ALMA observations of chemistry in planet-forming disks

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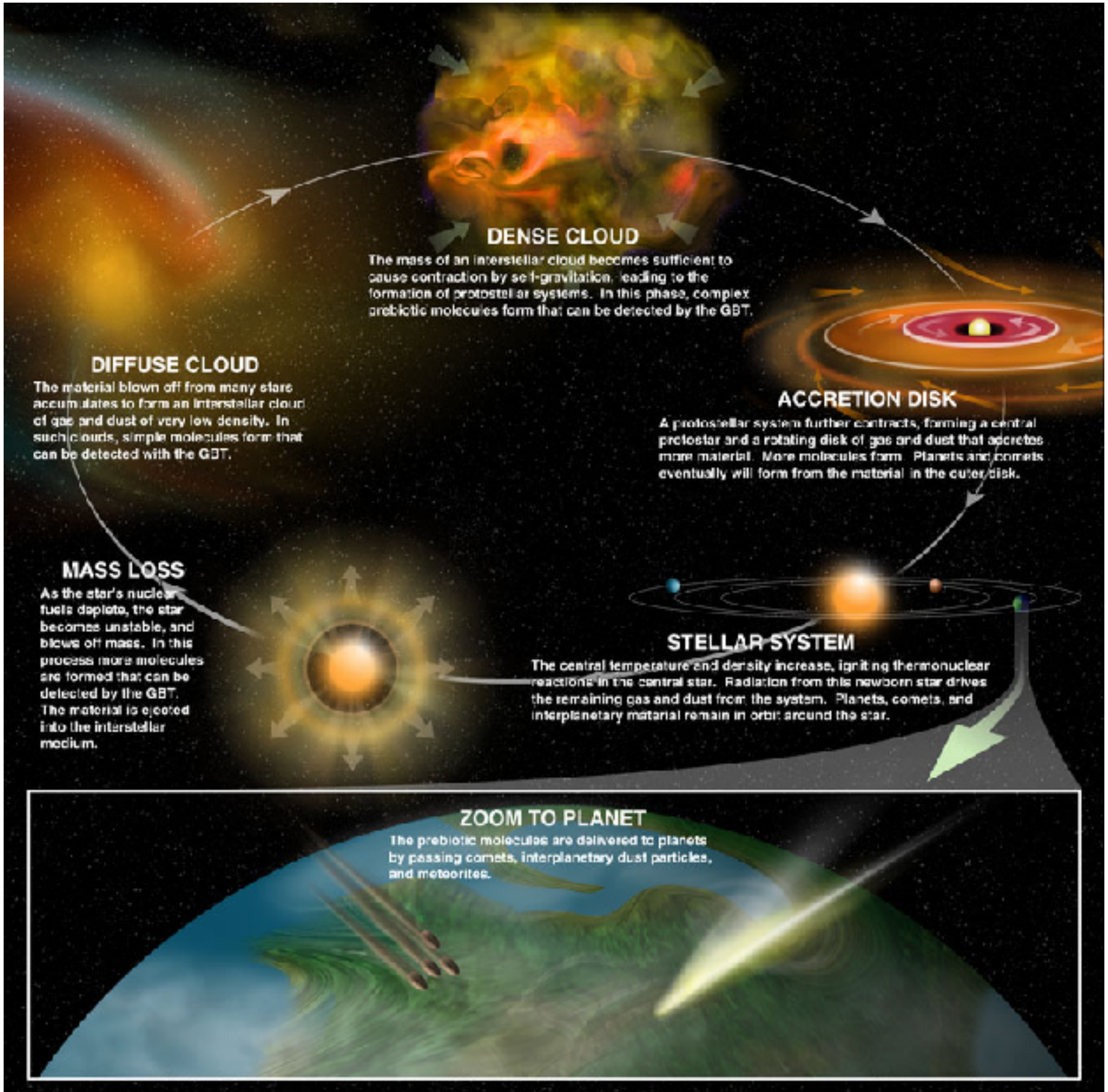
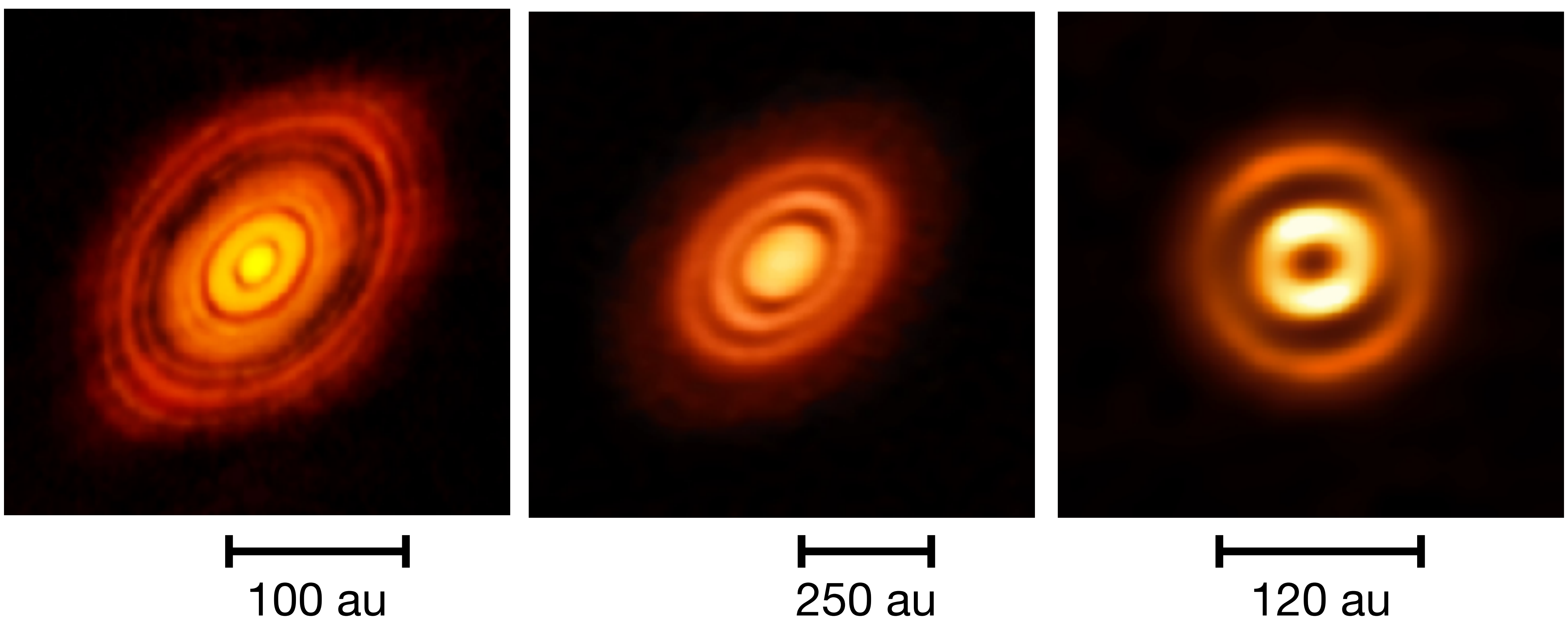
Standard model star and planet formation



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

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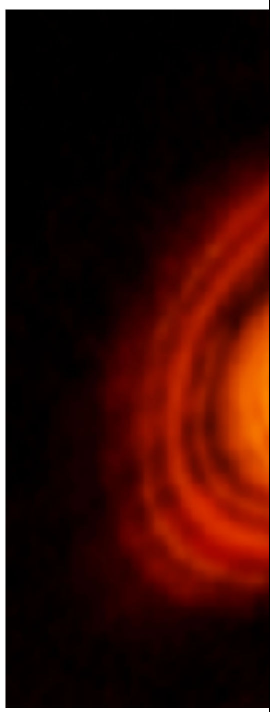
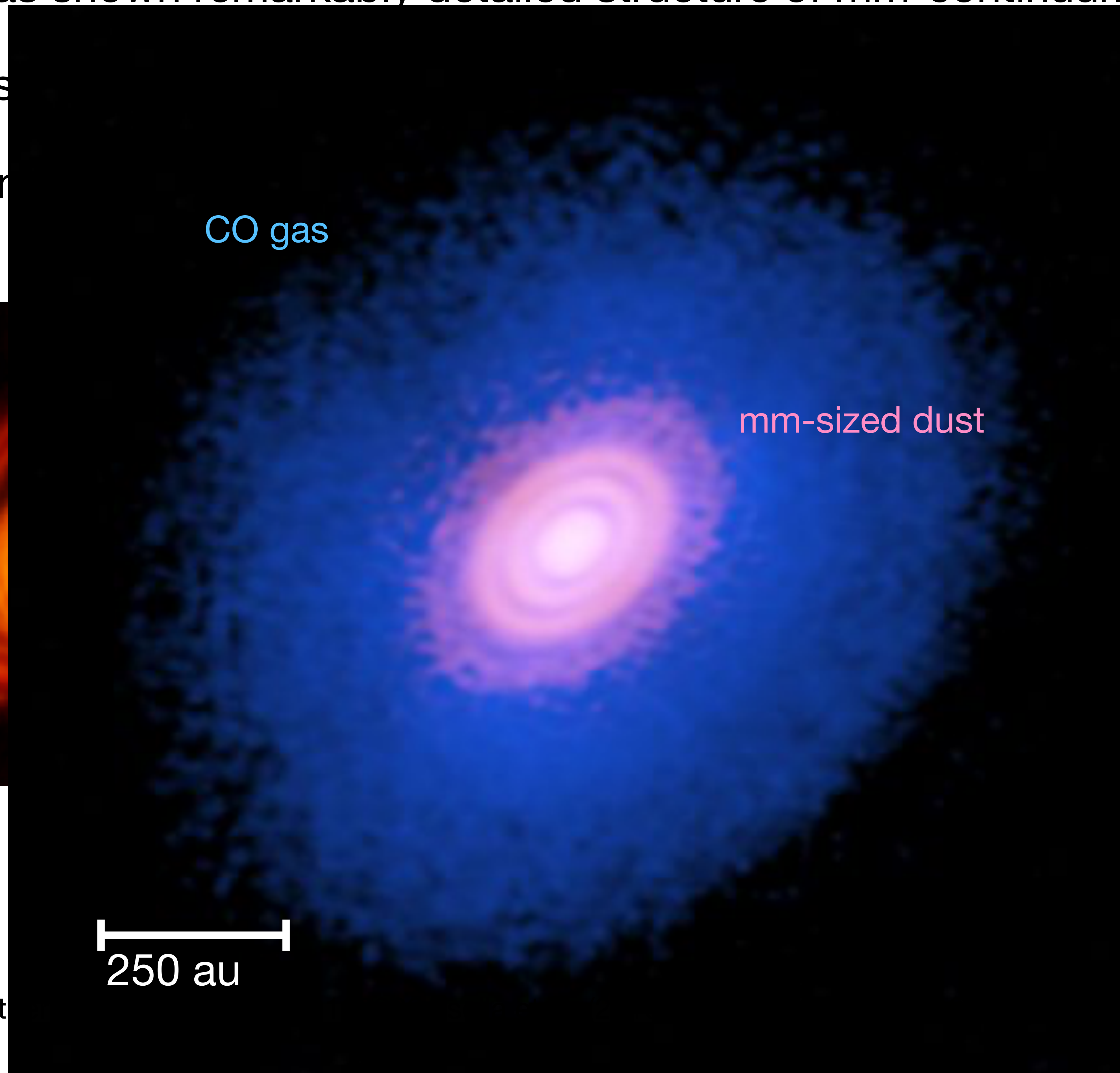
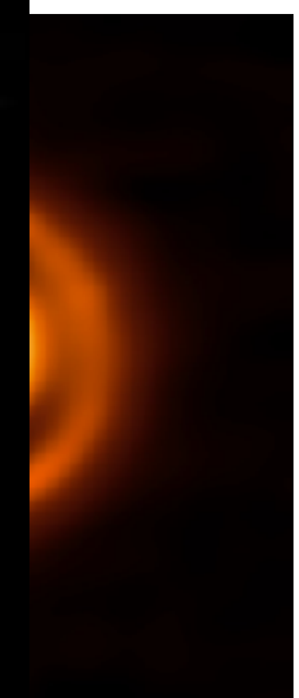
  - mm-s
  - and ir

Credit: Isella/Saxton (NRAO)







HL Tau: ALMA Part

rheijde et al. (2017)

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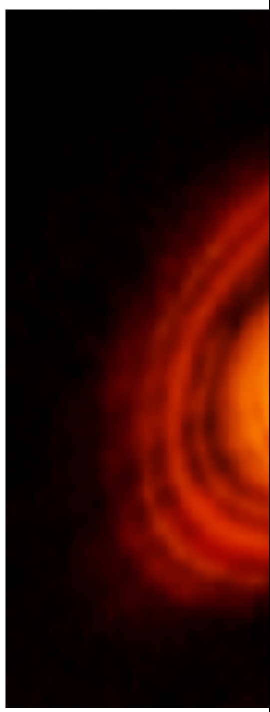
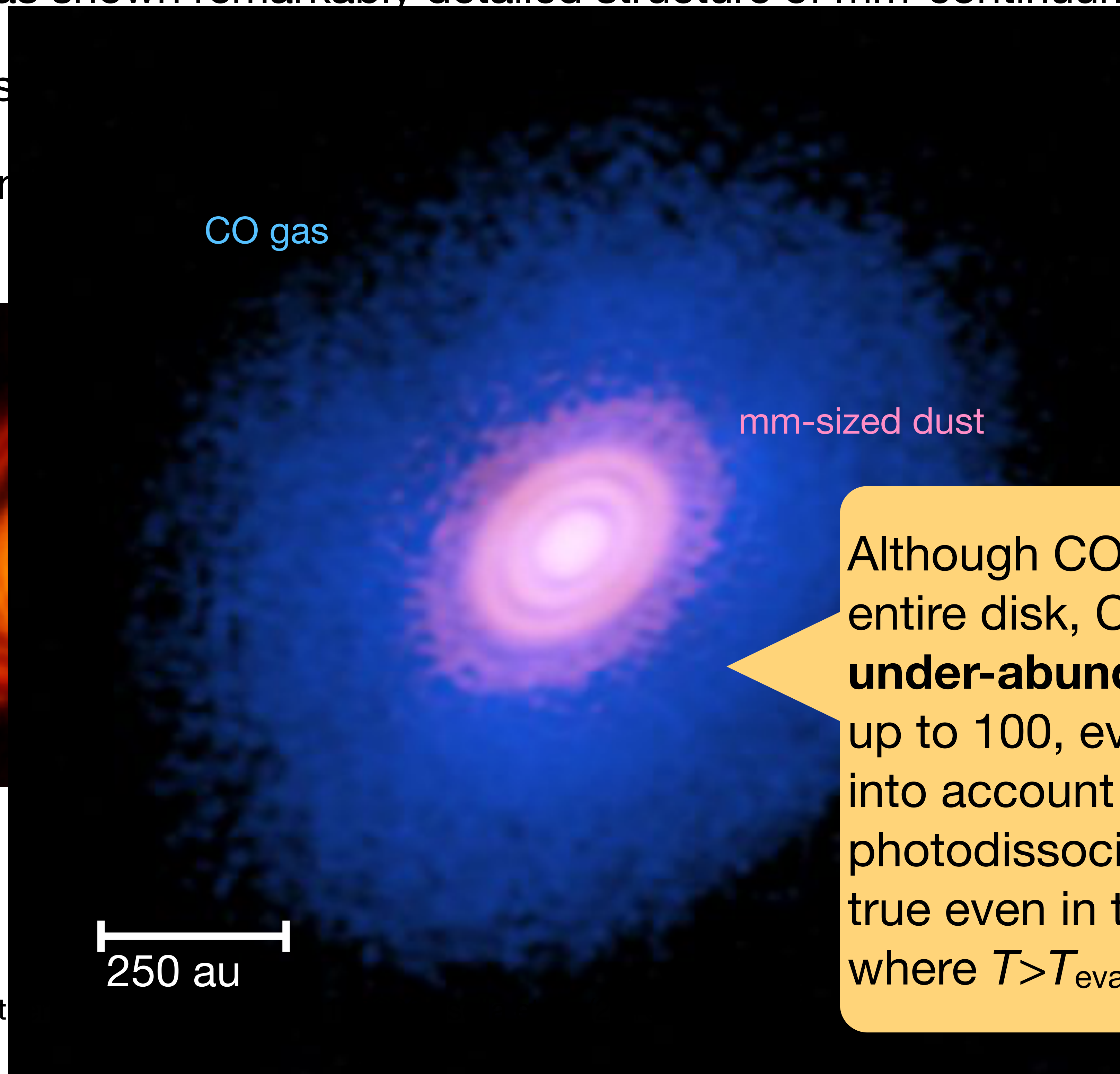
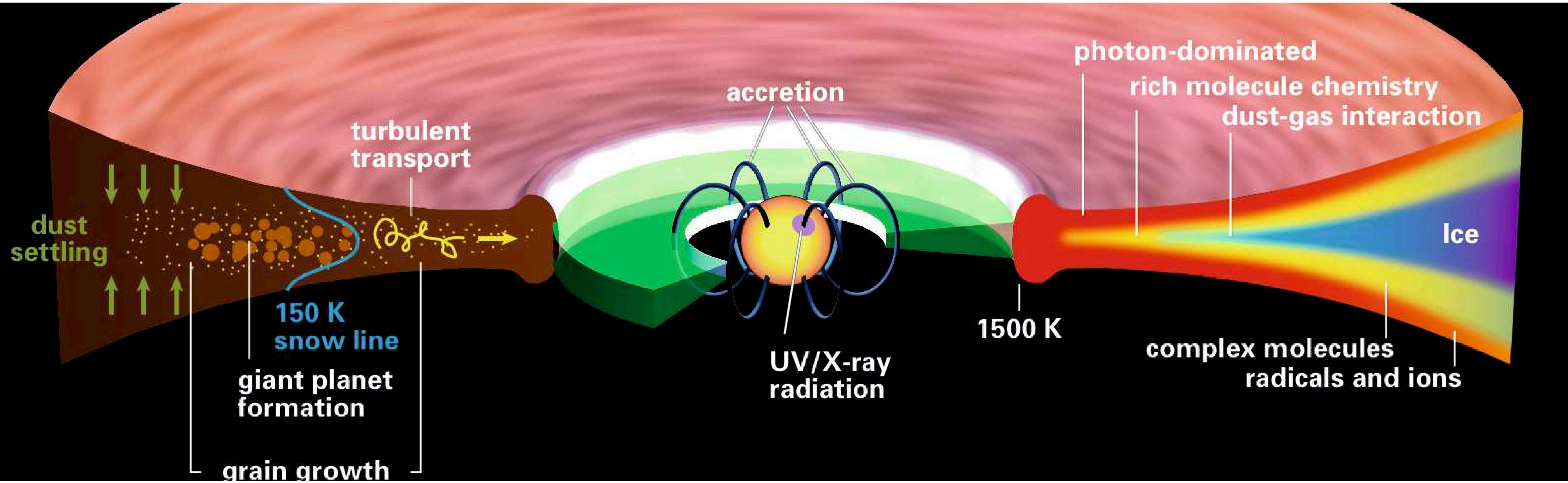




Although CO emits across entire disk, CO is often **under-abundant** by factors up to 100, even after taking into account freeze out and photodissociation. This is true even in the inner disk where $T > T_{evap}$

HL Tau: ALMA Part

Chemistry in the disk



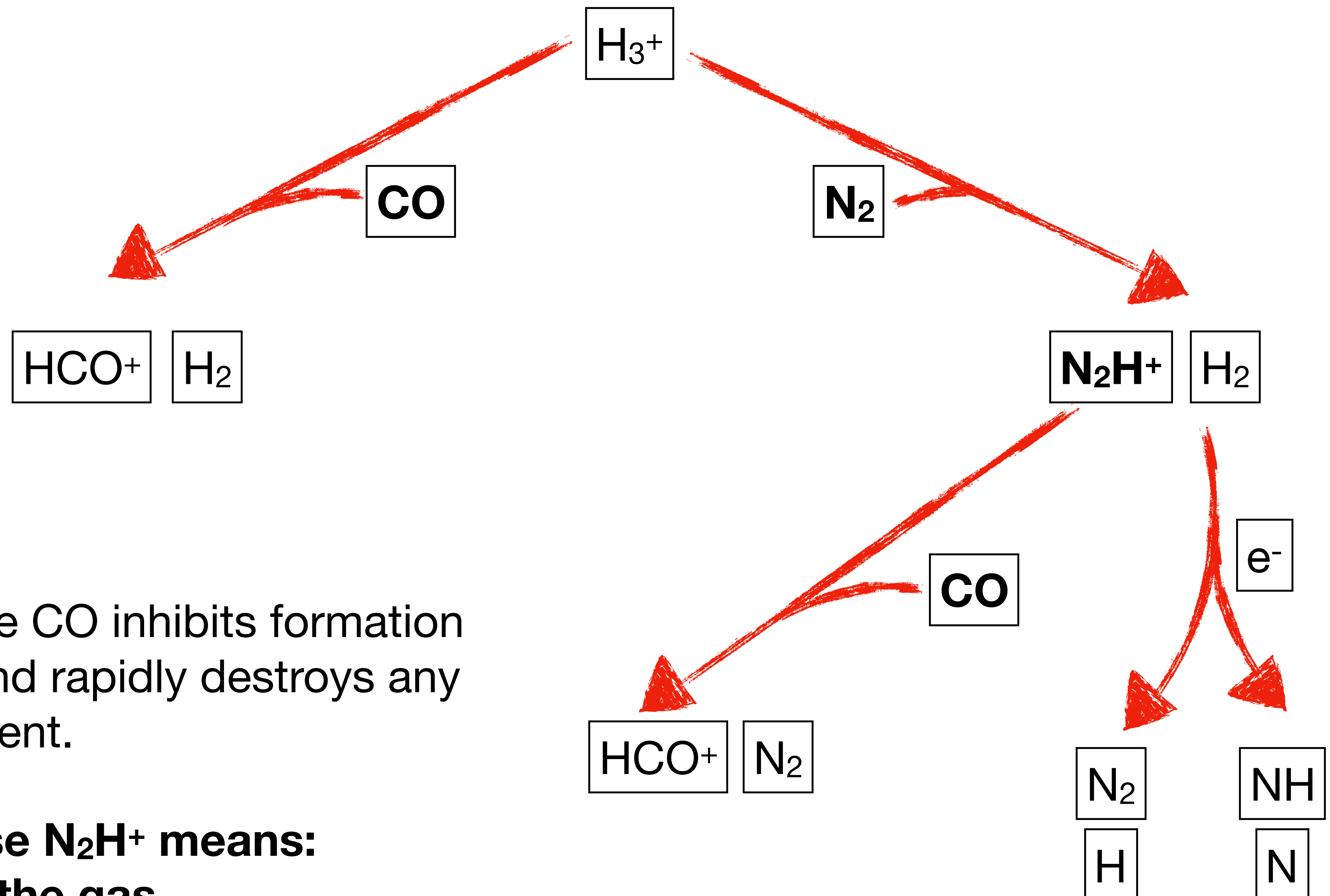
Three chemical zones

- **cold midplane**: most molecular species (ex. H_2) 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?

N_2H^+ as frozen-CO a tracer

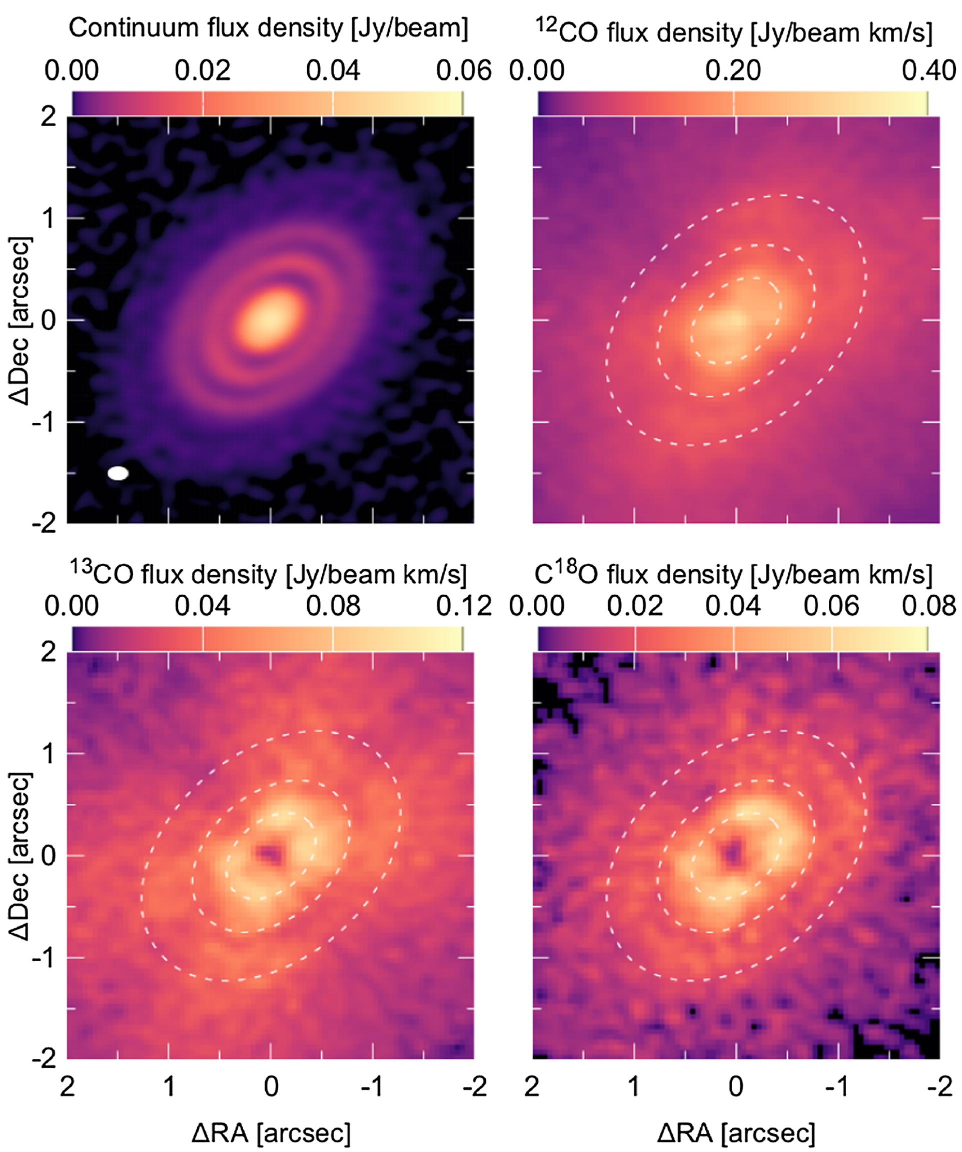


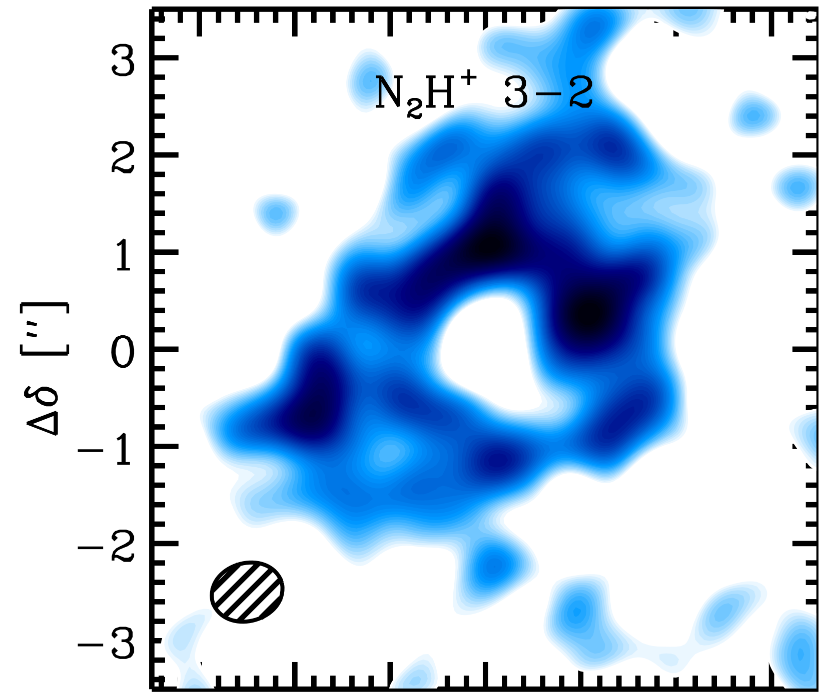
Gas-phase CO inhibits formation of N_2H^+ and rapidly destroys any N_2H^+ present.

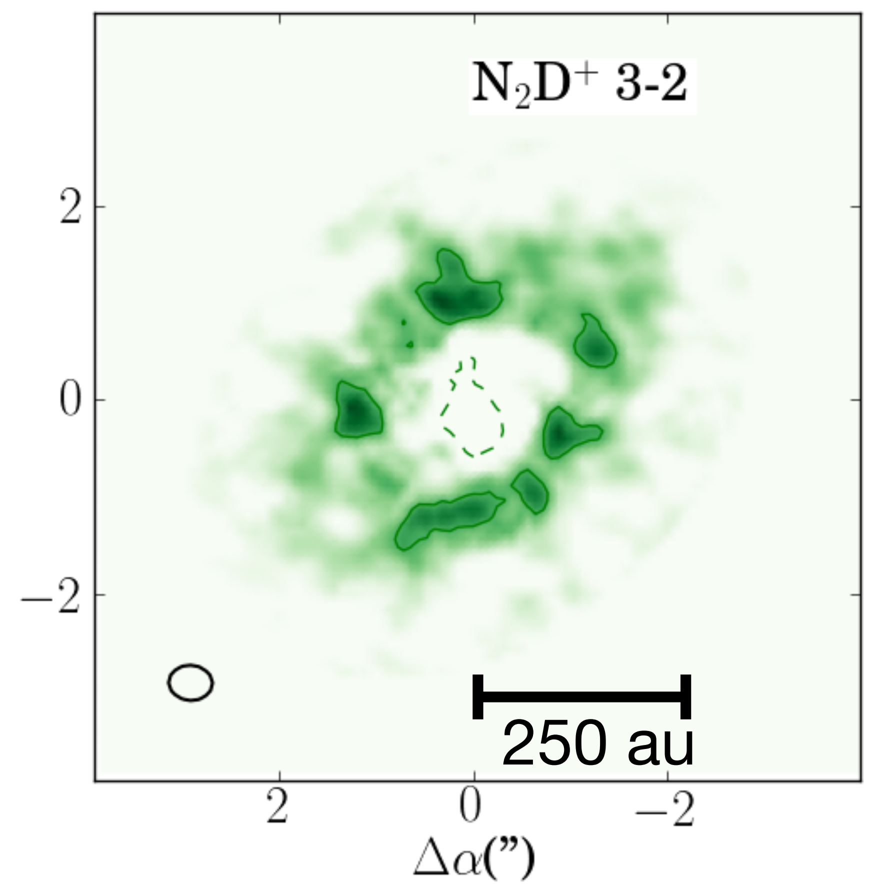
Gas-phase N_2H^+ means: no CO in the gas.

N_2H^+ and N_2D^+ in HD163296

- HD163296: d~120 pc, M_{star}~2.5 M_{sun}





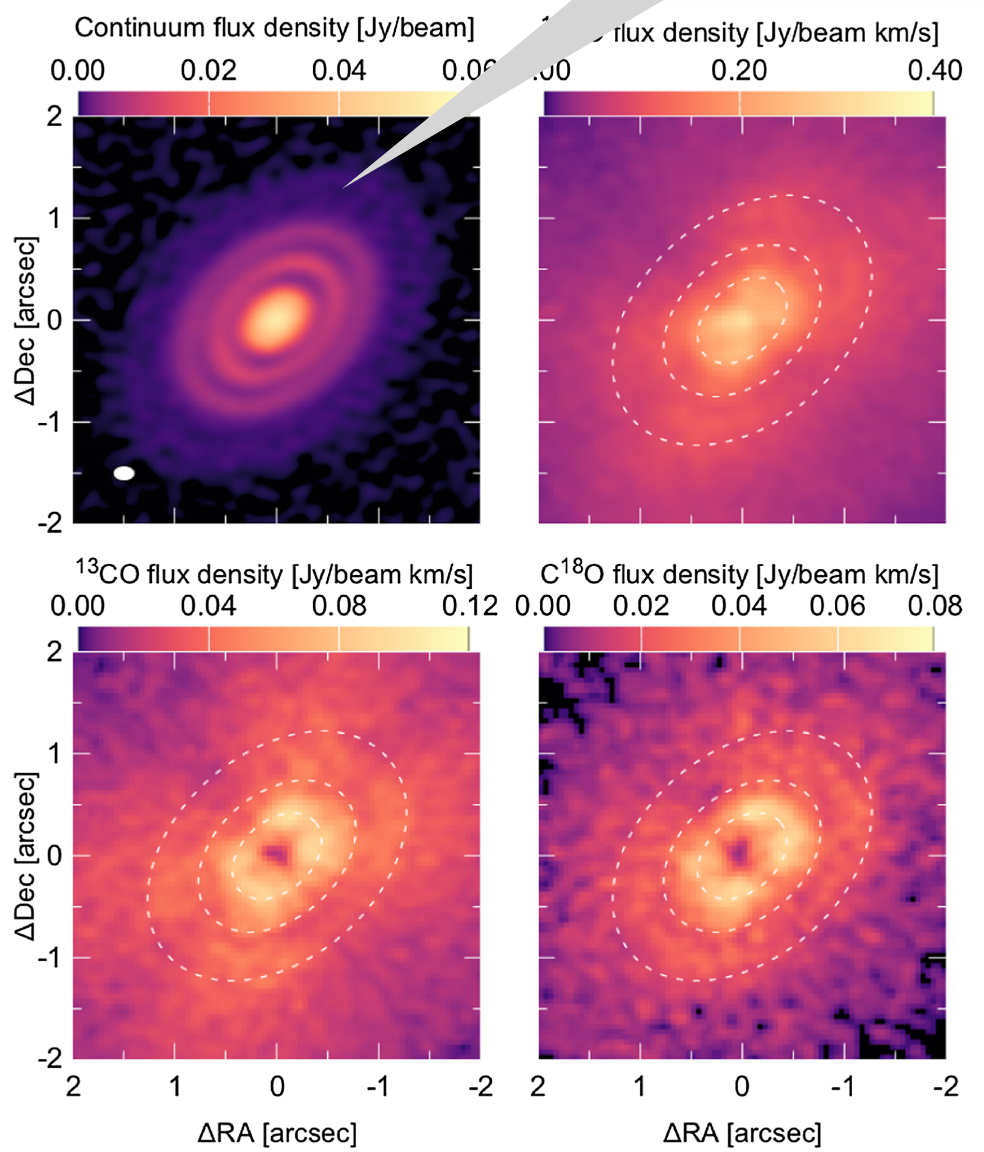


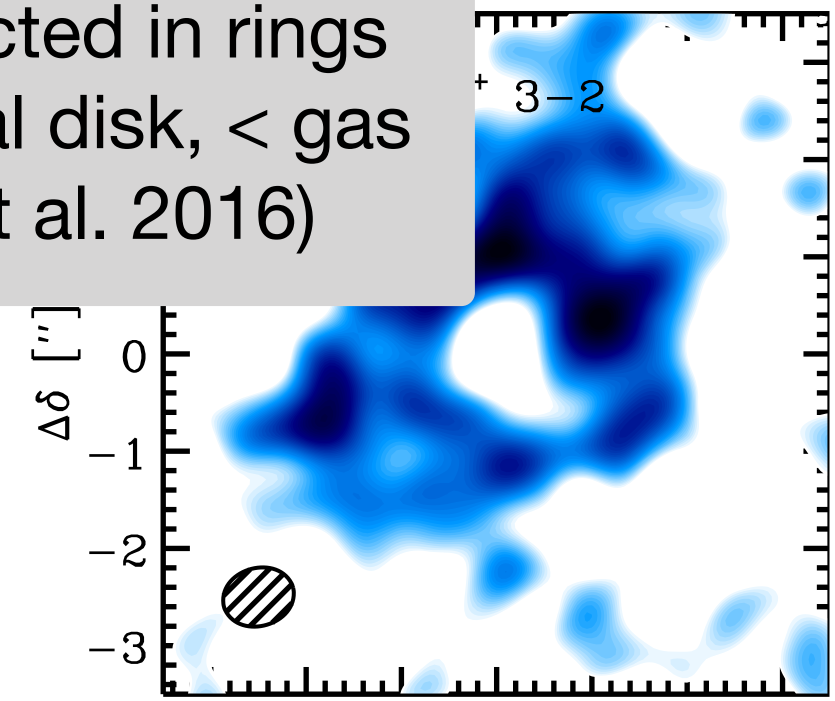
Salinas et al. (2017); Isella et al. (2016); Qi et al. (2015)

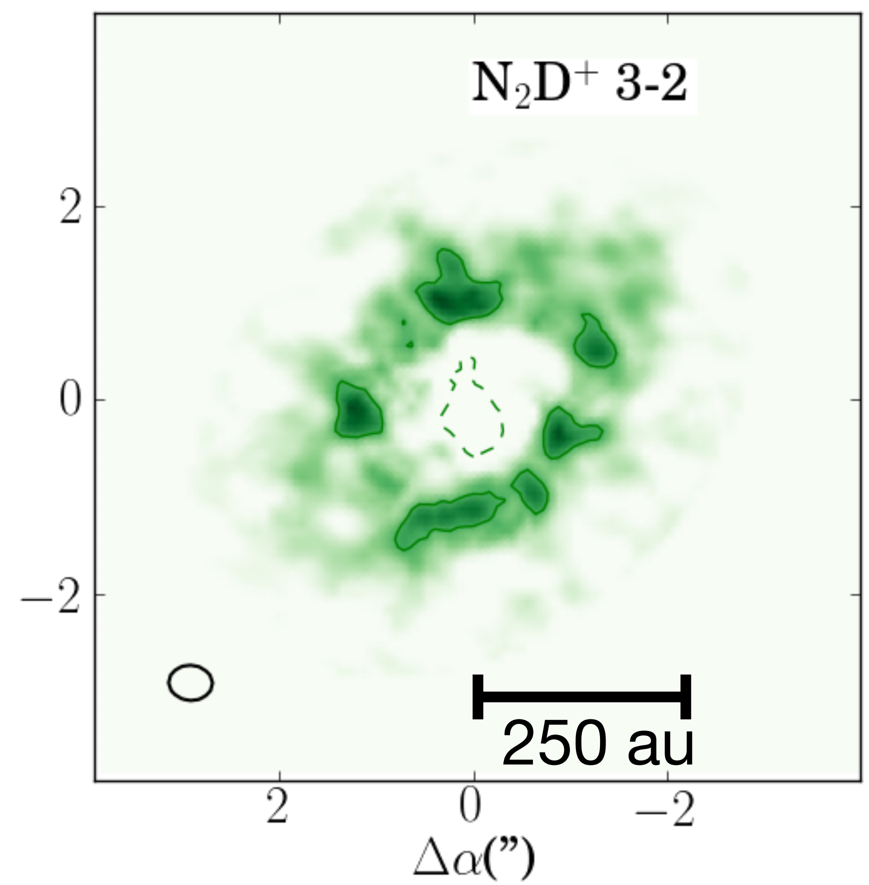
N_2H^+ and N_2D^+ in HD163296

- HD163296: d~120 pc,

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







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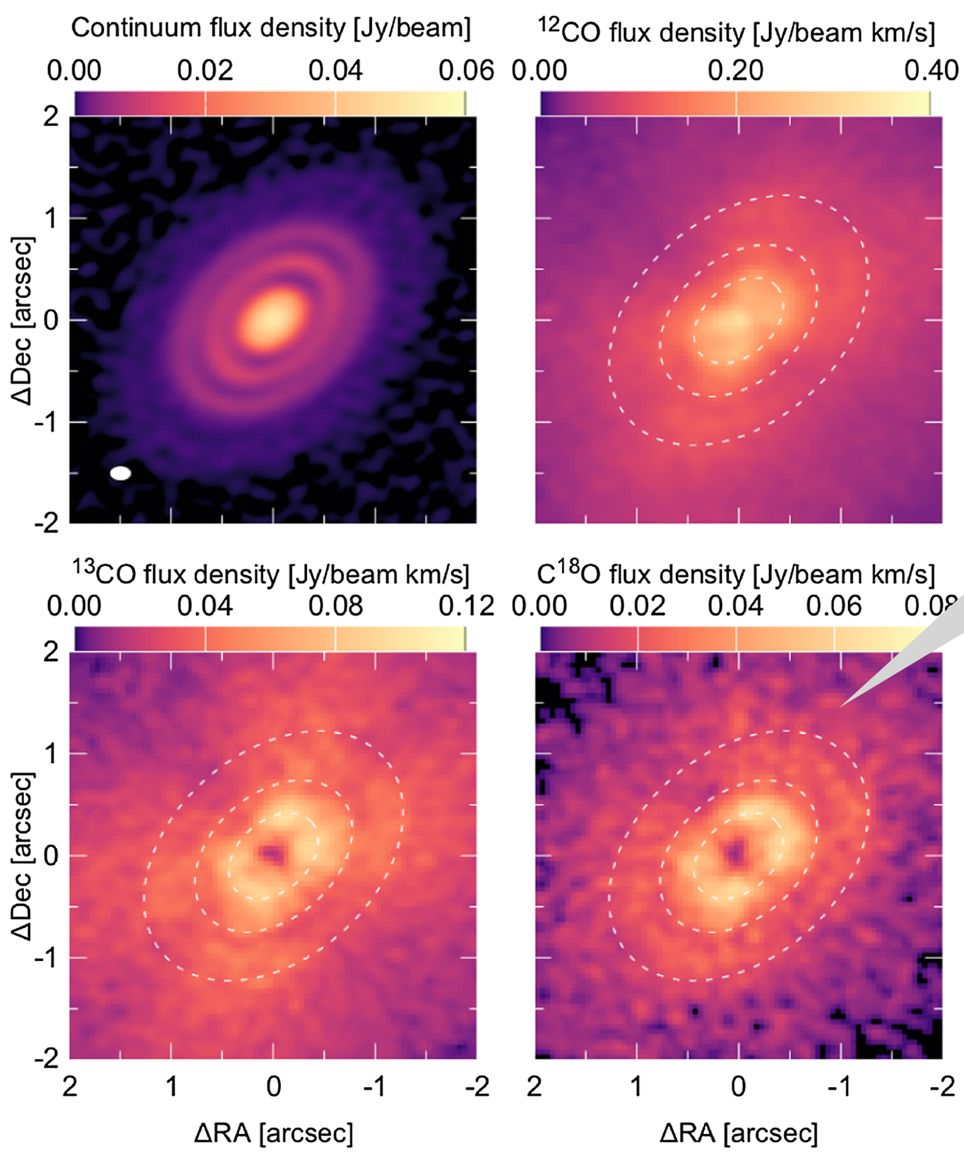
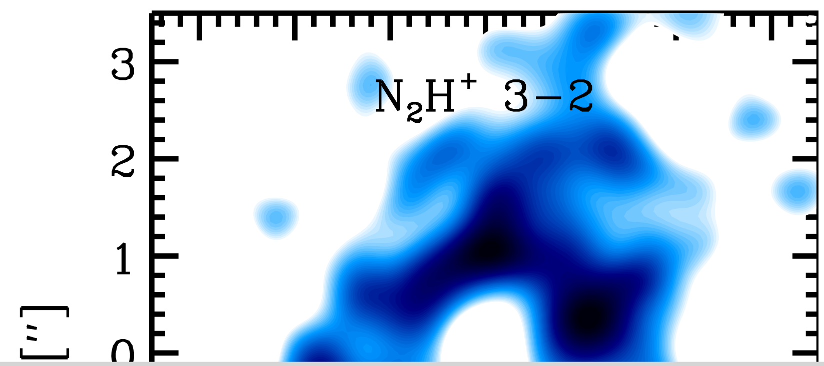
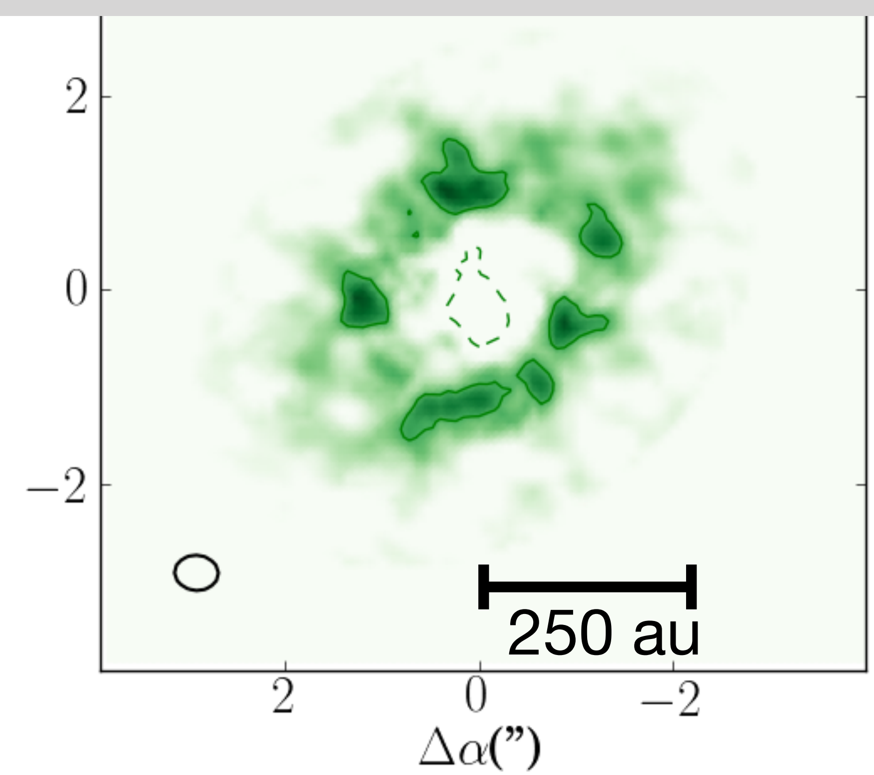




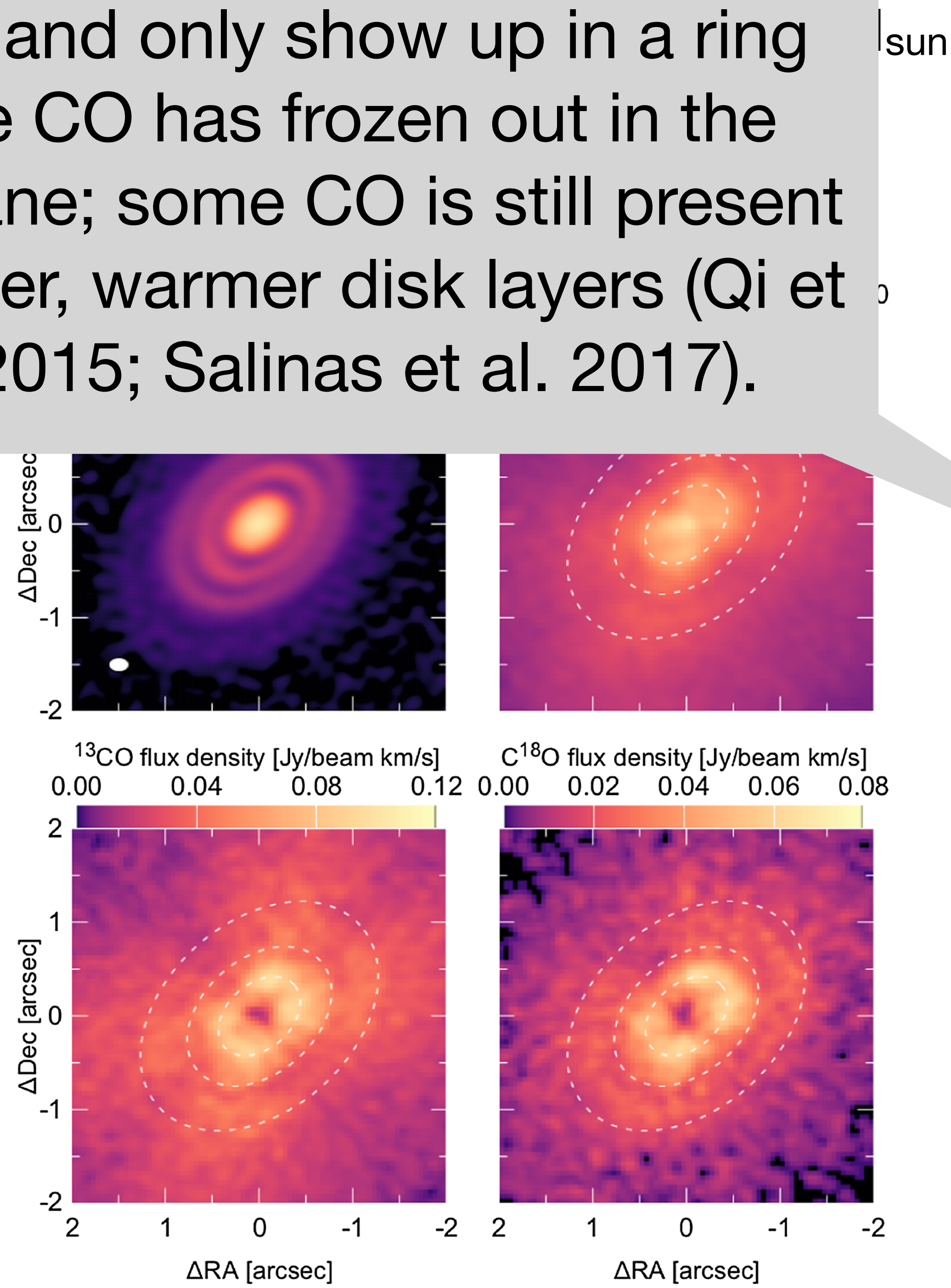
CO across the disk, but 'holes' in the ^{13}CO and $C^{18}O$ emission: result of dust & line opacity - not an absence of gas!

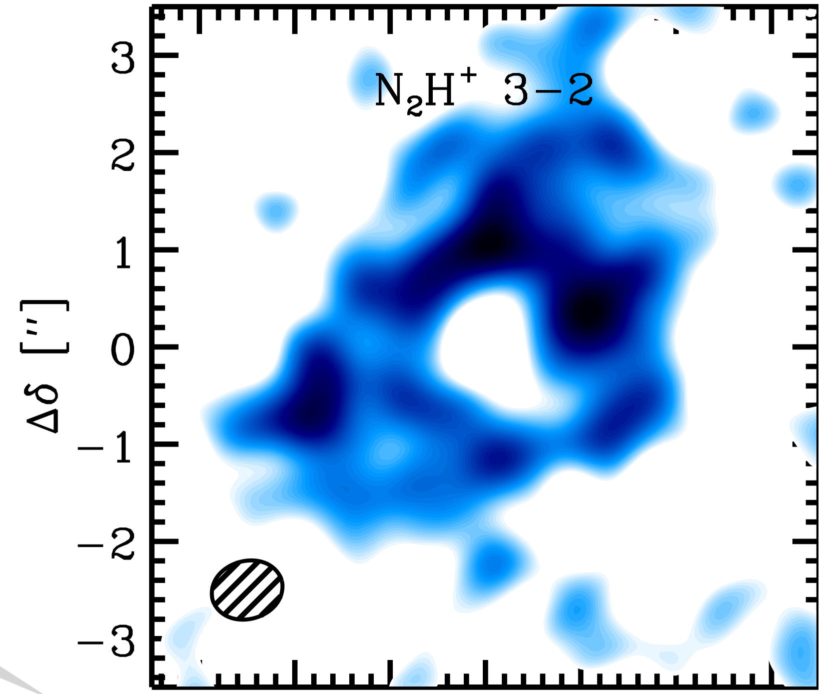


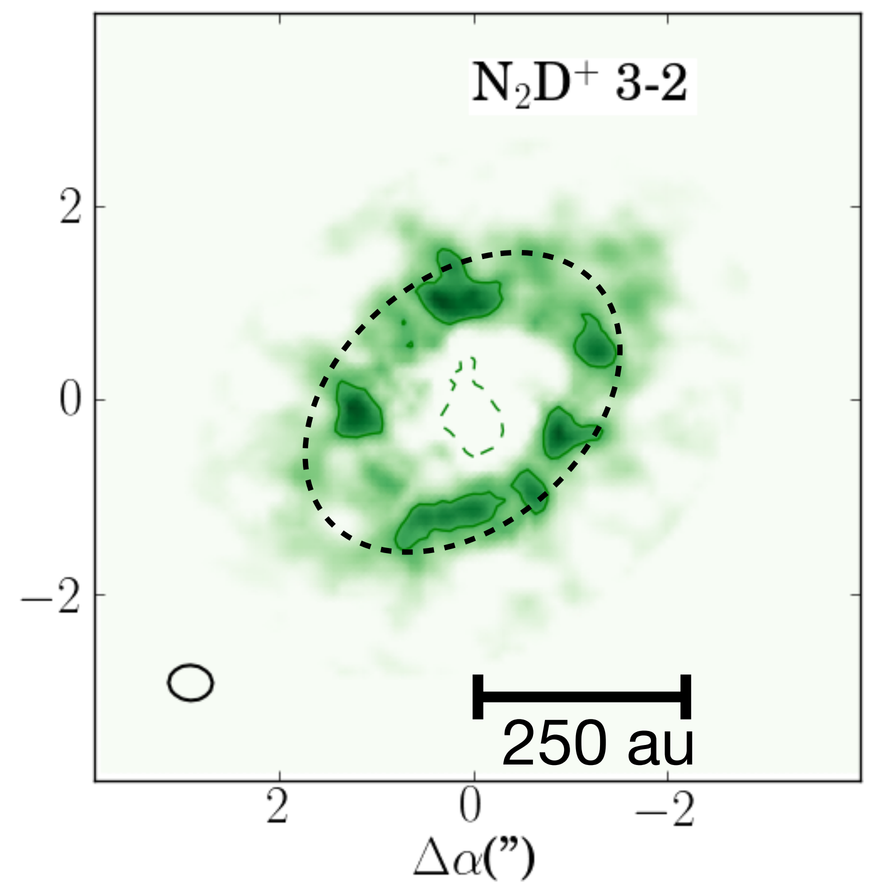
Salinas et al. (2017); Isella et al. (2016); Qi et al. (2015)

N_2H^+ and N_2D^+ in HD163296

N_2H^+ 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).

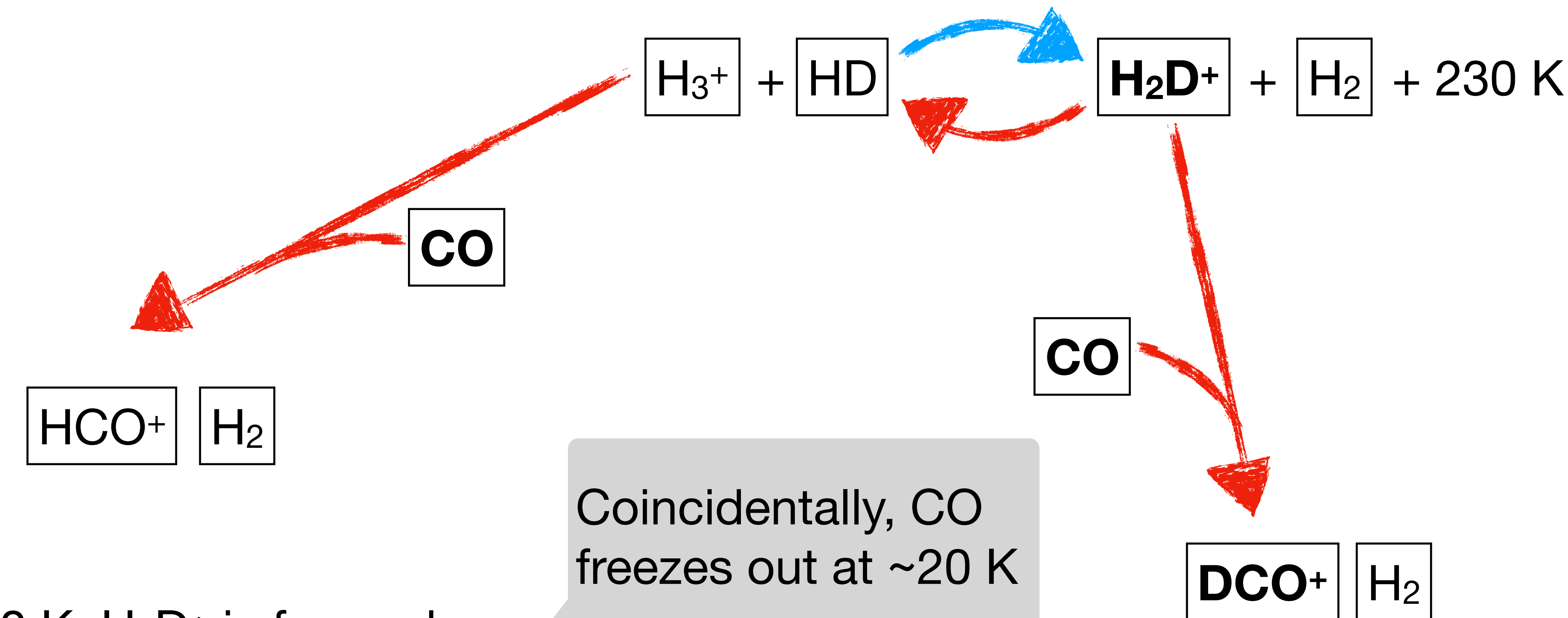






Salinas et al. (2017); Isella et al. (2016); Qi et al. (2015)

DCO^+ as a frozen-CO tracer



> Coincidentally, CO freezes out at ~20 K

Below ~20 K, H_2D^+ is favored.

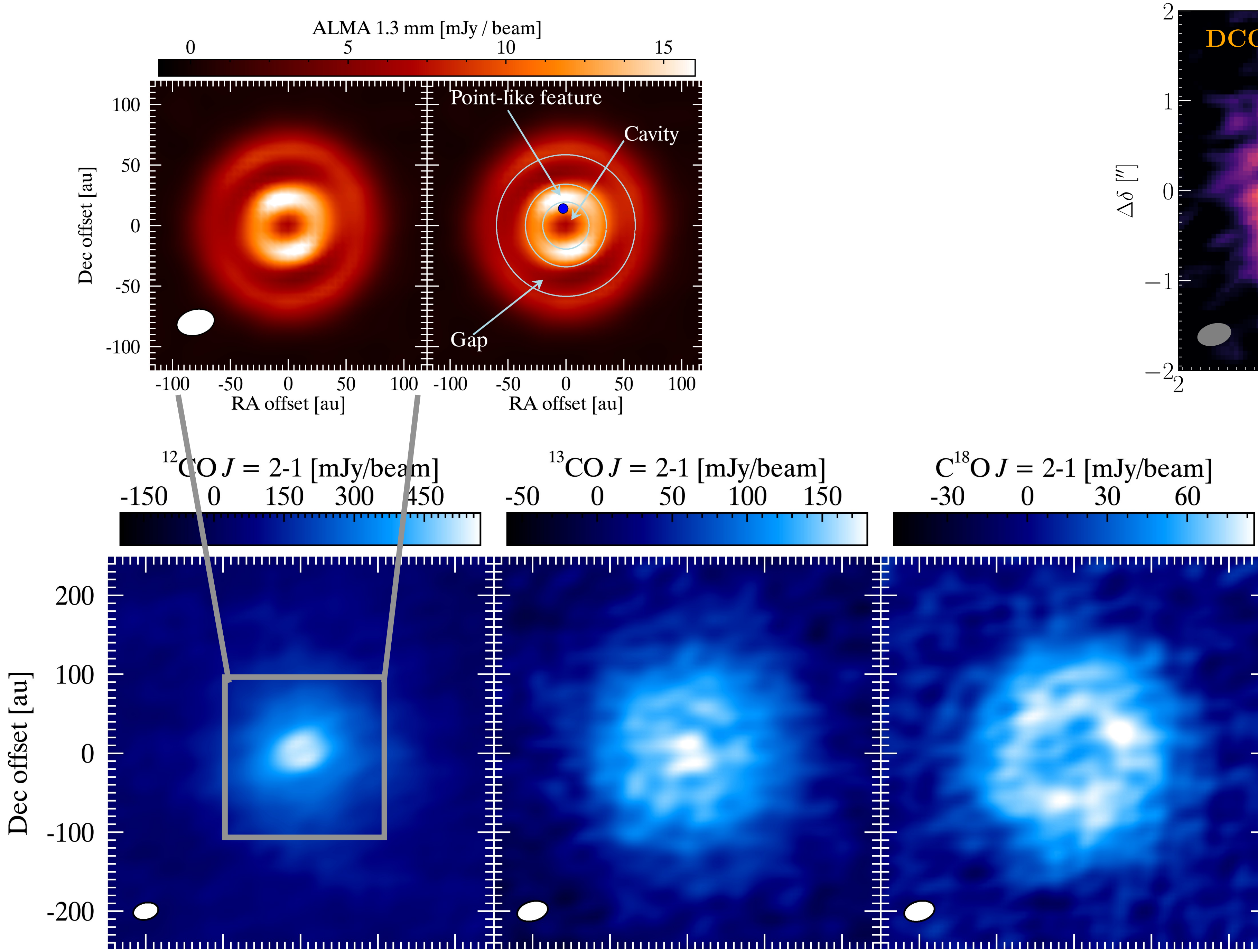
Gas-phase CO inhibits formation of H_2D^+.

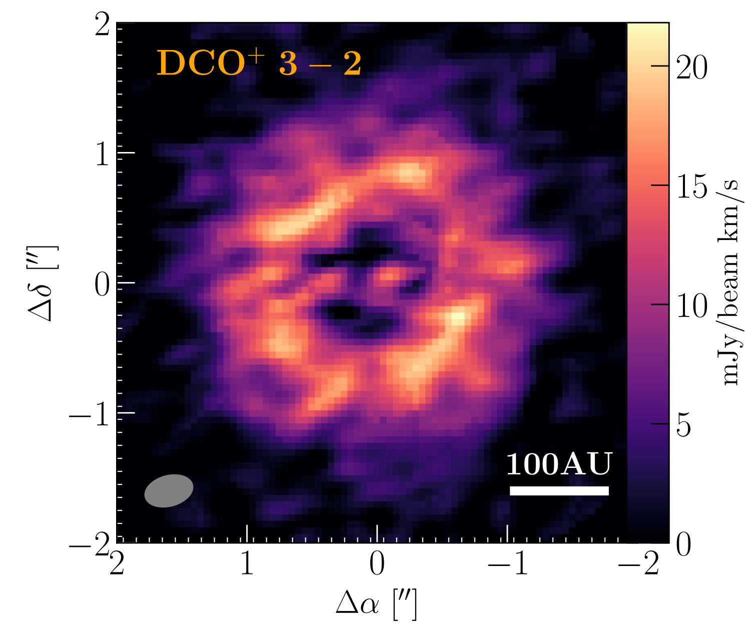
A small amount of CO is needed to convert H_2D^+ into DCO^+.

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

DCO+ in HD169142

- HD169142: d~120 pc, M_{star}~ 1.7 M_{sun}





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

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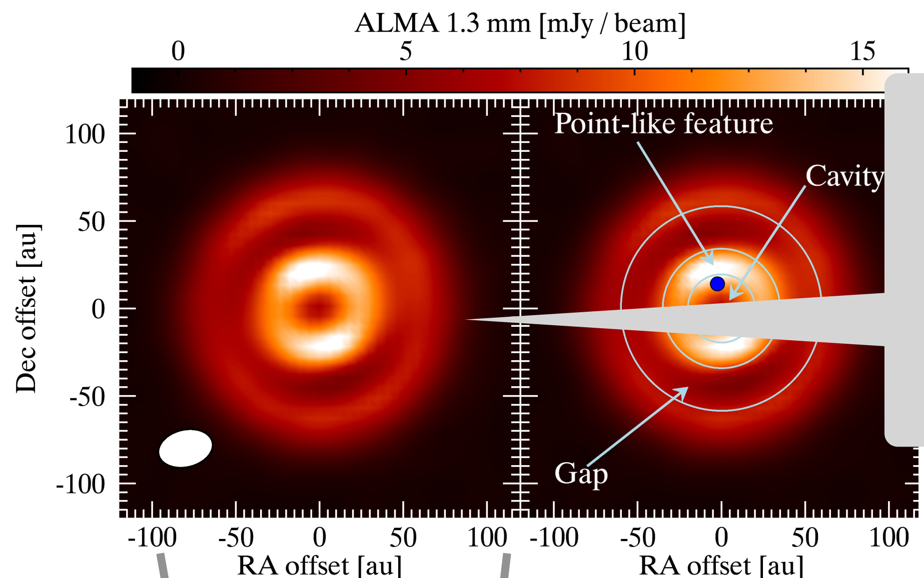
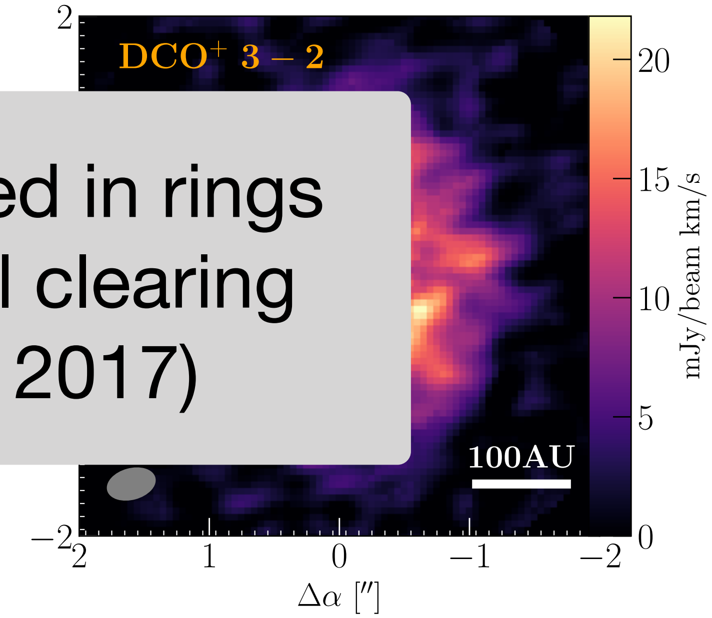
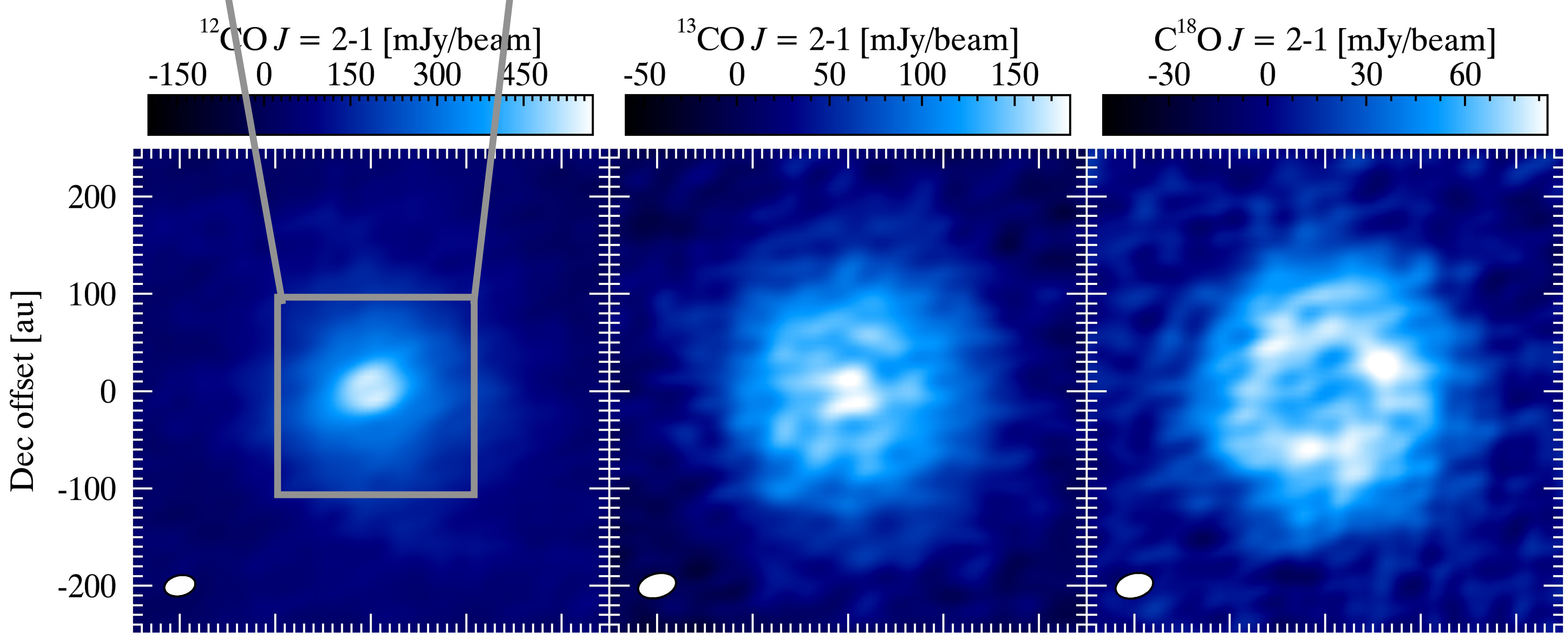


mm dust collected in rings around a central clearing (Fedele et al. 2017)





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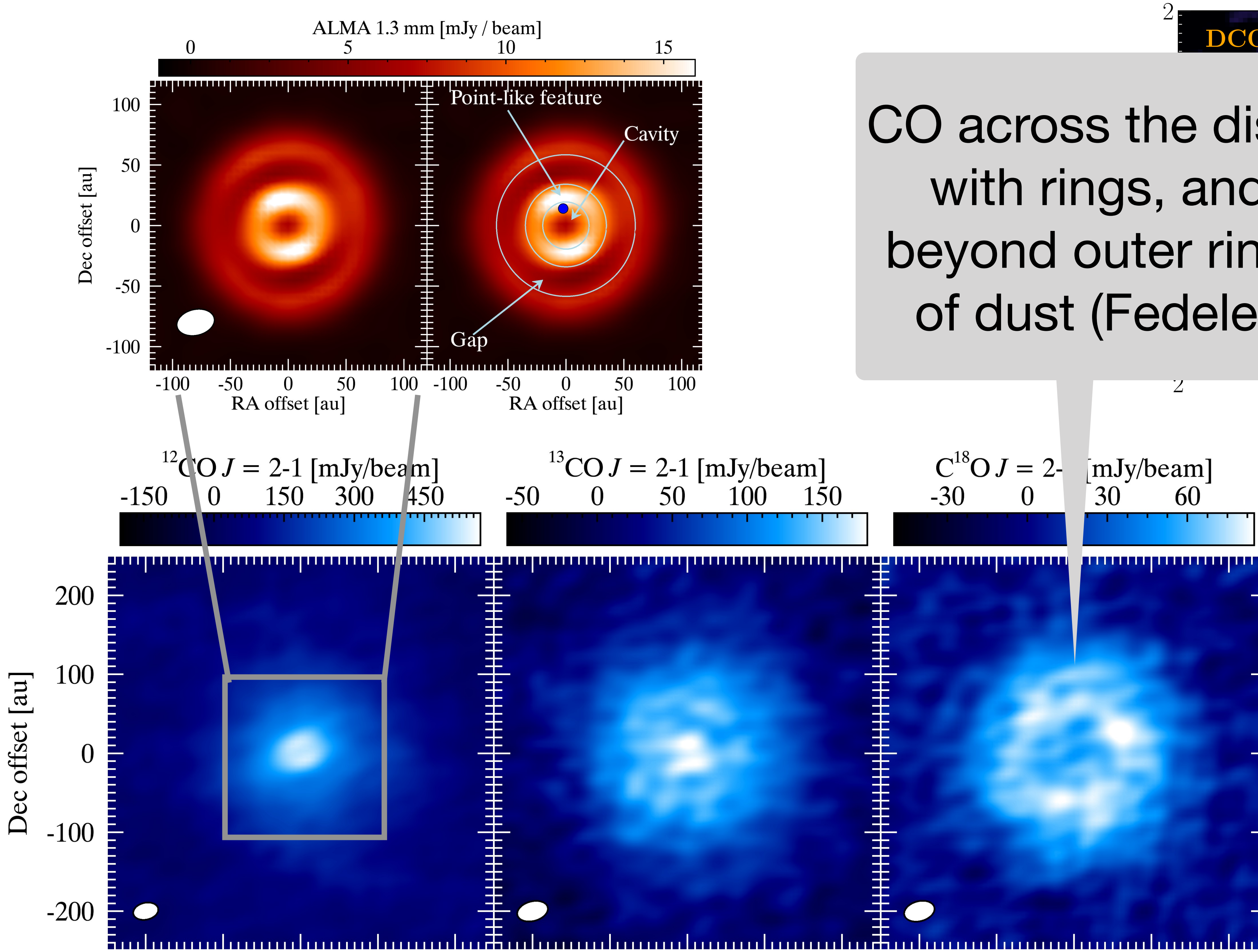

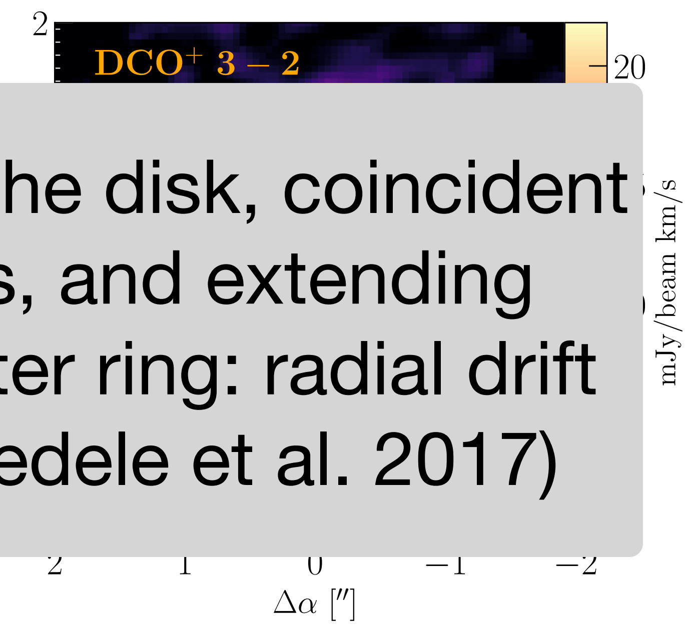

CO across the disk, coincident with rings, and extending beyond outer ring: radial drift of dust (Fedele et al. 2017)

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

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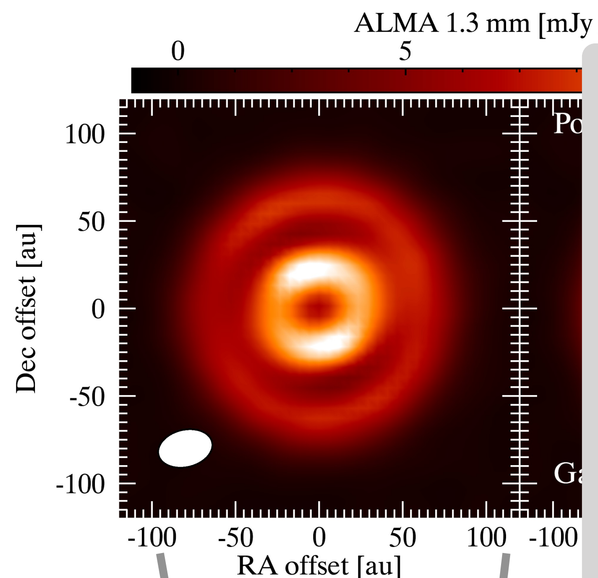
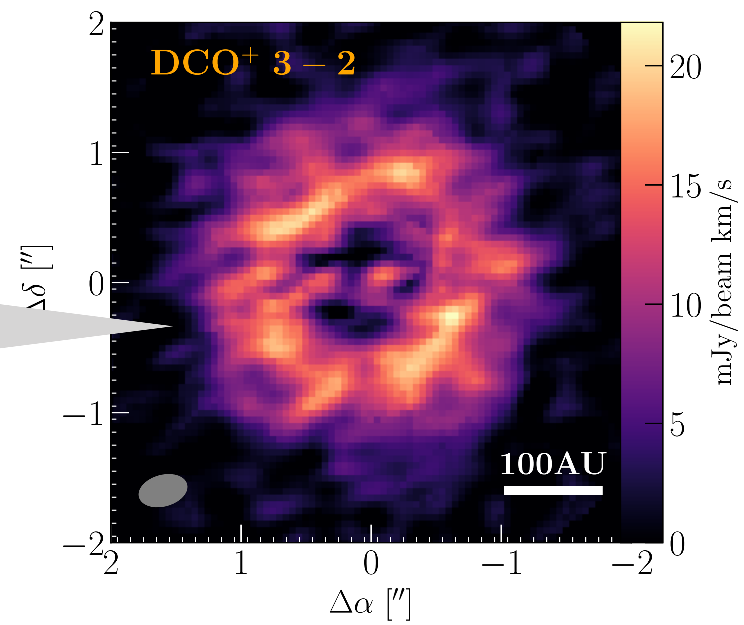
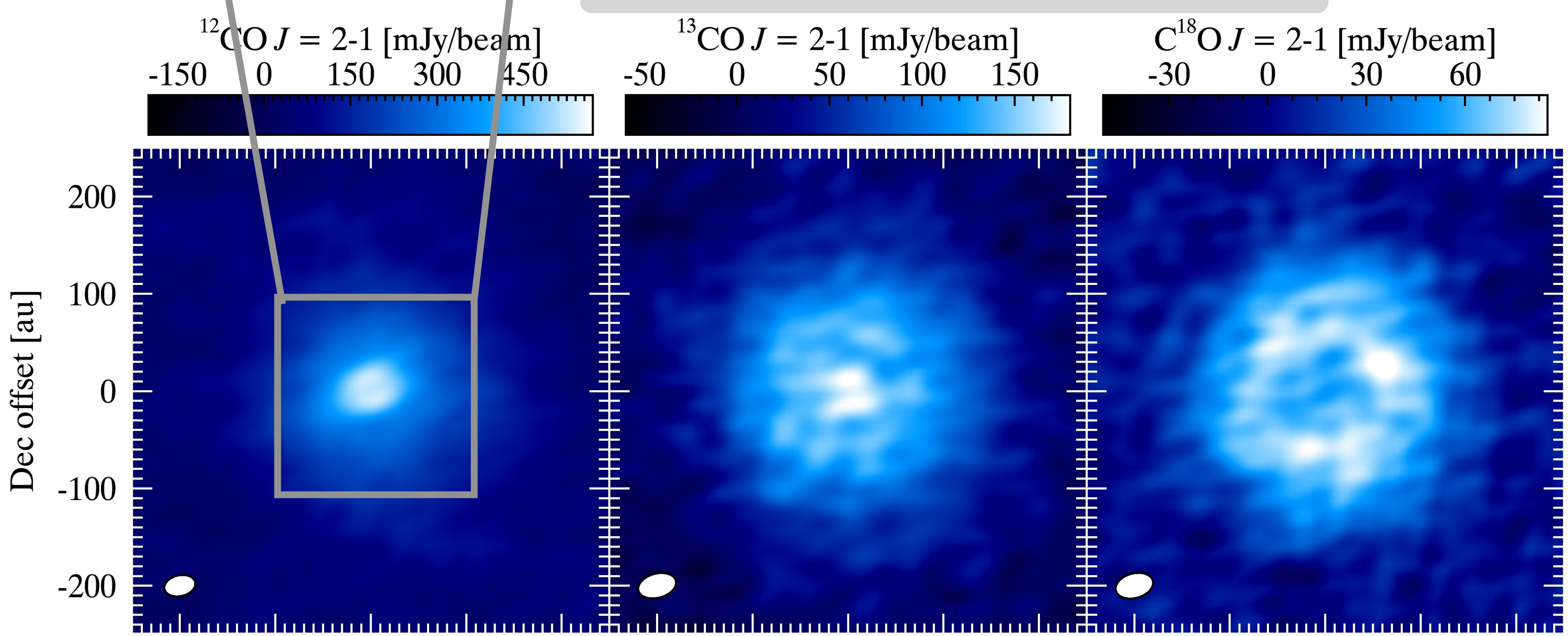


DCO+ in a ring outside the continuum rings. Requires very cold material in the midplane not even traced by CO (Carney et al. 2018)





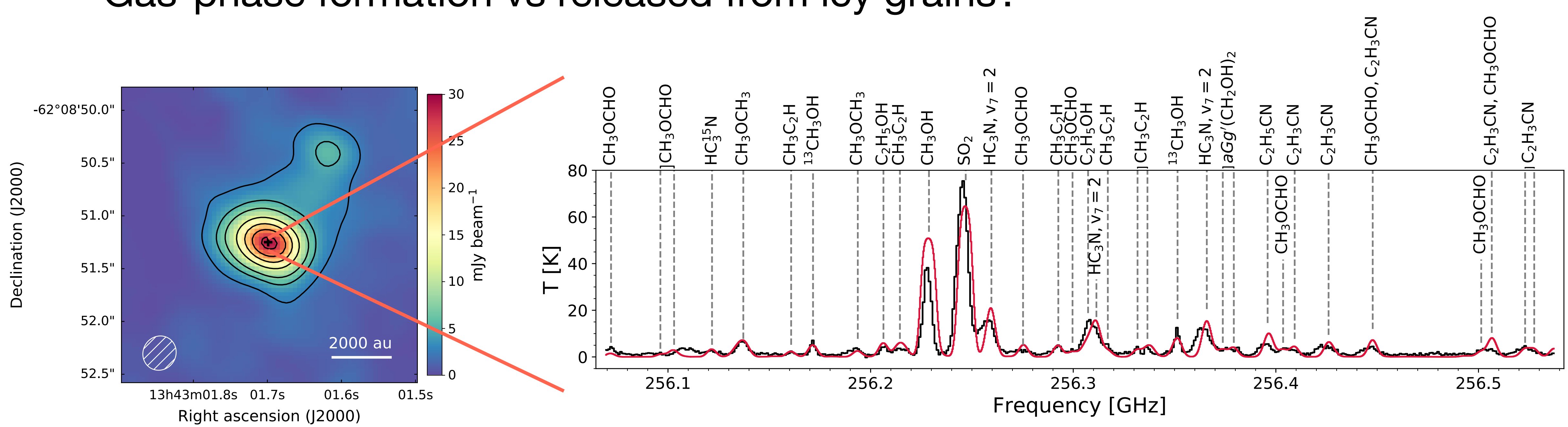
Fedele, Carney, Hogerheijde et al. (2017); Carney, Fedele, Hogerheijde et al. (2018)

2. Are simple organics present in the disk gas?

Organic chemistry in space

- Interstellar ices are known to contain organics such as CH_3OH
    - Sequential hydrogenation of frozen out CO
- Warm regions around protostars show many organics
    - Ice mantles evaporate
- Some simple organics have been found in disks
    - H_2CO, CH_3OH, HC_3N, CH_3CN, …
    - Gas-phase formation vs released from icy grains?

AFGL4176 (~2x10^5 L_{sun})
Bøgelund et al. (in prep)



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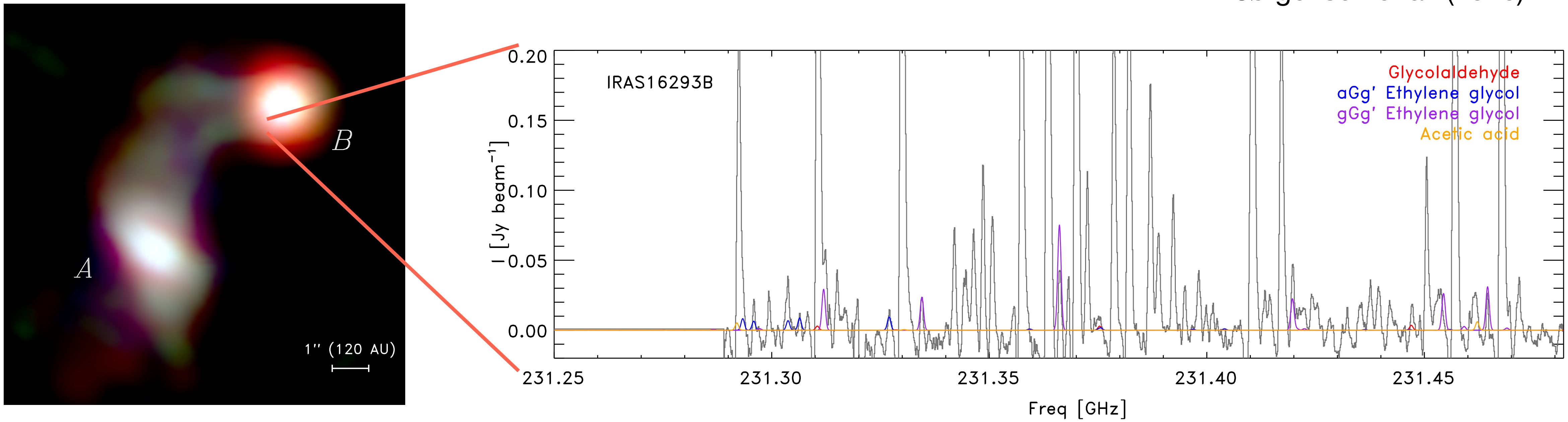
IRAS 16293-2422
Jørgensen et al. (2016)



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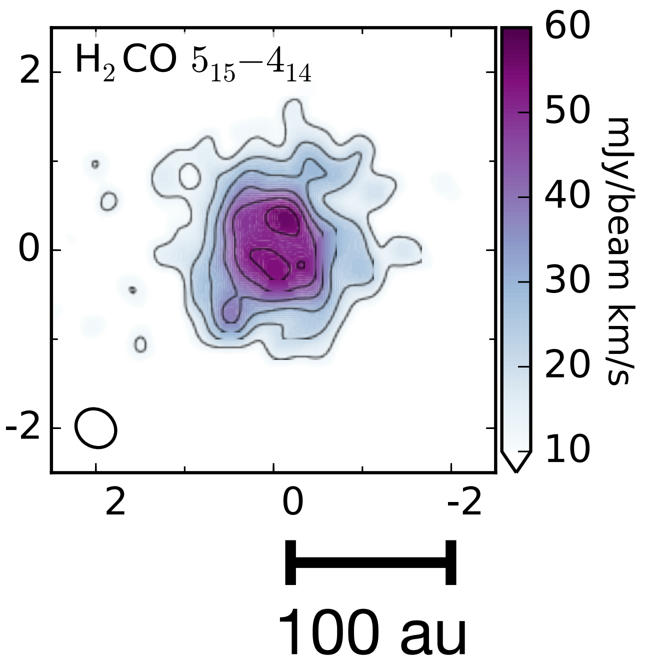
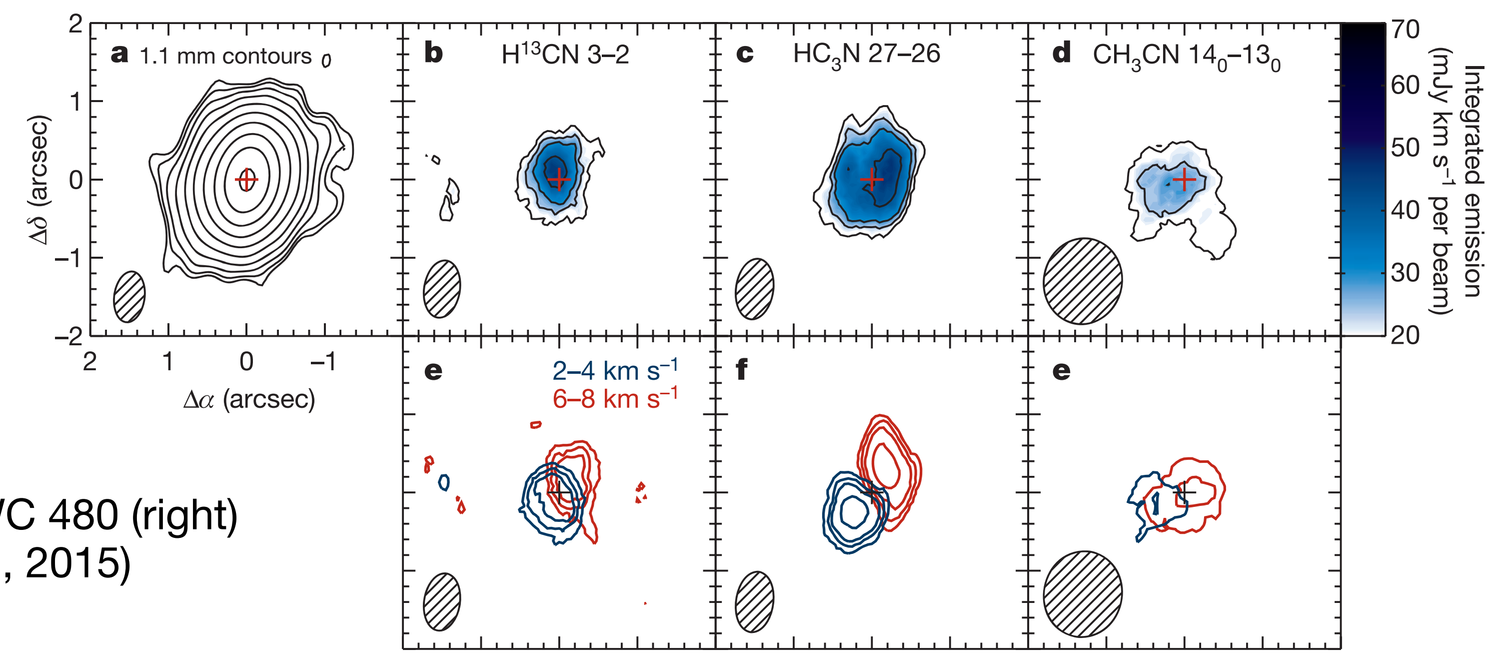
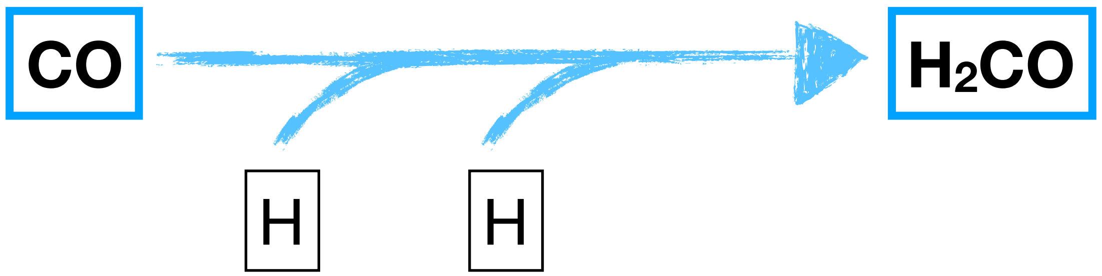




TW Hya (left), MWC 480 (right)
Öberg et al. (2017, 2015)

H_2CO chemistry

- Grain surface (ice) formation route



- Gas-phase formation route

H_2CO chemistry

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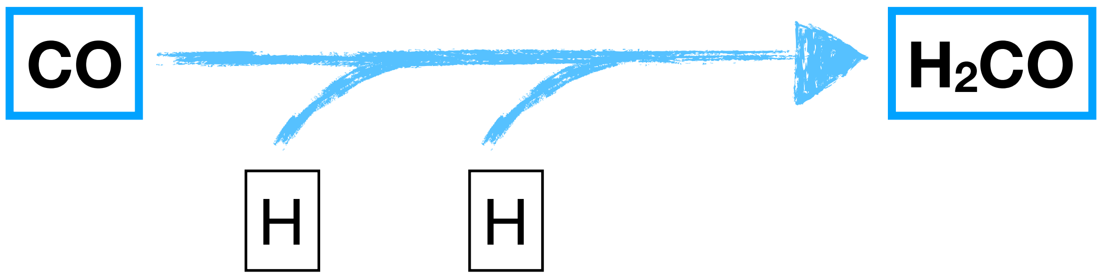
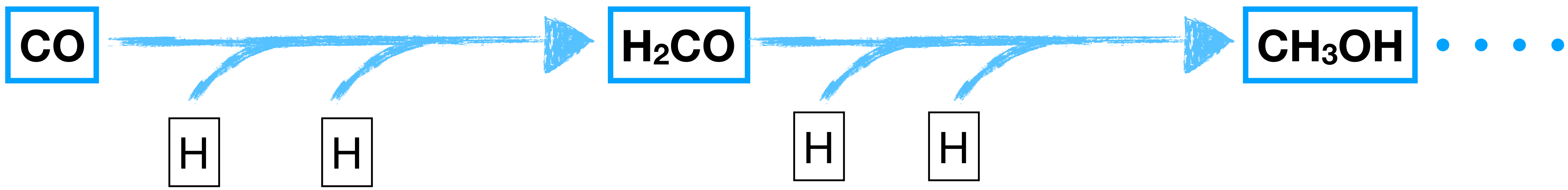


- Gas-phase formation route

Distribution of H_2CO across disks indicate *both* paths contribute (Öberg et al. 2017; Loomis et al. 2015)

CH_3OH chemistry

- Grain surface (ice) formation route



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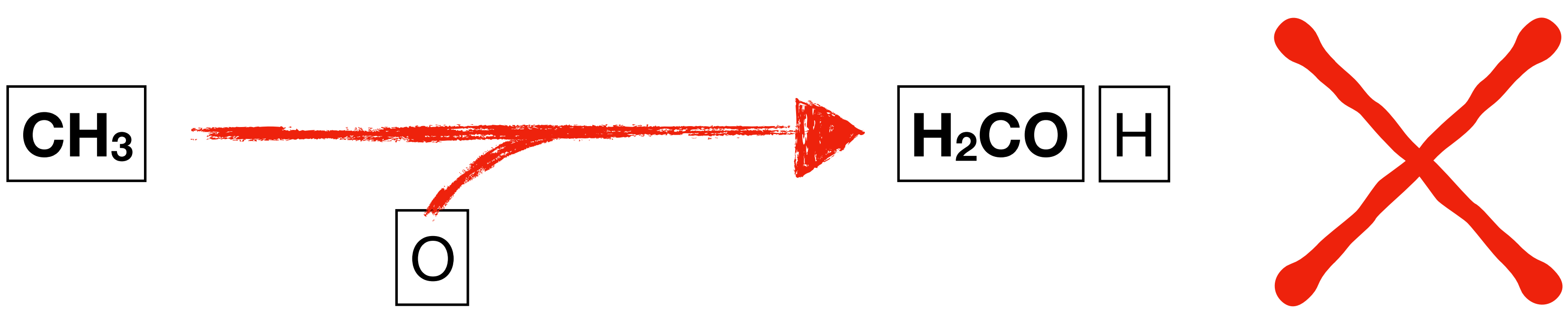

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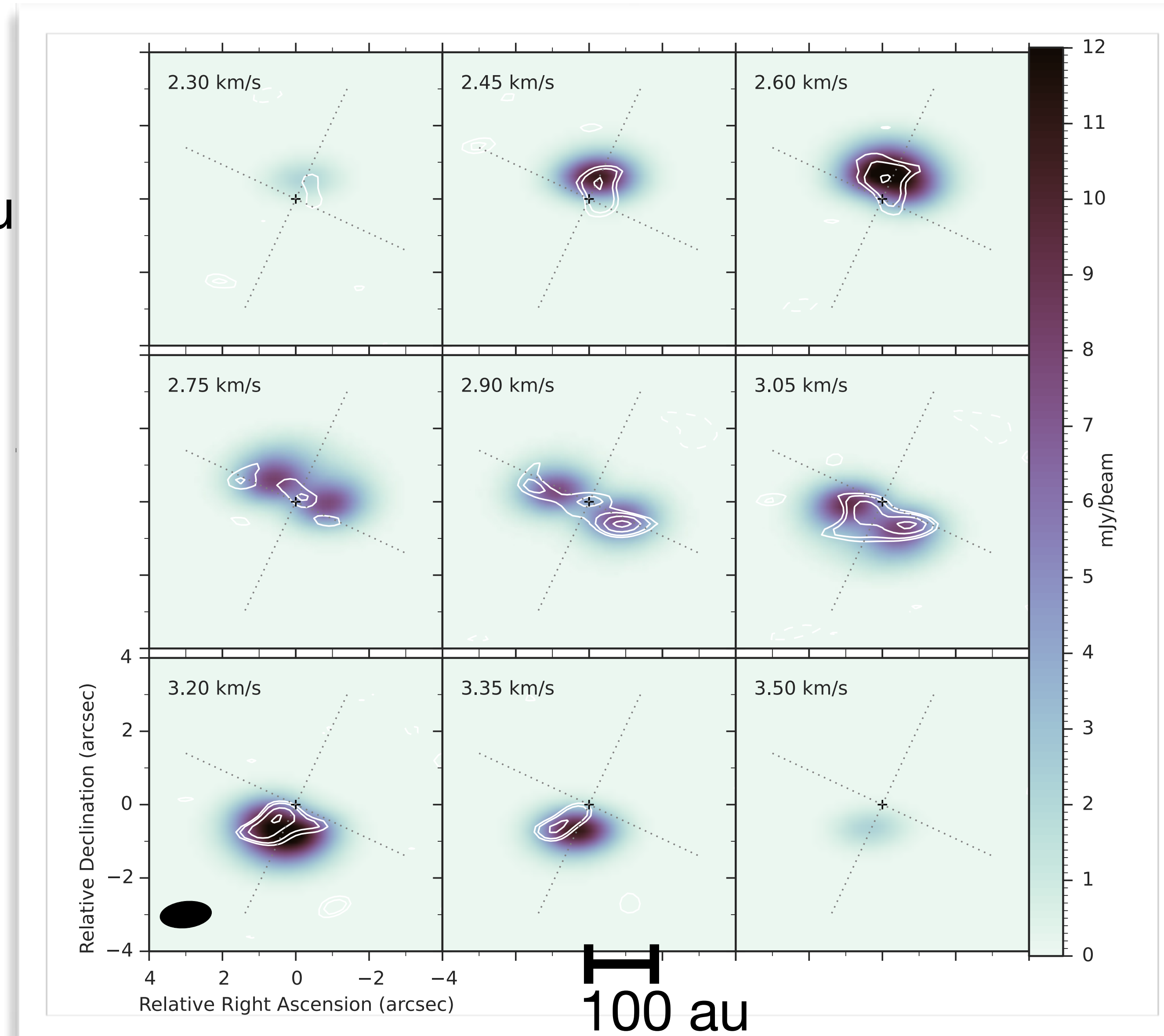
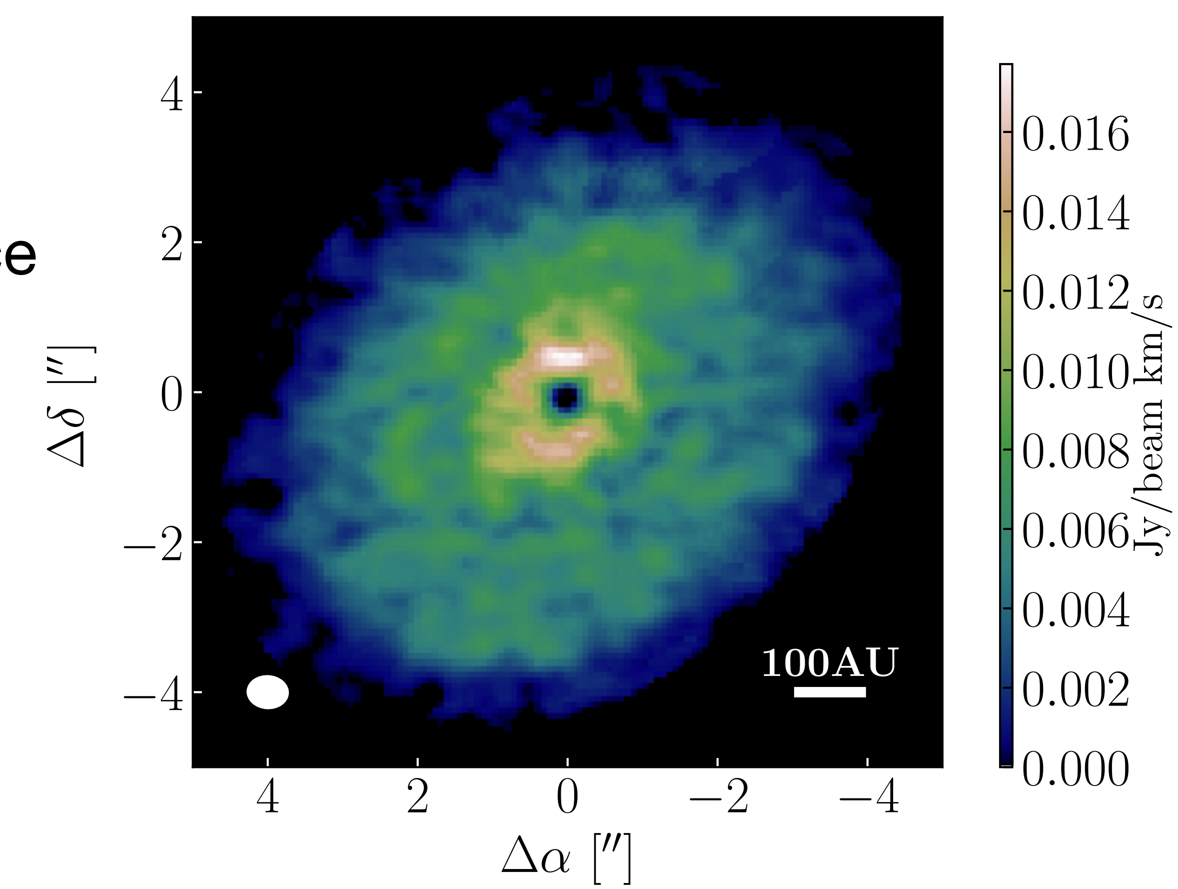
  - H_2CO, CH_3OH, HC_3N, CH_3CN, …
  - Gas-phase formation vs released



CH_3OH in planet forming disks has proven difficult to detect. First detection: TW Hya, Walsh et al. (2016)

H_2CO in HD163296

- H_2CO 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 $C^{18}O$ abundance by factor 5
- Increased penetration of stellar UV
    - Selectively photodissociates $C^{18}O$
    - Releases H_2CO from grains



Carney et al. (2016)

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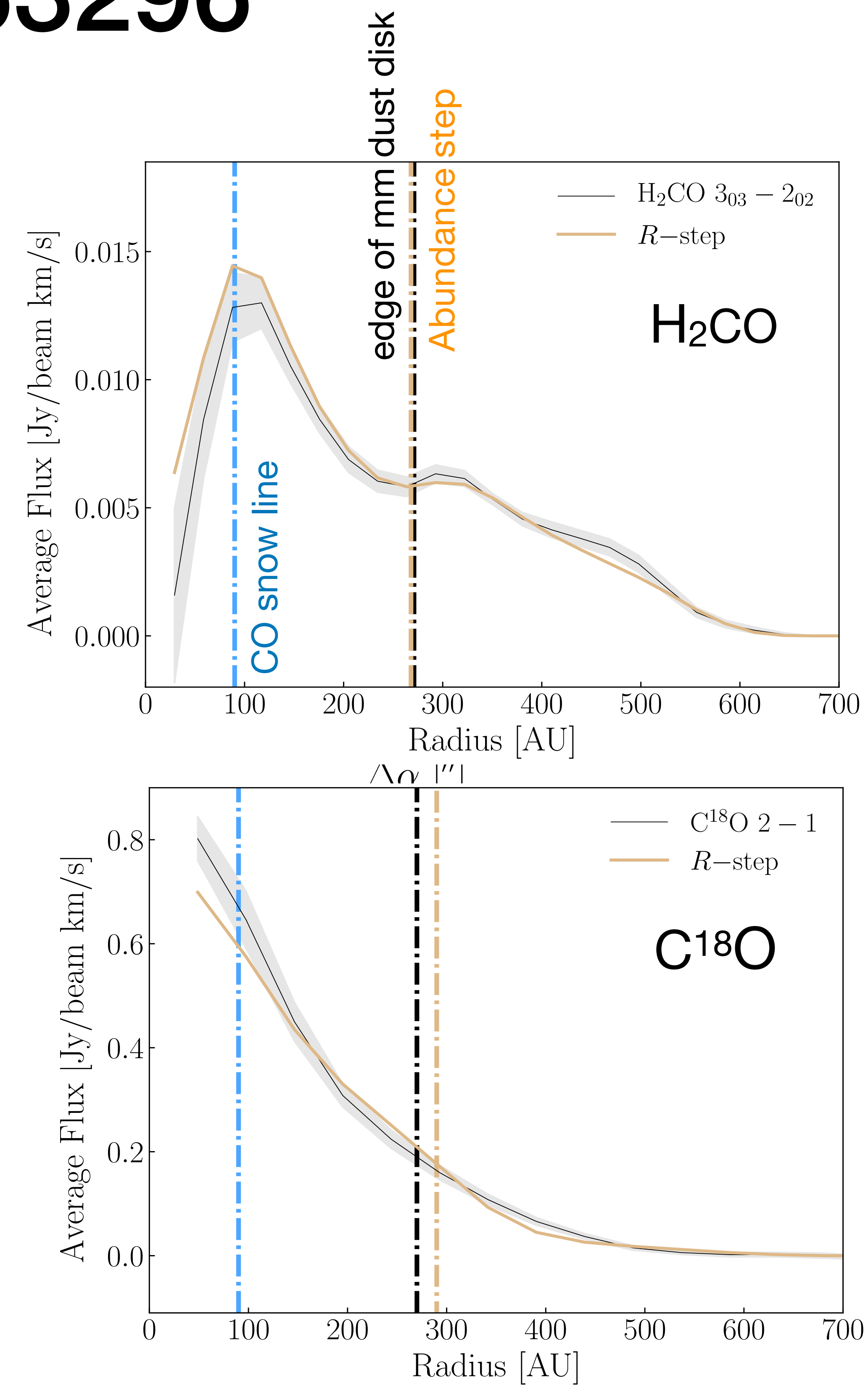


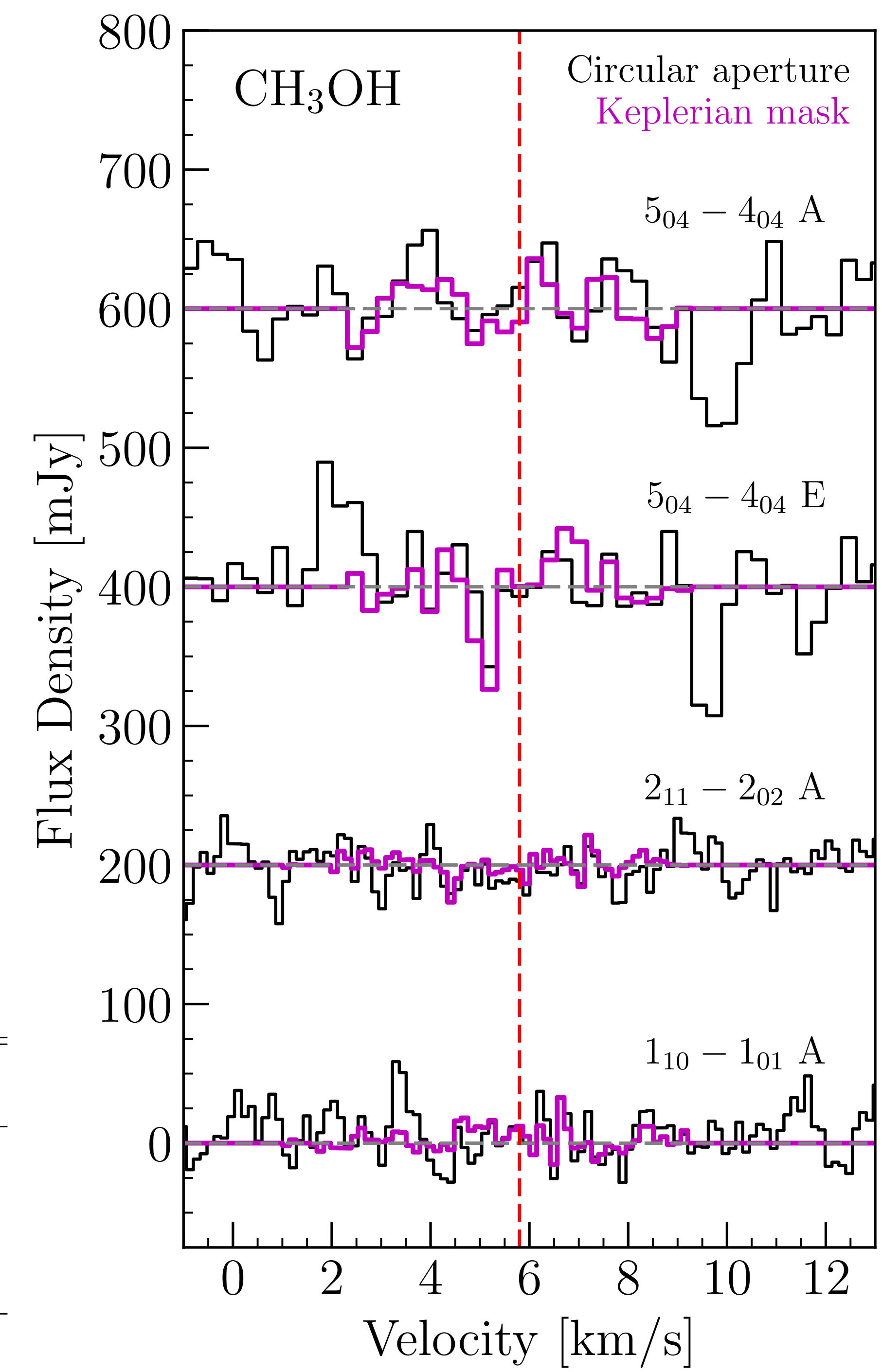
Carney et al. (2016)

…but no CH_3OH

- Deep limits on several CH_3OH lines
  - Strict upper limit of $CH_3OH/H_2CO<0.24$
  - cf. TW Hya: $CH_3OH/H_2CO\sim1.27$
- Harsher UV radiation from Herbig star destroys CH_3OH upon photodesorption?
- Recent thermal evaporation event in TW Hya?

Table 3: Disk-averaged column density and abundance of H_2CO in HD 163296 and TW Hya.

Target	Line	$\int I_\nu dv$ [mJy km s^{-1}]	E_u [K]	$\log(A_{ij})$ [s^{-1}]	n_{crit}[a] [cm^{-3}]	N_{avg} [cm^{-2}]	H_2CO/H_2	CH_3OH/H_2CO[†]
HD 163296	H_2CO 3_{12}–2_{11}	890 ± 89[b]	33.4	−3.55	5.7(06)	2.1(12)	6.3(−12)	< 0.24
TW Hya	H_2CO 3_{12}–2_{11}	291 ± 29[c]	33.4	−3.55	5.7(06)	3.7(12)	8.9(−13)	1.27 ± 0.13



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.
    - N_2H^+ reliably traces frozen-out CO, but beware that the peak of the N_2H^+ emission ≠ the CO now line.
    - N_2H^+ 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 N_2H^+ 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.
    - H_2CO 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.
    - CH_3OH remains elusive, and may only come off grains intact after thermal evaporation