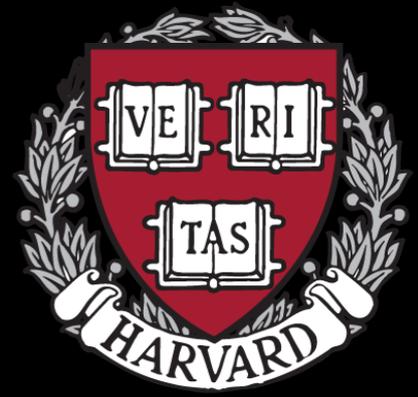
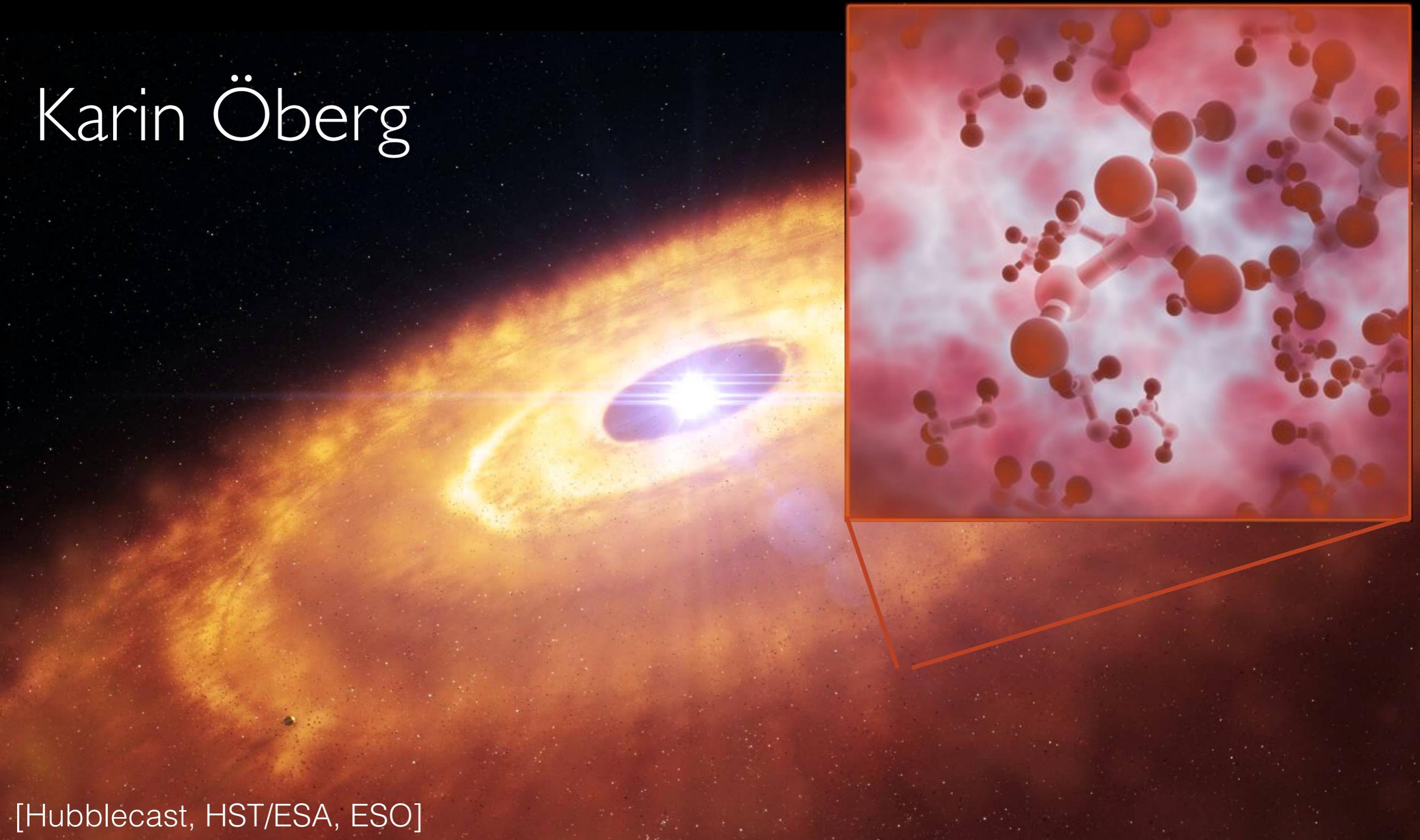


# Astrochemical Origins of Planets and Planetary Habitability



Karin Öberg



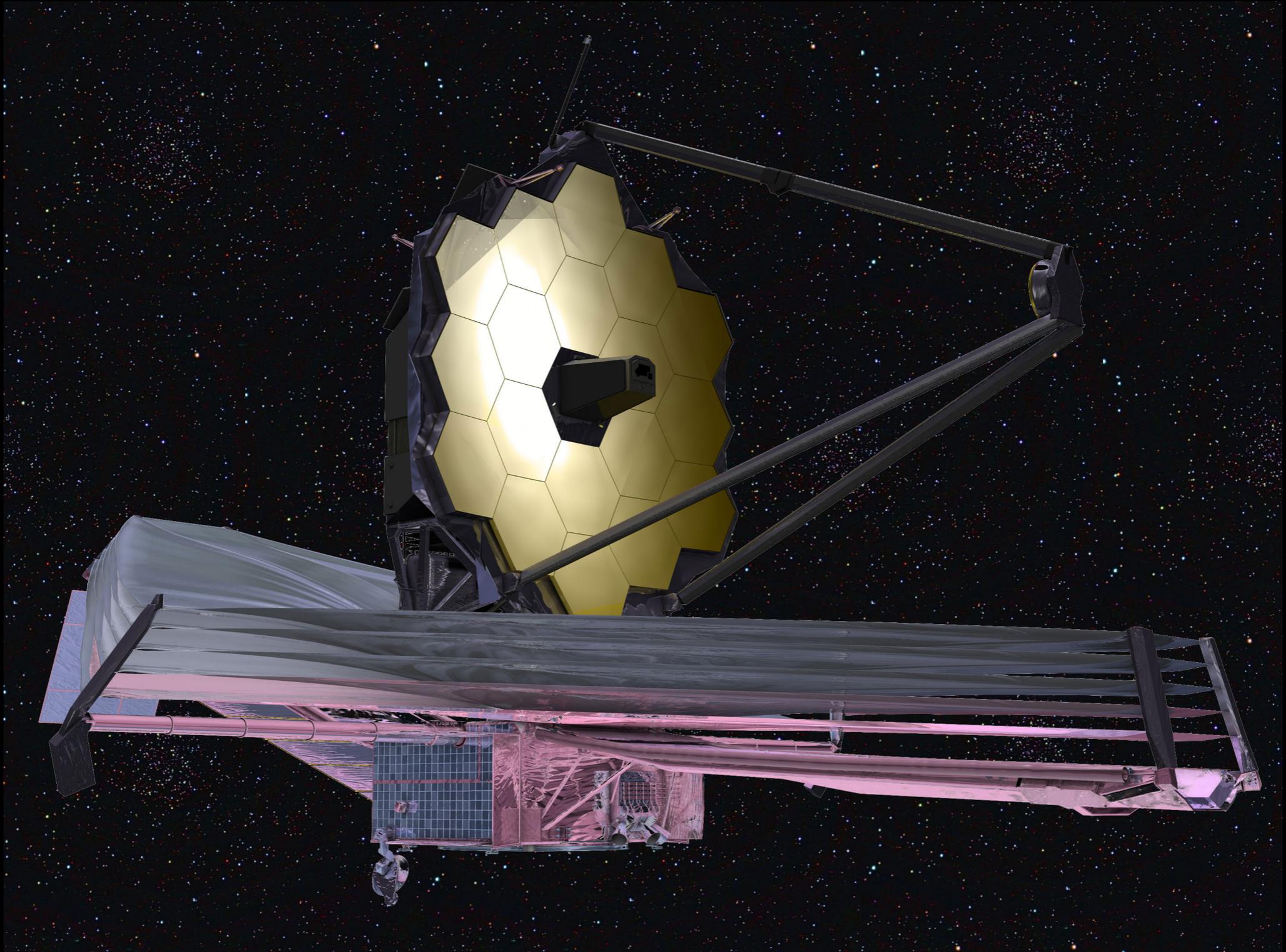
# Our origins



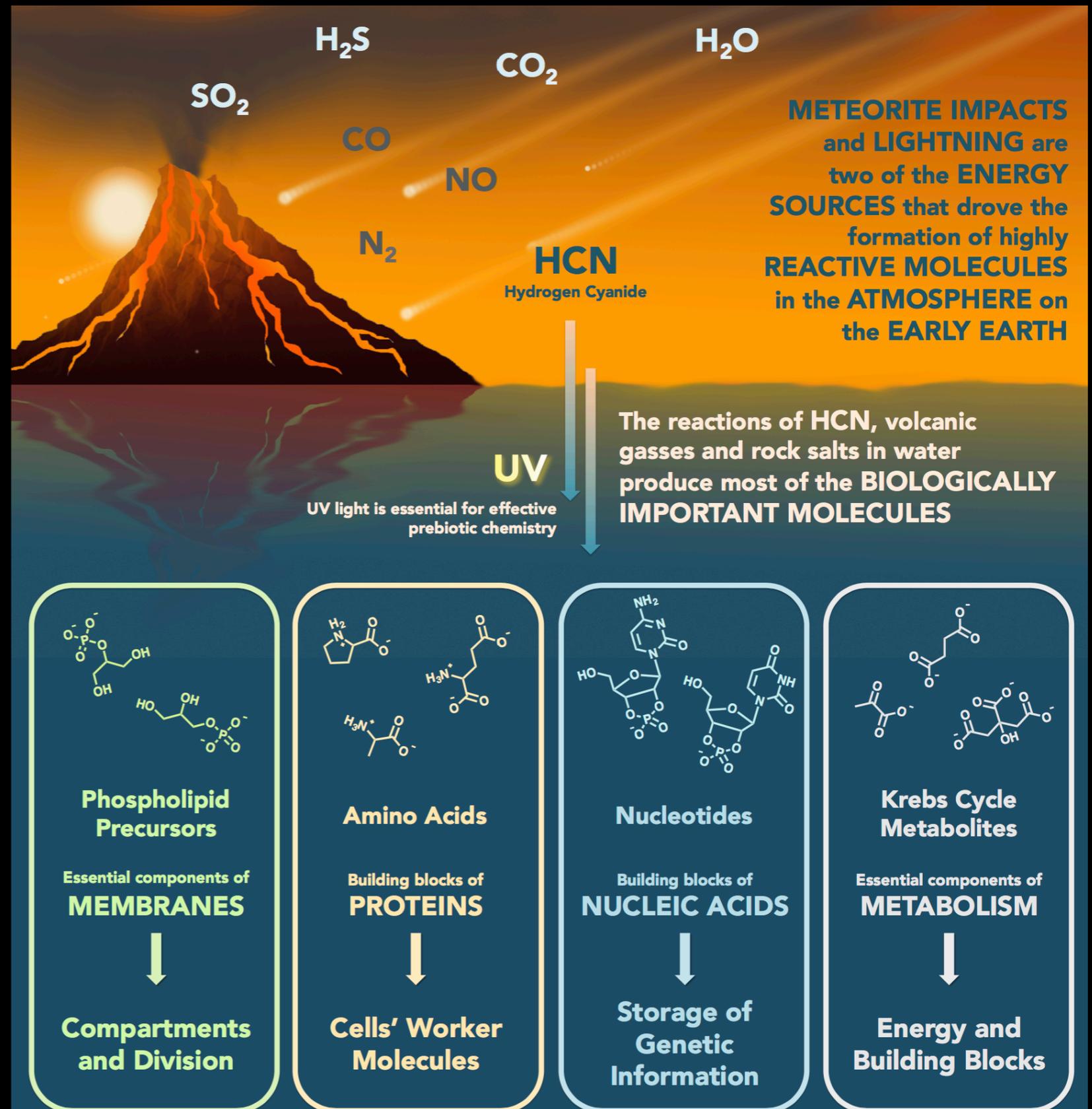
# Origins of Life Elsewhere?



# I. Characterizations of temperate and exotic exoplanets

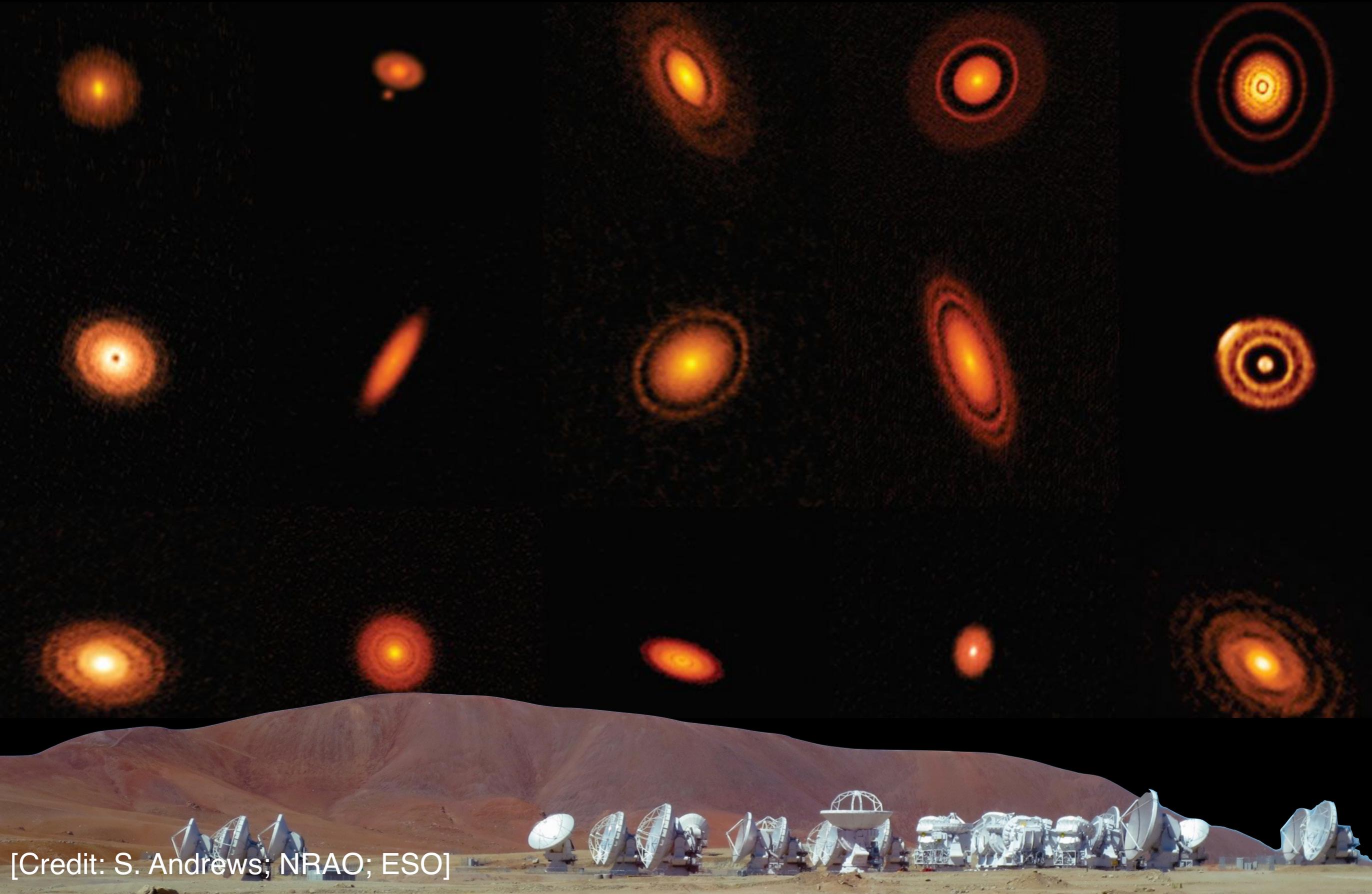


# II. Uncovering the Earth's prebiotic chemistry



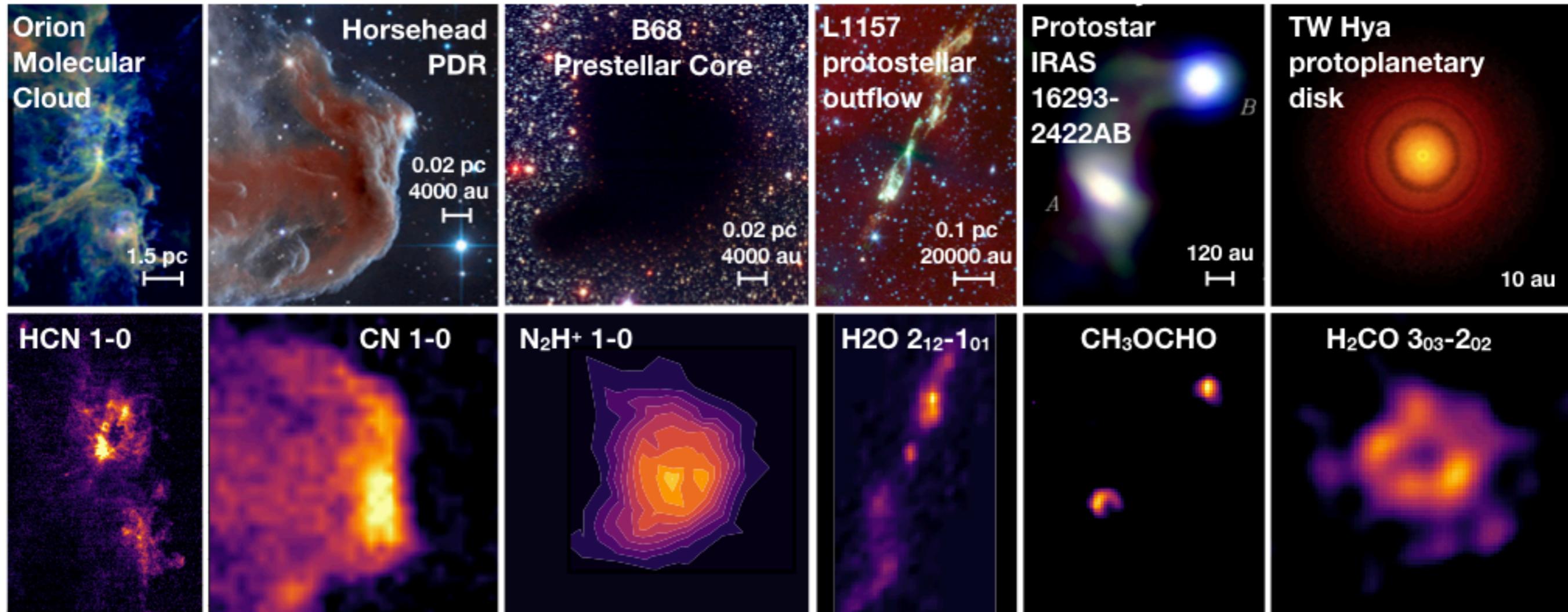
[Credit: Angelica Mariani, SCOL]

# III. Observing planets in the making



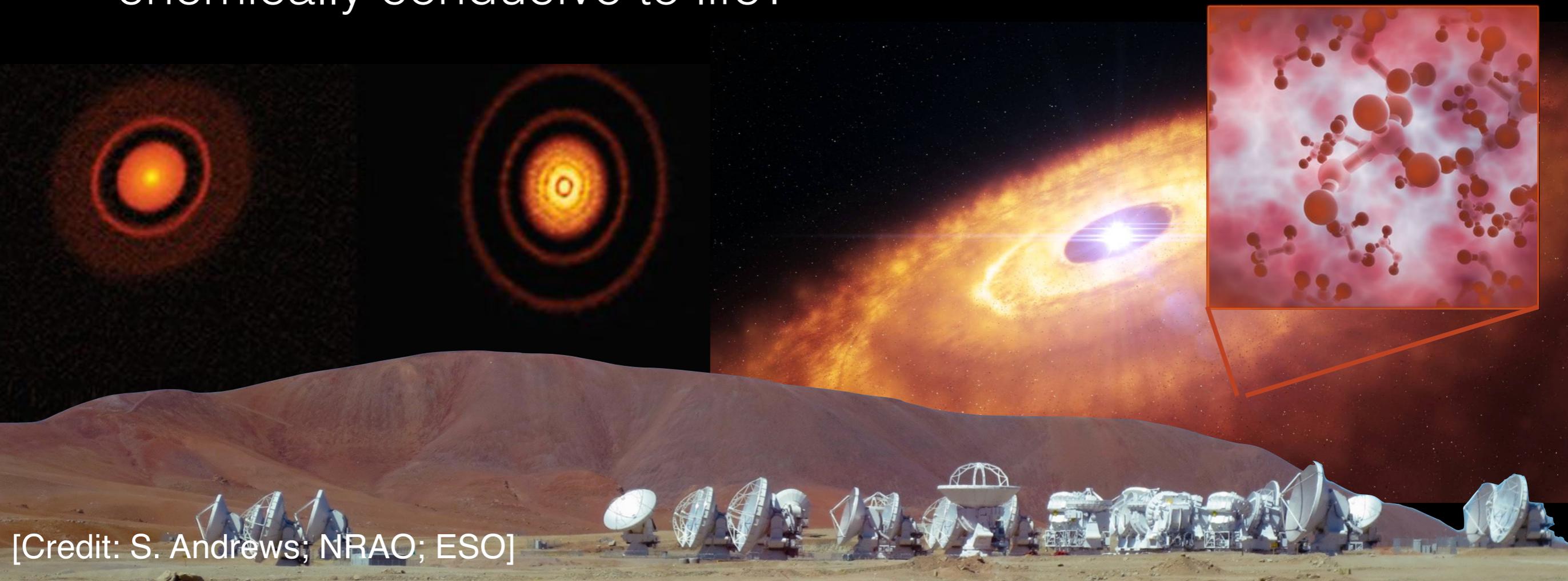
[Credit: S. Andrews; NRAO; ESO]

# Chemical structures during star and planet formation

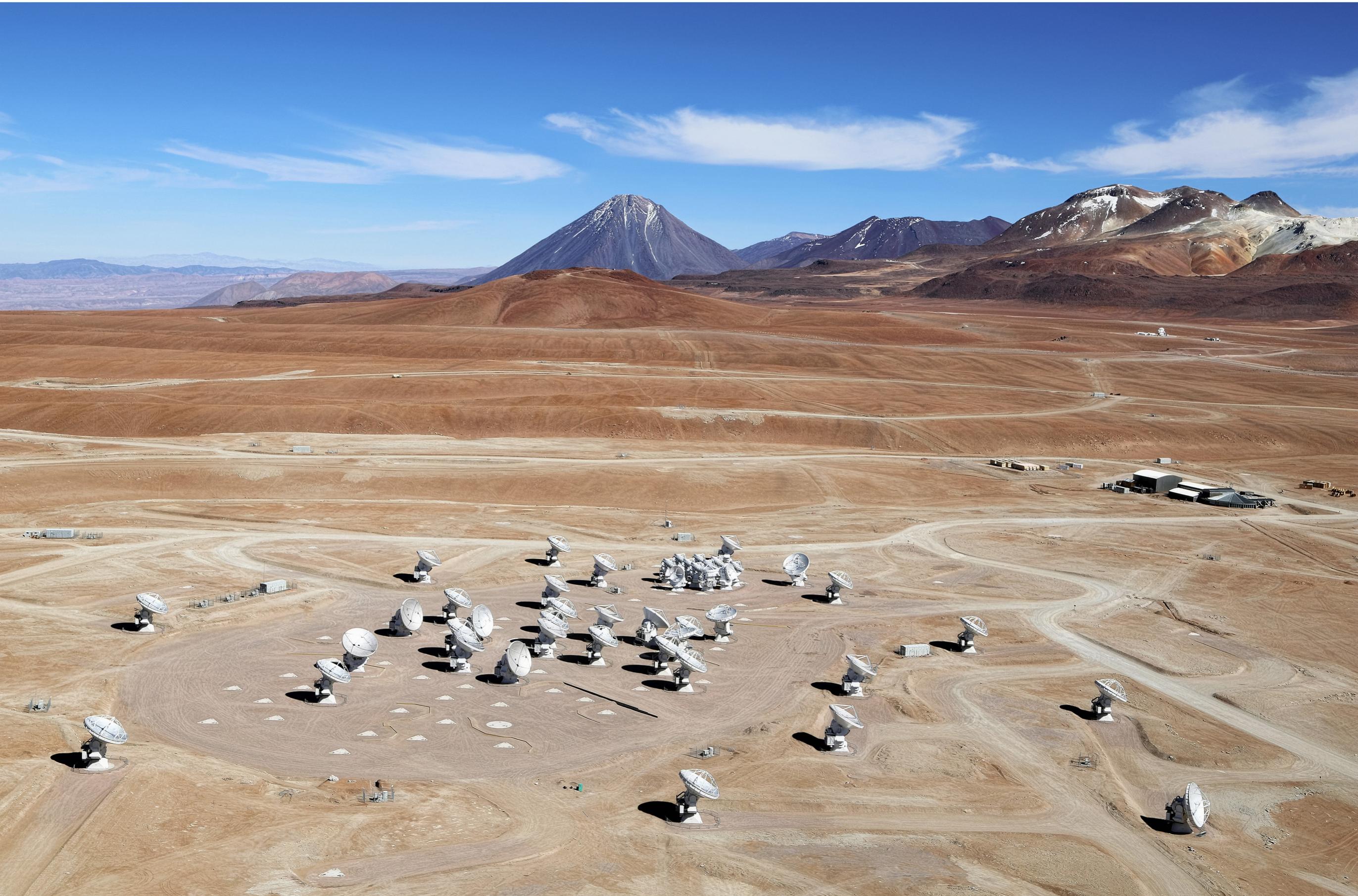


# Astrochemical Origins of Planets and Planetary Habitability

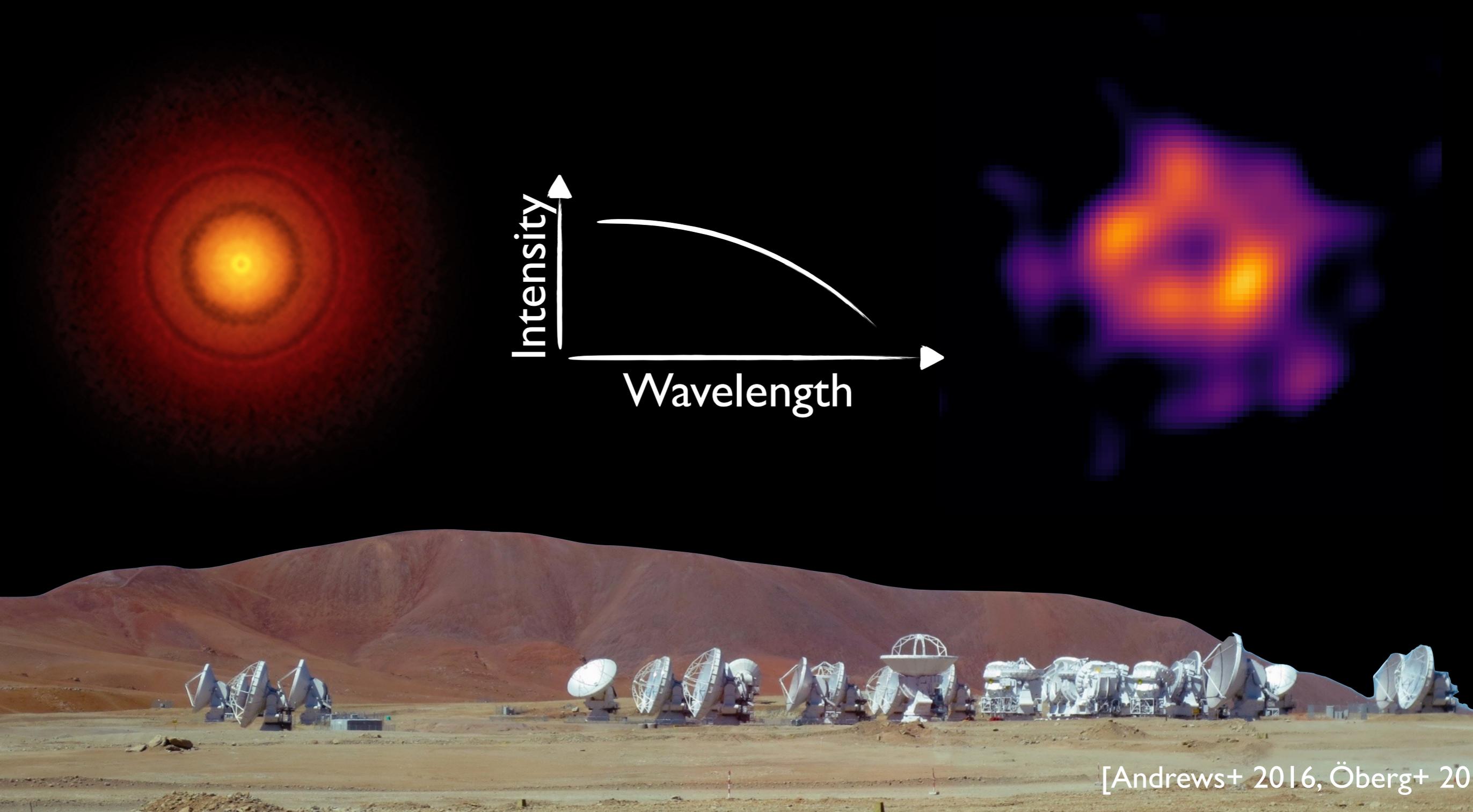
- I. Are there chemically preferred planet formation locations?
- II. How do planet bulk compositions depend on where they assemble?
- III. How often can we expect temperate planets to form chemically conducive to life?



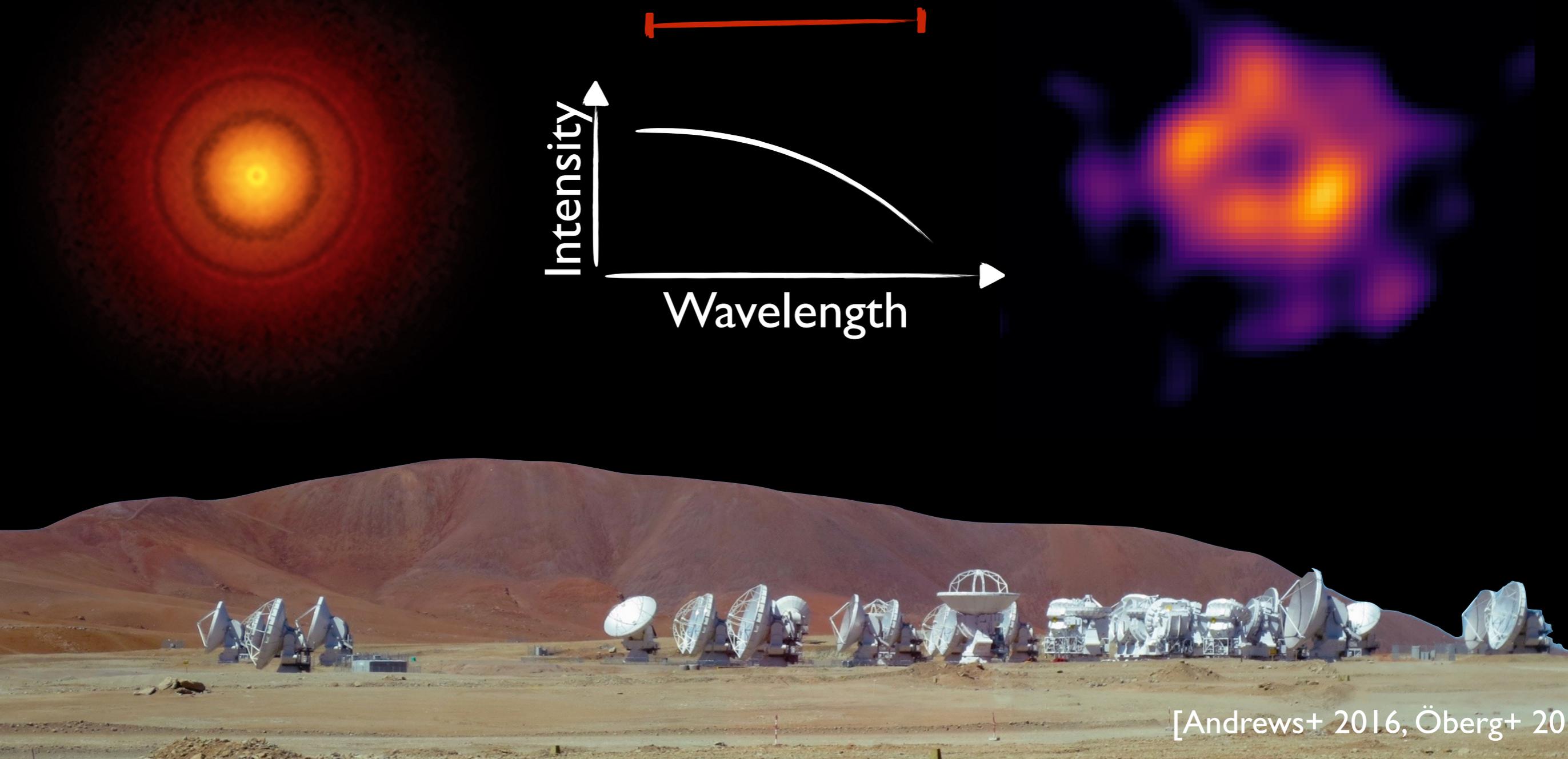
# ALMA



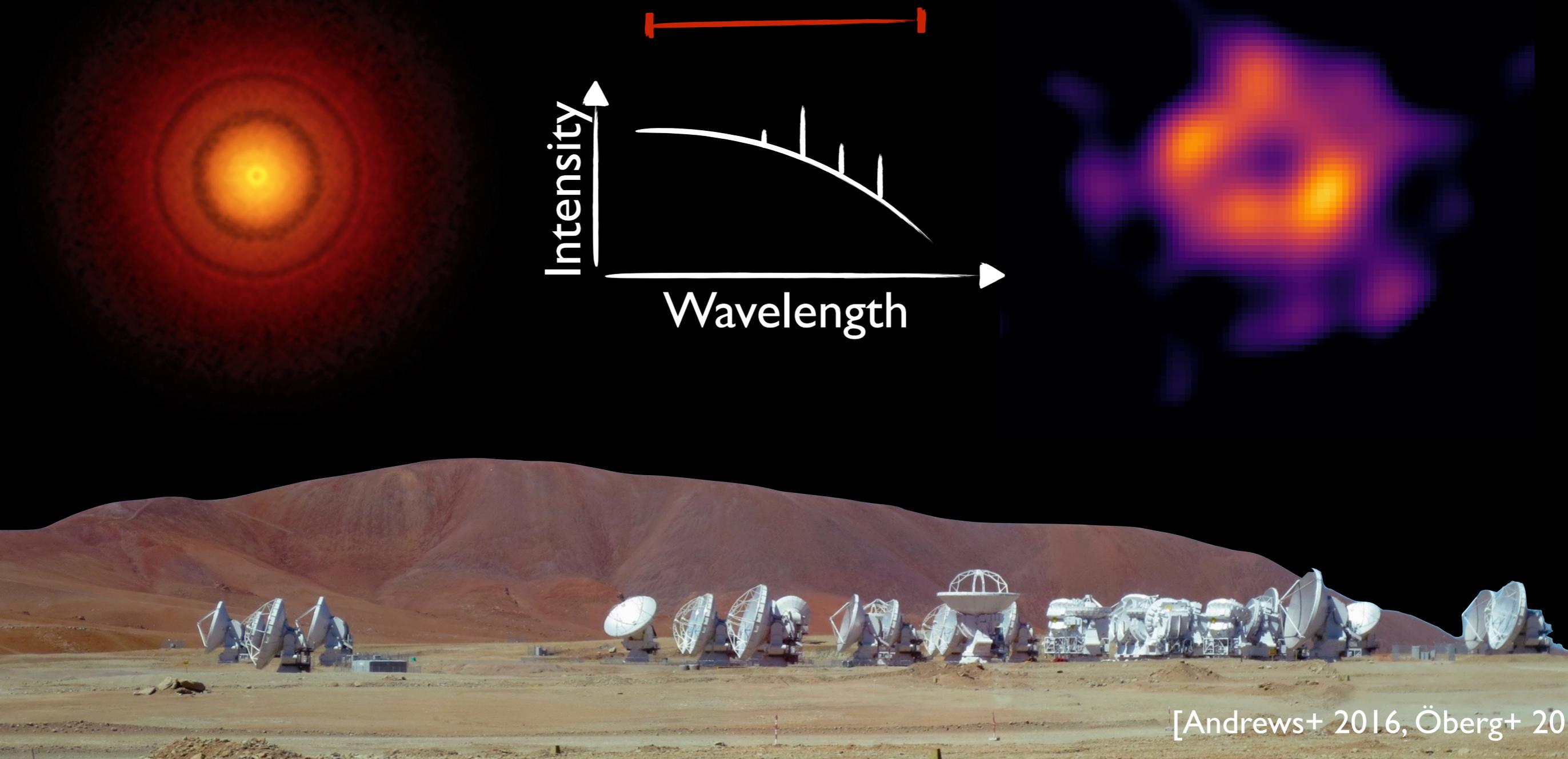
# Imaging of molecules in planet forming disks



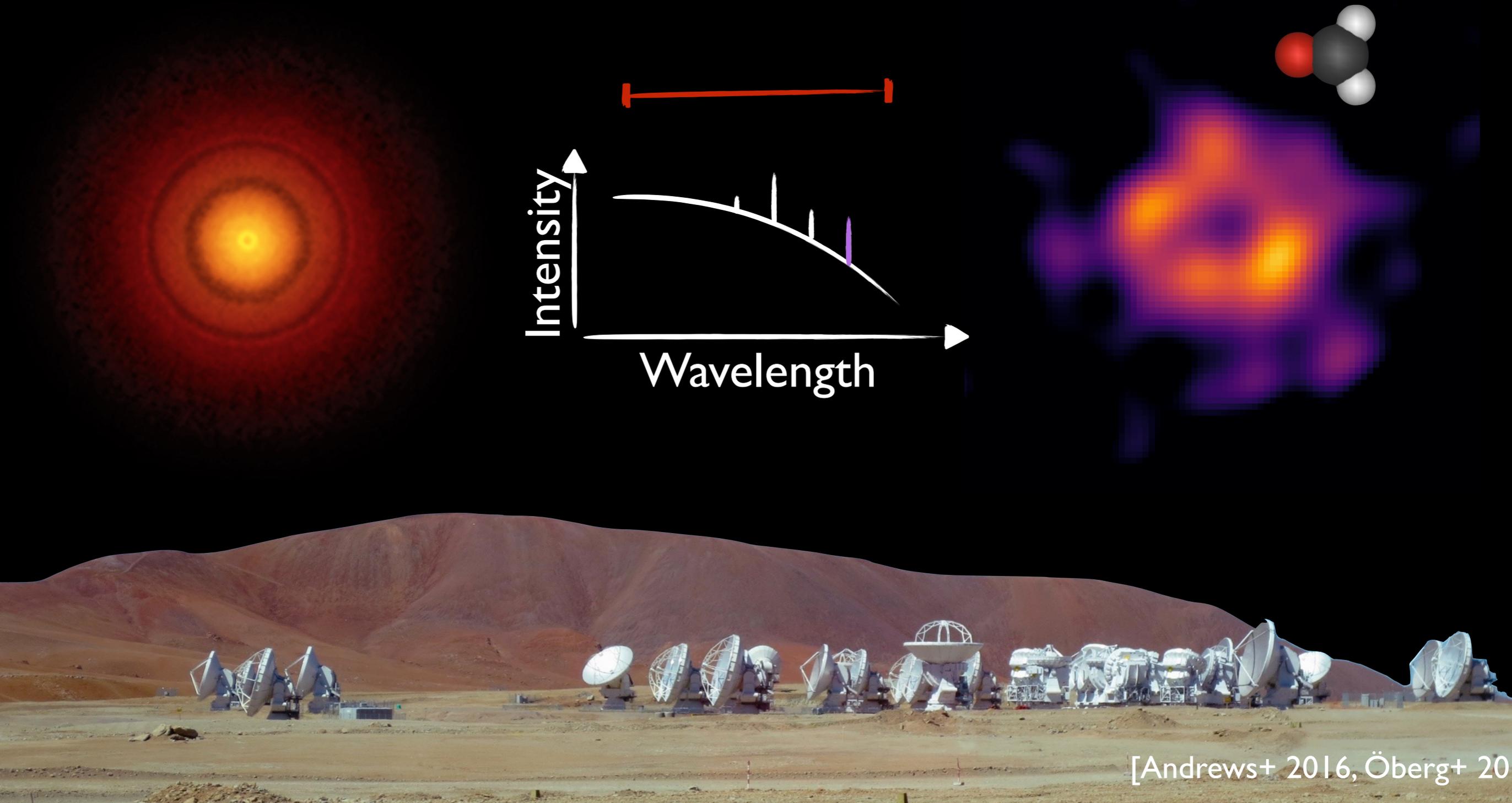
# Imaging of molecules in planet forming disks



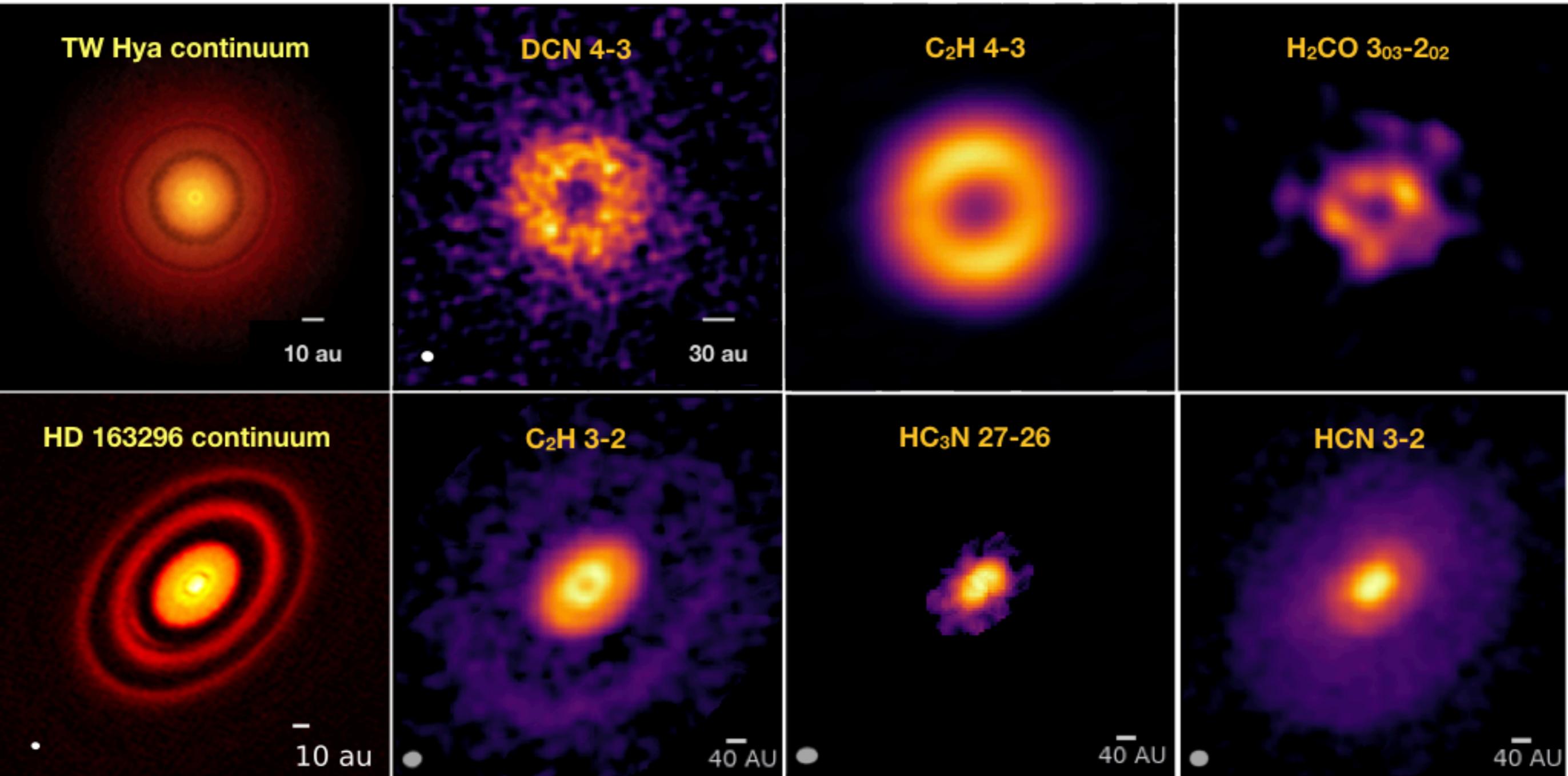
# Imaging of molecules in planet forming disks



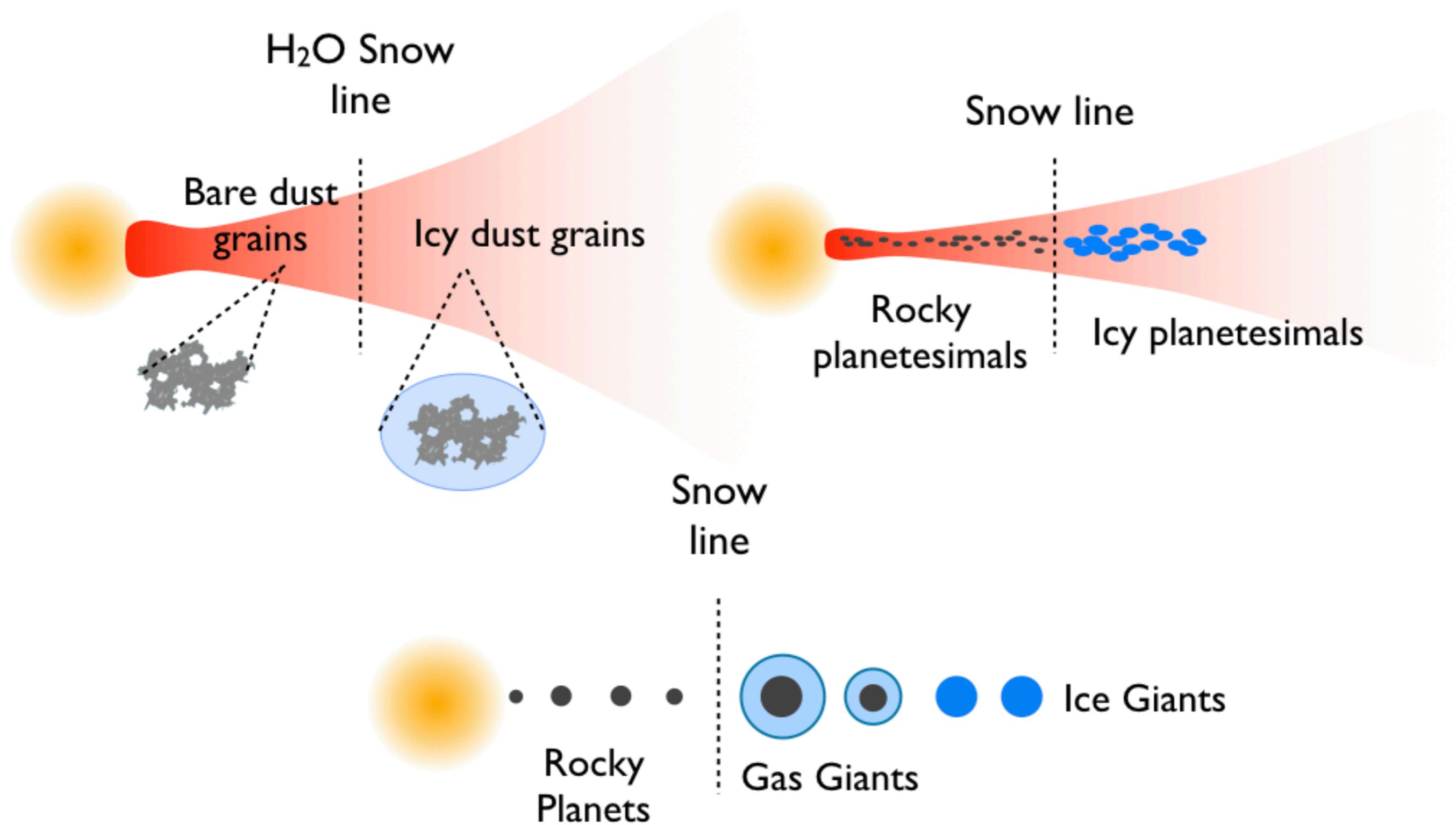
# Imaging of molecules in planet forming disks



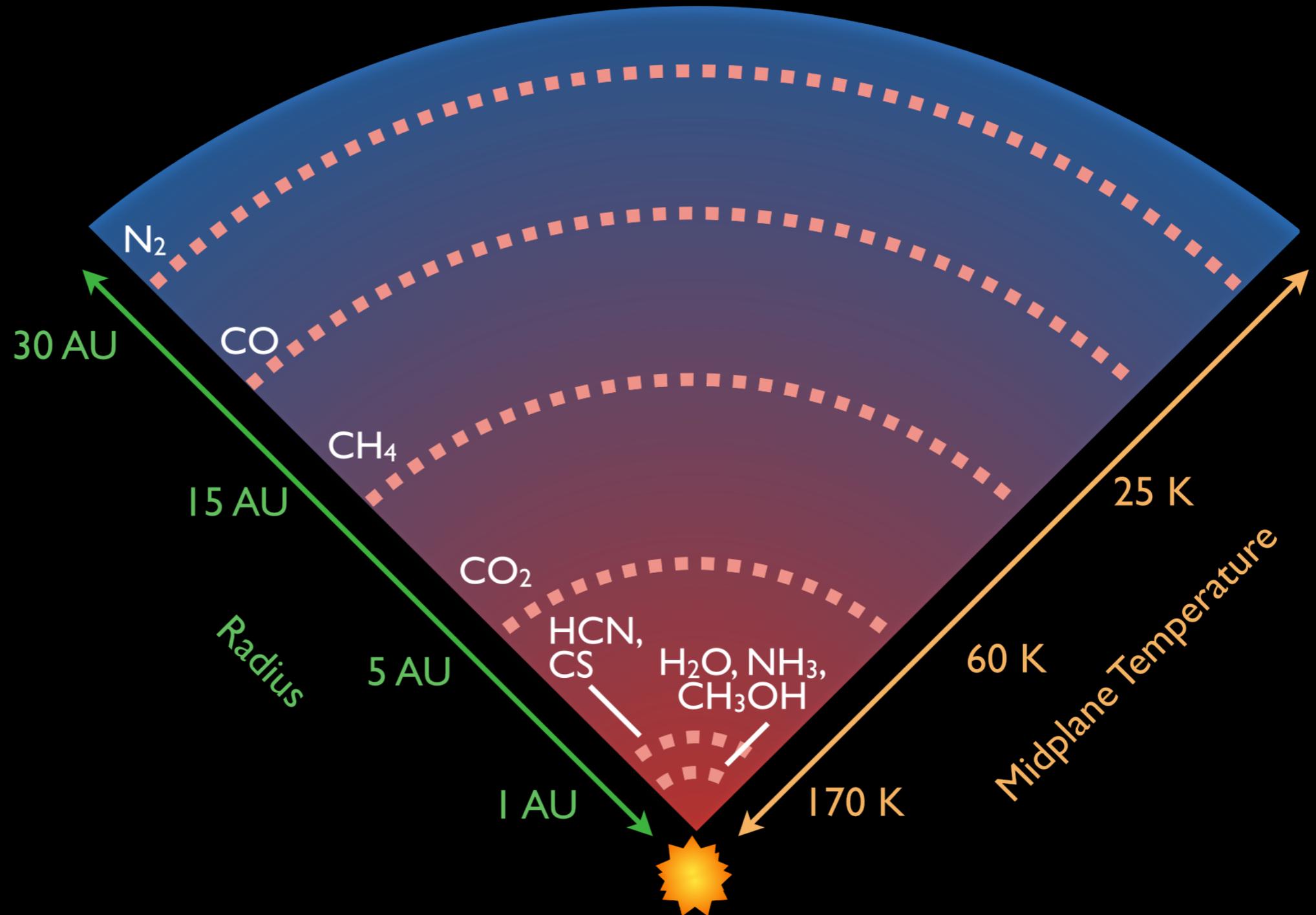
# ALMA images of disk chemistry



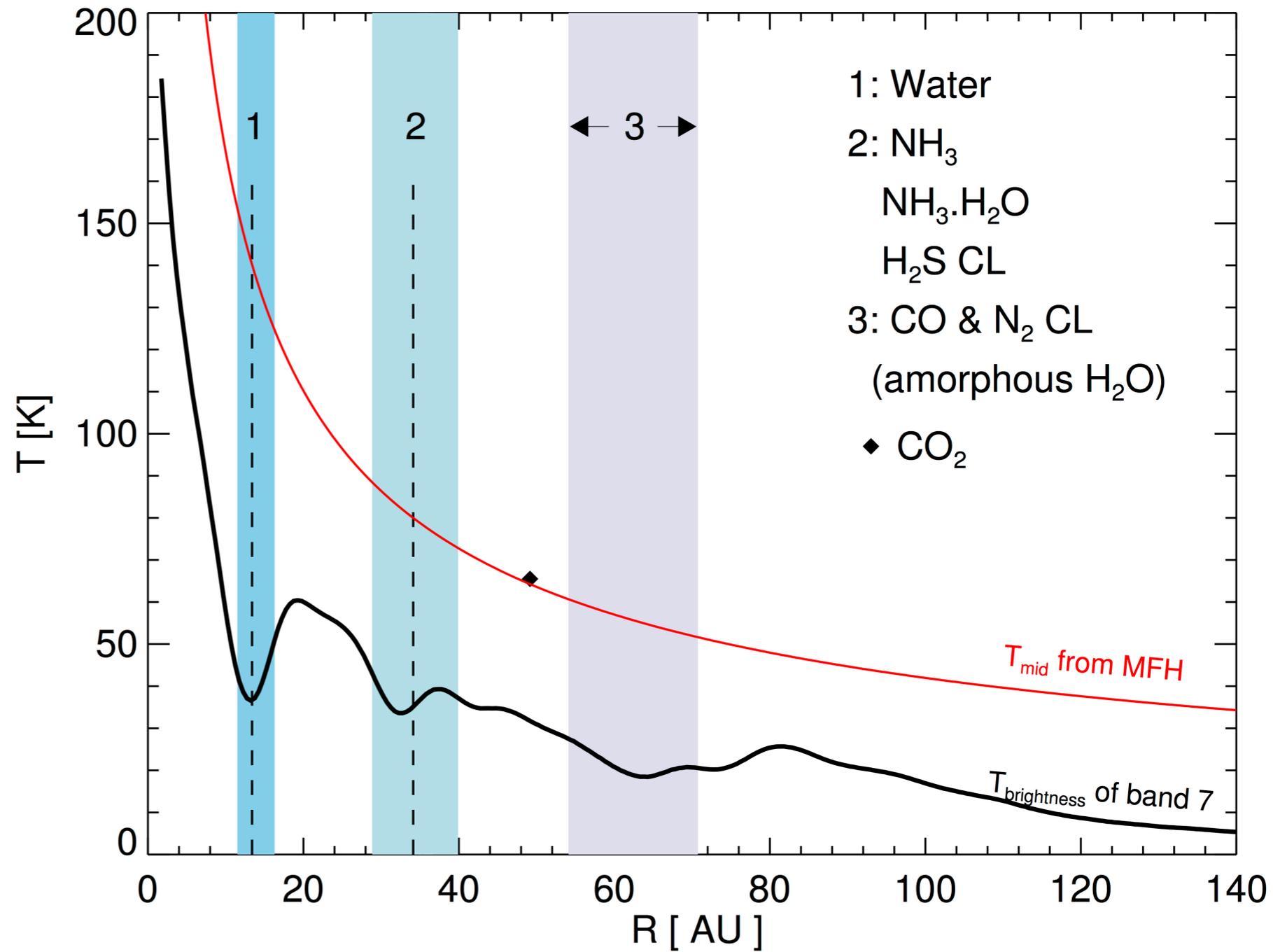
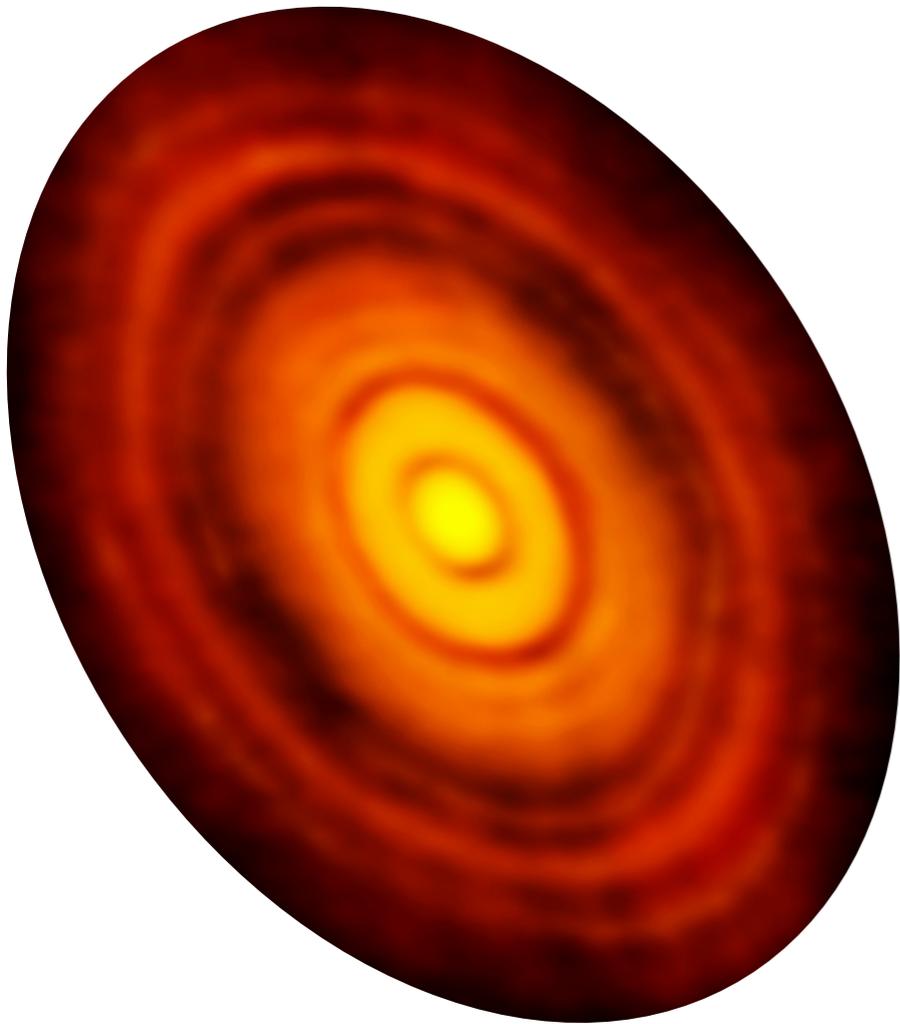
# Snowlines and planet formation



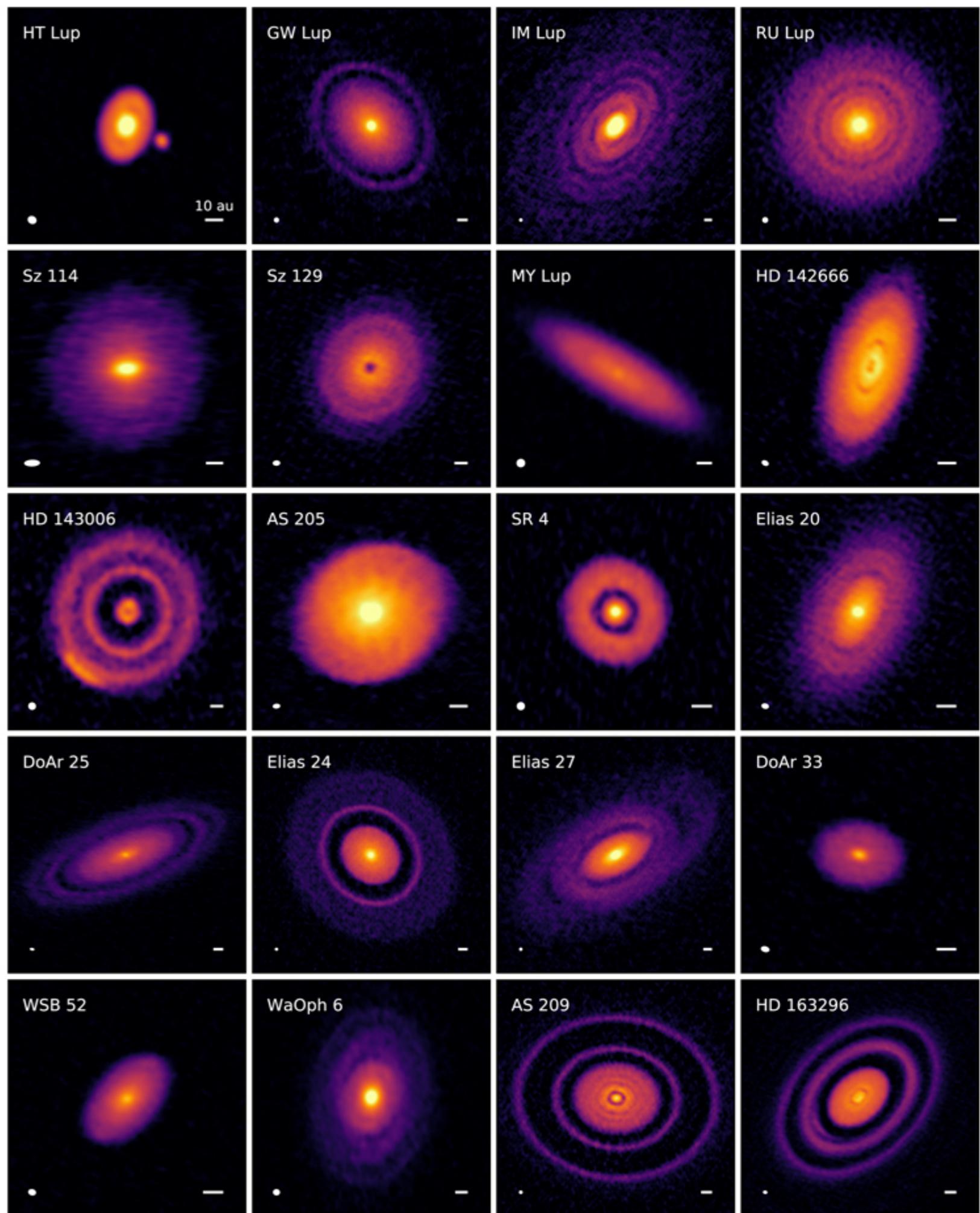
# A series of snowlines



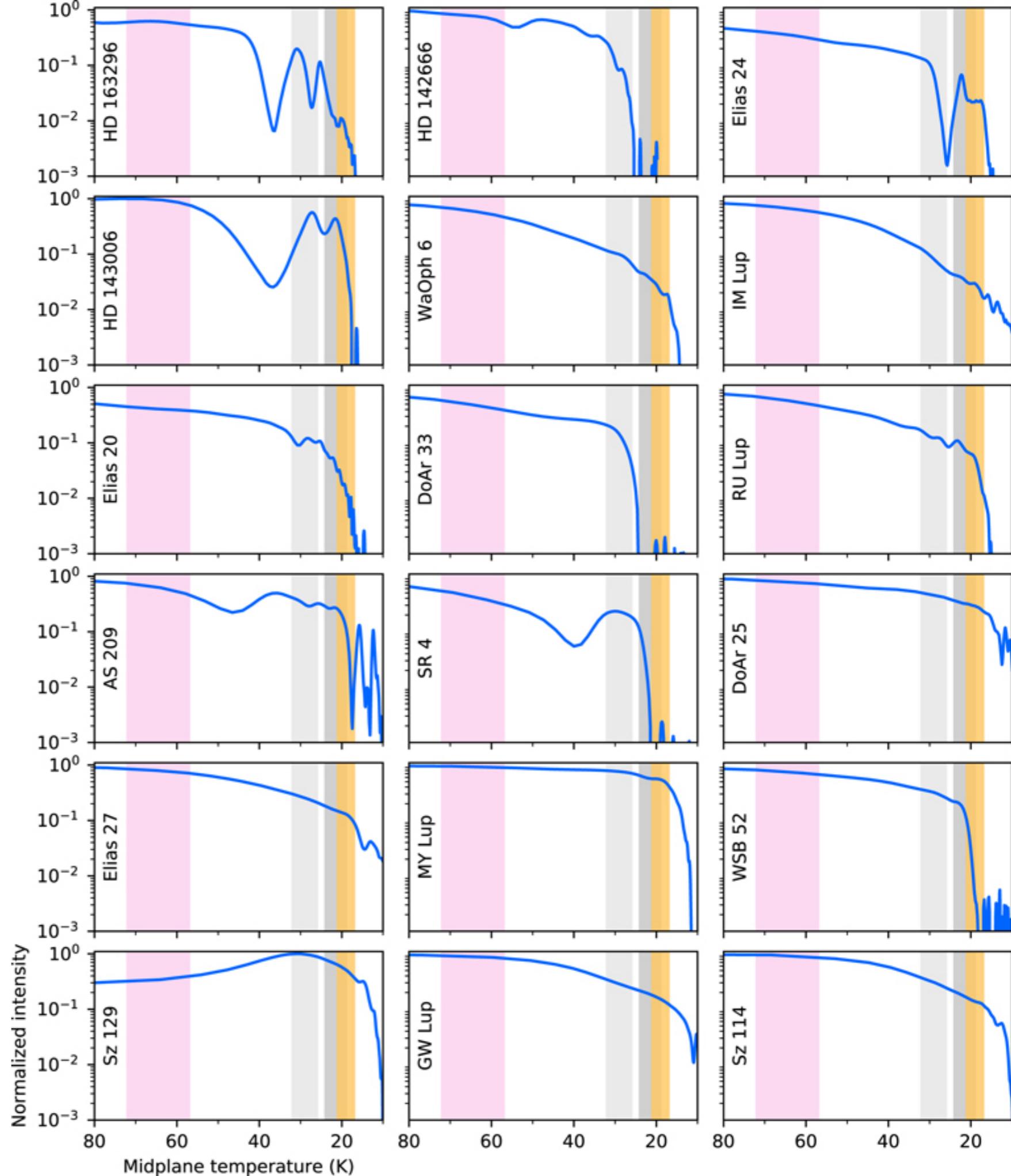
# Coincidences between sub-structure and snowlike locations



# Snowlines in DSHARP?

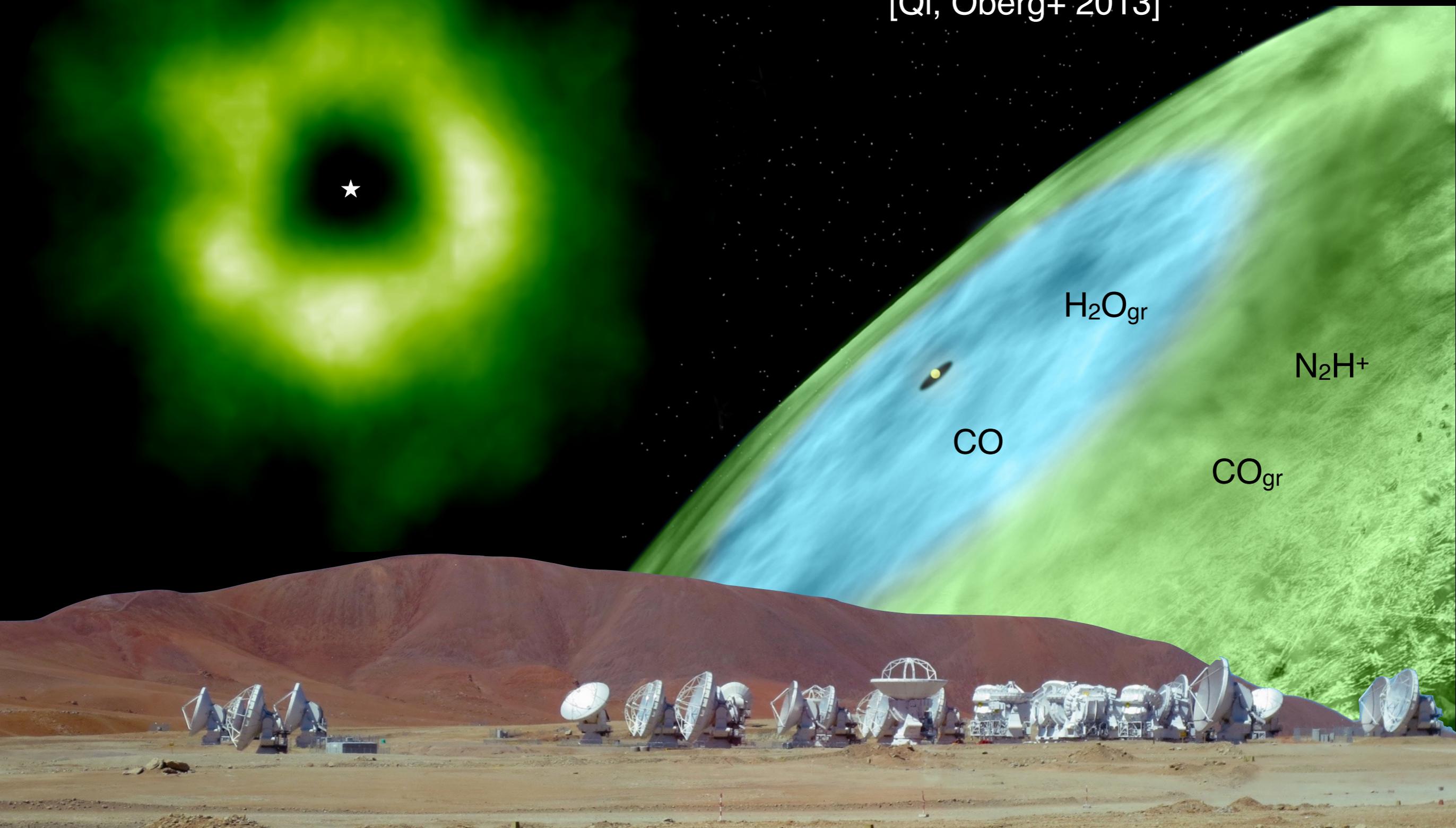


# Snowlines in DSHARP?

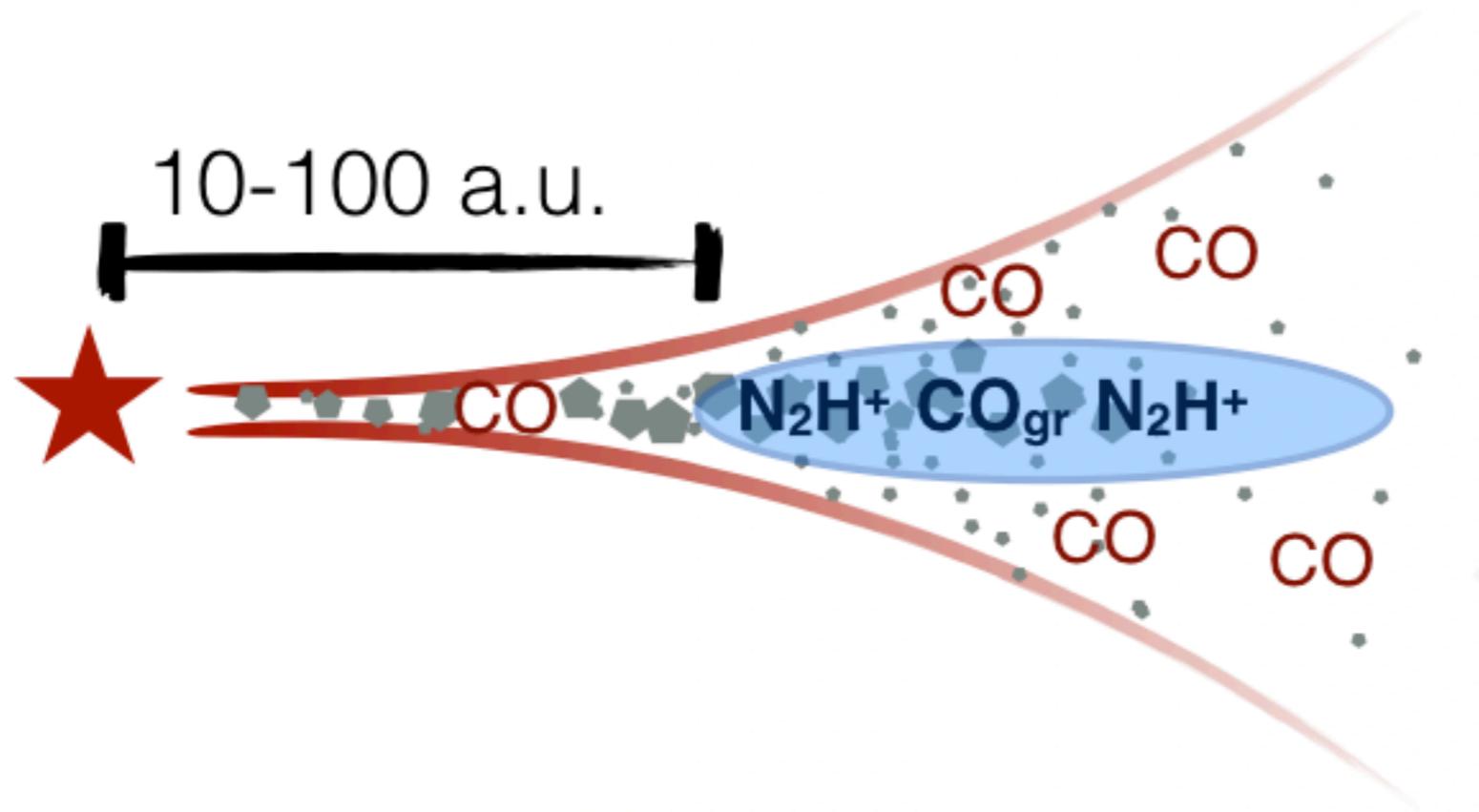


# A chemical image of the CO snowline using $\text{N}_2\text{H}^+$

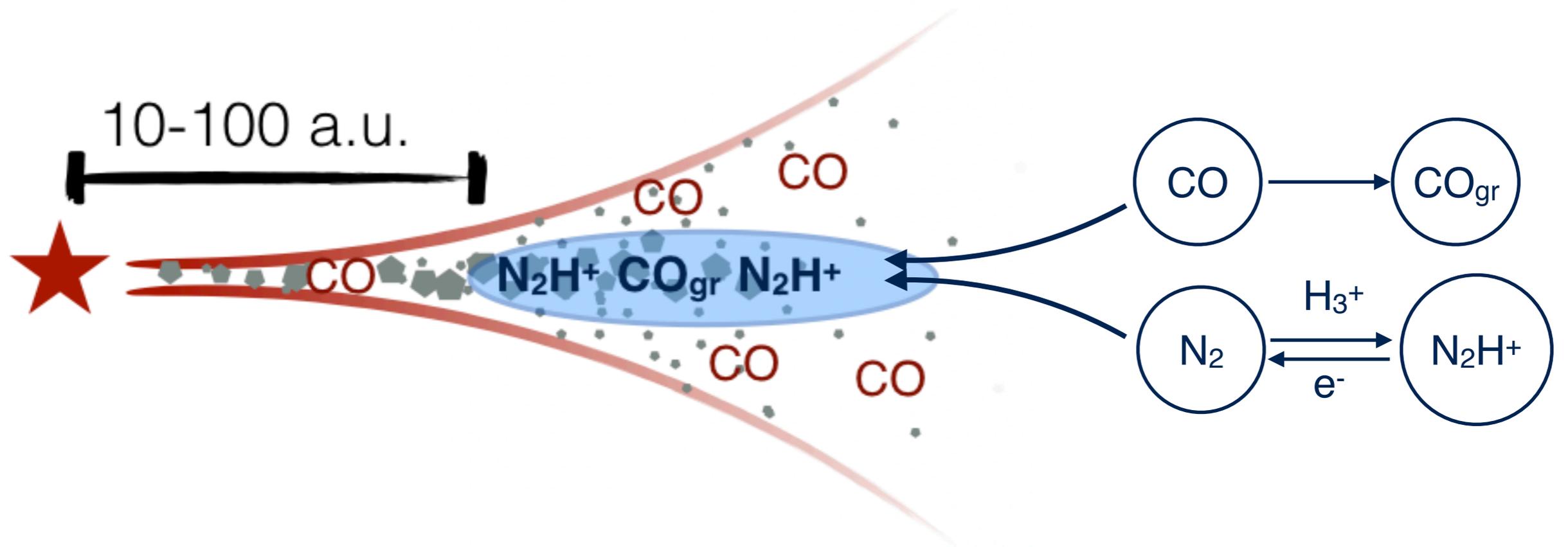
[Qi, Öberg+ 2013]



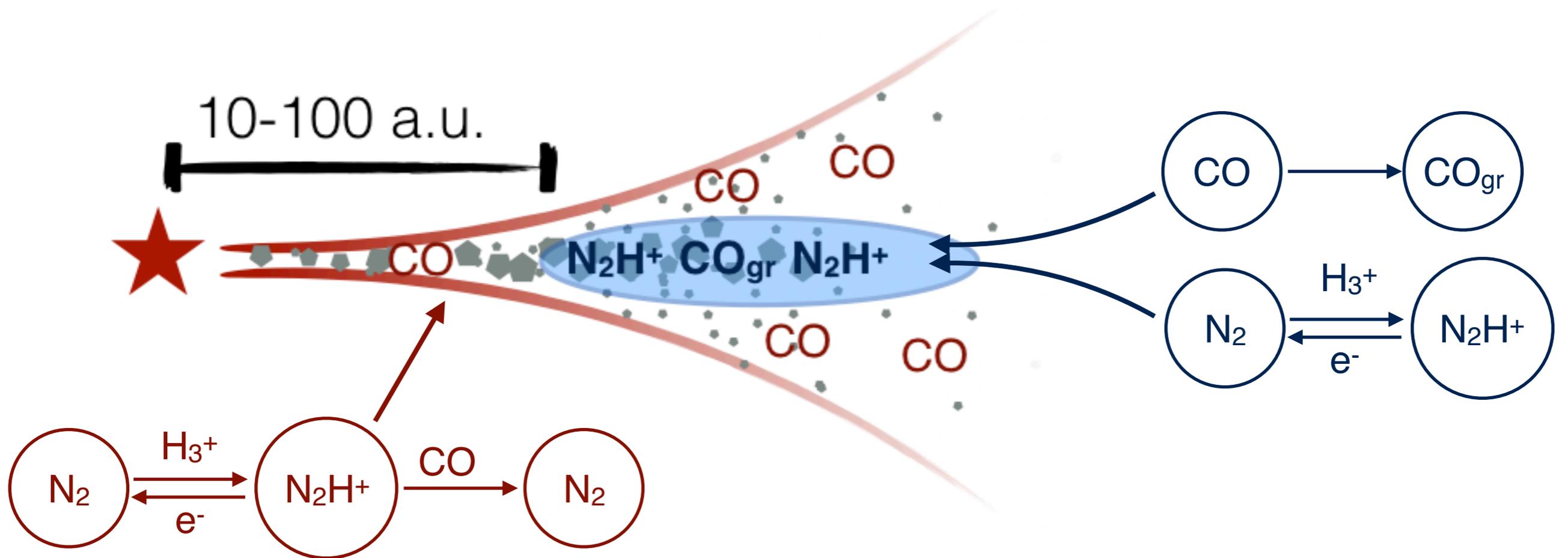
# Imaging the CO snowline in a disk



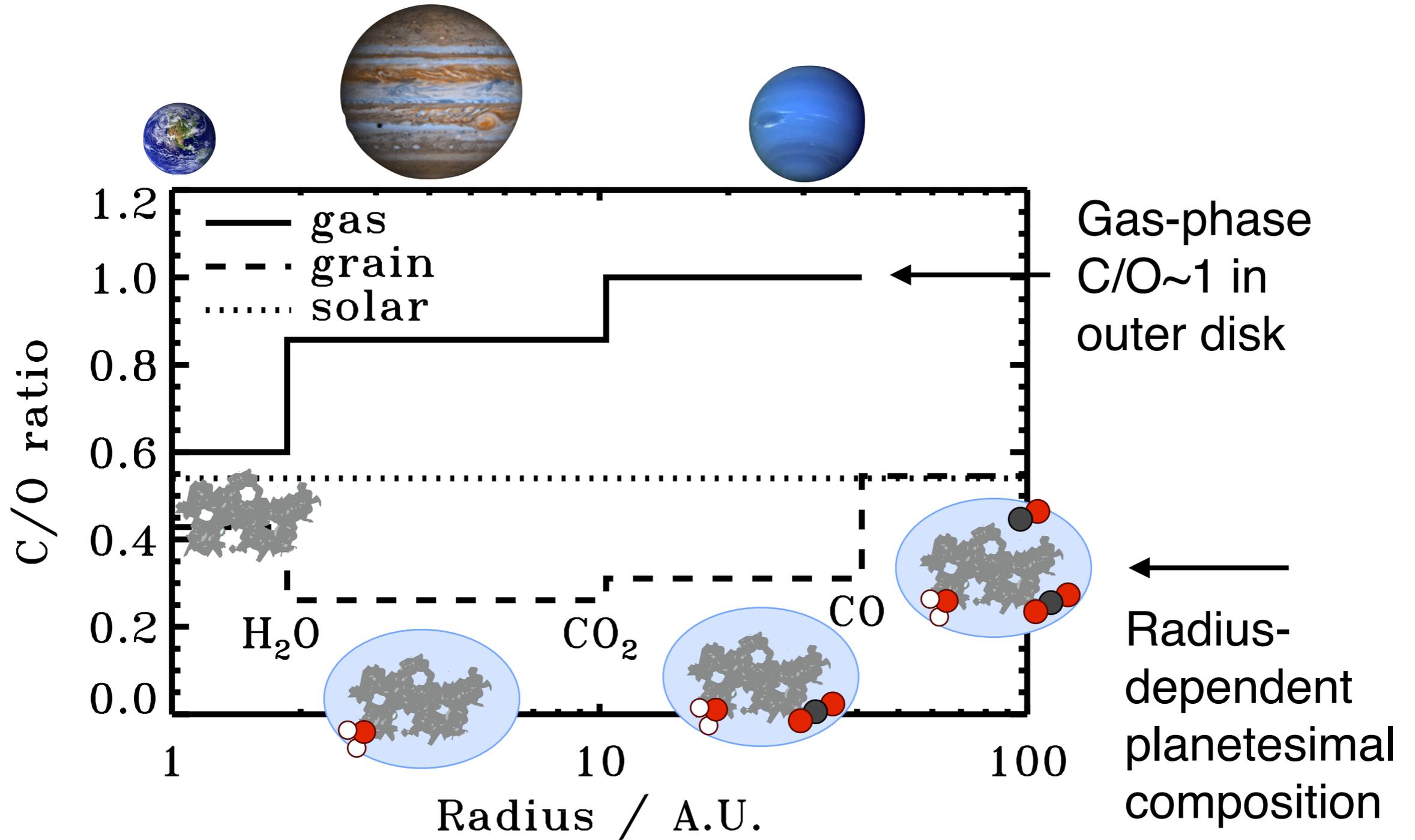
# Imaging the CO snowline in a disk



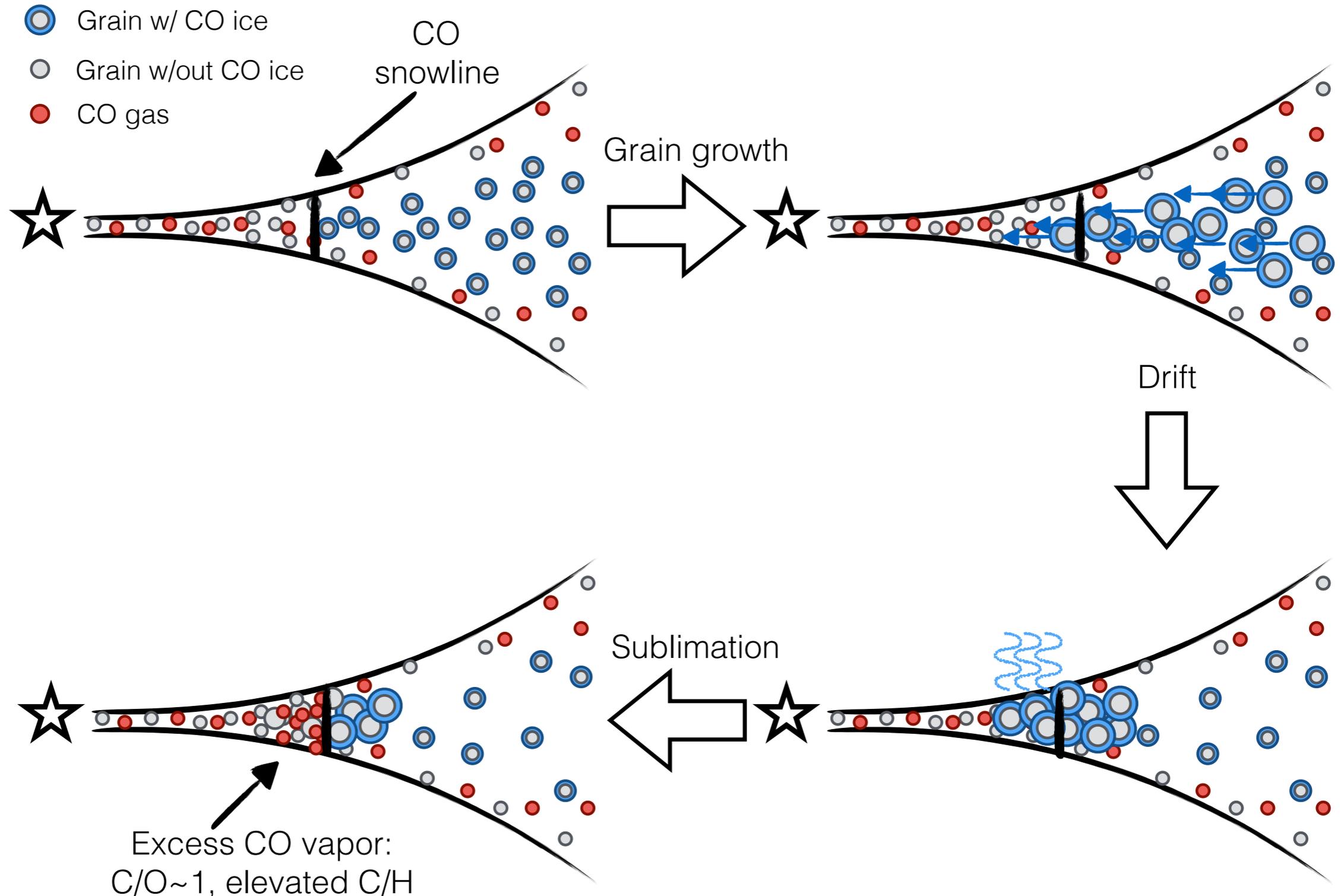
# Imaging the CO snowline in a disk



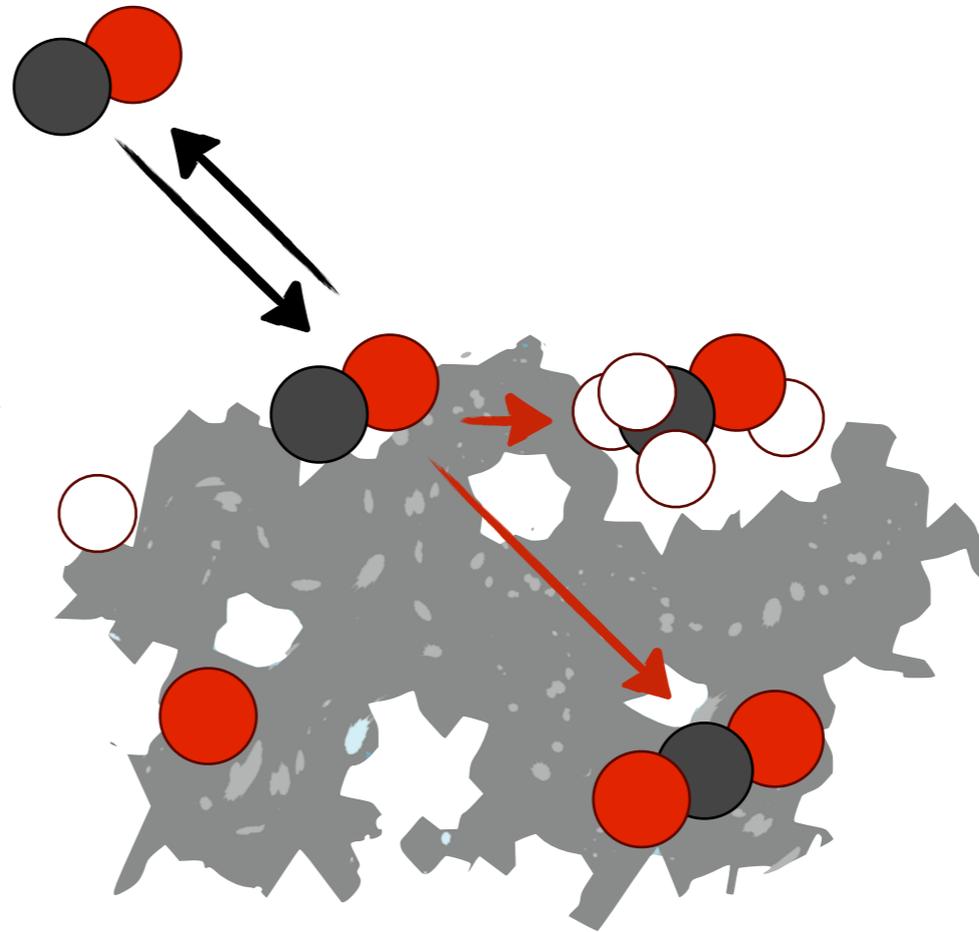
# Snowlines and Planet C/N/O ratios



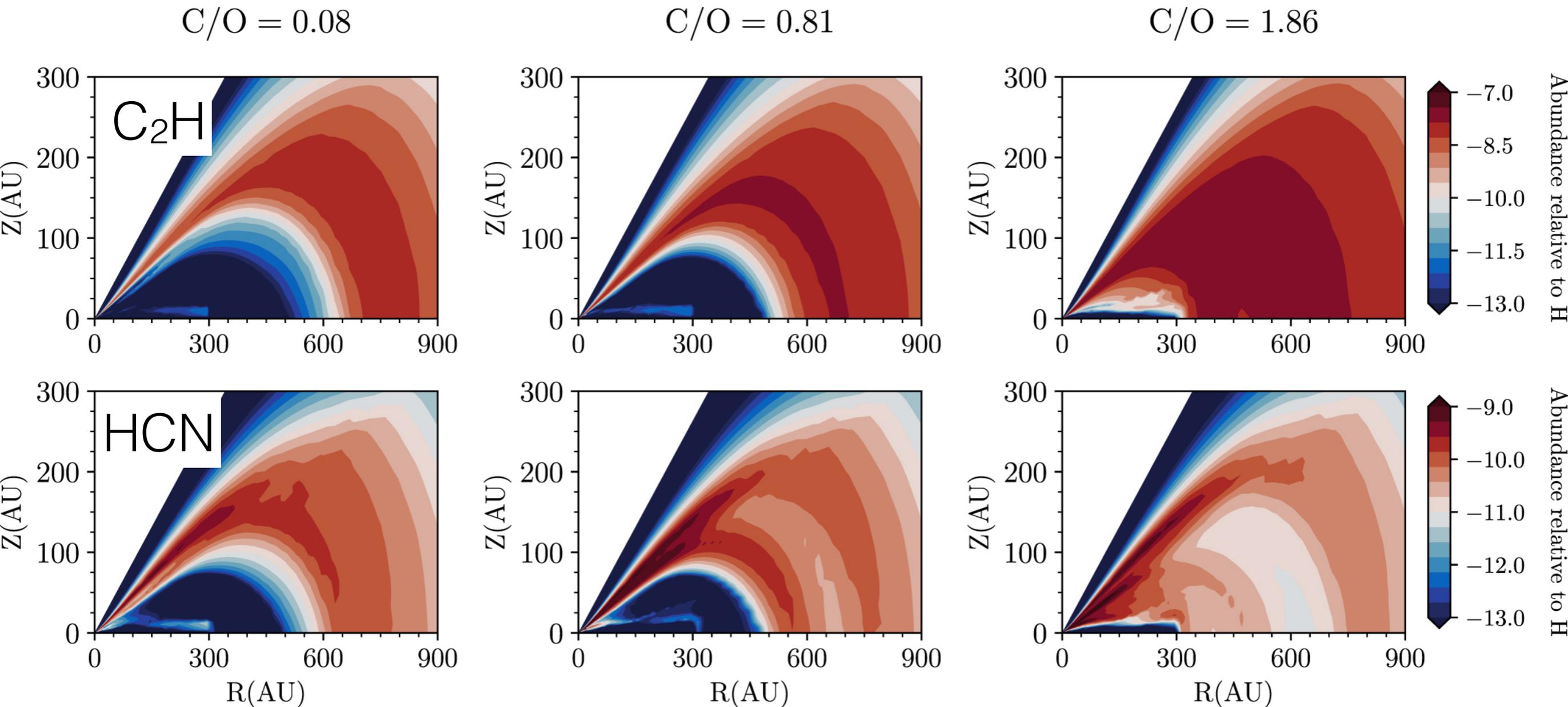
# Adding dynamics moves snowlines and changes local C/N/O ratios



C/N/O ratio in disks also depends on chemistry



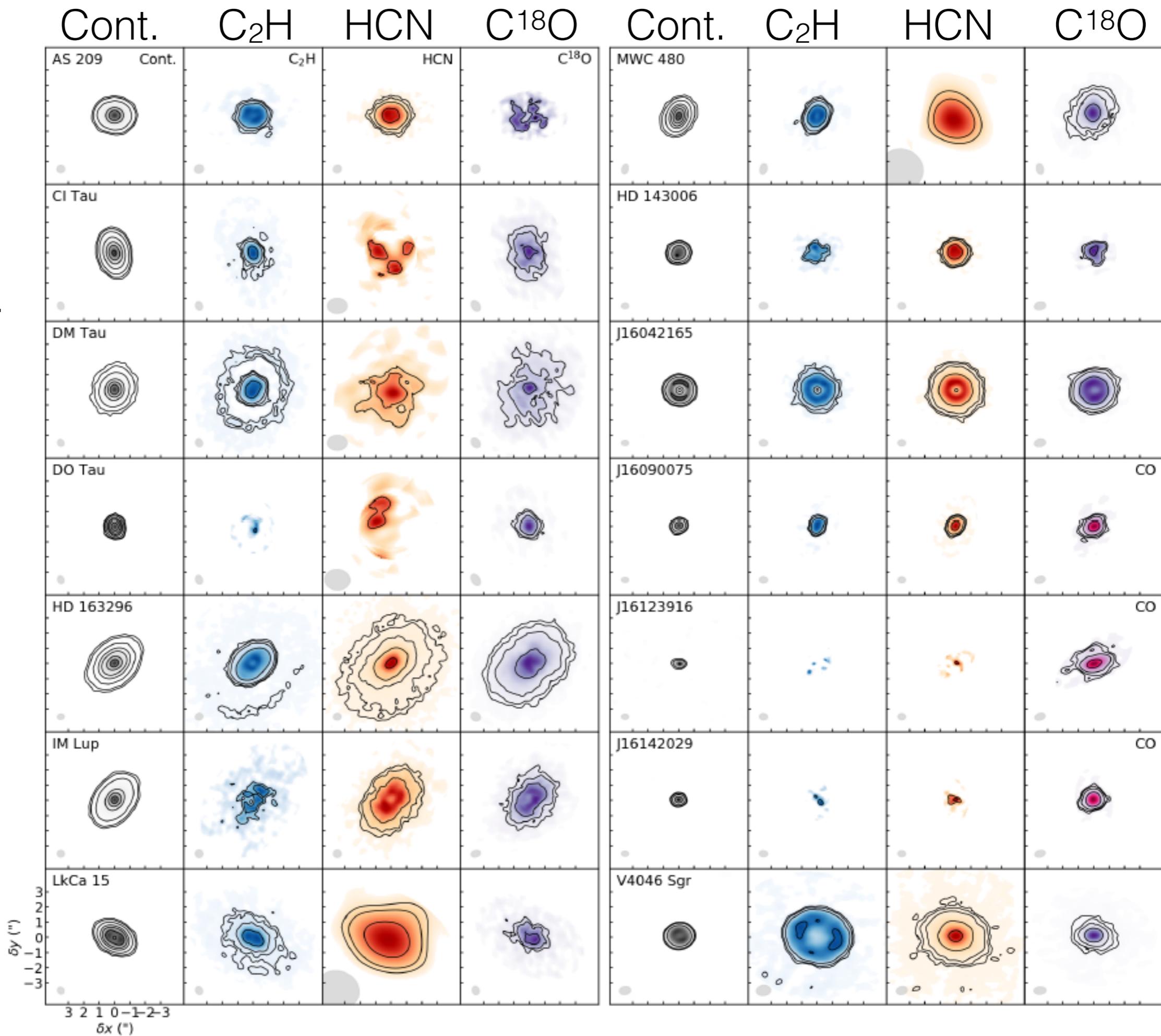
# O and C depletion, but no N depletion in the IM Lup disk



Modeling CO, HCN and  $C_2H$  results in  $C/O \sim 0.8$ ,  $N/O \sim 10$  in disk molecular layers

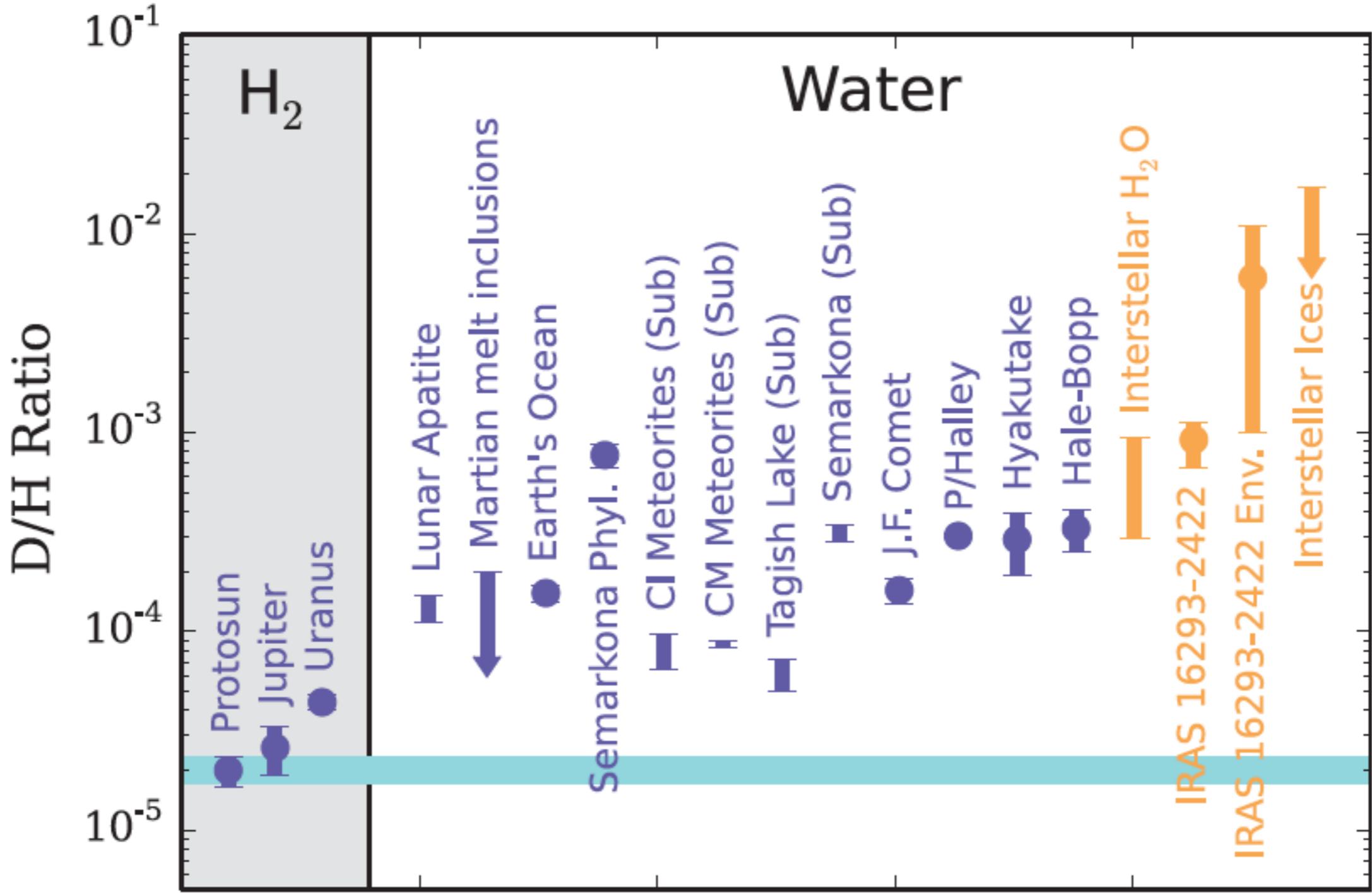
Super-solar  
N/C/O in  
all planet-  
forming  
disks?

Across all  
disks?



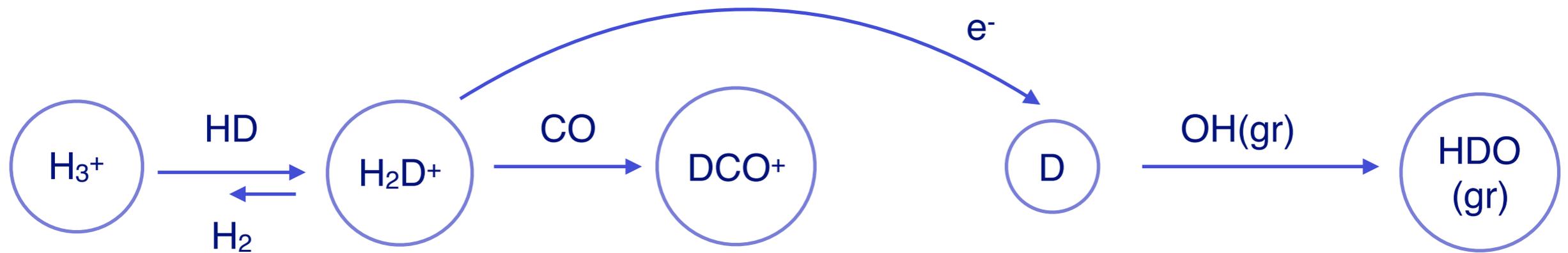
[Bergner+ 2019,  
subm.]

# Water delivery to young planets?

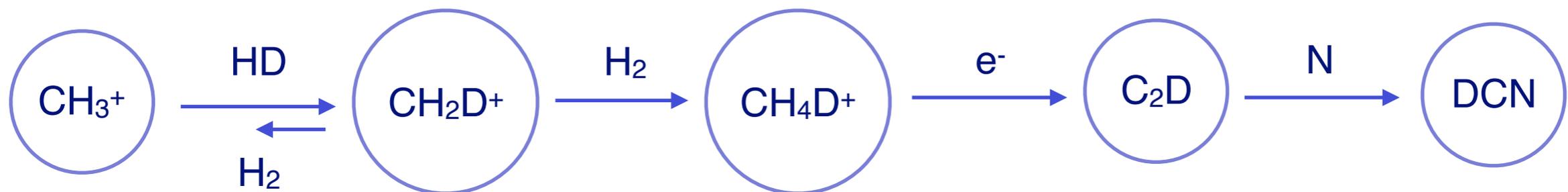


# Deuterium chemistry

1) cold ion-molecule fractionation chemistry (+ grain surface chemistry):

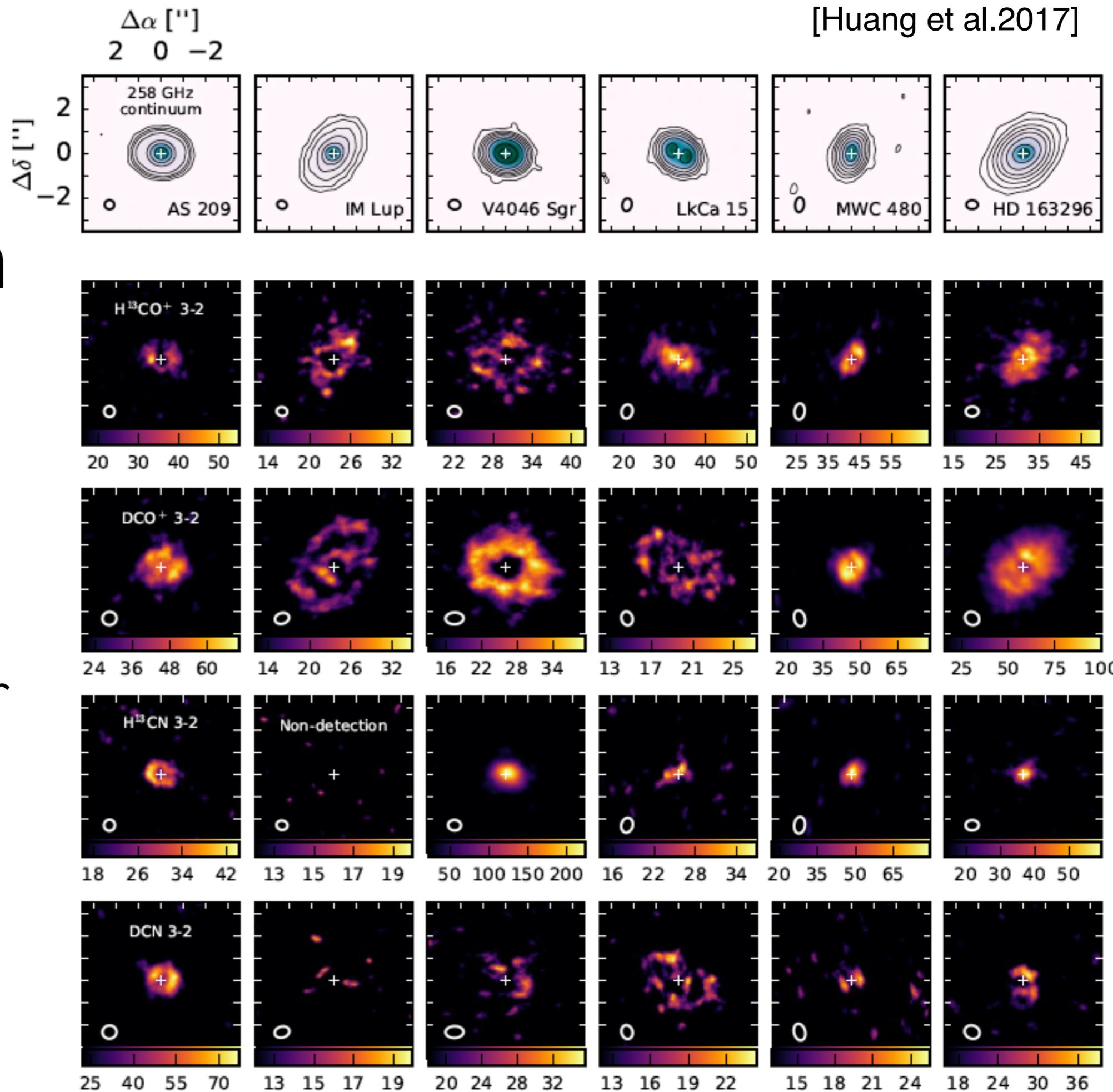


2) warm neutral or ion chemistry:



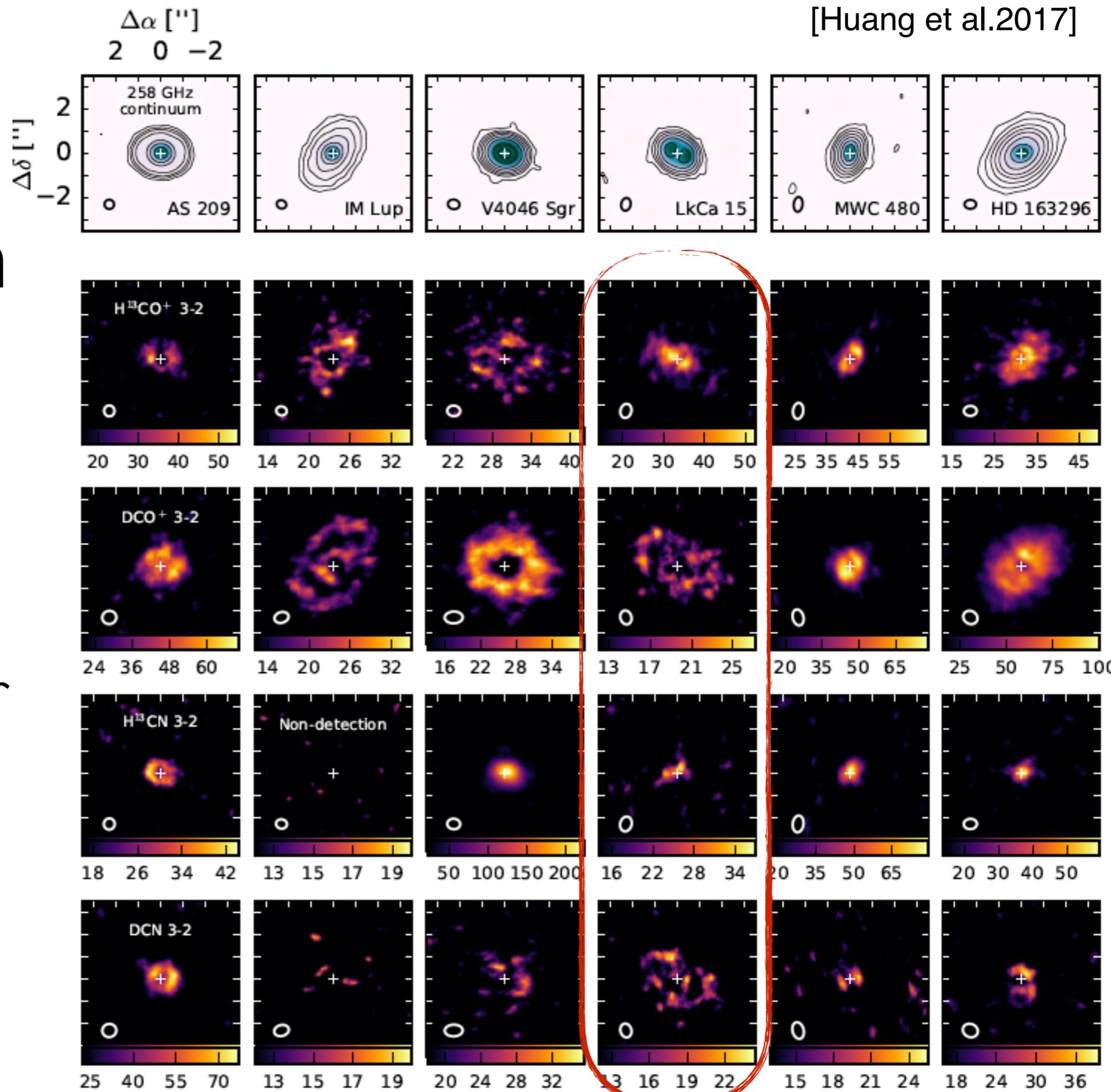
# ALMA

survey of  
deuterium  
chemistry:  
efficient  
deuterium  
chemistry in  
disk molecular  
layers

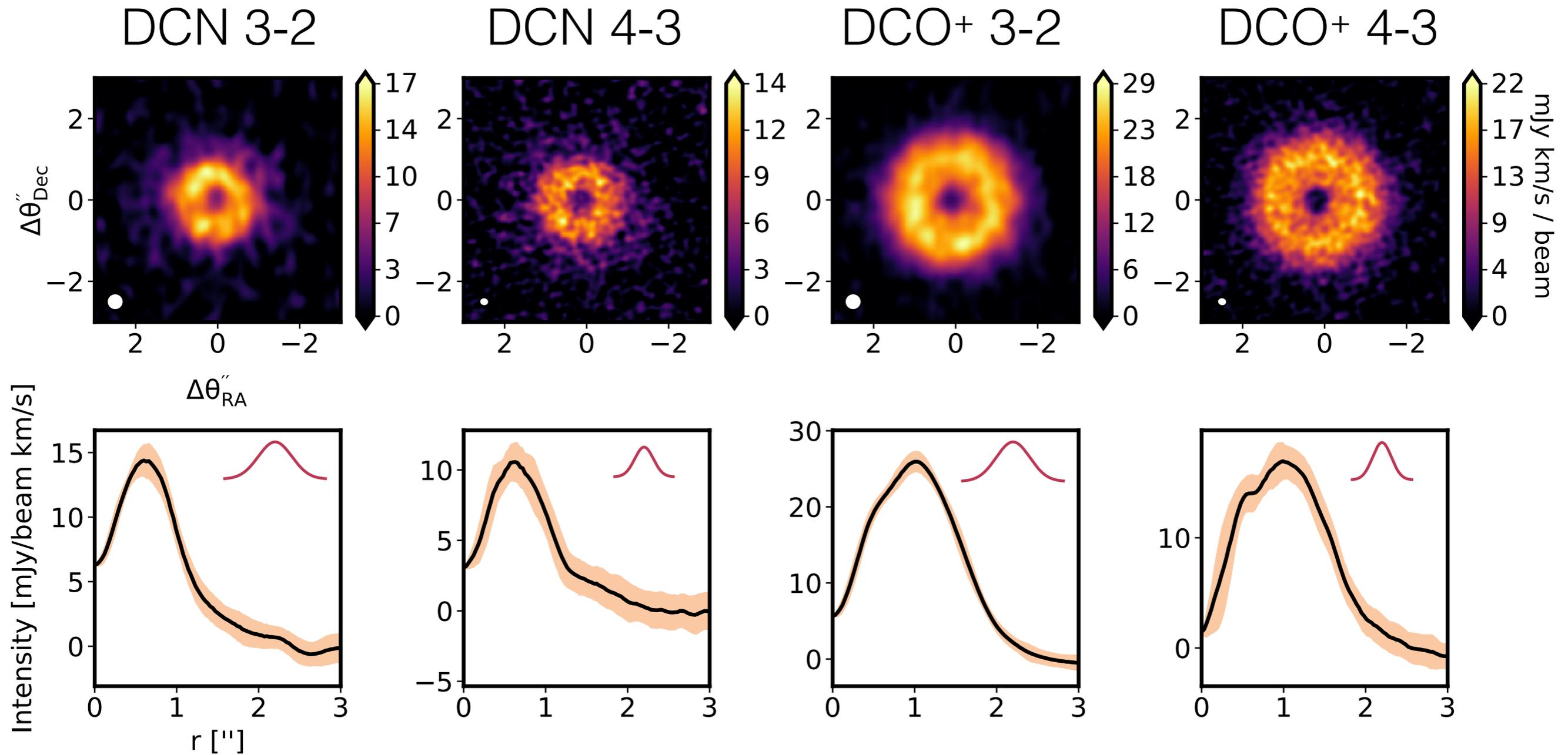


# ALMA

survey of  
deuterium  
chemistry:  
efficient  
deuterium  
chemistry in  
disk molecular  
layers



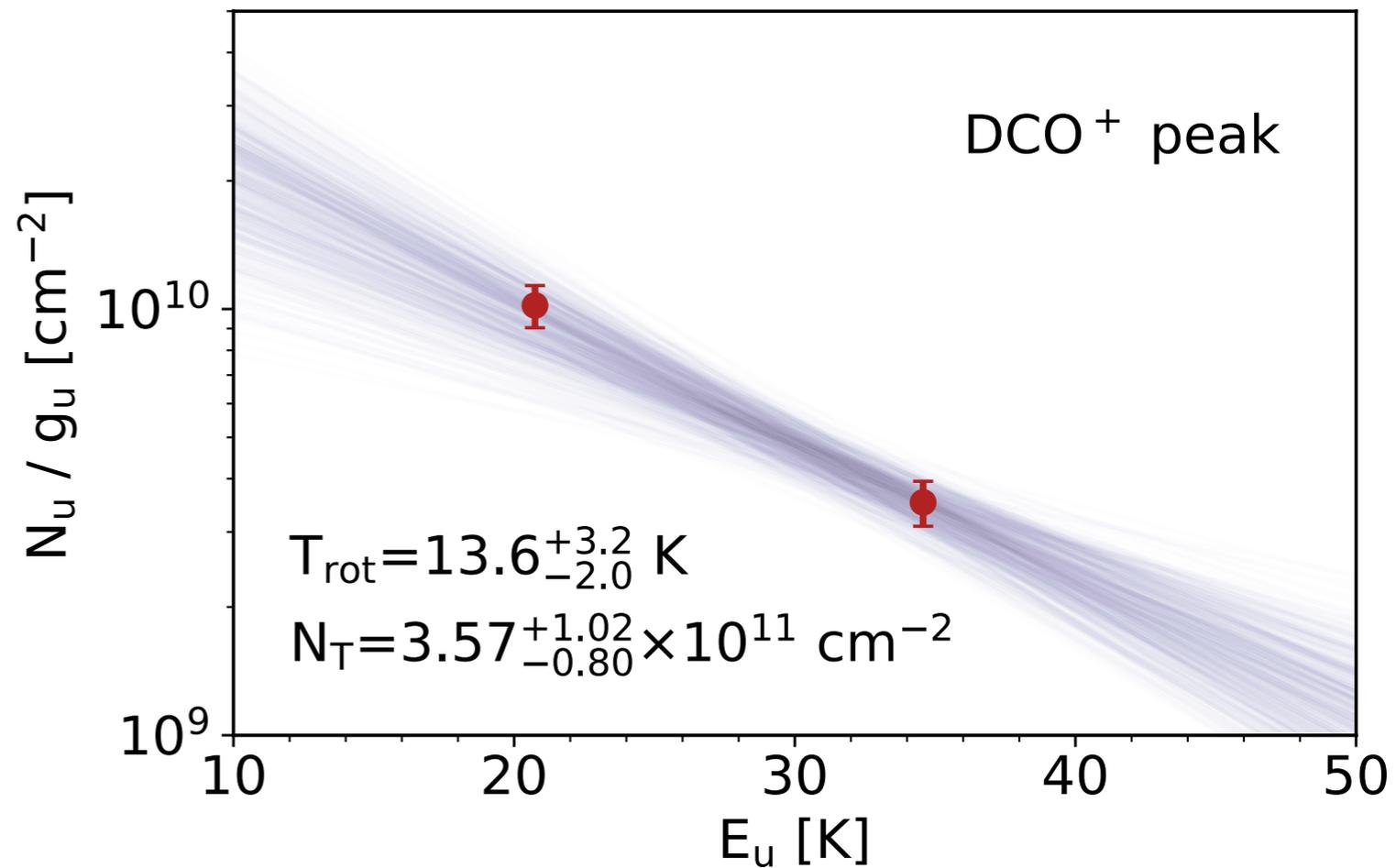
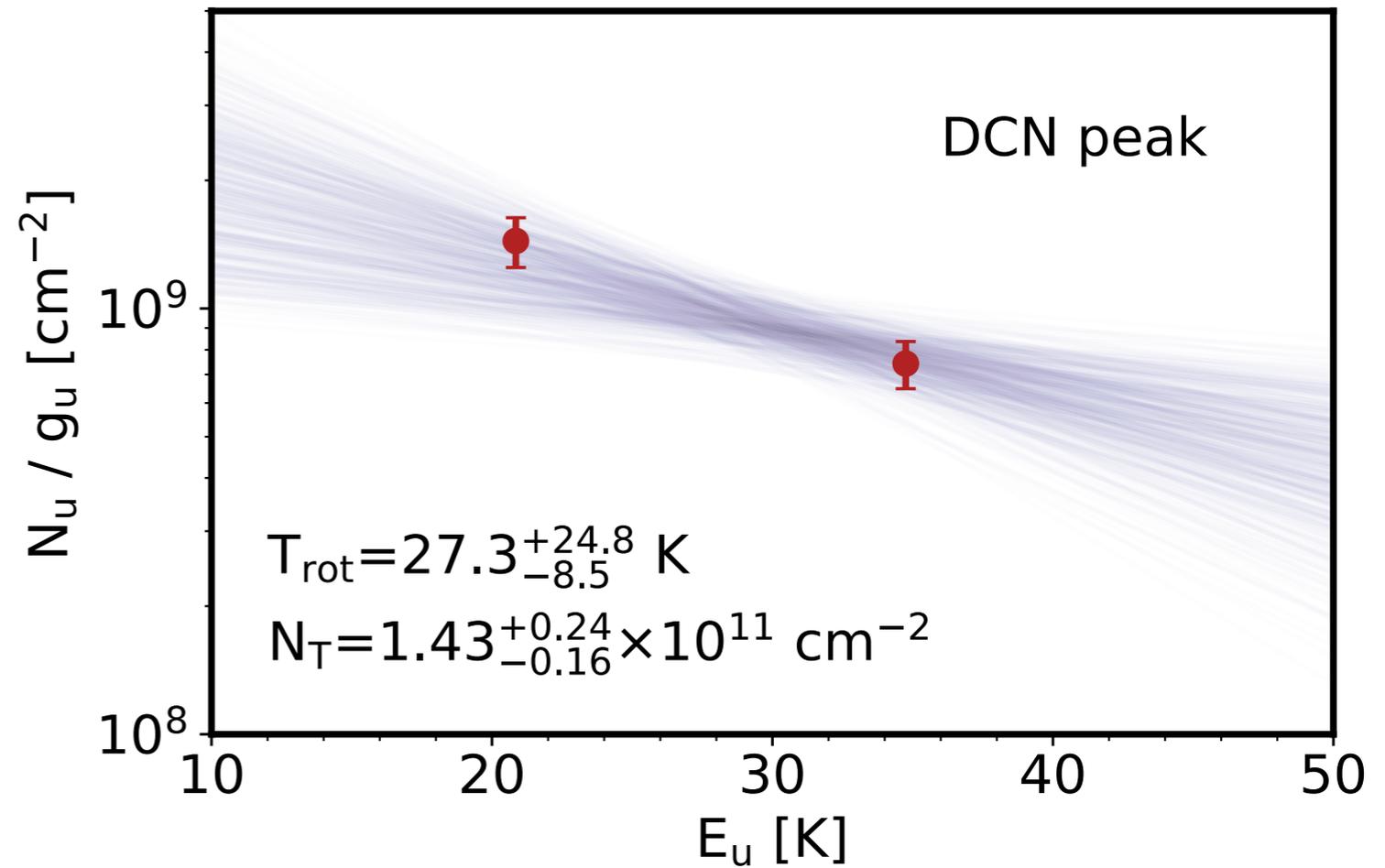
# TW Hya: a case study of different deuterium fractionation pathways



[see also Salinas+ 2017]

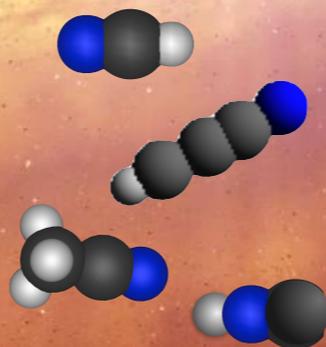
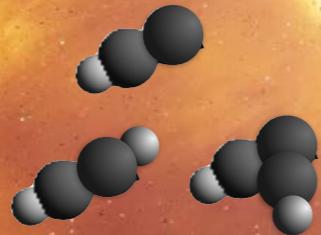
2+ lines needed for  
temperature  
constraints

Two deuterium  
fractionation paths  
characterized by  
moderate and cold  
temperatures

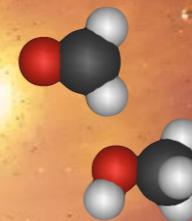


# Organics in protoplanetary disks

Hydrocarbons  
and carbon  
chains:  $C_2H_2$ ,  
 $C_2H$ ,  $c-C_3H_2$

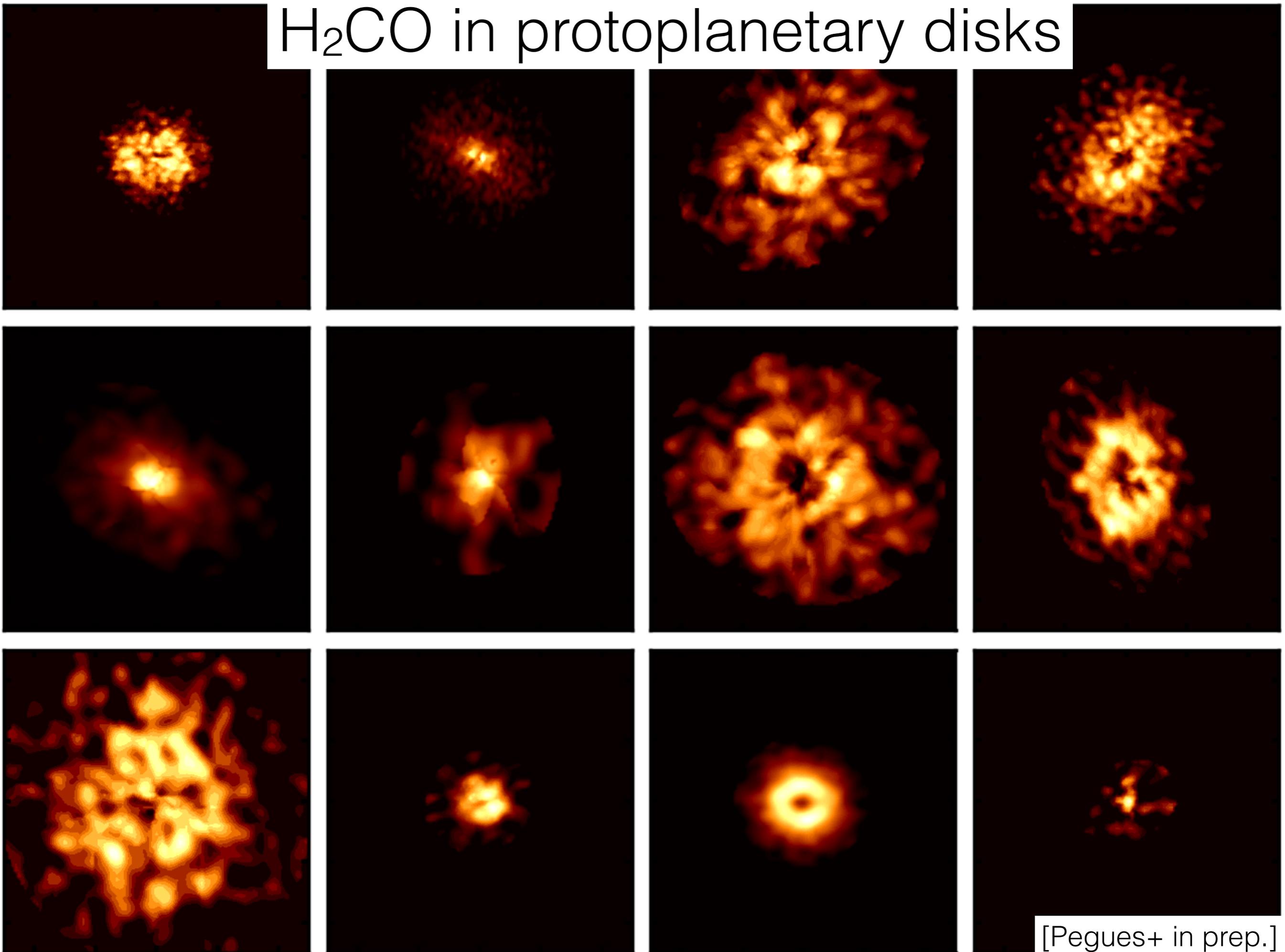


Nitrogen  
containing  
organics: HCN,  
HNC, HC<sub>3</sub>N and  
CH<sub>3</sub>CN



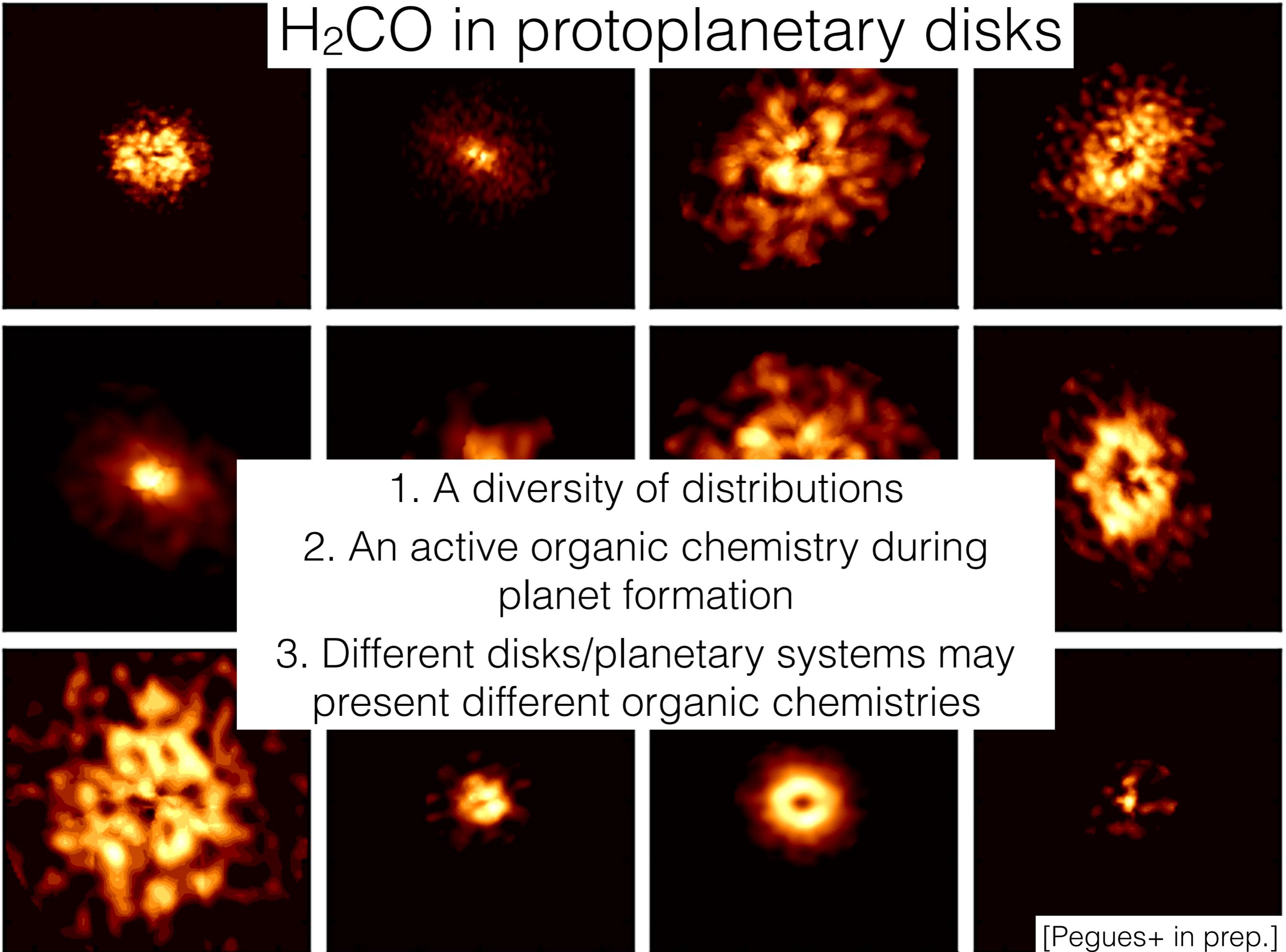
Oxygen bearing  
organics: H<sub>2</sub>CO,  
CH<sub>3</sub>OH &  
HCOOH

# H<sub>2</sub>CO in protoplanetary disks



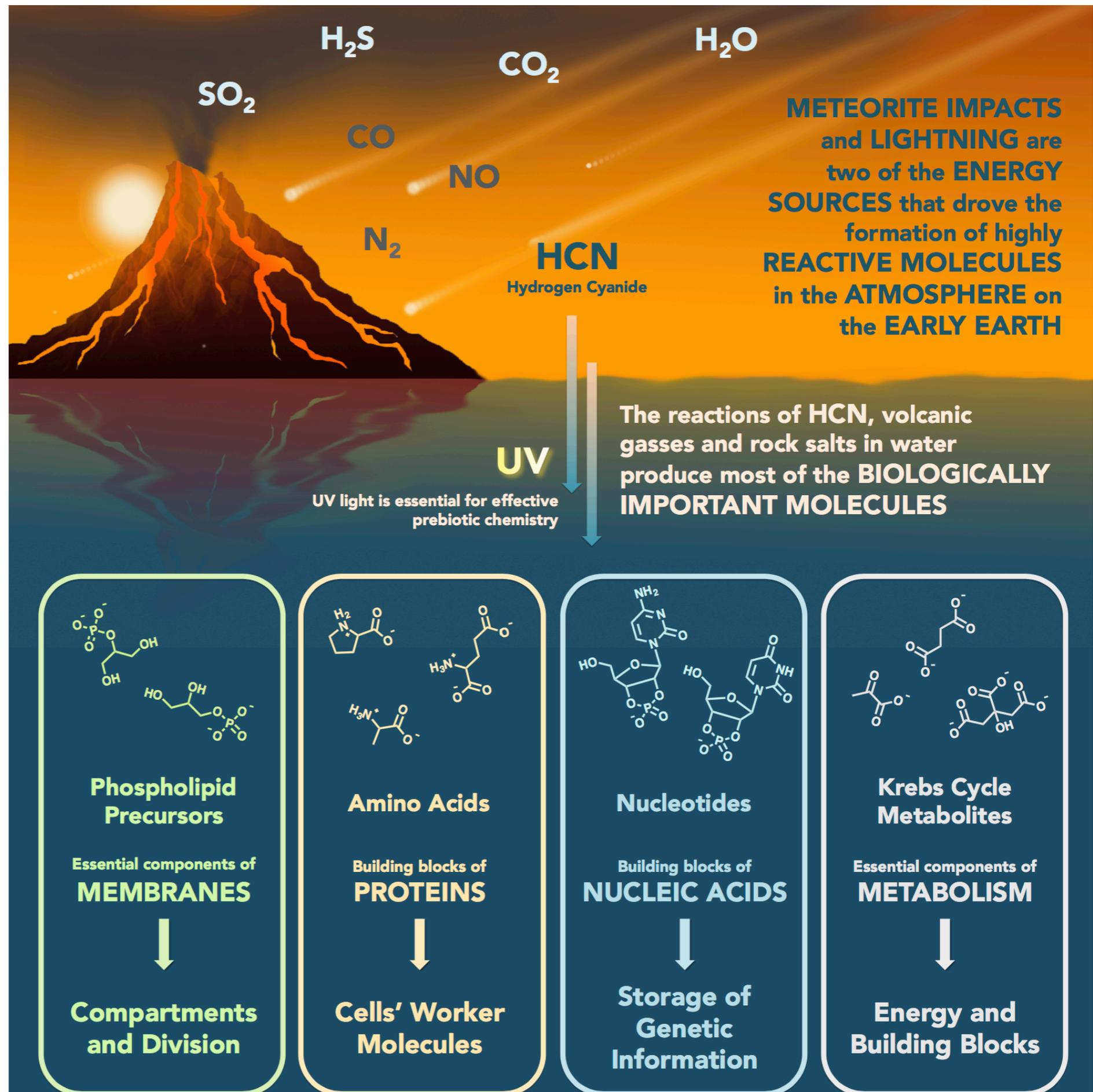
[Pegues+ in prep.]

# H<sub>2</sub>CO in protoplanetary disks



1. A diversity of distributions
2. An active organic chemistry during planet formation
3. Different disks/planetary systems may present different organic chemistries

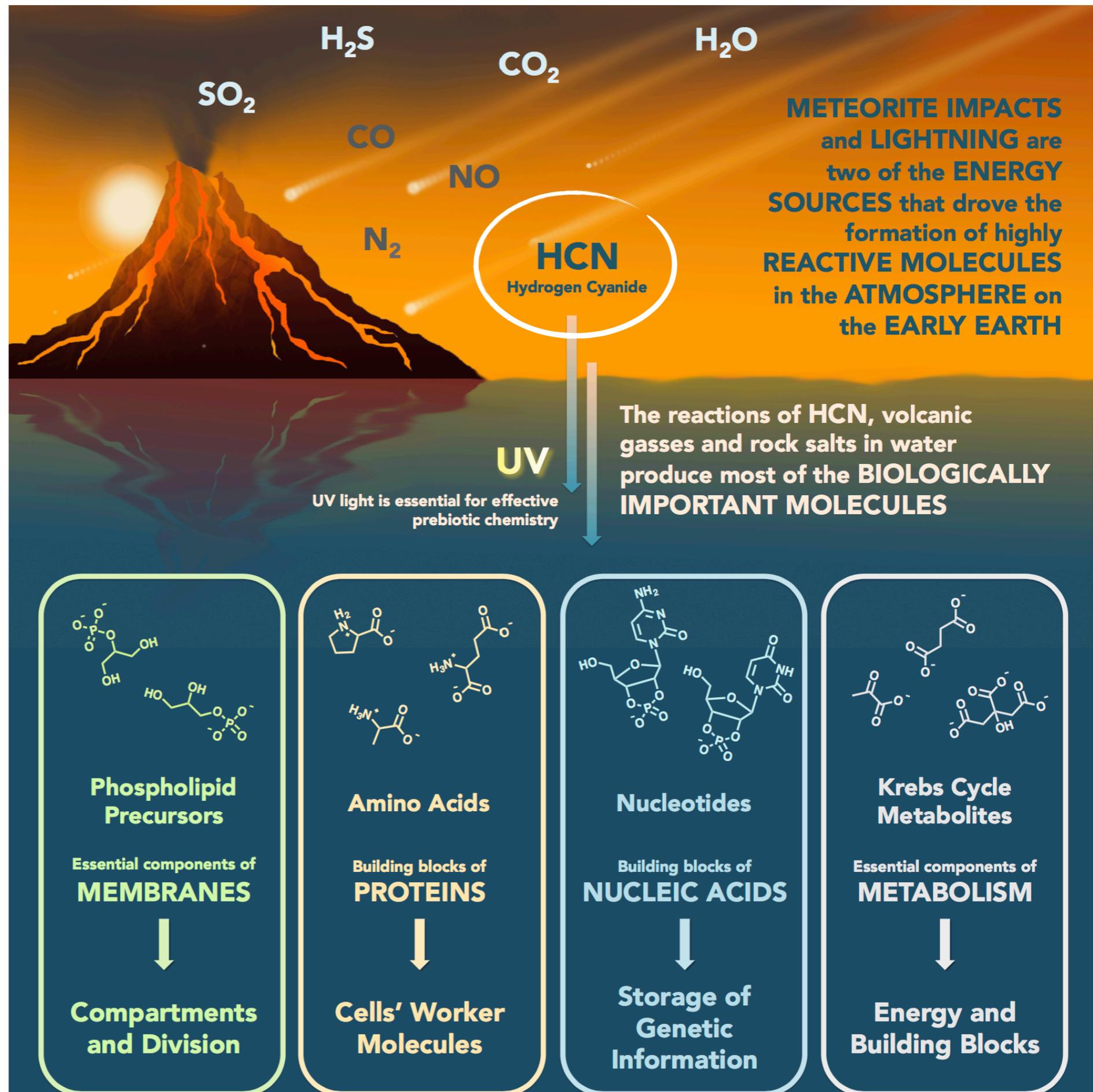
Not all organics are equally conducive to forming the building blocks of life



[Credit: Angelica Mariani]

[see e.g. Patel+ 2015]

Not all organics are equally conducive to forming the building blocks of life

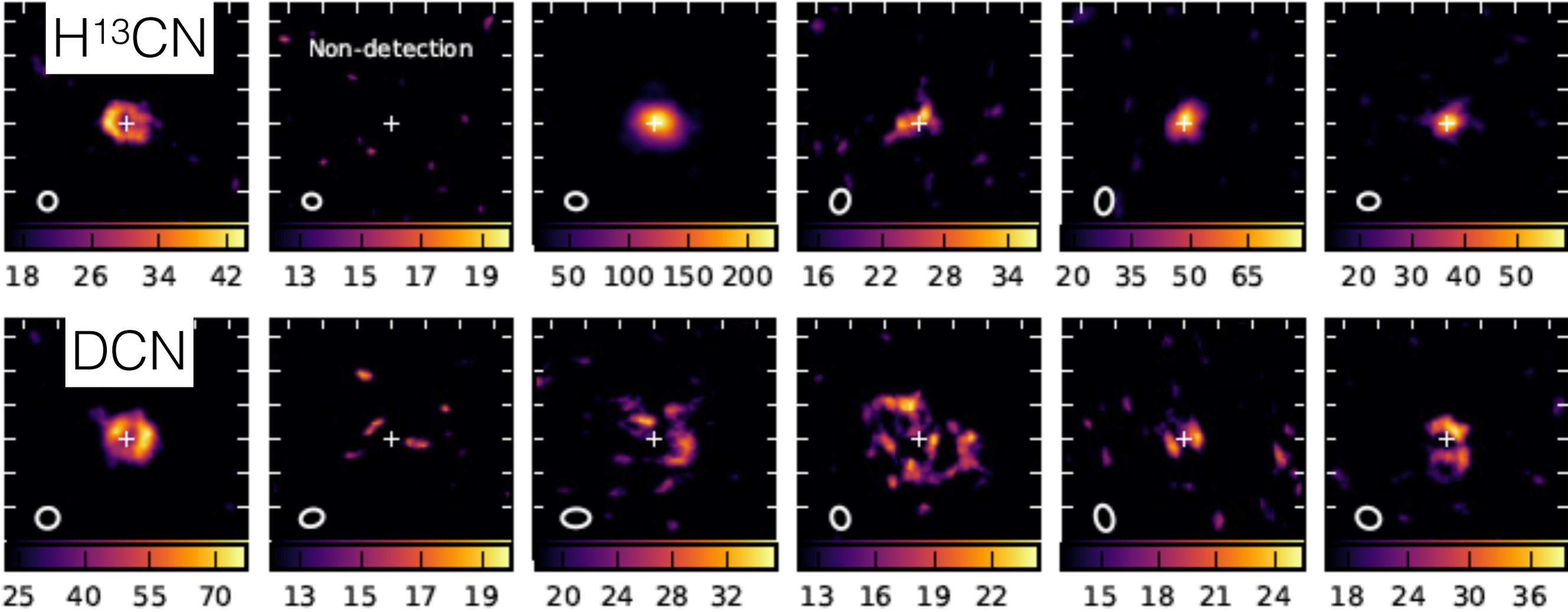


[Credit: Angelica Mariani]

[see e.g. Patel+ 2015]

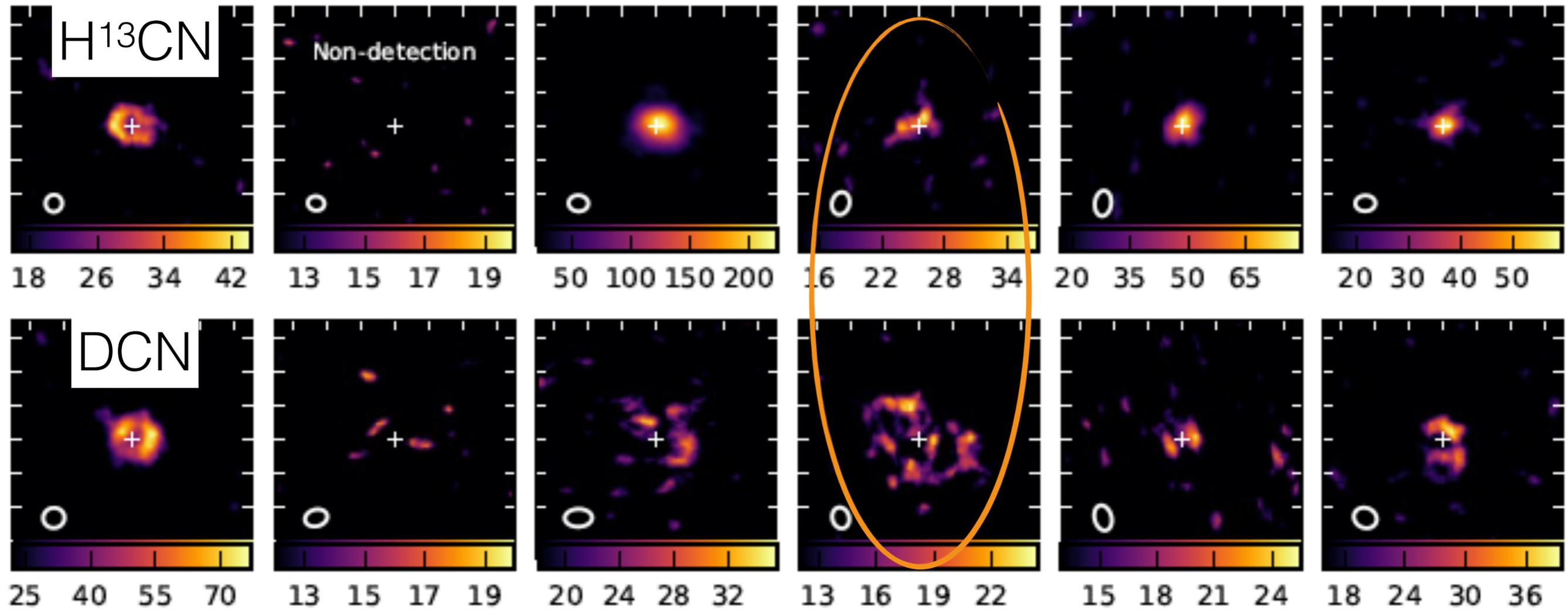
# H<sub>2</sub>CO chemistry is active in disks

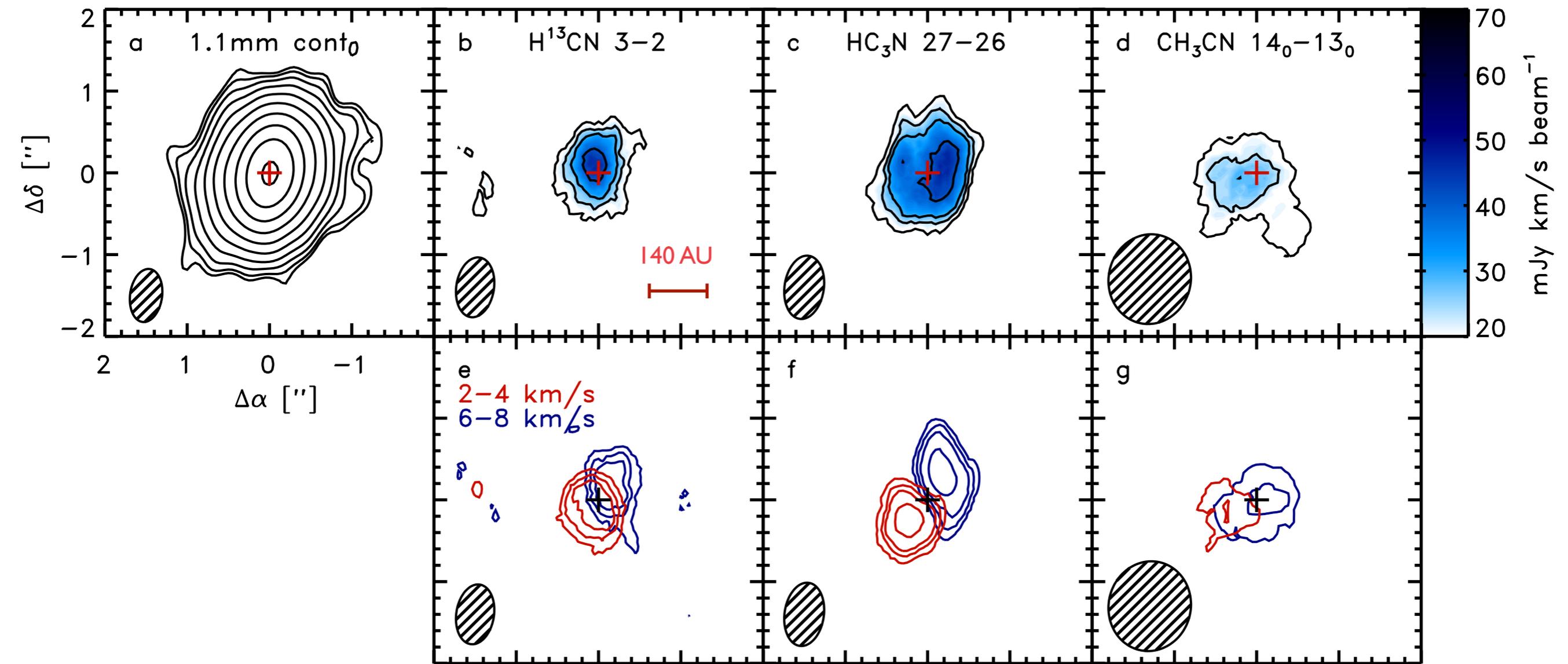
Different disks →



# H<sub>2</sub>CO chemistry is active in disks

Different disks →





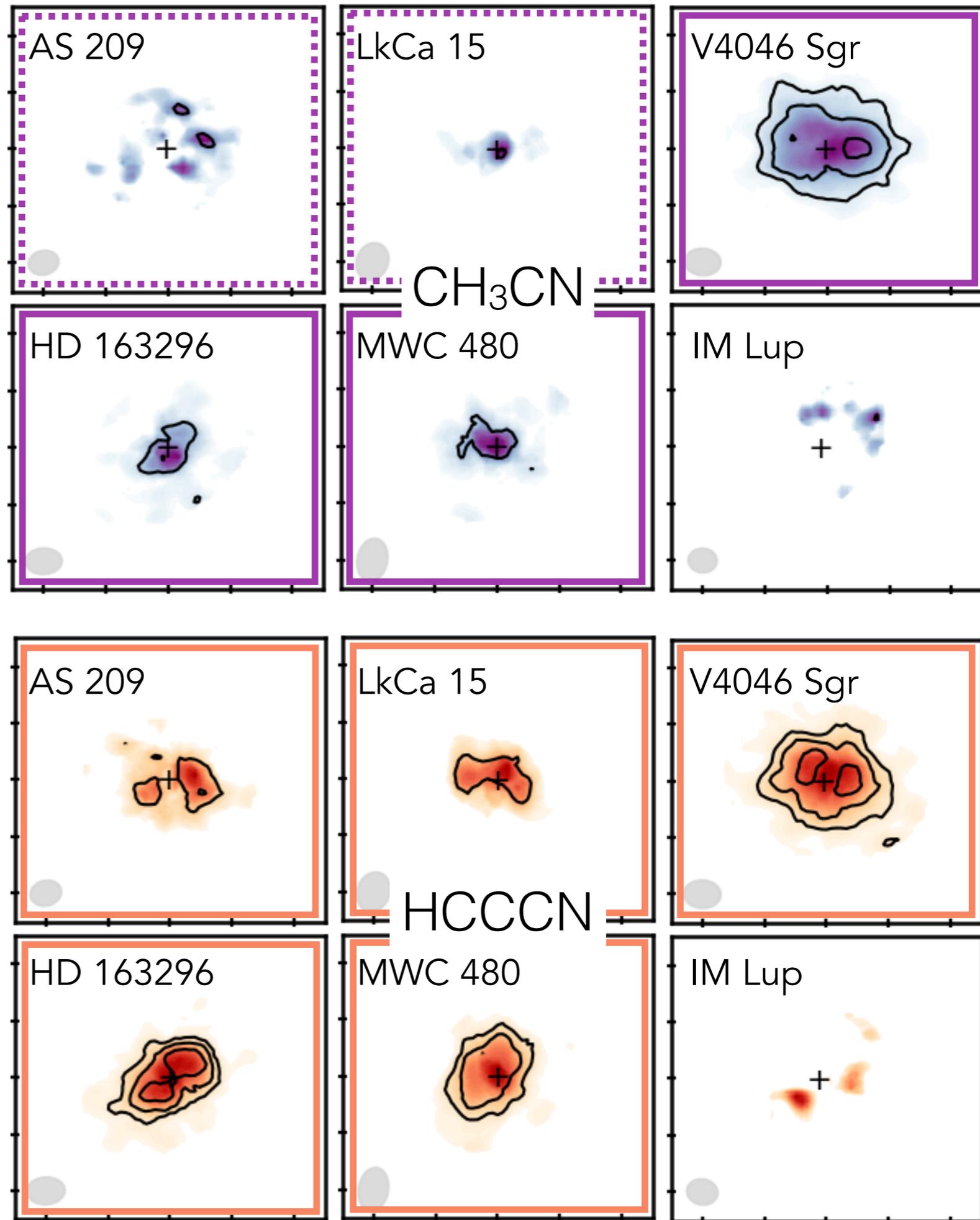
Complex cyanides in a protoplanetary disk

[Öberg+ 2015]

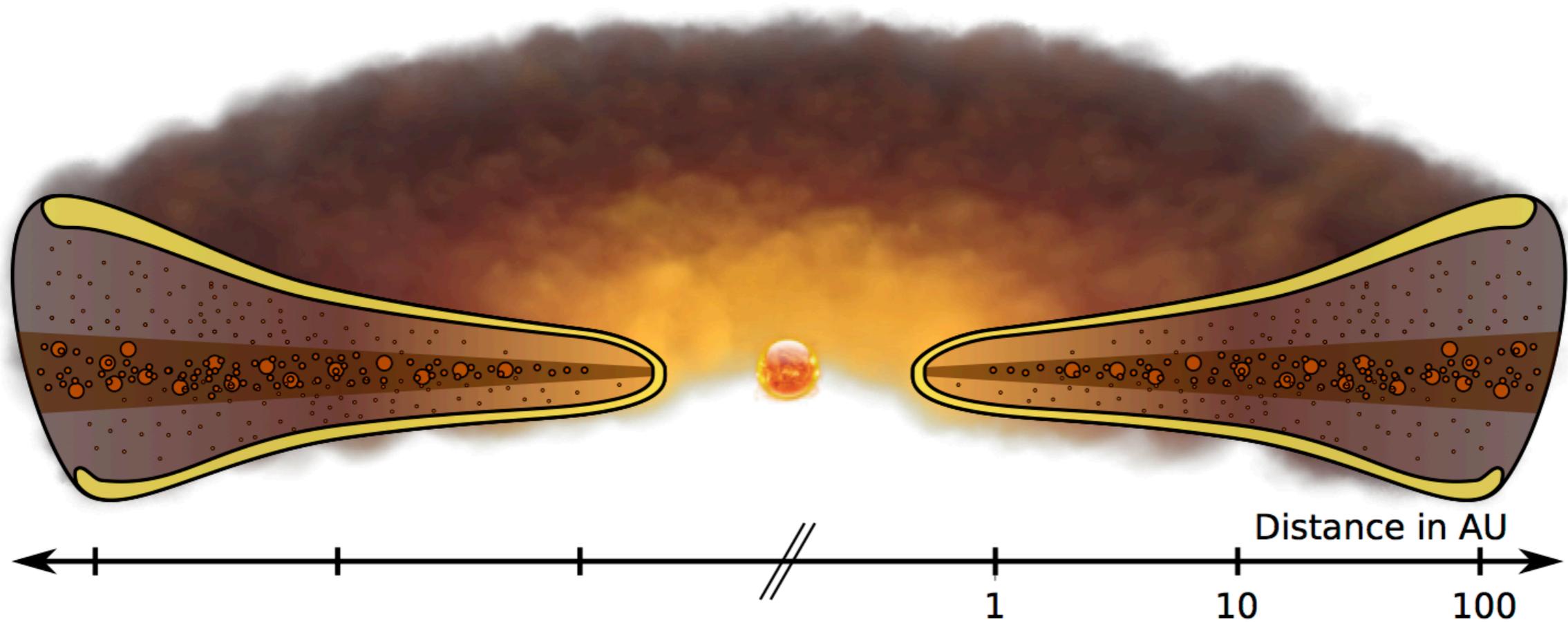


More complex cyanides are common as well, indicative of a robust cyanide chemistry

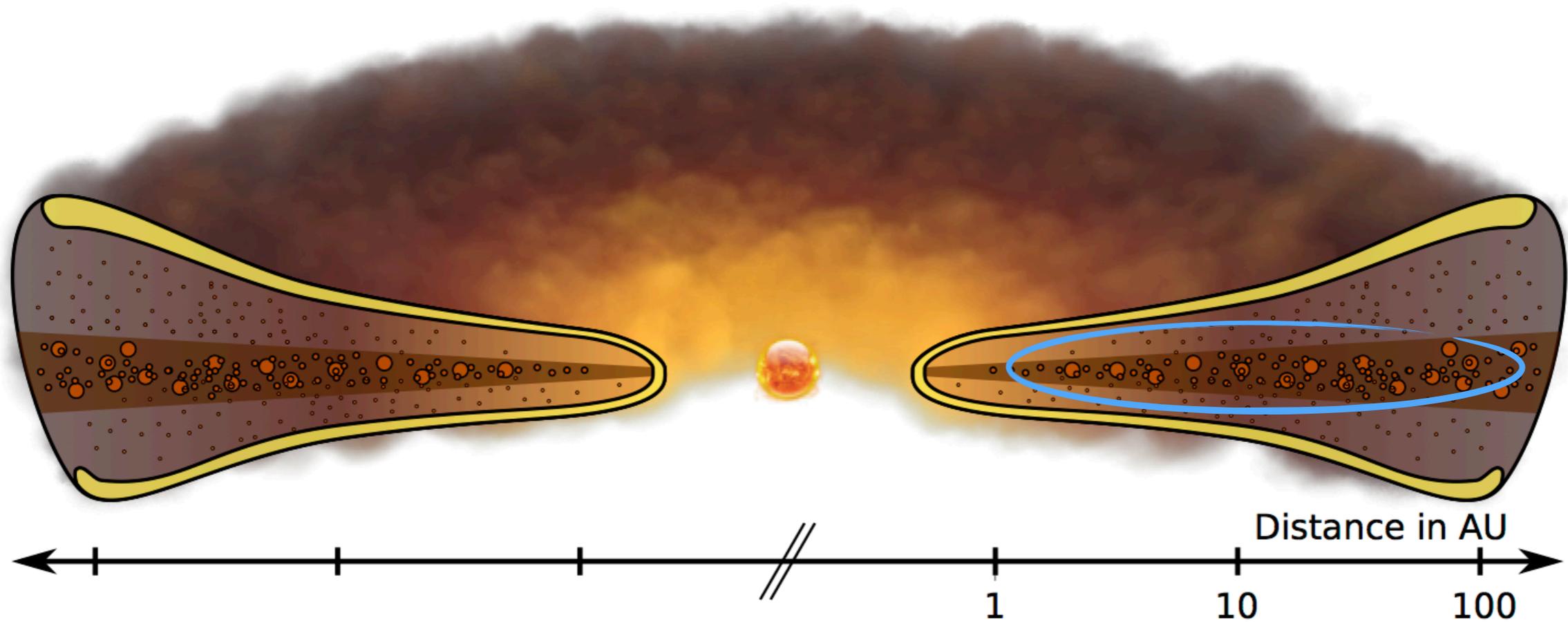
but distributions and abundances are source specific



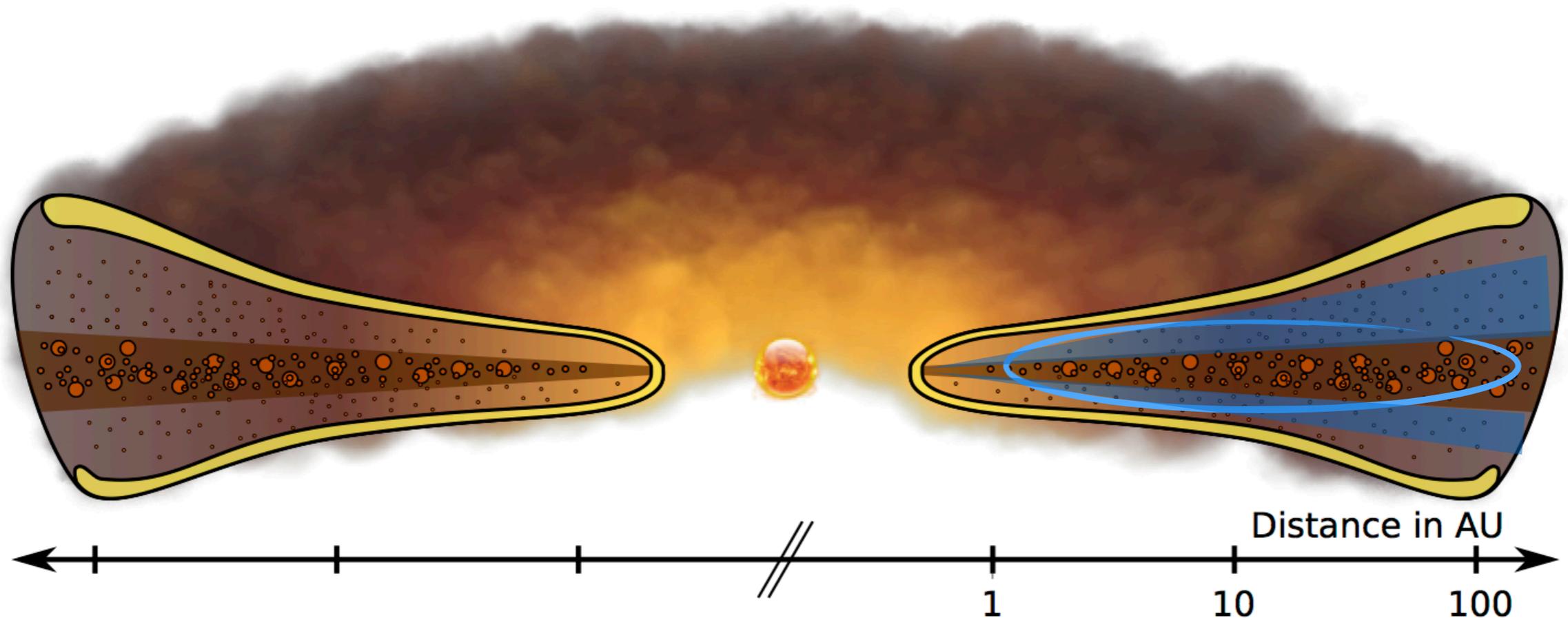
How do observed organics relate to the organic reservoir planets accrete from?



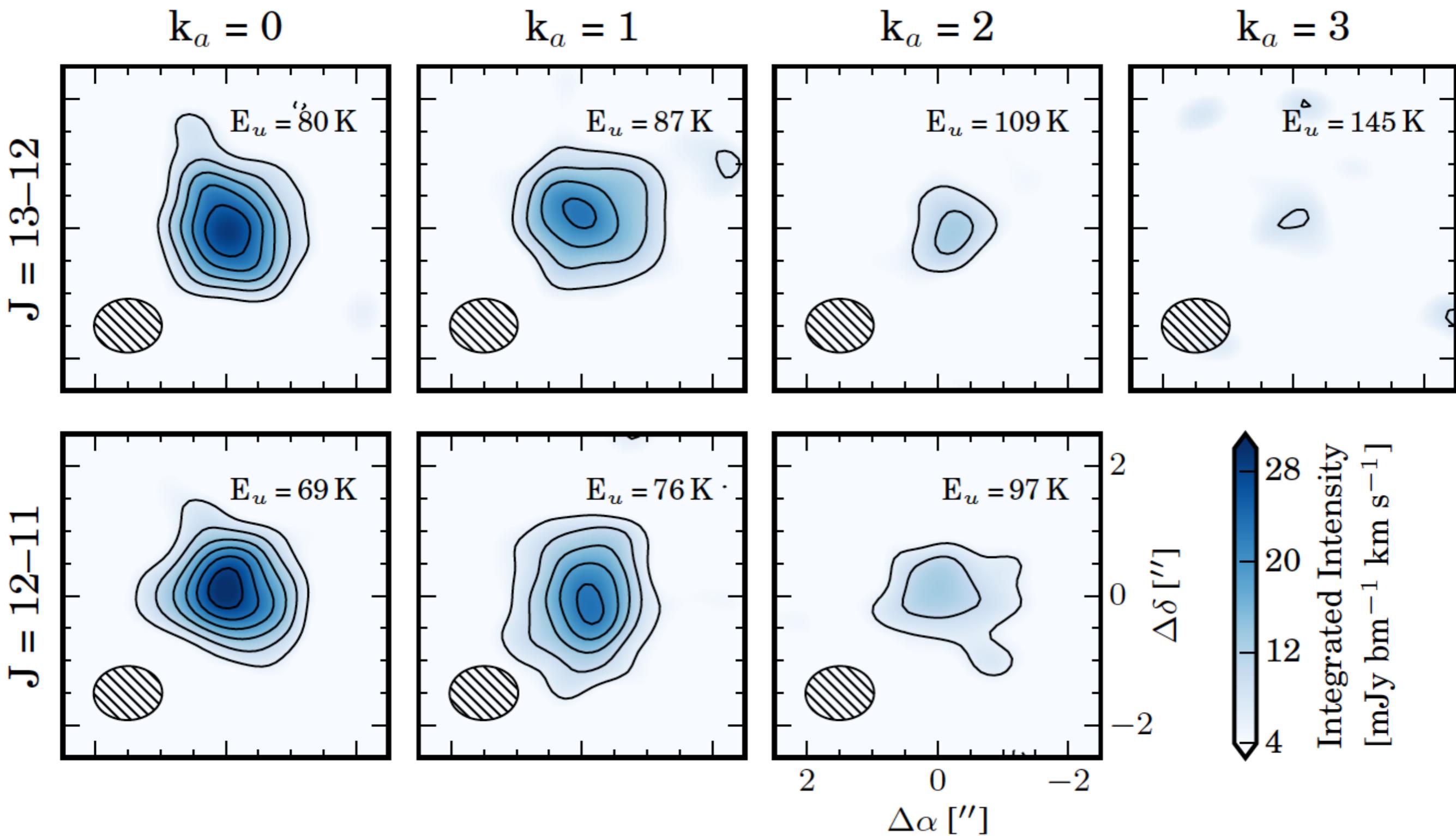
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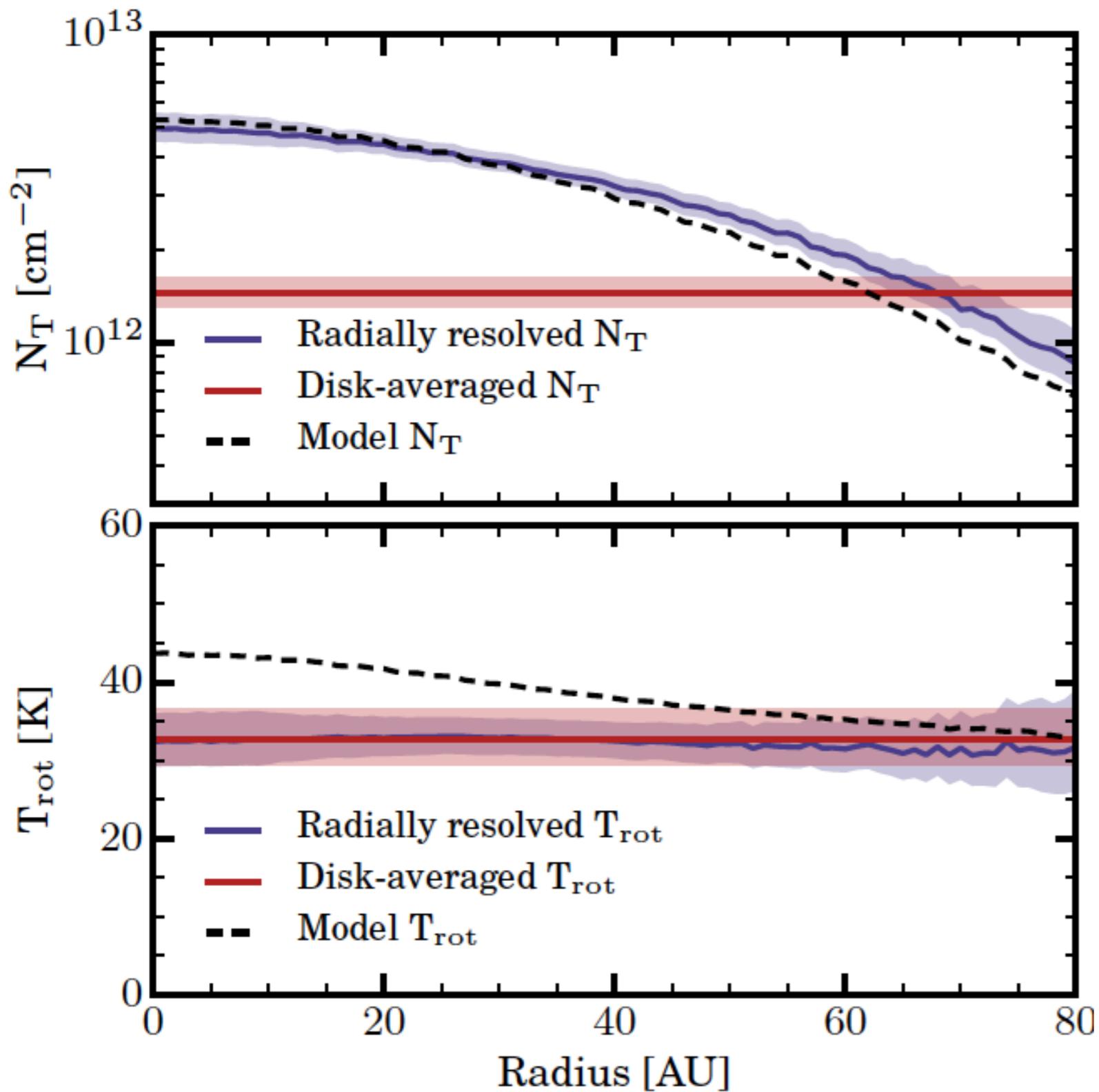
How do observed organics relate to the organic reservoir planets accrete from?



# Distribution of CH<sub>3</sub>CN in a disk

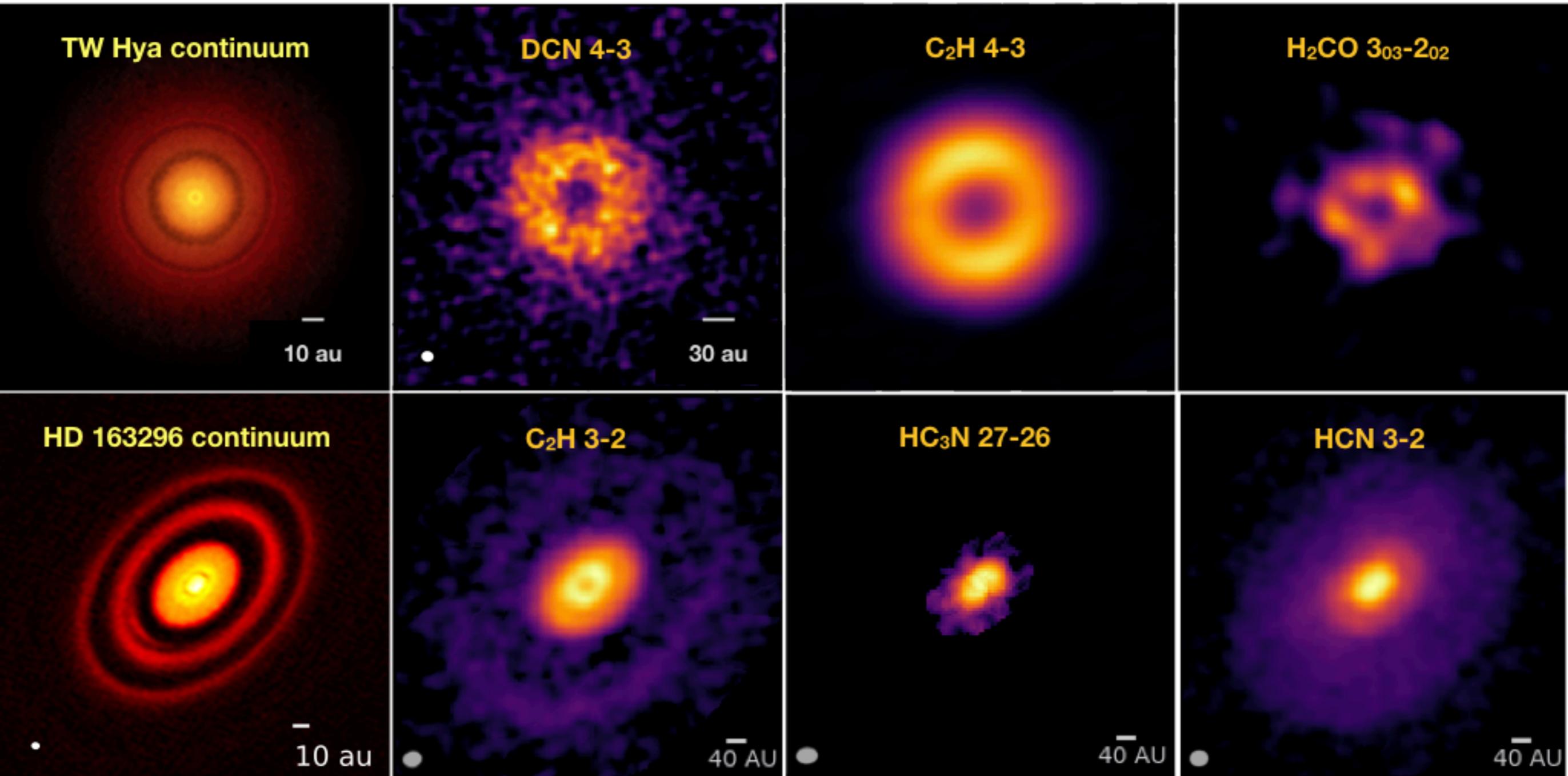


# Distribution of CH<sub>3</sub>CN in a disk

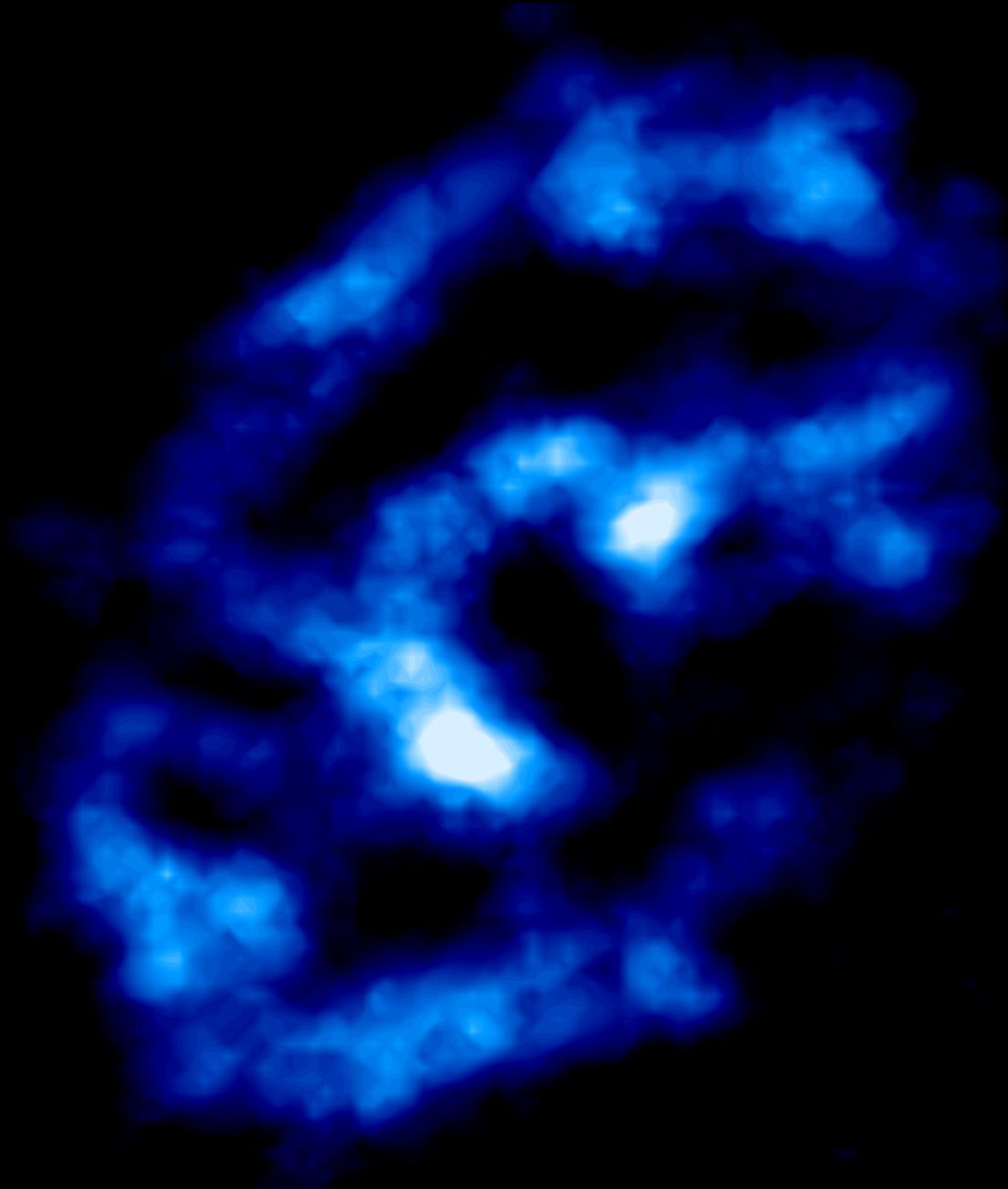


[Loomis+ 2018]

# ALMA images of disk chemistry

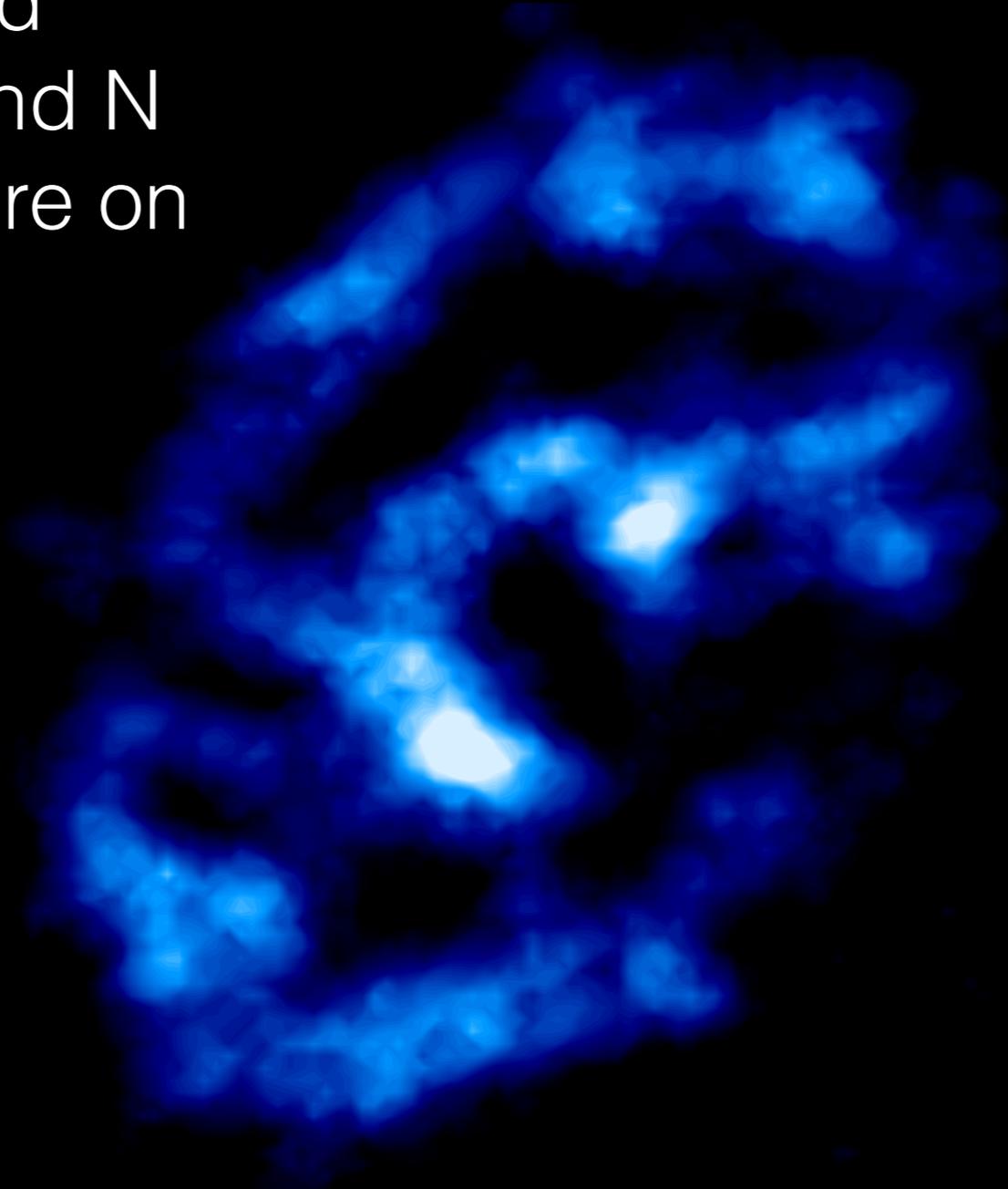


# Origins of chemical sub-structures



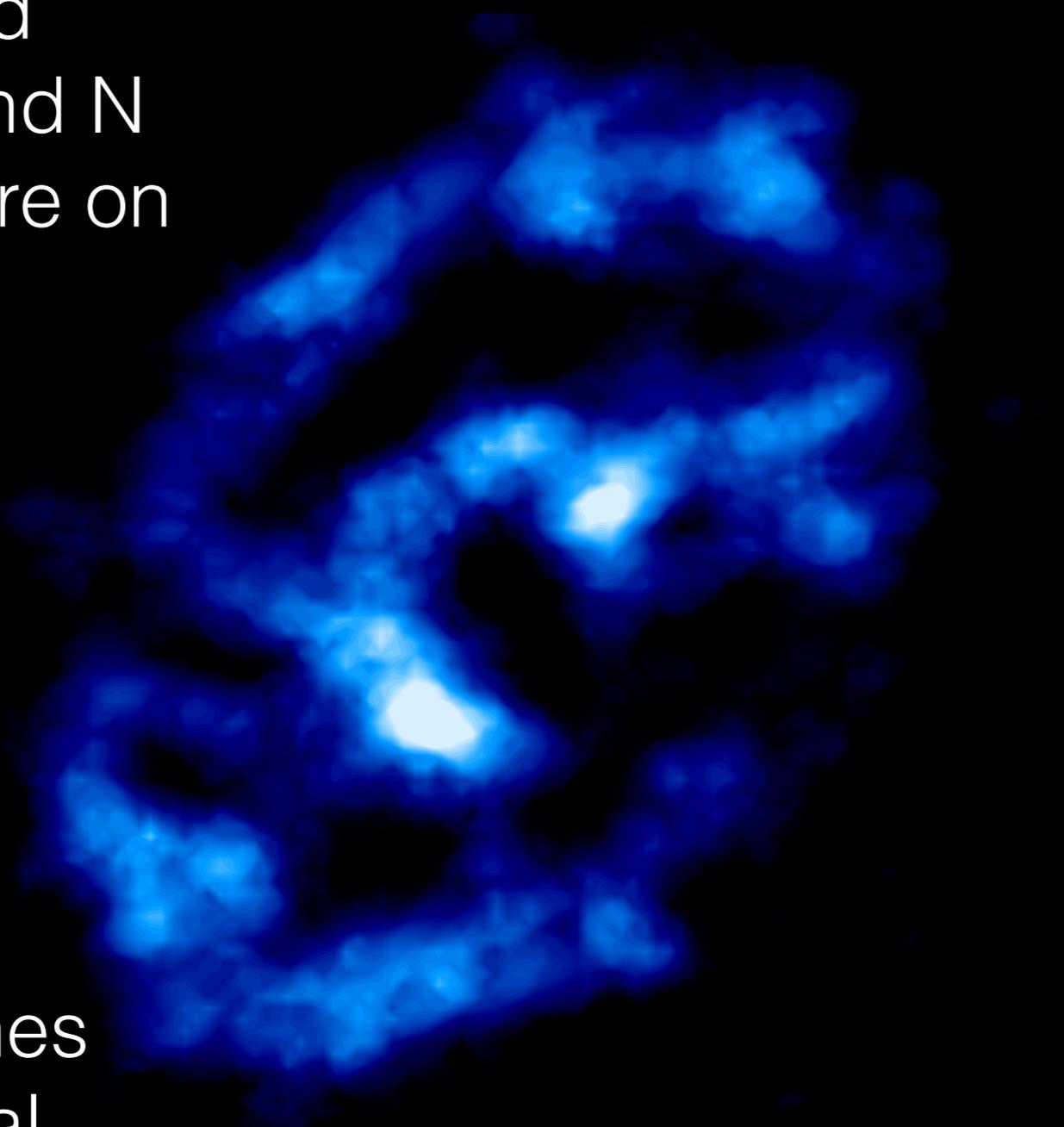
# Origins of chemical sub-structures

Major carriers and probes of O, C and N show sub-structure on 50-100 au scales



# Origins of chemical sub-structures

Major carriers and probes of O, C and N show sub-structure on 50-100 au scales

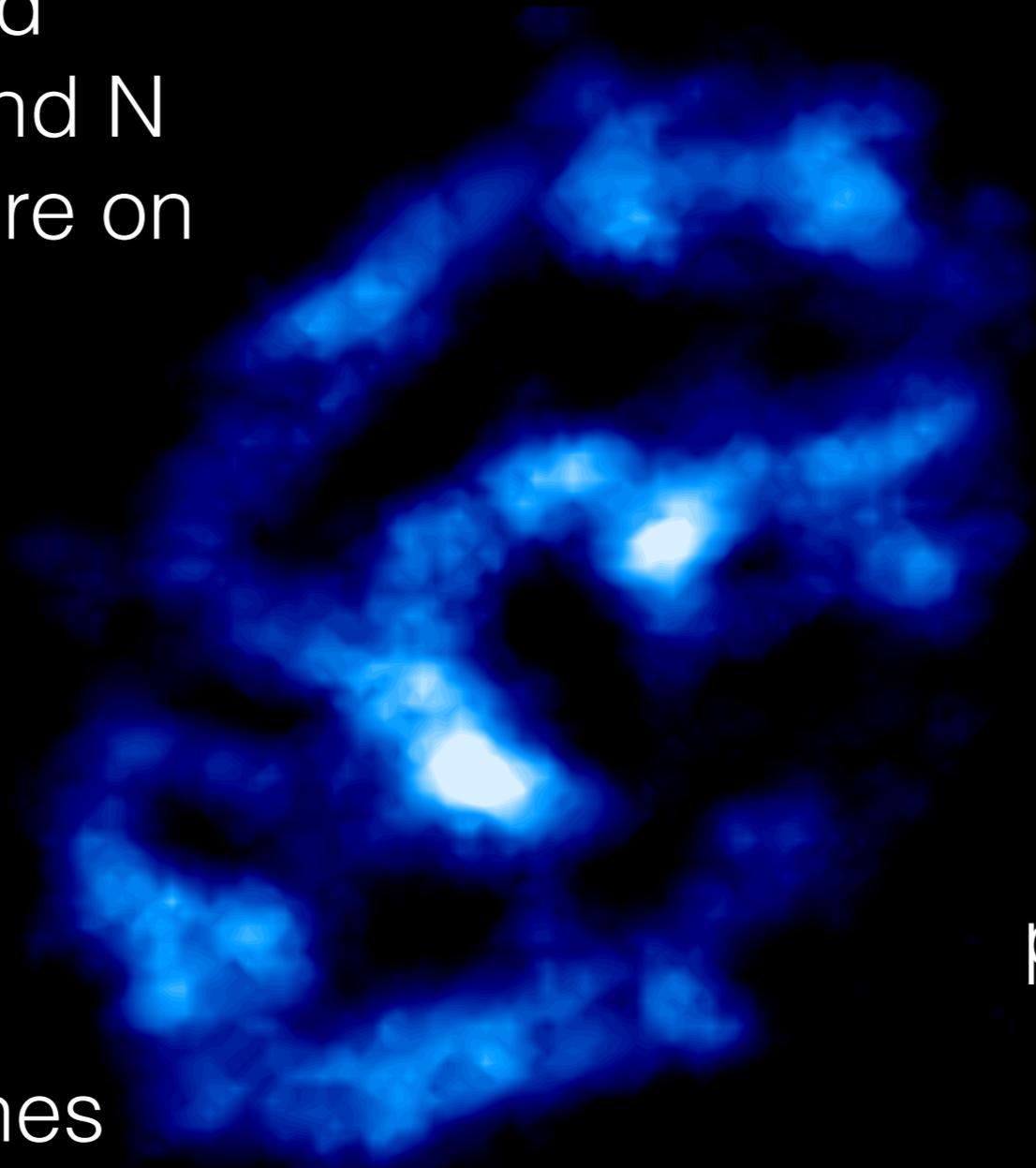


Some can be related to snowlines and their chemical effects

# Origins of chemical sub-structures

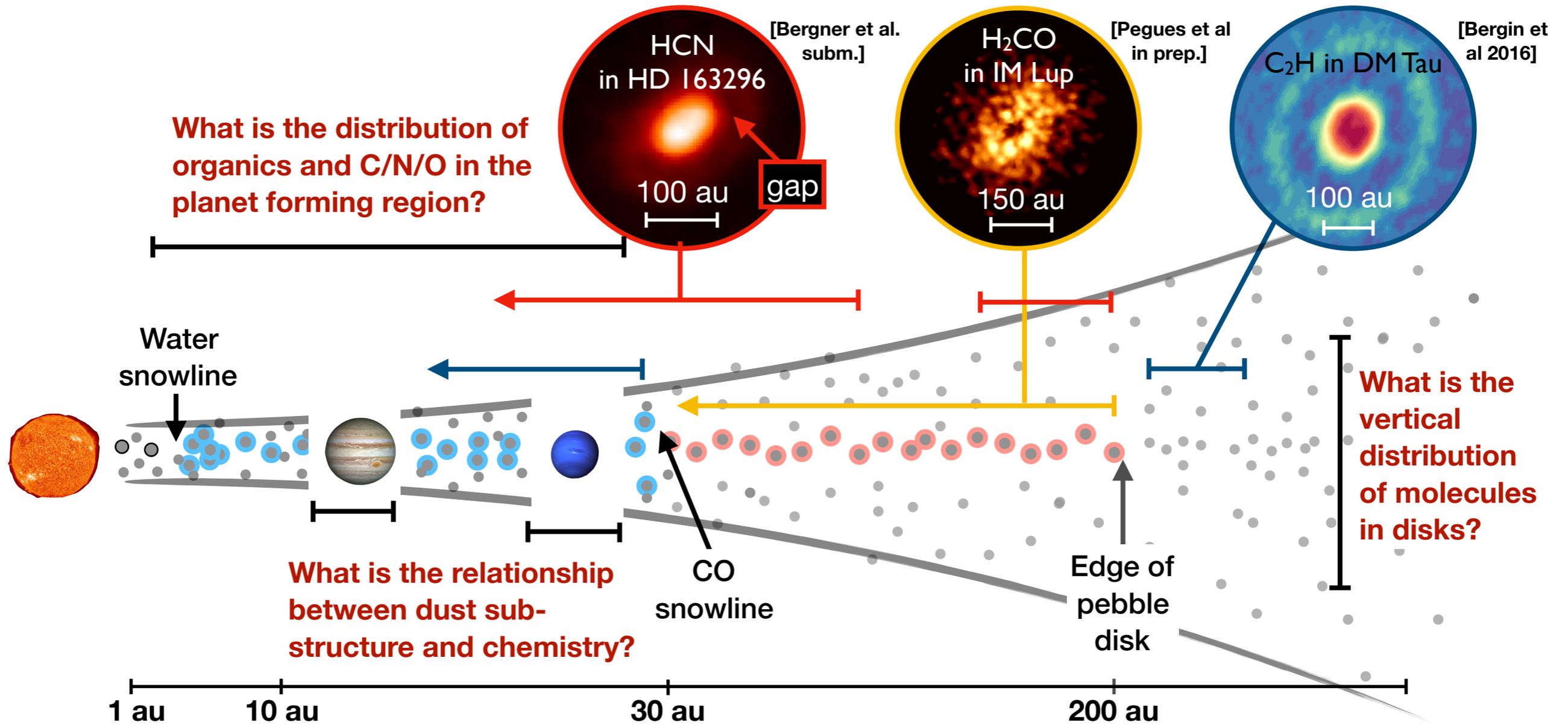
Major carriers and probes of O, C and N show sub-structure on 50-100 au scales

Some can be related to snowlines and their chemical effects

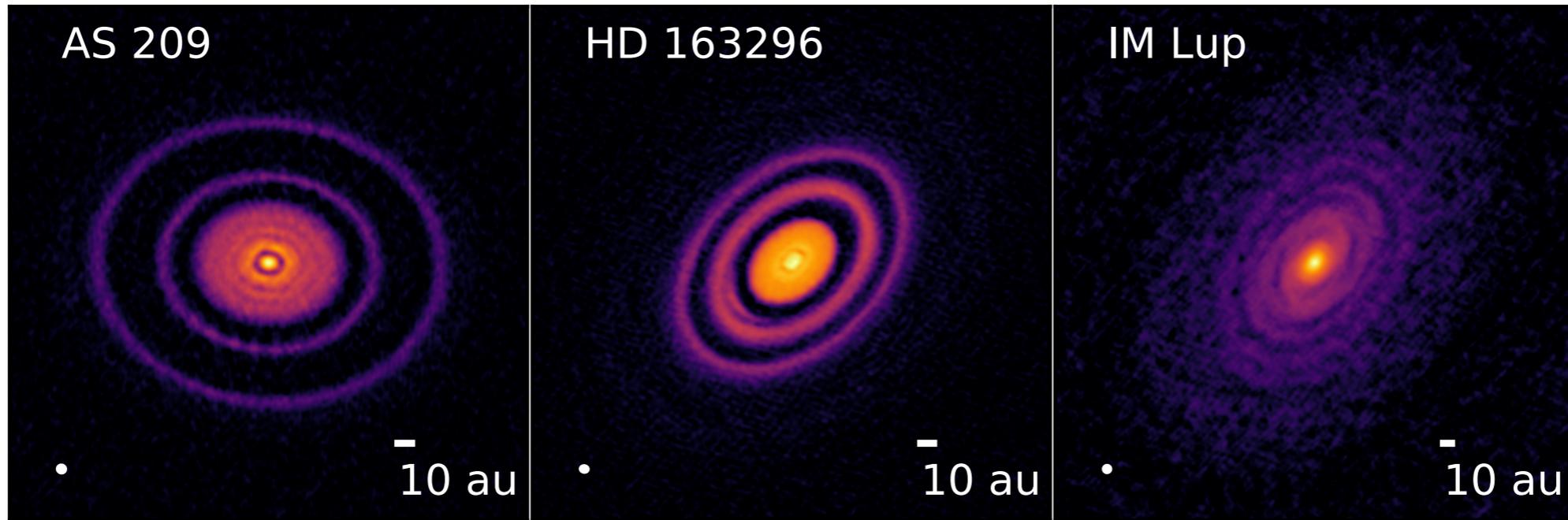


Others may reflect a sequential sequestration of O, C and N into solids, changing the gas and ice C/N/O ratios while planets are forming

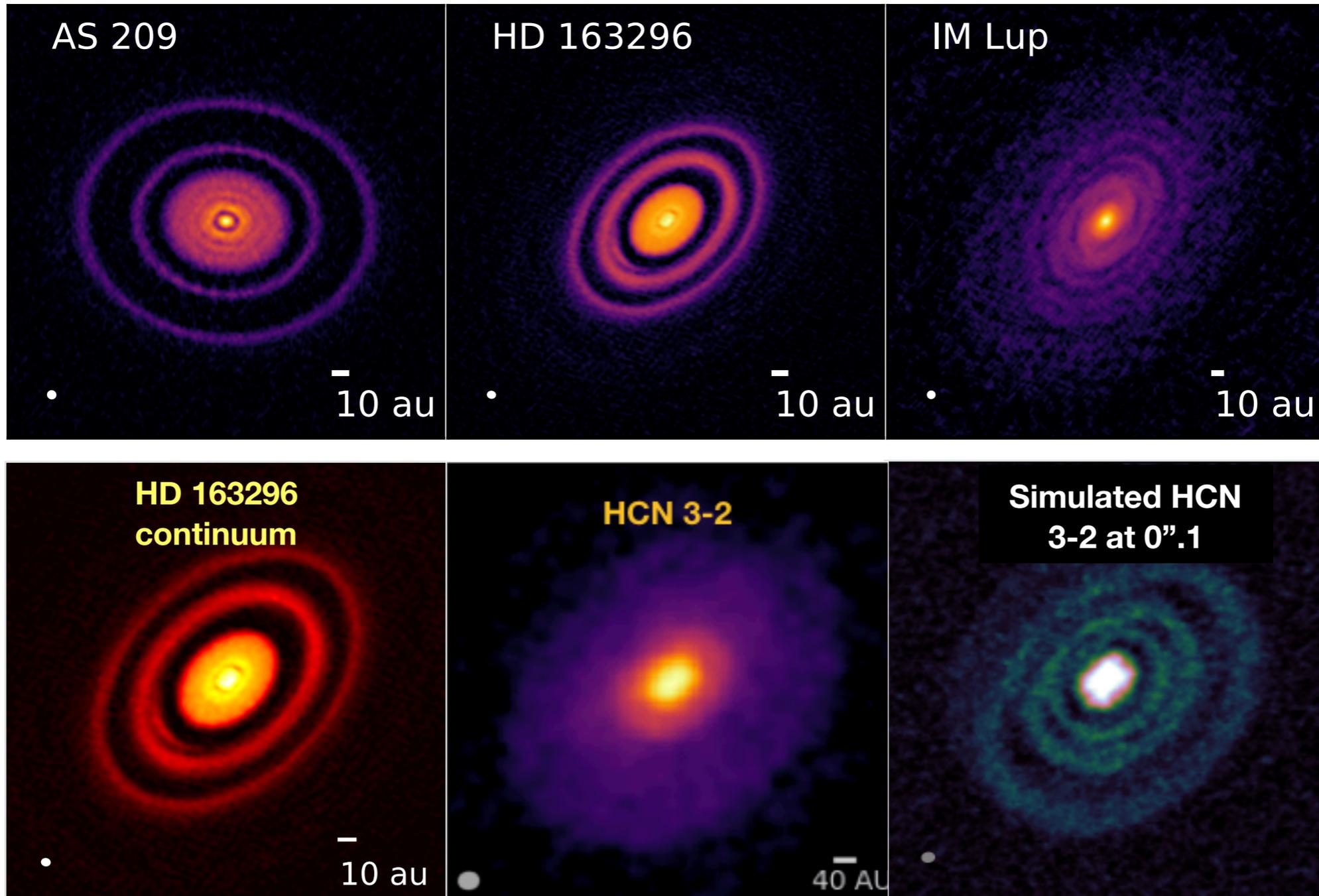
# High-resolution disk chemistry



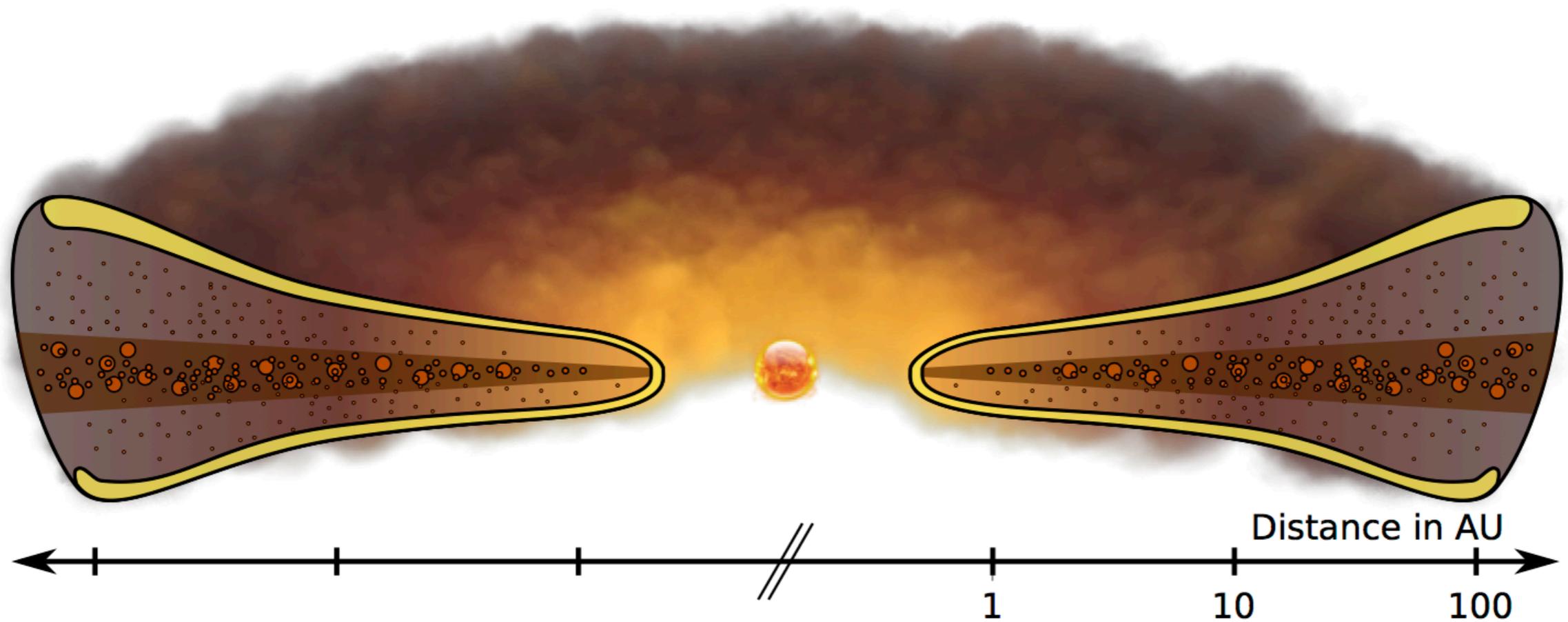
# MAPS: Molecules with ALMA in Planet-forming Systems



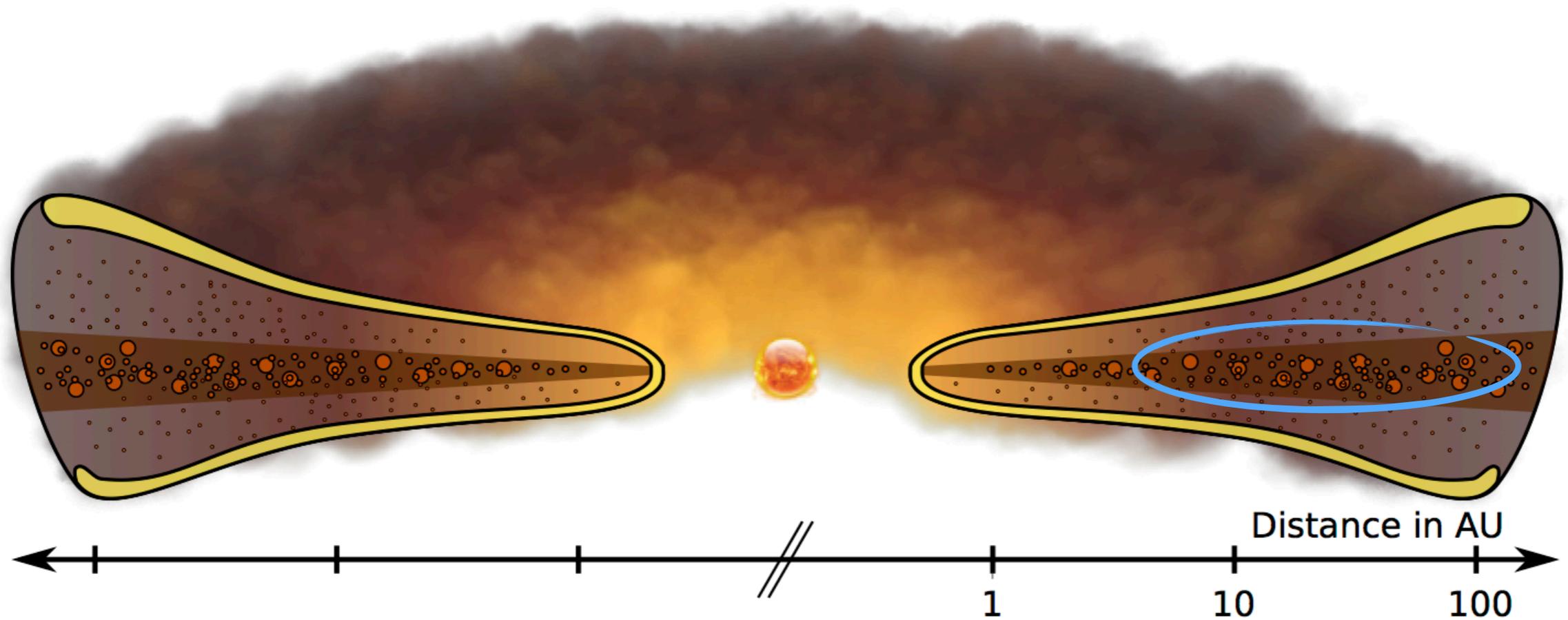
# MAPS: Molecules with ALMA in Planet-forming Systems



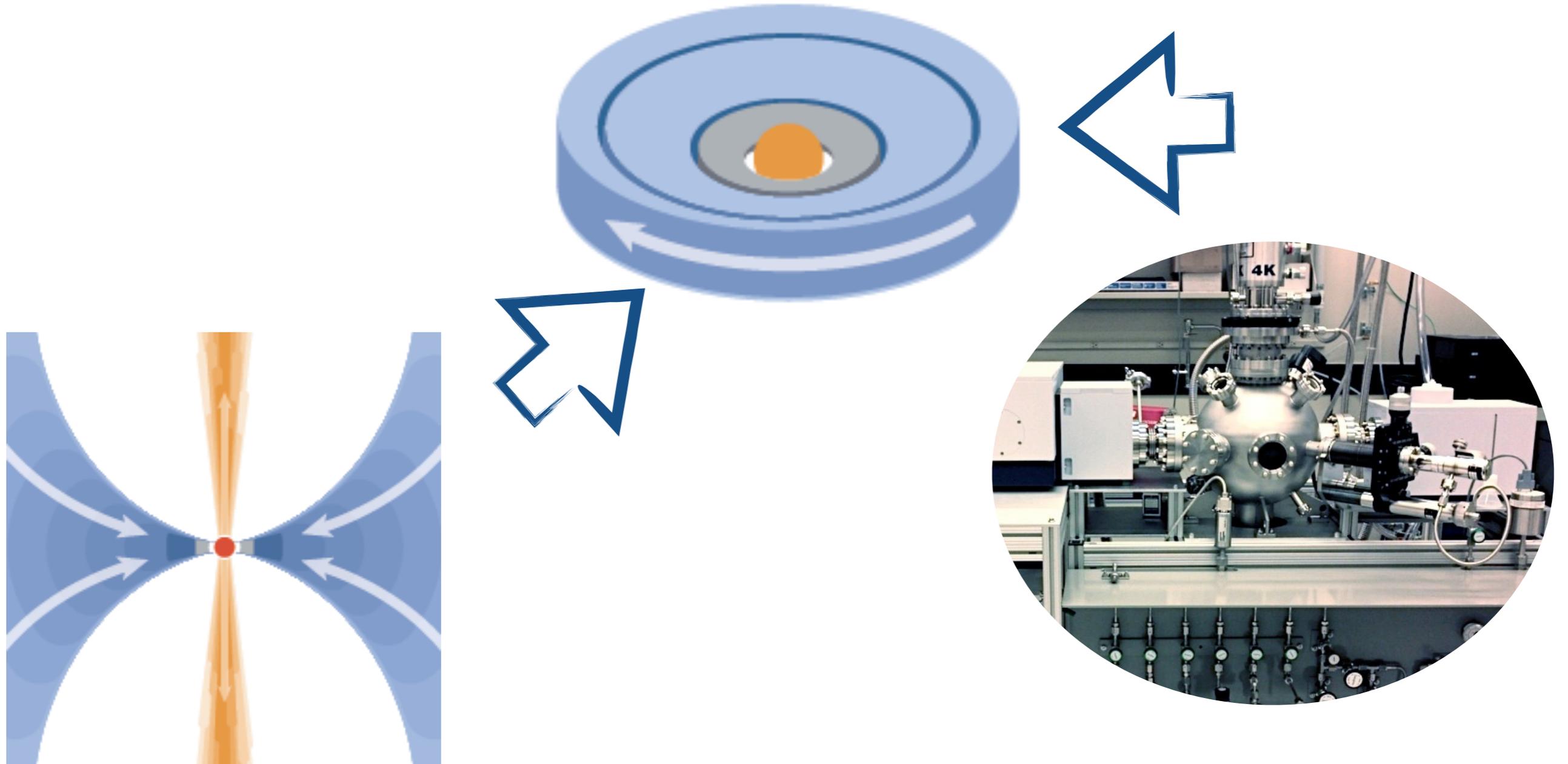
# Probing the icy organic reservoir and more complex organics



# Probing the icy organic reservoir and more complex organics

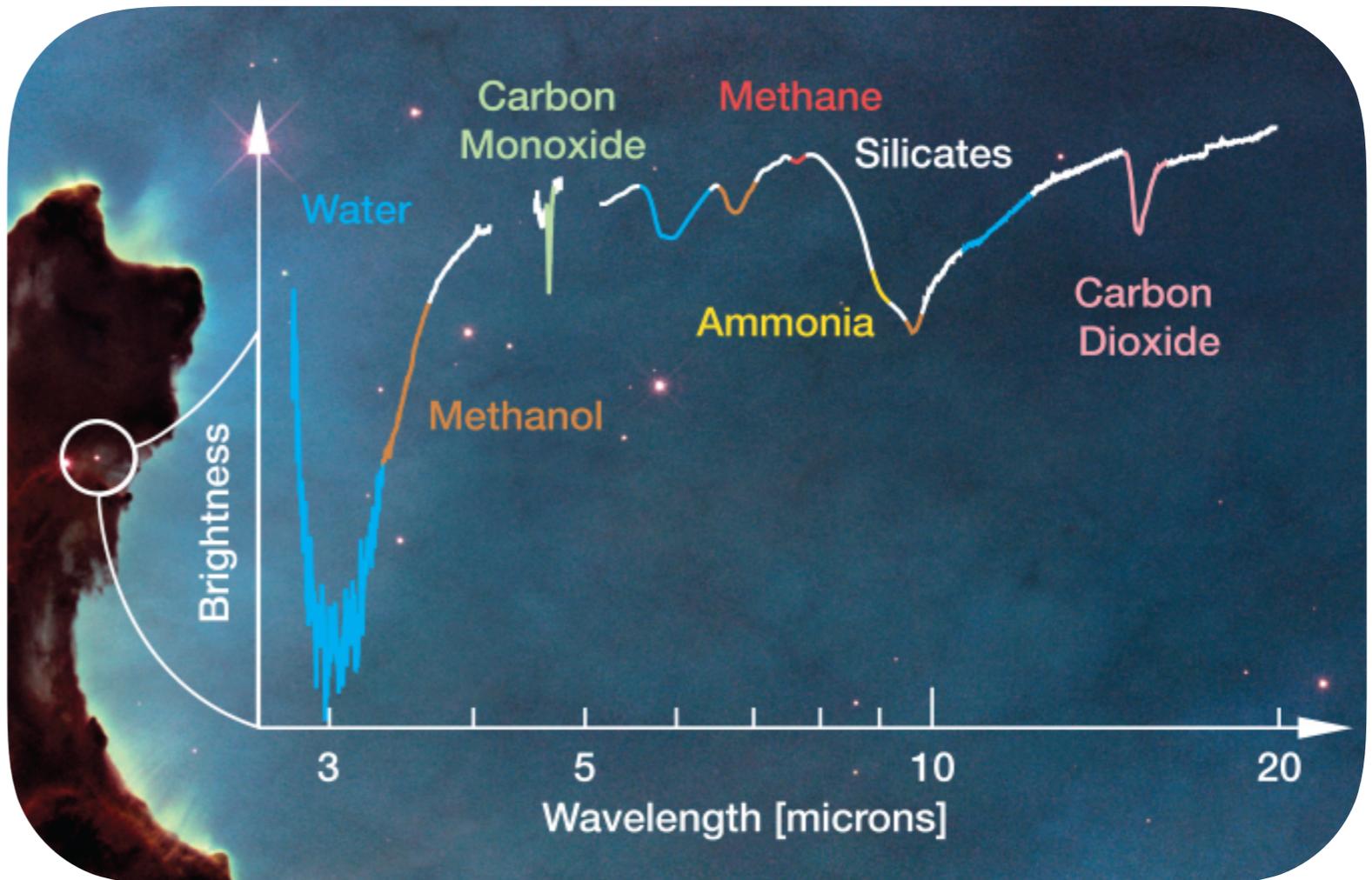
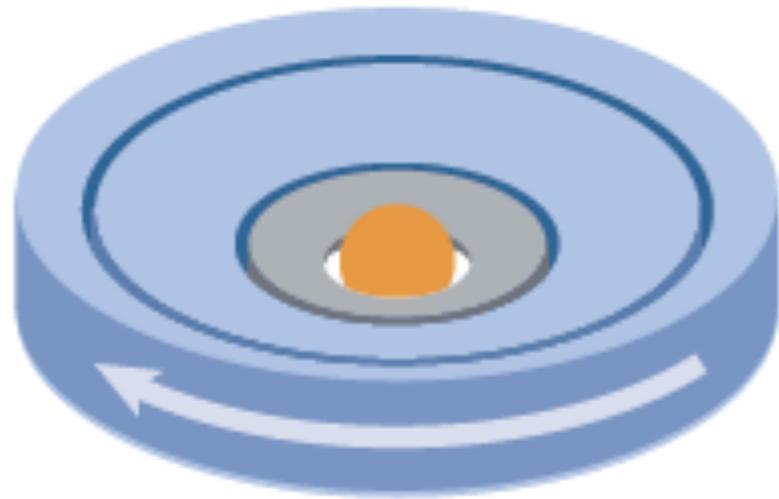
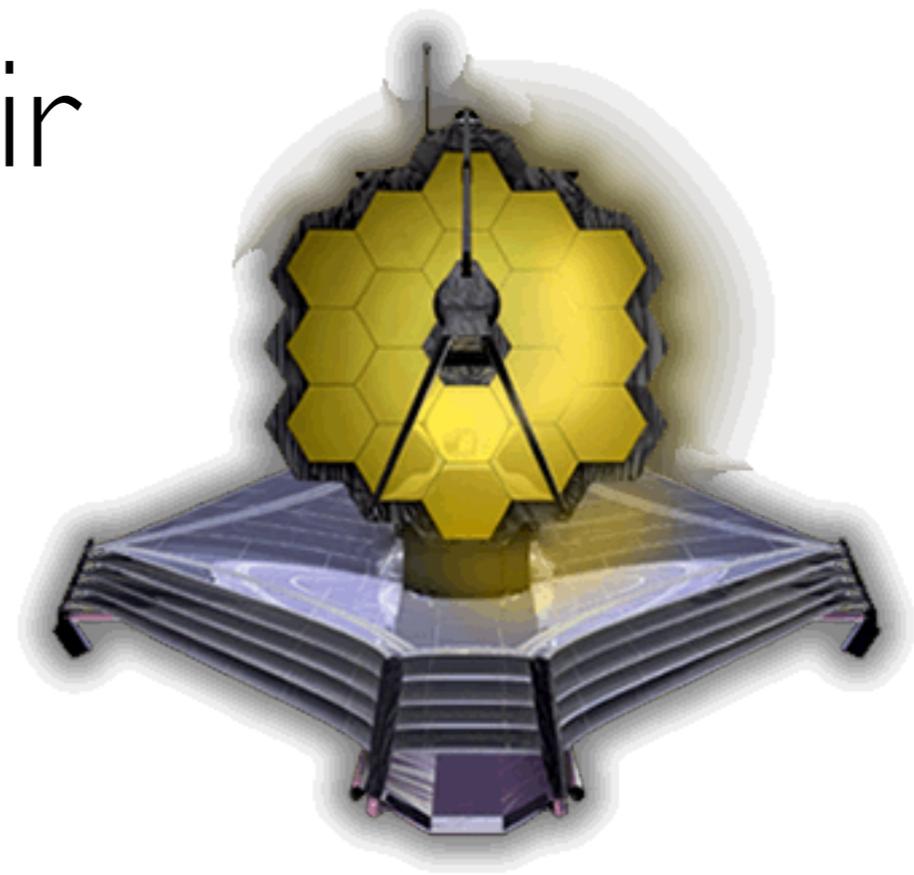


ALMA is blind to much further chemical complexity in disks

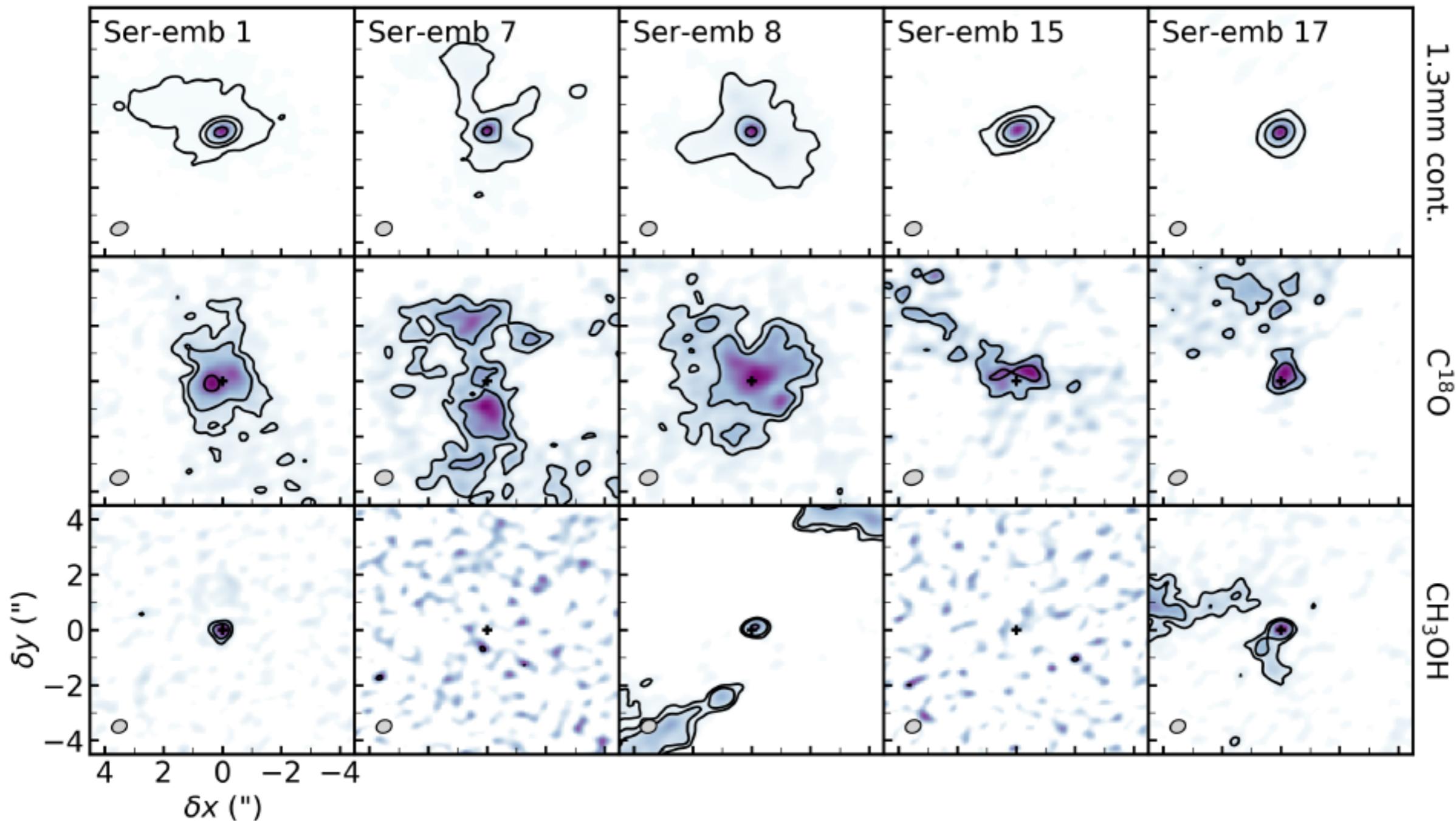
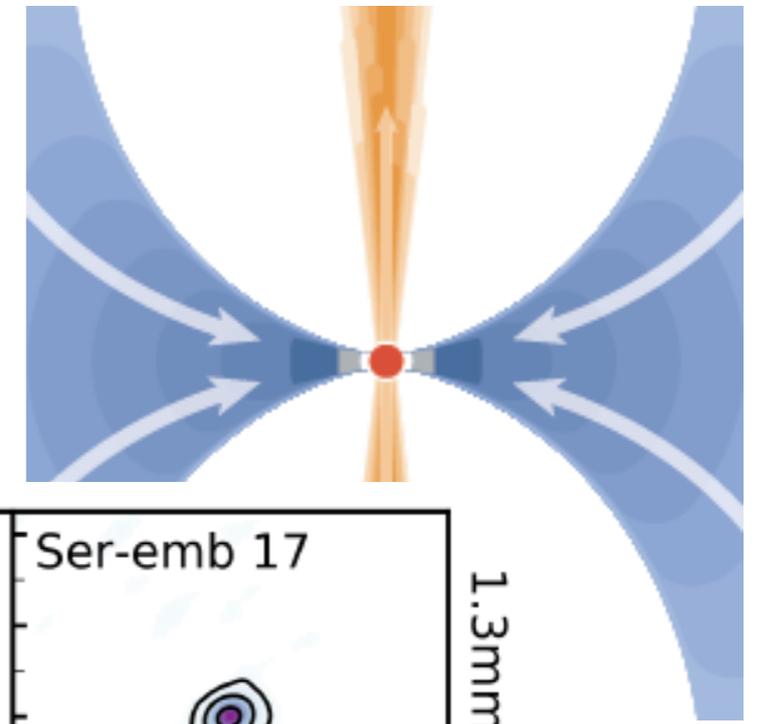


Need observations of complex molecules in other interstellar environments, and laboratory experiments to predict the complete disk organic composition

# Probing the ice reservoir in planet forming disks: JWST IceAge ERS

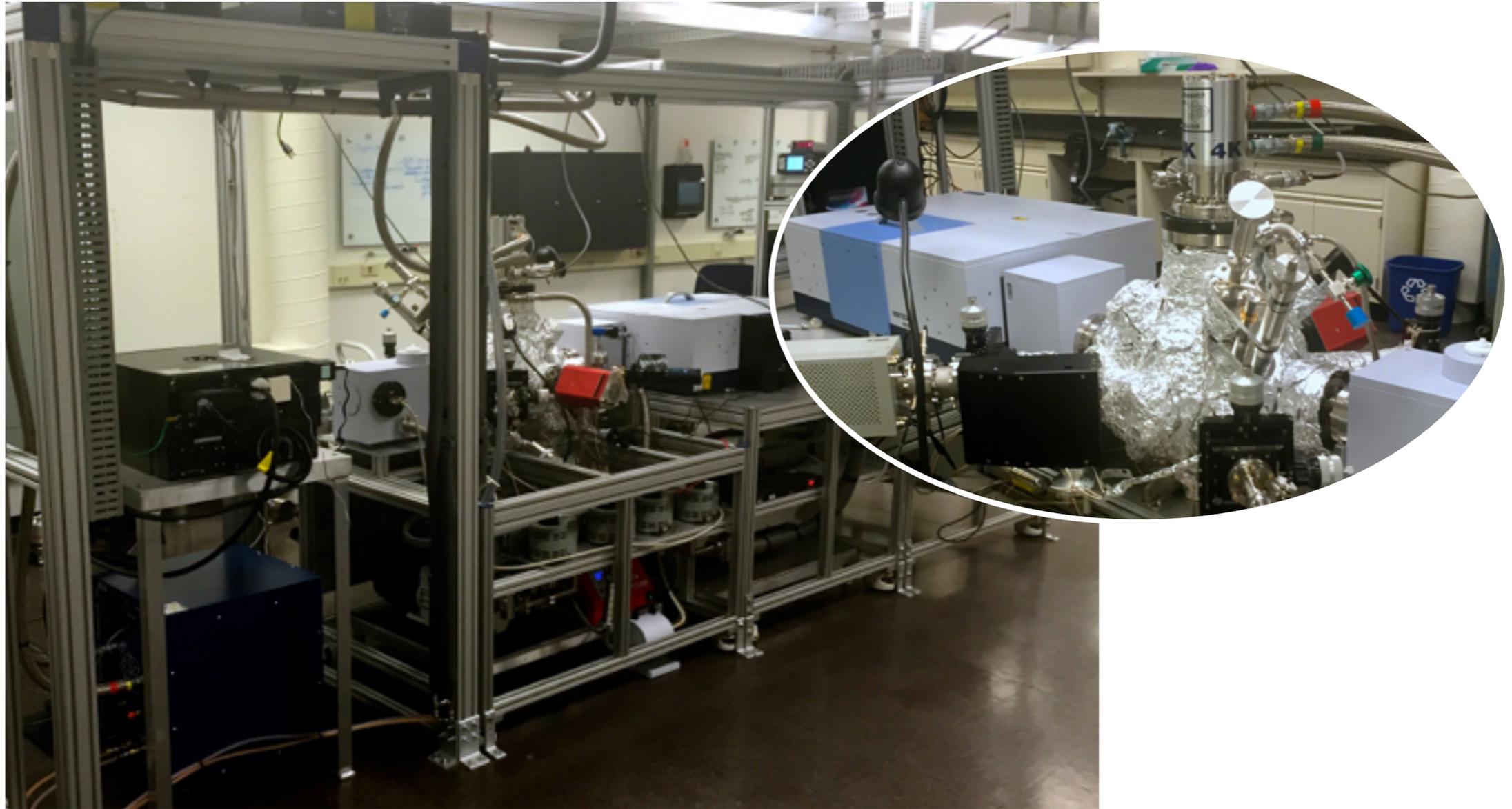


# Probing the chemistry in protostellar disks

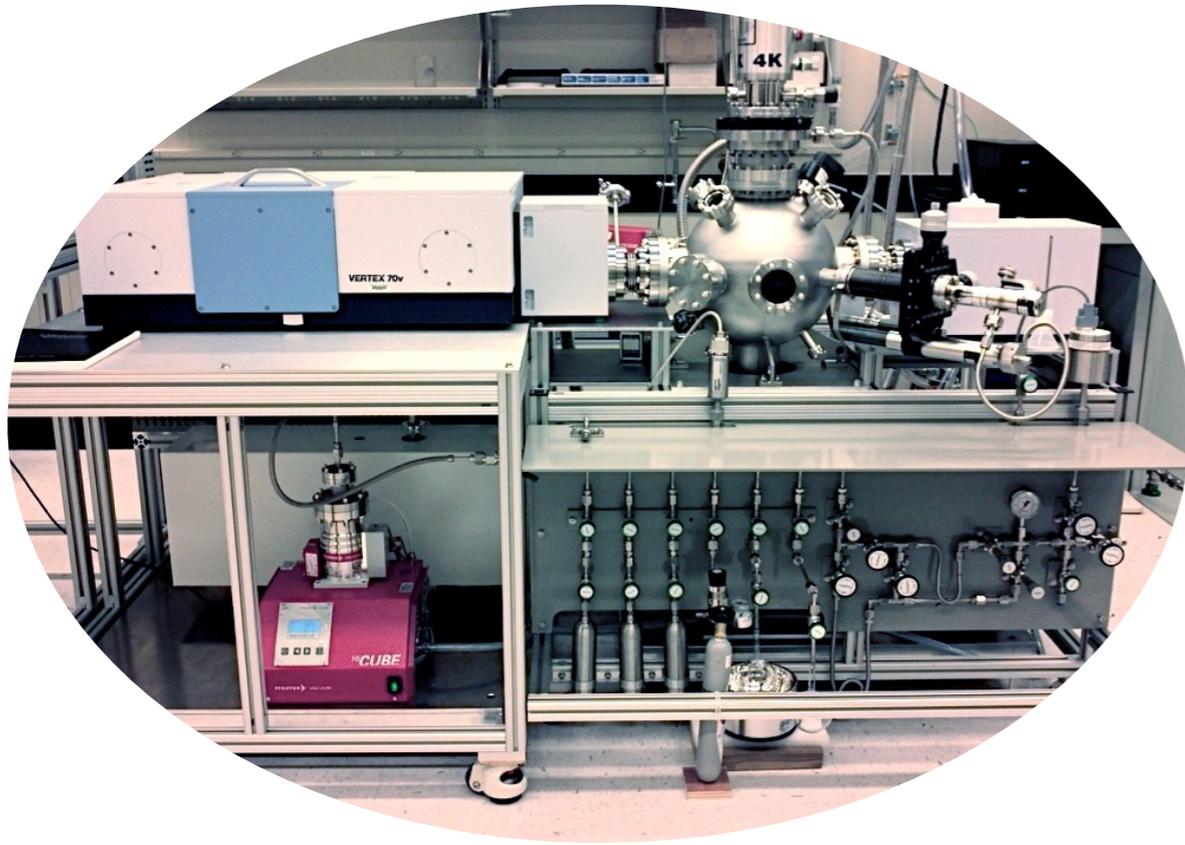


[Martin Domenech+ subm., Bergner+ subm.]

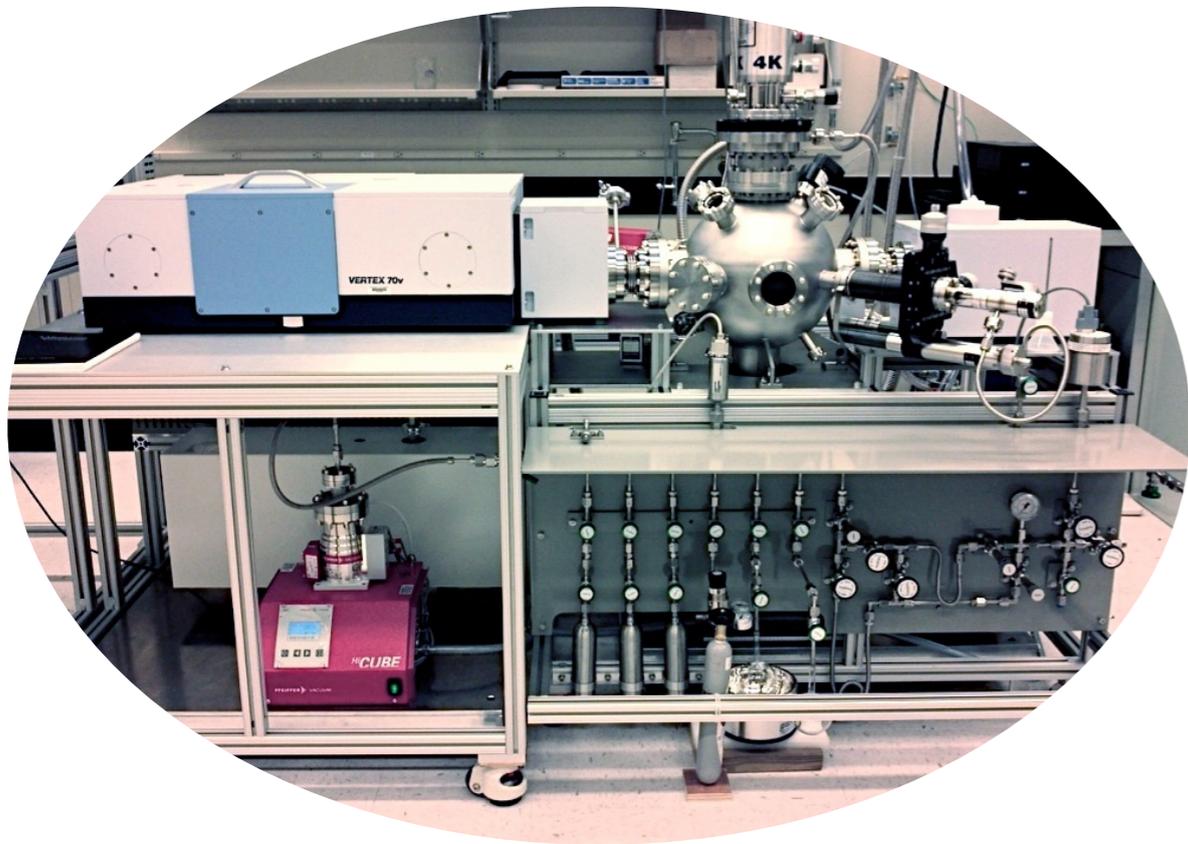
# Laboratory Ice Experiments to identify new, low-temperature pathways to complex organics



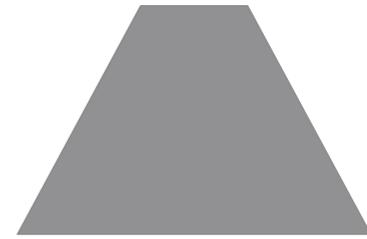
O insertion into hydrocarbons as a source of ice chemical complexity



# O insertion into hydrocarbons as a source of ice chemical complexity



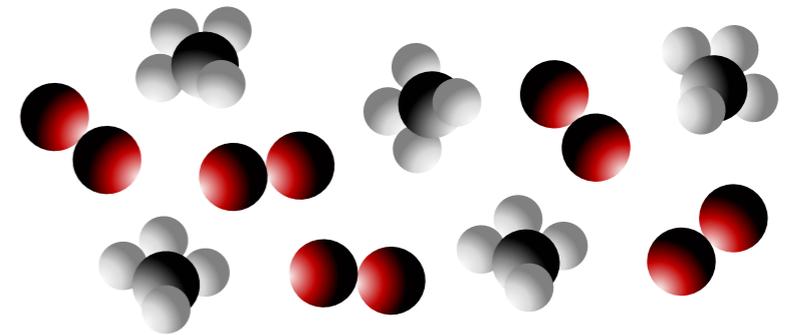
H<sub>2</sub>D<sub>2</sub> lamp



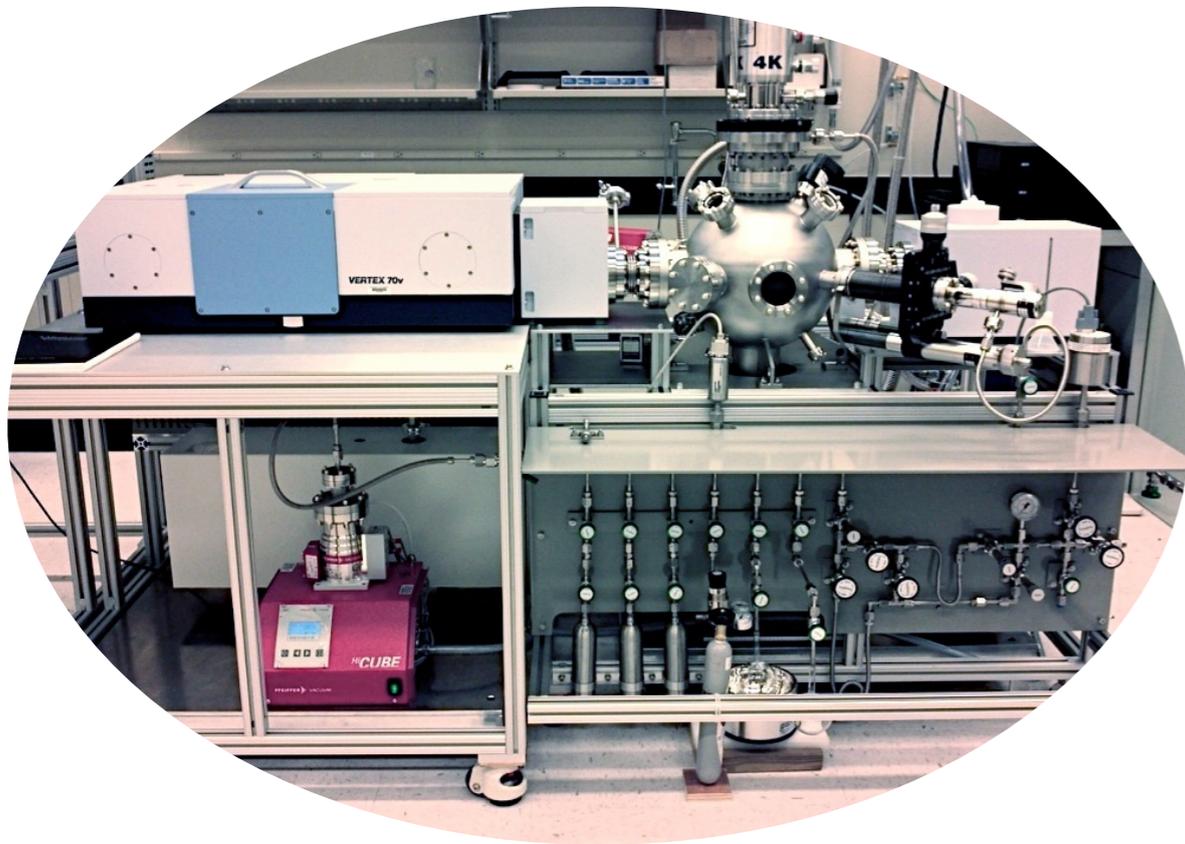
Sapphire window



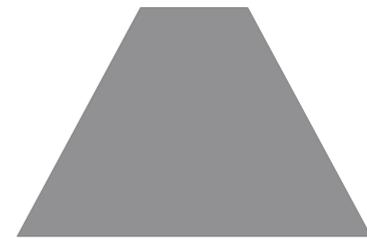
CH<sub>4</sub>:O<sub>2</sub> ice mixture



# O insertion into hydrocarbons as a source of ice chemical complexity



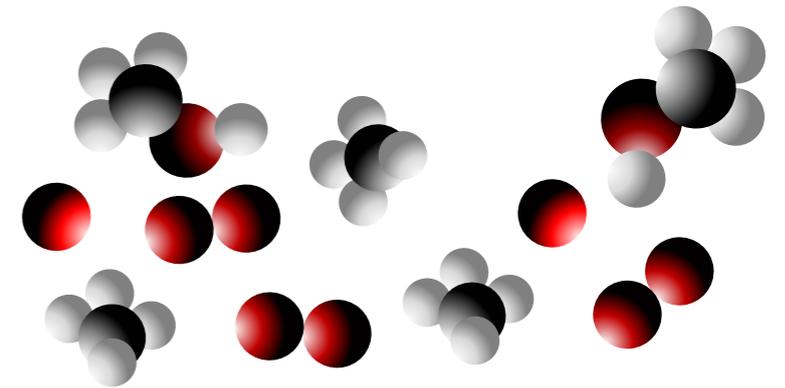
H<sub>2</sub>D<sub>2</sub> lamp

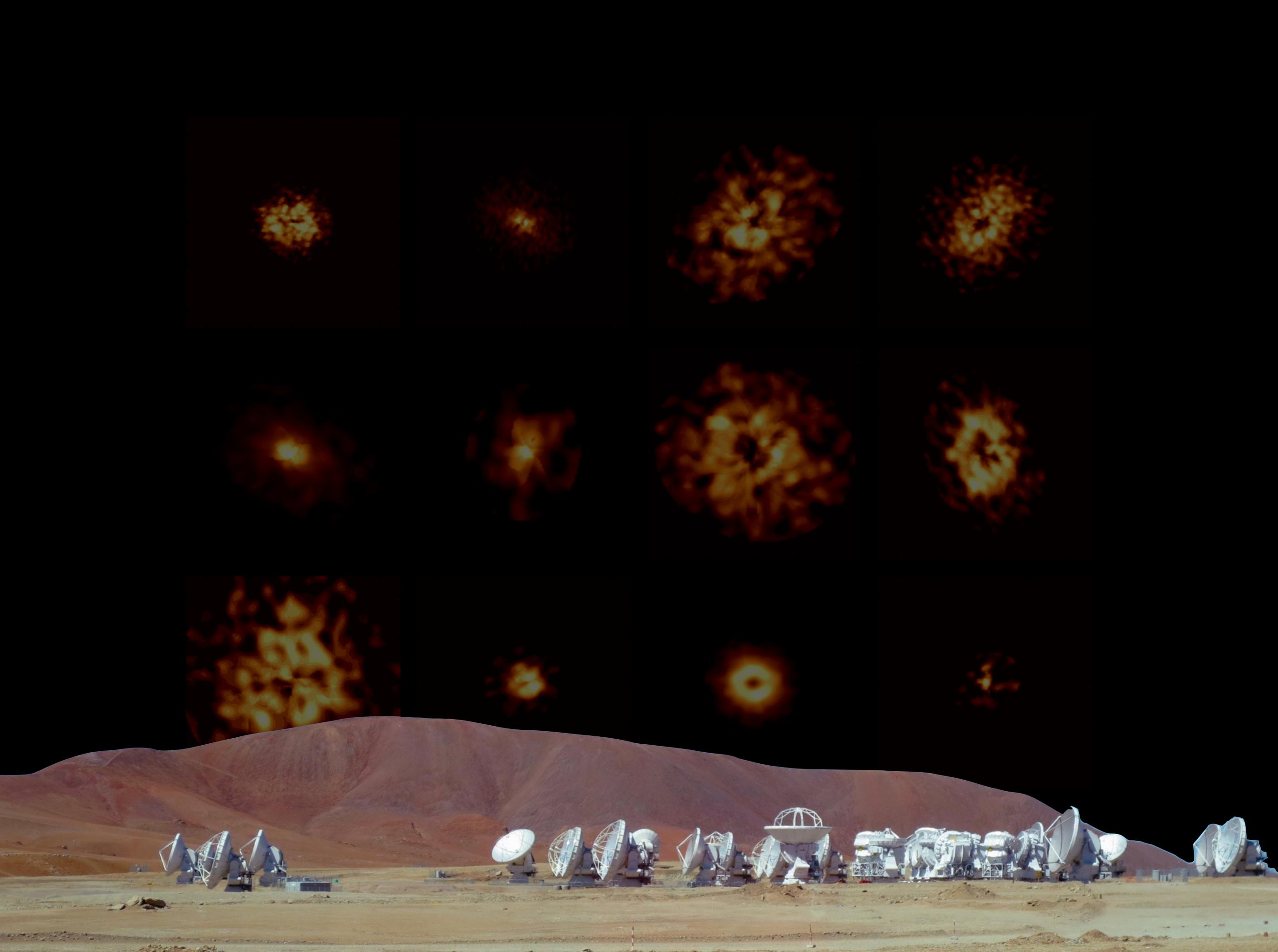


Sapphire window



CH<sub>4</sub>:O<sub>2</sub> ice mixture





# The Chemistry of Planet Formation

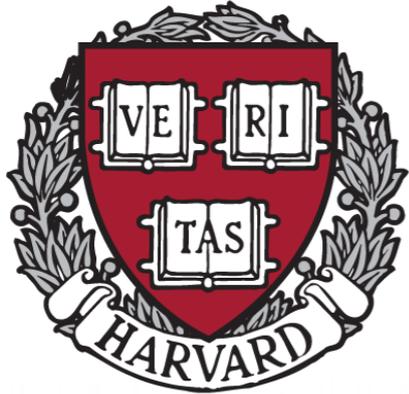
Planetary access to water and volatile organics depends on chemical processes and structures in planet forming disks around young stars.

ALMA lets us probe C/N/O gas phase ratios as well as small organics: the building blocks of life are common in planet forming disks, but their abundance may vary substantially between different systems.

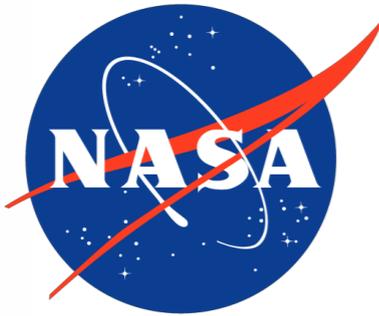
Experiments and observations of earlier phases of star formation are needed to constrain the complete volatile budget, and to probe more complex organic chemistry.



# Acknowledgements



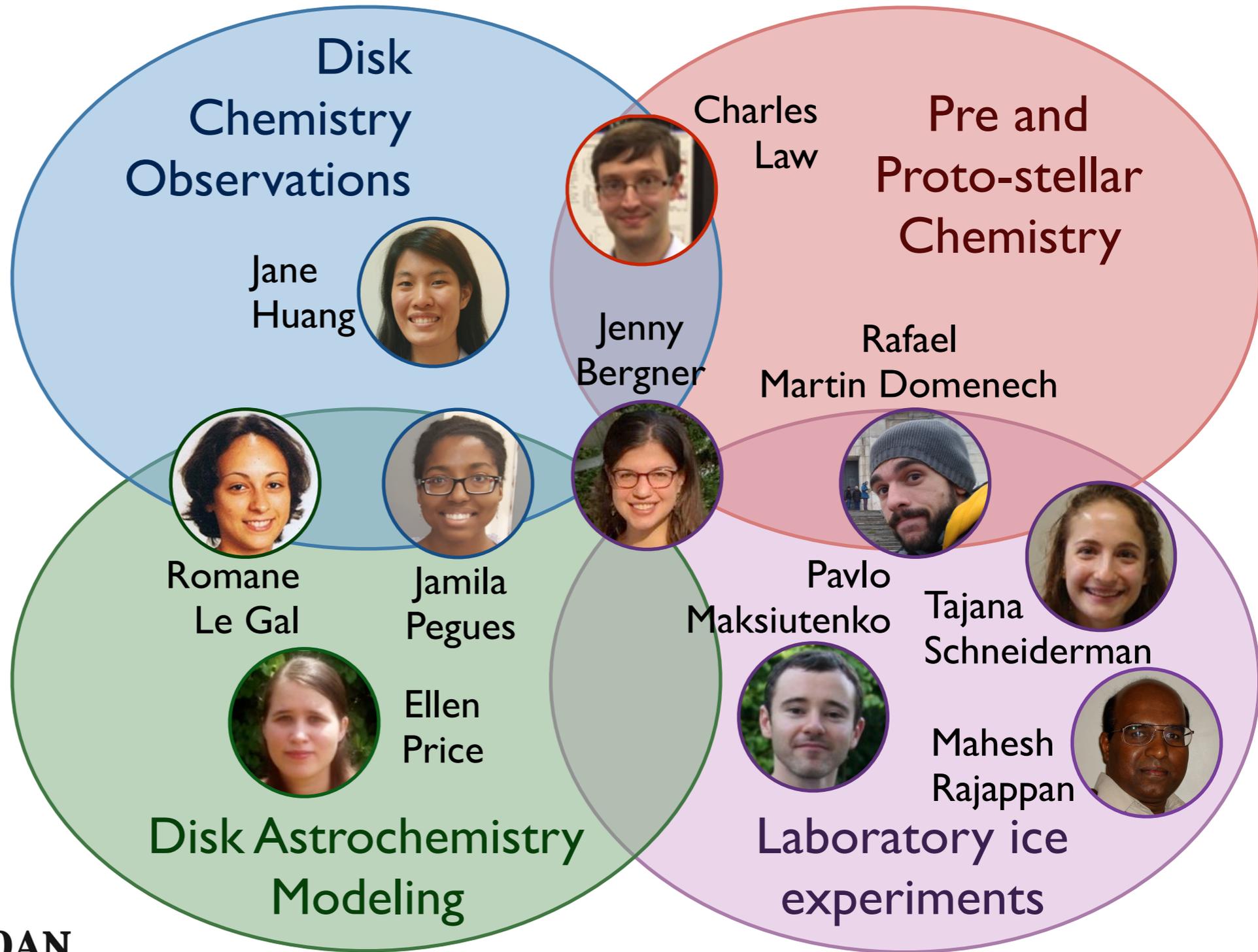
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