# Observations of planets and their satellites with Millimetron

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# Outline

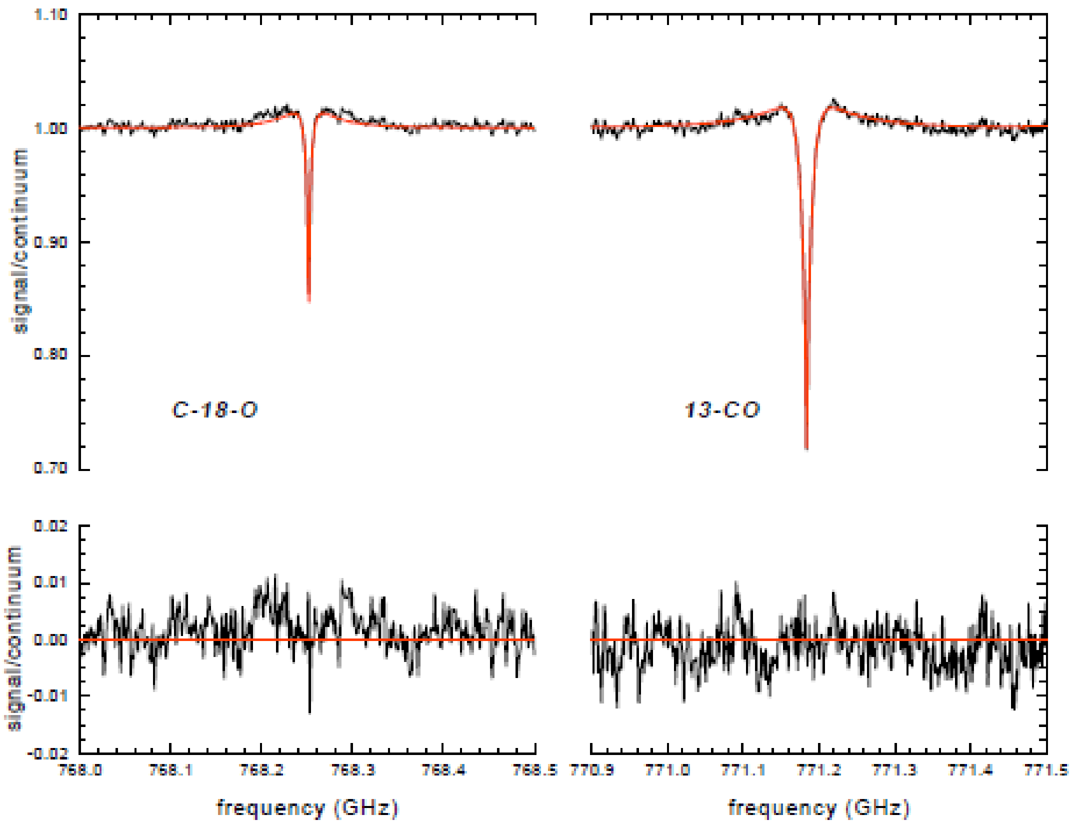
- Mars
- Outer planets
- Titan
- Galilean satellites

# Water vapour on Mars

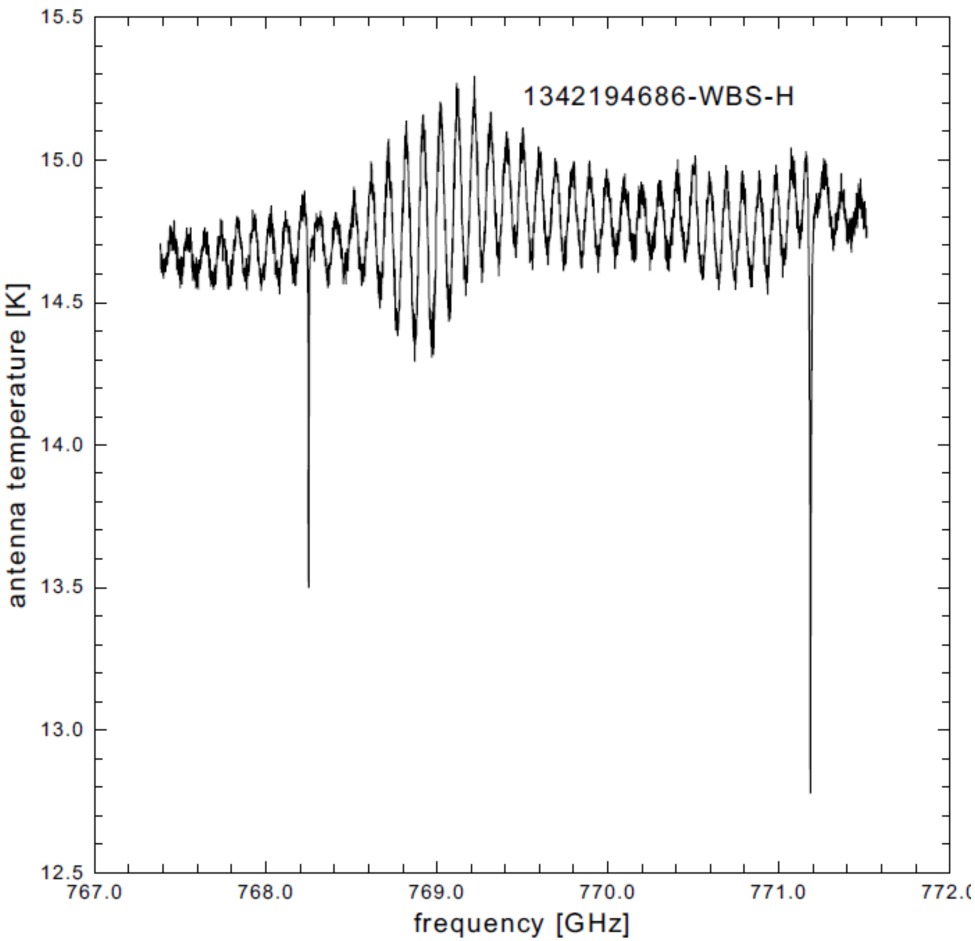
- Very important source gas for atmospheric chemistry
- Maximum column density around Northern summer (more water ice at North pole)
- Maximum vertical extension believed to be during southern summer (nearer to sun, warmer, different meridional circulation).
- Only recently vertical profiles from satellites (TGO) constraining the variable hygropause!
- Ls – coverage of vertical profile very important for understanding a number of phenomena in the Martian atmosphere.

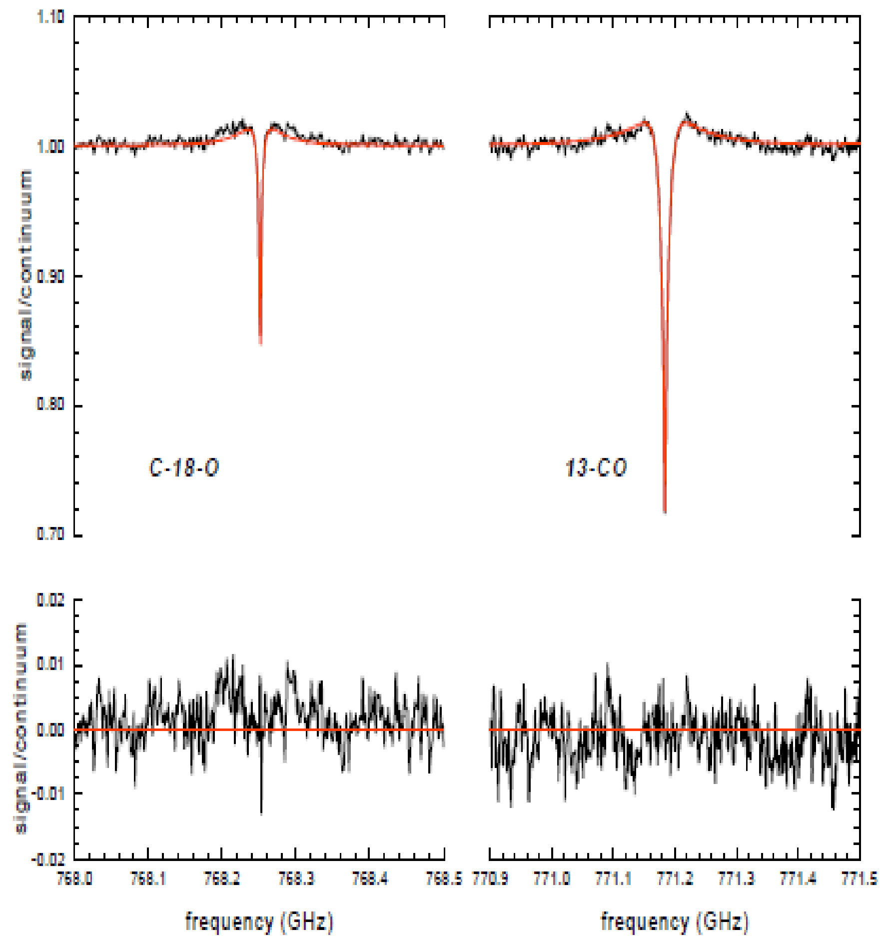
# HIFI Mars CO observations

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

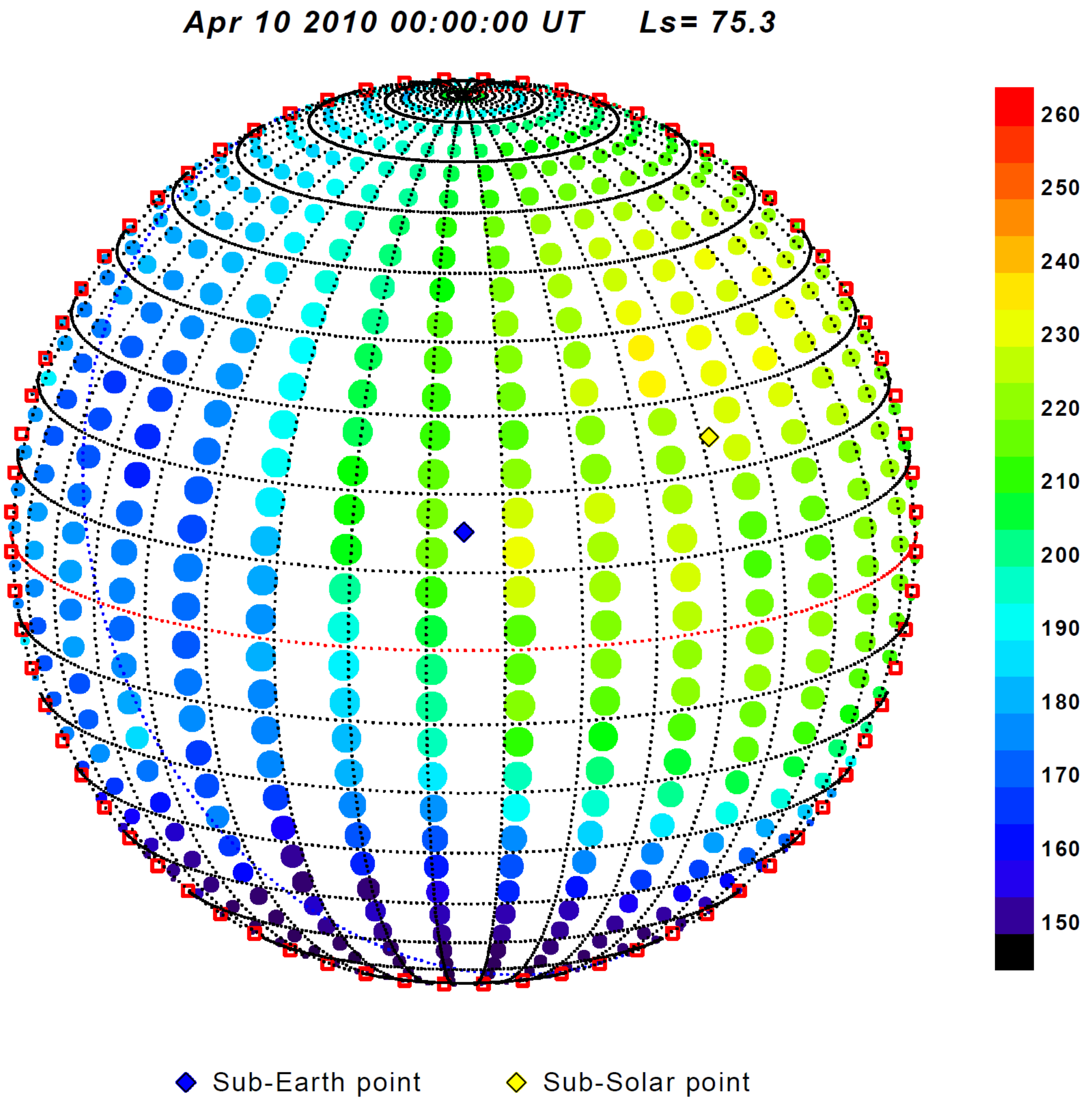


# Before and after (Lomb periodogram)

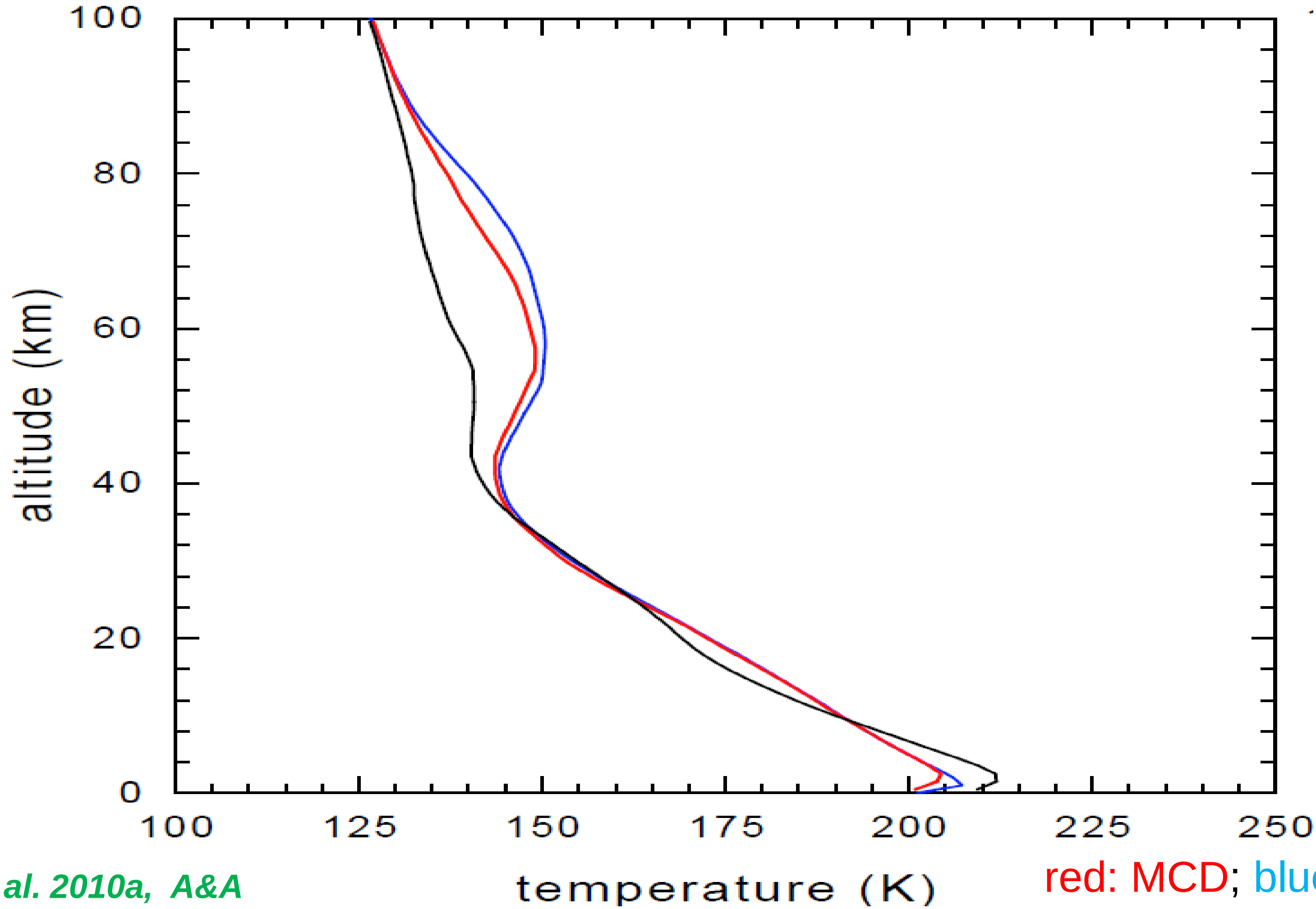


# Mars Surface Temperature during Northern Spring

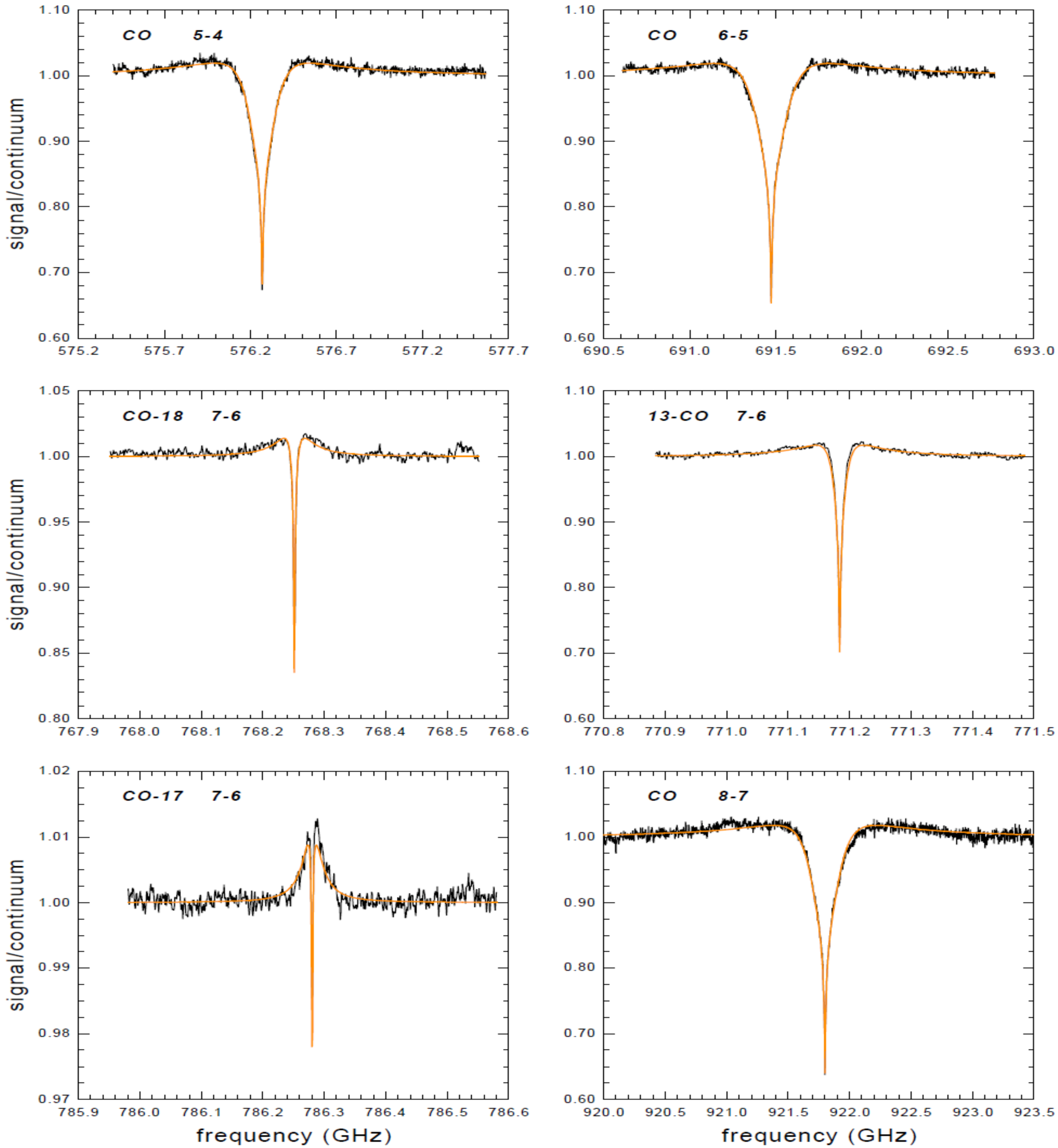


# Retrieved temperature profile and 980 ppm constant with altitude CO volume mixing ratio




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

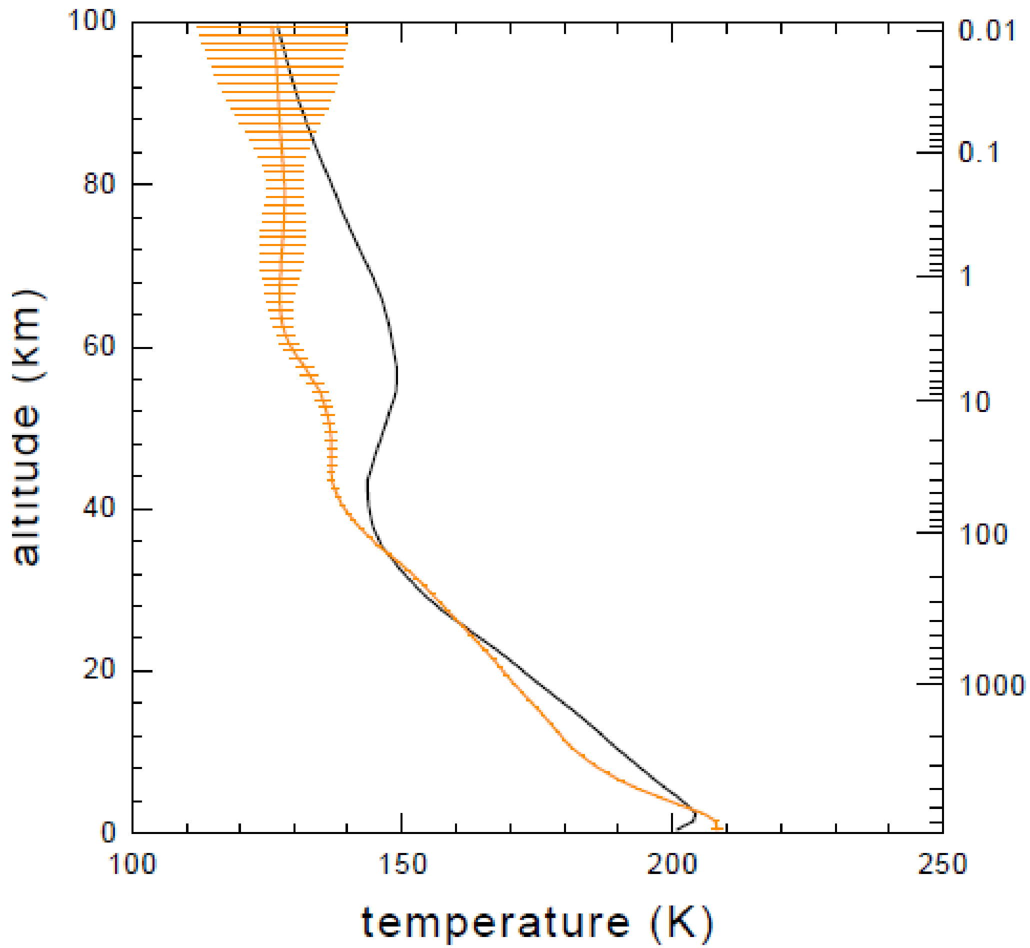
red: MCD; blue: MAOAM;
black: observation



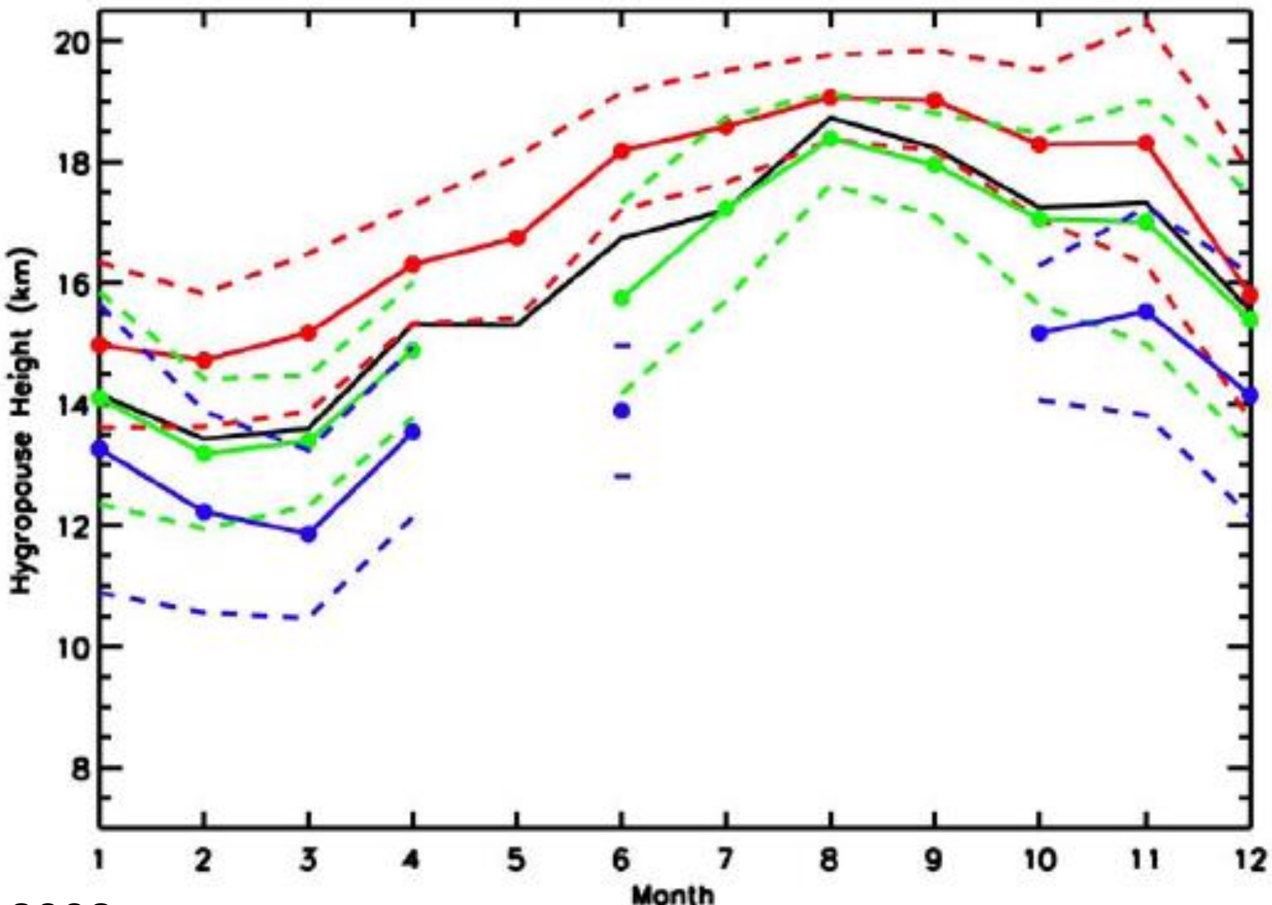

***Isotopic ratios derived from CO isotopologues are telluric! Deviations are < 5%.***

9

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

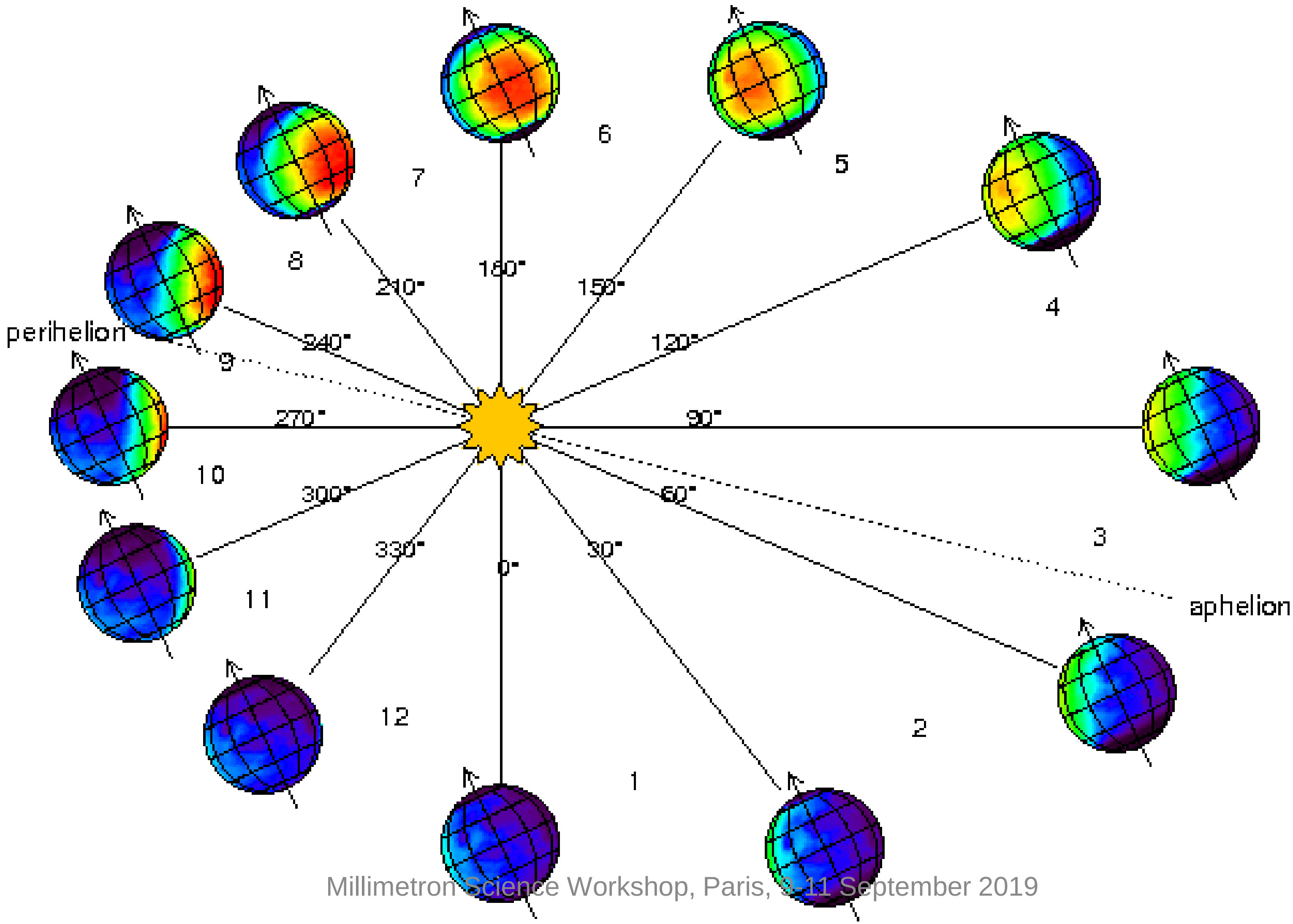


# Earth hygropause (25-60º lat.)

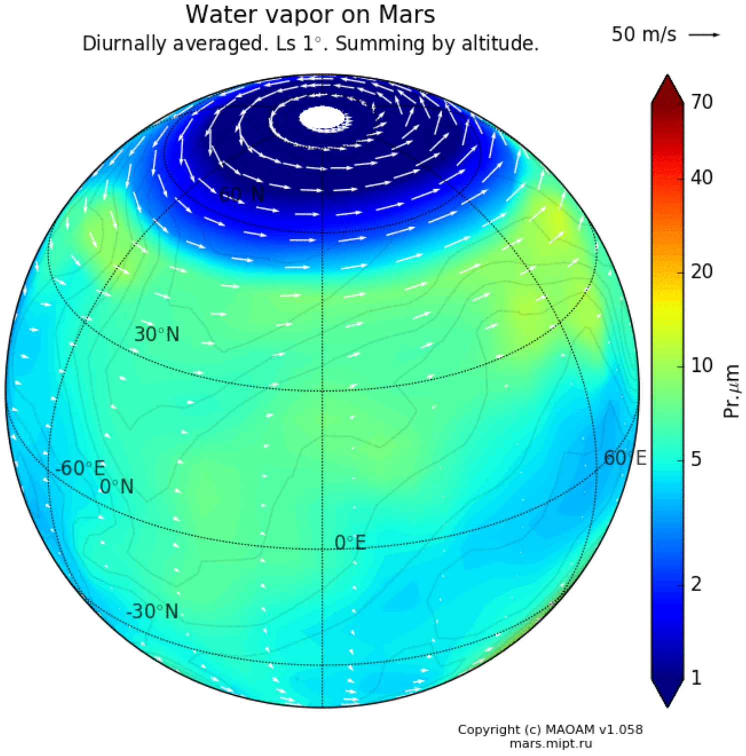


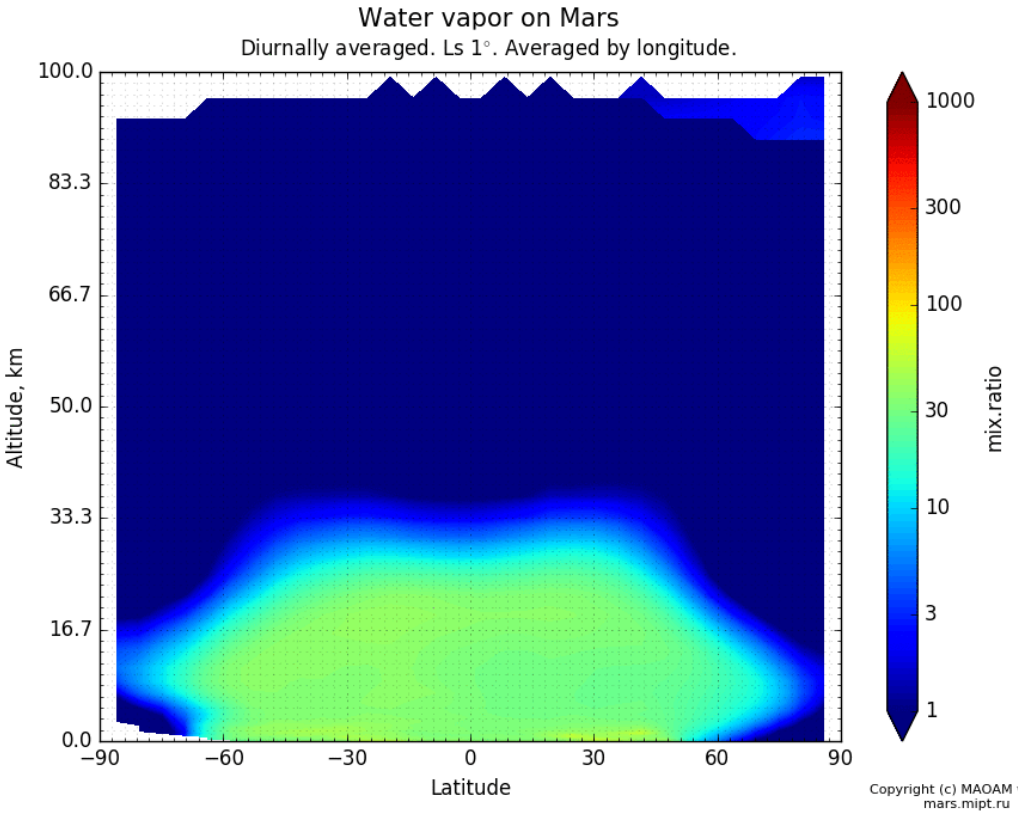

Follette et al, 2008

# Martian seasons



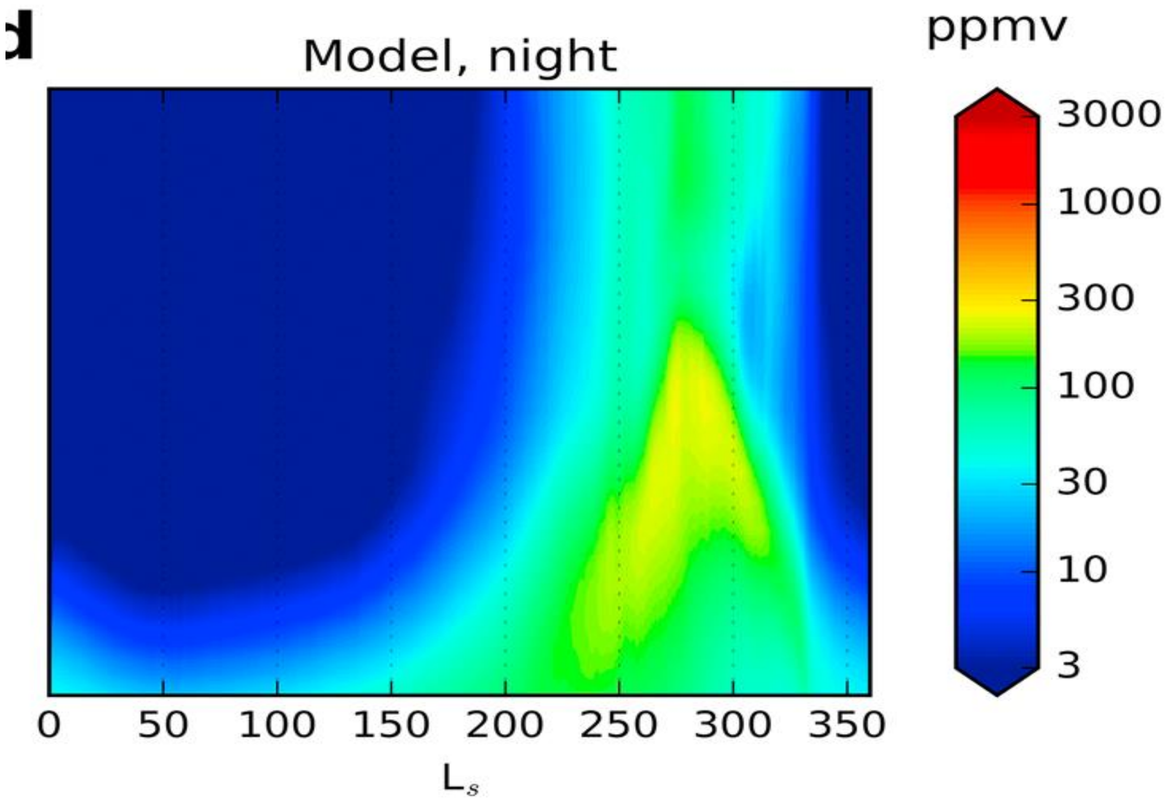
# MPI-MGCM simulation of water cycle




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

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

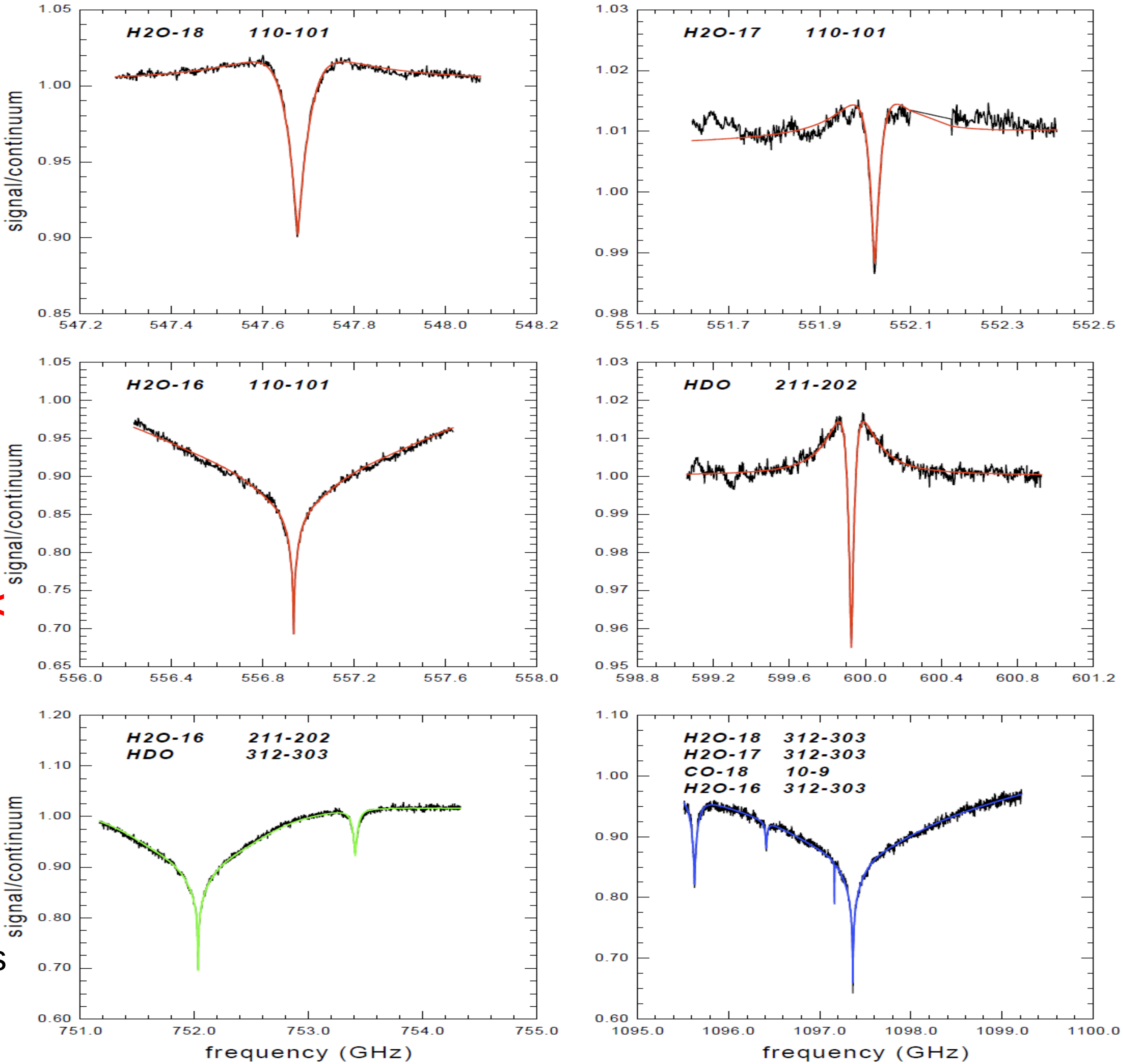



***Shaposhnikov et al. JGR, 2019 („water pump paper")***

# HIFI: 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)

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

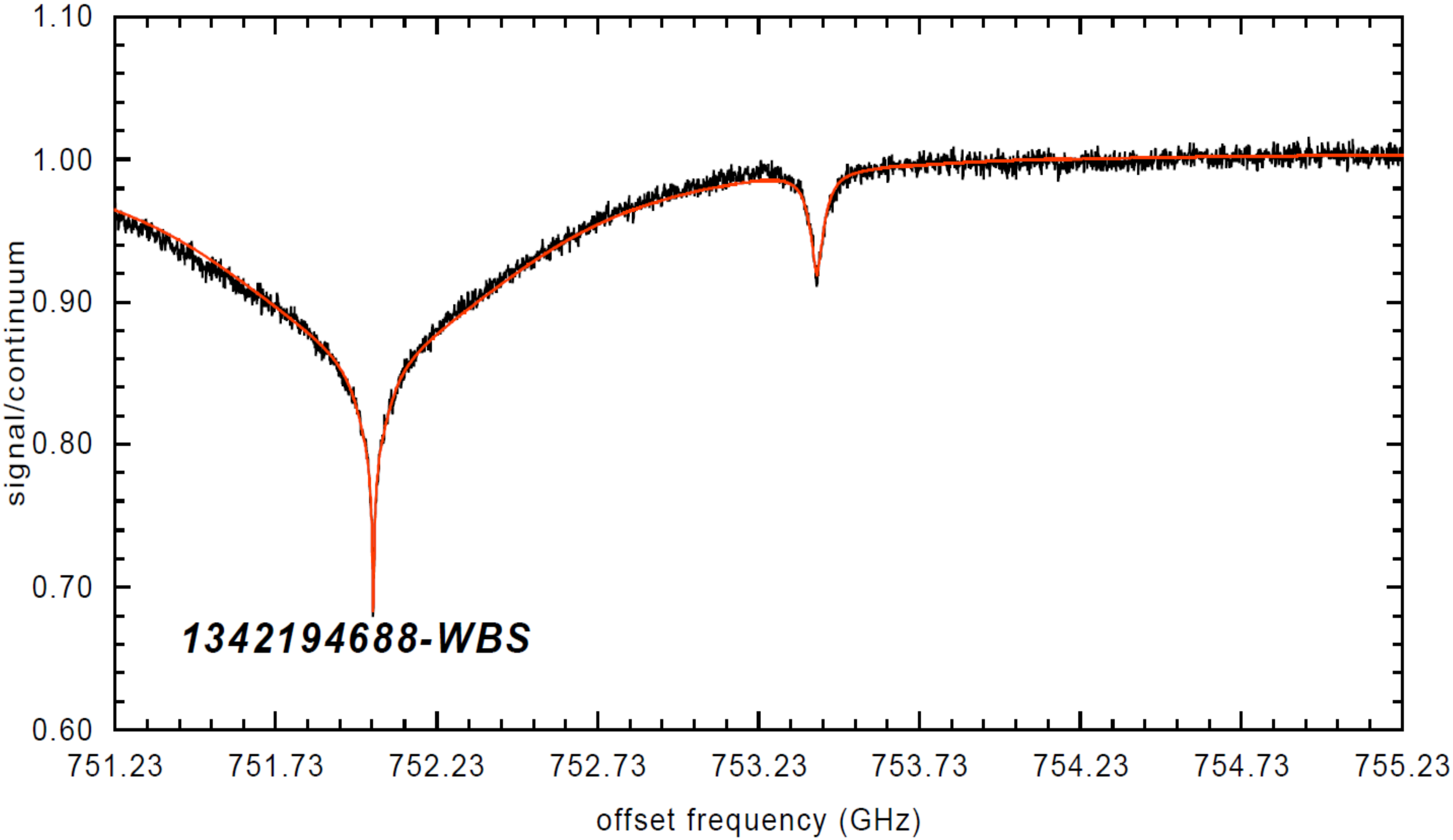



Optimum fit using VSMOW for oxygen. Deviations < 5 %.

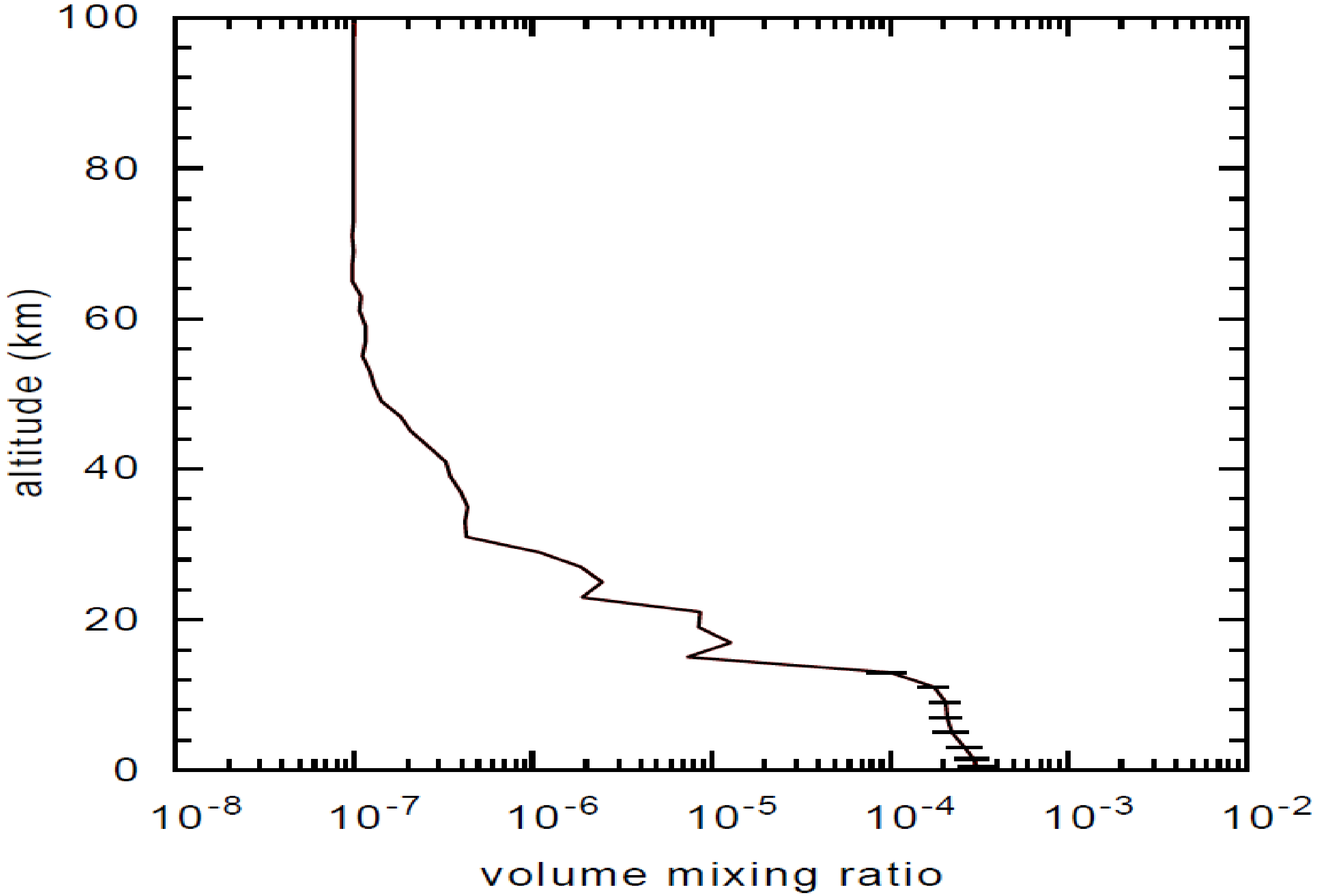
# HIFI: Oxygen Isotopes on Mars

- Consistent from CO and $H_2O$
- Seem to be telluric
- Difficult to derive fractionations < 5 %
- Required improvements:
  - precise flux calibration < 3 %
  - minimized baseline ripples

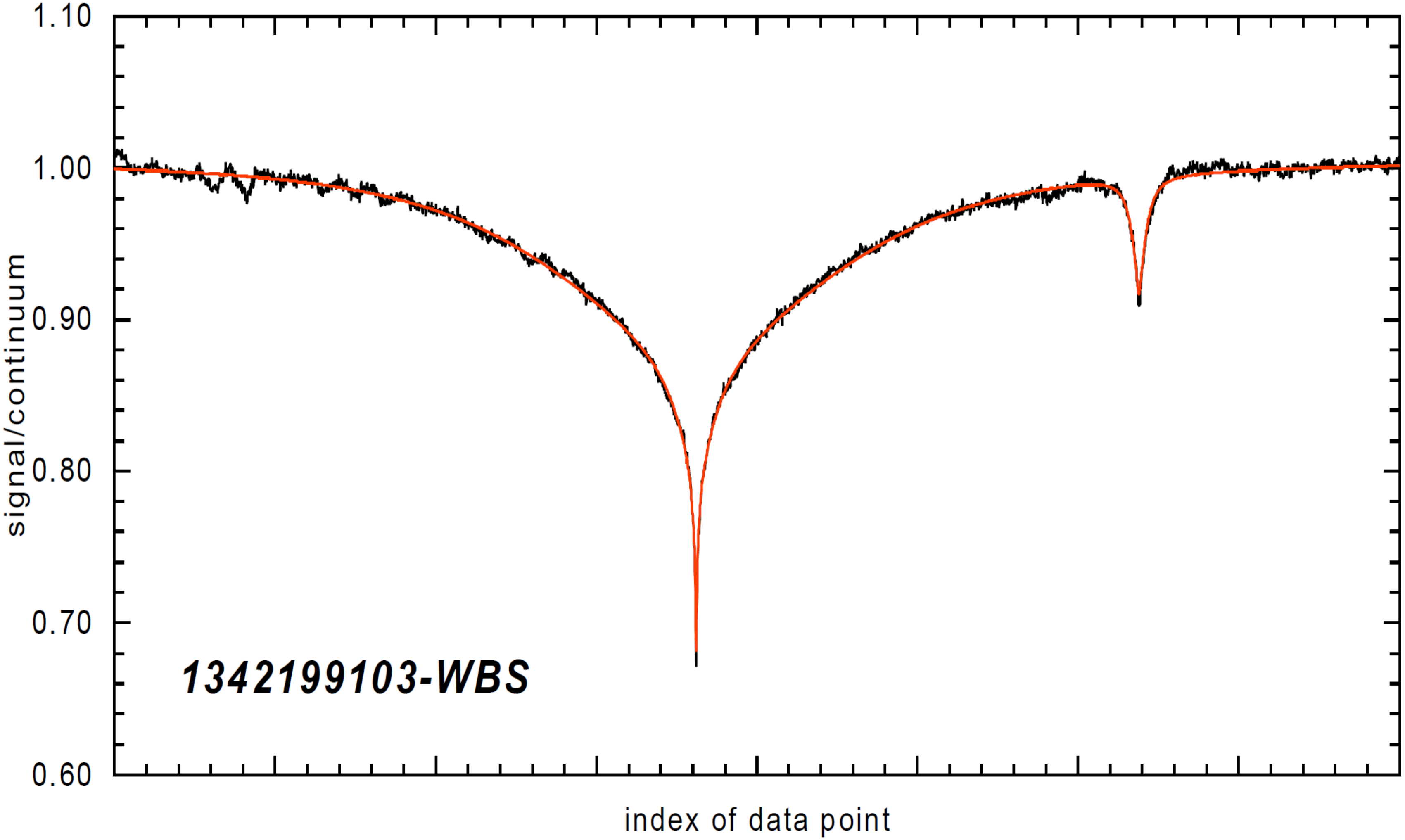
# $H_2O$ and HDO (4.5 x VSMOW) at $L_s = 78°$



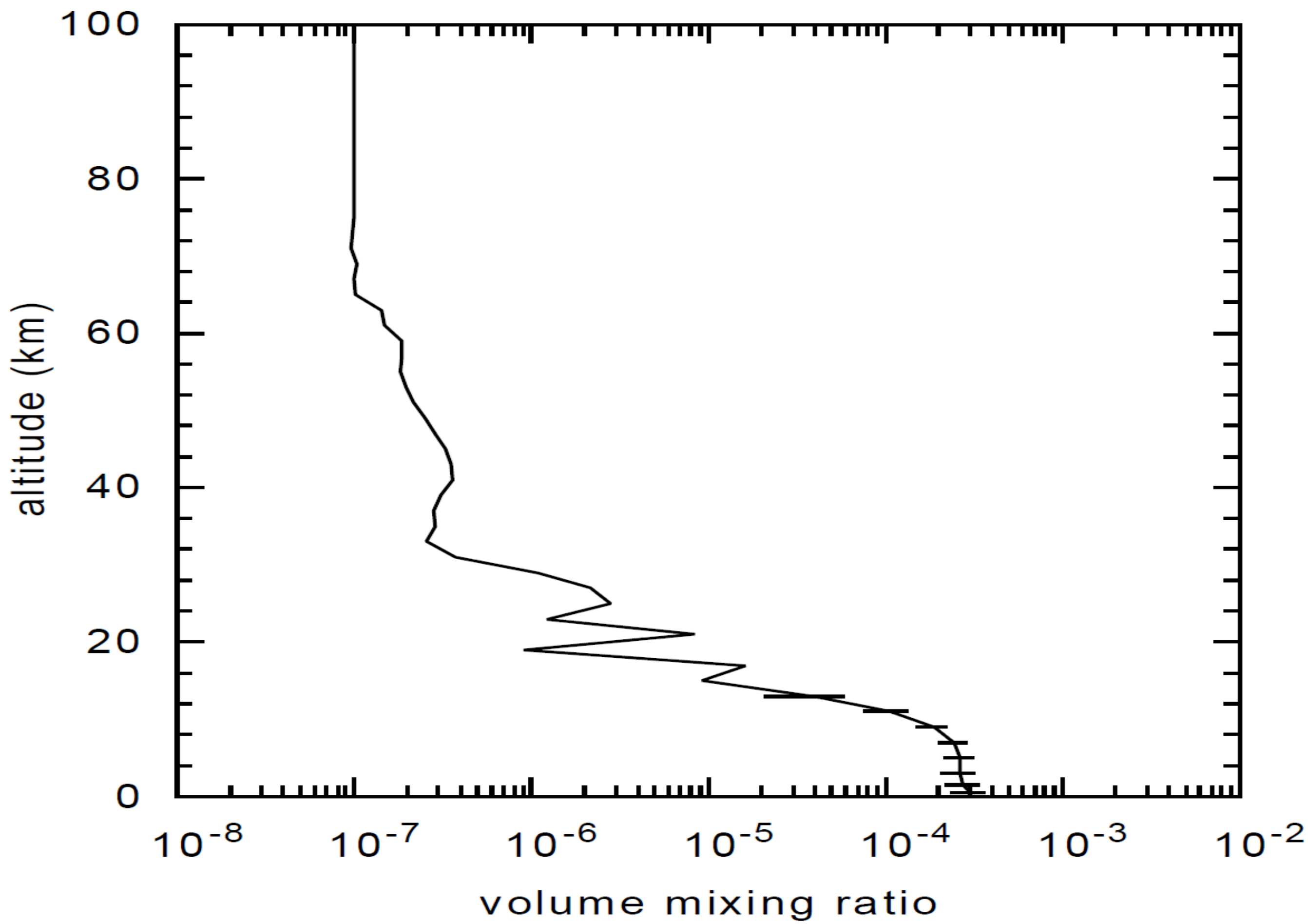
# Vertical profile of water at Ls = 78°



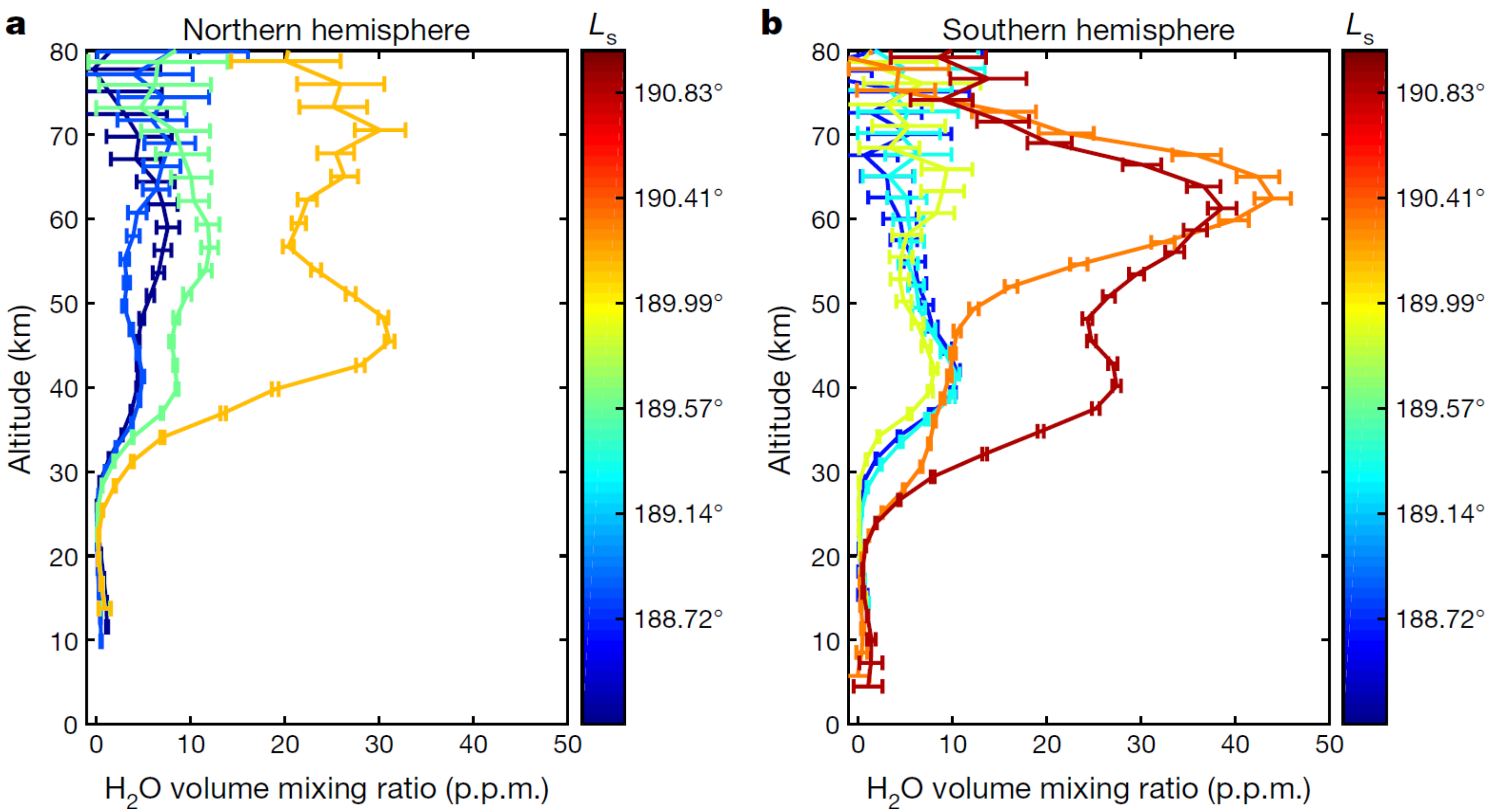
# $H_2O$ and HDO (4.6 x VSMOW) at $Ls = 110°$



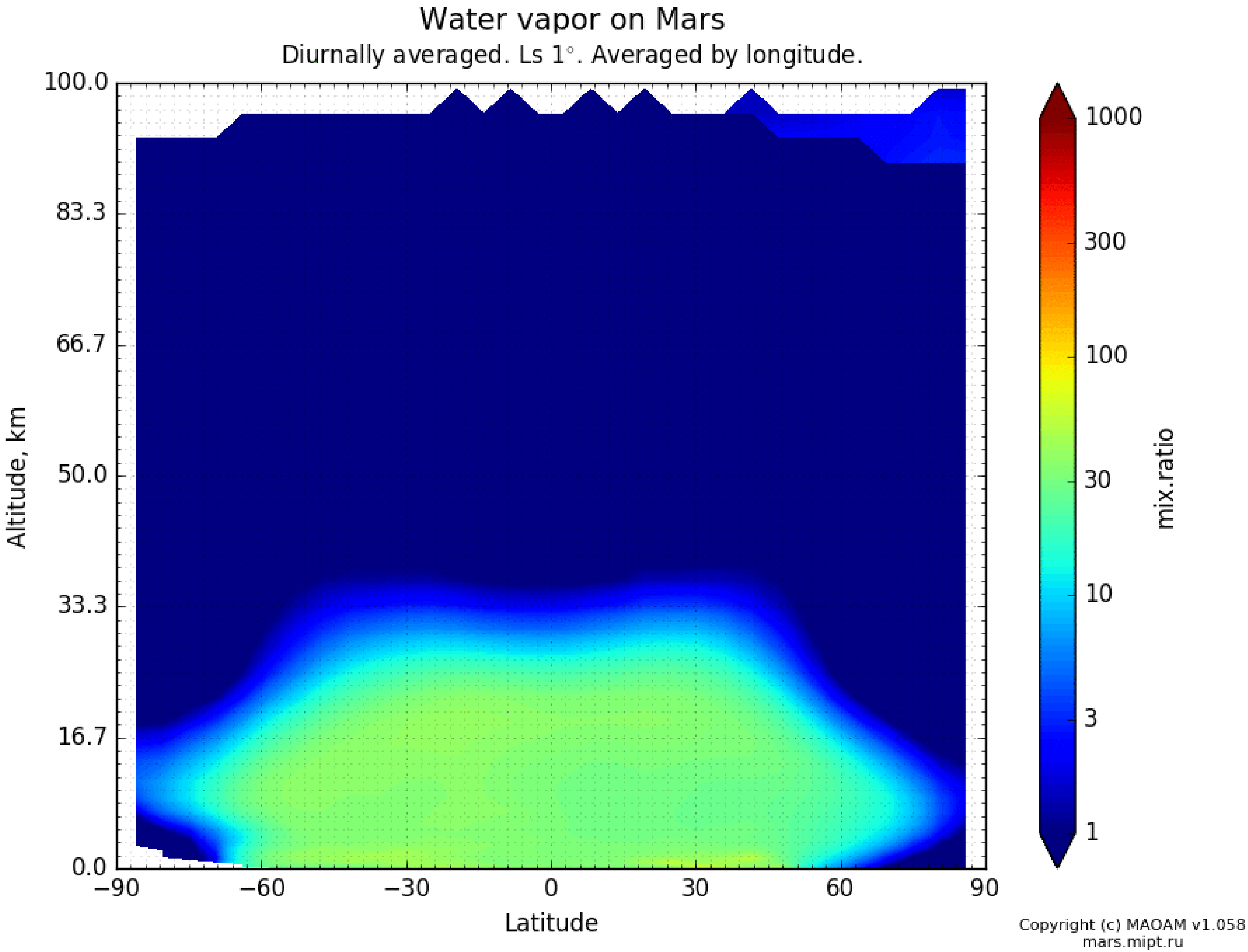
# Vertical profile of water at Ls = 110°



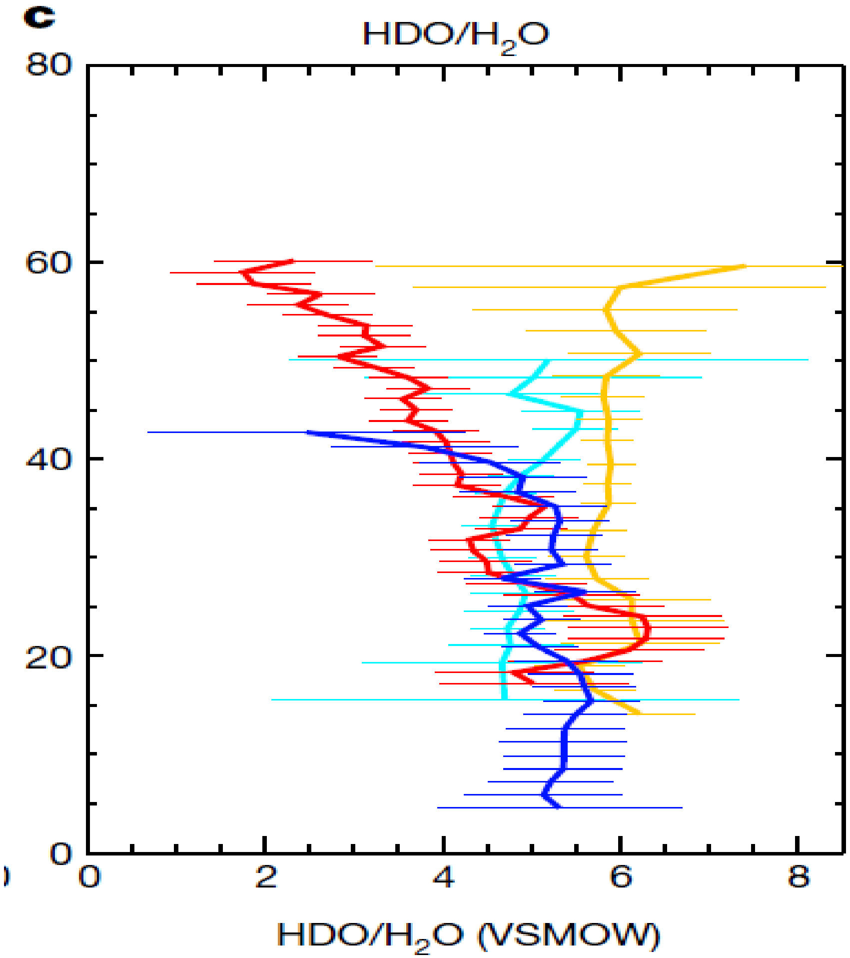
# Rapid upward transport of water vapour during a dust storm, polar latitudes




***Vandaele et al, Nature 2019***


Water vapor on Mars
Diurnally averaged. Ls 1°. Averaged by longitude.
100.0
83.3
66.7
50.0
33.3
16.7
0.0
Altitude, km
−90
−60
−30
0
30
60
90
Latitude
1000
300
100
30
10
3
1
mix.ratio
Copyright (c) MAOAM v1.058
mars.mipt.ru

# D/H with TGO (ACS and NOMAD)




Ls 197º, 82º N

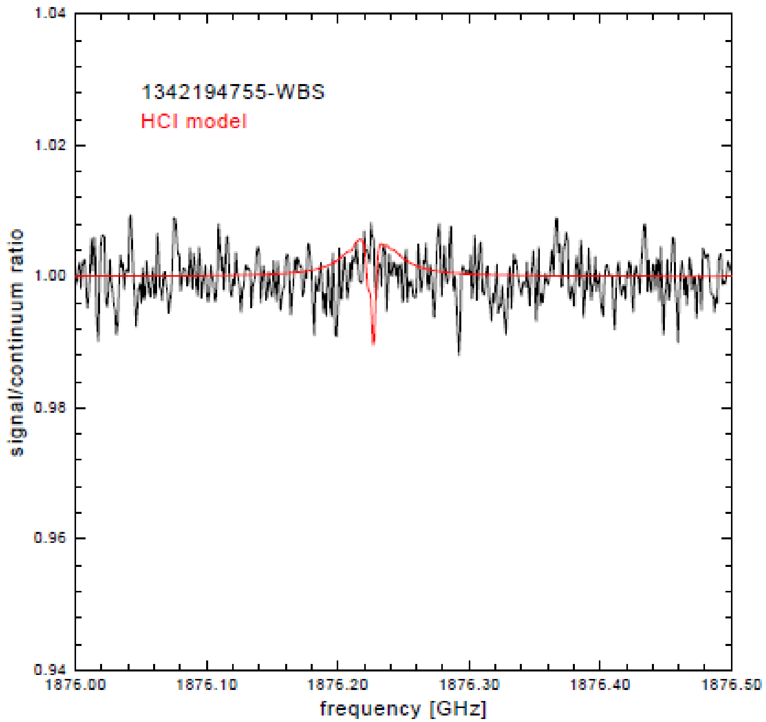
***Vandaele et al, Nature 2019***

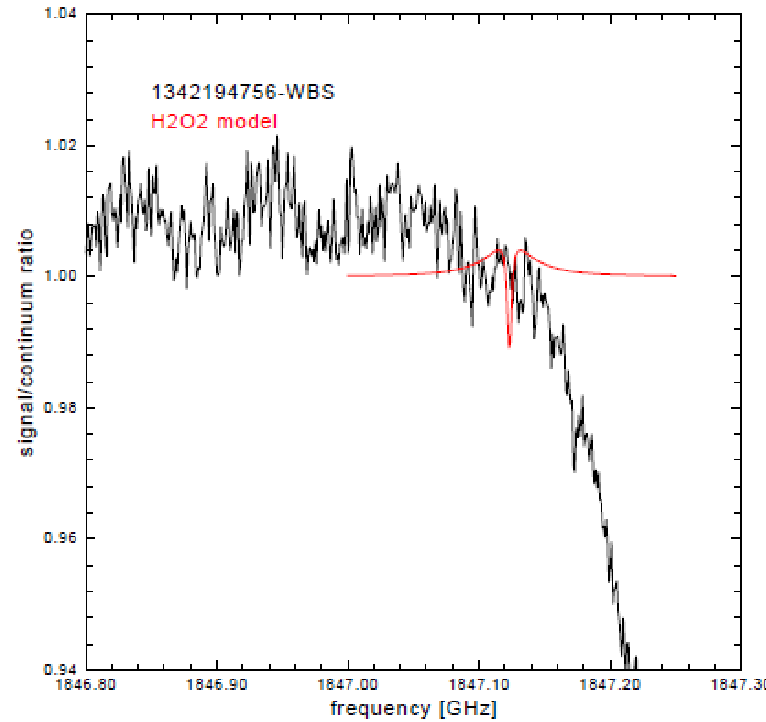
# HIFI results and MHIFI prospectives on water cycle

- HIFI failure
- Lost of important observations
- Only small Ls coverage around northern winter (hygropause level ~ 12 km)
- No observations around southern summer

- **MHIFI: Full Ls coverage**

# Upper limits on HCl and $H_2O_2$




< 200 ppt

< 2 ppb

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

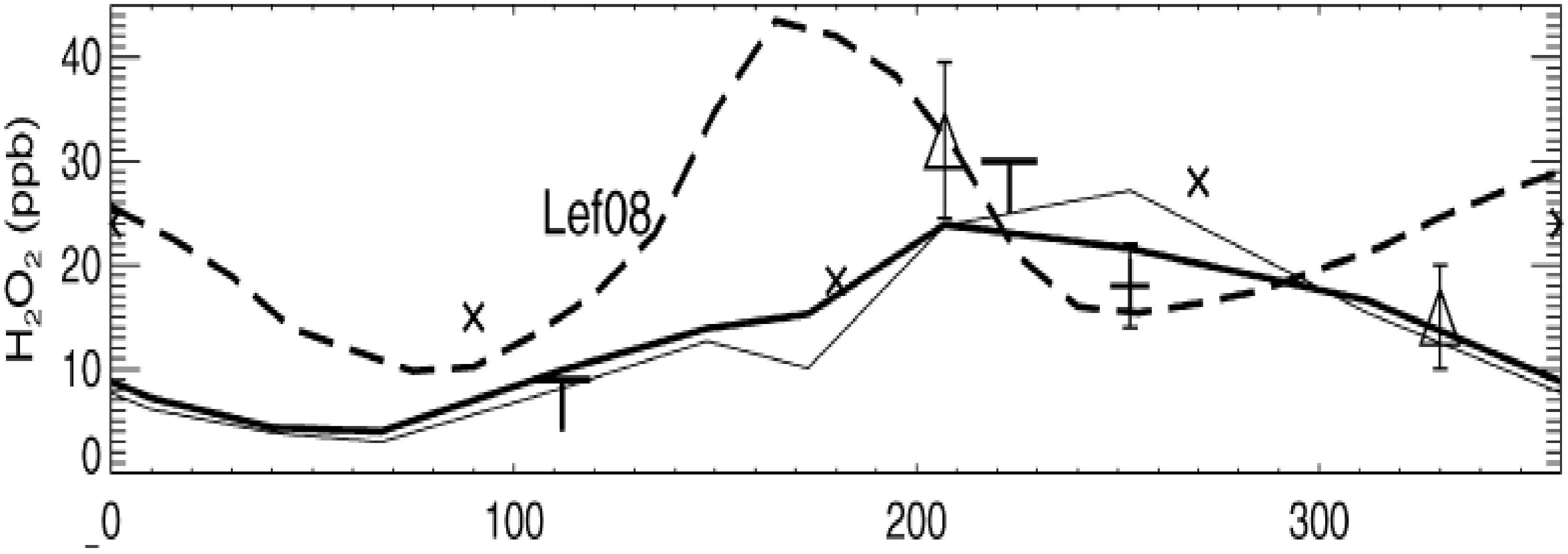
# What about HCl and $H_2O_2$ ?

- 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.

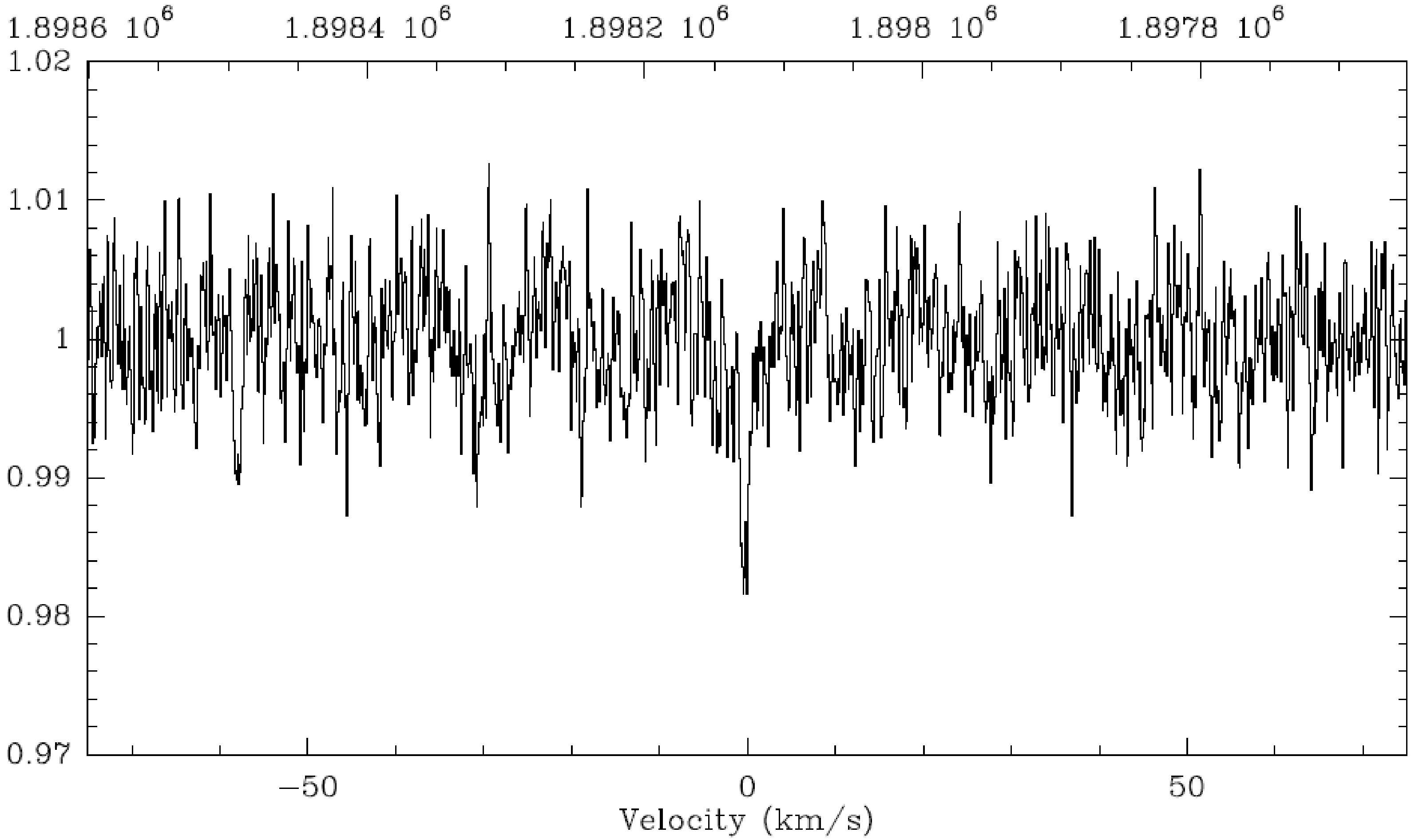
- $H_2O_2$ snow believed to kill all live on martian surface. Produced in eletrostatic discharge reaction during dust storms. (see Sushil Artreya‘s work)

# Model abundances of $H_2O_2$




*Krasnopolsky 2009, Icarus*

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



# HIFI & MHIFI relative sensitivities

**Table 1: DSB without calibration. SNR=100, Δf = 1 MHz, 70 K line amplitude**

| Frequency in GHz<br>Mars diameter arcsec | Spatial resolution HIFI (arcsec) | Spatial Resolution Millimetron (arcsec) | Line Amplitude HIFI (K) | Line Amplitude MHIFI (K) | Trec (K) | Integration-time HIFI (s) | Trec (K) | Integration-time MHIFI (s) |
|---|---|---|---|---|---|---|---|---|
| 557/10 | 38 | 13.5 | 4.75 | 38.4 | 100 | 4.4 | 100 | 0.067 |
| 557/5 | | | 1.2 | 9.6 | | 69.4 | | 1.085 |
| 750/10 | 28.6 | 10 | 8.56 | 70 | 180 | 4.4 | 80 | 0.013 |
| 750/5 | | | 2.14 | 17.5 | | 69.4 | | 0.21 |
| 1000/10 | 21.5 | 7.5 | 15.14 | 70 | 300 | 3.95 | 100 | 0.02 |
| 1000/5 | | | 3.78 | 31.1 | | 63 | | 0.104 |
| 1500/10 | 14.3 | 5 | 34 | 70 | 1500 | 19.5 | 400 | 0.33 |
| 1500/5 | | | 8.6 | 70 | | 304 | | 0.33 |

# Sensitivities and integration times HIFI & MHIFI

| F/GHz & Mars diameter(arcsec) | Integration time factor | Sensitivity factor |
|---|---|---|
| **557-10** | 65 | 8 |
| **557-5** | 65 | 8 |
| **750-10** | 338 | 18 |
| **750-5** | 330 | 18 |
| **1000-10** | 198 | 14 |
| **1000-5** | 606 | 25 |
| **1500-10** | 59 | 7.7 |
| **1500-5** | 921 | 30 |

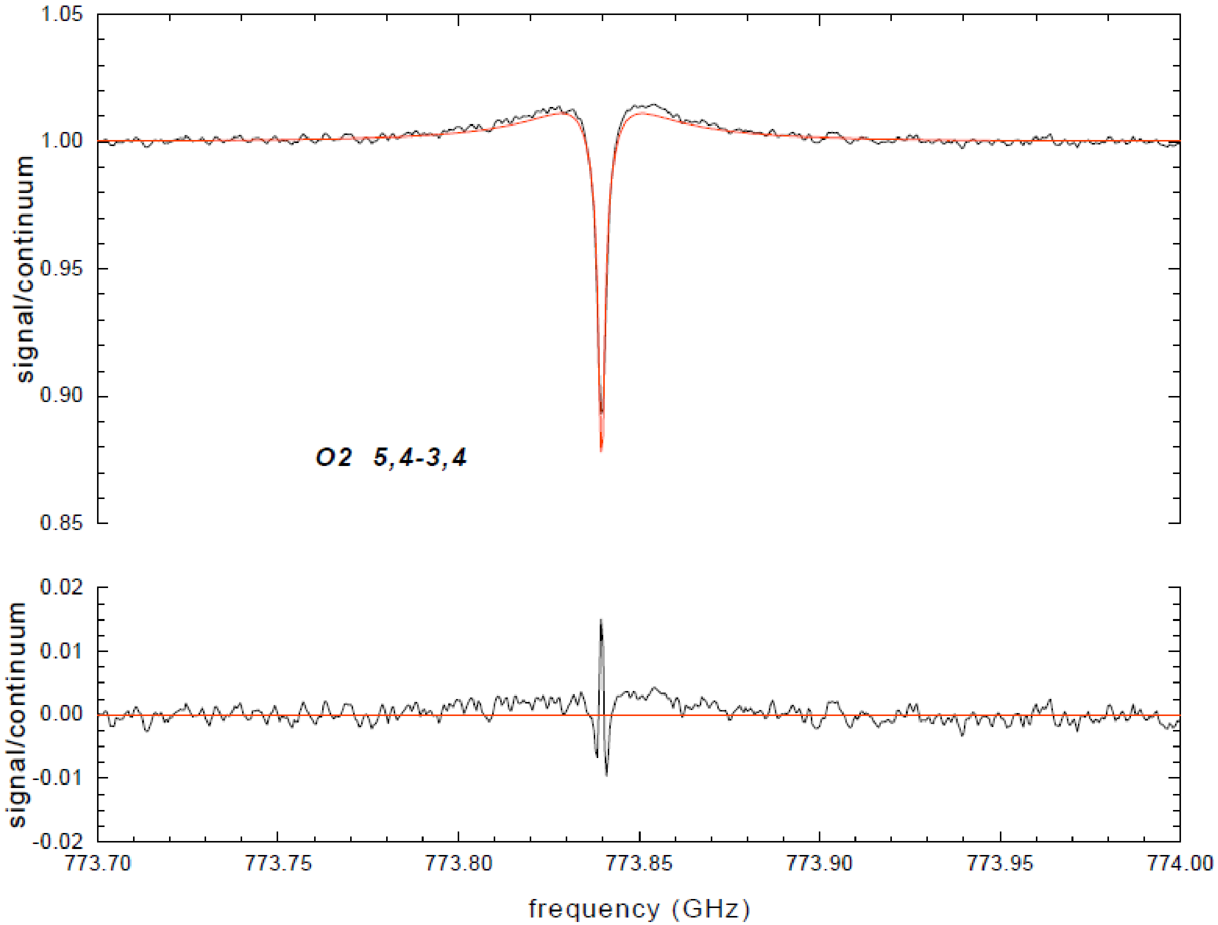
# HIFI -> MHIFI ($H_2O_2$)

- HIFI: 5-sigma detection after 1 hour integration time (Mars diameter ~ 10 arcsec)
- MHIFI: > 50 sigma after 1 h integration time will constrain the vertical profile
- Efficiency up to > 30 times better for smaller Mars diameters (e.g. at 5 arcsec), integration times about 1000 times shorter
- Reason: spatial resolution and improved receiver temperatures at higher frequencies

# 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.

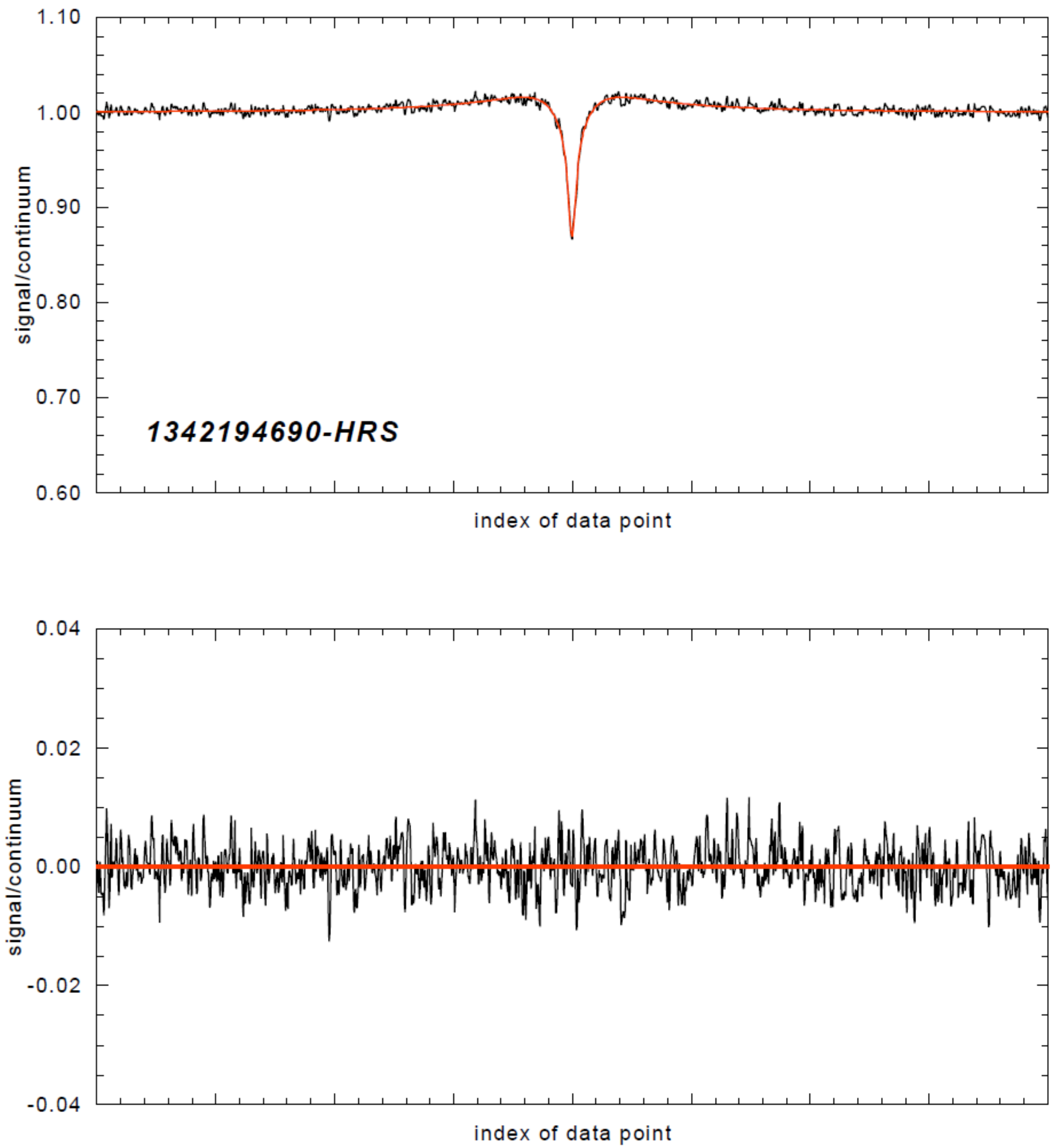
# First submm detection of $O_2$




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***

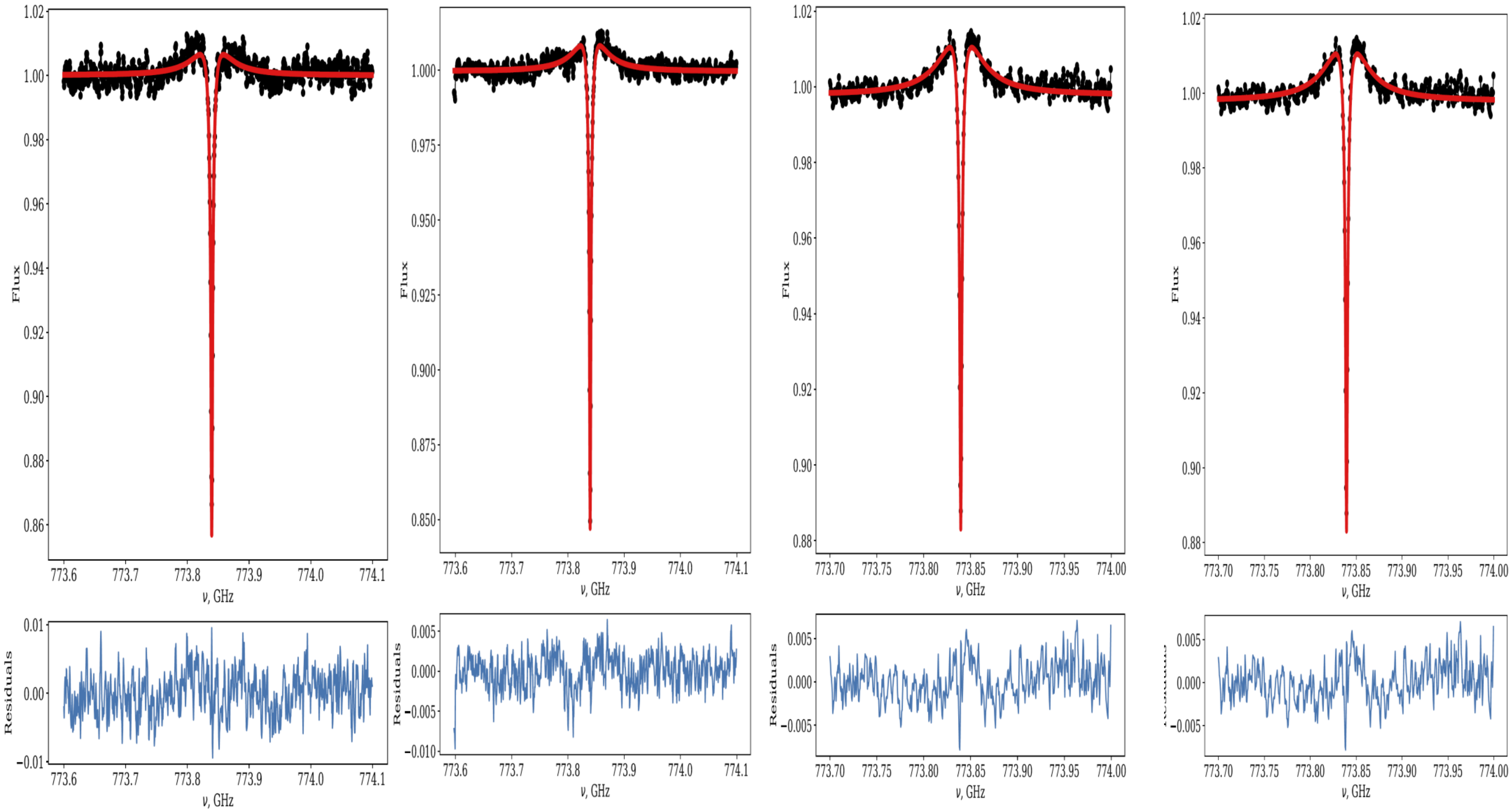
# Non-constant profile provides better fit



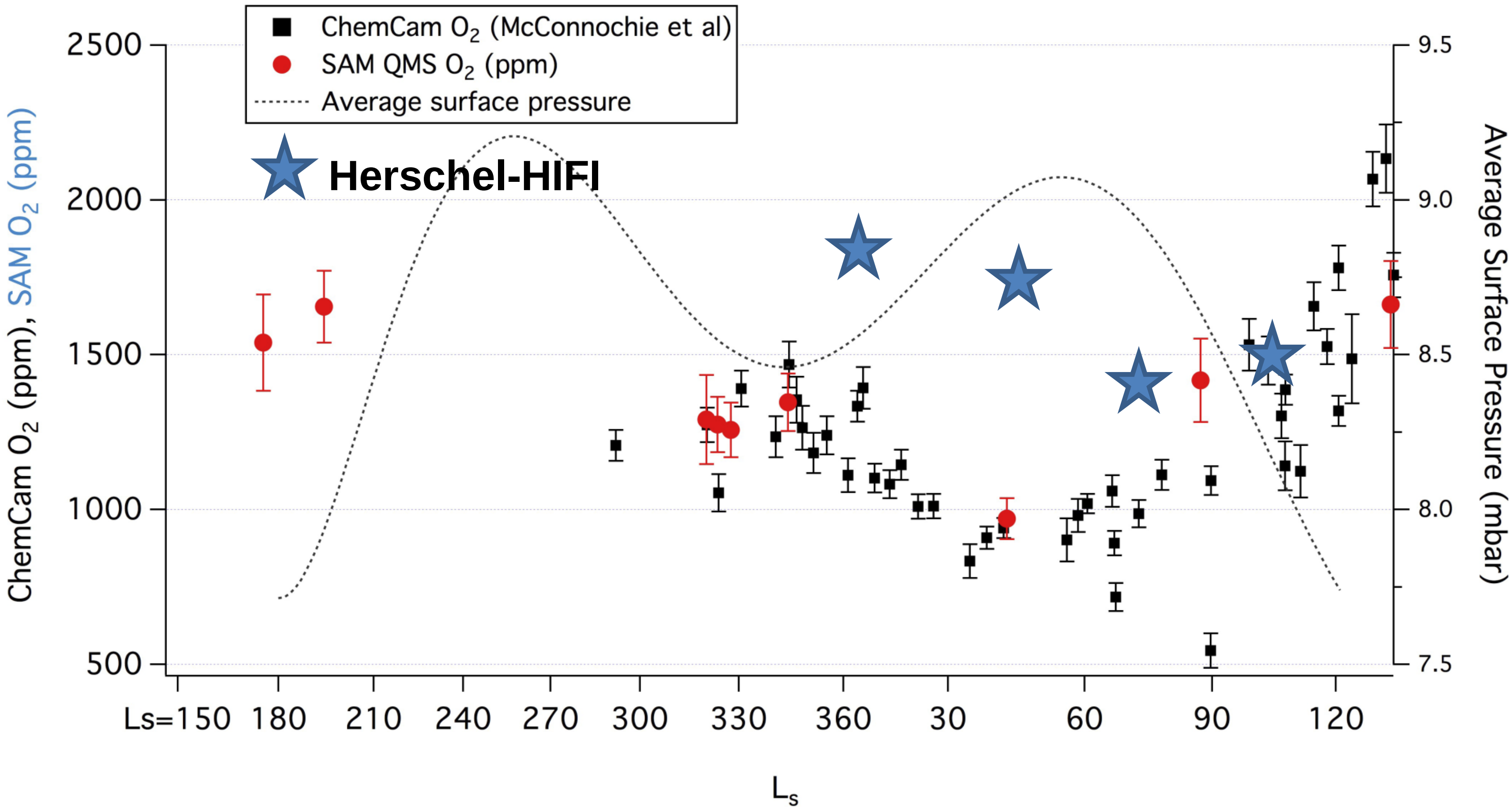
# Non-constant vertical profile?

- 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
- 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 $O_2$



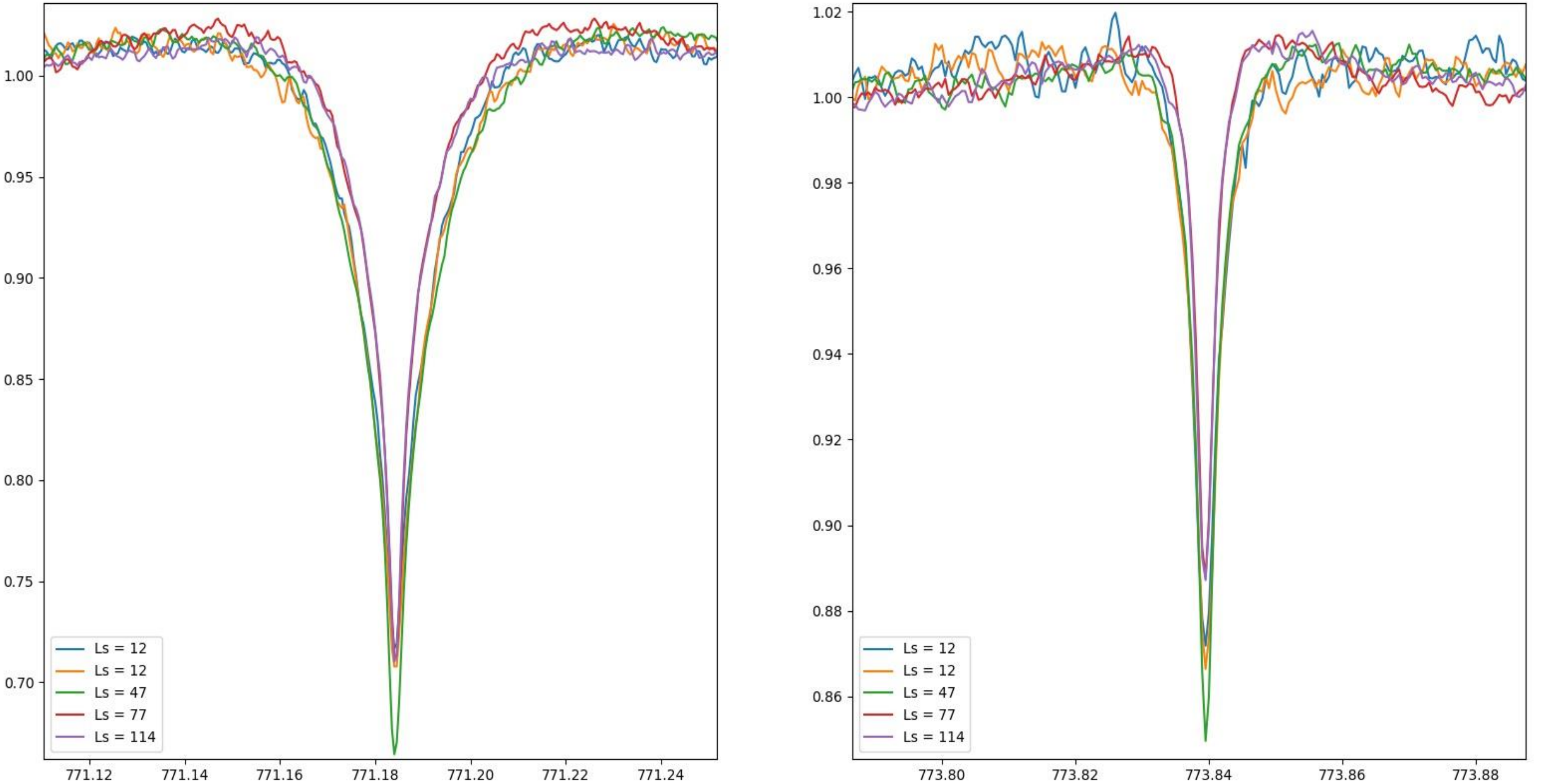
# VMR vs surface pressure

- 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**

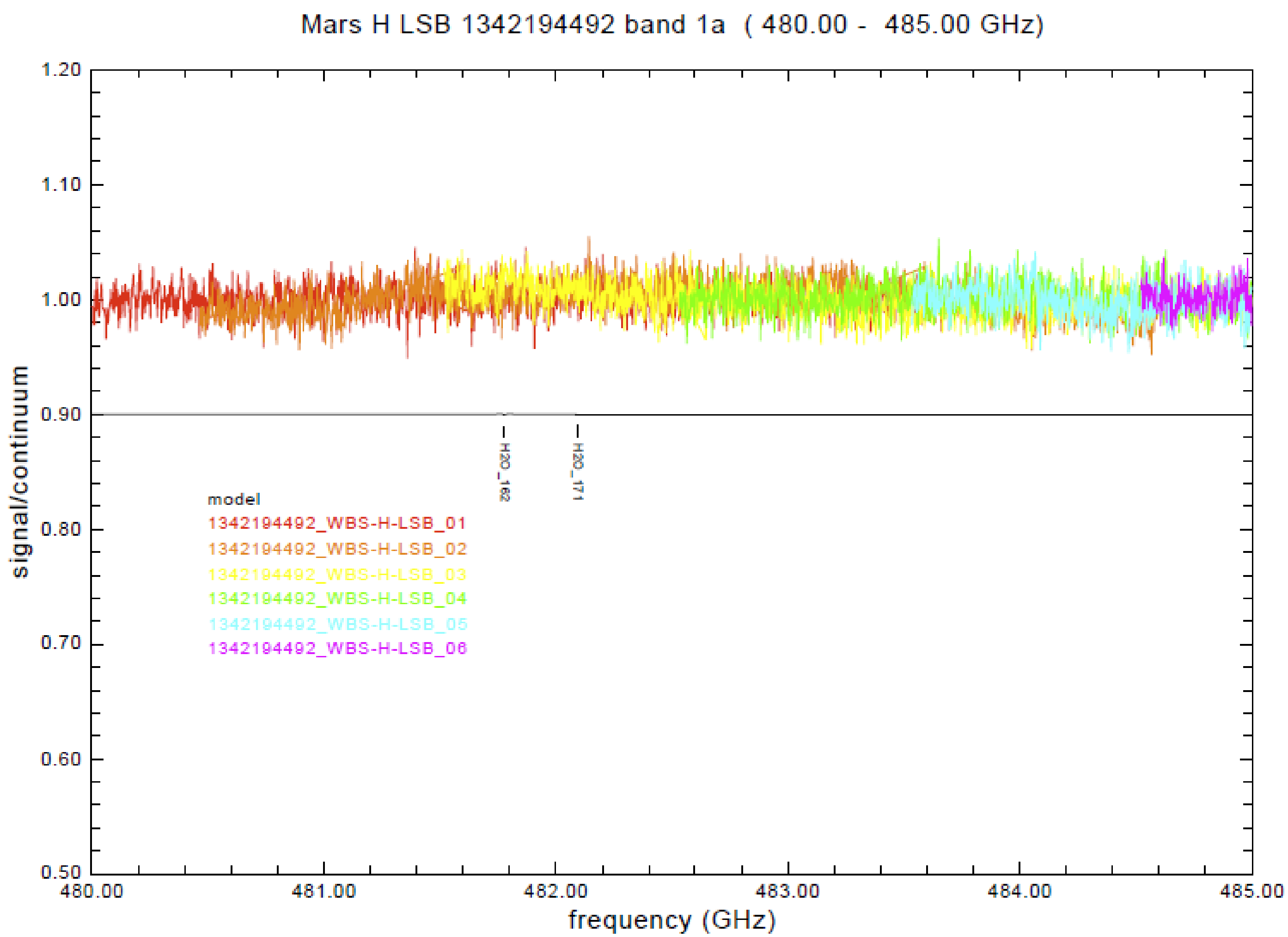
# CO and $O_2$ spectra comparison

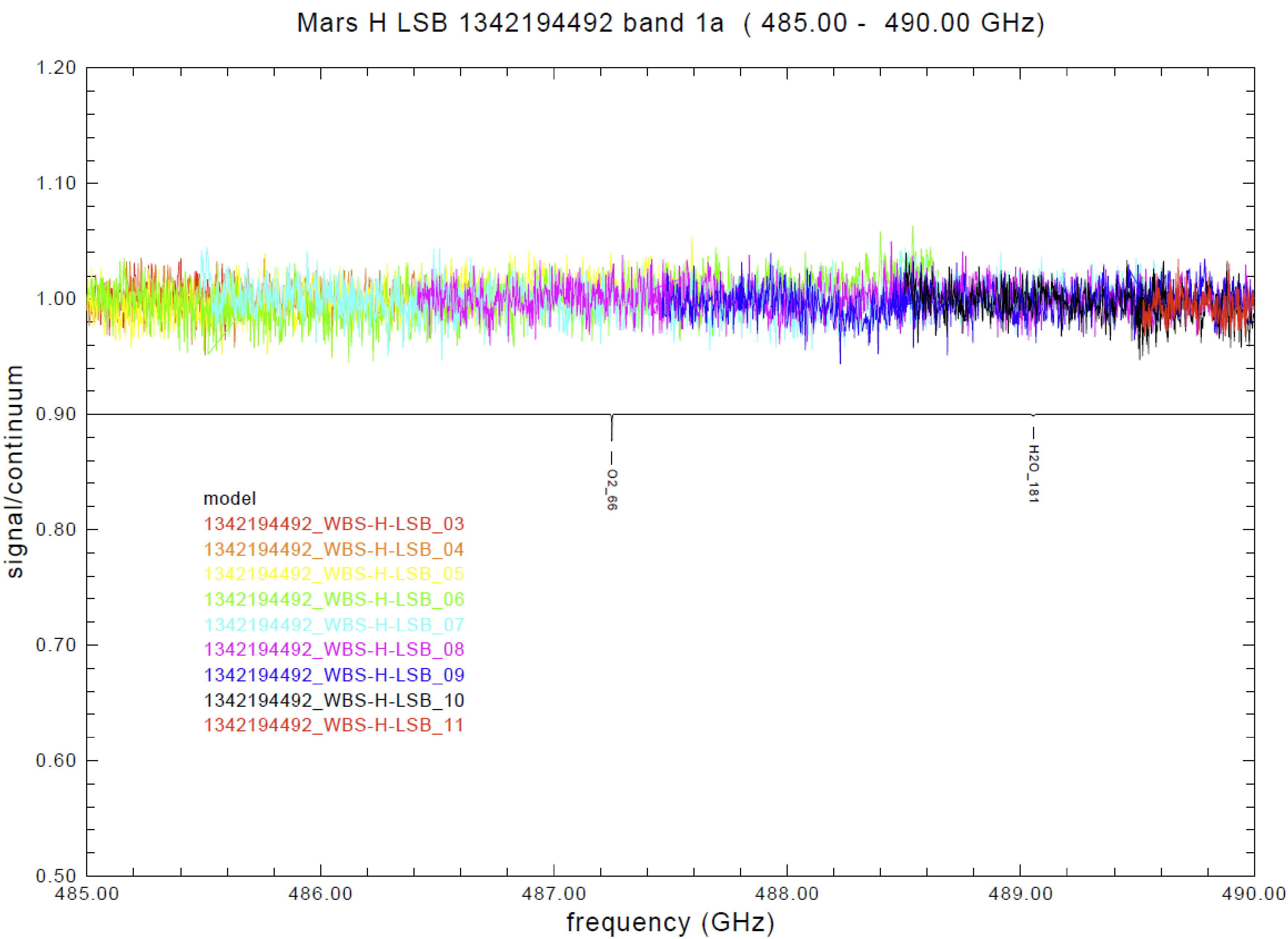


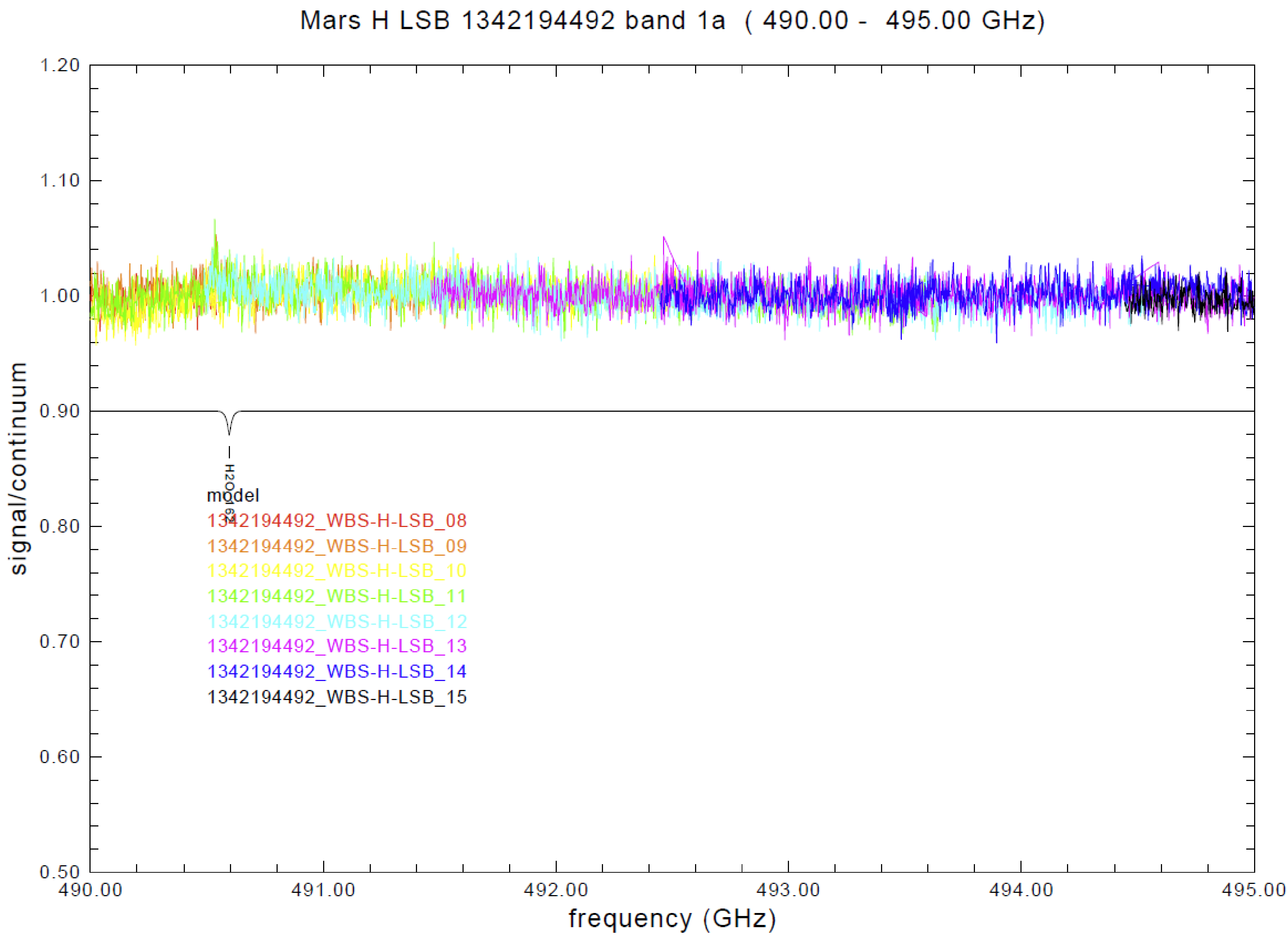
# Discussion

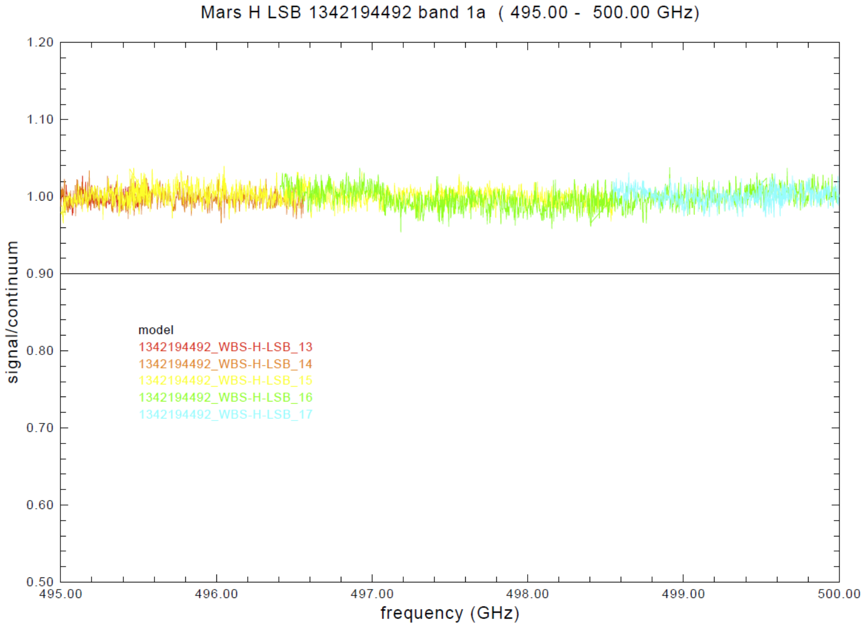
- All 3 instruments show larger variations than expected from $O_2$ as supervolatile (-Δp)
- HIFI shows smaller variations than CC and QMS
- If true, $O_2$ is not as well mixed as assumed
- Vertical profiles not shown here, because very sensitive on temperature profiles, derived from CO lines and related baseline ripples
- Comparison of CO and $O_2$ spectra however indicate deviation from constant vertical profile at Ls
- **Important for MHIFI: sideband separation mixers or other measure to make sure having small baseline ripples on continuum sources.**

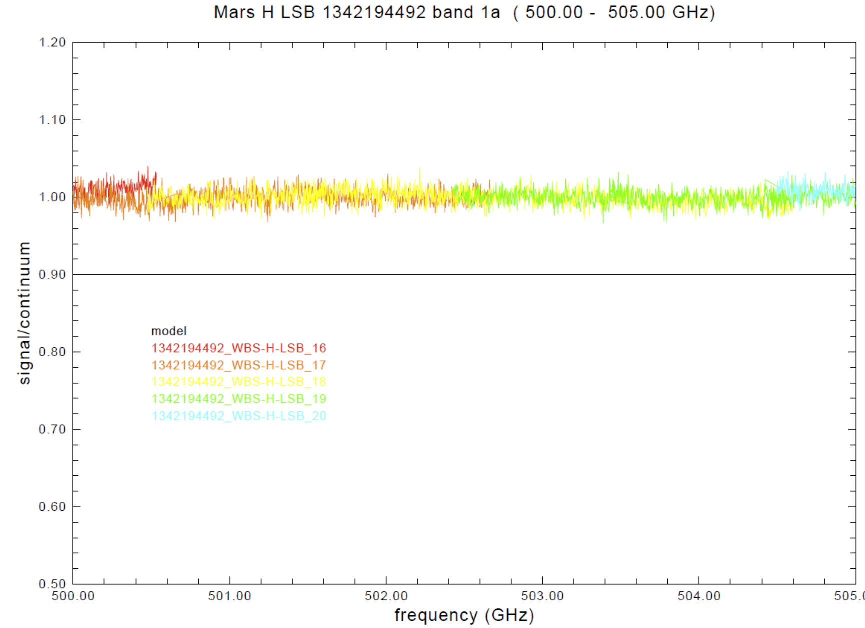
# Line Survey

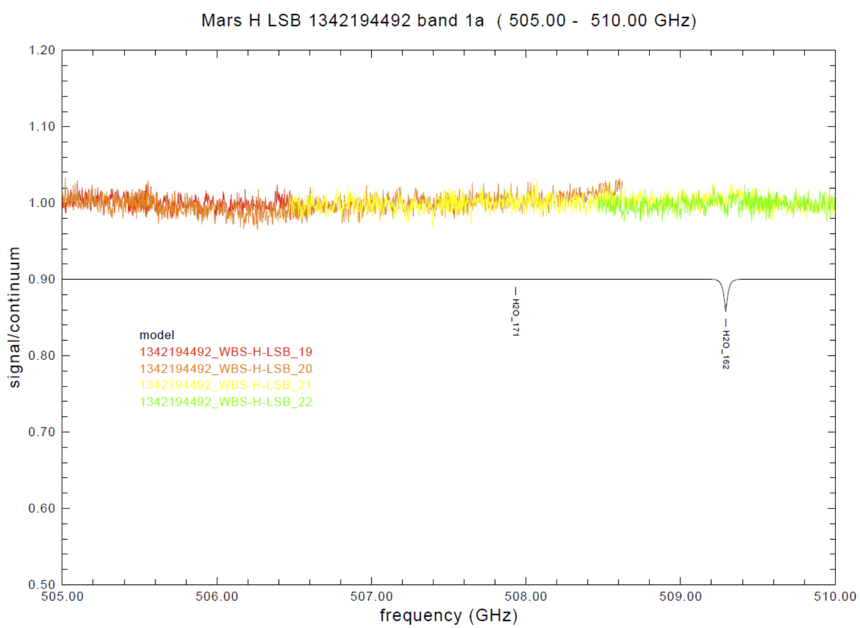

Mars H LSB 1342194492 band 1a ( 480.00 - 485.00 GHz)
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
signal/continuum
480.00
481.00
482.00
483.00
484.00
485.00
frequency (GHz)
H2O_162
H2O_171
model
1342194492_WBS-H-LSB_01
1342194492_WBS-H-LSB_02
1342194492_WBS-H-LSB_03
1342194492_WBS-H-LSB_04
1342194492_WBS-H-LSB_05
1342194492_WBS-H-LSB_06

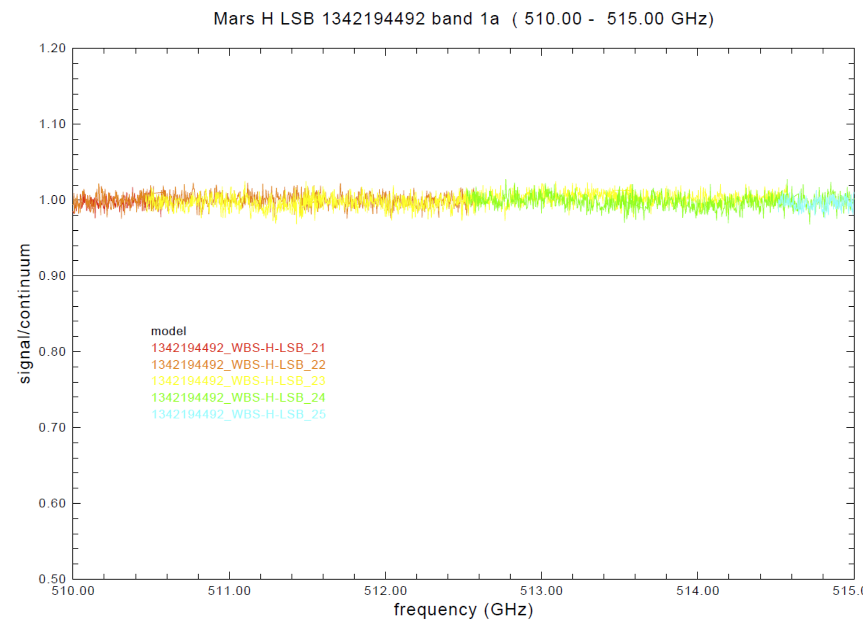

Mars H LSB 1342194492 band 1a ( 485.00 - 490.00 GHz)
signal/continuum
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
485.00
486.00
487.00
488.00
489.00
490.00
frequency (GHz)
O2_66
H2O_181
model
1342194492_WBS-H-LSB_03
1342194492_WBS-H-LSB_04
1342194492_WBS-H-LSB_05
1342194492_WBS-H-LSB_06
1342194492_WBS-H-LSB_07
1342194492_WBS-H-LSB_08
1342194492_WBS-H-LSB_09
1342194492_WBS-H-LSB_10
1342194492_WBS-H-LSB_11

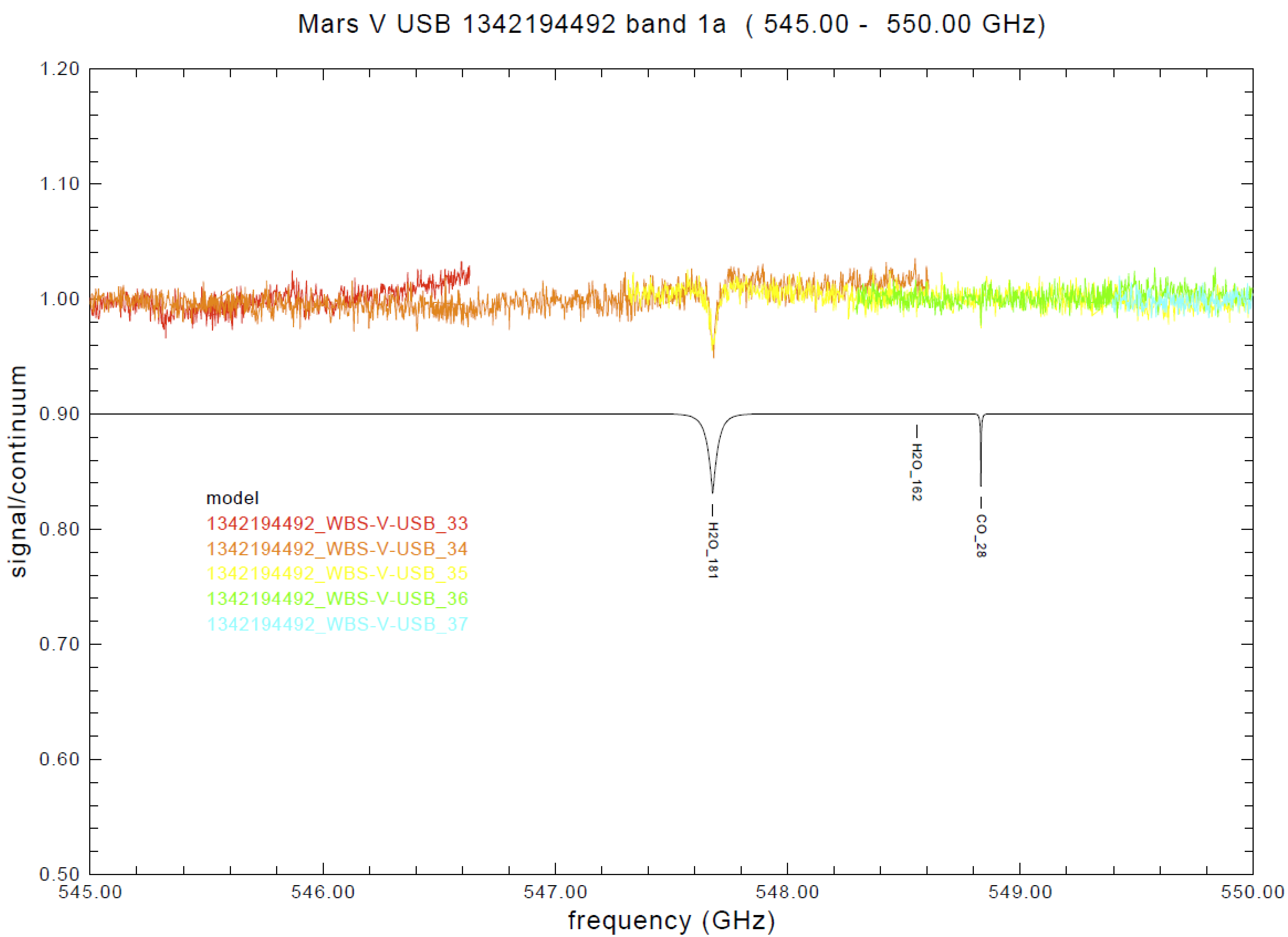

Mars H LSB 1342194492 band 1a ( 490.00 - 495.00 GHz)
signal/continuum
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
490.00
491.00
492.00
493.00
494.00
495.00
frequency (GHz)
H2O 162
model
1342194492_WBS-H-LSB_08
1342194492_WBS-H-LSB_09
1342194492_WBS-H-LSB_10
1342194492_WBS-H-LSB_11
1342194492_WBS-H-LSB_12
1342194492_WBS-H-LSB_13
1342194492_WBS-H-LSB_14
1342194492_WBS-H-LSB_15


Mars H LSB 1342194492 band 1a ( 495.00 - 500.00 GHz)
signal/continuum
frequency (GHz)
model
1342194492_WBS-H-LSB_13
1342194492_WBS-H-LSB_14
1342194492_WBS-H-LSB_15
1342194492_WBS-H-LSB_16
1342194492_WBS-H-LSB_17

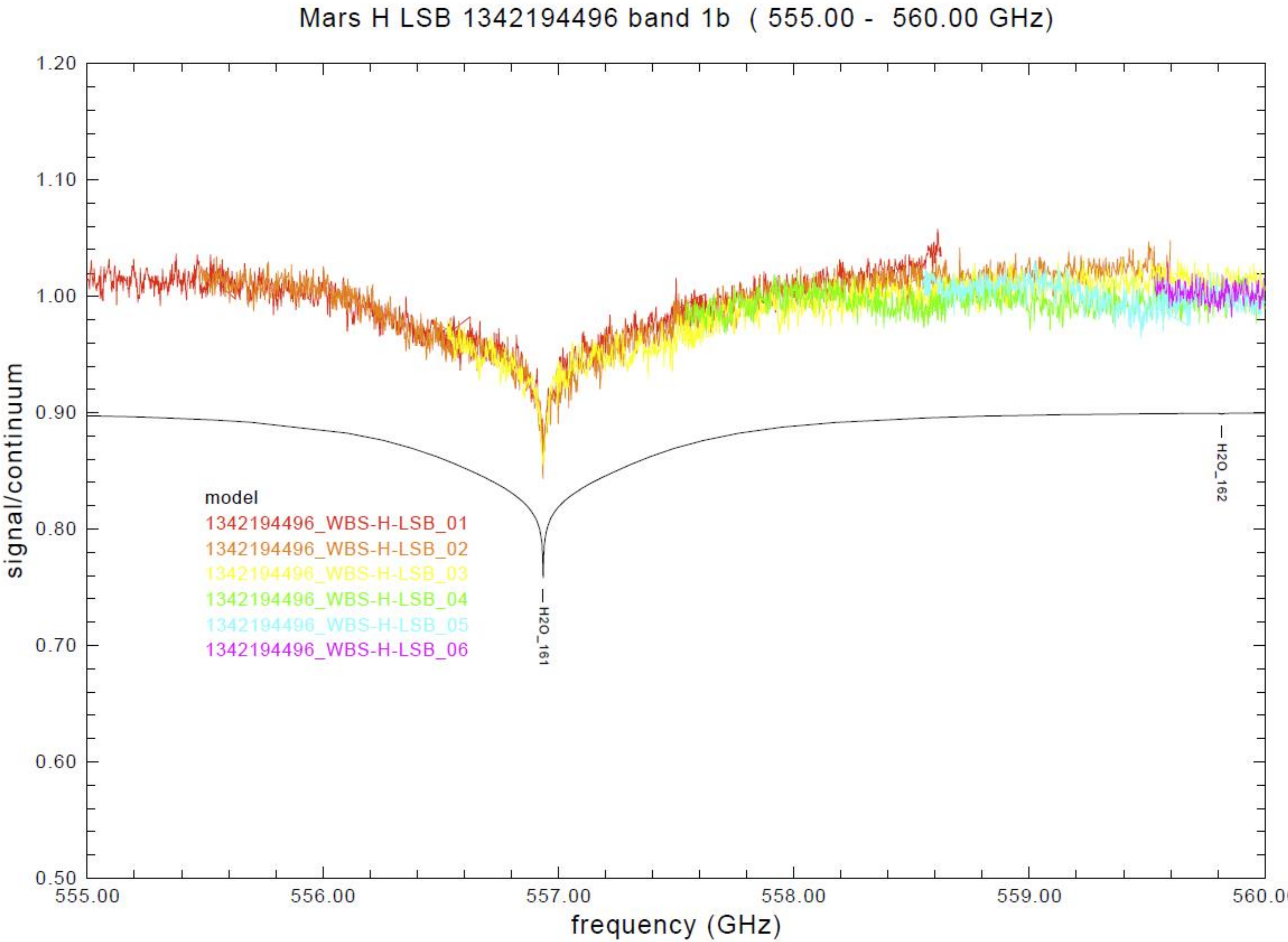

Mars H LSB 1342194492 band 1a ( 500.00 - 505.00 GHz)
signal/continuum
frequency (GHz)
model
1342194492_WBS-H-LSB_16
1342194492_WBS-H-LSB_17
1342194492_WBS-H-LSB_18
1342194492_WBS-H-LSB_19
1342194492_WBS-H-LSB_20


Mars H LSB 1342194492 band 1a ( 505.00 - 510.00 GHz)
signal/continuum
frequency (GHz)
H2O_171
H2O_162
model
1342194492_WBS-H-LSB_19
1342194492_WBS-H-LSB_20
1342194492_WBS-H-LSB_21
1342194492_WBS-H-LSB_22


Mars H LSB 1342194492 band 1a ( 510.00 - 515.00 GHz)
signal/continuum
frequency (GHz)
model
1342194492_WBS-H-LSB_21
1342194492_WBS-H-LSB_22
1342194492_WBS-H-LSB_23
1342194492_WBS-H-LSB_24
1342194492_WBS-H-LSB_25

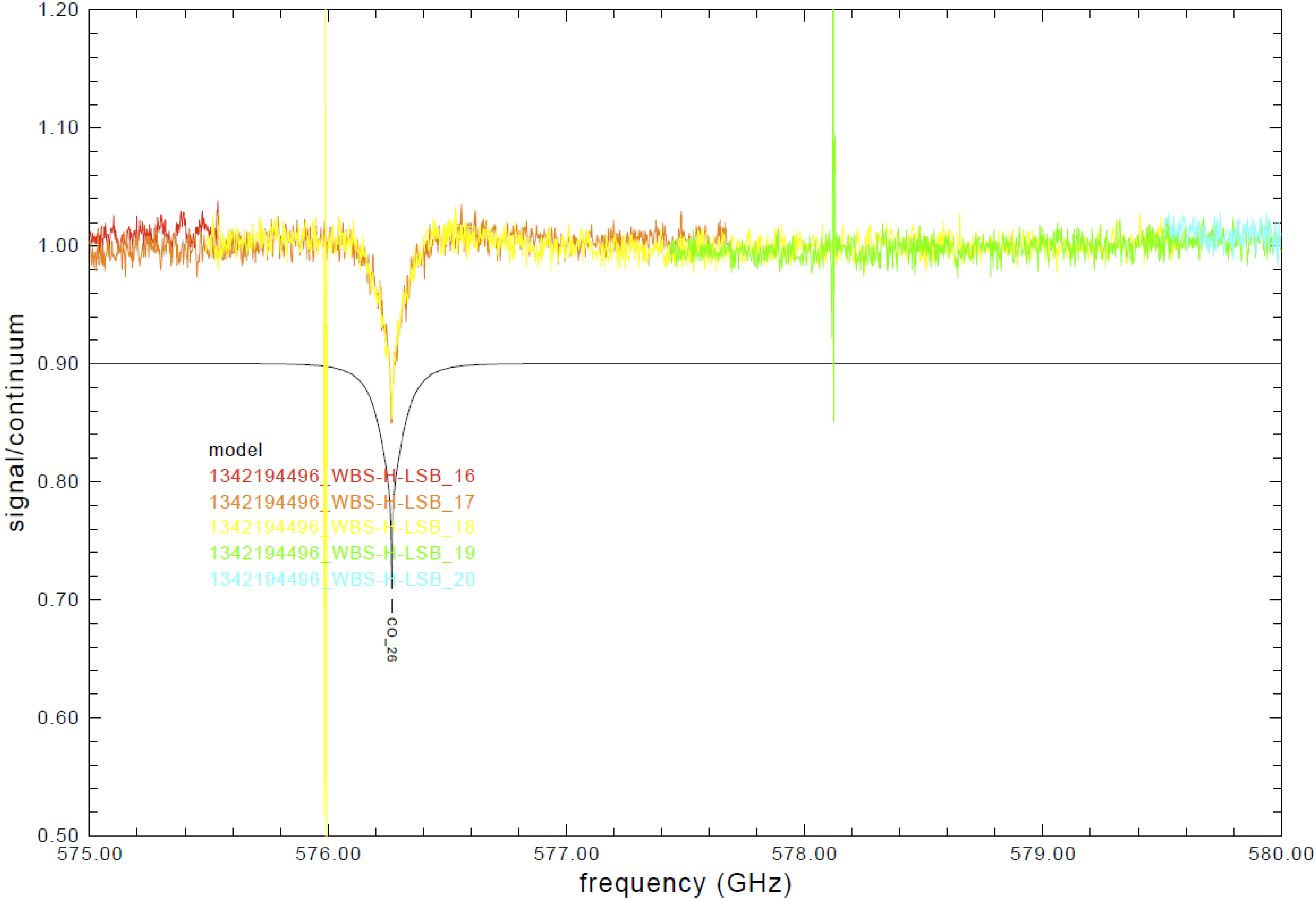


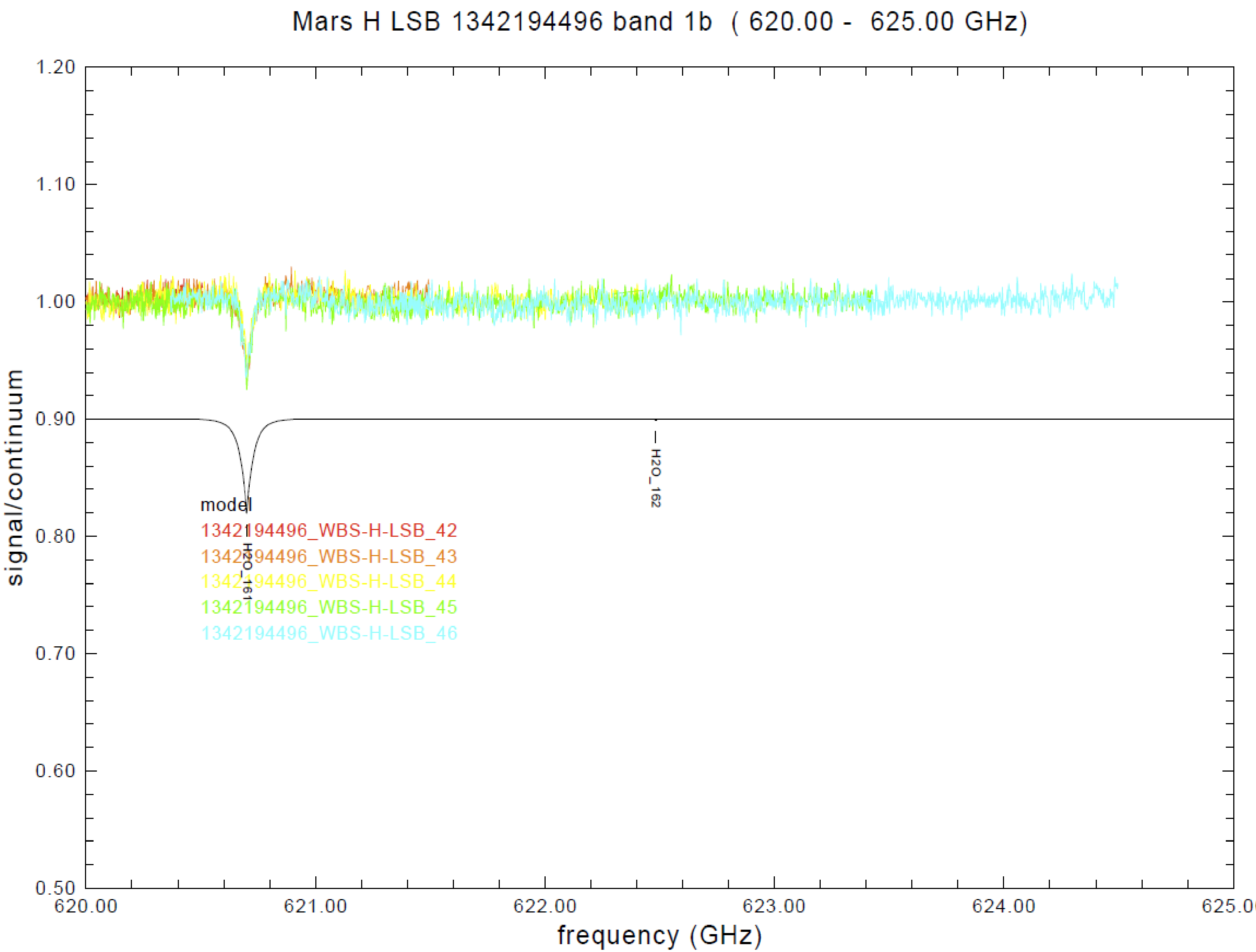
Mars V USB 1342194492 band 1a ( 545.00 - 550.00 GHz)
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
signal/continuum
545.00
546.00
547.00
548.00
549.00
550.00
frequency (GHz)
model
1342194492_WBS-V-USB_33
1342194492_WBS-V-USB_34
1342194492_WBS-V-USB_35
1342194492_WBS-V-USB_36
1342194492_WBS-V-USB_37
H2O_181
H2O_162
CO_28

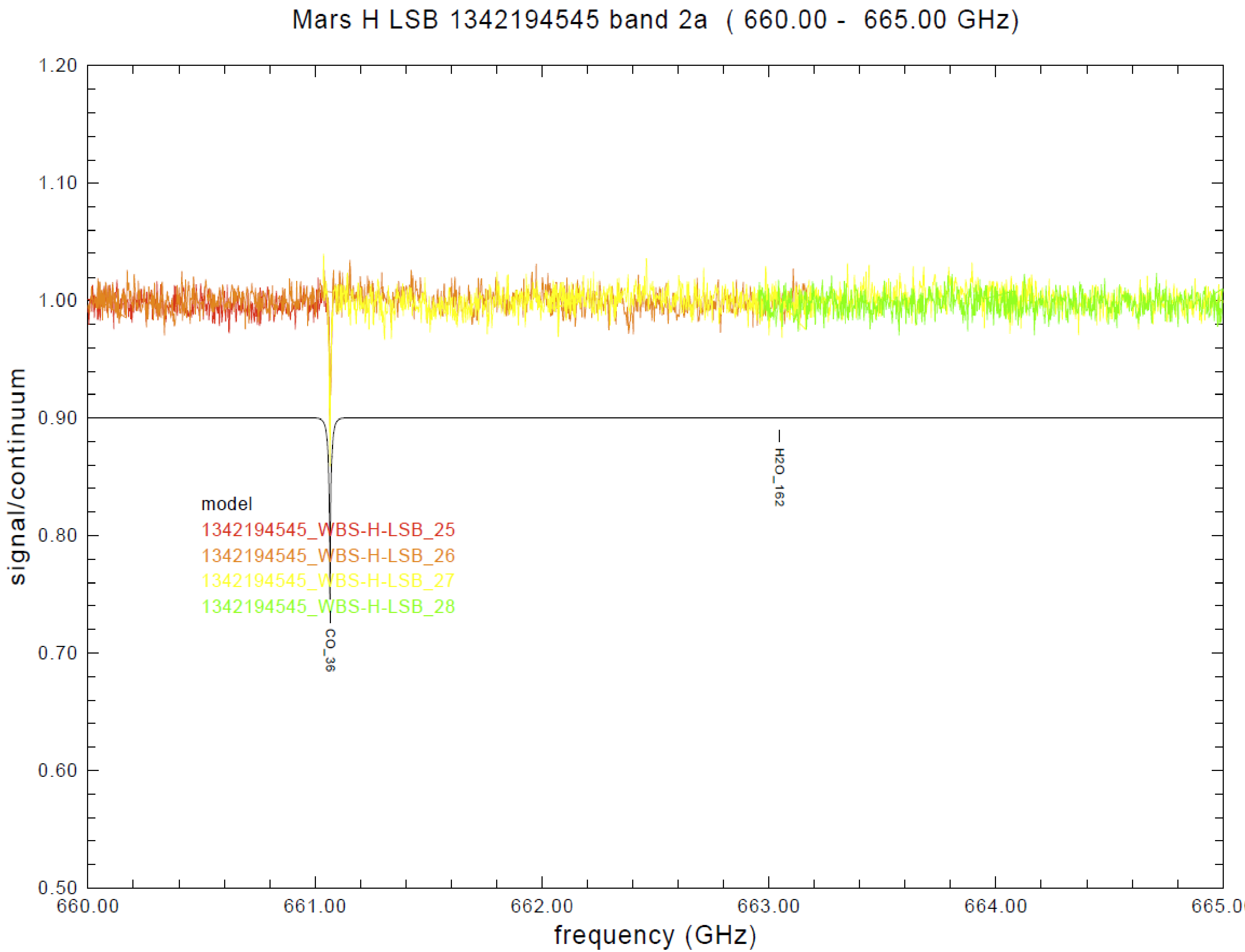


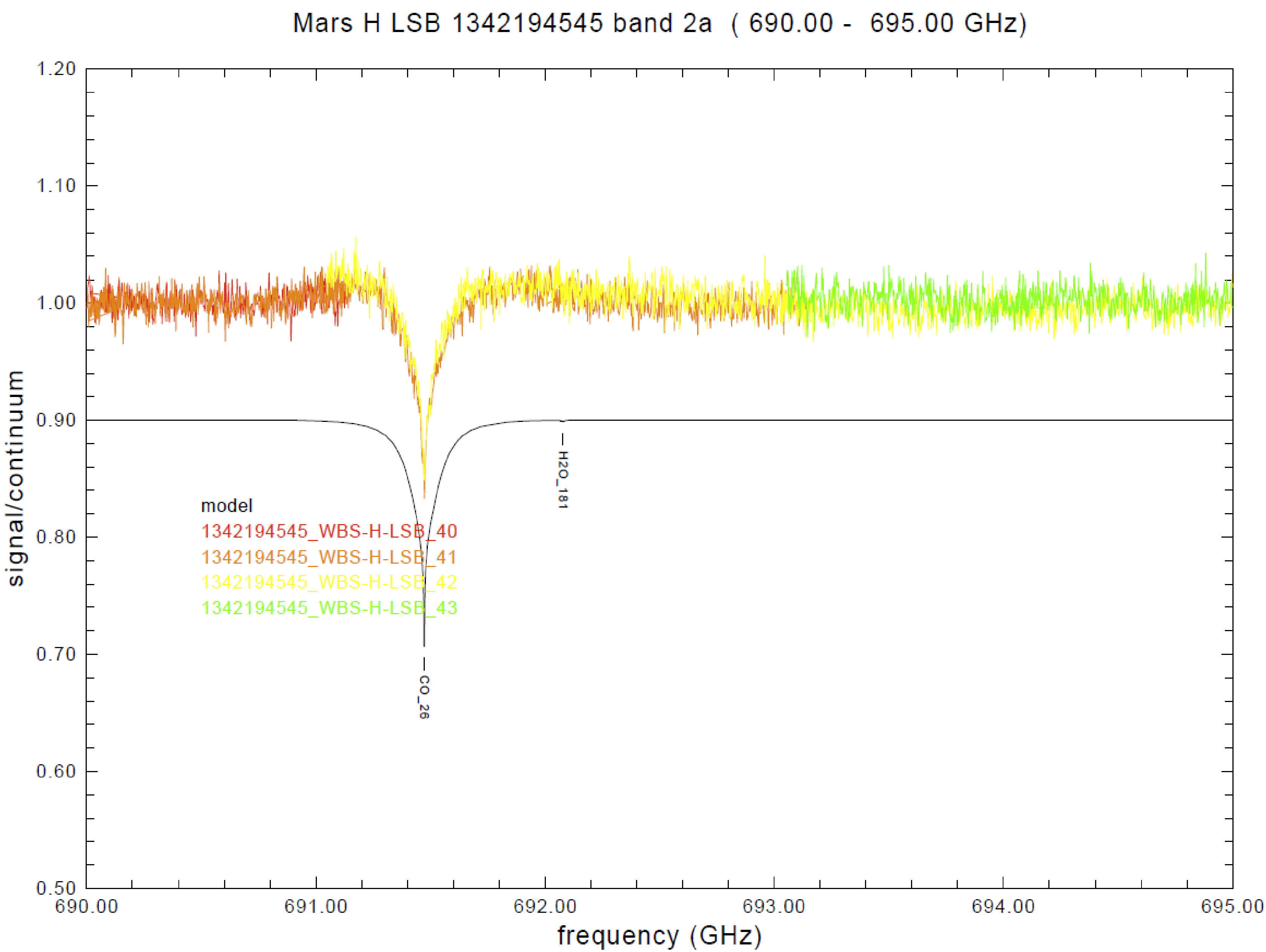
Mars H LSB 1342194496 band 1b ( 555.00 - 560.00 GHz)
signal/continuum
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
555.00
556.00
557.00
558.00
559.00
560.00
frequency (GHz)
model
1342194496_WBS-H-LSB_01
1342194496_WBS-H-LSB_02
1342194496_WBS-H-LSB_03
1342194496_WBS-H-LSB_04
1342194496_WBS-H-LSB_05
1342194496_WBS-H-LSB_06
H2O_161
H2O_162

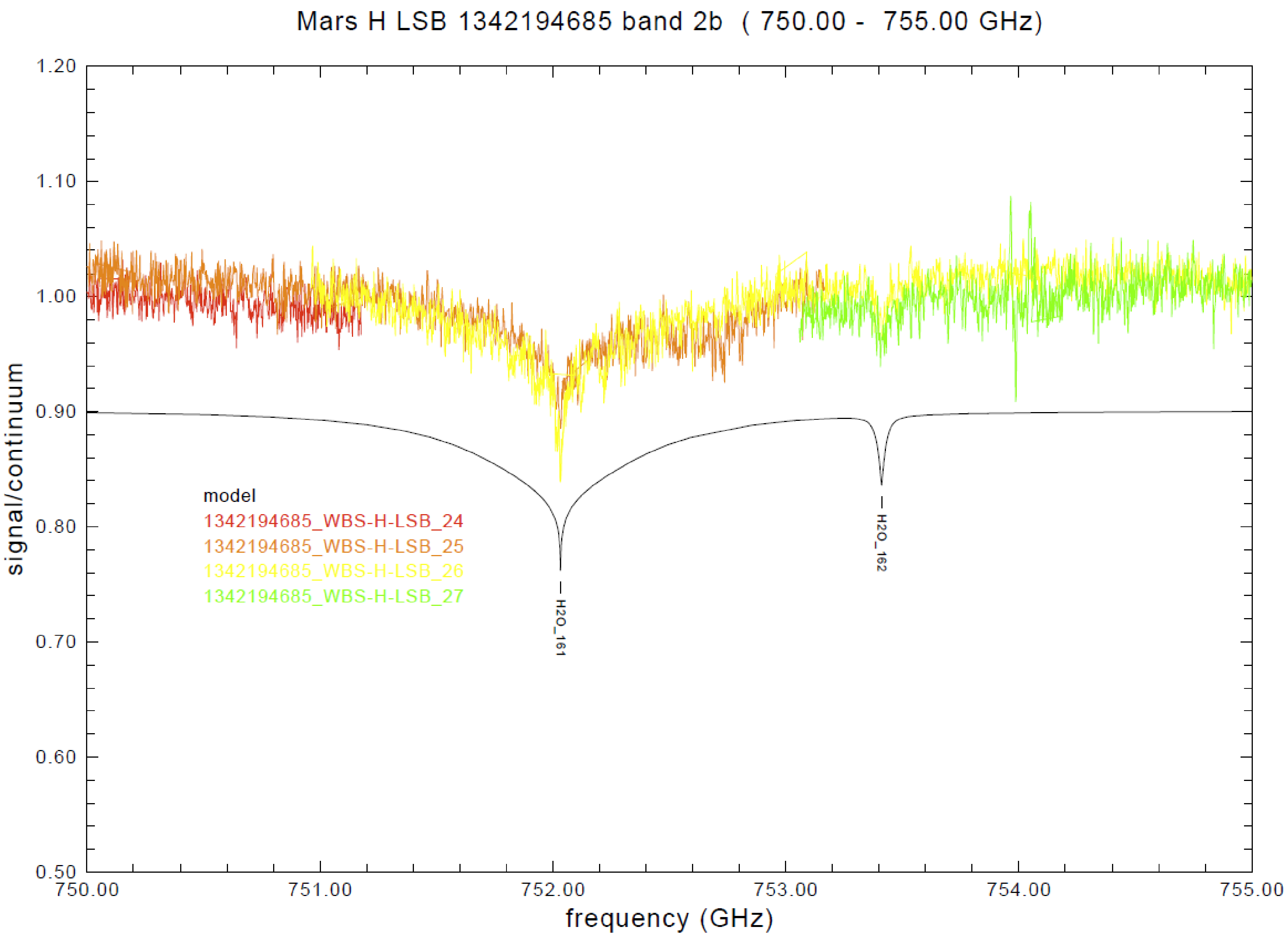
Mars H LSB 1342194496 band 1b ( 575.00 - 580.00 GHz)



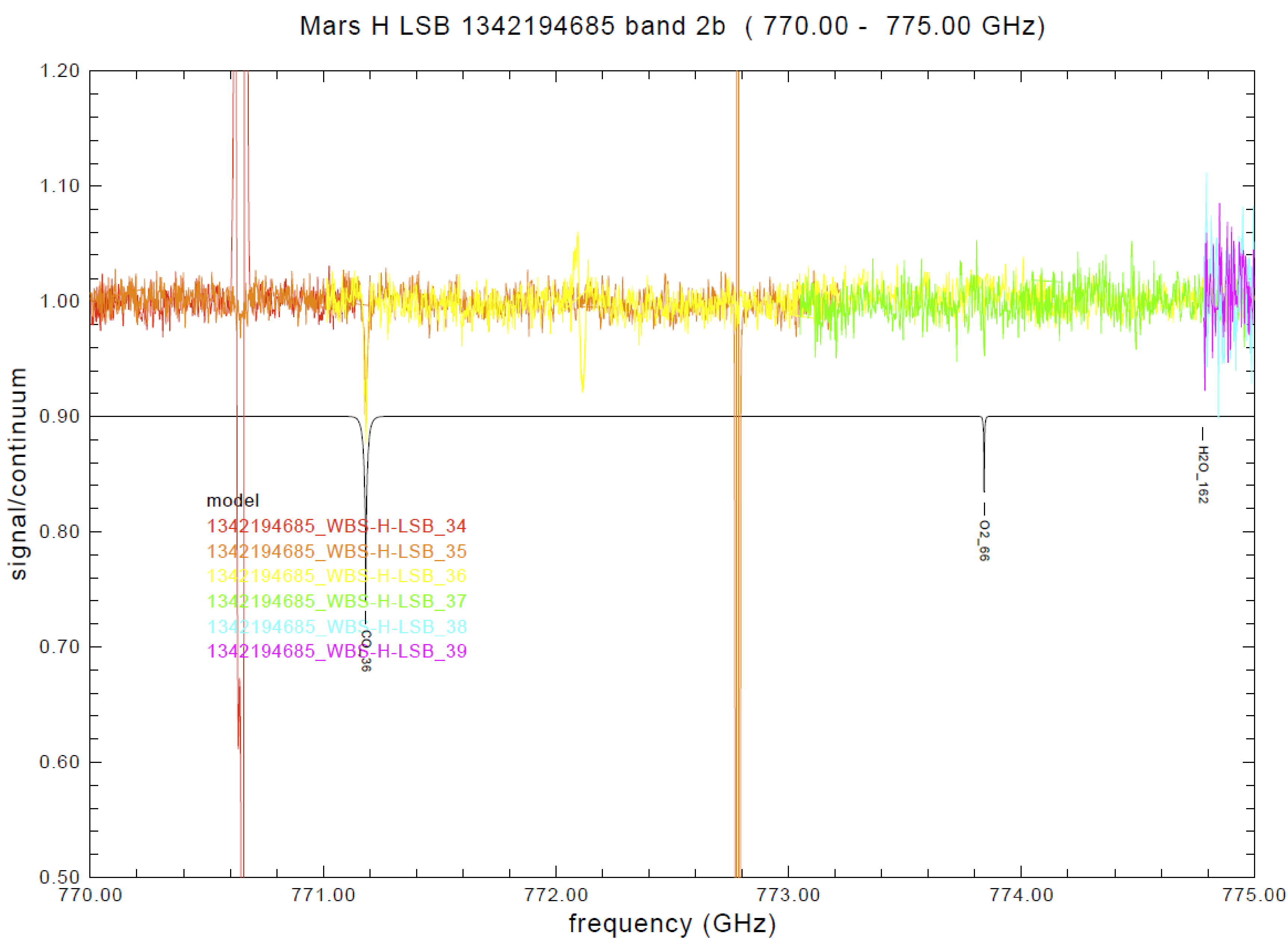

Mars H LSB 1342194496 band 1b ( 620.00 - 625.00 GHz)
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
signal/continuum
620.00
621.00
622.00
623.00
624.00
625.00
frequency (GHz)
H2O_161
H2O_162
model
1342194496_WBS-H-LSB_42
1342194496_WBS-H-LSB_43
1342194496_WBS-H-LSB_44
1342194496_WBS-H-LSB_45
1342194496_WBS-H-LSB_46

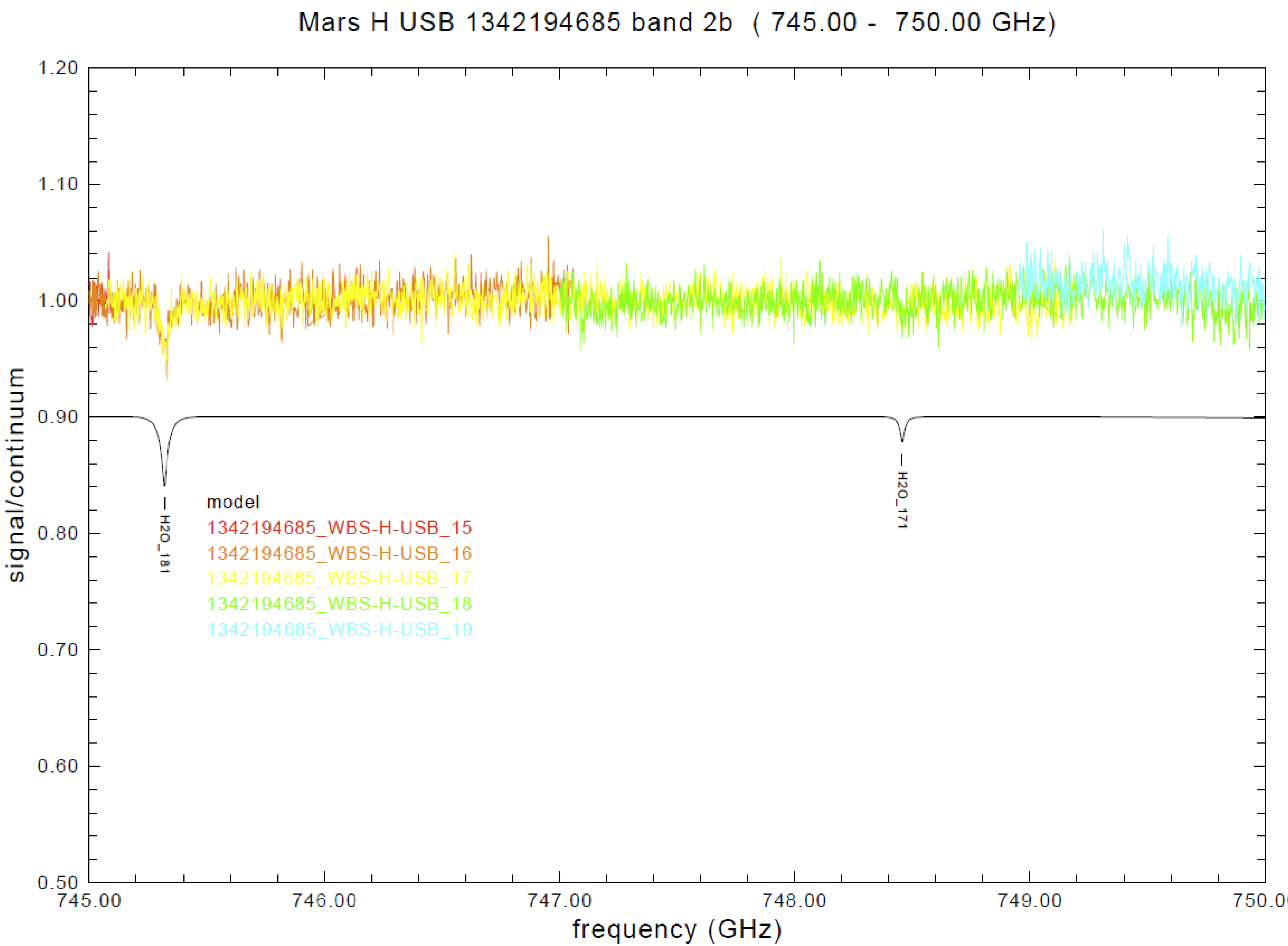

Mars H LSB 1342194545 band 2a ( 660.00 - 665.00 GHz)
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
signal/continuum
660.00
661.00
662.00
663.00
664.00
665.00
frequency (GHz)
model
1342194545_WBS-H-LSB_25
1342194545_WBS-H-LSB_26
1342194545_WBS-H-LSB_27
1342194545_WBS-H-LSB_28
CO_36
H2O_162


Mars H LSB 1342194545 band 2a ( 690.00 - 695.00 GHz)
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
signal/continuum
690.00
691.00
692.00
693.00
694.00
695.00
frequency (GHz)
model
1342194545_WBS-H-LSB_40
1342194545_WBS-H-LSB_41
1342194545_WBS-H-LSB_42
1342194545_WBS-H-LSB_43
CO_26
H2O_181

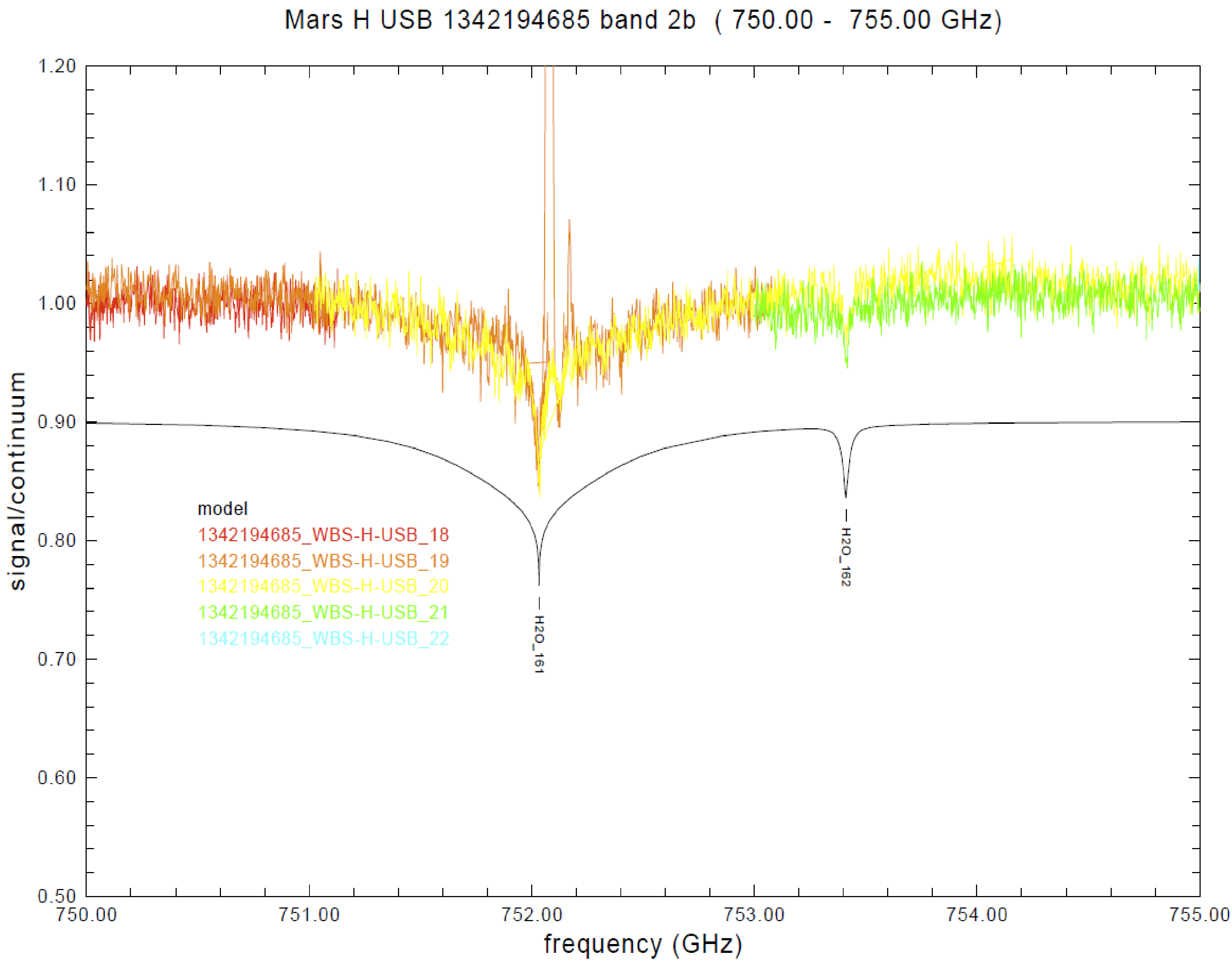


Mars H LSB 1342194685 band 2b ( 750.00 - 755.00 GHz)
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
signal/continuum
model
1342194685_WBS-H-LSB_24
1342194685_WBS-H-LSB_25
1342194685_WBS-H-LSB_26
1342194685_WBS-H-LSB_27
H2O_161
H2O_162
750.00
751.00
752.00
753.00
754.00
755.00
frequency (GHz)

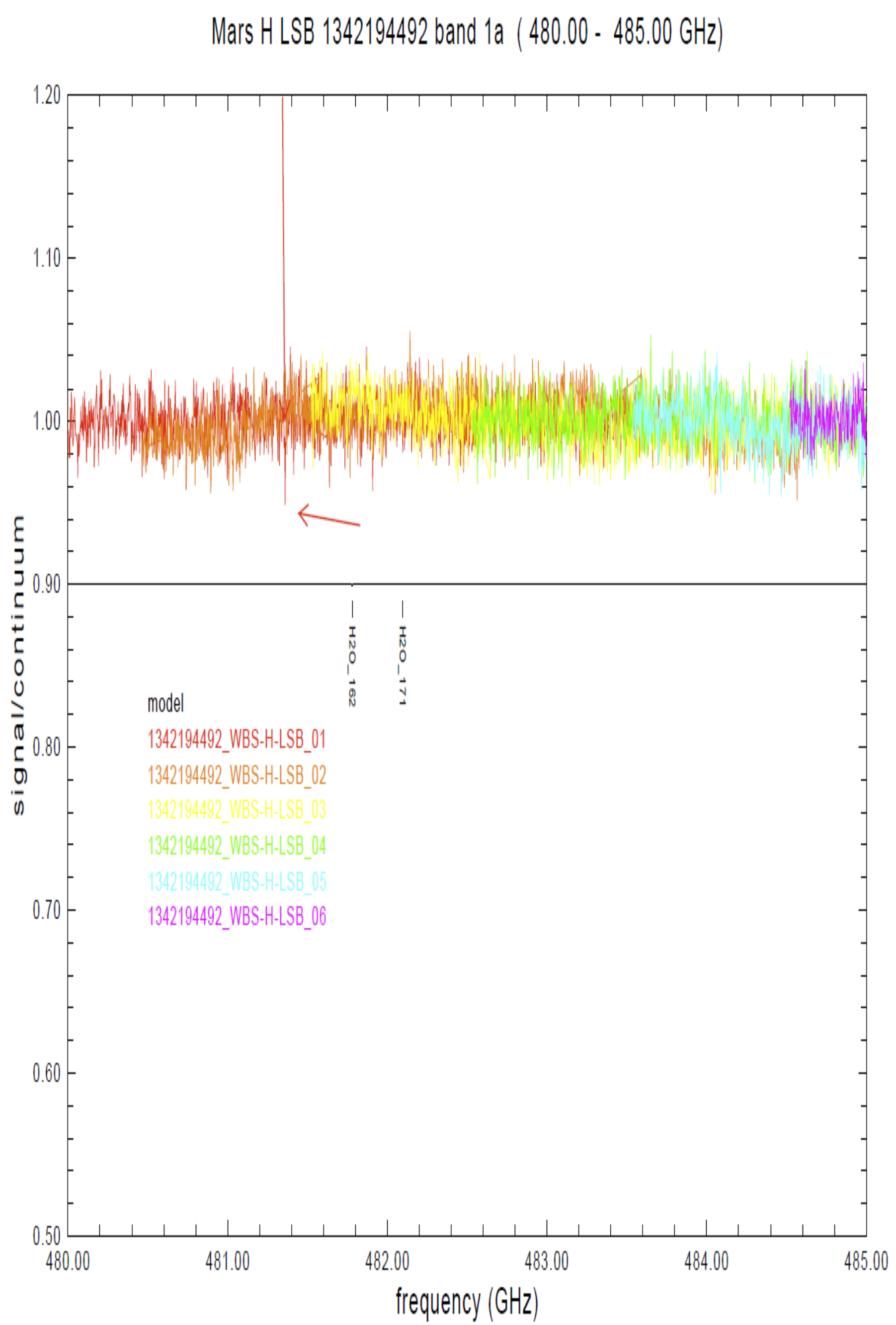

Mars H LSB 1342194685 band 2b ( 770.00 - 775.00 GHz)
signal/continuum
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
770.00
771.00
772.00
773.00
774.00
775.00
frequency (GHz)
model
1342194685_WBS-H-LSB_34
1342194685_WBS-H-LSB_35
1342194685_WBS-H-LSB_36
1342194685_WBS-H-LSB_37
1342194685_WBS-H-LSB_38
1342194685_WBS-H-LSB_39
CO_36
O2_66
H2O_162

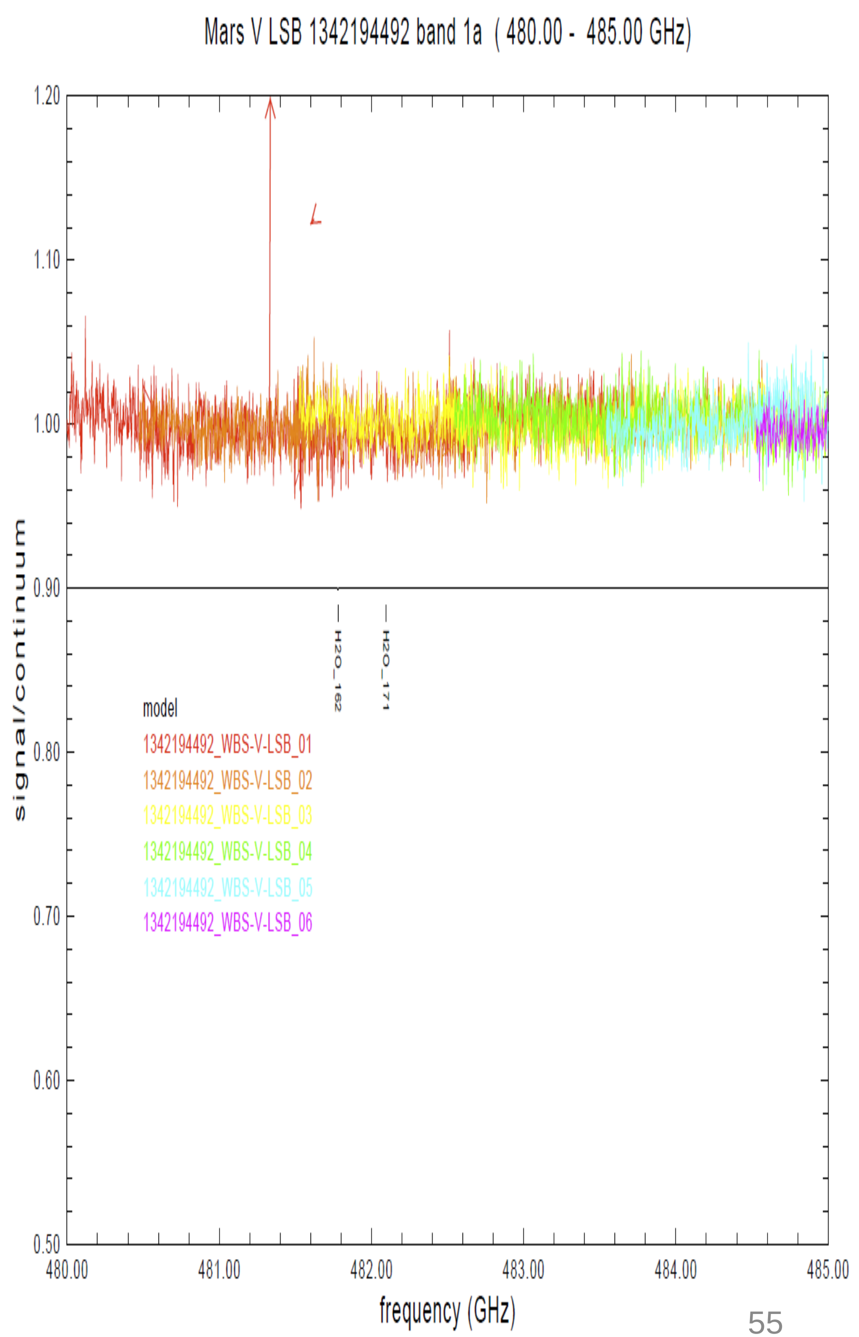


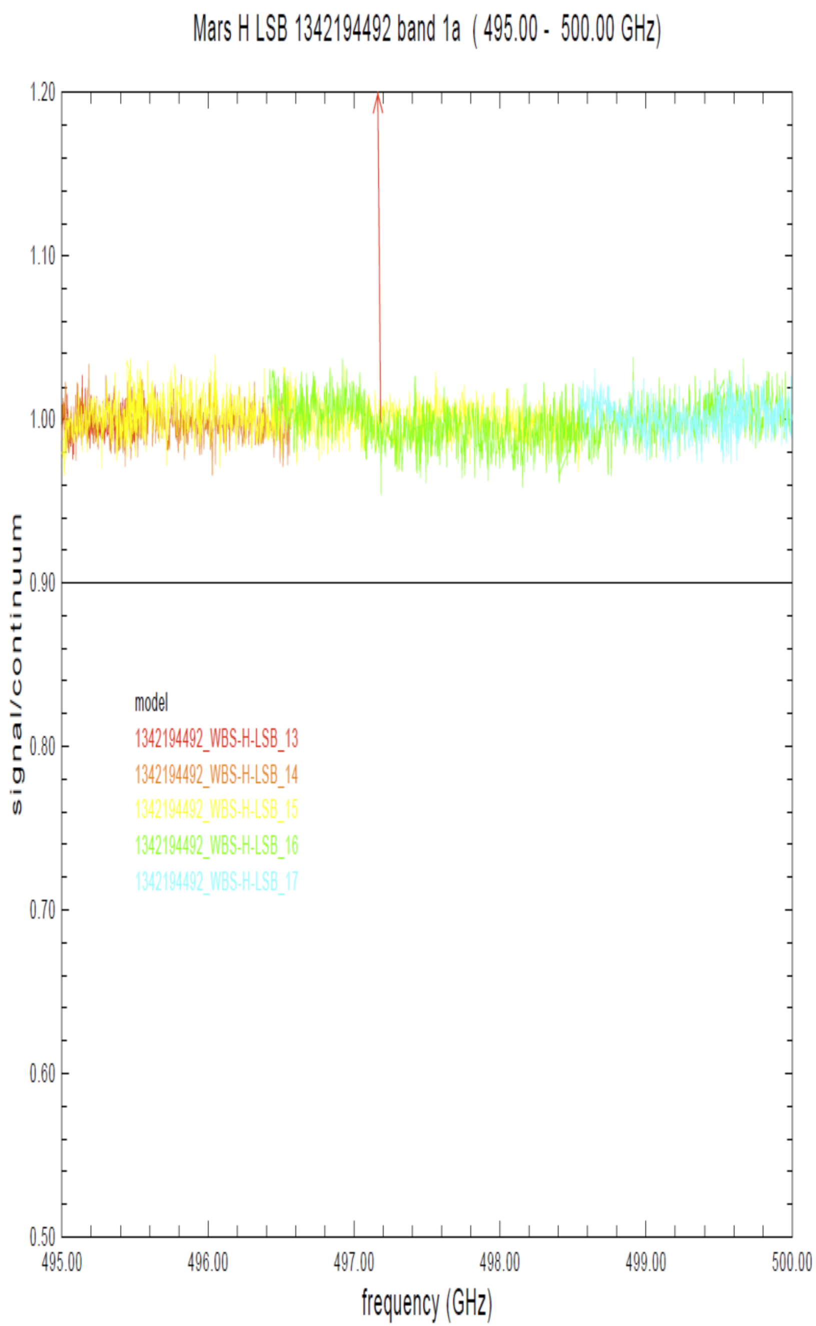
Mars H USB 1342194685 band 2b ( 745.00 - 750.00 GHz)
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
signal/continuum
745.00
746.00
747.00
748.00
749.00
750.00
frequency (GHz)
H2O_181
H2O_171
model
1342194685_WBS-H-USB_15
1342194685_WBS-H-USB_16
1342194685_WBS-H-USB_17
1342194685_WBS-H-USB_18
1342194685_WBS-H-USB_19

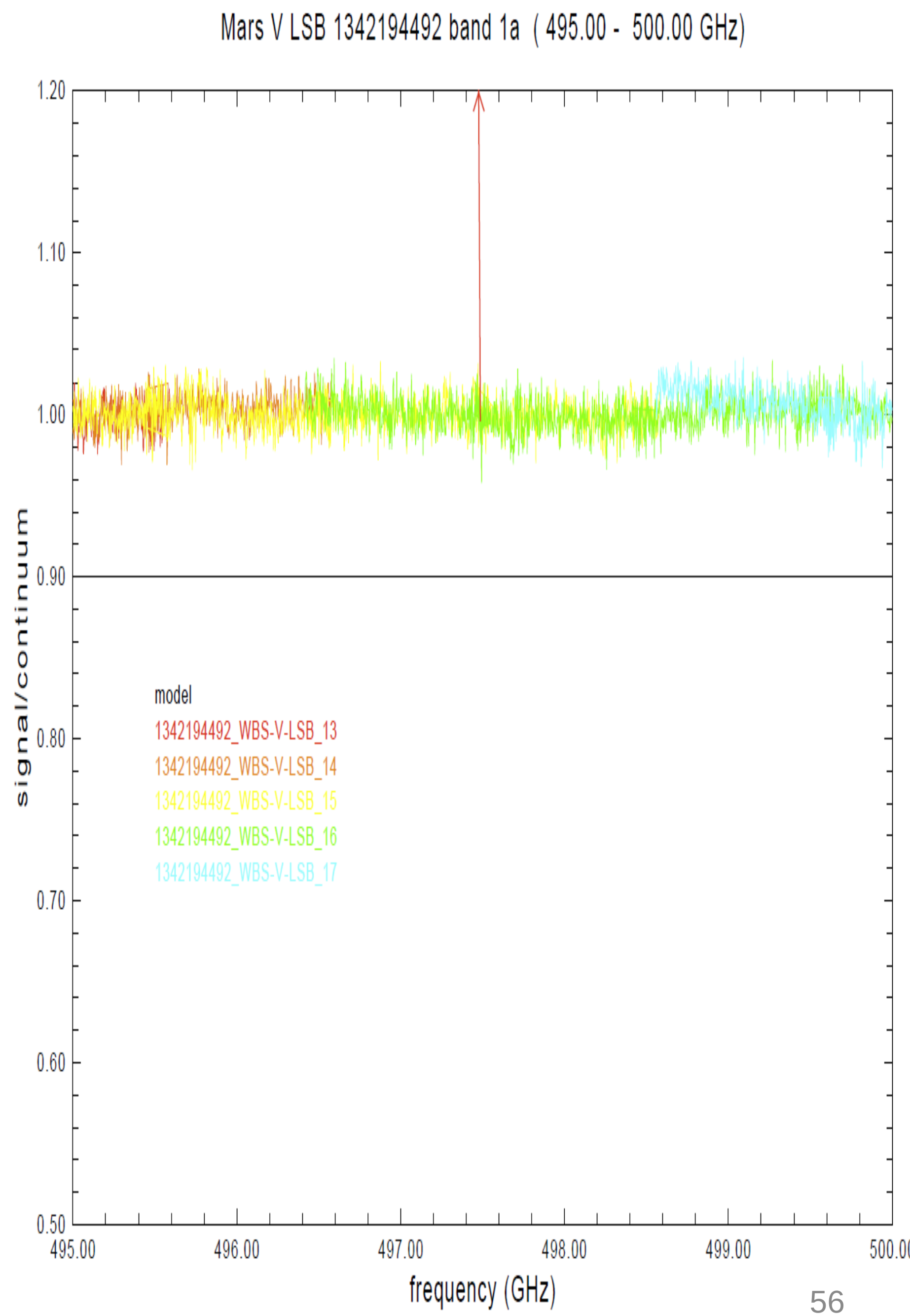


Mars H USB 1342194685 band 2b ( 750.00 - 755.00 GHz)
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
signal/continuum
750.00
751.00
752.00
753.00
754.00
755.00
frequency (GHz)
model
1342194685_WBS-H-USB_18
1342194685_WBS-H-USB_19
1342194685_WBS-H-USB_20
1342194685_WBS-H-USB_21
1342194685_WBS-H-USB_22
H2O_161
H2O_162


Mars H LSB 1342194492 band 1a ( 480.00 - 485.00 GHz)
signal/continuum
frequency (GHz)
H2O_162
H2O_171
model
1342194492_WBS-H-LSB_01
1342194492_WBS-H-LSB_02
1342194492_WBS-H-LSB_03
1342194492_WBS-H-LSB_04
1342194492_WBS-H-LSB_05
1342194492_WBS-H-LSB_06


Mars V LSB 1342194492 band 1a ( 480.00 - 485.00 GHz)
signal/continuum
frequency (GHz)
H2O_162
H2O_171
model
1342194492_WBS-V-LSB_01
1342194492_WBS-V-LSB_02
1342194492_WBS-V-LSB_03
1342194492_WBS-V-LSB_04
1342194492_WBS-V-LSB_05
1342194492_WBS-V-LSB_06


Mars H LSB 1342194492 band 1a ( 495.00 - 500.00 GHz)
signal/continuum
frequency (GHz)
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
495.00
496.00
497.00
498.00
499.00
500.00
model
1342194492_WBS-H-LSB_13
1342194492_WBS-H-LSB_14
1342194492_WBS-H-LSB_15
1342194492_WBS-H-LSB_16
1342194492_WBS-H-LSB_17


Mars V LSB 1342194492 band 1a ( 495.00 - 500.00 GHz)
signal/continuum
frequency (GHz)
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
495.00
496.00
497.00
498.00
499.00
500.00
model
1342194492_WBS-V-LSB_13
1342194492_WBS-V-LSB_14
1342194492_WBS-V-LSB_15
1342194492_WBS-V-LSB_16
1342194492_WBS-V-LSB_17

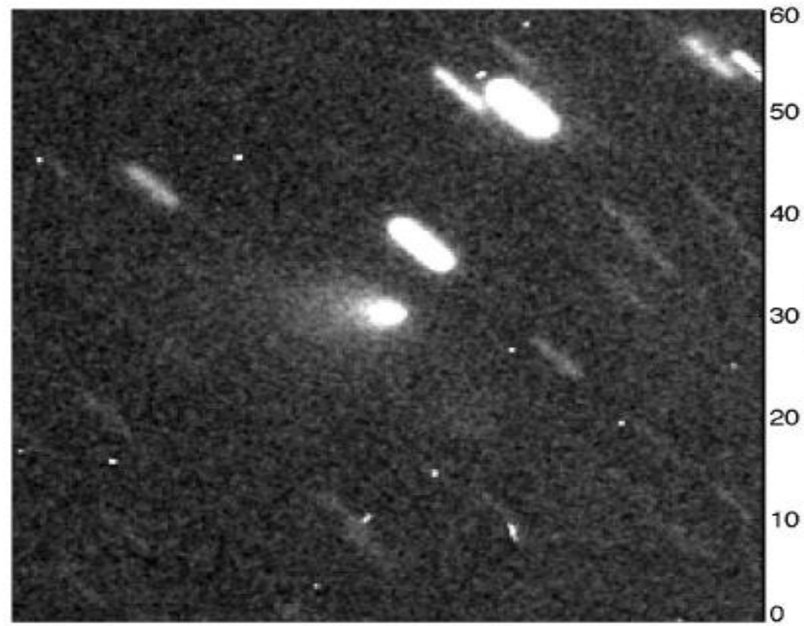
# MHIFI

- High SNR (100-300) observations of $O_2$
- Mapping observations at high frequencies and/or during opposition or in general times of large apparent diameters of Mars
- MHIFI line surveys: at least one order of magnitude better SNRs

# Main belt comets

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

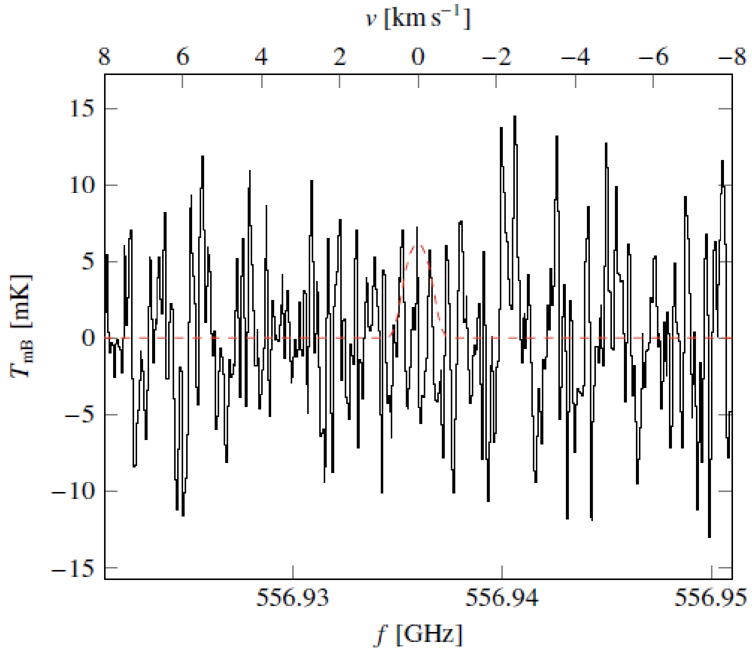
176P/LINEAR

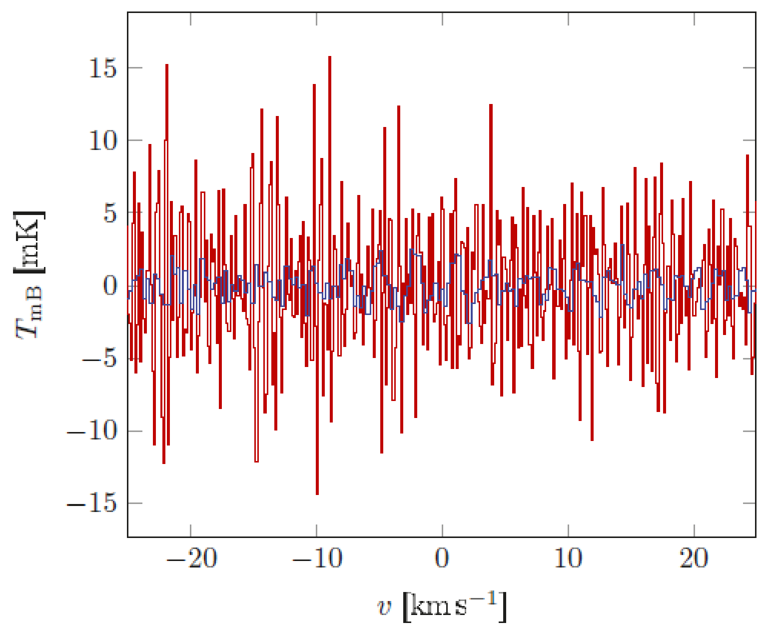



P/2012 T1 (Panstarrs)

# Production rates from HIFI obs: < 2 kg/s

# **MHIFI: < 0.2 kg/s**

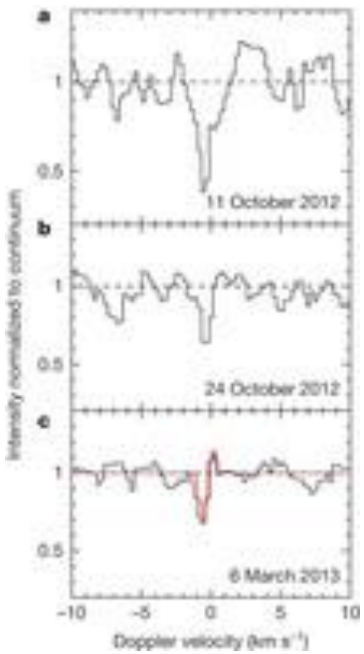


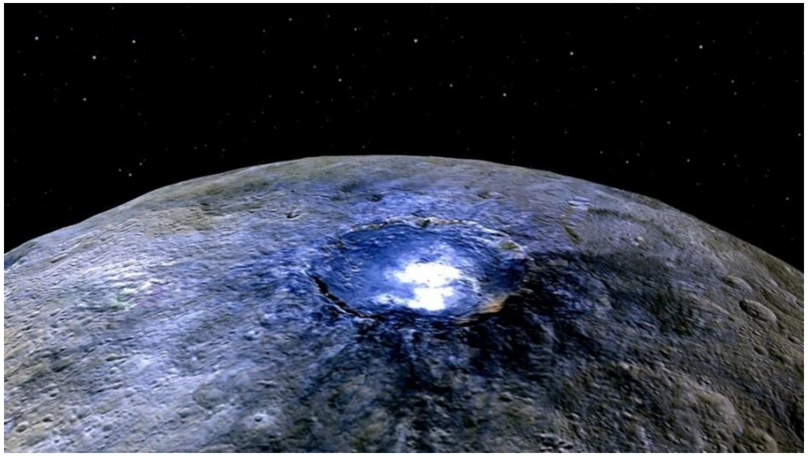




***de Val-Borro et al, A&A 2012***

***O`Rourke et. al, APJL 2013***

# HIFI detected water in CERES!



Production rate about 6 kg/s

**MHIFI: 0.6 kg/s**

*Küppers et al., Nature 2014*

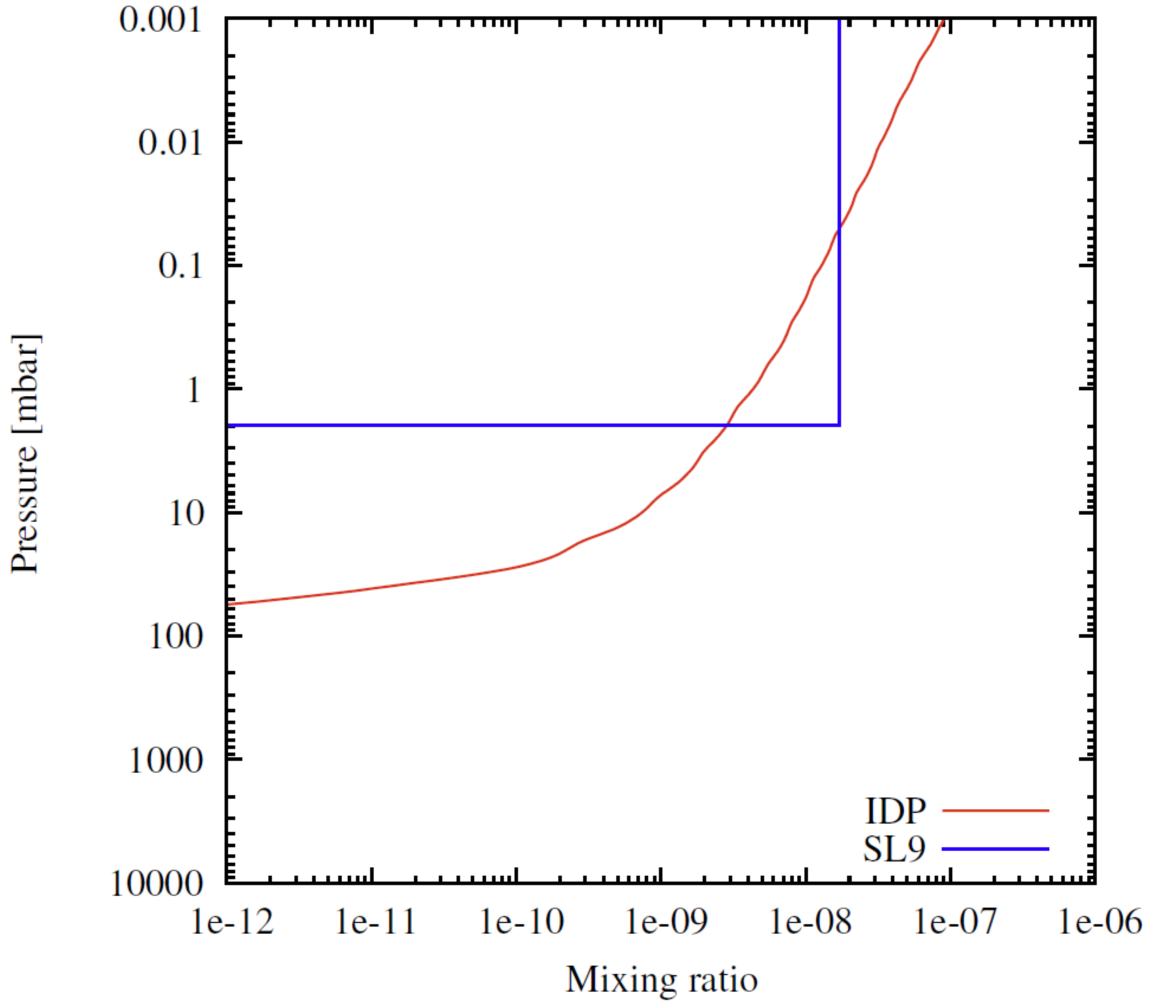
# ALMA

- Recently a number of line detections around asteroids and Galilean satellites were reported on conferences (e.g. AOGS 2019).
- The results are mostly not published yet, but are rather amazing, because in any case the detections represent very highly excited lines, e.g. $O_3$ $32_{3,29} - 32_{3,30}$ or J=26-25 NaCl and J= 44-43 KCl in the atmosphere of Ceres and similar highly excited lines of $SO_2$, $SO^{18}O$, $SO^{17}O$, $^{33}SO_2$, $^{34}SO_2$, $S^{18}O$, NaCl in the atmosphere of Europa. Proposals detecting highly excited water lines were successful (e.g. Callisto). The appearance of these lines is not compatible with present state-of-the art non-lte radiative transfer codes.

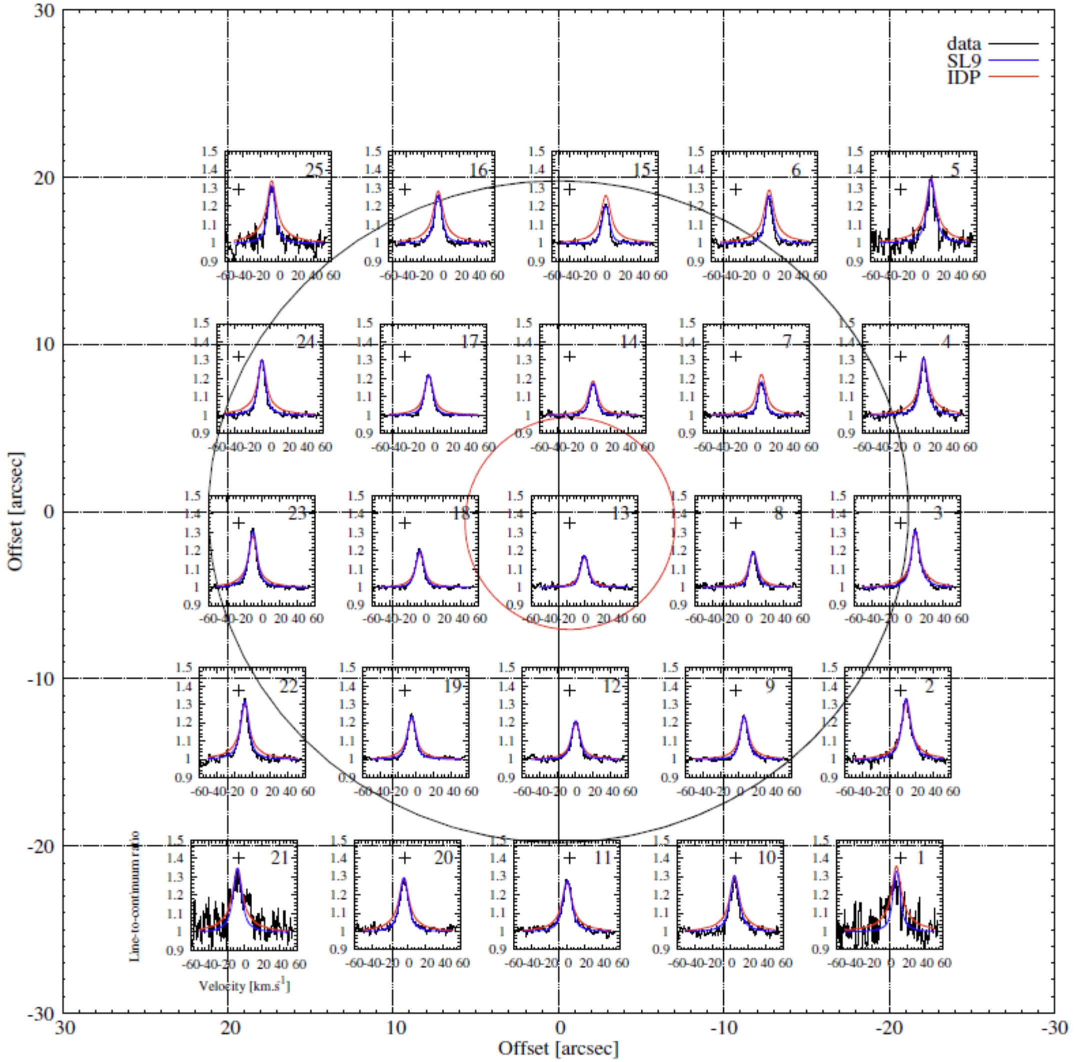
# Source of water in Jupiter's stratosphere?

- Stratospheric water discovered by ISO
- Must be of external origin, due to tropopause cold trap
- Three potential sources were identified:
  - Interplanetary dust particles (IDP)
  - Moons and rings
  - Cometary impacts (e.g. SL9)
- Leave different fingerprints that can be read by measuring the 3-d water distribution

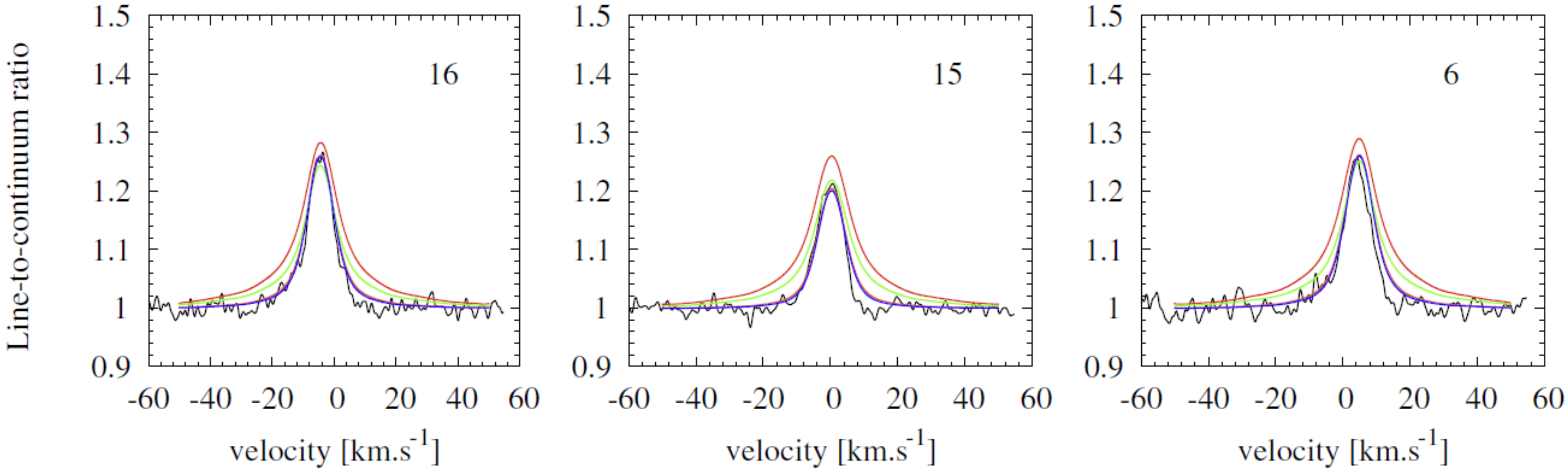
# Example: IDP vs SL9



# HIFI (1670 GHz) mapping observations

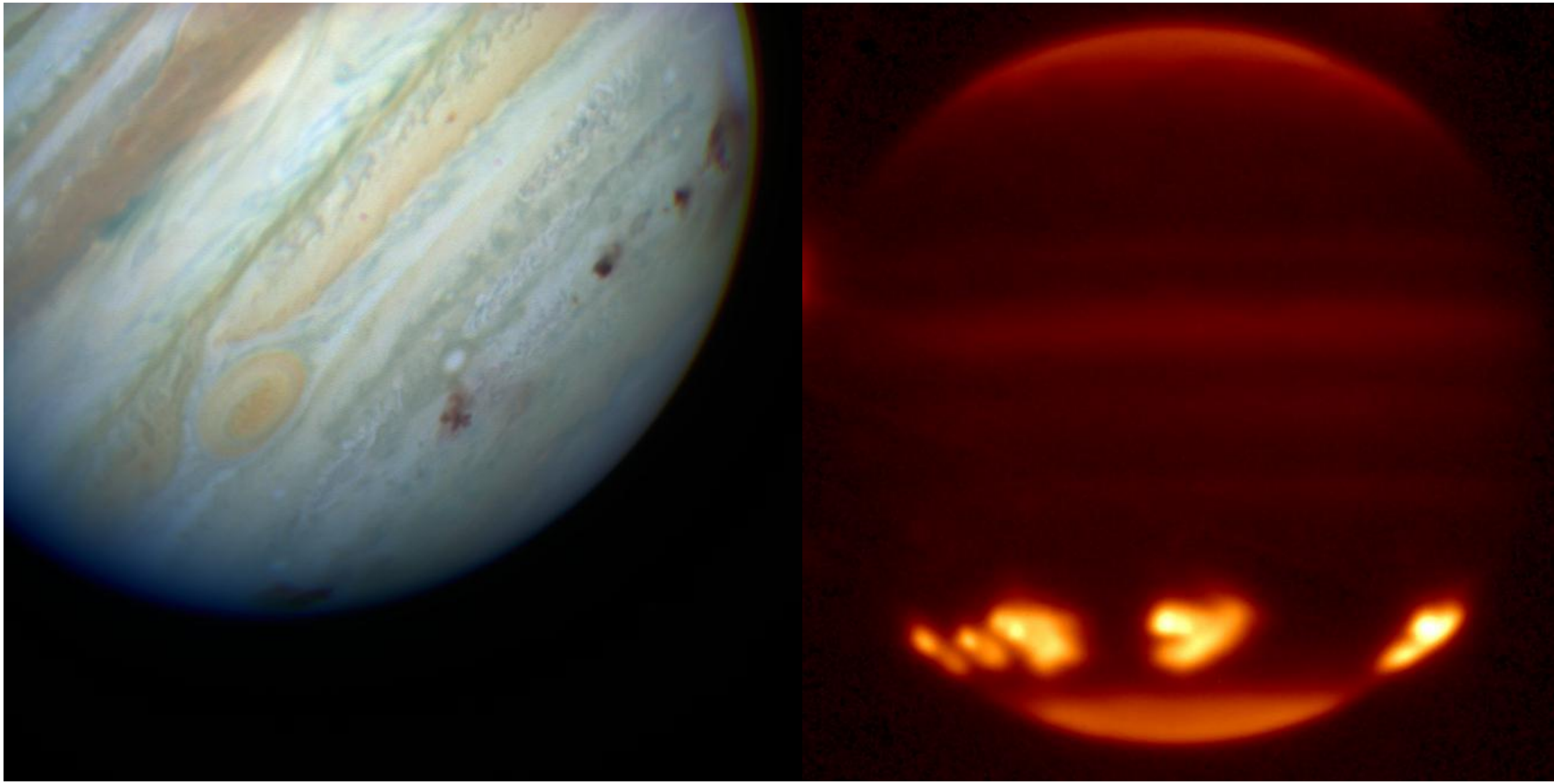


# Simulated spectra of IDP and SL9 vertical profiles



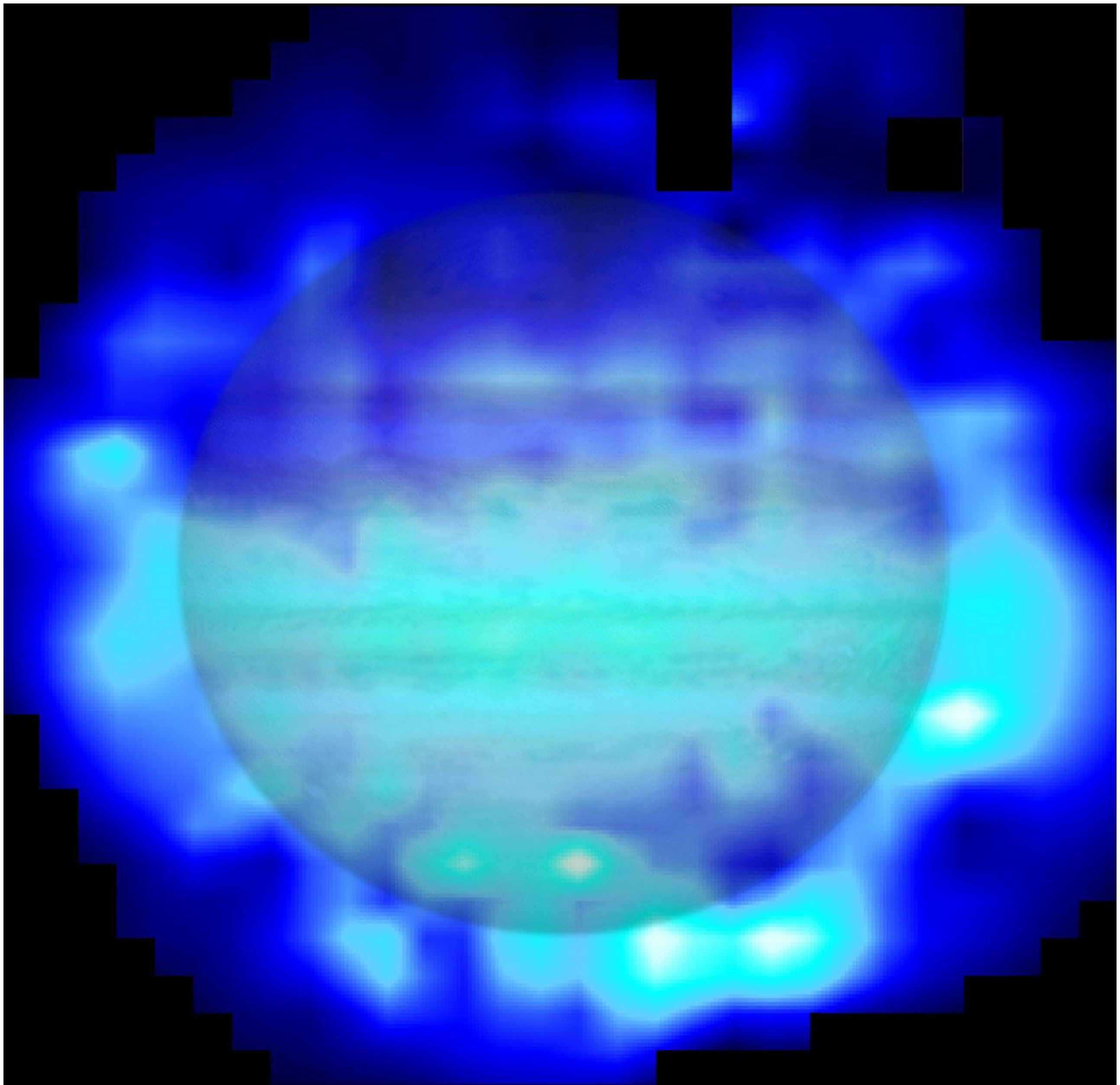

IDP profiles result in too broad lines
SLP profiles fit very good

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



Credits: NASA-HST/ U. Hawaii

# Water distribution observed by PACS



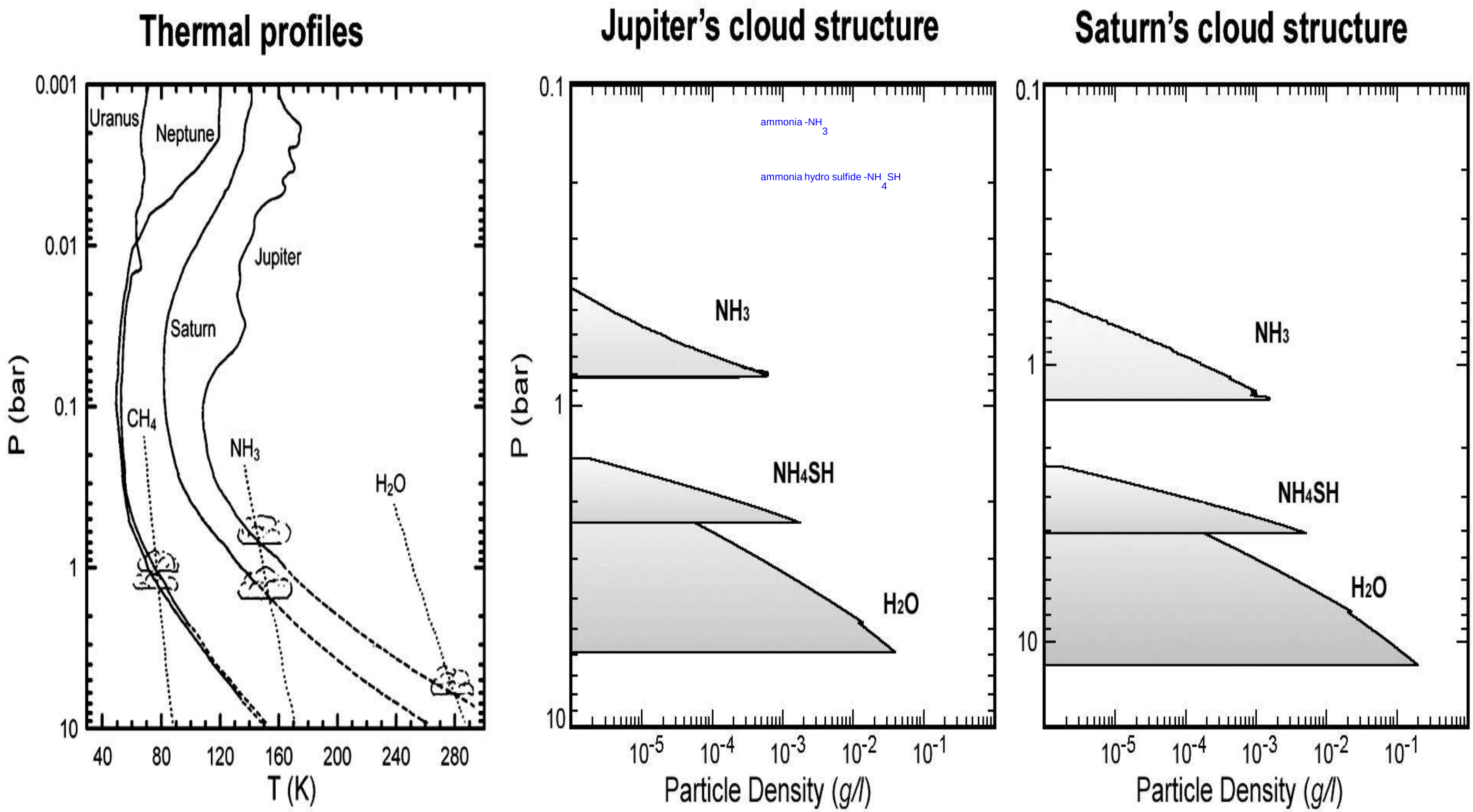
# SL9 impact main source of stratospheric water in Jupiter

- 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*

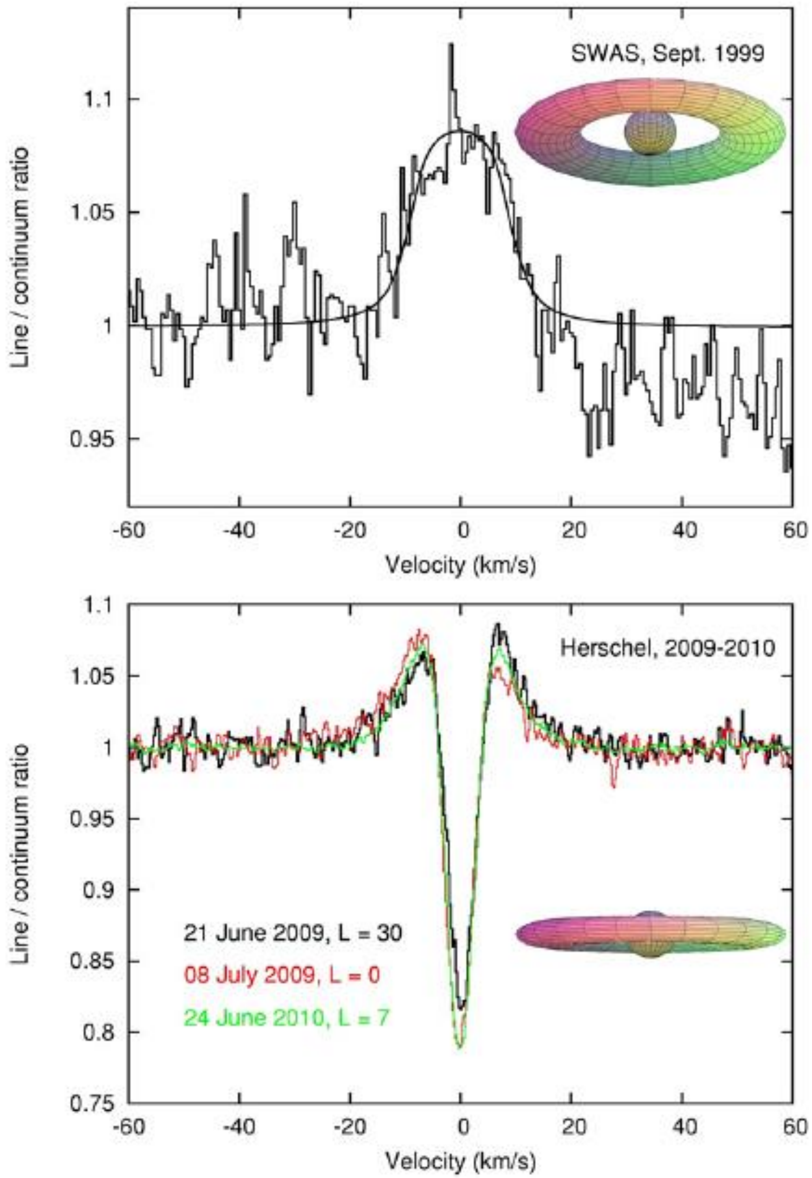
# Jupiter Millimetron

- Coherent maps (vertical profiles) with at least 10 times more pixels and/or maps of different water lines (sideband separation mixers desired)
- Monitoring of horizontal and vertical water distribution
- Water isotopologues

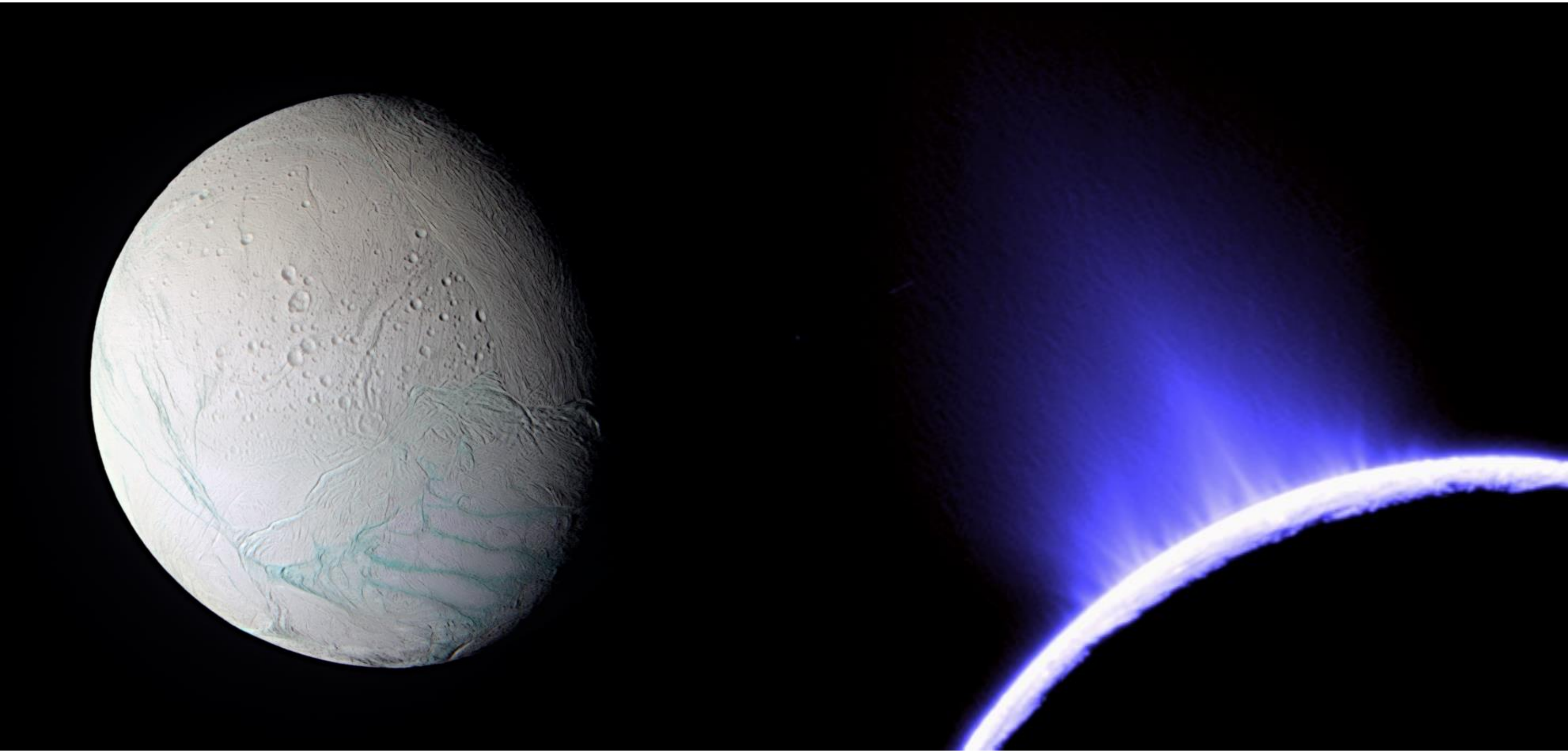


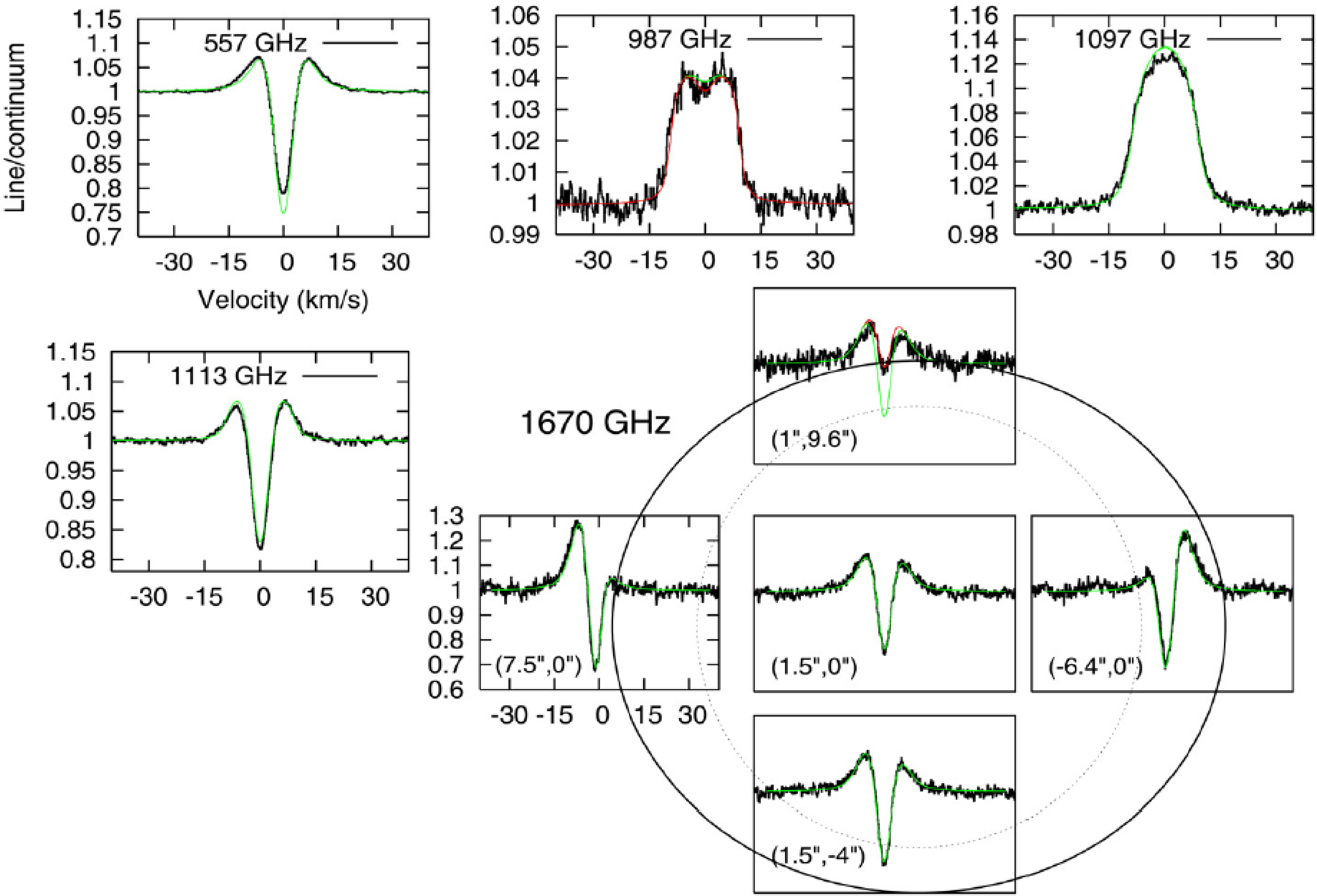

Vertical temperature profiles in the visible part of the four outer planets. The main composition and altitude of the main clouds are indicated. Center and Right: Altitude location and densities of the main clouds in Jupiter and Saturn as calculated from thermochemical models. (Sanchez-Lavega et al. 2004).

# Unexpected detection at 557 GHz pointing to Saturn



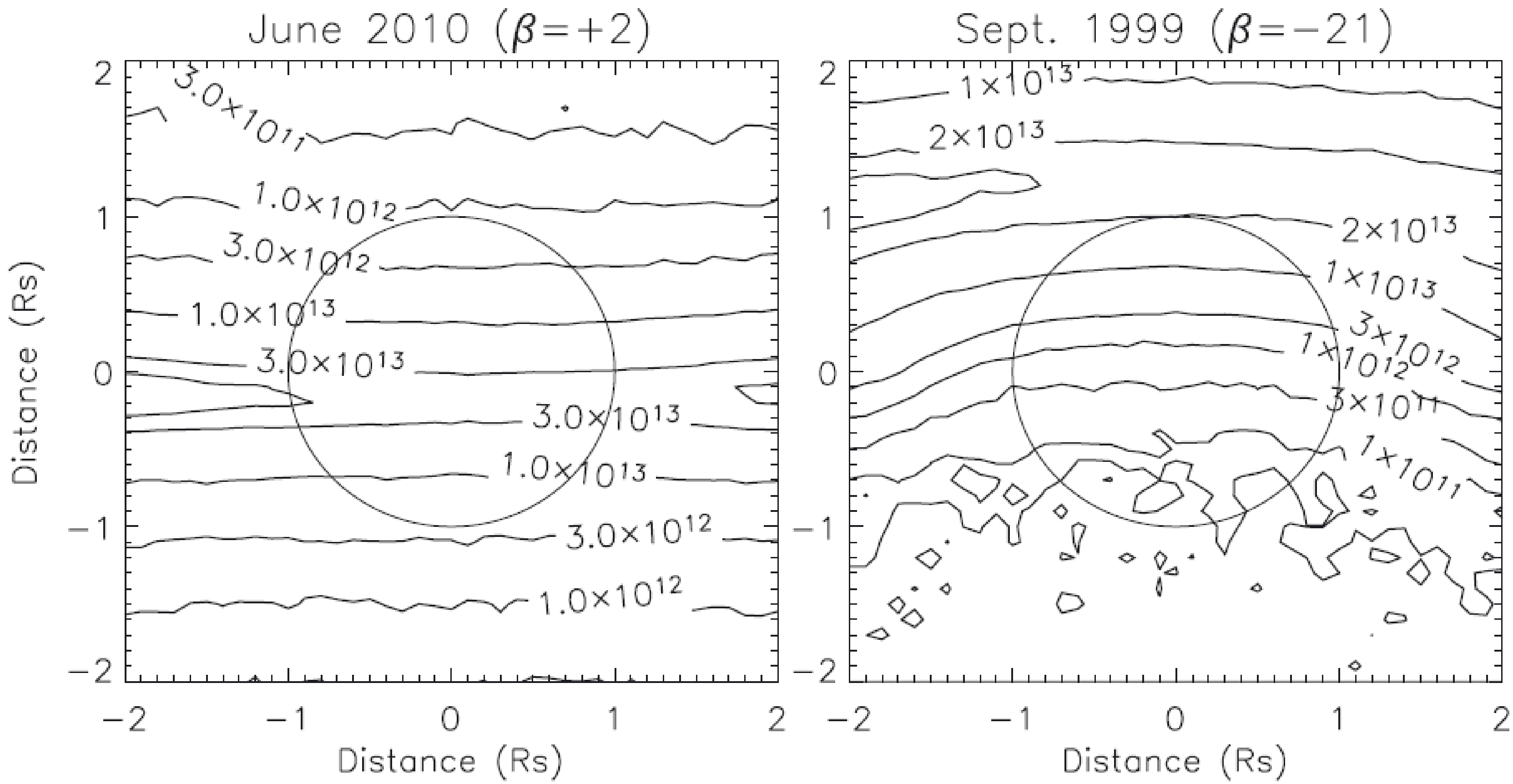
# Enceladus plumes





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

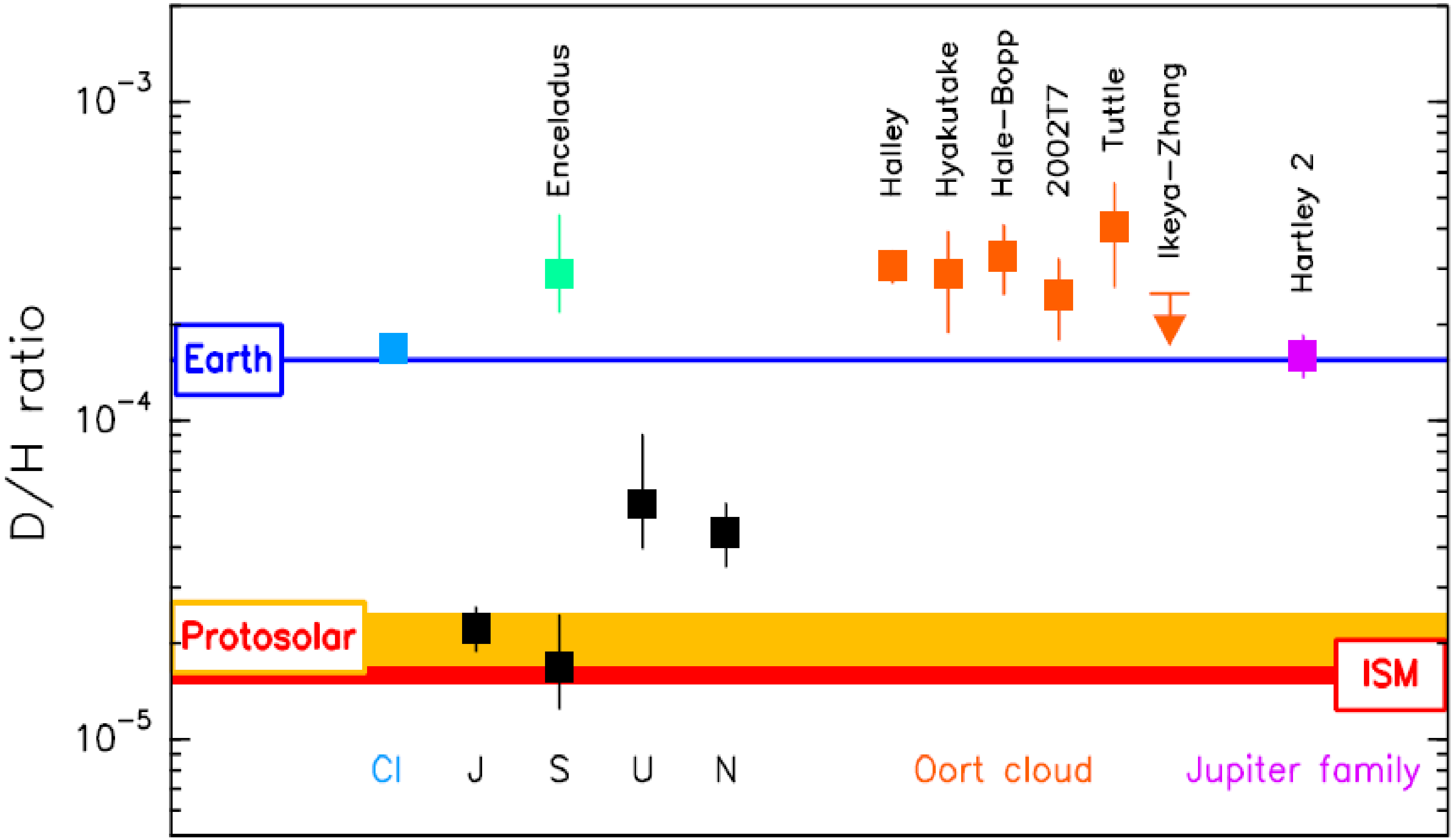
- Extension about 10 Saturn radii ($R_s$)
- Highest density around a distance of 4 $R_s$
- Thickness about 50000 km
- About 3 % of the water produced by Enceladus rains into the upper atmosphere of Saturn
- Enceladus is the source of stratospheric water in Saturn

*Hartogh et al, A&A 2011*

# MHIFI: monitoring water torus

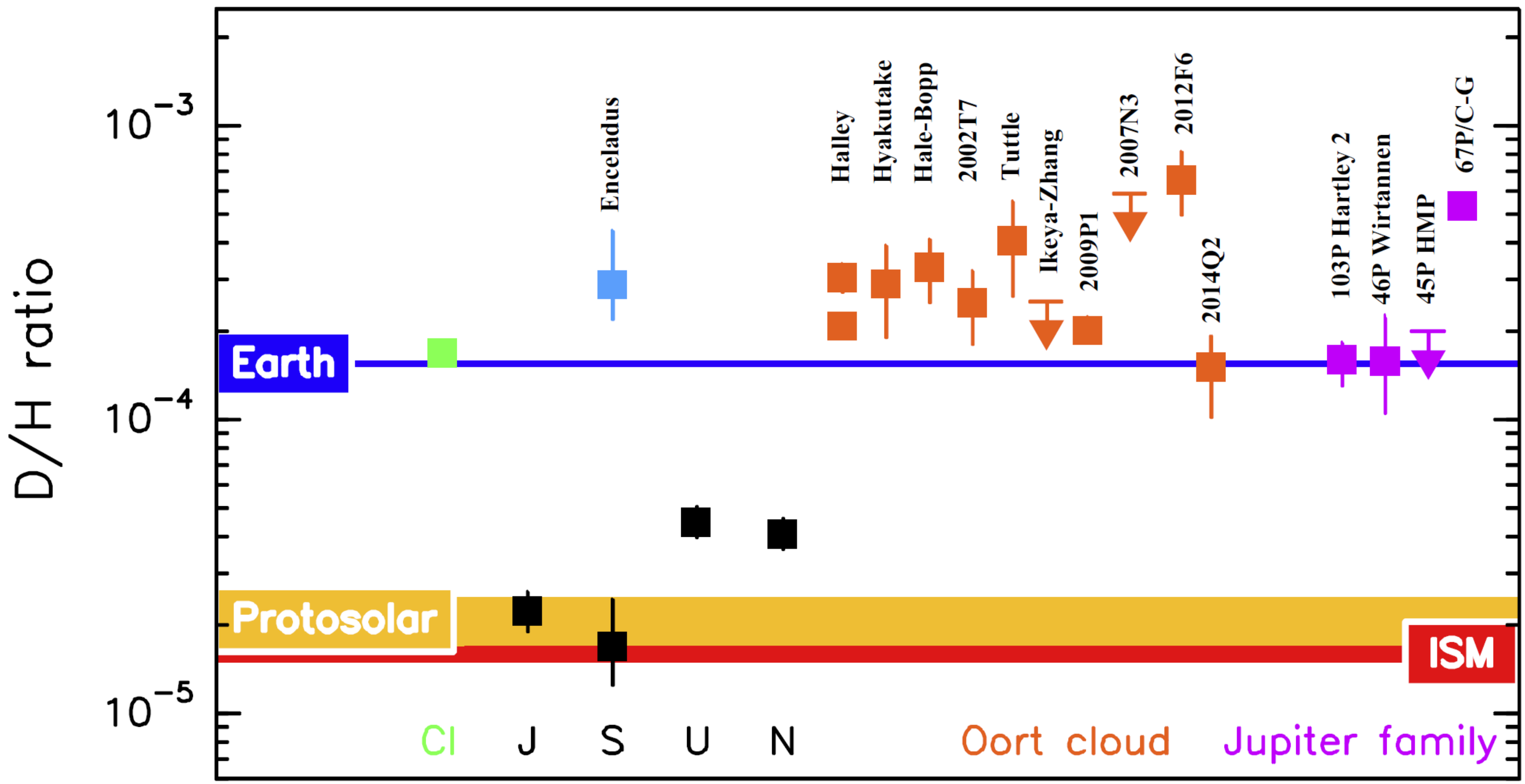
- Next opportunity in absorption between 2023 and 2026
- Monitoring in emission in principal also possible
- Higher spatial resolution
- Activity monitoring of Enceladus

# D/H ratio in the solar system




*Hartogh et al., Nature 2011*

# Situation 2019

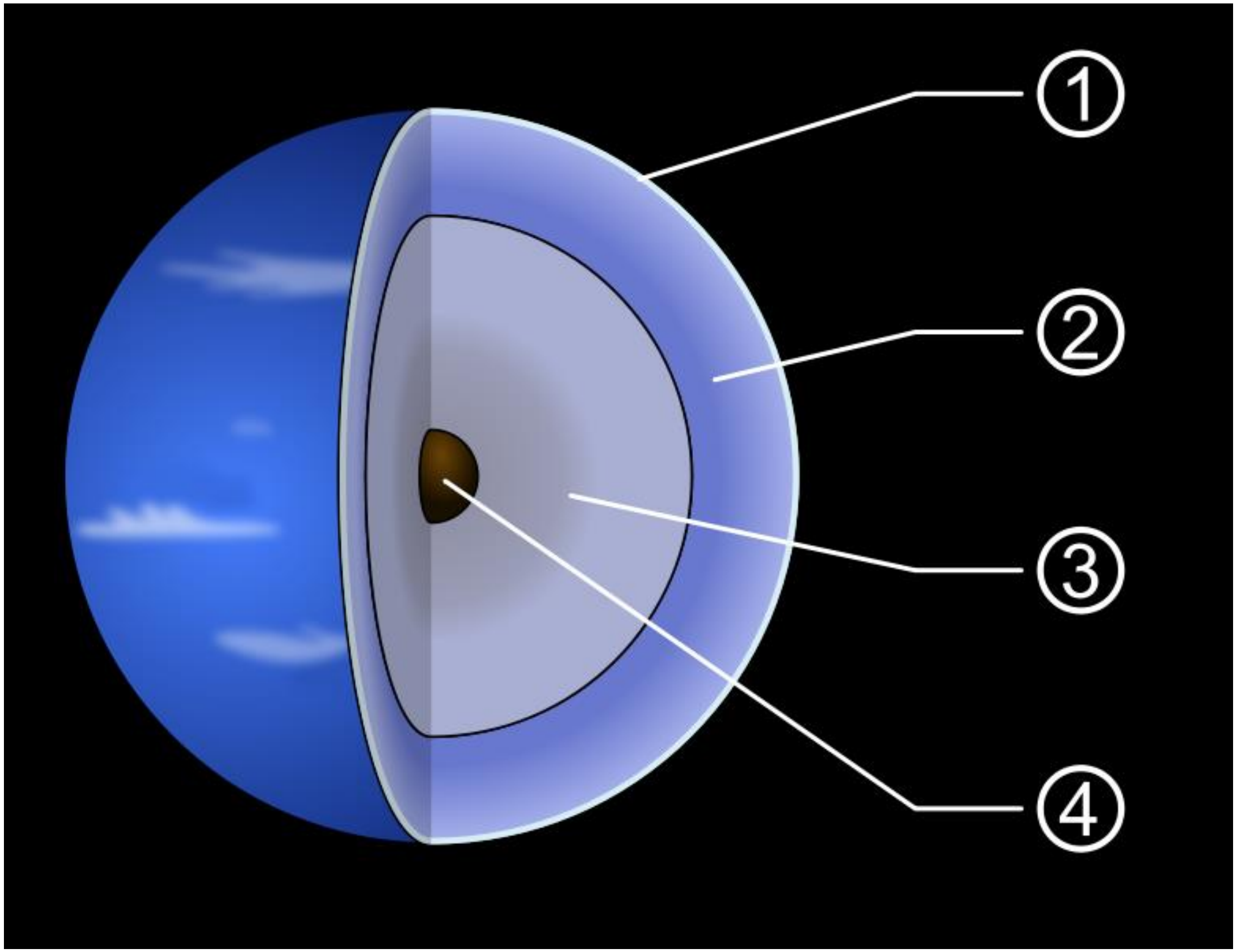



More precise D/H values in Uranus and Neptune
Another data analysis of D/H in Halley
Four additional OCC D/H measurements, smallest and largest values ever
Three more JFC D/H measurements, one large value (67P, in-situ), two Hartley 2 like ones (observed with HIFI and GREAT, both by ***Darek Lis et al. (APJL 2013 and A&A 2019)***

# D/H in Uranus and Neptune

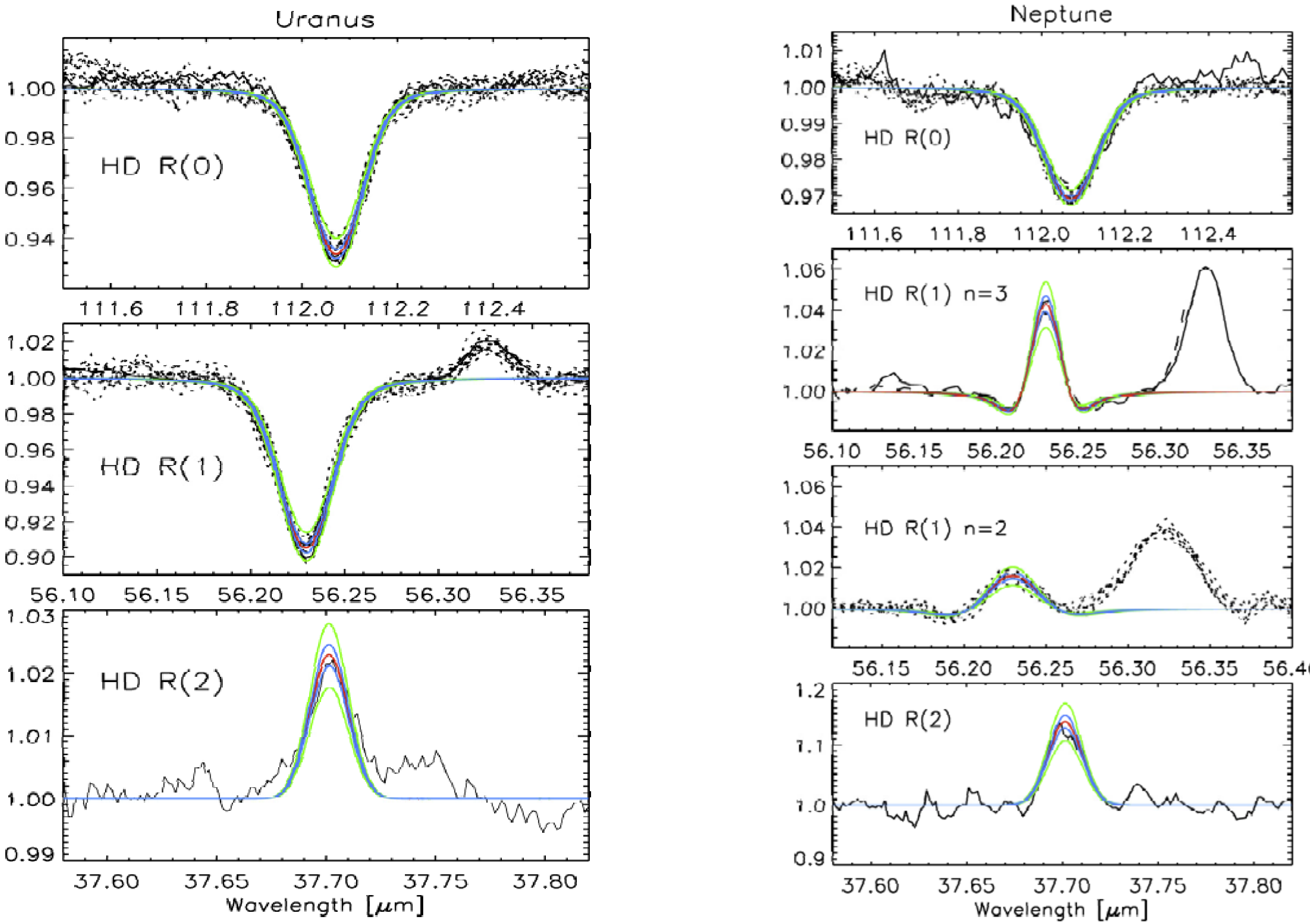
- D/H in Jupiter and Saturn protosolar, i.e. main component is hydrogen
- D/H Uranus and Neptune substantially higher => equilibrated water and possibly organic molecules (highly D-enriched in interstellar medium): “Ice giants”
- D/H in hydrogen may be used to constrain the D-enrichment of ices or the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



# Result D/H

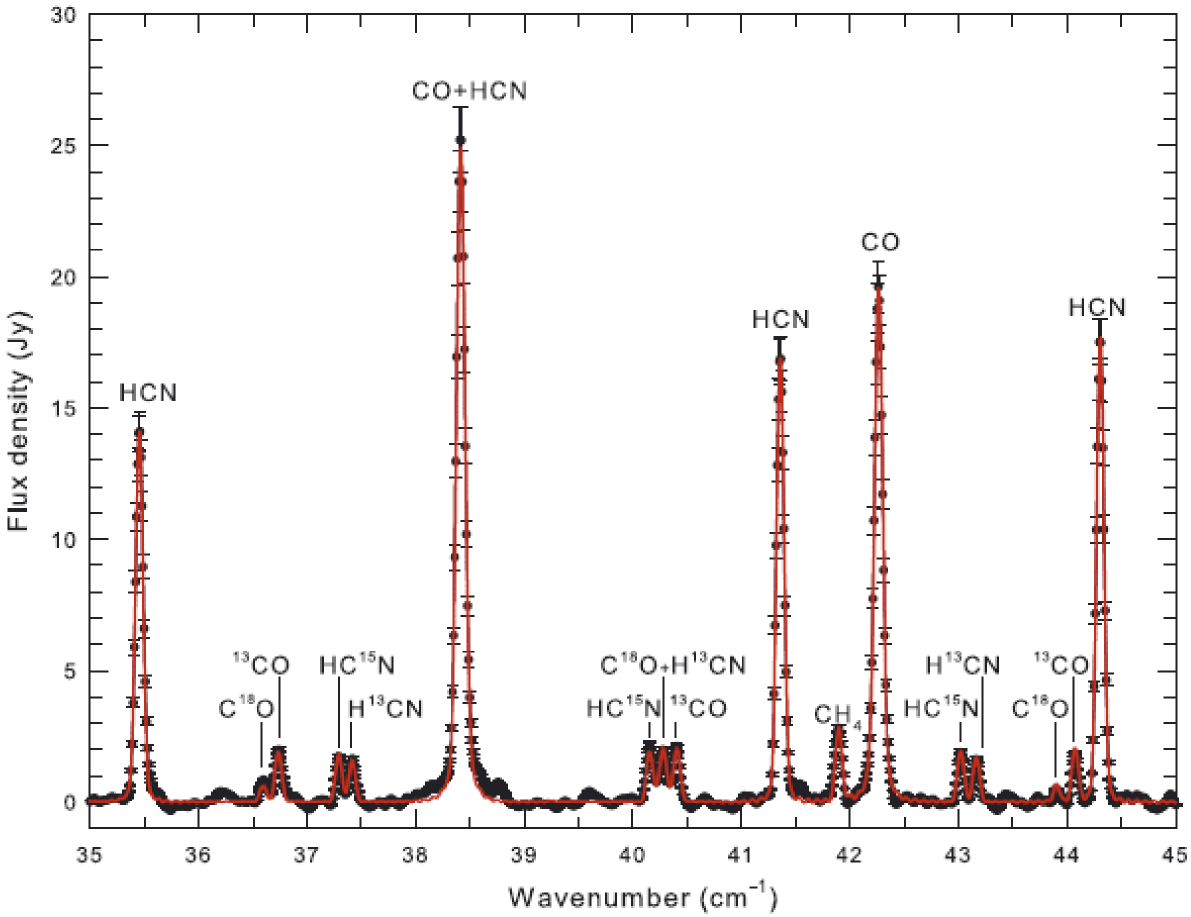
- PACS values show the same D/H for both planets
- PACS values smaller than ISO values:
  - Neptune: 41±4 ppm (65 ppm)
  - Uranus: 44±4 ppm (55 ppm)
- Formation models (e.g. Podolak, 1995) predict 70-100 % ice and a rather small amounts of rocky ($SiO_2$) material. Based on these models the very low (64 ppm) D/H of ices are derived.
- Assuming cometary (150-300 ppm) isotopic ratios we get an ice mass fraction of only 14-32 %, meaning that the planets are rock-dominated.

*(Feuchgruber et al., A&A 2013)*

# MHIFI

- Heterodyne observations o HD in all outer planets
- Vertical profiles of HD in all outer planets
- D/H in water

# Model fitted to observation (zoomed)

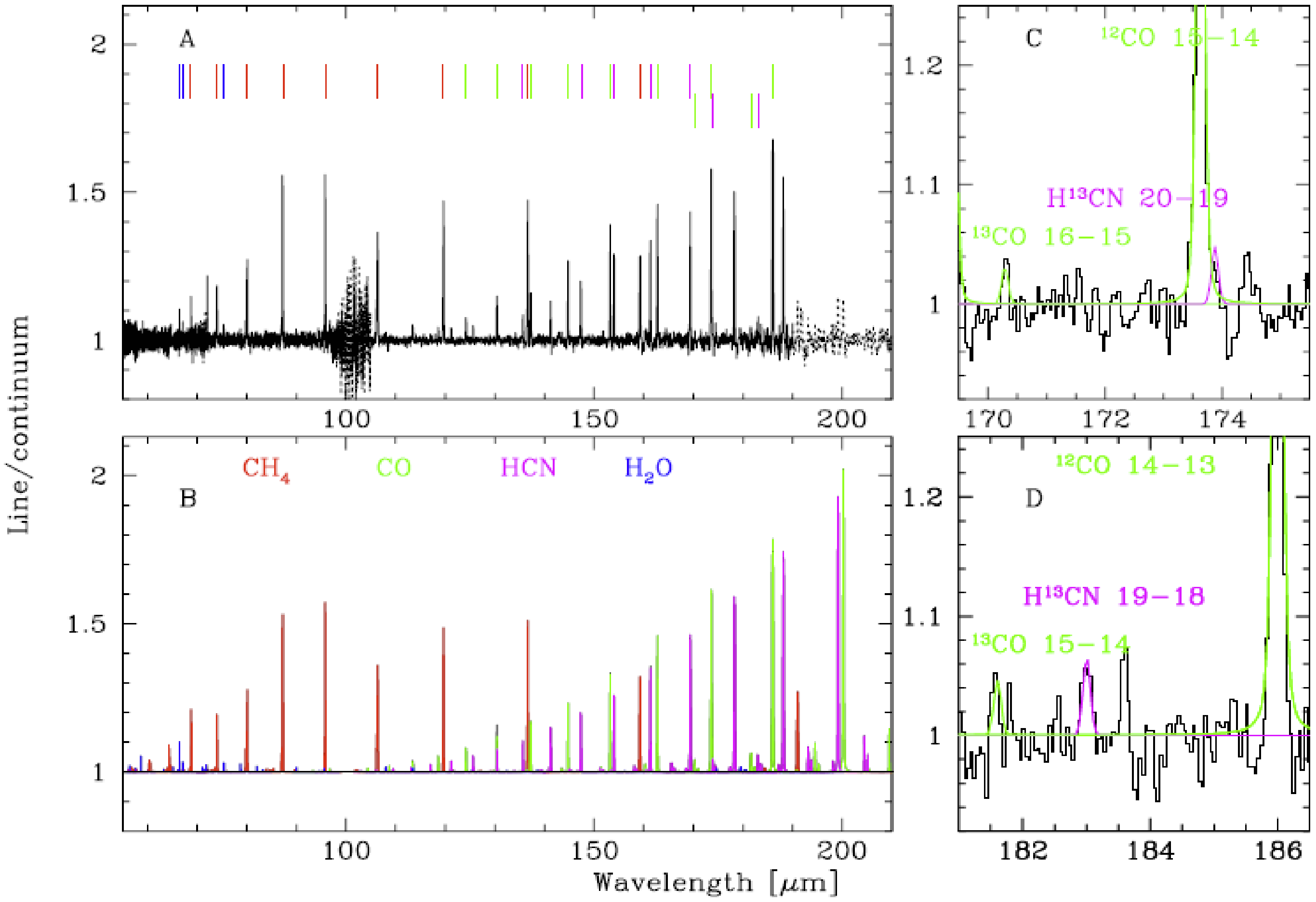


# Retrieved mole fractions and isotopic ratios

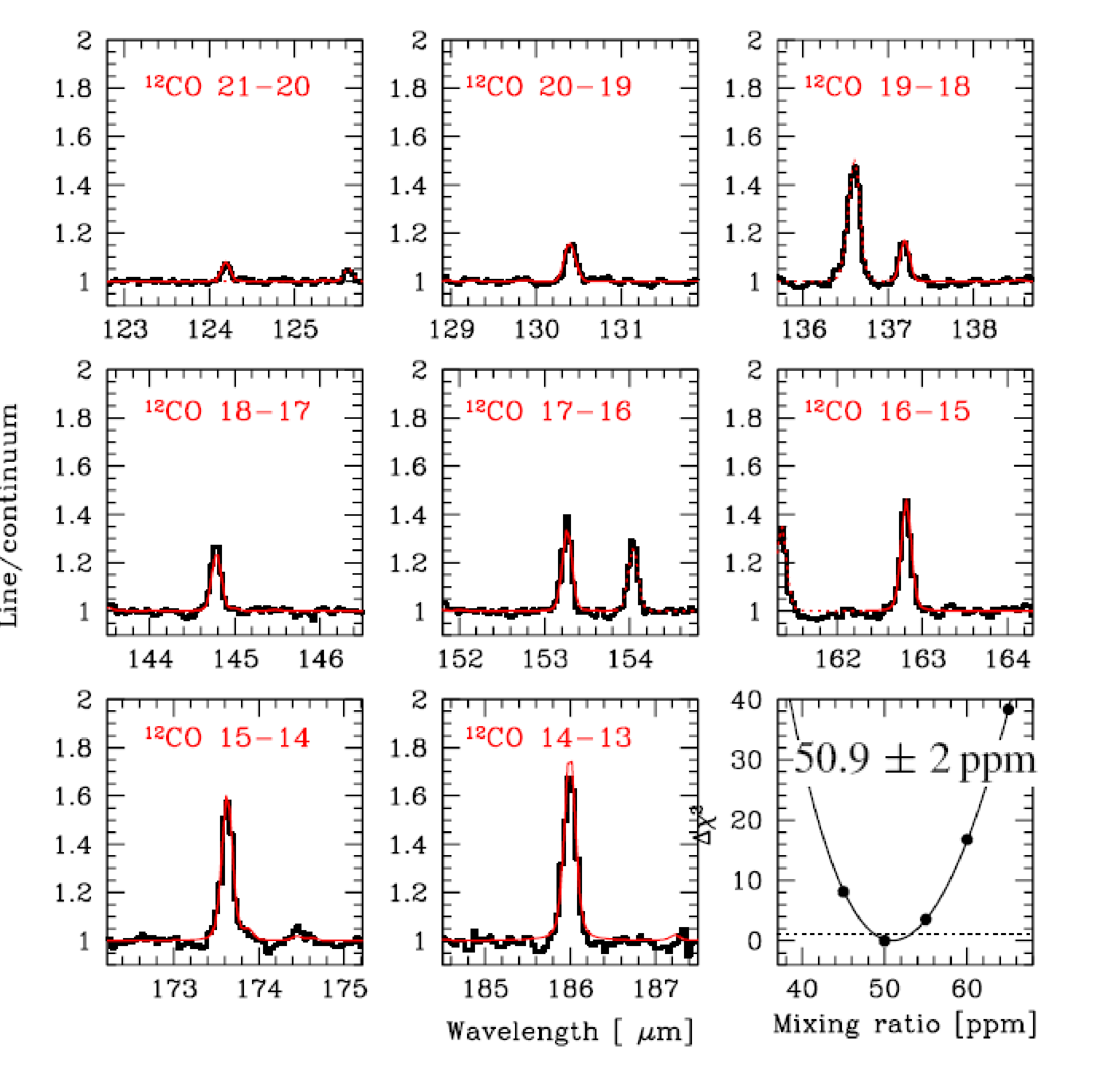
| Molecular species | Mole fraction | 1σ error | |
|---|---|---|---|
| $CH_4$ | 1.33% | 0.07% | |
| CO | 40 ppm | 5 ppm | |
| HCN[a] | 1.02 | 0.13 | |
| **Molecular species** | **Isotopic ratio** | **1σ error** | **Terr. ratio** |
| $^{12}C/^{13}C$ (CO) | 87 | 6 | 89.3 |
| $^{12}C/^{13}C$ (HCN) | 96 | 13 | 89.3 |
| $^{14}N/^{15}N$ | 76 | 6 | 272 |
| $^{16}O/^{18}O$ | 380 | 60 | 498.8 |

*Courtin et al. A&A, 2011*

# PACS Titan spectrum and fitted model



# CO: is CO primordial or external ? Viable via precipitation of O or $O^+$ from Enceladus Torus (*Hörst 2008; Cassidy & Johnson 2010; Hartogh et al. 2011*)




Observed and best-fit simulated CO lines

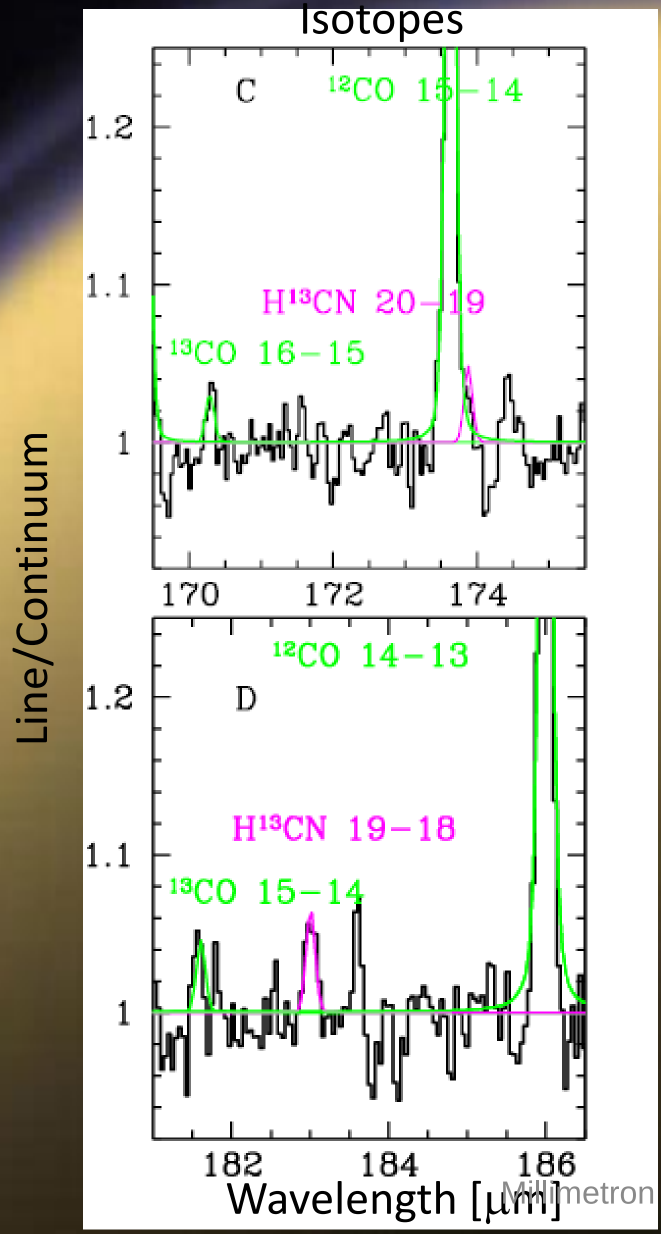
Consistent with previous studies:

| Facility | Value [ppm] | Reference |
|---|---|---|
| SPIRE | 40±5 | Courtin et al. 2011 |
| CIRS | 47±8 | De Kok et al 2007 |
| APEX | $30^{+15}_{-8}$ | Rengel et al. 2011 |
| SMA | 51±4 | Gurwell et al. 2012 |
| **PACS** | **51±2** | **This work** |

For the [60-170] km range altitude

*Rengel et al. 2013*

# Isotopic ratios $^{13}C/^{12}C$ in CO and HCN




Detection of the isotopes:
- $^{13}CO$(15-14) and (16-15)
- $H^{13}CN$ (19-18) and (20-19)

but marginal

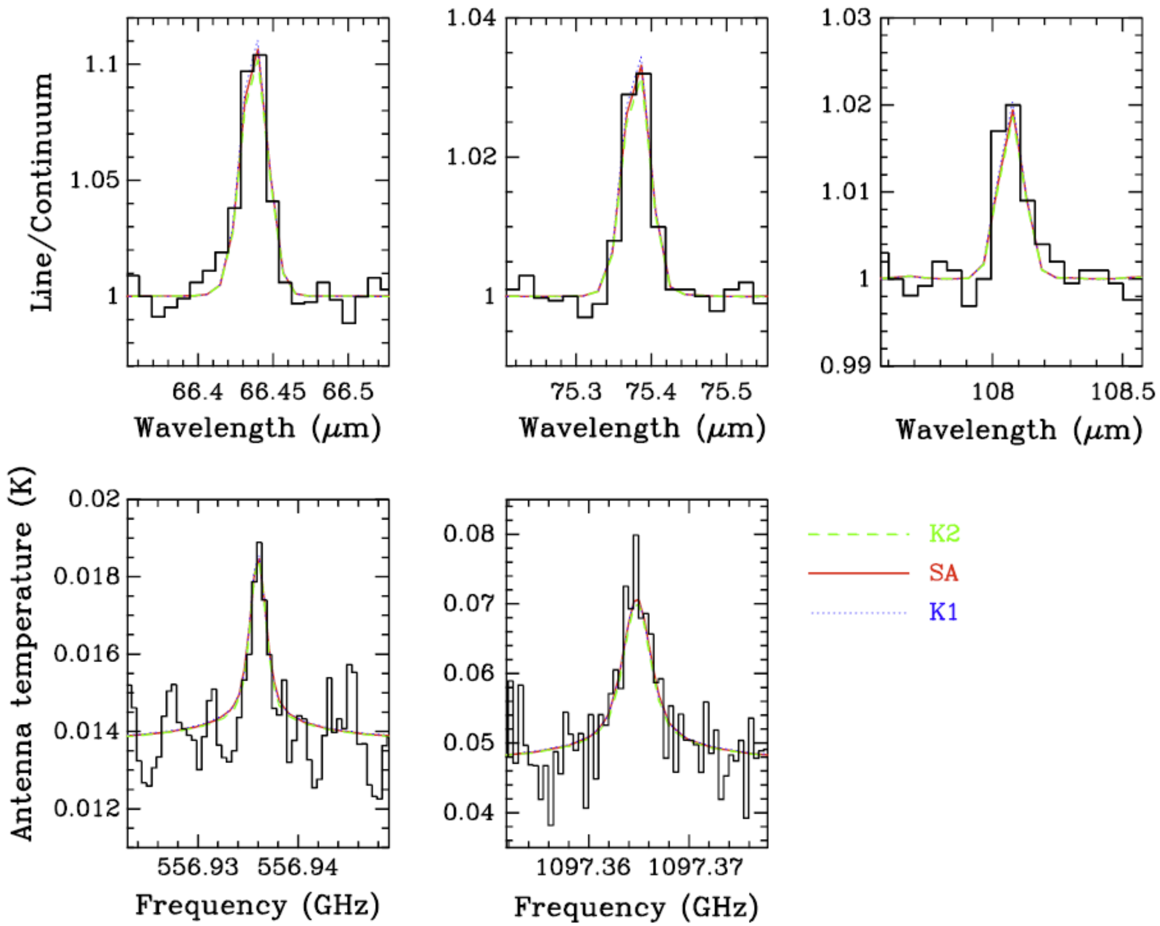
Results:
$^{12}C/^{13}C$ in CO : 124 ± 66
$^{12}C/^{13}C$ in HCN: 66 ± 33

**Consistent with previous works**

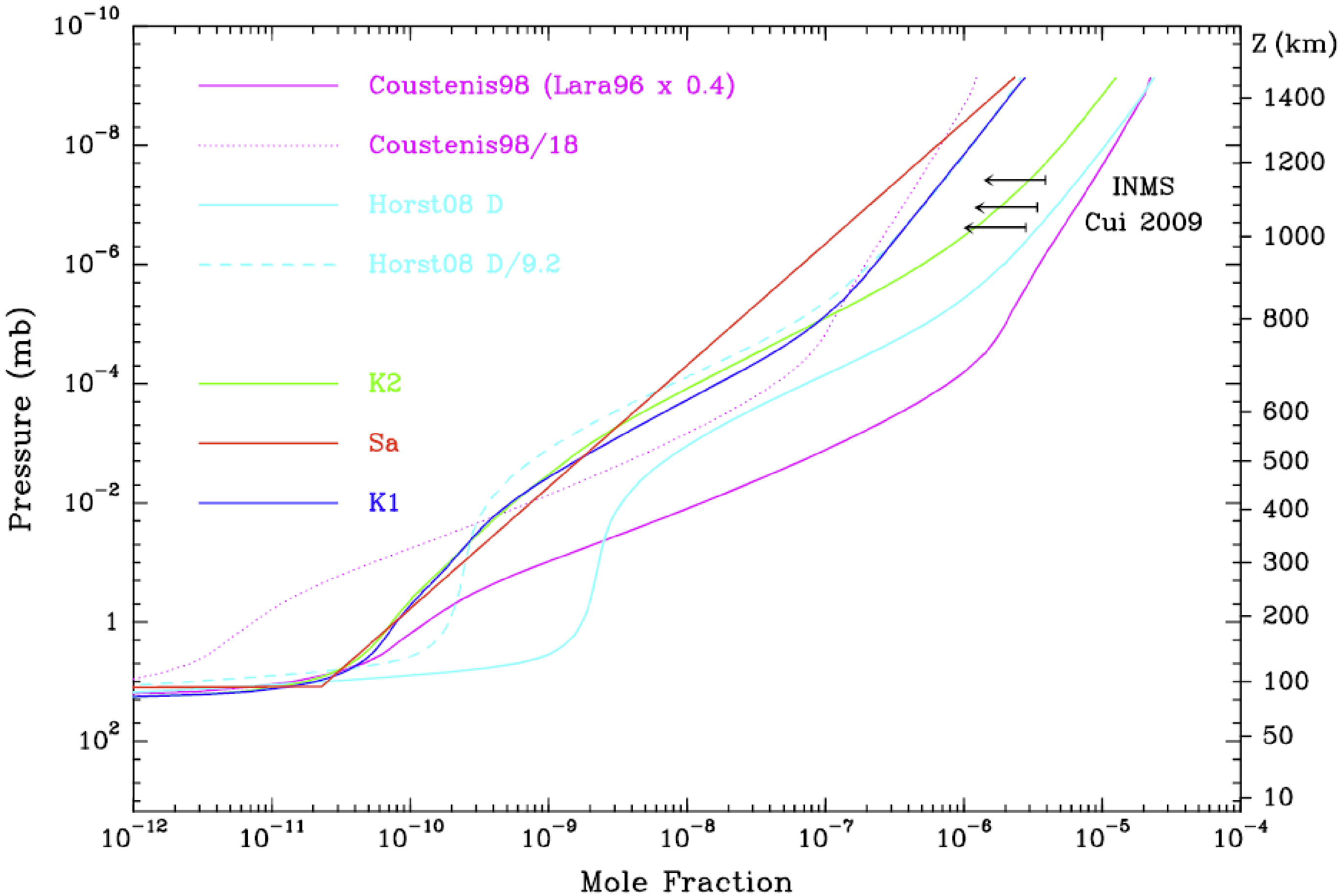


*Rengel et al. 2013, submitted*

# Titan water with PACS and HIFI



# Comparison of best fit profile with former results

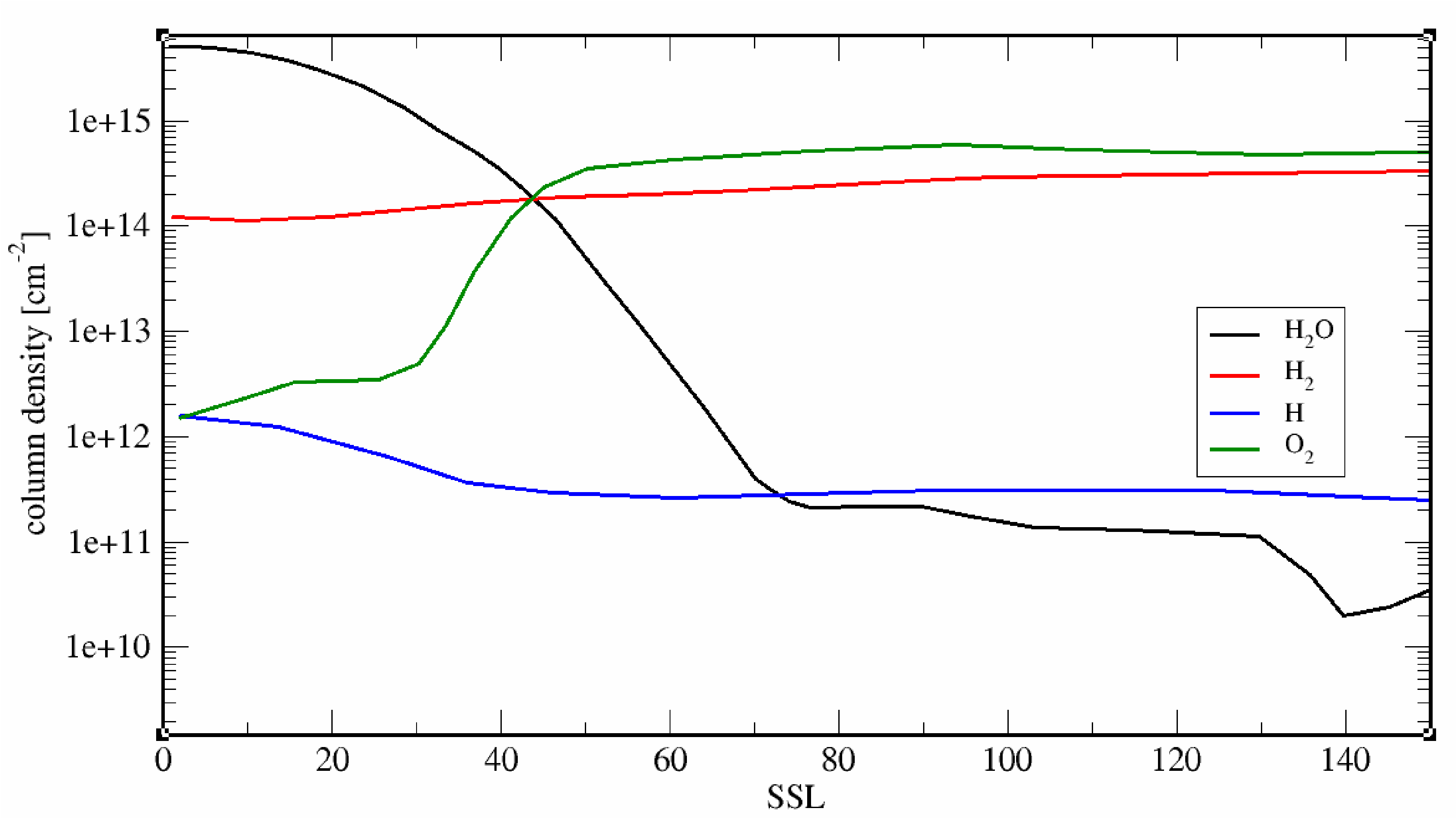



*Moreno et al., Icarus, 2012*

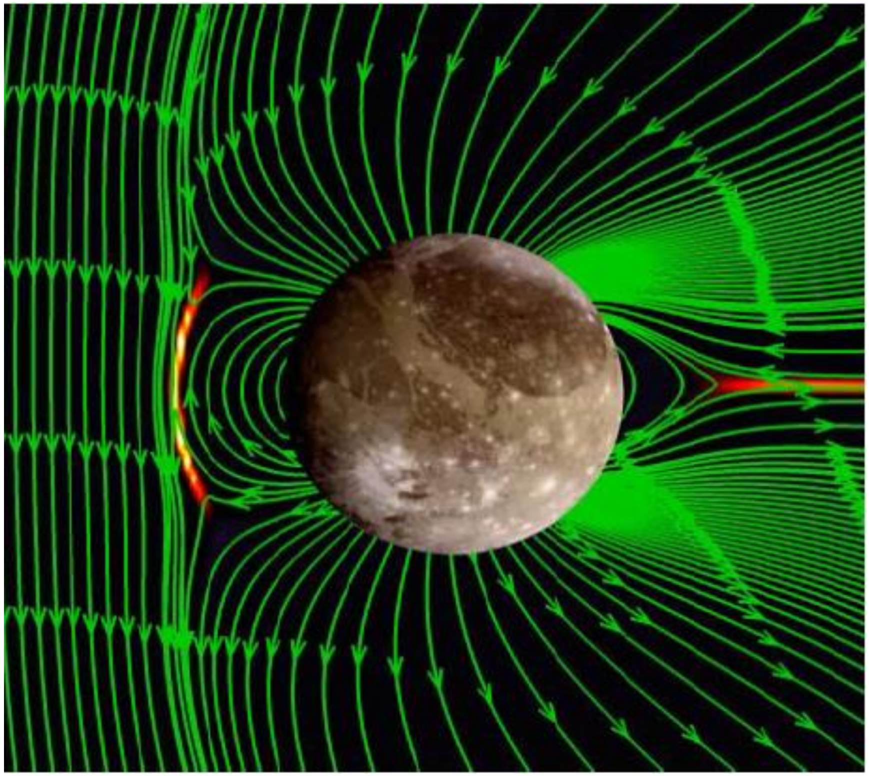
# Millimetron

- Deep searches for new species with SACS and LACS
- SNR > 100 observations of water and other species for vertical profiles (MHIFI efficiency better by factor of 25 at 1 THz)

# 2007: Marconi model on Ganymede



# Ganymede in the Jovian System:



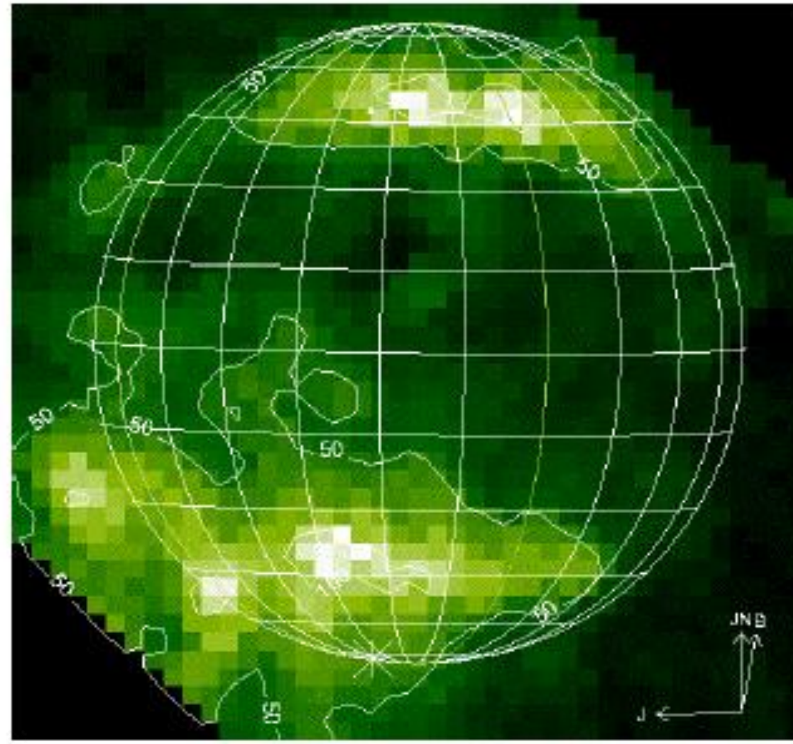
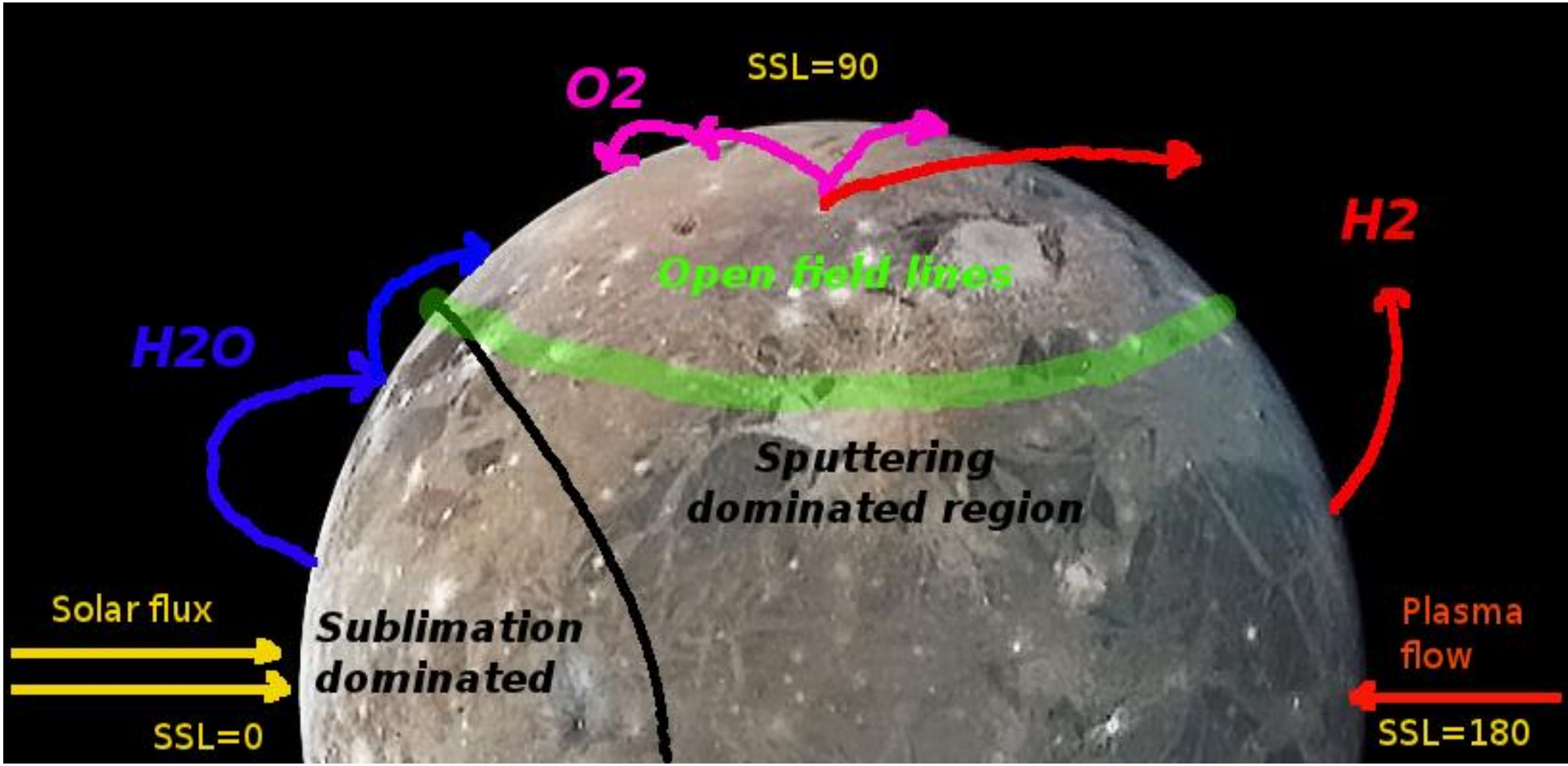



**Figure 19.12.** Ganymede auroral emission from oxygen (OI 1356 Å) observed with HST.

**Observations indicate that Ganymede has a significant $O_2$ atmosphere, probably a subsurface ocean, and is the only satellite with its own magnetosphere.**

**Images of Ganymede's OI 135.6 nm emission for HST orbits on 1998 October 30 (*Feldman et al., 2000*).**

# Schematic picture of processes creating the Ganymede atmosphere

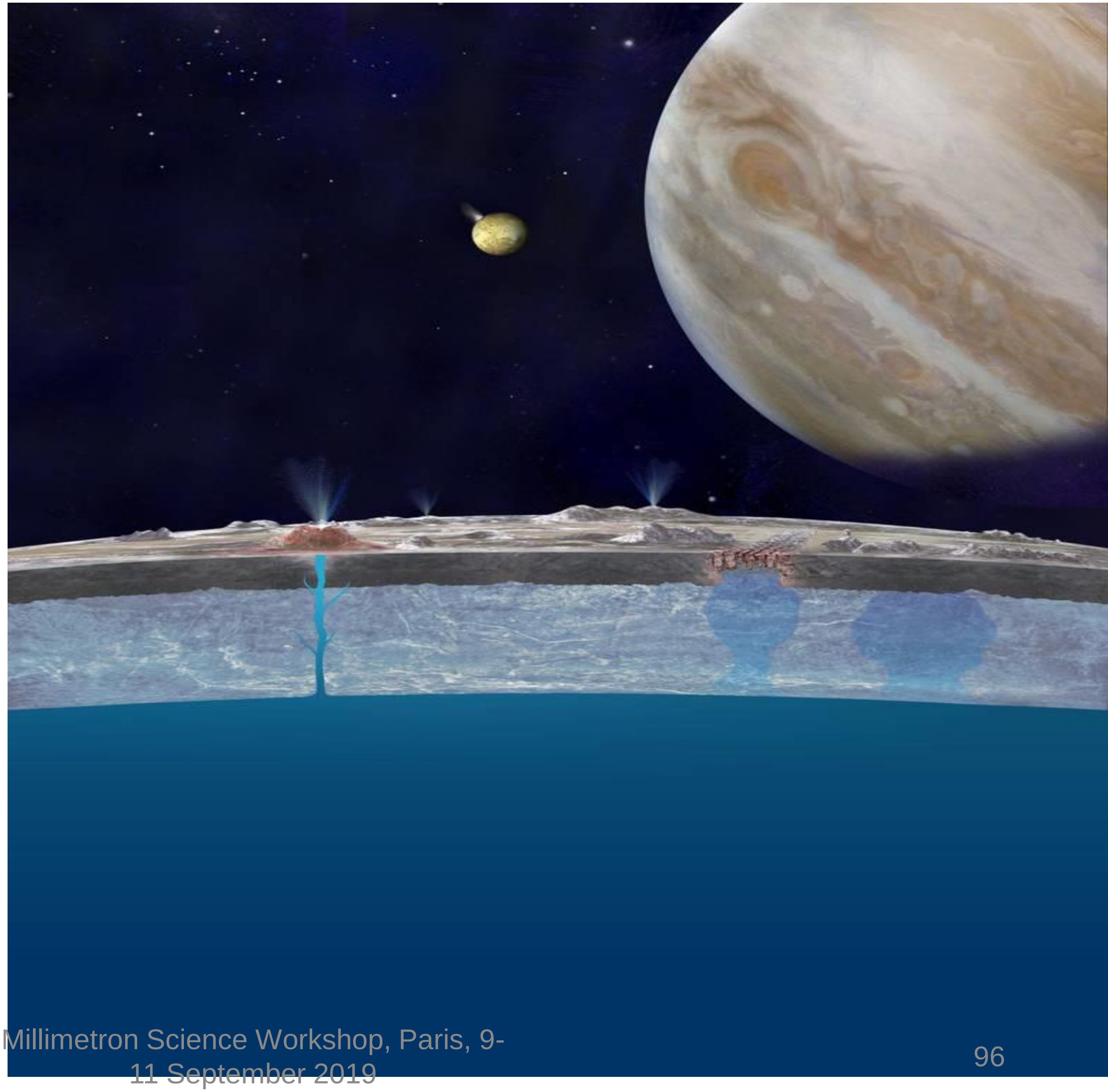


# Ganymede's water atmosphere

- Production processes of water are sputtering of heavy ions and electrons from the Jupiter co-rotating plasma and sublimation. The sublimation dominates 45 deg around the sub-solar point and while sputtering elsewhere. Sublimation produces a 3 orders of magnitude higher water vapour density than sputtering.
- Sublimation rates depend on types of ices: crystalline vs amorphous, impurities by different minerals/salts, ice-regolith mixtures
- HIFI detected a water atmosphere at the leading sides of Ganymede and Callisto

# Cryovolcanism like on Enceladus?

On leading sides
by chance?



# Summary Galilean Satellites

- First detection of predicted water atmosphere of Ganymede and Callisto.
- Properties of atmospheres different from predictions and not easy to understand
- Detected strong asymmetry may be an expression of strong local variations of temperatures or ice properites.
- Cryovolcanism cannot be excluded as potential atmospheric source.

# Millimetron

- Observations of water vapour of all Galilean satellites
- Observations of several lines constraining the atmospheric structure
- Observations of the diurnal variation of the water atmosphere