Just the tip of the iceberg: Our mid- and far-infrared ice legacy

Dr. Melissa K. McClure

ASSISTANT PROFESSOR & VIDI LAUREATE
LEIDEN UNIVERSITY

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LEIDEN, NL

Sterrewacht Leiden

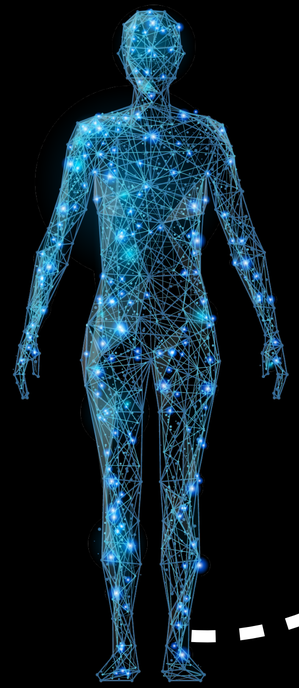
Volatile elements on Earth and other planets originated as ices.

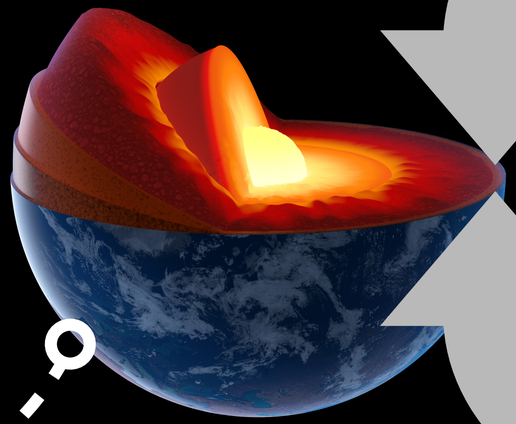
H (63%)

O (25.5%)

C (9.5%)

N (1.4%)



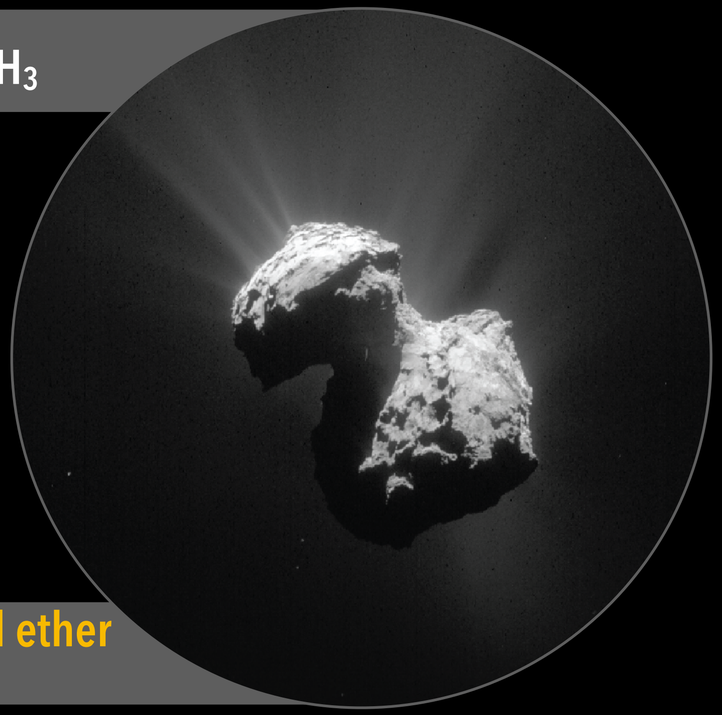


H_2O CO CO_2 CH_4 NH_3

(Simple ices)

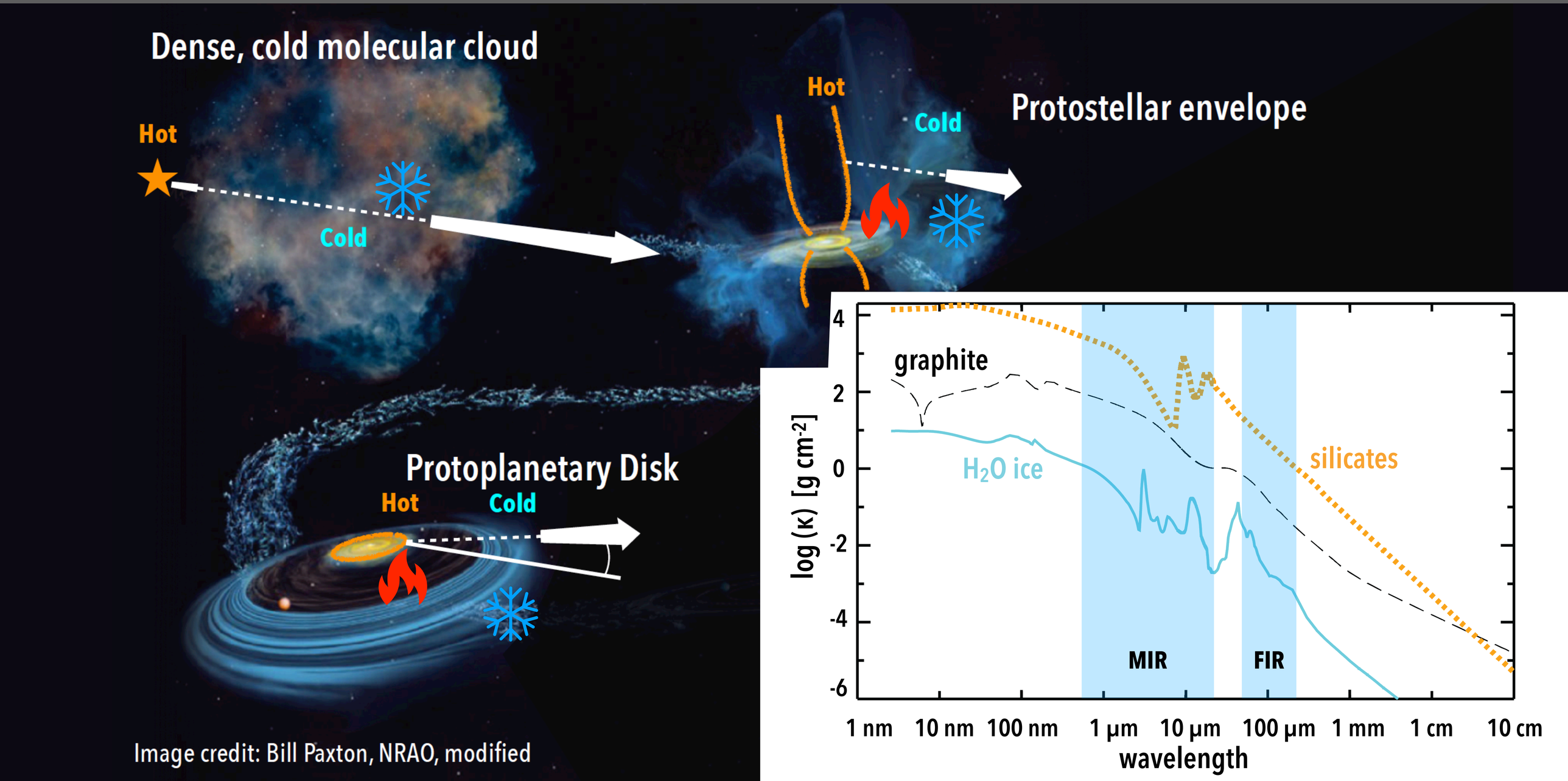
(Complex Organic Molecules)

methanol dimethyl ether acetaldehyde

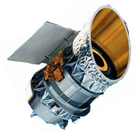


Martin & Livio (2021), Altwegg et al. (2016, 2018), Biver et al. (2015) Image credit: Rosetta Mission, ESA

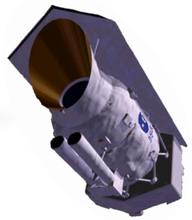
Planetary ices (partially?) inherited from molecular cloud ices



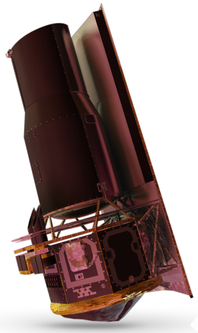
Icy legacy of space-based InfraRed telescopes



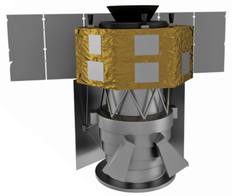
1983
IRAS



1995
ISO

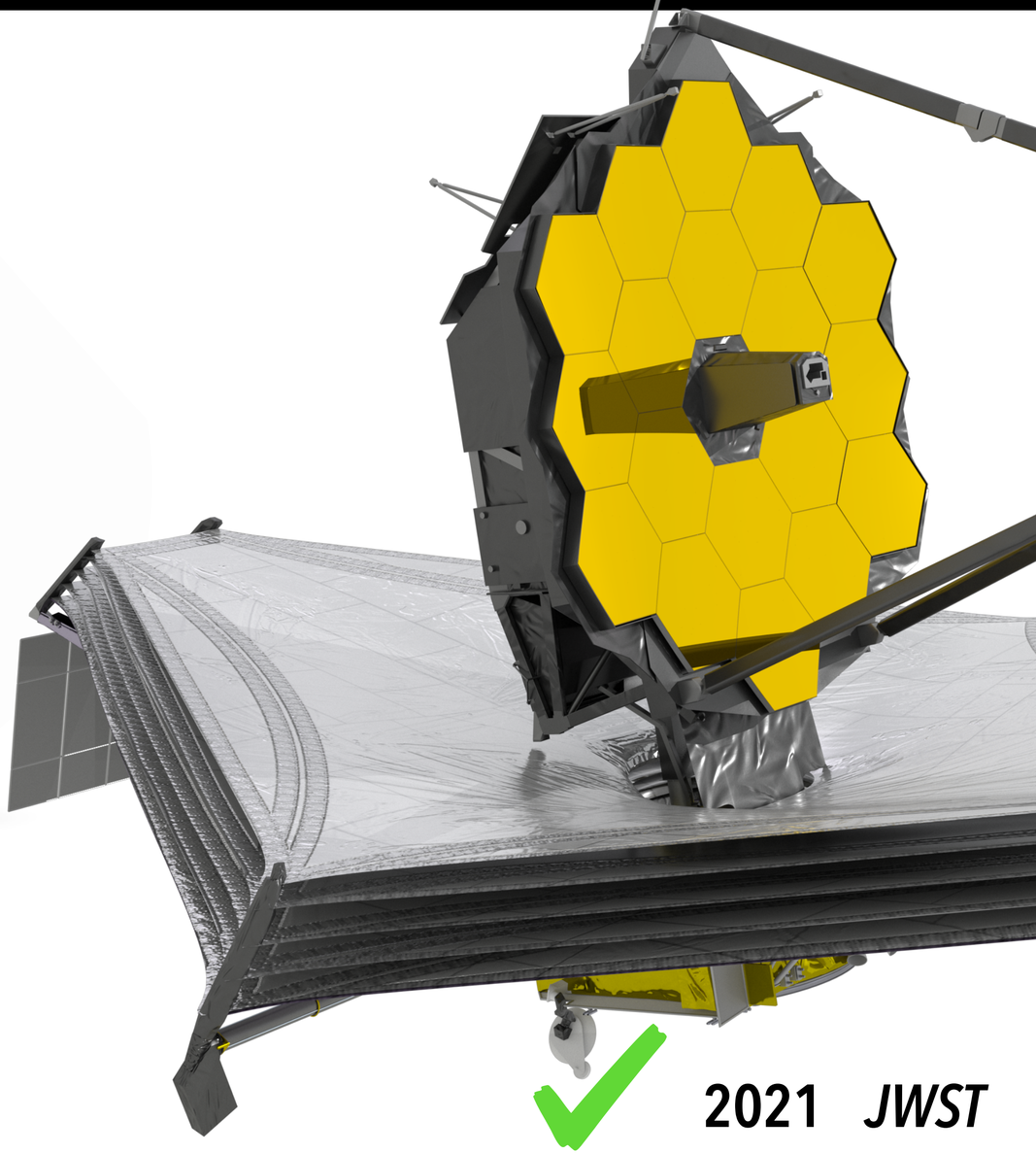


2003
Spitzer



2006
AKARI

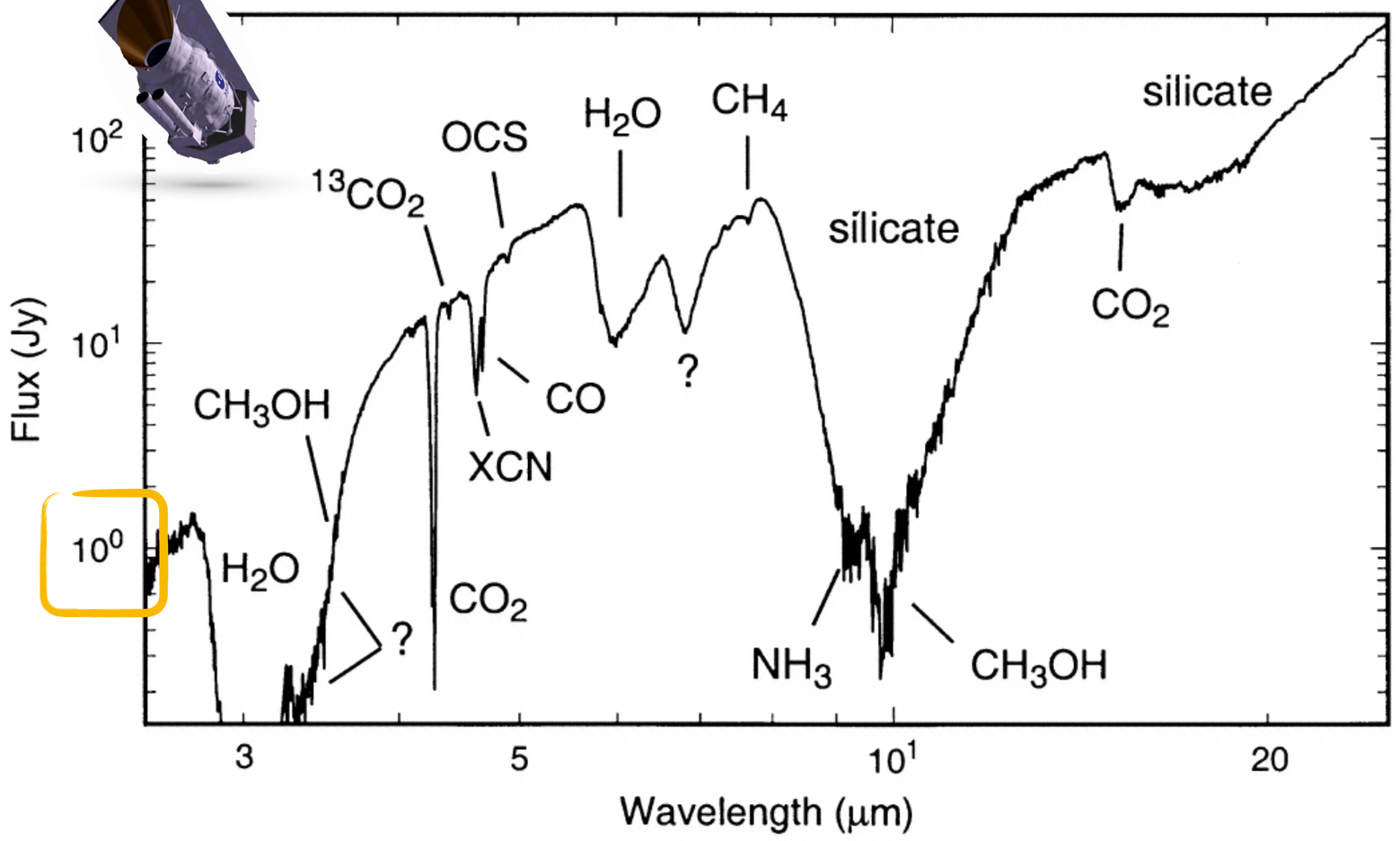
2009
Herschel



2021 *JWST*

ISO SWS/LWS: Diversity of ice species seen towards select, bright targets.

Observations: Simple ices + strong profiles

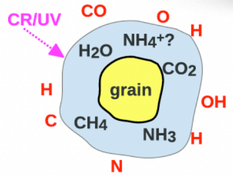


Chemistry theory

1. H_2O-rich layer:

T > 20 K,

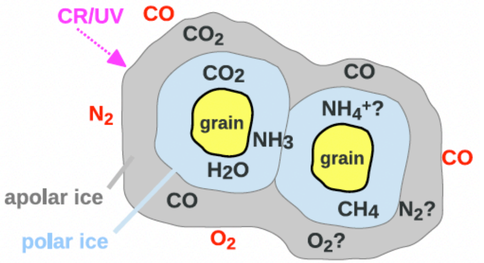
n ≥ 10^3 cm^{-3}



2. CO-rich layer:

T < 20 K,

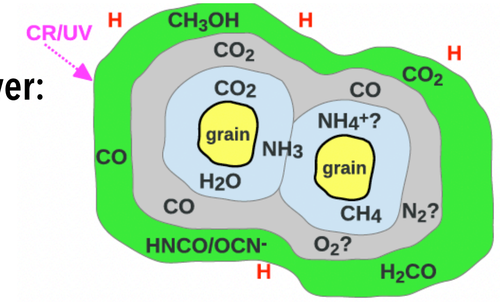
n ≥ 10^4 cm^{-3}



3. Methanol-rich layer:

T < 20 K,

n ≥ 10^5 cm^{-3}



(Left) Gibb et al. 2000, (Right) Boogert, Gerakines, & Whittet 2015, ARA&A review

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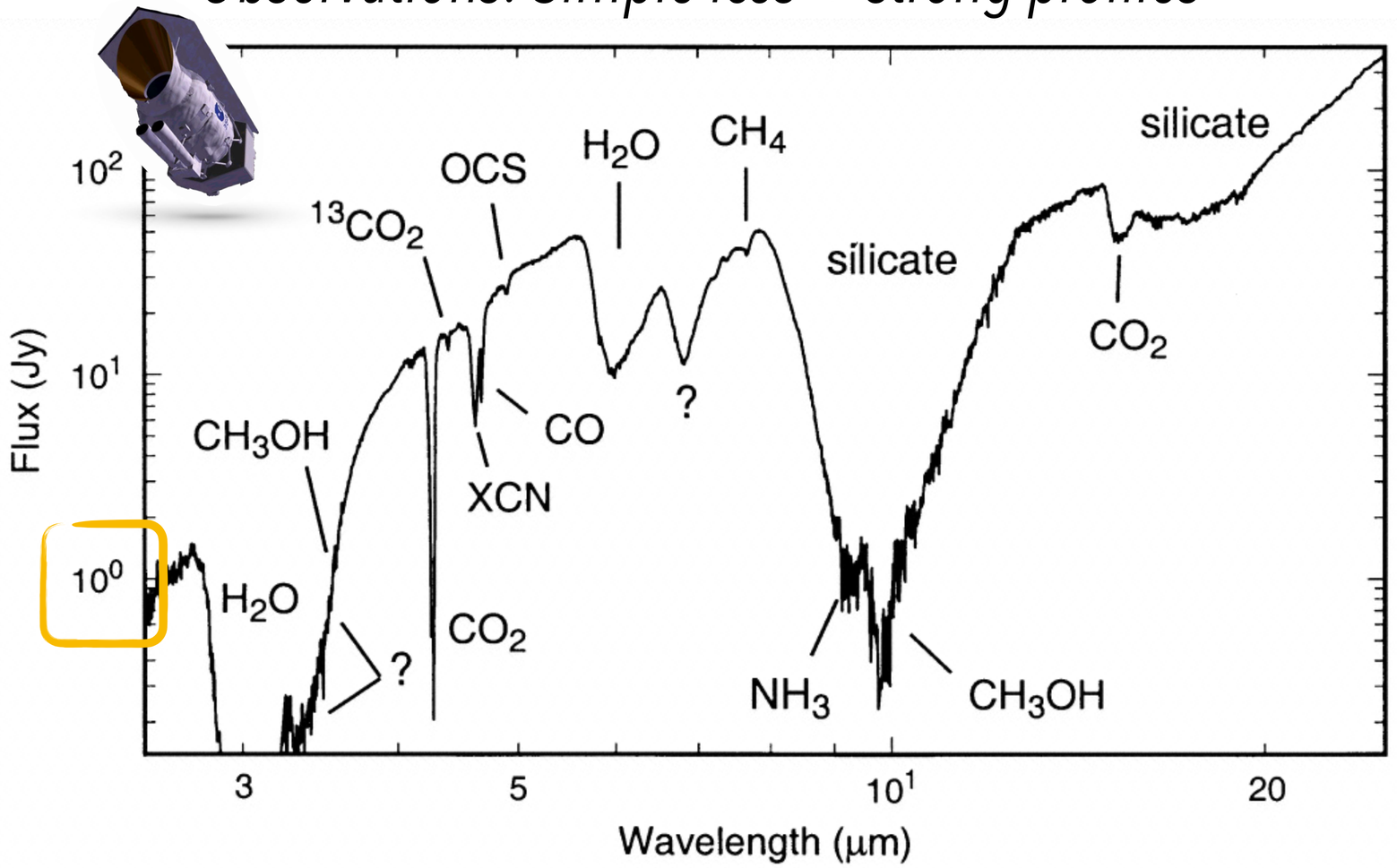
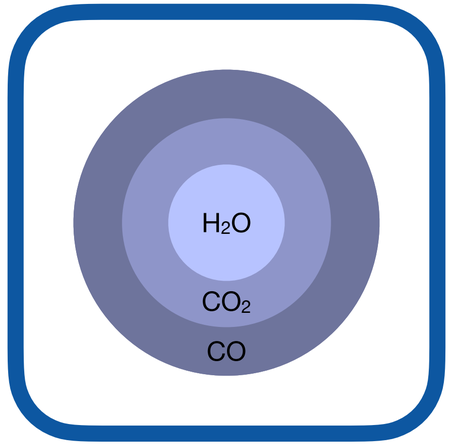


Astronomer approximation

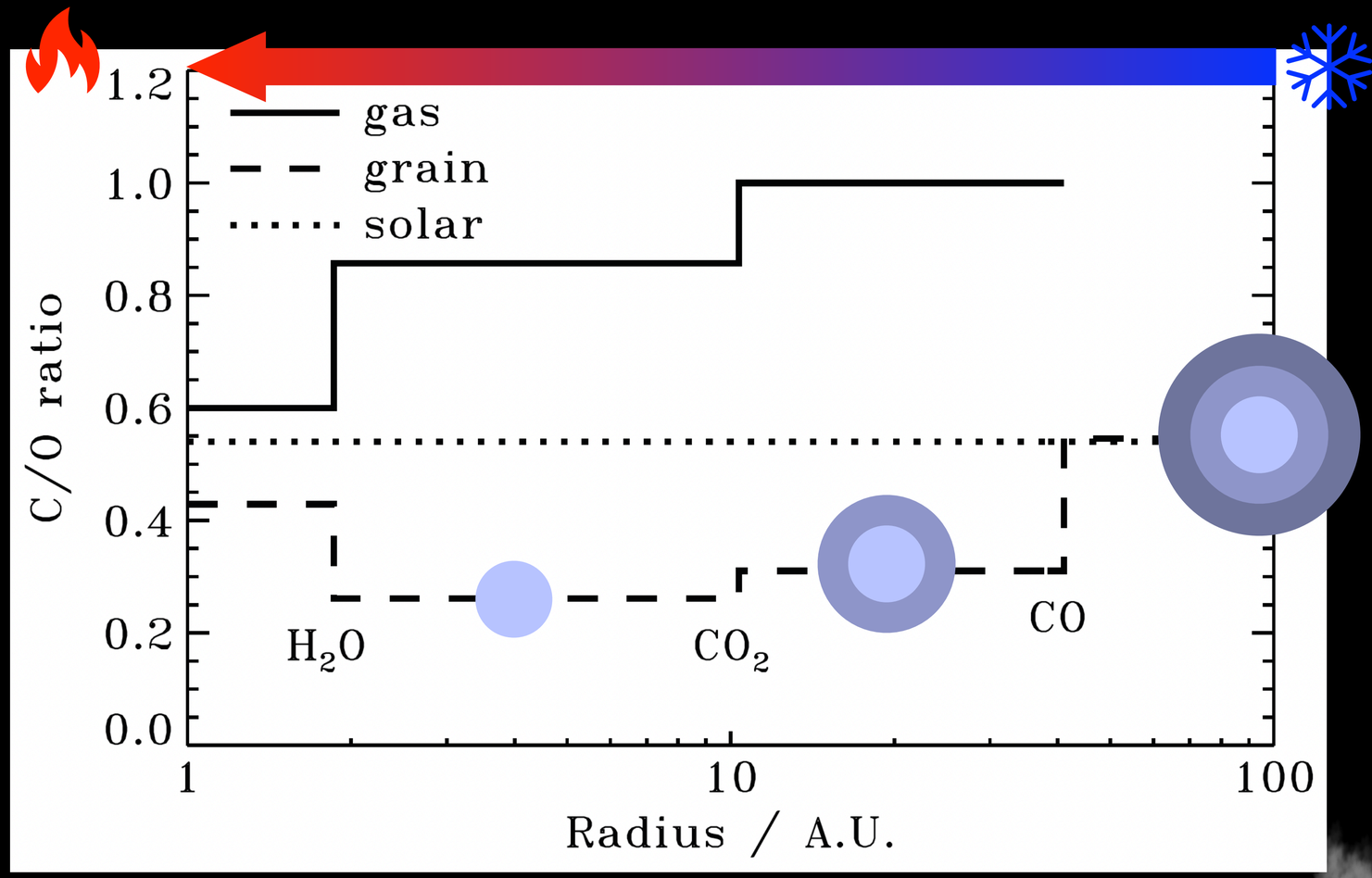
Pure ice layers.



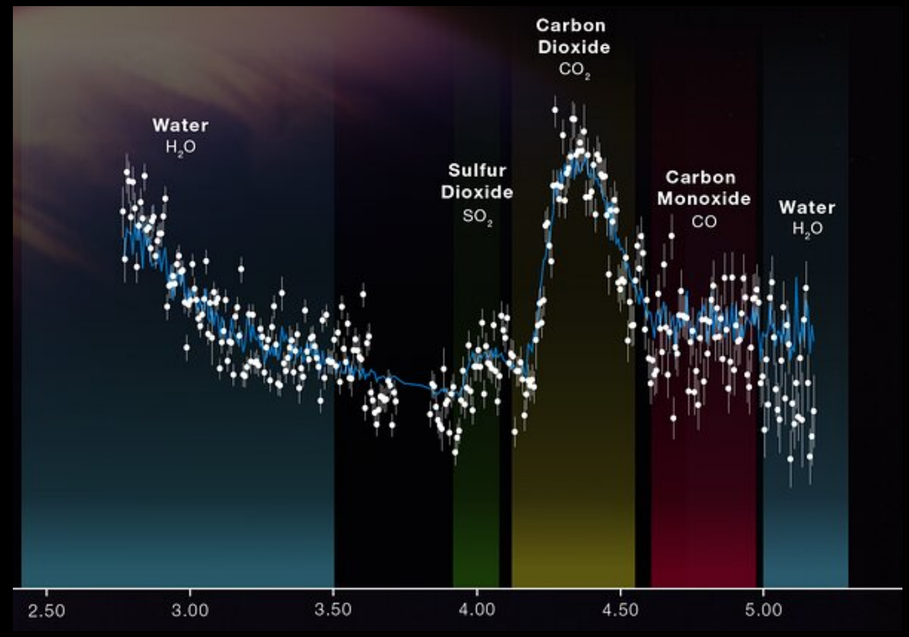
Last on, first off (with increasing T).

(Left) Gibb et al. 2000, (Right) Boogert, Gerakines, & Whittet 2015, ARA&A review

Ices determine initial exoplanet atmospheric compositions.



WASP-39 atmosphere: C/O ratio

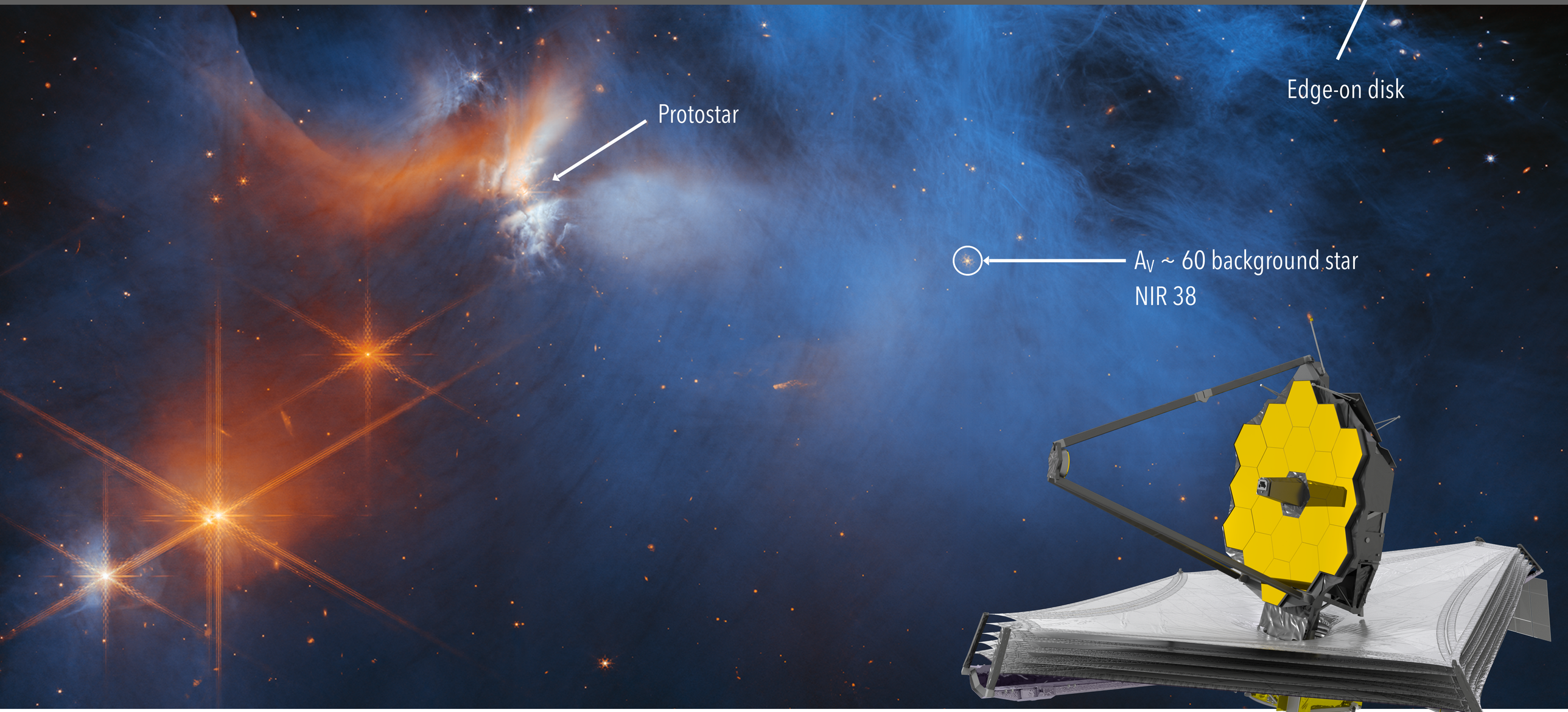


Wavelength [microns]

Oberg, Murray-Clay, & Bergin (2011), NASA

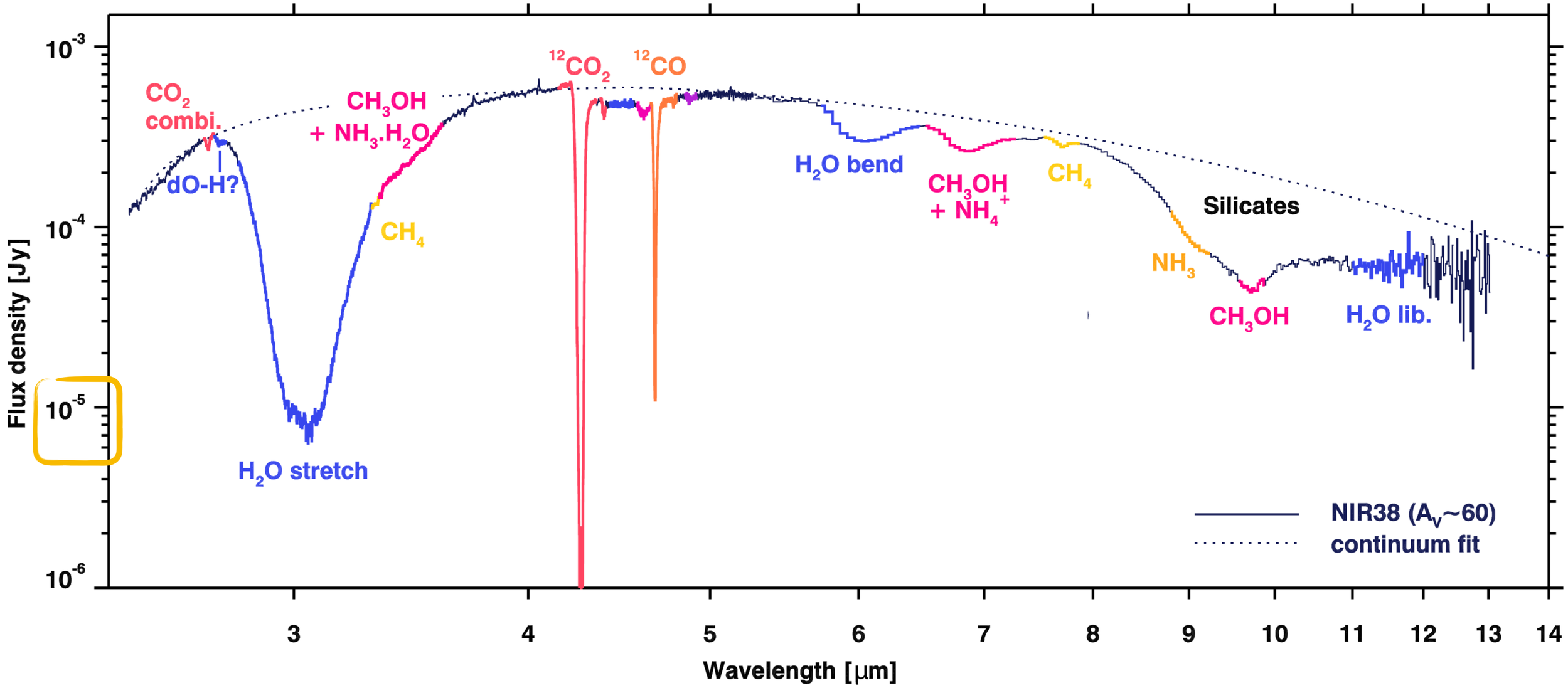
JWST ERS program "Ice Age"

PI. McClure, co-PIs Boogert, Linnartz†



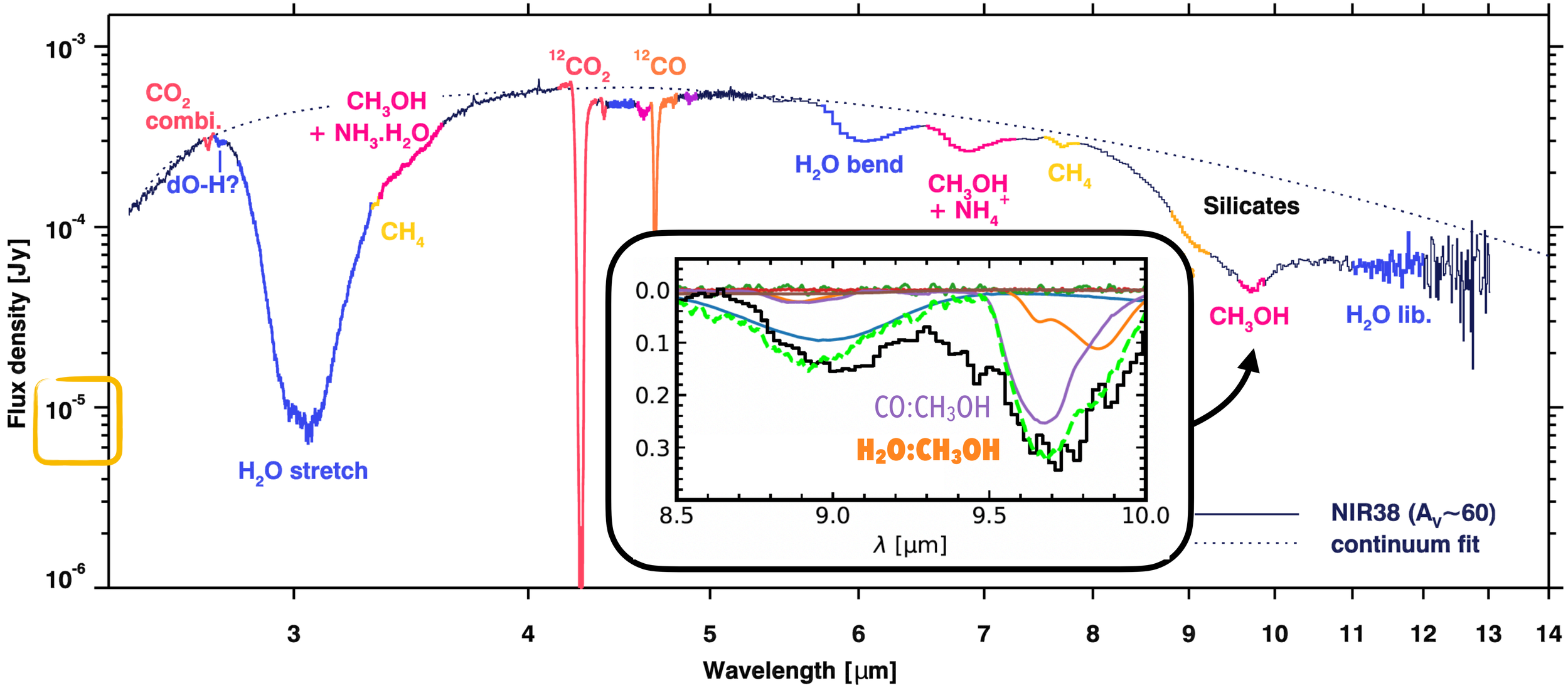
Credit: NASA, ESA, CSA, M. Zamani (ESA/Webb), **Fengwu Sun** (Steward Observatory), **Zak Smith** (The Open University)

JWST gets >ISO resolution, even towards extremely faint targets.



McClure + Ice Age team (2023), Nature Astronomy

Now see that ices are *highly* mixed with H_2O matrix, scrambling layers…



McClure + Ice Age team (2023), Nature Astronomy, Qasim et al. (2018, 2020), Lamberts et al. (2017, 2022), Pontoppidan et al. (2003)

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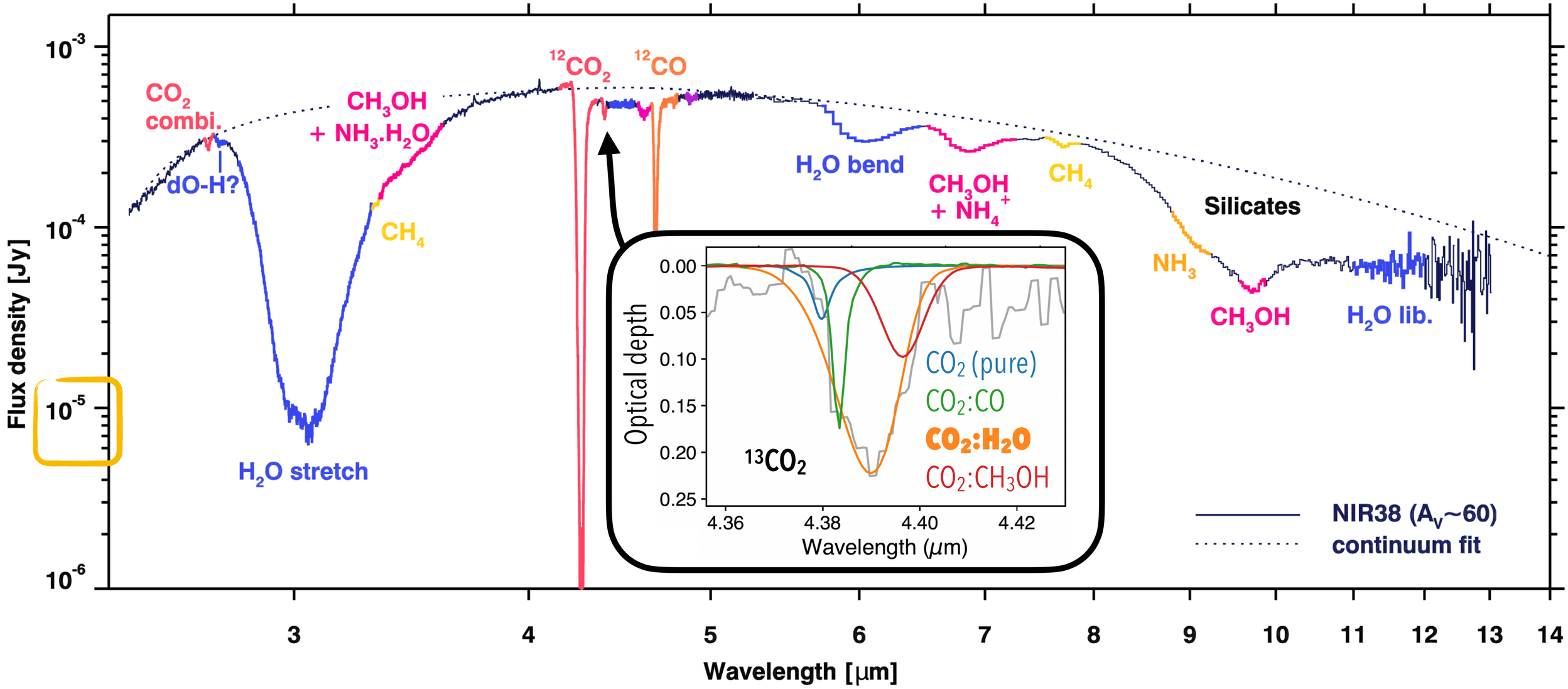

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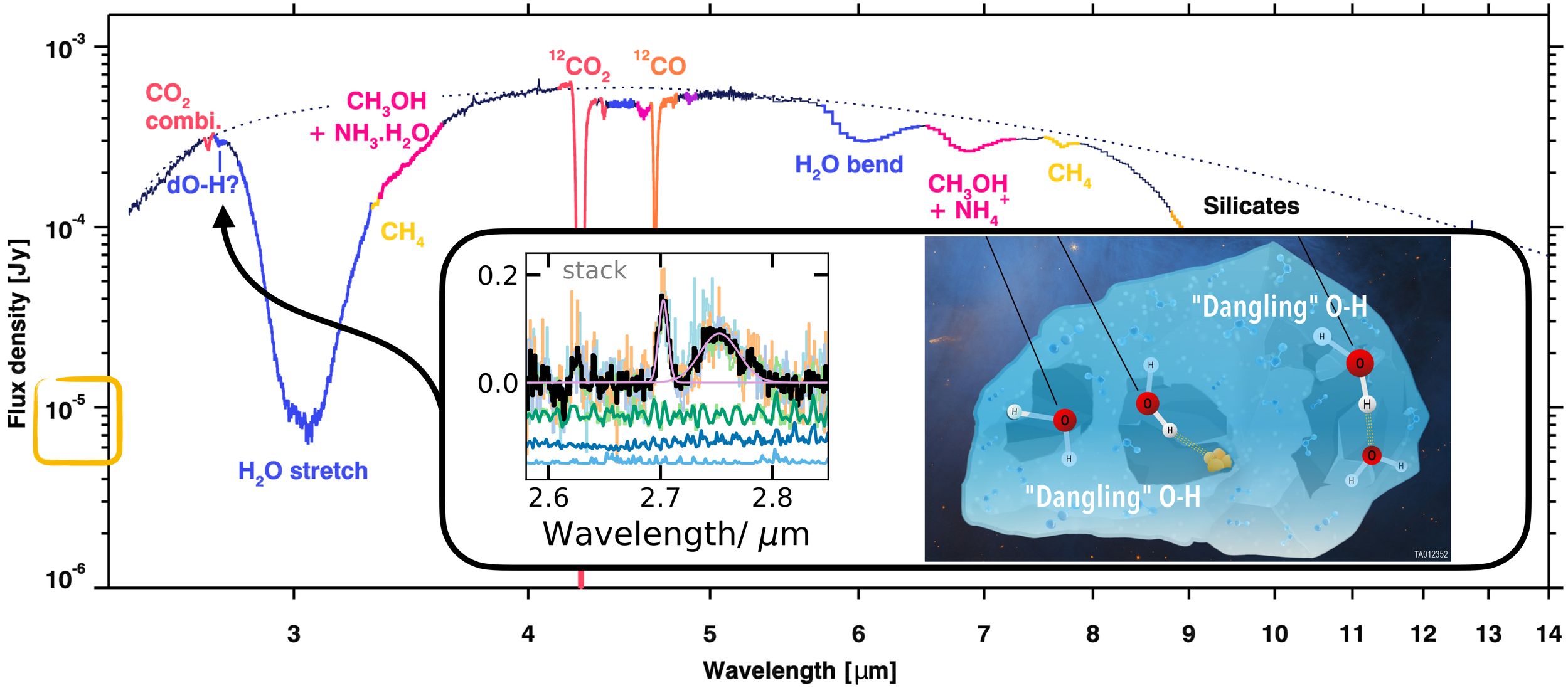
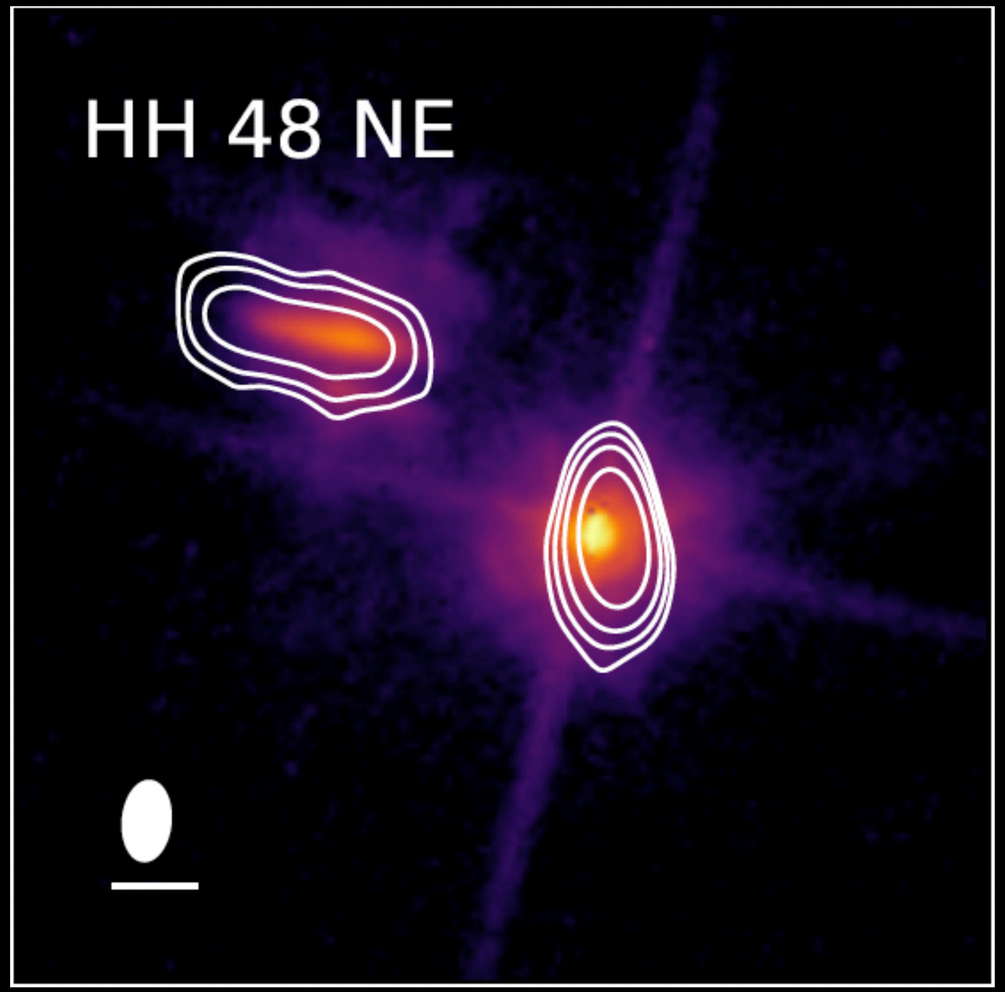


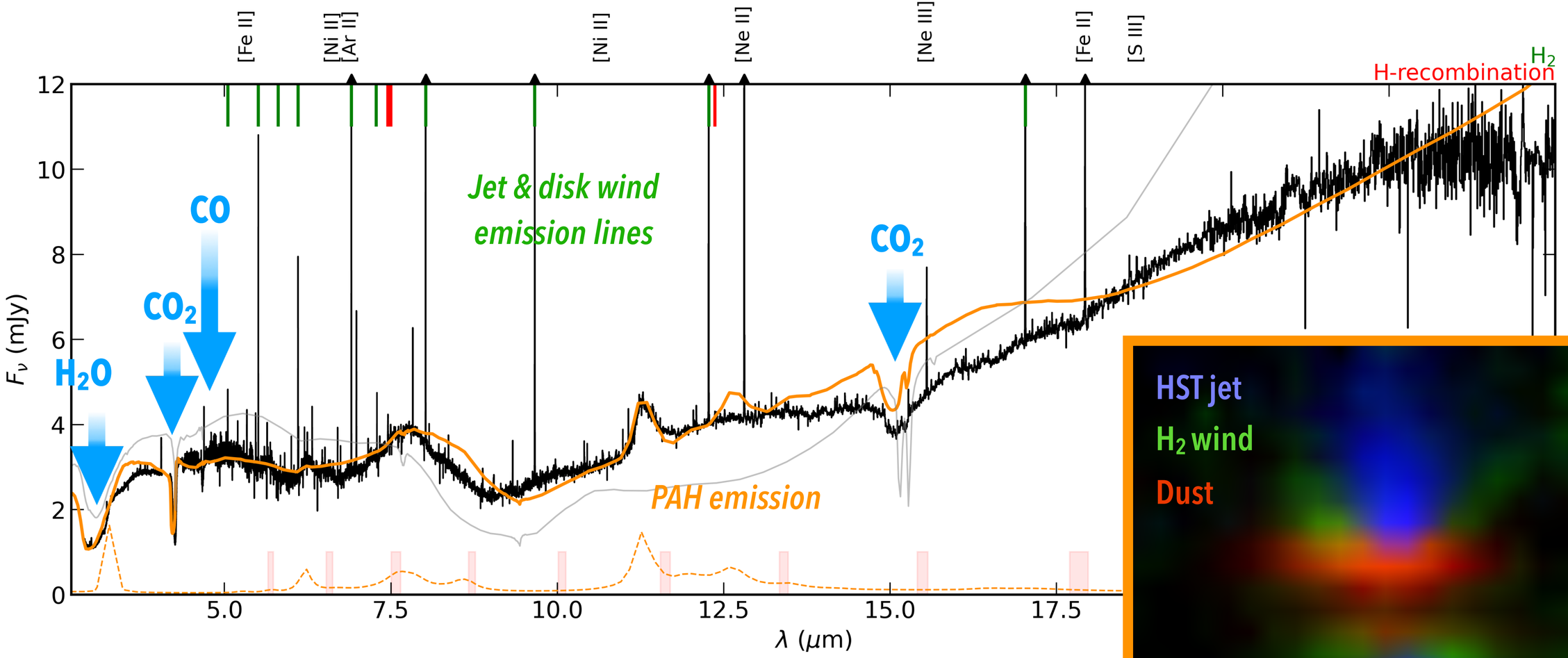
McClure + Ice Age team (2023), Nature Astronomy, **Noble + Ice Age team (2024), Nature Astronomy**

So what does an inheritance of mixed cloud ices mean for disks and exoplanets?



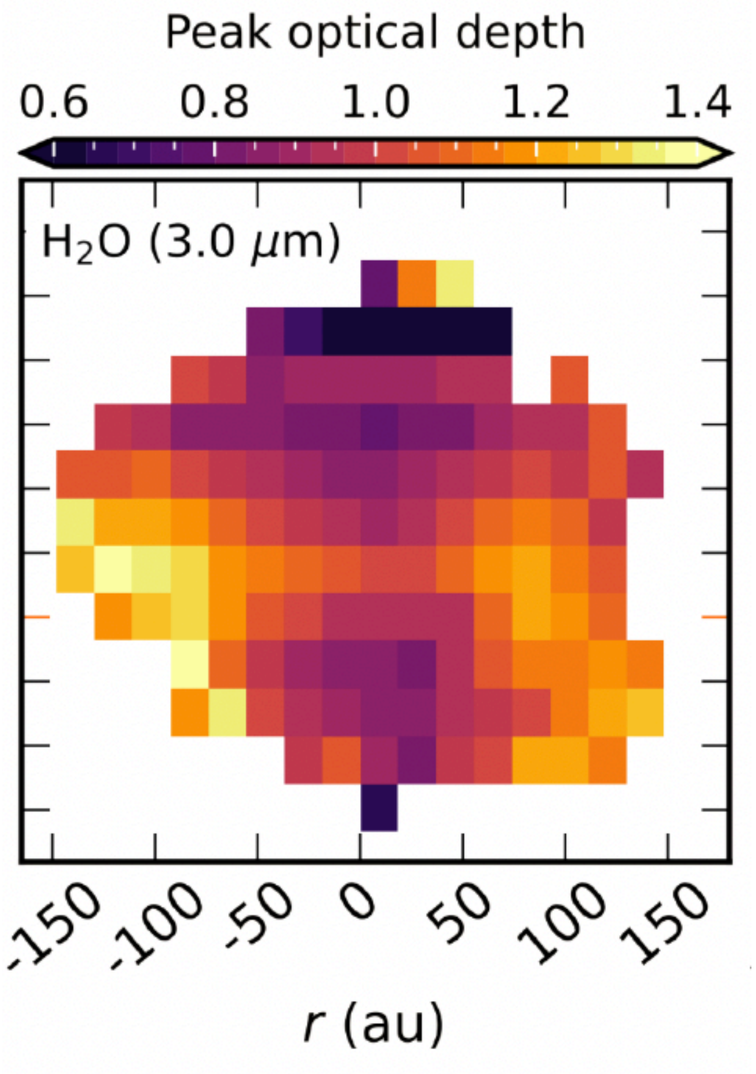
MIRI image of Tau 042021 disk, **Duchene** et al. (2023), ALMA/HST image of HH48 NE, Villenave et al. (2020)

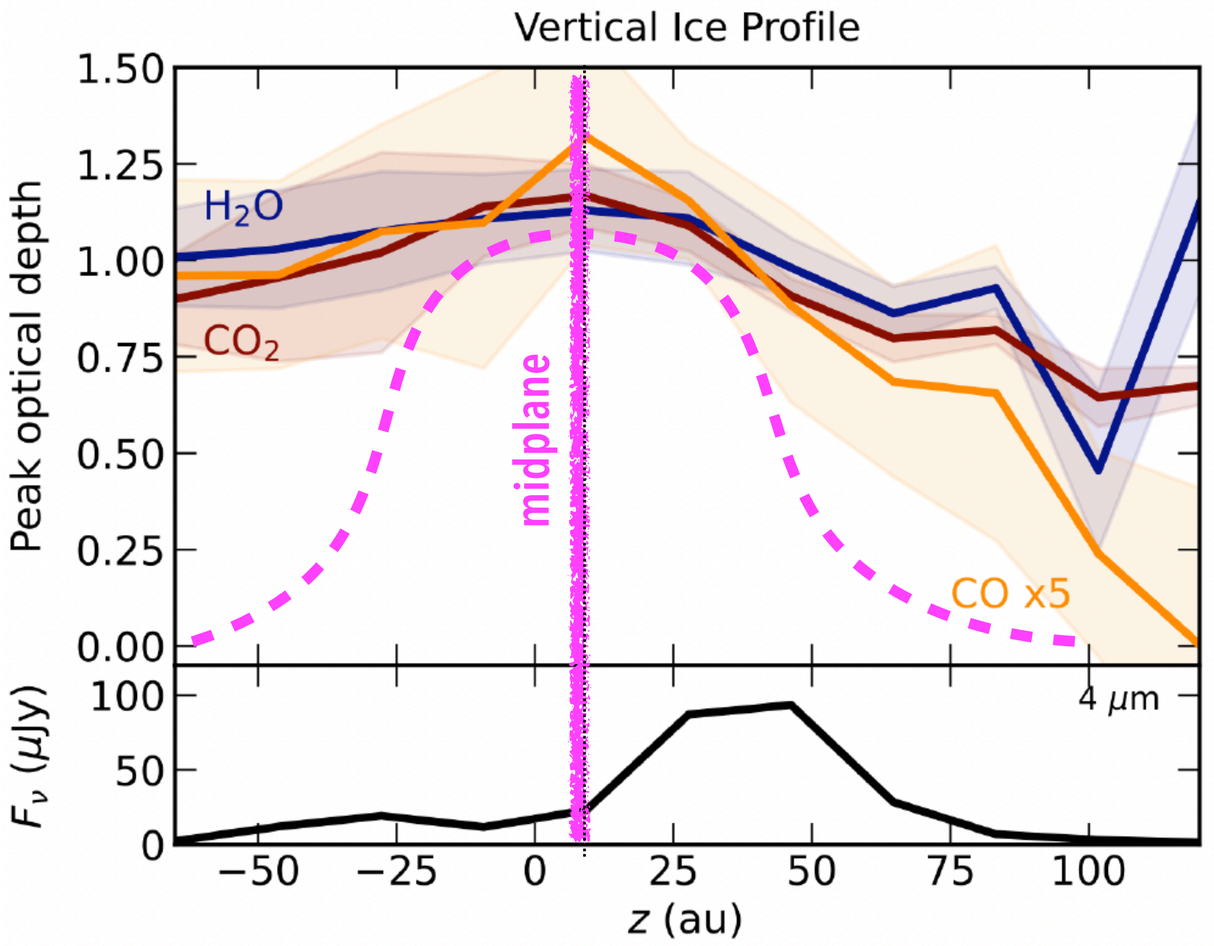
JWST Ice Age: NIRSpec+MIRI spatially resolve ice inventory in protoplanetary disks!



MIRI + model: Sturm et al. (2024); NIRSpec: Sturm et al. (2023d)

Ice maps show no radial or vertical snowlines, even for CO ice...

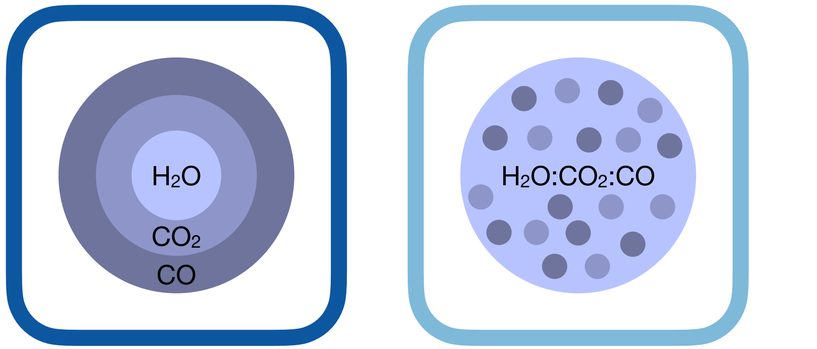


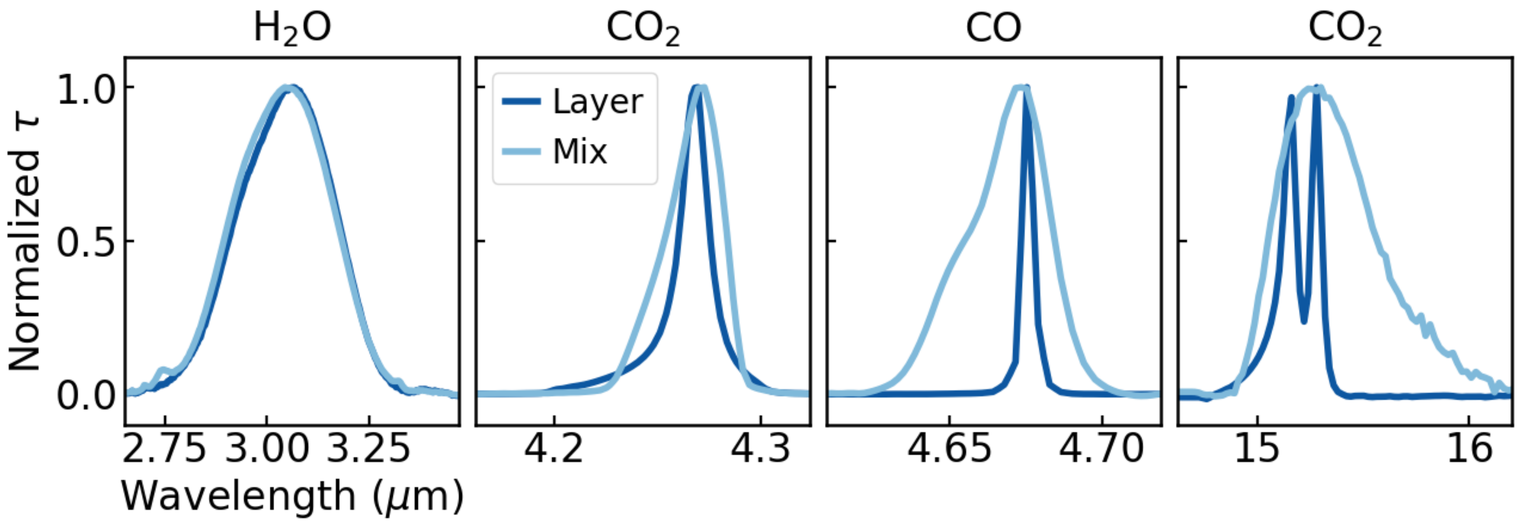


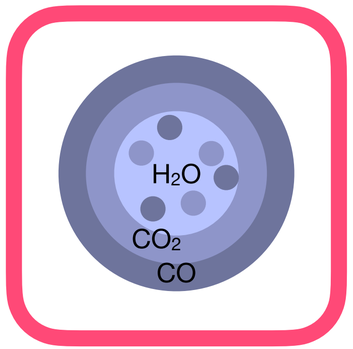
CO ice *trapping* + turbulent lofting?

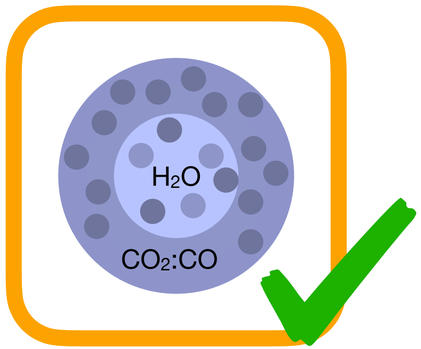
Sturm et al. (2023d), Lab studies: Lauk et al. (2015), Simon et al. (2019)

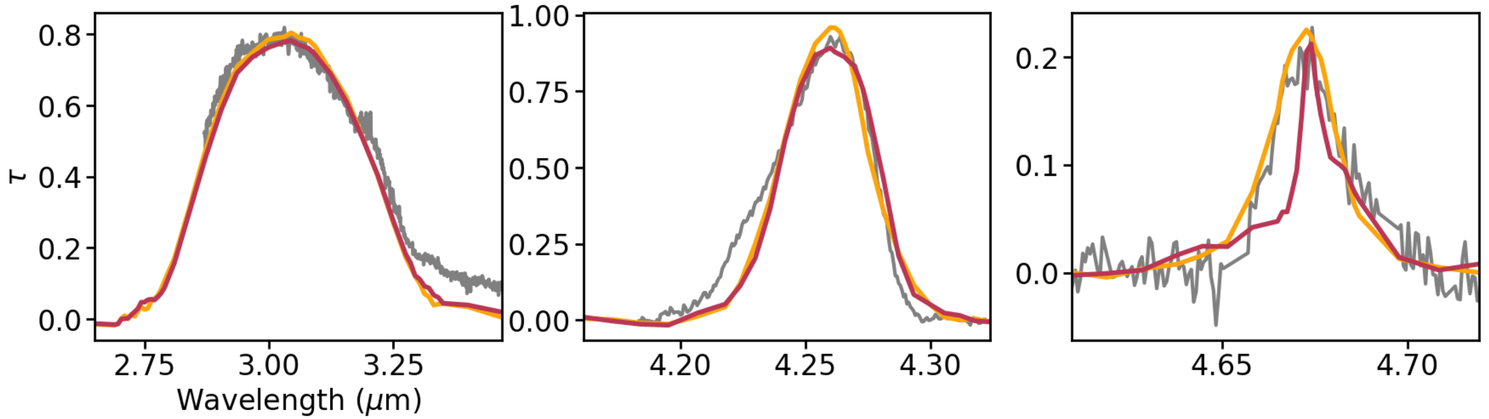
Ice profiles show CO ice doesn't form pure layer; diffuses into CO_2 ice matrix!





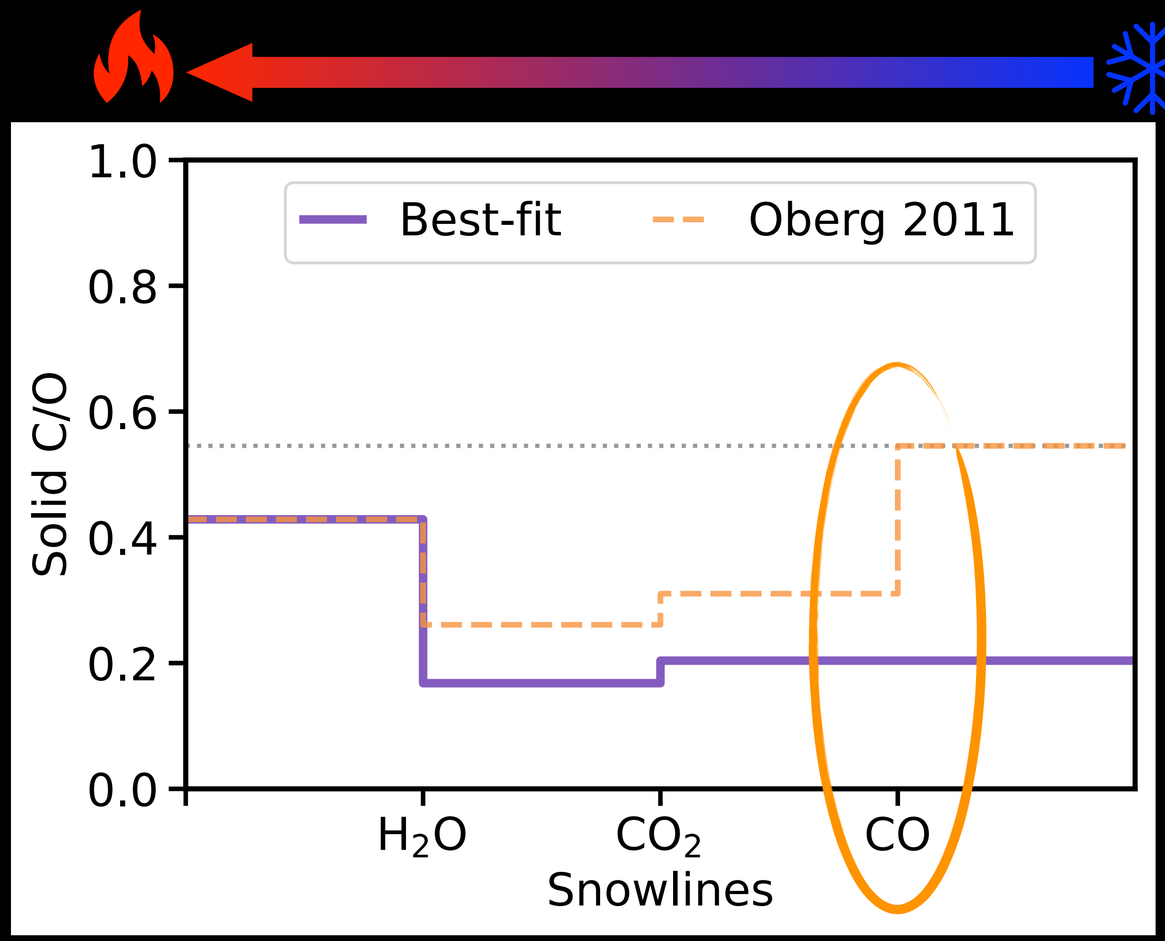


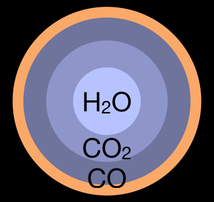


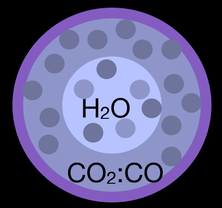


Bergner et al. (2024)

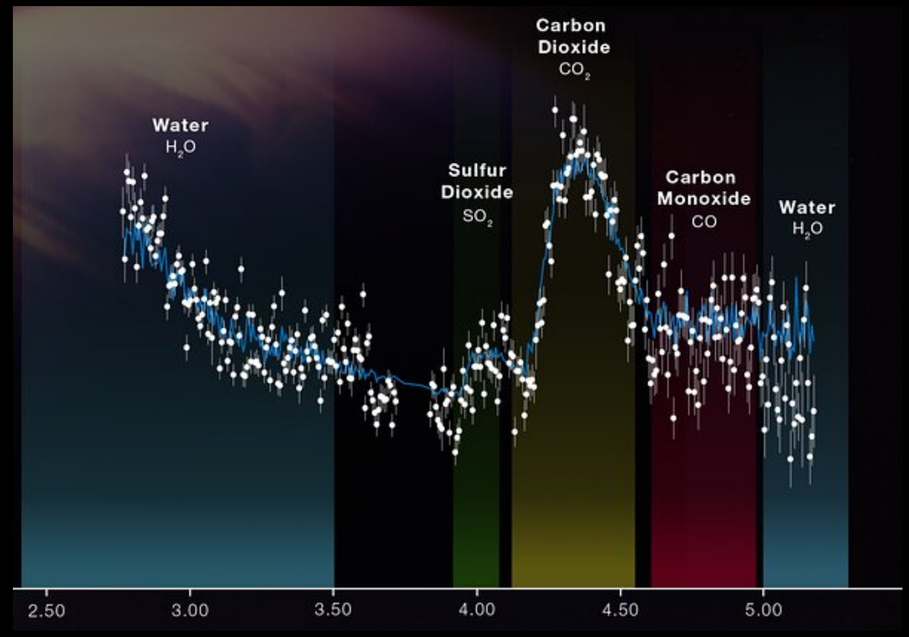
Mixed ice revision to exoplanet atmosphere formation tracer. Sufficient?



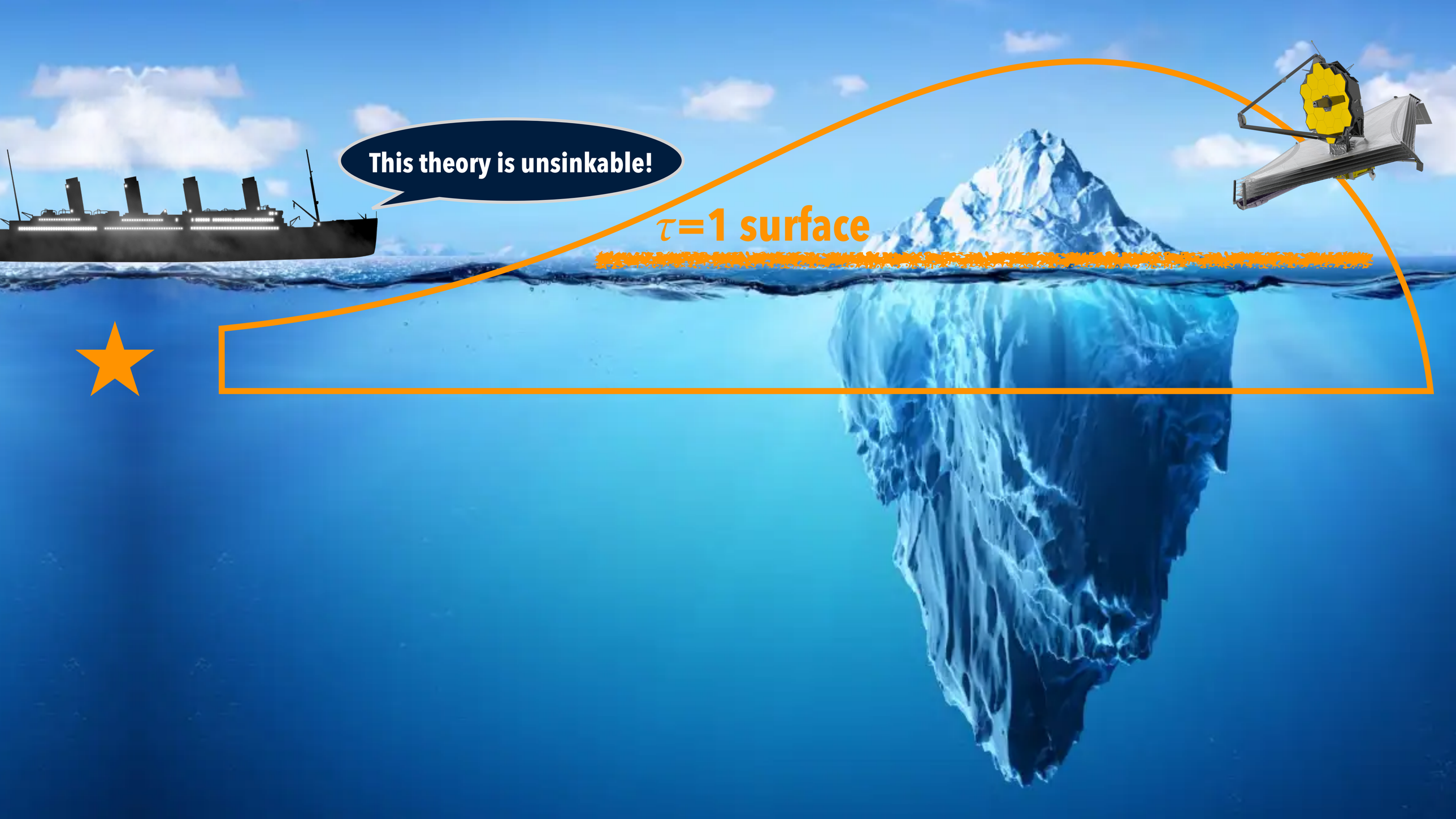


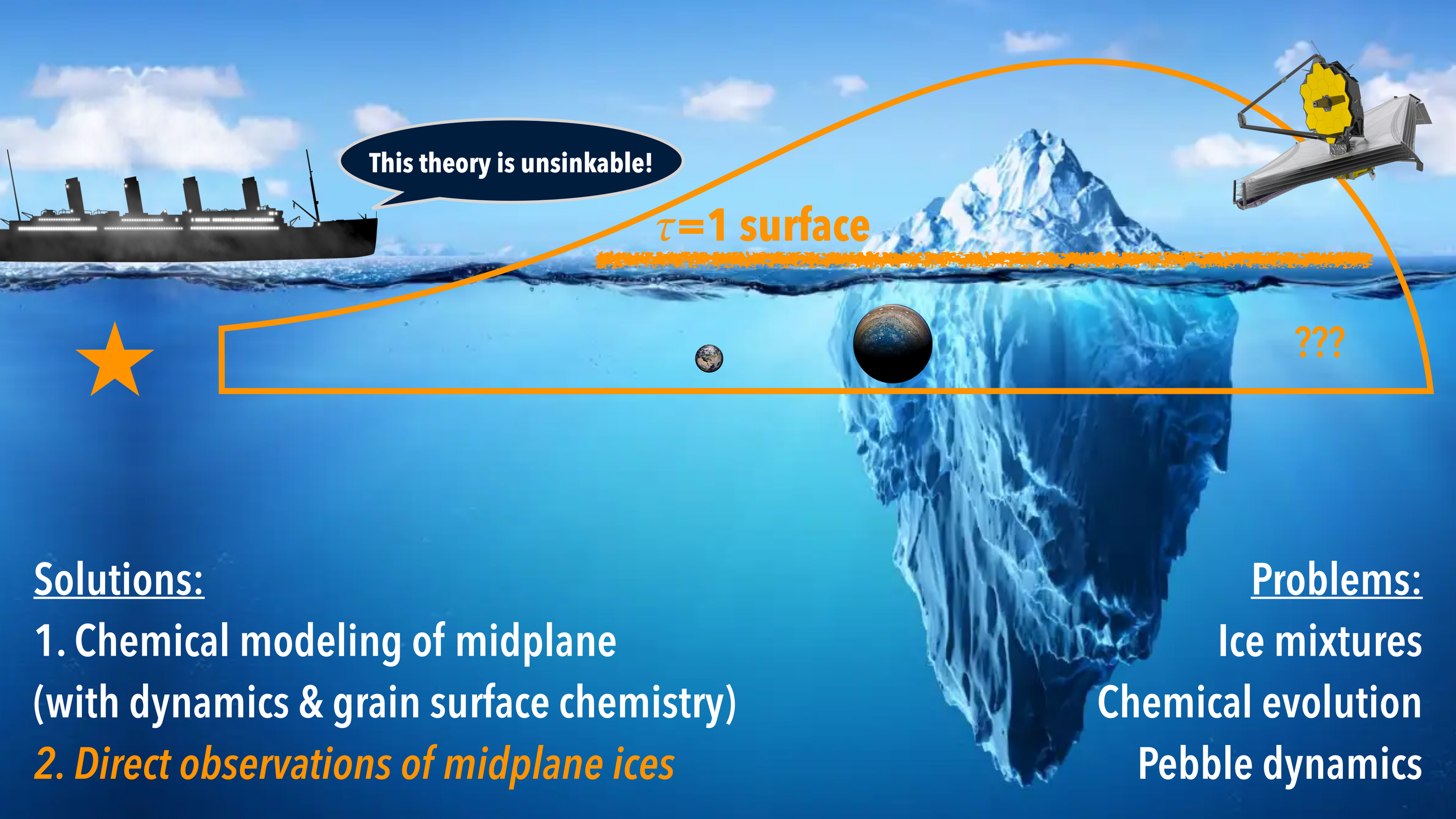


WASP-39 atmosphere: C/O ratio



Oberg, Murray-Clay, & Bergin (2011), NASA


This theory is unsinkable!
τ=1 surface



Solutions:

1. Chemical modeling of midplane (with dynamics & grain surface chemistry)

2. Direct observations of midplane ices

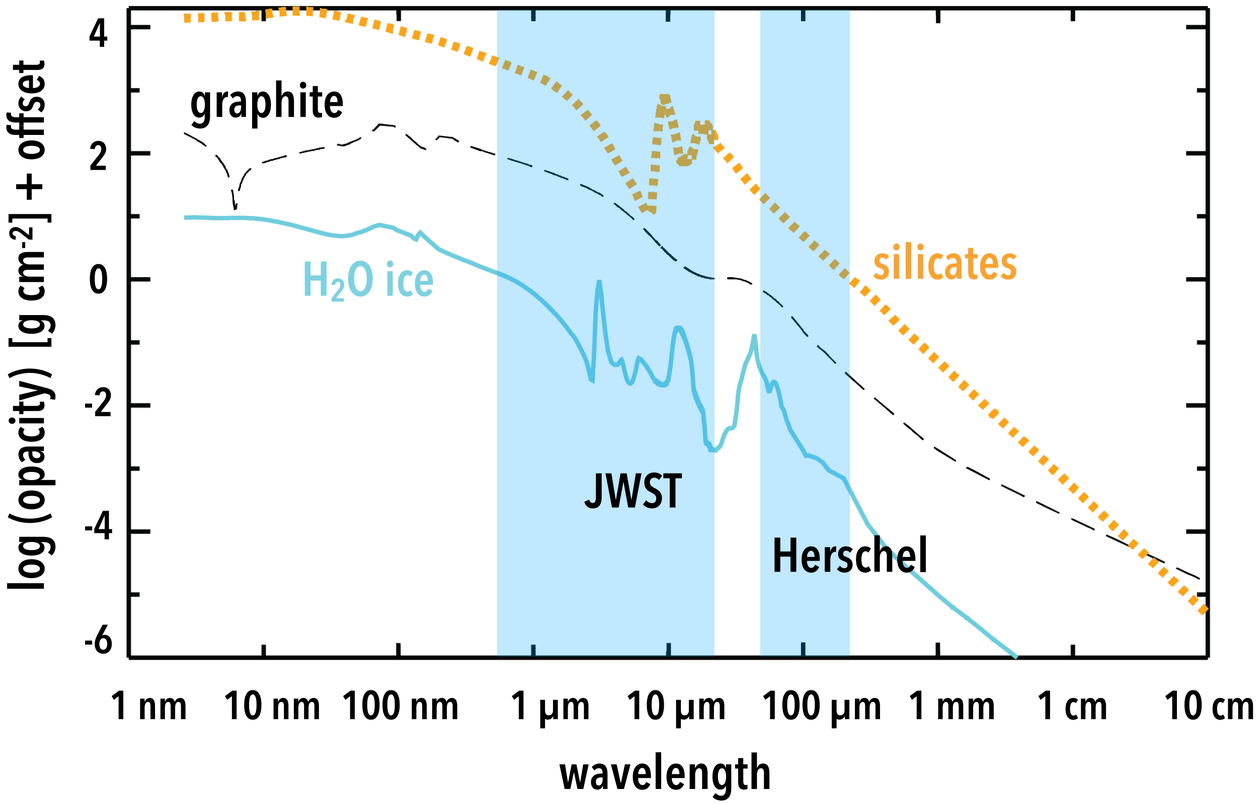
Problems:

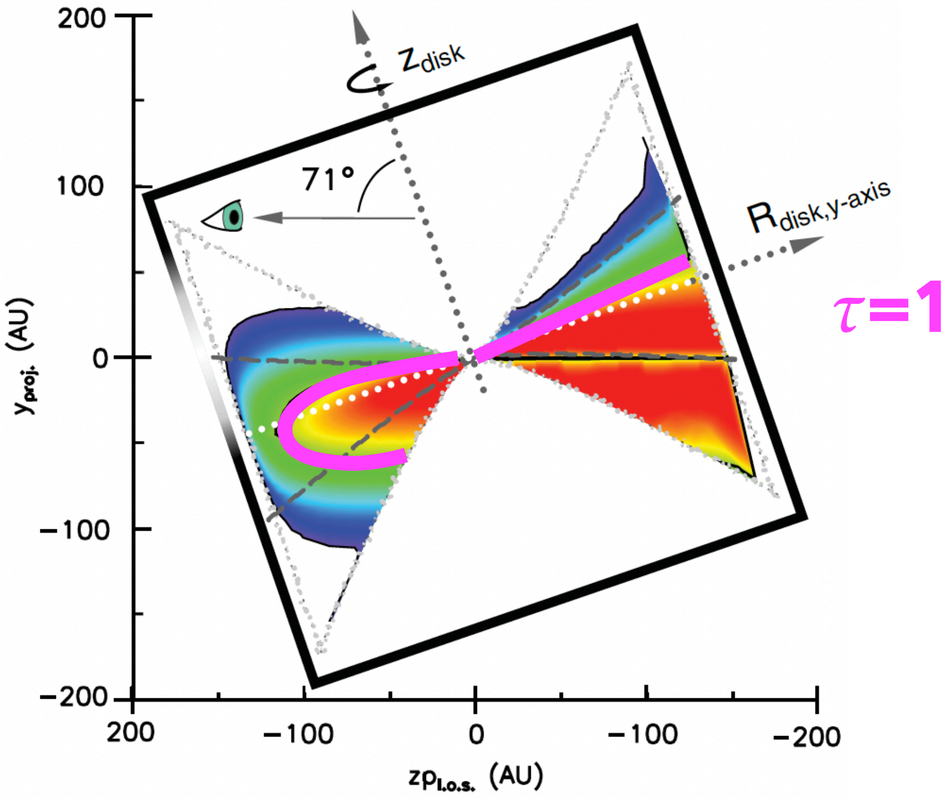
Ice mixtures

Chemical evolution

Pebble dynamics

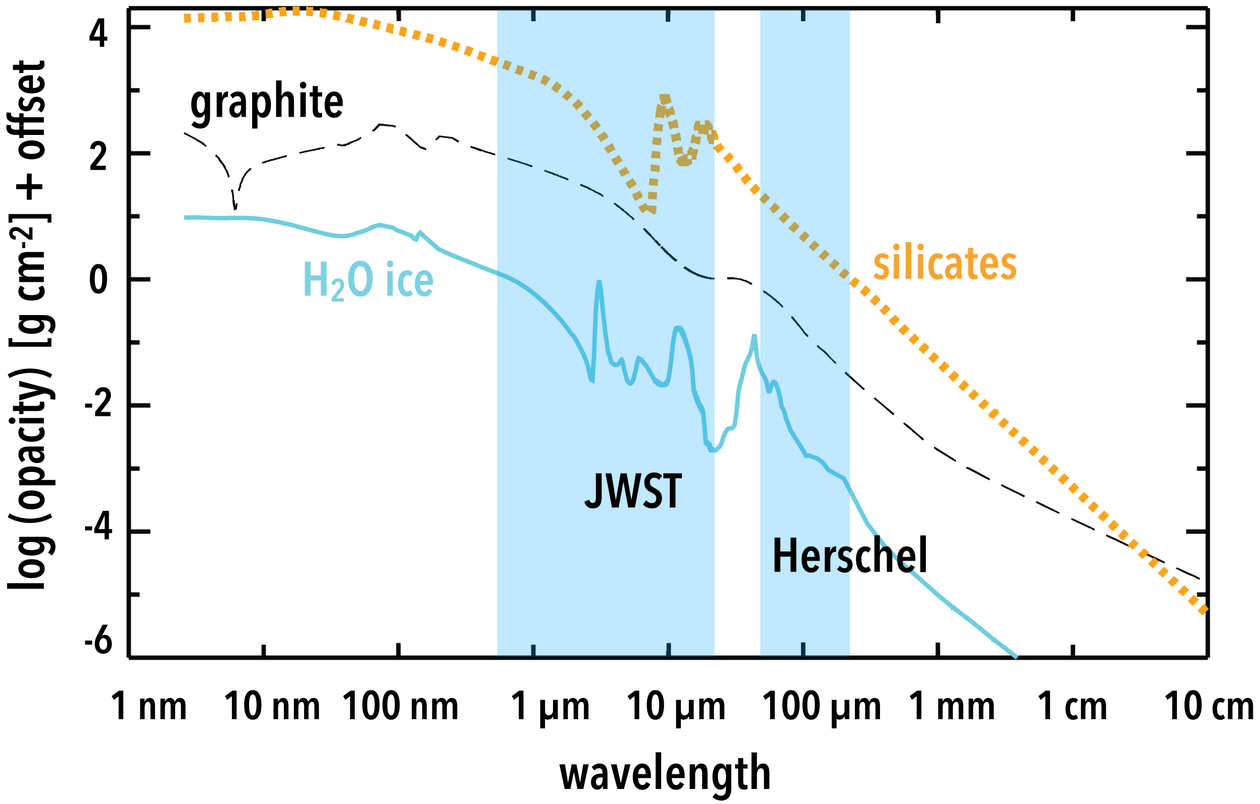
Far-infrared *thermal emission* reveals midplane ice composition!

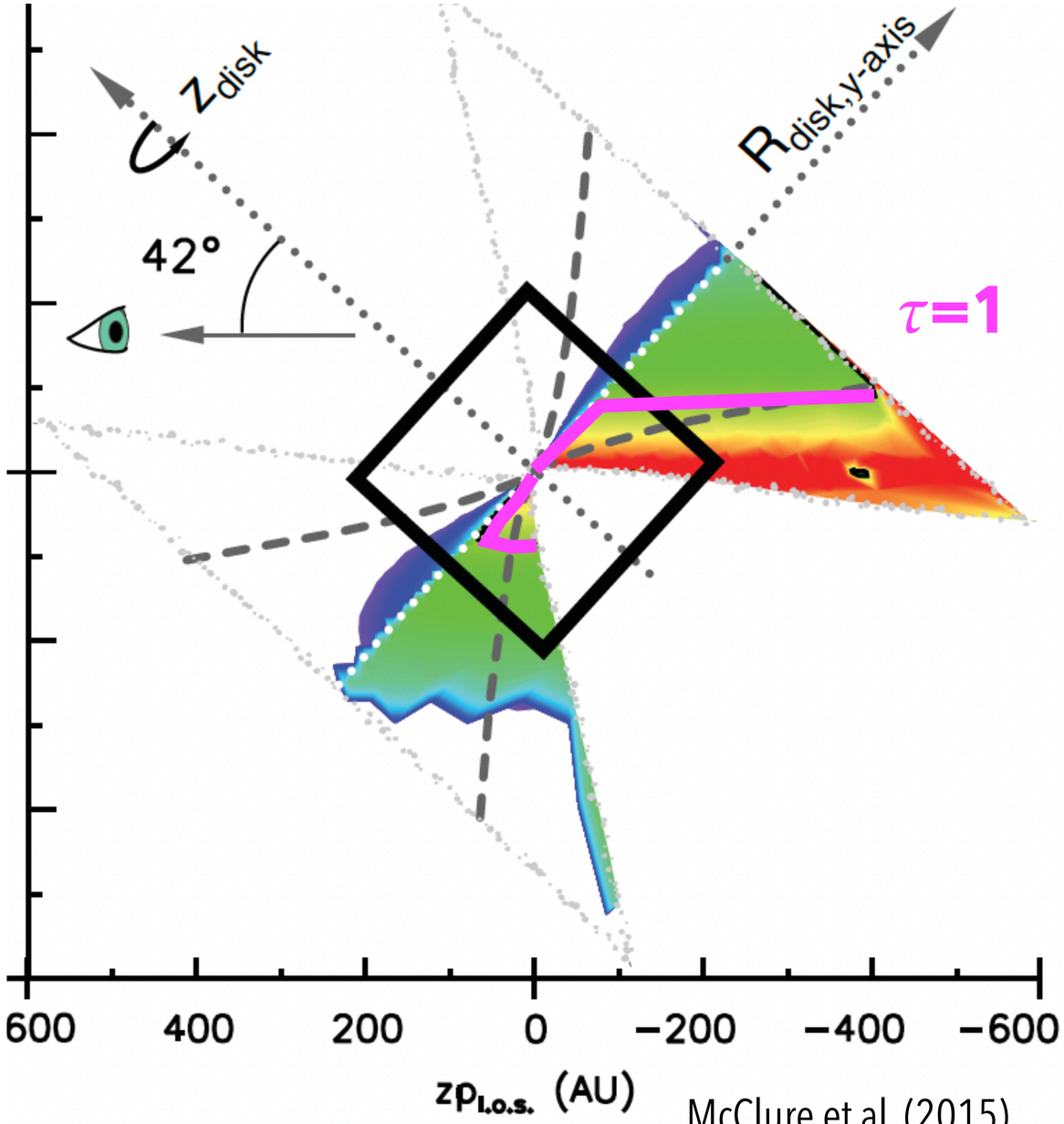




McClure et al. (2015)

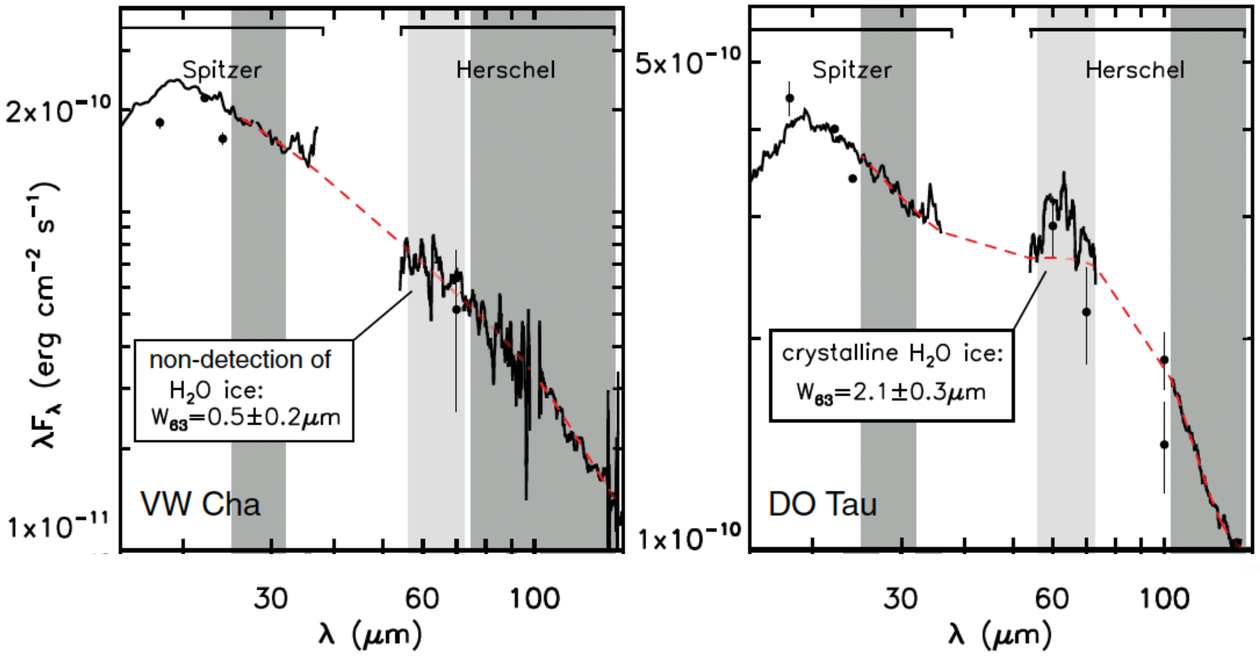
Far-infrared *thermal emission* reveals midplane ice composition!

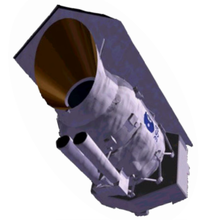




McClure et al. (2015)

Herschel + ISO: Different midplane "ice/rock" ratios for MK/AeBe disks.





Herschel: McClure et al. (2012, 2015)

Only 6% of 50 young disk sample show ice.

H_2O ice/silicate rock ~ 0.5

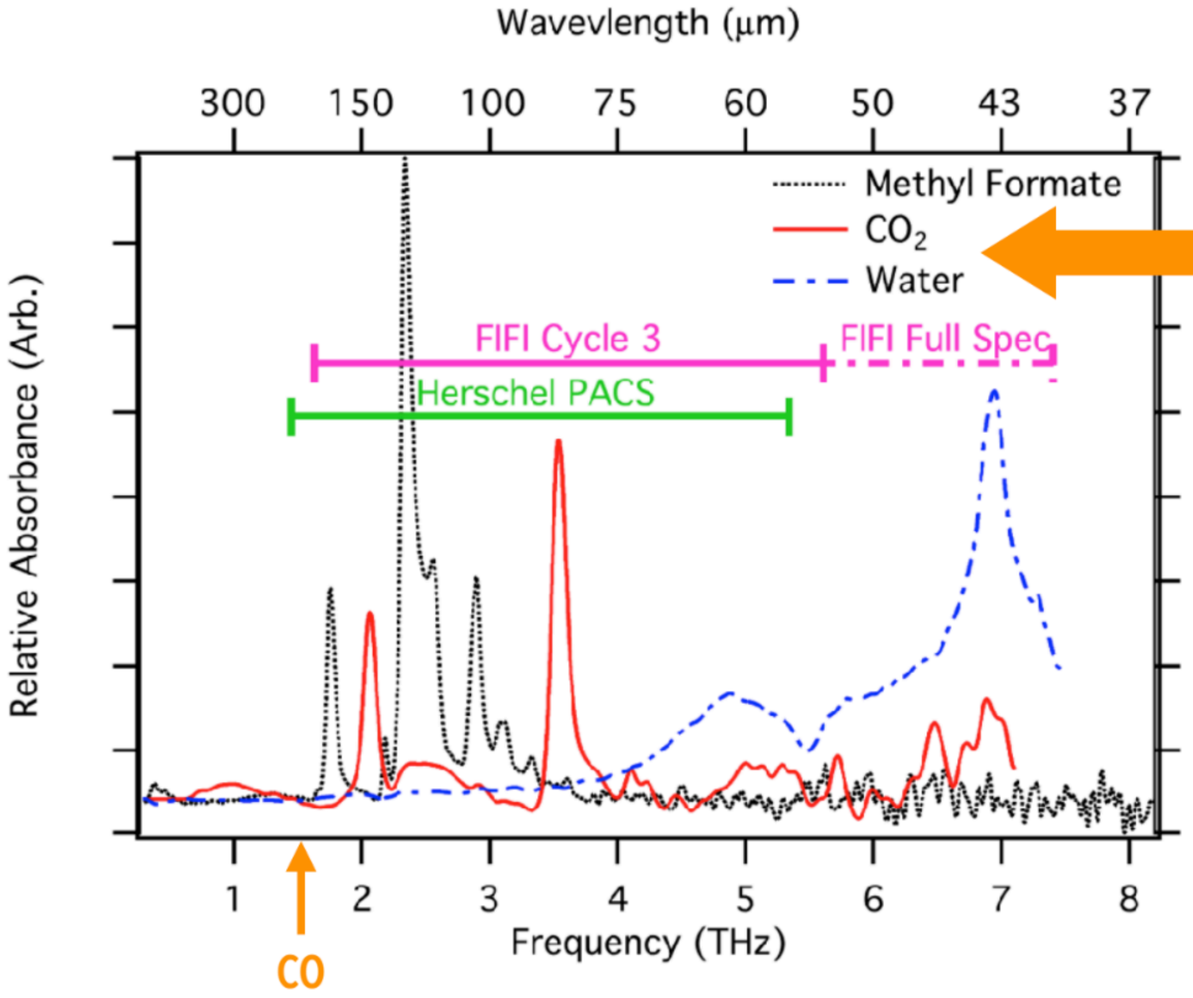
VS.

Min et al. (2016)

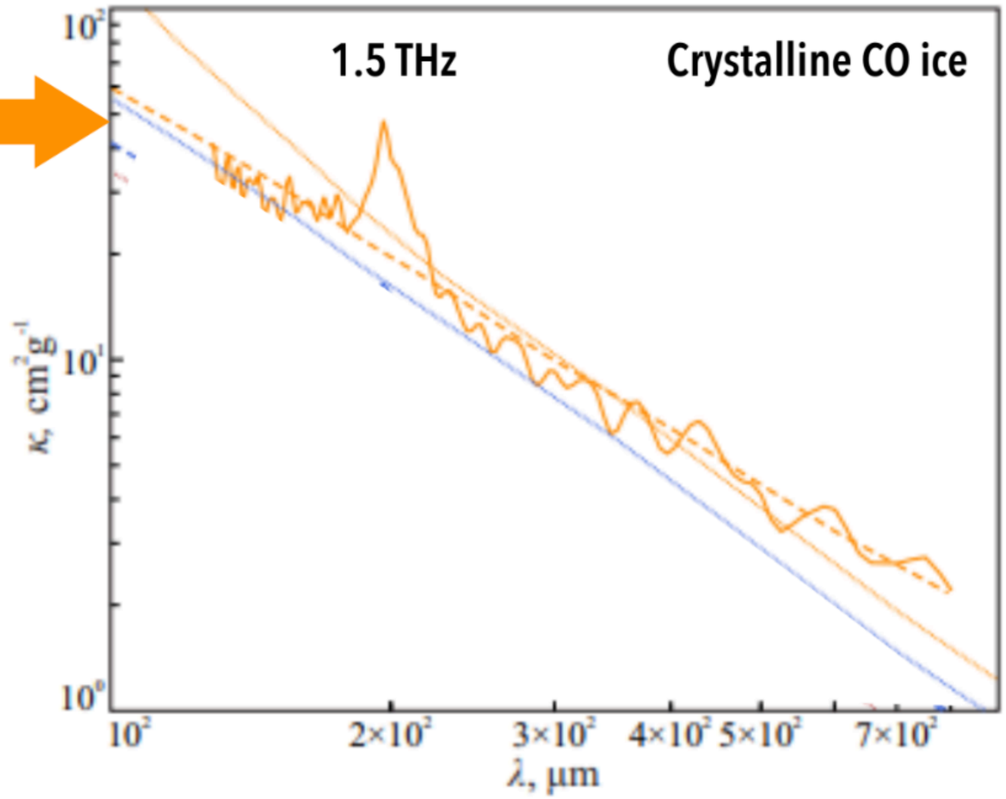
1 high-mass older disk

"Solar" ice/rock ~ 1.6

Three most abundant ice species (H_2O, CO, CO_2) have Far-IR features from 40-250 μm.

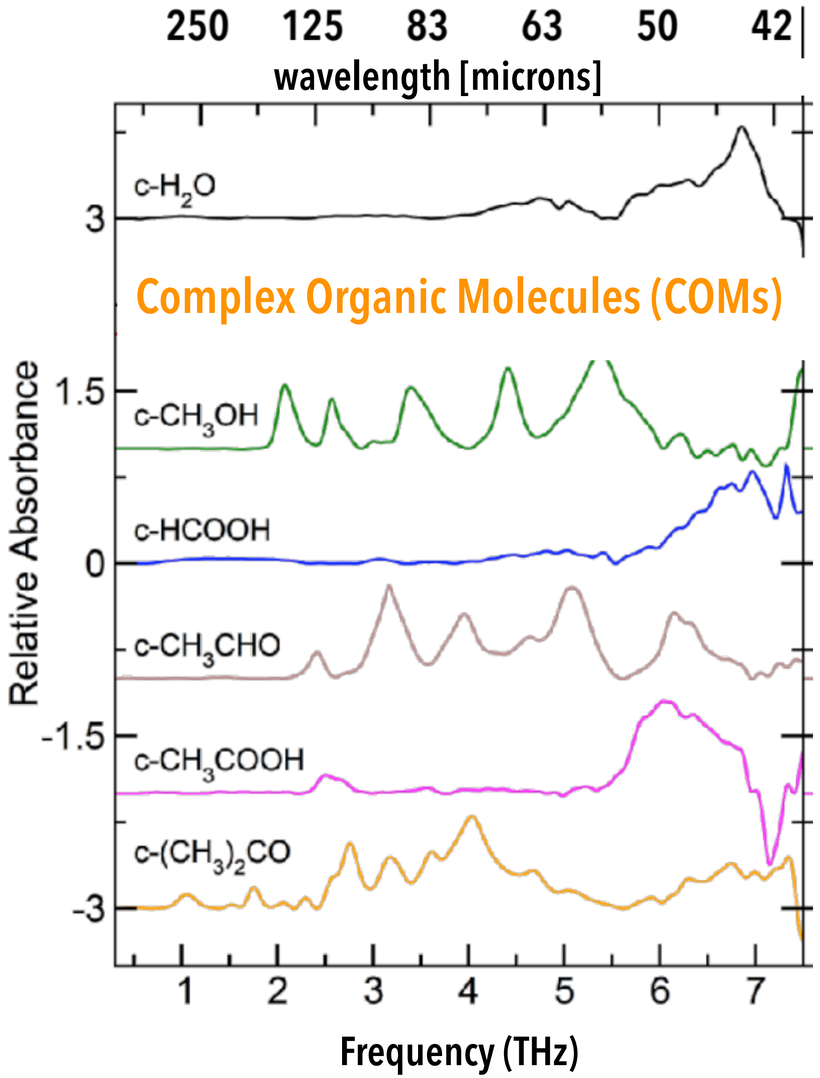


S. Ioppolo, private communication, McGuire, Ioppolo et al. (2016)

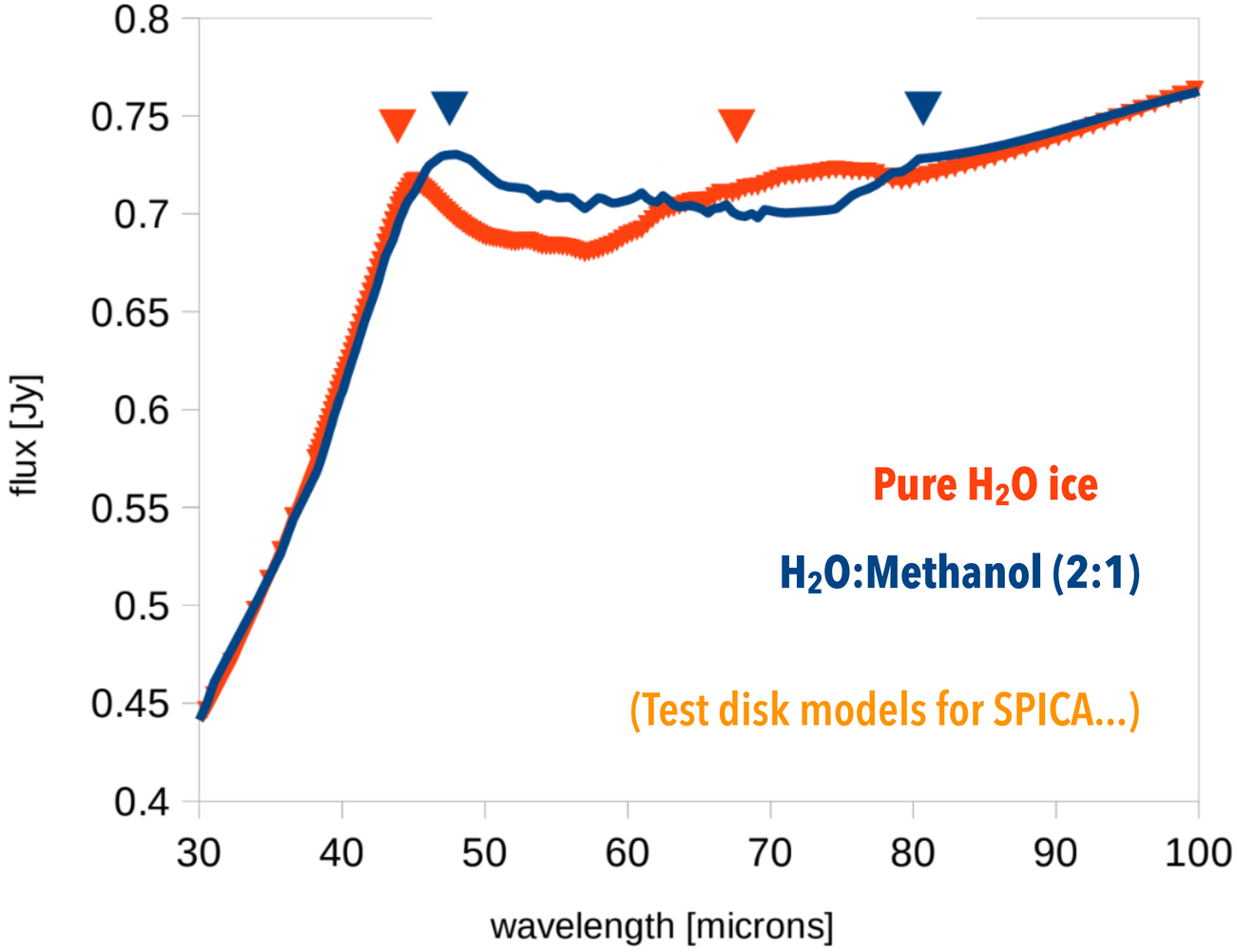


Giuliano et al. (2019)

Ice mixtures and COMs (potentially) identifable by wavelength shifts in Far-IR...



Ioppolo et al., FD168 (2014)



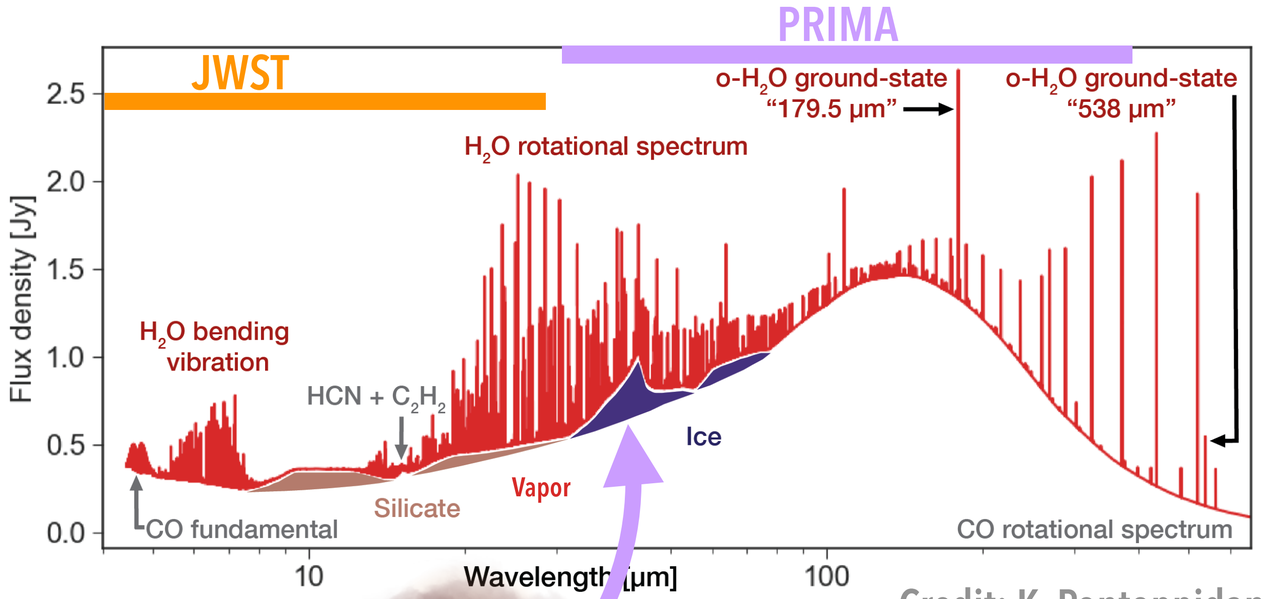
Opacities from Hudgins et al. (1993), models based on **McClure et al. (2015)**

PRobe far-Infrared Mission for Astrophysics (PRIMA): NASA FIR Probe candidate

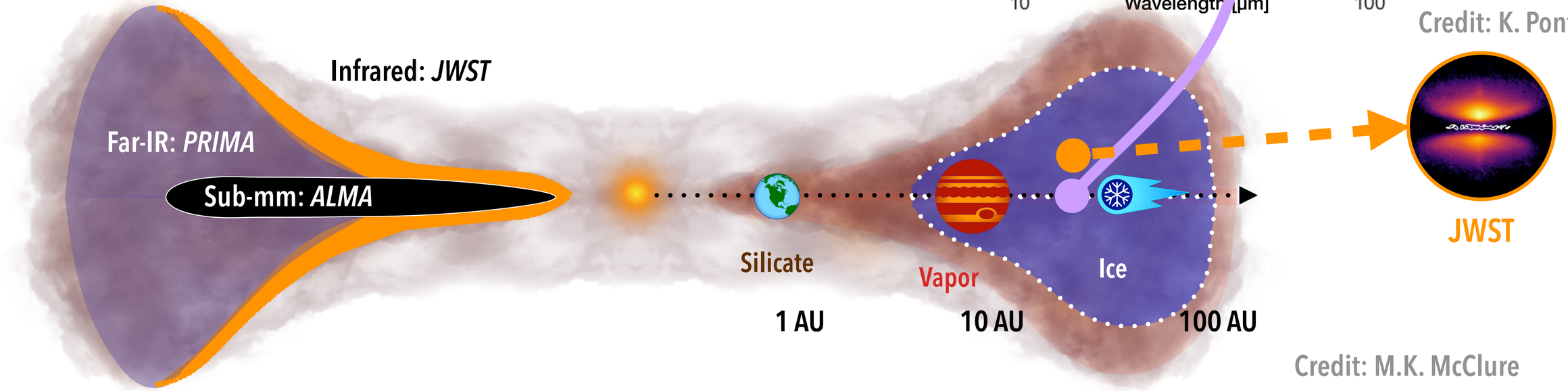
Direct access to composition and structure of midplane planetary birth zones.

PRIMA (launch 2031, if accepted fall 2025) would allow us to:

- **Detect water vapor & ice content in cometary ice reservoir for planetary delivery,**
- **Measure major ice species and degree of complexity?**
- **Chart the evolution of ice and gas distributions.**



Credit: K. Pontoppidan



Credit: M.K. McClure

Summary & Conclusions

- Ice composition details matter for exoplanet atmosphere formation theory
- JWST reveals new mixed ice complexities
- Far-IR midplane ice observations are missing link to exoplanets