FIR investigations of the solar system: present status and future prospects

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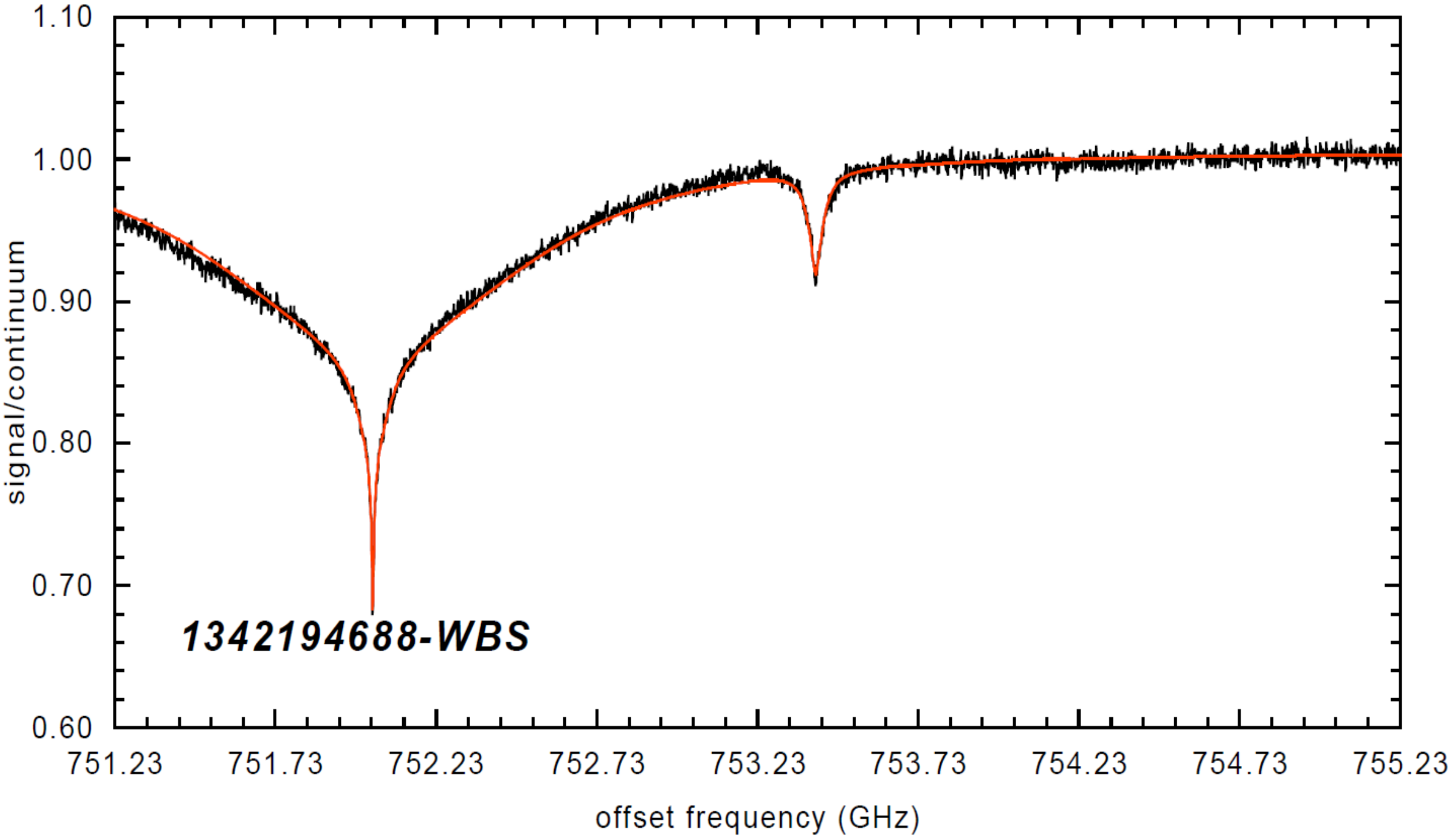
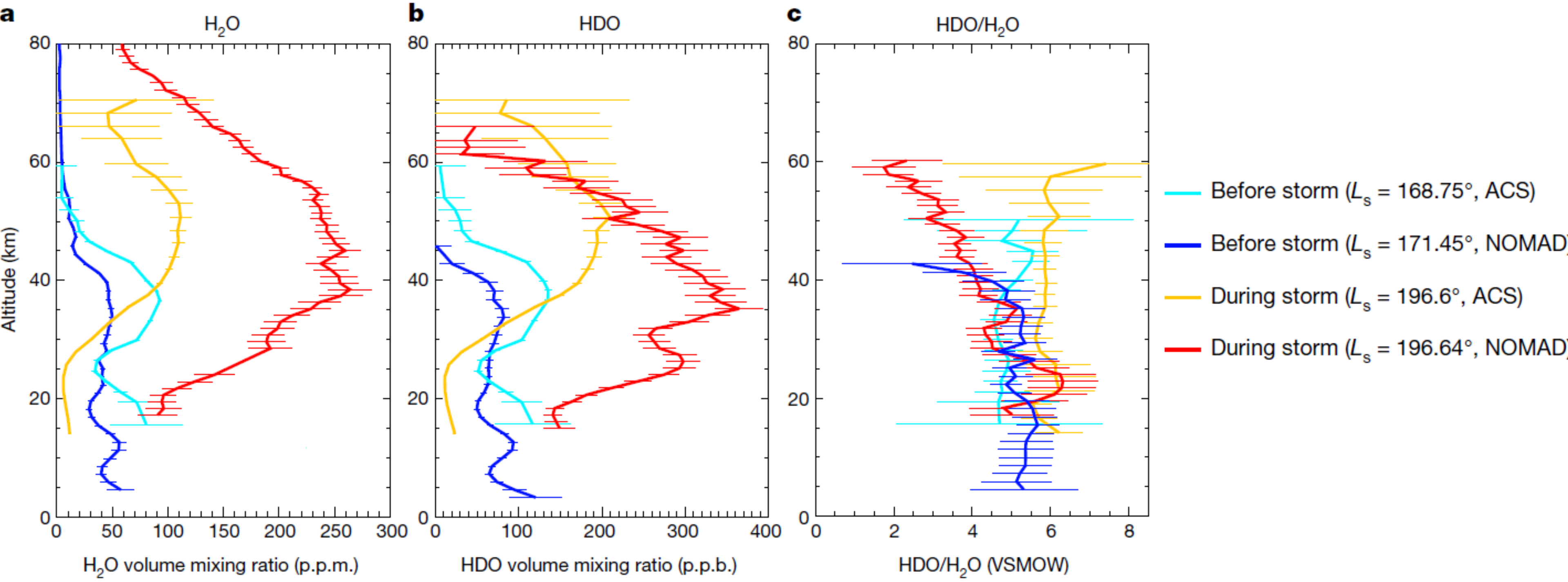
HIFI Mars H_2O and HDO (4.5 x VSMOW) at Ls = 78°



D/H on Mars

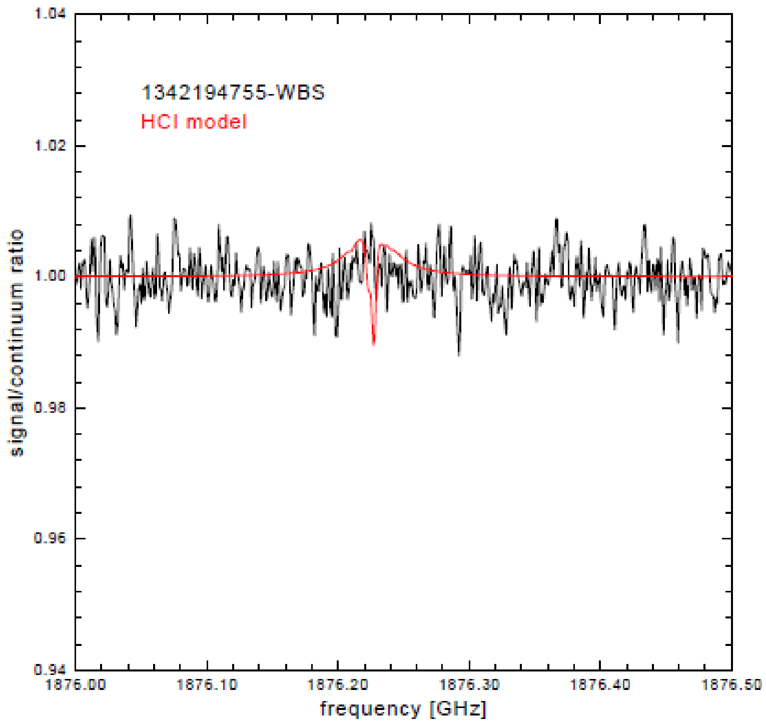
- Constrains the excape of water vapour
- Original D/H believed to be near VSMOW (from Mars meteroids)
- Photolysed water: Jeans escape of H much higher than of D
- FIR (e.g. SALTUS): < 5 arcsec maps of vertical profiles.
- FIR measurements not interfered by dust.
- Vertical profiles from ground to 80 km: determination of mass dependent fractionation and effect of phase changes on D/H

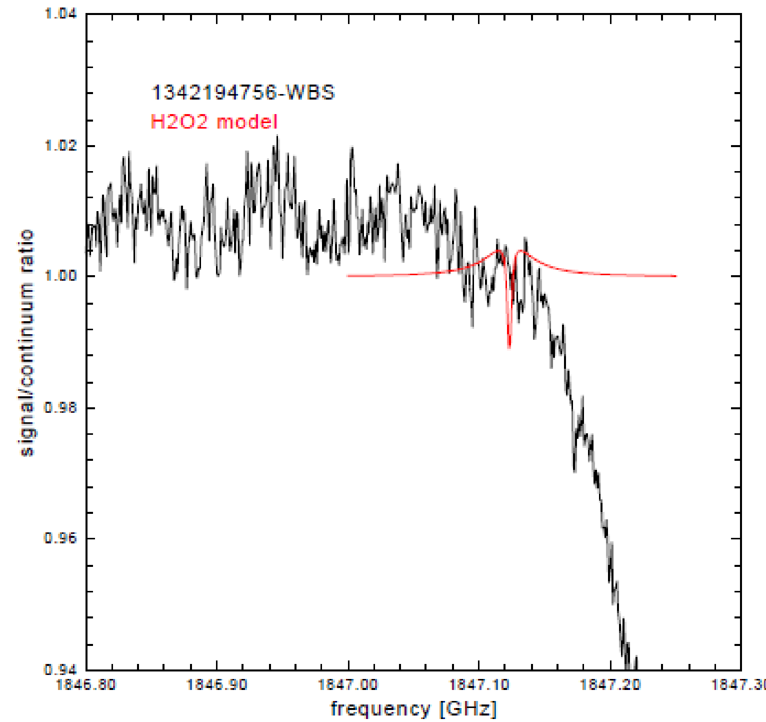
D/H variability (TGO)



Vandaele et al, 2019

Upper limits on HCl and H_2O_2





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Hartogh et al. 2010b, A&A

HCl and H_2O_2

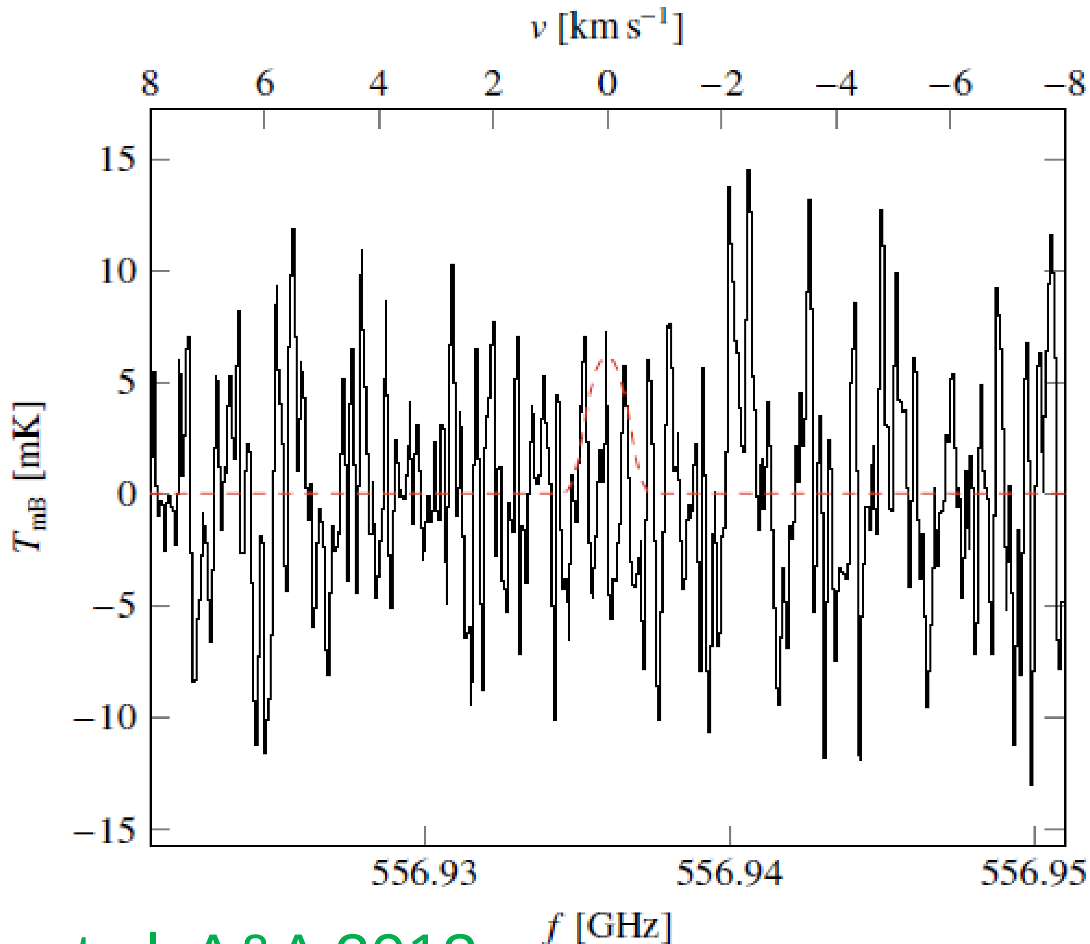
- HCl volcanic gas: upper limit with HIFI. Recently detected by TGO during dust storms with values 20 times the upper limit (Korablev et al, 2021)

- H_2O_2 not detected by HIFI, because constrained to the lower atmosphere, requiring a strong temperature gradient (contrast) to be detectable. Only possible during certain times of the year.
- Integration times for large distances (Mars 5 arcsec apparent diameter) about 100 x shorter (SALTUS/HIFI)

Other detections

- Water in main belt comets: HIFI upper limits (de Val-Borro et al. 2012, O'Rourke 2013: 4/8 x 10^25/s), JWST detection Kelley 2023, < 10^25/s. SALTUS sensitivity < 10^24/s
- Europa water plumes, Roth et al. 2014, Paganini et al, 2019. Sensitivity about 600 t, SALTUS < 100 t
- Ceres active regions (water emissions) with HIFI, Küppers et al, 2014
- Ganymede water (Roth 2022)

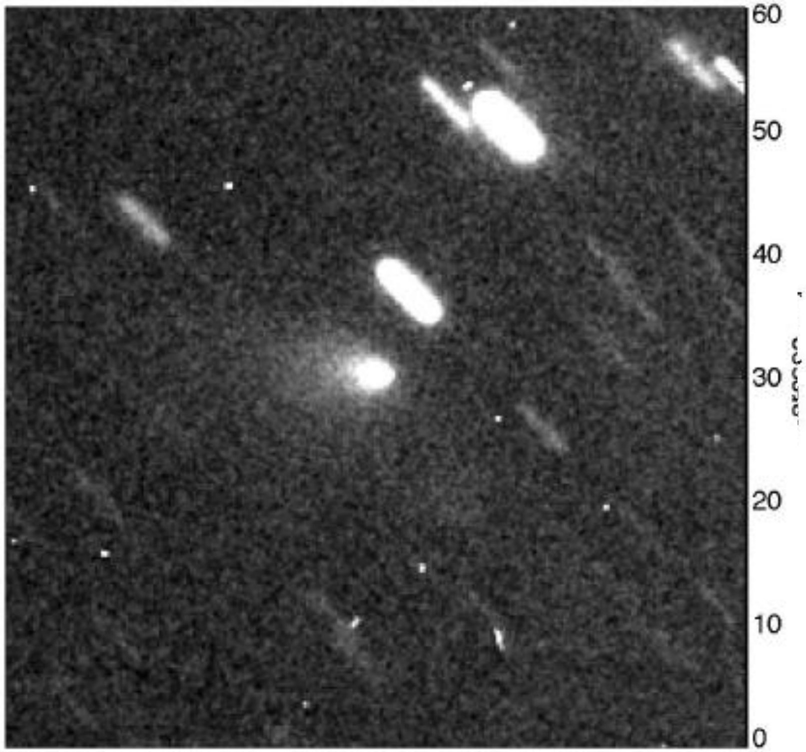
Spectrum at rotational ground-state

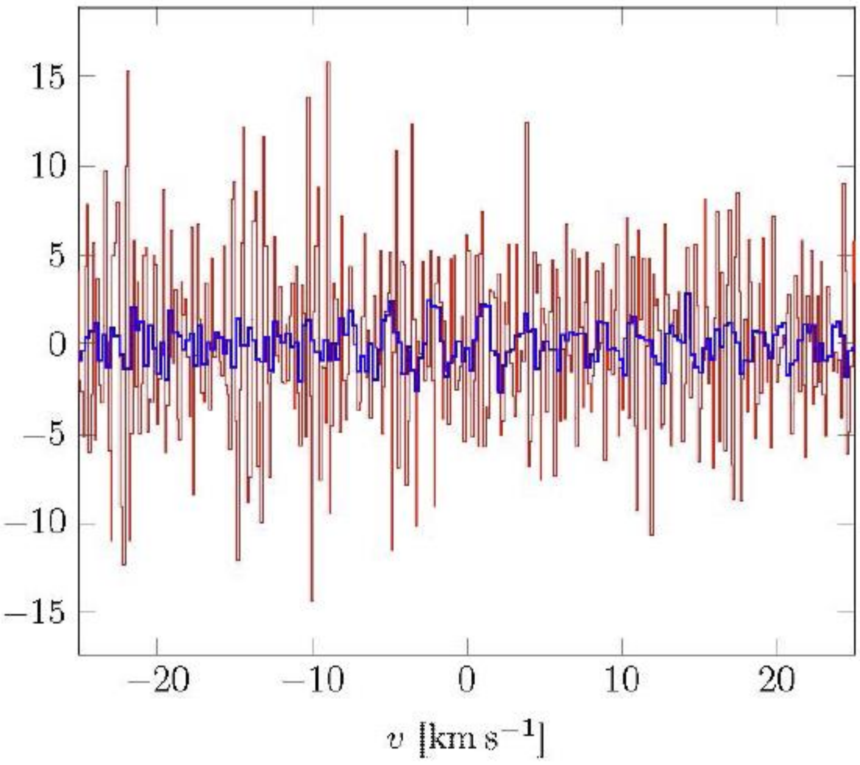


de Val-Borro et al. A&A 2013


Kevin Heider

Another try: P/2012 T1 (PANSTARRS)

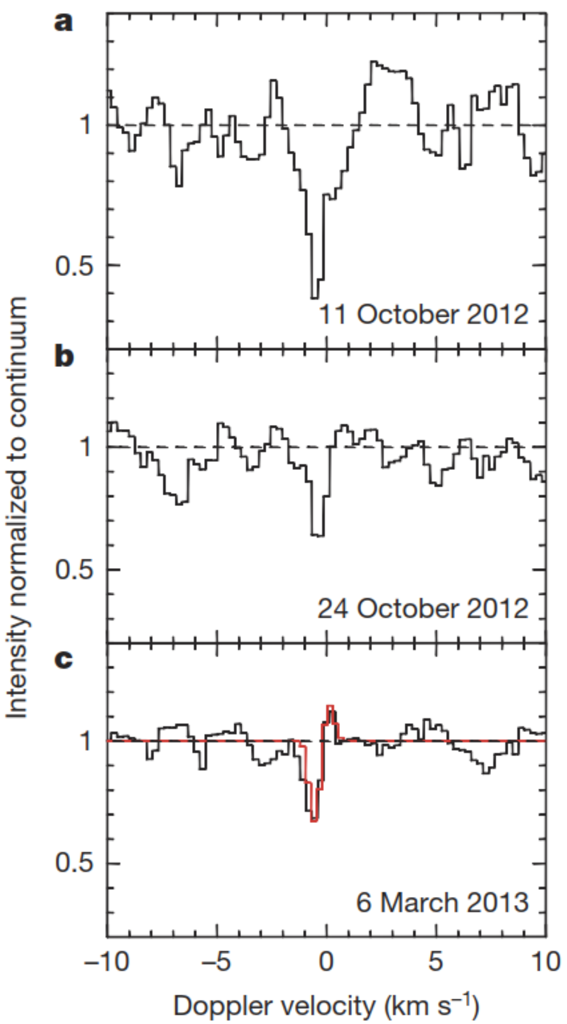




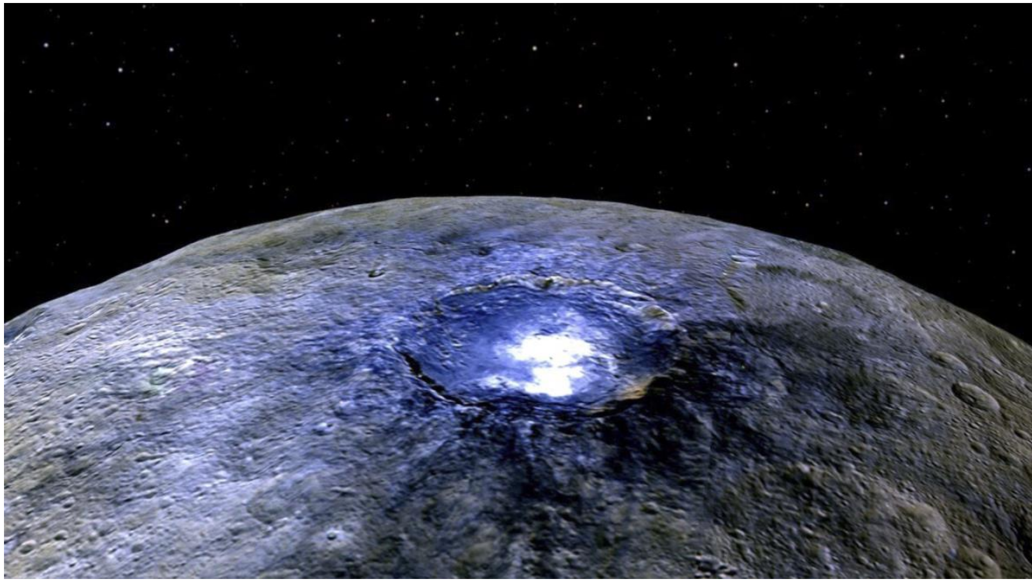
ESO VLT FORS 2

O'Rourke et al, 2014

Water atmosphere of Ceres



Water vapor production: about 6 kg per second 1 sigma corresponds to 1 kg (10 h integration time). DAWN finds potentially active regions *[Nathues et al., Nature 2015].*



Integration times: HIFI 600 min, SALTUS < 1 min Monitoring, survey of outgassing of other asteroids. Main belt comets monitoring

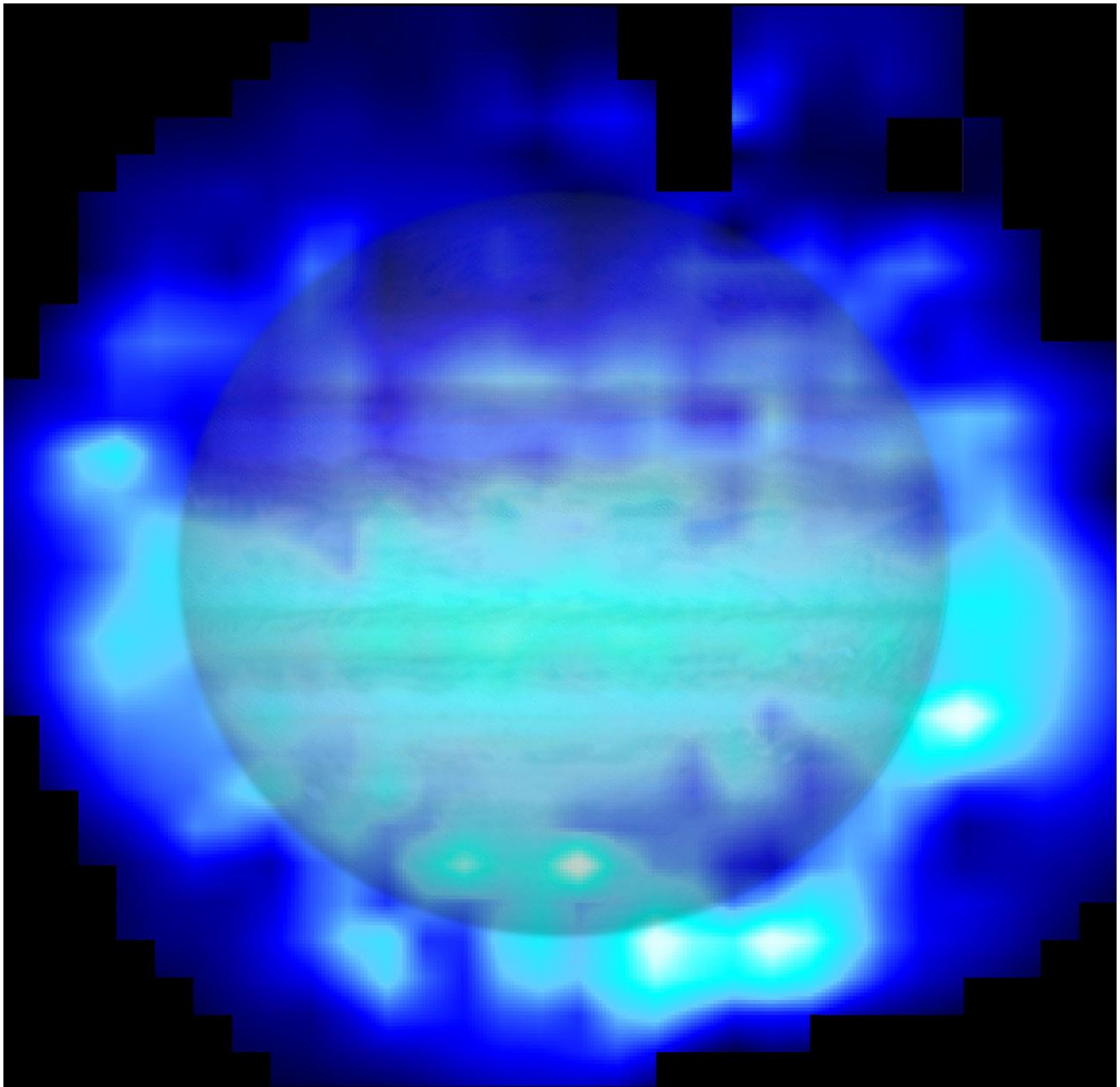
Küppers et al., Nature 2014

SL9 impact main source of stratospheric water in Jupiter

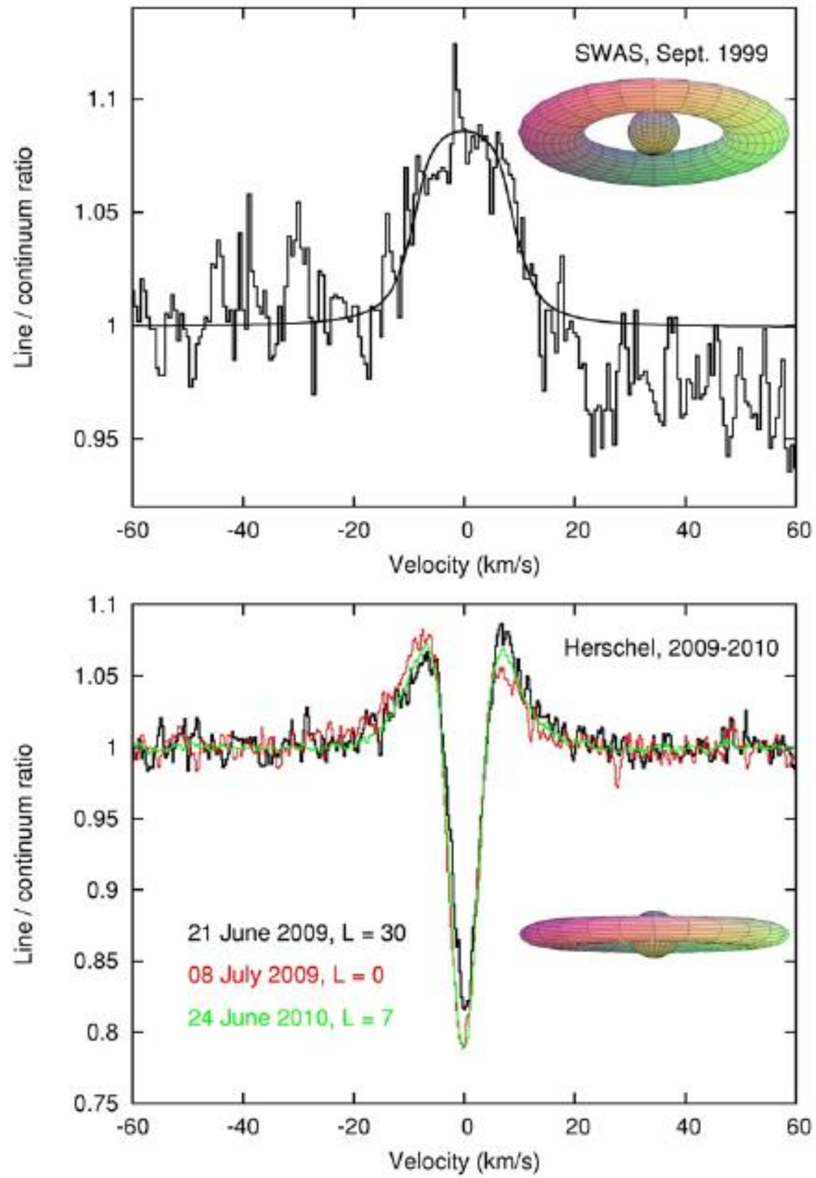
- No feature found indicating a satellite/ring source
- Vertical distribution does not fit IDP source
- Horizontal distribution of water favors SL9 impact, hemispheric asymmetry: Globally averaged column density $3x10^{15}cm^{-2}$ with 2-3 times more water in the south. *Cavalie et al., A&A 2013*

SALTUS monitoring observations with much higher temporal and spatial resolution. Detection of D/H and OPR in water: more clues for origin of water.

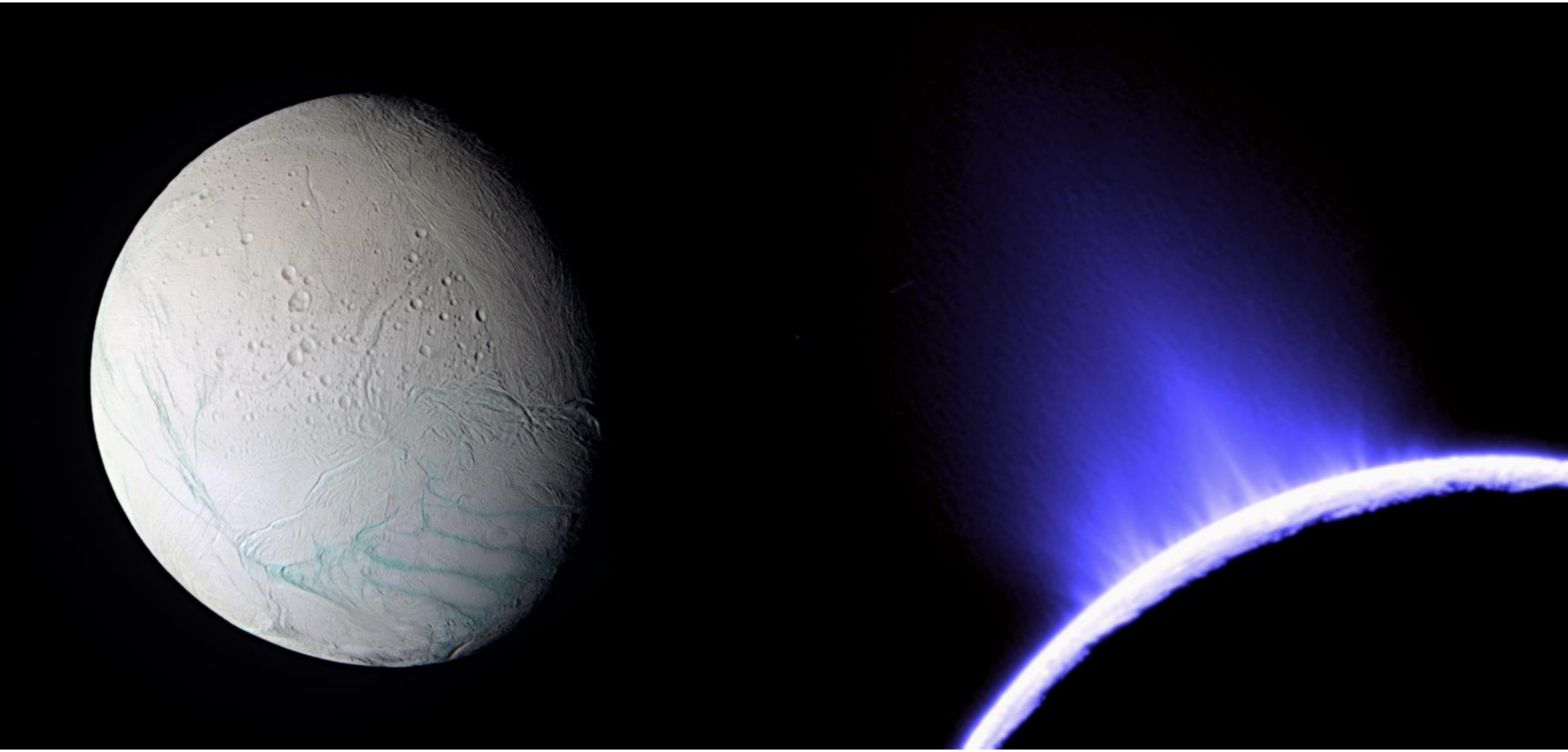
Water distribution observed by PACS

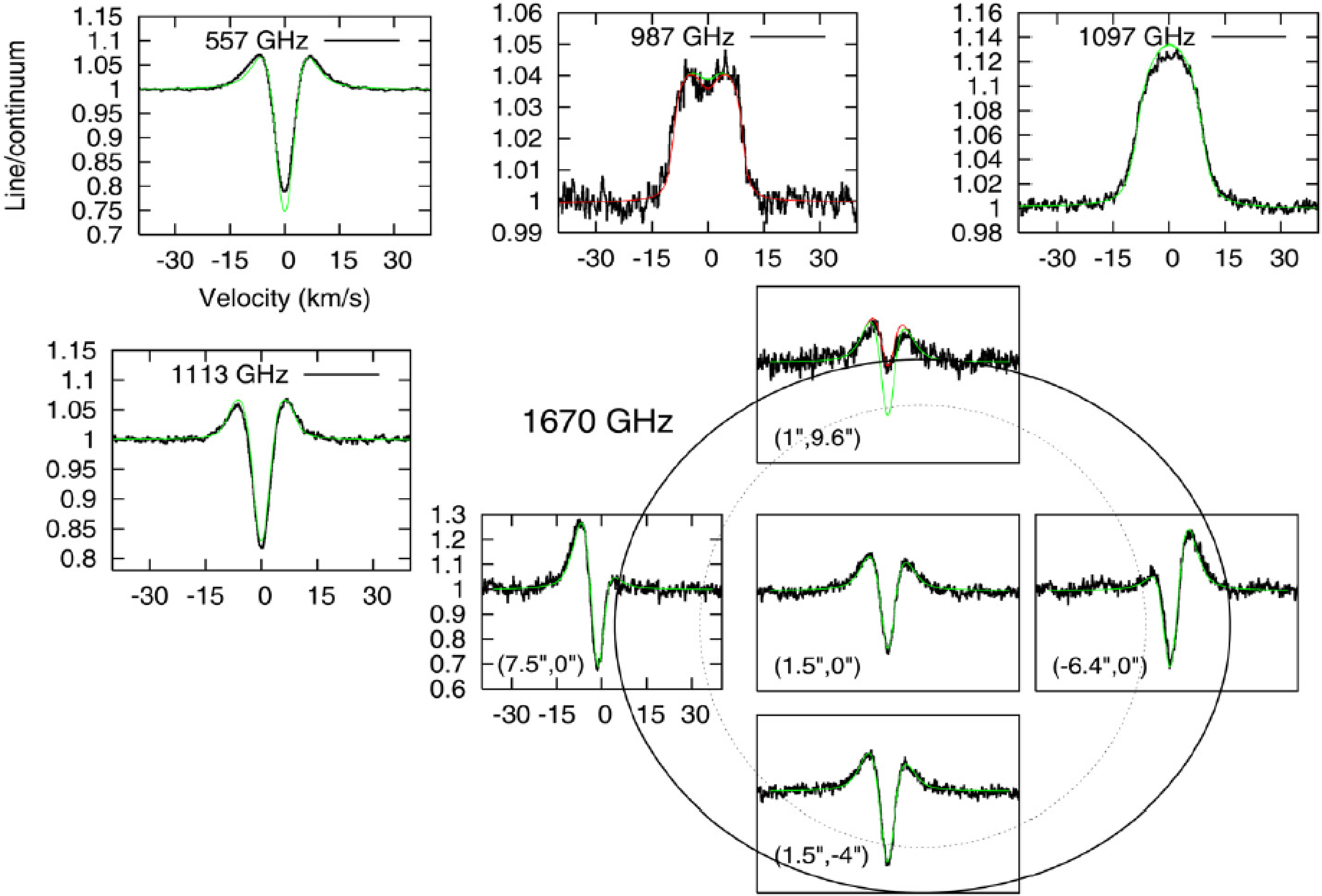


Unexpected detection at 557 GHz pointing to Saturn



Enceladus plumes

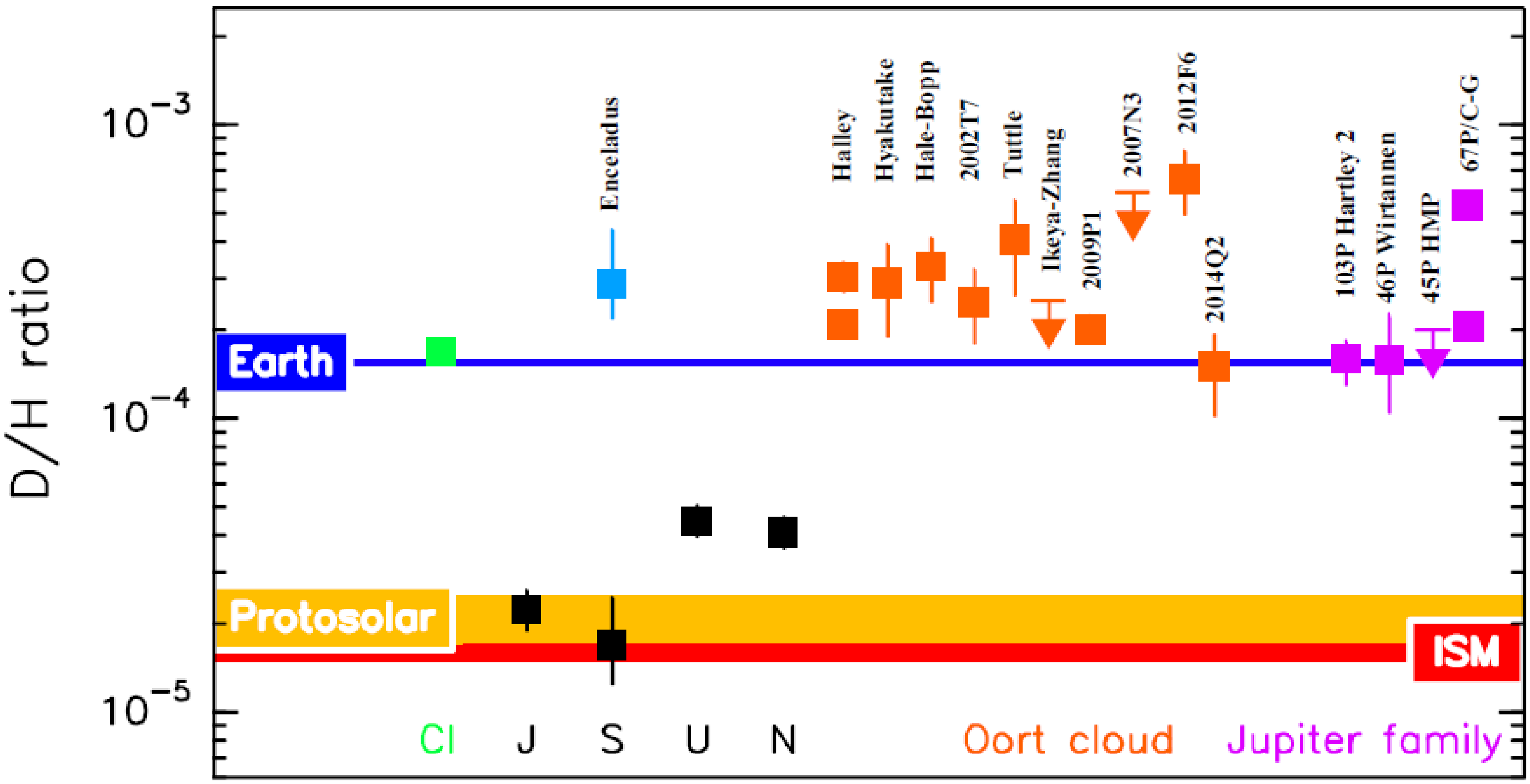



557 GHz
Line/continuum
Velocity (km/s)
987 GHz
1097 GHz
1113 GHz
1670 GHz
(1",9.6")
(7.5",0")
(1.5",0")
(-6.4",0")
(1.5",-4")

SALTUS: monitoring water torus

- Monitoring in emission
- Higher spatial resolution resolution
- Water isotopes and OPR
- Activity monitoring of Enceladus

D/H ratio in the solar system

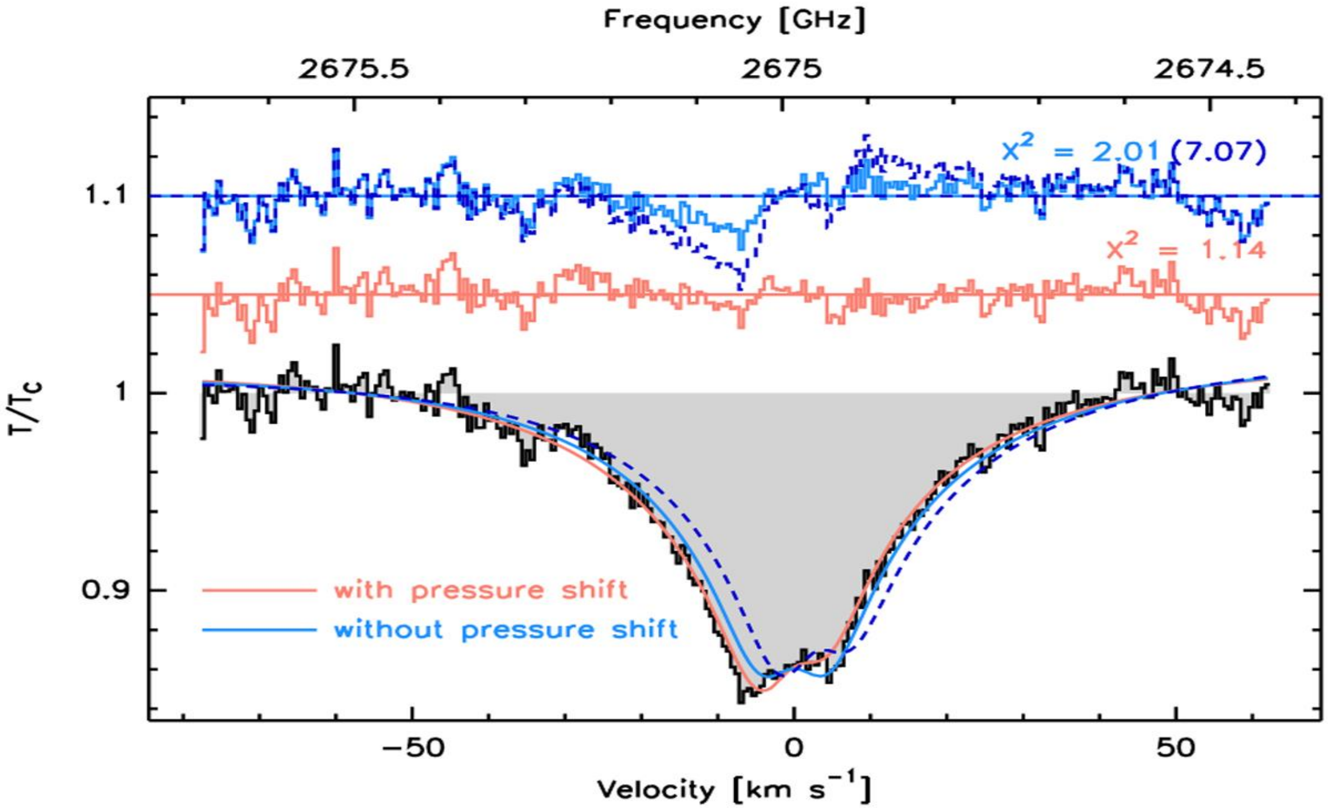


Hartogh et al., Nature 2011, updated 2024

D/H in cometary water and Uranus/Neptune hydrogen

- HIFI: 103 P (VSMOW) and 45 P (upper limit)
- SALTUS: 10 to 20 JFCs and targets of opportunity (OCCs)
- SALTUS: all giant planets (HD): heterodyne observations (not available for HIFI)

GREAT HD (Wiesemeyer et al, 2024)

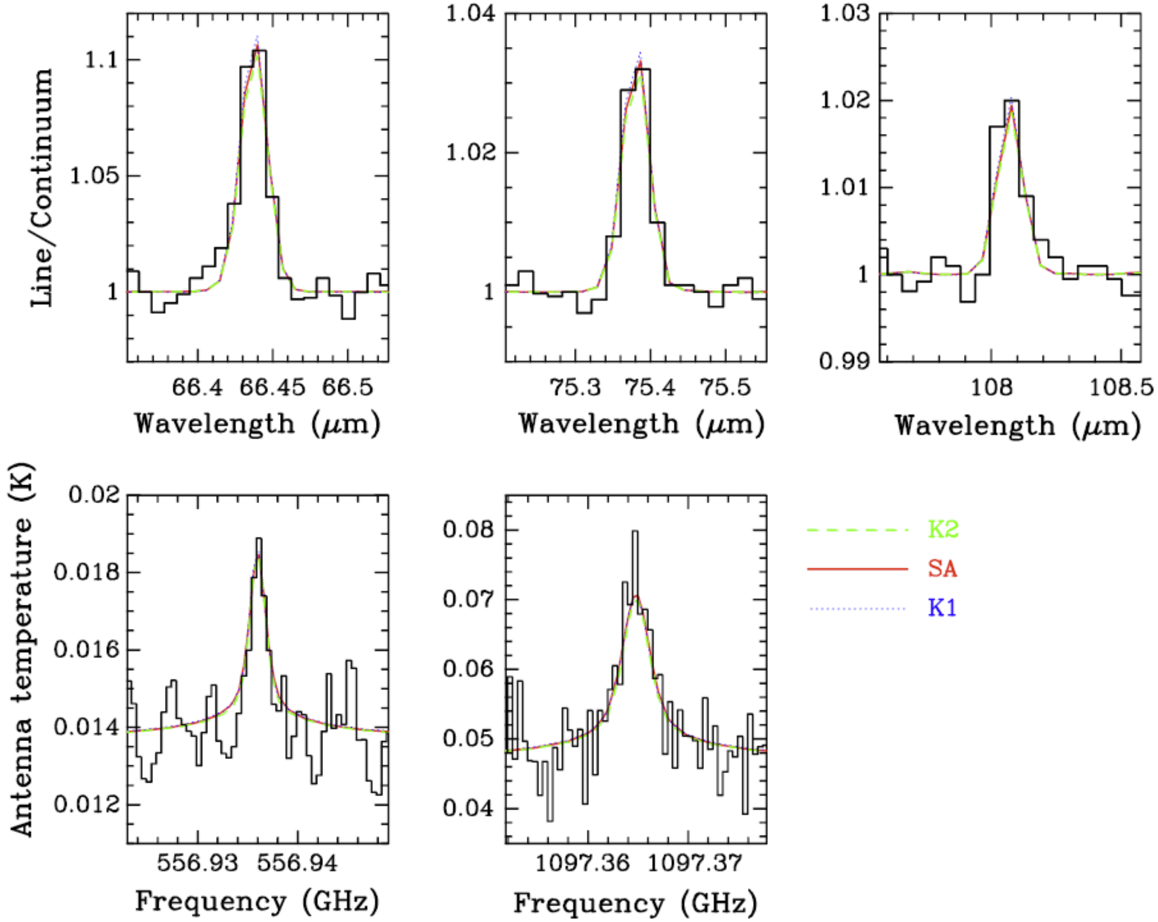


First heterodyne detection of HD (protosolar)

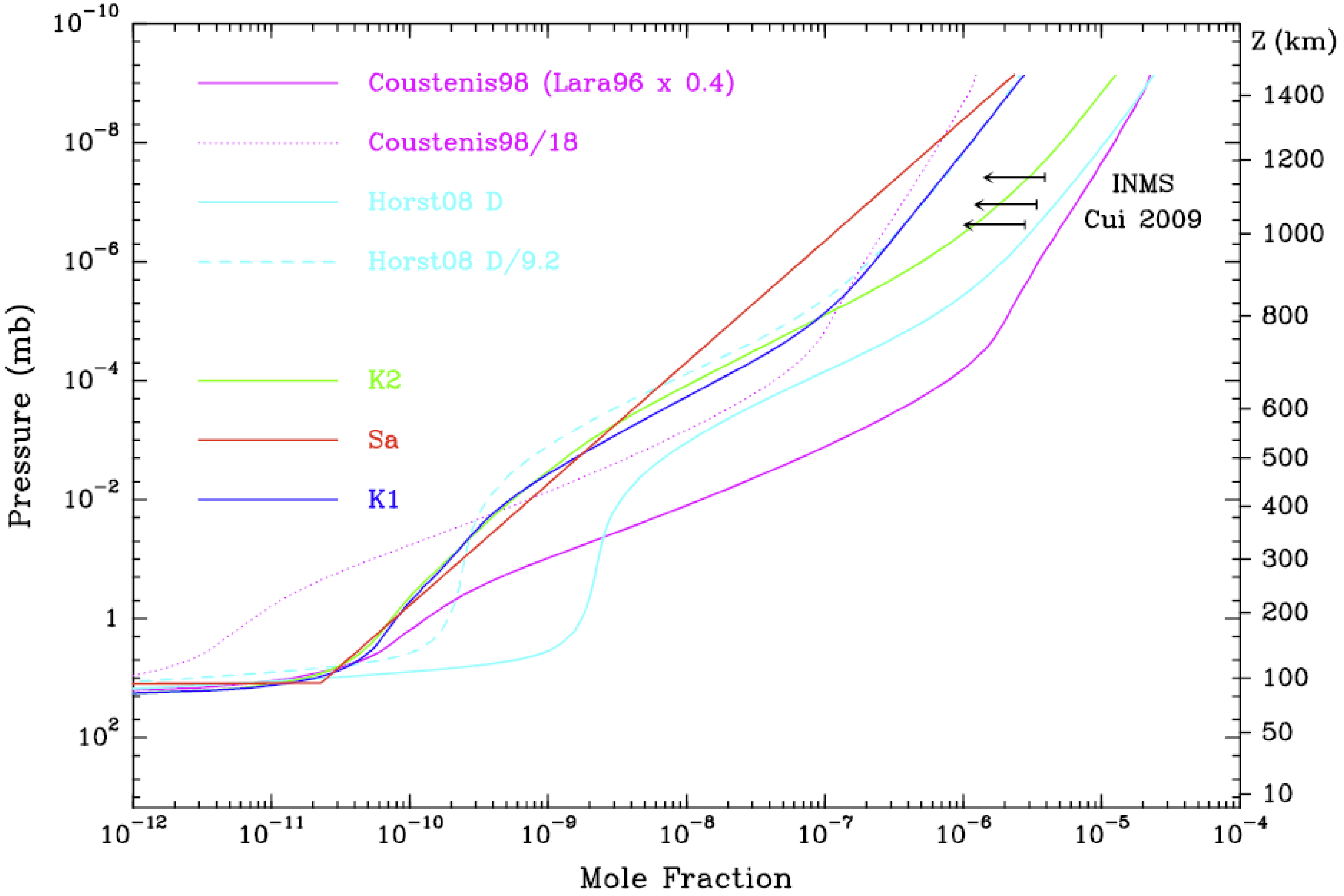
First detected pressure induced line shift

For details see Helmut's poster

Titan water with PACS and HIFI



Comparison of best fit profile with former results

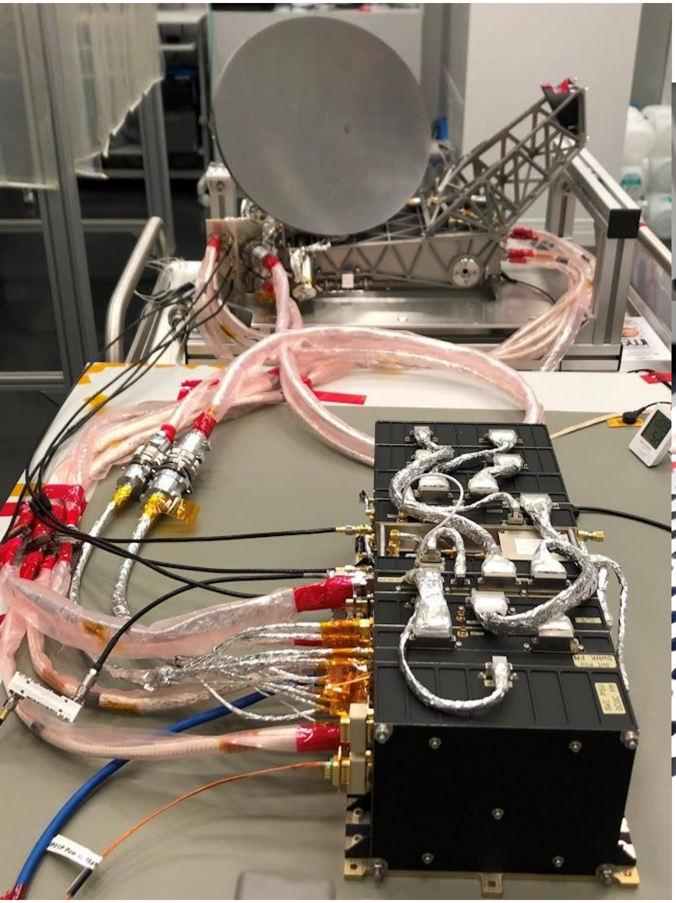


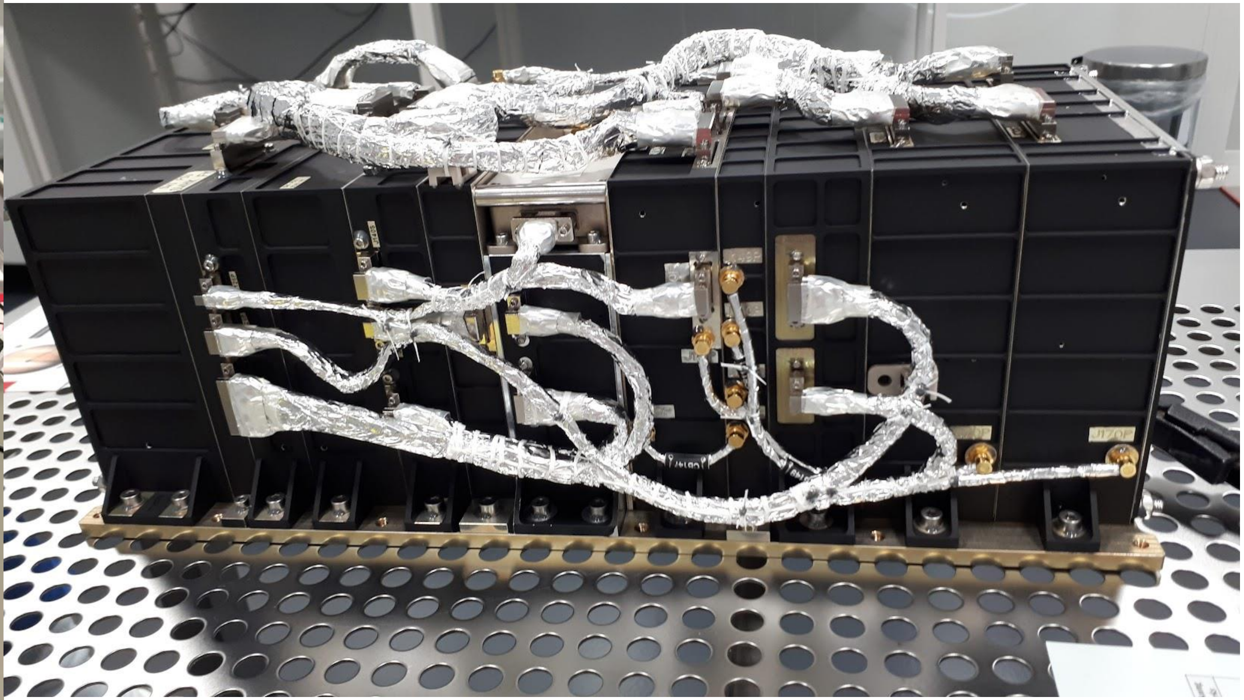
Moreno et al., Icarus, 2012

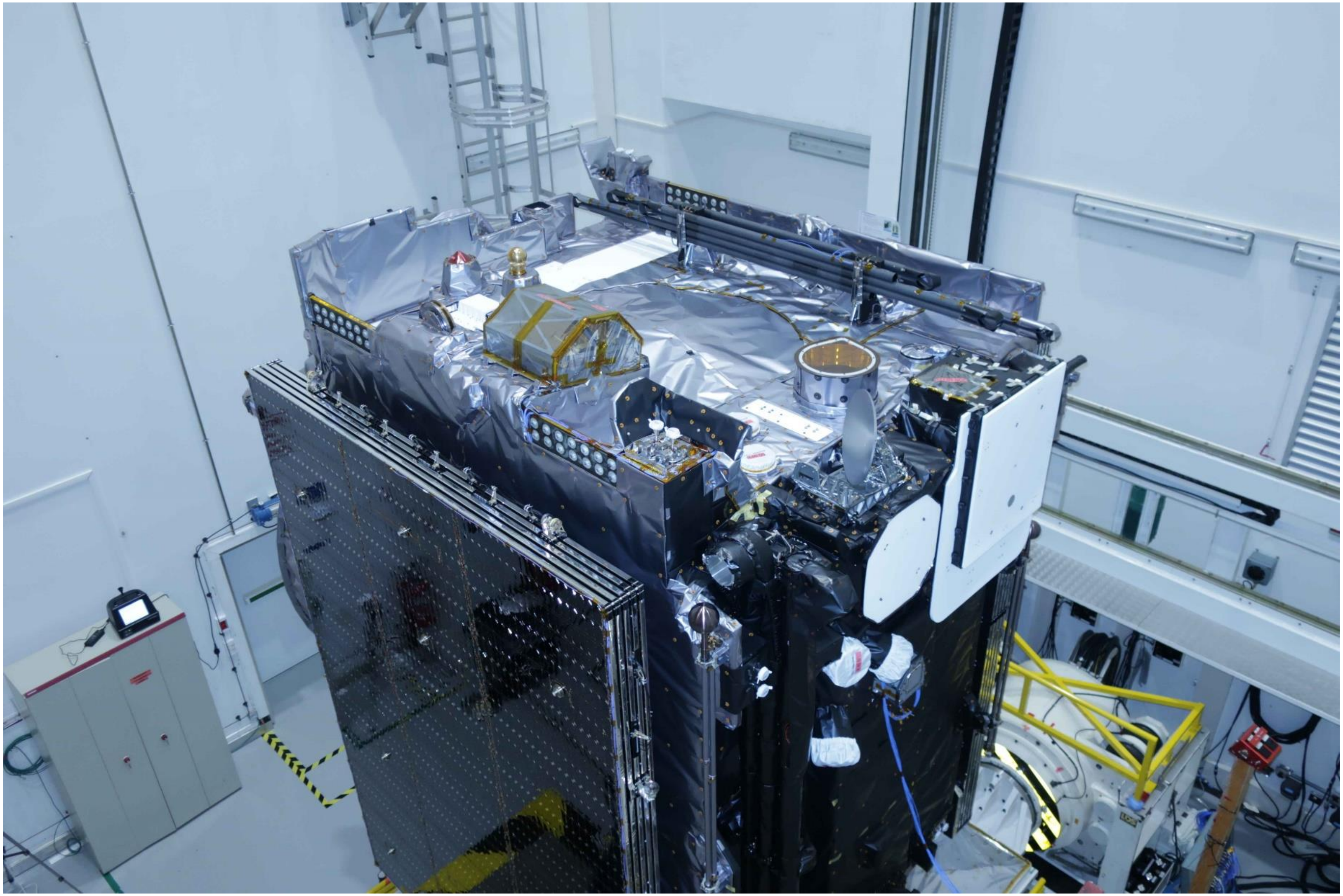
SALTUS

- Deep searches for new species
- SNR > 100 observations of water and other species for vertical profiles (SALTUS efficiency better by factor of 25 at 1 THz) retrieved from line shape
- Monitoring observations, detection of plumes.

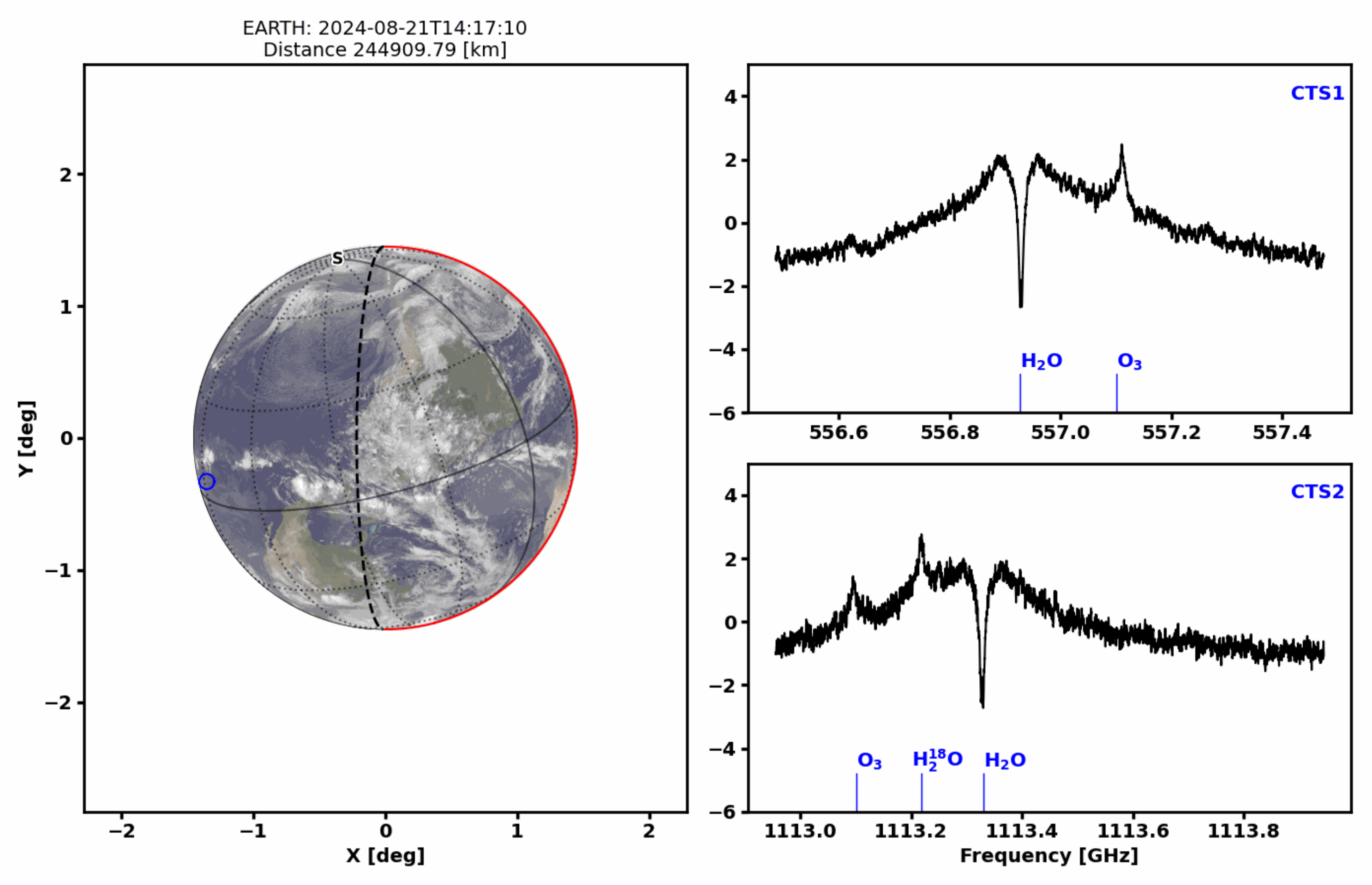
PFM: TRU and EU & connected (MPS clean room)





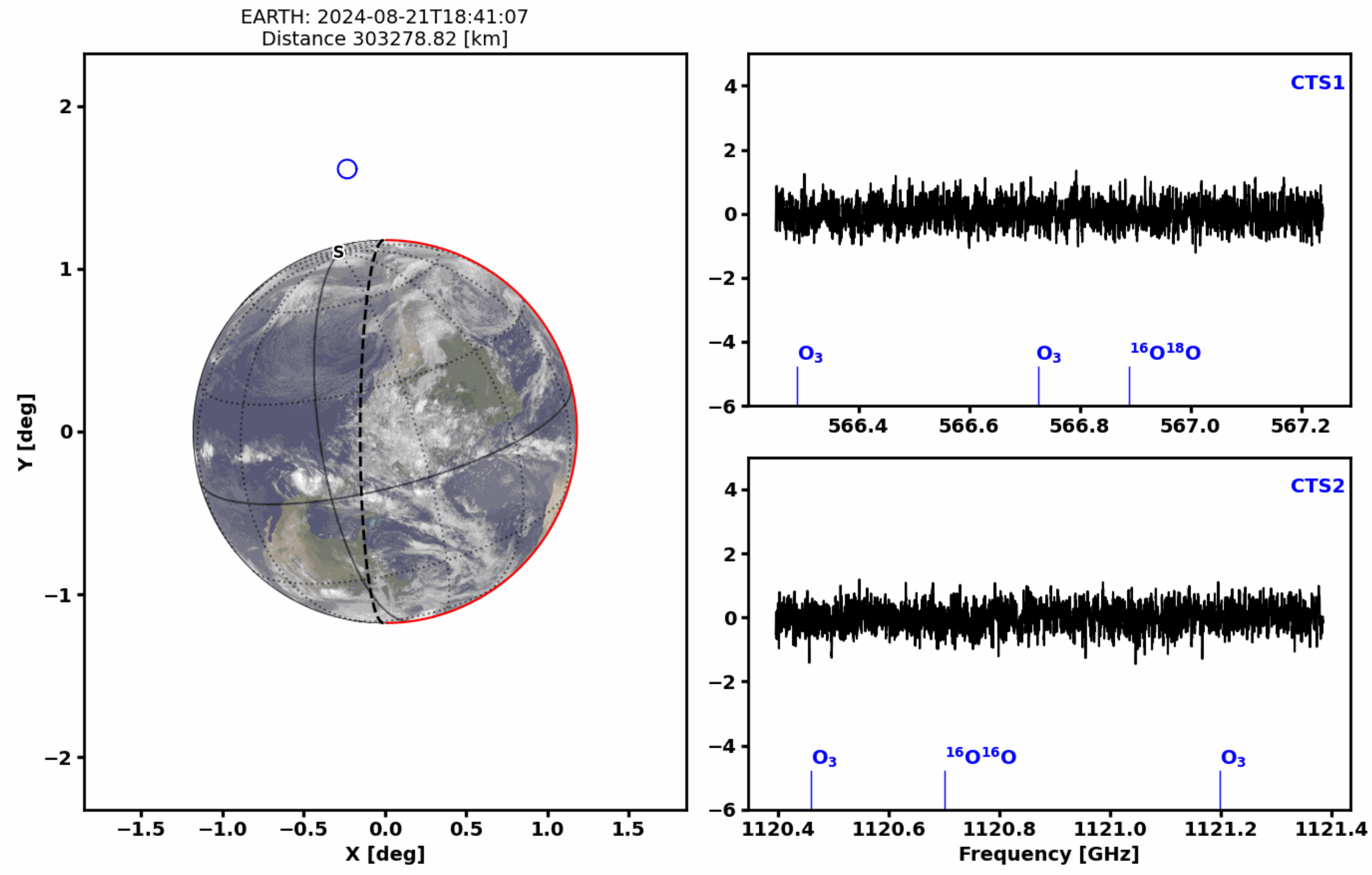


From press release (MPS & ESA websites)

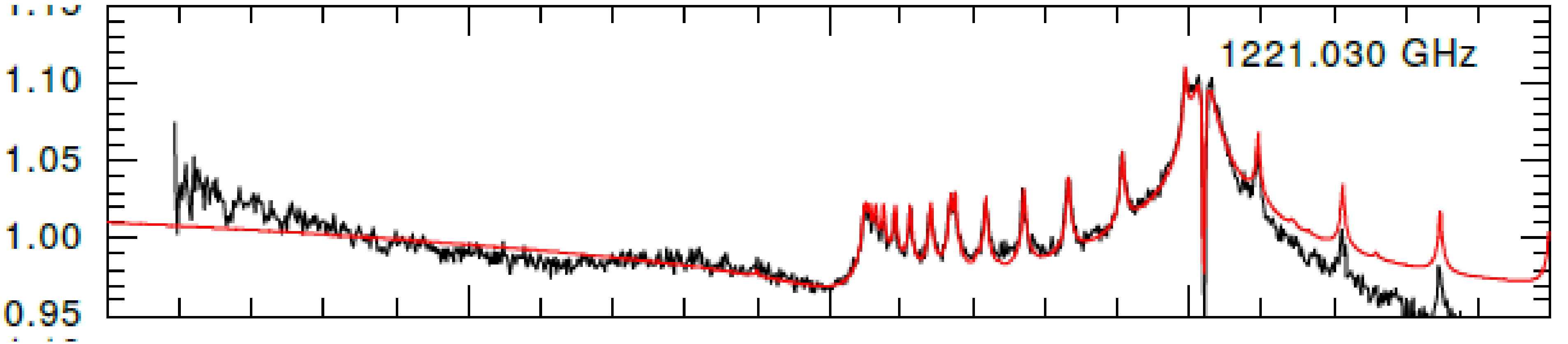


If you want to see the movie, click on the link below

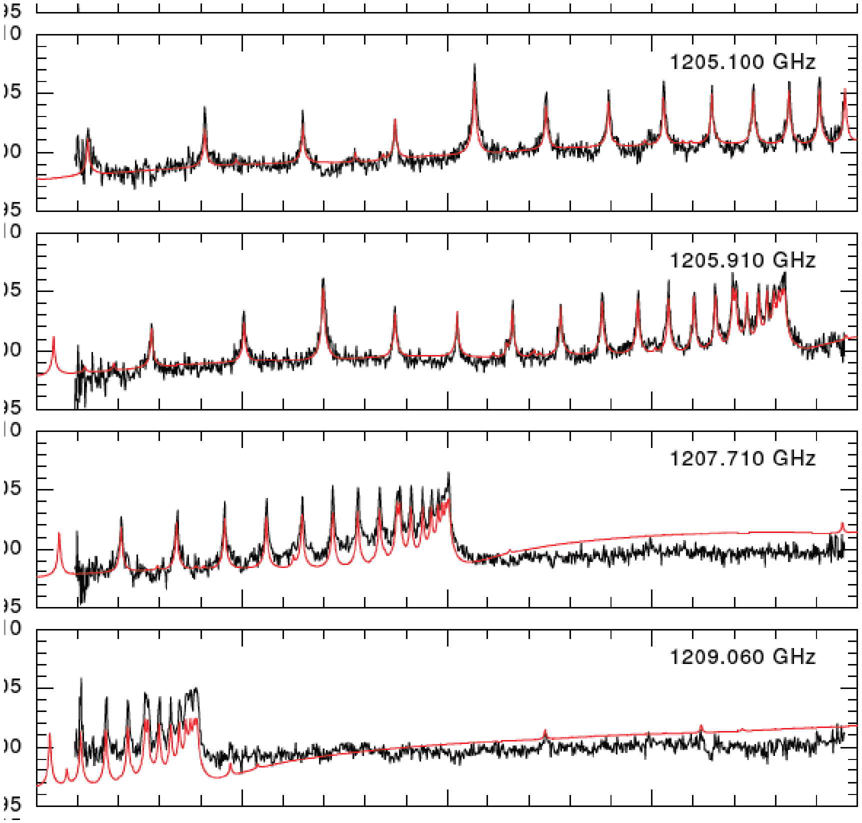
https://www.esa.int/Science_Exploration/Space_Science/Juice/Juice_confirms_that_Earth_is_habitable


EARTH: 2024-08-21T18:41:07
Distance 303278.82 [km]
Y [deg]
X [deg]
S
CTS1
CTS2
O3
16O18O
16O16O
Frequency [GHz]

Earth spectral scan obsid 421 (PS), ozone and water with 1221 GHz LO (LSB/USB)

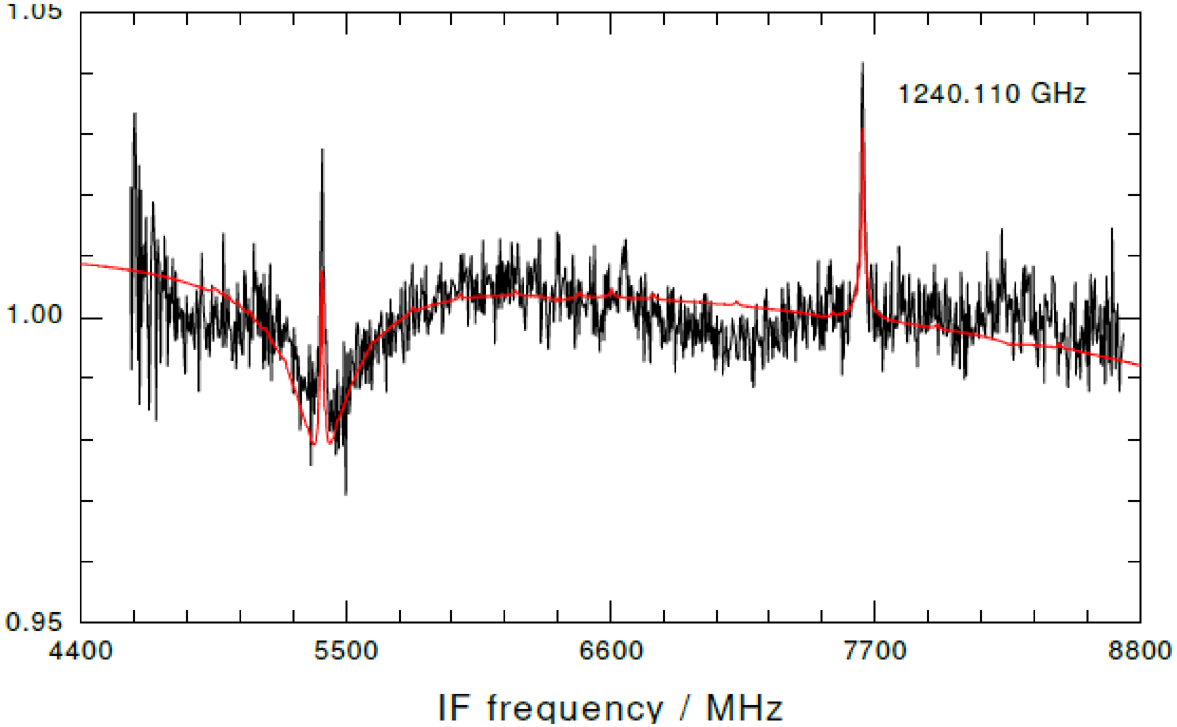


Ozone everywhere!



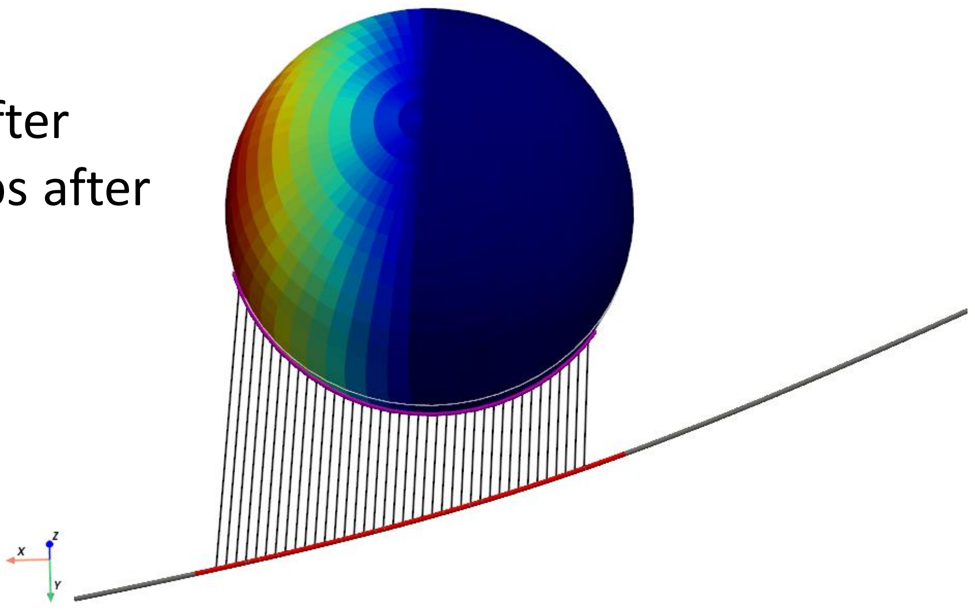
HF at 1232.47623 GHz (7.7 GHz)

This is the first heterodyne detection of HF in Earth' atmosphere

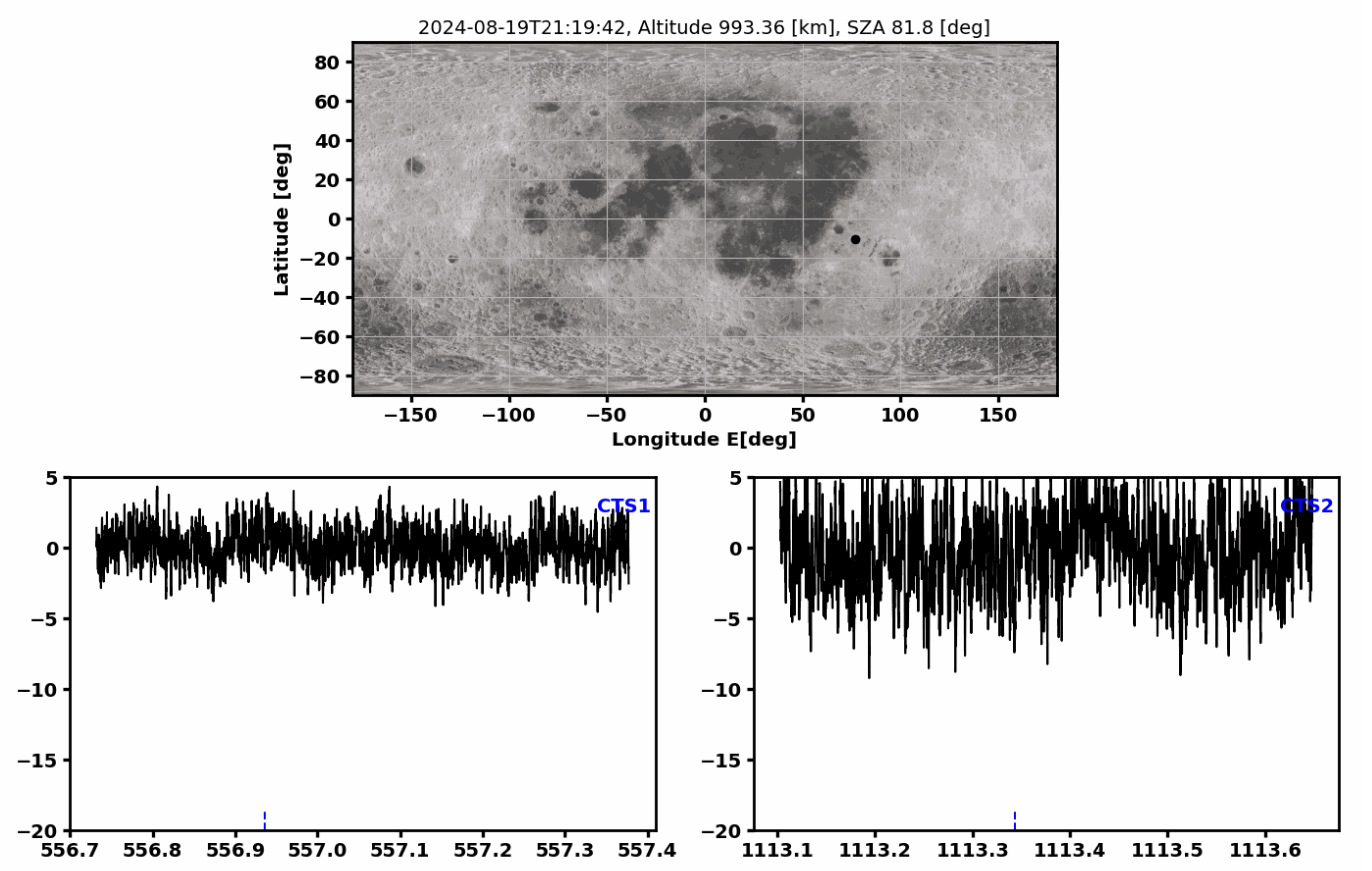


Moon flyby (SWI obs, right to left)

Water detection starts shortly after passing the terminator and stops after leaving the lunar disk



Nadir staring during moon flyby (DSB spectra)



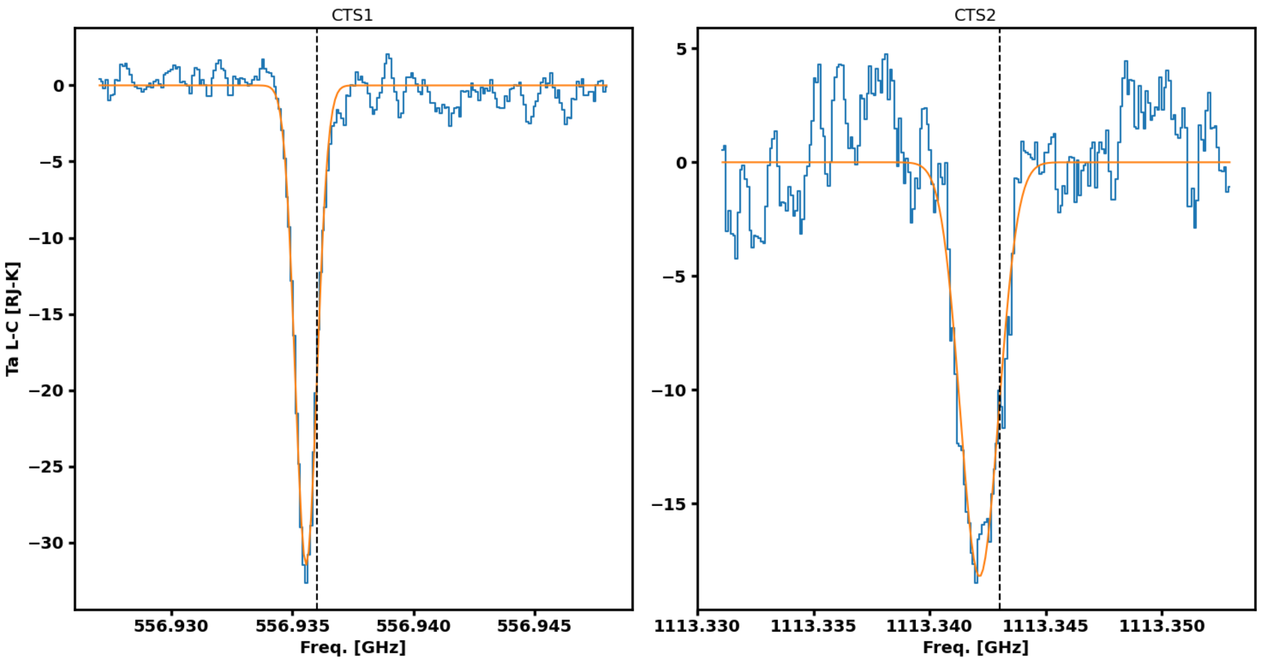
Ortho- and para water ground-state spectra (SSB)

The para water line is weaker than expected. The derived OPR is ~4, which is physically impossible.

The para water line is narrower than expected, although there is no reason why the temperatures should be different for the two lines.

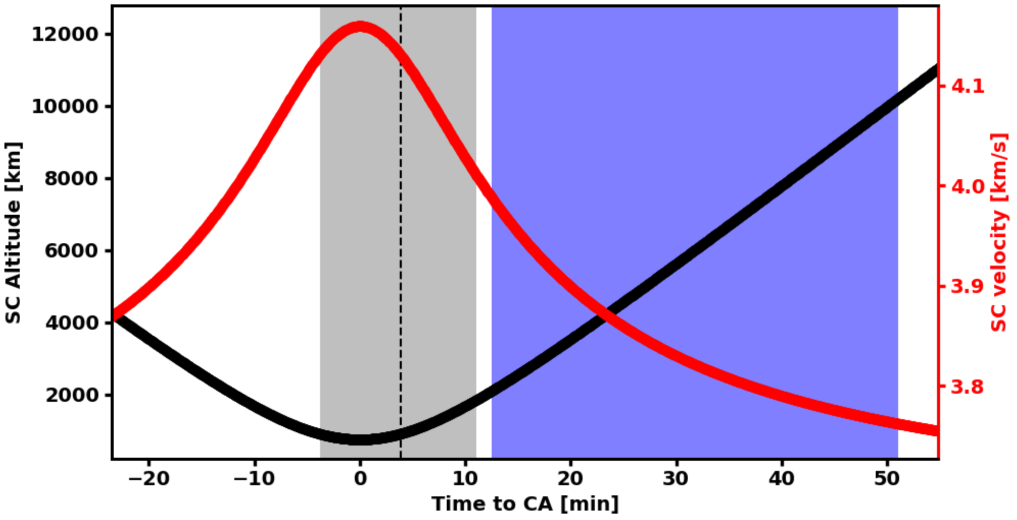
The Doppler shift of both lines is compatible and does not rule out a source on the moon.

There is no detection, pointing to the non-illuminated lunar disk and to cold space, although from the line width derived temperatures there should be emission spectra.



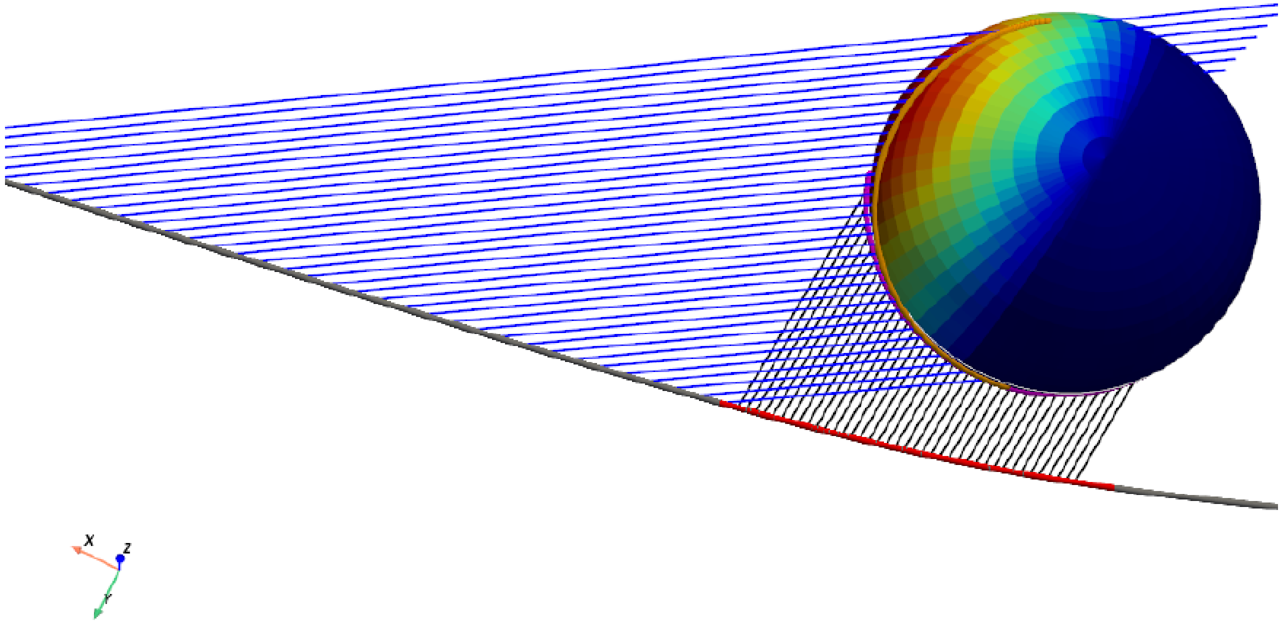
Water on the moon?

- Although the detected line features were not completely understood at the beginning, it could very well be that we see a water atmosphere near th



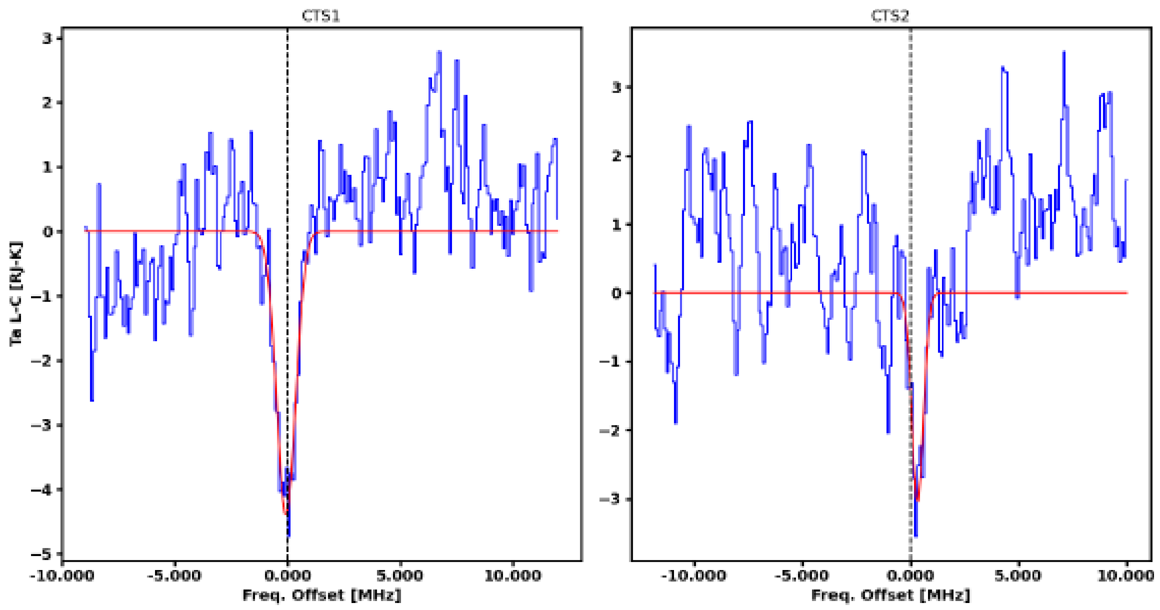
However later observations rule out a lunar source.
In the graph right the grey area shows the time SWI points on the moon. The blue area shows looking back towards the moon.

Looking backwards ~12 to 52 min after CA



Moving away from the moon, Doppler shift shall be much larger, but the measurement shows lower Ds

Conclusion: the water signal cannot originate in the moon. Most likely we see a source on the spacecraft.



Hypothesis 1: Haser model approach

- Outgassing like in a comet. $1/r^2$ decay. Homogeneous distribution of water vapour.
- Sphere around S/C with 2-10 km radius (detection limit of SWI)
- Sphere flies with S/C speed and expands with a few 100 m/s
- Gas temperature 100-130 K (explains at least the 557 GHz line width)
- Para-water line at 1113 GHz line should be twice as broad as the ortho-water line 557 GHz line, but is only 1.8 x wider. Also the amplitude is smaller than expected: we derive an ortho-to-para ratio of 4 which is not physical.
- Emission lines vs cold space and cold lunar surface shall pop up, but not observed

Hypothesis 2: 1/r2, but inhomogeneous expanding

- Inhomogeneous distribution of water over distance
- Macroscopic speed variations within water vapour cloud (turbulence)
- Gas expands adiabatically to very low temperatures of < 20 K (comp. Hartogh et al. A&A 2011 on Enceladus torus)
- Initial lines narrower, line broadening by macroscopic processes (turbulence).
- Emission lines not detectable, because contrast at <20 K gas temperature against cosmic background (2.7 K) too low. For the cold lunar areas it shall be in absorption, but not observed, because the vapour production started after passing the terminator.
- Lines can be fitted and line shape parameters can be explained.
- Deviation from initially expected line width can be explained by different volumes being sampled by the two beams (1113 GHz narrower, sampling only half of the area and thus smaller speed variations, i.e. explains the factor of 1.8 rather than 2).

Hyphothesis 2 results thus far:

- Water production rate about 66 mg/s while flying over the moon, total mass ~ 22 g (~ 6 min).
- If 50 % are directed into - S/C velocity vector direction, platform temperature of 240 K required to accelerate S/C by 0.7mm/s (initial speed of water vapour molecules ~ 400 m/s).
- Water vapour column density ~ 1E16 m^{-2} down looking
- Water vapour column density ~ 1E15 m^{-2} back looking
- Doppler shift of the line is likely associated on some preferred outgassing direction => future work.
- First guess of upper limit for lunar water vapour.

Results

- First highly resolved (1E6 and 1E7) spectral measurements of 1075 to 1280 GHz range of the Earth atmosphere from space with exiting results
- Some spectral features not understood yet
- First detection and characterization of S/C water vapour atmosphere by a remote sensing instrument (including some fundamental hydrodynamics studies)
- Quantification of the “solid state booster” effect