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Ground-based thermal mapping of Venus: HDO & SO₂ monitoring and upper limits of PH₃, NH₃ and HCN at the cloud top

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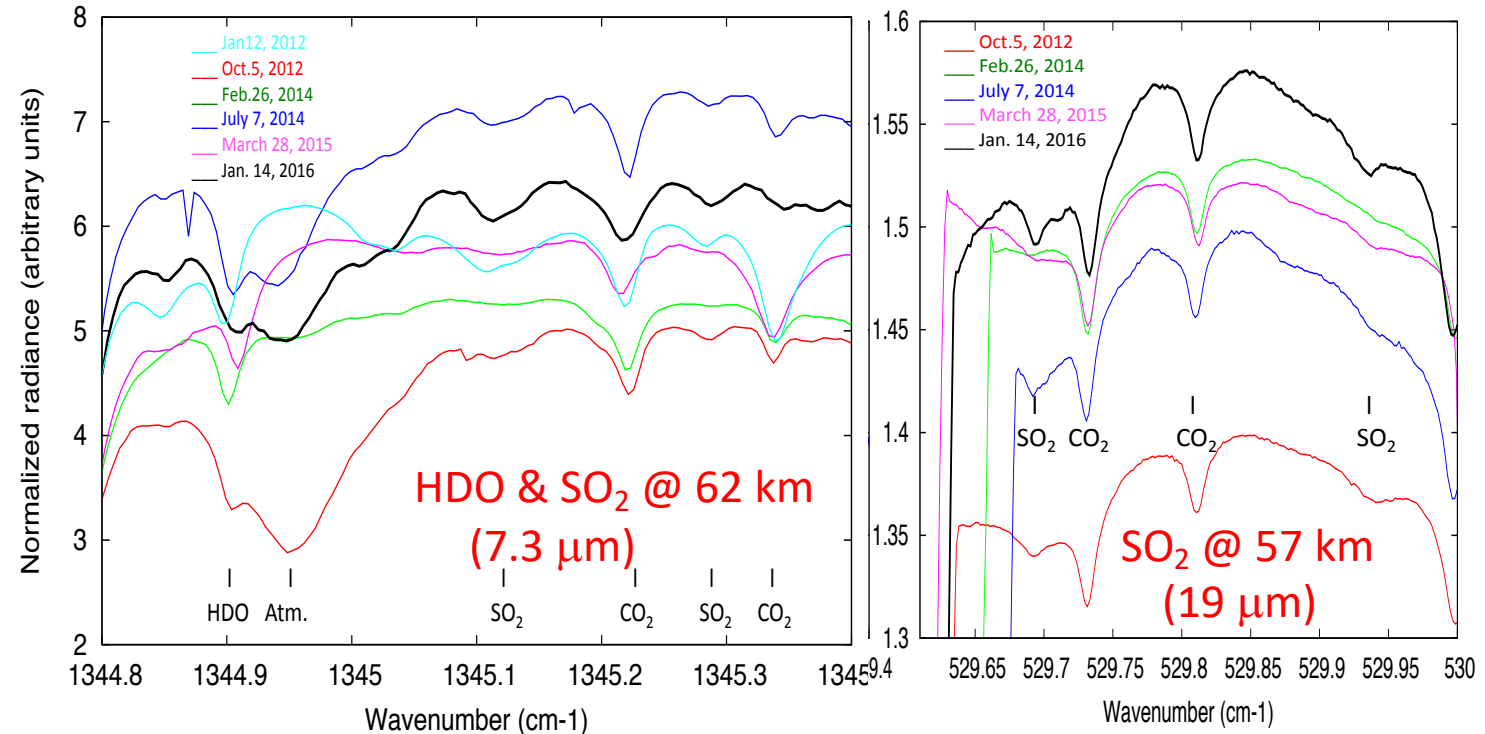
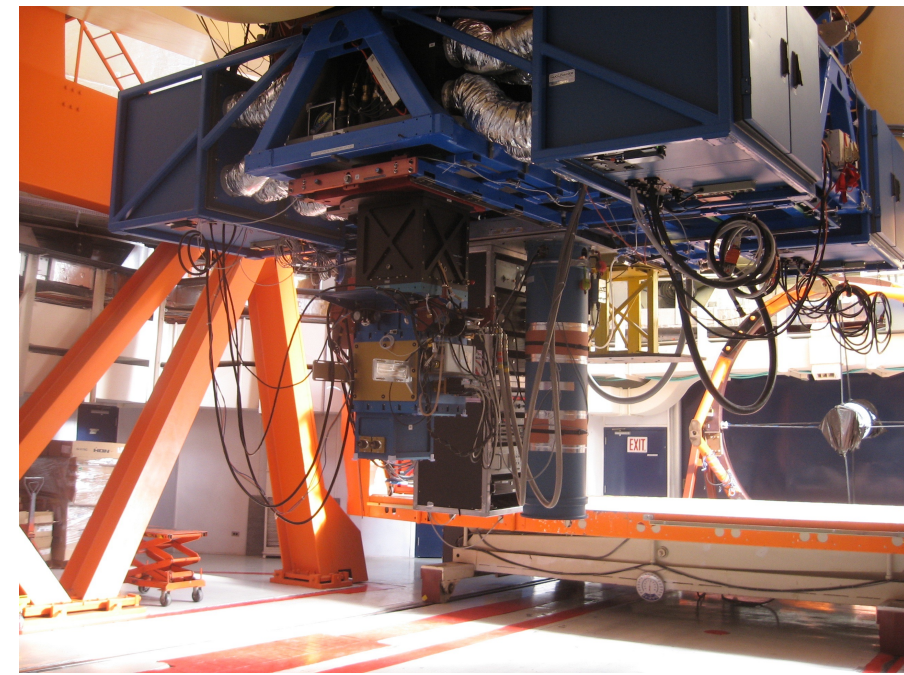
TEXES @ IRTF, Mauna Kea Observatory, Hawaii

TEXAS Echelon Cross Echelle Spectrograph 5 – 25 μm ,
 $R = 8 \times 10^4$ @ 7 μm

Main question: To understand the SO_2 & H_2O cycles
above and within the clouds

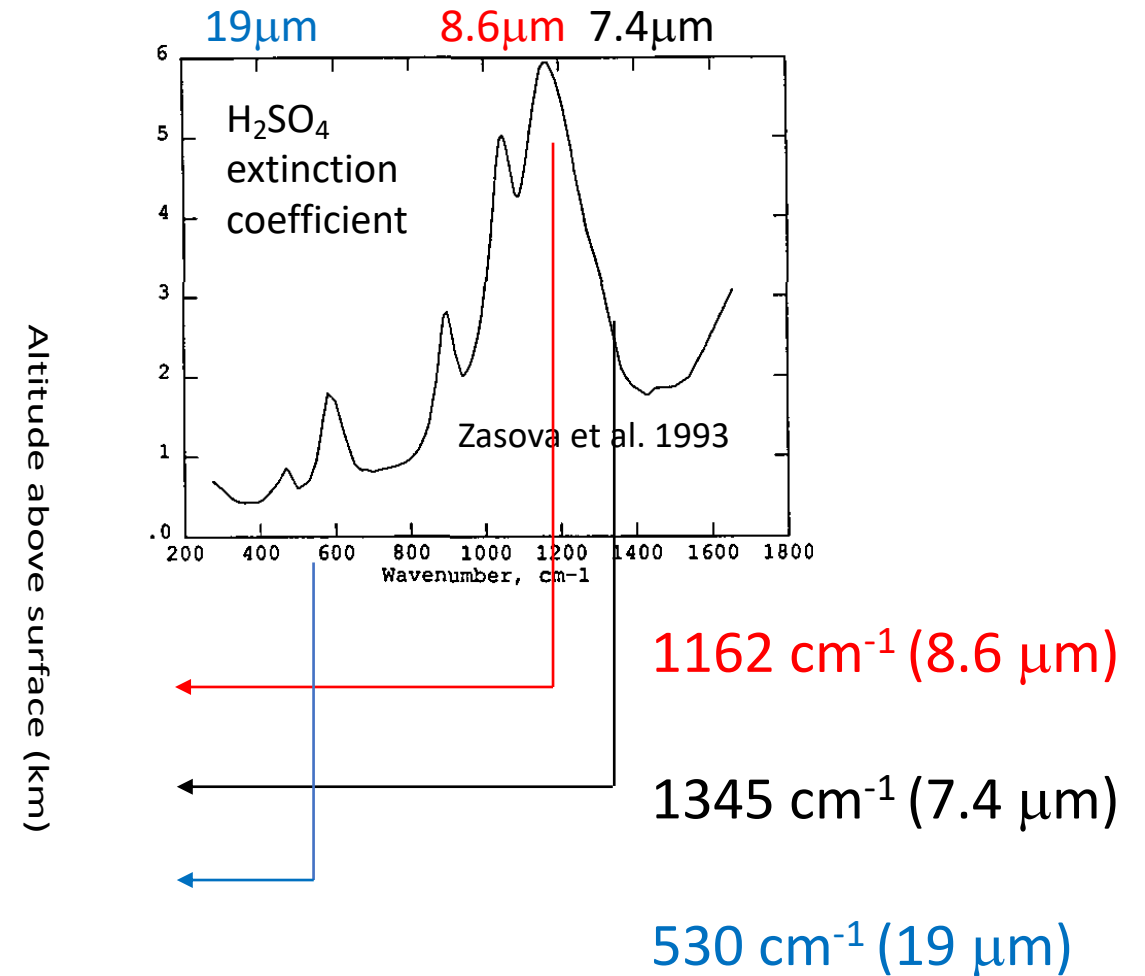
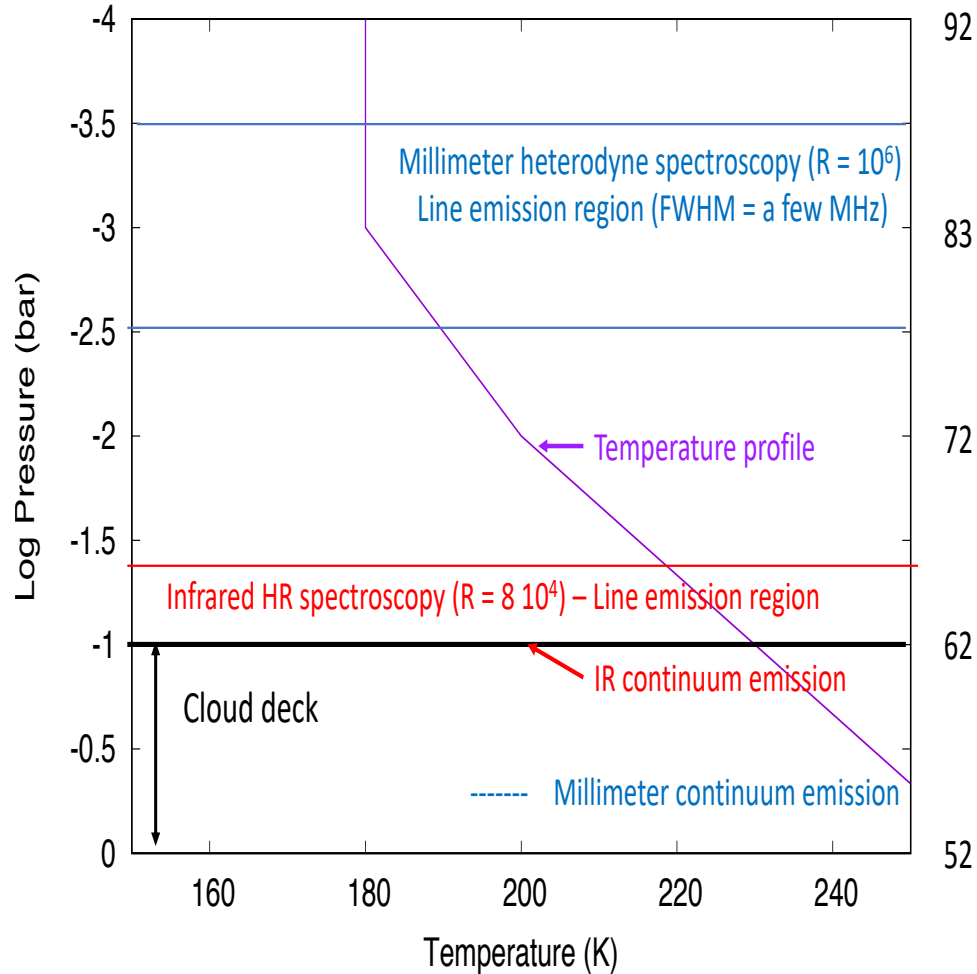
Observing program: Mapping of SO_2
(at 7 and 19 μm) and H_2O (through
HDO) at 7 μm

- Cloud top probed at 7 μm ($z = 62$ km, $T = 235$ K, $P = 150$ mbar)
- Within the cloud at 19 μm ($z = 57$ km, $T = 241$ K, $P = 250$ mbar)
- Above the clouds at 8.6 μm ($z = 67$ km)
- 12 campaigns between January 2012 and April 2019; 11 campaigns since 2021: June, Sept. & Nov. 2021, Feb. & June 2022, March, July, Oct. & Dec. 2023, Feb. 2024



Where does the radiation come from?

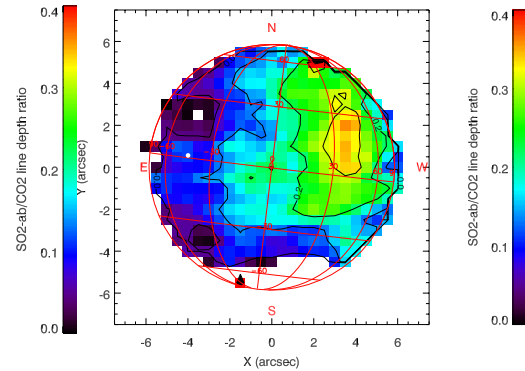
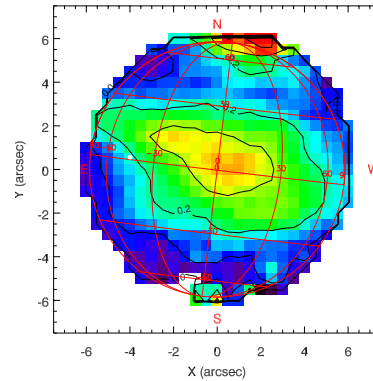
Due to the spectral dependence of the H_2SO_4 absorption coefficient, different levels are probed at 1162 cm^{-1} (67 km), 1345 cm^{-1} (62 km) and 530 cm^{-1} (57 km)



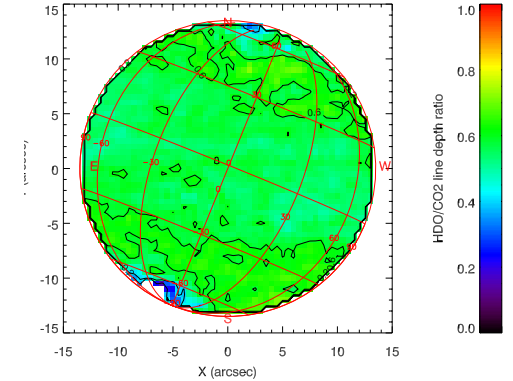
SO₂ & HDO maps exhibit a different behavior

The SO₂ plume follows the 4-day rotation of the clouds at the cloud top over a time scale of a few hours

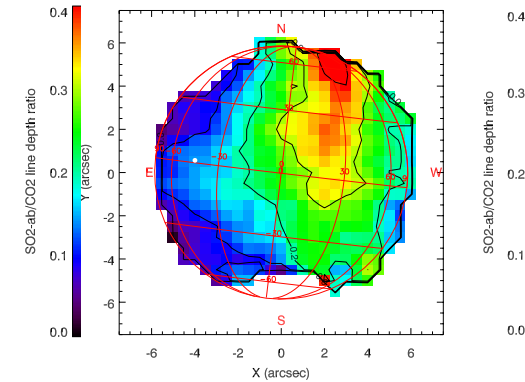
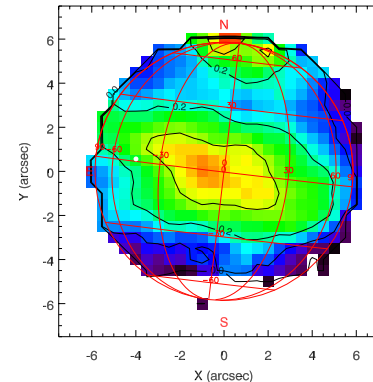
July 7, 2014
17:00 UT



January 21, 2017

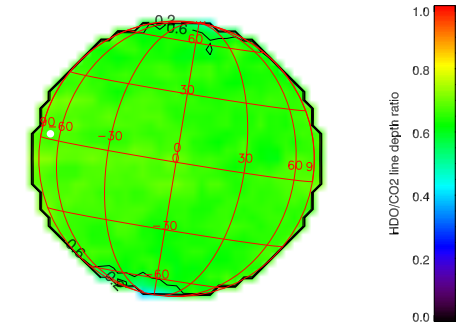


July 7, 2014
19:00 UT



July 8:2014
19:00 UT

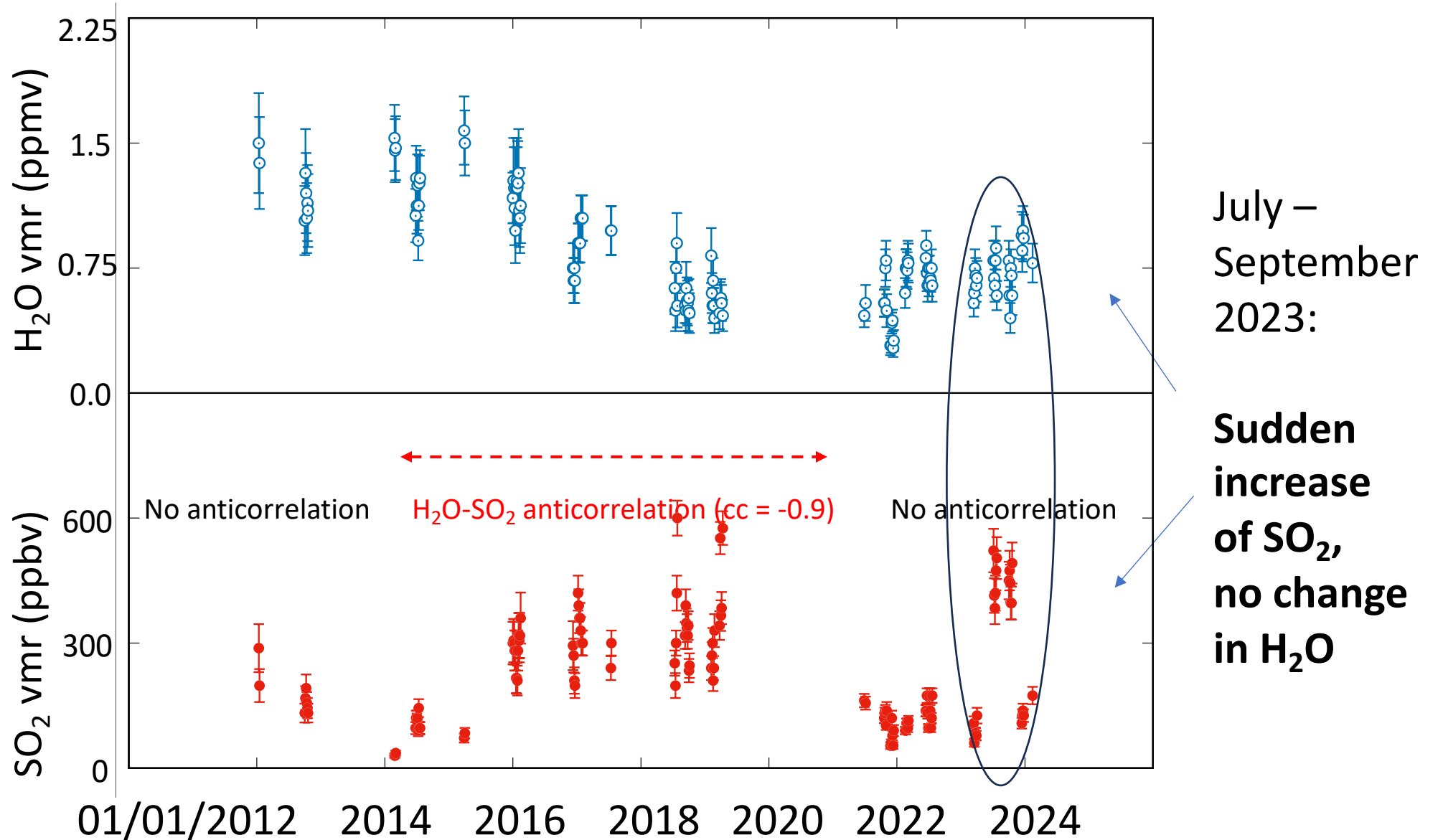
July 12, 2017



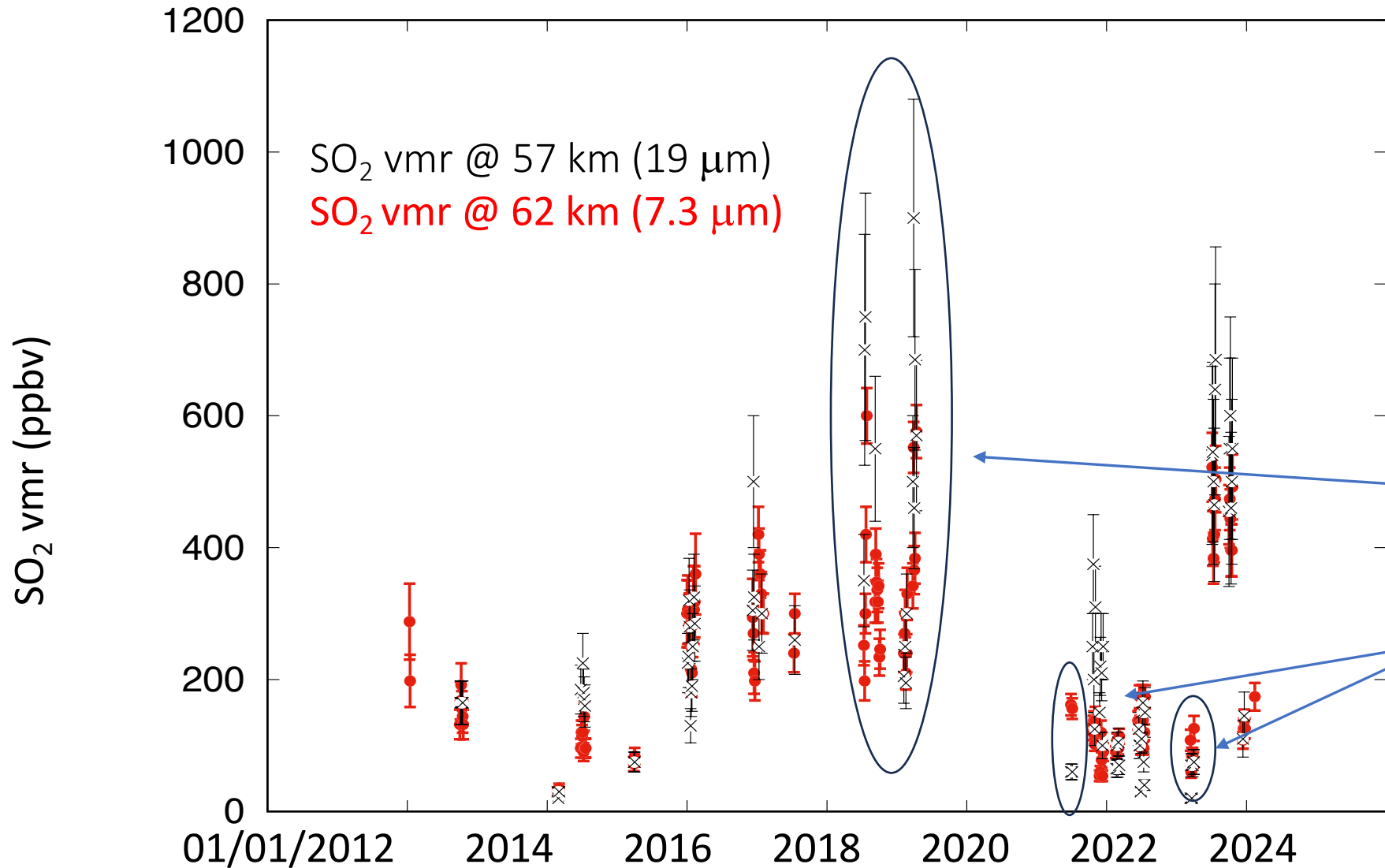
SO₂ maps are very inhomogeneous over the disk and show strong variations with time

HDO maps are uniform over the disk and +/- constant over time

Long-term variations of H₂O and SO₂ at the cloud top (z = 62 km)

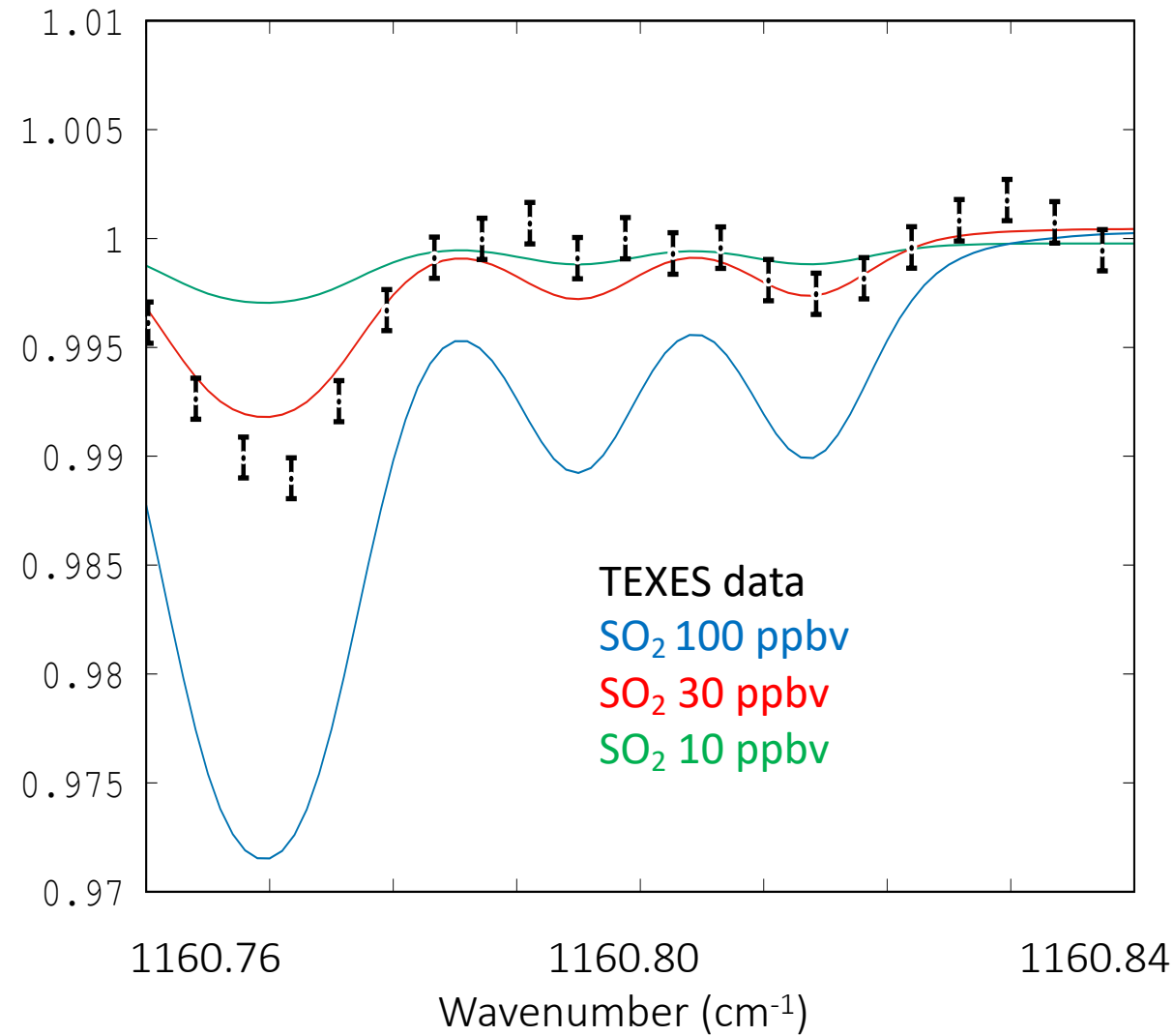
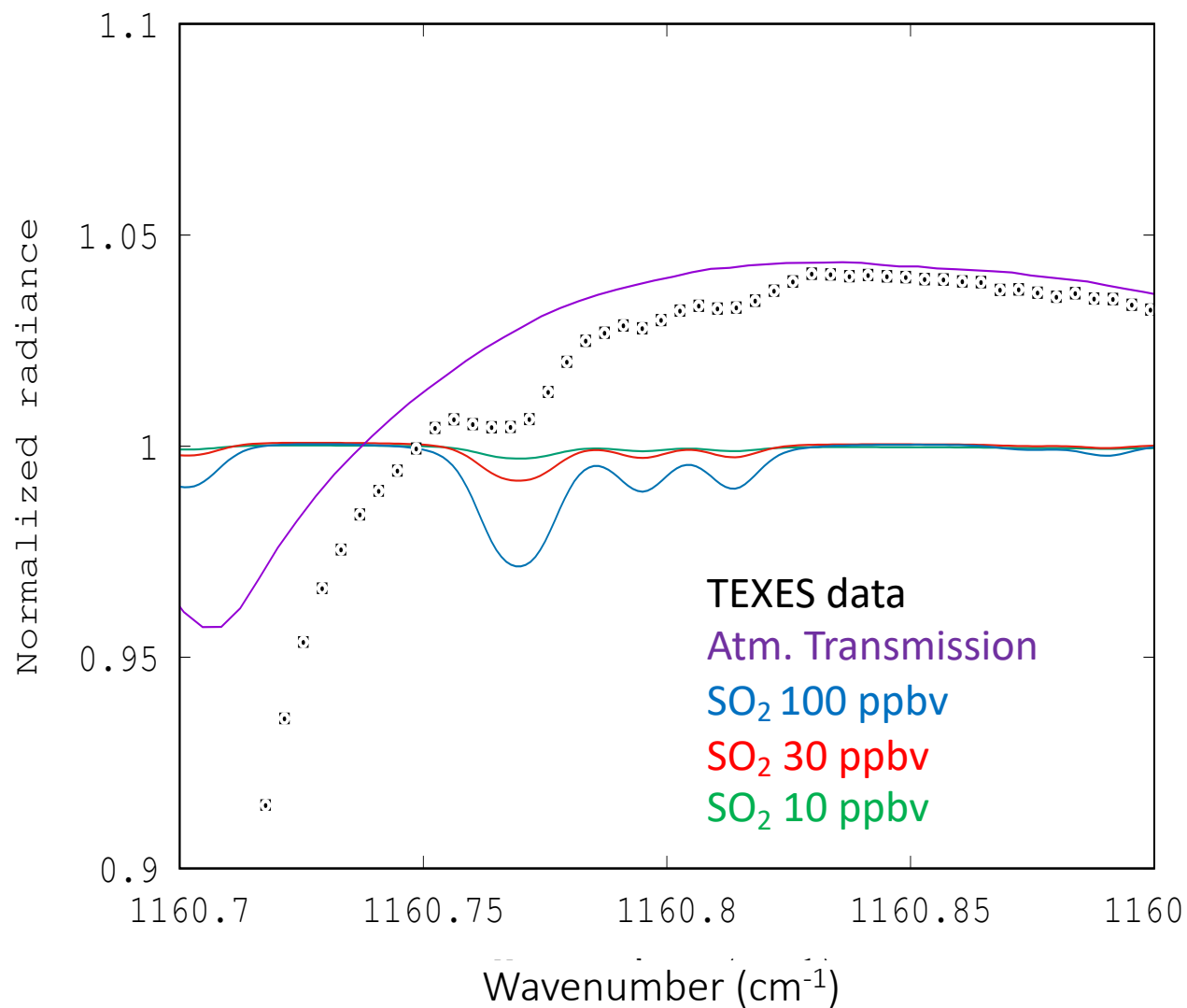


Long-term SO₂ variations at the cloud top (z = 62 km) and within the cloud (z = 57 km)



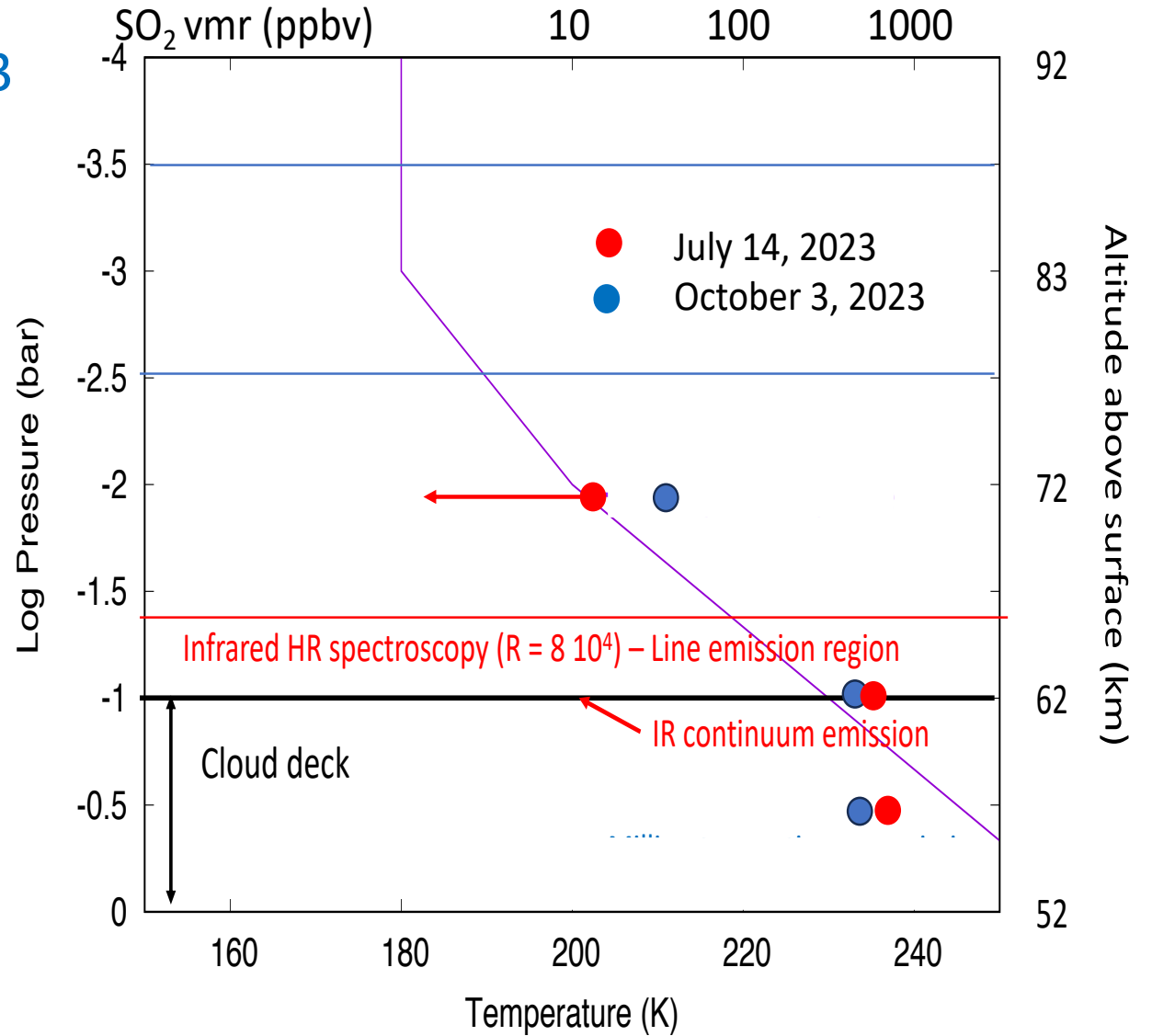
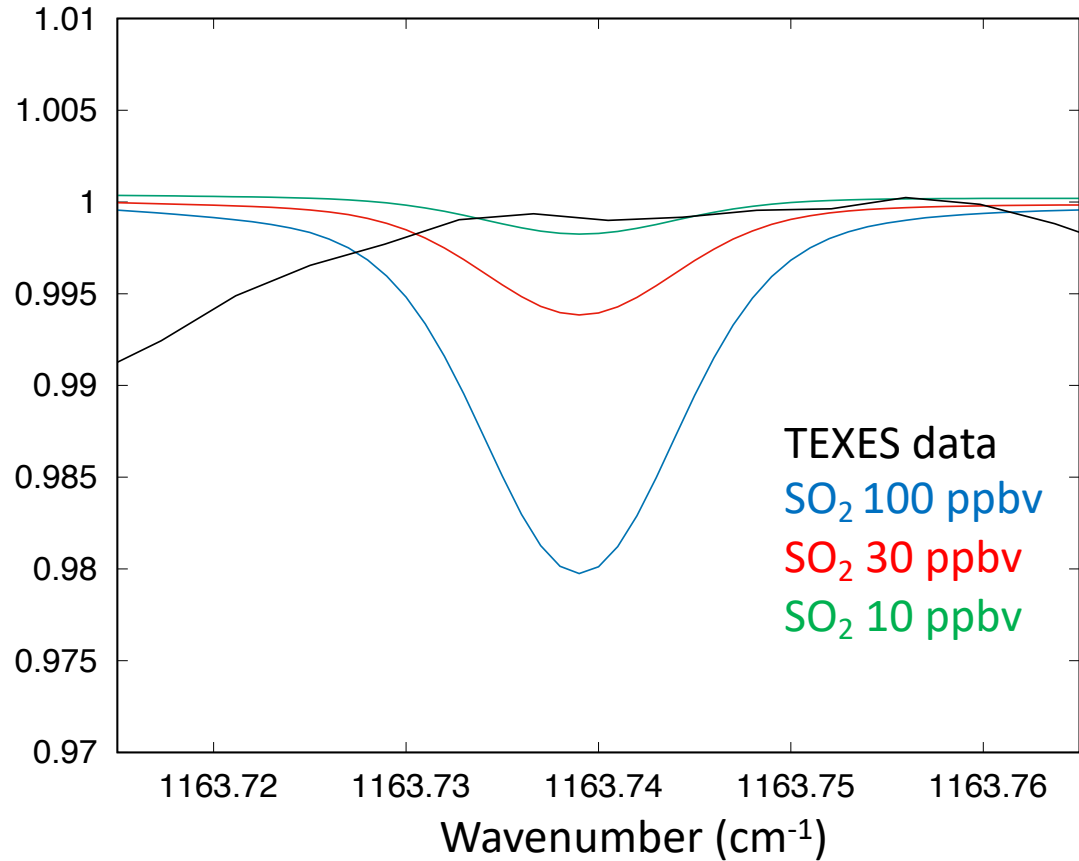
SO₂ @ 57 km is usually comparable to SO₂ @ 62 km, but, in some cases, may be **much larger** (2019) or **even lower** (June 2021, March 2023)

First detection of SO₂ in the ν_1 SO₂ band at 1160 cm⁻¹ (8.6 μ m) October 3, 2023



Detection of SO₂ at 67 km on Oct. 3, 2023

Upper limit of SO₂ @ 67 km, 14 July 2023



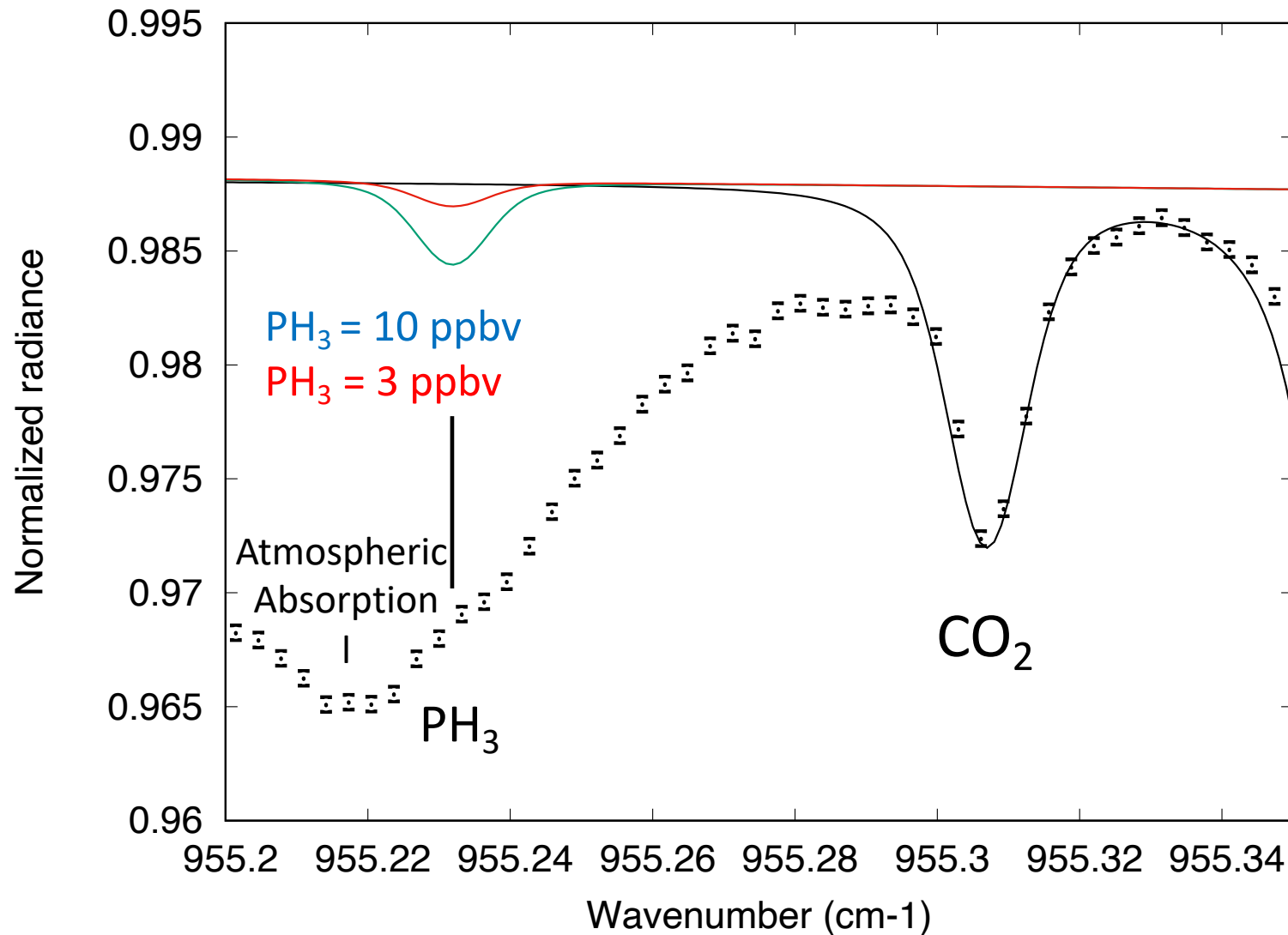
July 14, 2023: SO₂(67km)/SO₂(62km) < 50

October 3, 2023: SO₂(67km)/SO₂(62km) = 20

Upper limits of minor species at the cloud top of Venus

- Attempts to detect minor species in Venus have been reported in the literature :
 - PH₃: detection, up to 20 ppbv (Greaves et al. 2020, +)
 - HCN: upper limit, 38.3 +/- 7.9 ppmv @ 80 km (Mahieux et al. 2023)
 - NH₃: upper limit, 0.69 +/- 0.28 ppmv @ 80 km (Mahieux et al. 2023)
- New upper limits have been obtained with TEXES (present work):
 - PH₃: **1 ppbv** (σ) at the cloud top (62 km)
 - NH₃: **0.1 ppbv** (σ) at the cloud top (62 km)
 - HCN: **0.1 ppbv** (σ) at the cloud top (62 km)

PH₃ upper limit at the cloud top

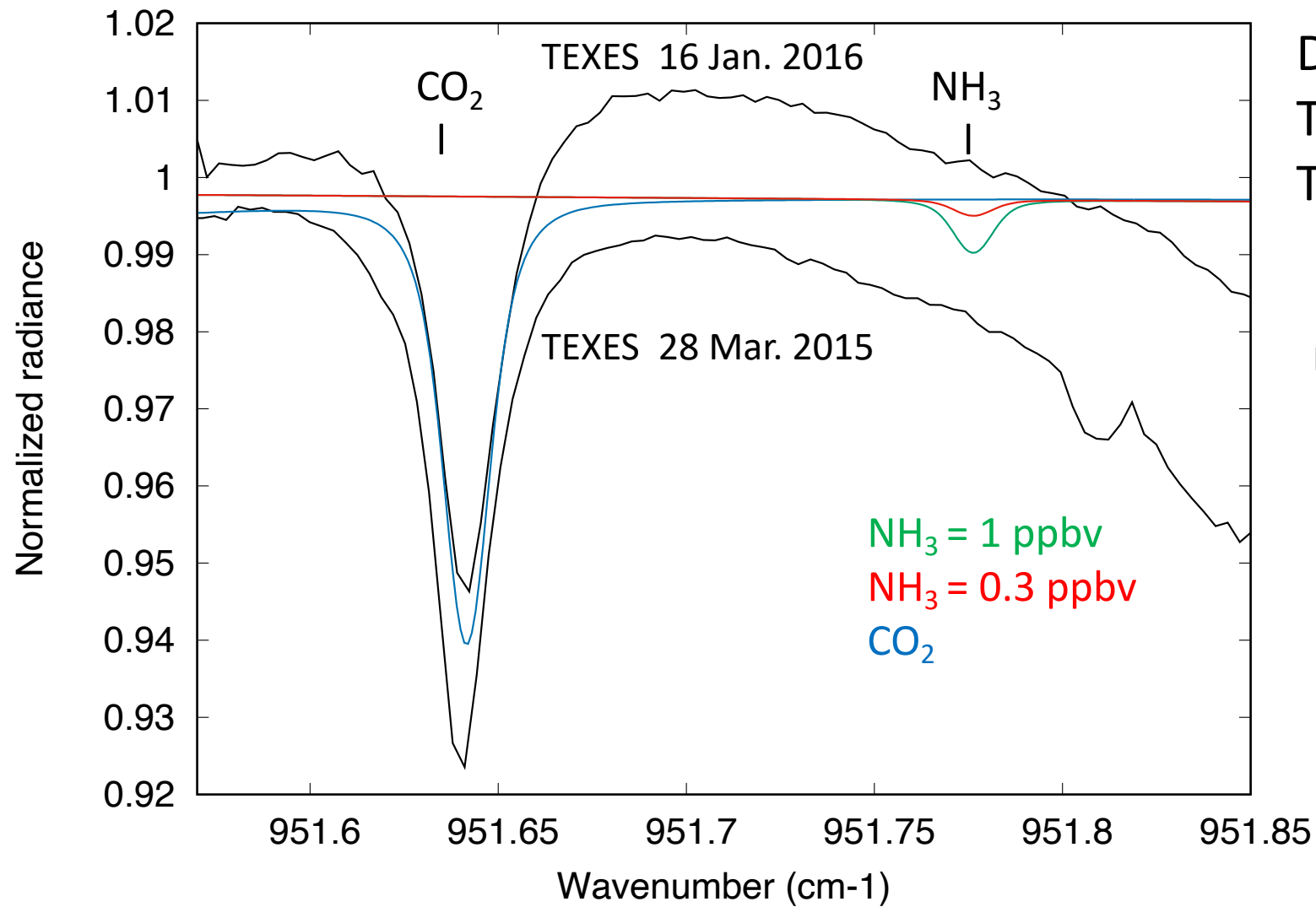


Data: TEXES, July 16, 2023

Upper limit:
PH₃ < 3 ppbv (3 σ)

Confirms our earlier
analysis:
PH₃ < 5 ppbv (3 σ)
(Encrenaz et al.
A&A 643, L5 (2020))

NH₃ upper limit at the cloud top



Data:

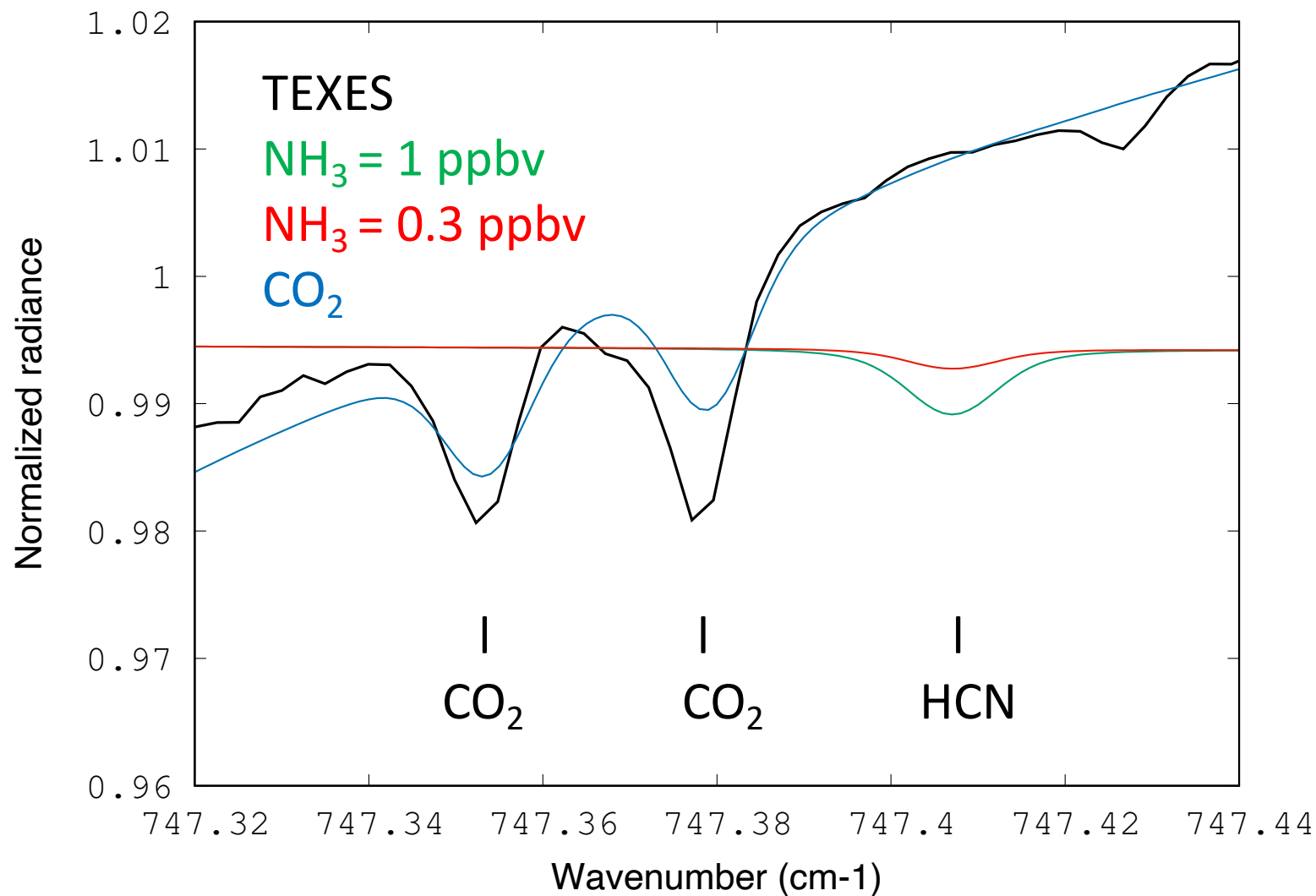
TEXES, March 28, 2015

TEXES, January 16, 2016

Upper limit:

NH₃ < 0.3 ppbv (3 σ)

HCN upper limit at the cloud top



Data:
TEXES, July 15, 2023

Upper limit:
HCN < 0.3 ppbv (3 σ)

Conclusions

- Since 2012, SO₂ has been mapped over the Venus disk and monitored at z = 62 km (cloud top, 7.4 μm) and 57 km (19 μm); it was searched for without success at 67 km (8.6 μm) until 2023.
- H₂O (using HDO as a proxy) was simultaneously mapped and monitored at the cloud top (7.4 μm).
- H₂O & SO₂ exhibit different behaviors at the cloud top of Venus:
 - H₂O is uniform over the disk and shows moderate temporal variations.
 - SO₂ shows strong spatial and temporal variations in the form of transient plumes and strong long-term variations .
- The long-term variations of H₂O and SO₂ were clearly anti-correlated between 2012 and 2019, but not before nor after.
 - The anticorrelation might be the result of photochemical processes, while convection might favor the mixing of the two species. The lack of anticorrelation after 2019 might indicate a change of regime within or below the clouds.
- **Main results:**
- **SO₂ is detected for the first time on Oct.3, 2023; SO₂(67km)/SO₂(62km) = 1/20 (< 1/50 on 14/07/ 2023)**
- **Stringent upper limits** are obtained for PH₃, NH₃ and HCN at the cloud top:
 - **PH₃ < 1 ppbv (1σ), NH₃ < 0.1 ppbv (1σ), HCN < 0.1 ppbv (1σ)**