Dense core chemistry as seen by Herschel, NOEMA and ALMA

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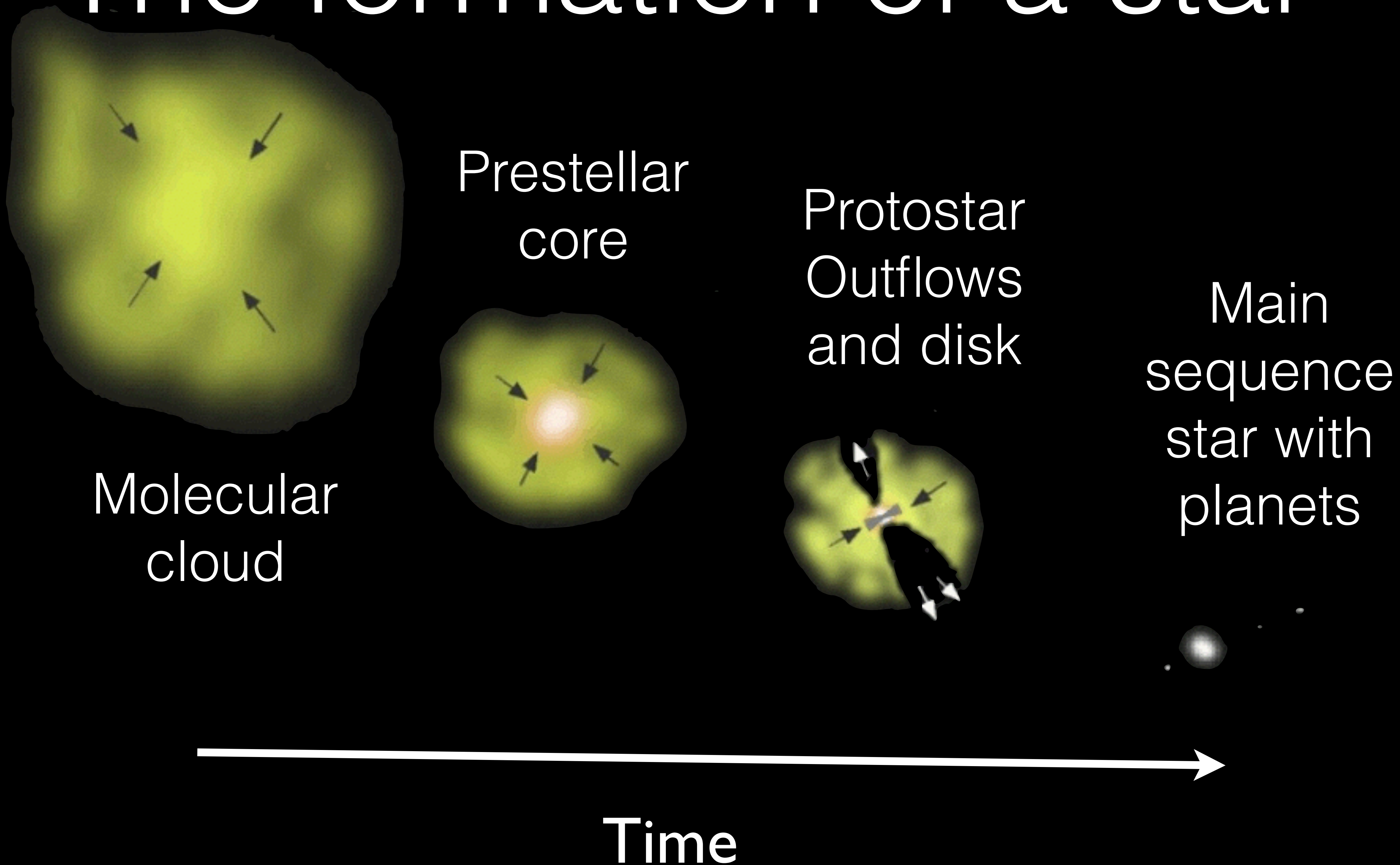
The formation of a star



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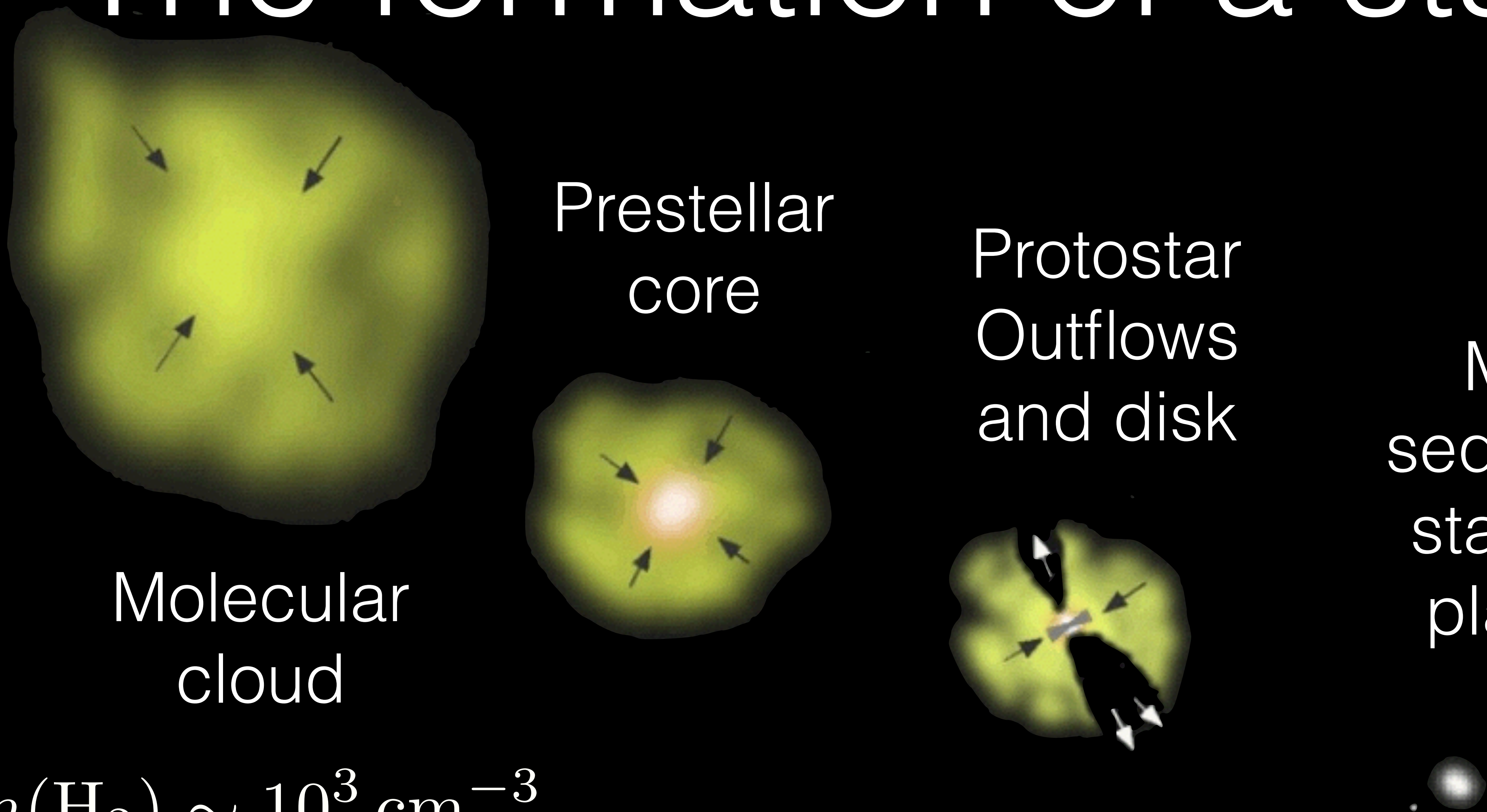
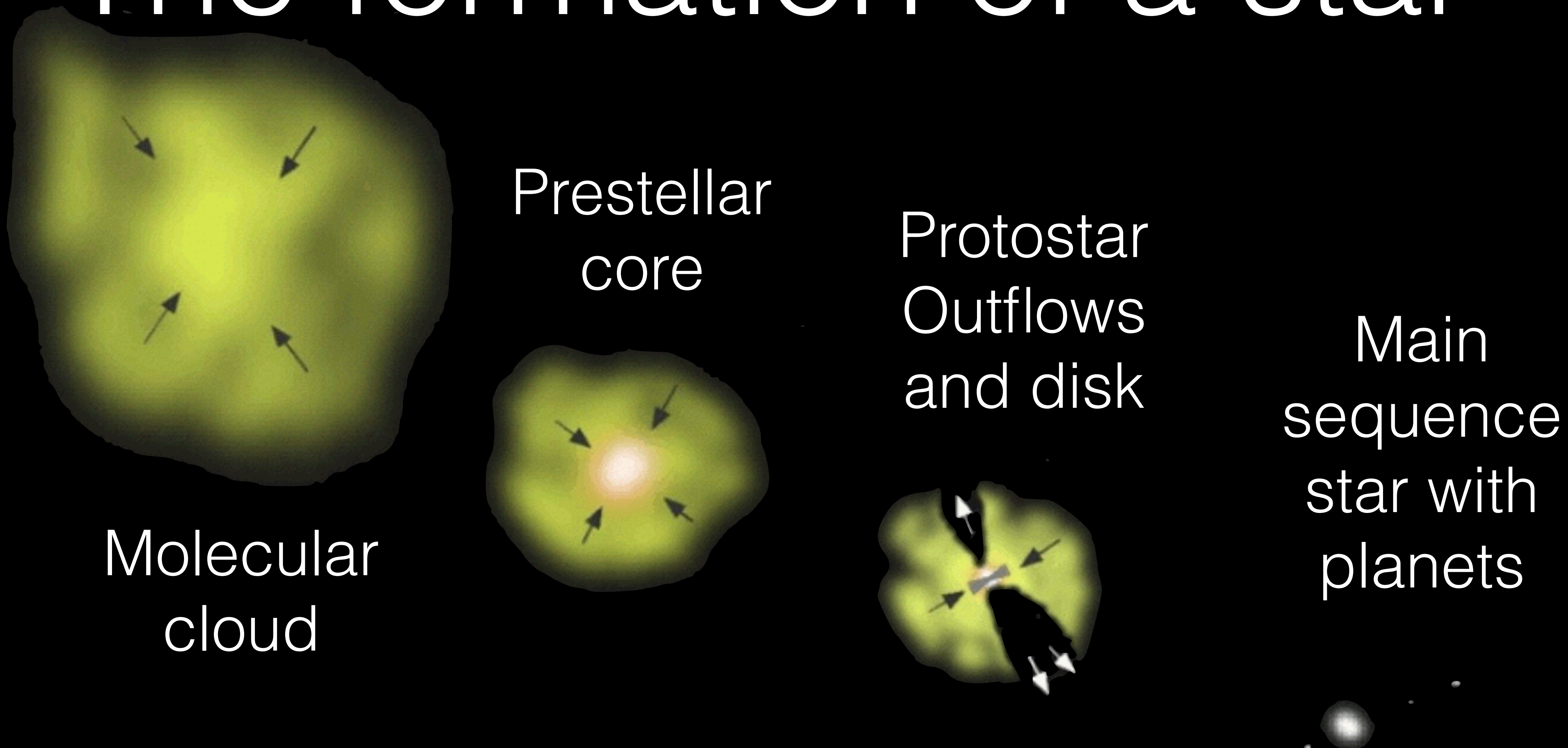


$$n(\mathrm{H_2}) \sim 10^3\,\mathrm{cm}^{-3}$$
$$T \sim 10\,\mathrm{K}$$

$$n(\mathrm{H_2}) \sim 10^7\,\mathrm{cm}^{-3}$$
$$T \gtrsim 100\mathrm{K}$$

The formation of a star



➡The gas composition is altered significantly (e.g. freeze-out, ices evaporation...)

Why study chemistry?

- Chemistry and the physics of **the star formation process** are coupled (gas temperature, ionization fraction...)

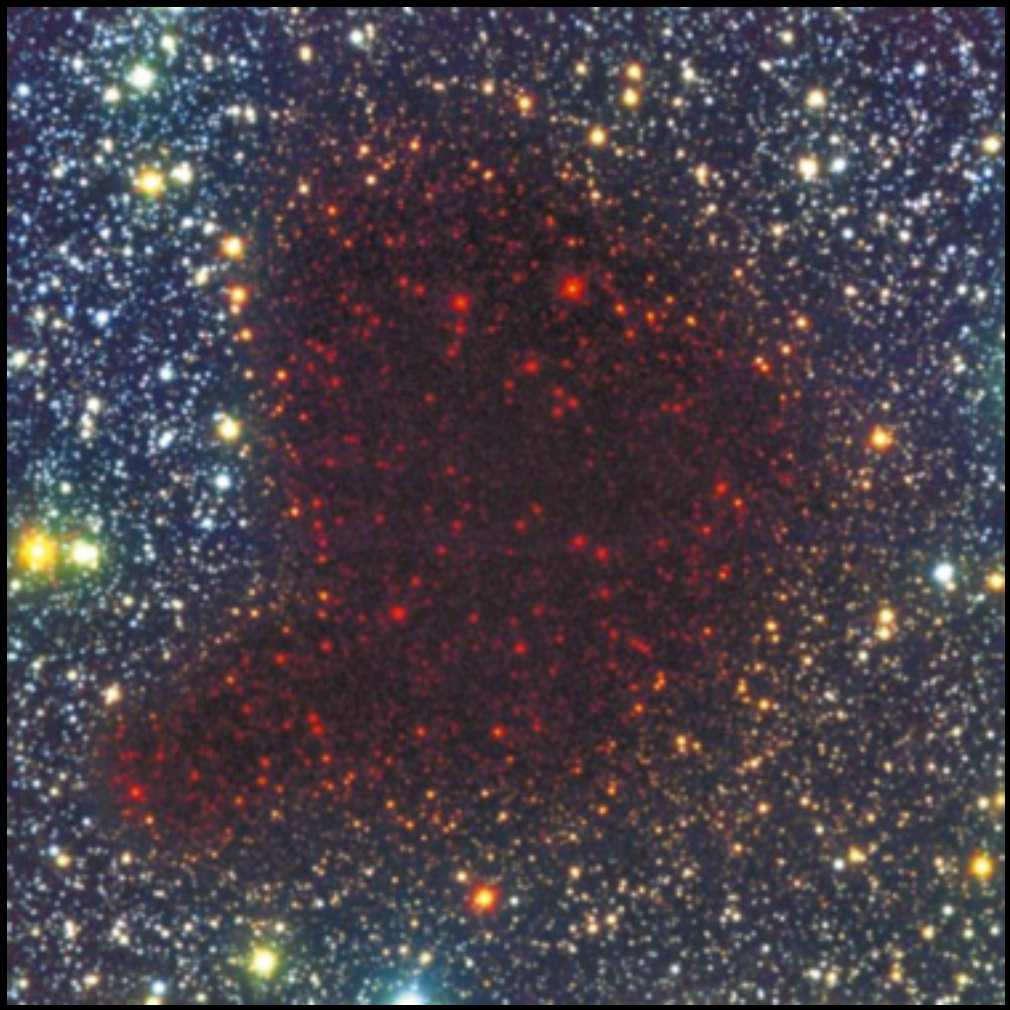
- Molecular lines can be used as **probes of the gas physical conditions** (temperature, density, gas velocity)

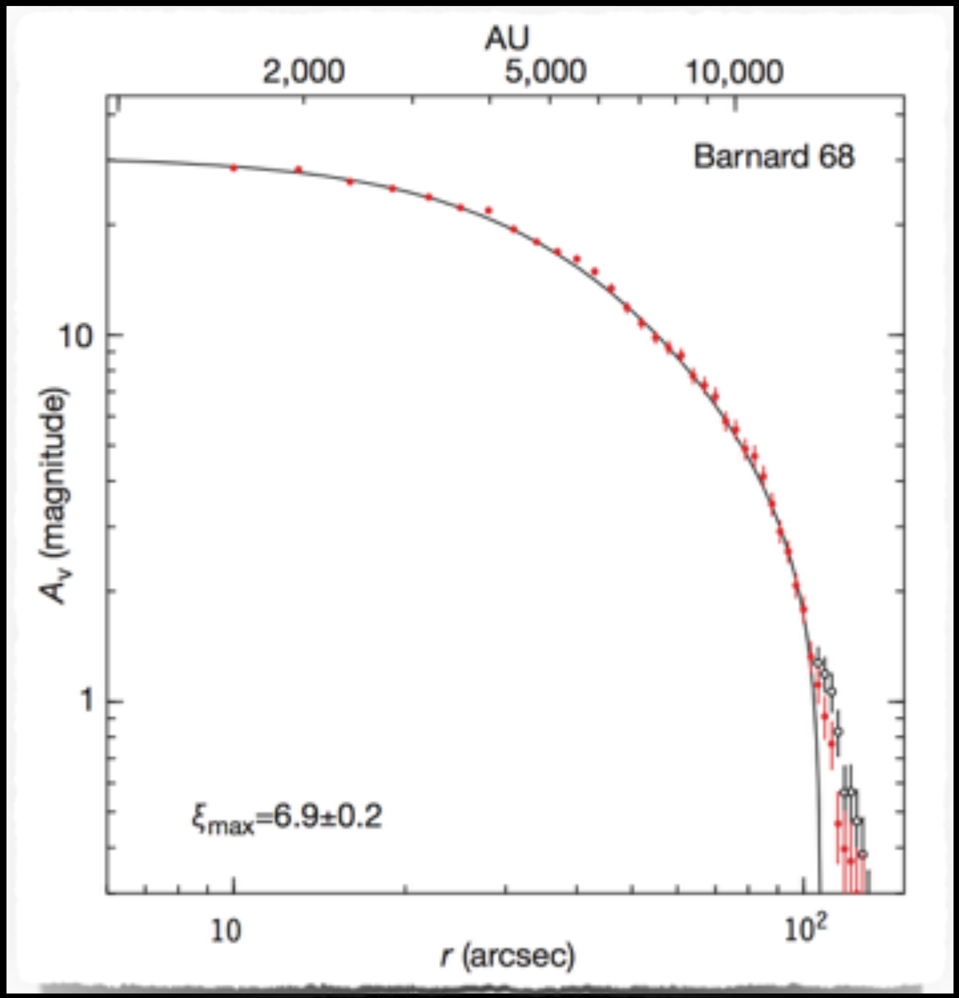
- Planetary system may **inherit** of some of the species that are formed during the early phases

In this talk…

- I will the review the recent progress in our understanding of the dense core chemistry
- I will also present a few results on the chemistry in embedded (Class 0) protostars obtained with NOEMA
- I will discuss some perspectives for the study of dense core chemistry with ALMA and NOEMA

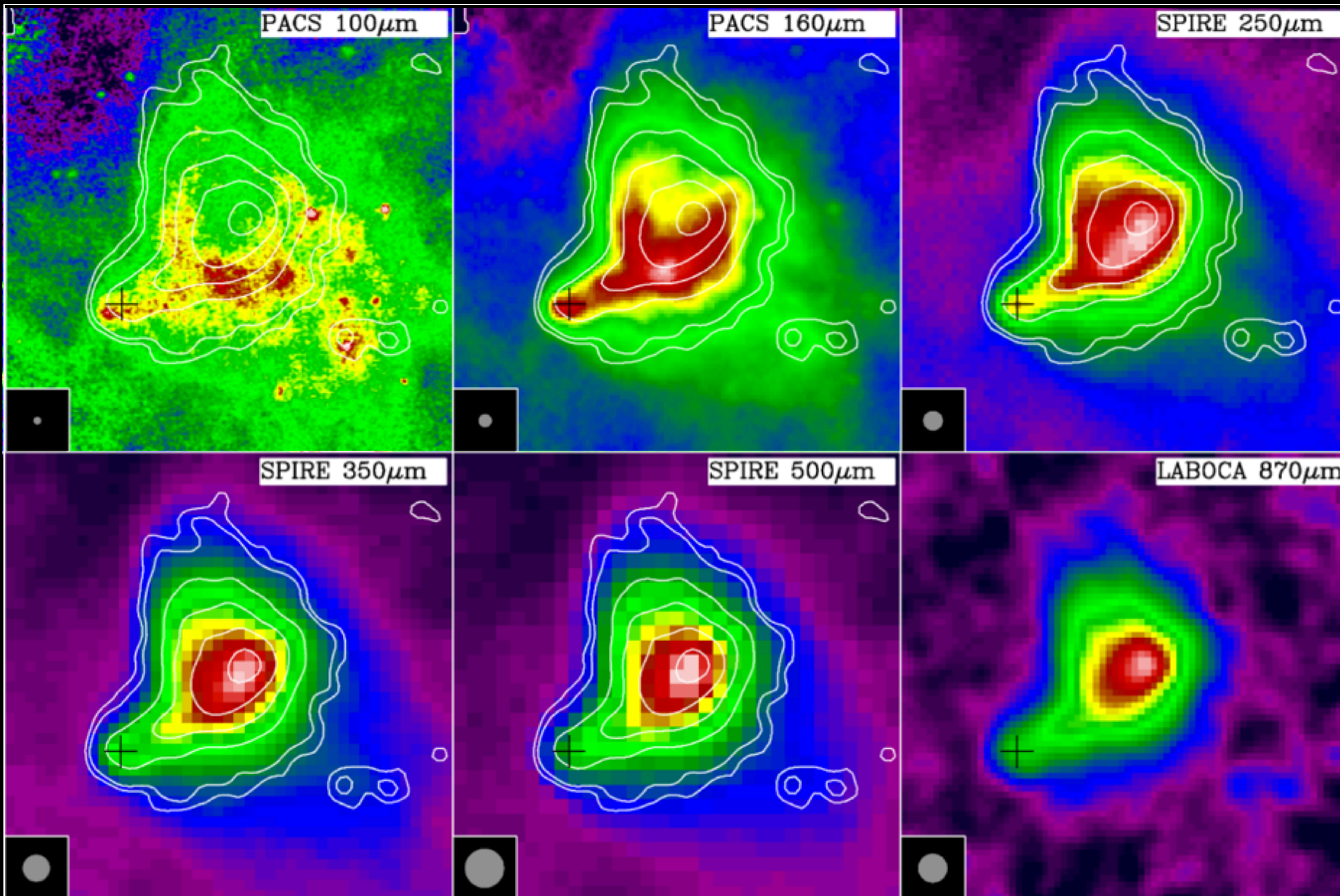
Physical conditions in cores





- Density in the cloud determined from the extinction of background stars

Alves et al. (2001)

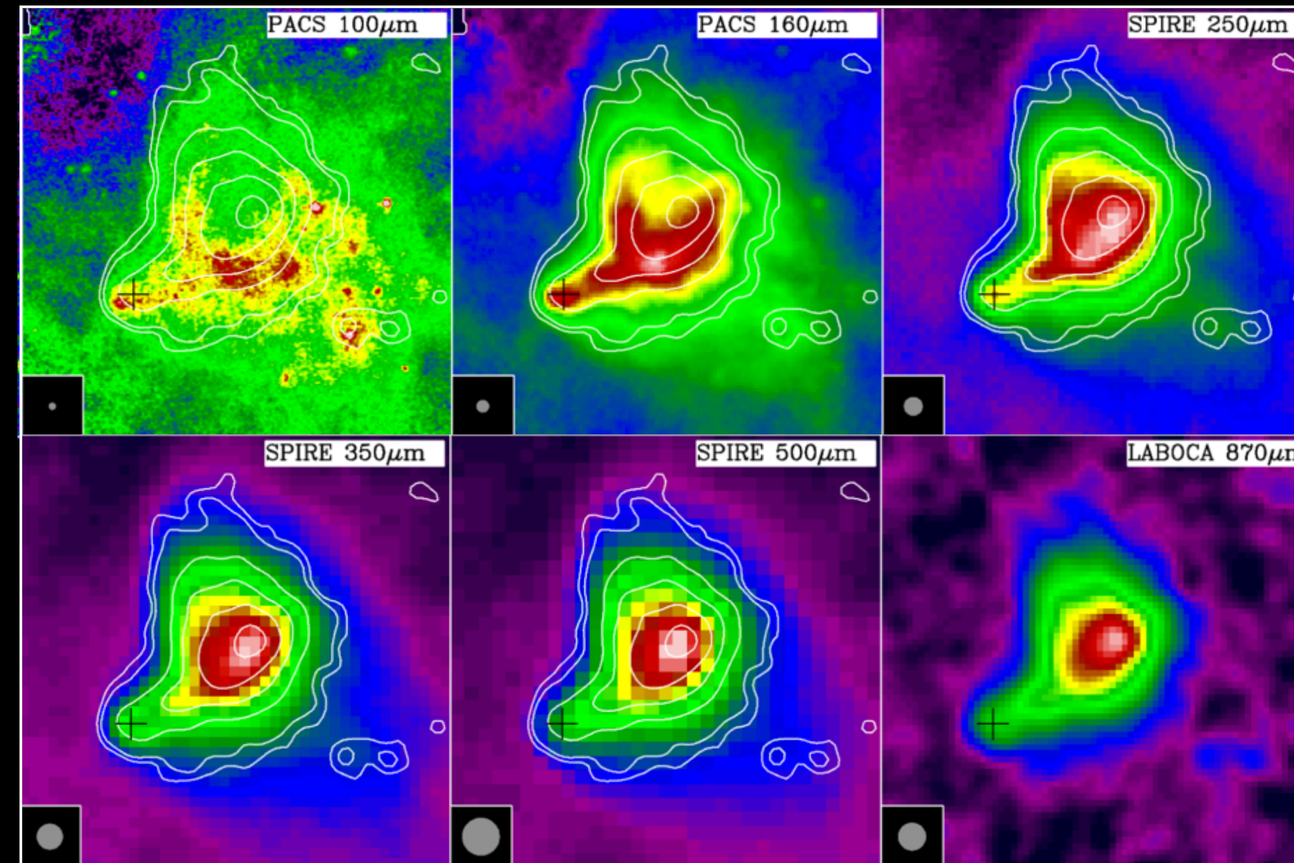


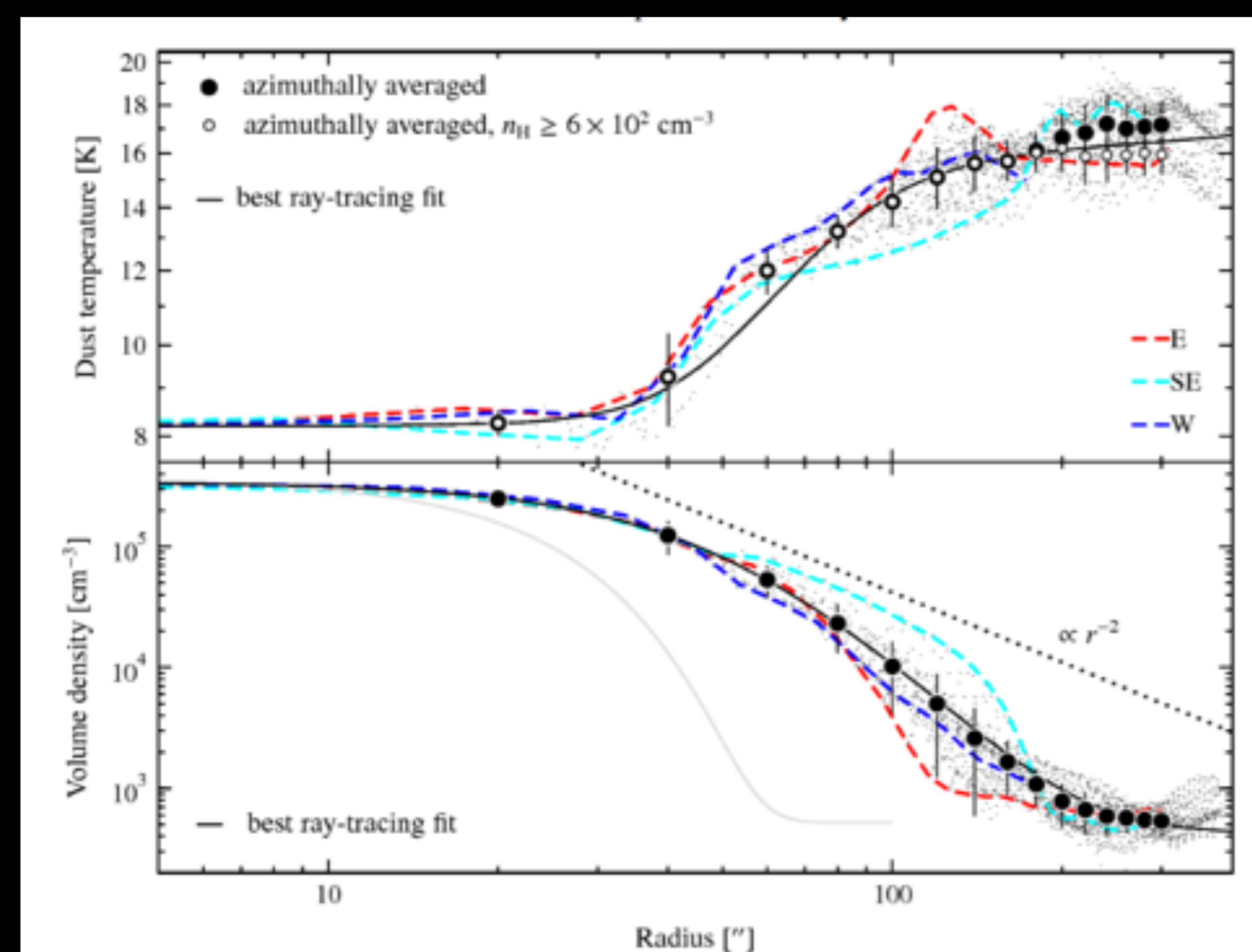
Nielbock et al. (2012)

- At the core center:

$$n(\mathrm{H_2}) = 3 \times 10^5 \mathrm{cm}^{-3}$$

$$T_{\mathrm{dust}} \simeq 8\,\mathrm{K}$$





Freeze-out on grains

- Depletion timescale (Tielens et al. 1982):

$$\tau_{\rm dep} = (\sigma_{\rm gr} v S n_{\rm gr})^{-1}$$

- Typical grain radius: $0.1\,\mu{\rm m}$

$$\tau_{\rm dep} = \frac{10^9}{n({\rm H_2})}\,{\rm yr}$$

- B68 : $n({\rm H_2}) = 3 \times 10^5\ {\rm cm^{-3}}$

$$\tau_{\rm dep} = 3000\,{\rm yr}$$

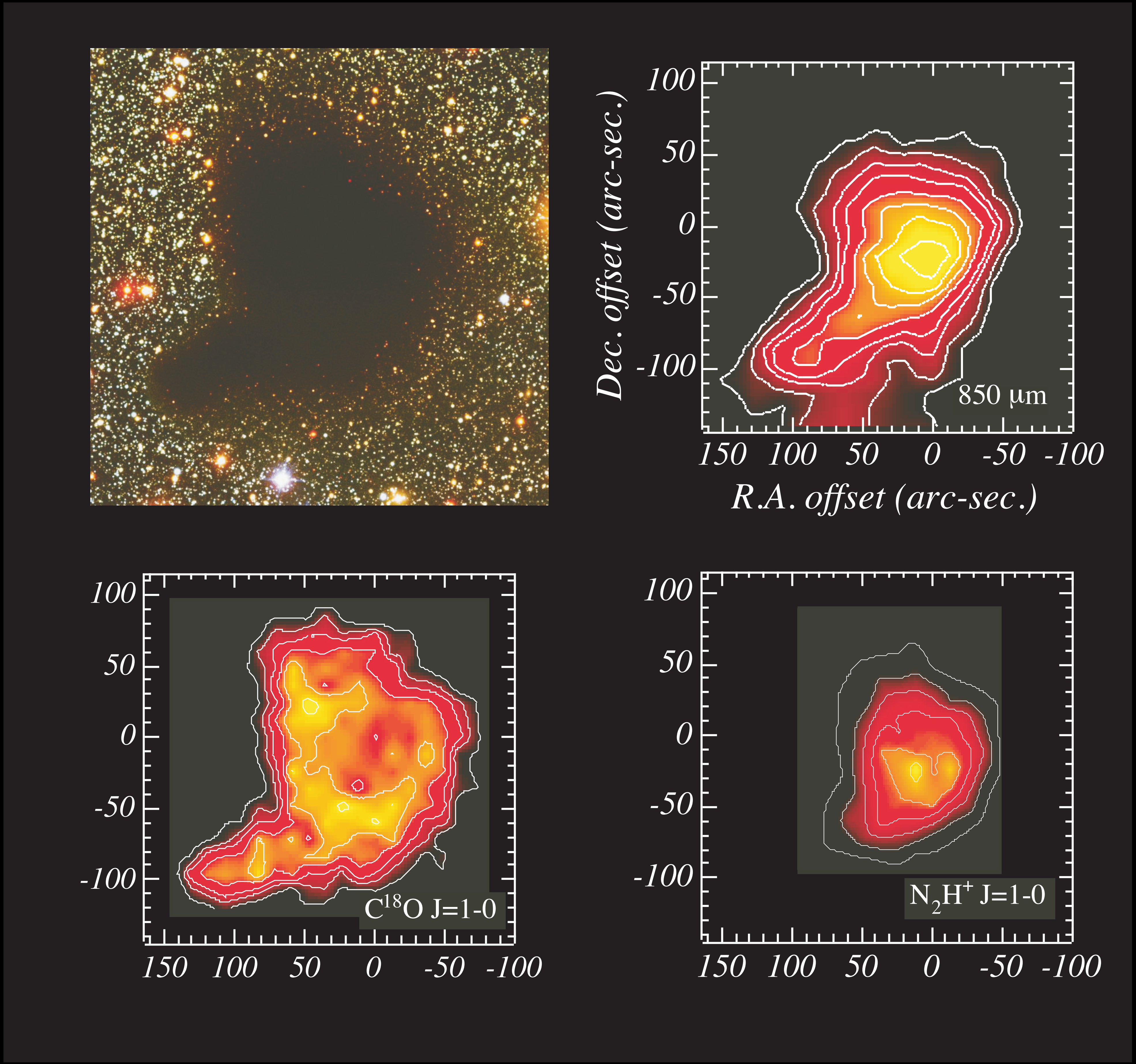
- Thermal desorption:

$$\tau_{\rm des} = \left(10^{12} \, e^{\frac{-E_{\rm b}}{kT_{\rm dust}}} \right)^{-1} \quad s$$

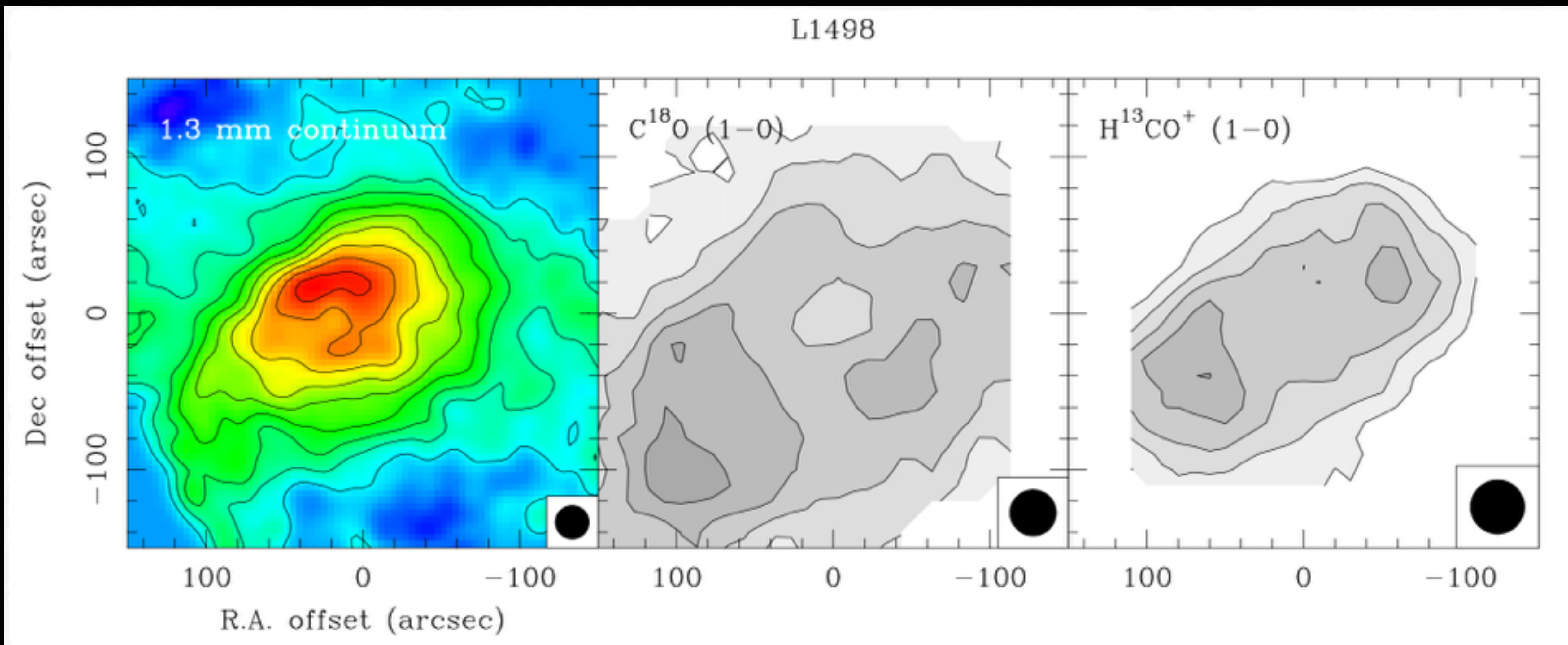
- Binding energy: $E_{\rm b} \sim 1000 - 2000\,{\rm K}$

- At 10 K, thermal desorption is extremely slow

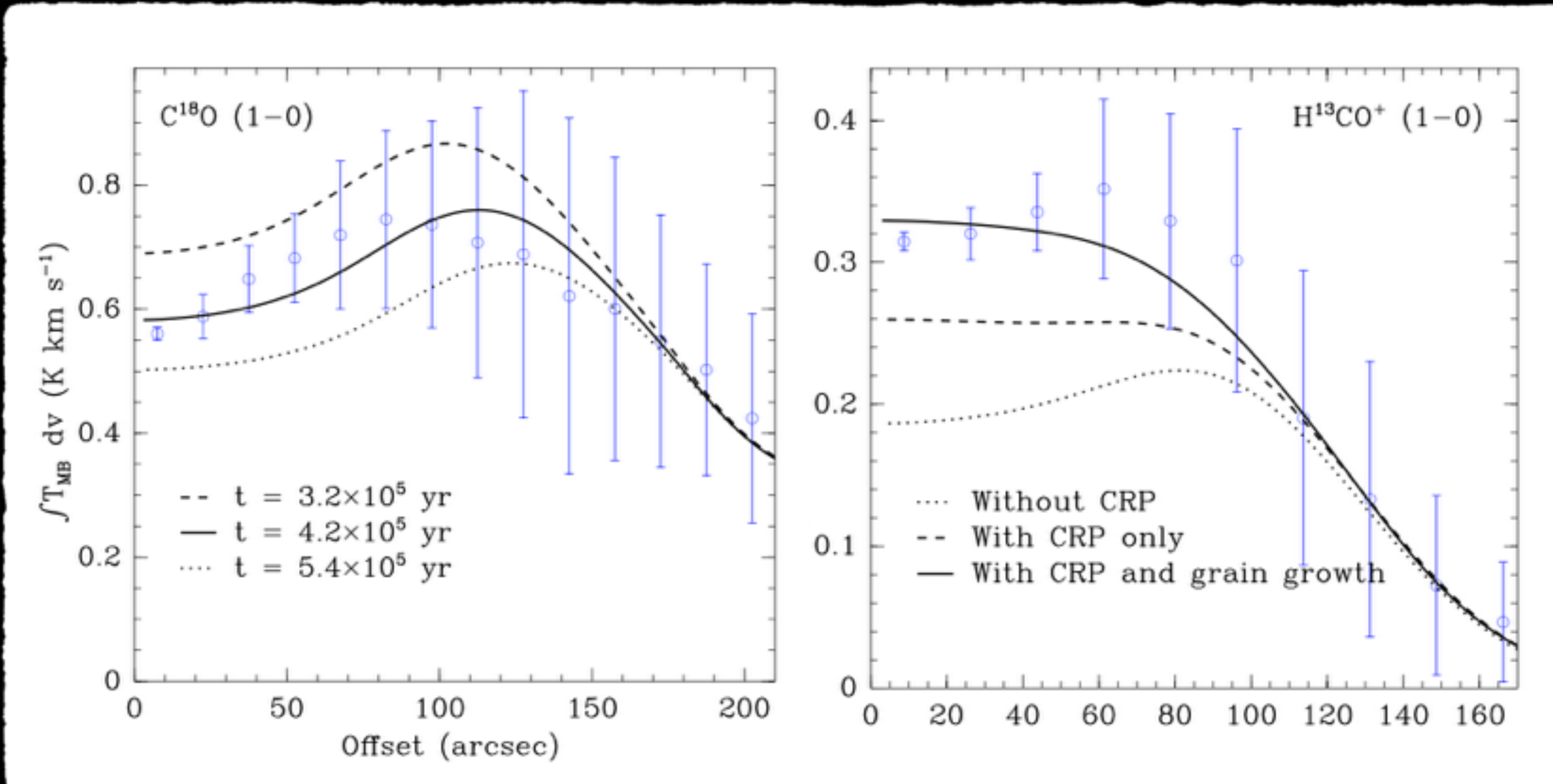
- Non-thermal desorption processes exist, e.g. cosmic rays photodesorption



Bergin & Tafalla (2007)



Maret, Bergin & Tafalla (2013)



- The $H^{13}CO^{+}$ (1-0) line observations and models indicate:
  - Cosmic-ray photodesorption (CRP)
  - Grain growth at the core center

Maret, Bergin & Tafalla (2013)

Deuterium fractionation

Deuterium fractionation:

$$H_3^+ + HD \rightleftharpoons H_2D^+ + H_2$$

The reverse reaction has an activation barrier of ~ 200 K, so the reaction is irreversible at 10 K:

$$H_3^+ + HD \rightarrow H_2D^+ + H_2$$

At low temperature:

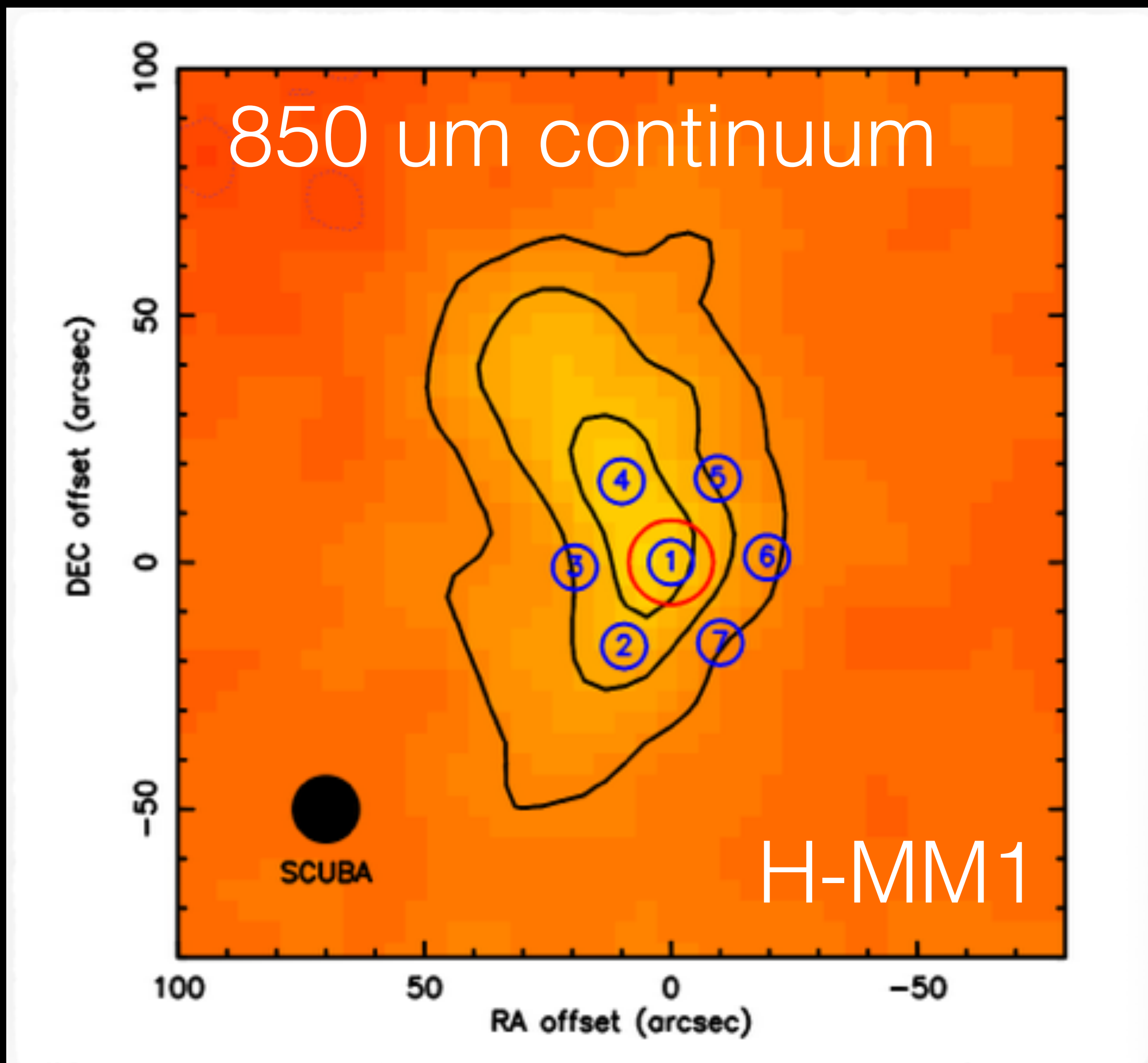
$$\frac{H_2D^+}{H_3^+} >> \frac{HD}{H_2}$$

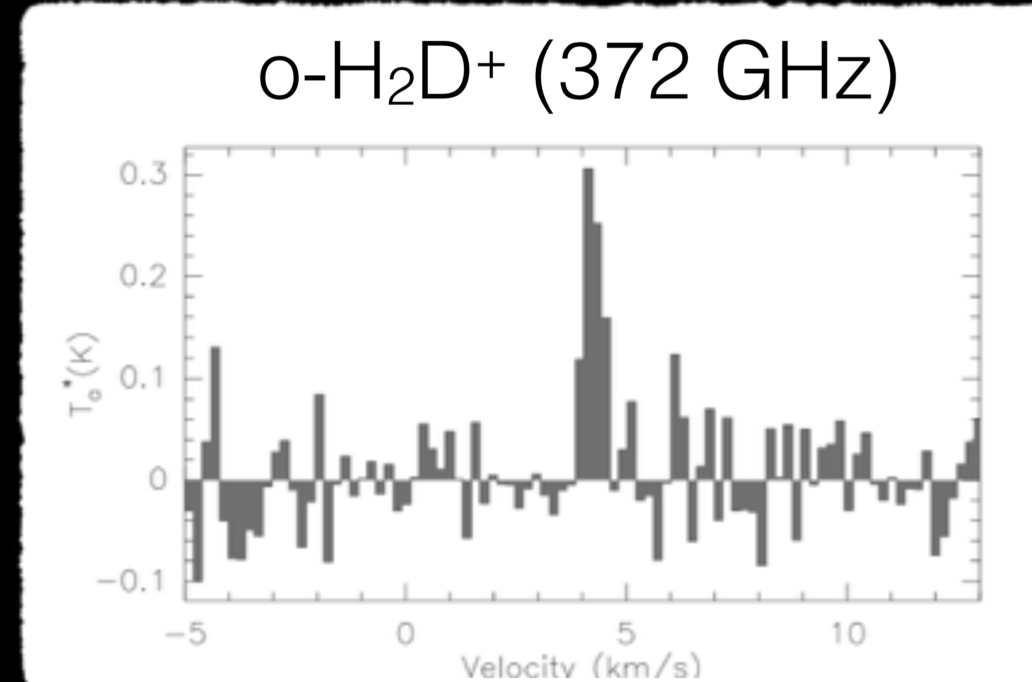
- H_2D^+ can itself react with HD:

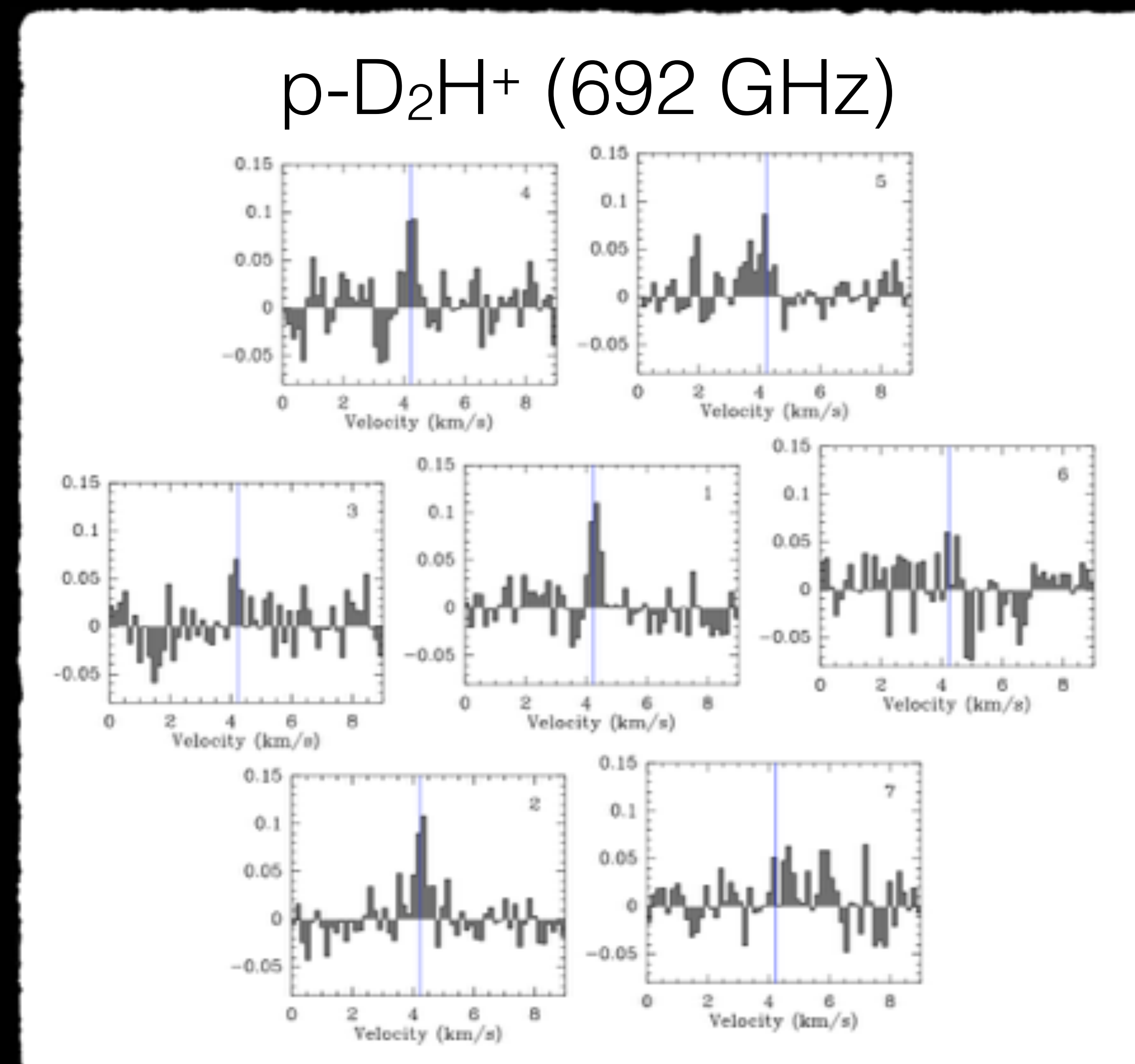
$$H_2D^+ + HD \rightarrow D_2H^+ + H_2$$

- Deuterium is then transfered to ions, e.g. DCO^+, N_2D^+, etc…

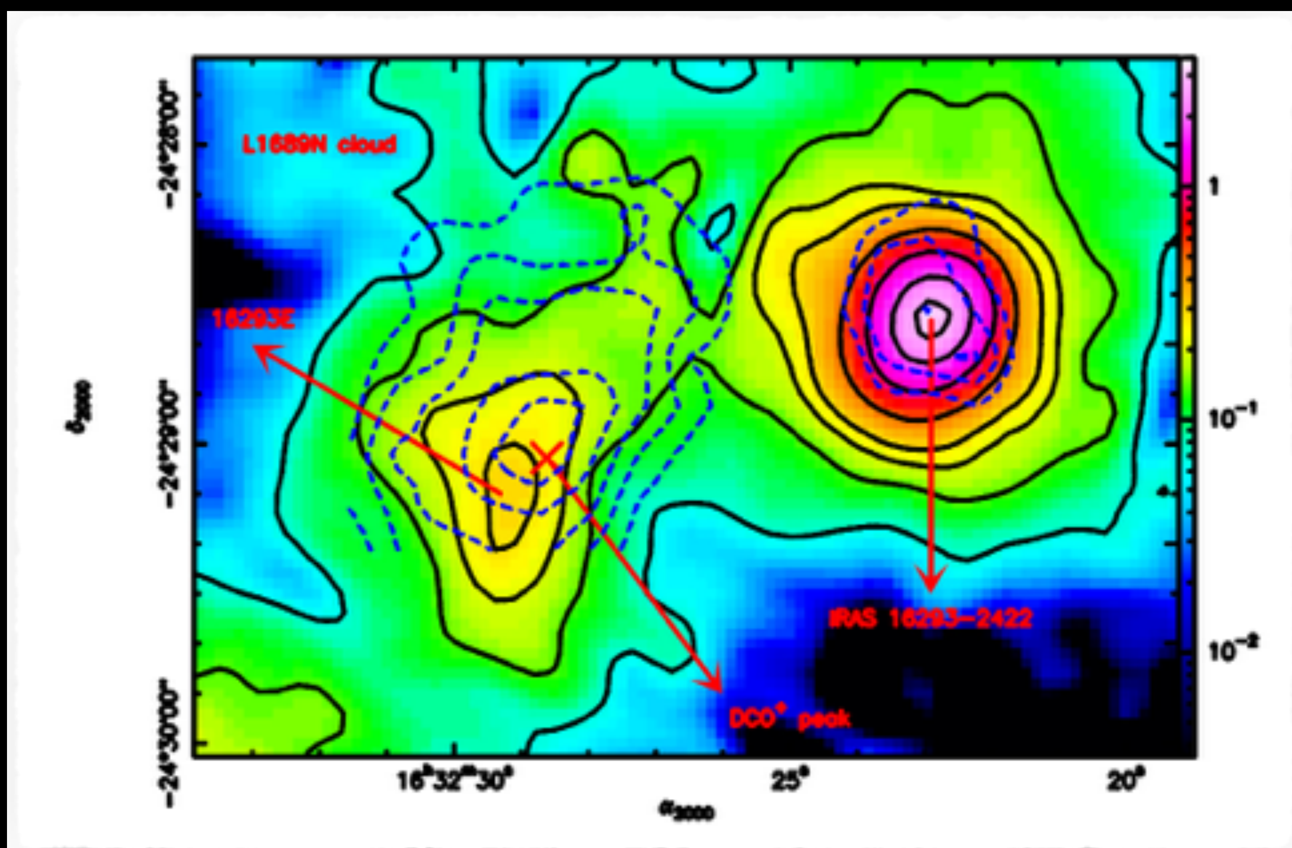
- CO is the major destroyer of H_2D^+ and therefore the H_2D^+ abundance increases as CO freezes-out

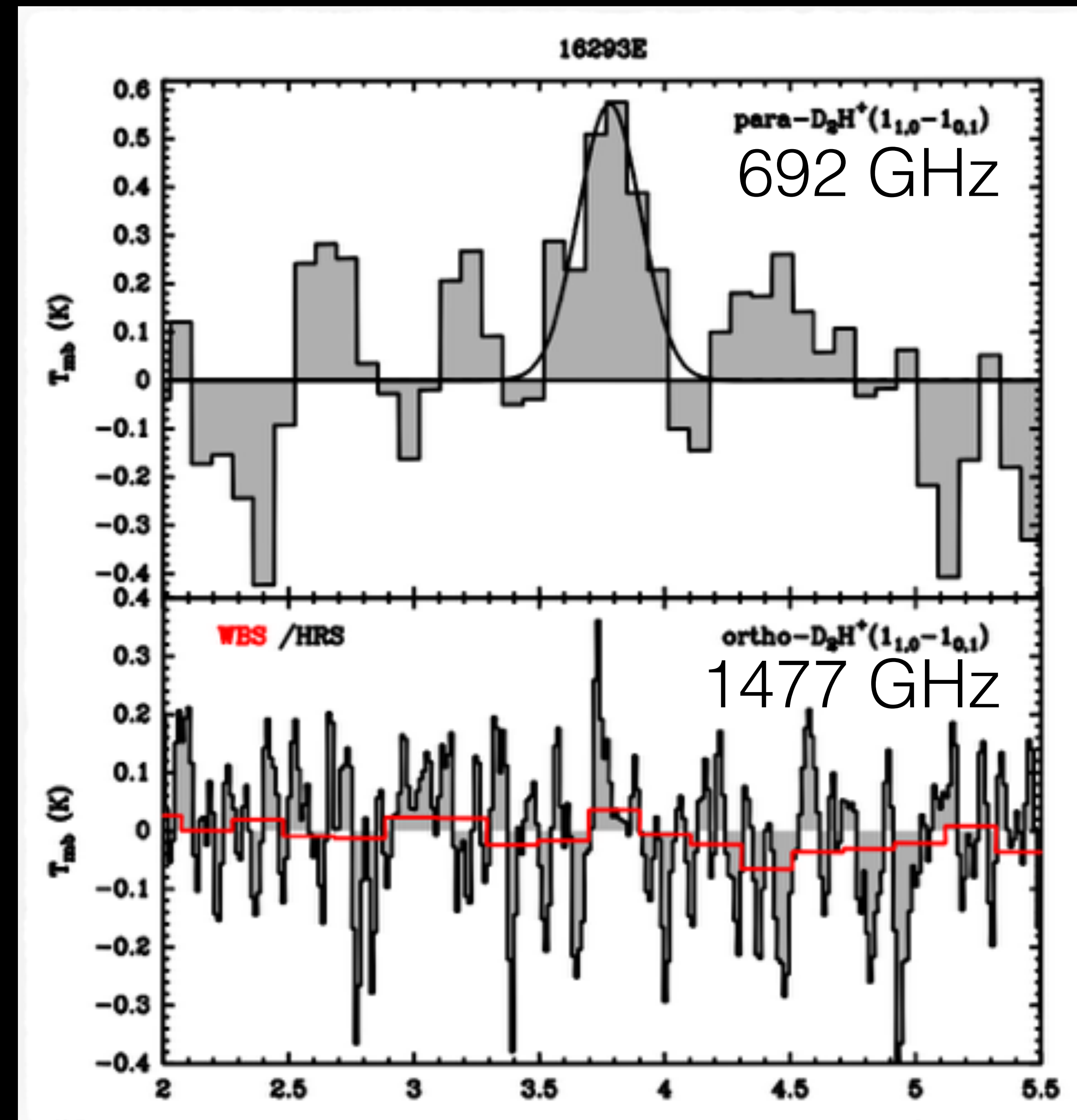






Parise et al. (2011)

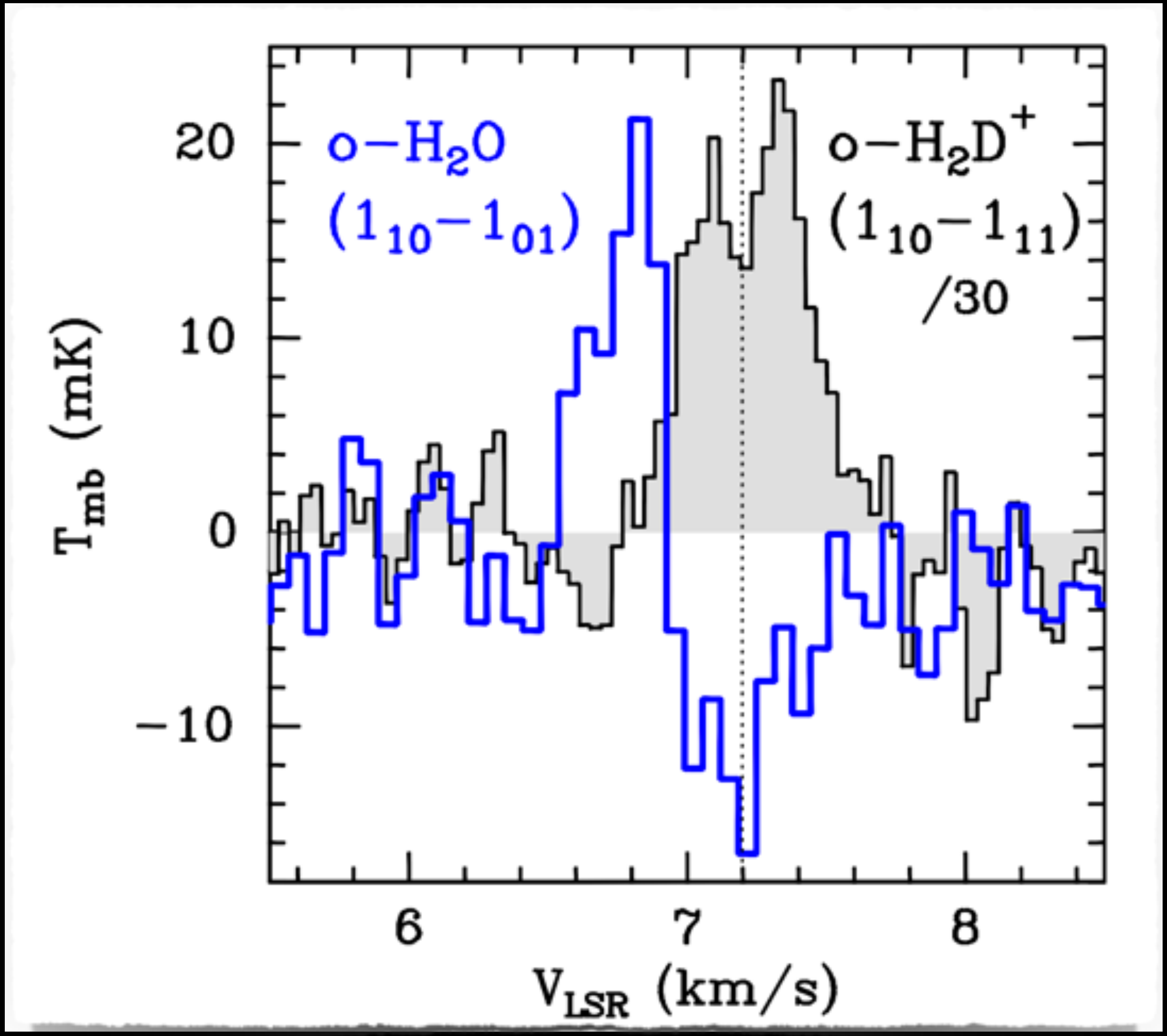




Vastel et al. (2012)

Water vapour

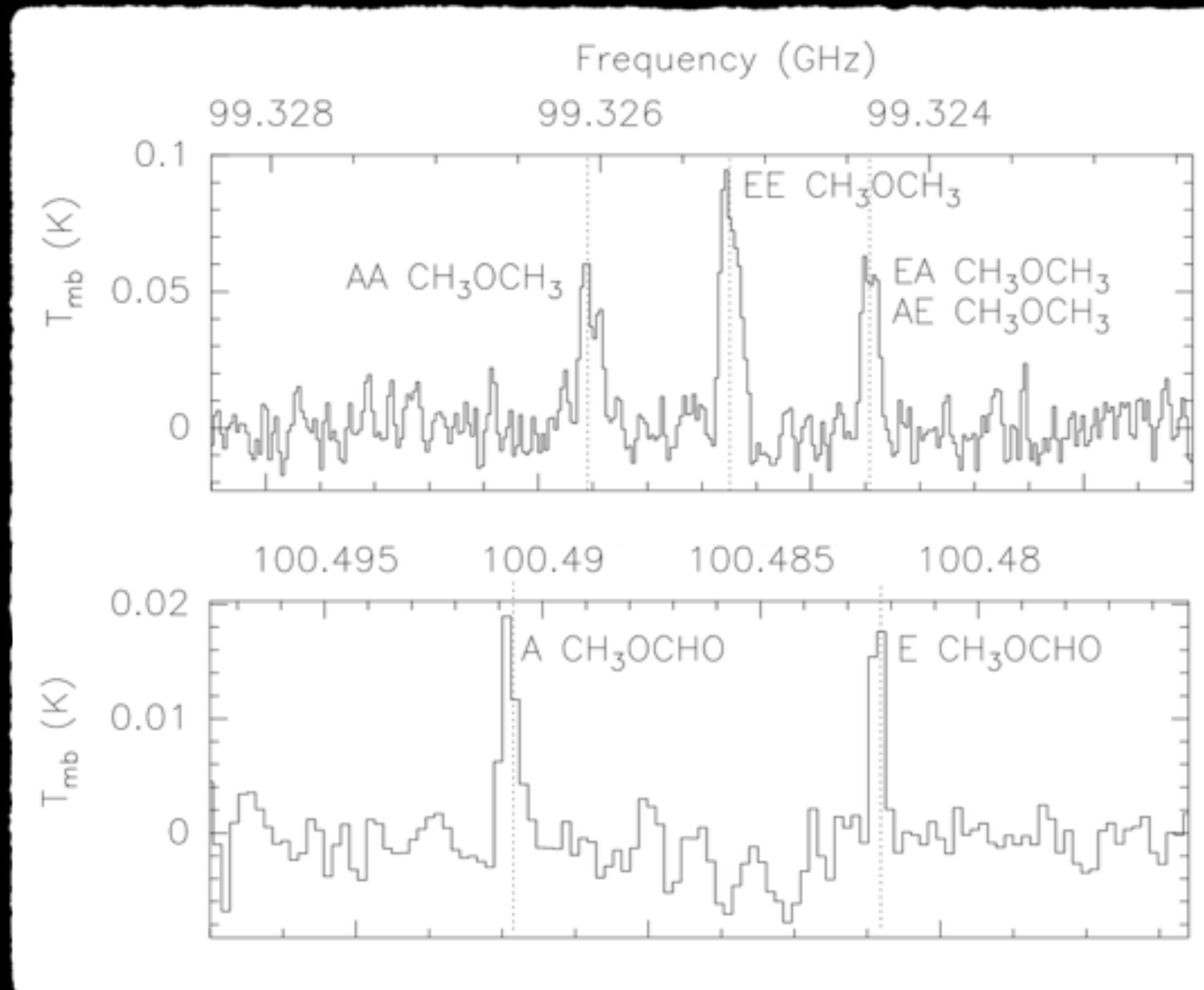
- First detection of water vapor in a prestellar core (c.f. Eric's talk)



Caselli et al. (2012)

Complex organics

- Detection of complex organic molecules in a prestellar core (L1689B)
- Challenge for chemical models



Bacmann et al. (2012)

Pre-stellar phase

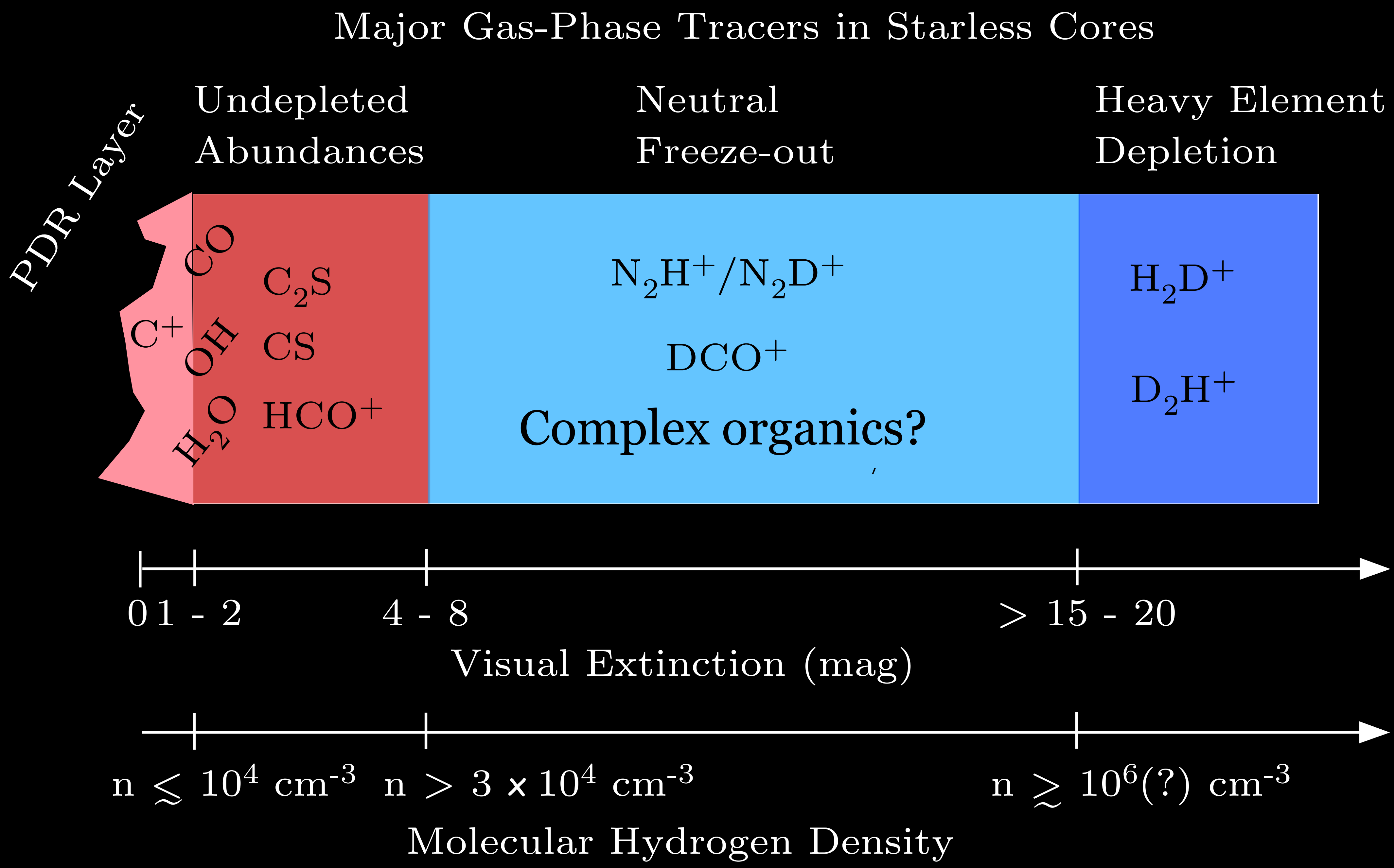
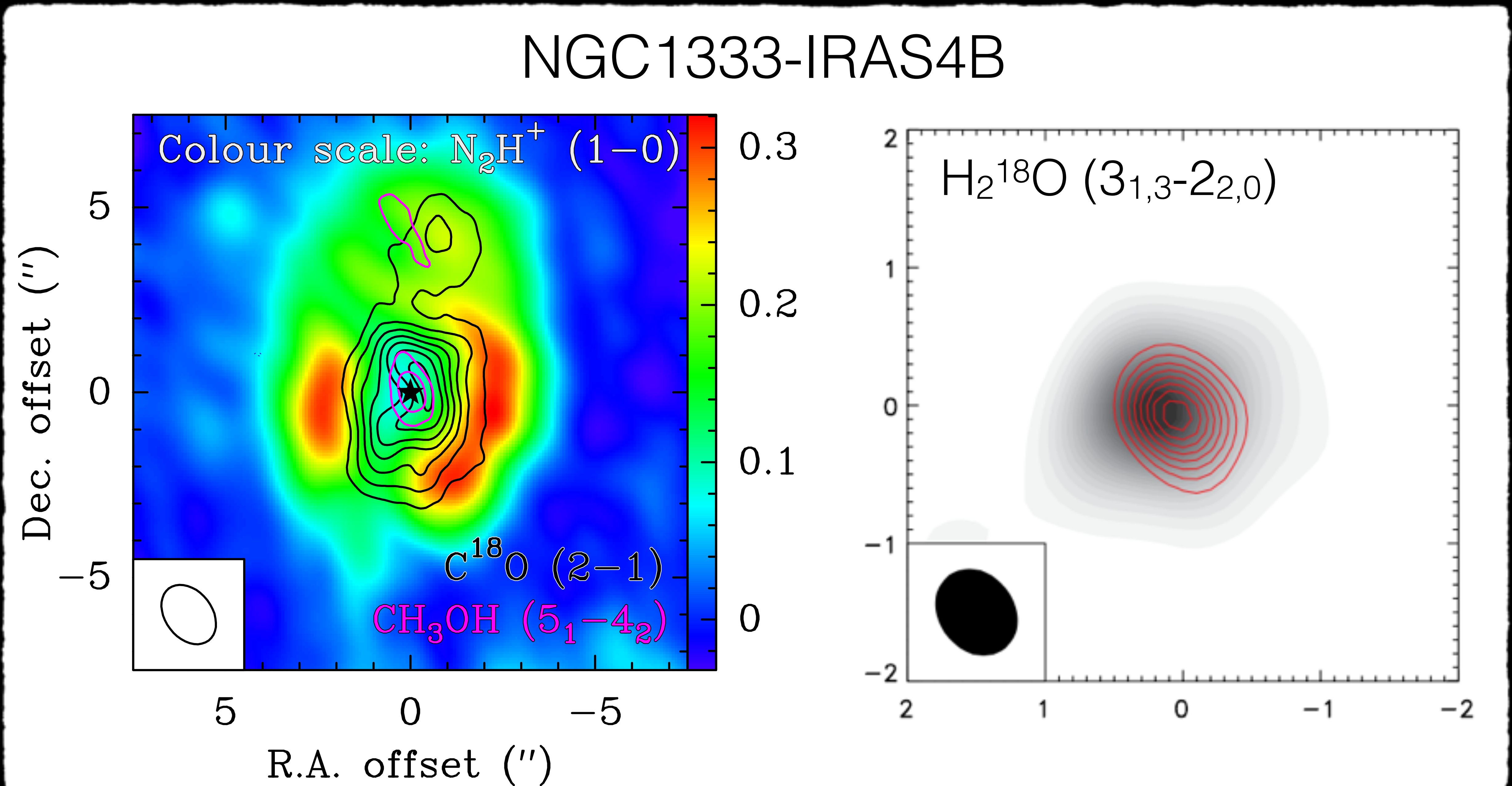


Fig. courtesy of T. Bergin

Ice lines in Class 0 protostars

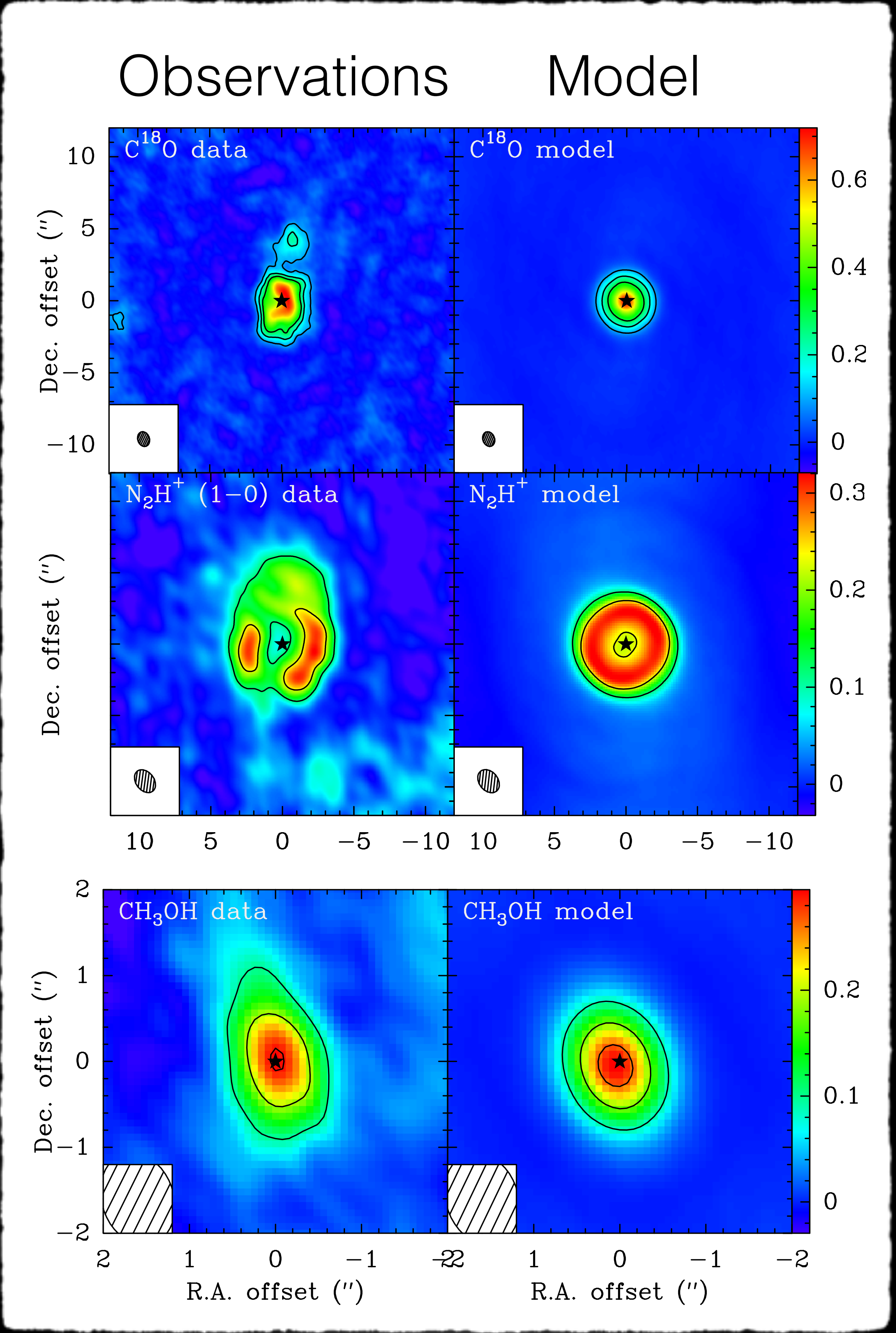


Anderl et al. (in prep)

Jørgensen et al. (2010)

- The differences in the observed $C^{18}O$, N_2H^+ and CH_3OH line maps are likely due to the **carbon monoxyde and water ice lines**

Anderl et al. (in prep)



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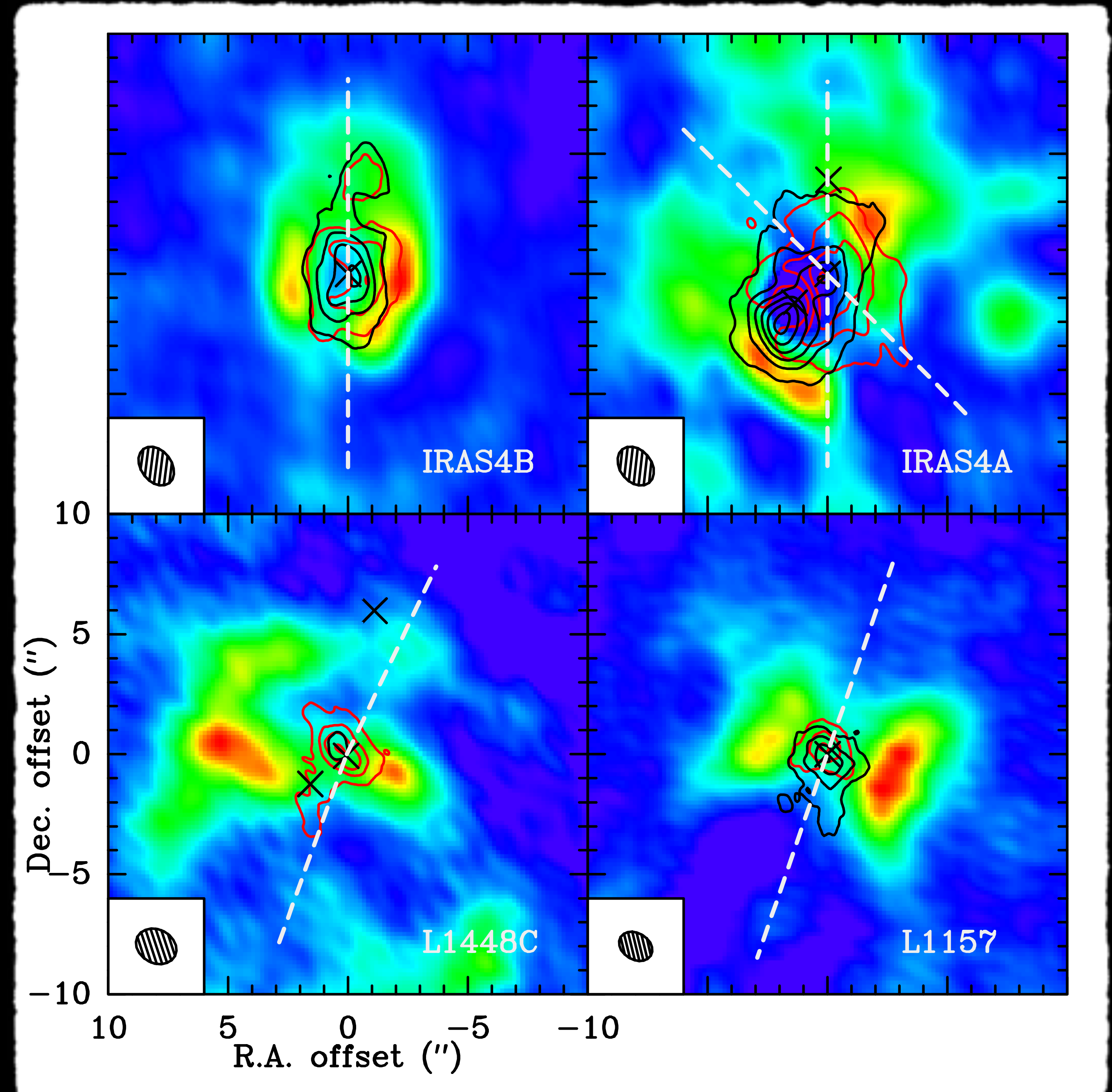
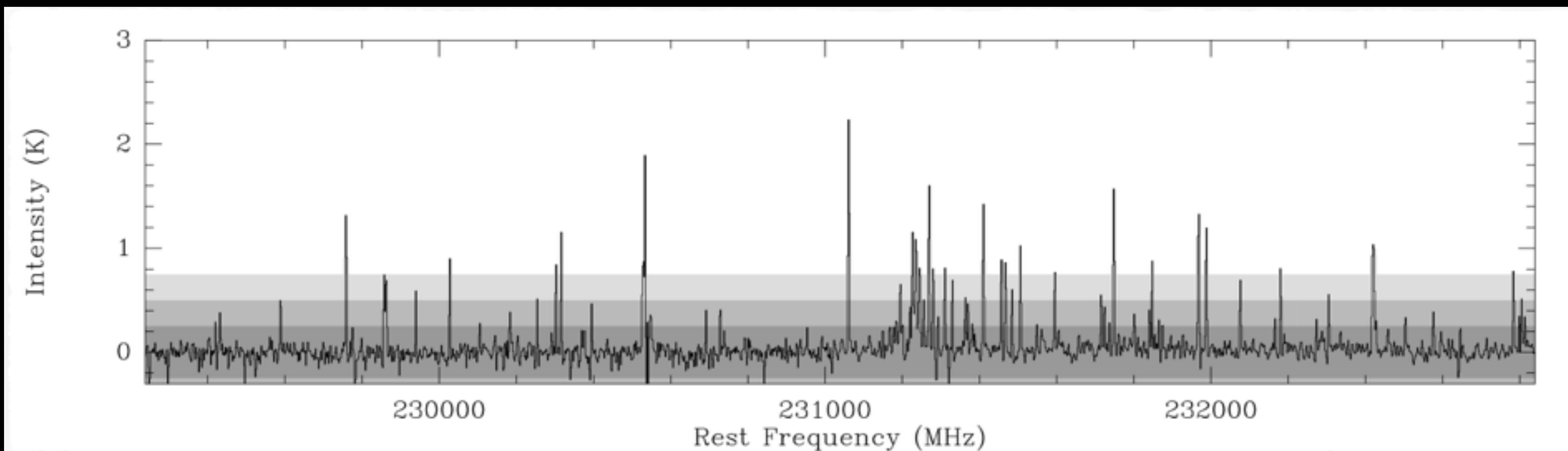


Anderl et al. (in prep)

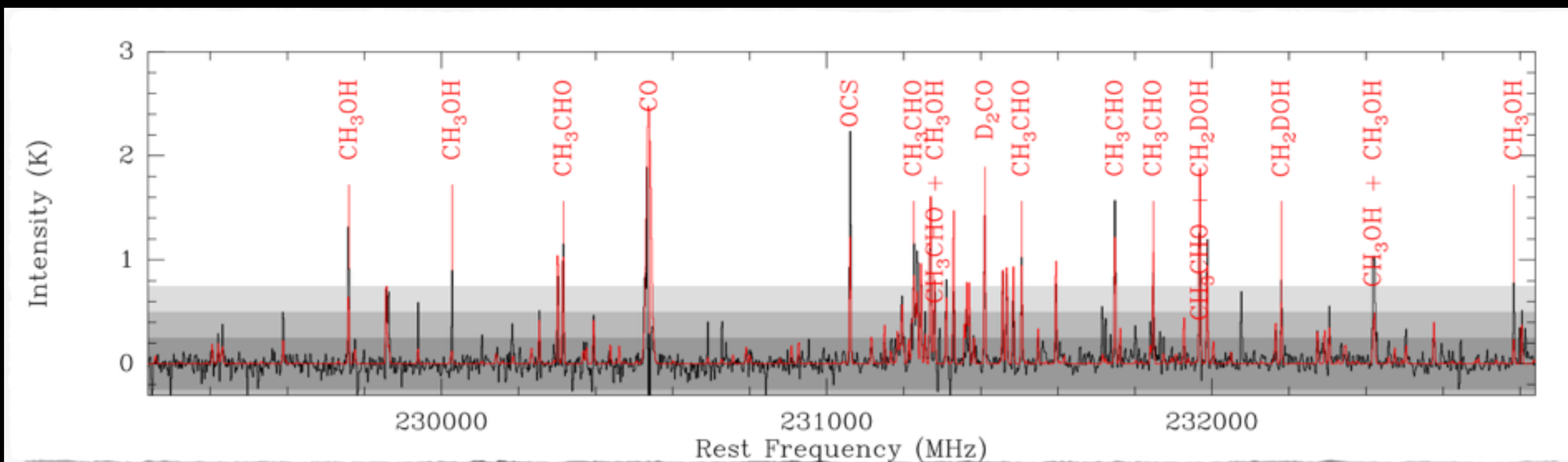
Complex organics



- COM emission observed in the most luminous sources ($L_{bol} \geq 6\,L_{\odot}$)

Belloche et al. (in prep.)

Complex organics



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Belloche et al. (in prep.)

Proto-stellar phase

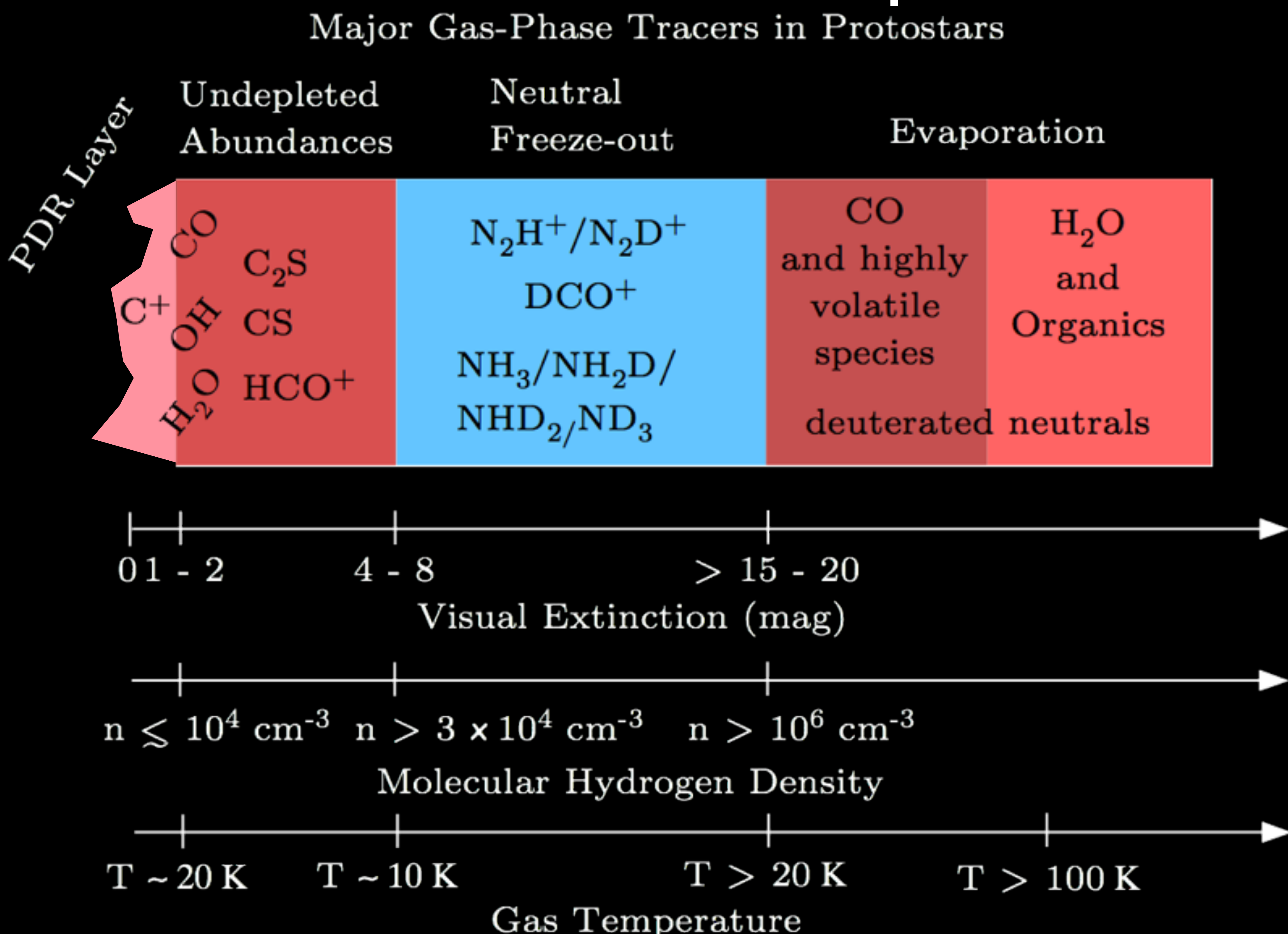

Fig. courtesy of T. Bergin

Conclusions

- Dense core chemistry is characterized by:
  - The **freeze-out of heavy species** (CO, H_2O, etc.)
  - Large **deuteration fractionation** (H_2D^+, D_2H^+)
  - Growing evidence of the **important role of secondary UV photons** (desorption, COM formation)
- Class 0 protostar chemistry is dominated by the t**hermal evaporation of CO and H_2O ices**
- Important progresses expected in the coming years as ALMA and NOEMA ramp up to their full capacities

Perspectives

- ALMA will allow to make **high resolutions images** of several tracers (H_2D^+, D_2H^+) to study the chemistry/physical conditions on the small scales (or in more distant cores)

- NOEMA is also well suited to study cores; its large instantaneous bandwidth (16 GHz) and dual band capability should allow for an **inventory of species** (e.g. COMs) in cores