COLLISION-INDUCED ABSORPTION IN PLANETARY ATMOSPHERES: PRESENT DATA AND FUTURE PERSPECTIVES

F. Vitali[1,2]

S. Stefani[1], G. Piccioni[1], H. Tran[3], M. Snels[4], D. Grassi[1], C. Boulet[5], D. Biondi[1] and A. Boccaccini[1]

[1]IAPS-INAF, Rome, Italy, [2]Università degli studi di Roma "Tor Vergata", Rome, Italy, [3]Laboratoire de Météorologie Dynamique/IPSL, CNRS, École Polytechnique, Institut Polytechnique de Paris, Sorbonne Université, École Normale Supérieure, PSL Research University, France, [4]ISAC-CNR, Rome, Italy, [5]Institut des Sciences Moleculaires d'Orsay (ISMO), CNRS, Universite Paris-Sud, Universite Paris-Saclay, Orsay, France

PLANETARY AND EXOPLANETARY INVESTIGATION

Our Solar System presents a significant planetary variety

Different evolutionary paths → presence of an atmosphere

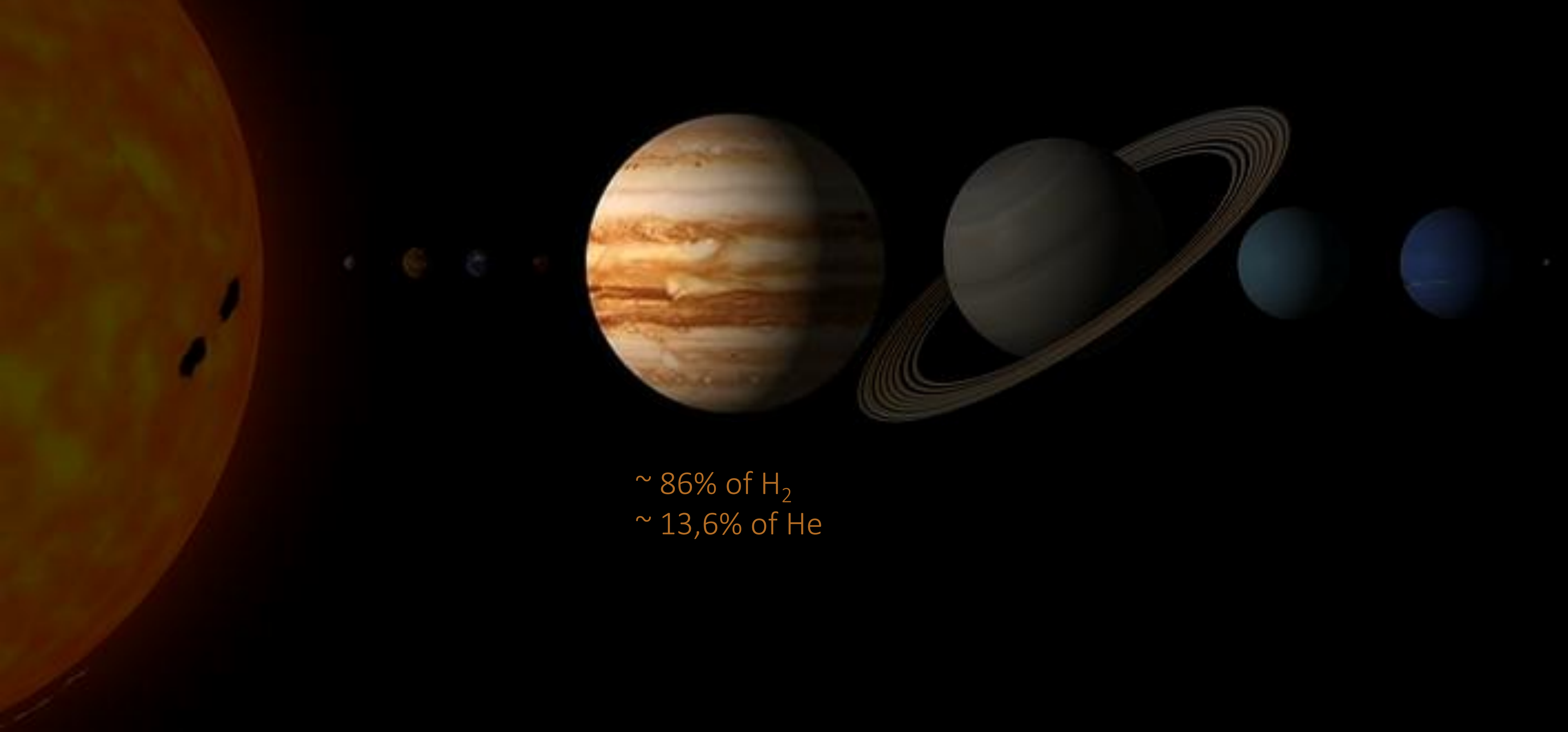
The latter is important to determine planetary environments and climate

It is also crucial to investigate the possible habitability conditions of the exoplanetary worlds

We also need detailed spectroscopic databases for Collision-Induced Absorption (CIA), which is a critical opacity source for planetary atmospheres, especially in high-density environments.

PLANETARY AND EXOPLANETARY INVESTIGATION

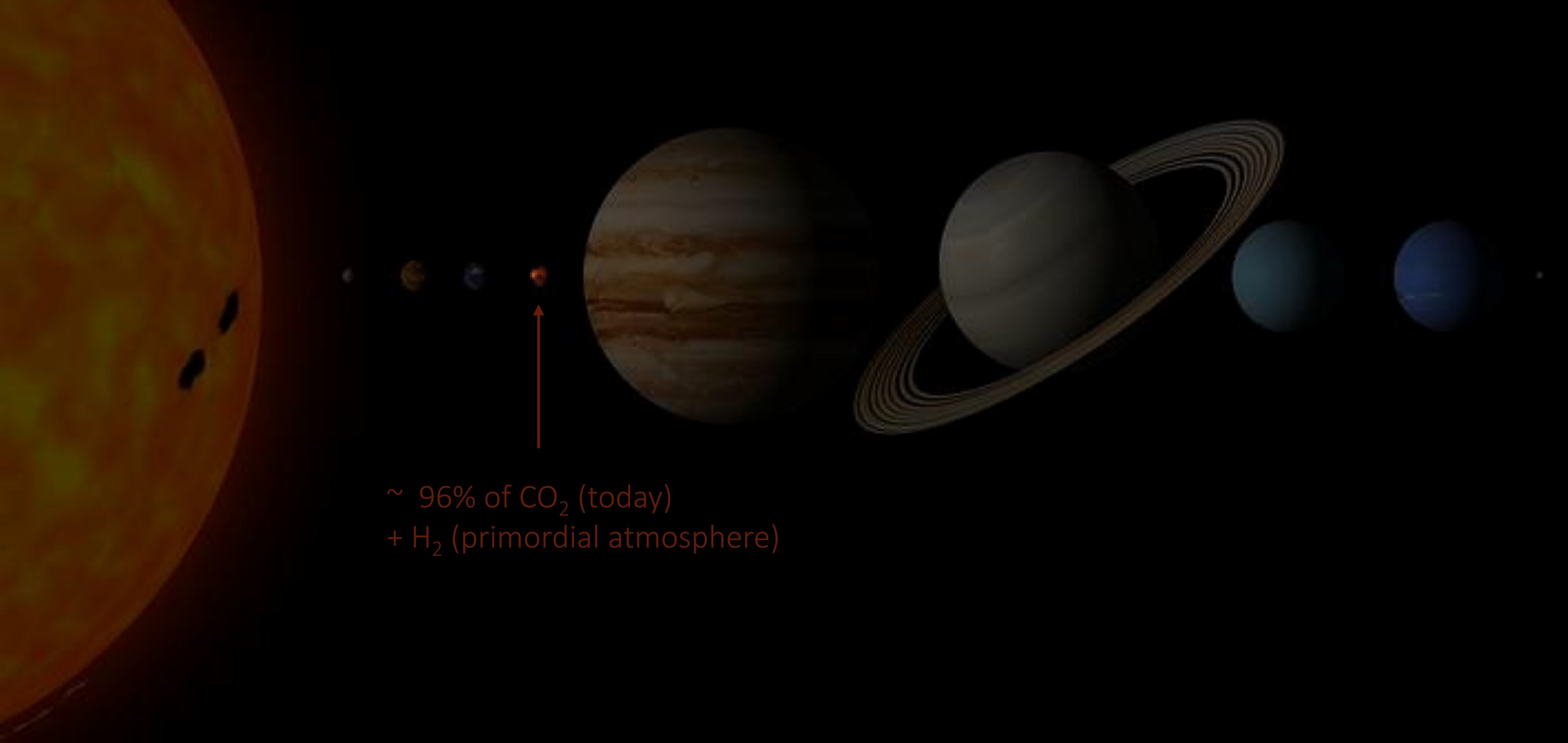
We started studying the CIA of both **pure H_2** gas and a **H_2-He mixture**, as they represent the main components of Jupiter's atmosphere



~ 86% of H_2
~ 13,6% of He

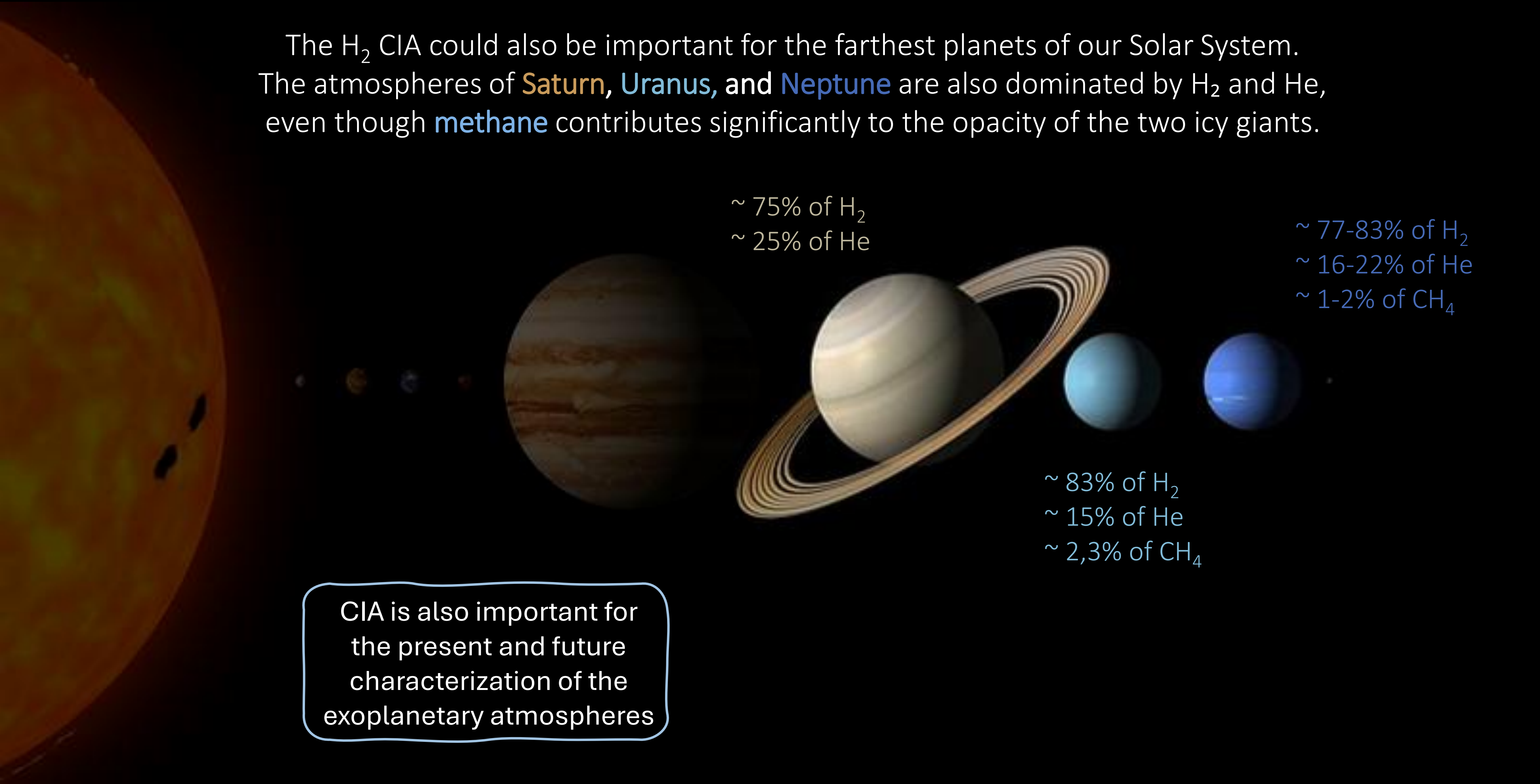
PLANETARY AND EXOPLANETARY INVESTIGATION

Furthermore, we investigated the CIA of a H_2-CO_2 mixture
Important for the improvement of the early Martian climate models



PLANETARY AND EXOPLANETARY INVESTIGATION

The H_2 CIA could also be important for the farthest planets of our Solar System.
The atmospheres of Saturn, Uranus, and Neptune are also dominated by H_2 and He, even though methane contributes significantly to the opacity of the two icy giants.



CIA is also important for the present and future characterization of the exoplanetary atmospheres

EXPERIMENTAL SETUP

- Max pressure: 70 bar
- T range: [100, 550] K
- Max res: 0.002 cm^{-1}
- Optical path: 3.27 m
- Entirely in vacuum

H_2-H_2 AND H_2-HE CIA

We measured the H_2-H_2 and H_2-He CIA in the [4000, 5000] cm^{-1} spectral range for temperatures ranging from 121 to 504 K, at a resolution of 1 cm^{-1}

Those data have been published in the Journal of Quantitative Spectroscopy and Radiative Transfer…

Vitali et al. (2025)

…and inserted in the HITRAN database

Terragni et al. (2025)

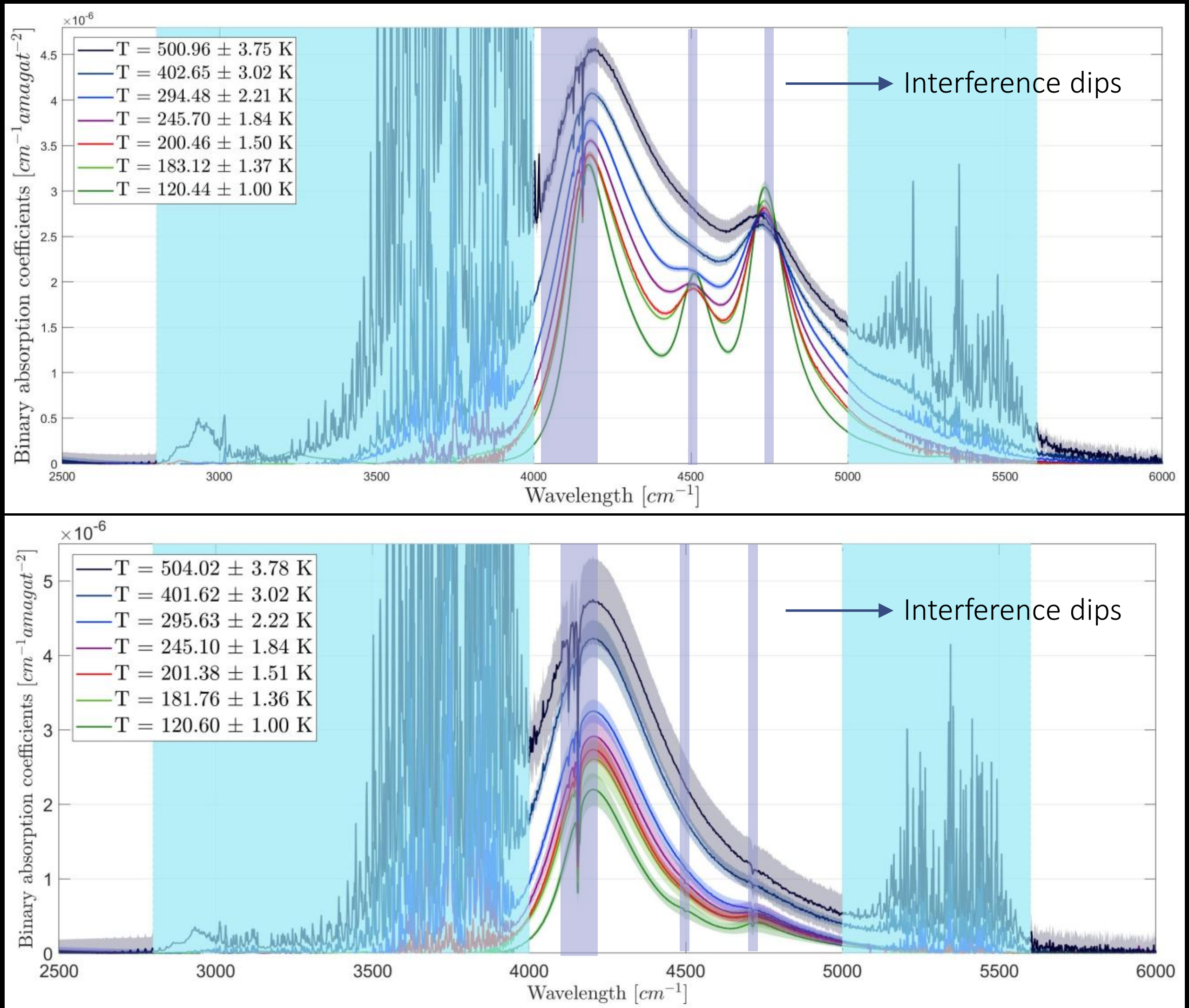


Fig. 2: H_2-H_2 and H_2-He binary absorption coefficients (respectively upper and lower panel)

HIGH-RESOLUTION H_2 COLLISION-INDUCED ABSORPTION

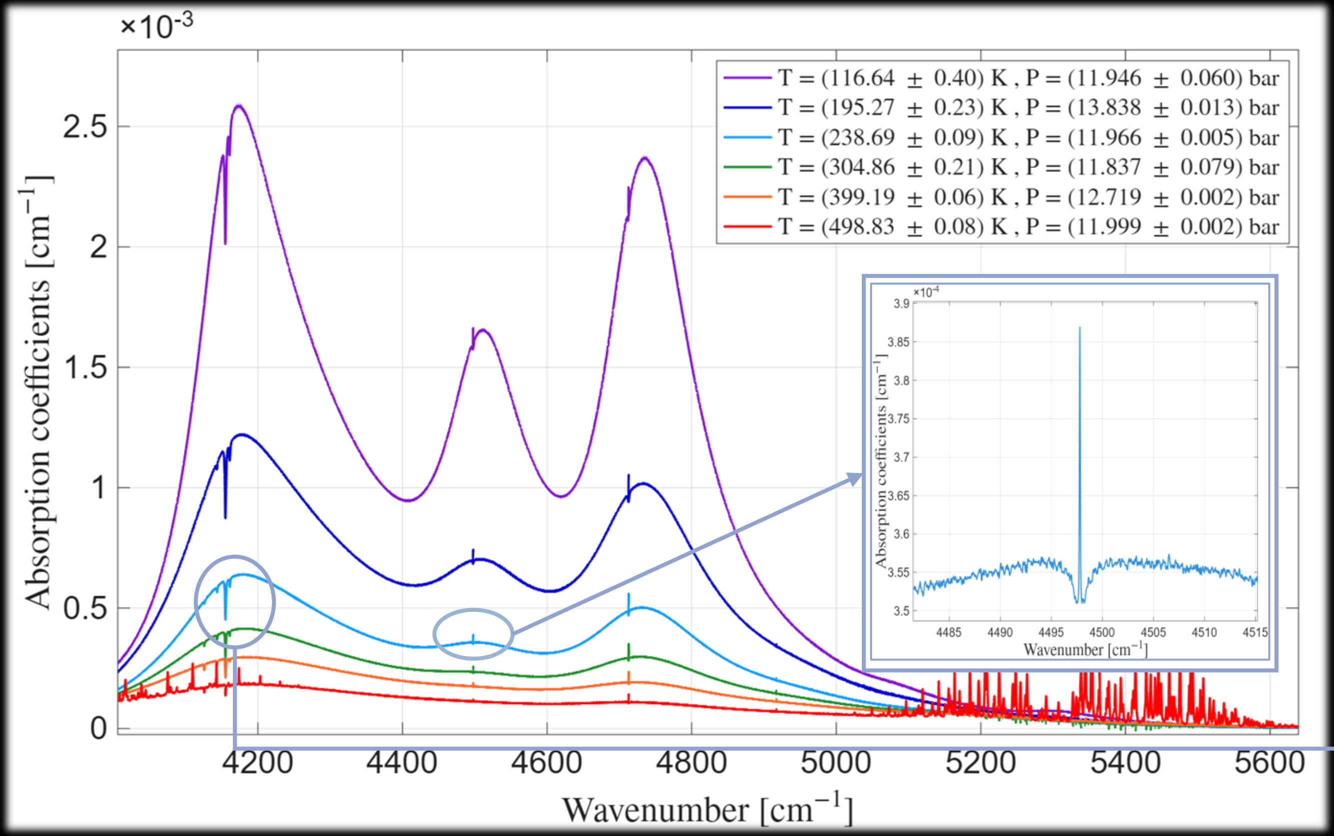


Fig. 3: H_2- H_2 CIA for six temperatures. On the right part the blowout of the S(0) interference dips and the H_2 quadrupolar line can be visualized

We performed measurements at a resolution of 0,05 cm^{-1} for a pure H_2 gas at temperatures going from 117 to 499 K, in the [4000, 5500] cm^{-1} spectral range (Fig. 3).

We resolved both the interference dips and the H_2 quadrupolar lines visible on the H_2 CIA band (Fig. 3) and on the blow out in Fig. 4

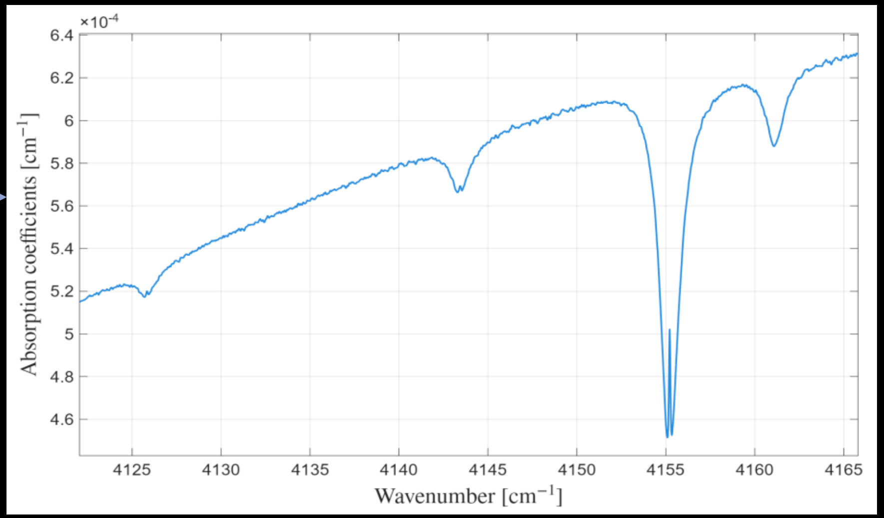
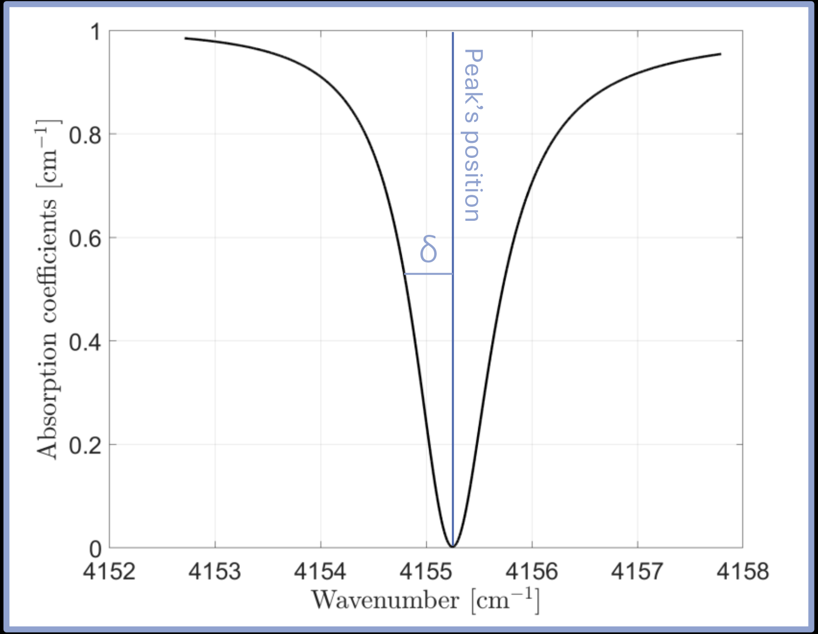


Fig. 4: Blow out of the main peak of the H_2-H_2 CIA band. Here the Q(3), Q(2), Q(1), Q(0) interference dips and the H_2 quadrupolar lines can be visualized.

THEORETICAL PROFILES

Those features are caused by the **interference of induced dipole moments in consecutive collisions** (Van Kranendonk, 1968).

Starting from the Van Kranendonk theory, a theoretical profile has been developed by **Kelley and Bragg** (Kelley and Bragg, 1984), which takes into account the observed asymmetry of the dip



Kelley and Bragg's profile

$$F(\nu) = \frac{1 - \cos\alpha + \left(\frac{\nu-\nu_C}{\delta}\right)^2 - \left(\frac{\nu-\nu_C}{\delta}\right)\sin\alpha}{1+\left(\frac{\nu-\nu_C}{\delta}\right)^2}$$

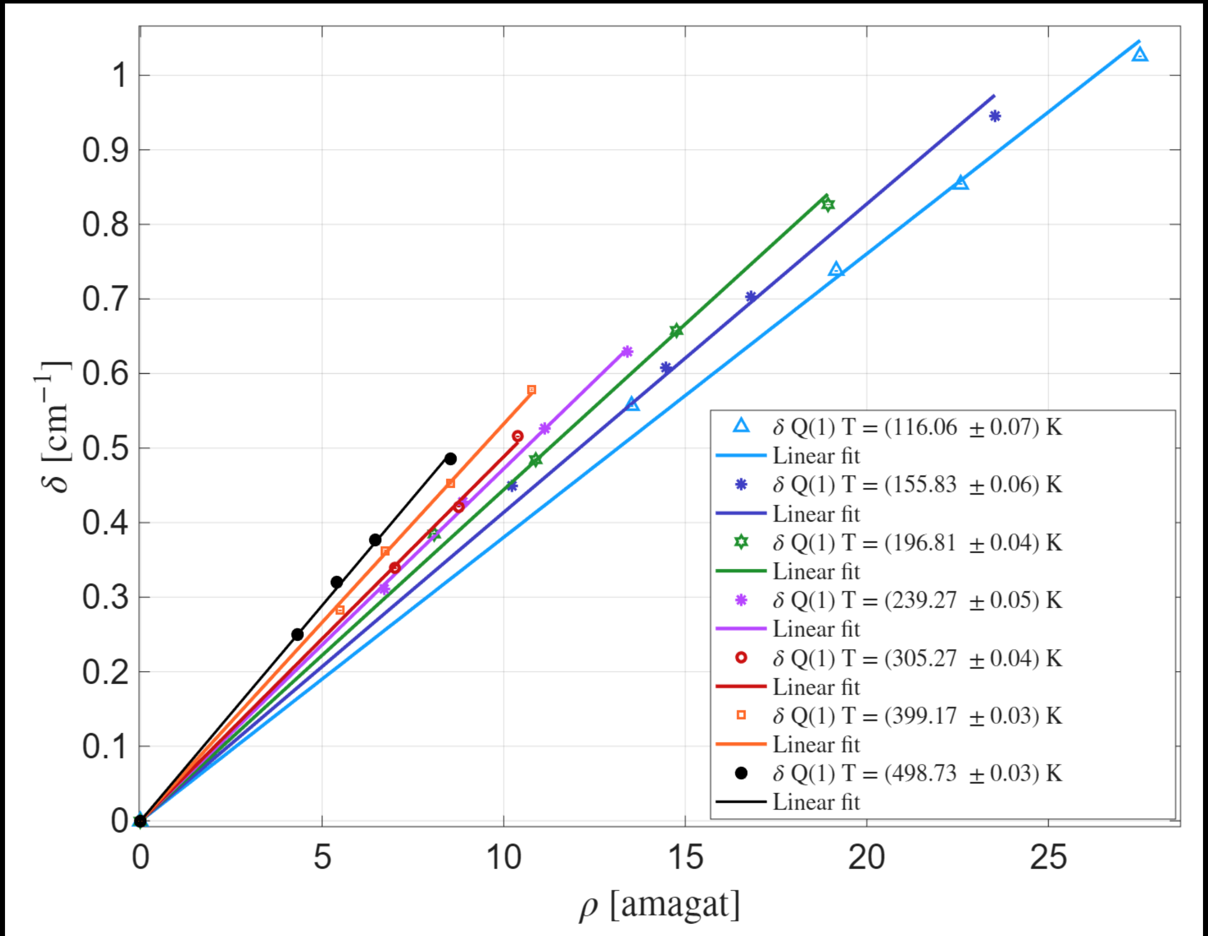
Intracollisional halfwidth

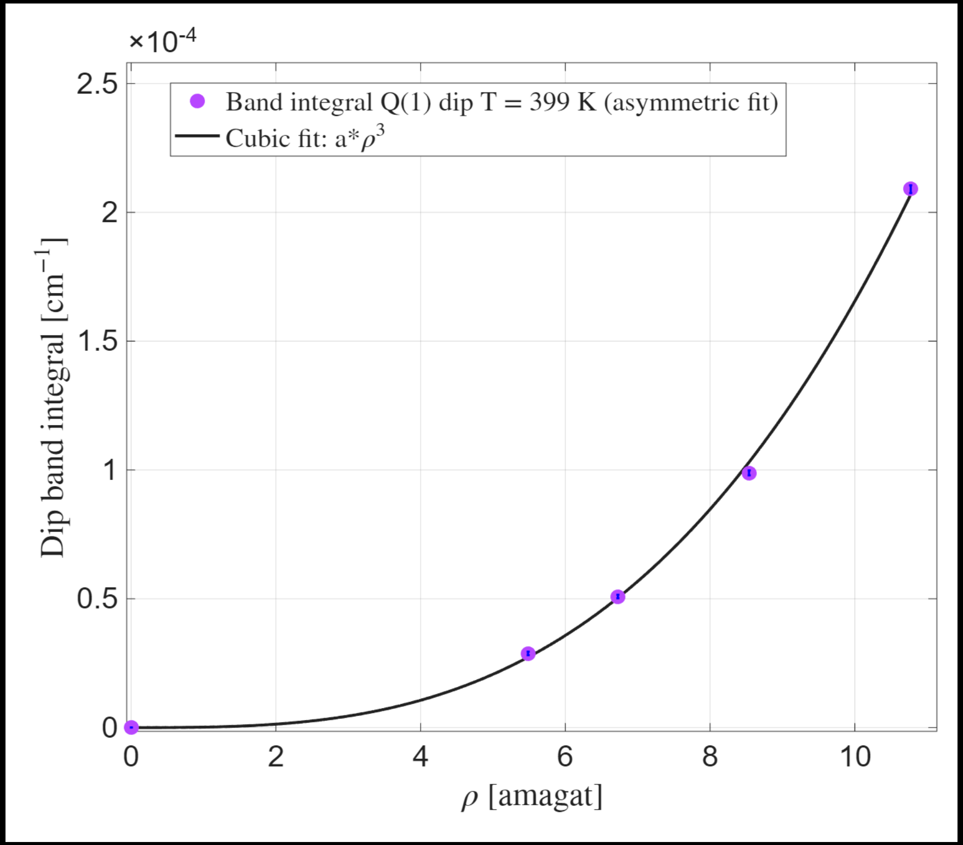
Van Kranendonk's theory predicts that δ will follow a **linear trend with density**

We fitted the observed interference dips to study this **behavior for all the investigated temperatures**

THE INTRACOLLISIONAL HALFWIDTH

For all the temperatures, a linear behavior of δ with respect to the density has been found (Fig. 6), according to Van Kranendonk's theory…



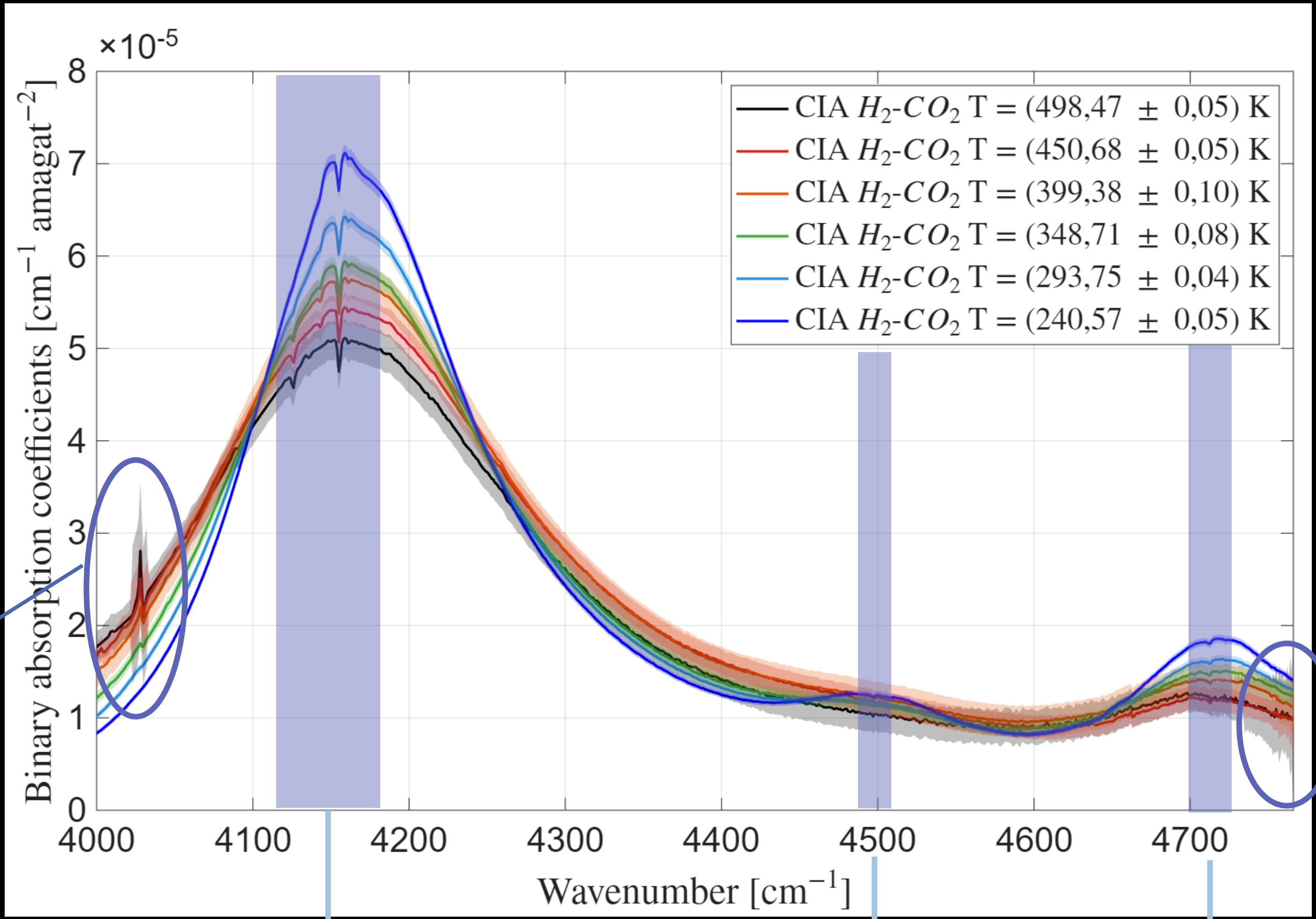


…while, the dips' band integral results in following a cubic behavior with density

H_2-CO_2 CIA

We measured the H_2-CO_2 CIA for six temperatures from 241 to 498 K, in the [3907, 4770] cm^{-1} spectral range

QR code to the article

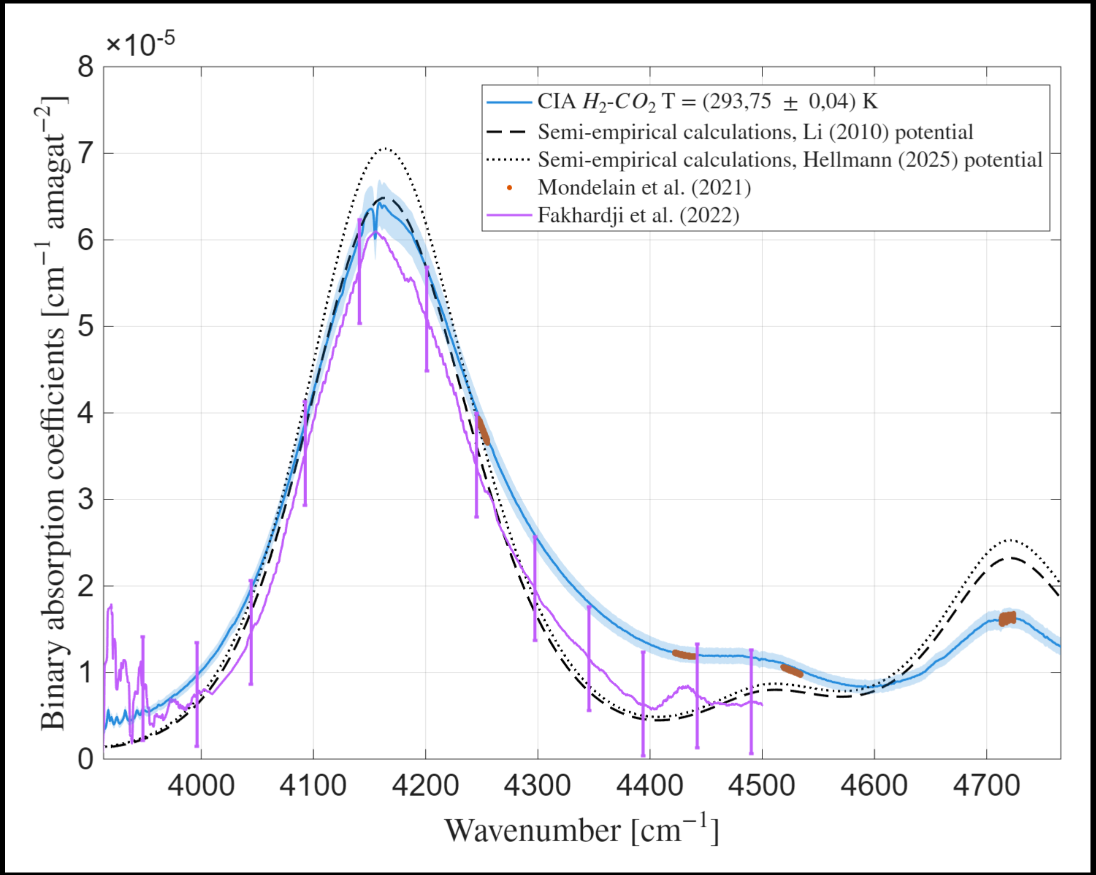


Residual coming from the non-perfect removal of the CO_2 permitted band at 4020 cm^{-1}

Residual coming from the non-perfect removal of the strong CO_2 permitted band at 4800 cm^{-1}

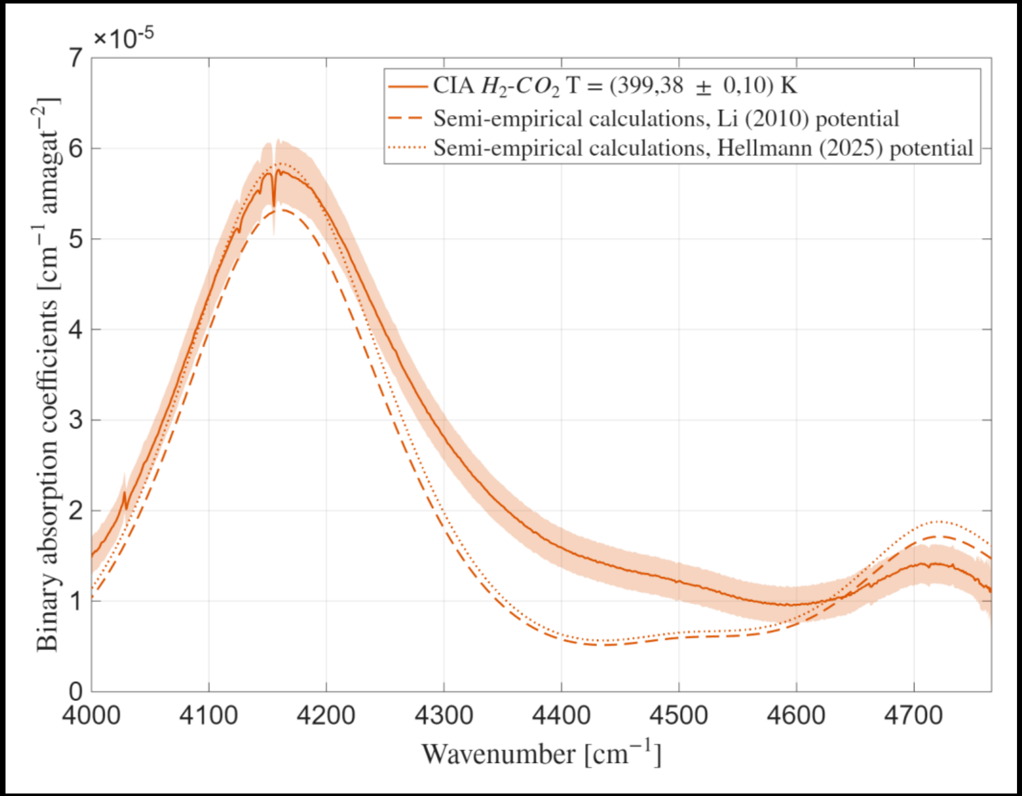
Interference dips: Q(3), Q(2), Q(2), Q(1), S(0) and S(1)

COMPARISON WITH LITERATURE DATA



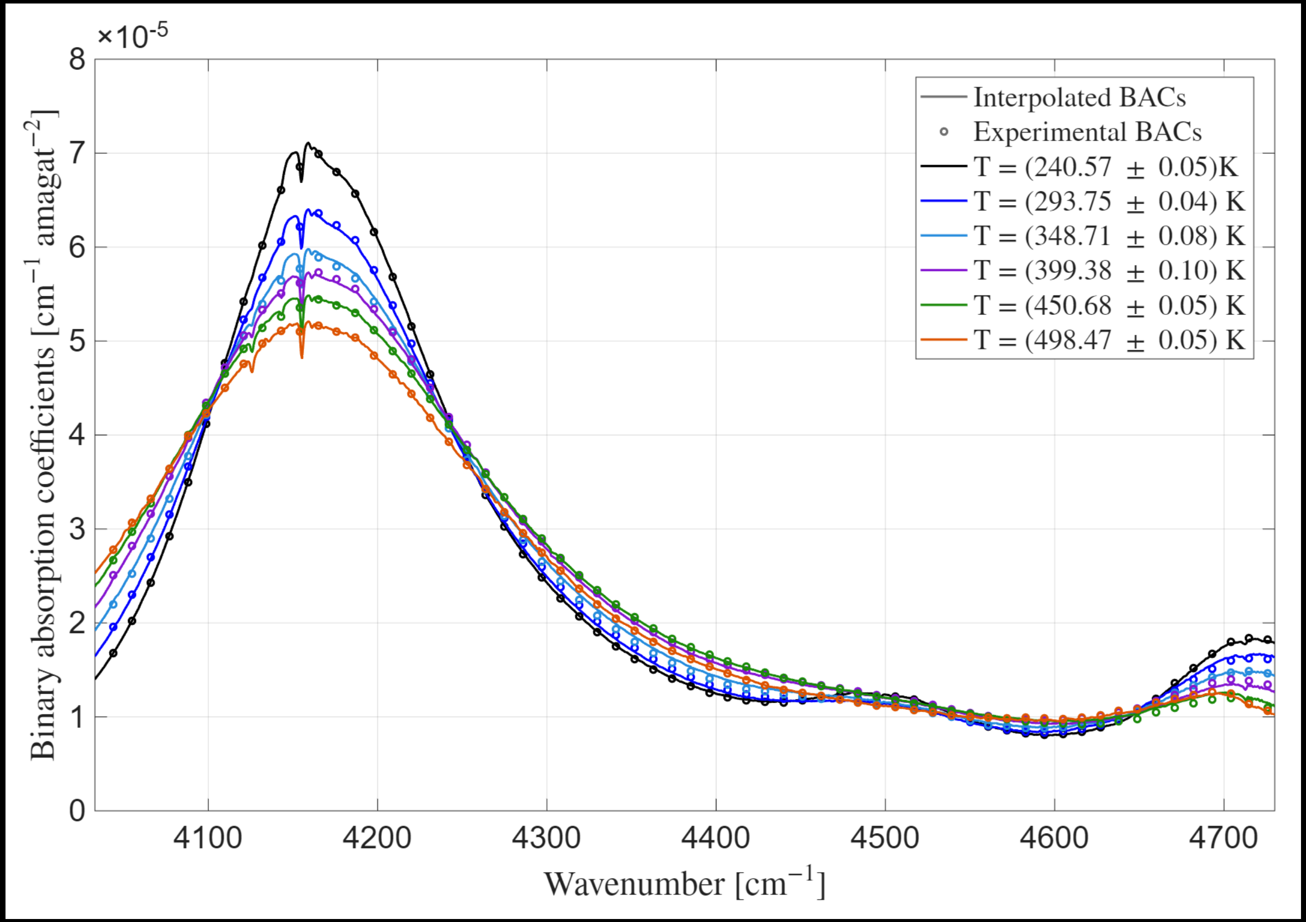
Excellent agreement with room-temperature data from Mondelain et al. [2021] , where a CDRS has been used. The data from Fakhardji et al. [2022] present an overall lower absorption

Comparison with the semi-empirical calculations (Turbet et al. [2020]) involving two potentials: one from Li [2010] (dashed lines) and the more recent one from Hellmann [2025] (dotted lines)



Discrepancies in the band shape –
Good agreement in the total band's integral

INTERPOLATION OF THE EXPERIMENTAL DATA



Following the empirical approach employed in Tran et al. [2024], we fitted the H_2-CO_2 BACs at each wavenumber using an exponential profile depending on the following parameters:

- $\boldsymbol{a_n(\sigma)}$: fit parameters, wavenumber-dependent
- T : temperature
- T0 : reference temperature = 296 K
- $\boldsymbol{k_{CIA}^{norm}}$: costant equal to 1 cm^{-1} $amagat^{-2}$

We retrieved the $a_n(\sigma)$ parameters, which allows to calculate the BACs at each desired temperature within the studied temperature range.
The $a_n(\sigma)$ can be found on Zenodo in tabular form.

$$k_{CIA}(\sigma,T) = k_{CIA}^{norm}\ exp\left\{a_1(\sigma) + a_2(\sigma)\cdot\left(\frac{T}{T_0}\right) + a_3(\sigma)\cdot\left(\frac{T}{T_0}\right)^2 + a_4(\sigma)\cdot\left(\frac{T}{T_0}\right)^3\right\}$$

SUMMARY AND FUTURE PERSPECTIVES

Study of the H_2 CIA in different mixtures

H_2-H_2 and H_2-He

- New measurements in a temperature range not yet investigated
- Study of the interference dips and their behavior with density

H_2-CO_2

- New measurements in a temperature range not yet investigated
- Comparison with semi-empirical calculations → difference in the band's shape, but good agreement in the total band's integral

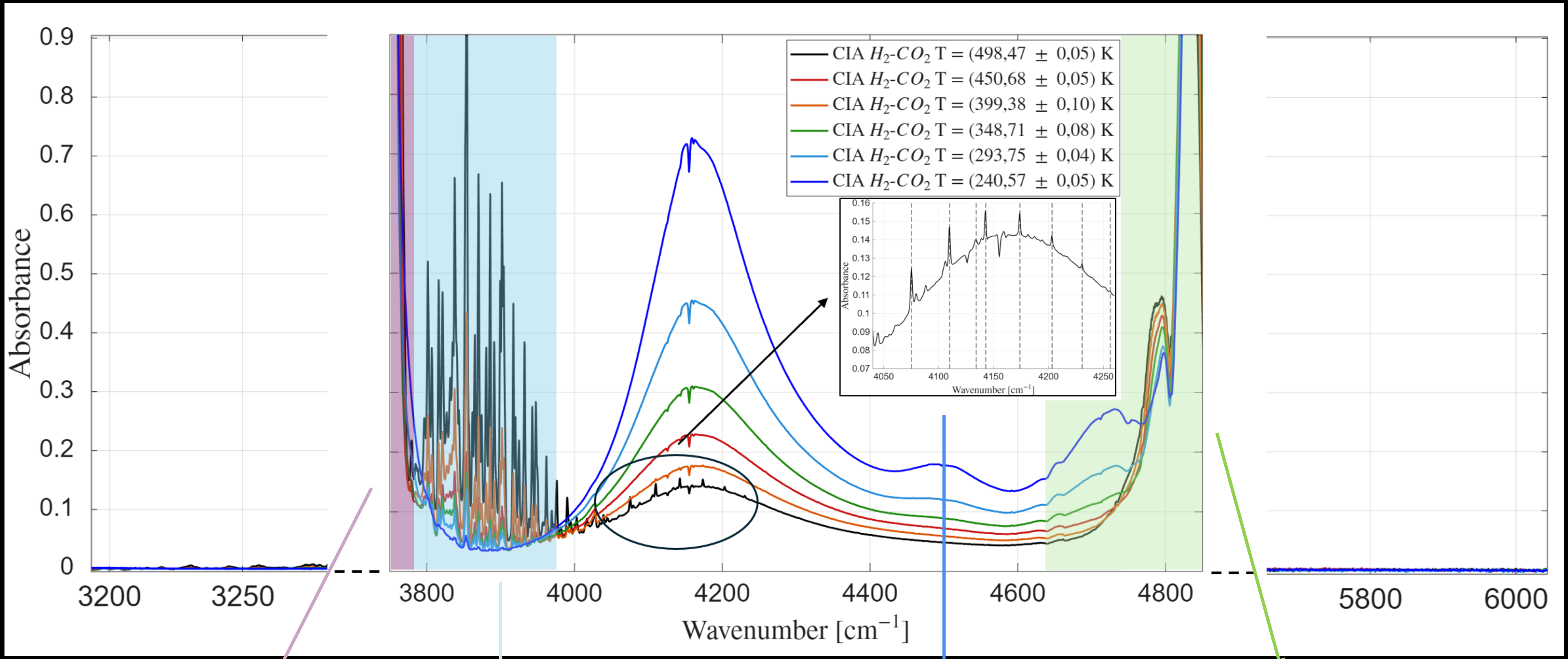
❑ Use of an empirical approach to fit the data and find a mathematical expression able to reproduce the behavior of the single-frequency BACs with temperature

! All those results are important not only for the investigation of our Solar System's planets, but also for the exoplanetary atmospheric characterization

This work has been supported under the ASI-INAF agreement n. 2023-6-HH.0, and the EMM (Earth Moon Mars) project of PNRR (task 1500-13)

BACKUP SLIDES

EXPERIMENTAL PROCEDURE



Saturated CO_2 permitted band

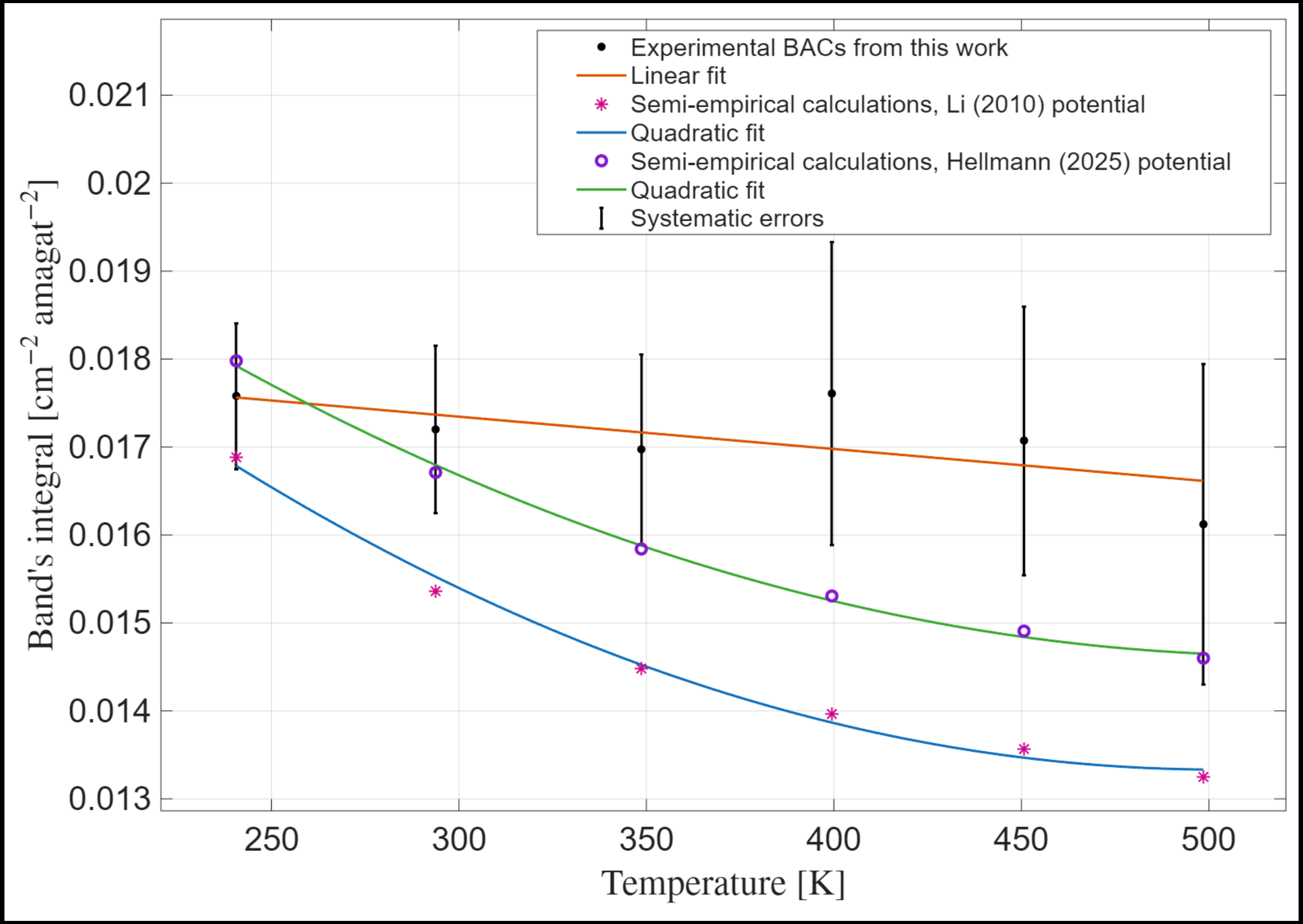
H_2O absorption lines

HF absorption lines

CO_2 permitted bands at 4800 cm^{-1}

Removed with the theoretical modelling approach used in Cole [2024] and Tran [2010]

BAND'S INTEGRAL



We calculated the integrated binary coefficients in the [4033, 4730] cm^{-1} for both our experimental data and the semi-empirical calculations performed using both Li [2010] and Hellmann [2025] potentials

Our data appear to follow a slightly decreasing trend, even if nothing can be firmly established due to comparable uncertainties and variation

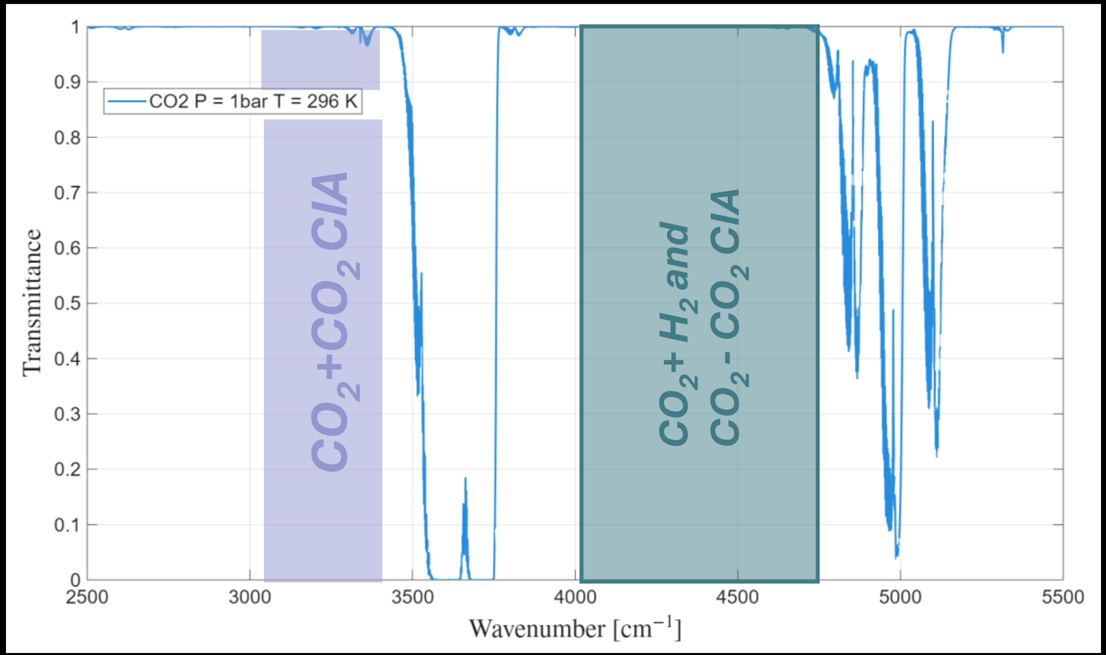
The trend followed by the integrated theoretical BACs results to be almost quadratic

H_2-CO_2 COLLISION-INDUCED ABSORPTION

In the [3000, 5500] cm^{-1} spectral range, a H_2+CO_2 mixture show different absorption due both to the CO_2 permitted transitions and CIA bands.

The total opacity in the spectral range of interest, around the H_2-H_2 CIA fundamental band, can be described as the sum of two contributions

$$K(\nu)_{TOT} = K(\nu)_{CO2} + K(\nu)^{CIA}_{mix}$$



Transmittance of CO2 at 1 bar and 296 K simulated with HITRAN for a path length of 3.27 m

$$K(\nu)^{CIA}_{mix} = k_{H2-H2}\,\rho_{H2}\,\rho_{H2} + k_{H2-CO2}\,\rho_{CO2}\,\rho_{H2} + k_{CO2-CO2}\,\rho_{CO2}\,\rho_{CO2}$$

CIA from the H_2-H_2 collisions

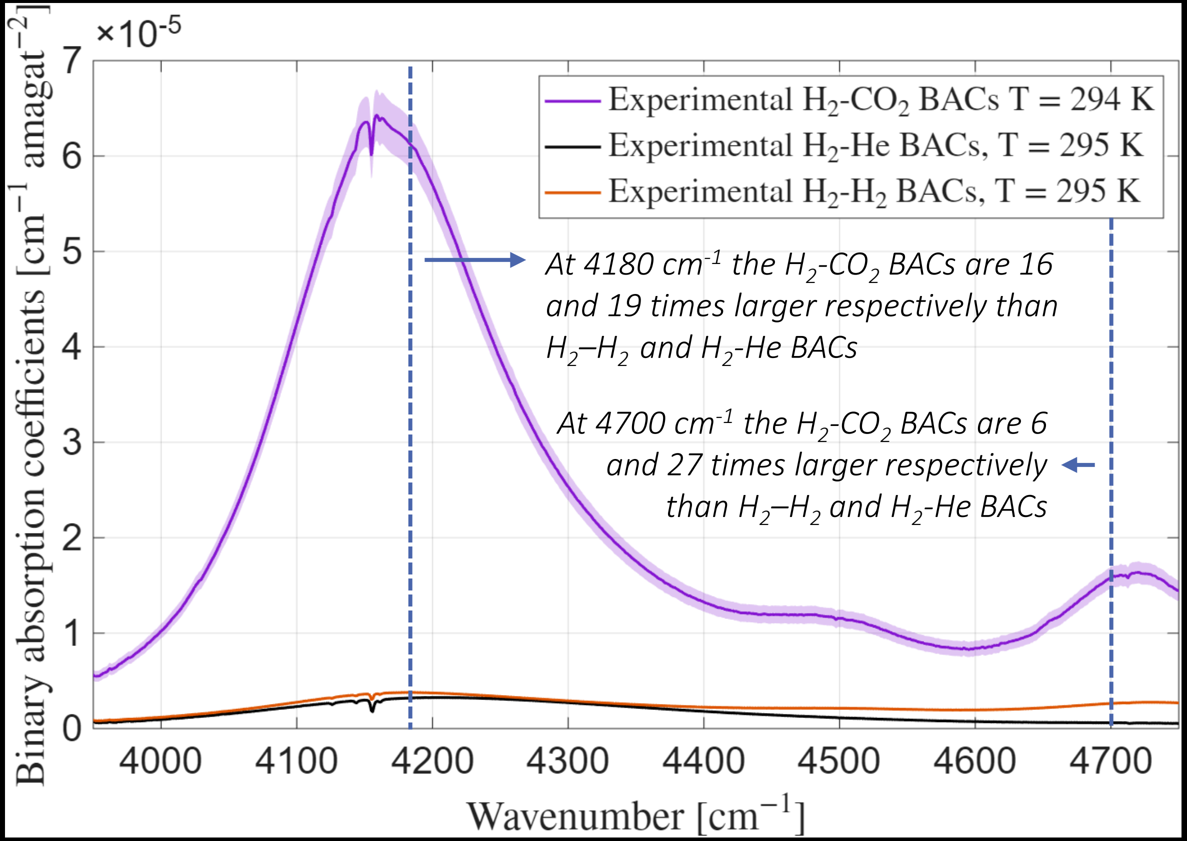
CIA from the H_2-CO_2 collisions → Target of this study

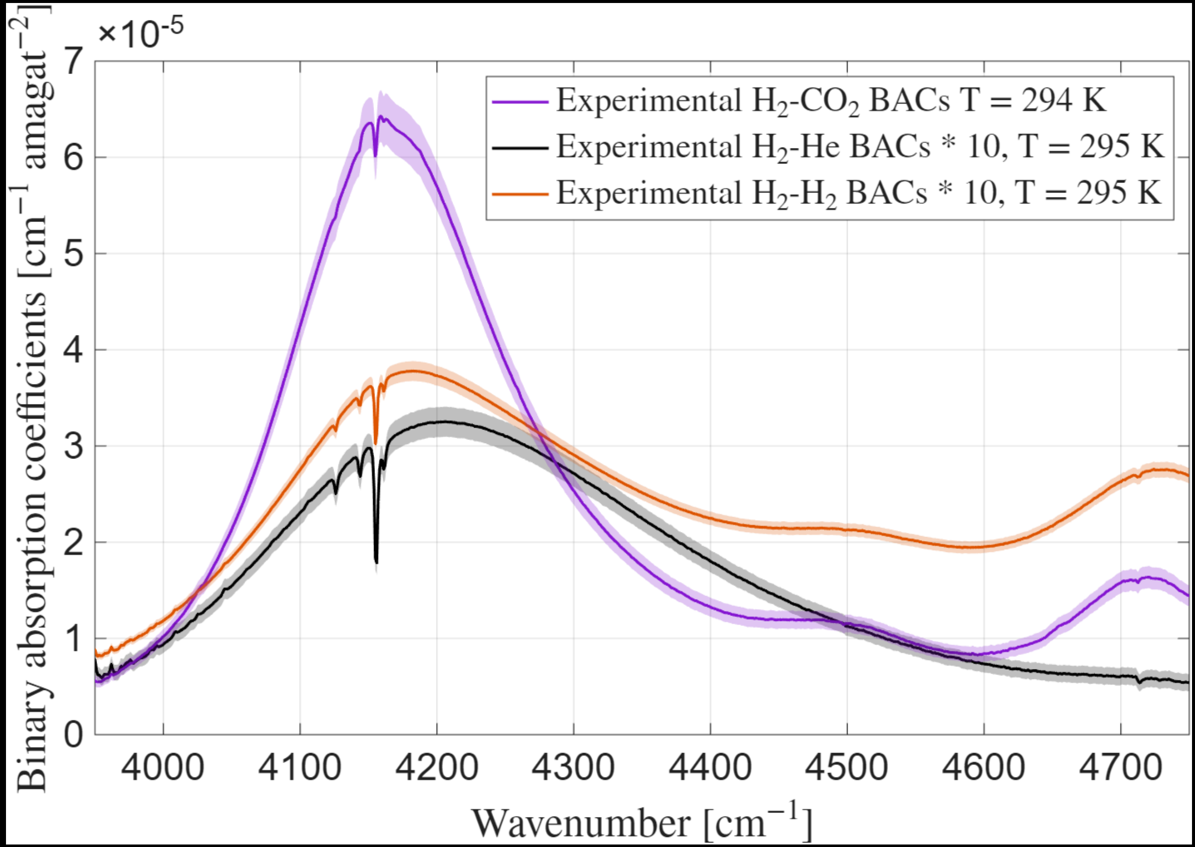
CIA from the CO_2- CO_2 collisions → Negligible under the density conditions considered here

COMPARISON WITH DIFFERENT MIXTURES

We compared the H_2–CO_2 CIA BACs with the H_2–H_2 and H_2-He BACs presented in our previous work (Vitali et al. [2025])

Higher absorption of the H_2-CO_2 CIA across the whole range





Interesting for the H_2-dominated atmospheres

A VMR of CO_2 20 times smaller than He provides a comparable opacity of an H_2-He mixture