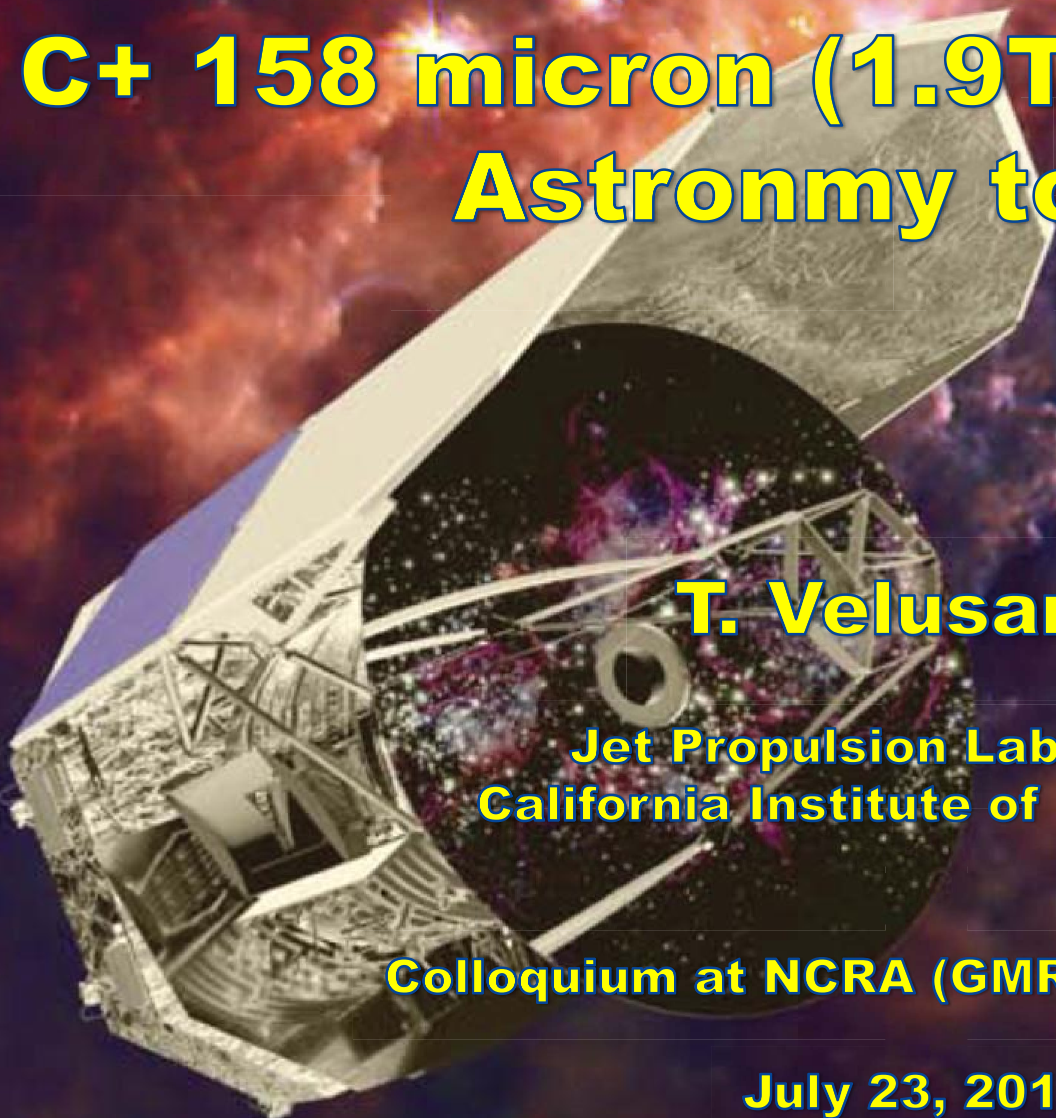
C+ 158 micron (1.9THz) line as Astronmy tool



T. Velusamy

Jet Propulsion Laboratory,
California Institute of Technology

Colloquium at NCRA (GMRT), Pune, India

July 23, 2012

Outline

- The "cool" Infrared Universe
- Carbon and C+ line emissions tracing the ISM gases
  - C+ as diagnostic tool for "H_2 Dark gas"
- GOT C+ survey of Galactic Plane: demonstrate the utility of CII
  - Transition Clouds
  - WIM in Spiral tangencies
  - CRRL and C+ in a "local" HI self absorption cloud
- **C^+ for external galaxies**
- **Summary**

ESA image

Collaborators

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(PI GOT C+ project)

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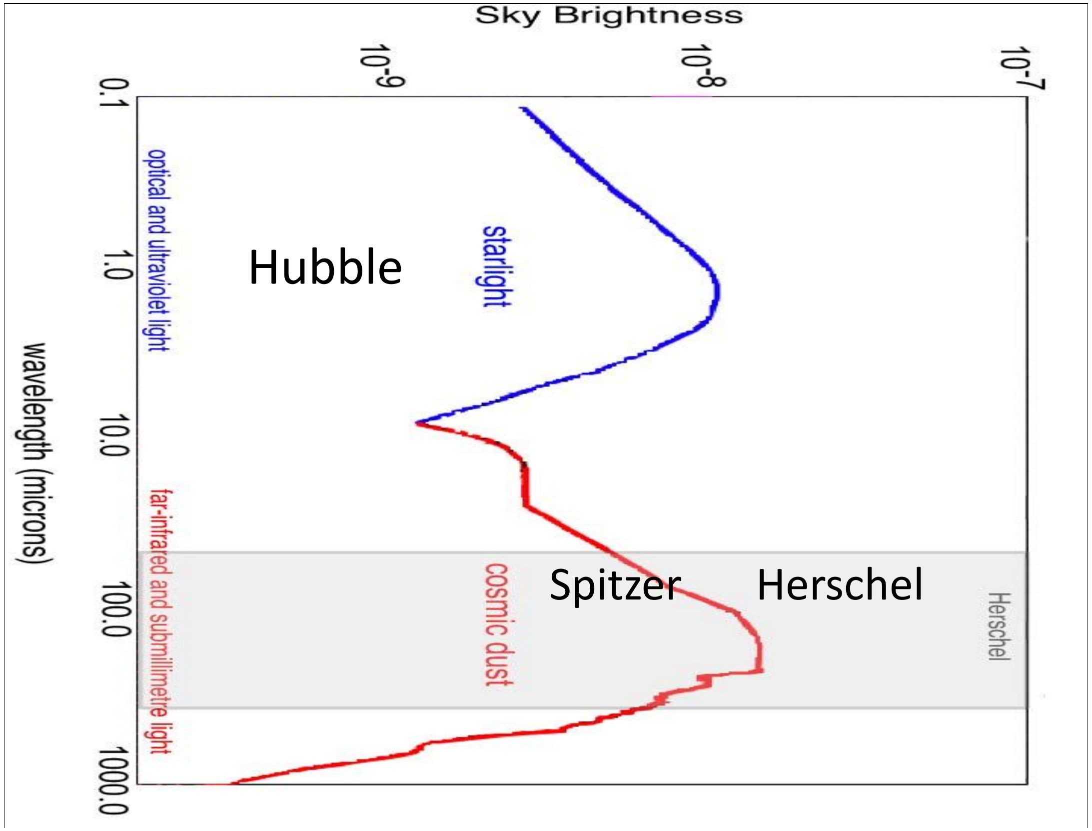
Jet Propulsion Laboratory
California Institute of Technology

The Universe is Cool!!

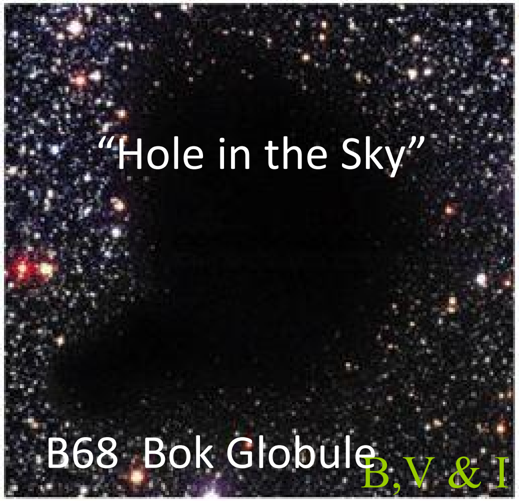


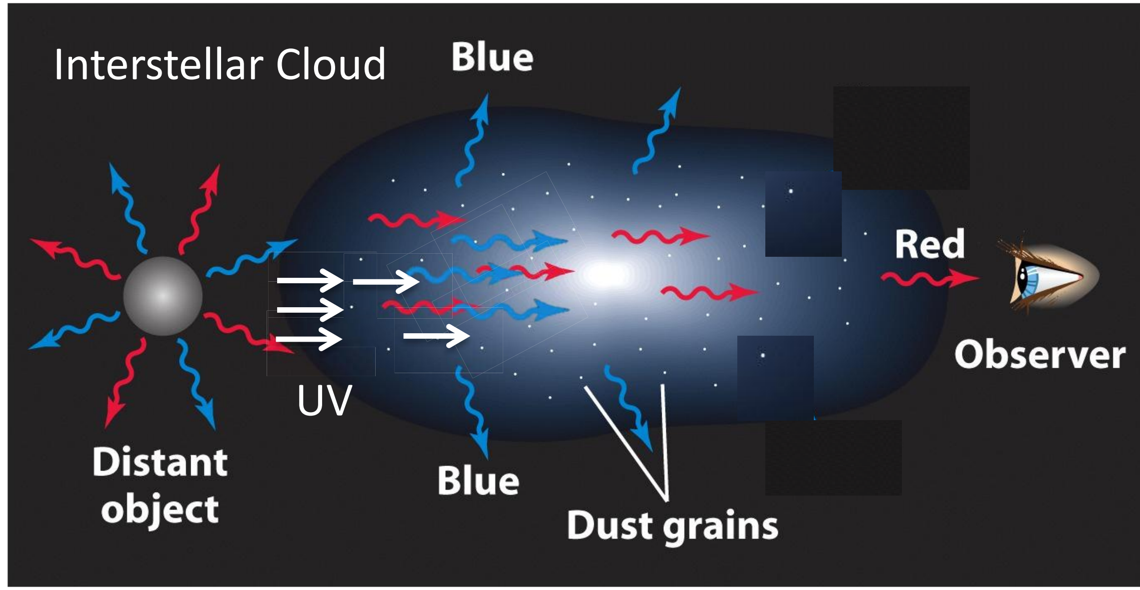
About 50% of the energy created since the formation of the Cosmic Microwave Background (CMB) has been reprocessed into the infrared!!

Most of the universe's photons are in the InfraRed (IR)!!

Infrared Radiation is Recycled Starlight from Dust and Gas

Dust Extinction – Blocks Out Starlight





Dust scatters and absorbs visible & UV efficiently

(red less than blue less than UV)

Dust does not absorb infrared efficiently

Absorbed radiation heats dust and gas

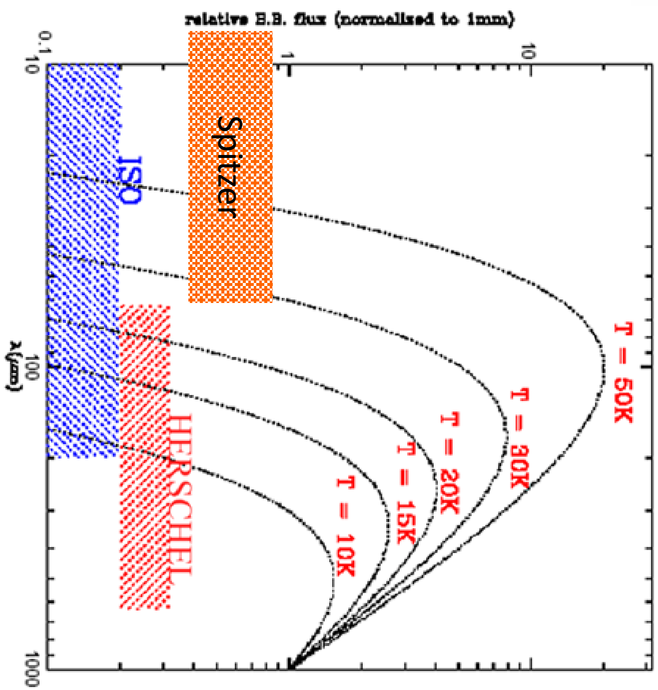
UV ionizes atoms and photodissociates (breaks up) molecules

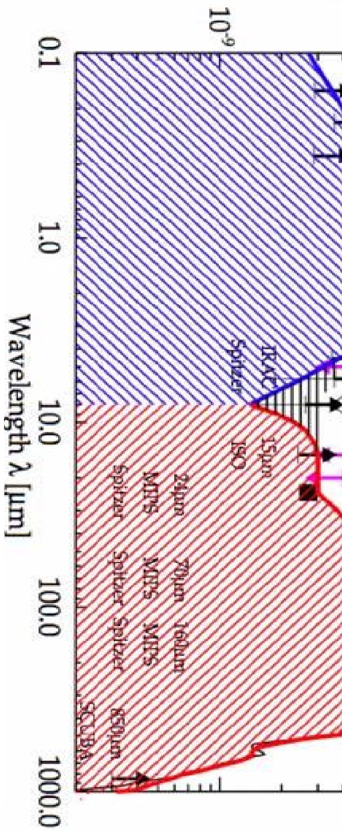
Adapted from D. Koerner

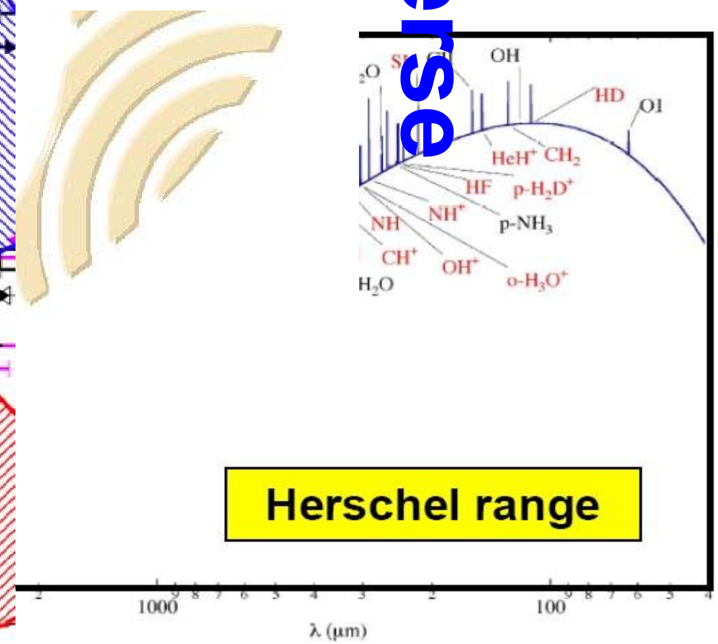
Dust & gas cool by

Importance of the FIR

Universe







Dust radiates over a continuum of wavelengths (black body radiation)

radiates via narrow spectral lines & every atom, ion, and molecule has distinct spectral signatures

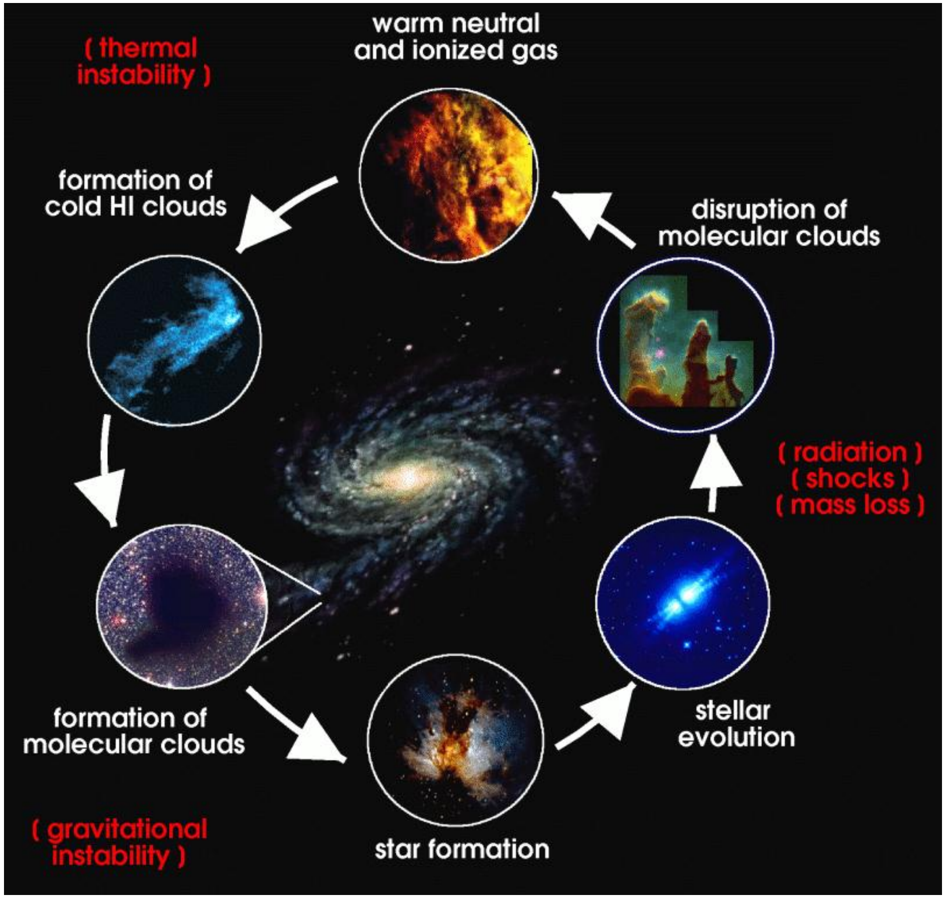
alf of the energy created i

CMB has been reprocessed

– Herschel covers the IR peal

submillimetre: cold black-b

Gas to Stars to Gas to Stars to Gas ....



Most abundant molecules

H_2 molecular hydrogen

CO – carbon monoxide

Stars form out of interstellar gas clouds

Stars produce heavy elements: C, N, O, Fe, … (we are stardust)

Stars eject gas back and disrupt clouds

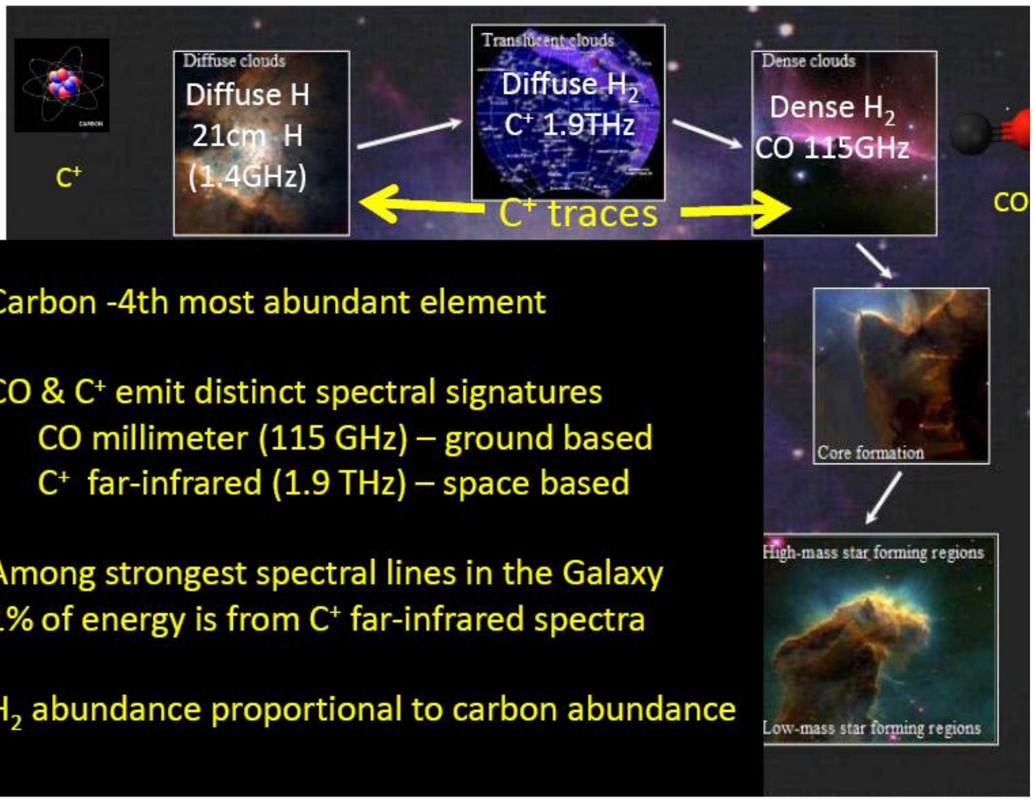
Elemental Abundances

- 91% Hydrogen + 9% Helium
- 0.1% Oxygen, Carbon, Nitrogen,
- 0.01% Everything else: Silicon, Iron, etc

WHY CARBON SPECIES

"So it happens, therefore, that every element says something to someone (something different to each) …… One must perhaps make an exception for carbon, because it says everything to everyone … .

-- Primo Levi, chemist and author, in The Periodic Table, Chapter 21 on Carbon (1975).

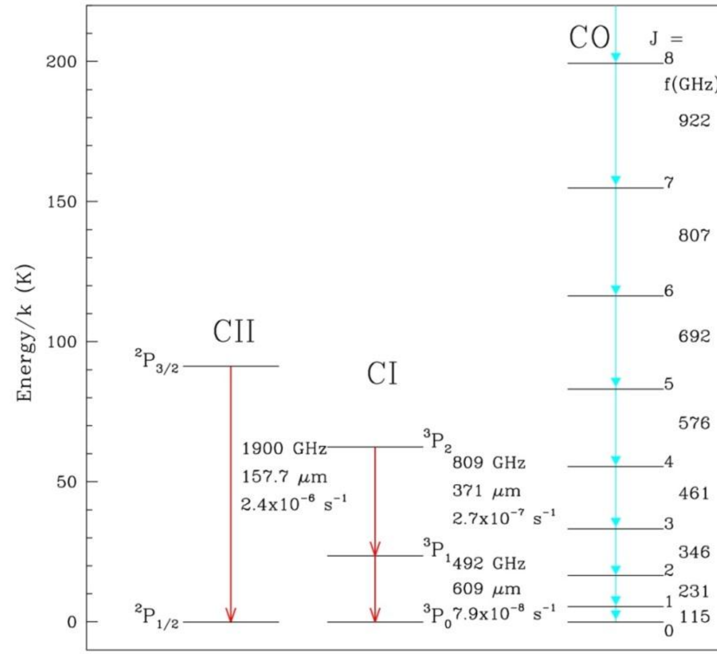


Carbon -4th most abundant element

CO & C^+ emit distinct spectral signatures
- CO millimeter (115 GHz) – ground based
- C^+ far-infrared (1.9 THz) – space based

Among strongest spectral lines in the Galaxy
1% of energy is from C^+ far-infrared spectra

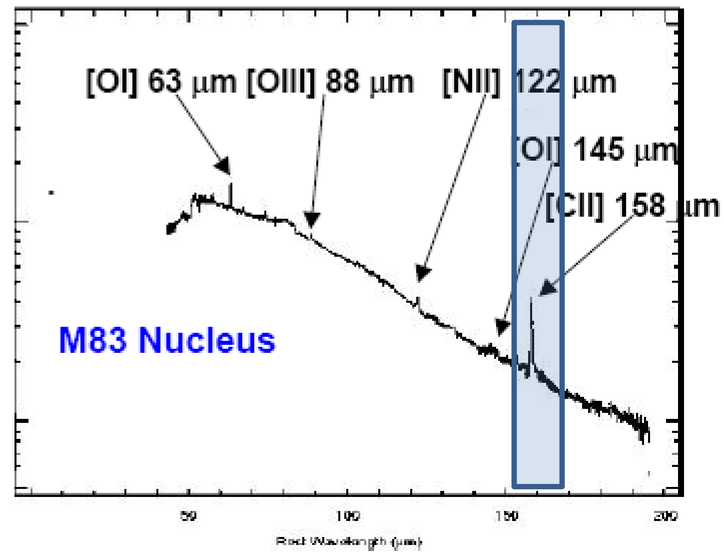
H_2 abundance proportional to carbon abundance



Important as star-formation rate in galaxies ➔ galaxy evolution

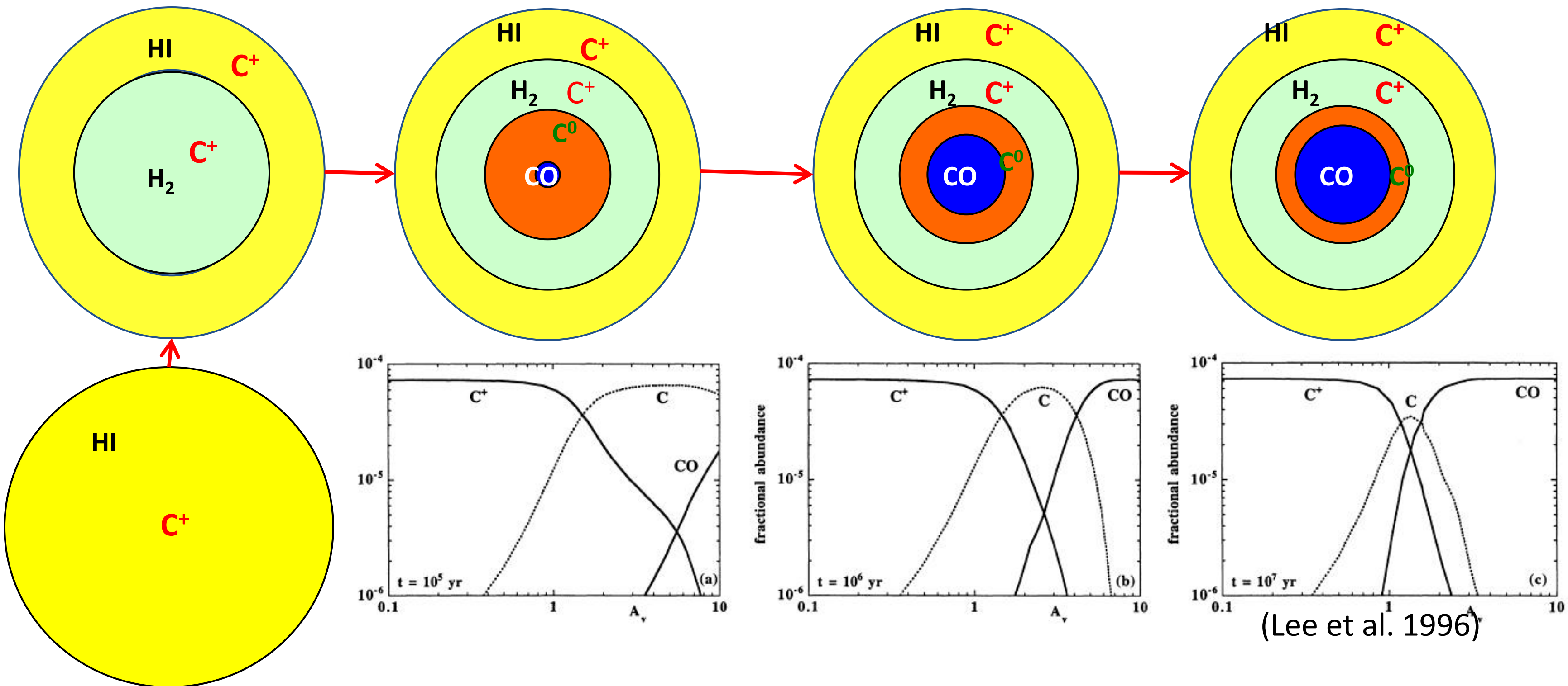
WHY C^+ 158 micron line

- C^+ is ubiquitous. Atomic carbon exists mostly ionized (C^+), except in a thin layer in PDRs as neutral (C^0)
- C^+ 158um is the brightest submm spectral line
- A robust tracer of total interstellar gas
  - Emitted under a wide range of interstellar environments: From fully ionized to cold dense clouds, excited by collisions with
    - electrons, (in warm ionized medium: WIM),
    - atomic hydrogen (in Warm Neutral Medium: WNM)
    - molecular hydrogen (in Cold Neutral Medium:
- Tracer of star-formation
  - Galaxy evolution throughout the universe: nearest to highest redshift galaxies
- New opportunities
  - Access from space: Herschel, SOFIA
  - THz Heterodyne technology provide spectrally resolved C+ line data (HIFI on Herschel and GREAT on SOFIA)



Collider	Temperature (K)	n_{cr} (cm^{-3})
e^-	500	15
	10000	48
H^0	20	3800
	100	3000
	1000	2100
	8000	1200
H_2	20	7700
	100	6100
	500	4800

[CII] Tracks Interstellar Cloud Evolution



(Lee et al. 1996)

- Diffuse Atomic Clouds

  HI traces N(H)

  [CII] traces warm, dense H

- Diffuse Molecular Clouds

  [CII] traces warm HI & H_2

  No CO

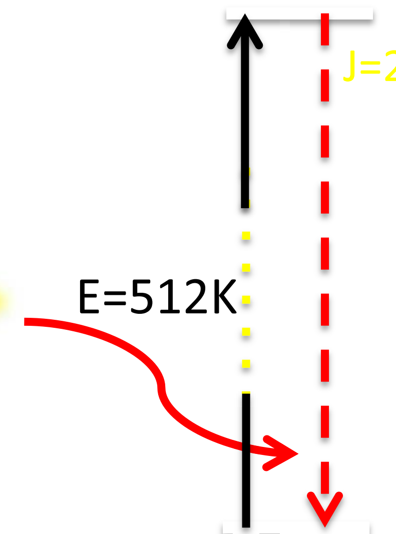
- Transition Clouds
  - H_2 & C^+,
  - C^0 & CO
  - [CII] -> warm, dense H_2

- Dense Molecular Clouds
  - ^{12}CO & ^{13}CO

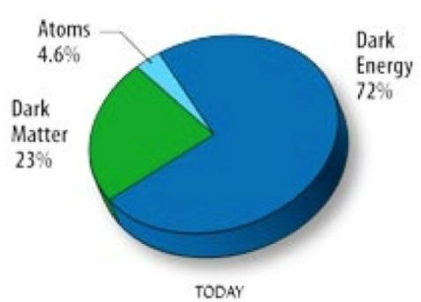
“H_2 Dark Gas”: How much H_2 gas is missed?

- In cold, star-forming environments H2 is not detected directly, but inferred from other molecular lines observed, usually CO.
- CO line intensities are used to infer the amount of H2
- Presence a significant amount H_2 in the Galactic ISM, which is not raced by CO emission was evident from:
  - Star forming cloud models show H_2 layer without CO (Wolfire et al. 2010, ApJ 716, 1191)
  - Dust emissions (Reach et al. 1994, ApJ 429, 672)
  - Gamma ray observations (Abdo, et al. 2010, ApJ 710, 133
- Recent Herschel HIFI C^+ 158um line survey (GOT C+) detected this “H_2 Dark Gas” component by the C^+ emission from the H_2 layers without CO, thus missed by CO data. (Velusamy, Langer et al. 2010, A&A 521, L18), & Langer, Velusamy et al. 2010, A&A 521, L17)

Lowest Molecular Hydrogen line



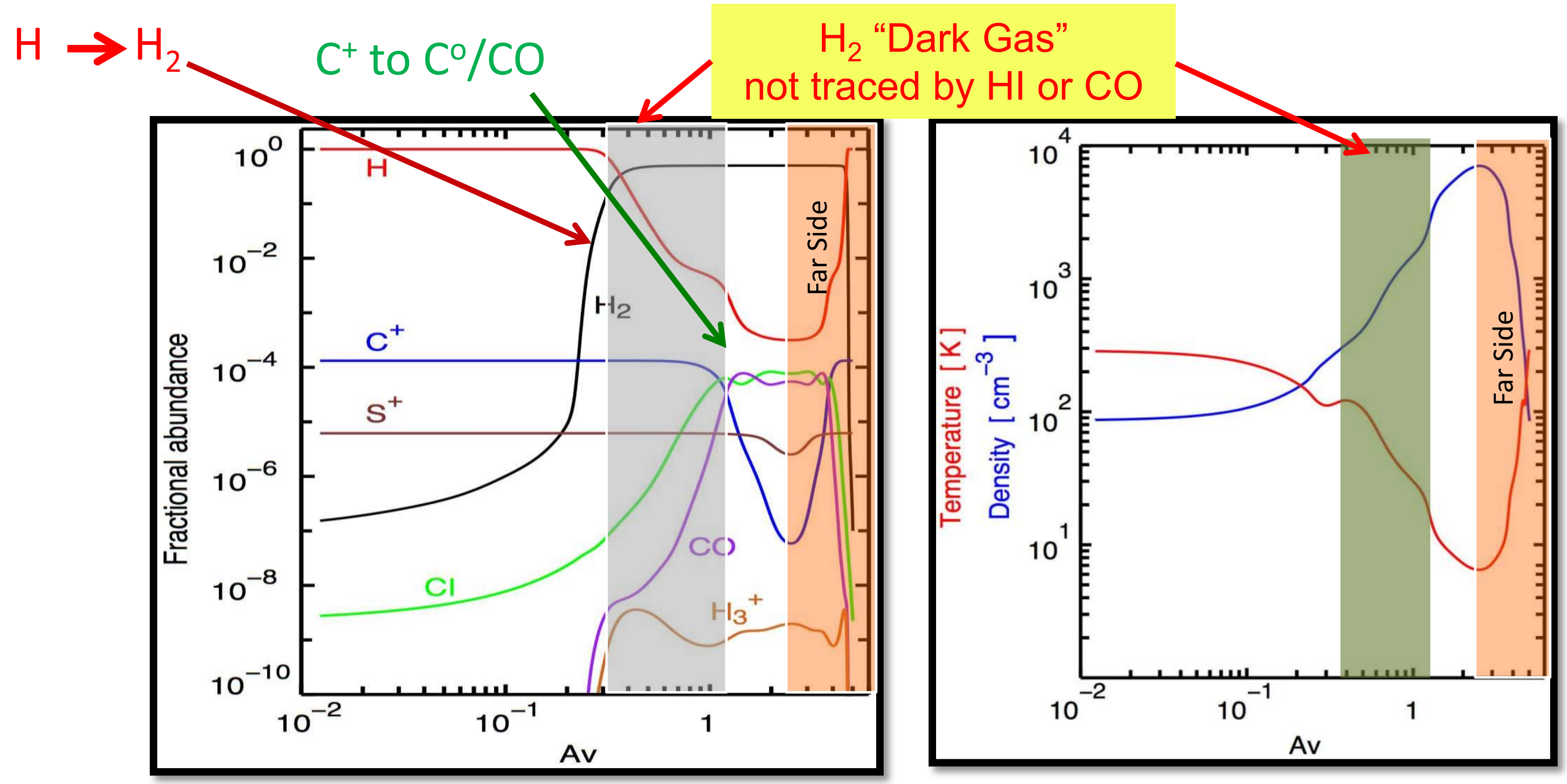
H_2 (28 µm; ≈10 THz)



Caution: This is something else!

“Dark Gas” is NOT “Dark Matter”. It is ordinary molecular hydrogen, H_2, in regions where it is <u>too cold</u> to radiate and so is “Dark”

Transition Cloud Model of HI and [CII]



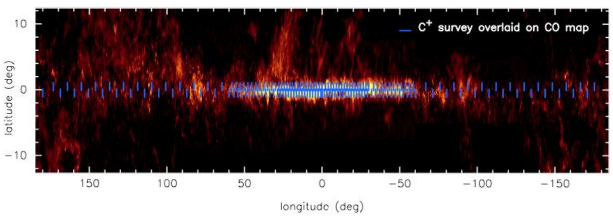
- $|_0$ ~ 50 (finite slab - both sides illuminated) & P ~2 x10^4 K cm^{-3}
- n(HI) ~ 50 - 100 cm^{-3} , T_{kin} ~ 100 to 200K
- n (H_2,CII) ~ 2-8 x10^2 cm^{-3} & T_{kin} ~ 50 – 100K

GOT C+ [CII] 1.9 THz Survey

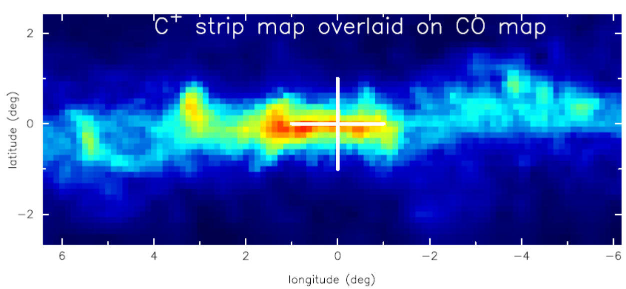
A OT Key project (PI: Langer)

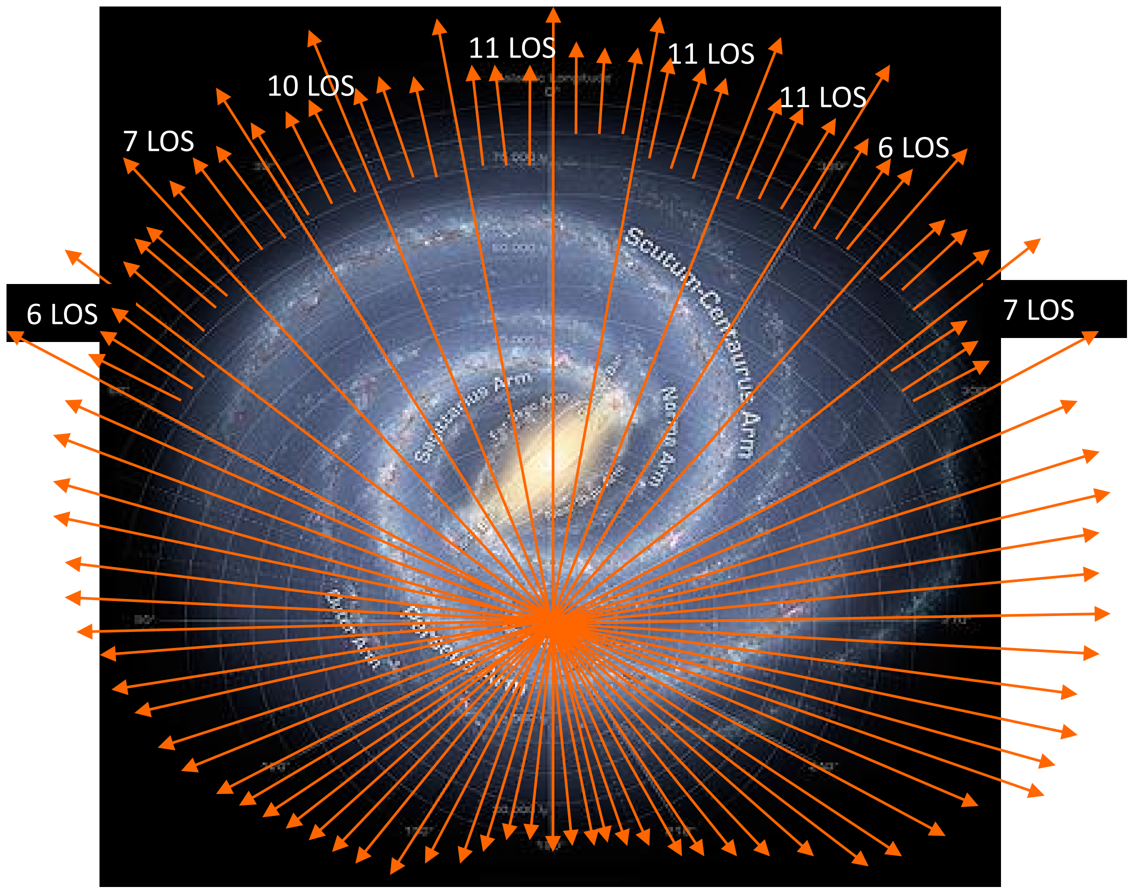
Galactic Plane Survey - systematic volume weighted sample of ≈500 LOSs in the disk

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

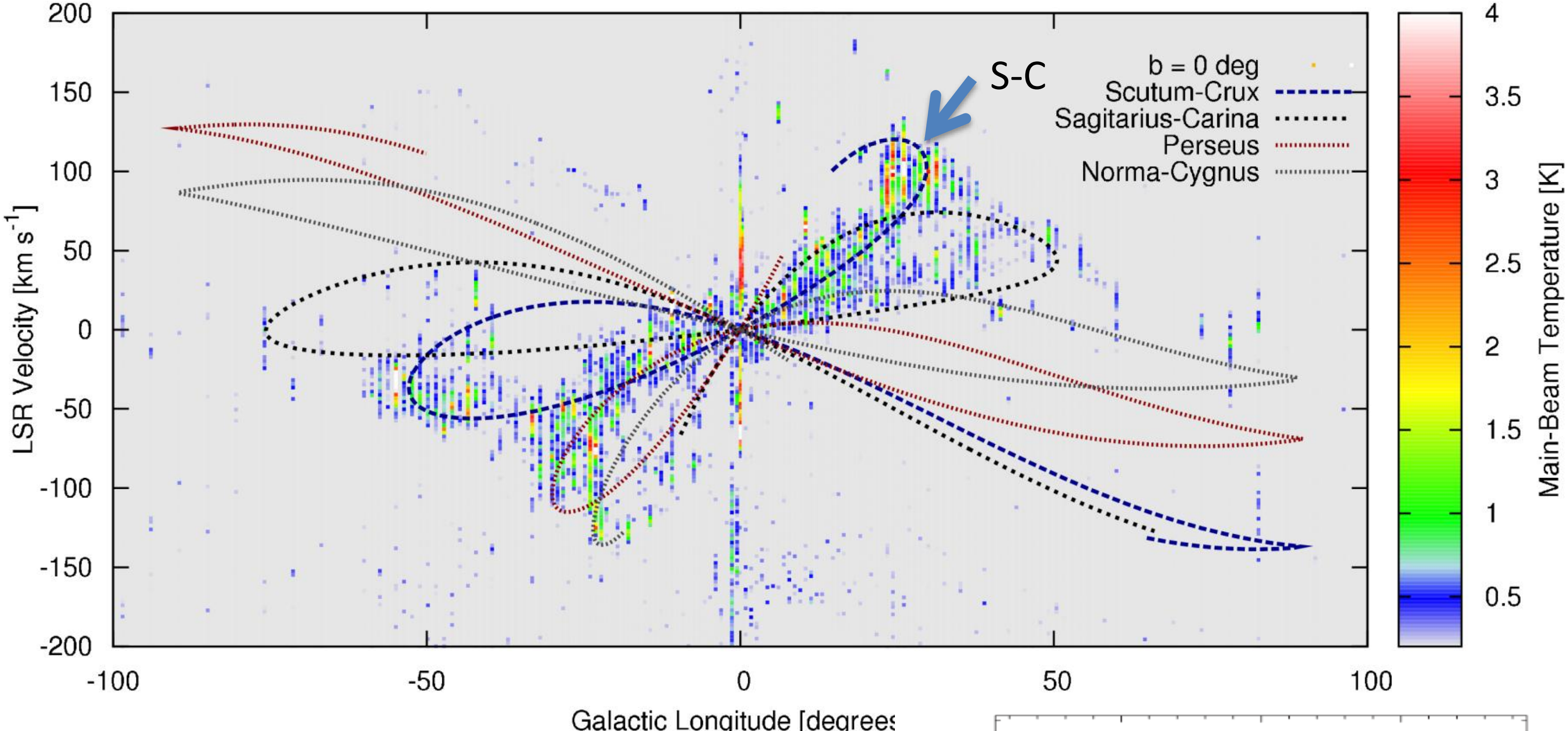


Galactic Central Region: CII strip maps sampling ≈300 positions in On The Fly (OTF) mapping mode.

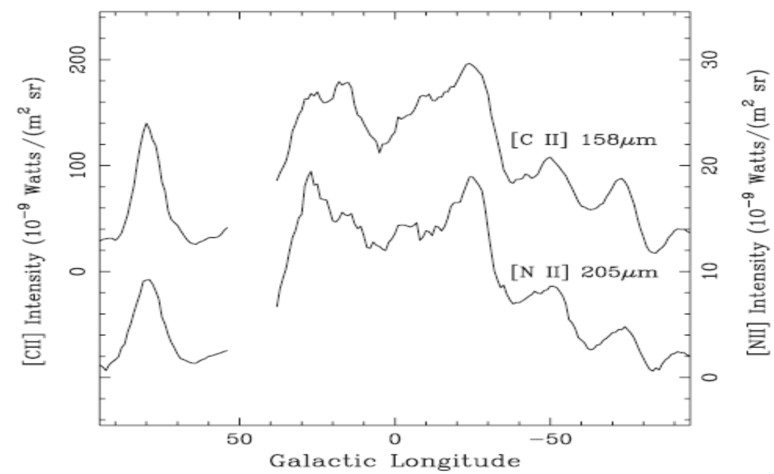




[CII] Distribution in the Milky Way: GOTC+ (*l*-*v*) map

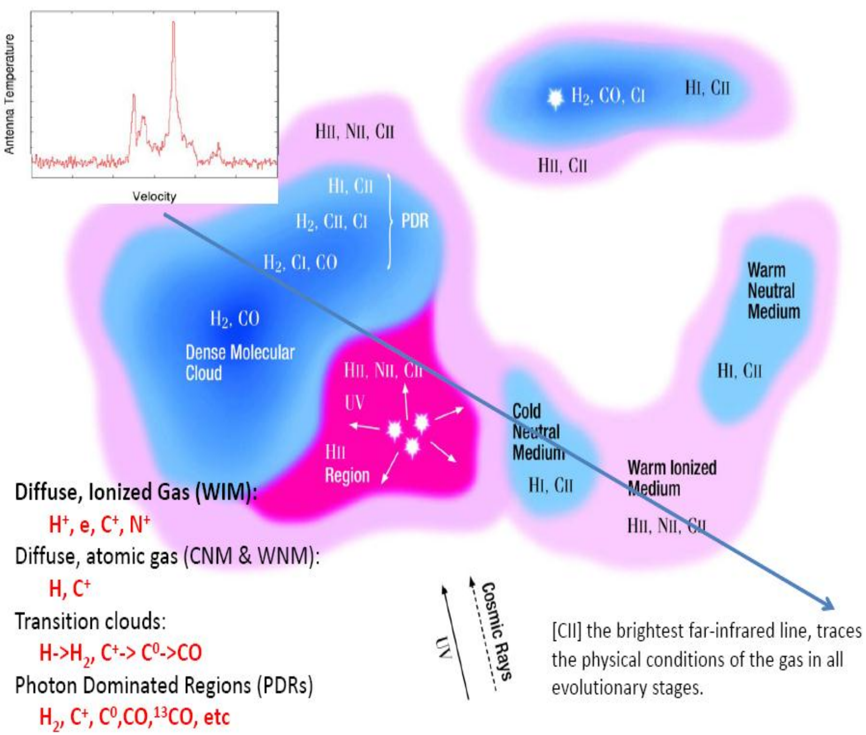


GOT C+ Spectrally resolved [CII] Galactic Plane Survey: Global Distribution of ISM Gas - Pineda et al. (2012) in preparation.

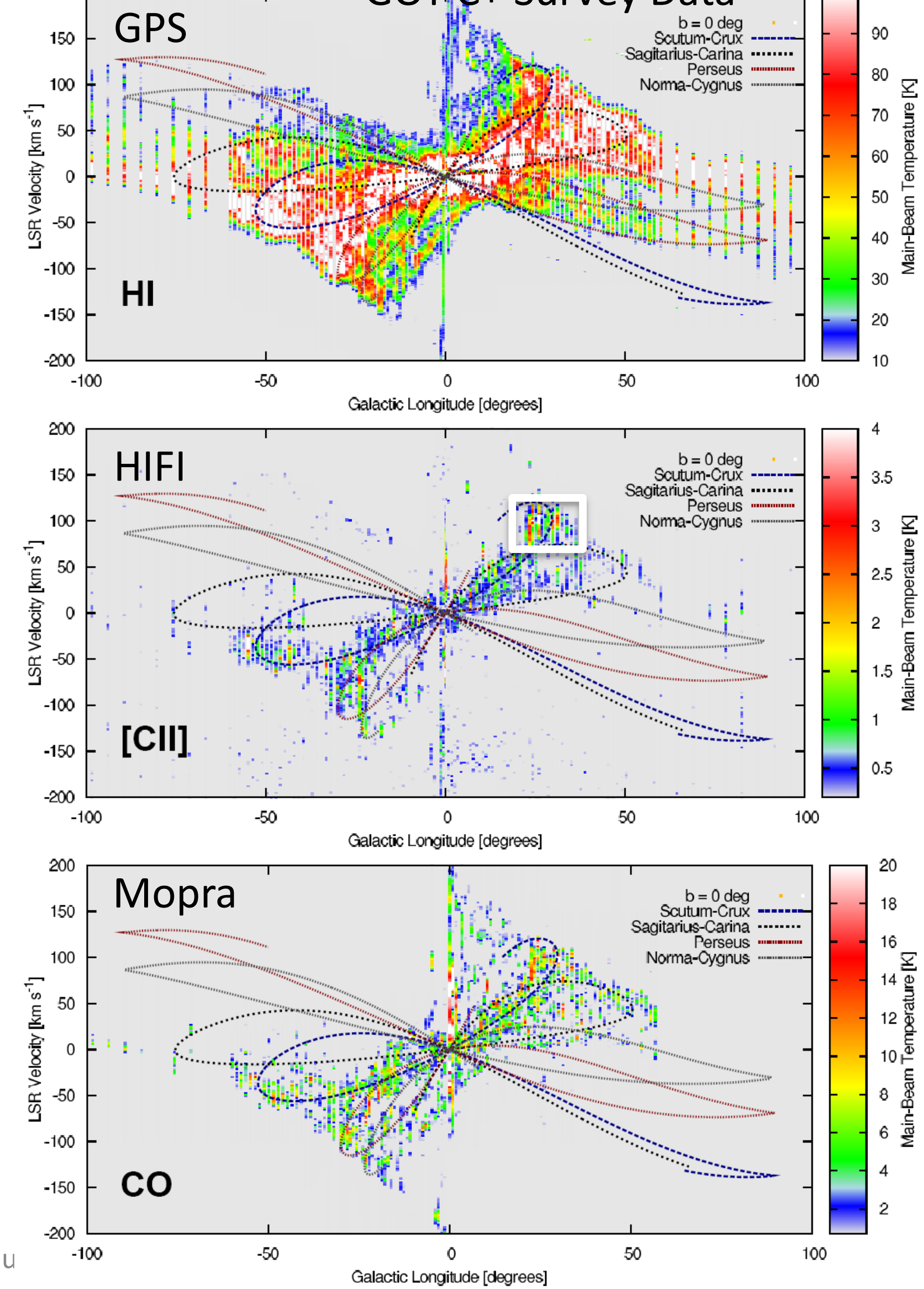


COBE data (Stieman-cameron et al. 2010)

Interstellar Medium (ISM) components: Spectra based extraction Using GOT C+ Survey Data

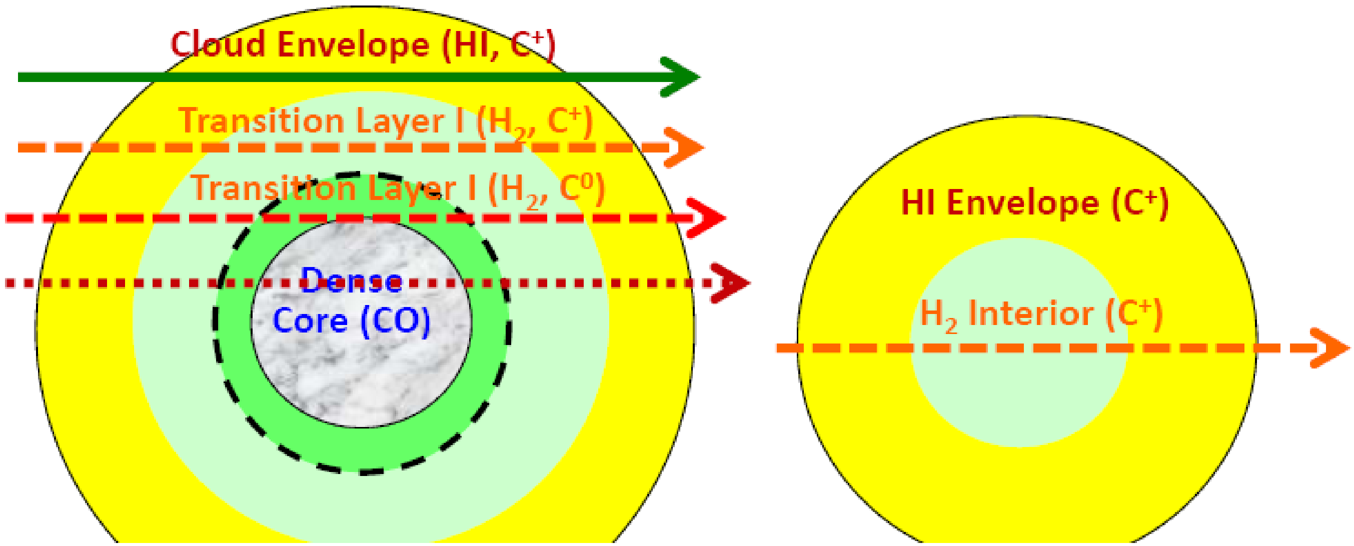


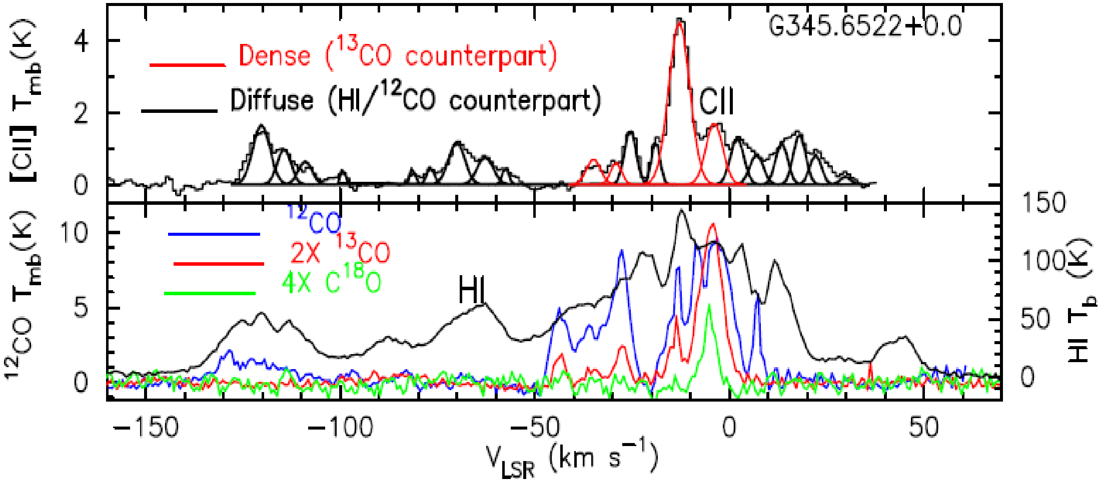
GOT C+ Survey Data



Statistical analysis of transition clouds -2

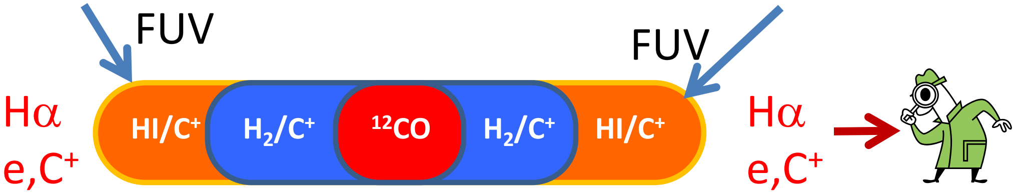
What is observed by single LOS?





Models estimate about 30% H_2 gas in the transition layers which is not traced by CO (Wolfire et al. 2010)

Statistical analysis of transition clouds -3



$I(CII,e) + I(CII,HI) + I(CII,H_2)$

$I(CII) \rightarrow N(HI) + N(H_2)$ up to $C^+/C^o/CO$ transition

Clouds selected by [CII] + 12CO, but no 13CO emissions

$N(HI)\ \alpha\ I(HI)$

$I(CII)_{HI} = f(n_{HI},T_K)\ N(HI)\ x(C^+)$

(f = excitation of C^+)

[CII] sensitive to (n,T) or P

$I(CII)_{H2} = I(CII) - I(CII)_{HI}$

where $I(CII)_{H2}$ indicates the CII emission from the H_2 layer

$N(C^+)_{H2} = f(n_{H2},T_K)^{-1}\ I(CII)_{H2}$

$N(H_2)_{C+} = N(C^+)_{H2}/x(C^+)_{H2}$

Langer, (2010, 2011) & Velusamy, et al. (2010, 2011)

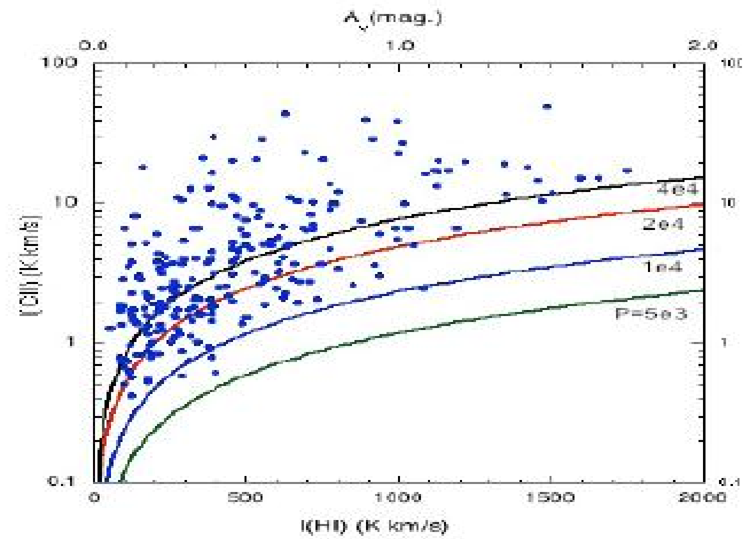


Fig. 4 [CII] *versus* HI intensities

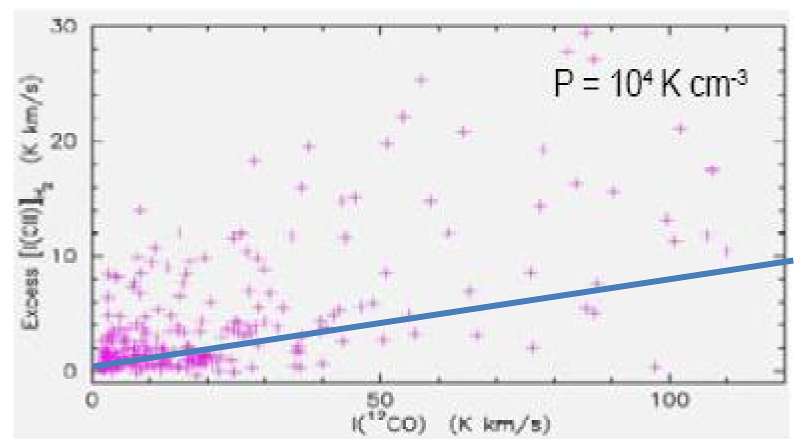
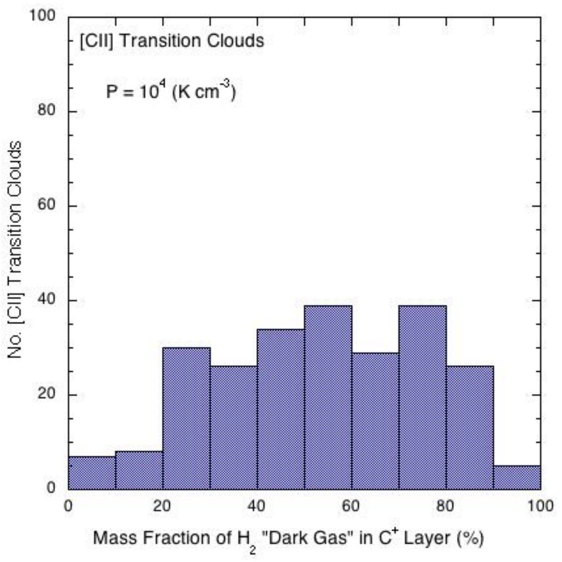


Fig. 6 Excess [CII] *versus* 12CO intensities

"Dark H_2 Gas" Mass Fraction



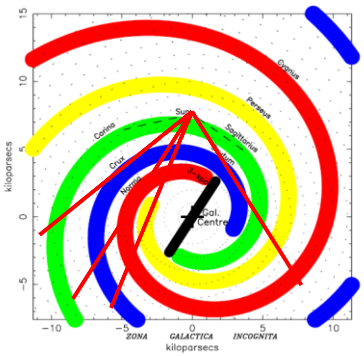
- Use excess I(CII) to estimate $N(H_2)_{CII}$
  - $I(CII)_{H2} = I(CII)_{tot} - I(CII)_{HI}$
- Fractional H_2 mass in the H_2–C^+ layer of transition clouds

$$f = \frac{M(H_2)_{CII}}{M(HI) + M(H_2)_{CII} + M(H_2)_{CO}}$$

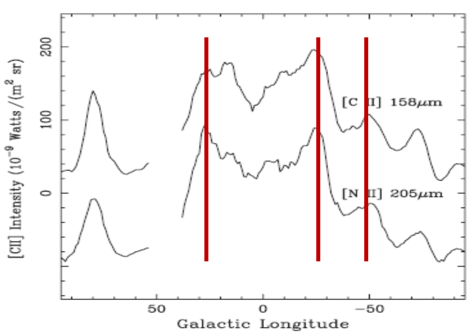
- Higher Pressure corresponds to a narrower distribution
- [CII] diffuse and transition clouds have significant amounts of warm dense H_2 in addition to a warm dense HI layer
- Need more information about the C^o/CO transition zone from [CI] and high-J CO

We have OT1 (PI: Velusamy) HIFI OTF mapping in [CII]

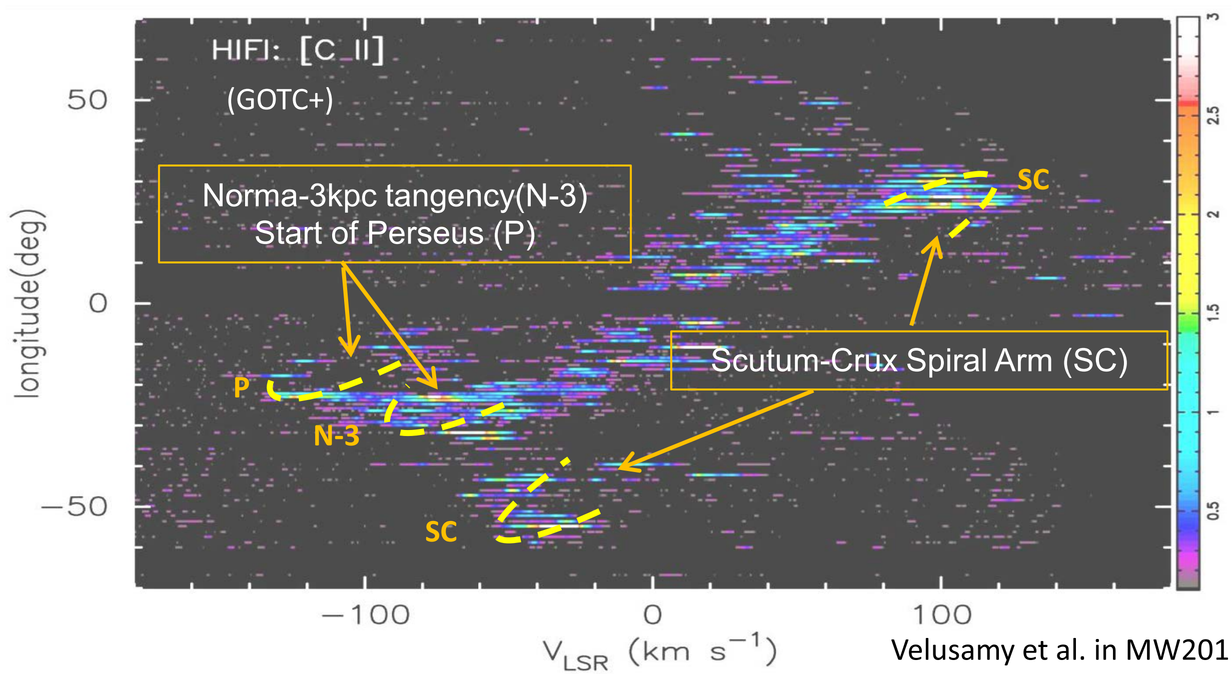
GOT C+ survey detects strong [CII] in Galactic Spiral arm tangencies



Vallee (2008)

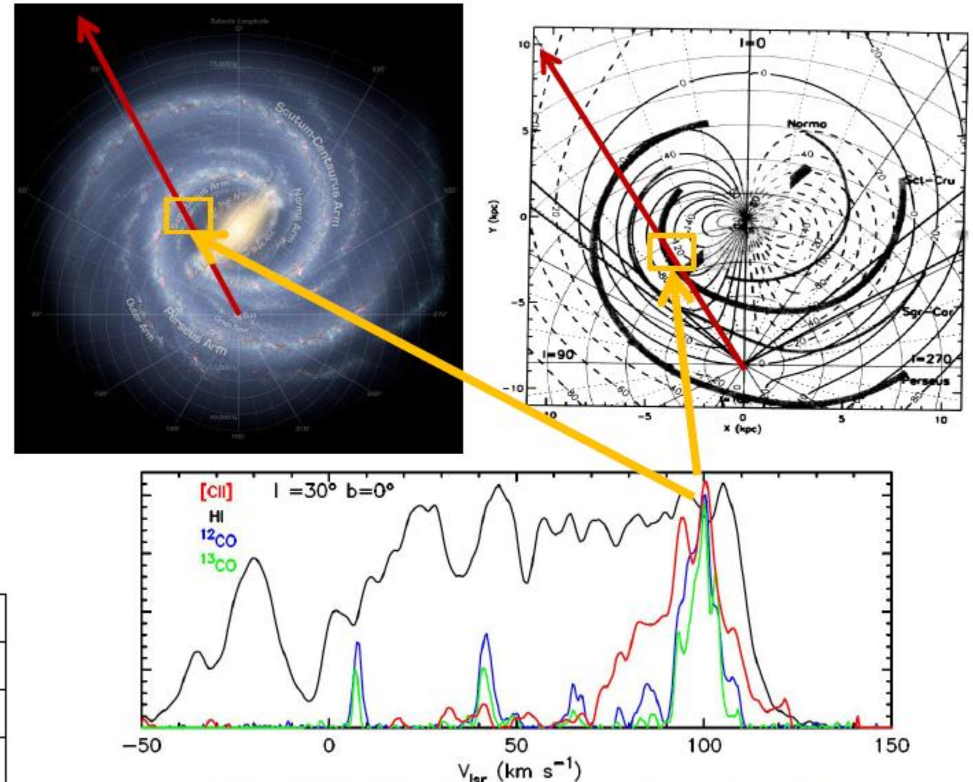


COBE data – Steiman-Cameron et al. (2010)

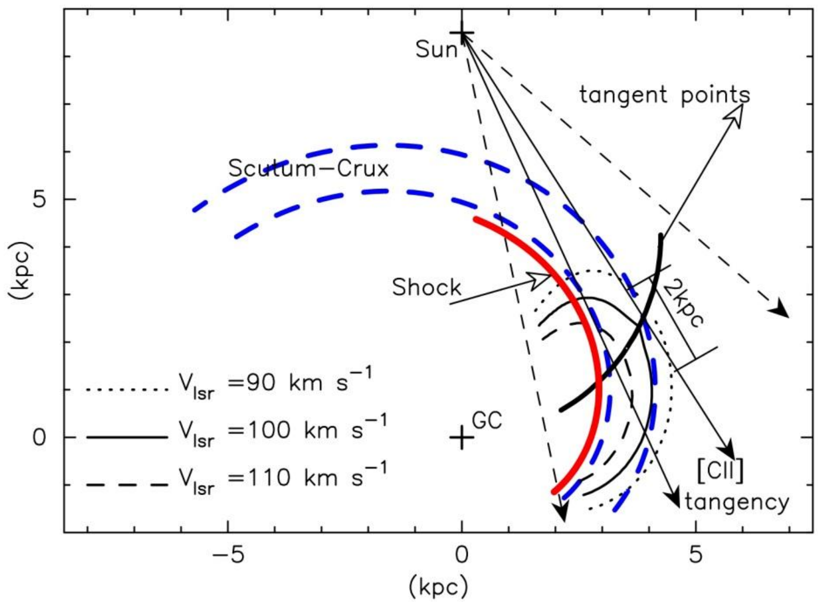


Velusamy et al. in MW2011

Isolating Different ISM Regions with HI, CO, and [CII] In the Scutum-Crux Tangency

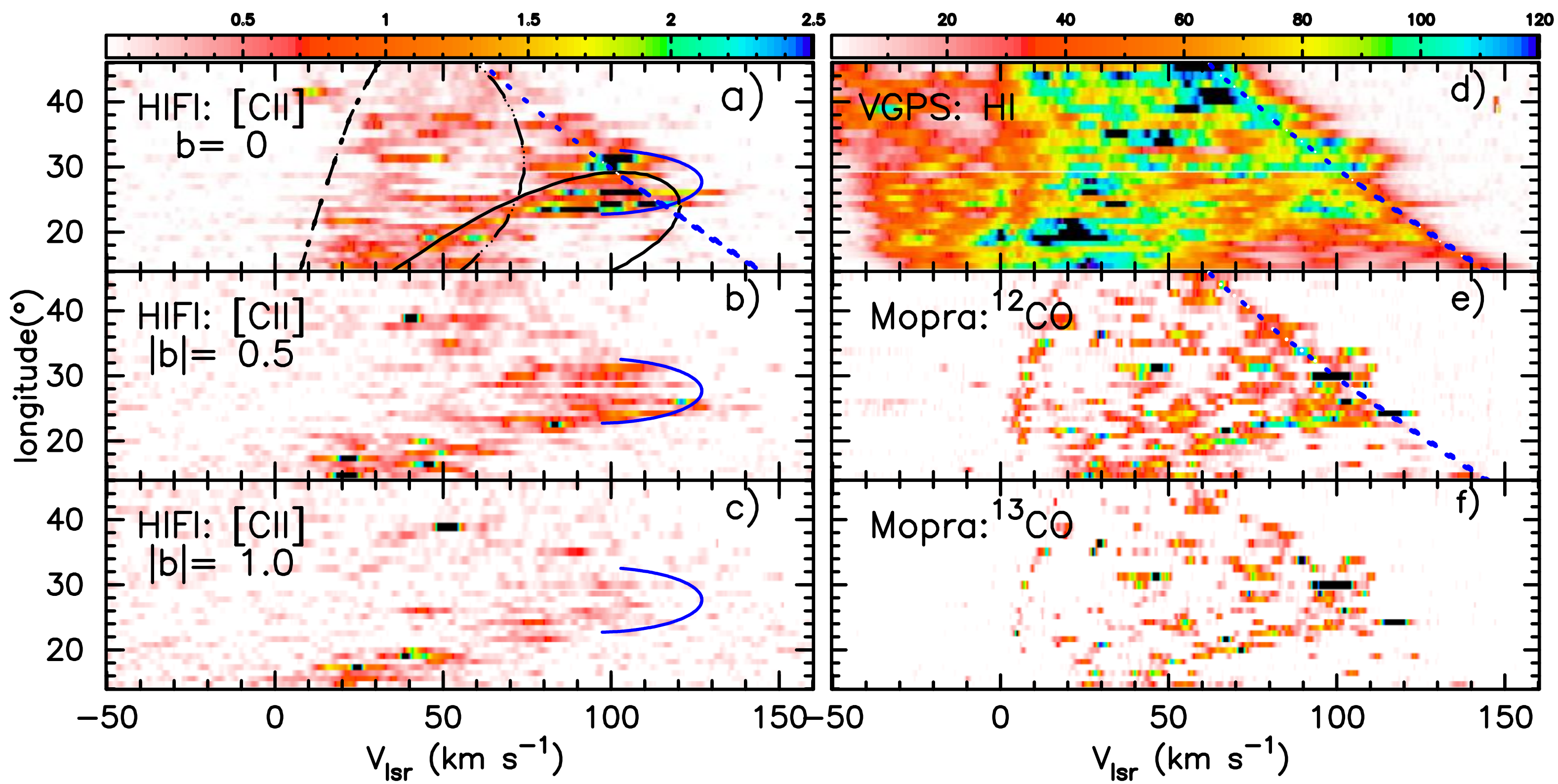


Velusamy, Langer et al. 2012, A&A 541,L10



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

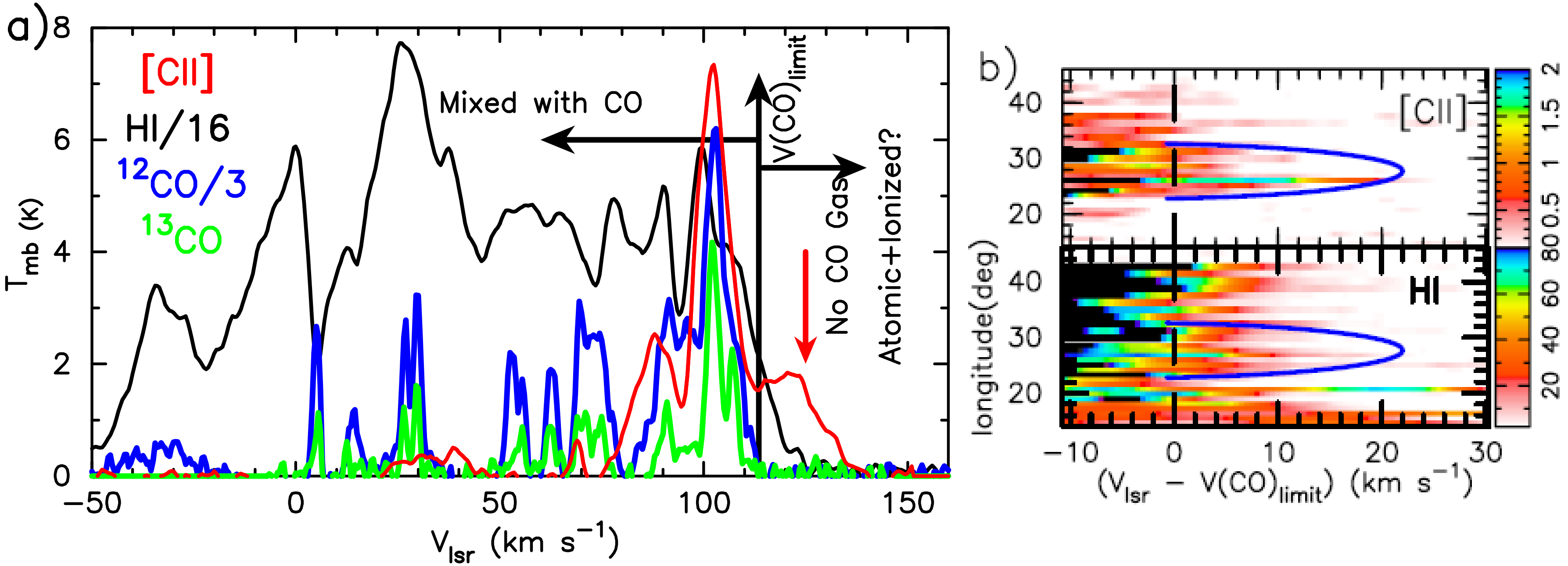
CII, HI, and CO Isolate WIM in Spiral Tangency



(l,v) maps of CII, HI, CO near Scutum-Crux tangency. Blue arc = loci of velocities traced by CII. The loci of the spiral arm velocities are: S-C (solid line) and Sagittarius – Carina (dashed). The dashed blue line shows the tangent velocity as a function of longitude.

CII, HI, and CO in Spiral Tangency -2

[CII] detected along spiral arm tangencies (long path length) with no CO and little HI. [CII] determines the WIM density and electron abundance



Near the S-C tangency CII and HI show emission significantly beyond the tangent velocities and well above ^{12}CO. Red arrow – bright anomalous CII at V > tangent velocity (110 km/s) associated with weak HI.

The excess emission at high velocities, > $V(CO)_{limit}$, is seen at all longitudes for HI, but only in the S-C longitudes for [CII].

WIM Properties From [CII]

In the optically thin low density limit

$$I(CII) = I_{CNM} + I_{WNM} + I_{WIM}$$

$$I_{WIM}(CII) = a\frac{n(e)}{n_c(e)}N_{WIM}(C^+)e^{-\Delta/T}$$

$$I_{CNM}(CII) = a\frac{n(HI)}{n_c(HI)}N_{CNM}(C^+)e^{-\Delta/T}$$

$$I_{WNM}(CII) = a\frac{n(e,HI)}{n_c(e,HI)}N_{WNM}(C^+)e^{-\Delta/T}$$

Critical Densities

$$n_c(HI) = A_{ul} / < \sigma v >_{ul}$$

$$n_c(HI)_{T=100K} \approx 3.2 \times 10^3\, cm^{-3}$$

$$n_c(HI)_{T=8000K} \approx 1.3 \times 10^3\, cm^{-3}$$

$$n_c(e)_{T=8000K} = 46 cm^{-3}$$

$n(e)/n(HI) > 0.05$ Electrons Dominate

Electron excitation dominates in WIM

[CII] from CNM HI Clouds?

$$I(CII) = a\frac{n(H)}{n_c(H)}e^{\square\square/T}N(C^+)\ Kkm/s$$

$$N(C^+) = n(H)x(C^+)L$$

$$N(H) = n(H)L\ \mu\ I(HI)$$

$$n(H)\ \mu\ \frac{n(H)e^{\square/T}I(CII)}{x(C^+)I(HI)}$$

$$n(H;T = 100K) = 6.3\square10^4\frac{I(CII)}{x_{\square4}(C^+)I(HI)}\ cm^{\square3}$$

$$n(HI)\square160\square500\ cm^{\square3}$$

But Observed < 1cm^{-3}

➔ [CII] is from WIM

WIM Properties from [CII]

$$I(CII) = a\frac{n(e)}{n_c(e)}e^{\square\square/T}N(C^+)\ Kkm/s$$

$$N(C^+) = n_t x(C^+)L \qquad n(e) = x(e)n_t$$

$$n_t = 0.32\left[\frac{T_3^{0.37}I(CII)}{x_{-4}(C^+)x(e)L_{kpc}}\right]^{0.5} cm^{-3}$$

$$n_t = 0.27\left[\frac{I(CII)}{L_{kpc}}\right]^{0.5} cm^{-3}$$

WIM Properties in S-C Arm from [CII]

CII & HI Intensities and Derived Parameters for S-C Tangency

LOS	I(CII)	I(HI)	L(kpc)*	n(e) (=n(H+))	<n(HI)>	f(WIM)	<n(e)> cm(-3)
G23.5+0.0	1.8	217	0.6	0.38	0.21	0.64	0.47
G24.3+0.0	2.9	186	0.8	0.46	0.14	0.77	0.52
G25.2+0.0	5.7	262	2.7	0.37	0.06	0.87	0.40
G26.1+0.0	26.5	184	2.3	0.90	0.05	0.95	0.93
G27.0+0.0	4.9	548	2.9	0.30	0.11	0.73	0.35
G27.8+0.0	1.8	222	2.6	0.20	0.05	0.80	0.23
G28.7+0.0	4.0	141	1.8	0.38	0.05	0.89	0.41
G30.0+0.0	3.1	210	1.0	0.42	0.12	0.77	0.48
G31.3+0.0	4.4	325	1.0	0.49	0.19	0.72	0.57
G32.6+0.0	2.7	291	1.0	0.37	0.17	0.68	0.45
Avg b=0.0	6.7	530	1.8	0.45	0.17	0.72	0.53
Avg b=0.5	3.3	740	2.2	0.25	0.20	0.56	0.33
Avg b=1.0	1.5	672	3.5	0.13	0.11	0.54	0.18

* Constrained by the highest velocity contours in the *(l-v)* maps

- <n(e)> = 0.45 cm^{-3} at $b=0^{o}$, 3-7 times larger than WIM outside spiral tangencies
- <n(e)> decreases with b, consistent with lower gravitational potential of arms
- Comparison of CNM/WNM HI clouds with WIM -> 50% - 70% linear filling factor

WIM in S-C Arm from [CII]

The relatively weak HI emission implies we are detecting WIM and not WNM.

The average densities derived from the [CII] excess are several times higher than the LOS averaged densities inferred from pulsar dispersion and H-alpha measurements.

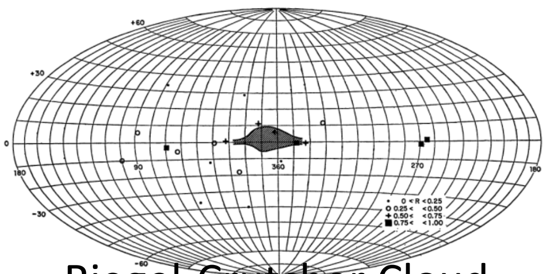
Larger mean densities may be a result of compression by the interaction of the WIM with the gravitational well of the spiral arms and that it is on the path to becoming WNM.

Additional sensitive [CII] observations, along with those of [NII], are needed to trace the dynamics of the arm-WIM interaction.

In OT2 (PI: Velusamy) HIFI [CII] Mapping of 15deg longitude covering the 3-kpc and Norma tangencies and start of Perseus arm with adequate sampling (@ 40arcsec) is being observed. → more complete picture of the ISM gas properties and phases in spiral arm tangencies

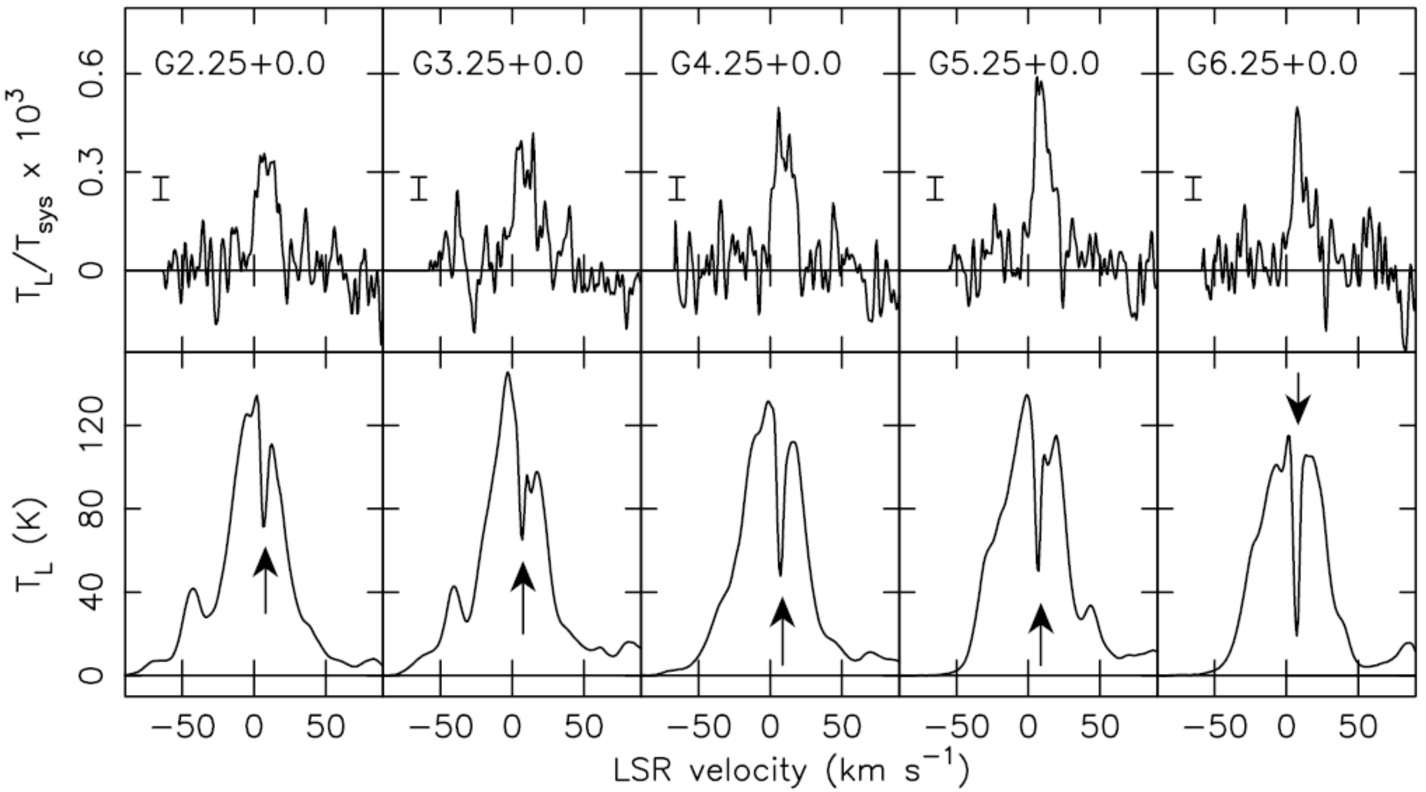
Ancillary data H- Radio recombination line survey of this region will be useful (possibility with GMRT 1.4GHz ?)

ORT Carbon RRL in HI self absorbed cloud



Riegel-Crutcher Cloud

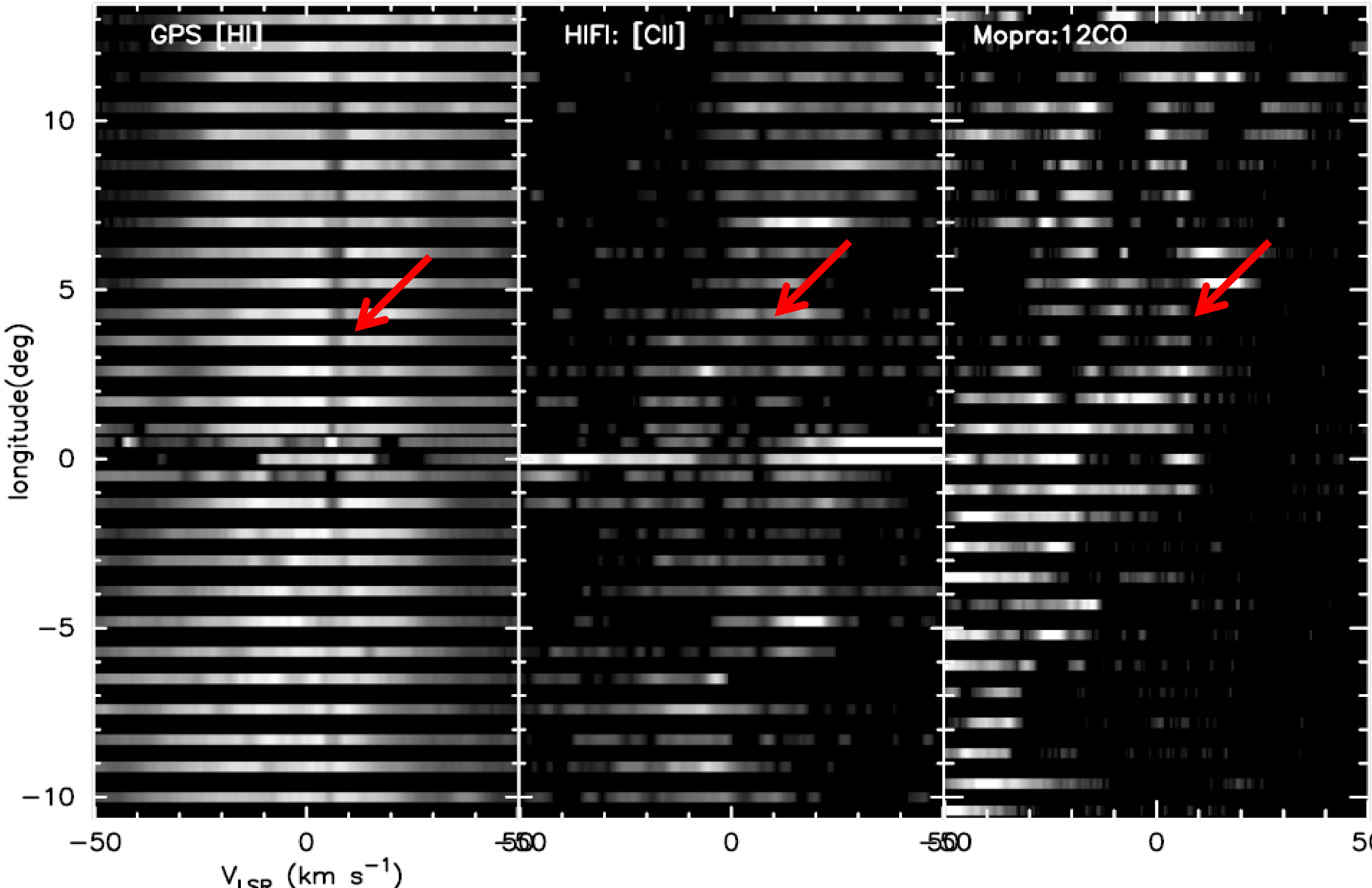
Roshi & Kantharia, 2011,MNRAS, 414, 519



ORT
327MHz
CRRL

HI

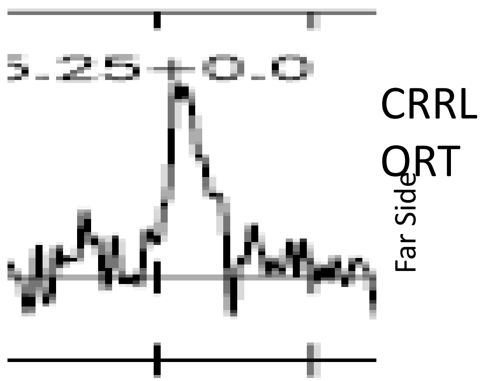
[CII] in HI self- absorbed cloud GOT C+ survey and ancillary data

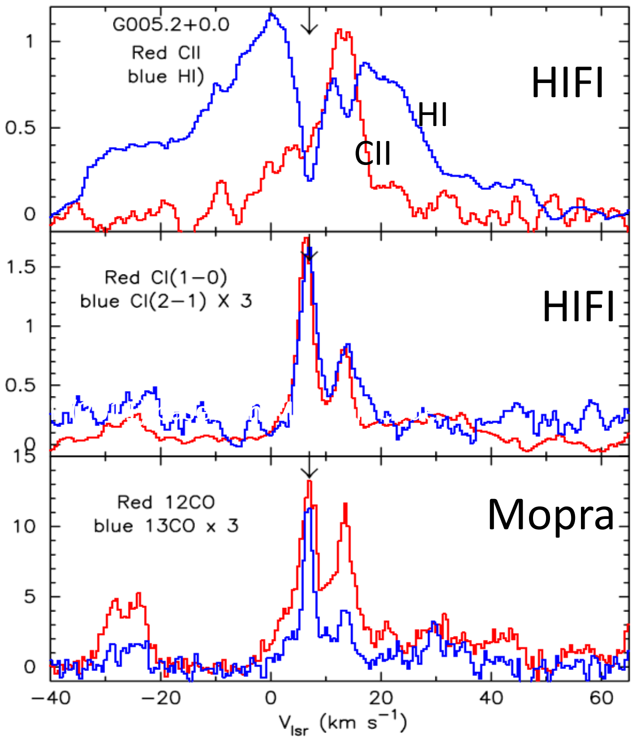


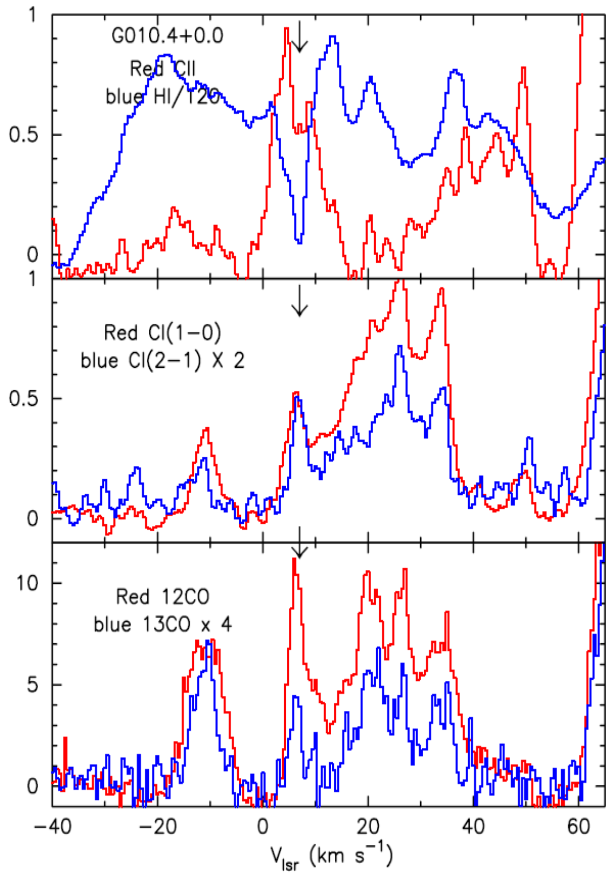
Additional data at selected longitudes:

HIFI: CI(1-0) & CI(2-1); CSO: CO(2-1) & CO(3-2)

[CII], CI, CO in HI self- absorbed cloud



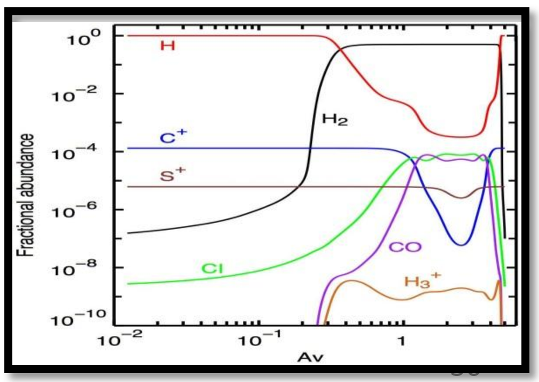




CRRL + HI predict
H2 layer
[CII] emission

GOT C+ HIFI [CII] results
no enhancement
local minimum?
absorption?
Too cold (T < 35K) for [CII]

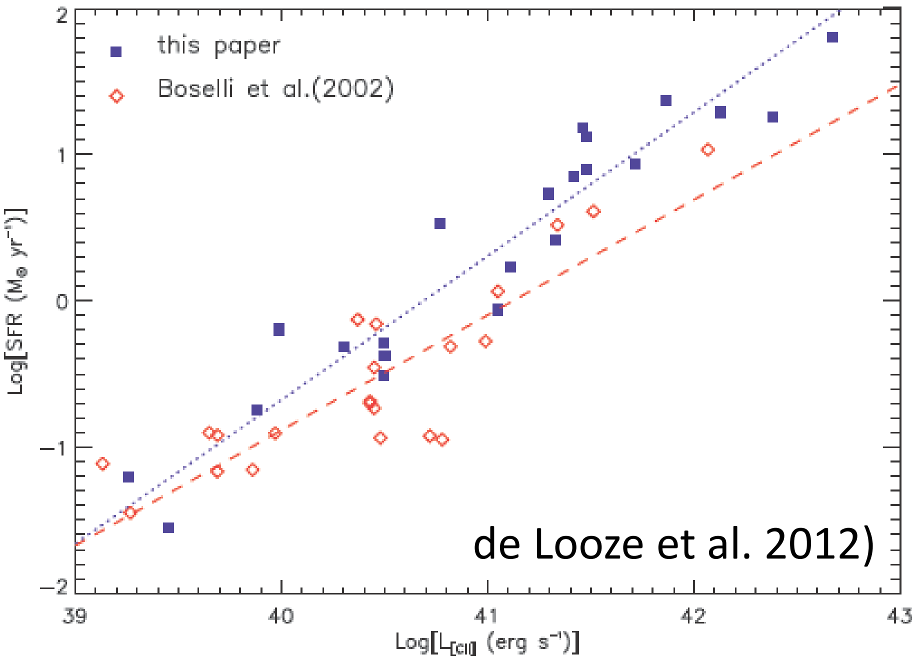
But, strong
CI (1-0) & CI(2-1)
^{12}CO & ^{13}CO



Detailed modeling
Work in progress

[CII] emission as probe of SFR in galaxies

ISM thermal balance ➔ Heating = Cooling
Primary source of heating is by UV radiation from star formation via SVGs and PHAs
[CII] is a primary coolant
Heating traced by e.g Spitzer IRAC 8um band
Cooling traced by [CII] emission



- ➔ [CII] emission is a measure of Star-formation rate (SFR)
  - ➔ A tool for galaxy evolution throughou the universe
  - ➔ At high redshifts 1.9THz [CII] line is observable in ALMA bands
- ➔ NEED to understand Galactic [CII] emissio.. for calibrating its use as tracer of SFR in external galaxies

[CII] in GMC in M33

CII emitting gas closely linked to molecular gas:

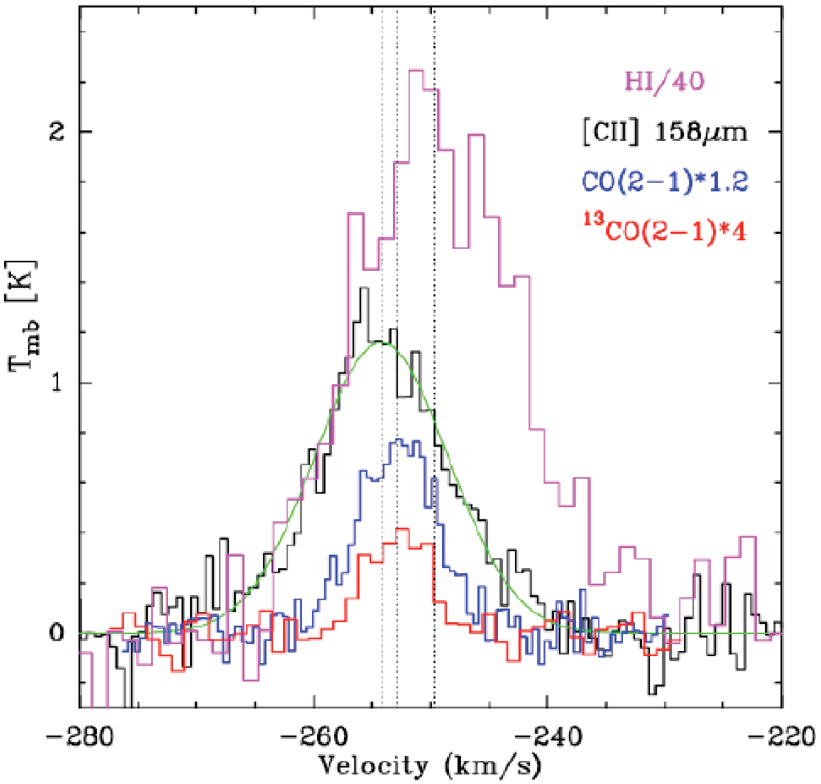
CO found but ***not*** proportional to CII emission

CII follows dust and Hα emission with 24 and 100 μm

No "diffuse" CII emission detected, whether related to HI or WIM

Model where GMCs are surrounded by some H2 w/o CO seems justified

SFR ∝ I(CII)$^{1.5}$ in in a star forming region



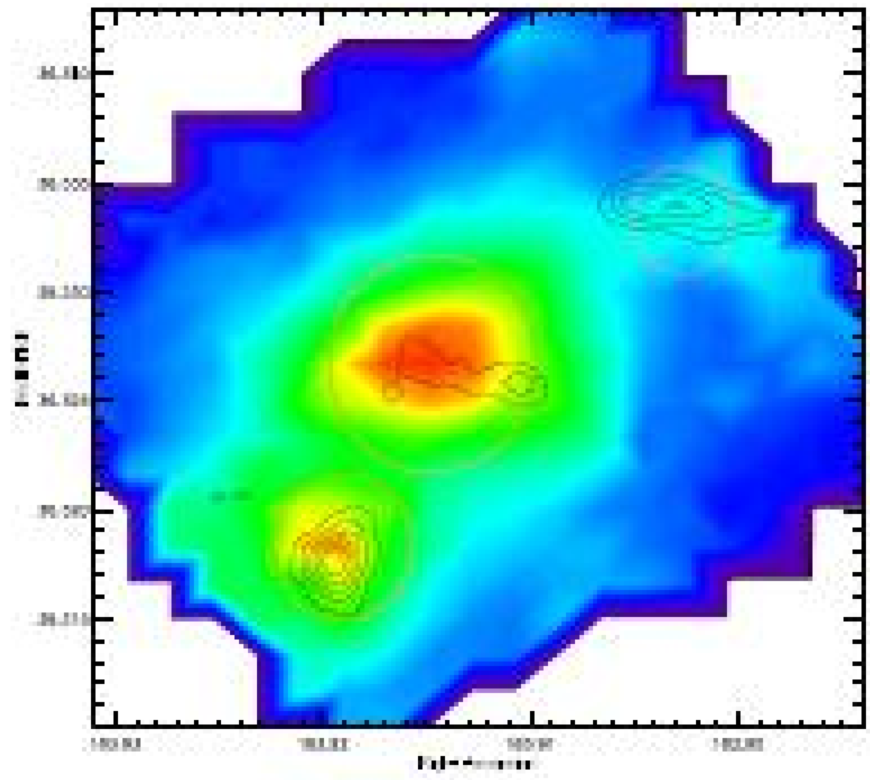
Mookerjea+ 2011

[CII] NGC 4214

CO contours overlaid on [CII] image:

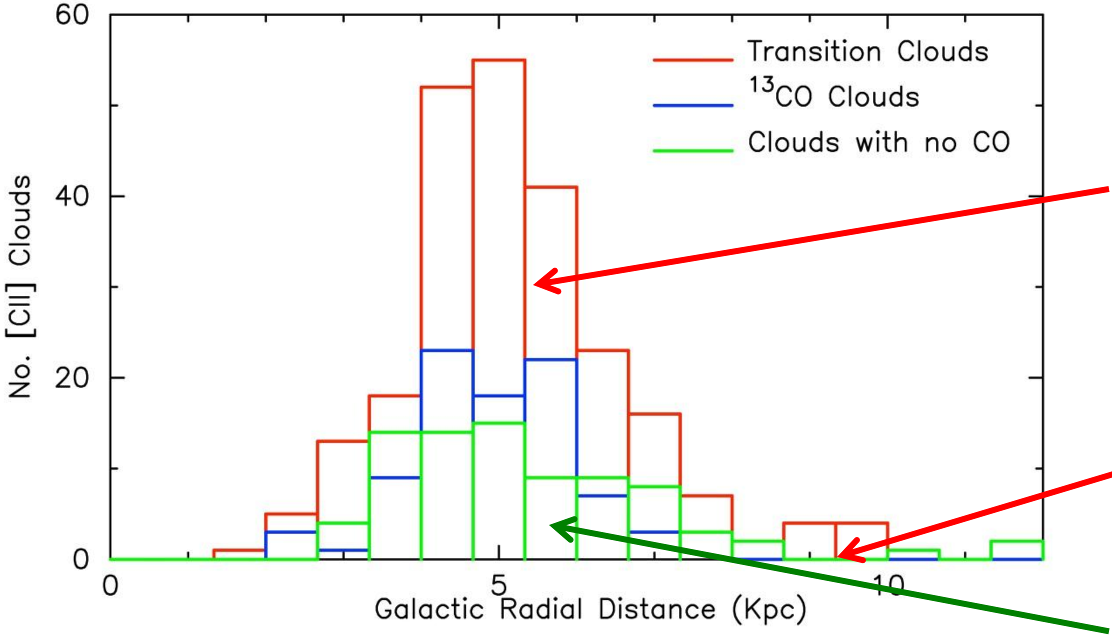
- extreme $L_{[CII]}/L_{CO}$ values
- the low metallicity and clumpy ISM:
- a consequence of the lower dust abundance
  - Deep penetration of FUV into molecular clouds, photodissociating the CO
  - larger C^+ emitting envelope surrounding a small CO core.

Sue Madden 011



Global properties of Galactic 158 μm [CII] emission

Distribution of [CII] Clouds with R_{Gal}



~ 60% of Transition Clouds are located at R = 4 - 6 kpc

Few clouds detected in local ISM (R~8 kpc)

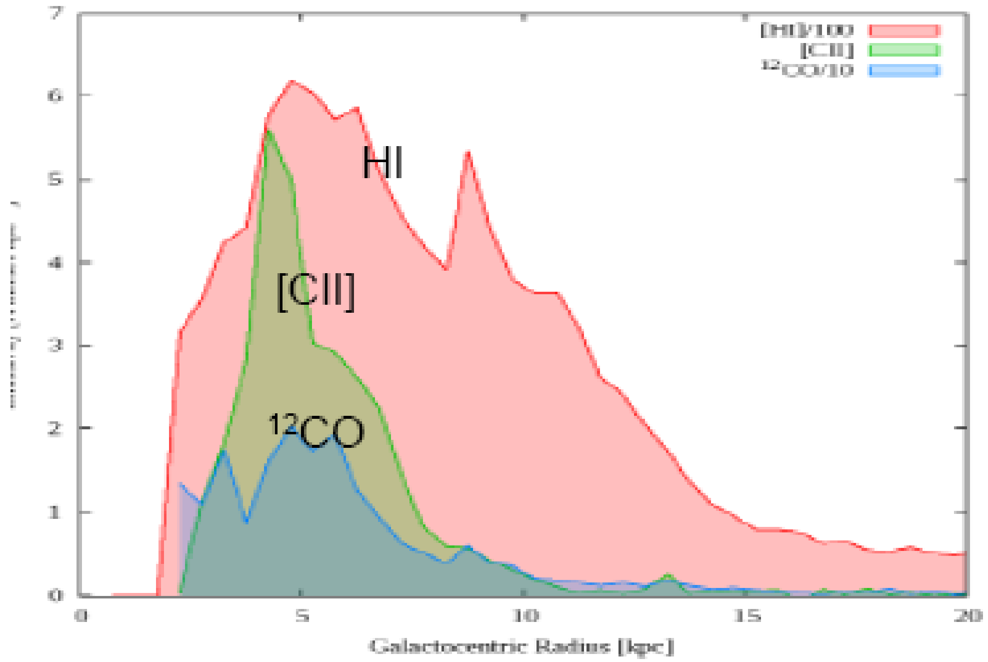
[CII] clouds with no CO have a flatter radial distribution

- 429 [CII] narrow components (in a small sample in the inner Galaxy)
- HI associated with all CII Clouds
- 88 have no CO emission
- 247 with ^{12}CO, but no ^{13}CO
- 94 with $^{13}CO(1\text{-}0)$ emission

Global properties of Galactic 158 μm [CII] emission

Radial distribution of [CII], HI, ^{12}CO intensities

Pineda, Langer, Velusamy, Goldsmith, 2012

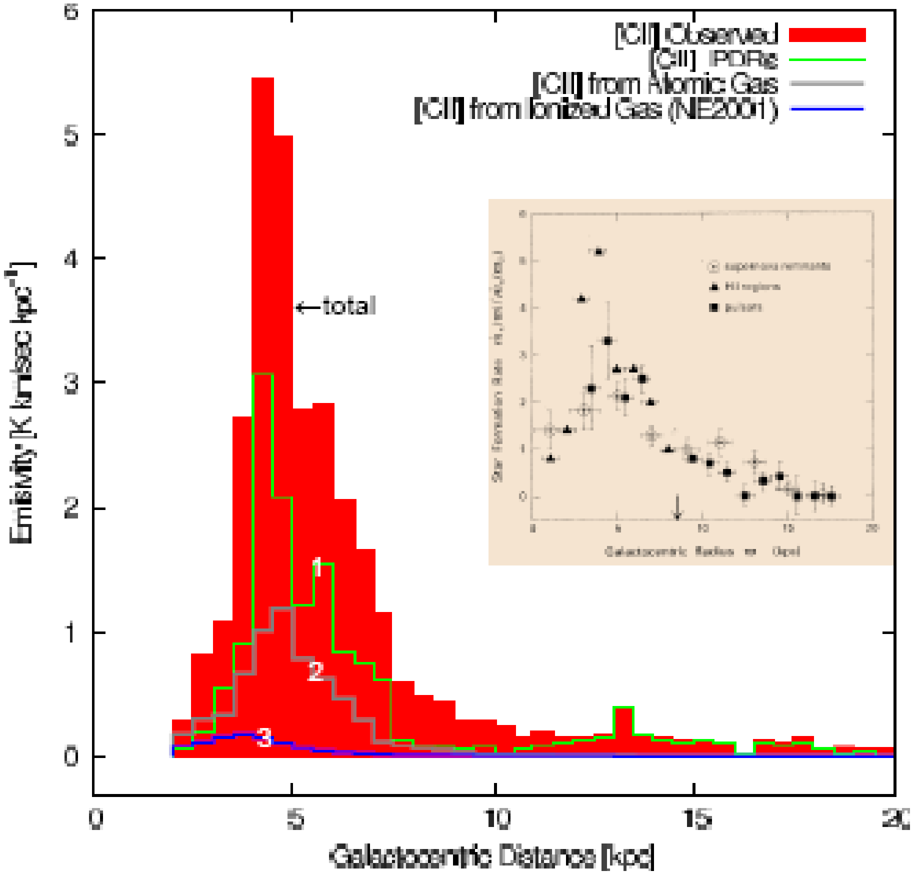


Galactocentric distribution of the [C II], HI, and CO integrated intensity. Note the concentration of [CII] in the inner Galaxy within 7 kpc radius (peak near 5kpc) suggesting that it is tracing the UV field and hence the star formation in the Galaxy.

Global properties of Galactic 158 μm [CII] emission:

Preliminary results on Relative ISM contribution to [CII] intensity

Pineda, Langer, Velusamy, Goldsmith, 2012



➔We find that in the Galaxy at least 70% of the [CII] intensity is tracing star formation. (work in progress)

Relative contribution to the observed total [CII] intensity from different ISM components:

1.(*green line)* represents [CII] emission from PDRs (traced by ^{13}CO emission defining the warm molecular gas);

2. (*grey line)* represents [CII] emission from the HI gas, estimated for cloud gas pressure of 10^4 Kcm^{-3};

3. (blue line), the [CII] emission from ionized gas, estimated for the NE2001 electron density model (Cordes & Lazio 2002).

The remaining [CII] intensity (about 30%) is tracing the "dark H_2 gas", in which hydrogen is primarily in H_2 and carbon transitioning from C^+ to CO.

(inset) Distribution of the Galactic SFR (reproduced from Stahler & Palla, 2005)

Summary

- The 1.9 THz [CII] line (at 158 μm) is often the single brightest emission line in galaxies.
- The [CII] emission in the ISM can arise from a wide range of temperatures excited by collisions with electrons as well as atomic and molecular hydrogen.
- [CII] line is a primary coolant , thus extremely useful as a robust tracer of total gas mass and a quantitative Star Formation Rate (SFR) measure for high-redshift galaxies.
- Herschel HIFI and PACS spectroscopy are enormously successful studying [CII]
- GOTC+ survey of Galactic [CII] emission reveals new details on the distribution and characteristics of the warm, dense and atomic and molecular components of the interstellar medium: WIM, WNM, CNM, including the so-called "dark H_2 gas" in cloud transitions which is missed by both HI and CO as tracers.
- GOT C+ results on the global distribution of [CII] emission and its characterization as function Galactic radius is a first step towards calibrating the [CII] emission as a probe for Star Formation Rate (SFR) in external galaxies.
- More to follow in Herschel OT1 & OT2 observations
- New opportunities on SOFIA with GREAT and in future with array receivers
- The high luminosity of [CII] makes the 158 μm line readily detectable beyond z = 5 in ALMA bands.