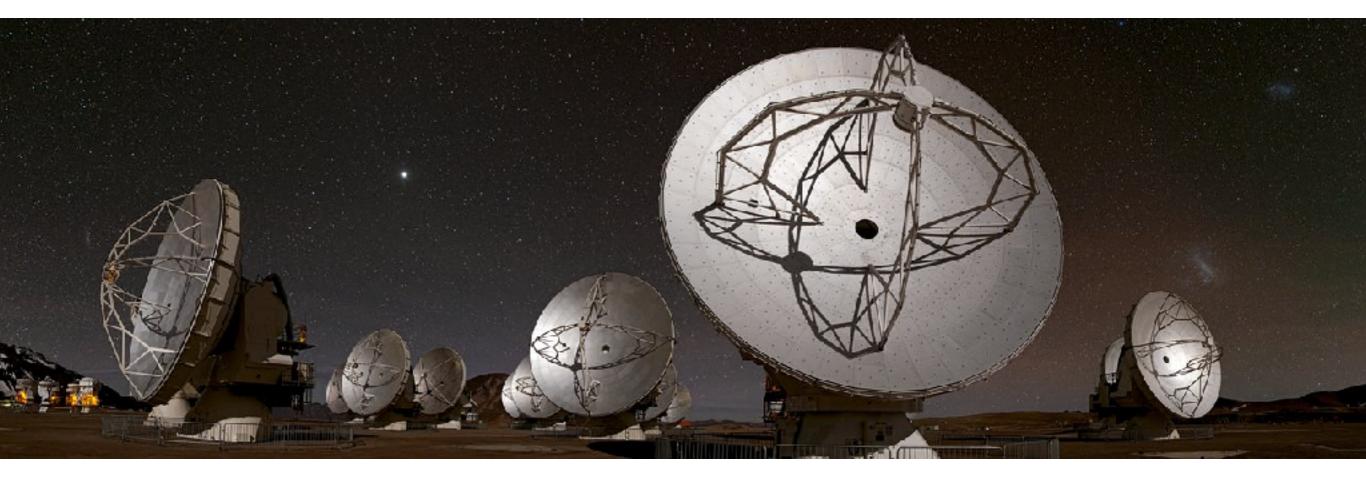
ALMA observations of chemistry in planet-forming disks

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University of Amsterdam





Netherlands Organisation for Scientific Research

Standard model star and planet formation

DENSE CLOUD

The mass of an interstellar cloud becomes sufficient to cause contraction by self-gravitation, leading to the formation of protostellar systems. In this phase, complex problotic molecules form that can be detected by the GBT.

DIFFUSE CLOUD

The material blown off from many stars accumulates to form an interstellar cloud of gas and dust of very low density. In such clouds, simple molecules form that can be detected with the GBT.

ACCRETION DISK

A protostellar system further contracts, forming a central protostar and a rotating disk of gas and dust that adoretes more material. More molecules form. Planets and comets eventually will form from the material in the outer/disk.

MASS LOSS

As the star's nuclear fuels deplete, the star becomes unstable, and blows off mass. In this process more molecules are formed that can be delected by the GBT. The material is ejected into the interstellar medium.

STELLAR SYSTEM

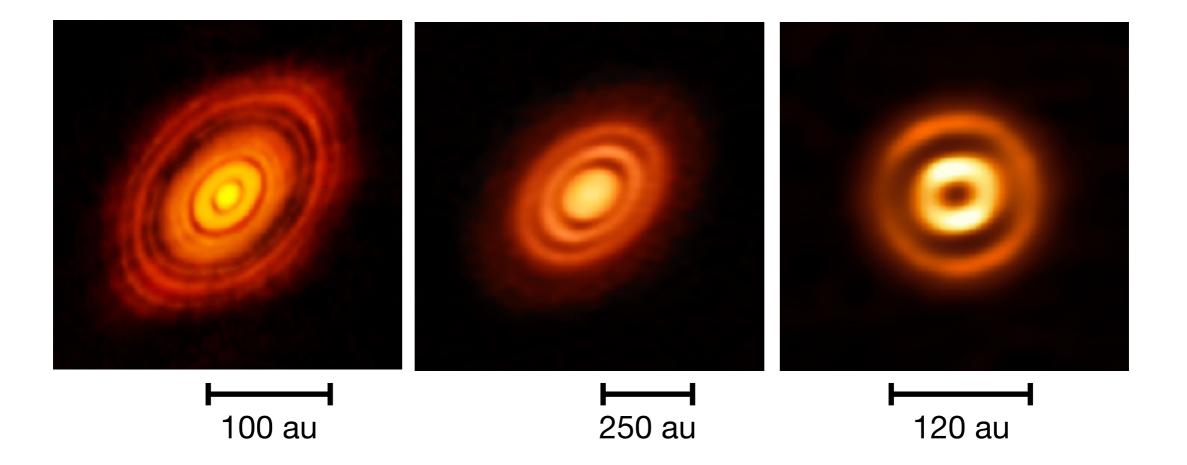
The central temperature and density increase, igniting thermonuclear reactions in the central star. Radiation from this newborn star drives the remaining gas and dust from the system. Planets, comets, and interplanetary material remain in orbit around the star.

ZOOM TO PLANET The prebiotic moleculae are delivered to planets by passing comets, interplanetary dust particles, and meteorites.

> credit: Bill Saxton, NRAO/AUI/NSF

ALMA observations of dust in disks

- ALMA has shown remarkably detailed structure of mm-continuum emission
 - mm-sized grains collect in rings, separated by gaps
 - and in general have drifted inward relative to the gas extent



HL Tau: ALMA Partnership et al. (2015); HD163286: Isella et al. (2016); HD169142: Fedele, Canrey, Hogerheijde et al. (2017)

ALMA observations of dust in disks

- ALMA has shown remarkably detailed structure of mm-continuum emission
- mm-s and ir Credit: Isella/Saxton (NRAO) CO gas mm-sized dust 250 au HL Tau: ALMA Part heijde et al. (2017) DAIN-II meeting • Leiden • 28 November 2018

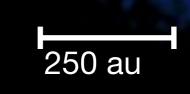
ALMA observations of dust in disks

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 - mm-s
 and ir
 CO gas

Credit: Isella/Saxton (NRAO)

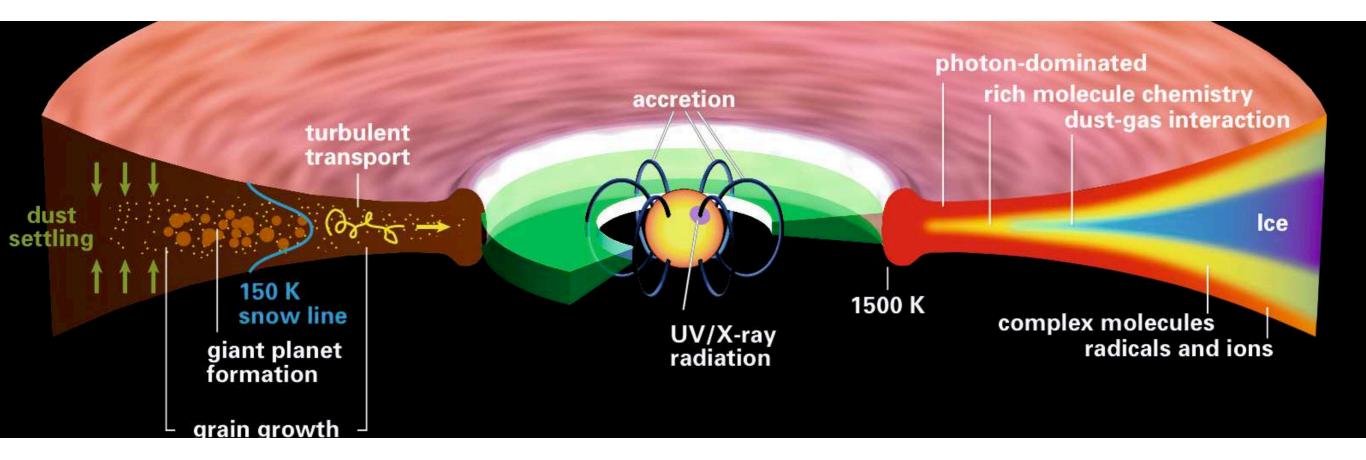
mm-sized dust

Although CO emits across entire disk, CO is often **under-abundant** by factors up to 100, even after taking into account freeze out and photodissociation. This is true even in the inner disk where $T > T_{evap}$



HL Tau: ALMA Part

Chemistry in the disk



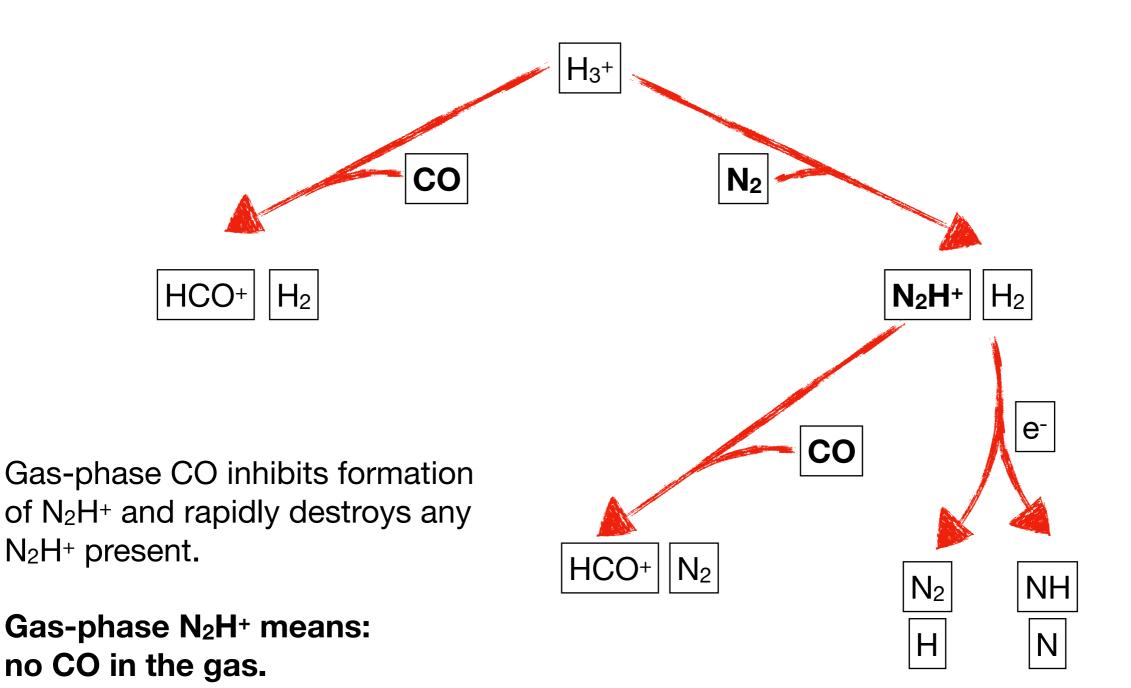
Three chemical zones

- **cold midplane**: most molecular species (ex. H₂) frozen out
- intermediate height and inner disk: rich in molecules
- **disk surface**: molecules photodissociated

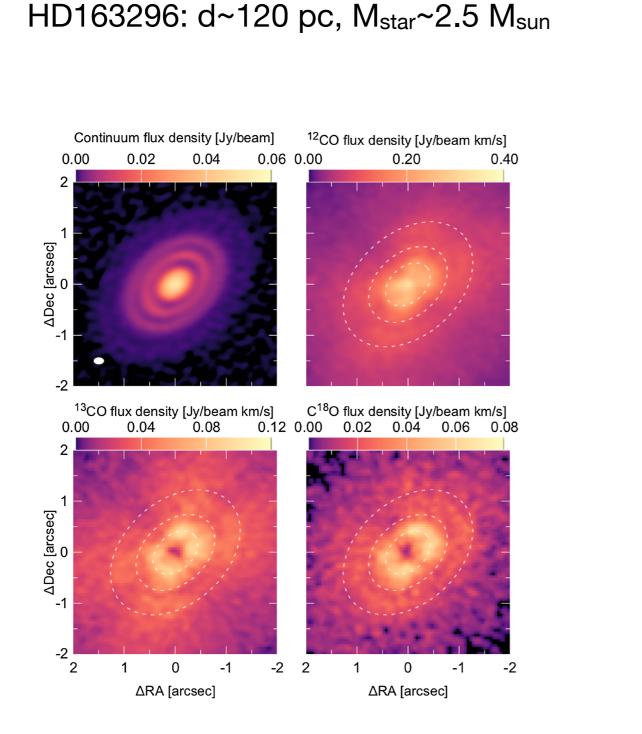
Henning & Semenov (2013)

1. Can we use chemistry to find snow lines?

N₂H+ as frozen-CO a tracer



3



 ${\bullet}$

Salinas et al. (2017); Isella et al. (2016); Qi et al. (2015)

 $N_{2}H^{+}3-2$ 2 1 Δδ [''] 0 -1-2 -3 N_2D^+ 3-2 2 0 -2 \cap 250 au -22 0 $\Delta \alpha$ (")

• HD163296: d~120 pc,

mm dust collected in rings around a central disk, < gas disk (Isella et al. 2016)

LLLL

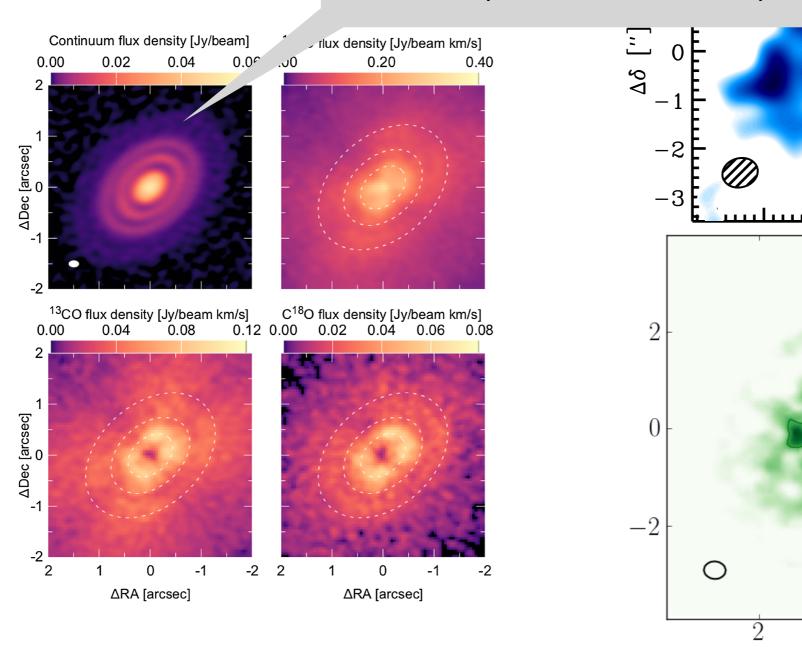
3-2

 N_2D^+ 3-2

250 au

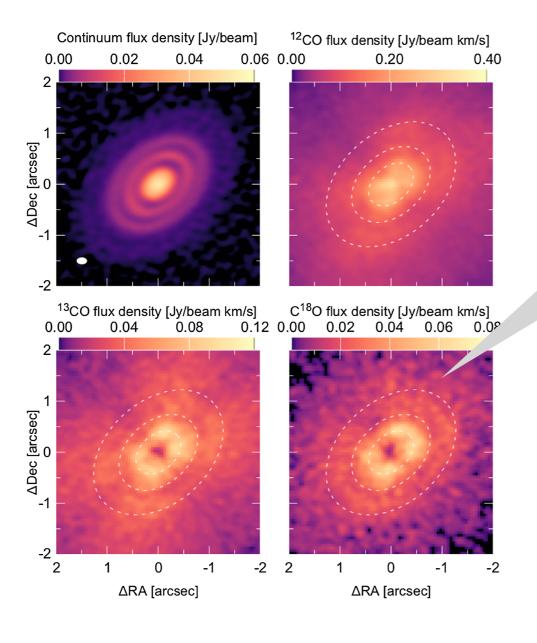
 $\begin{array}{c} 0\\ \Delta \alpha(") \end{array}$

-2



Salinas et al. (2017); Isella et al. (2016); Qi et al. (2015)

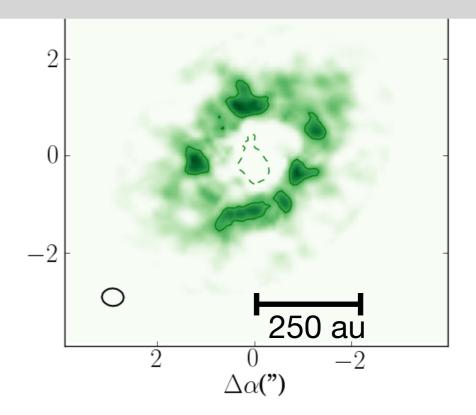




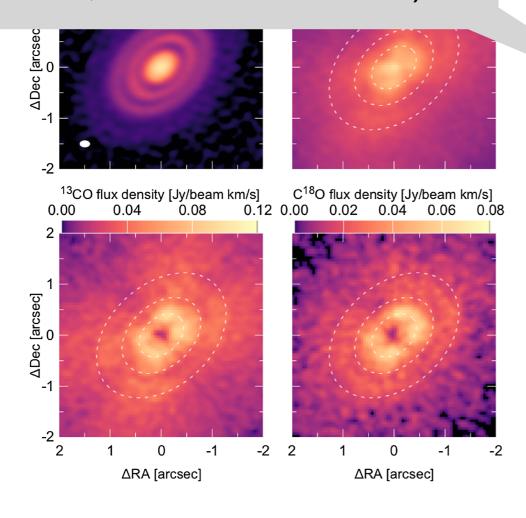
Salinas et al. (2017); Isella et al. (2016); Qi et al. (2015)

 $\begin{array}{c}
3 \\
N_{2}H^{+} 3-2 \\
2 \\
1 \\
\end{array}$

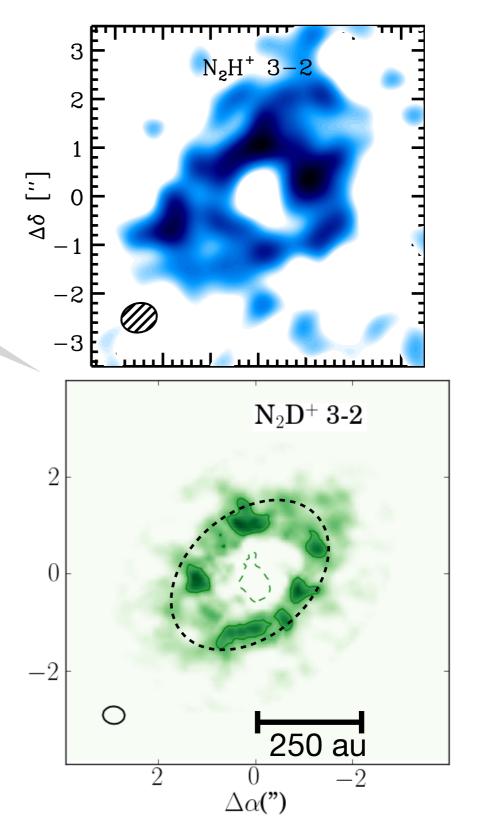
CO across the disk, but 'holes' in the ¹³CO and C¹⁸O emission: result of dust & line opacity - not an absence of gas!



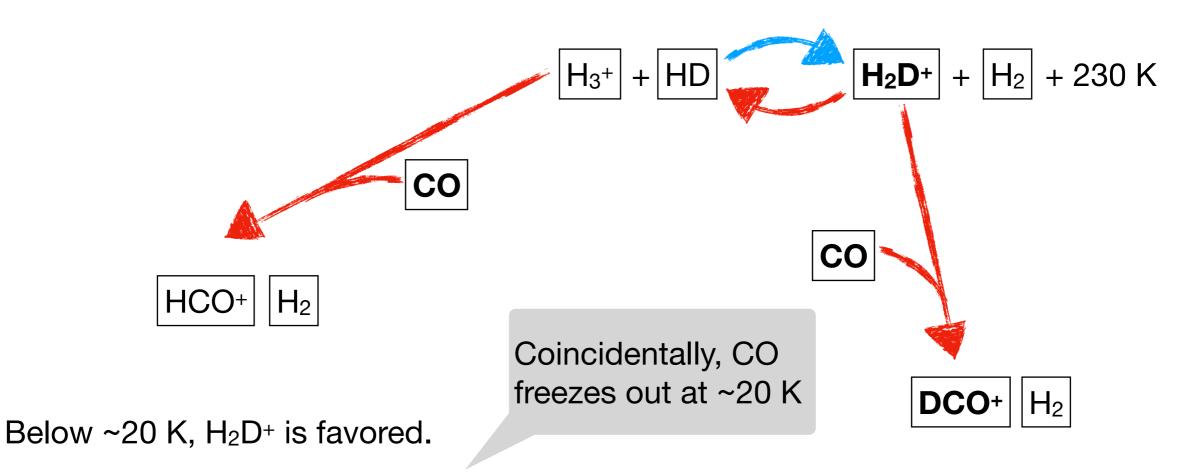
N₂H⁺ and only show up in a ring once CO has frozen out in the midplane; some CO is still present in higher, warmer disk layers (Qi et al. 2015; Salinas et al. 2017).



Salinas et al. (2017); Isella et al. (2016); Qi et al. (2015)



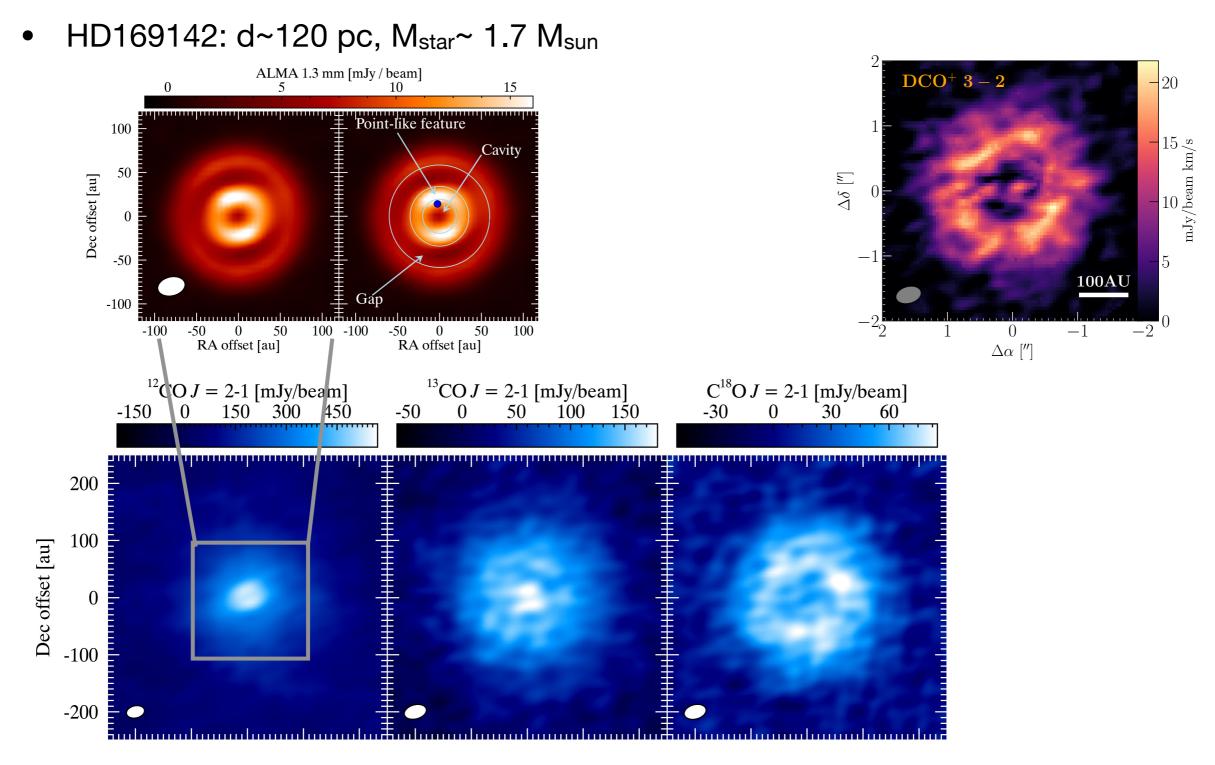
DCO+ as a frozen-CO tracer



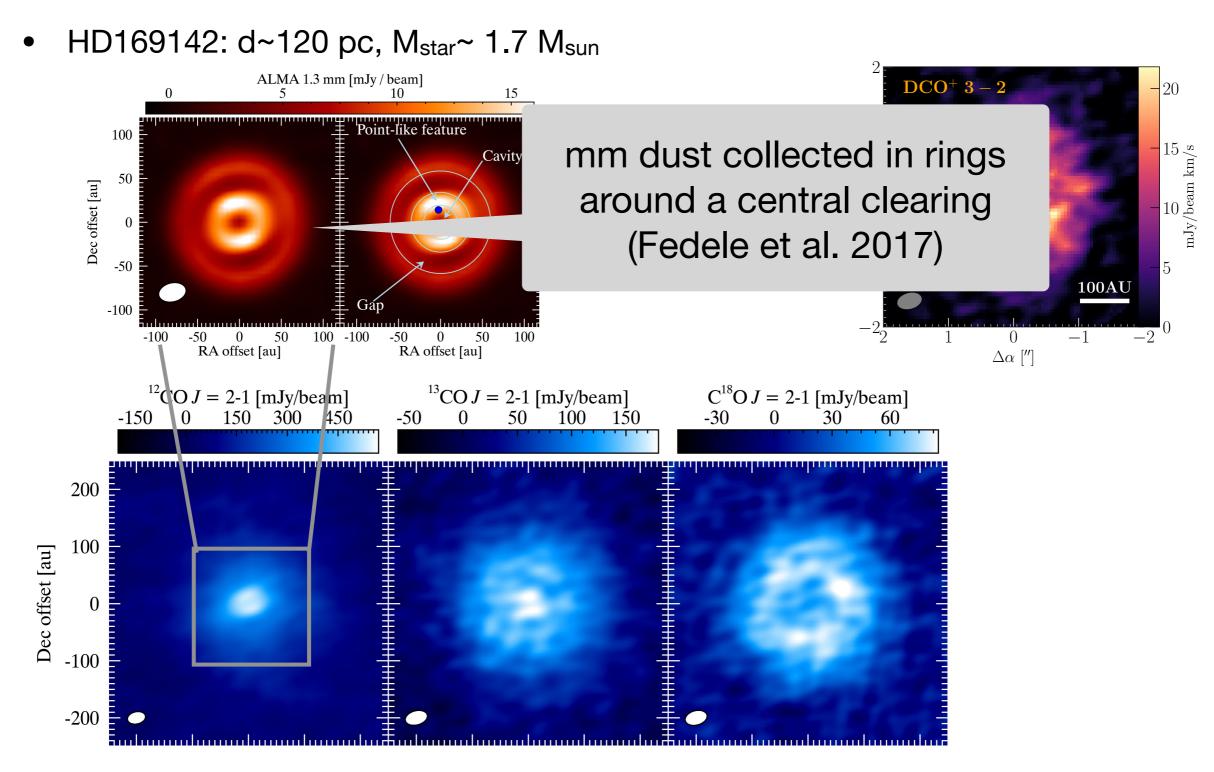
Gas-phase CO inhibits formation of H₂D⁺.

A small amount of CO is needed to convert H_2D^+ into DCO⁺.

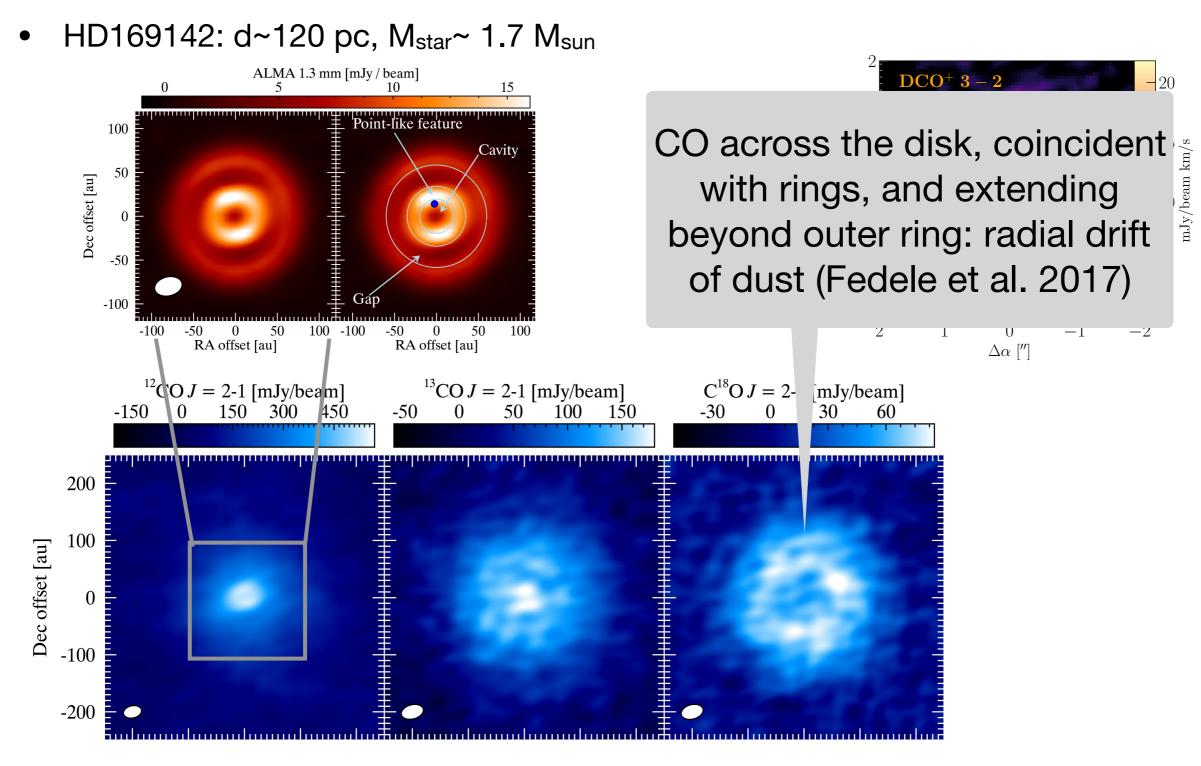
Gas-phase DCO⁺ means: CO is largely, but not completely, gone from the gas.



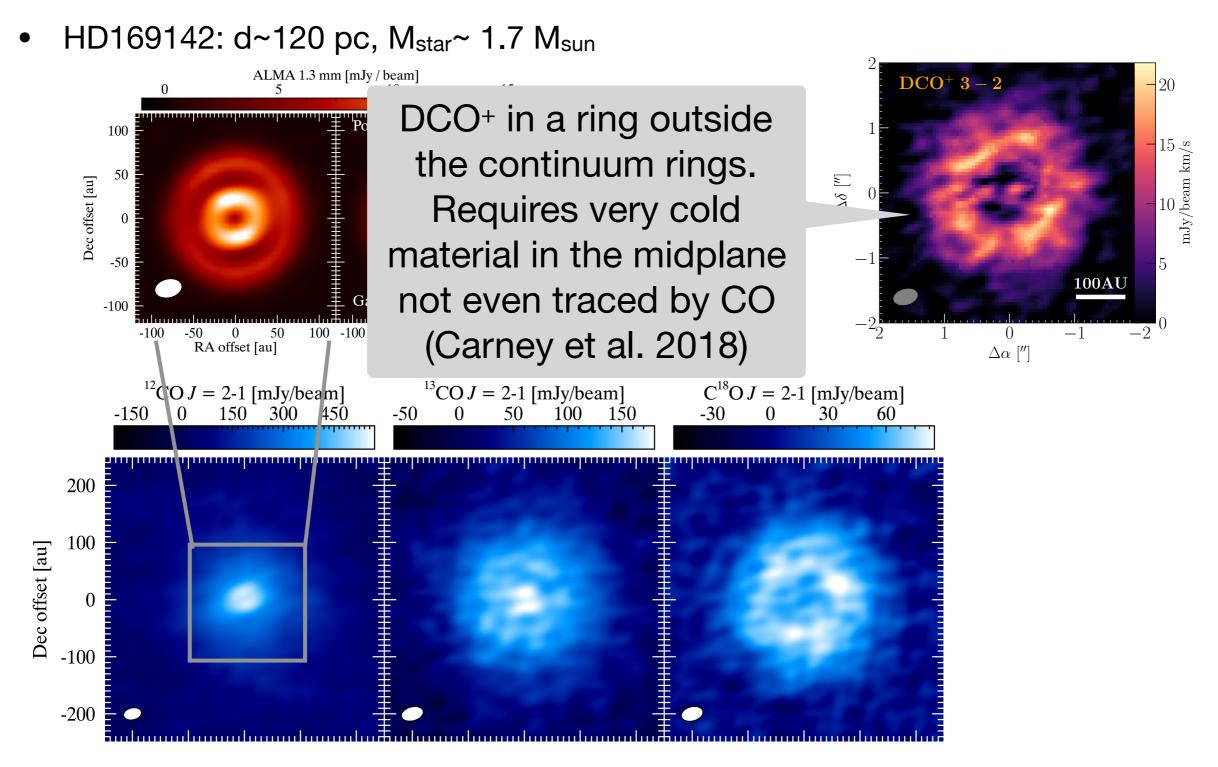
Fedele, Carney, Hogerheijde et al. (2017); Carney, Fedele, Hogerheijde et al. (2018)



Fedele, Carney, Hogerheijde et al. (2017); Carney, Fedele, Hogerheijde et al. (2018)



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2. Are simple organics present in the disk gas?

- Interstellar ices are known to contain organics such as CH₃OH
 - Sequential hydrogenation of frozen out CO
- Warm regions around protostars show many organics

Gas-phase formation vs released from icy grains?

- Ice mantles evaporate
- Some simple organics have been found in disks
 - H₂CO, CH₃OH, HC₃N, CH₃CN, ...

AFGL4176 (~2x10⁵ L_{sun}) Bøgelund et al. (in prep)

<u>снзосно</u> _{С2}нзси, снзосно CH₃OCHO, C₂H₃CN HC_3N , $v_7 = 2$ $laGg'(CH_2OH)_2$ HC_3N , $v_7 =$ сн₃осно сн₃осно сн₃осно ¹³CH₃OH CH₃OCH₃ СН₃С₂Н ¹³СН₃ОН CH₃OCH₃ C₂H₅OH CH₃C₂H CH₃C₂H C₂H₅CN C₂H₃CN -62°08'50.0" C_2H_3CN C_2H_3CN CH₃OH HC¹⁵N SO_2 50.5" Declination (J2000) 80 H₃OCHO - 15 - 15 mJA peam 10 51.0" 60 Σ 40 51.5" ⊢ 20 52.0" 2000 au 0 52.5" 256.1 256.2 256.4 256.3 256.5 13h43m01.8s 01.7s 01.6s 01.5s Frequency [GHz] Right ascension (J2000)

DAN-II meeting • Leiden • 28 November 2018

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1.2

IRAS16293B

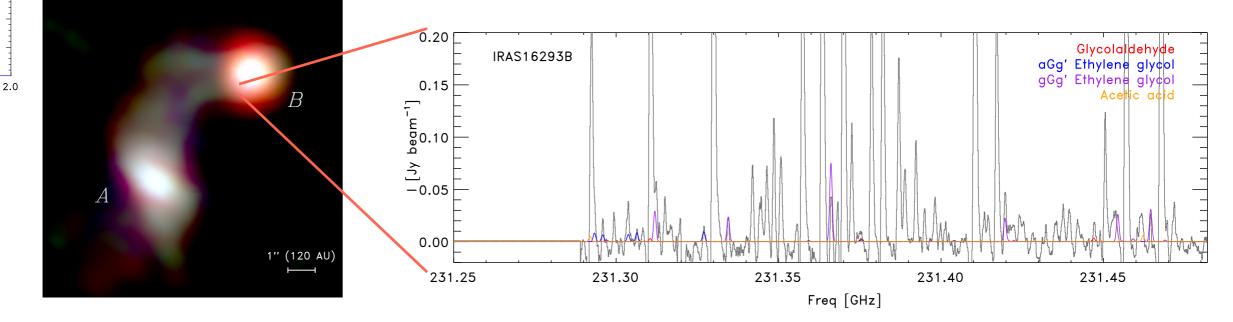
1.8

Jy beam⁻¹]

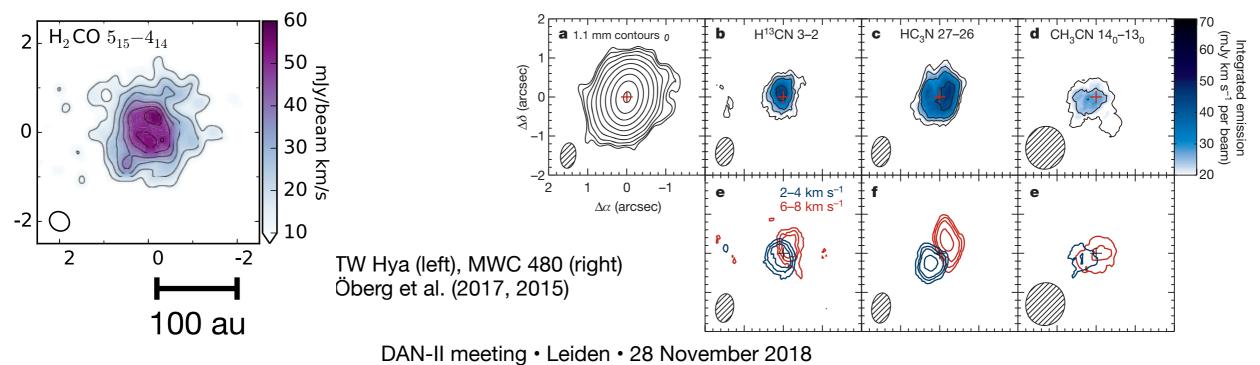
1.6 Jy beam⁻¹]

- Some simple organics have been found in disks
 - H₂³³⁰CO, CH₃³⁵⁰OH, HC₃N, CH₃CN, ...
 - Gas-phase formation vs released from icy grains?

IRAS 16293-2422 Jørgensen et al. (2016)

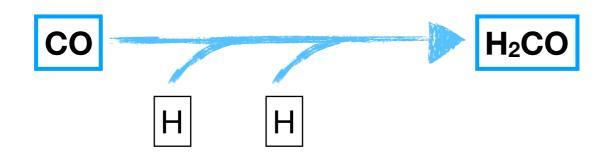


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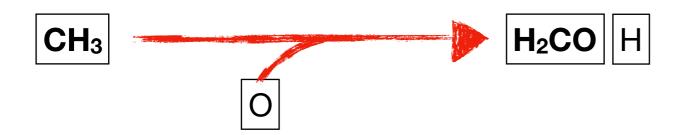


H₂CO chemistry

• Grain surface (ice) formation route

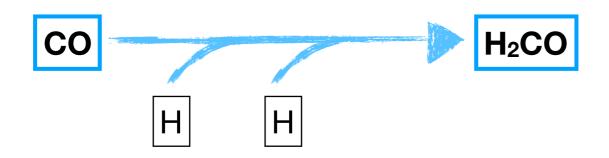


• Gas-phase formation route

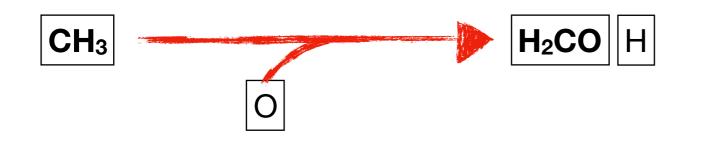


H₂CO chemistry

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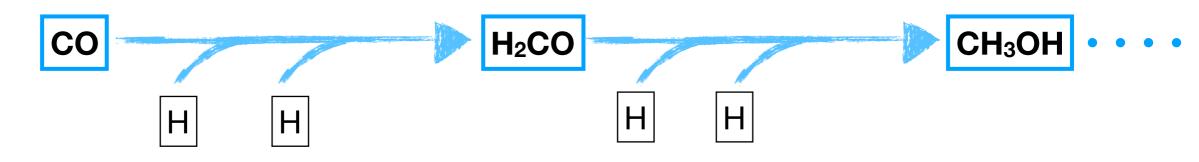
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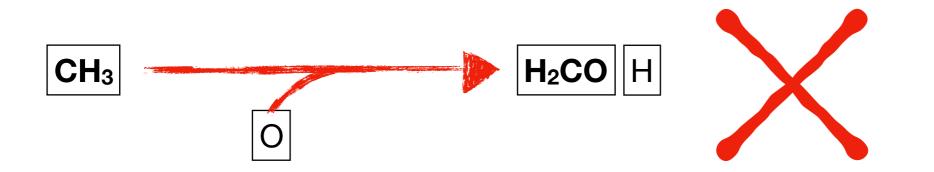
Distribution of H₂CO across disks indicate *both* paths contribute (Öberg et al. 2017; Loomis et al. 2015)

CH₃OH chemistry

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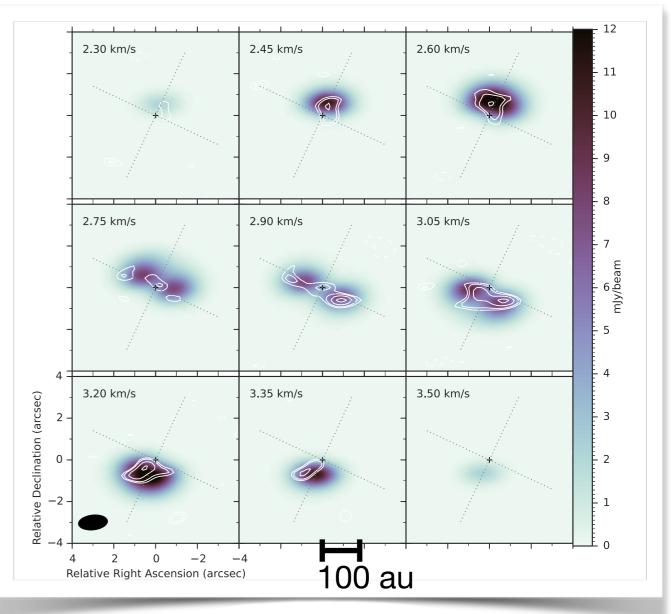


• Gas-phase formation route



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 - H₂CO, CH₃OH, HC₃N, CH₃CN, ...
 - Gas-phase formation vs released

CH₃OH in planet forming disks has proven difficult to detect. First detection: TW Hya, Walsh et al. (2016)

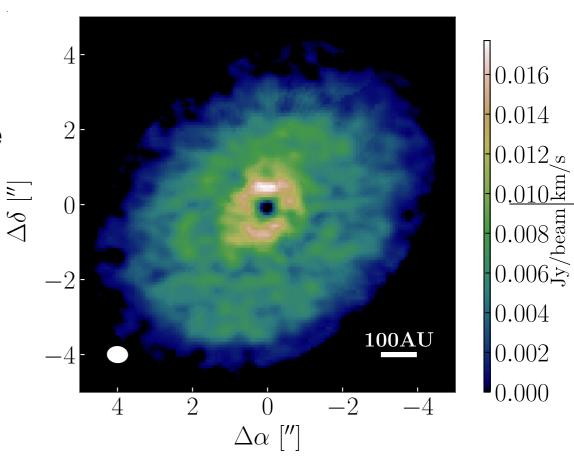


H₂CO in HD163296

- H₂CO emission from full disk
 - Inner 'hole' an artefact due to dust opacity
- Radial profile requires 2x abundance increase at ~280 au
 - Coincident with outer edge of mm dust disk
 - Coincident with drop in C¹⁸O abundance by factor 5

- Increased penetration of stellar UV
 - Selectively photodissociates C¹⁸O
 - Releases H₂CO from grains

Carney et al. (2016)



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4

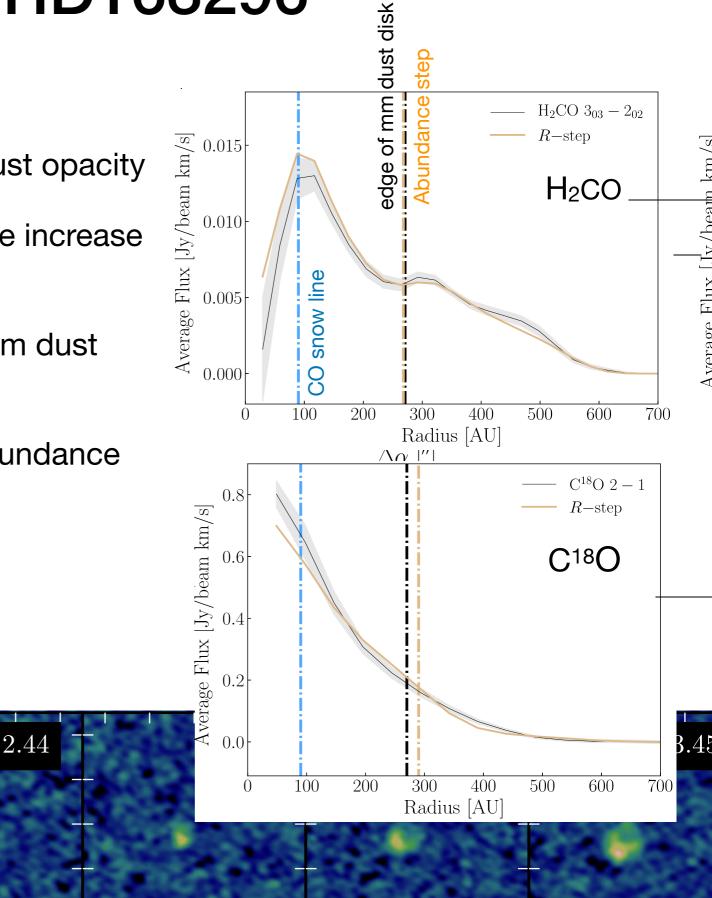
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- Increased penetration of stellar UV
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 - Releases H₂

Carney et al. (2016)



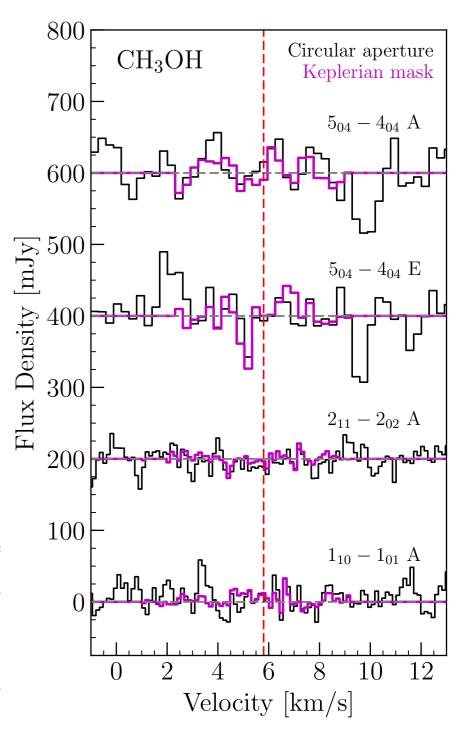
...but no CH₃OH

- Deep limits on several CH₃OH lines
 - Strict upper limit of CH₃OH/H₂CO<0.24
 - cf. TW Hya: CH₃OH/H₂CO~1.27

- Harsher UV radiation from Herbig star destroys CH₃OH upon photodesorption?
- Recent thermal evaporation event in TW Hya?

Target CH₃OH/H₂CO[†] H_2CO/H_2 Line $\int I_{v}dv$ $log(A_{ii})$ Navg $E_{\rm u}$ $n_{\rm crit}^{a}$ $[s^{-1}]$ $[cm^{-3}]$ $[cm^{-2}]$ $[mJy km s^{-1}]$ [K] HD 163296 H₂CO 3₁₂-2₁₁ 890 ± 89^{b} < 0.24 33.4 -3.555.7(06) 2.1(12)6.3(-12) 1.27 ± 0.13 TW Hya $H_2CO 3_{12}-2_{11}$ 291 ± 29^{c} 33.4 -3.555.7(06) 3.7(12) 8.9(-13)

Table 3: Disk-averaged column density and abundance of H₂CO in HD 163296 and TW Hya.



Carney et al. (submitted)

Conclusions

Is CO a reliable tracer of the full gas mass of planet forming disk?

- No. When using CO as a mass tracer, even when taking into account freeze out and isotope-selective photodissociation, we're missing a factor of 10-100 of the gas. Something may be locking up carbon on the grains.
- Can we trace frozen-out CO?
 - Yes.
 - N₂H⁺ reliably traces frozen-out CO, but beware that the peak of the N₂H⁺ emission ≠ the CO now line.
 - N₂H⁺ may be a good way to discriminate disks with low gas mass from disks with missing CO.
 - DCO⁺ has a somewhat complicated chemistry and traces the *disappearing* CO.
 - Together, DCO⁺ and N₂H⁺ provide the *gradient* and the *minimum* of the CO.
- Are simple organics present in the disk gas?
 - Yes, but most species remain locked up in ices in cold disk regions.
 - H₂CO ubiquitous; both gas-phase and grain-surface formation and its abundance increases in outer disk regions where UV can penetrate more easily due to low(er) dust content.
 - CH₃OH remains elusive, and may only come off grains intact after thermal evaporation