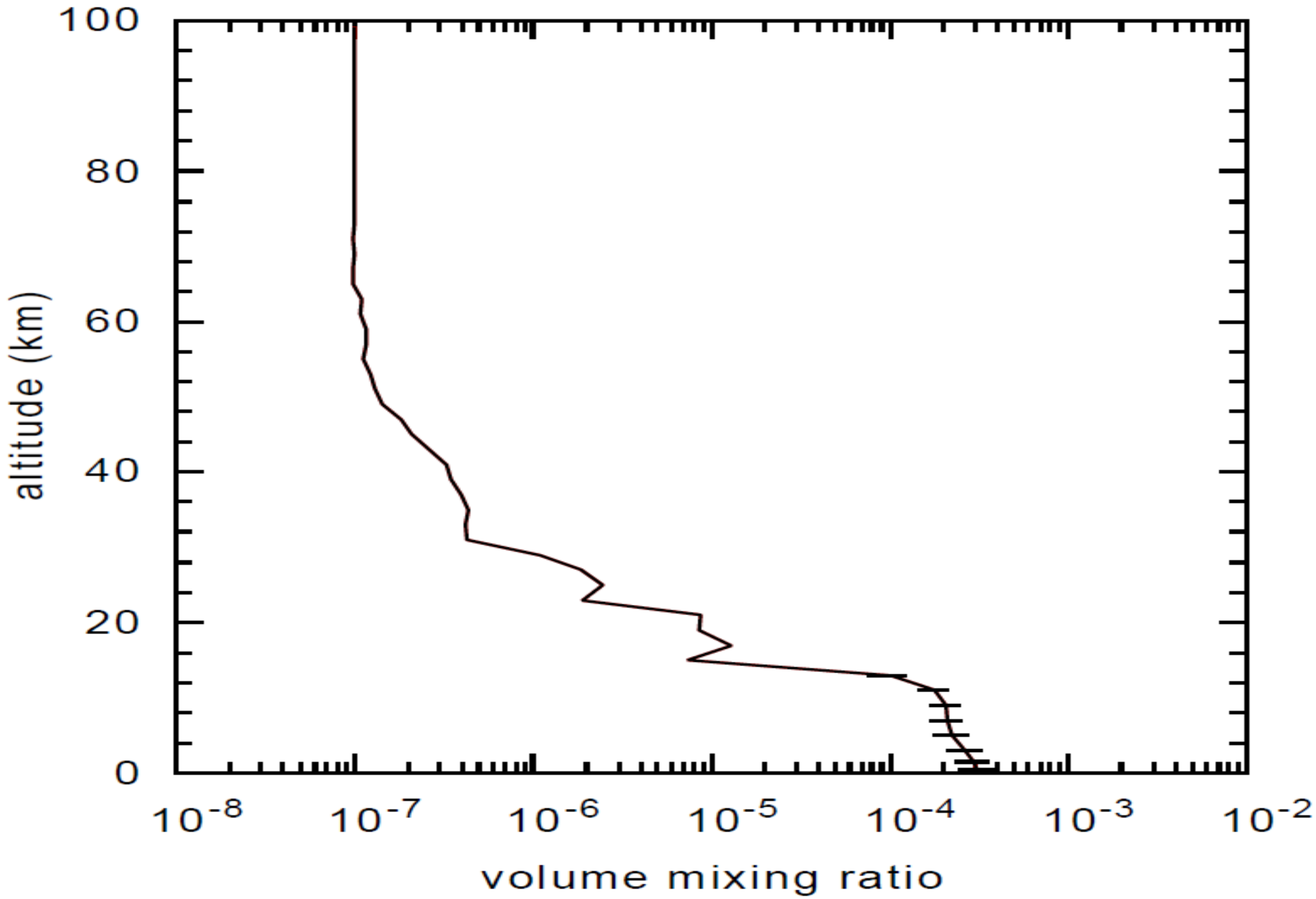
Only northern summer observations

- HIFI failure
- Loss of Ls 270-330 observations
- Only small Ls coverage around northern winter (hygropause level ~ 16 km)
- Confirmation of low hygropause level ~ 16 km
- Compared to satellite obs high sensitivity below 15 km (not sensitive to dust)

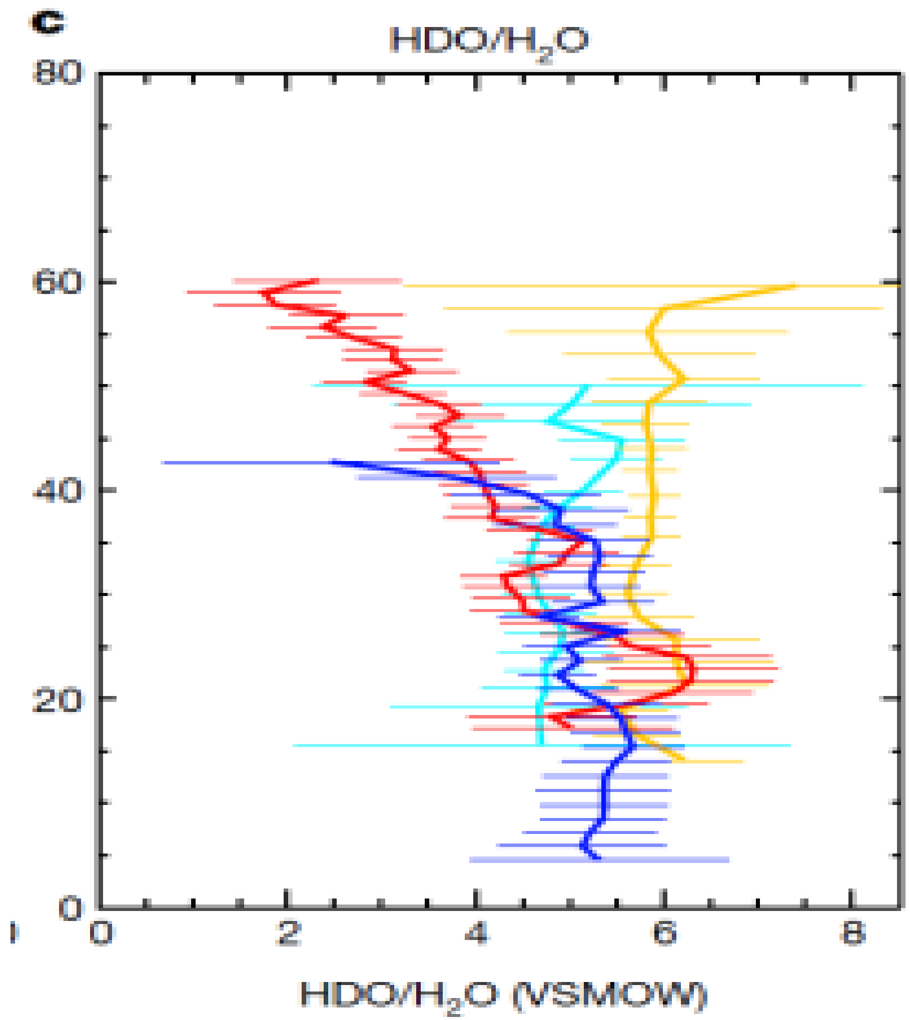
H_2O and HDO (4.5 x VSMOW) at Ls = 78°



Vertical profile of water at Ls = 78°

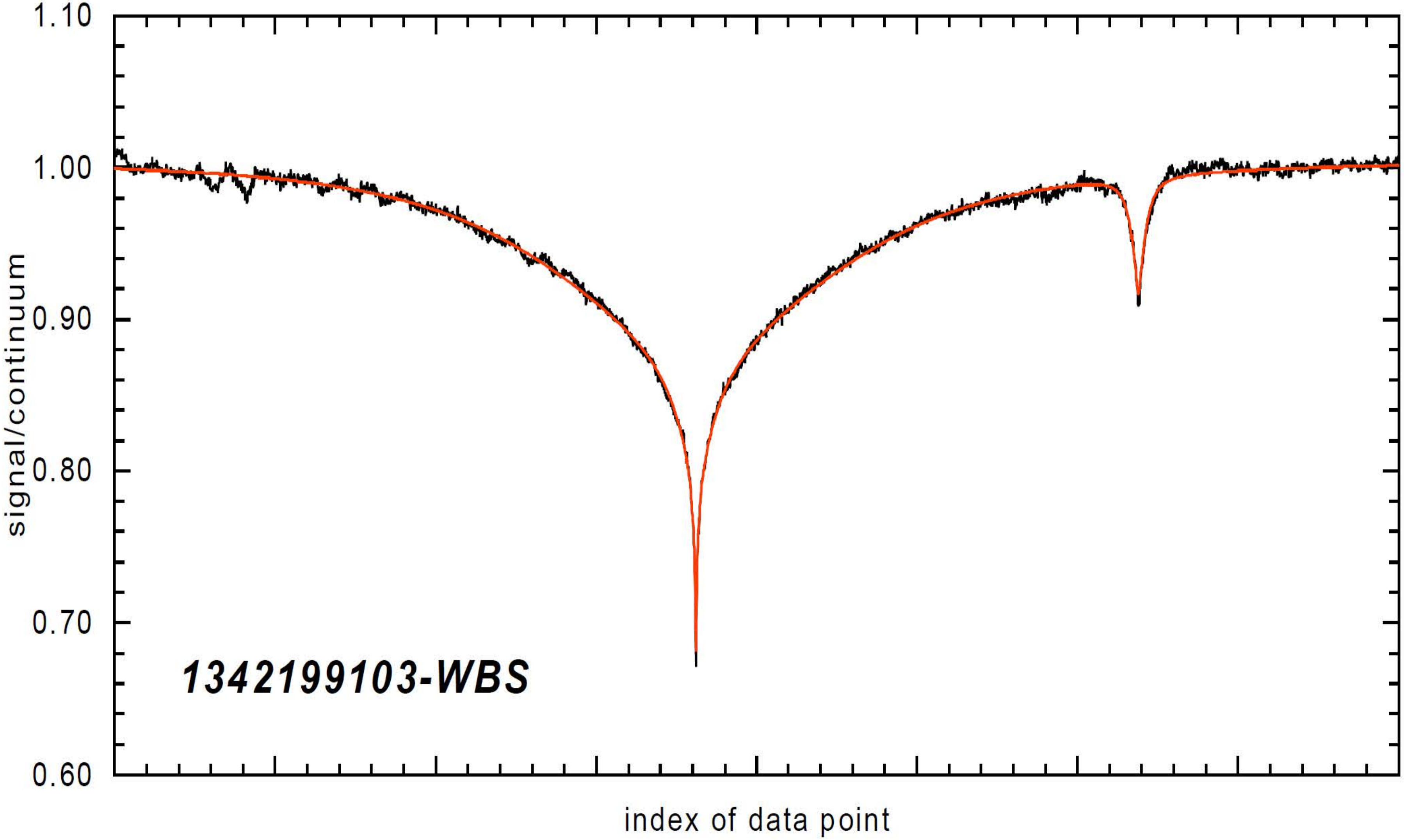


D/H with TGO (ACS and NOMAD)

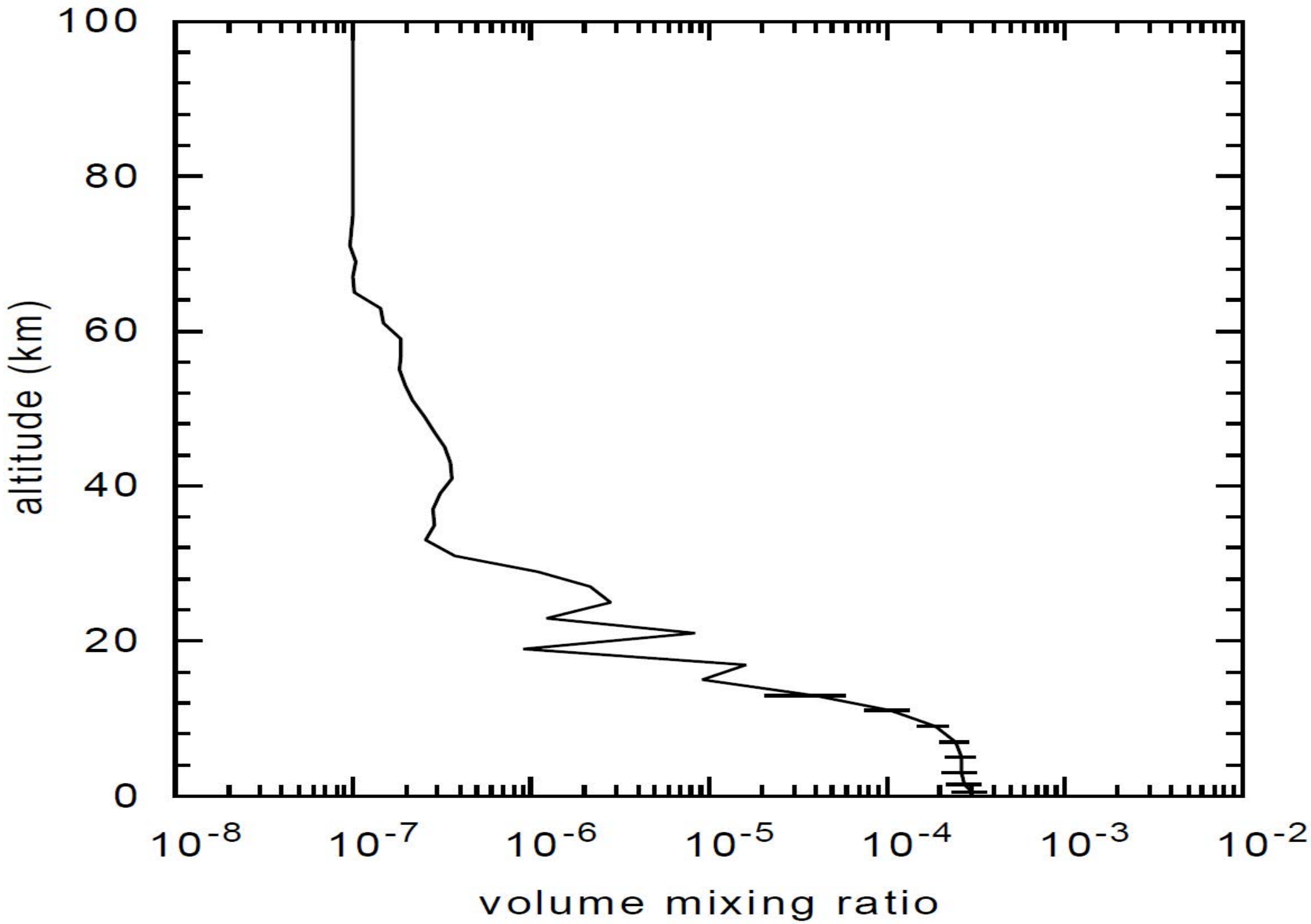


Vandaele et al, Nature 2019

H_2O and HDO (4.6 x VSMOW) at Ls = 110°



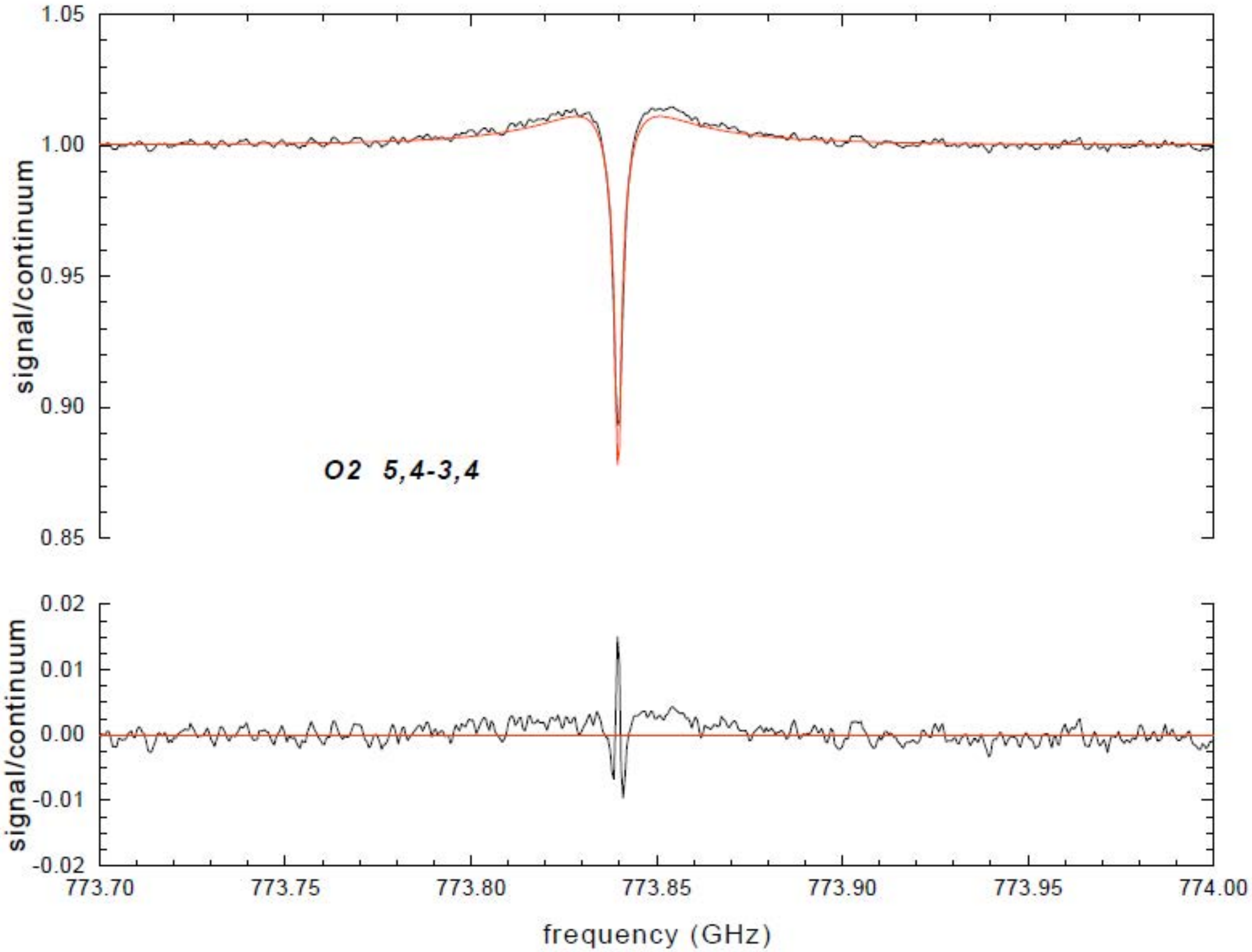
Vertical profile of water at Ls = 110°



Molecular oxygen on Mars

- First and last observation in visible range (oxygen A bands) in 1972!
- No observational constraint about the vertical profile!
- Believed to be uniformly mixed like on Earth
- Believed to be produced by photolysis of CO_2 and H_2O.
- If high enough on ground it can be used for rocket propulsion and astronaut supply.

First submm detection of O_2



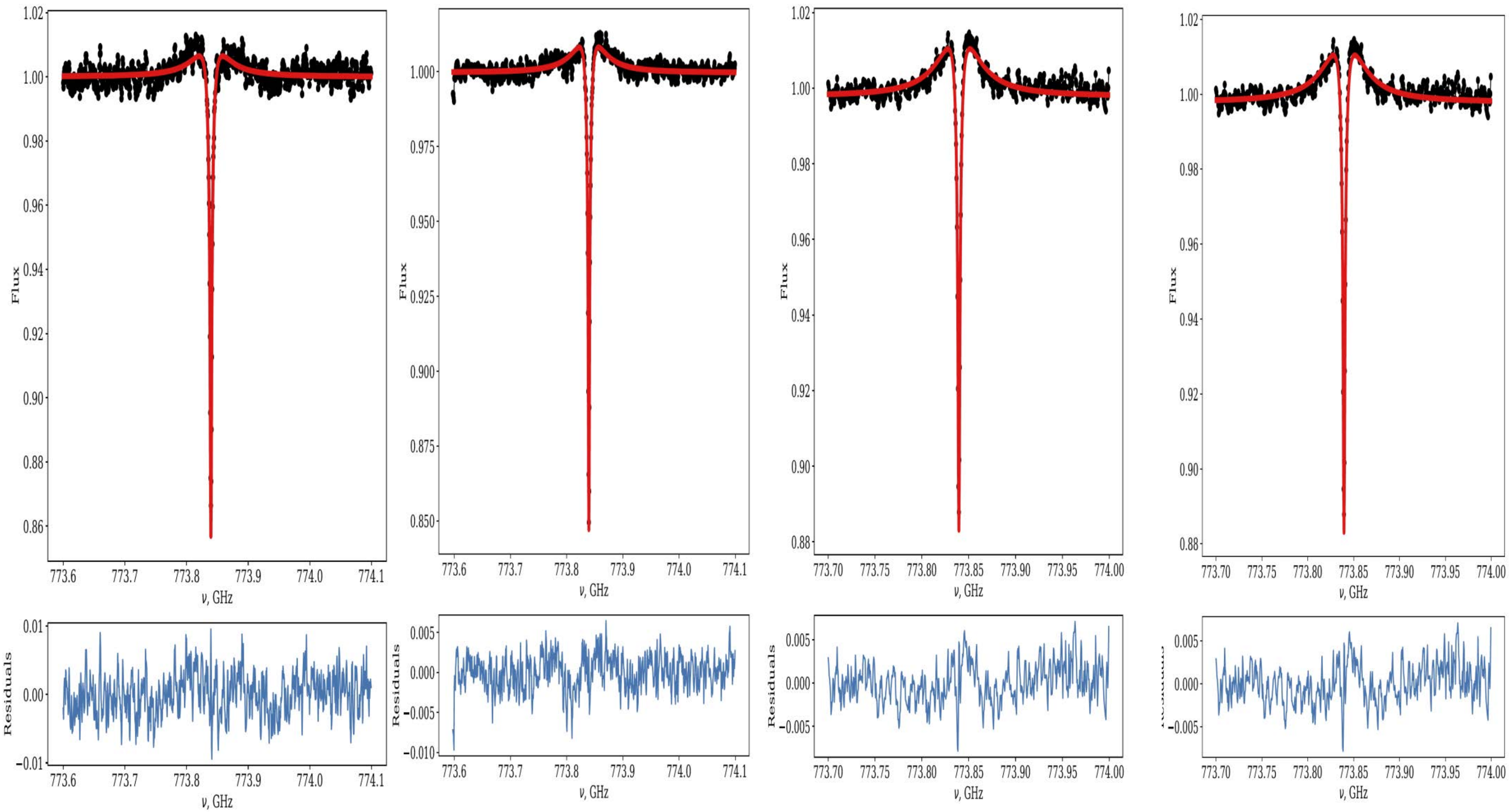
Fit of constant profile provides volume mixing ratio of 1400 ppm. However residual indicates that profile is not constant with altitude.

Hartogh et al. 2010b, A&A

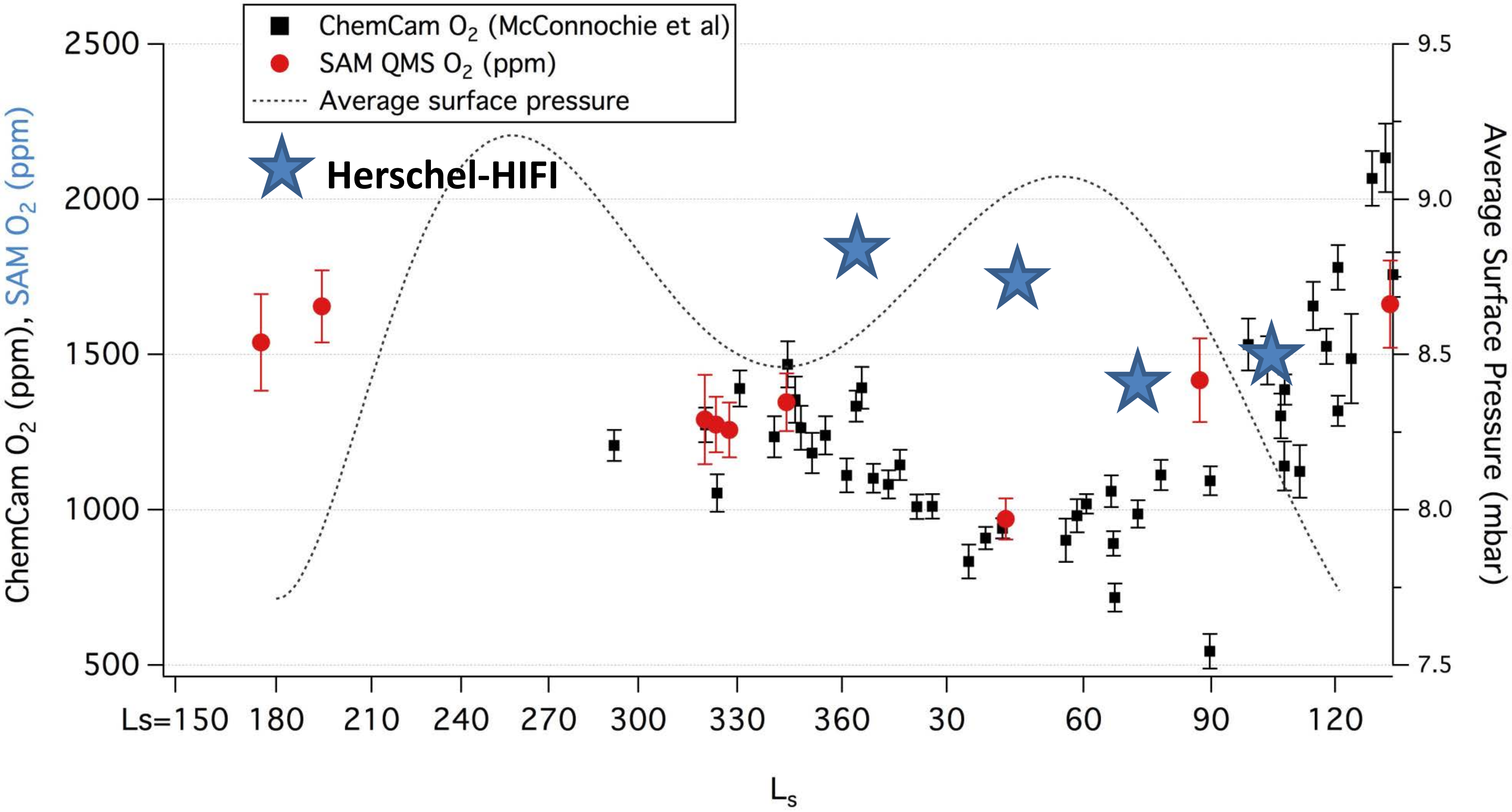
Non-constant vertical profile?

- Photochemical lifetime expected to be 8 years
- Mixing time in lower atm about 2 weeks
- Should be well mixed (constant VMR) through the whole atmosphere until homopause
- Publication pending (working on it since 8 years)
- Deviation from constant with altitude VMR points to smaller photochemial lifetime
- Similar problem found by ChemCam: while atm pressure varies by < 20 %, O_2 changes by >100 %.

Fits for LS 12, 47, 77, 114



Semi-annual variability assuming constant VMR O_2



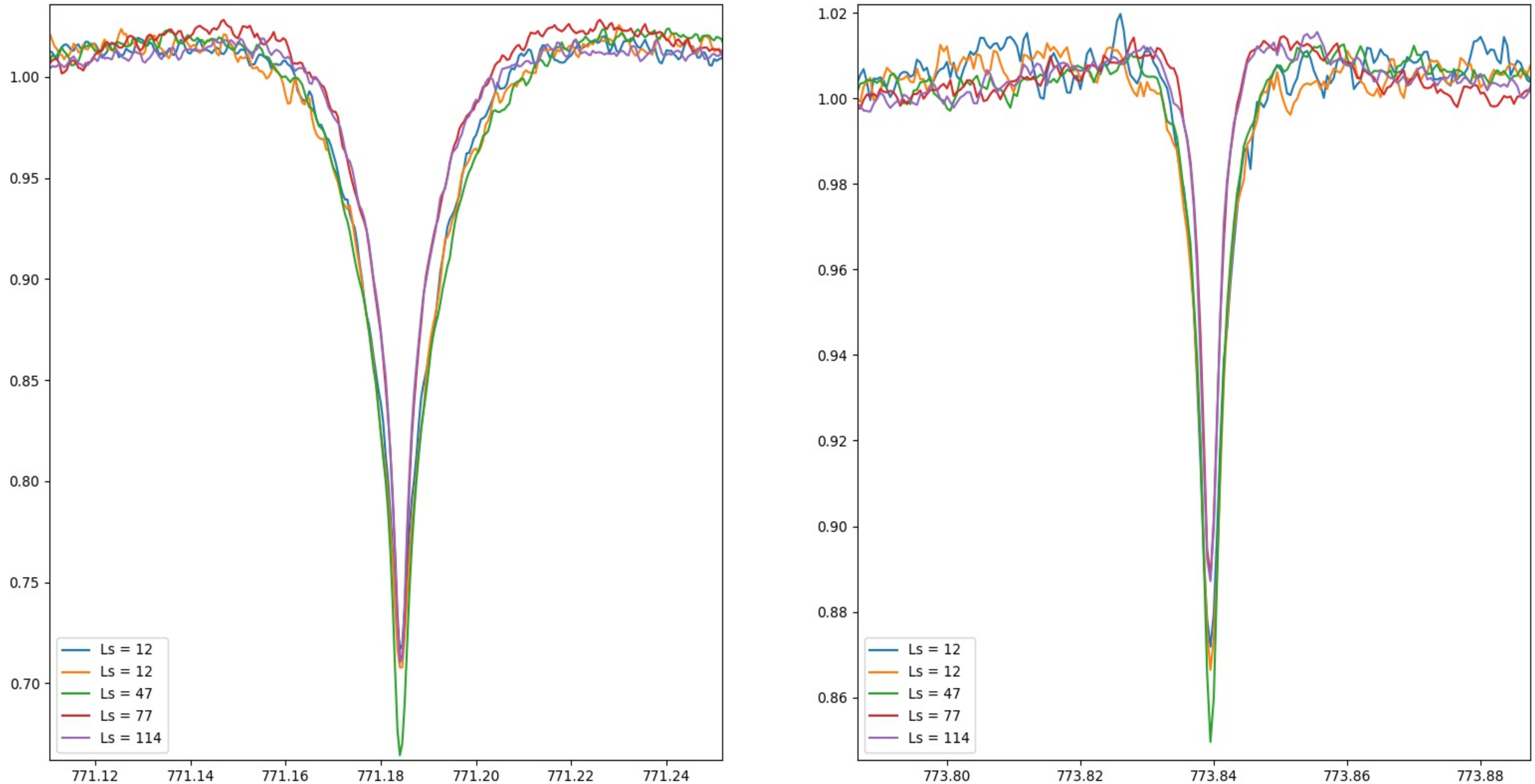
VMR vs surface pressure

- ChemCam:
  - 2100 ppm/700 ppm = 3.0
  - 8.8 hPa/7.75 hPa = 1.14
  - **Variation 2.6 times larger than expected for super volatiles**

- SAM QMS:
  - 1600 ppm/950 ppm = 1.68
  - 9.0 hPa/7.75 hPa = 1.16
  - **Variation 1.45 times larger than expected for super volatiles**

- Herschel HIFI:
  - 2100 ppm/1400 ppm = 1.5
  - 8.9 hPa/7.75 hPa = 1.15
  - **Variation 1.30 times larger than expected for super volatiles**

CO and O_2 spectra comparison



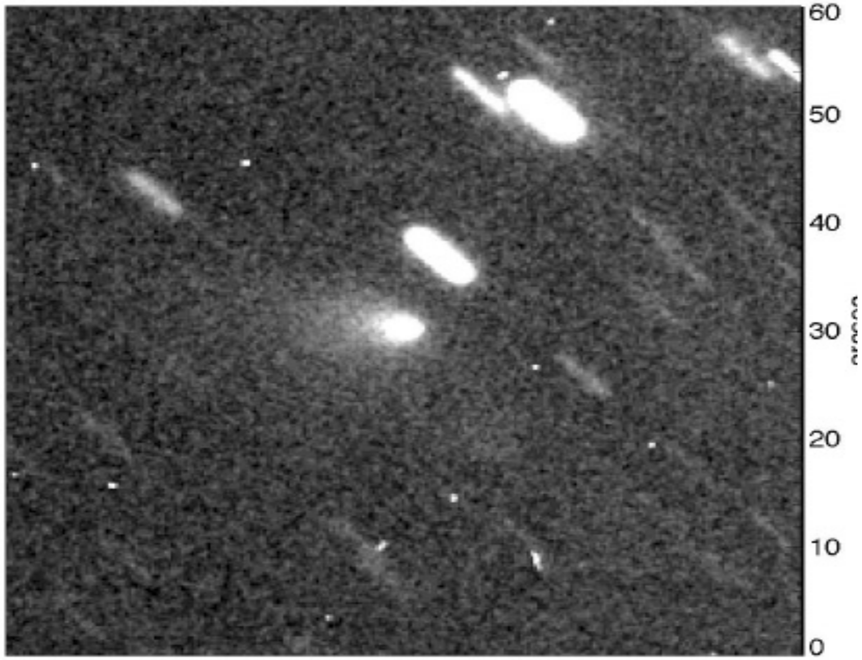
Discussion

- All 3 instruments show larger variations than expected from O_2 as supervolatile (-Δp)
- HIFI shows smaller variations than CC and QMS
- If true, O_2 is not as well mixed as assumed
- Vertical profiles not shown here, because discrepancies between temperature retrievals using CO and
- Comparison of CO and O_2 spectra however indicate deviation from constant vertical profile at Ls

Main belt comets

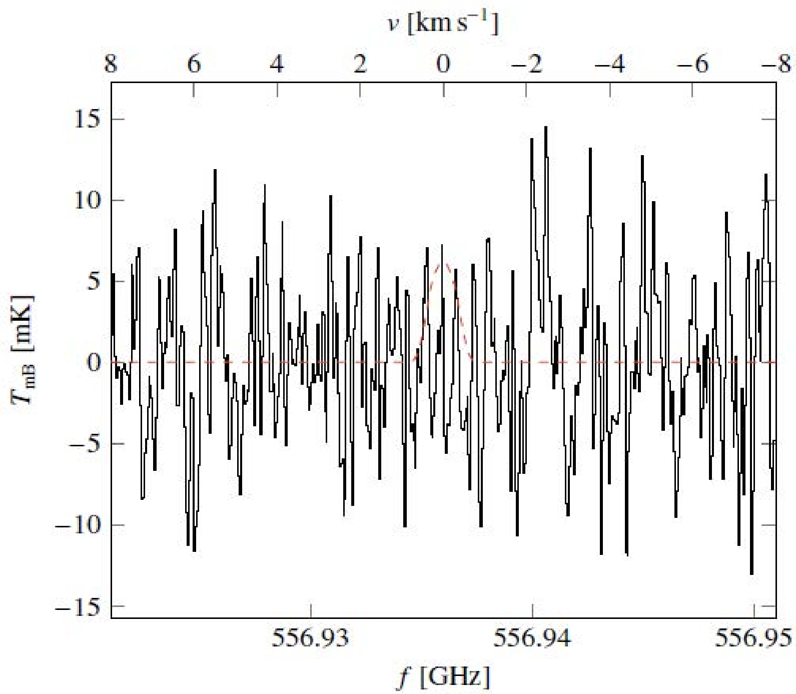
- Does the gas drag of water lift dust particles and create the observed dust tails of MBC?

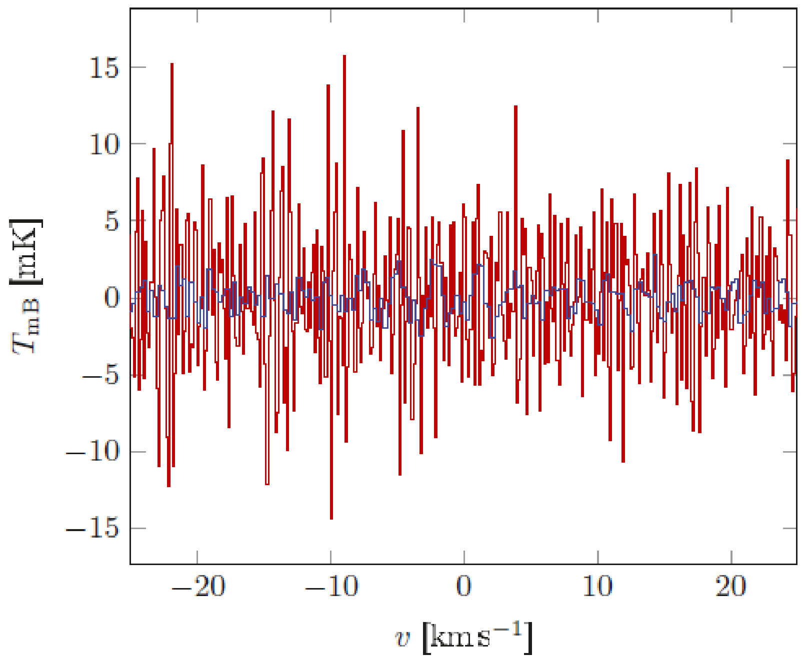
176P/LINEAR



P/2012 T1 (Panstarrs)

Production rates from HIFI obs: < 2 kg/s

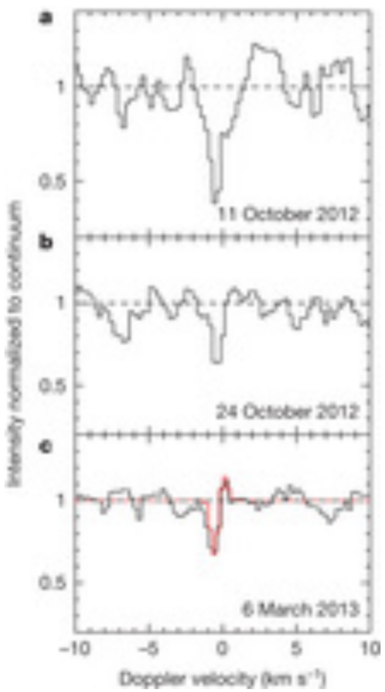


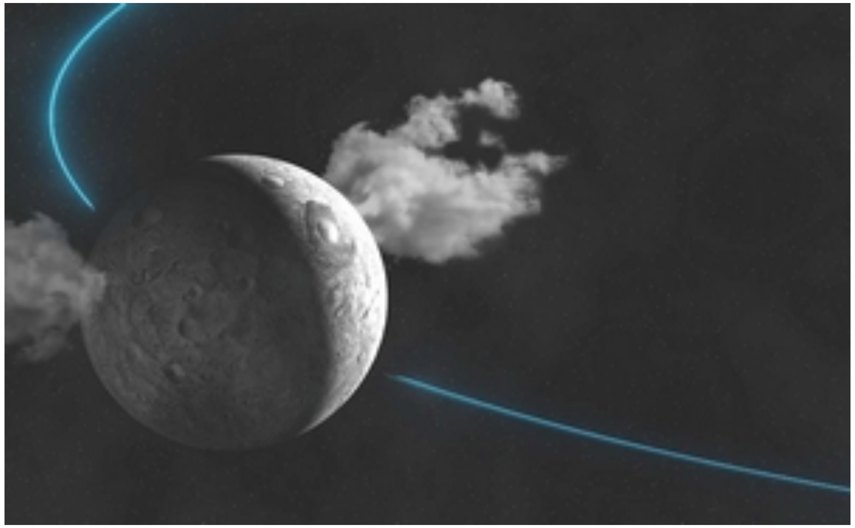


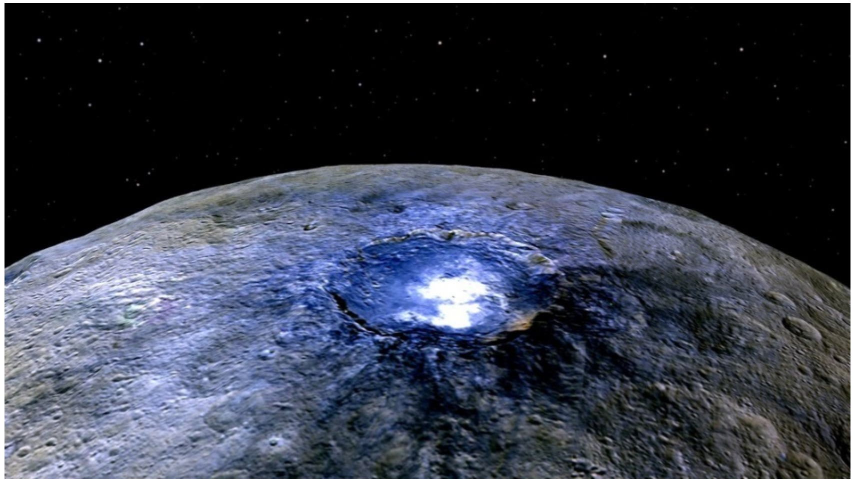
de Val-Borro et al, A&A 2012

O`Rourke et. al, APJL 2013

HIFI detected water in CERES!







Production rate about 6 kg/s

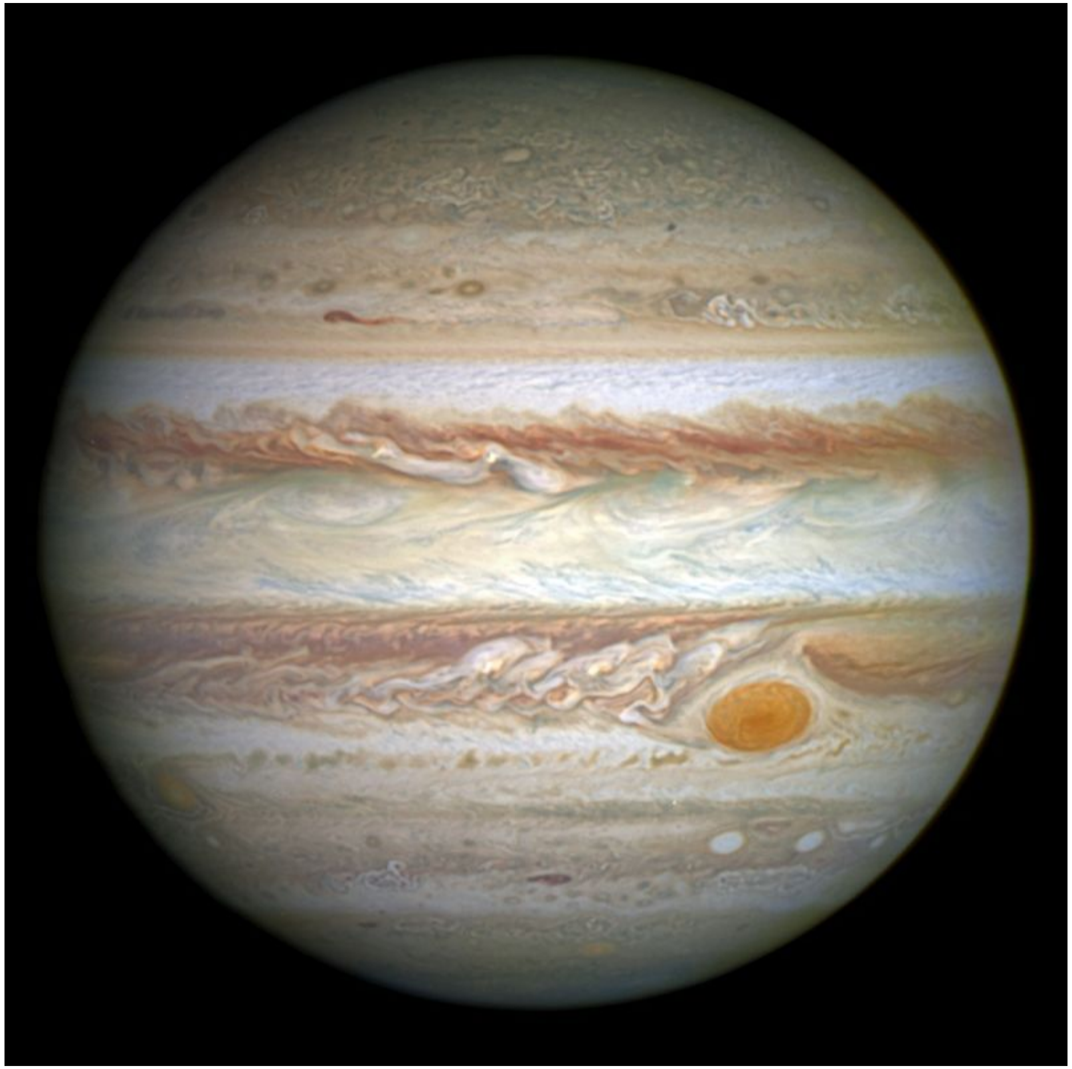
Küppers et al., Nature 2014

Source of external water in Jupiter?

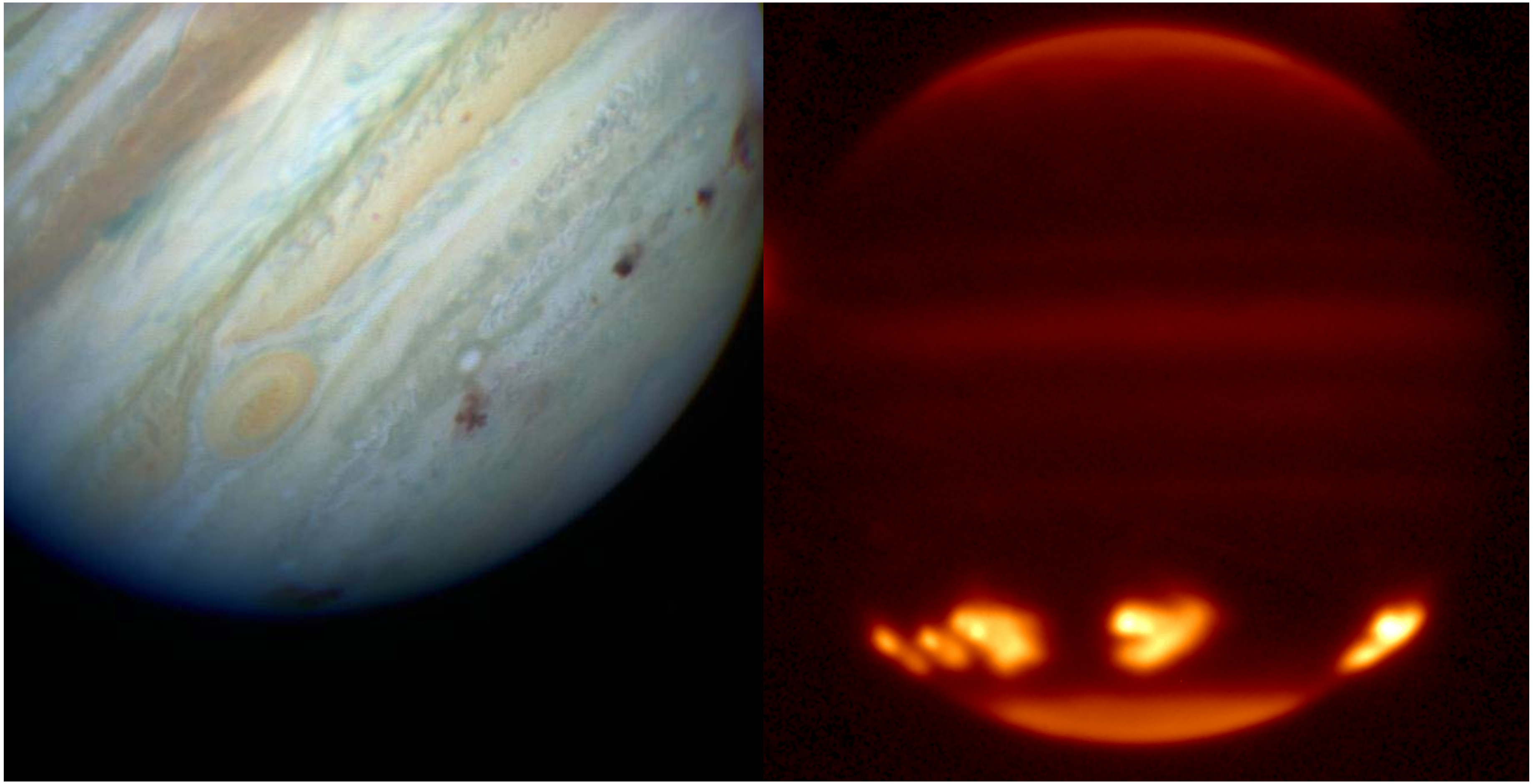
Large amounts of water are expected in the lower atmosphere. However the Galileo probe did not find anything even in depths of 23 bars.

Instead ISO observed stratospheric water that must be of external origin (tropospheric cold trap).

What is the source of external water was one of the big HssO questions

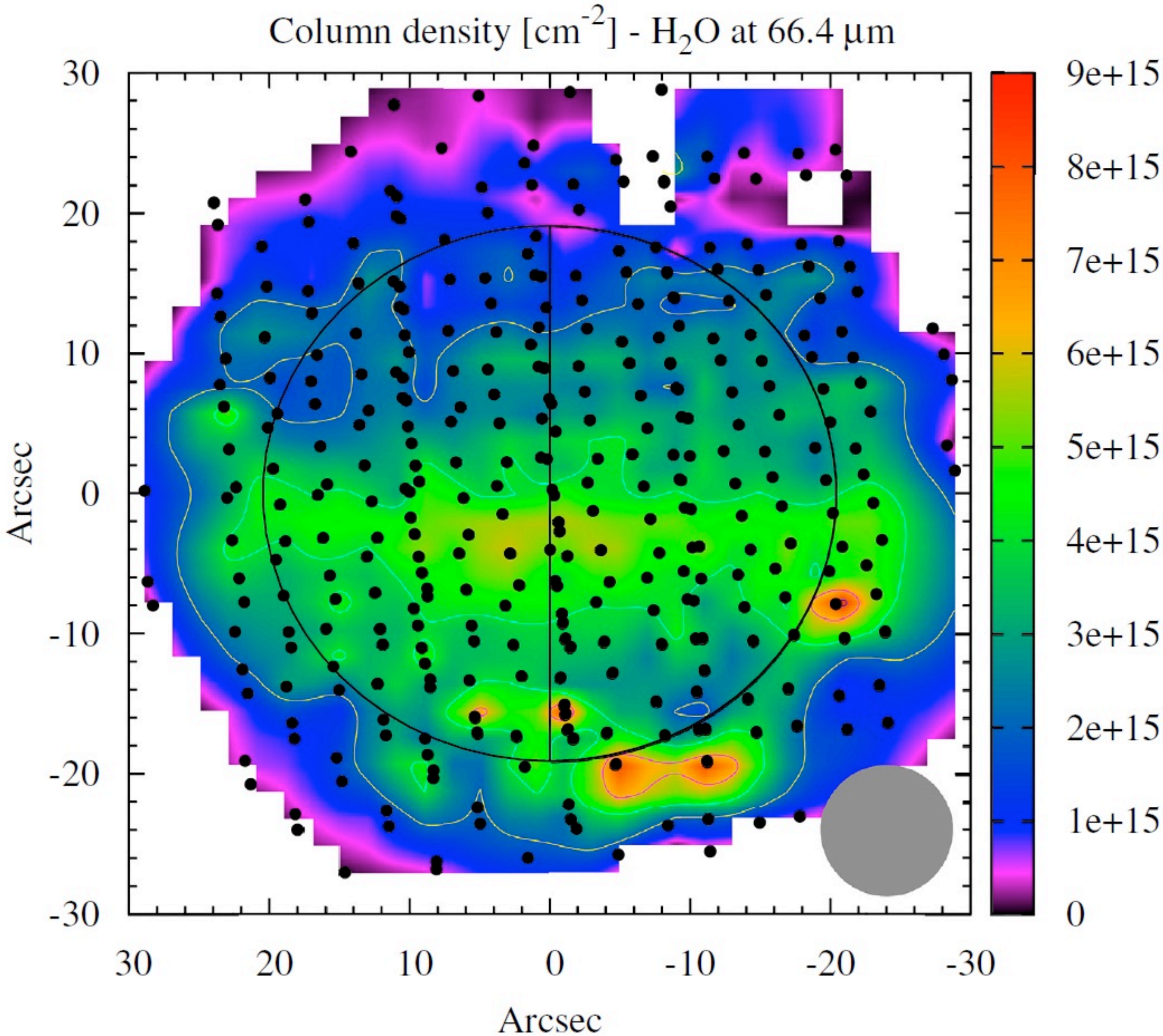


Shoemaker Levy 9 (1994)



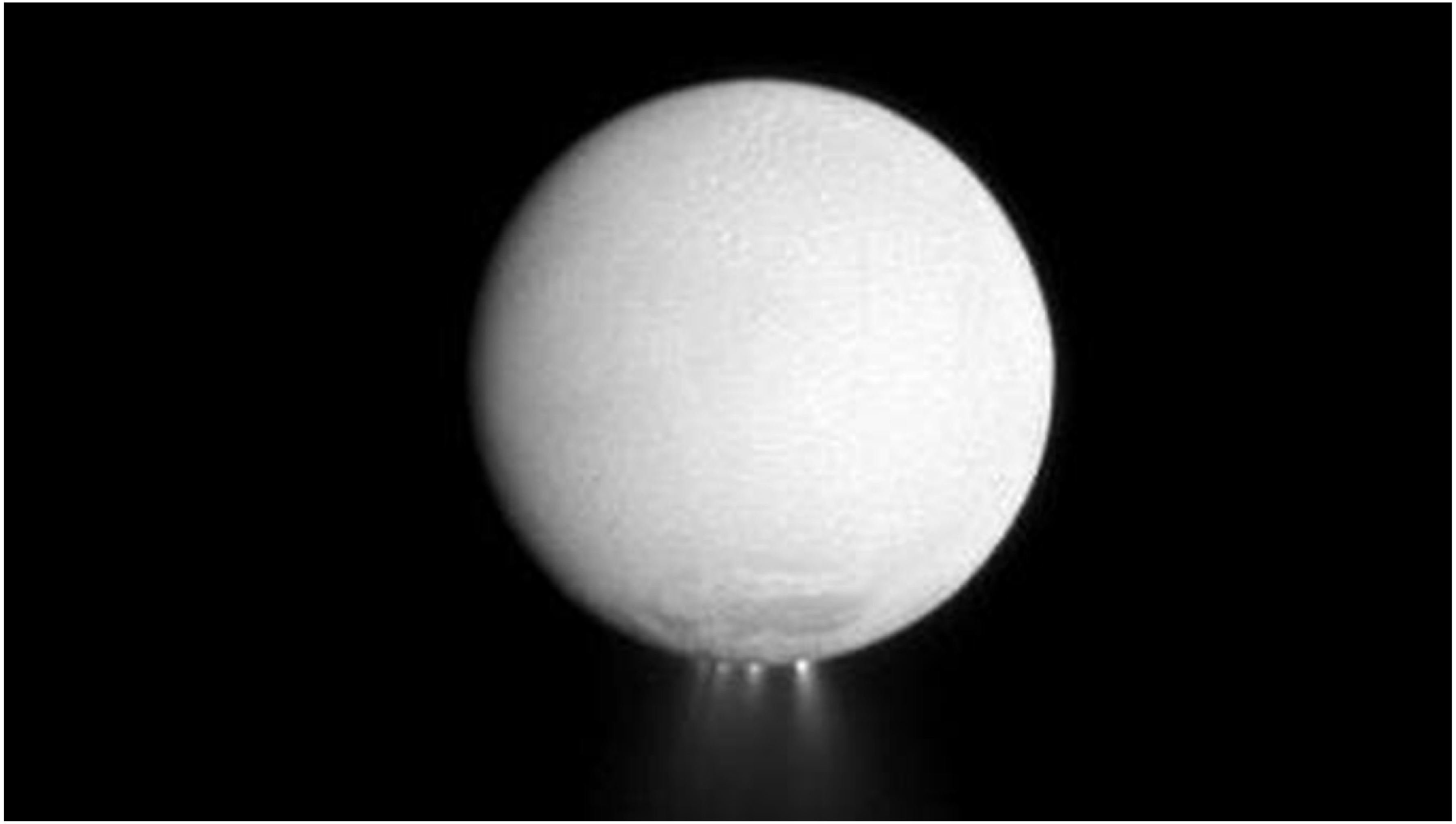
Herschel Messung der H_2O Verteilung

The vertical profile derived from HIFI observations and the latitudinal distribution determined with PACS indicate that SL-9 delivered the water found in Jupiter's stratosphere.



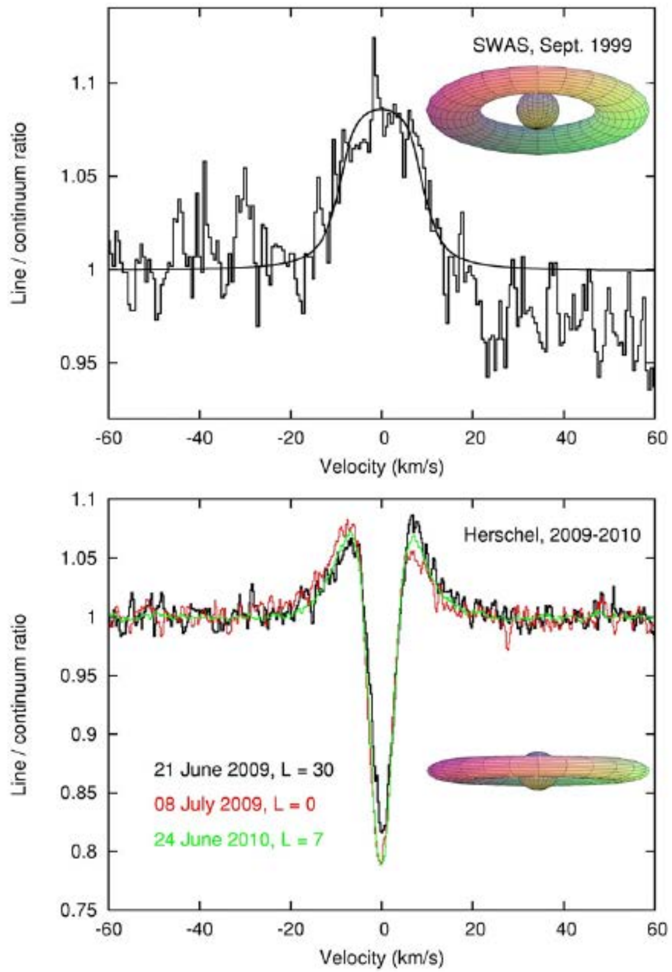
Cavalie et al, A&A 2013

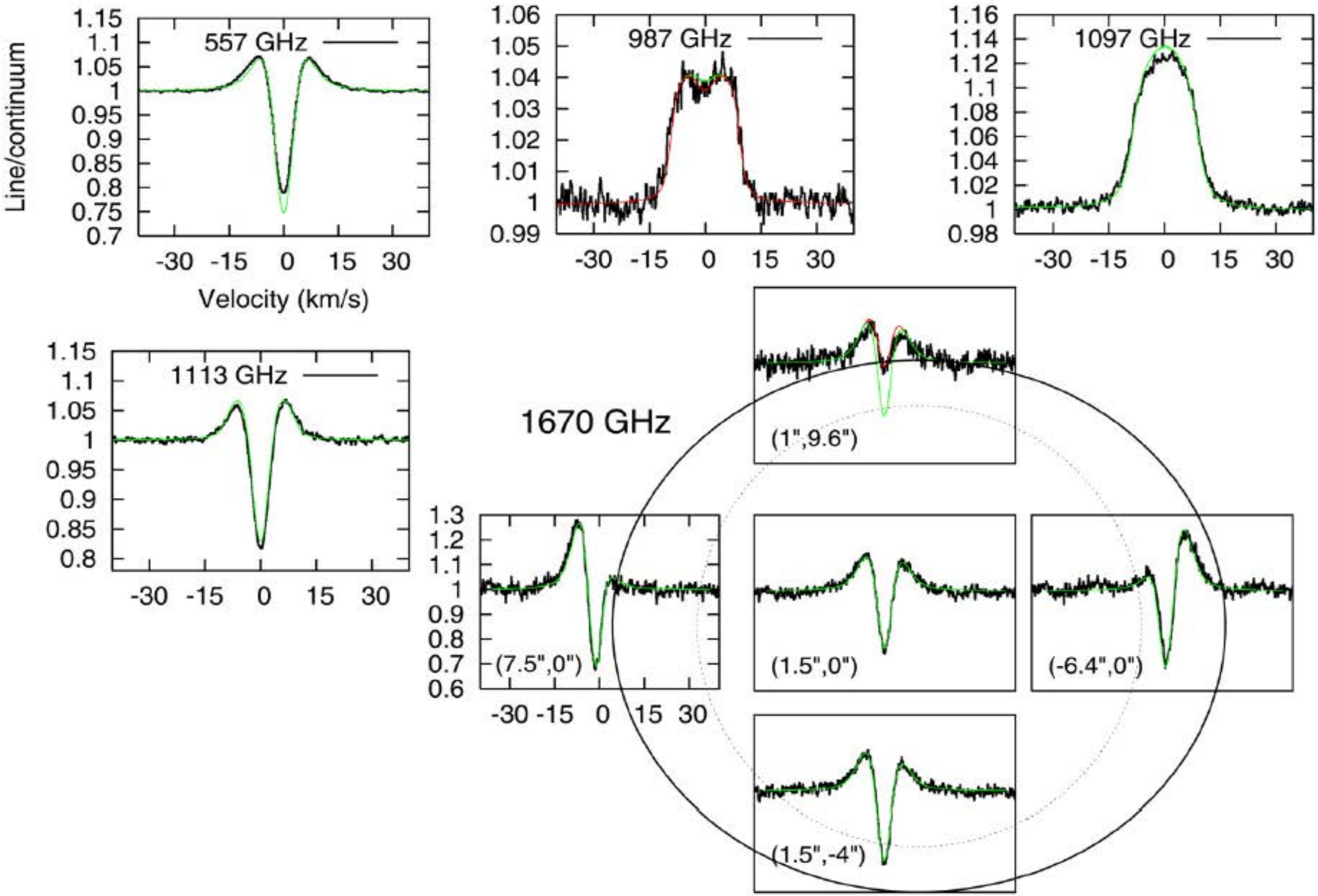
Enceladus



Die Geisire in der Südpolarregion “spucken” ca. 250 kg Wasser pro Sekunde

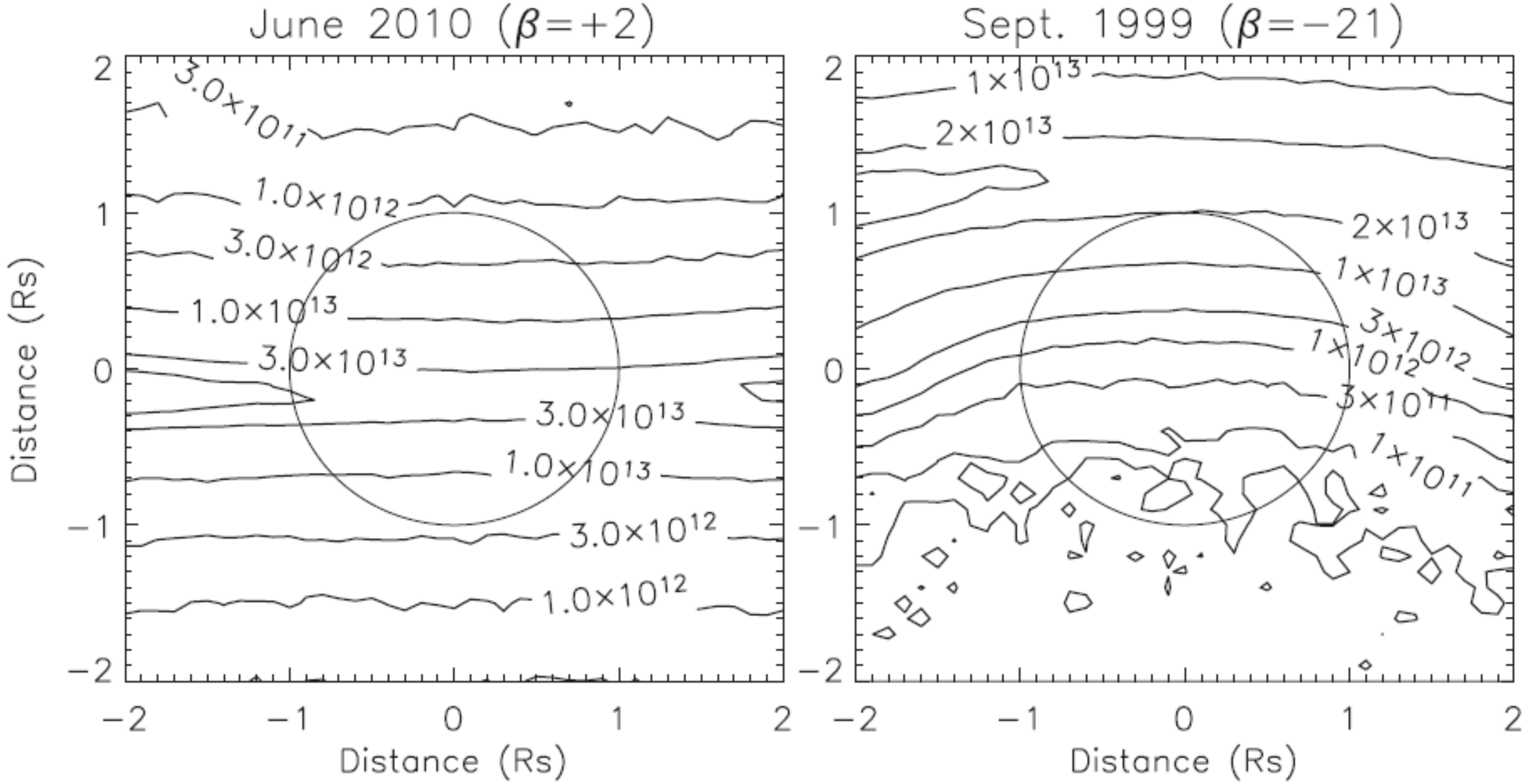
Unexpected absorption line: Enceladus water torus





Line/continuum
557 GHz
Velocity (km/s)
987 GHz
1097 GHz
1113 GHz
1670 GHz
(1",9.6")
(7.5",0")
(1.5",0")
(-6.4",0")
(1.5",-4")

Water vapour number densities in Enceladus Torus

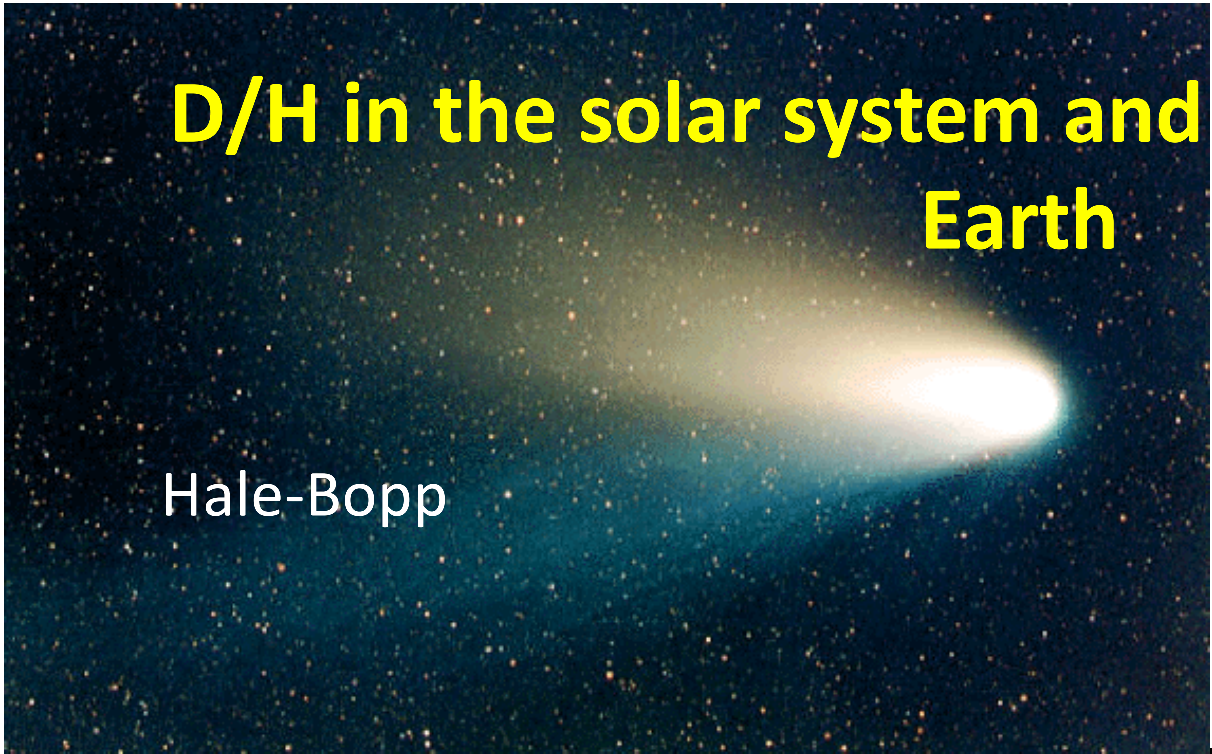


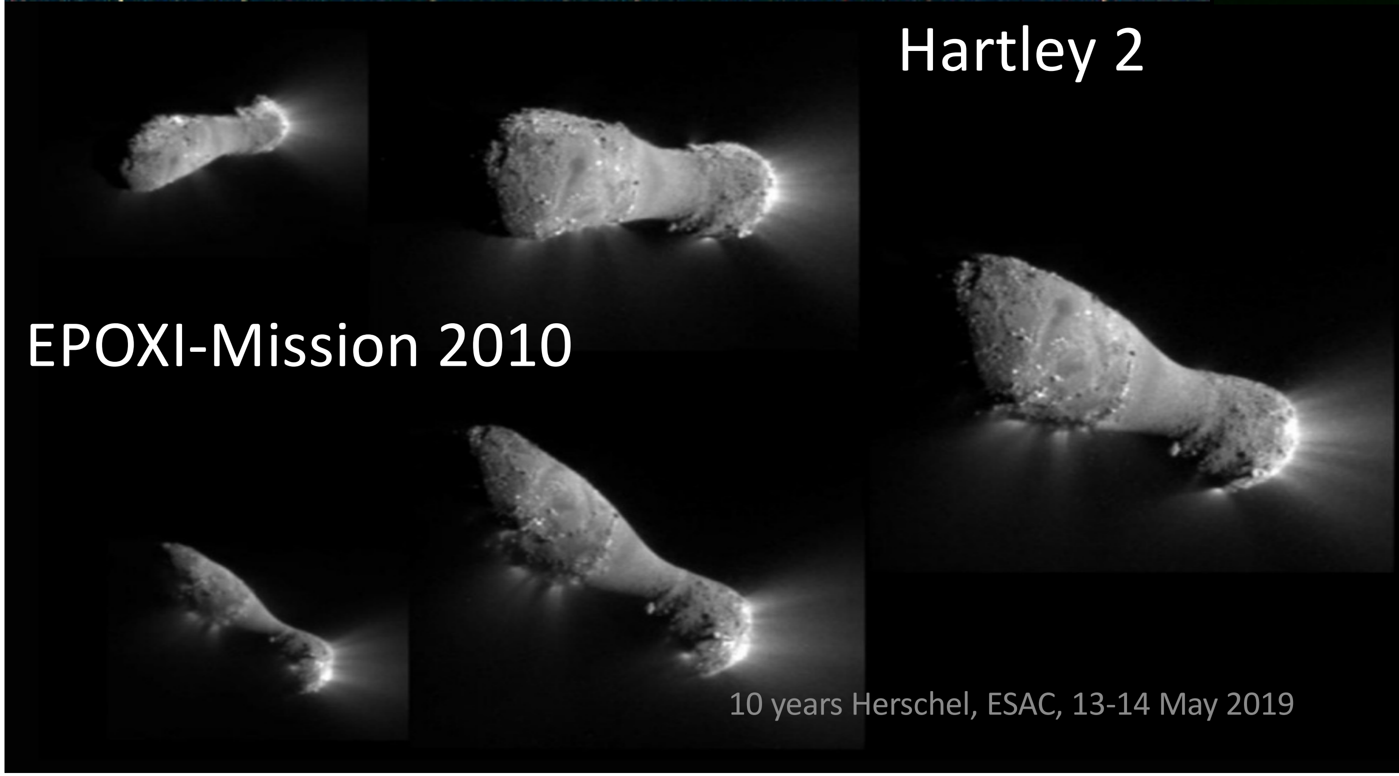
Results of HIFI findings

- Torus extension about 10 Saturn radii(R_s)
- Larges density of torus around 4 R_s
- About 3 % of the torus water "raining" into the upper atmosphere of Saturn is enough to explain its stratospheric water

Hartogh et al., A&A 2011

D/H in the solar system and orgin of water on Earth





What about water on Earth?

- Newton and Halley: water on Earth delivered by comets
- Earth probably accreted dry (bulk isotopic composition of ECs) and volatiles were delivered later (e.g. Javoy, Earth Planet. Sci. Lett. 2010)
- Urey (*Nature 1957*): comets interacted with Earth (Tektites)
- Oro (*Nature 1961*): comets brought organics and water
- Wänke (*Phil. Trans. R. Soc. 1981*): Earth accreted wet (third phase of heterogeneous accretion brought 1 % or the total mass)
- Delsemme (*J. Chem. Phys. 1983*): comets from Jupiter zone delivered water for a 4 km deep global ocean, trans-Neptunian comets delivered another km.
- Balsiger (*JGR 1995*): In situ analysis of material from comet Halley shows that the composition of cometary water differs from the one on Earth (D/H). Later confirmed by remote sensing (spectra) of 5 other Oort cloud comets (OCCs). Average D/H of OCCs about 2 x VSMOW ~ 3×10^{-4} .

Water on Earth II

- Morbidelli (Meteorit. Planet. Sci., 2000) : Water delivered by a few planetoids at the end of Earth formation. Max. 10 % delivered from comets
- Gomes (*Nature, 2005*): Main water delivery during LHB with max. 6 % from comets.

LETTER

doi:10.1038/nature10519

Ocean-like water in the Jupiter-family comet 103P/Hartley 2

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Formation of water

- Three proposed reactions:

1) In cold gas: dissociative recombination (&UV-radiation):

$O + H_3^+ \rightarrow OH^+ + H_2$; $OH^+ + H_2 \rightarrow H_2O^+ + H$;

$H_2O^+ + H_2 \rightarrow H_3O^+ + H$; $H_3O^+ + e \rightarrow H_2O + H$

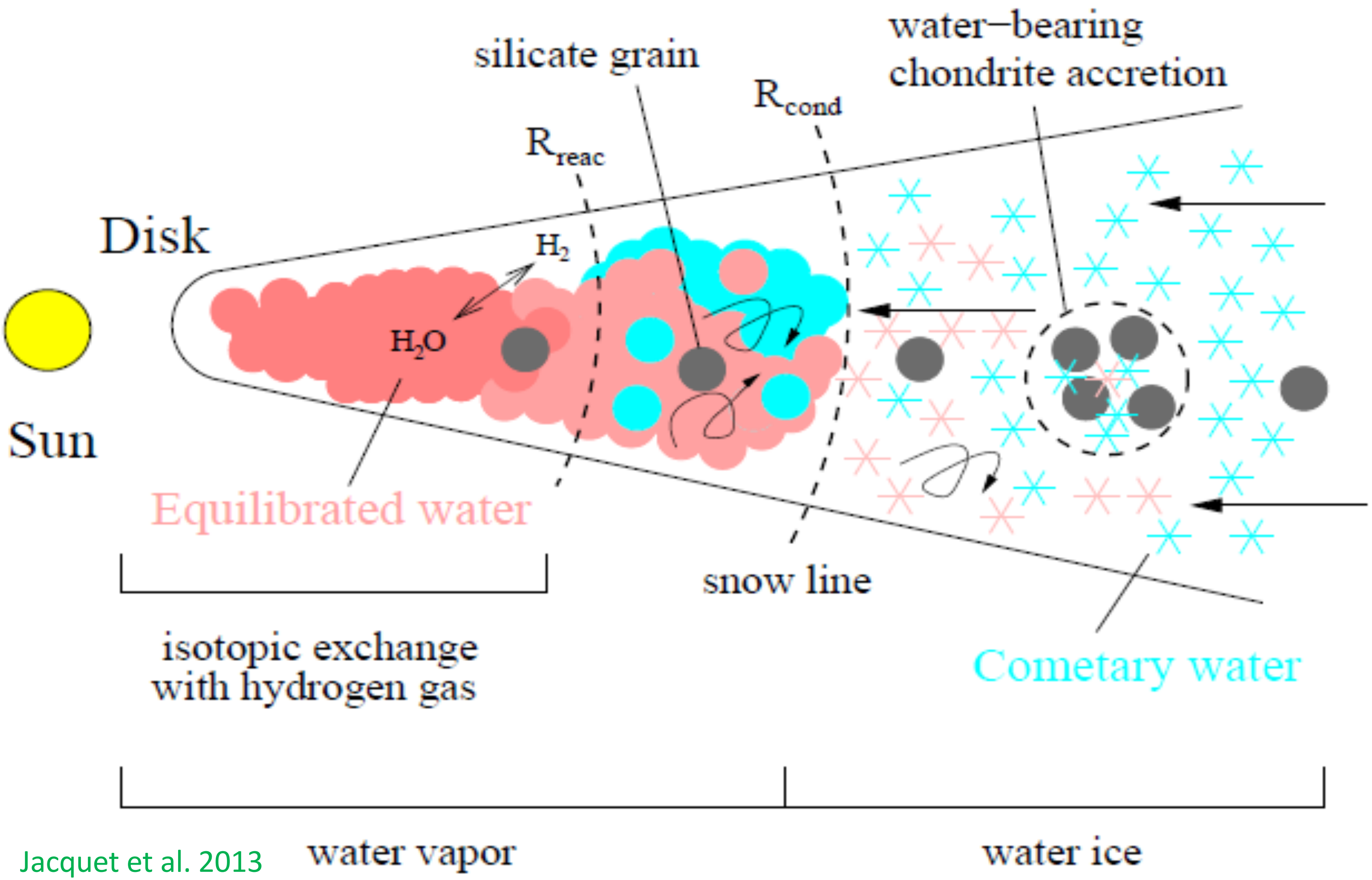
The reaction $H_3^+ + HD \rightarrow H_2D^+ + H_2$ enriches D in water

2) In warm gas (> 200 K): endothermic reaction: $O + H_2 \rightarrow OH + H \rightarrow H_2O$

3) In cold, low density gas: reactions on dust particles.

Water may get heavily enriched in D during its formation. This fingerprint should be found in primordial matter, e.g. in comets

D/H gradient in the solar system?



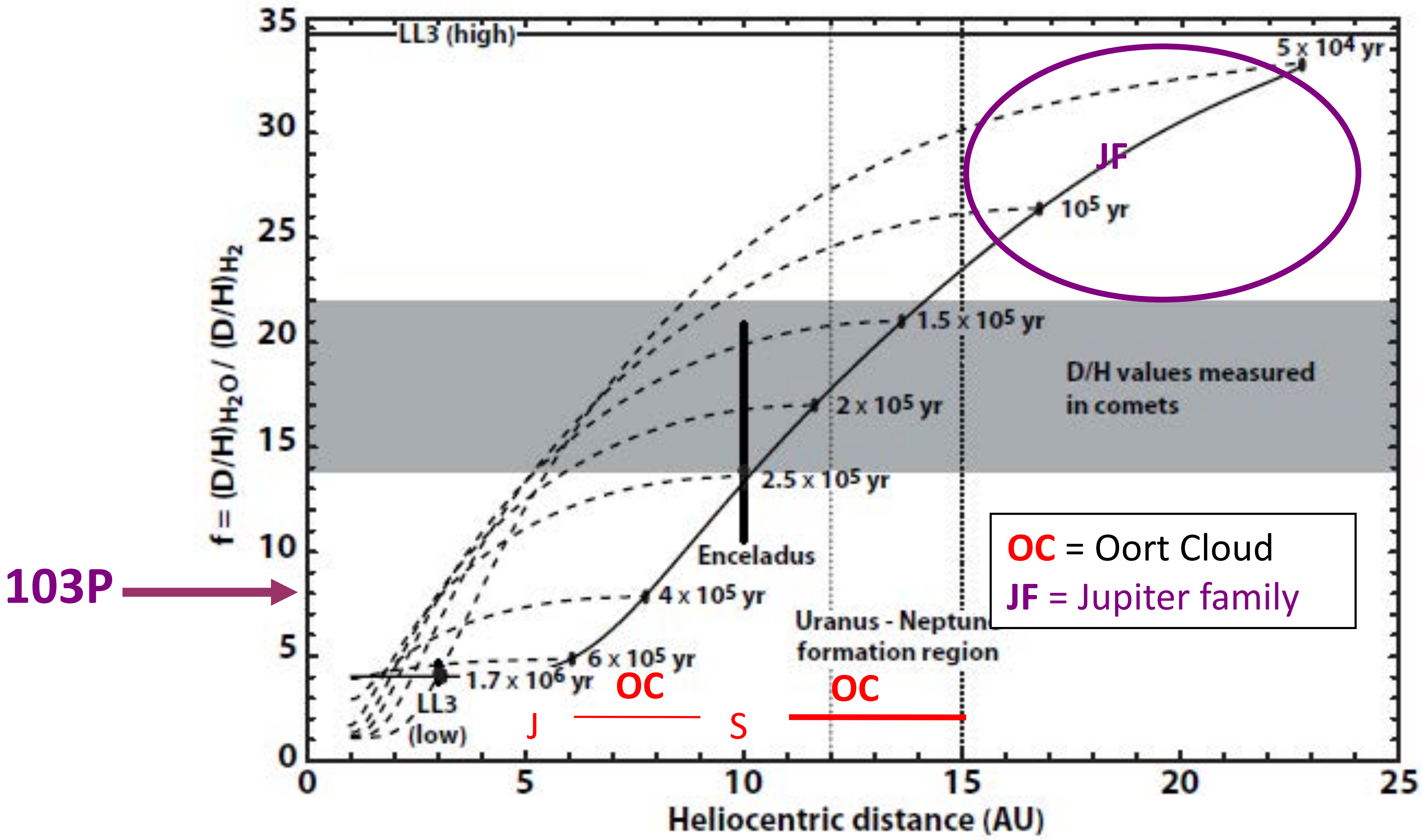
Jacquet et al. 2013

D/H gradient

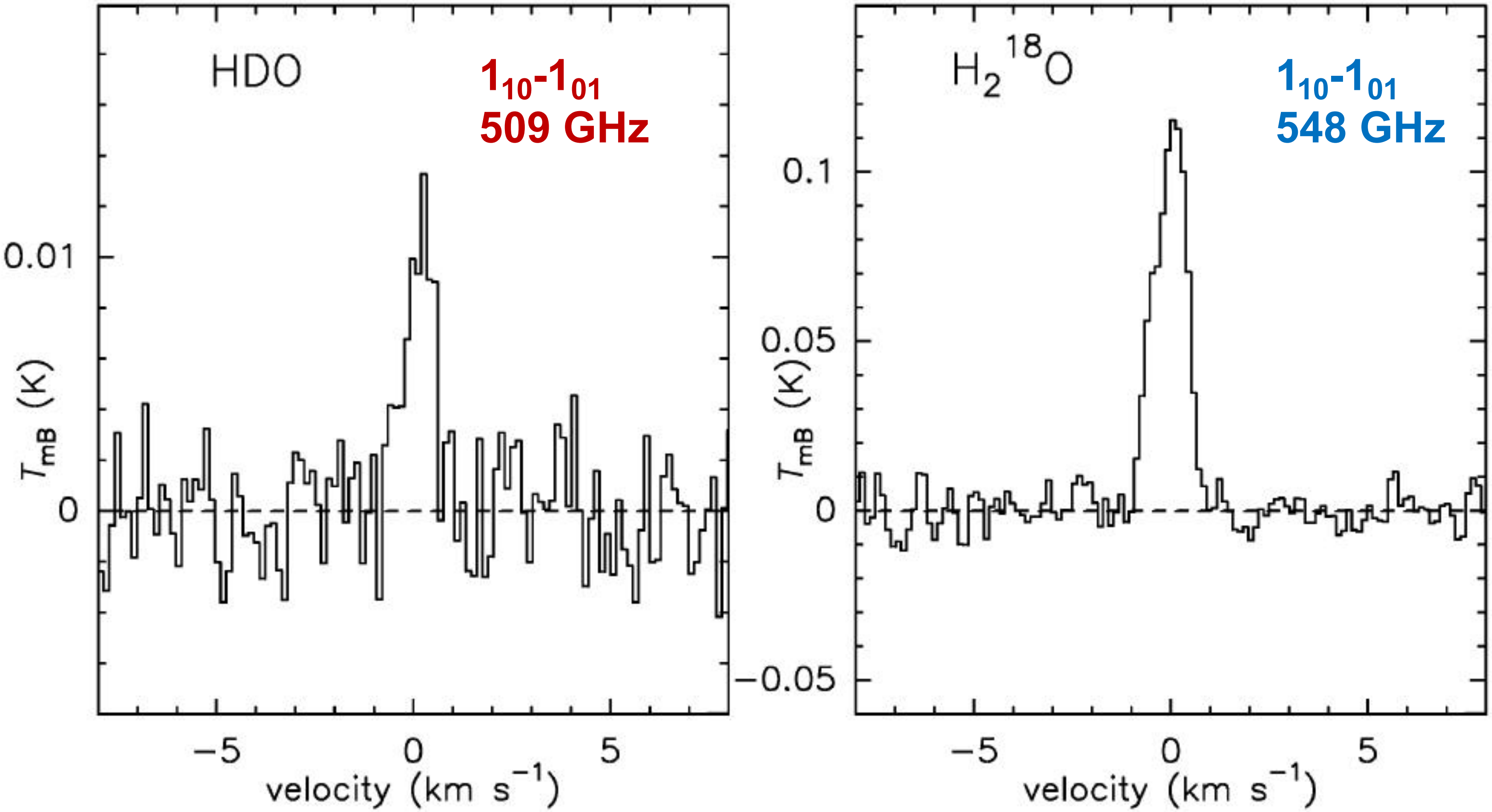
- Isotopic exchange reactions in disk near the sun
- Volume mixing ratio water/hydrogen 10E-4
- D-depletion in water to that of hydrogen (equilibration)
- Mixing of equilibrated water vapour with cometary water vapor within snow line
- Depending on formation distance, cometary water composition should be different.

D/H Modell für das Sonnensystem

Kavelaars et al. (2011)



Observed spectra:



S/N = 10 **S/N = 60**

Analysis of the observations

- Excitation model : collisions with H_2O, electrons and infrared pumping, gas temperature determined by other observation (e.g. methanol lines at IRAM/CSO/SMT)

- → the HDO/$H_2{}^{18}O$ production rate ratio is not very sensitive to the model parameters (similar transition: J = 1_{10}-1_{01})

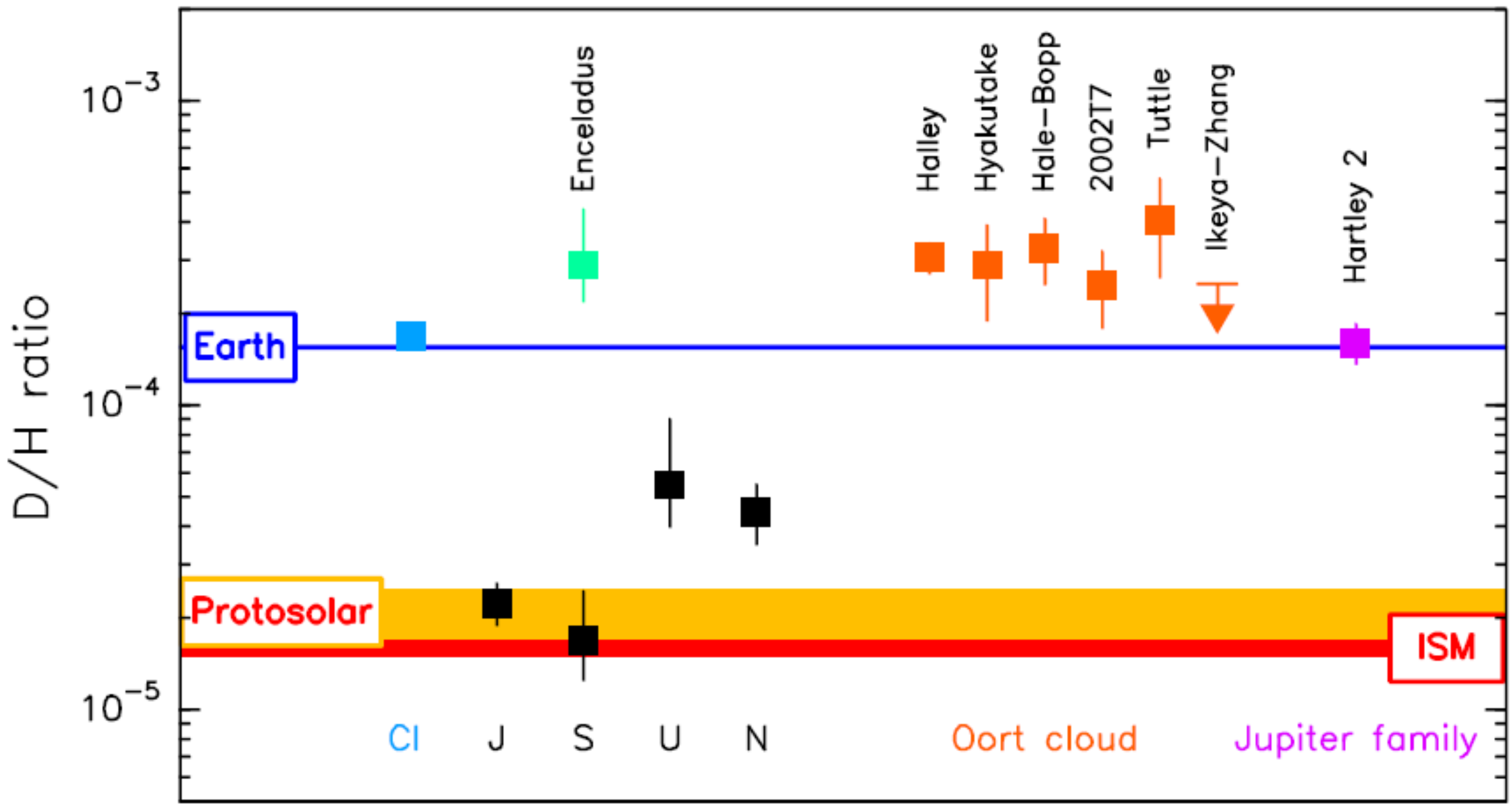
- Hypothesis : $^{16}O/^{18}O$ = 500 (+/- 10%) (VSMOW)

  (520±30 in 4 comets with Odin)

=> **D/H = (1.61 ± 0.24) x 10^{-4}**

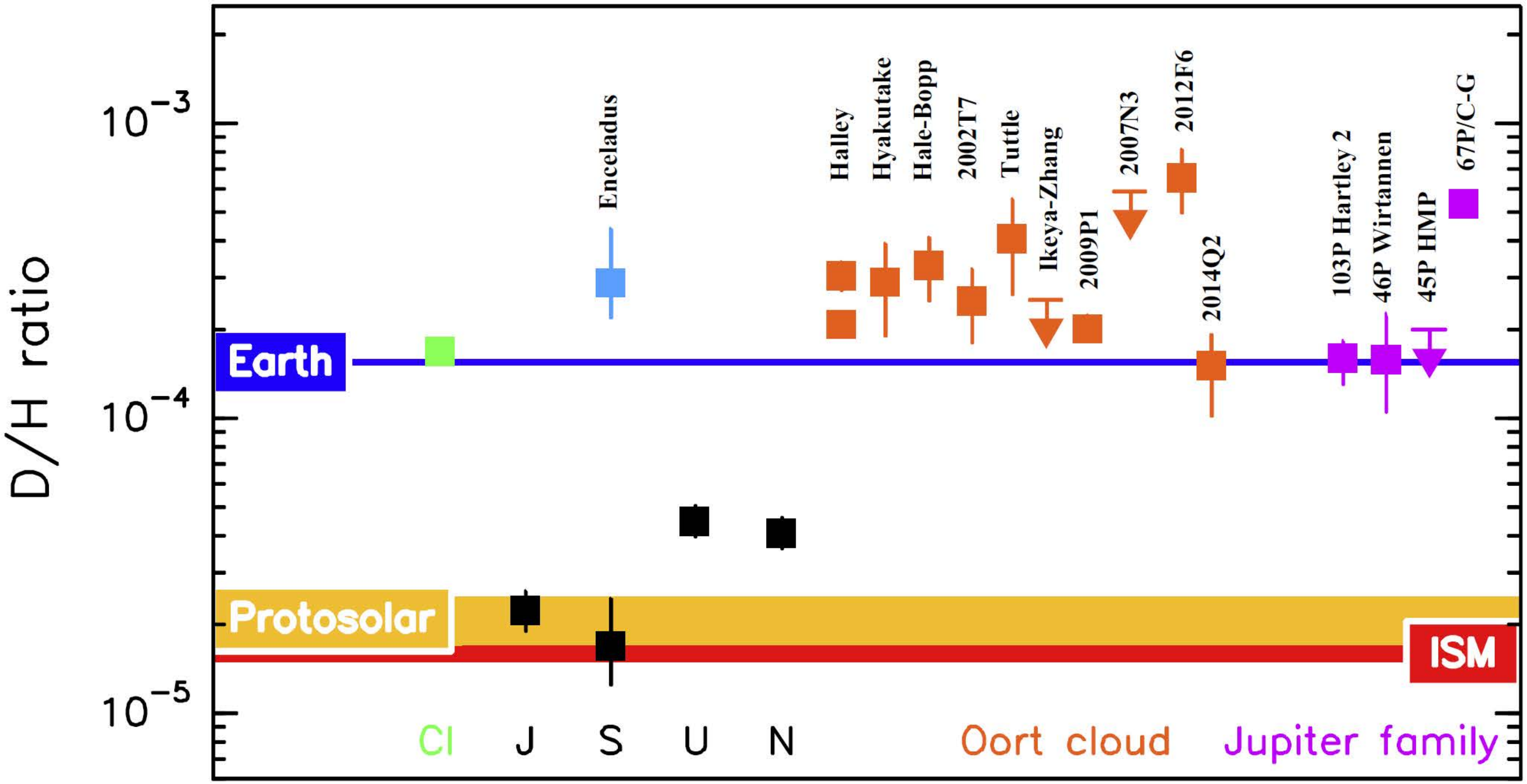
D/H(VSMOW) = 1.558 ± 0.001 x 10^{-4}

D/H in solar system as known in 2011



Hartogh et al. Nature (2011)

Situation 2019



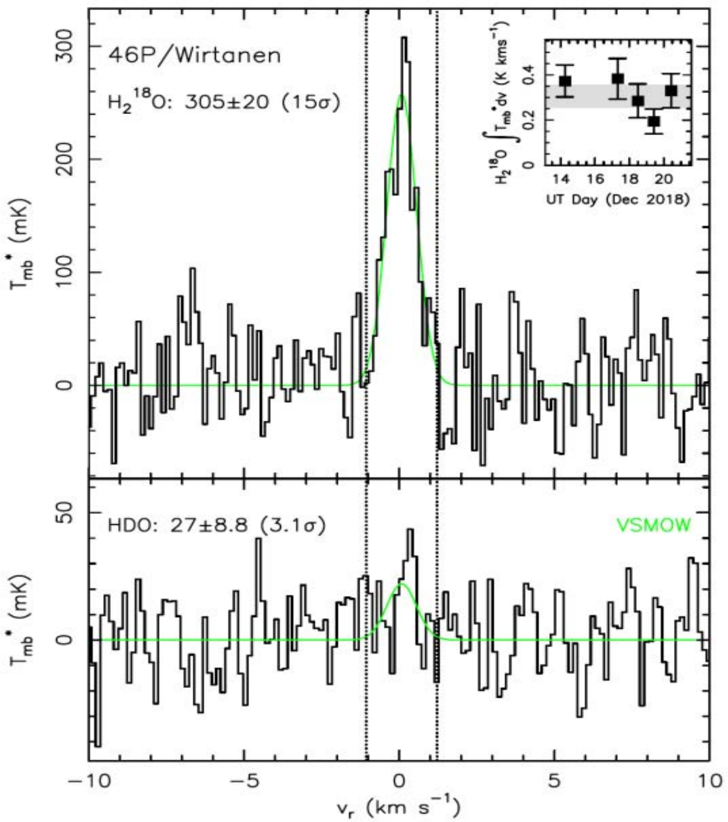
More precise D/H values in Uranus and Neptune

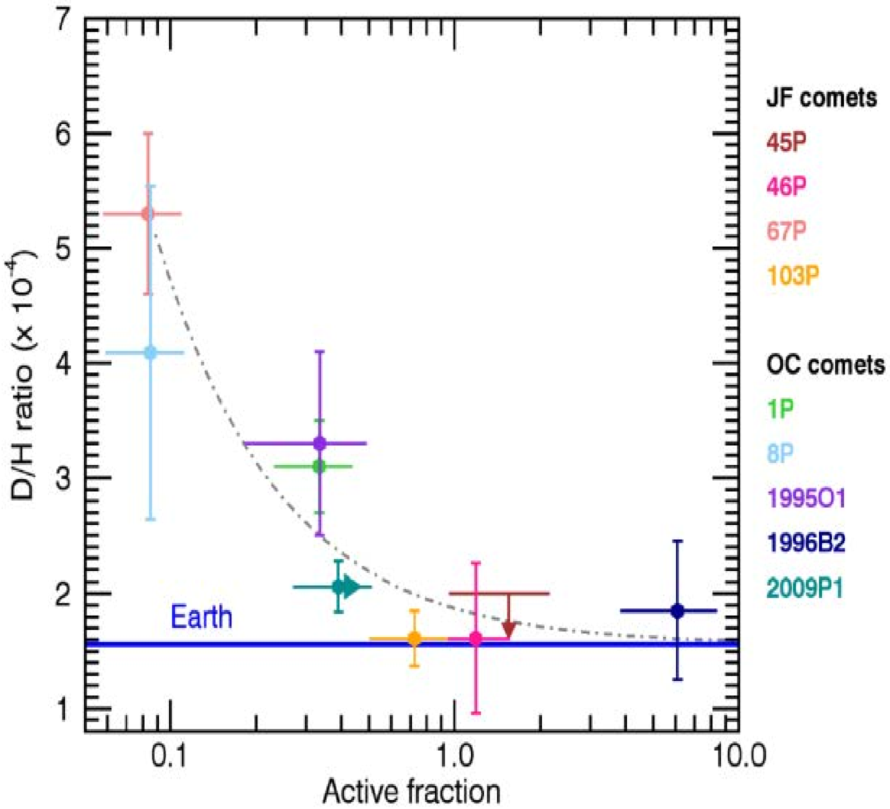
Another data analysis of D/H in Halley

Four additional OCC D/H measurements, smallest and largest values ever

Three more JFC D/H measurements, one large value (67P, in-situ), two Hartley 2 like ones (observed with HIFI and GREAT, both by ***Darek Lis et al. (APJL 2013 and A&A 2019)***

GREAT D/H 46P Wirtannen





Darek believes that "VSMOW-comets" all belong to the class of "hyperactive" comets.

Lis et al, A&A 2019

Interpretation

- Classical models do not fit
- A number of new disk models and solar system formation models developed or under development
- Formation regions of OCCs and JFCs debated
- New classification („hyperactive“)
- Cometary delivery to Earth cannot be excluded, at least taking into account D/H found in OCCs and JFCs recently.
- Discussions on error bars and compatiblity of different methods (in-situ, IR, submm)
- Set of observations still to small for good statistics

Outlook

- More HDO observation to come with GREAT (potentially also of 67P in Jan 2022)
- D/H observations in water planned with JUICE-SWI and JUICE-PEP in the Jupiter system after 2029 (Jupiter‘s stratosphere, Galilean satellites‘ exospheres)
- SWI covers the bands 530-625 GHz and 1080 1275 GHz.
- Launch of JUICE in 2022

JUICE Submm Wave Instrument