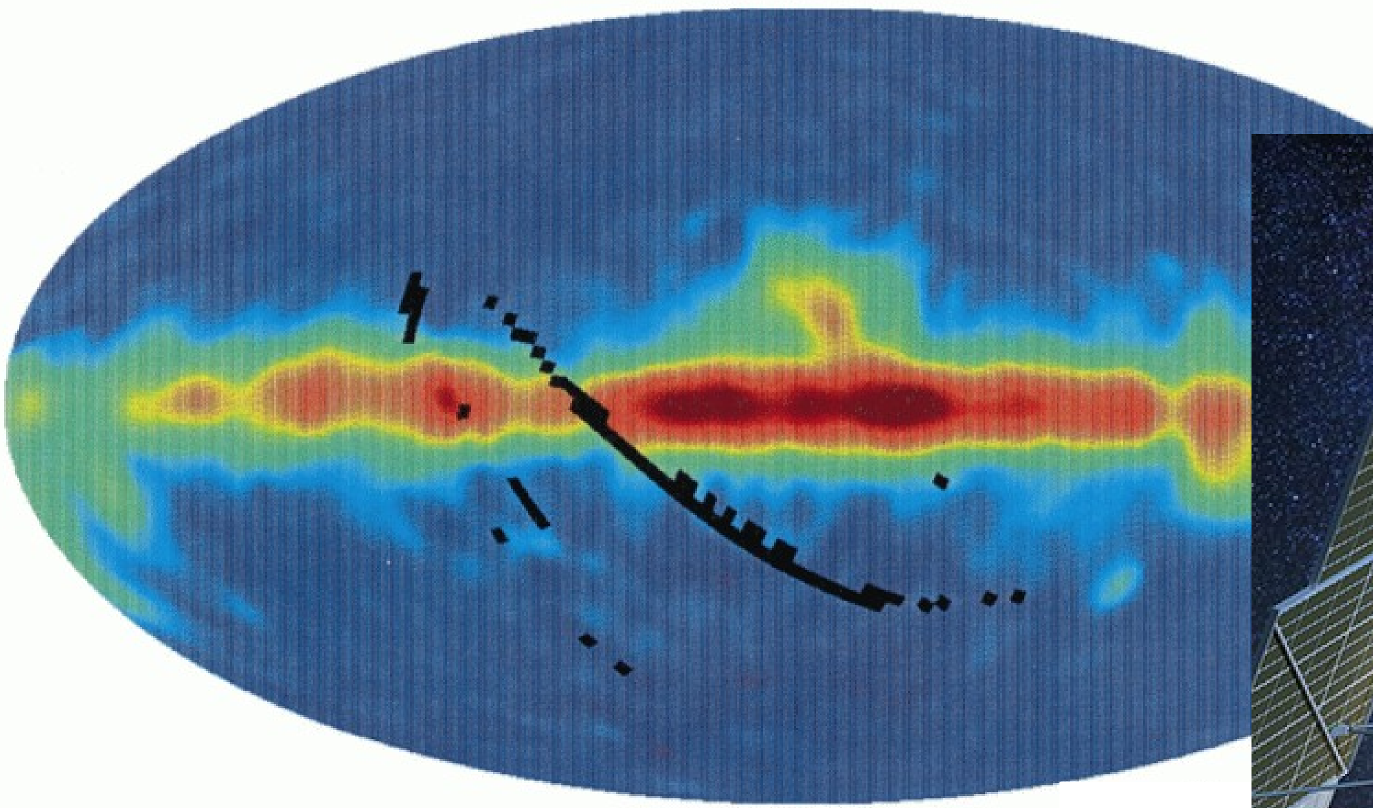
FIR Heterodyne Mapping Missions



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Boundaries:

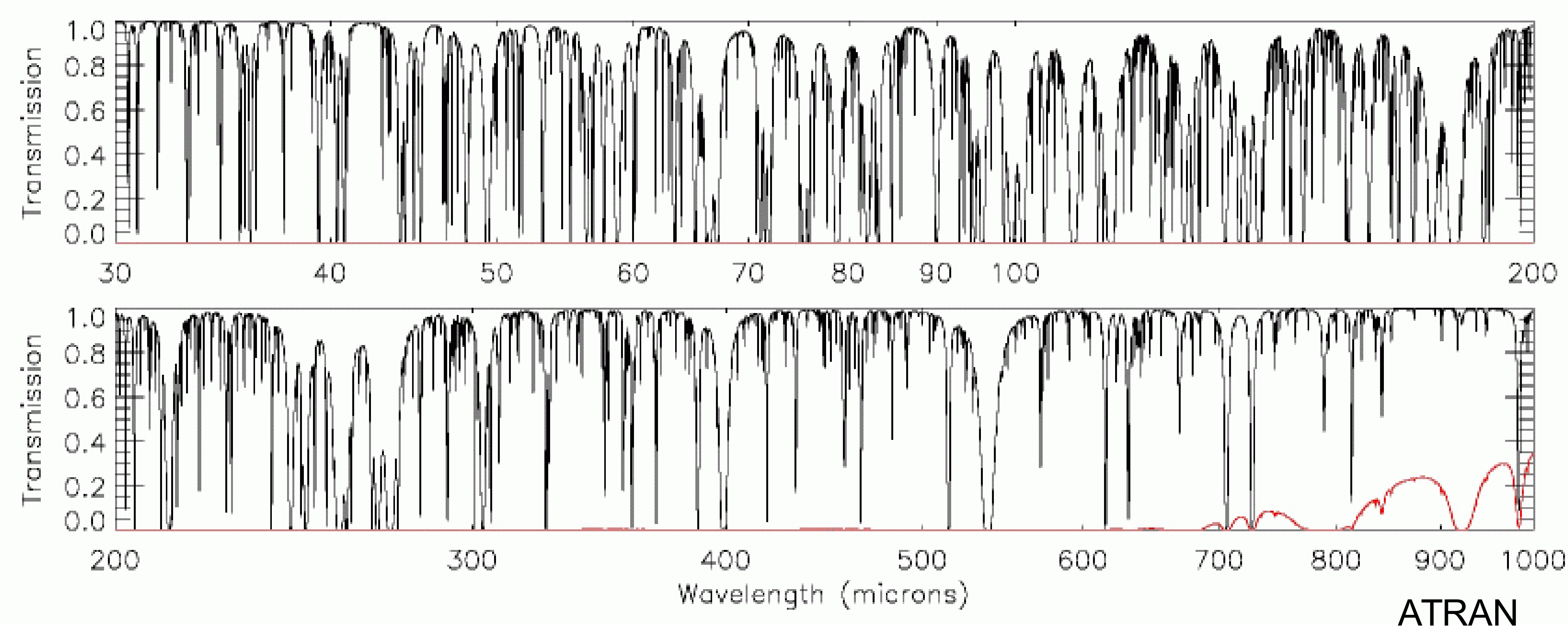
- SOFIA with instrument upgrades
- ALMA up to 600GHz, APEX up to 810GHz
- CCAT-p (2021) up to 850GHz (some 1.4THz)
- GUSTO (2021) with 8 pixels at 1.4, 1.9, 4.7 THz
- SAFARI onboard SPICA, up to 230µm, R=300

Advantages:

- Sky coverage by small telescope → first significant statistics
  - major fraction of the Milky Way, including diffuse regions
  - 10 times more than any existing/expected survey
- Costs small compared to space and SOFIA
- Data link/data storage compared to space
  - 2.4MB/s
- Atmosphere

The need for a balloon (or higher)

- Comparison to SOFIA:

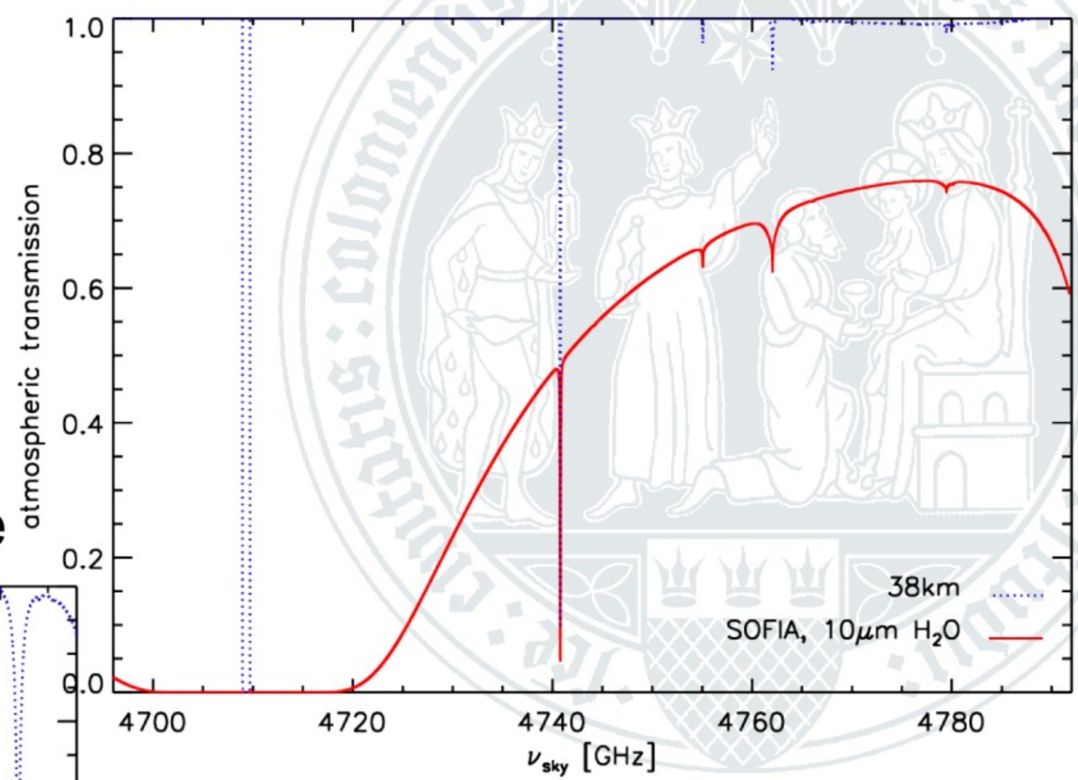


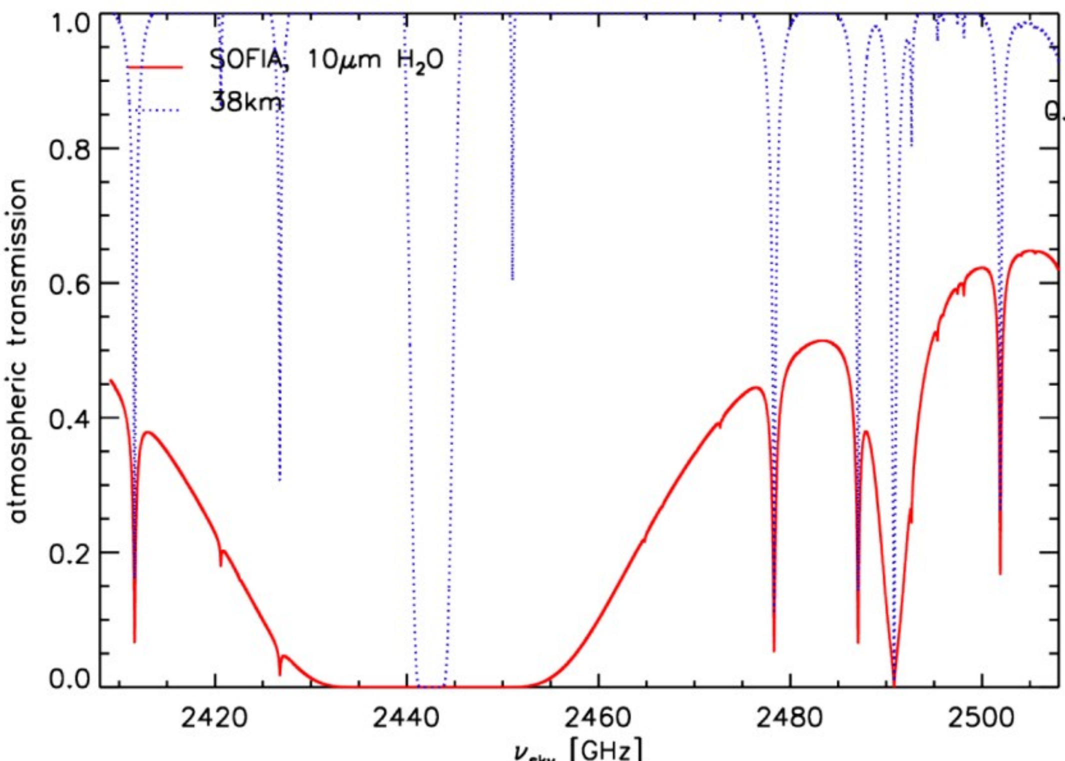
ATRAN

  - In spite of average good transmission, coverage with many gaps
  - Big challenge: Water: see Paola's talk
  - Balloon experiment: limited number of lines for simplicity: FS transitions

The need for a balloon (or higher)

- Comparison to SOFIA:
  - [CII] fine for Galactic sources
  - [OI] 63µm only for few frequencies
  - [OI] 145µm often difficult
  - [NII] 122µm almost impossible

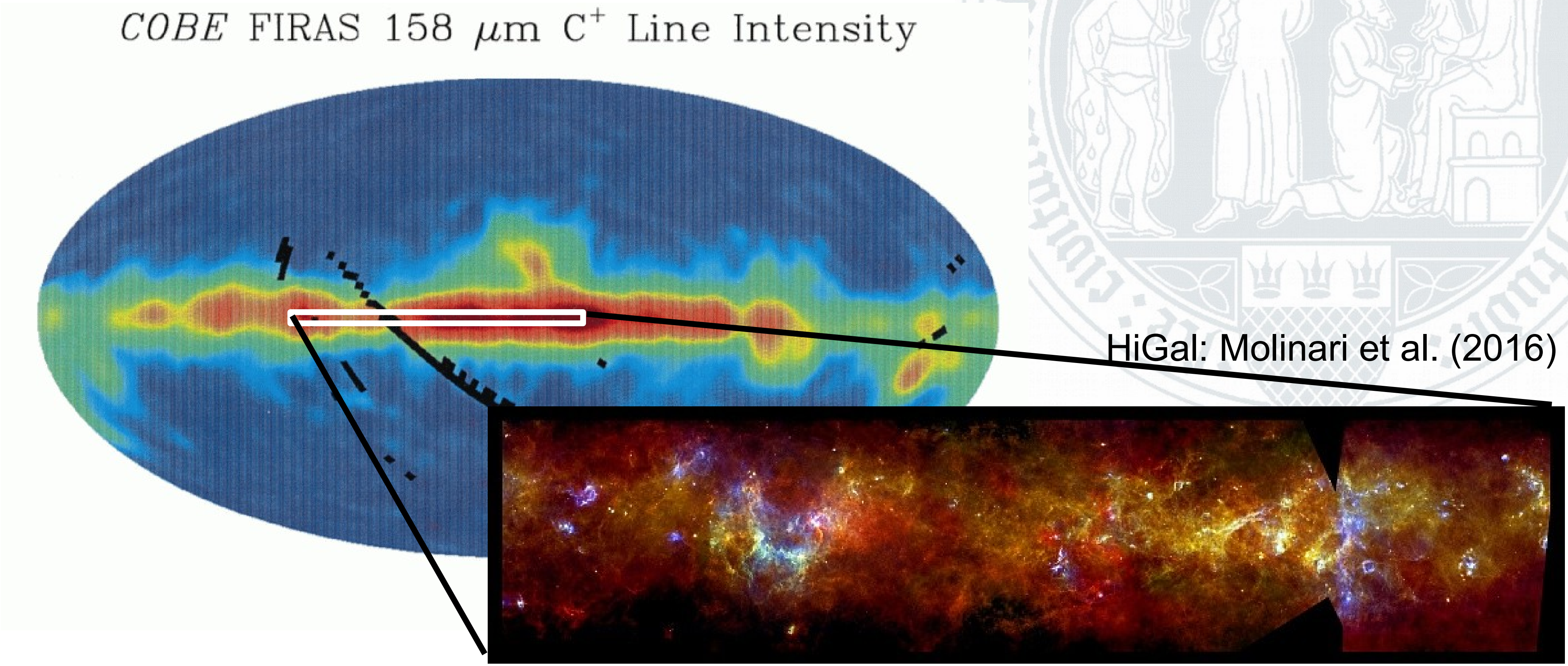




- excludes SOFIA for many nearby galaxies and even Galactic sources

Unique science from a FIR balloon mission

Large-scale spectroscopic mapping of the diffuse structure in the Milky Way and nearby galaxies



Velocity-resolved (3-D) distribution of the different phases of the ISM, their evolution under dynamic and radiative impacts, and the transitions between the phases

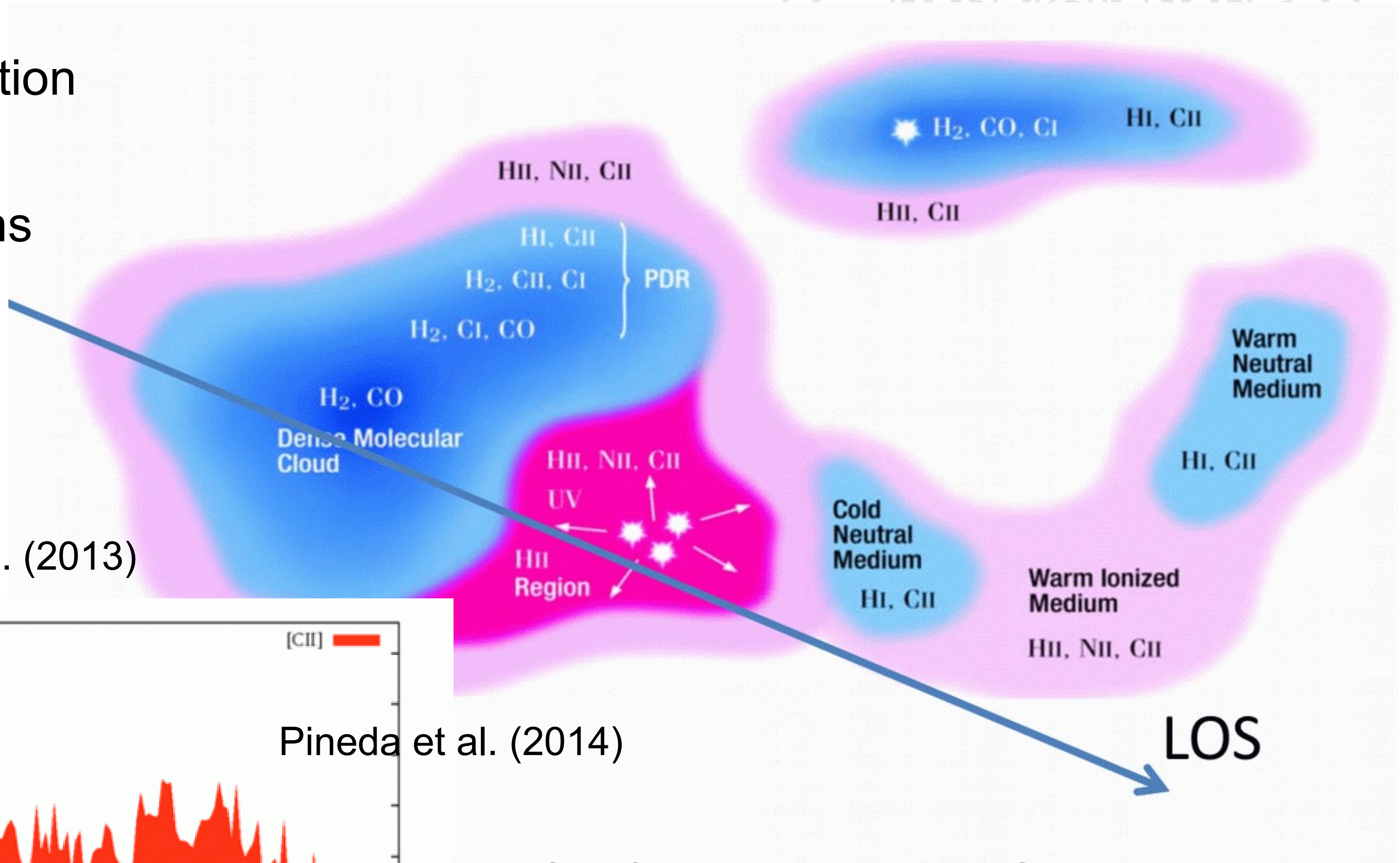
Unique science from a FIR balloon mission

Global statistics

- Widely distributed gas
  - Not (yet) forming molecular clouds
  - Feeding
    - Galactic disk
    - Molecular clouds
    - Turbulence in the ISM
  - Follow assembly of clouds in the Milky Way
    - Delineate the transition of atomic to molecular clouds
    - Formation, evolution, and disruption of diffuse clouds
- Heated gas around young (massive) stars
  - Global star formation tracer
  - Impact of star-formation on large scales
- Distribution of elements in Milky Way ISM

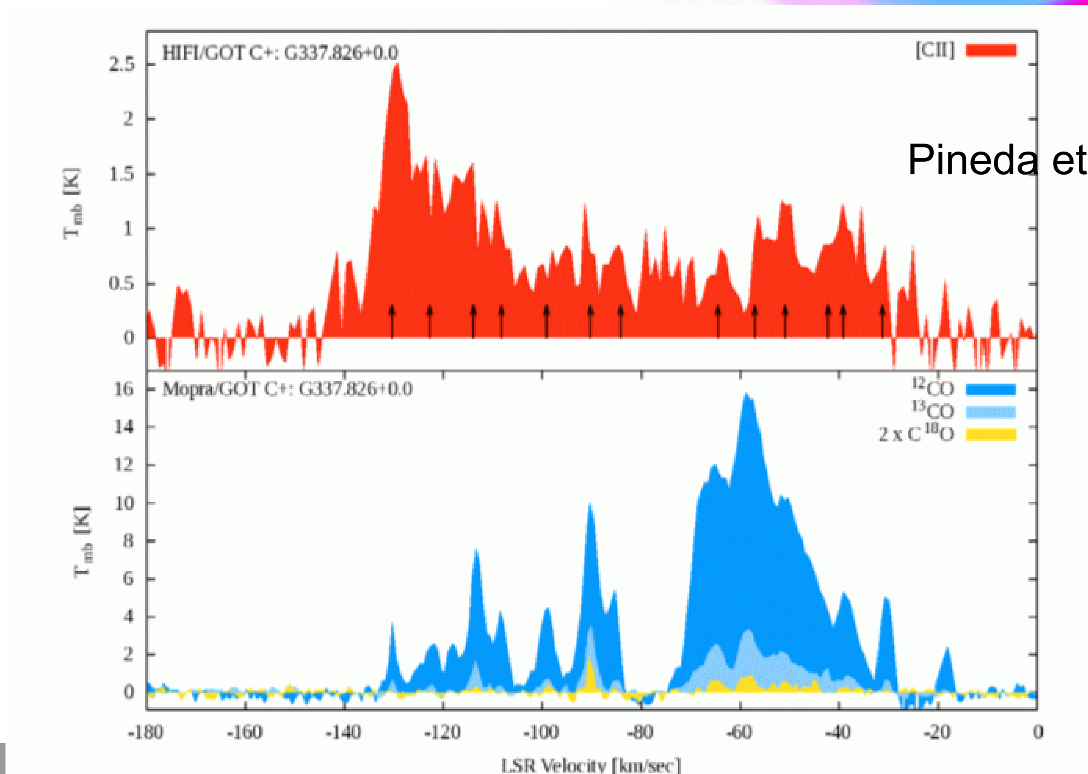
How to probe the different ISM phases

- Complex configuration
- Mixture of phases including HII regions
- Separated only in velocity space



Pineda et al. (2014)

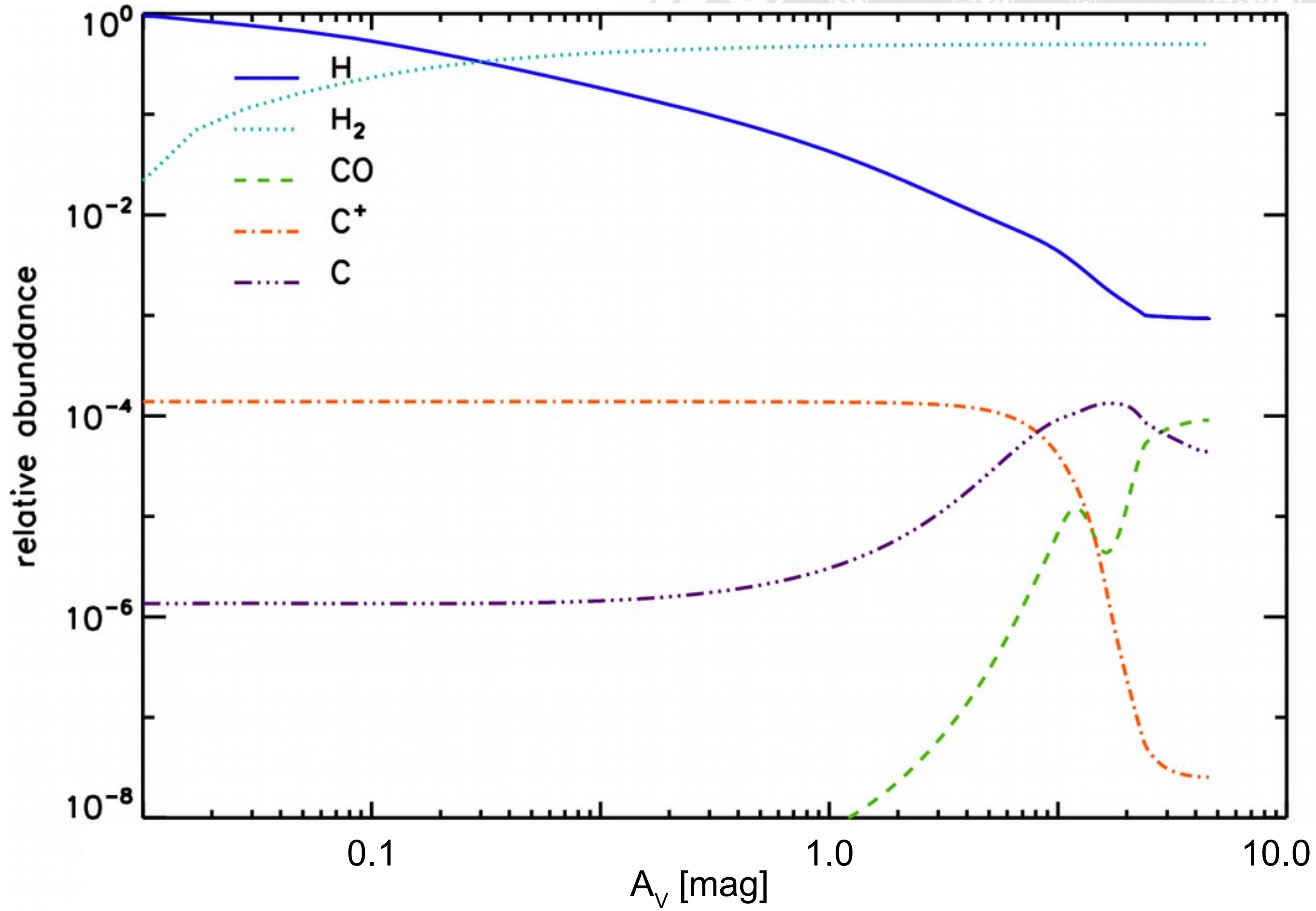
Velusamy et al. (2013)



- [CII] from HII regions, CNM, PDRs, CO-dark gas
- [NII] from HII regions, little from WIM
- [OI] for hot dense gas, absorption from CNM and CO-dark molecular gas

Critical component - CO dark gas:

- PDR model for $\chi=1$, $n=10^3$ cm^{-3}:

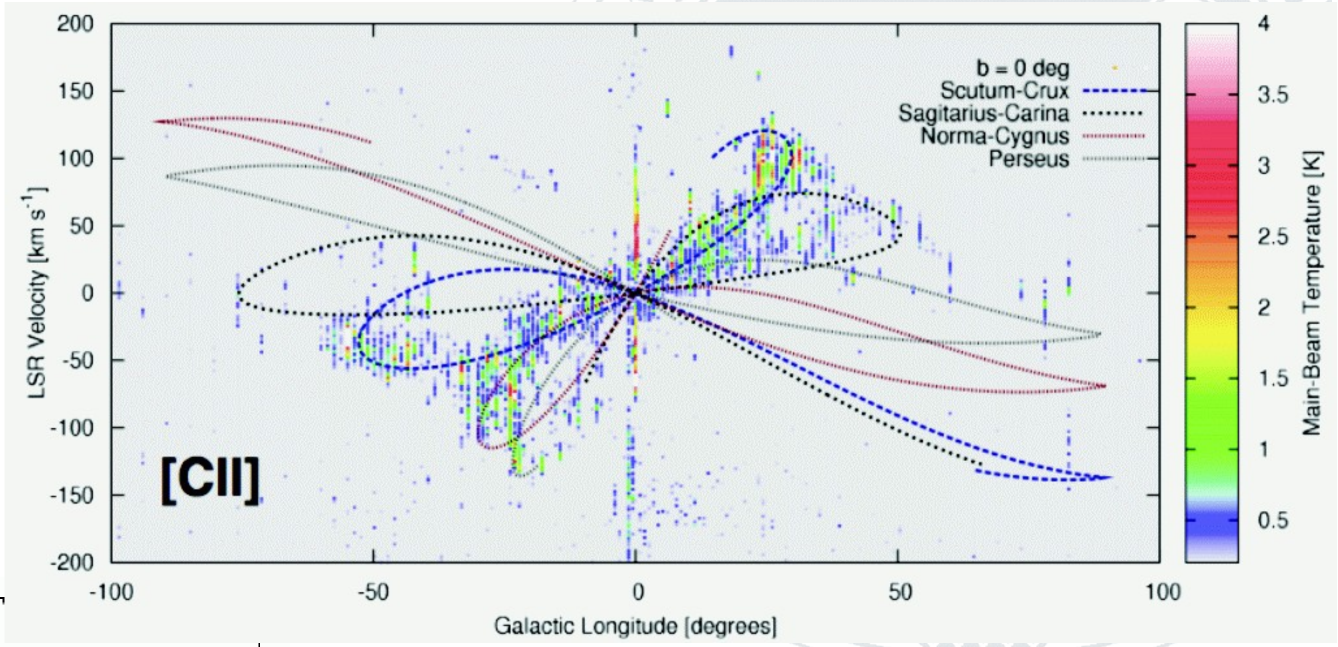


- Large fraction of H_2 not traced by CO
- Visible in [CII] , [OI], (HF, CH, CH^+)
  - [OI] throughout the whole cloud → temperature and density tracer

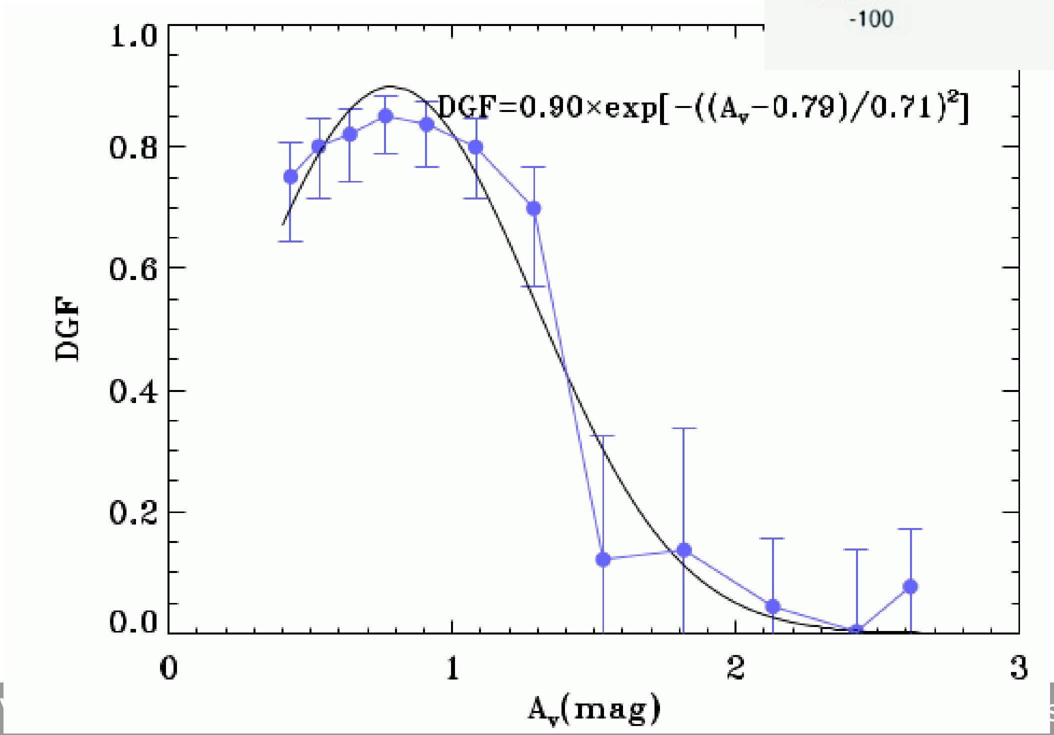
CO dark gas

Fraction of material

- In Galactic Plane (GOTC+, Pineda, Langer et al. 2010, 2013, 2014)
  - 20-75%
  - Highest in diffuse clouds
  - Not much information yet for $b \neq 0$



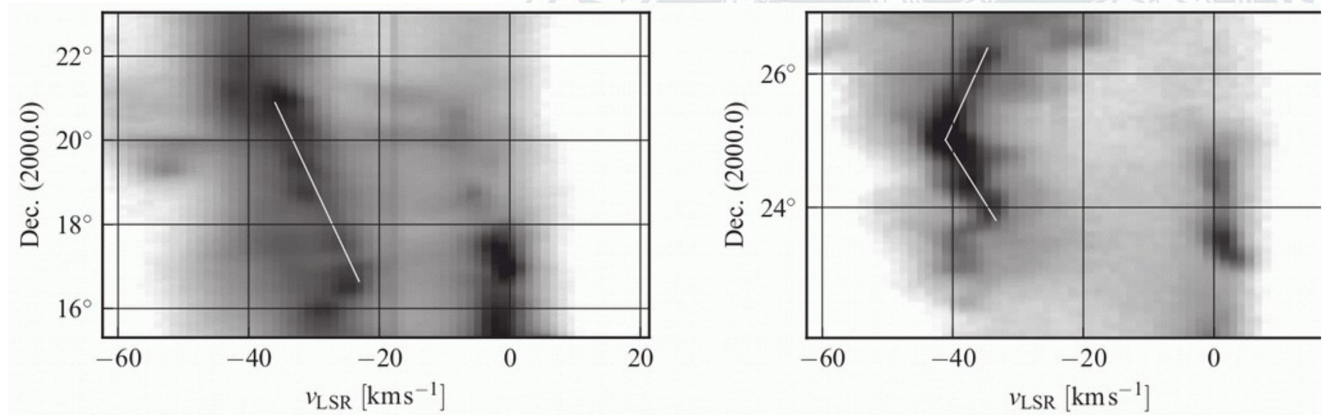
b=0 [CII] p-v diagram

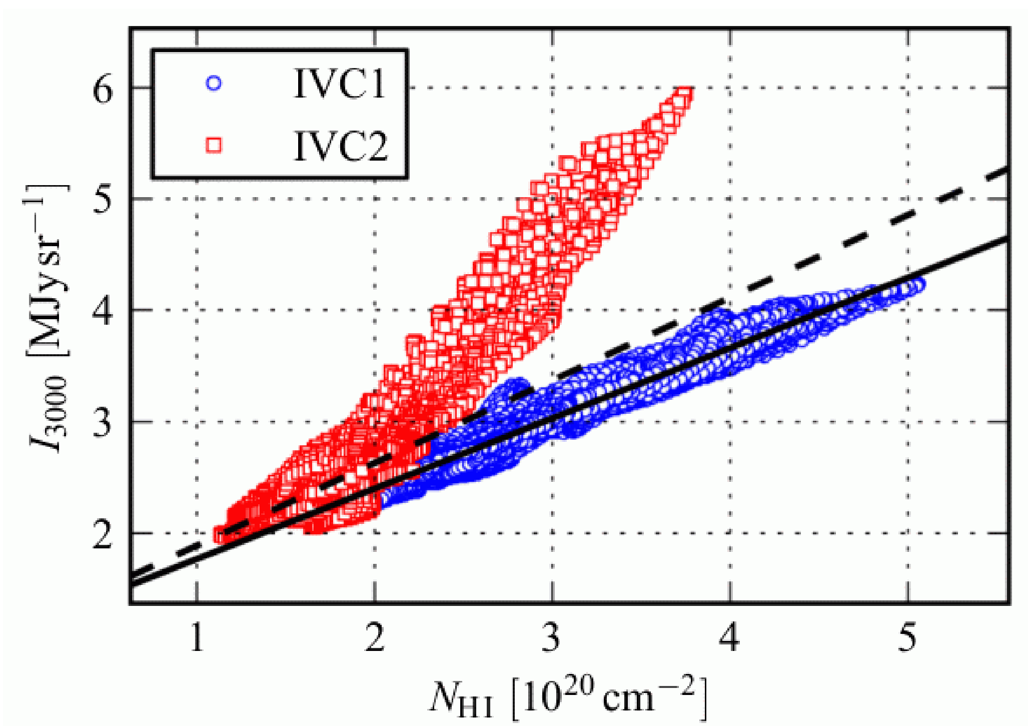


- Across molecular cloud boundaries:
  - up to 80% (Xu 2016)
- Estimates for global fraction: 25-90%
- We may still miss the majority of the interstellar gas today!

Mass assembly of the Milky Way disk

- Disk ISM fed by infall of high- and intermediate velocity clouds
  - Ejected material?
  - Intergalactic material?
  - Dwarfs?

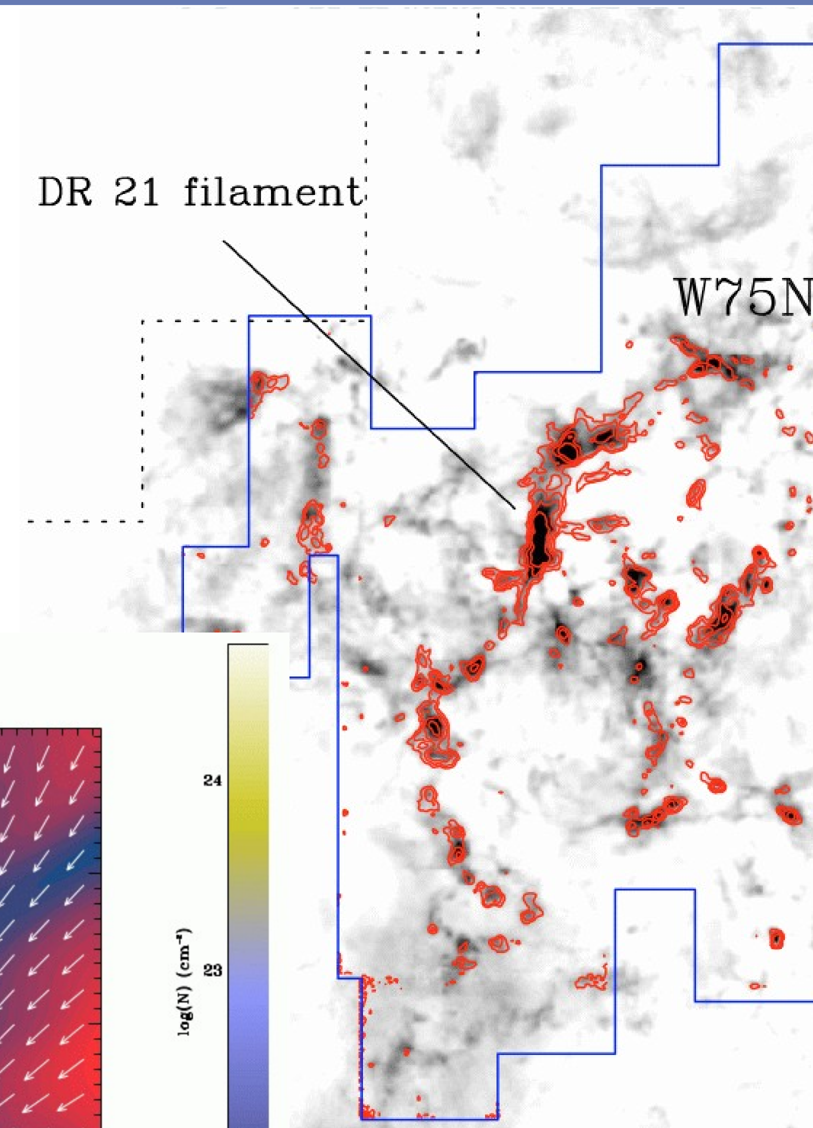


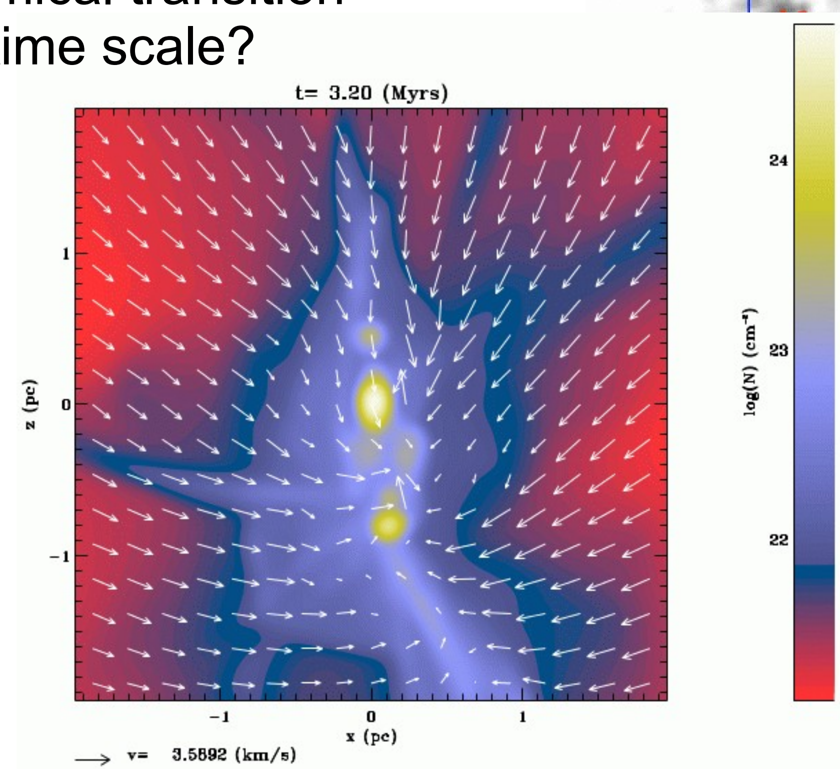


- 2 Intermediate-velocity clouds mapped by Röhser et al. (2014)
  - p-v-diagrams show interaction with disk material at Δv ~ few km/s
  - Dust column vs. HI column shows very different dust content
  - Clouds dense but invisible in CO

Open questions

- Inflow of material along filaments and spurs
  - Does the magnetic field direct the gas or does the gas assemble the magnetic field?
  - At which column density does the material turn molecular?
  - Relation between chemical transition time scales and infall time scale?
  - What is the infall velocity?
  - Does the infall create shocks?





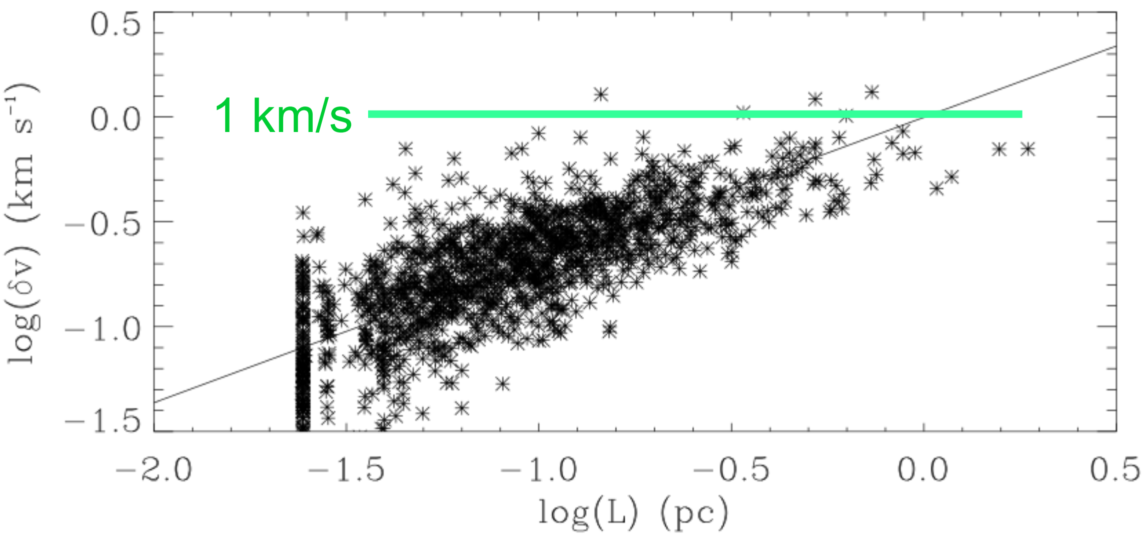
Schneider et al. (2010)

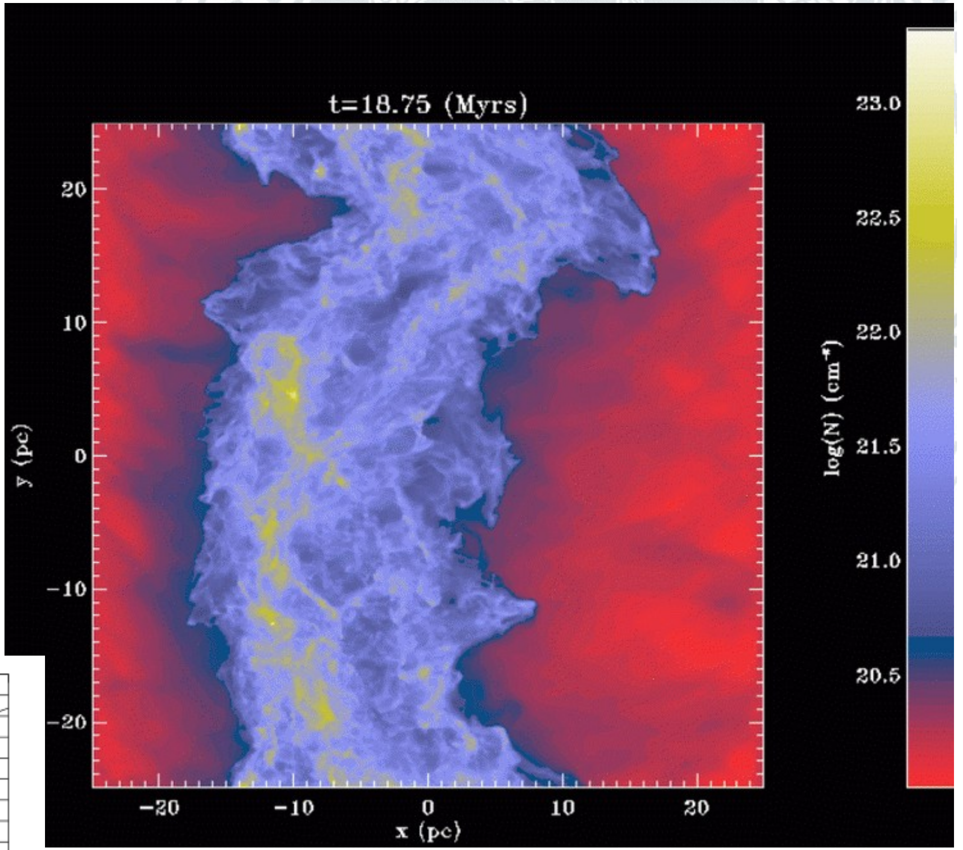
Driver of interstellar turbulence

ISM feeding as main driver of interstellar turbulence?

- Colliding flows unavoidably create turbulence
  - Mach-number of infall?
  - Impact relative to Galactic shear?
- Flows always chemically unstable
  - CO-dark material tracers

Size-linewidth relation of clumps in colliding flow





Colliding-flow simulation
(column density map)

Klessen & Hennebelle (2010)

Open questions

Driver of large-scale turbulence in the ISM

- Mass accretion as a feed of turbulent motions
  - Primarily diffuse atomic gas, but too confused in HI emission lines
  - Low density molecular hydrogen:
    - *CO-dark* molecular gas
- Deconvolve the effect of Galactic shear
- Quantify SN driving

Hierarchy of intermittent scales of turbulence dissipation

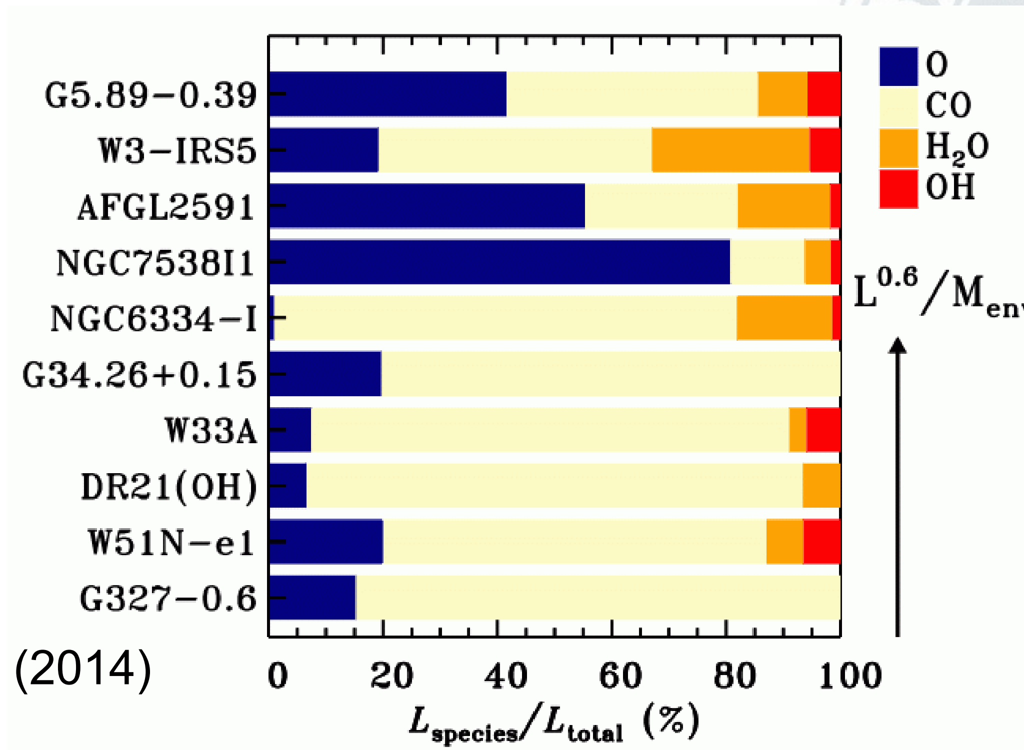
- Low velocity shocks as tracers of intermittency
- Line cooling of shocks
- Localized and direct measure of energy losses due to turbulent dissipation observed in post-shock gas

Role of stellar feedback on galactic scales

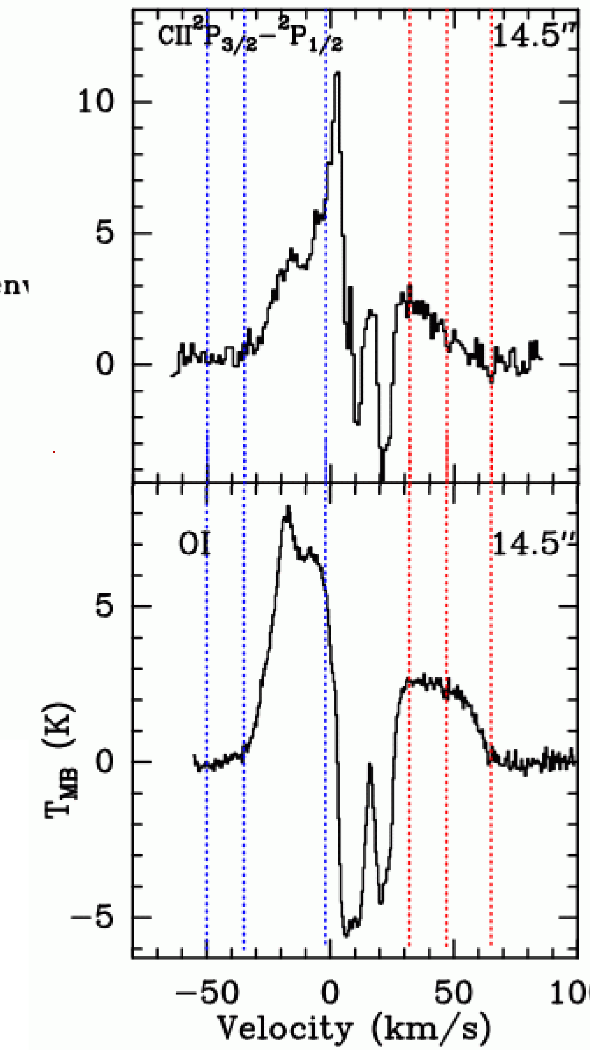
[CII] and [OI] as cooling lines and star-formation tracers:

- The Herschel view:
  - [OI] main cooling line
  - [CII] SF tracer
    - But line deficits

Karska et al. (2014)



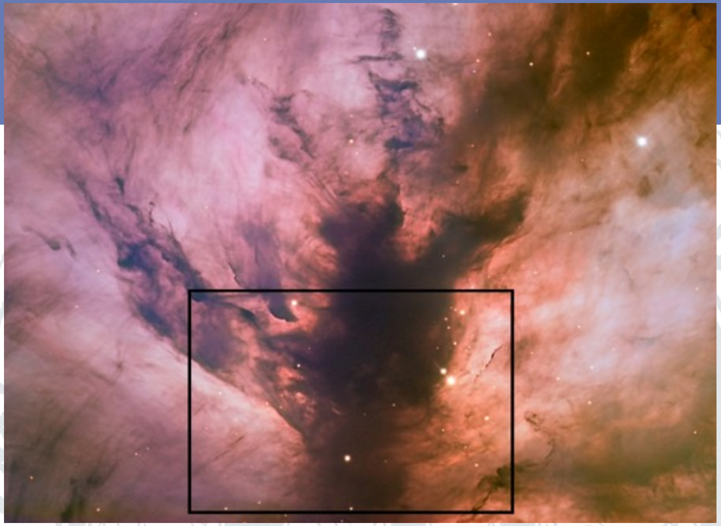
G5.89-0.39:



(Leurini et al. 2015)

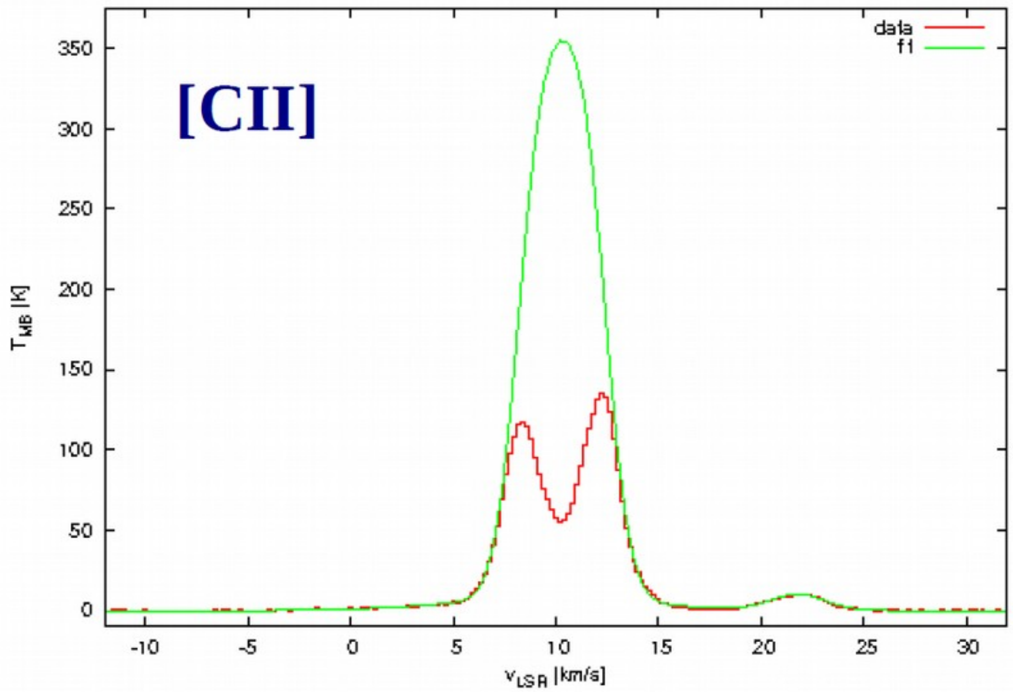
- News from SOFIA:
  - Complex [CII] and [OI] profiles
- Spectral resolution is the key!
- Explanation of FIR line deficit needs resolved lines

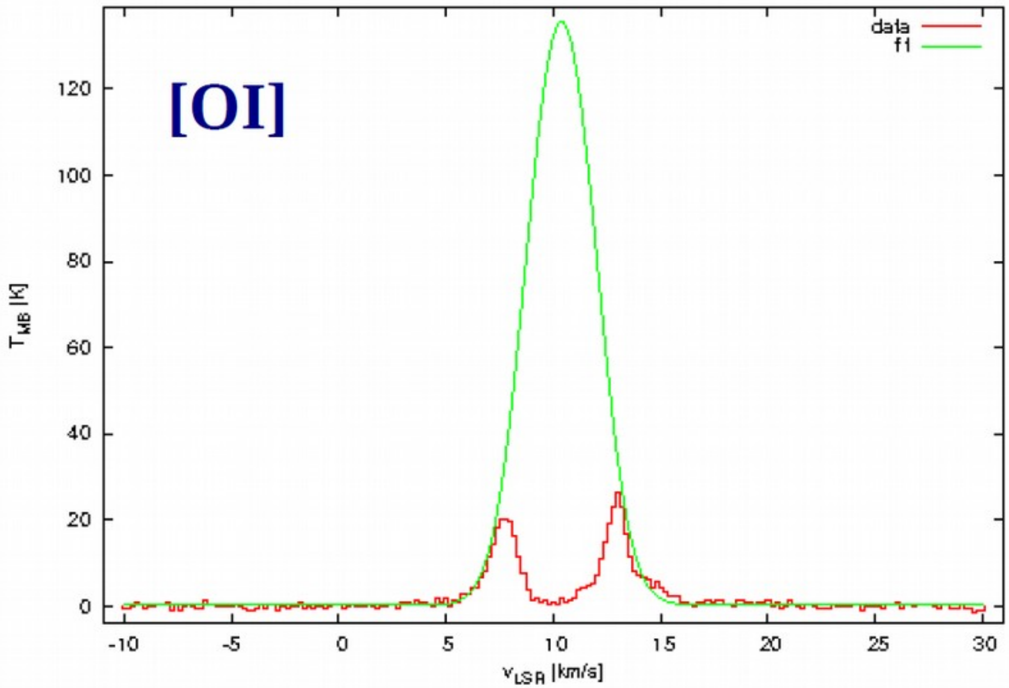
Extreme example: NGC2024



SOFIA/upGREAT observations:

Graf et al. 2012, Graf et al. in prep.





- 85% of [OI] emission obscured by foreground
- Consistent with foreground hydrogen column density 10^{22} cm^{-2}

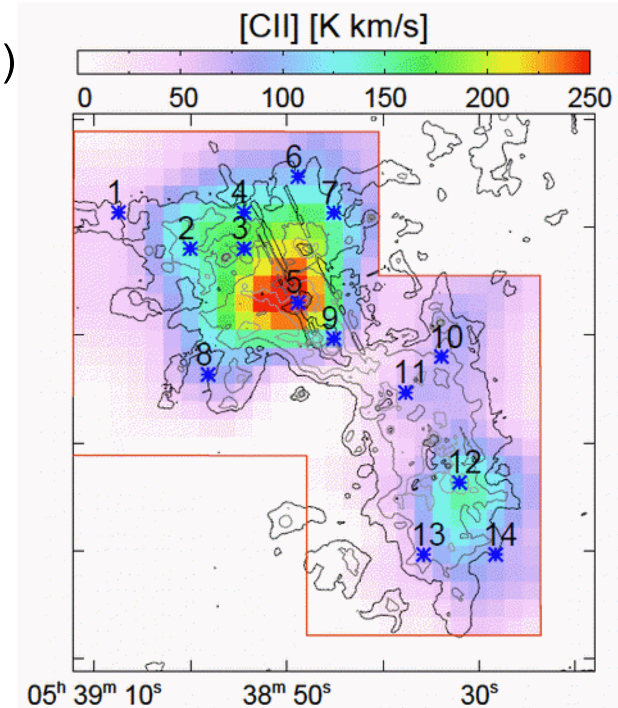
Open questions:

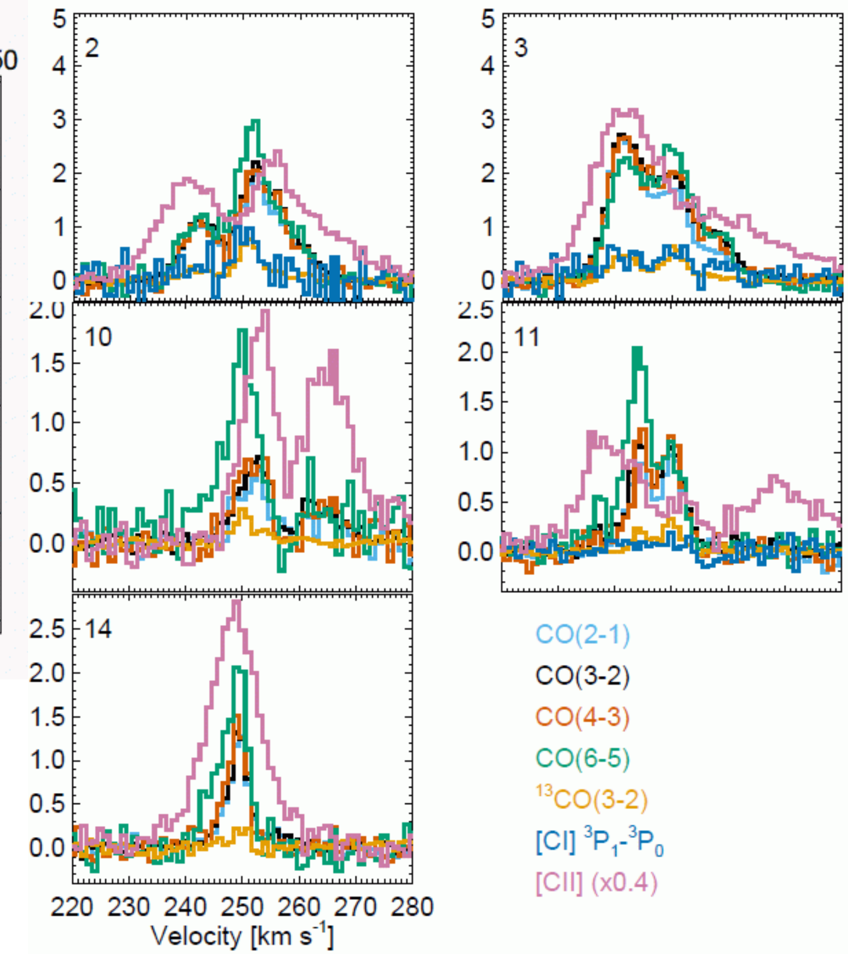
- Role of stellar feedback on the Galactic scale
  - What are good star-formation tracers ?
  - Contributions of different phases to Galactic emission of [OI], [NII], [CII]
  - Role of PDRs in the total line cooling of a galaxy

Dependence on galactic environment

Same measurements for resolved galaxies

30Dor (Okada et al. 2018)





- Quantify the amount of each ISM phase
- Determine how the phase distribution varies
  - for different type of galaxies.
  - as function of environment
- Deduce how these properties affect star formation rates

But: For most nearby galaxies both [OI] lines not observable from SOFIA

Mission profile

Long duration scan mapping with heterodyne array

- 1m-class telescope
- Channels to be decided: [CII], [NII] 122µm, 205µm, [OI] 63µm, 145µm
  - Estimates for [CII]
- 60 days of operation
  - Altitude 38km
  - from Antarctica
- 64-pixel heterodyne array
  - Main challenge: 64 pixels would currently require ≈ 2kW (mainly FFTS (B. Klein): 30W/backend) → $8m^2$ solar cells, dissipation (?)
  - Wet dewar (can be closed cycle if backends need less power)

→ Experiment, not observatory: 1800 square degrees mapping

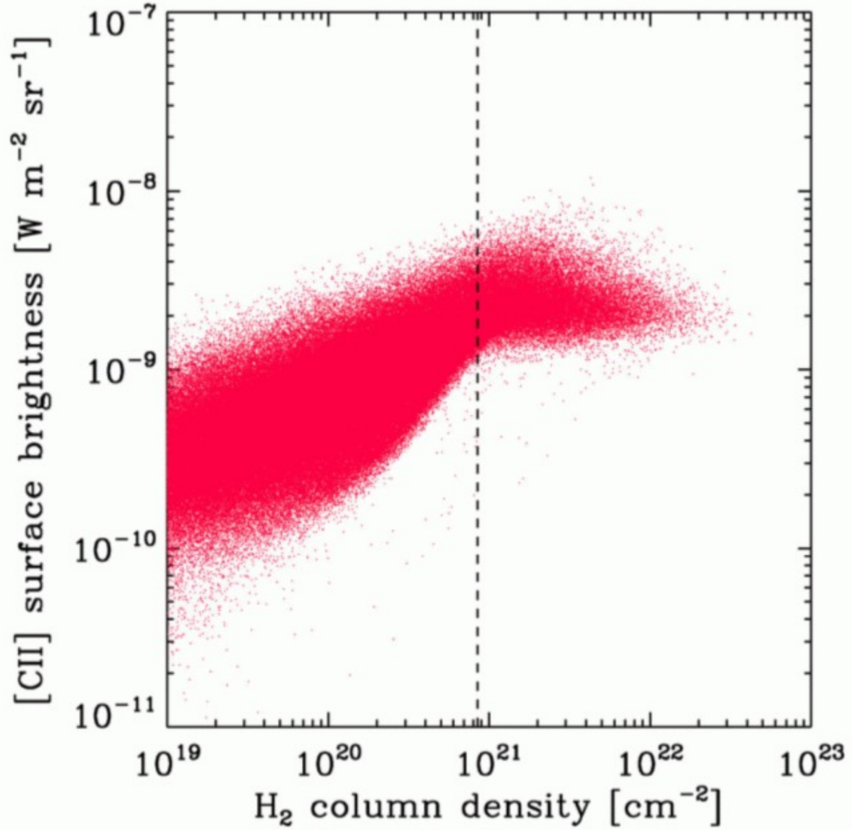
- Most of the Milky Way visible from southern sky (up to $|b| < 15°$)
- Magellanic clouds
- Other nearby galaxies

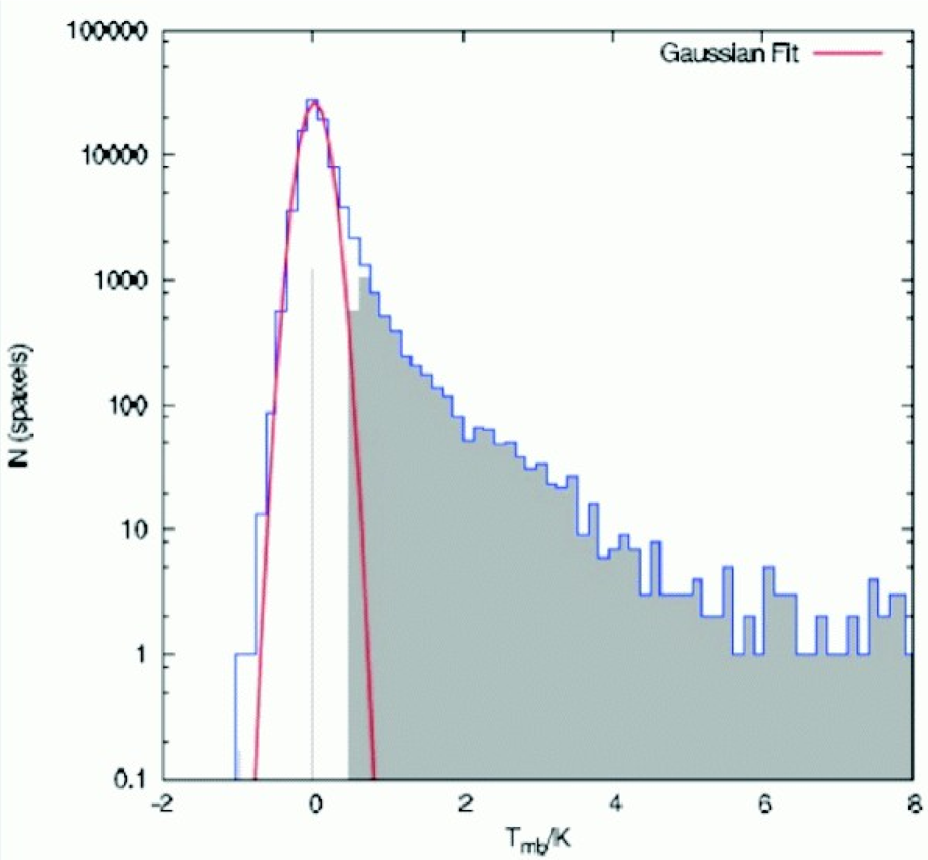
Sensitivities

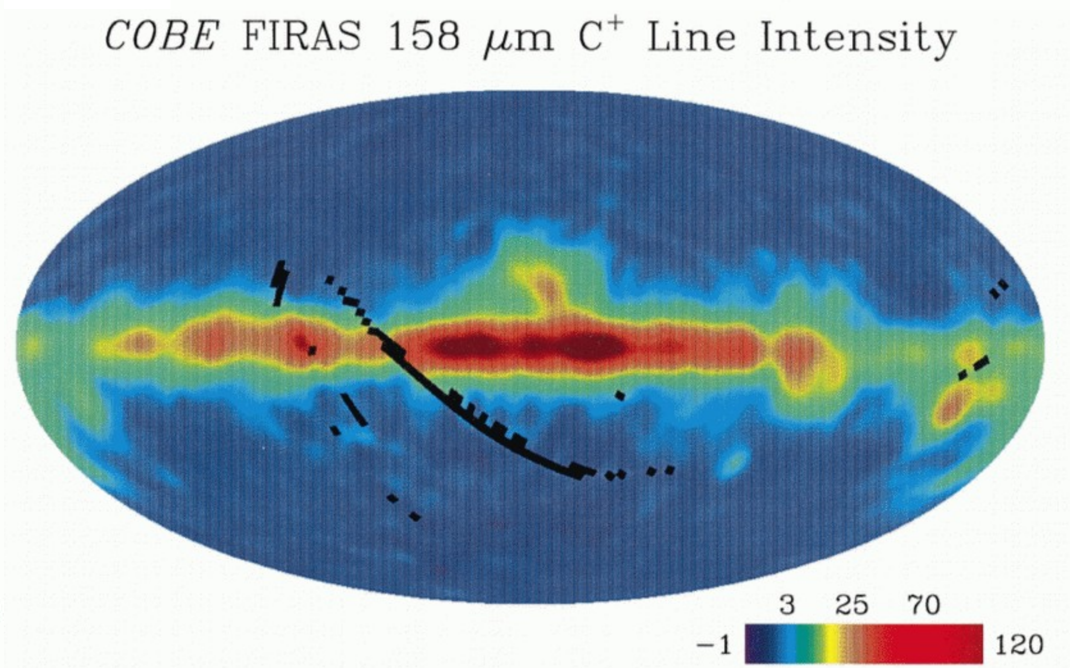
Simulations by Glover et al. (2015,16):
- Narrow lines
  - 2nW m^{-2} sr^{-1} ≈ 0.14 K (CII)

COBE (Fixsen et al. 1999)
- Full plane above 7nW m^{-2} sr^{-1}

GOTC+ (Langer et al. 2010, 13, 14)
- Scratched only the surface







Mission profile

Conservative estimate

- 1m-class telescope; resolution for [CII]: 40" at 1.9THz
- 64-pixel heterodyne array, T_{sys}=400K
- Spectral resolution: 0.5km/s to resolve inflow and turbulence
- 1800 square degrees coverage

→ Noise level of 50mK

– Resolves dynamics of all the CO-dark molecular and CNM gas

  - [^{13}CII] when averaging over 5 square arcminutes

Mission profile

- [NII] 205 µm at a resolution of 52''
  - lower noise of 40mK
  - << COBE level throughout most of the Galactic plane
  - [NII] 122µm undersampled
  - Detection of all extended HII regions, diffuse WIM only on much lower effective resolution

- [OI] 63µm sparsely sampled
  - Emission bright from PDRs, very concentrated,
  - Absorption from CO-dark gas when background available
  - no emission from diffuse gas
  - Optical depth correction challenging

Overall science case

What determines the ISM structure that drives star and planet formation in galaxies?

- Formation, growth, evolution, and dispersal of ISM clouds
  - Accretion of high-latitude material onto the Milky Way
  - Mass assembly of molecular clouds
  - Galactic scale statistics on the CO-dark molecular gas
  - 3-D distribution of the different phases
- Main driver of turbulent flows in the ISM
  - Mass accretion as a feed of turbulent motions
- Role of stellar feedback on the ISM dynamics on Galactic scale
  - [CII] as a star-formation tracer ?
- Large scale chemical and metallicity structure of the Galaxy
  - Including isotopes

All requires spectral resolution **better than 1 km/s**.