



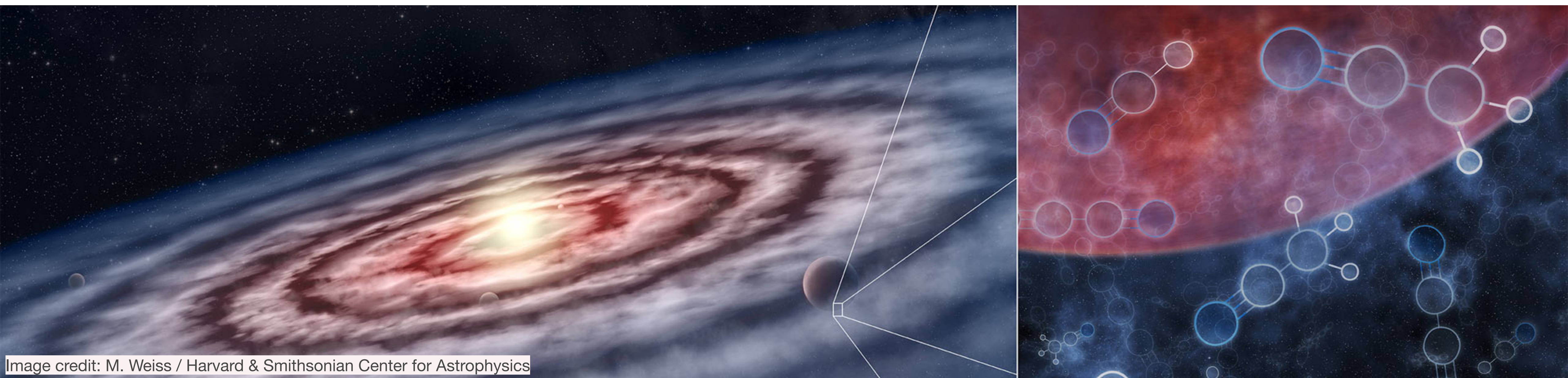
Chemistry Surveys of Protoplanetary disks

Ke (Coco) Zhang

University of Wisconsin-Madison

AAS 245th meeting,

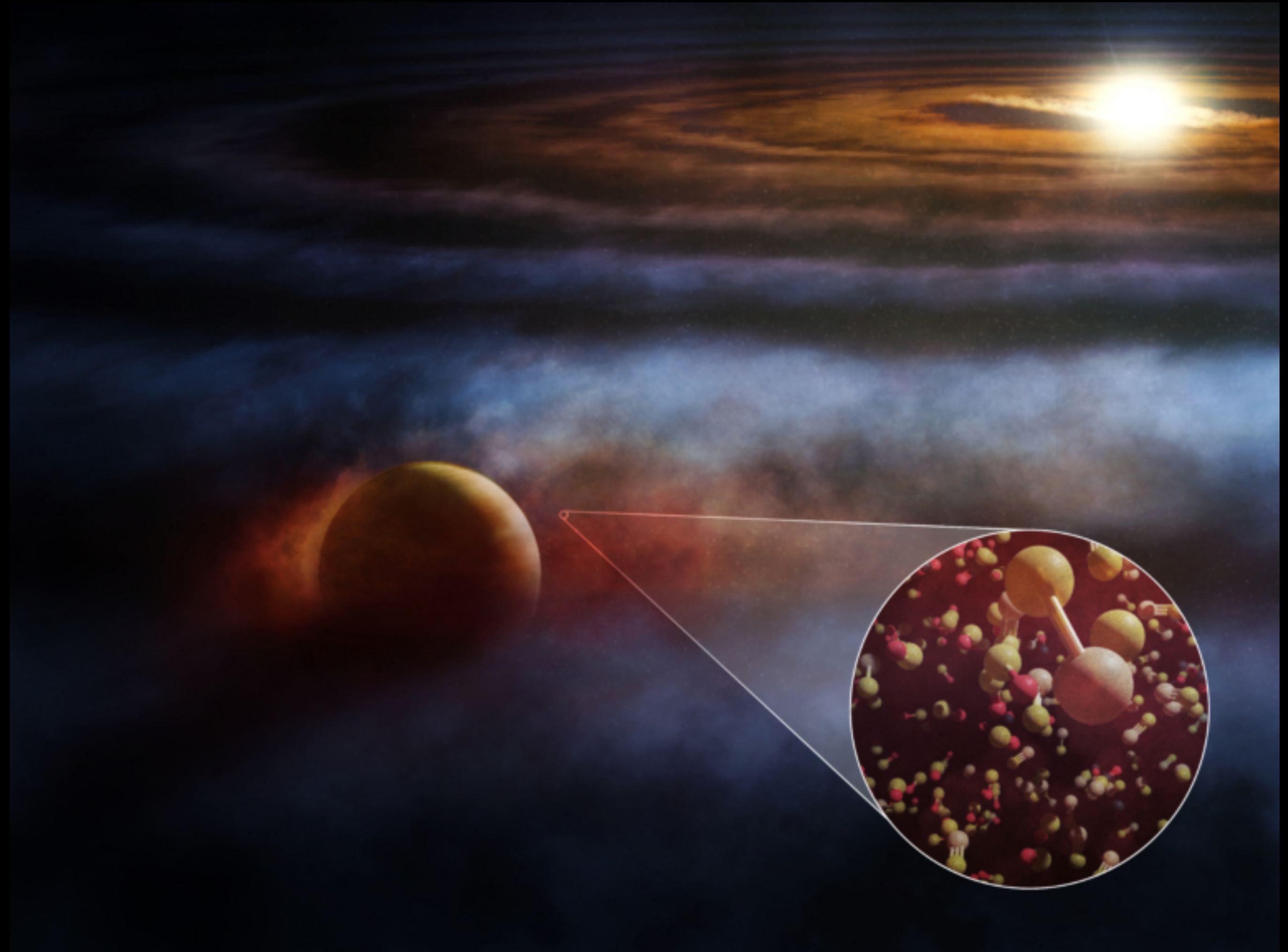
New perspectives on protoplanetary disks in the era of JWST and the
ALMA Wideband Sensitivity Upgrade, Jan 14th, 2025



Why study disk chemistry

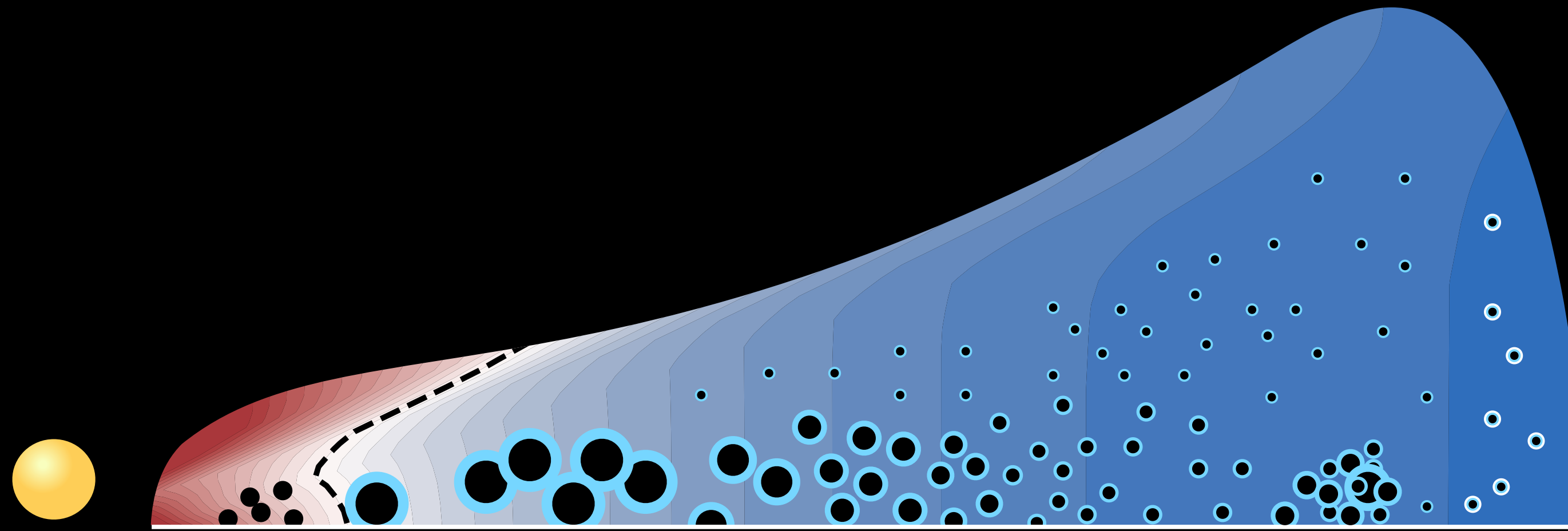
Disk composition to
planetary composition

Physical conditions
and formation
processes of planets

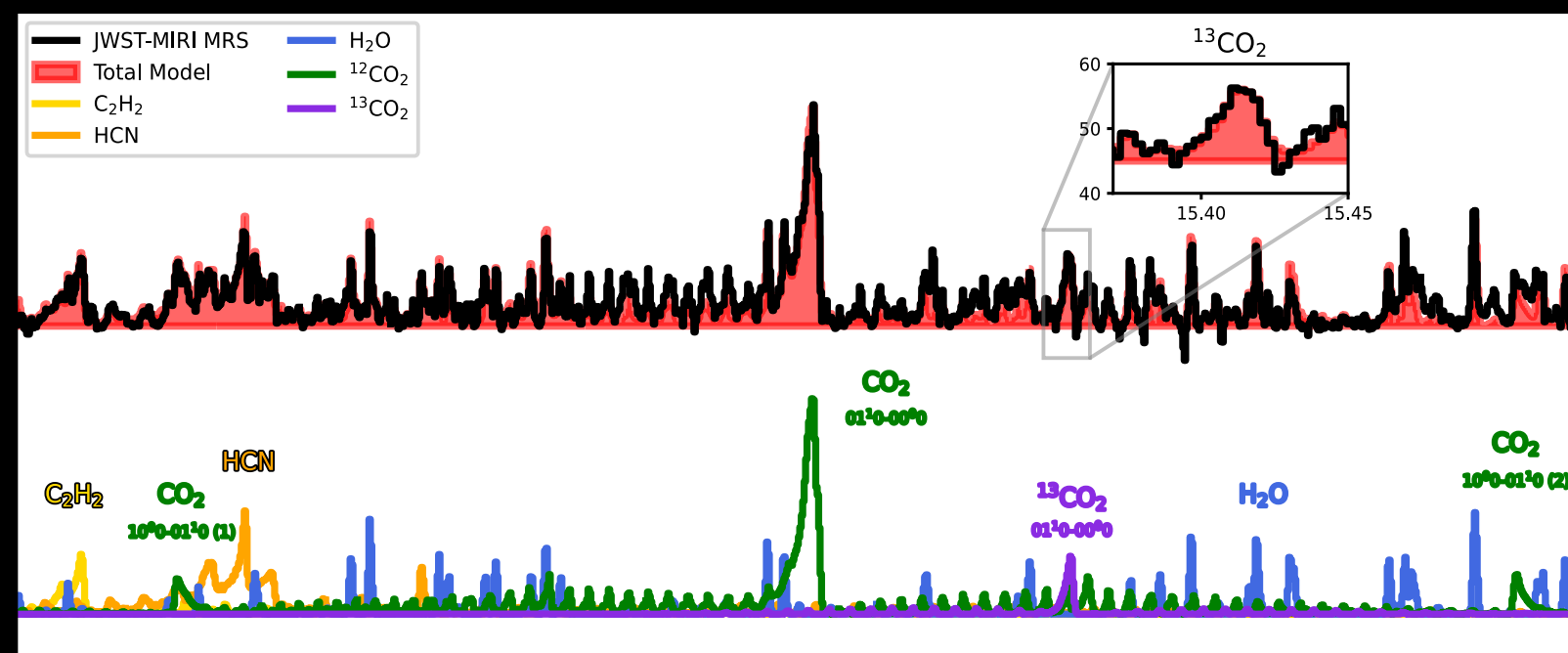


Credit: ALMA (ESO/NAOJ/NRAO), M. Weiss (NRAO/AUI/NSF)

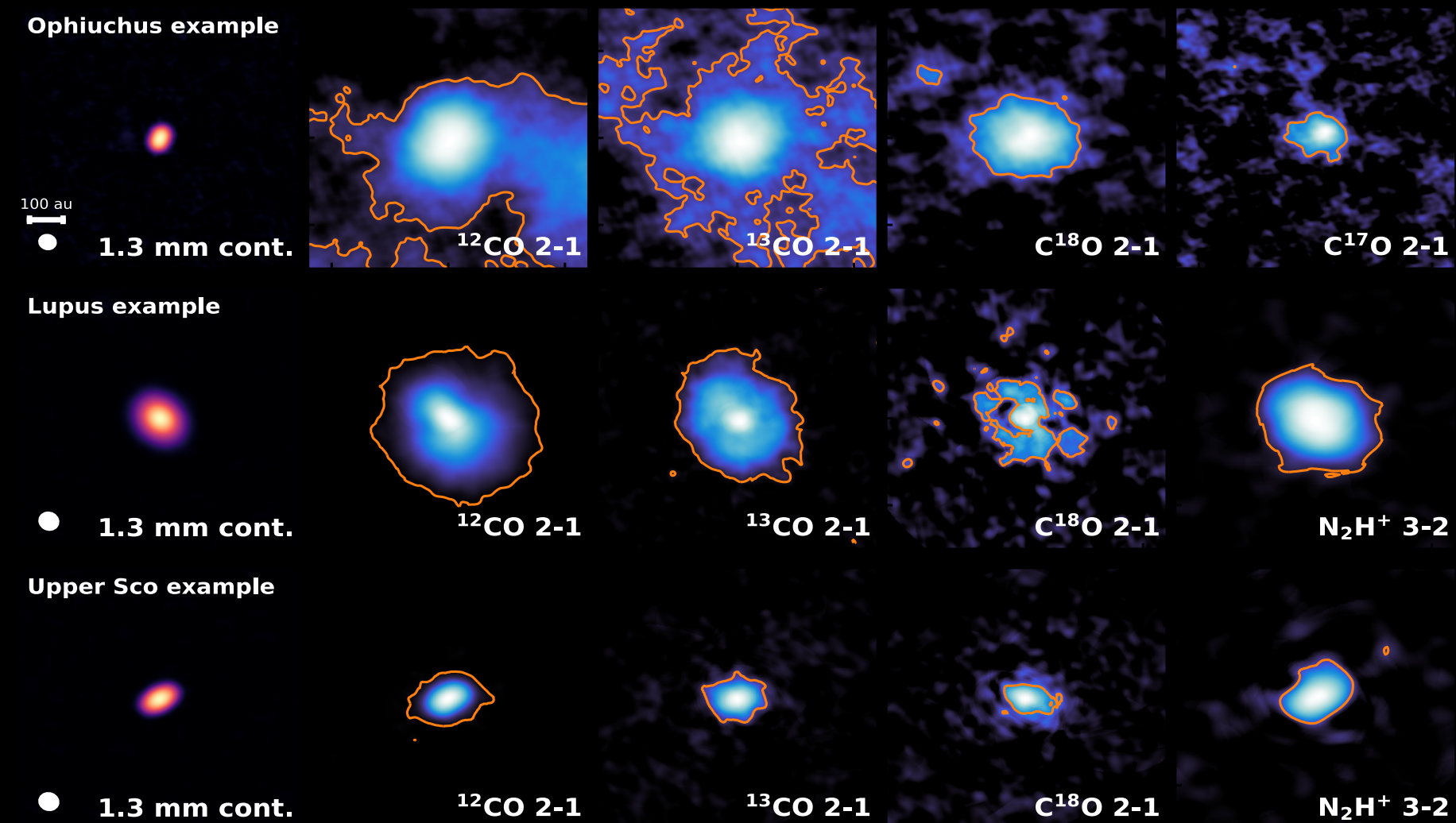
Multi-wavelength observations of disks



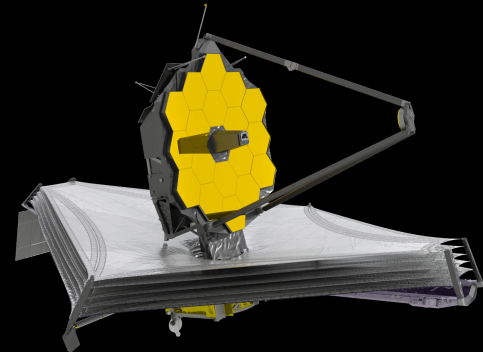
<10 au, probed by JWST



10-200 au, probed by ALMA



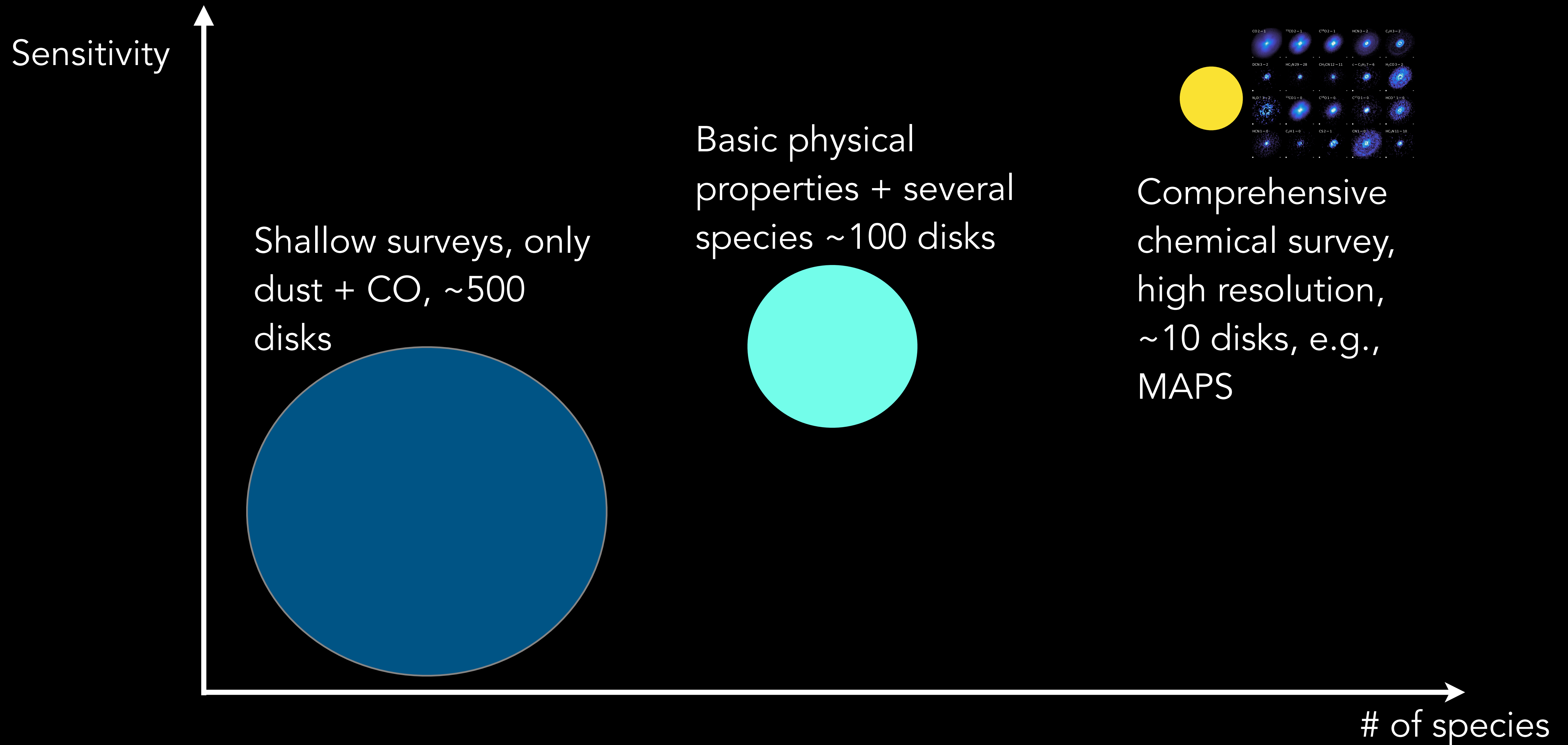
JWST

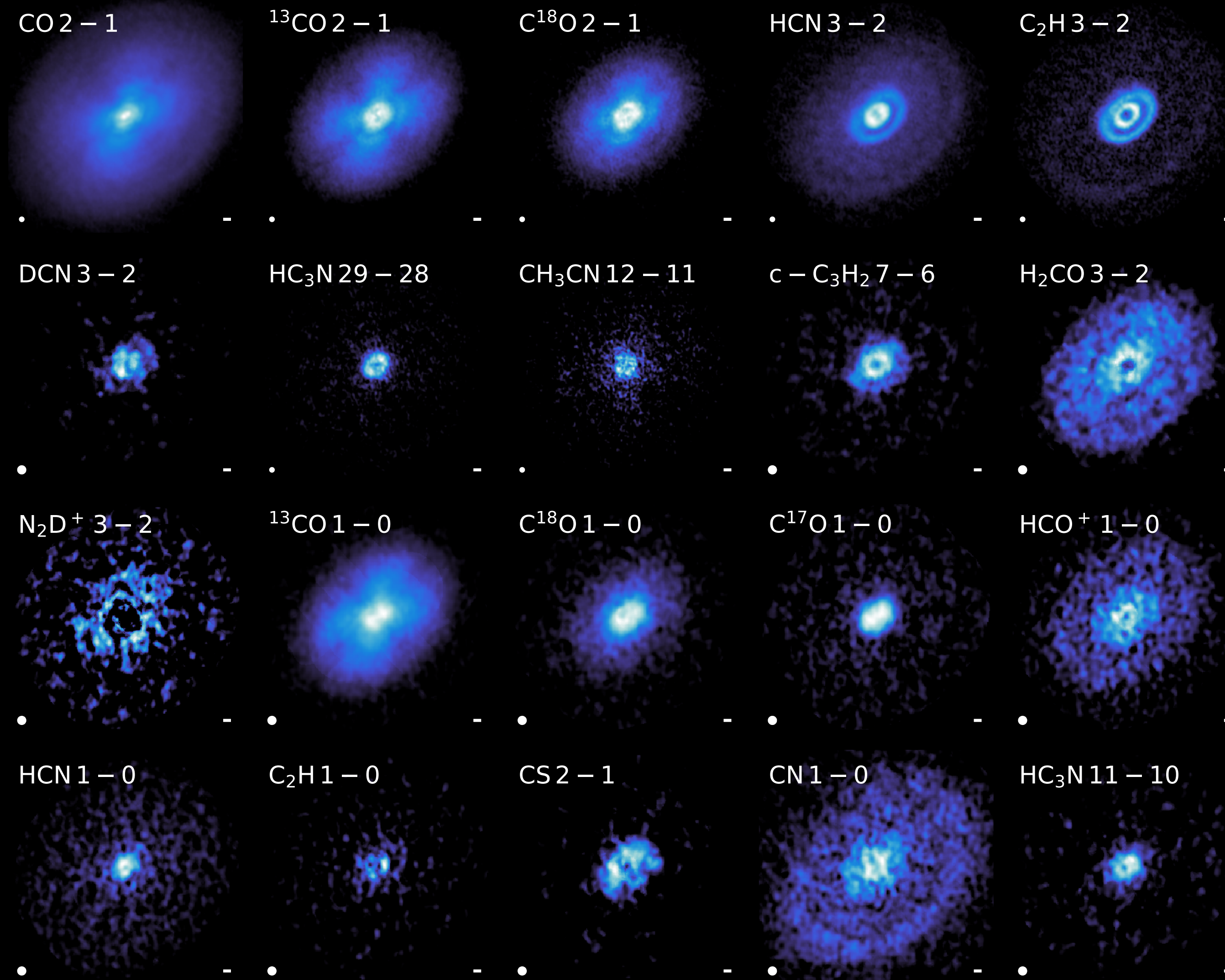


ALMA



Current ALMA chemical surveys



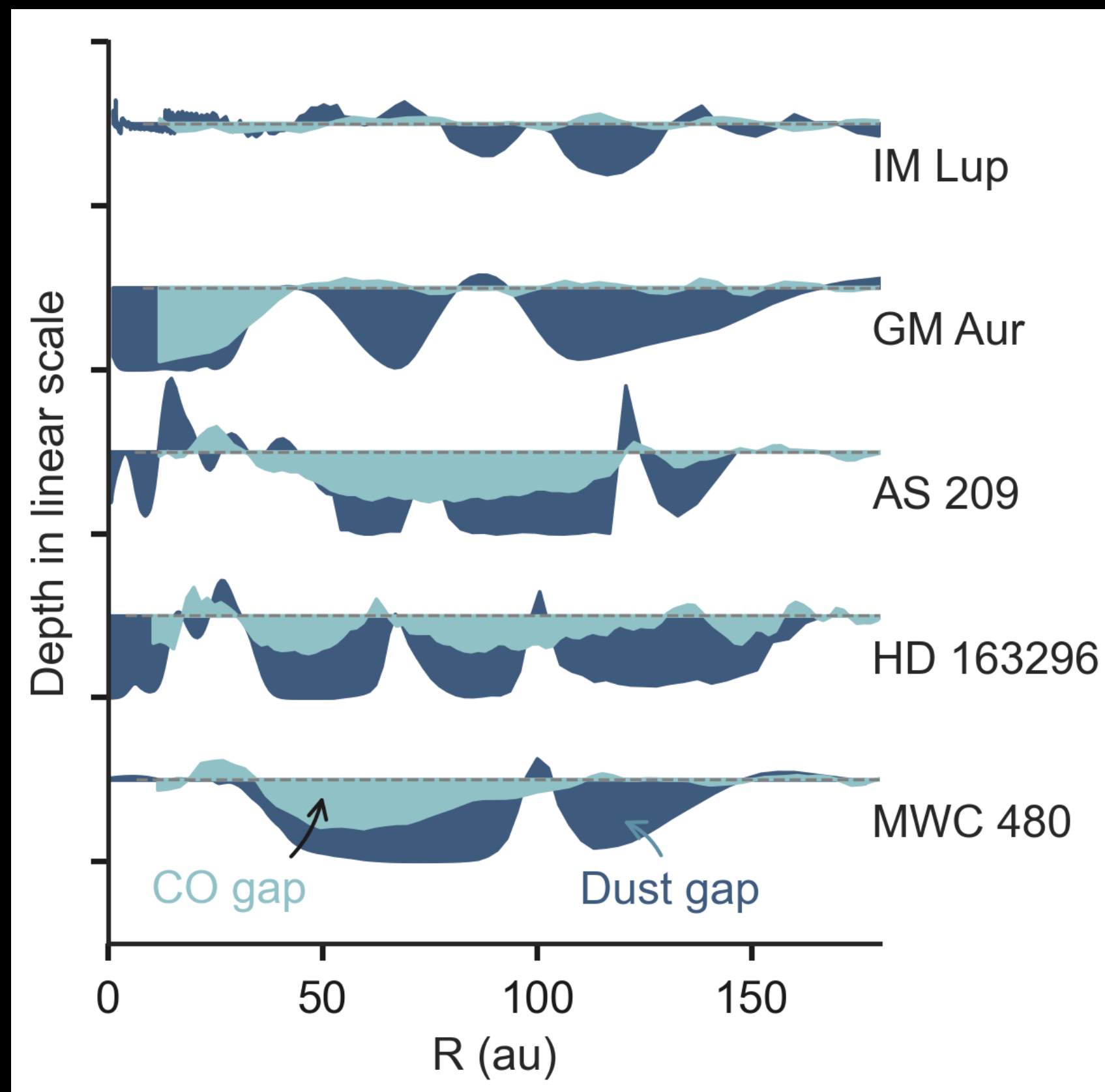


Disks often show rings, gaps, and spirals in the distribution of dust and gas molecules.

Oberg et al. 2021,
MAPS survey

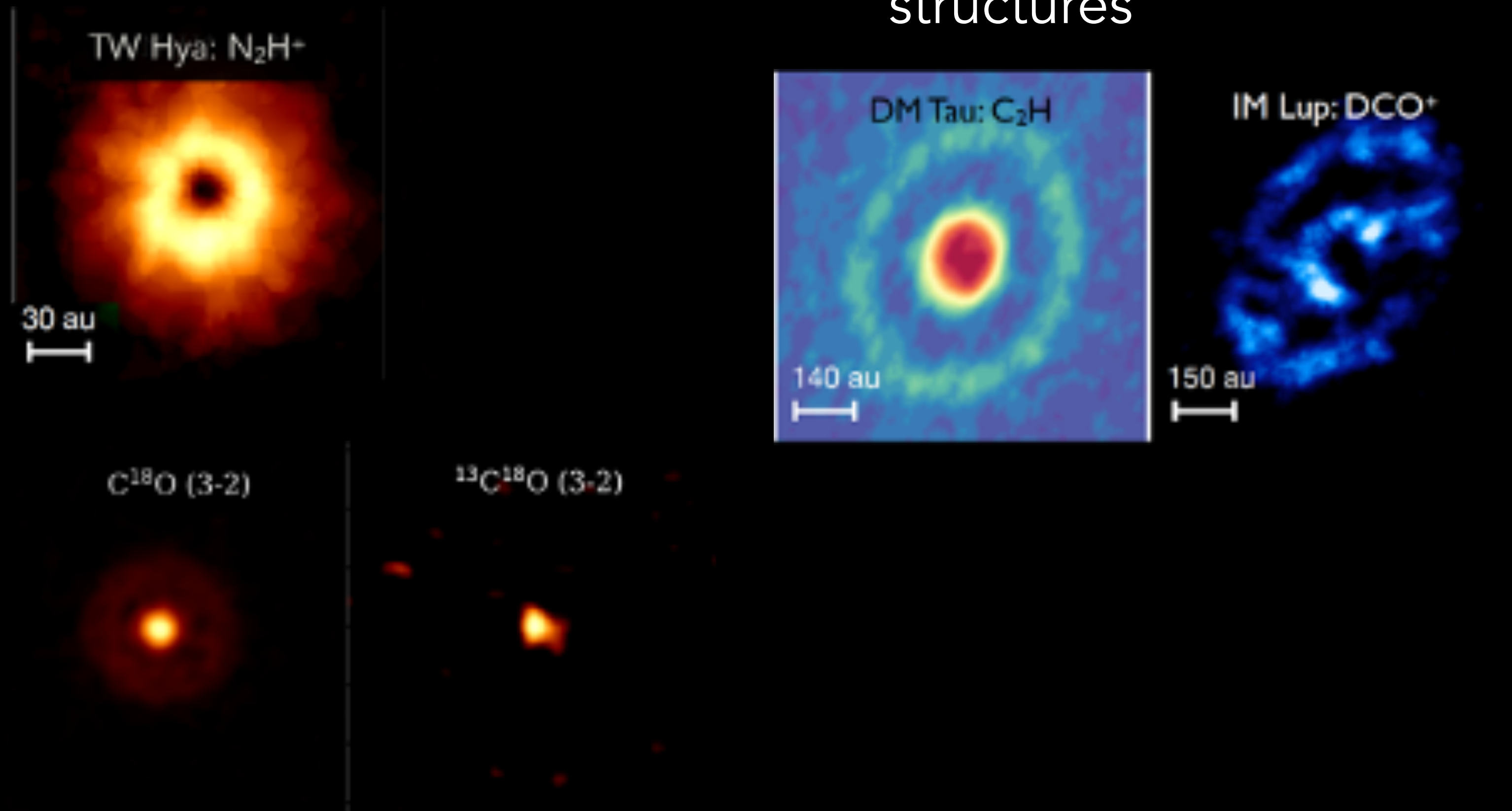
Chemical substructures are diverse, and their origins are not fully understood

- Gas gap



Zhang+2021

- Snowline

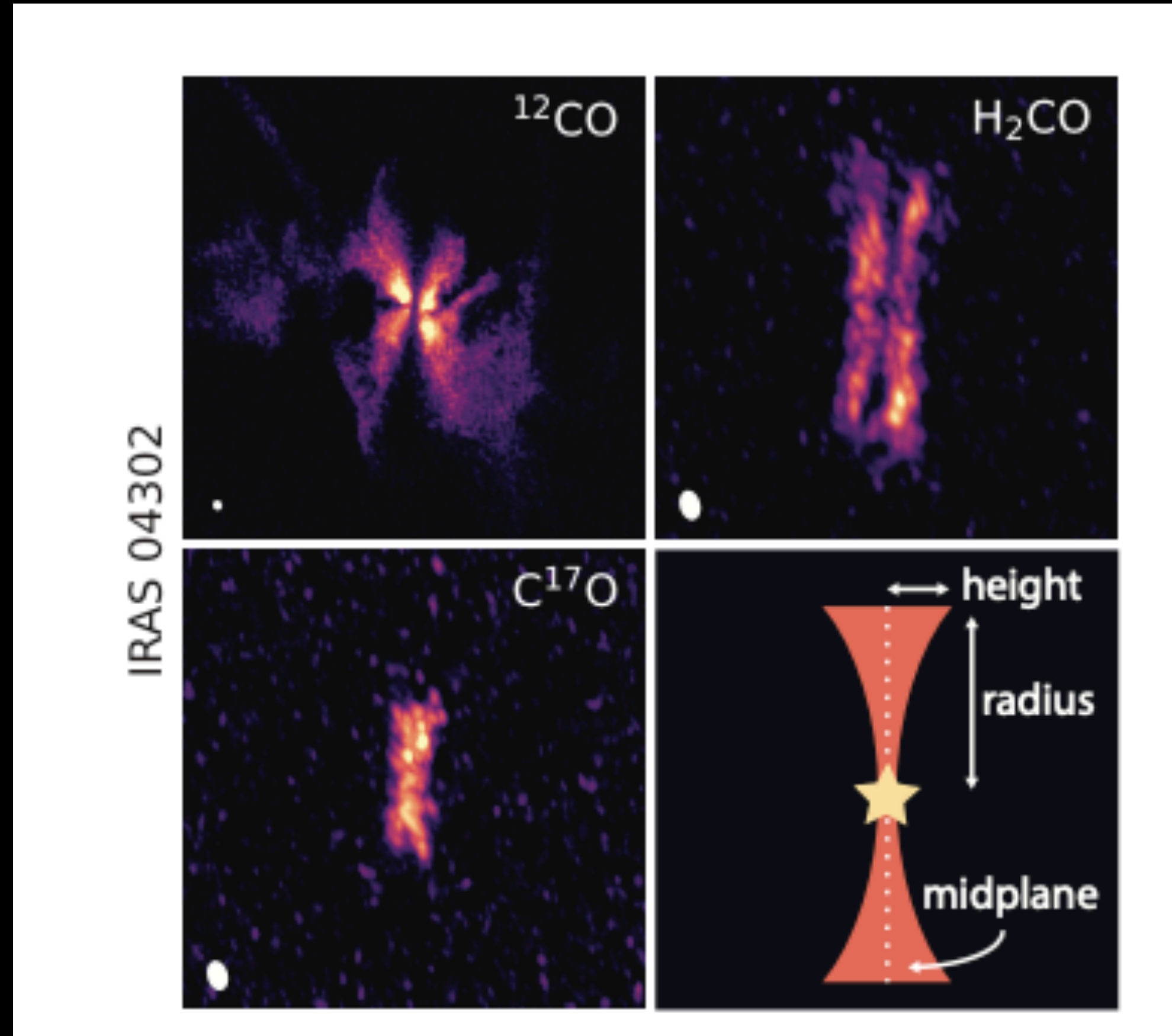


Qi+2013, Schwarz+2016, Zhang+2017

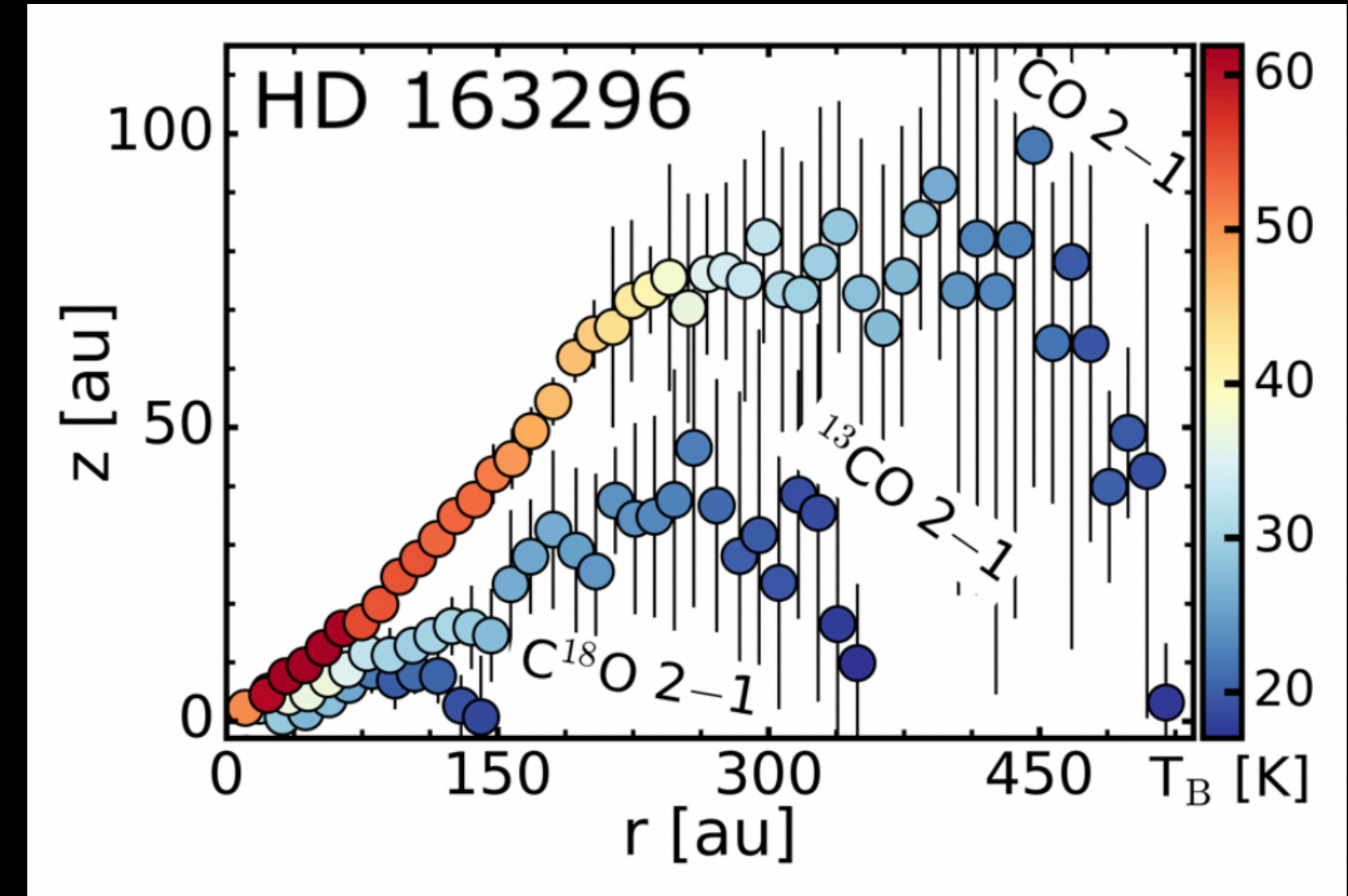
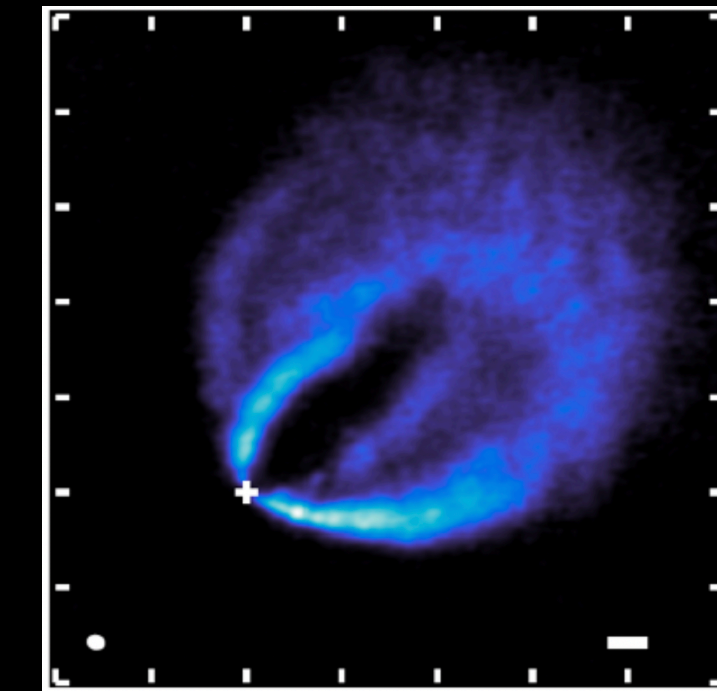
- Other chemical structures

Bergin+2016, Oberg+2015,
Law+2021, Guzman+2021

Vertical structure



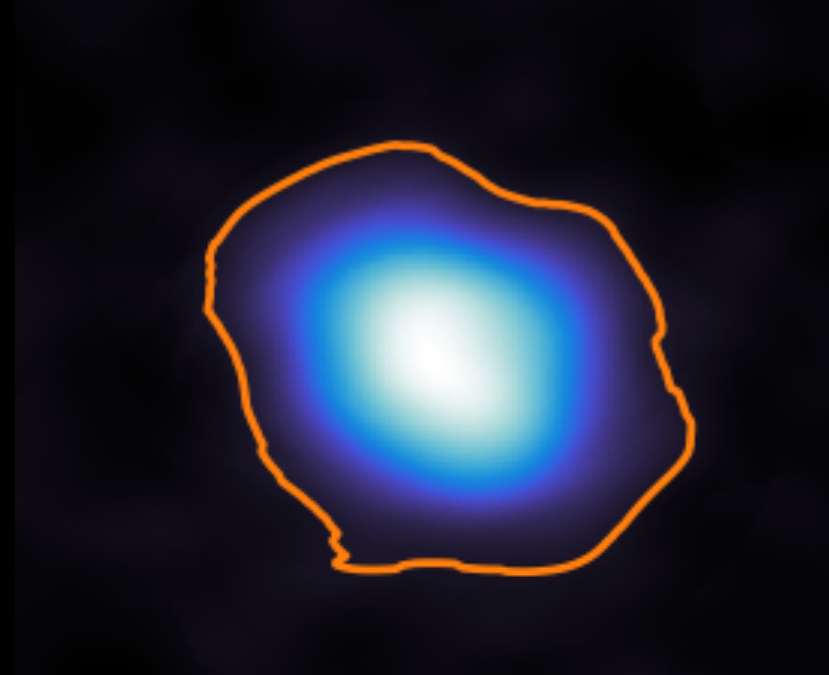
Dutrey+2017, van 't Hoff+2020, Lin+2023



Pinte+2018, Law+2021, 2023, Paneque-Carreño+2023

Gas disk masses

Intensity of radiation



Continuum flux

(assume gas-to-dust mass ratio of 100)

Line flux: e.g., HD, 

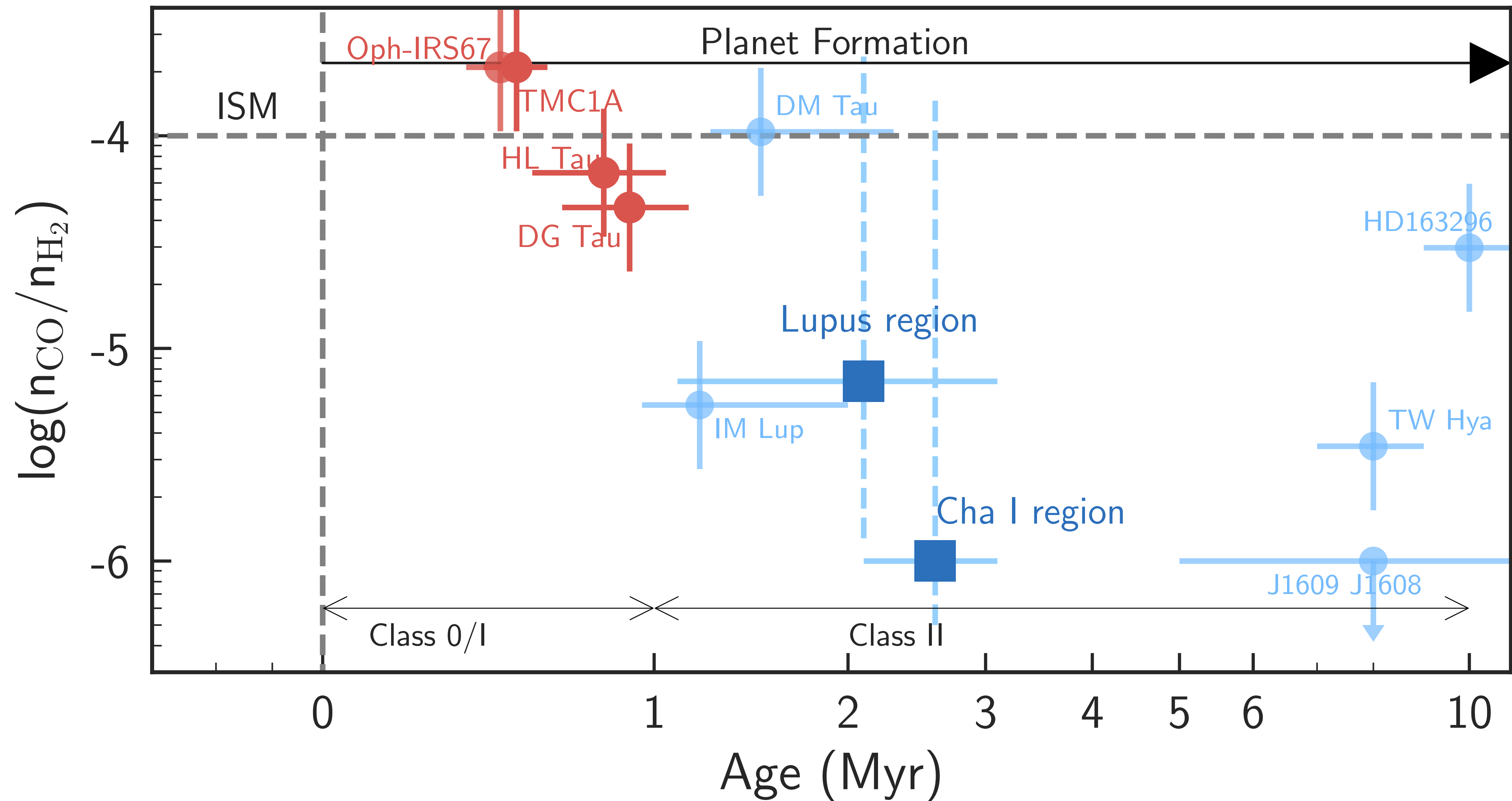
CO (need abundance conversion)

Bergin+2013, McClure+2016, Trapman+2017

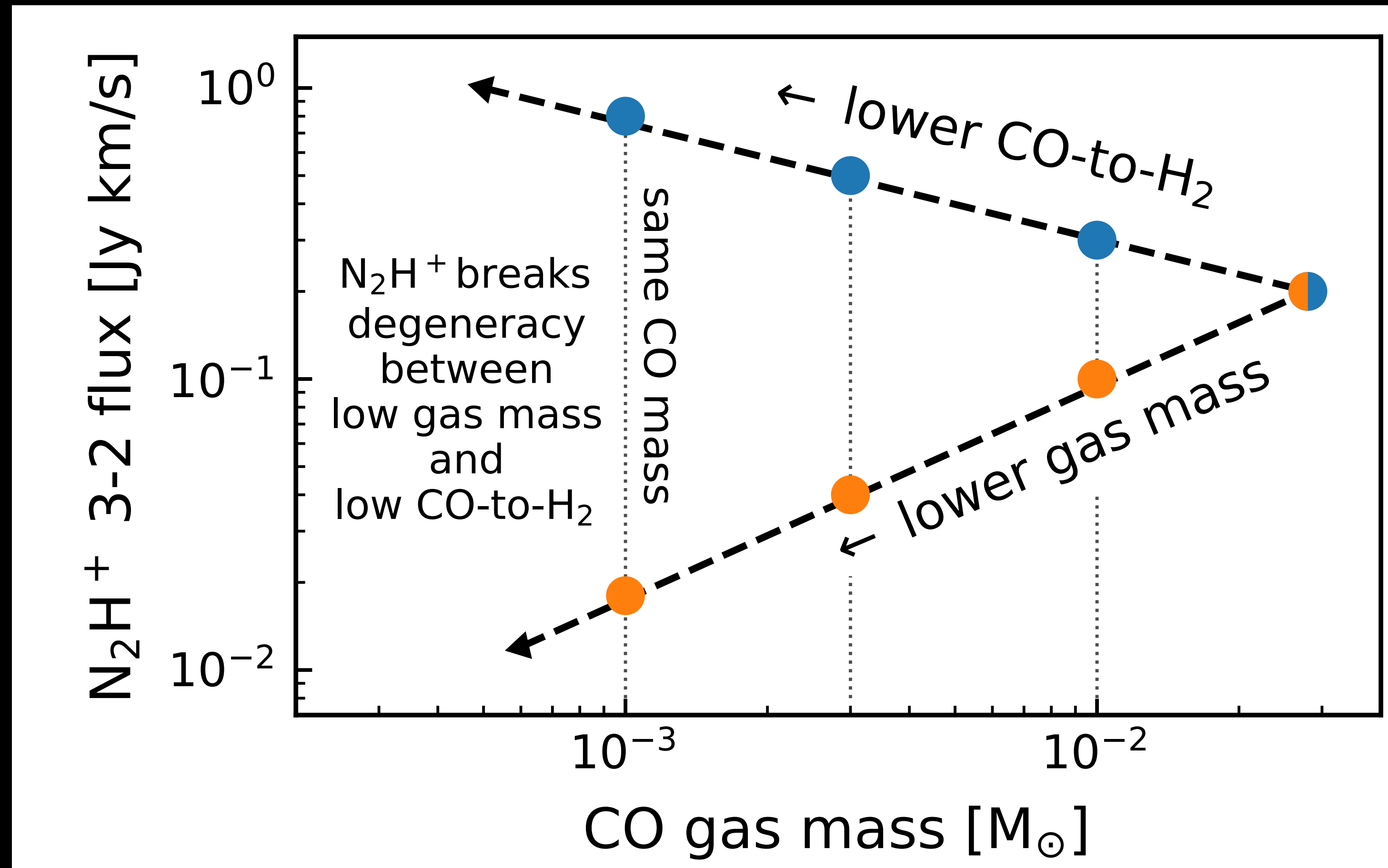
Ansdell+2016, Miotello+2017

Calahan+2021, Trapman+2022

bulk CO-to-H₂ abundance appears to decrease on a timescale of ~ 1 Myr



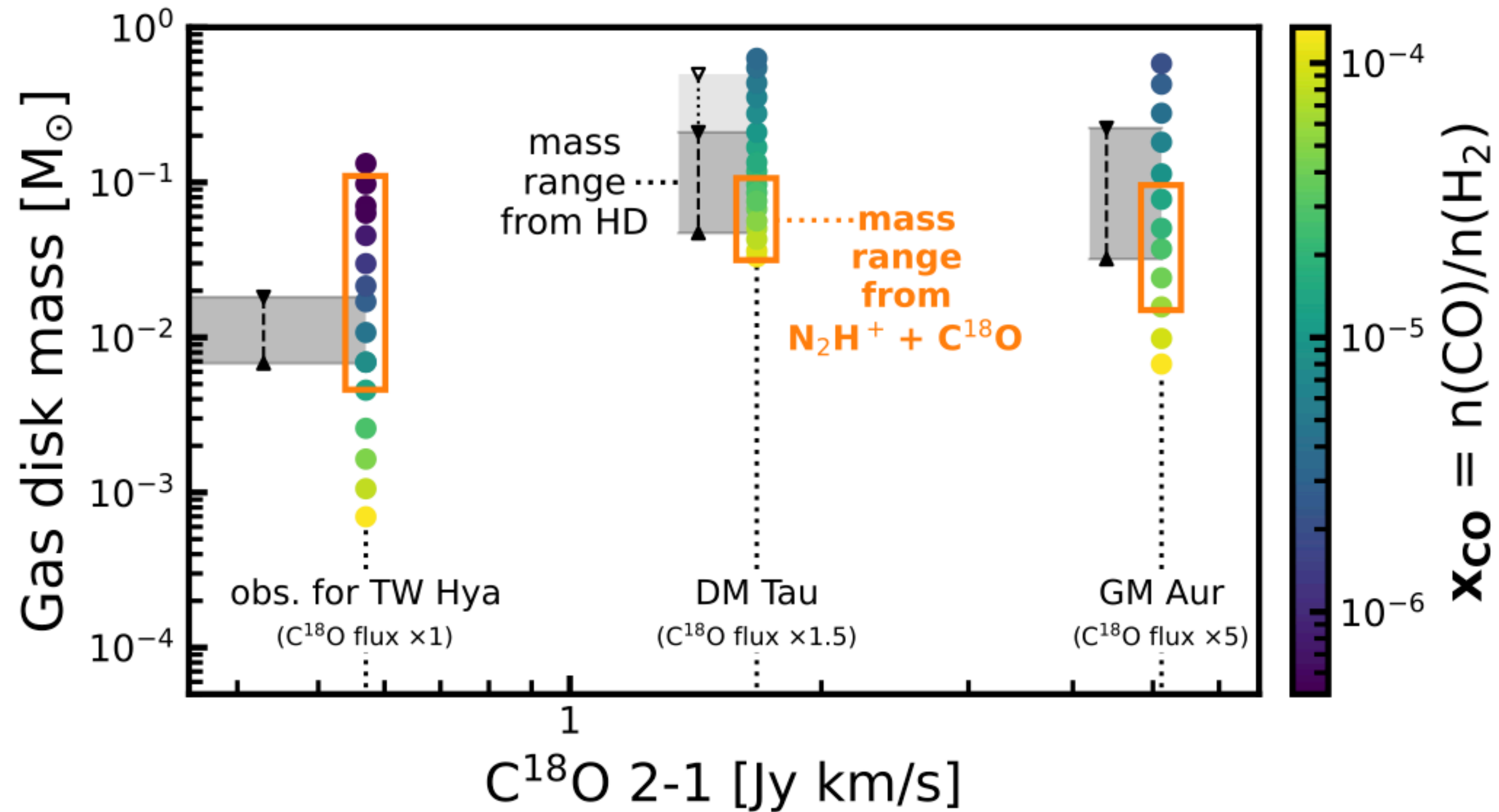
A new method to measure gas disk mass



Trapman, Zhang et al. 2022

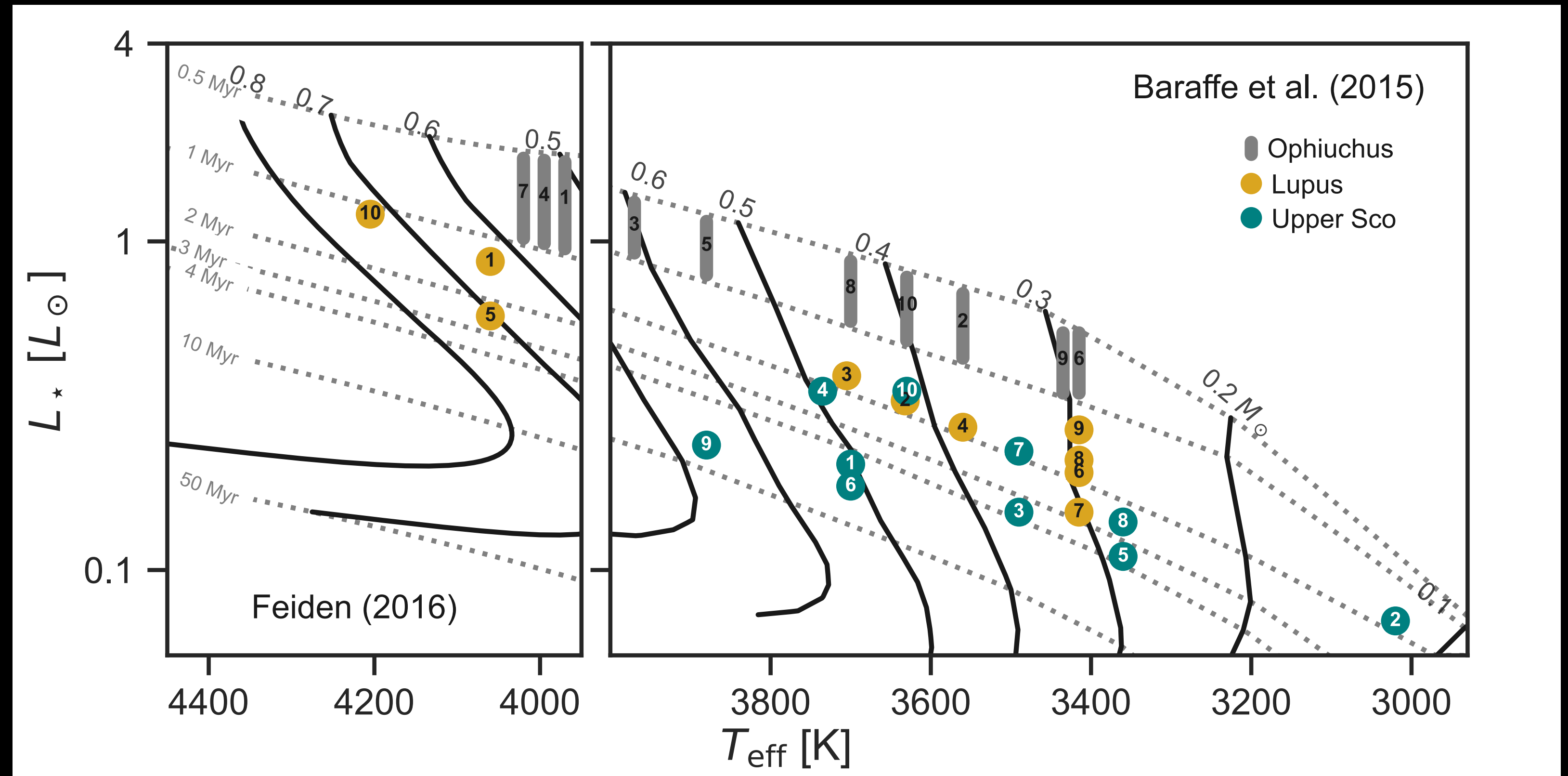
See also: Anderson et al. 2019, 2022

Successful benchmark test in three disks with HD detections



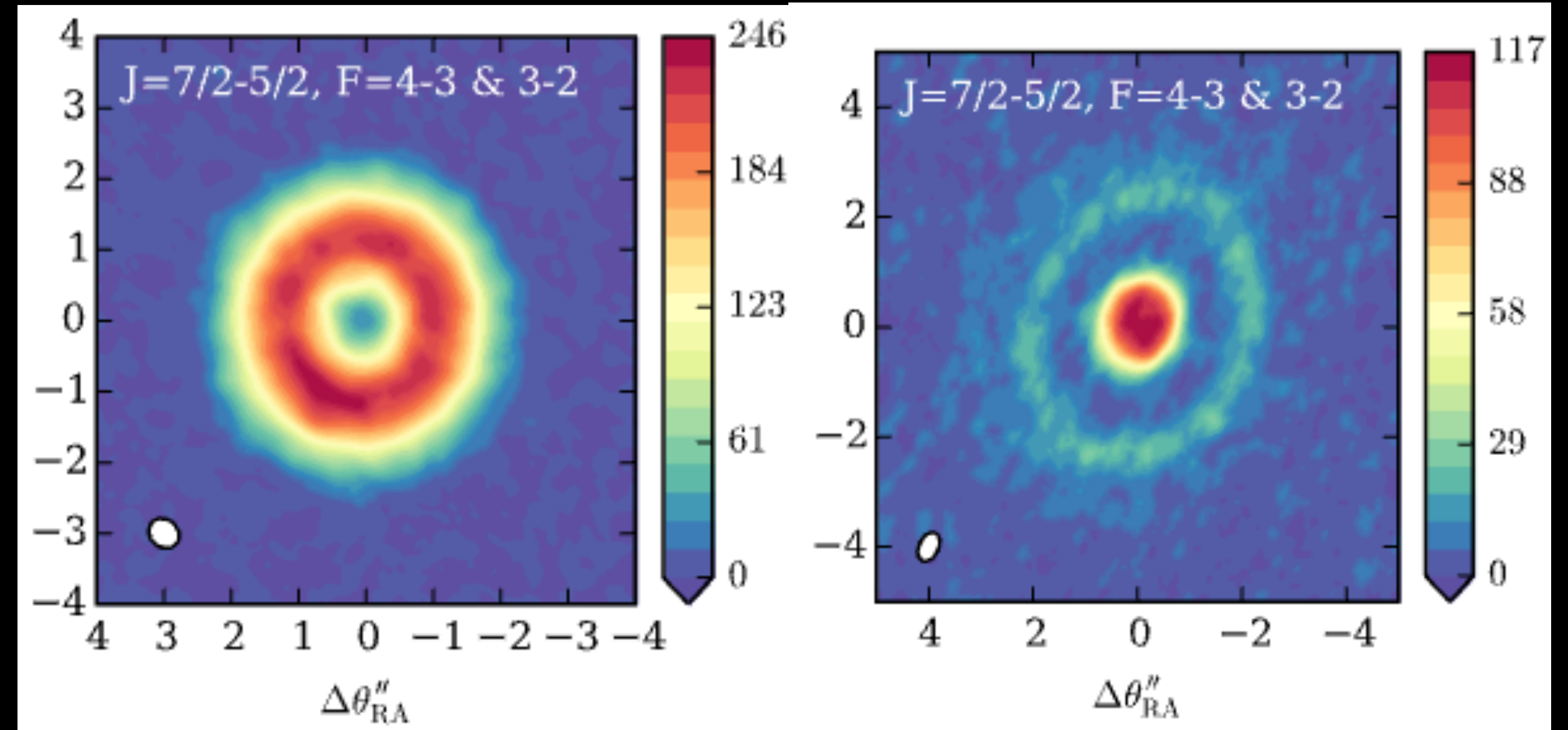
The ALMA Survey of Gas Evolution in Protoplanetary disks

- AGE-PRO (PI. Zhang)
- Survey of 30 disks at different ages



C/O ratio

- Strong hydrocarbon emission
 - C_2H , $c-C_3H_2$
- Suggest gas-phase $C/O > 1$

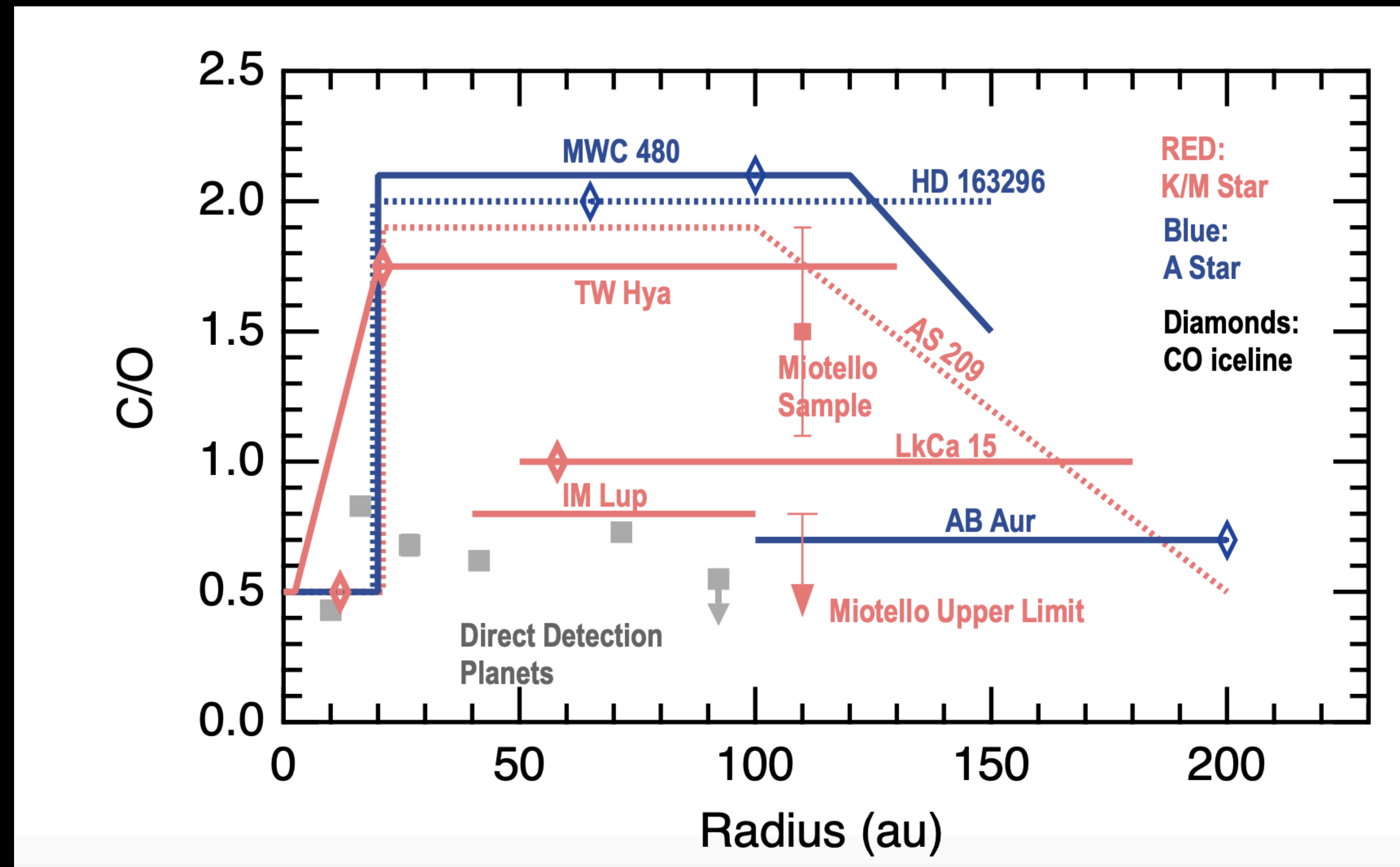


- DECO survey of 80 disks (PI. Cleeves)

e.g., Bergin+2016, Miotello+2019

Bosman+ 2021, LeGal+ 2021, Calahan+2022

Super solar C/O ratio often seen in outer disk region (>50au)



Bergin et al. 2024

Complex Organic Molecules

- $c\text{-C}_3\text{H}_2$, CH_3CN , and HC_3N are commonly detected in deep chemical surveys
[Oberg+2015](#), [Bergin+2016](#), [Loomis+2018](#), [Bergner+2018](#), [Lee+2021](#)
- Larger O-containing organics are harder
 - CH_3OH [Walsh+2016](#), [Booth+2021](#)
- The detected COMs are generally concentrated in the inner 50au
e.g., [Lee+ 2021](#)

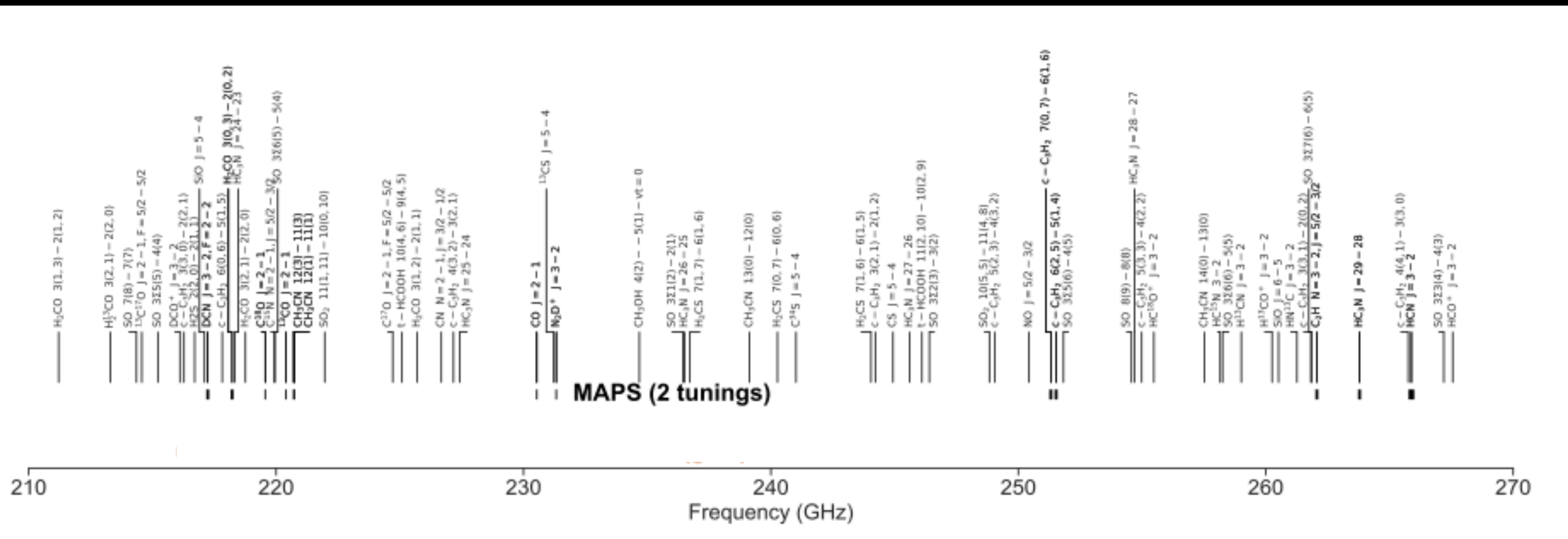
ALMA large programs of protoplanetary disk chemistry

- Cycle 6: MAPS (Molecules with ALMA at Planet-forming Scales, PI. Oberg)
- Cycle 8: AGE-PRO (the ALMA survey of Gas Evolution in PROtoplanetary disks, PI. Zhang)
- Cycle 9: DECO (The ALMA Disk-Exoplanet C/Onnection, PI. Cleeves)
- Cycle 11:
 - A Survey of Planet-Forming Chemistry in the Precursor Environments of Giant Planets (PI. Pegues)
 - DiskStrat: The first comprehensive picture of chemical vertical structures in protoplanetary disks (PI. Le Gal)

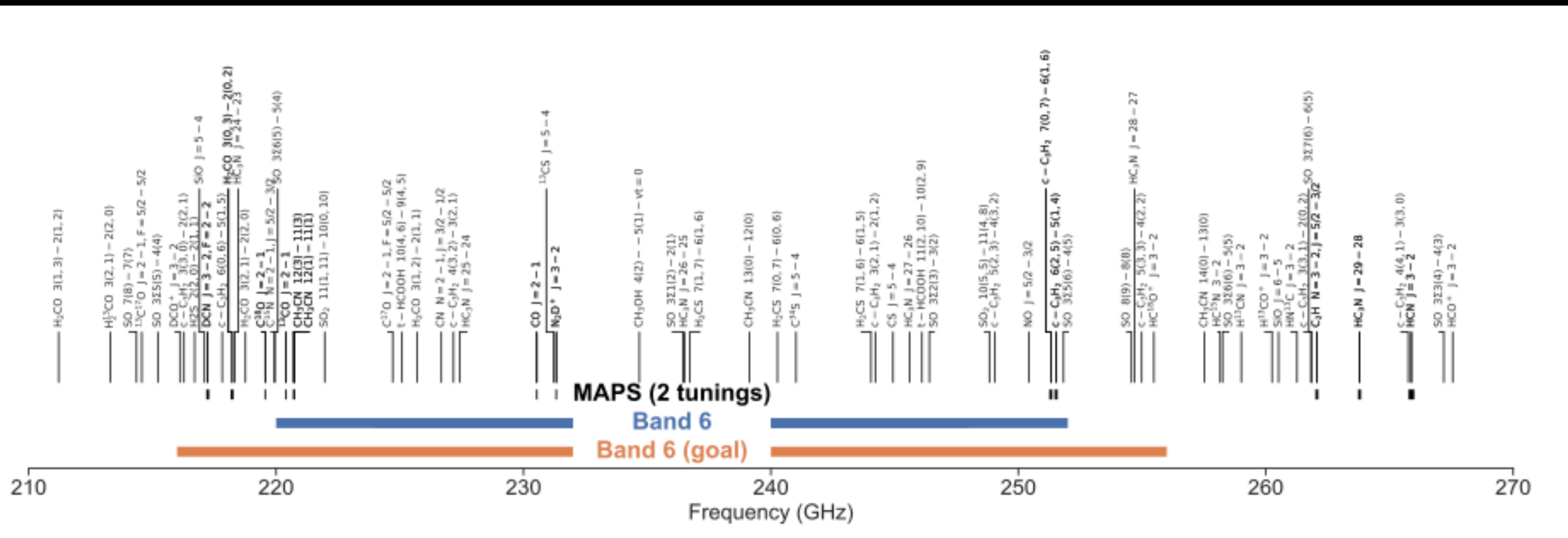
Challenges in current chemical studies

- Observational challenges
 - Limited understanding of the physical structures (mass, temperature)
 - Key abundance tracers are optically thin lines
 - Limited coverage of multiple species and line transitions
 - The majority of disks are compact (<150 au)

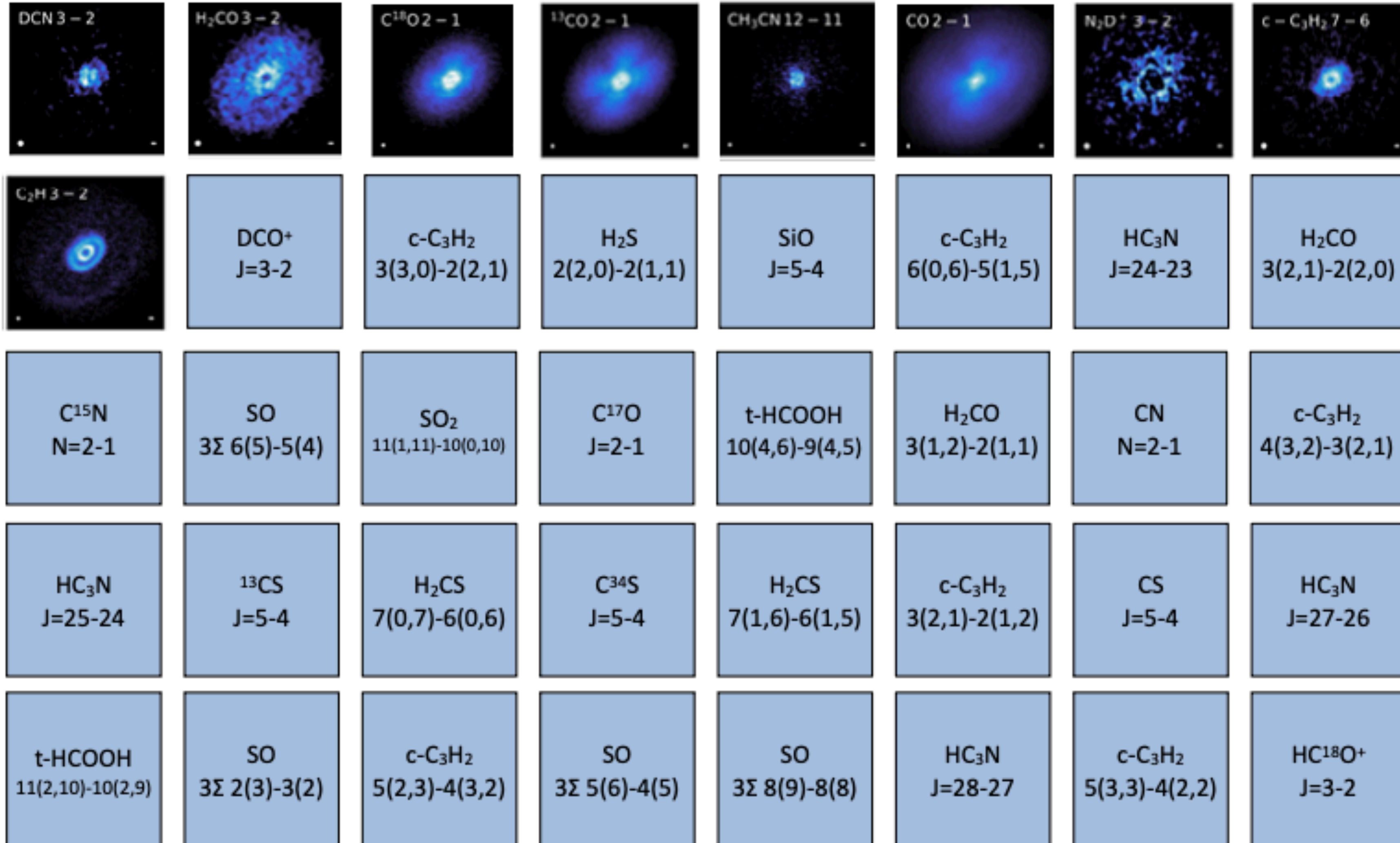
Wideband Sensitivity Upgrade



Wideband Sensitivity Upgrade

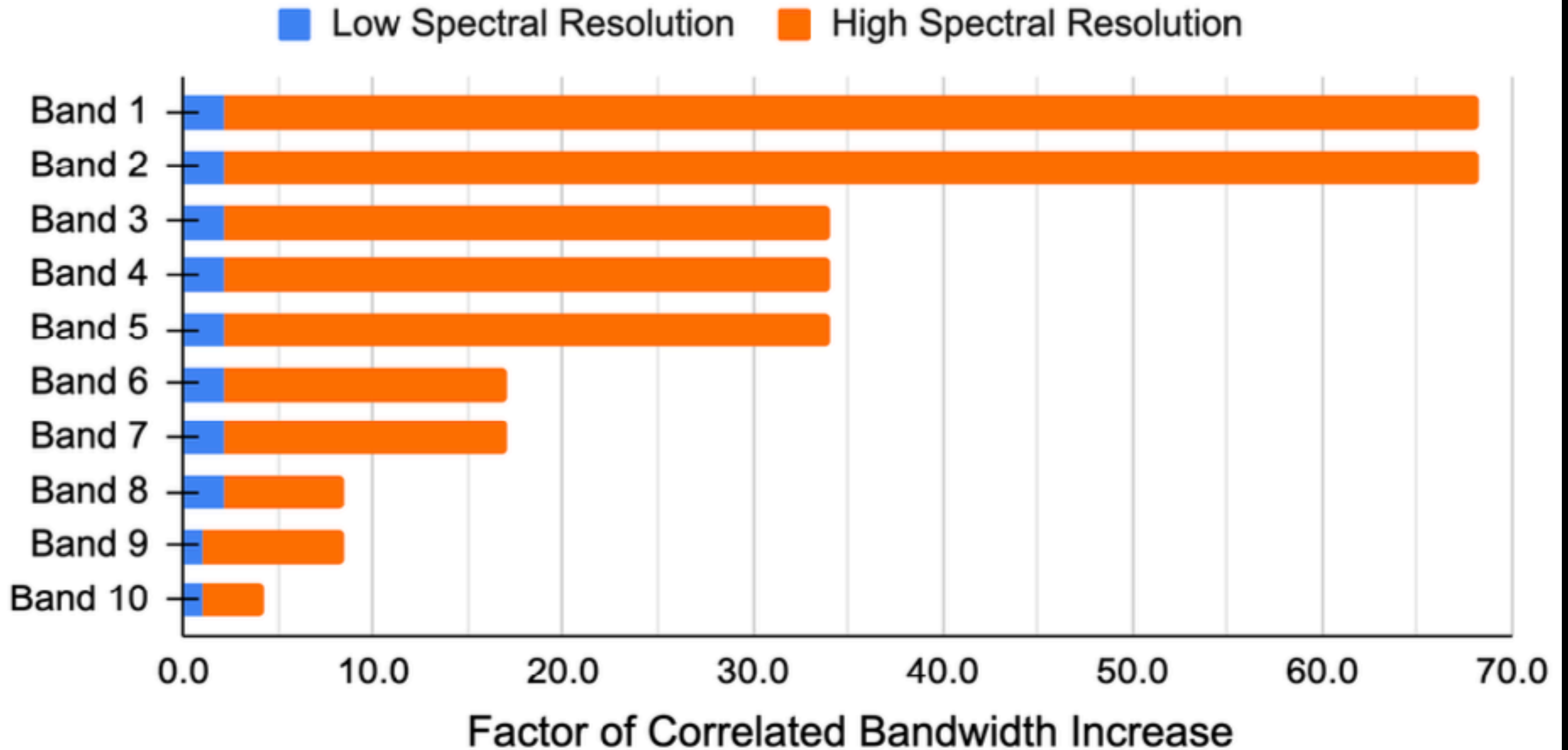


Carpenter+ 2022



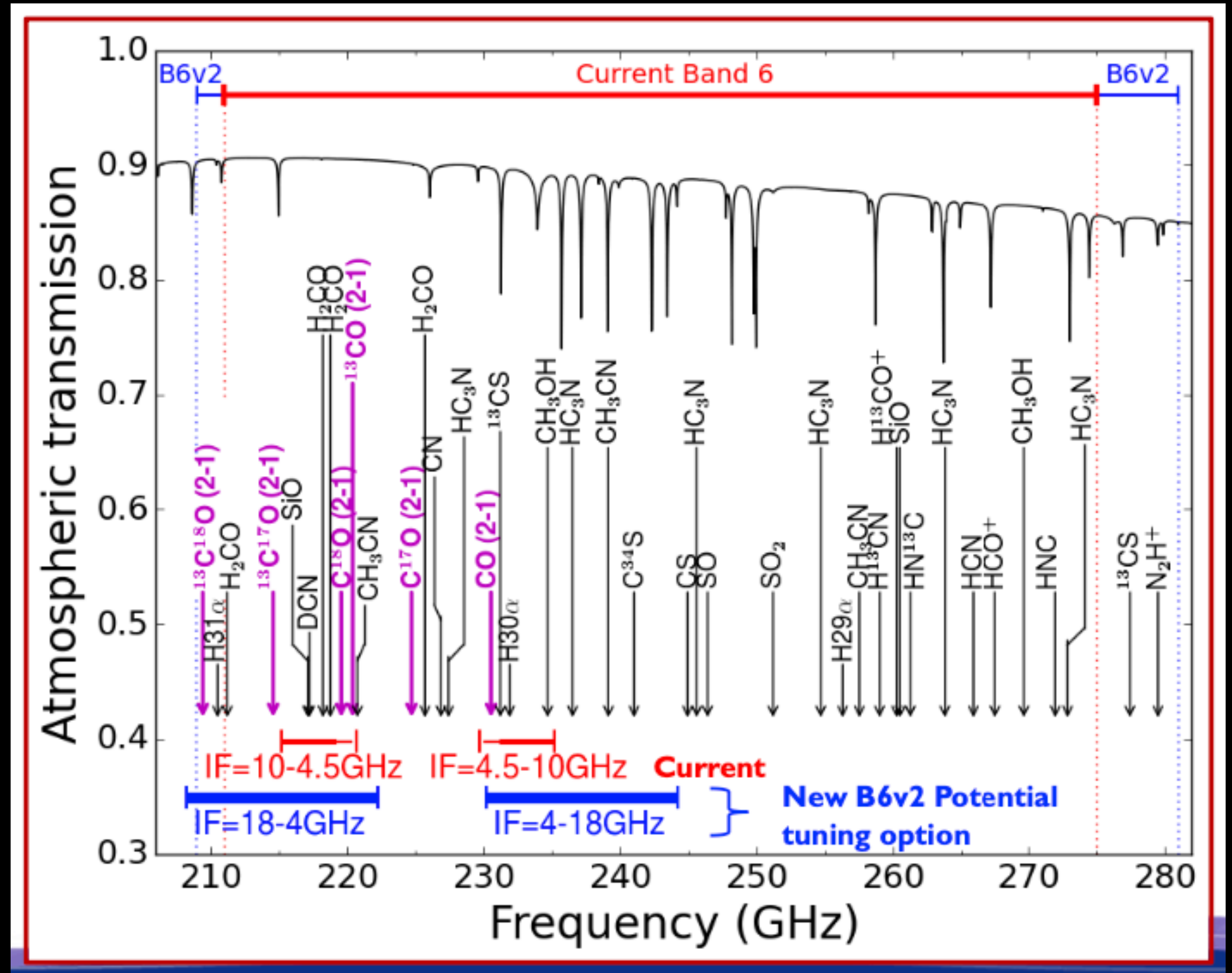
Carpenter+ 2022

Increase in Correlated Bandwidth



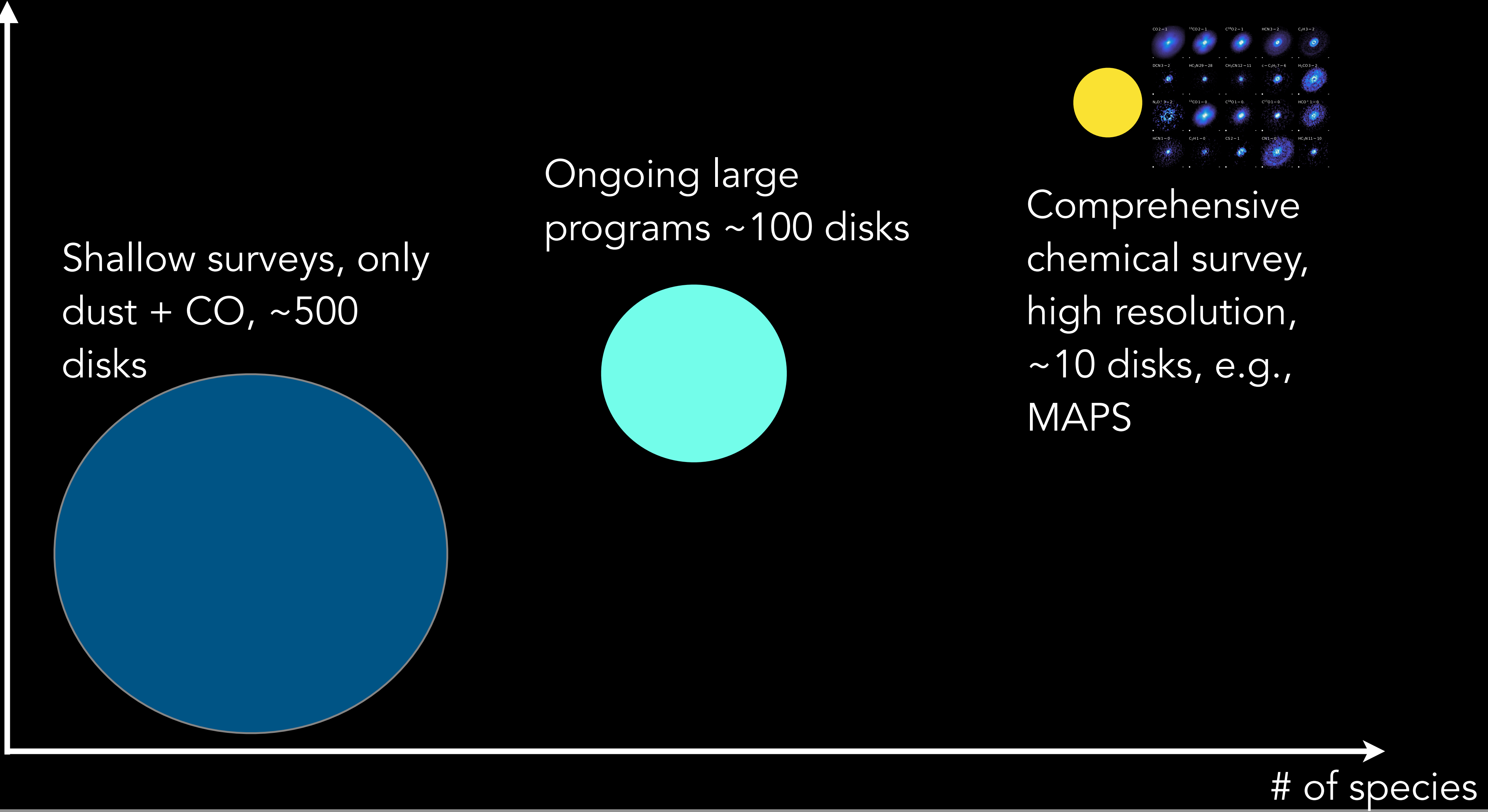
Expanded Band 6 wavelength coverage

- Simultaneous CO isotopologue coverages
 $^{12}\text{CO}/^{13}\text{CO}/\text{C}^{18}\text{O}/$
 $\text{C}^{17}\text{O}/^{13}\text{C}^{18}\text{O}/^{13}\text{C}^{17}\text{O}$
- B6 covers N_2H^+



Current ALMA chemical studies

Sensitivity



Shallow surveys, only dust + CO, ~500 disks

Ongoing large programs ~100 disks

Comprehensive chemical survey, high resolution, ~10 disks, e.g., MAPS

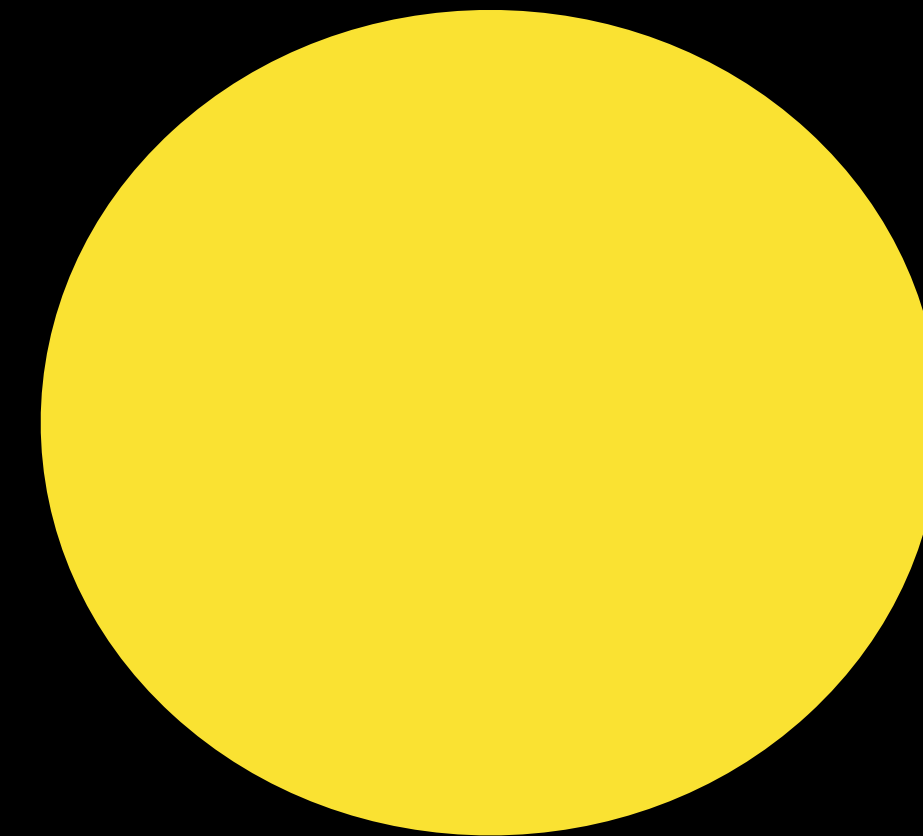
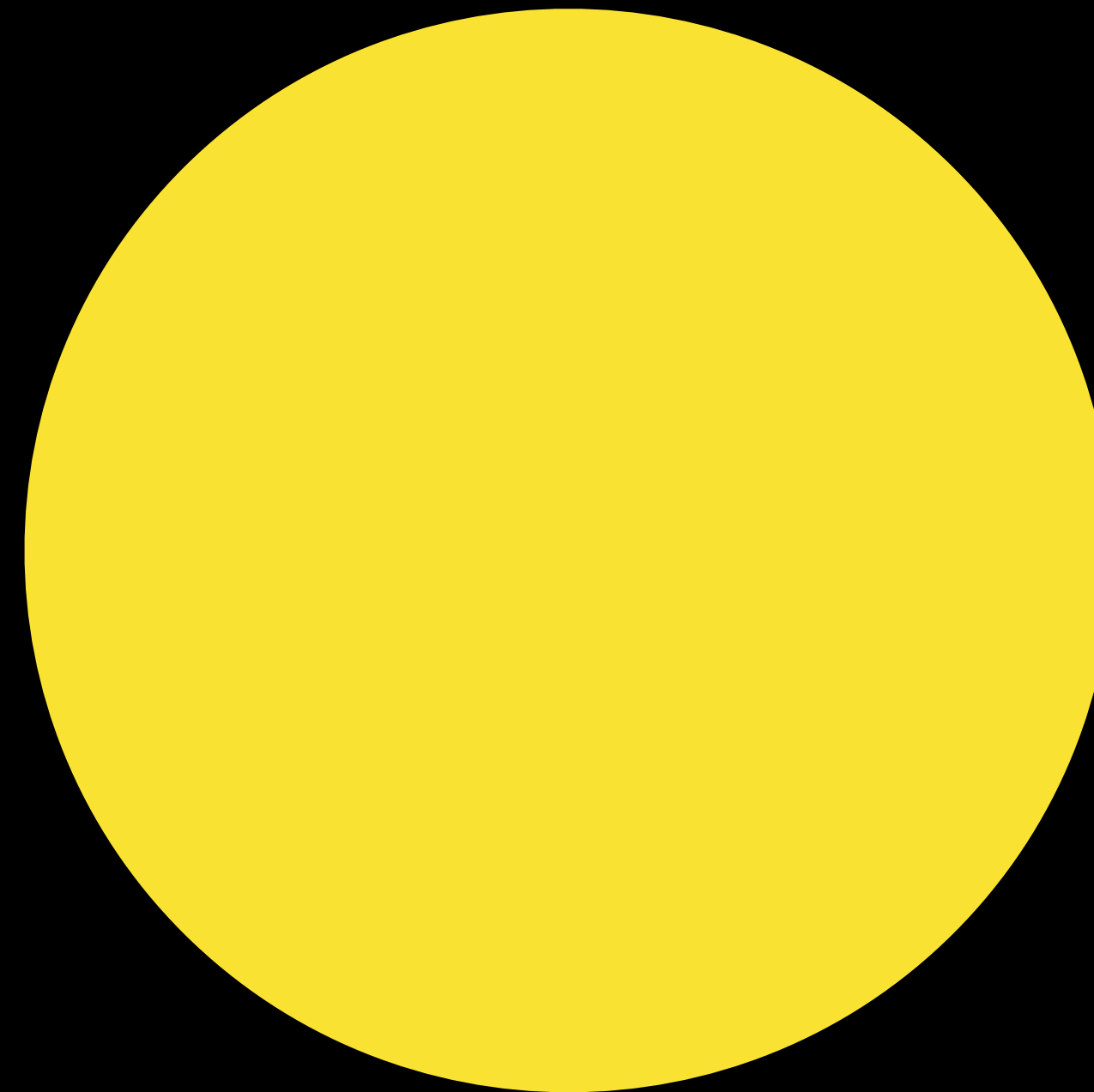
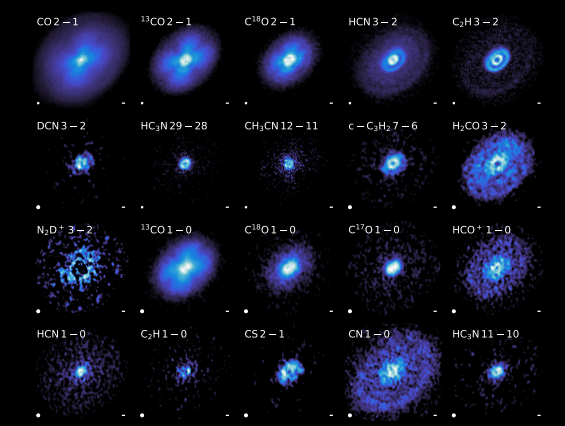
ALMA chemical studies with WSU

Survey depth



physical properties
and key chemical
tracers, for ~500
disks

Comprehensive
chemical survey,
for ~100 disks



of species



Revolution of chemical studies of protoplanetary disks

- Physical structures characterization for a few hundred disks
- Wide coverage of chemical species
- Search for COMs with spectral scan, line stacking