

Examples of astro analysis tools: ENIIGMA



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.....
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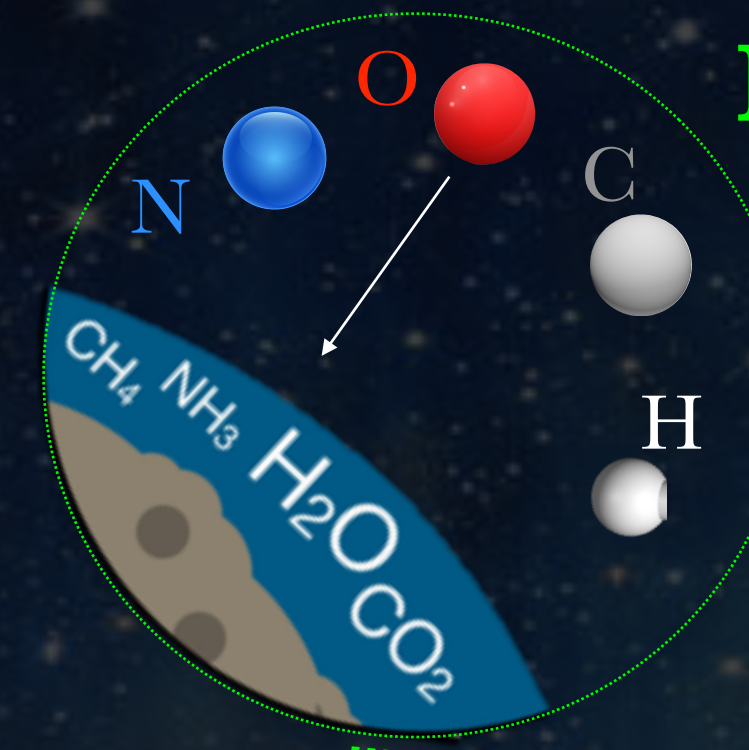
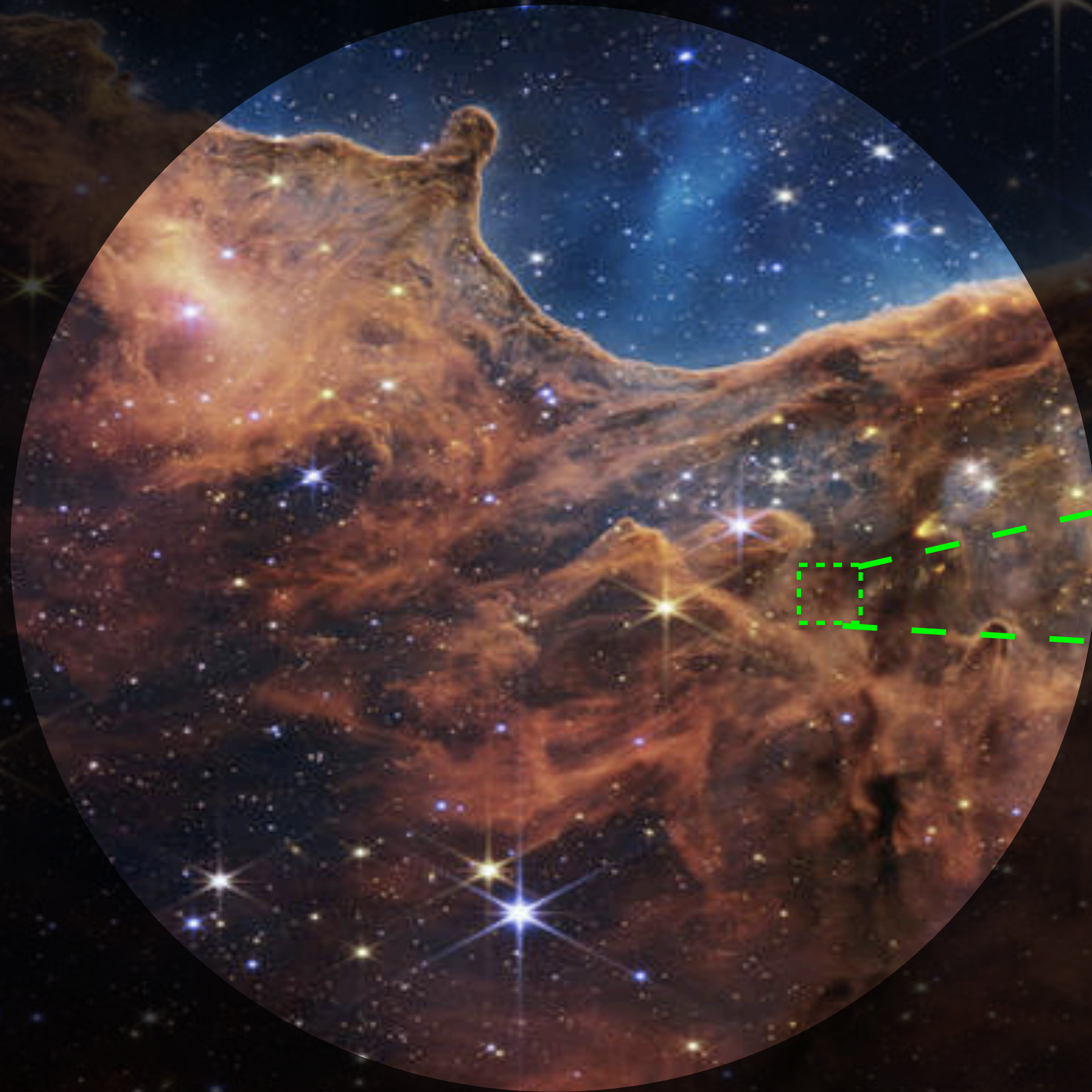
Collaborators

Jes Jørgensen,
Lars Kristensen,
Giulia Perotti

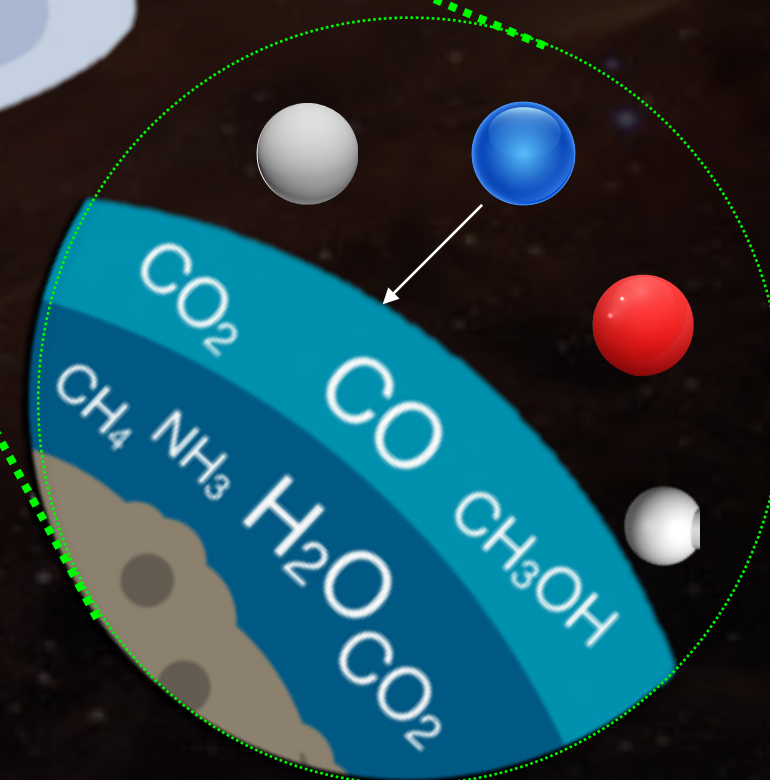
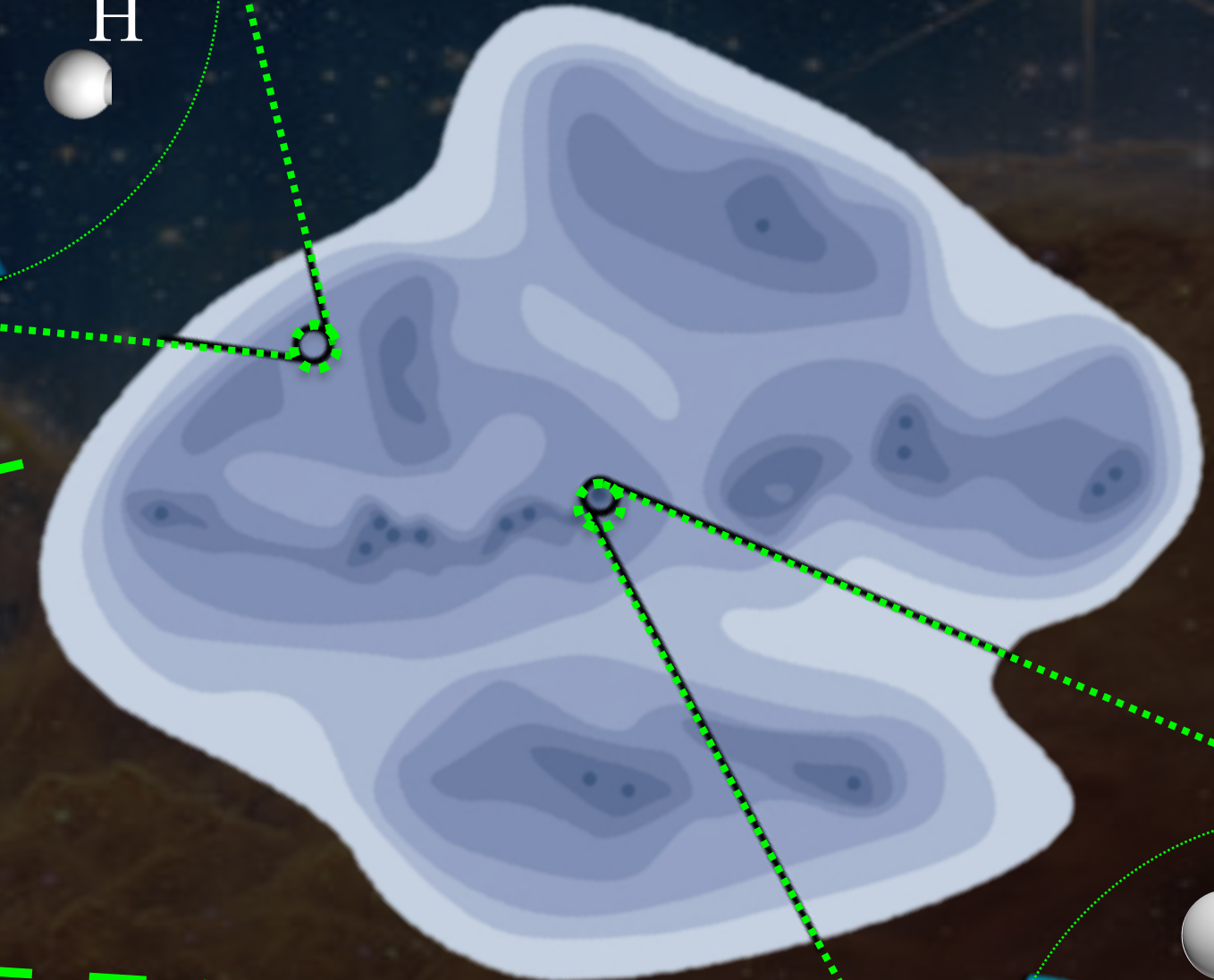
General context

Background image: Carina Nebula (JWST)
Credits: NASA, ESA, CSA, and STScI

General context



Low extinction



High extinction

Adapted from Öberg & Bergin 2020

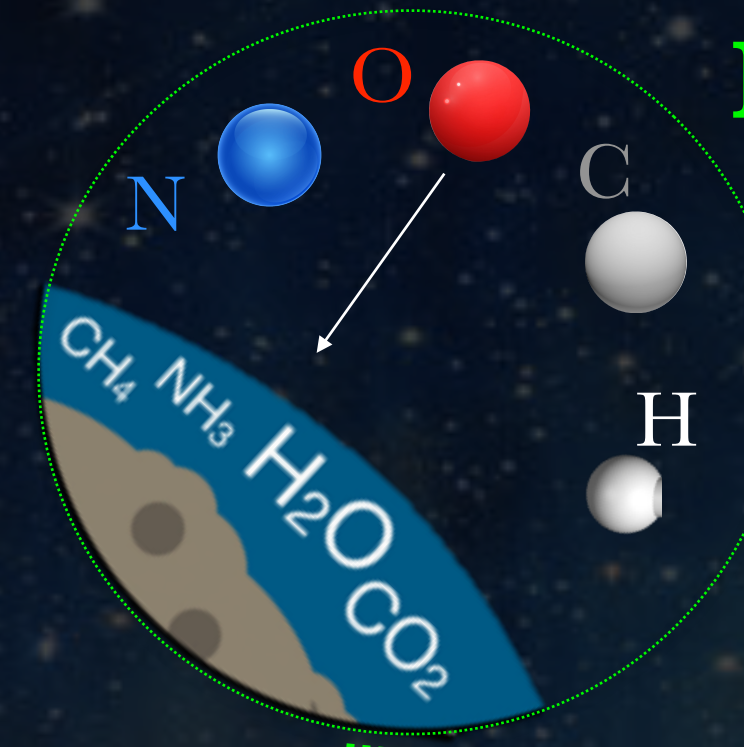
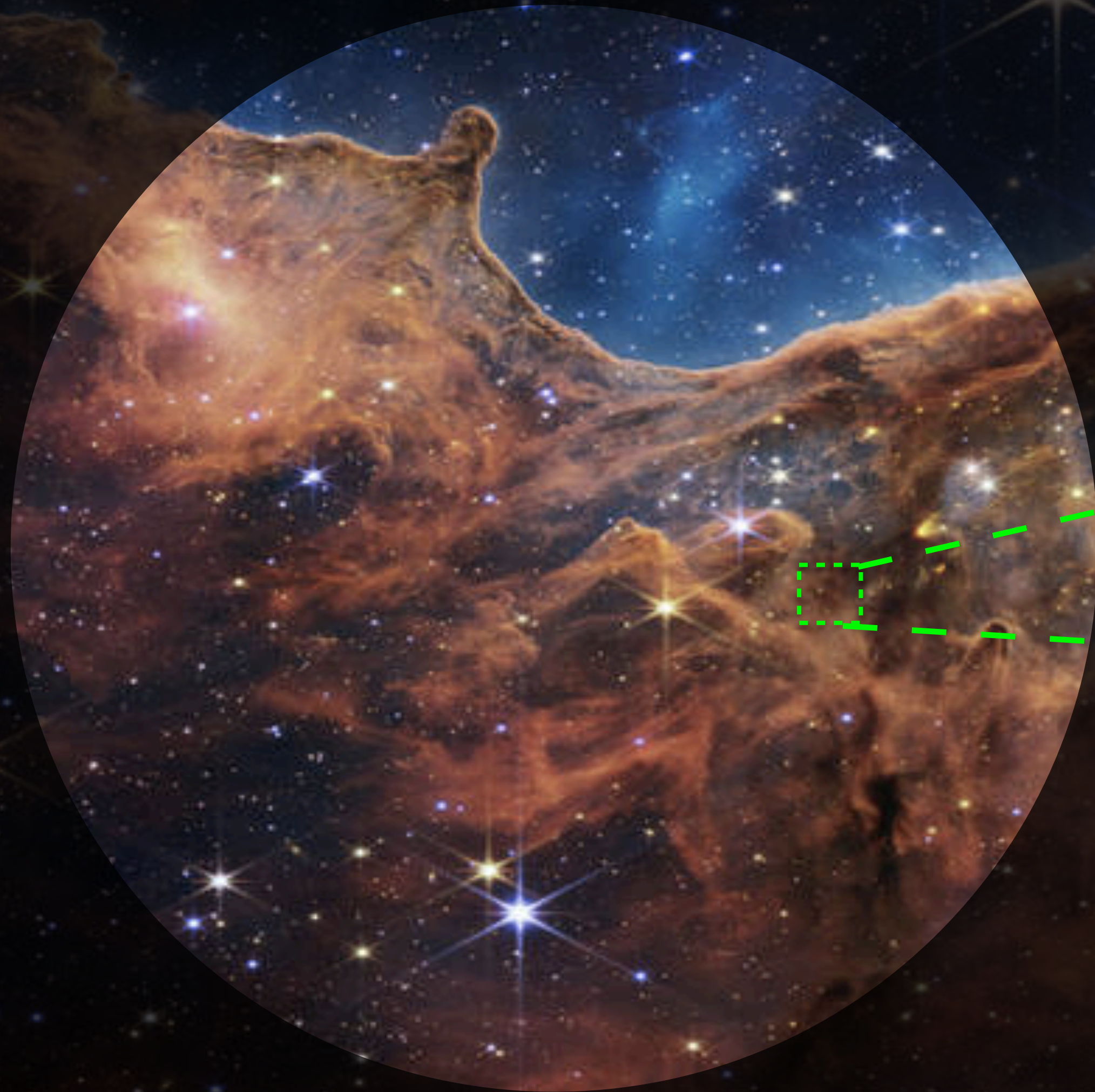
See also:

Öberg (2015)

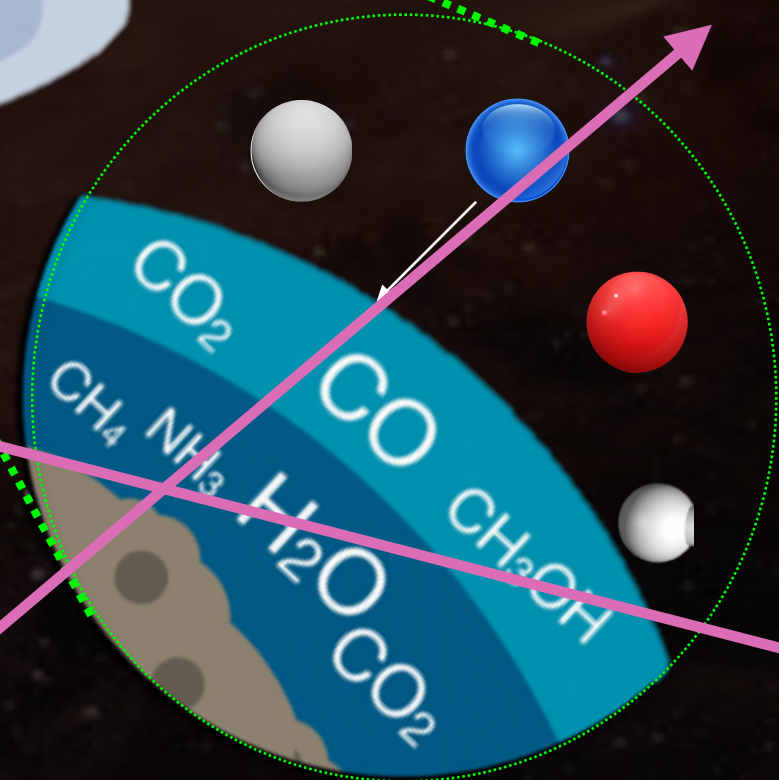
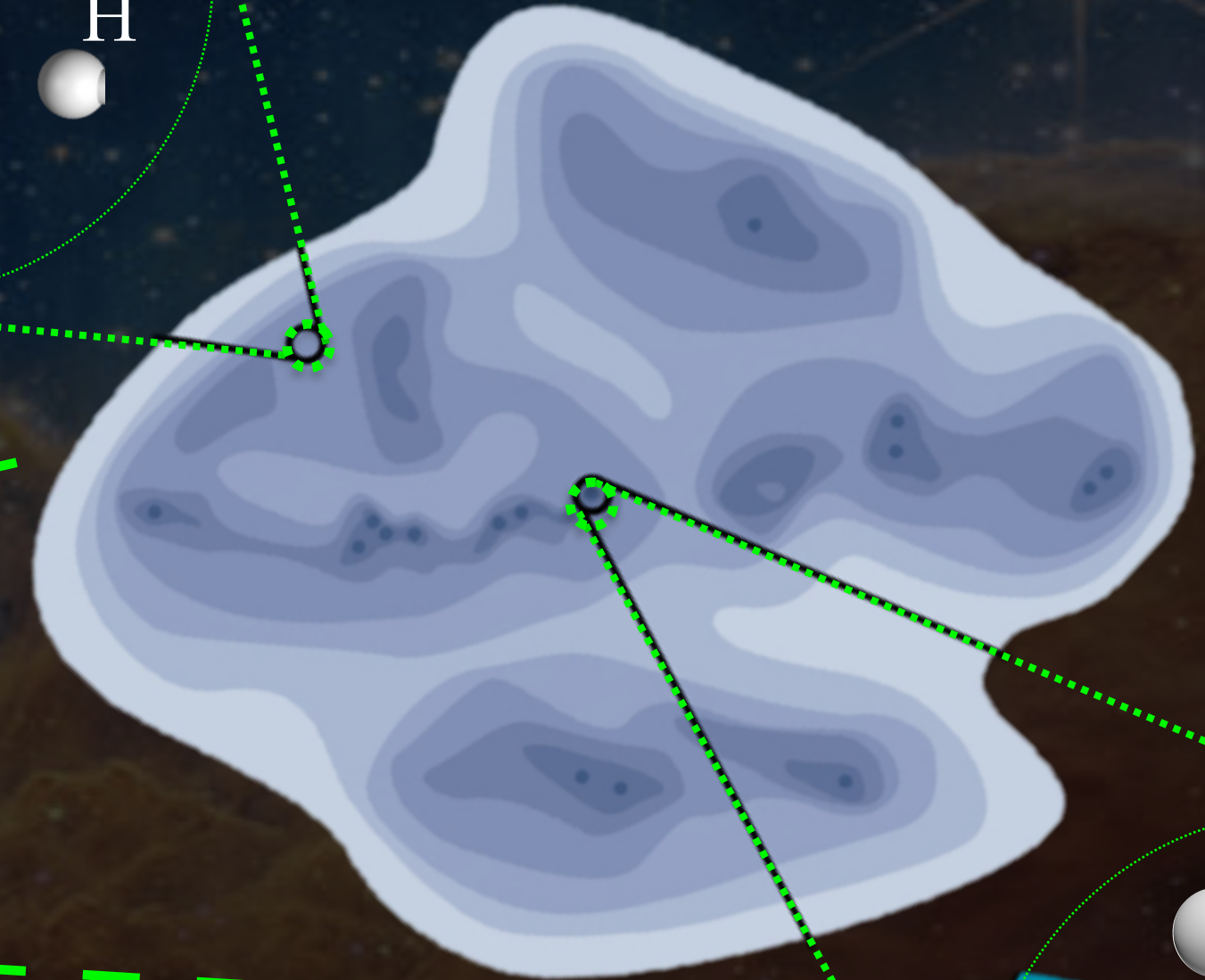
Meinert et al. (2016)

Iopollo et al. (2021)

General context



Low extinction



High extinction

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See also:

Öberg (2015)

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Cosmic rays

General context

Low extinction

BIG QUESTION:

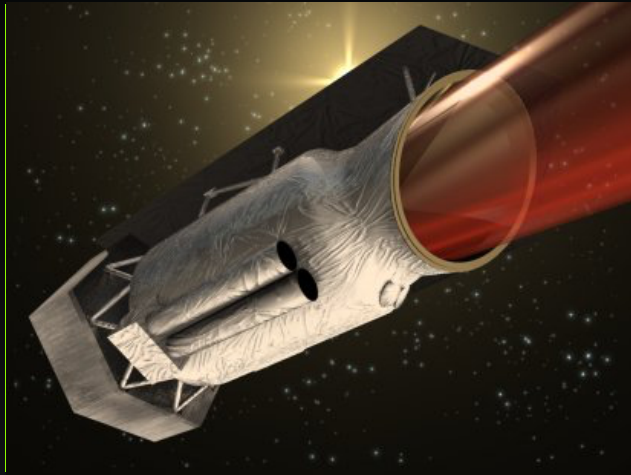
How abundant are the icy complex organic molecules in star-forming regions?

High extinction

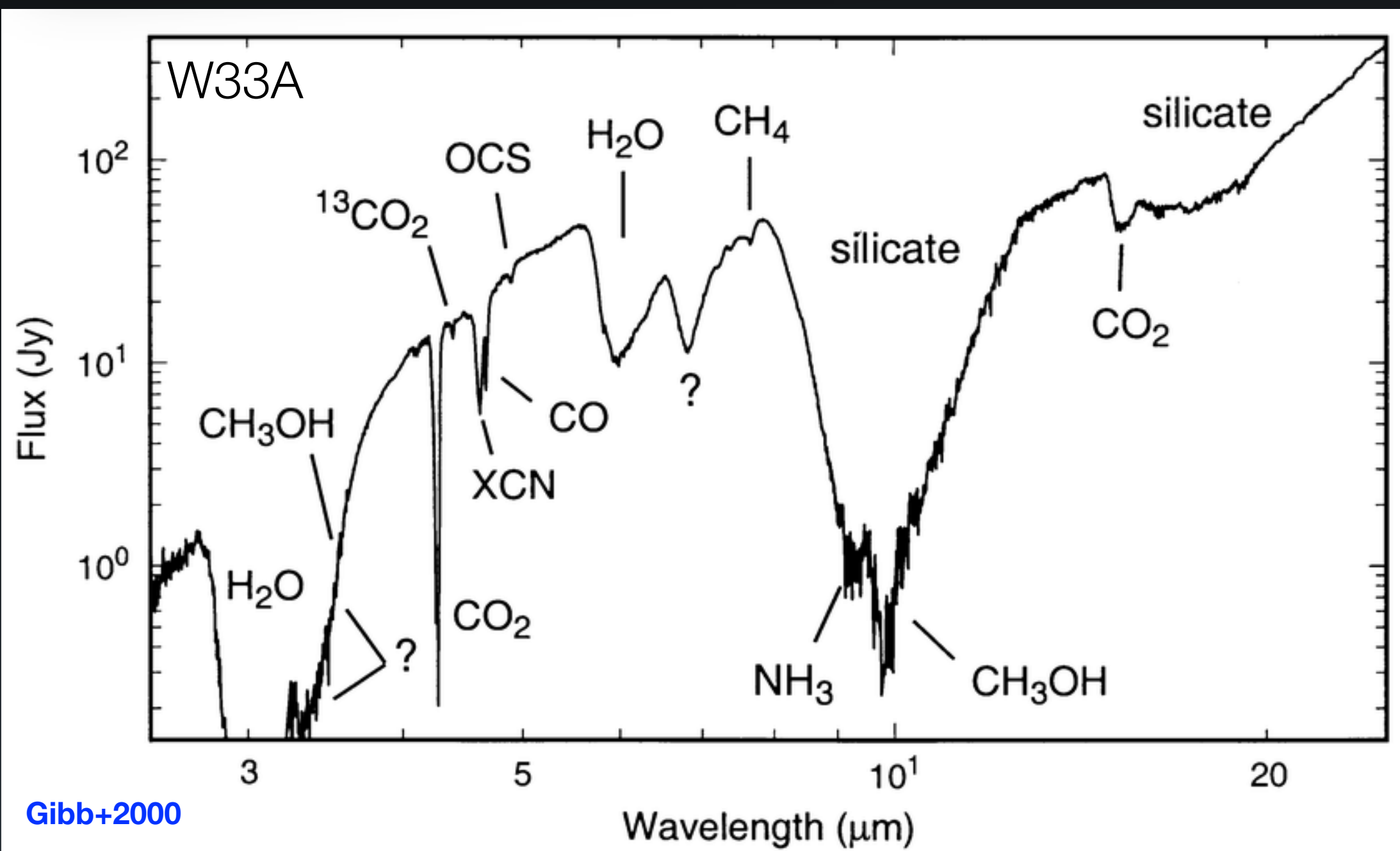
Cosmic rays

Adapted from Öberg & Bergin 2020

Decades of ice observations

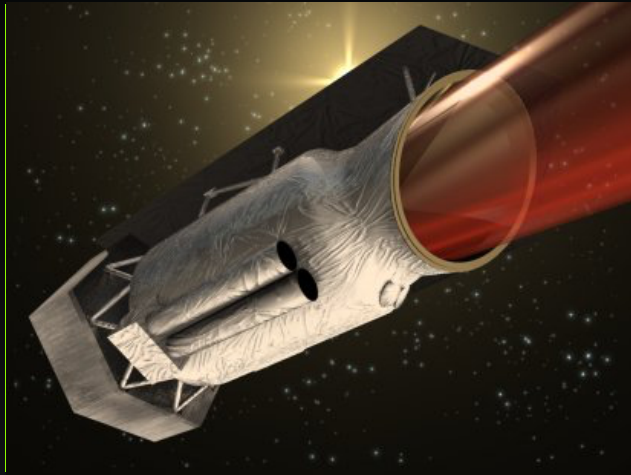


ISO (1995 - 98)

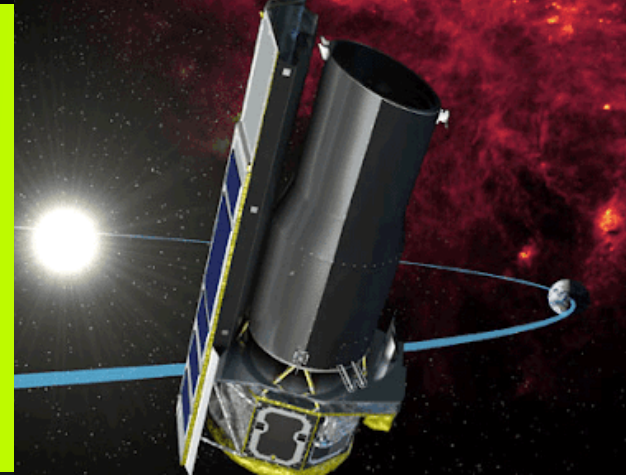


Ices identified: H_2O , NH_3 , CH_4 , CO , CO_2 , HCOOH , CH_3OH , NH_4^+ , XCN^- , OCS , SO_2 , H_2CO .

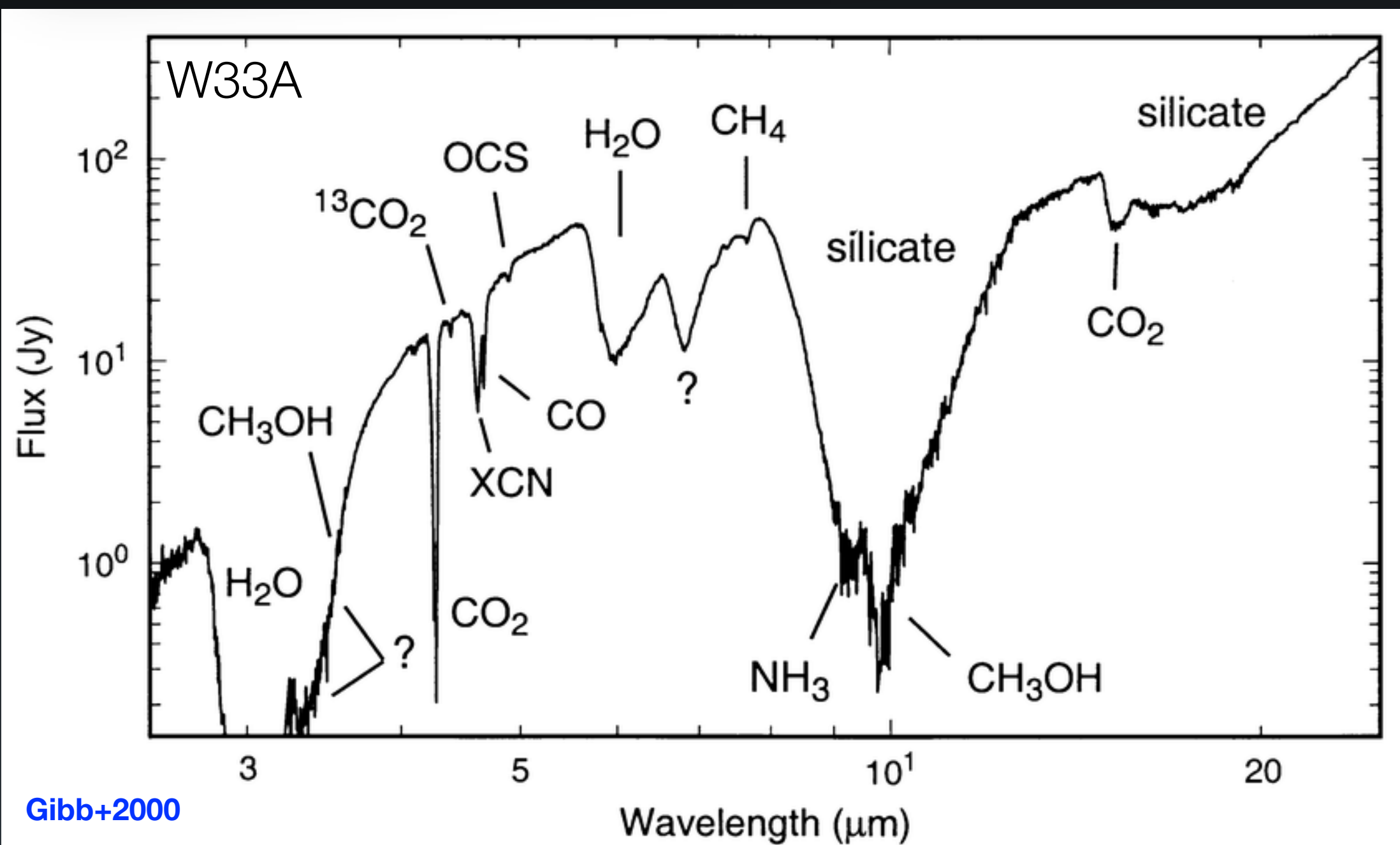
Decades of ice observations



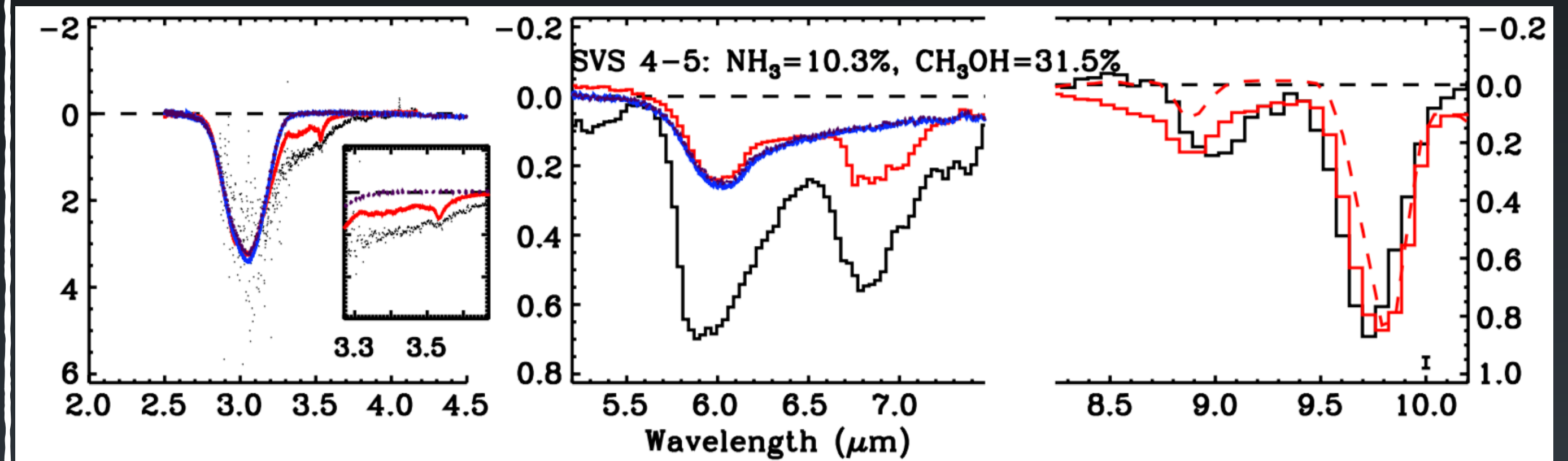
ISO (1995 - 98)



Spitzer (2003 - 20)

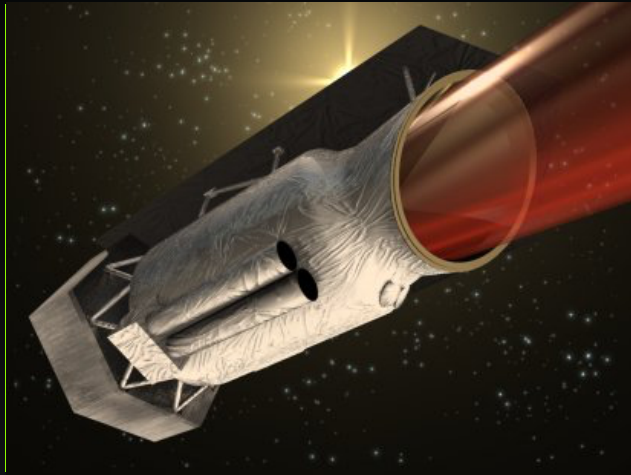


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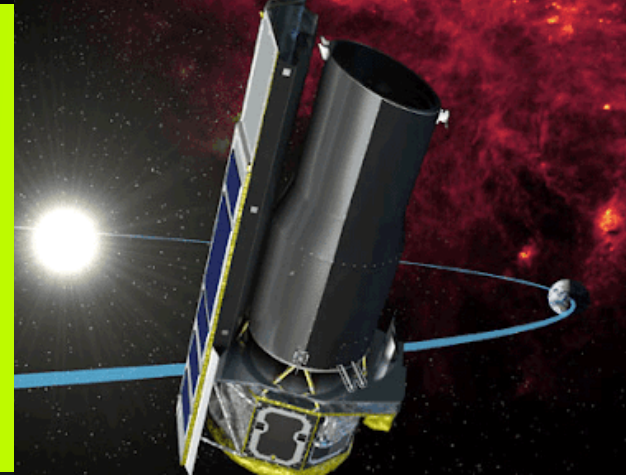


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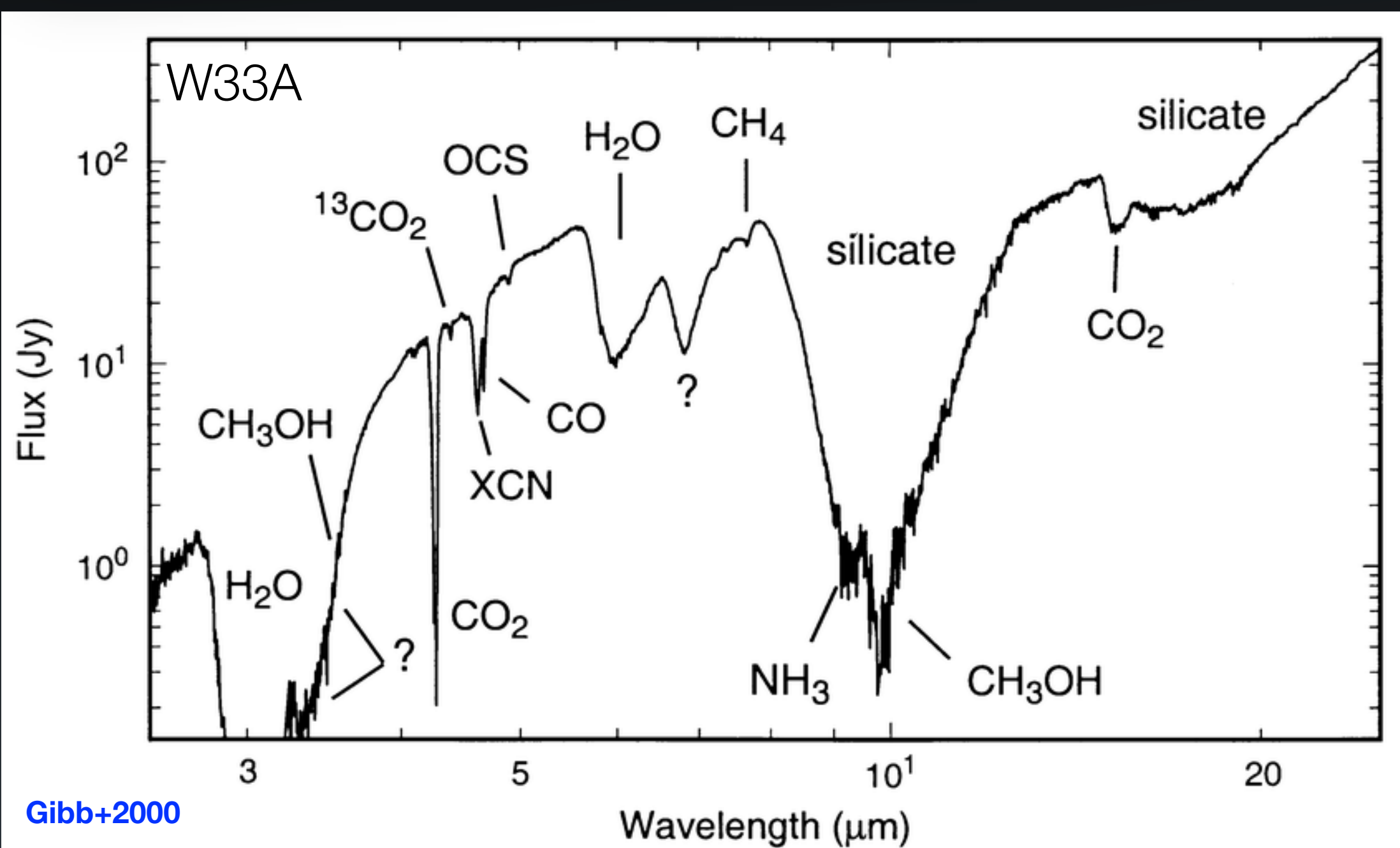
Decades of ice observations



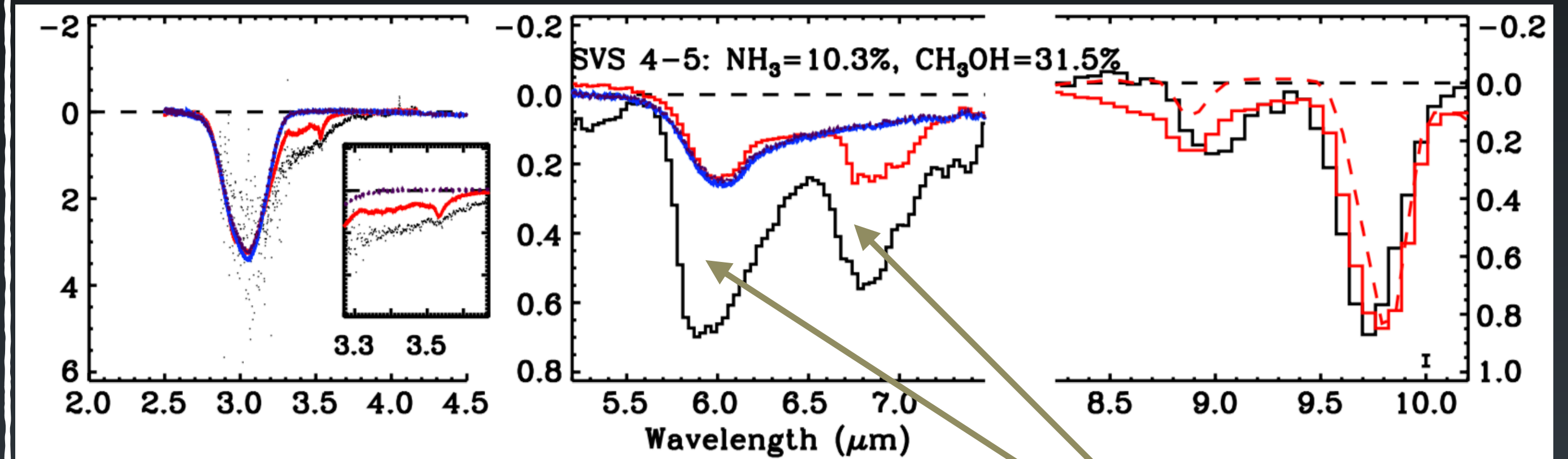
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Ices identified: H_2O , NH_3 , CH_4 , CO , CO_2 , HCOOH , CH_3OH , NH_4^+ , XCN^- , OCS , SO_2 , H_2CO .

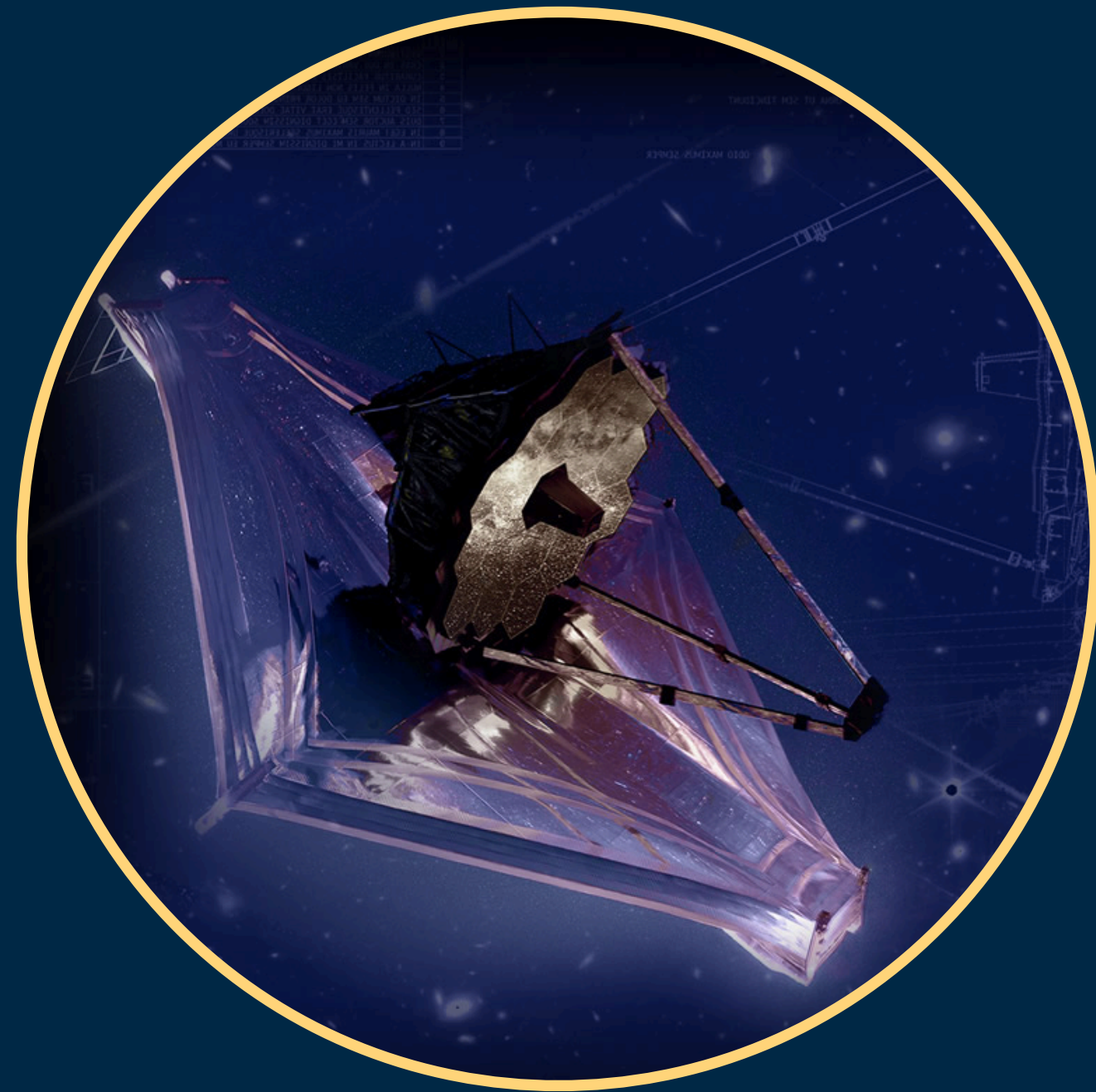


Bottinelli+2010

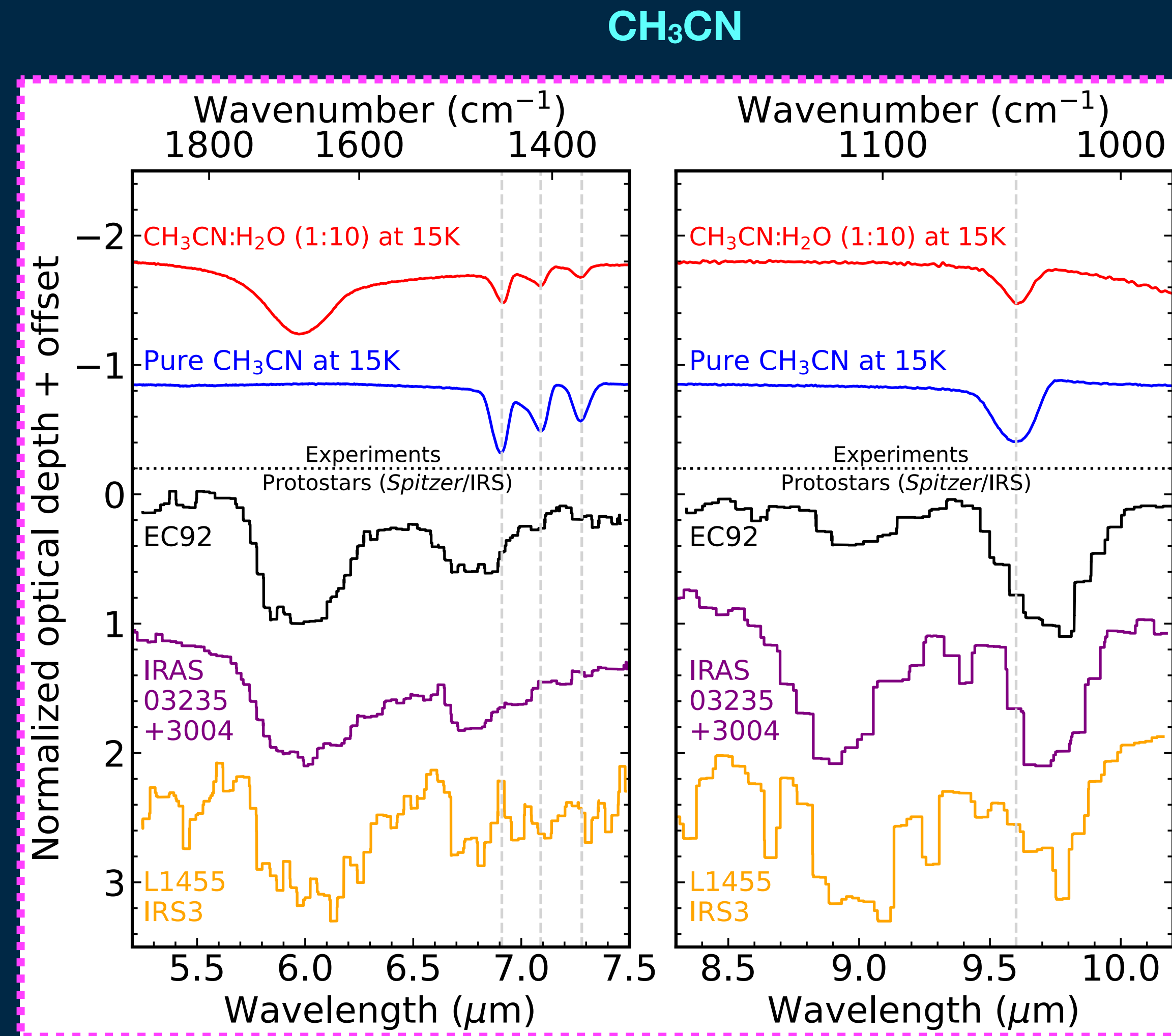
Ices identified: H_2O , NH_3 , CH_4 , CO , CO_2 , HCOOH , CH_3OH , NH_4^+ , OCN^- , OCS , SO_2 , H_2CO .

Not only
 H_2O and CH_3OH

Future with JWST (2021-)



Commissioning is **complete!**
JWST exceeds all expectations!

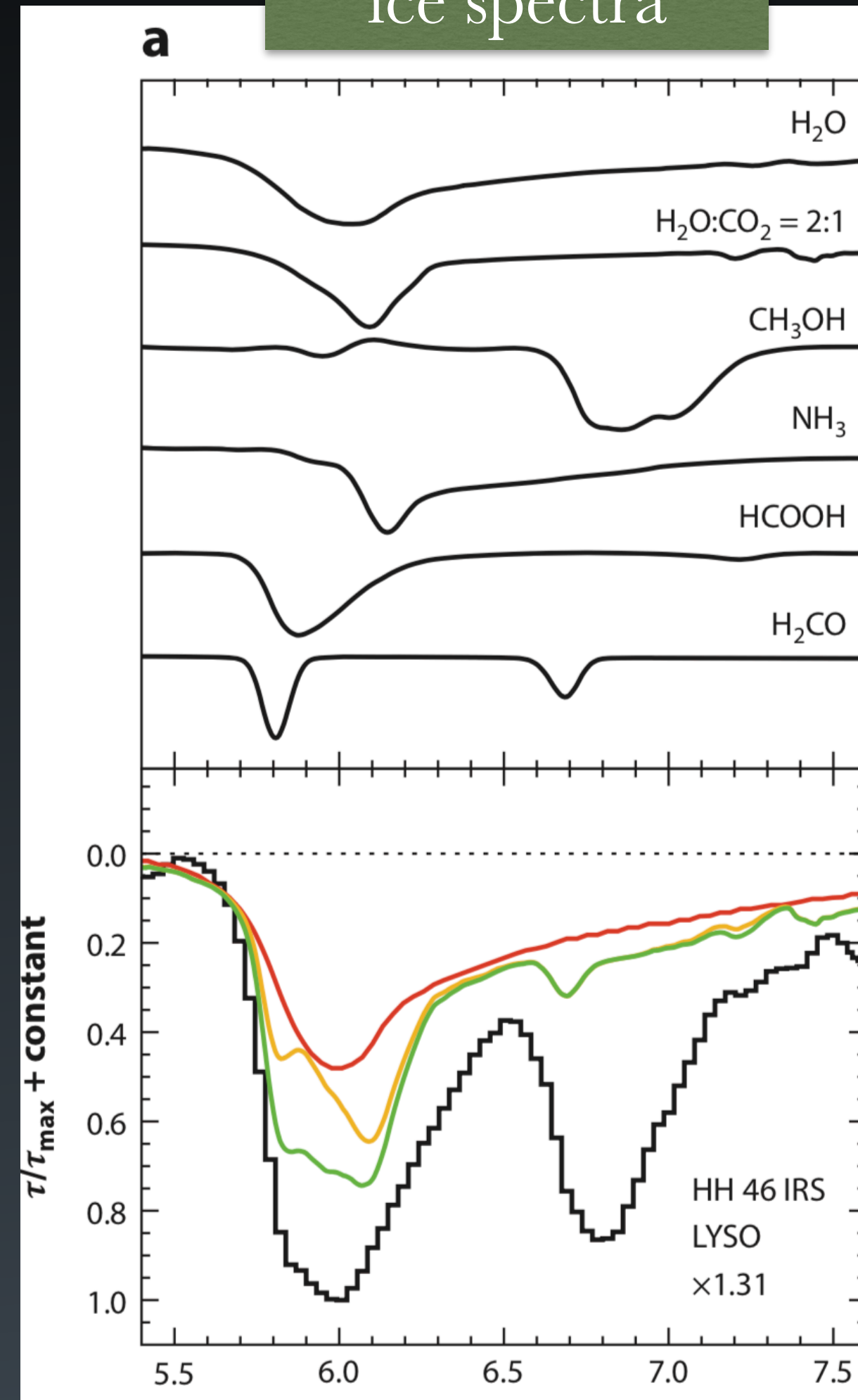


Rachid, **Rocha**, Linnartz (2022)

See also:
Terwisscha van
Scheltinga+2018, 2021
Rachid+2020, 2021

Methodologies used so far

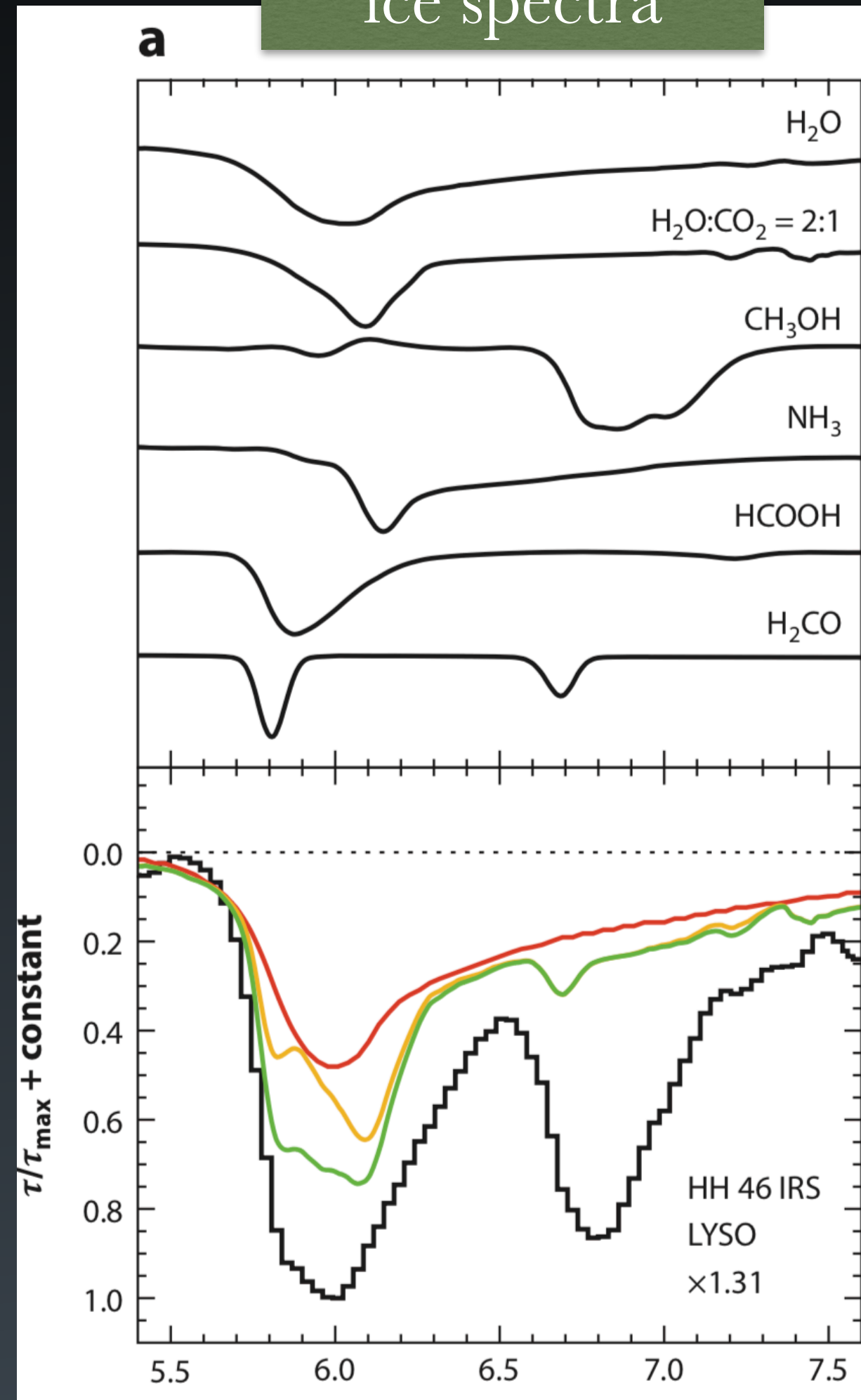
Method 1:
combination of
ice spectra



Methodologies used so far

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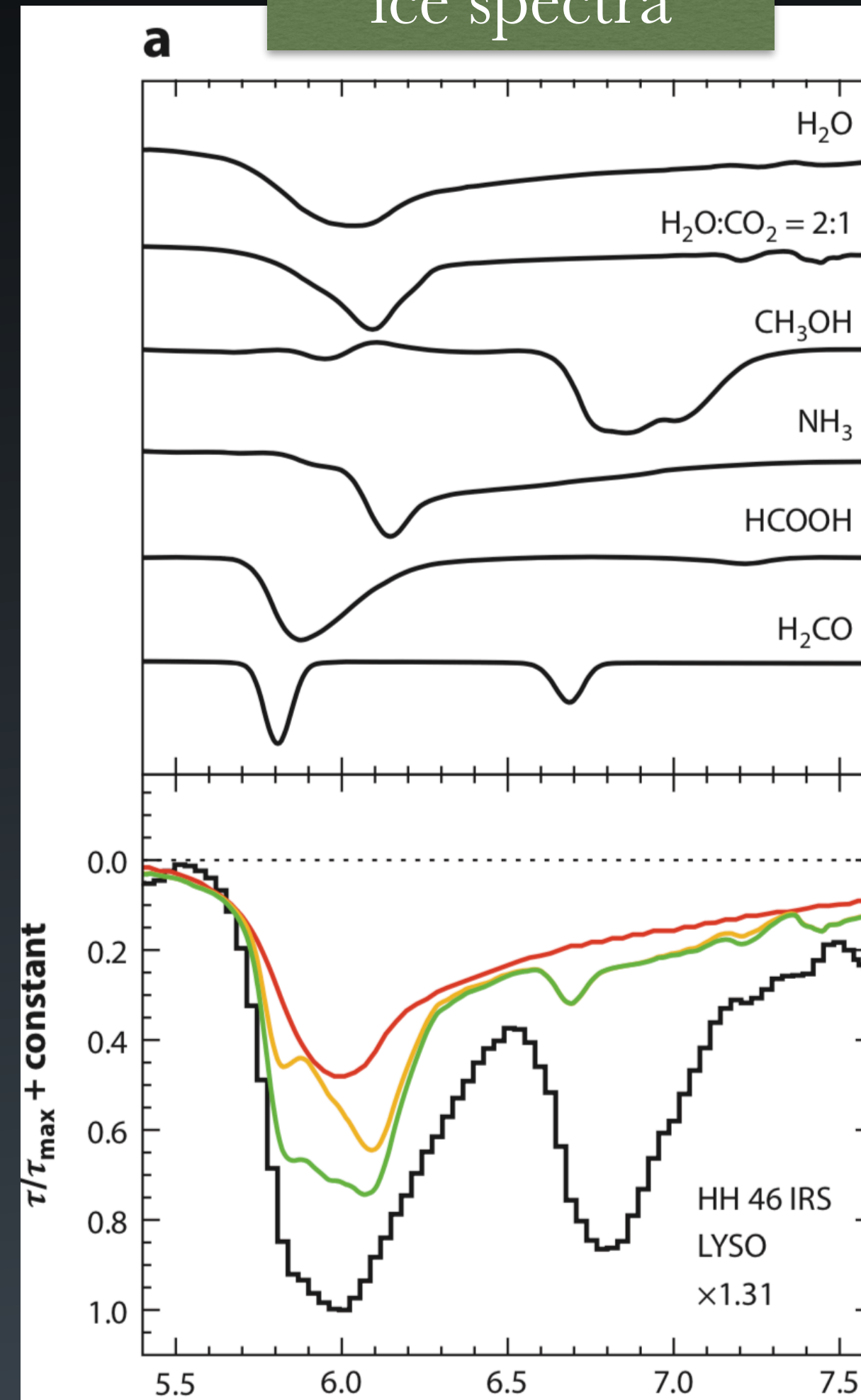
- **Method 1:** more obvious approach, but..
 - ▶ difficult to handle by hand;
 - ▶ comes with high degeneracy.



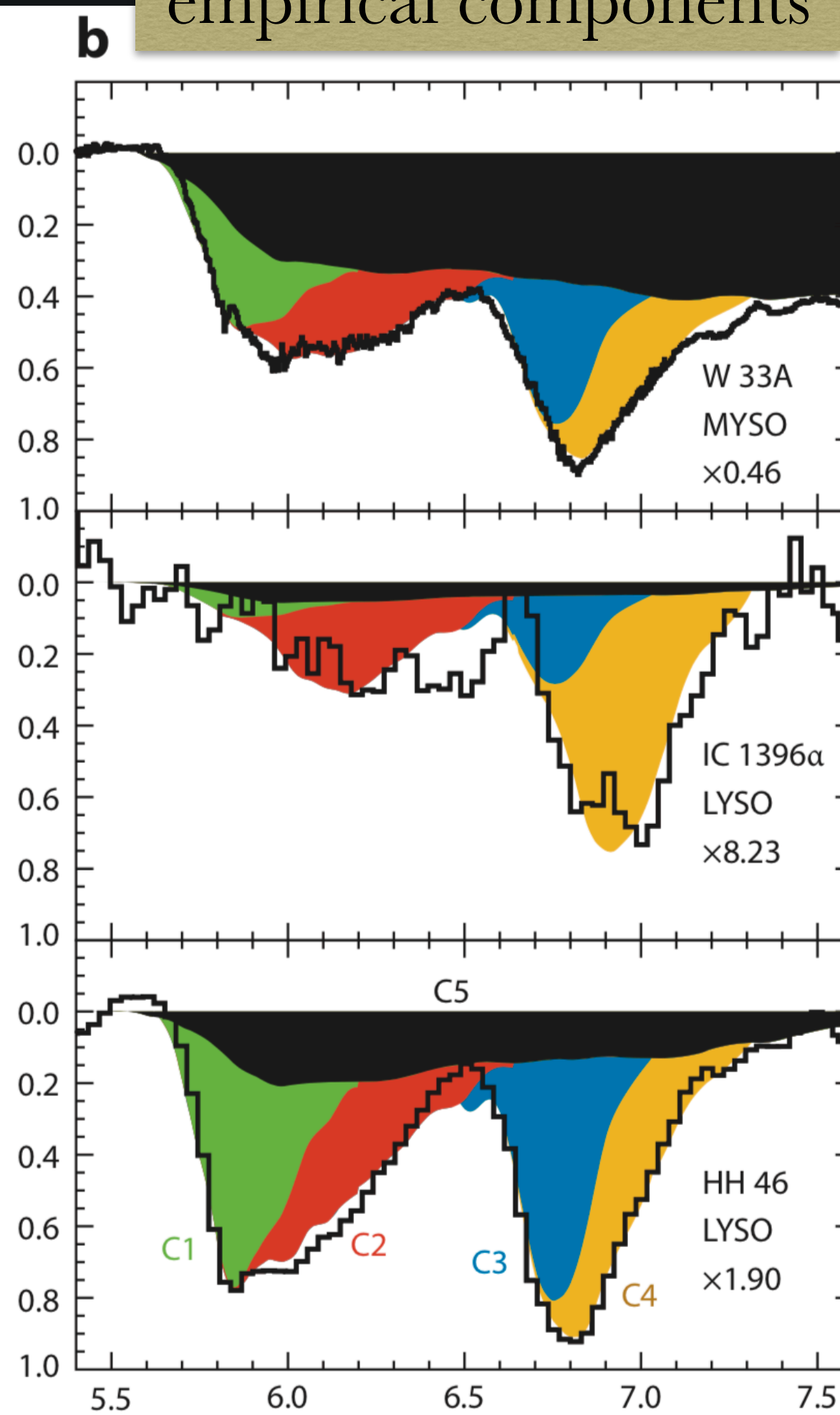
Methodologies used so far

- **Method 1:** more obvious approach, but..
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Method 1:
combination of
ice spectra



Method 2:
combination of
empirical components



- **Method 2:** Fit of the residual spectrum after removing the pure H_2O (10 K) component.
 - ▶ 5 empirical components;
 - ▶ carriers not well known.

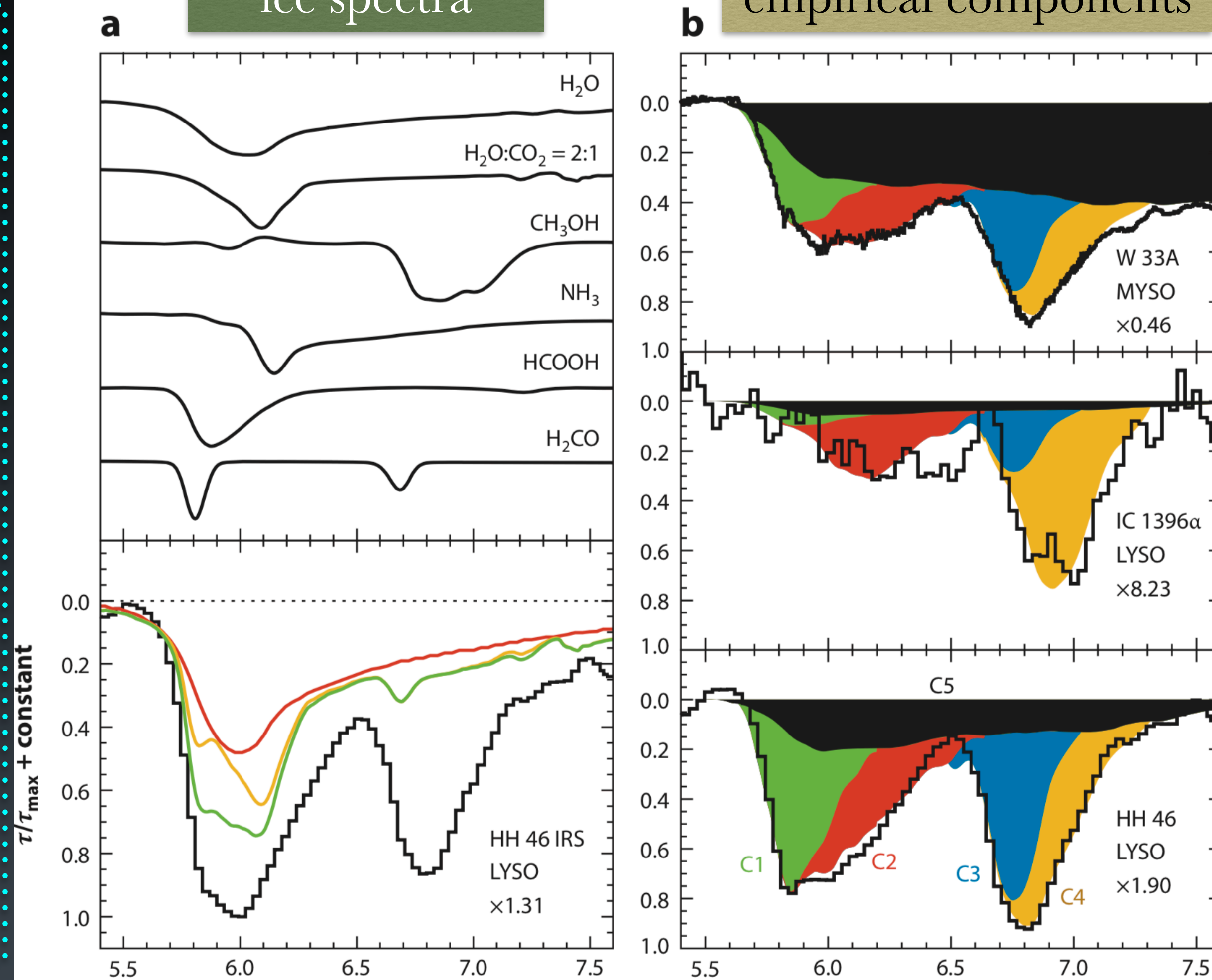
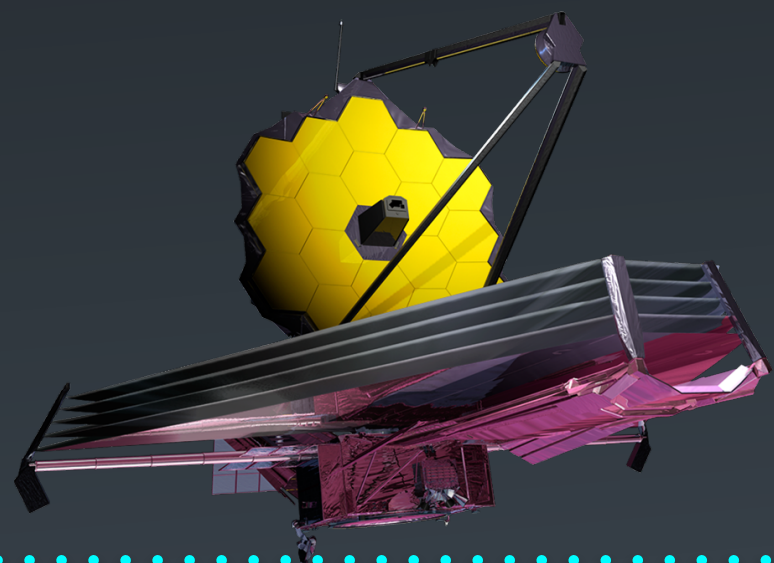
Boogert et al. (2015)

Methodologies used so far

Method 1:
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Method 2:
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- **Method 1:** more obvious approach, but..
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- **Method 2:** Fit of the residual spectrum after removing the pure H₂O (10 K) component.
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Boogert et al. (2015)

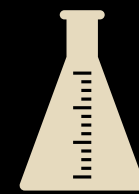
ENIGMA fitting tool

(Rocha+2021)

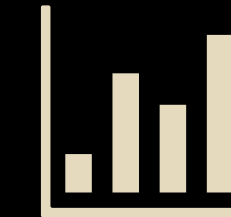
(dEcomposition of Infrared Ice features using Genetic Modeling Algorithms)



Genetic algorithm optimisation



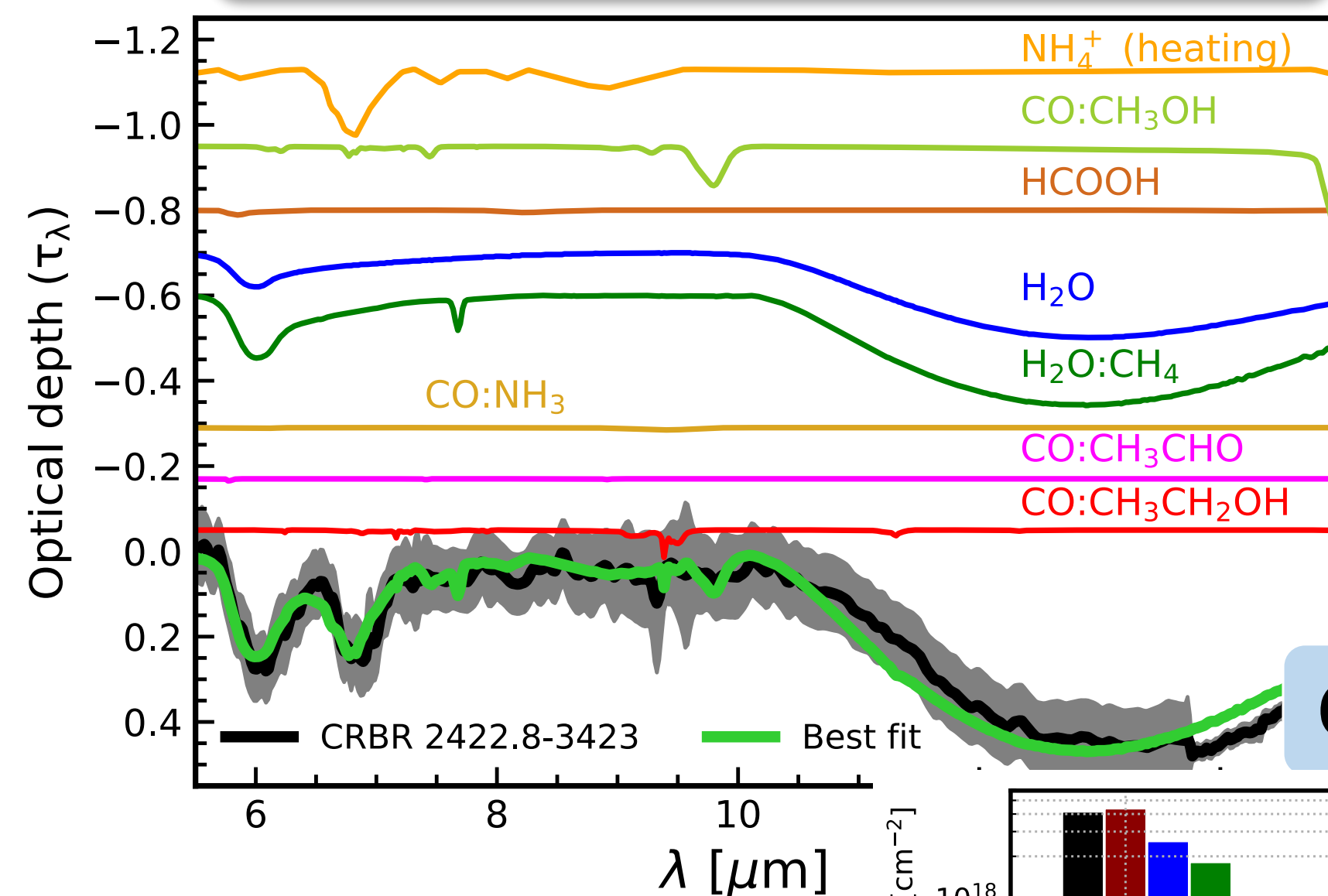
Large laboratory database



Robust statistical analysis

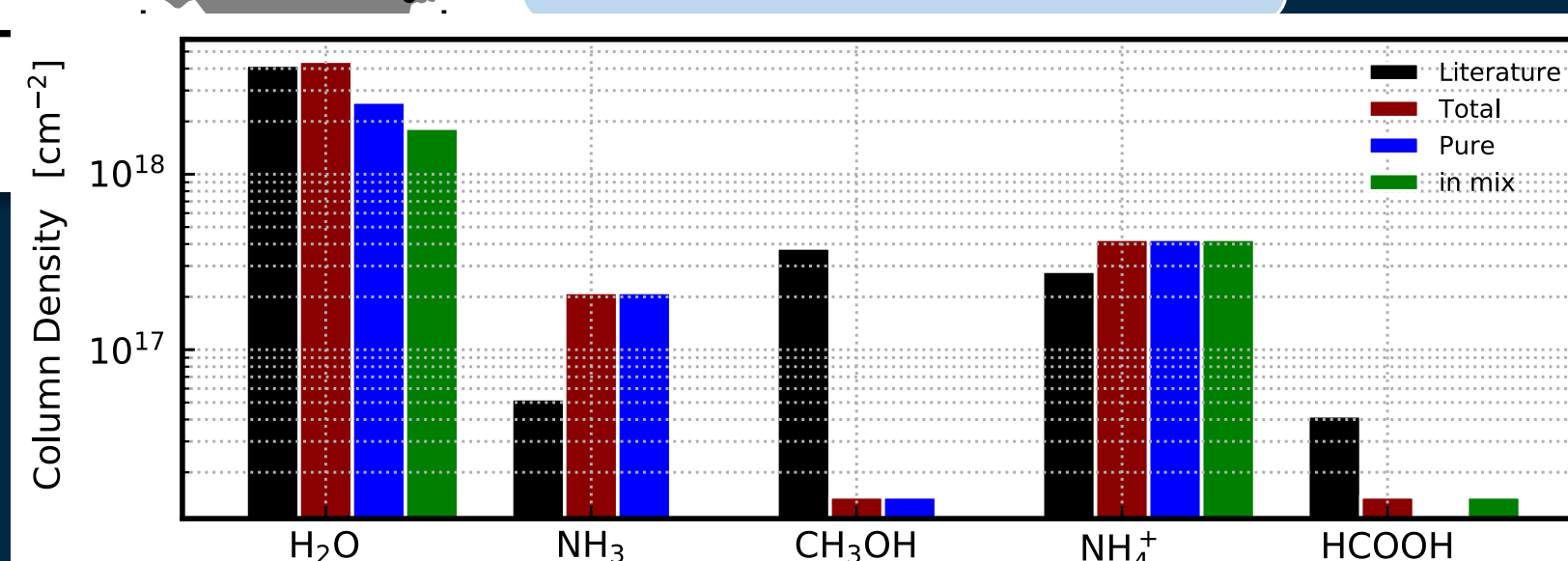
ICE COMPONENTS AND ABUNDANCES

Spectral decomposition



(Rocha+ in prep.)

Column density



STATISTICAL ANALYSIS

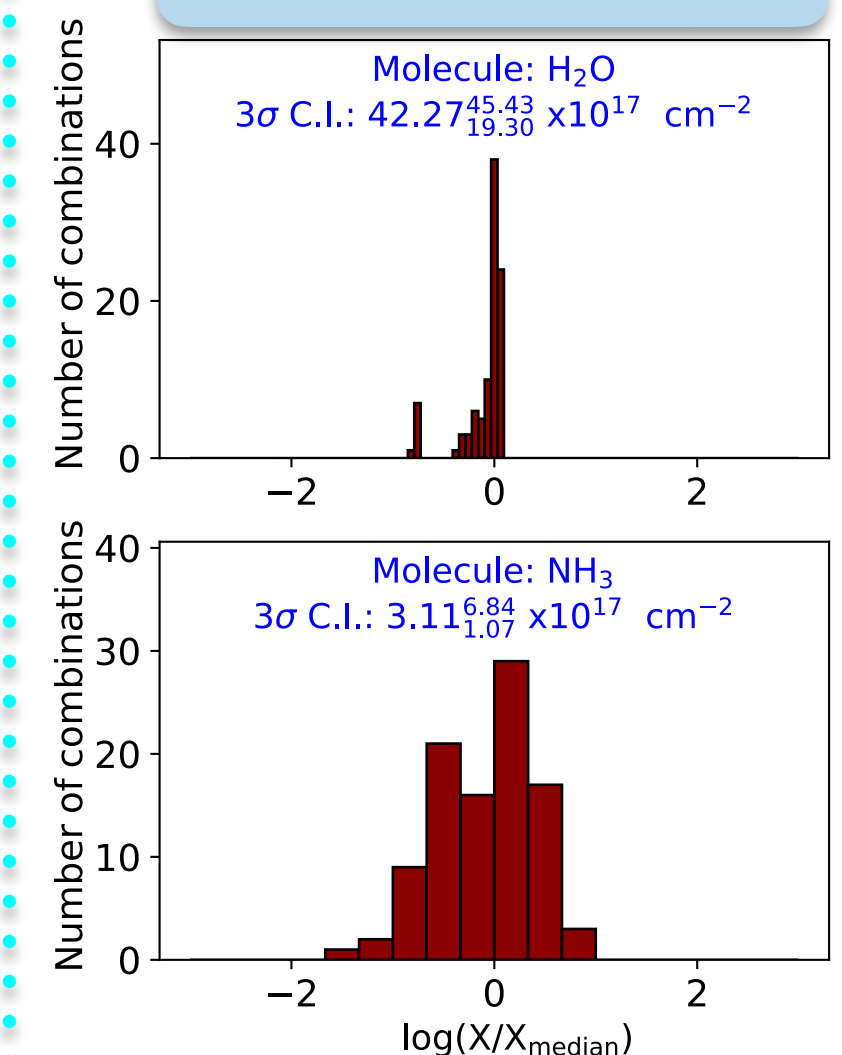
Recurrence plot:

CRBR2422.8-3423



1. H₂O:CH₄: 100%
2. H₂O: 94.3%
3. CO:CH₃OH: 86.4%
4. NH₄⁺ (heating): 65.2%
5. HCOOH: 54.9%
6. CO:NH₃: 54.2%
7. CO:CH₃CHO: 54.4%
8. CO:CH₃CH₂OH: 52.0%
9. NH₃:CH₃OH: 51.3%
10. H₂CO: 49.5
11. CH₃CN: 48.0%
12. CO:CH₃OCH₃: 46.5%
13. H₂O:NH₃:CO₂:CH₄-CR: 45.4%

HISTOGRAMS



ELIAS 29

- **Region:** *Ophiuchus molecular cloud.*
- **Luminosity:** $36 L_{\text{sun}}$
- **Distance:** 120 pc

Image: NASA, JPL-Caltech, Harvard-Smithsonian CfA

ELIAS 29

- **Region:** *Ophiuchus molecular cloud.*
- **Luminosity:** $36 L_{\text{sun}}$
- **Distance:** 120 pc

JWST/GO 1959 (PI: Will Rocha)
6 protostars externally
heated by B-type stars

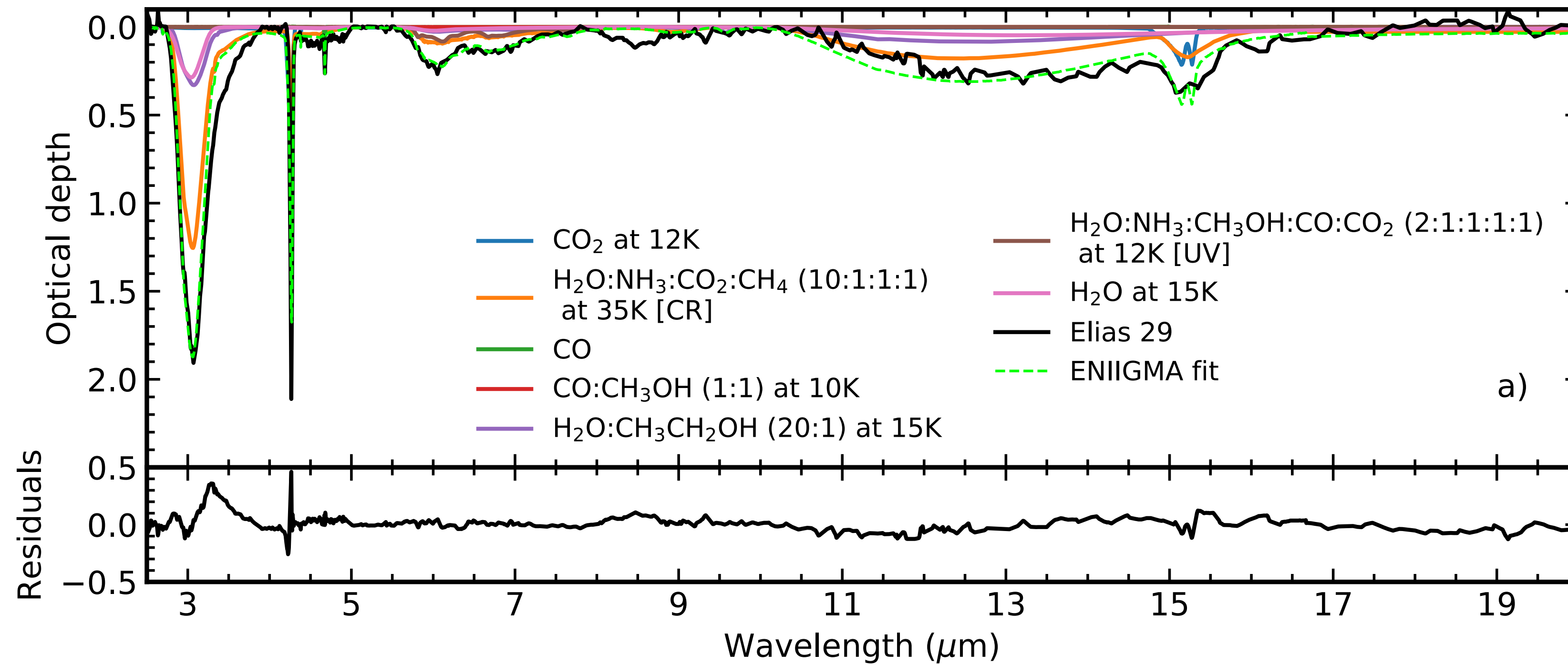
Liseau+1999; Ceccarelli+2000;
Lindberg+2017 Rocha+2018

MIRI/IFU

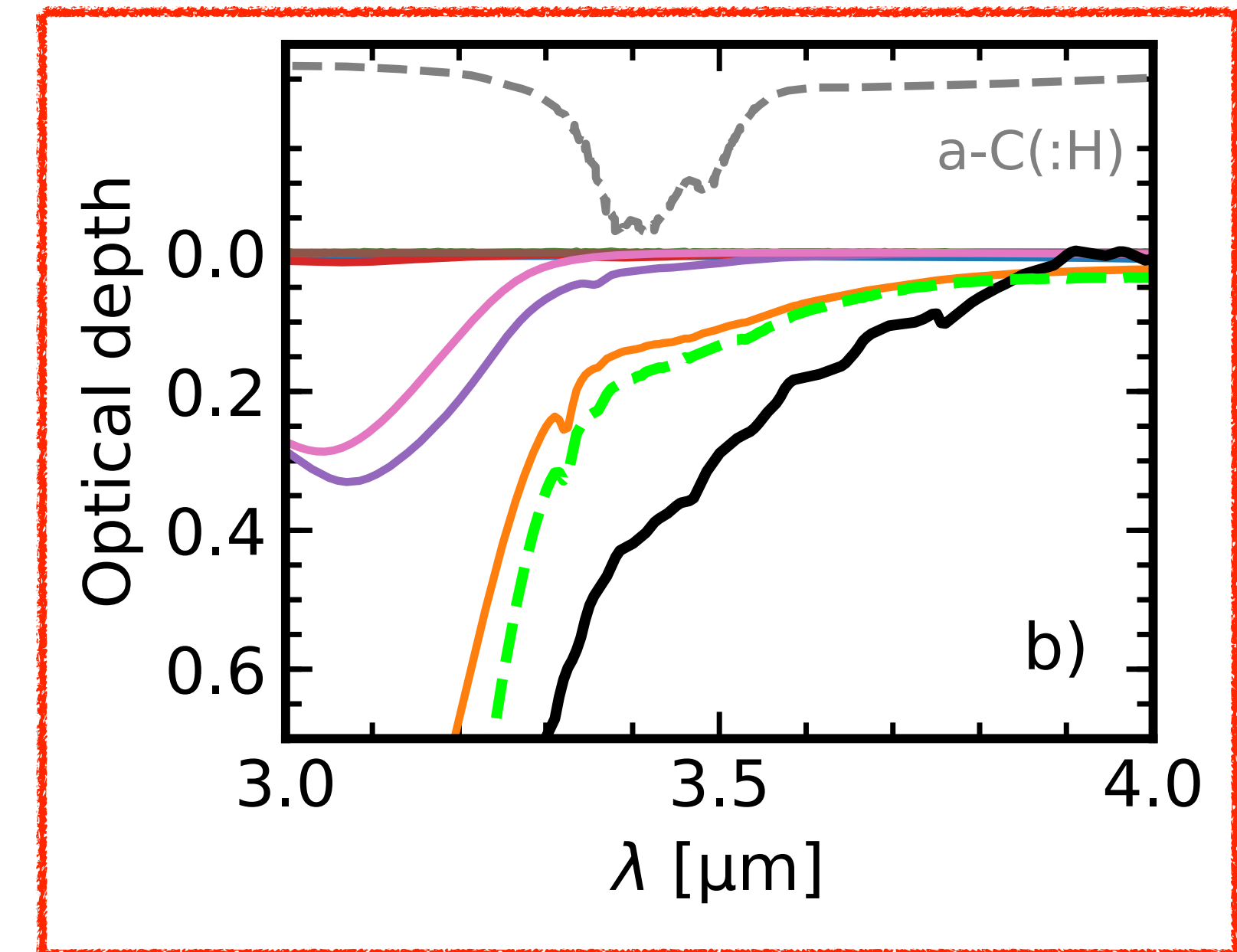
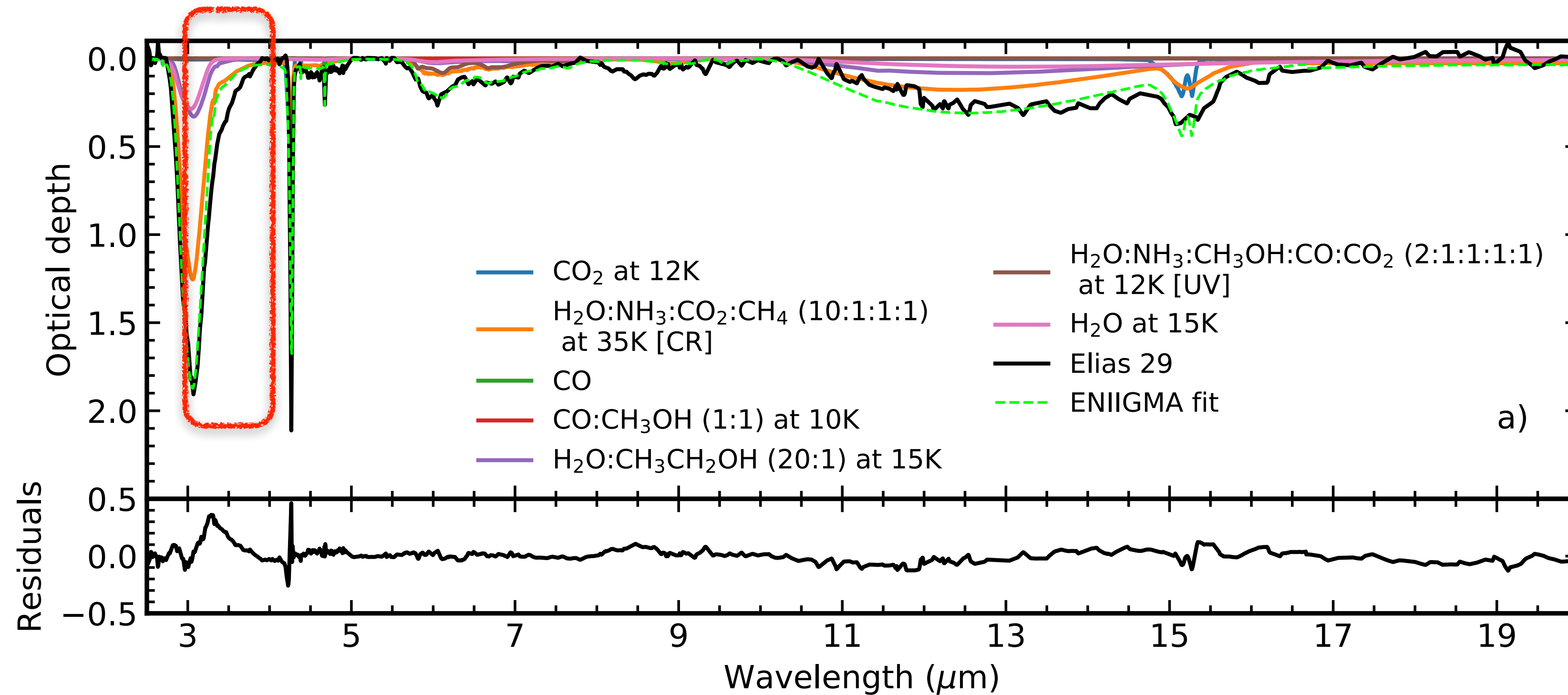
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SPECTRAL DECOMPOSITION: ELIAS 29



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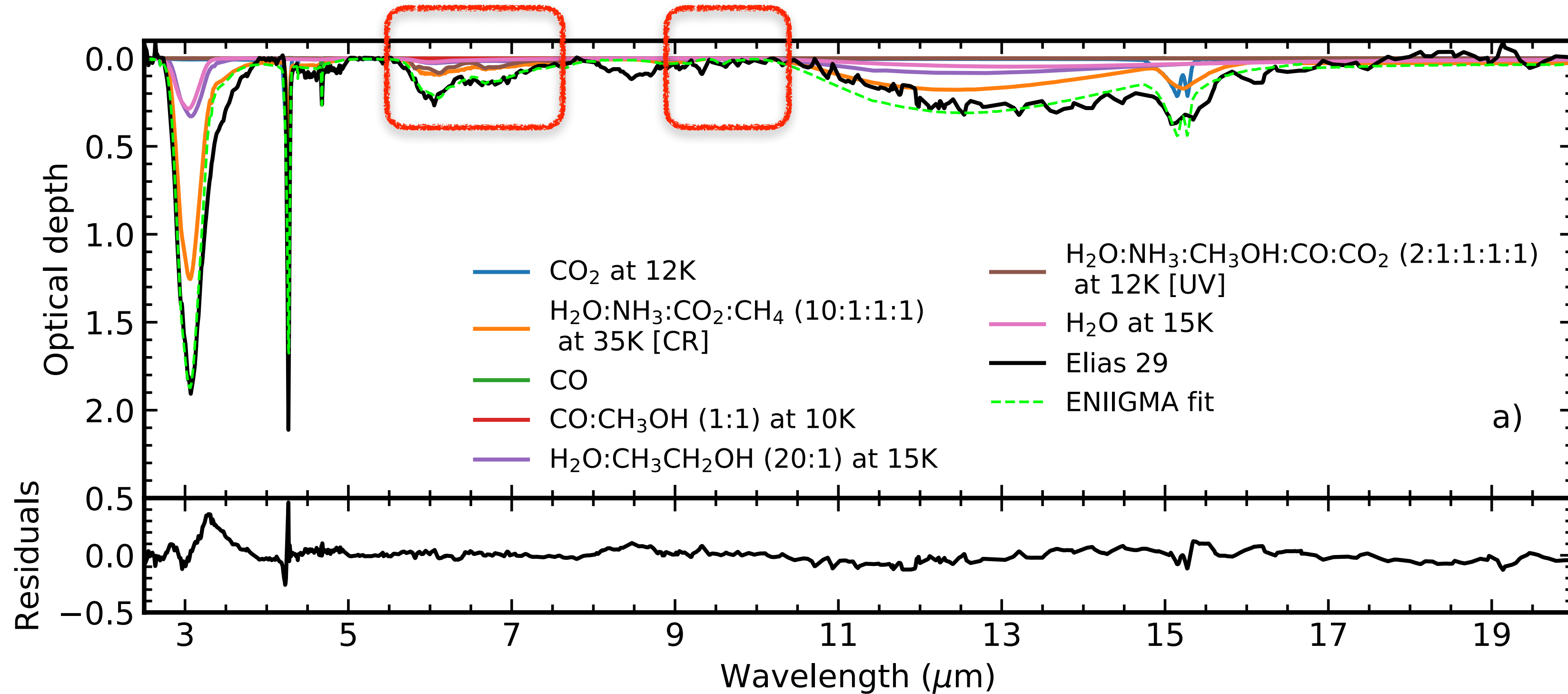


See also:

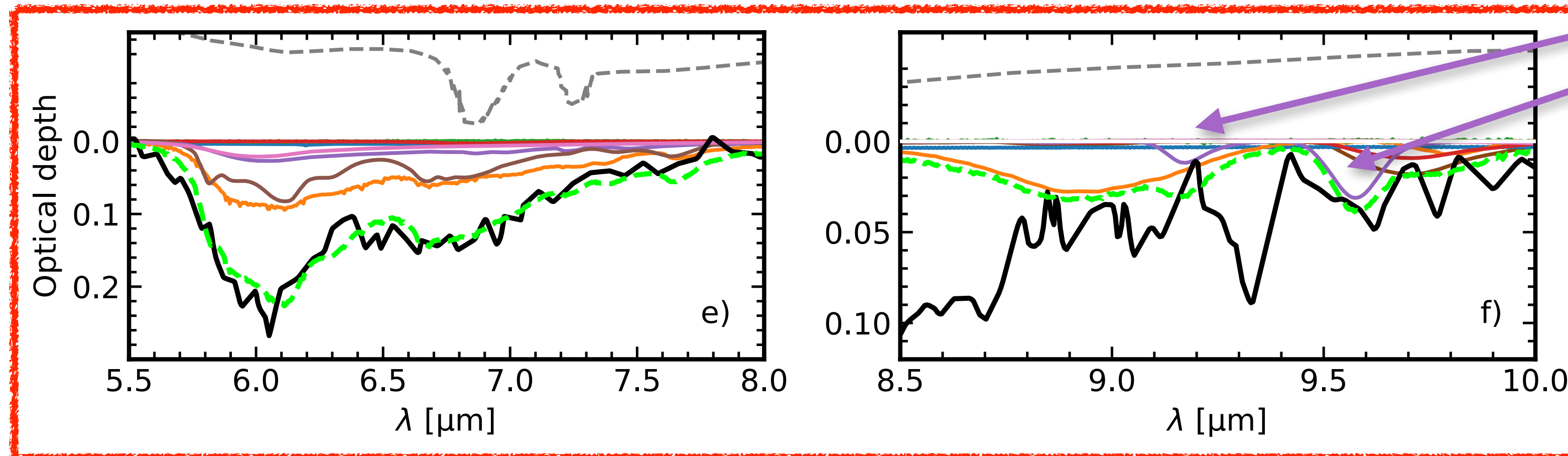
- Water-rich ice: major component.
- Strong IR excess not explained. Large grains or something else? (Rocha et al. to be submitted soon)
- Potential contribution of a-C(:H)?

- Boogert et al. (2000)
- Pontoppidan et al. (2004)
- Shimonishi et al. (2010)
- Rocha & Pilling (2015)
- Perotti, Rocha et al. (2020)

SPECTRAL DECOMPOSITION: ELIAS 29



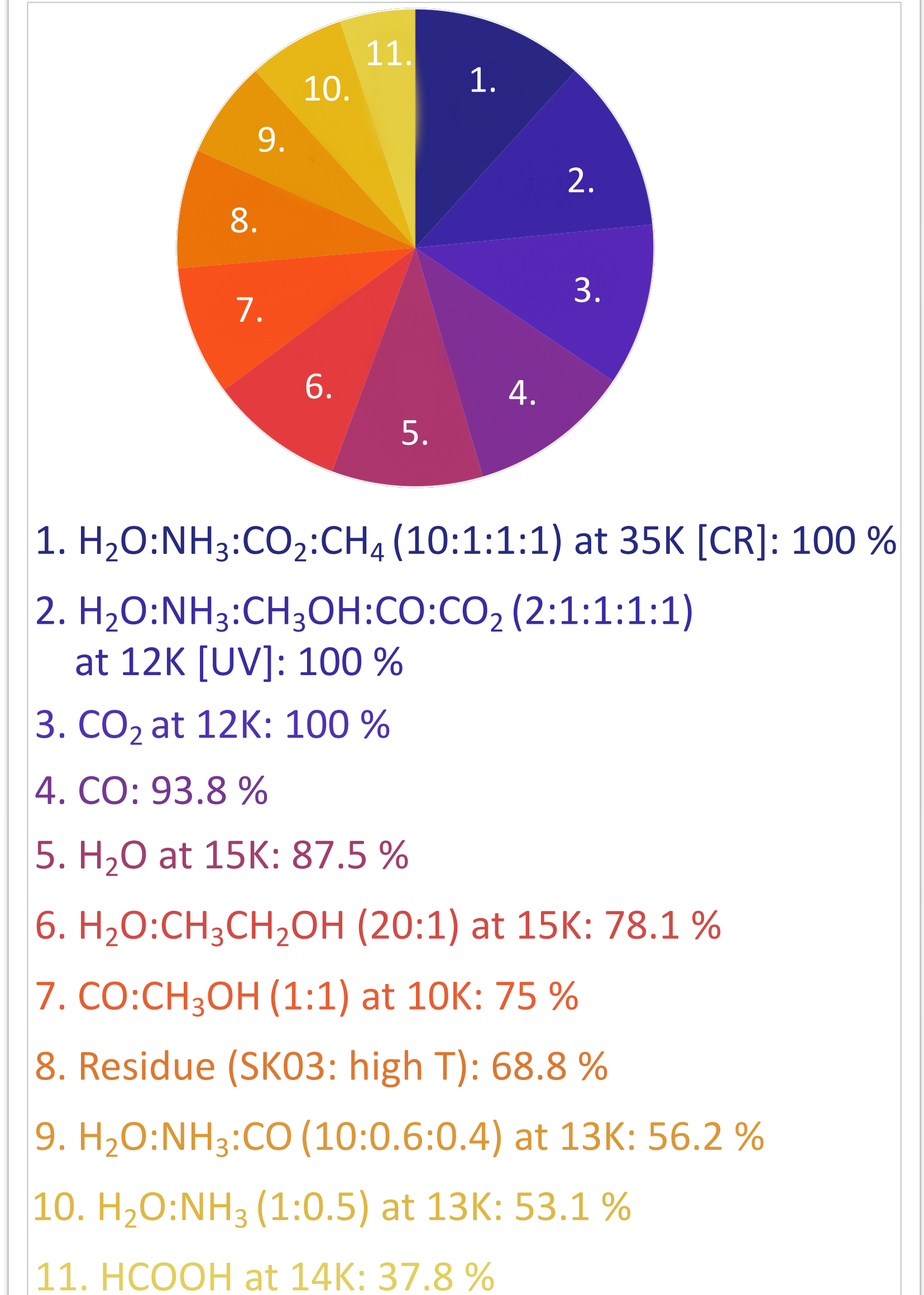
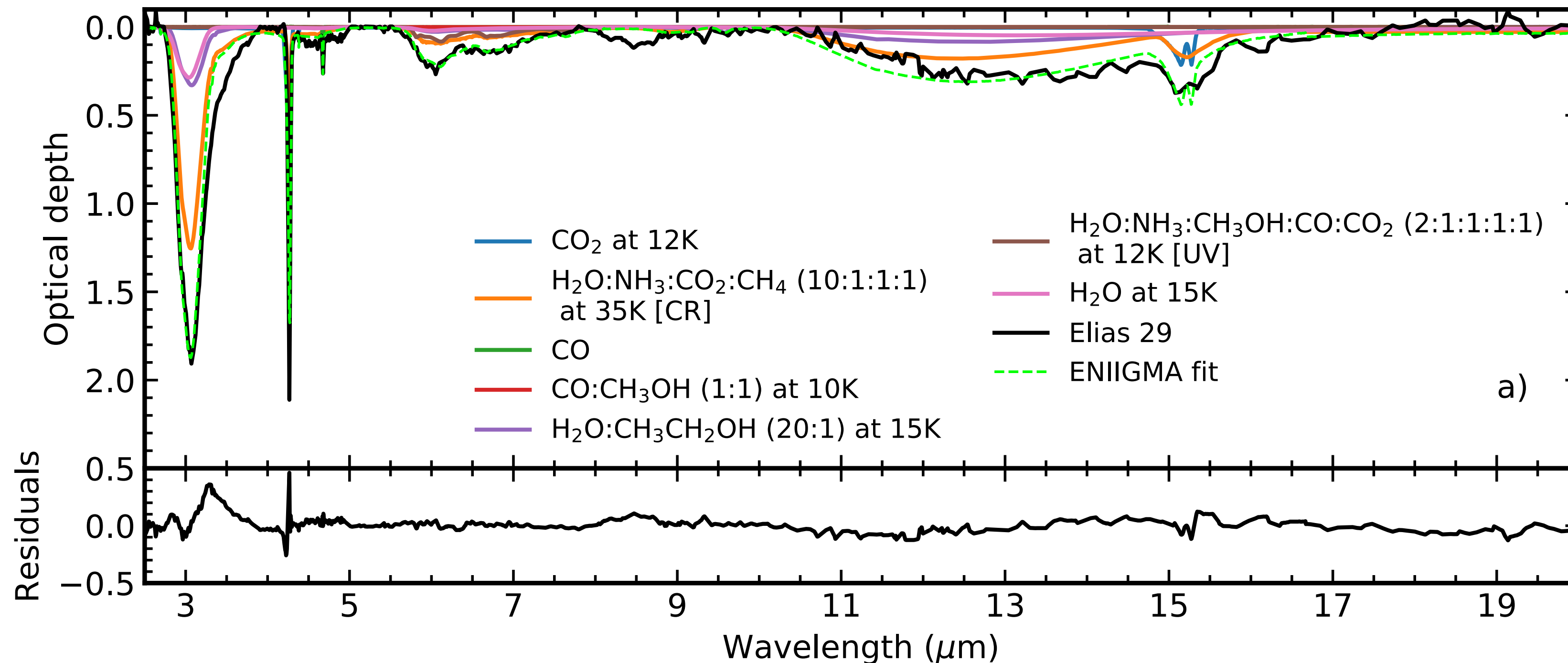
- Unlikely contribution of amorphous carbon.
- Simultaneous fit of the 3 and 6 micron component!
- Material formed after UV/CR ice processing.
- NH₃ and CH₃OH present;
- Tentative detection of CH₃CH₂OH



See also:

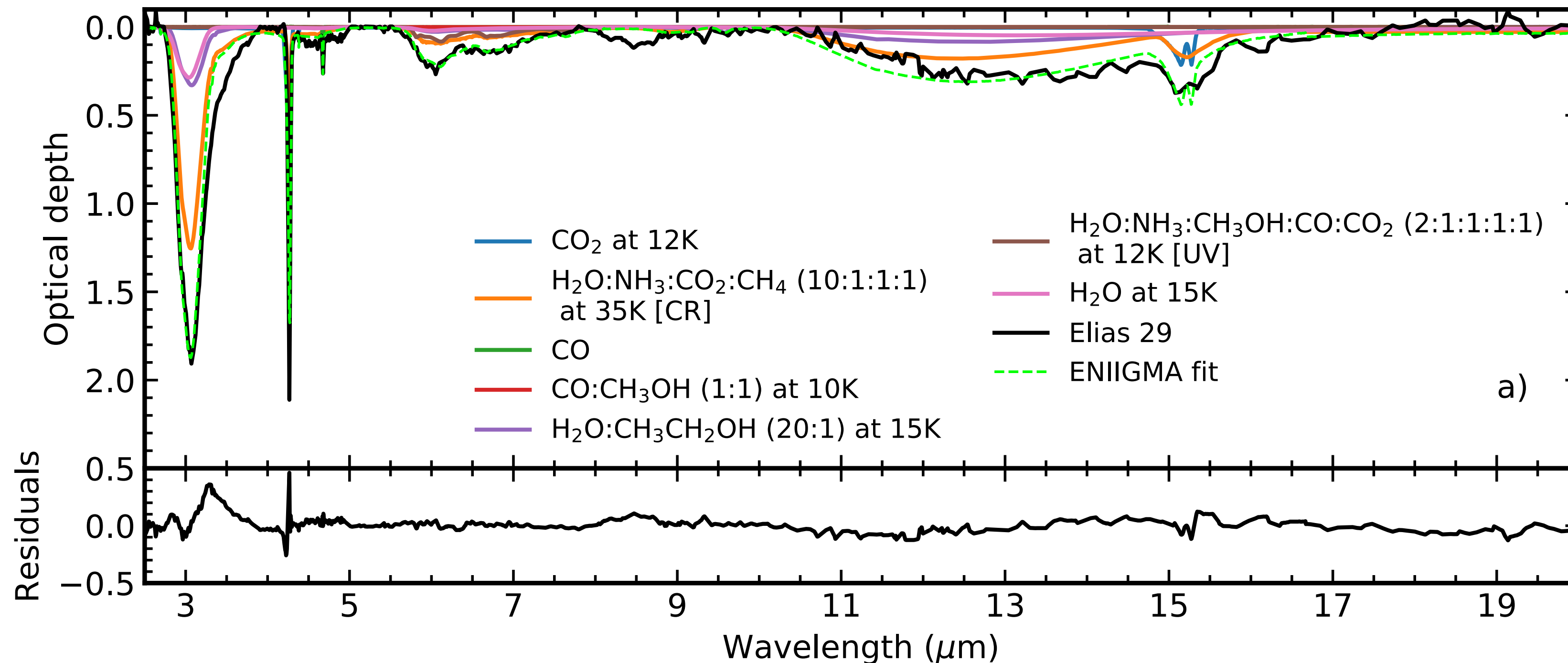
- Boogert et al. (2008)
- Bottinelli et al. (2010)
- Rocha & Pilling (2015)

Degeneracy analysis: ELias 29



- Components 8-11 could replace some of the components 1-7.
- Fit remains inside 3σ confidence interval.

Degeneracy analysis: ELias 29

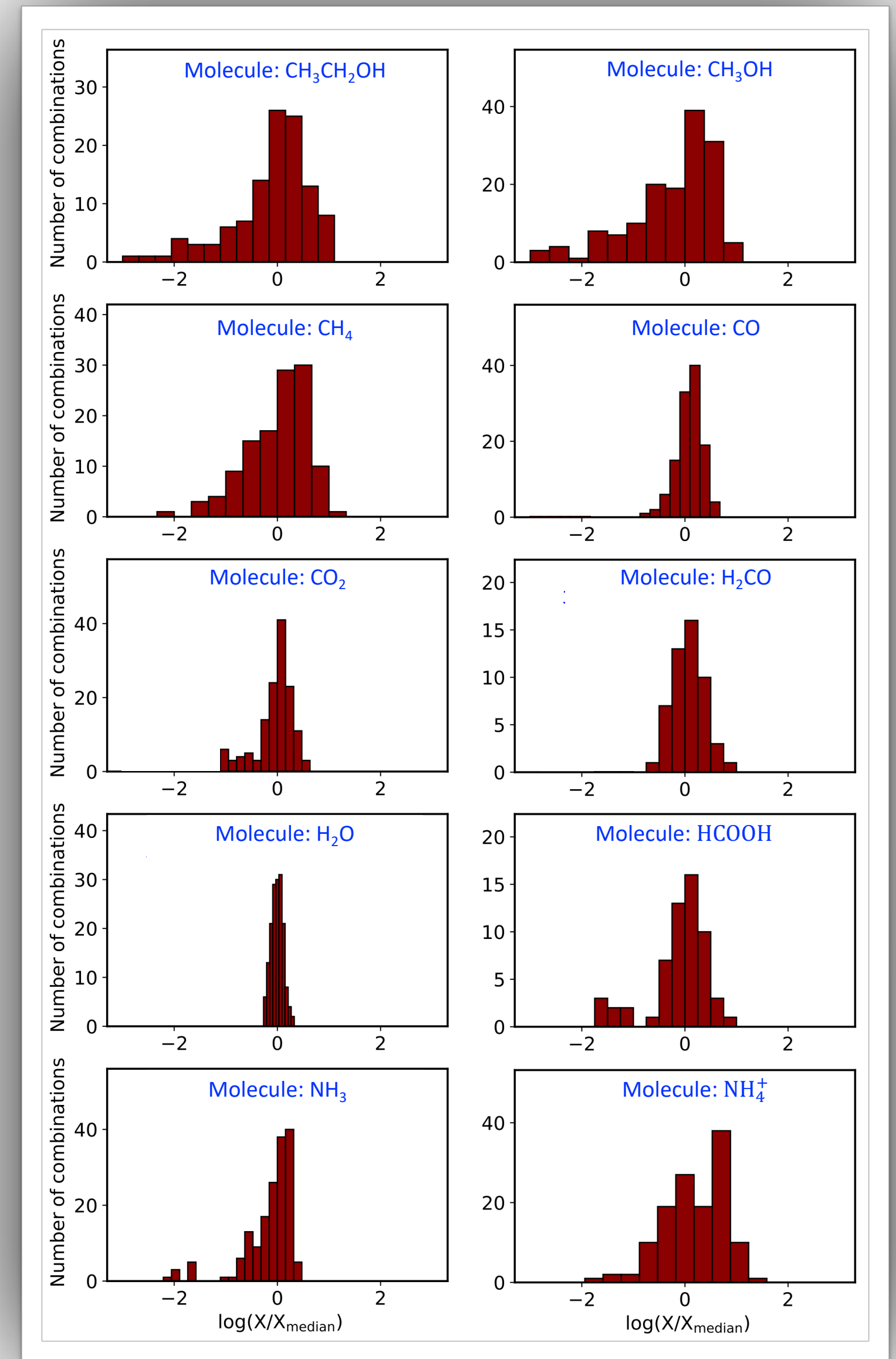


1. H₂O:NH₃:CO₂:CH₄ (10:1:1:1) at 35K [CR]: 100 %
2. H₂O:NH₃:CH₃OH:CO:CO₂ (2:1:1:1:1) at 12K [UV]: 100 %
3. CO₂ at 12K: 100 %
4. CO: 93.8 %
5. H₂O at 15K: 87.5 %
6. H₂O:CH₃CH₂OH (20:1) at 15K: 78.1 %
7. CO:CH₃OH (1:1) at 10K: 75 %
8. Residue (SK03: high T): 68.8 %
9. H₂O:NH₃:CO (10:0.6:0.4) at 13K: 56.2 %
10. H₂O:NH₃ (1:0.5) at 13K: 53.1 %
11. HCOOH at 14K: 37.8 %

- Components 8-11 could replace some of the components 1-7.
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Column densities: ELias 29

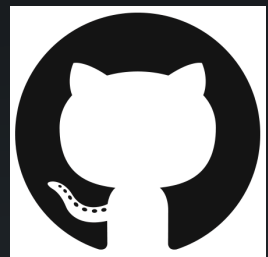
Specie	$N_{\text{ice}} [10^{17} \text{ cm}^{-2}]$	This paper: $N_{\text{ice}} [10^{17} \text{ cm}^{-2}]$	
	Boogert et al. (2000)	Global minimum	Median (Histogram ^b)
H ₂ O	34 (6)	33.11 ^{41.13} _{21.09}	35.42 ^{41.87} _{25.23}
NH ₃	< 3.5	1.01 ^{1.47} _{0.75}	2.42 ^{3.88} _{0.43}
CO	1.7 (0.3)	1.55 ^{1.81} _{0.73}	1.42 ^{1.87} _{1.23}
CO ₂	6.7 (0.5)	5.22 ^{7.13} _{3.4}	4.42 ^{6.87} _{2.23}
CH ₄	< 0.5	0.38 ^{0.51} _{0.17}	0.42 ^{1.12} _{0.02}
H ₂ CO	< 0.6	0.38 ^{0.42} _{0.13}	0.27 ^{0.52} _{0.03}
CH ₃ OH	< 1.5	0.86 ^{1.16} _{0.06}	1.70 ^{2.38} _{0.21}
CH ₃ CH ₂ OH	NA	0.08 ^{0.11} _{0.03}	0.12 ^{0.40} _{0.02}
NH ₄ ⁺	1.01 (0.3) ^a	1.15 ^{0.72} _{0.3}	1.02 ^{3.12} _{0.23}
HCOOH	< 0.3	NA	0.55 ^{0.91} _{0.13}
OCS	< 0.015	NA	NA
OCN ⁻	< 0.067	NA	NA



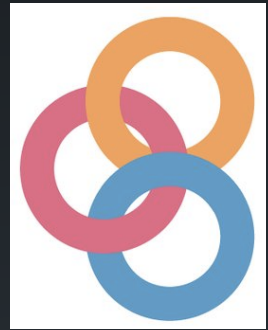
Where to find ENIIGMA?



Read the docs: <https://eniigma-fitting-tool.readthedocs.io/en/latest/>



Github: <https://github.com/willastro/ENIIGMA-fitting-tool>



Binder: https://mybinder.org/v2/gh/willastro/ifw_miri_gto_pstars/HEAD

Take-home messages

- **ENIIGMA provides global fit of the IR broad-range of protostars;**
- **A variety of experimental data is crucial for ENIIGMA (See talk about LIDA: Will Rocha@14:00 - IAUS371)**
- **ENIIGMA fits simultaneously the bands at 3 and 6 micron of Elias 29 spectrum;**
- **Ethanol is detected towards Elias 29**
- **ENIIGMA is an open-source tool. Suggestions and comments are welcome!**

Acknowledgements

