Wrap-up: The Solar System and its Evolution

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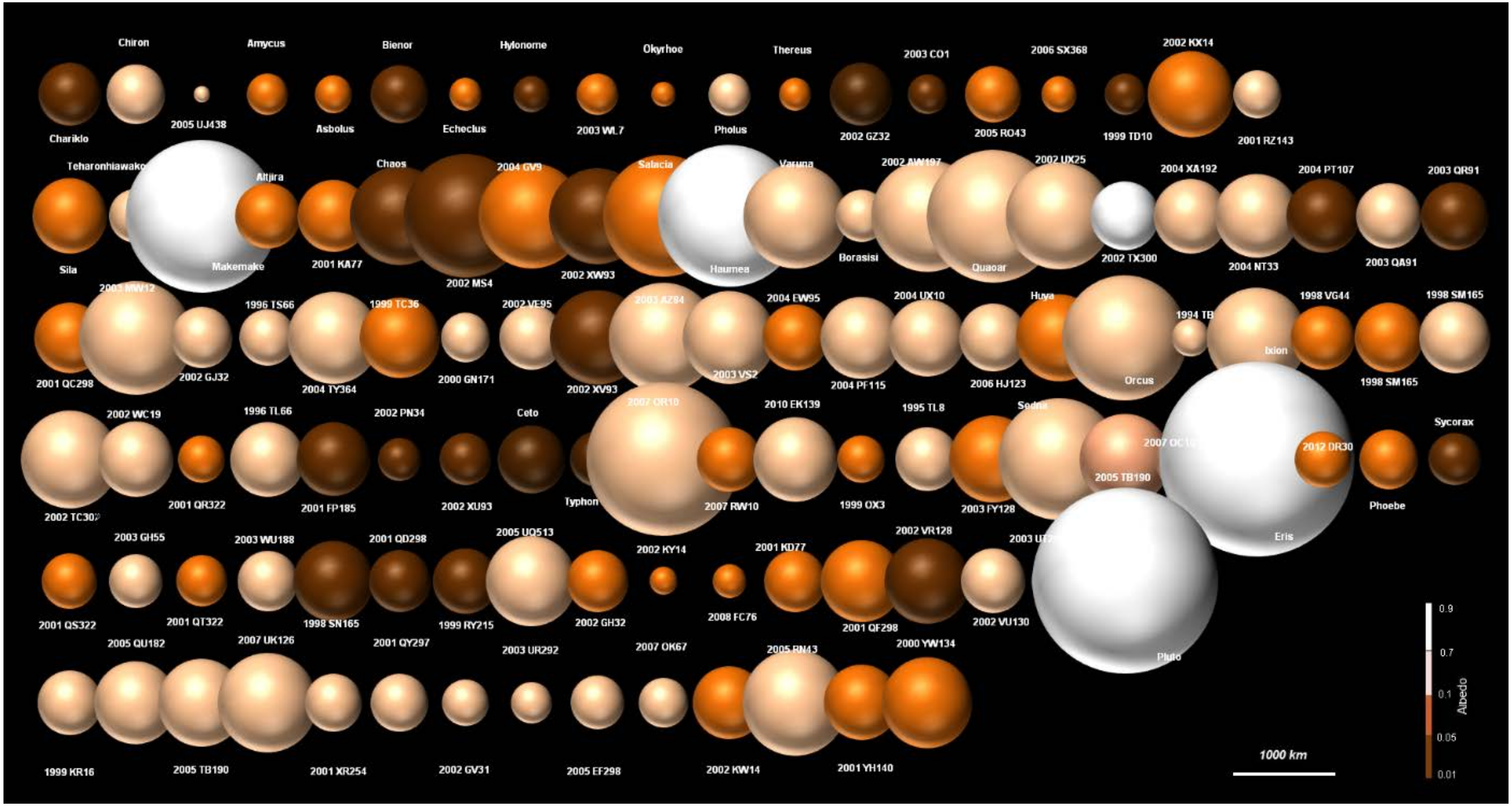
TNO Fundamental Properties: Size & Albedos



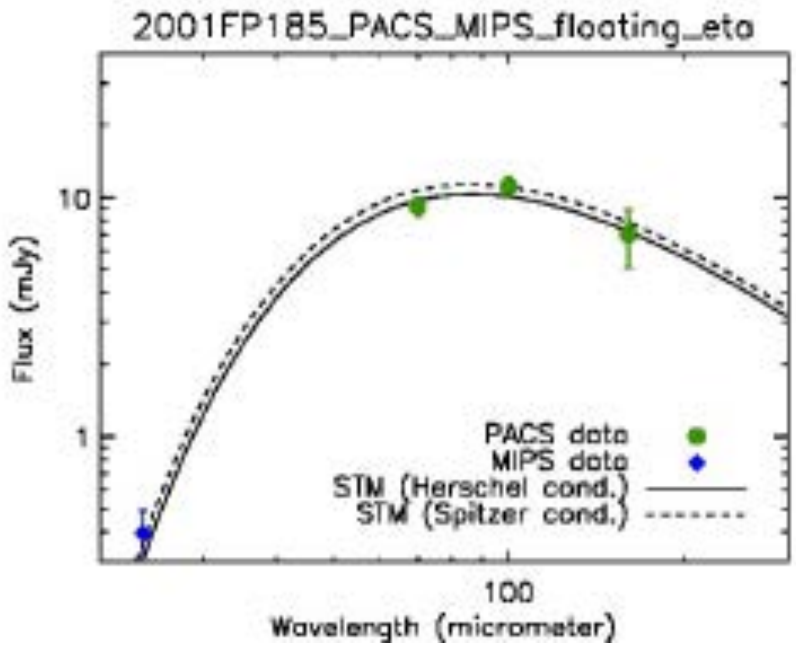
Müller et al. 2010, Lellouch et al. 2010, Lim et al. 2010
Mommert et al. 2012, Vilenius et al. 2012, Santos-Sanz et al. 2012
Fornasier et al. 2013, Duffard et al. 2013, Vilenius et al. 2013

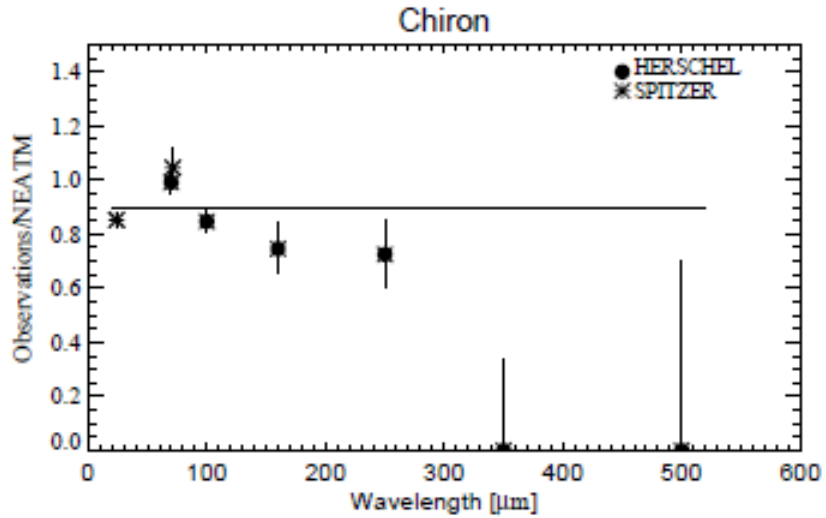
TNOs

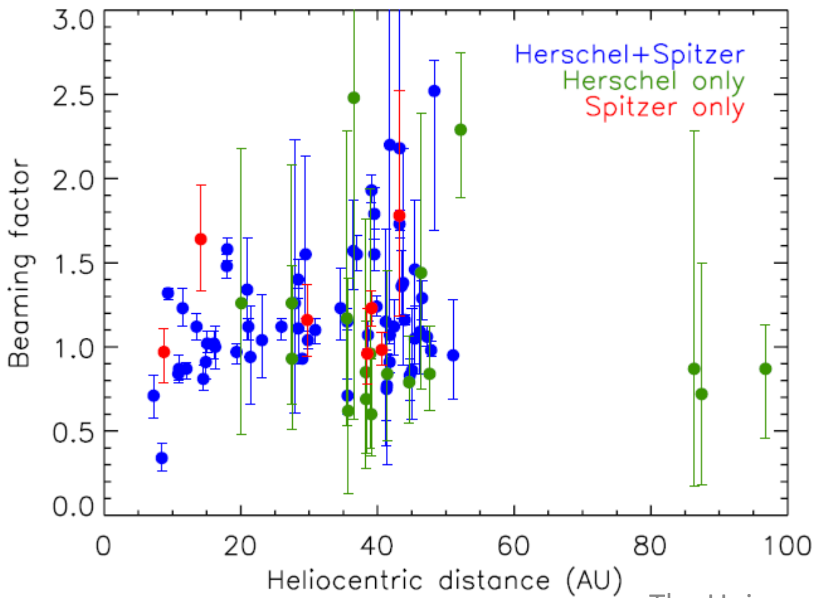
- Diameter and albedo of 115 objects with sizes from 100 to 2400 km (Pluto/Eris) and albedos from 3 to 100 %.
- Very different from the main-belt objects. Very large diversity. Object properties point to different evolution processes for different dynamic classes.
- Very high albedos require resurfacing process to maintain such a high albedo over longer timescales. Cryovolcanism for the large and high albedo objects?

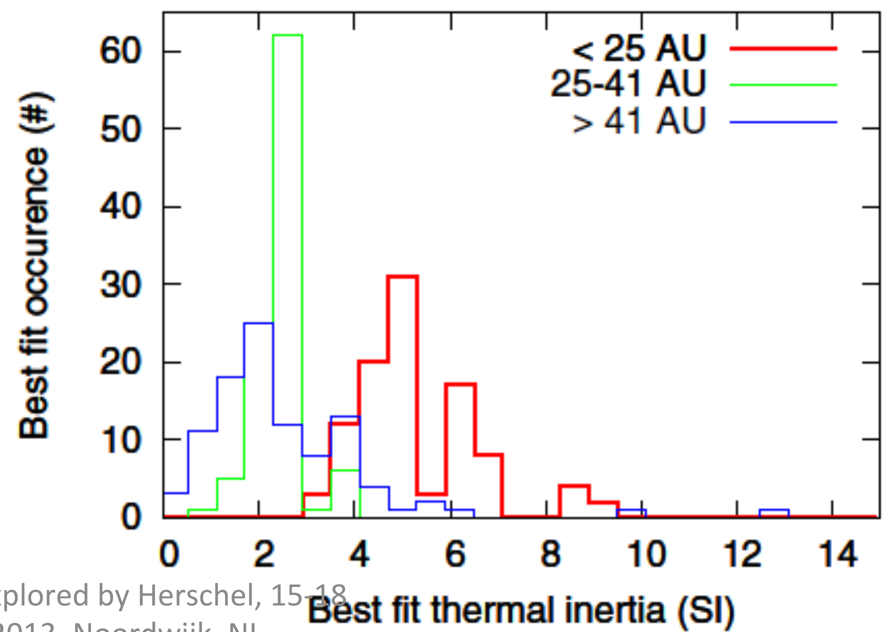
TNOs

- Densities for about 25 binary systems: 0.4 ... 2.5 g/cm3: different formation mechanism?
- Thermal lightcurves (for 5 objects) show rotationally deformed bodies.
- Thermal properties point towards very rough, porous, extremely low thermal conductivity surfaces.
- TNOs have very low thermal inertia:
  - Mean value = 2.5 $Jm^{-2}s^{-1/2} K^{-1}$
  - Decreases with increasing heliocentric distance
- Spectral emissivity of TNOs decreases with increasing wavelength

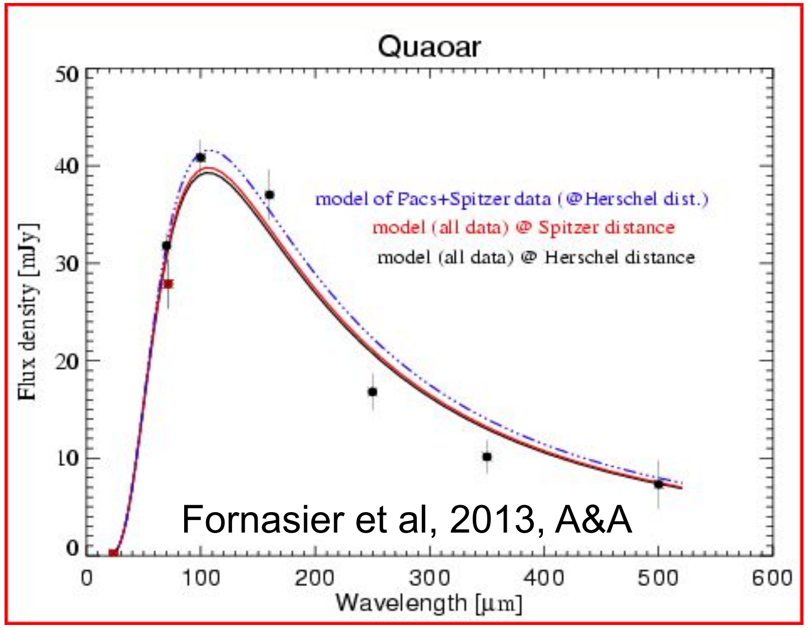

2001FP185_PACS_MIPS_floating_eta
Flux (mJy)
Wavelength (micrometer)
PACS data
MIPS data
STM (Herschel cond.)
STM (Spitzer cond.)


Chiron
Observations/NEATM
Wavelength [µm]
HERSCHEL
SPITZER


Beaming factor
Heliocentric distance (AU)
Herschel+Spitzer
Herschel only
Spitzer only


Best fit occurence (#)
Best fit thermal inertia (SI)
< 25 AU
25-41 AU
> 41 AU

Classical TNO: 50000 Quaoar



NEATM RESULTS:

p_V (%) = 12.7 ± 1.0

D = 1074 ± 38 km

η = 1.73 ± 0.08

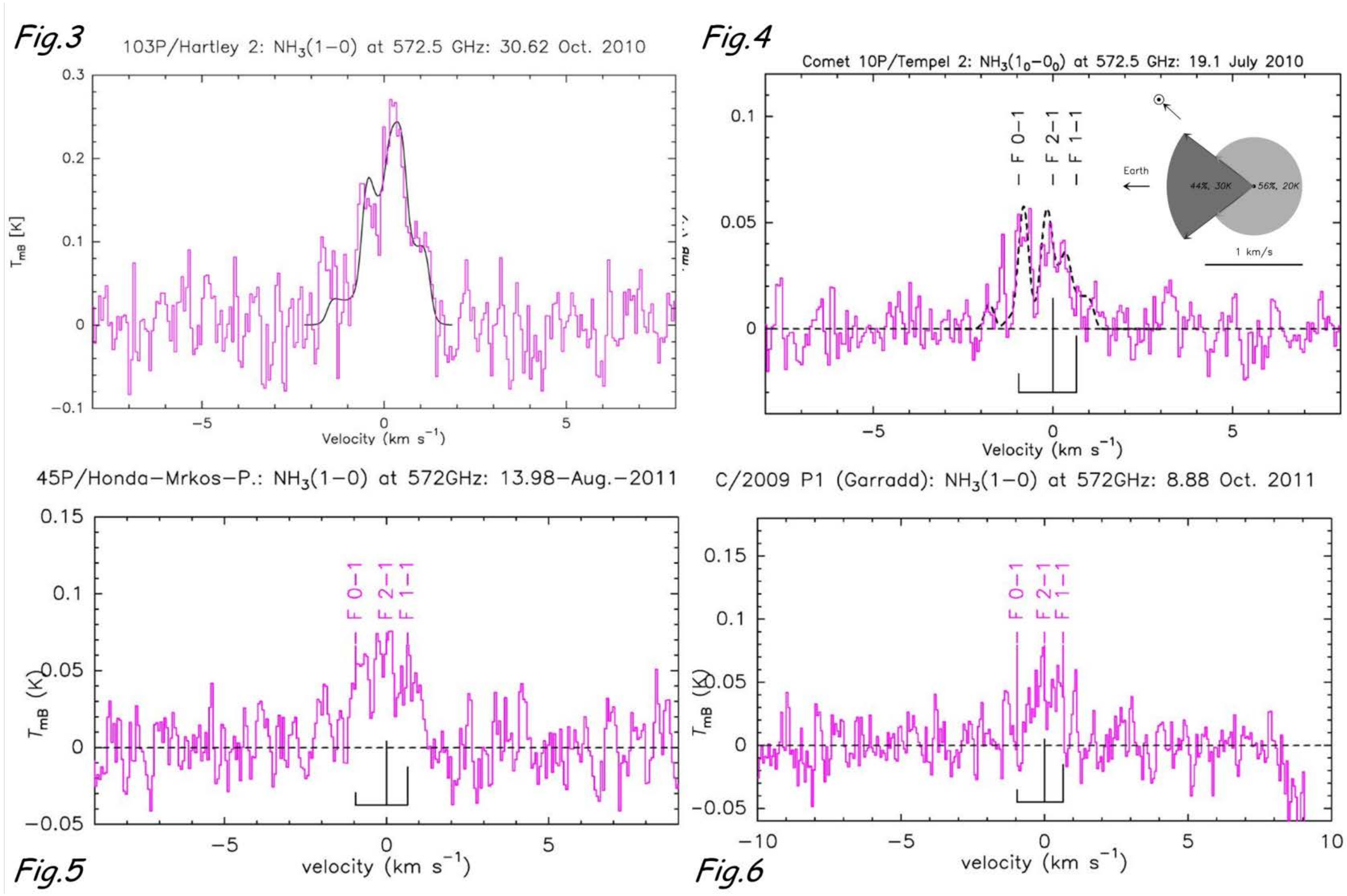
ηmean = 1.47 ± 0.43 (19 classicals, from Vilenius et al 2012)

Previous size estimates: Hubble direct: 1260 ± 190 km (Brown & Trujillo 2004); 870±70 km (Frazer &Brown 2010) Spitzer radiometric: 844 ± 207 km (Stansberry et al. 2008) Spitzer radiometric: 908 ± 118 km (Brucker et al. 2009)

New occultation effective size estimate: 1111 ± 5 km (Braga-Ribas et al. 2013)

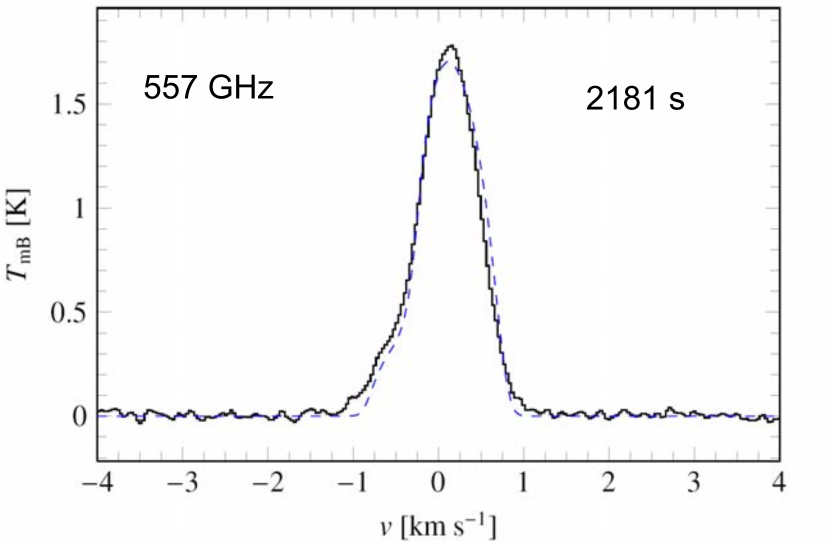
Quaoar is a binary system of known mass (1.6 ± 0.3) x10^{21} kg with a smaller companion, Weywot.
With the size determined from Herschel data we derive a density of 2.2± 0.5 g/cm^3, similar to that of Pluto (Frazer & Brown (2010) got an unlikely density of 4.2±1.3 g/cm^3, from their HST Quaoar size estimation). Assuming the same albedo for the 2 bodies, we derive a diameter of 1070 ± 38 km for Quaoar, and 81 ± 11 km for Weywot.

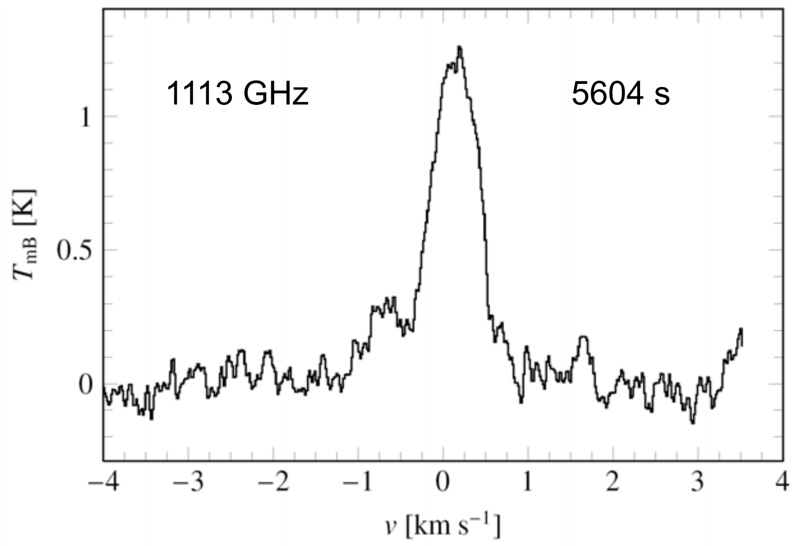
Ammonia in comets with HIFI

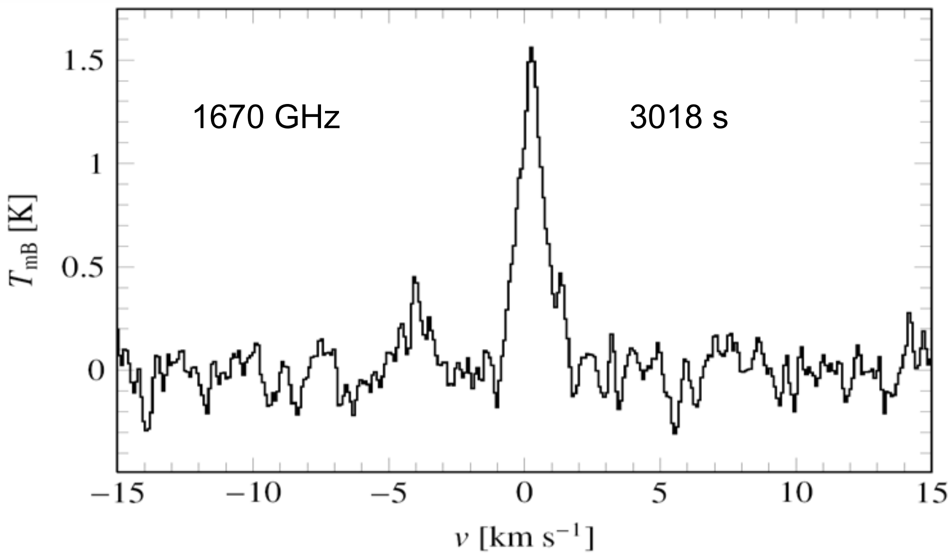


NH_3/H_2O ~ 1/200 Biver et al, 2012

HIFI: 3 water transition in C/2008 Q3 (Garradd) constraining water excitation models







Observed relative line intensities in good agreement with models.

Models agree within 5%

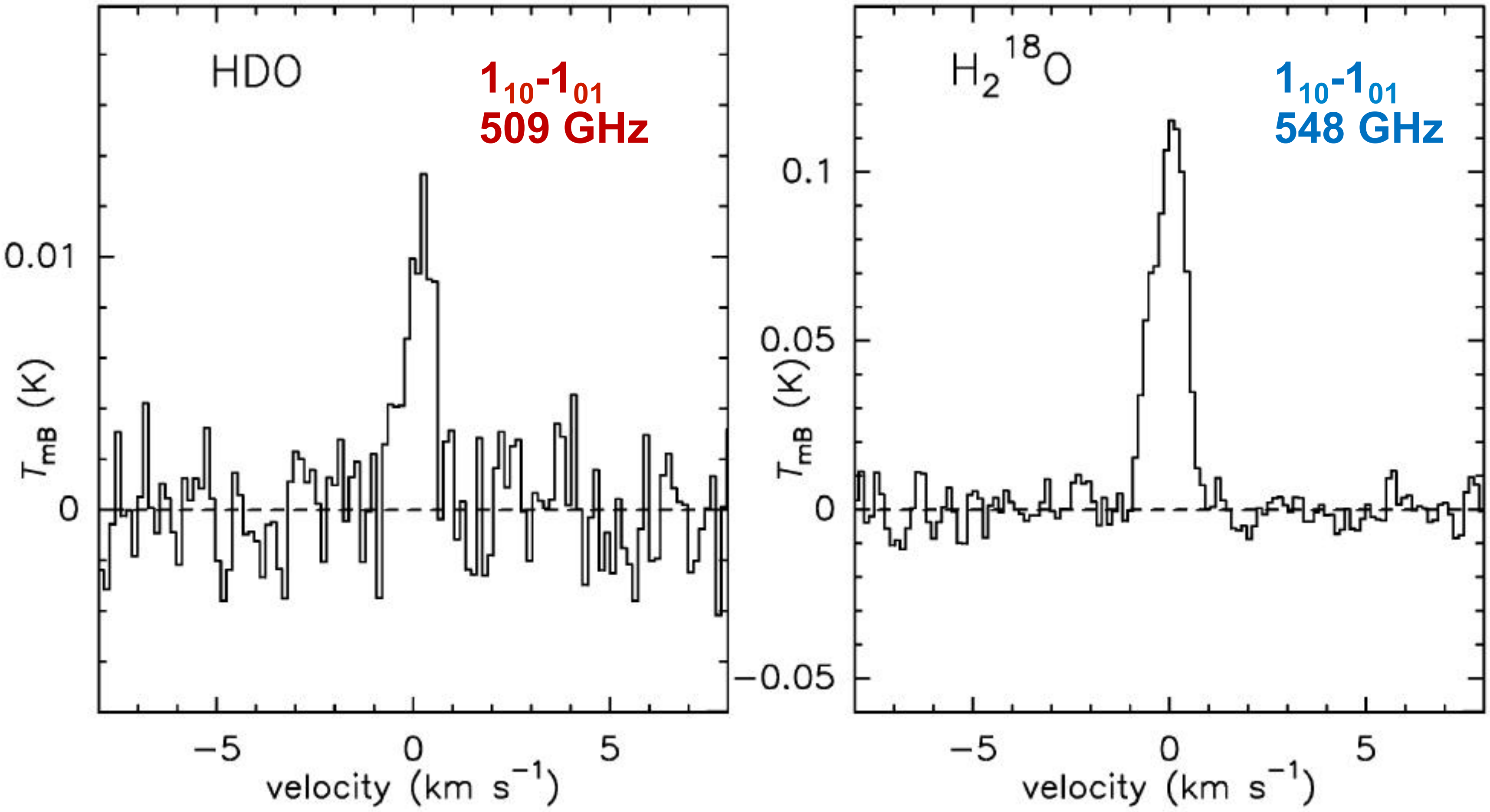
Hartogh et al. (2010), A&A

First D/H in Jupiter family comet

103P/Hartley 2

Observed spectra:

Hartogh et al. Nature (2011)



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

Analysis of the observations

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

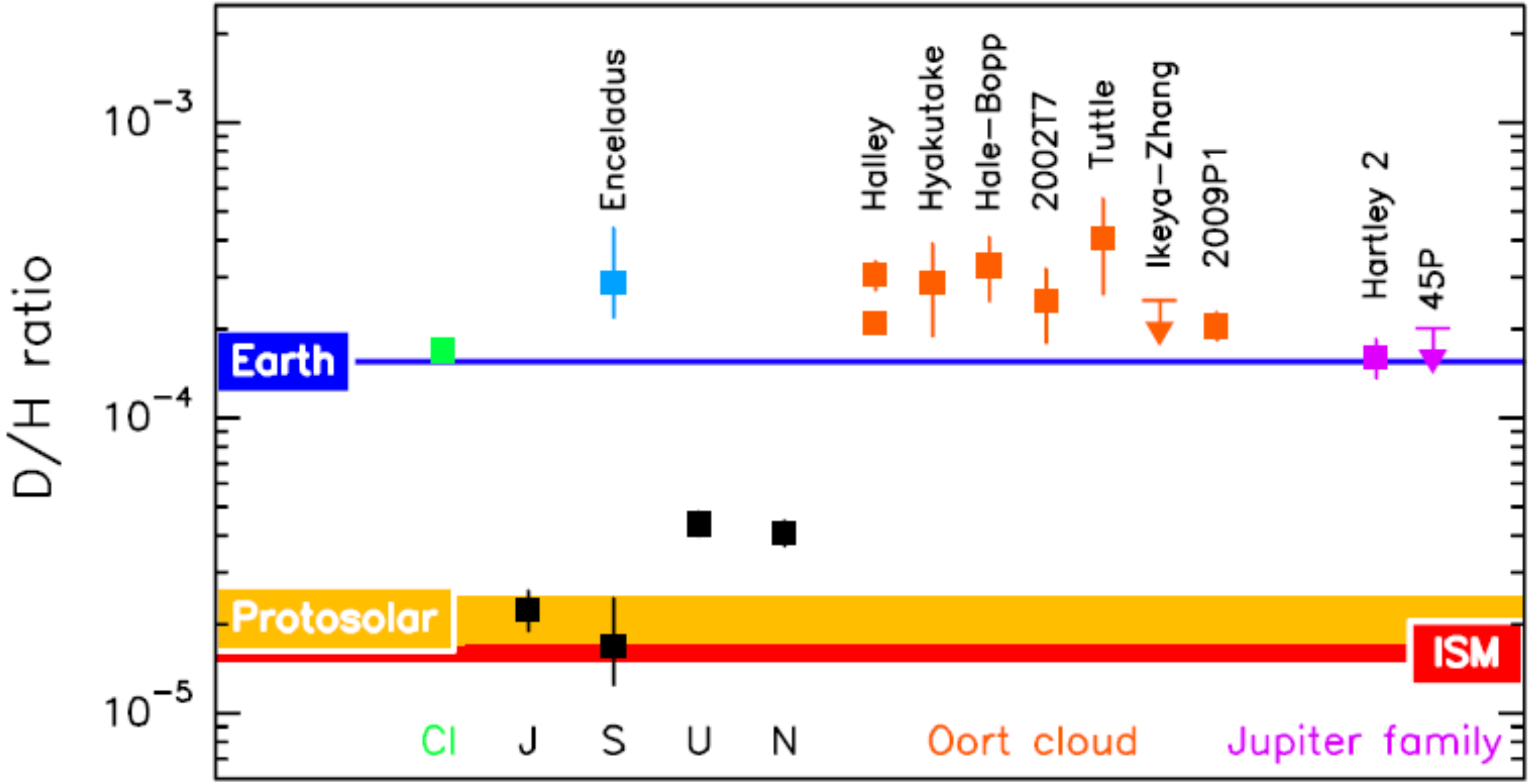
- → the $HDO/H_2^{18}O$ production rate ratio is not very sensitive to the model parameters (similar transition: $J = 1_{10}$-1_{01})

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

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

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

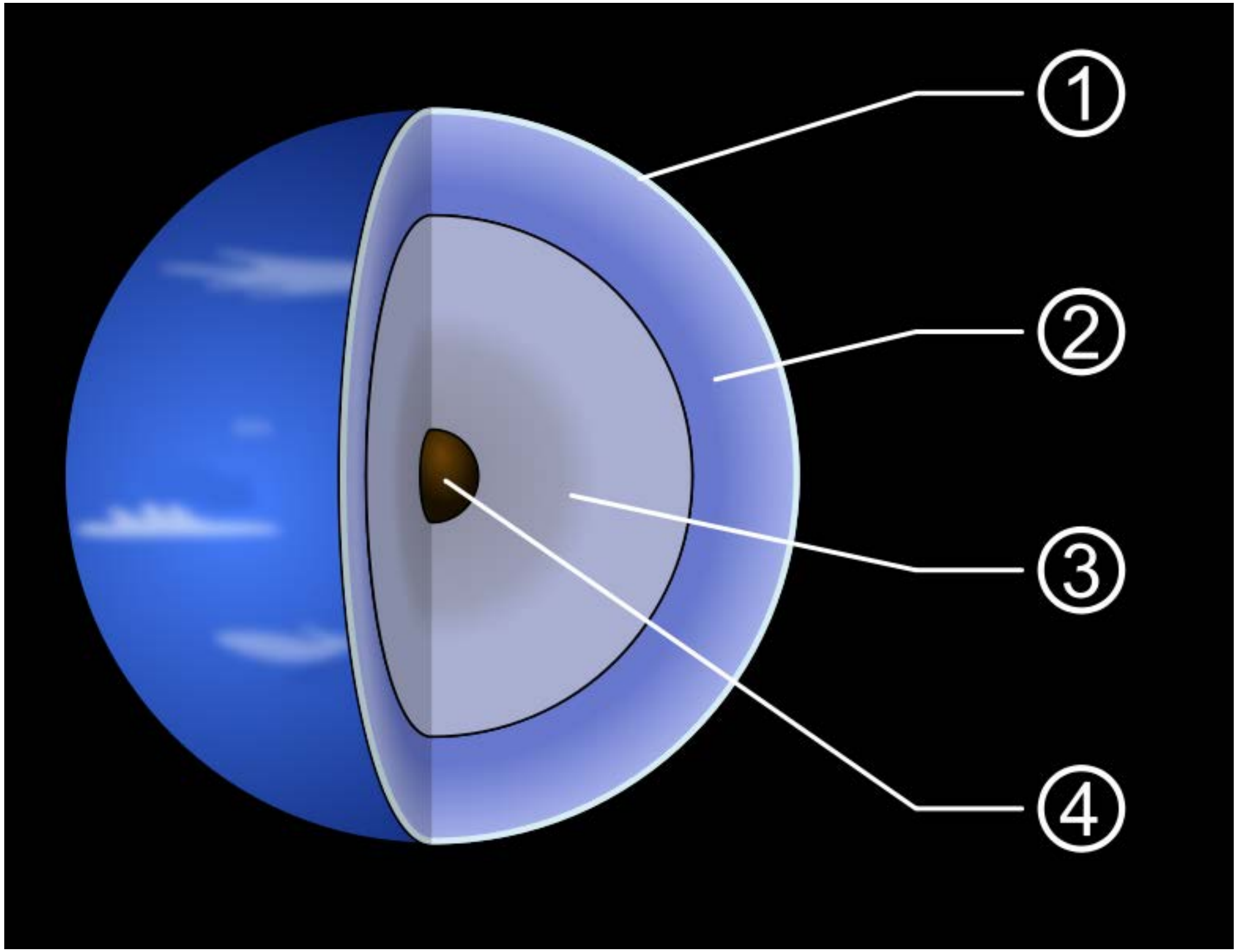
Deuterium in Solar System after Herschel



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



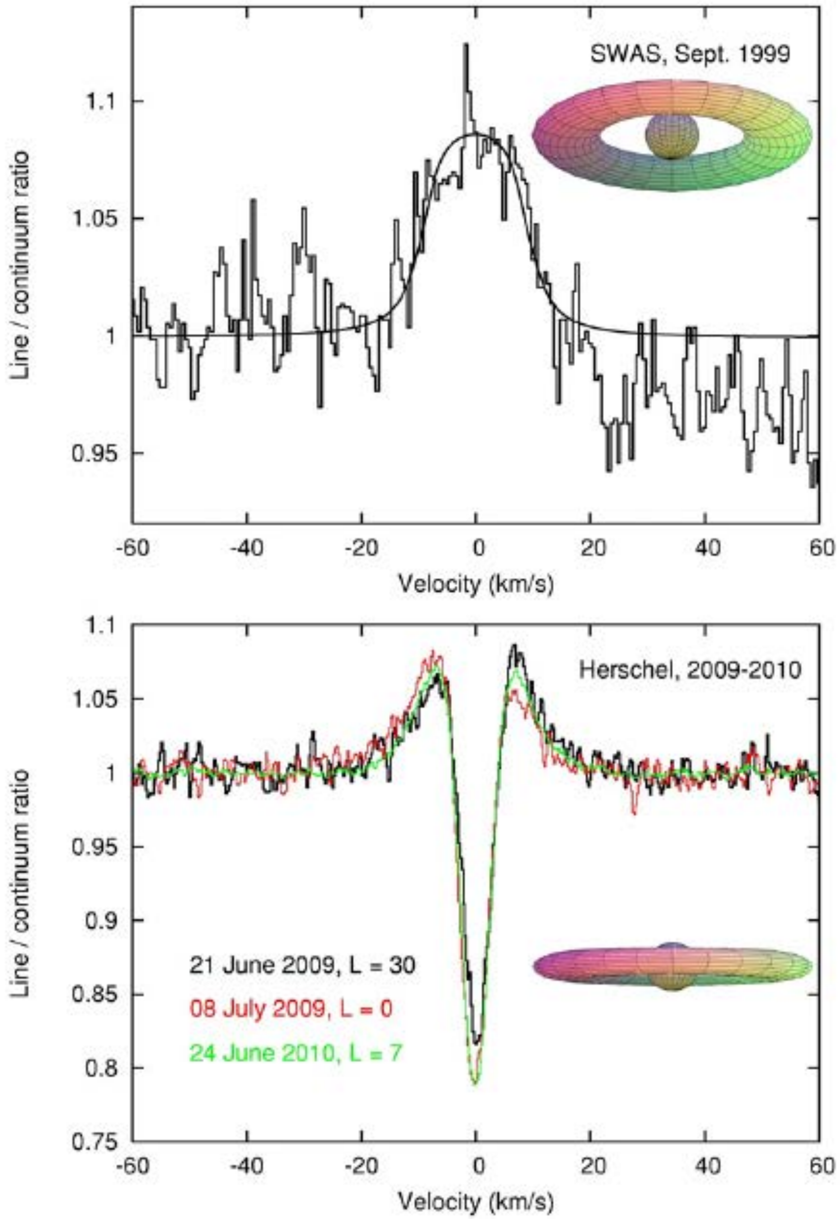
1. Upper atmosphere, top clouds
2. Atmosphere consisting of hydrogen, helium and methane gas
3. Mantle consisting of water, ammonia and methane ices
4. Core consisting of rock (silicates and nickel-iron

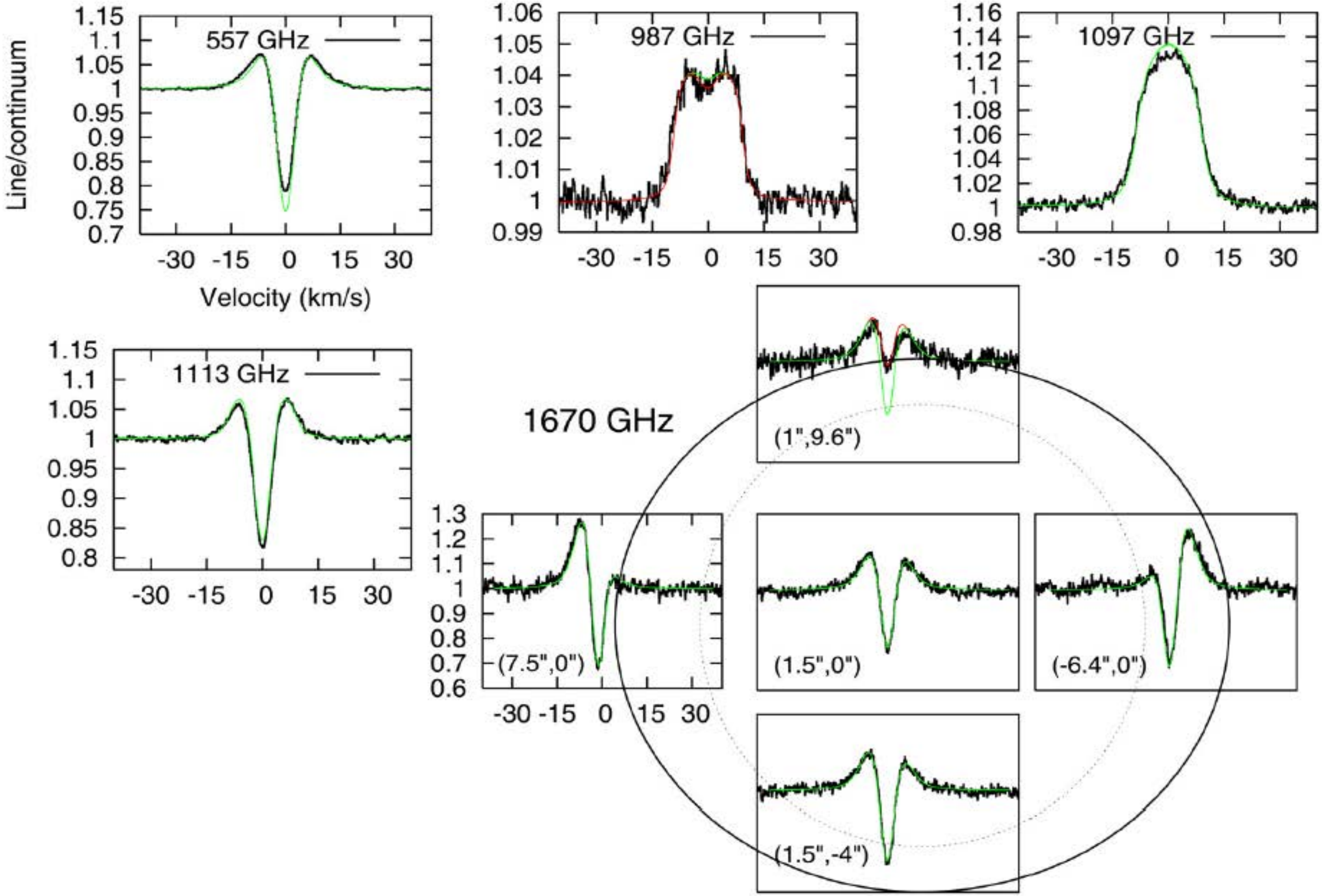
Ice Giants may be Rock Giants

- 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.

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

First detection of the Enceladus water torus




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

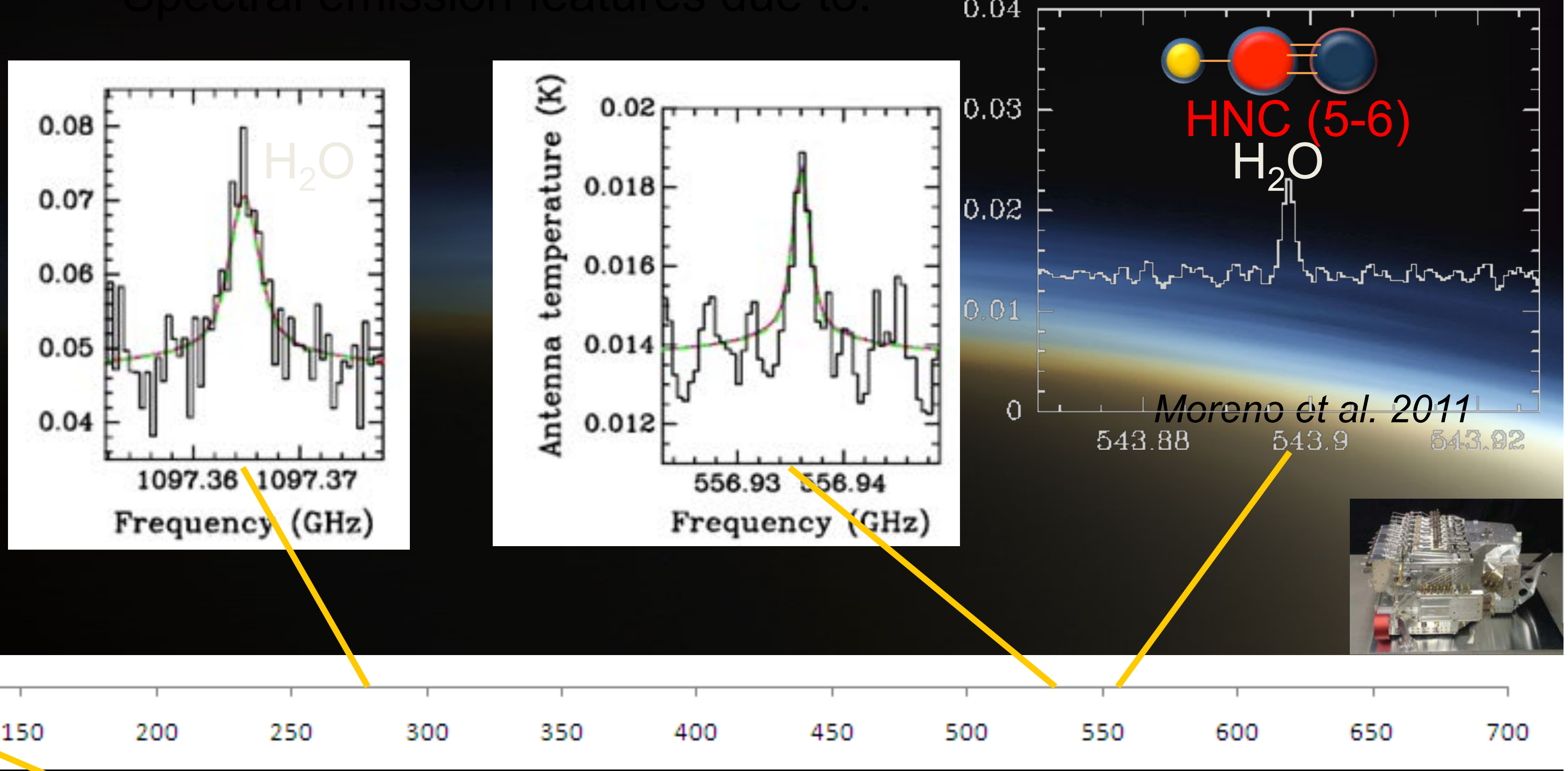
Conclusions Enceladus water torus

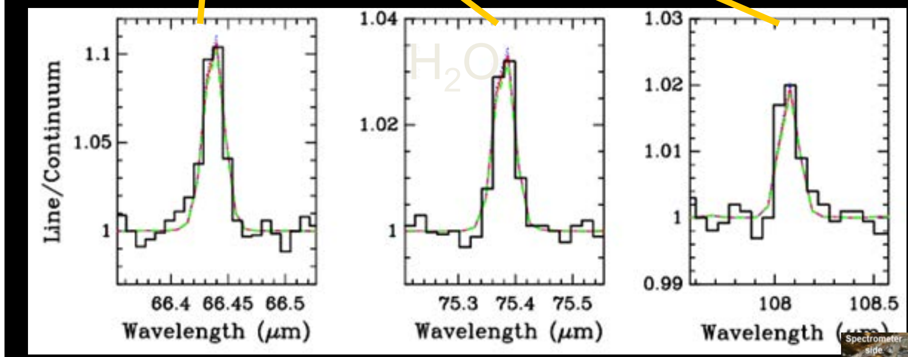
- Extension about 10 Saturn radii (R_s)
- Highest density around a distance of 4 R_s
- Thickness about 50000 km
- About 3 % of the water produced by Enceladus rains into the upper atmosphere of Saturn
- Enceladus is rather likely the source of stratospheric water in Saturn and Titan

Hartogh et al, A&A 2011

1.- Molecular Inventory of Titan with Herschel

Spectral emission features due to:





Surprise: Unexpected detection of hydrogen isocyanide a specie not previously identified in Titan´s atmosphere

Isotopic ratios $^{14}N/^{15}N$ in HCN and $^{16}O/^{18}O$ in CO

Measurement	$^{14}N/^{15}N$	Reference
IRAM-30m	60-70	Marten et al. 2002
SMA	72 ± 9 or 94 ±13	Gurwell 2004
Cassini/CIRS	56 ± 8	Vinatier et al. 2007
Huygens/GCMS (in N_2)	183 ± 5	Niemann et al. 2010
Herschel/SPIRE	76 ± 6	Courtin et al. 2012

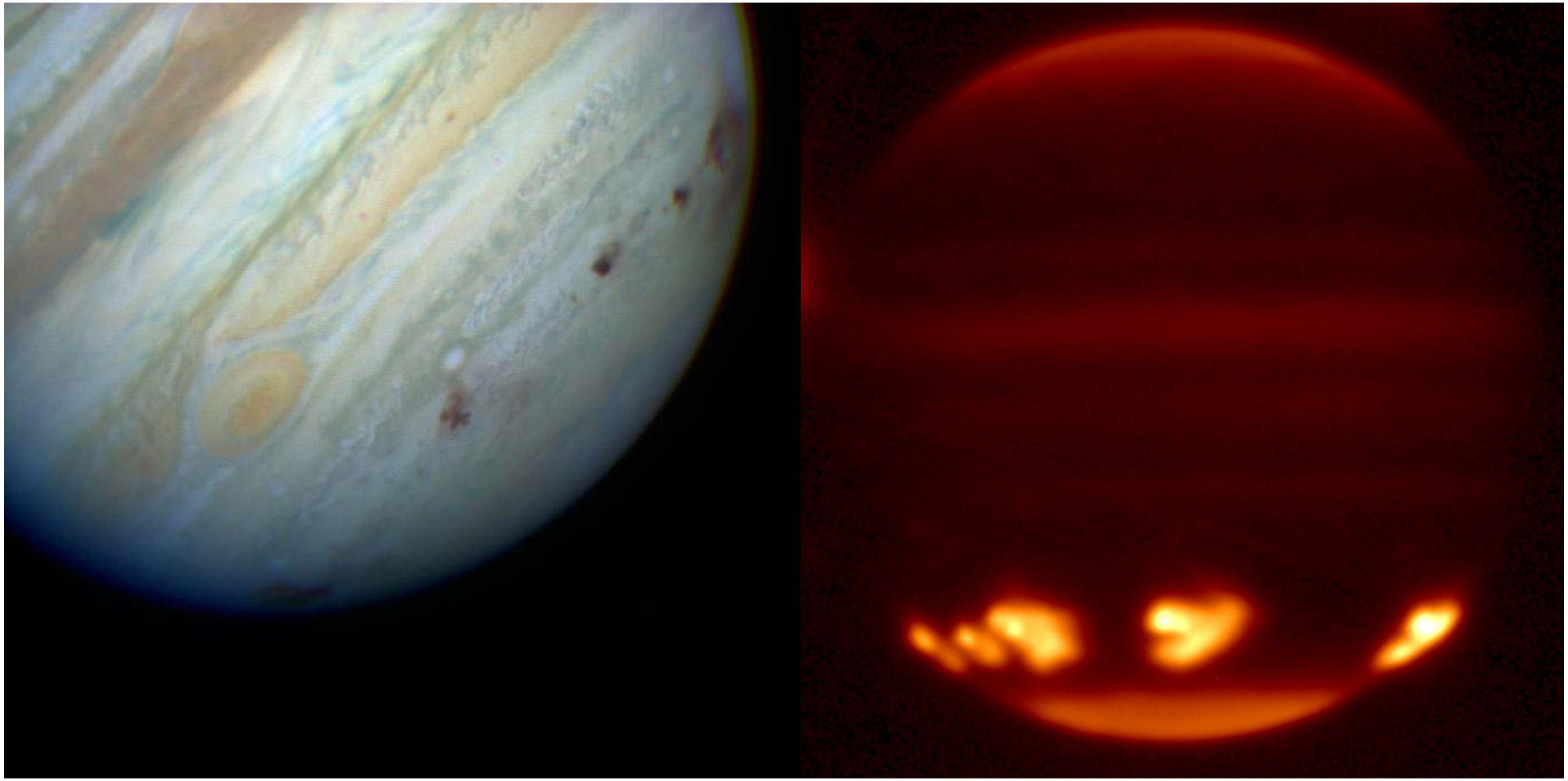
Photolytic fractionation of $^{14}N^{14}N$ and $^{14}N^{15}N$ (Earth = 272)

Measurement	$^{16}O/^{18}O$	Reference
JCMT	~250	Owen et al. 1999 (never-published)
SMA	400 ± 41	Gurwell 2008 (unpublished)
Herschel/SPIRE	380 ± 60	Courtin et al. 2012

First documented measurement of Titan´s $^{16}O/^{18}O$ in CO, value 24% lower than the Terrestrial ratio (Earth = 500) ➔ $^{16}O/^{18}O$ depletion in Titan

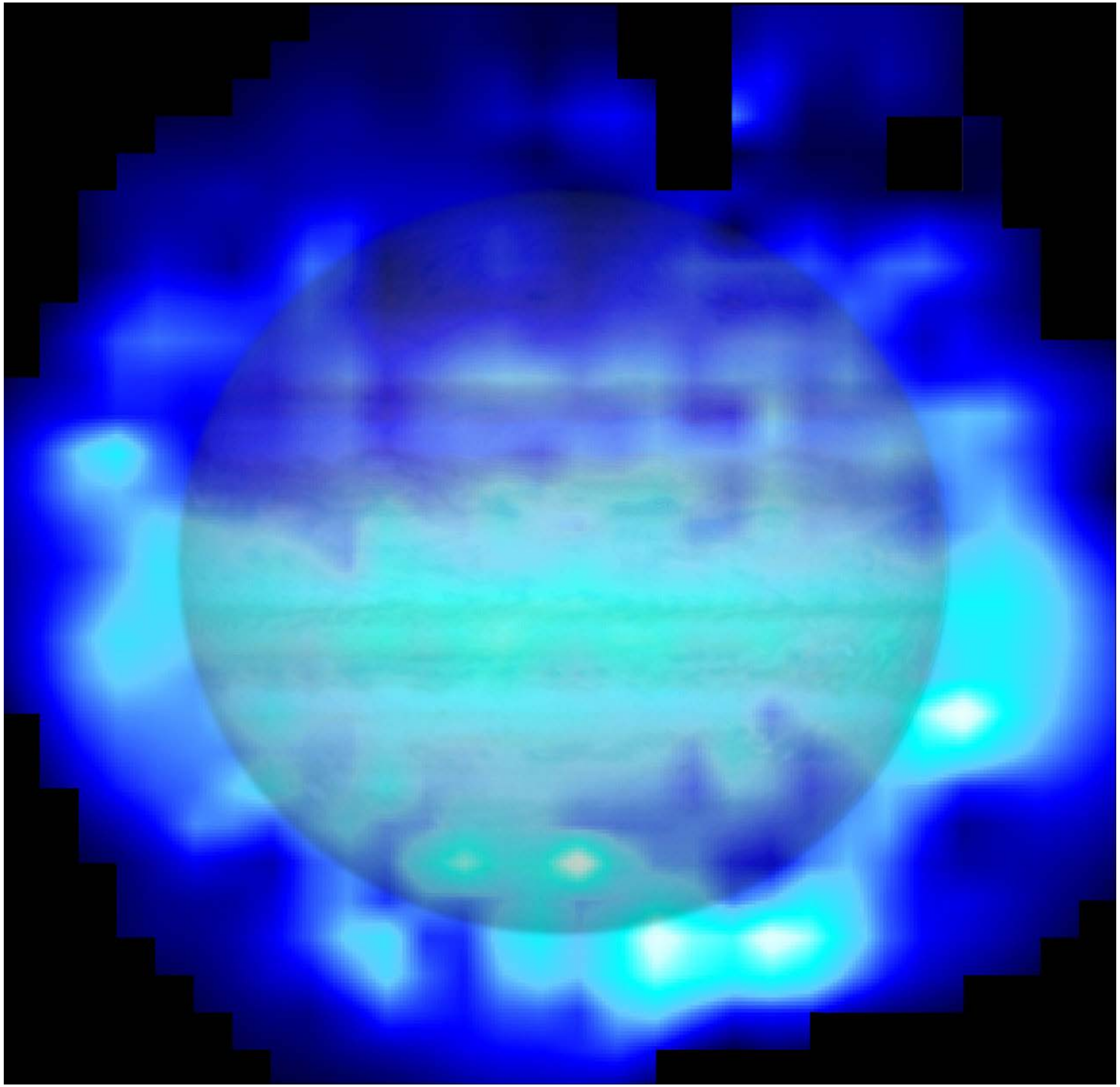
Precipitation of O^+ or O from the Enceladus Torus

SL9 impacts 1994 (VIS/IR) at 44 S



Credits: NASA-HST/ U. Hawaii

Water distribution observed by PACS

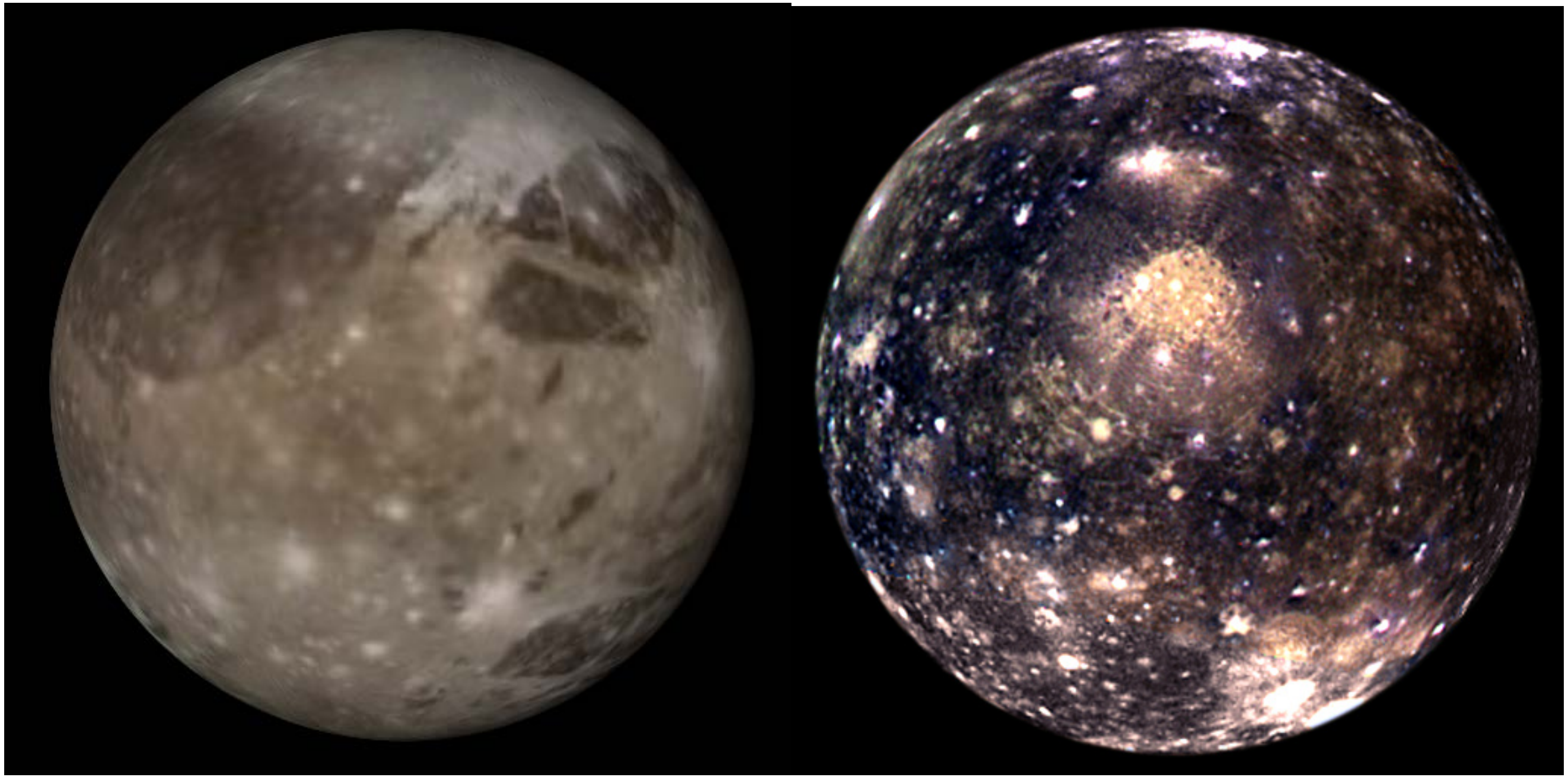


SL9 impact main source of stratospheric water in Jupiter

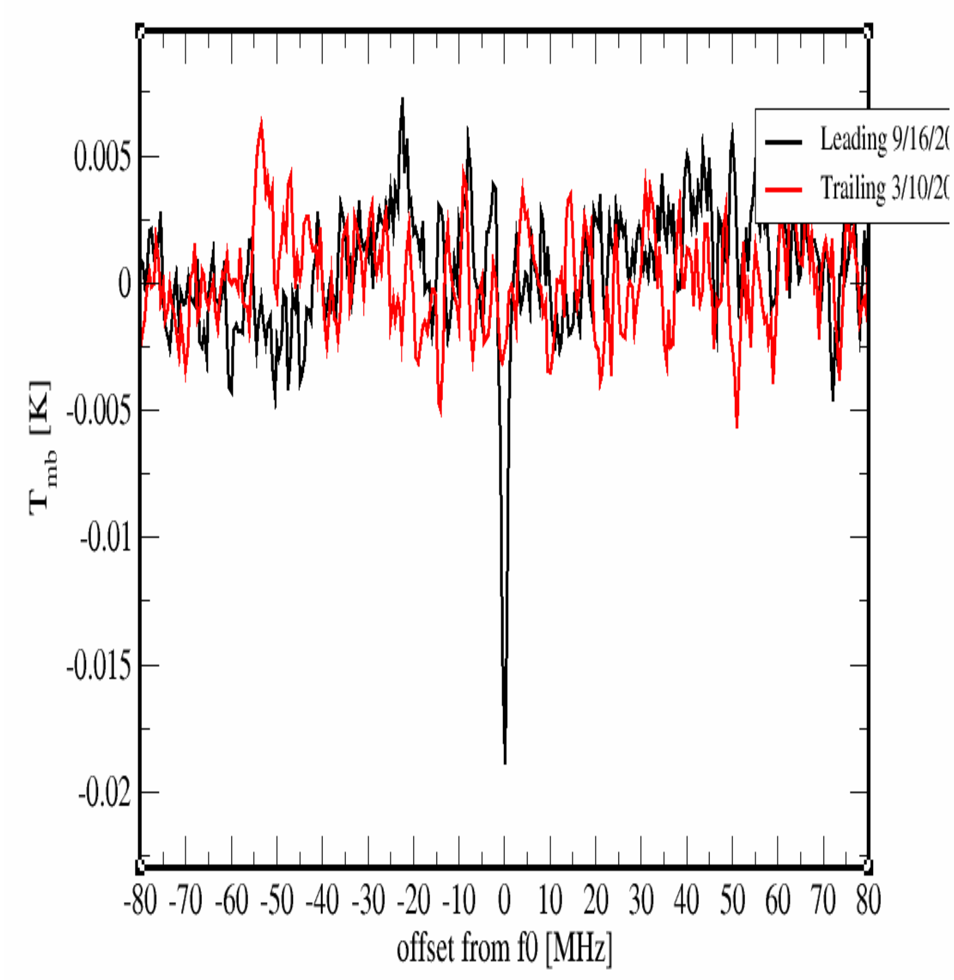
- No feature found indicating a satellite/ring source
- Vertical distribution does not fit IDP source
- Horizontal distribution of water favors SL9 impact, hemispheric asymmetry: Globally averaged column density $3x10^{15}cm^{-2}$ with 2-3 times more water in the south.

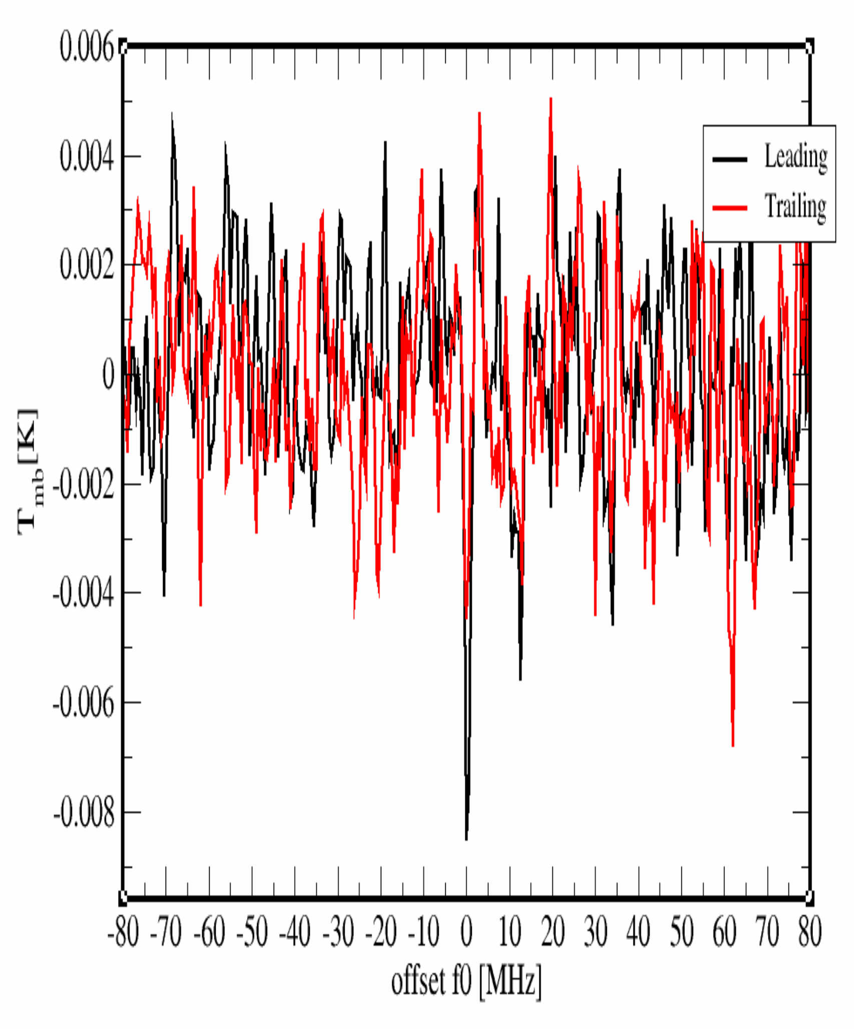
Cavalie et al., A&A 2013

Ganymede and Callisto leading sides

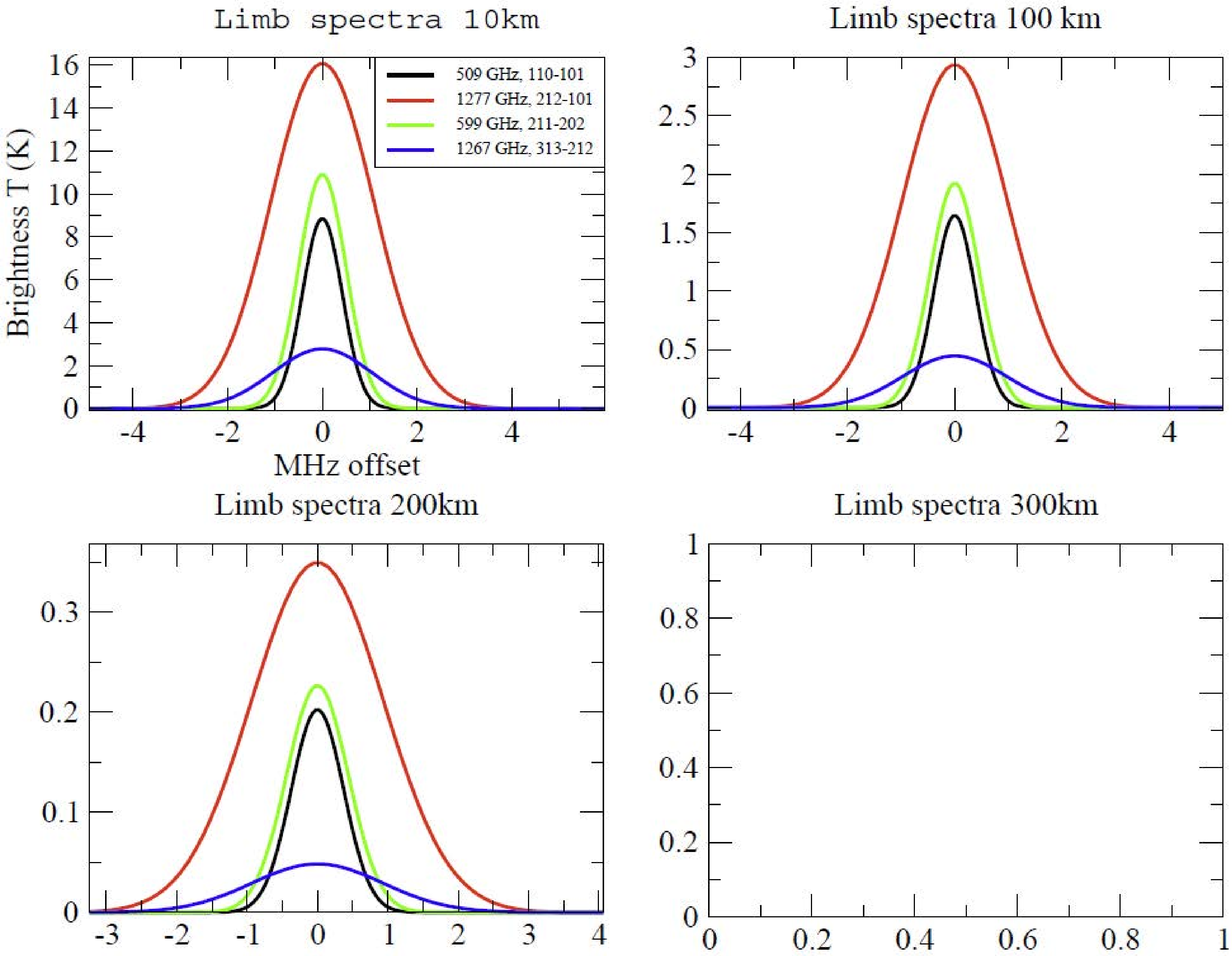


Ganymede and Callisto have leading sides water atmosphere

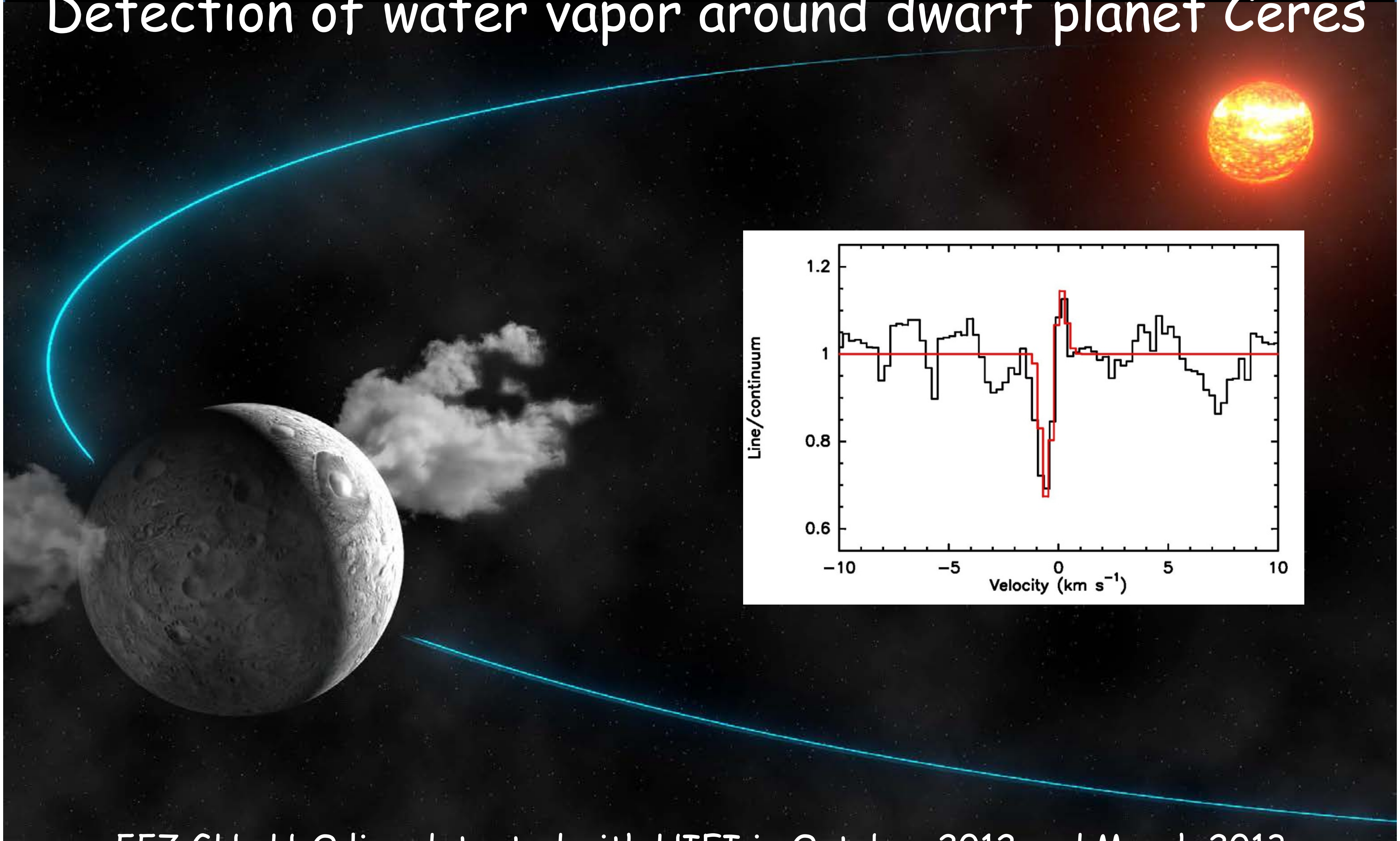




JUICE-SWI: Ganymede, SSL 10, HDO limb spectra simulation

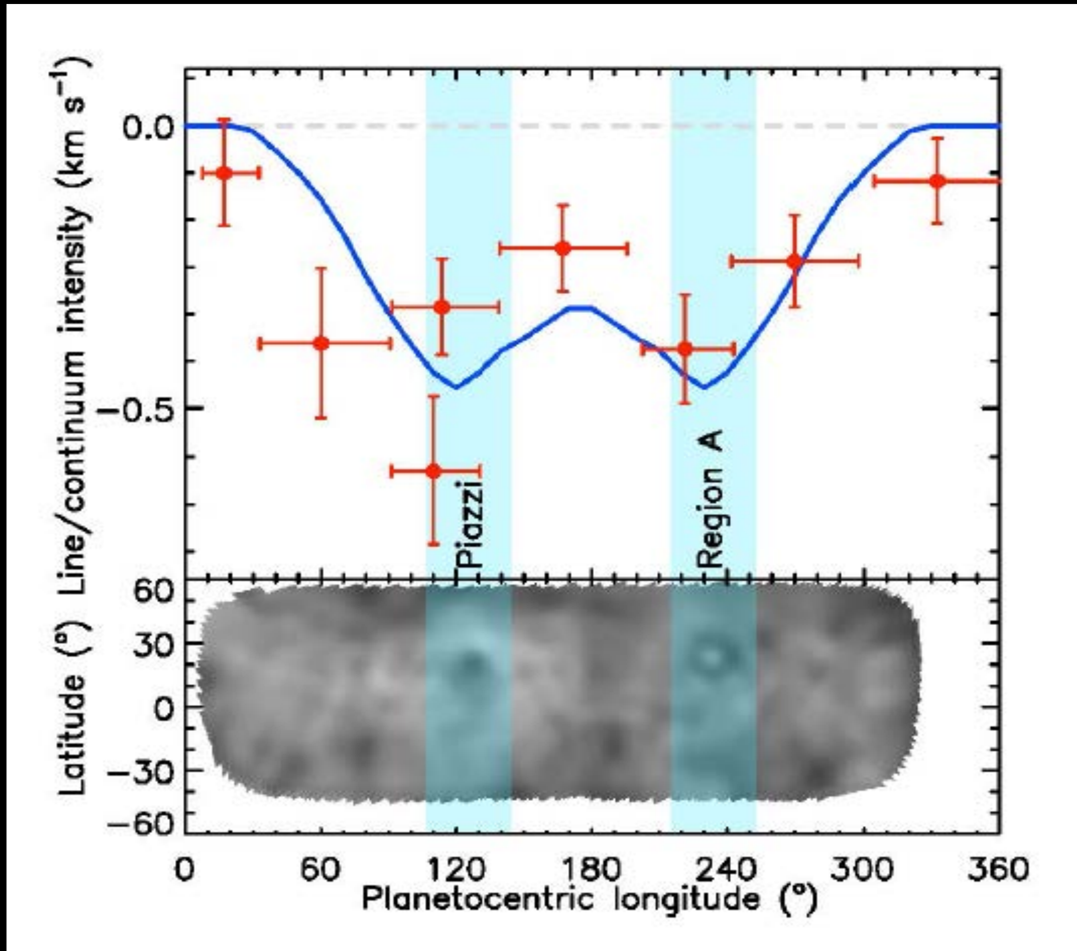


Detection of water vapor around dwarf planet Ceres



557 GHz H_2O line detected with HIFI in October 2012 and March 2013
Kueppers et al., Nature, in press

Detection of water vapor around dwarf planet Ceres



Variation of the signal along Ceres's rotation


Kevin Heider

Astronomy & Astrophysics manuscript no. 176P
August 29, 2012

LETTER TO THE EDITOR

An upper limit for the water outgassing rate of the main-belt comet 176P/LINEAR observed with *Herschel*/HIFI★

M. de Val-Borro[1,★★], L. Rezac[1], P. Hartogh[1], N. Biver[2], D. Bockelée-Morvan[2], J. Crovisier[2], M. Küppers[3], D. C. Lis[4], S. Szutowicz[5], G. A. Blake[4], M. Emprechtinger[4], C. Jarchow[1], E. Jehin[6], M. Kidger[7], L.-M. Lara[8], E. Lellouch[2], R. Moreno[2], and M. Rengel[1]

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4 California Institute of Technology, Pasadena, CA 91125, USA
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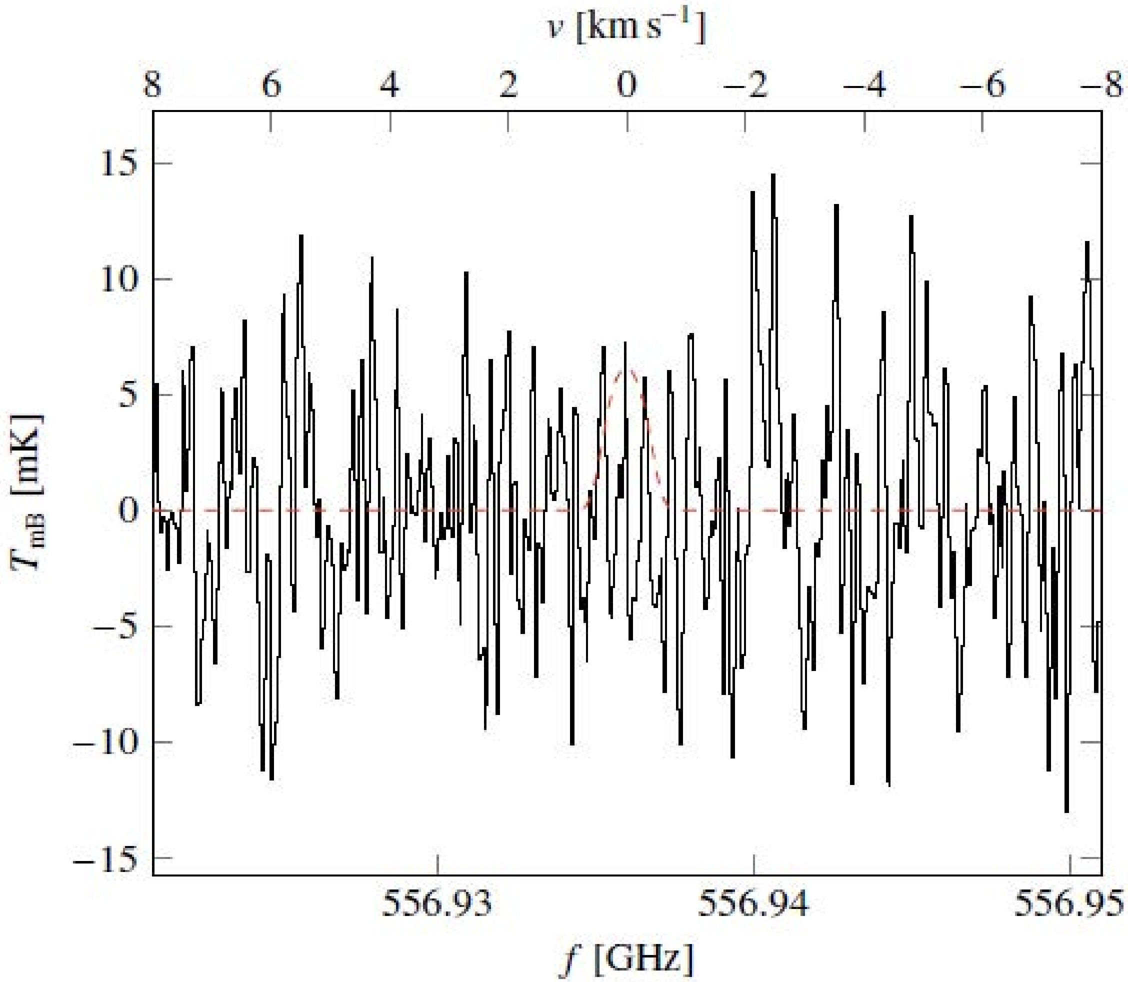
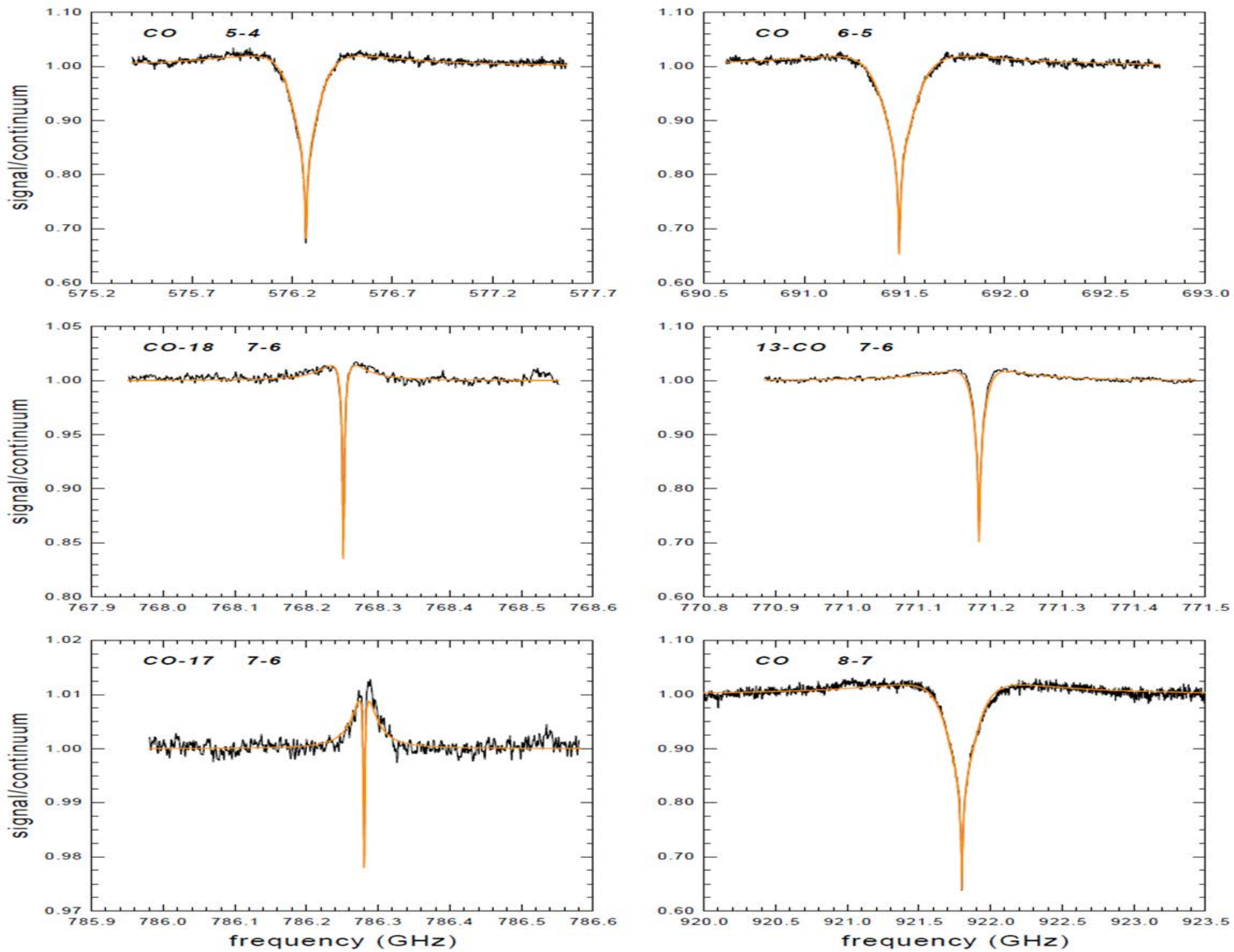
Main belt extends from about 2.5 – 3.6 AU. MBCs probably originate in the outer main belt. Comet-like (dust) tails observed. Origin of tail not clear. Tails are usually volatiles driven, however difficult to understand for main belt comets. Search for volatiles with Herschel

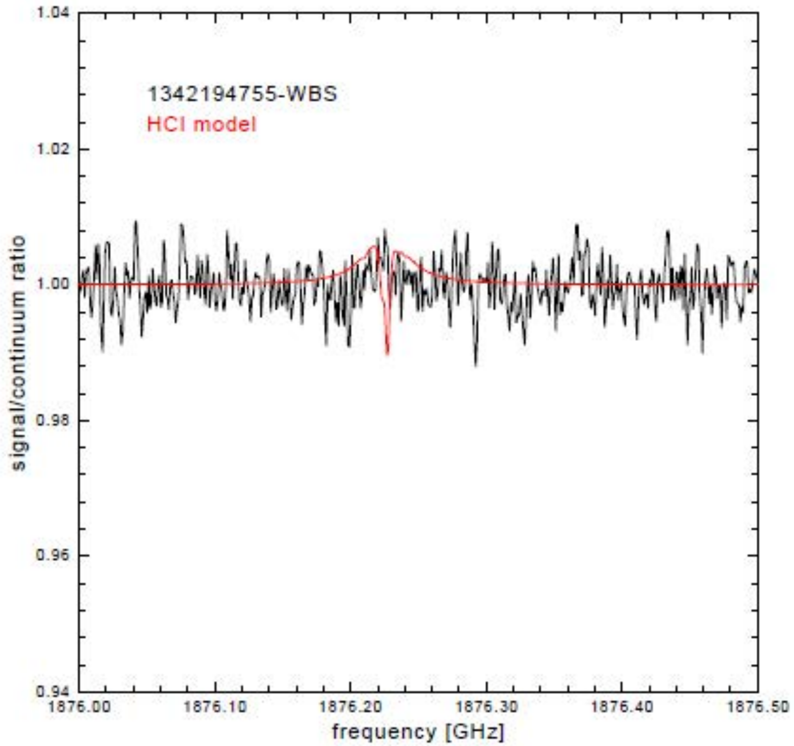
Upper limit of water production < 4 x 10^{25} molecules/s



Mars: Oxygen isotopic ratios telluric



Upper limits on HCl and H_2O_2, Ls=78°



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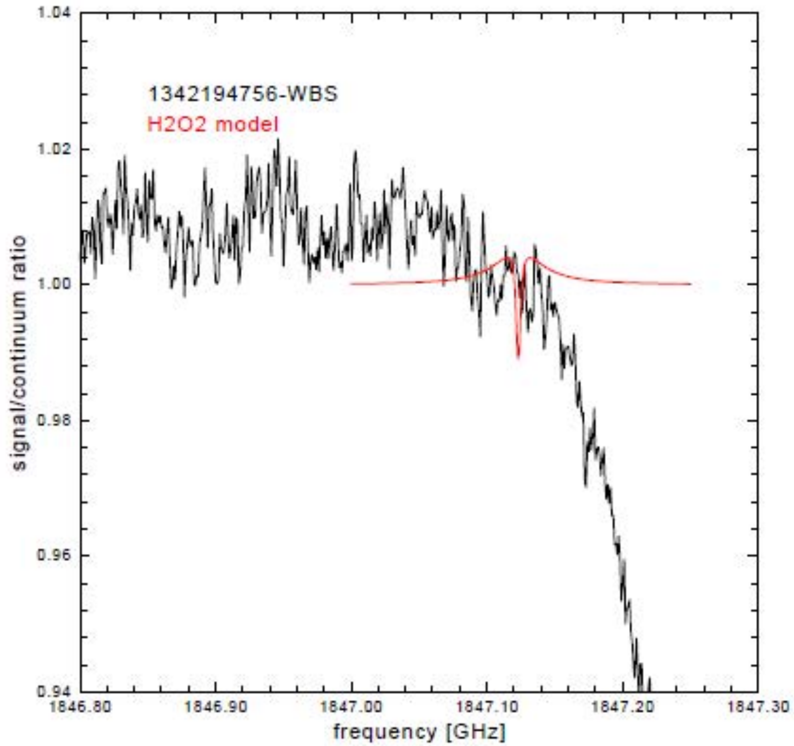
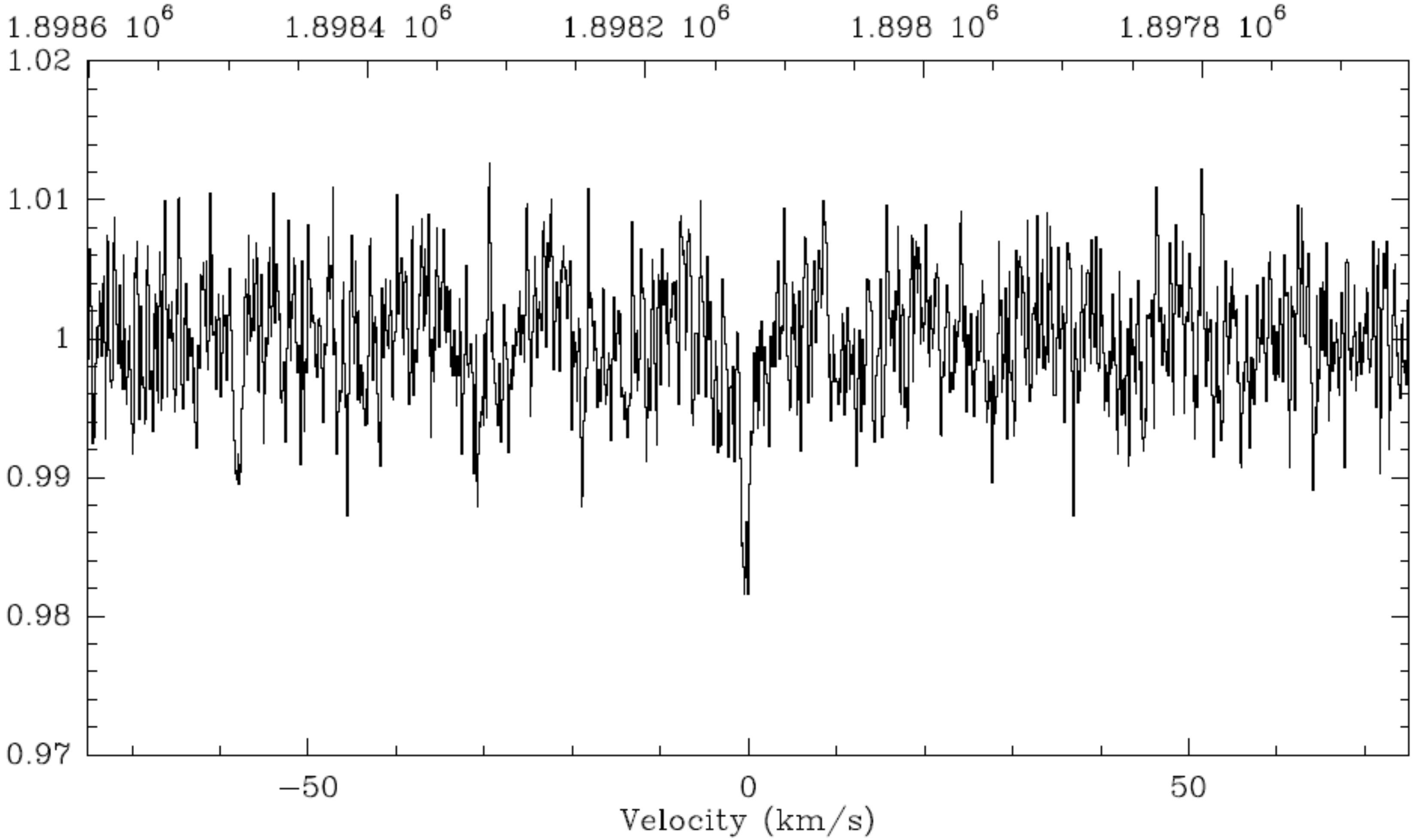


< 2 ppb

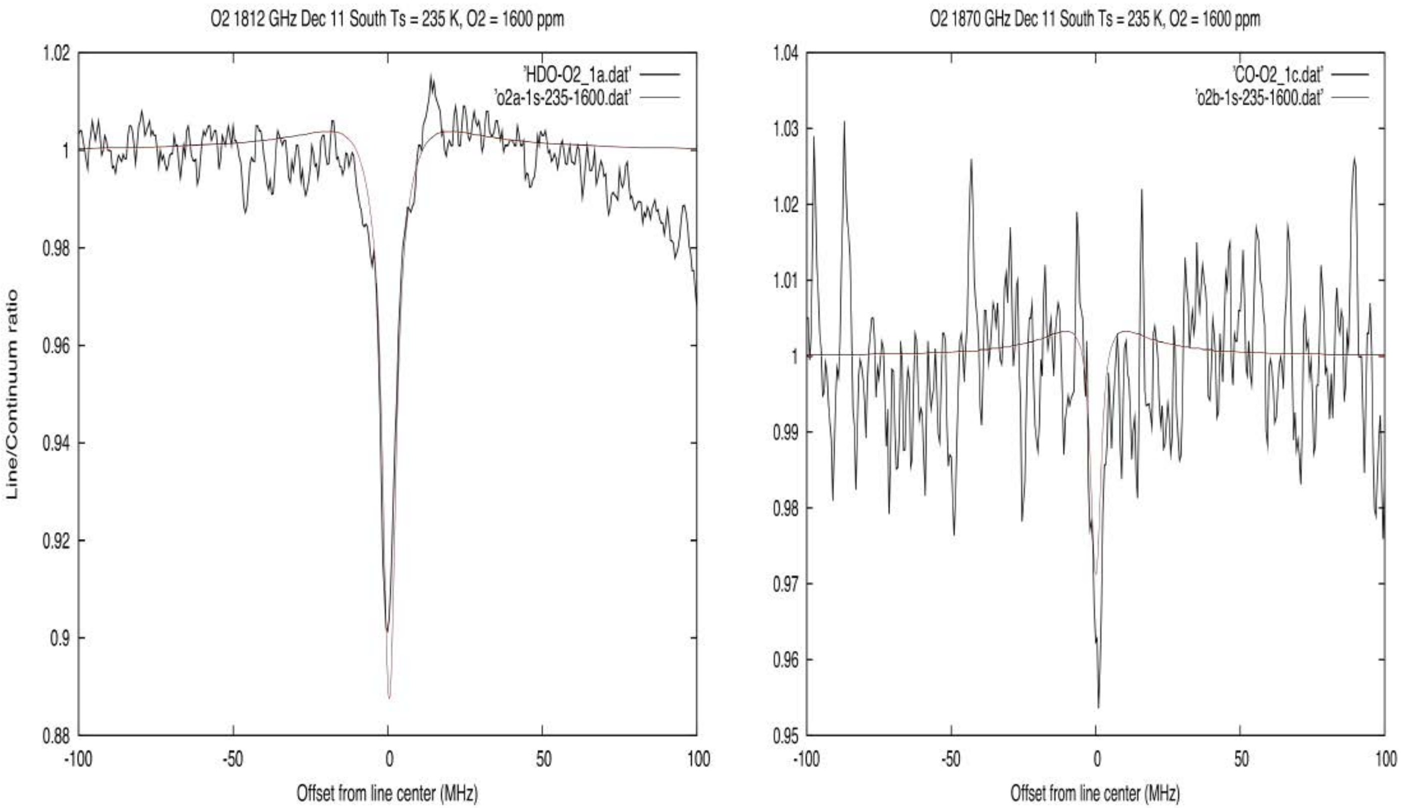
Hartogh et al. 2010b, A&A

Fall 2011: detection of H_2O_2! Ls=10°



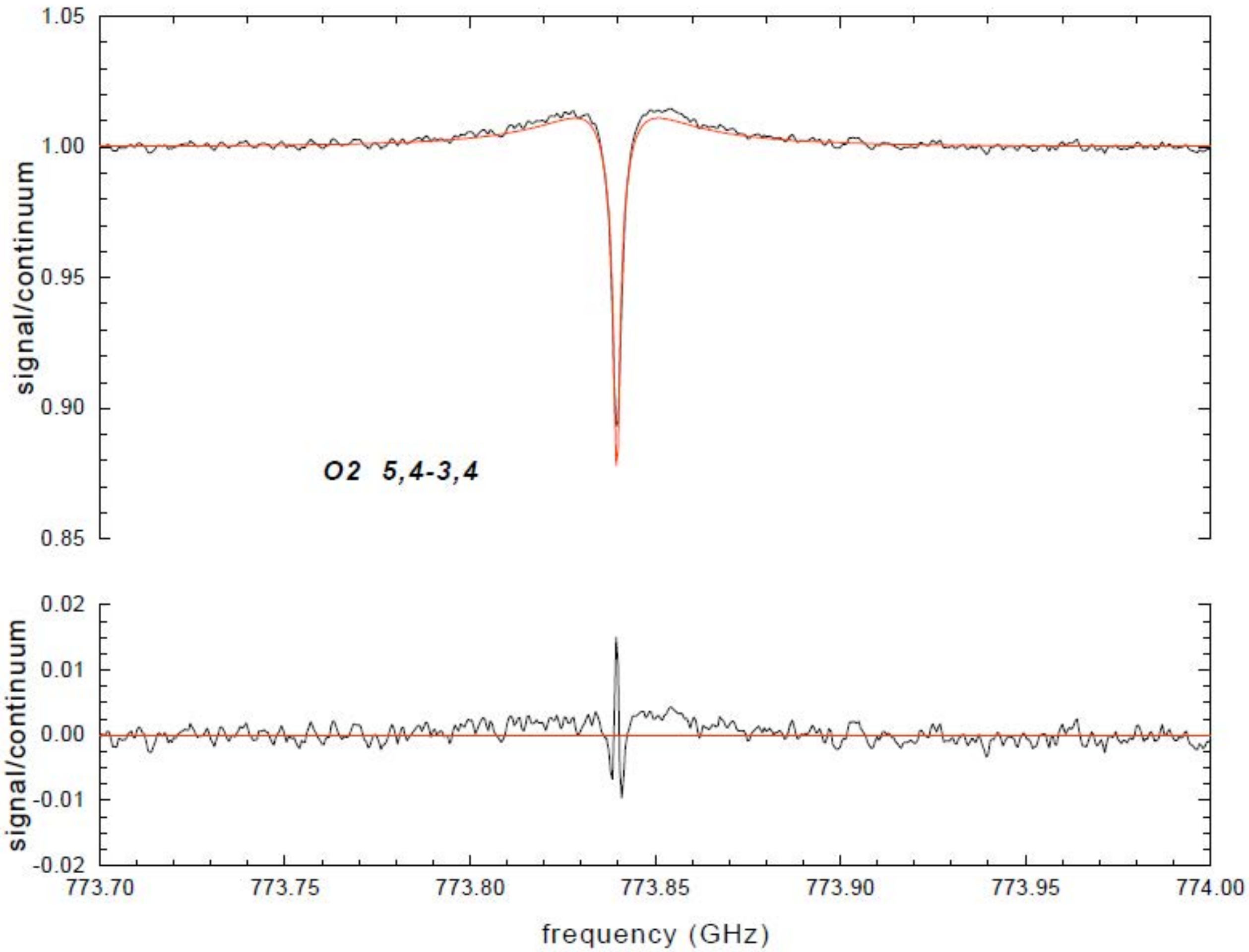
O2 at 1812 GHz Ls=47°

HIFI/Herschel, Dec 22, 2011, South – Ls = 47° - O_2 = 1600 ppm



T. Encrenaz et al.: no detectable spatiotemporal variation

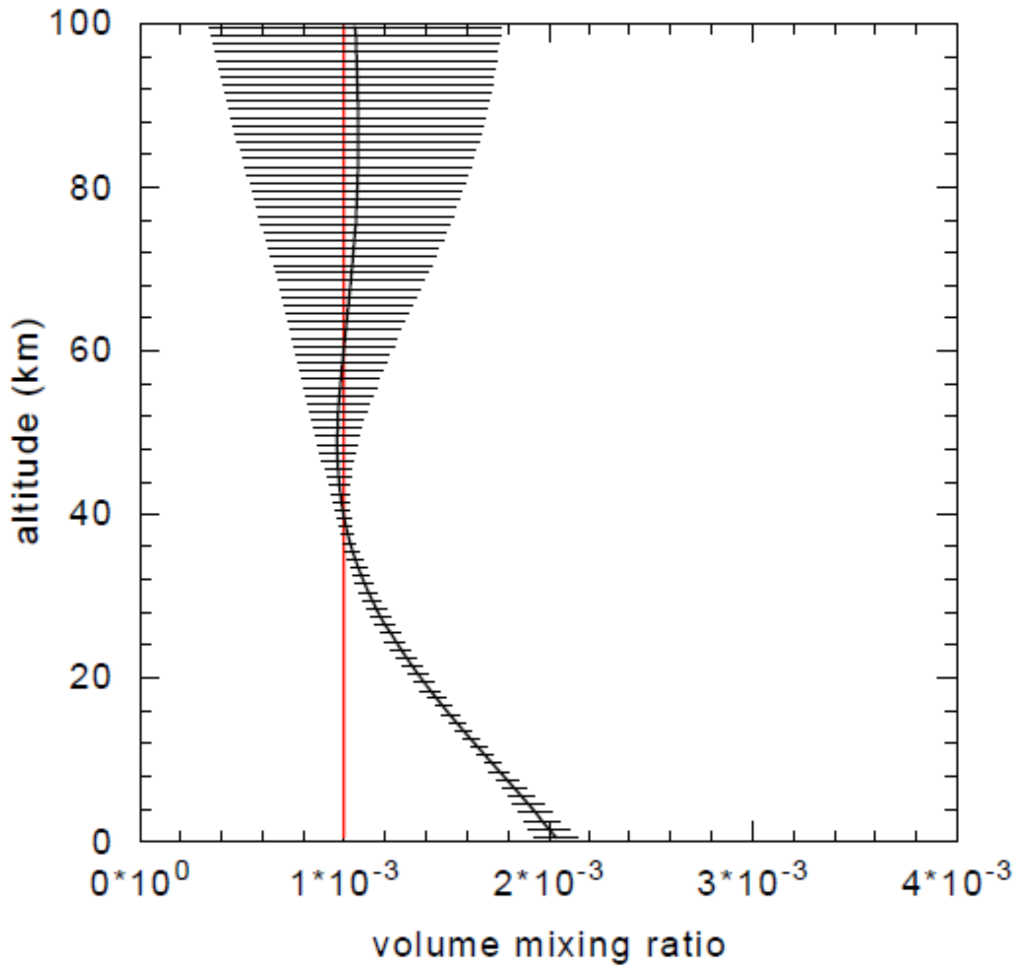
First submm detection of O_2



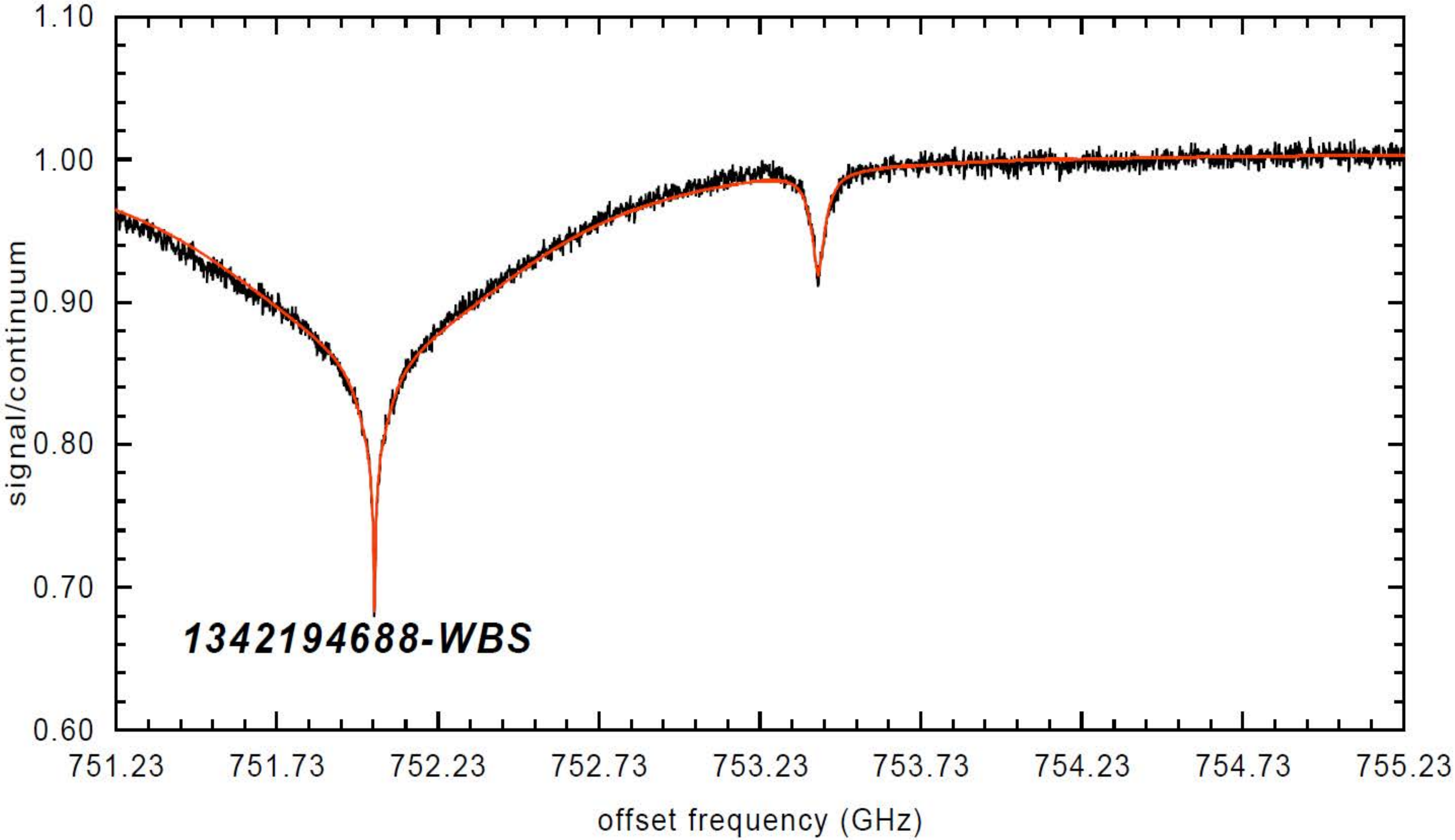
Fit of constant profile provides volume mixing ratio of 1400 ppm. However residual indicates that profile is not constant with altitude.

Hartogh et al. 2010b, A&A

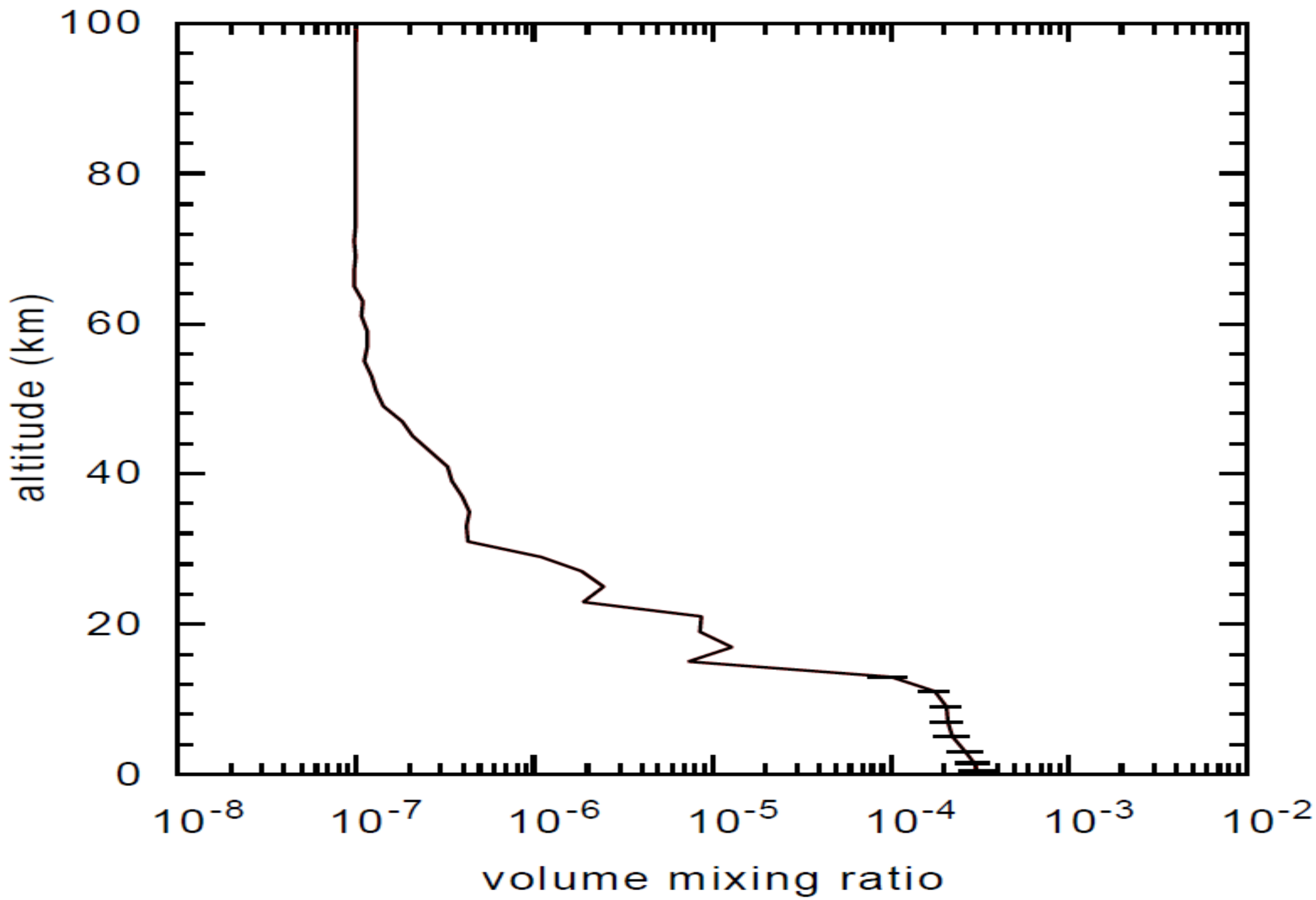
First results: vertical profile of O_2 on Mars, TBC



H_2O and HDO at Ls = 78°



Vertical profile of water at Ls = 78°



Summary

- Herschel provided exciting solar system data (3 % of the total Herschel observing time)
- Numerous new discoveries:
  - new molecules (e.g. in Titan)
  - new atmospheres (e.g. Ceres, Ganymede, Callisto)
  - new water cloud (Enceladus water torus)
  - ocean like water in comets (e.g. 103P Hartley 2)
  - new views about planet formation (e.g. Uranus/Neptune)
  - new exciting questions (e.g. oxygen on Mars)
- More to come soon….