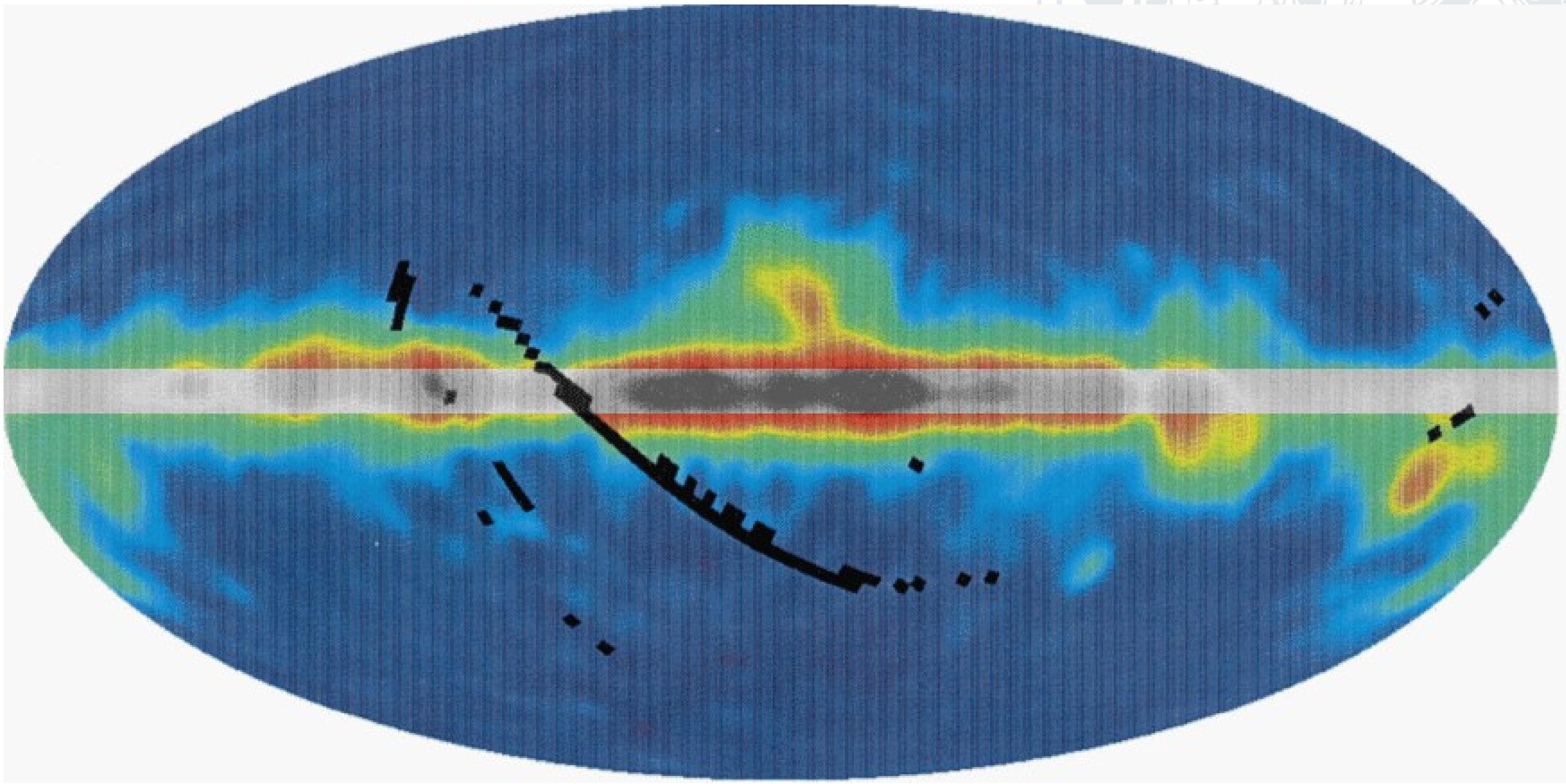
The FIRSPEX Galactic Plane Survey



Volker Ossenkopf-Okada, Paul Goldsmith, Dimitra Rigopoulou

The Galactic Plane survey

Spectroscopic equivalent to Herschel continuum survey of Galactic Plane

Measure the 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

- formation, disruption, evolution of diffuse clouds
- formation of molecular clouds
- impact of massive of star formation

FIRSPEX target

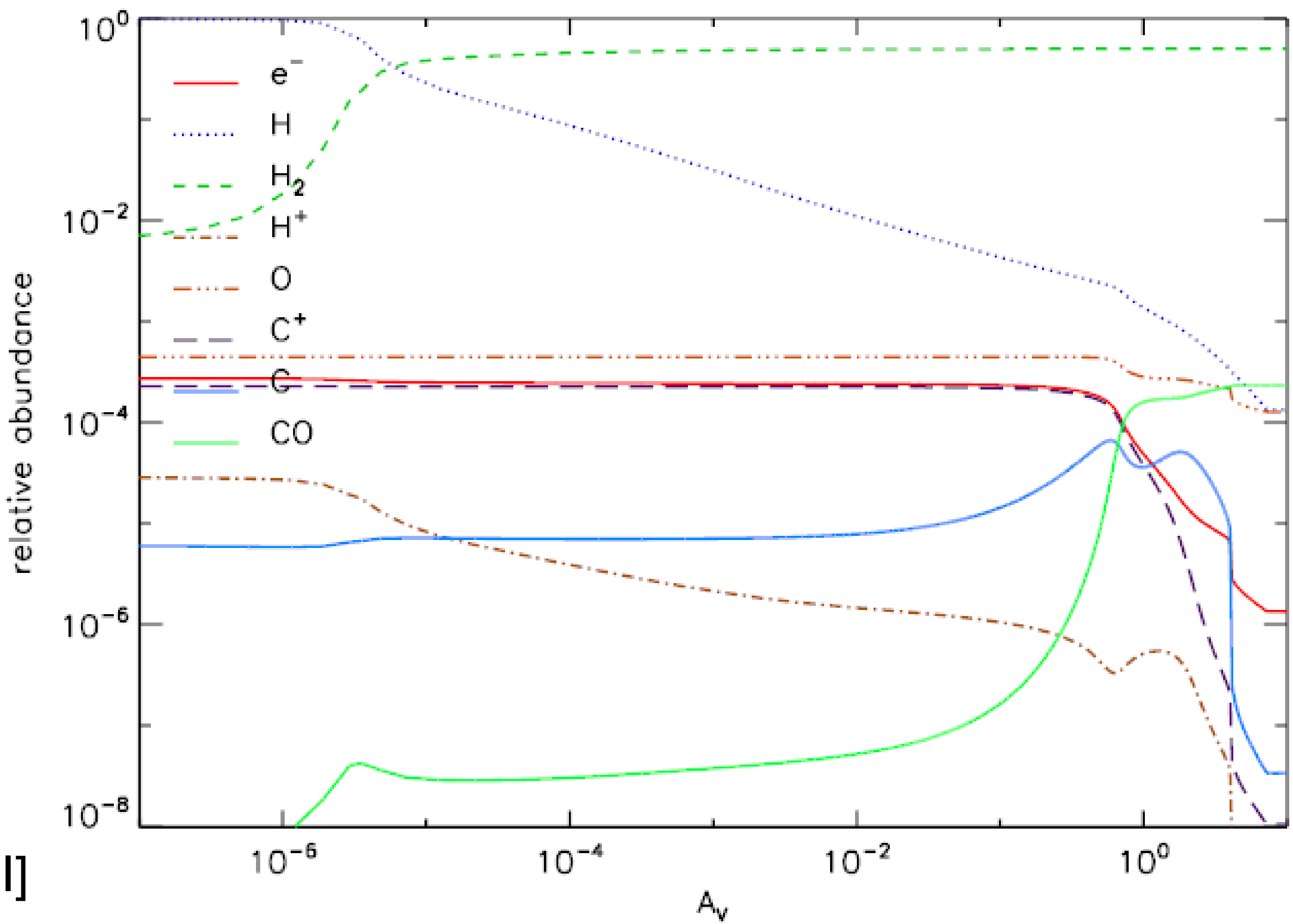
- Widely distributed gas
  - Not (yet) forming molecular clouds
  - Feeding
    - Molecular clouds
    - Galactic disk
    - Turbulence in the ISM
  - Follow assembly of clouds in the Milky Way
    - Delineate the transition of atomic to molecular clouds
- Heated gas around young (massive) stars
  - Global star formation tracer
- Distribution of elements in Milky Way ISM

Science questions

- Mass assembly of molecular clouds
  - Accretion of high-latitude material onto the Milky Way, feeding the clouds
  - Galactic scale statistics on the CO-dark molecular gas
  - Verification of transition time scales by direct observation of velocity structures
- Main driver of turbulent flows in the ISM
  - Mass accretion as a feed of turbulent motions
  - Deconvolution of the effect of Galactic shear
  - Quantify SN driving
- Role of stellar feedback on the Galactic scale
  - Calibrate [CII] as a star-formation tracer
  - Contributions of different phases to Galactic emission of [OI], [NII], [CII]
  - Role of PDRs in the total line cooling of a galaxy
- Large scale structure of the Galaxy
  - Metallicity gradient
  - 3-D distribution of the different phases

CO dark gas:

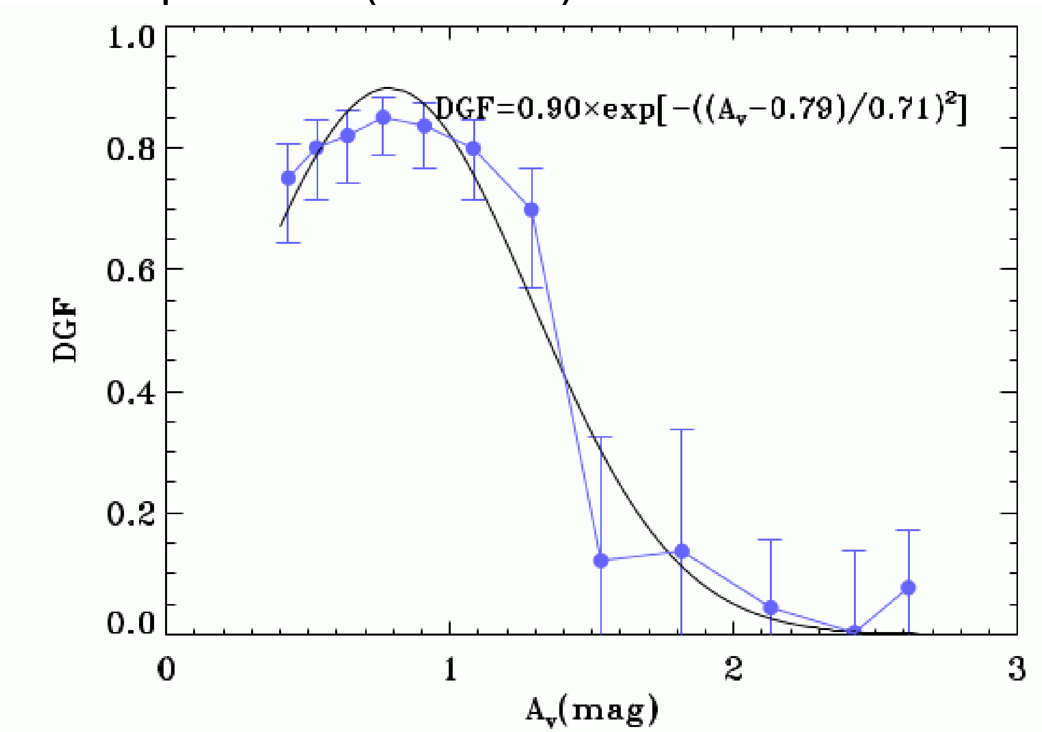
- PDR model for $\chi=1$, $n=10^3$ cm^{-3}:

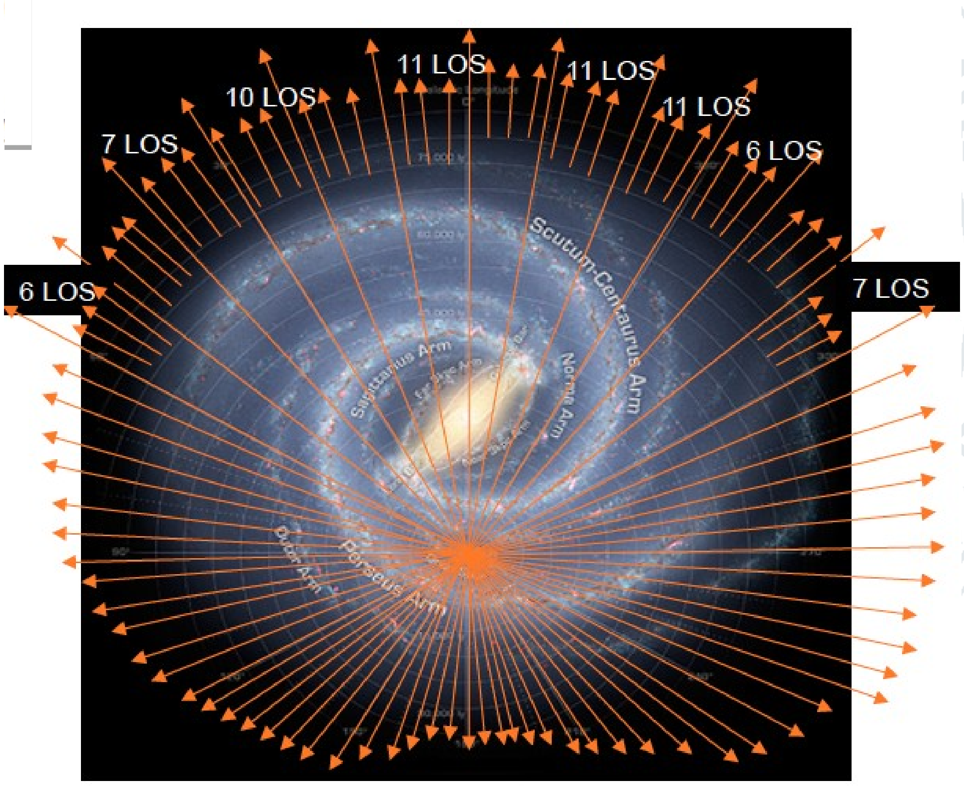


- Large fraction of H_2 not traced by CO
- Visible in [CII] and [CI]
- No other abundant tracer
- [OI] throughout the whole cloud → temperature and density tracer

Fraction of material

- In Galactic Plane (GOTC+, Pineda, Langer et al. 2010, 2013, 2014)
  - 20-75%
  - Highest fraction in diffuse clouds
- Across molecular cloud boundaries:
  - Up to 80% (Xu 2016)



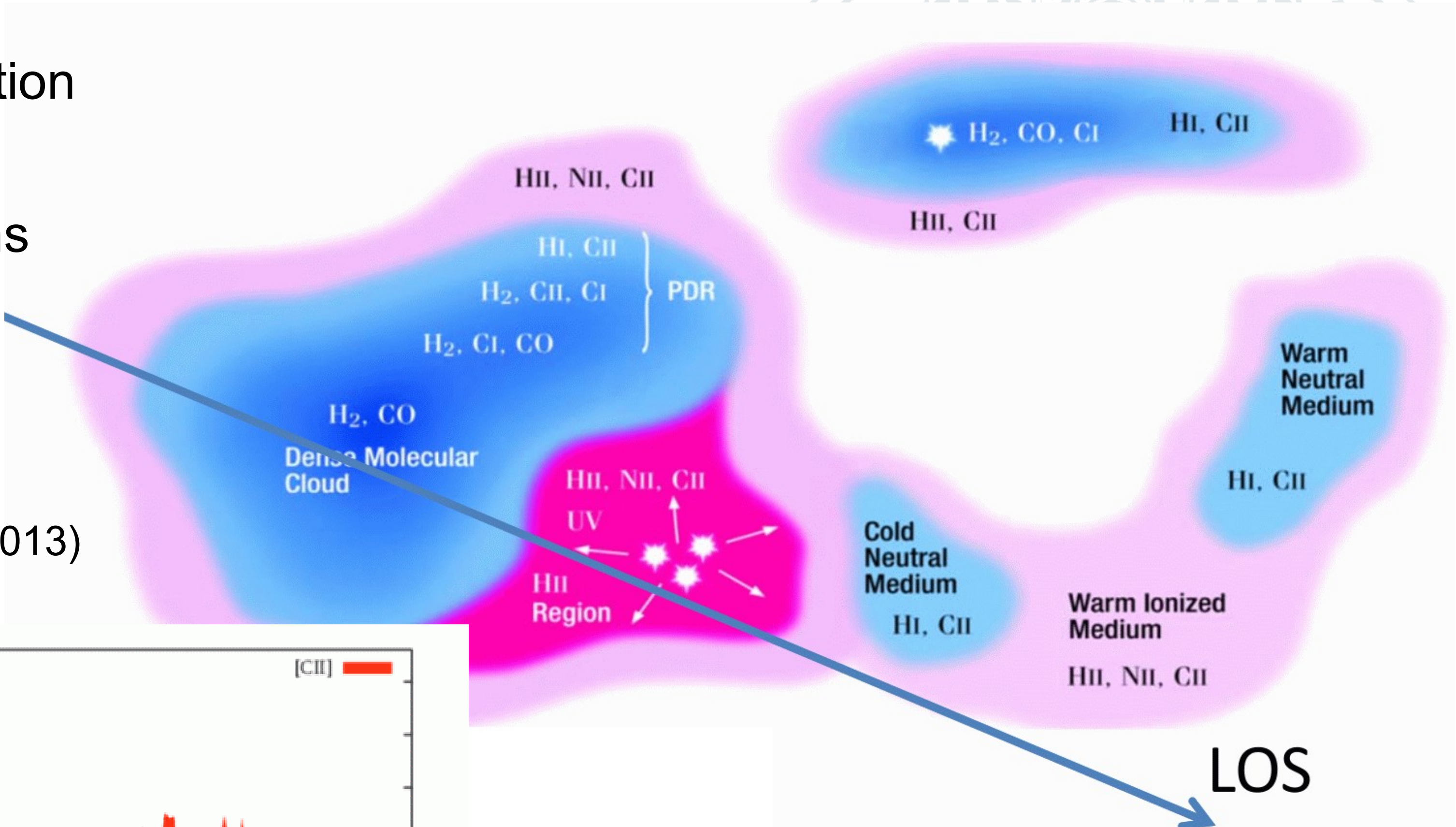


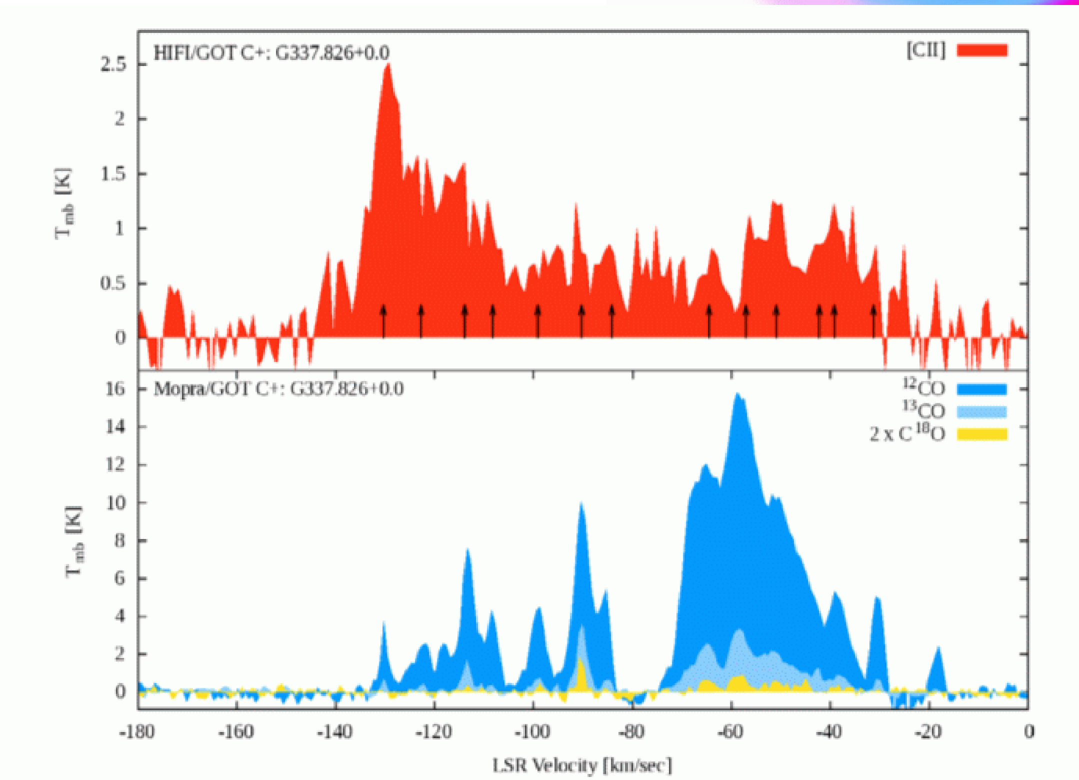
- Not much information yet for $b \neq 0$
- Fraction certainly higher
- We may still miss the majority of the interstellar gas today!

Probing the different phases

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

Velusamy et al. (2013)



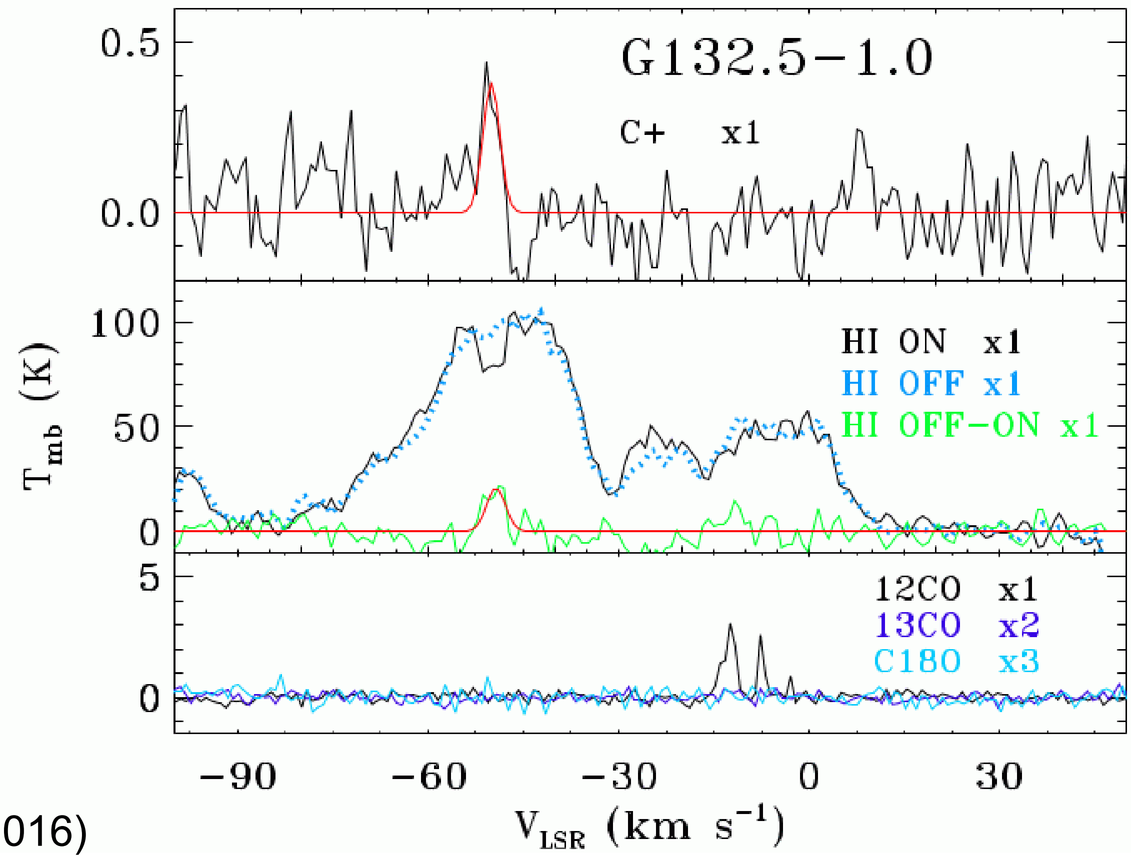


- [CII] from HII regions, CNM, PDRs
- [NII] from HII regions, little from WIM
- [OI] for hot dense gas
- [CI] for part of CO-dark gas
  - need all data at same velocity resolution

Pineda et al. (2014)

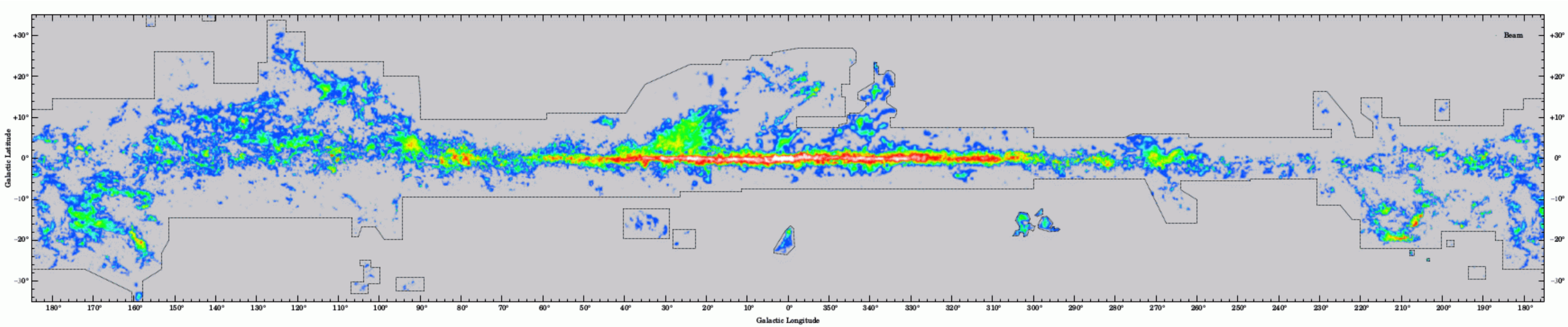
Probing the different phases

- Complementary data:
  - HI traces CNM and WNM
    - Only available at lower spatial resolution (11-16')
  - CO for molecular gas
    - Well covered
  - Dust for total column
    - Limited value



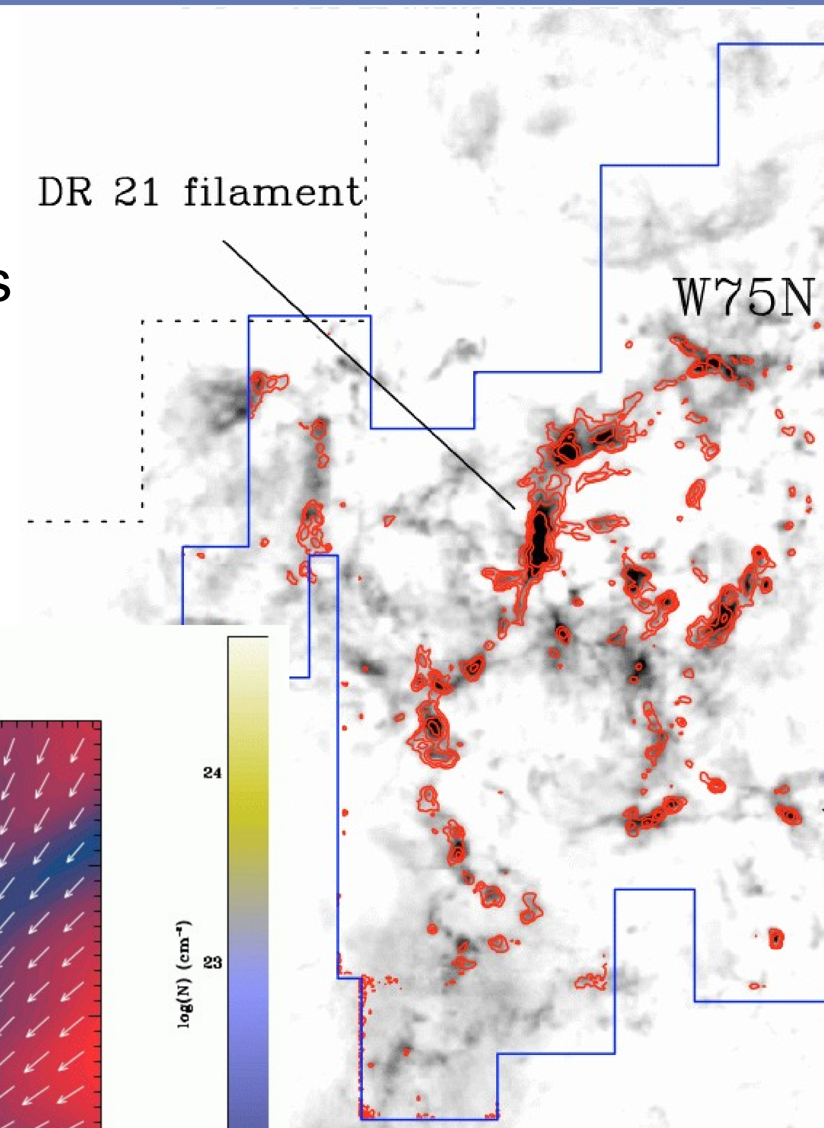
Tang et al. (2016)

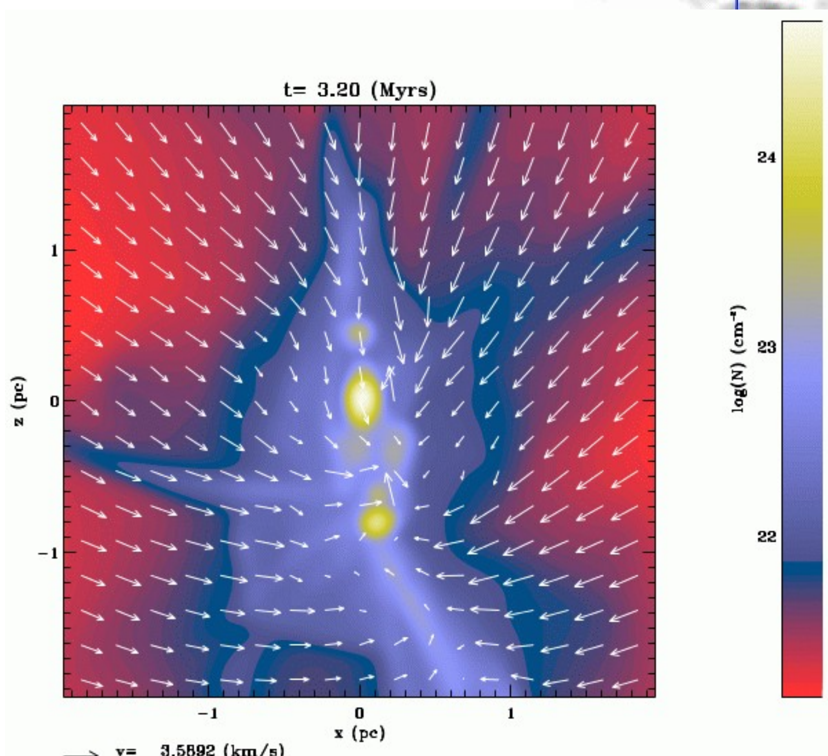
Dame (2001)



How are molecular clouds assembled?

- 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?
  - What is the infall velocity?
  - Does the infall create shocks?

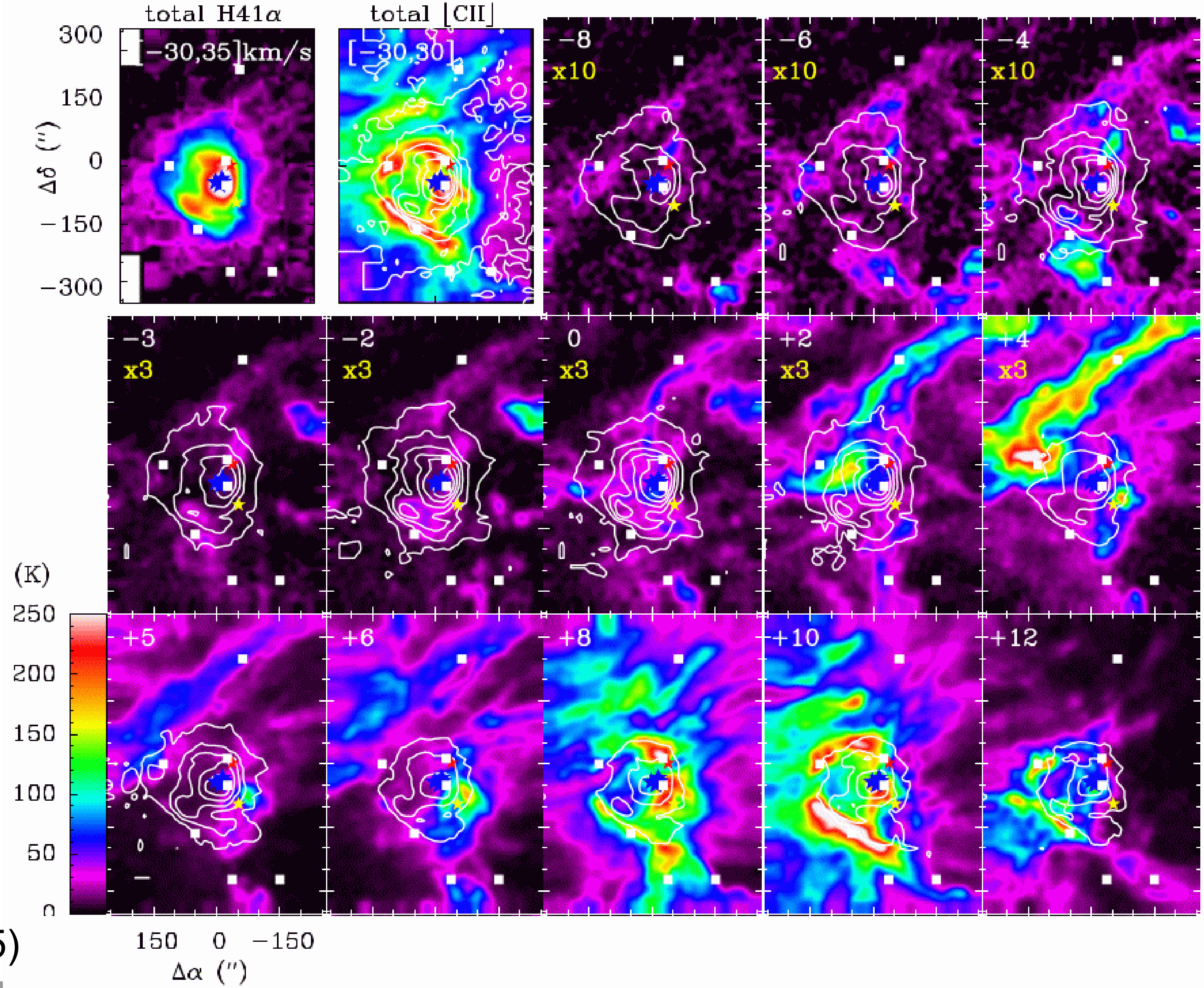




Schneider et al. (2010)

How are molecular clouds assembled?

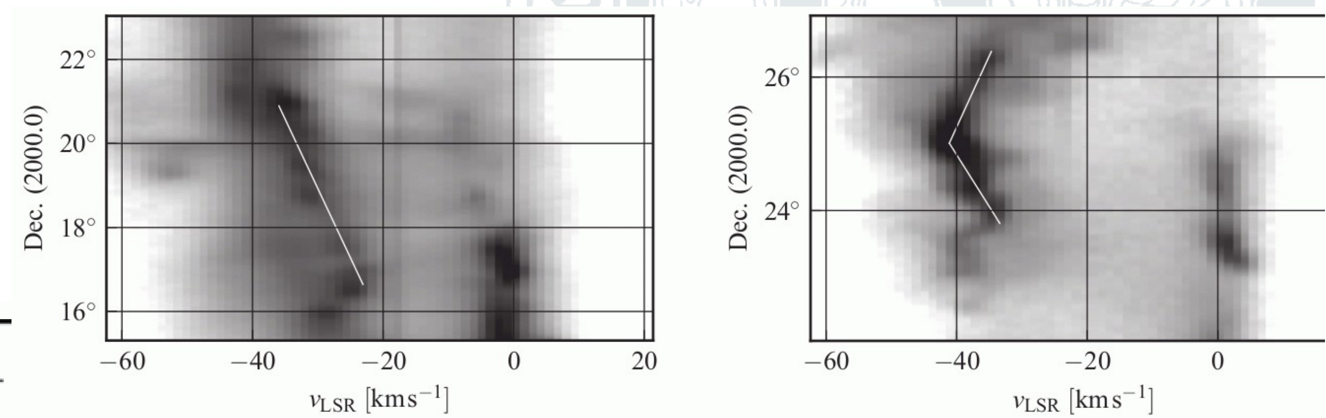
- Inflow as [CII] observed:
  - Orion A

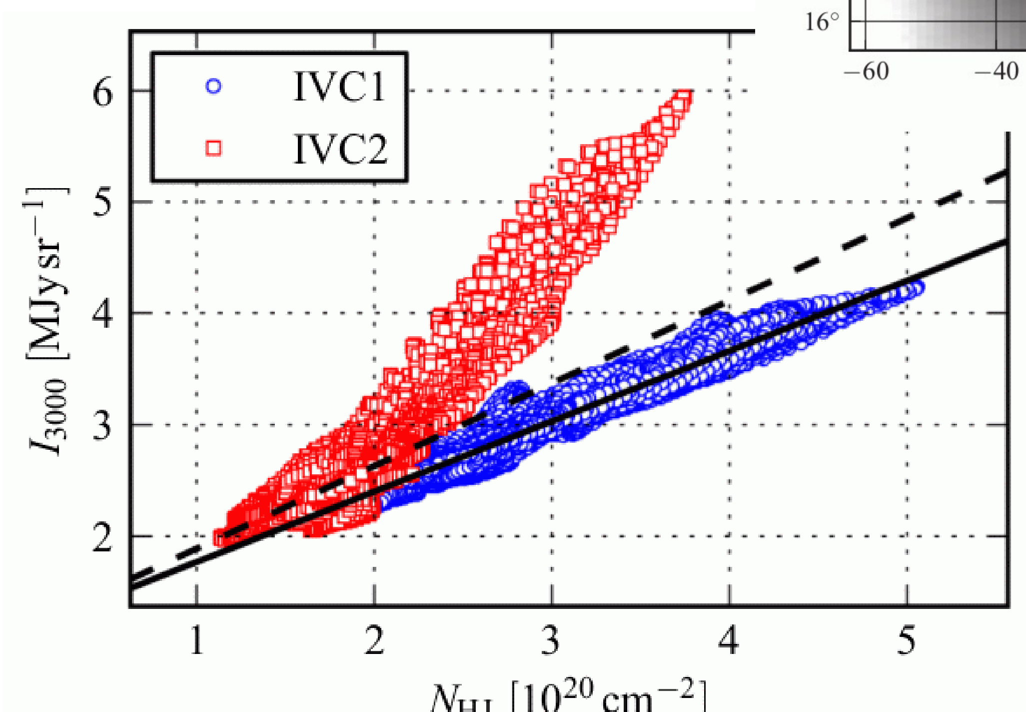


Goicoechea et al. (2015)

How are is the Milky Way ISM assembled?

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

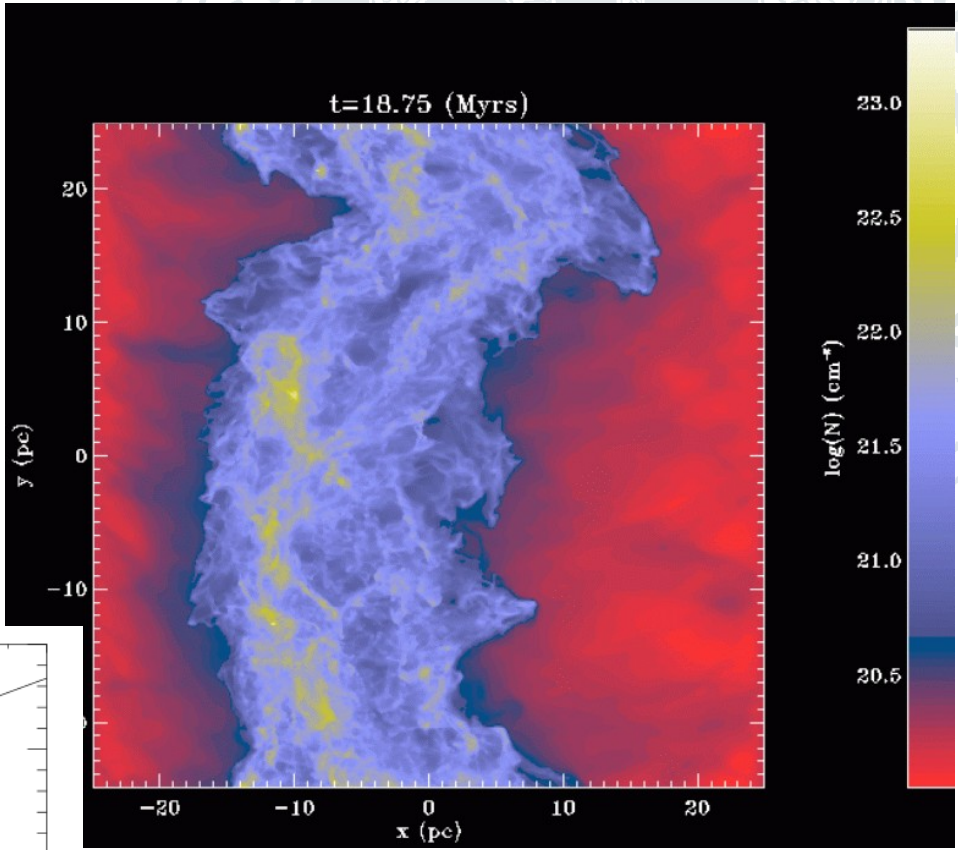




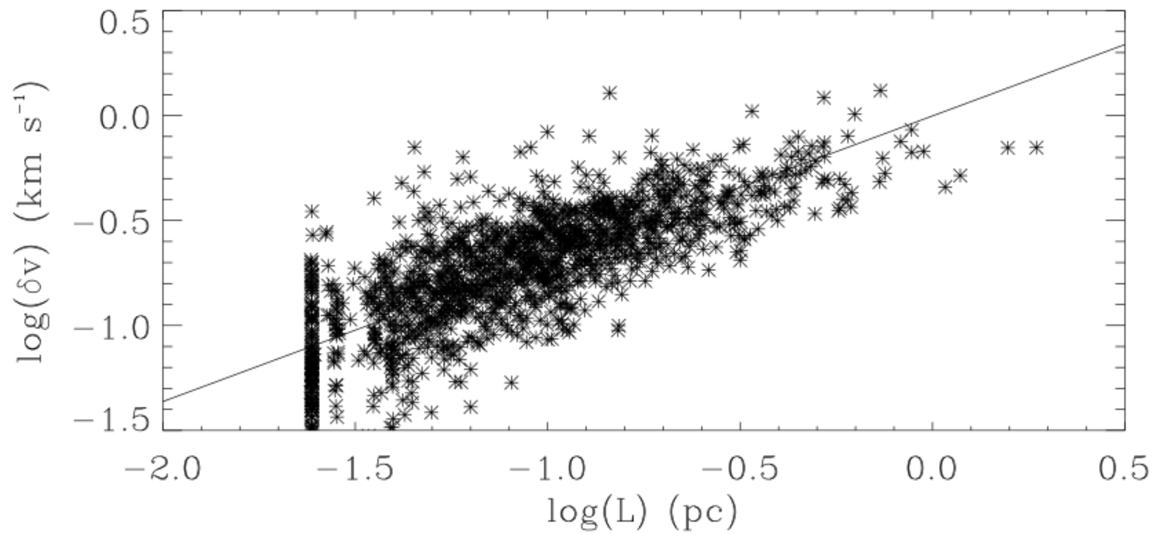
- 2 Intermediate-velocity clouds mapped by Röhser et al. (2014)
  - p-v-diagrams
  - Dust column vs. HI column (both clouds invisible in CO)
  - Material largely dark gas

How does the feeding drive interstellar turbulence?

- Colliding flows unavoidably create turbulence
  - Mach-number of infall?
  - Impact relative to Galactic shear?



Size-linewidth relation of clumps identified in colliding flow

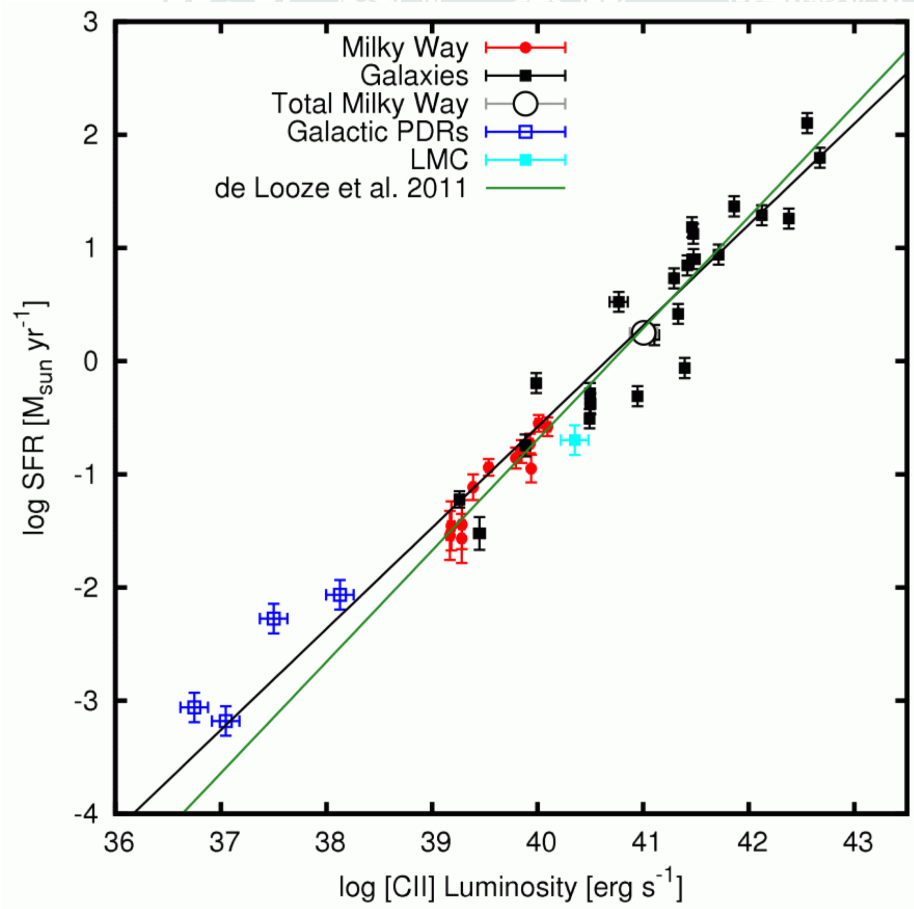


Colliding-flow simulation (column density map)

Klessen & Hennebelle (2010)

[CII] as a star-formation tracer

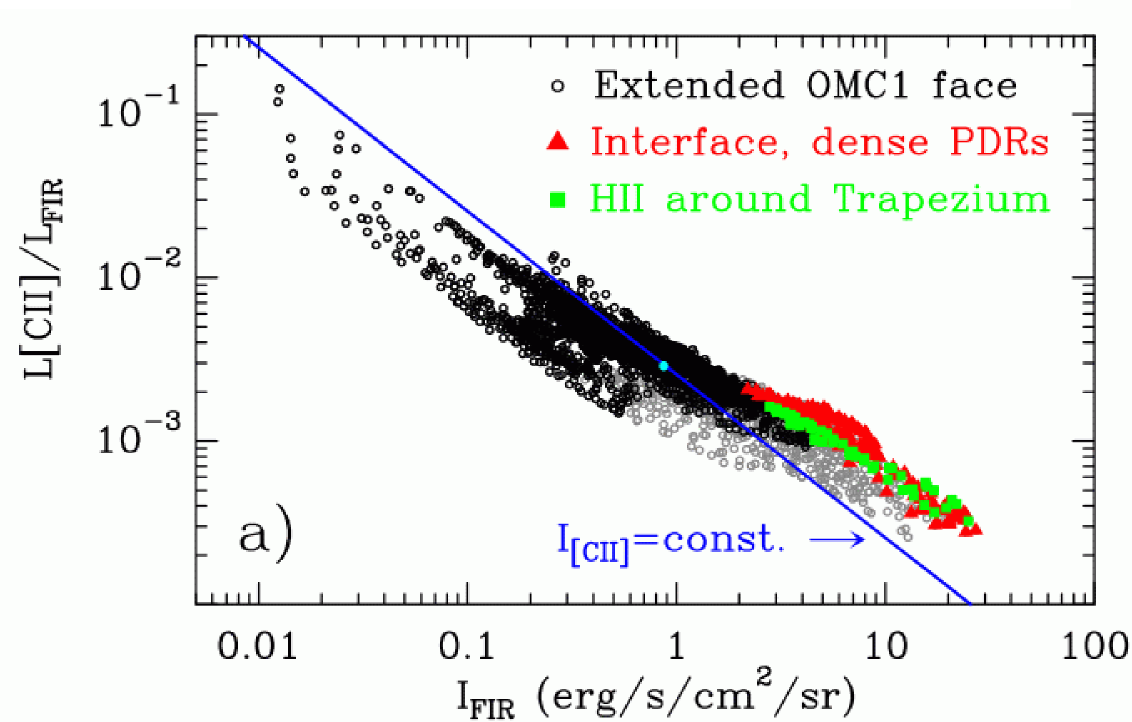
- C^+ in dense medium mainly produced and excited from FUV radiation
  - Highest efficiency: B stars
  - Therefore SF tracer for last 10Mio a
- But: Efficiency varying by factor > 100
  - FIR line deficit

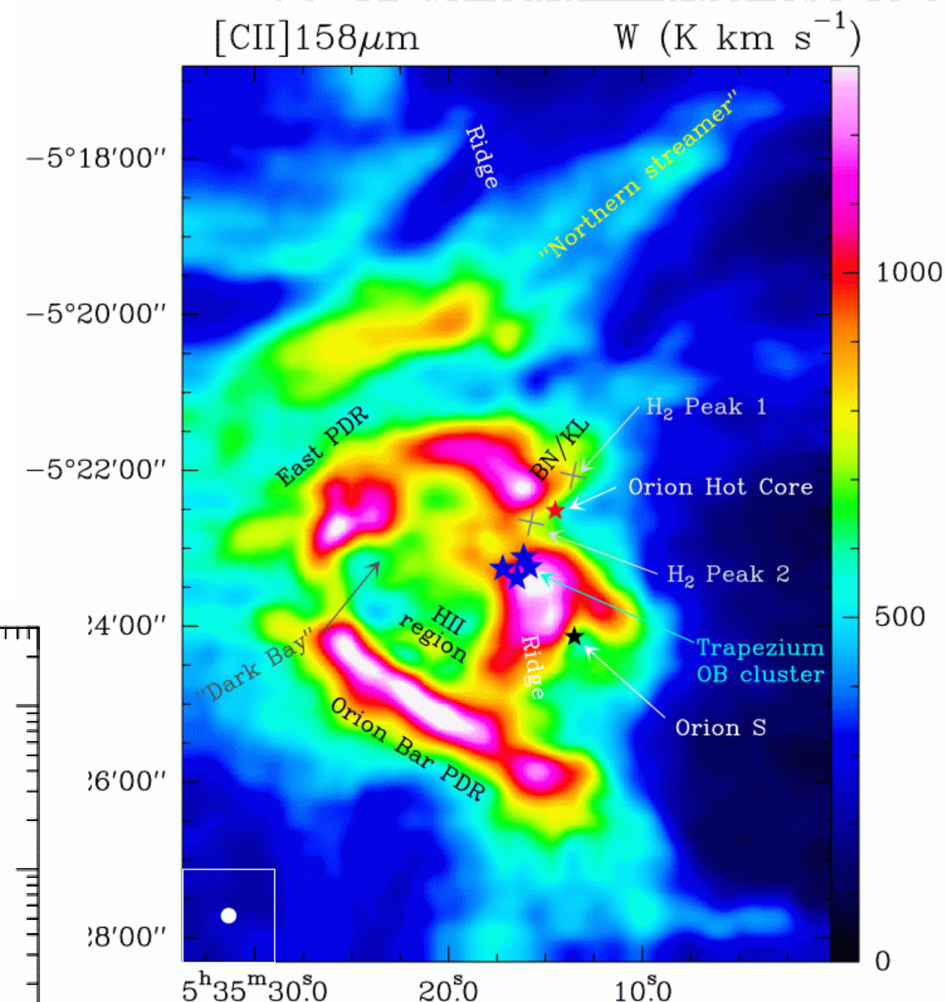


Pineda et al. (2014)

[CII] as a star-formation tracer

- Orion: [CII] dominated by widely distributed thin gas
- Contribution from SF small even in massive SF region
- Relative fraction on Milky Way scale unknown



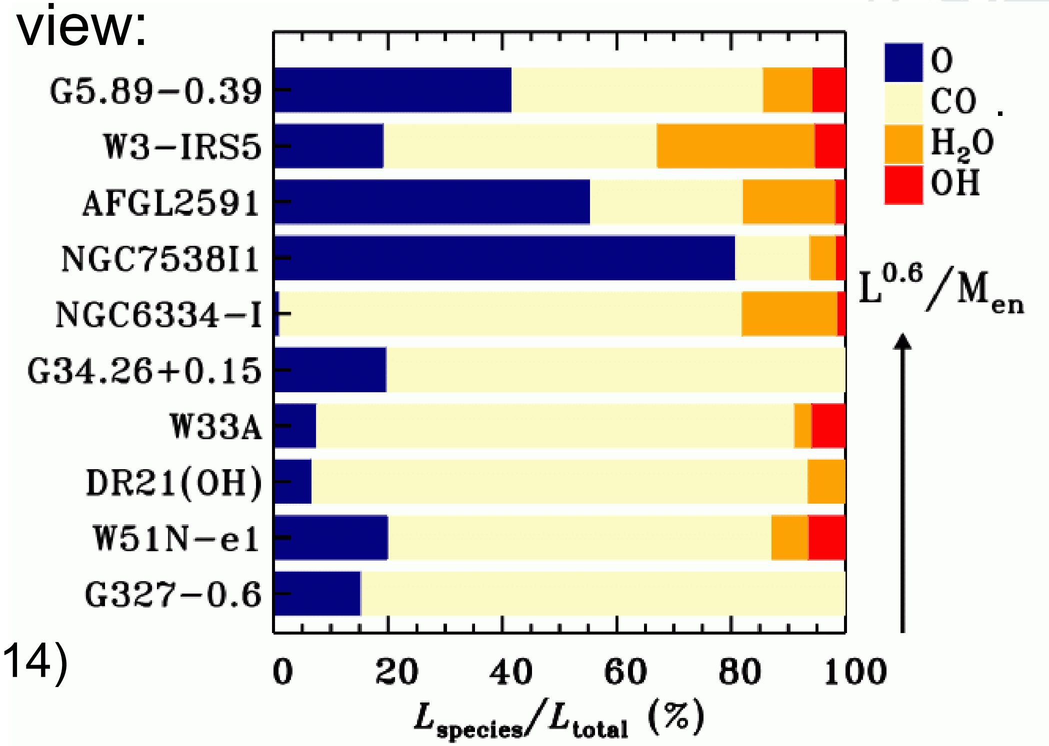


HIFI Orion map of [CII]

Goicoechea et al. (2015)

YSO line cooling dominated by [OI]:

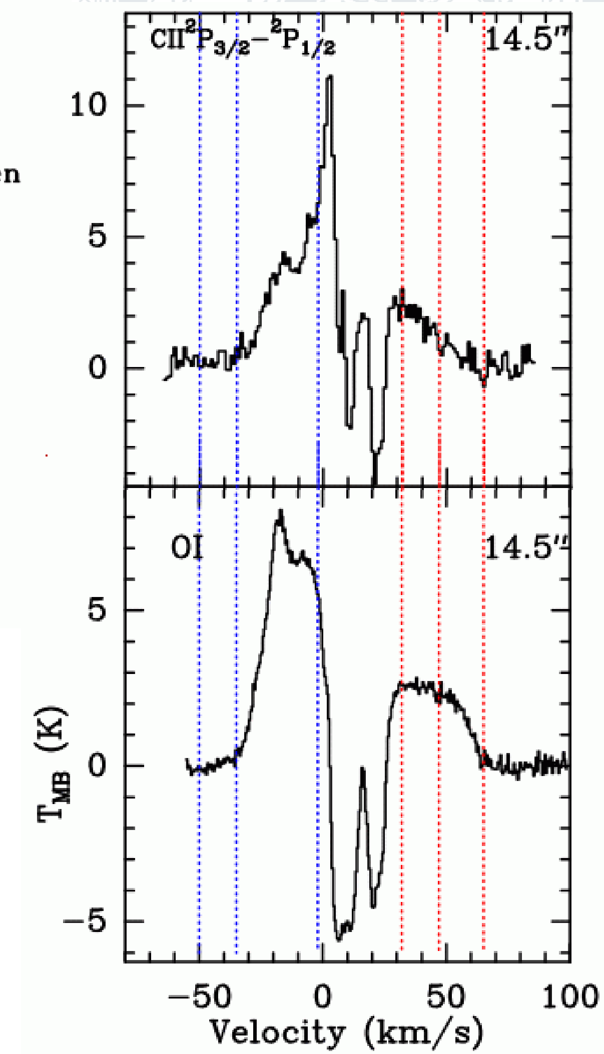
- The Herschel view:



Karska et al. (2014)

G5.89-0.39:

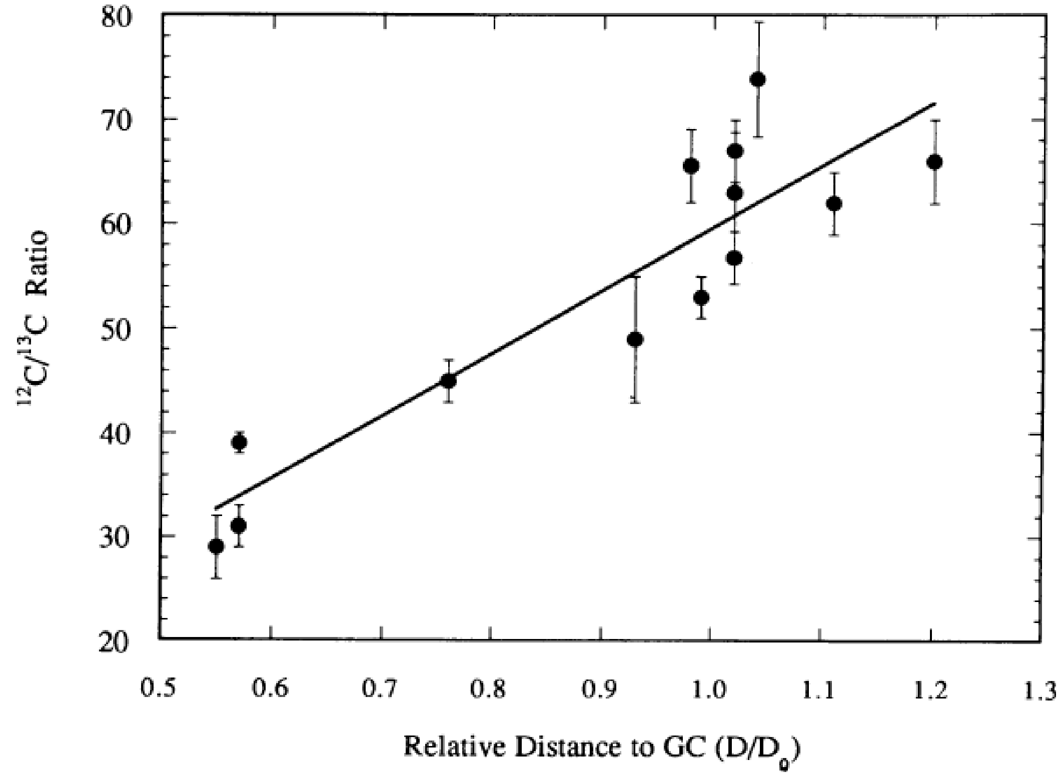
(Leurini et al. 2015)



- News from SOFIA:
  - Complex [OI] profile with broad wings
- Spectral resolution is the key!
- Explanation of FIR line deficit needs resolved lines

Decompose the Galaxy

- Distribution of fundamental elements: C, N, O
  - isotopes
- Census of atomic, ionic, and molecular material
- Cold and warm material above the Galactic plane

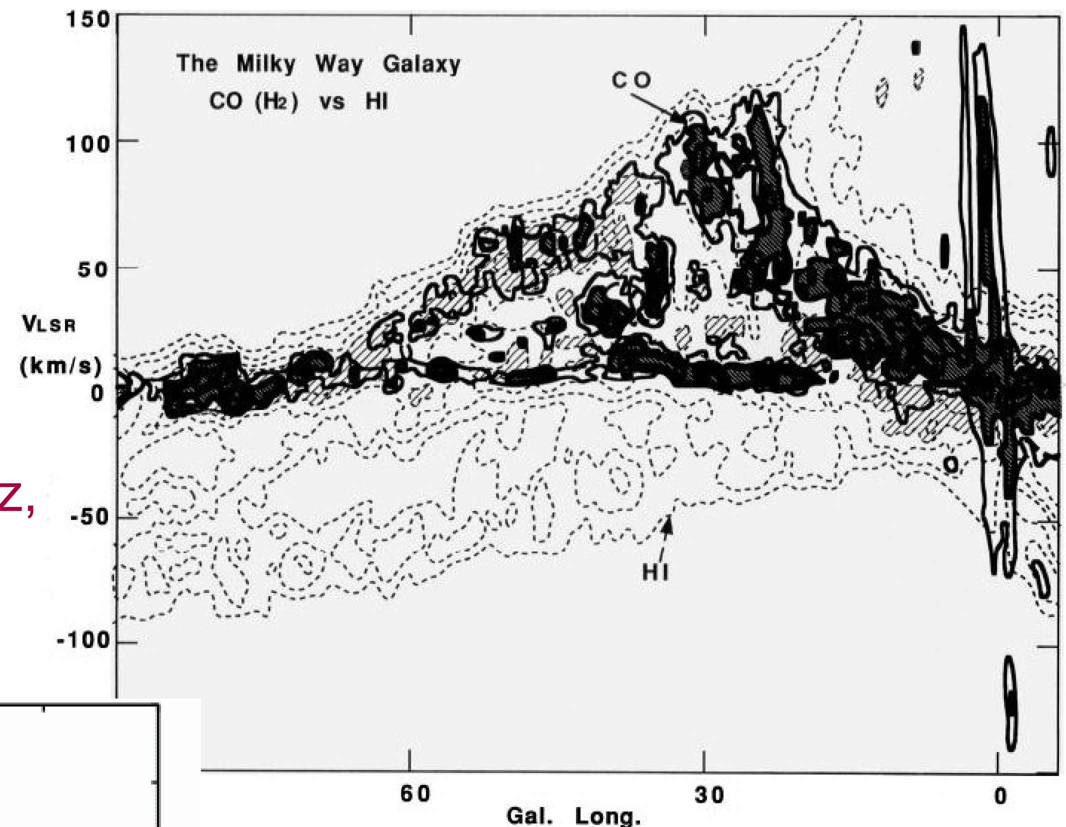


Langer & Penzias (1993)

Requirements

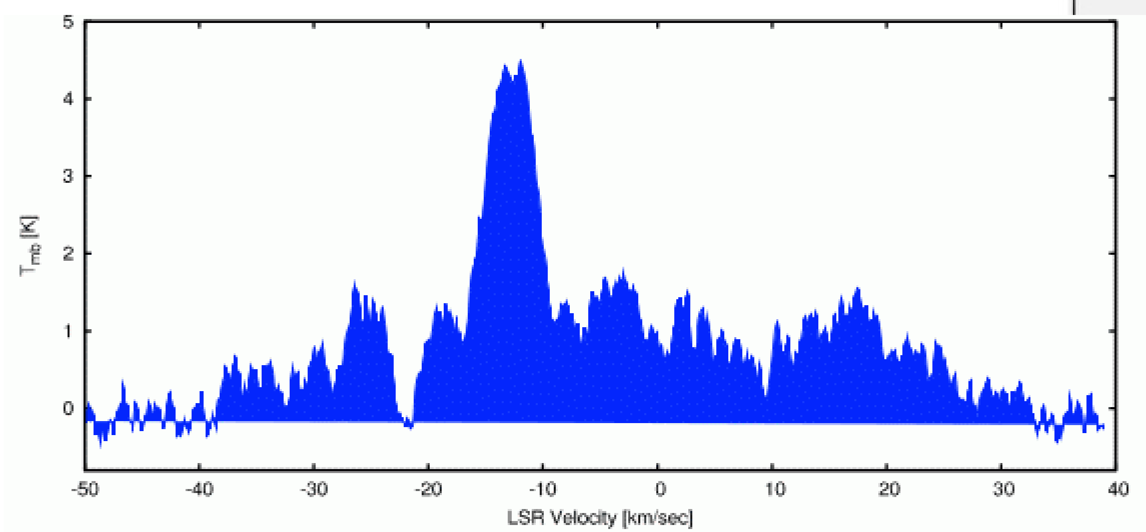
Velocity structure

- Cover at least Galactic rotation, i.e. > 400km/s
- [CII] probably also at higher velocities
- Required min. bandwidth: [CI] 1.4GHz, [NII] 2GHz, [CII] 3GHz, [OI] 7GHz



Velocity distribution of HI and CO 1-0 at *b*=0 (Sofue et al. 1995)

- Many components as narrow as 2-3km/s
- Needs velocity resolution of 0.3km/s to resolve details of line structure



[CII] Spectrum towards massive SF region G345.65+0.0 (Pineda et al. 2010)

Practical approach

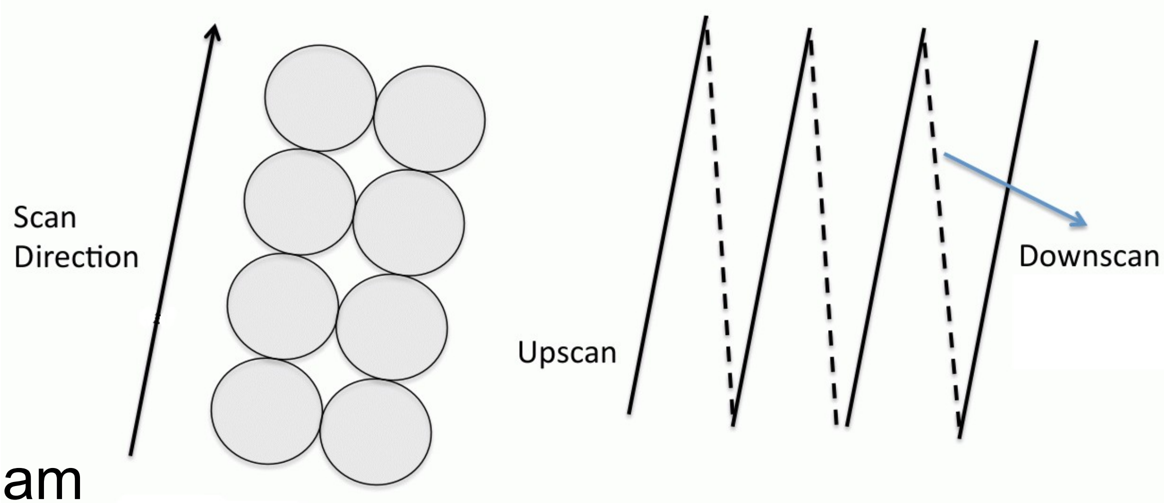
Band	Bandwidth [GHz]	= km/s	Number of channels	= resolution [km/s]	= [MHz]
CI	2.0	741	2048	0.36	1.0
NII	3.0	616	2048	0.30	1.5
CII	4.0	631	2048	0.31	1.9
OI	4.0	253	1024	0.25	3.9

- Additional coverage of CO 7-6 line still to be specified
- Science data volume per dump: 196608 bits
- Open question:
  - Postprocessing in ICU or adjusted FFT readout

Observing strategy

Full coverage of the 10° strip:

- $3600°^2/0.86'^2 = 1.752\ 10^7$
- 1 year coverage
  or 6 month coverage
  with 2 pixels:
  - 1.8s/beam
  - Without overheads: 1.6s/beam
  - Reasonable science data rate: 123kbit/s



- Problem: Reference measurement needed
  - Calibration unit
  - Provides missing spots on the sky

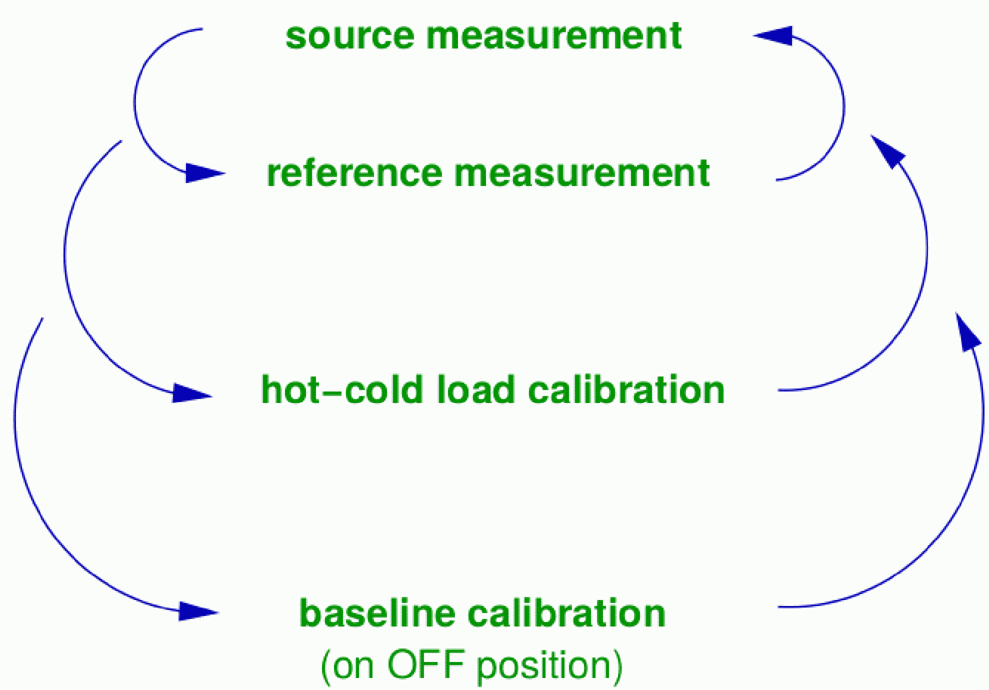
Composition of observing modes

Hierarchical structure of reference and calibration loops:

Reference loop
length determined by system Allan time t_A

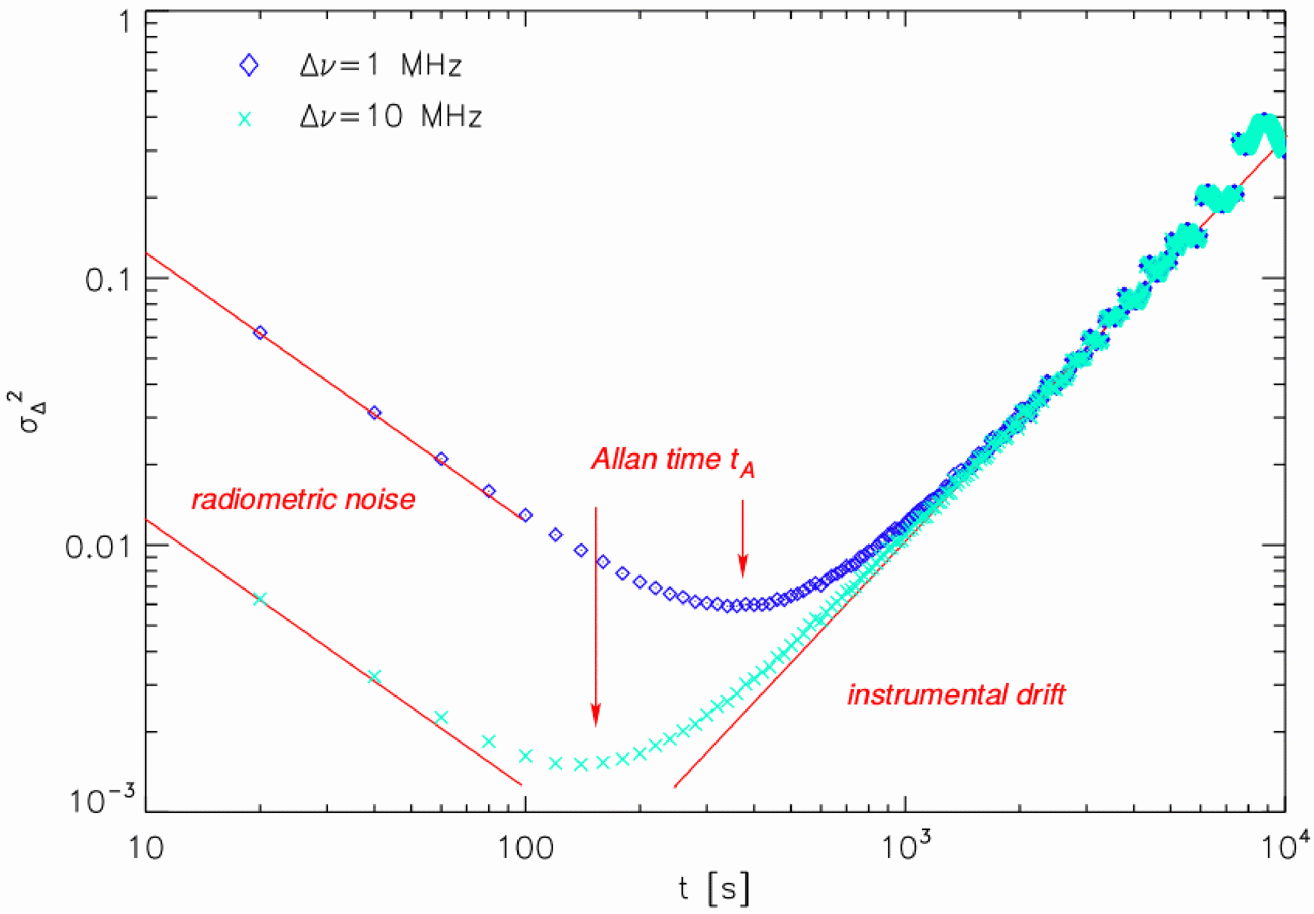
Bandpass calibration loop
length determined by band-pass stability time $t_{A,\mathrm{load}}$

Baseline calibration loop
length determined by standing wave Allan time $t_{A,\mathrm{sw-diff}}$



The three different Allan times determine the period of the three loops.

The Allan time depends on the frequency resolution



- The minimum is given by the balance between radiometric noise and instrumental drift
- Radiometric noise depends on the fluctuation bandwidth
  → The loop timing depends on the desired frequency resolution of the observation

Observing strategy

Expected stability at goal resolution

- > 80s
- OTF reference strategy:
  - Cold-load measurement every 80-150s
  - Duration

Spatial goal resolution	Period [s]	OFF time [s]
0.86'	80	10.5
0.86'	150	14.5
2.4'	80	19.5
2.4'	150	25.0

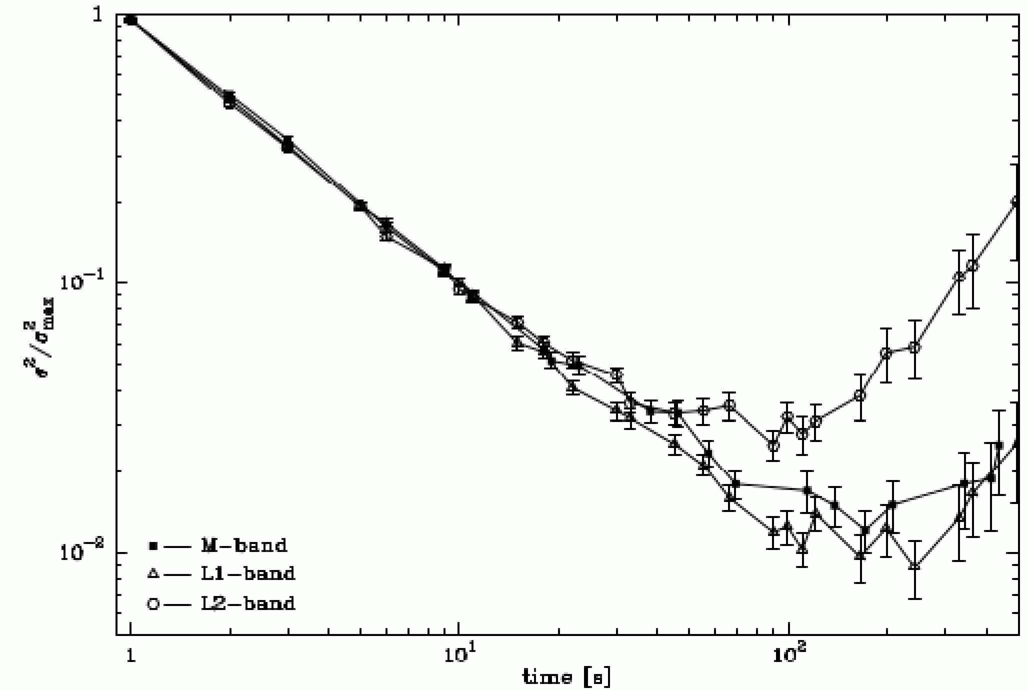


Fig. 7. Spectroscopic Allan variance plots for bands L1, L2 and M, calculated between two AFFTS channels separated by 750 MHz. The channel width was set to 850 kHz.

Noise contribution: 5% - 12%

- Significant gaps: No problem for science if they coincide for all bands

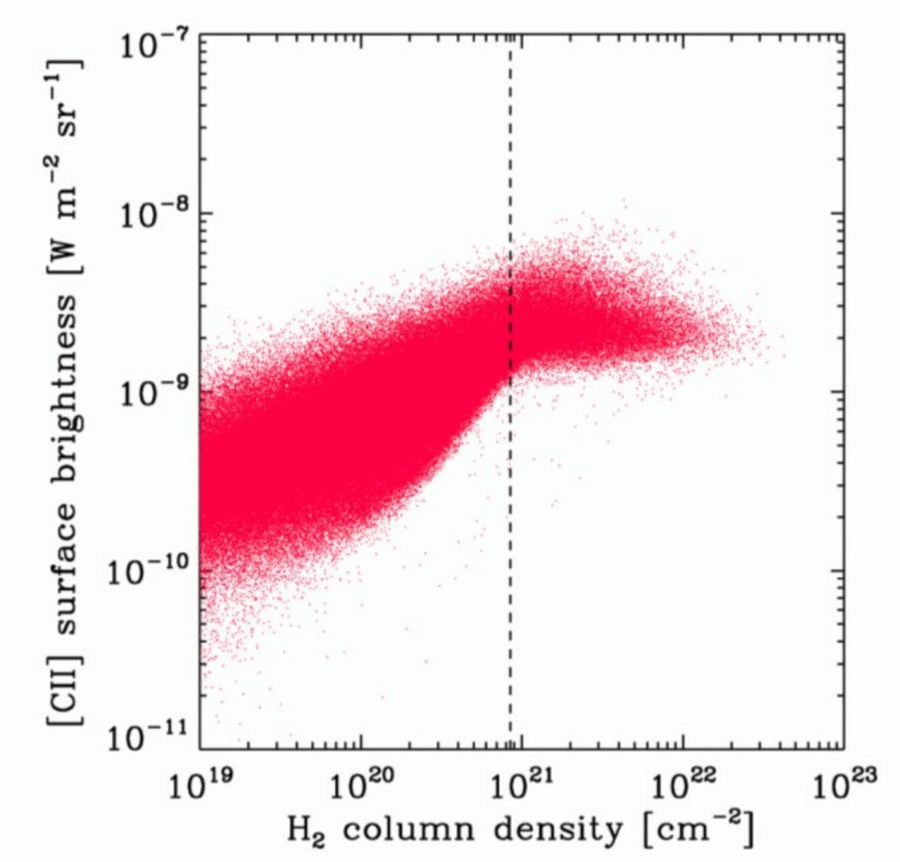
Sensitivities

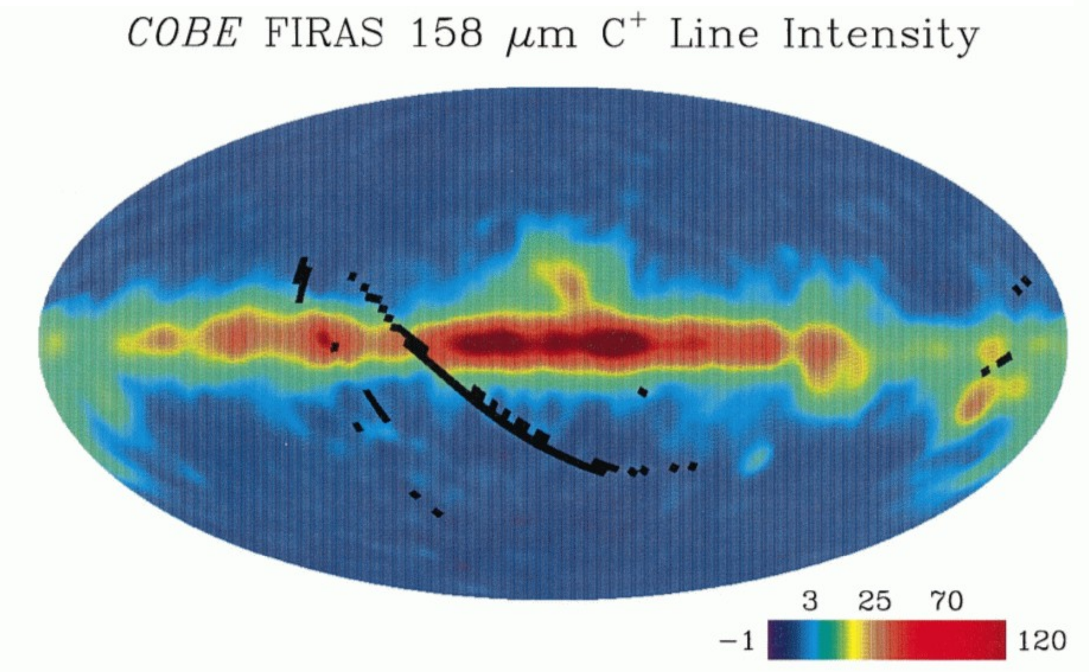
Milky Way simulations by Glover et al. (2015,16):

- Narrow lines
  - 1nW m^{-2} sr^{-1} ≈ 0.07 K (CII)

COBE (Fixsen et al. 1999)

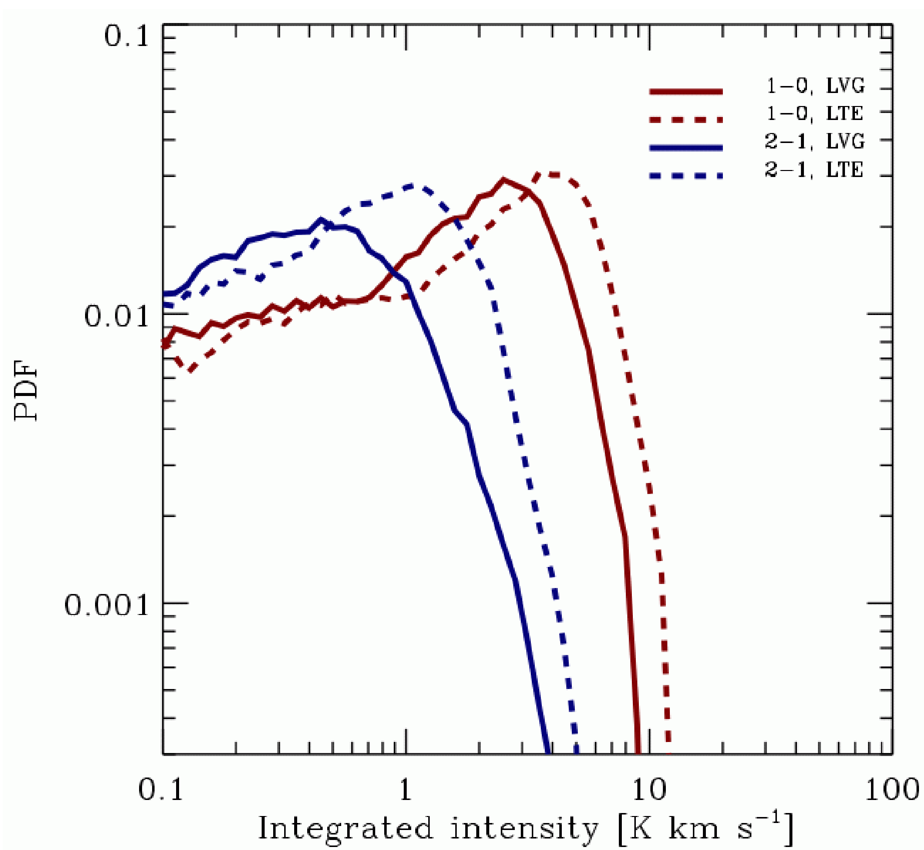
- Broad lines with many components
  - Full plane above 7nW m^{-2} sr^{-1}

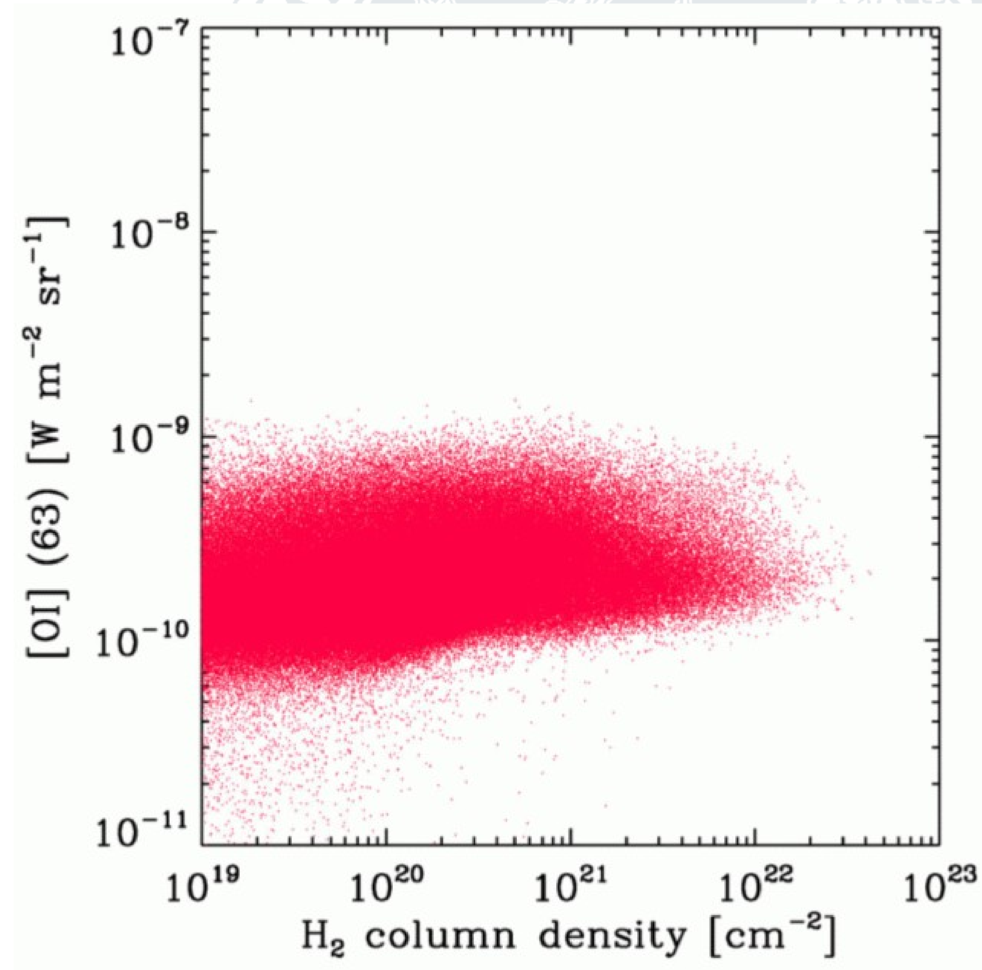




Milky Way simulations by Glover et al. (2015,16):

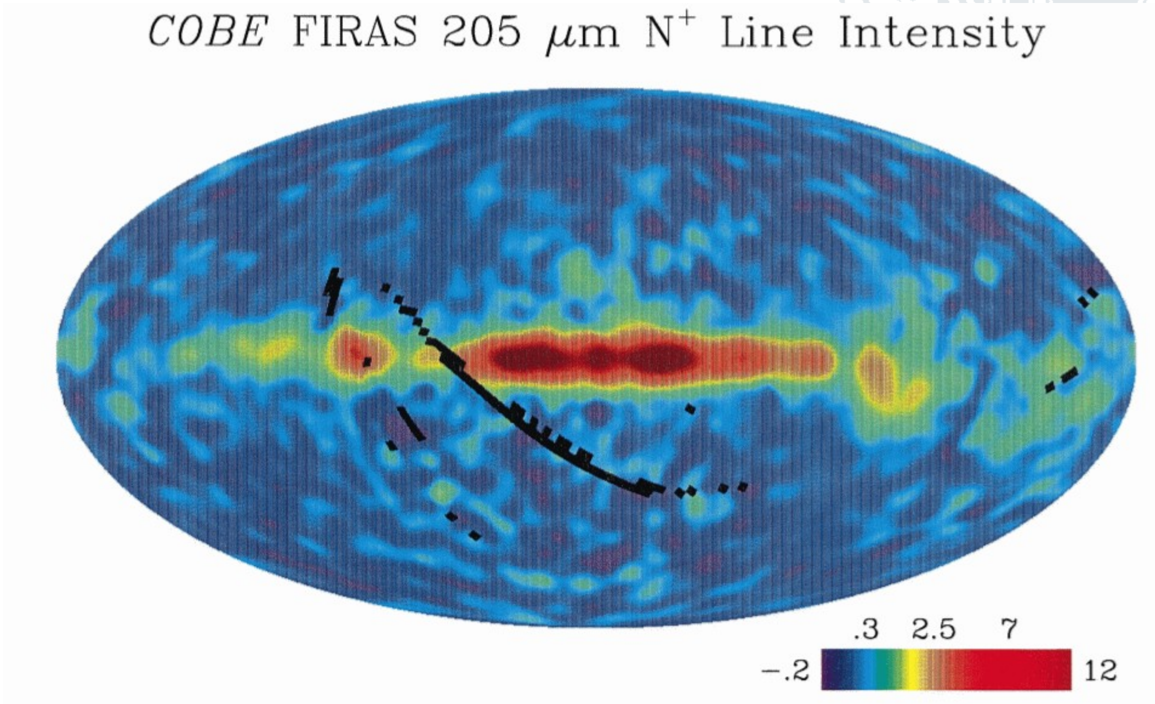
- Narrow lines
  - 1nW m^{-2} sr^{-1} ≈ 0.005 K (OI)
  - CI peaks at 0.25 K





COBE (Fixsen et al. 1999):

- Broad lines with many components
  - Large fraction of the plane above 1nW m^{-2} sr^{-1}
  - Narrow-line translation: 1nW m^{-2} sr^{-1} ≈ 0.16 K (NII) (favourable)



Sensitivities

Estimates based on proposed technology and 2 years survey:

	CI	NII	CII	OI
Line frequency [GHz]	809.3	1461.3	1900.5	4745.8
System temperature (DSB) [K]	180	350	400	500
Bandwidth for 0.3km/s [MHz]	0.8	1.4	1.9	4.7
Beam width [arcmin]	1.71	0.86	0.86	0.8
Noise T_{mb} (for long ref., η=0.79) [K]				
$\Delta v = 0.3$ km/s, $t_{int} = 1.6$s, $\theta = \theta_{native}$	0.20	0.58	0.58	0.46
$\Delta v = 0.8$ km/s, $t_{int} = 1.6$s, $\theta = \theta_{native}$	0.12	0.35	0.35	0.28
$\Delta v = 0.8$ km/s, $t_{int} = 3.2$s, $\theta = \theta_{native}$	0.087	0.25	0.25	0.20
$\Delta v = 0.8$ km/s, $t_{int} = 3.2$s, $\theta = 2.4'$	0.061	0.090	0.090	0.066
$\Delta v = 0.8$ km/s, $t_{int} = 3.2$s, $\theta = 2.4'$, 2 pixel	0.061	0.064	0.064	0.047

Averaging over larger area needed for [^{13}CII]

Summary

- [CII]: All science goals can be achieved from a 2 years survey on a 2.4' spatial scale
- [NII]: Detection of all extended HII regions, diffuse WIM probably only on much lower effective resolution
- [OI]: Emission bright from PDRs, but very concentrated, no detection from diffuse gas expected, optical depth correction challenging
- [CI]: All dense cloud boundaries expected, diffuse gas probably not

Open issues:

- OFF duration depends on spatial goal resolution
- OFF period depends on spectral goal resolution
- Effect of gaps in coverage must be minimized
- Sensitivity computations here still with favourable assumptions