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Therese Encrenaz, Thomas Greathouse, Rohini Giles, Thomas Widemann, Bruno Bezard, Franck Lefèvre, Maxence Lefevre, Wencheng Shao, Hideo Sagawa, Emmanuel Marcq, et al.

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# Ground-based thermal mapping of Venus: HDO & SO<sub>2</sub> monitoring and upper limits of PH<sub>3</sub>, NH<sub>3</sub> and HCN at the cloud top

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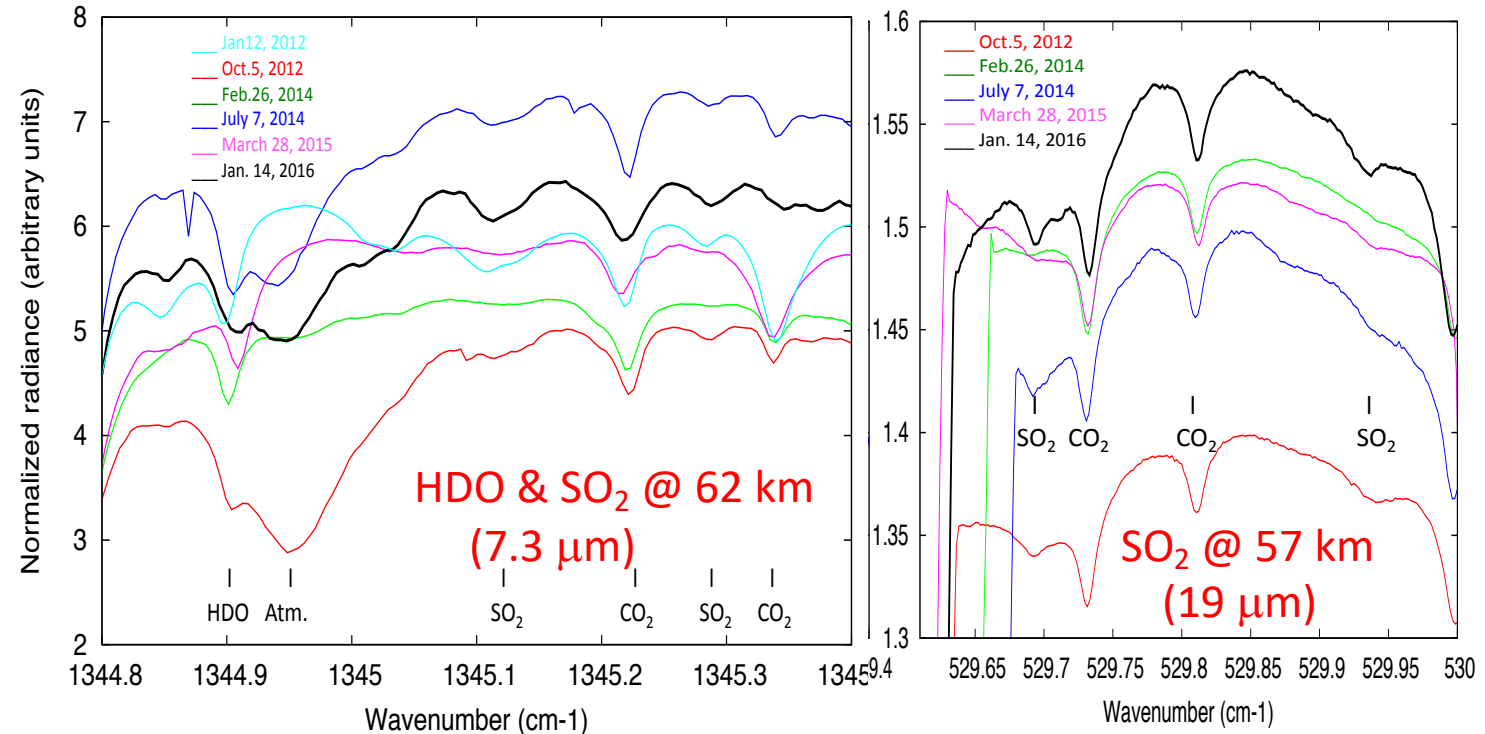
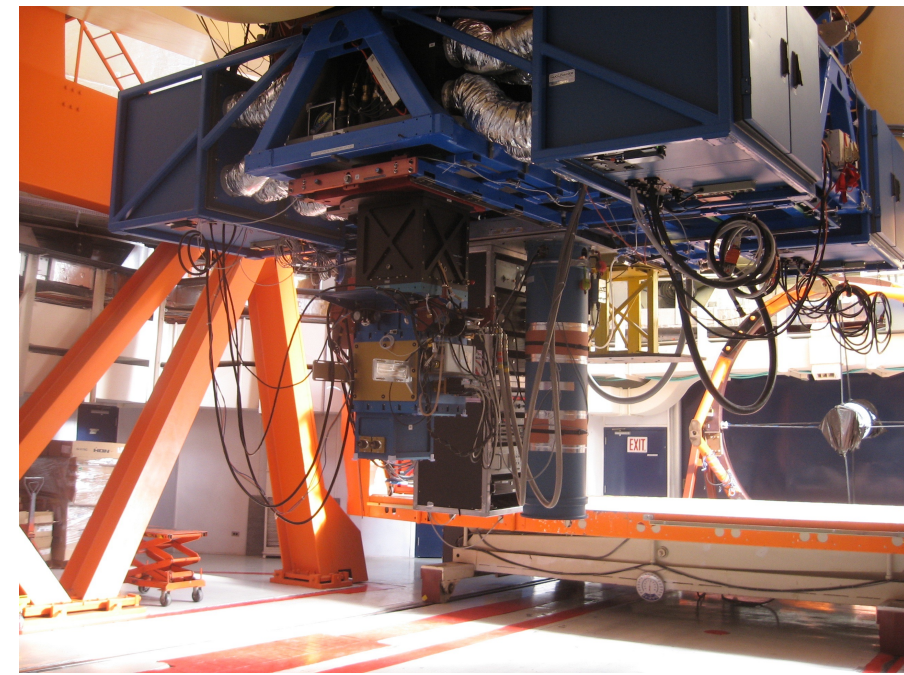
# TEXES @ IRTF, Mauna Kea Observatory, Hawaii

TEXAS Echelon Cross Echelle Spectrograph 5 – 25  $\mu\text{m}$ ,  
 $R = 8 \times 10^4$  @ 7  $\mu\text{m}$

**Main question:** To understand the  $\text{SO}_2$  &  $\text{H}_2\text{O}$  cycles  
above and within the clouds

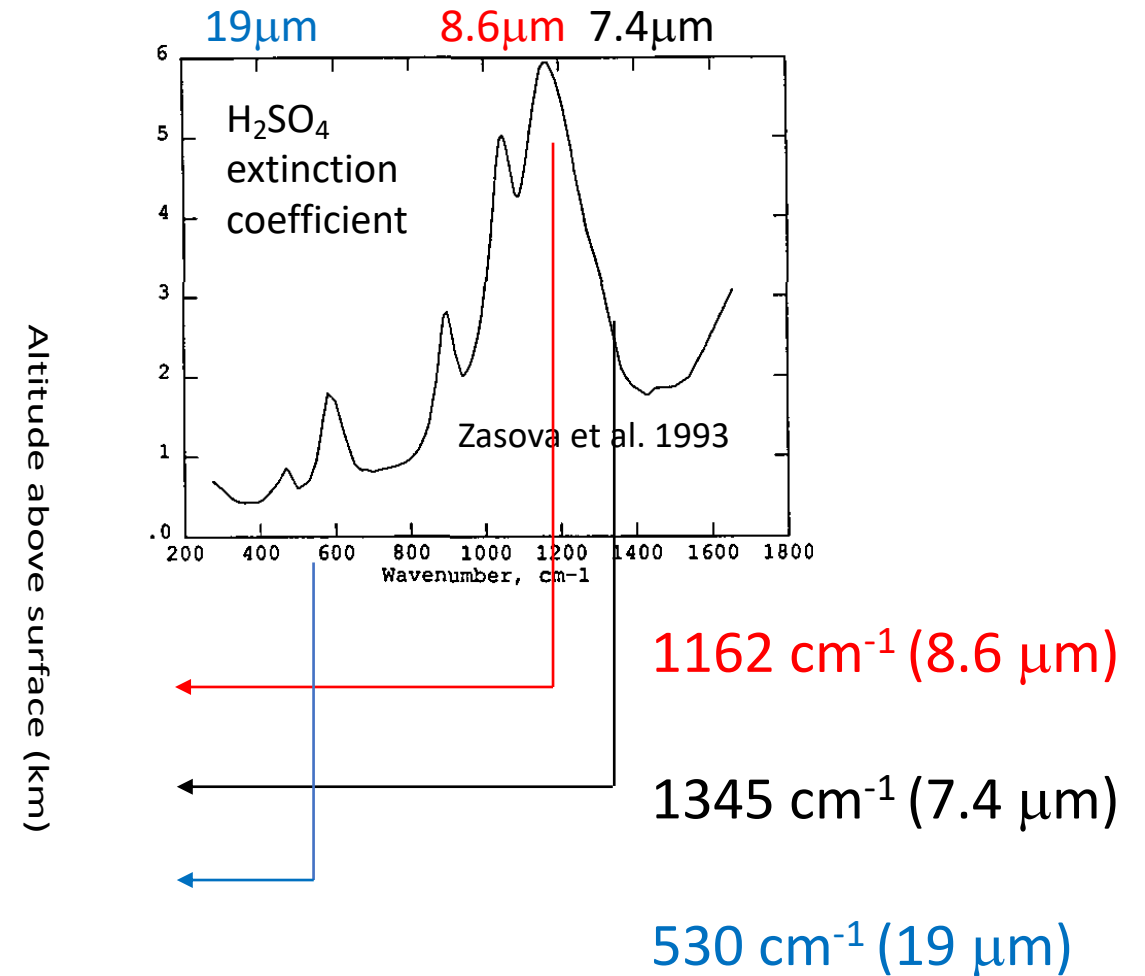
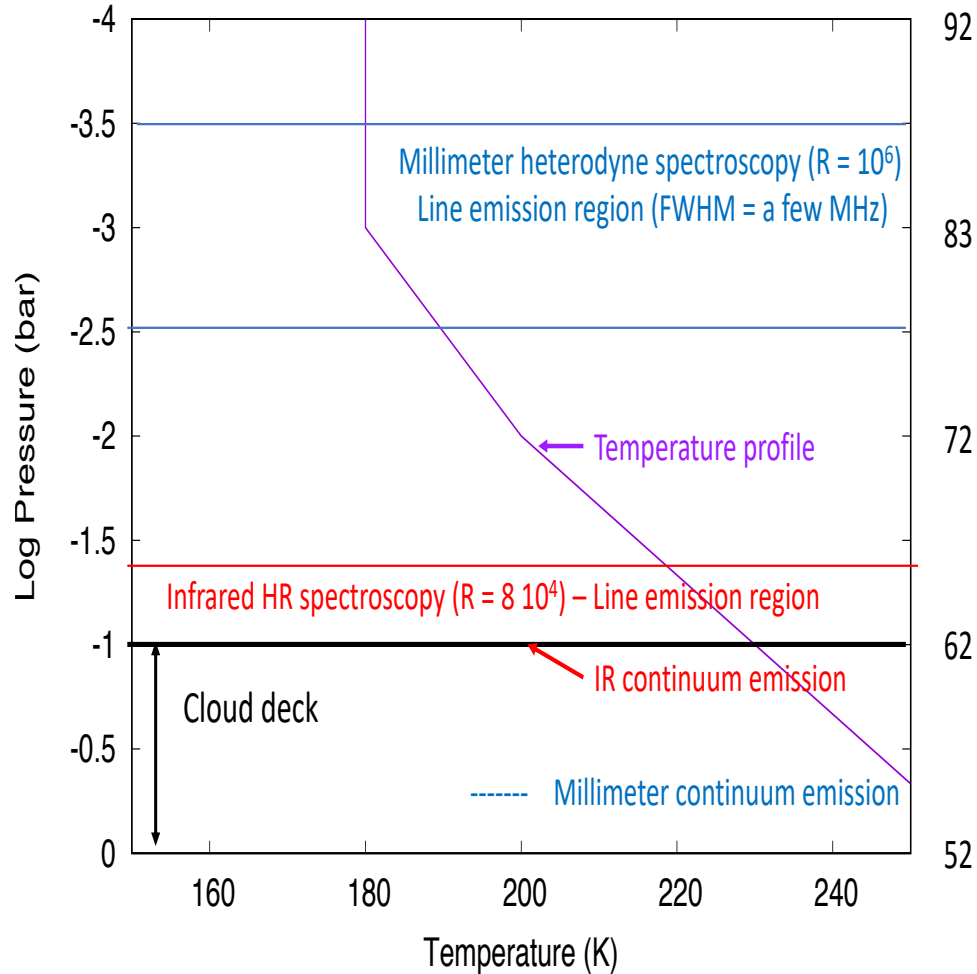
**Observing program:** Mapping of  $\text{SO}_2$   
(at 7 and 19  $\mu\text{m}$ ) and  $\text{H}_2\text{O}$  (through  
HDO) at 7  $\mu\text{m}$

- Cloud top probed at 7  $\mu\text{m}$  ( $z = 62$  km,  $T = 235$  K,  $P = 150$  mbar)
- Within the cloud at 19  $\mu\text{m}$  ( $z = 57$  km,  $T = 241$  K,  $P = 250$  mbar)
- Above the clouds at 8.6  $\mu\text{m}$  ( $z = 67$  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  $\text{H}_2\text{SO}_4$  absorption coefficient, different levels are probed at  $1162\text{ cm}^{-1}$  (67 km),  $1345\text{ cm}^{-1}$  (62 km) and  $530\text{ cm}^{-1}$  (57 km)



Altitude above surface (km)

92

83

72

62

52

$1162\text{ cm}^{-1}$  ( $8.6\mu\text{m}$ )

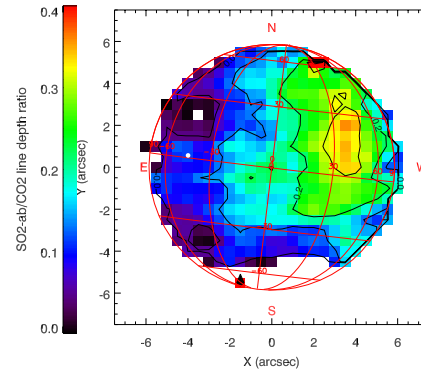
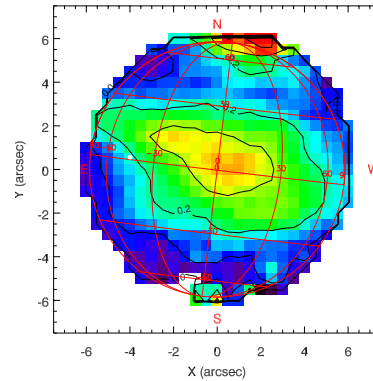
$1345\text{ cm}^{-1}$  ( $7.4\mu\text{m}$ )

$530\text{ cm}^{-1}$  ( $19\mu\text{m}$ )

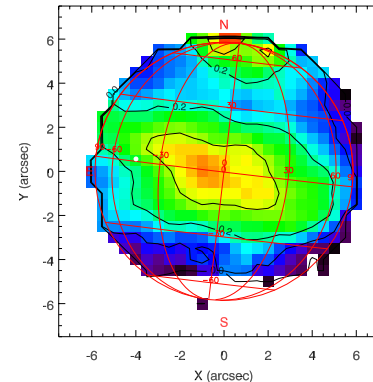
# SO<sub>2</sub> & HDO maps exhibit a different behavior

The SO<sub>2</sub> plume follows the 4-day rotation of the clouds at the cloud top over a time scale of a few hours

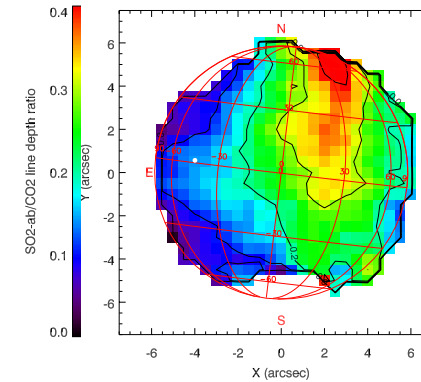
July 7, 2014  
17:00 UT



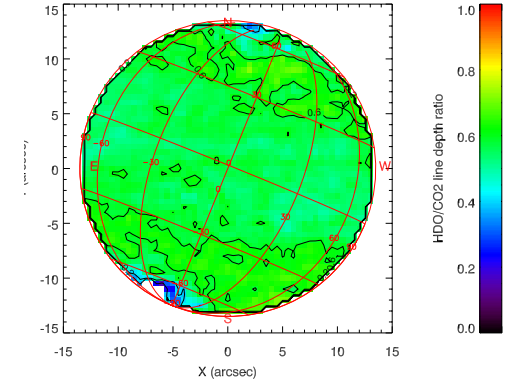
July 7, 2014  
19:00 UT



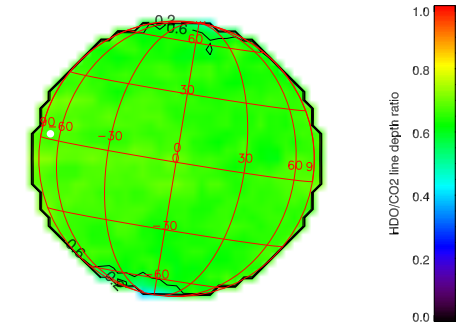
July 8, 2014  
17:00 UT



January 21, 2017



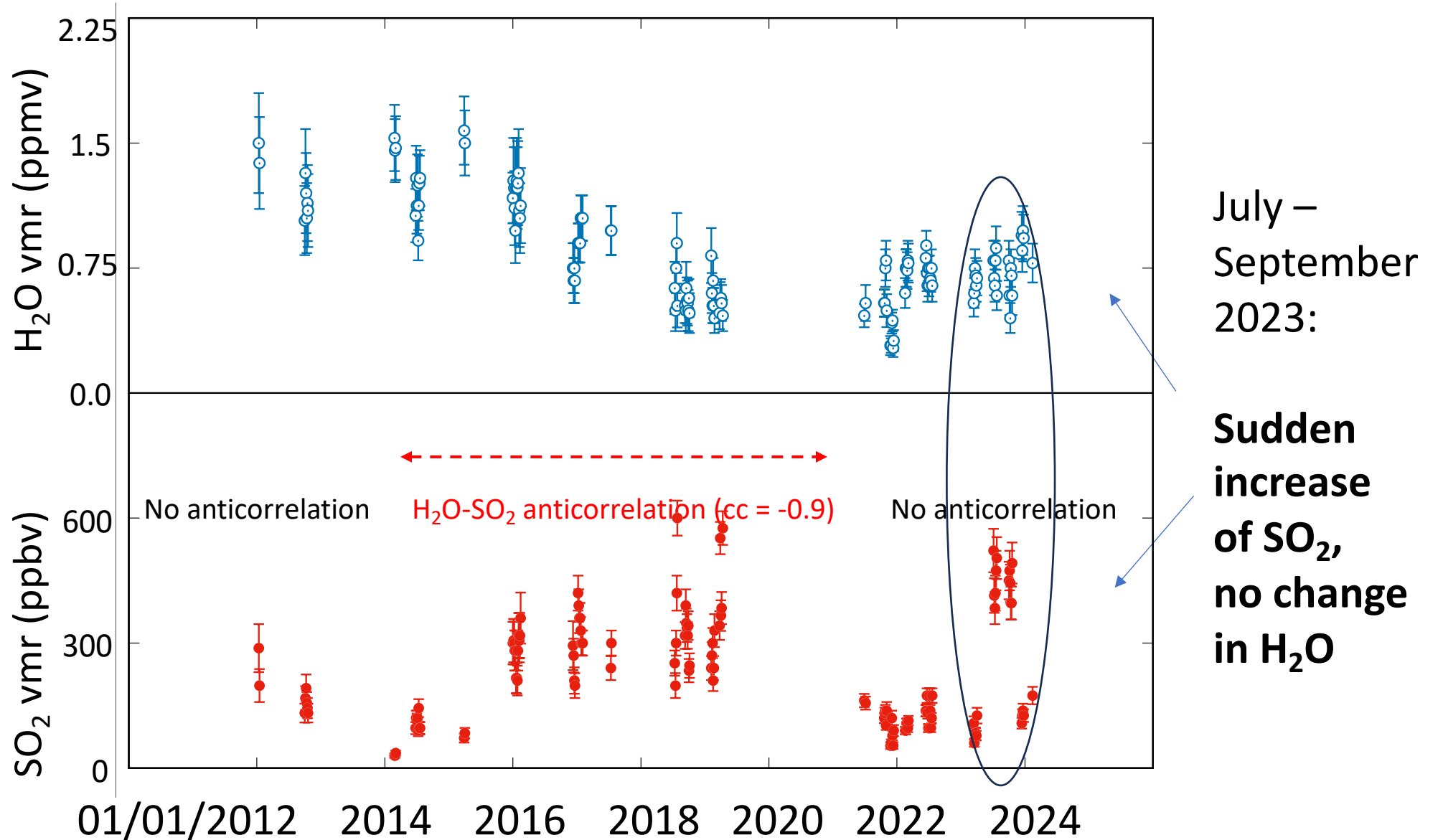
July 12, 2017



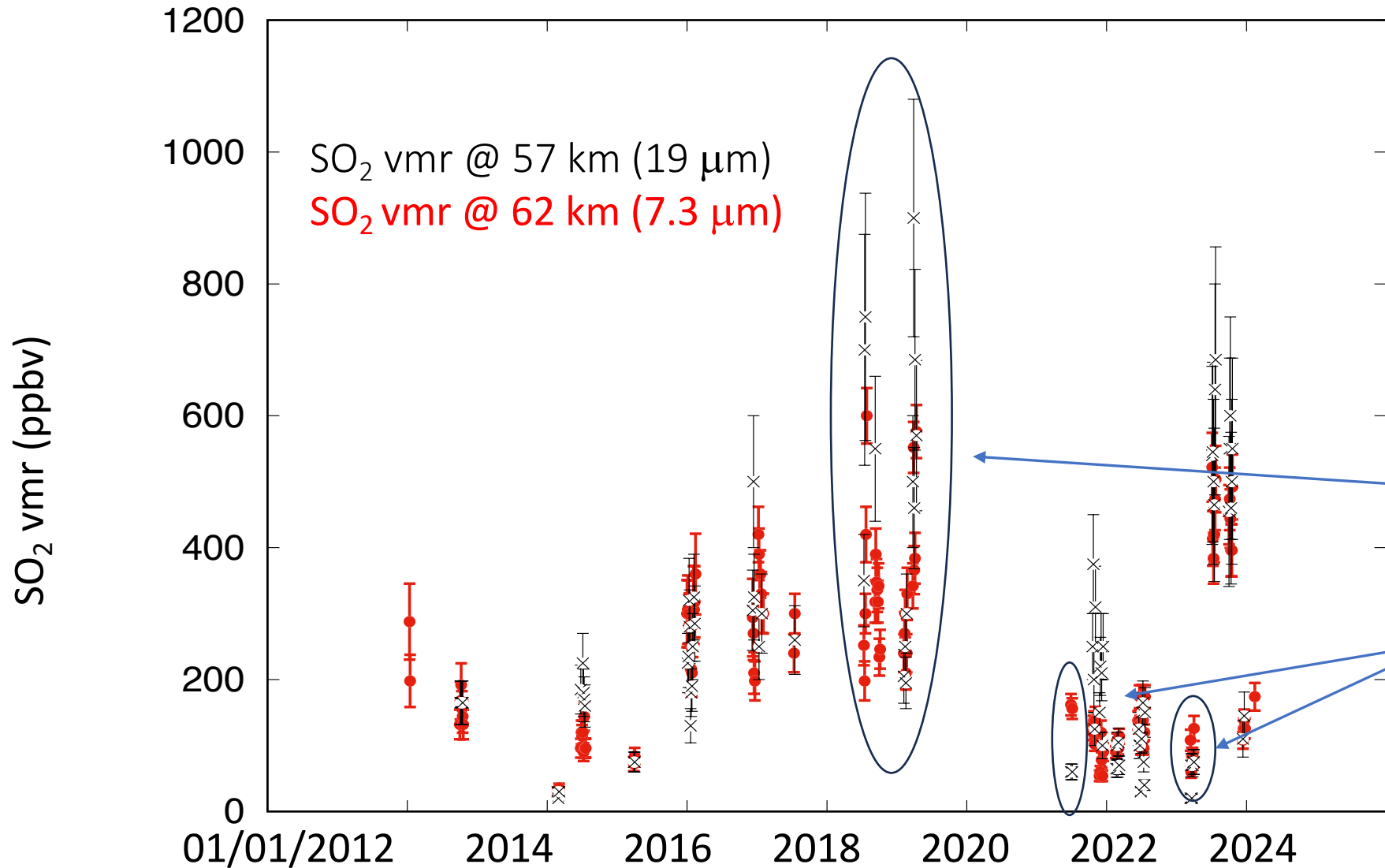
SO<sub>2</sub> maps are very inhomogeneous over the disk and show strong variations with time

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

# Long-term variations of H<sub>2</sub>O and SO<sub>2</sub> at the cloud top (z = 62 km)

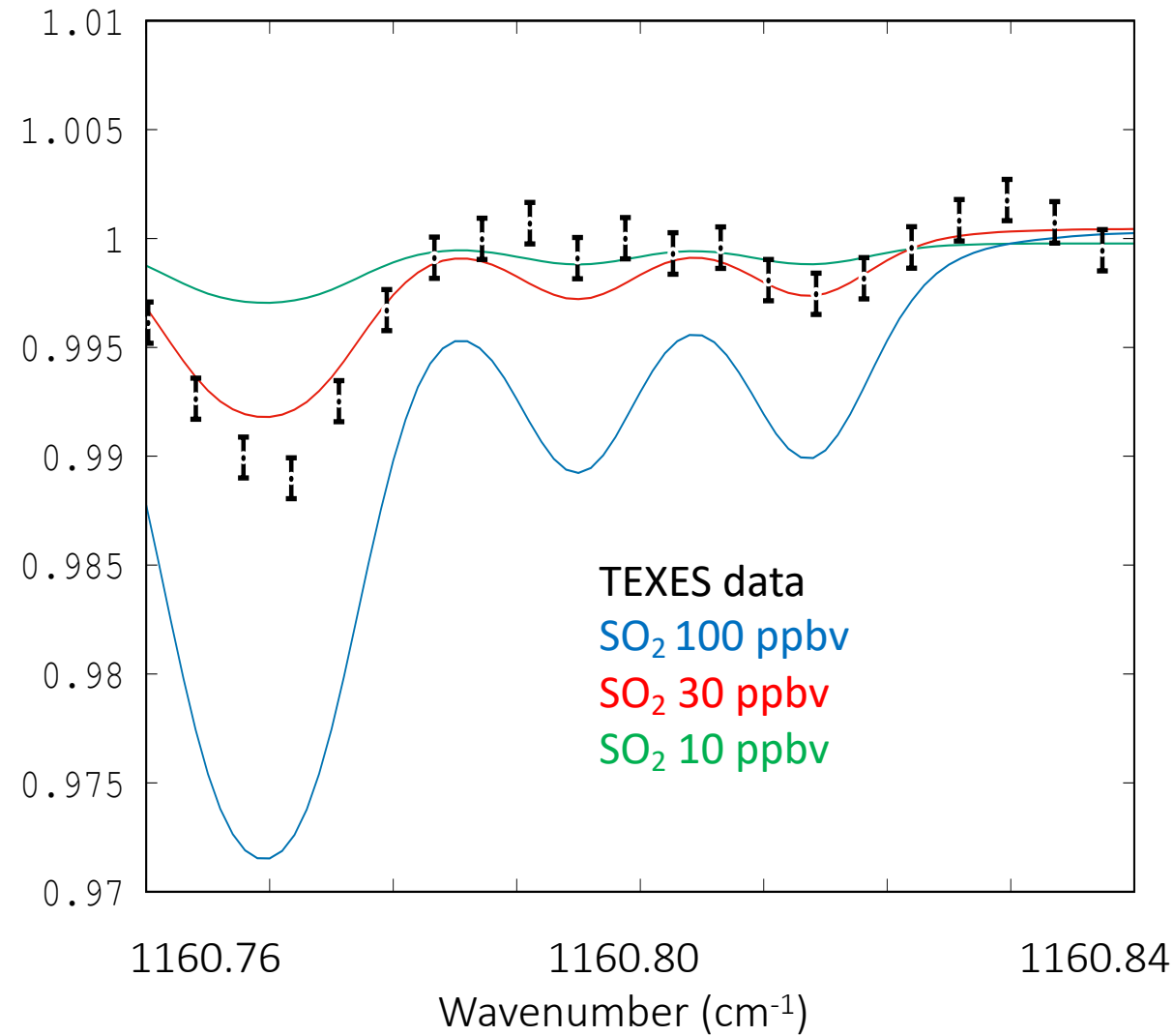
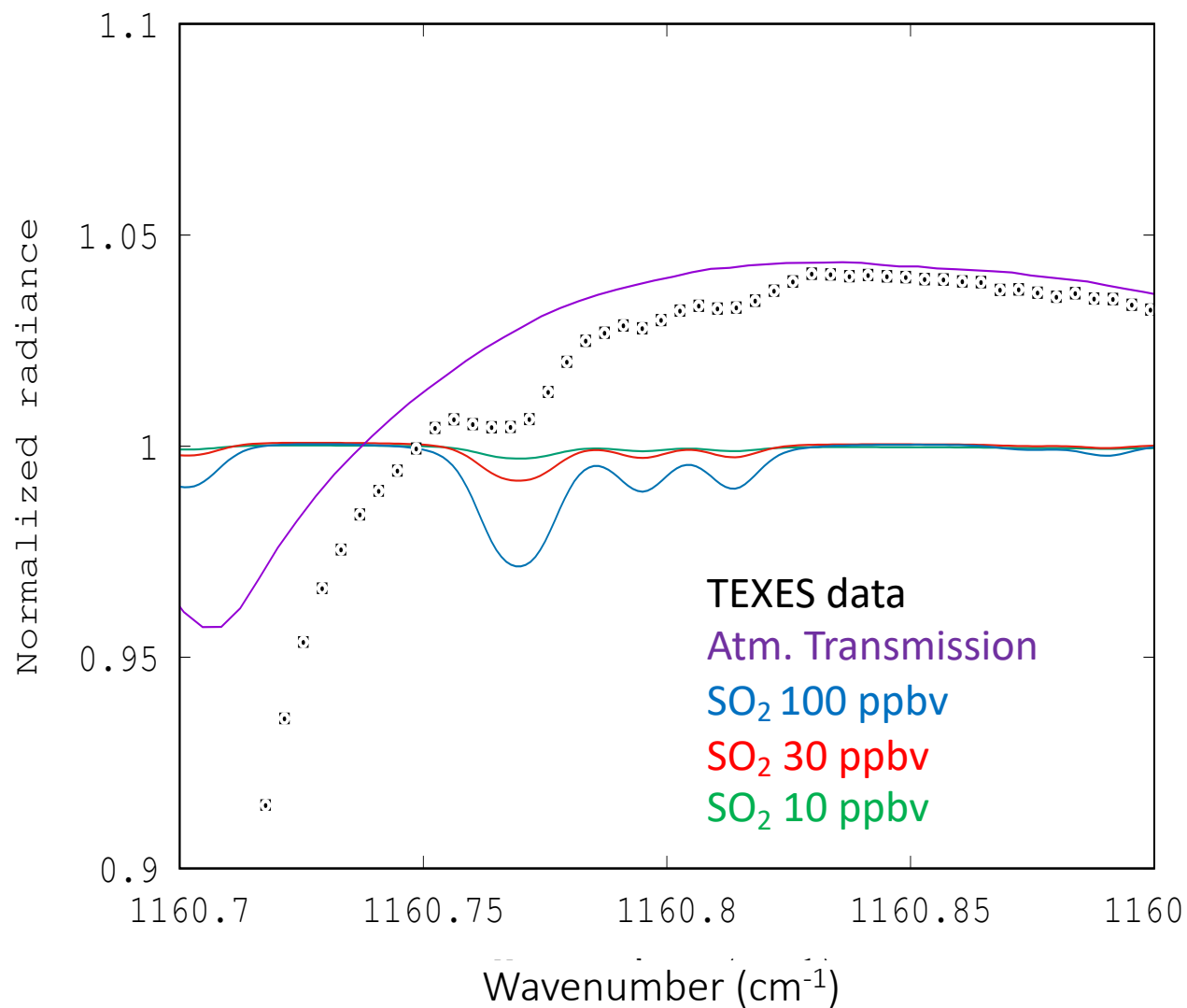


# Long-term SO<sub>2</sub> variations at the cloud top (z = 62 km) and within the cloud (z = 57 km)



SO<sub>2</sub> @ 57 km is usually comparable to SO<sub>2</sub> @ 62 km, but, in some cases, may be **much larger** (2019) or **even lower** (June 2021, March 2023)

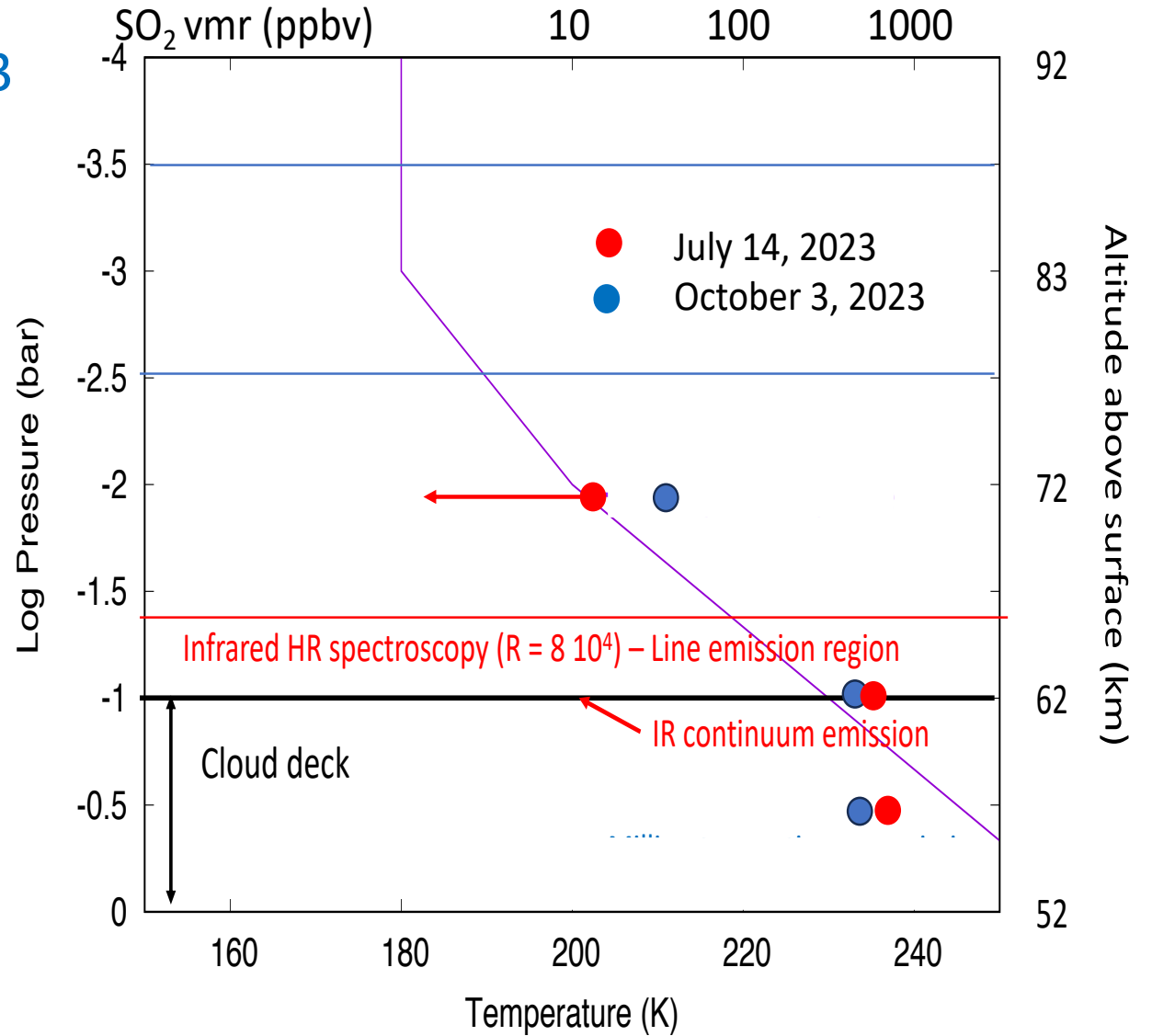
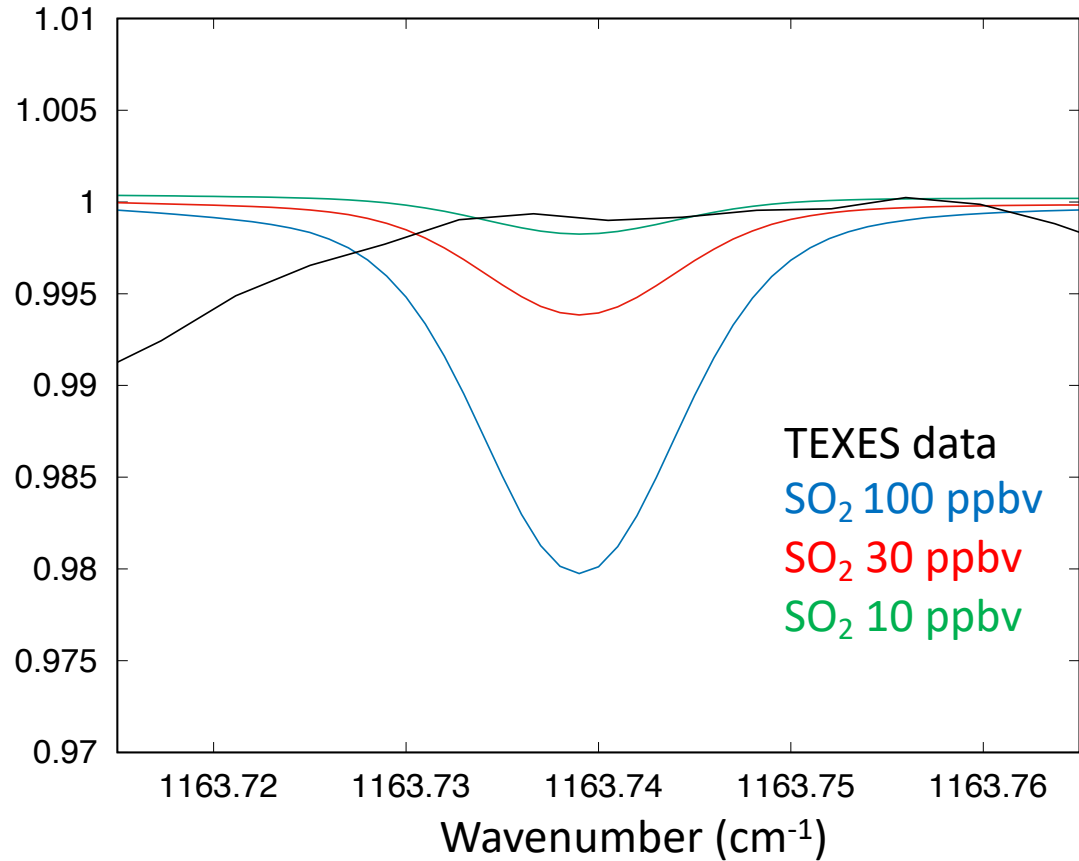
# First detection of SO<sub>2</sub> in the $\nu_1$ SO<sub>2</sub> band at 1160 cm<sup>-1</sup> (8.6 $\mu$ m) October 3, 2023





# Detection of SO<sub>2</sub> at 67 km on Oct. 3, 2023

## Upper limit of SO<sub>2</sub> @ 67 km, 14 July 2023



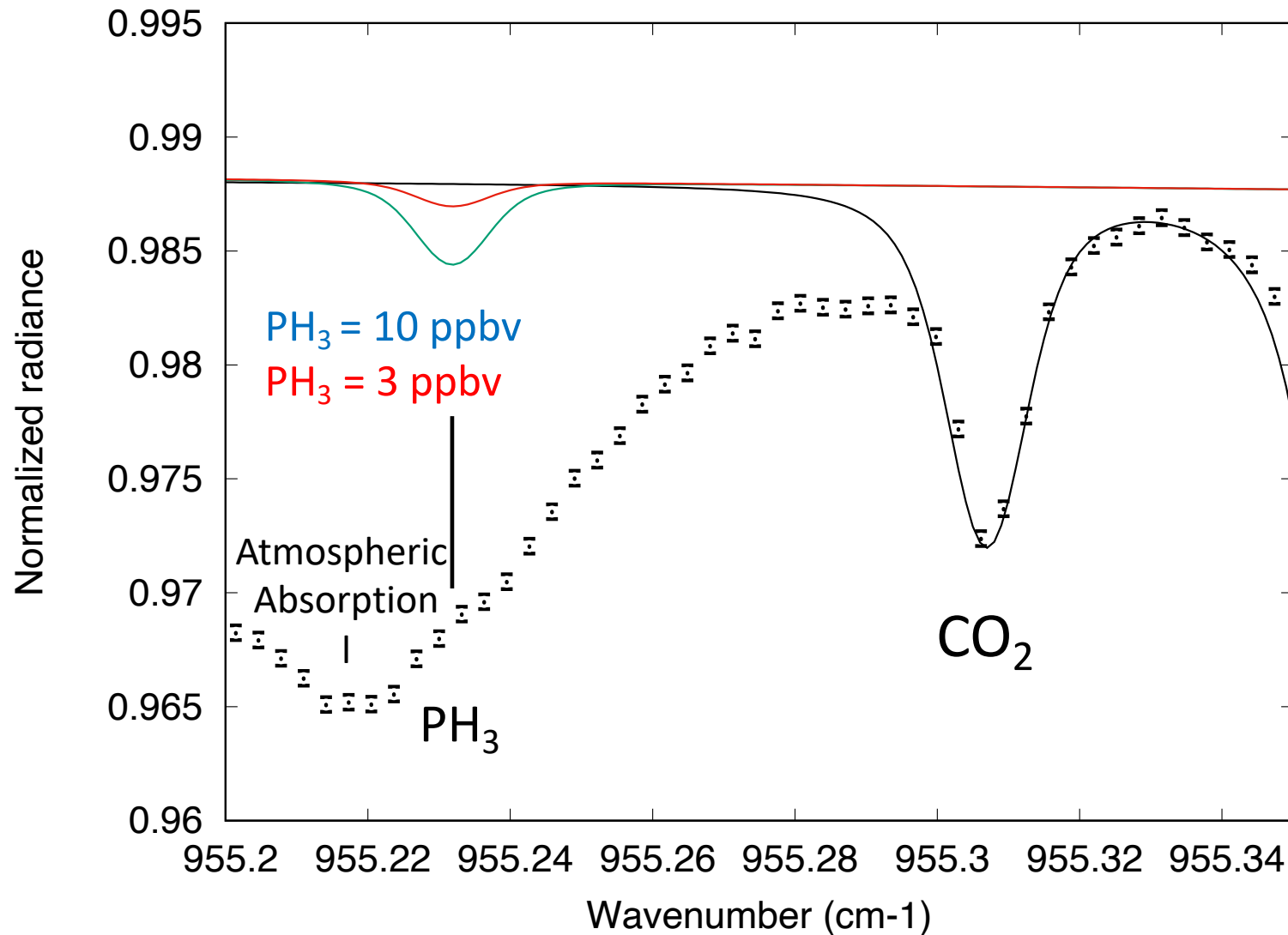
July 14, 2023: SO<sub>2</sub>(67km)/SO<sub>2</sub>(62km) < 50

October 3, 2023: SO<sub>2</sub>(67km)/SO<sub>2</sub>(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 :
  - PH<sub>3</sub>: detection, up to 20 ppbv (Greaves et al. 2020, +)
  - HCN: upper limit, 38.3 +/- 7.9 ppmv @ 80 km (Mahieux et al. 2023)
  - NH<sub>3</sub>: upper limit, 0.69 +/- 0.28 ppmv @ 80 km (Mahieux et al. 2023)
- New upper limits have been obtained with TEXES (present work):
  - PH<sub>3</sub>: **1 ppbv** ( $\sigma$ ) at the cloud top (62 km)
  - NH<sub>3</sub>: **0.1 ppbv** ( $\sigma$ ) at the cloud top (62 km)
  - HCN: **0.1 ppbv** ( $\sigma$ ) at the cloud top (62 km)

# PH<sub>3</sub> upper limit at the cloud top

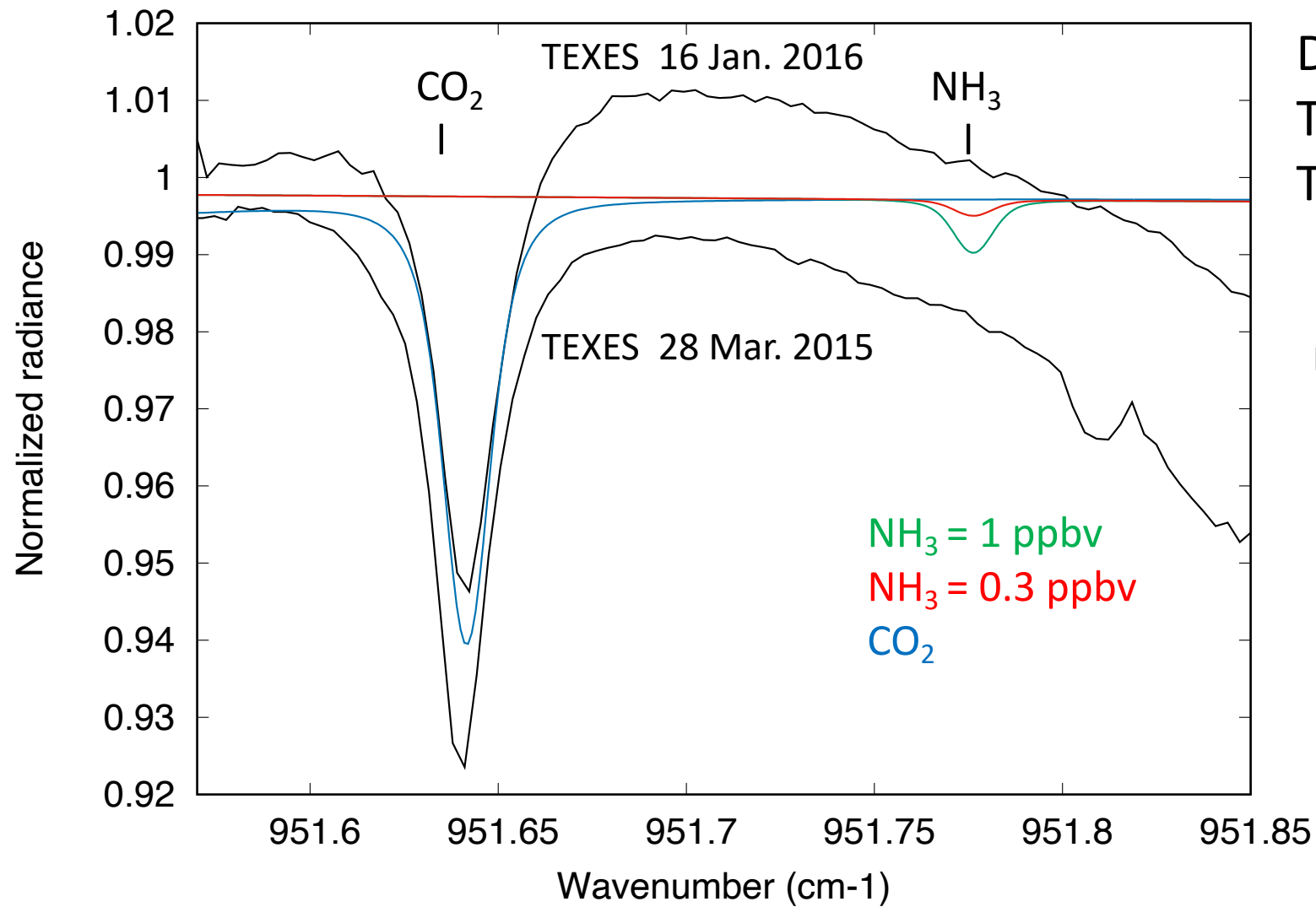


Data: TEXES, July 16, 2023

**Upper limit:**  
PH<sub>3</sub> < 3 ppbv (3 $\sigma$ )

Confirms our earlier  
analysis:  
PH<sub>3</sub> < 5 ppbv (3 $\sigma$ )  
(Encrenaz et al.  
A&A 643, L5 (2020))

# NH<sub>3</sub> upper limit at the cloud top



Data:

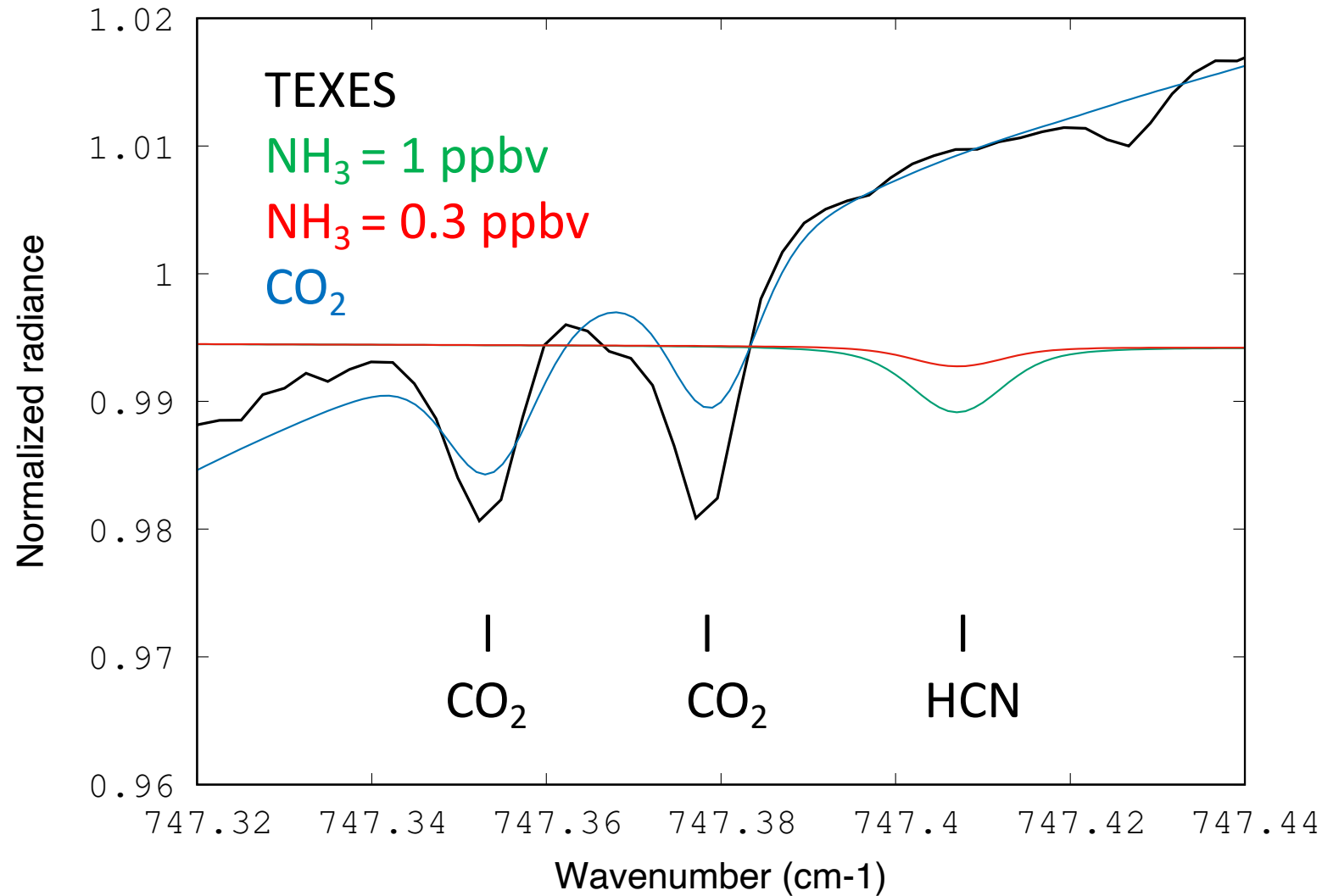
TEXES, March 28, 2015

TEXES, January 16, 2016

**Upper limit:**

NH<sub>3</sub> < 0.3 ppbv (3 $\sigma$ )

# HCN upper limit at the cloud top



Data:  
TEXES, July 15, 2023

**Upper limit:**  
HCN < 0.3 ppbv (3 $\sigma$ )

# Conclusions

- Since 2012, SO<sub>2</sub> 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.
- H<sub>2</sub>O (using HDO as a proxy) was simultaneously mapped and monitored at the cloud top (7.4 μm).
- H<sub>2</sub>O & SO<sub>2</sub> exhibit different behaviors at the cloud top of Venus:
  - H<sub>2</sub>O is uniform over the disk and shows moderate temporal variations.
  - SO<sub>2</sub> shows strong spatial and temporal variations in the form of transient plumes and strong long-term variations .
- The long-term variations of H<sub>2</sub>O and SO<sub>2</sub> 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:**
- **SO<sub>2</sub> is detected for the first time on Oct.3, 2023; SO<sub>2</sub>(67km)/SO<sub>2</sub>(62km) = 1/20 (< 1/50 on 14/07/ 2023)**
- **Stringent upper limits** are obtained for PH<sub>3</sub>, NH<sub>3</sub> and HCN at the cloud top:
  - **PH<sub>3</sub> < 1 ppbv (1σ), NH<sub>3</sub> < 0.1 ppbv (1σ), HCN < 0.1 ppbv (1σ)**