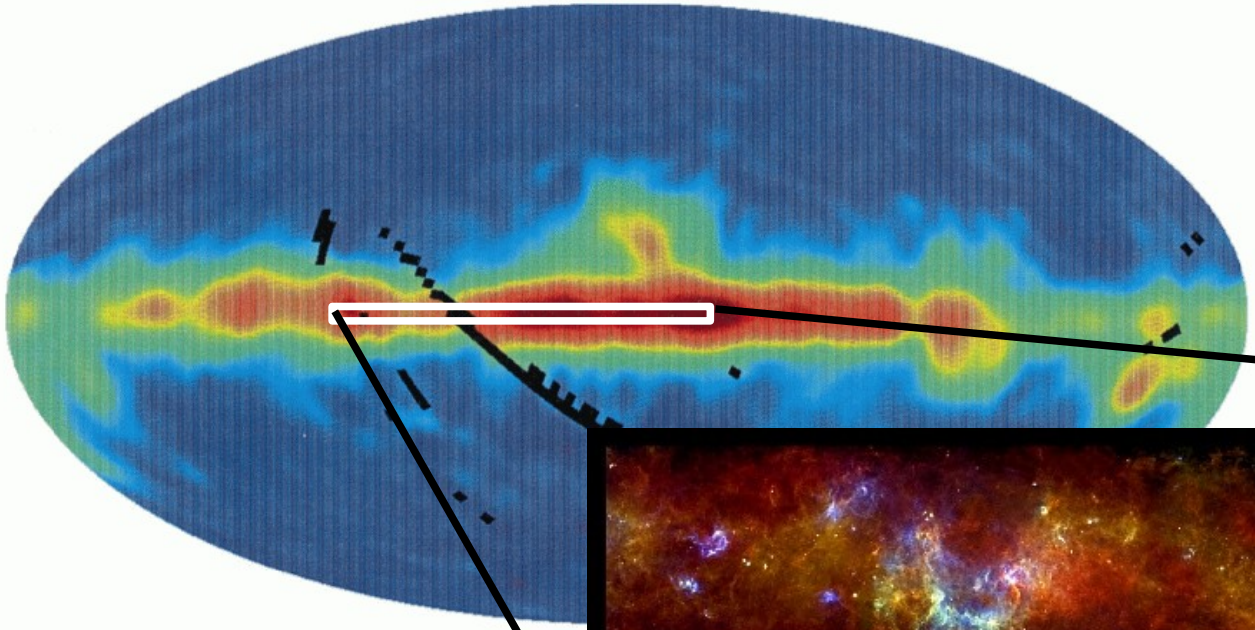
The need for FIR heterodyne observations to understand the Milky Way interstellar medium



COBE: Fixsen et al. (1999)

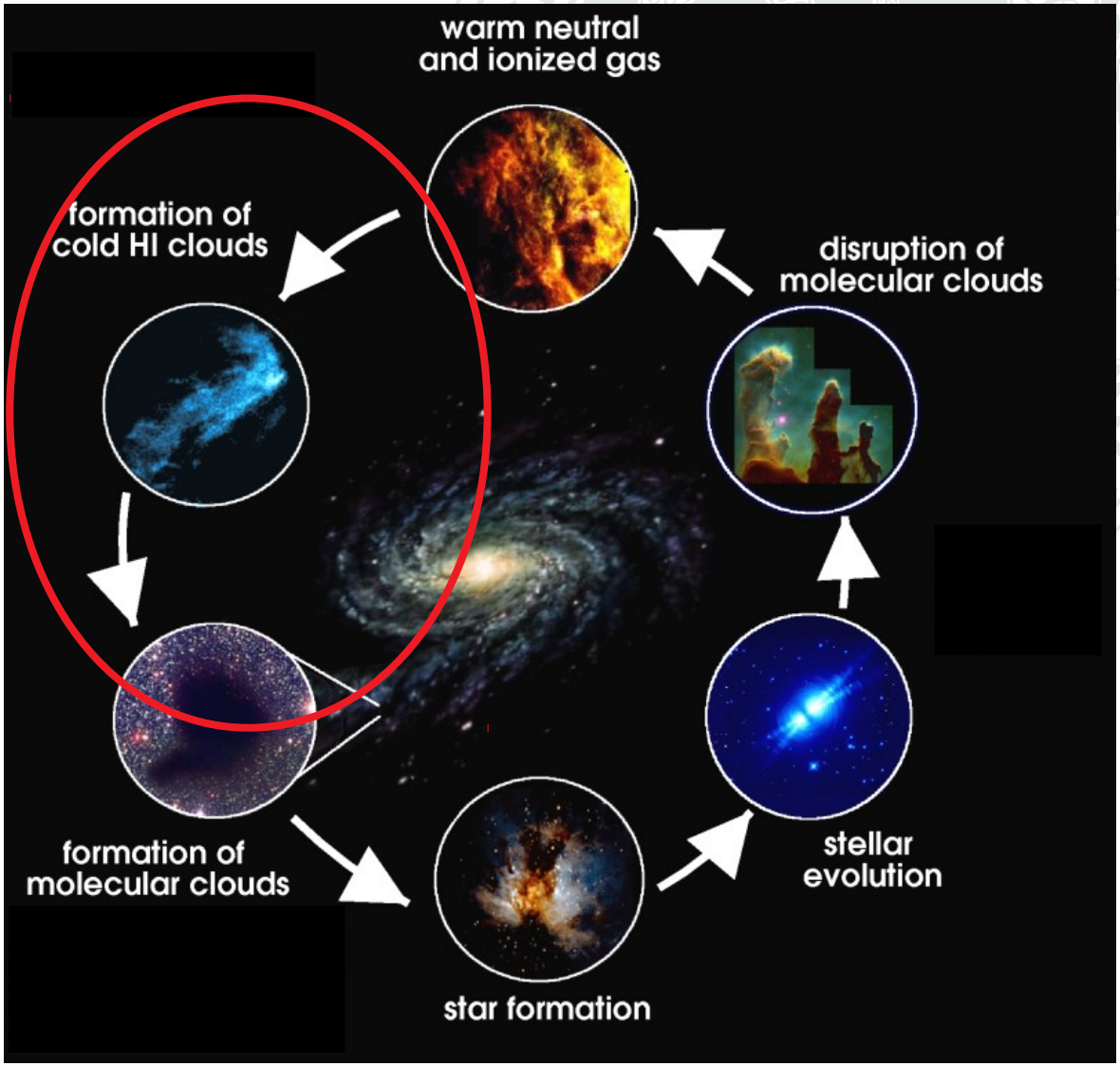
HiGal: Molinari et al. (2016)

Volker Ossenkopf-Okada

Universität zu Köln, I. Physikalisches Institut

Assembly of the Galactic ISM and molecular clouds

- The life cycle of matter in galaxies:
  - Transition from WNM to molecular clouds hardly observationally constrained
    - HI only in absorption
    - Large fraction of H_2 not traced by CO
  - Covers large fraction of the ISM in the Milky Way
  - Determines the turbulent cascade down to the star-formation

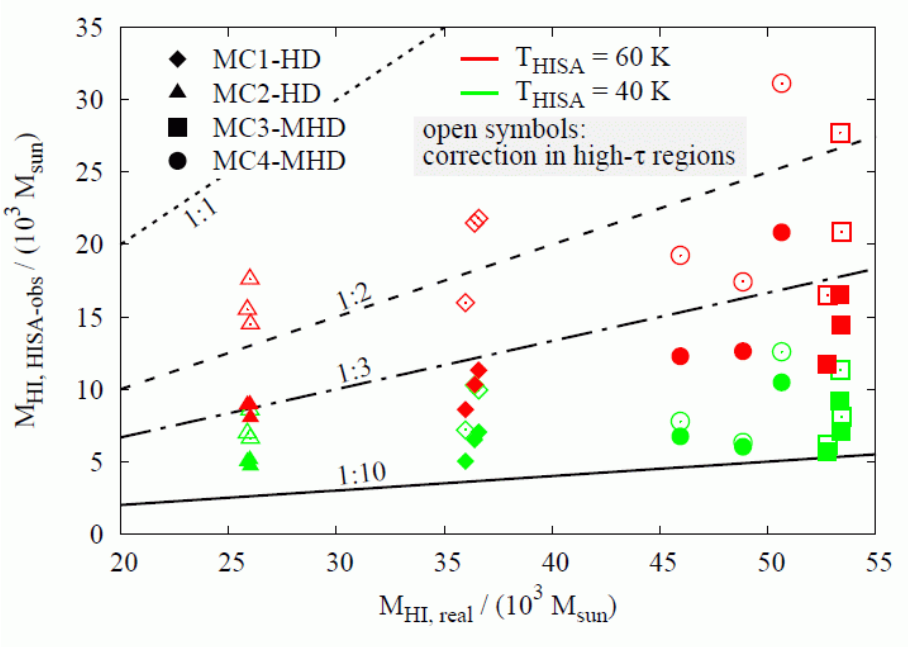


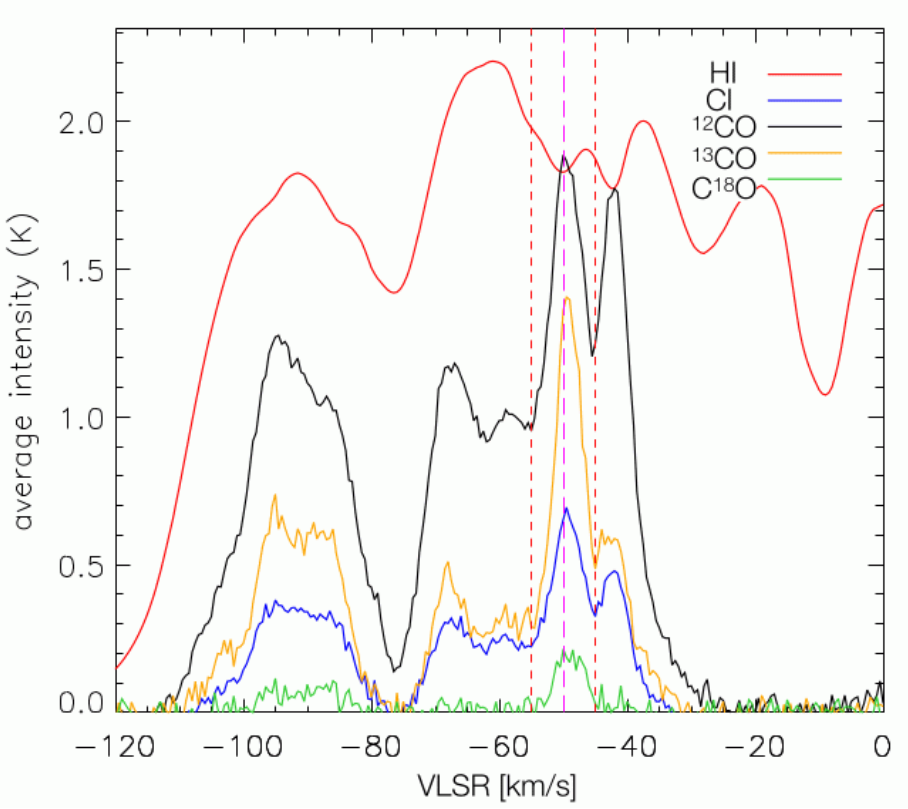
Credit: High Elevation Antarctic Telescope (HEAT) consortium, Steward Observatory, Radio Astronomy Laboratory

Typical observation

HI-Self-Absorption (HISA)

- Correlation to molecular tracers proves transition from HI to H_2:
- But no reliable quantitative assessment of cold atomic gas from HISA possible:





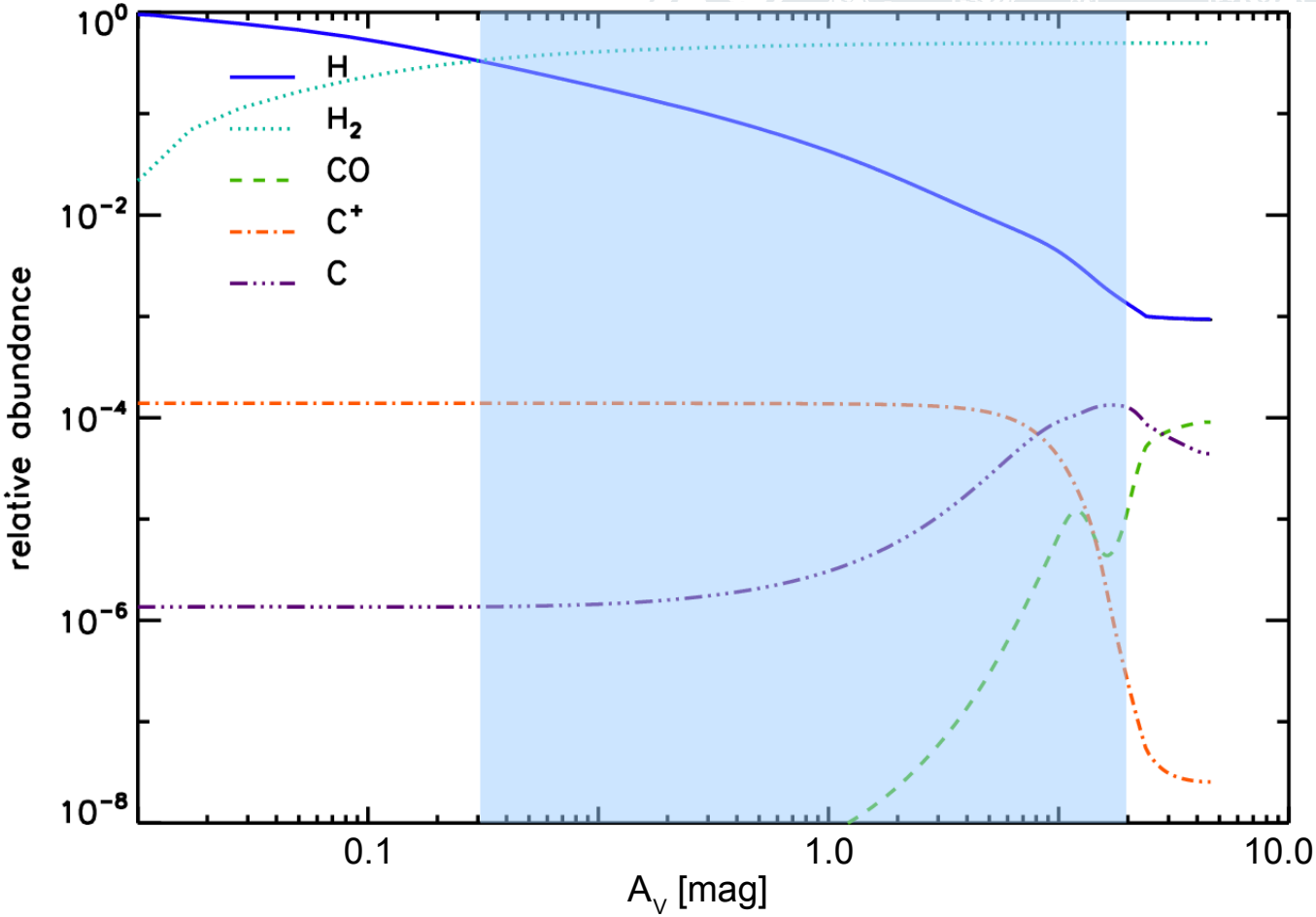
Romano et al. (2019), Galactic Ring at l=332°

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

- Further complication: CO-dark molecular material

The stationary picture

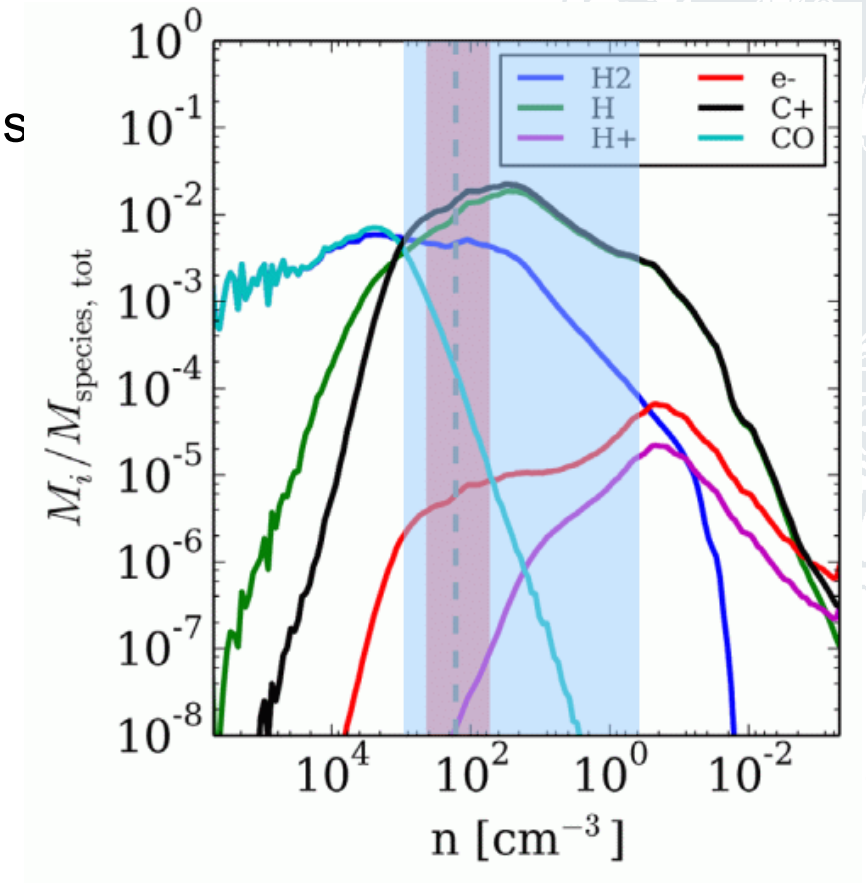
- PDR model for χ=1, n=10^3 cm^{-3}:



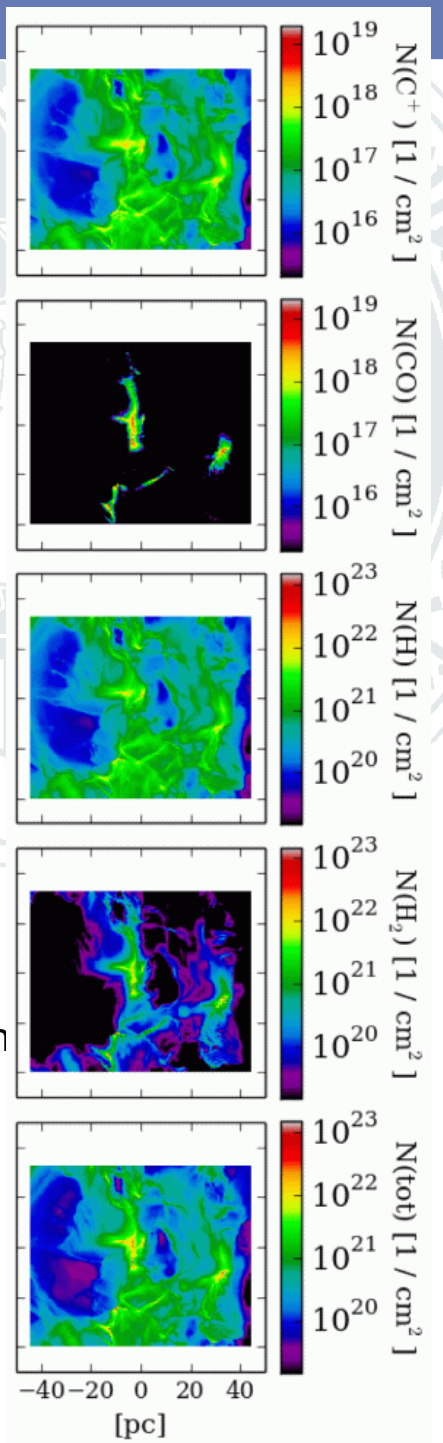
- Large fraction of H_2 not traced by CO
- Visible in [CII] , [OI], (HF, CH, CH^+)
  - [OI] throughout the whole cloud → temperature and density tracer

The dynamic picture

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



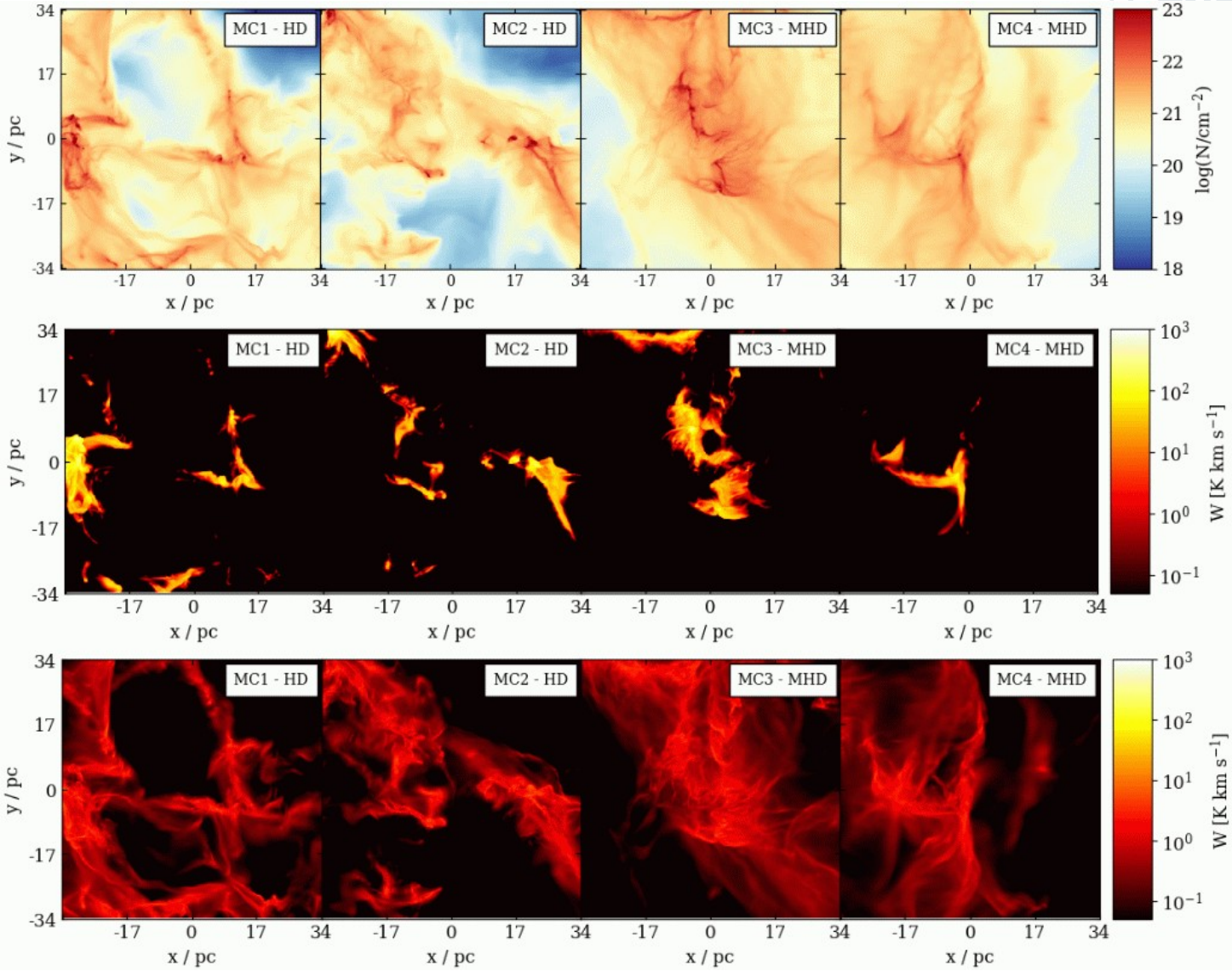
an



Franeck et al. (2018)
based on SILCC simulations
(talk of S. Walch)

The dynamic picture

- Formation of molecular clouds in MHD simulations:



Total gas column density

^{12}CO $(1 \rightarrow 0)$ integrated intensity

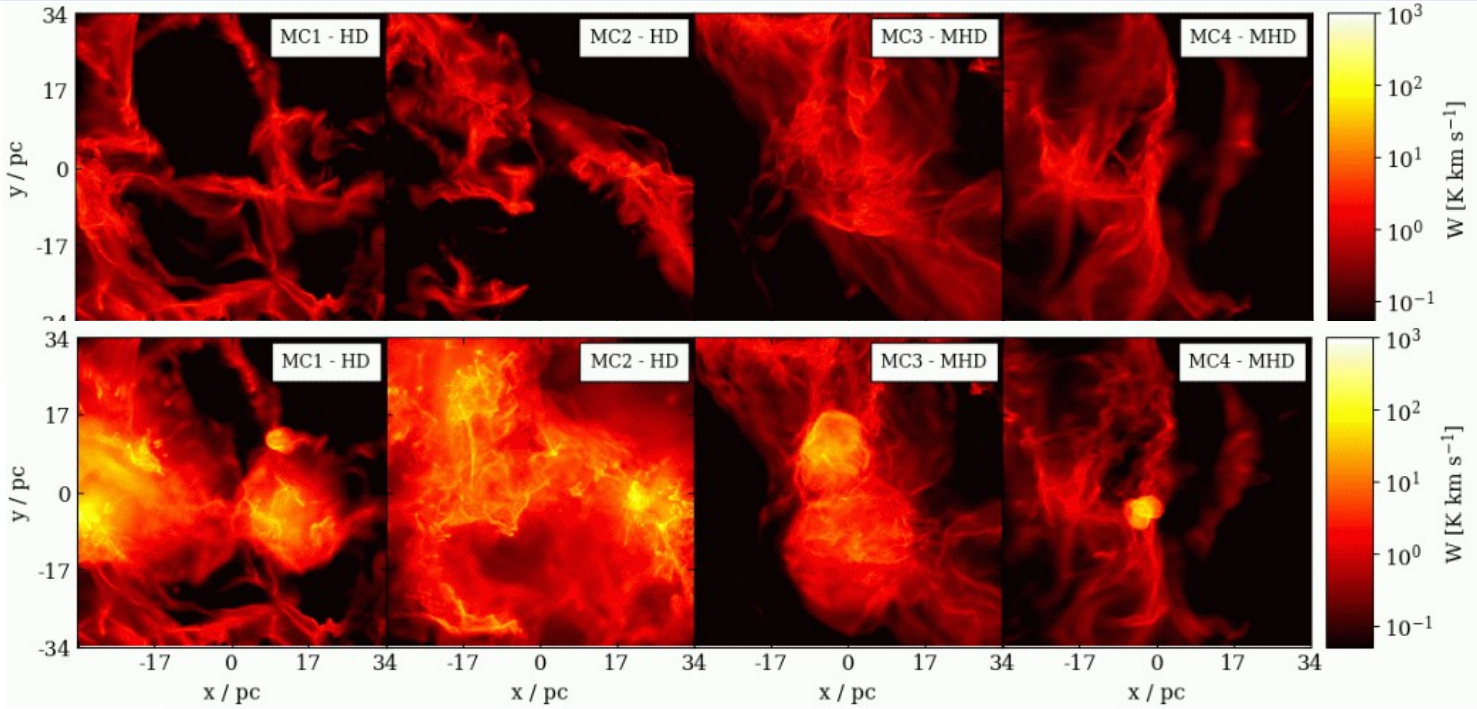
[CII] integrated intensity

Ebagezio et al. (in prep.)

Practical problem in interpretation [CII] observations

- Excitation:
  - With stellar feedback the PDRs created by the UV radiation dominate the [CII] intensity

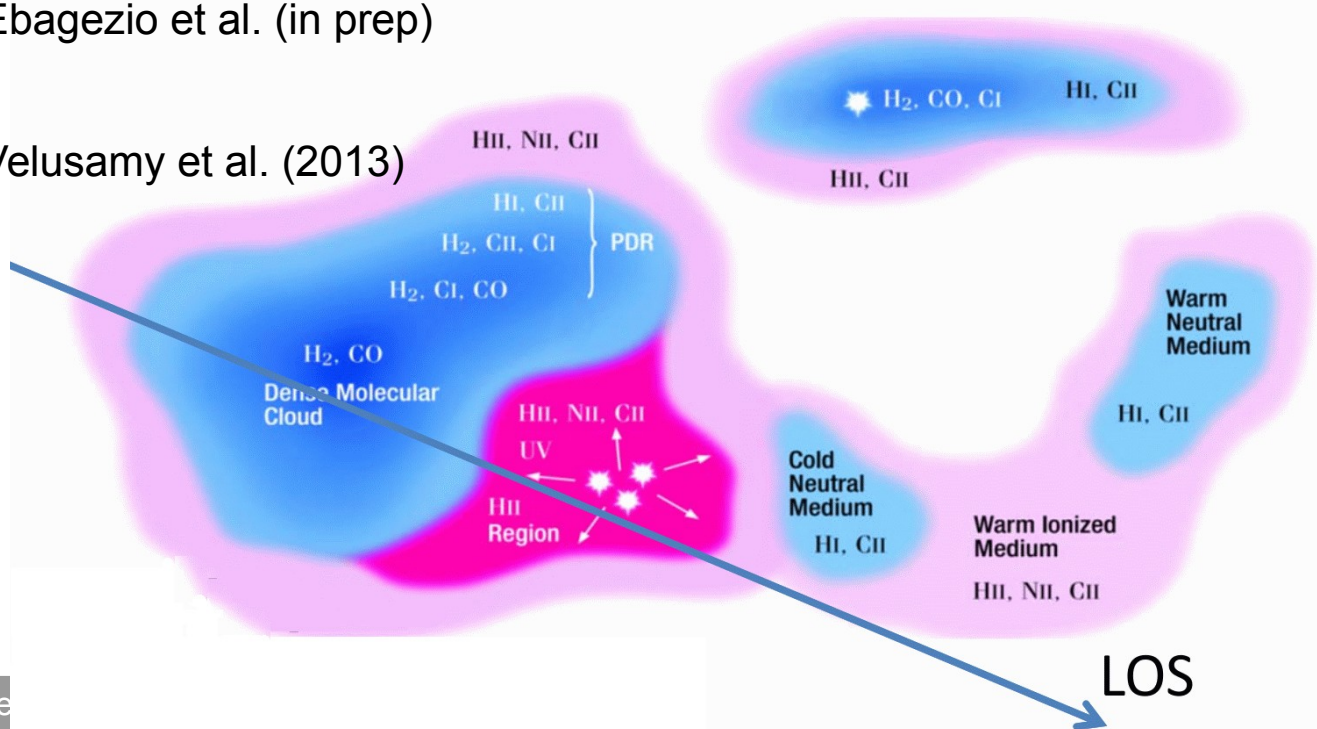
→ Feedback tracer, not dark-gas tracer



Ebagezio et al. (in prep)

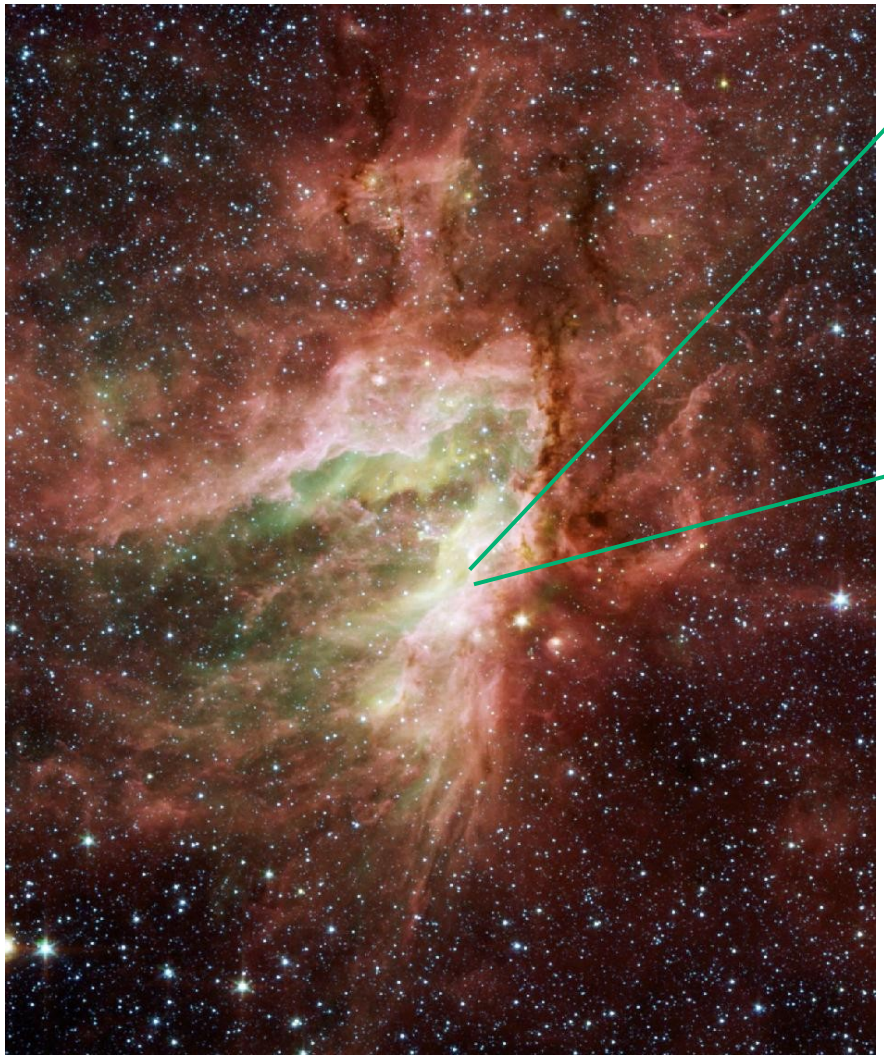
- In general
  - Complex configuration with mixture of phases
  - [CII] from PDRs and HII regions
  - Partially separated in velocity space

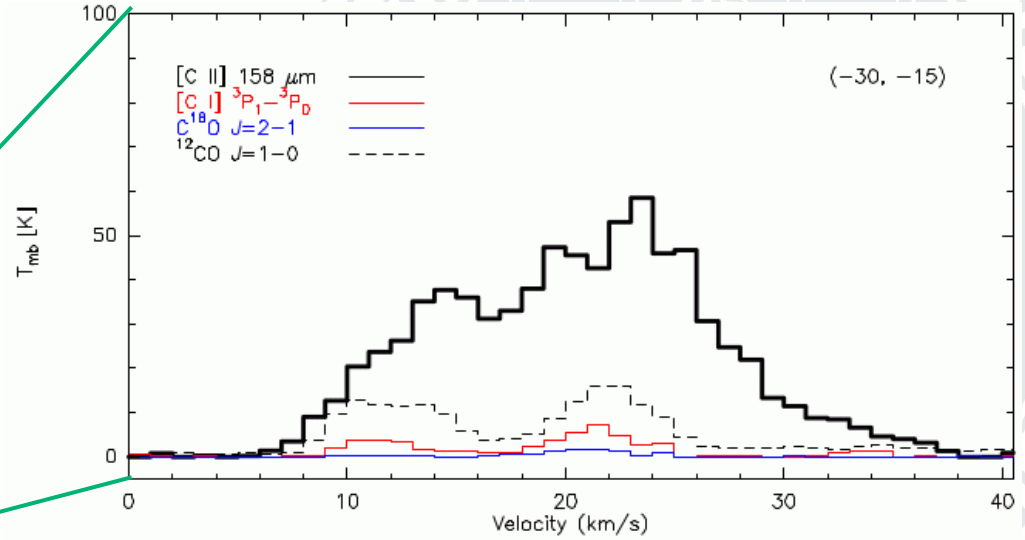
Velusamy et al. (2013)

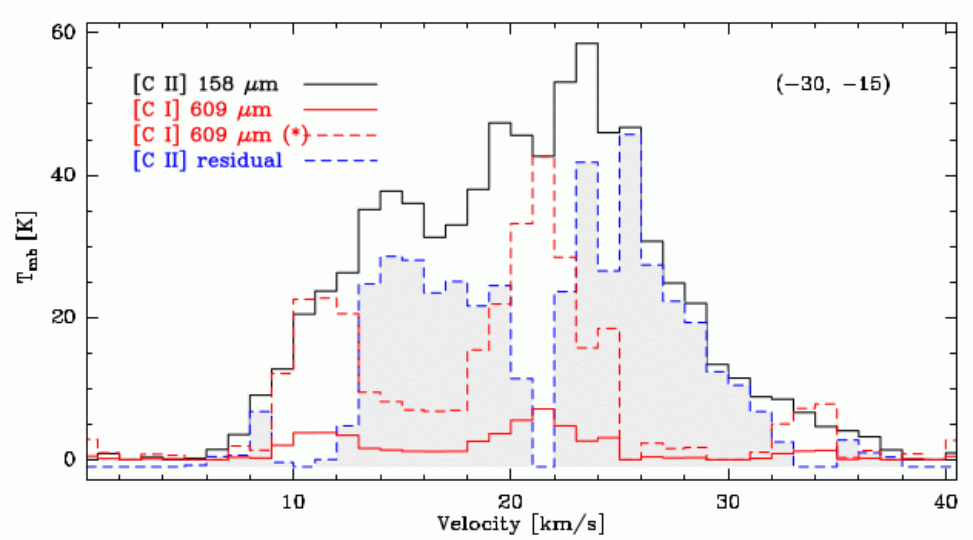


Example M17SW

- Early SOFIA [CII] observations





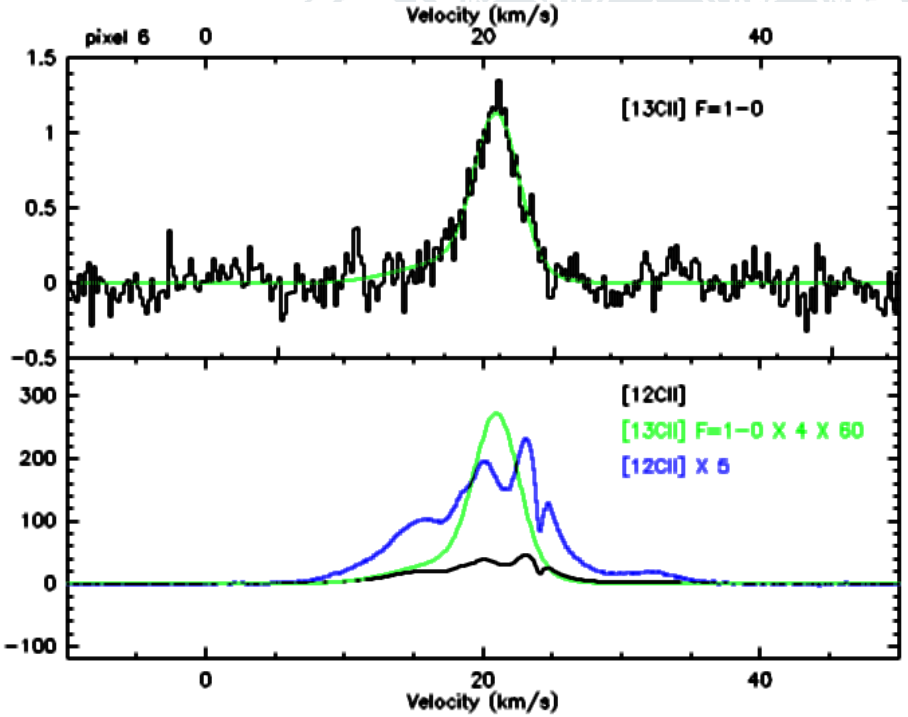


Perez-Beaupuits et al. (2012, 2015)

- Interpretation as superposition of emission from different components

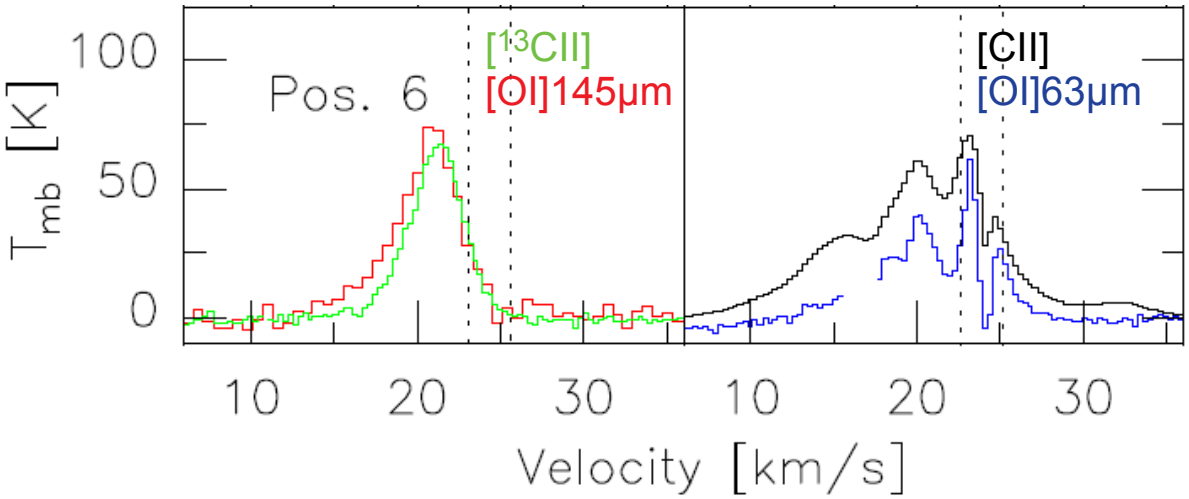
A closer look

- [^{13}CII]
  - Complex [CII] spectrum mainly created by foreground absorption



Guevara et al. (2019)

- [OI] 63µm and 145µm



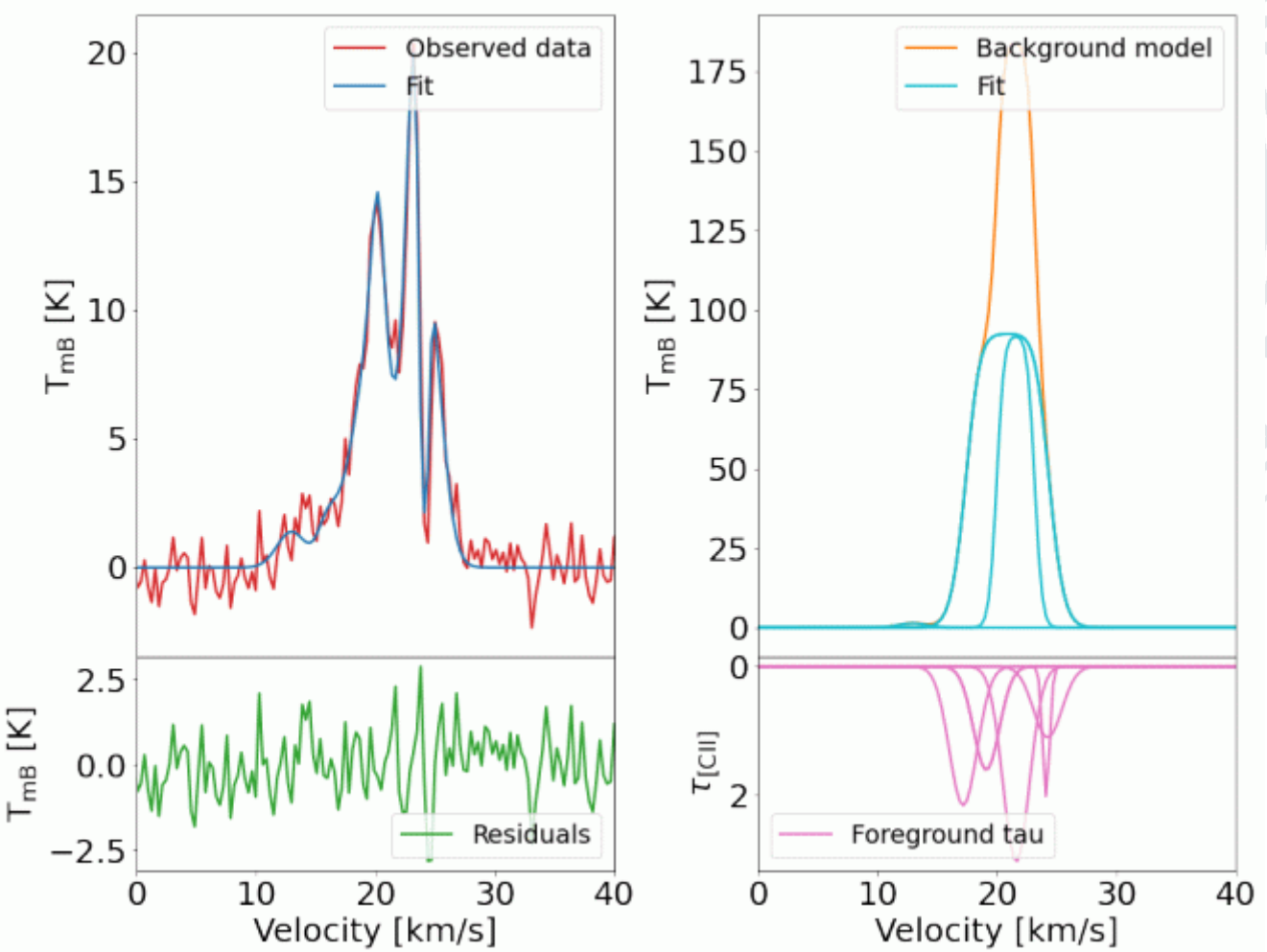
Guevara et al. (in prep.) → see next talk

- [CII] and [OI] see same components in emission and absorption

→ Tracer for same transitional gas

Quantitative analysis

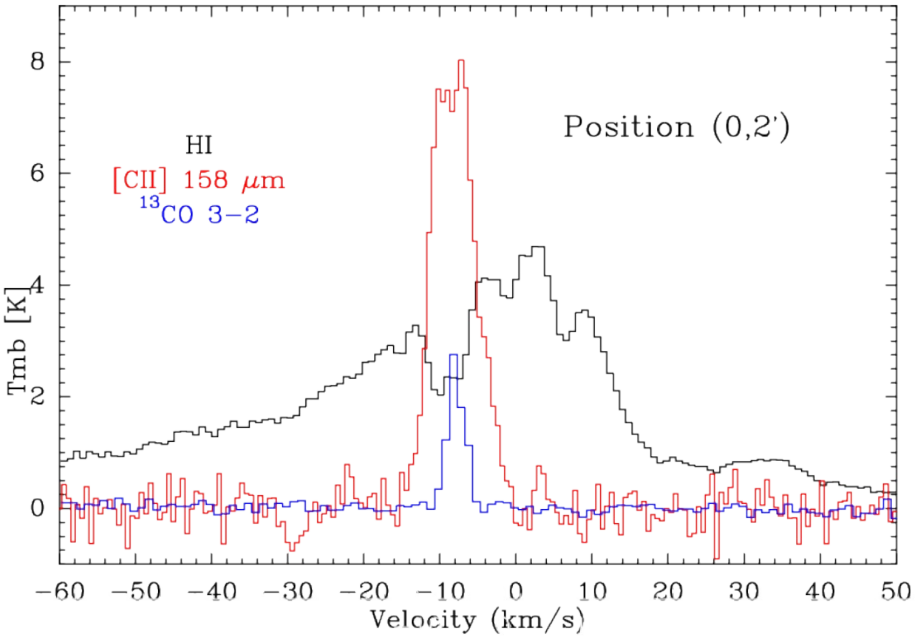
- Guevara et al. (in prep.) → see next talk
  - Fit of components
    - Emitting background ≙ A_V = 20..30
    - Absorbing foreground ≙ A_V = 8
    - Columns much larger than expected from PDR models

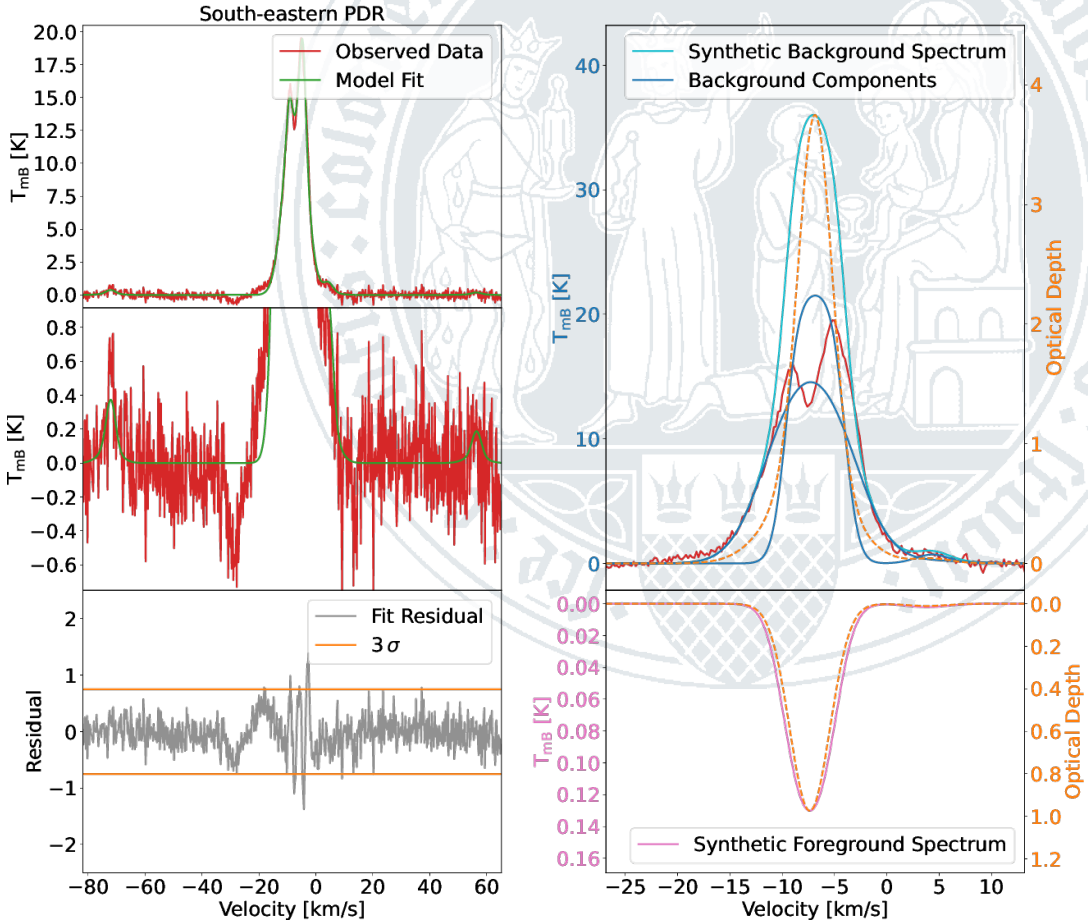


- Same behaviour observed now in many sources e.g. NGC2024 (Graf et al. 2012), Mon R2 (Guevara et al. 2019), S235 (Kirsanova et al. 2020), S1 (Mookerjea et al. 2021, see talk in 50 minutes), W3 (Goldsmith et al. 2021)

Fine structure line absorption from HI or CO-dark H_2?

- Example: RCW120





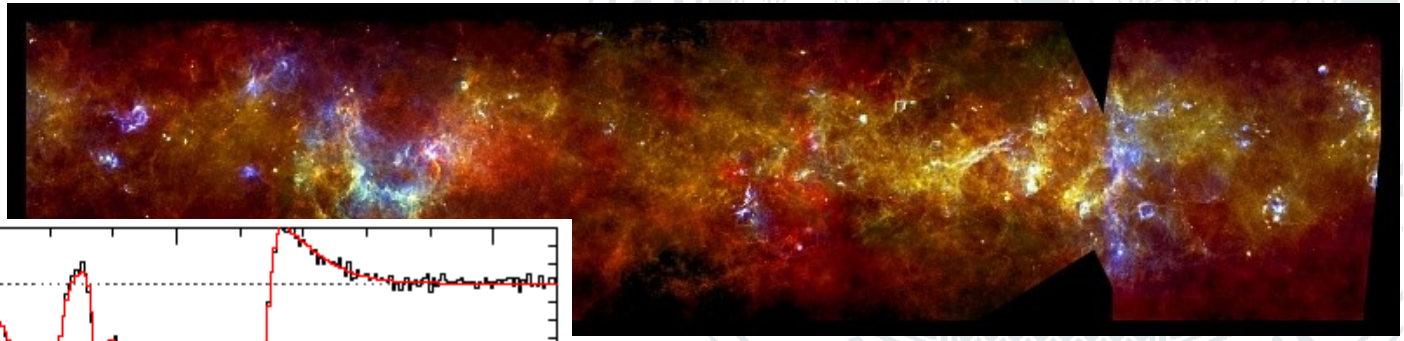
- [CII] in HI self absorption

- Consistent with [CII] absorption from 100K HI gas
  - Emitting background ≙ A_V = 10..15
  - Absorbing foreground ≙ A_V = 3..4

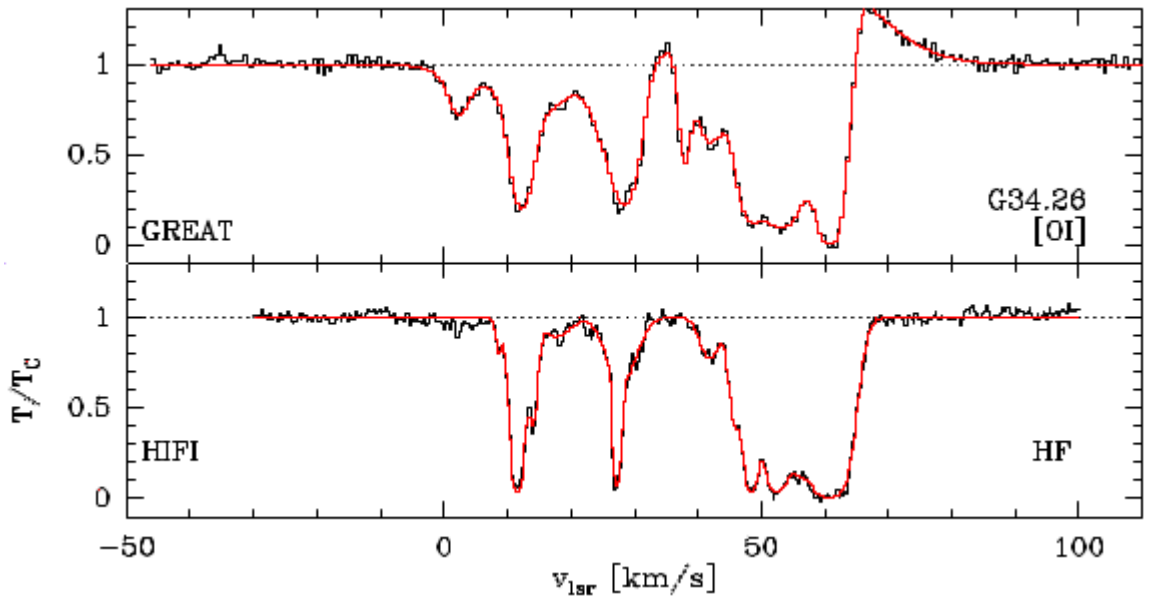
Kabanovic et al. (in prep.)
→ see poster 3-p1

Answer needs reliable correlations

- Column density measurement needs reliable background emission
  - [^{13}CII] requires long integrations
  - [OI] 145μm requires hot gas
  - Possible way out: continuum



Wiesemeyer et al. (2016)



  - Traces also cold H_2 gas
  - Loop to [CII] absorption not closed yet

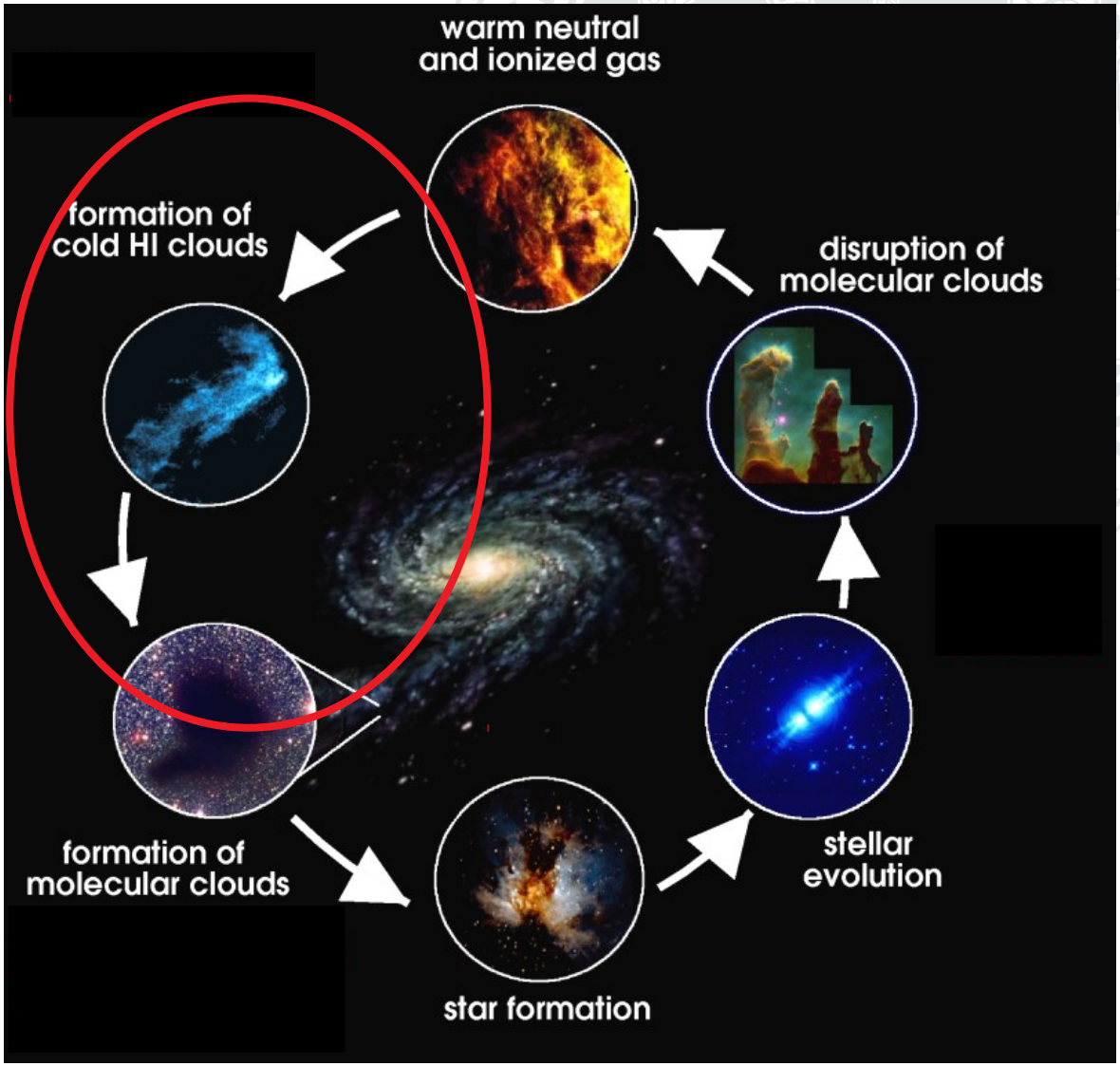
- So far insufficient statistics
  - Largest sample: FEEDBACK project (but only bright sources, only 35% observed, no source completed yet)
  - Many loose ends

[CII] and [OI] keys to study the assembly of the Galactic ISM

Open questions:

- Fraction of CNM and CO-dark molecular gas traced by the [CII] and [OI] absorption?
- Cloud formation, growth, evolution, and dispersal
- Galactic scale statistics of the CO-dark molecular gas
- Mass accretion as a feed of turbulent motions
- Role of stellar feedback on the ISM dynamics

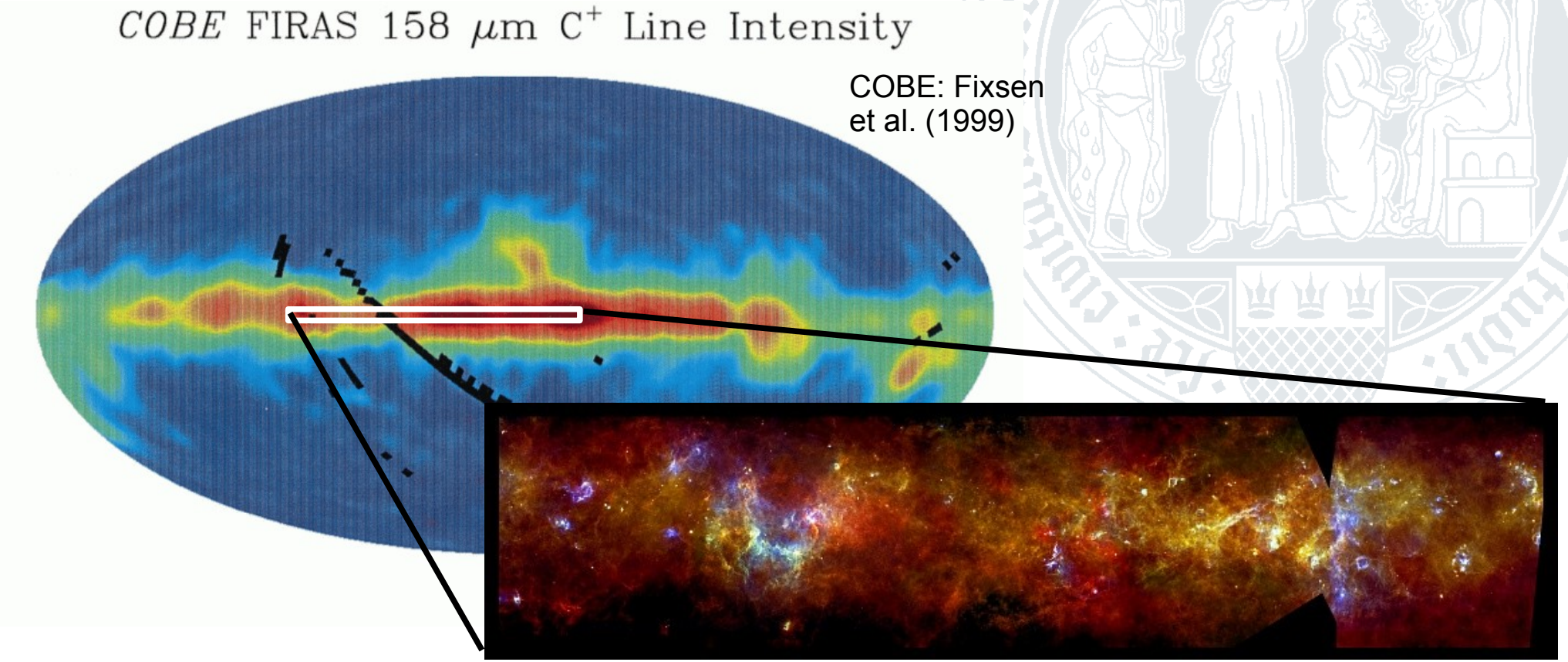
- Fine structure lines as star-formation tracers ?



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

Answers require large-scale statistics

Spectroscopic mapping of the diffuse structure in the Milky Way and nearby galaxies



COBE: Fixsen et al. (1999)

HiGal: Molinari et al. (2016)

- Velocity-resolved (Δv ≤ 1km/s) observations of emission and absorption in [CII] 158μm, [OI] 63μm and [OI] 145μm
- Distinguish CNM and CO-dark H_2-gas: H_2 in emission/absorption at 28μm