JWST’s view on the inner rocky planet forming region

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Some numbers in the life of Thomas and me …

1

number of failed MINDS observations

119

days I spent in Heidelberg on my mini-sabbatical in 2023

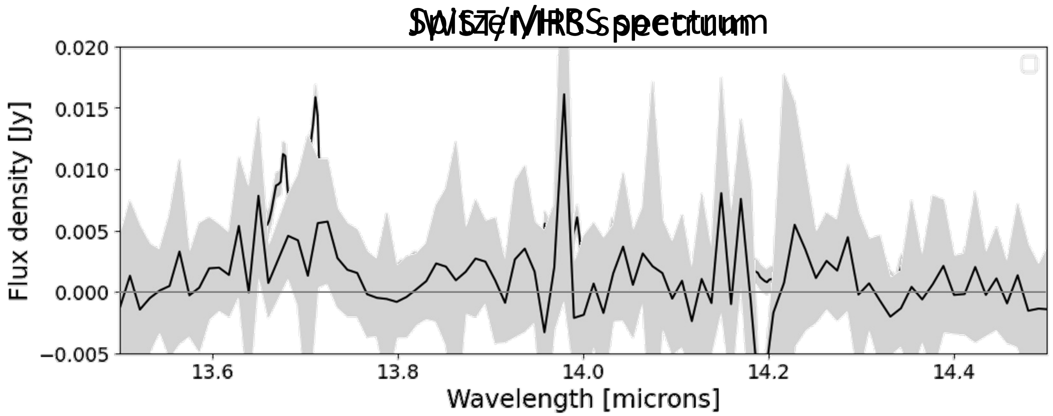
27

number of changes in MINDS observing program between 2016 and 2023

1632

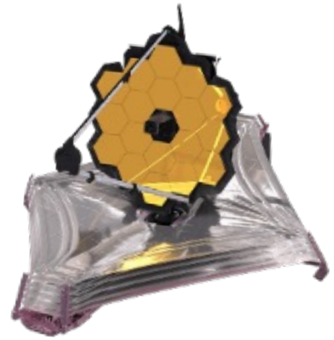
number of emails Thomas sent related to JWST since 2009

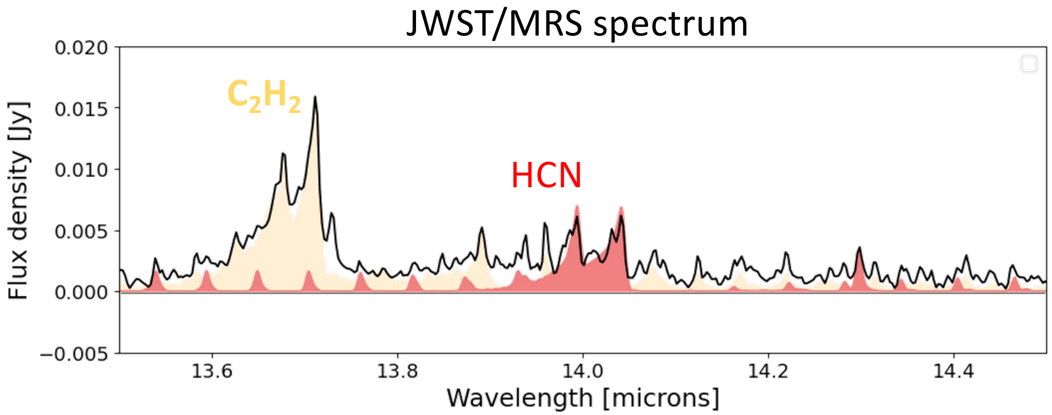
A jump in sensitivity & spectral resolution



[Spitzer: Carr & Najita 2008, Pascucci+2009, Pontoppidan+2010, Salyk+2011, Najita+2013, Pascucci+2013, …]

A jump in sensitivity & spectral resolution

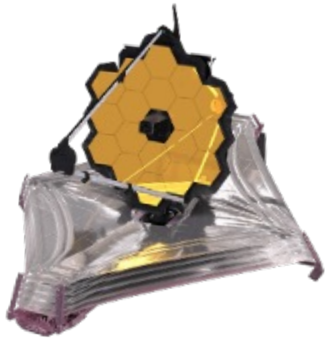


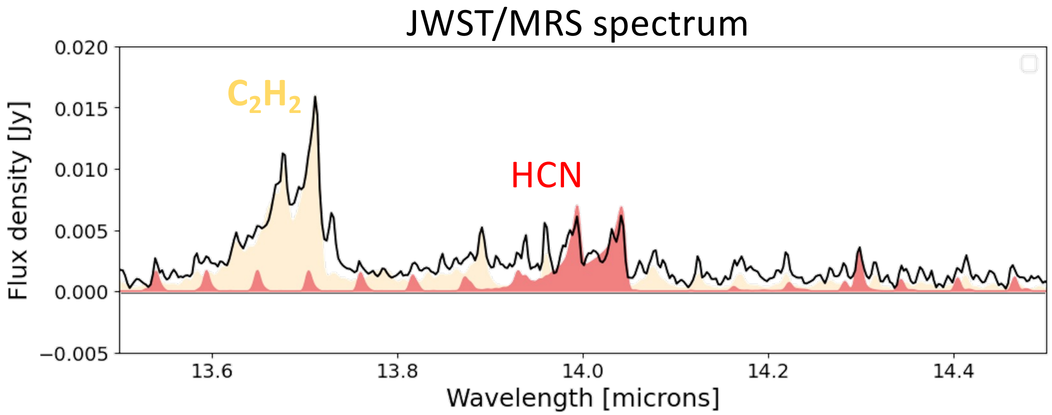


mid-IR spectra encode physical and chemical information of the inner disk

– the rocky planet forming region –

A jump in sensitivity & spectral resolution





mid-IR spectra encode physical and chemical information of the inner disk
– the rocky planet forming region –

the mid-IR emission is the product of many processes:

physics, chemistry, dynamics & radiative transfer (opacity, excitation processes, reaction pathways and rates)

The MINDS observing program

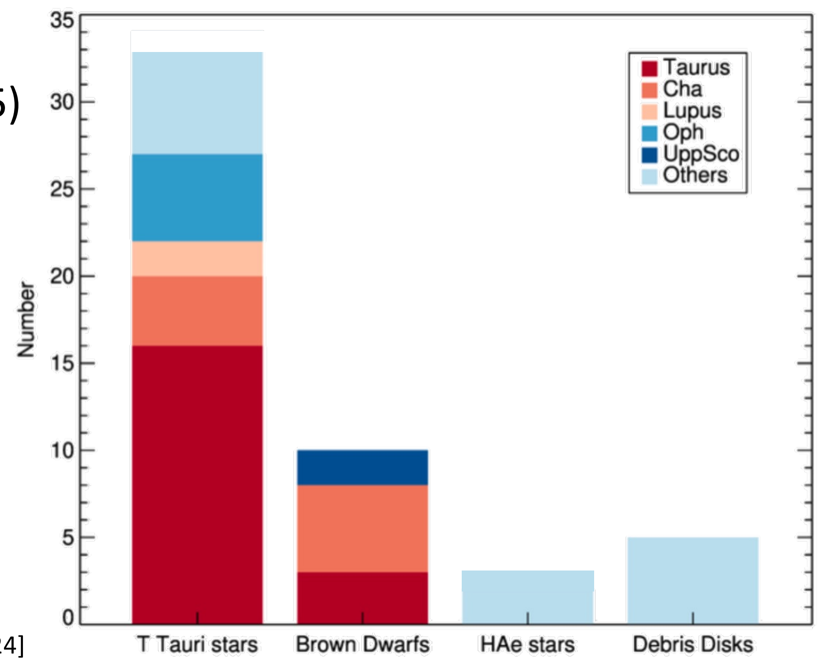
Full MIRI IFU spectroscopy (aim: S/N~300-500)
(4-point dithers, for a few sources separate bg positions)

- 33 T Tauri disks (16 Taurus, 5 Oph, 2 Lup, 4 Cha, 6 other)
  - 5 of them also with NIRSpec (G395H/F290LP 2.87–5.14 mm): AATau, HKTauB, PDS453, XXCha, PDS70, flying saucer
- 4 Herbig disks (HD35929, HD135344B, PDS144N)
- 5 Debris disks (49Cet, HD32297, HD131835, HD138813, HD172555)
- 10 Brown Dwarf/VLMS disks

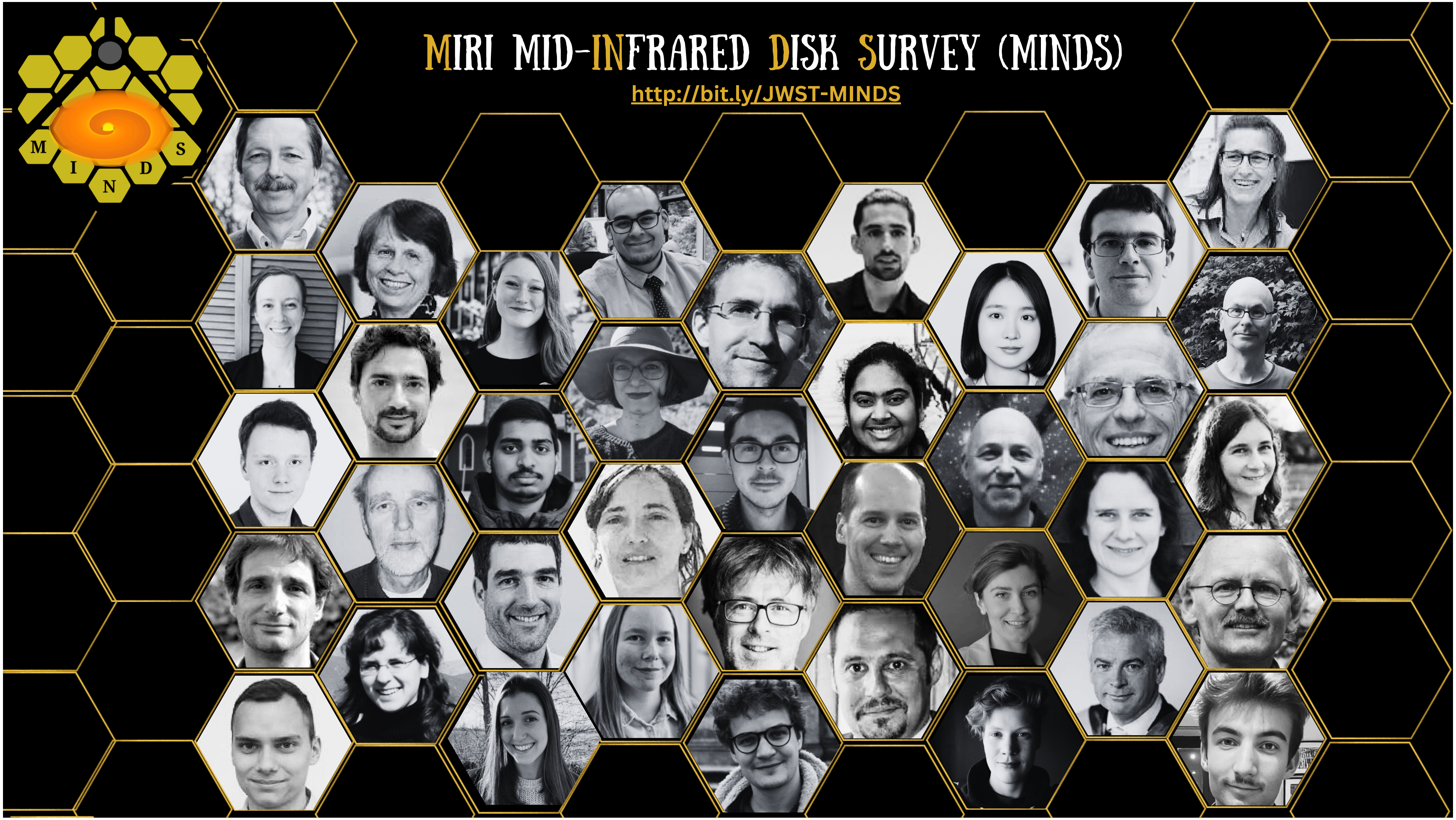
MIRI imaging of TWHya with coronagraph
(4QPM/F1550C, 2 PAs)

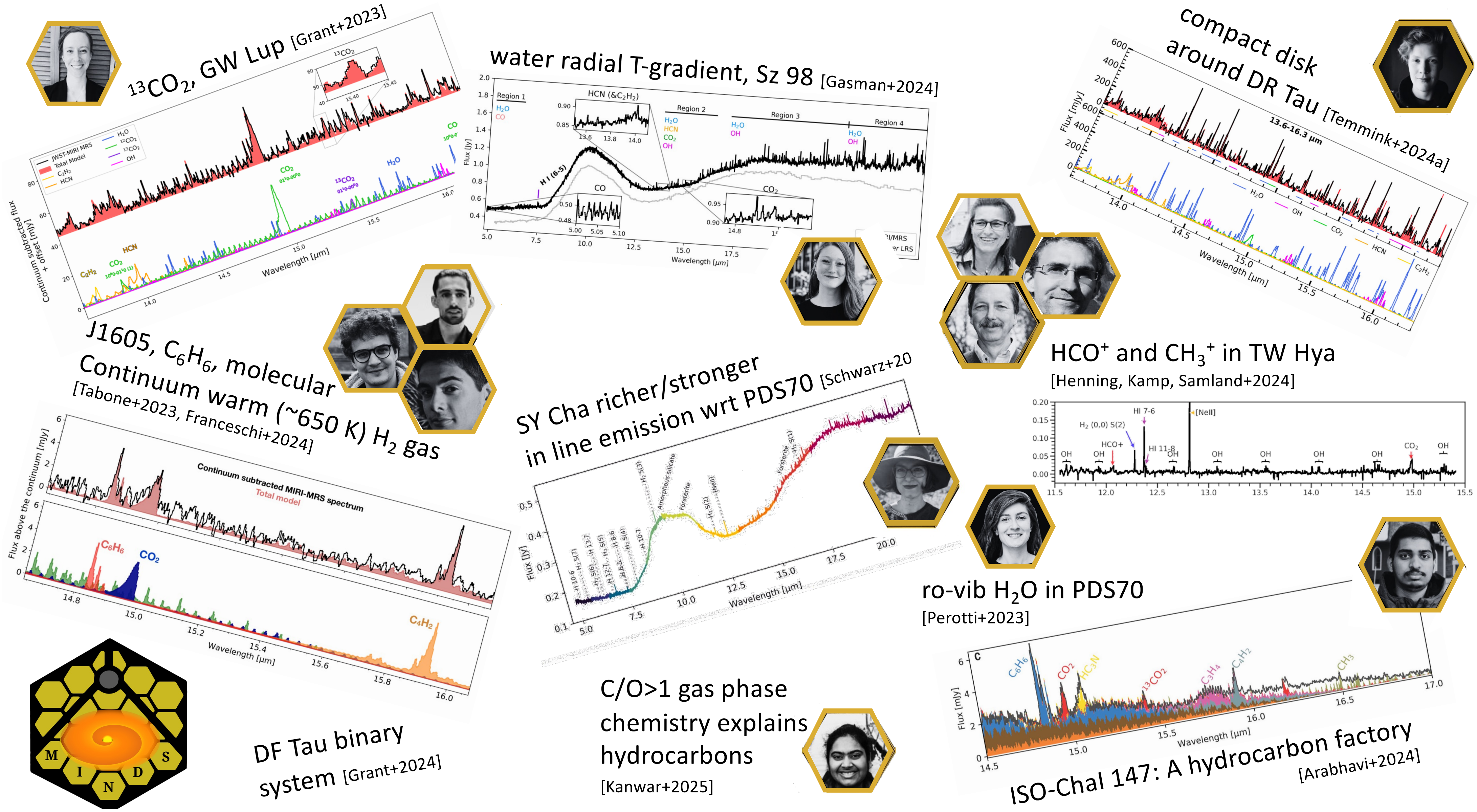
NIRCam imaging of PDS70
(F480M, F187N, 2 PAs)

HD169142: MIRI/IFU & coronagraph (4QPM/F1065C, 2 PAs)
– joint with ExOMIRI

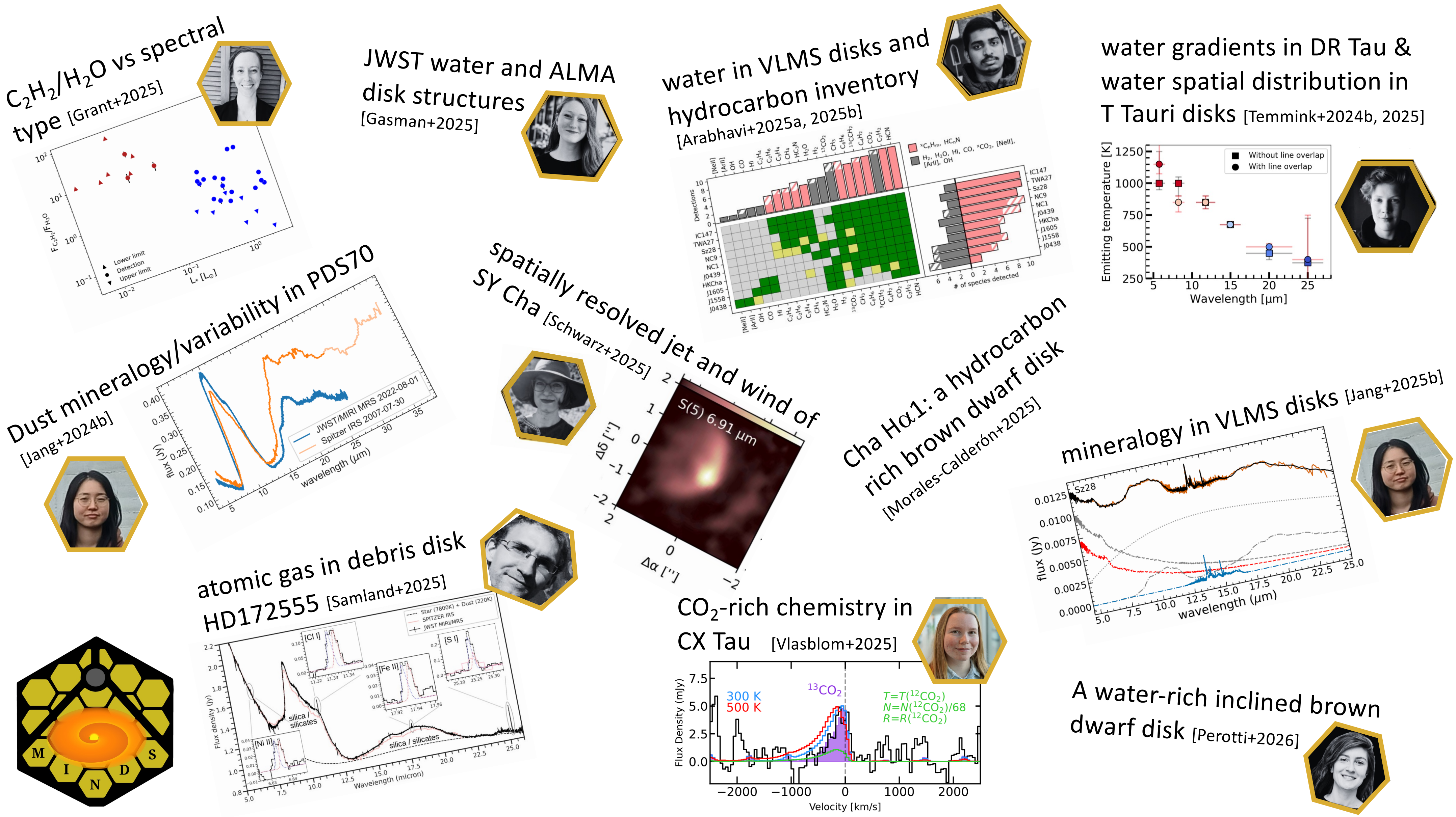


[Kamp, Henning + MINDS team 2023, Henning, Kamp + MINDS team 2024]


MIRI MID-INFRARED DISK SURVEY (MINDS)
http://bit.ly/JWST-MINDS

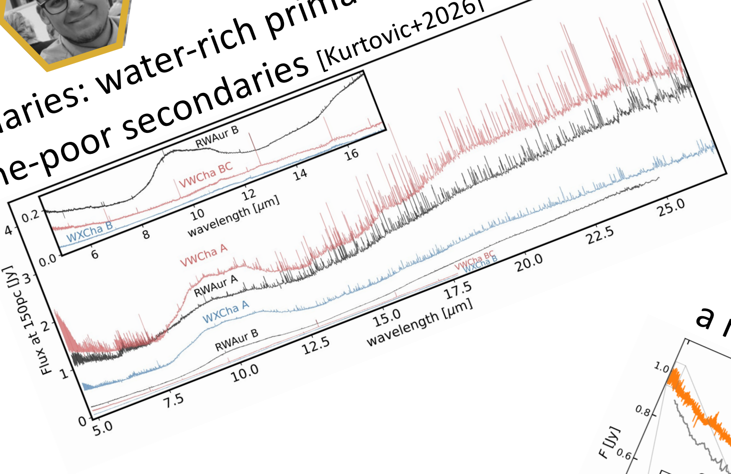


$^{13}CO_2$, GW Lup [Grant+2023]
water radial T-gradient, Sz 98 [Gasman+2024]
compact disk around DR Tau [Temmink+2024a]
J1605, C_6H_6, molecular
Continuum warm (~650 K) H_2 gas
[Tabone+2023, Franceschi+2024]
SY Cha richer/stronger in line emission wrt PDS70 [Schwarz+20
HCO^+ and CH_3^+ in TW Hya
[Henning, Kamp, Samland+2024]
ro-vib H_2O in PDS70
[Perotti+2023]
DF Tau binary system [Grant+2024]
C/O>1 gas phase chemistry explains hydrocarbons
[Kanwar+2025]
ISO-Chal 147: A hydrocarbon factory
[Arabhavi+2024]
M I N D S



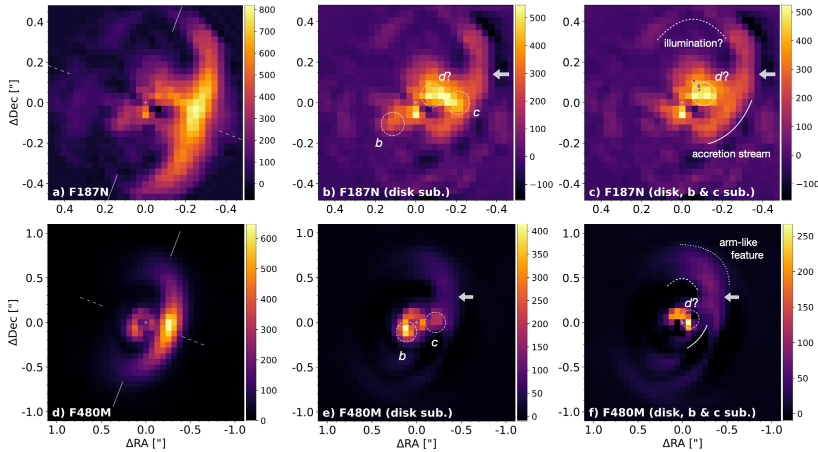
C2H2/H2O vs spectral type [Grant+2025]
JWST water and ALMA disk structures [Gasman+2025]
water in VLMS disks and hydrocarbon inventory [Arabhavi+2025a, 2025b]
water gradients in DR Tau & water spatial distribution in T Tauri disks [Temmink+2024b, 2025]
Dust mineralogy/variability in PDS70 [Jang+2024b]
spatially resolved jet and wind of SY Cha [Schwarz+2025]
Cha Hα1: a hydrocarbon rich brown dwarf disk [Morales-Calderón+2025]
mineralogy in VLMS disks [Jang+2025b]
atomic gas in debris disk HD172555 [Samland+2025]
CO2-rich chemistry in CX Tau [Vlasblom+2025]
A water-rich inclined brown dwarf disk [Perotti+2026]
M I N D S
Emitting temperature [K]
Wavelength [μm]
Without line overlap
With line overlap
JWST/MIRI MRS 2022-08-01
Spitzer IRS 2007-07-30
wavelength (μm)
flux (Jy)
S(5) 6.91 μm
Sz28
300 K
500 K
Flux Density (mJy)
Velocity [km/s]
Flux density (Jy)
Wavelength (micron)
silica / silicates
[Cl I]
[Fe II]
[S I]
[Ni II]

Binaries: water-rich primaries, line-poor secondaries [Kurtovic+2026]

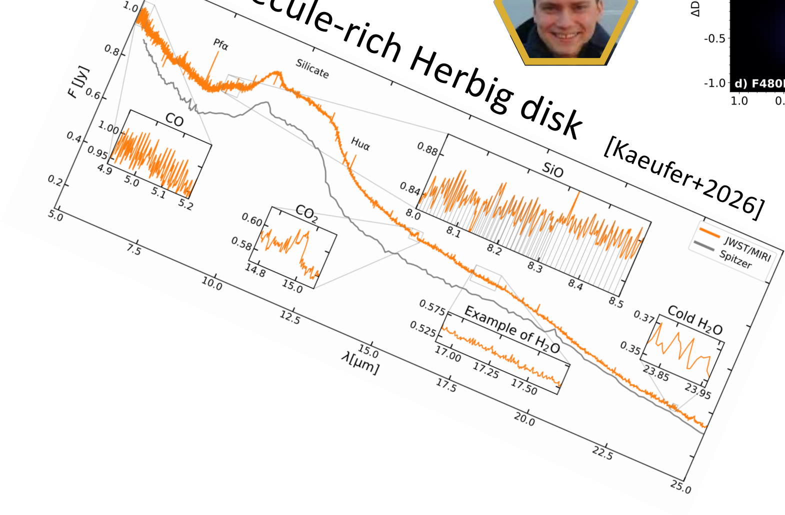


PDS70 – planets, CPDs + accretion streamer

[Christiaens+2024]



a molecule-rich Herbig disk [Kaeufer+2026]

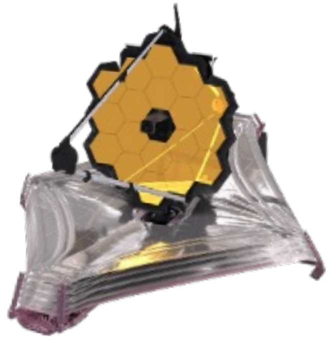


2D disk modeling of J1605 MIRI spectrum

[Kanwar+2026]

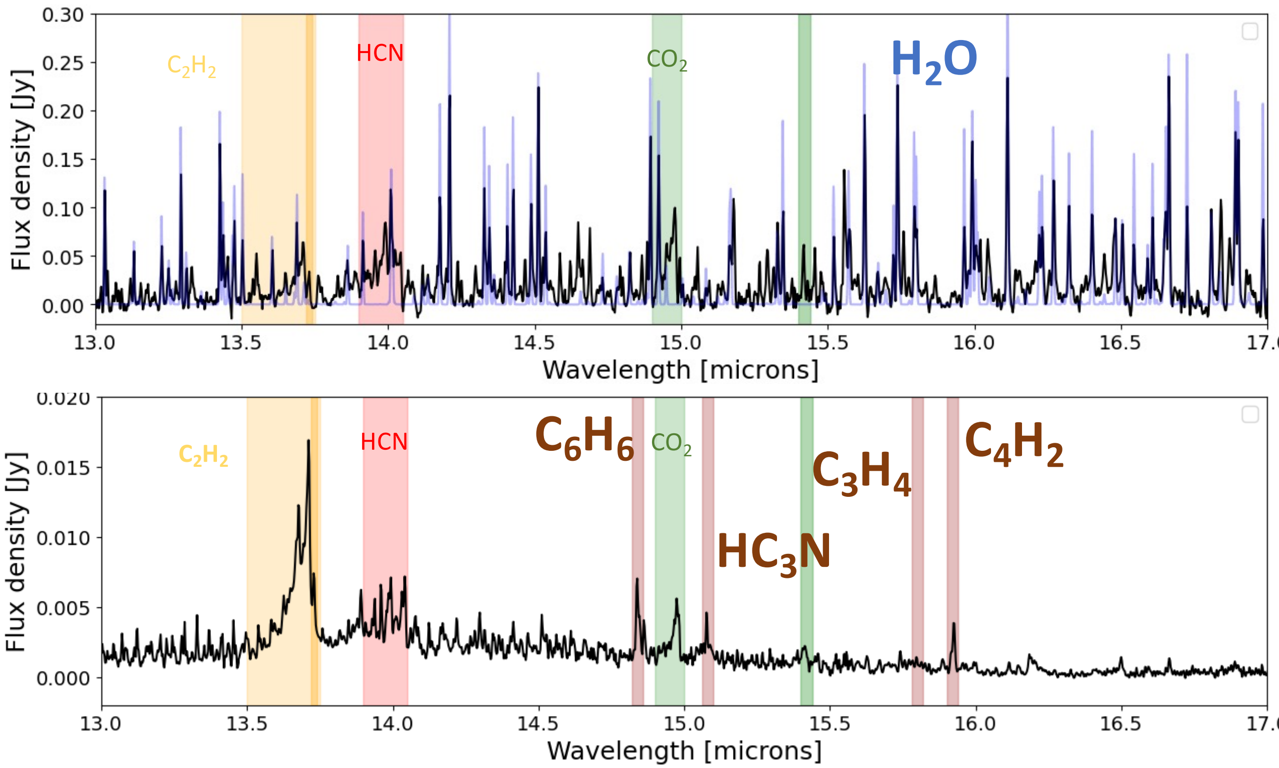
... > 30 papers ... and still more results coming

A dichotomy in disk spectra



T Tauri star

Very Low Mass star

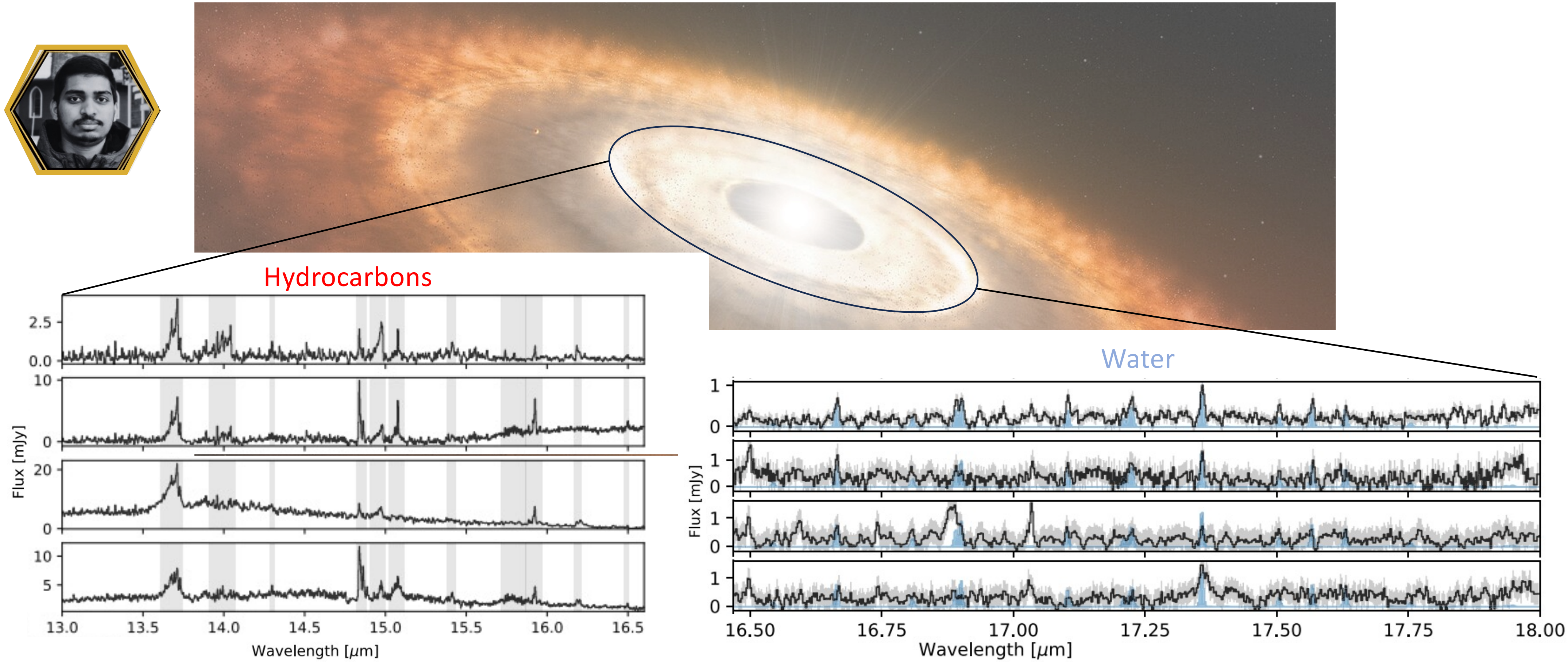


Oxygen-rich

Carbon-rich

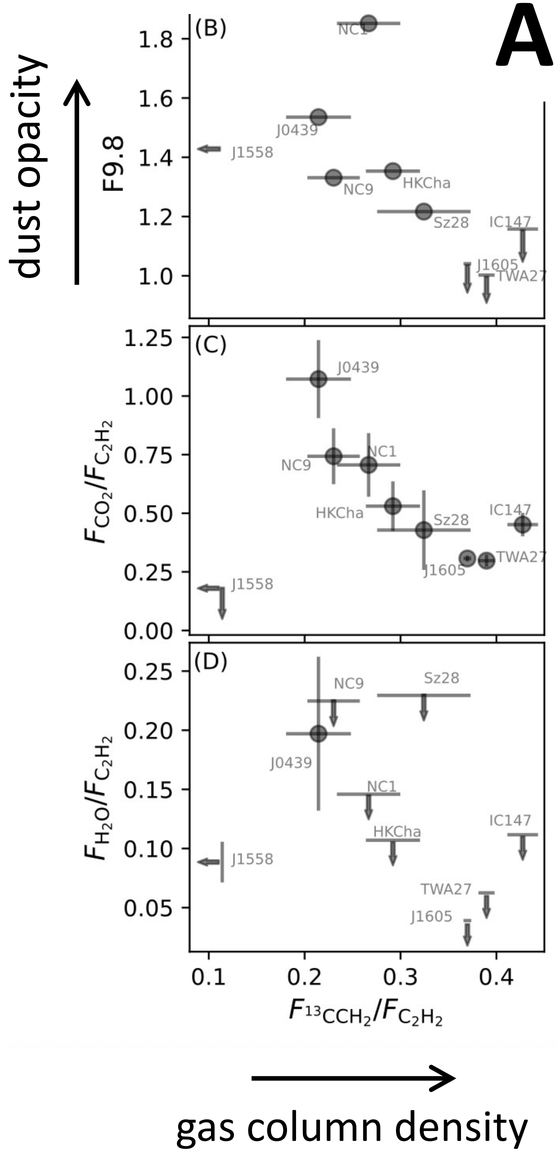
[Spitzer: Pascucci et al. 2009, 2013; average JWST spectra: Grant+2025]

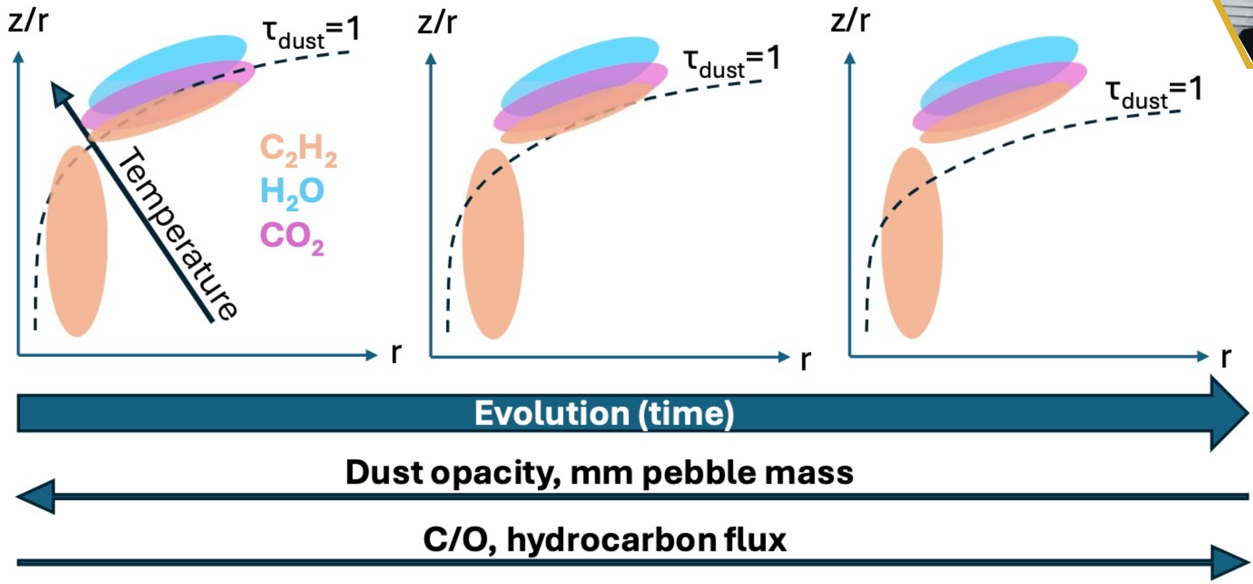
JWST shows ‘hidden’ water in disks around VLMS



[Arabhavi, Kamp, Henning, van Dishoeck et al. 2024, Science; Arabhavi, Kamp, van Dishoeck, Henning et al. 2025, ApJL]

A scenario for the disks around VLMS

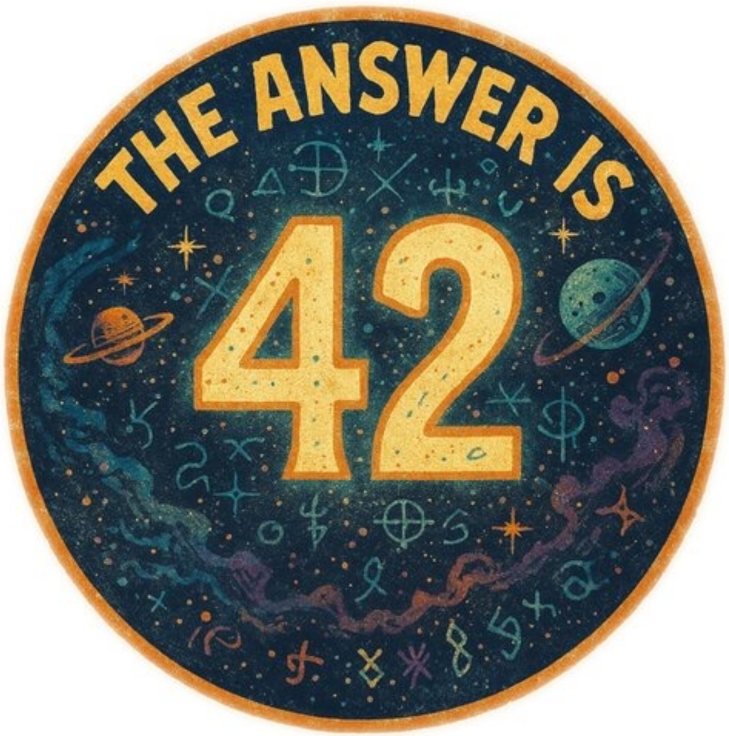




C/O > 1 AND low dust opacity

[Jang+2025, Grant+2025, Arabhavi+2025b]

Interpretation of JWST data – modeling



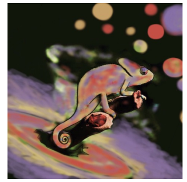
Pick the right model complexity for your question:

- 0D slab model gas retrieval
- Radially, vertically stacked 0D slab gas retrieval (multiple components)
- 1D slab model gas+dust retrieval
- 2D thermo-chemical disk retrieval, or forward modeling

Key: atomic/molecular data, dust, ice opacities, chemical rates

[HITRAN, Geisa, Exomol, Jena database, LAMDA, LIDA, UMIST, KIDA … or ask your favorite quantumchemist, lab colleague etc.]

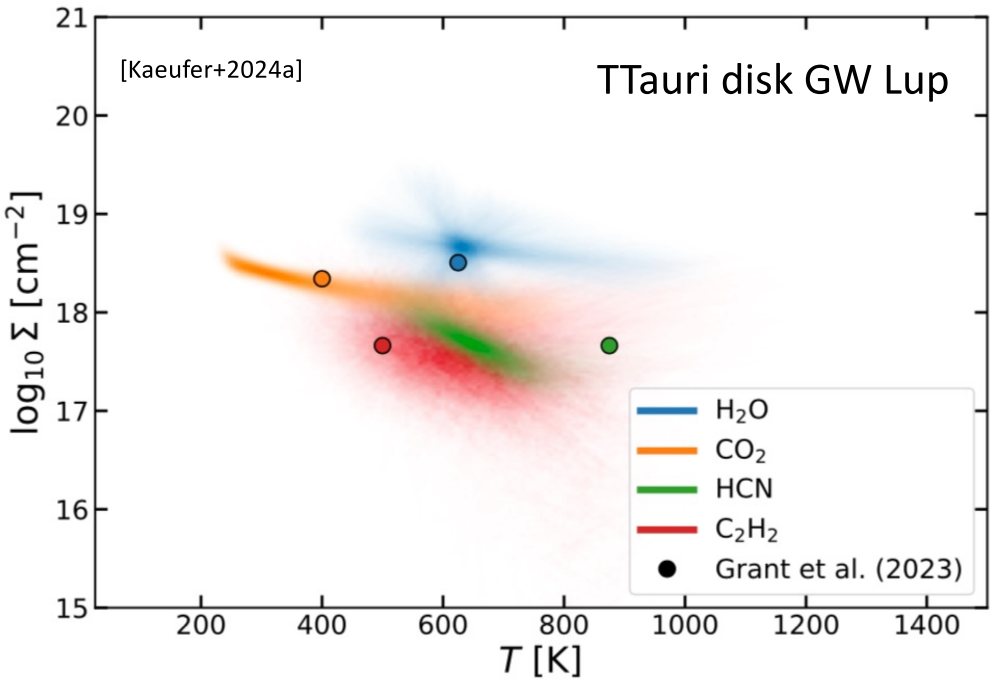
DuCKLinG: A new fast 1D retrieval

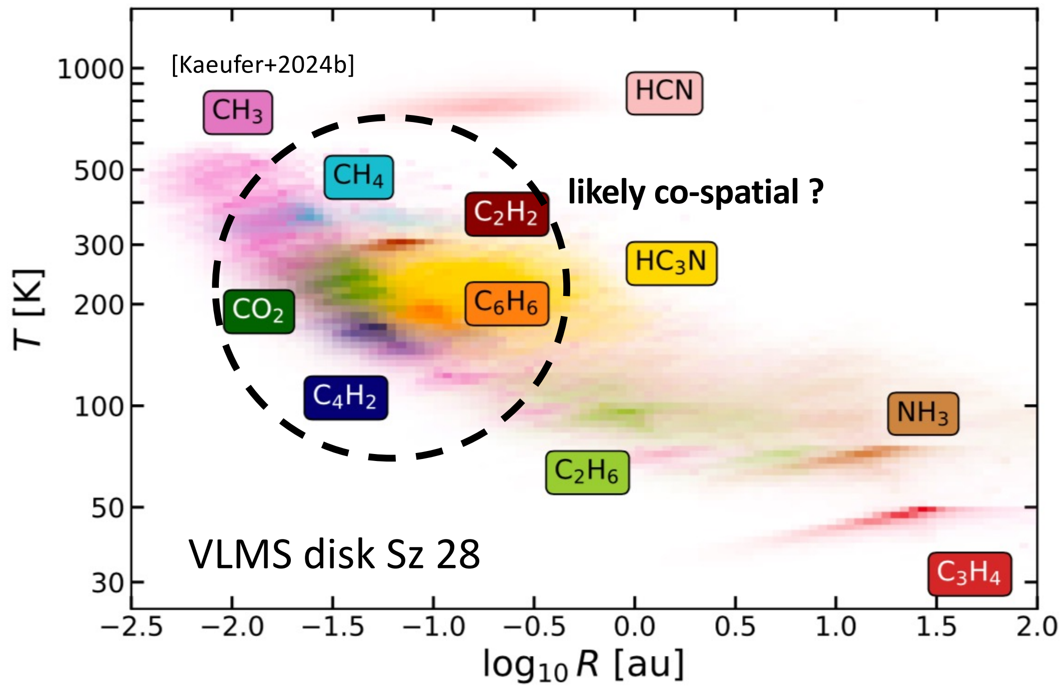


radial temperature gradients for H_2O and CO_2 like have been seen in Sz 98, FZ Tau, DR Tau, and several more

[Gasman+2023, Banzatti+2023, Pontoppidan+2024, Temmink+2024, …]

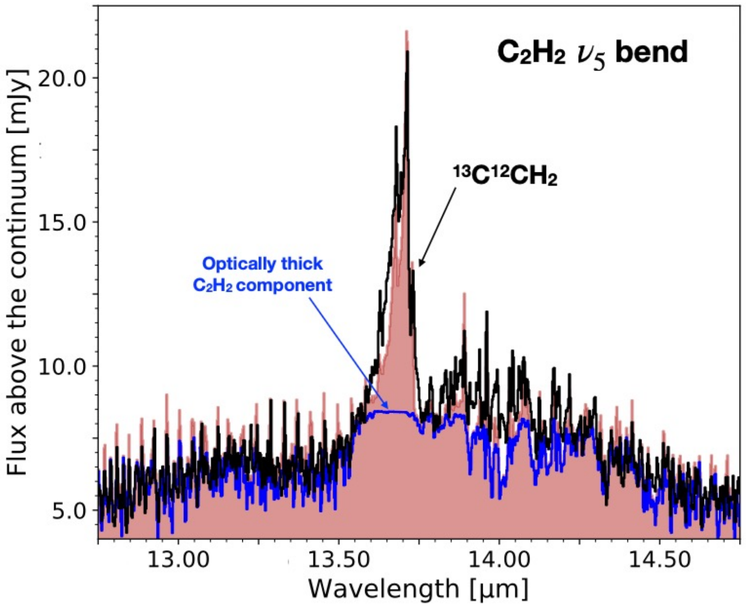
retrieved columns densities, temperatures and emitting areas can be compared with 2D chemical models





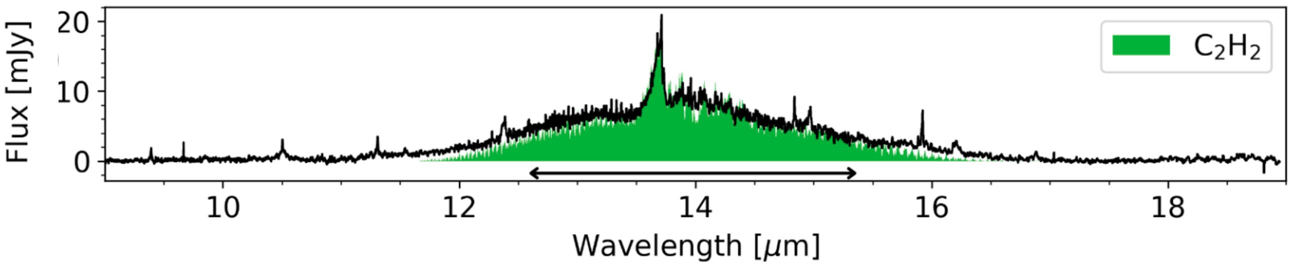
Hydrocarbons – looking ‘deep’ into the disks?

N_{C2H2}=2.4 x 10^{20} cm^{-2}, N_{C2H2}=2.5 x 10^{17} cm^{-2}



[Tabone, Bettoni, van Dishoeck & MINDS 2023, Nature Astronomy]

[Kanwar et al. 2025b]

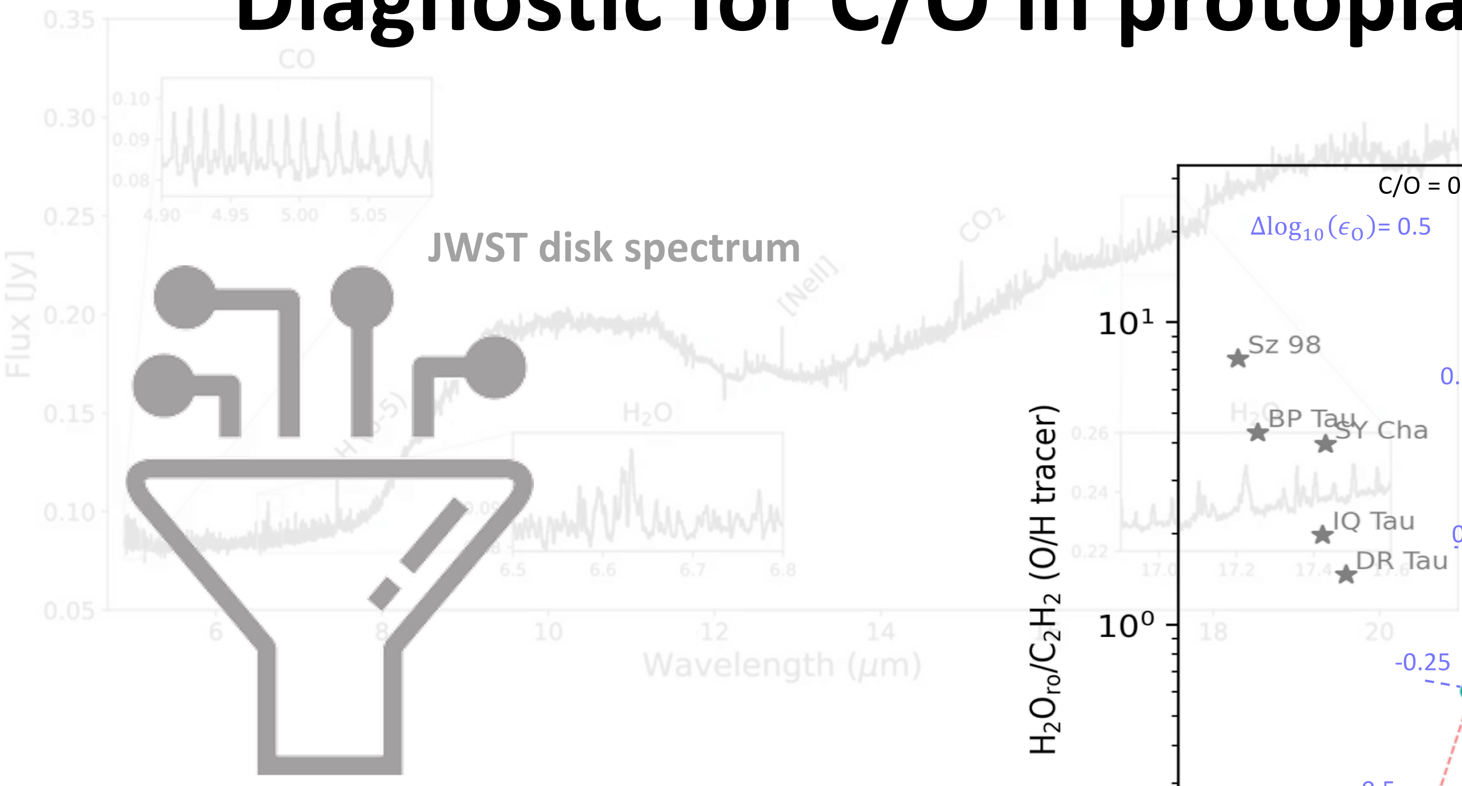


A 2D thermo-chemical disk model naturally produces the observed C_2H_2 pseudo-continuum

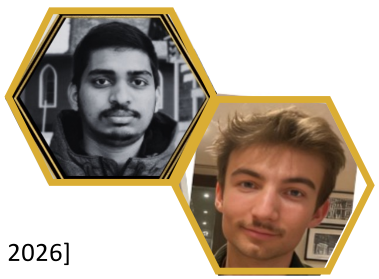
… that can be fitted with two slab models
(N_{C2H2}~10^{20} cm^{-2} + N_{C2H2}~10^{17} cm^{-2})

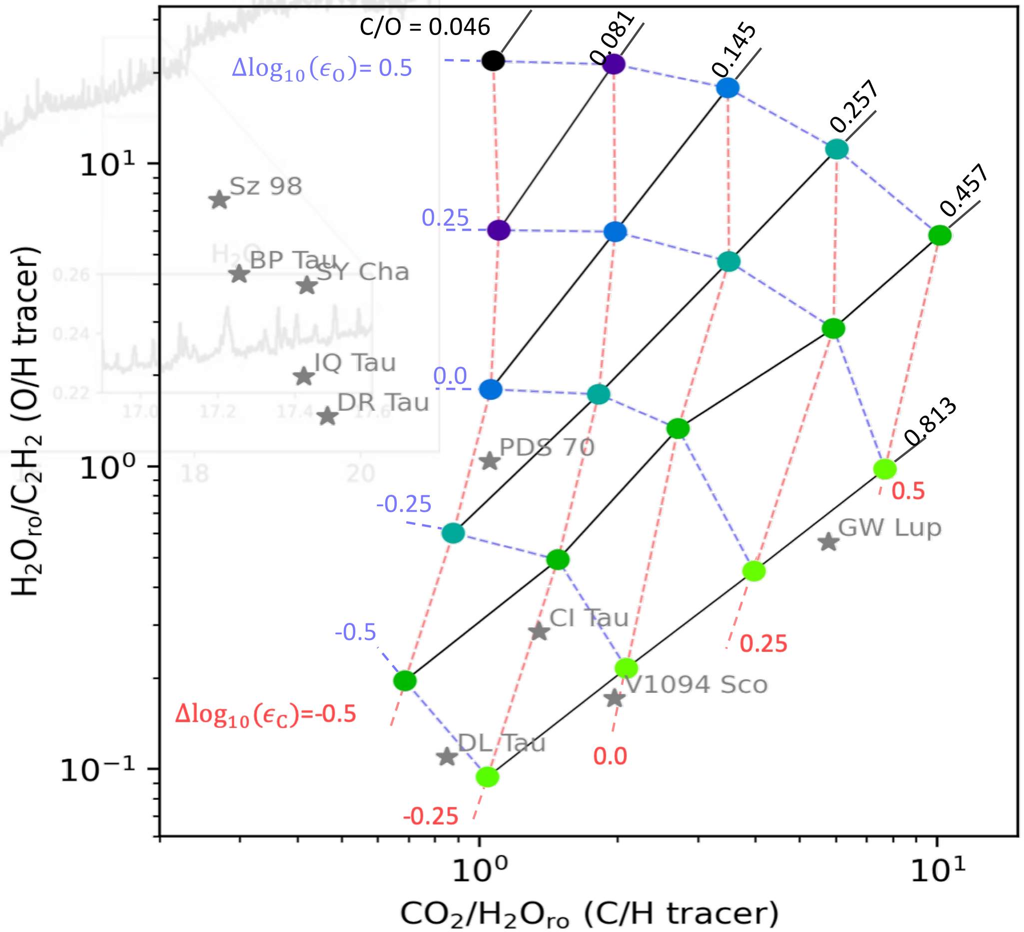
MIRI spectrum shows a molecular pseudo continuum
=> two slab model fit (optically thick + thin)

Diagnostic for C/O in protoplanetary disks



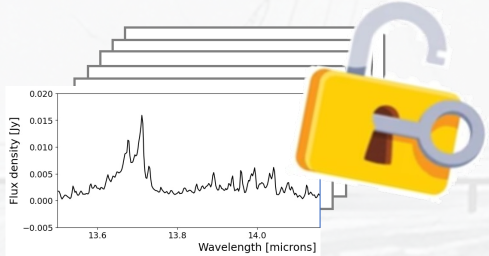
C and O elemental abundances





[Arabhavi, Kamp, van Dishoeck et al. 2026; Esteve et al. 2026]

What is next?



Improve chemical models

- three-body reactions – link to atmosphere chemistry
- warm surface chemistry, destruction of carbonaceous solids – dust becomes active part of chemistry

Observations

- Disk substructure at au scales – interferometers, ELT
- Collect large disk samples with JWST+ALMA data
- Far-IR – the missing link

Expand molecular data/ice opacities

- unidentified features beyond 16 μm – candidates: C_2, C_2H, C_3, CH_2CCH, C_3H_2, C_5H_2, CH_3C_4H, C_6, C_6H_2
- non-LTE effects require collisional data
- ice opacities for RT models

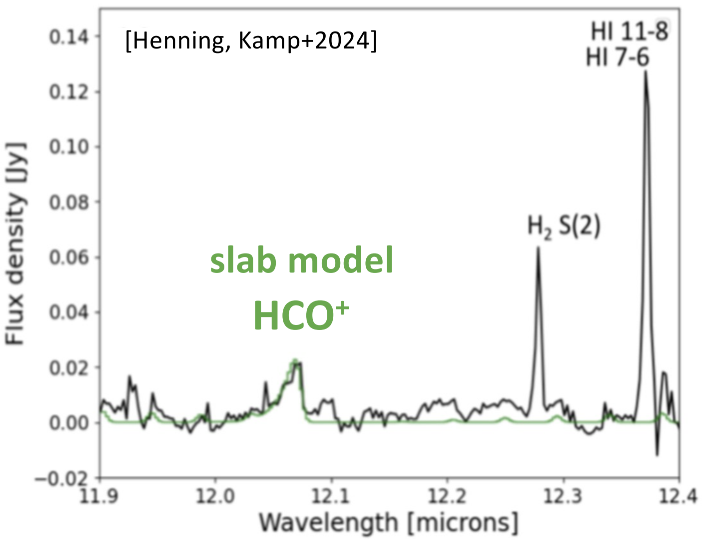
DANII Dutch Astrochemistry Network III

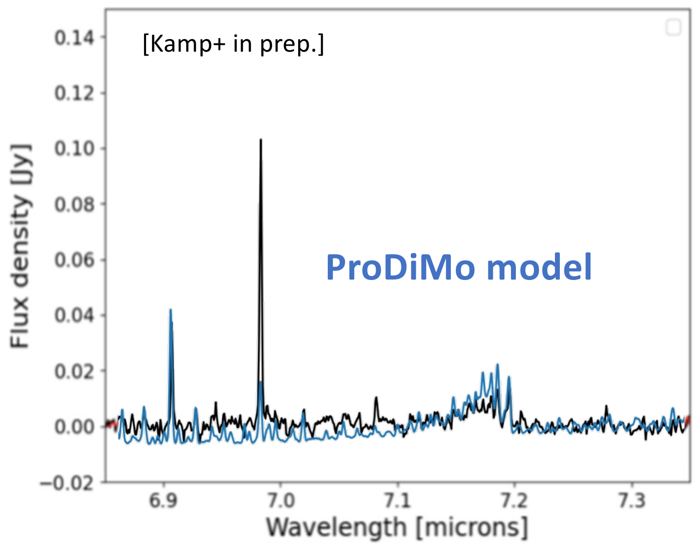
Conclusions

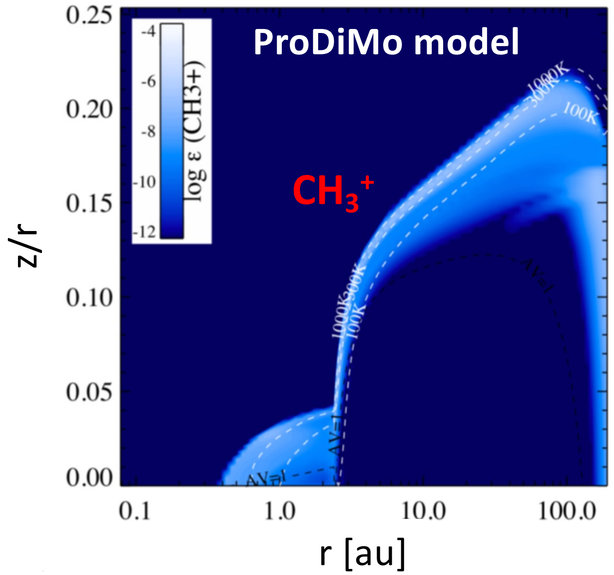
- There is a huge diversity in mid-IR spectra of disks – no two disks look alike.
- Disks around T Tauri stars are oxygen-rich, disks around VLMS carbon-rich – different evolutionary timescales?
- Many large hydrocarbons are detected in VLMS disks, e.g. ethane, benzene, with high column densities, especially C_2H_2 – dust more evolved, allowing us to look deeper into disks?
- 2D thermo-chemical models can reproduce the rich hydrocarbon chemistry with a bottom-up approach in high C/O conditions
- Disks around VLMS still have water in their spectra – 2D thermo-chemical models confirm that water can form in high C/O environments

Do rocky planets around VLMS resemble Earth?

Molecular ions – UV photochemistry in TW Hya







$n_{<H>} \ll n_{crit}$ => non-LTE excitation

weak CO_2 emission, absence of HCN, C_2H_2 emission

The rounded rim of the disk is a very high density PDR …

$n_{<H>} \sim 10^9$ cm^{-3}

$T_{gas} \sim$ few 100 K

$G_0 \sim 10^4$

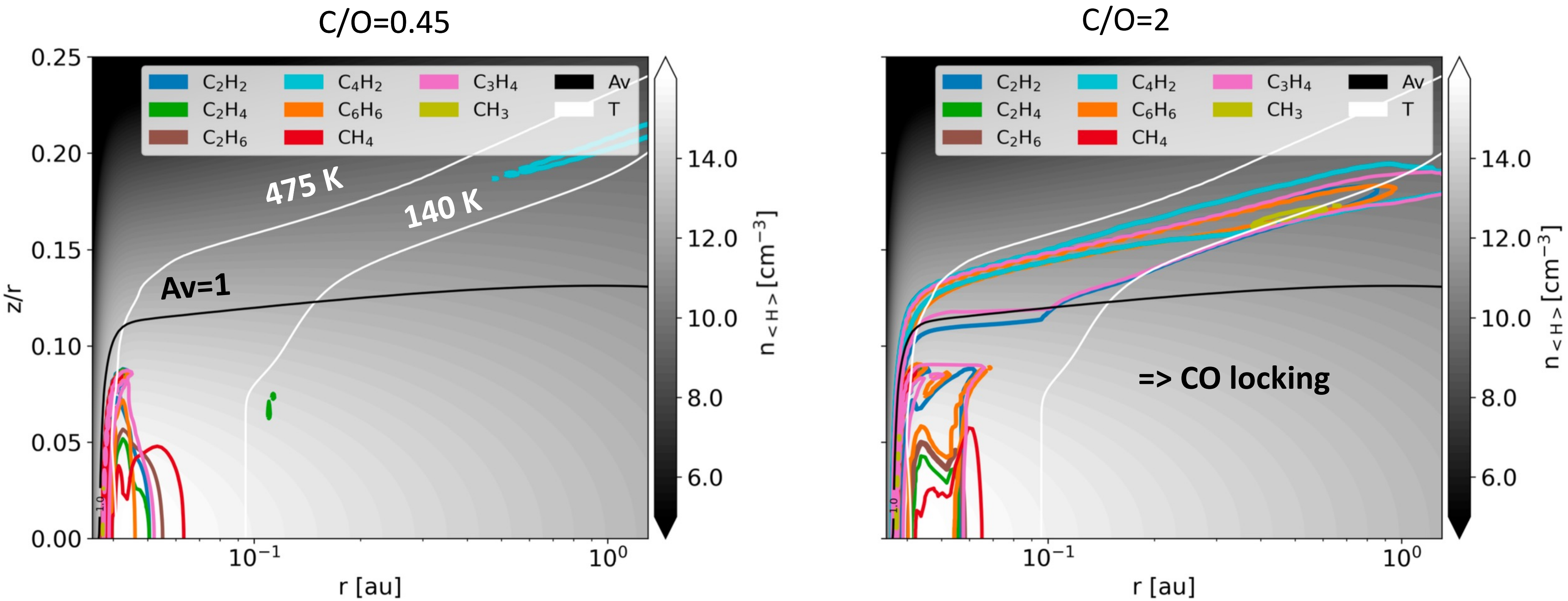
$$C^+ + H_2^* \rightarrow CH^+$$

$$CH^+ \xrightarrow{H_2} CH_2^+ \xrightarrow{H_2} CH_3^+$$

[d203-506 Orion: Berne+2023, Changala+2023]

Hydrocarbons – high C/O gas chemistry

2D thermo-chemical disk model (ProDiMo) for a disk around a VLMS [Greenwood+ 2017]



With a C/O>1, we recover all detected hydrocarbons in the disk surface layer of a thermo-chemical disk model

... and we predict many more (e.g. C_3H_2, C_5H_2, CH_3C_4H, C_6H_2)

[Kanwar+2024b]