UK Research and Innovation

Chemical complexity in planet-forming disks: insights from ALMA and future prospects

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UNIVERSITY OF LEEDS

Our interstellar origins

Rich in complex
organic molecules

Image credit: Bill Saxton/NRAO

Our interstellar origins

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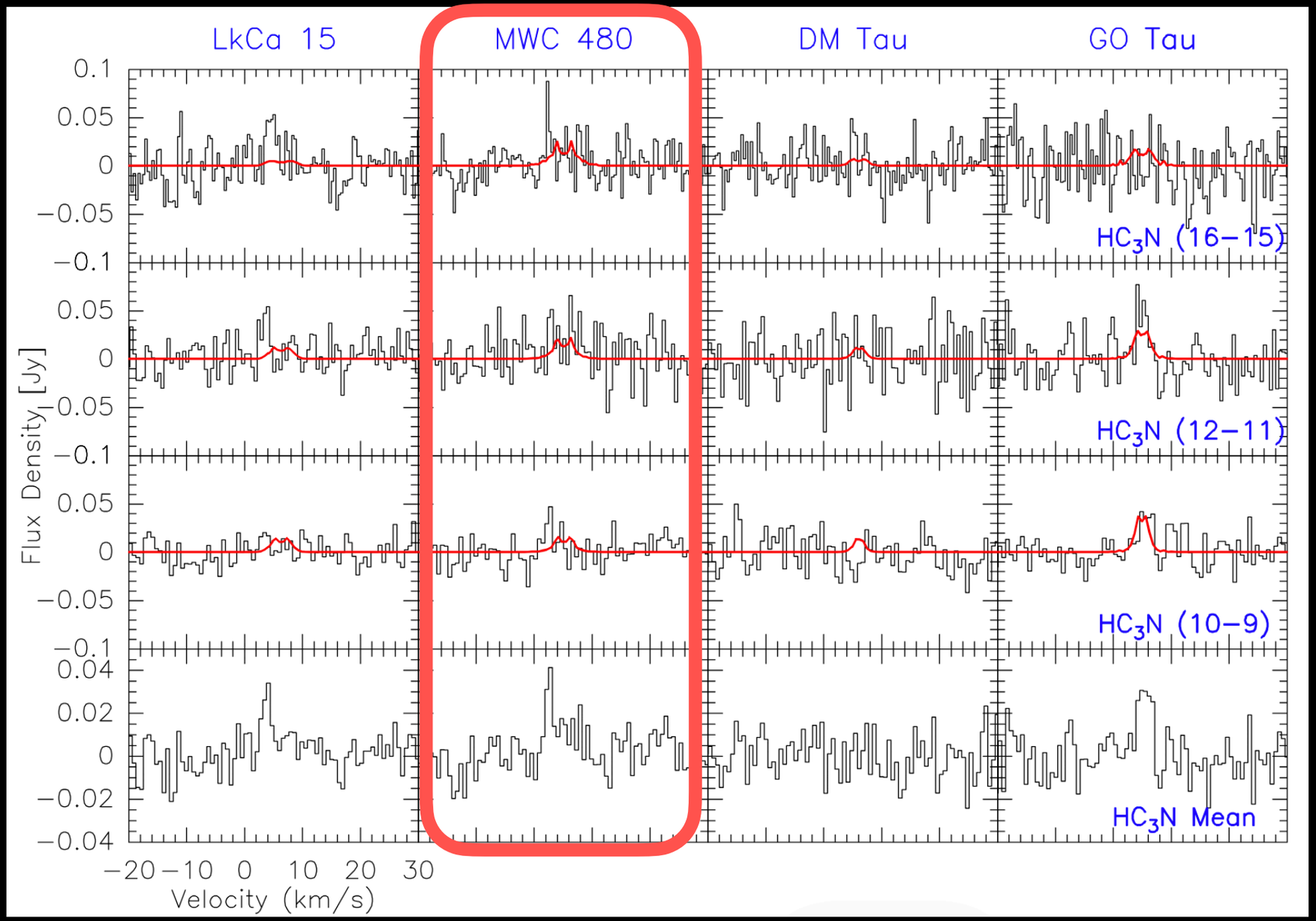
Our interstellar origins

Does organic matter formed in earlier phases get inherited and survive in the protoplanetary disk?

Image credit: Bill Saxton/NRAO

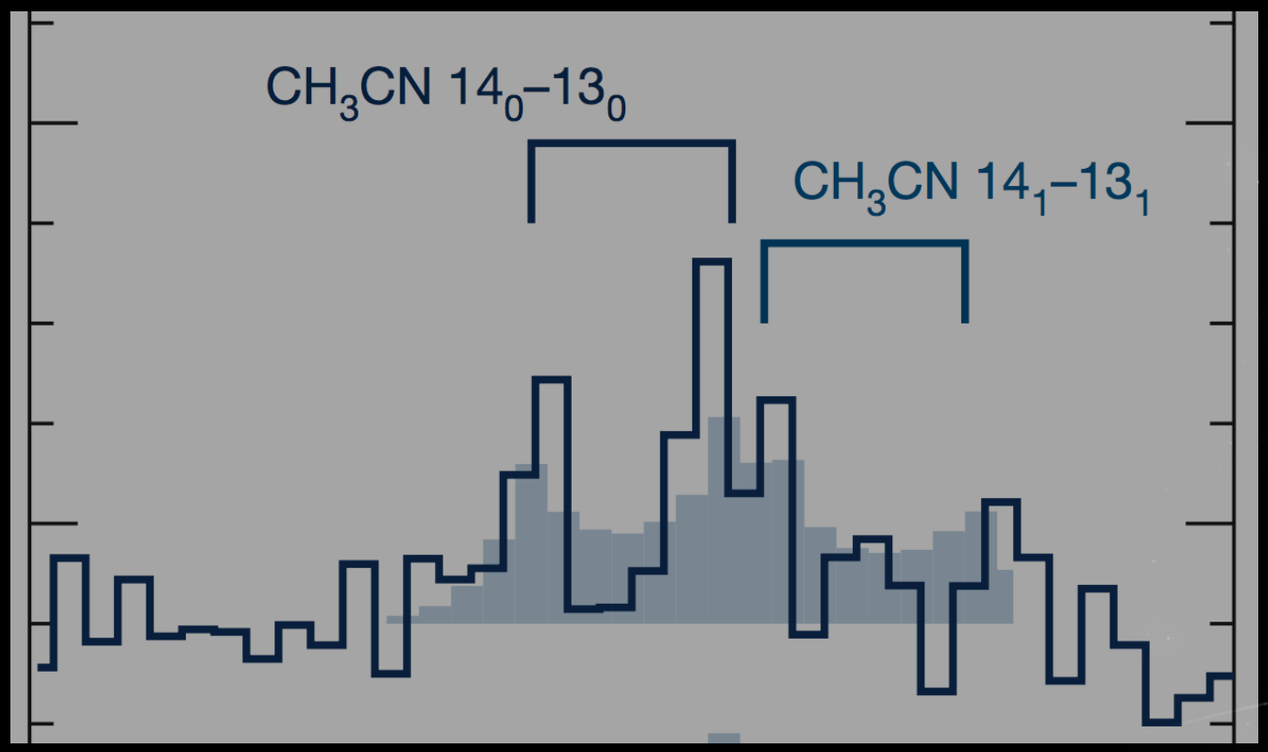
Searching for complex organic molecules

Chemistry in Disks VII:
First detection of HC_3N in protoplanetary disks



Chapillon et al. incl. Henning 2012, ApJ, 756, 58

Searching for complex organic molecules

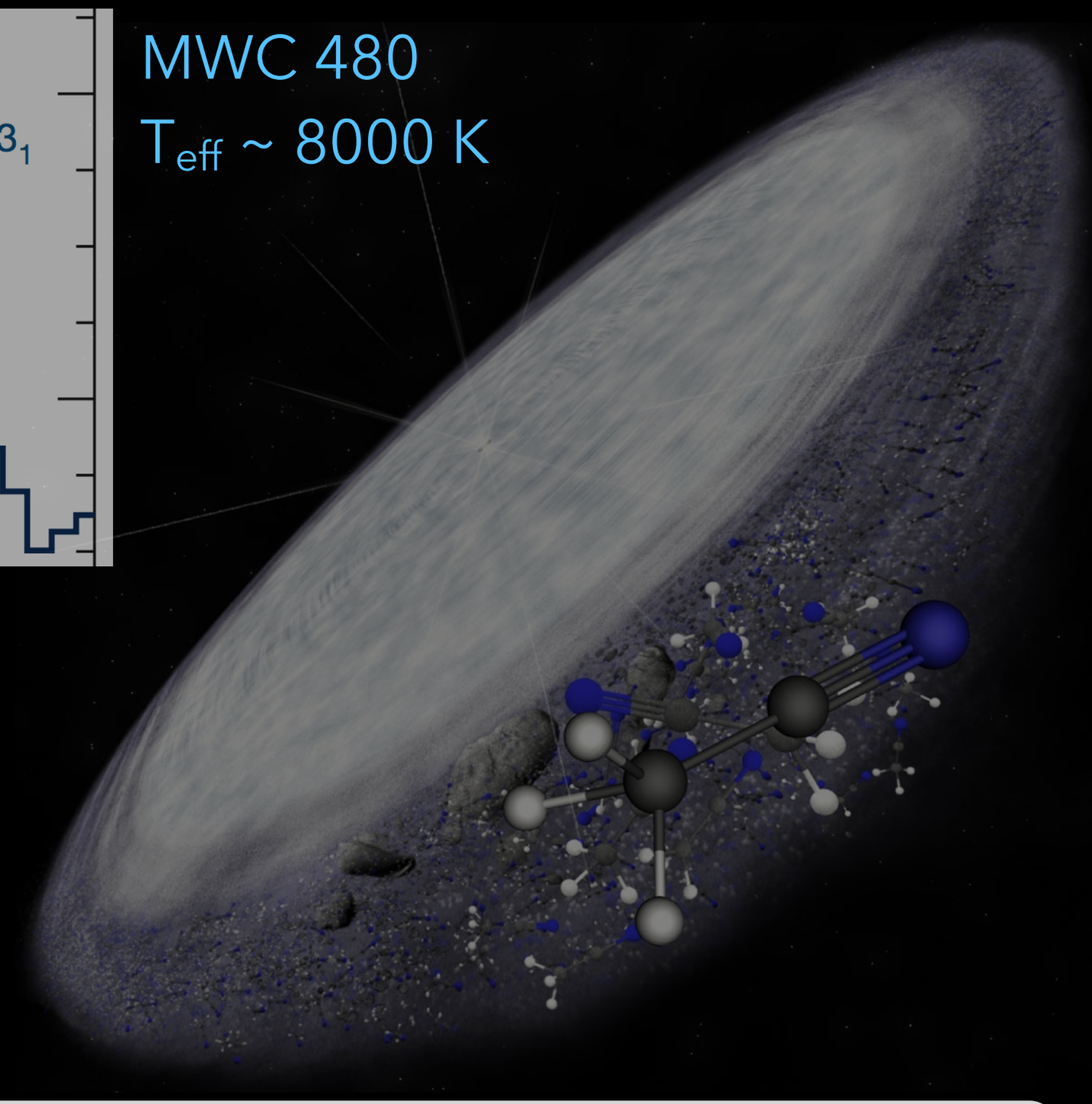


Cyanides (-CN) play a role in the synthesis of amino acids

CH_3CN/HCN ~ 5 - 20%

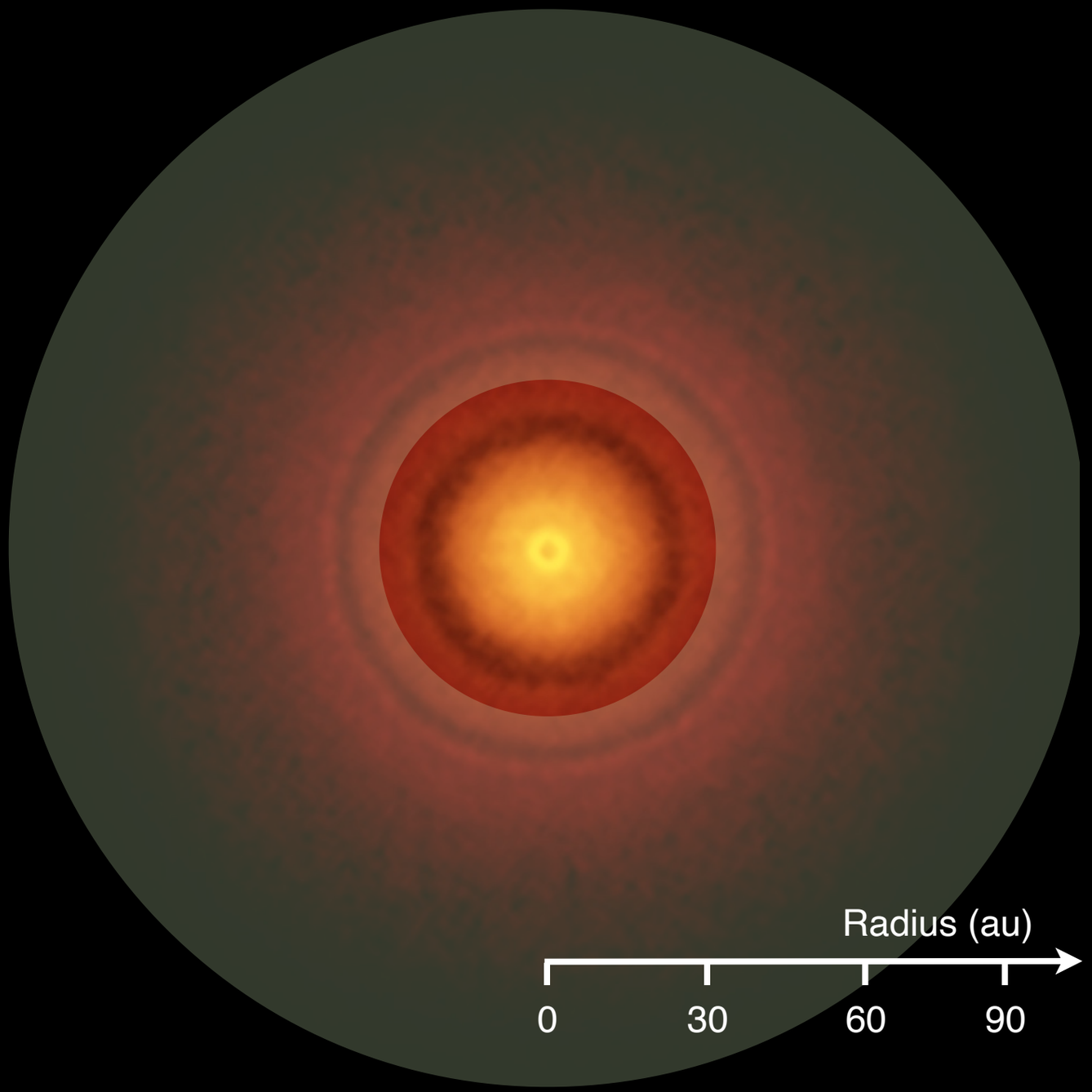
MWC 480

T_{eff} ~ 8000 K

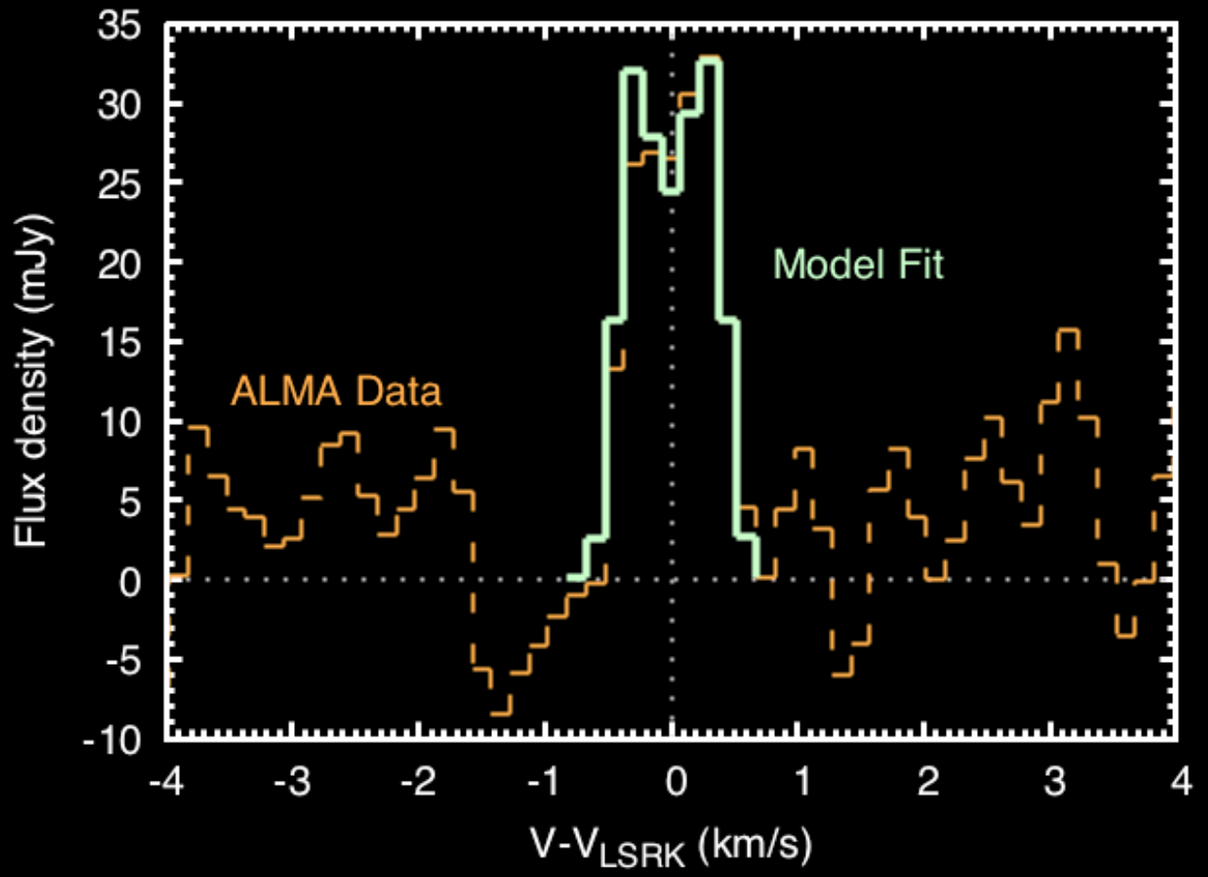


Credit: B. Saxton (NRAO/AUI/NSF); Öberg et al. 2015, Nature, 520, 198; Loomis et al. 2018, ApJ, 859, 13

Searching for complex organic molecules



Detection of methanol in the TW Hya protoplanetary disk



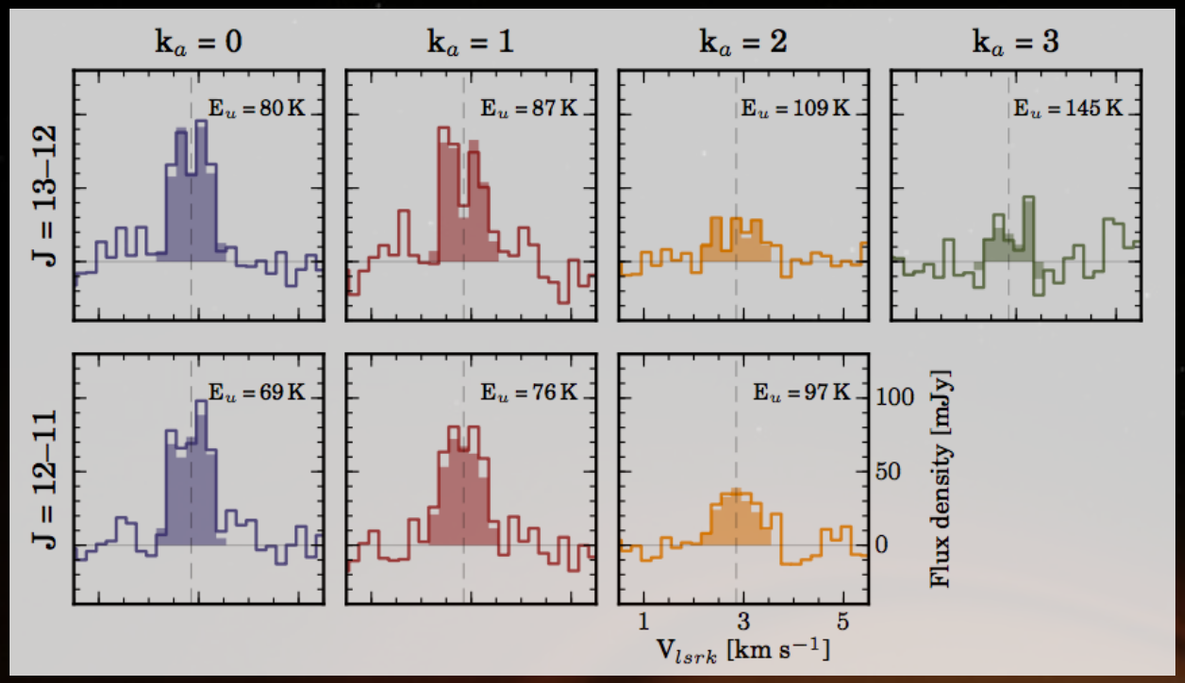
Abundance is low:

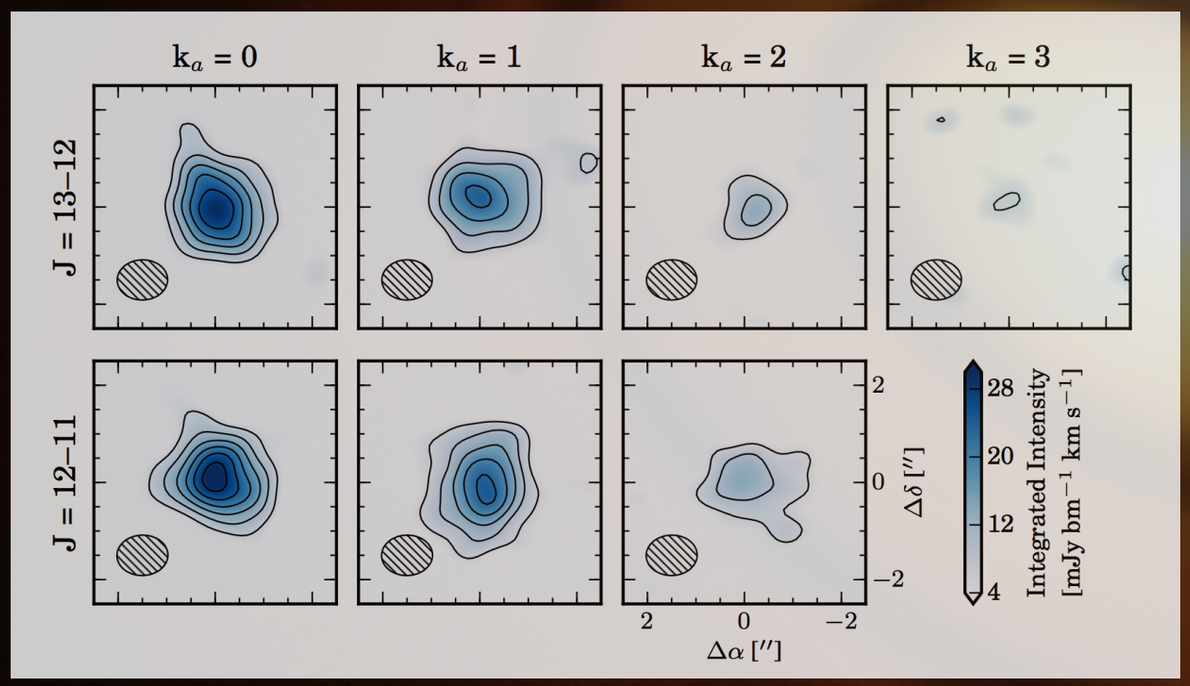
~ 3 - 40 x 10^{-12} / H_2

~ 3 x 10^{-3} / H_2O

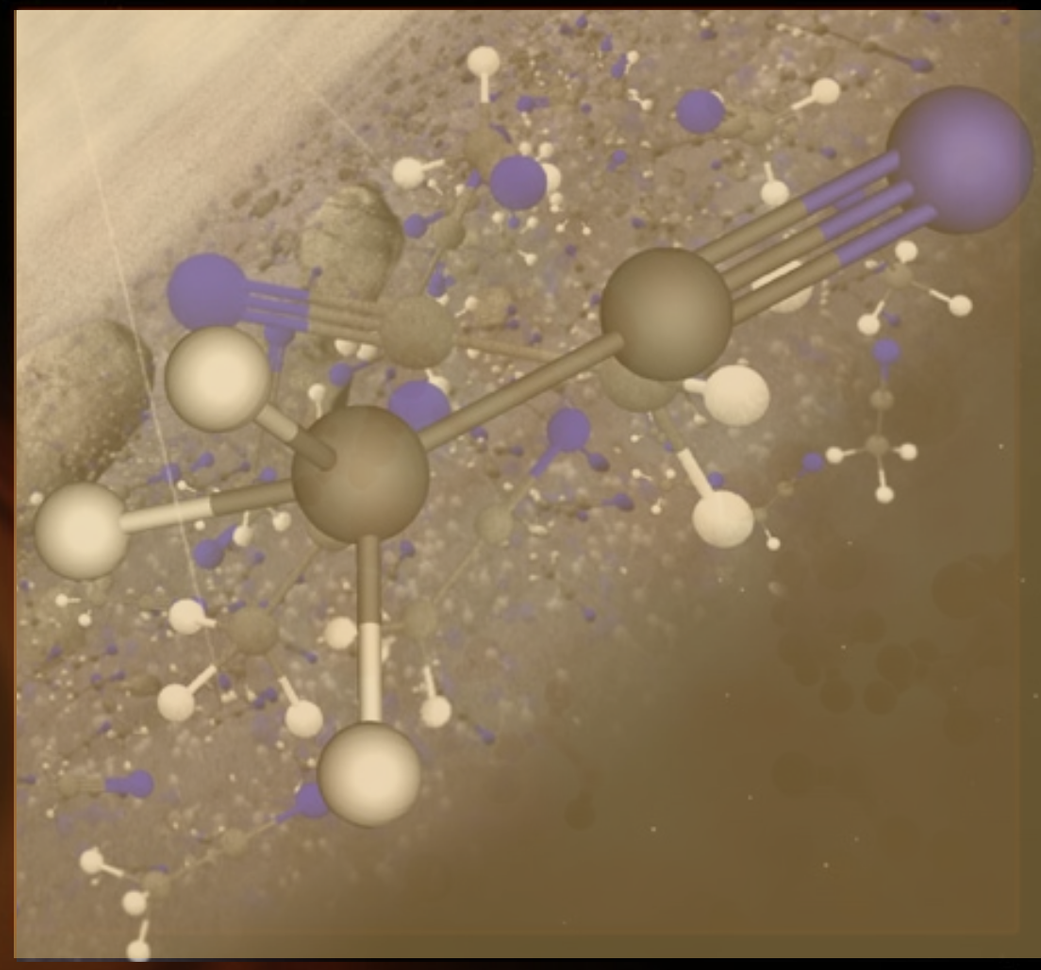
Walsh, C., et al. 2016; Andrews, S. M., et al. 2016; Salinas, V. N., et al. 2016; Parfanov, S. Y., et al. 2017

Searching for complex organic molecules





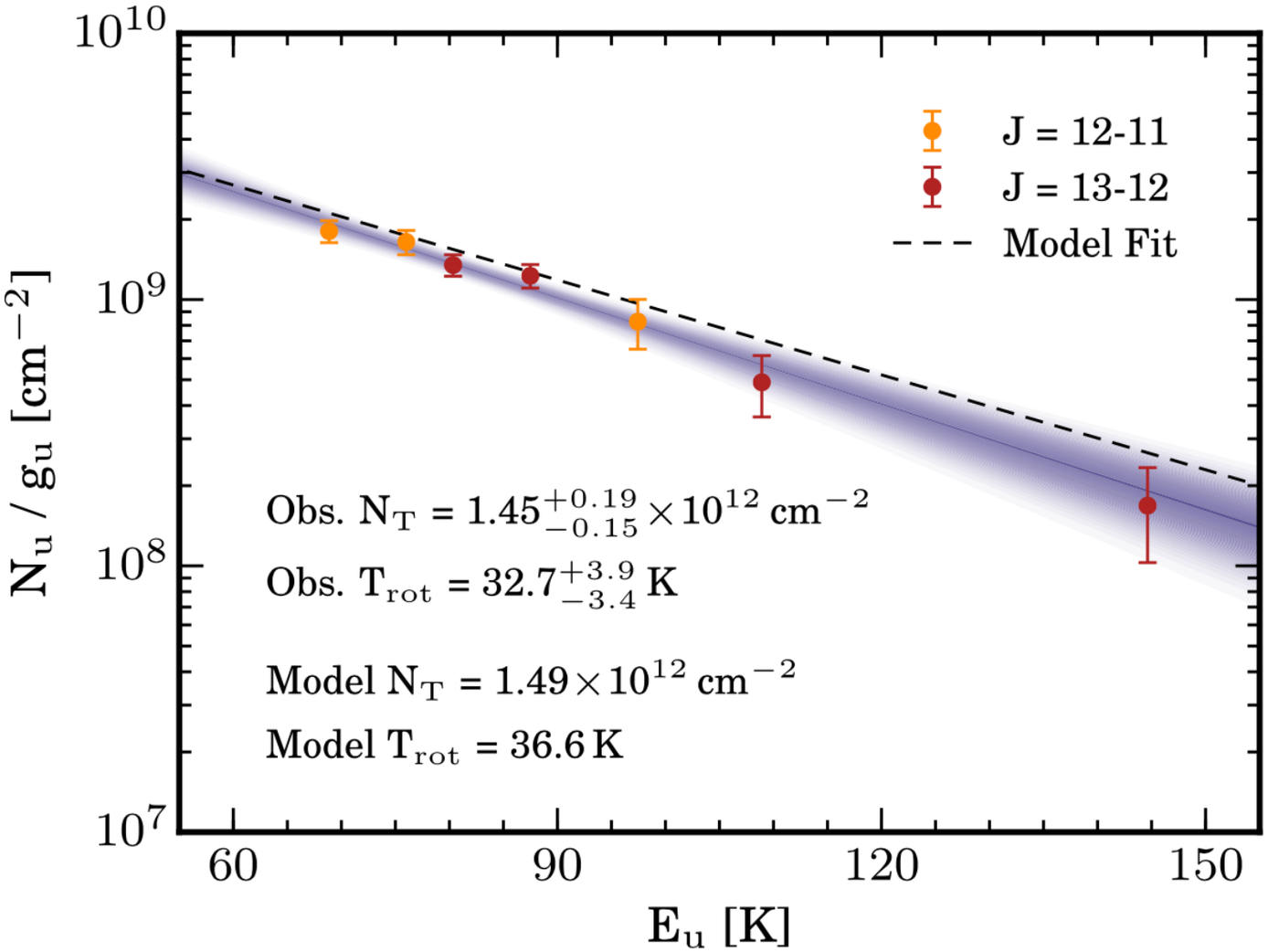
Detection of multiple transitions of methyl cyanide (CH_3CN) in TW Hya



Loomis, R. et al. 2018, ApJ, 859, 131

Searching for complex organic molecules

Multiple rotational lines across a range of excitation energies allow construction of a rotational energy diagram

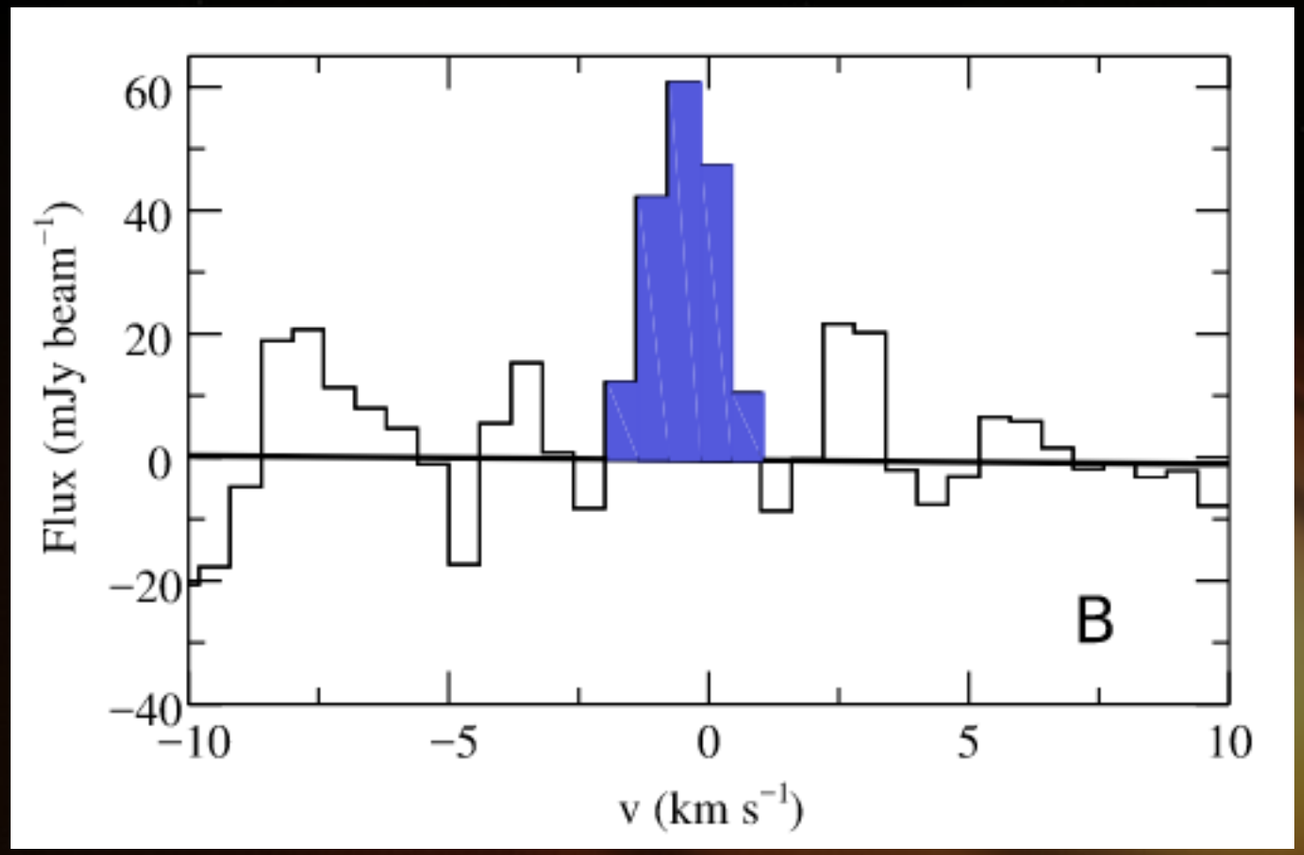


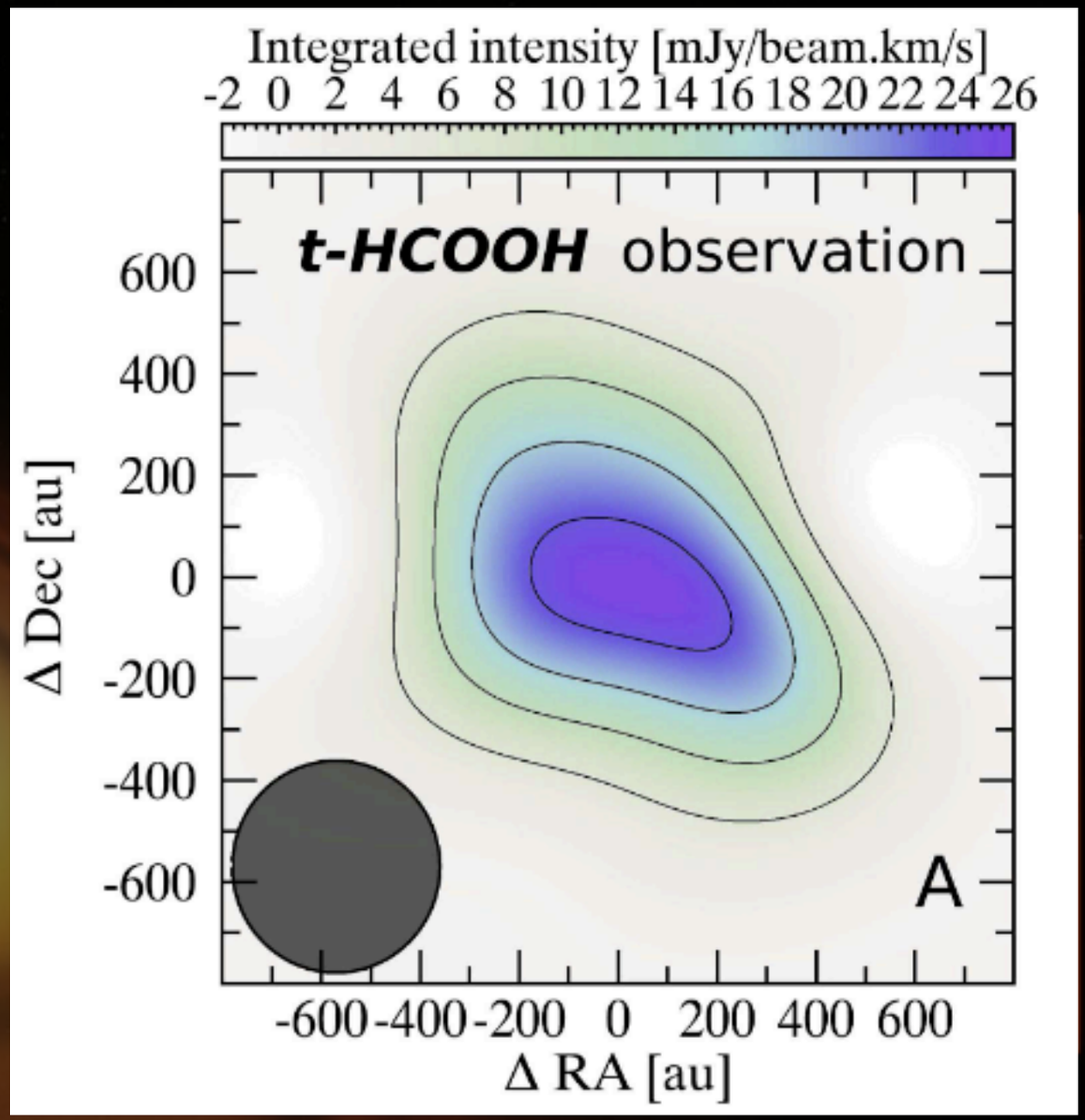
The CH_3CN is arising from a mild molecular layer, ~ 33 K, and ice chemistry is needed reproduce its abundance

Loomis, R. et al. 2018, ApJ, 859, 131

Searching for complex organic molecules

Detection of HCOOH in TW Hya





$HCOOH/CH_3OH \sim 1$

Favre, C. et al. 2018, ApJL, 867, L2

Searching for complex organic molecules

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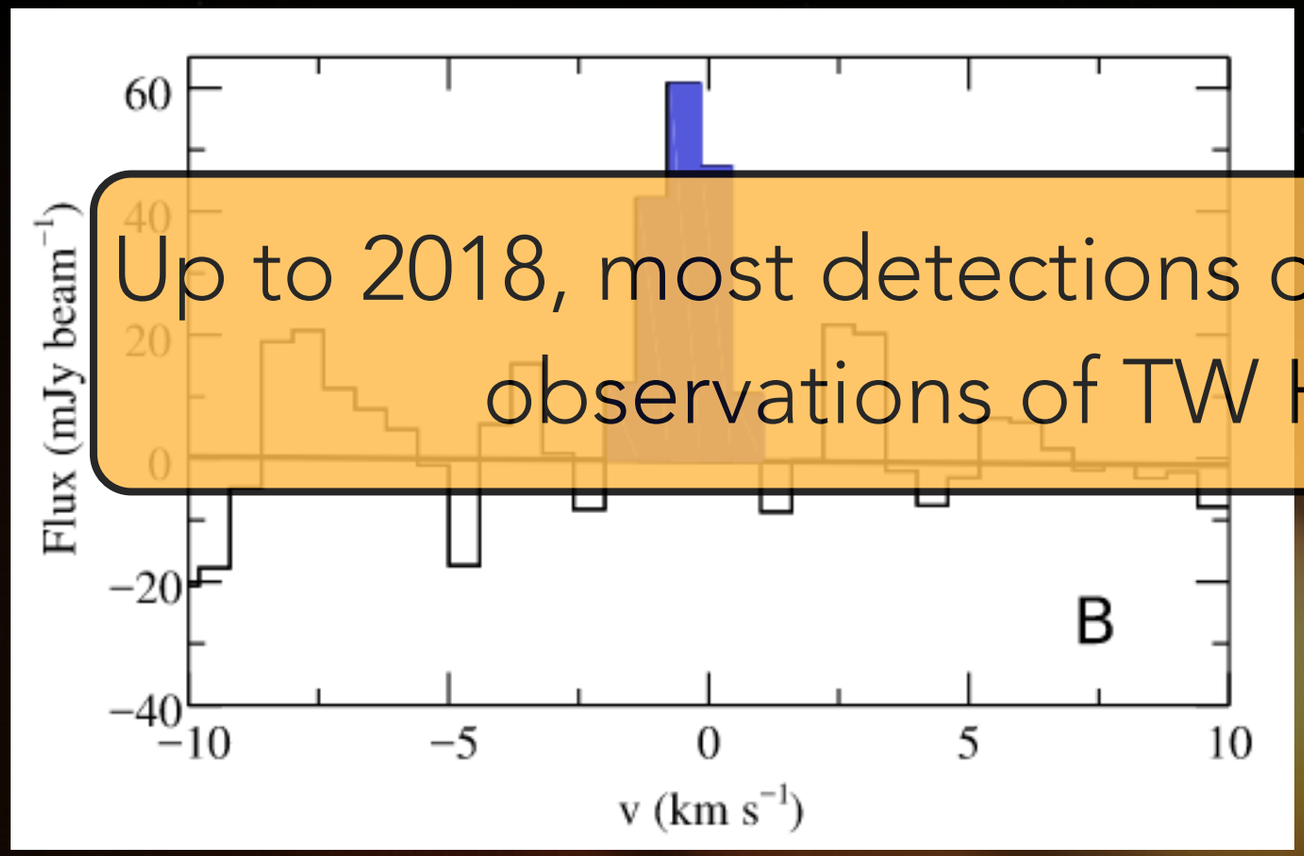
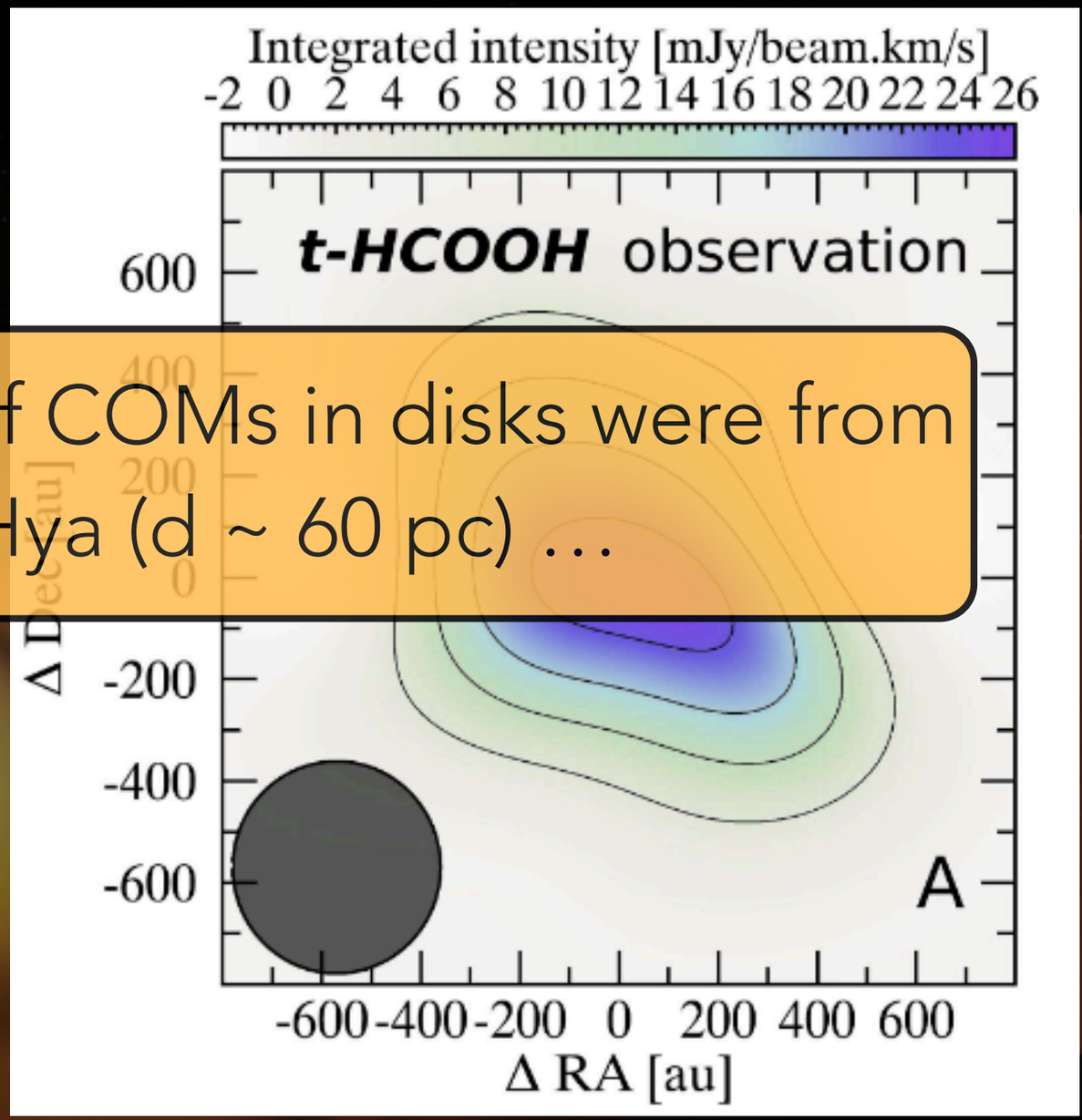




Up to 2018, most detections of COMs in disks were from observations of TW Hya (d ~ 60 pc) ...

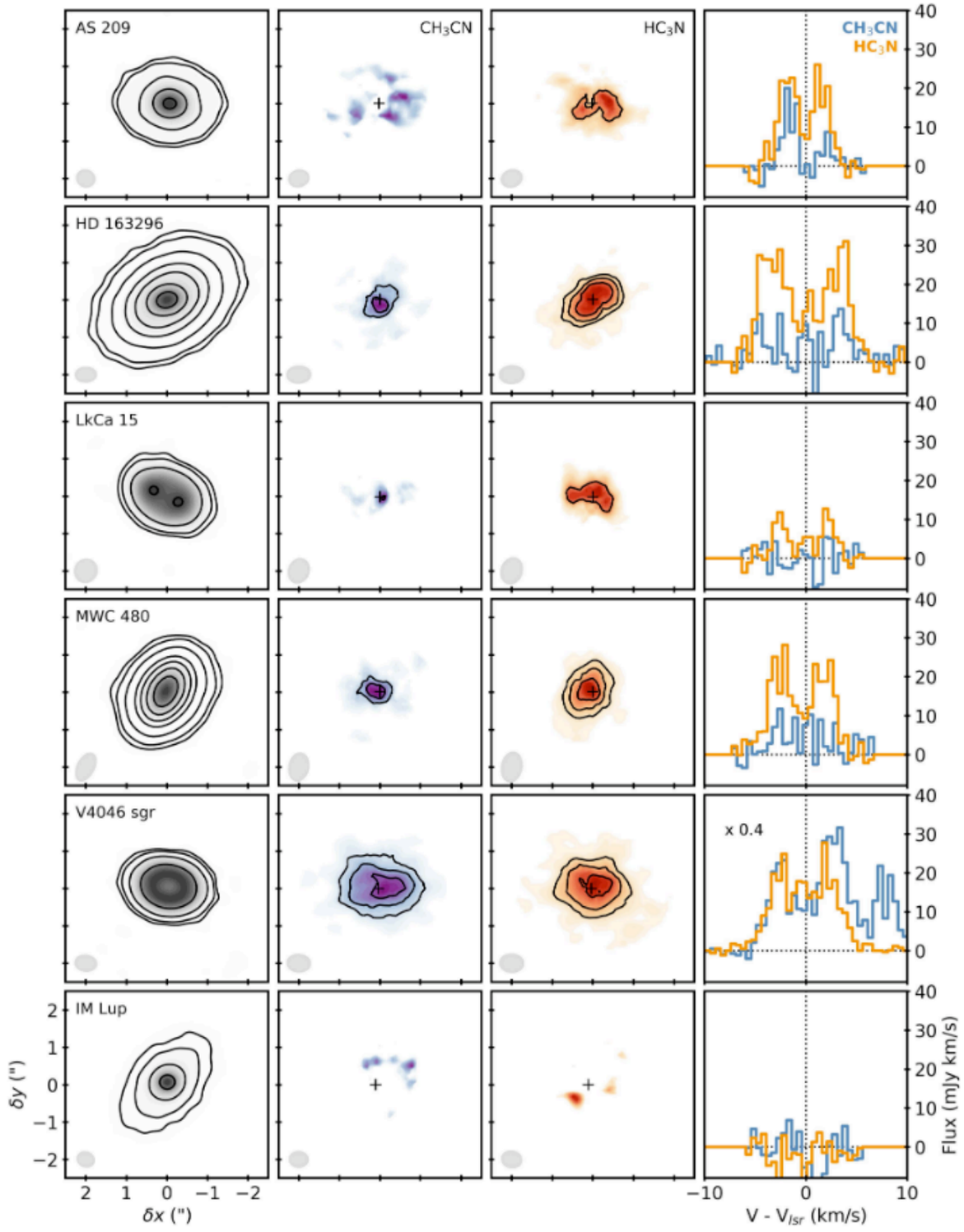
$HCOOH/CH_3OH \sim 1$

Favre, C. et al. 2018, ApJL, 867, L2

Towards surveys, more sources, and higher angular resolution …

Dr Alice Booth | Clay Fellow
Centre for Astrophysics | Harvard & Smithsonian

First survey of nitriles in disks



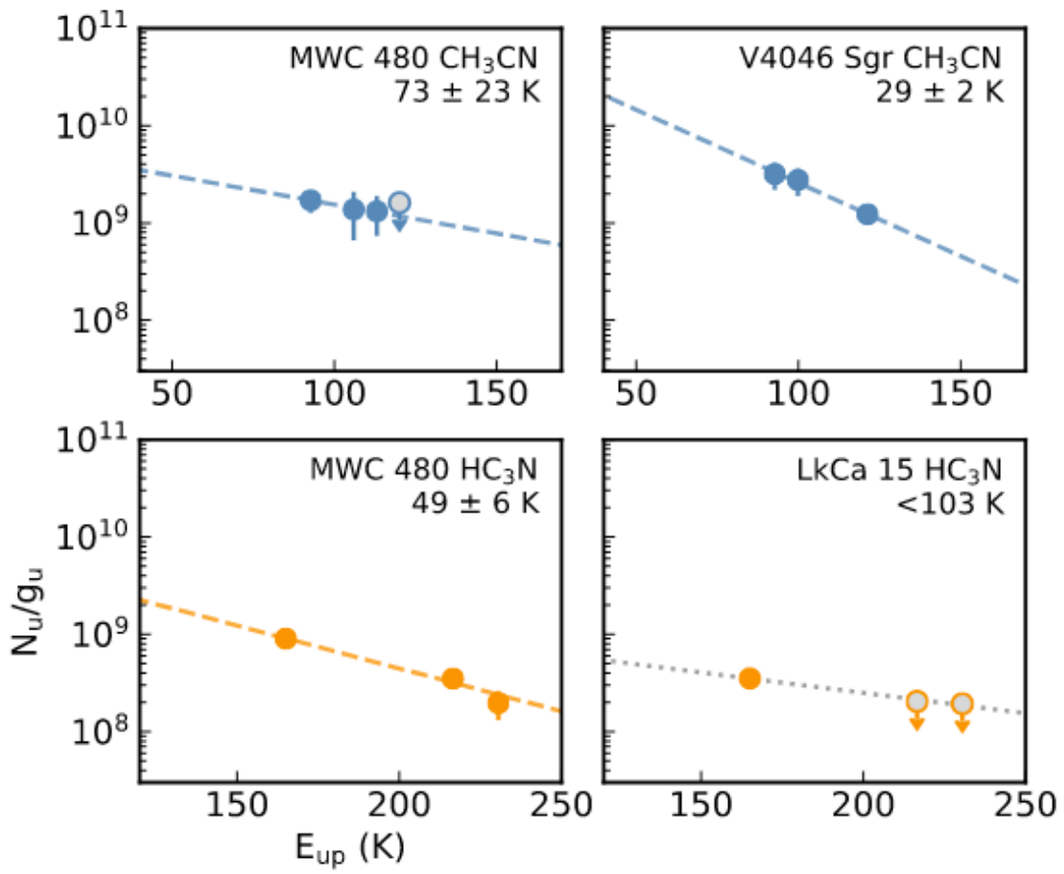
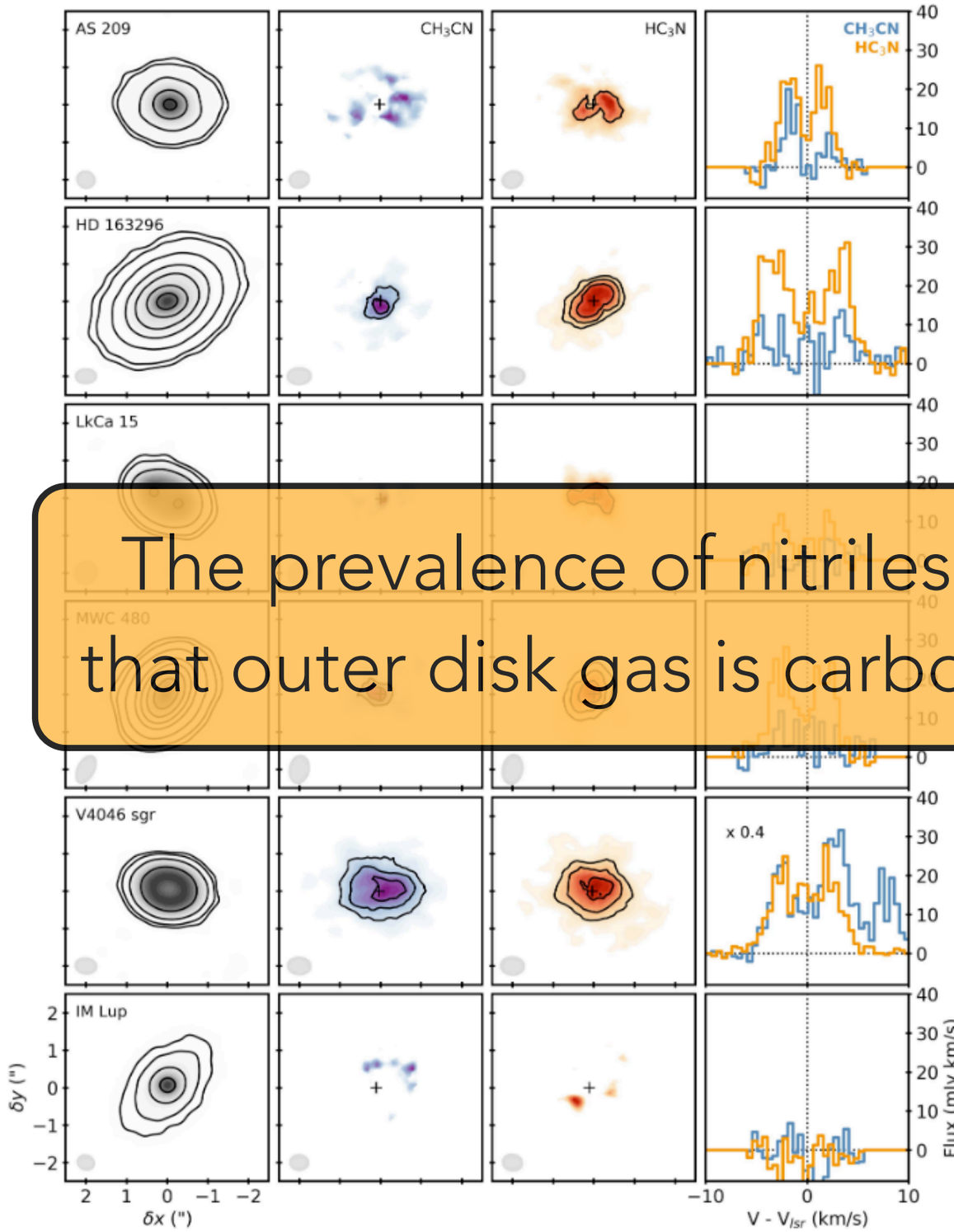


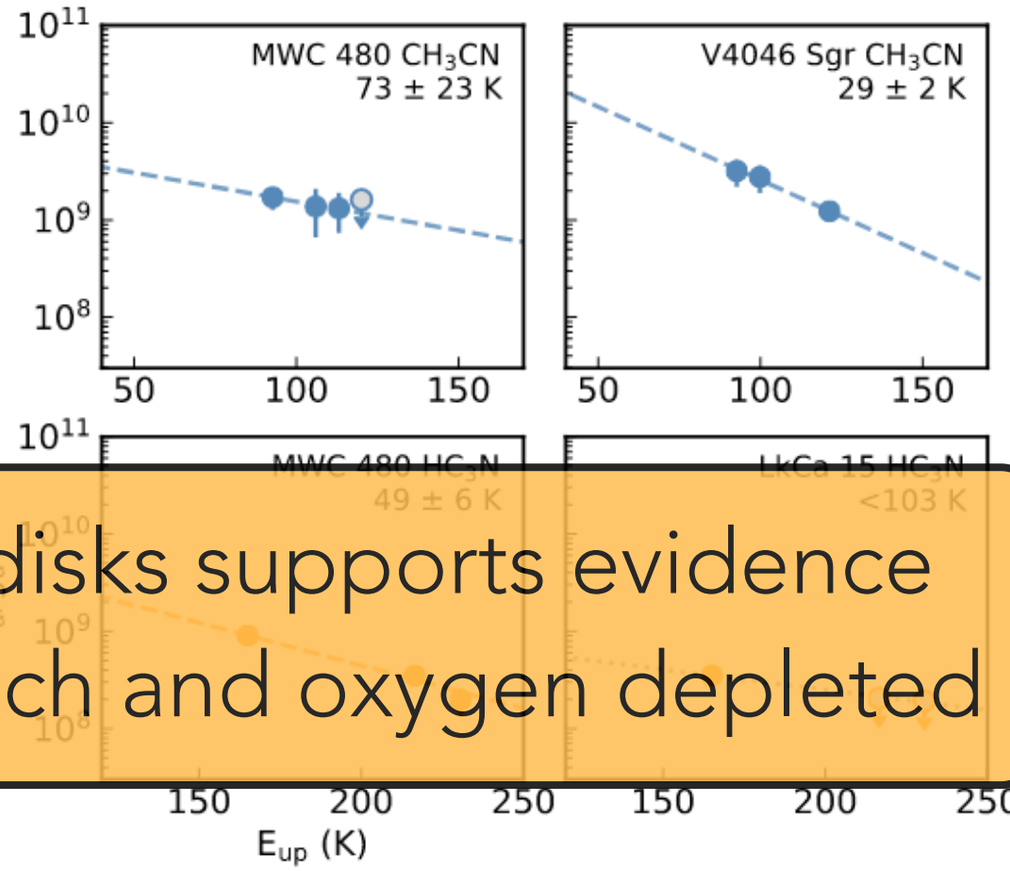
Table 3
Best-fit Column Densities and Rotational Temperatures

Source	Molecule	N_T (10^{12} cm^{-2})	$T_{\rm rot}$ (K)
MWC 480	CH_3CN	1.8 ± 0.4	73 ± 23
V4046 Sgr	CH_3CN	6.2 ± 1.8	29 ± 2
MWC 480	HC_3N	5.8 ± 2.8	49 ± 6
LkCa 15	HC_3N	>0.8	<103

Bergner, J. B., et al. 2018, ApJ, 857, 69

First survey of nitriles in disks





The prevalence of nitriles in disks supports evidence that outer disk gas is carbon rich and oxygen depleted

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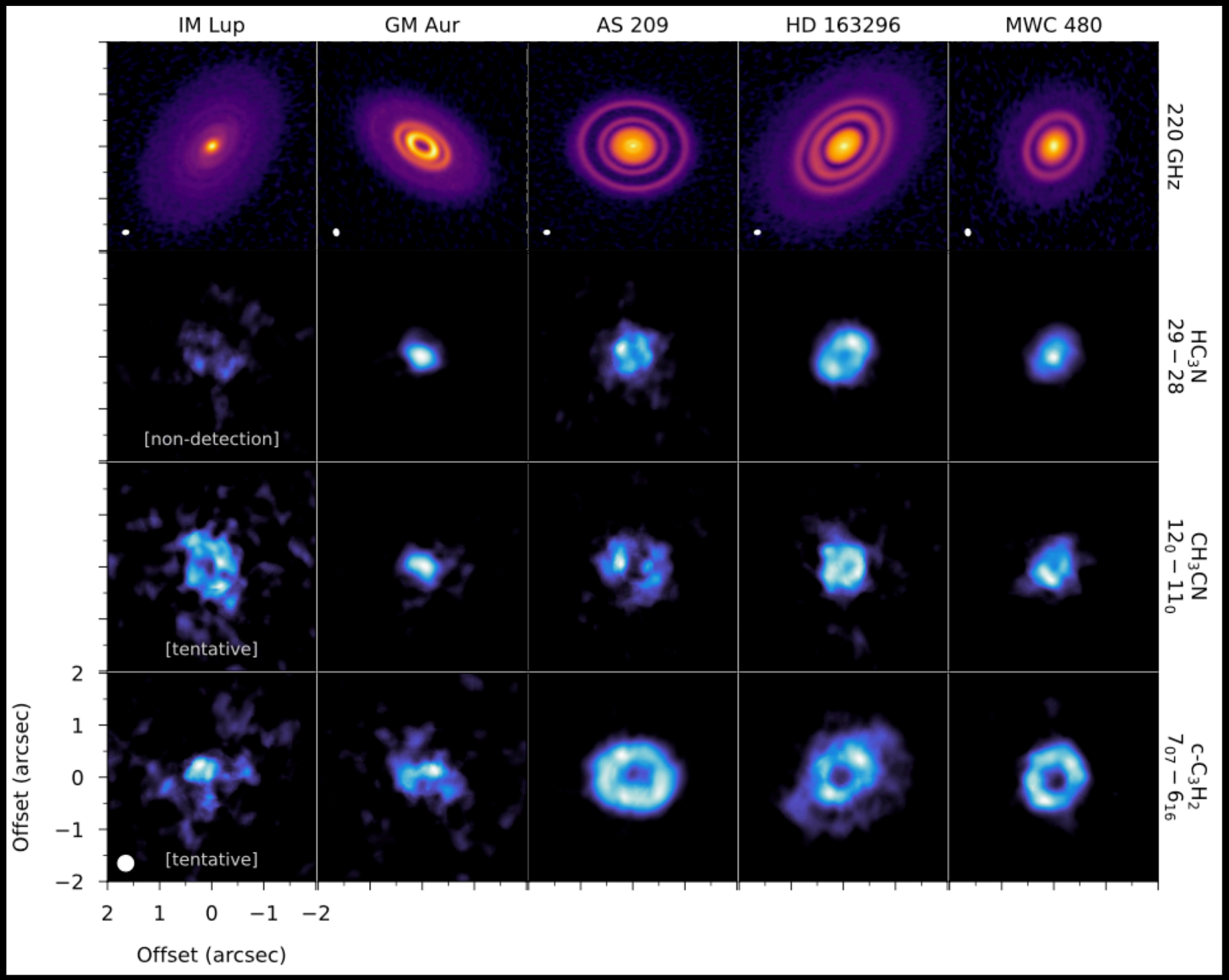
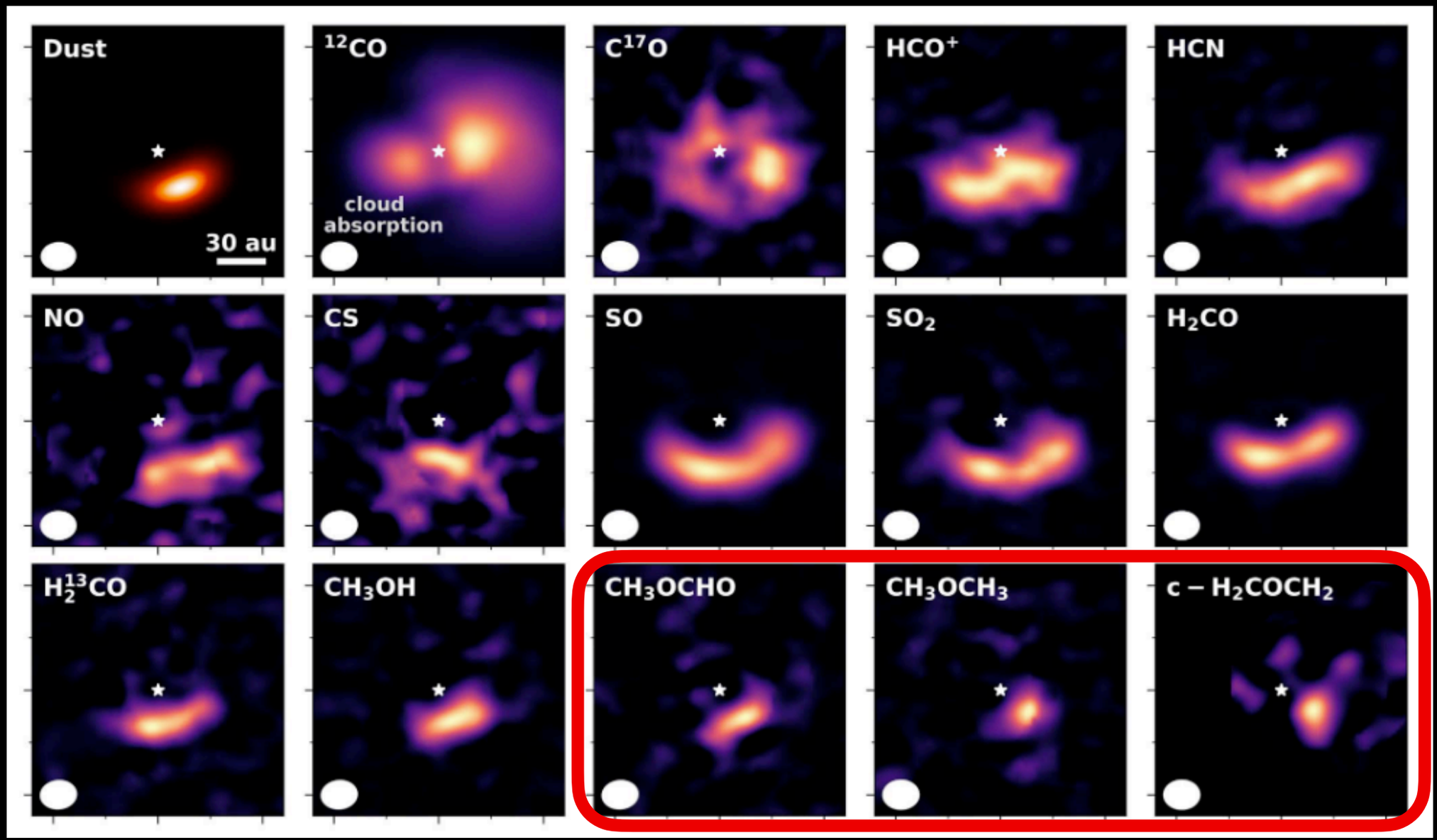
Nitriles at higher resolution

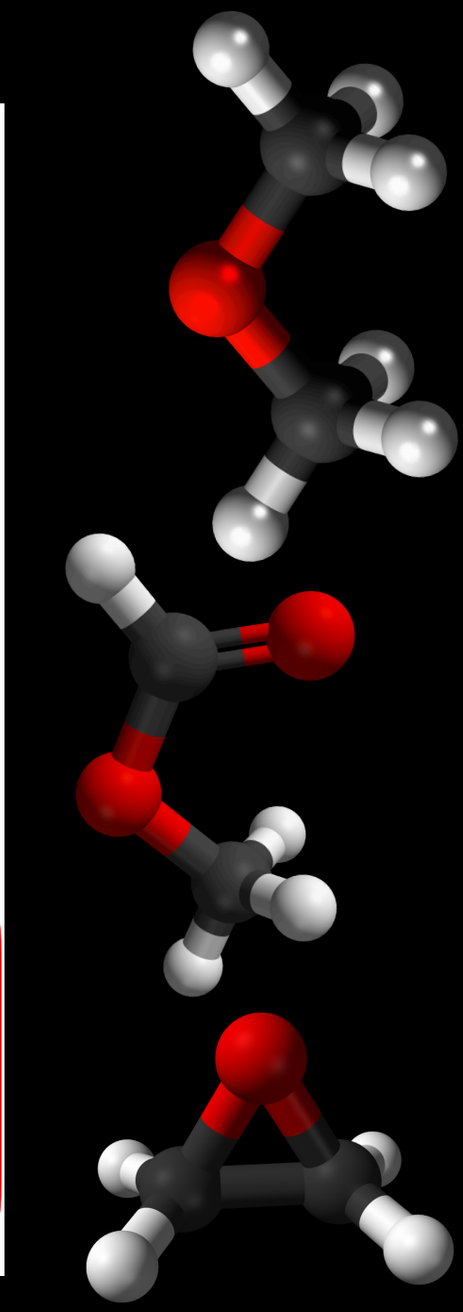


Oberg, K. I., et al. 2021, ApJS, 257, 1; Ilee, J. D., Walsh, C., et al. 2021, ApJS, 257, 9

A new source of O-bearing complex organics

New detections of multiple complex organic molecules in the highly asymmetric disk around IRS 48

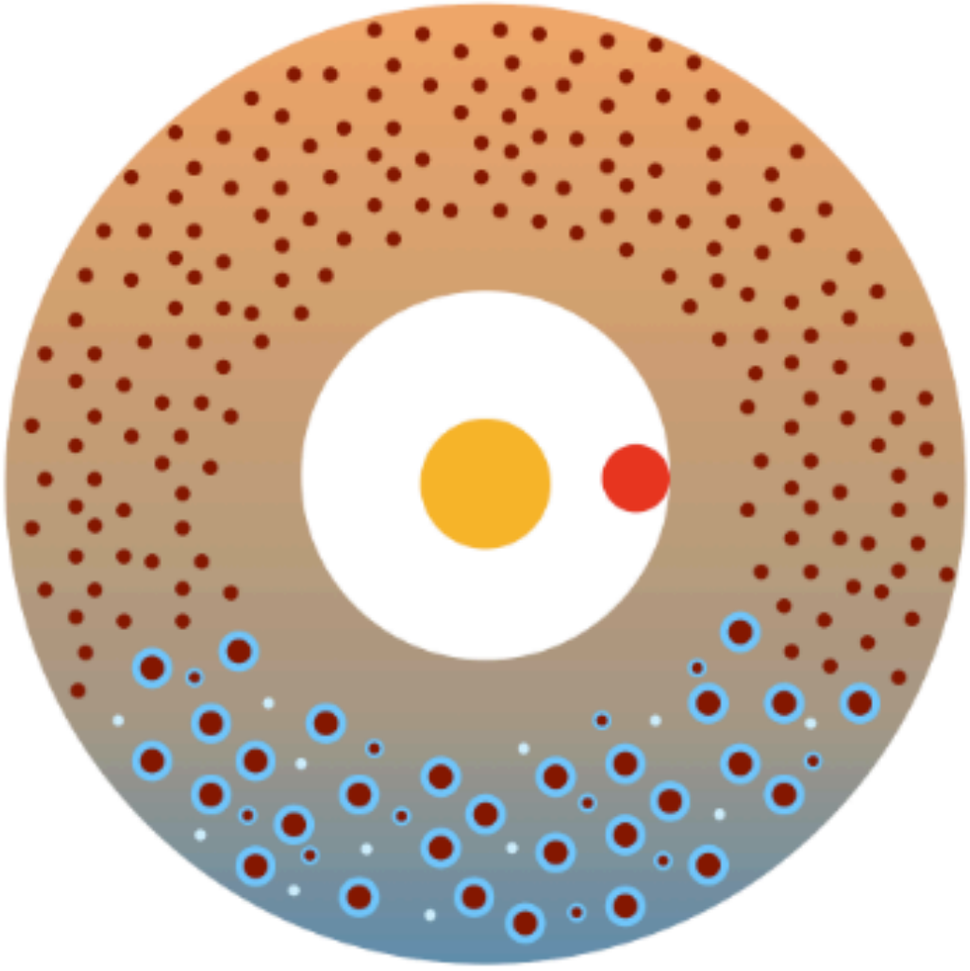


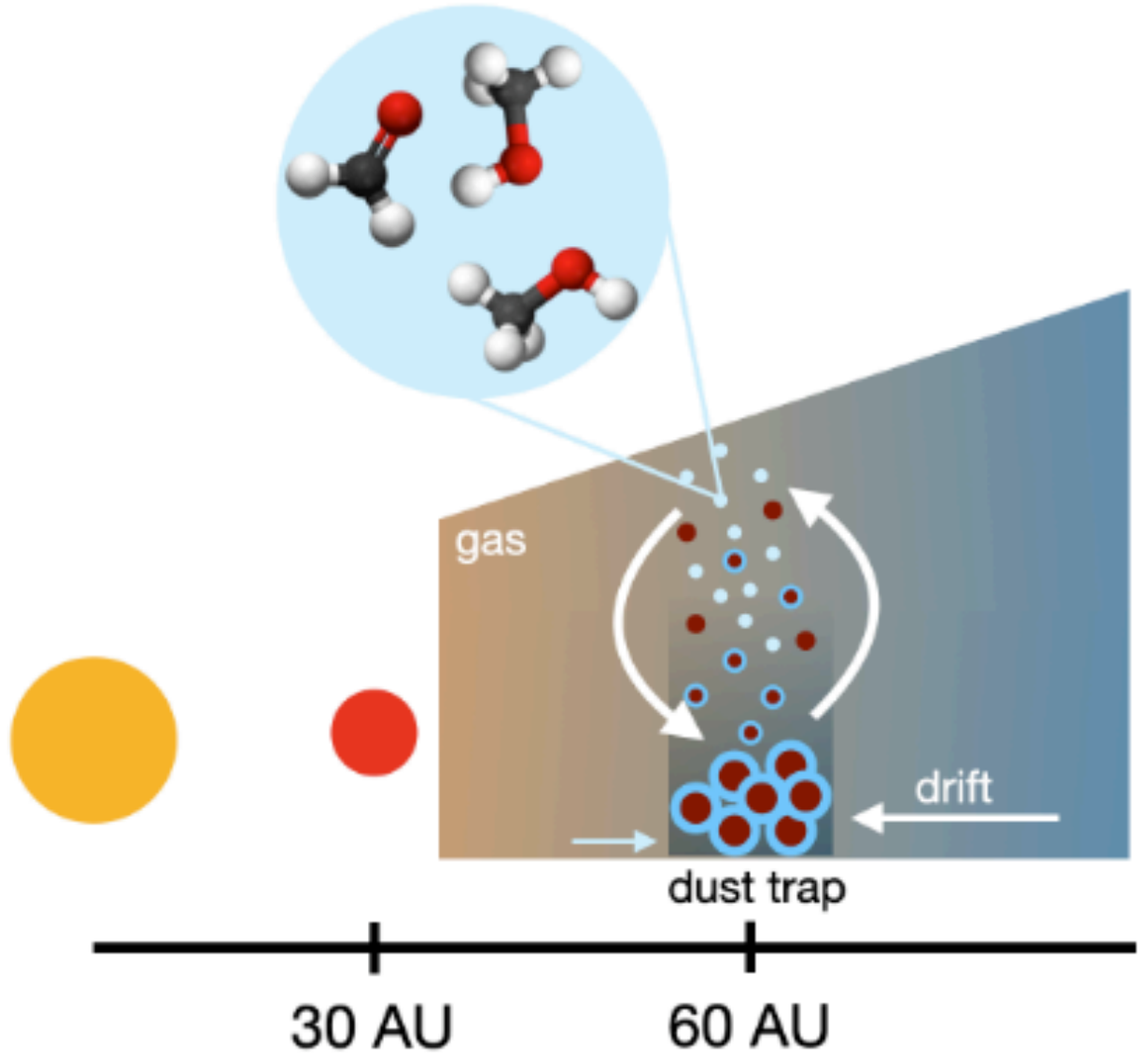


Van der Marel et al. 2021, A&A, 651, L5; Brunken et al. 2022, A&A, 659, A29; Booth, A. S. et al. 2024, AJ, 167, 165

A new source of O-bearing complex organics

The dust trap is also an ice trap?



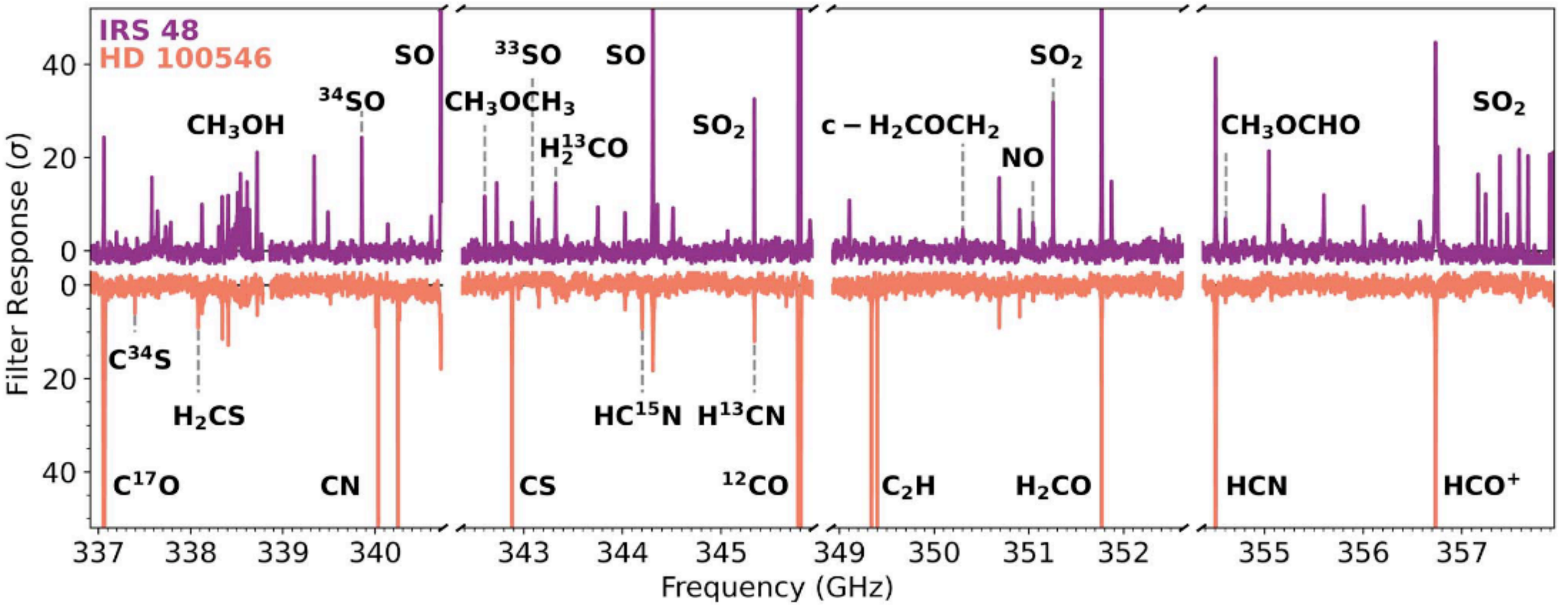


Mixing of small ice-coated grains into the upper atmosphere can reach temperatures high enough to trigger desorption of ices

van der Marel et al. 2021, A&A, 651, L5

Warm disks around Herbig stars are O-rich

The inner regions of the transition disks around Herbig Ae/Be stars are rich in S-bearing molecules, and O-bearing complex organic molecules

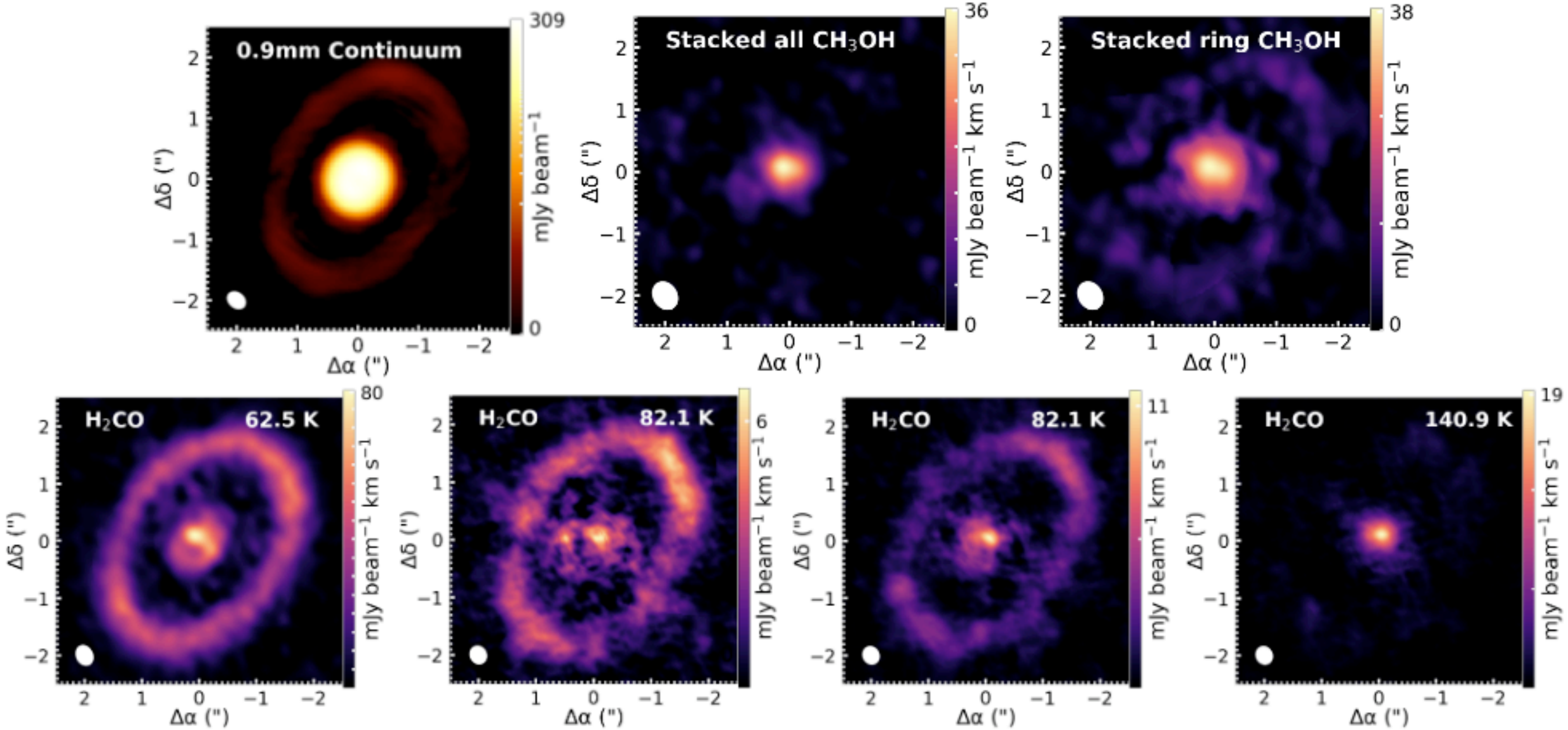


Larger nitriles (HC_3N and CH_3CN) are notably missing: direct sublimation of the O-rich ice reservoir at the inner cavity edge?

Booth, A. S. et al. 2024, AJ, 167, 164

Warm disks around Herbig stars are O-rich

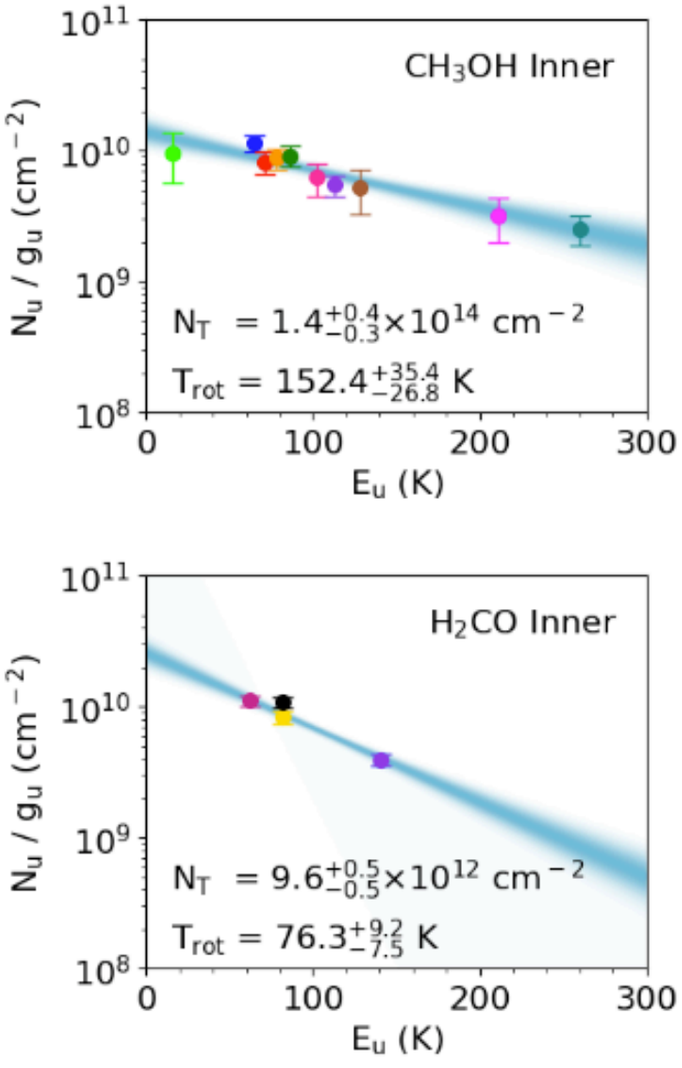
The multi-ringed disk around HD 100546 also shows multiple rings of methanol and formaldehyde: dust rings are ice rings?



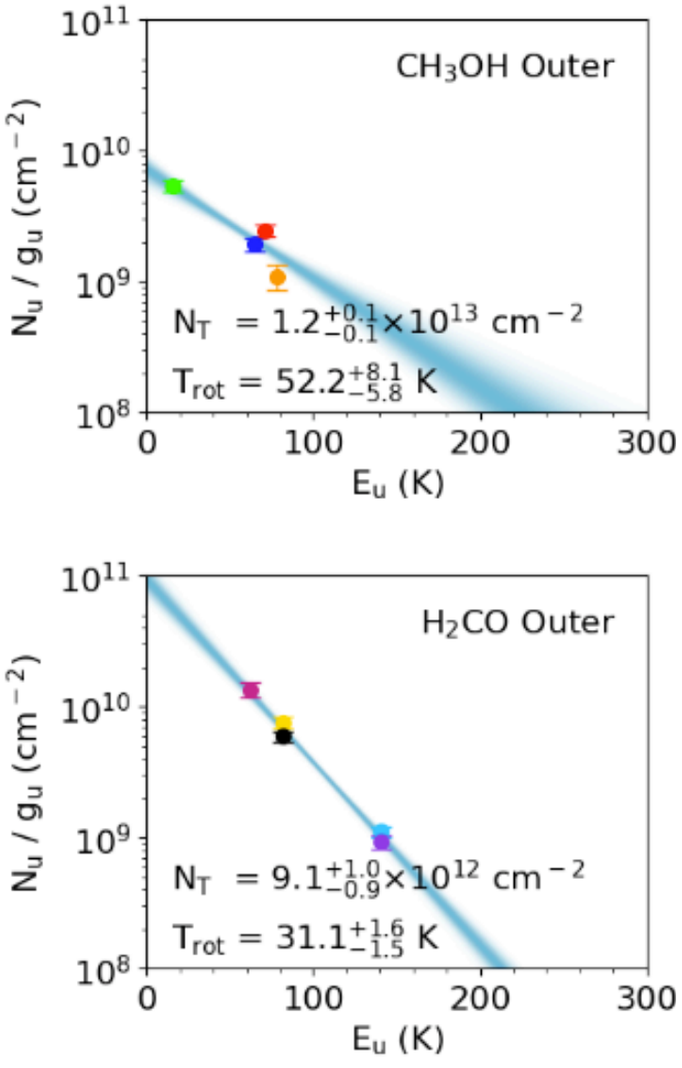
Booth, A. S. et al. 2024, AJ, 167, 165; Evans L. E. et al. 2025, ApJ, 982, 62

Warm disks around Herbig stars are O-rich

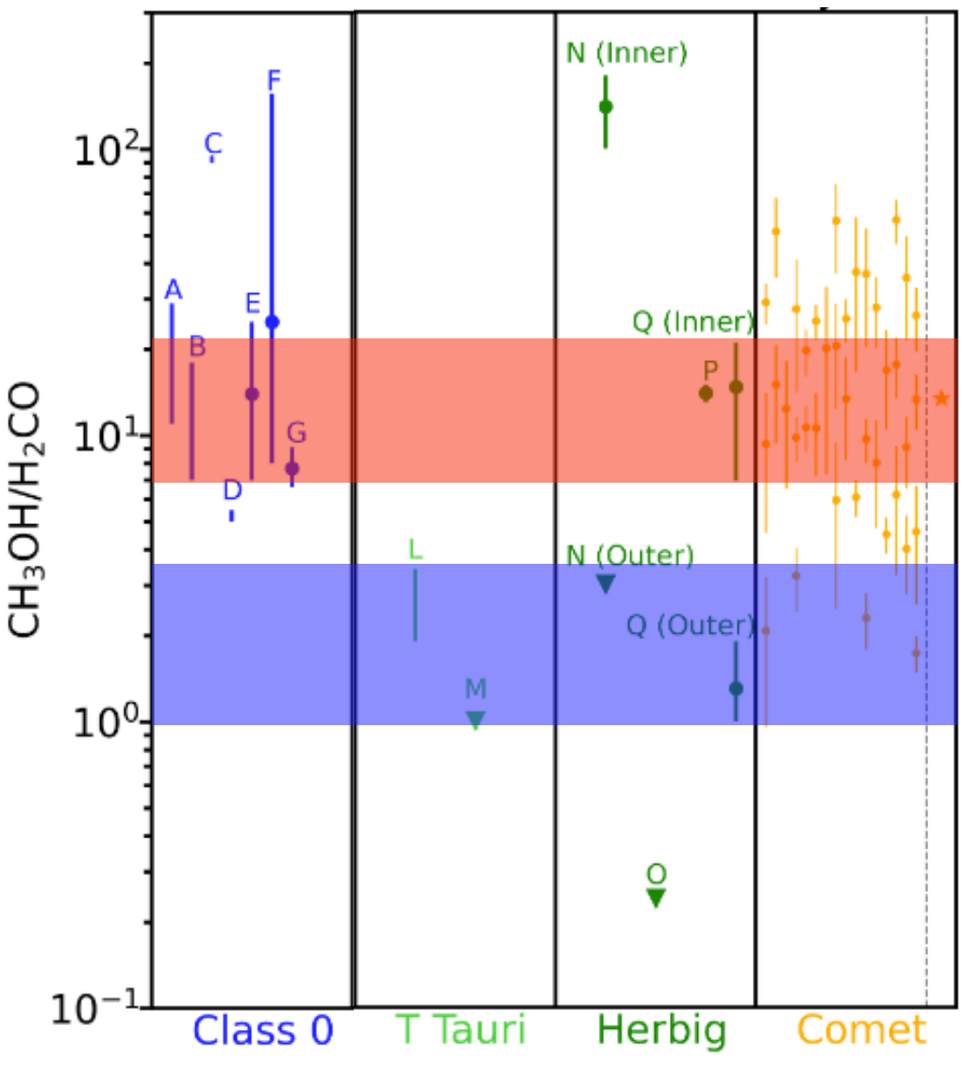
The ratio of CH_3OH/H_2CO in the inner disk is similar to that in Class 0 protostars and comets: the ratio in the outer disk is similar to that in TW Hya



Thermal desorption



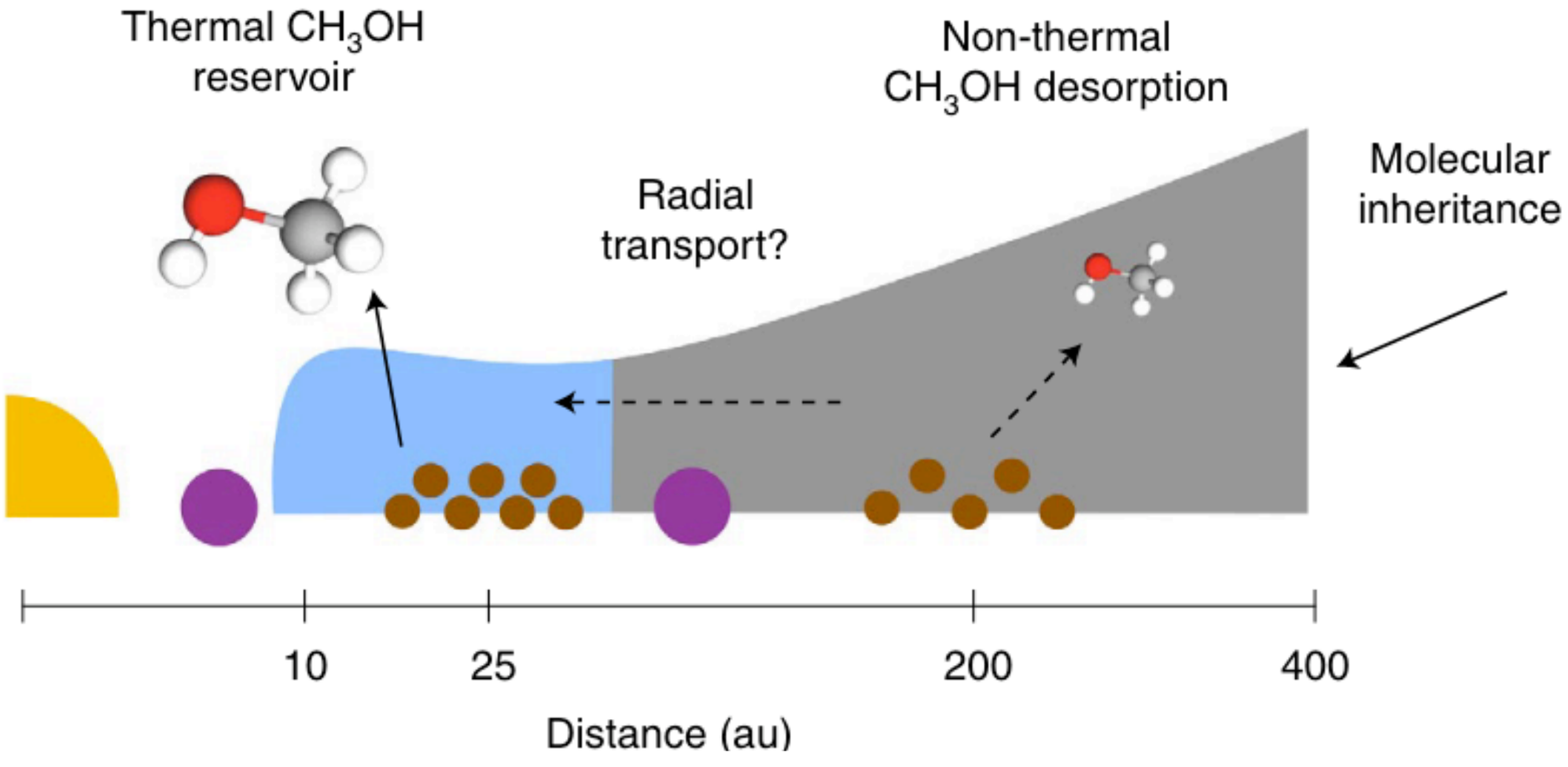
Non-thermal desorption



Evans L. E. et al. 2025, ApJ, 982, 62; Lippi, M., et al. 2024, ApJ, 970, L5

Inheritance of methanol ice?

Models predict that the disk around HD 100546 is too warm for methanol ice to form in situ (needs dust temperatures < 25 K for CO ice to freeze out)

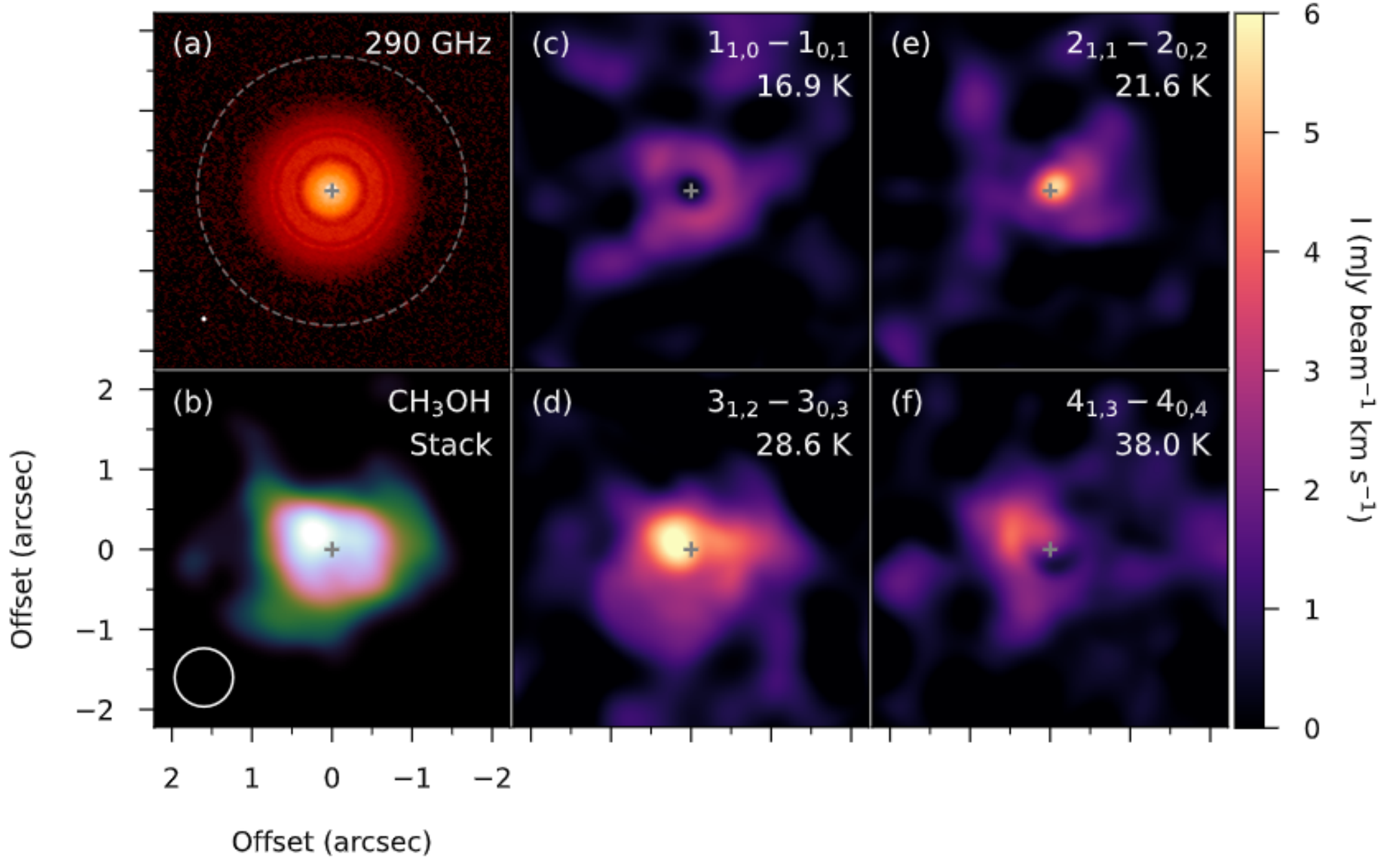


Beginning the calculations with no methanol ice in the disk results in too little methanol gas being formed to explain the observations

Booth, A. S., et al. 2021, Nature Astronomy, 5, 684

Back to methanol in TW Hya …

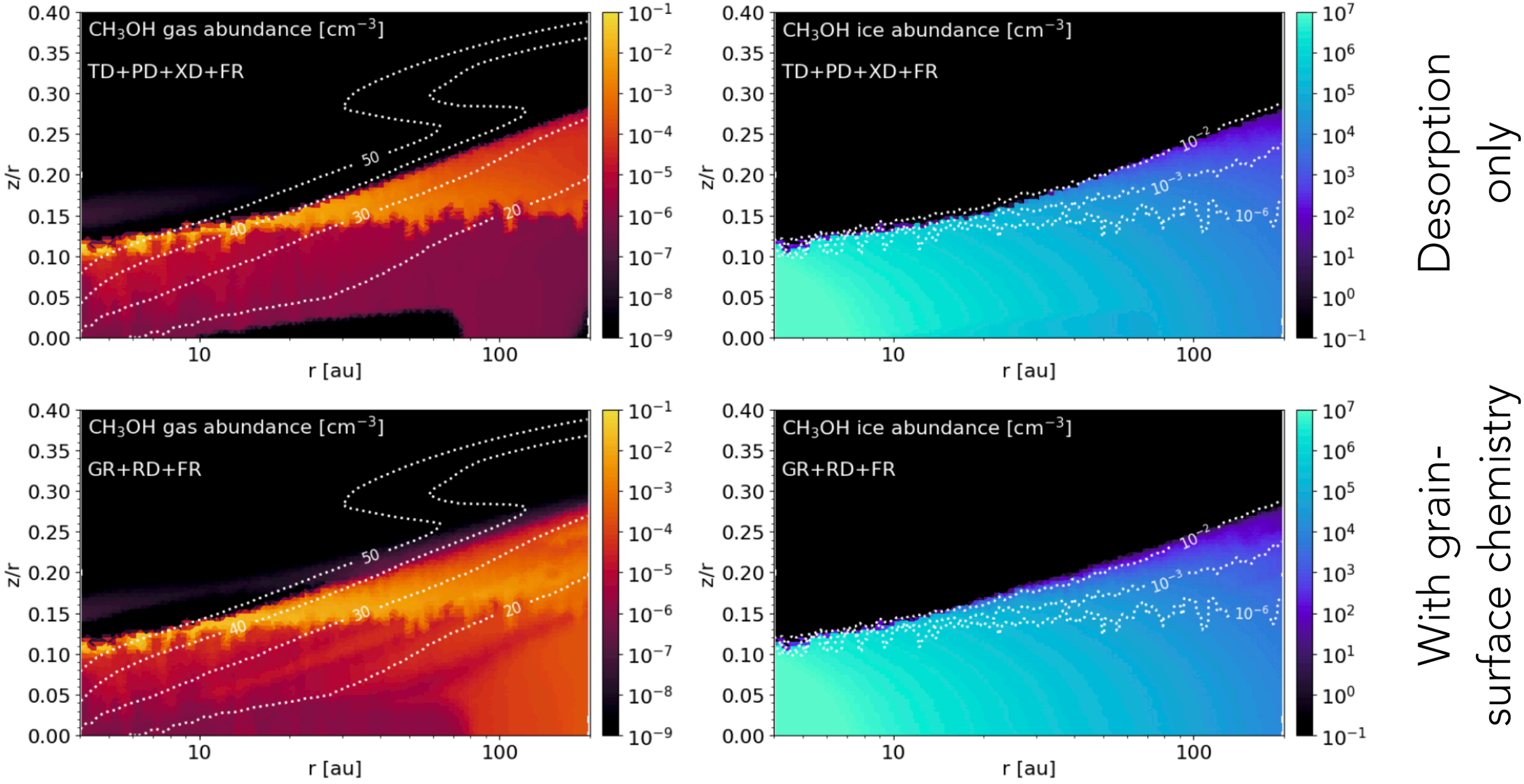
Deeper ALMA data (10 hours on source) for TW Hya has confirmed the presence of gas-phase methanol and detected individual transitions



Ilee, Walsh, & Calahan 2026, AJ, 171, 3

Back to methanol in TW Hya …

Chemical models for a structure specific to TW Hya show gas-phase methanol in the warm molecular layer



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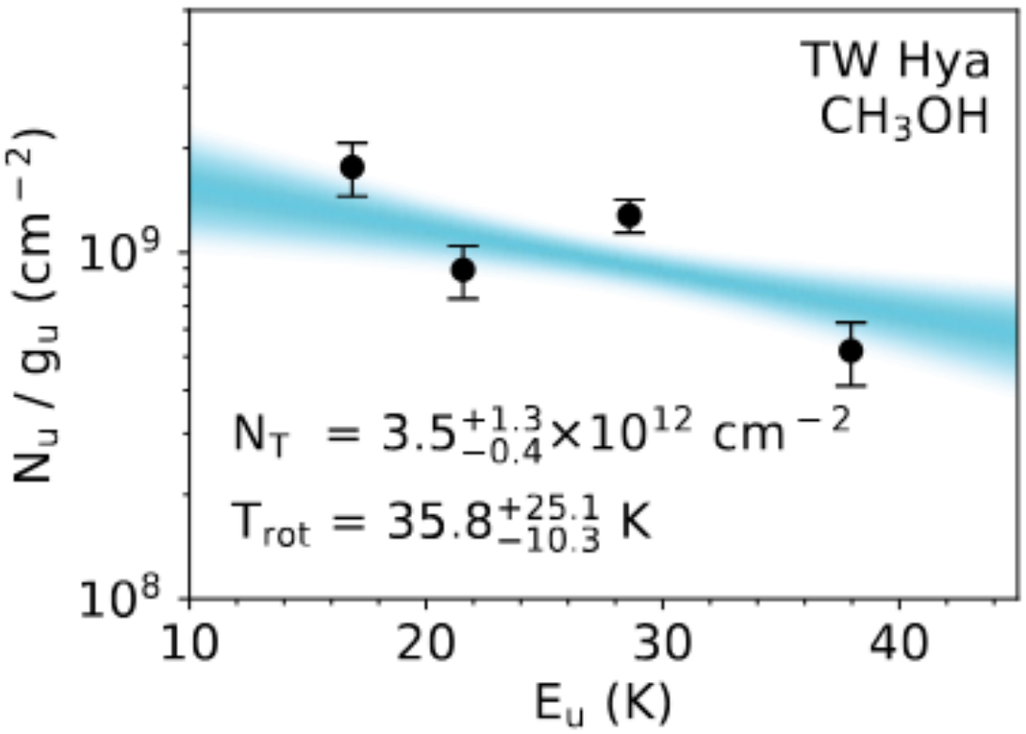

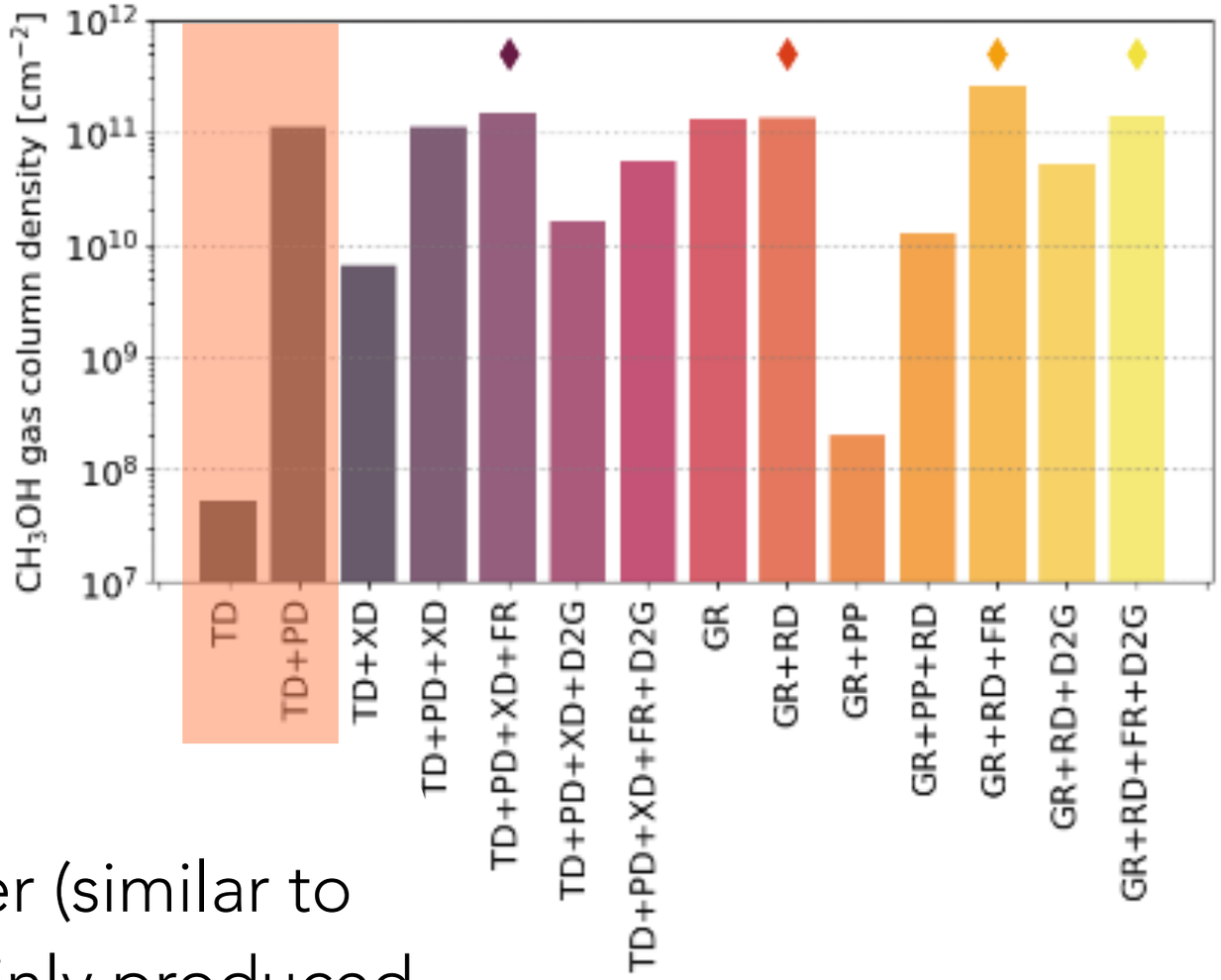

Methanol is in a mild molecular layer (similar to CH_3CN), and models suggest it is mainly produced by photodesorption from the ice reservoir

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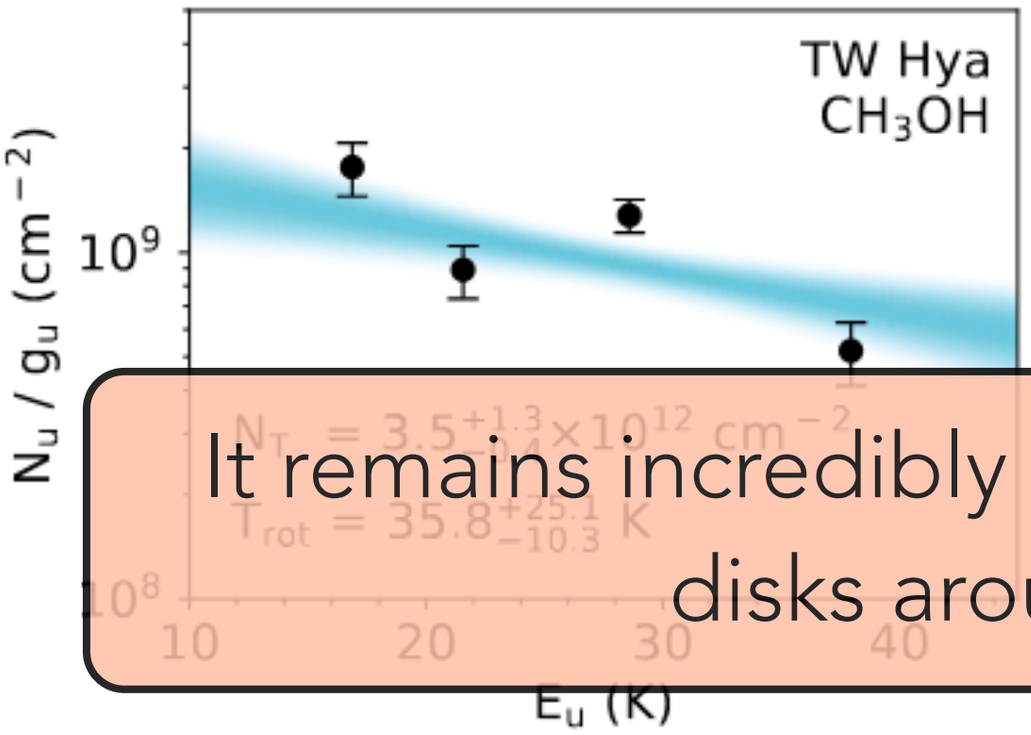
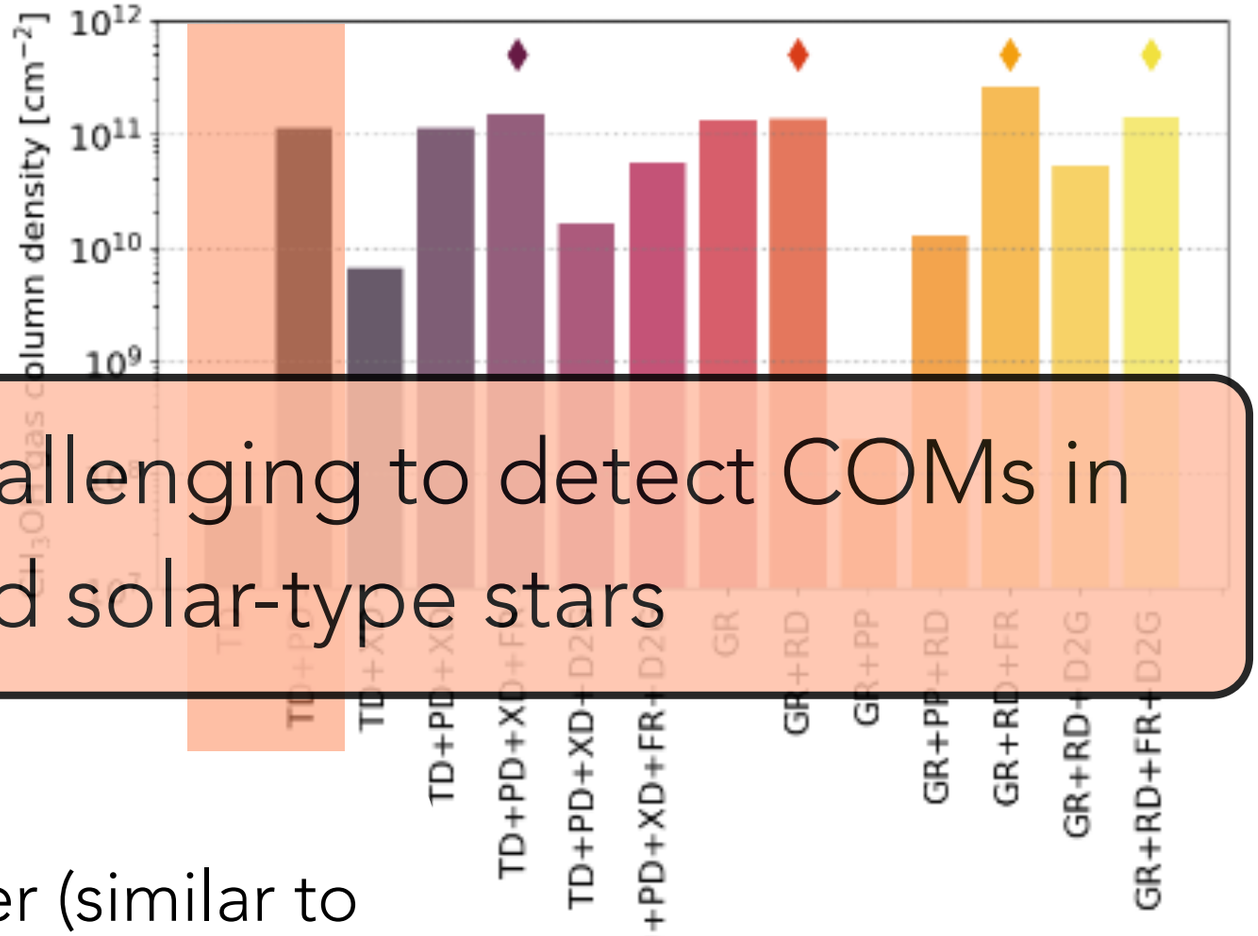




It remains incredibly challenging to detect COMs in disks around solar-type stars

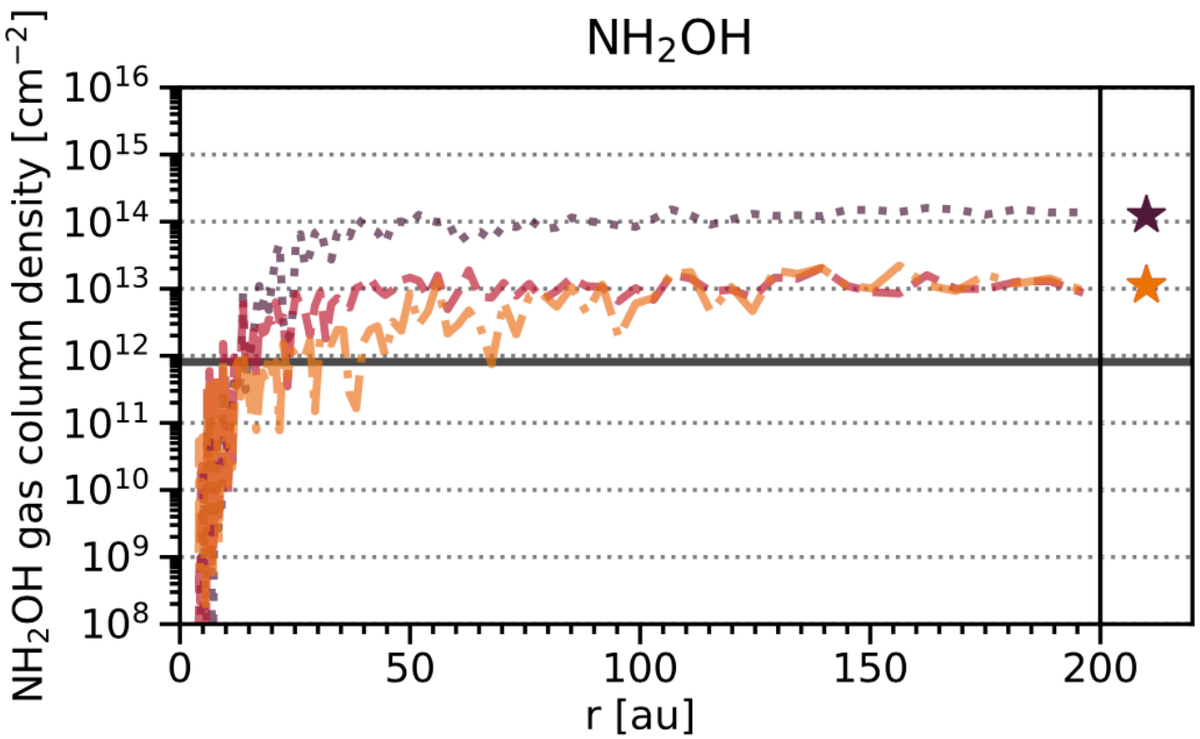
Methanol is in a mild molecular layer (similar to CH_3CN), and models suggest it is mainly produced by photodesorption from the ice reservoir

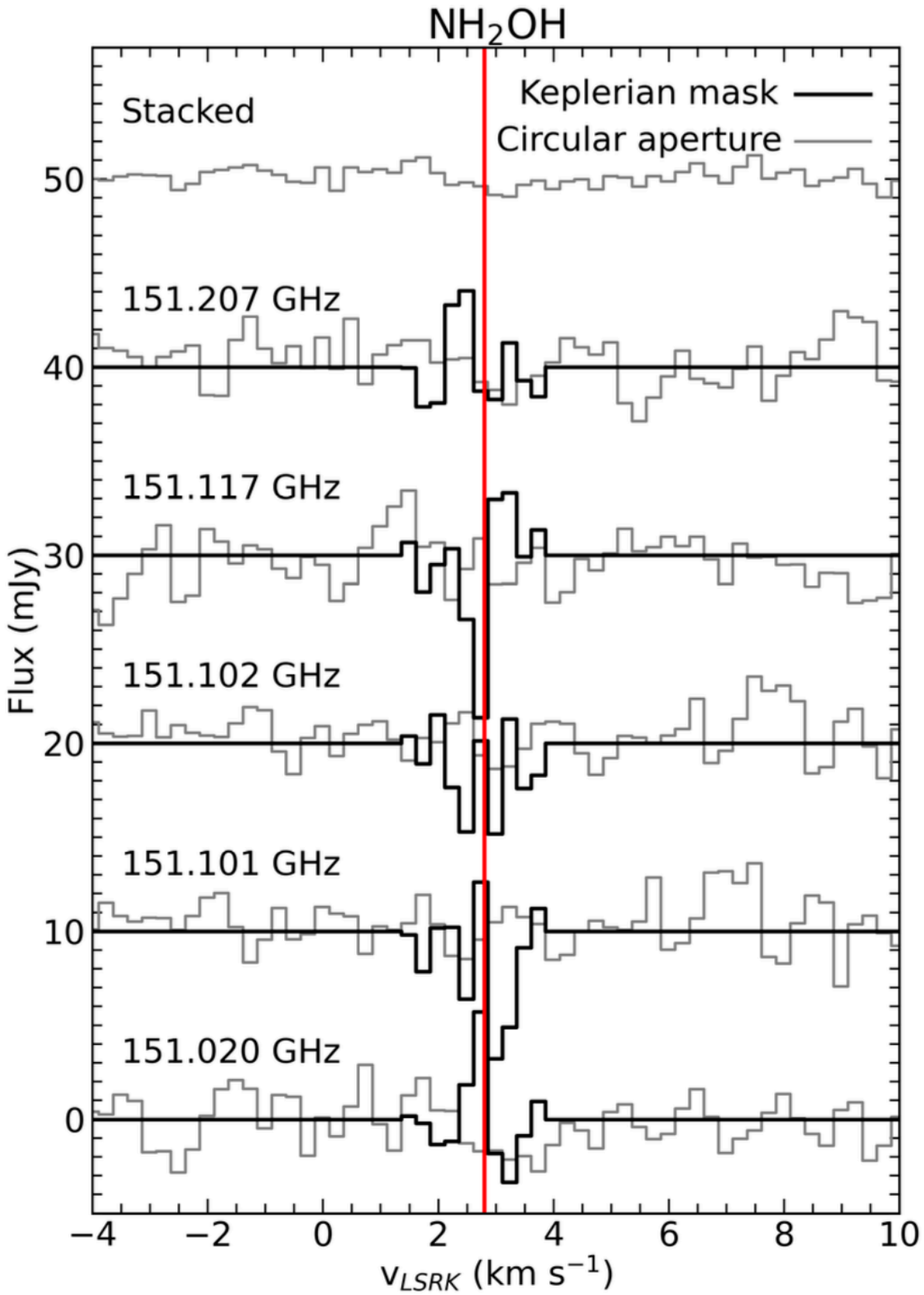
Ilee, Walsh, & Calahan 2026, AJ, 171, 3

Where are the amines?

Deep upper limits (~ 1 mJy/beam) for NH_2OH in TW Hya; $N < 8.1 \times 10^{11}$ cm^{-2}

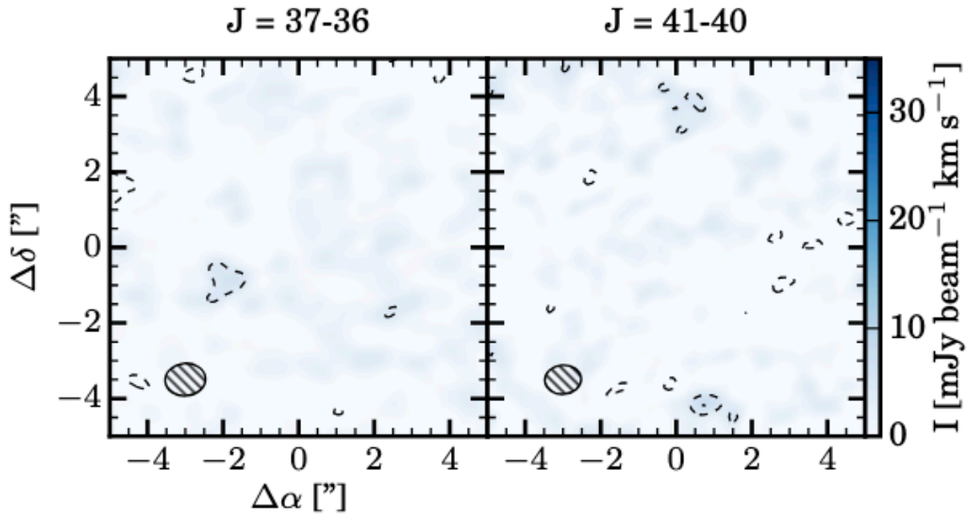
Models overpredict its abundance, even with x 100 oxygen depletion - lack of destruction mechanisms in network?

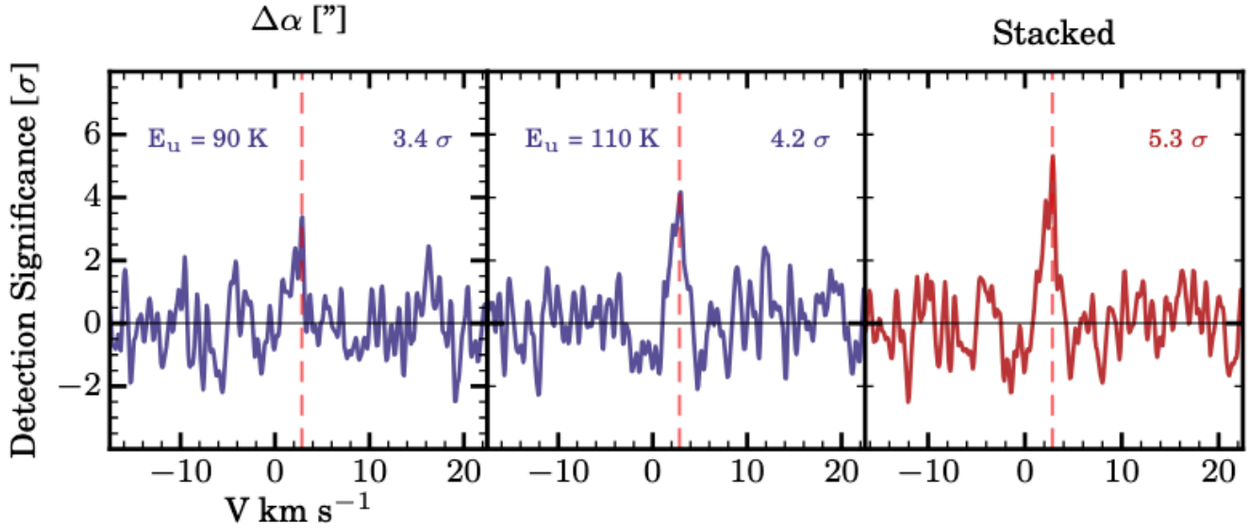


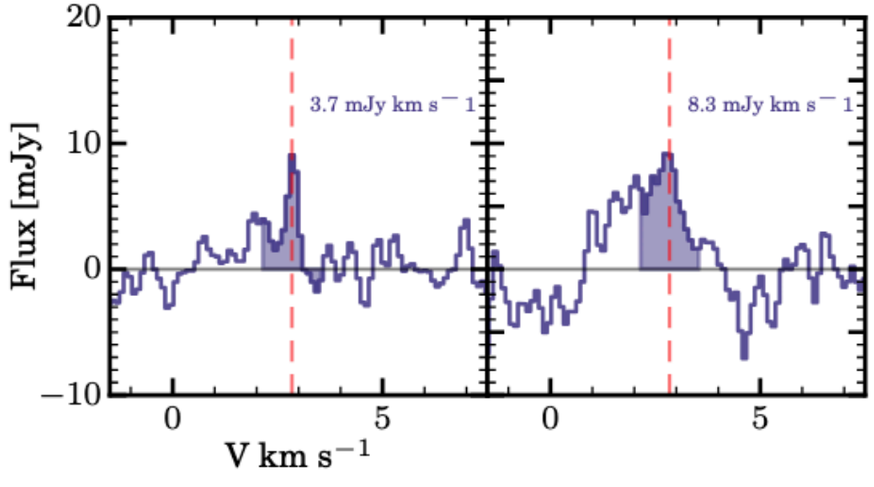


Evans & Walsh 2026, ApJ, submitted

Towards larger cyanopolyynes







First detection of HC_5N in a protoplanetary disk!

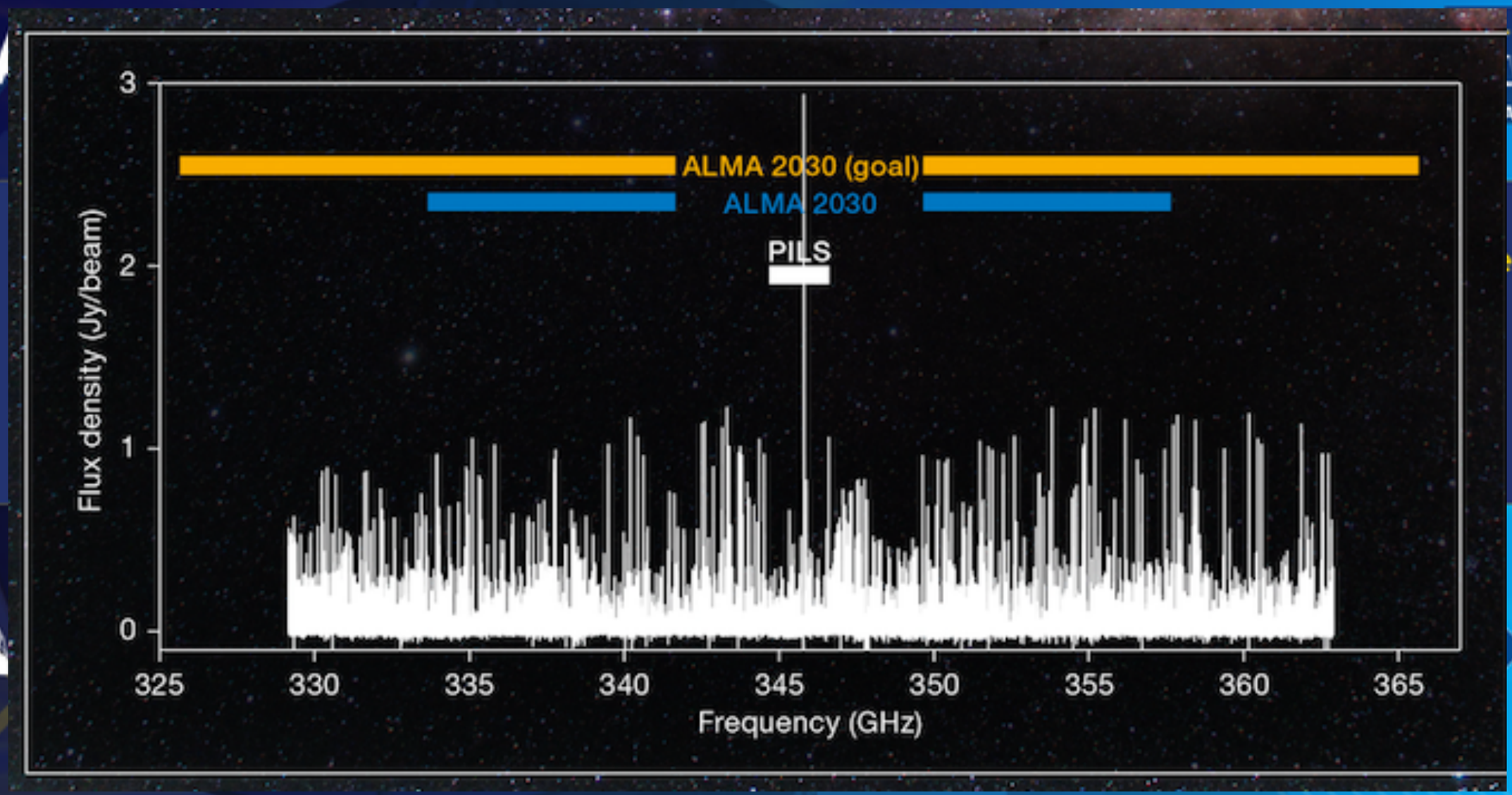
Points to a C-rich outer disk: how to reconcile with CH_3OH detection?

Wampler et al. 2026, ApJ, 1003, L30

The future!

https://science.nrao.edu/facilities/alma/science_sustainability/wideband-sensitivity-upgrade

The future!



https://science.nrao.edu/facilities/alma/science_sustainability/wideband-sensitivity-upgrade

The future!

Design concept for a future (sub)mm interferometer:
increase in sensitivity by ~ 10, increase in resolution by ~ 3

The ALMA2040 collaboration is fully open: contact me if you would like to join and get involved!

https://www.euroalma2040.com/

Take-home messages

ALMA is now routinely detecting complex organic molecules in planet-forming disks around Herbig stars: how complex can we go (WSU/ALMA2040)?

ALMA has revealed chemical substructure in COMs emission from planet-forming disks: are dust traps also ice traps?

We have revealed the common composition of Solar System comets, protostars, and planet-forming disks: the basic ingredients for life appear to be everywhere

Need to revisit models with chemistry, dust evolution and dynamics (mixing and transport)

Thank you!