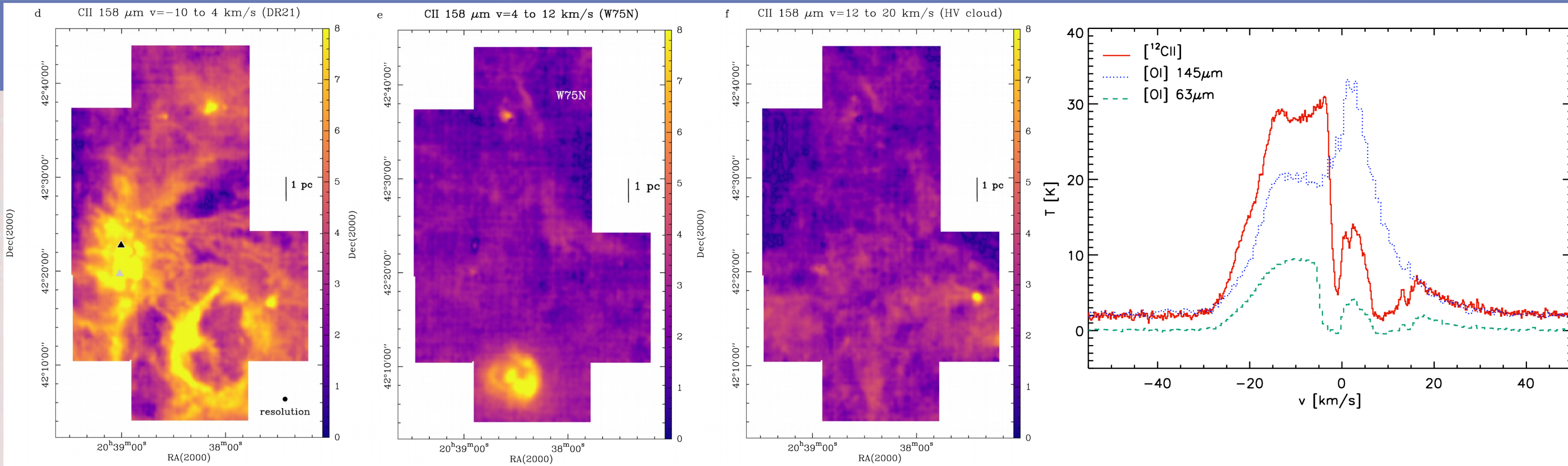

Molecular Cloud Formation

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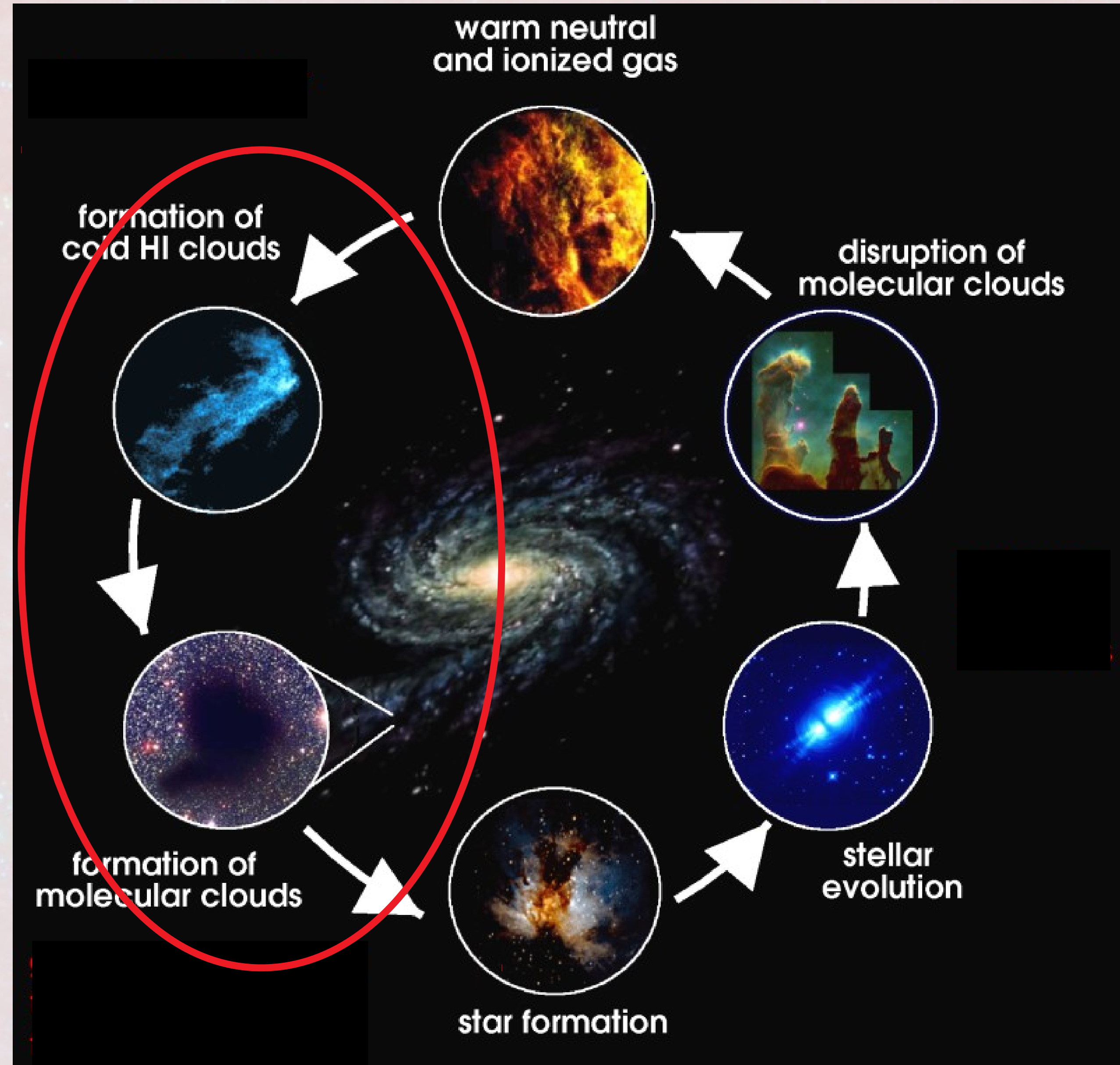
Summary

- **There are no Molecular Clouds!**
  - What we observe in molecular lines are just the “tips of the iceberg”
  - The mass reservoir for star-formation includes the whole iceberg
- Assessing the mass of CO-dark molecular and cold atomic material is very difficult
  - Currently we have no way of obtaining any reliable star-formation efficiency

Background

What is the question?

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

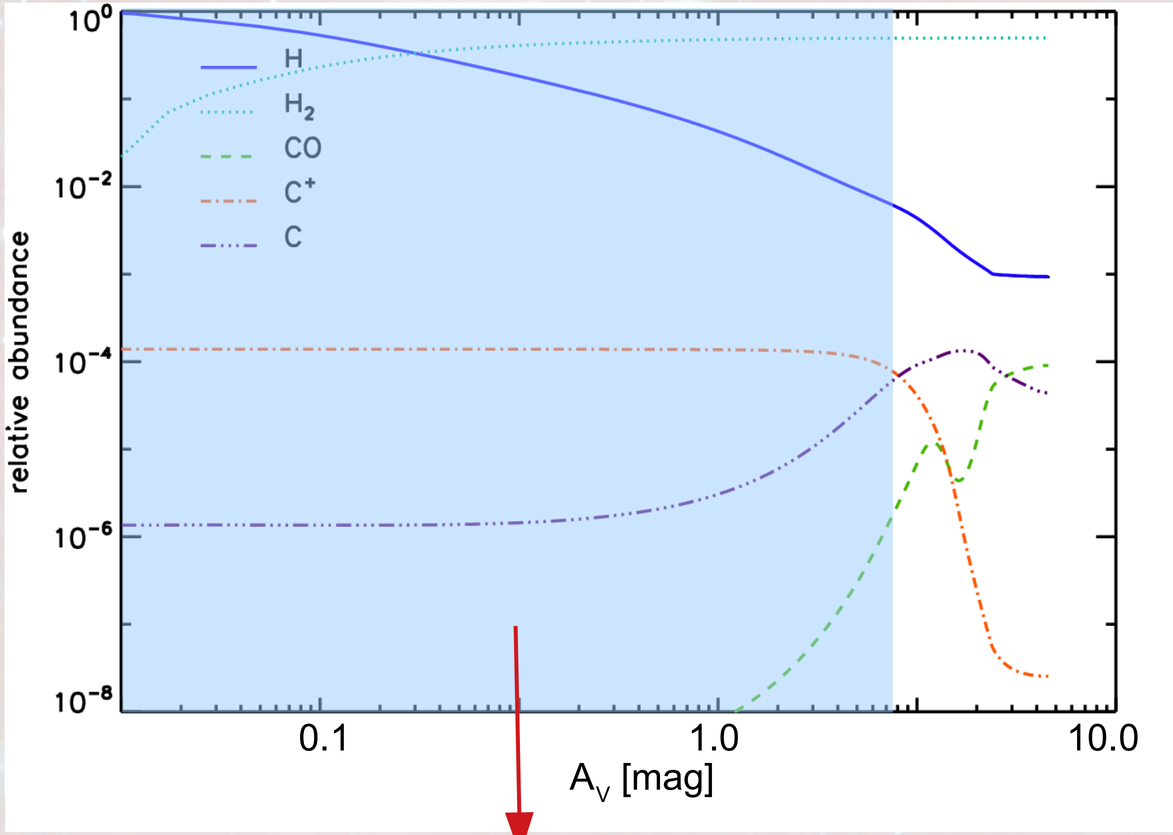


Credit: High Elevation Antarctic Telescope (HEAT) consortium, Steward Observatory, Radio Astronomy Laboratory

Theory

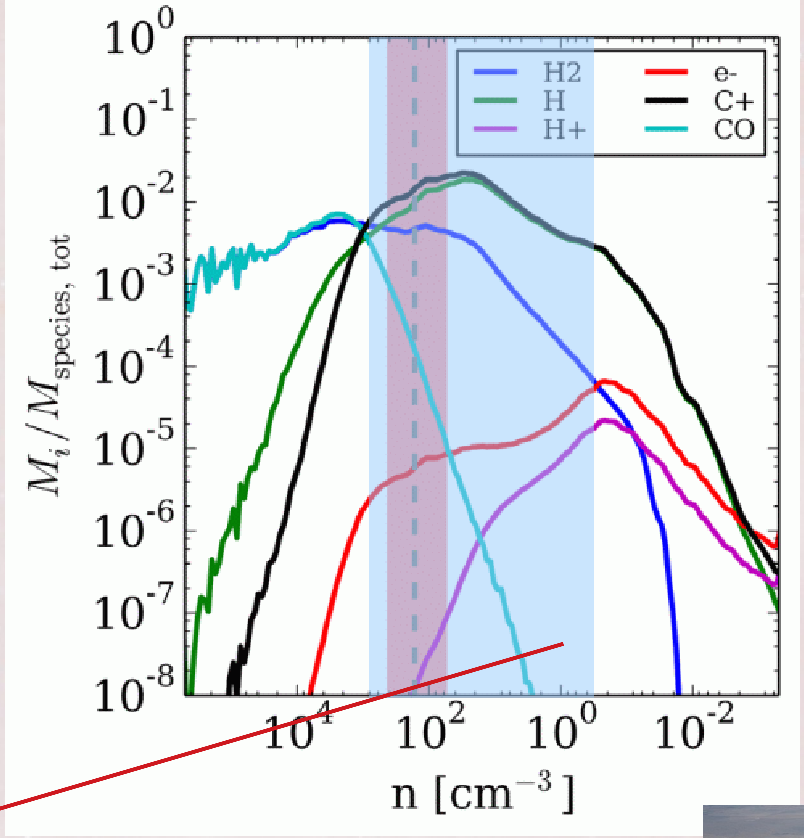
The stationary picture

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



The dynamic picture

- Cloud formation in MHD simulations:



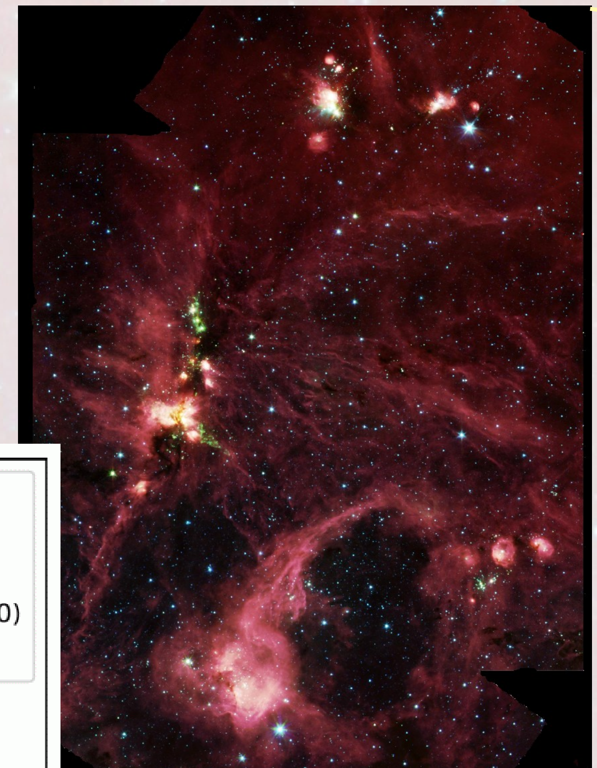
Franeck et al. (2018)

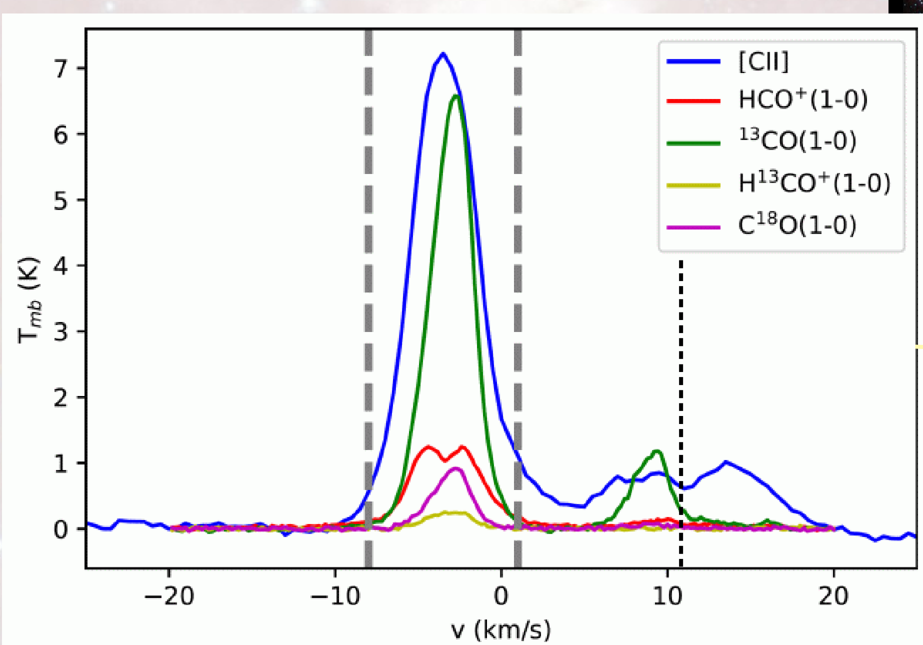
- Emission only in [CII], OH, H_2O, CH
- Absorption in HI, H_2, [OI], hydrides like HF, CH, CH^+, ArH^+, OH^+, H_2O^+

Observations

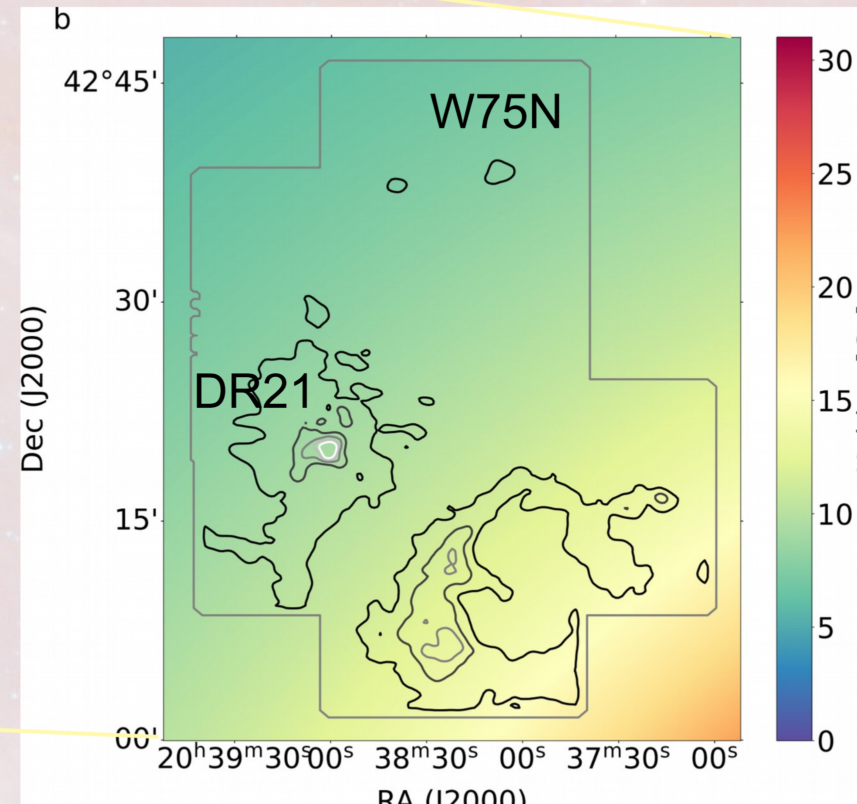
Example: Molecular cloud formation in Cygnus X

- SOFIA Legacy project FEEDBACK (PIs: N. Schneider, X. Tielens):
  - [CII] mapping around the DR21 ridge



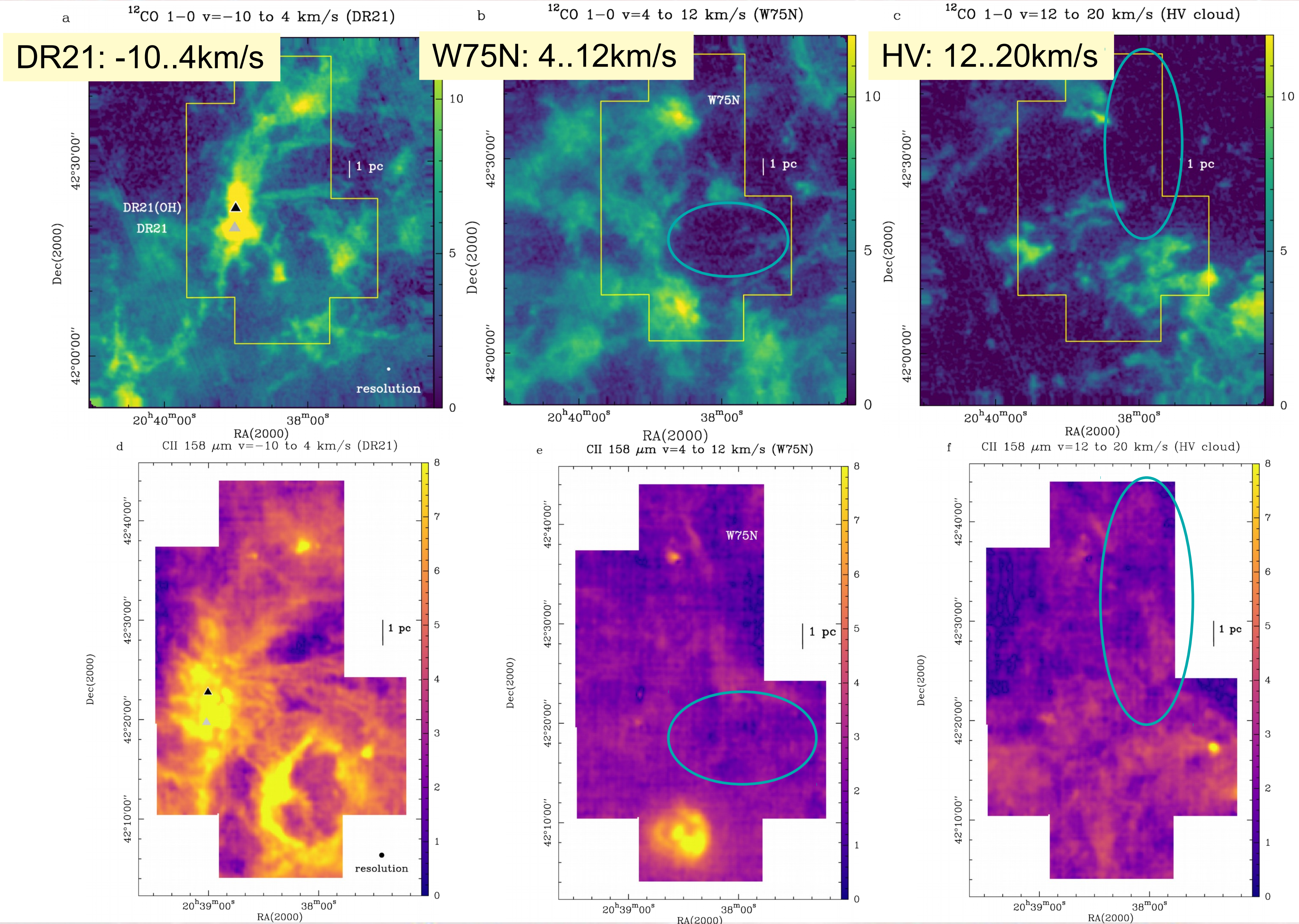


Average spectra in the central region (Bonne et al. 2022): 3 velocity ranges with different behaviour



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

Cygnus X observations



CO 1-0

[CII]

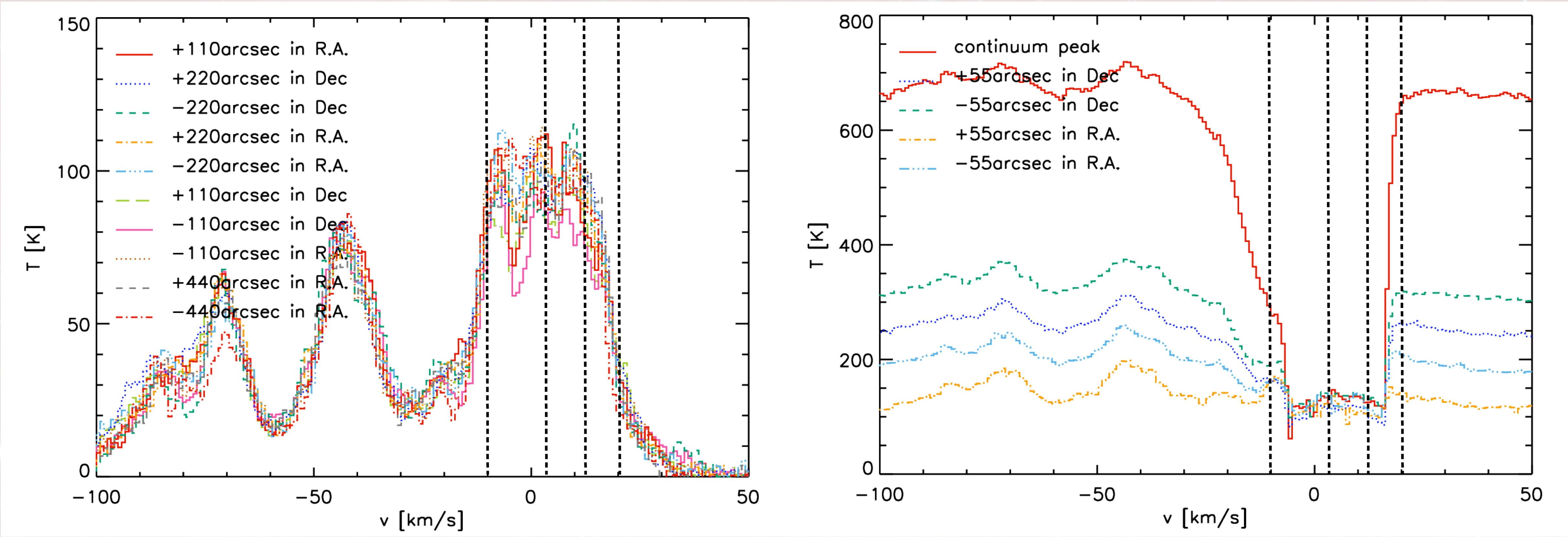
- Large regions at higher velocities that are dark in CO but filled with diffuse [CII] emission

(Schneider et al. 2023)

Compare with HI

HI gas or CO-dark H_2 gas?

- HI emission is mixture of WNM emission and CNM absorption
  - HI Self Absorption (HISA) analysis for foreground: component assignment uncertain

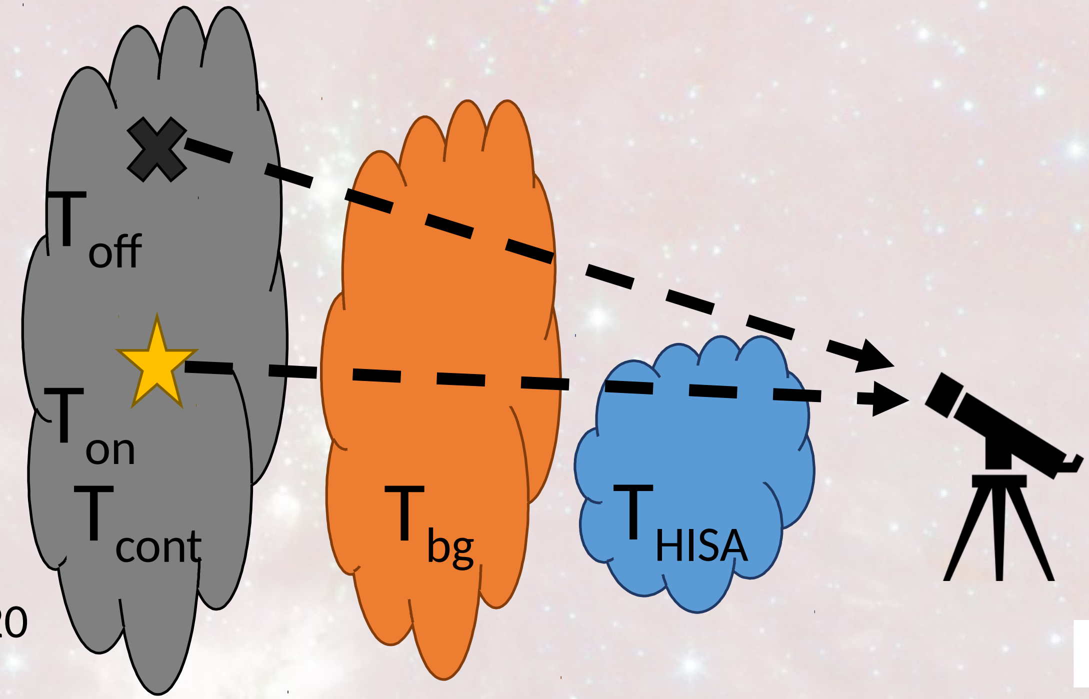


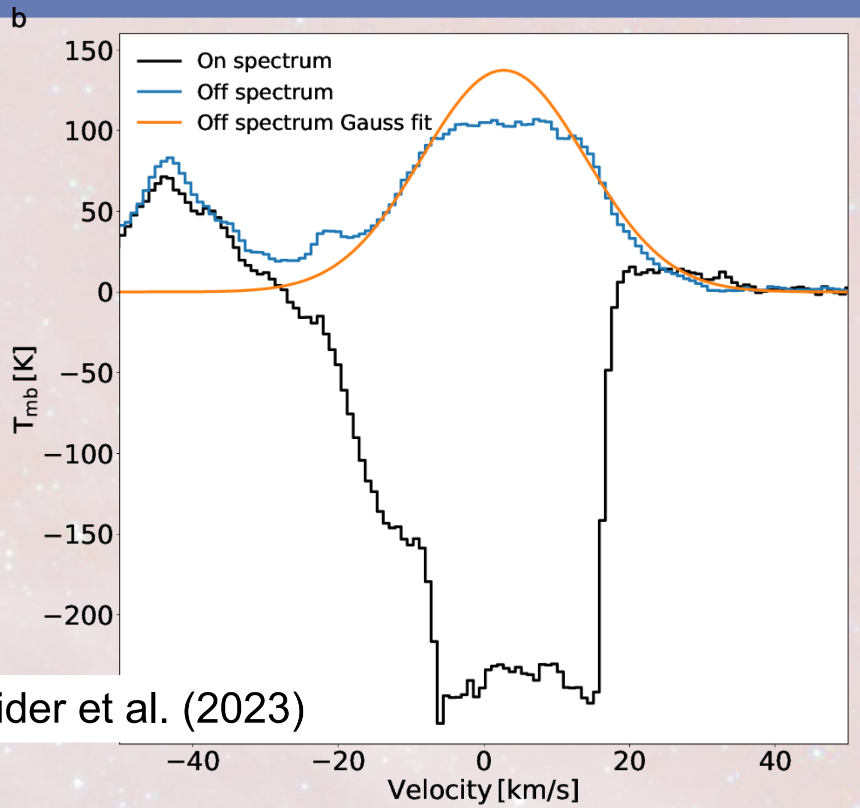
DRAO/CGPS data, resolution 1’, Taylor et al. (2003)

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

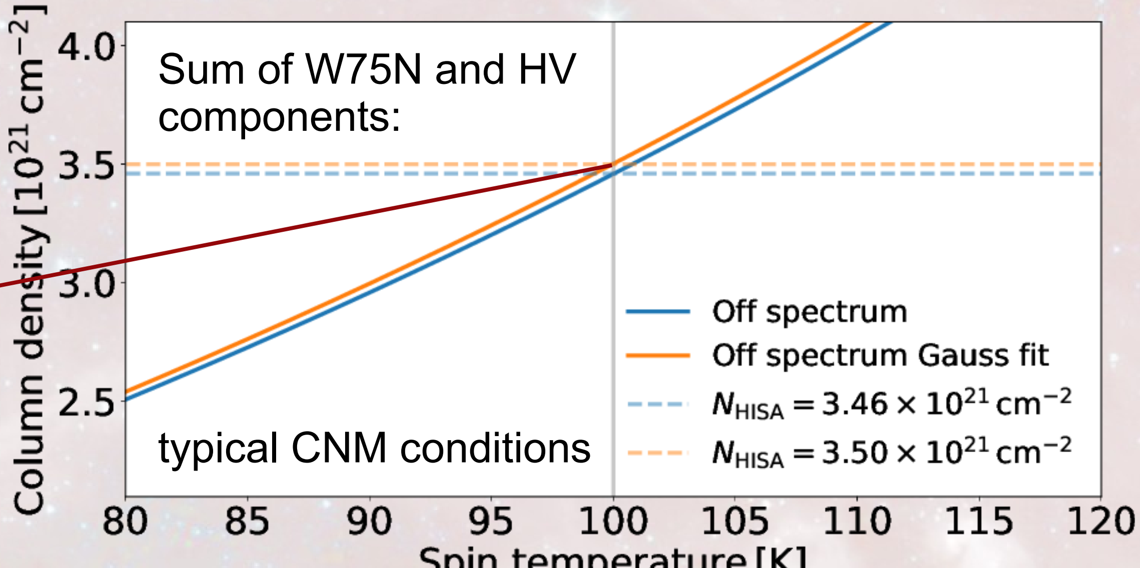
HISA (HI Self Absorption)

Analysis





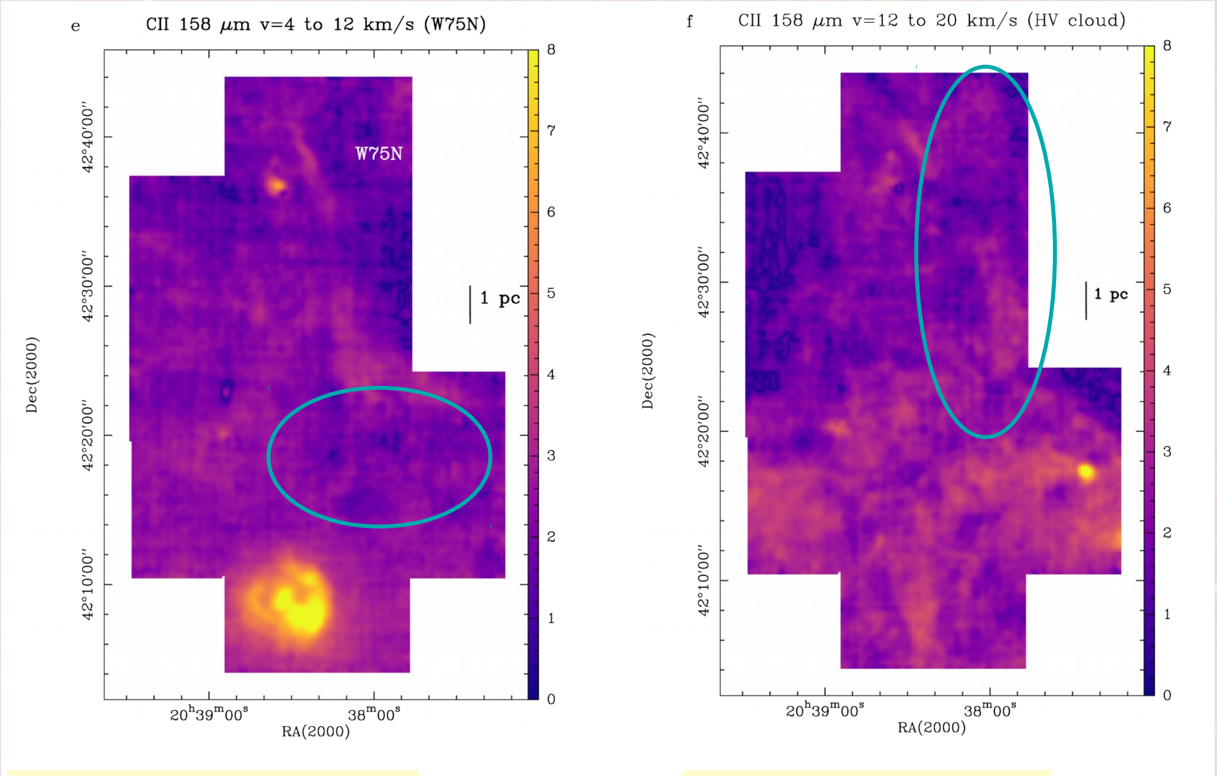
- HI foreground well constrained:
  - **3.7 × 10²¹ cm⁻²** for DR21 velocities
  - **2.0 × 10²¹ cm⁻²** for W75N
  - **1.5 × 10²¹ cm⁻²** for HV component



Properties of the [CII]-bright, CO-dark gas

Gas partly molecular

- Molecular fraction:
  - W75N: 23%
  - HV component: 14%
- Mass:
  - W75N: 7800 $M_\odot$
  - HV component: 9900 $M_\odot$
  - Compare DR21 ridge: 15000 $M_\odot$



W75N: 4..12km/s

HV: 12..20km/s

- Falling towards the DR21 ridge:
  - accretion time: 1 Mio a
  - conversion time H→ H_2: 10 Mio a
  - n ~ 100 cm^{-3}, T_{kin} ~ 100K

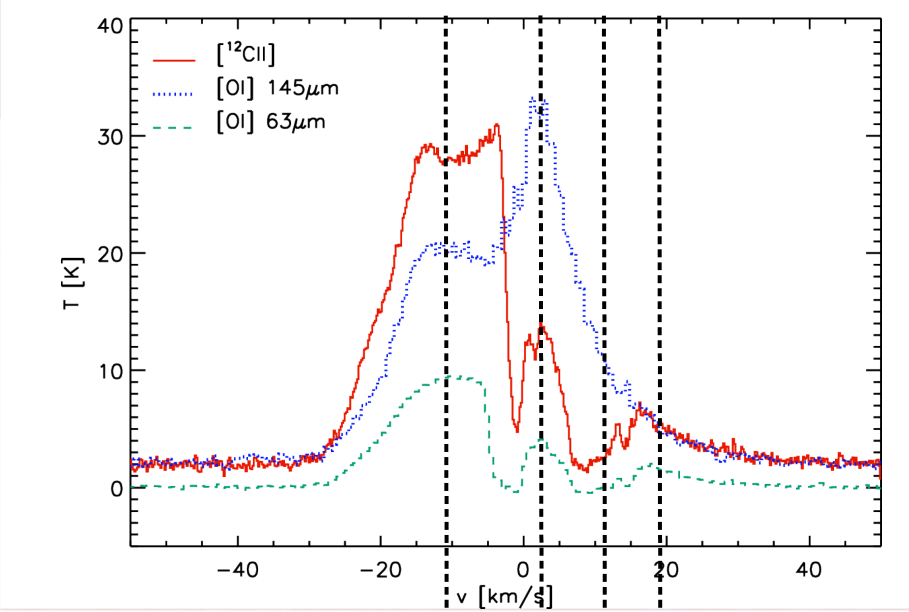
Schneider et al. (2023)

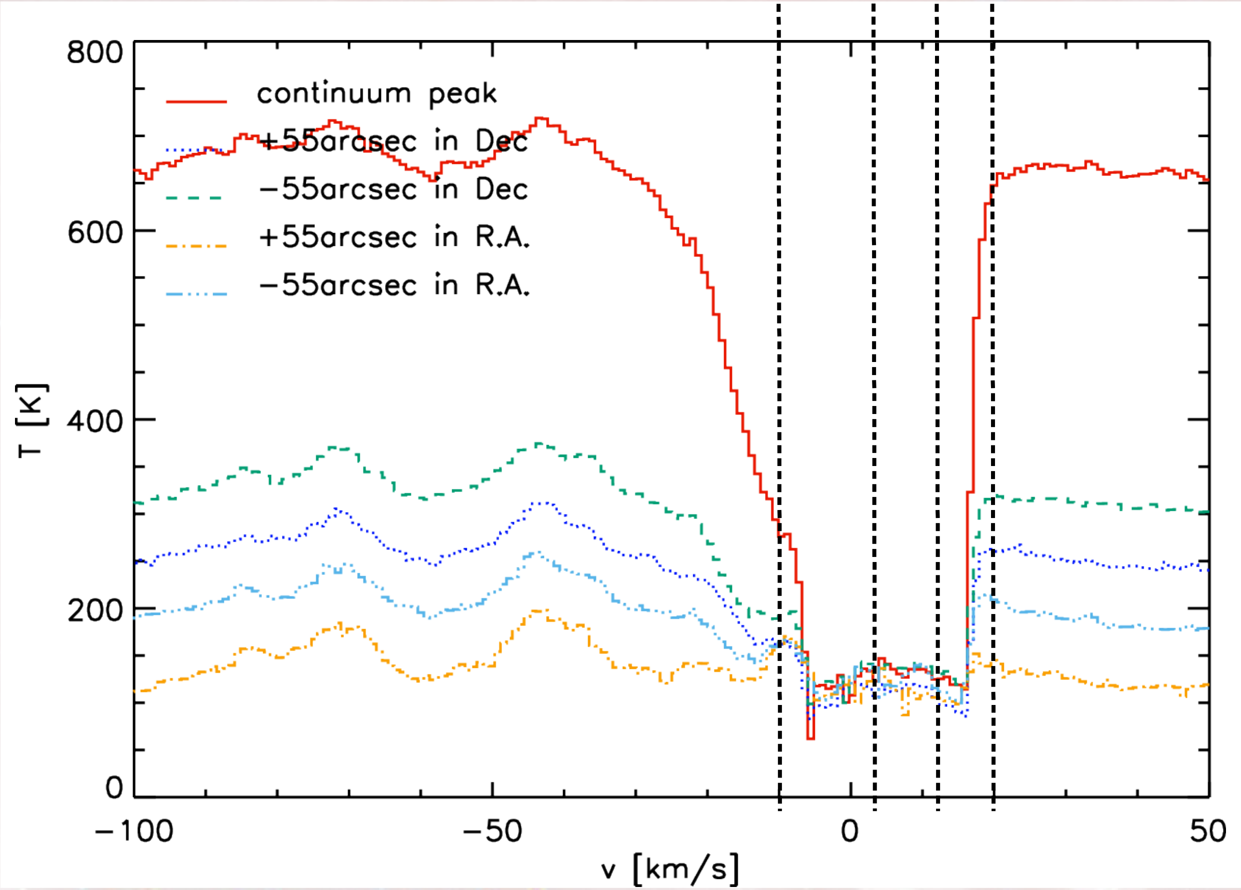
[CII]-dark, CO-dark, HI-dark gas

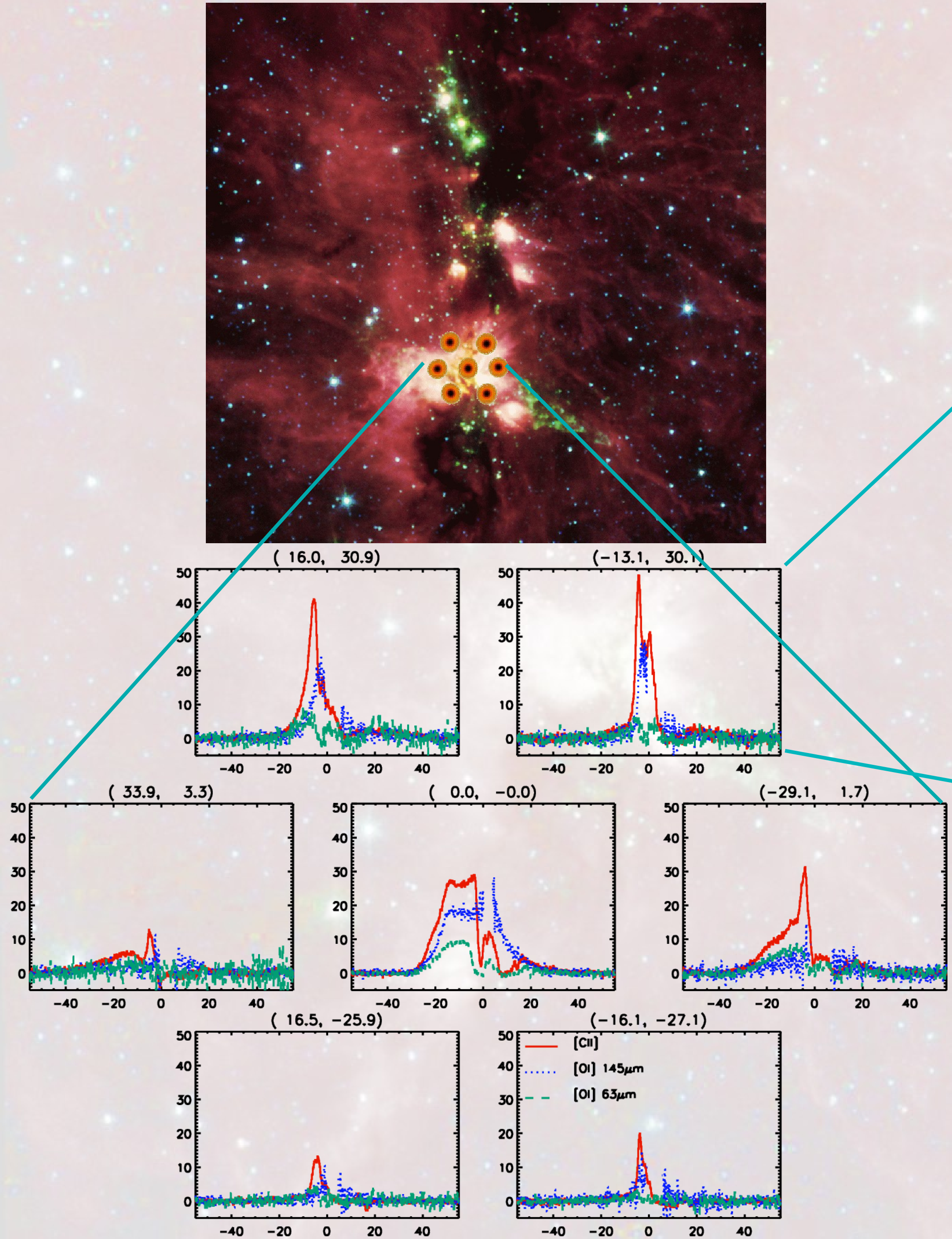
Gas < 50K only seen in absorption!

- 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

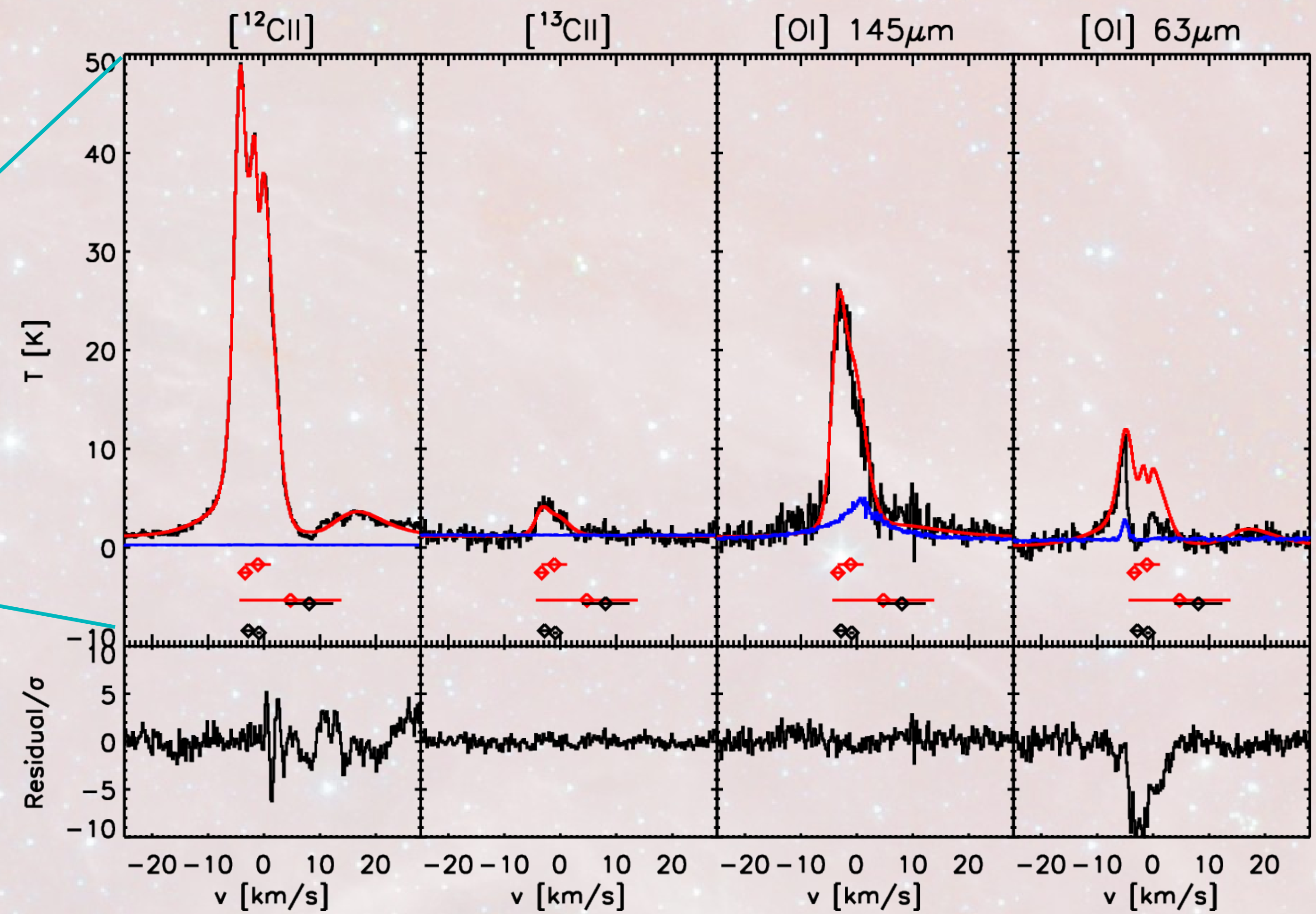






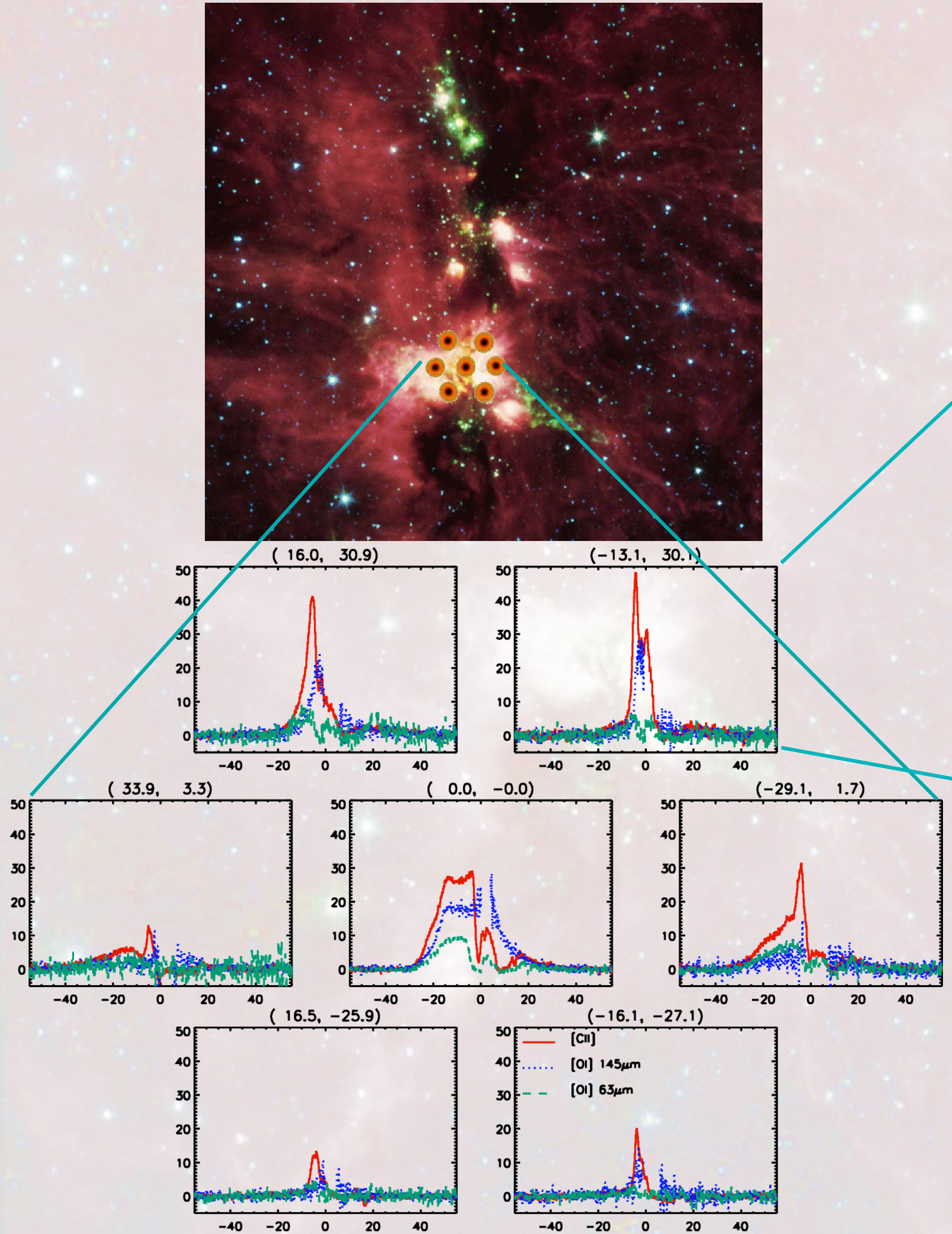
The perfect case

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



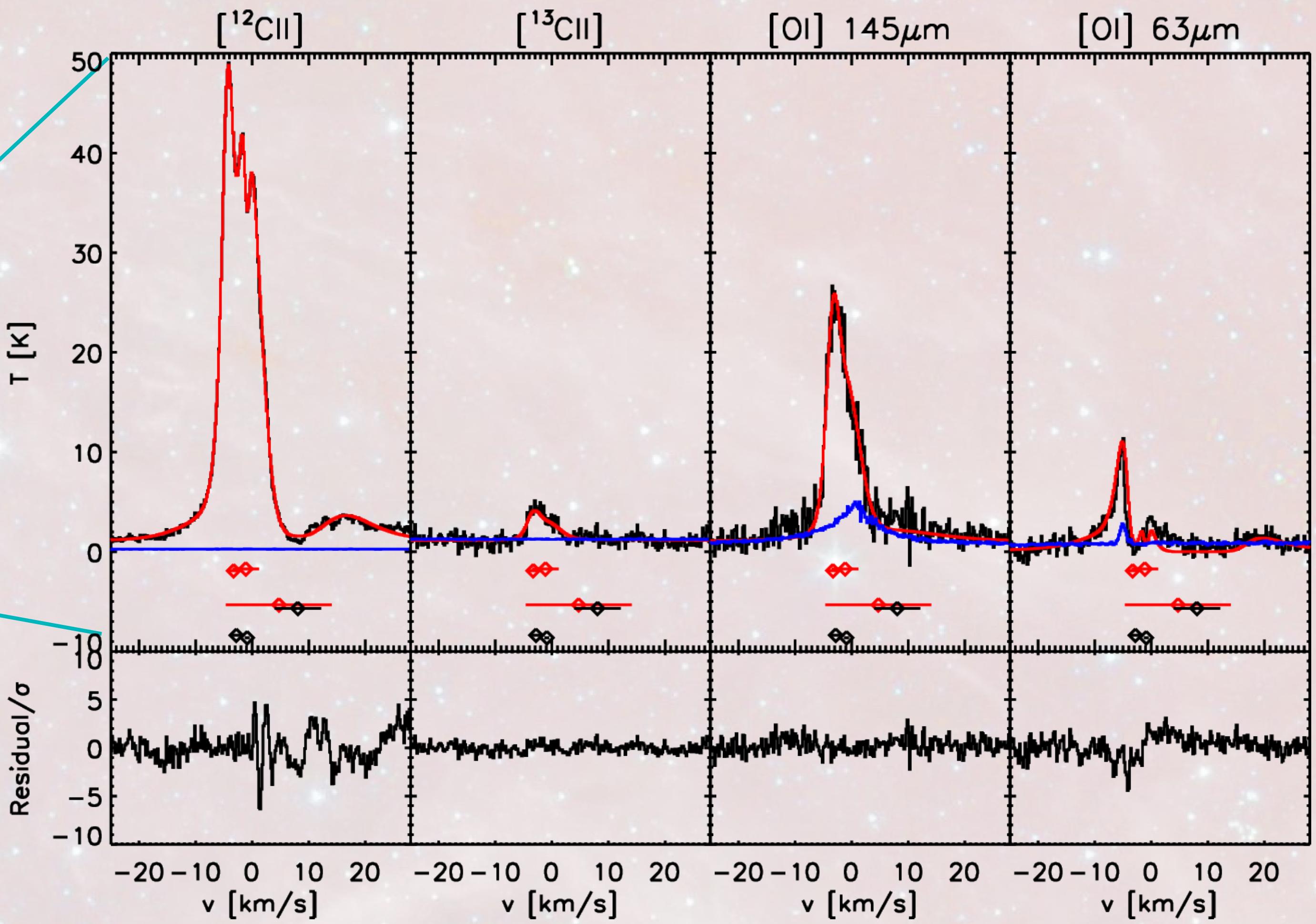
- [OI] 63µm line not well fitted by abundance given by [CII]. Needs more cold atomic oxygen in foreground.

Example 1: Pixel 3



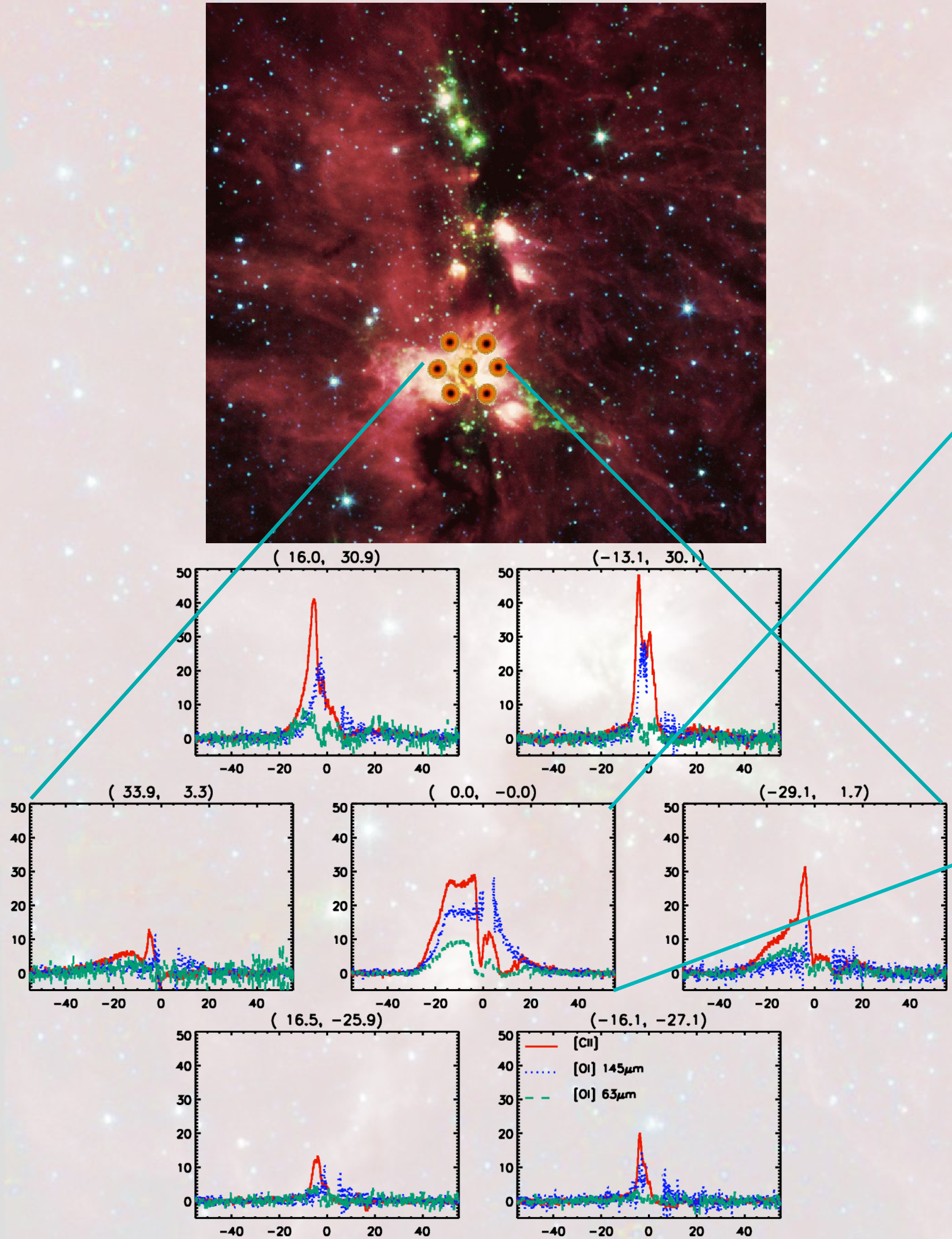
The perfect case

- Common fit of all lines with 3+3 Gaussians



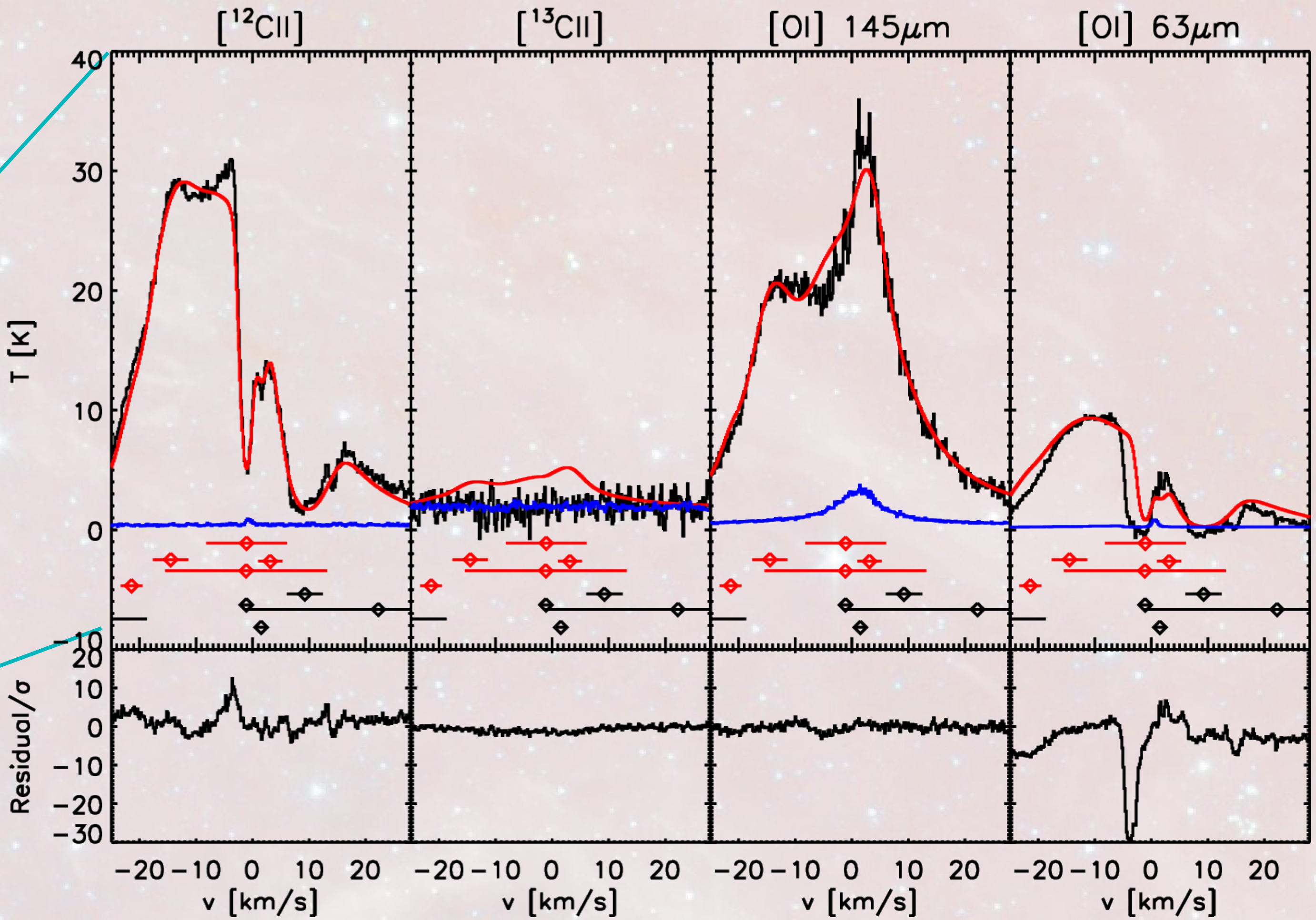
- [OI] 63μm line not well fitted by abundance given by [CII]. Needs more cold atomic oxygen in foreground.

Example 2: Pixel 0



The worst case

- Outflows from the source in [CII], [^{13}CII] hidden

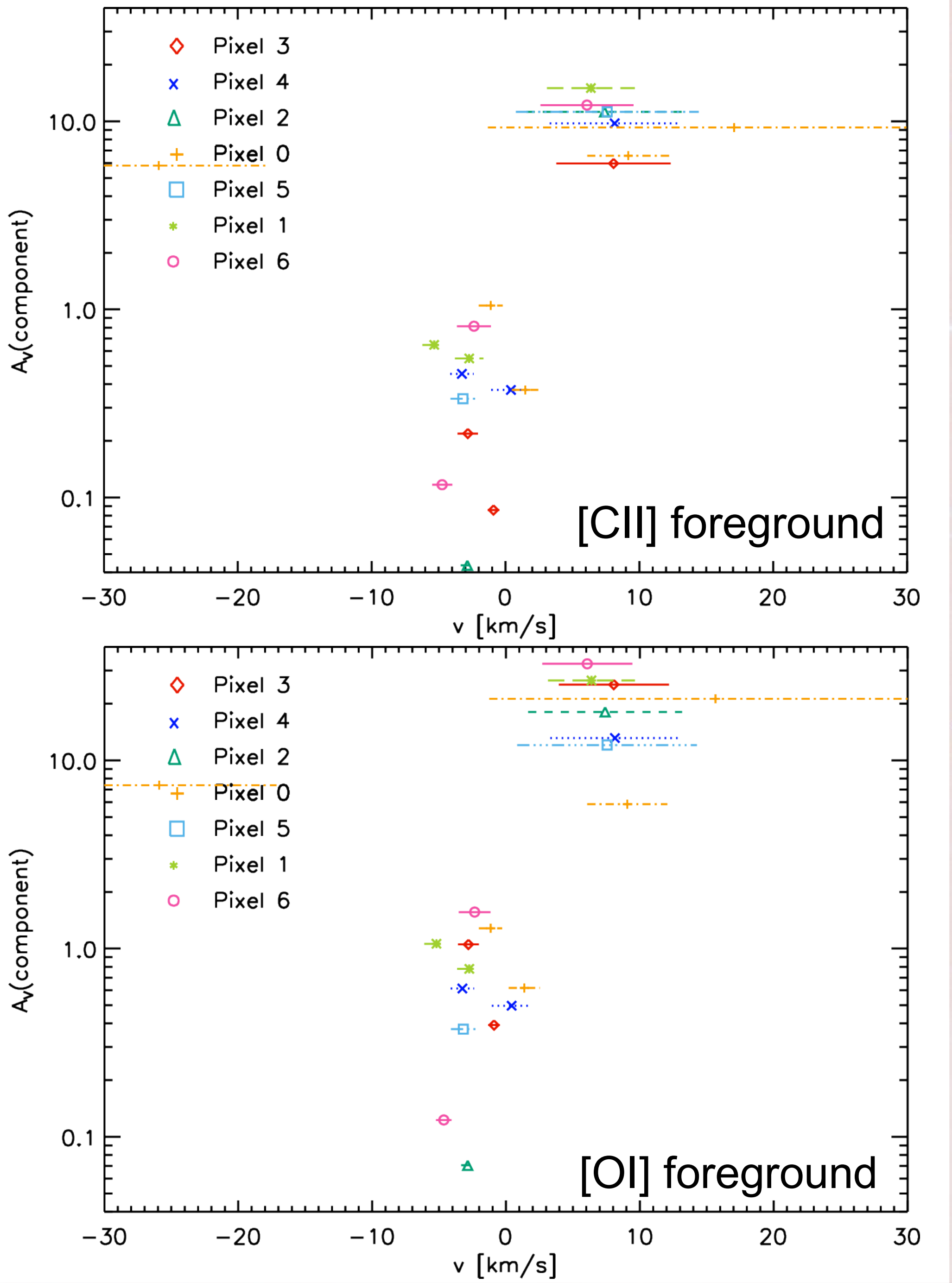


- Outflows require more components.
- Same fore- and background components still present.

Commonality

Similar foreground component at 8km/s

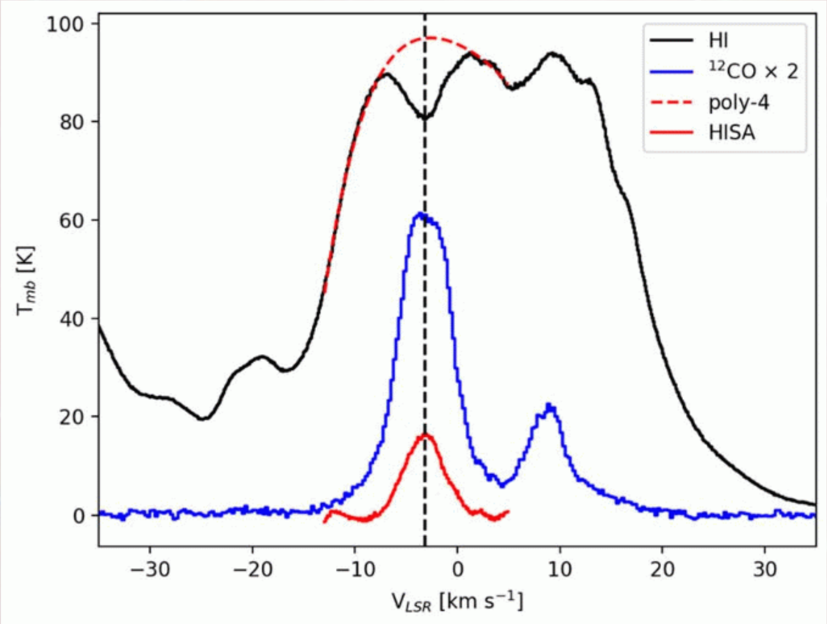
- **Common foreground: $N_H \sim 15 \times 10^{21}$ cm^{-2}**
  - even higher by factor ~2 when oxygen absorption needed
- Background instead strongly variable from pixel to pixel
- Local foreground at -2km/s also strongly variable



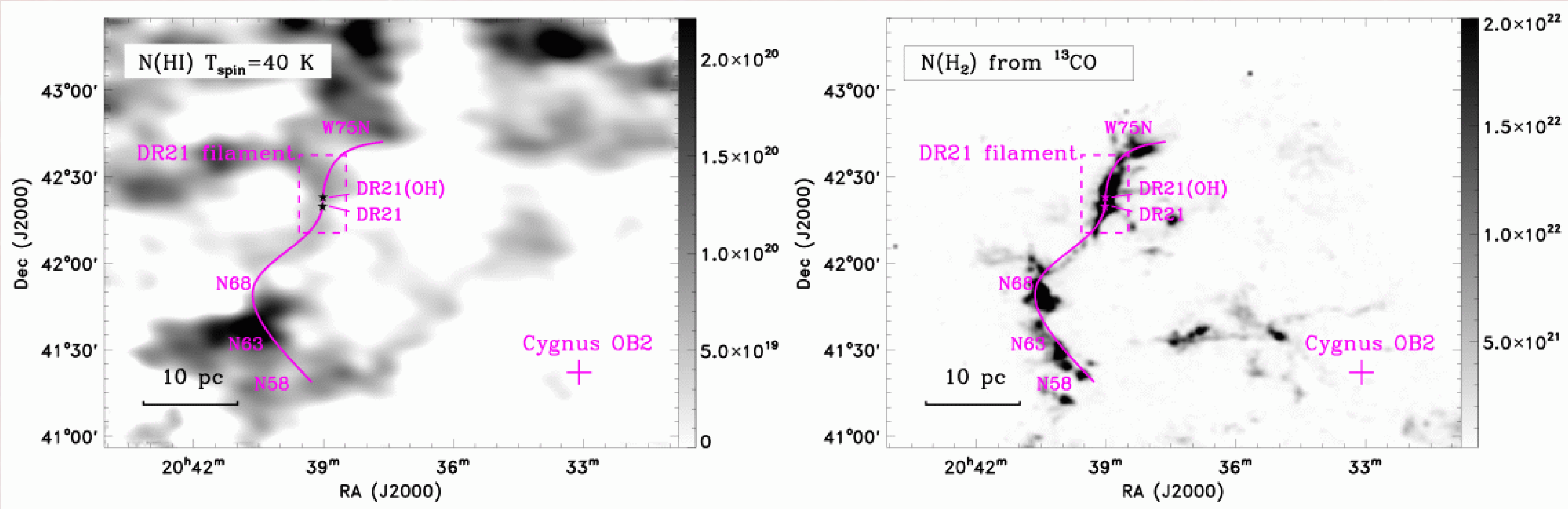
New results: FAST mapping of HISA (HI Self Absorption)

Li et al. (2023):

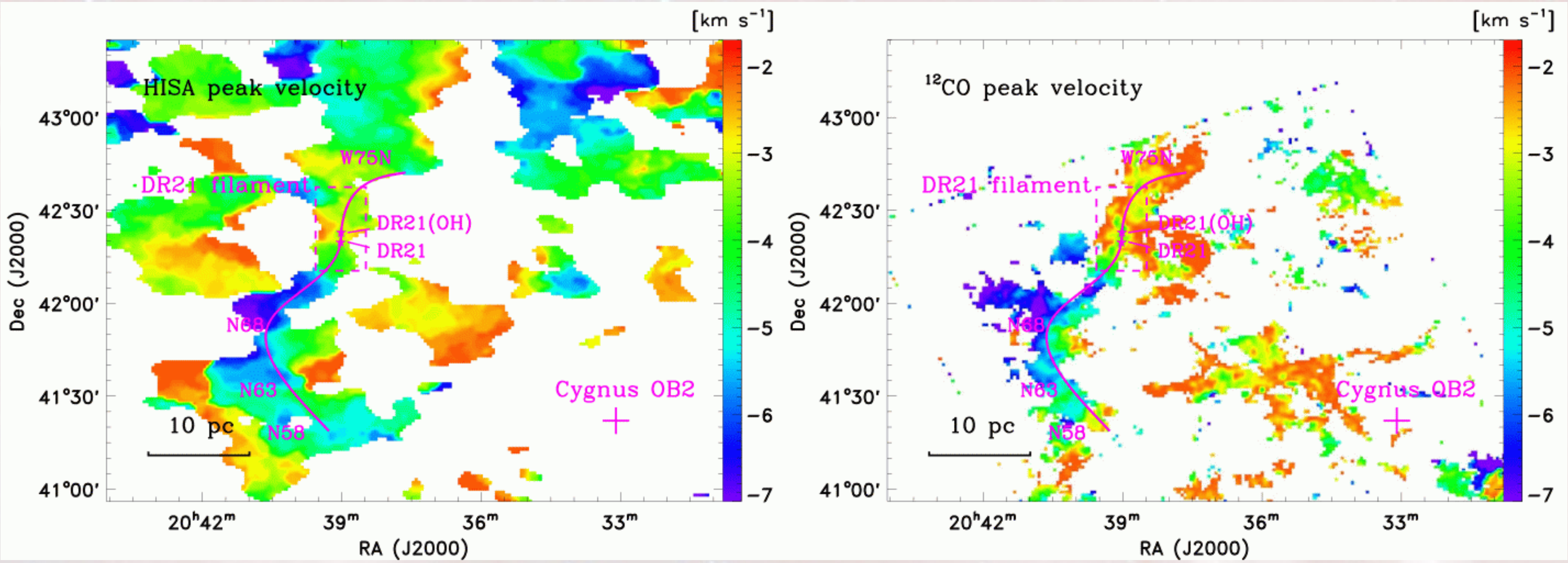
- Large-scale mapping:
  (resolution 3')



- Velocity structure of HISA proves association to molecular gas



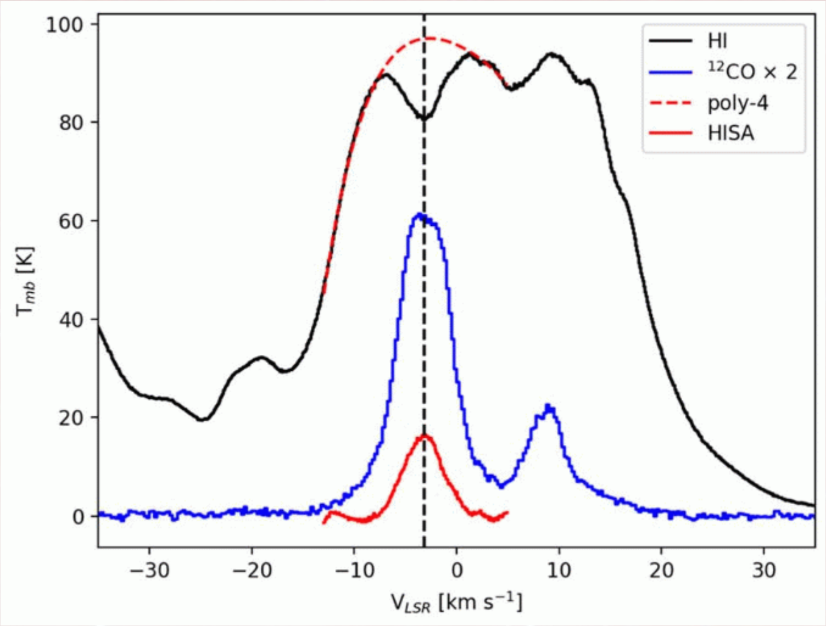
Column of HI:
- 10^{20} – 3×10^{20} cm^{-2}; density ~ 20 cm^{-3}
- much lower than molecular gas, but more extended

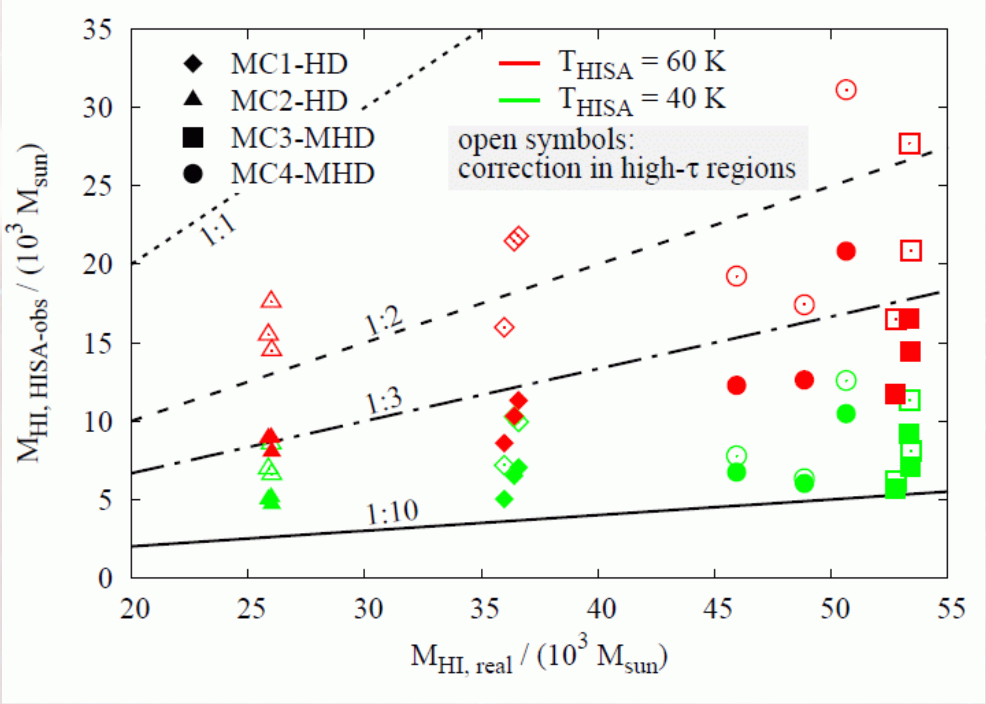


HISA (HI Self Absorption)

Problems

- Analysis always suffers from uncertain emission baseline:
- Possible mixing with some WNM along the LOS
- Excitation temperature basically unknown
  - No reliable quantitative assessment of cold atomic gas from HISA possible:



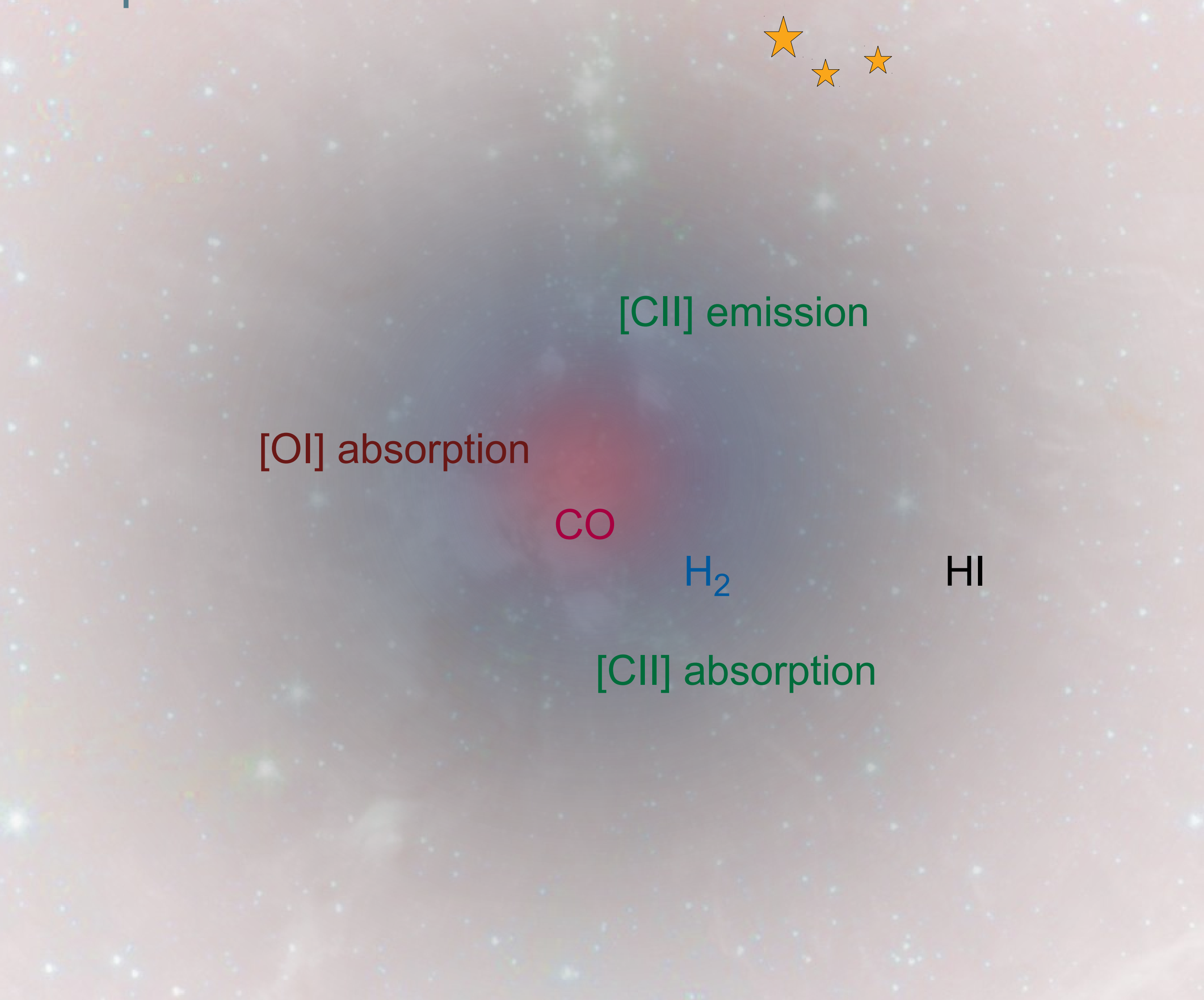


HISA systematically underestimates the amount of cold HI by factors > 2, typically rather 5-10 (Seifried et al. 2021)

- HI columns from HISA are usually lower limits

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 CO emission or absorption?

Summary

- **There are no Molecular Clouds!**
  - 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 of obtaining any reliable star-formation efficiency