A map of D/H on Mars using EXES aboard Sofia

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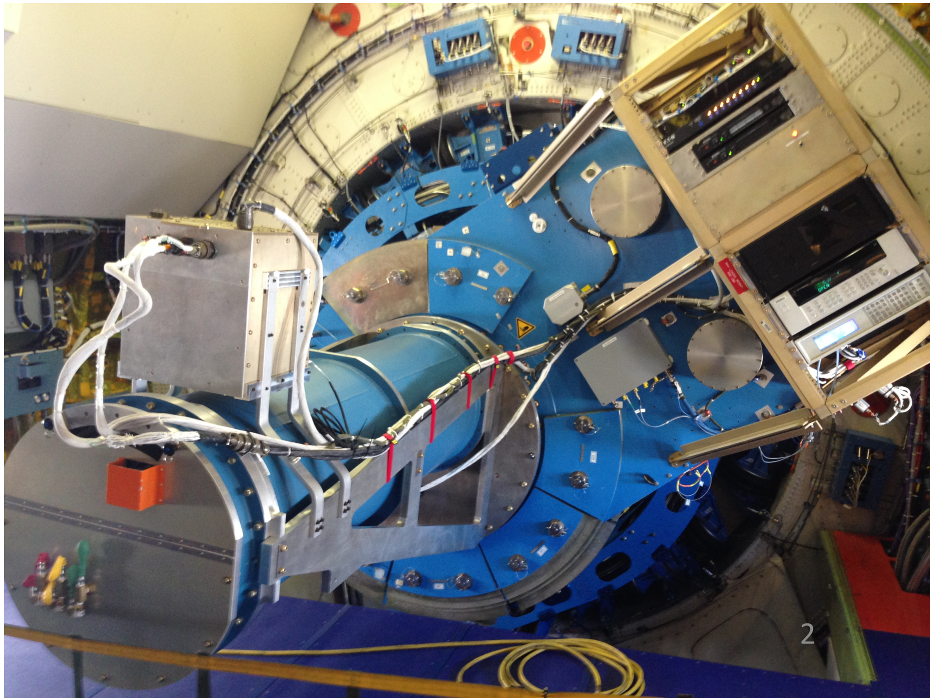
EXES aboard SOFIA

SOFIA: A Stratospheric Observatory for Infrared Astronomy (NASA/DLR)

- Boeing 747 + 3.5m telescope
- First operation: 2010

EXES: Echelon Cross-Echelle spectrograph

- PI: M.J. Richter, UC Davis, CA
- λ range: 4.5 – 28.3 μm,
- R = 10^5, 15000, 4000
- Heritage: TEXES at IRTF
- First operation: 2014



Why study D/H on Mars ?

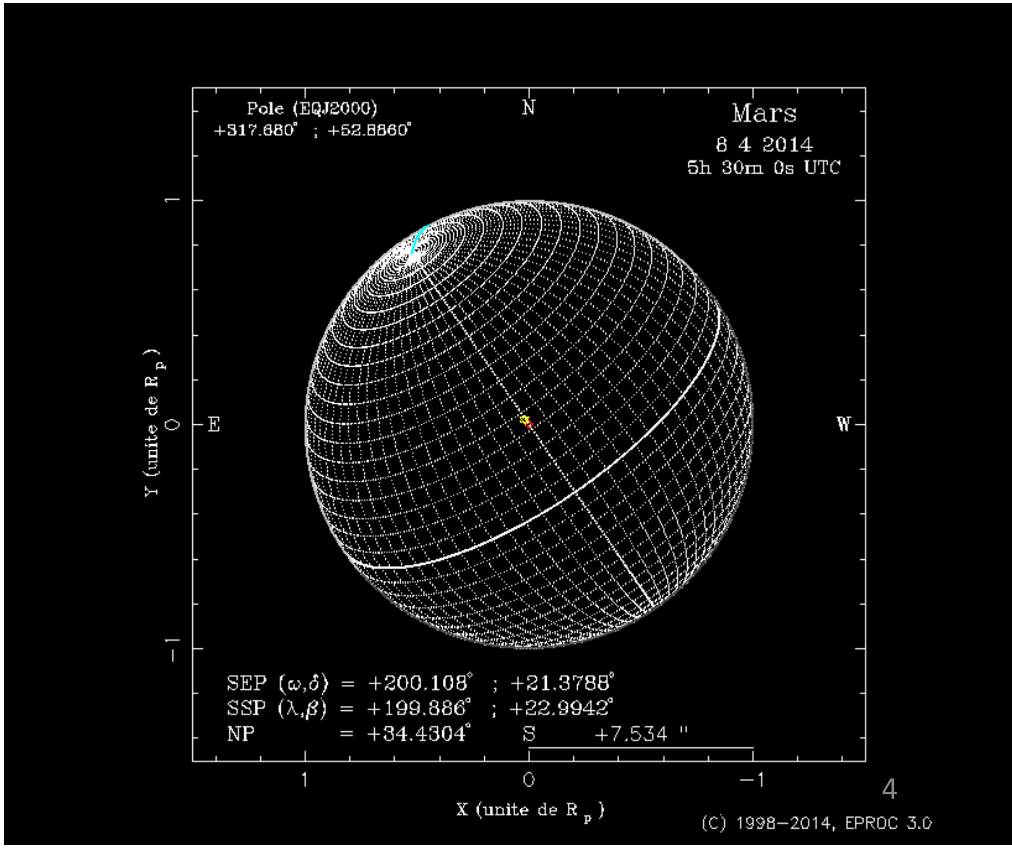
- An indicator of the **loss of water** over the history of Mars, through differential escape
- -> A diagnostic of past water content
  - Owen et al. 1988: D/H = 6 SMOW

- An indicator of **the water cycle** through fractionation due to differential condensation processes
- -> A diagnostic of the water cycle and exchange with surface reservoirs
  - Montmessin et al. Icarus 2005; Villanueva et al. Science 2015

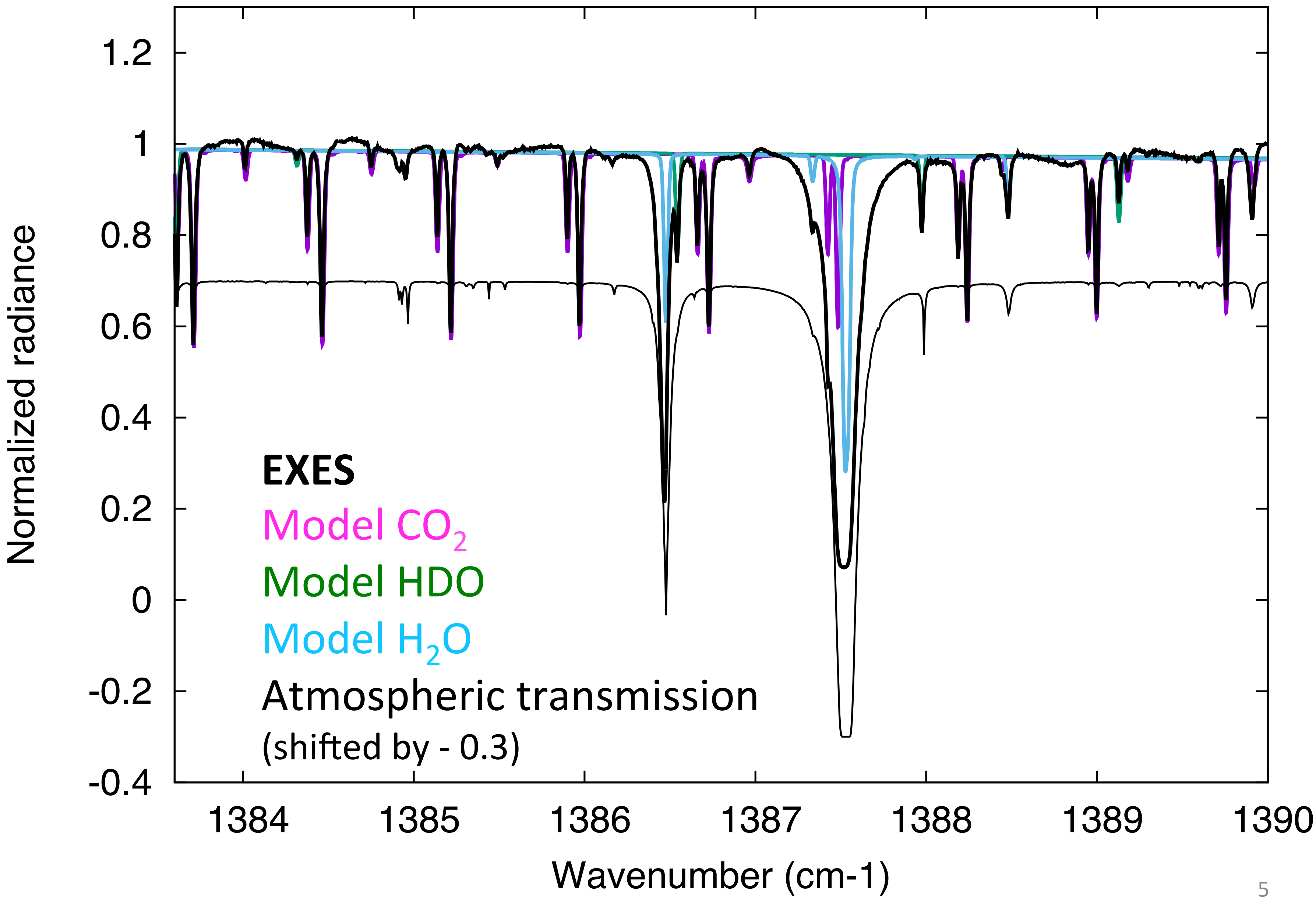
A map of D/H on Mars with EXES/SOFIA

- **Objective:** Simultaneous mapping of H_2O and HDO in the thermal infrared (7 μm)
- First commissioning flights: April 7-8, 2014
- **Mars observation**: April 8, 5:00-5:30 UT

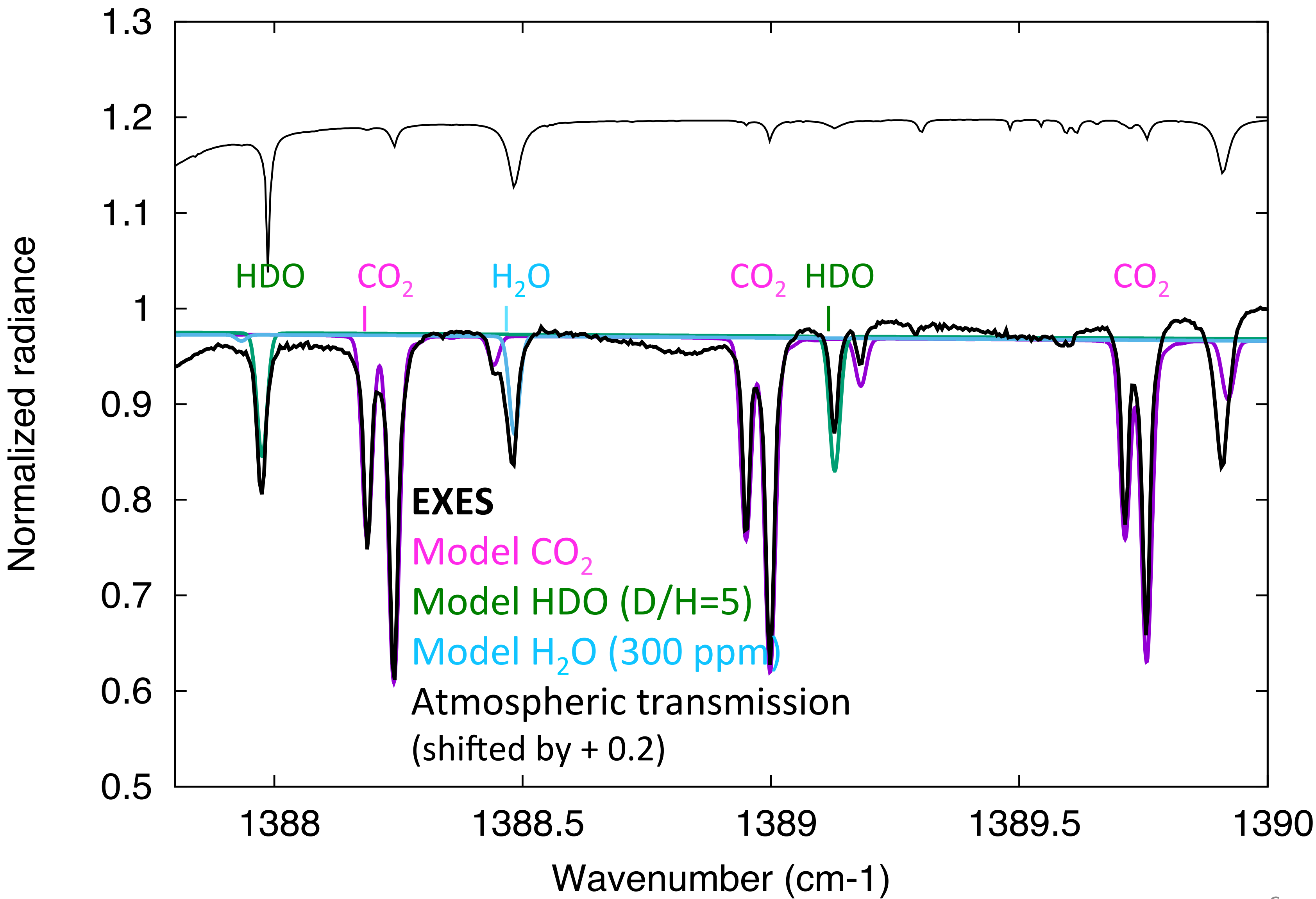
  - Diameter: 15.3 arcsec (near opposition)
  - Season: Ls = 113° (near Northern Summer solstice)
  - Spectral range: 1383-1390 cm^{-1} (7.19 – 7.23 μm)
  - Resolution: 0.028 cm^{-1} (R = 5 10^4)



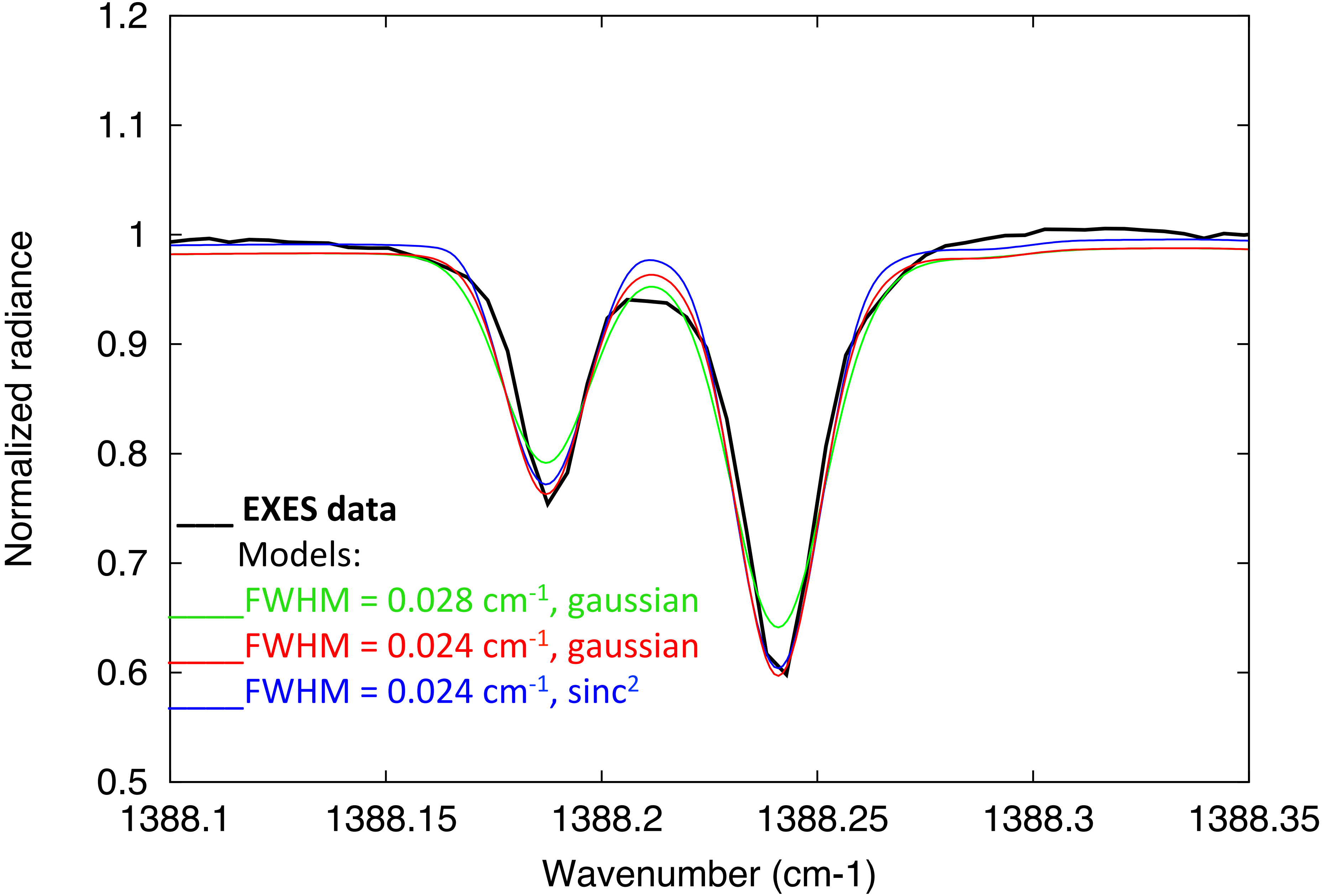
The EXES spectrum of Mars (disk averaged)



The EXES spectrum of Mars (disk averaged)



Determination of the FWHM using CO_2 transitions



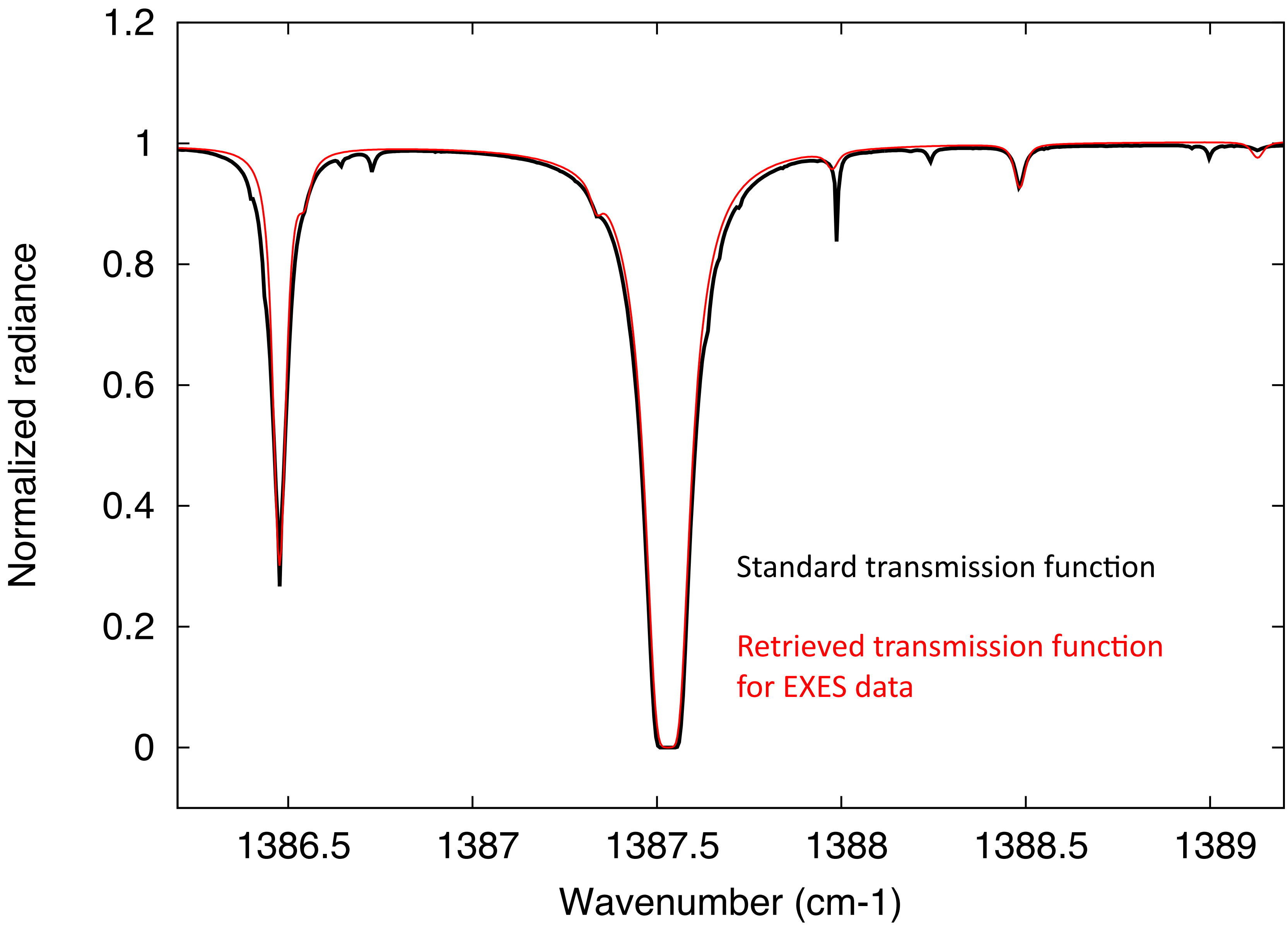
Retrieval of H_2O and HDO maps

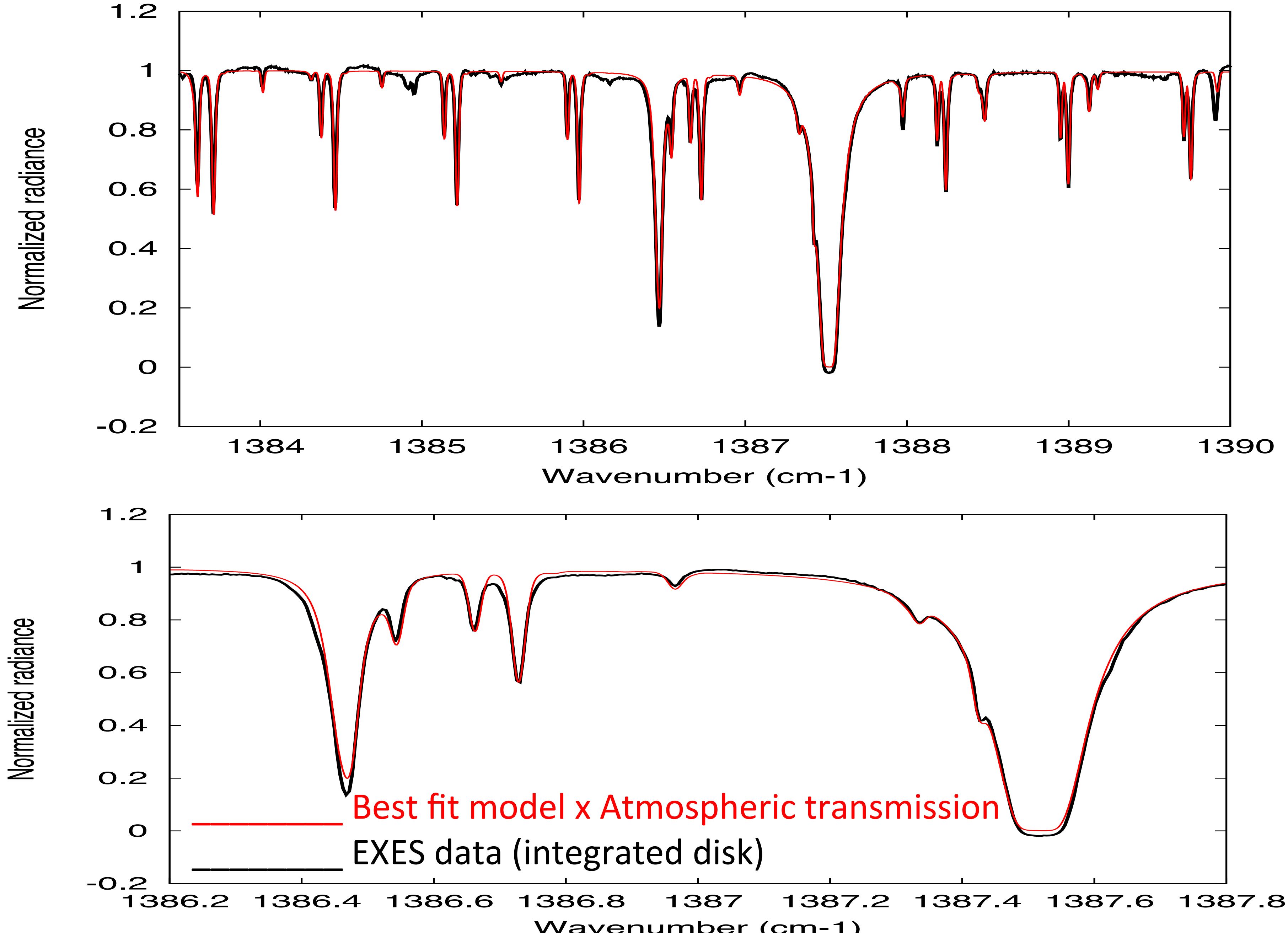
- Mixing ratios of H_2O and HDO (vs CO_2) are measured from the line depth ratios of weak transitions vs weak CO_2 lines
- The HDO/H_2O ratio is measured from the line depth ratio of HDO and H_2O lines
- This method allows to eliminate, to first order, effects due to thermal structure and geometry
- This method has been previously used to study and monitor H_2O_2 & HDO on Mars (Encrenaz et al. PSS 2012, A&A 2015), and SO_2 & HDO on Venus (Encrenaz et al. A&A 2012, 2013)
- In the case of EXES, the main question is how to cancel properly the terrestrial atmospheric absorption
- Results of this study have been published in A&A (2016)

Removal of the terrestrial contribution

- At 1386.5-1387.5 cm^{-1}, the spectrum is dominated by terrestrial absorption due to H_2O
- The terrestrial absorption is modelled for a best fit of this part of the spectrum
- The inferred terrestrial absorption is used to correct the 1388-1390 cm^{-1} region used for D/H retrieval
- Terrestrial atmospheric model:
  - Z = 11 km
  - Ps = 0.17 bar, T = 185 K
  - $[H_2O]$ = 8 10^{-5} (11 km), 2 10^{-5} (16 km), 5 10^{-6} (21 km)

Retrieved transmission function from the terrestrial atmosphere



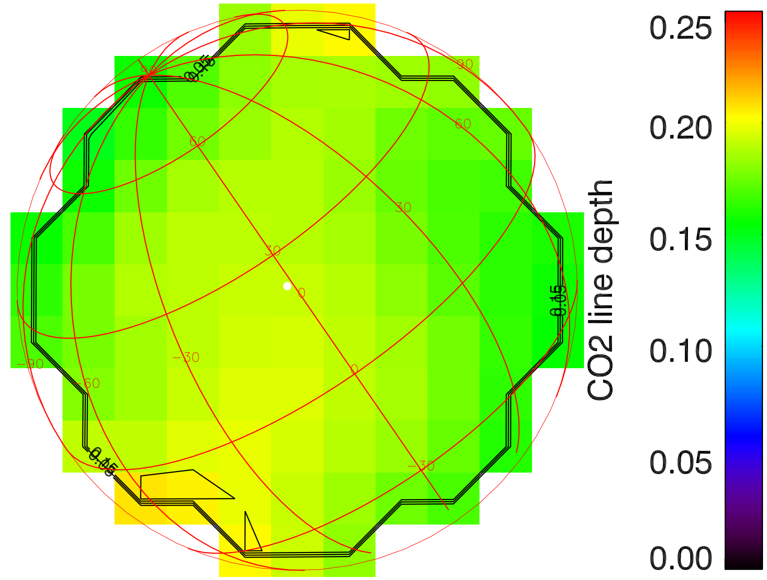


Normalized radiance
Wavenumber (cm-1)
Best fit model x Atmospheric transmission
EXES data (integrated disk)

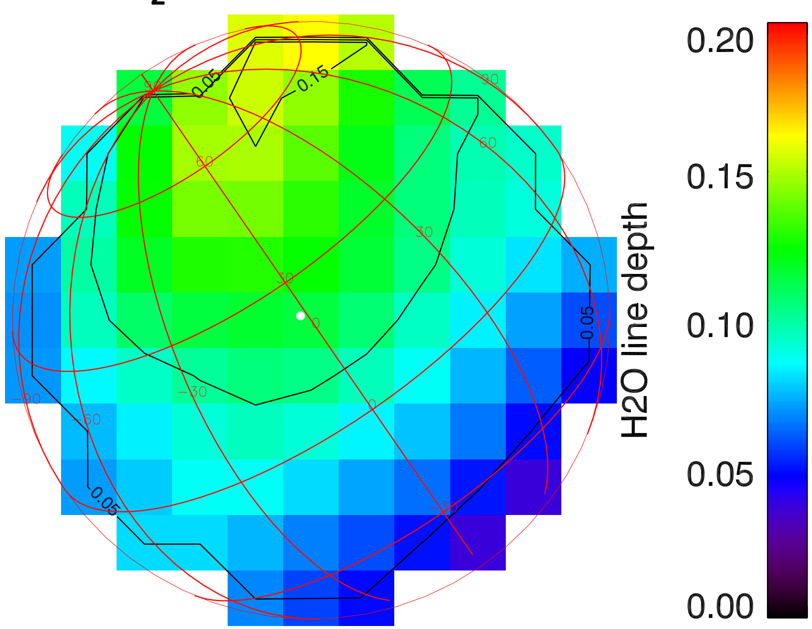
Line depth maps

EXES data, April 8, 2014
Ls = 113°

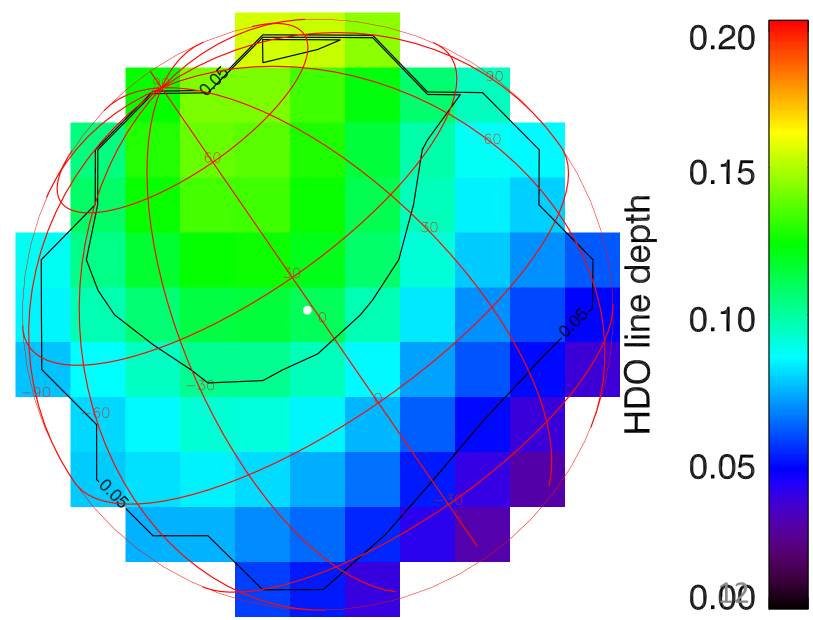
CO_2
1388.95 cm^{-1}



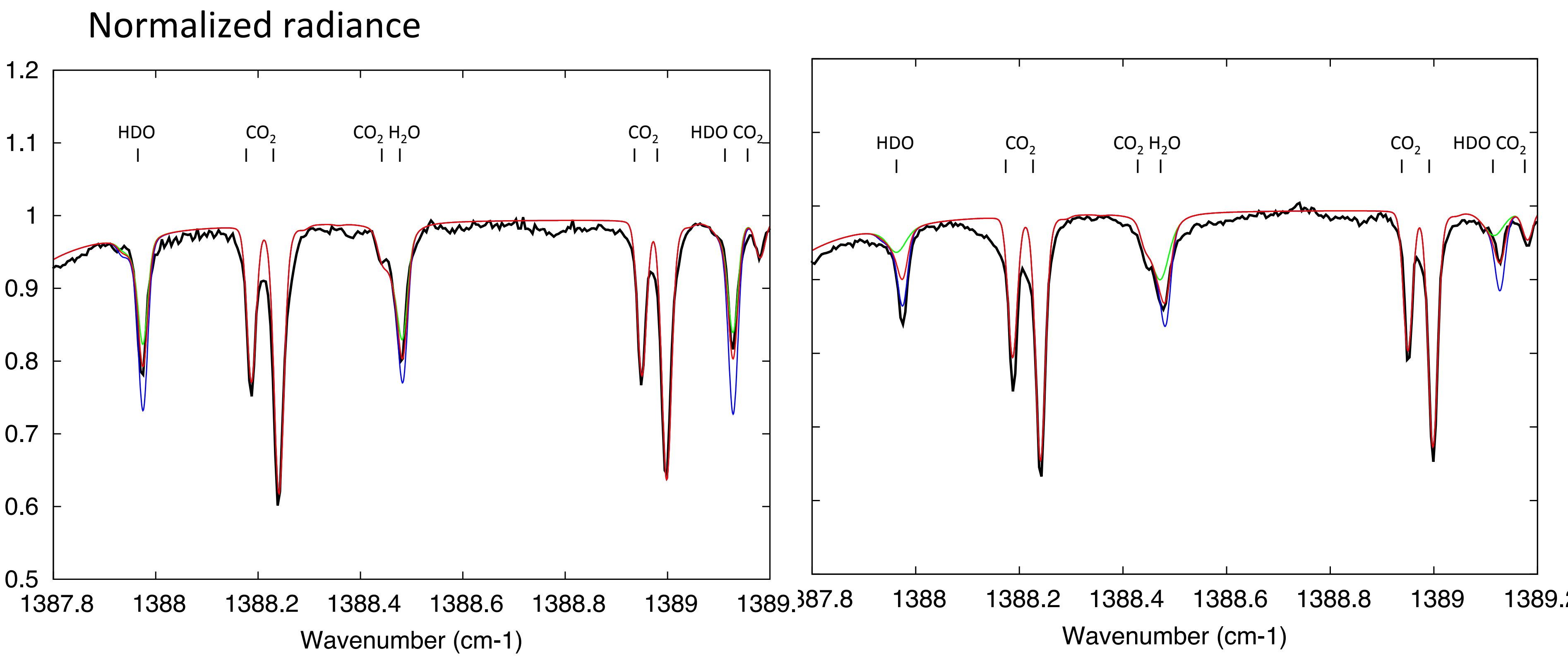
H_2O – 1388.47 cm^{-1}



HDO – 1389.13 cm^{-1}



Best fits of Northern and Southern regions



Northern region

H_2O = 375 +/- 64 ppmv

HDO = 550 +/- 17 ppbv

D/H = 4.7 (+0.8,-0.6) VSMOW

Southern region

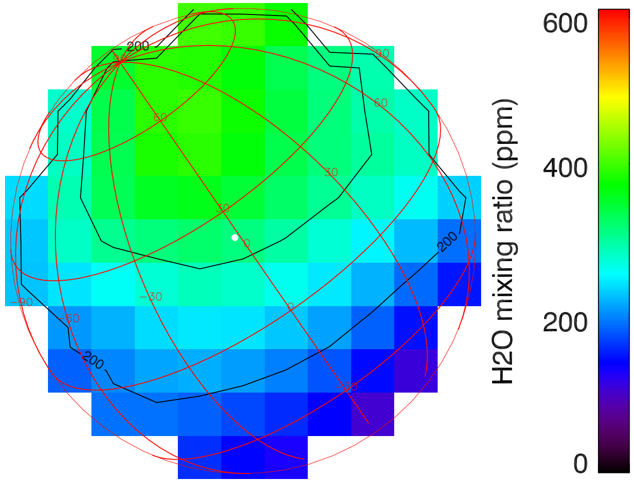
H_2O = 125 +/- 45 ppmv

HDO =150 +/- 15 ppbv

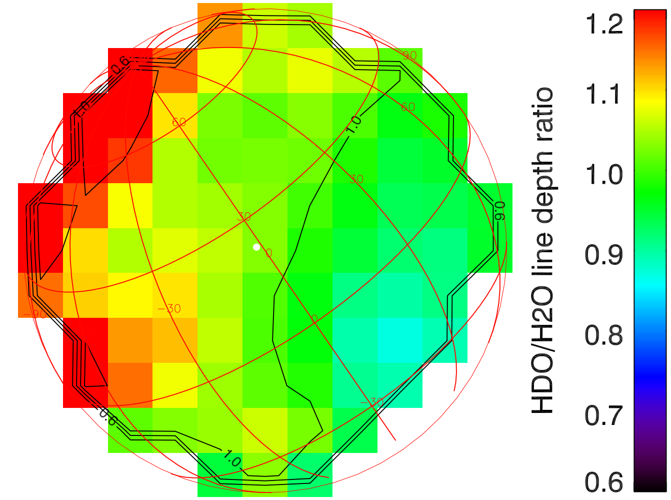
D/H = 3.9 (+1.5, -0.8) VSMOW

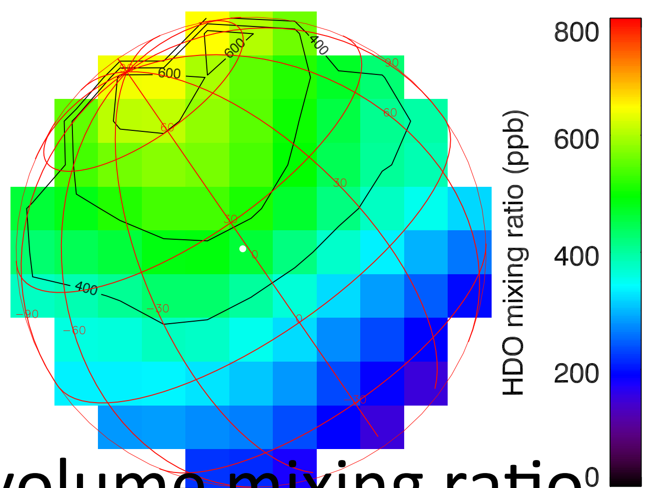
Integrated disk: D/H = 4.4 (+1.0, -0.6) VSMOW

H_20 volume mixing ratio

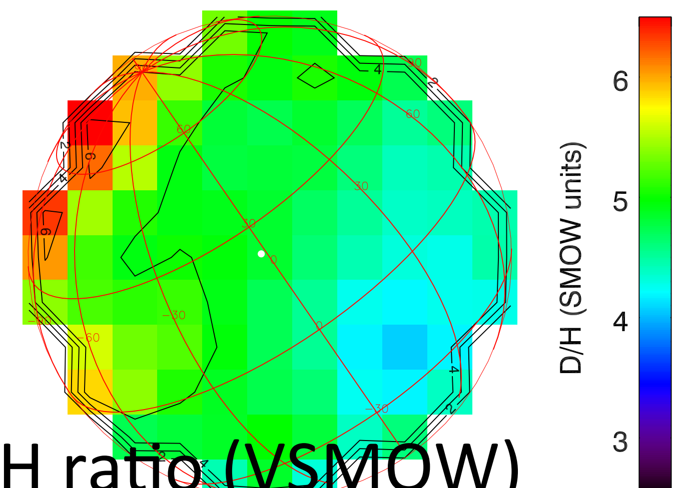


HDO/H_2O line depth ratio





HDO volume mixing ratio



D/H ratio (VSMOW)

Comparison with Villanueva et al. 2015

Ground-based, Near IR (IRTF, Keck)

Good agreement around long=200-230

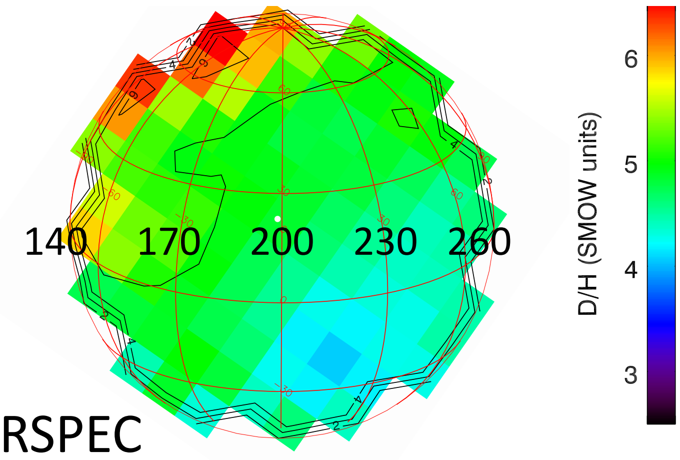
But:

- EXES value is globally lower

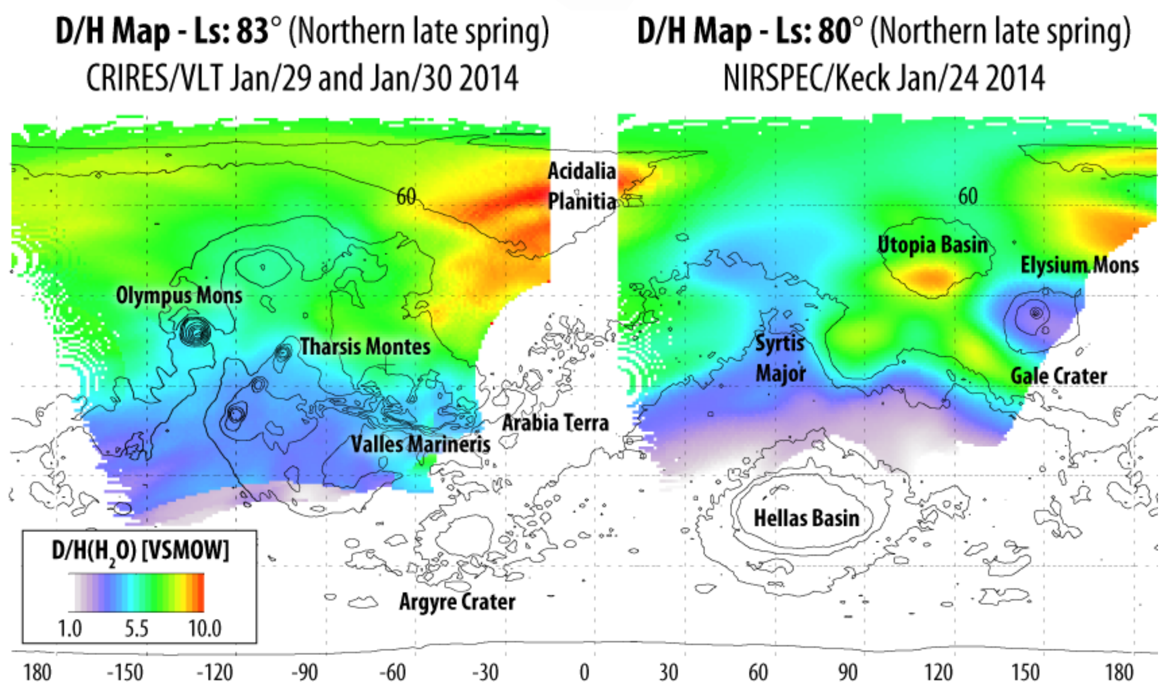
-EXES spatial distribution is more uniform
-> in better agreement with VPIE model (vapor pressure isoptopic effect)

EXES

Ls = 113°

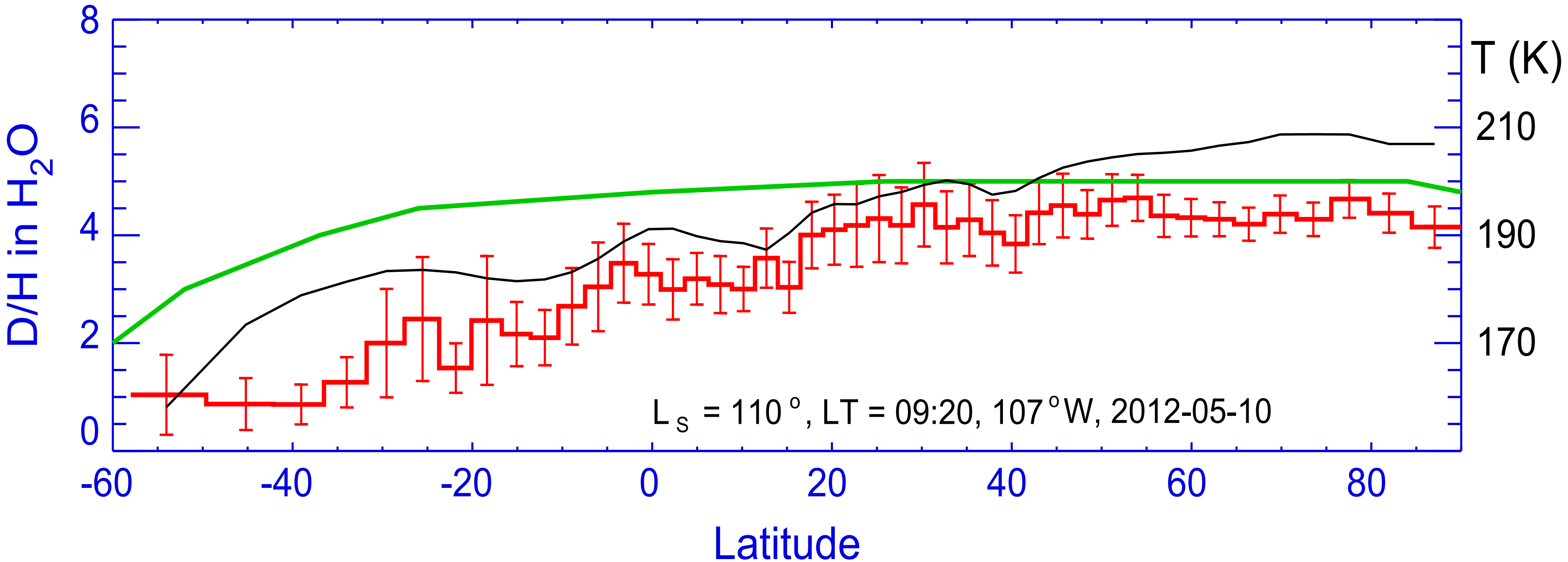


CRIRES/NIRSPEC



Comparison with Krasnopolsky 2015

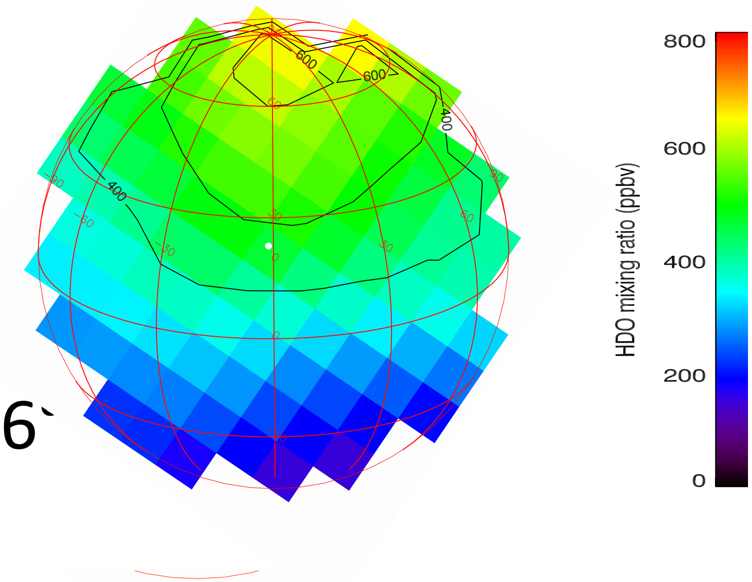
Ground-based, near IR (IRTF)
Latitudinal variations of D/H, no mapping



-Good agreement on latitudinal variations
-D/H EXES data are globally slightly higher than Krasnopolsky 2015
(EXES: 4.4 VSMOW / Krasno: 3.5 VSMOW)

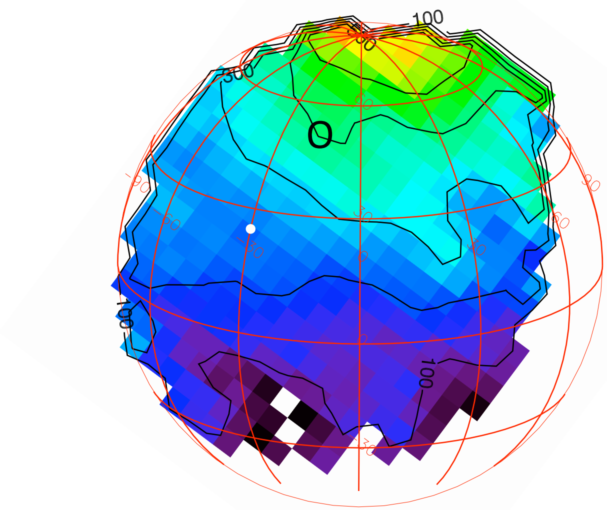
Comparison with TEXES and the GCM
HDO mixing ratio

EXES, Ls =113°
April 8, 2014

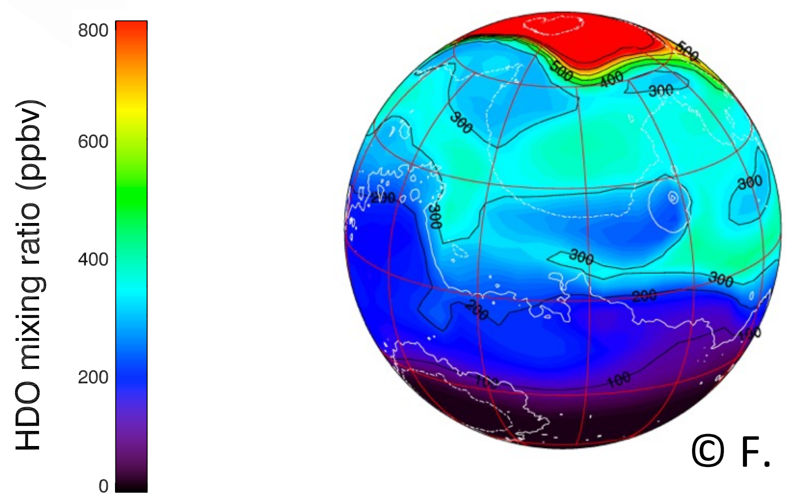


TEXES & GCM, Ls = 96`
March 1, 2014

TEXES HDO/CO_2 mixing ratio



GCM HDO/CO_2 mixing ratio



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Encrenaz et al. 2015

Good agreement except a the North pole

Conclusions and perspectives

- **For Ls = 113°:**
  - Moderate increase of D/H from South to North (4 to 5 VSMOW)
  - In agreement with theoretical models based on VPIE
  - Mean value over the disk: 4.4 (+1.0,-0.6) VSMOW
  - In global agreement with previous studies, both globally and locally
  - Implies less early water content than inferred by Villanueva +15
- **Future work:**
  - Observe maps of D/H for various seasons with EXES, for a more complete determination of the global D/H enrichment
  - Two observations planned with SOFIA in March 2016

Thanks to the EXES and SOFIA Teams!