Dissecting early phases of star formation

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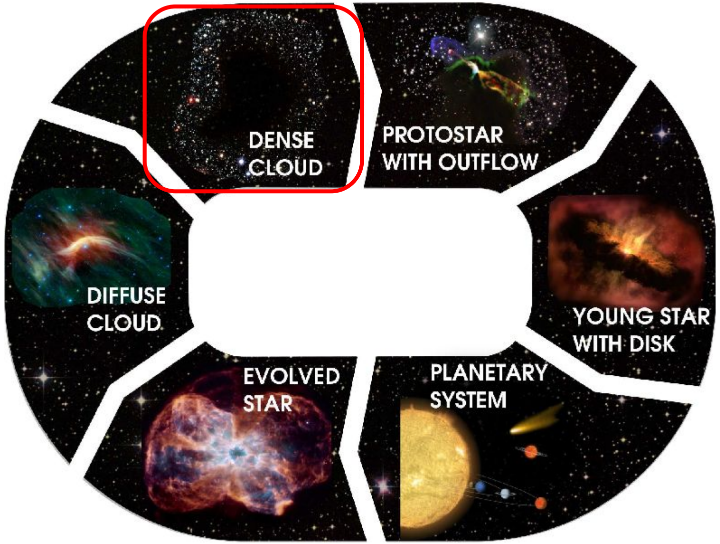
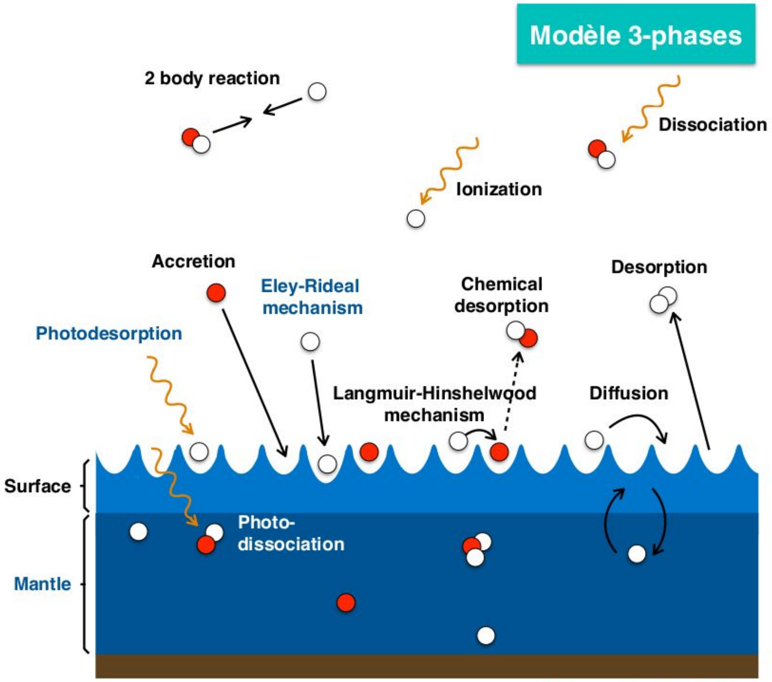
Introduction

- Cold (~10 K) dense (>10^5 cm^{-2}) core is one of the first step of star formation
- It is followed by the infalling phase where matter falls toward the center of the core and condensates to form a proto-star.
- Ice formation on grain surface is a complex phenomenon:
    - Needs very cold region (10-20K)
    - IR wavelength is a hellish nightmare to observe from Earth, JWST is game-changing (IceAge)
    - Certain molecules forming mainly at the surface of the grains (eg, Methanol)



Desorption mechanisms

- The case of methanol: the formation route in **gas-phase** is not enough to account for the abundance **observed**
    - **Main pathways are in the solid-phase**
- So… thermal desorption from grains? Nope, too cold
- Non-thermal desorption ? A few known mechanisms:
    - Cosmic rays (CR) heating
    - Chemical desorption
    - Photo-desorption
    - Sputtering by CR
- Defining efficiency constraint on non-thermal desorption mechanism (both lab and obs) is very difficult

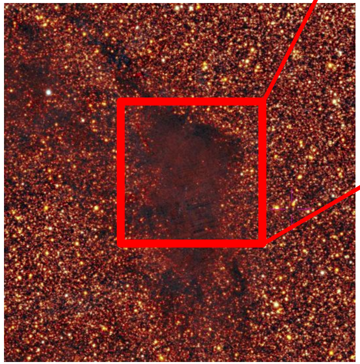


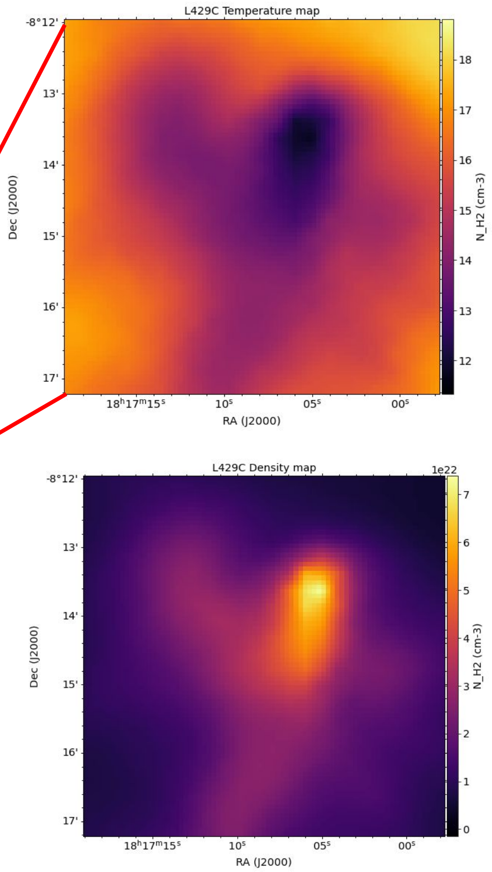
Ruaud et al. 2016

Gas and ice study: **L429-C**

- **L429-C** - cold dense core in the Aquila Rift, at 200 pc
- Methanol ices have been observed with Spitzer (Boogert+2011)
- With our 30m data, we have constraints on gas phase abundance of methanol

PanSTARRS i, r, g bands

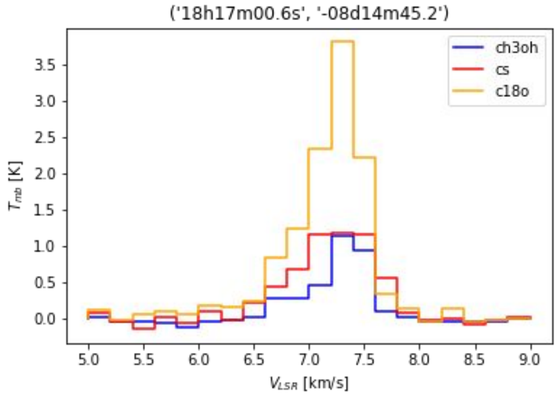


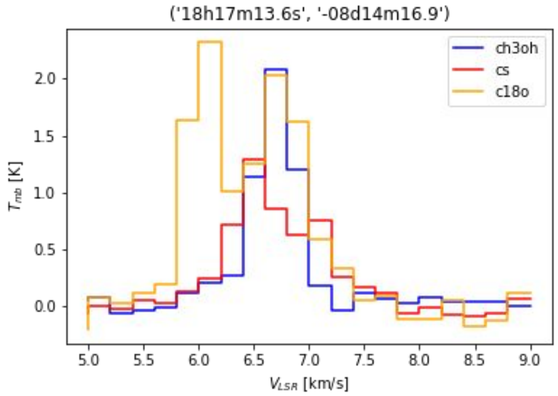


Herschel temperature map & density

Observations & Methods

- Gas observations: NOEMA and 30m at IRAM
  - 3mm 360x360" map at 0.2 km/s velocity resolution
  - NOEMA data showed no evidence of small scale structure
  - **11 Molecules detected:** CH_3OH, OCS, CCS, HC_3N, CS, SO, CO, ^{13}CO, $C^{17}O$, $C^{18}O$, CN, H_2S





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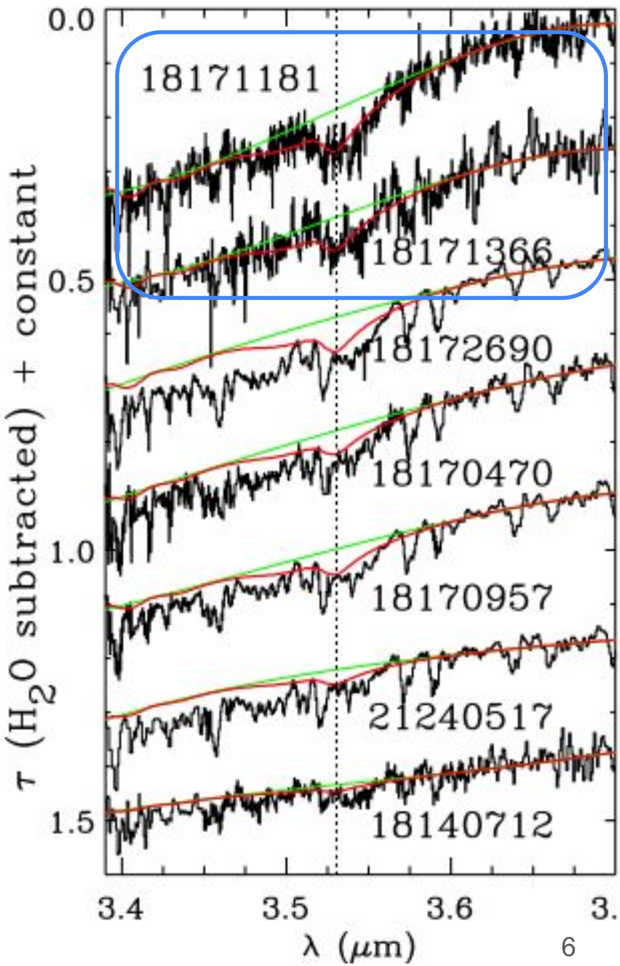
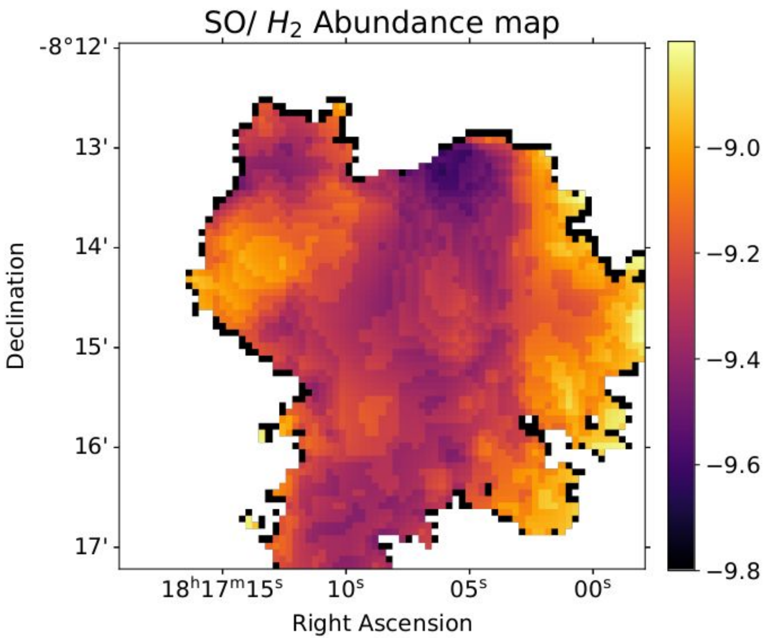
- Ice observations (Boogert+2011) :
  - 4 background stars done with Spitzer of the C-H stretching mode of solid CH_3OH at 3.53 μm)



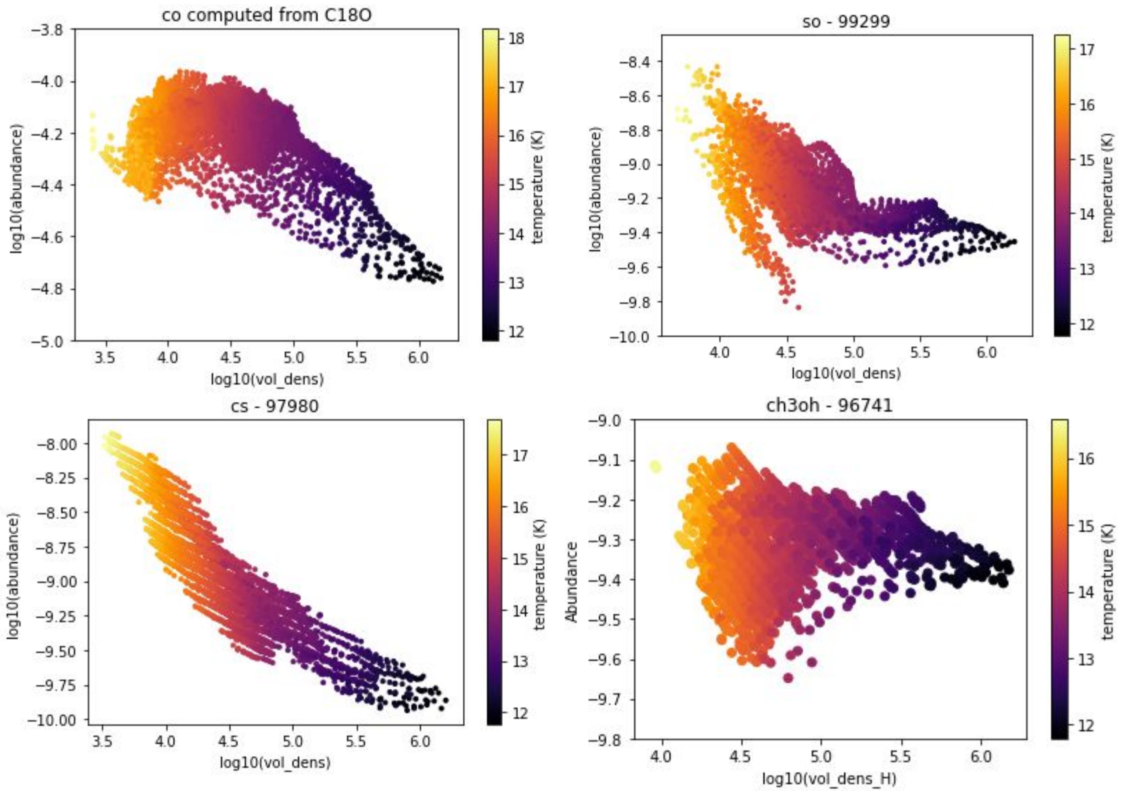
Abundances maps wrt H_2

- Abundance maps obtained using a radiative transfer inversion code
- Based on physical parameters (T_{kin}, n_{H2}, dv, N) grid created using non-LTE RADEX code
- We add constraints for each pixel:
  - For dv: compute FWHM using ROHSA (Marchal+2019)
  - For T_{kin}: *Herschel* data
  - For n_{H2}: density computed from N_{H2} assuming isotropy (Bron+2018)
  - Best column densities are converted to abundance by dividing by N_{H2} derived from *Herschel* maps



Observations results

- Most molecule abundances are decreasing (SO, CS, CO, H_2S) with the visual extinction (and n_{H2})
- CH_3OH abundance stays constant



Chemical model - Nautilus

- **Nautilus** simulates the chemical evolution in the gas, on the grain surface within the ice mantle (3 phases) developed at the LAB (Ruaud+2016)
  - Based on kinetic rates and surface data from lab experiments and theoretical calculations
- Inputs parameters are gas and dust temperatures, density n_H, visual extinction Av coming from the observations and cosmic-rays (CR) ionization rate
- Output: abundances of gas and ice as a function of time
- Available: https://astrochem-tools.org/codes

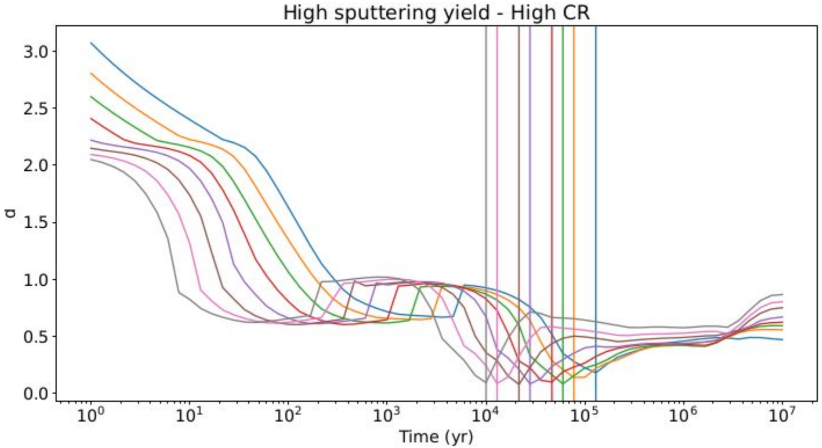
- CR interactions with grains appear to be the main non-thermal desorption mechanism for CH_3OH
  -> sputtering yield
  -> CR ionisation rate

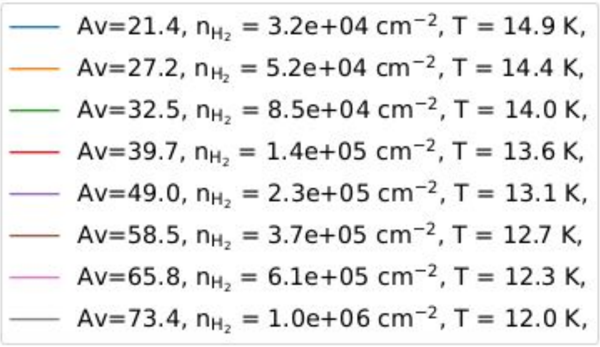
Chemical model sets

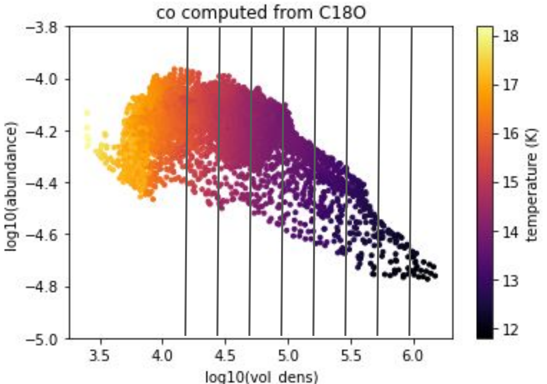
- Determination of the “best model” by using the distance of disagreement *d* using 4 molecules:

$$d(t) = \frac{1}{N_i} \sum_i |\log(X_{mod,i}(t)) - \log(X_{obs,i})|$$

- T, n, Av, constrained by observational data
- Only free parameter is the time

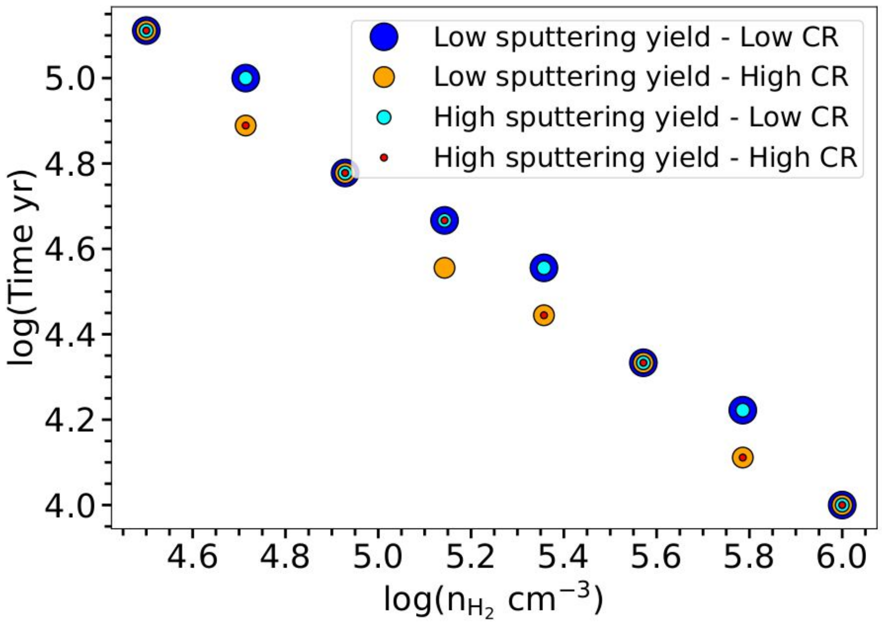






Chemical model - Results

- “Best time” = decreases with density for all sets of models
- Overall, abondances are well reproduced within a factor of 10

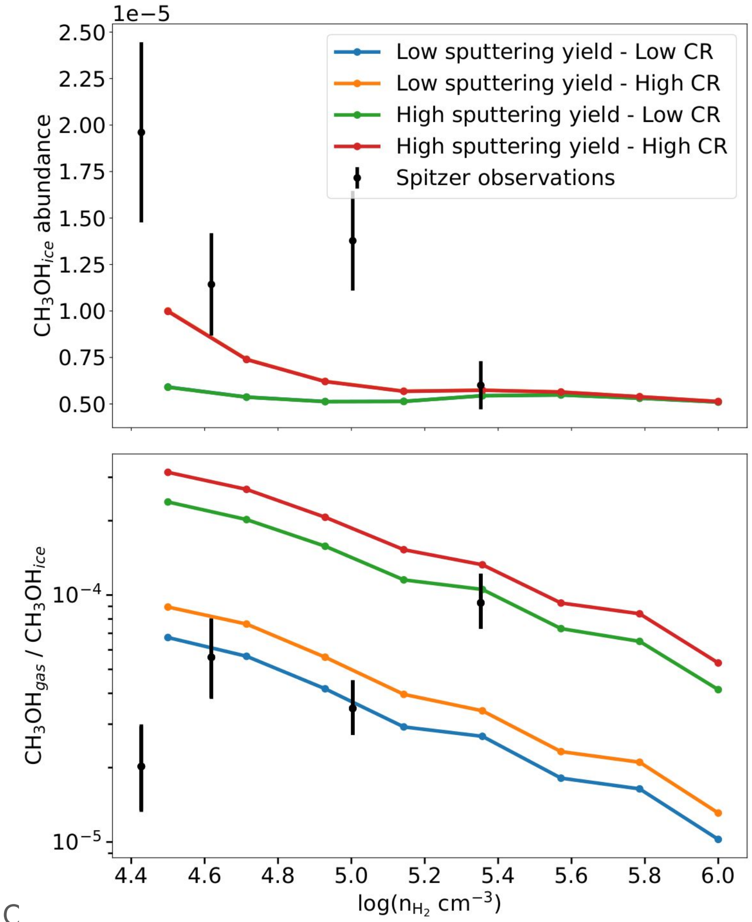


Budget of gas and ice in CH_3OH

- Reservoir of methanol (both obs & mod) **is in the ices**
- Observed gas-to-ice methanol ratio:

  0.002% (low density) to **0.09%** (high density)

- Observed gas-to-ice ratio seems to increase with density for obs



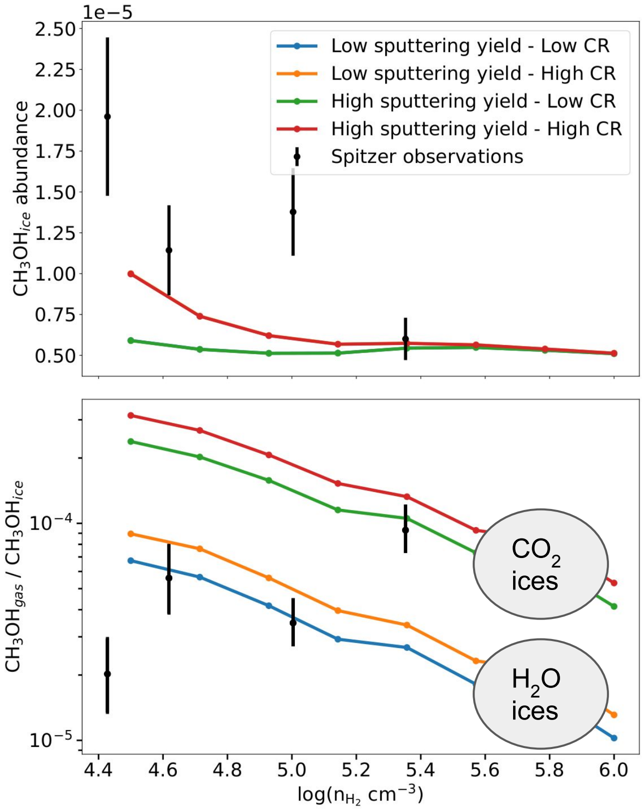
Budget of gas and ice in CH_3OH

- Models:
  - Reproduced within a factor 2 for high yield
  - Reproduced within a factor 3 for low yield
- **However**: trend is decreasing for models.

→ Is the observed trend an indication of ice composition change (lower yield at low density for H_2O ices)?

→ Such change in ice composition could occur during the catastrophic CO freeze-out

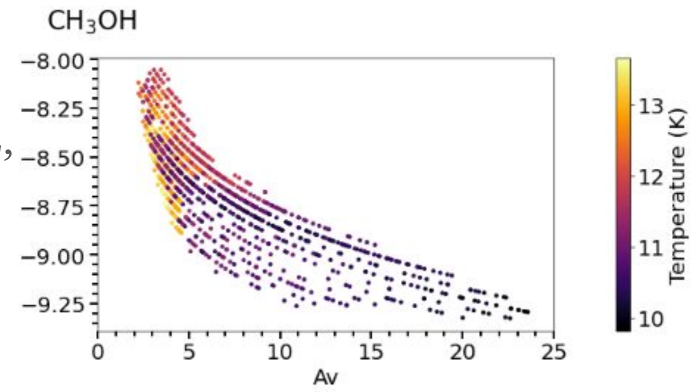
→ Only four observed points with strong uncertainties

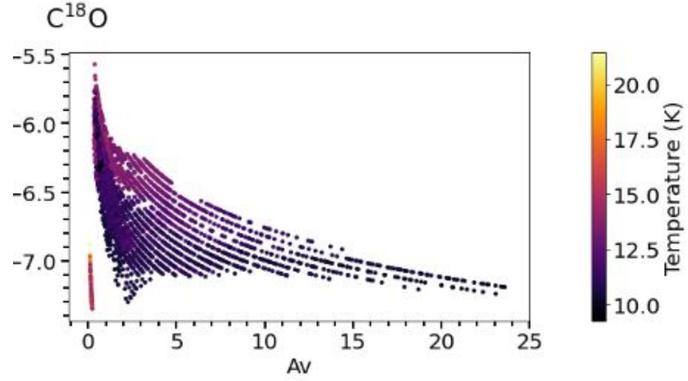


Work in progress - Preliminary abundances

Next step: L694

- L694 is a cold core with similar features as L429-C, but more advanced (**infalling**)
- Methanol ices have been observed as well by Chu+2020 from the ground
- **Is being observed by JWST** (PI: K. Hodapp)
- Gas observations were done with IRAM 30m in november 2021 (PI: Taillard)
- Identified molecules: N_2H^+, N_2HD, $C^{34}S$, CS, CH_3OH, ^{34}SO, SO,^{13}CO, $C^{17}O$, $C^{18}O$



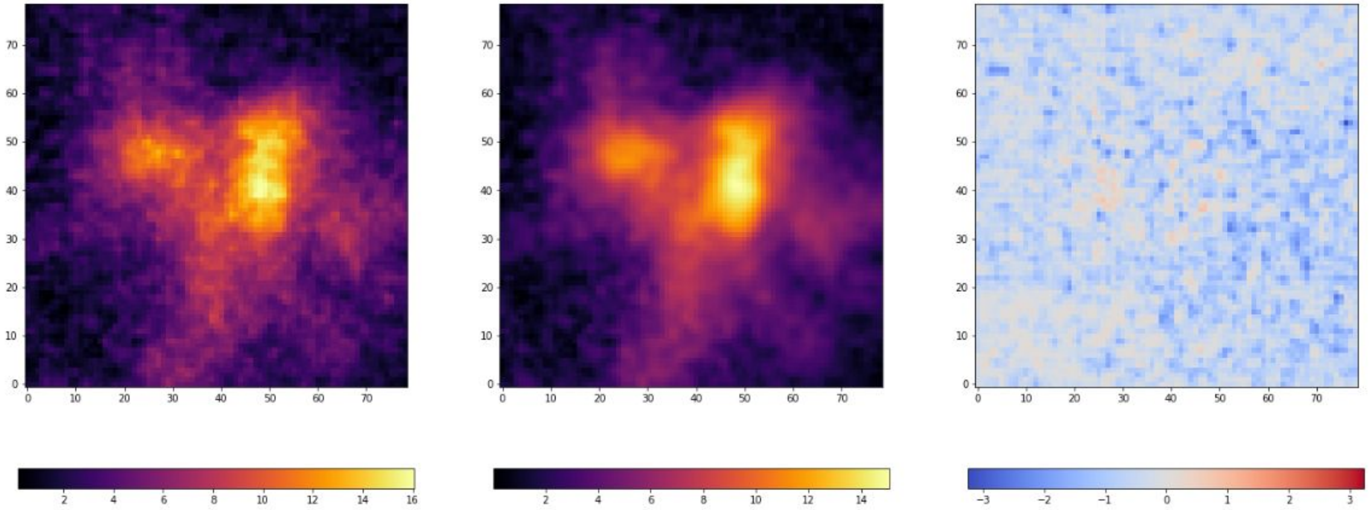


Conclusions

- L429-C observations:
  - gas: 30m data
  - ice: Spitzer
- Gas abundances show depletion at higher densities, except for CH_3OH
- Shorter time needed to reproduce observations in higher density (and opposite is true)
- Observations: 0.002-0.09% methanol gas-to-ice ratio, increasing with density
- In models, we have an opposite trend:
  - Change in ice composition ?
- Overall, **CR sputtering and CR ionization** are the most dominant non-thermal desorption mechanisms in our model
- Next cloud, L694, will receive a similar method of analysis + JWST data!!

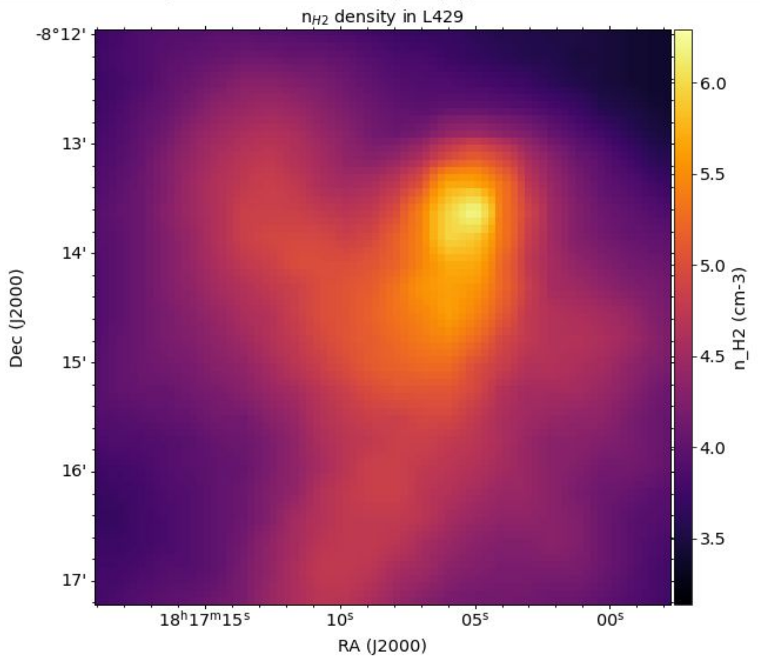
Constraints on dv - ROHSA developed by Marchal et al. (2019)

- Allow us to fit multiple gaussians on each spectra per pixel to obtain an equivalent FWHM
- Creates a “denoised” intensity map
- We use this new intensity map for the next steps



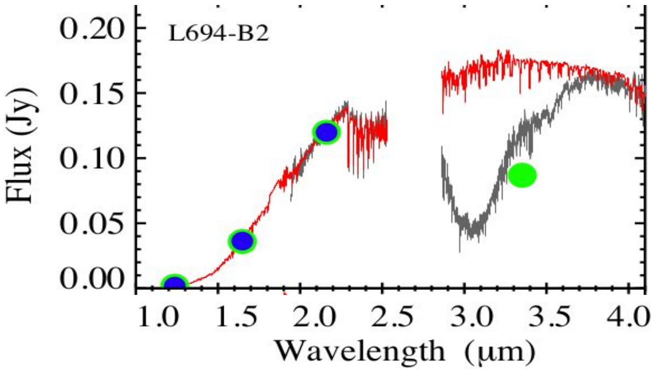
Constraints on n_{H2} - Bron et al. (2018) method

- Estimates the volume density from the column density for simple source
- Makes the assumption of isotropy and that the density is smoothly increasing from outer to inner region of the cloud.
- Hypothesis: no privileged direction for the spatial density.
- Estimates the typical length scales *l* of the cloud, using N_H threshold masks
- Finally, $n_H = N_H / l$



Radex

- RADEX is a one-dimensional non-LTE radiative transfer code, that uses the escape probability formulation assuming an isothermal and homogeneous medium without large-scale velocity fields.
- We input multiple parameters:
  - Line ID (frequency) - multiple transitions for some molecules (CN & CH_3OH)
  - Kinetic temperature
  - Line width
  - Volume density
  - Column density
- Output parameter: integrated intensity (T_{ex} & line opacities)



Chu et al, 2020