# Solar System Science with SOFIA/GREAT

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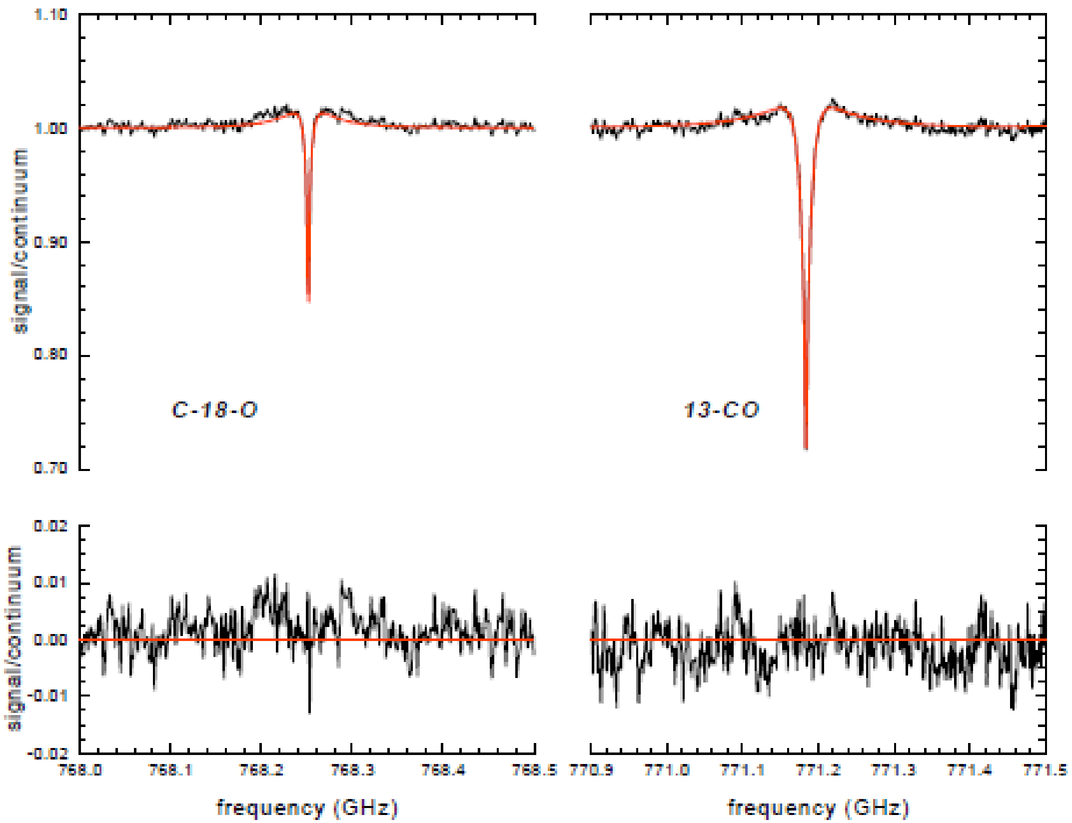
# Outline

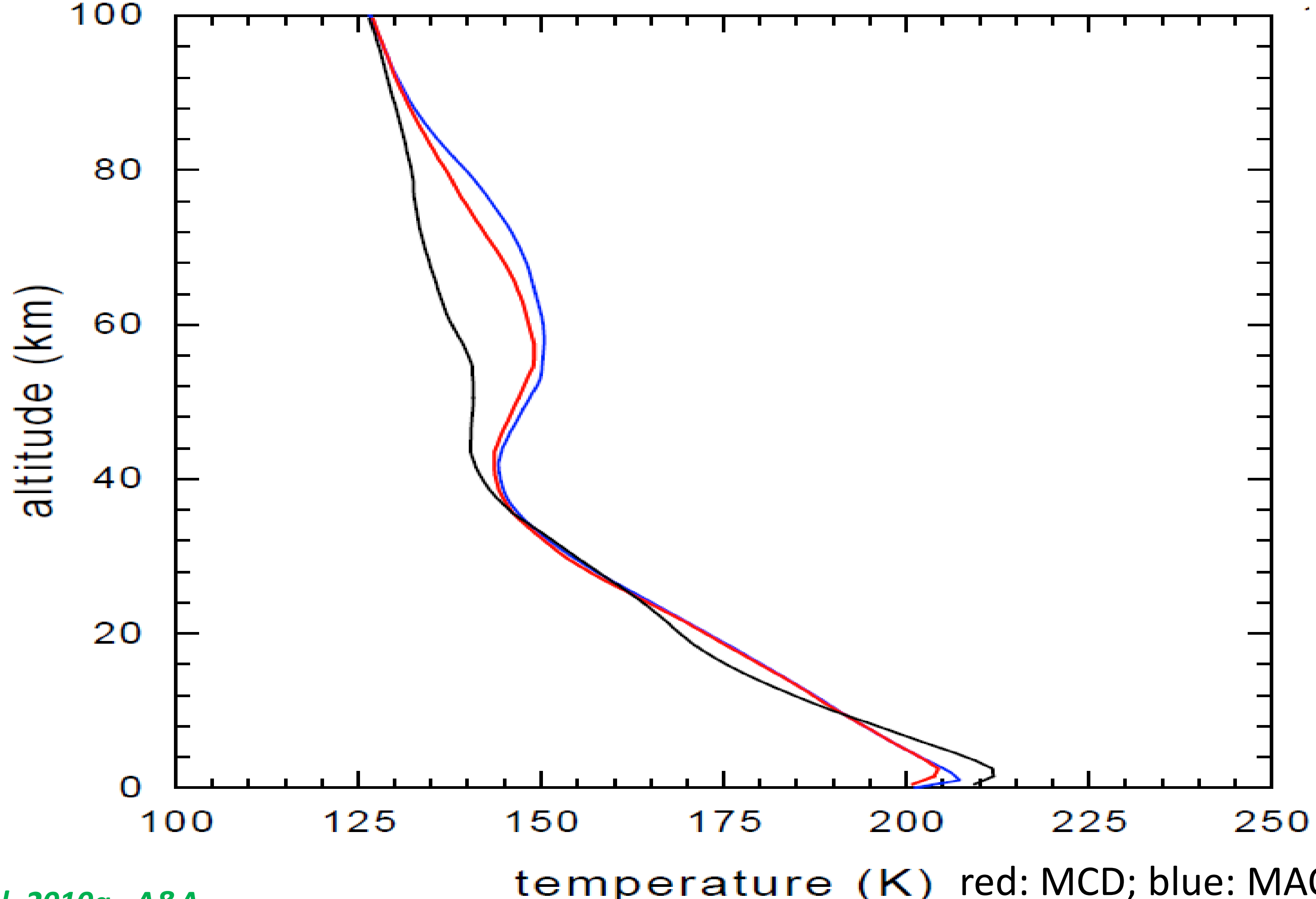
- Solar System Science with Herschel and APEX  and proposed complementary SOFIA observations
- SOFIA unique solar system observations
- GREAT outer planets
- GREAT Venus and Mars
- GREAT comets

# HIFI Mars CO observations

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

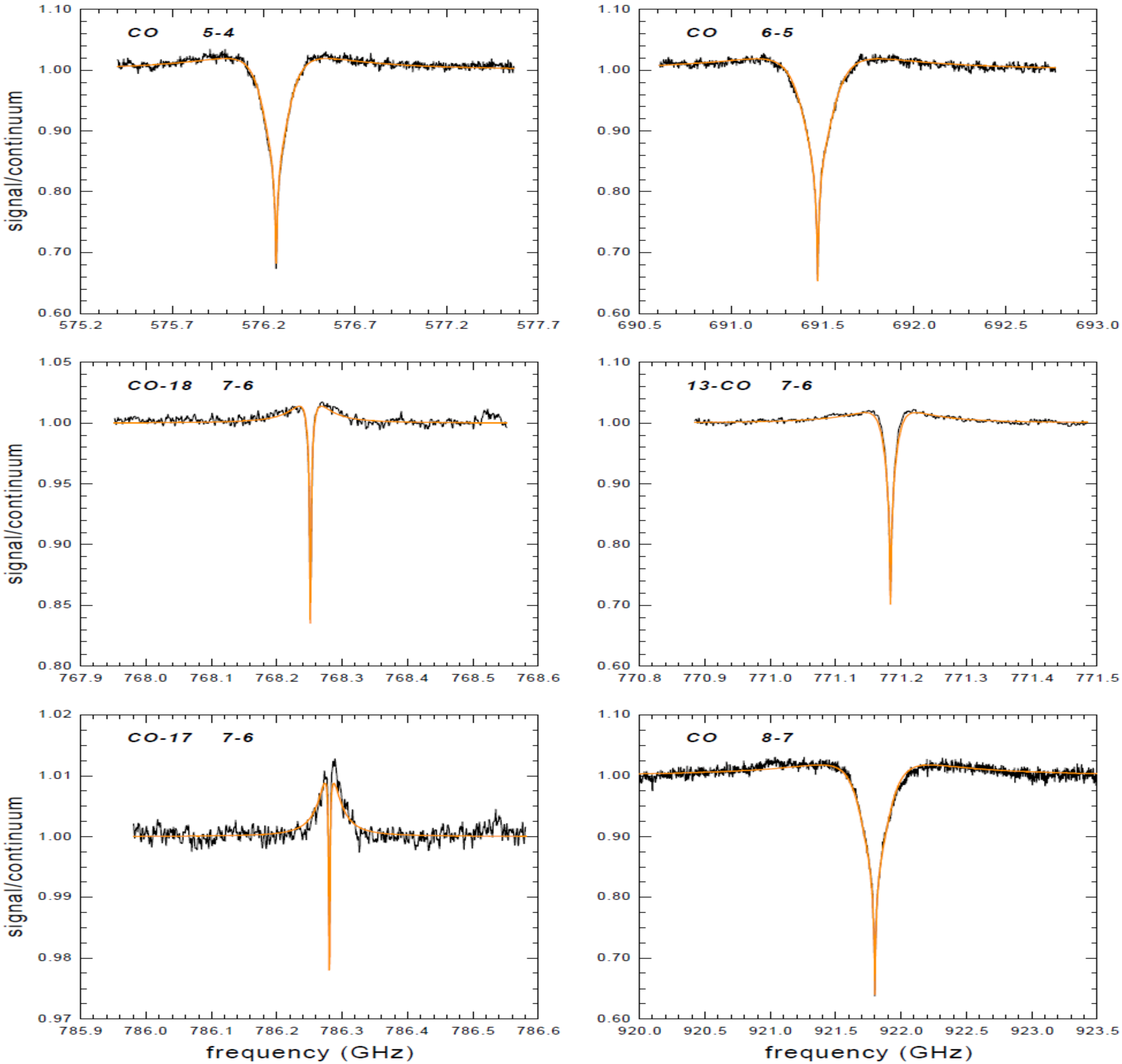


# Retrieved temperature profile and 980 ppm constant with altitude CO volume mixing ratio

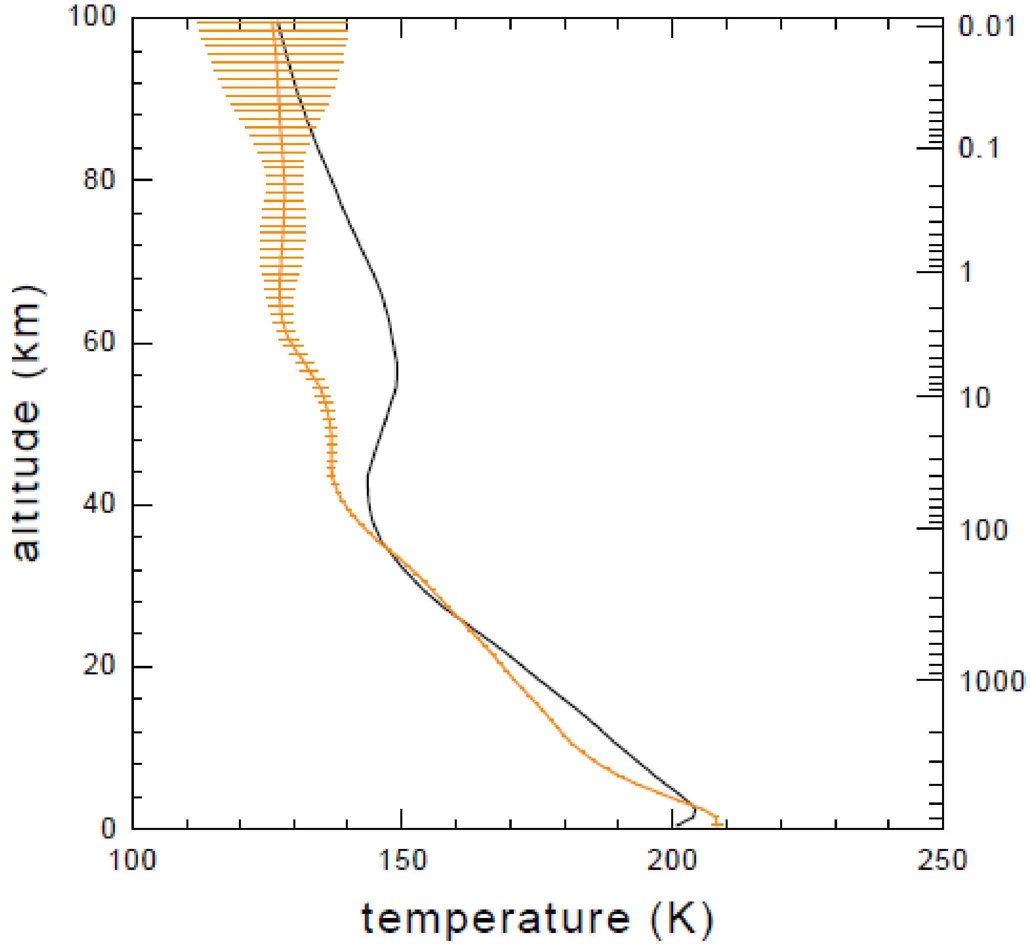



red: MCD; blue: MAOAM; black: observation

*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)
1.10
1.00
0.90
0.80
0.70
0.60
1.05
0.95
0.85
1.02
1.01
0.99
0.98
0.97
575.2 575.7 576.2 576.7 577.2 577.7
690.5 691.0 691.5 692.0 692.5 693.0
767.9 768.0 768.1 768.2 768.3 768.4 768.5 768.6
770.8 770.9 771.0 771.1 771.2 771.3 771.4 771.5
785.9 786.0 786.1 786.2 786.3 786.4 786.5 786.6
920.0 920.5 921.0 921.5 922.0 922.5 923.0 923.5

# Temperature profile retrieved with all CO lines confirms the one derived before (deviating from models), but is more sensitive in upper atmosphere



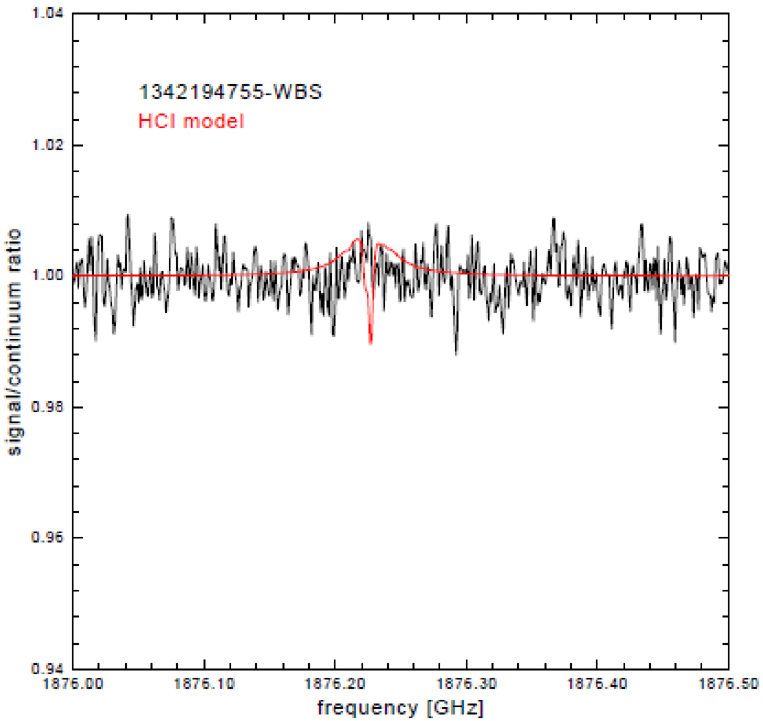
# CO with SOFIA

- Higher transitions generally provide more sensitivity in the upper atmosphere, i.e. temperature and CO profiles can be constrained up to the mesosphere.
- Observations during opposition provide spatial information
- Isotopic observations (13-C, 17-0, 18-O) possible, however accuracy requirements very challenging

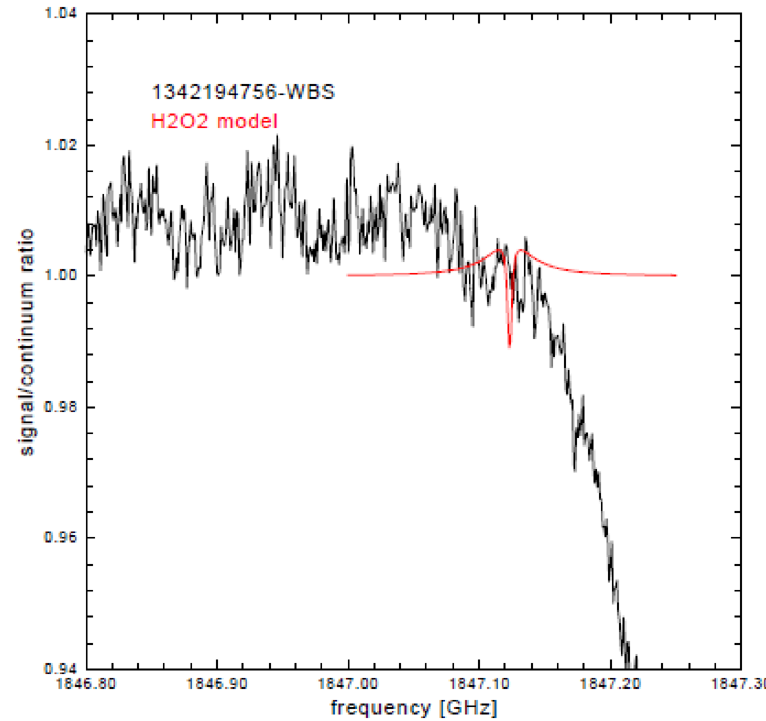
# What about HCl and $H_2O_2$ ?

- HCl volcanic gas. Detection would constrain volcanic outgassing. Potentially important also for destruction of methane (see for instance M. Mumma or C. Webster)
- $H_2O_2$ important constraint for hydrogen / oxygen photochemistry on Mars.
- $H_2O_2$ snow believed to kill all live on martian surface. Believed to be produced in eletrostatic discharge reaction during dust storms. (see Sushil Artreya's work)

# HIFI upper limits on HCl and $H_2O_2$




< 200 ppt

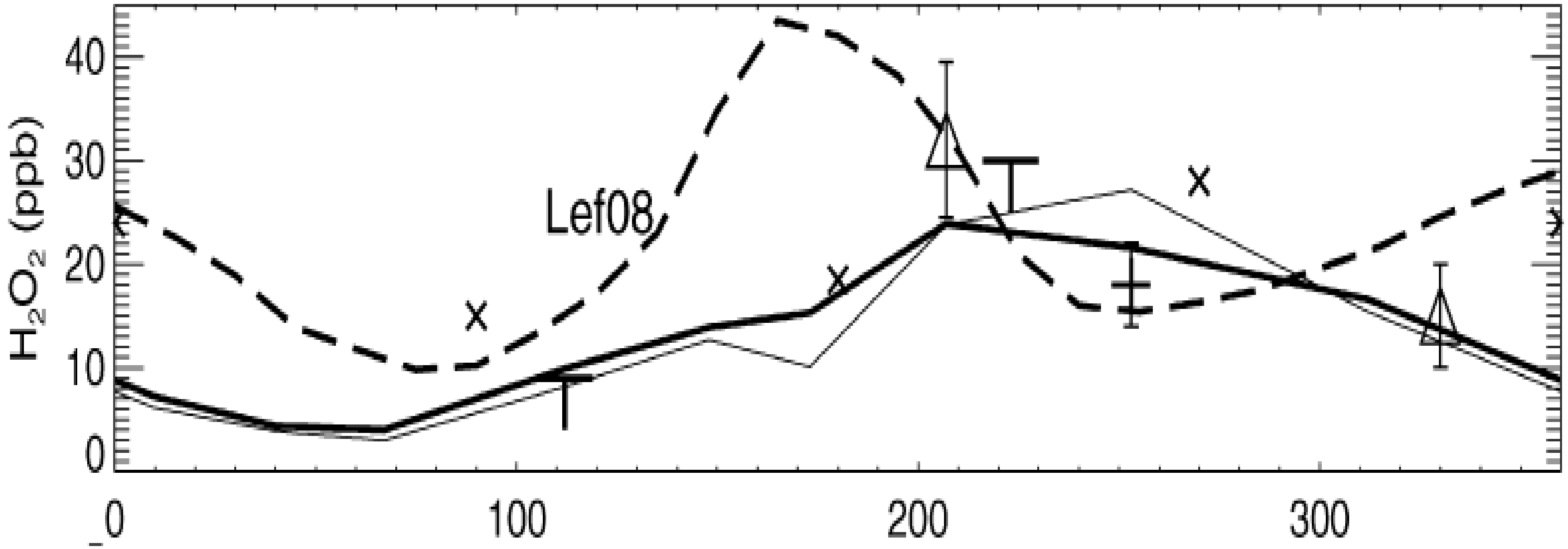



< 2 ppb



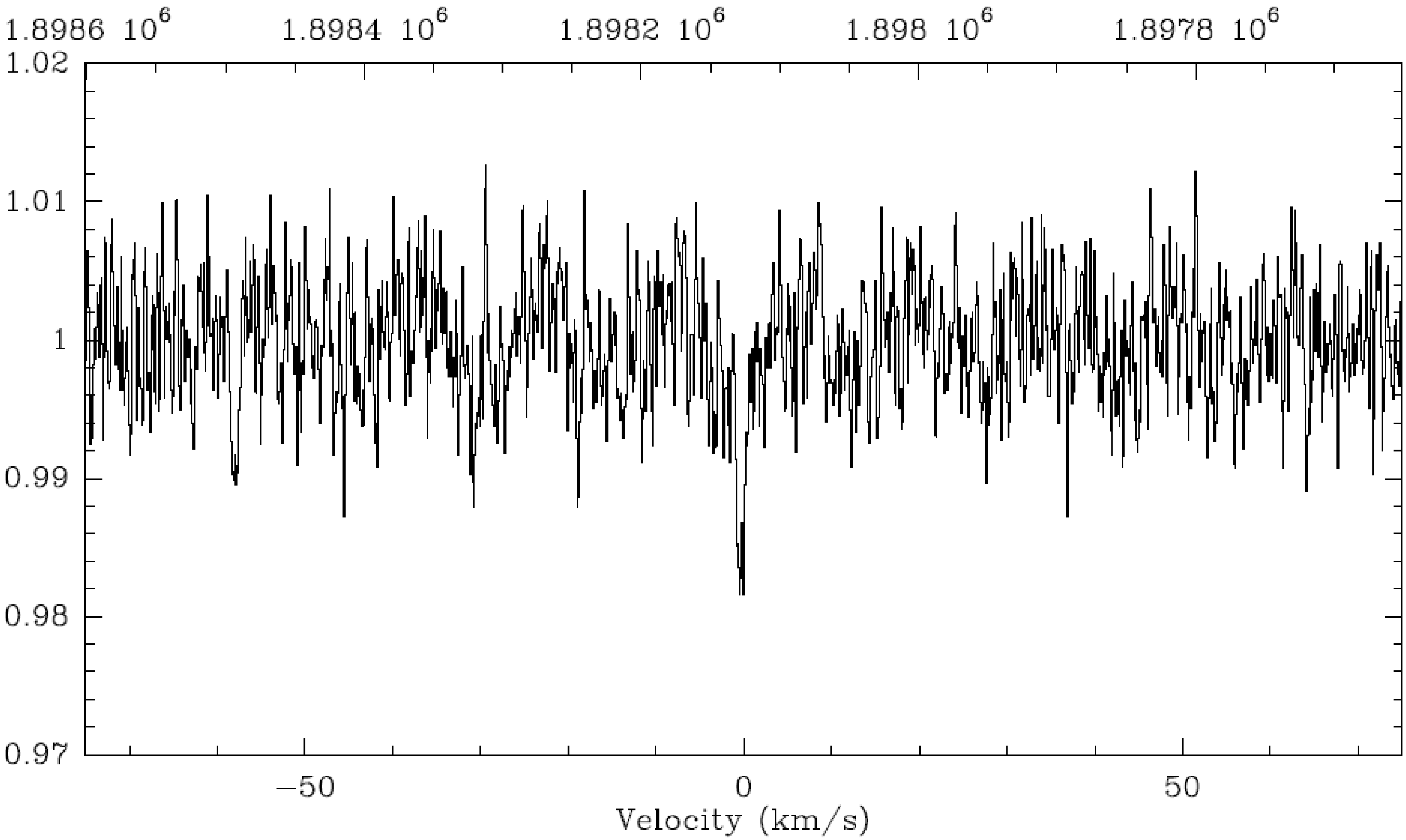
***Hartogh et al. 2010b, A&A***

# Model abundances of $H_2O_2$




*Krasnopolsky 2009, Icarus*

# Fall 2011: detection of $H_2O_2$! Ls=10°



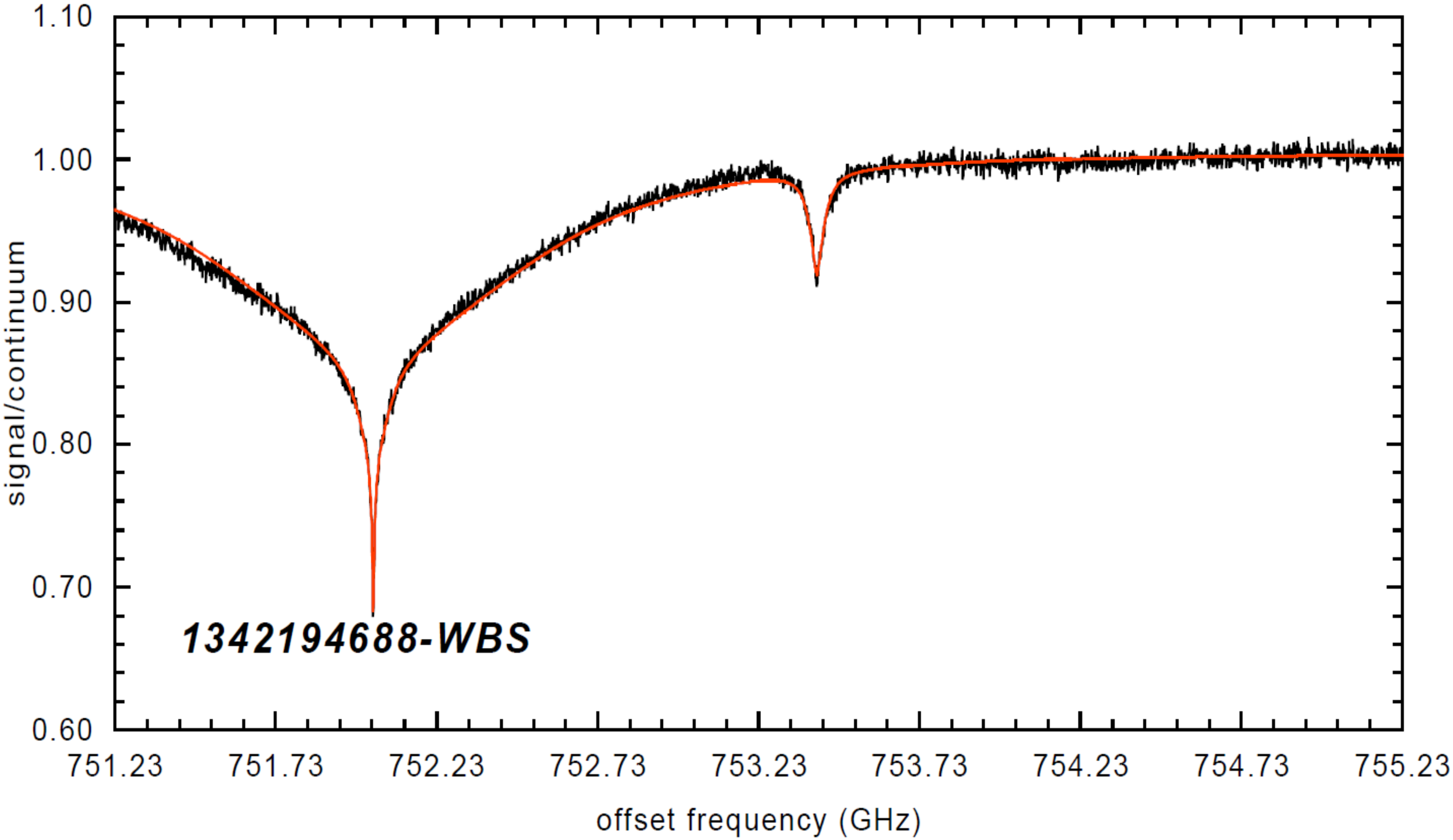
# GREAT HCl and $H_2O_2$

- Decrease the lower limit of HCl and $H_2O_2$(HIFI 1 h observation time)
- Constrain photo(electro)chemical models by monitoring of the seasonal variation.
- GREAT sensitivity comparable with or better than the one of HIFI

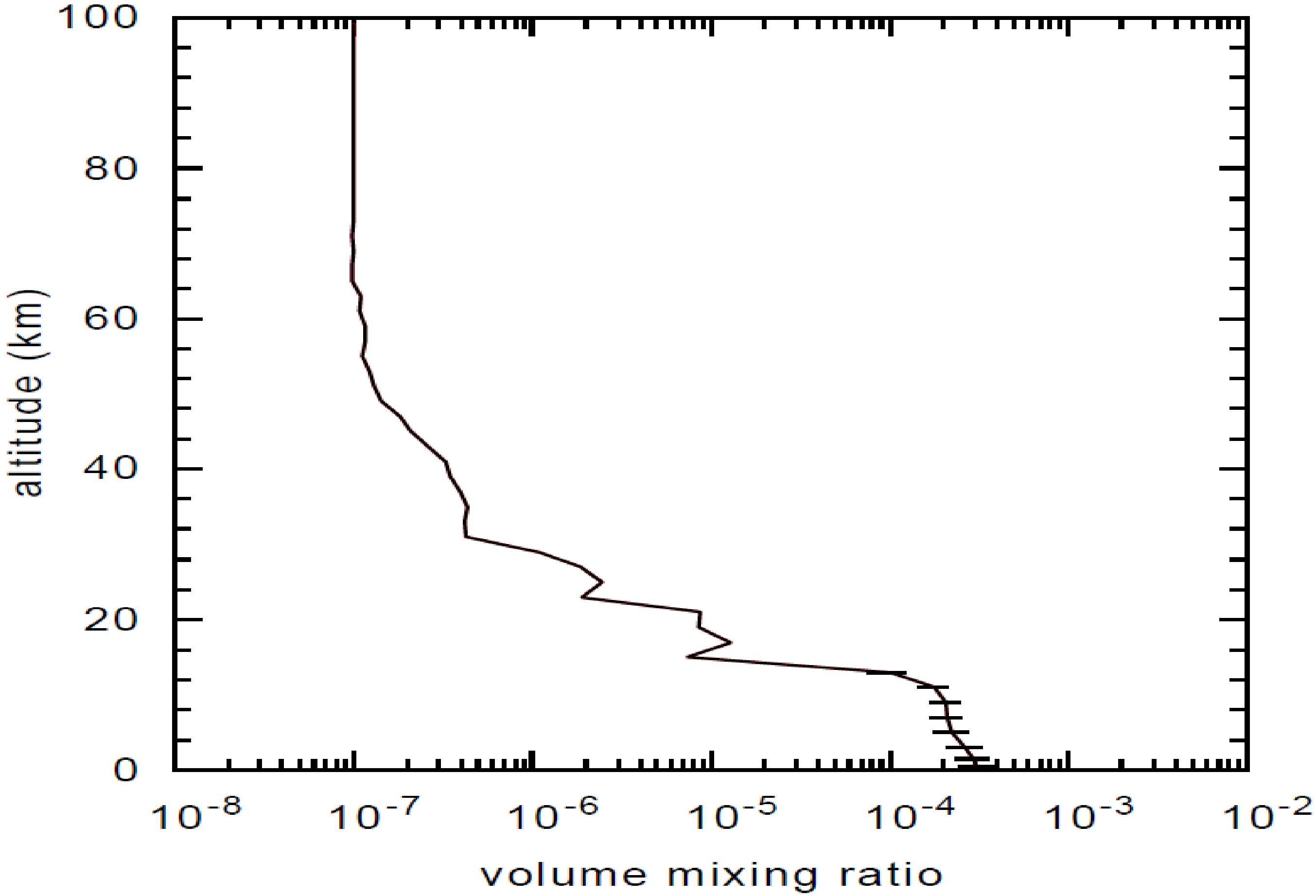
# Water vapor

- Very important source gas for atmospheric chemistry
- Maximum column density around Northern summer (more water ice at North pole)
- Maximum vertical extension believed to happen during southern summer (higher solar flux, 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.

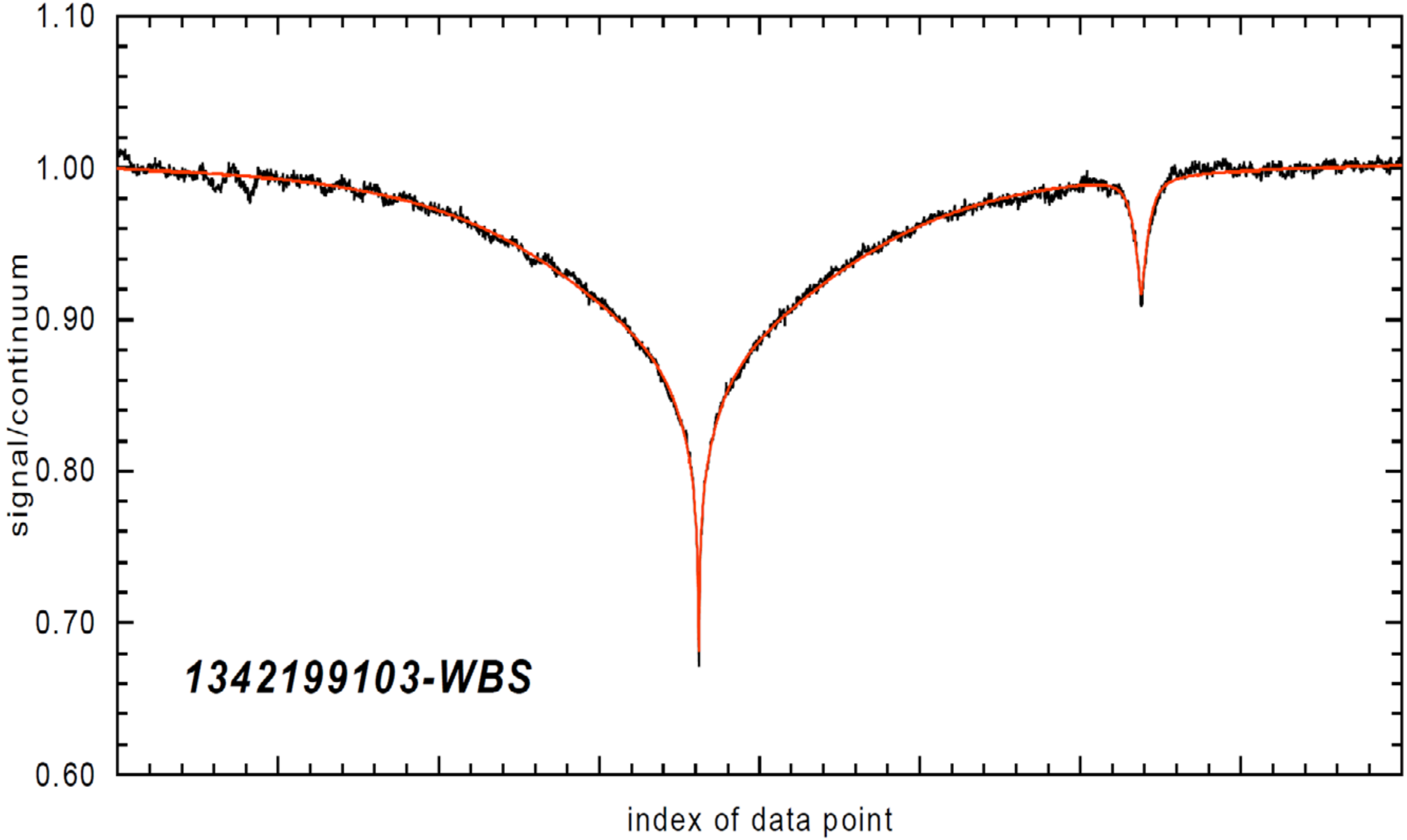
# $H_2O$ and HDO at Ls = 78°



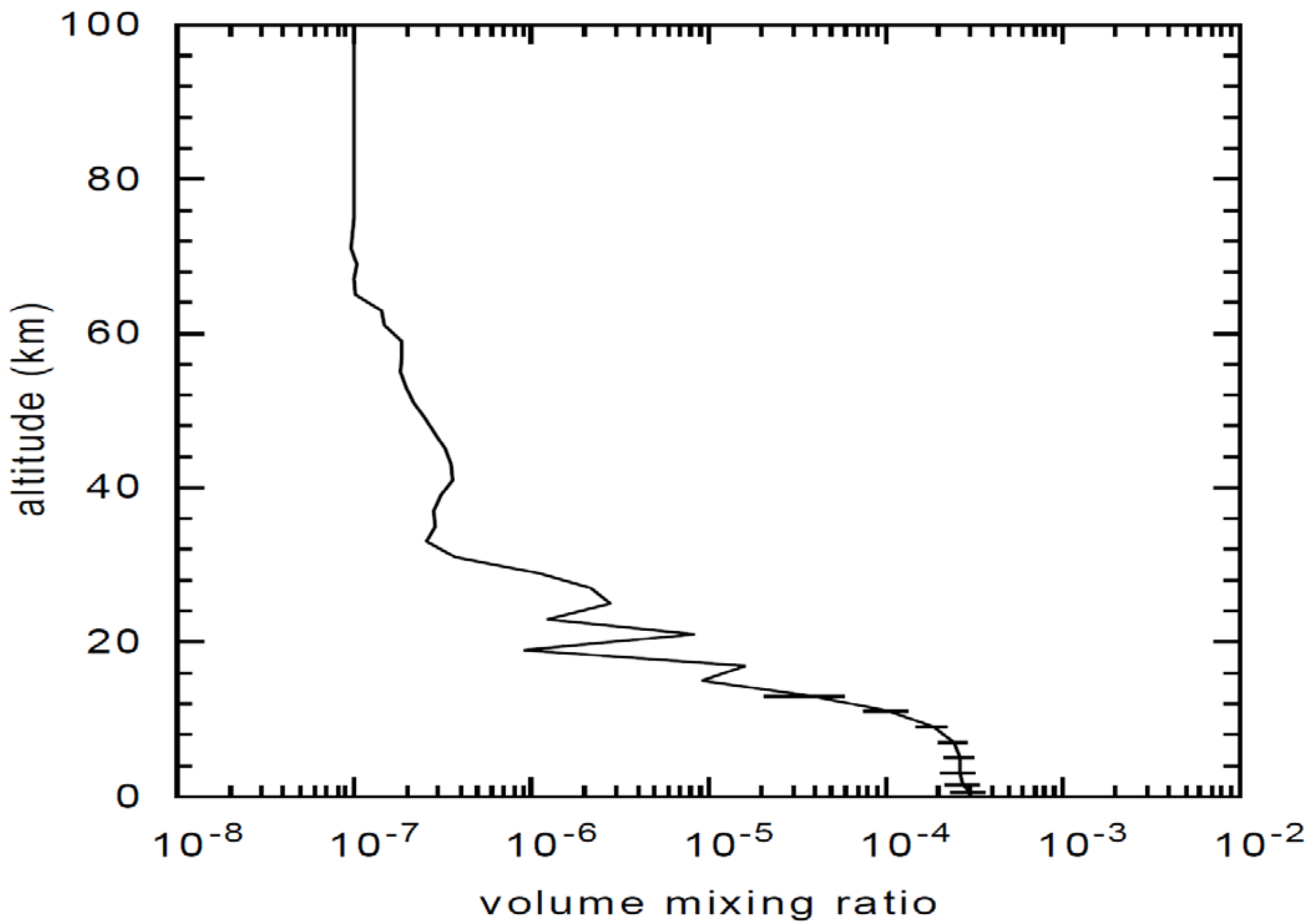
# Vertical profile of water at Ls = 78°



# $H_2O$ and HDO at Ls = 110°



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



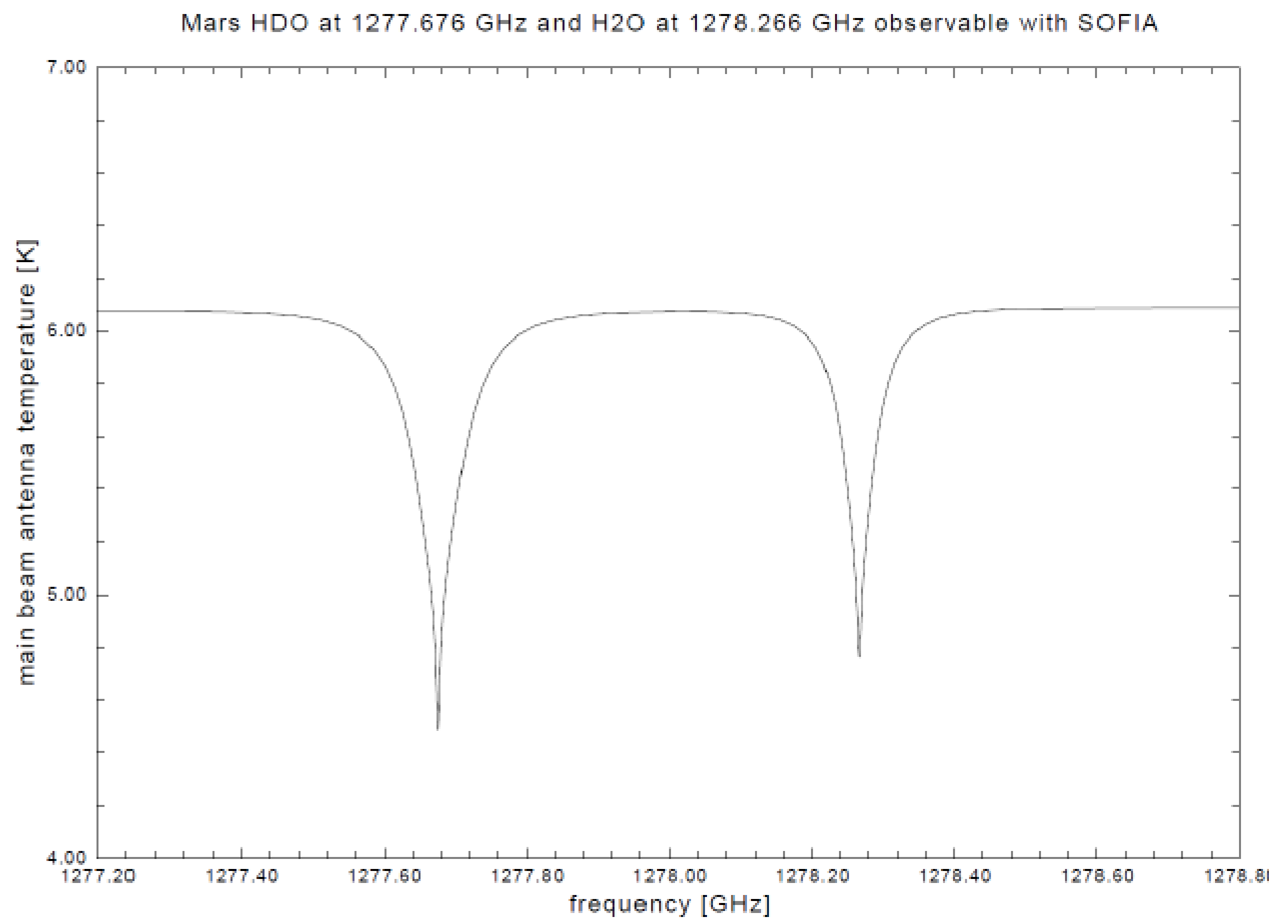
# Proposed SOFIA Observations

- Vertical profiles of water during solar elongations not covered by Herschel: water cycle

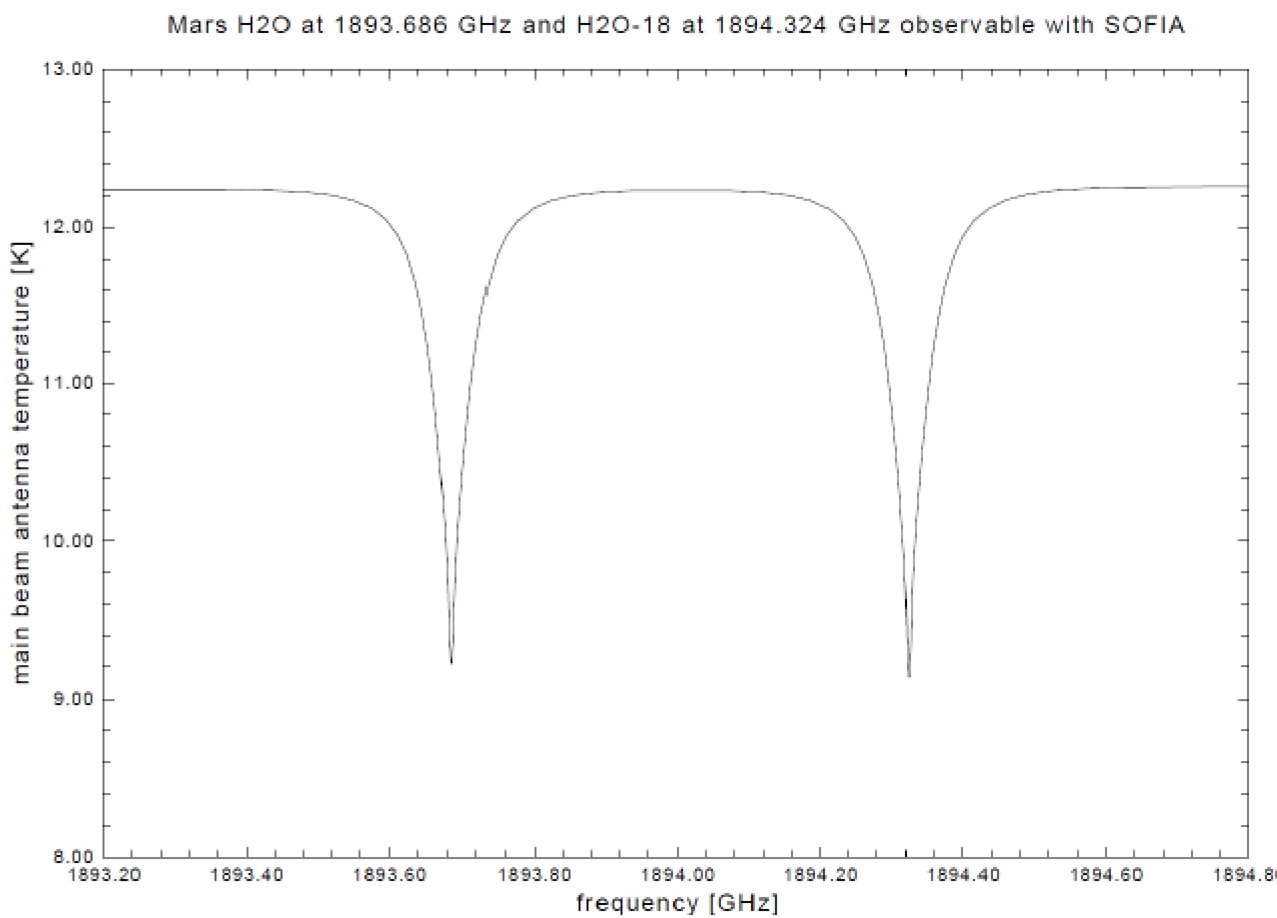
- Vertical profiles during global dust storms

- Optically thin GREAT lines: isotopes (D, 17-O, 18-O) and their vertical, latitudinal and seasonal fractionation

# Mars: proposed (GREAT L1) for September 2011



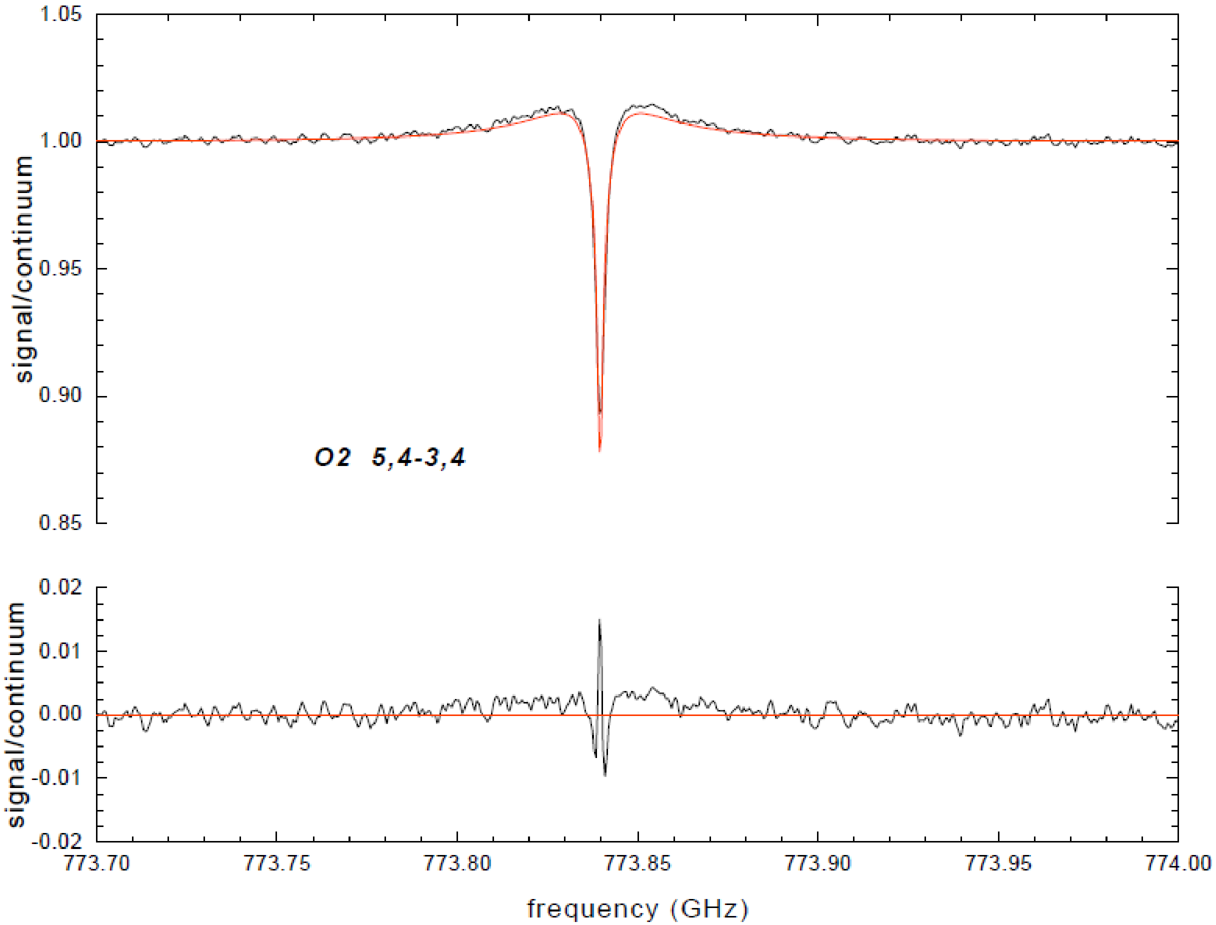
# Mars: proposed (GREAT L2) for September 2011 with angular diameter of 5 deg. Today: amplitudes x 4, 8 April 2014 x 9, May 2016 x 13.



# 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.

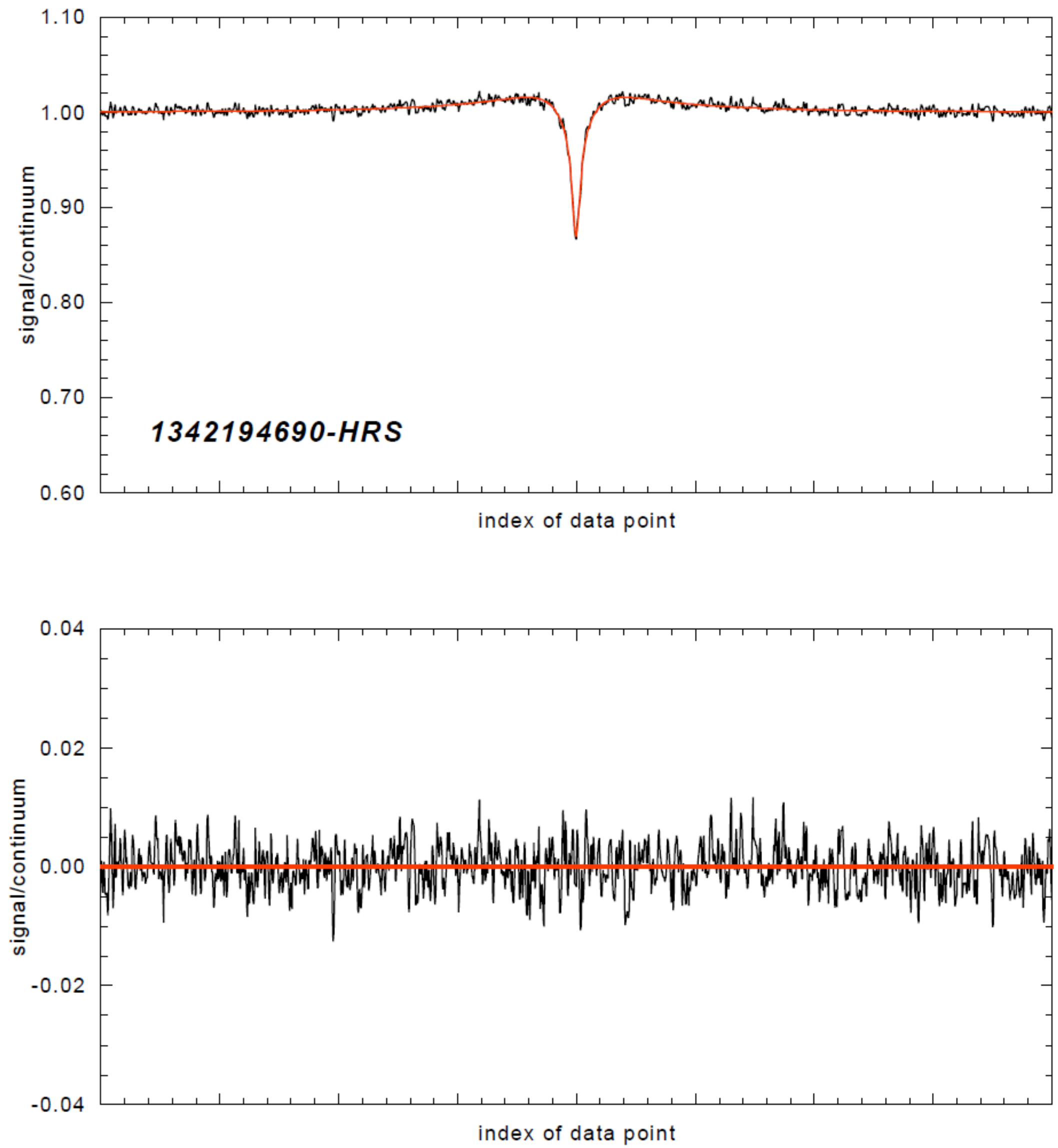
# First submm detection of $O_2$




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***

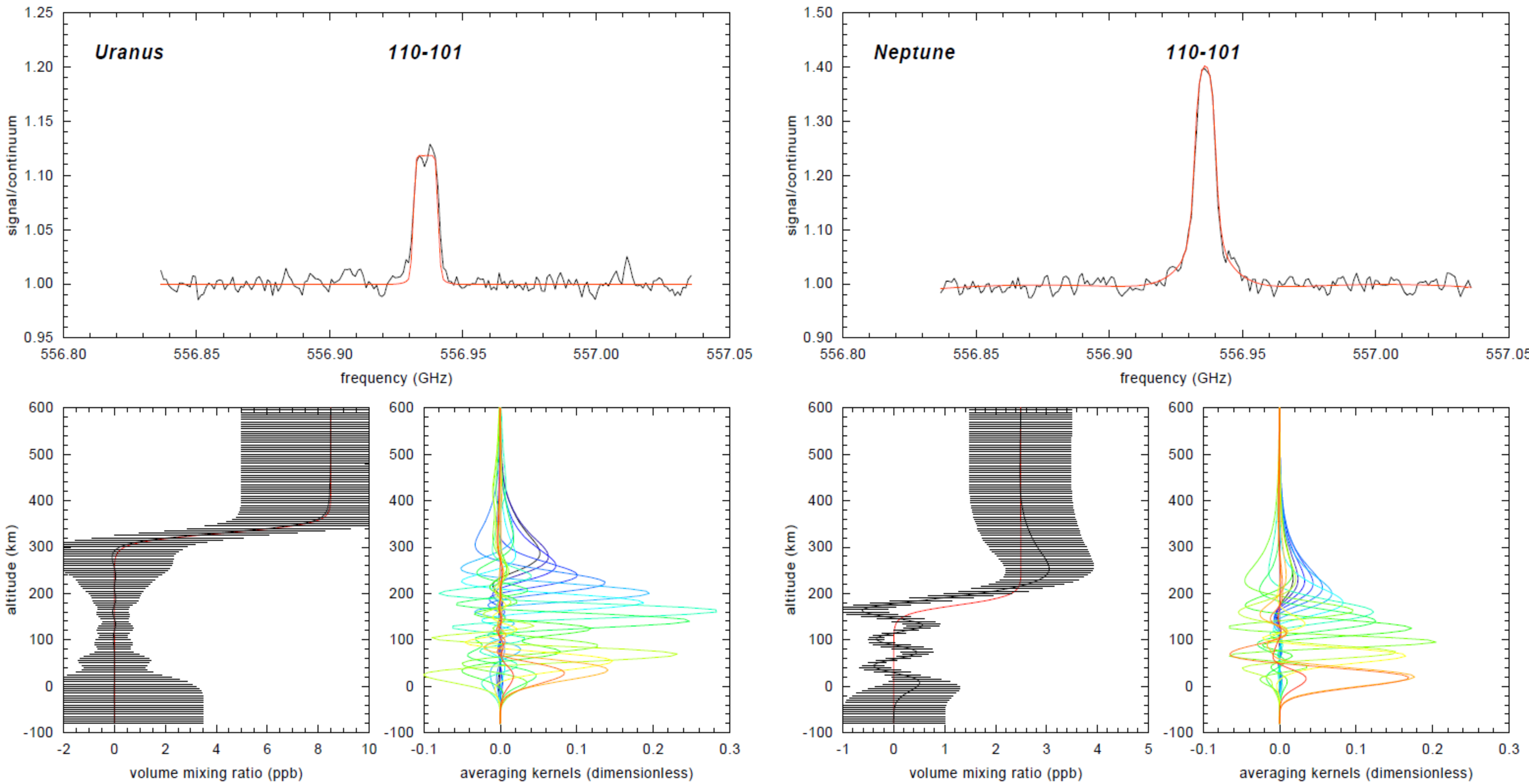
# Non-constant profile with vertical decay provides better fit



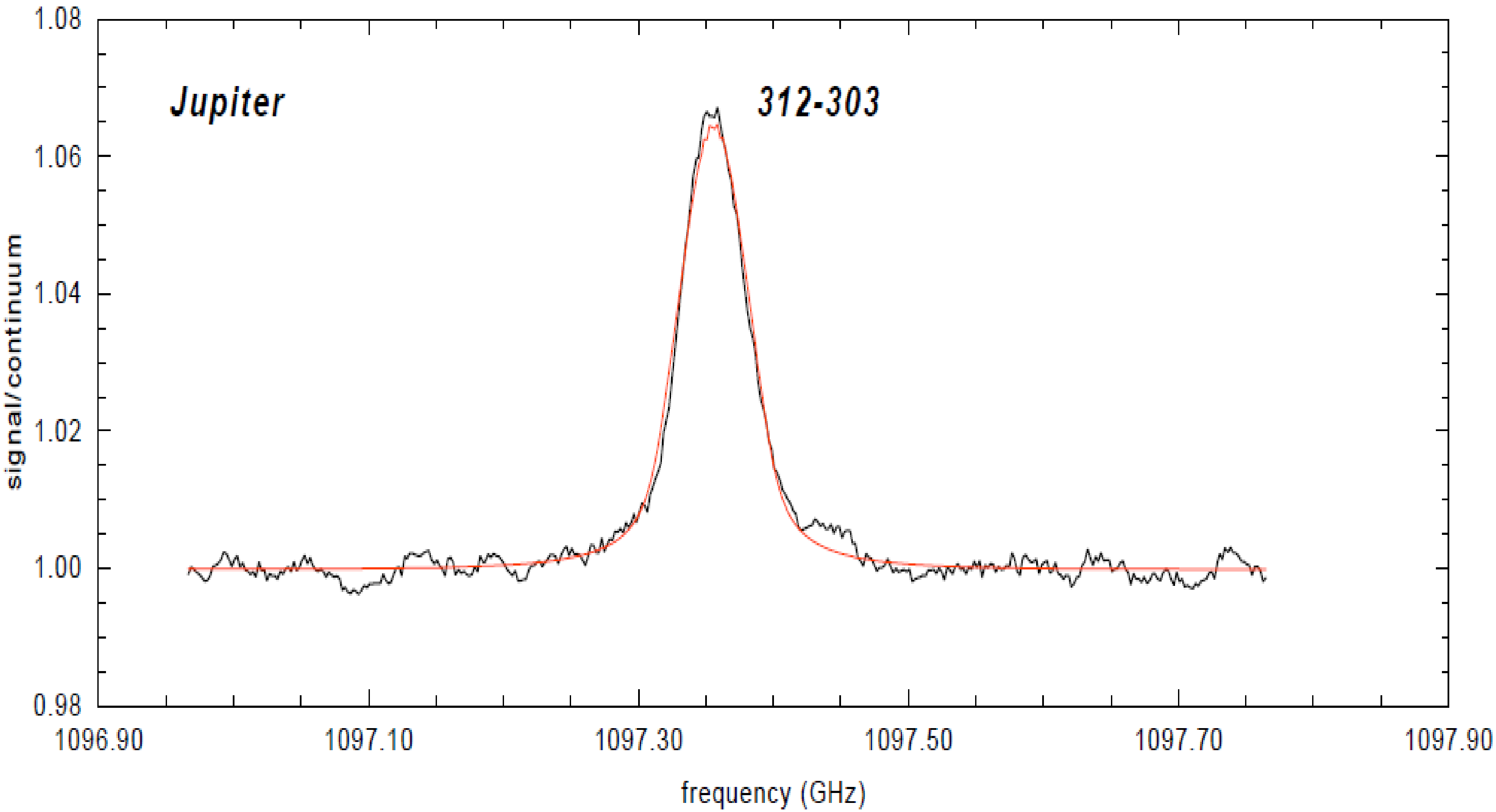
# $O_2$ with GREAT

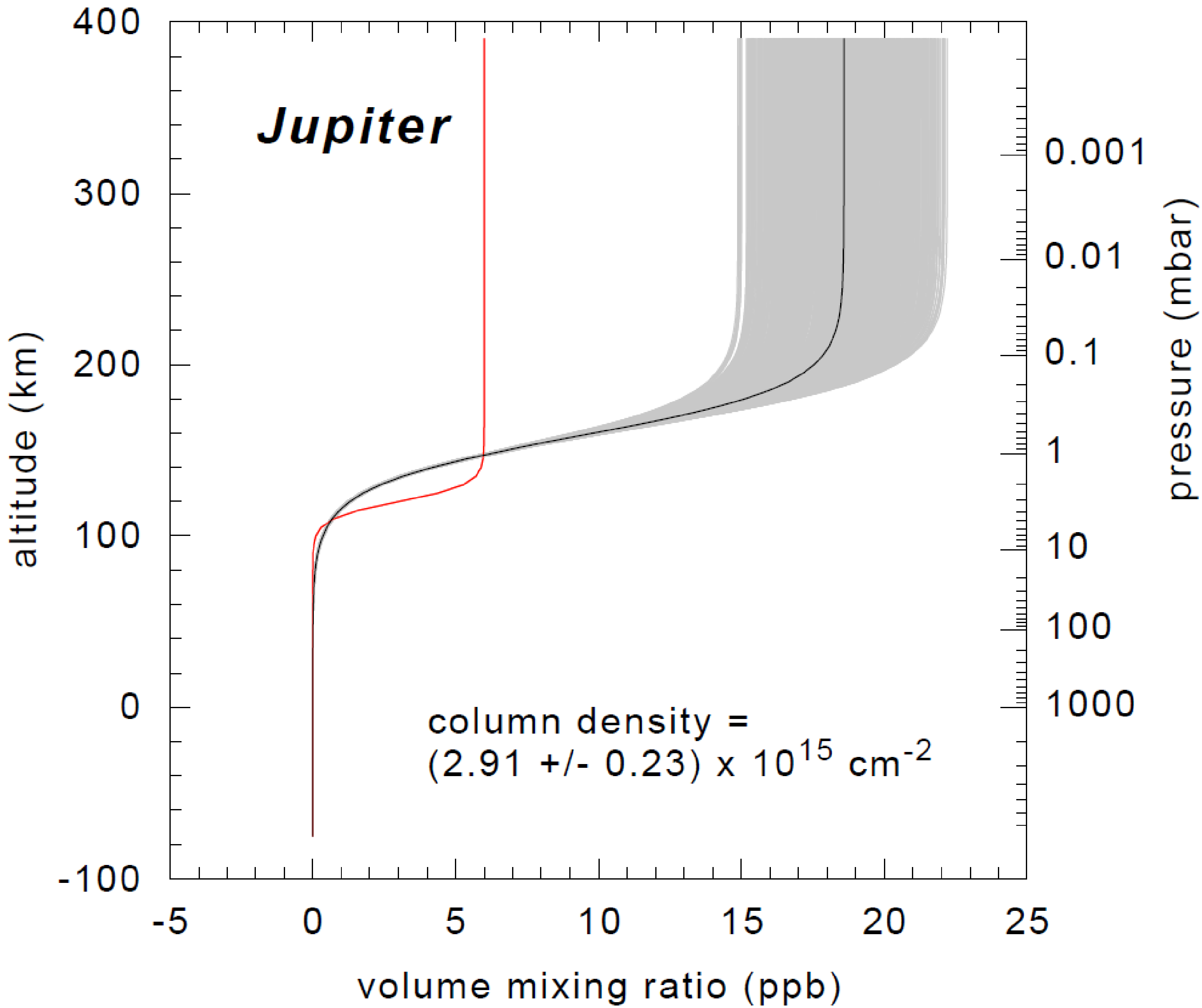
- Does not work!

# Observation water and OEM retrieval Uranus and Neptune

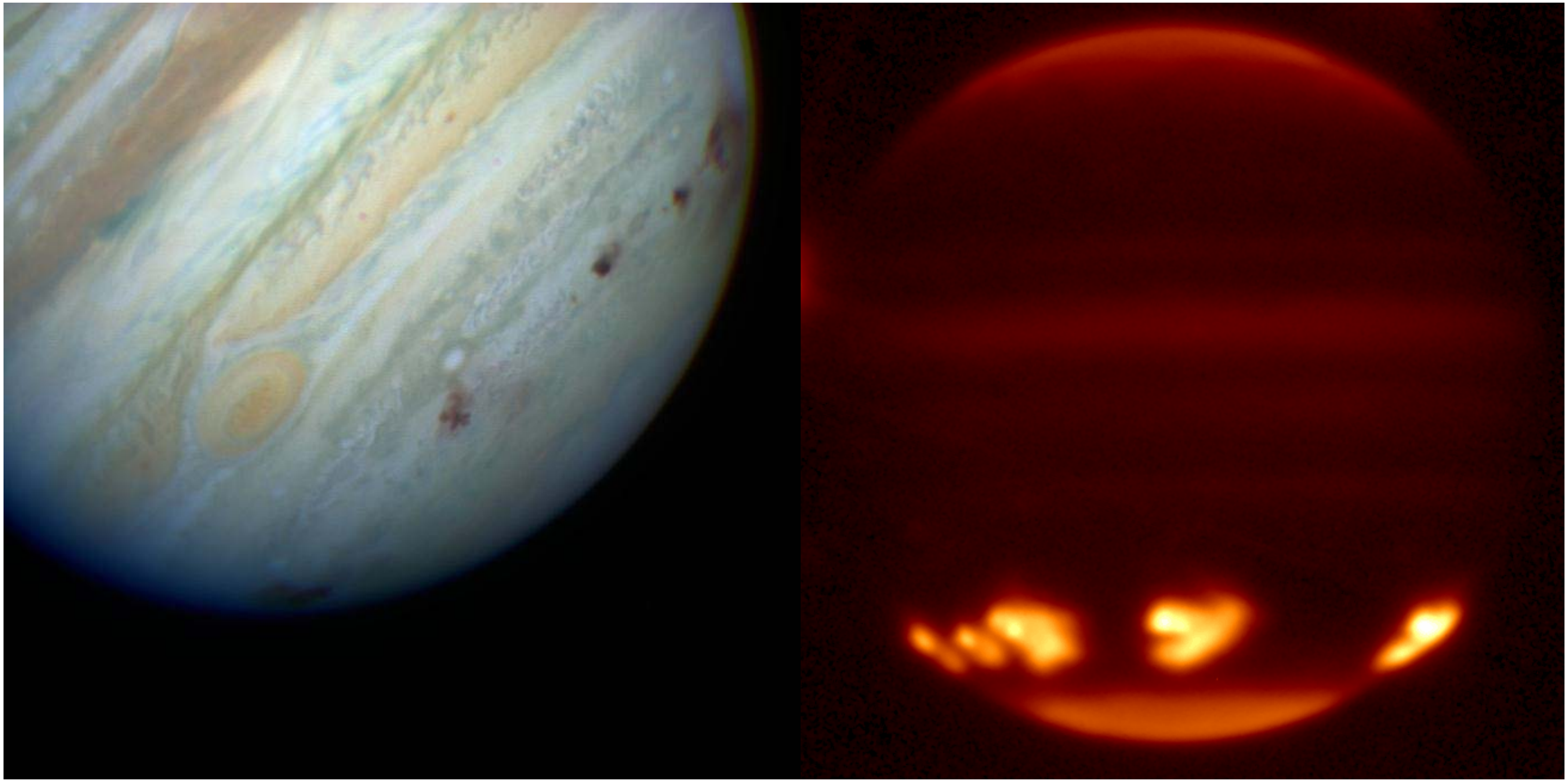


# Jupiter water December 2010



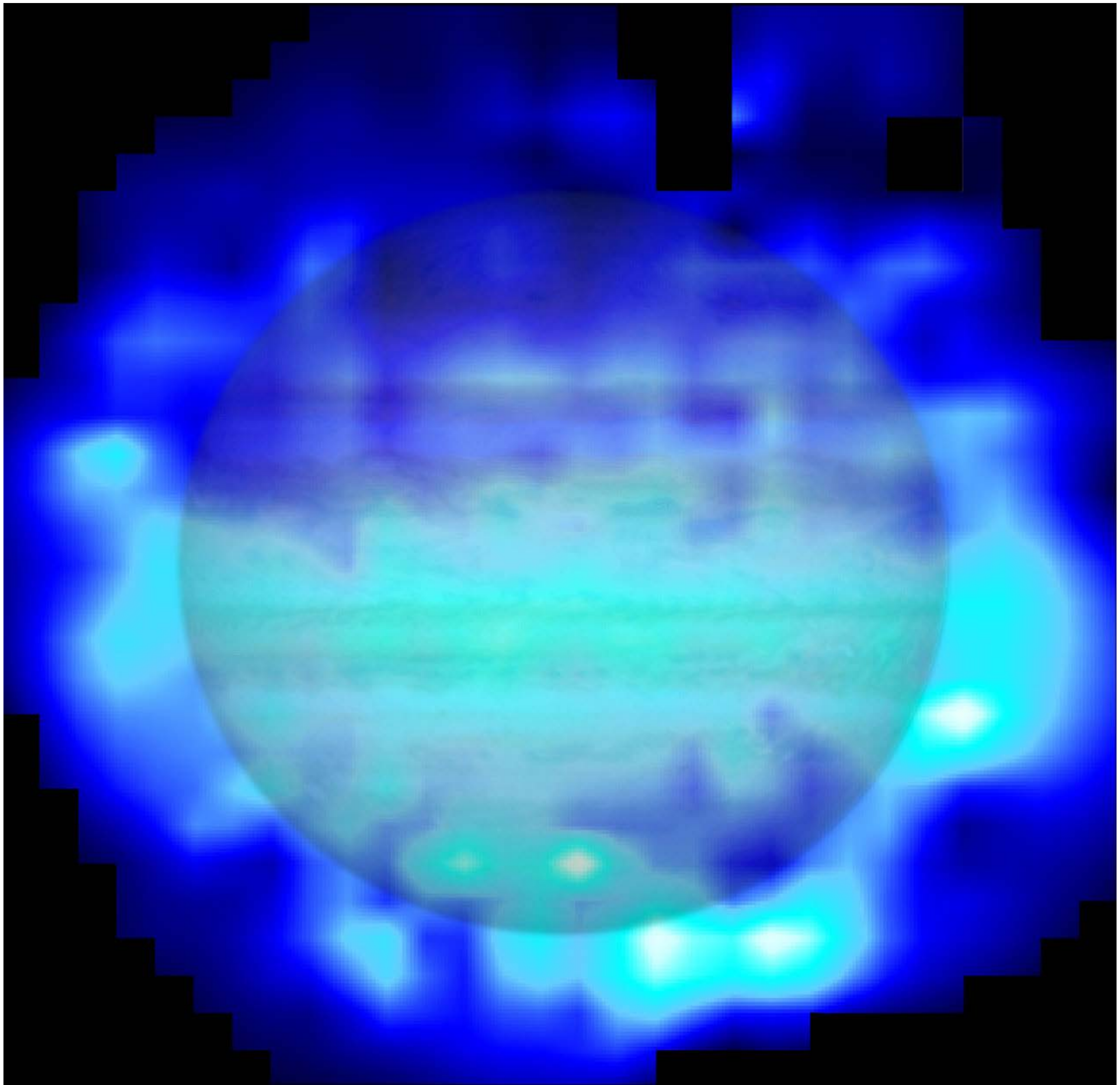

Jupiter
altitude (km)
400
300
200
100
0
-100
-5
0
5
10
15
20
25
volume mixing ratio (ppb)
pressure (mbar)
0.001
0.01
0.1
1
10
100
1000
column density =
(2.91 +/- 0.23) x 10^15 cm^-2

# SL9 impacts 1994 (VIS/IR) at 44 S



Credits: NASA-HST/ U. Hawaii

# Water distribution observed by PACS

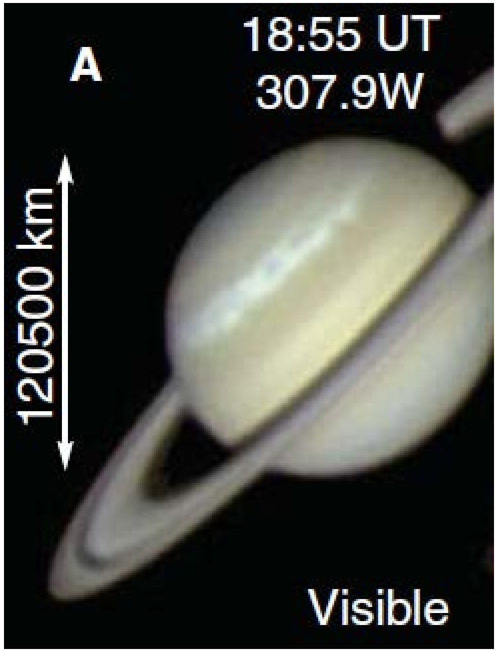


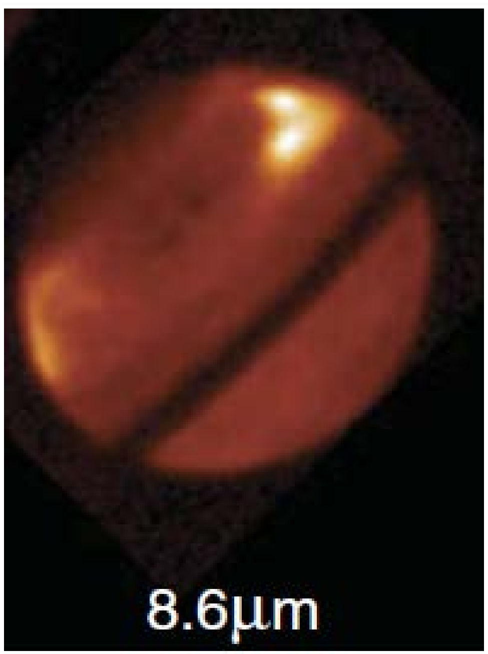
# SL9 impact main source of stratospheric water in Jupiter

- No feature found indicating a satellite/ring source
- Vertical distribution does not fit IDP source
- Horizontal distribution of water favors SL9 impact, hemispheric asymmetry: Globally averaged column density $3x10^{15}cm^{-2}$ with 2-3 times more water in the south.

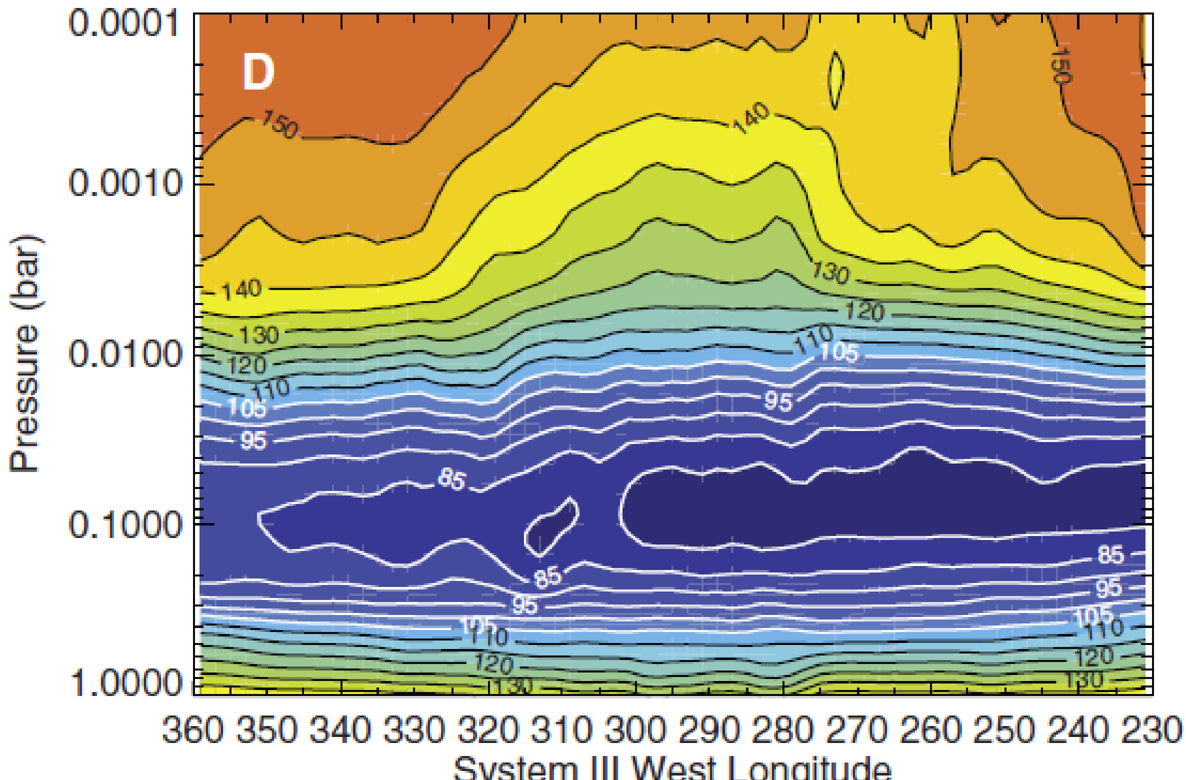
*Cavalie et al., A&A 2013*

# Saturn beacon

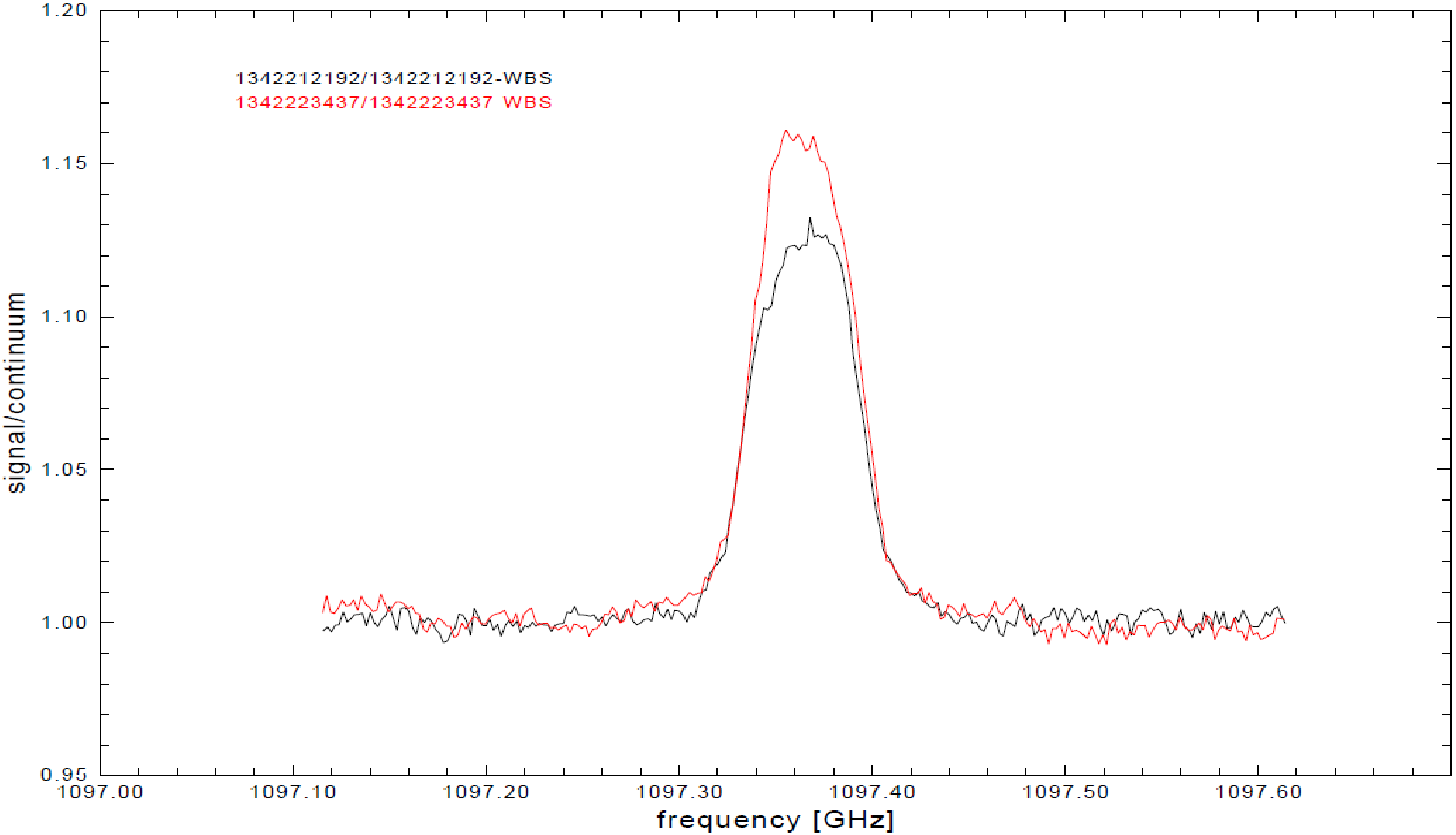


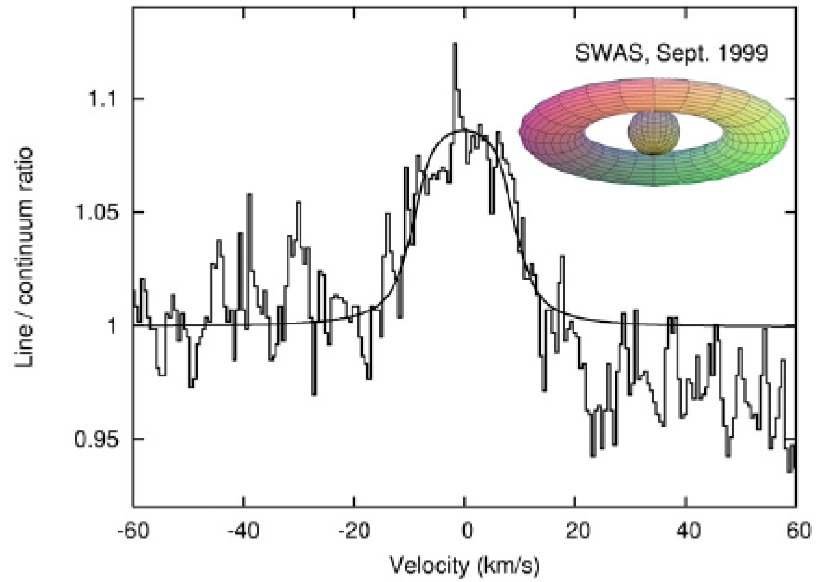

Fletcher et al. 2011

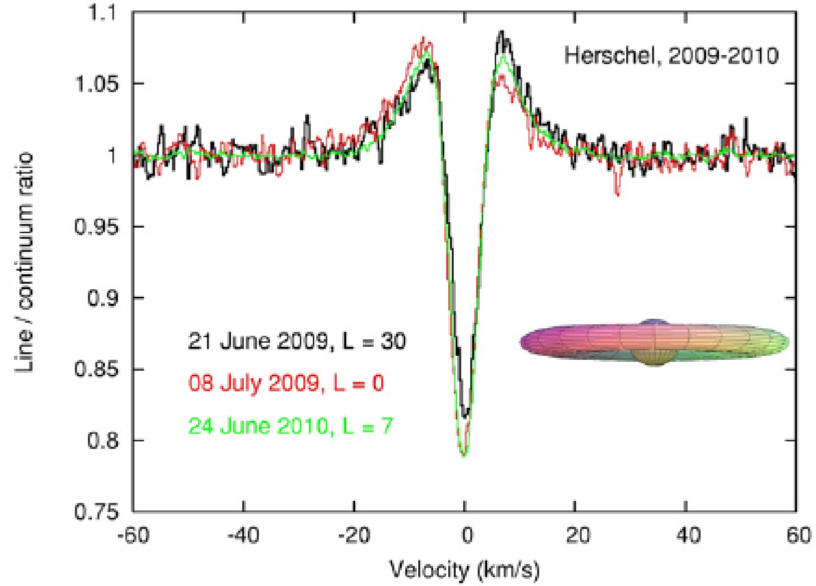


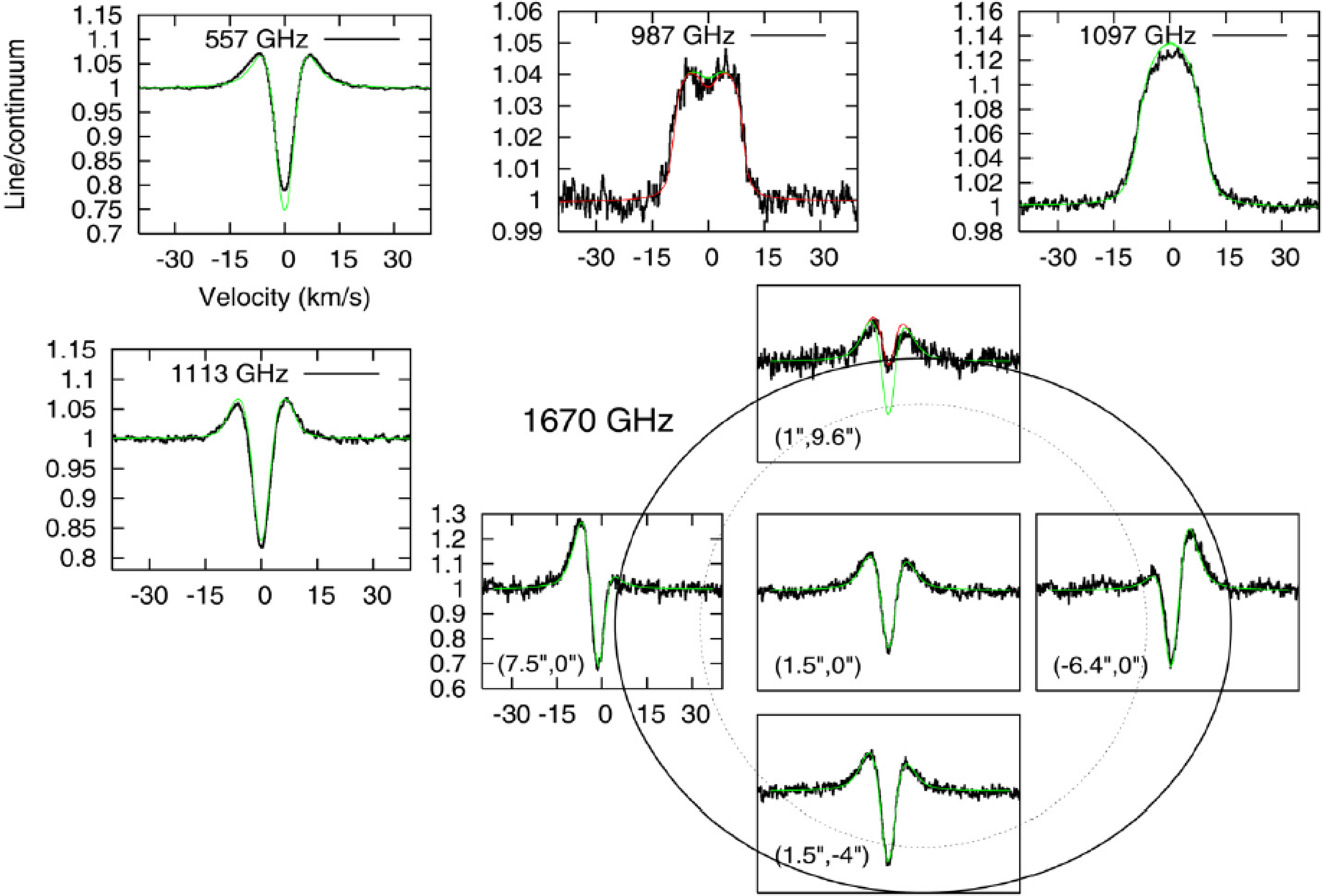
# Saturn water December 2010/July 2011: Global increase by a factor of 3, local by 100!



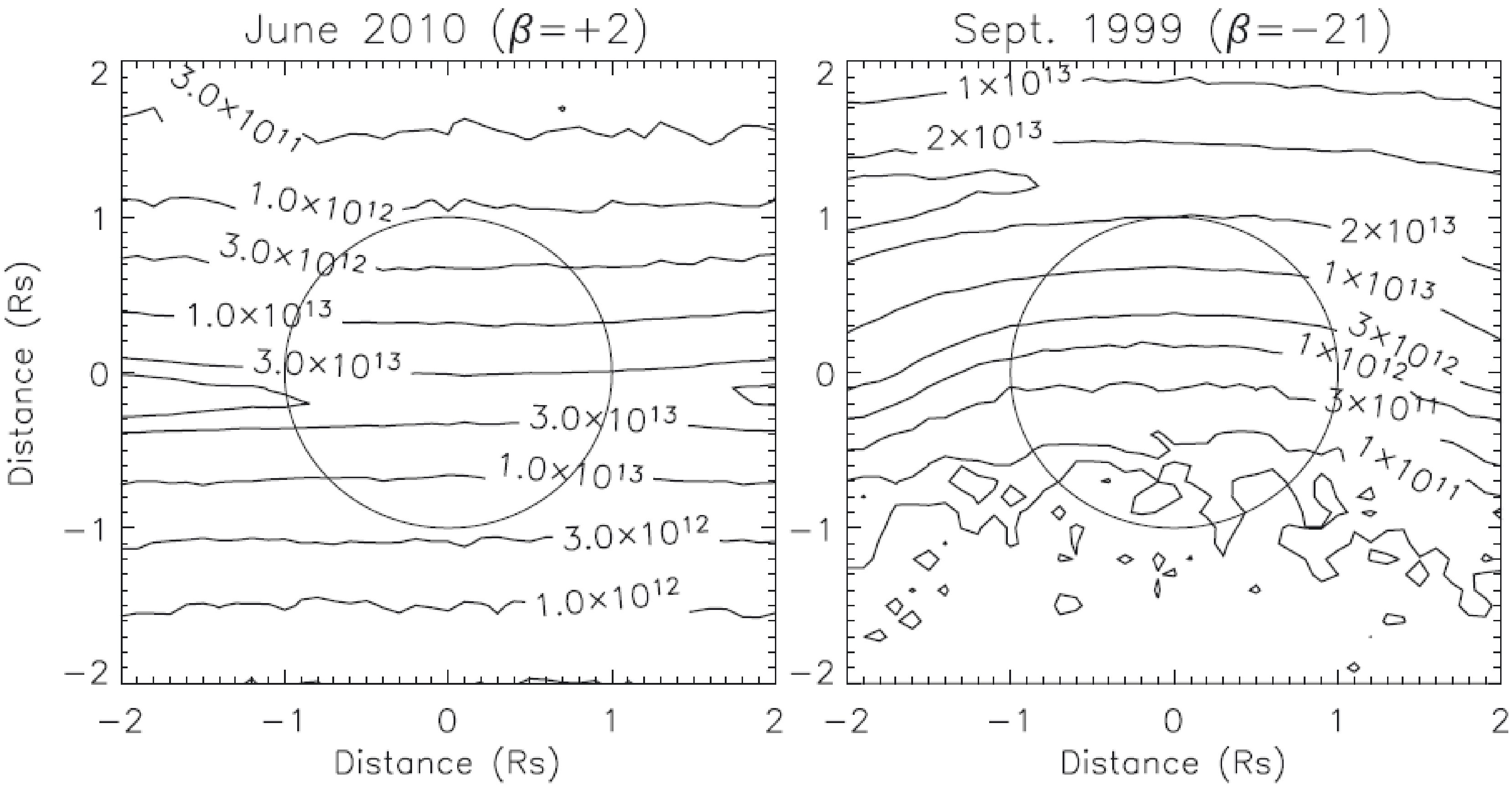
# Unexpected detection at 557 GHz pointing to Saturn




557 GHz
Line/continuum
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

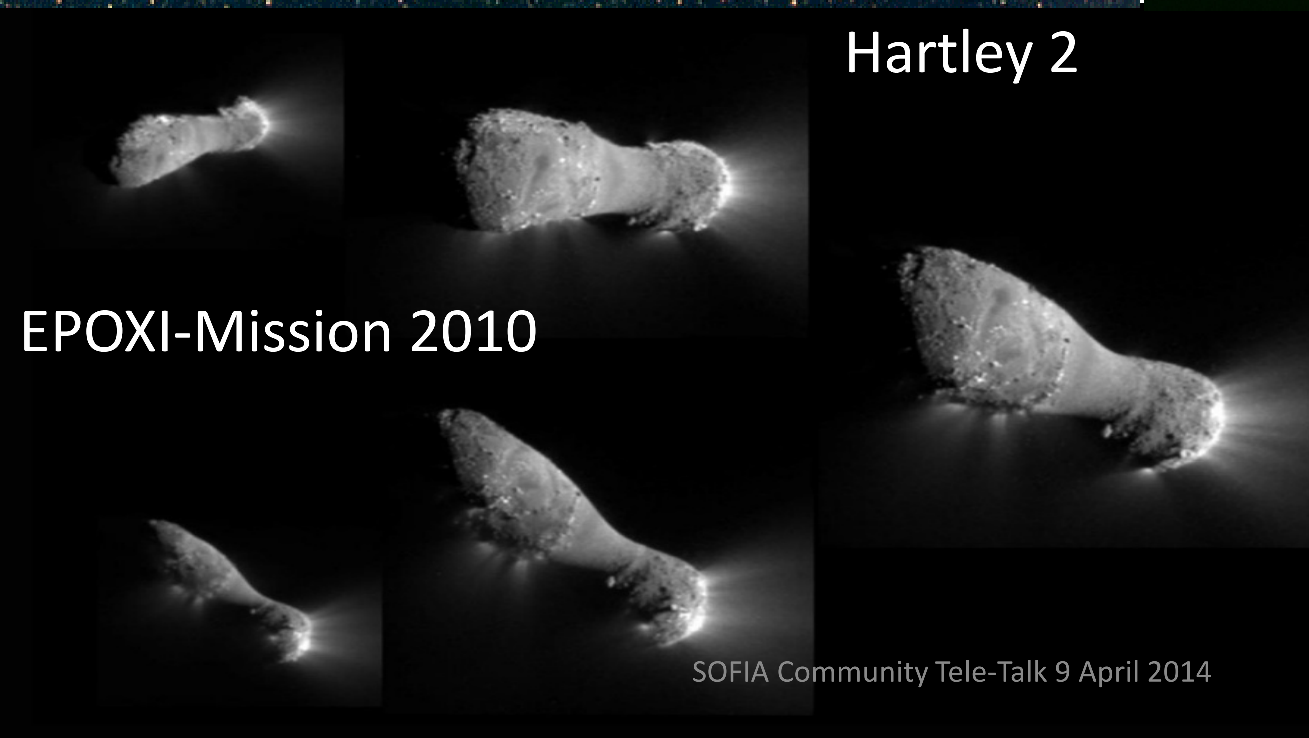
Hartogh et al, A&A 2011a

# Water in outer planets by SOFIA

- Although the opacity of some water lines are very high, it is not high enough for reasonable detections by GREAT (weaker lines). During the great storm on Saturn there was an increase of stratospheric water by up to 2 orders of magnitude in the area with highest Eliassen-Palm flux divergence. However the corresponding area was too small to be resolved by GREAT(~1 arcsec x 5 arcsec)

# D/H in the solar system and origin of water on Earth/Planets

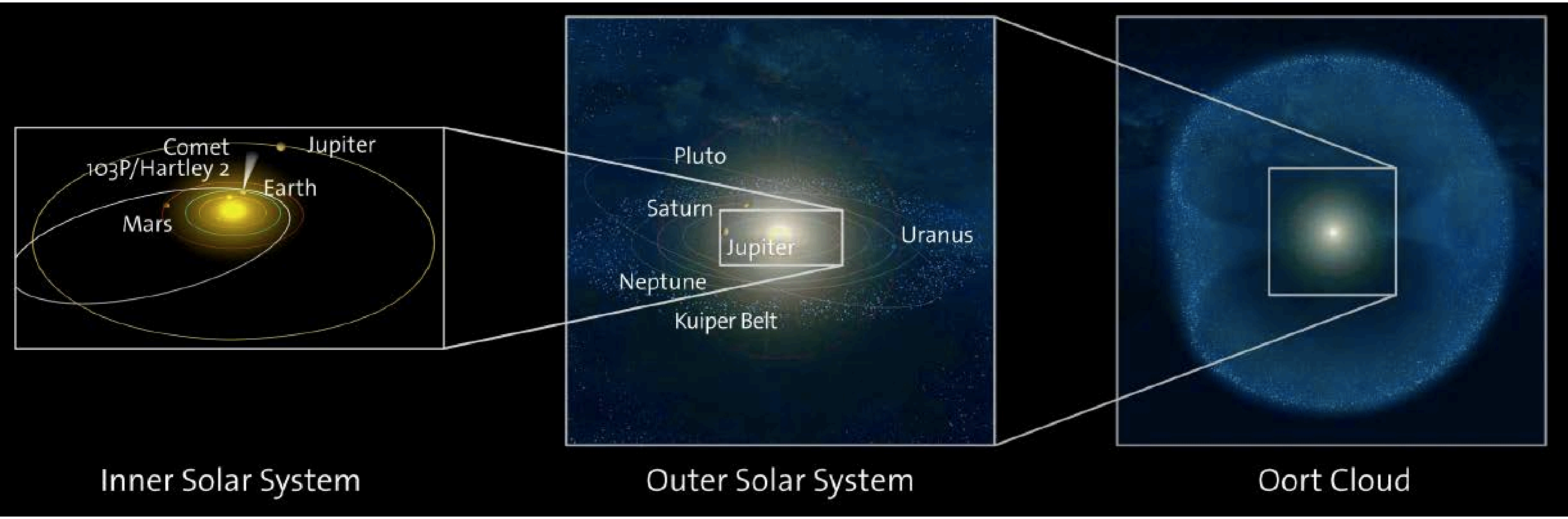





# Origin of water on Earth (1/2)

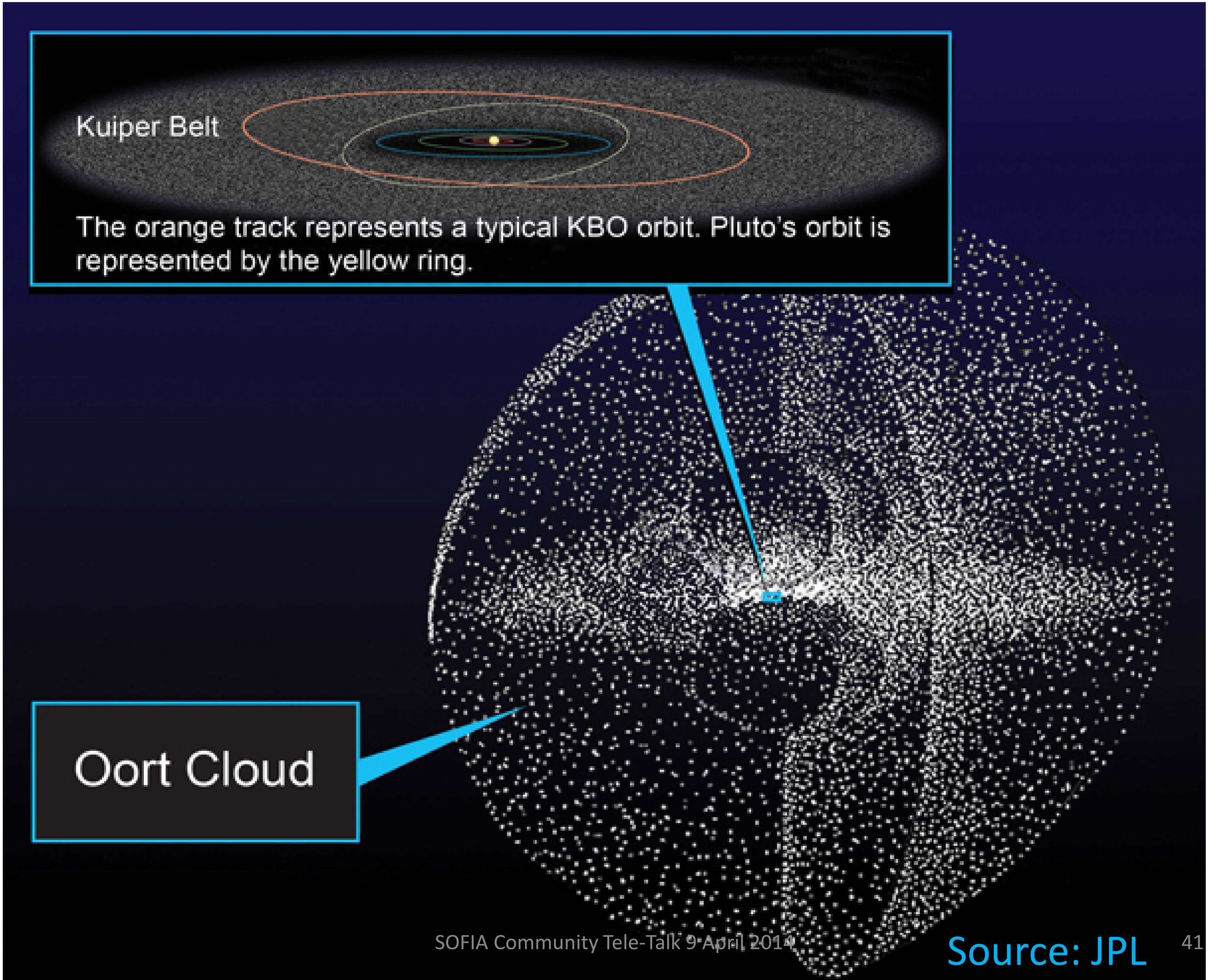
- Newton and Halley: comets delivered water to Earth
- Urey (*Nature 1957*): comets interacted with Earth (Tektites)
- Oro (*Nature 1961*): comets brought organics and water
- Wänke (*Phil. Trans. R. Soc. 1981*)/Drake (M&PS 40, 2005) Earth accreted wet: heterogeneous accretion/nebular gas adsorption
- Earth probably accreted dry (bulk isotopic composition of ECs) and volatiles were delivered later (e.g. Javoy, Earth Planet. Sci. Lett. 2010)
- 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 ~ $3 \times 10^{-4}$ .

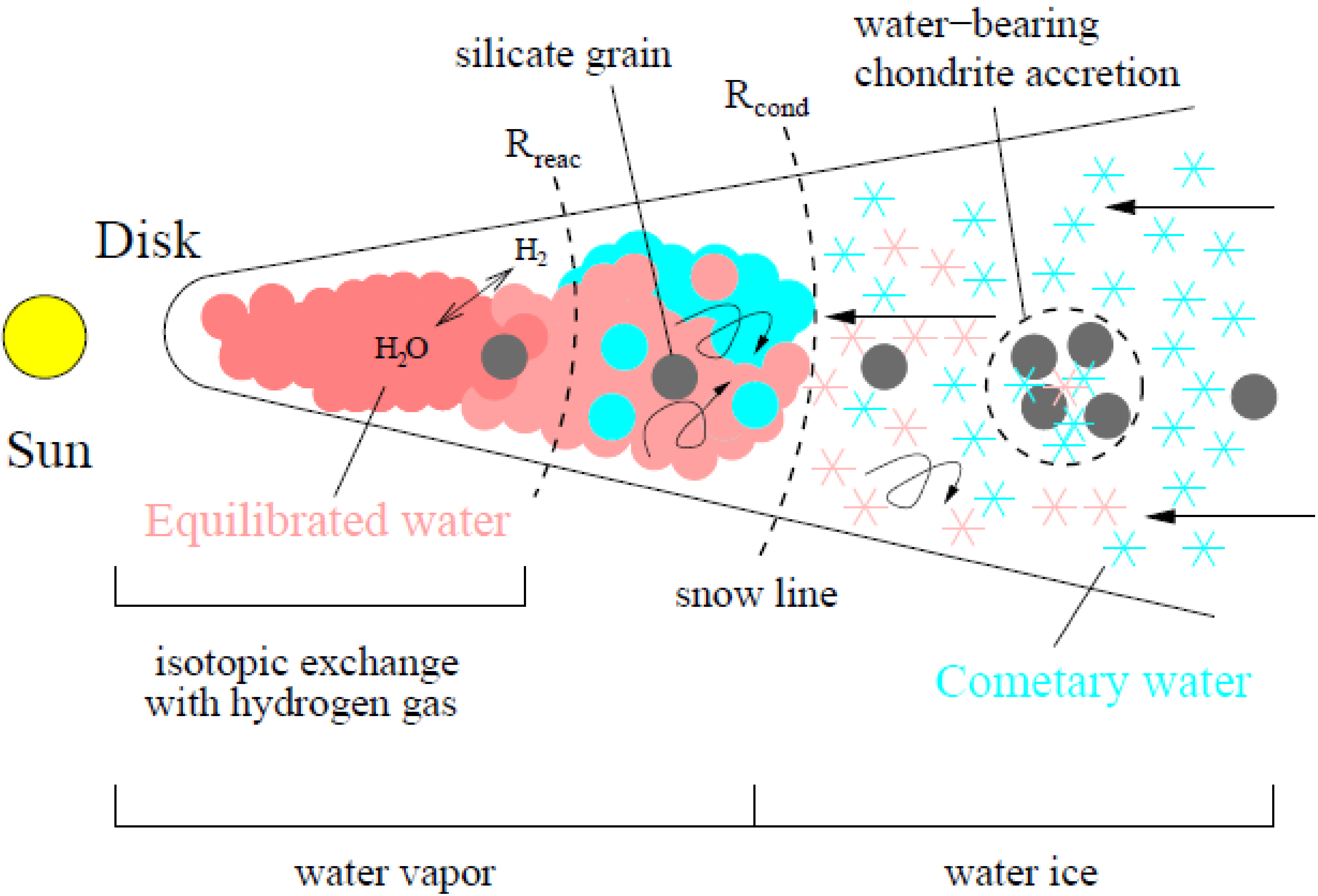
# Solar System: Comets




- ***Jupiter Family** comets* are thought to originate in the **Kuiper Belt**, or associated with the **scattered disc**, beyond the orbit of Neptune
- ***Long-period** comets* come from the **Oort cloud** (> 10000 UA), but formed in **Jupiter-Neptune region** (ejected by giant planets). Some confirmation by Enceladus D/H

Sent toward the Sun by gravitational perturbations from the outer planets **(Kuiper Belt objects)** or nearby stars/galactic tides **(Oort Cloud objects)**

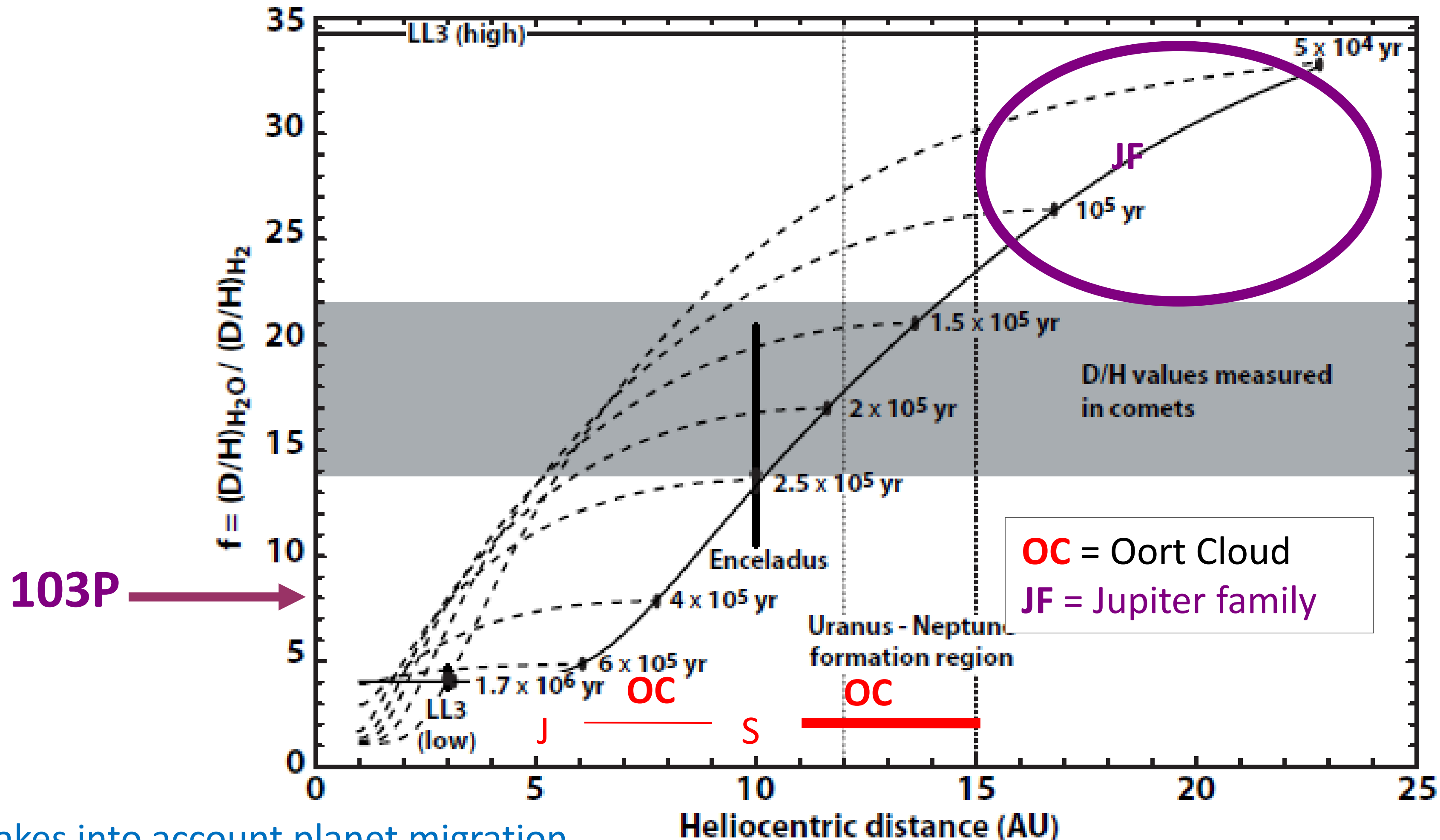

Kuiper Belt
The orange track represents a typical KBO orbit. Pluto's orbit is represented by the yellow ring.
Oort Cloud
Source: JPL




Jacquet et al. 2013

# D/H model for the solar system

*Kavelaars et al. (2011)*




Takes into account planet migration

# First detection of D/H in a JFC

- Herschel solar system Observations (HssO) key programme: observation of 103P/Hartley 2 with all instrument near perihelion in fall 2010

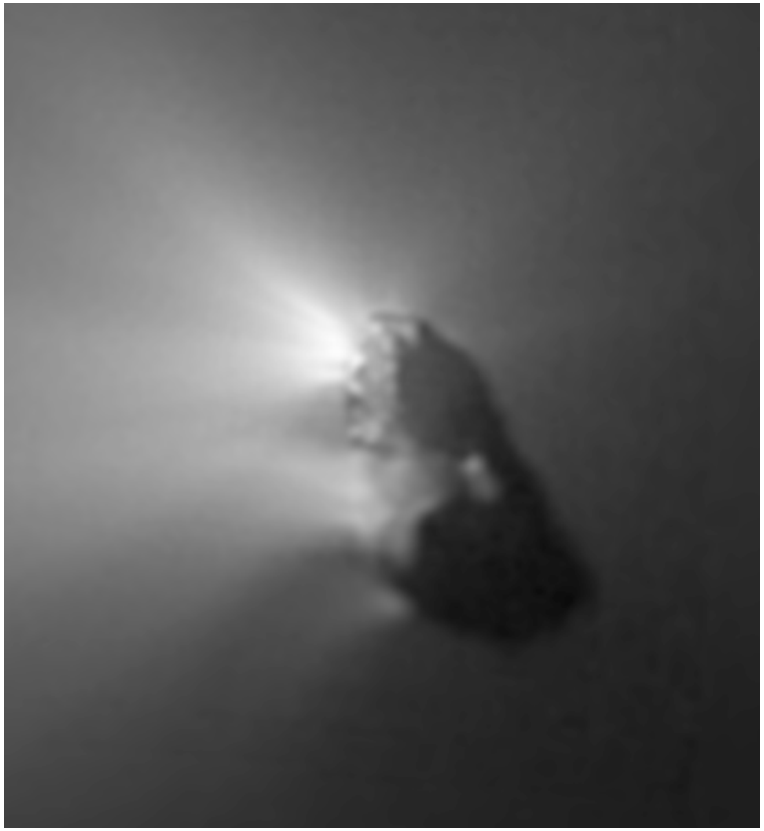
# D/H in Oort cloud comets

- Average D/H detected in 6 Oort cloud comets is about 300 ppm, i.e. about twice as high as the Vienna Standard Mean Ocean Water (VSMOW) value.
- Conclusion: only a small fraction of water (maximum 10 %) can originate from comets. Most likely most of the water delivered by carbonaceous chondrites (originating in the outer asteroid belt), since D/H fits better.

1P/Halley

103P/Hartley 2

(Credit: NASA-EPOXI)



(Credit: ESA-HUK)

perihelion: 1.05 AU, aphelion: 5.87 AU, OP: 6.46 y, $P_{rot}$: 18 h. 17
Nov 2010: d- Herschel: 0.212 AU, d- sun: 1.095 AU

# First detection of D/H in a JFC

- Herschel solar system Observations (HssO) key programme: observation of 103P/Hartley 2 with all instrument near perihelion in fall 2010
- Spectroscopic observations of water isotopes with the very high resolution ($4x10^6$) "Heterodyne Instrument for the Far Infrared", HIFI on 17 November 2010

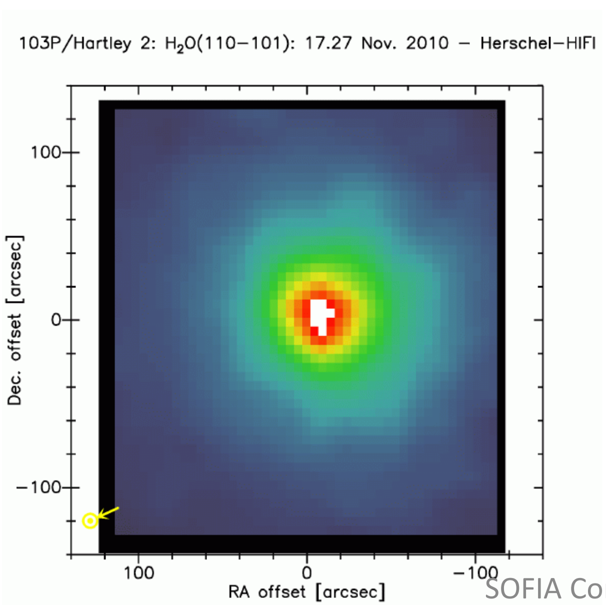
# Variability of 103P: interleaved observations

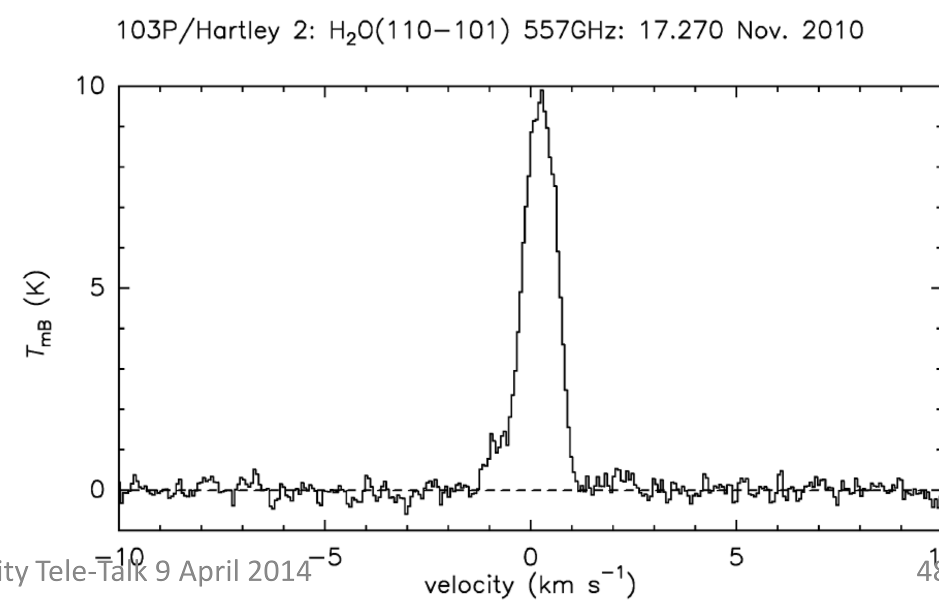
**Date: 17.28 – 17.64 November 2010**

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)

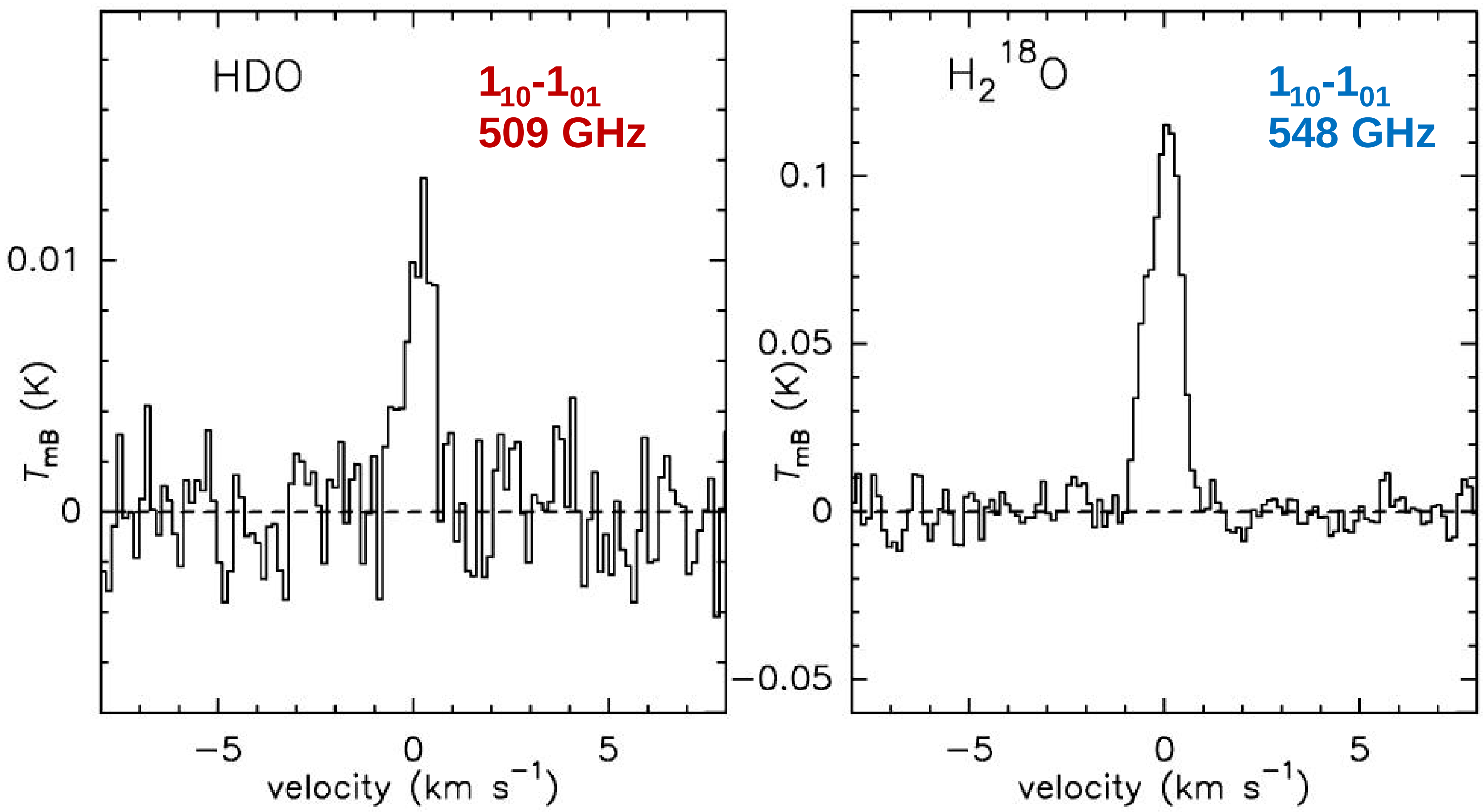
Same receiver, same HIFI band → similar field of view (~39'', 6500 km)

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



# Observed spectra:




**S/N = 10**

**S/N = 60**

# Analysis of the observations

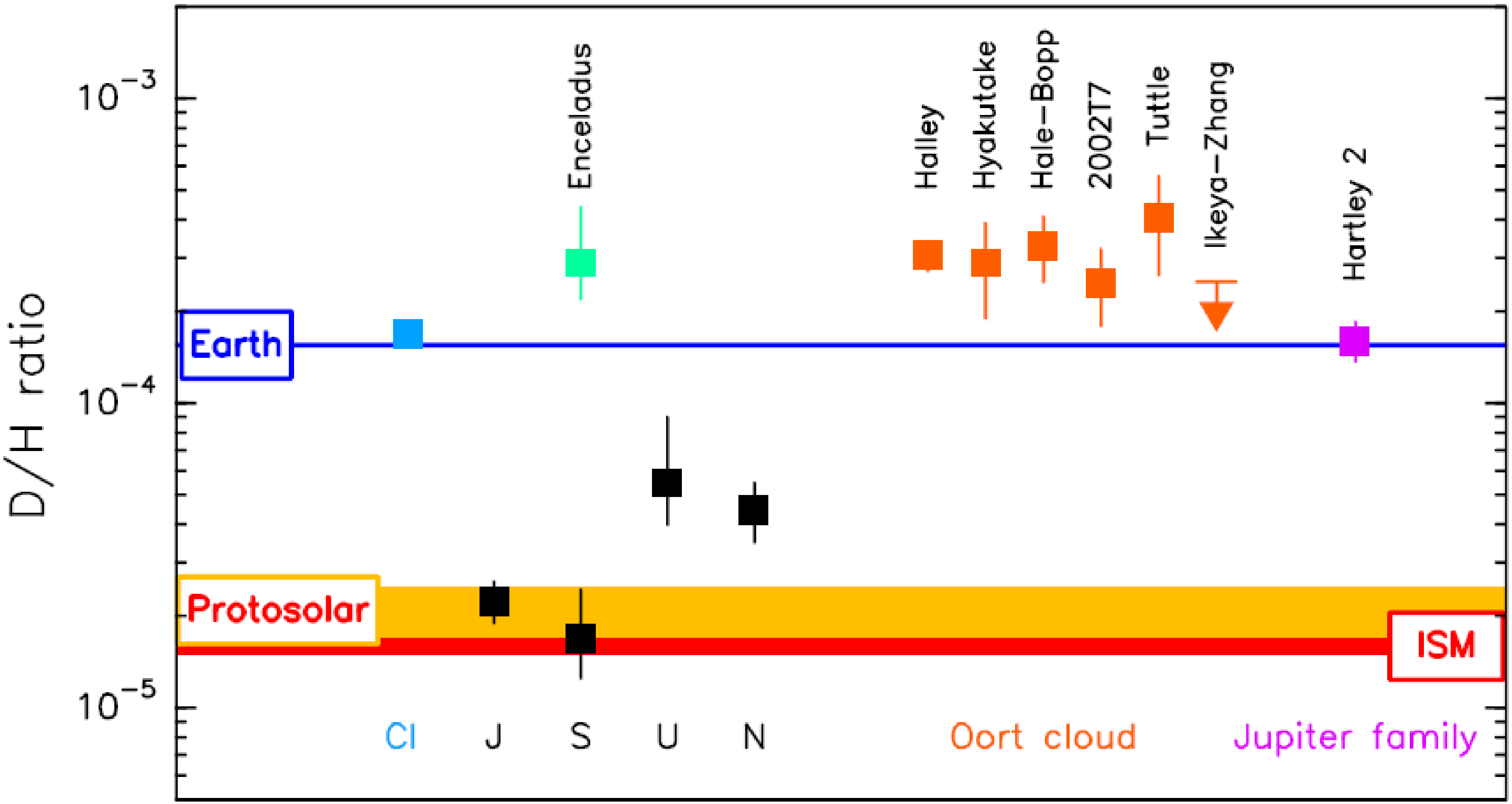
- Excitation model : collisions with $H_2O$, electrons and infrared pumping, gas temperature determined by other observation (e.g. methanol lines at IRAM/CSO/SMT)

- → 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)

=> **D/H = (1.61 ± 0.24) x $10^{-4}$**

D/H(VSMOW) = 1.558 ± 0.001 x $10^{-4}$

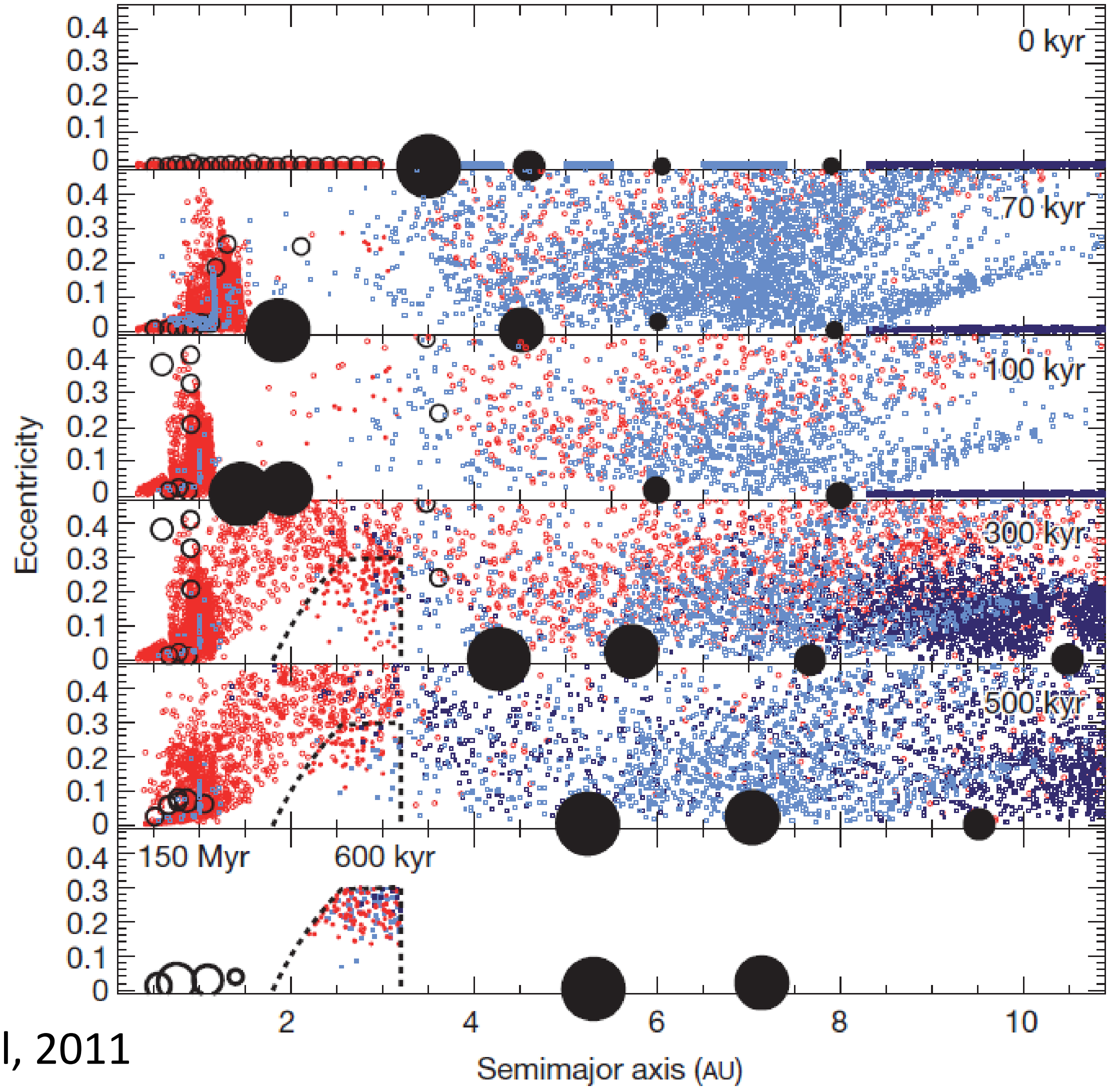



*Hartogh et al. Nature (2011)*

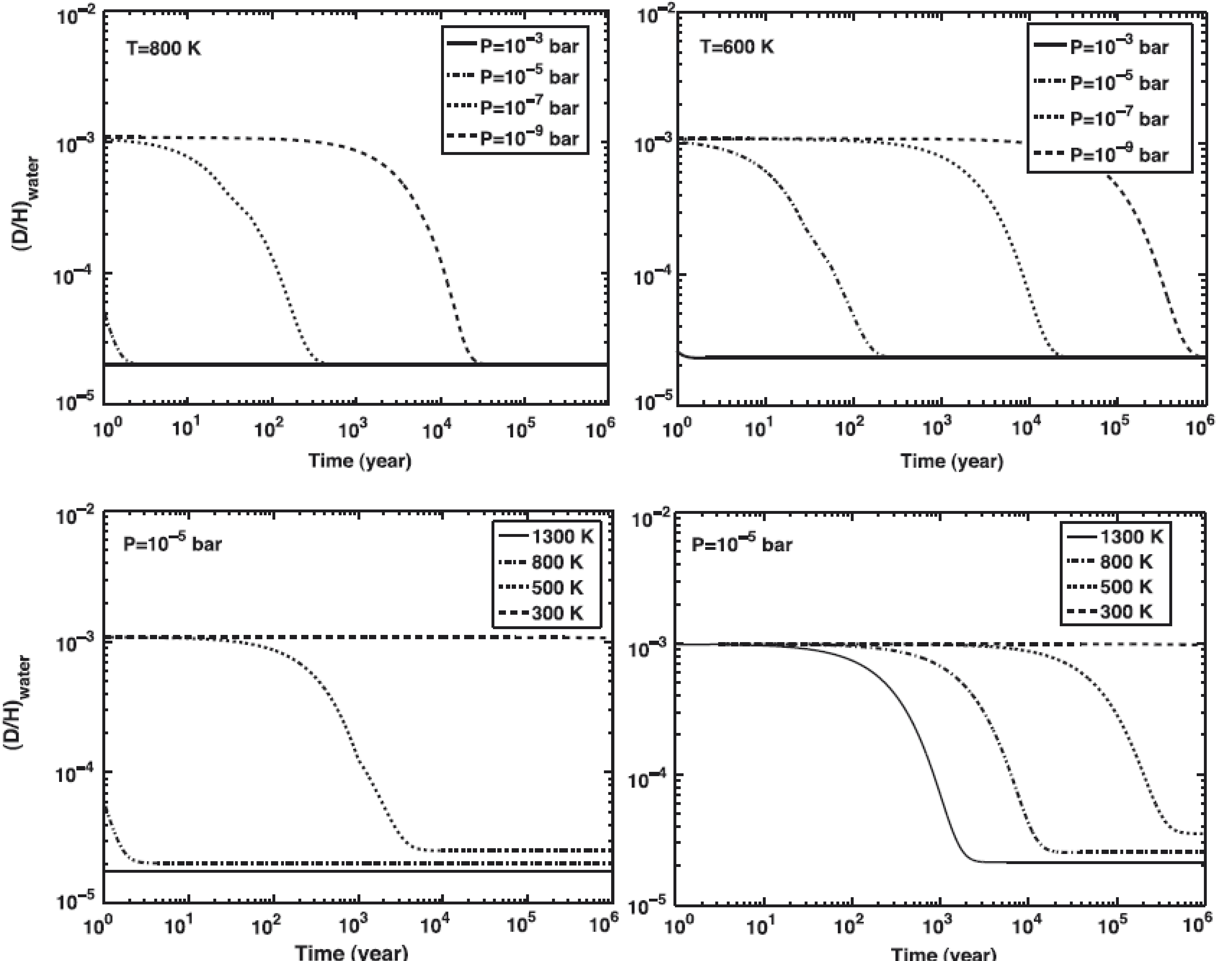
# What could be wrong?

- 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?

# Grand Tack: material mix from ~ 1 to > 13 AU => C-type asteroids and comets form in the same regions

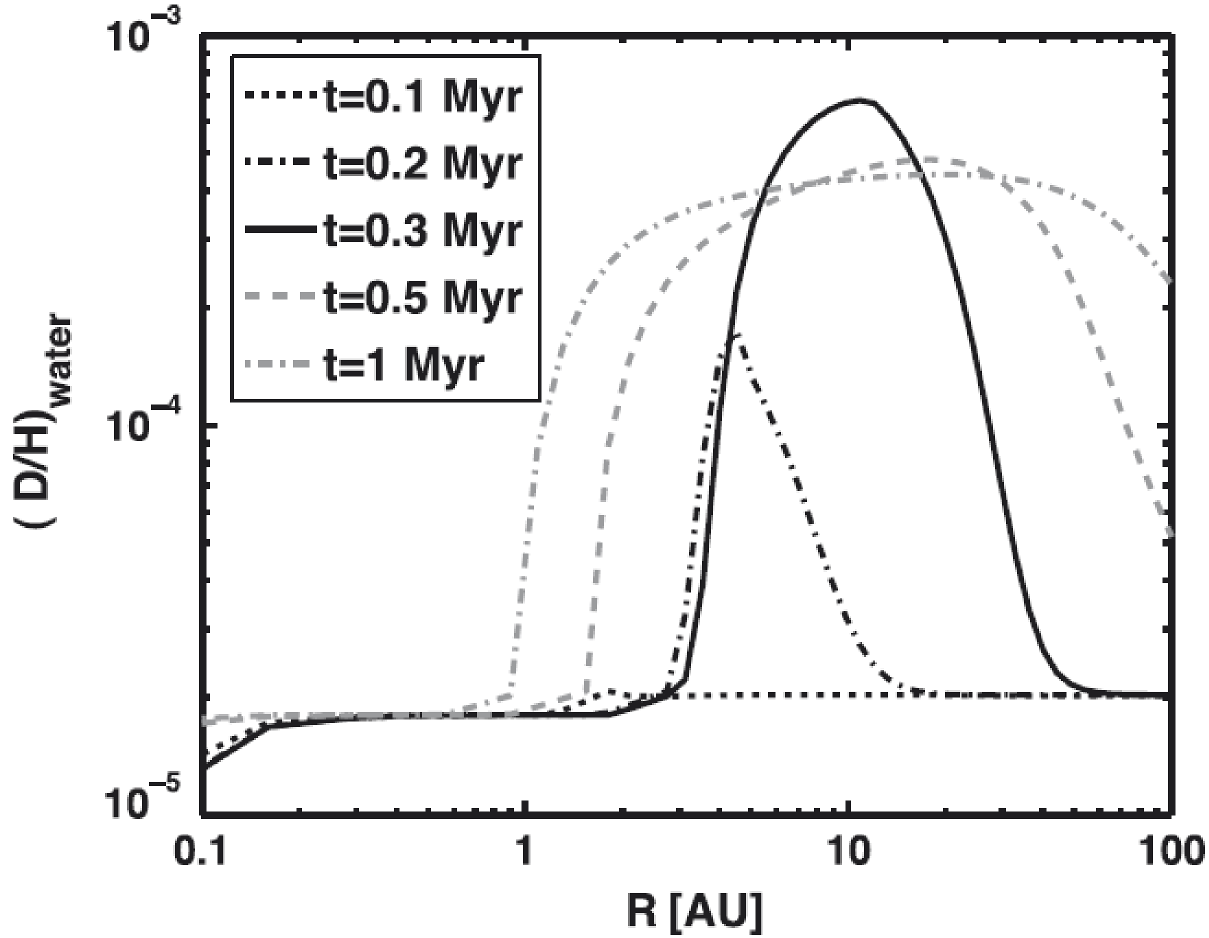



Walsh et al, 2011



T=800 K
P=10^−3 bar
P=10^−5 bar
P=10^−7 bar
P=10^−9 bar
(D/H)water
Time (year)
T=600 K
P=10^−3 bar
P=10^−5 bar
P=10^−7 bar
P=10^−9 bar
Time (year)
P=10^−5 bar
1300 K
800 K
500 K
300 K
(D/H)water
Time (year)
P=10^−5 bar
1300 K
800 K
500 K
300 K
Time (year)

# D/H$_{water}$ during and after infall



# Le Yang 2013:

- Equilibrated water transported to outer solar system while there was still infall of material in the disk formation phase. This explains the low D/H measured in 103P/Hartley 2
- Crystalline silicate found in Oort cloud comets for similar reasons (formed in inner solar system)
- Correlation between low D/H and crystalline silicates in comets expected

# Summary D/H Hartley 2

- 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.

# What can SOFIA contribute

- SOFIA may detect weak water lines, $H_2{}^{18}O$ and HDO, provided the production rate is high enough (~ > 10E29/s) and the distance of the comet is small < 1 AU. Other isotopic measurements are also possible however most of them can be done from ground, too.

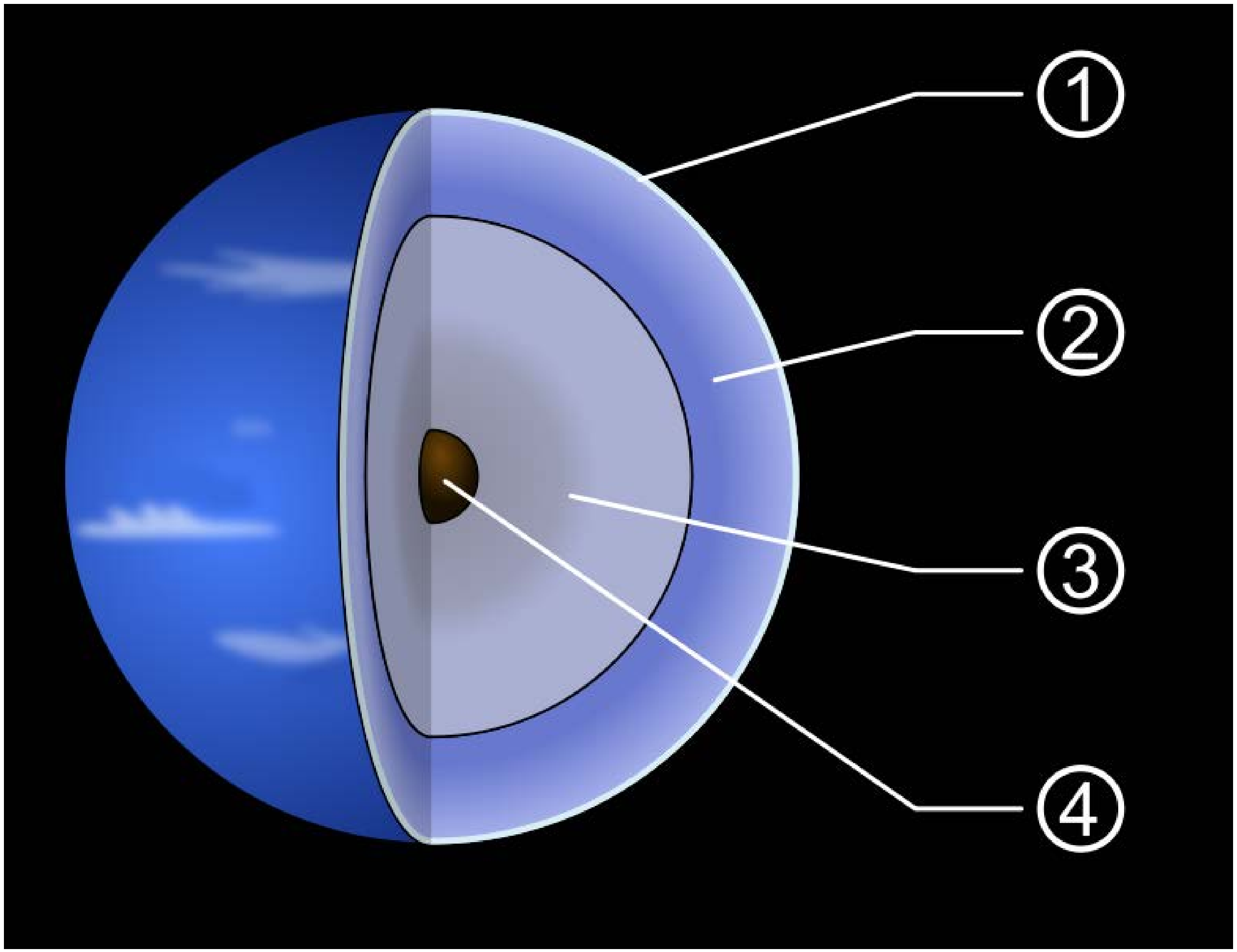
# Other recent discoveries

- Water (or not) in main belt comets (de Val-Borro et al. 2012)
- Europa water plumes (with Hubble), Roth et al. 2014
- Ceres active regions (water emissions) with HIFI, Küppers et al, 2014
- Ganymede and Callisto asymmetric water atmospheres with HIFI, Hartogh et al, 2014 in preparation
- SOFIA is not sensitive enough

# D/H in Uranus and Neptune

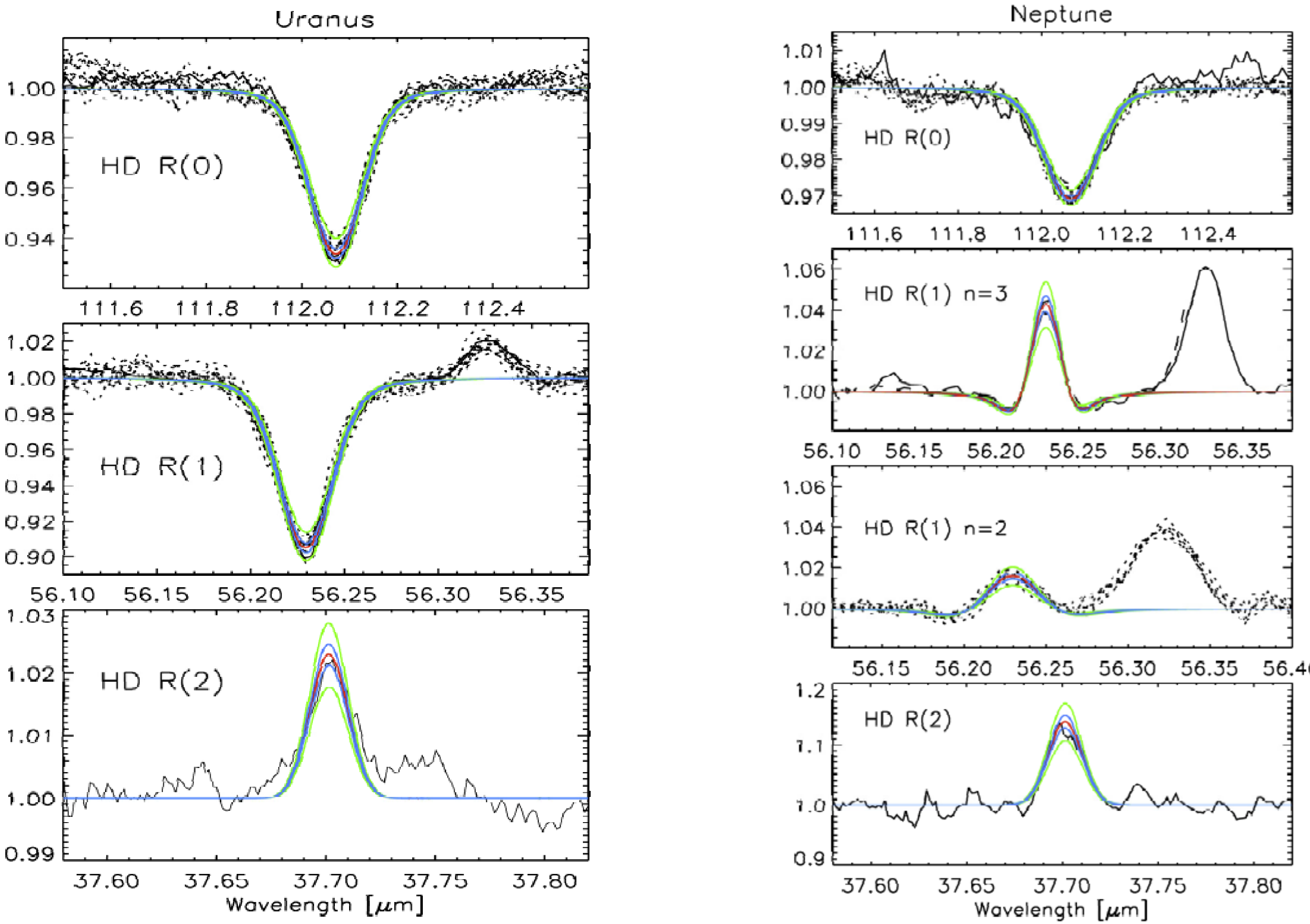
- D/H in Jupiter and Saturn protosolar, i.e. main component is hydrogen
- D/H Uranus and Neptune substantially higher => equilibrated water/hydrogen and possibly organic molecules (highly D-enriched in interstellar medium): "Ice giants"
- D/H in hydrogen may be used to constrain the D-enrichment of ices or the amount of ices for a given D/H.

# The internal structure of the ice giants




1. Upper atmosphere, top clouds
2. Atmosphere consisting of hydrogen, helium and methane gas
3. Mantle consisting of water, ammonia and methane ices
4. Core consisting of rock (silicates and nickel-iron

# PACS/ISO HD-spectra of Uranus and Neptune

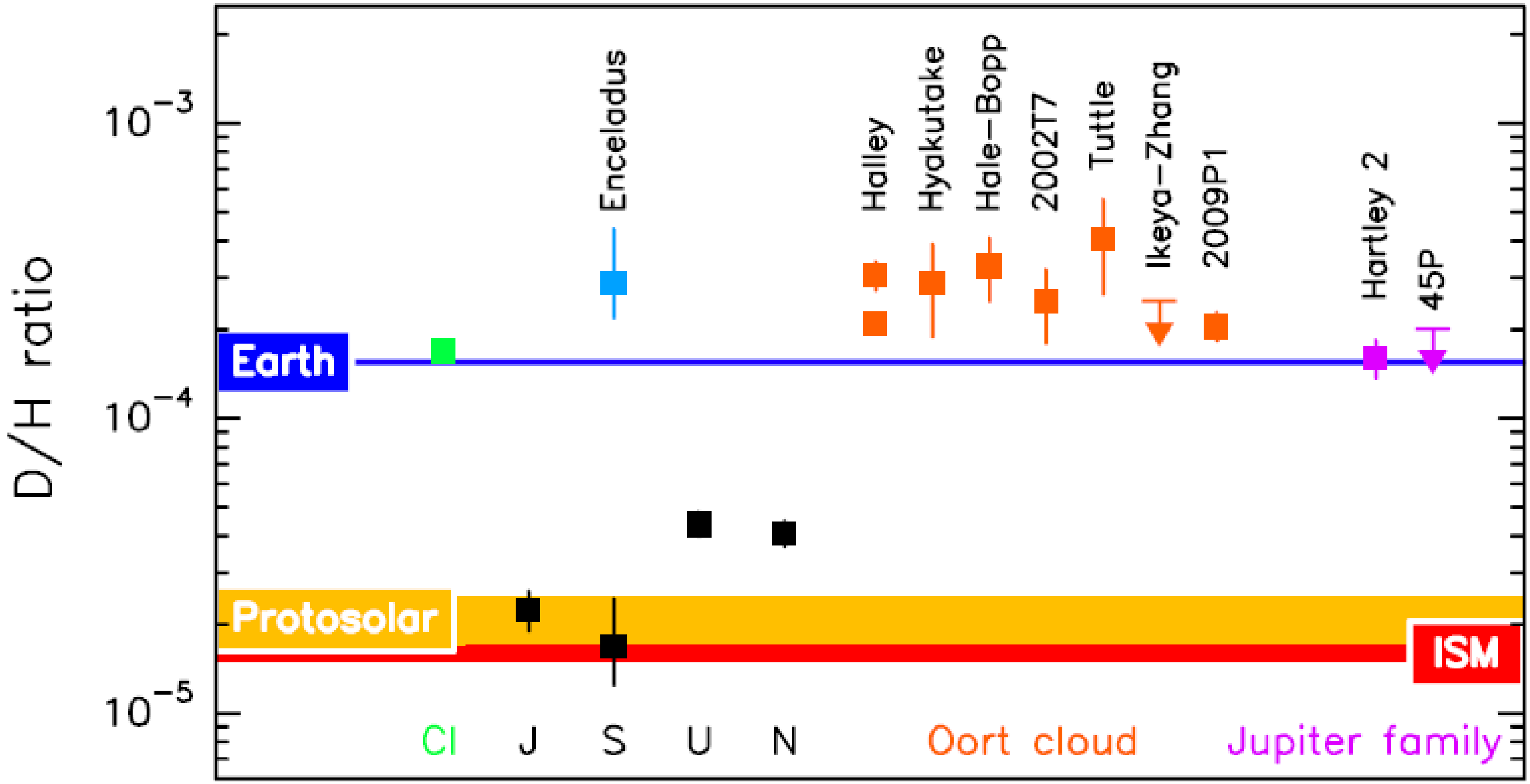


# Ice Giants may be Rocky Giants

- PACS values show the same D/H for both planets (from HD observations)
- PACS values smaller than ISO values:
  - Neptune: 41±4 ppm (65 ppm)
  - Uranus: 44±4 ppm (55 ppm)
- Formation models (e.g. Podolak, 1995) predict 70-100 % ice and rather small amounts of rocky ($SiO_2$) material. Based on these models the very low (64 ppm) D/H of ices are derived.
- Assuming cometary (150-300 ppm) isotopic ratios (lower values were never detected in the solar system) we get an ice mass fraction of only 14-32 %, meaning that the planets masses are rock-dominated.

*Lellouch et al, 2010, A&A; Feuchtgruber et al., A&A 2013*

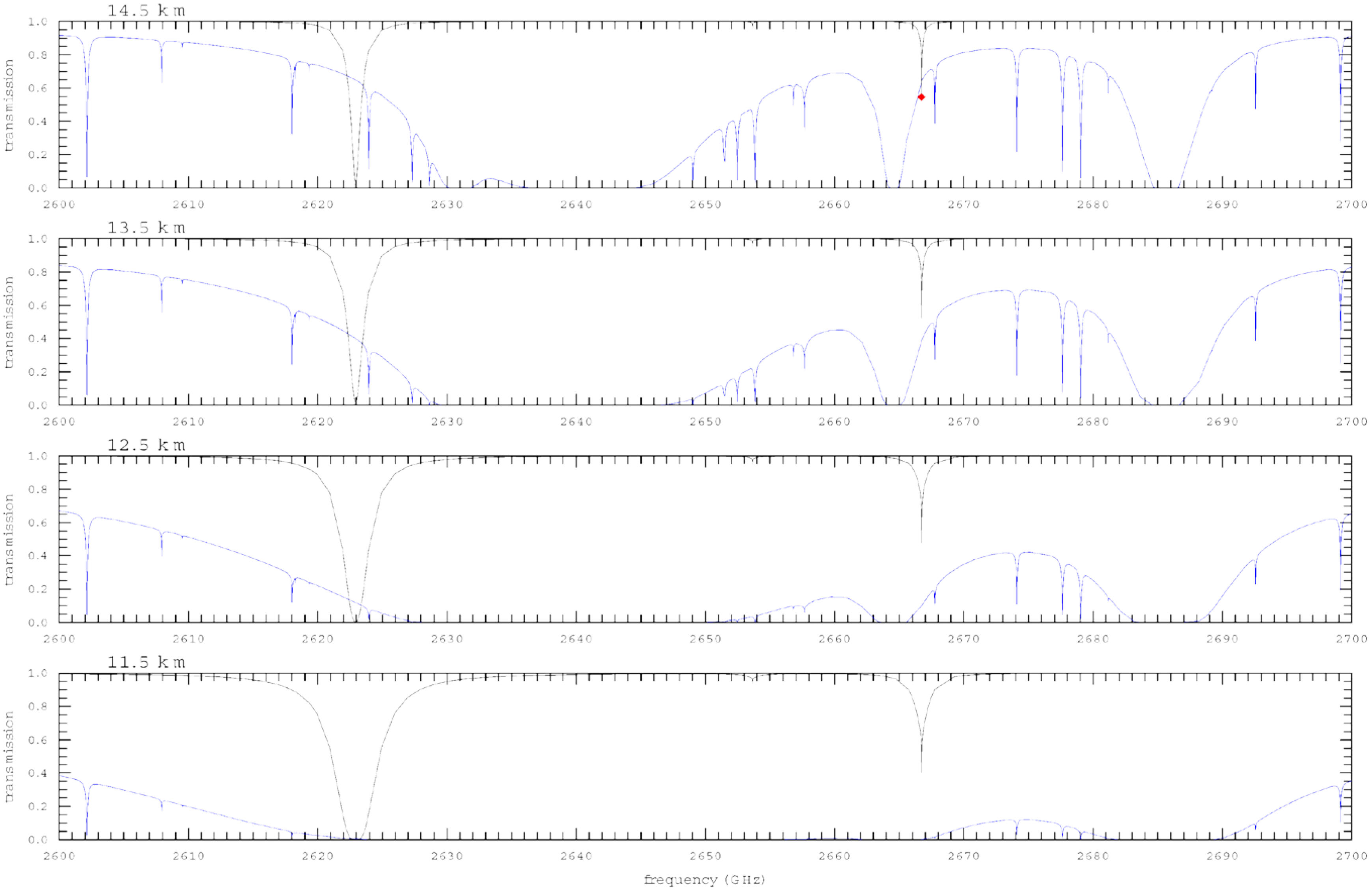
# Including 45 P and U/N updated



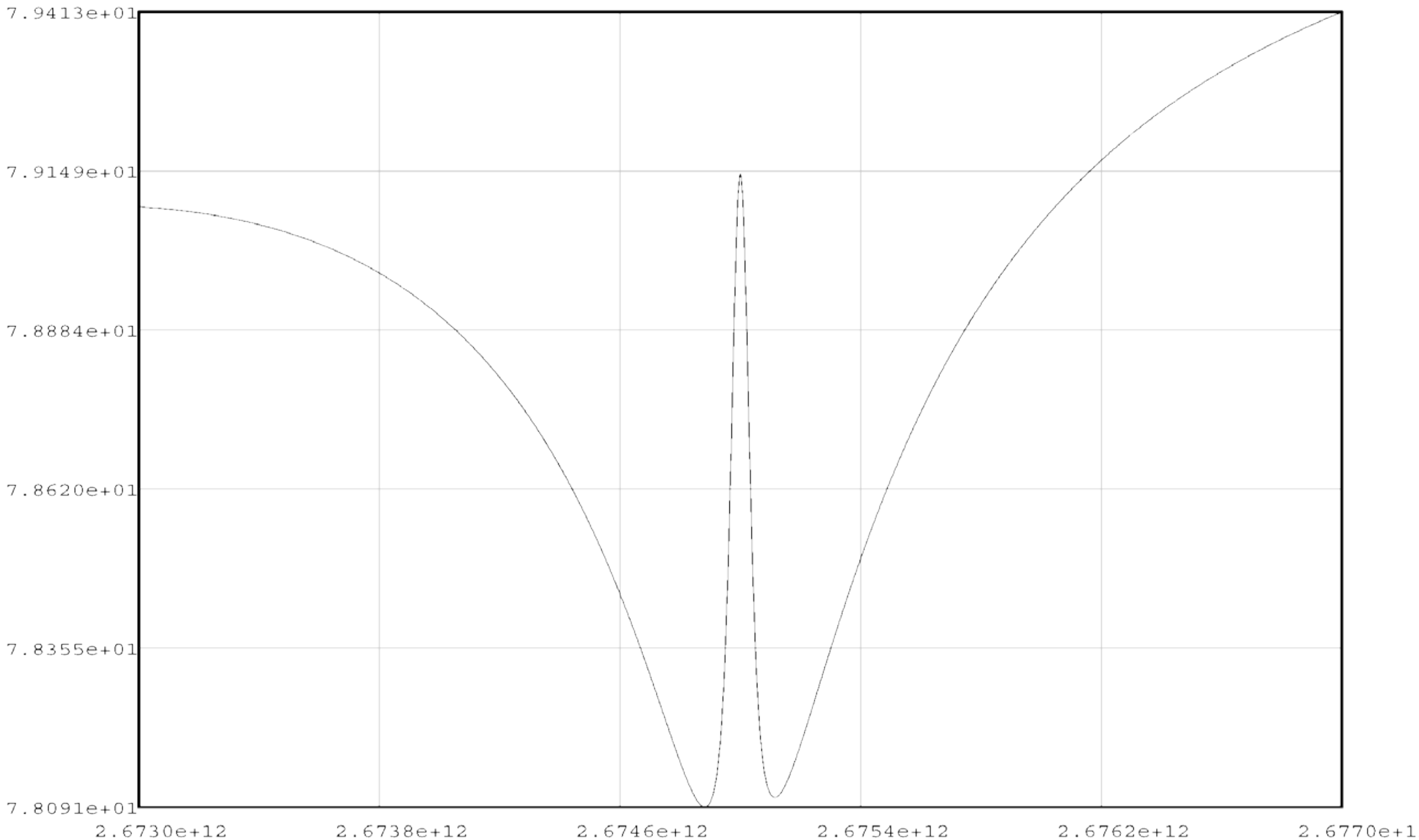
# Science cases for SOFIA outer planets

- Very few HD observations available (ISO LWS/Herschel PACS).
- Results between ISO and Herschel not compatible for ICE giants, data analysis for Saturn and Jupiter still on-going, because very difficult (both planets too bright for PACS)
- Lower D/H in Saturn compared to Jupiter incompatible to all models and not understood.
- GREAT HD observations extremely important

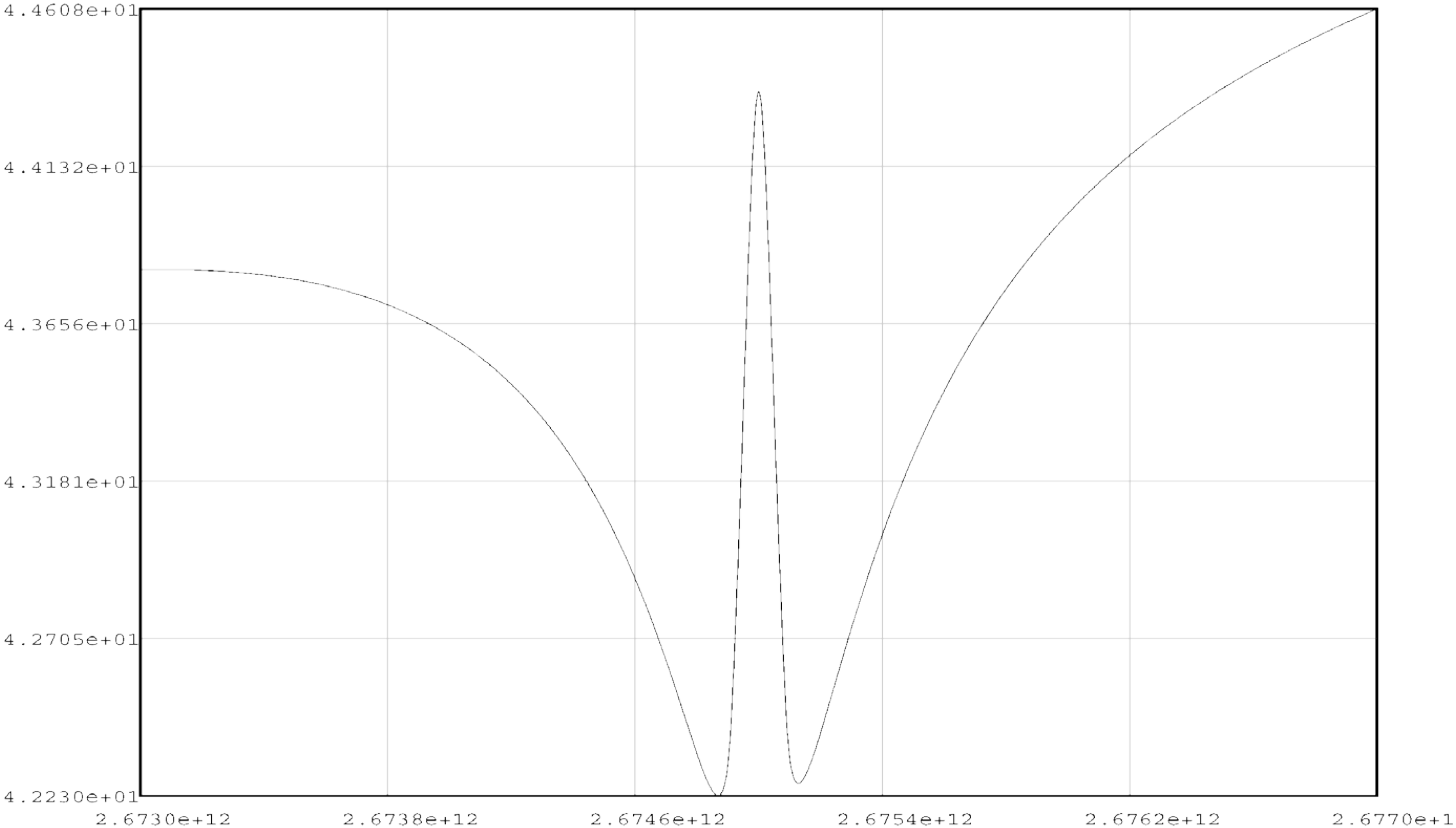
# Atmospheric Transmission near 2675 GHz (HD)



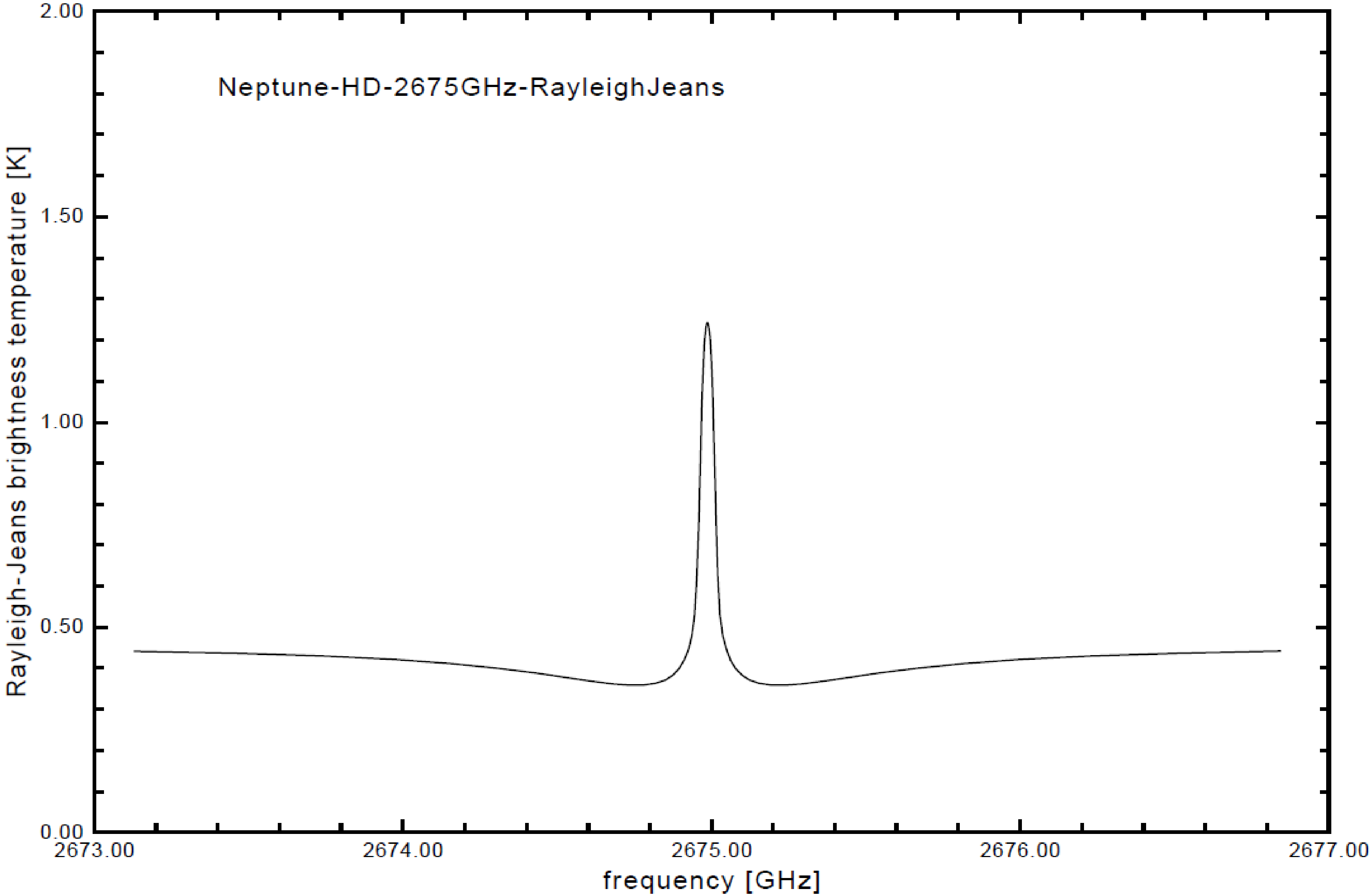
# HD spectrum of Jupiter



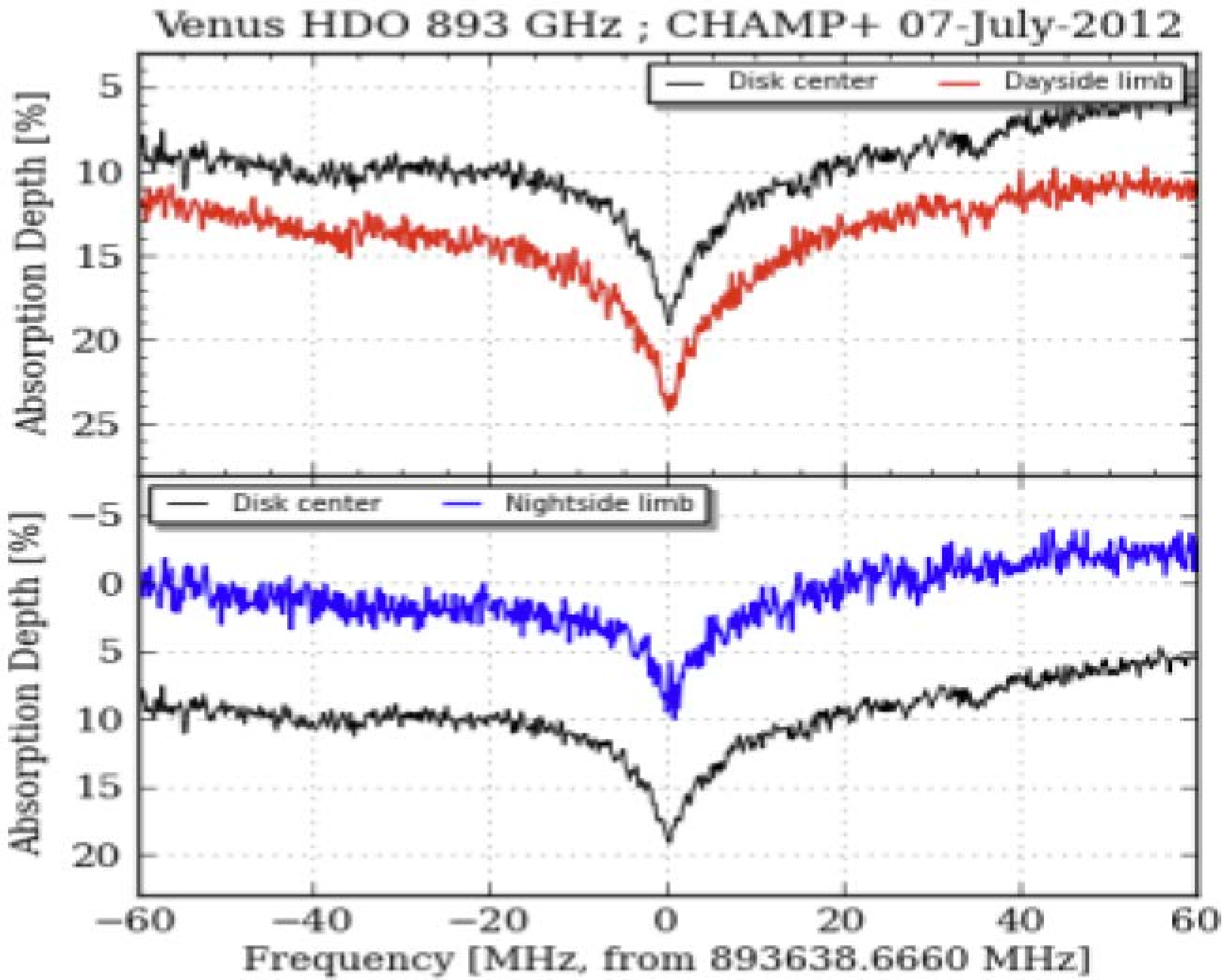
# HD spectrum of Saturn



Neptune: HD at 2675 GHz



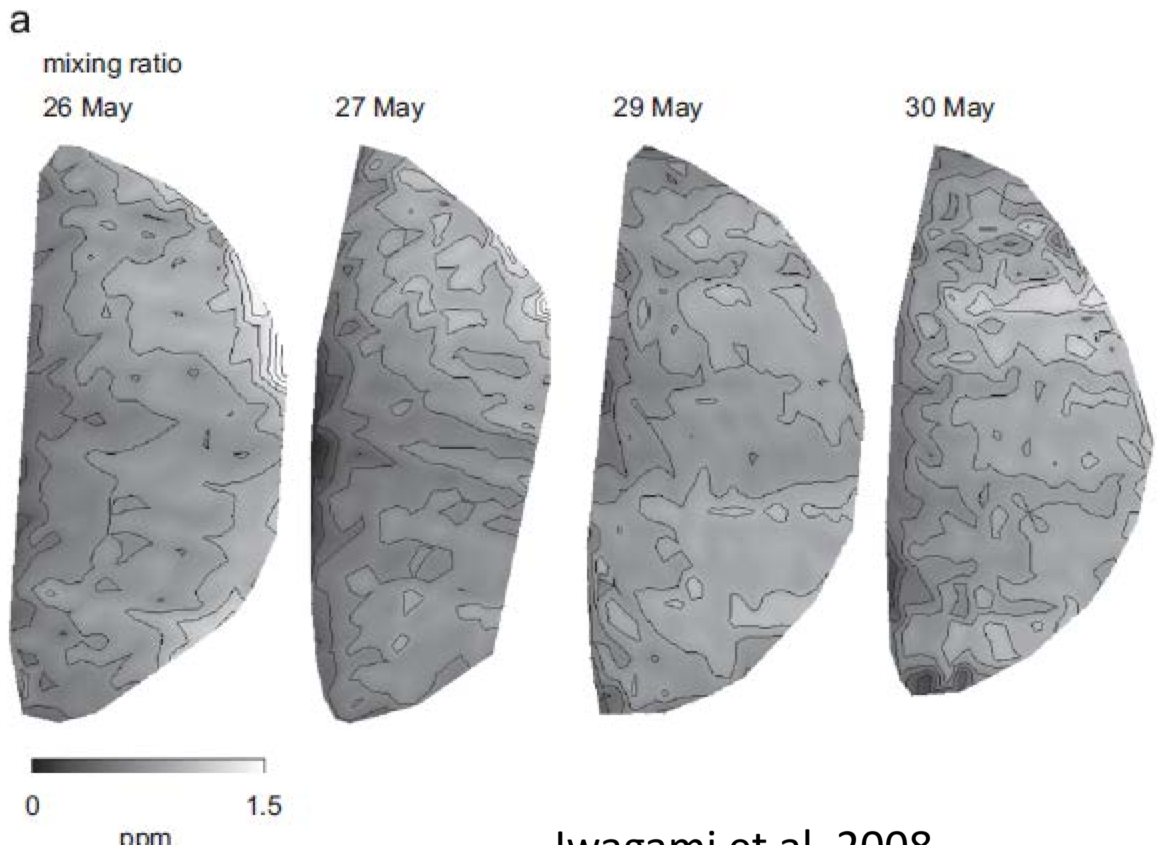
# APEX: first detection of the 893 GHz line in Venus



# Venus HCl

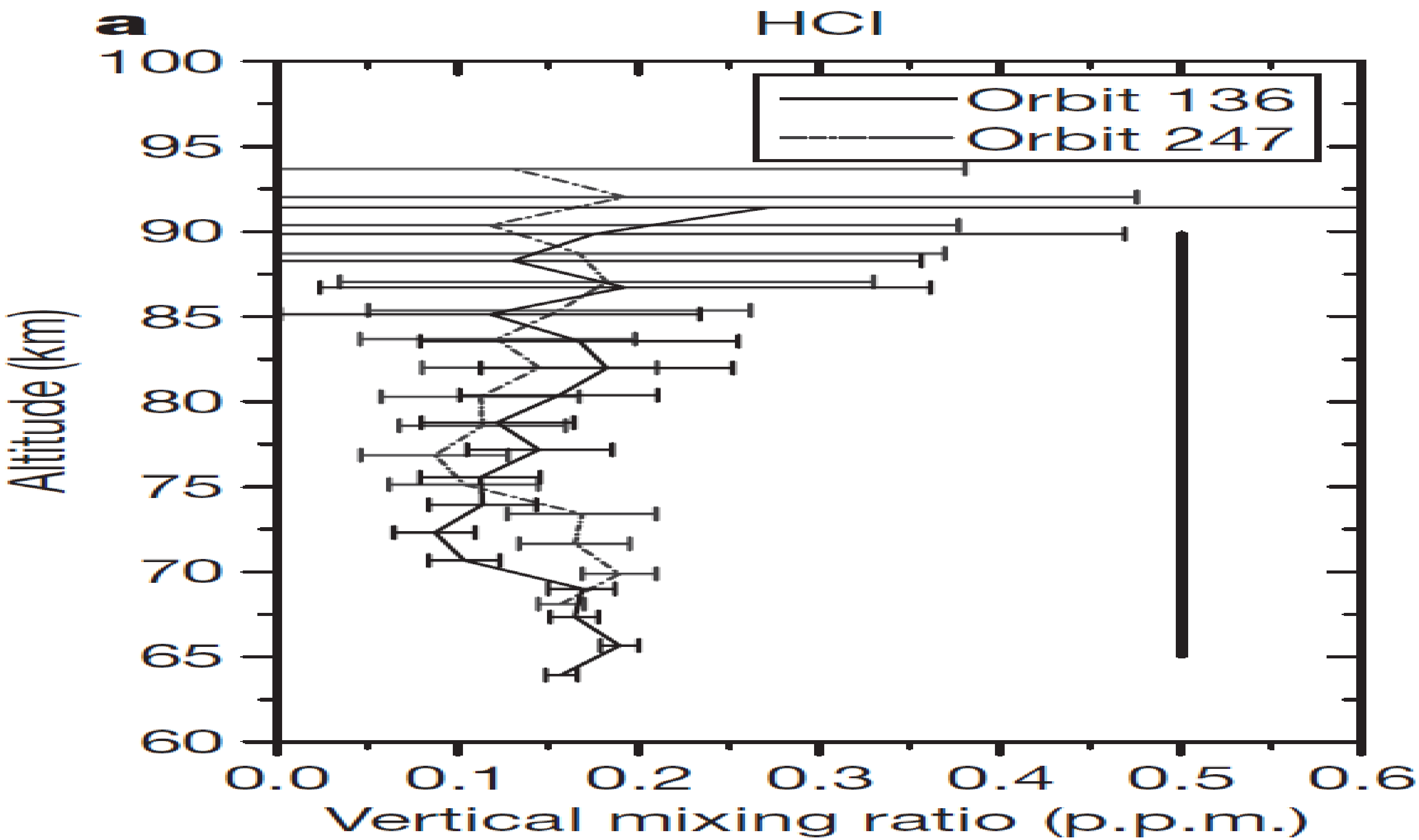
- Source and sink for chlorine
- Chlorine is believed to play an important role in photochemical reactions stabilizing the $CO_2$ atmosphere of Venus.
- Detected values thus far highly uncertain

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

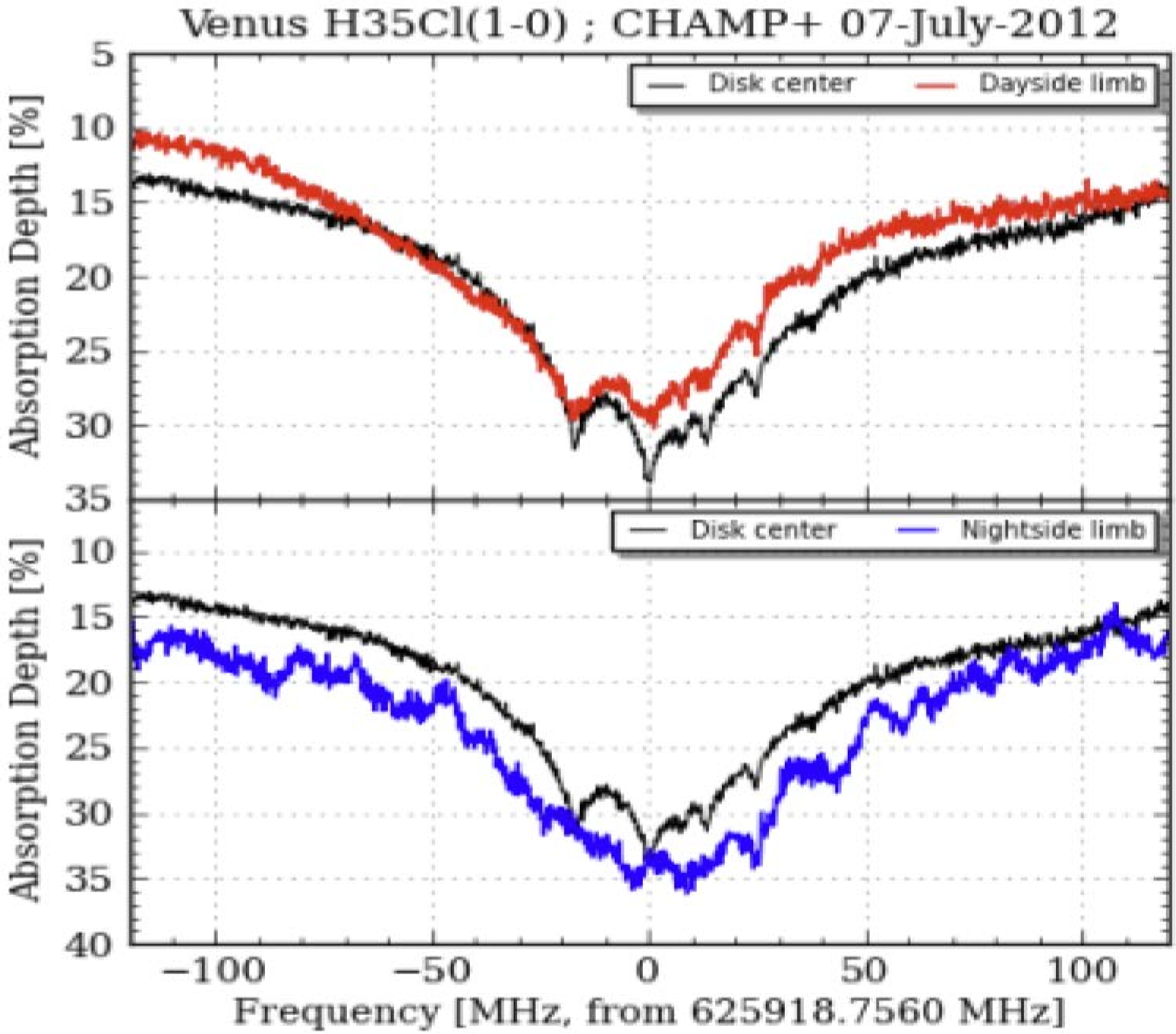



Iwagami et al, 2008

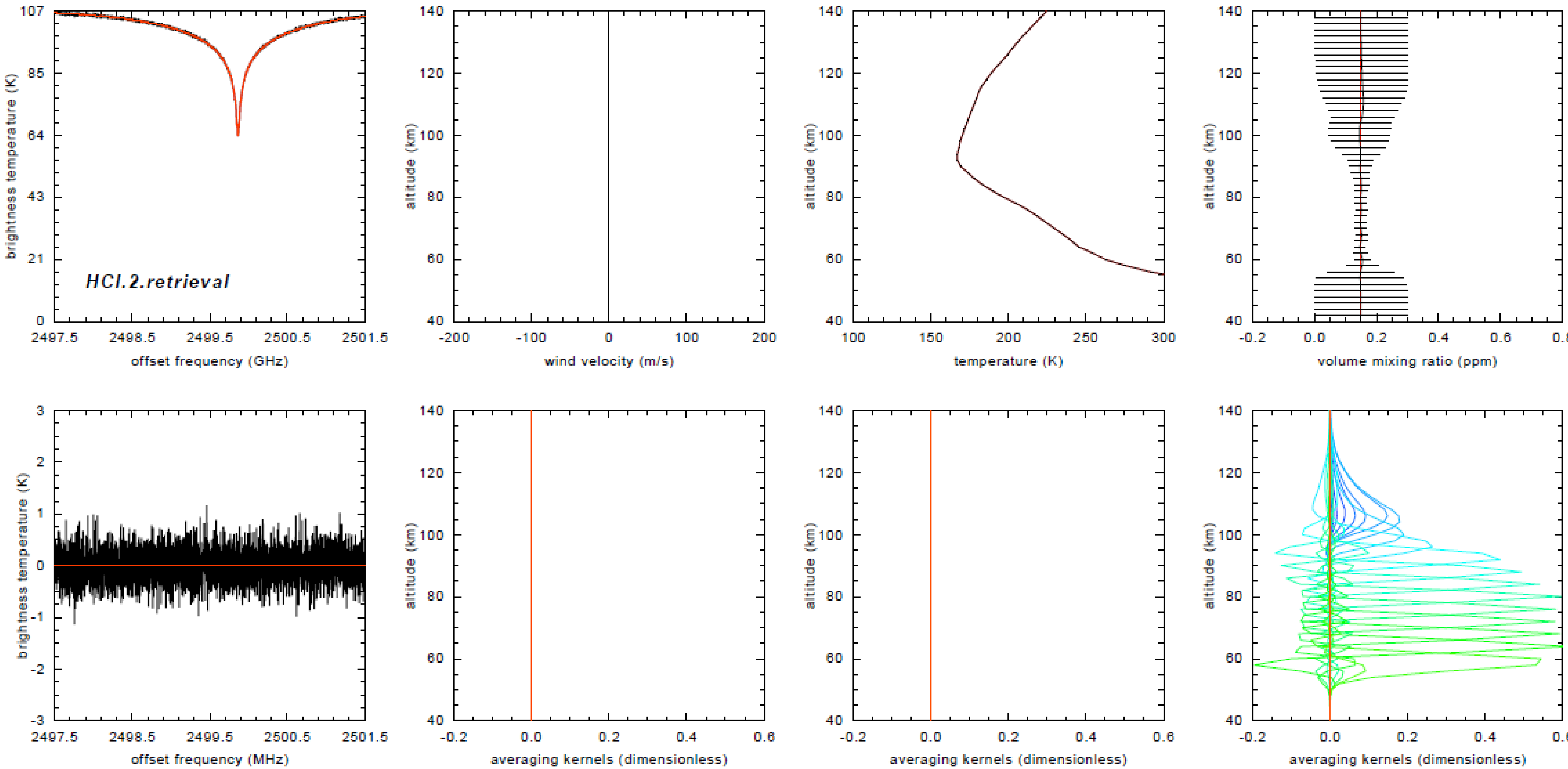
# Berteaux et al., 2007 (SOIR, Nature): 0.15 ppm



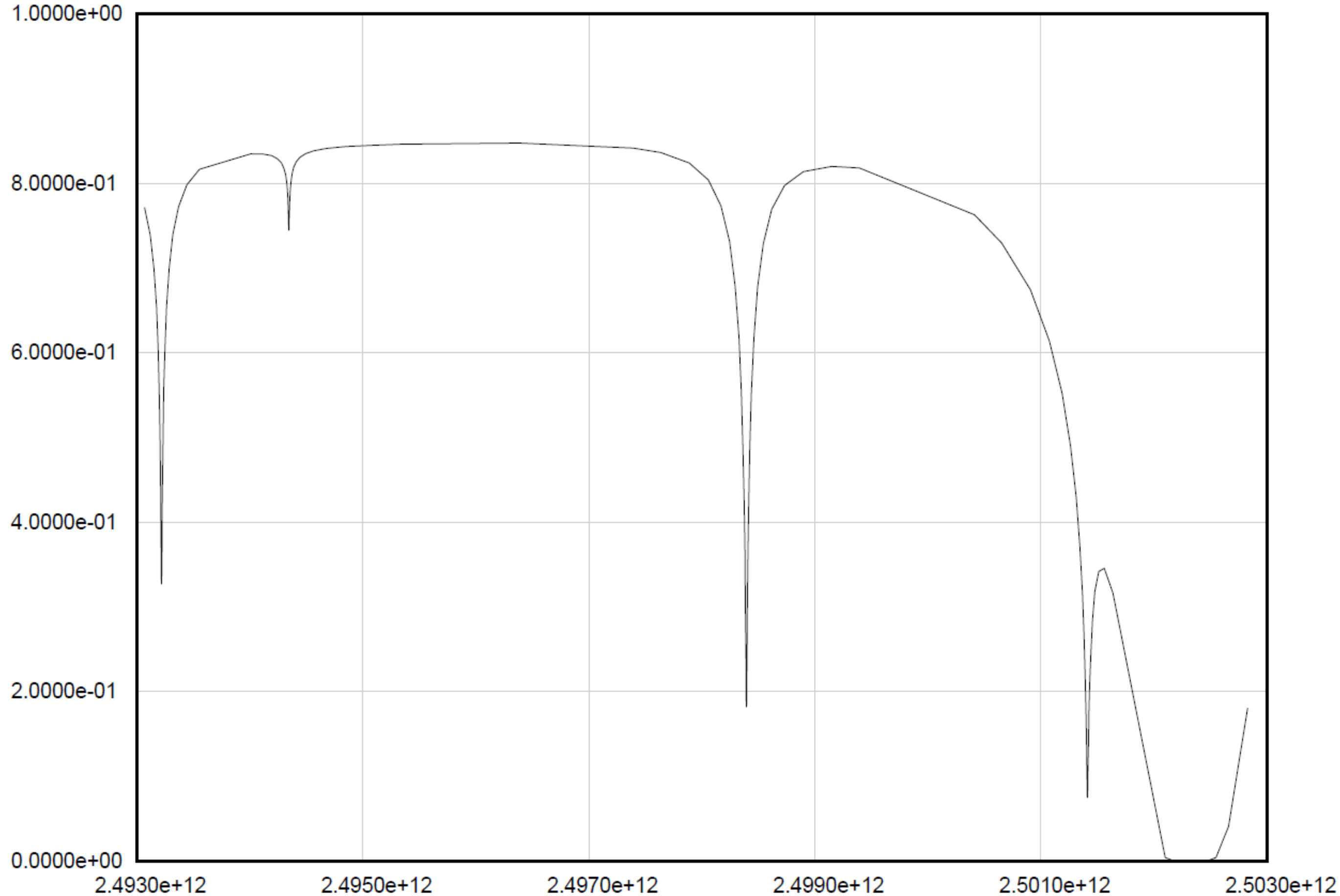
# HCl with APEX: 0.5 ppm from 60-80 km



# HCl retrieval M



# Transmission M



# Summary

- After Herschel a number of very exciting and important solar system observations are to be done by SOFIA.
- 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 problems!
- Cross fingers for the future!