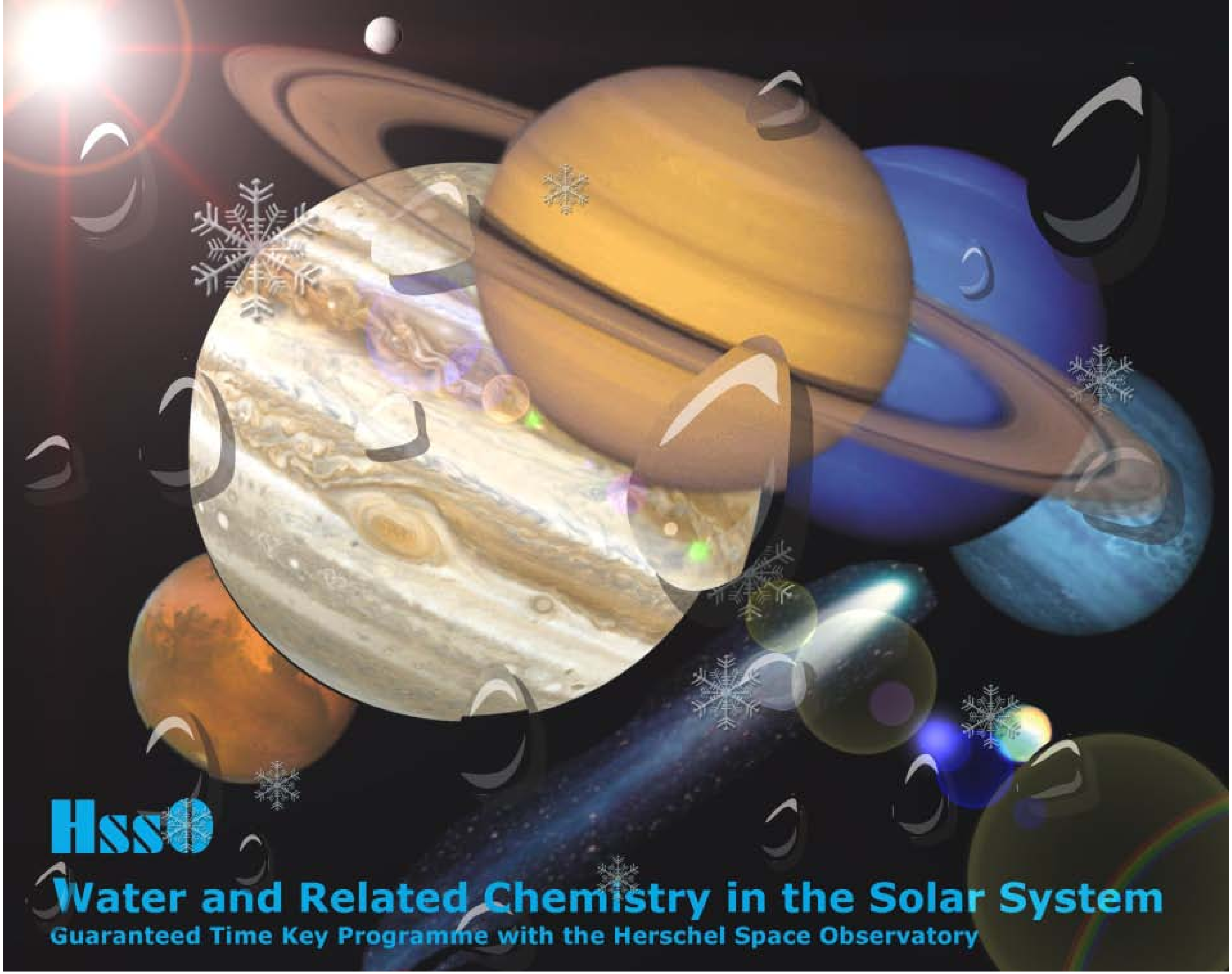
Planetary Science with GREAT after Herschel/HIFI

Paul Hartogh, MPS

Outline

- HssO: focus on water
- HIFI observations of Mars
- HIFI and the outer planets
- HIFI comets: Garradd and Hartley 2 - D/H in the solar system
- GREAT outer planets
- GREAT Venus and Mars
- GREAT comets

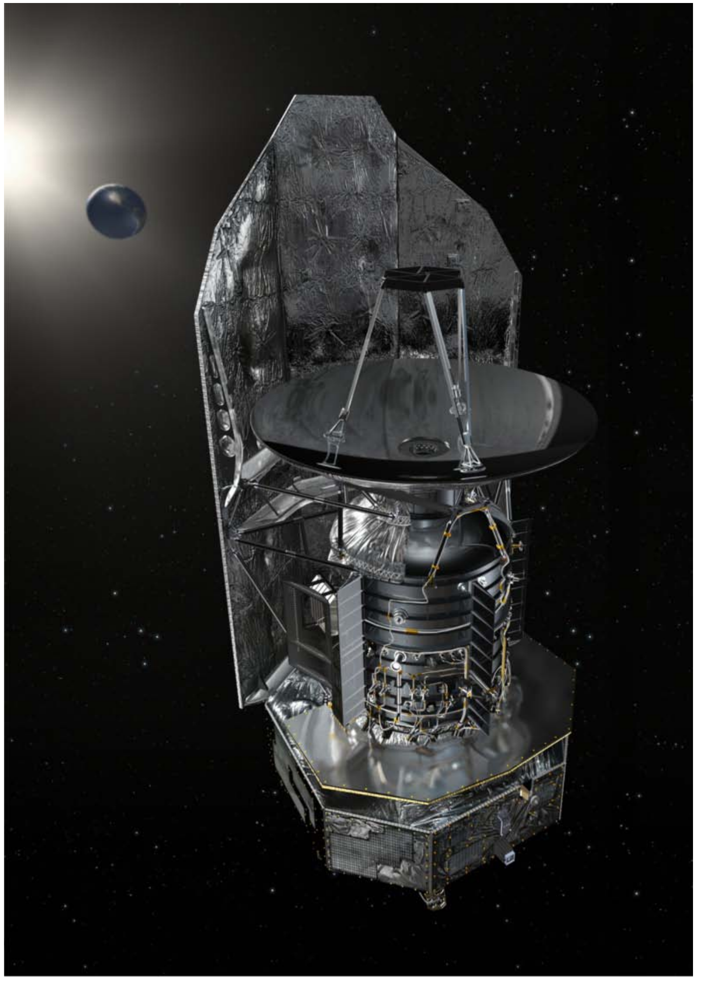


HssO Team: 50 scientists from 10 countries, see URL

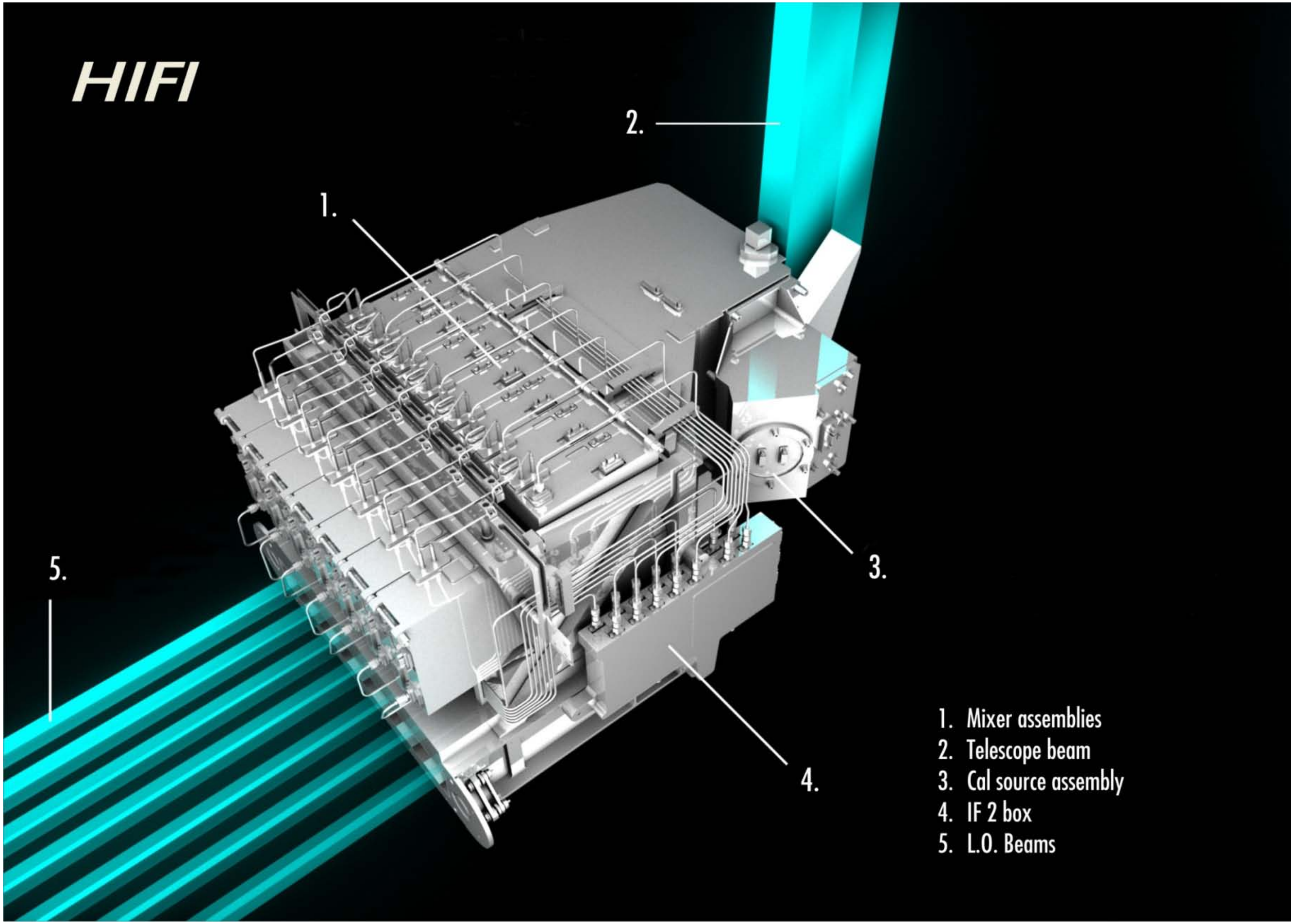
http://www.mps.mpg.de/projects/herschel/HssO/index.htm

Herschel spacecraft specs

- telescope (eff) diam 3.5 m
- *telescope WFE < 6 µm*
- *telescope temp < 90 K*
- *telescope emissivity < 4%*
- *abs/rel pointg (68%) < 3.7" / 0.3"*
- science instruments 3
- science data rate 130 kbps
- *cryostat lifetime > 3.5 years*
- height / width ~ 7.5 / 4 m
- launch mass ~ 3200 kg
- power ~ 1500 W
- orbit 'large' Lissajous around L2
- solar aspect angle 60-120 deg
- launcher (w Planck) Ariane 5 ECA



Heterodyne Instrument for the Far Infrared



HIFI designed for:

- Spectral Scans and Spectral line surveys
- Very high spectral resolution
- Widest possible coverage in the unexplored FIR/Submm range

1. Frequency coverage:

480 – 1250 GHz (625-240 μm)
1410 – 1910 GHz (212-157 μm)

2. Sensitivity

Near-quantum noise limit sensitivity

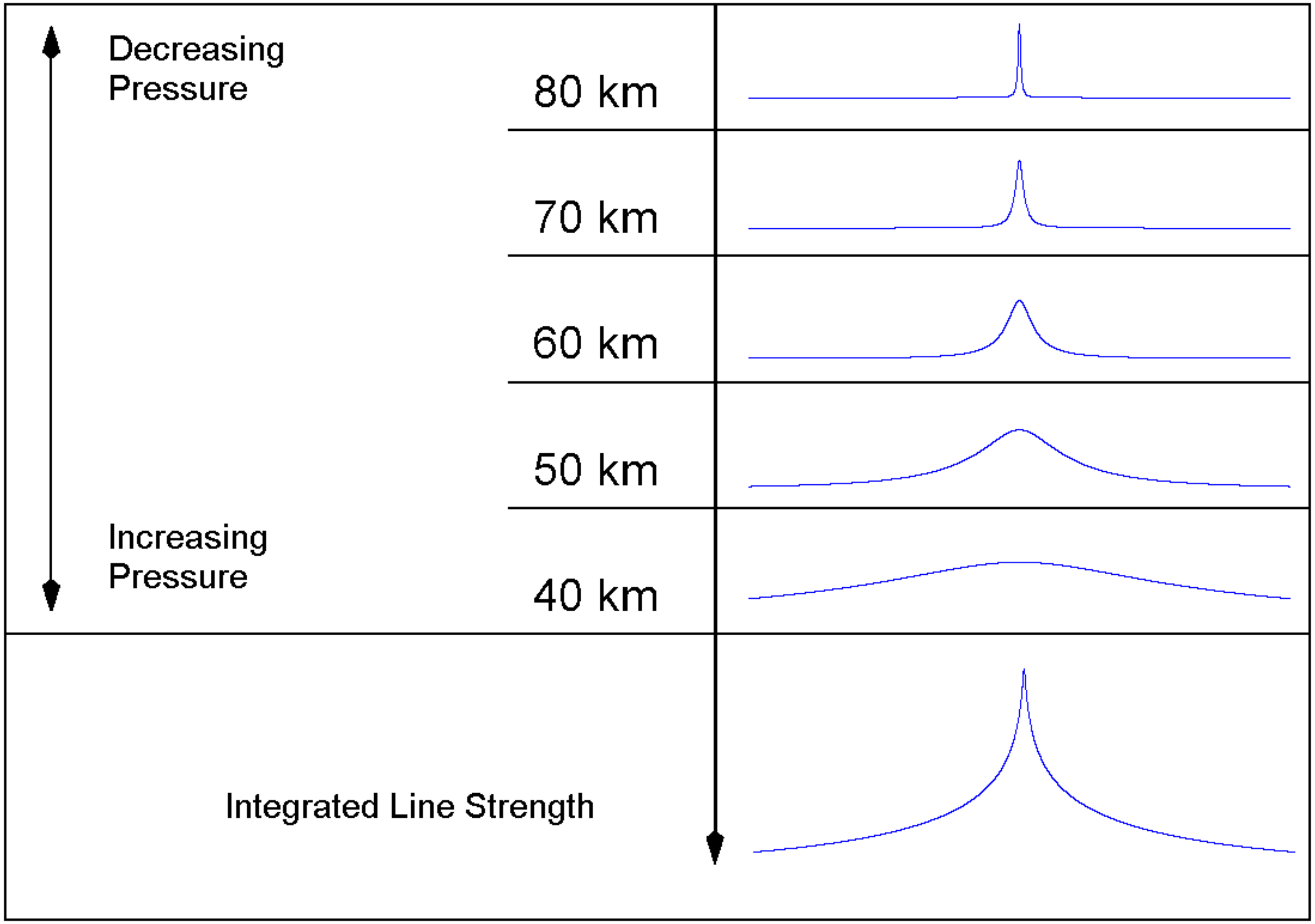
- IF bandwidth/Resolution:
  - 4 GHz (in 2 polarisations)
  - 140 – 280 kHz –0.5 and 1 MHz

3. Calibration Accuracy: 10% baseline; 3% goal

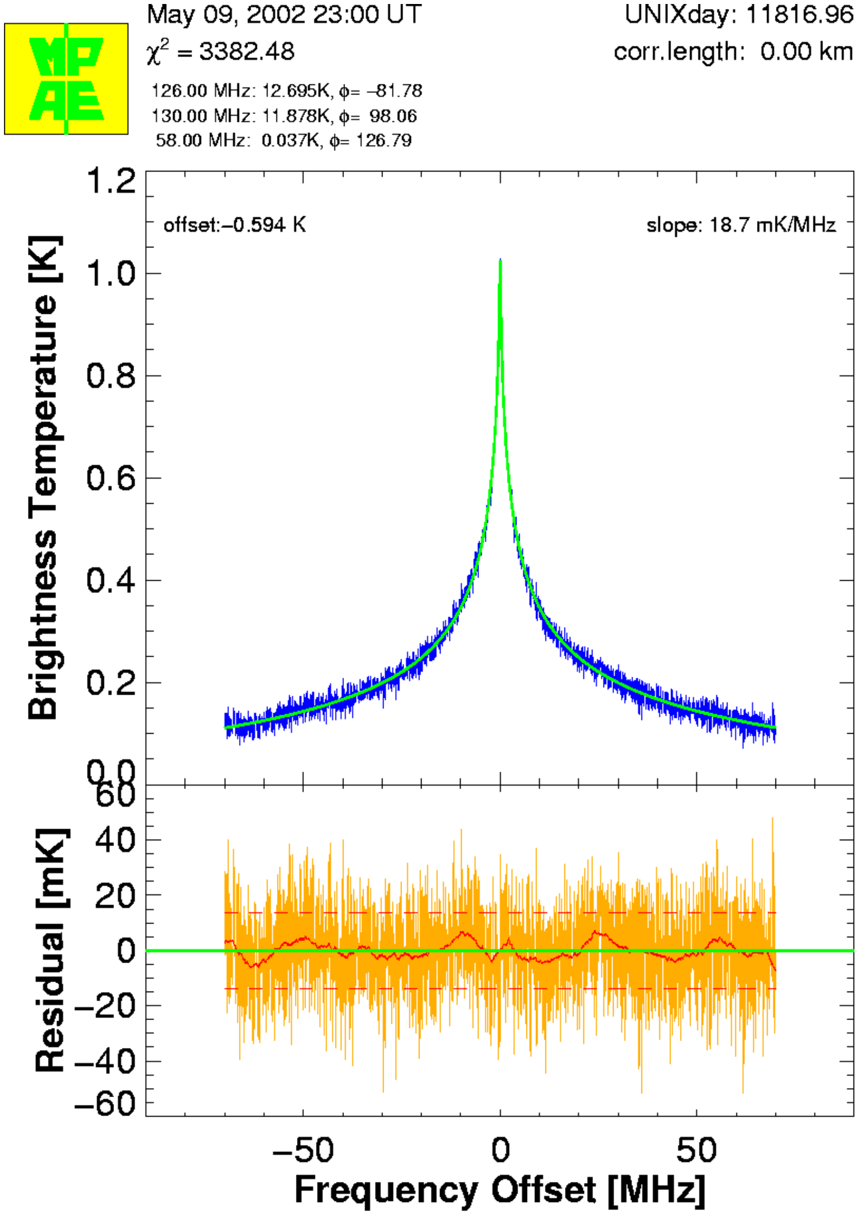
- **Heterodyne spectroscopy**
  - single pixel on the sky
  - very high spectral resolution
- **7 dual-pol mixer bands**
  - 480-1250 GHz (625-240 μm) 5x2 SIS mixers, IF 4-8 GHz
  - 1410-1910 GHz(212-157 μm; 2x2 HEB mixers, IF 2.4-4.8 GHz
- **14 LO sub-bands**
  - LO source unit in common
  - LO multiplier chains
- **2 spectrometer systems;**
  - for each polarisation
    - auto-correlator spectrometer
    - acousto-optical spectrometer

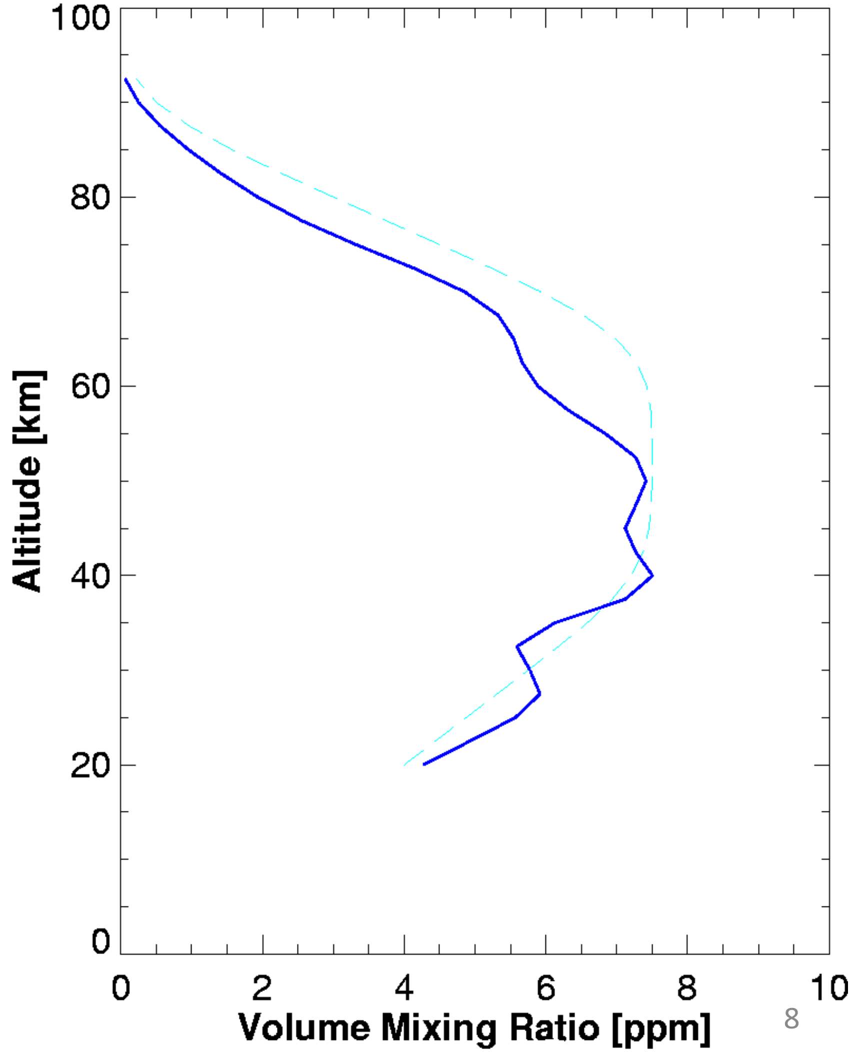
Angular Resolution (with Herschel): 12″- 40″

Vertical information in line shape via collisional broadening and opacity Lines may be detected in emission or absorption, depending on temperature profile. HIFI resolves the line shapes (resolution > 10^6)

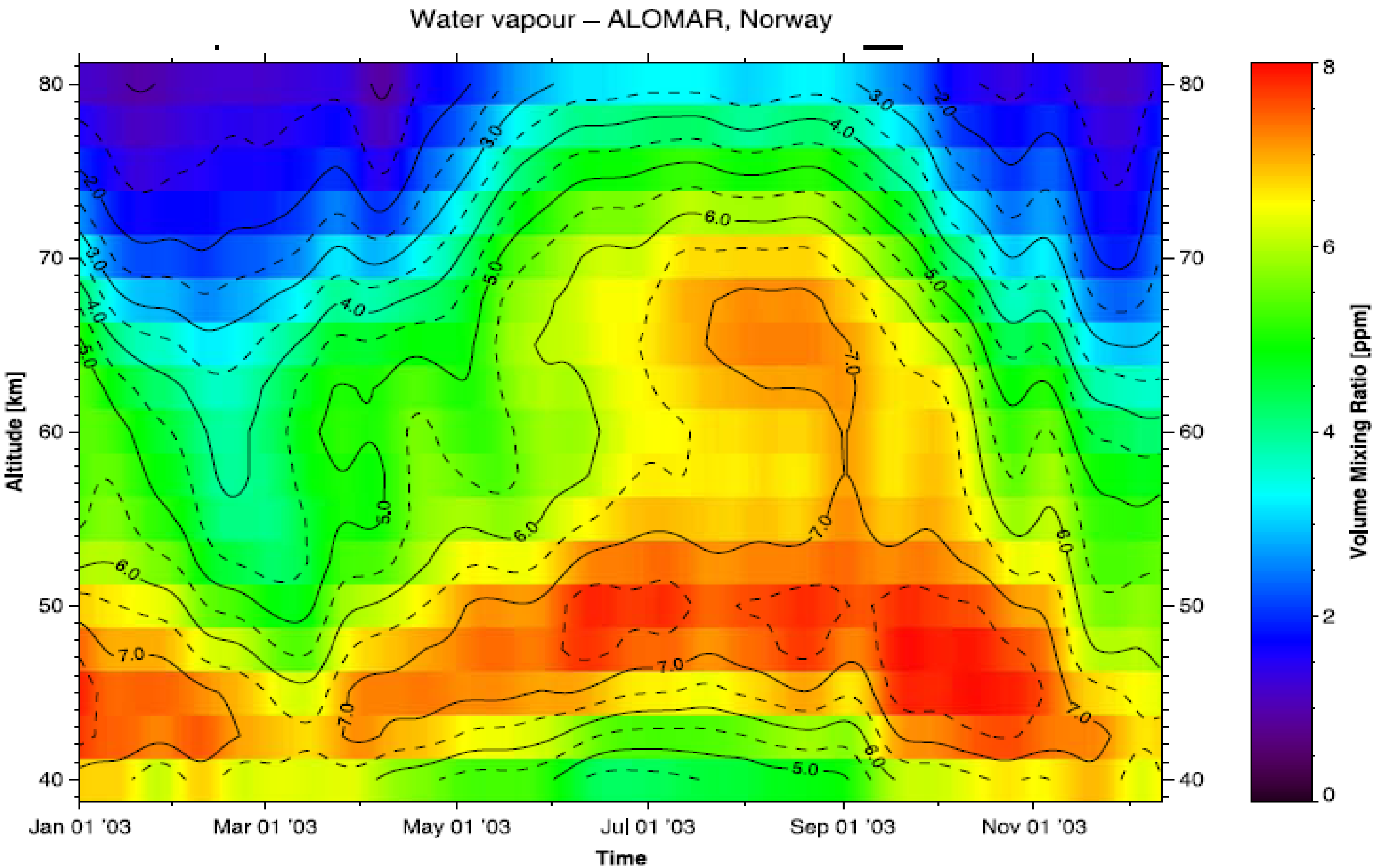


WASPAM Water Vapor spectrum and vertical profile



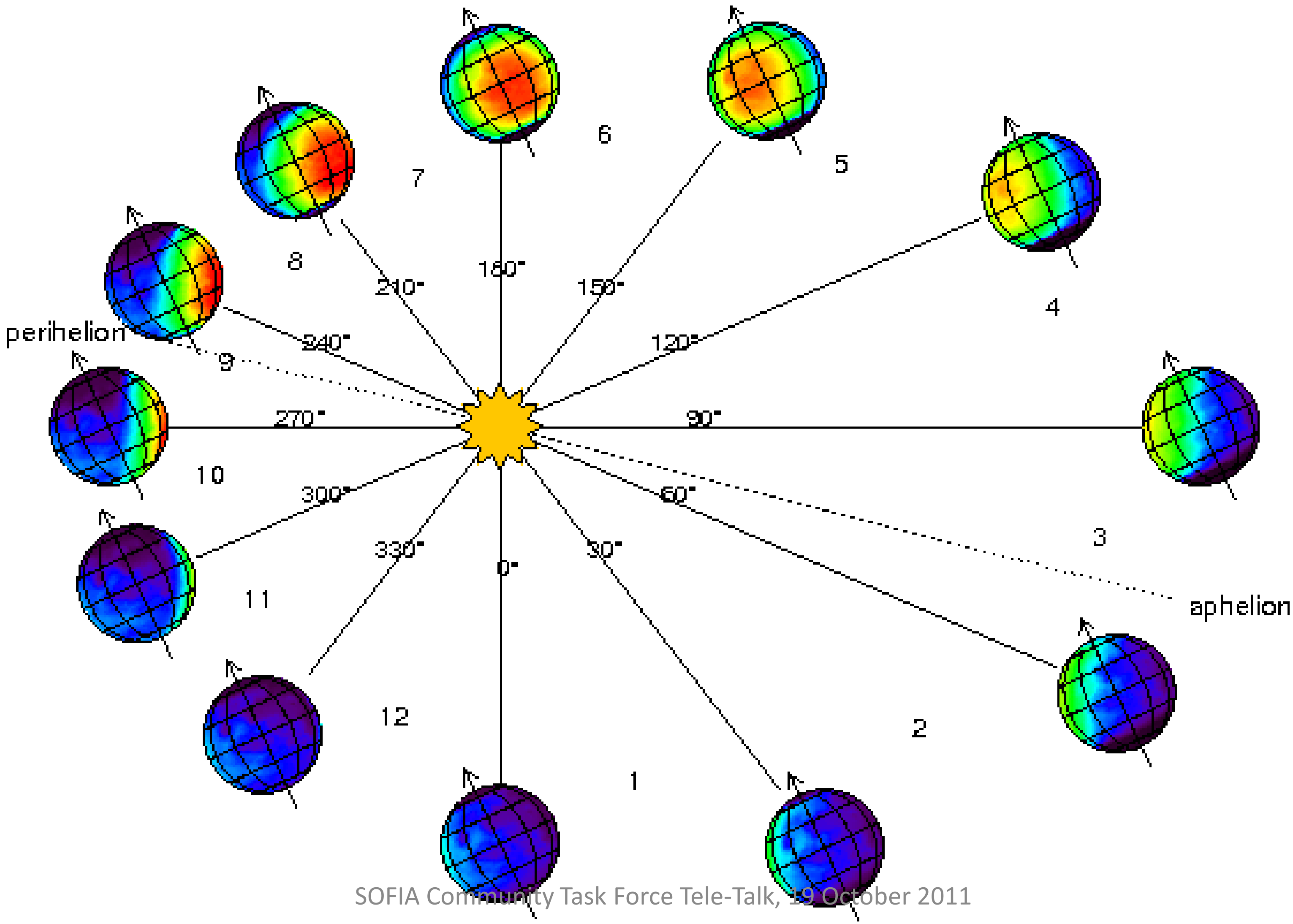


Annual water vapor variation in 2003 at ALOMAR

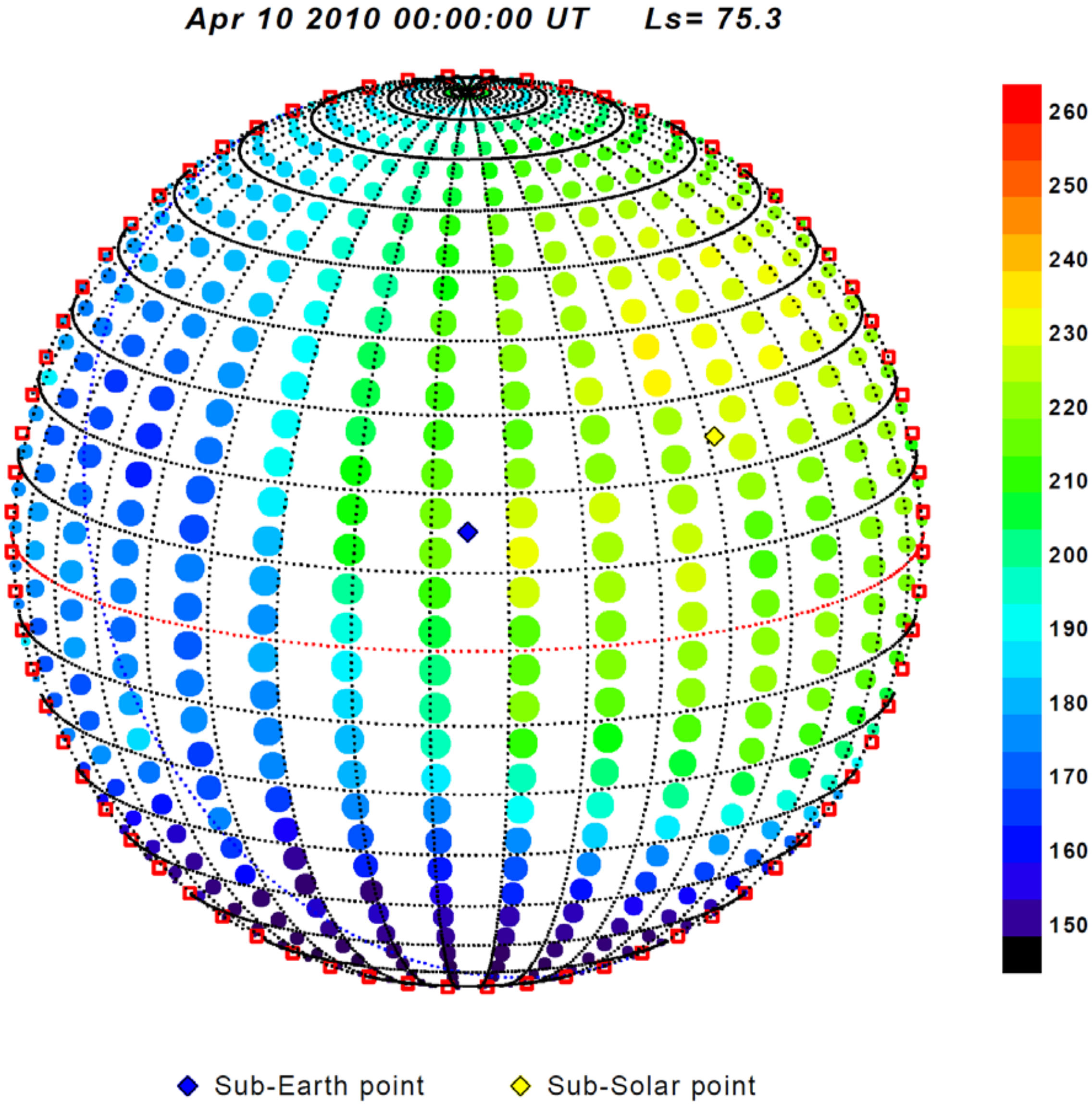


Hartogh et al, 2004

Martian seasons

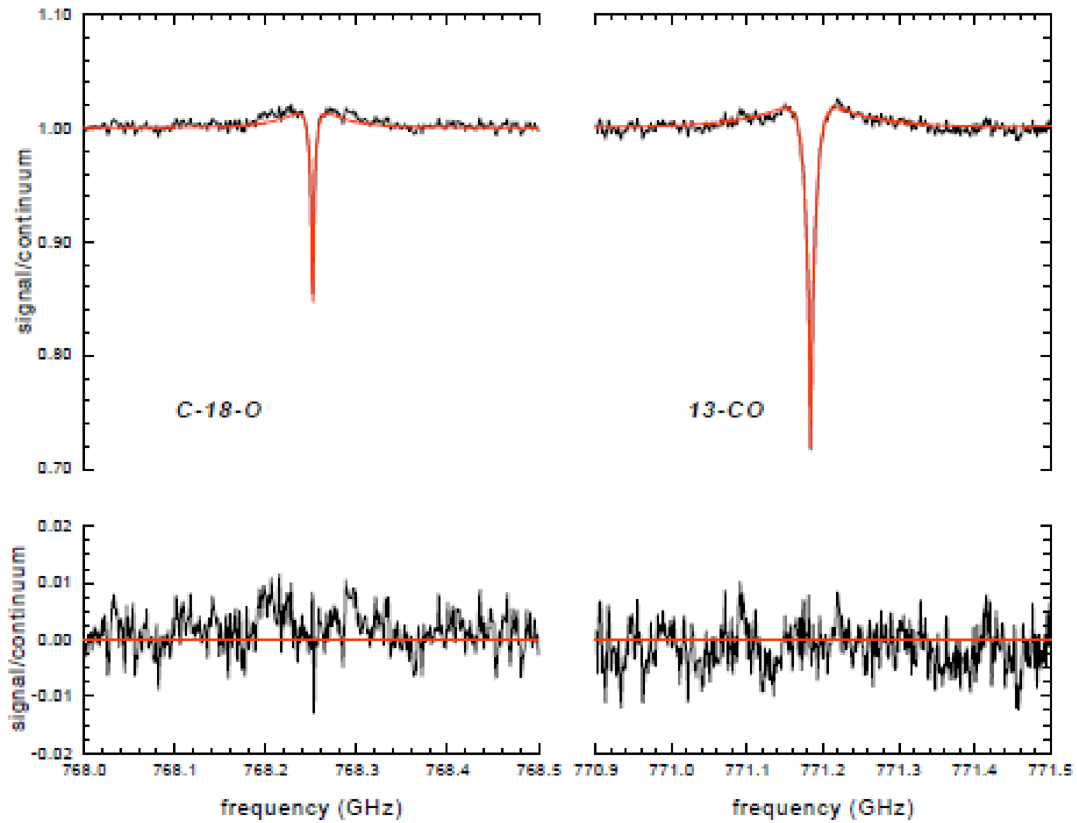


Mars Surface Temperature during Northern Spring

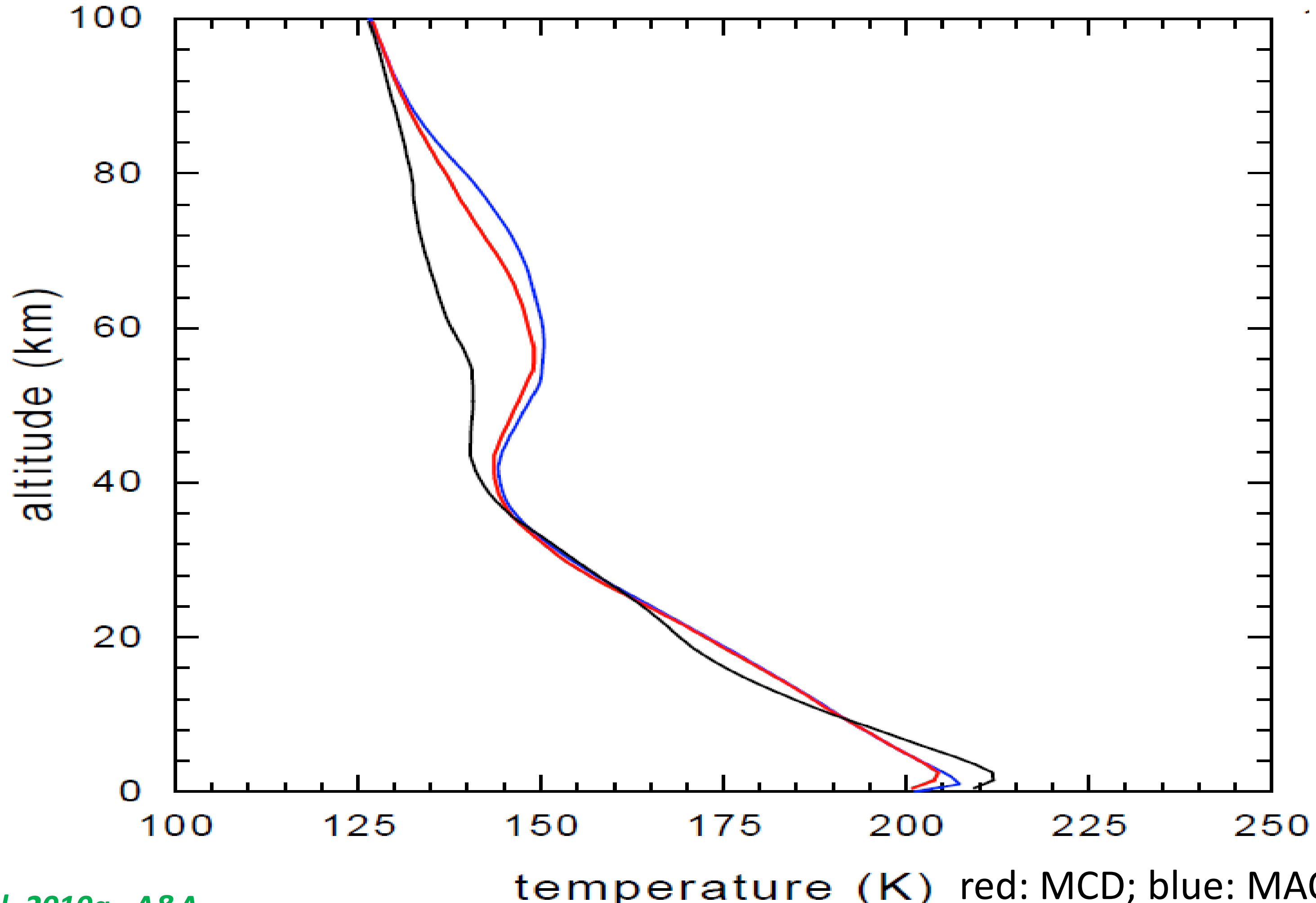


HIFI Mars CO observations

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

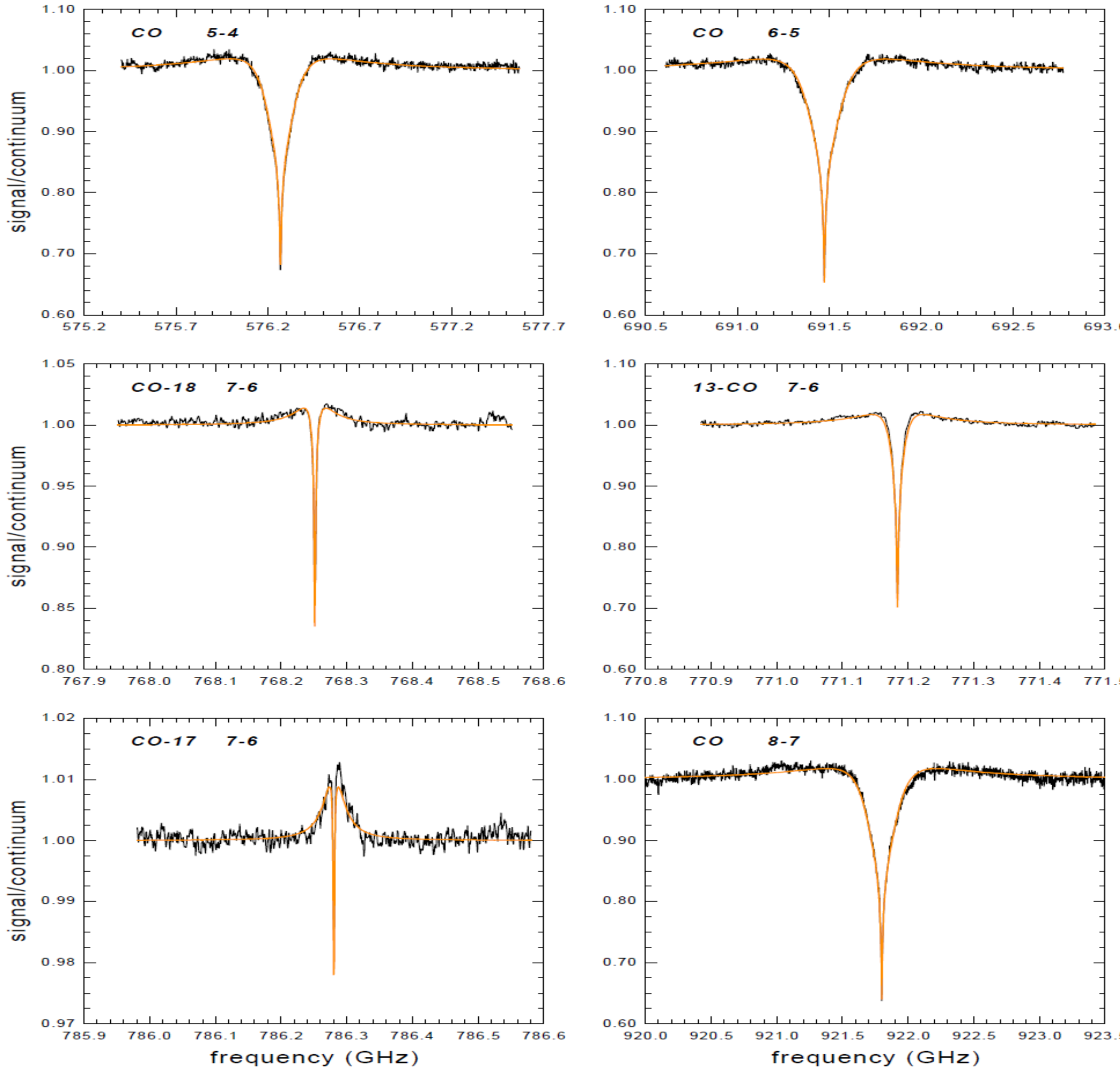


etrieved temperature profile and 980 ppm constant with altitude CO volume mixing ratio

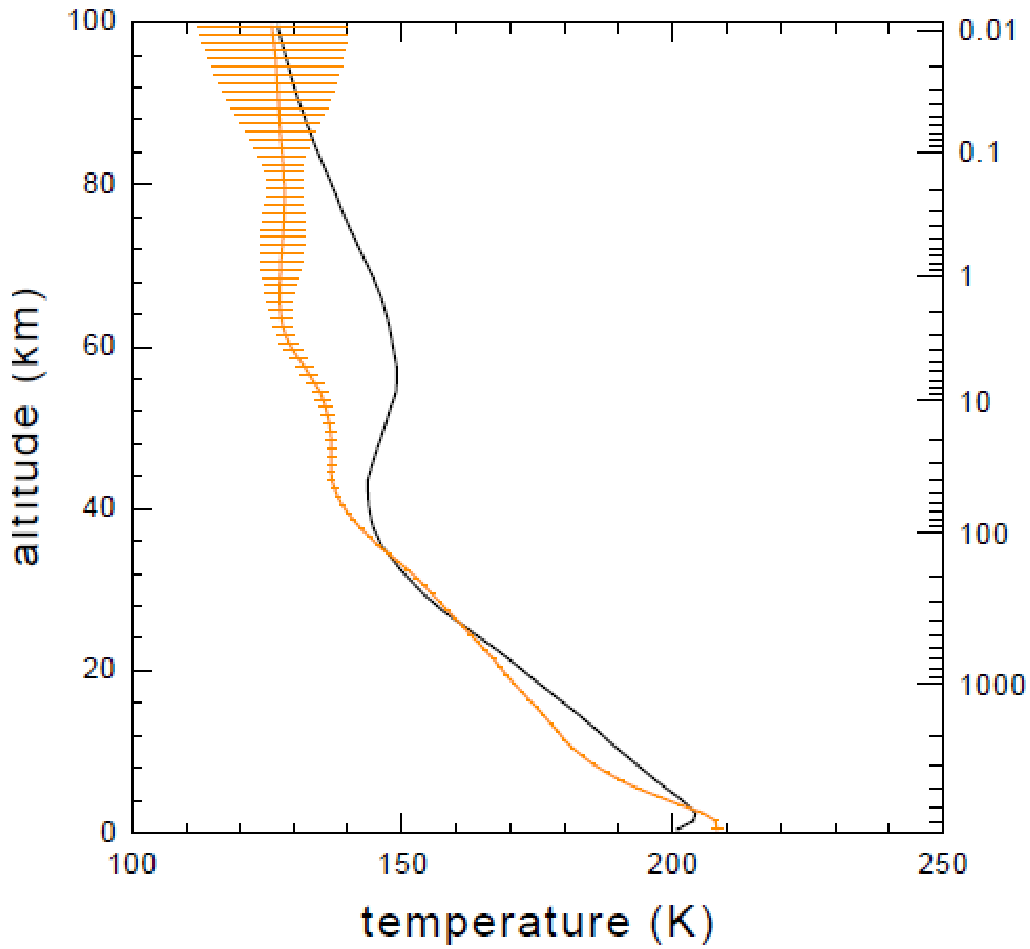


red: MCD; blue: MAOAM; black: observation

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


CO 5-4
CO 6-5
CO-18 7-6
13-CO 7-6
CO-17 7-6
CO 8-7
signal/continuum
frequency (GHz)

Temperature profile retrieved with all CO lines confirmes the one derived before



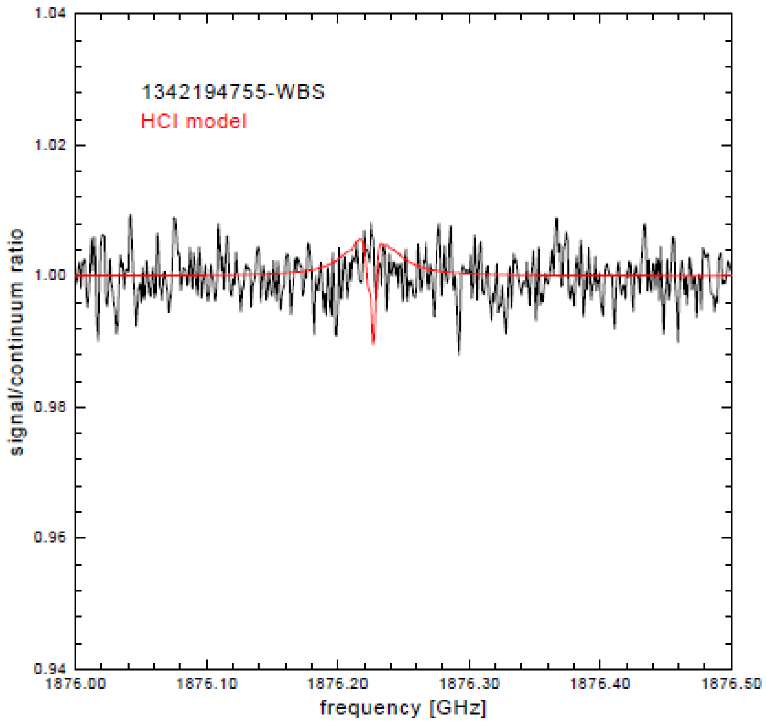
What about HCl and H_2O_2 ?

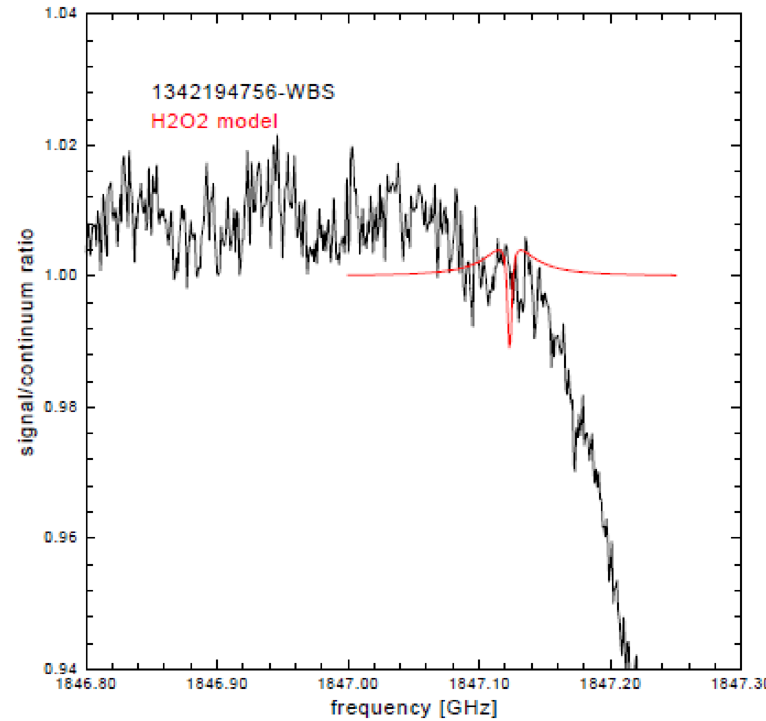
- HCl volcanic gas. Detection would constrain volcanic outgassing. Potential important also for destruction of methane (M. Mumma‘s work)

- H_2O_2 important constraint for hydrogen / oxygen photochemistry on Mars.

- H_2O_2 snow believed to kill all live on martian surface. Produced in eletrostatic discharge reaction during dust storms. (see Sushil Artreya‘s work)

Upper limits on HCl and H_2O_2



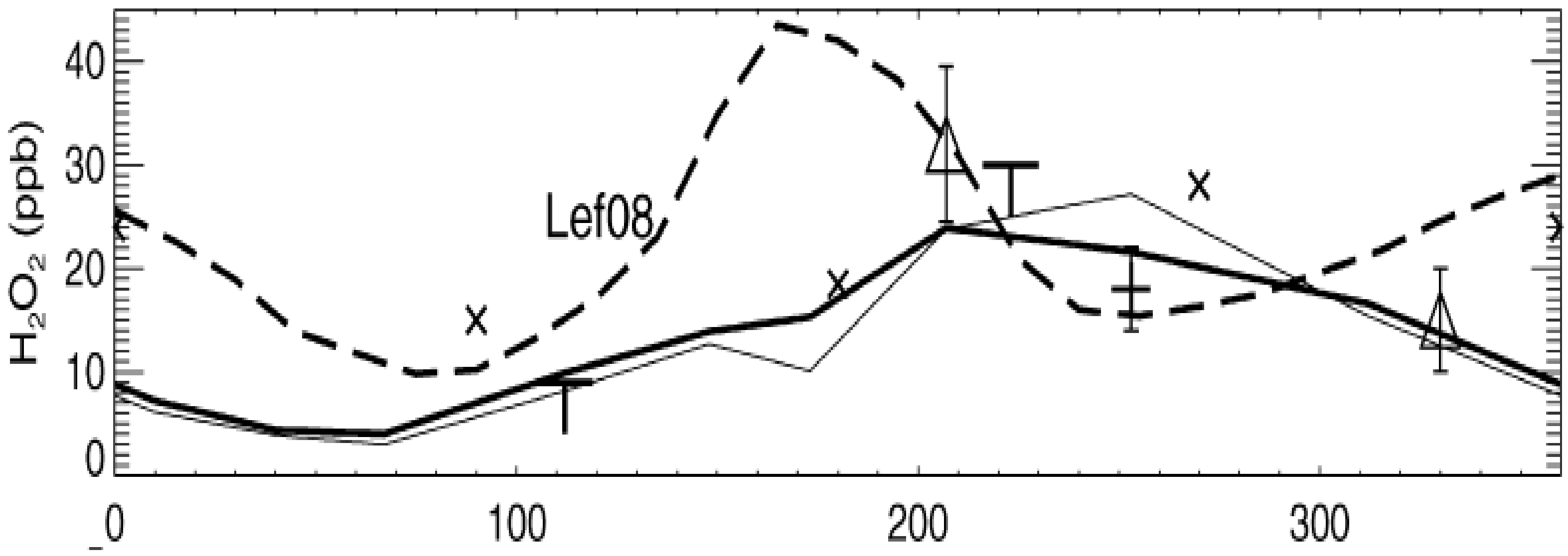


< 200 ppt

< 2 ppb

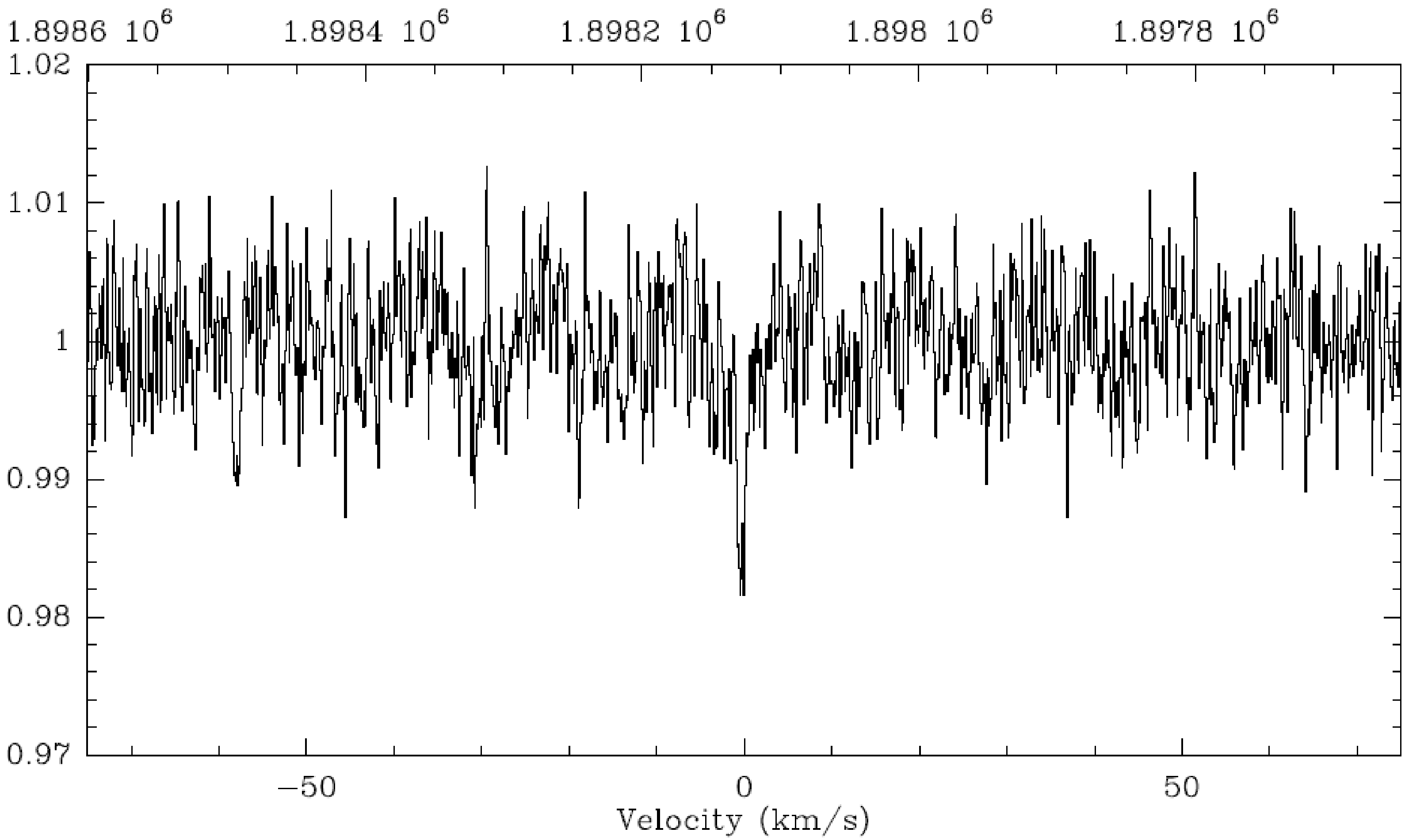
Hartogh et al. 2010b, A&A

Model abundances of H_2O_2



Krasnopolsky 2009, Icarus

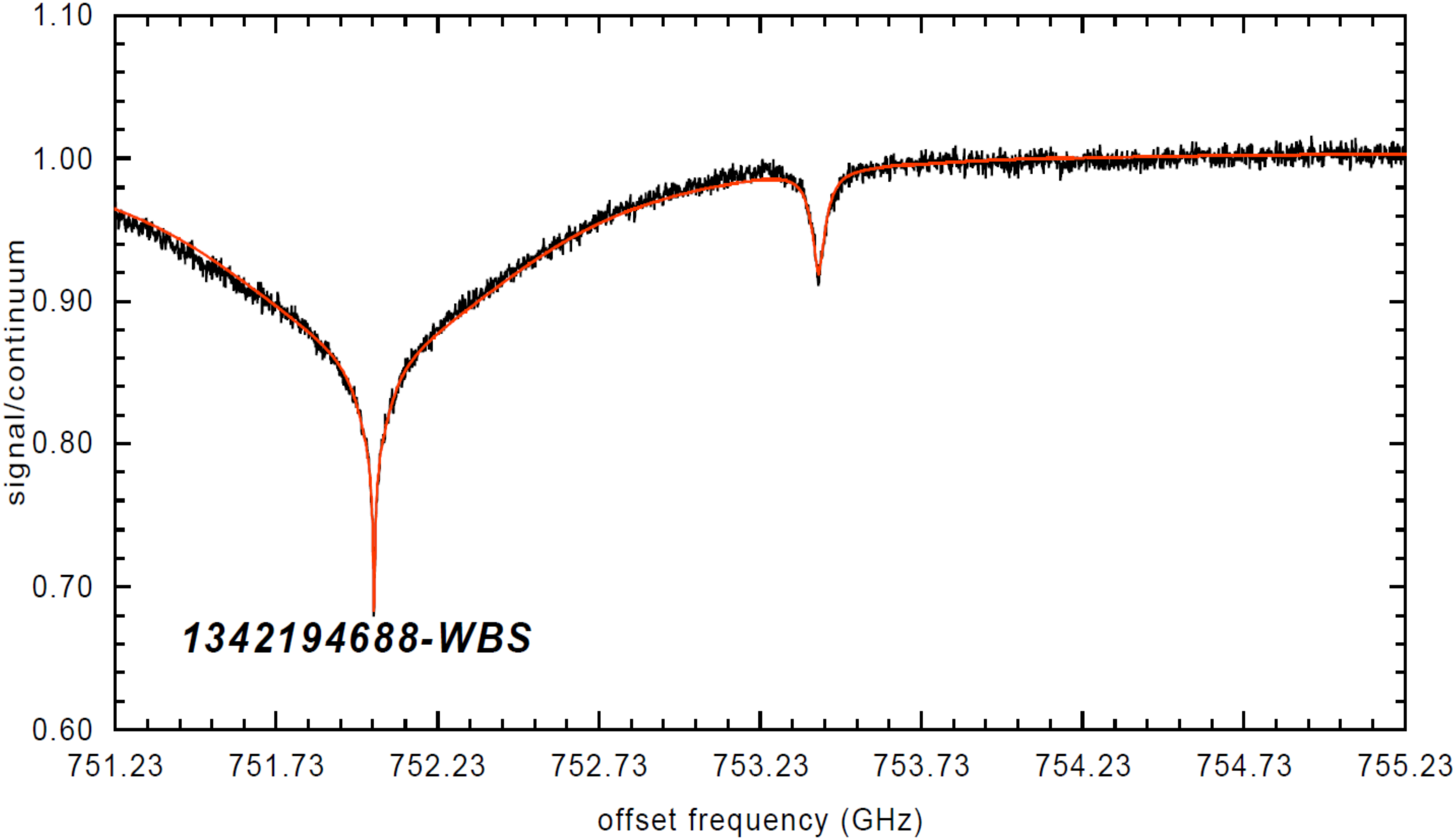
Fall 2011: detection of H_2O_2! Ls=10°



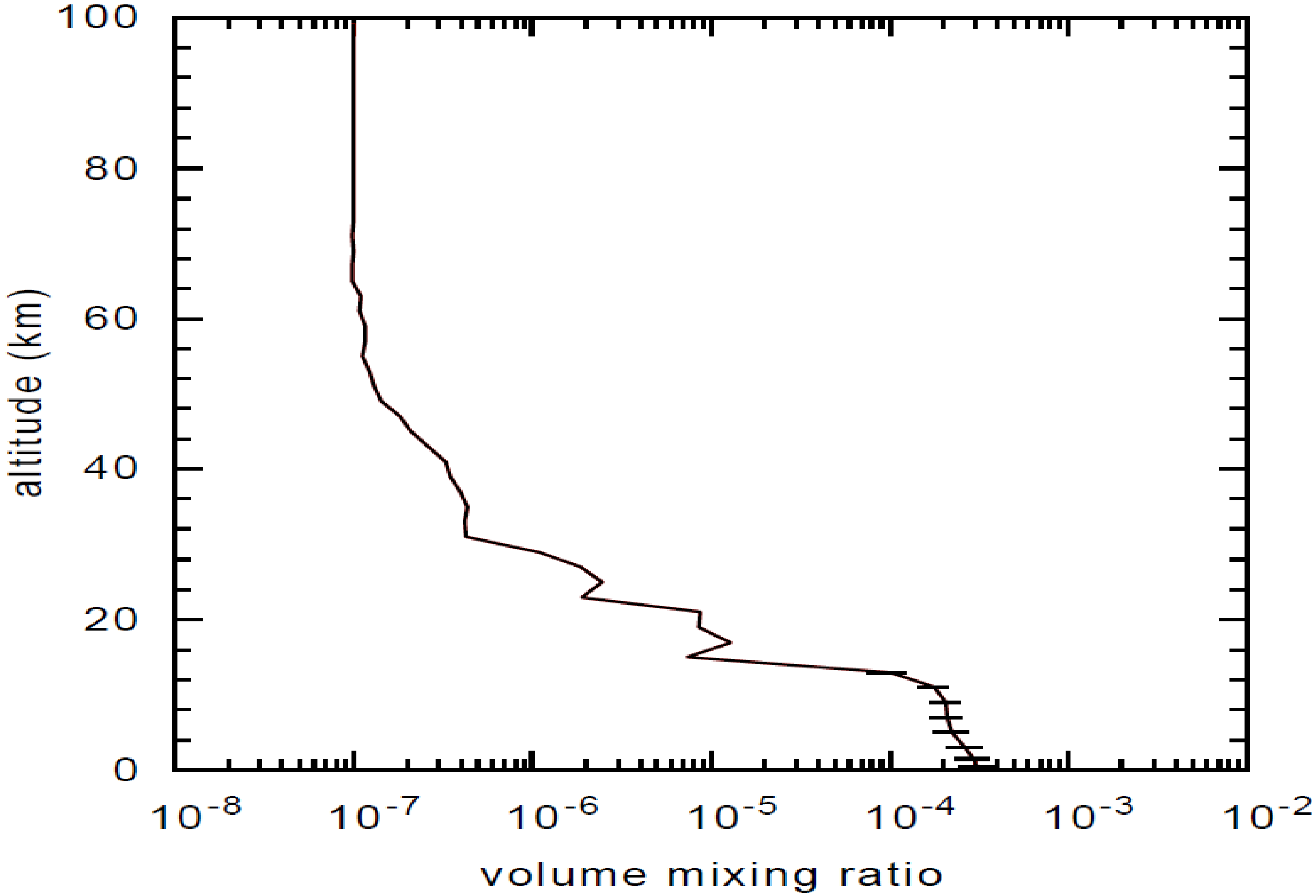
Water vapor

- Very important source gas for atmospheric chemistry
- Maximum column density around Northern summer (more water ice at North pole)
- Maximum vertical extension believed to be during southern summer (nearer to sun, warmer, different meridional circulation, e.g. Hartogh et al, JGR 2005).
- No vertical profiles from satellites constraining the variable hygropause!
- Ls – coverage of vertical profile very important for understanding a number of phenomena in the Martian atmosphere.

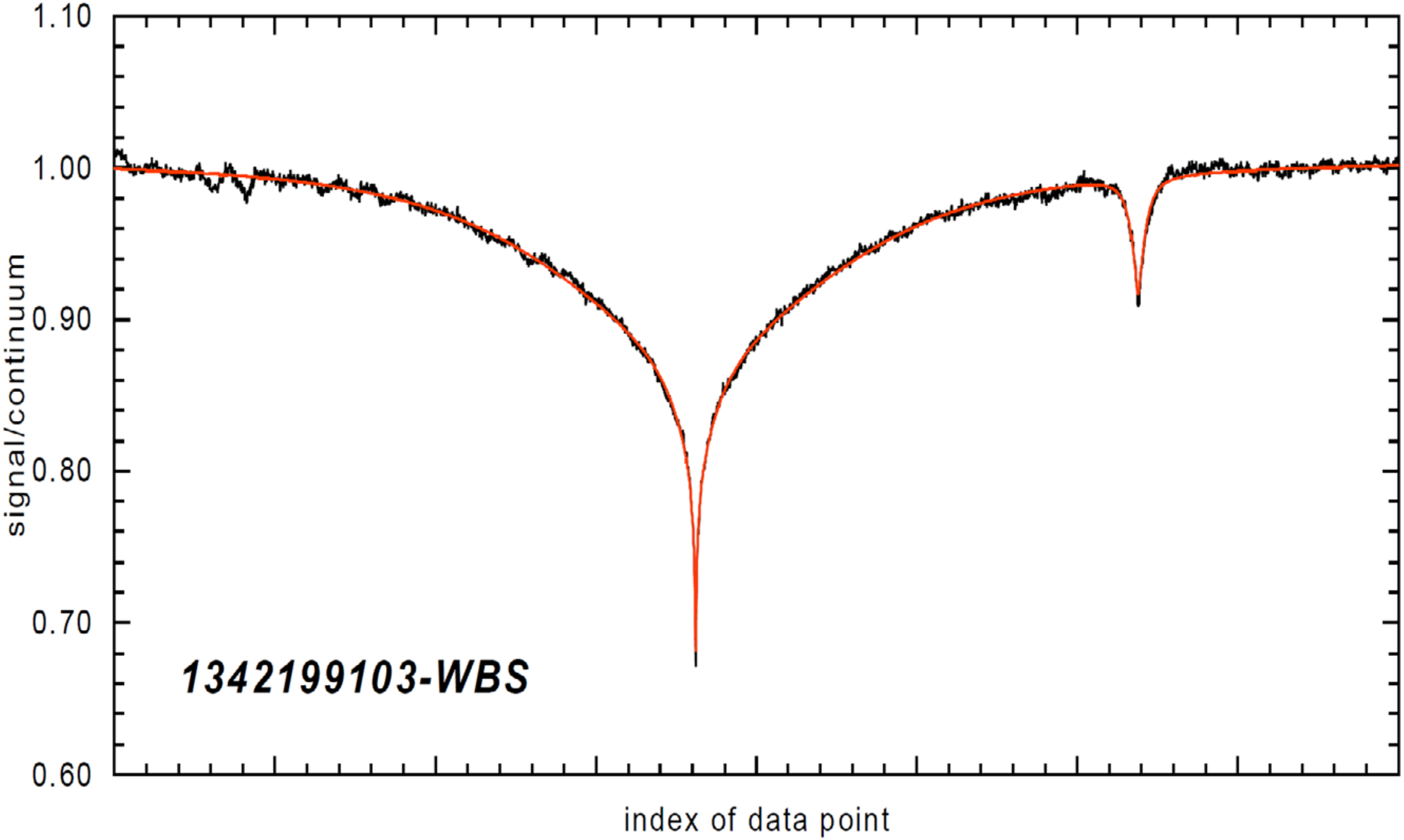
H_2O and HDO at Ls = 78°



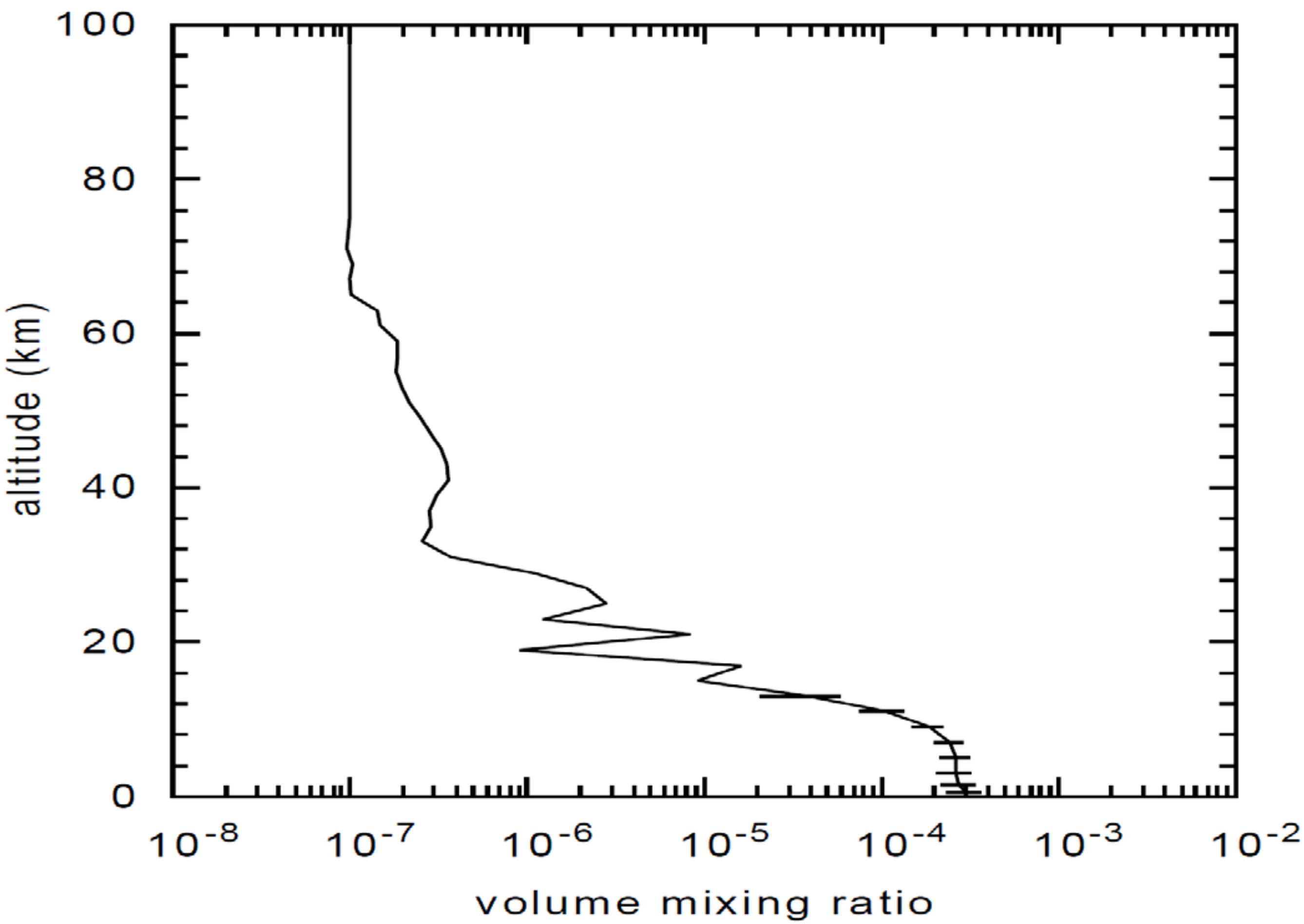
Vertical profile of water at Ls = 78°



H_2O and HDO at Ls = 110°



Vertical profile of water at $\mathrm{Ls} = 110°$



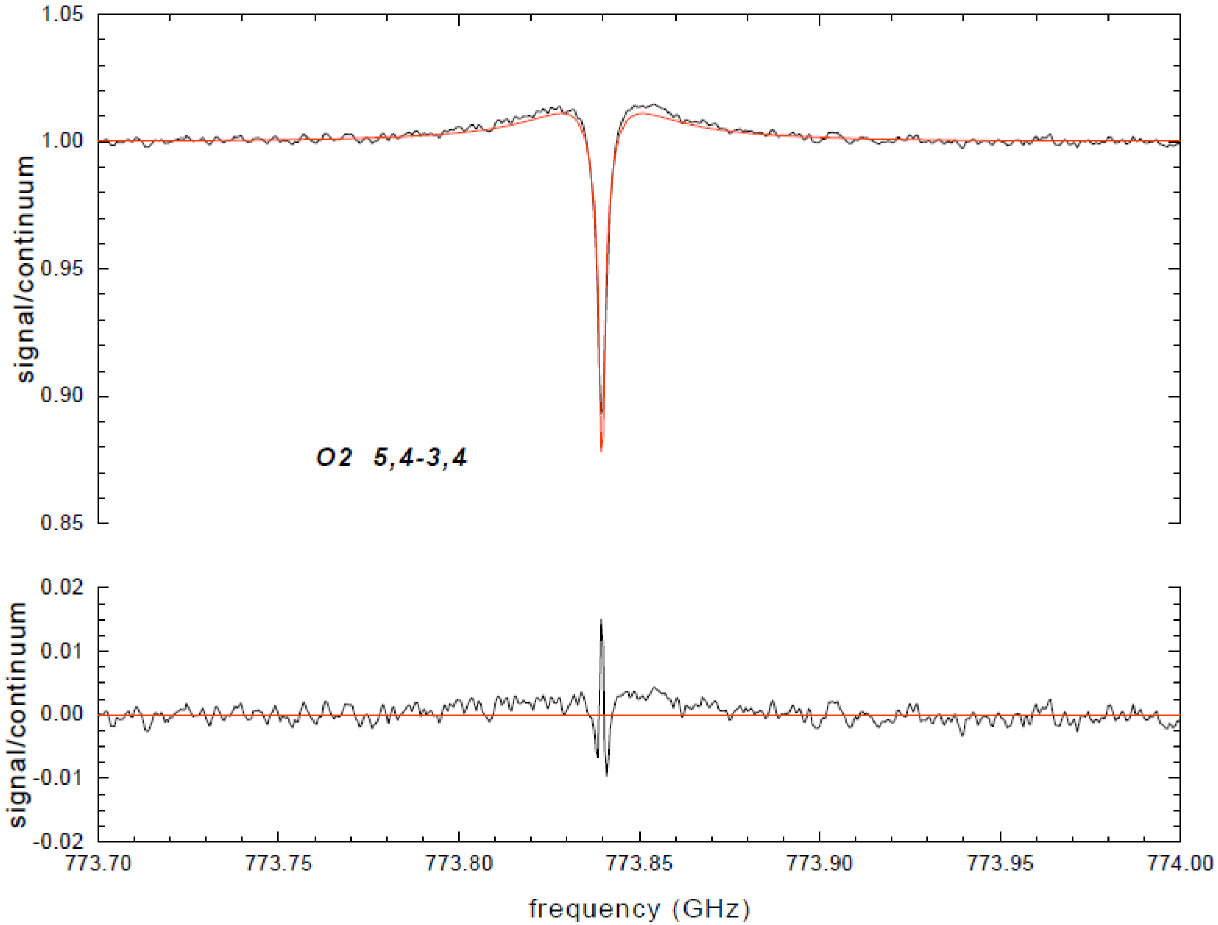
Urgently required GREAT observations

- Vertical profiles of water during seasons not covered by Herschel.
- Very bad: missed data points due to HIFI failure in 2009.
- GREAT can provide this information (see below)!
- Optically thin GREAT lines have advantages!!!

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.

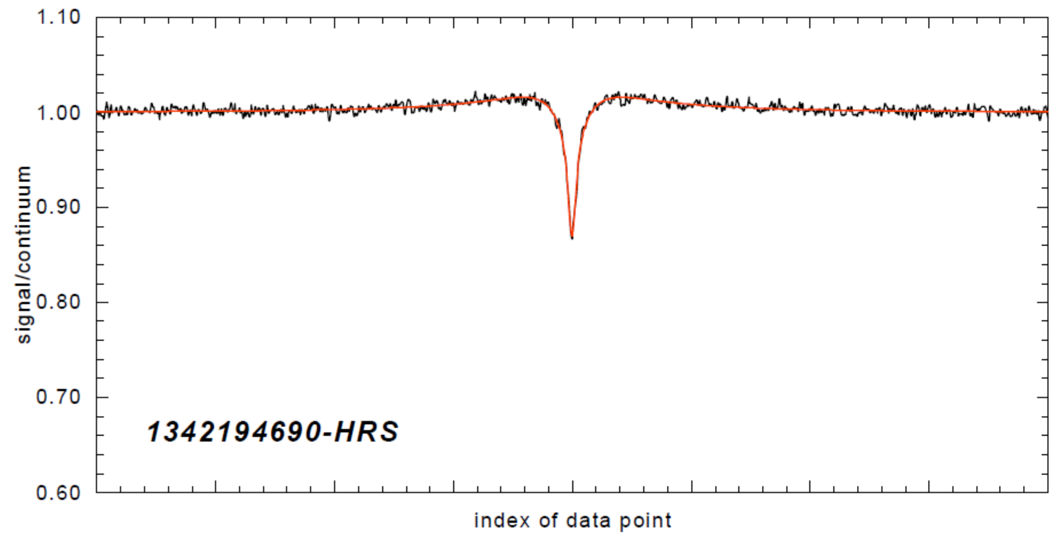
First submm detection of O_2

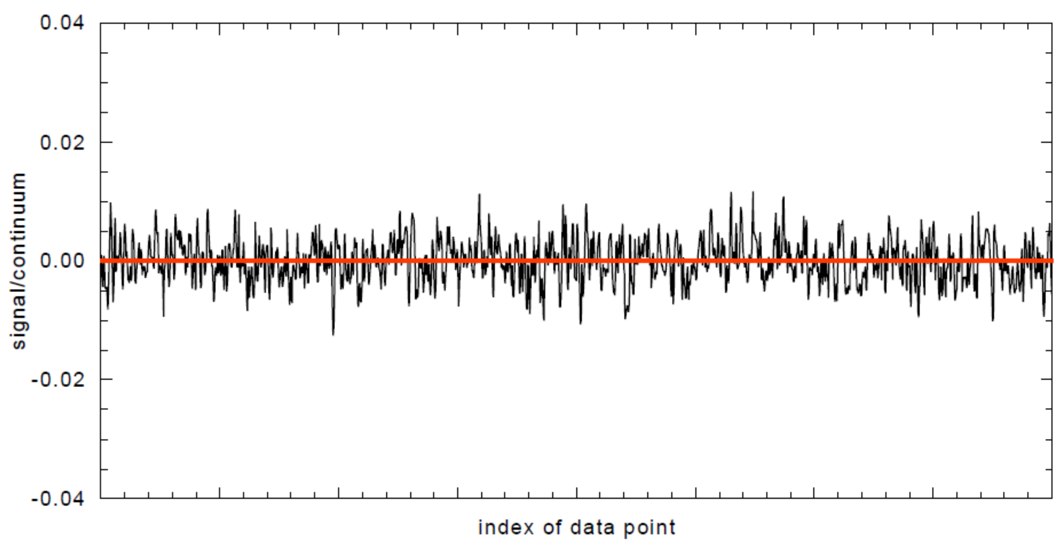


Fit of constant profile provides volume mixing ratio of 1400 ppm. However residual indicates that profile is not constant with altitude.

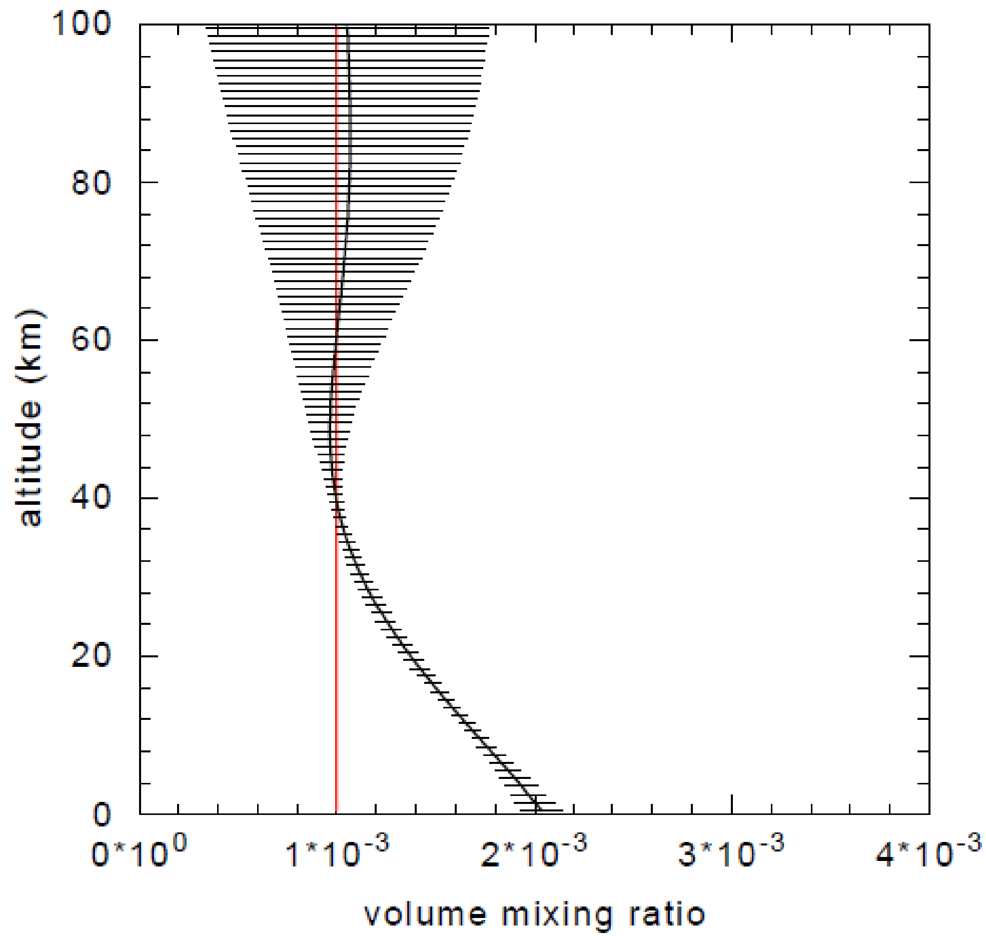
Hartogh et al. 2010b, A&A

Non-constant profile provides better fit

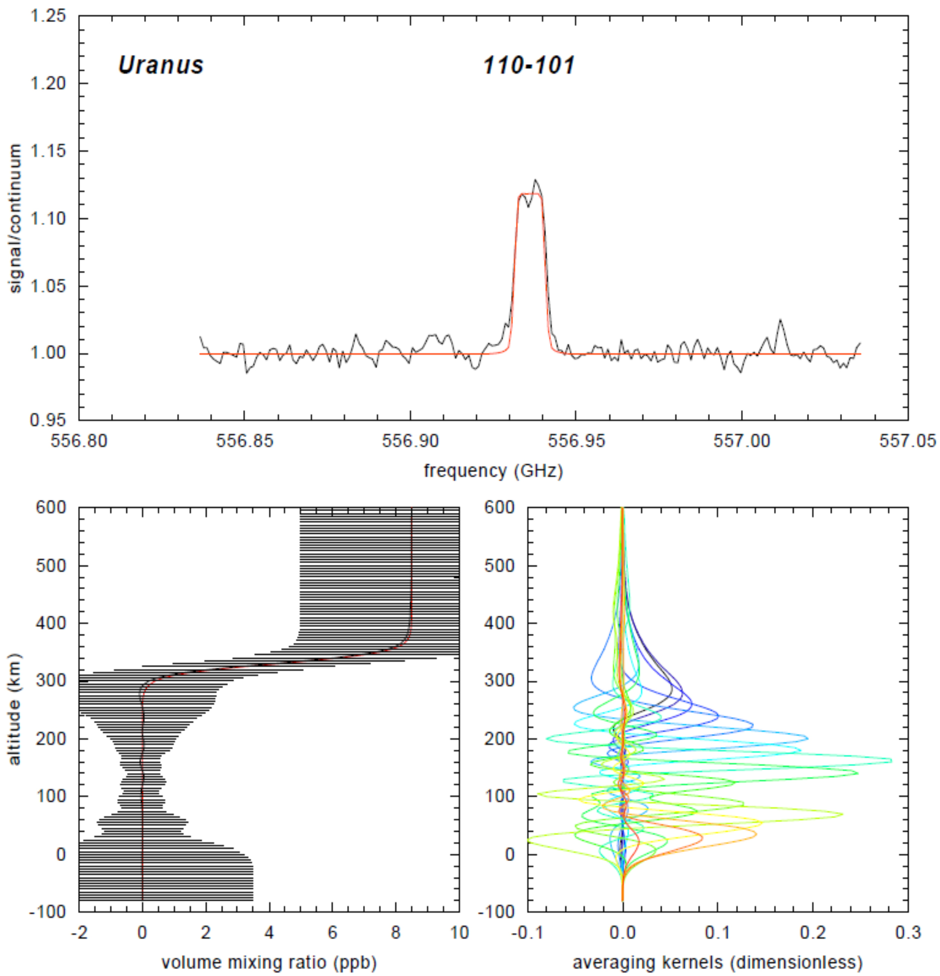


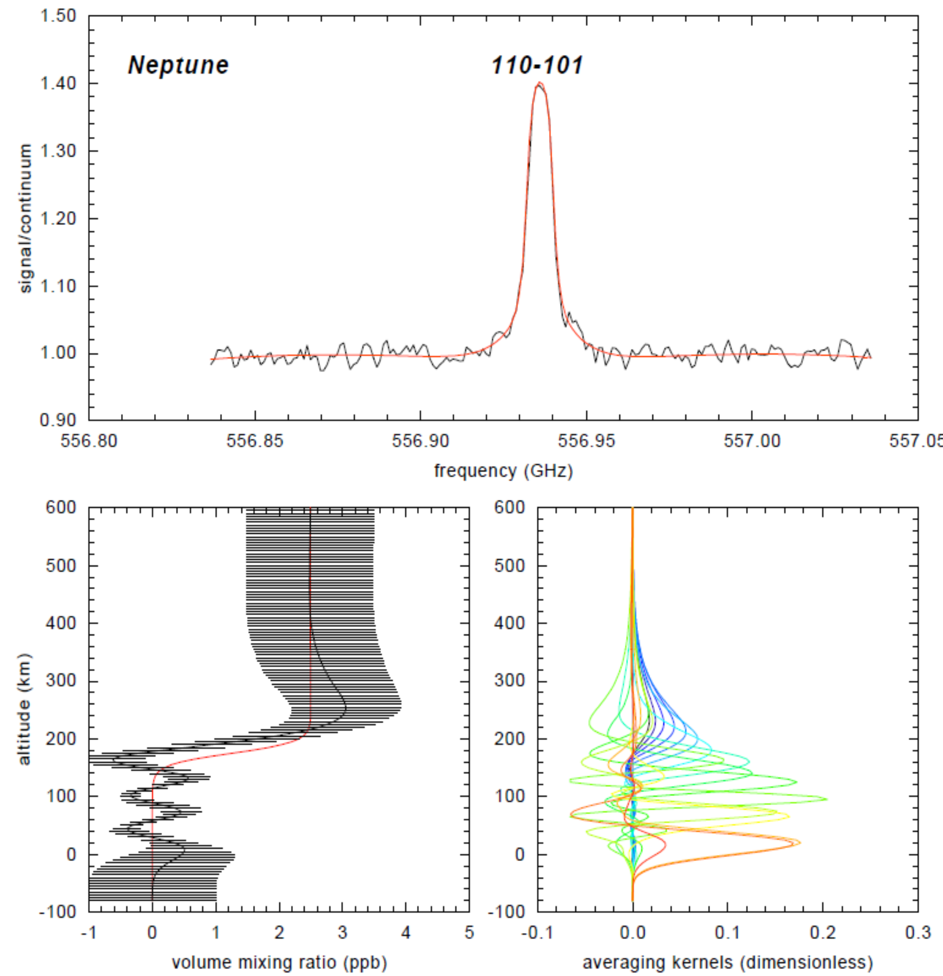


First results: vertical profile of O_2 on Mars, TBC

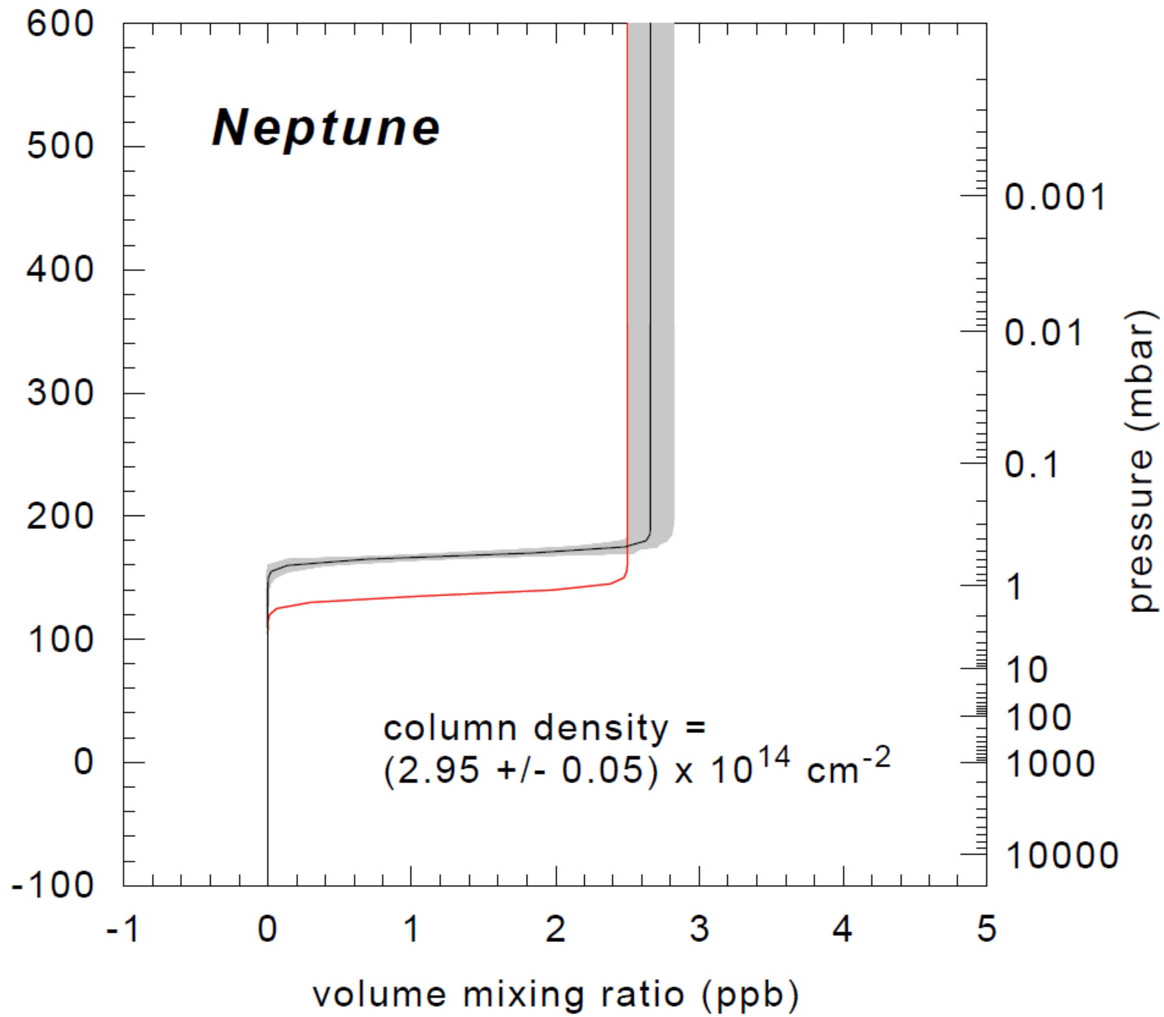


Observation water and OEM retrieval Uranus and Neptune

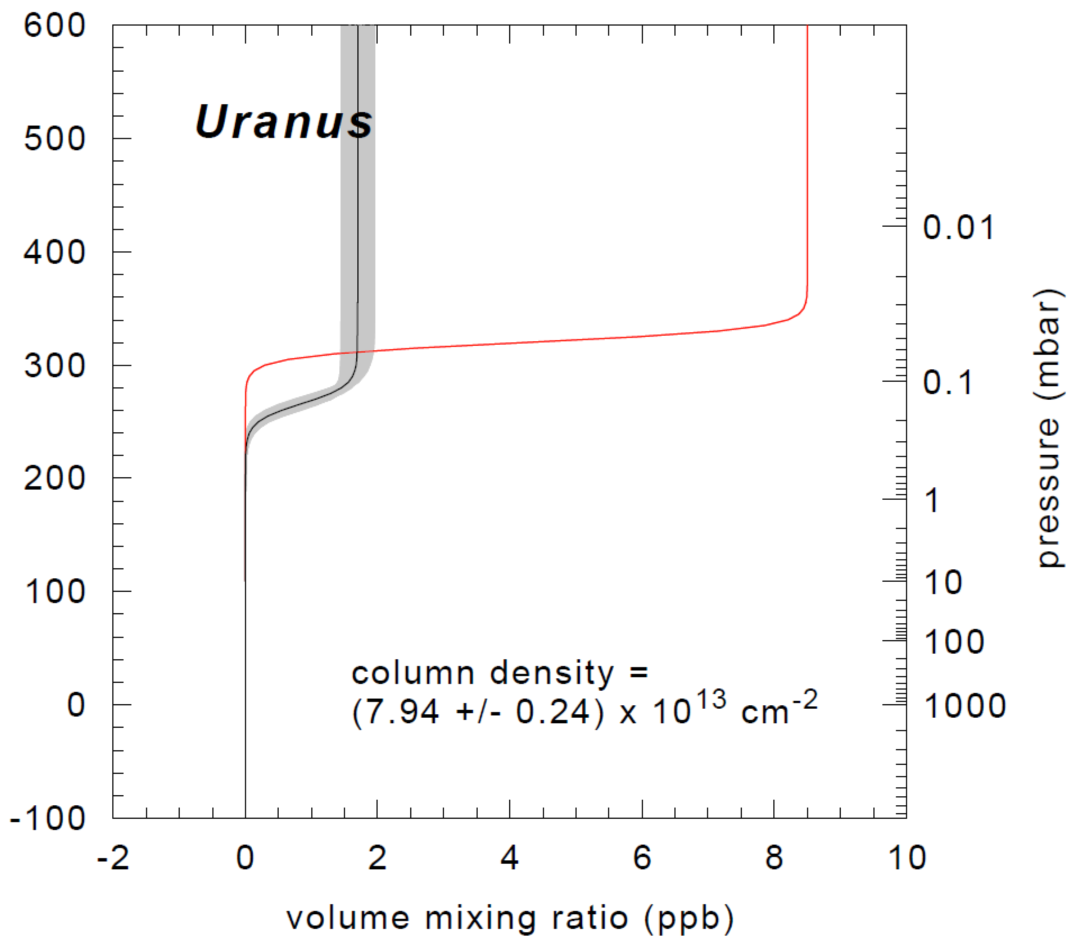




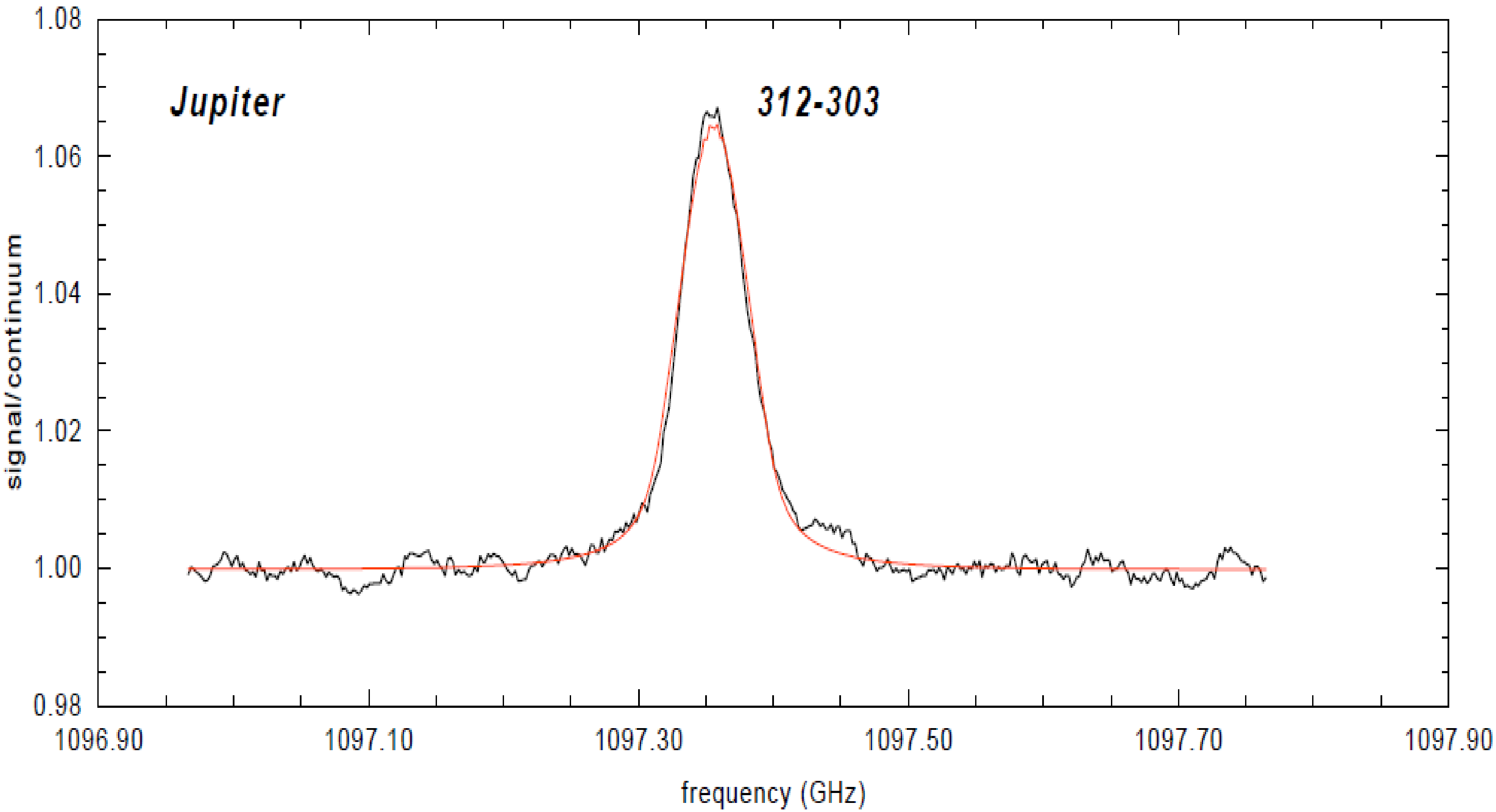
3 parameter fit Neptune

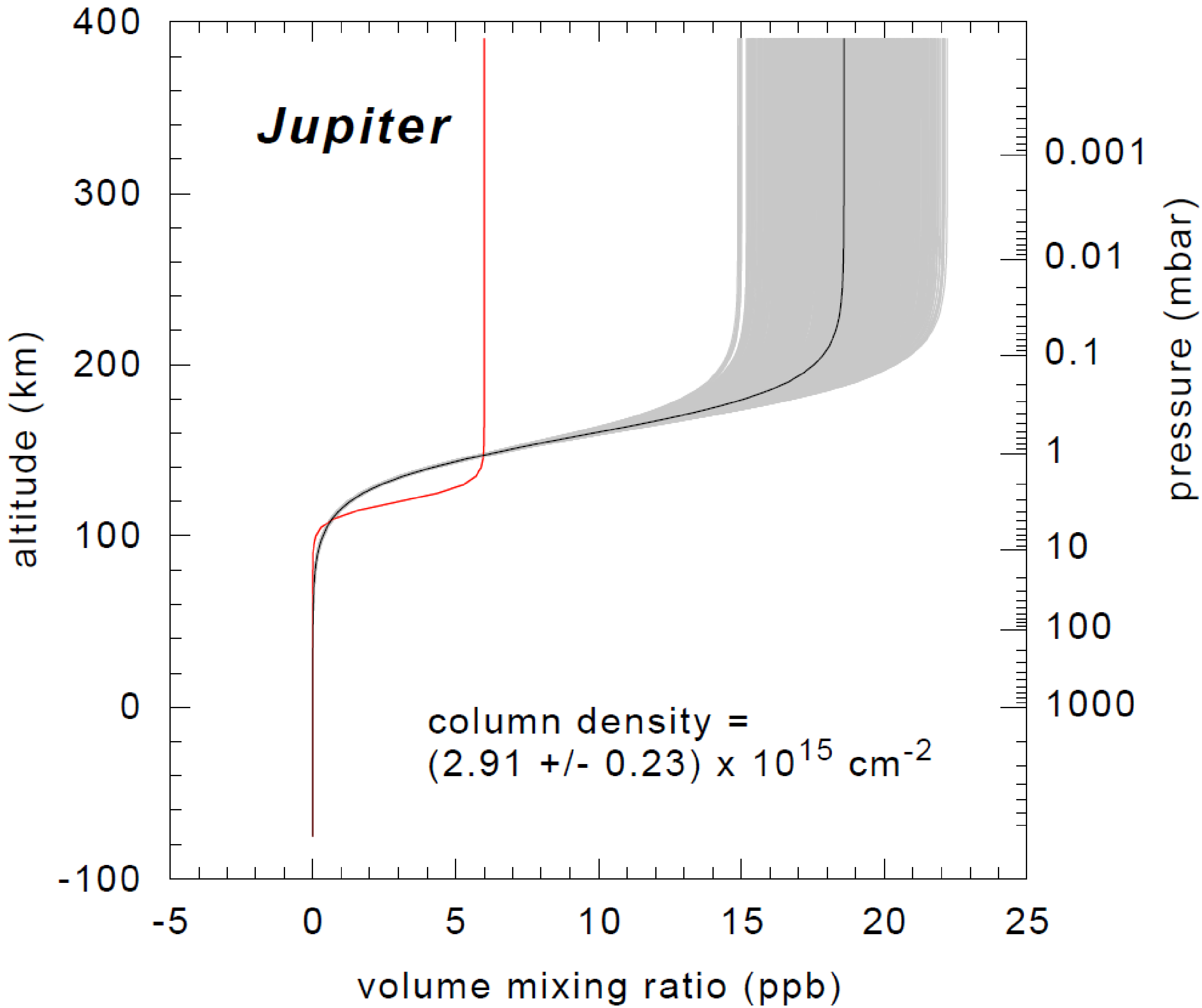


3 parameter fit Uranus

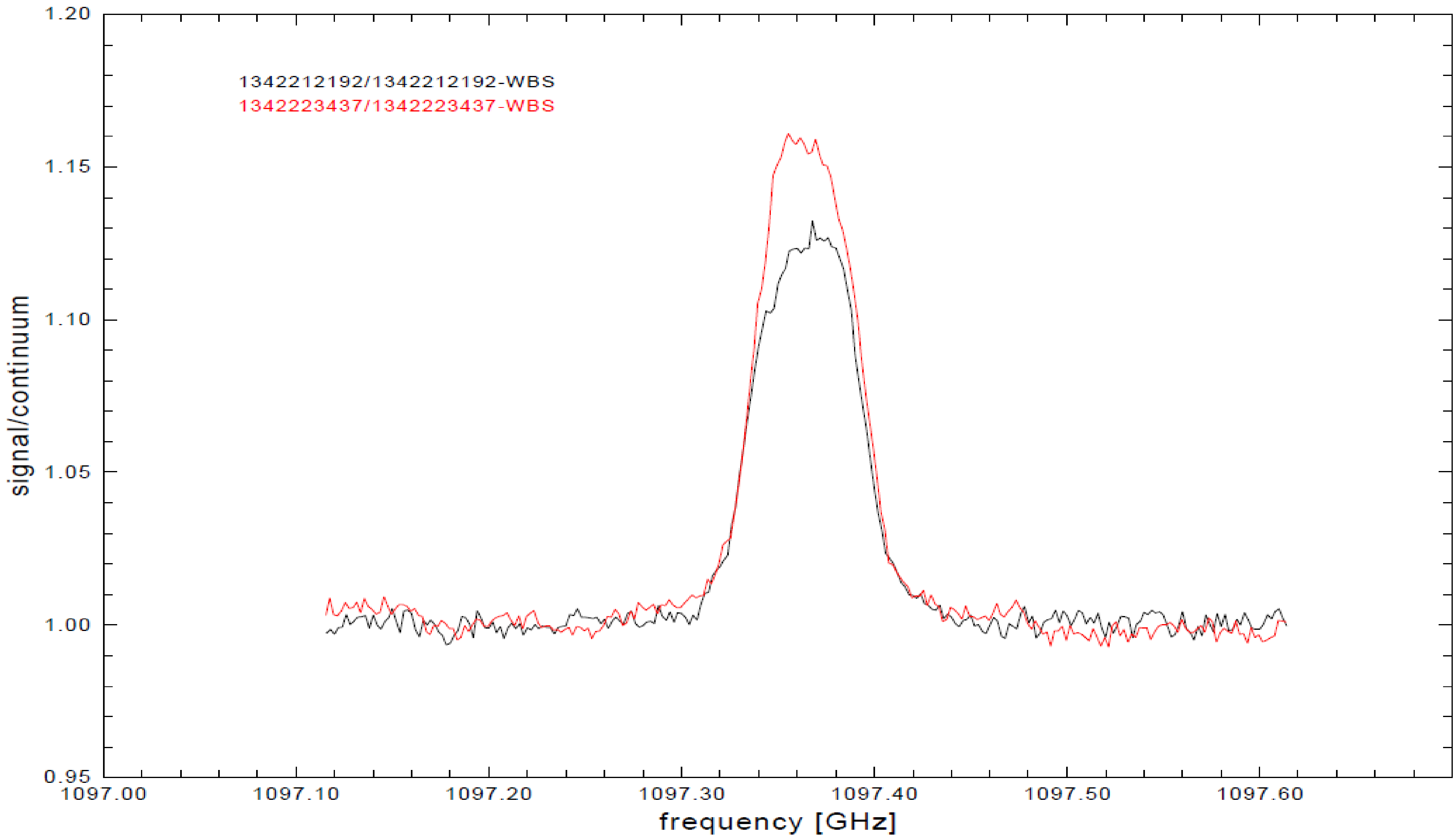


Jupiter water December 2010

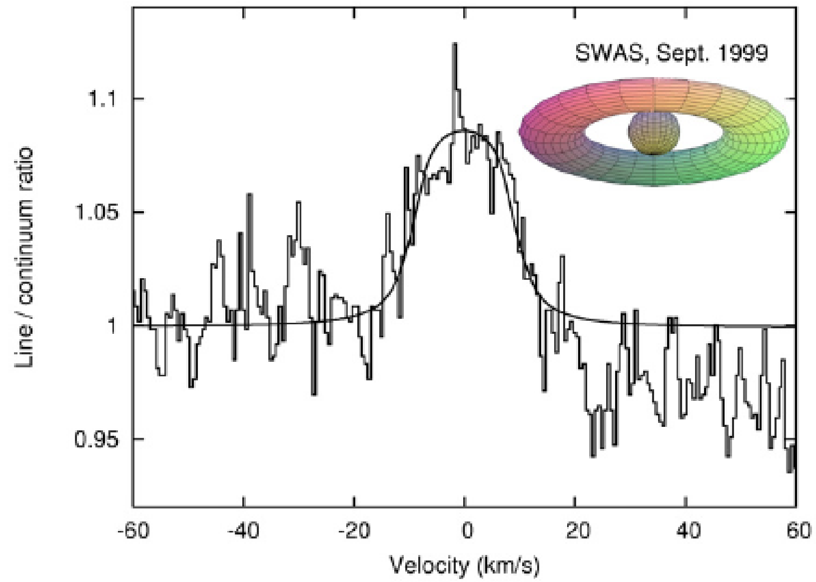


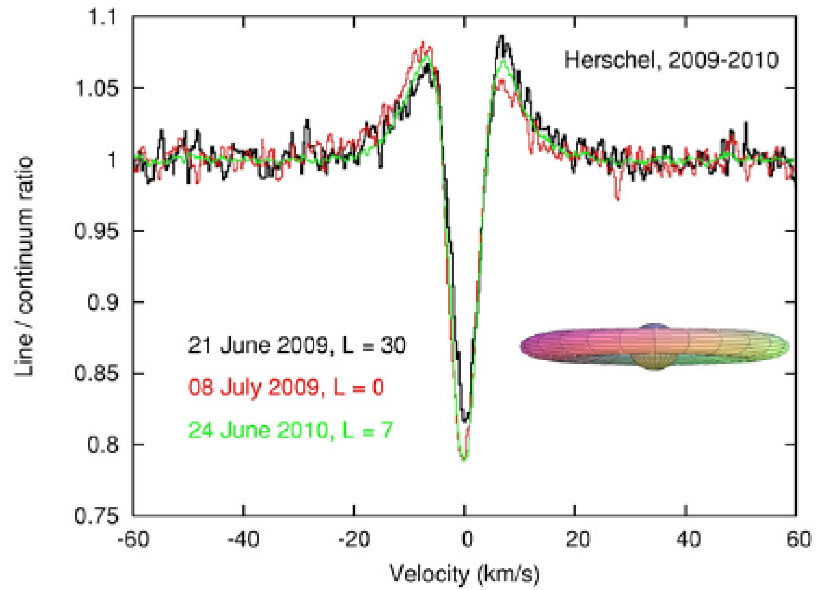

Jupiter
column density =
(2.91 +/- 0.23) x 10^15 cm^-2
altitude (km)
pressure (mbar)
volume mixing ratio (ppb)
400
300
200
100
0
-100
0.001
0.01
0.1
1
10
100
1000
-5
0
5
10
15
20
25

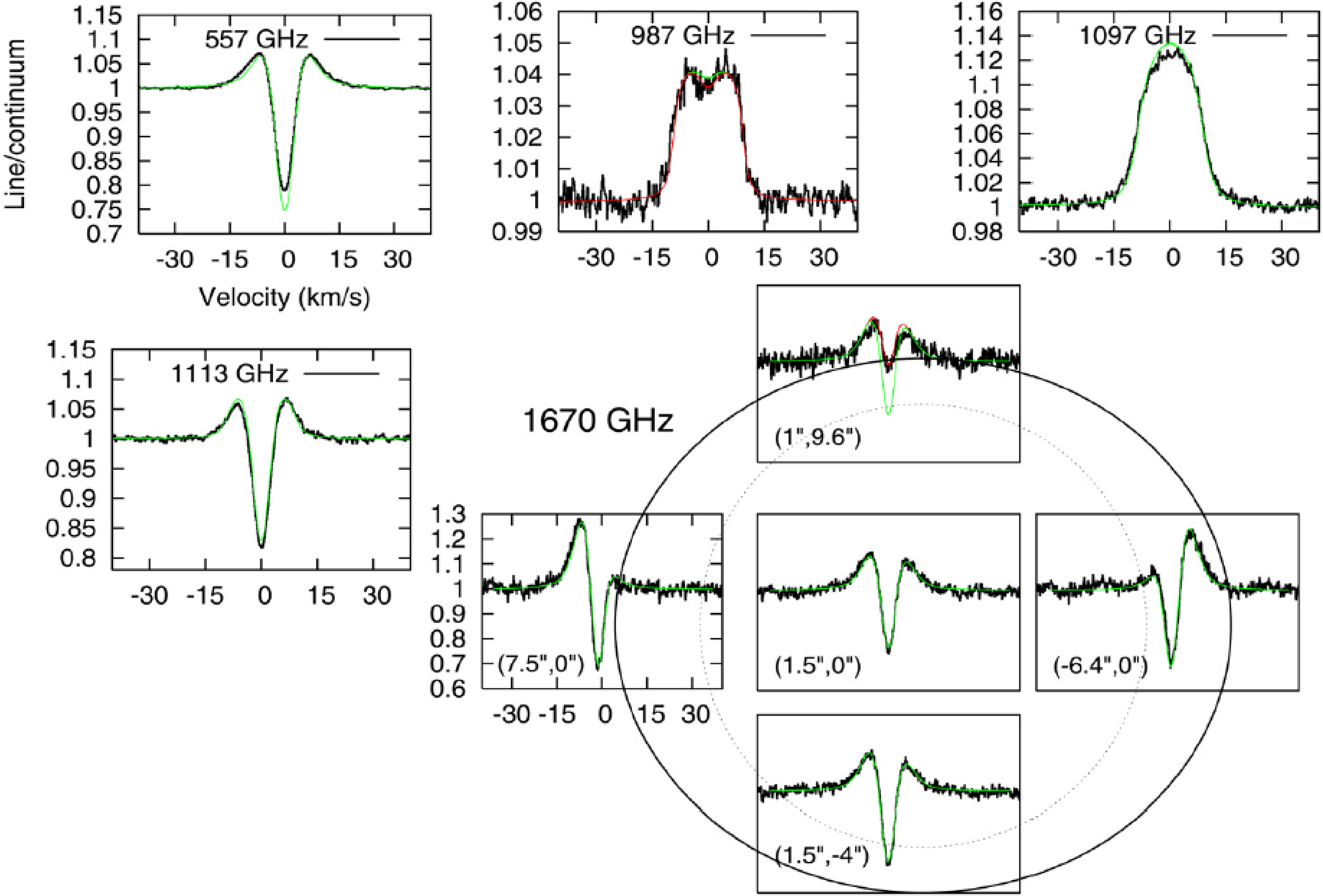
Saturn water December 2010/July 2011



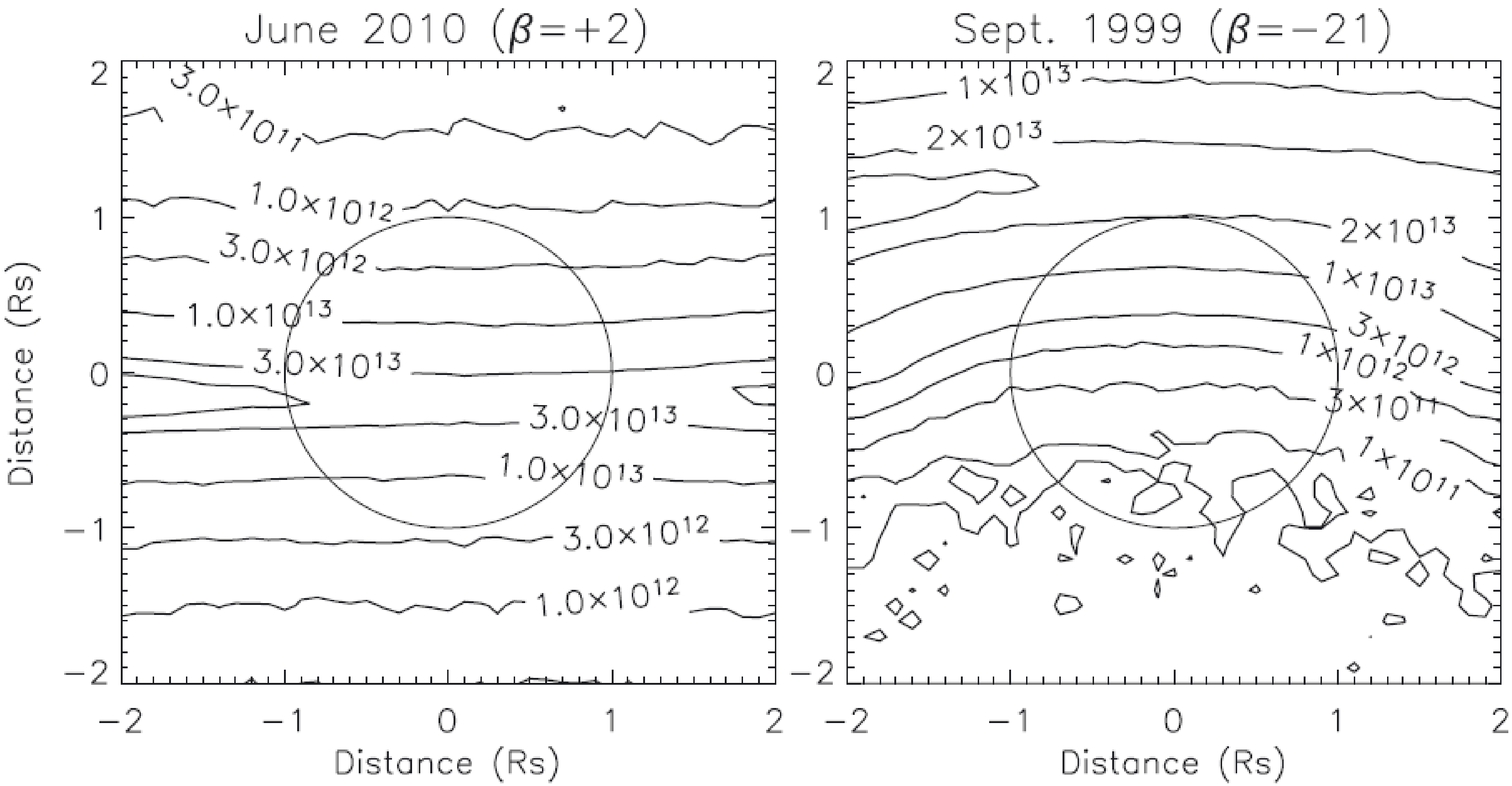
Unexpected detection at 557 GHz pointing to Saturn






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")

Modeled water number densities in the torus



Conclusions Enceladus water torus

- Extension about 10 Saturn radii (R_s)
- Highest density around a distance of 4 R_s
- About 3 % of the water produced by Enceladus rains into the upper atmosphere of Saturn
- Enceladus is the source of stratospheric water in Saturn

Hartogh et al, A&A 2011a

C/2008 Q3 (Garradd)

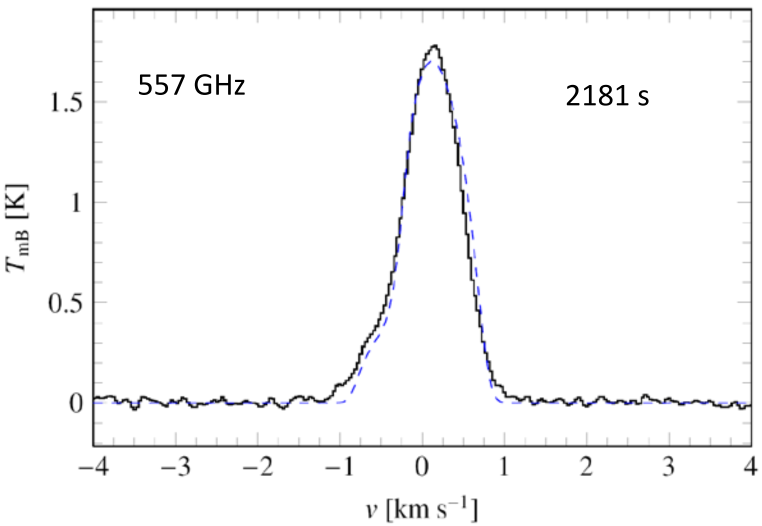
Credit: JPL
Wide-field Infrared Survey Explorer (WISE)

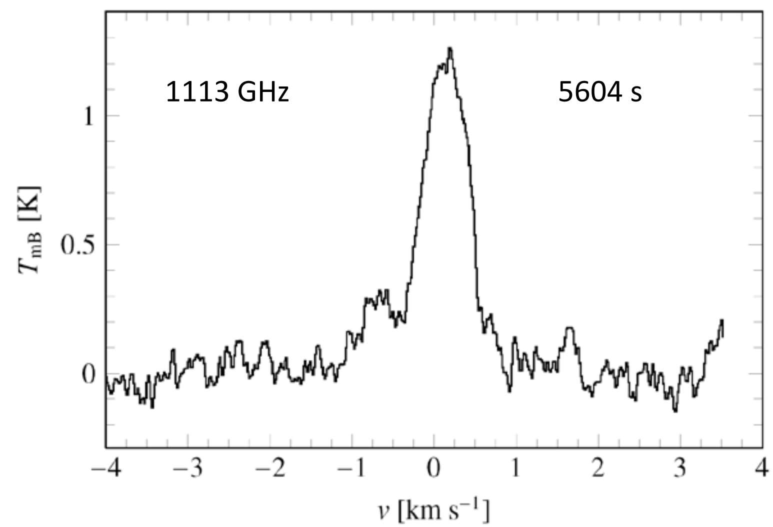
- A long-period comet (P = 190,000 yr) from the Oort cloud
- Distance : perihelion on 23 Jun. 2009 at 1.8 AU
  from Herschel
- Rather Bright (mv = ~ 7 @1.8 AU)
- Date of observations: 20 – 27 July 2010 at 1.8 AU (Sun) and 1.9 AU (Herschel)

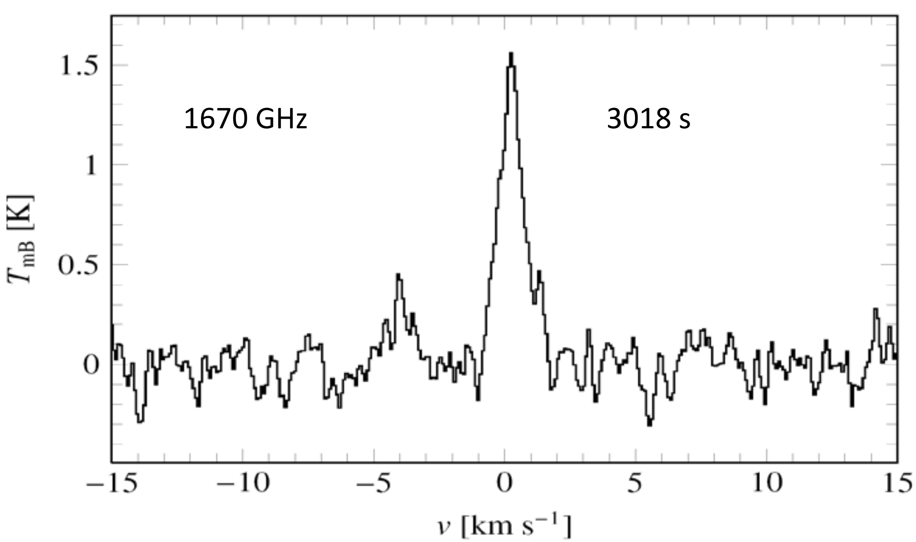
HIFI observations

- Water lines:
  - 110-101 (ortho) 556.936 GHz 38.1 ’’ (52000 km)
  - 111-000 (para) 1113.343 GHz 19.2 ’’ (34000 km)
  - 212-101 (ortho) 1669.9 GHz 12.7 ’’ (18000 km)
- First detection in a comet (lower 2 lines)
- Better constraints on excitation models

All lines in FSw mode







Production rates at 22/27 July 2009

22 July 2009 (1113 GHz) : 1.8 ±0.03 x 10^28 / s

27 July 2009 (1670 GHz) : 2.1 ±0.30 x 10^28 / s

27 July 2009 (1113 GHz) : 1.7 ±0.03 x 10^28 / s

Results on C/2008 Q3

HIFI observations of Comet C/2008 on 20-27 July 2009

First detection of the 111-000 and 212-101 rotational transitions in a comet

Derived parameters:

- Neutral gas temperature: 15 K
- Gas expansion velocity: 0.55 km/s
- Water production rates: 1.7 – 2.7 x 10^28/s

Decrease of production rates from 20 – 27 July 2009

First direct constraint for water excitation models in comets

Hartogh et al. 2010c, A&A

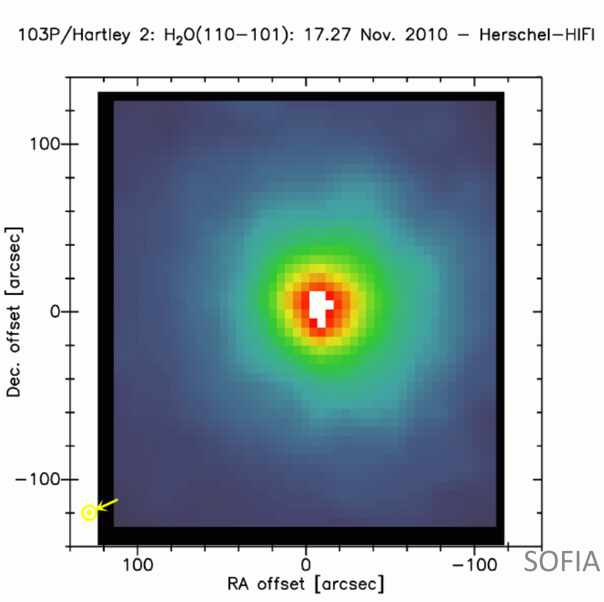
Variability of 103P: Alternating observations

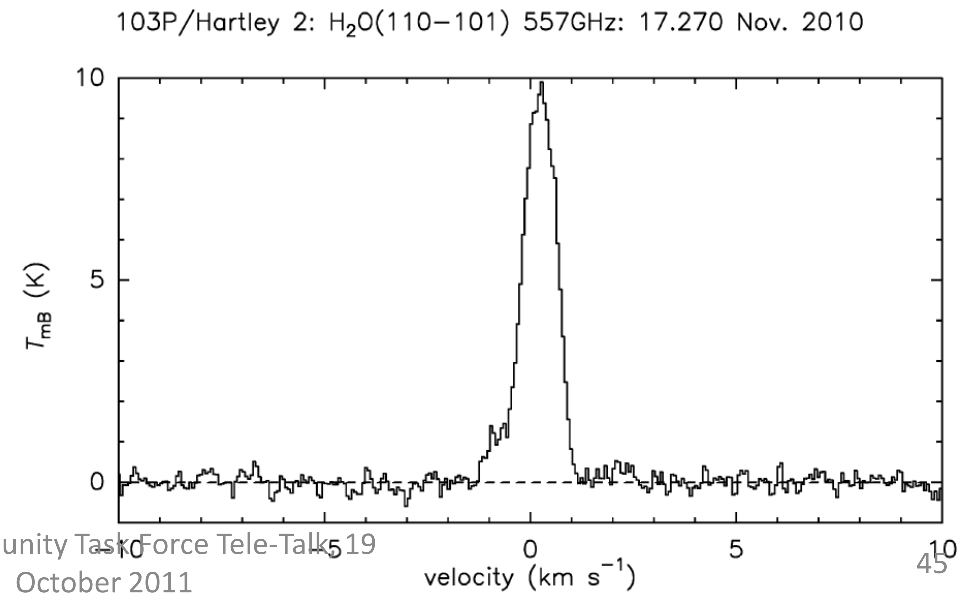
Date: 17.28 – 17.64 November 2010

11 observations of H_2O (557 GHz) + $H_2{}^{18}O$ (548 GHz) with 10 of HDO (509 GHz) and five maps of H_2O: total 66 + 320 + 80min (~8h)

Same receiver, same HIFI band → similar field of view (~39'', 6500 km)

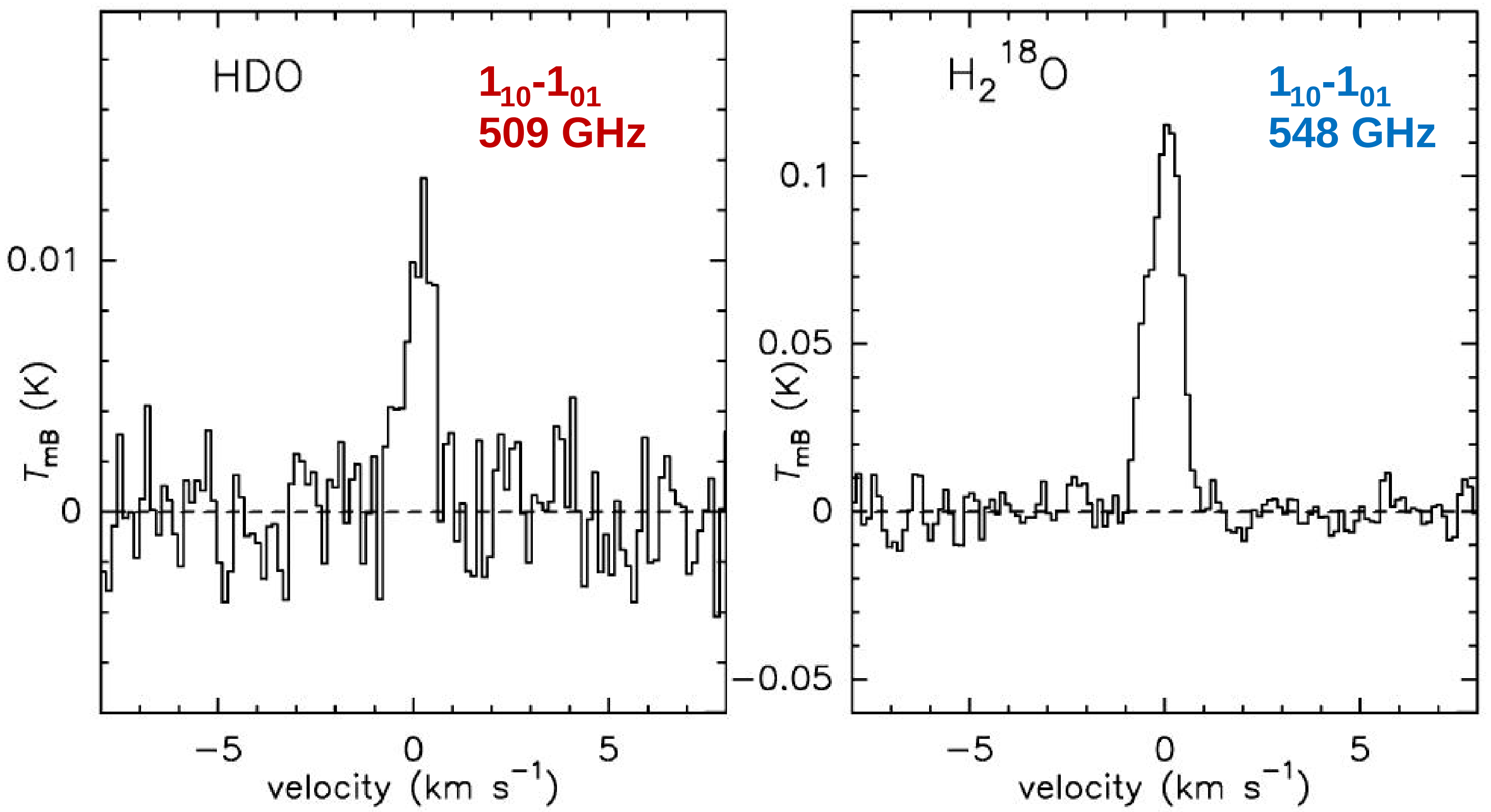
Observed variation: smooth decrease by ~20% of Q_{H2O} during the observation





Observed spectra:

Hartogh et al. (2011b)



S/N = 10

S/N = 60

Analysis of the observations

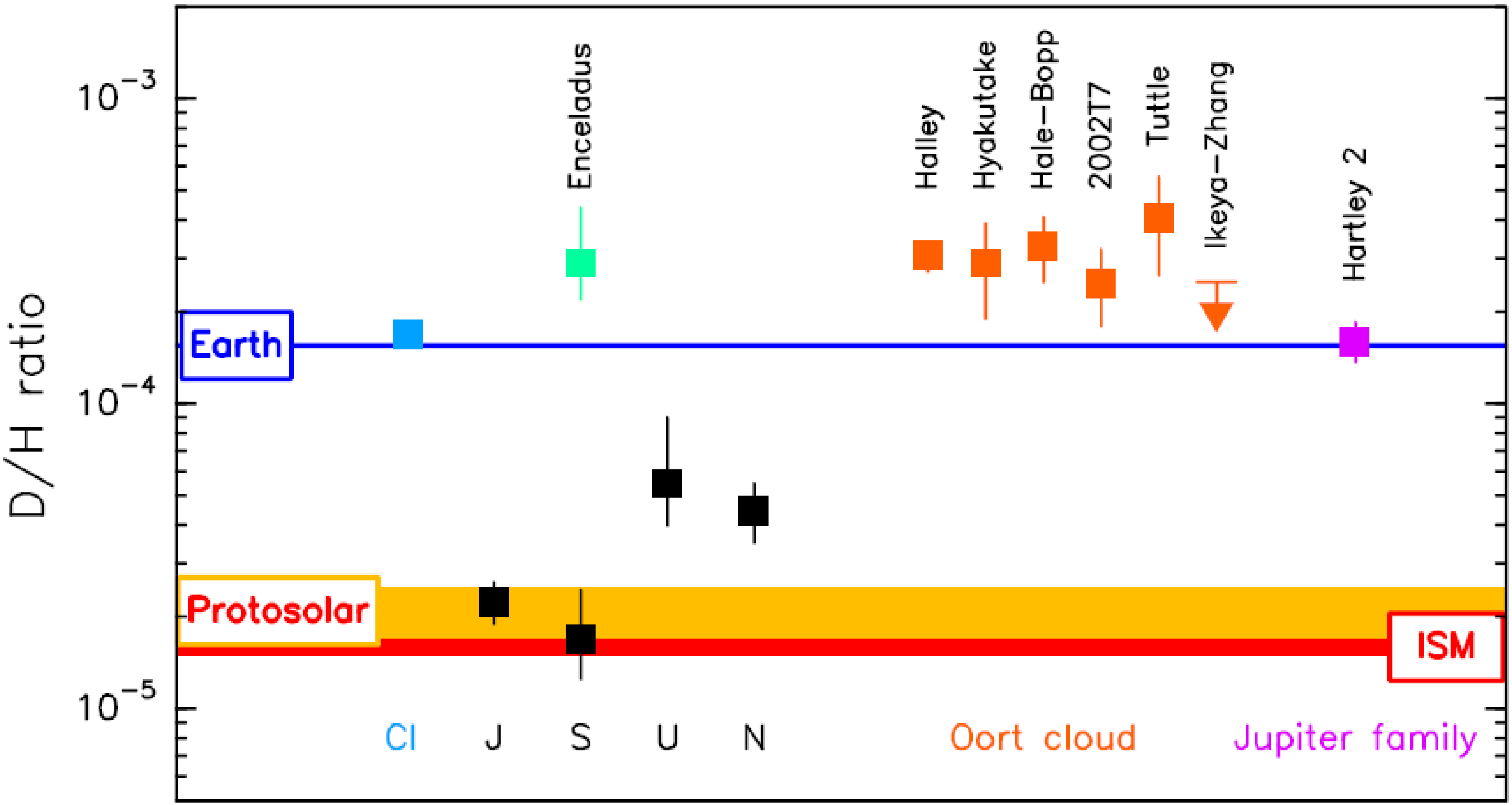
- Excitation model : collisions with H_2O, electrons and infrared pumping, gas temperature determined by other observation (e.g. methanol lines at IRAM/CSO/SMT)

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

- Hypothesis : $^{16}O/^{18}O = 500$ (+/- 10%) (VSMOW)
  (520±30 in 4 comets with Odin)

=> $\boxed{\mathbf{D/H = (1.61 \pm 0.24) \times 10^{-4}}}$

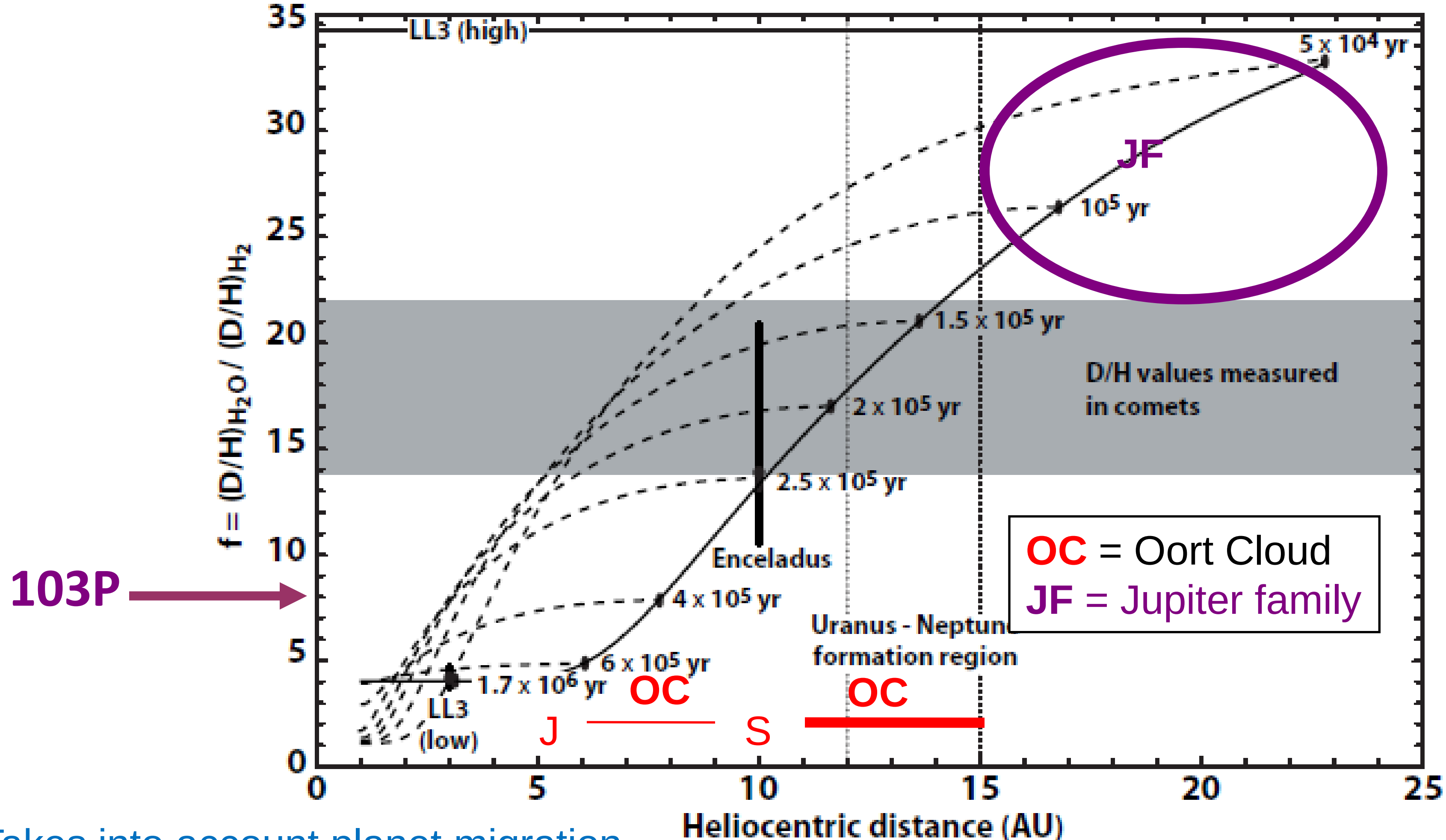
$D/H(VSMOW) = 1.558 \pm 0.001 \times 10^{-4}$



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

D/H model for the solar system

Kavelaars et al. (2011)



Takes into account planet migration

What could be wrong?

- Model of D/H fractionation with heliocentric distance?
- 103P may not come from the Kuiper belt. Is it a Trojan (Horner et al. 2007) originating near Jupiter?
- Perhaps OCCs did not form in the vicinity of the giant planets and/or do not represent the solar system at all (Levison et al, 2010)
- In the early phase of the solar system formation material was mixed over large distances (Walsh, 2011).
- Models of the dynamical evolution of the solar system?

- What about delivery of water to Earth?

Earth accreted wet

- Wänke: Heterogeneous accretion. 3 phases of accretion with a late third phase (~ 1% of Earth mass) providing also water

Phil. Trans. R. Soc. Lond. 303, (1981)

- *Morbidelli 2001: early delivery of water by a few planetary embryos formed in the outer asteroid belt. Maximum 10 % water delivered by comets*

Origin of water in the terrestrial planets

Michael J. DRAKE

M&PS 40 (2005)

Lunar and Planetary Laboratory, University of Arizona, Space Sciences Building, P. O. Box 210092, Tucson, Arizona 85721–0092, USA
E-mail: drake@lpl.arizona.edu

(Received 19 January 2005; revision accepted 11 March 2005)

Abstract–I examine the origin of water in the terrestrial planets. Late-stage delivery of water from asteroidal and cometary sources appears to be ruled out by isotopic and molecular ratio considerations, unless either comets and asteroids currently sampled spectroscopically and by meteorites are unlike those falling to Earth 4.5 Ga ago, or our measurements are not representative of those bodies. However, the terrestrial planets were bathed in a gas of H, He, and O. The dominant gas phase species were H_2, He, H_2O, and CO. Thus, grains in the accretion disk must have been exposed to and adsorbed H_2 and water. Here I conduct a preliminary analysis of the efficacy of nebular gas adsorption as a mechanism by which the terrestrial planets accreted "wet." A simple model suggests that grains accreted to Earth could have adsorbed 1–3 Earth oceans of water. The fraction of this water retained during accretion is unknown, but these results suggest that examining the role of adsorption

Earth accreted dry

- *Javoy, E&PS 2010: Earth bulk isotopic composition similar to E-chondrites. Volatiles were delivered later.*

- *Gomes et al, 2005: sudden massive delivery of planetesimals from the trans-Neptunian region to the inner Solar System caused by rapid migration of the giant planets, (LHB). Comets provided maximum 6 % of the water on Earth, compatible with the D/H measurement in comets.*

Summary 103 P

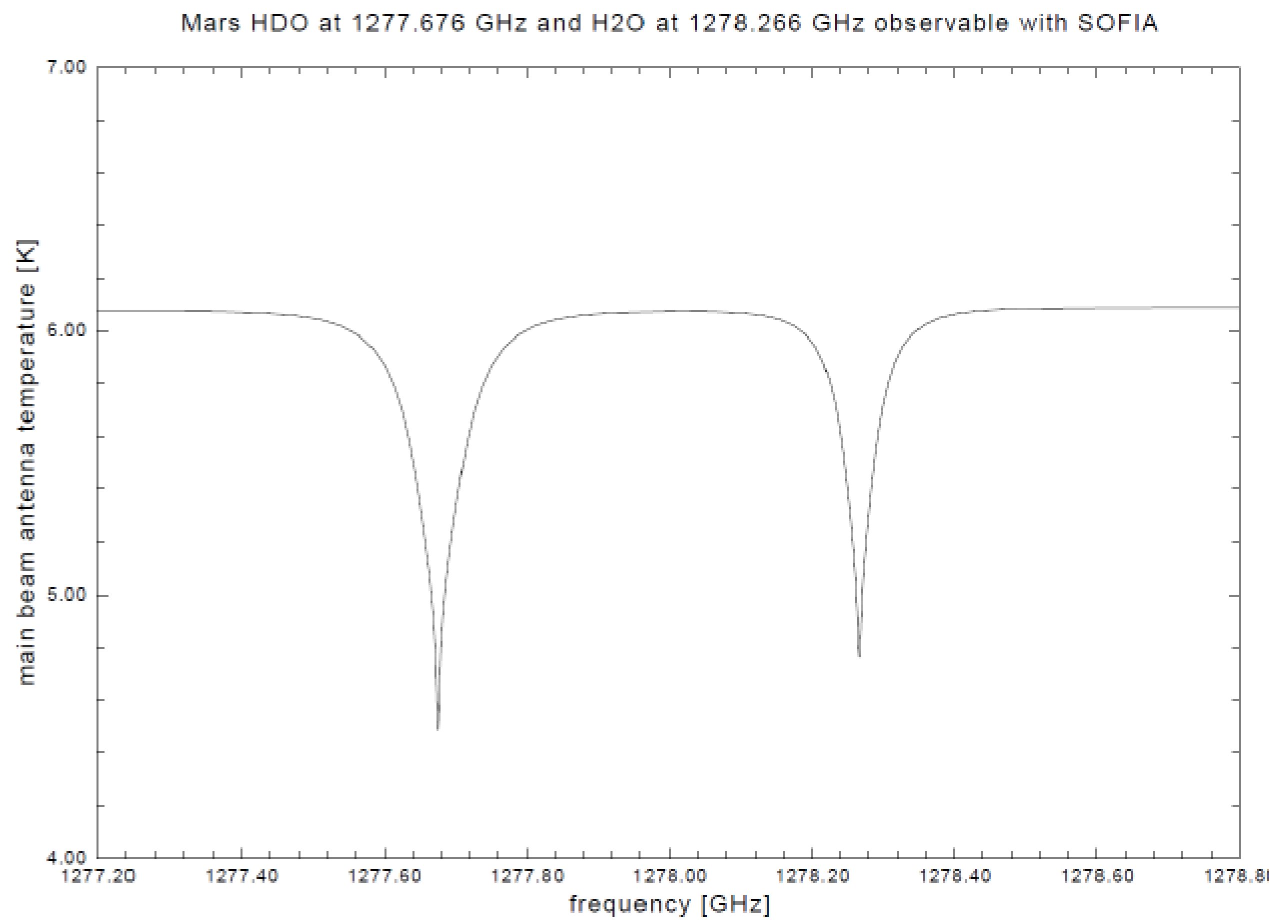
- Ocean like water found for the first time in a comet
- Finding does not fit present models on origin of cometary material and/or isotopic fractionation with heliocentric distance.
- Paradigma of maximum 10 % cometary water in hydrosphere based on composition arguments disproved.

Hartogh et al., Nature, 2011

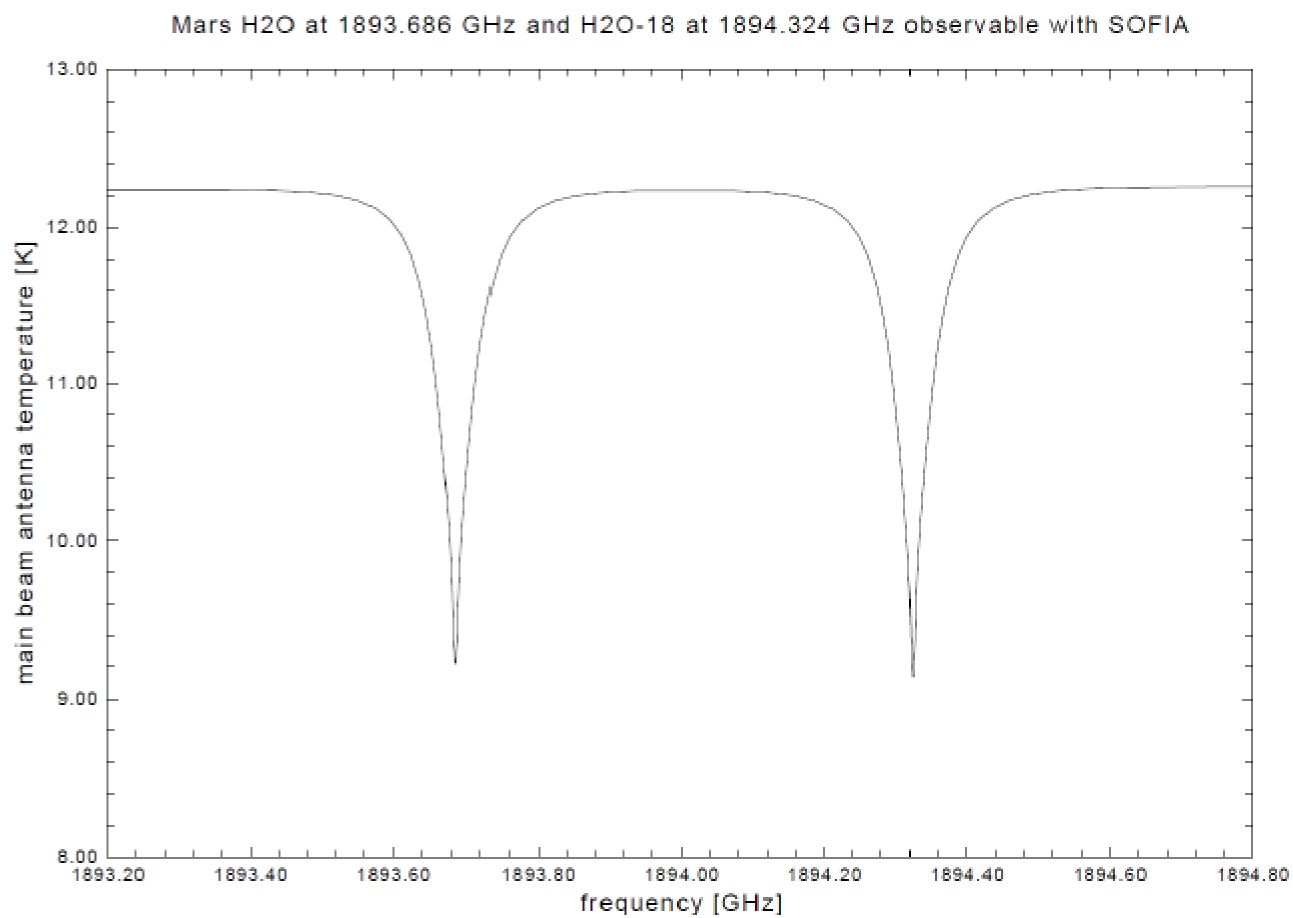
What can GREAT contribute?

- Water only works for Mars and some comets
- Annual variation of H2O2 on Mars
- HD in outer planets is a hot topic!
- Venus cannot be observed by Herschel!

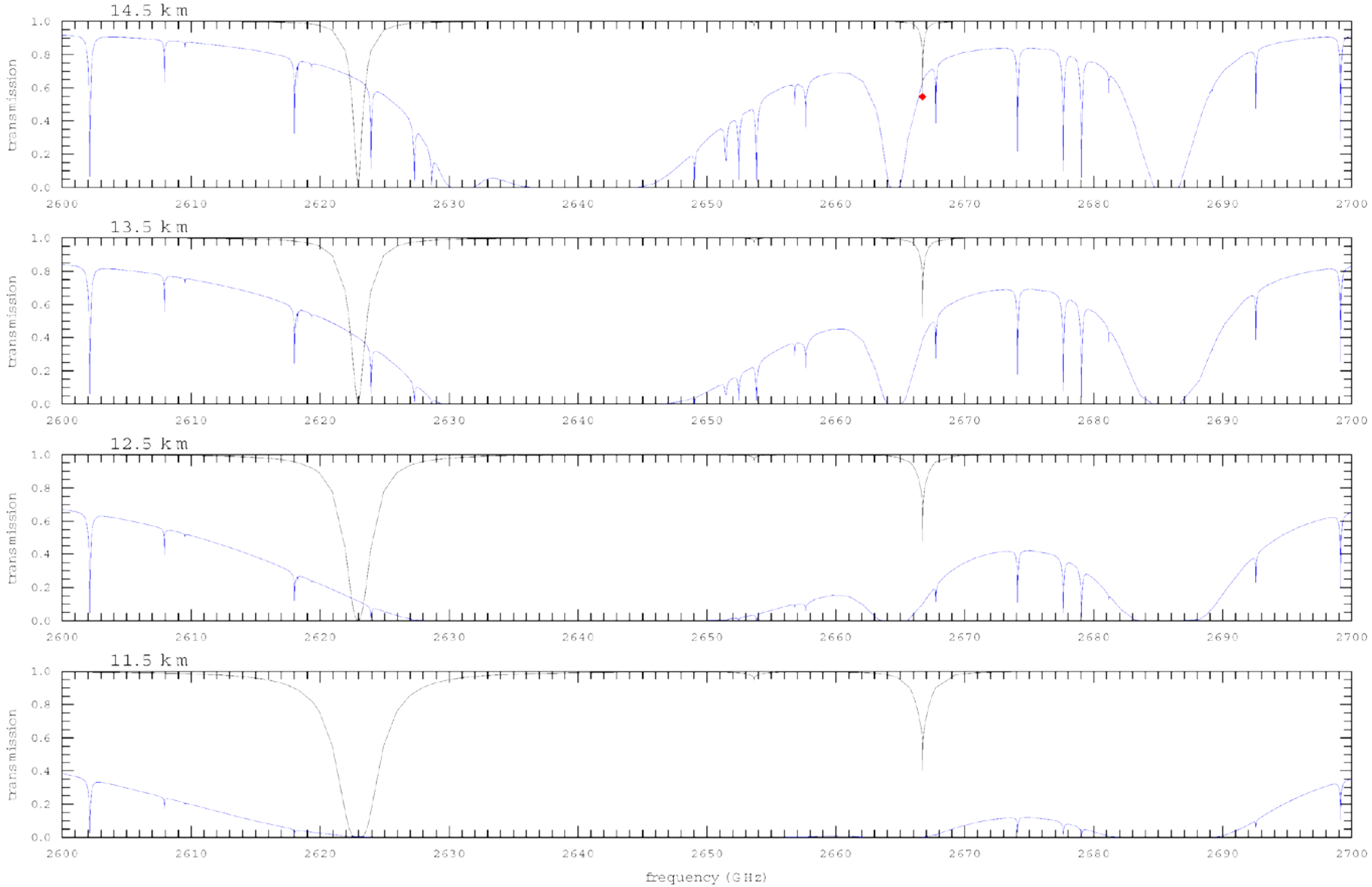
Mars: proposed (GREAT L1) for September 2011



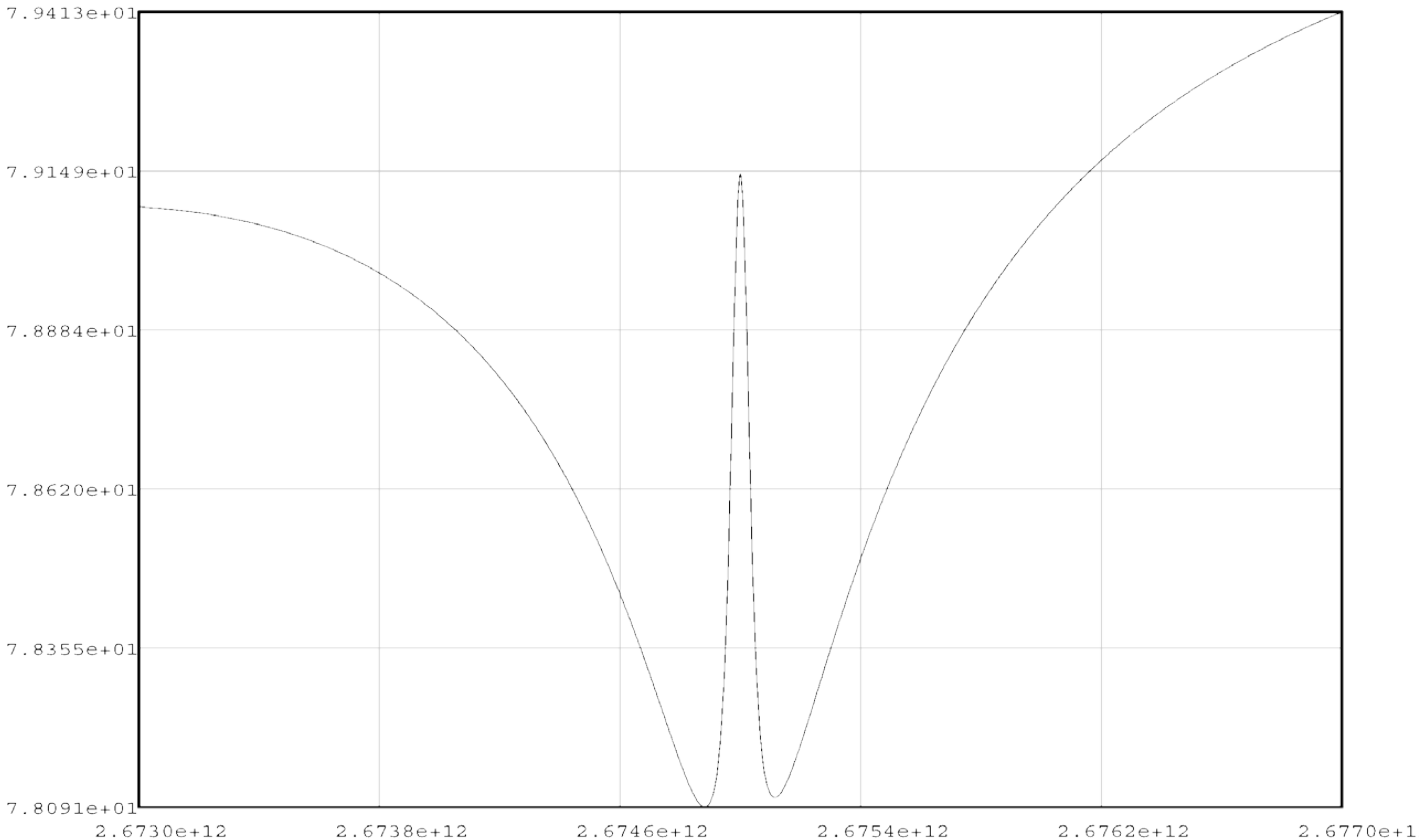
Mars: proposed (GREAT L2) for September 2011



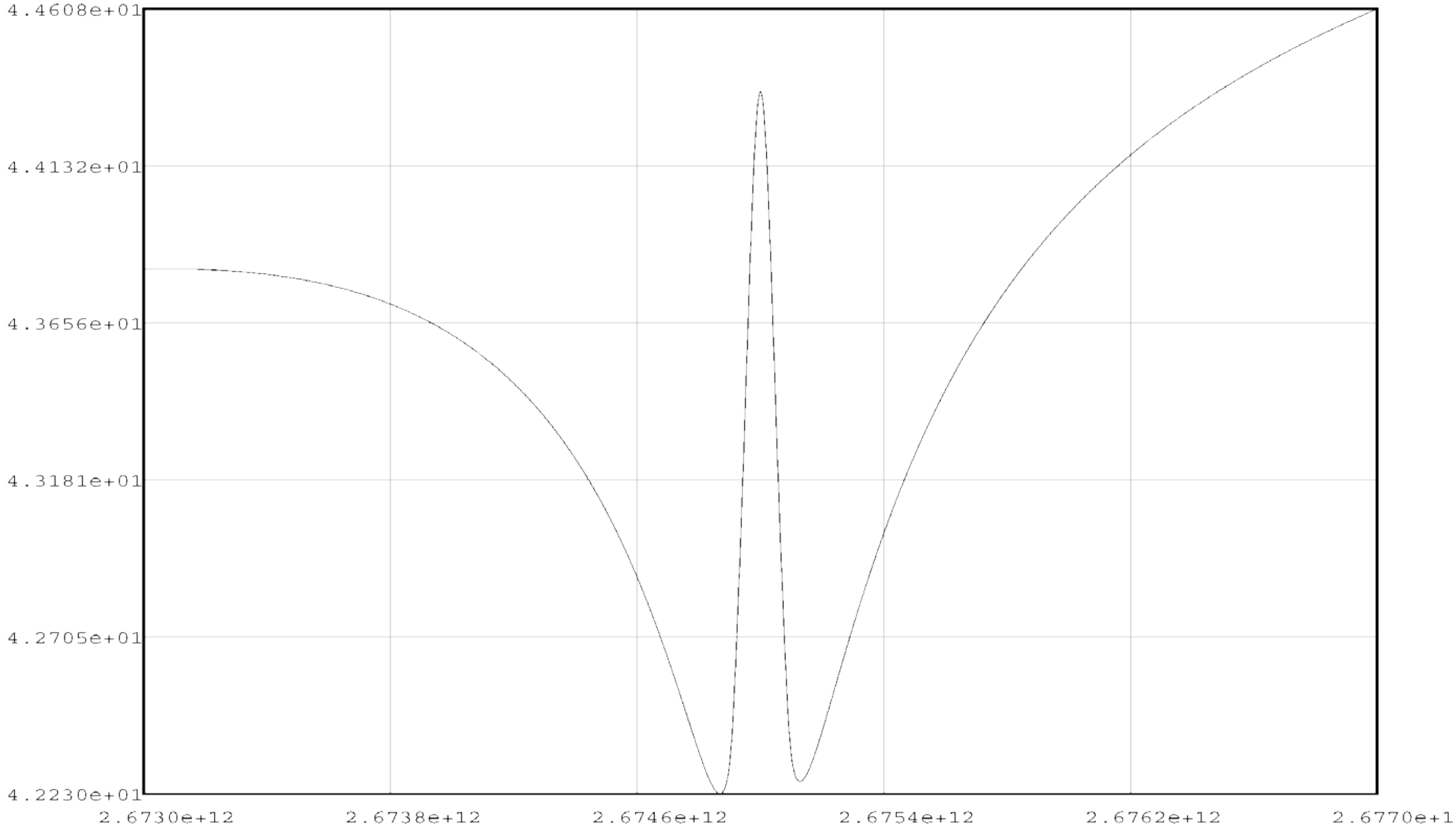
Atmospheric Transmission near 2675 GHz (HD)



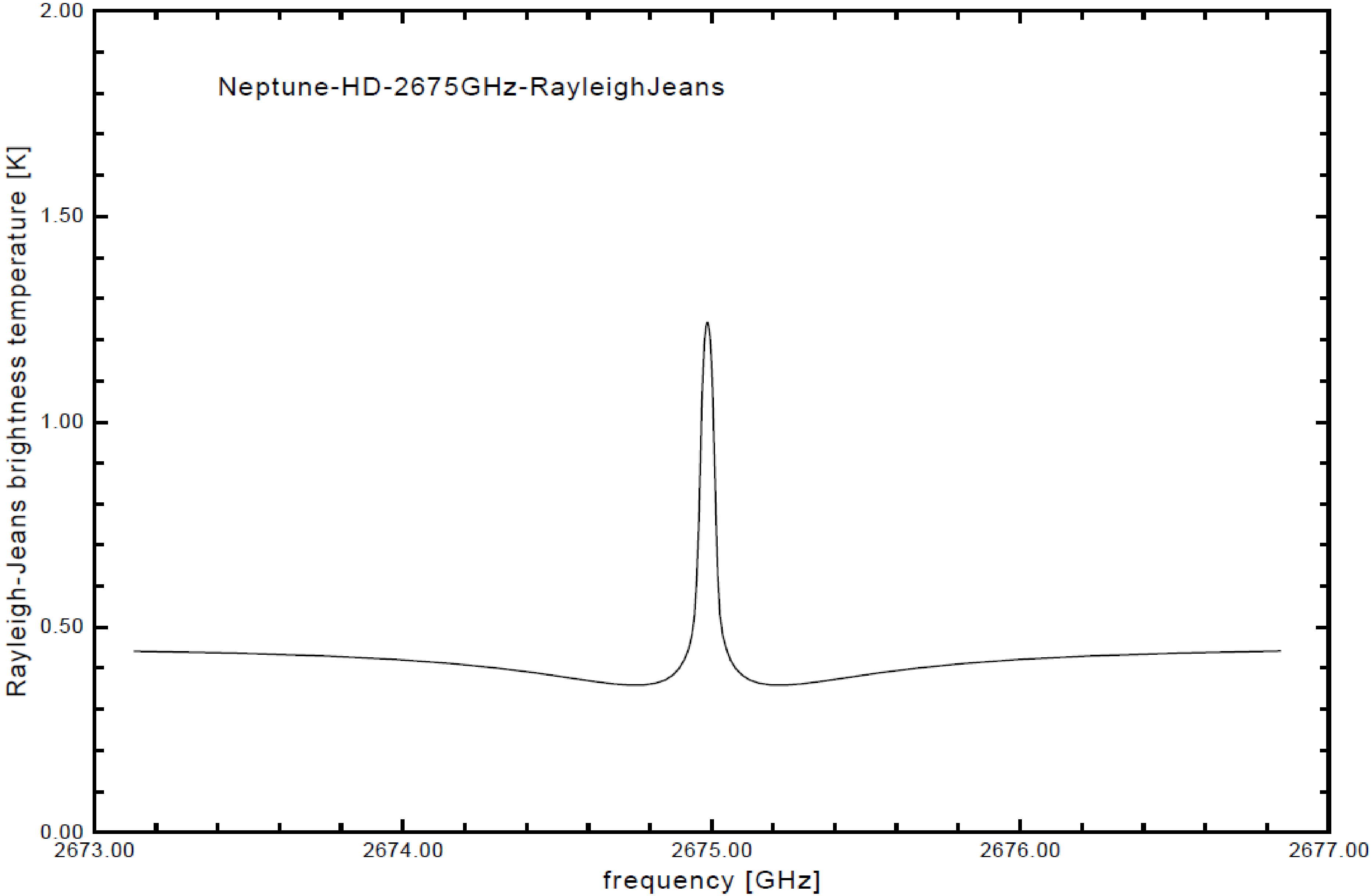
HD spectrum of Jupiter

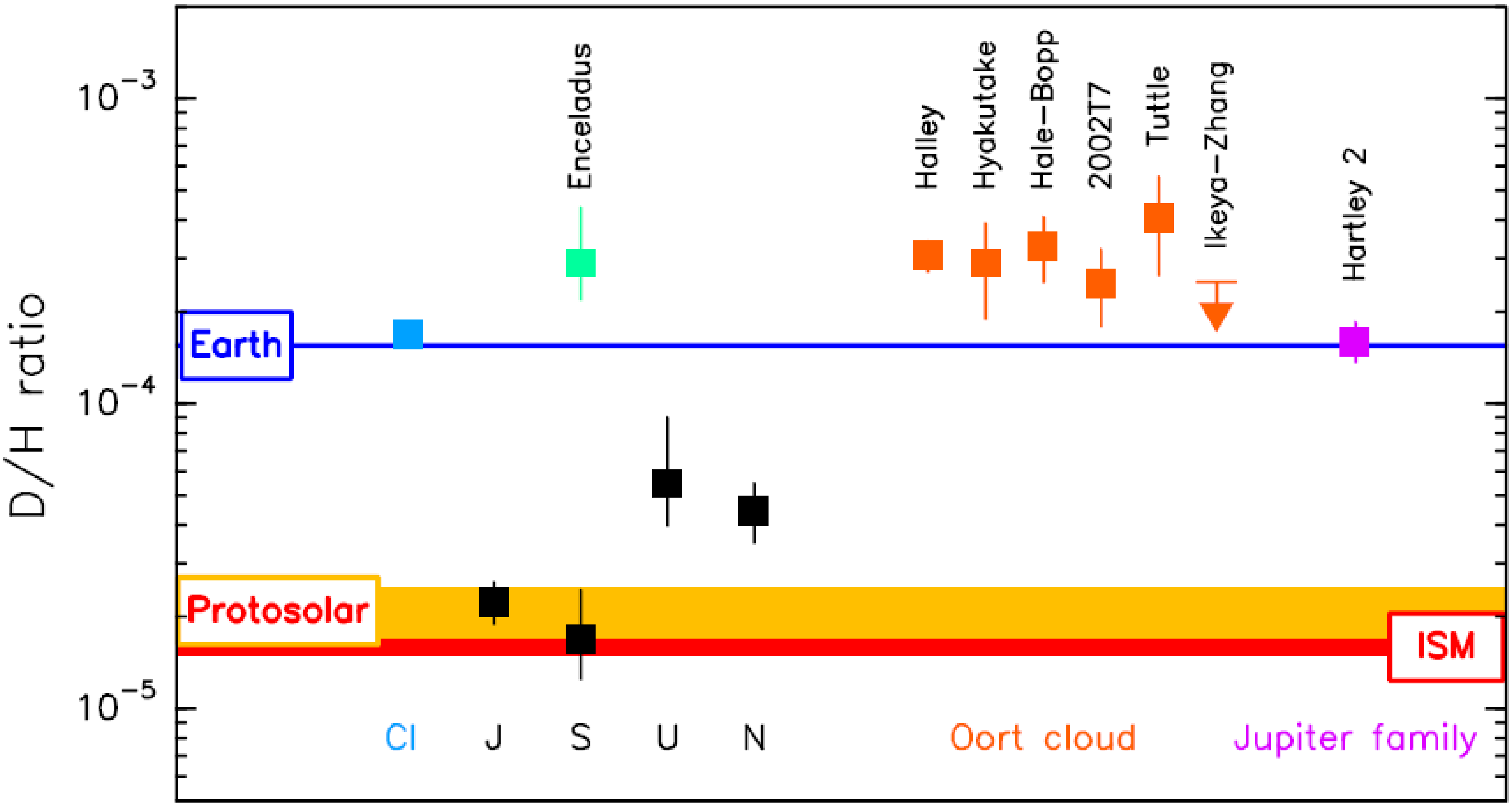


HD spectrum of Saturn



Neptune: HD at 2675 GHz

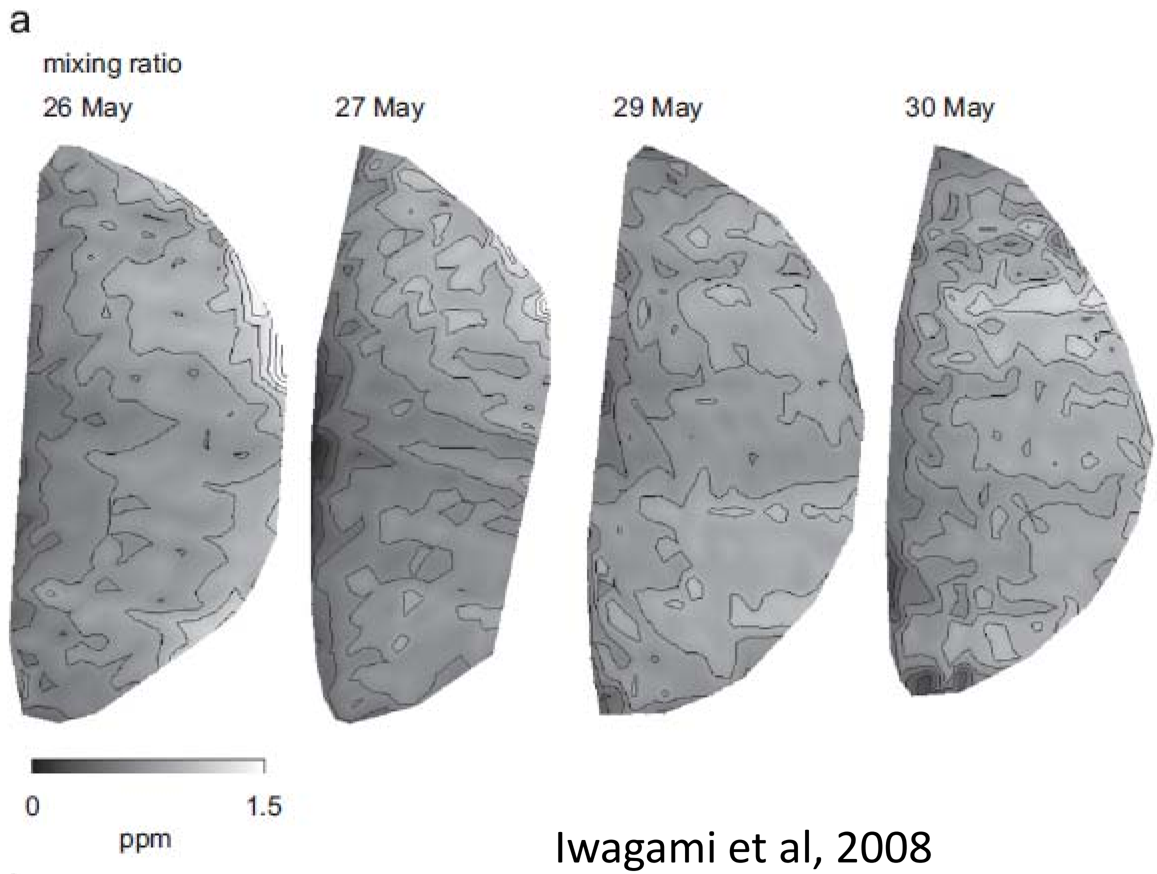



D/H ratio
10^{-3}
10^{-4}
10^{-5}
Enceladus
Halley
Hyakutake
Hale–Bopp
2002T7
Tuttle
Ikeya–Zhang
Hartley 2
Earth
Protosolar
ISM
CI
J
S
U
N
Oort cloud
Jupiter family

Venus HCl

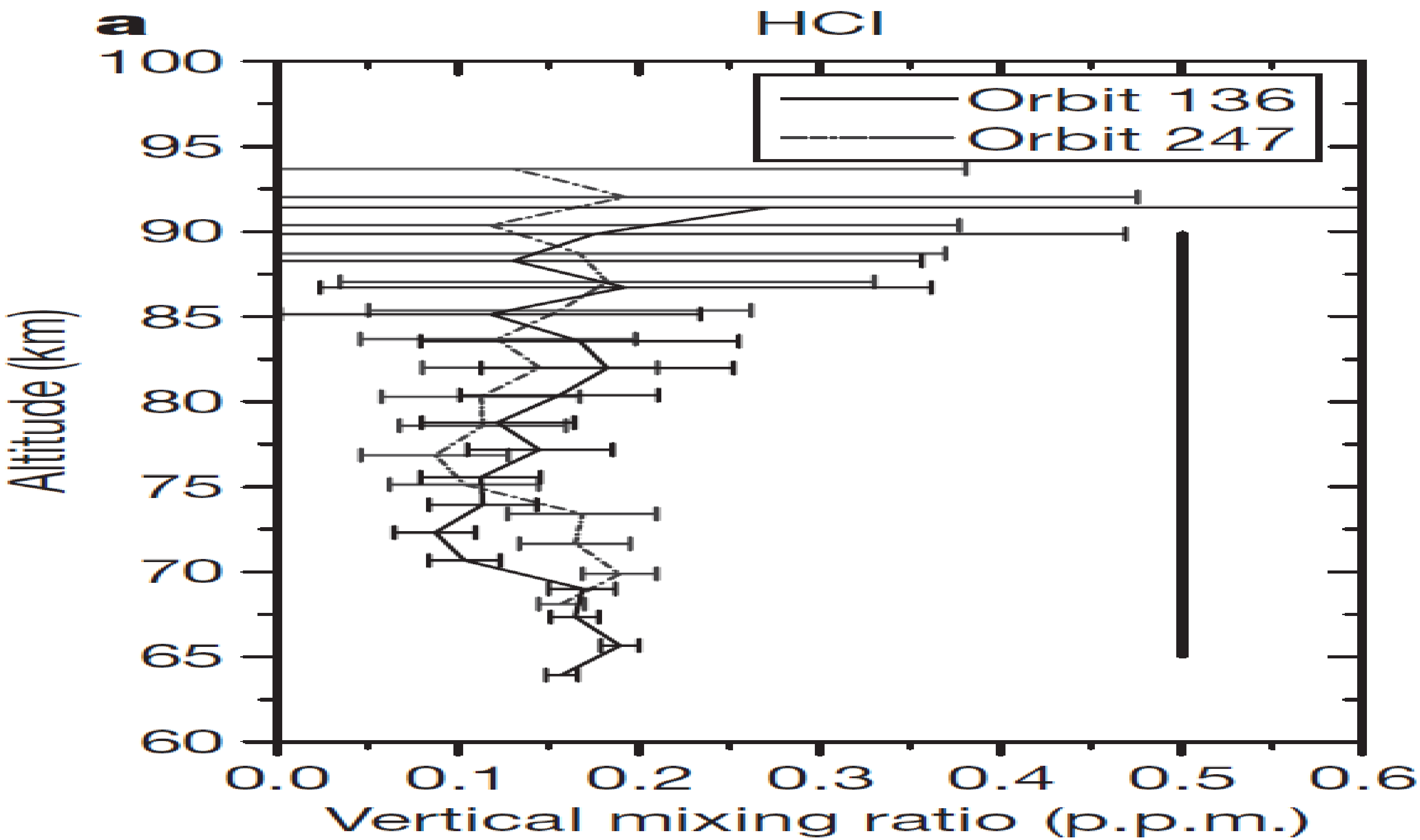
- Source and sink for chlorine
- Chlorine is believed to play an important role in photochemical reactions stabilizing the CO_2 atmosphere of Venus.
- Detected values thus far highly uncertain

Models assume for the bulk HCl: 1 ppm. Disk average HCl 0.4 ppm from Iwagami NIR observations

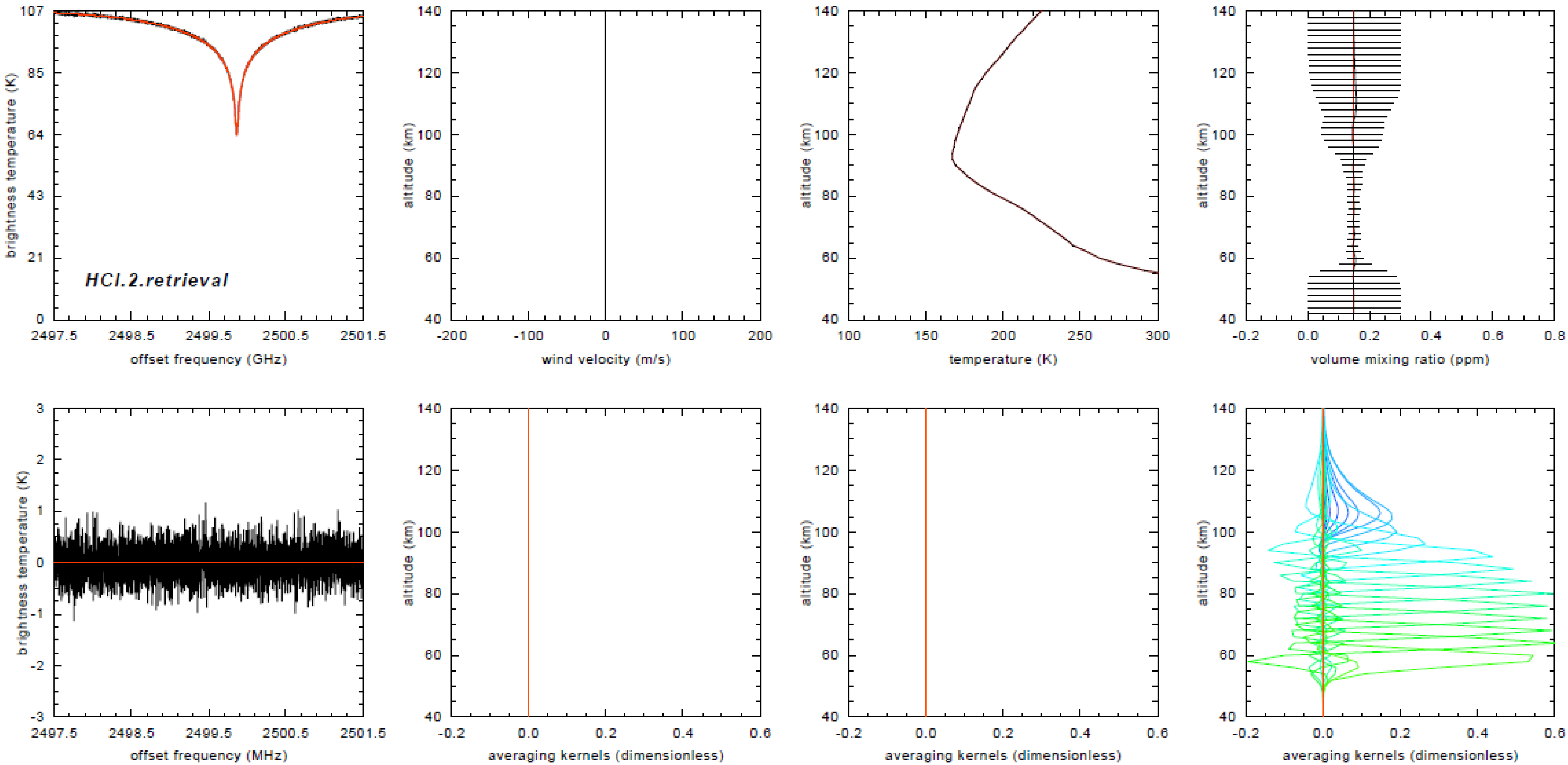


Iwagami et al, 2008

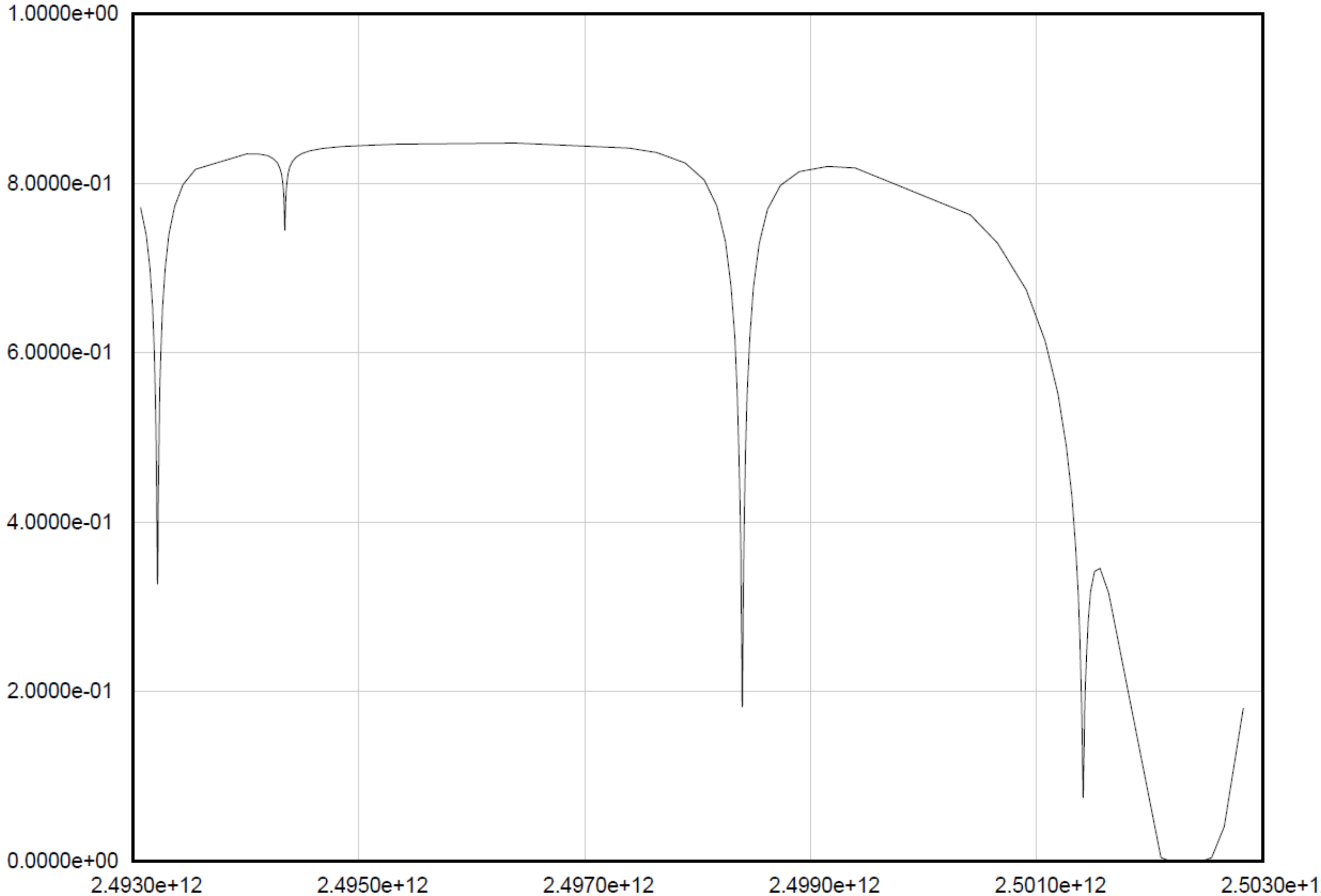
Berteaux et al., 2007 (Nature): 0.15 ppm



HCl retrieval M



Transmission M



Summary

- Even after Herschel a number of very exciting and important solar system observations are remaining for GREAT.
- None of them have been performed thus far due to several problems, e.g. efficiency of observations, availability of bands, time reserved for solar system, observing conditions, **door mechanism!**
- Cross fingers for the future!