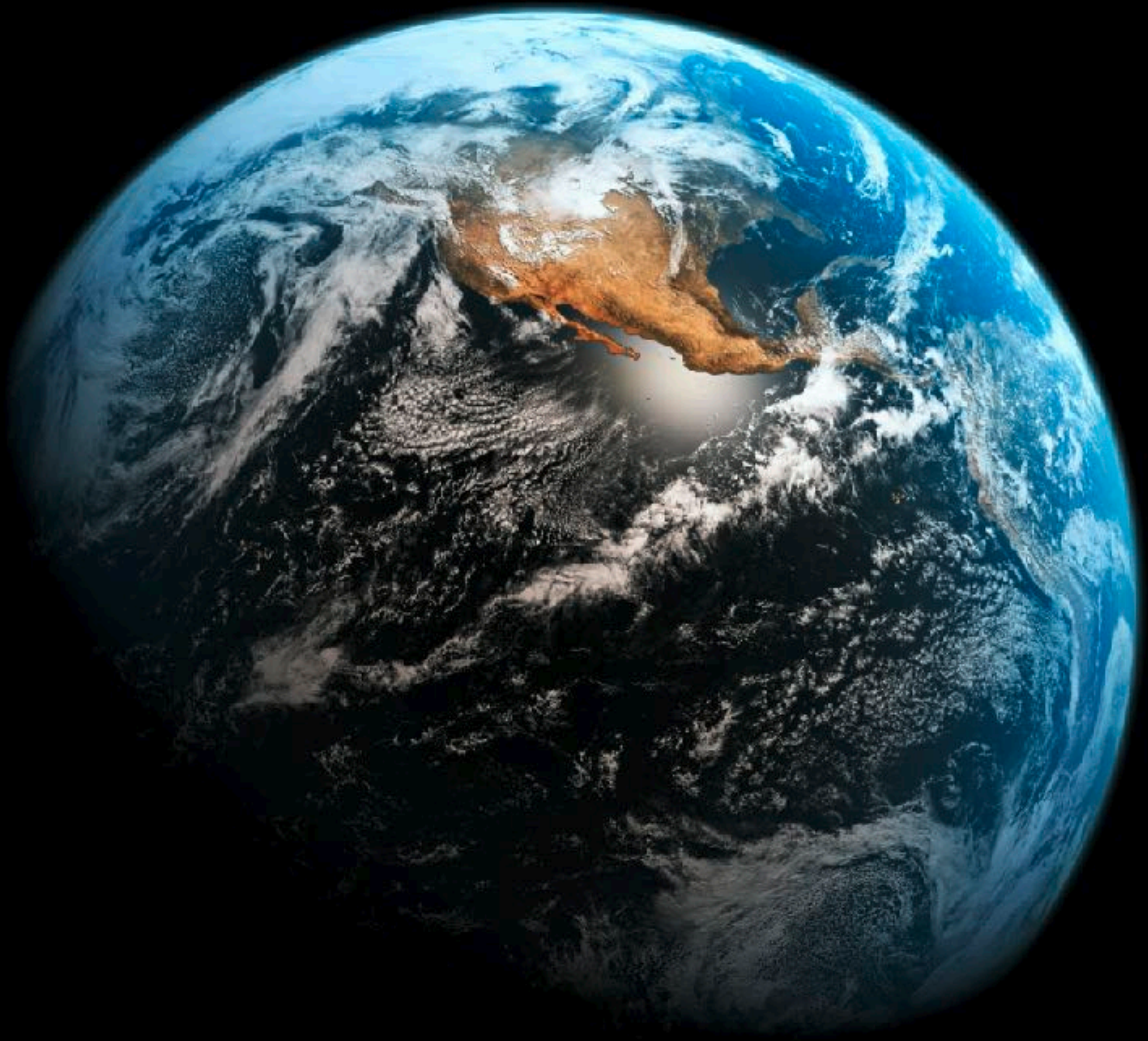


Tracing the icy path to form life

Dr. Melissa K. McClure

ASSISTANT PROFESSOR & VENI LAUREATE
LEIDEN UNIVERSITY

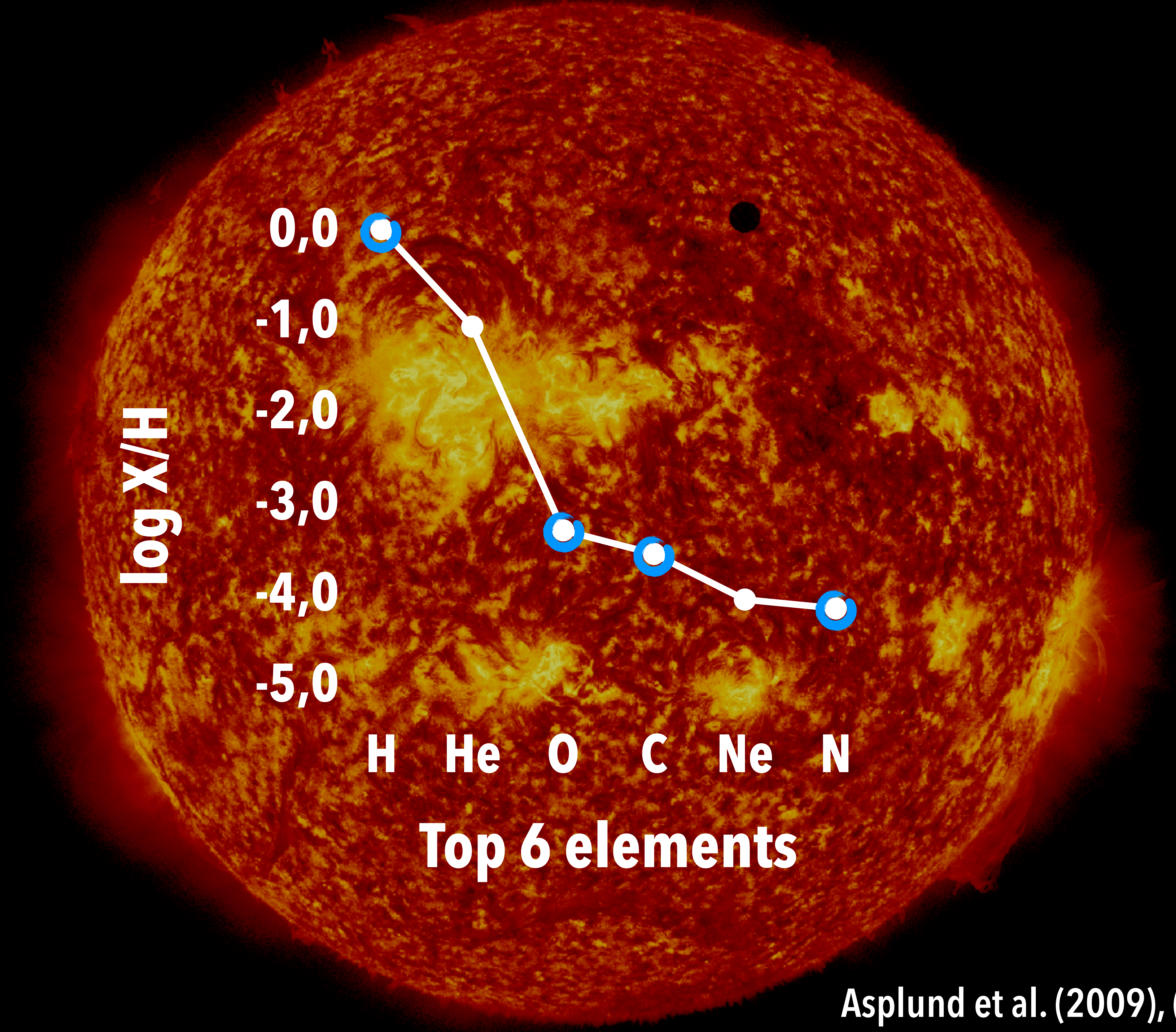
Sterrewacht Leiden

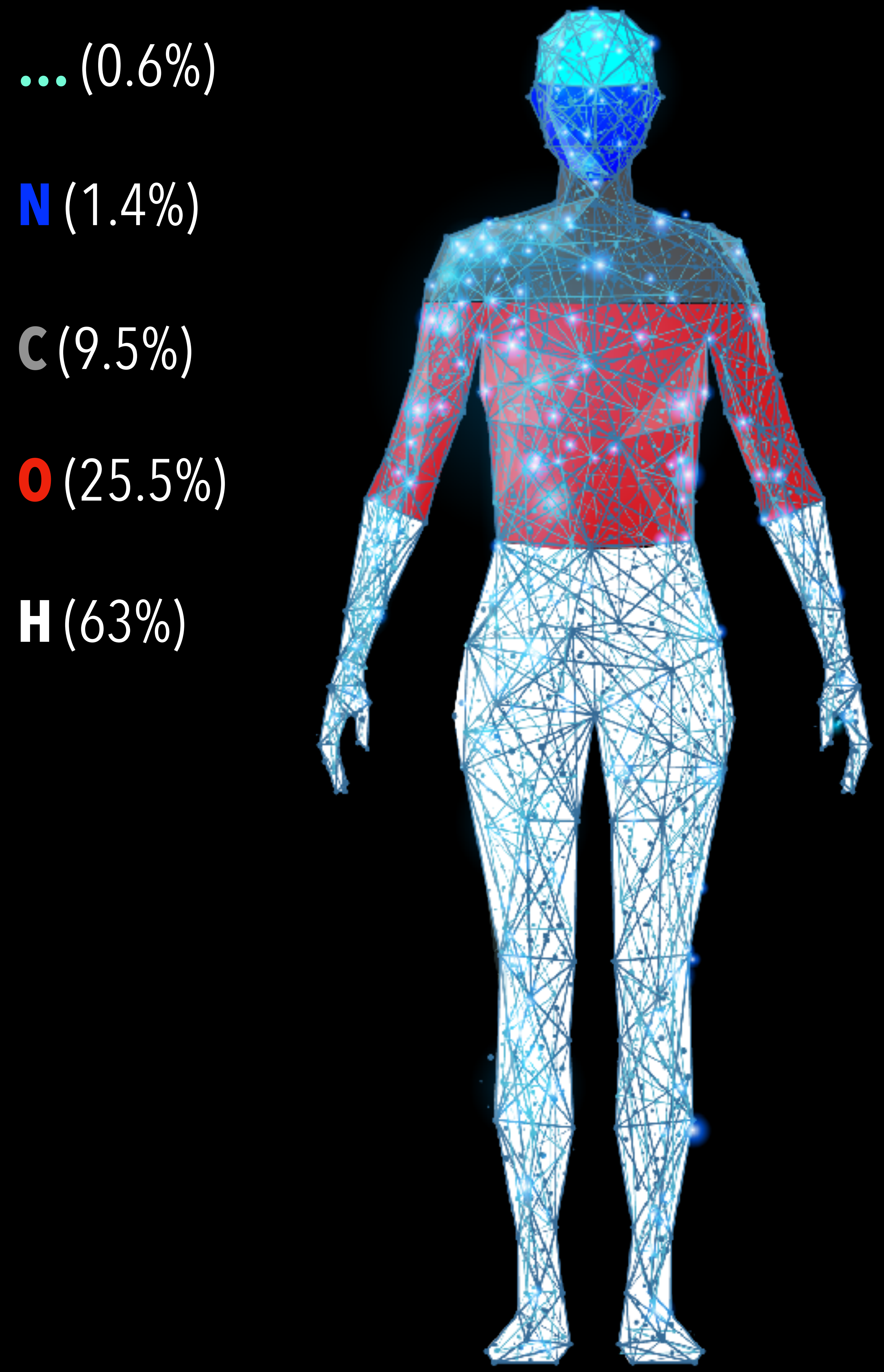
NWO

BUILDING THE SOFIA 2020-2025 INSTRUMENT ROADMAP

JUNE 23, 2020 EVERYWHERE, EARTH

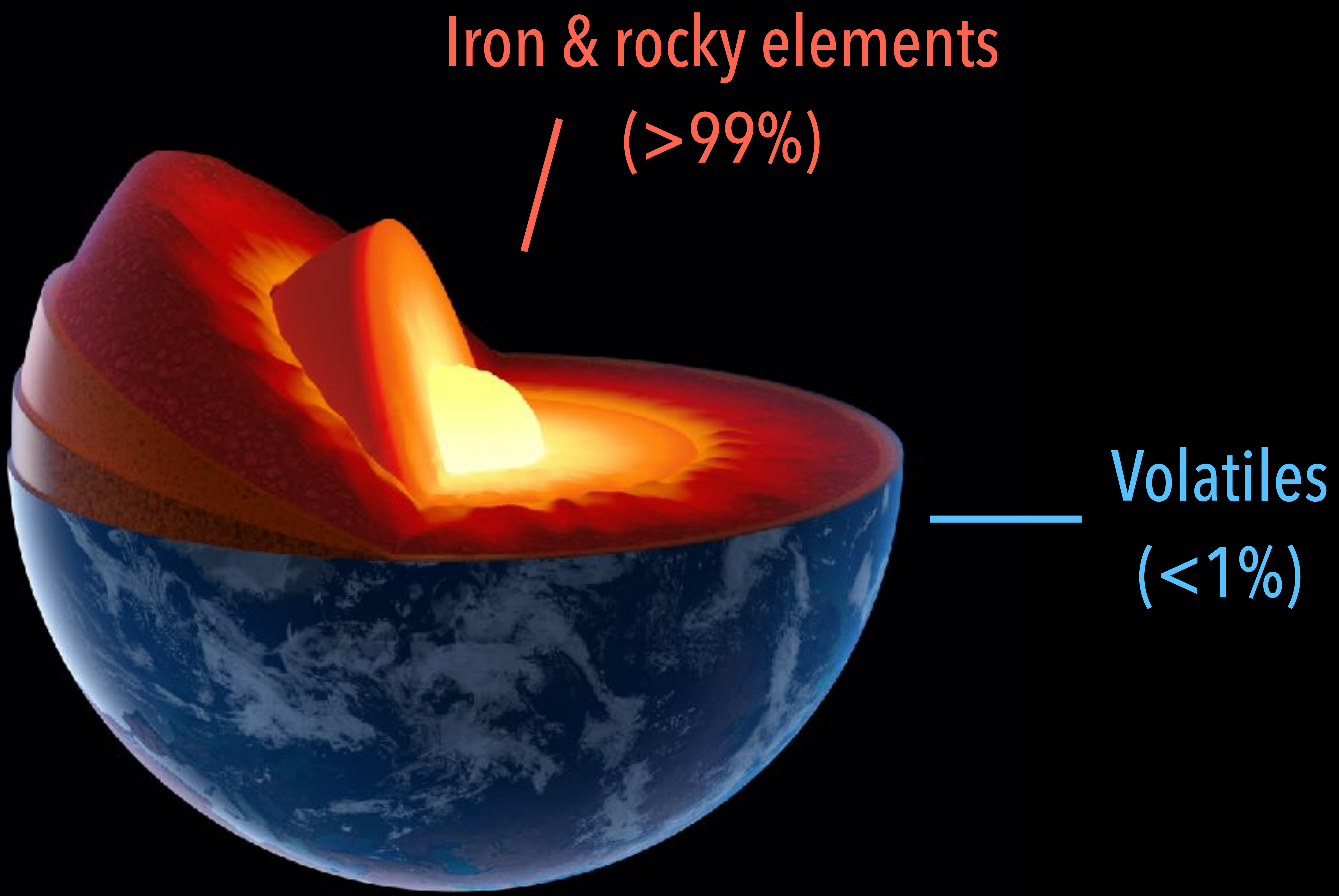
Volatile elements dominate cosmo-, astro-, and bio-chemistry.





Asplund et al. (2009), (Lewis & Prinn 1984), Sun image credit: NASA/Goddard/SDO

...but volatile elements are depleted on Earth.



Morgan & Anders (1980), NASA/JPL

(Complex Organic Molecules: COMs carbon-based, >=6 atoms)

(Simple ices)

H_2O

CO_2

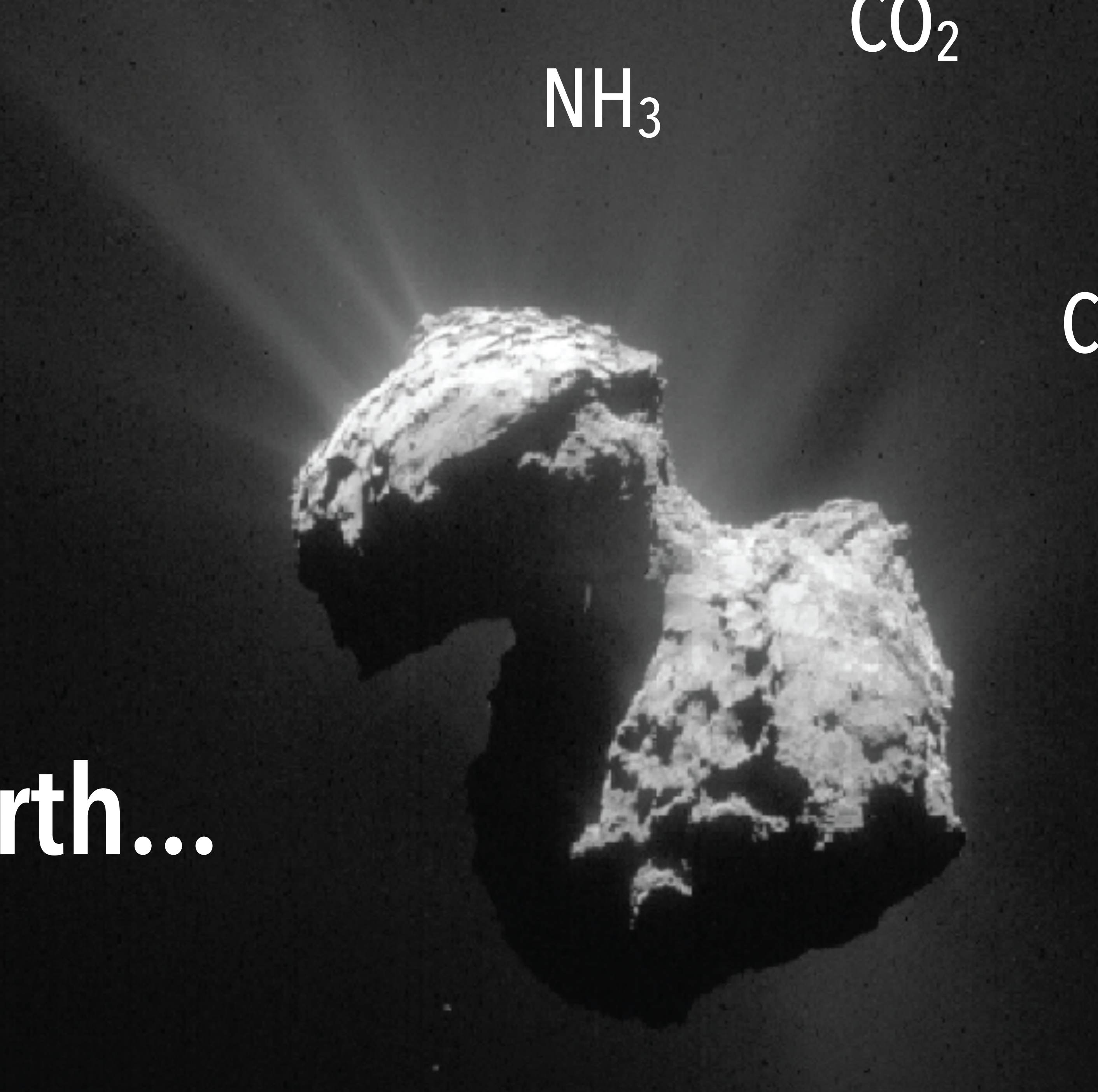
NH_3

CH_4

CO

methanol

acetaldehyde



Planetesimal impacts brought volatile organics to Earth...

...and may have kick-started Earth's biochemistry.

ethanol

glycine **(biomolecule!)**

polycyclic aromatic hydrocarbons (PAHs)

Altwegg et al. (2016, 2018), Biver et al. (2015), Cleeves et al. (2014), Image credit: Rosetta Mission, ESA

Comet 67P/ Churyumov-Gerasimenko

Planets and comets are leftover solid material from the star formation process.

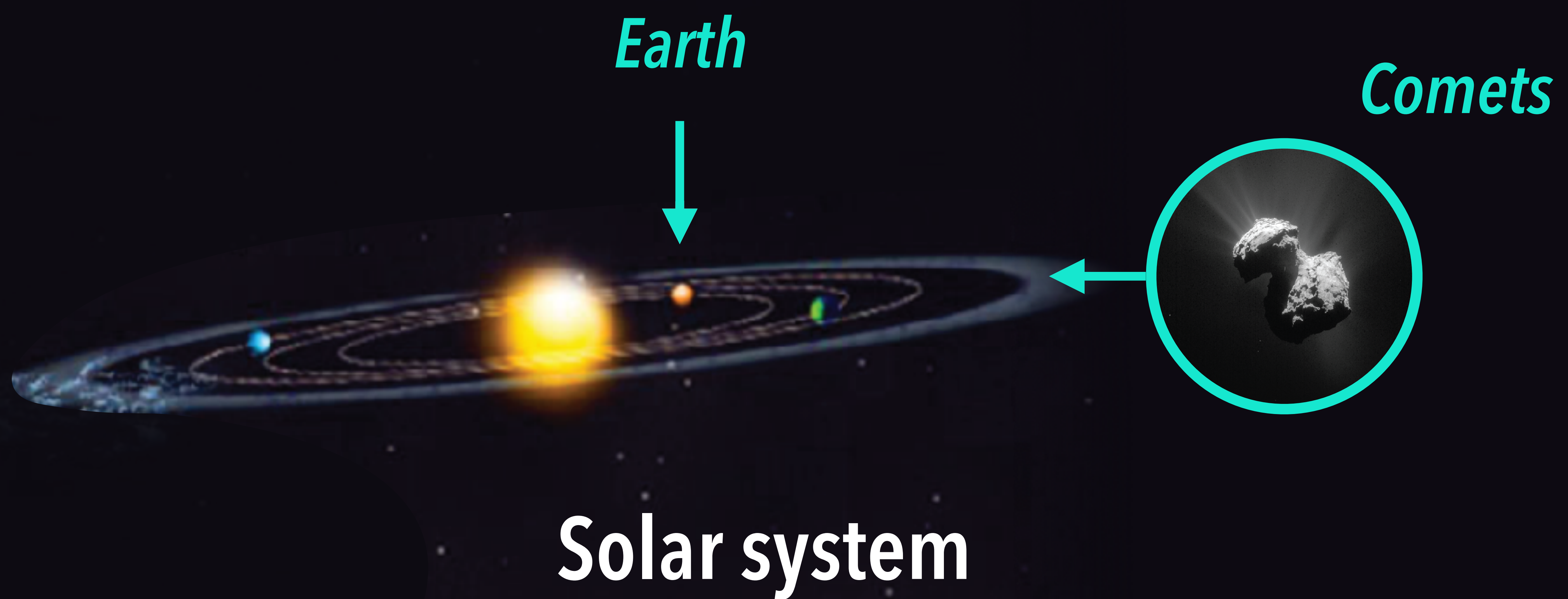


Image credit: Bill Paxton, NRAO, modified

Image credit: Bill Paxton, NRAO, modified

Big Picture

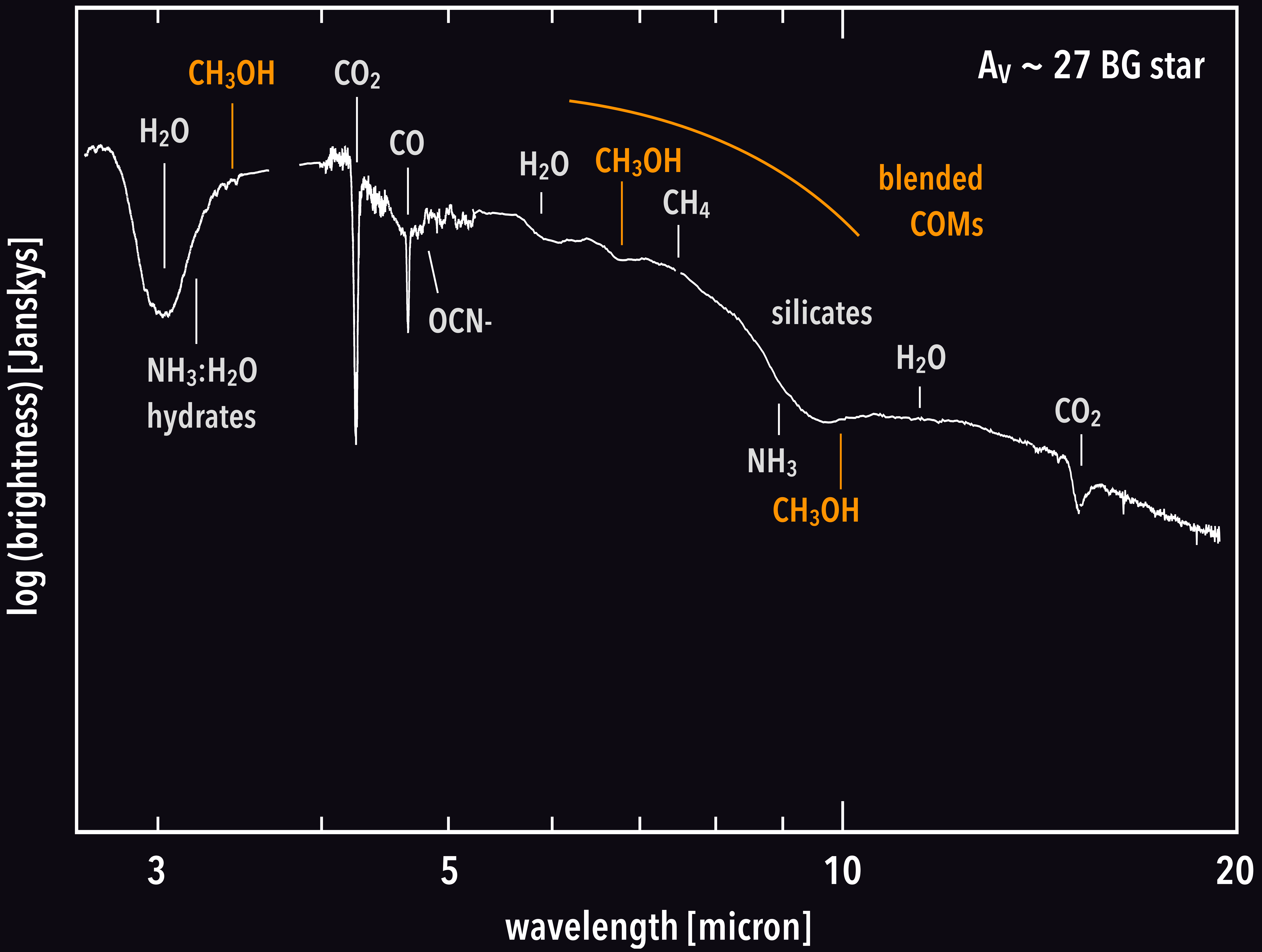
If planets inherit ices & COMs from molecular clouds,
then life may be universal, not unique to solar system.

Battle plan to probe ice evolution

#	Technique	Wavelengths	Science	Facility
1	**Absorption spectroscopy**	Near-, mid-Infrared	• ***Relative*** abundances of all simple ices • COM detections • Thermal processing & grain size signatures	JWST, SPHEREx
2	**Thermal emission spectroscopy**	Far-infrared	• ***Absolute*** abundance of ice(s) versus rocks • ***Directly probe comet-forming regions (in disks)*** • Alternative COM detections?	*(OST, SPICA, formerly SOFIA HIRMES)*
3	**Scattered light imaging**	Near-infrared	• Spatially resolved ice distributions (compare with spiral arms/known exoplanets)	*(limited ground-based)*

#1


Dense, cold molecular cloud
Hot
Cold
Hot
Cold
Protostellar envelope
Near-, mid-IR absorption spectroscopy
Protoplanetary Disk
Hot
Cold
Background star
Protostars
Edge-on
disk
log (flux)
3
5
10
20
wavelength [microns]
Image credit: Bill Paxton, NRAO, modified

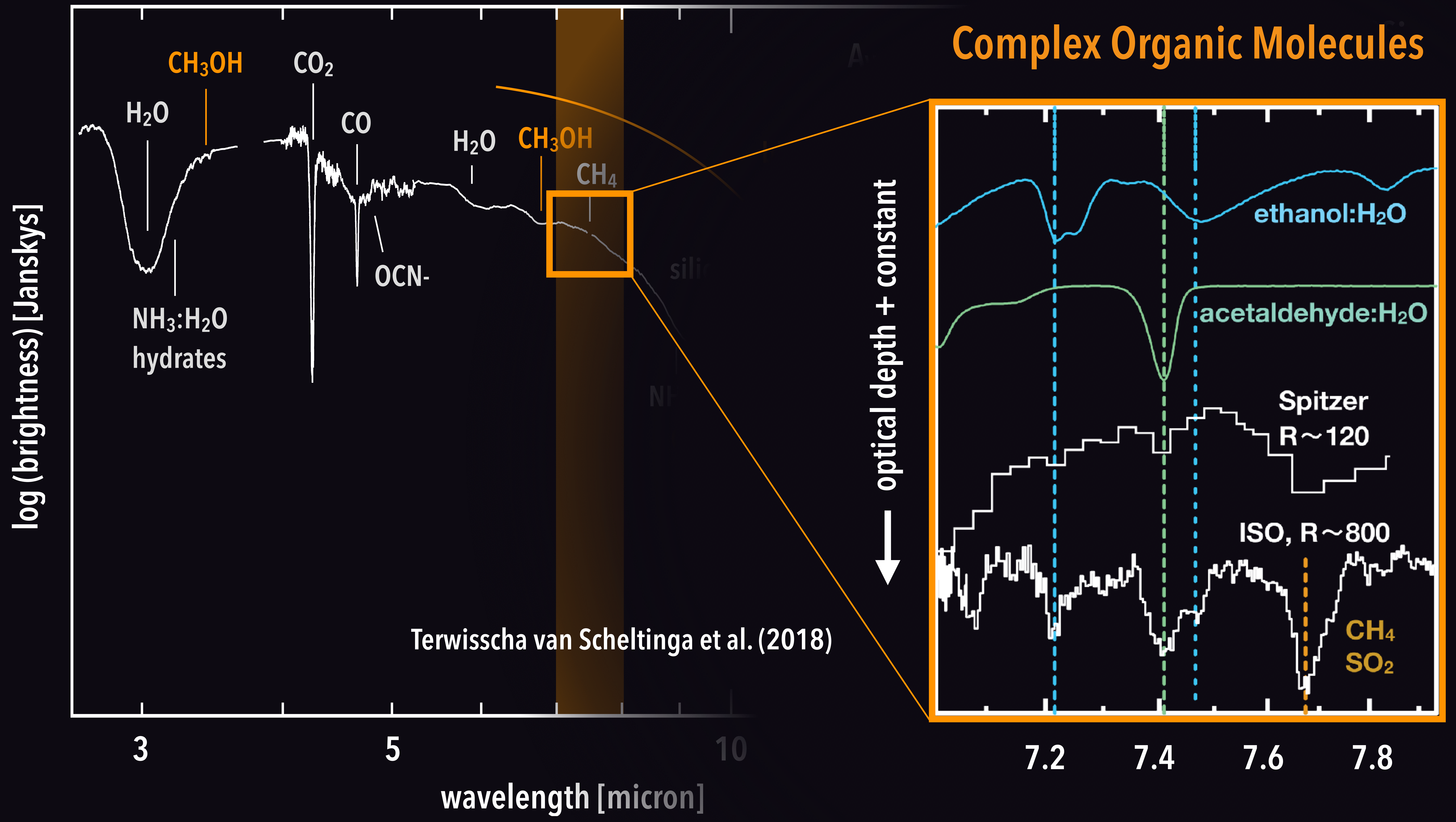


Science cases

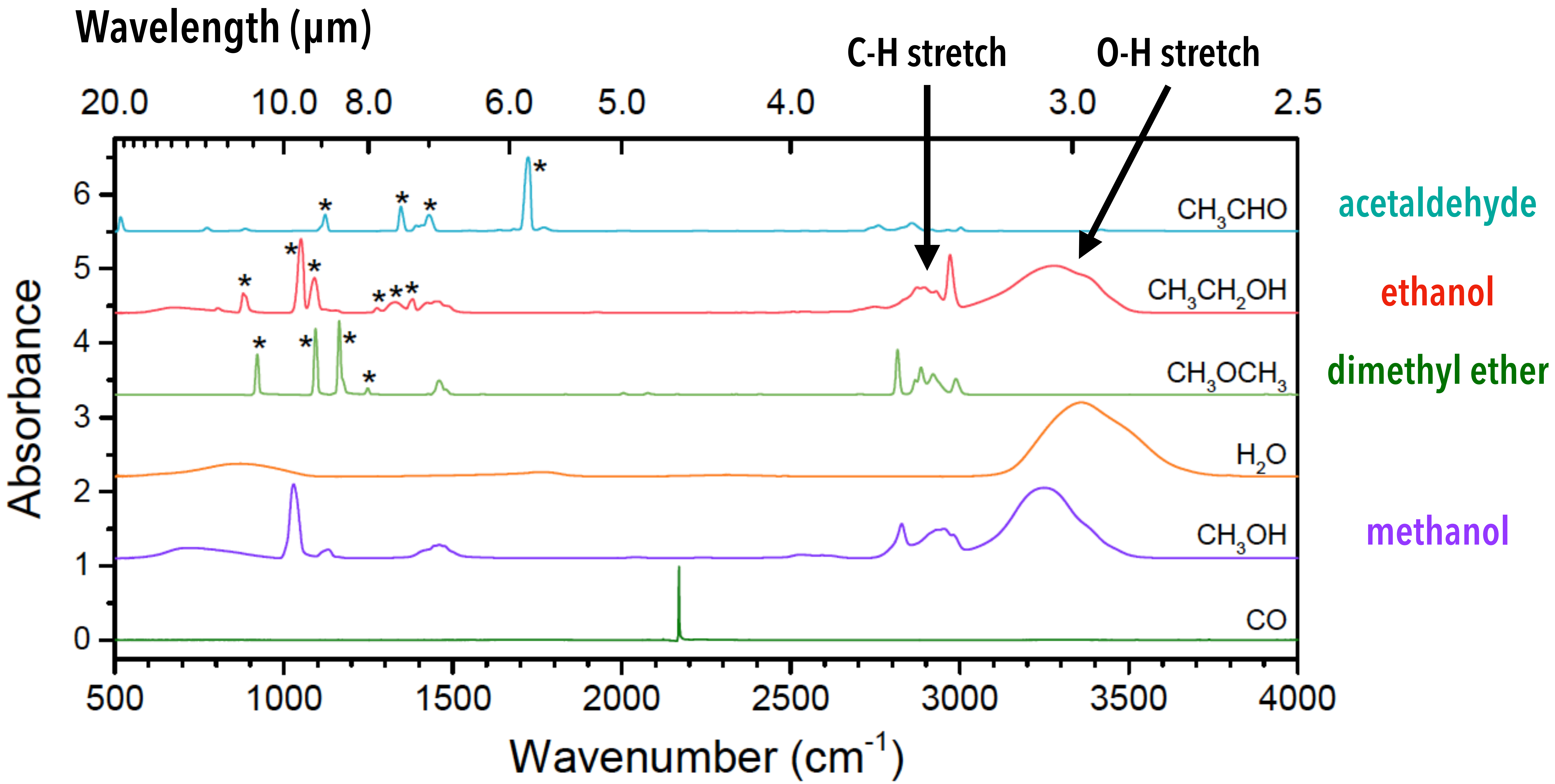
1) Relative abundances, 5 simple ice species, plus methanol

2) COM detection, I.D.

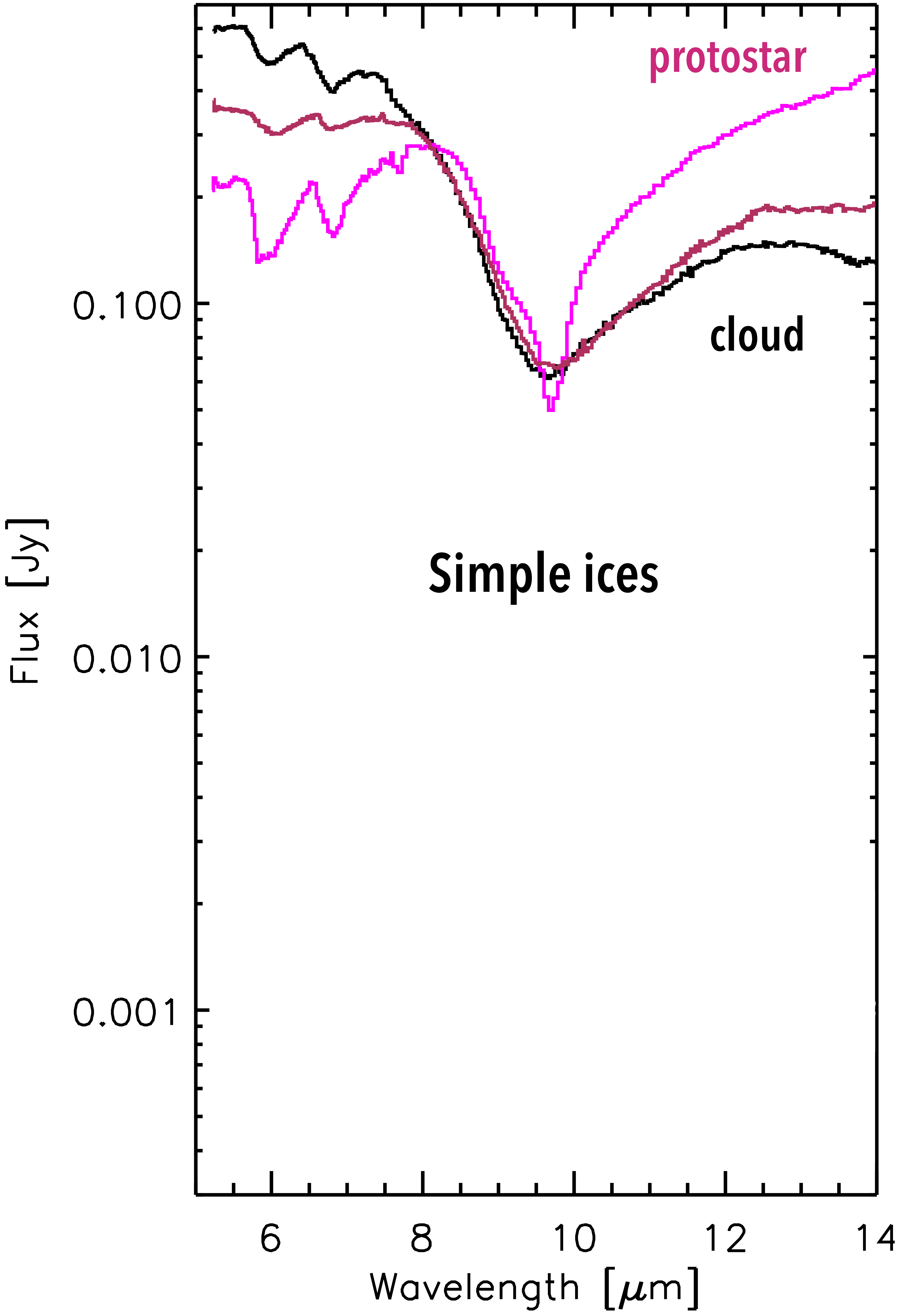
Complex Organic Molecules



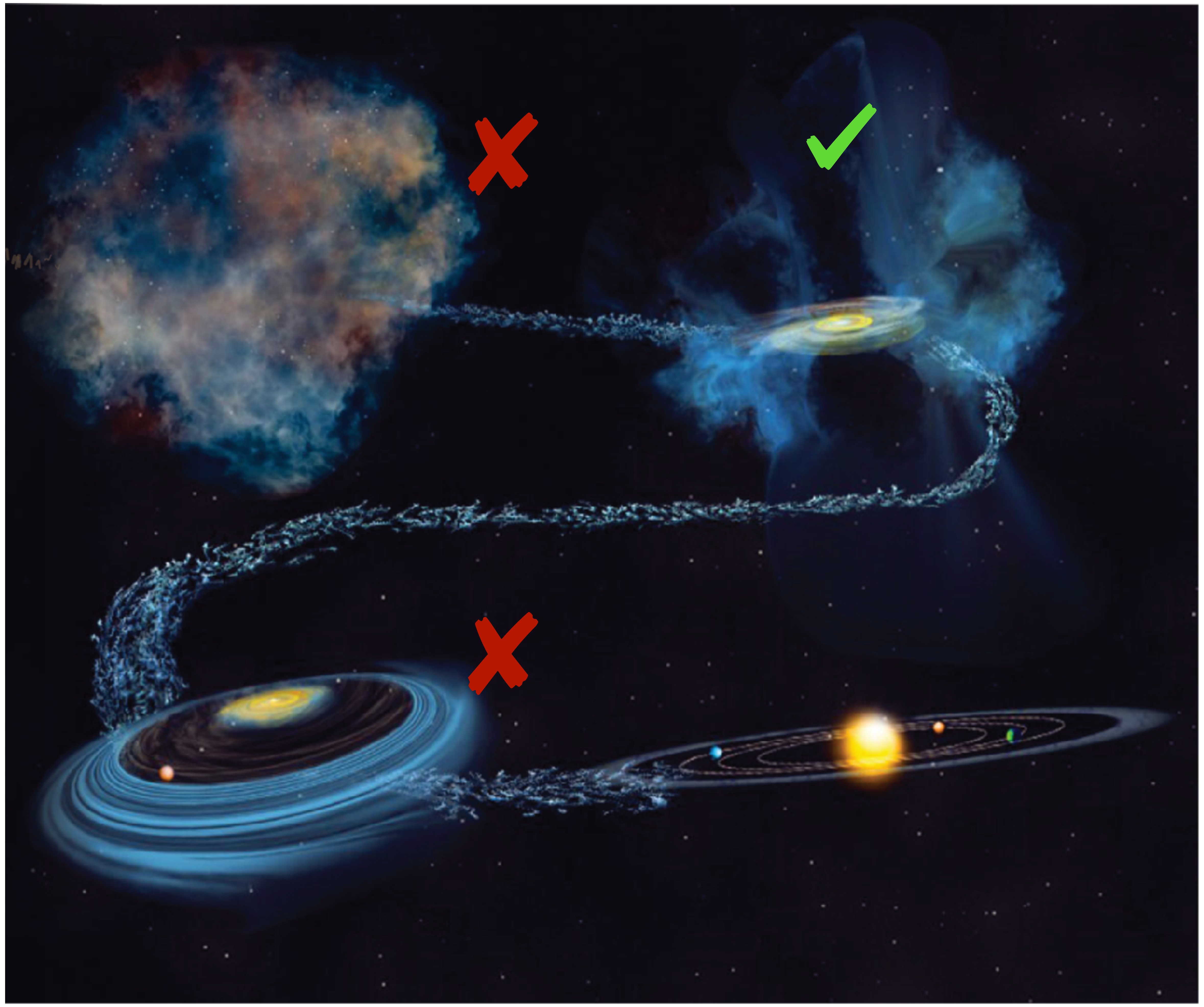
Lab spectra identify COMs via weaker features: at least 5 COMs should be ID'able.



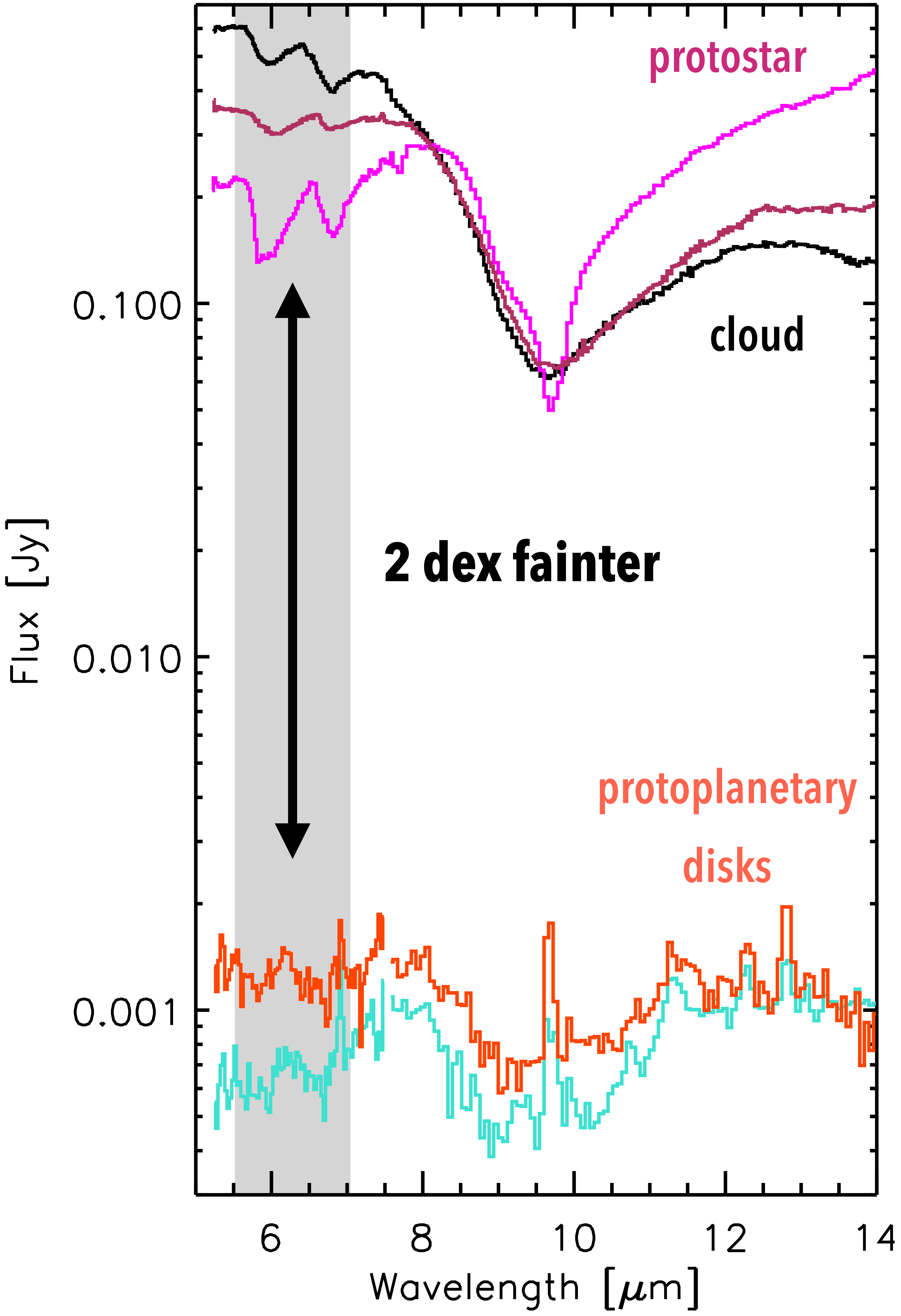
Terwisscha van Scheltinga et al. (2018), Leiden's Laboratory for Astrophysics

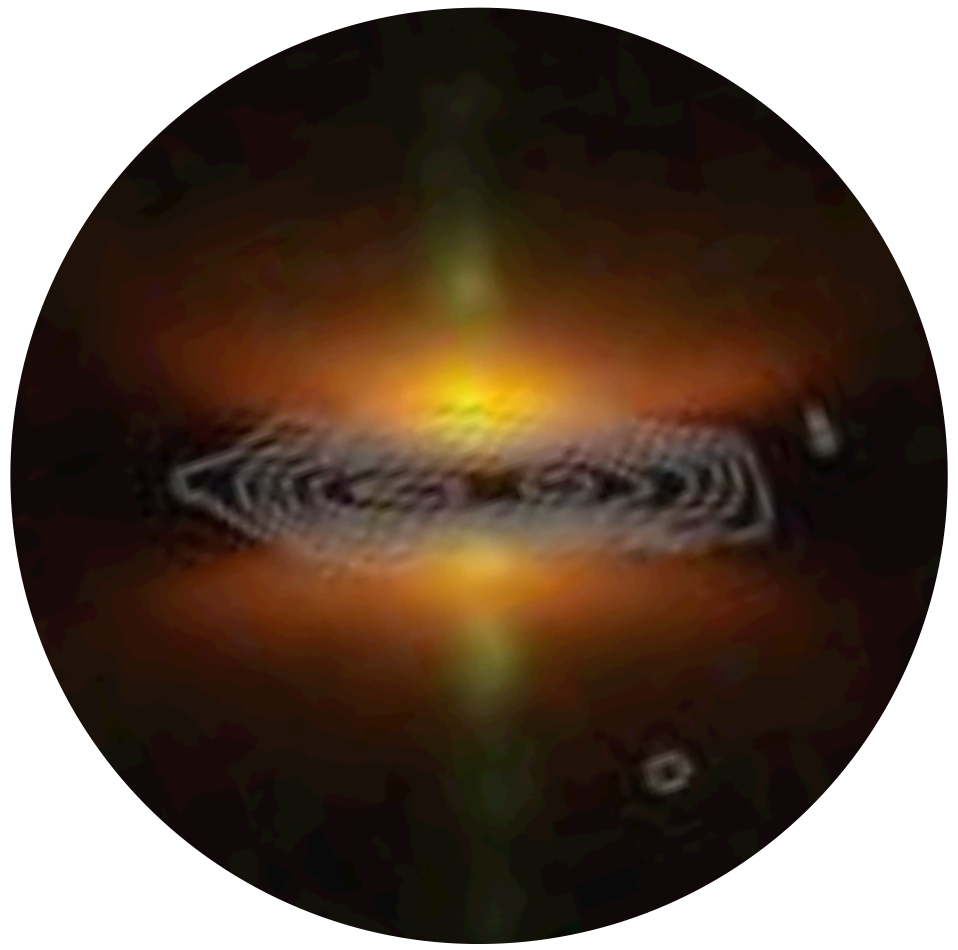


Observations need to catch up to laboratory.

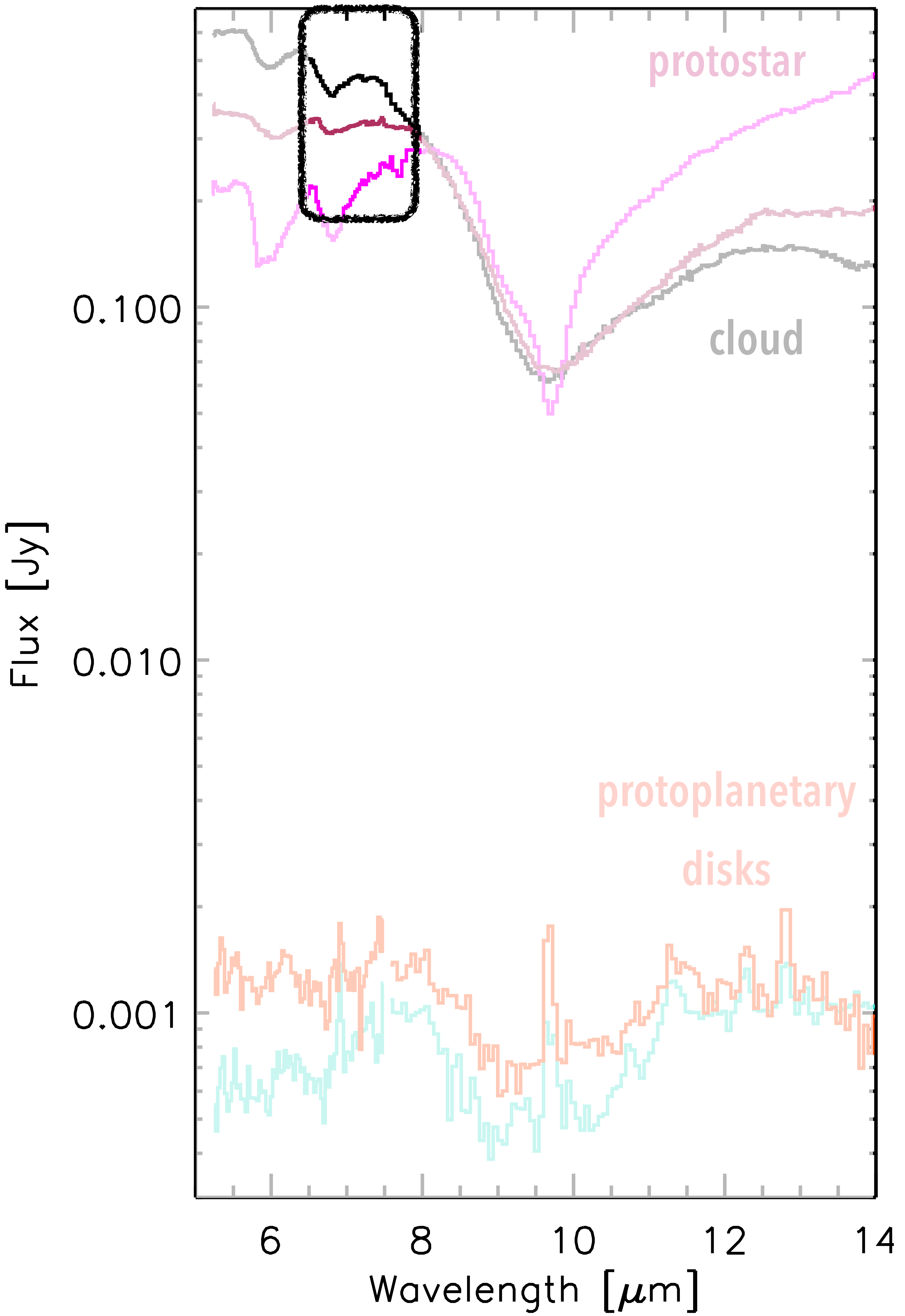


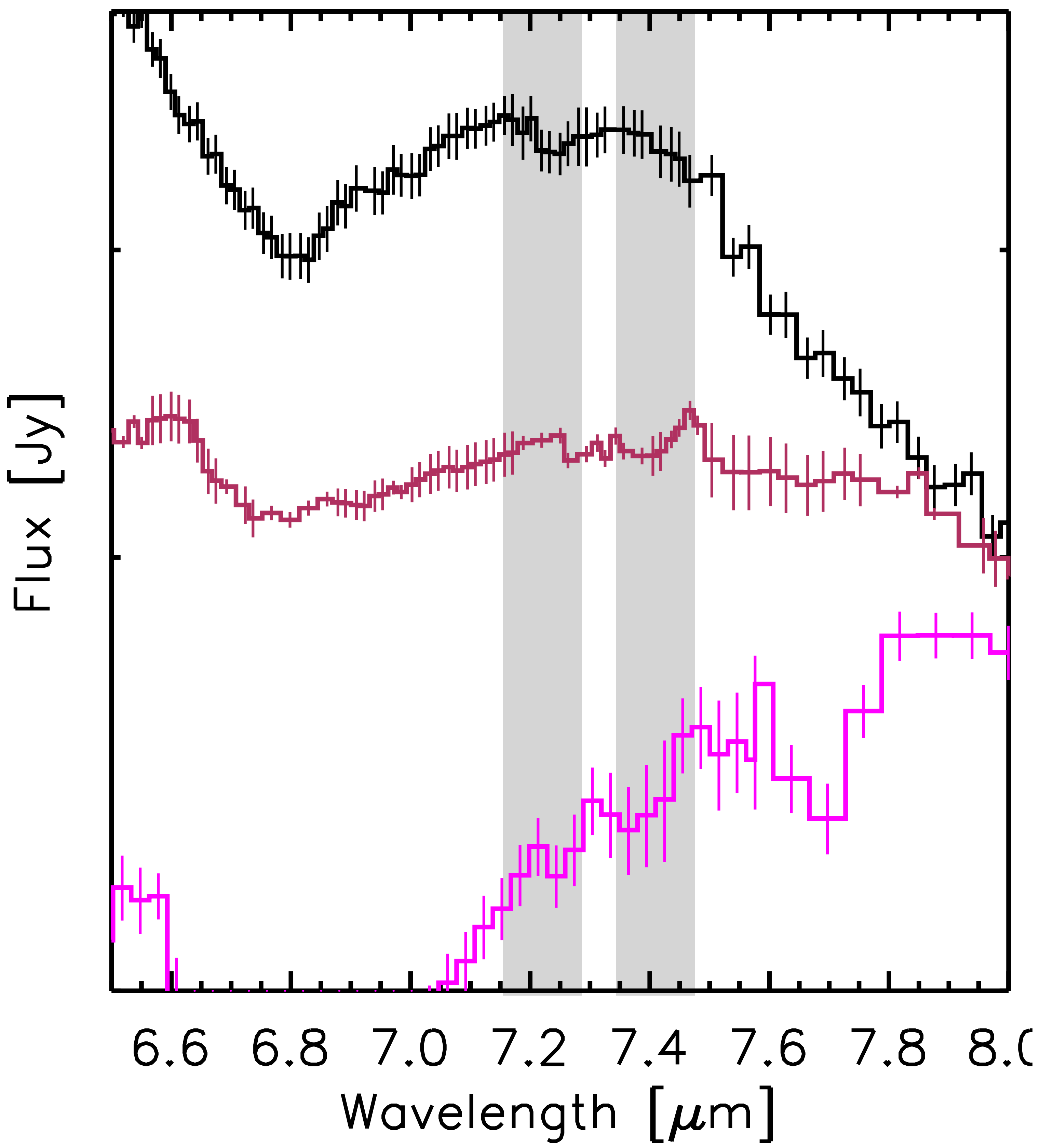
Chiar et al. (2007), McClure (2009), Boogert et al. (2010), (2015), Oberg et al. (2011)



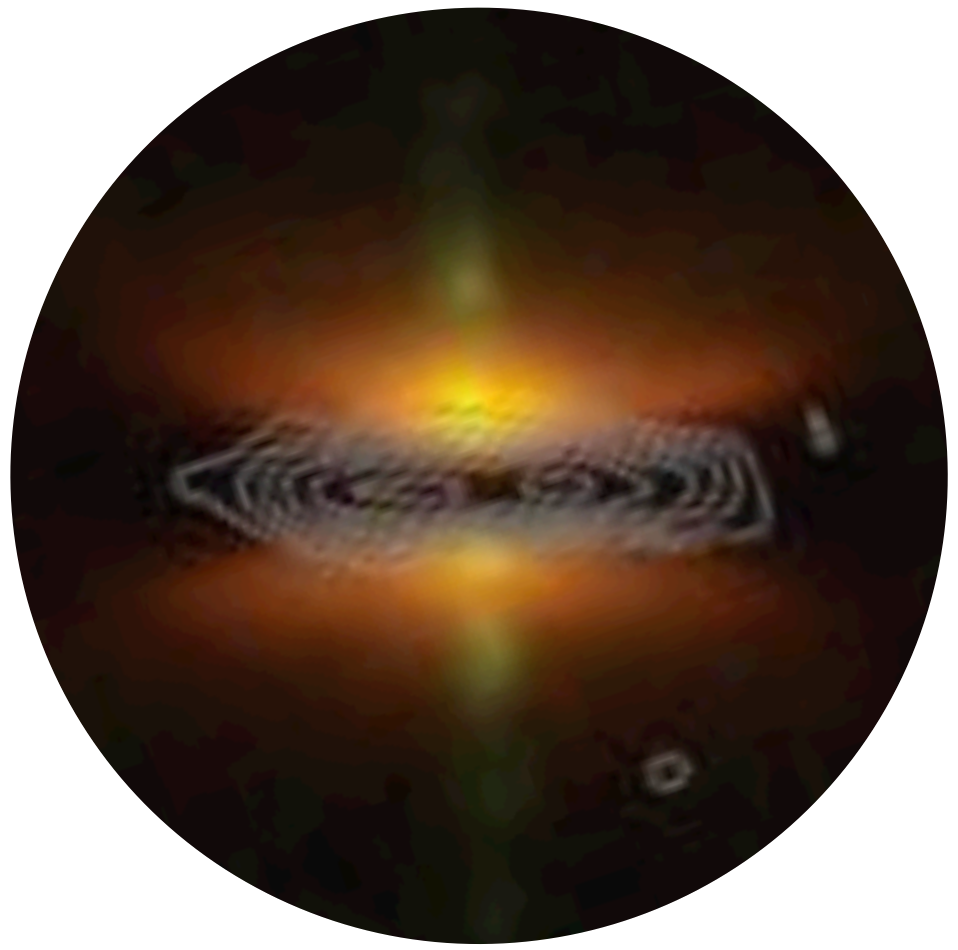


McClure, Linnartz, Boogert et al. (in prep.)





COMs ~ 1-3% of continuum



Require R>~800, high sensitivity to characterize ices/COMs in disks.

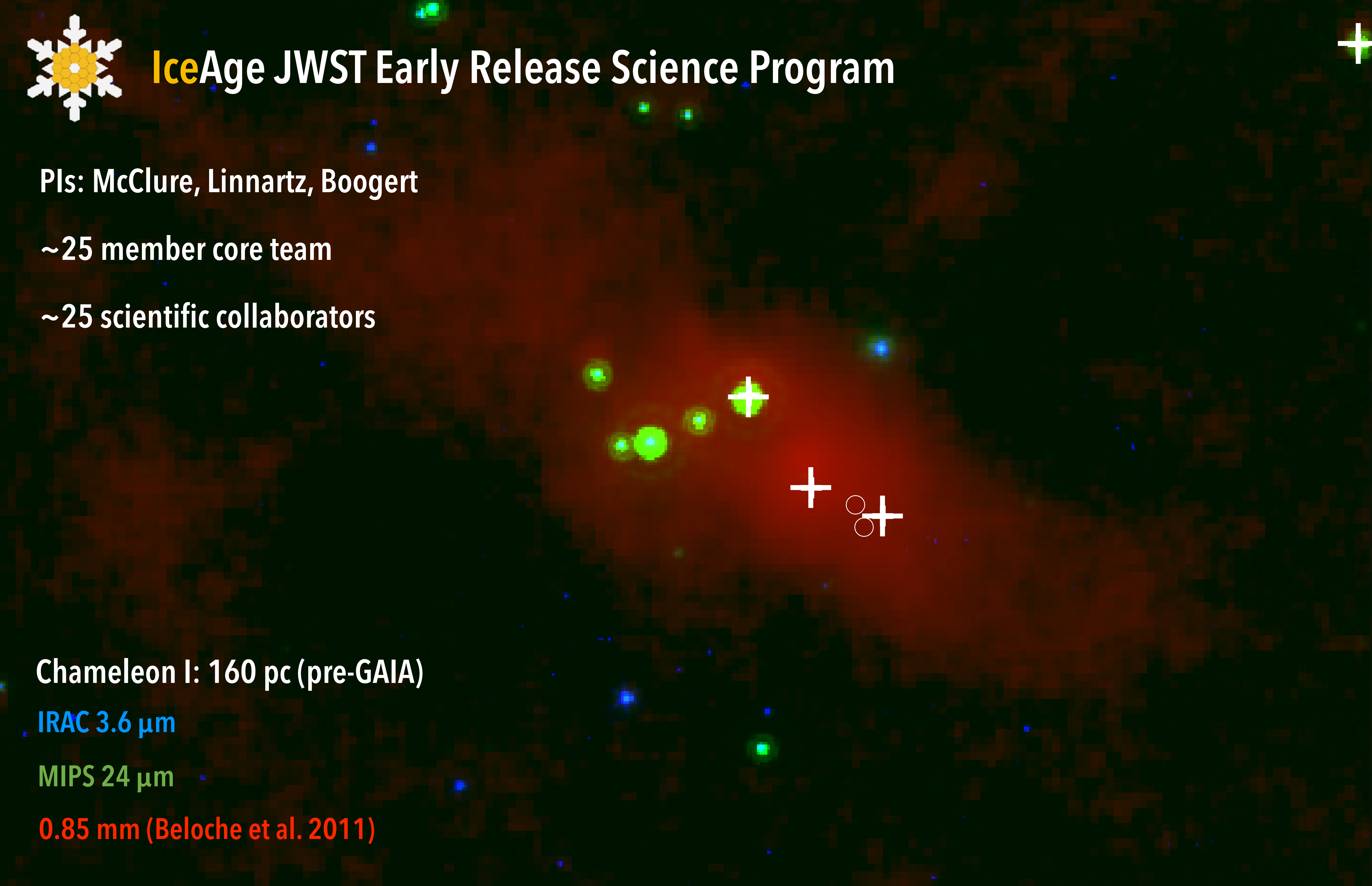
McClure, Linnartz, Boogert et al. (in prep.)

IceAge JWST Early Release Science Program

PIs: McClure, Linnartz, Boogert

~25 member core team

~25 scientific collaborators



Chameleon I: 160 pc (pre-GAIA)

IRAC 3.6 µm

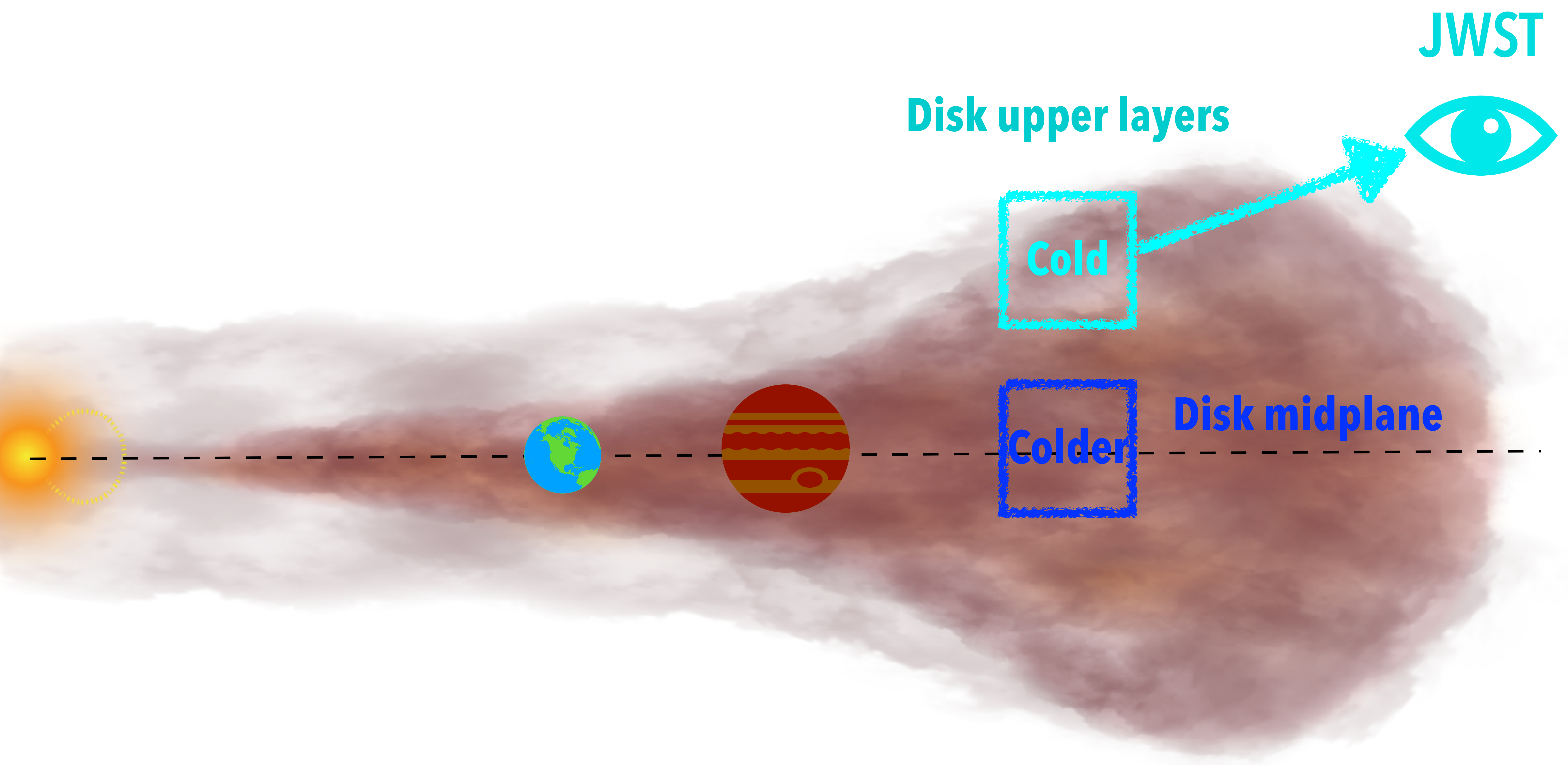
MIPS 24 µm

0.85 mm (Beloche et al. 2011)


IceAge JWST Early Release Science Program
But favorite bright objects saturate.
FORCAST update?
Edge-on Class I protostar
*
Edge-on disk
**
Known background stars
Class 0 protostar
Pre-stellar core
A_V ~ 60, 95 background stars
H_2O
CH_3OH
CO_2
CO
COMs
silicates
NH_3:H_2O hydrates
H_2O
CH_3OH
CH_4
NH_3
CH_3OH
NIRCam WFSS/NIRSpec FS & IFU
MIRI LRS & MRS
BG stars: Persi et al (2001), K. Luhman, priv. comm.
*Persi et al. (2001), **Stapelfeldt et al. (2013)

#2

Far-infrared thermal emission measures midplane <u>absolute</u> ice abundances.



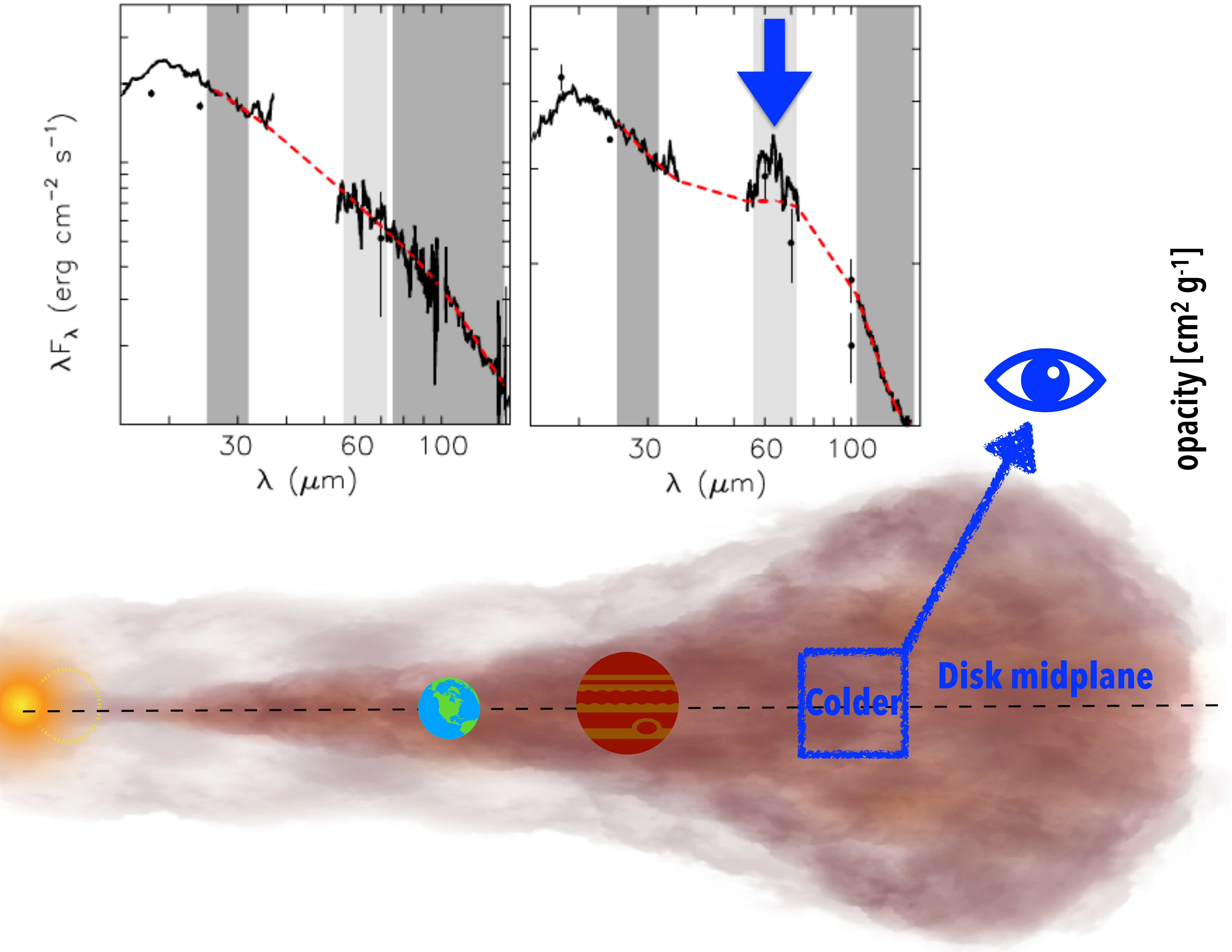
JWST science cases

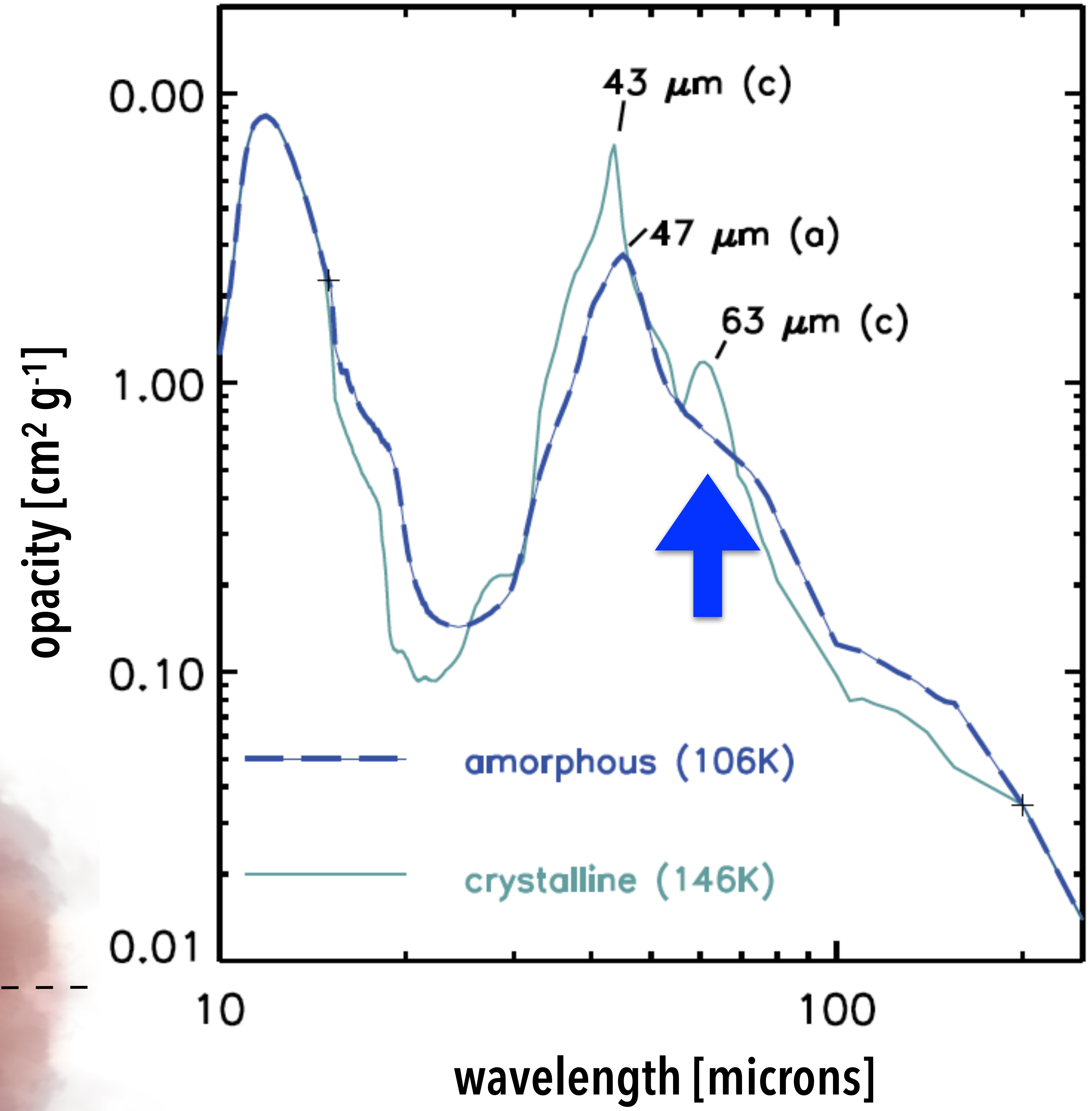
1) *Relative* abundances, 5 simple ice species, plus methanol

2) COM detection, I.D., 5 species

But how to convert to absolute abundances (relative to rock)?

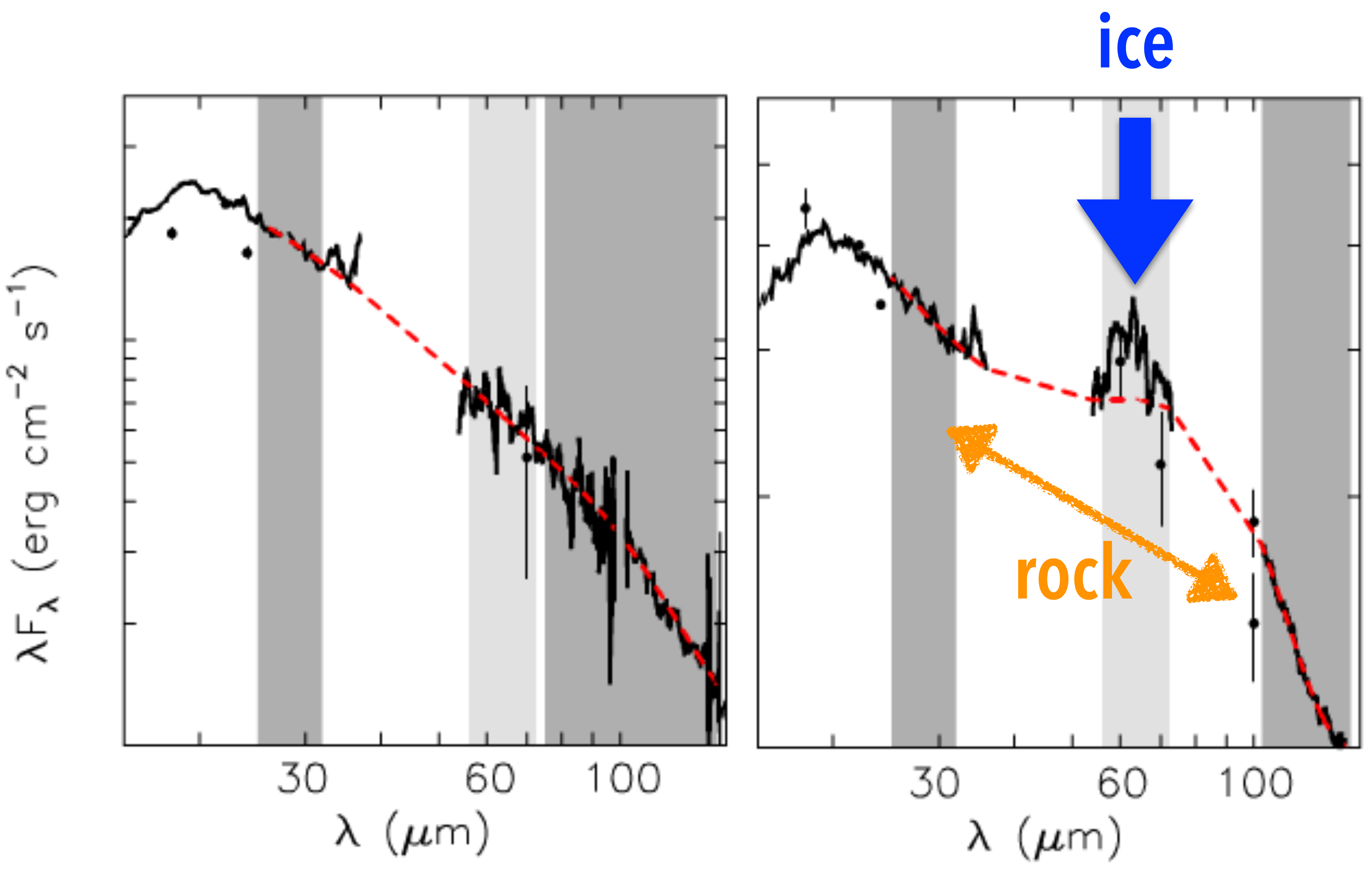
Far-infrared thermal emission measures midplane absolute ice abundances.

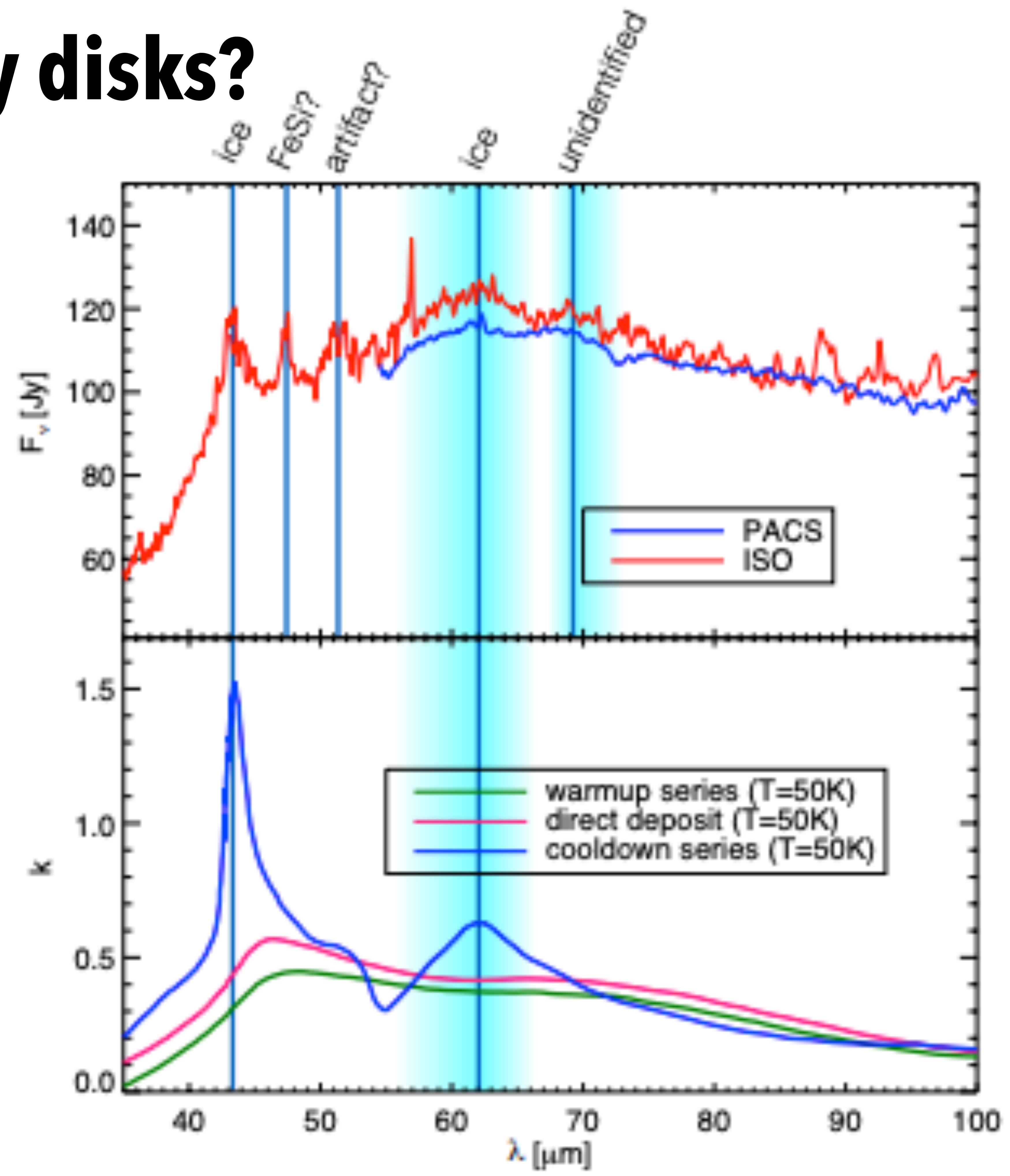




McClure et al. (2015), *Herschel* PACS spectrograph

Are water ice abundances reduced in protoplanetary disks?





Only 6% of sample show water ice.

3 low-mass disks, ice/rock ~ **0.5**

VS.

"Solar abundance" ice/rock ~ **1.6**

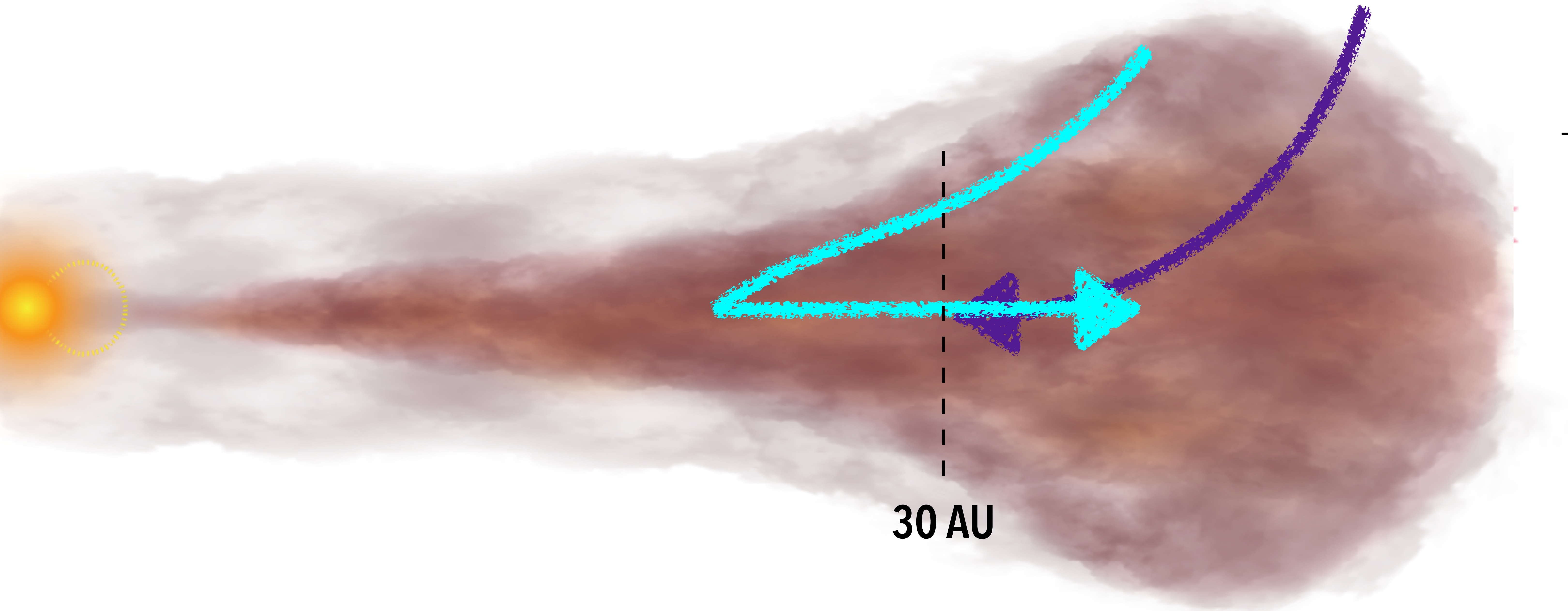
1 high-mass disk

McClure et al. (2012, 2015)

Min et al. (2016)

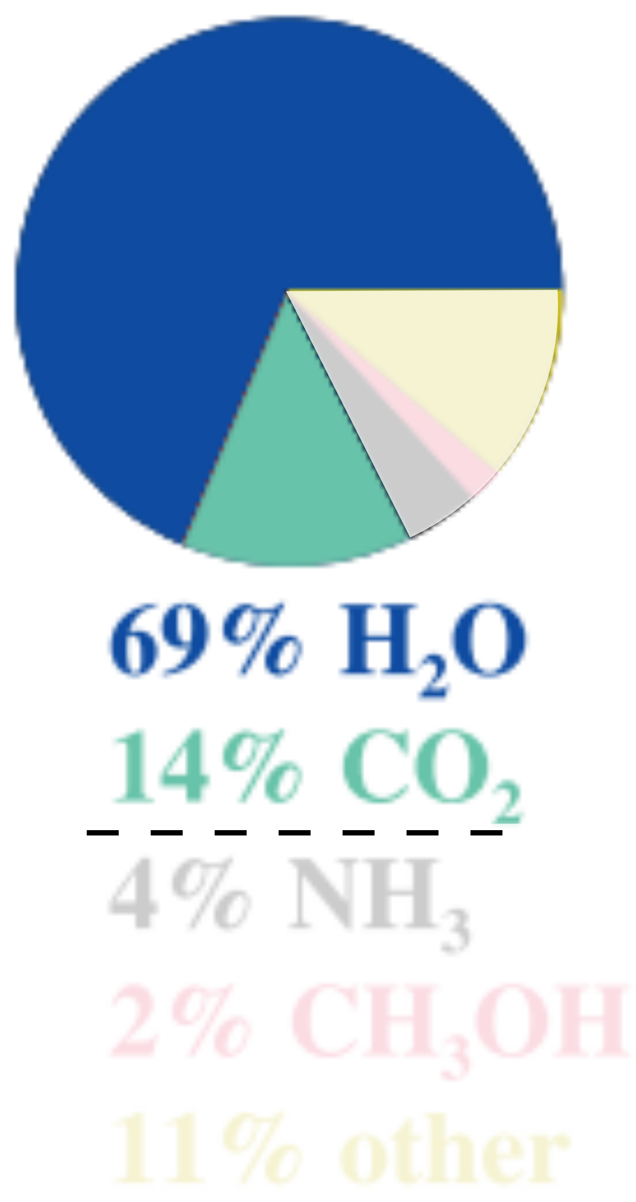
Water ice/rock variations predicted by different initial conditions/chemistry.

80-90% of midplane ice mass carried by 3 ice species.

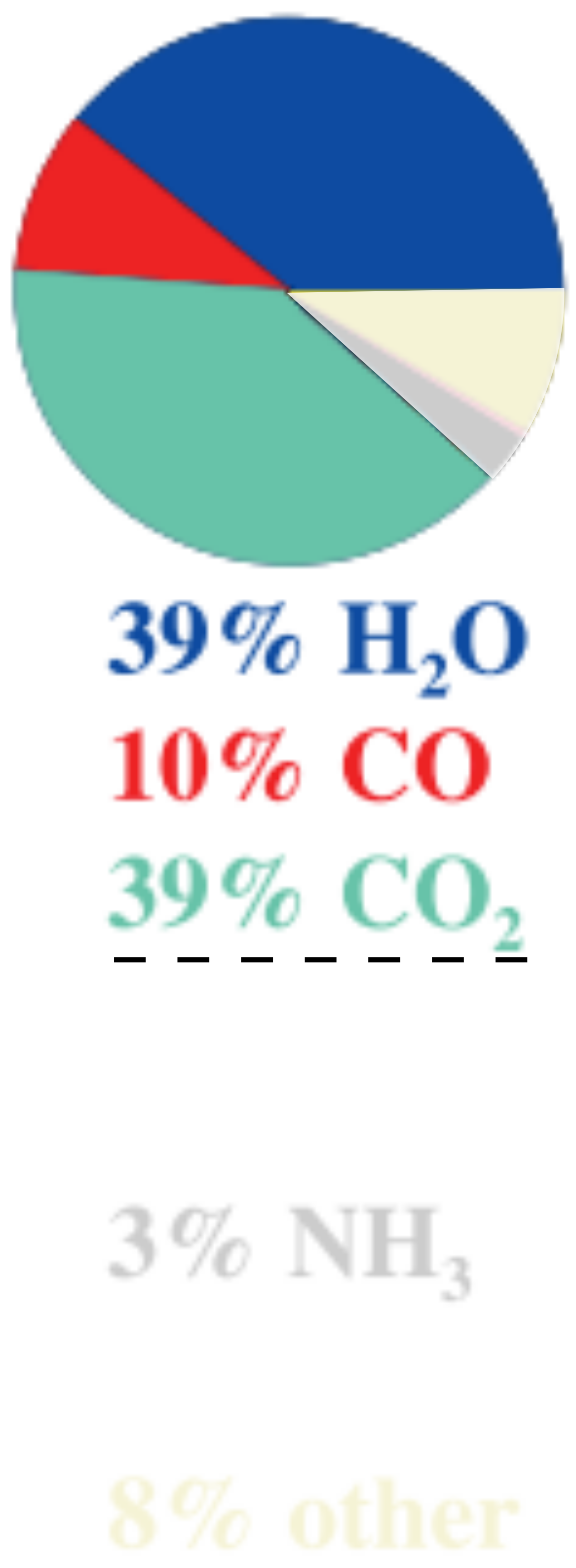


Ice abundances >30 AU

Infall + viscous spread
(inert grain interior)

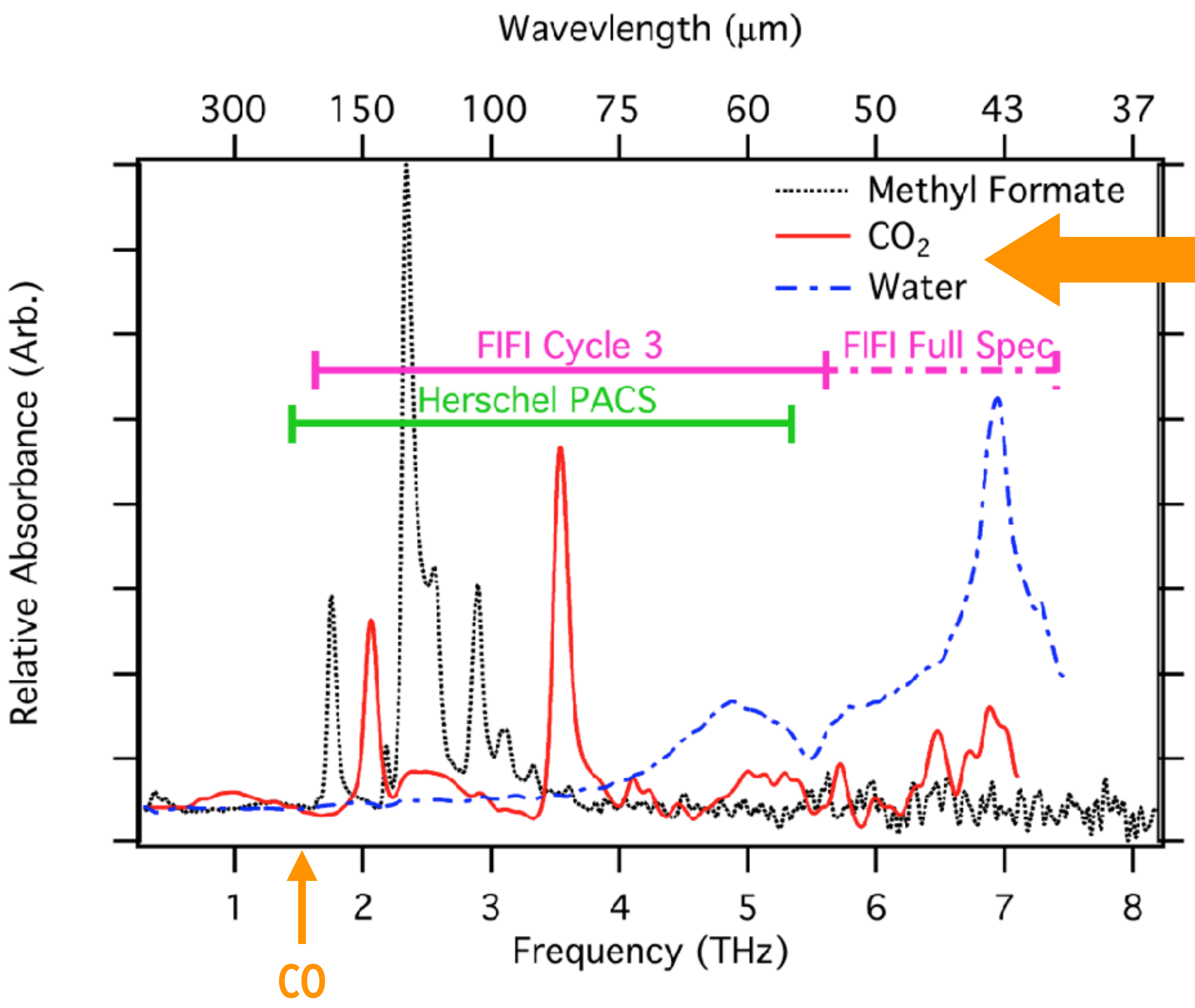


Infall
(active grain interior)

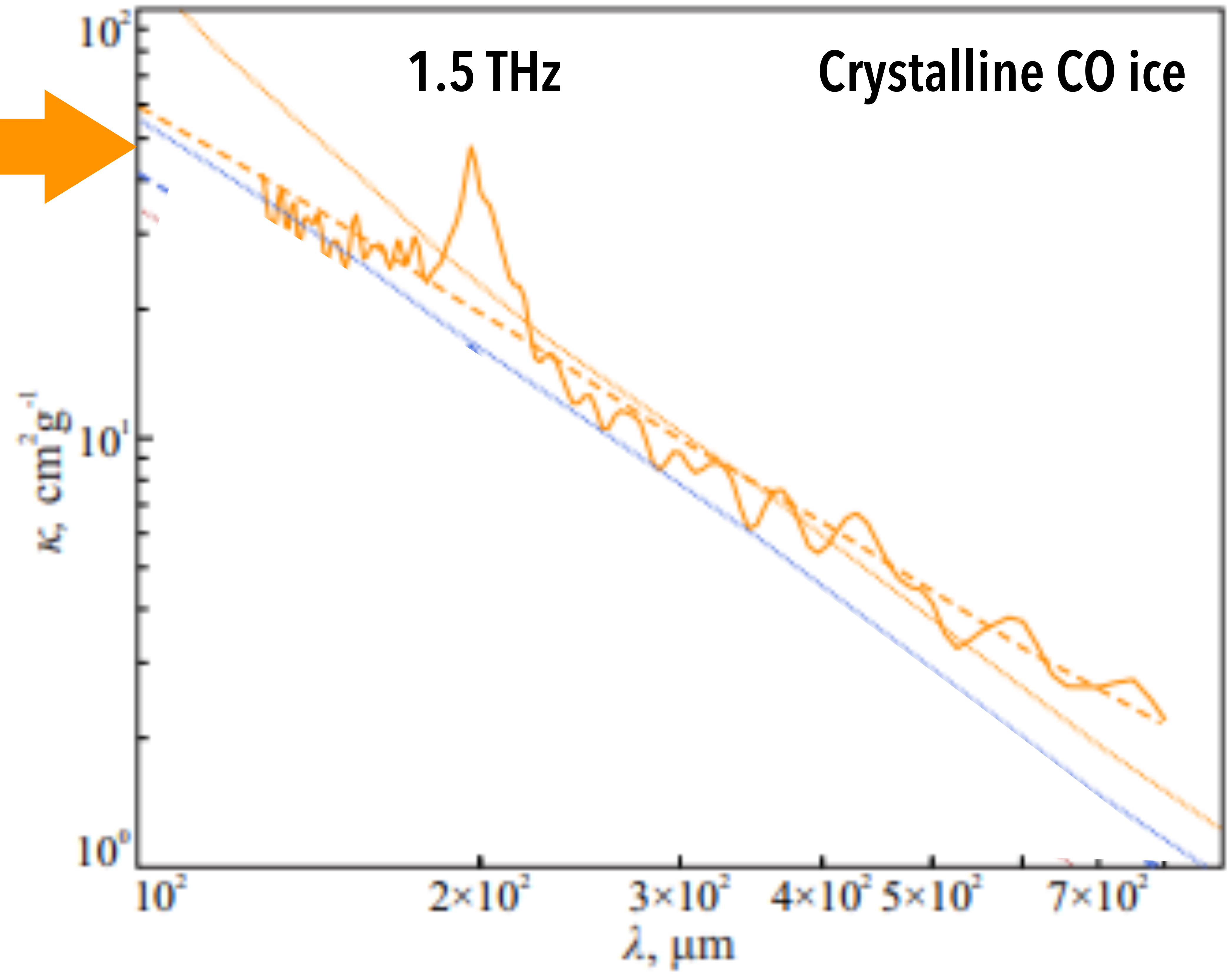


Drozdovskaya et al. (2017)

Far-Infrared hosts features from all of these 3 simple ices…

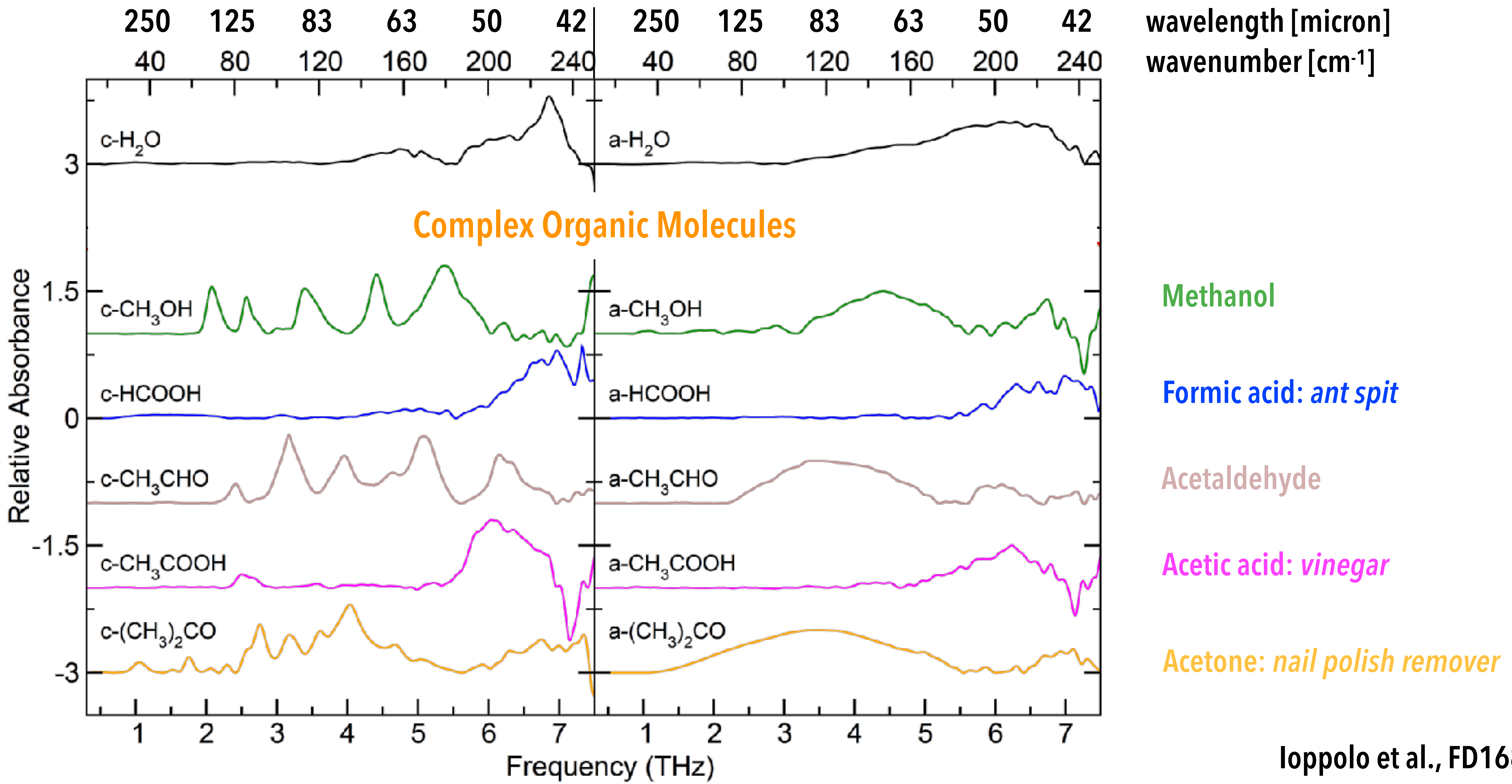


S. Ioppolo, private communication, McGuire, Ioppolo et al. (2016)



Giuliano et al. (2019)

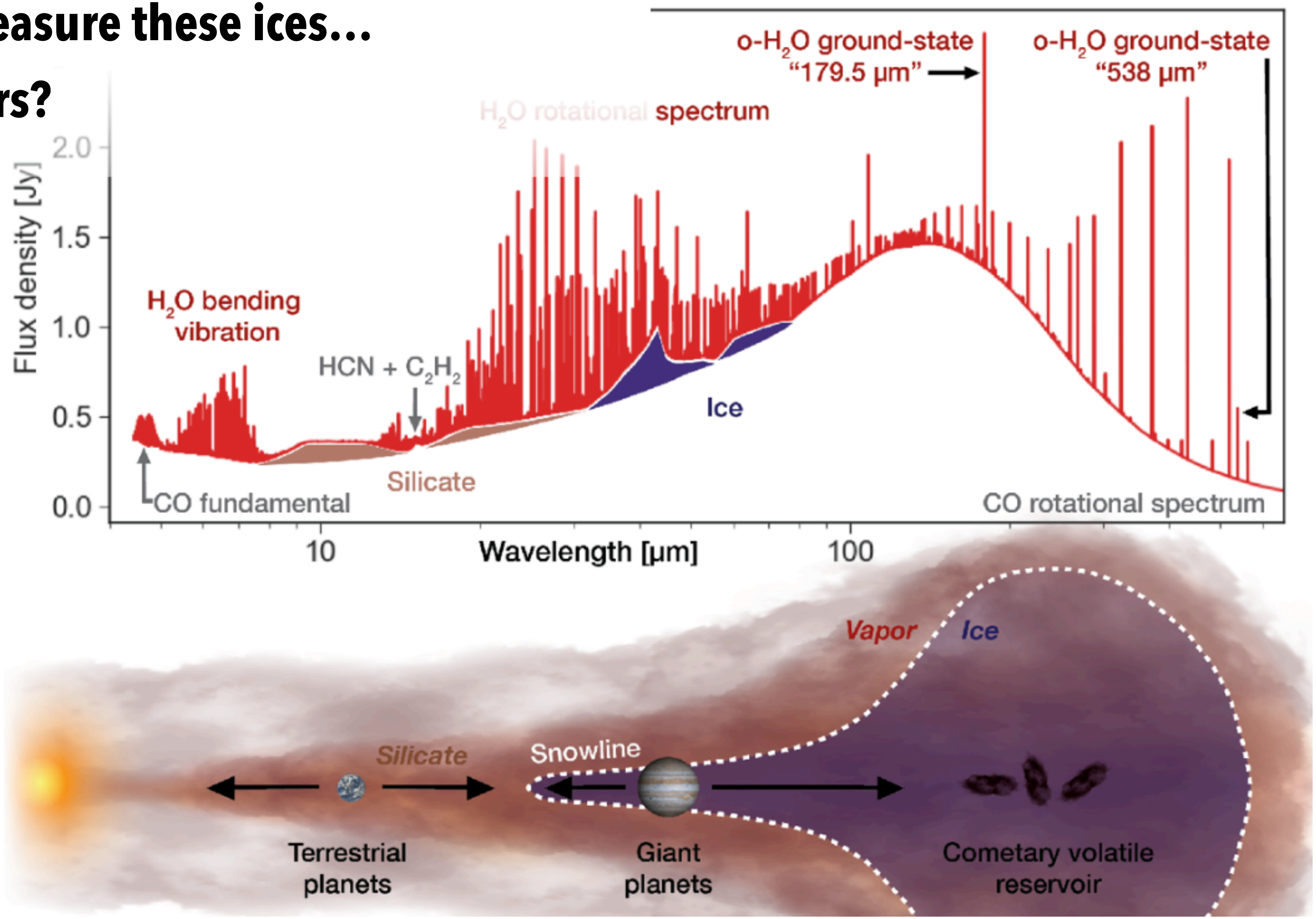
…and COM ices! Easier to separate than at mid-IR wavelengths (JWST).



Ioppolo et al., FD168 (2014)

OST/SPICA can measure these ices…

…but in >10 years?

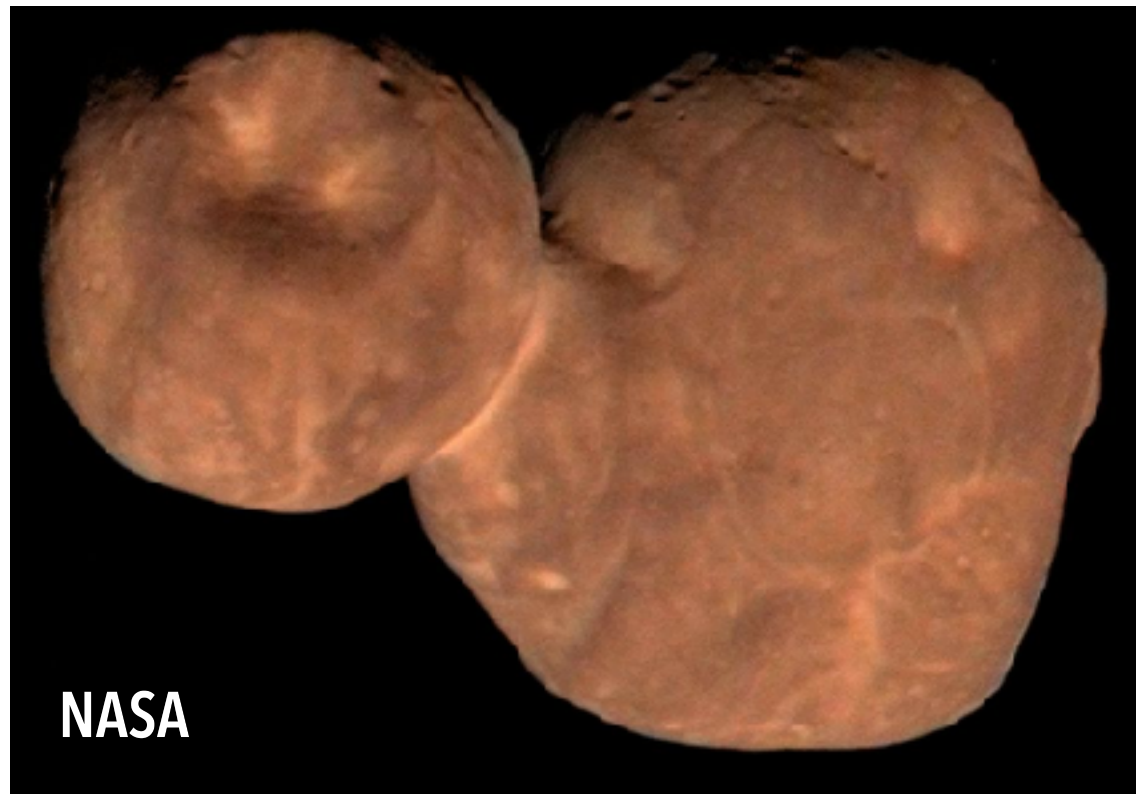


Pontoppidan et al. (2019)
OST white paper

(Timely) far-IR ice abundances connect disk compositions with Solar System.

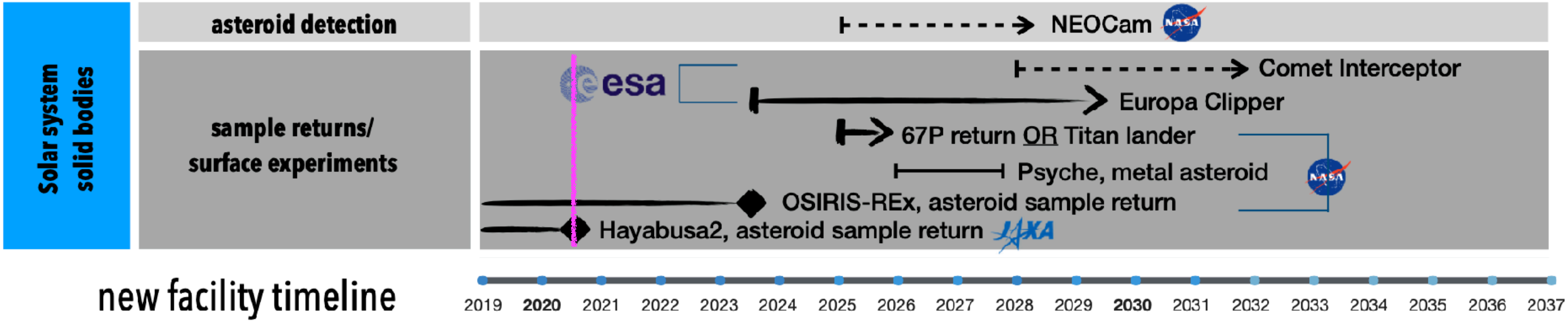
Comet 67P:
Excess C-solids
(Rubin et al. 2019)

C/2016 R2 (PanSTARRS):
Excess N_2, low H_2O
(Opitom et al. 2019)



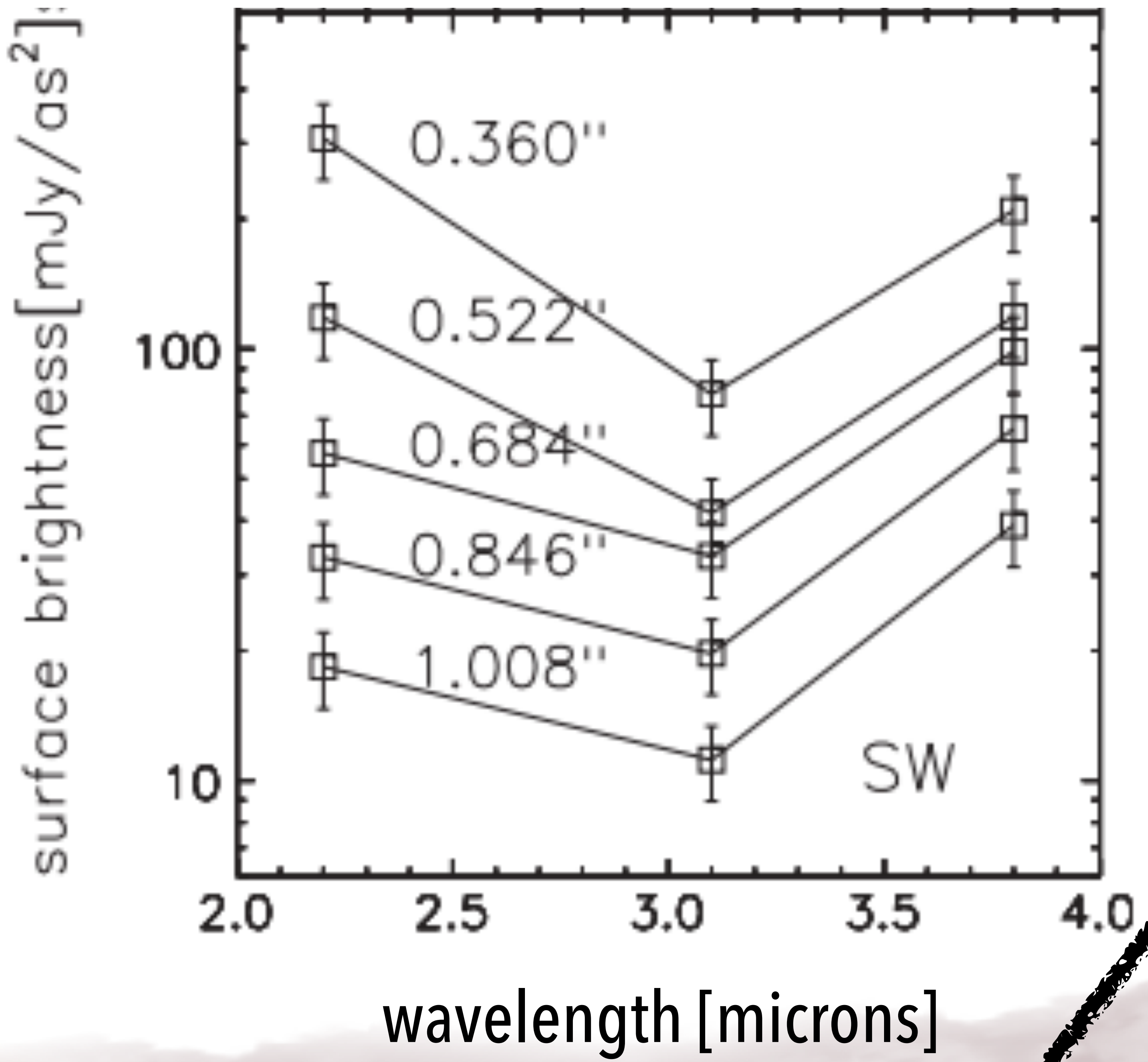
KBO Arrokoth:
Low H_2O, excess methanol
(Grundy et al. 2020)

Interstellar Oumuamua:
Red colour: organics, ices?
(Fitzsimmons et al. 2018)

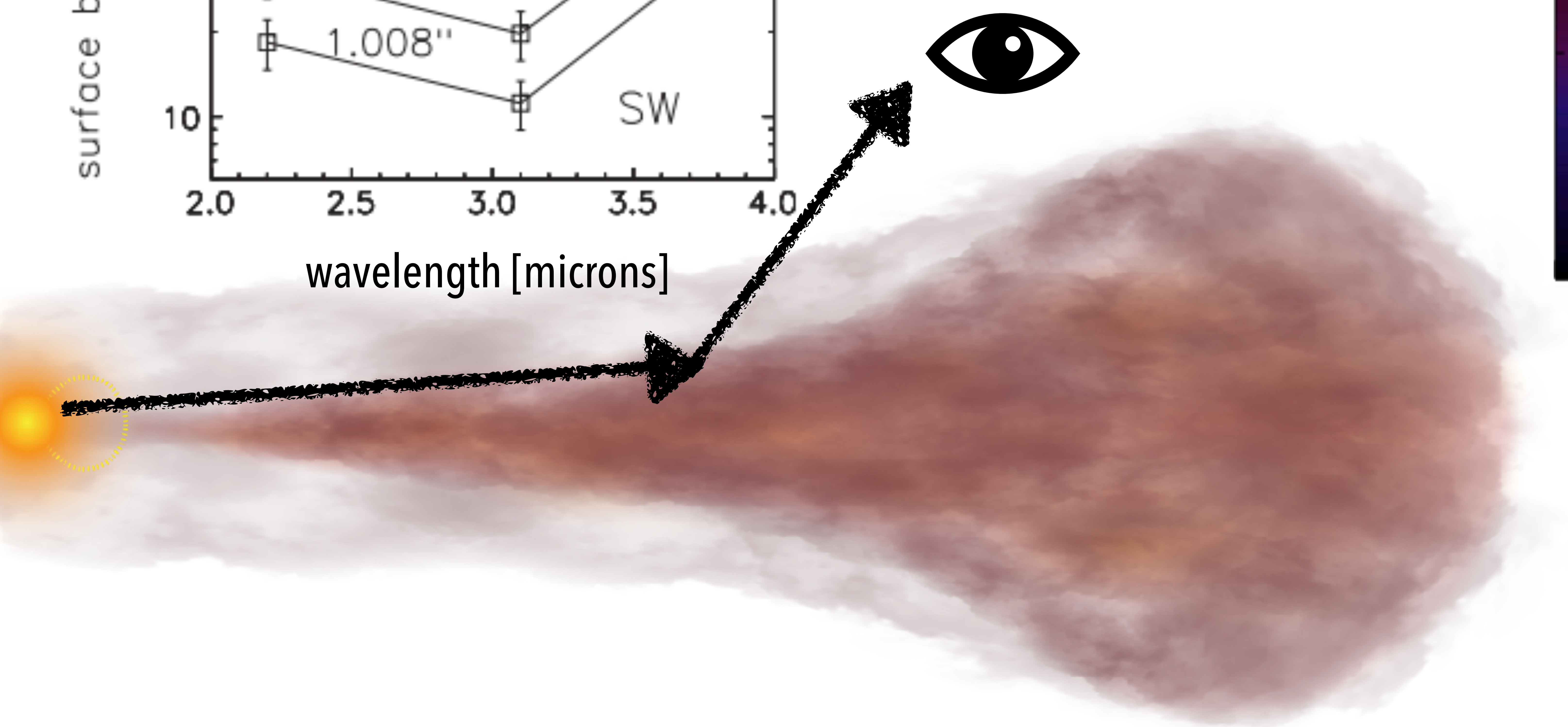


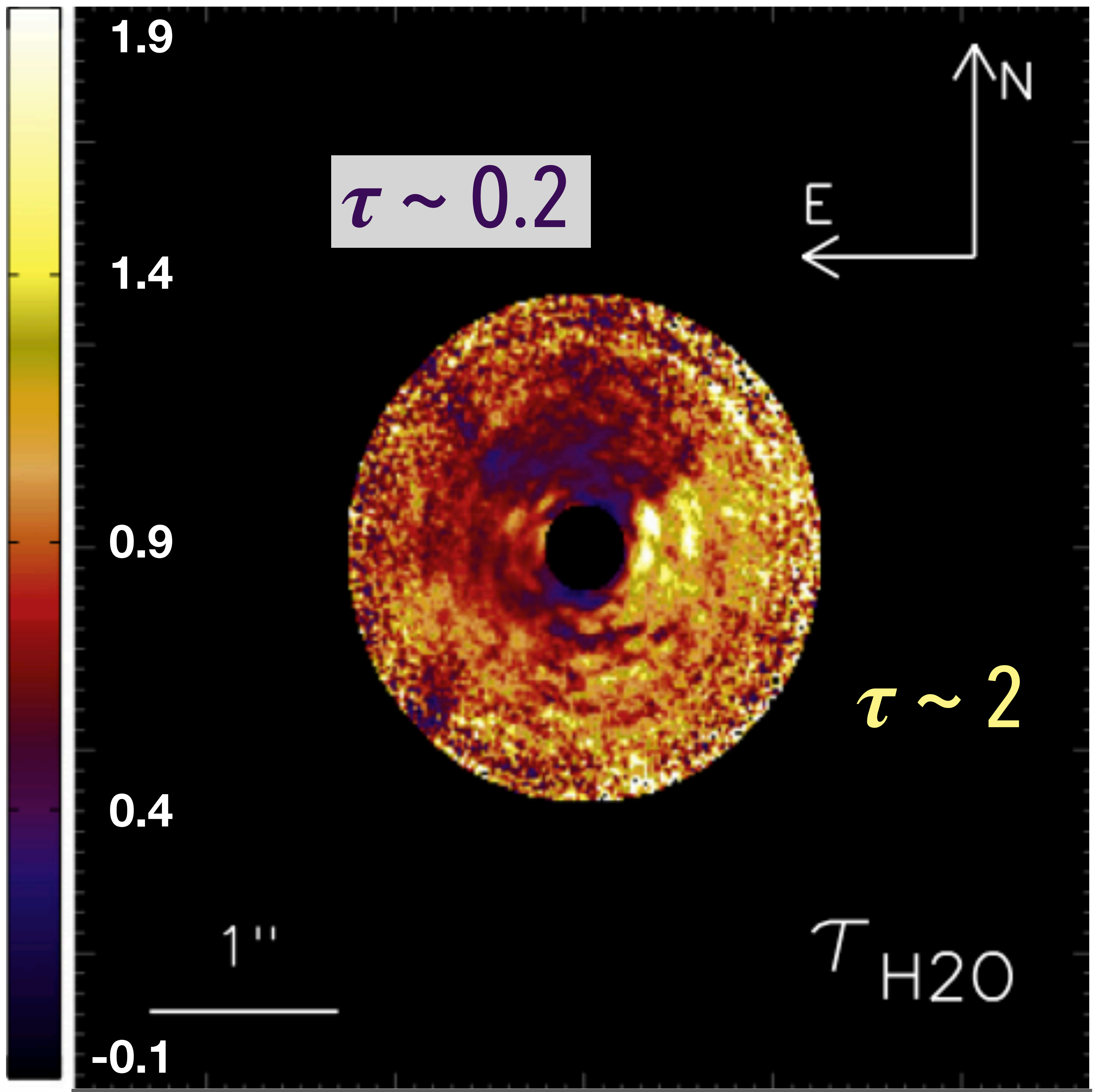
#3

Near-IR scattered light imaging probes ice spatial distribution.



- Narrow-band imaging, continuum + H_2O ice feature
- Stellar PSF removal

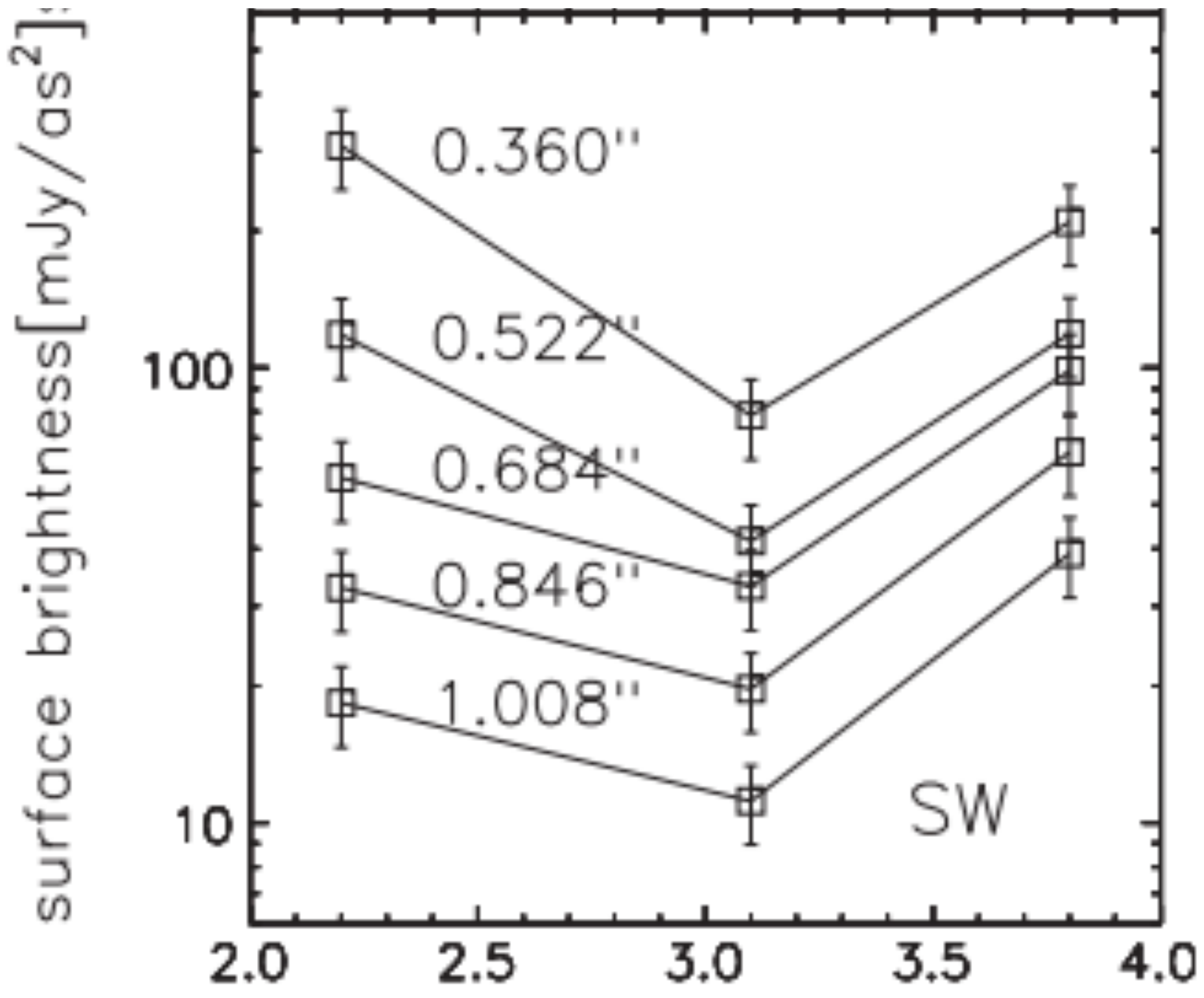




Honda et al. (2015), Gemini NICI, no coro.

HD 100546, 45° inclination

Near-IR scattered light imaging probes ice spatial distribution.



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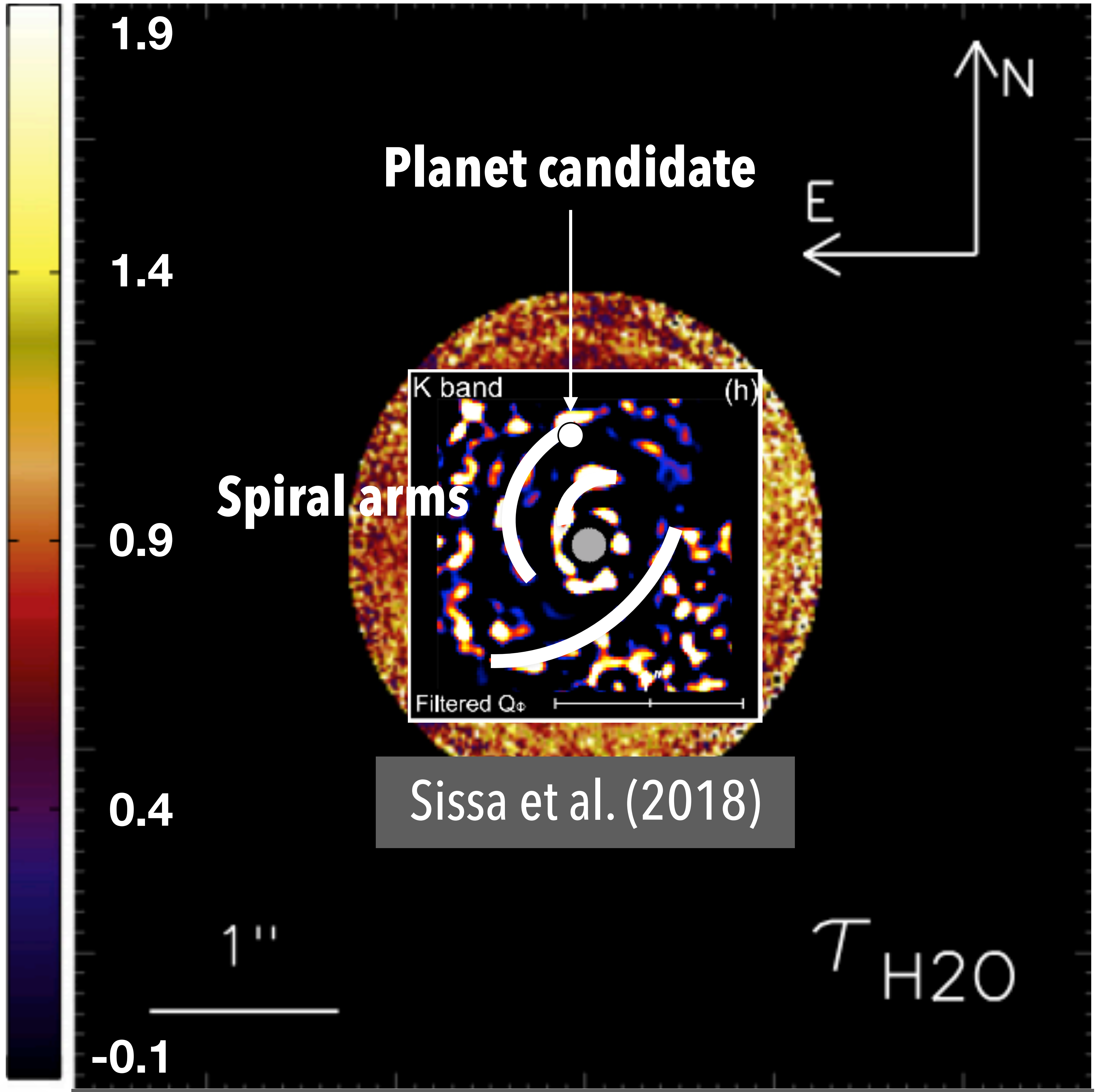
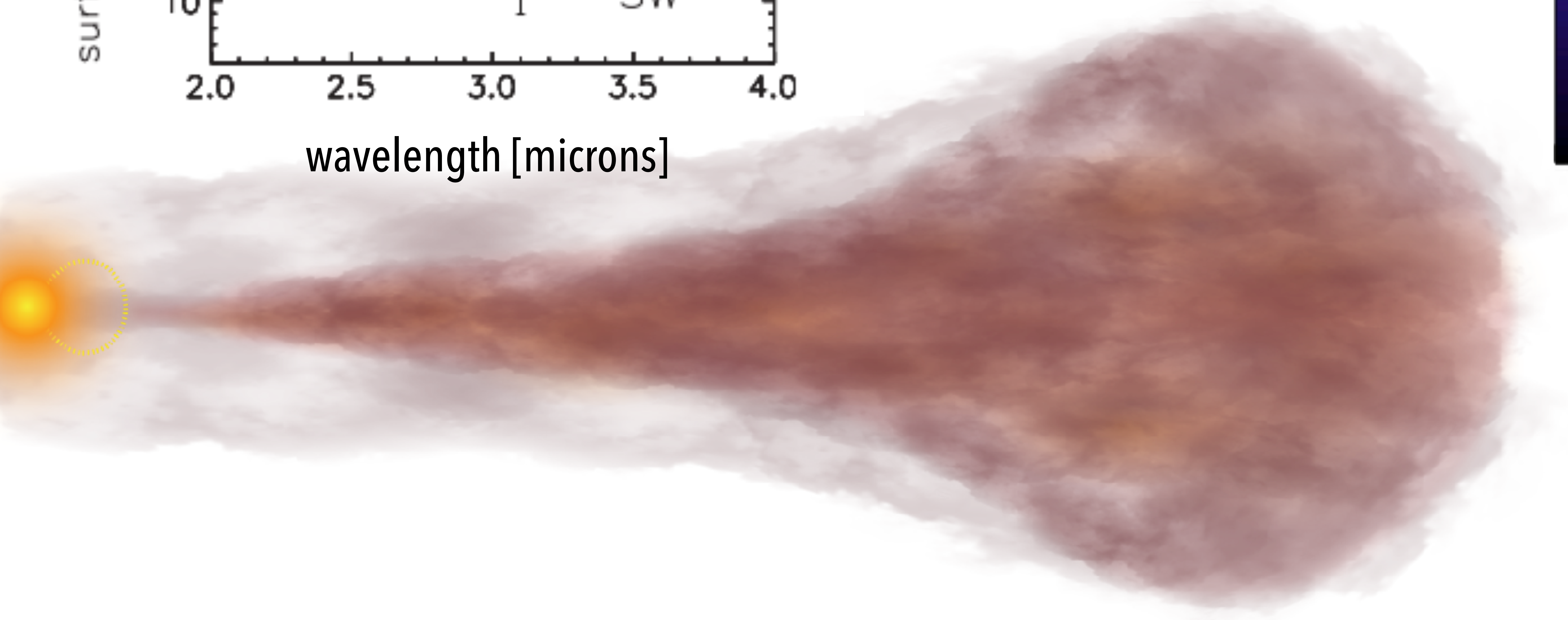
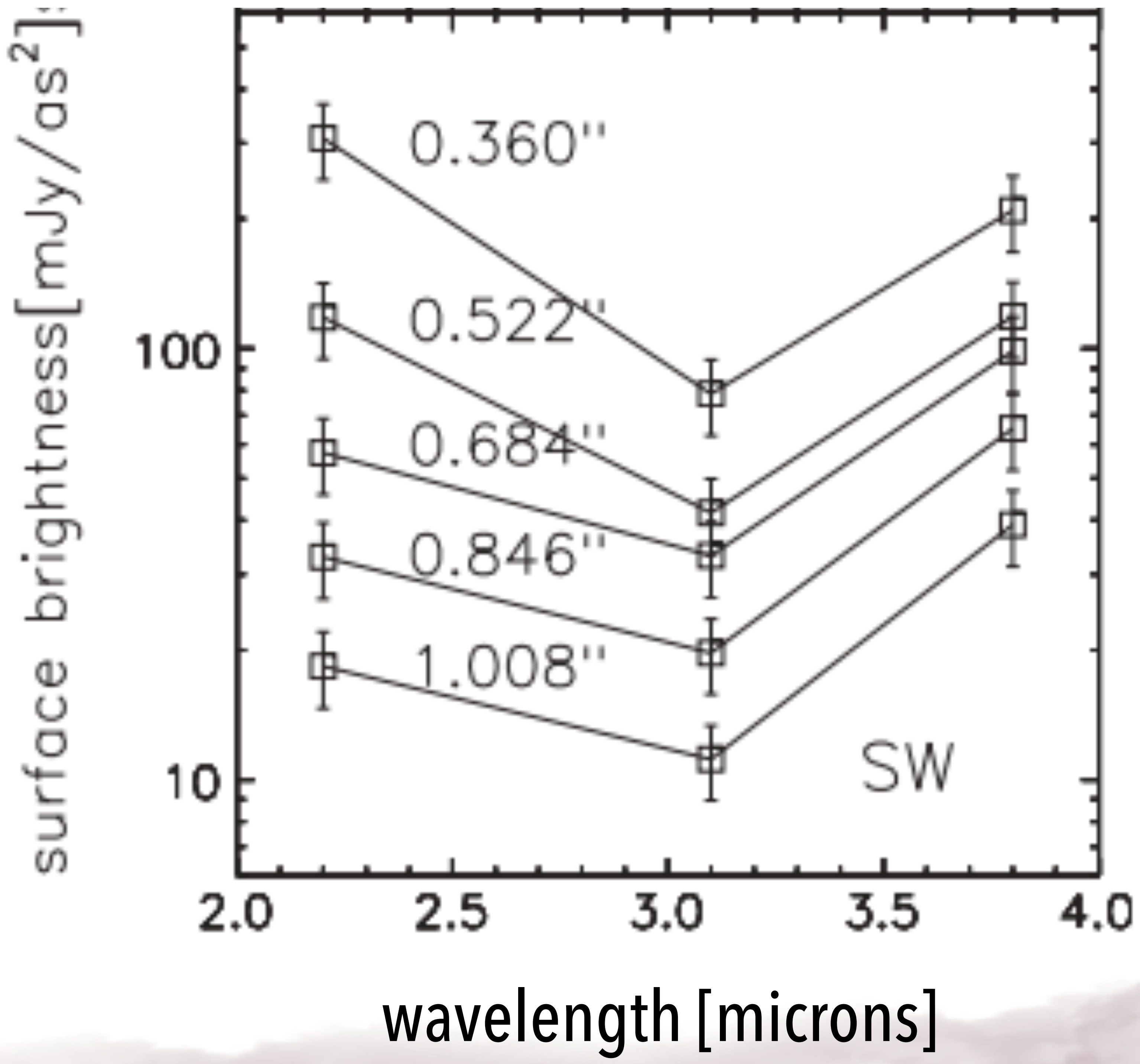


Honda et al. (2015), Gemini NICI, no coro.

HD 100546, 45° inclination



Near-IR scattered light imaging probes ice spatial distribution.



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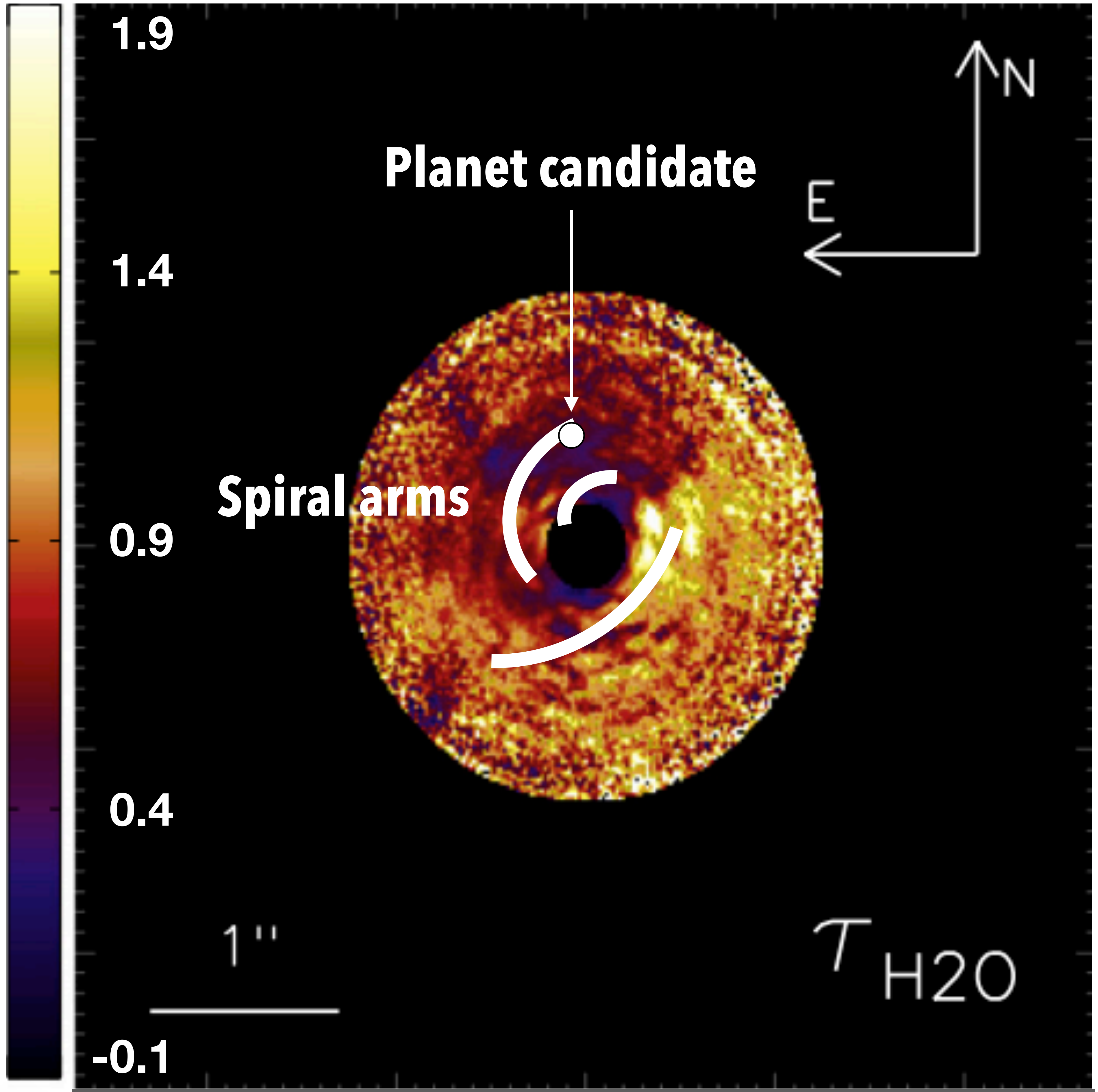
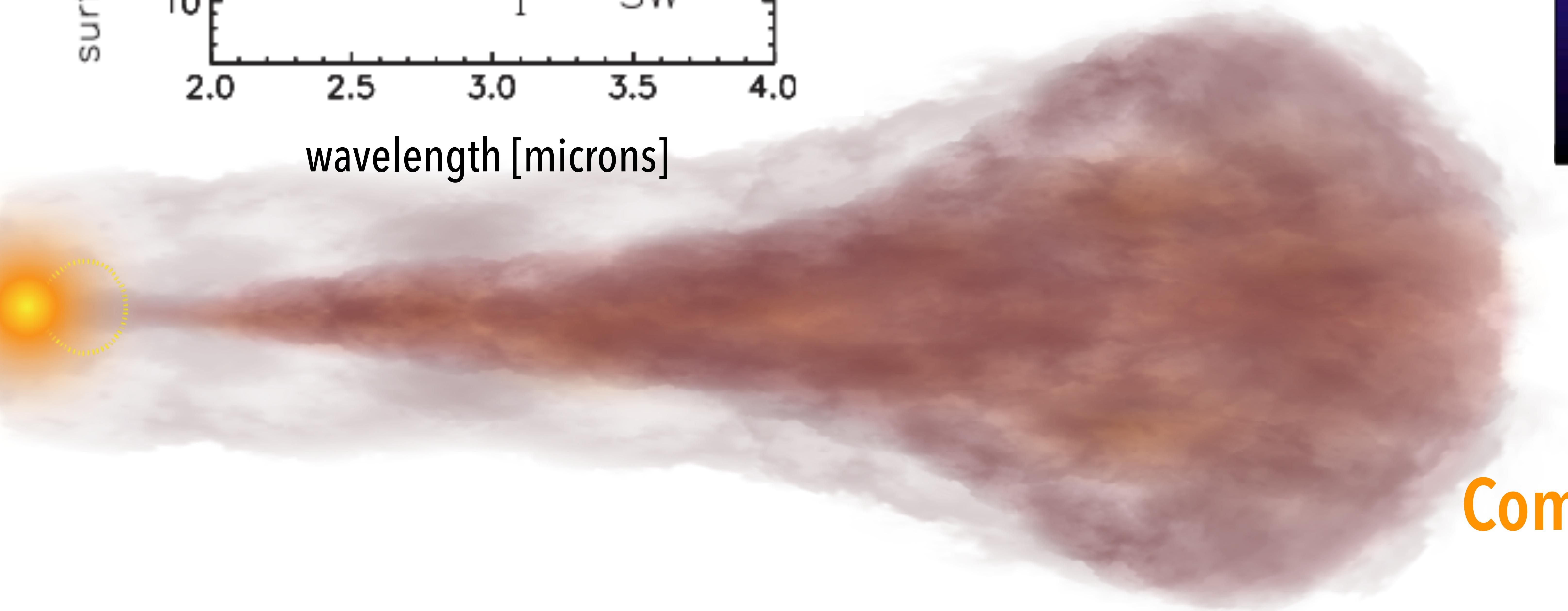
- Stellar PSF removal



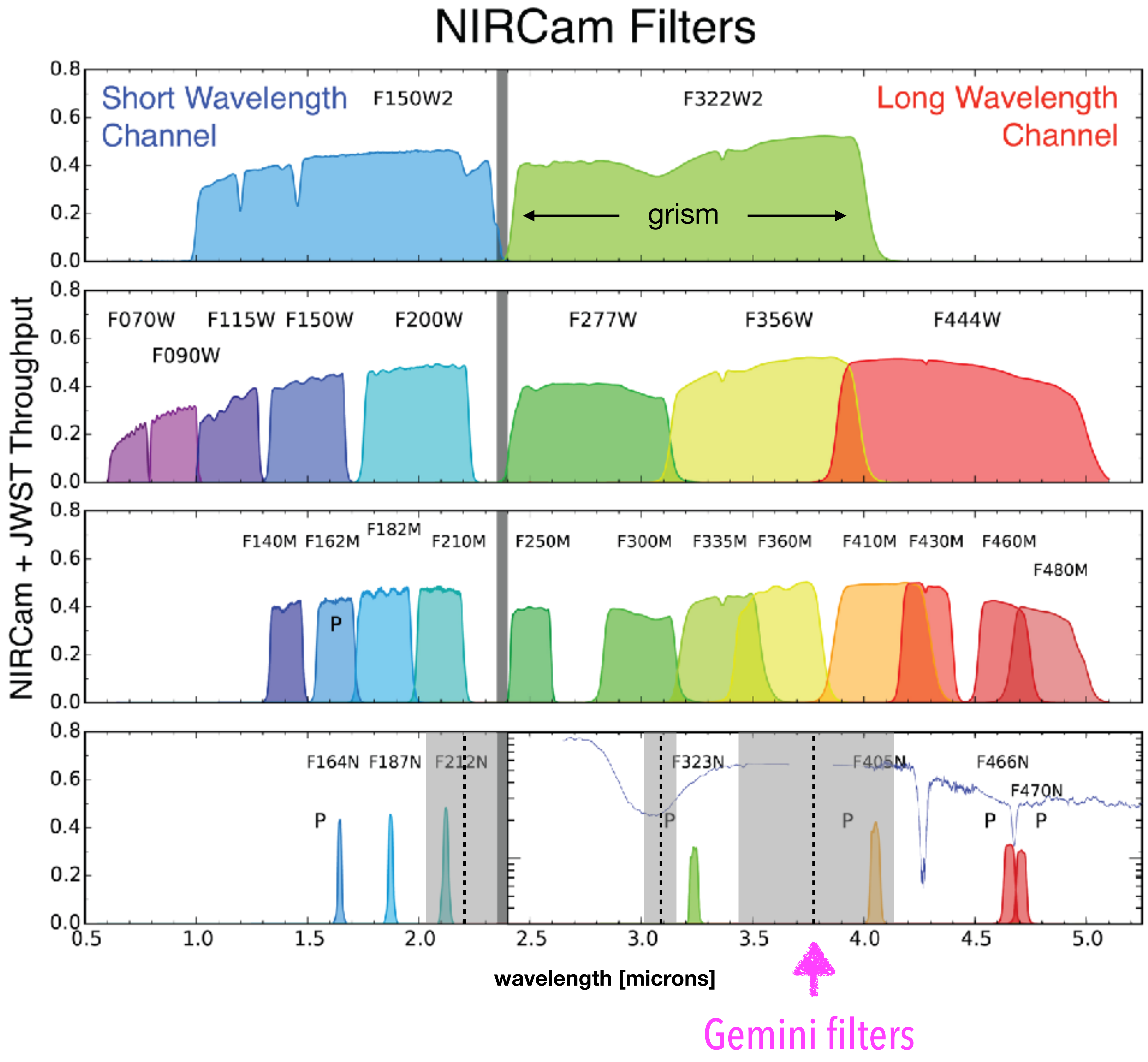
Honda et al. (2015), Gemini NICI, no coro.

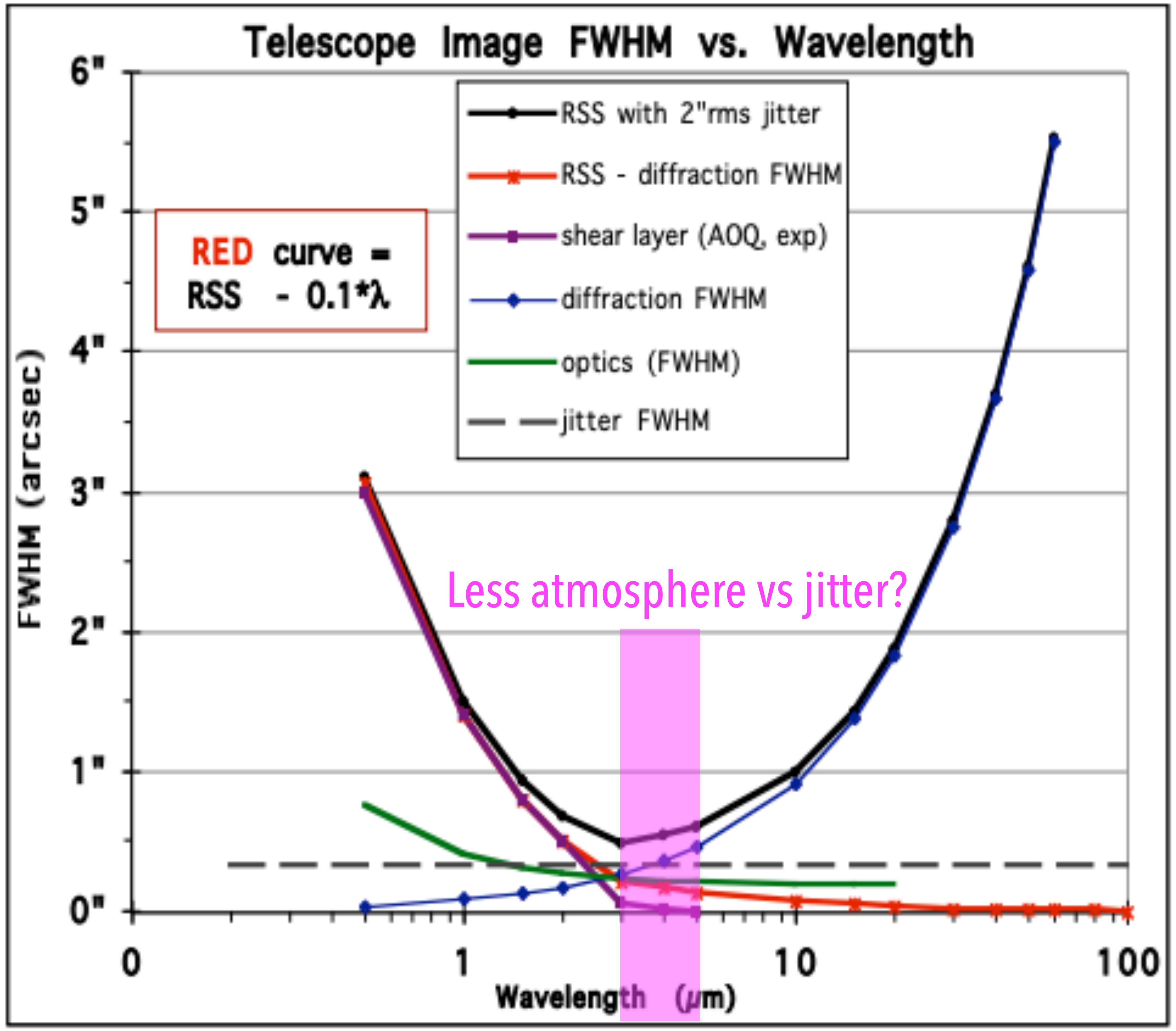
HD 100546, 45° inclination



Composition of accreting exoplanet?

JWST NIRCam lacks appropriate filters. NIRSpec IFU spaxels are 0."1: Room for SOFIA?





Potential targets with large enough disks.

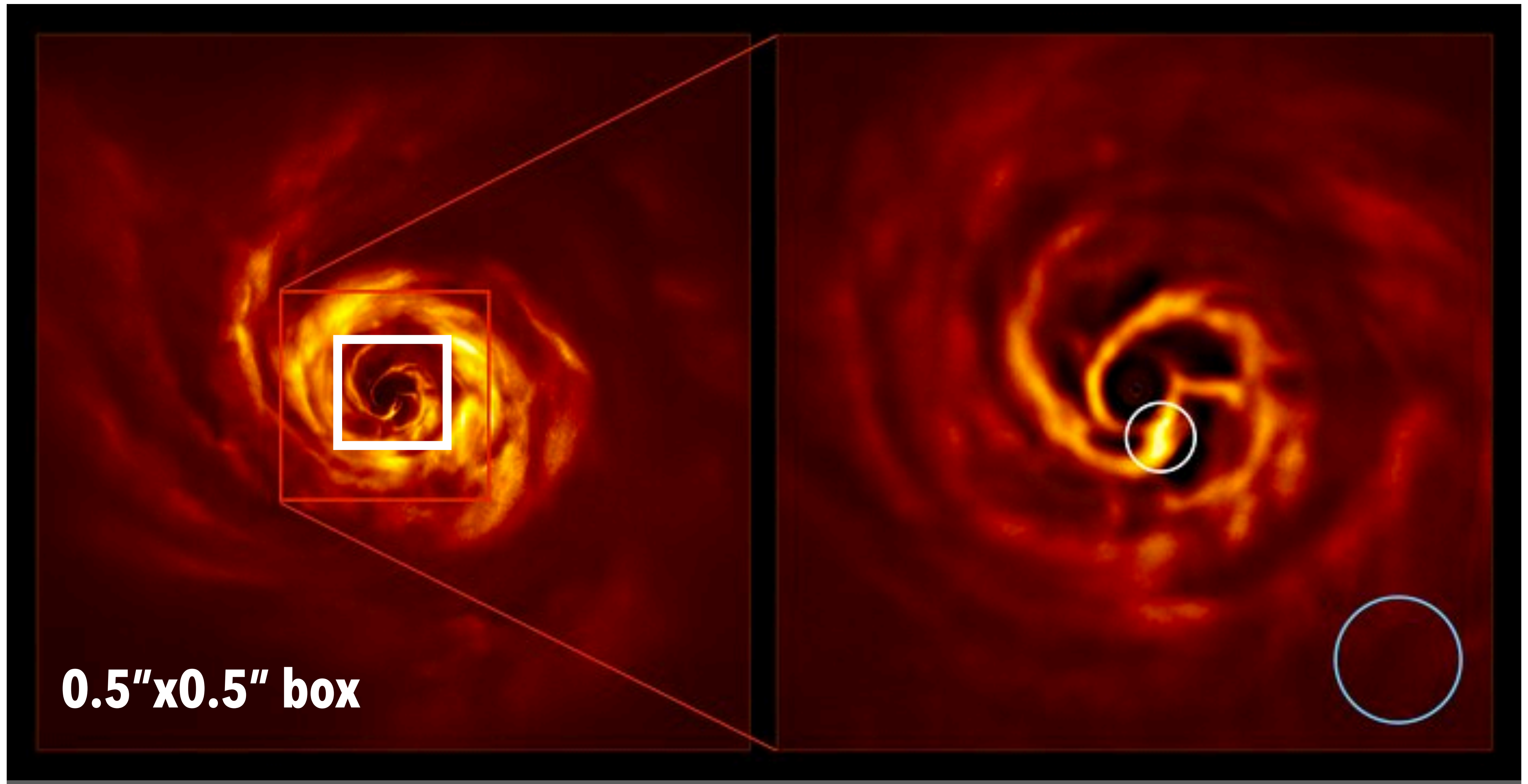


Image: ESO, SPHERE, AB Aurigae

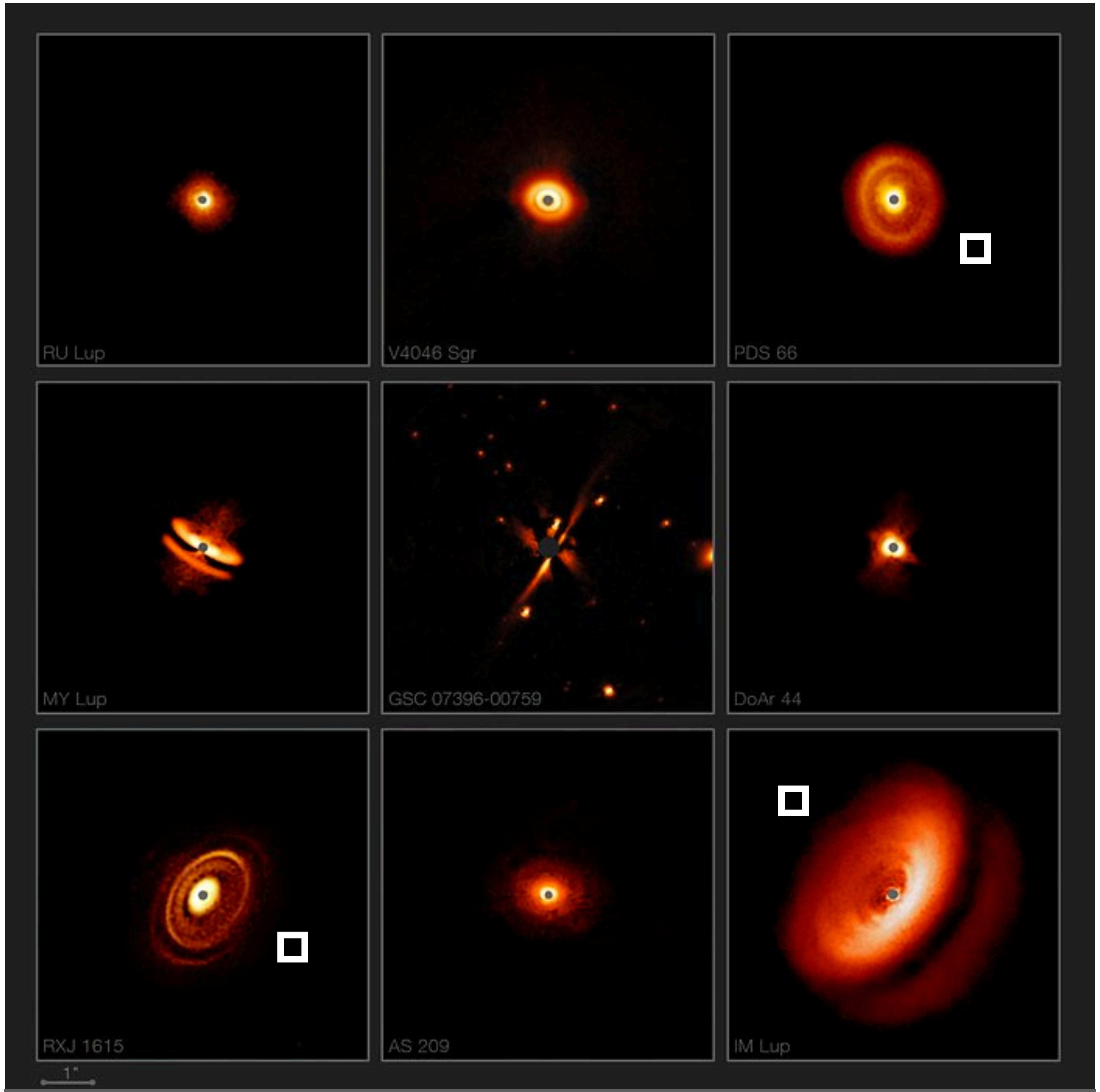
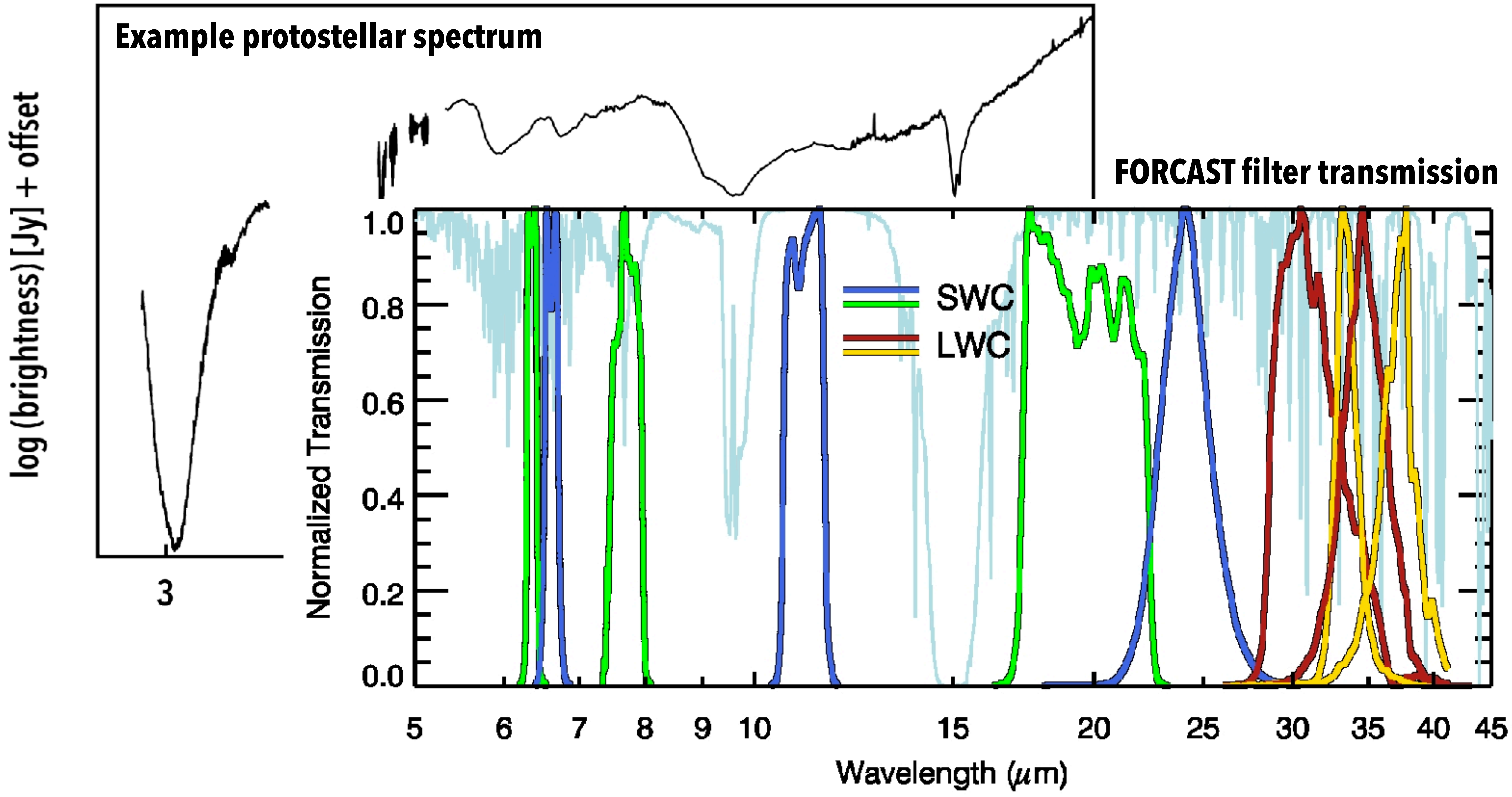


Image: ESO, SPHERE, DARTTS program, Avenhaus

Could additional narrow-band FORCAST filters provide similar measurements?



Summary & Conclusions

- **JWST and Solar System missions will make enormous gains in next 5-10 years for the "Origins of life" community.**

- **Thermal ice spectroscopy is key to connect and captialize on these results. Pre-OST/SPICA, we need a HIRMES-like instrument on SOFIA.**

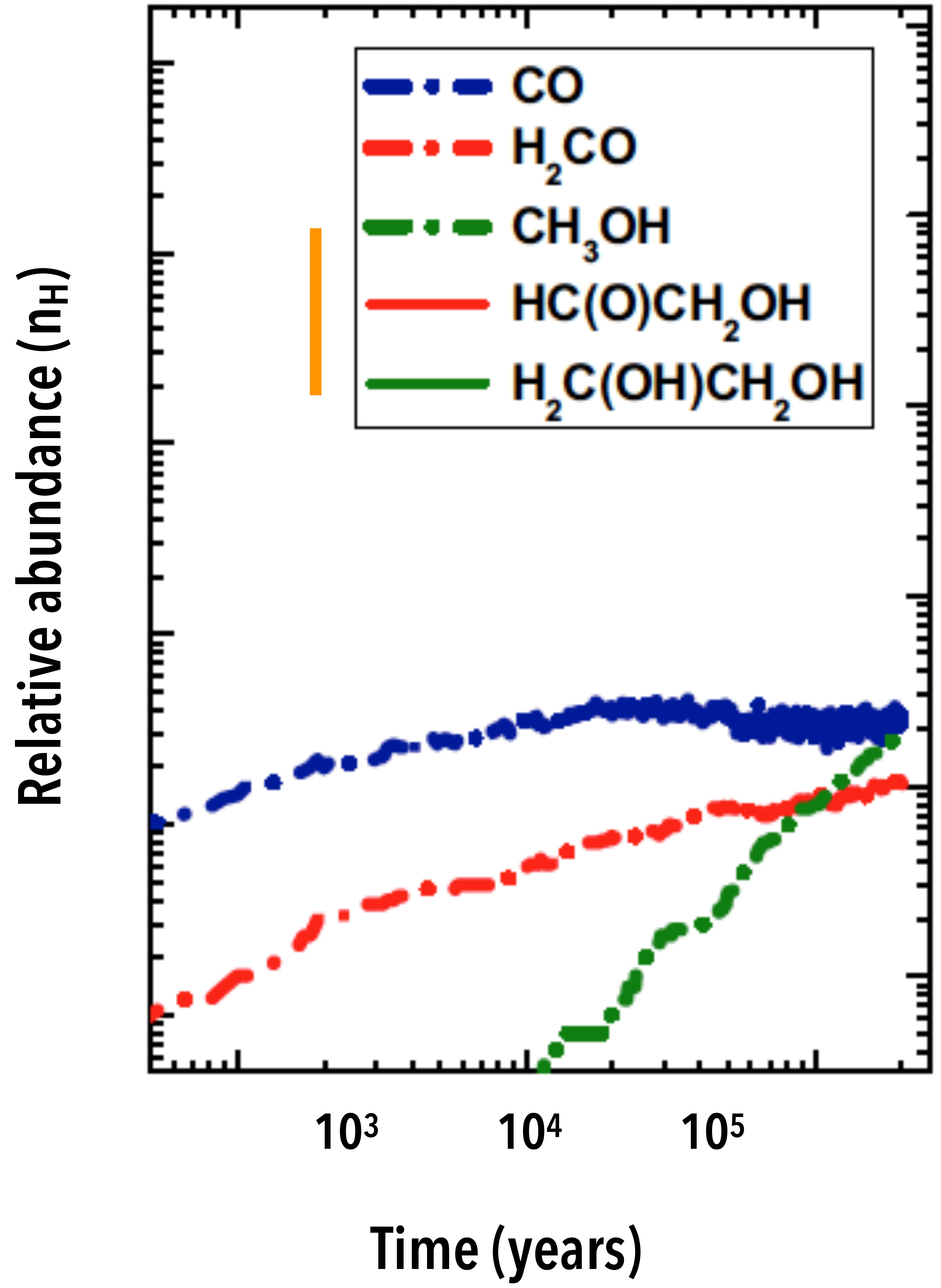
- **There are potential upgrades to FORCAST imaging that could help, but they cannot replace HIRMES' utility for this science case.**

Back-up slides…

Lab experiments show COMs readily form under cloud-like conditions.

Diffuse cloud

T=16.5 K, n_H=1 cm^{-3}



"simple" ices (methanol ~ CO)

Fedoseev et al. (2015), Leiden's Laboratory for Astrophysics

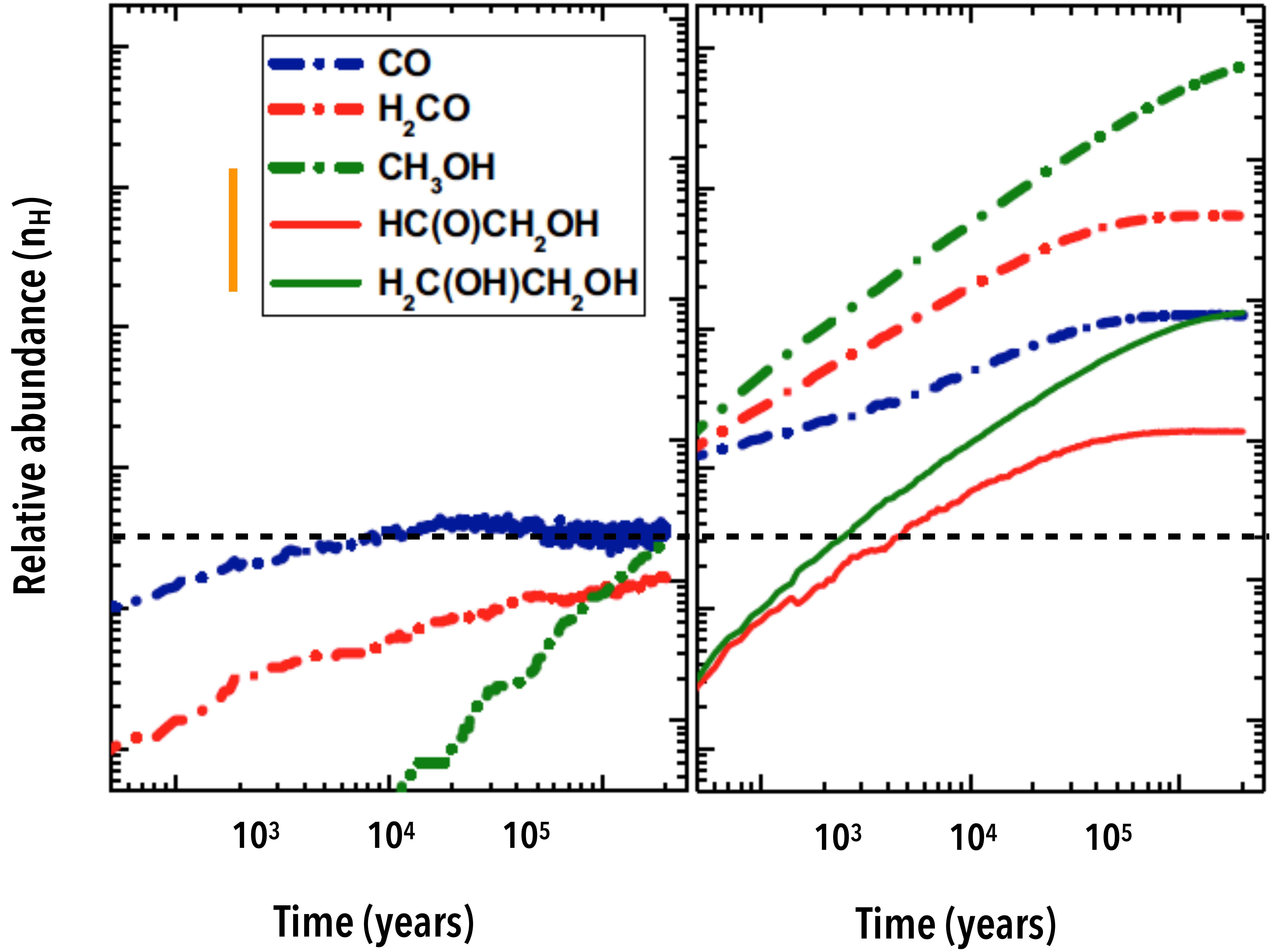
Lab experiments show COMs readily form under cloud-like conditions.

Diffuse cloud

$T=16.5$ K, $n_H=1$ cm^{-3}

Dense core

$T=12$ K, $n_H=10$ cm^{-3}



methanol

1.5 dex > CO

ethylene glycol

~ CO

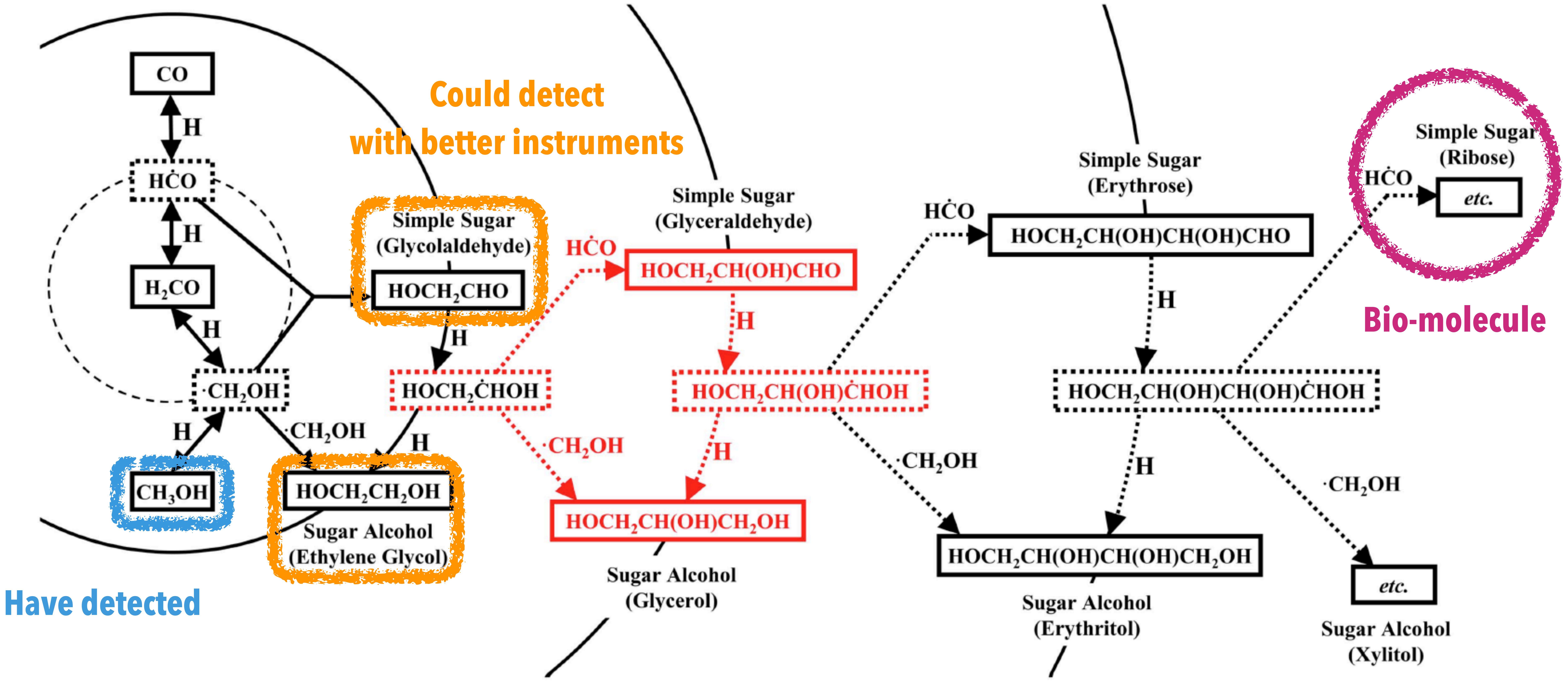
glycolaldehyde

= 1 dex < CO

COMs

Fedoseev et al. (2015), Leiden's Laboratory for Astrophysics

Forming simple sugars through atom-addition reactions in cold, dense cores.



Fedoseev et al. (2017), Leiden's Laboratory for Astrophysics

High quality observations should identify at least 5 COMs in ices.

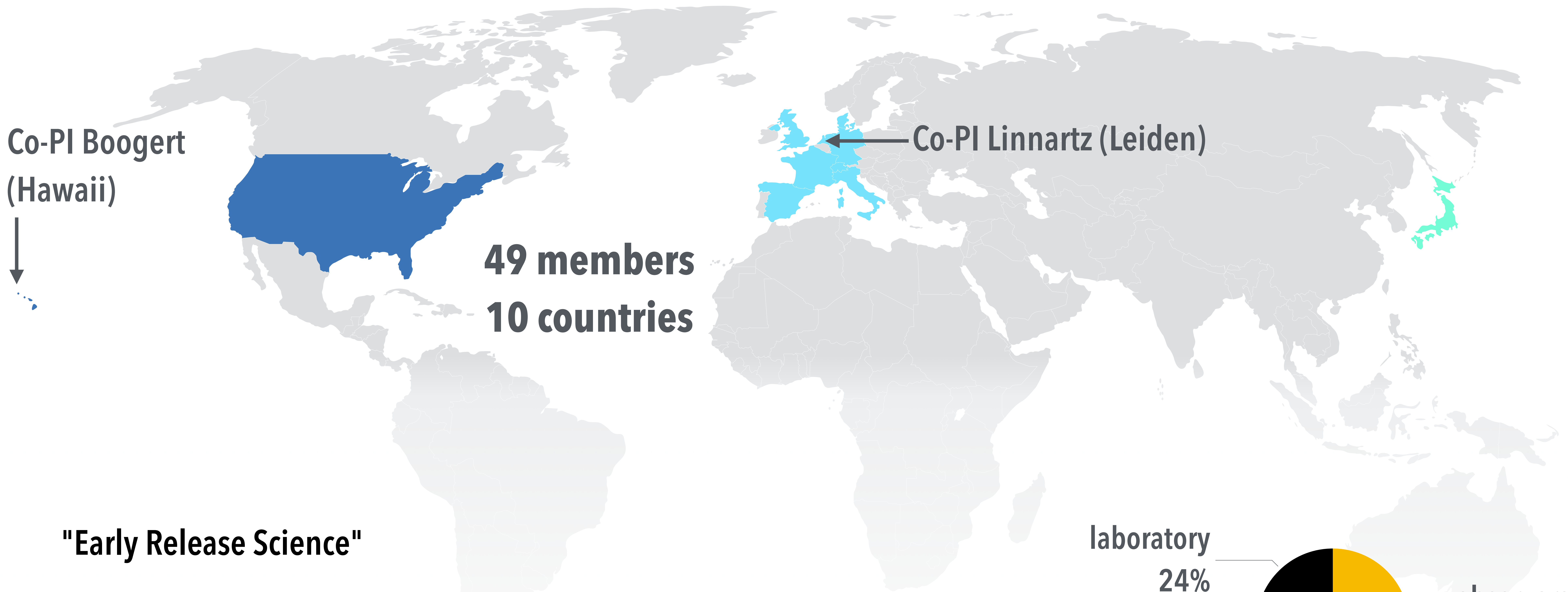
COM	formula	best ID features	References
methanol	CH_3OH	3.9, 6.75, 9.74 μm	Boogert et al. (2015)
ethanol	CH_3CH_2OH	7.24, 11.36 μm	Terwisscha van Scheltinga et al. (2018)
acetaldehyde	CH_3CHO	5.88, 7.427 μm	Terwisscha van Scheltinga et al. (2018)
dimethyl ether	CH_3OCH_3	8.011, 8.592 μm	Terwisscha van Scheltinga et al. (2018)
glycolaldehyde	$HC(O)CH_2\ OH$	5.88, 7.14, 9.1 μm	Fedoseev et al. (2017)
ethylene glycol	$H_2\ C(OH)CH_2\ OH$	~9.1 – 10 μm	Fedoseev et al. (2017)

High quality observations should identify at least 5 COMs in ices.

COM	formula	best ID features	References
methanol	CH_3OH	3.9, 6.75, 9.74 µm	Boogert et al. (2015)
ethanol	CH_3CH_2OH	7.24, 11.36 µm	Terwisscha van Scheltinga et al. (2018)
acetaldehyde	CH_3CHO	5.88, 7.427 µm	Terwisscha van Scheltinga et al. (2018)
dimethyl ether	CH_3OCH_3	8.011, 8.592 µm	Terwisscha van Scheltinga et al. (2018)
glycolaldehyde	$HC(O)CH_2$ OH	5.88, 7.14, 9.1 µm	Fedoseev et al. (2017)
ethylene glycol	H_2 $C(OH)CH_2$ OH	~9.1 – 10 µm	Fedoseev et al. (2017)

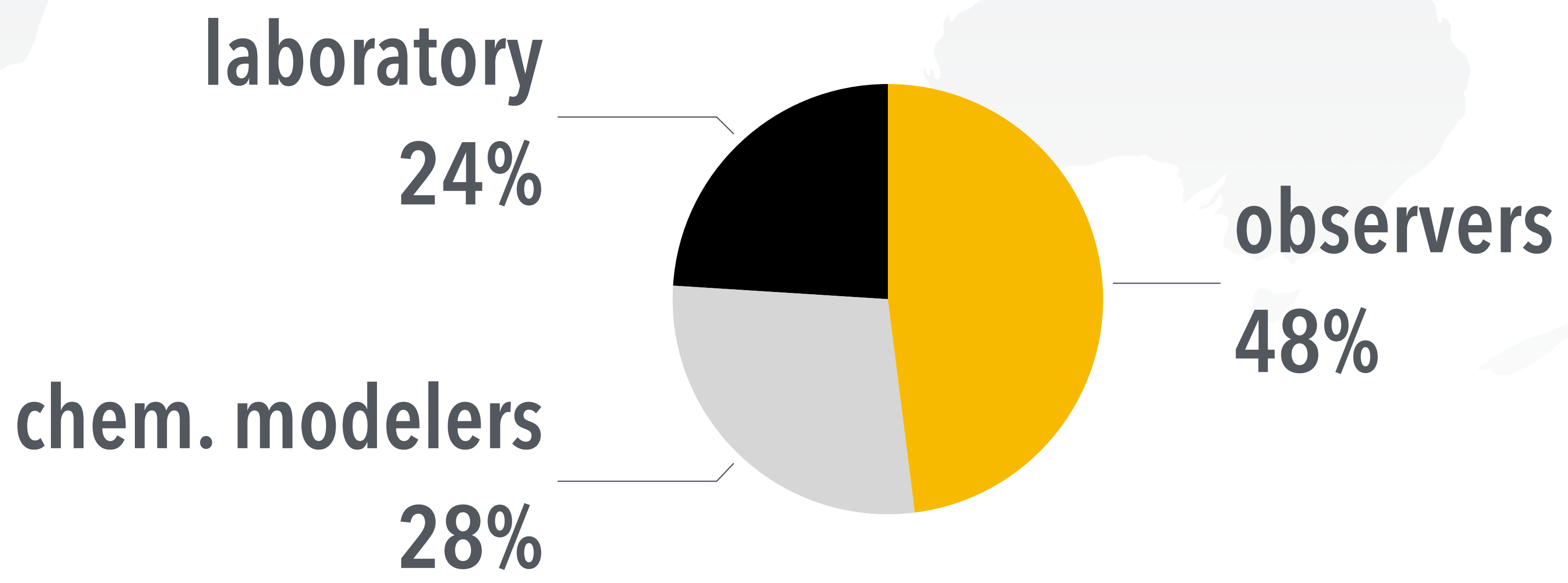
More COMs to come from
Leiden Laboratory for Astrophysics

JWST IceAge ERS Program (PI McClure)



"Early Release Science"

- will be executed in the ***first 5 months of observations***
- competitively selected (13 of 106 proposals)
- only 1 star formation proposal



Feedback between observations, laboratory work, and chemical modeling is critical.

2. Models

- Physical conditions of individual regions + laboratory absorbances/opacities

↓

- Simple ice + COM abundances
- Object brightness vs wavelength

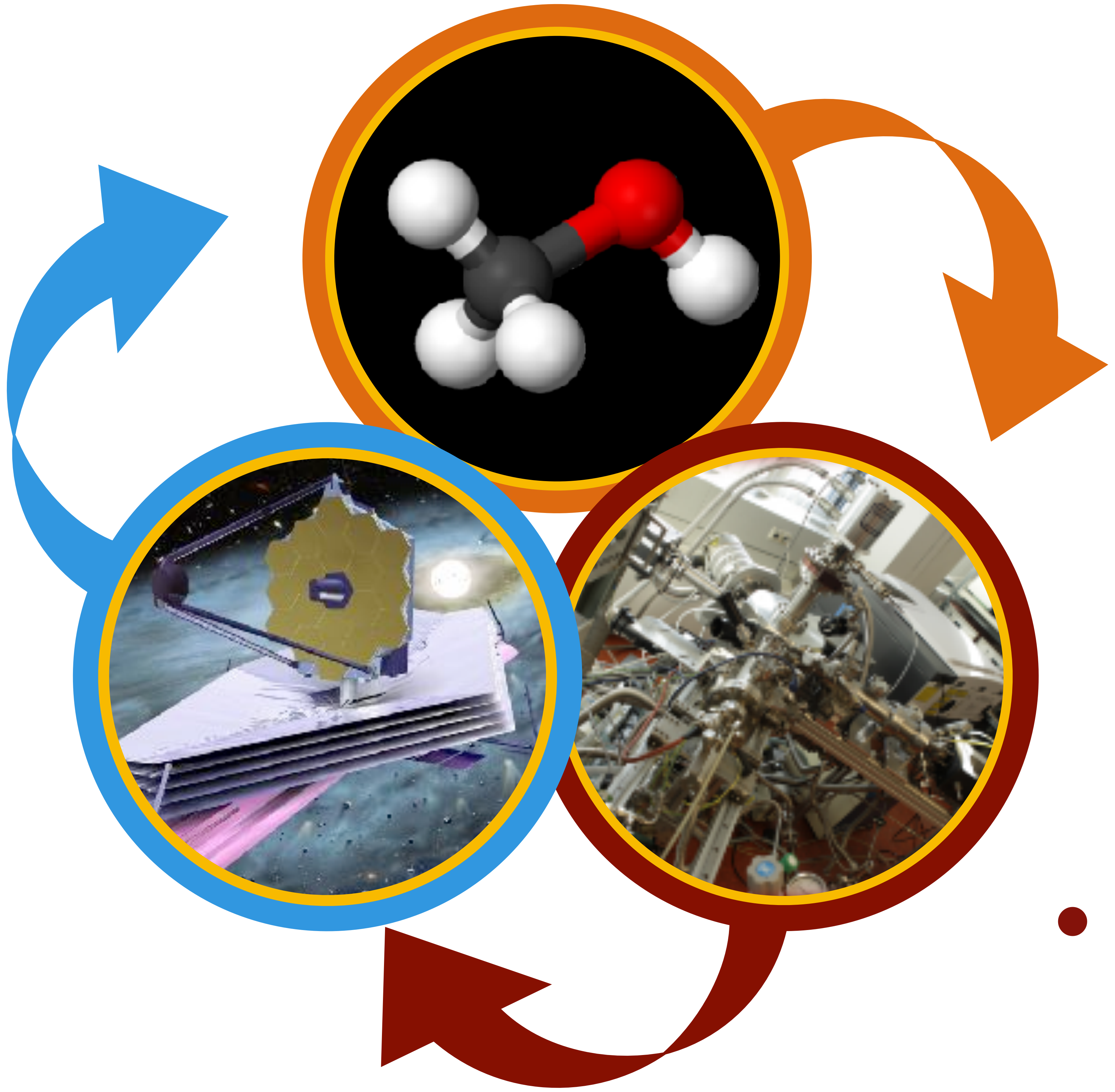
1. Observations

(JWST launches March 2021)

- dense core (#0)
- one disk (#2)

↓

Detect 5 simple ices + 5 pre-biotic, icy COMs.



3. Laboratory Data

Leiden Laboratory for Astrophysics

- Spectroscopy of simple ices, range of T, mixing ratios

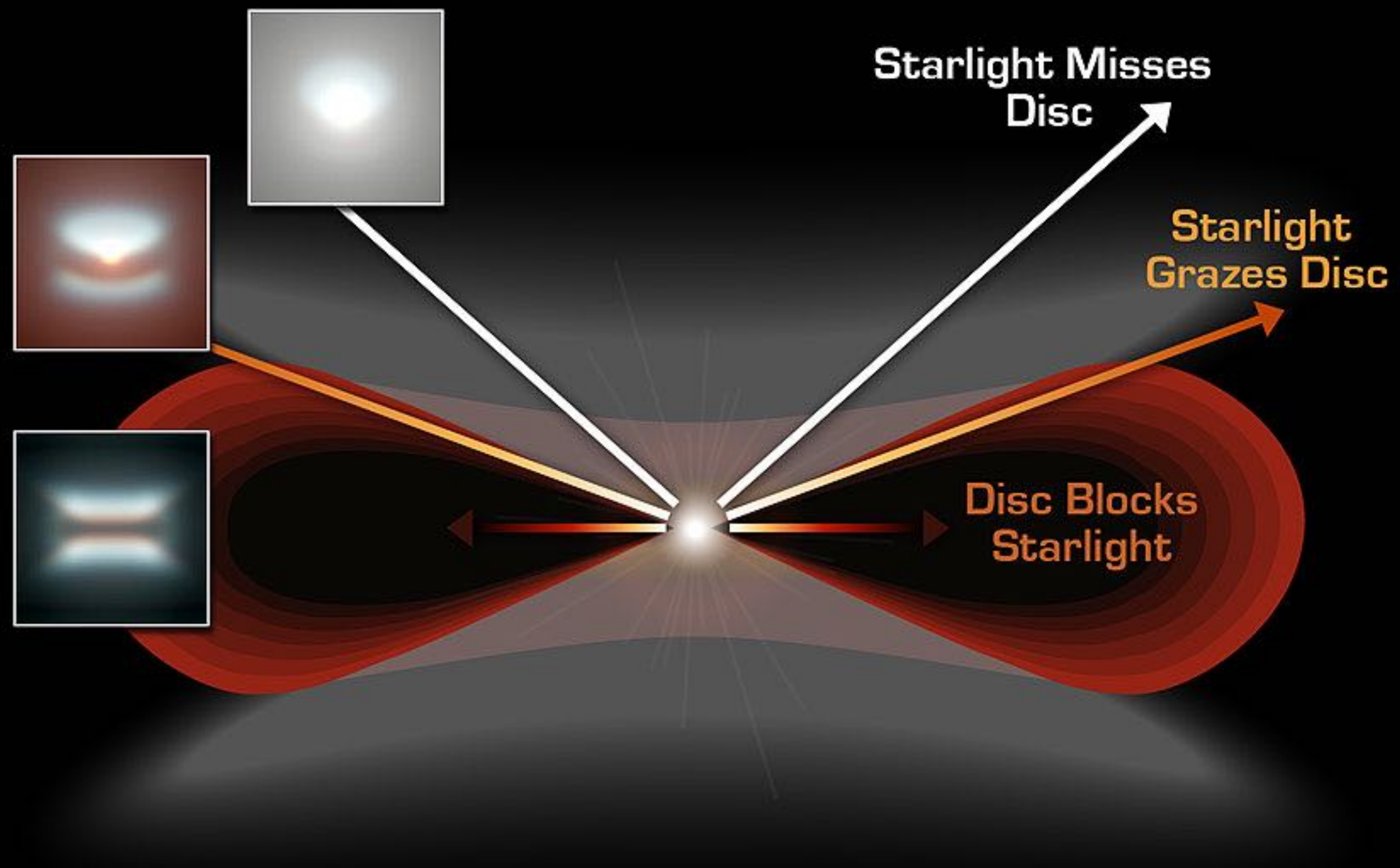
(new: 2010 - present)

- COM formation rates under cloud conditions
- Spectroscopy of COM ices (to identify in mid-infrared)

informs observational requirements

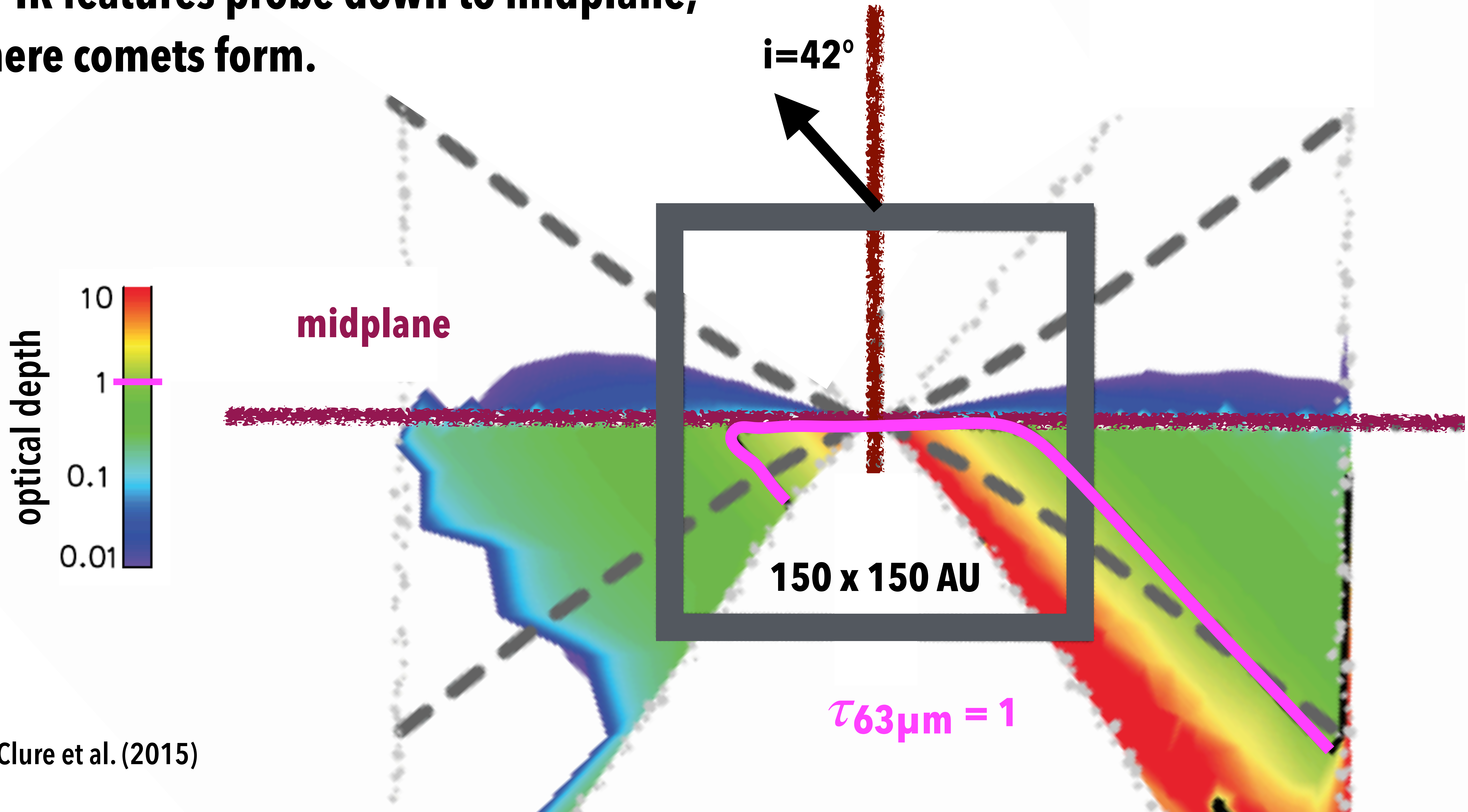
JWST-MIRI EU Guaranteed Time Observations star formation program

Observations of 12 protostars & 4 edge-on disks (ices), 36 other disks, probe ice in different heights.



Pontoppidan et al. 2005

Far-IR features probe down to midplane, where comets form.

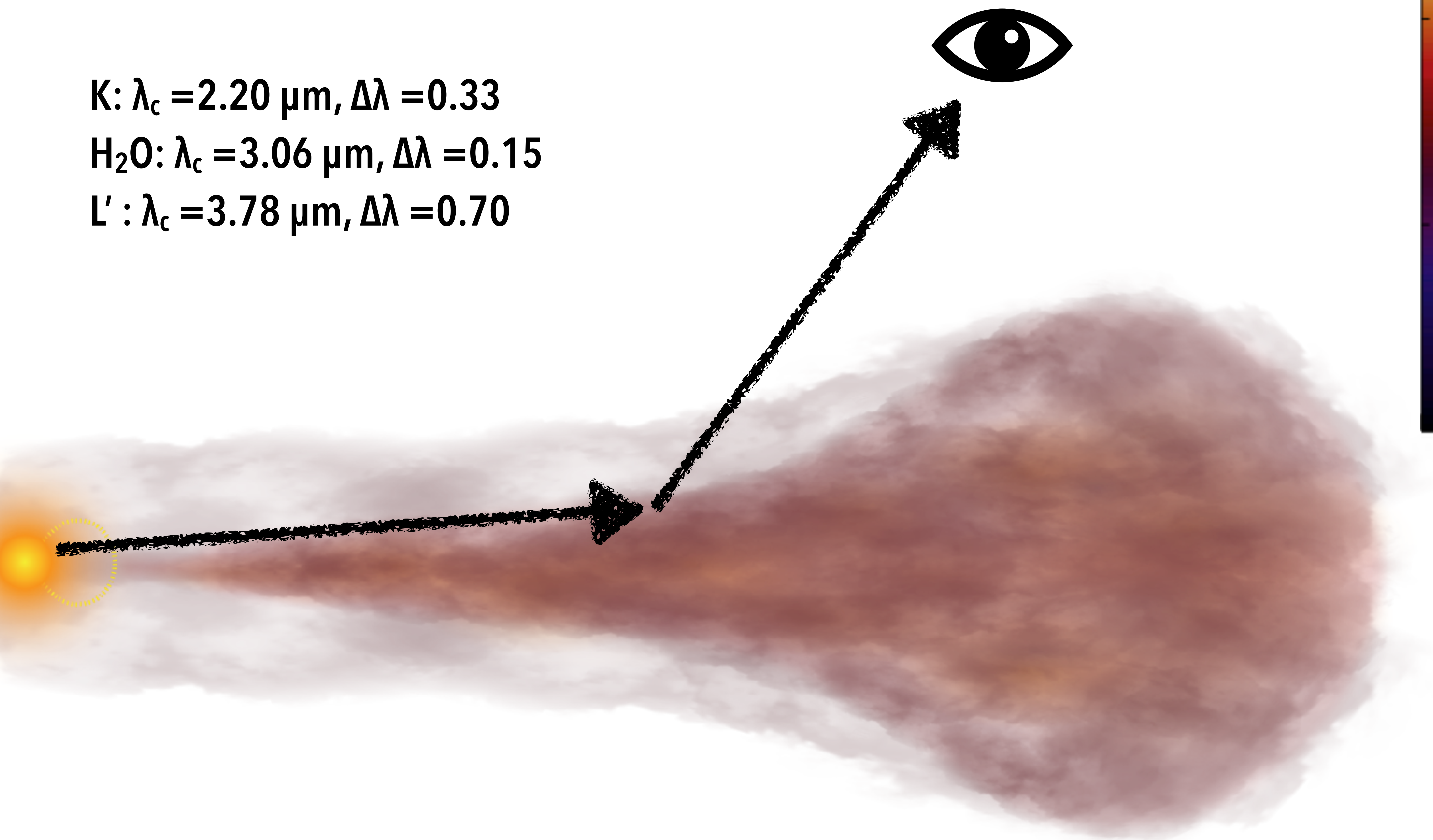


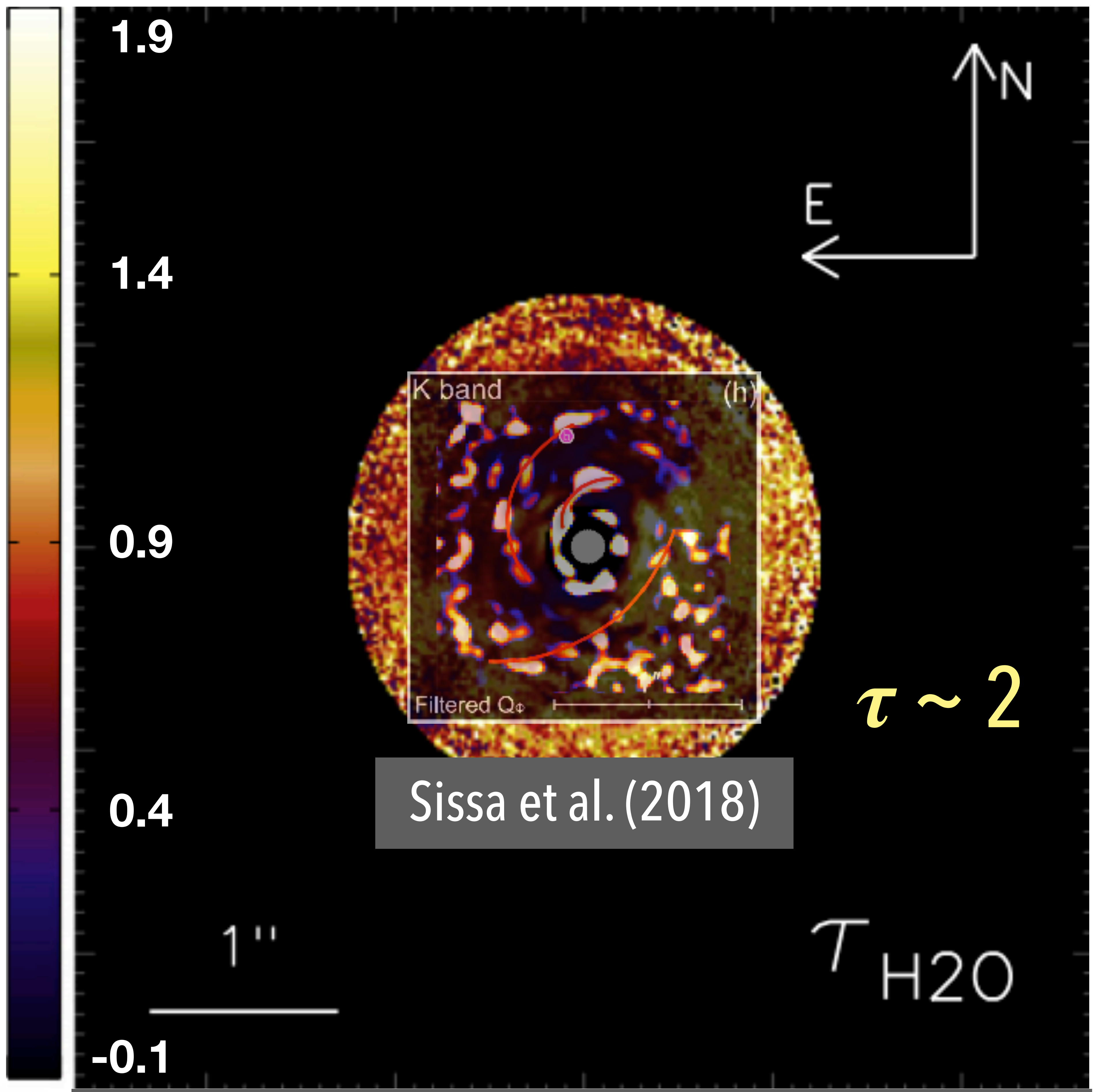
McClure et al. (2015)

Near-IR scattered light imaging connects ices to disk structure and exoplanets

Narrow-band AO-imaging in continuum + H_2O ice feature
Stellar PSF removal

K: λ_c =2.20 μm, Δλ =0.33
H_2O: λ_c =3.06 μm, Δλ =0.15
L′ : λ_c =3.78 μm, Δλ =0.70





Honda et al. (2015), Gemini NICI, no coro.

Exoplanet mission timelines.