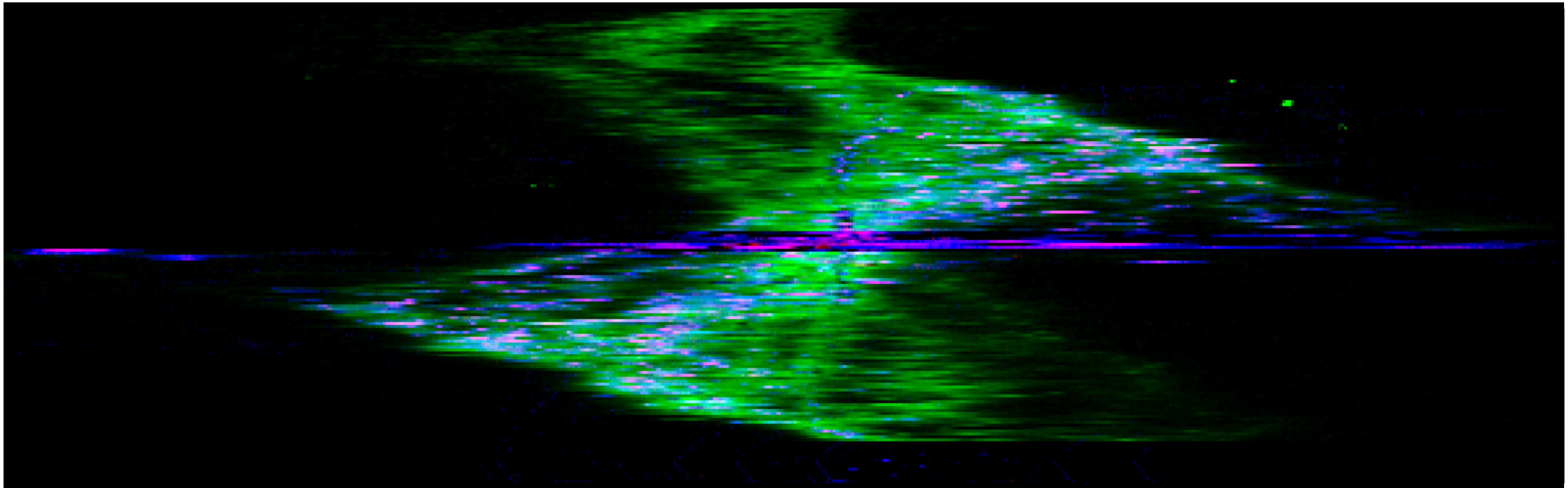


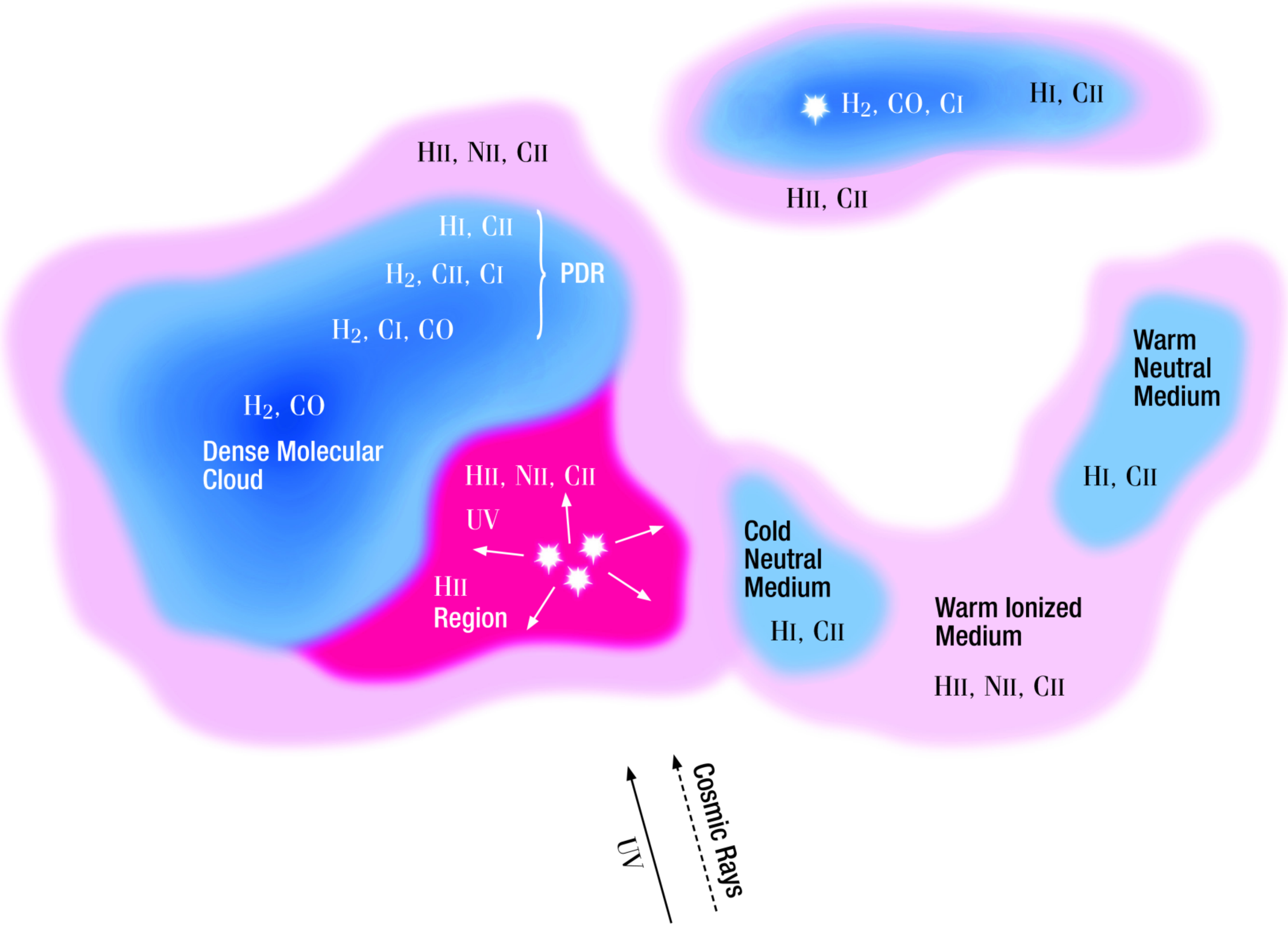
The Distribution of the Milky Way ISM as revealed by the [CII] 158um line.

Jorge L. Pineda

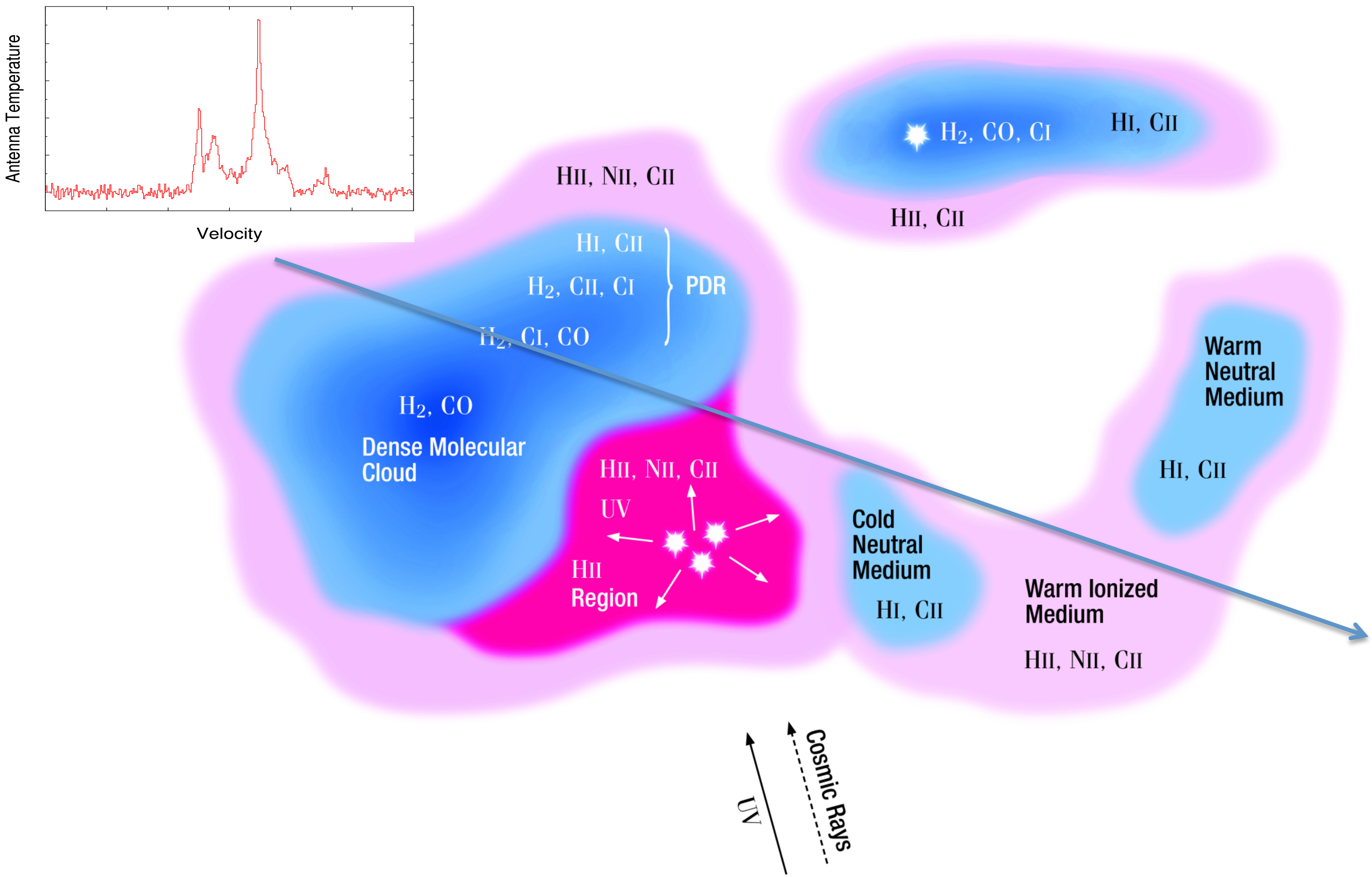
Jet Propulsion Laboratory, California Institute of Technology

August 2013

William D. Langer, Thangasamy Velusamy and Paul Goldsmith

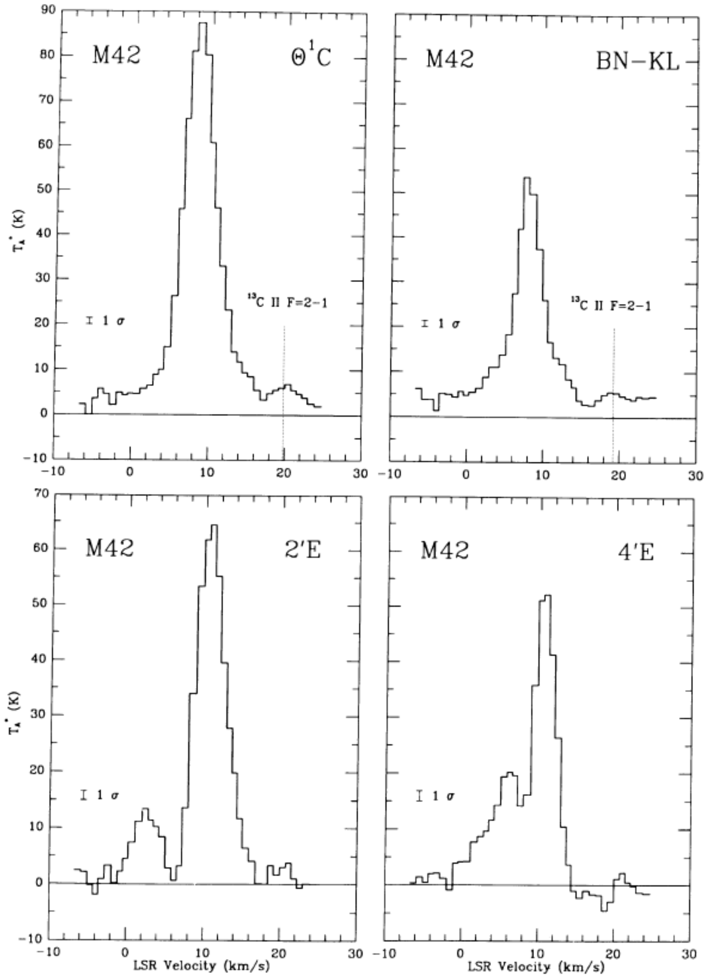


HII, NII, CII
HI, CII
H2, CII, CI
H2, CI, CO
PDR
H2, CO
Dense Molecular Cloud
HII, NII, CII
UV
HII Region
H2, CO, CI
HI, CII
HII, CII
Warm Neutral Medium
HI, CII
Cold Neutral Medium
HI, CII
Warm Ionized Medium
HII, NII, CII
UV
Cosmic Rays

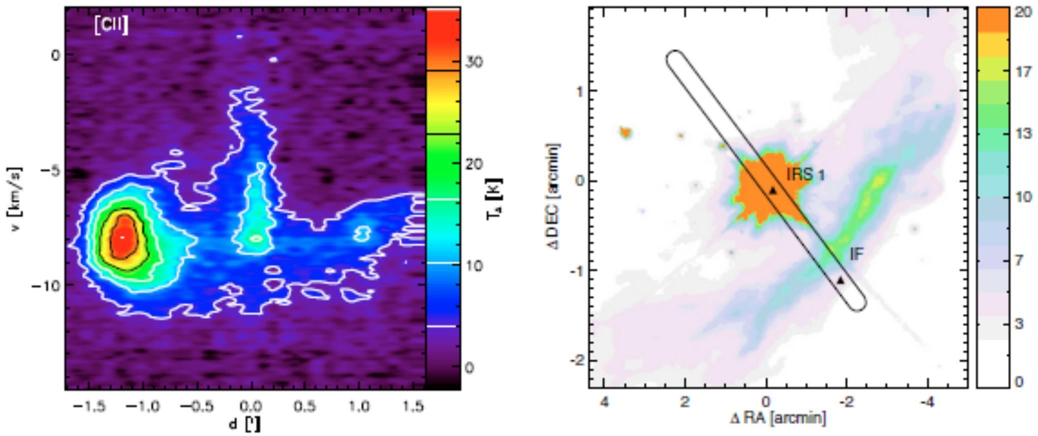


Antenna Temperature
Velocity
HII, NII, CII
HI, CII
H2, CII, CI
H2, CI, CO
PDR
H2, CO
Dense Molecular Cloud
HII, NII, CII
UV
HII Region
H2, CO, CI
HI, CII
HII, CII
Warm Neutral Medium
HI, CII
Cold Neutral Medium
HI, CII
Warm Ionized Medium
HII, NII, CII
UV
Cosmic Rays

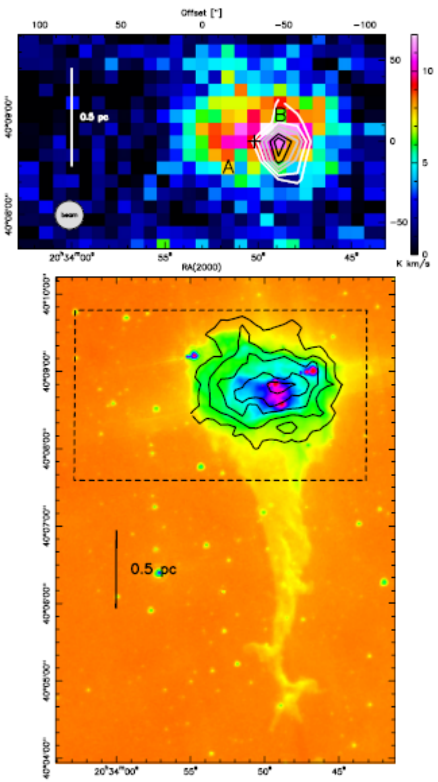
Photon Dominated Regions (PDRs)



KAO: e.g. Boreiko et al. 1998

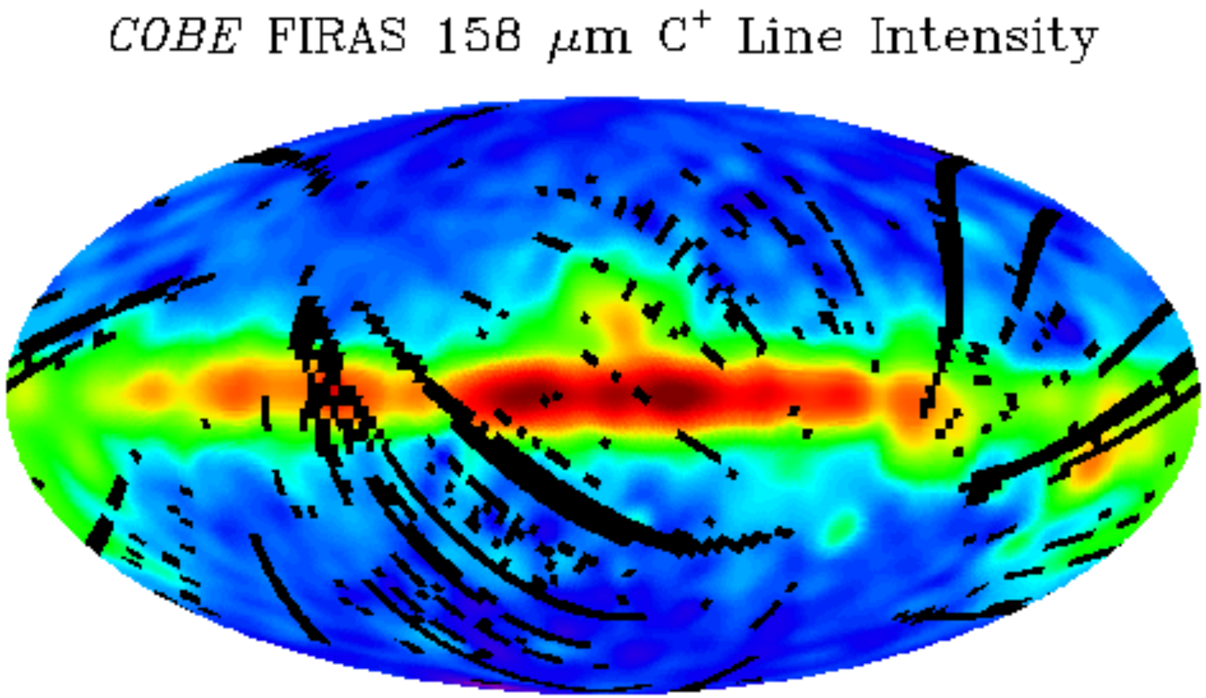


Herschel/WADI ; e.g. Dedes et al. 2010



SOFIA ;
e.g. Schneider et al. 2012

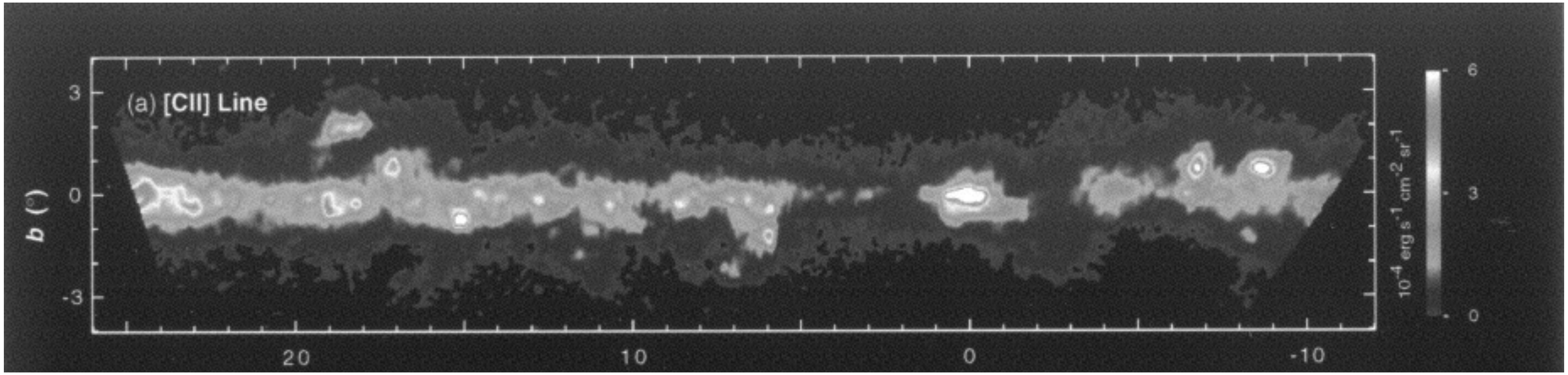
COBE/FIRAS;
7 deg angular resolution;
1000 km/sec velocity resolution



Origin?

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

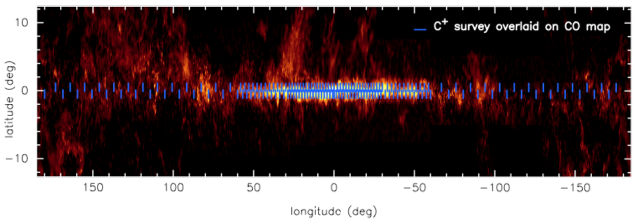
BICE;
15 arcmin angular resolution;
175 km/sec velocity resolution



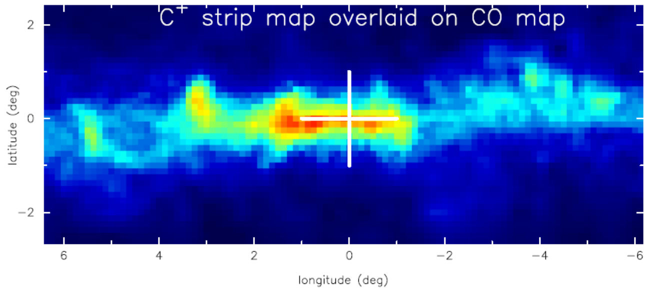
Galactic Longitude [Degrees]

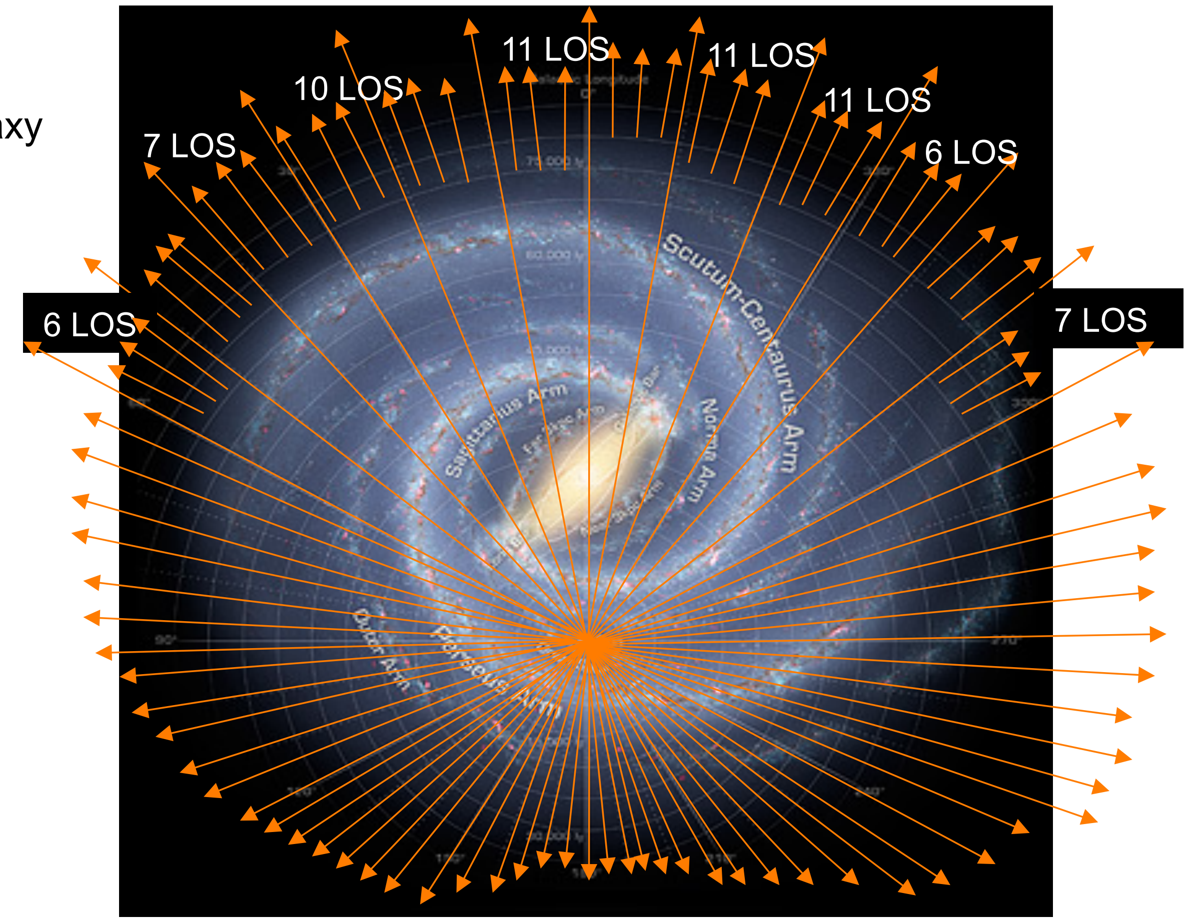
GOT C+ [CII] 1.9 THz Survey

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

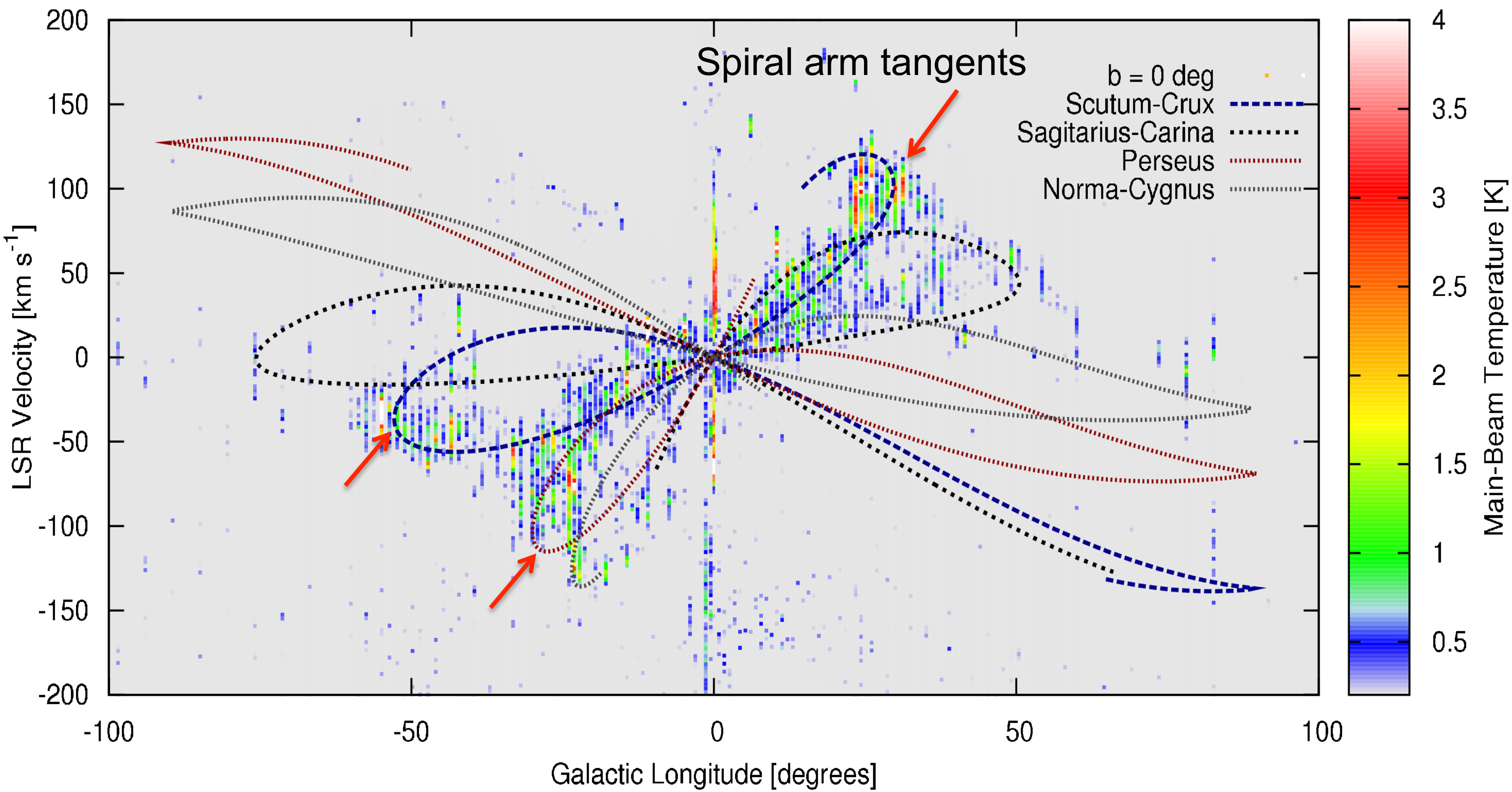


Galactic Central Region: CII strip maps sampling ≈300 positions in On The Fly (OTF) mapping mode.



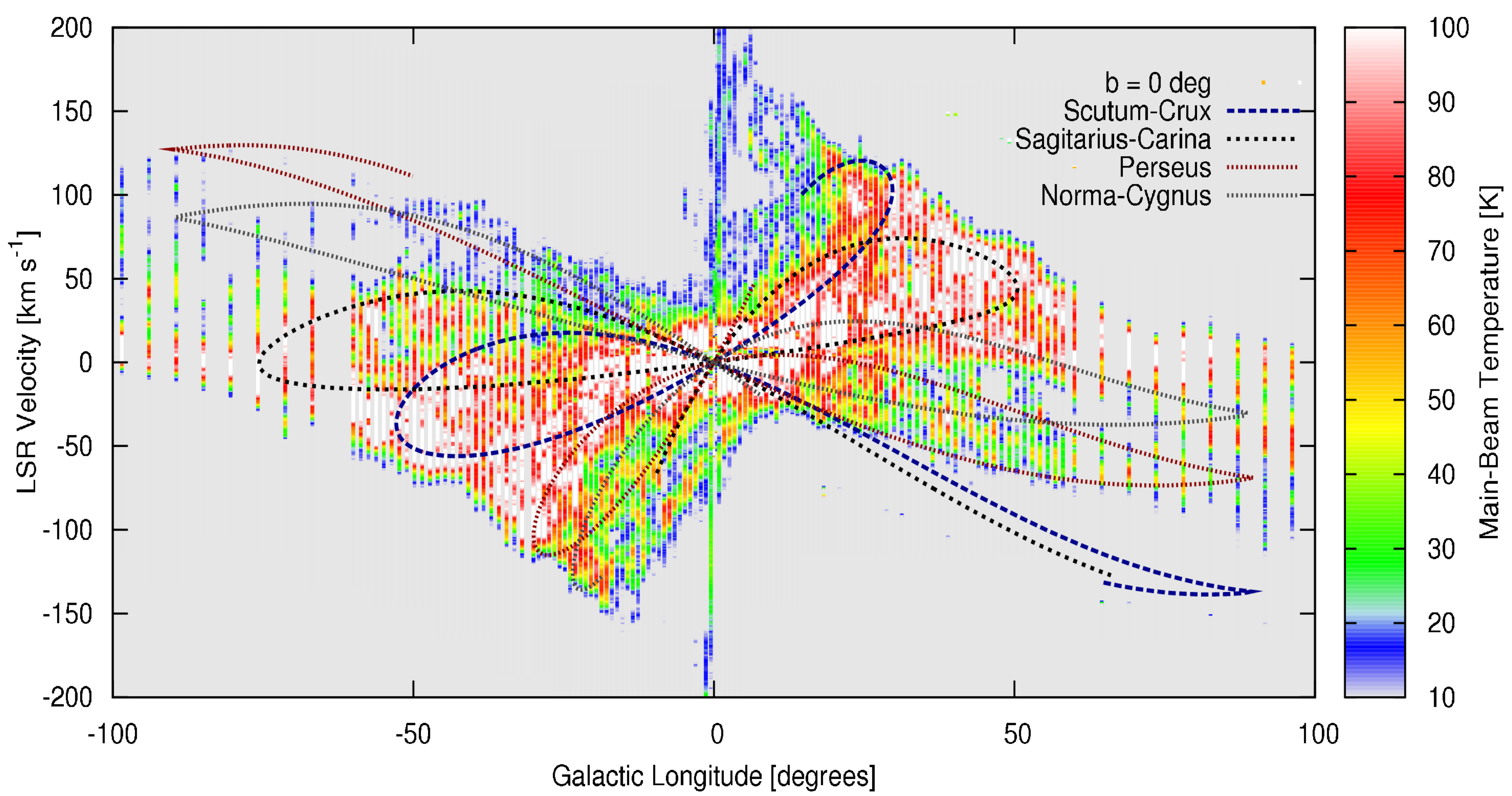


GOT C+ [CII] Distribution in the Milky Way

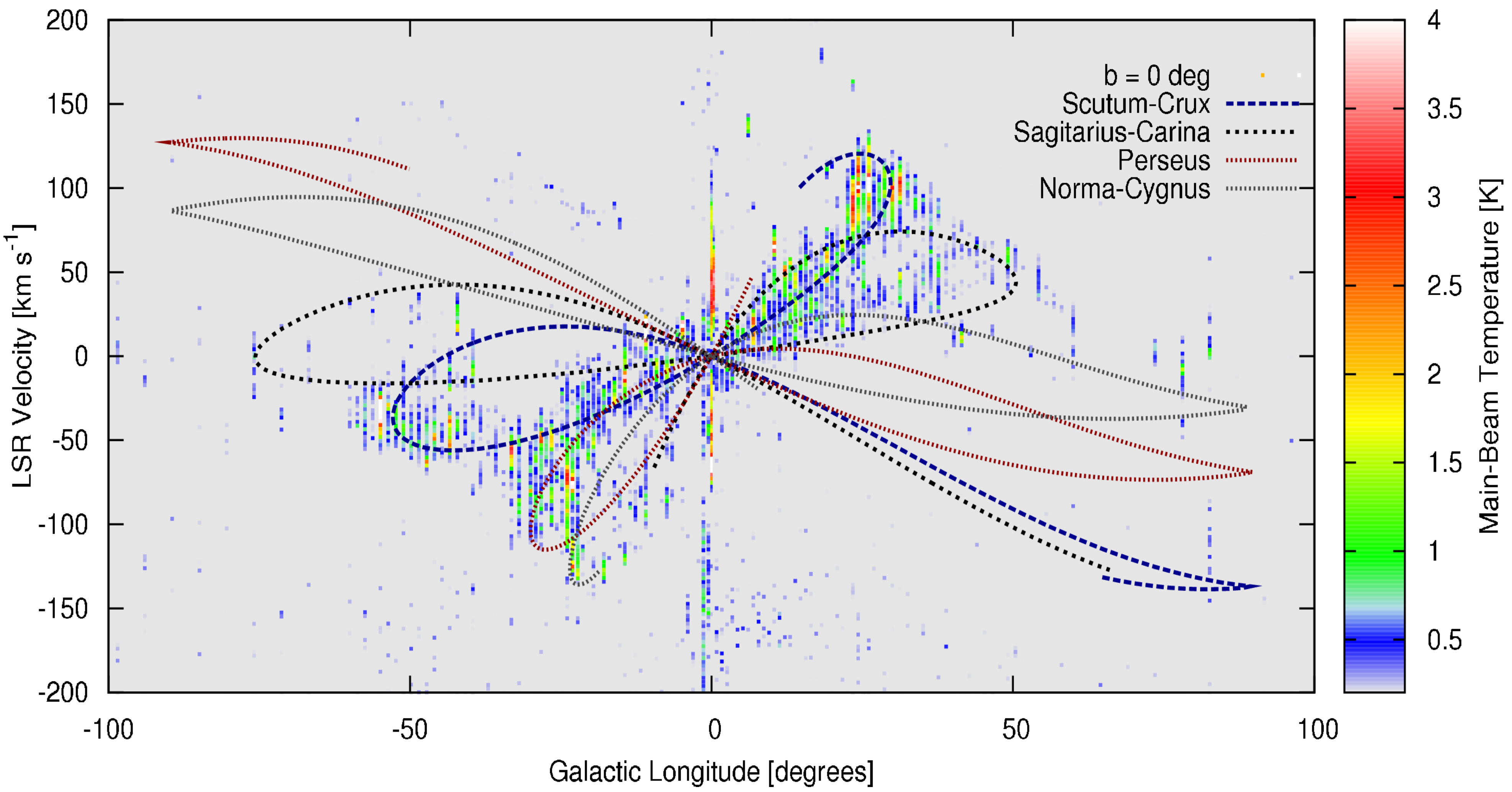


Pineda et al. (2013) A&A 554, A103

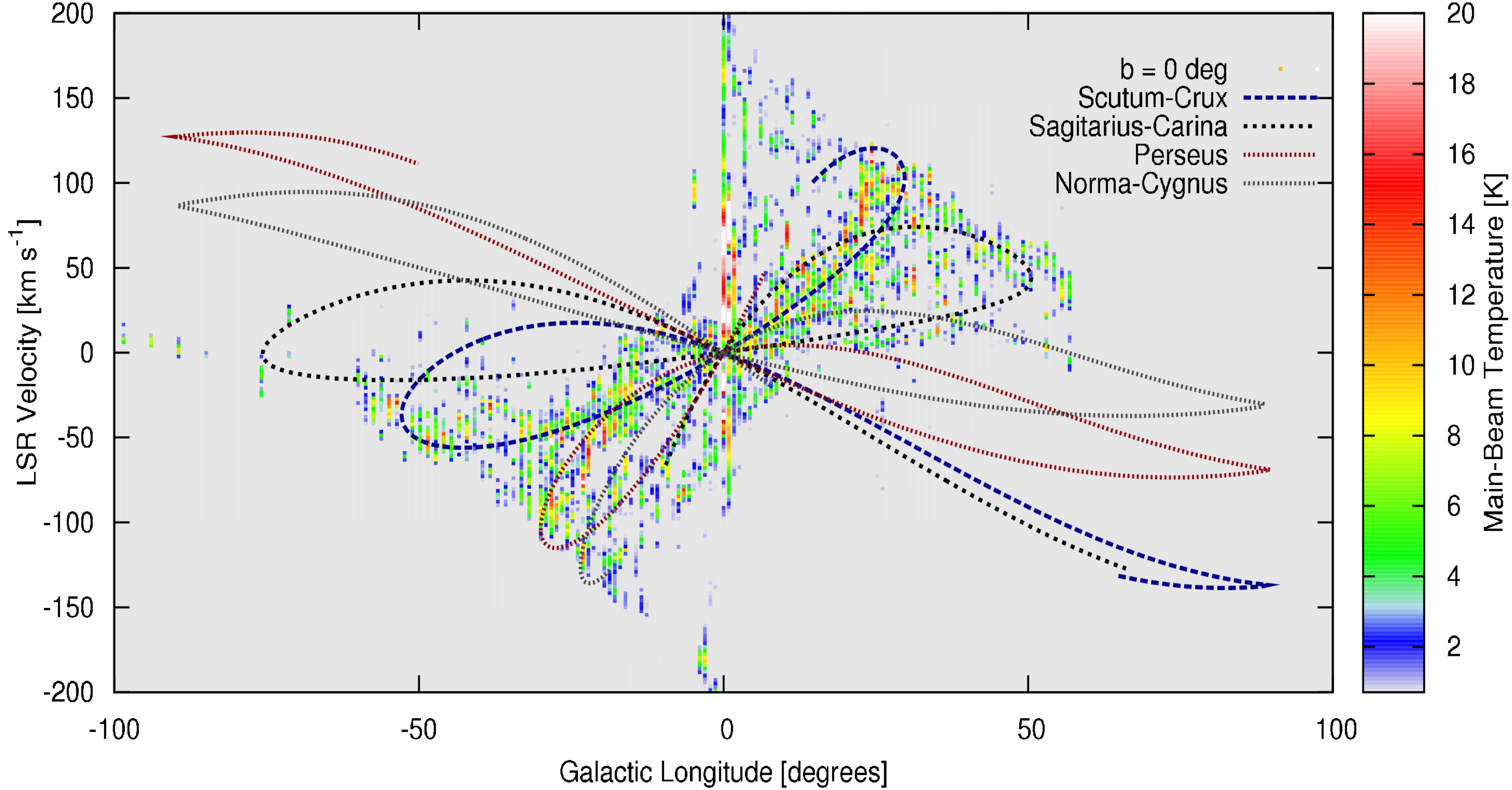
Atomic Gas (HI)



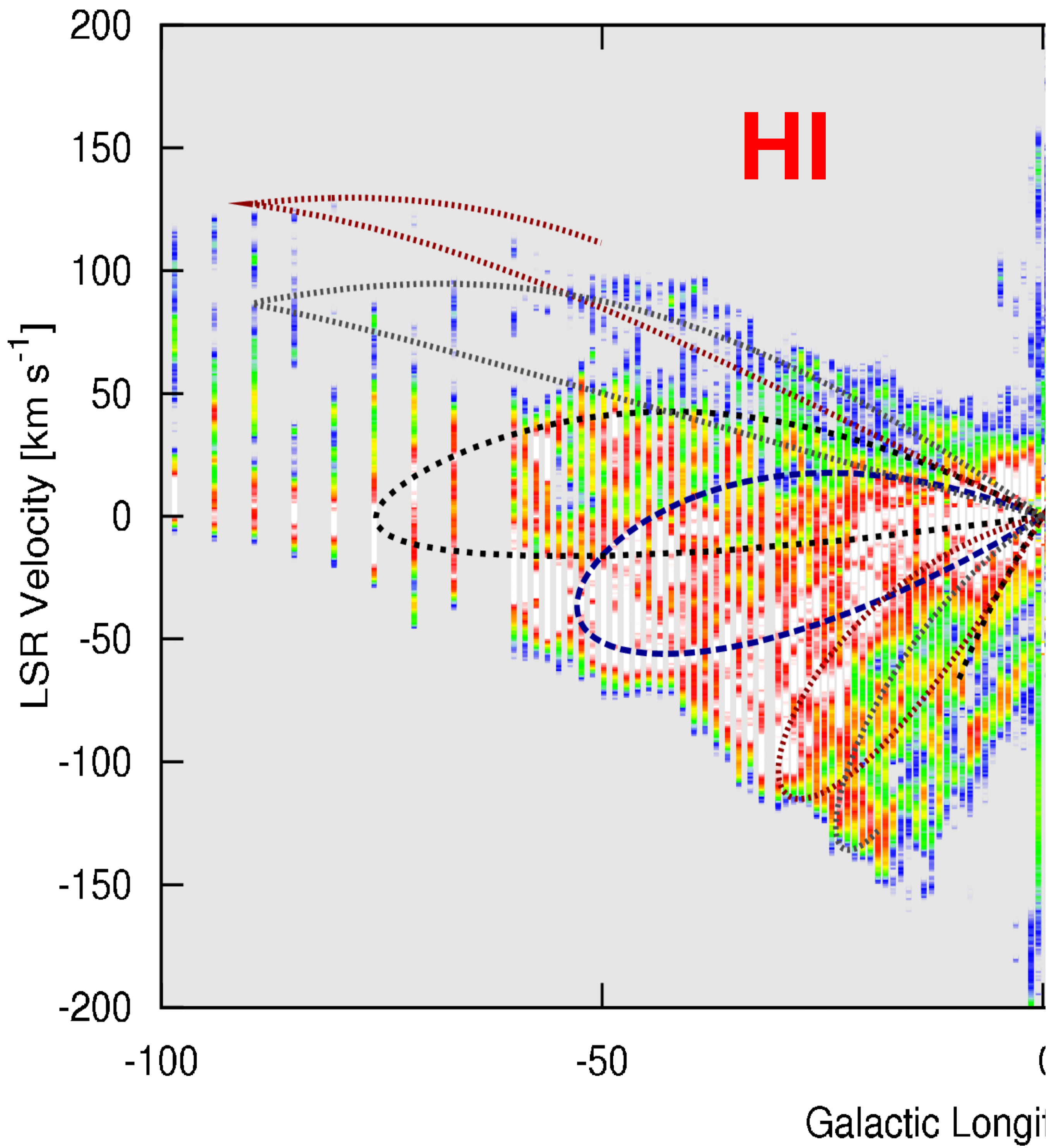
GOT C+ [CII] Distribution in the Milky Way



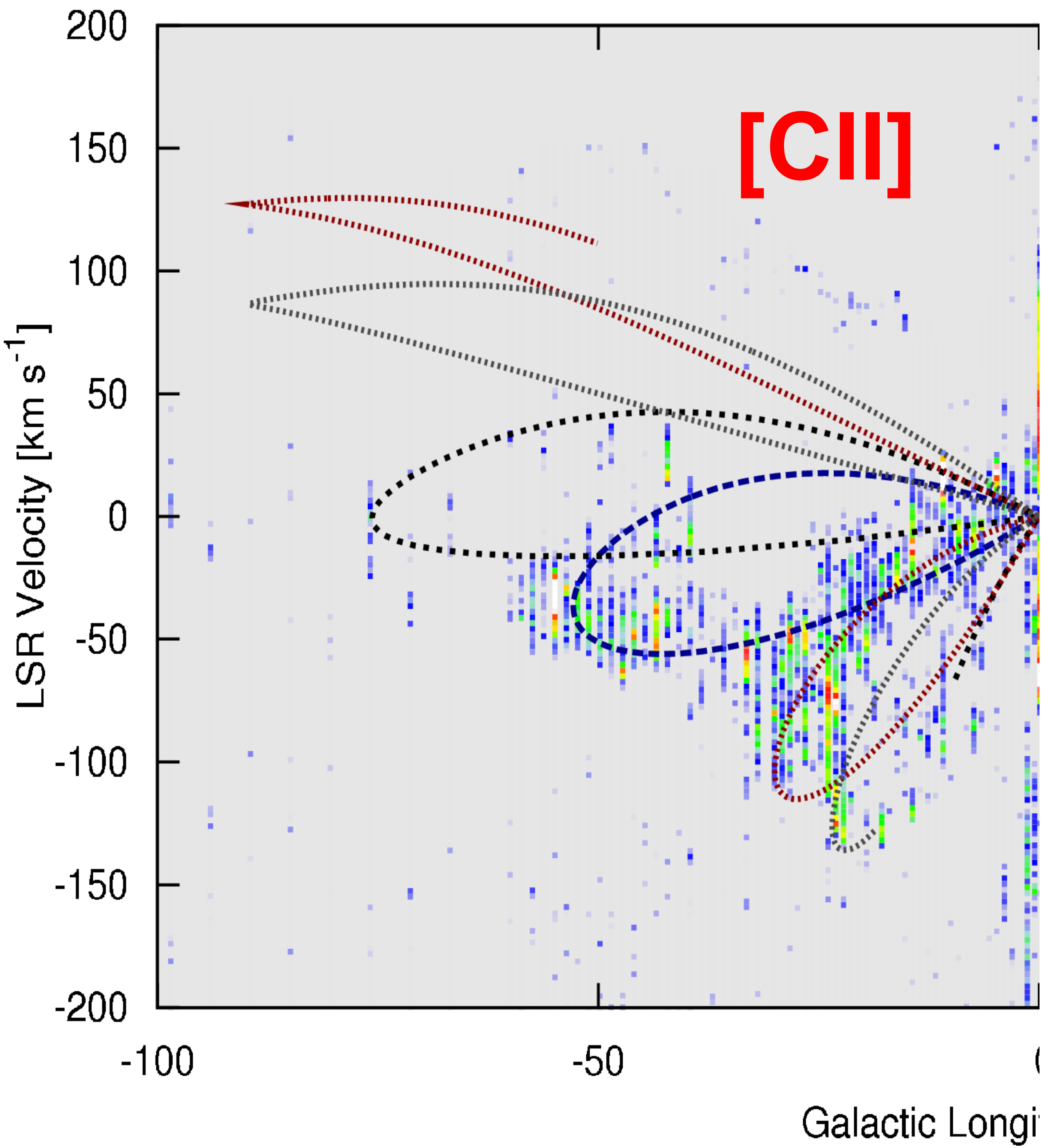
Dense and Cold Molecular Gas (CO)



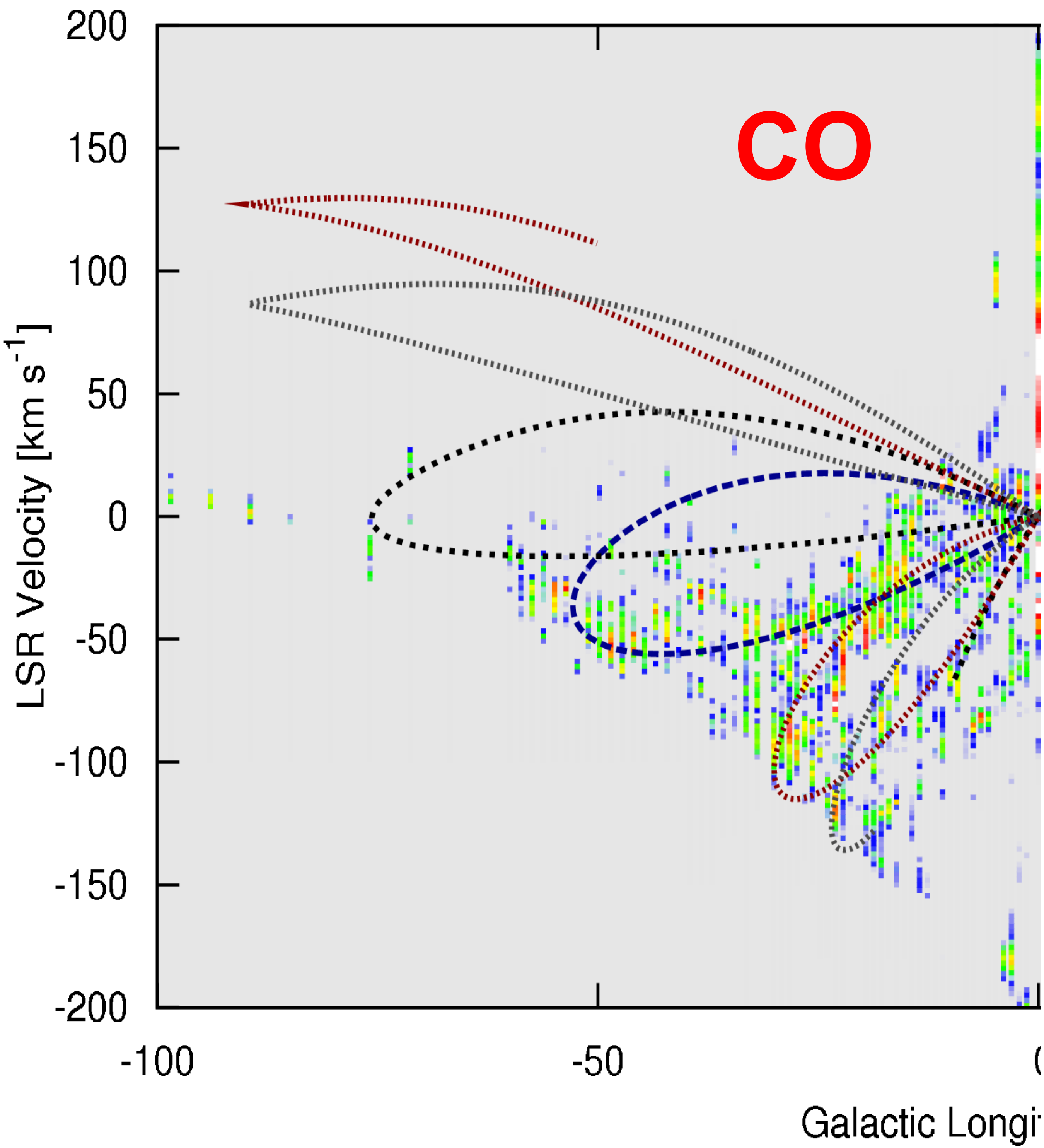
[CII] traces the transition between atomic and molecular clouds.



HI
LSR Velocity [km s-1]
200
150
100
50
0
-50
-100
-150
-200
-100
-50
Galactic Longi

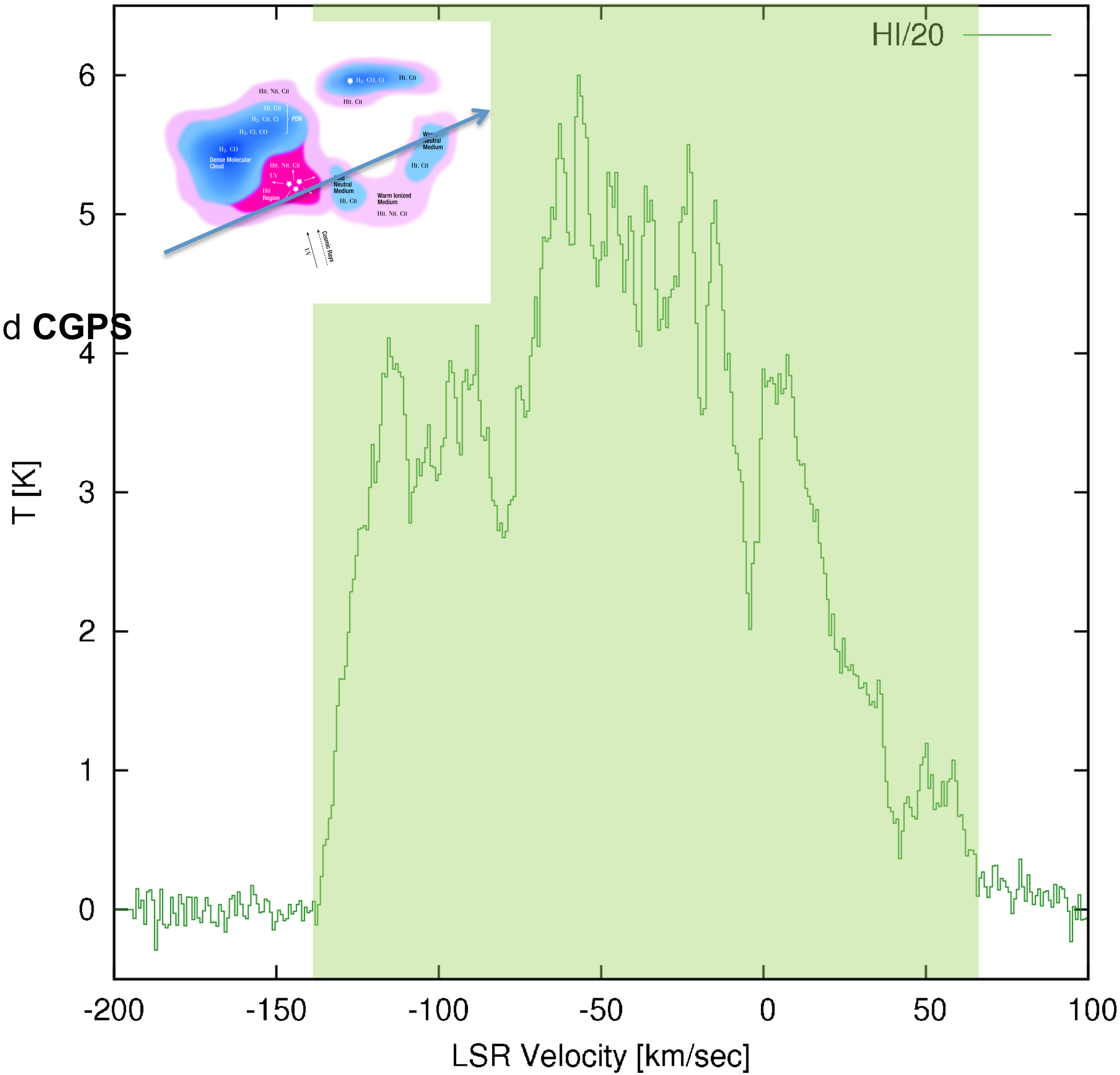


[CII]
200
150
100
50
0
-50
-100
-150
-200
LSR Velocity [km s^{-1}]
-100
-50
Galactic Longi


CO
LSR Velocity [km s^{-1}]
200
150
100
50
0
-50
-100
-150
-200
-100
-50
Galactic Longi

HI

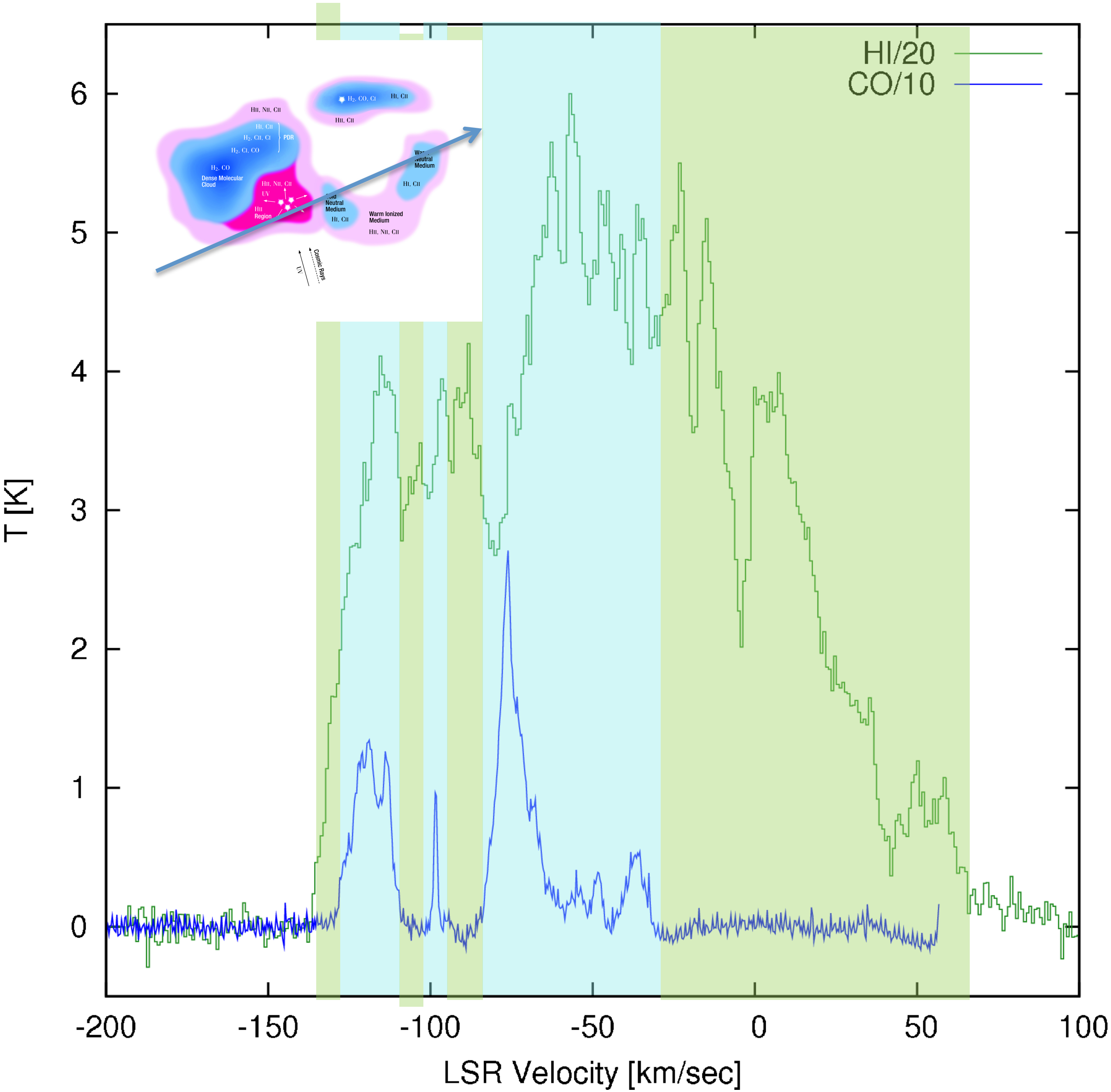
Data from:
SGPS, **VGPS**, and **CGPS**

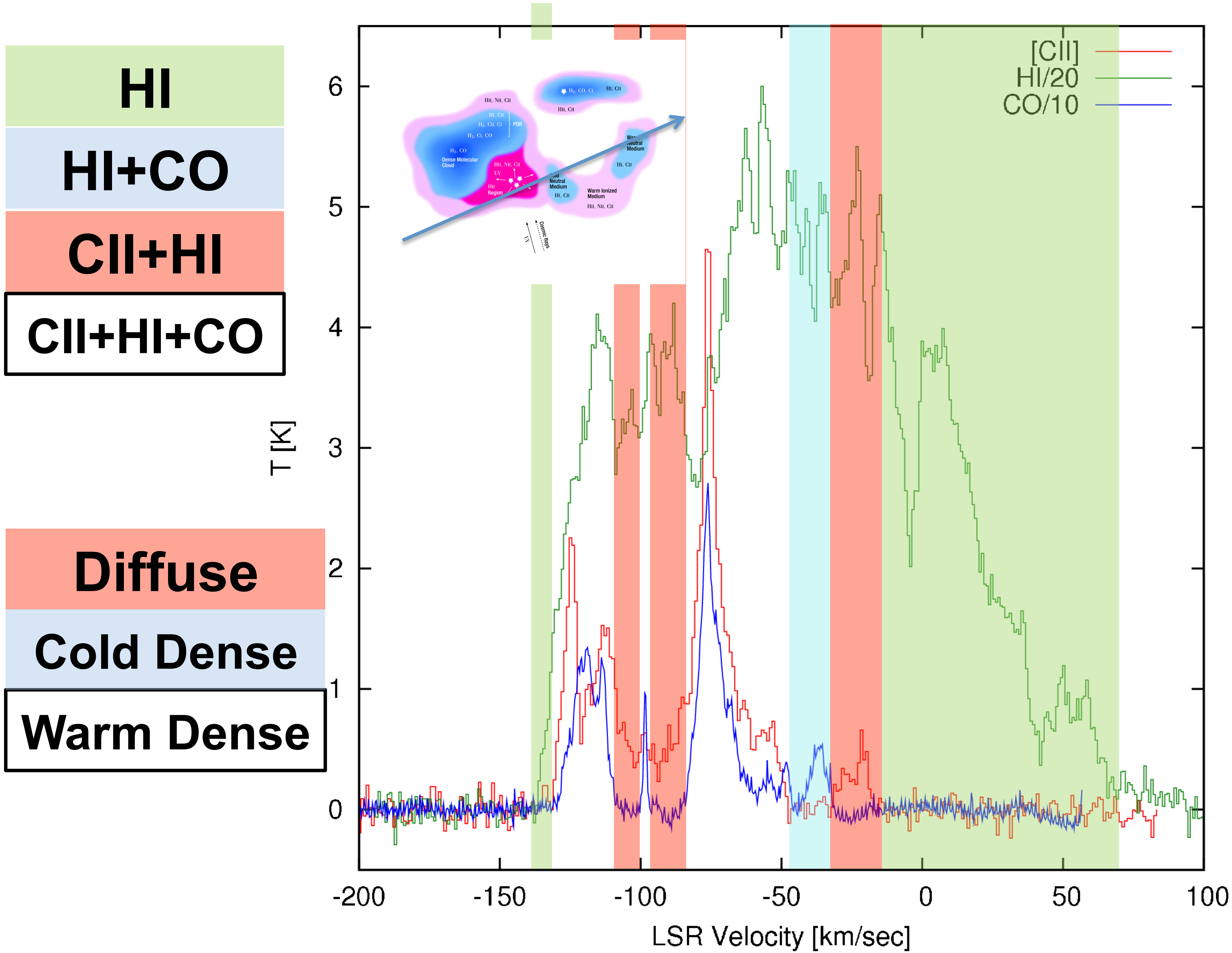


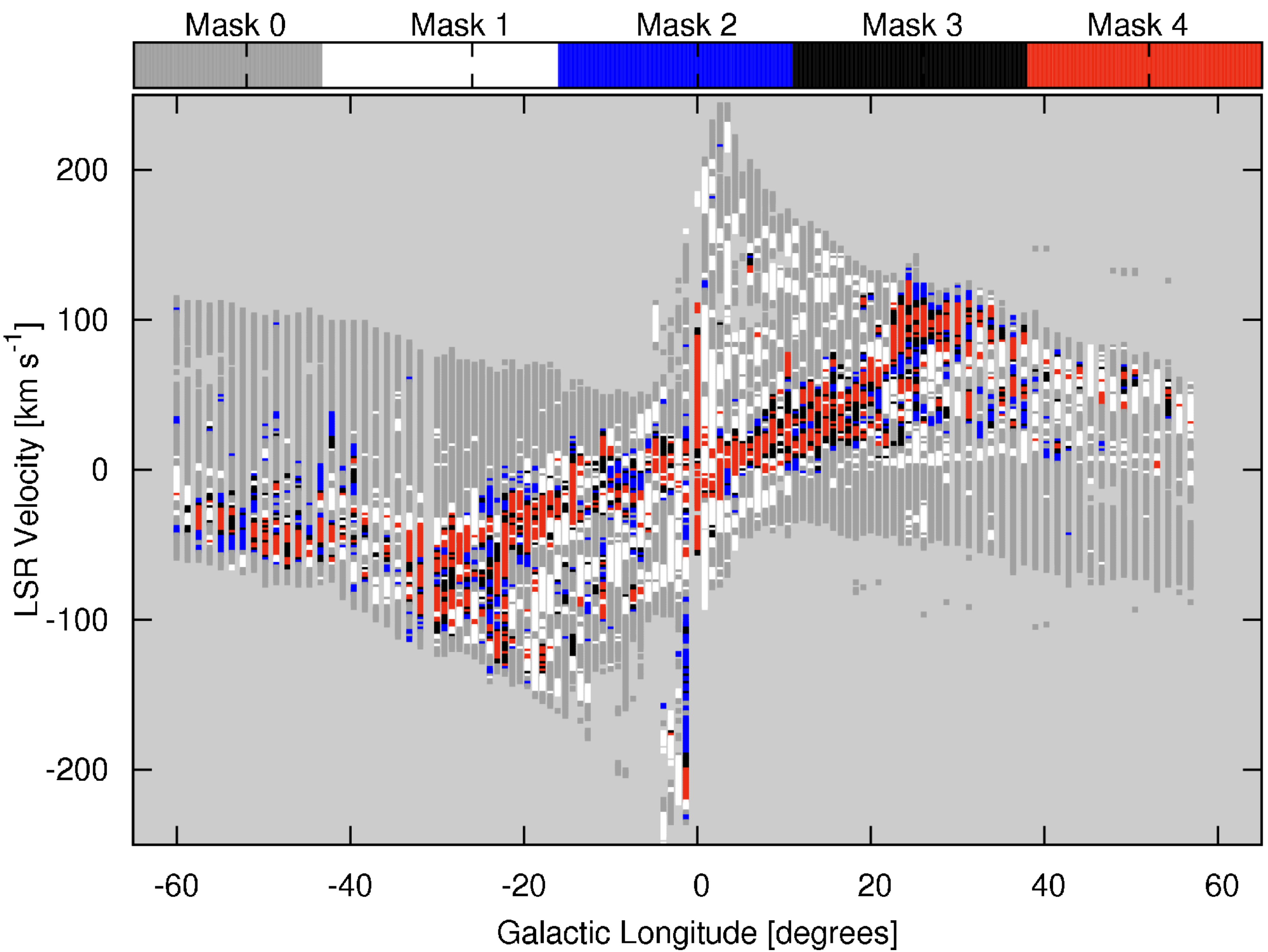
HI

HI+CO

Data from:
Mopra and **CSO**

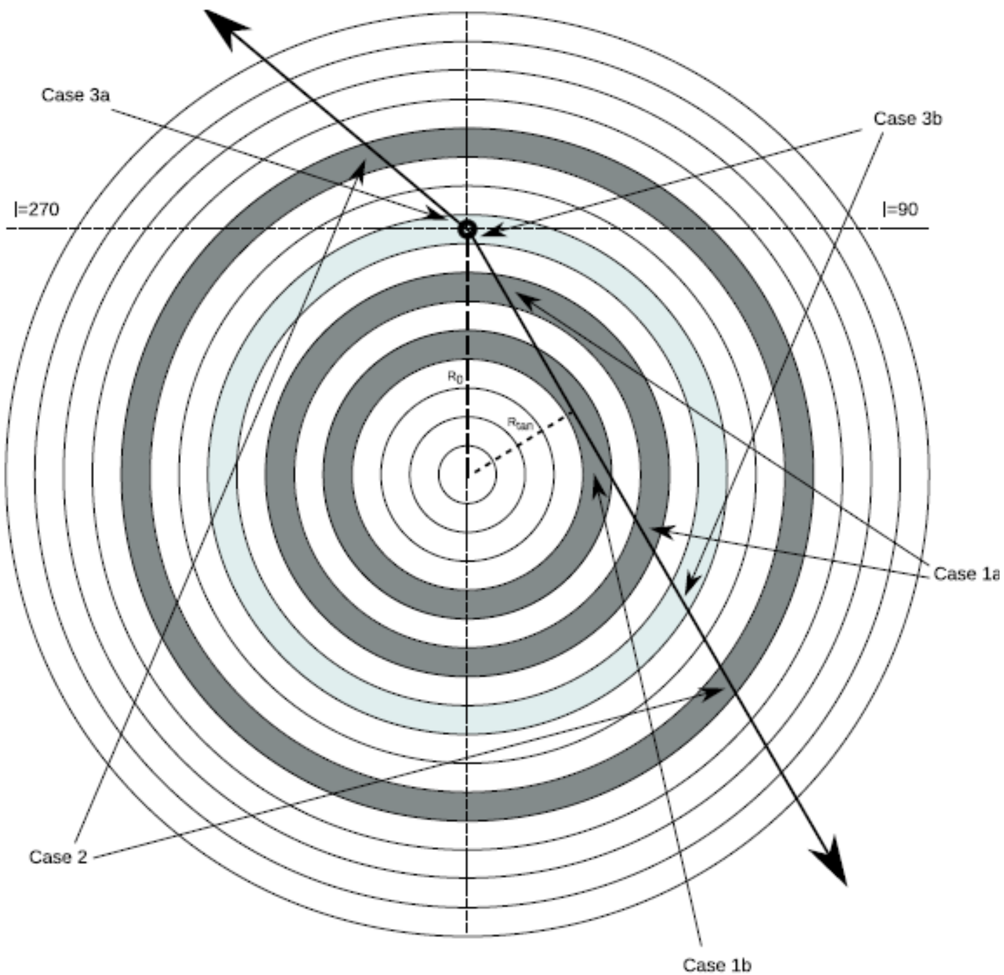


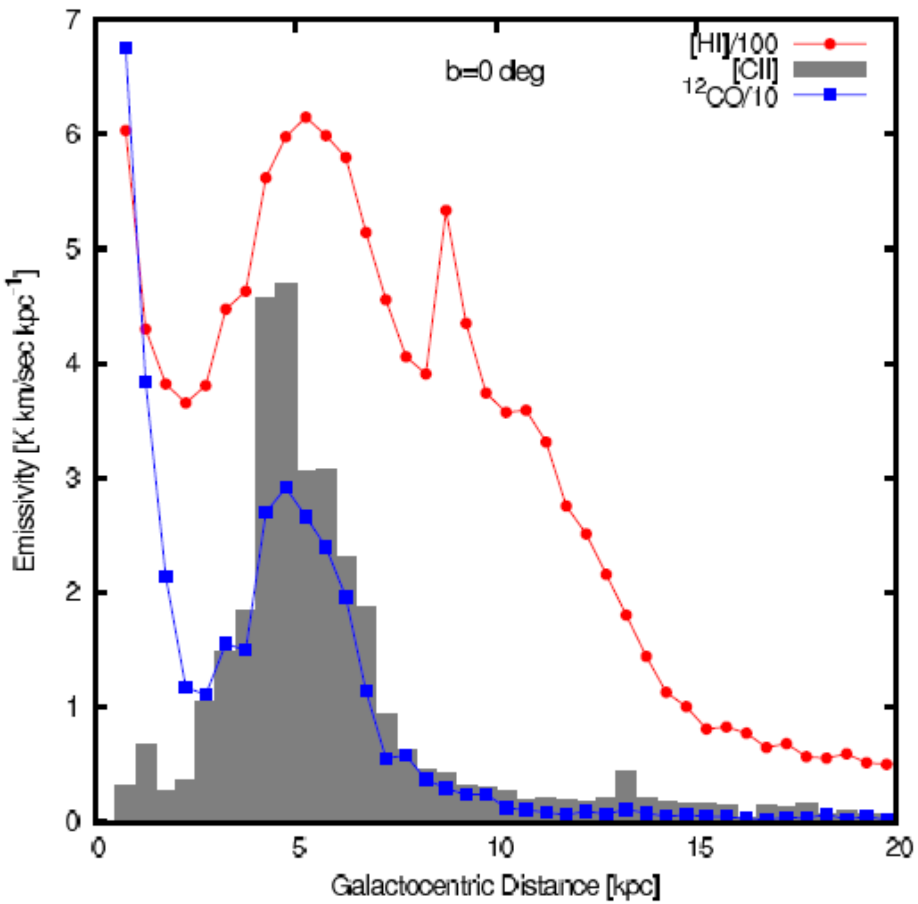

HI
HI+CO
CII+HI
CII+HI+CO
Diffuse
Cold Dense
Warm Dense
[CII]
HI/20
CO/10
T [K]
LSR Velocity [km/sec]
-200
-150
-100
-50
0
50
100
0
1
2
3
4
5
6
Dense Molecular Cloud
HII Region
Warm Ionized Medium
PDR
Cosmic Rays
UV



Mask 0
Mask 1
Mask 2
Mask 3
Mask 4
LSR Velocity [km s-1]
200
100
0
-100
-200
-60
-40
-20
0
20
40
60
Galactic Longitude [degrees]

Galactocentric Distribution



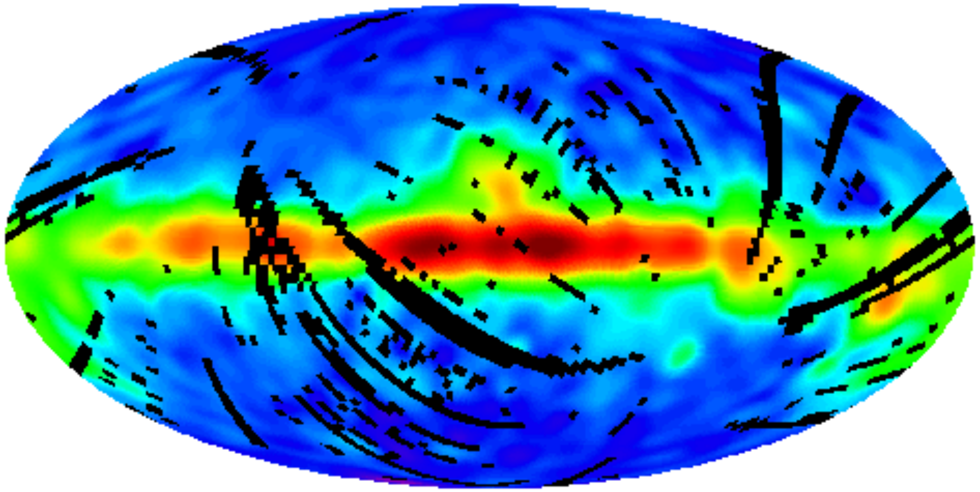


[CII] as a tracer of the Warm Ionized Medium

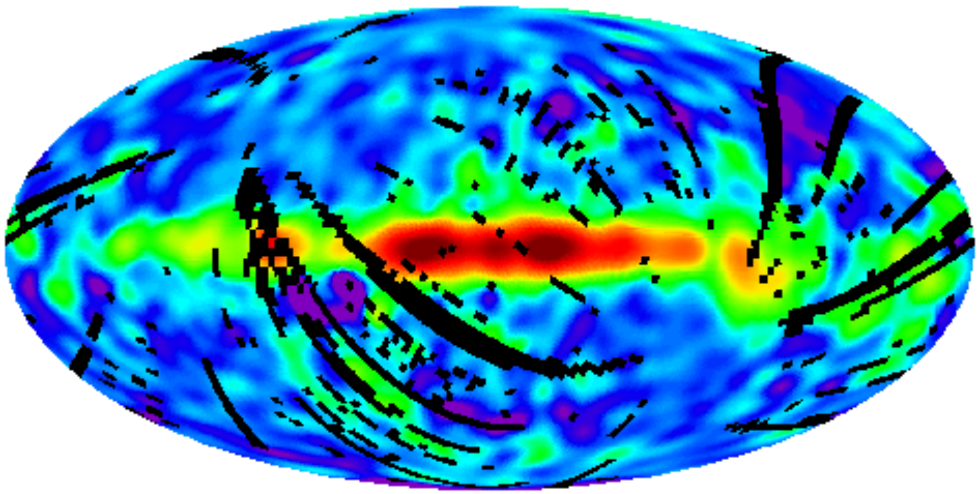
WIM: T=8000K, low volume densities, traced by [CII] and [NII], H-alpha, and radio continuum.

- 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).

COBE FIRAS 158 μm C^+ Line Intensity



COBE FIRAS 205 μm N^+ Line Intensity



Bennett et al. 1994

[CII] as a tracer of the Warm Ionized Medium

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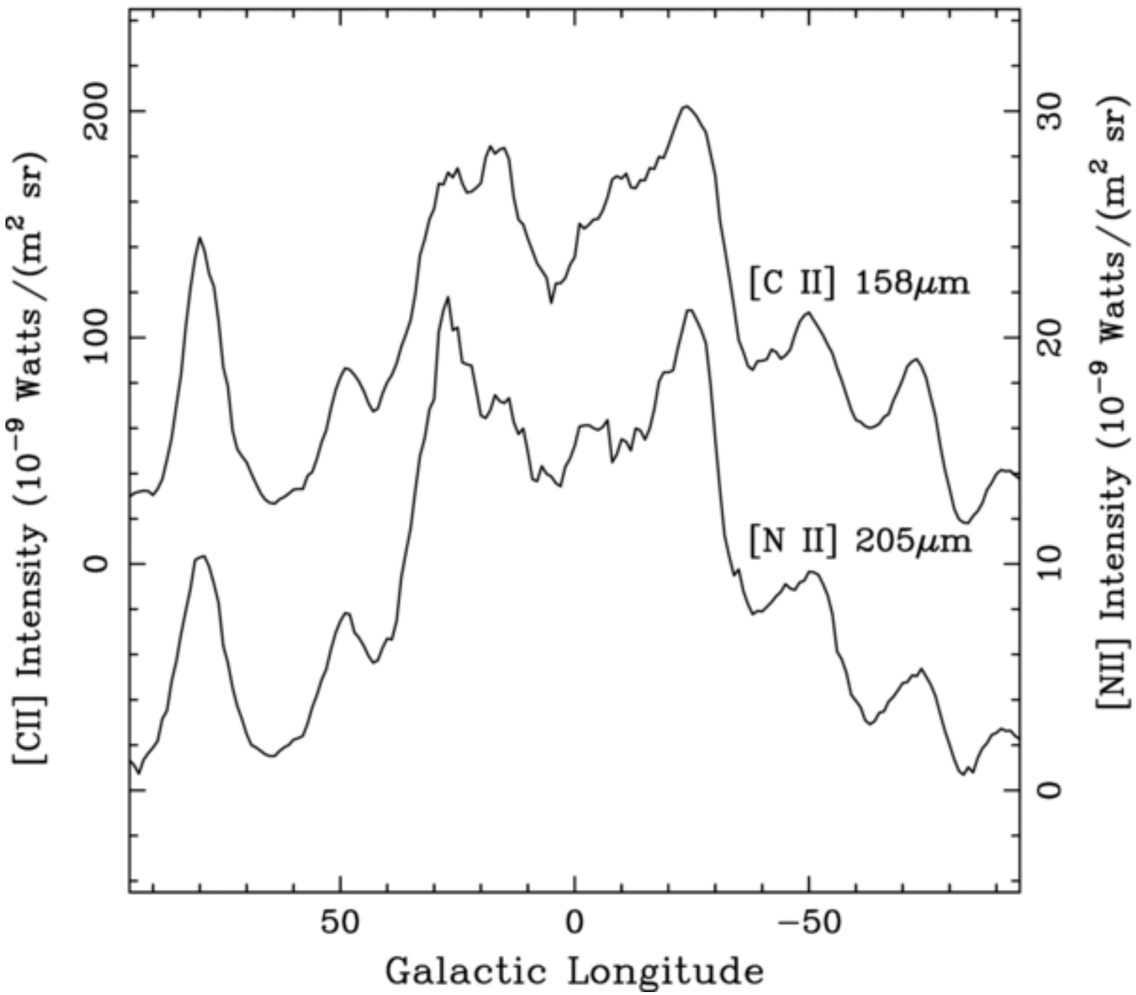
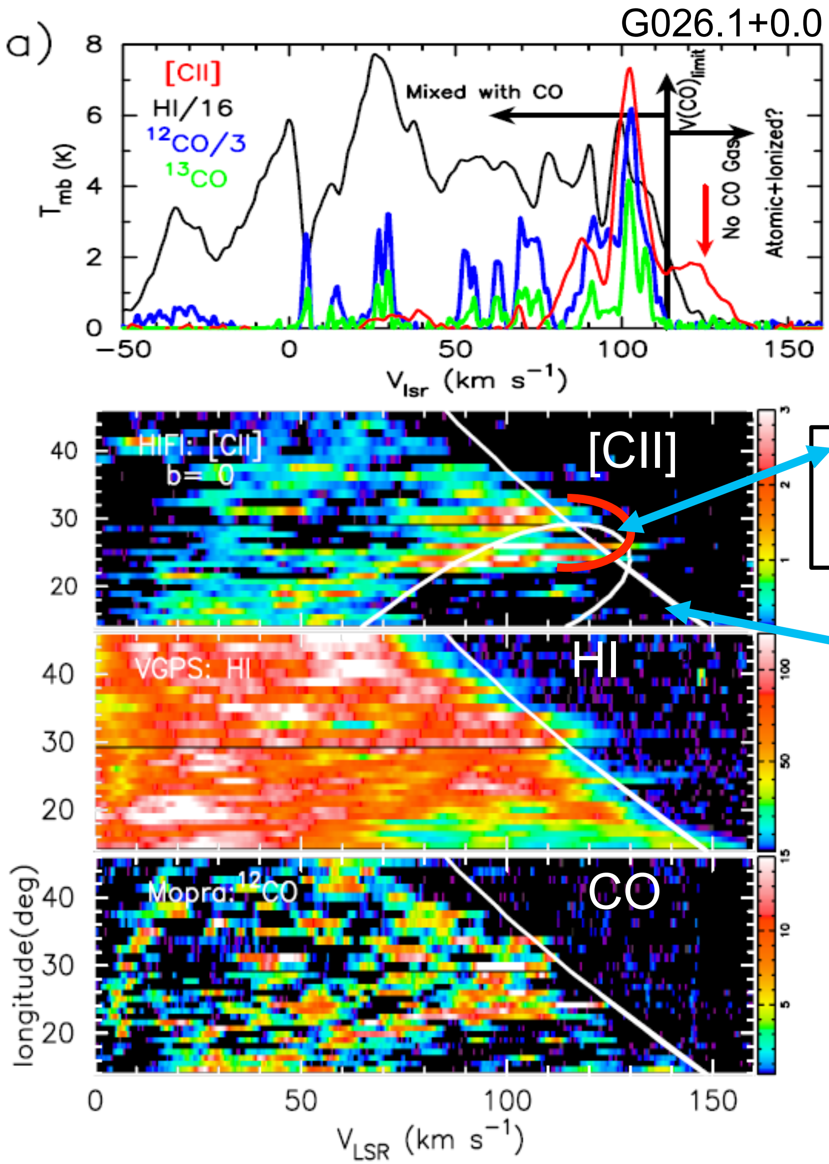
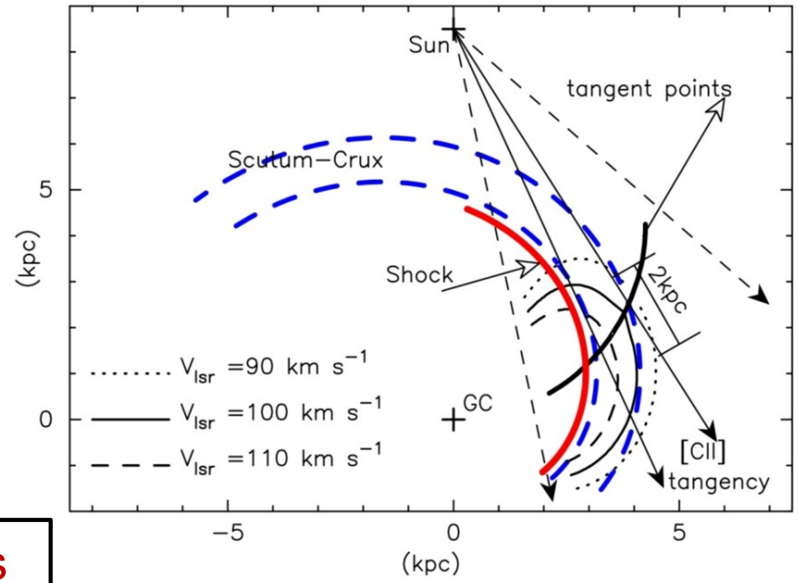


Steiman-Cameron et al. 2008

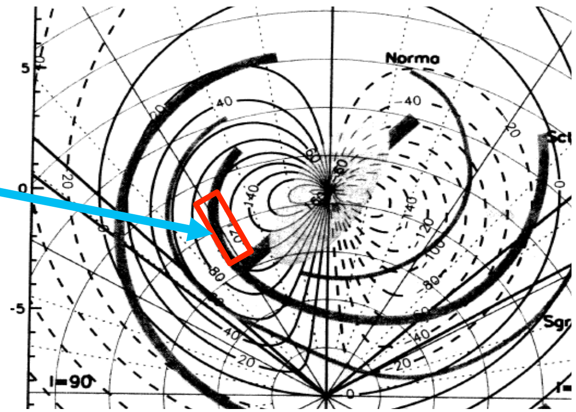
GOT C+ [CII] detection of WIM in Spiral Arm Tangency

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



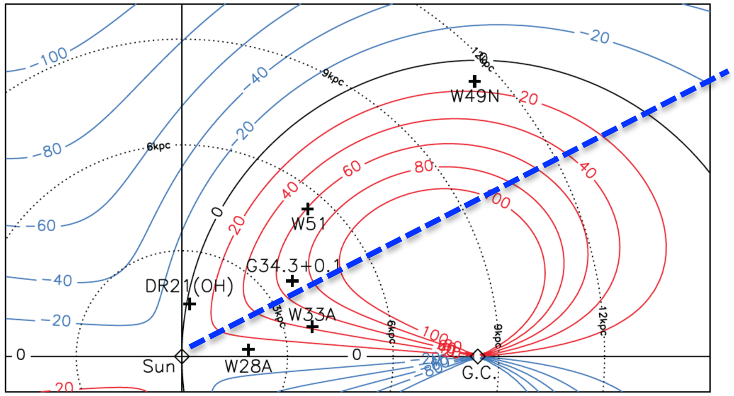


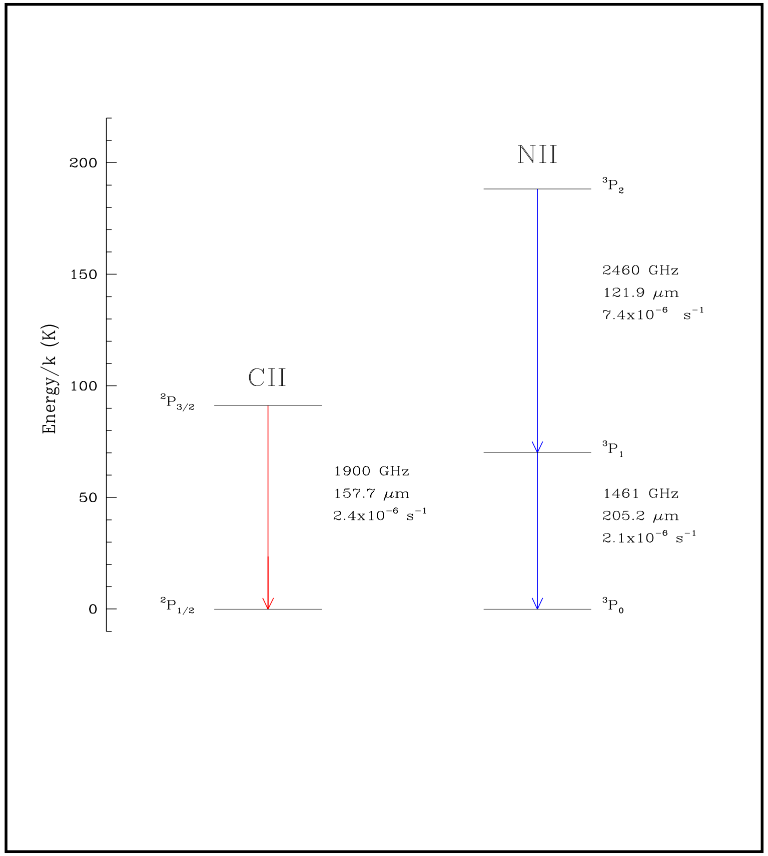
[CII] excess tracing WIM

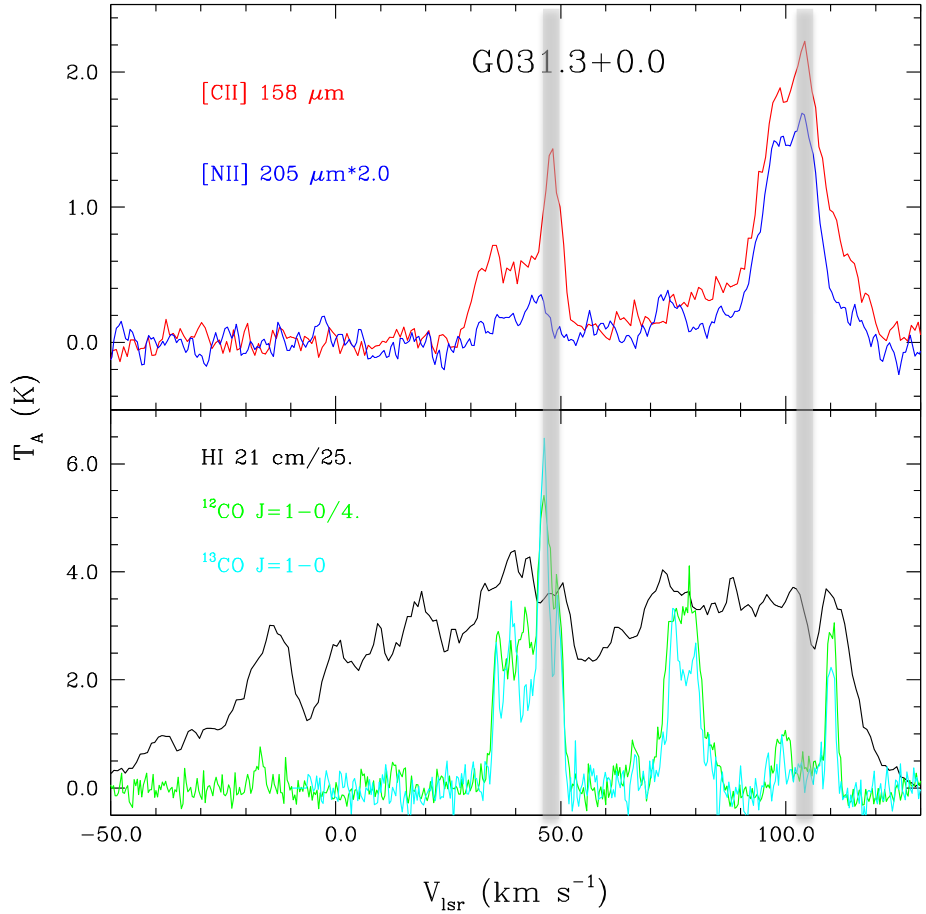


The geometry of the Scutum-Crux (S-C) arm is very favorable to detect weak [CII] emission from the WIM and study its structure and kinematics

Warm Ionized Medium: [NII]

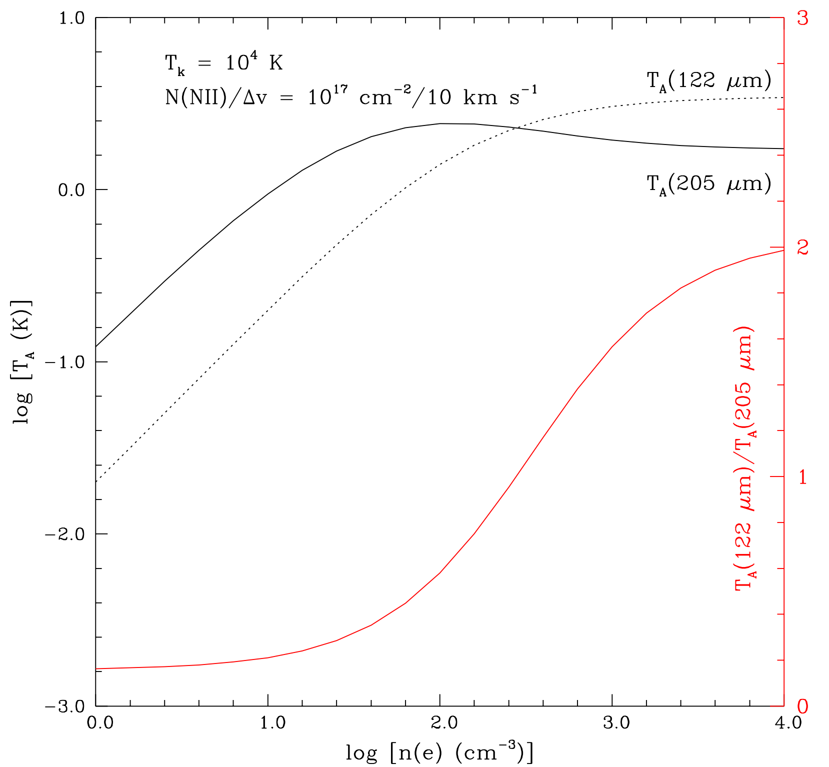


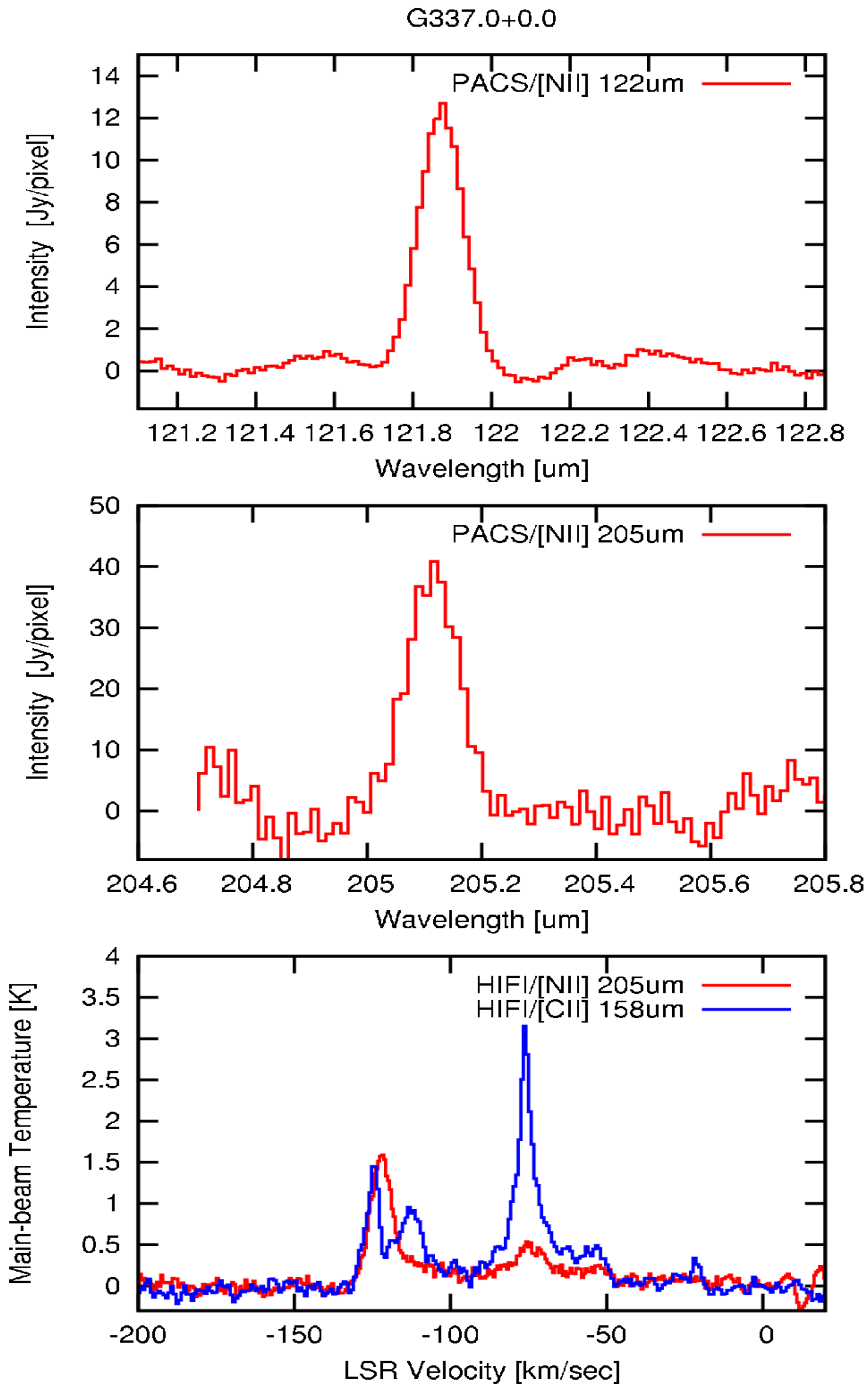




Goldsmith et al. (2013) in prep

Herschel PACS/HIFI [NII]

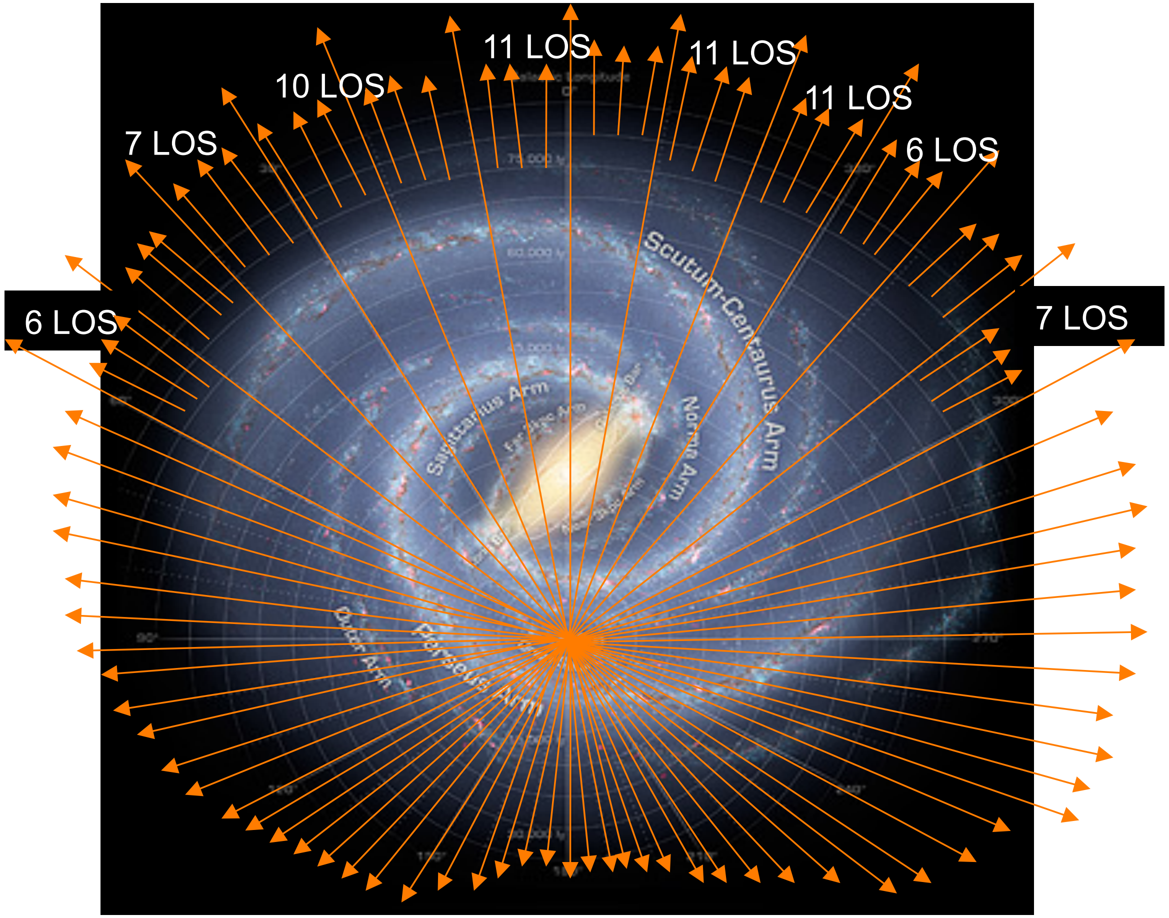




- Relative Intensity of Two [NII] Lines Yields n(e).
- [NII] 122um/205um = 1.4 → ne=30 cm^{-3}.
- Radio Continuum observations give EM=6500 cm^{-6} → N(H+)=2x21 cm^{-2}.
- In this region 30% of the [CII] emission comes from ionized gas.

GOT N+ Survey

- OT2 Project. PI: Paul Goldsmith
- All GOT C+ LOSs with b=0, observed in [NII] 205 um and 122um with PACS
- Selected lines of sights in [NII] 205um with HIFI

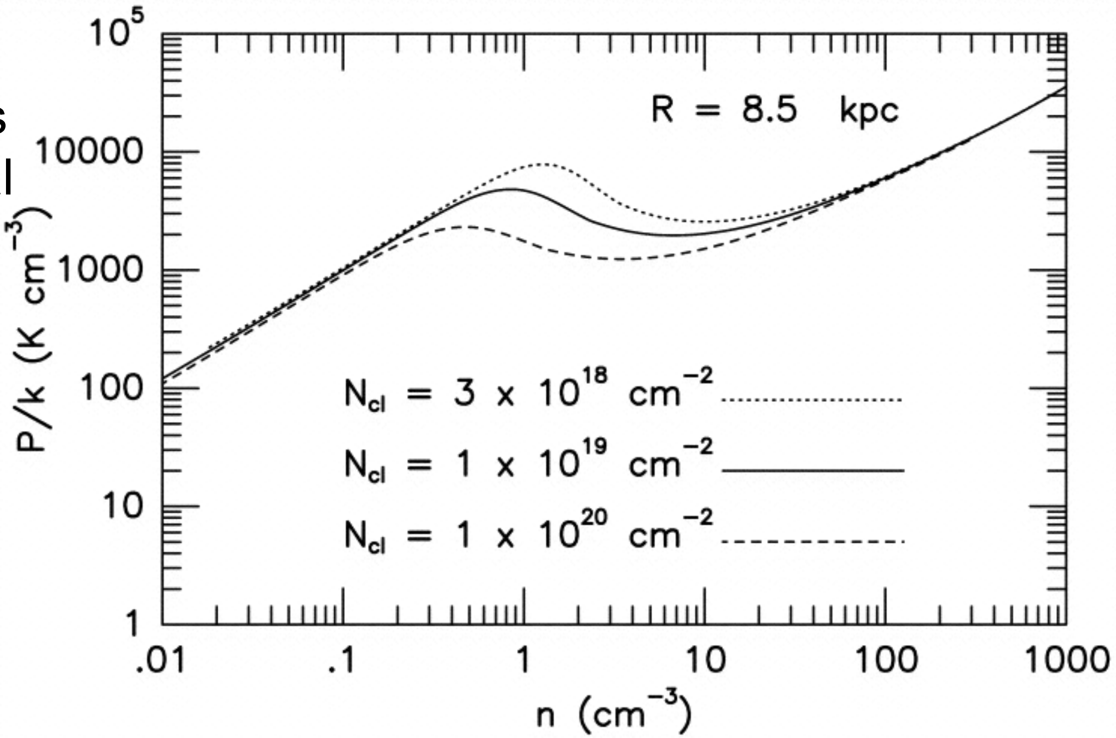


Warm and Cold Neutral gas:

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)

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

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



Wolfire et al. (2003)

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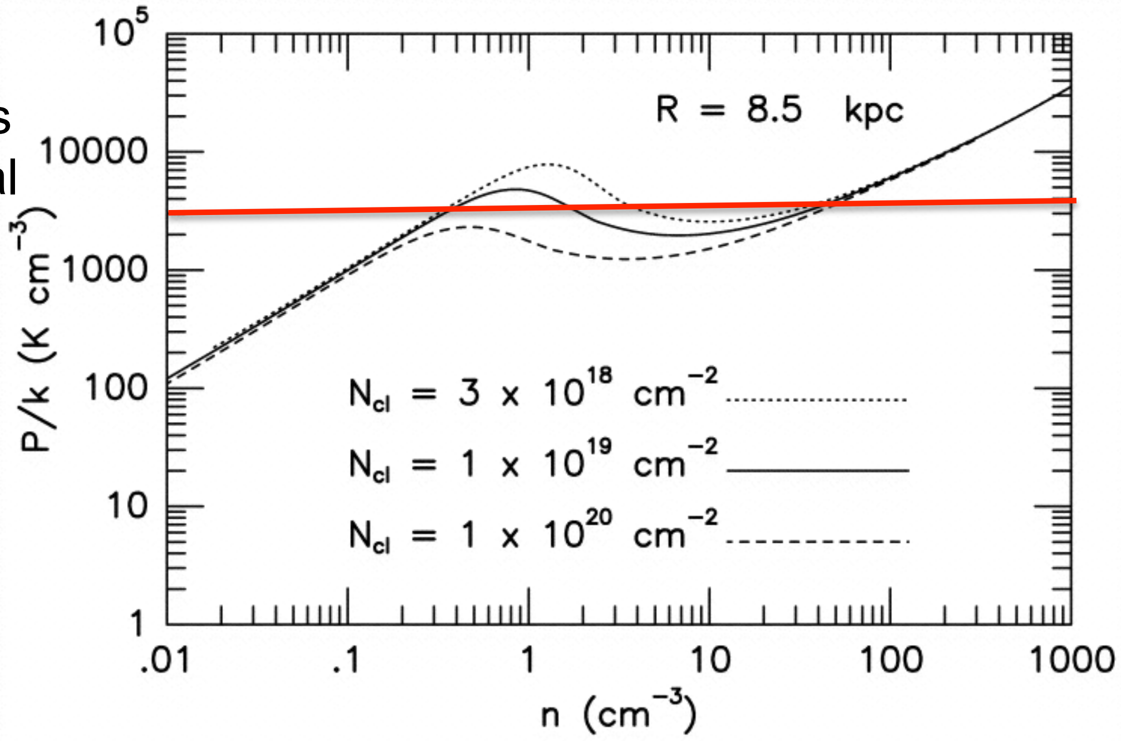


Wolfire et al. (2003)

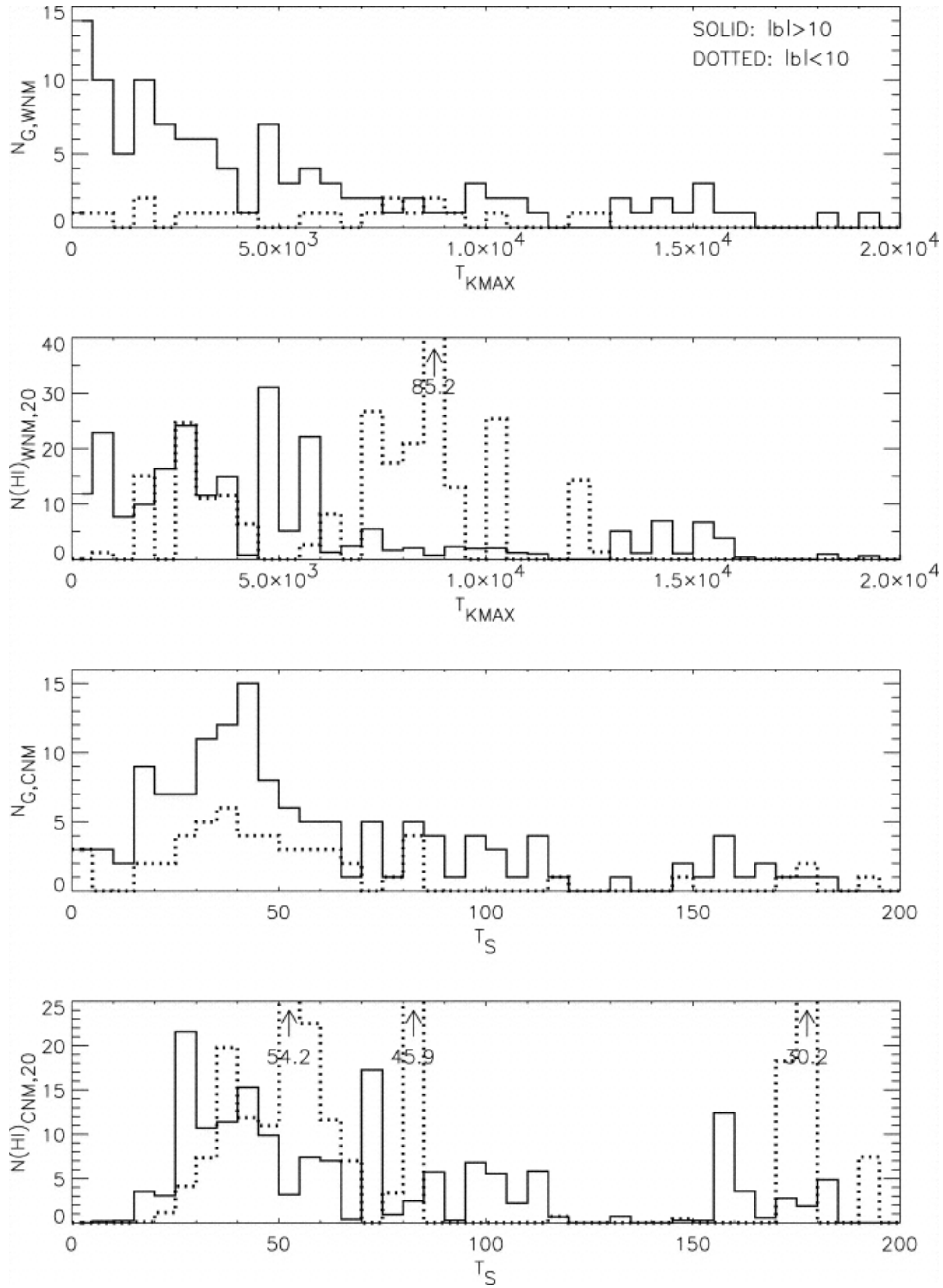
Warm and Cold Neutral gas:

- 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).

- Heiles & Troland 2003: 50% of the mass in unstable conditions -> Turbulence dominates over Thermal instability (Vasquez-Semadeni 2009)

- Wolfire 2010, IAU: 15% of the mass in unstable conditions -> Thermal Instability still important



Heiles & Troland (2003) ApJ 586, 1067

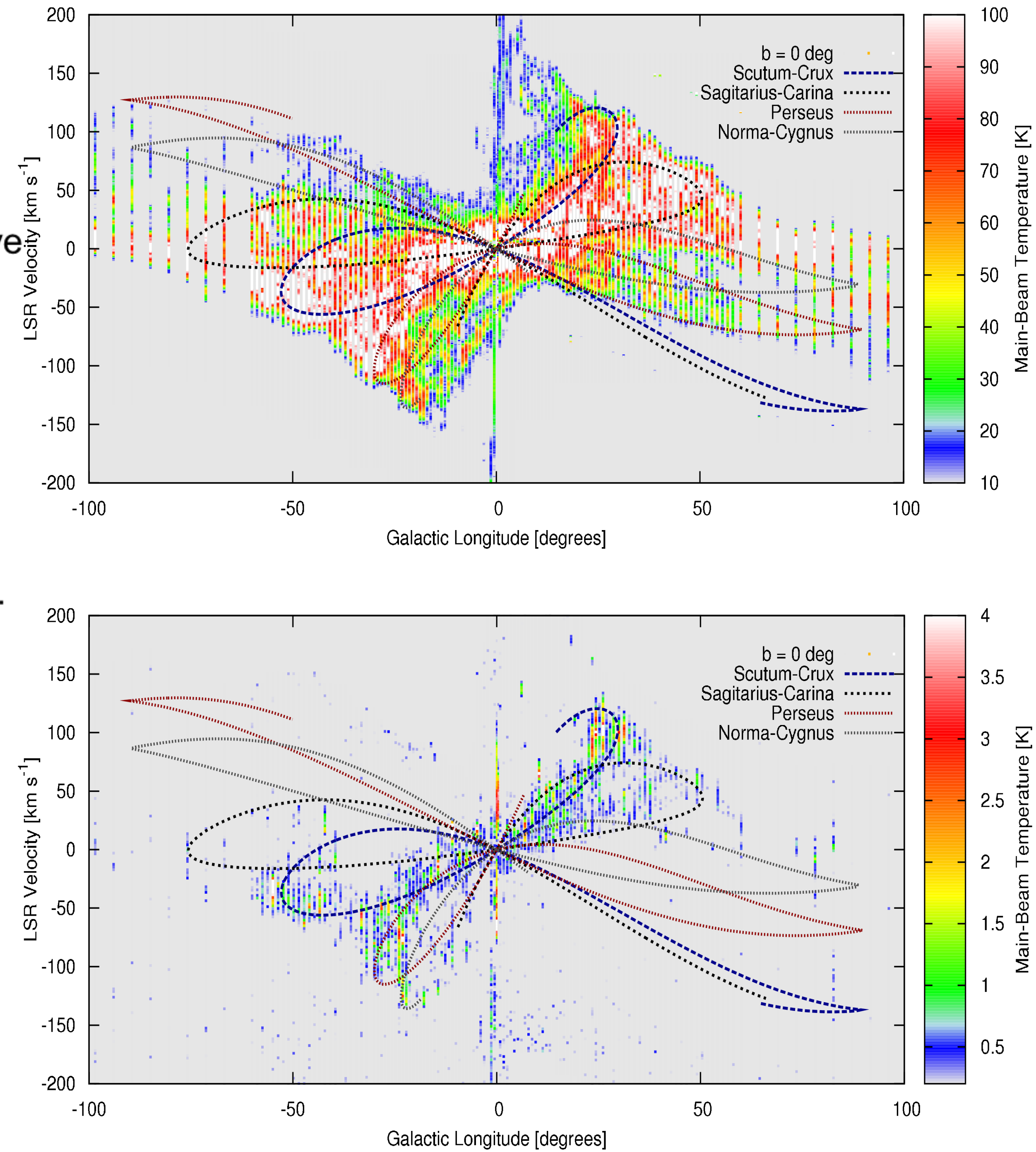
Warm and Cold Neutral gas:

- 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.



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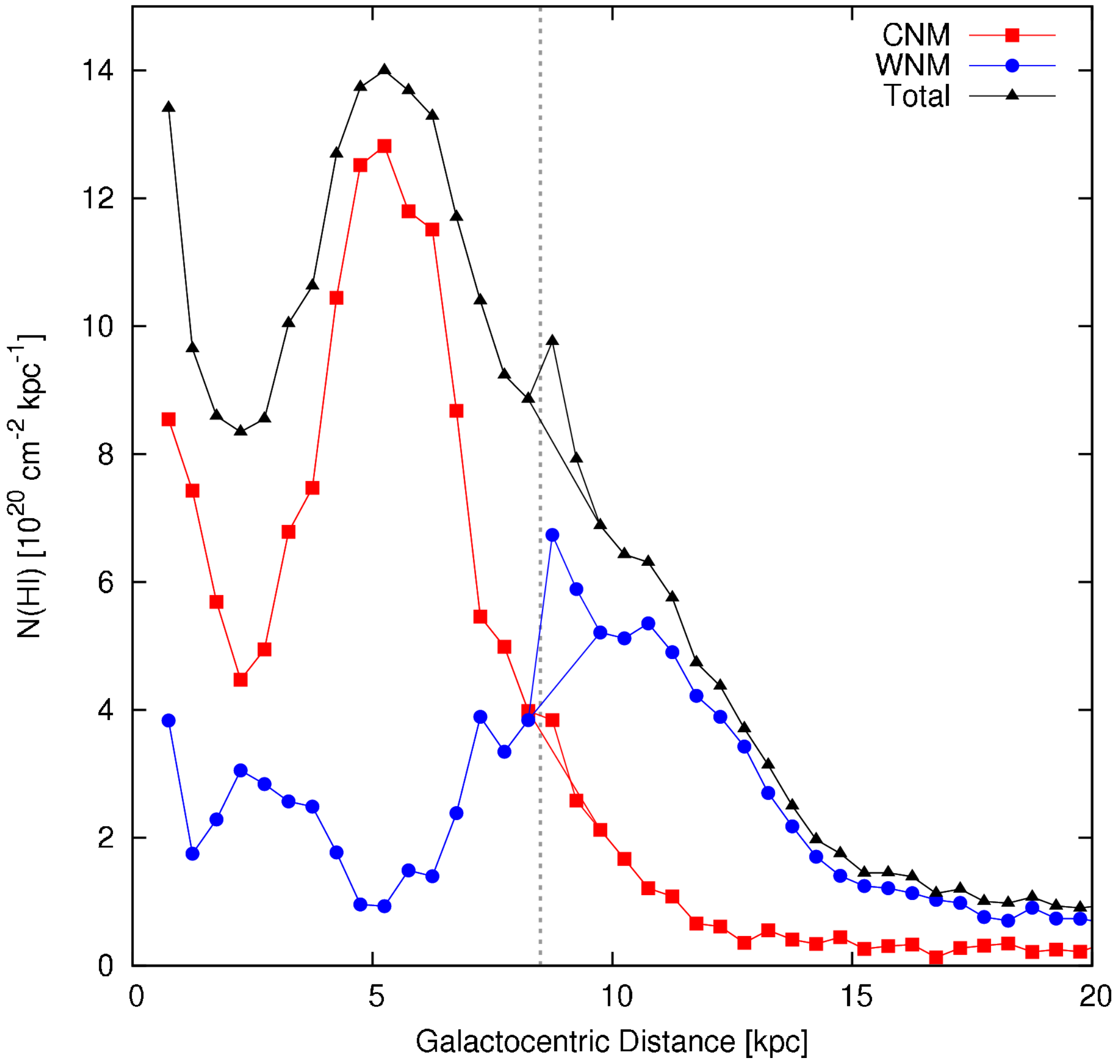
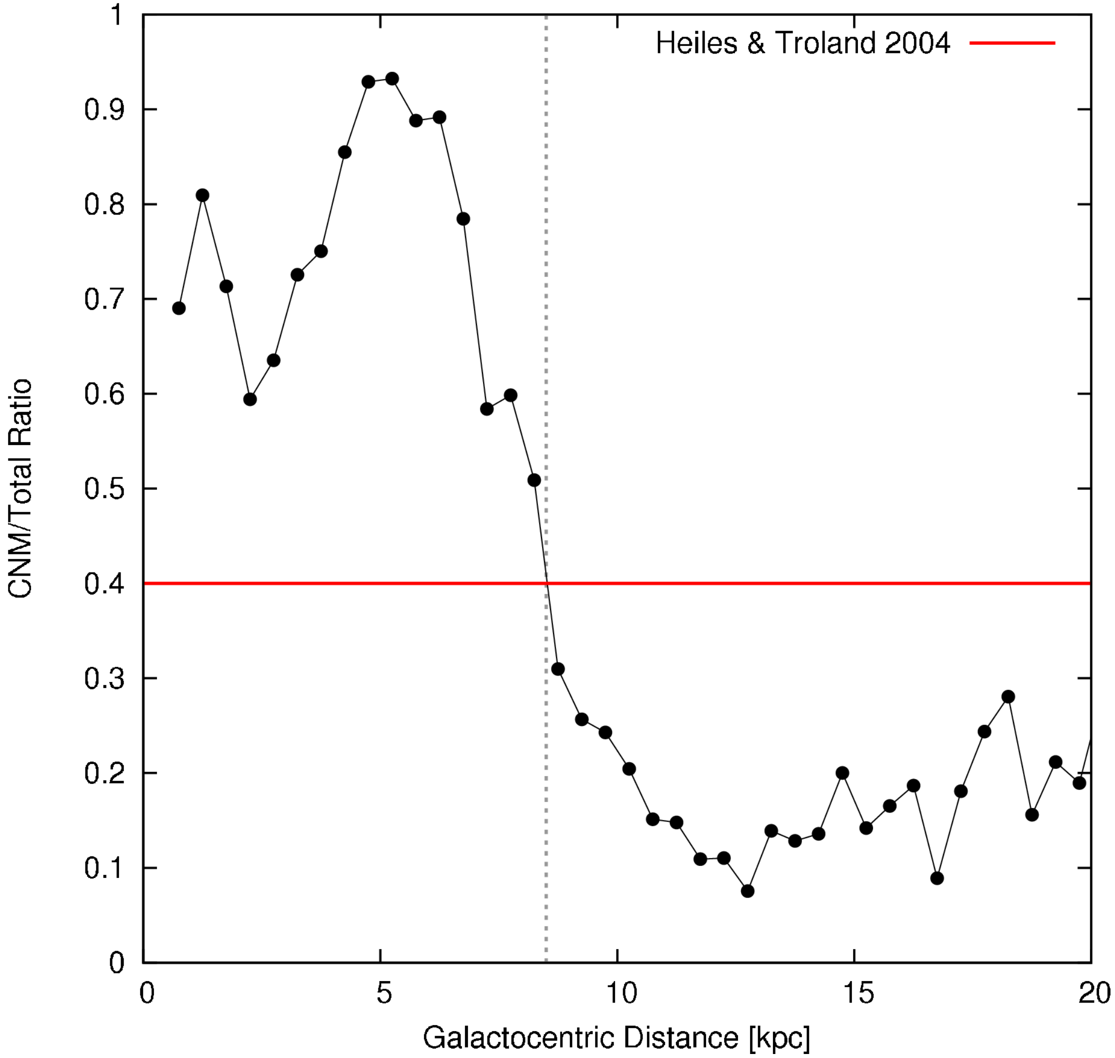


Pineda et al. (2013) A&A 554, A103

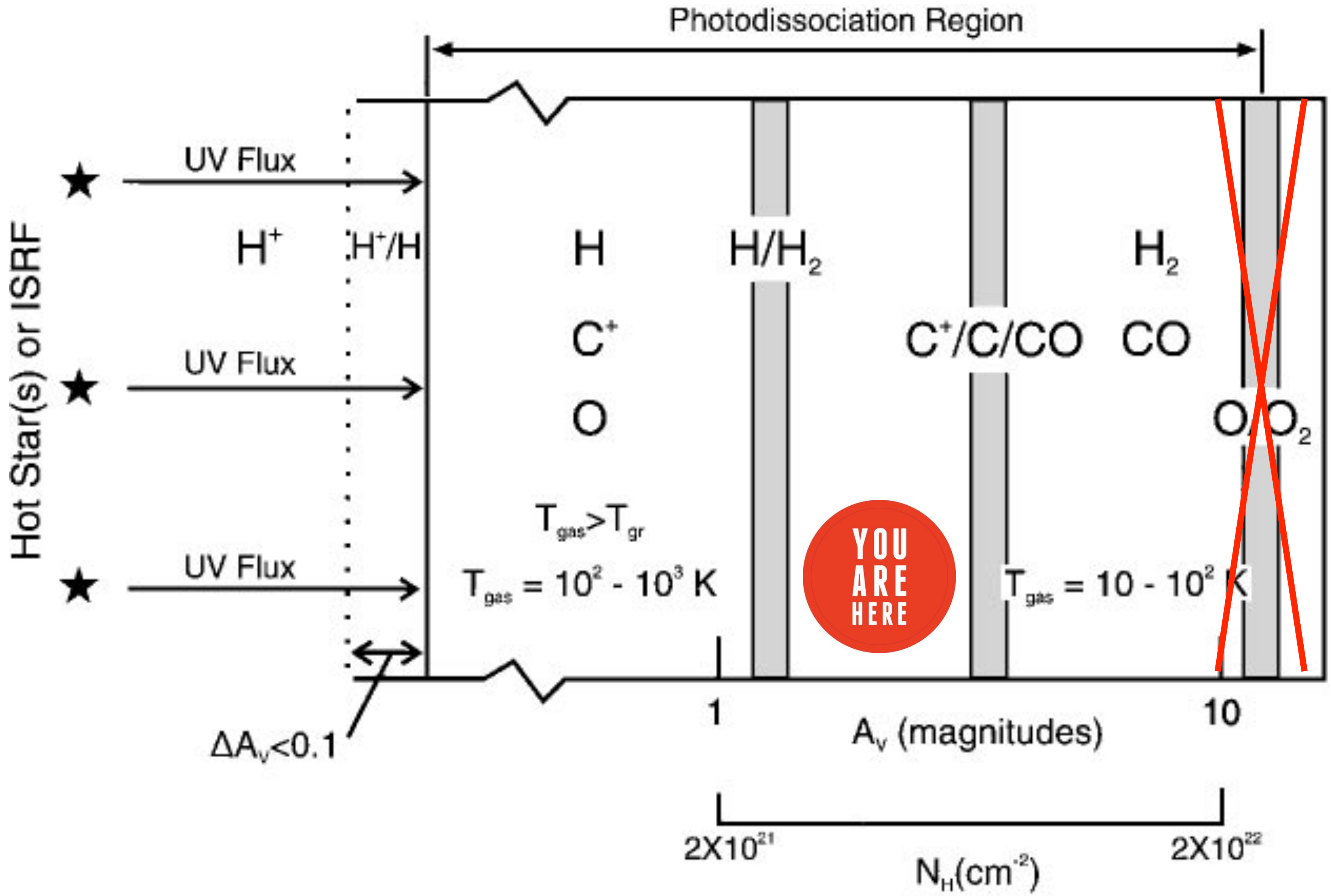
Warm and Cold Neutral gas:

- 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).



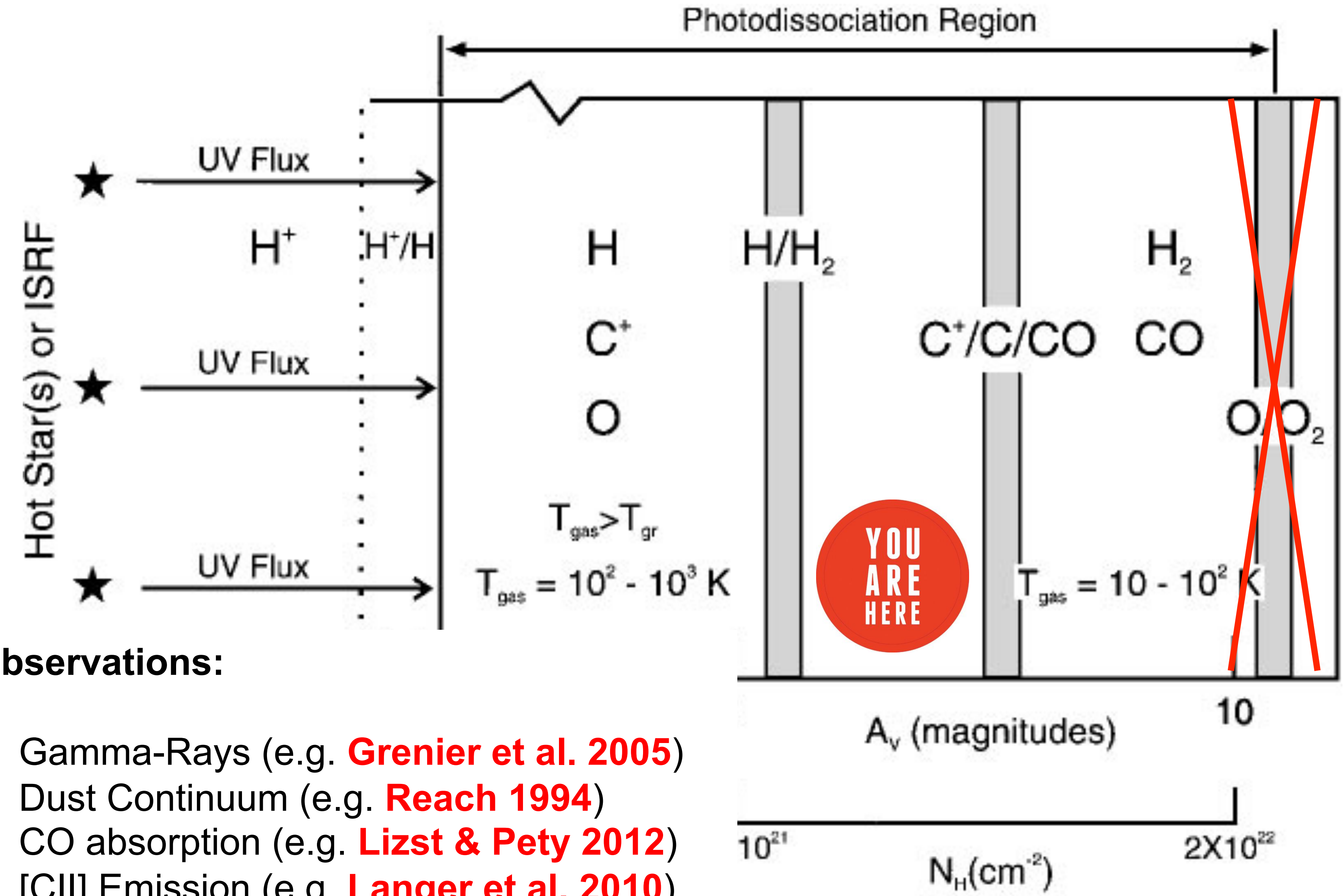
Pineda et al. (2013) A&A 554, A103

CO-"Dark" H_2 Gas



Hollenbach and Tielens (1997)

CO-"Dark" H_2 Gas



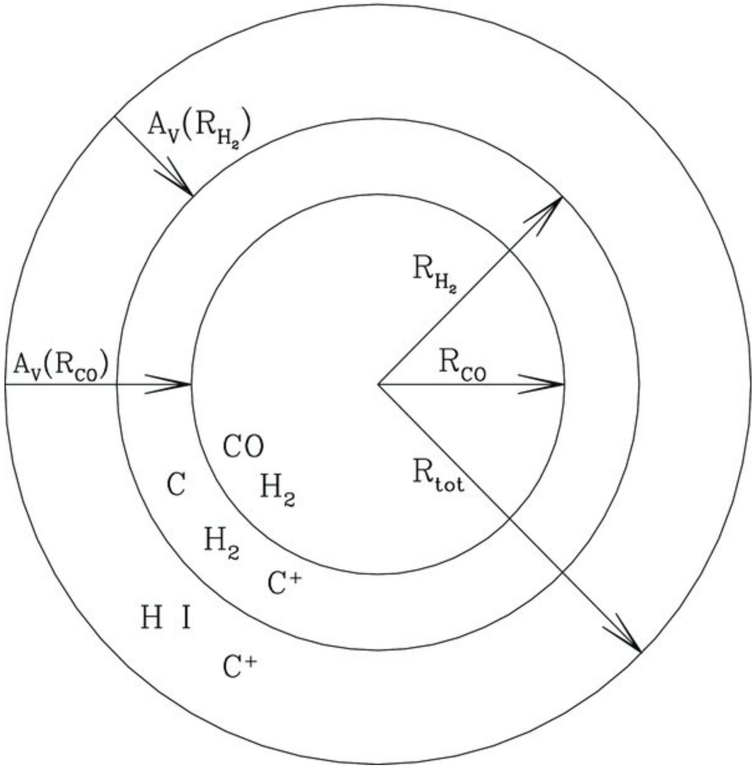
Observations:

- 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**)

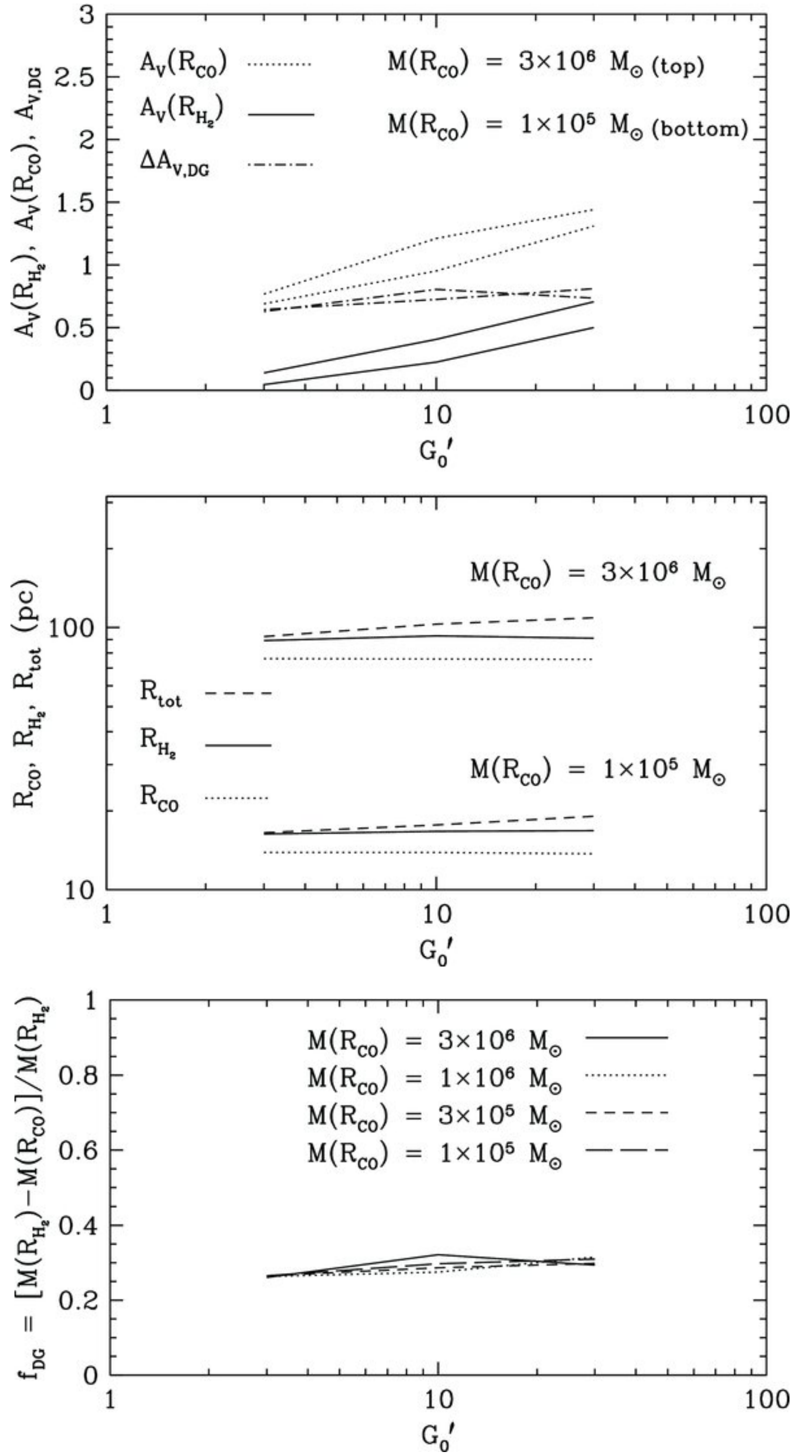
Hollenbach and Tielens (1997)

CO-Dark H_2 : Theory

(Wolfire et al. 2010, ApJ 716 1191)

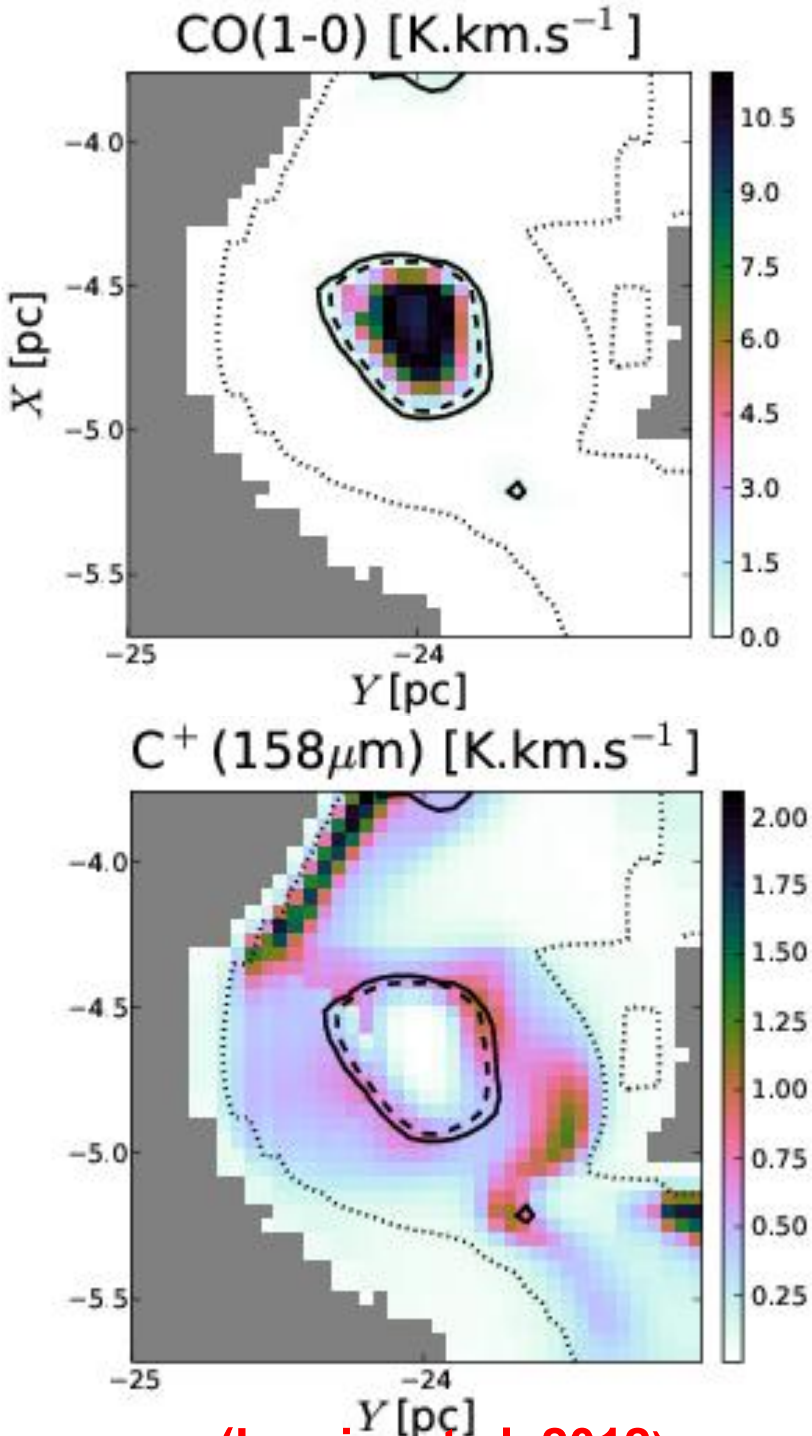


- Assumes two-phase turbulent medium
- Thickness of CO-dark H_2 layer constant
- Mass fraction of CO-dark H_2 constant; f~0.3



CO-Dark H_2 : Theory

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



(Levrier et al. 2012)

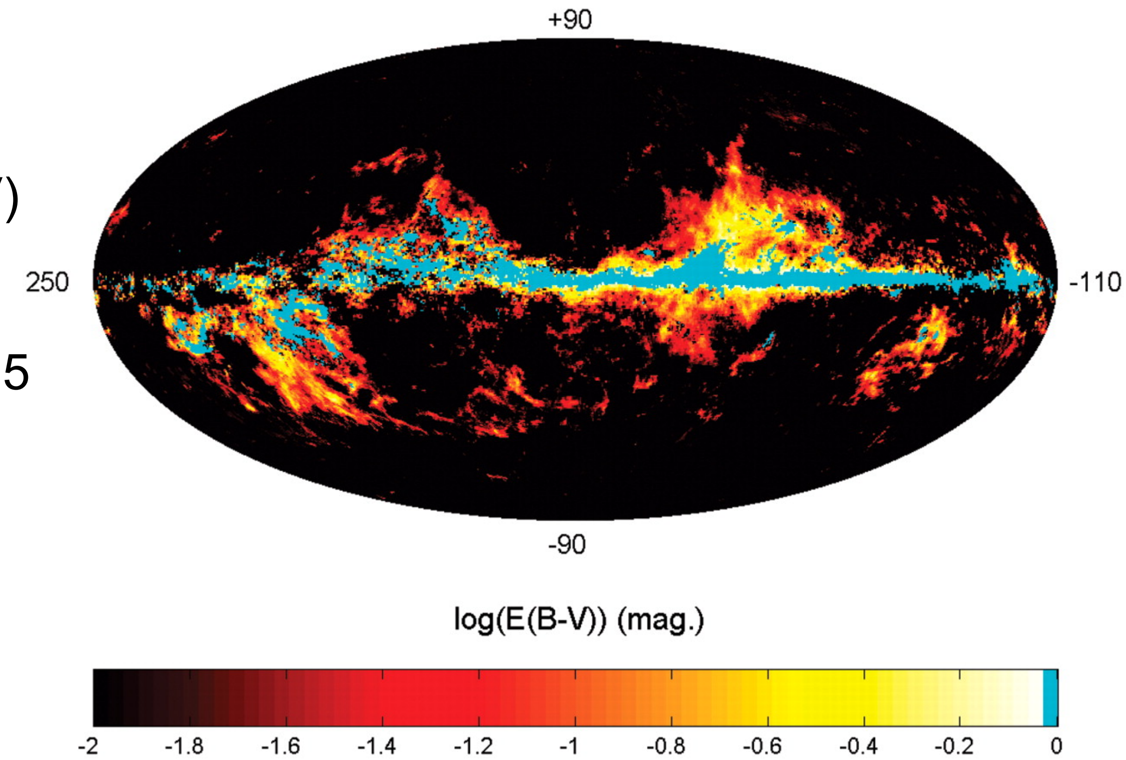
CO-Dark H_2 : Observations in 2D: Technique: Gamma-Rays

Method: Correlate the Gamma-ray intensity and N(HI), X_{co}*W_{co}, E(B-V)

Results: CO-dark H_2 fraction of ~0.5

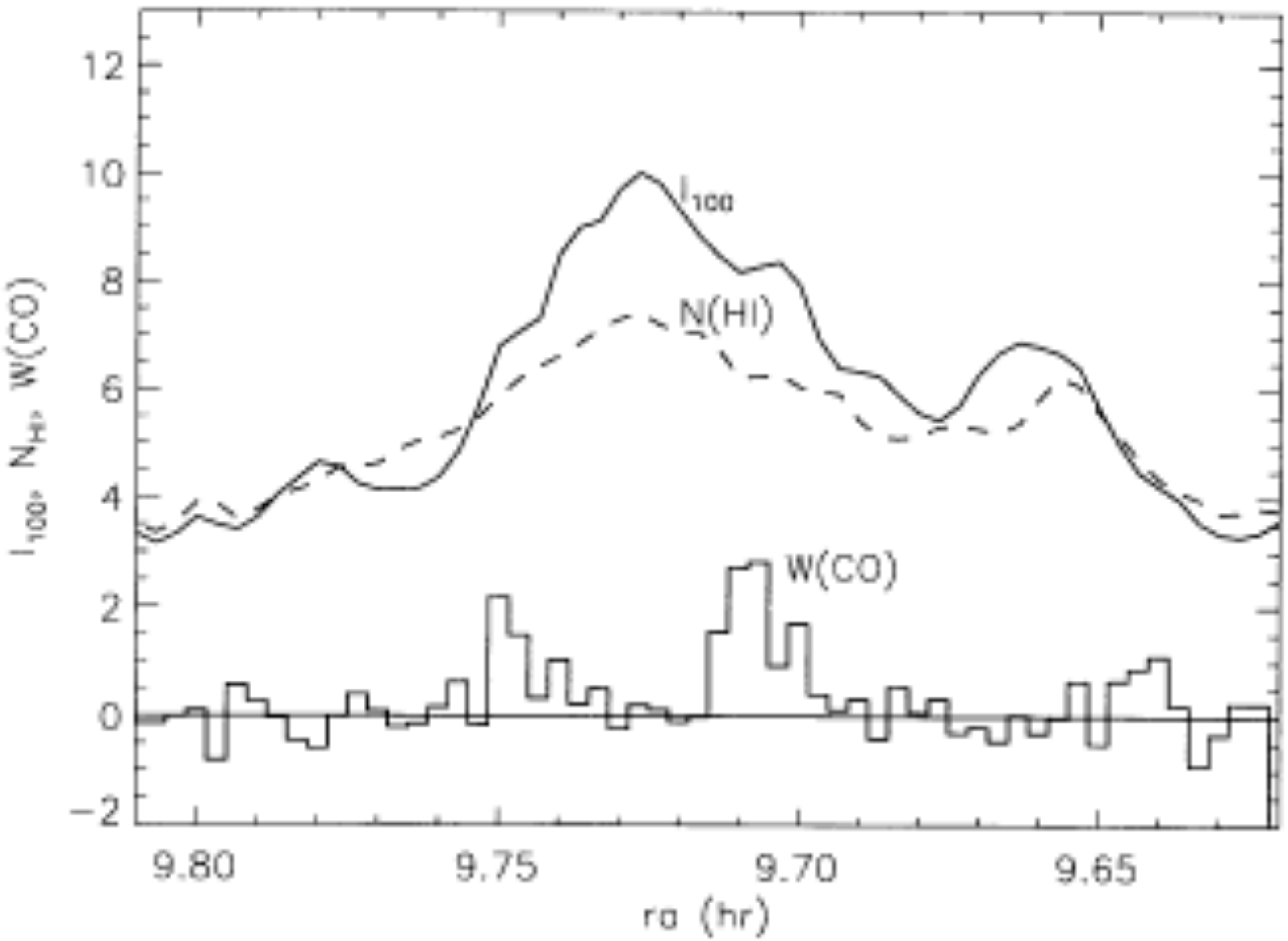
Applies to: Solar Neighborhood

Caveats: Depends on gamma-ray propagation model (e.g. GALPROP), which in turn depends on a model of the Galaxy.



Grenier et. al (2005) Science 307, 1292

CO-Dark H_2 : Observations in 2D: Technique: Dust Continuum



Reach et al. (1994) ApJ 429,

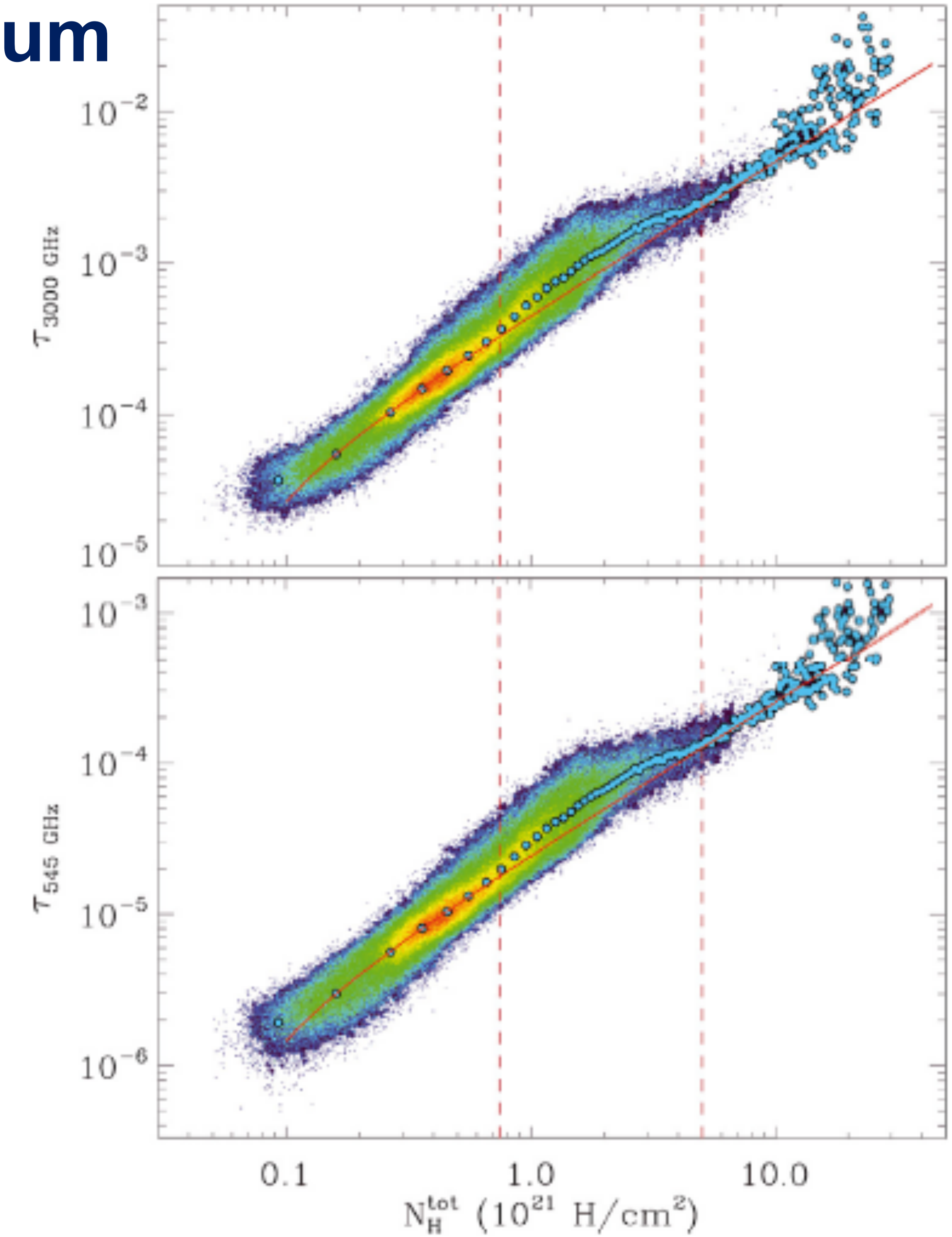
CO-Dark H_2 : Observations in 2D: Technique: Dust Continuum

Method: Correlate the dust opacity and N(HI), X_{co}*W_{co}, and (Tau/N_H)

Results: CO-dark H_2 fraction of ~1.1

Applies to: Solar Neighborhood

Caveats: Unknown Dust properties (temperature, emissivity, etc).



Planck Collaboration (2011), A&A, 536, A19

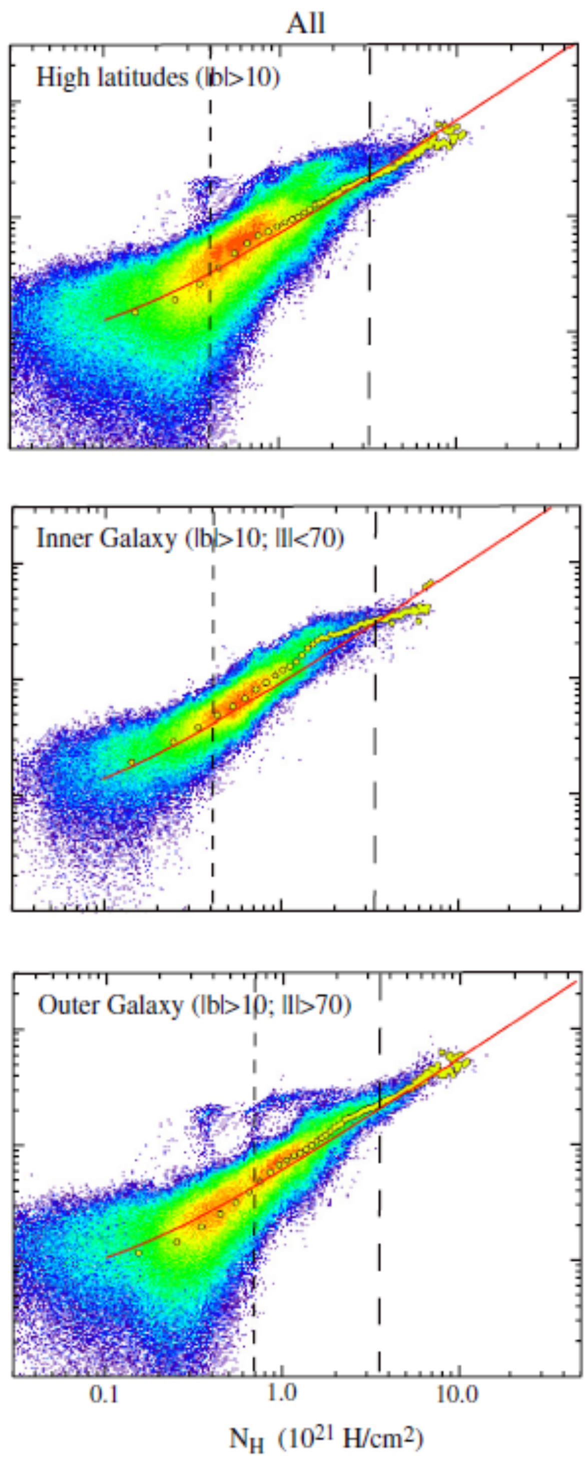
CO-Dark H_2 : Observations in 2D: Technique: Dust Extinction

Method: Correlate the visual extinction and N(HI), X_{co}*W_{co}, and (Av/ N_H)

Results: CO-dark H_2 fraction of ~0.6

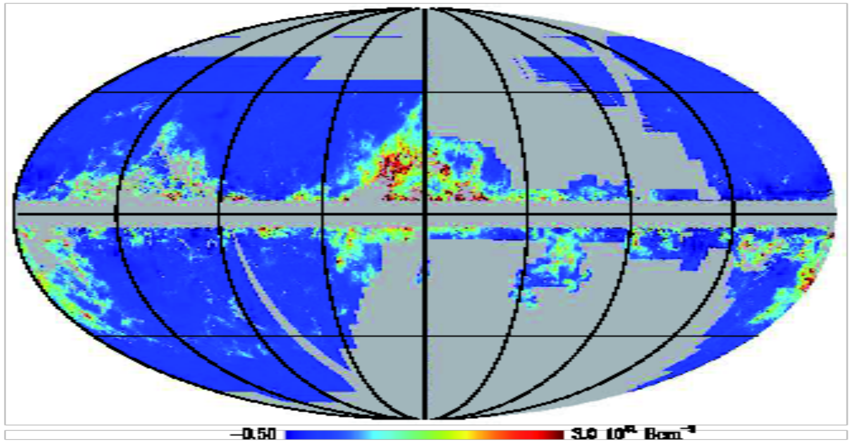
Applies to: Solar Neighborhood

Caveats: Noisy.



Paradis et al. (2012) 543, A103

CO-Dark H_2 : Observations in 2D:
Technique: Dust Continuum

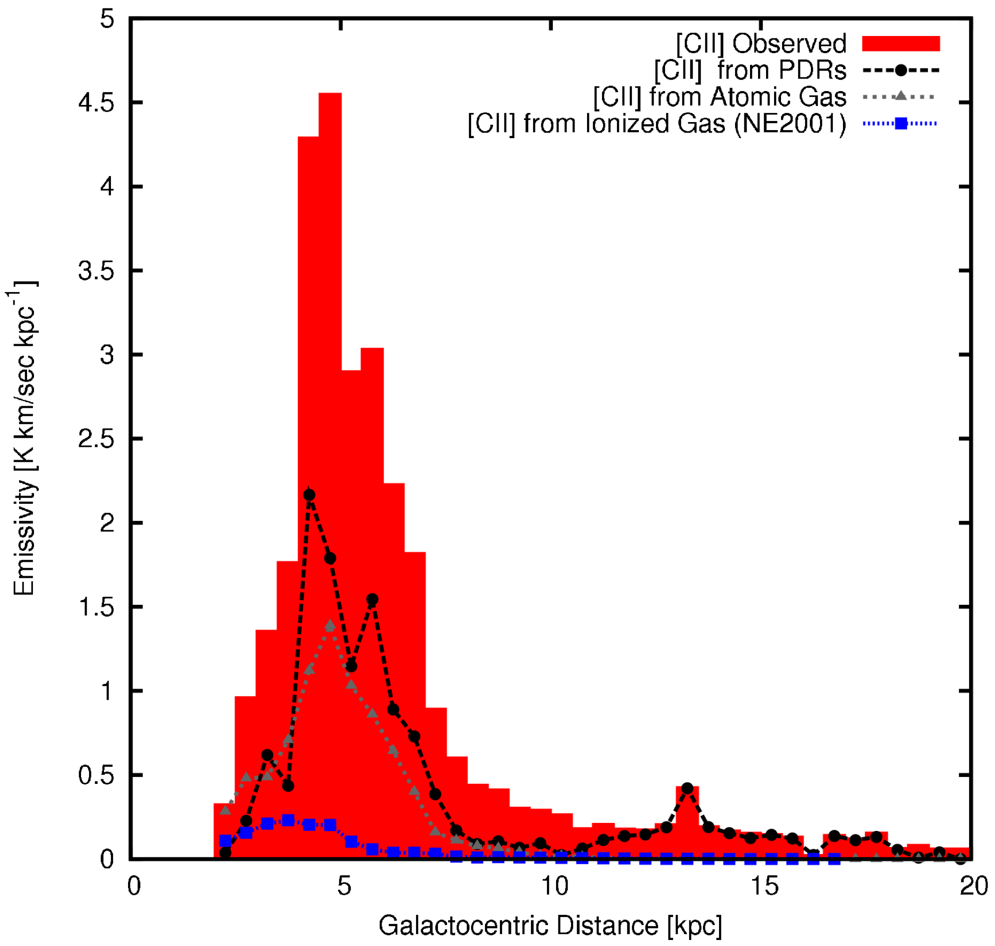


Planck Collaboration (2011), A&A, 536, A19

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 $T=10^4K$.



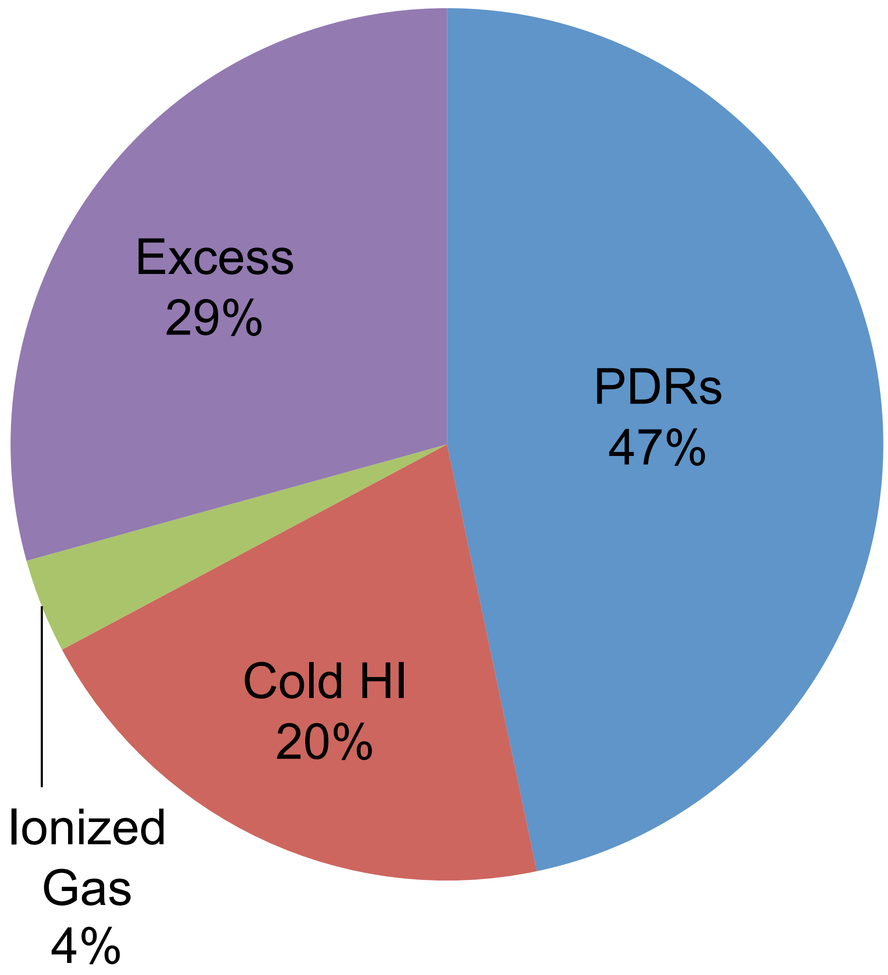
Pineda et al. 2013 A&A 554, A103

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

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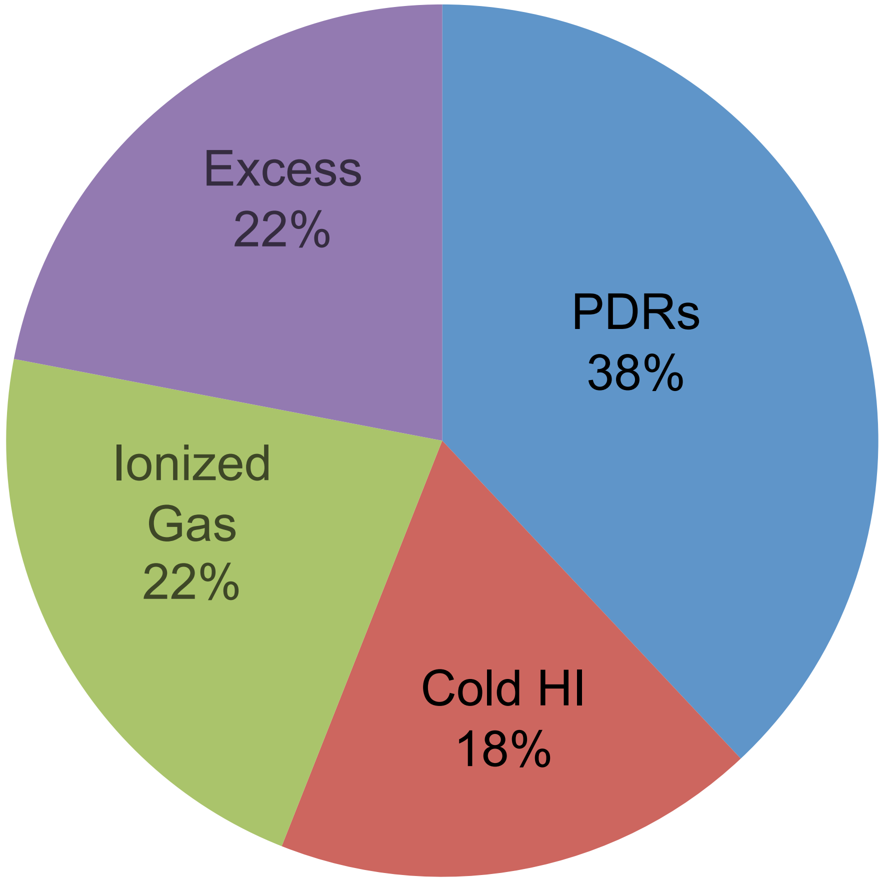
[CII] Luminosity



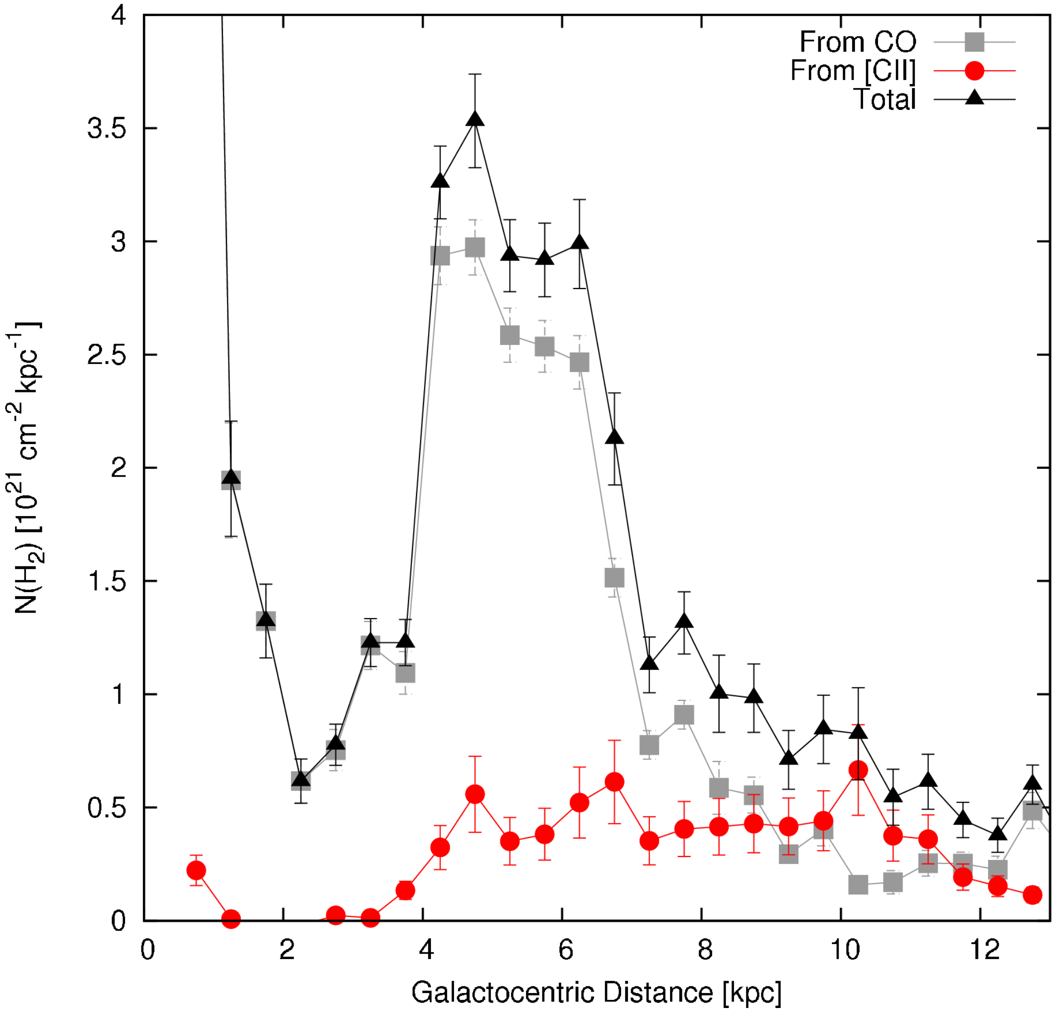
FWHM (PDRs, CNM, CO-dark H_2) = 130 pc
FWHM (ELDWIM) = 1000 pc (Kulkarni & Heiles 1987)

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.

Assumes:

- Galactic metallicity gradient (**Rolleston et al. 2000**).
- Pressure gradient from **Wolfire et al. 2003** multiplied by a factor 1.5.



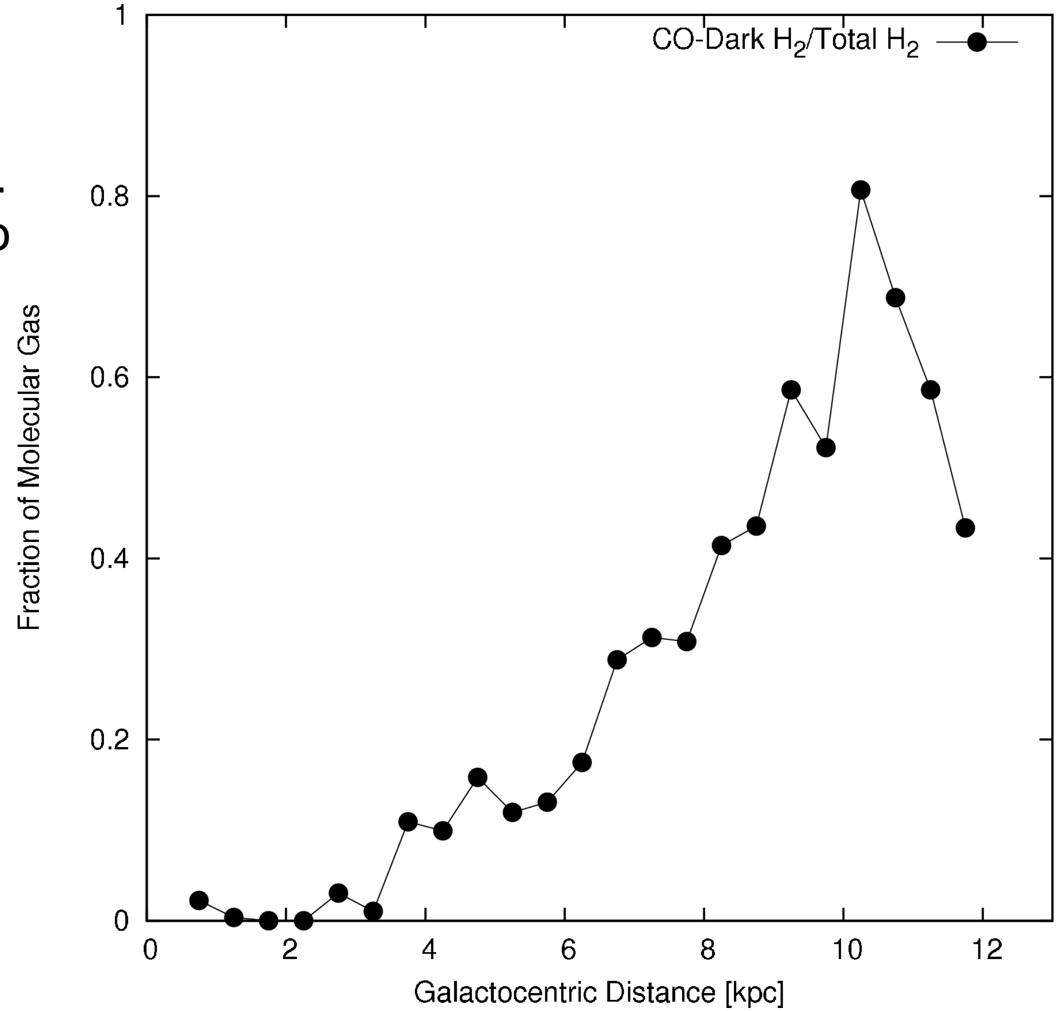
CO-Dark H2 : Observations in "3D": Technique - 1: [CII]

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.

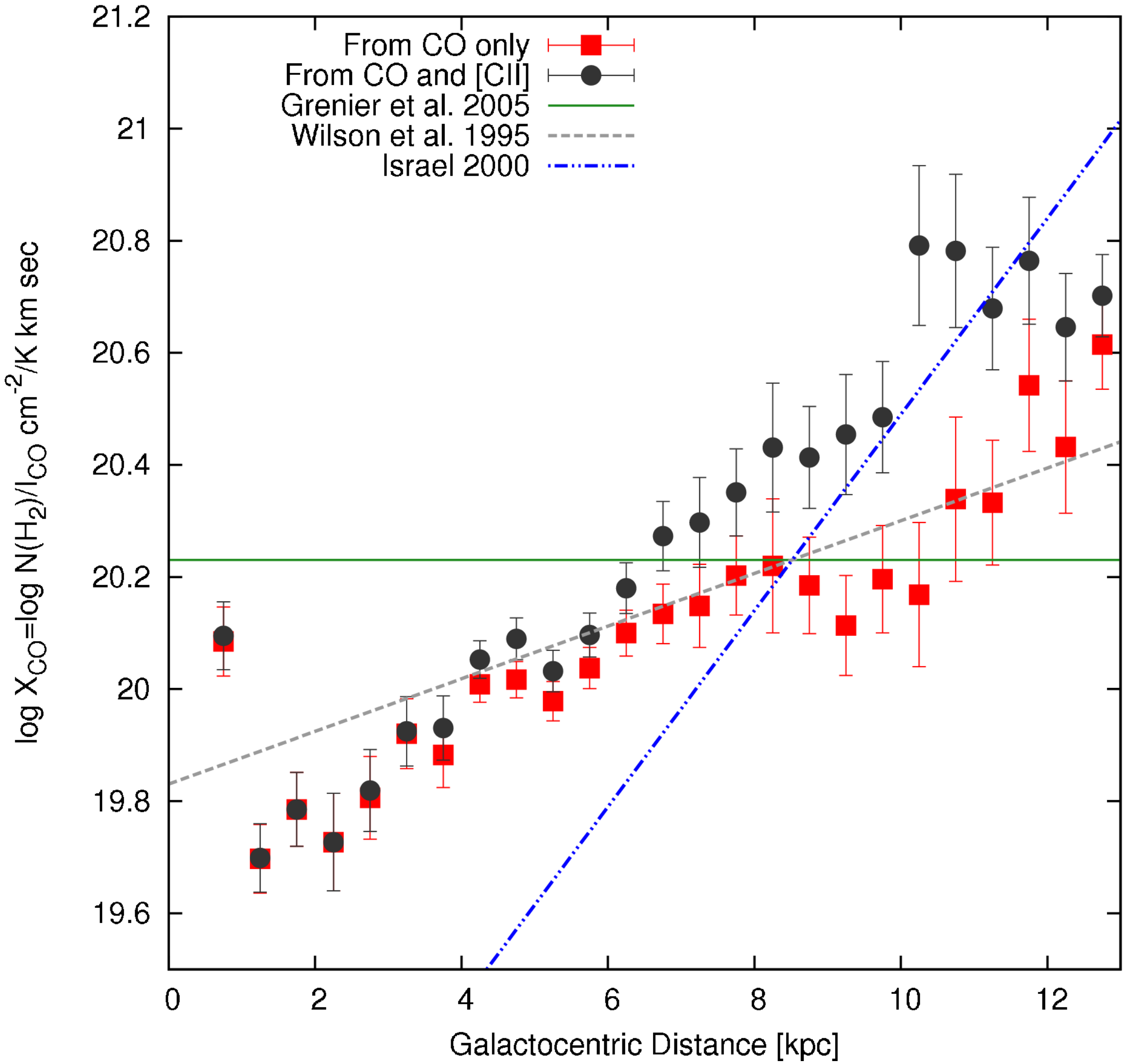


The CO-to-H2 conversion factor (X_{CO}= $N(H_2)/W_{CO}$)

- "CO-traced" H_2 column density derived from ^{12}CO and ^{13}CO following method in **Goldsmith et. al 2008** and **Pineda et al. 2010**
- The X_{CO} gradient follows the metallicity gradient of the Galaxy.
- Steeper X_{CO} gradient when CO-dark H_2 gas contribution is included.

Wilson 1995: X_{CO}=Virial Mass/ CO luminosity.

Israel 2000: Mass derived from FIR/CO luminosity.



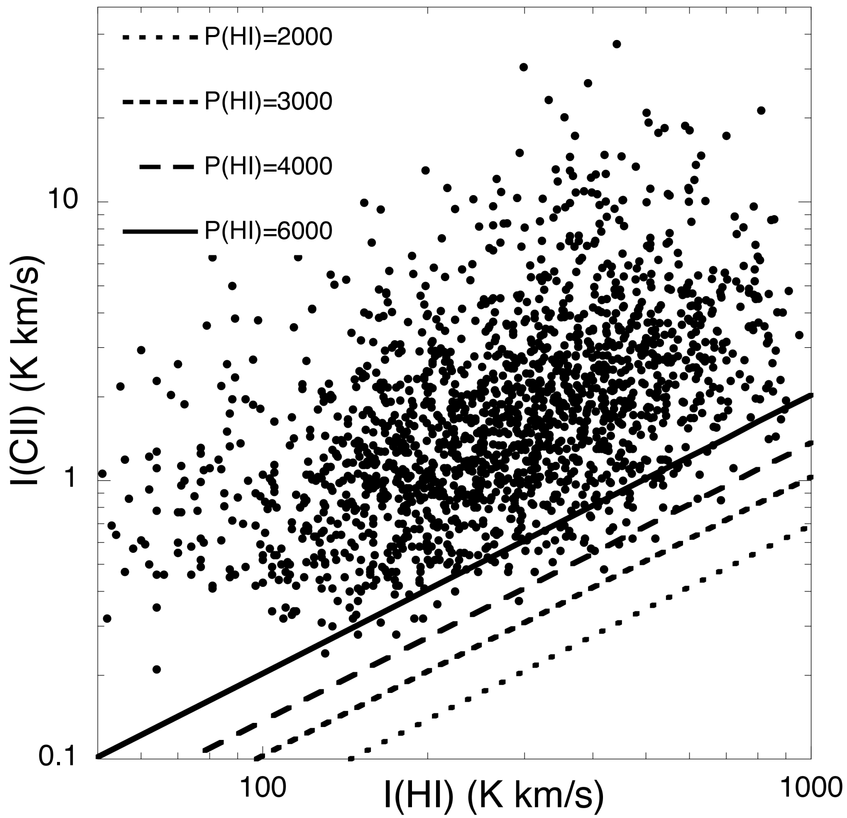
CO-Dark H2 : Observations in “3D”: Technique - 2: [CII]

Method: Gaussian decomposition of components along the LOS. 2000 components identified. 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.

See also:

Velusamy et al. (2012), IAU Symposium

Langer et al. (2010), A&A. 521, L17

Velusamy et al. (2010), A&A. 521, L18

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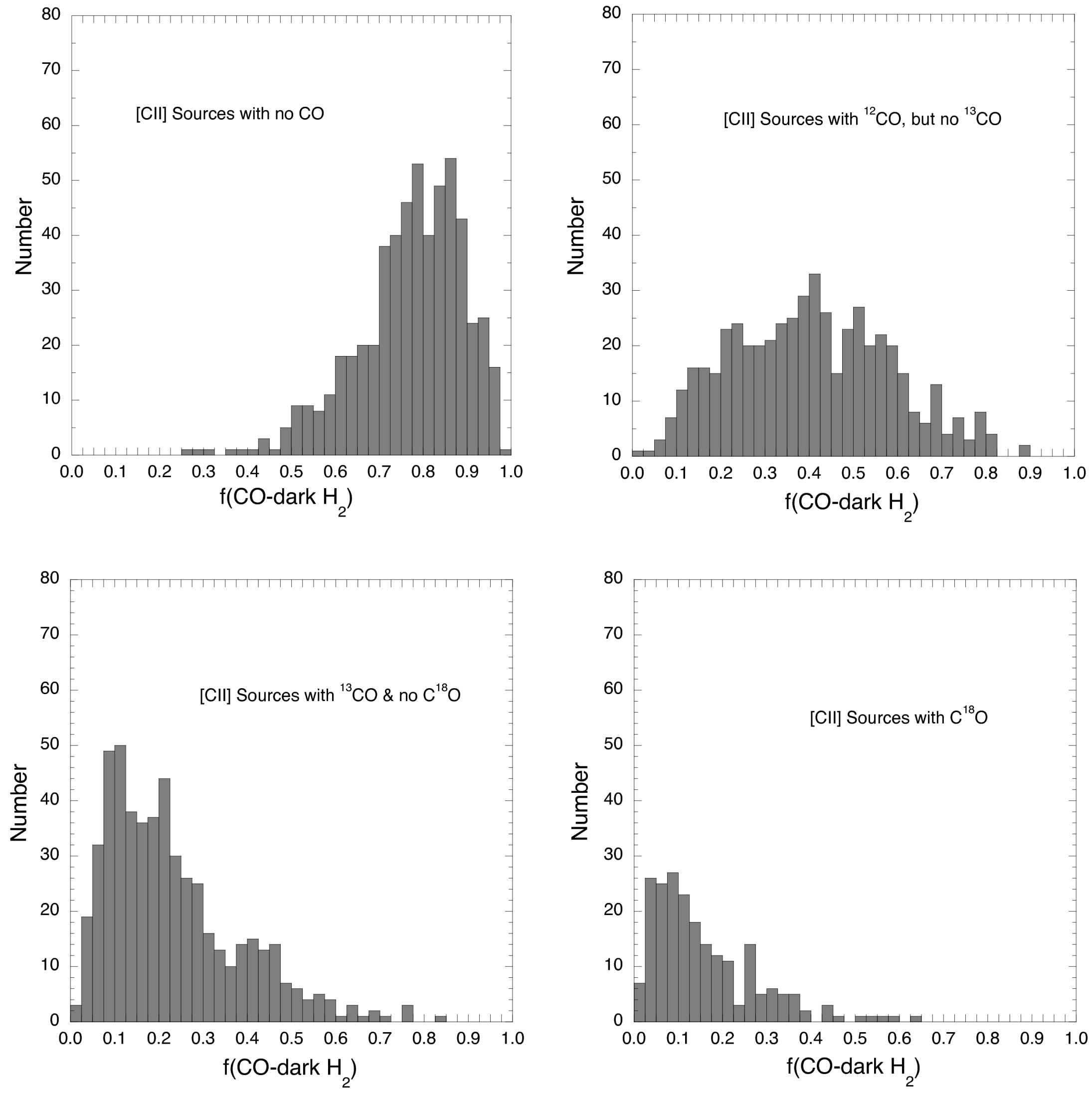
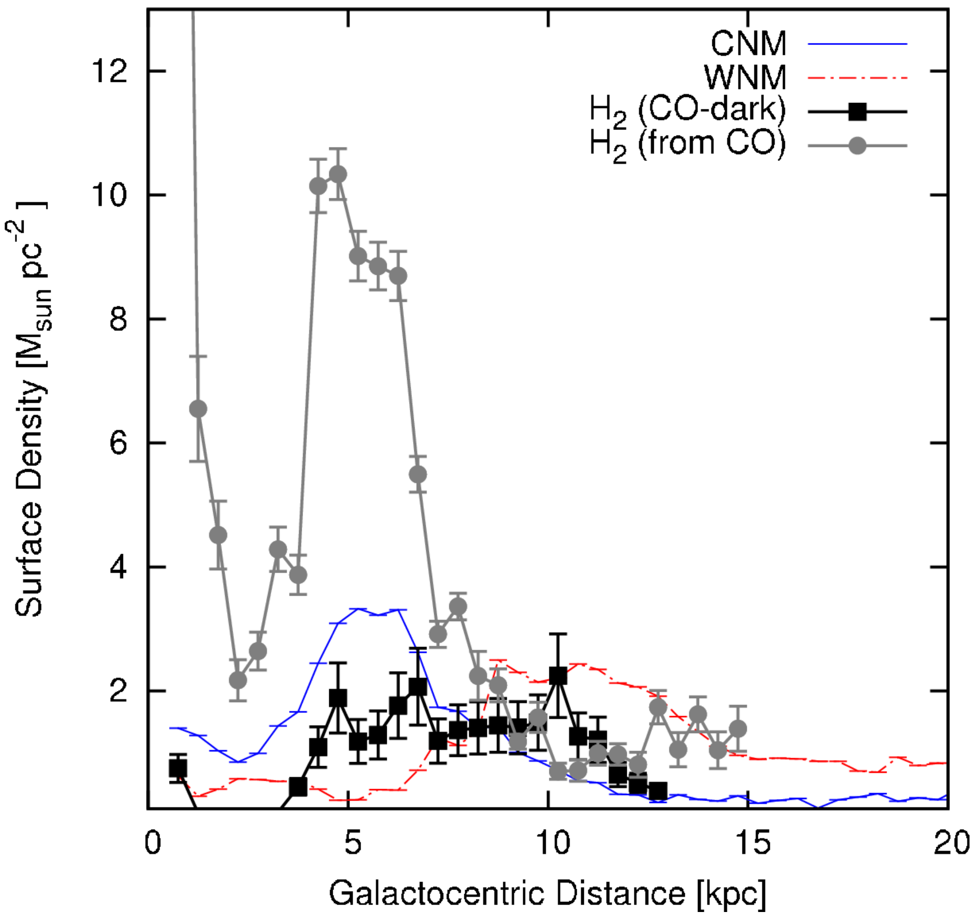
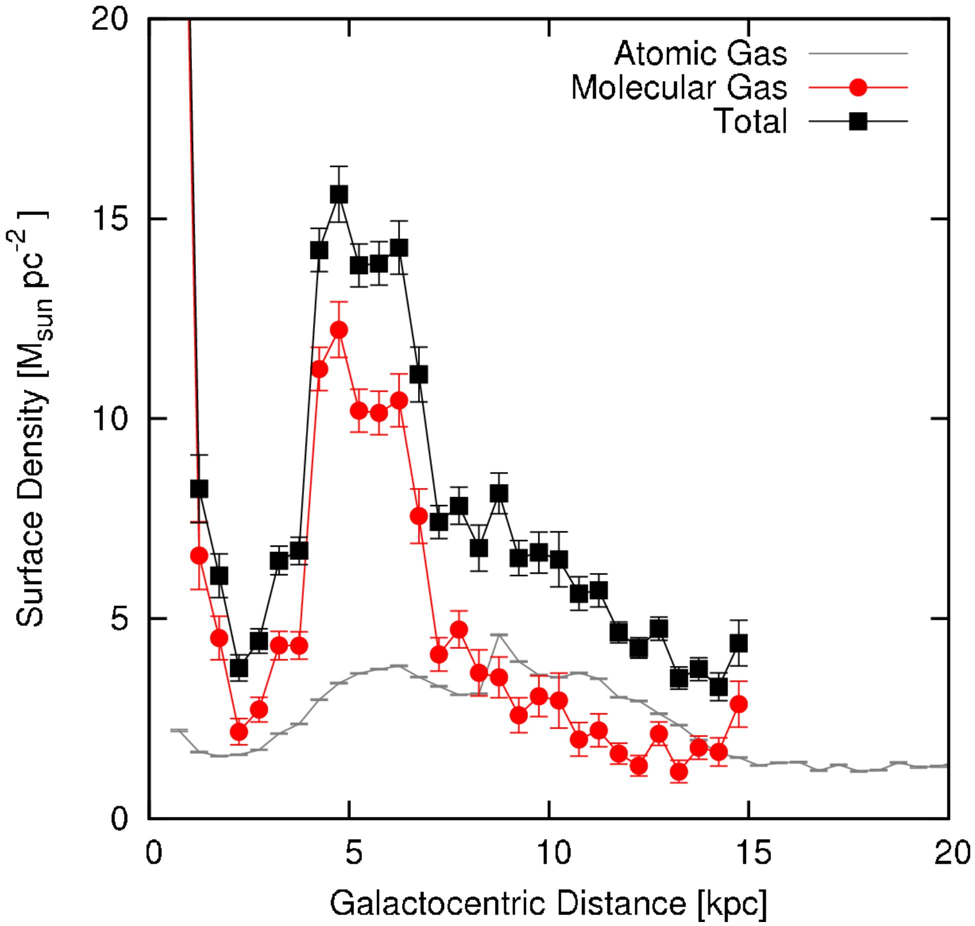
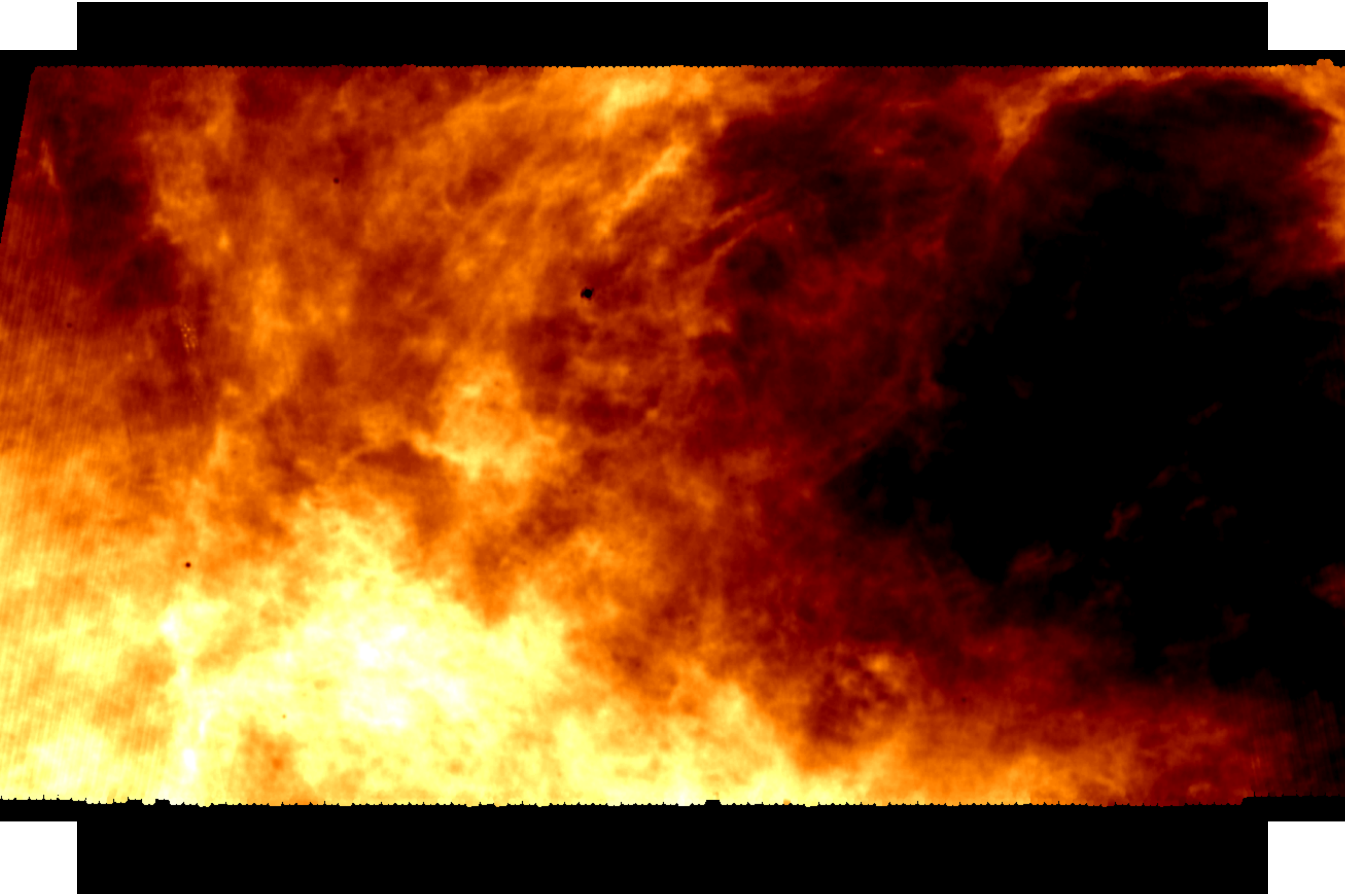


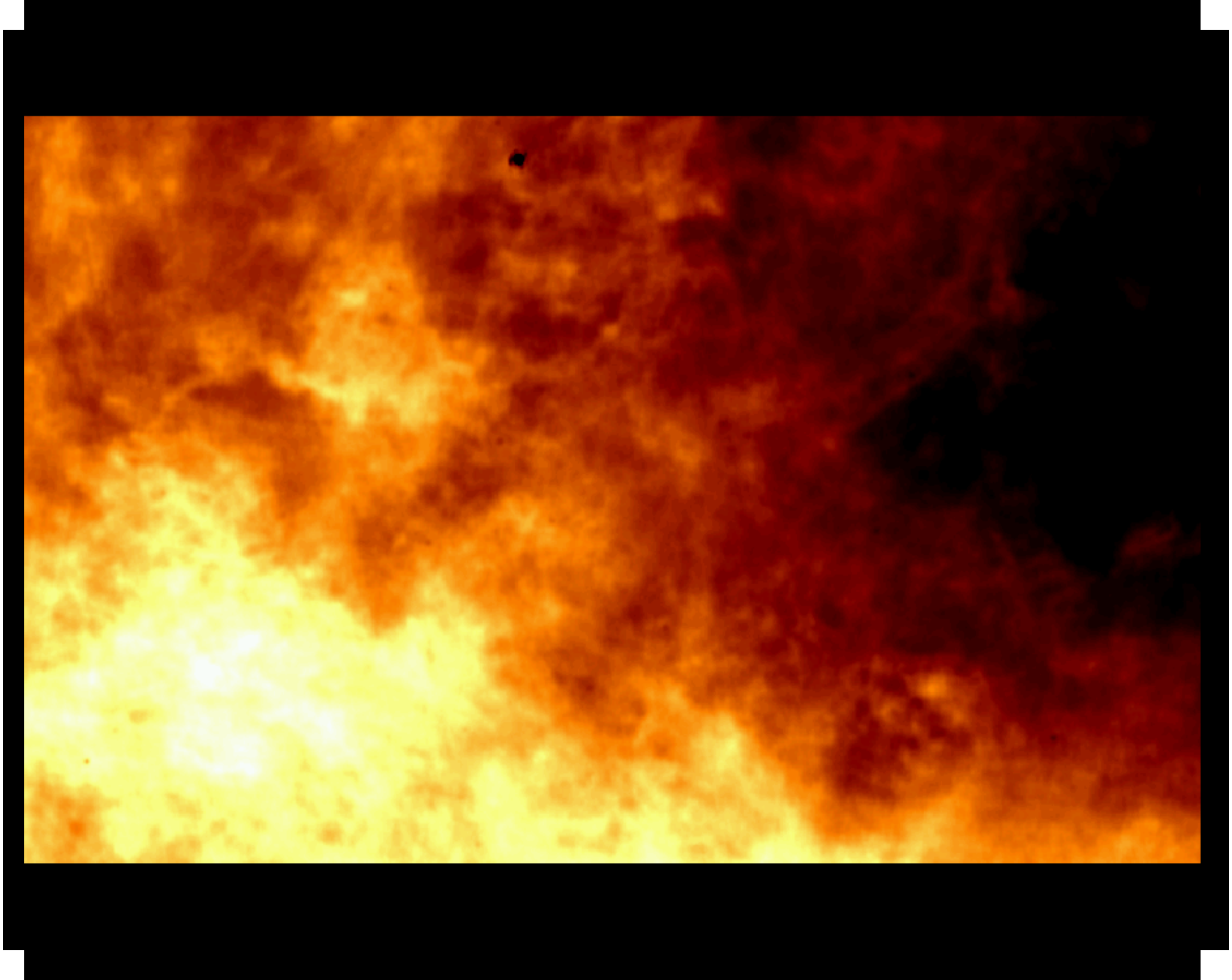
Langer et al. (2013), A&A. submitted.

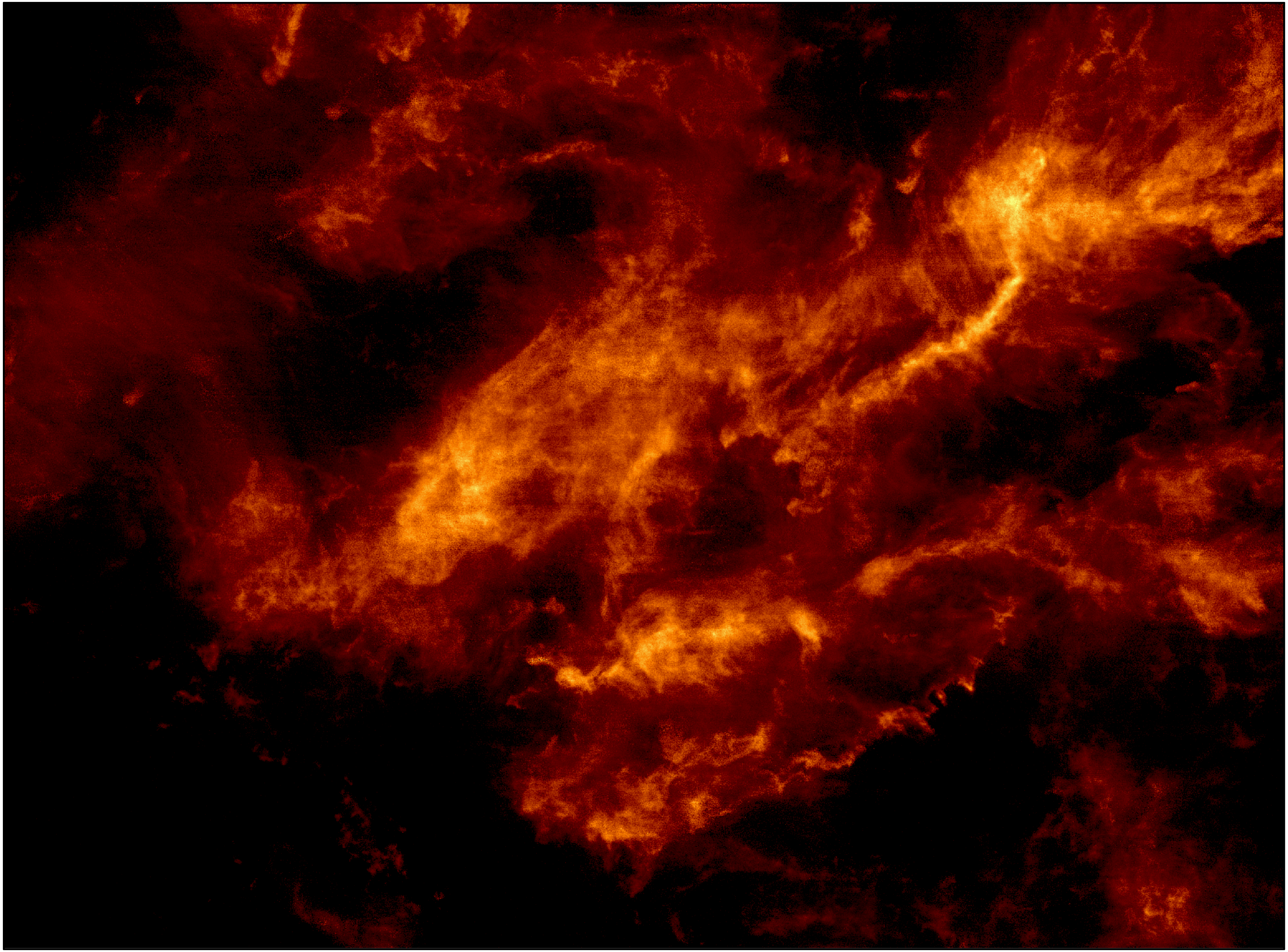
Surface Density Distribution of the ISM phases in the Milky Way

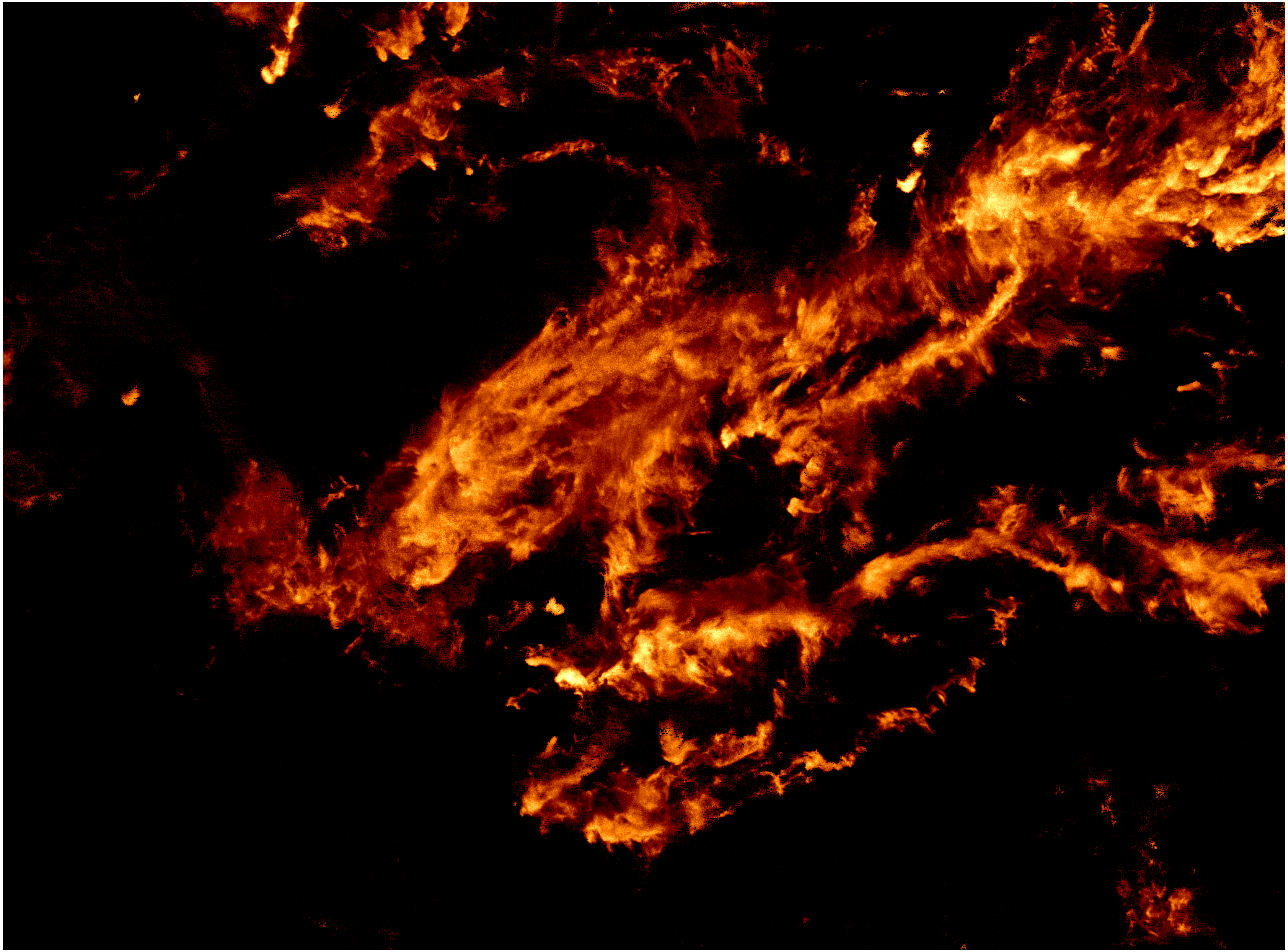


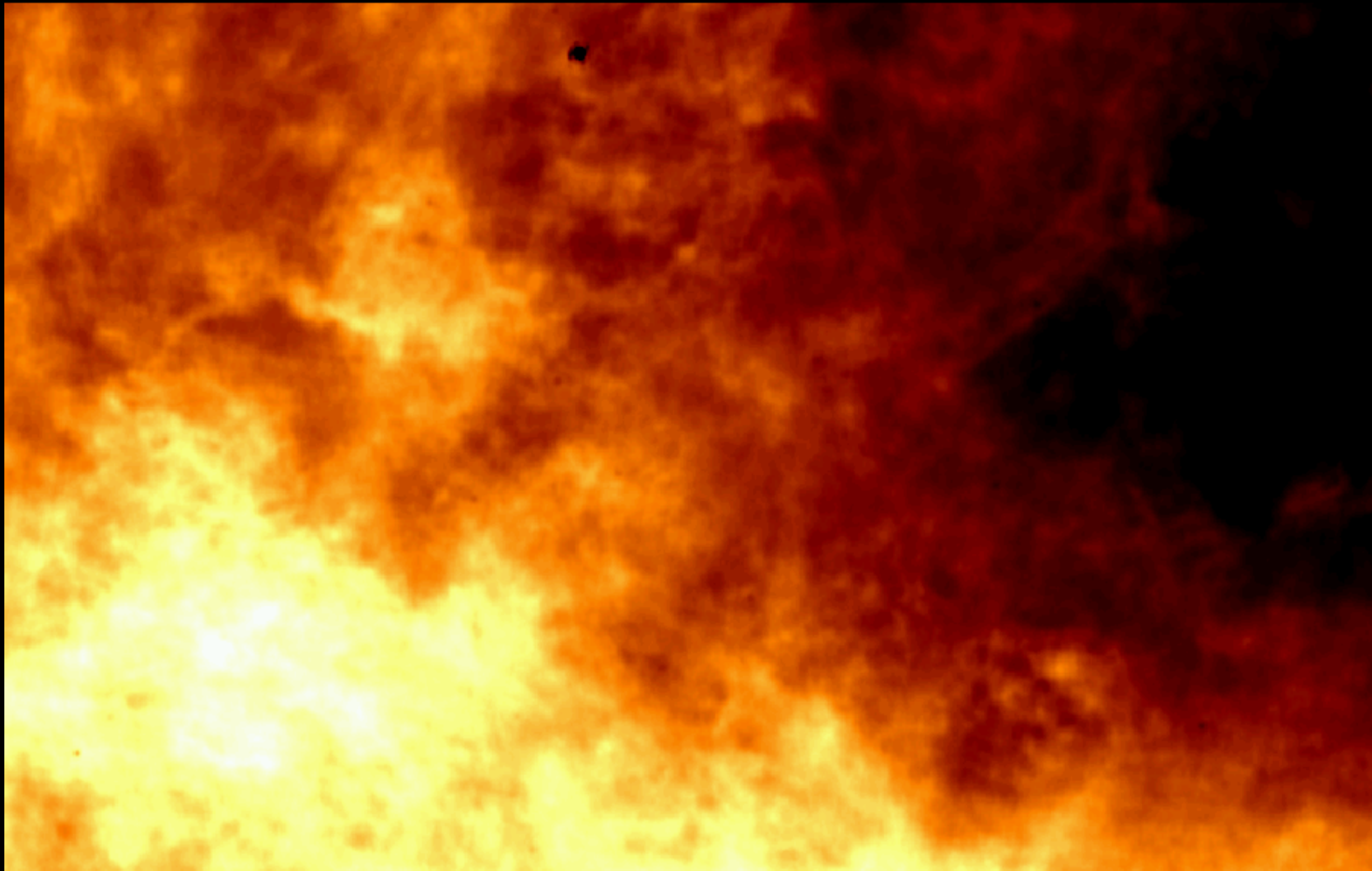


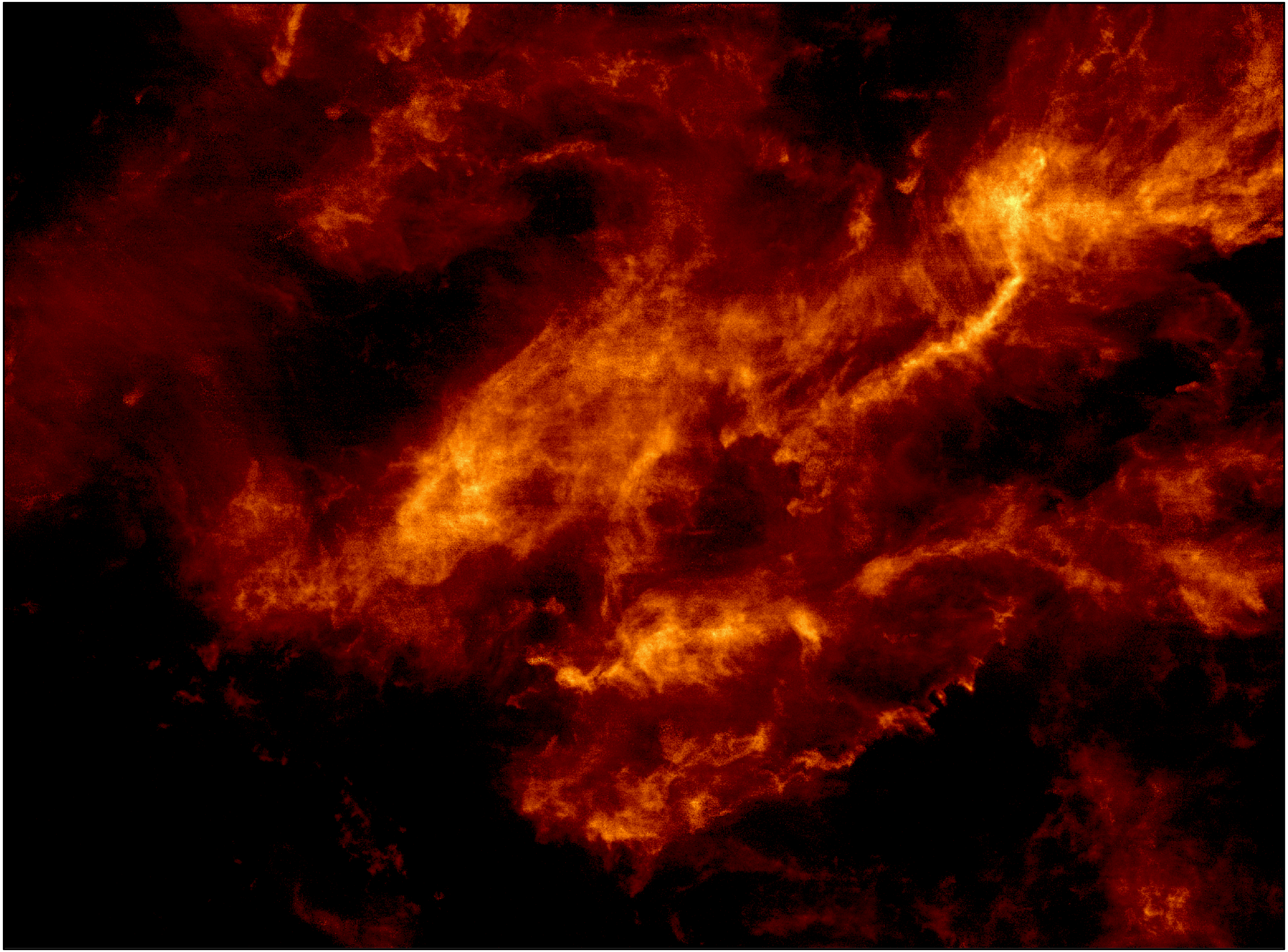












Conclusions

- The [CII] emission in the Galaxy is mostly associated with spiral arms, tracing the envelopes of evolved clouds as well as clouds in the transition between atomic and molecular.
- Most of the [CII] emission emerges from Galactocentric distances between 4 and 11 kpc.
- PDRs contribute 47% of the observed emissivity at b=0, CNM 20%, ionized gas 4%, and CO-dark H_2 29%,
- We find that 43% of the atomic gas in the Galactic plane is in the form of CNM.
- The CO-dark H_2 component is more extended in Galactocentric distance compared with the gas traced by CO. The CO-dark H_2 fraction increases from 20% at 4 kpc to 80% at 10kpc. On average the CO-dark H_2 gas component accounts for 30% of the total molecular mass of the Galaxy.