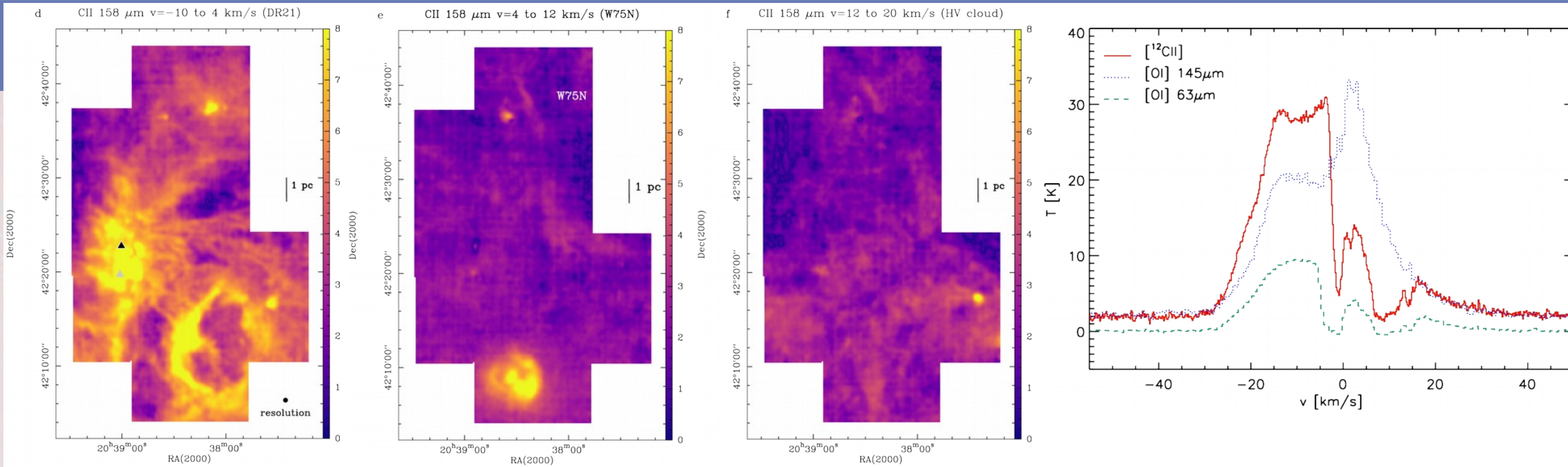

Is the concept of molecular clouds outdated?

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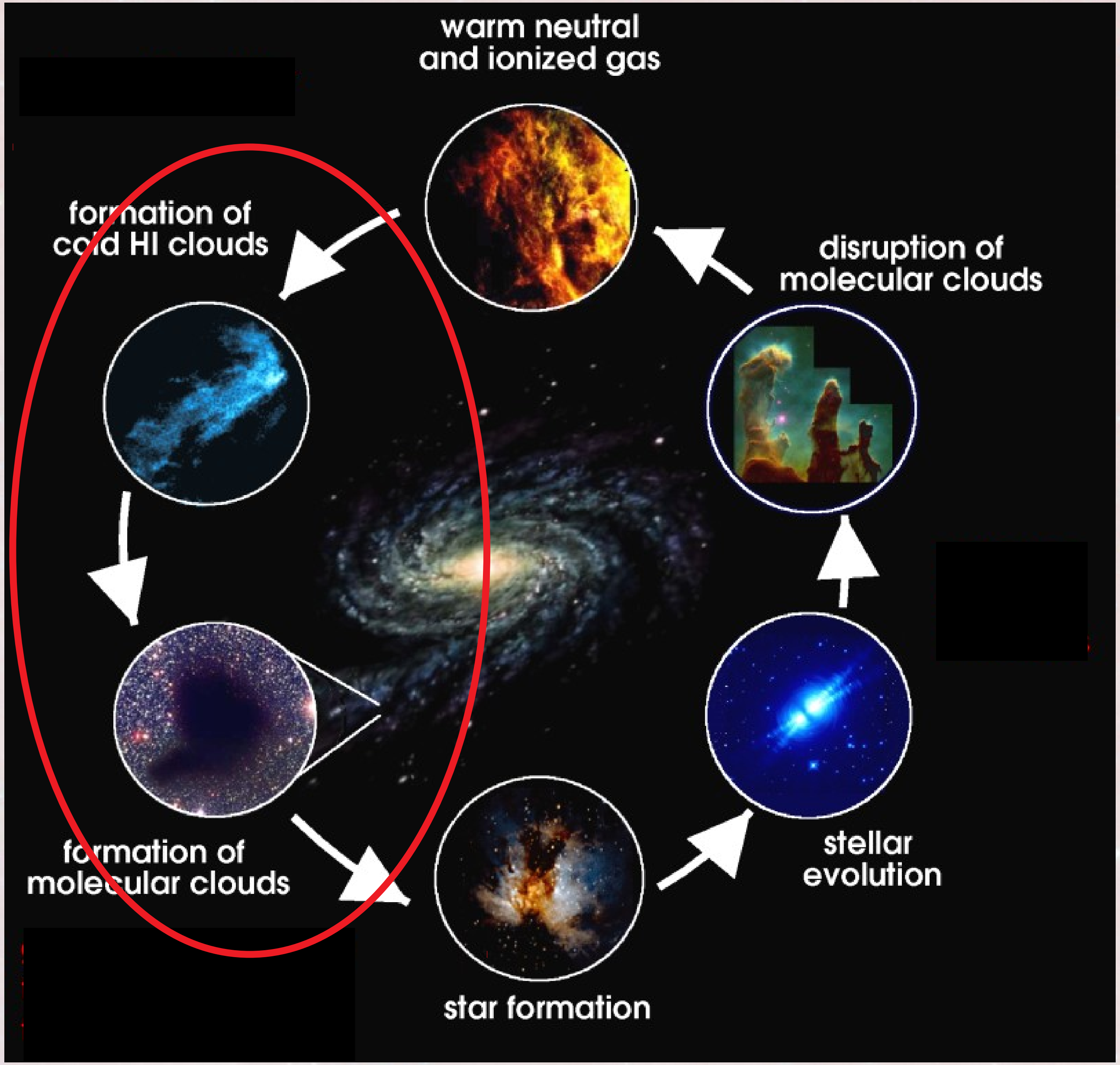
Background

What is the question?

- The life cycle of matter in galaxies:
  - How is the material assembled on the way to star formation?
- Observational problems:
  - Cold HI shone out by WNM
  - Molecular gas only visible when rich in CO

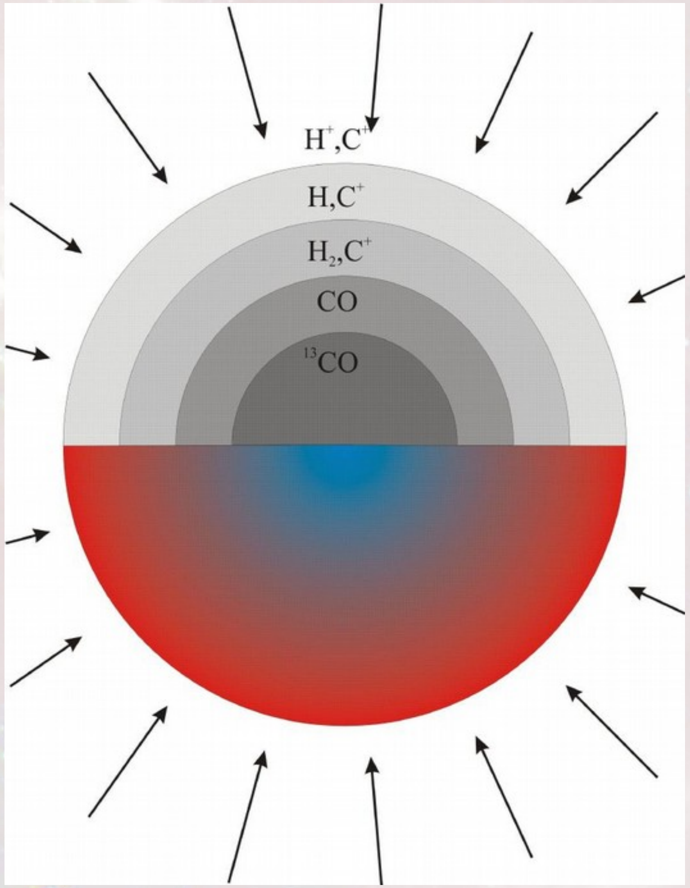


Credit: High Elevation Antarctic Telescope (HEAT) consortium, Steward Observatory, Radio Astronomy Laboratory

What are molecular clouds? - Theory

The stationary picture

- Molecular clouds = dense blobs visible in CO:
- Chemical representation: PDR model (e.g. KOSMA-τ) (based on Röllig & Ossenkopf-Okada 2022)
  - Layered structure

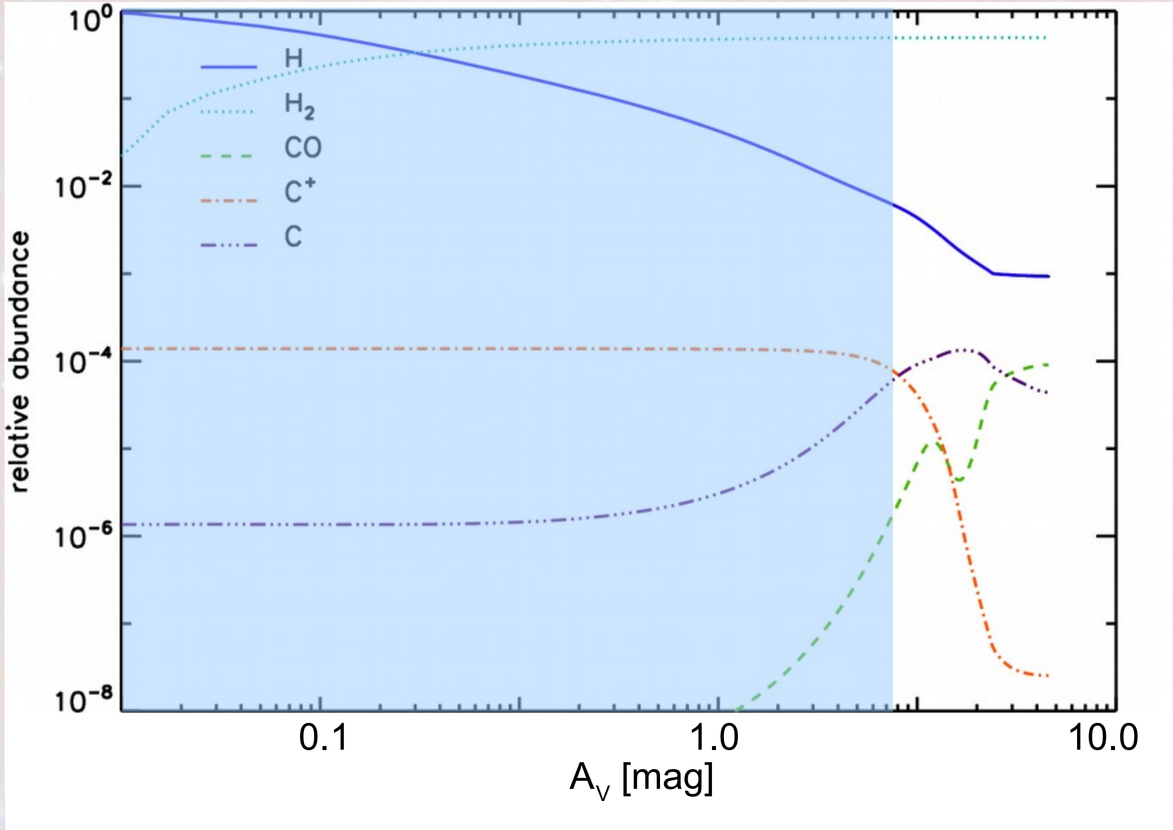


Hogerheijde et al. (1998)

What are molecular clouds? - Theory

Quantitative description

- Layers in KOSMA-τ PDR model (based on Röllig & Ossenkopf-Okada 2022)



- $0 < A_V < 0.25$: H (CNM)
- $0.25 < A_V < 1$: H_2, no CO, mainly C^+
- $A_V > 1$: CO

} invisible in H and CO

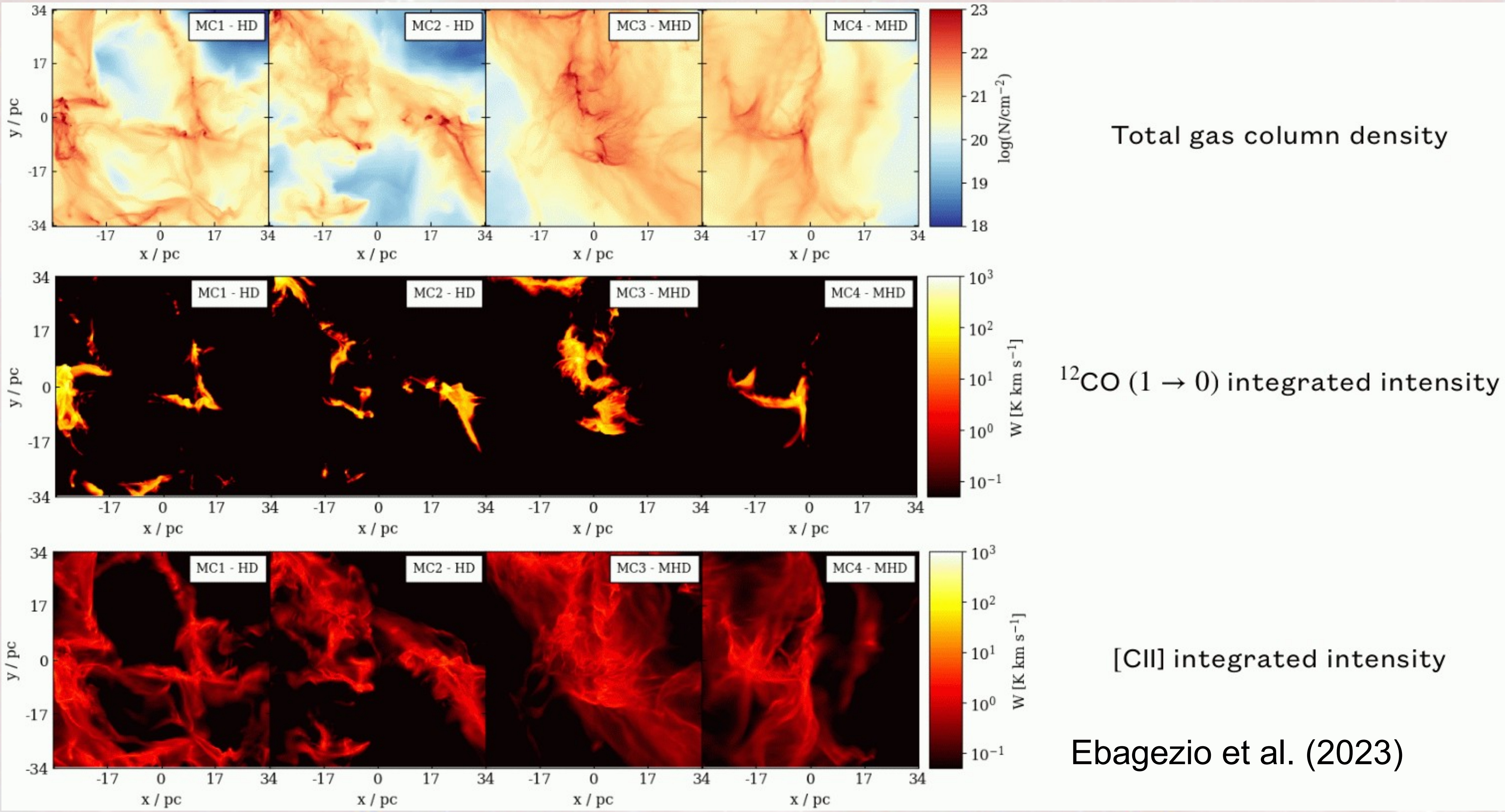
Problems:

- Clouds are not planar or spherical
  - increases fraction of outer layers: H^+, H, CO-dark H_2 gas
- Timescales
  - Example: $n = 300 cm^{-3}$, $A_{V,cloud} = 5$ → width = 10pc, v_{turb} = 5km/s
  - τ_{chem,H_2} = 3Ma, $\tau_{chem,CO}$ = 2Ma, τ_{chem,C^+} = 0.3Ma, τ_{mix} = 2Ma

    (e.g. Joshi et al. 2018)
  - requires dynamical models

Molecular cloud formation in simulations

- SILCC: Large fraction of the gas only visible in [CII]:



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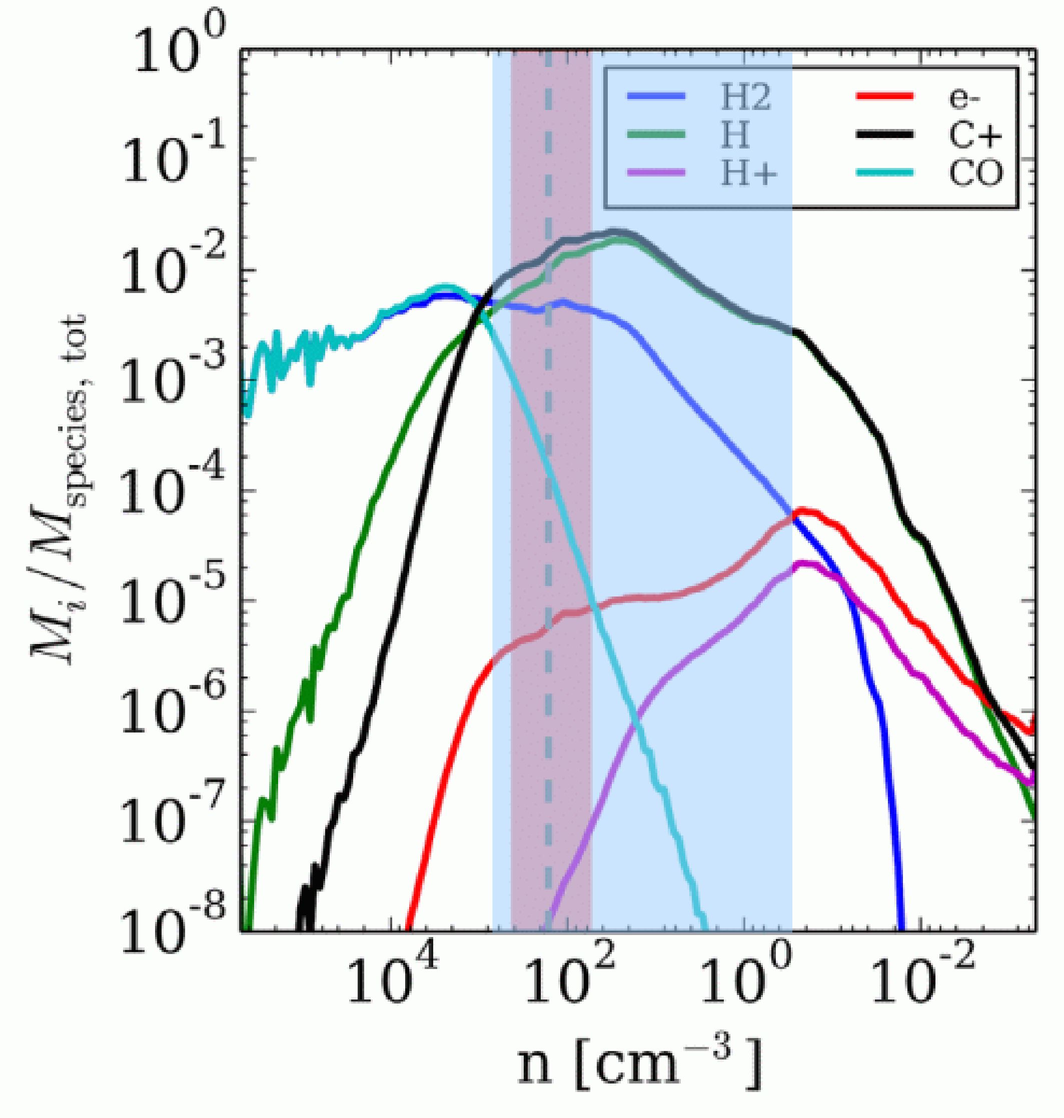
Ebagezio et al. (2023)

The dynamic picture

Molecular cloud formation in simulations

- Quantitative analysis:



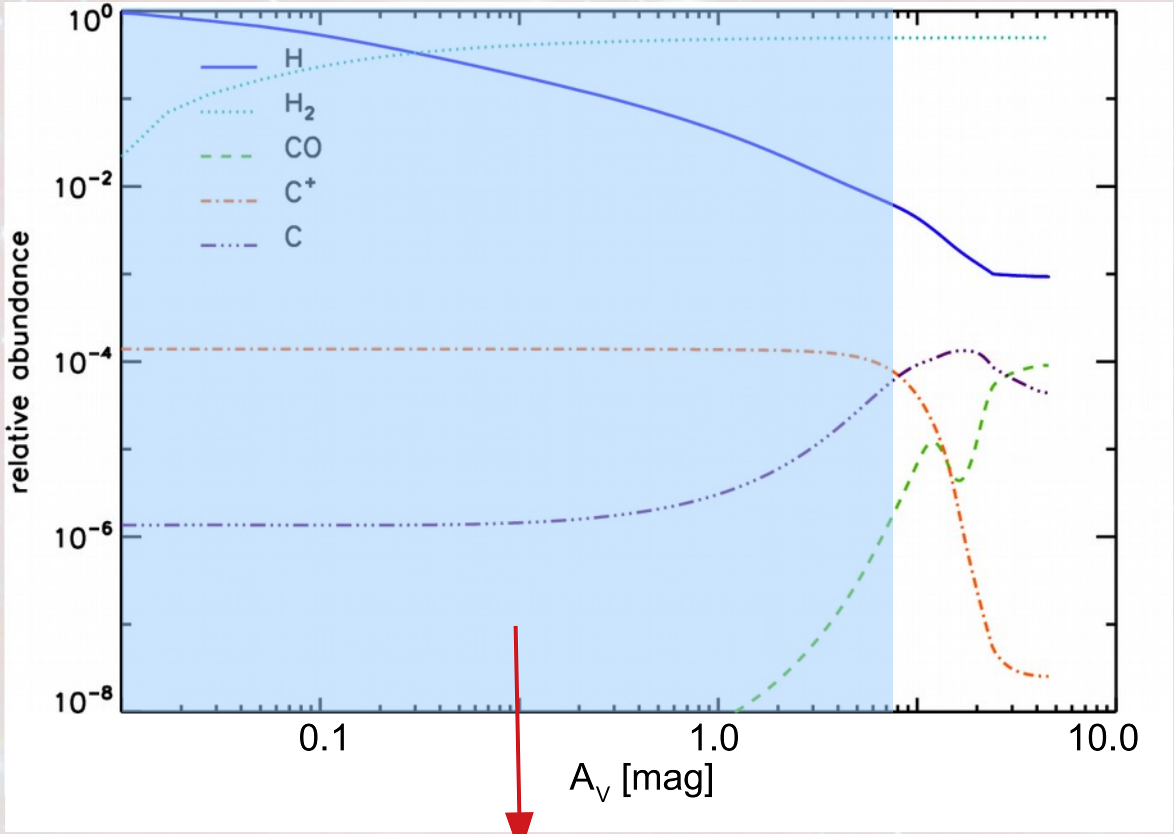
- The majority of the gas (peak of the density PDF) is invisible in CO
- Best traced by C^+.
- [CII] emission is weak due to low temperature and density.

Franeck et al. (2018)

Common problem: large fraction of the gas is "hidden"

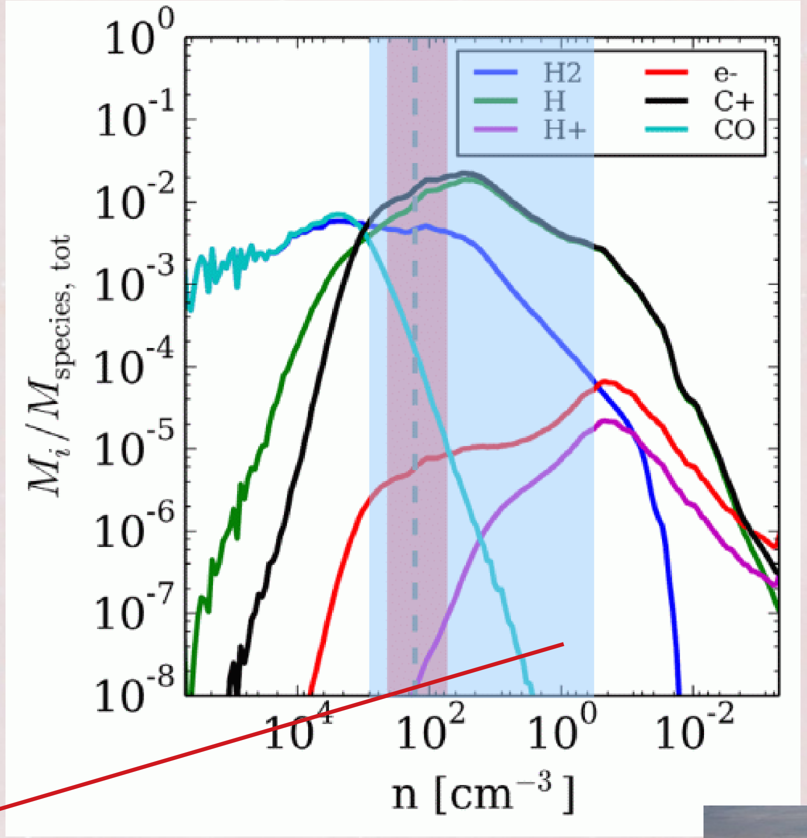
The stationary picture

- PDR model for χ=1, n=10^3 cm^{-3}:
  (based on Röllig & Ossenkopf-Okada 2022)



The dynamic picture

- Cloud formation in MHD simulations:



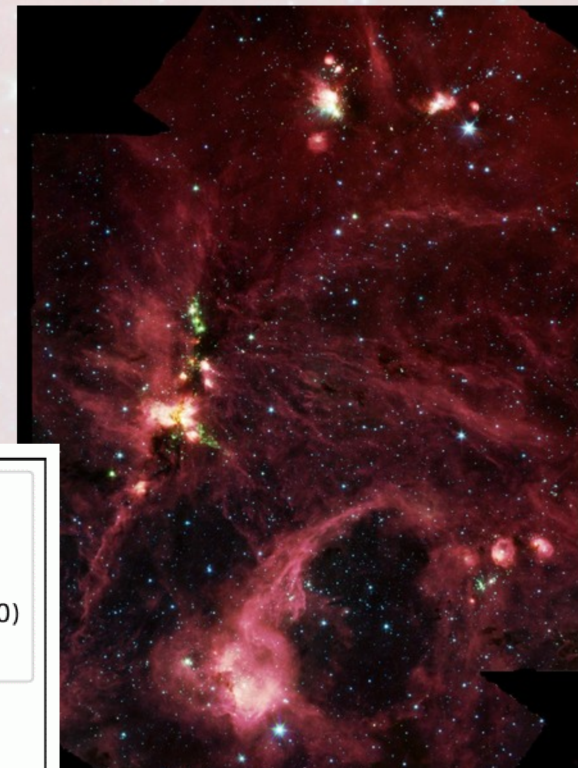
Franeck et al. (2018)

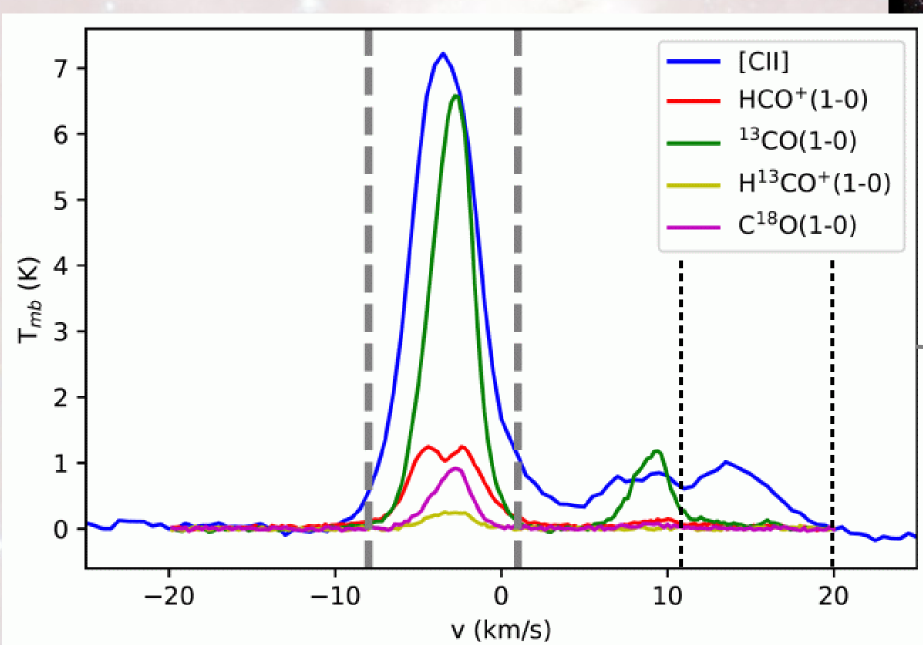
- Emission only in [CII], OH, H_2O, CH

- Absorption in HI, H_2, [OI], hydrides like HF, CH, CH^+, ArH^+, OH^+, H_2O^+

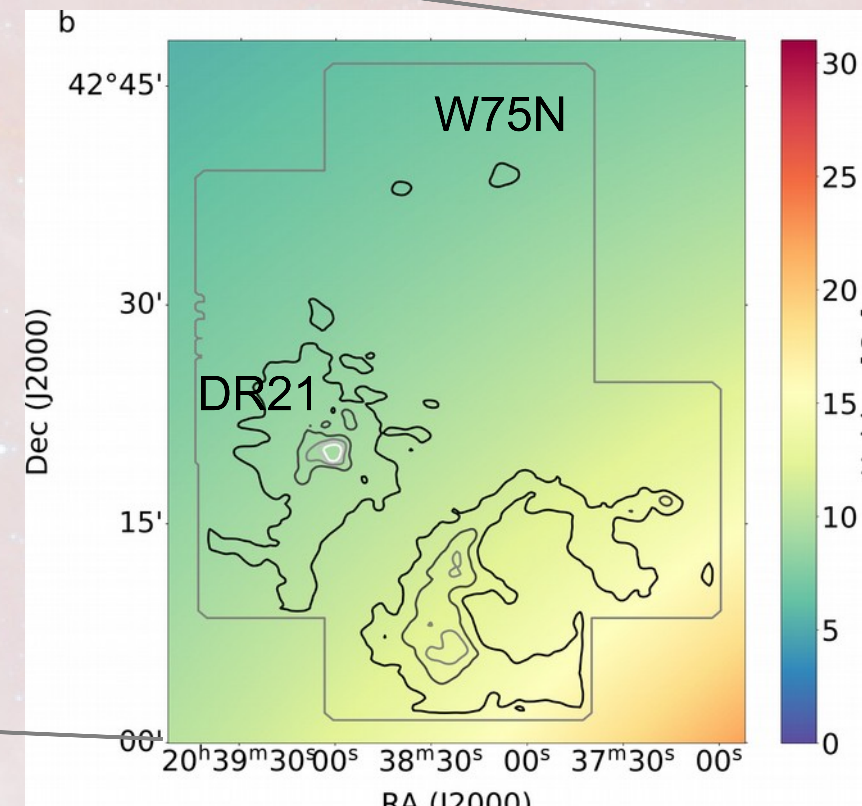
Example: Molecular cloud formation in Cygnus X

- SOFIA Legacy project FEEDBACK (PIs: N. Schneider, X. Tielens): → talk by S. Kabanovic
  poster by S. Dannhauer
  - [CII] mapping around the DR21 ridge
  - 3 distinct velocity components



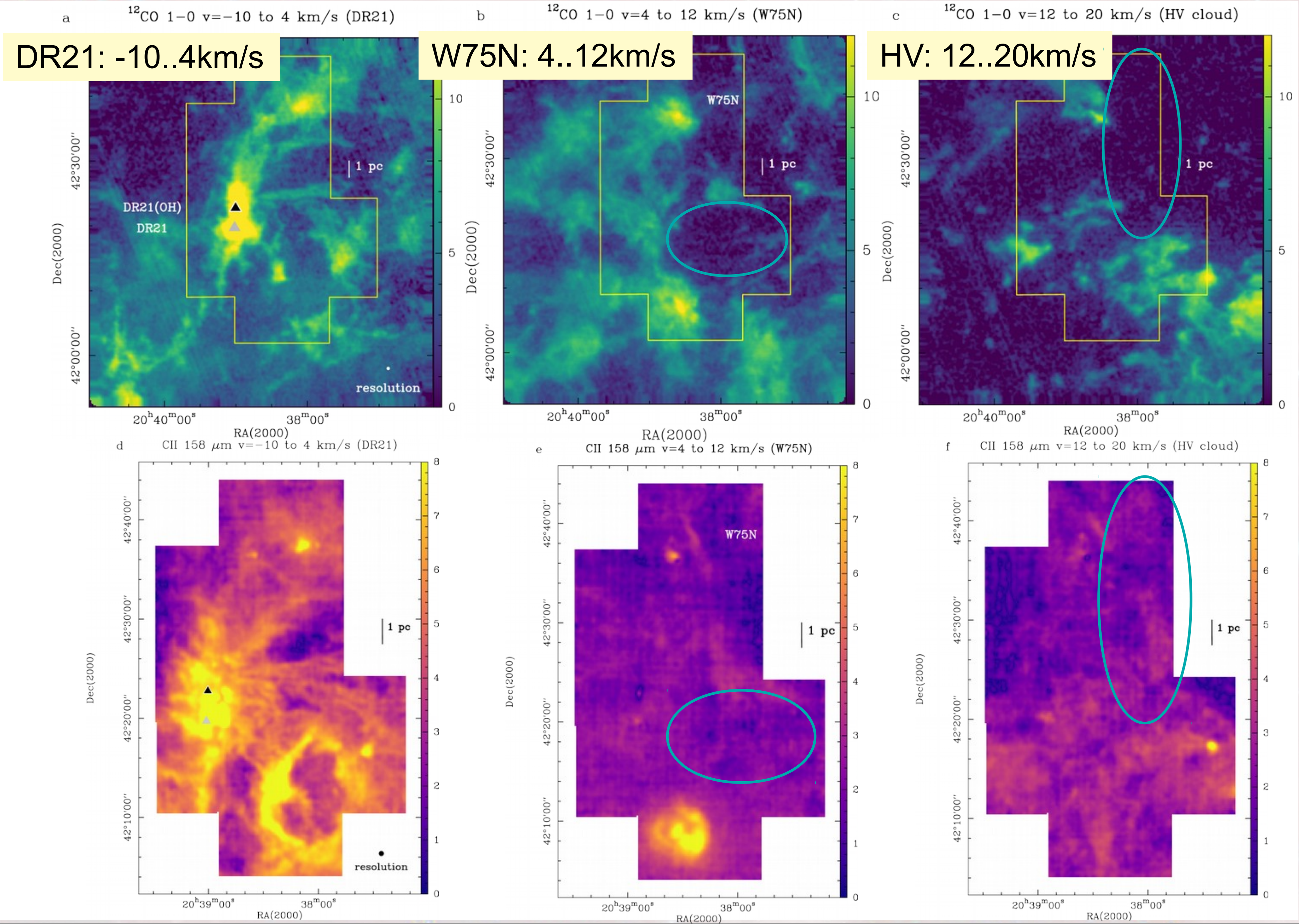


Average spectra in the central region (Bonne et al. 2022)



External radiation field (colors) and integrated [CII] intensity (contours) (Schneider et al. 2023, Nature Astronomy)

Cygnus X observations



CO 1-0

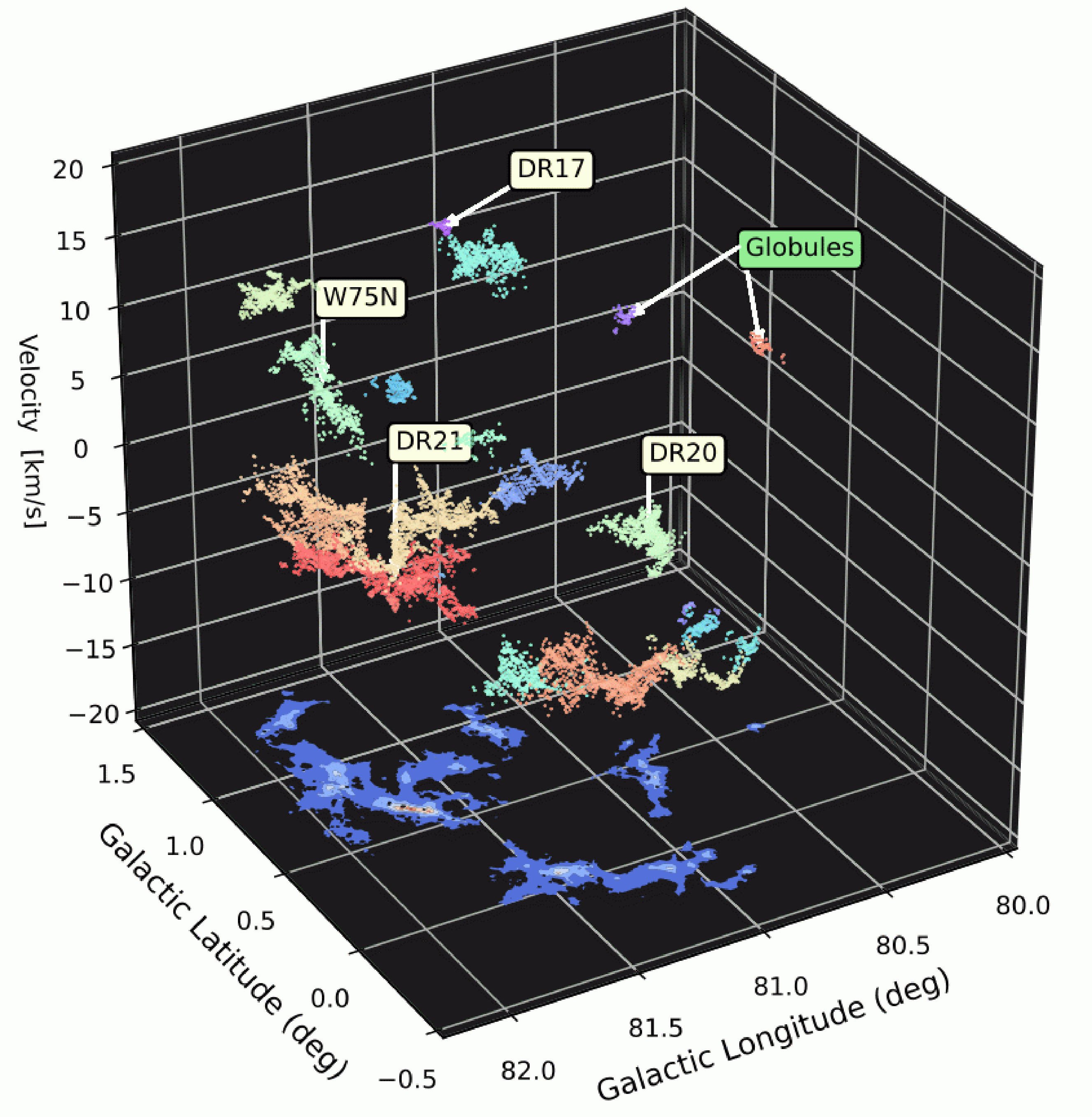
[CII]

- Large regions at higher velocities that are dark in CO but filled with diffuse [CII] emission
(Schneider et al. 2023)

Molecular gas

Structure seen in CO spatially clearly assigned

- HV component that is only traced in [CII] not known so far



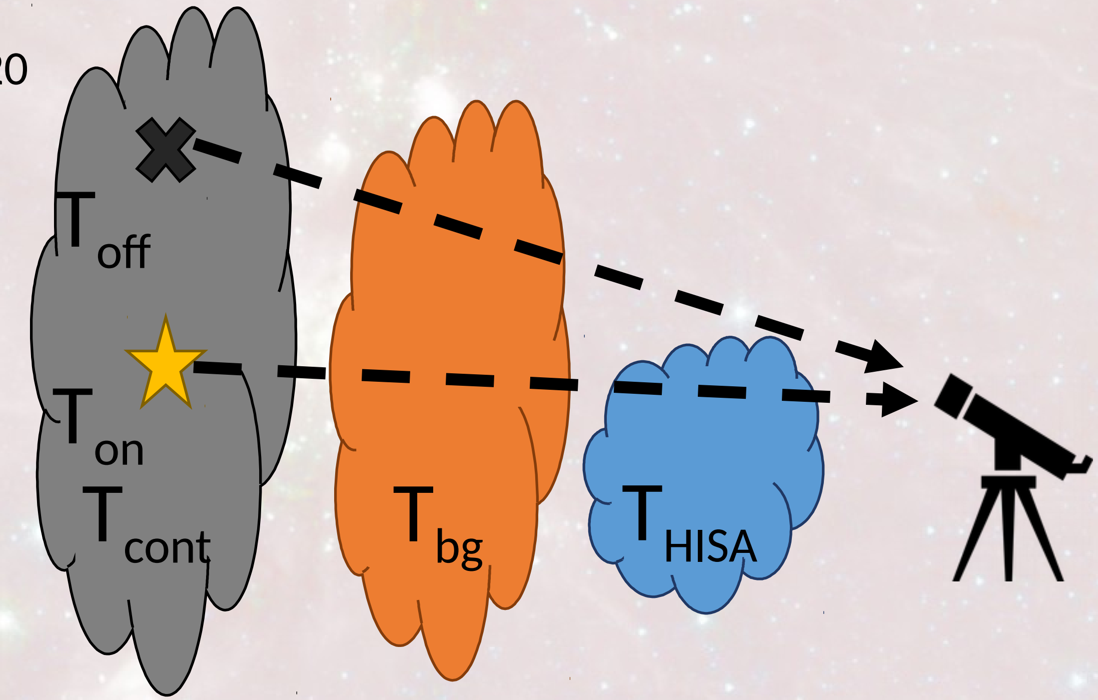
Zhang et al. 2024

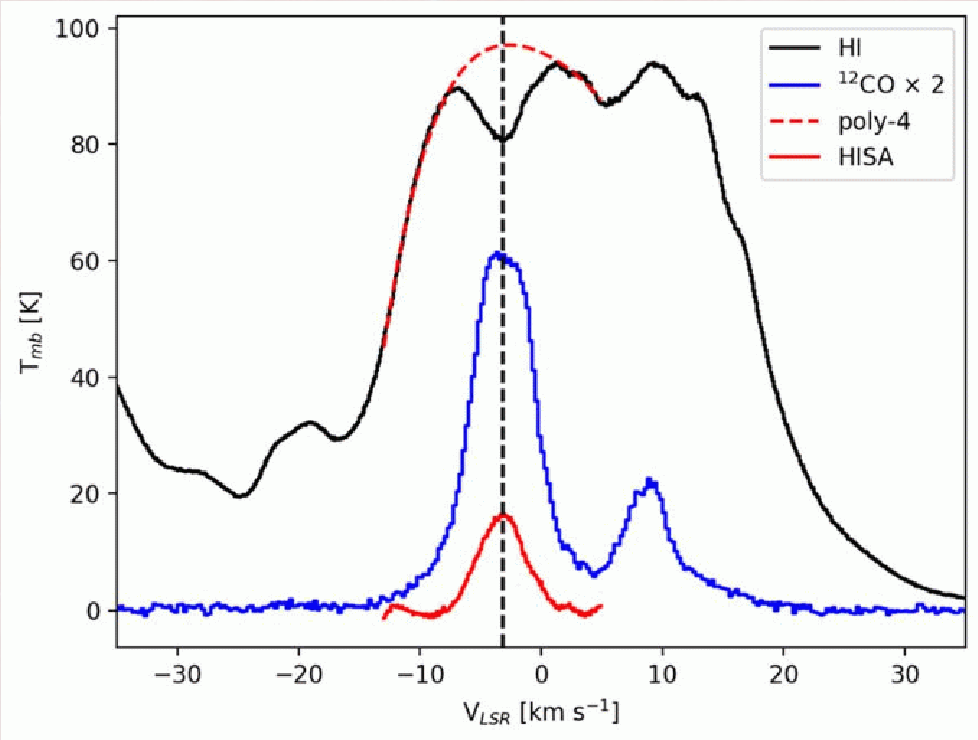
HI gas or CO-dark H_2 gas?

Compare to HI

- HI shows a mixture of WNM emission and CNM absorption
  - HI Self Absorption (HISA) analysis for foreground

Wang et al. 2020





Li et al. (2023): FAST observations

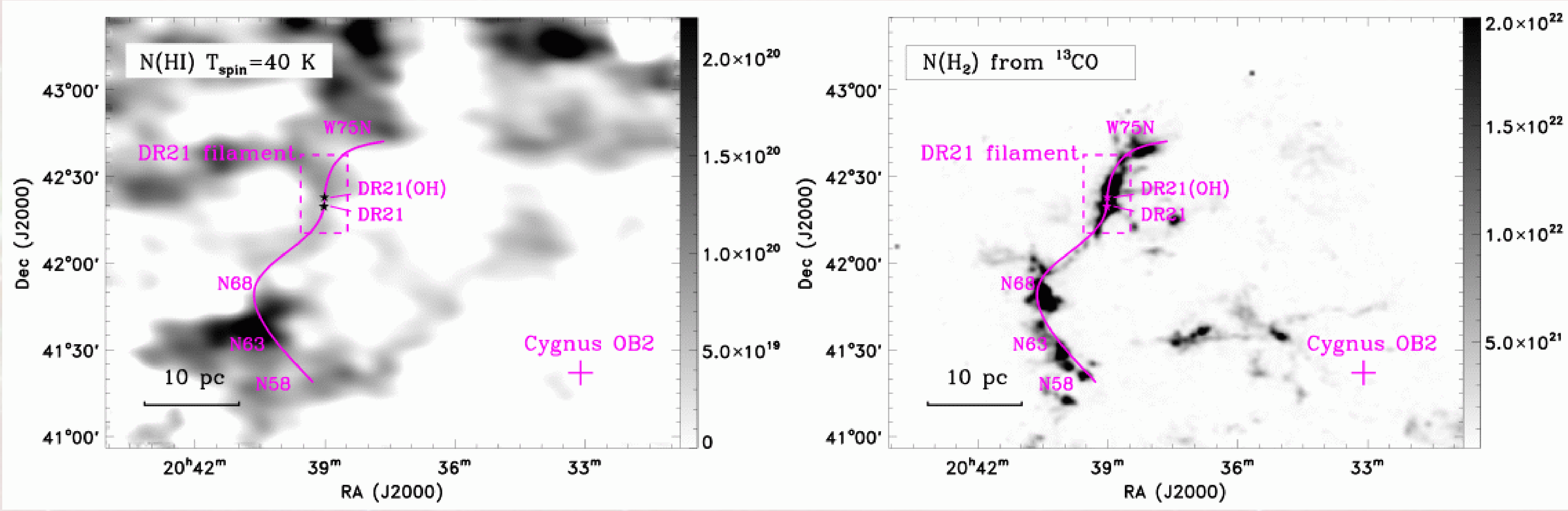
Problems

- Analysis always suffers from uncertain emission baseline
- Possible mixing with some WNM along the LOS

HISA (HI Self Absorption) analysis

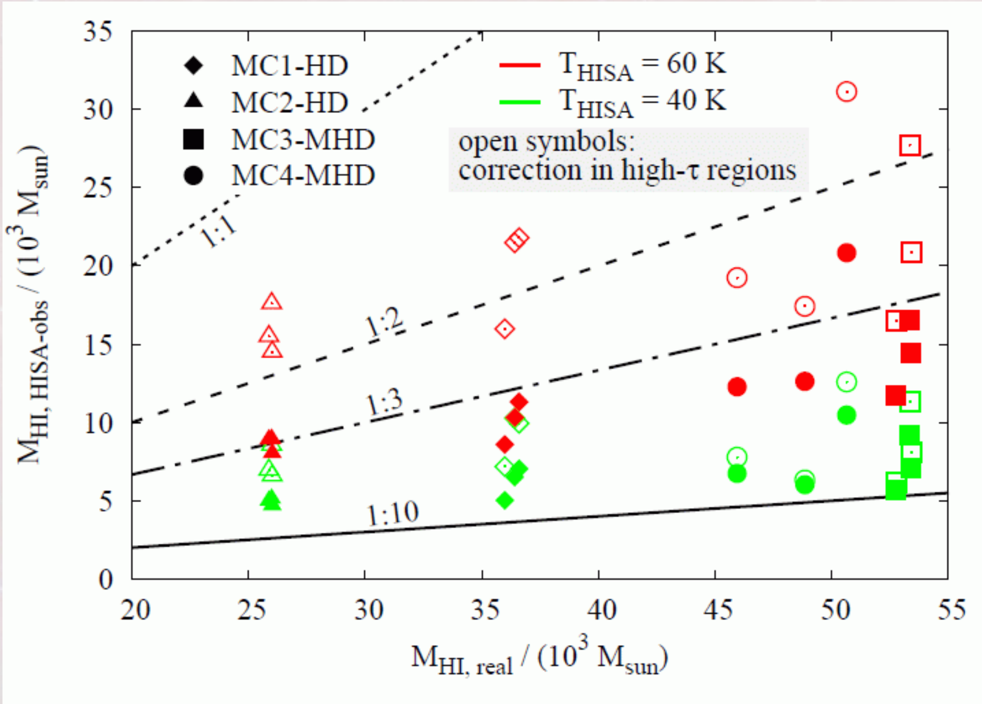
FAST mapping:

- Column of HI:
  - **10^{20} – 3×10^{20} cm^{-2}** density ~ 20 cm^{-3}
  - much lower than molecular gas, but more extended



But:

- Baseline uncertainty
- Excitation temperature basically unknown
- No reliable quantitative assessment of cold atomic gas from HISA possible
  - only lower limits



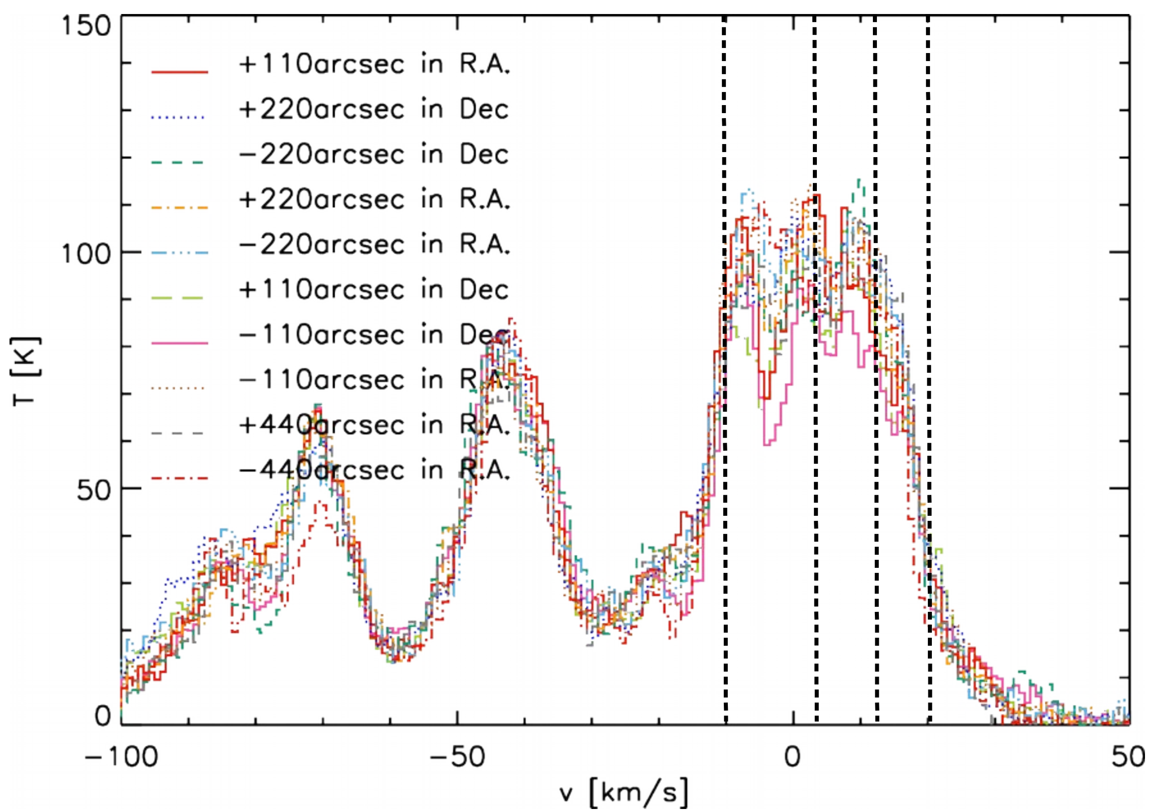
Li et al. (2023), 3' resolution

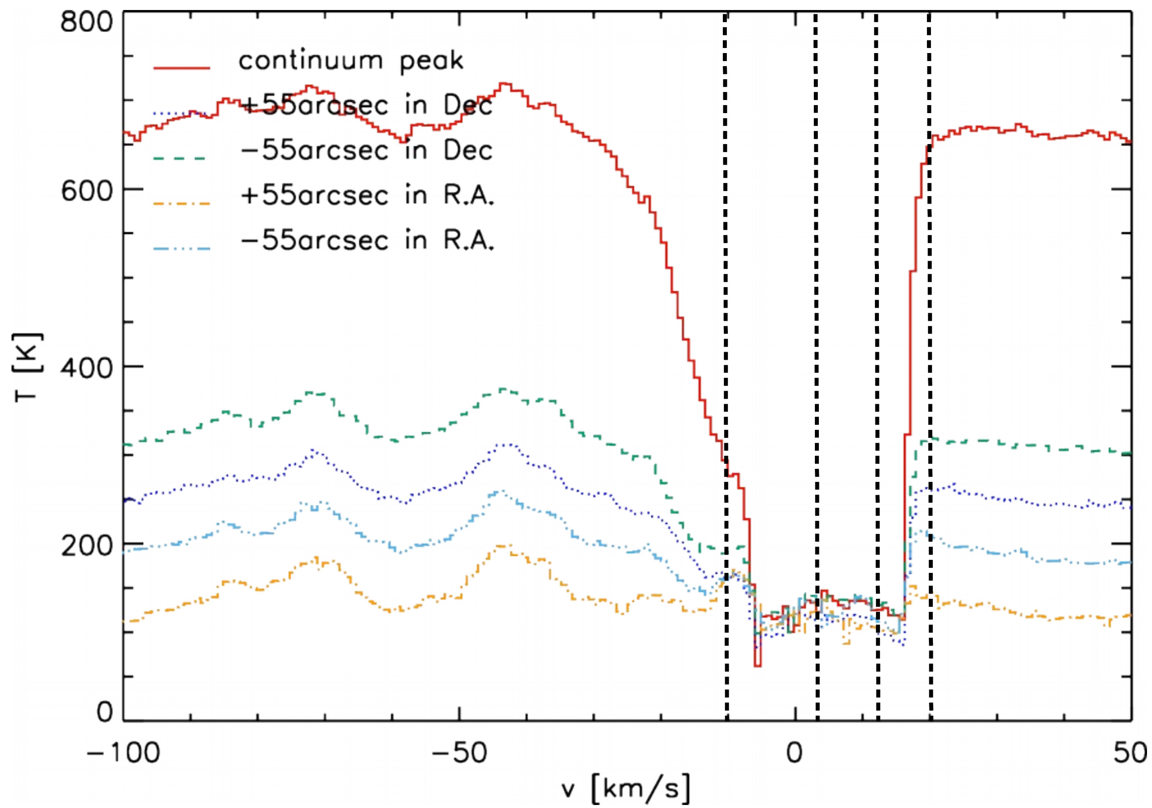
HISA systematically underestimates the amount of cold HI by factors > 2, typically rather 5-10 (Seifried et al. 2021)

HI gas or CO-dark H_2 gas?

HI analysis

- Absorption towards DR21 continuum allows to much better constrain the foreground column of cold HI there (assuming T_{ex})



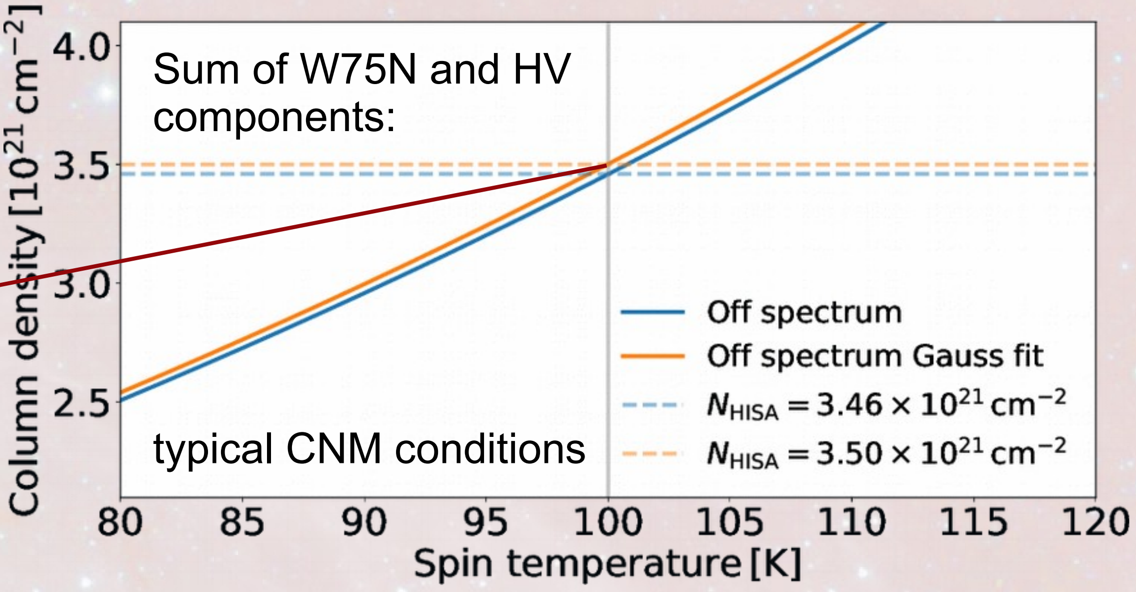


DRAO/CGPS data, resolution 1',
Taylor et al. (2003)

Result

HI analysis:

- HI foreground well constrained:
  - **3.7 × 10^{21} cm^{-2}** for DR21 velocities
  - **2.0 × 10^{21} cm^{-2}** for W75N
  - **1.5 × 10^{21} cm^{-2}** for HV component
- Factor 10 above Li et al (2023) but less than CO bright gas (DR21 ridge: 15000 $M_\odot$)



Schneider et al. (2023)

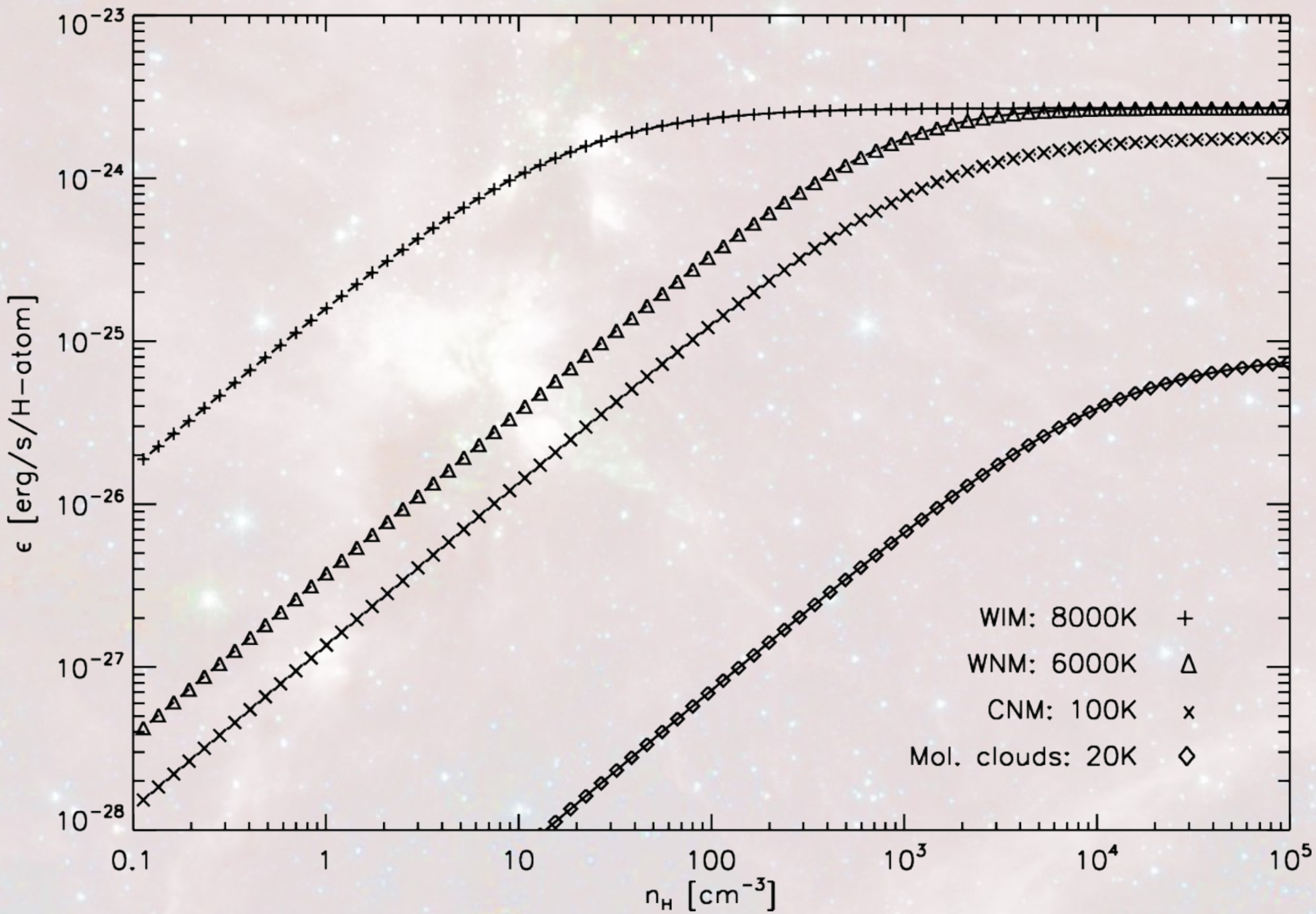
Compare to [CII] emission

- Gas is partially molecular:
  - Molecular fraction: W75N: 23% HV component: 14%
  - Mass: W75N: 7800 $M_\odot$ HV component: 9900 $M_\odot$
  - Falling towards DR21 ridge:
    - accretion time: 1 Mio a
    - conversion H→ H_2: 10 Mio a
  - n ~ 100 cm^{-3}, T_{kin} ~ 100K, radiation field ~ $10G_0$

But ...

Is CO-dark gas always [CII] bright?

- Collisional excitation



- No significant [CII] emission from
  - cool C^+ [< 50K]
  - warm C^+ at densities below 100 cm^{-2}
- But traceable in absorption

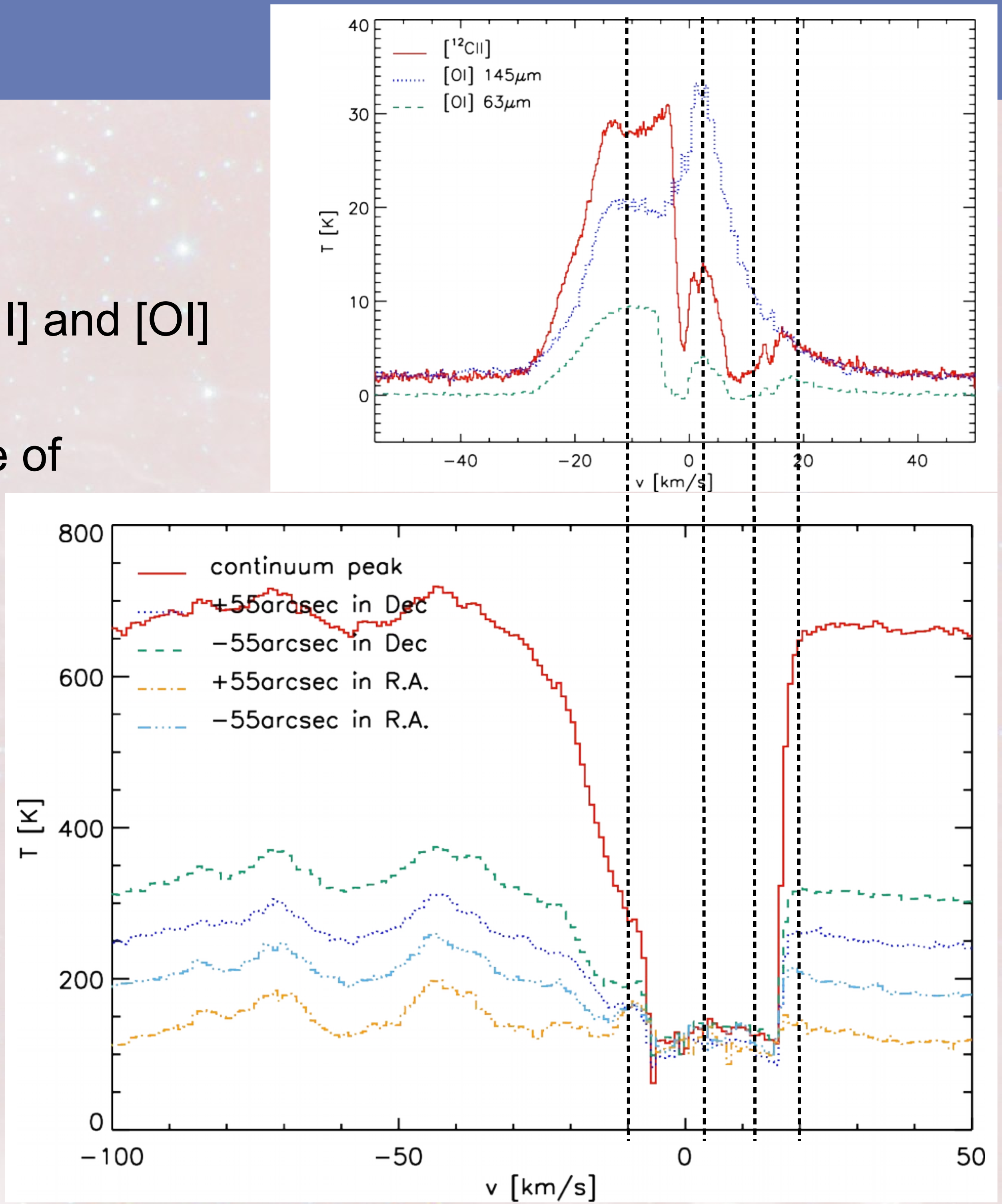
Ossenkopf (2014), see also Goldsmith et al. (2012)

Look for [CII]-dark, CO-dark gas

Gas < 50K only seen in absorption!

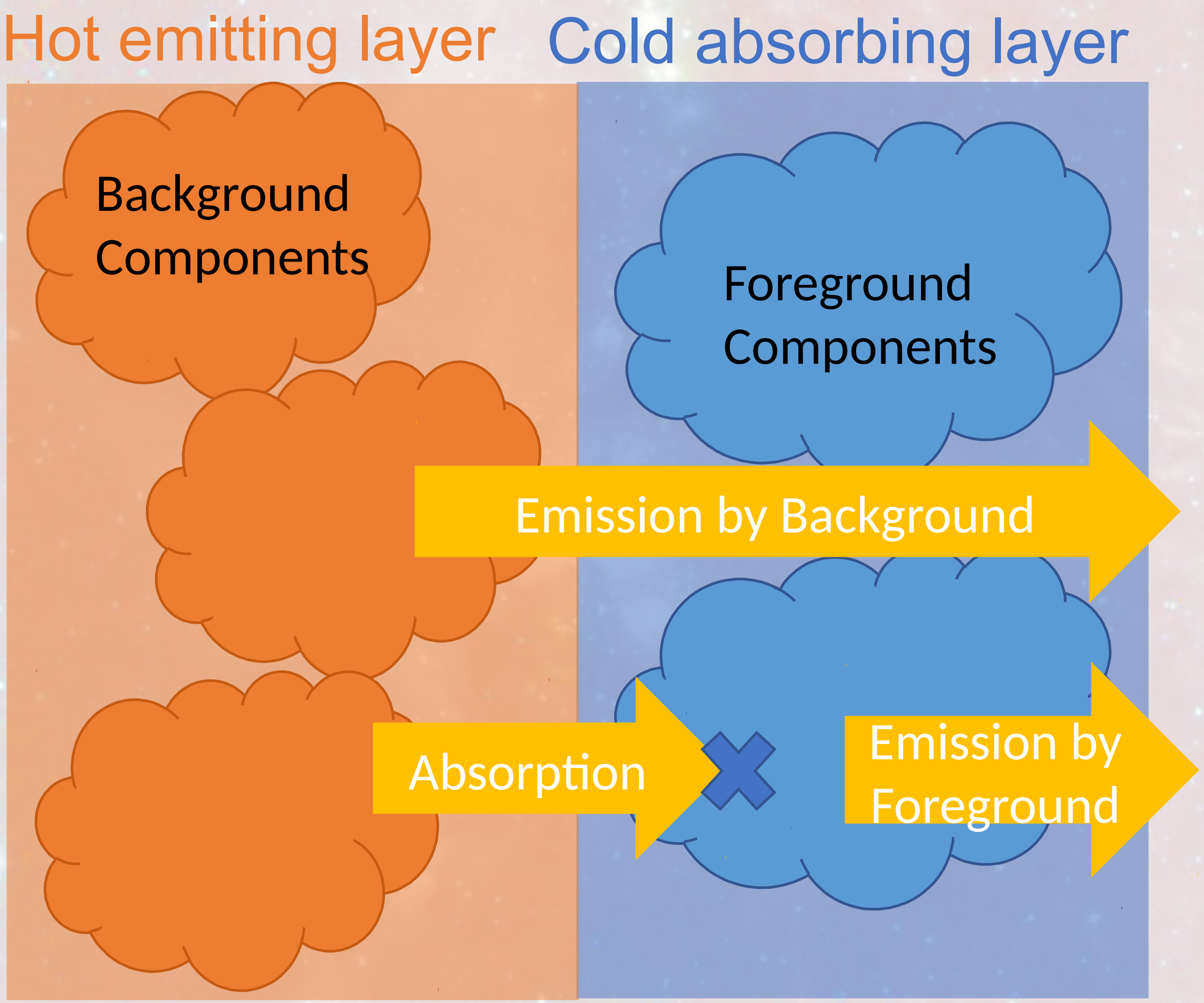
- Absorption dips of ground-state lines of [CII] and [OI] coincide:
  - Quantitative analysis requires knowledge of background emission
  - For [CII] possible if [^{13}CII] was observed
  - For [OI], if 145μm line was observed

- Simplifying assumption:
  - Same material responsible for different fine-structure lines



Two-layer mulitcomponent model

Guevara et al. (2020), Kabanovic et al. (2022):



Radiative transfer equations for multiple components distributed in two layers:

Background

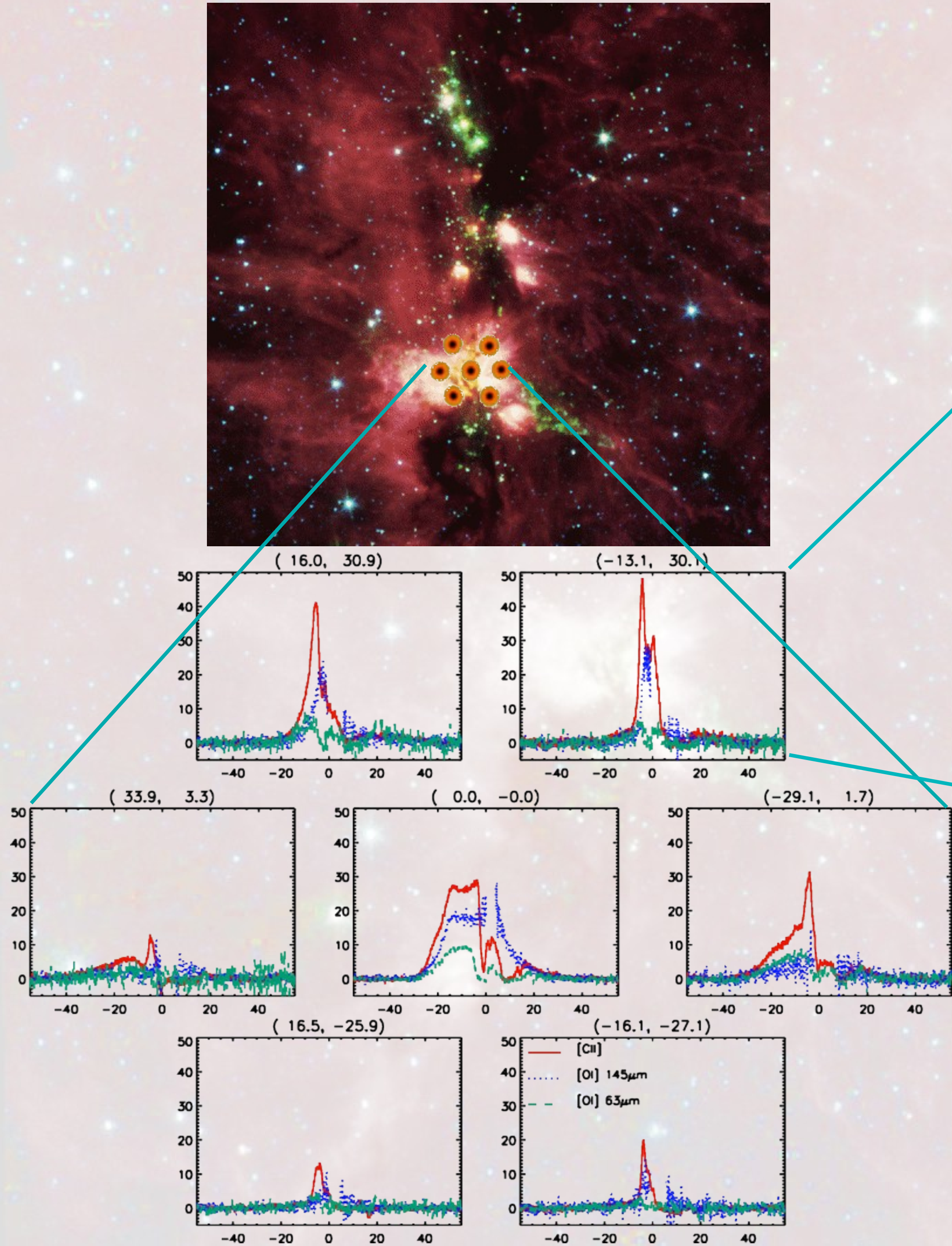
$$T_{\mathrm{mb}}(v) = \left[\mathcal{J}_\nu(T_{\mathrm{ex,bg}})\left(1 - e^{-\sum_{i_{\mathrm{bg}}} \tau_{i_{\mathrm{bg}}}(v+\Delta v_\nu)}\right)\right] \times e^{-\sum_{i_{\mathrm{fg}}} \tau_{i_{\mathrm{fg}}}(v+\Delta v_\nu)} + \mathcal{J}_\nu(T_{\mathrm{ex,fg}})\left(1 - e^{-\sum_{i_{\mathrm{fg}}} \tau_{i_{\mathrm{fg}}}(v+\Delta v_\nu)}\right)$$

Foreground

The optical depth follows Gaussian profiles of emitters and absorbers

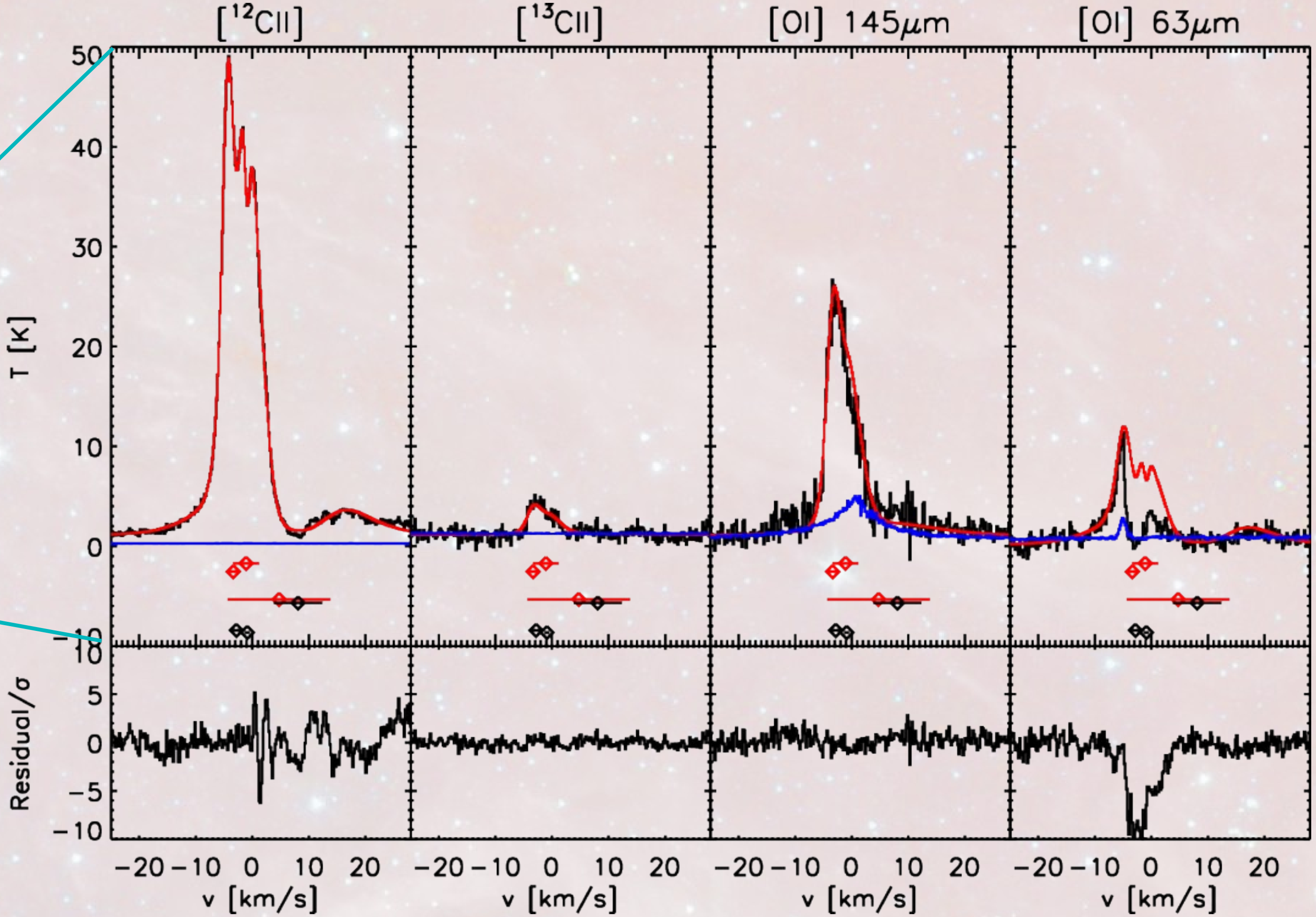
$$\tau(v) = \tau_0 e^{-4\ln 2\left(\frac{v-v_0}{w}\right)^2}$$

Fitting results



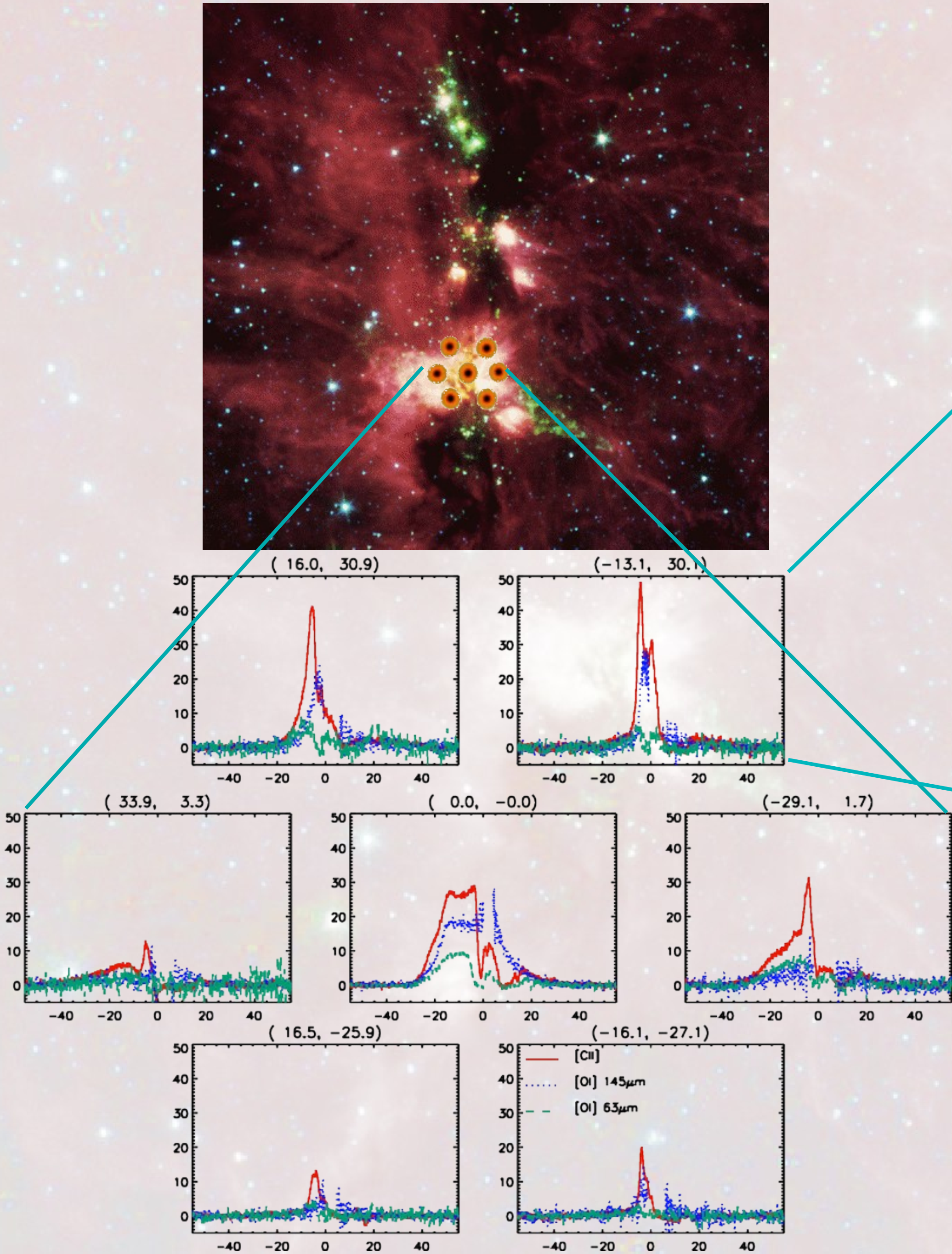
Example: pixel 3

- Common fit of all lines with 3+3 Gaussians:



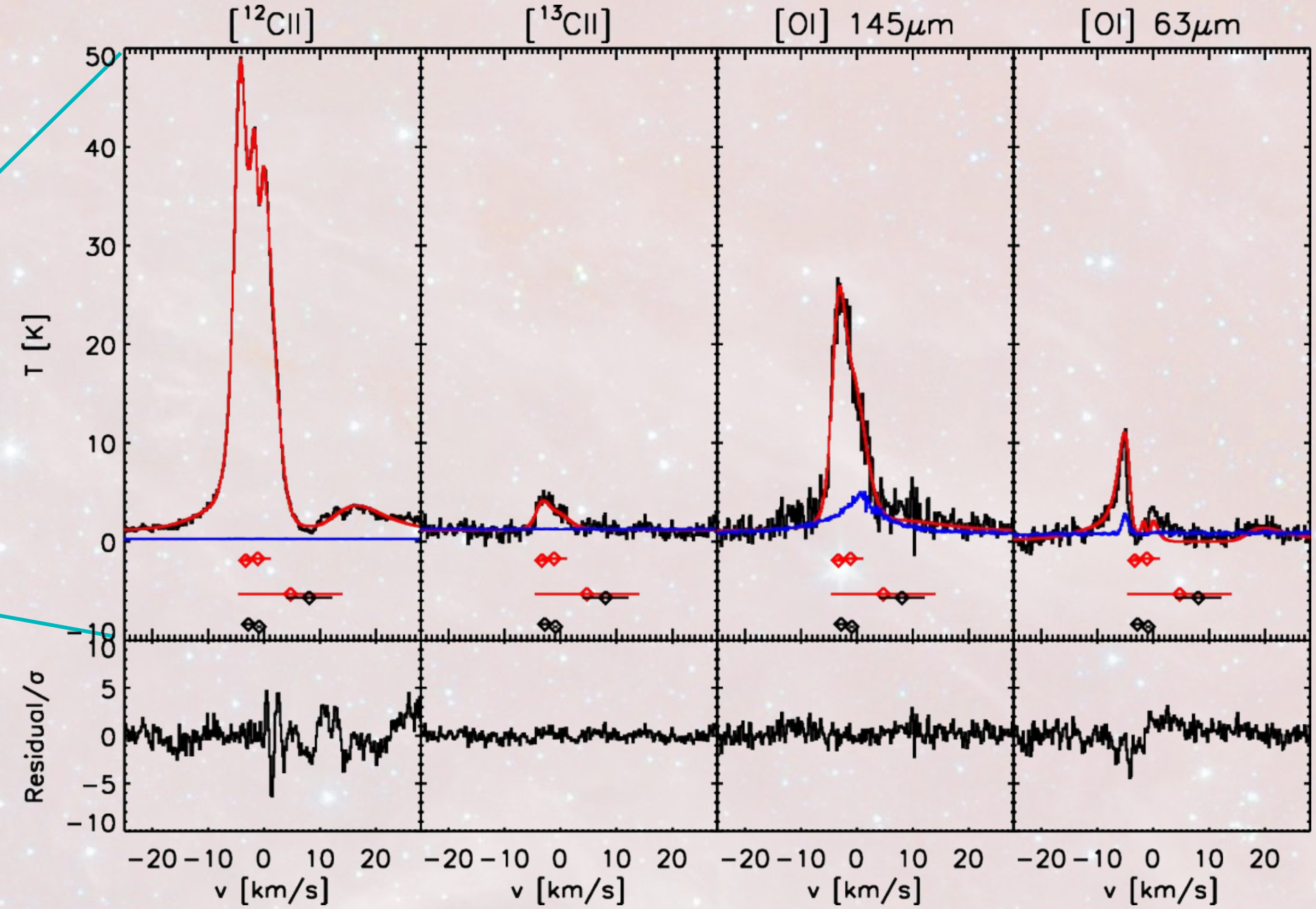
- [OI] 63μm line not well fitted if abundance given by [CII].
  Assuming standard gas-phase elemental abundances:
  X(C)=$2.5\cdot10^{-4}$, X(O)=$4.5\cdot10^{-4}$ (Simón-Díaz & Stasińska 2011)

Fitting results



Example: pixel 3

- Common fit of all lines with 3+3 Gaussians



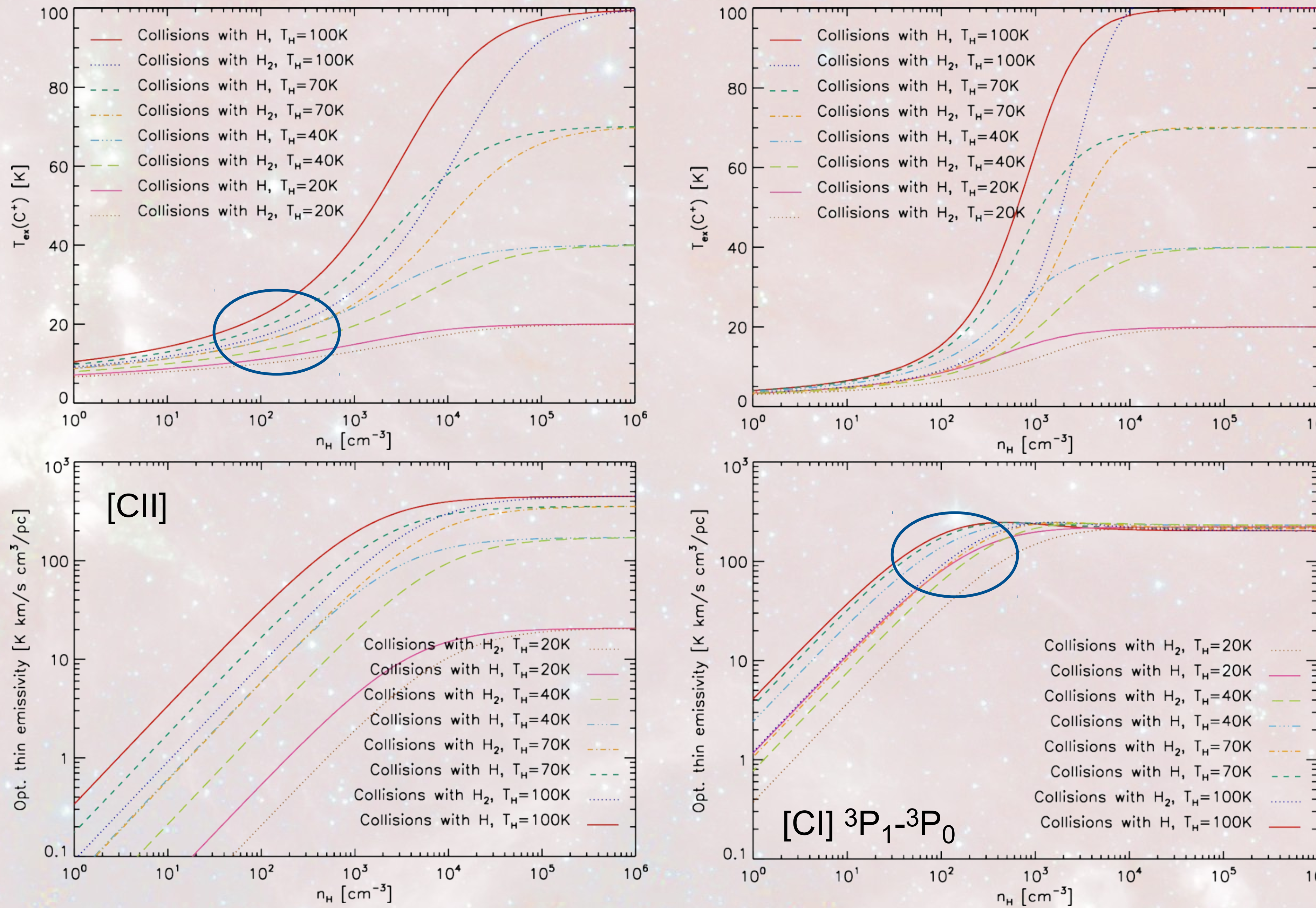
- [OI] 63μm line not well fitted if abundance given by [CII]. Needs more cold atomic oxygen in foreground.

Where is the carbon for the additional oxygen absorption?

Atomic carbon?

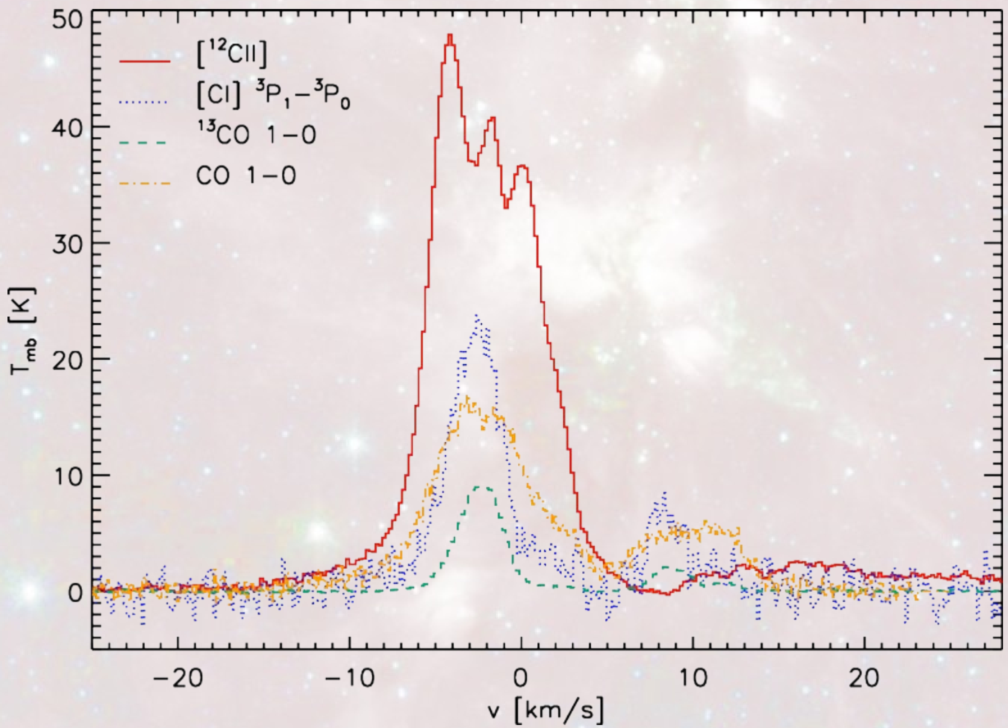
Favourable level structure

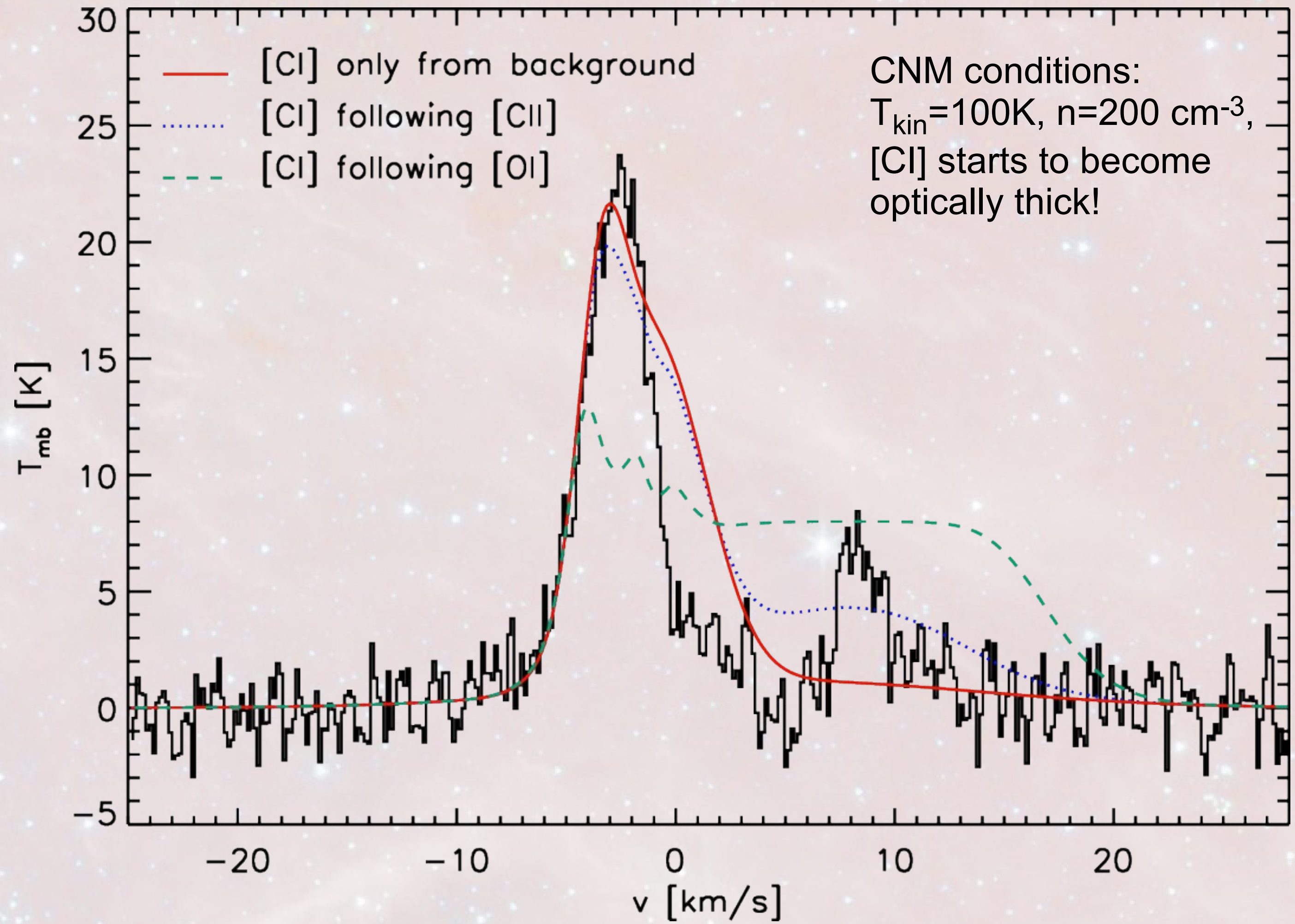
- Very constant emissivity at 492GHz
  - even for cold foreground gas



Does it explain the missing carbon?

- **No!**
- Rather matching the embedded molecular gas traced through ^{13}CO.





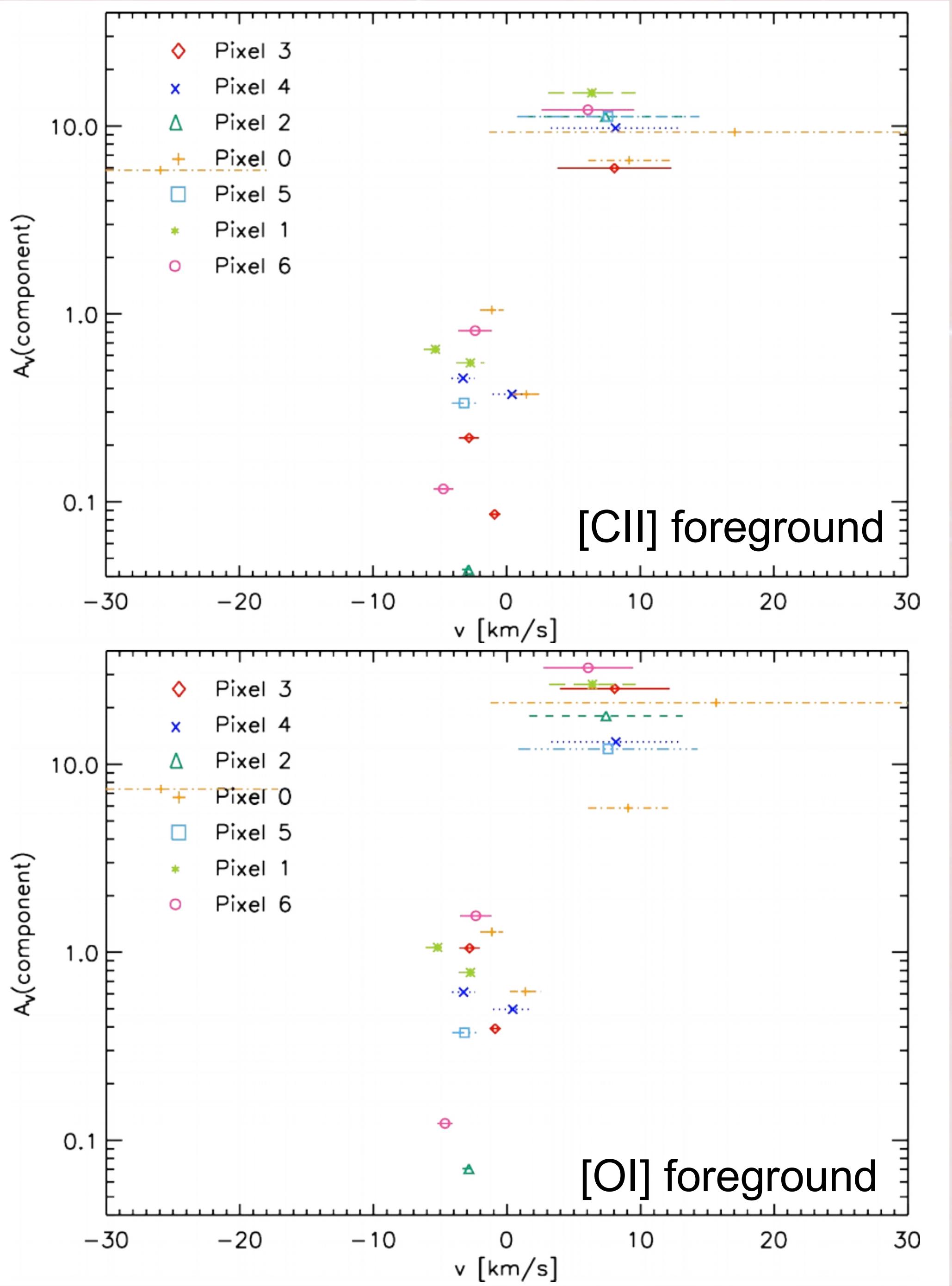
- [CI] hardly associated to absorption components
  - weakly to emission components – violates the PDR scenario

Disclaimer: not observed at the same resolution. 52'' FWHM only

Result

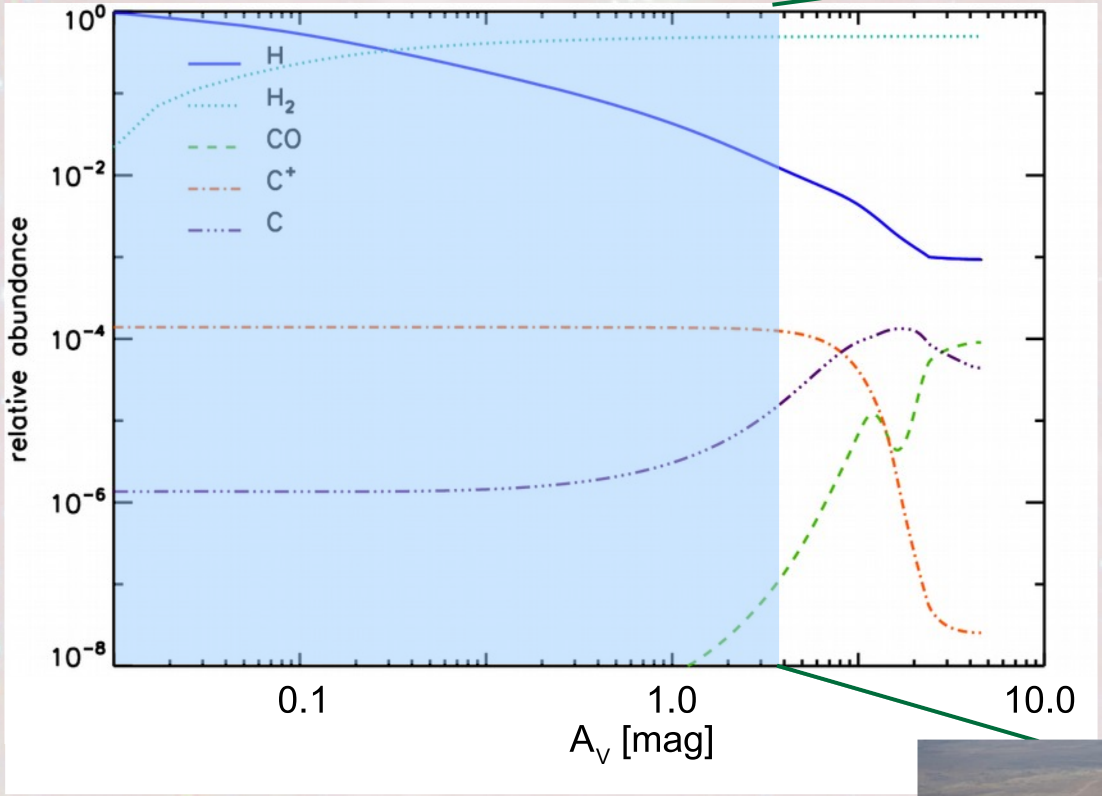
Thick cold foreground at 8km/s

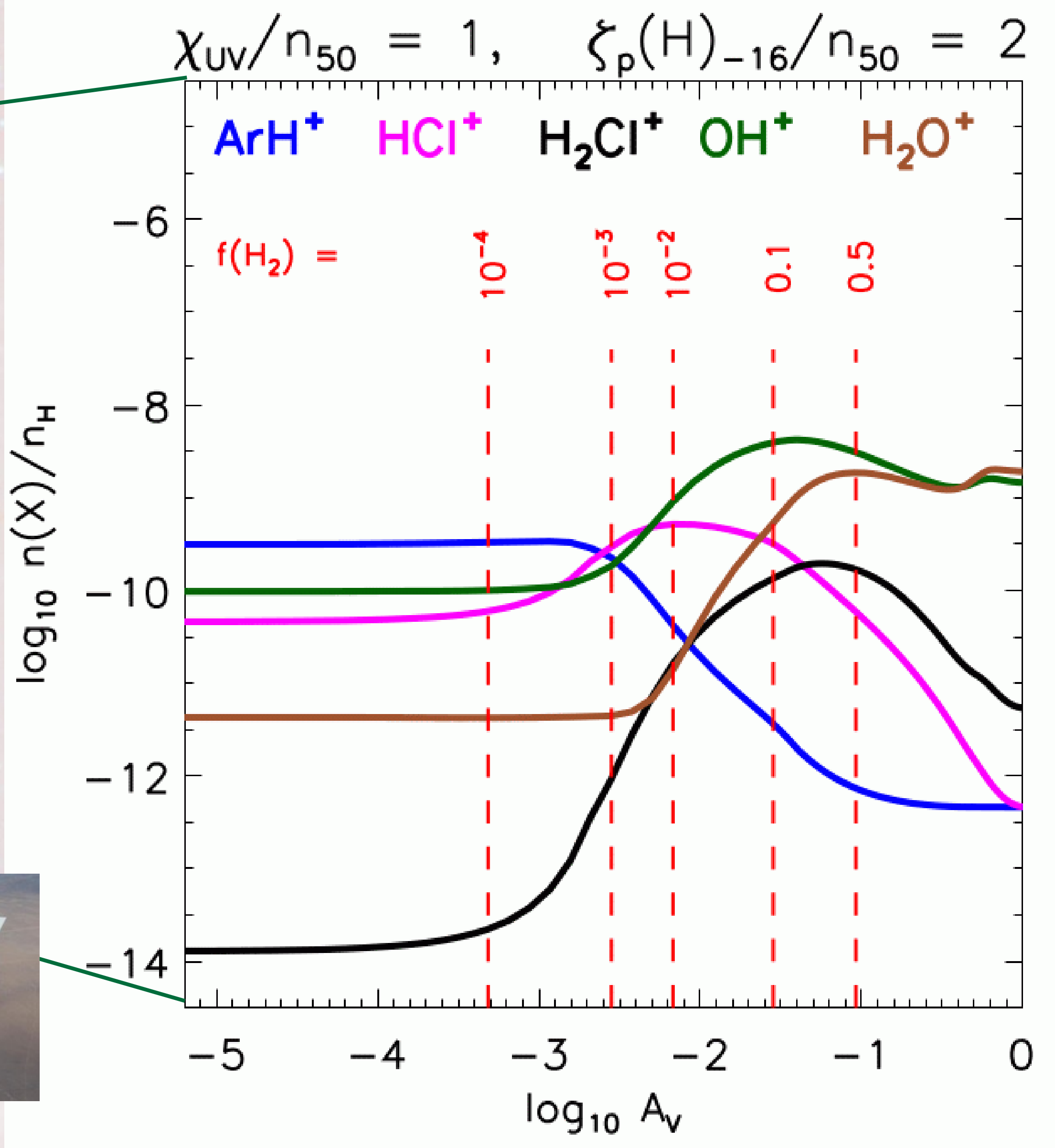
- **Common foreground for all pixels:** **$N_H \sim 15 \times 10^{21}$ cm^{-2}**
  - even higher by factor ~2 when oxygen absorption needed
- Background instead strongly variable from pixel to pixel
- Local foreground at -2km/s also strongly variable
- Practical problems in measurement:
  - [^{13}CII] often affected by [CII] foreground absorption at other velocities
  - [OI] 145µm rarely observed



Alternatives

Hydrides trace the CO-dark, partially molecular gas





- **HyGAL** SOFIA legacy program (Pis: D. Neufeld, P.Schilke)
  - Columns: typically 2 – 6 × 10^{21} cm^{-2}

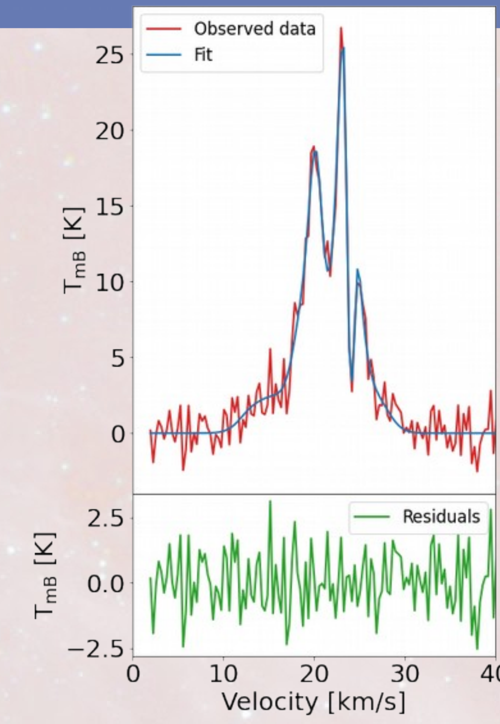
Neufeld & Wolfire (2016)

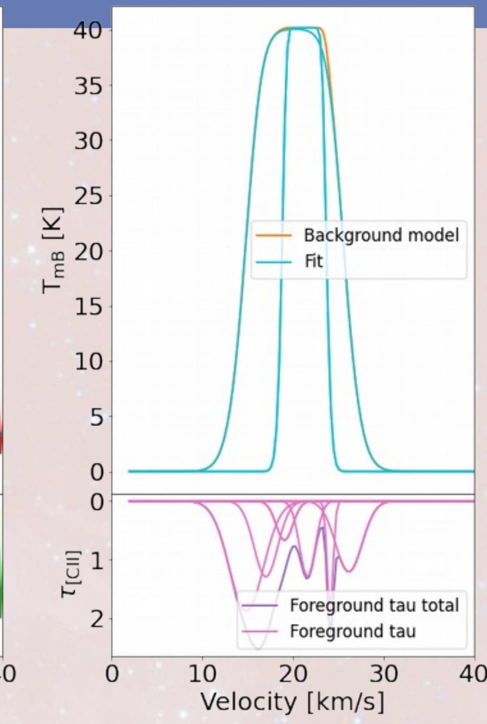
→ talks by A. Jacob, K. Menten, W.-J. Kim and Poster by M. Busch

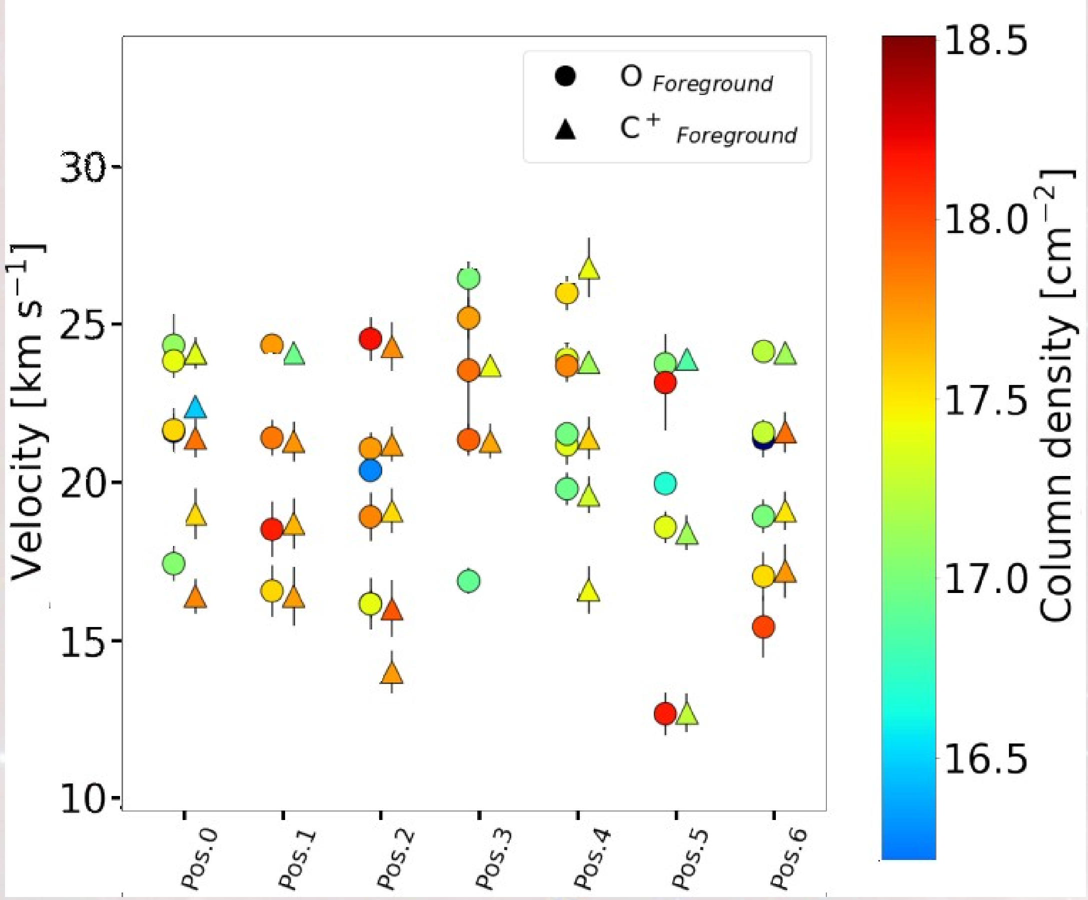
More complications

M17SW
(Guevara et al. 2020, and subm.)

- Same type of [CII], [^{13}CII] and [OI] 63µm and 145µm observations
  - Fit allowed for independent [OI] and [CII] foreground



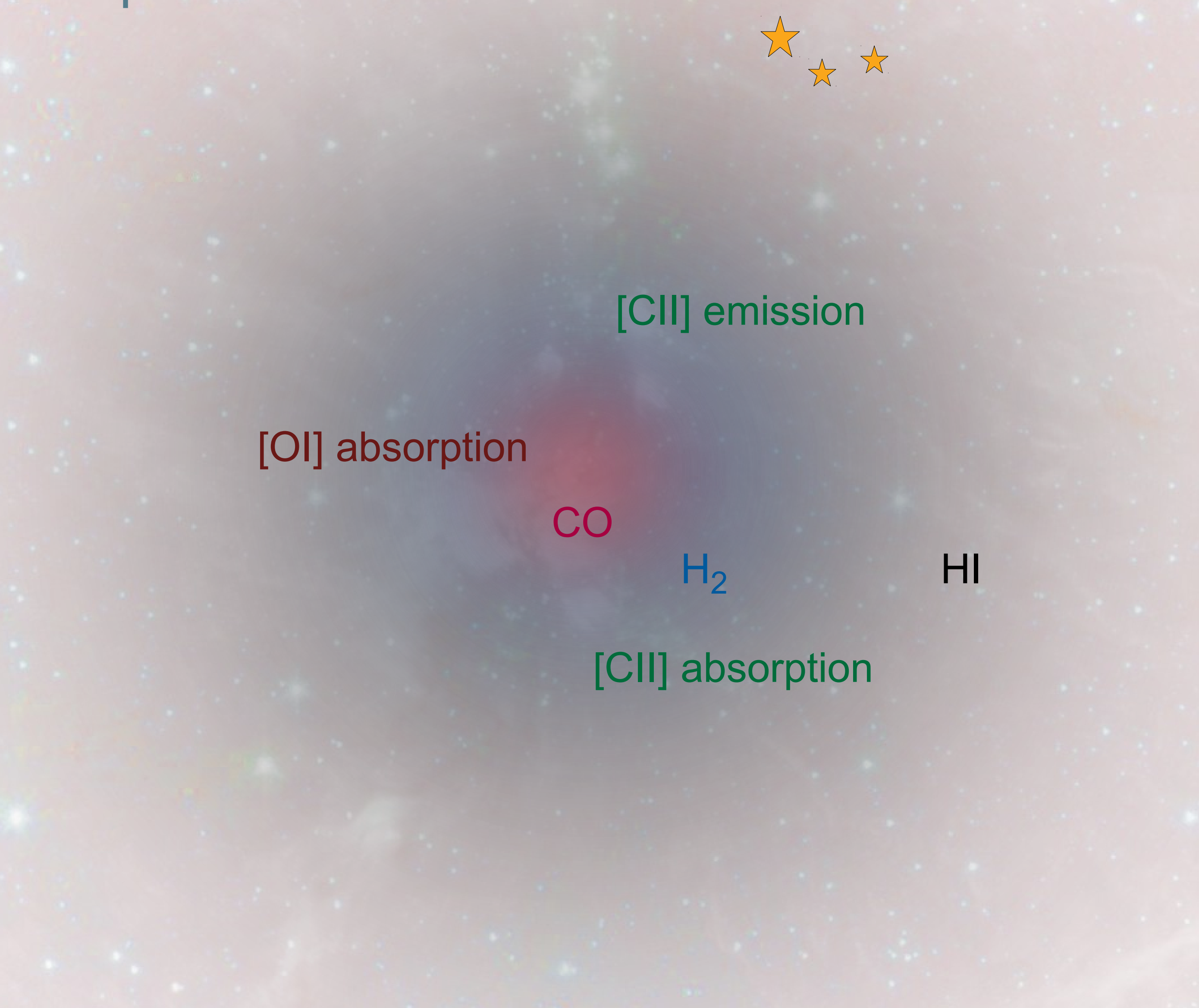




- Foreground components vary by $N(C^+) \approx 5\times10^{17}$ cm^{-2} corresponding to **4×10^{21} cm^{-2}** over 30''=0.28pc
- In isotropic case this indicates a density of 5000 cm^{-3}!
  - Should be molecular

More questions

Spatial structure



Schematics of the overall cloud structure

- How much is the HI and H_2 gas mixed?
  - How much WNM is mixed into the CNM?
- What are realistic geometries?
  - Streamers, collisions, …?
- What is the mass accretion flow rate before and after the first SN goes off?
- Where is the C in gas seen in [OI] absorption but not in [CII] and [CI], CO emission or absorption?

Summary

- **Is the concept of Molecular Clouds outdated?**
  - What we observe in molecular lines are just the “tips of the iceberg”
  - The mass reservoir for star-formation includes the whole iceberg
    - transitional gas: partially atomic, partially molecular
    - bright in [CII] when warm and dense, otherwise only visible in absorption
- Assessing the mass of this CO-dark molecular and cold atomic material is very difficult
  - Currently we have no way to measure the mass reservoir for star-formation
- CCAT may answer some questions
- For final answers we would need a new SOFIA