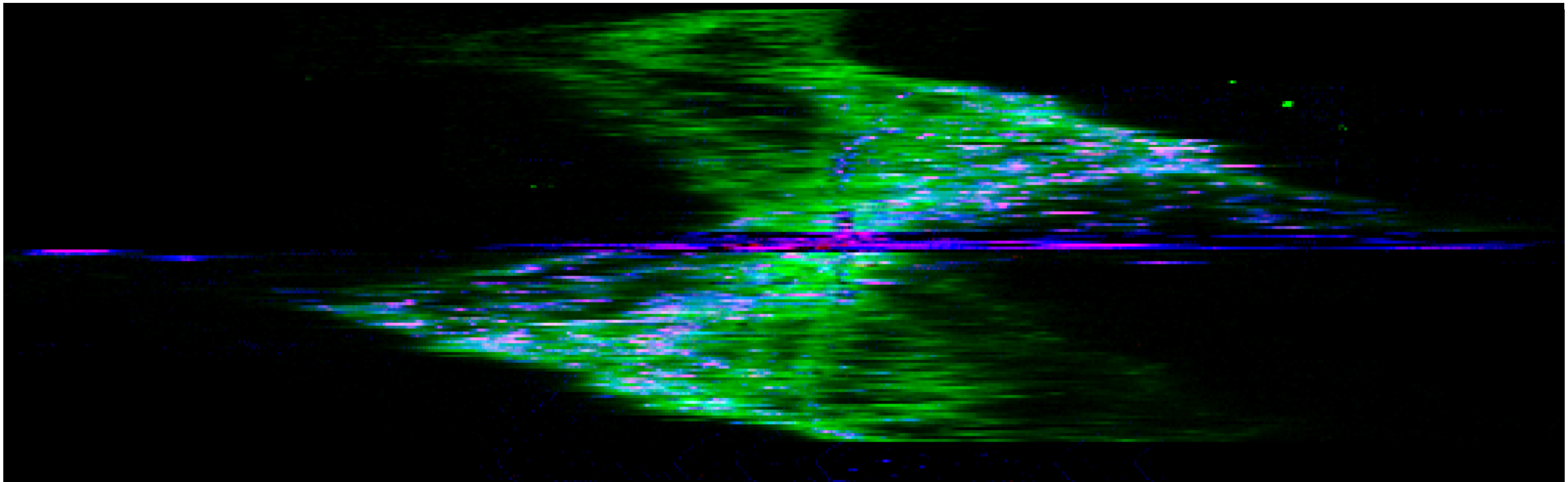


What We Learned from Surveying the Galaxy in [CII] with Herschel HIFI

Paul F. Goldsmith

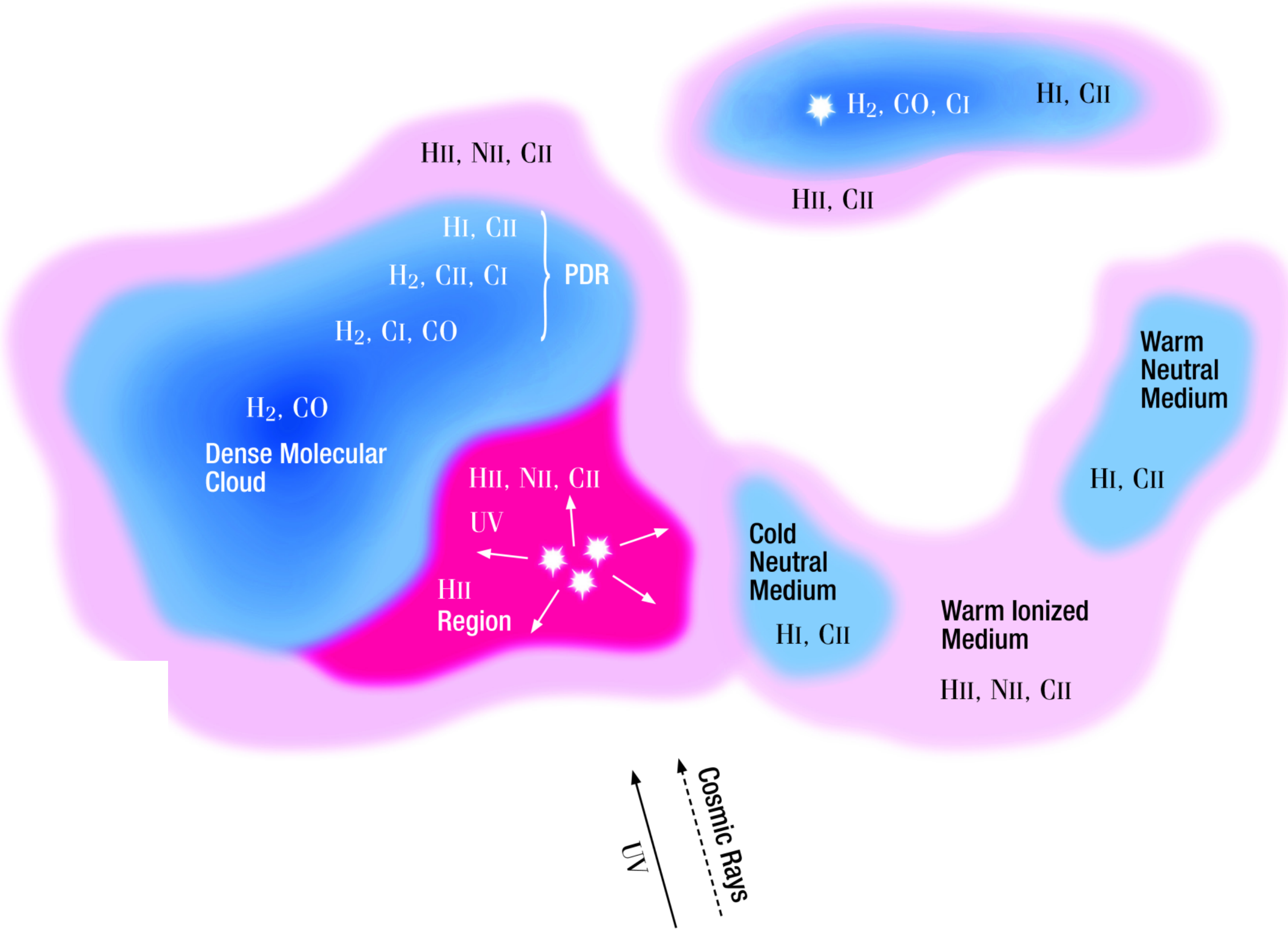
Jet Propulsion Laboratory, California Institute of Technology

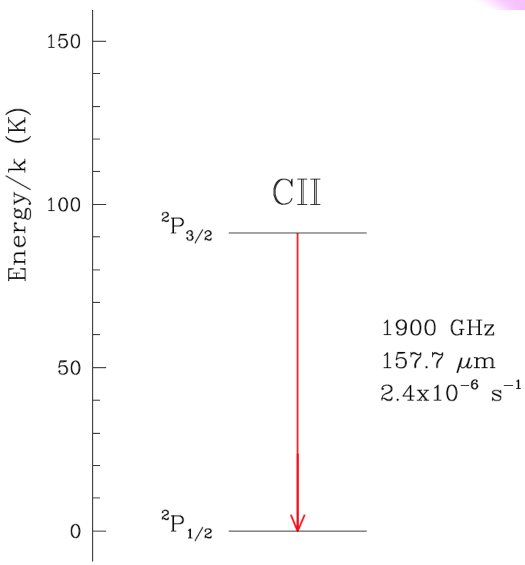
October 2013

For the GOT C+ Team-

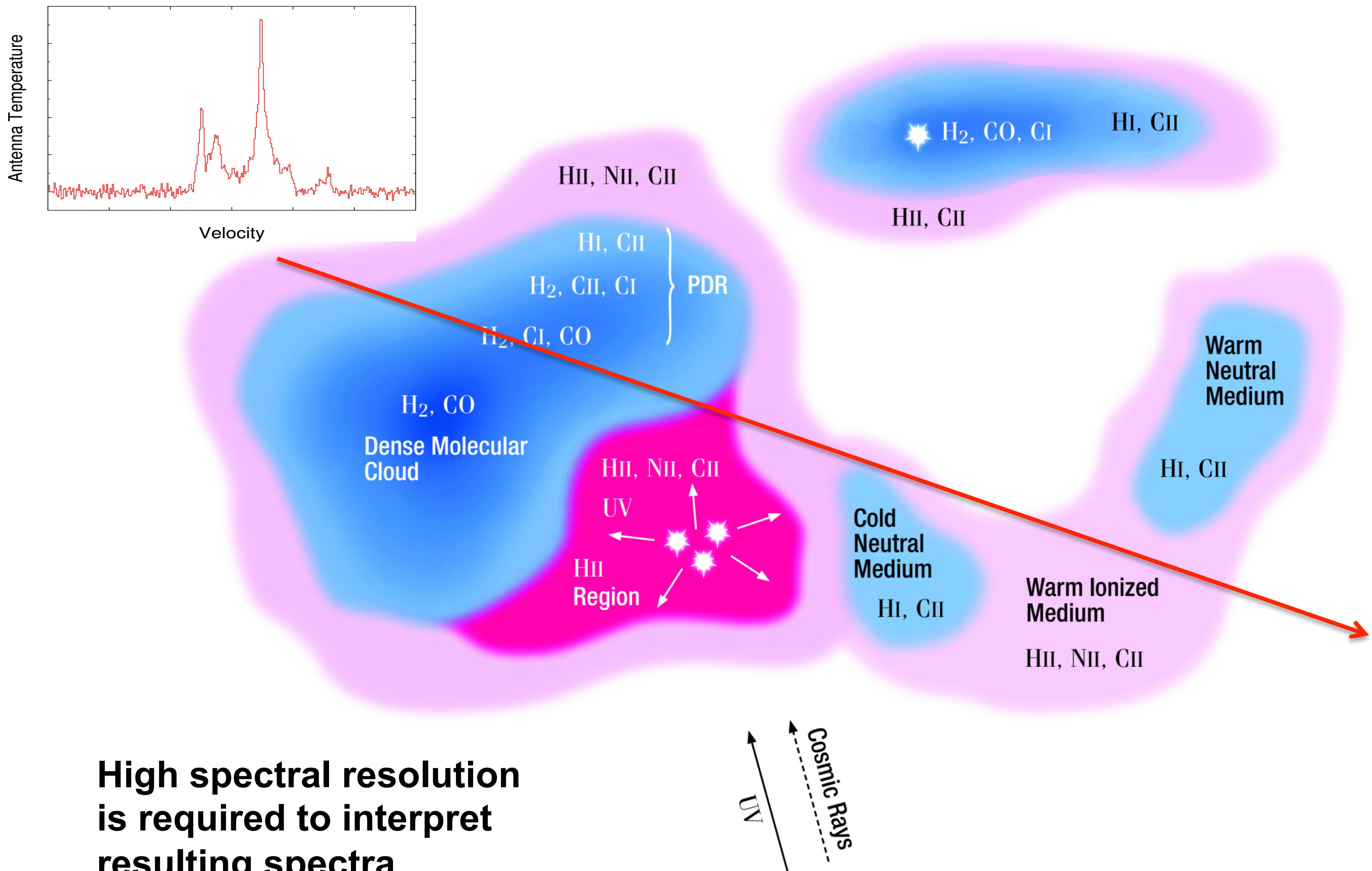
William Langer, Jorge Pineda, Thangasamy Velusamy, and Paul Goldsmith

The Interstellar Medium is Diverse and Complex…



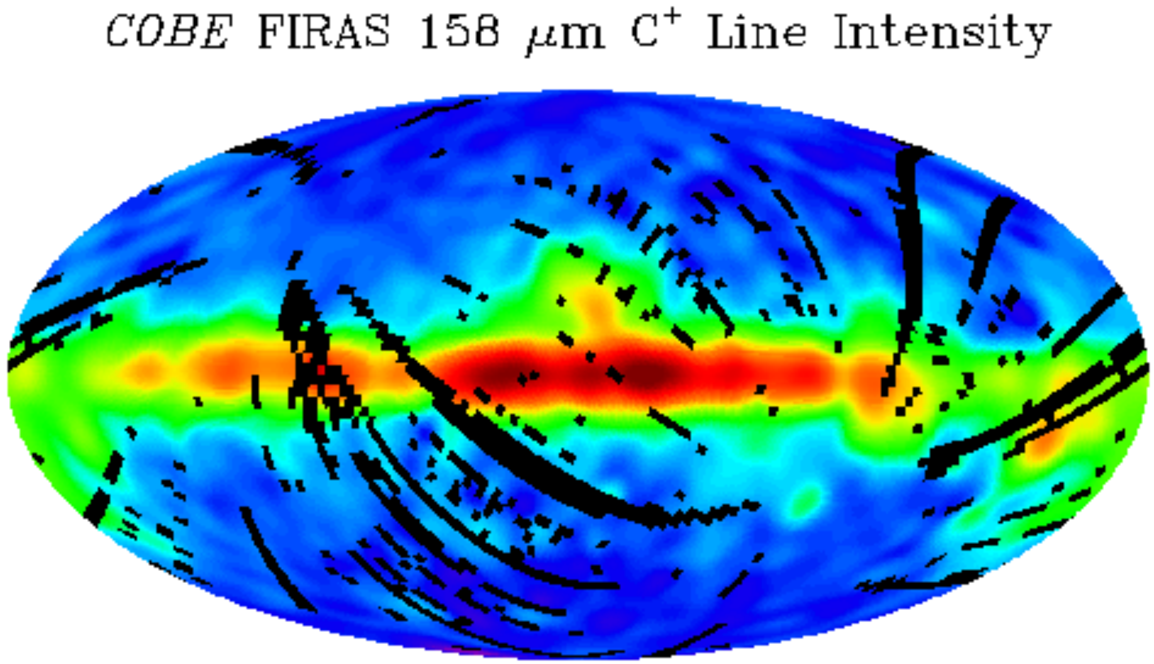


The fine structure transition of C^+ at 158µm traces many components of the ISM



High spectral resolution is required to interpret resulting spectra

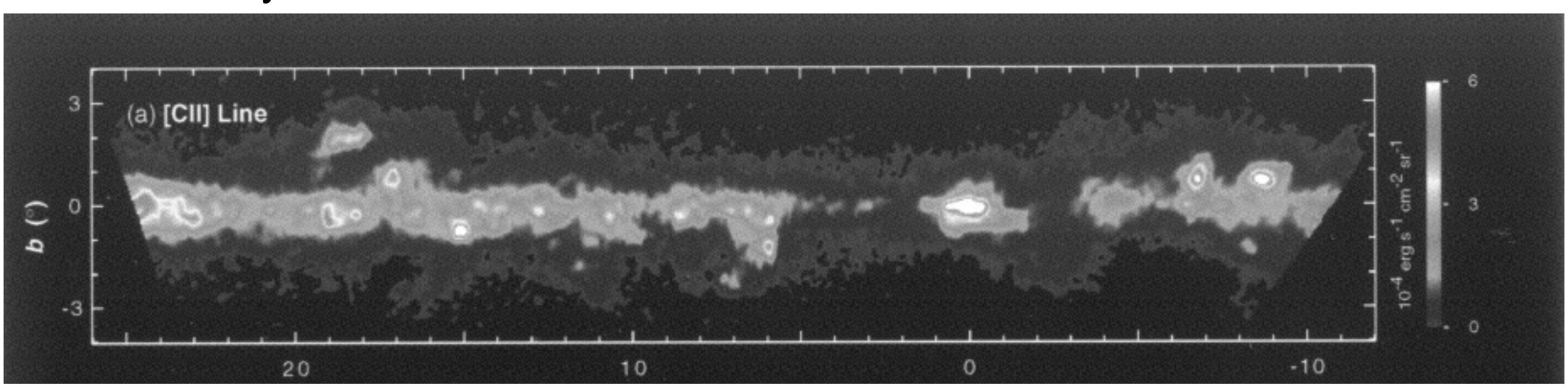
COBE/FIRAS;
7 deg angular resolution;
1000 km/sec velocity resolution



Origin?

WIM (Heiles et al. 1994)
CNM (Bennett et al. 1994)
PDRs (e.g. Cubick et al. 2008)

BICE;
15 arcmin angular resolution;
175 km/sec velocity resolution

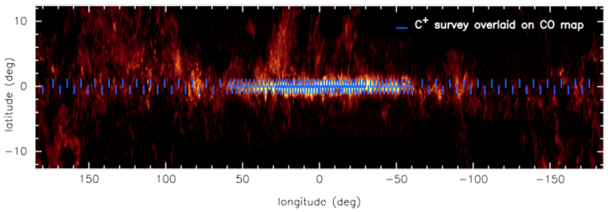


Galactic Longitude [Degrees]

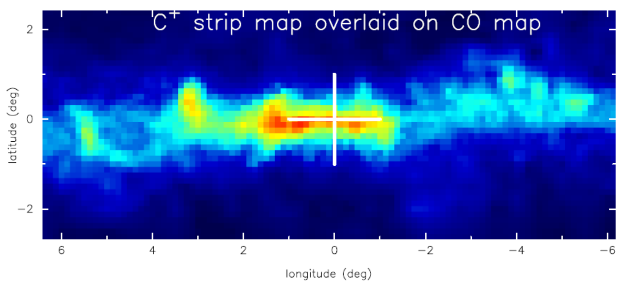
GOT C+ [CII] 1.9 THz Survey

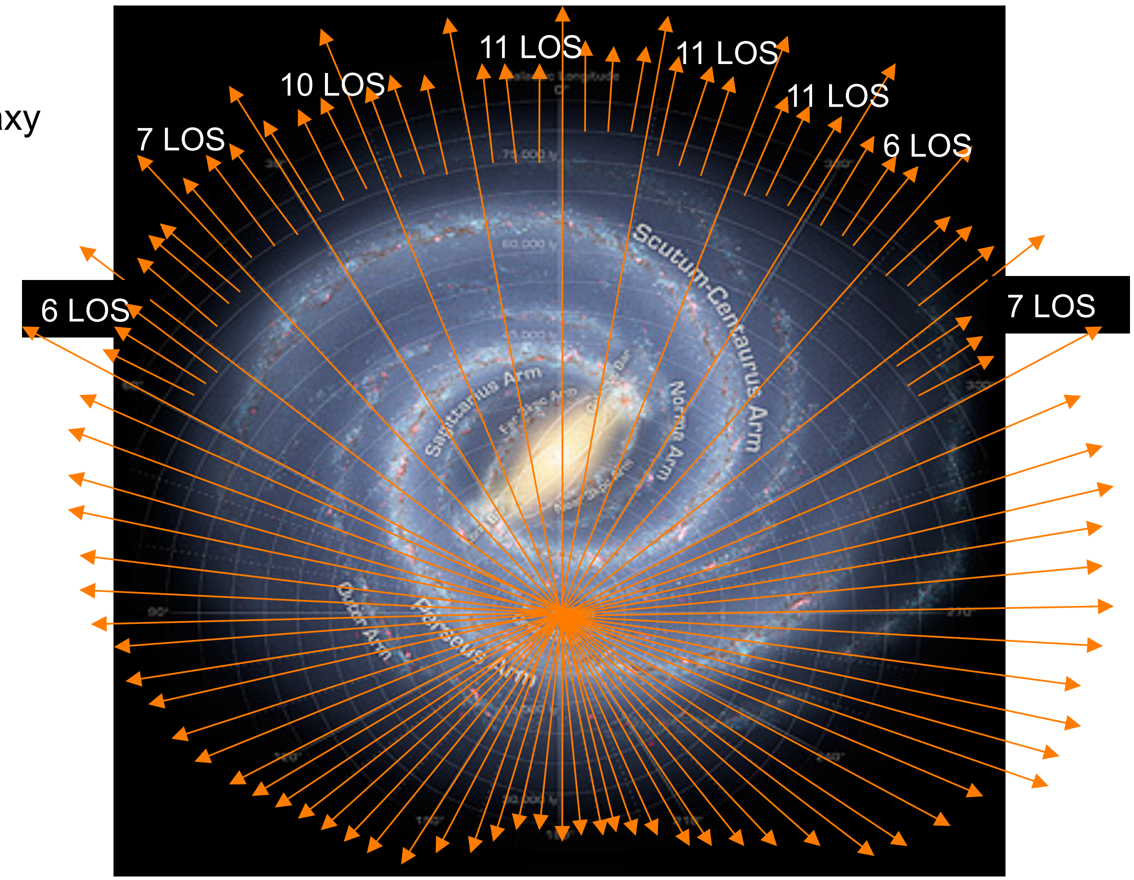
Galactic Plane Survey - systematic volume weighted sample of ≈500 LOSs in the disk

- Concentrated towards inner Galaxy
- Sampled *l* at *b* = 0º, +/- 0.5º & 1º

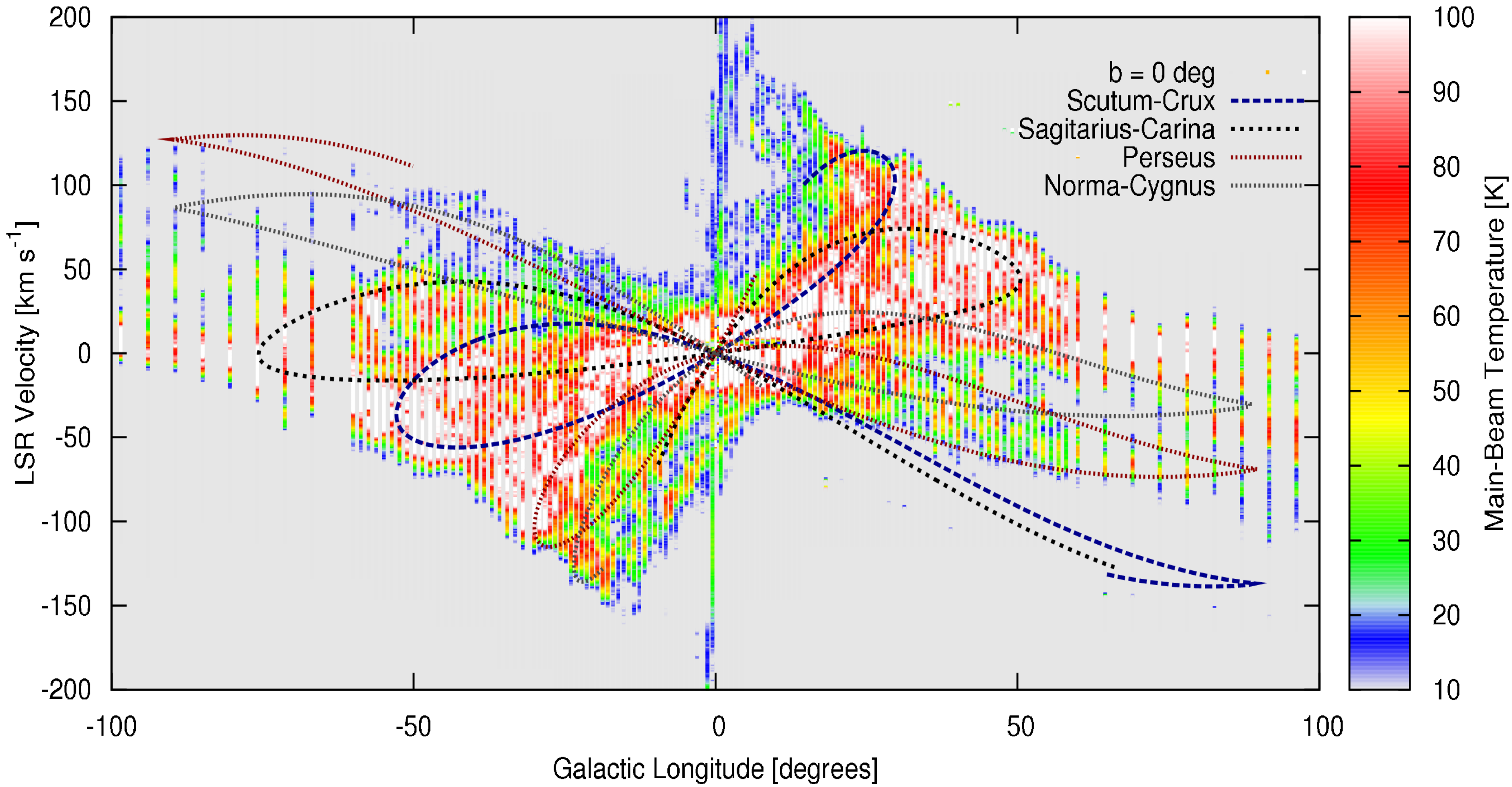


Galactic Central Region: CII strip maps sampling ≈300 positions in On The Fly (OTF) mapping mode.

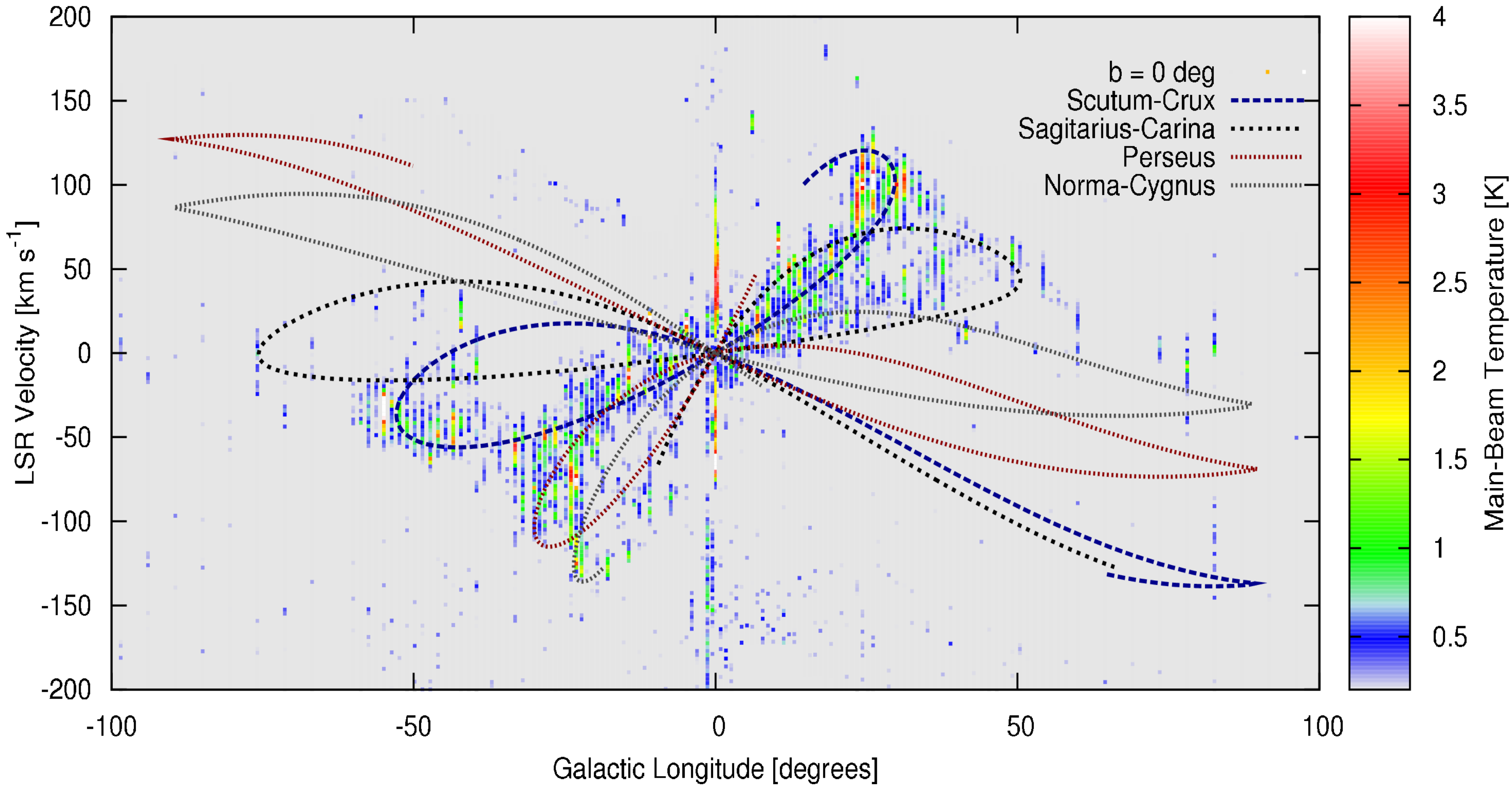




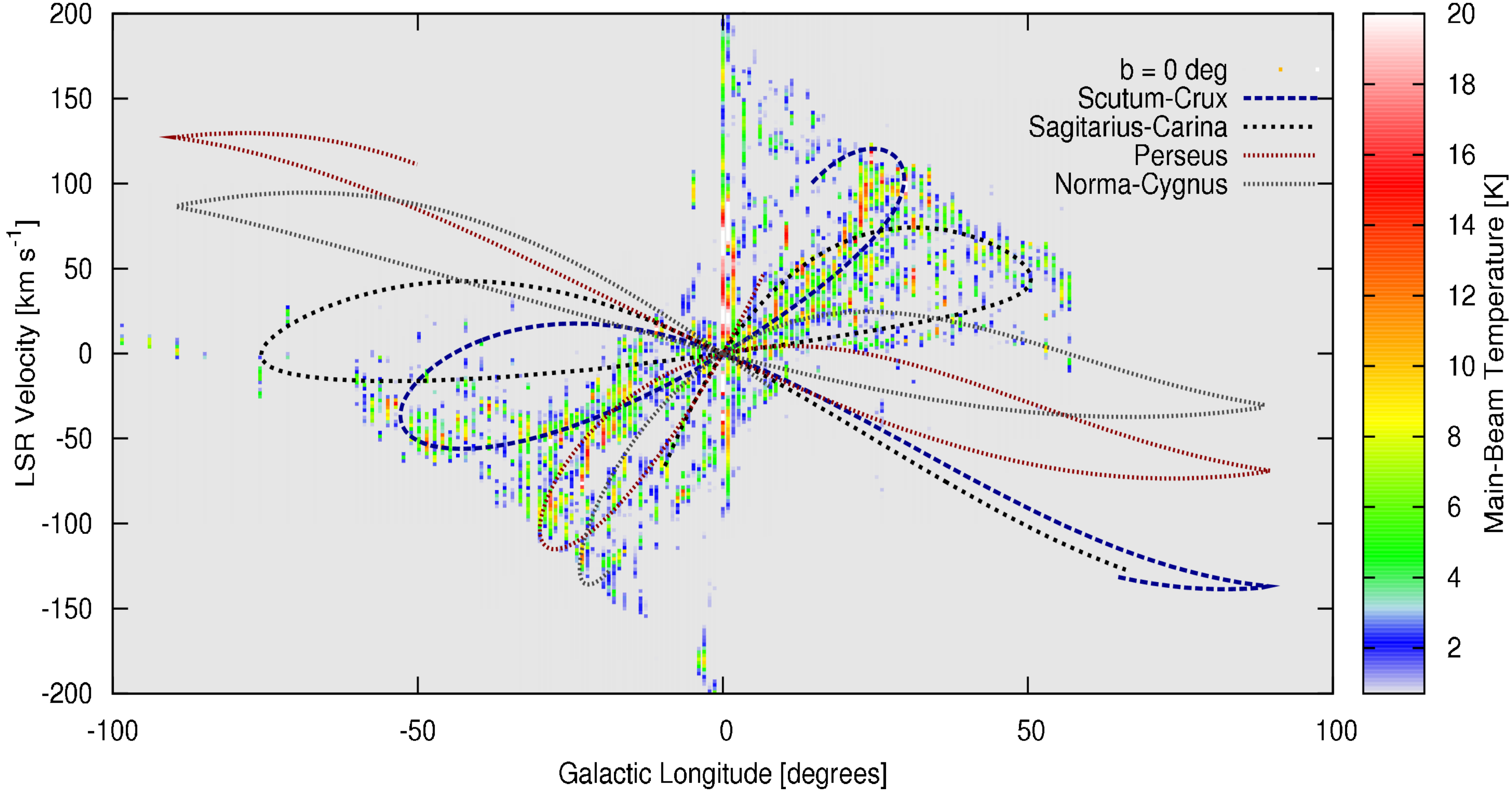
Atomic Gas (HI)



GOT C+ [CII] Distribution in the Milky Way



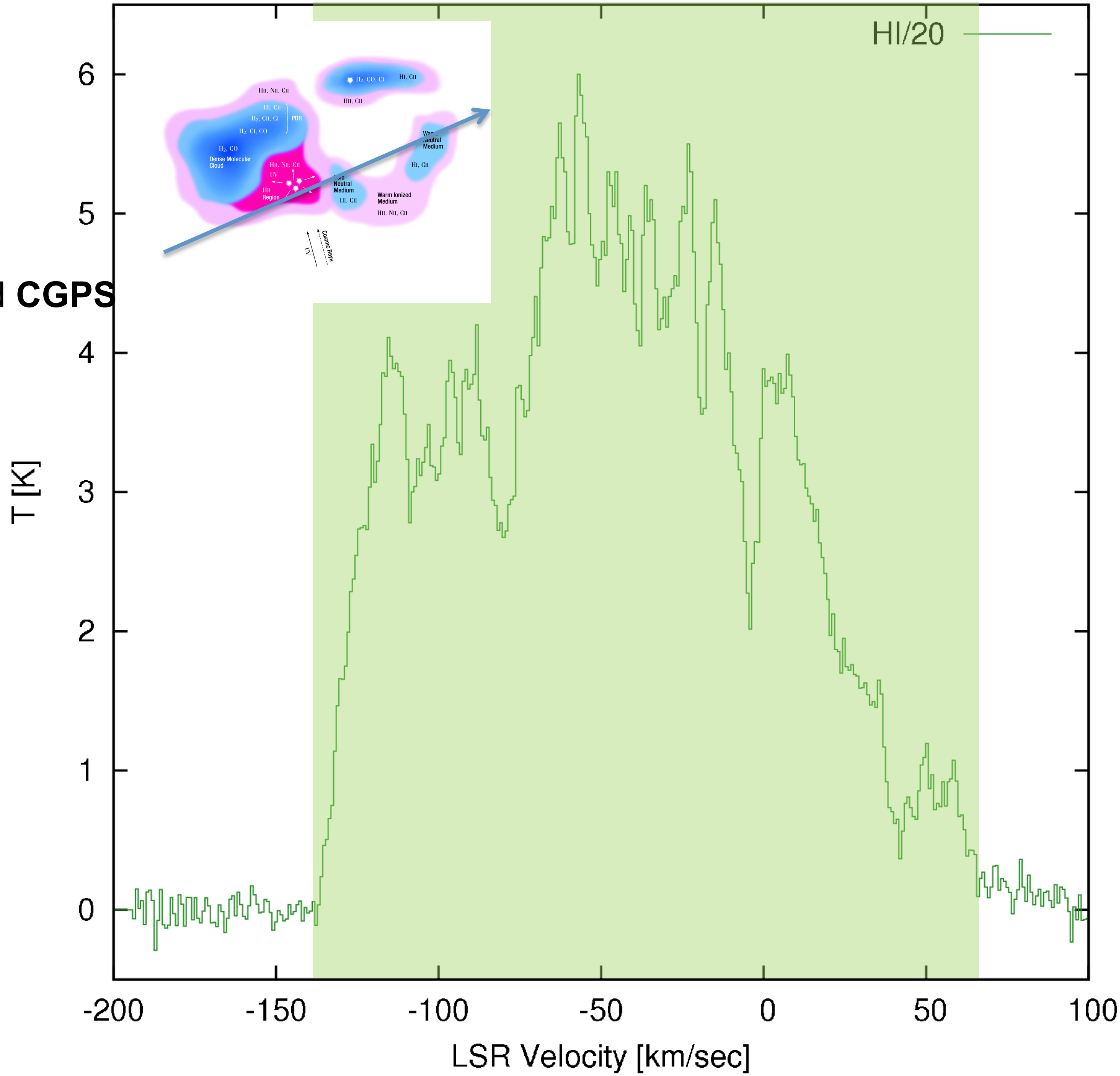
Dense and Cold Molecular Gas (CO)



[CII] traces the transition between atomic and molecular clouds.

HI

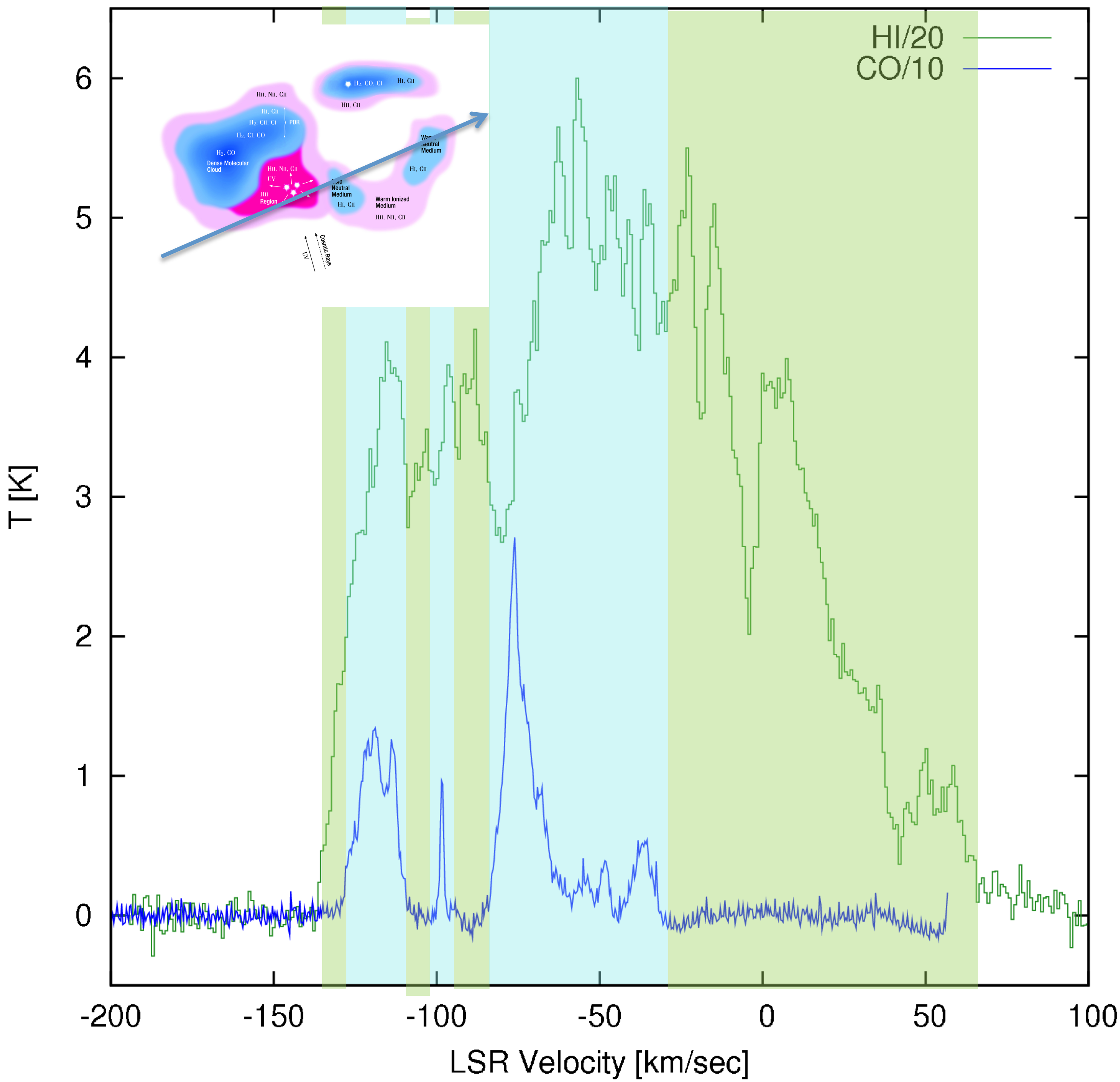
Data from:
SGPS, **VGPS**, and **CGPS**

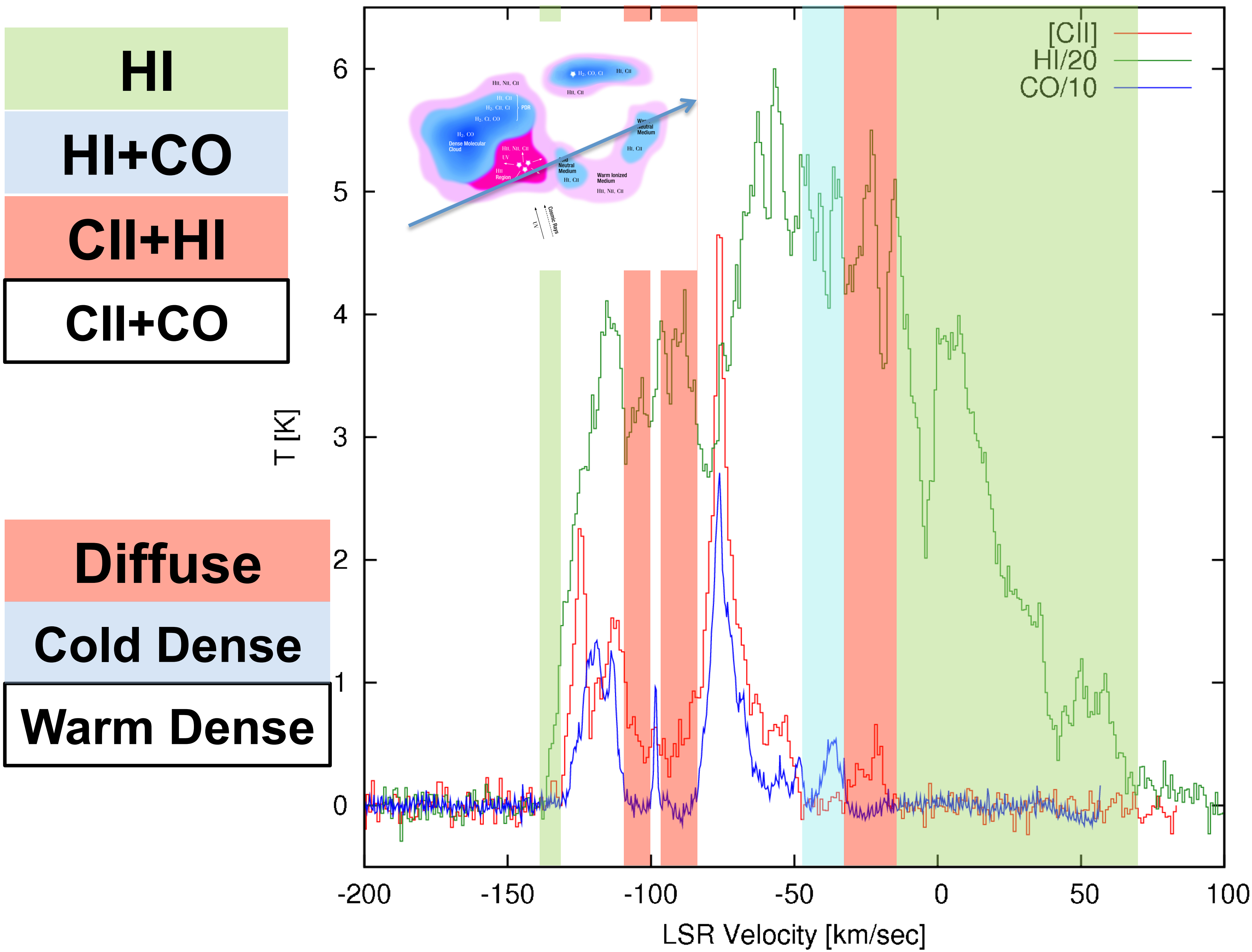


HI

HI+CO

Data from:
Mopra and **CSO**




HI
HI+CO
CII+HI
CII+CO
Diffuse
Cold Dense
Warm Dense
[CII]
HI/20
CO/10
T [K]
LSR Velocity [km/sec]
-200
-150
-100
-50
0
50
100
0
1
2
3
4
5
6
Dense Molecular Cloud
Cold Neutral Medium
Warm Ionized Medium
Cosmic Rays

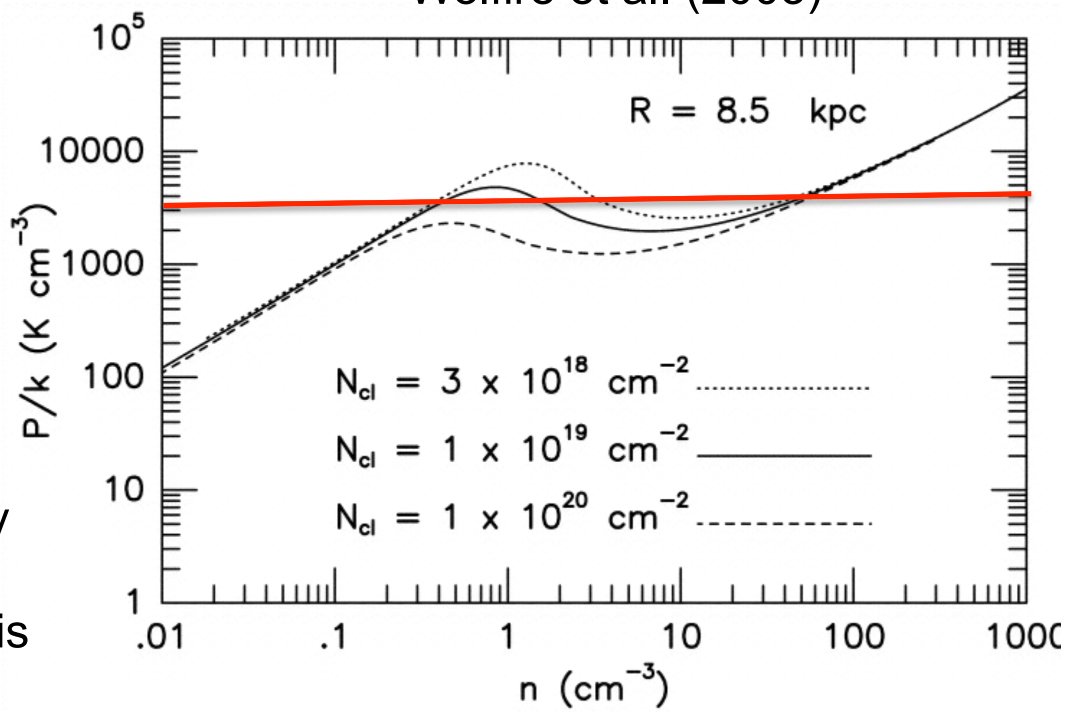
Warm and Cold Neutral gas:

- Thermal balance of diffuse atomic gas results in two phases in nearly thermal equilibrium (Pike'Ner 1968; Field et al 1969;Wolfire et. al. 1995, 2003)

- The 21cm line traces column density only; it is impossible to discern between CNM or WNM gas using this line.

- But CNM can be observed with HI seen in absorption towards extragalactic continuum sources (e.g. Heiles & Troland 2003, Dickey et al. 2009).

Wolfire et al. (2003)



Cold Neutral Medium (CNM):
T=80 K, n=50 cm^{-3}

Warm Neutral Medium (WNM):
T=8000 K, n=0.5 cm^{-3}

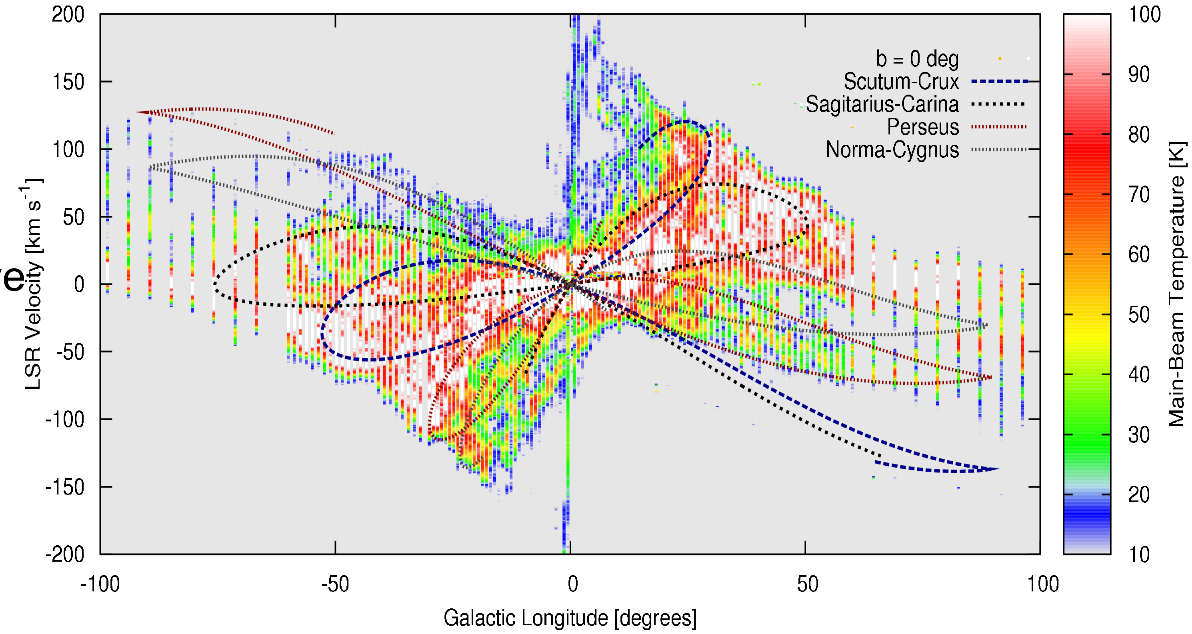
Warm and Cold Neutral gas:

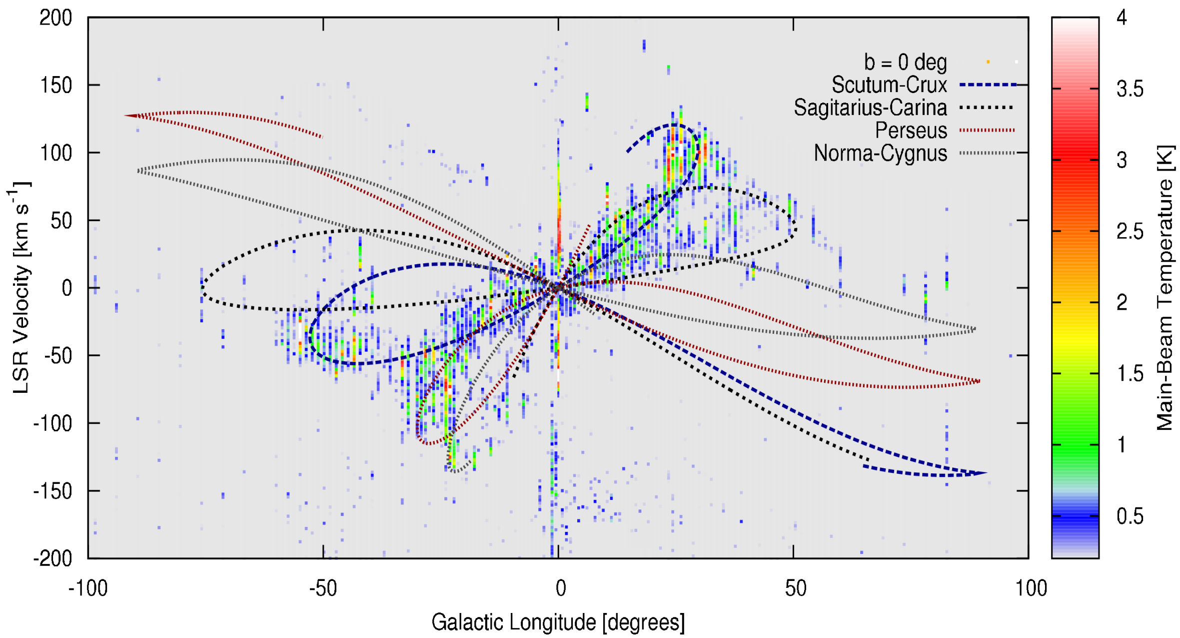
- The [CII] emission traces the diffuse neutral gas but is sensitive to density and temperature.

$$I_{CII} \propto N(C^+)n_h * \exp(-91.3K/T_{kin})$$

- For typical WNM and CNM conditions, the [CII] associated with WNM is a factor of ~20 weaker than that from the CNM. WNM is below our sensitivity limit.

- We use the GOT C+ survey to separate the CNM and WNM components from the HI position velocity map of the Galaxy.





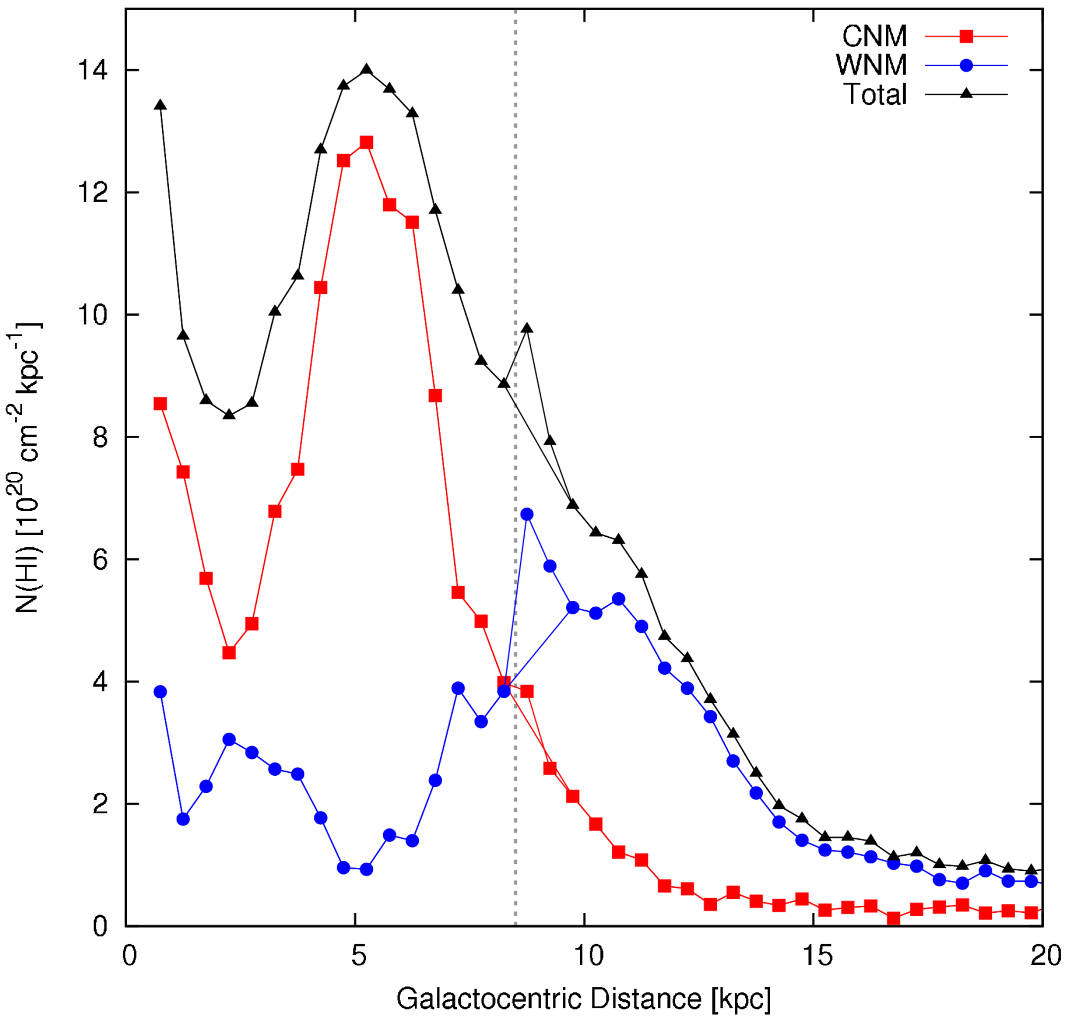
Warm and Cold Neutral Gas

- The [CII] emission traces the diffuse neutral gas but is sensitive to density and temperature.

$$I_{CII} \propto N(C^{+}) n_h * \exp(-91.3K/T_{kin})$$

- For typical WNM and CNM conditions, the [CII] associated with WNM is a factor of ~20 weaker than that from the CNM. WNM is below our sensitivity limit.

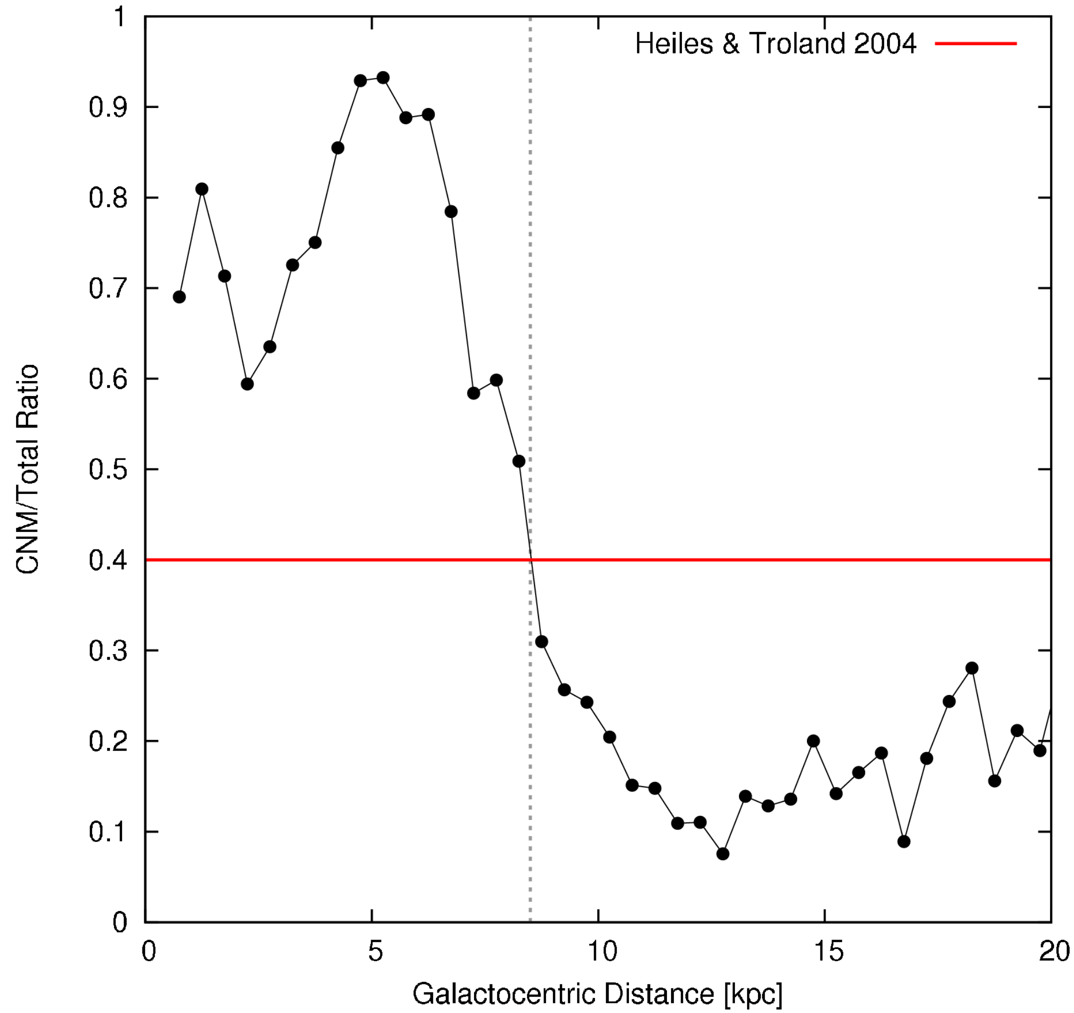
- We use the GOT C+ survey to separate the CNM and WNM components from the HI position velocity map of the Galaxy.



Pineda et al. (2013) A&A 554, A103

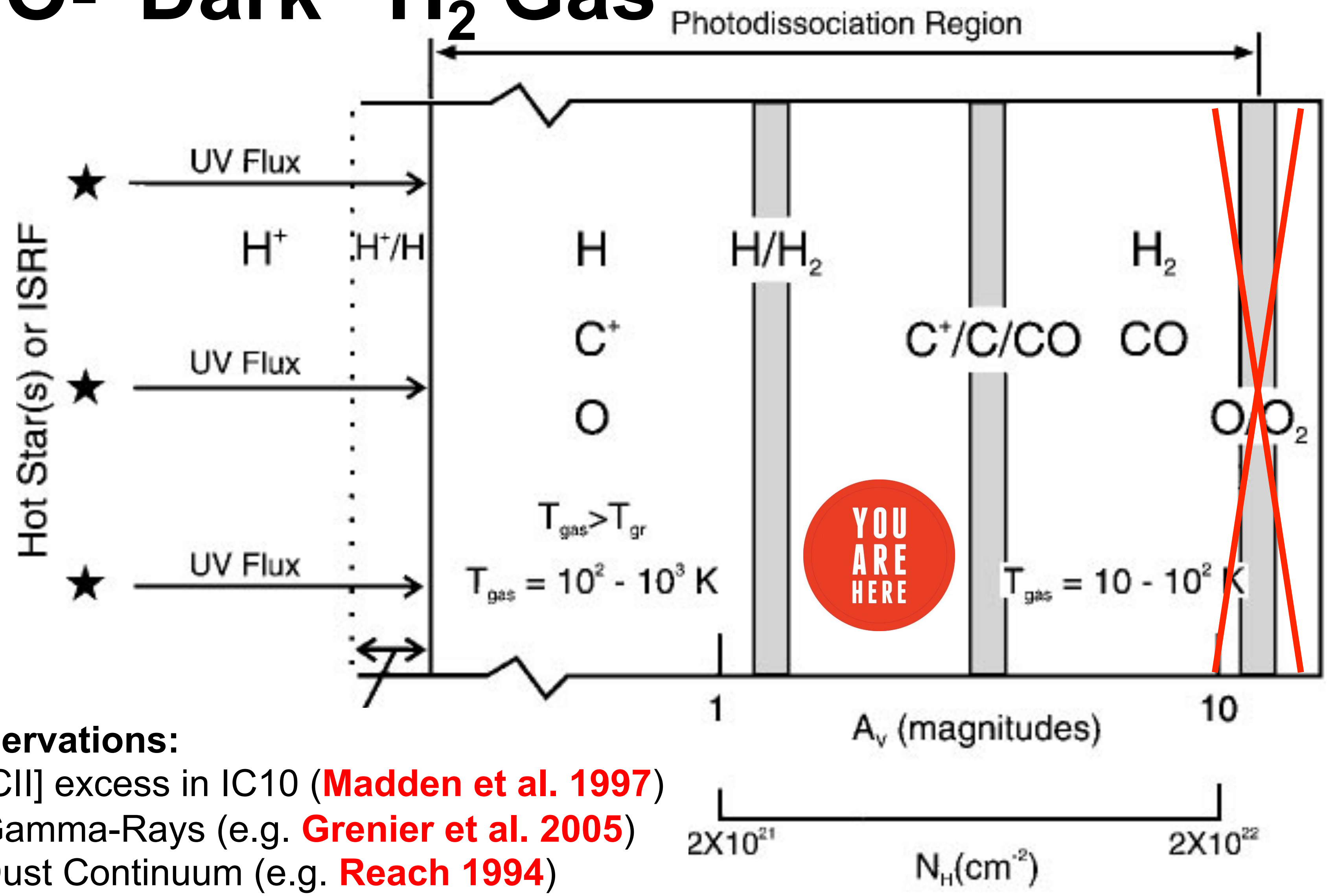
Warm and Cold Neutral gas

- Atomic gas in the inner galaxy dominated by CNM gas.
- Inner Galaxy results consistent with those from Kolpak et. al 2002.
- Outer galaxy is 10-20% CNM, consistent with Dickey et al. (2009).
- Average CNM fraction is **43%.**
- Local CNM fraction of the total gas consistent with Heiles & Troland (2003).



Pineda et al. (2013) A&A 554, A103

CO-“Dark” H_2 Gas



Observations:

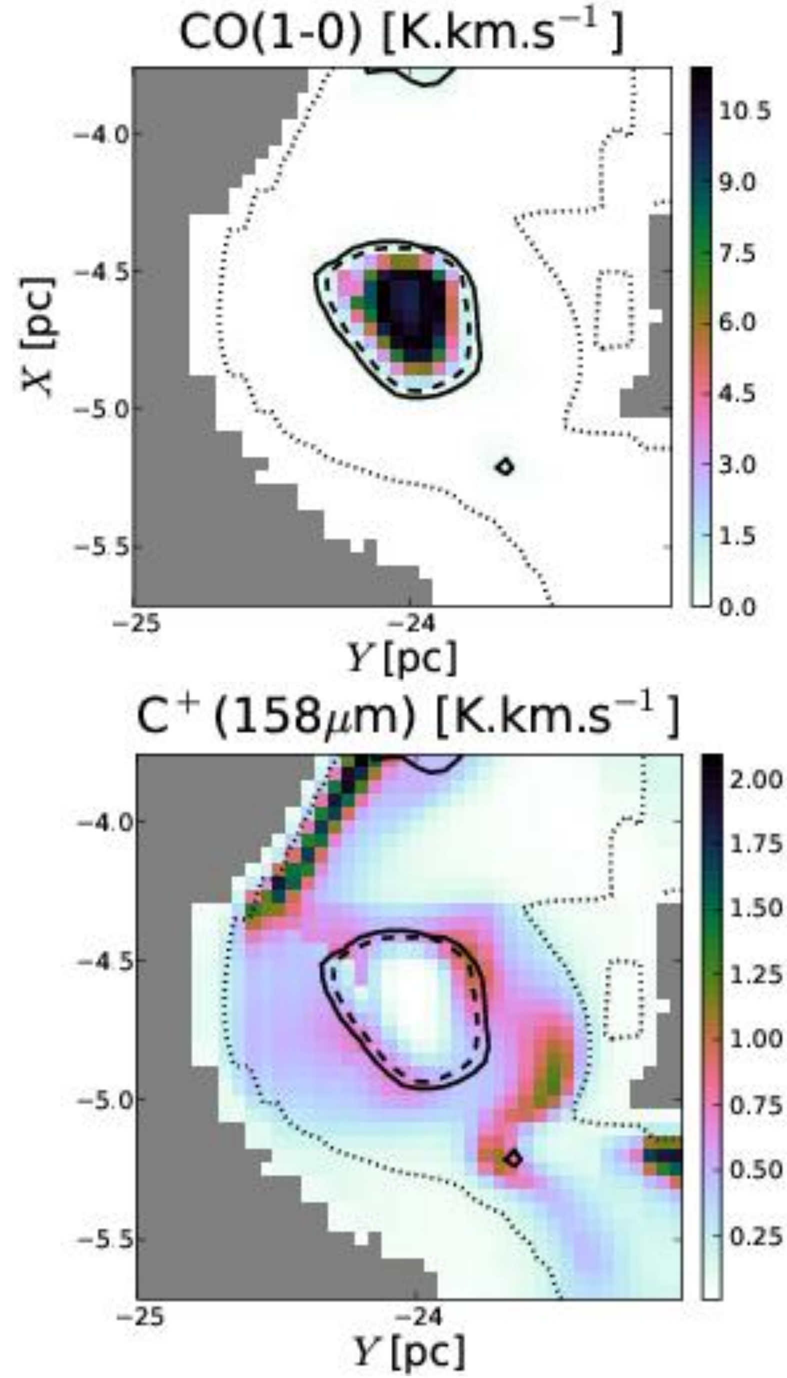
- [CII] excess in IC10 (**Madden et al. 1997**)
- Gamma-Rays (e.g. **Grenier et al. 2005**)
- Dust Continuum (e.g. **Reach 1994**)
- CO absorption (e.g. **Lizst & Pety 2012**)
- [CII] Emission (e.g. **Langer et al. 2010**)

Hollenbach and Tielens (1997)

CO-Dark H_2: Theory

- Thickness of CO-dark H_2 layer constant: Mass fraction of CO-dark H_2 is ~ constant; f~0.3
  (Wolfire et al. 2010, ApJ 716 1191)

- Simulations are incorporating treatment of chemistry and grain physics, allowing improved comparison with observations (e.g. Shetty et al. 2012, Levrier et al. 2012).



CO-Dark H_2 : Observations in 2D

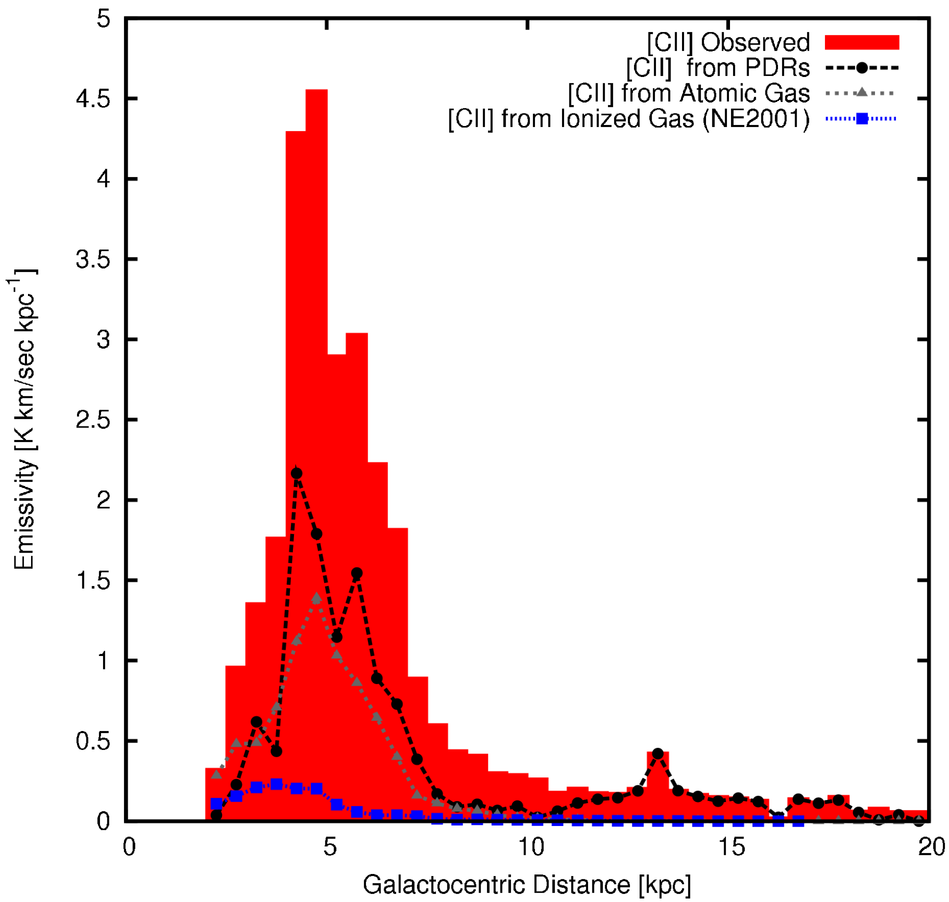
Method:	Fraction of total molecular gas in form of CO-Dark H_2
Gamma-Rays Grenier et al. (2005) Science 307,1292	50%
Dust Continuum Planck Collaboration (2011) A&A, 536, A19	54%
Dust Extinction Paradis et al (2012) A&A, 534, A103	62%

Applies to Solar Neighborhood only.

CO-Dark H_2 : Observations in "3D": Technique - 1: [CII]

Method: Calculate CII, HI, CO and ^{13}CO azimuthally averaged emissivity. Subtract HI, e^-, PDRs, contributions to [CII] intensity.

PDRs: [CII] components associated with ^{13}CO emission (large column densities).
CNM: HI emission gives HI column density (including an opacity correction), n and T estimated from thermal pressure profile from Wolfire et al. (2003).
Ionized gas: Use electron density model of the galaxy from NE2001 model (constrained with pulsars) and T=10^4K.



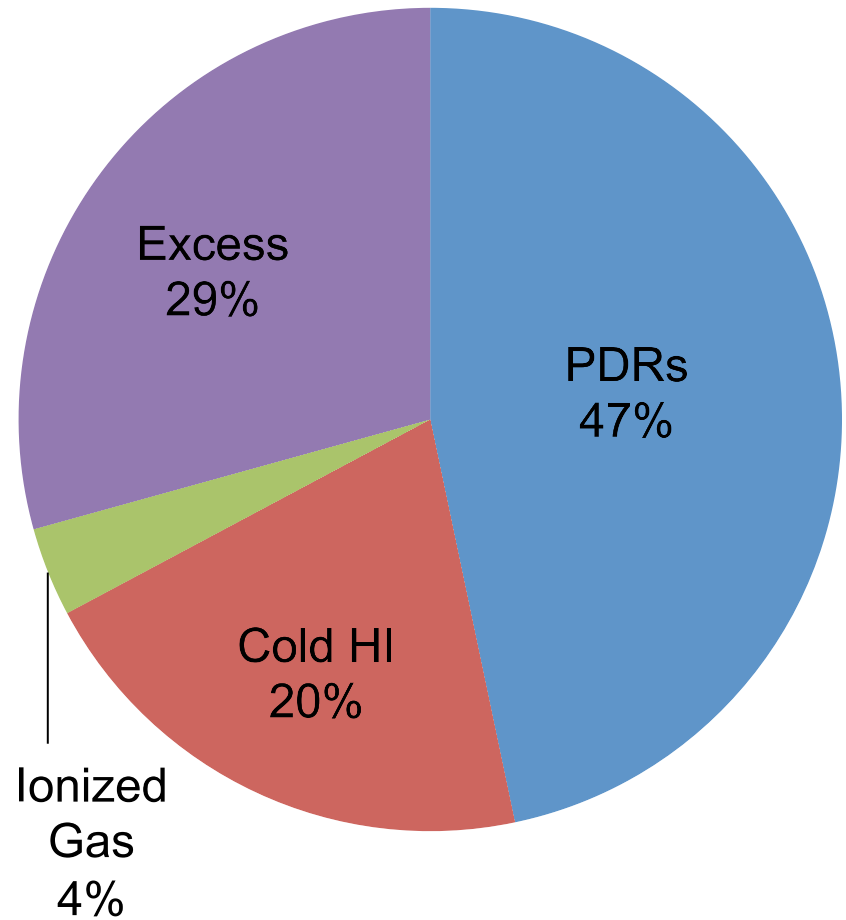
Pineda et al. 2013 A&A 554, A103

CO-Dark H_2 : Observations in “3D”: Technique - 2: [CII]

Method: Calculate [CII], HI, CO and ^{13}CO azimuthally averaged emissivity. Subtract HI, e^-, PDRs, contributions to [CII] intensity.

- **PDRs:** [CII] components associated with ^{13}CO emission (large column densities).
- **CNM:** HI emission gives HI column density (including an opacity correction), n and T estimated from thermal pressure profile from Wolfire et al. (2003).
- **Ionized gas**: Use electron density model of the galaxy from NE2001 model (constrained with pulsars) and $T=10^4K$.

[CII] Emissivity at b=0.



“PDRs” are exposed to modest FUV fields (1-30 X Draine’s field)

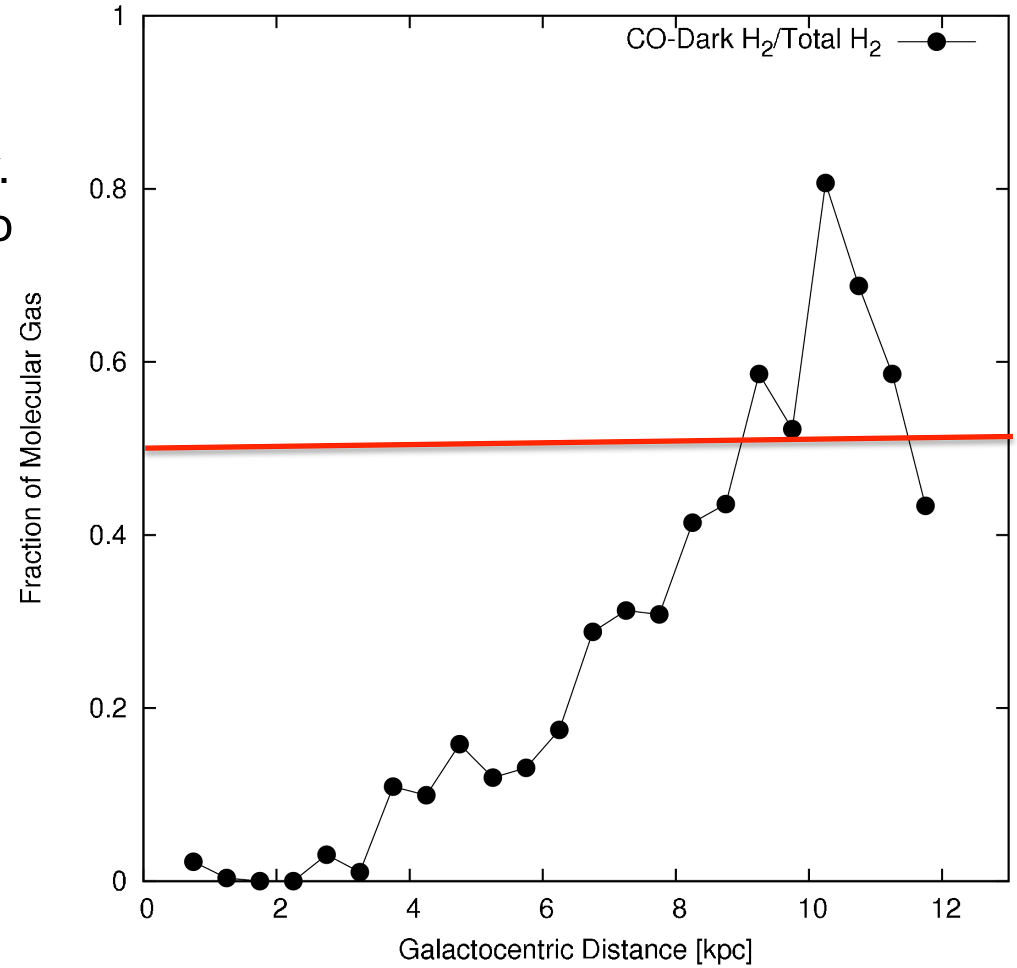
CO-Dark H2 : Observations in “3D”: Technique - 1: [CII]

Method: Calculate CII, HI, CO and ^{13}CO azimuthally averaged emissivity. Subtract HI, e^-, PDRs, contributions to [CII] intensity.

Results: Gives the galactic distribution of the CO-dark gas component. **Average CO-dark H_2 fraction of ~0.3.**

Applies to: Entire Galactic plane

Caveats: Needs assumptions on the physical conditions (n,T) of the CO-dark H_2 layer.



What We Have Learned from GOTC+?

- The [CII] emission in the Galaxy is mostly associated with spiral arms, tracing the envelopes of evolved clouds as well as clouds making the transition between atomic and molecular phase.

- Most of the [CII] emission emerges from Galactocentric distances between 4 and 11 kpc.

- The CO-dark H_2 component is more extended in Galactocentric distance compared to the gas traced by CO. The CO-dark H_2 fraction increases from 20% at 4 kpc to 80% at 10kpc. **From the GOTC+ survey, the CO-dark H_2 gas component accounts for 30% of the total molecular mass of the Galaxy**.

The Future: Next Steps

- **GOT C+ has shown the importance of [CII] in combination with other tracers to elucidate the properties of the ISM.**

- **Further progress will require large scale maps of the [CII] and [CI] emission in the Milky Way and nearby galaxies to understand the lifecycle of the interstellar medium and the transition from atomic to molecular gas.**

STO-2 Antarctic Balloon Mission

80 cm telescope
Heterodyne receivers with digital spectrometers $\delta v = 1\ \mathrm{km s^{-1}}$
4 pixels for [CII] & 4 pixels for [NII] 205 μm

Launch in 2017-2018
Fully-sampled maps of Galactic plane $305^{o} < l < 340^{o}$
~1’ angular resolution

University of Arizona, APL, JPL, ASU, CfA, JHU

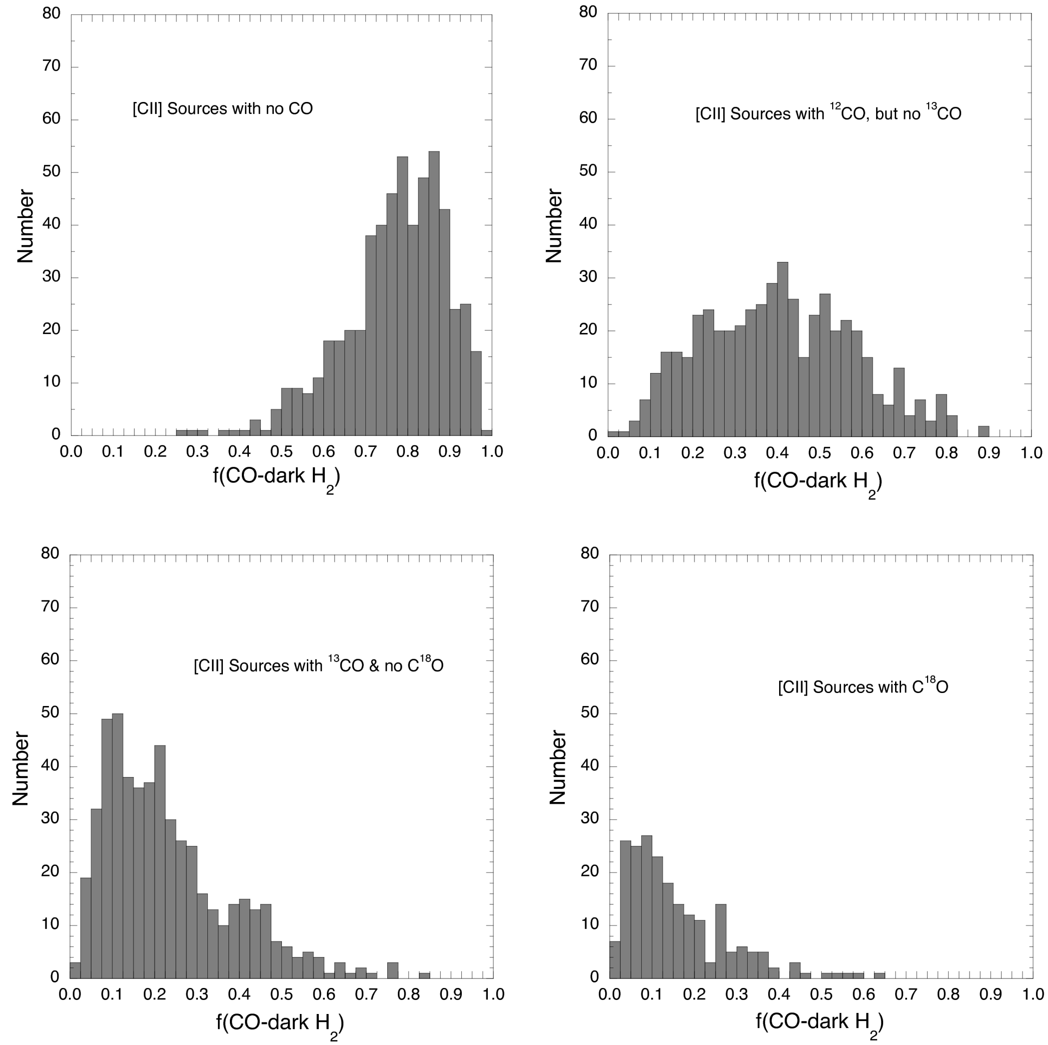
CO-Dark H_2 : Observations in "3D": Technique - 2: [CII]

Method: Gaussian decomposition of components along the LOS. 2000 components identified, in CO isotopologues. HI contribution to CII intensity subtracted.

Results: CO-dark H_2 fraction varies for different types of clouds

Applies to: Entire Galactic plane

Caveats: Gaussian decomposition is not easy. Needs assumptions on the physical conditions (n,T) of the CO-dark H_2 layer.

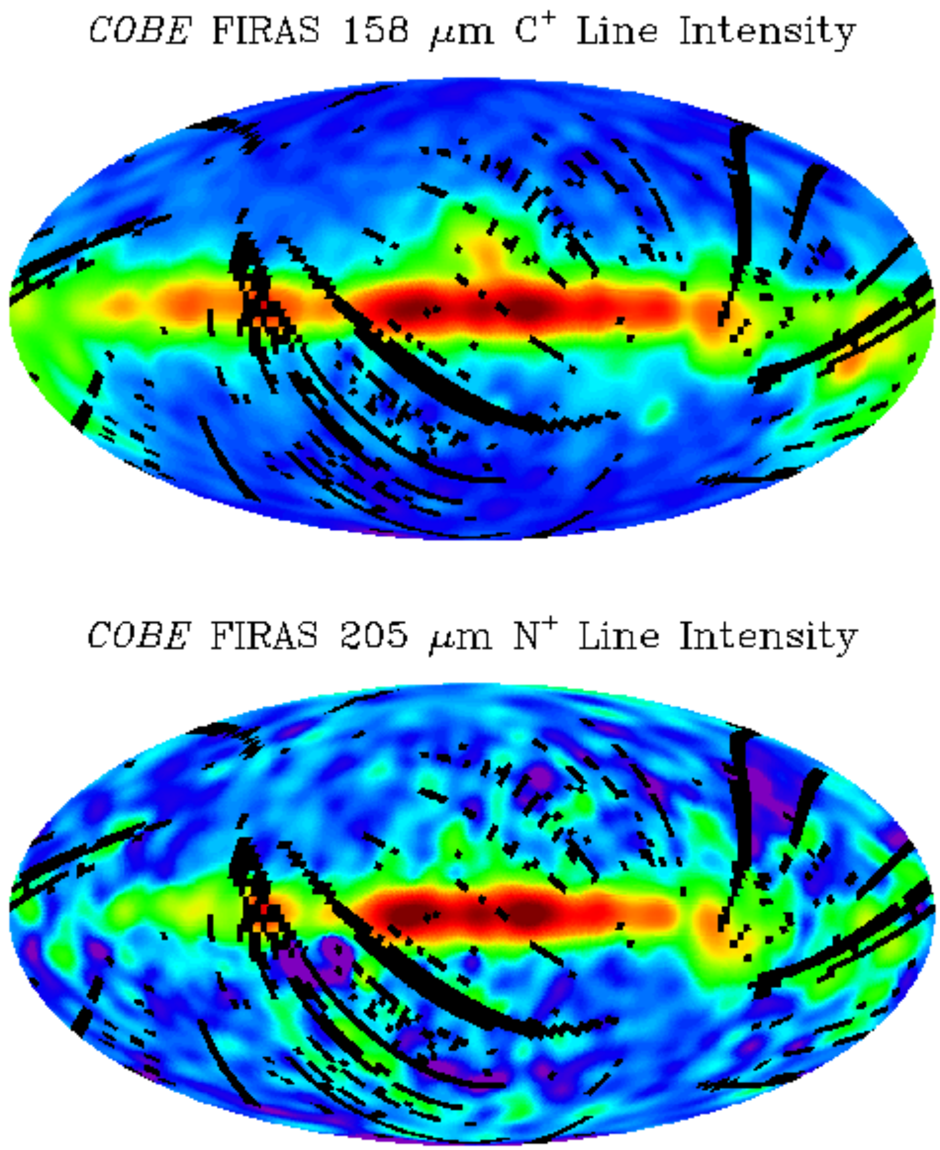


Langer et al. (2013), A&A. submitted.

[CII] as a tracer of the Warm Ionized Medium

WIM: T=8000K, low volume densities, traced by [CII] and [NII], H-alpha, and radio continuum.

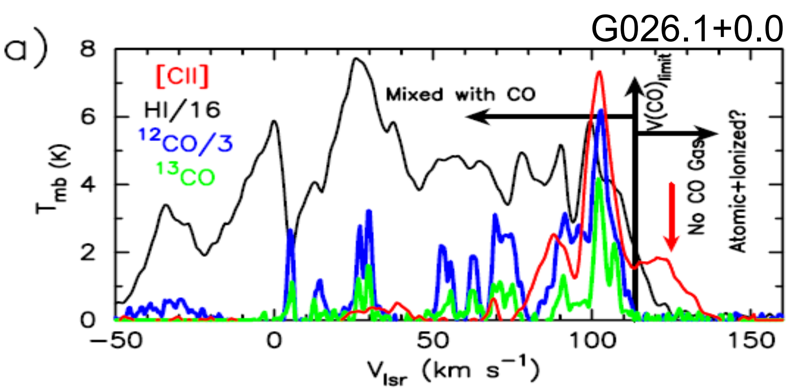
- Suggested to be the origin of the [CII] emission in the Milky Way observed by COBE (Heiles et al. 1994).
- But it is a small fraction of **total** [CII] observed by GOTC+ (Pineda et al. 2013, see later).

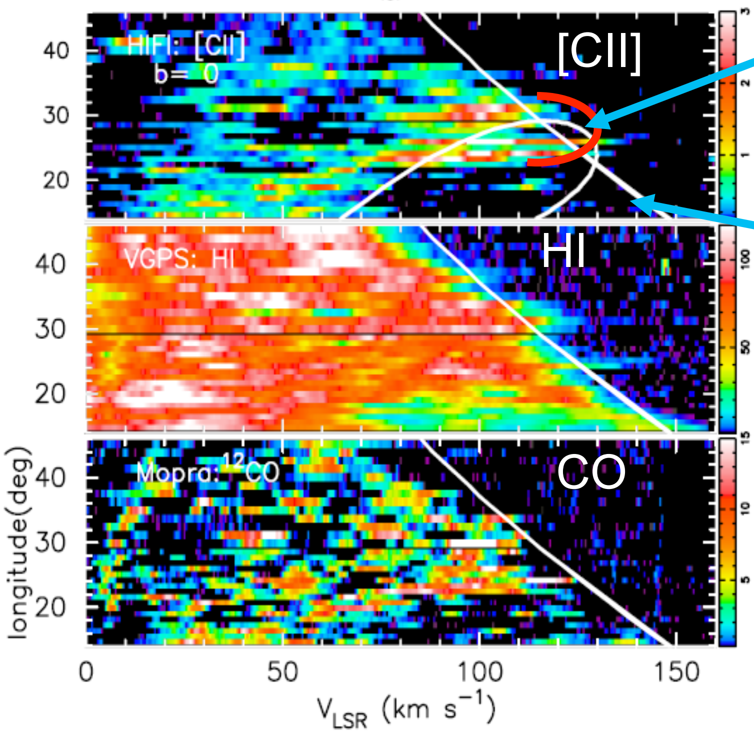


Bennett et al. 1994

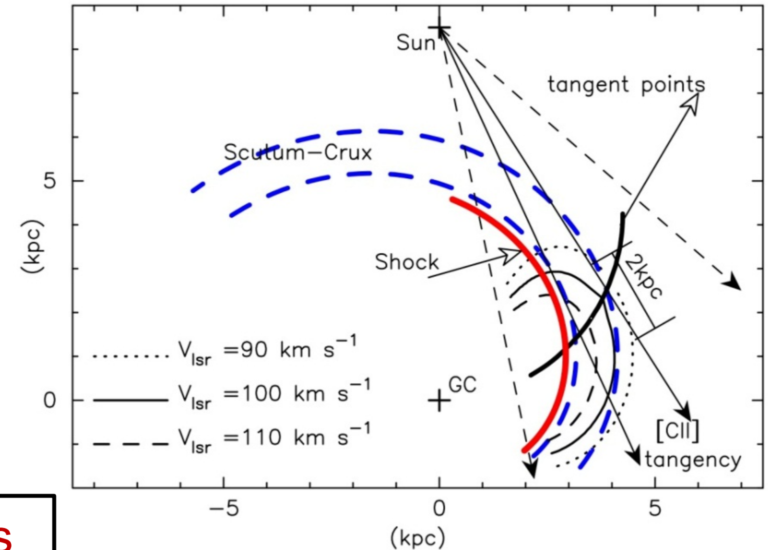
[CII] Detection of WIM in Spiral Arm Tangency

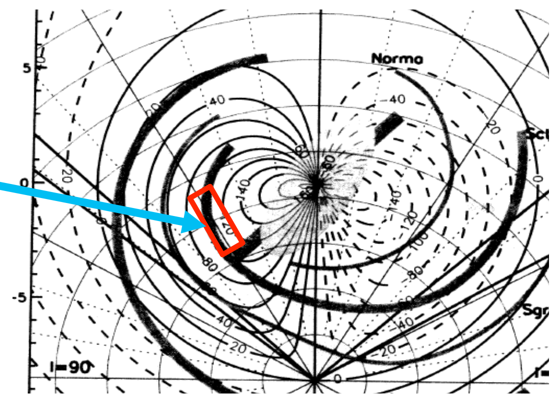
Velusamy, Langer et al. 2012, A&A 541,L10





[CII] excess tracing WIM





The geometry of the Scutum-Crux (S-C) arm is very favorable to detect weak [CII] emission from the WIM and study its structure and kinematics