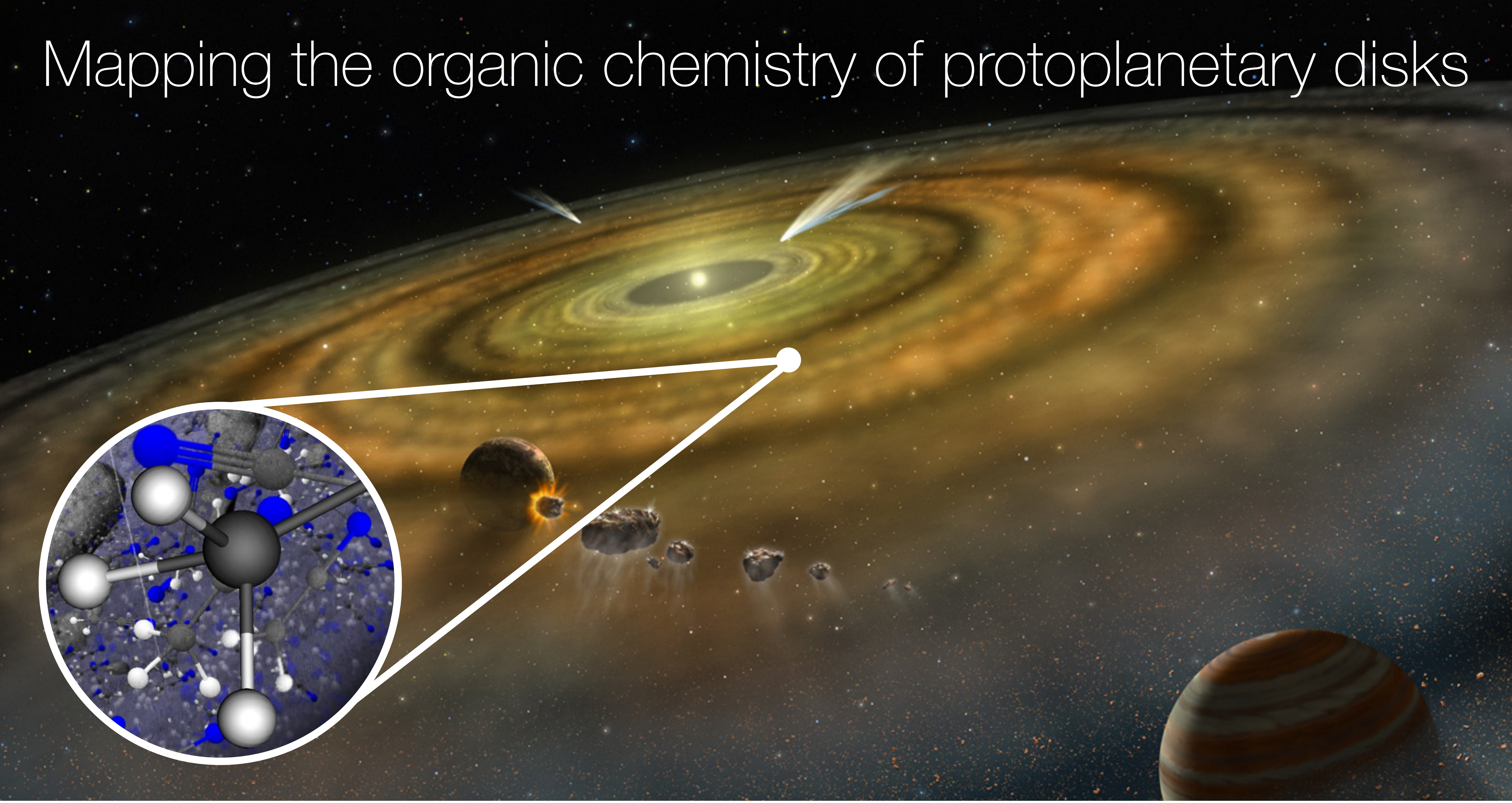
Mapping the organic chemistry of protoplanetary disks



John D. Ilee

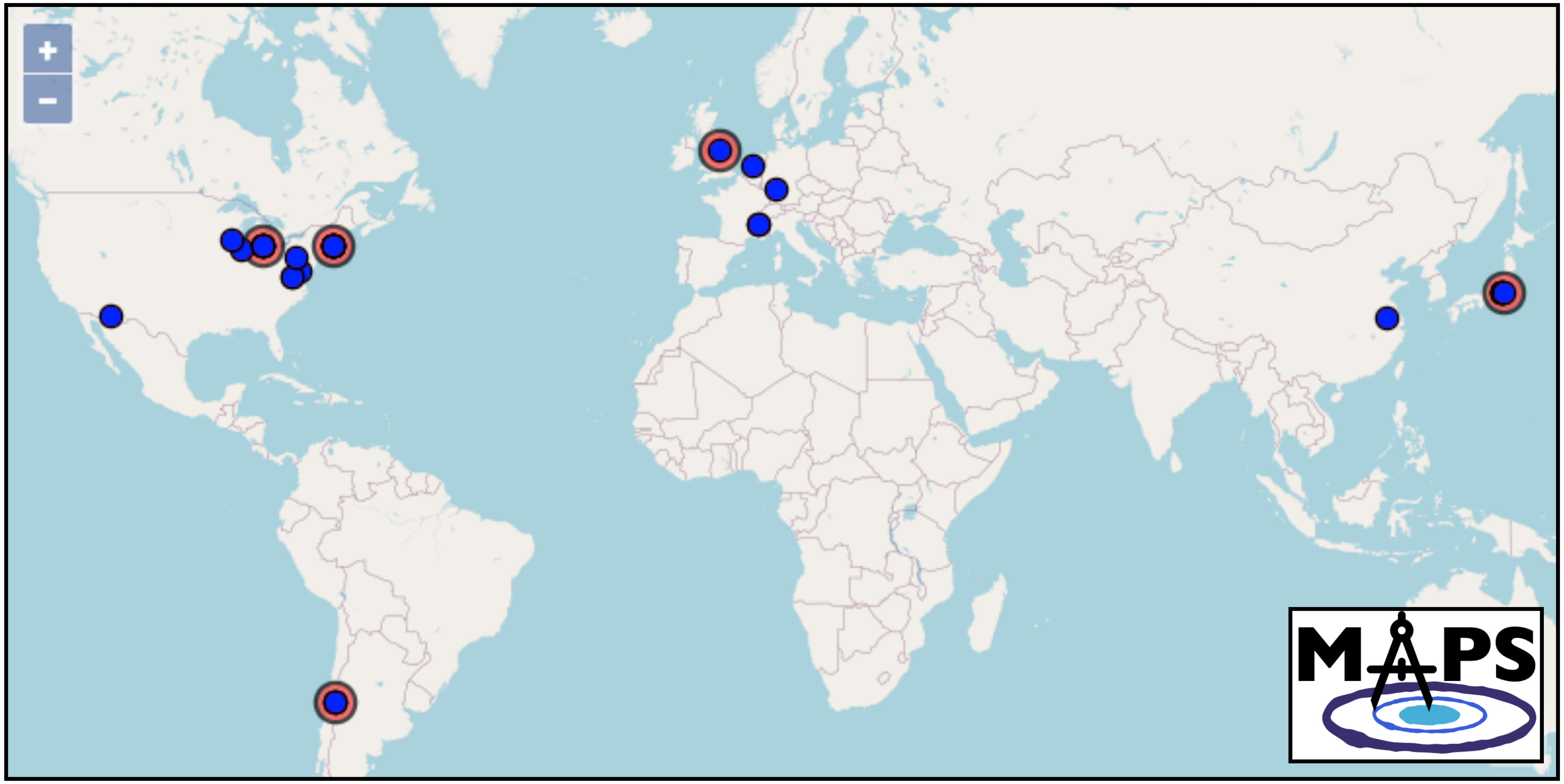
University of Leeds, UK

and the ALMA MAPS team

MAPS

The MAPS map

39 people, 19 institutions, 8 countries, lots of telecons…

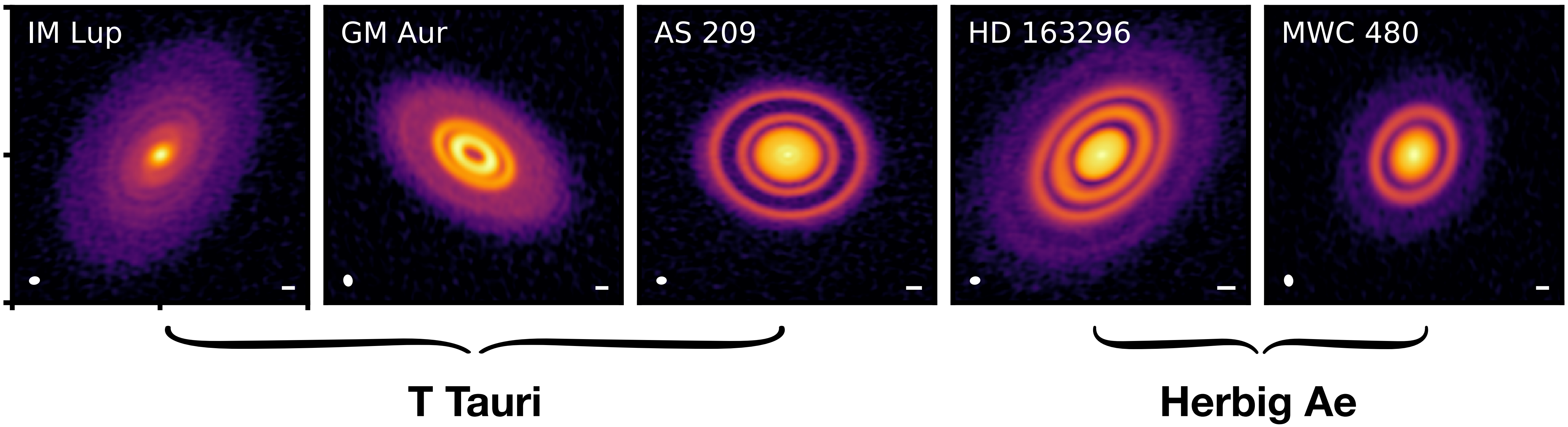


Co PIs: Karin Öberg, Viviana Guzmán, Catherine Walsh, Yuri Aikawa, Edwin Bergin
Co Is: Felipe Alarcón, Sean Andrews, Jaehan Bae, Jennifer Bergner, Yann Boehler, Alice Booth, Jenny Calahan, Gianni Cataldi, Ilse Cleeves, Ian Czekala, Kenji Furuya, Jane Huang, John Ilee, Nicolas Kurtovic, Charles Law, Romane Le Gal, Yao Liu, Ryan Loomis, Feng Long, François Ménard, Hideko Nomura, Laura Pérez, Charlie Qi, Kamber Schwarz, Anibal Sierra, Daniela Soto, Richard Teague, Takashi Tsukagoshi, Yoshihide Yamato, Merel van't Hoff, Abygail Waggoner, David Wilner, Ke Zhang

Molecules with **A**LMA at **P**lanet-forming **S**cales

- ALMA Large Program to survey chemistry of five discs with signatures of on-going planet formation…

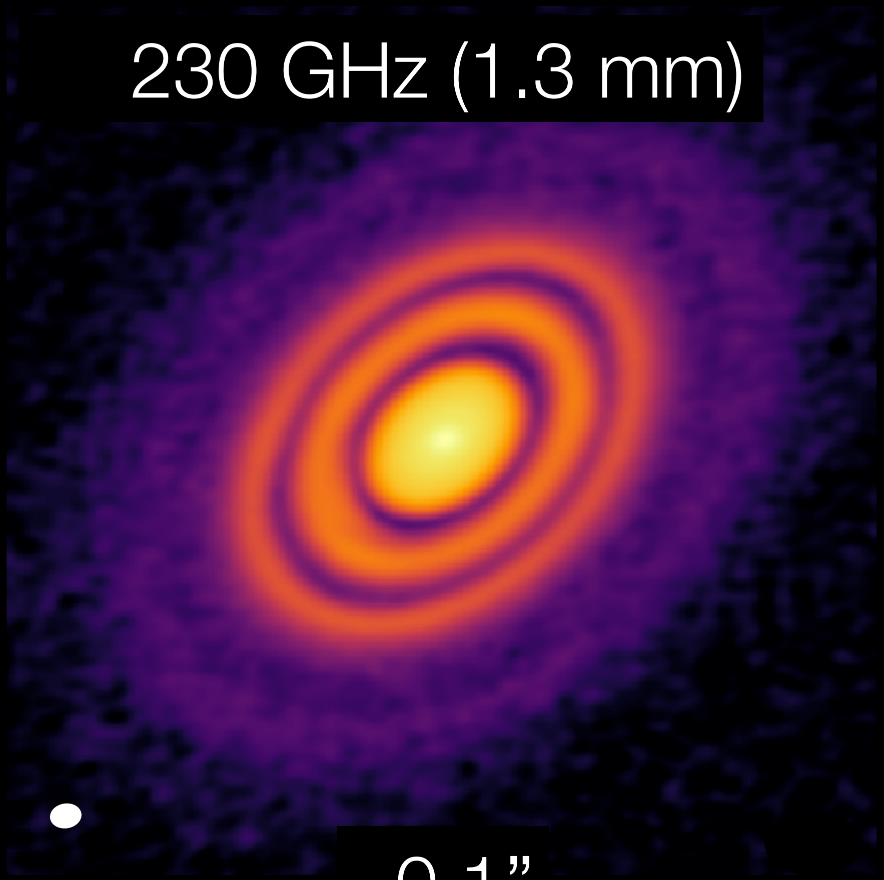
230 GHz continuum

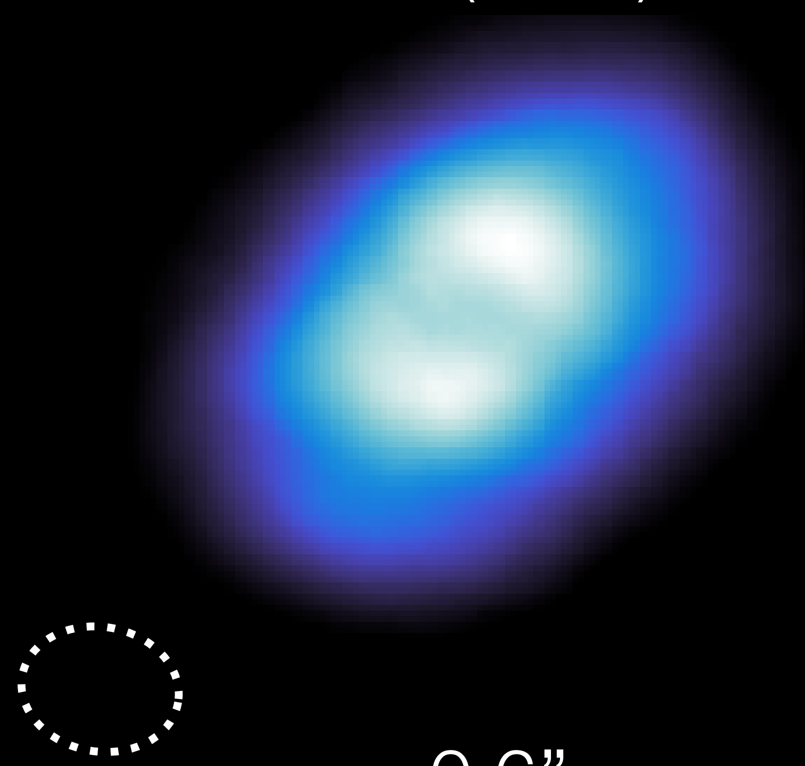


- Four spectral settings across B3 & B6 — 20 species, 40 lines, 130 hrs
- Targets include simple species up to complex organics
- Goal: ***understand the chemistry of planet formation***

How do the MAPS data compare?

HD 163296





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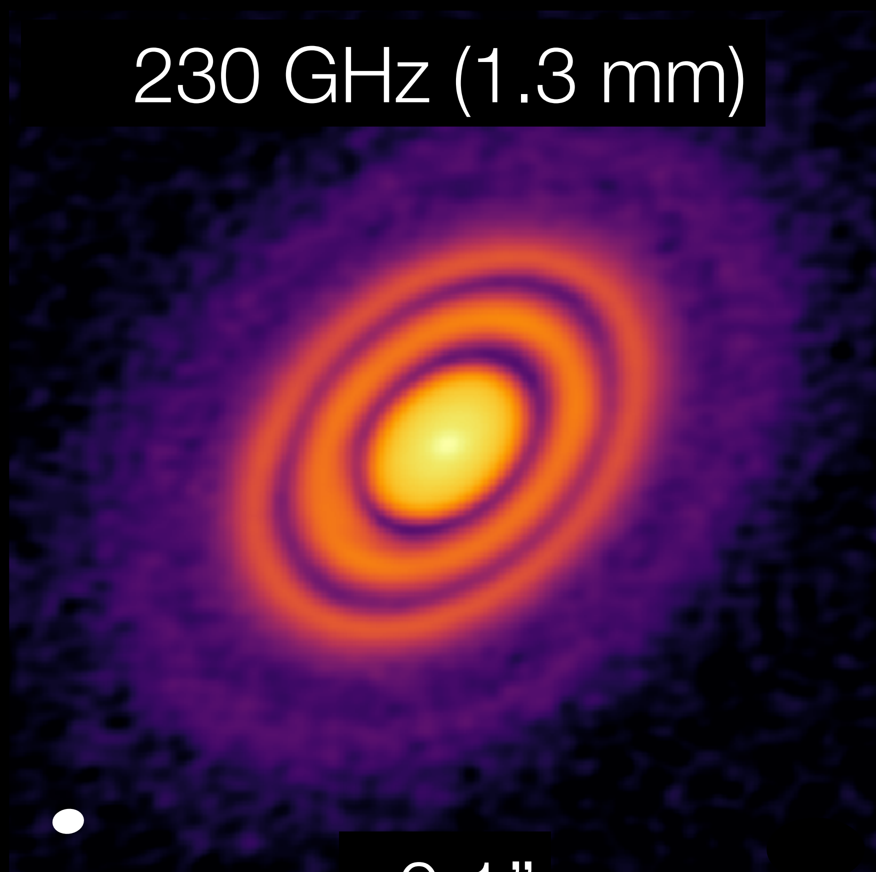

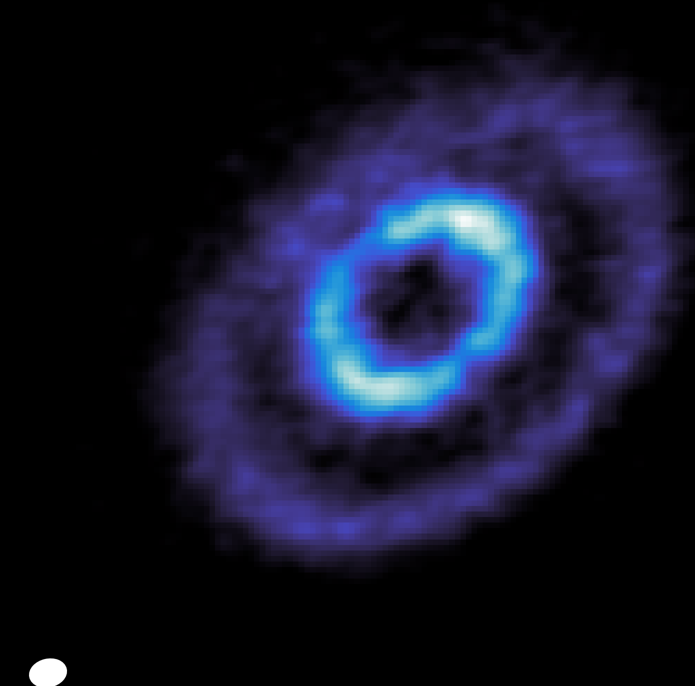

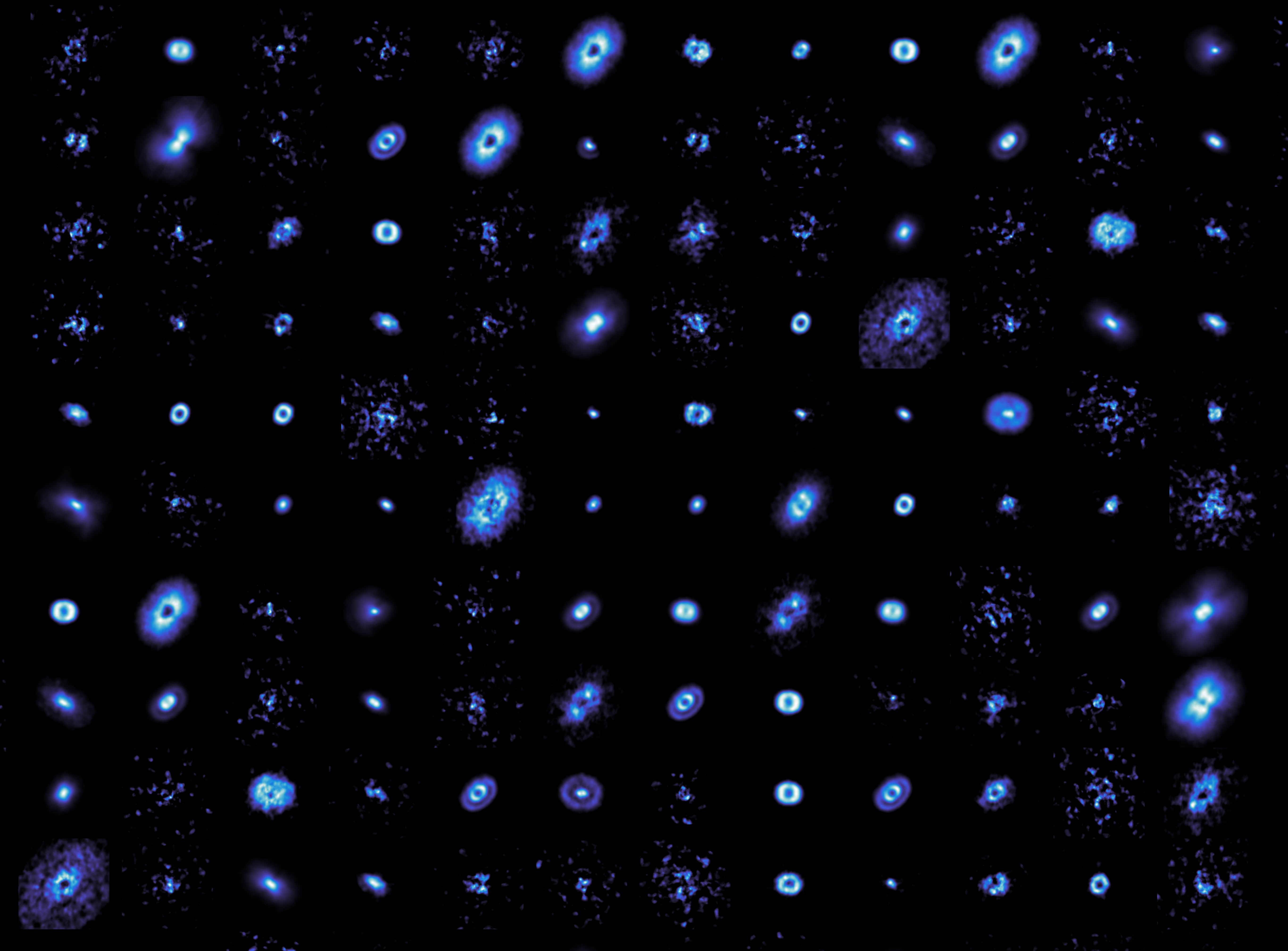

Organic molecules in protoplanetary disks — why?

- Small organics are some of the ***main carriers*** of C, N, O
    - Important to understand the elemental budget in disks
    - Key to linking disk and planet compositions (e.g. C/O)

(Öberg et al. 2011, + many more)

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- Some organics are ***useful probes*** of physical and/or radiative conditions
    - CH_3CN ladder is thermometer (E_{up} ~ 50–150K within ~55 km/s)

      (e.g. Loomis et al. 2018)
    - Molecular ratios can probe local and global UV field variations

      (e.g. Dutrey et al. 1997)

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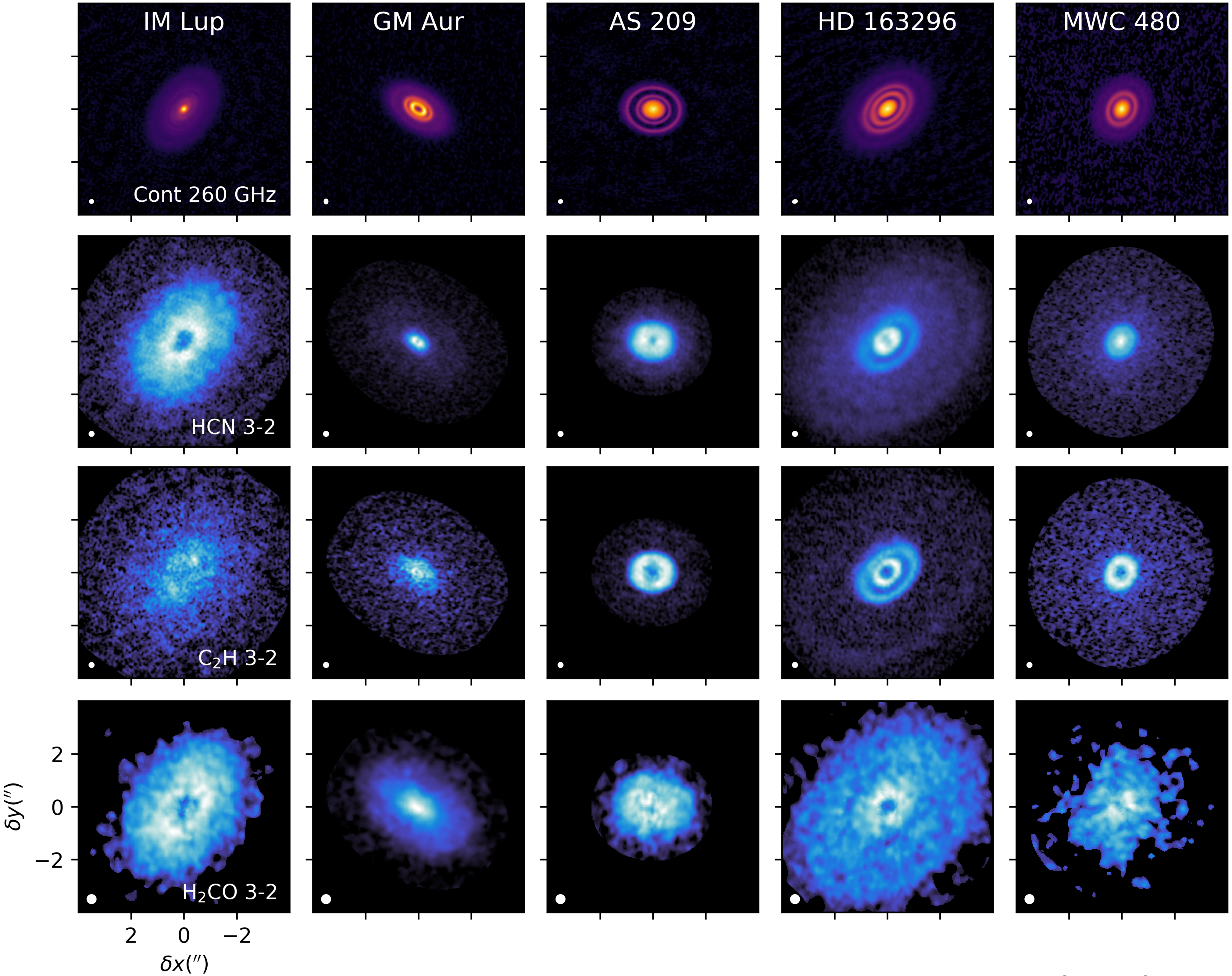
    - Molecular ratios can probe local and global UV field variations

      (e.g. Dutrey et al. 1997)

- Larger organics are ***stepping stones*** to important prebiotic chemistry
    - Nitrile pathways to, e.g., RNA bases, amino acids and proteins

(Powner et al. 2009; Patel et al. 2015; Becker et al. 2019)

The small organics HCN, C_2H & H_2CO



MAPS VI: Guzmán et al. (2021)

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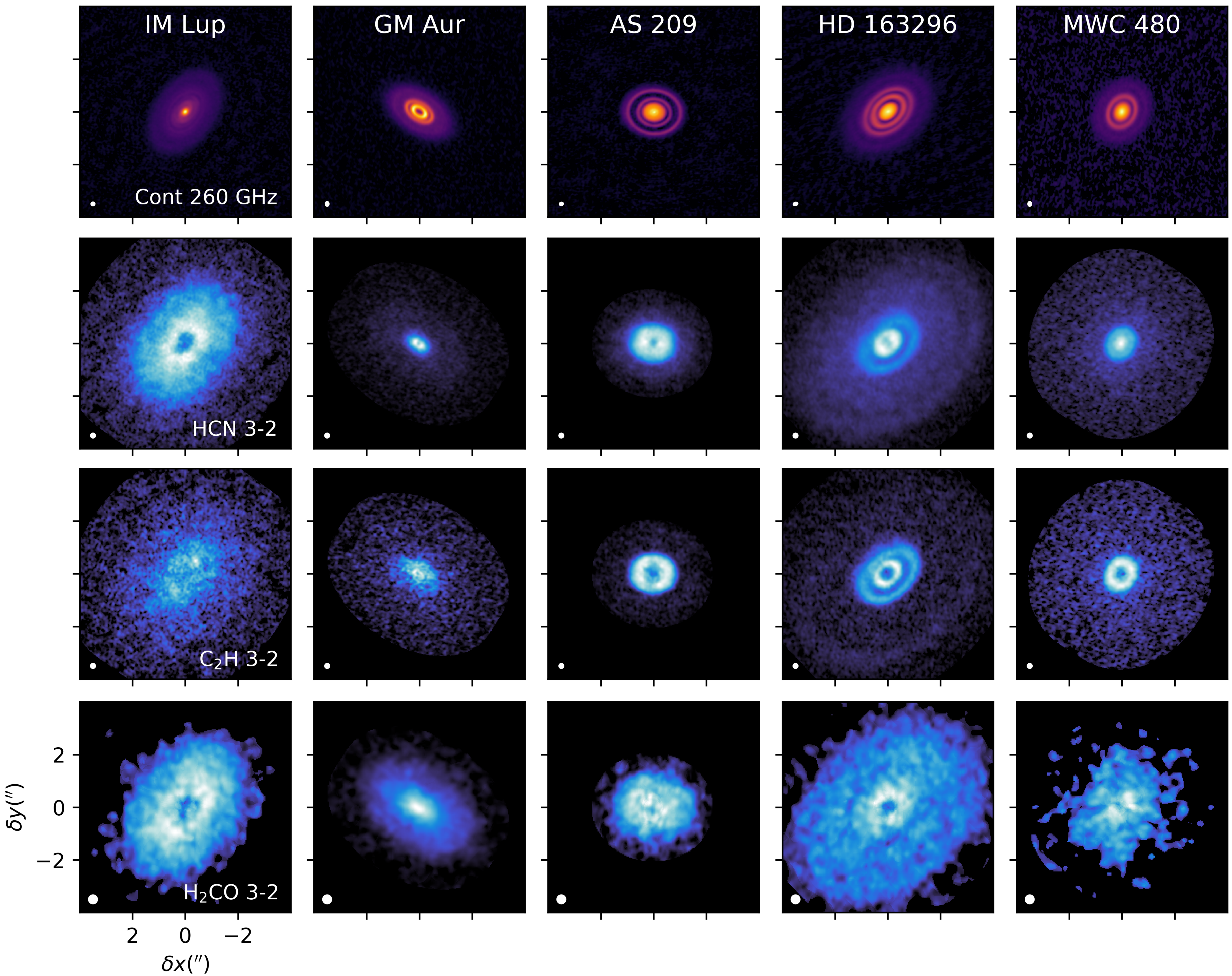
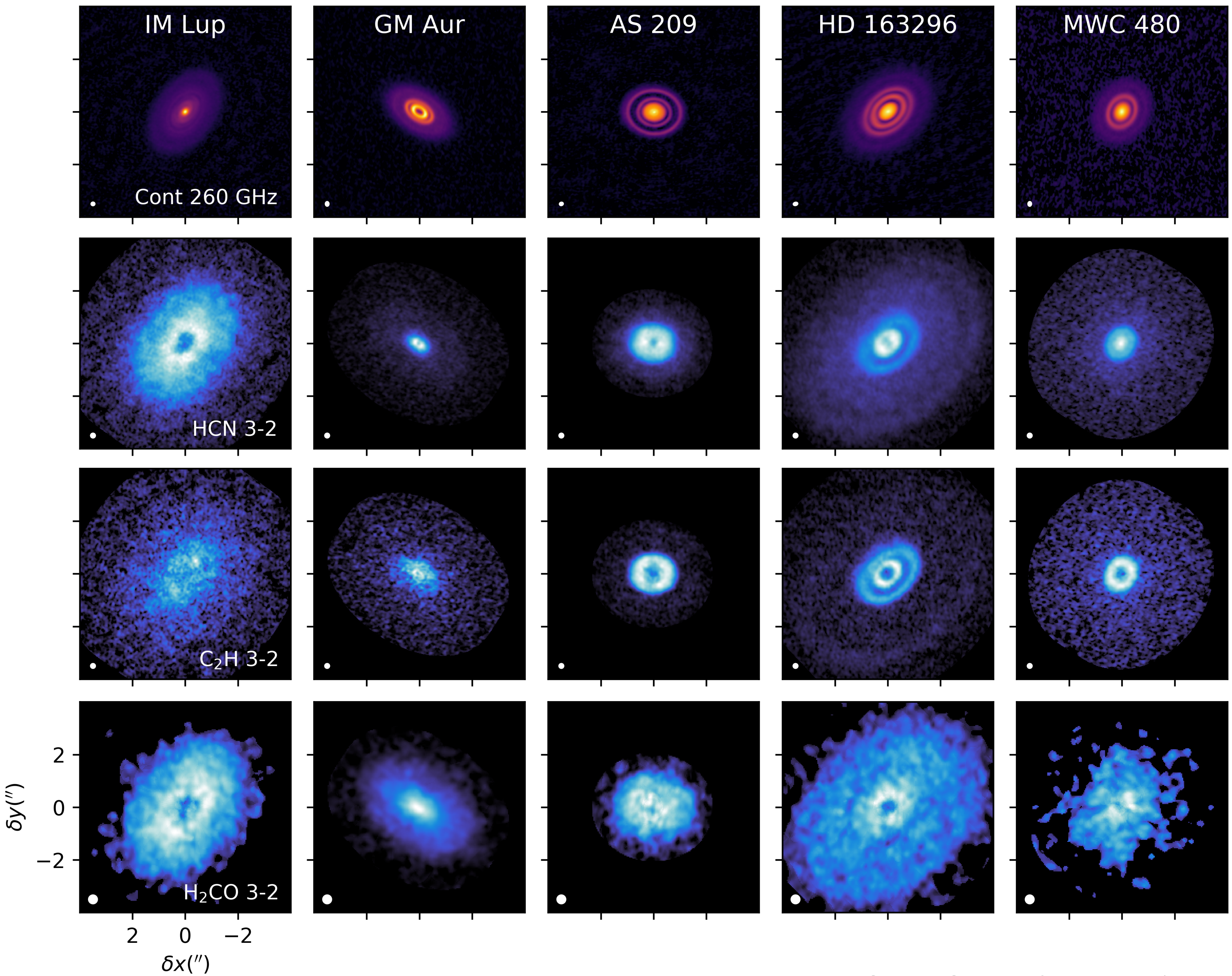


MAPS VI: Guzmán et al. (2021)

The small organics HCN, C_2H & H_2CO

All show diverse morphologies:

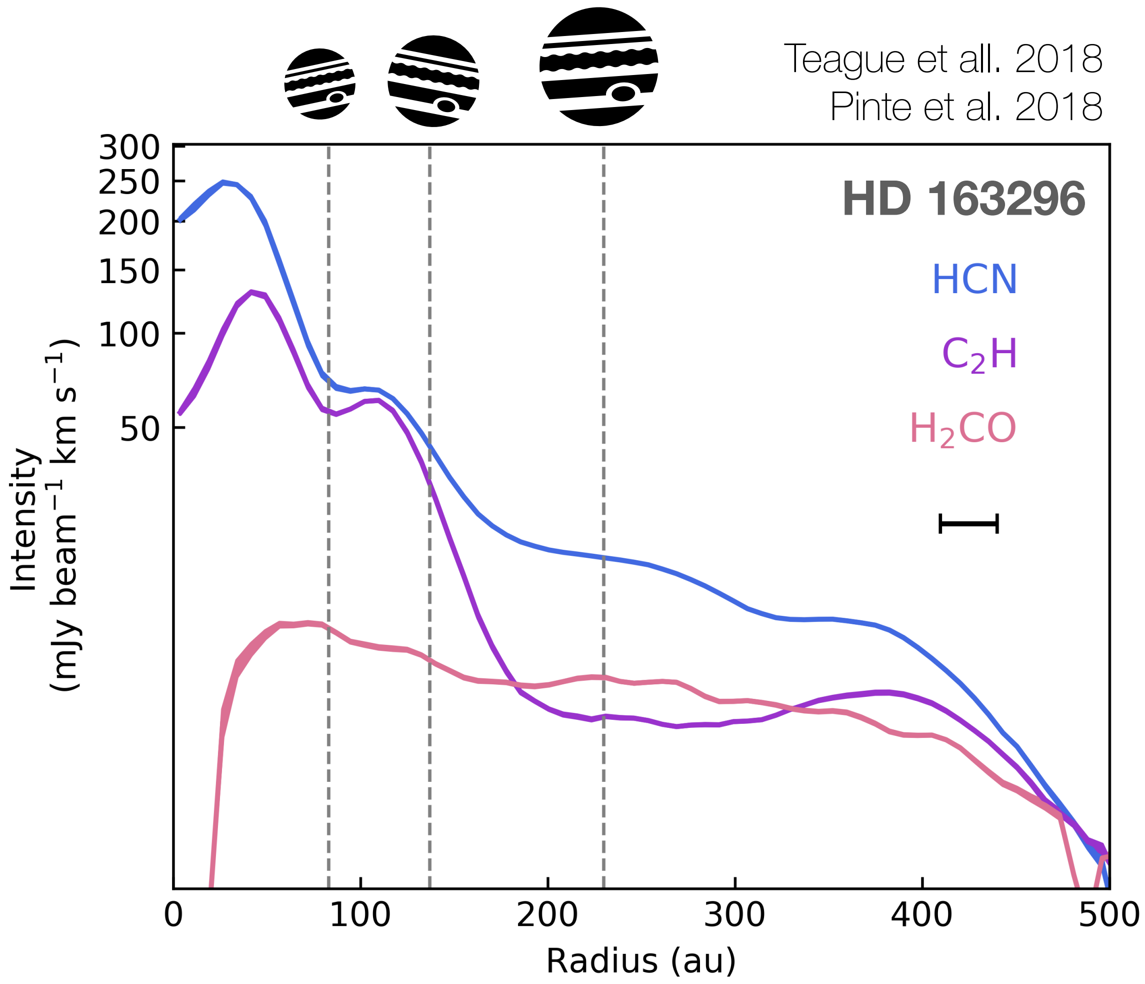
- Compact
- Extended
- Diffuse
- Single rings
- Double rings
- Peak & shelf



MAPS VI: Guzmán et al. (2021)

The small organics HCN, C_2H & H_2CO: brief highlights

- Probes of gas substructures



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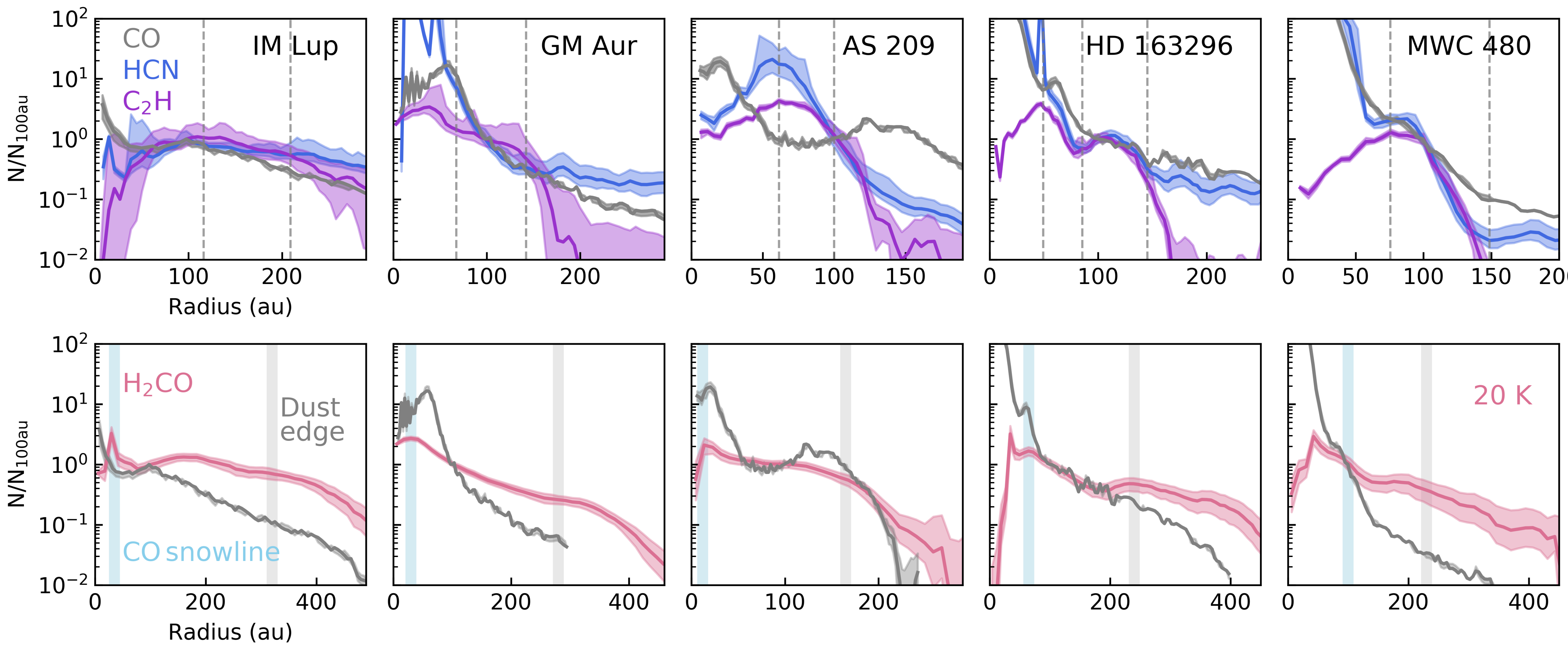
- HCN column peaks in inner disk
  → active warm cyanide chemistry



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- Probes of gas substructures
    - HCN column peaks in inner disk → active warm cyanide chemistry
- High mass of organics within 50au (1—2% of total H_2O)

Source	Gas+ice mass w.r.t. H_2O ice[†] HCN (% H_2O)	C_2H (% H_2O)	H_2CO (% H_2O)
IM Lup	< 0.001	< 0.001	0.001
GM Aur	0.56	0.06	0.02
AS 209	1.09	1.80	0.08
HD 163296	0.68	0.09	0.004
MWC 480	0.45	0.02	0.01

[†] Assuming an ice-to-gas ratio of 1000

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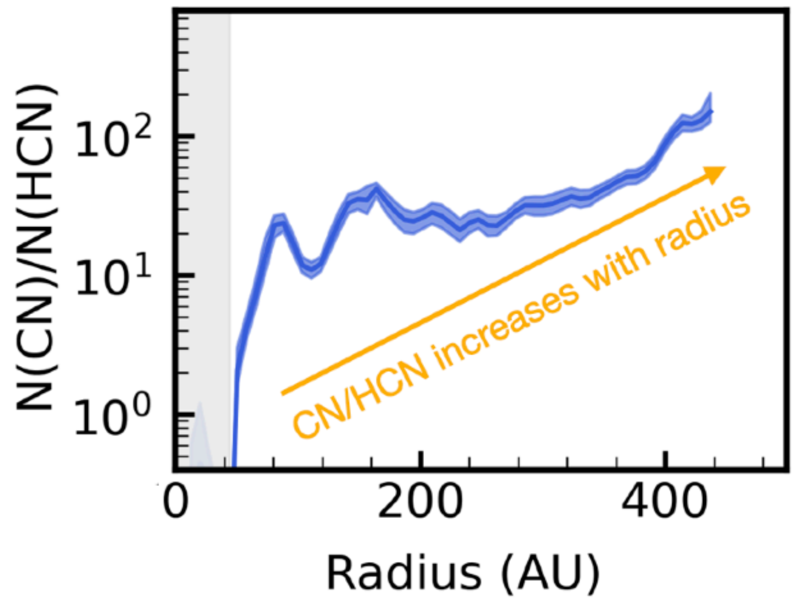

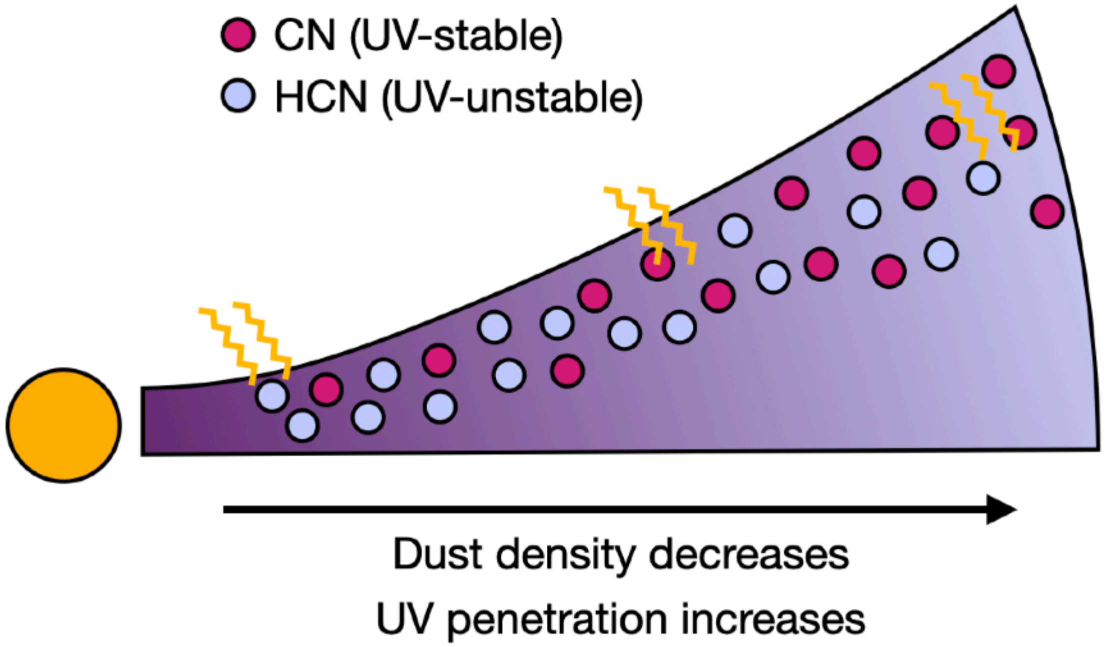

MAPS XI: Bergner et al. (2021)

Credit: J. Bergner

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- CN/HCN probes UV penetration
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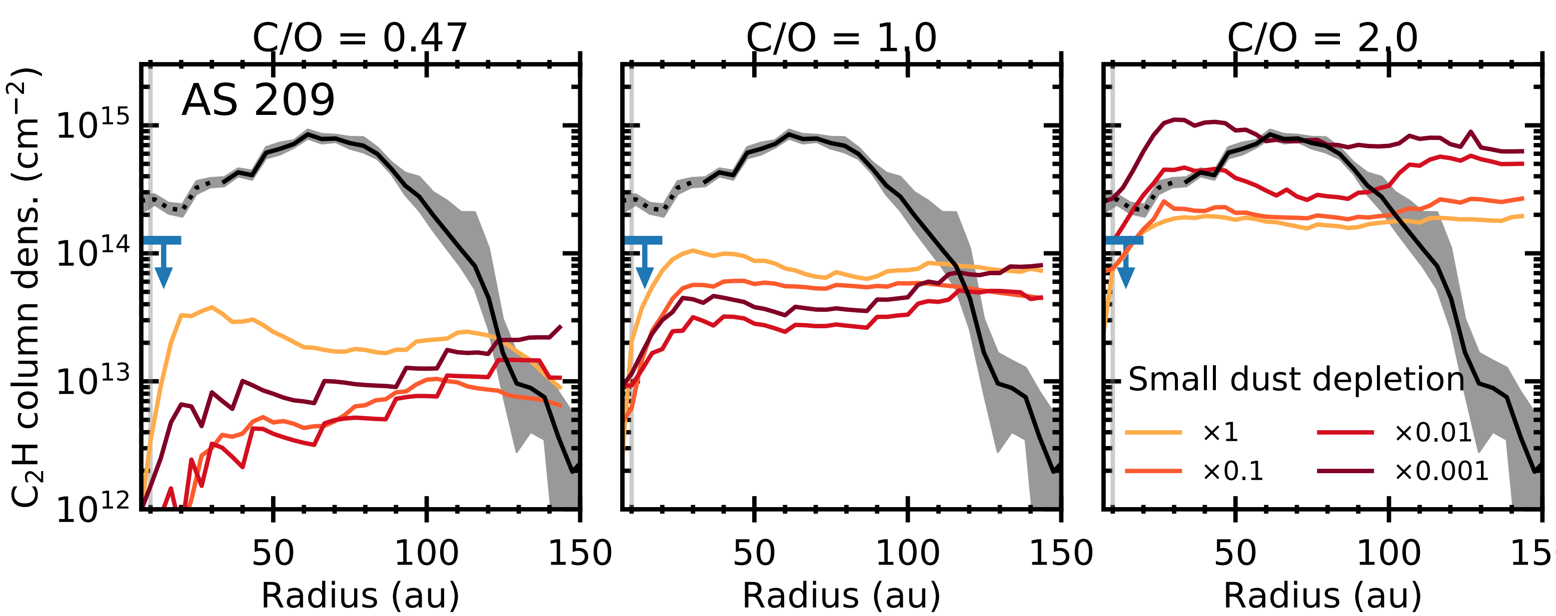
- C_2H implies elevated C/O ratios



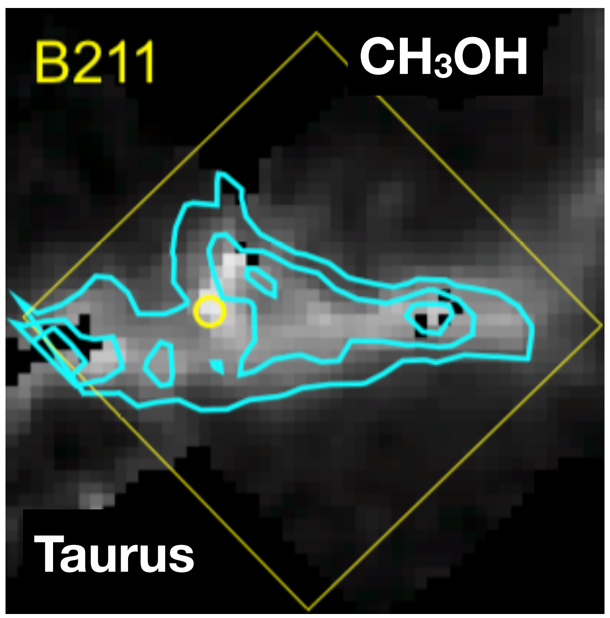
MAPS VII: Bosman et al. (2021)

Complex organic molecules in star and planet formation

- Complex* organics detected in many different stages of star formation

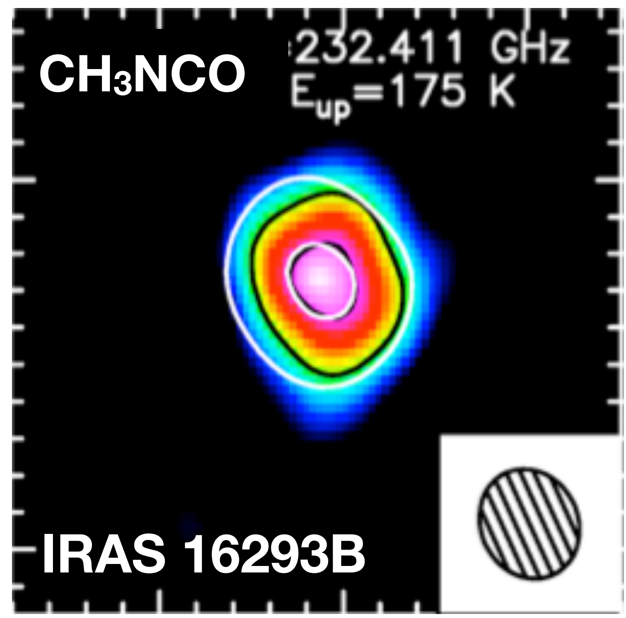
(* ≳ 6 atoms)

Star forming clouds



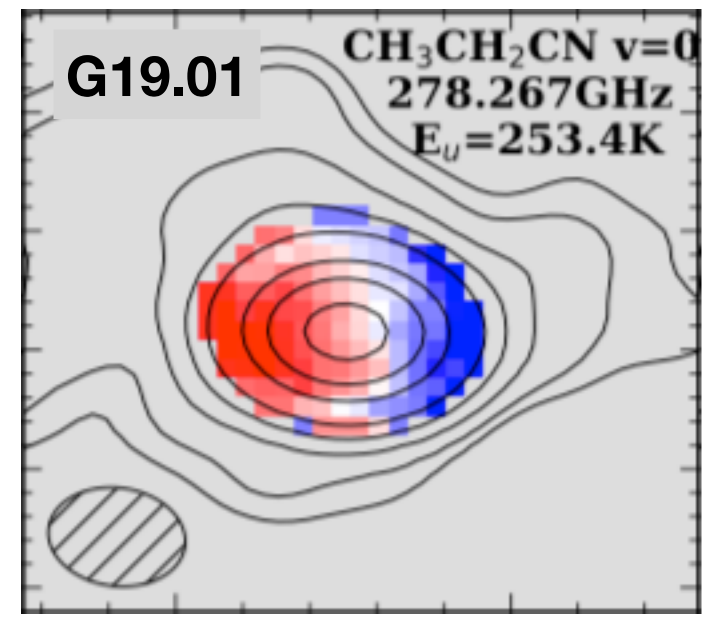
Scibelli & Shirley 2020

Protostars



Martín-Doménech et al. 2017

Young massive stars



Williams et al. 2021

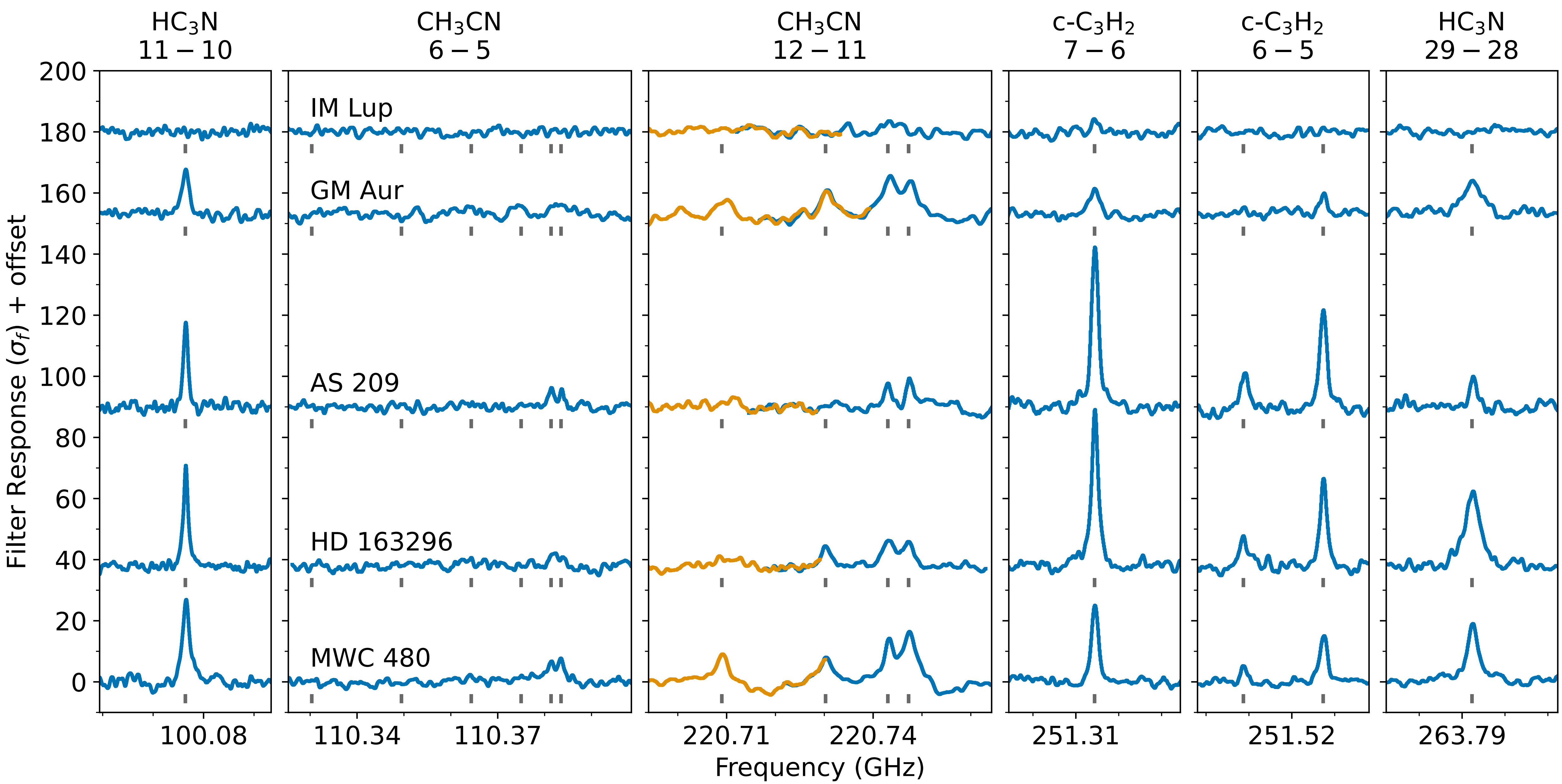
- Q: Can this complexity be built up (or retained) in the vicinity of forming planets?
- A: Need to search for (and characterise) emission from large molecules in protoplanetary disks…

see also Öberg+ 2015, Walsh+ 2016, Favre+ 2018, van der Marel+ 2021, Booth+ 2021, +++

MAPS IX: Distribution & properties of large organics

- Detailed analysis of emission from HC_3N, CH_3CN & *c*-C_3H_2
- Potentially weak, obtain robust detections from ***matched filtering:***

(`VISIBLE`, Loomis et al. 2018)



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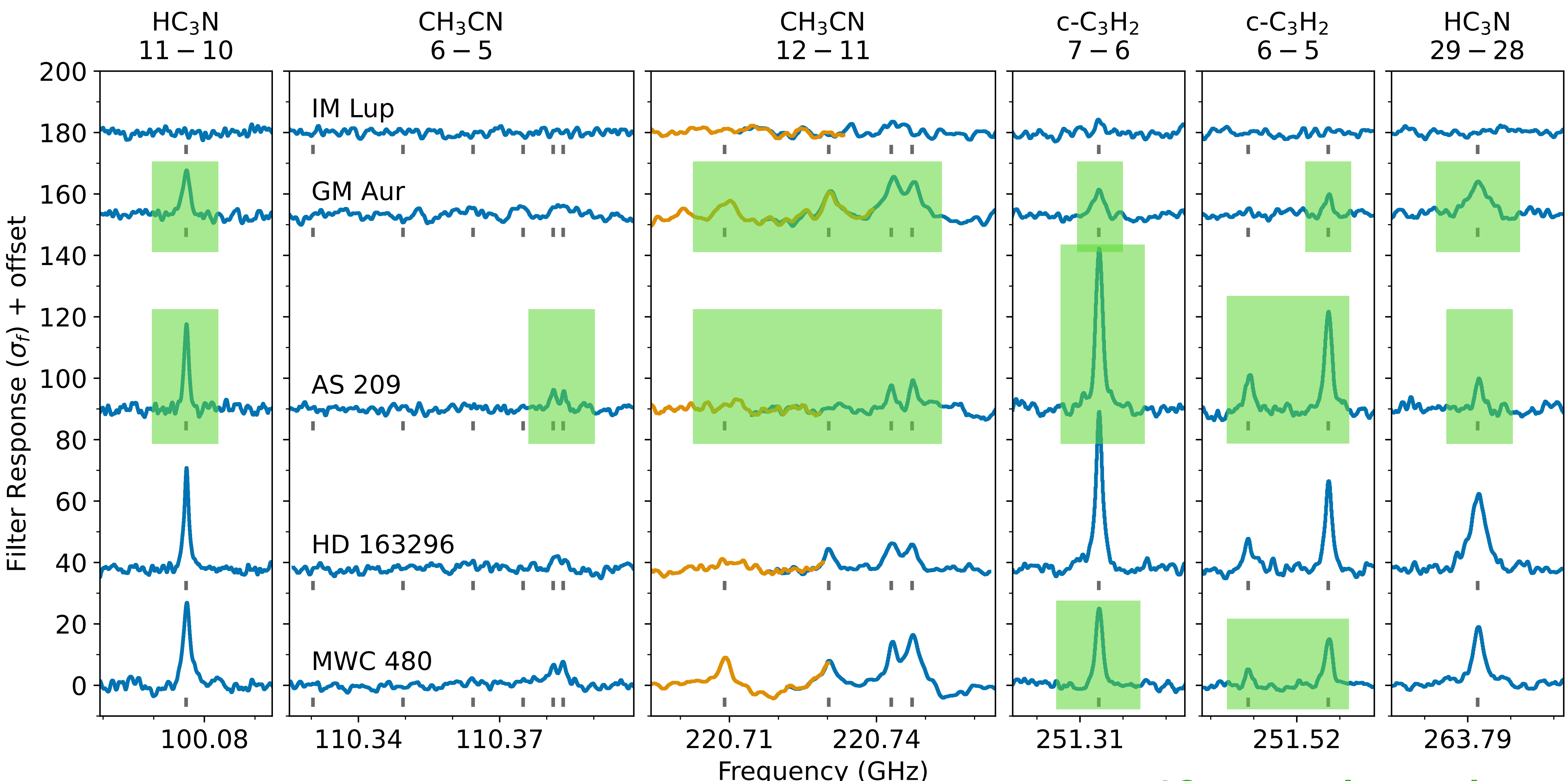
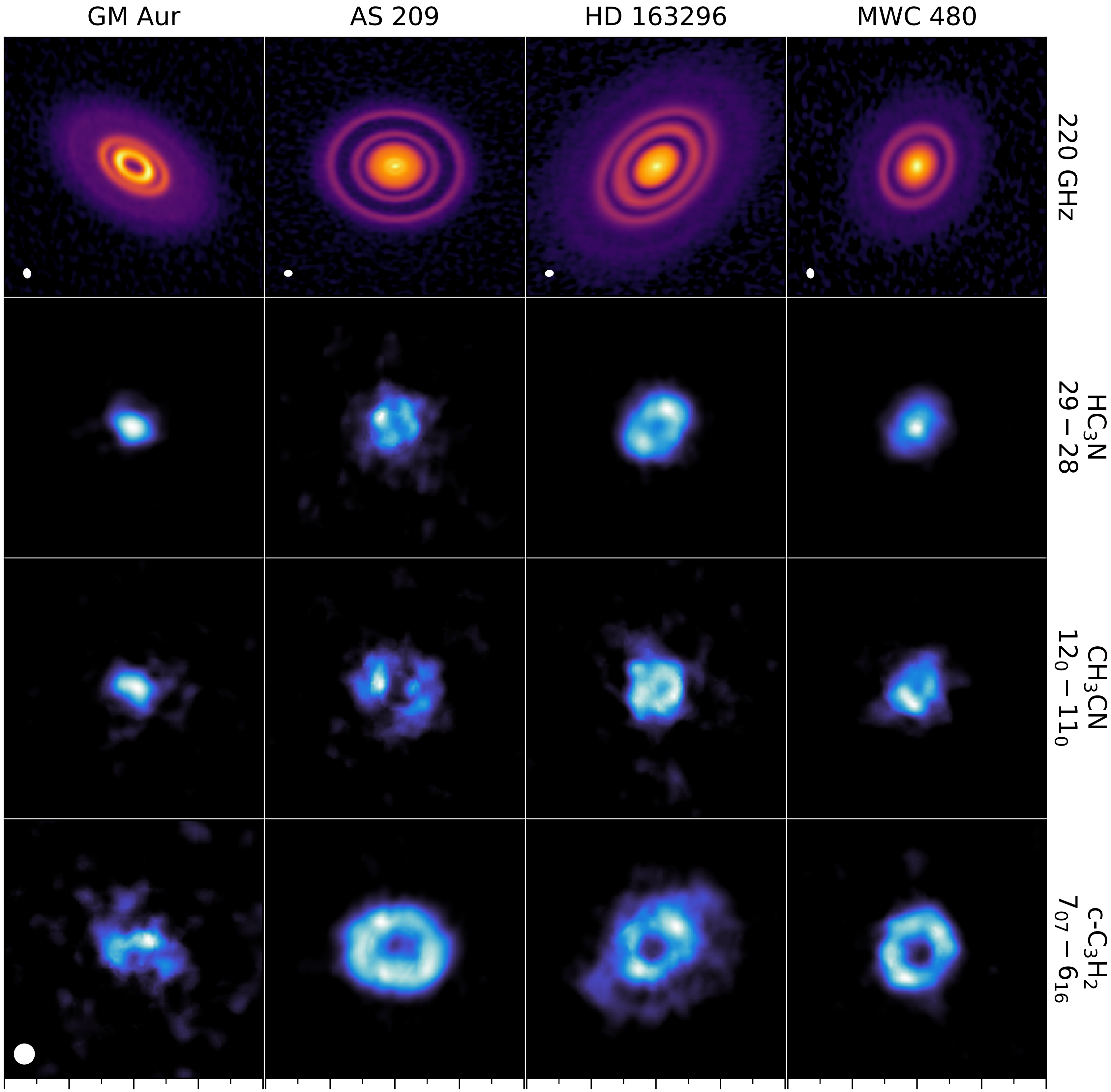


MAPS IX: Ilee et al. (2021)

19 new detections

Imaging of the large organics

- Analysis on lines with "strong" detections (filter σ ≳ 5)
- Imaging at 0.3'' resolution



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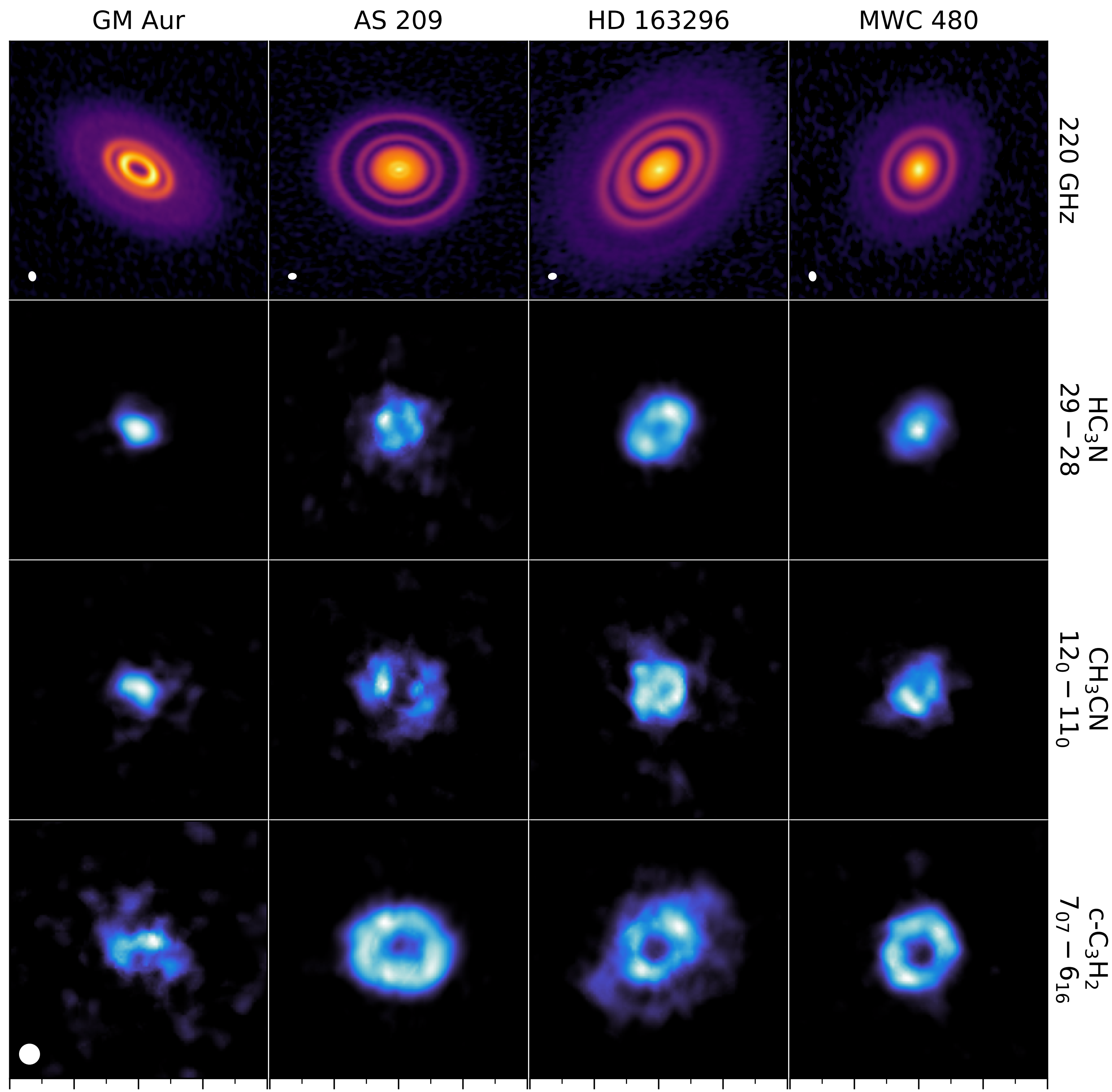
  - Central peaks
  - Single/double rings



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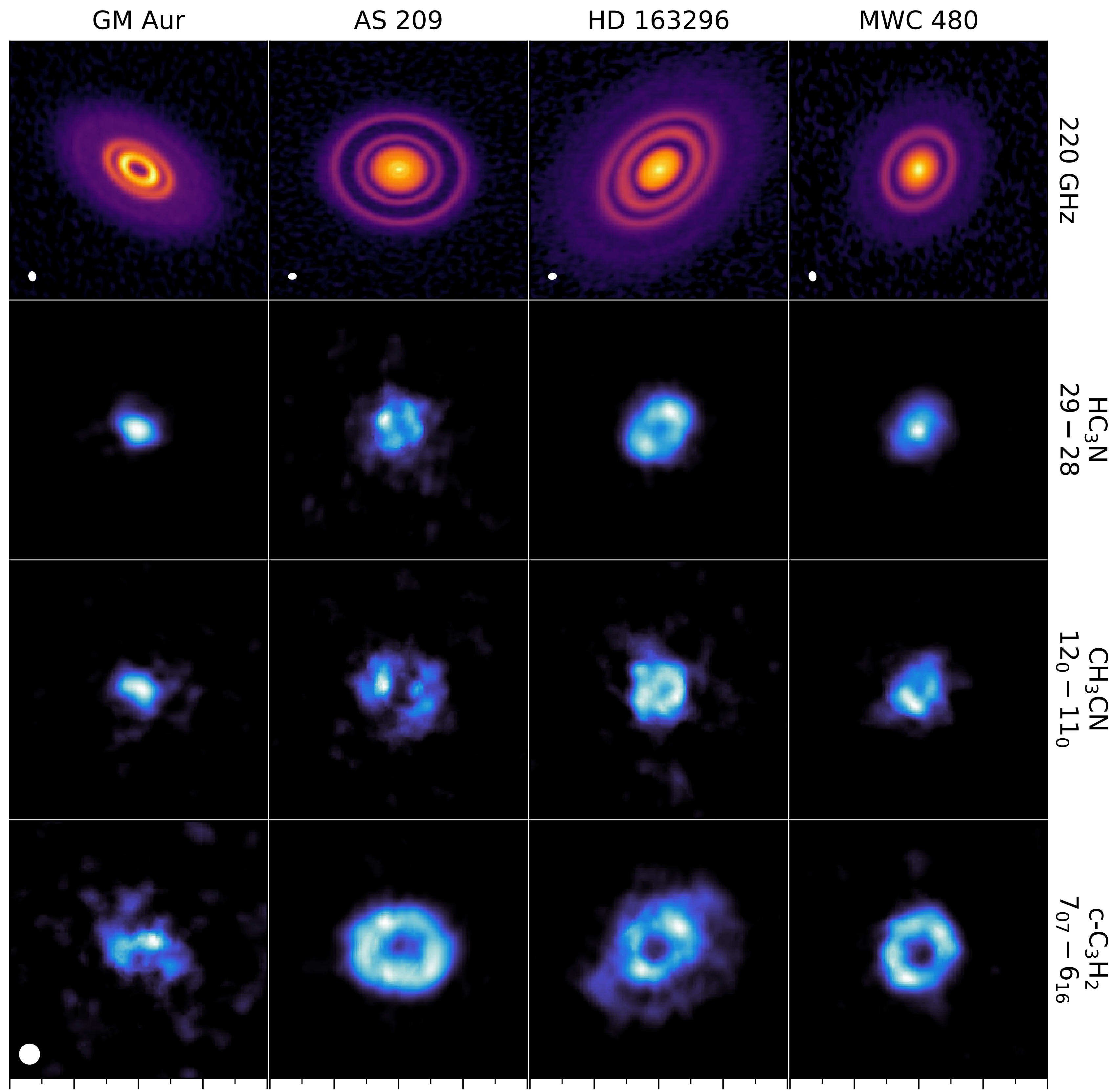
➔ ***All compact, on scales of mm dust***



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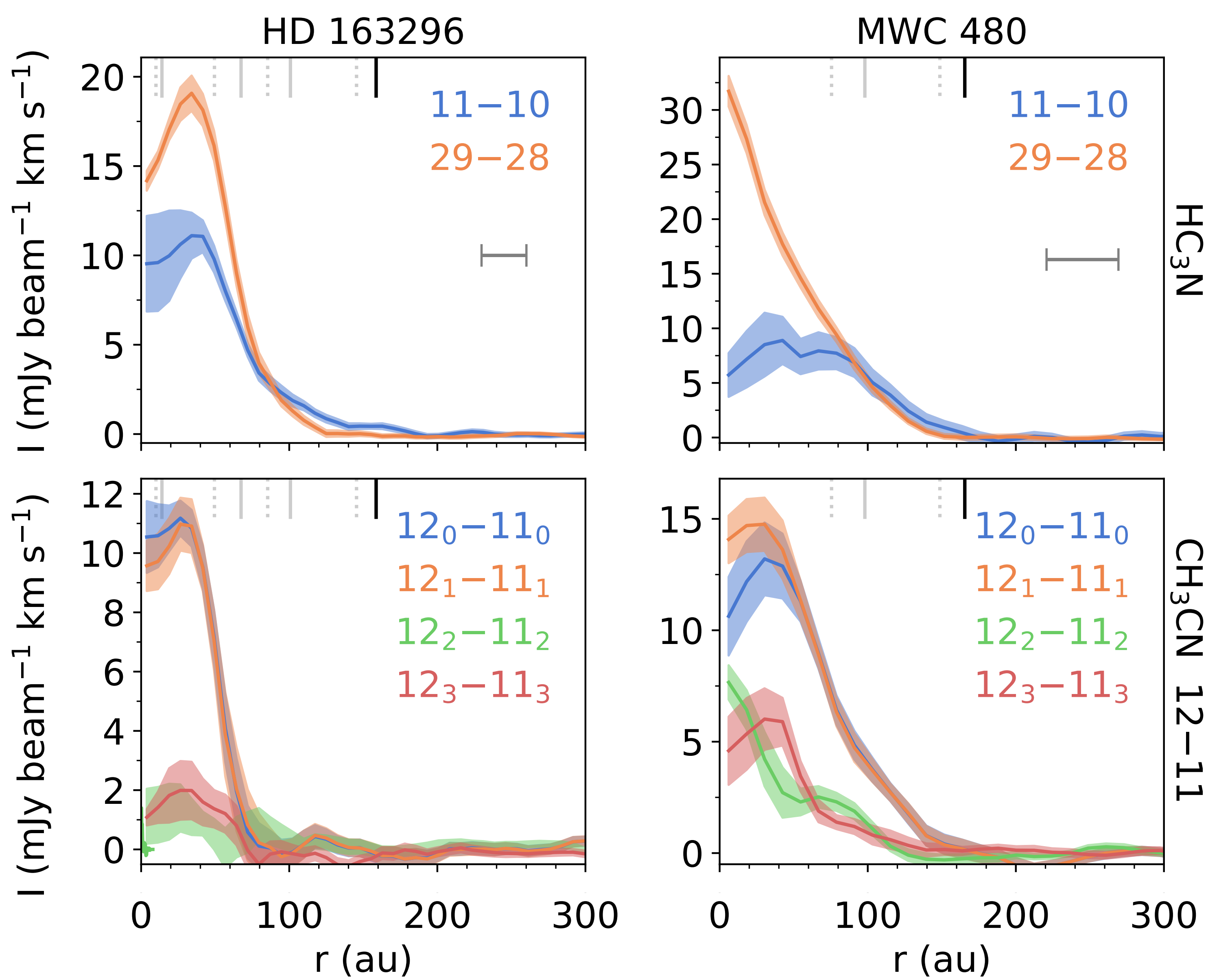
Excitation analysis

- Many of these transitions were previously spatially unresolved
- Can perform a radially resolved excitation analysis for the first time:



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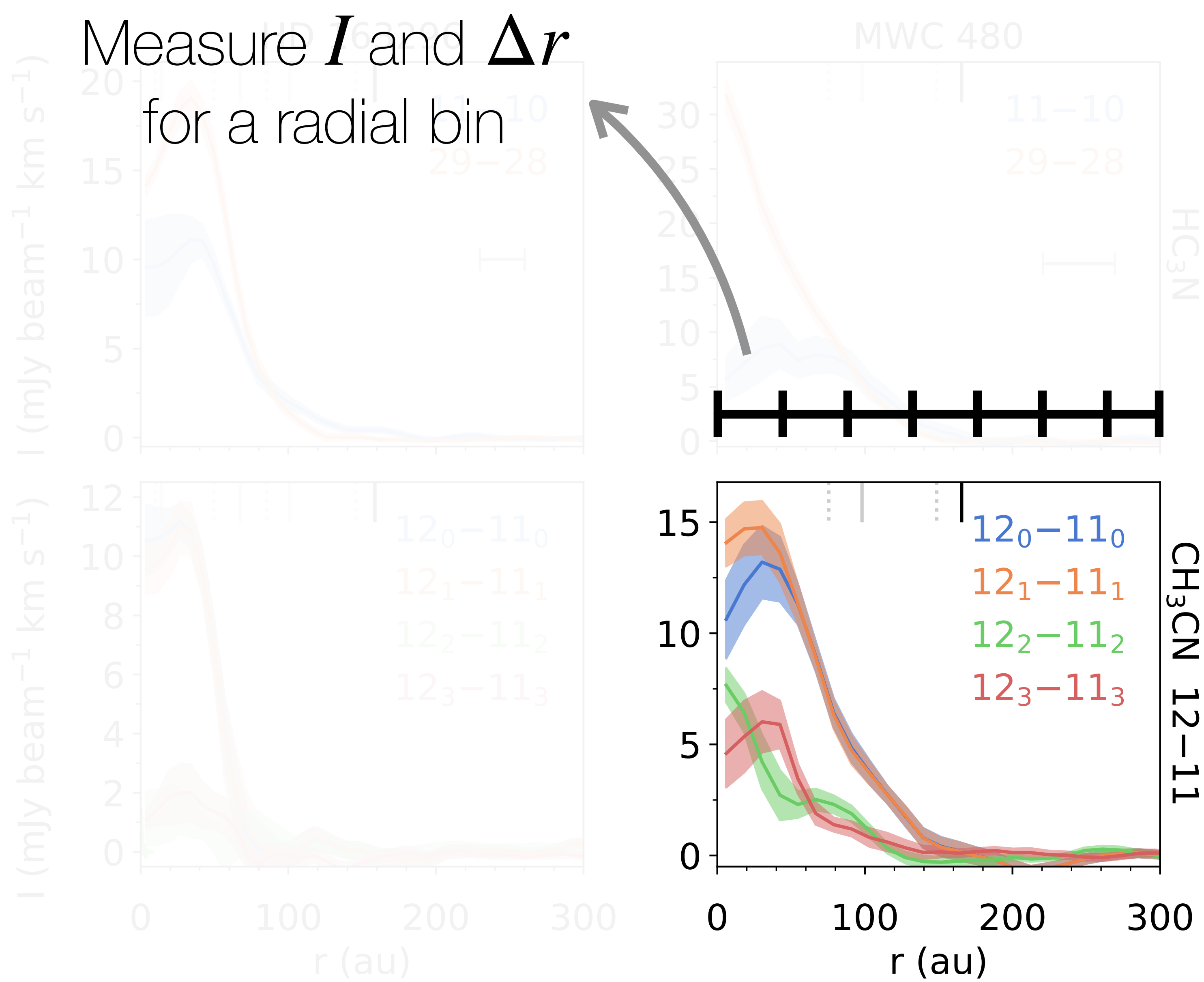

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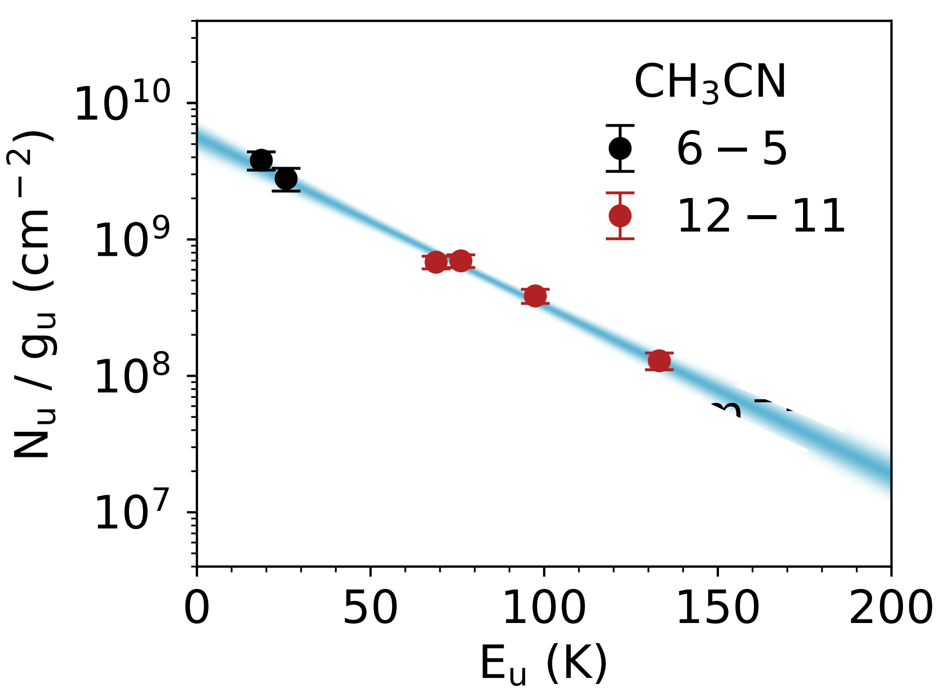
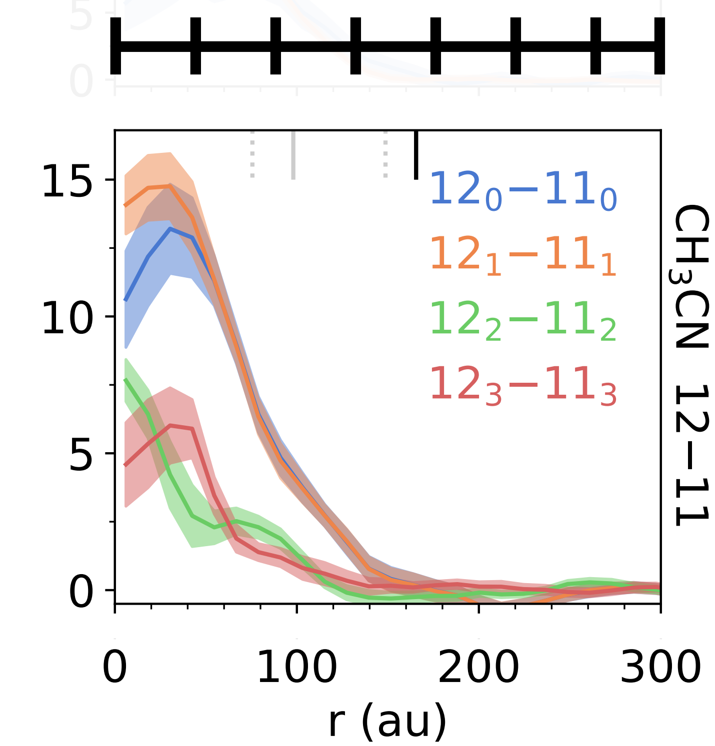
Measure I and Δr for a radial bin

Calculate rotational diagram per bin





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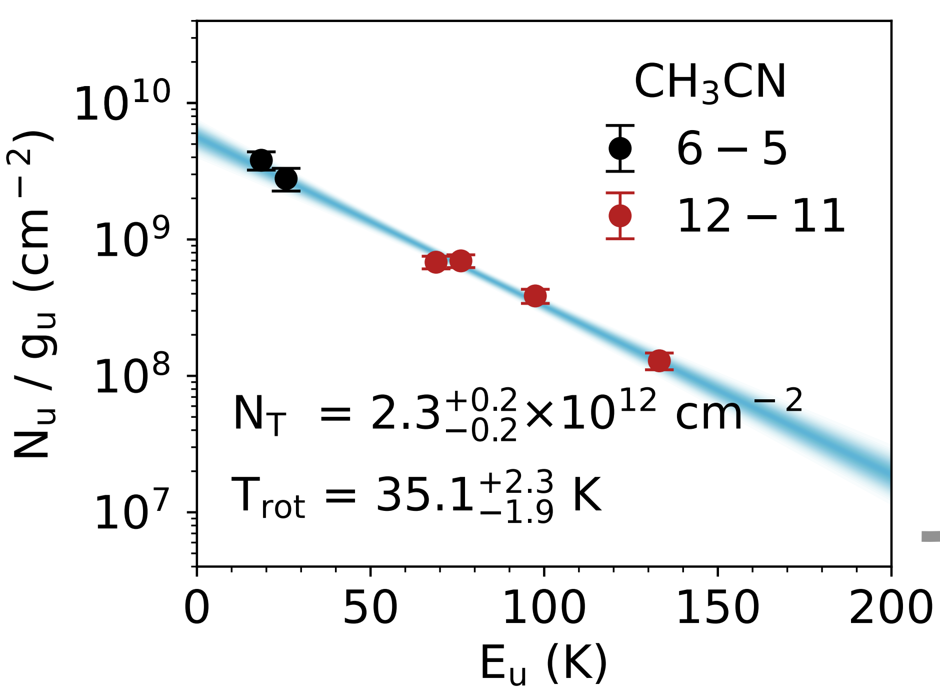
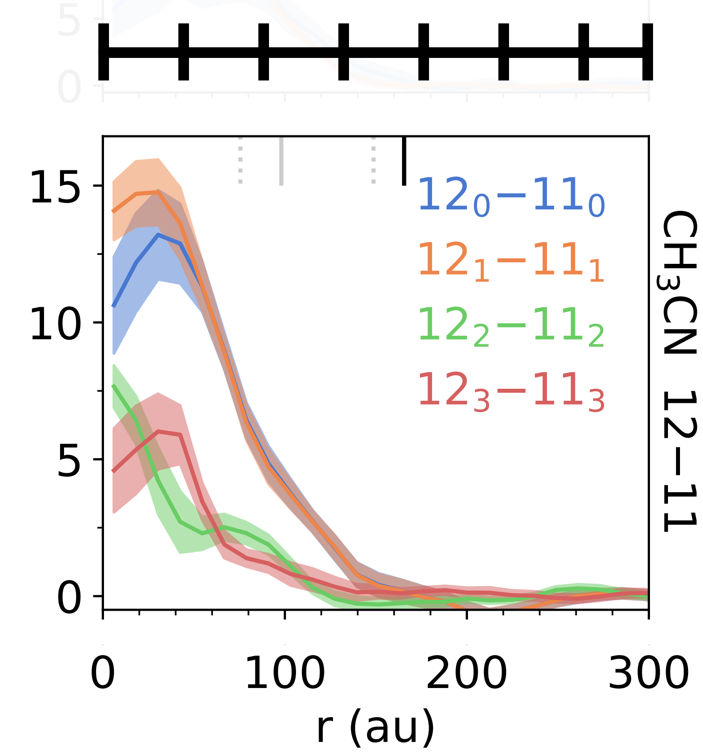


Get N_T and T_{rot} from intercept & slope



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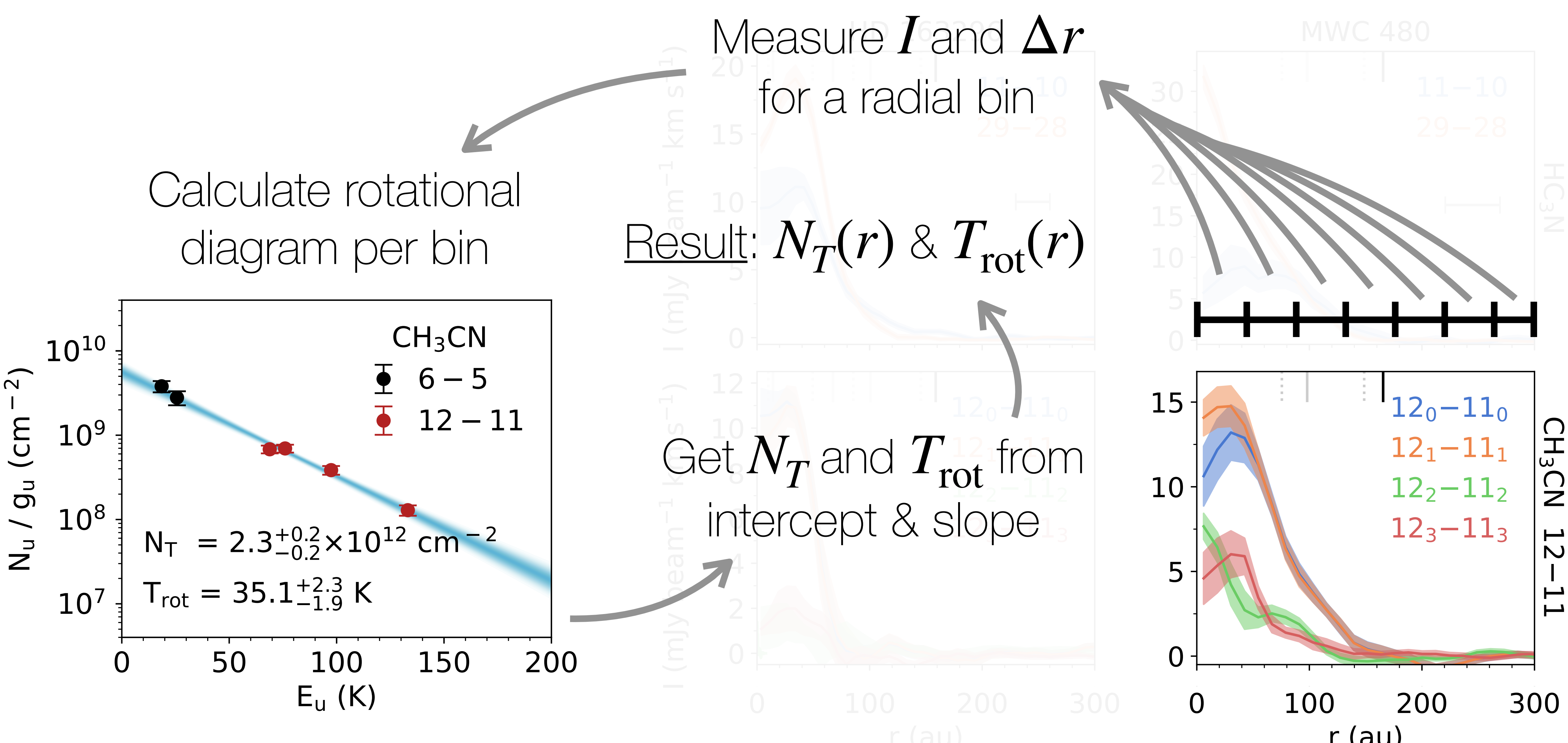

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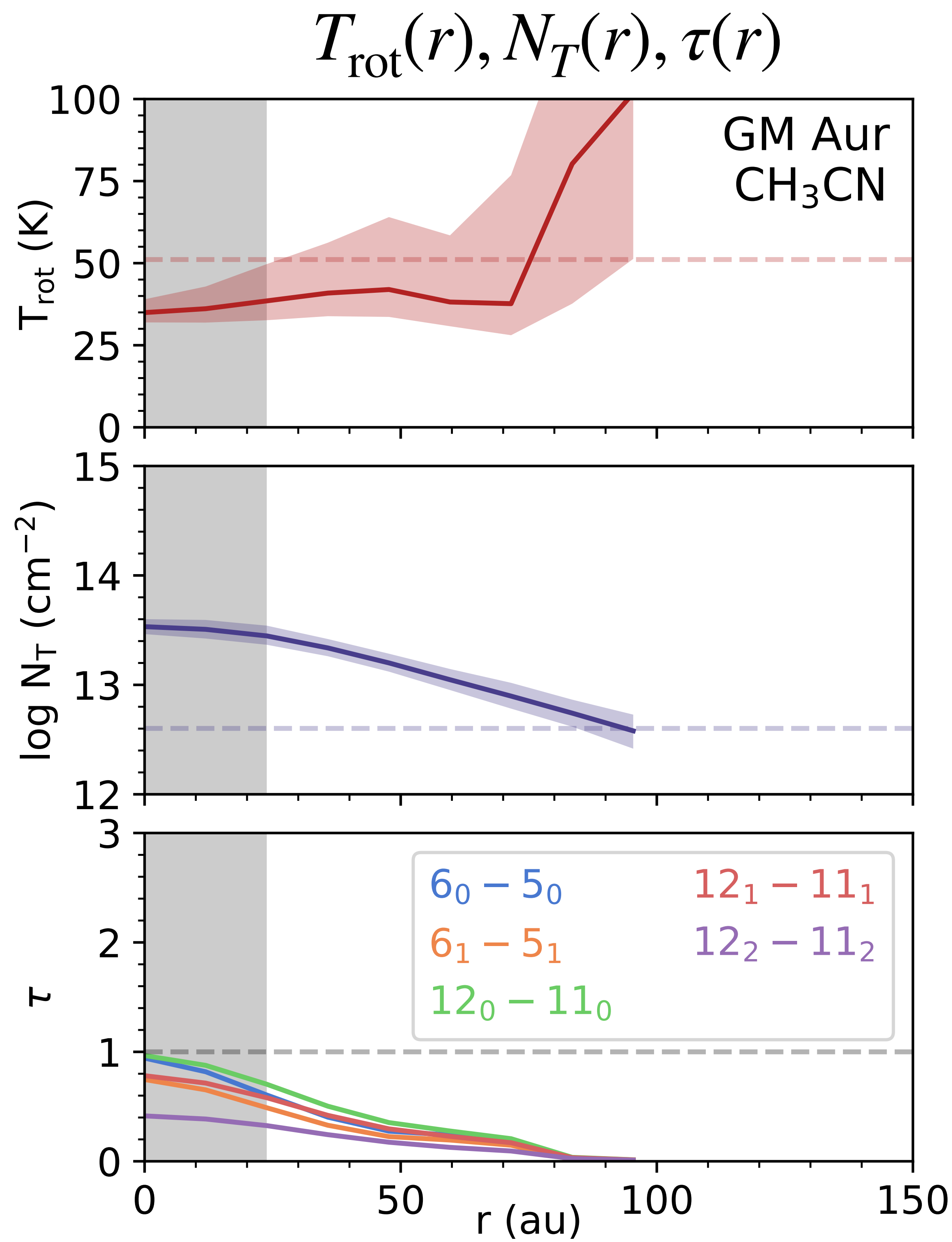
Excitation analysis

- Example: CH_3CN in GM Aur
- Three immediate takeaways…



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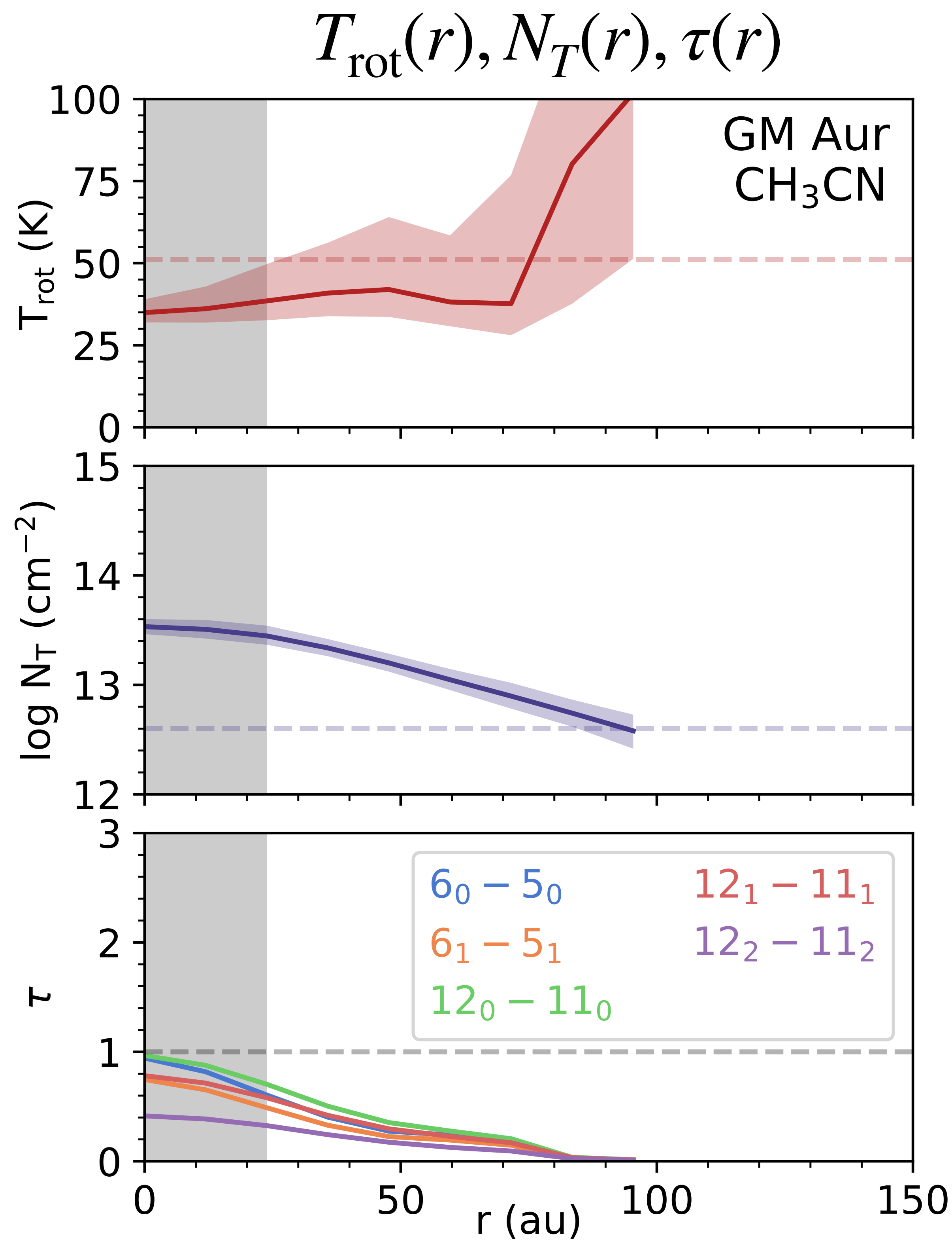

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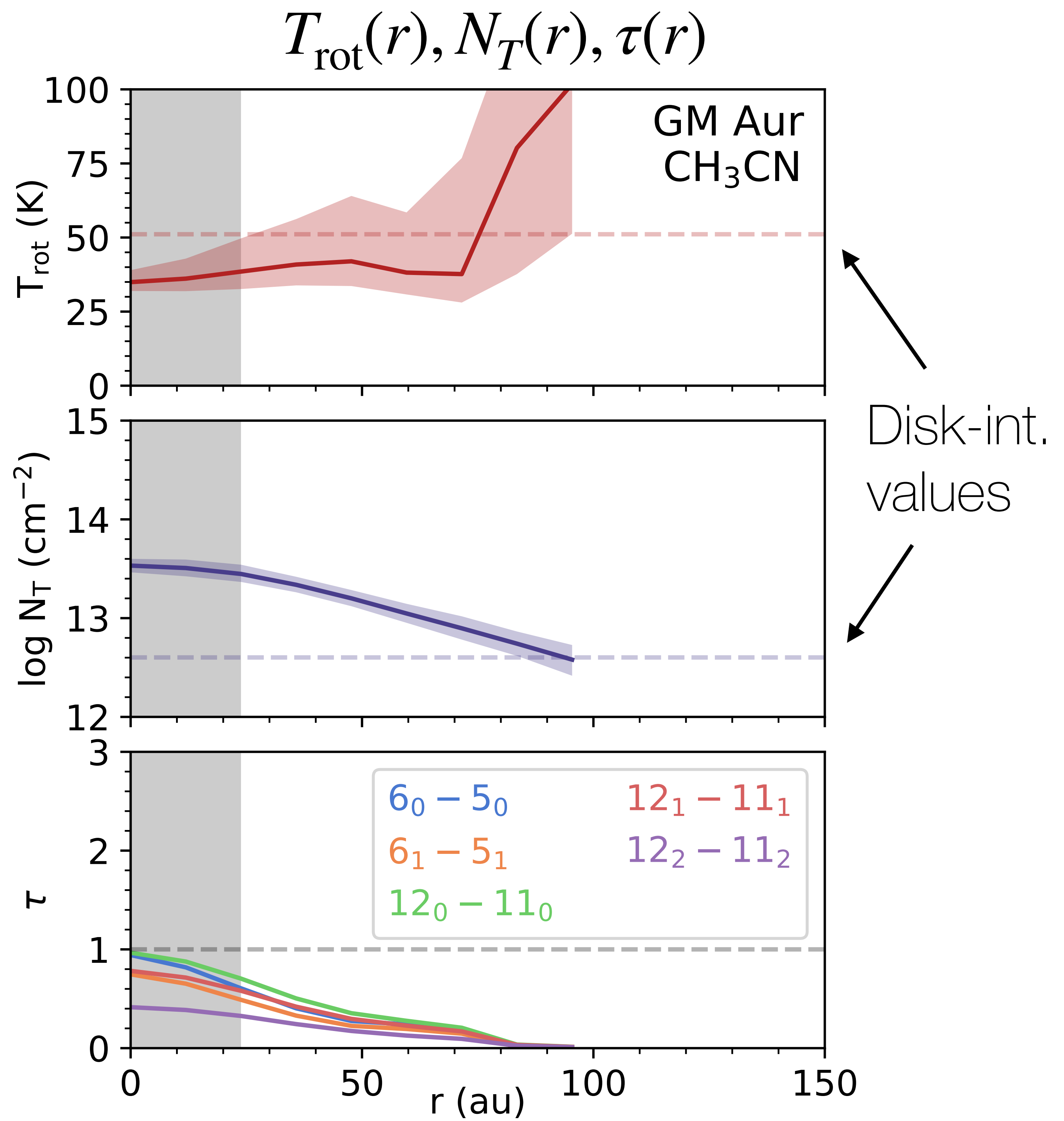

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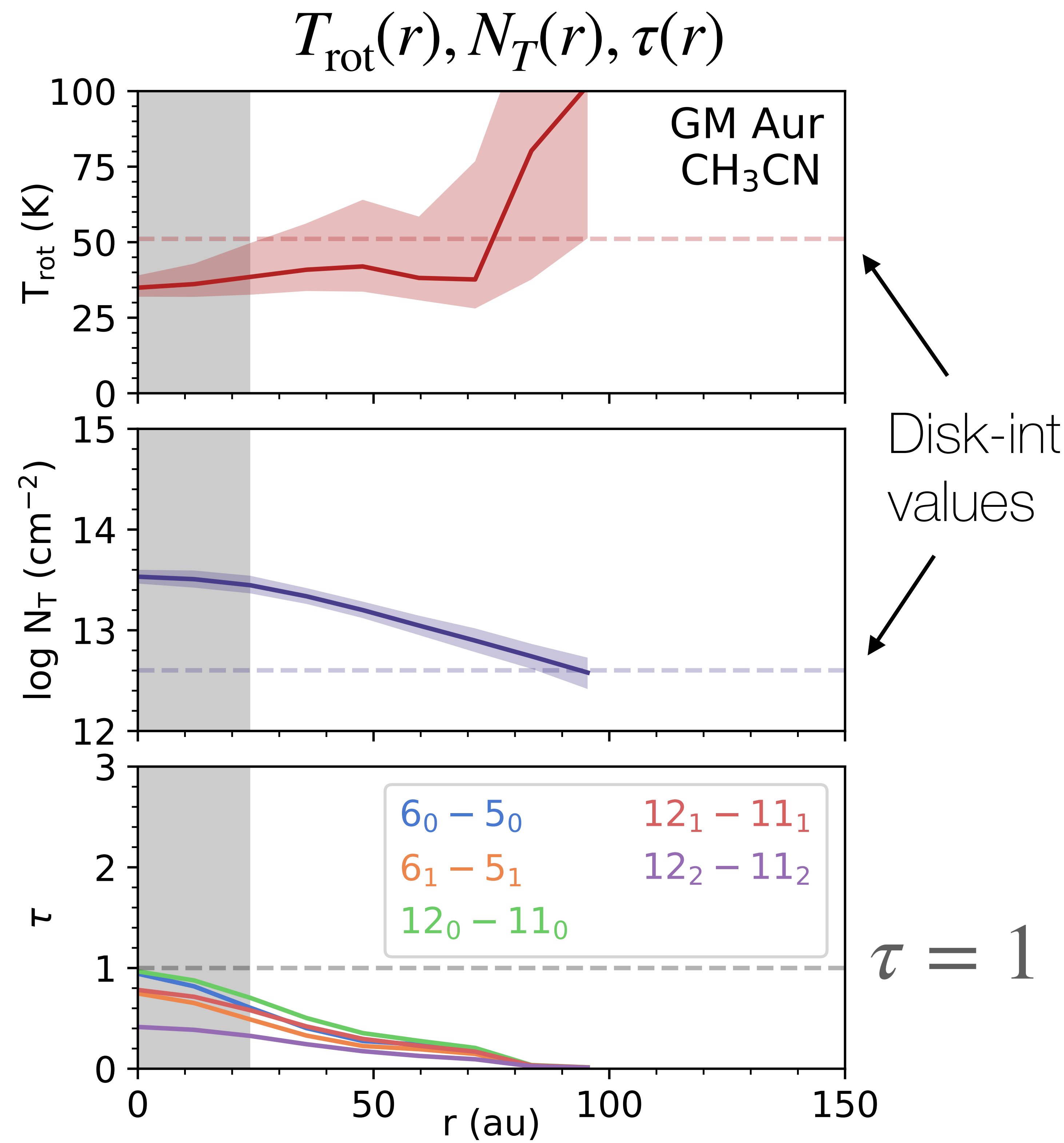

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True for both HC_3N and CH_3CN in each of the four disks

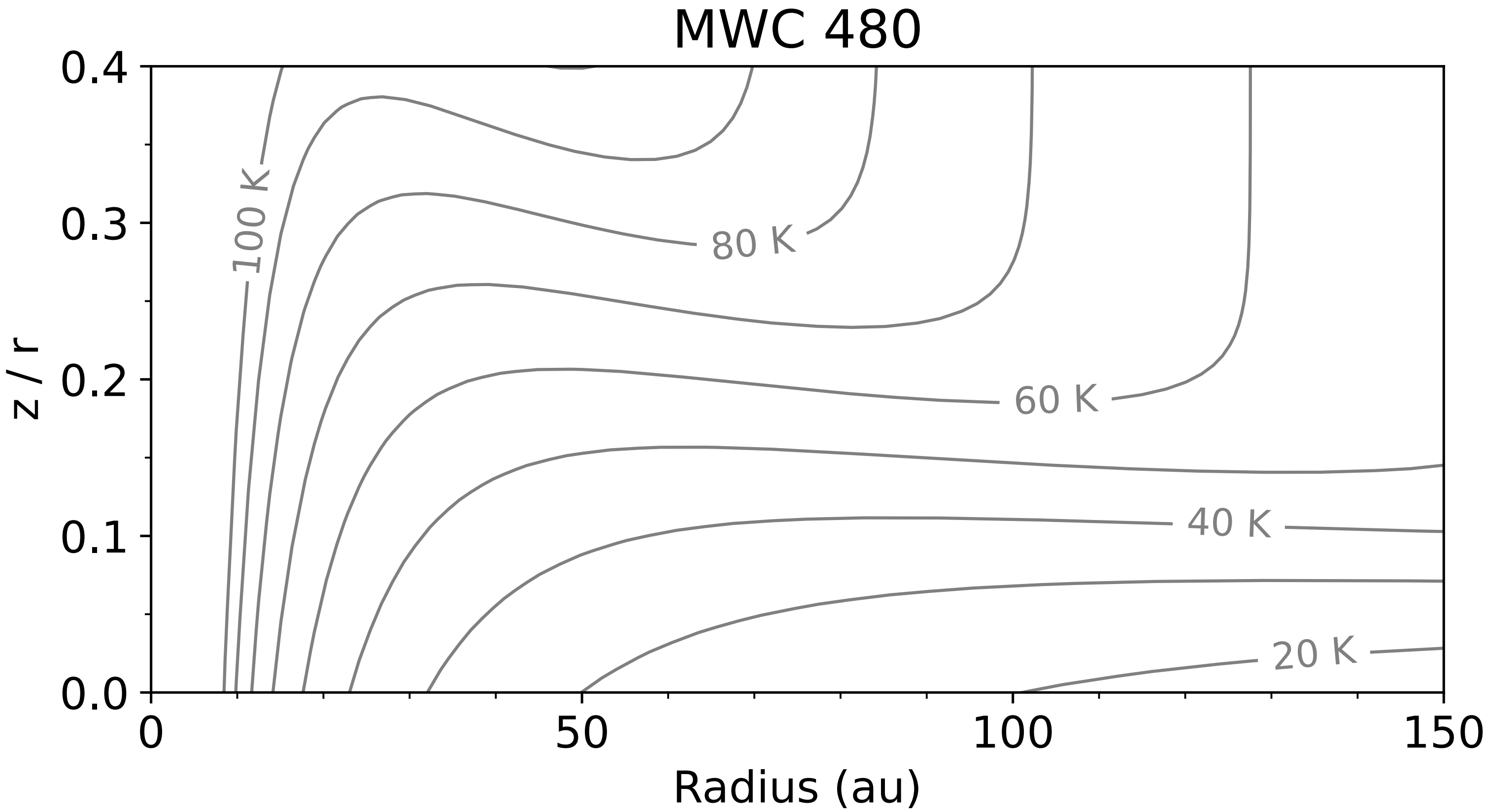
Peak columns are between 10—100 times higher than previous chemical models predict (Walsh et al. 2014)

MAPS IX: Ilee et al. (2021)

Spatial origin of the line emission

- We can combine data across MAPS studies for further understanding
- Disk 2D temperature structures have been empirically determined

(Law & MAPS 2021b)



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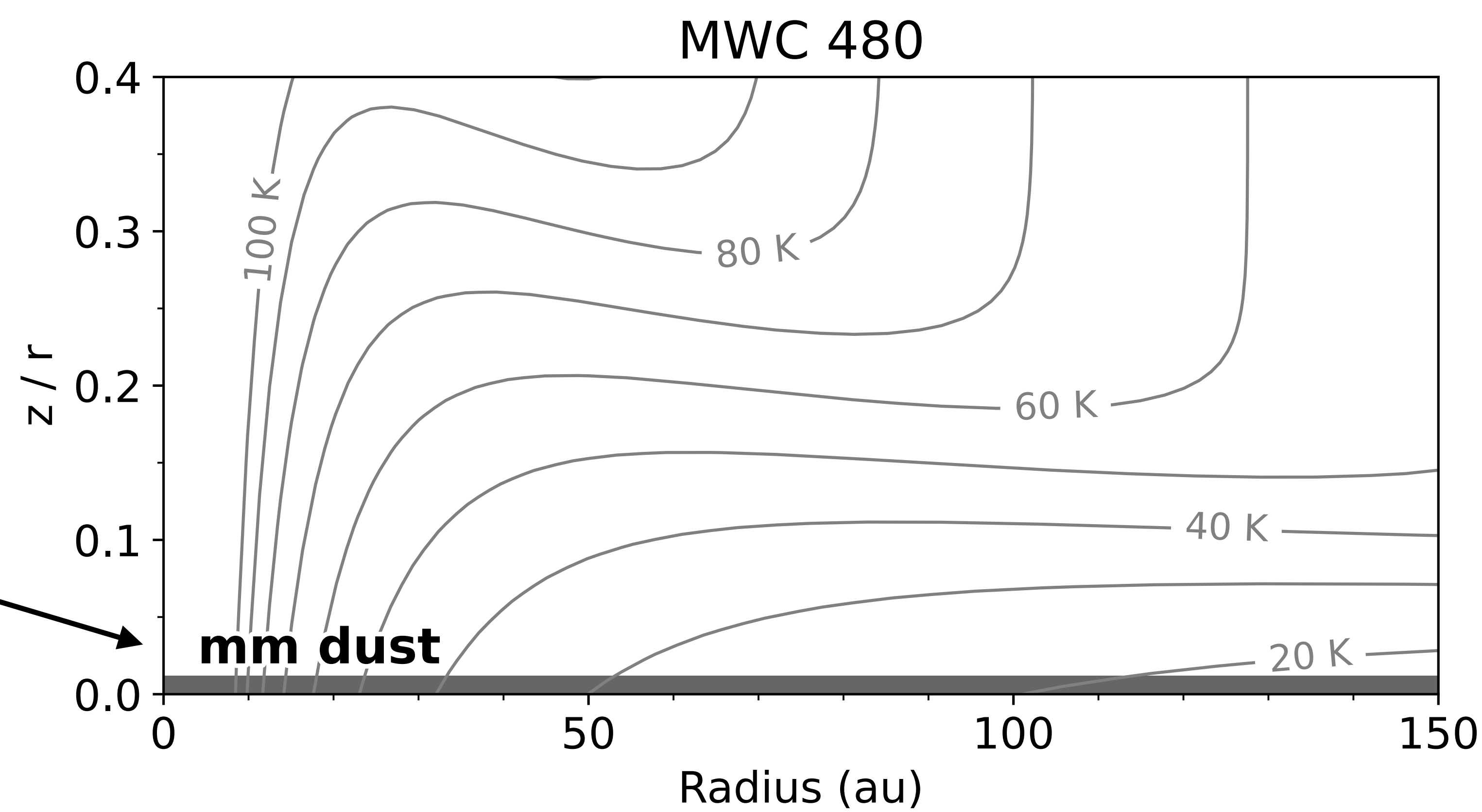
Midplane



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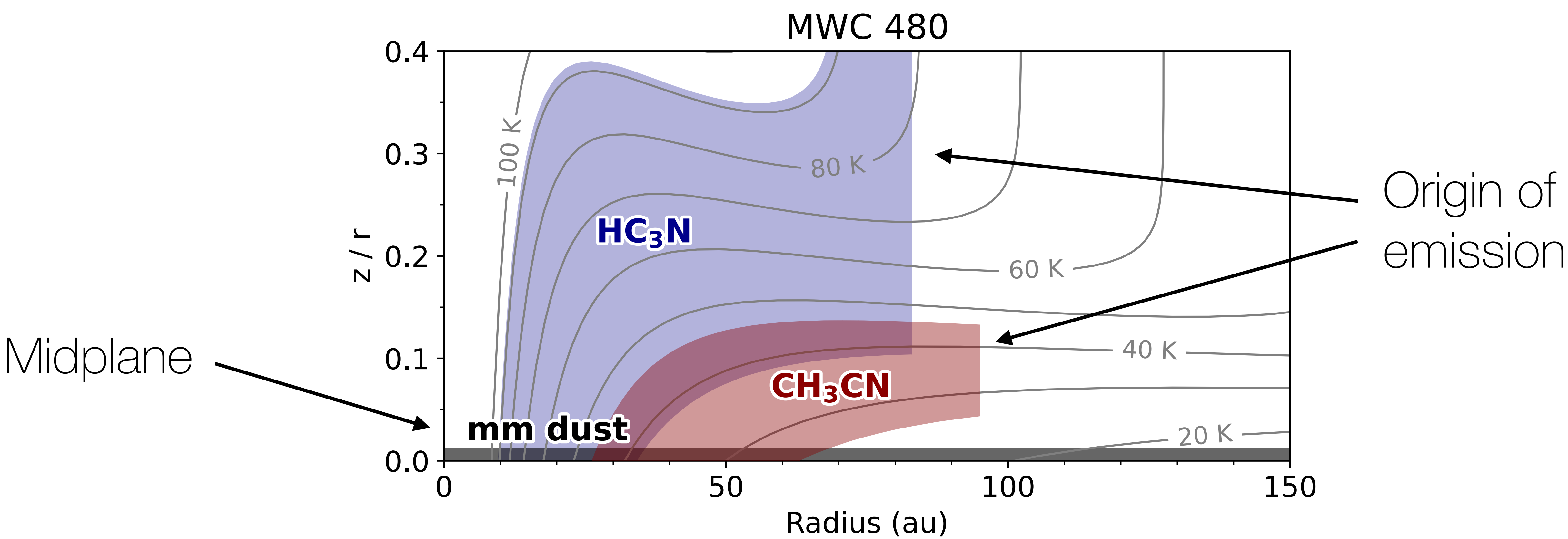

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* assuming T_{rot} ~ T_{gas}

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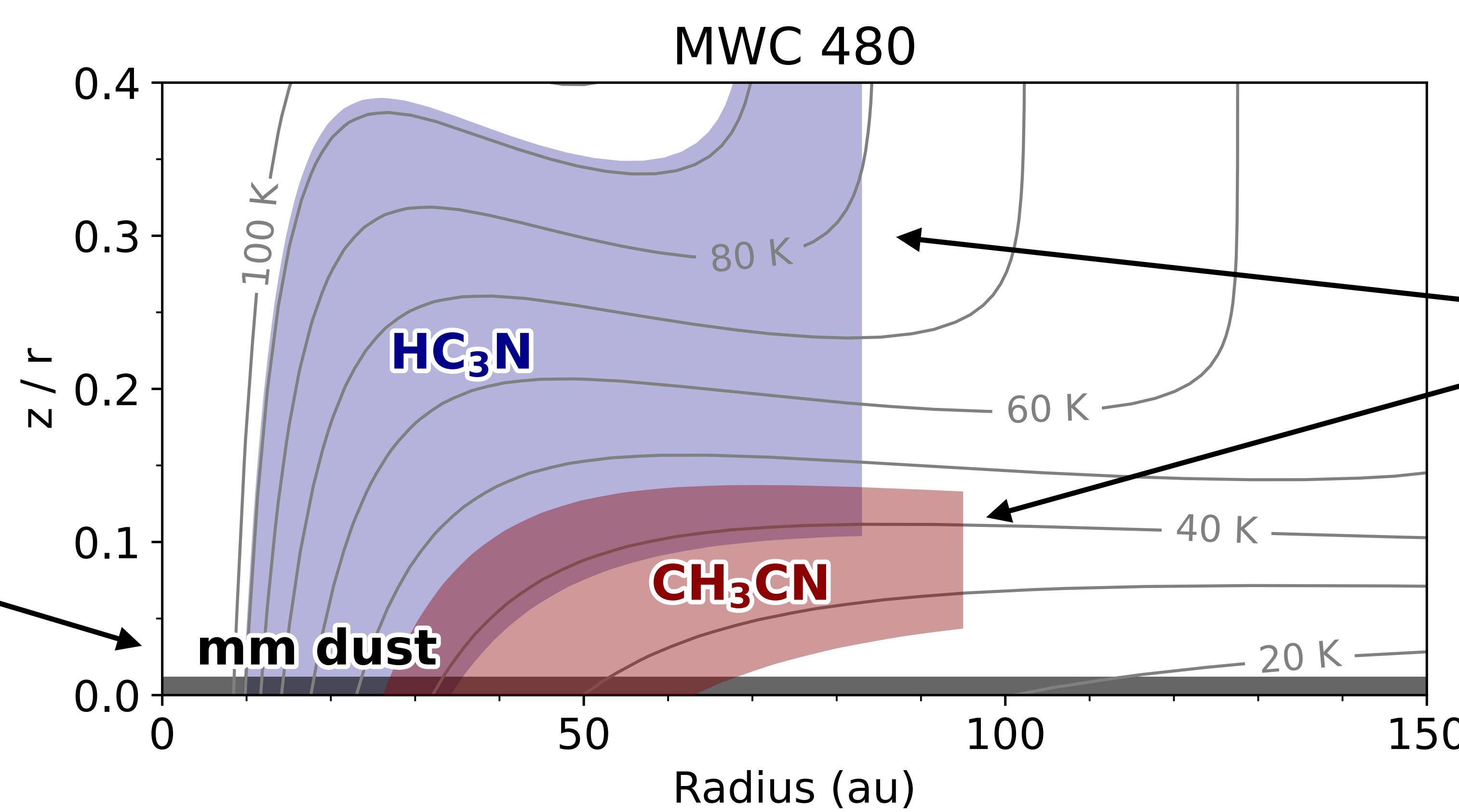


Midplane

Origin of emission

➔ *Large organics emit from, or very close to, the midplane*

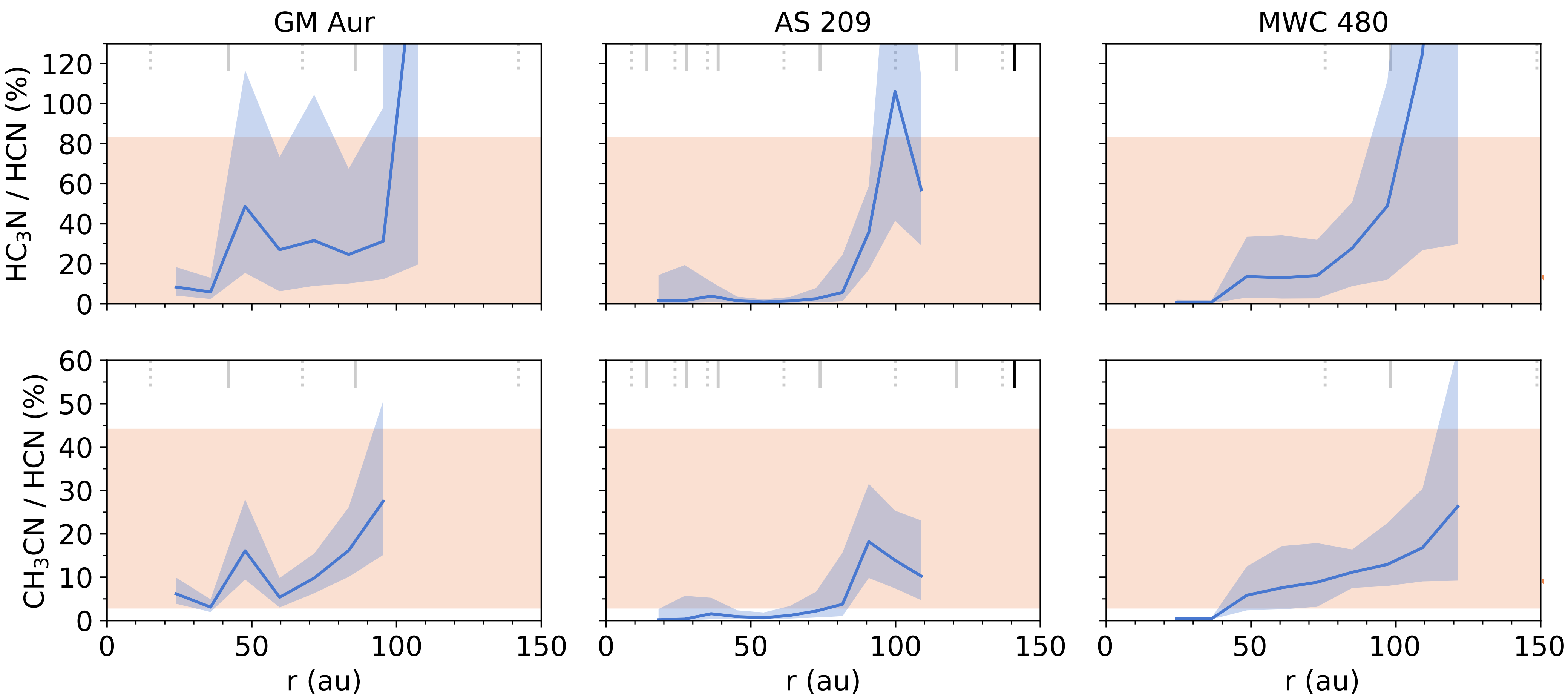
MAPS IX: Ilee et al. (2021)

* assuming $T_{rot} \sim T_{gas}$

Compositional comparison with the Solar System

- We can combine data across MAPS studies for further understanding (II)
- Comparison of the ratio of large to small organics across each disk

(with Guzmán & MAPS 2021)



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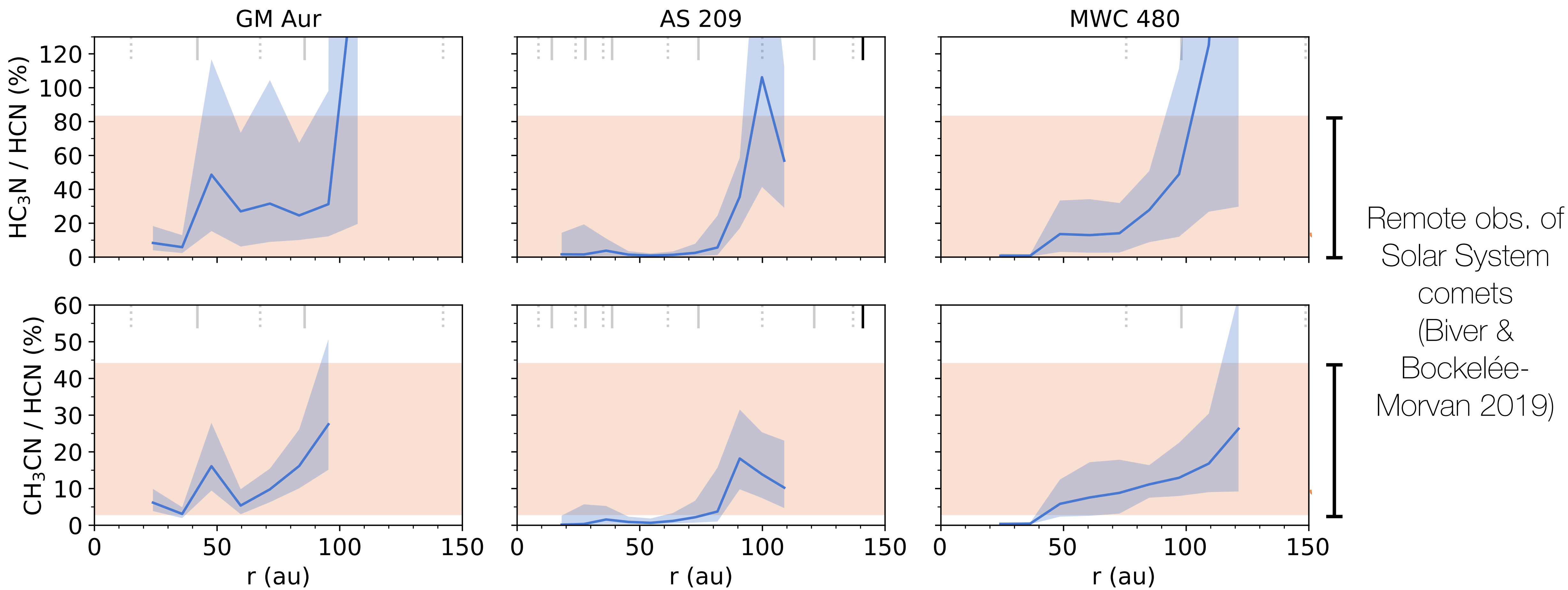

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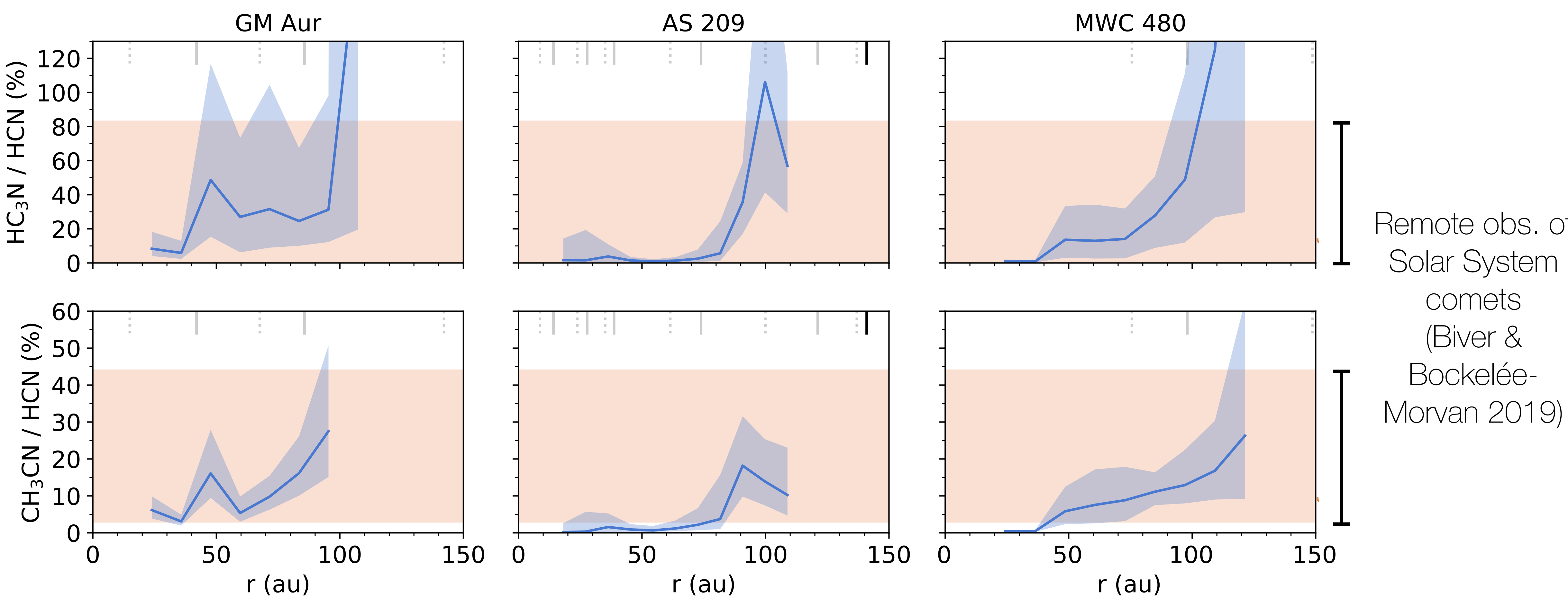


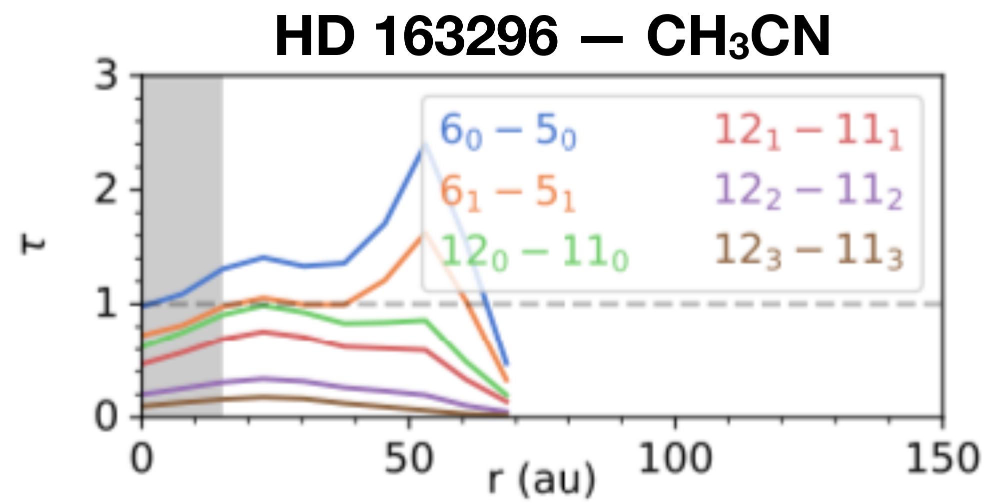
➔ ***Disk organic composition is consistent with Solar comets***

(beyond ~50 au where $\tau < 1$)

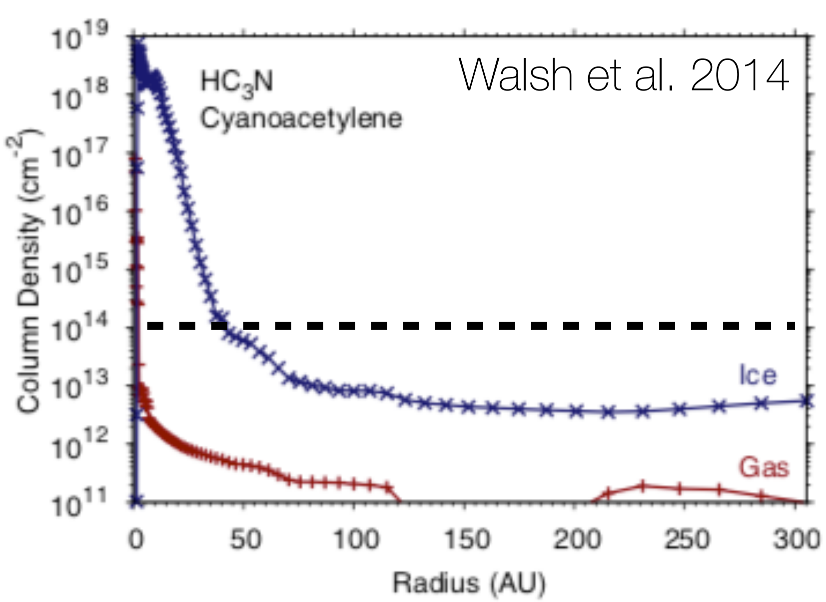
MAPS IX: Ilee et al. (2021)

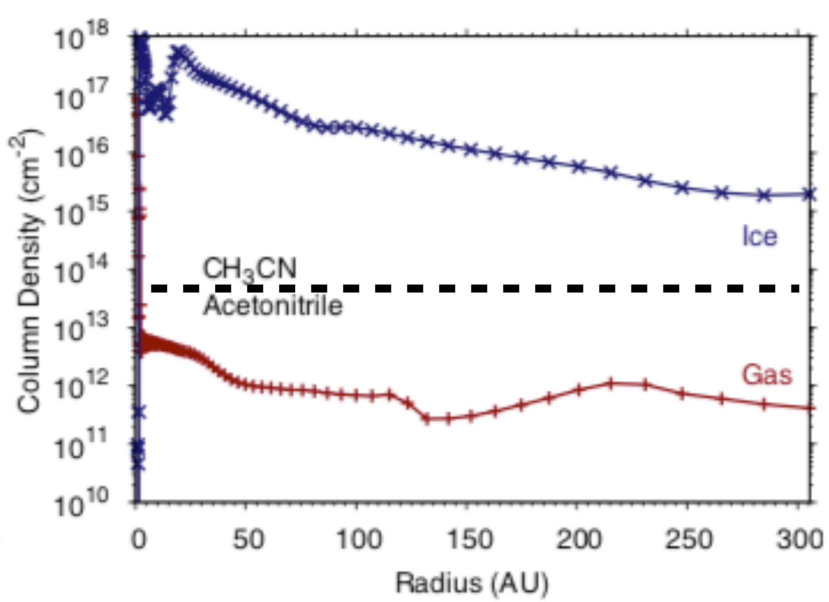
Open questions / what next?

- Significant optical depths at small radii, will need lower frequencies…
  - ALMA Band 1 (2023?)
  - ngVLA / SKA (late 2020s?)



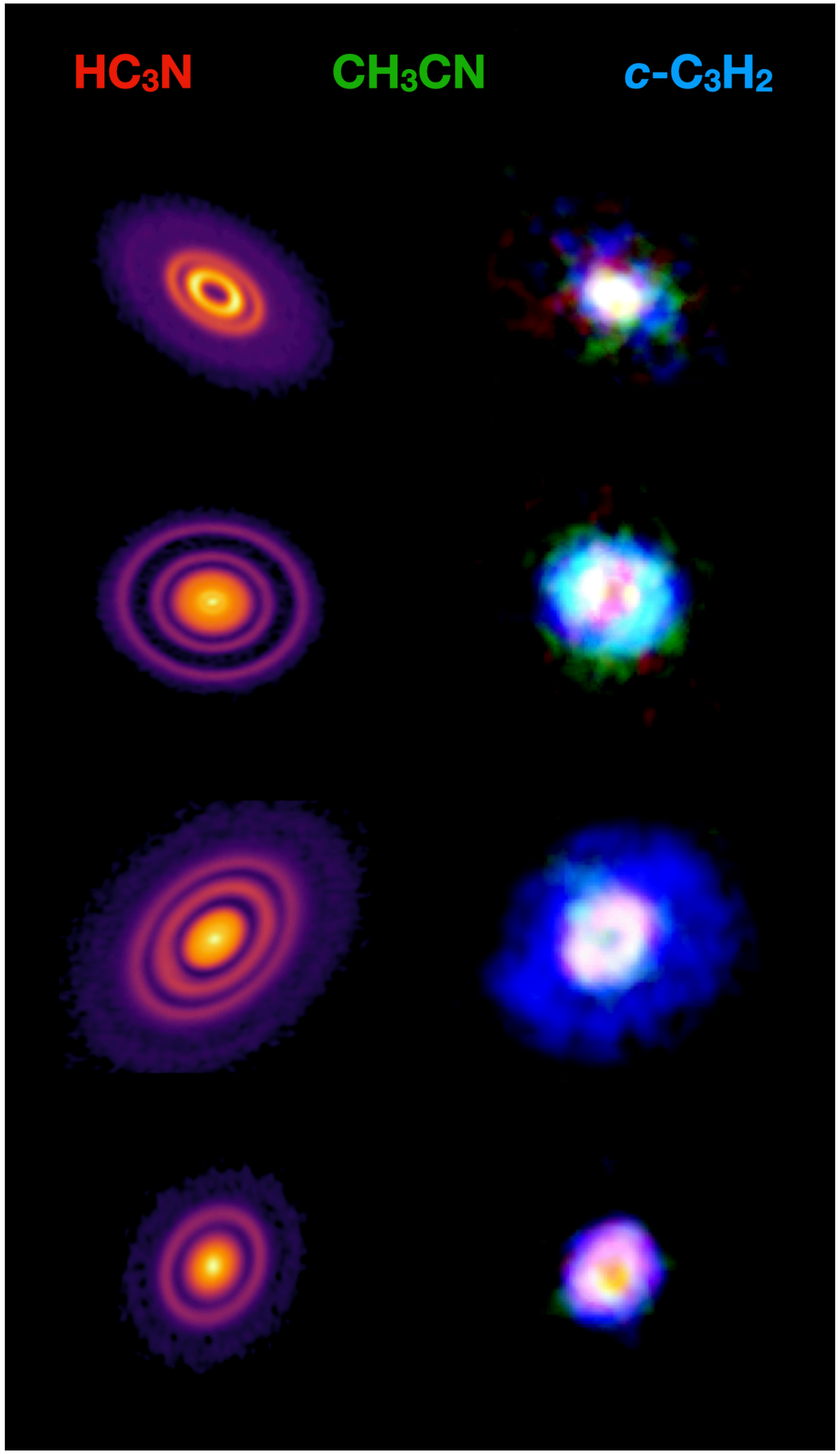
- Large columns incompatible with previous chemical model predictions
  - Missing chemistry? Further grain surface processes needed?
    e.g. Garrod et al. 2021
  - Missing physics? Drift & processing of icy grains from outer disk?
    e.g. R. Booth & Ilee 2019

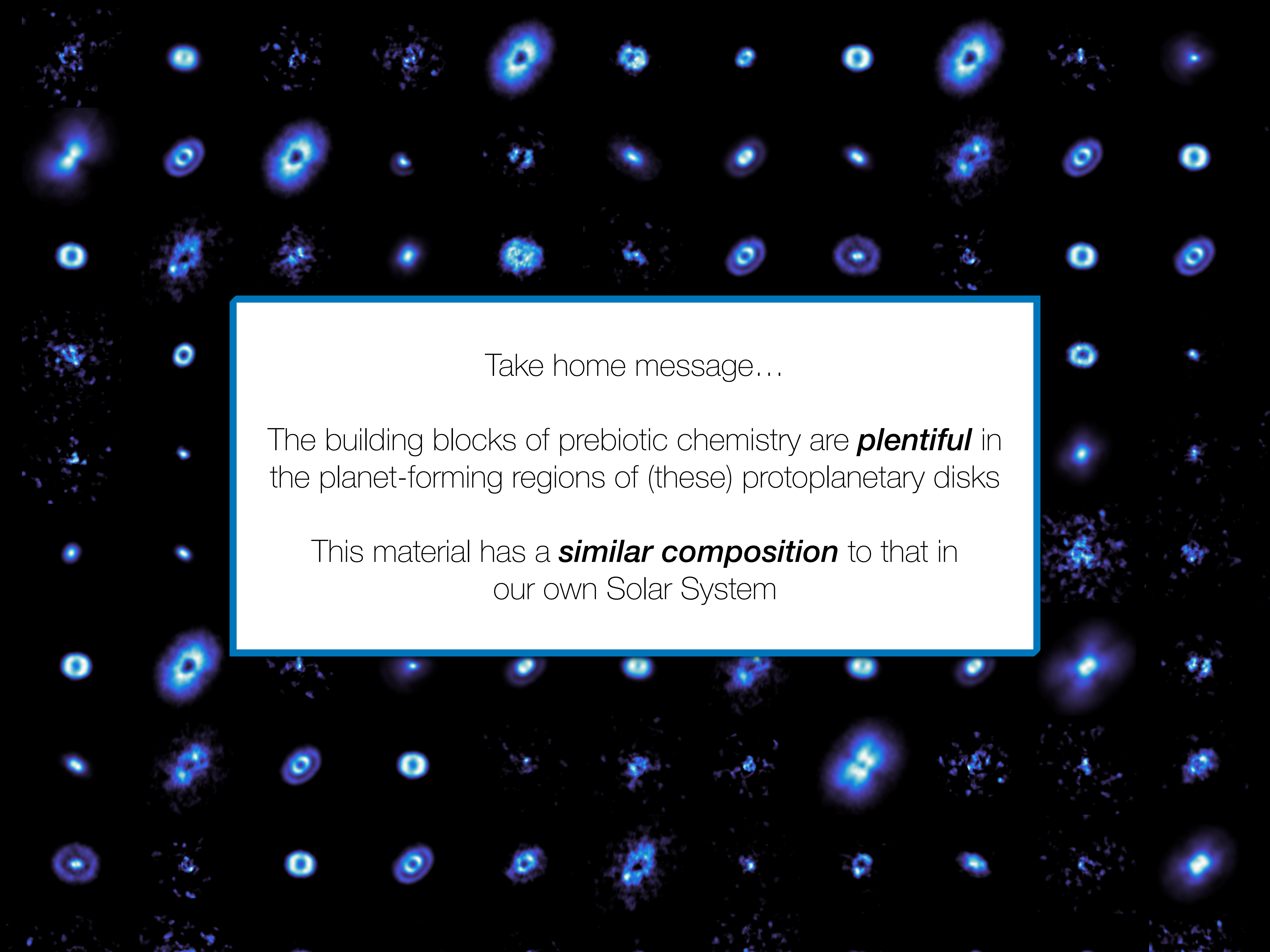




Summary

- The MAPS disks host significant reservoirs of small and large organic molecules
- Small organics approach 1–2% of total H_2O mass within 50 au
- Large organics similarly enhanced in inner disk (10—100x model predictions)
- Emission originates at low z/r (or midplane)
- Ratios consistent with Solar System comets





Take home message…

The building blocks of prebiotic chemistry are ***plentiful*** in the planet-forming regions of (these) protoplanetary disks

This material has a ***similar composition*** to that in our own Solar System

MAPS Home Overview Disks Visualizations Publications Press Team Data

- All final (& intermediate) data products are publicly available

  - Self calibrated measurement sets ✓
  - Imaging scripts & toolsets ✓
  - Image cubes ✓
  - Moment maps ✓
  - Radial profiles ✓
  - Emission surfaces ✓

- User-friendly interface to grab specific data products
  - e.g. *"everything for AS 209"*, *"all radial profiles for CO"*

- BibTeX automatically generated for simple referencing

http://alma-maps.info

MAPS