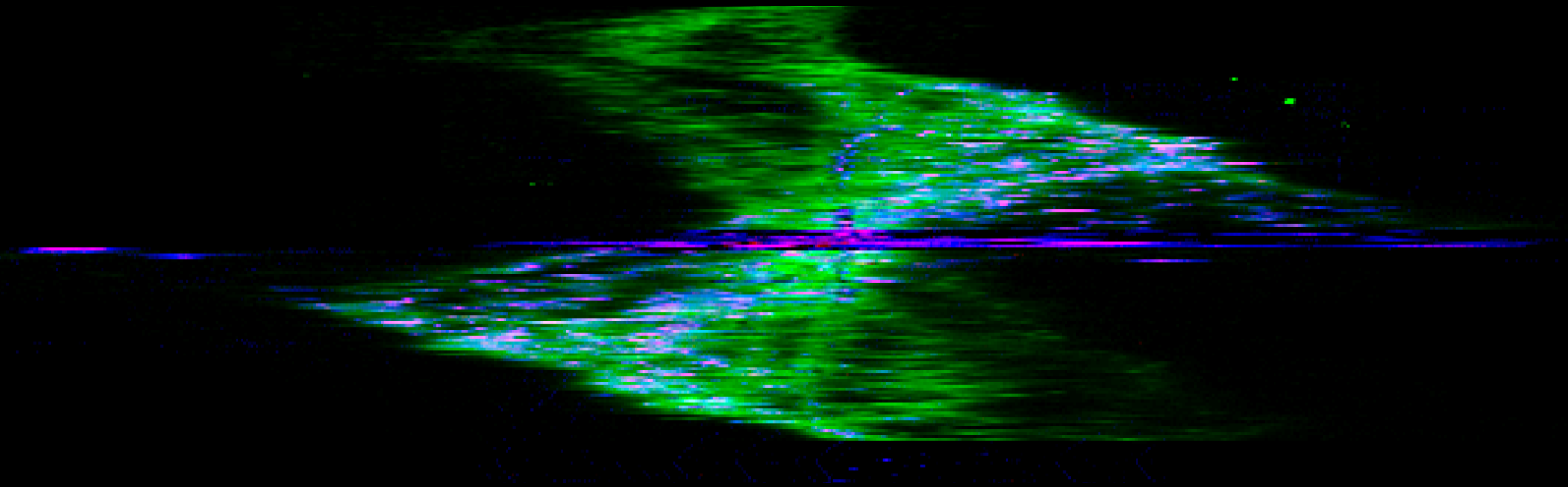


What Are We Learning from Fine Structure Line Observations?

Paul F. Goldsmith

Jet Propulsion Laboratory, California Institute of Technology

With thanks to my collaborators

William D. Langer, Jorge, Pineda, Thangasamy Velusamy, Matt Orr, Javier Goicoechea, Tie Liu, & Maryvonne Gerin

October 2016

Atomic & Ionic Fine Structure Lines Play a Central Role in ISM Physics

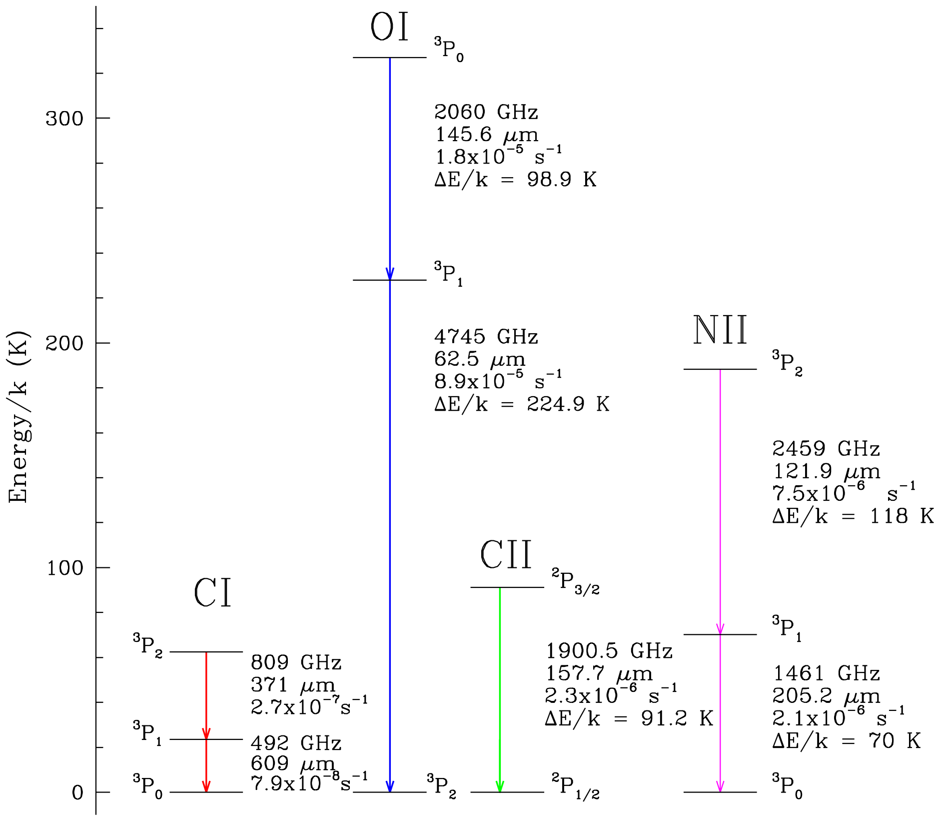
- Ionized carbon is the primary coolant of diffuse ISM – establishes parameters of atomic gas and cooler Photon Dominated Regions (PDRs)
- Neutral oxygen is major coolant of warmer PDRs
- Fine structure lines (FSLs) provide information about evolution of clouds from diffuse (atomic) to dense (molecular) form (and back)
- FSLs are potentially excellent tracers of star formation—but there are some questions

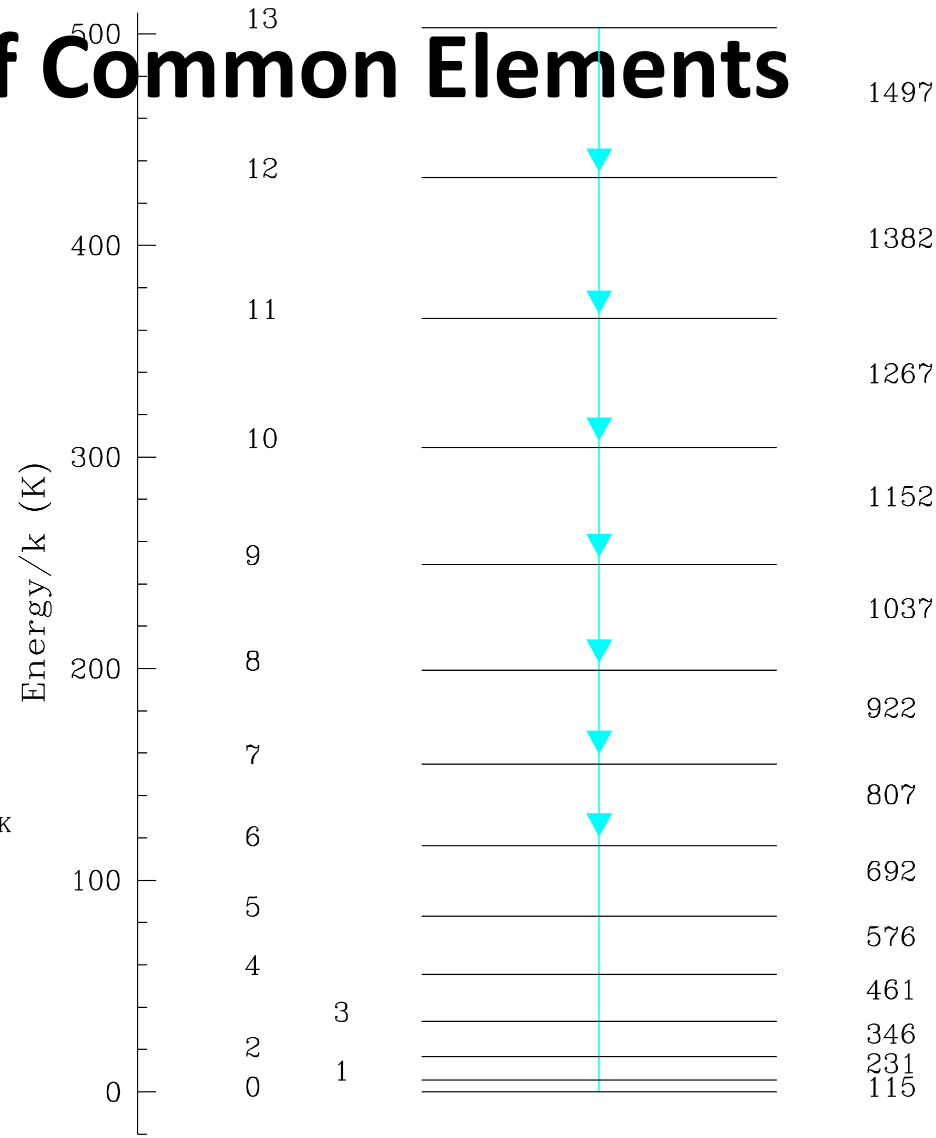
Major Topics in this Talk

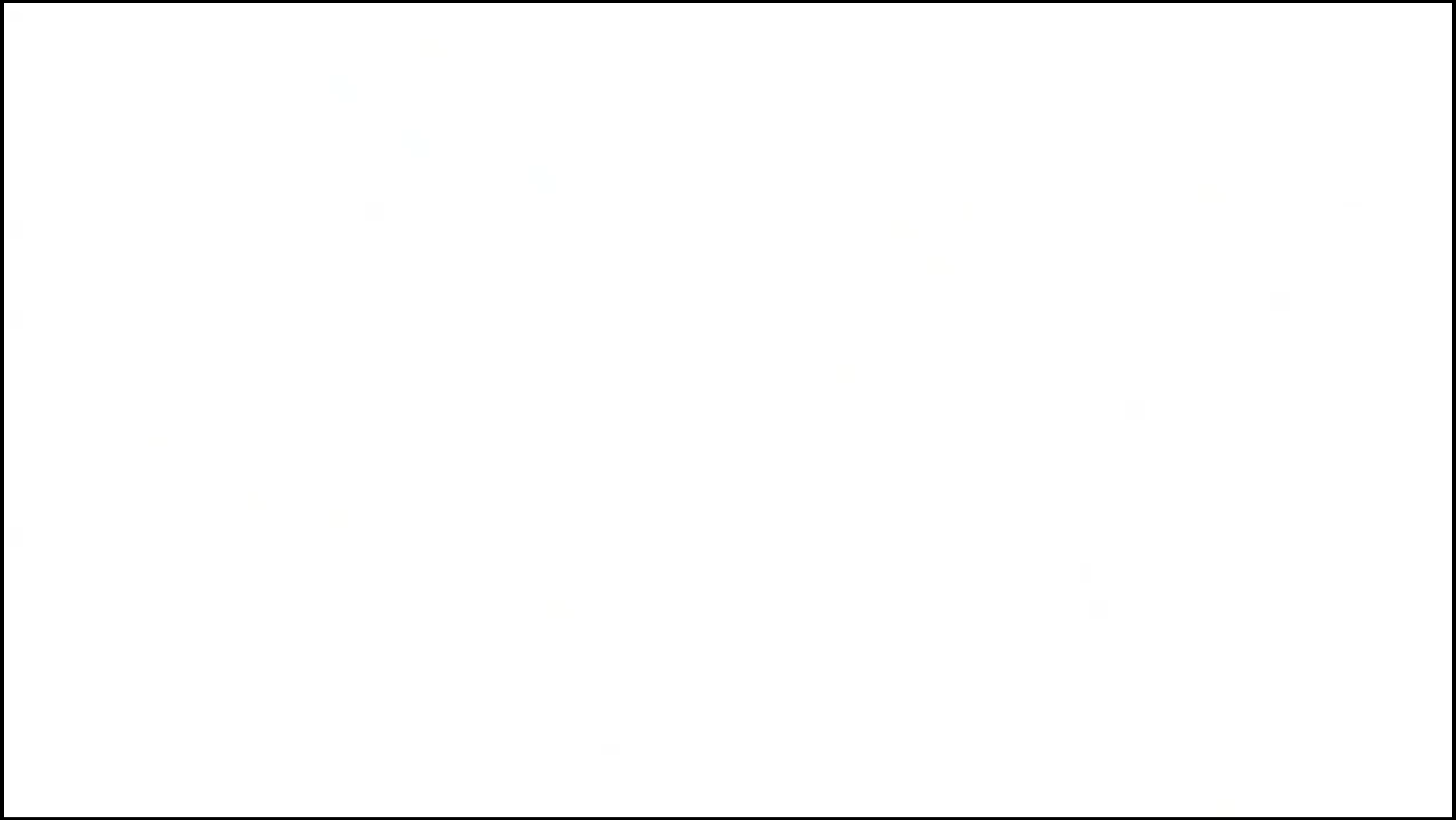
- Large-scale surveys of [CII] and [NII] FSLs in MW
- Studies of individual regions in differing environments
- Issues with interpretation of FSLs

Fine Structure Transitions of Important Ionization States of Common Elements

CO Cooling can be important if regions are fully molecular and have high temperatures Spontaneous decay rates are rapid for FIR lines: $A(J, J\text{-}1) \cong 10^{-7}J^3$





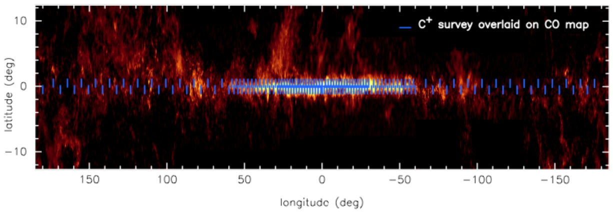


The excitation of ionized carbon is related to the energy input from newly formed stars.

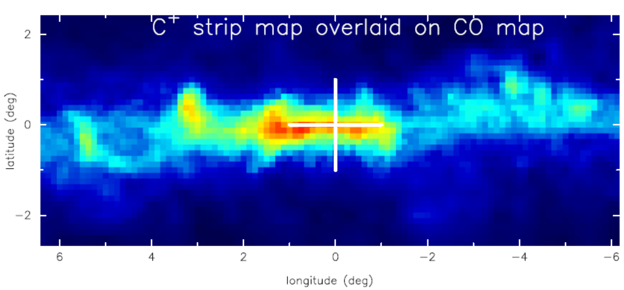
GOT C+ [CII] 1.9 THz Survey
Herschel OT Key Project; W. Langer PI

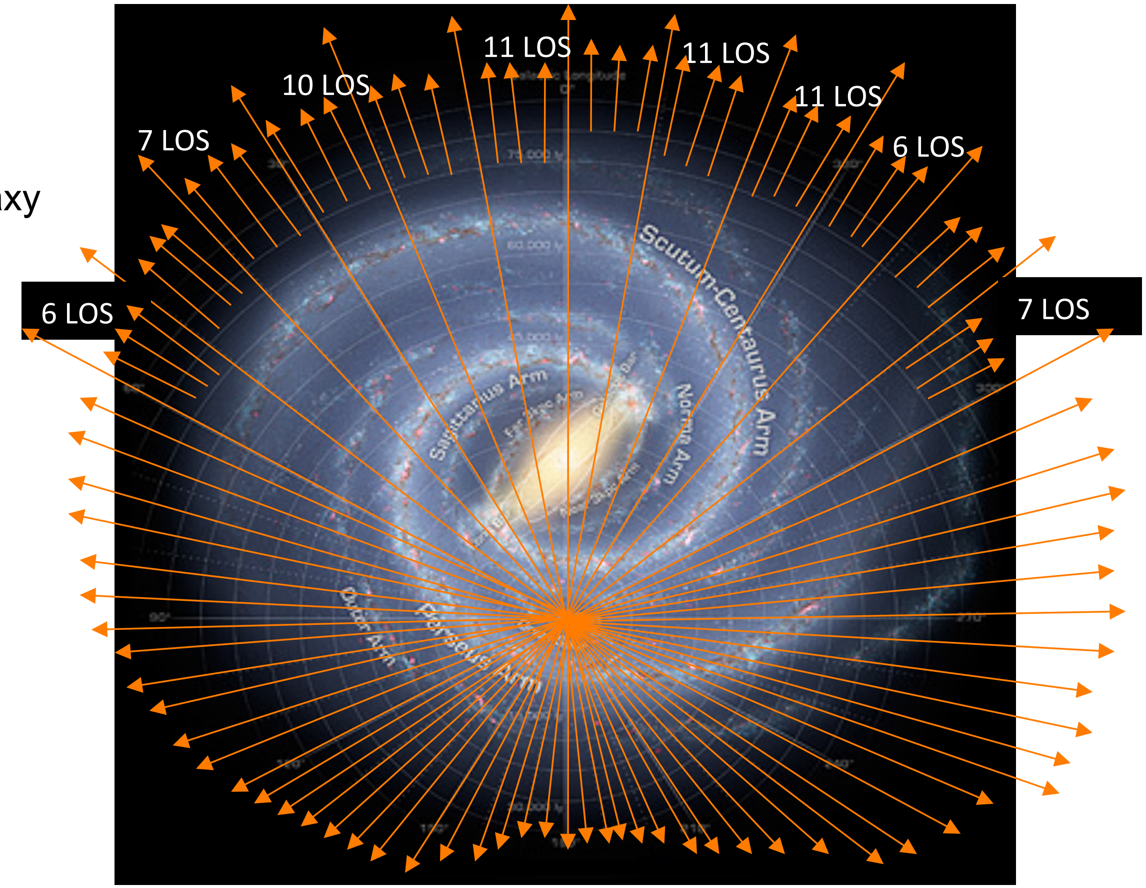
Galactic Plane Survey: systematic volume weighted sample of ≈ 500 LOSs in the disk

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



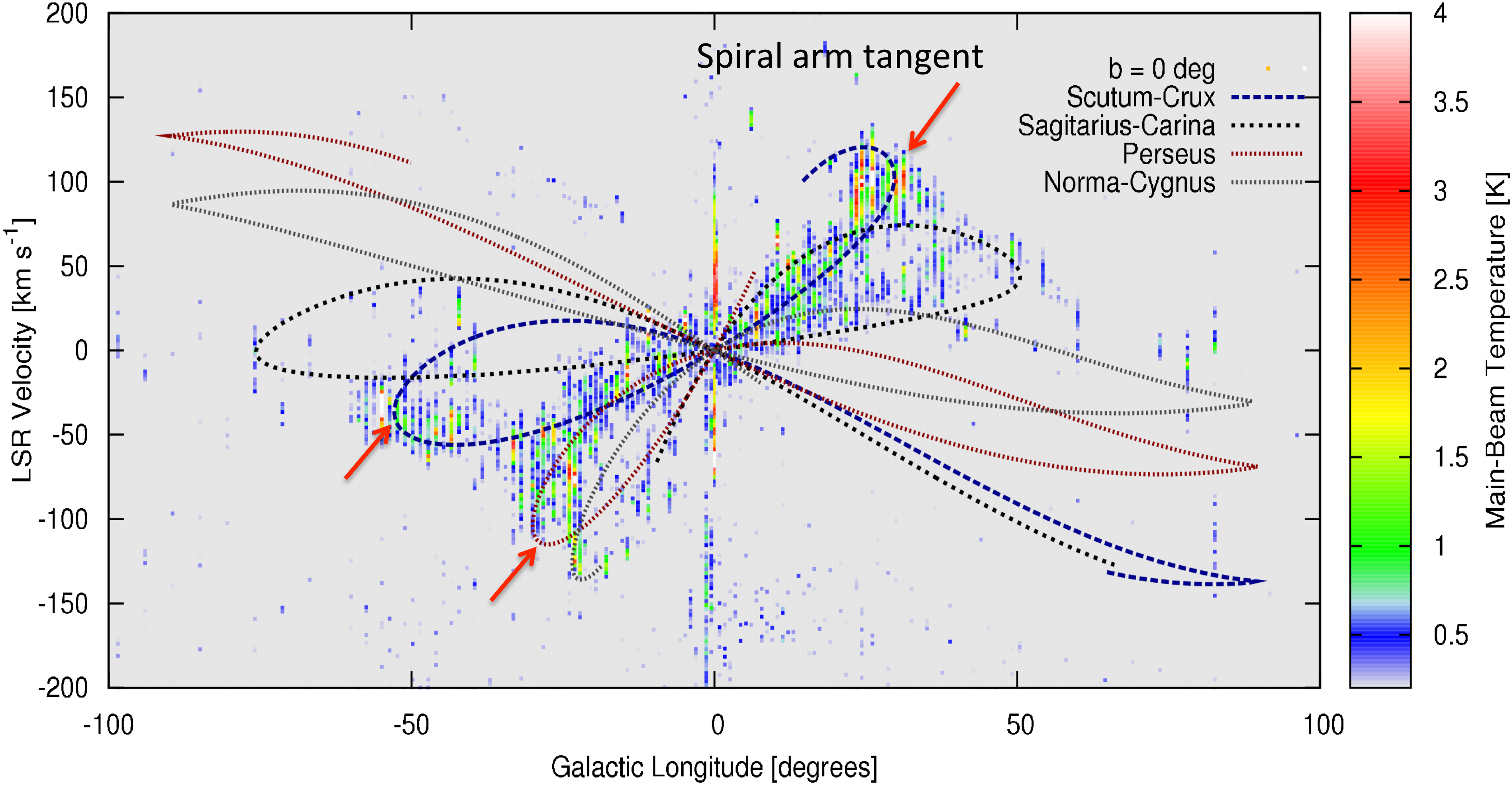
Galactic Center Region: CII strip maps sampling ≈300 positions in On The Fly (OTF) mapping mode.





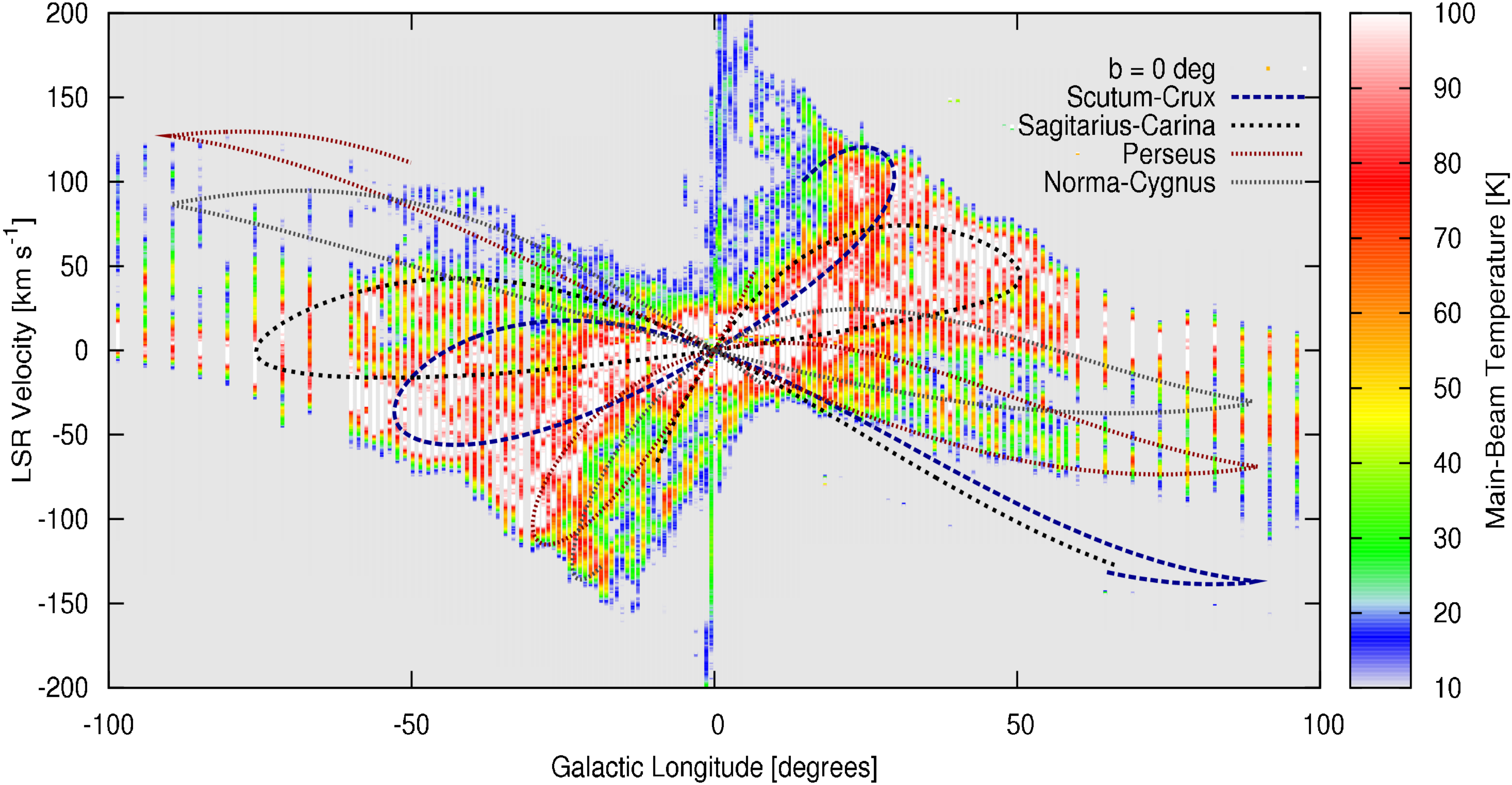
Two large publications to date:
Pineda et al. 2013, A&A 554, A103
Pineda et al. 2014 A&A 570, A121

GOT C+ [CII] Distribution in the Milky Way

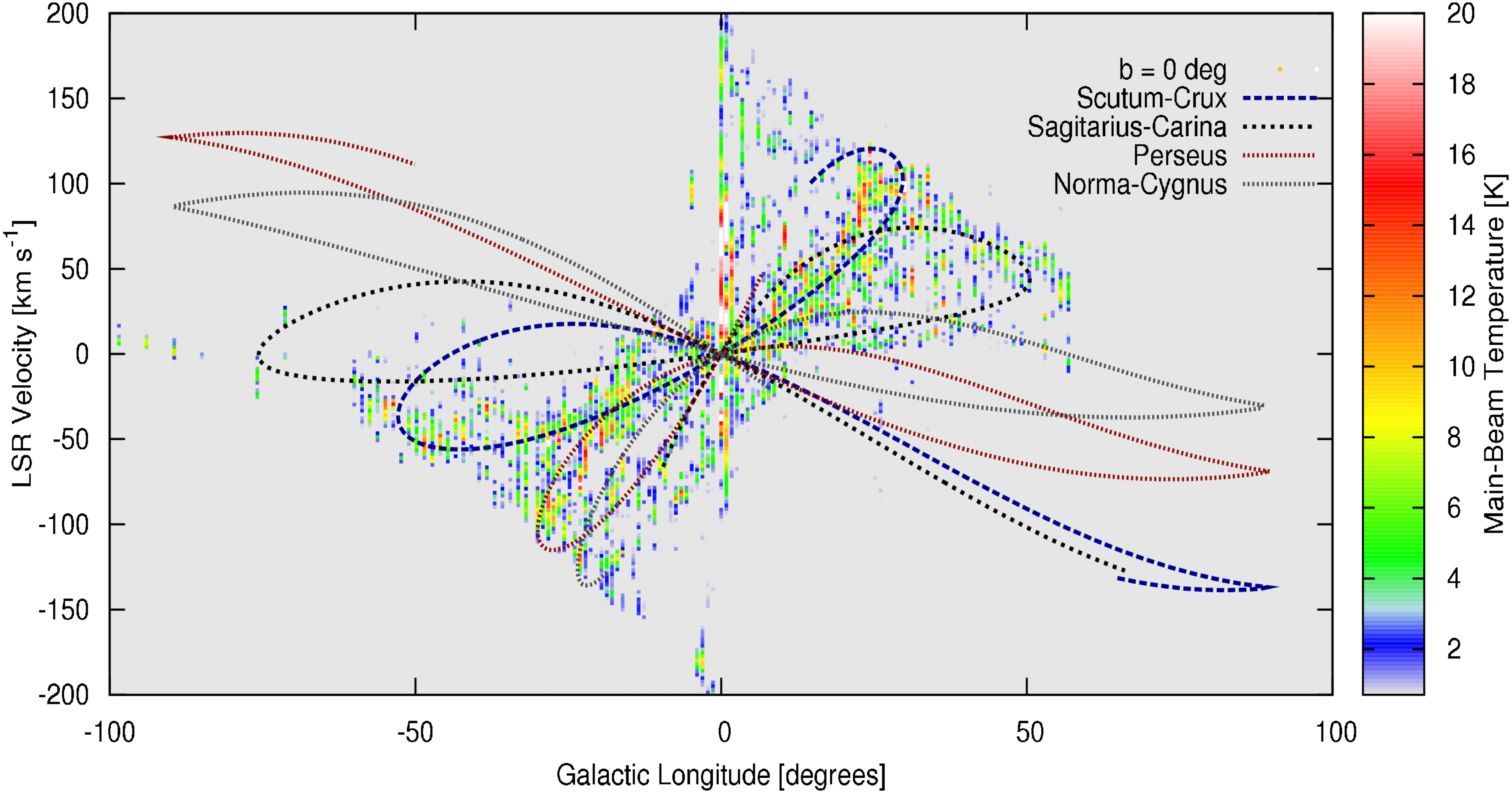


Pineda et al. (2013) A&A 554, A103

Atomic Gas (HI)

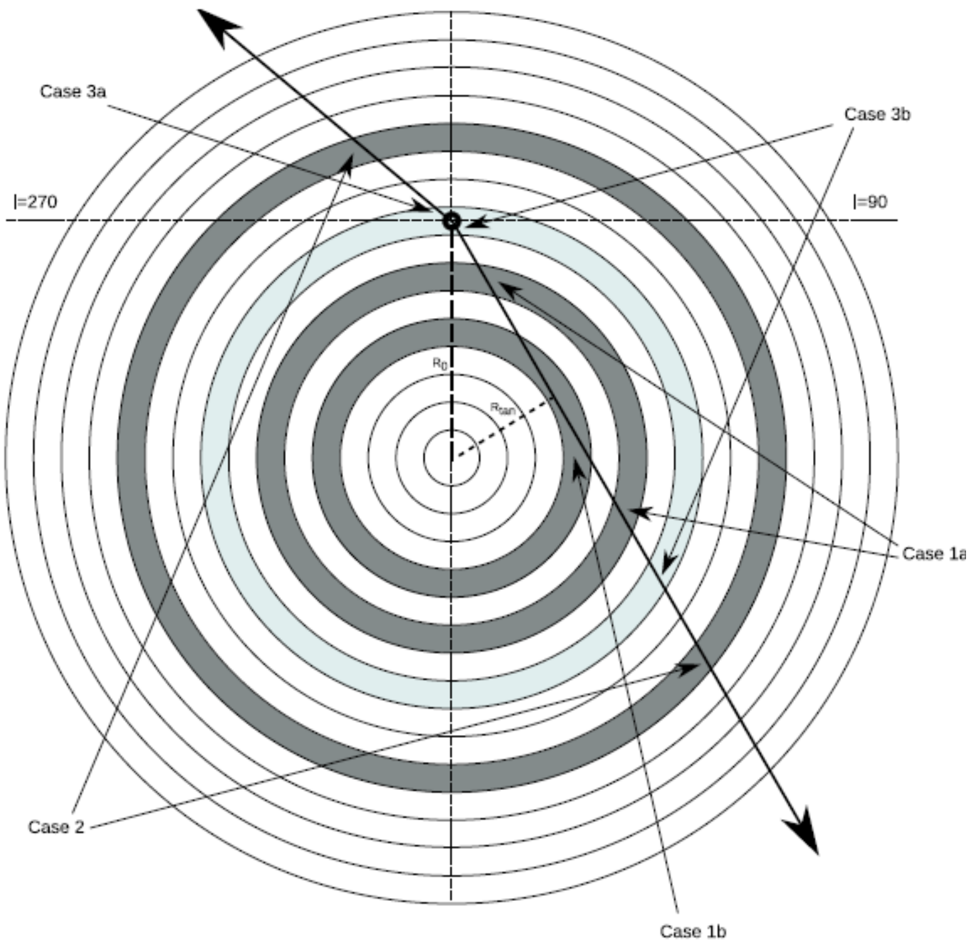


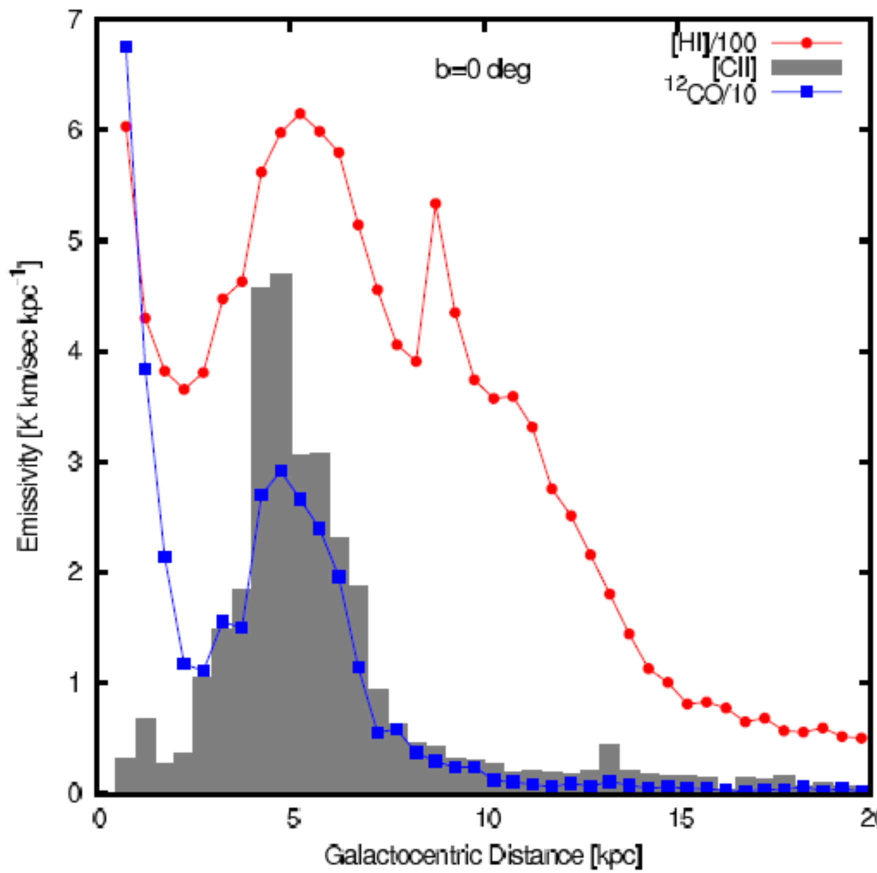
Dense and Cold Molecular Gas (CO)



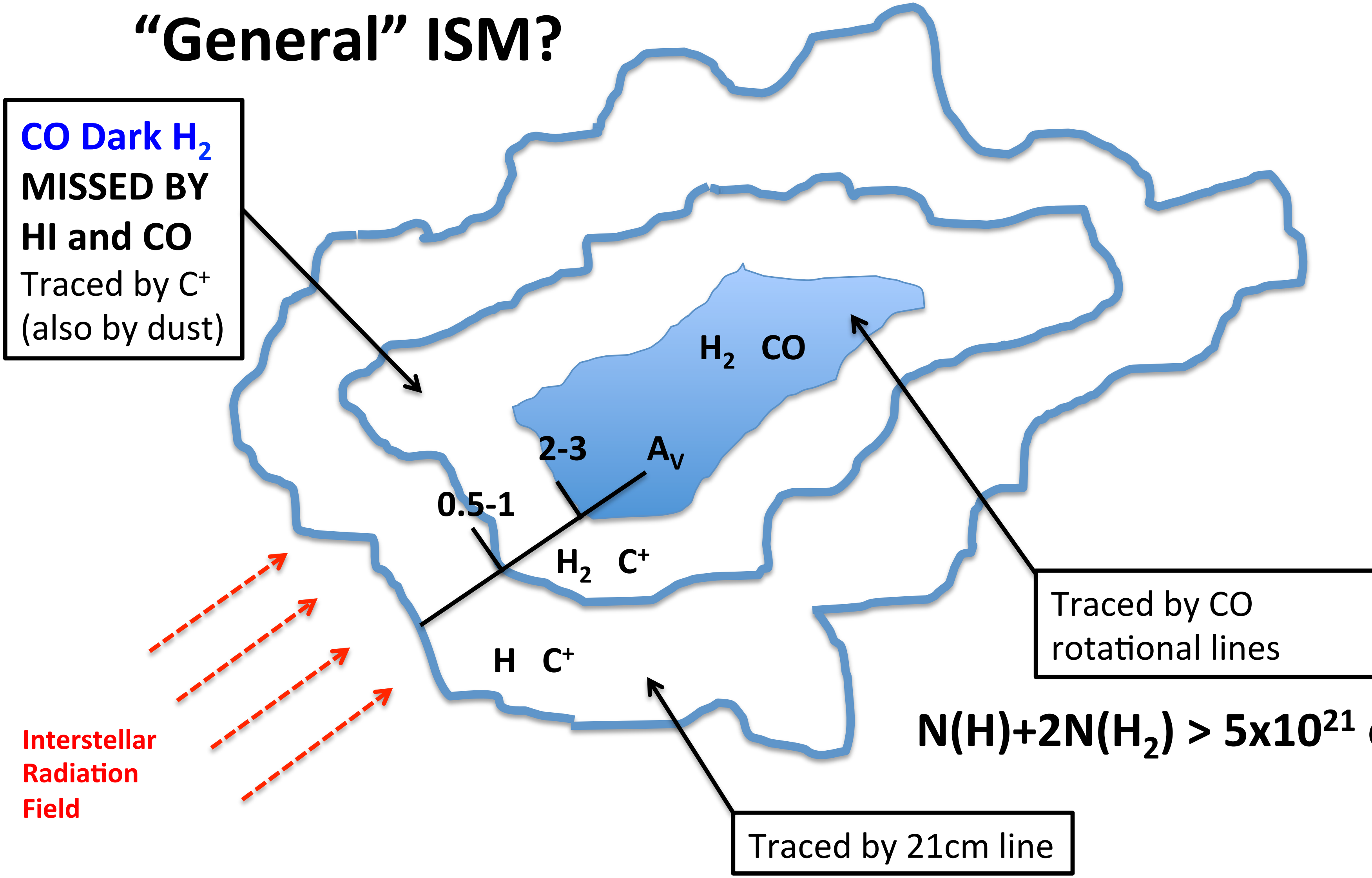
Galactocentric Distribution

Use Galactic Rotation Model
Adopt kinematic distances



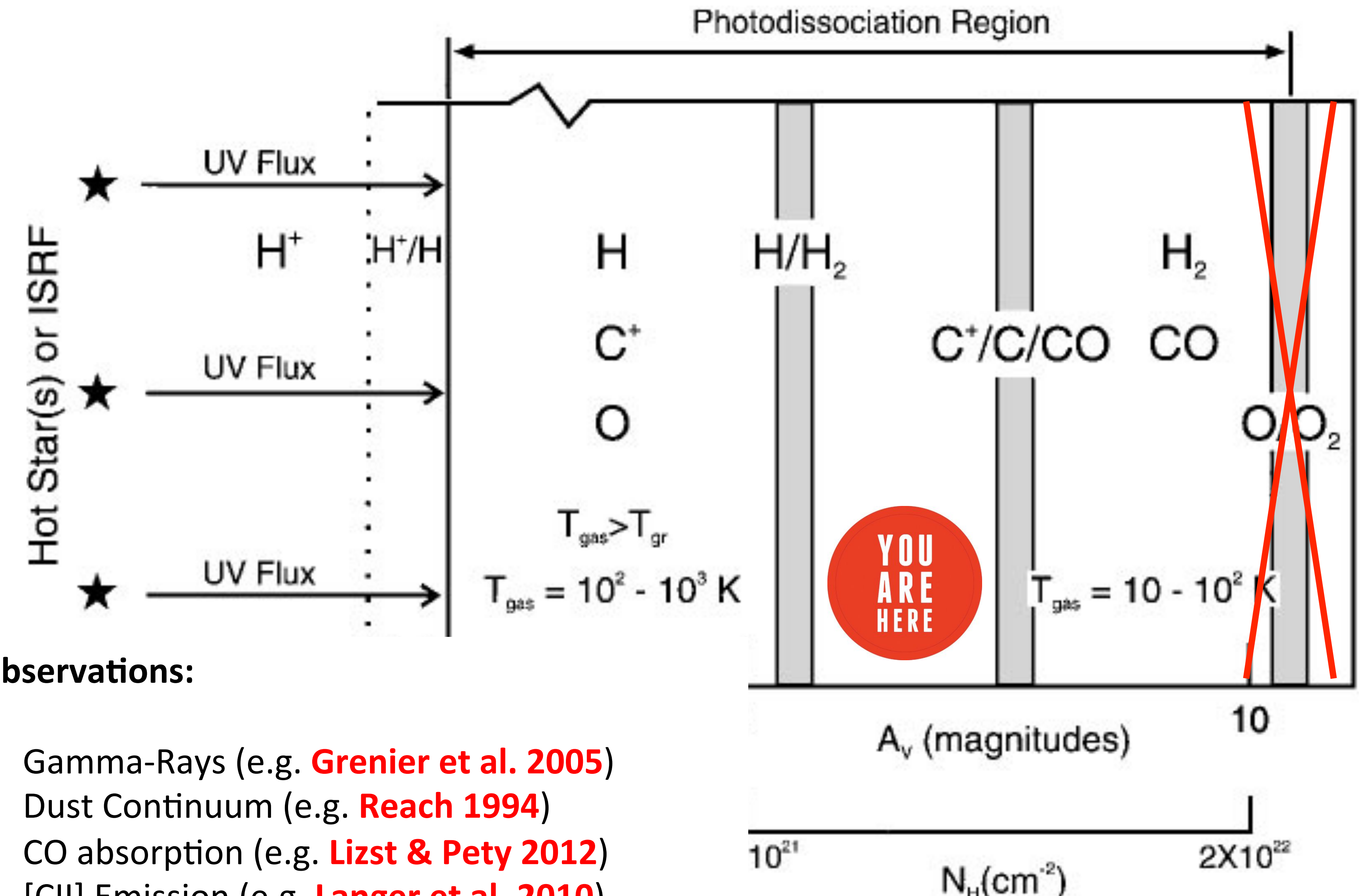


What is Ionized Carbon (C^+) Measuring in "General" ISM?



$N(H)+2N(H_2) > 5x10^{21}\ cm^{-2}$

The “new” Component of the ISM: CO-Dark H_2



Hollenbach and Tielens (1997)

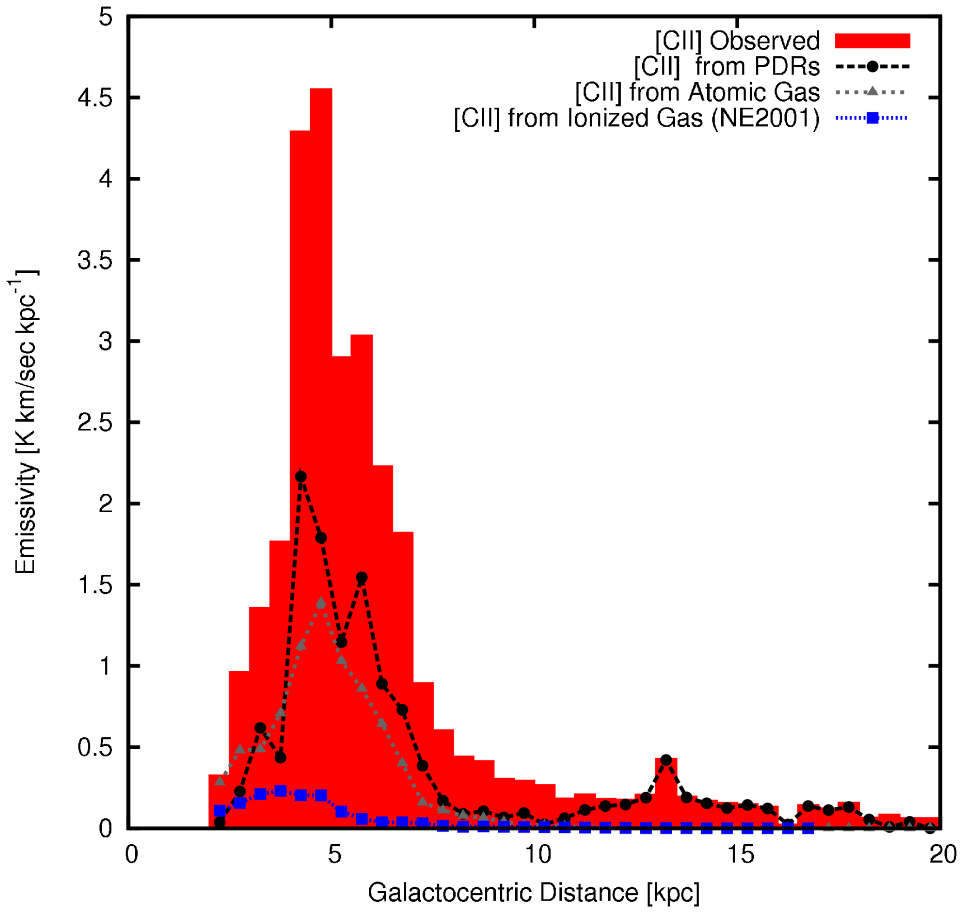
Observations:

- 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**)

CO-Dark H_2

Calculate CII, HI, CO and ^{13}CO azimuthally averaged emissivity
Subtract HI, e^-, PDRs, contributions to the [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 $T_e = 10^4$K.



Pineda et al. 2013 A&A 554, A103

CO-Dark H_2

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

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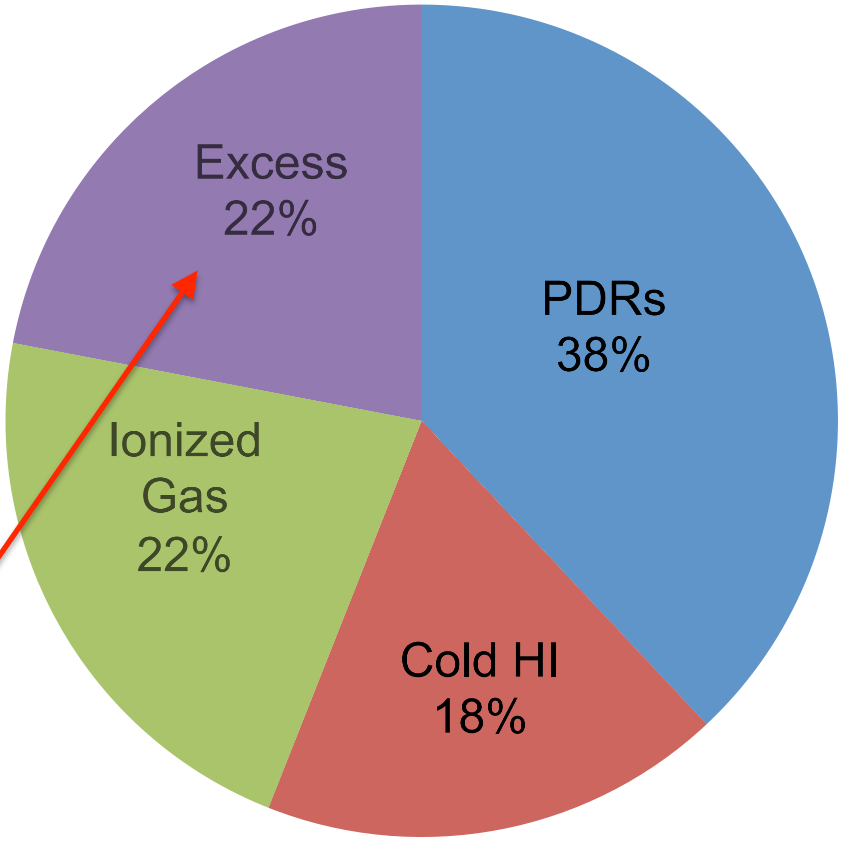
Ionized gas: Use electron density model of the galaxy from NE2001 model (constrained with pulsars) and $T=10^4K$.

Excess – what is not accounted for by sum of above = **"CO-Dark H_2"**

[CII] Luminosity



FWHM (PDRs, CNM, CO-dark H2) = 130 pc
FWHM (ELDWIM) = 1000 pc (Kulkarni & Heiles 1987)

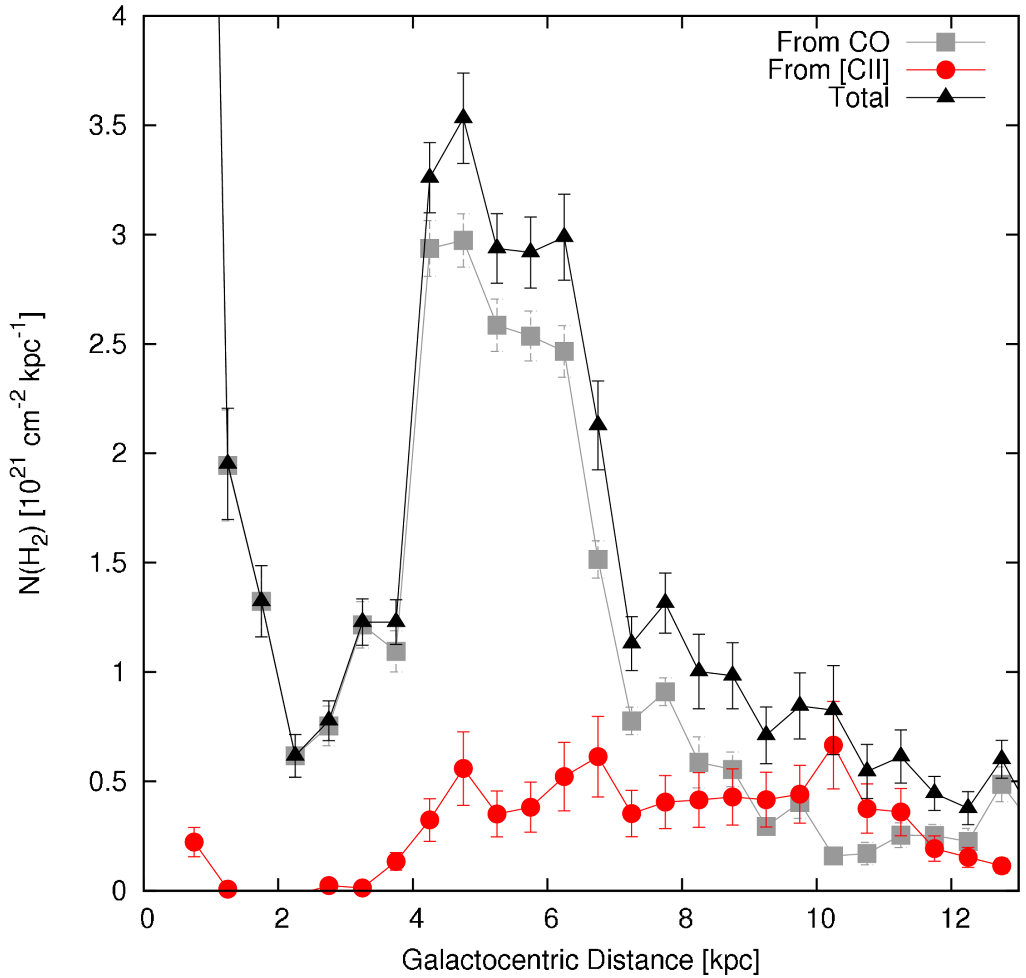
CO-Dark H_2

Method:

- Estimate azimuthally-averaged H_2 column density from ^{12}CO and ^{13}CO emission
- Use "excess" [CII] emission to estimate azimuthally-averaged H_2 column density of "CO-dark H_2" gas

Assumes:

- Galactic metallicity gradient (Rolleston et al. 2000)
- Pressure gradient from Wolfire et al. 2003 multiplied by a factor 1.5 to get the density (assume T = 100 K) Pressures are reasonable based on absorption data (discussed later)



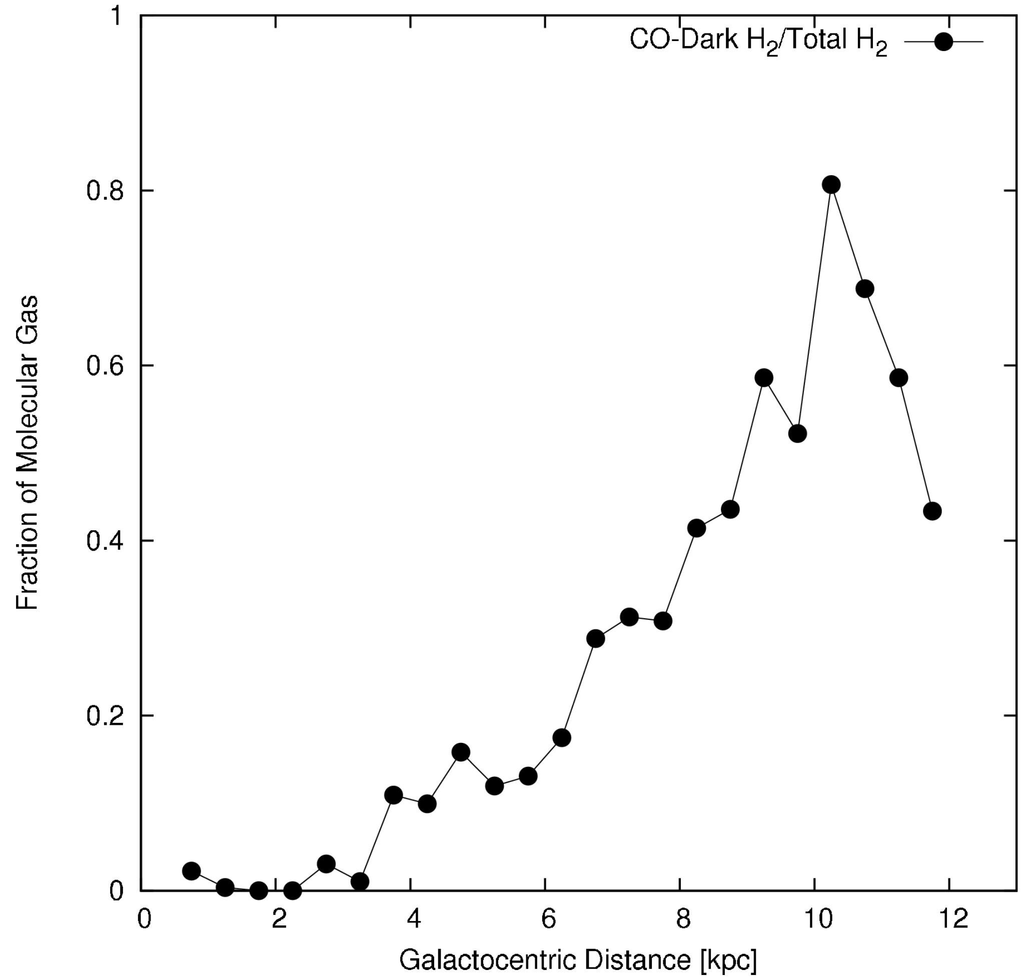
CO-Dark H_2: [CII] Observations

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

Result: **Gives the Galactic radial distribution of the CO-dark gas component. Average CO-dark H_2 fraction ~0.3 .**

Applies to: Entire Galactic plane

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



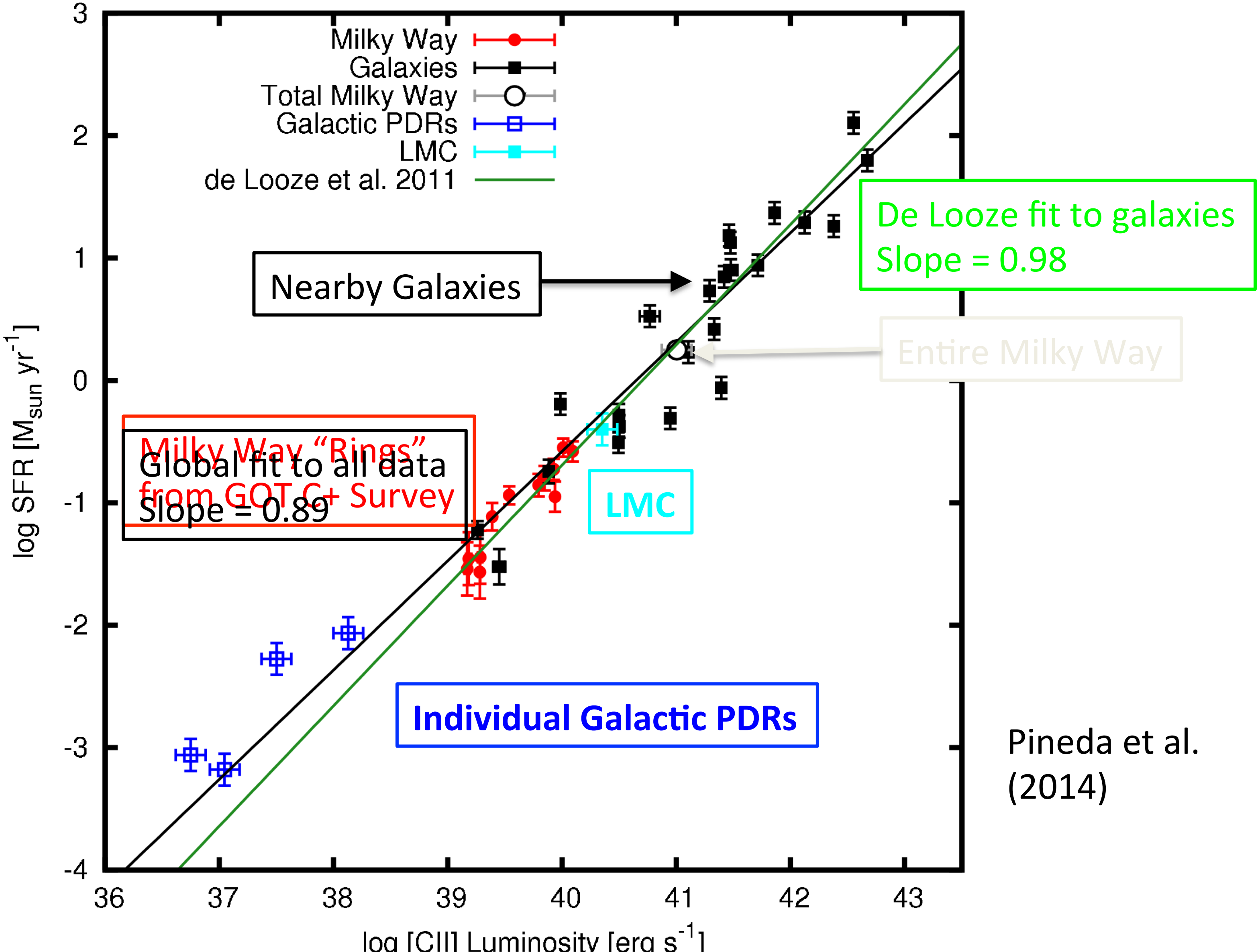
CO-Dark H_2 Fraction of Molecular Gas

Implications for [CII] Studies of External Galaxies

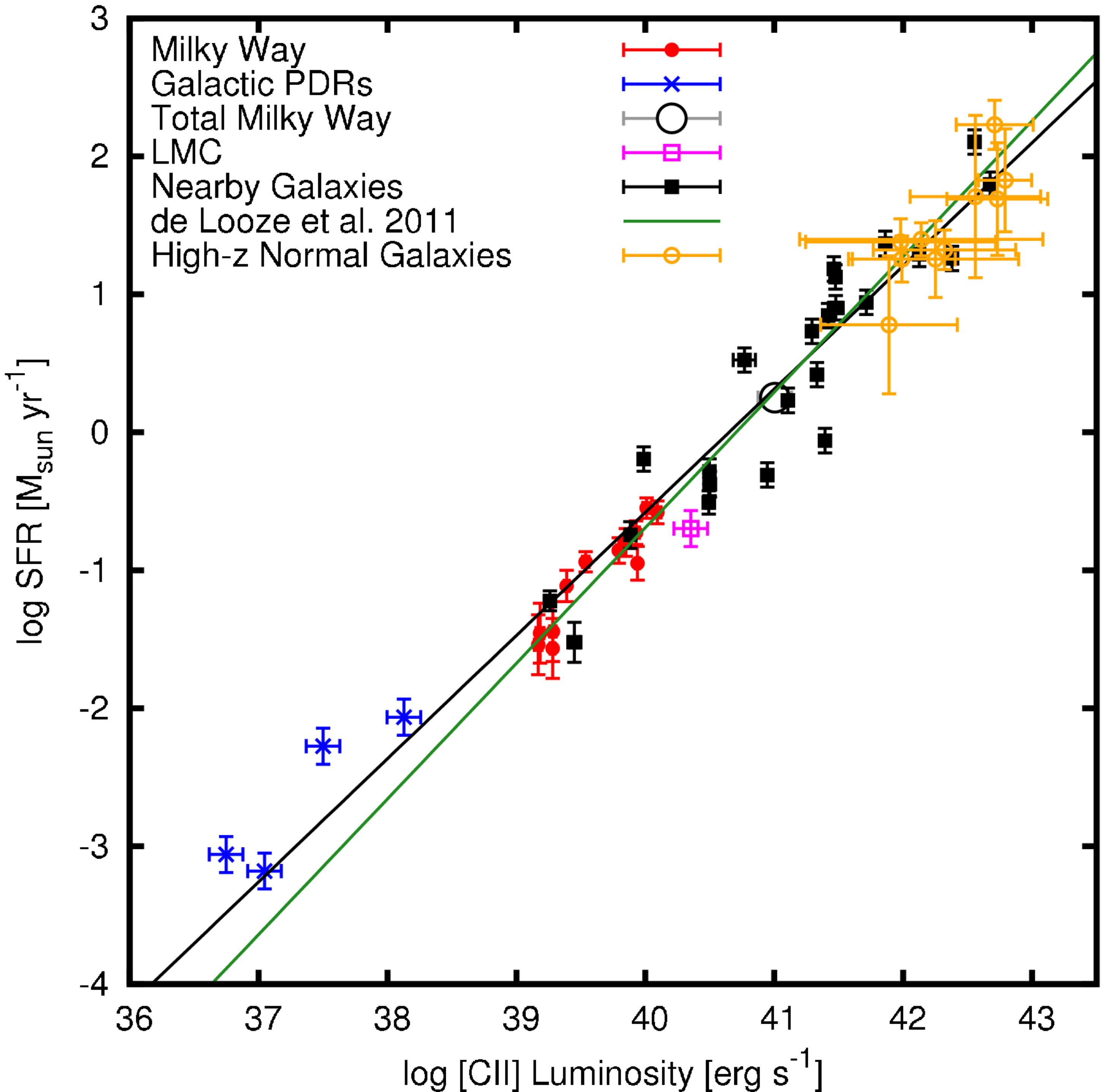
The Question: Does [CII] Emission Trace Star Formation?

Implications for [CII] Studies of External Galaxies

Q: Does [CII] Emission Trace Star Formation?



Pineda et al. (2014)



Milky Way
Galactic PDRs
Total Milky Way
LMC
Nearby Galaxies
de Looze et al. 2011
High-z Normal Galaxies
log SFR [M$_{sun}$ yr^{-1}]
log [CII] Luminosity [erg s^{-1}]
3
2
1
0
-1
-2
-3
-4
36
37
38
39
40
41
42
43

Conclusions About [CII] as a Star Formation Tracer

[CII] works well for local galaxies

Concern has been raised for ***ULIRGs*** and other "exotic" galaxies

Of interest not only for understanding individual galaxies but also for modeling results of "Intensity Mapping" studies of high-redshift galaxies in which individual galaxies are NOT resolved, but collective emission is measured

[NII] and the Structure of the ISM

Various components have dramatically different properties

(1) Molecular: very cold (10K) to warm (100K)

(2) Atomic: cool (20K) to warm (few x 100K)

(3) Ionized: hot (~8000K)

N^+ is presumably coming only from (3)

Even here there are various contributors including **HII Regions**, Extended Low Density Warm Ionized Medium (**ELDWIM**) and Ionized Boundary Layers (**IBL**) of clouds

All of these require energy input – to maintain ionization

What is the source of [NII] emission?

How is it related to structure of ISM and star formation?

N^+ Fine Structure Levels & Lines

Electronic ground state of N^+ is split into 3 fine structure levels

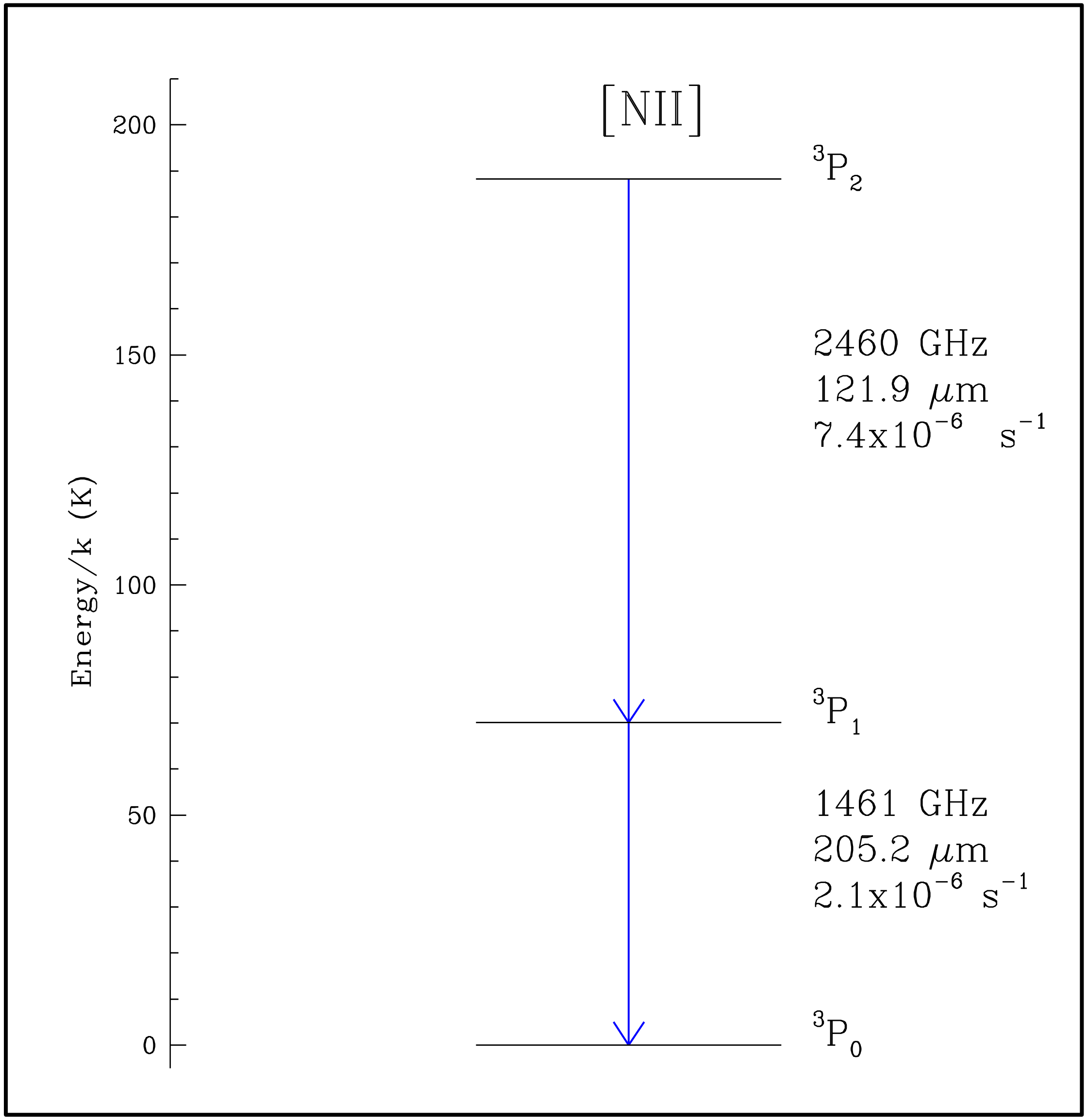
Two allowed transitions at 122 microns and 205 microns wavelength

Nitrogen IP is 14.5 eV so found **only** in regions where H completely ionized. Electron collisions dominate (rates calculated by Tayal)

CRITICAL DENSITIES for [NII] FSLs

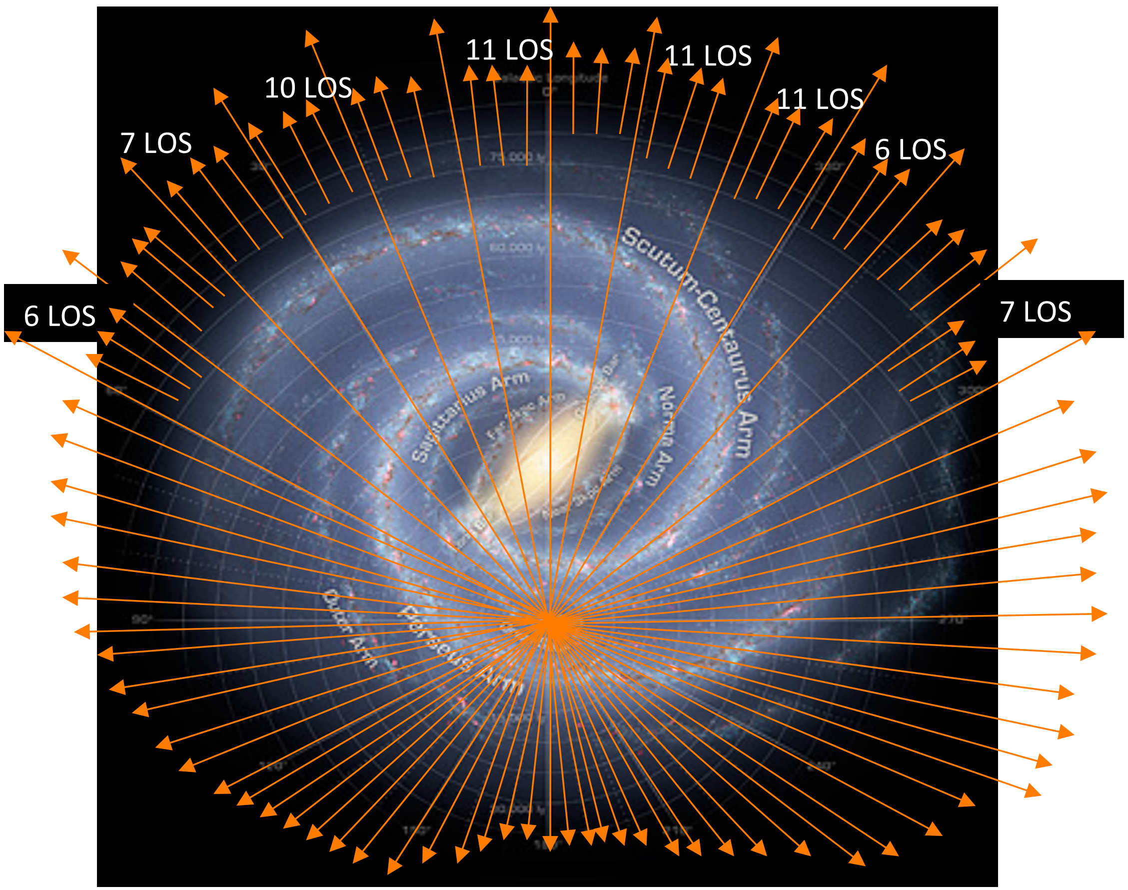
Transition	n_{cr} $\lvert\Delta J\rvert = 1$	n_{cr} All ΔJ
$^3P_2$–$^3P_1$ (2–1)	264	220
$^3P_1$–$^3P_0$ (1–0)	175	100

Note.
[a] In units of cm^{-3}. Collision rates from Tayal (2011) for a kinetic temperature of 8000 K.

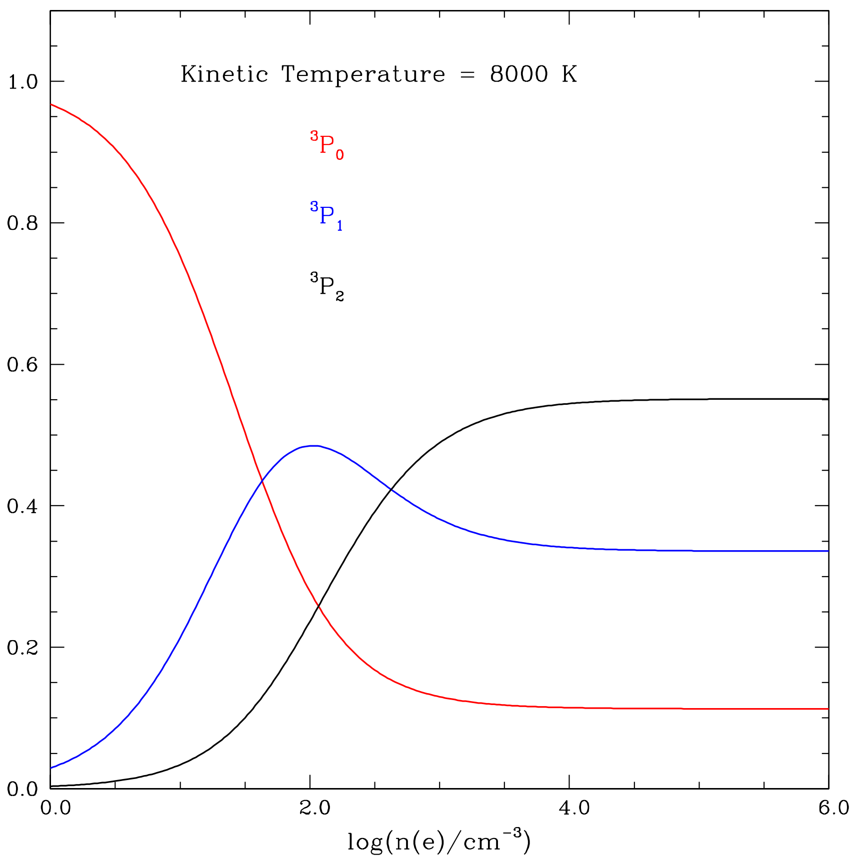


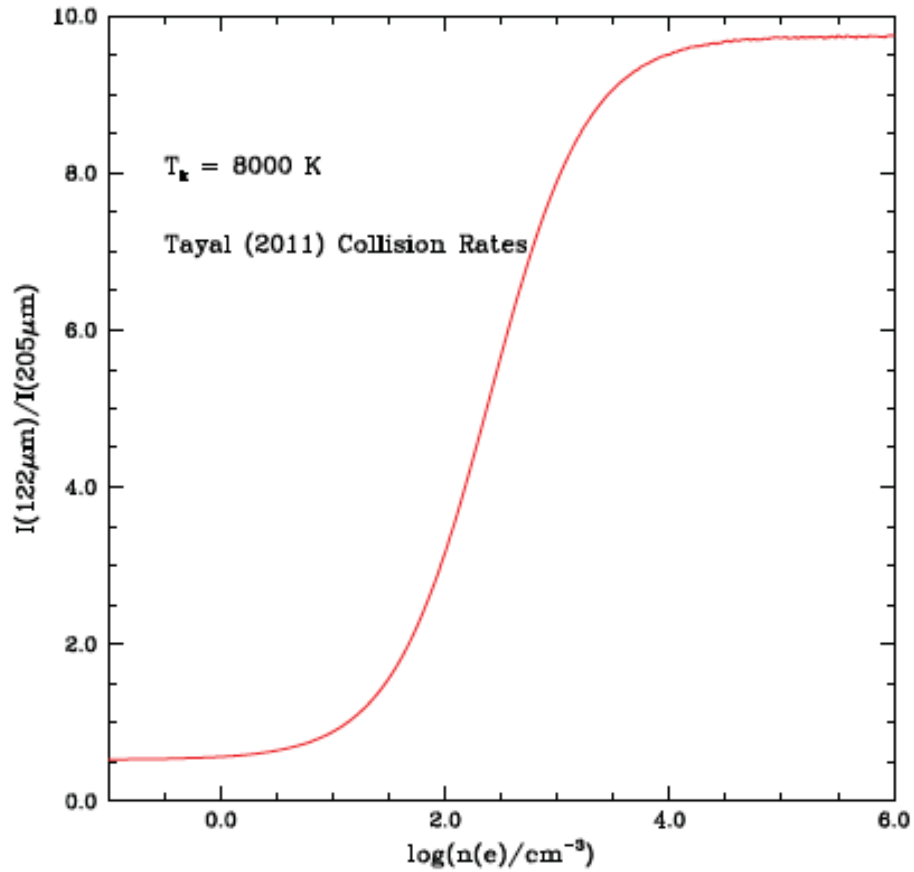
The Herschel [NII] Galactic Plane Survey

- Herschel OT2 Project. PI: Paul Goldsmith
- 140 GOT C^+ lines of sight at $b=0^o$ observed in [NII] 205 um and 122um with PACS (897 s per observation)
- 10 selected lines of sight in [NII] 205um with HIFI (7041 s per observation)



Collisional Excitation of N^+ Fine Structure Line Emission





For low densities, most of population is in the ground state and hence detectable ONLY in absorption

For a single density along LOS n(e) determines **I(122)/I(205)** and vice-versa

Analytic Solution for the Electron Density as Function of the Observed Intensity Ratio

$$R(I) = \frac{I_{122}}{I_{205}} = \frac{I_{32}}{I_{21}} = \frac{A_{32} f_{32}}{A_{21} f_{21}} R(3/2)$$

$$X = 0.169 R(I)$$

R_{ij} = C_{ij} n(e)
Collision rate coefficients C_{ij} are all known

$$a = R_{23}R_{12} + R_{23}R_{13} + R_{13}R_{21}$$

$$b = R_{13}A_{21}$$

$$c = R_{32}R_{12} + R_{32}R_{13} + R_{31}R_{12}$$

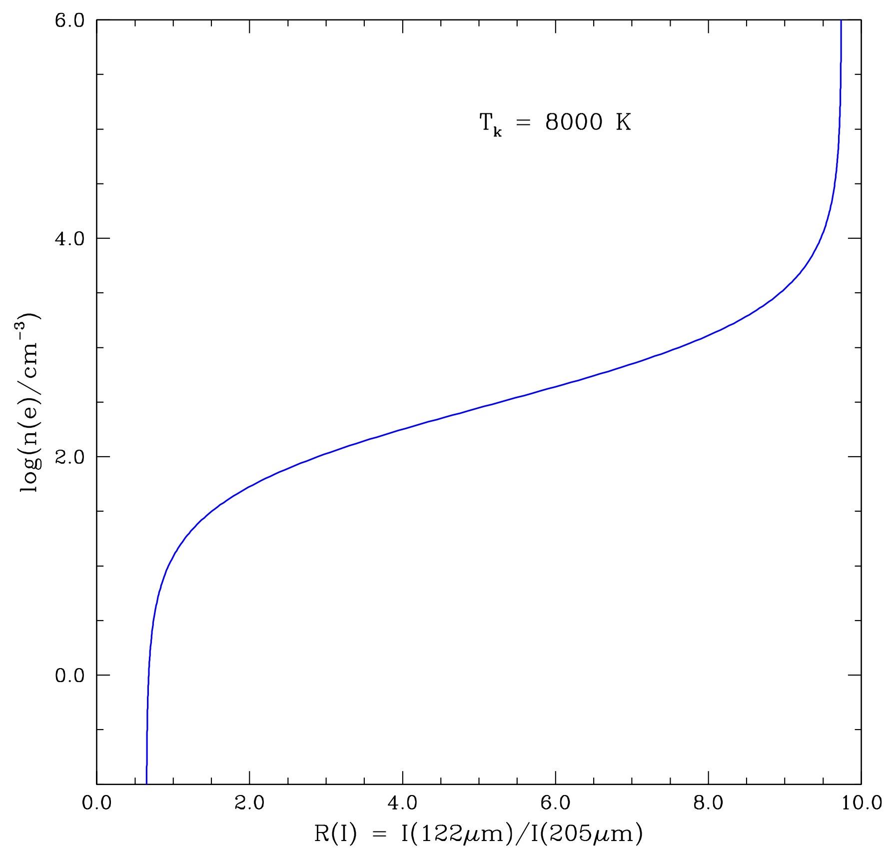
and

$$d = (R_{13} + R_{12})A_{32} \ ,$$

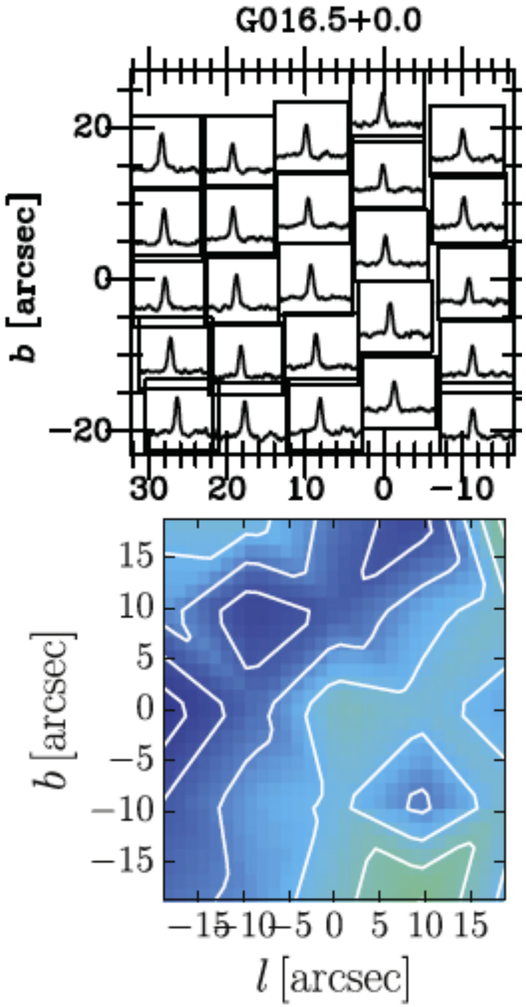
$$R_{min} = b/d$$

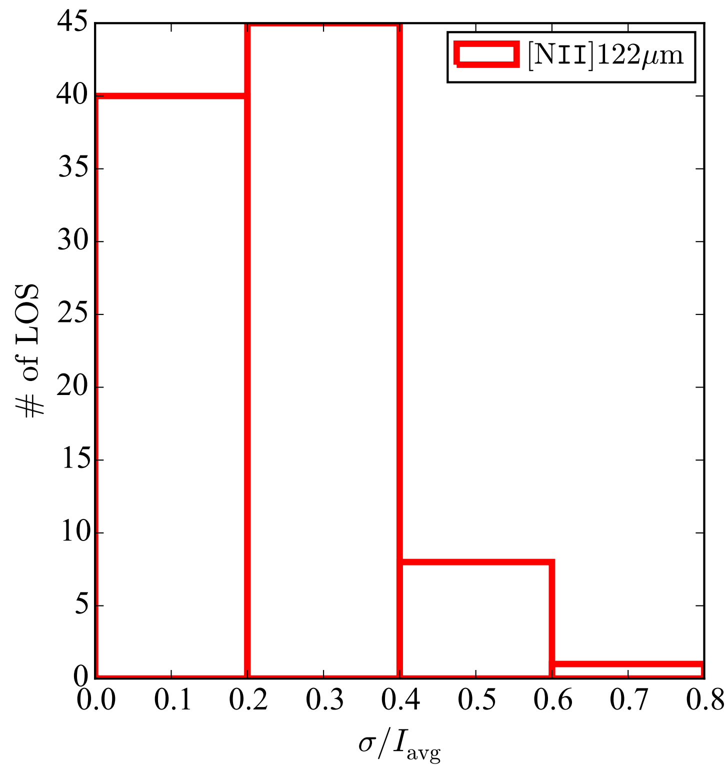
$$R_{max} = a/c$$

$$n(e) = \frac{d}{c} \frac{X - R_{min}}{R_{max} - X}$$



Fractional Variation of Intensity at 122 μm is Relatively Small Among 25 PACS Spaxels Observed for Each Pointing

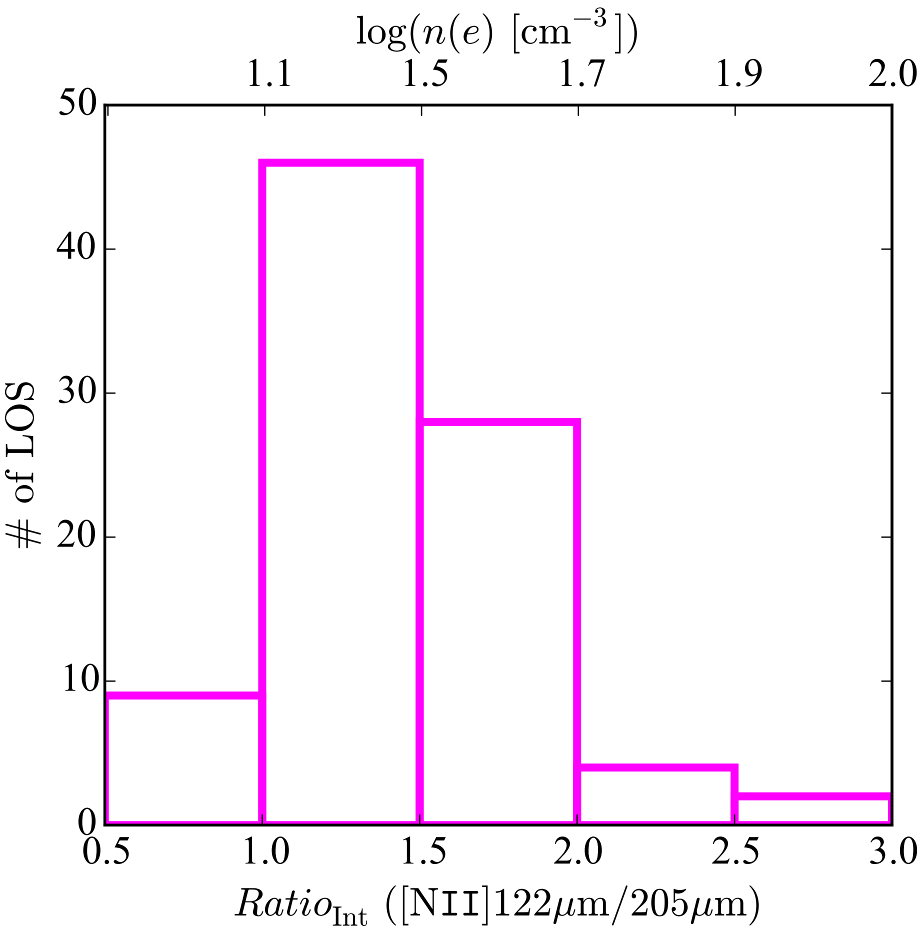


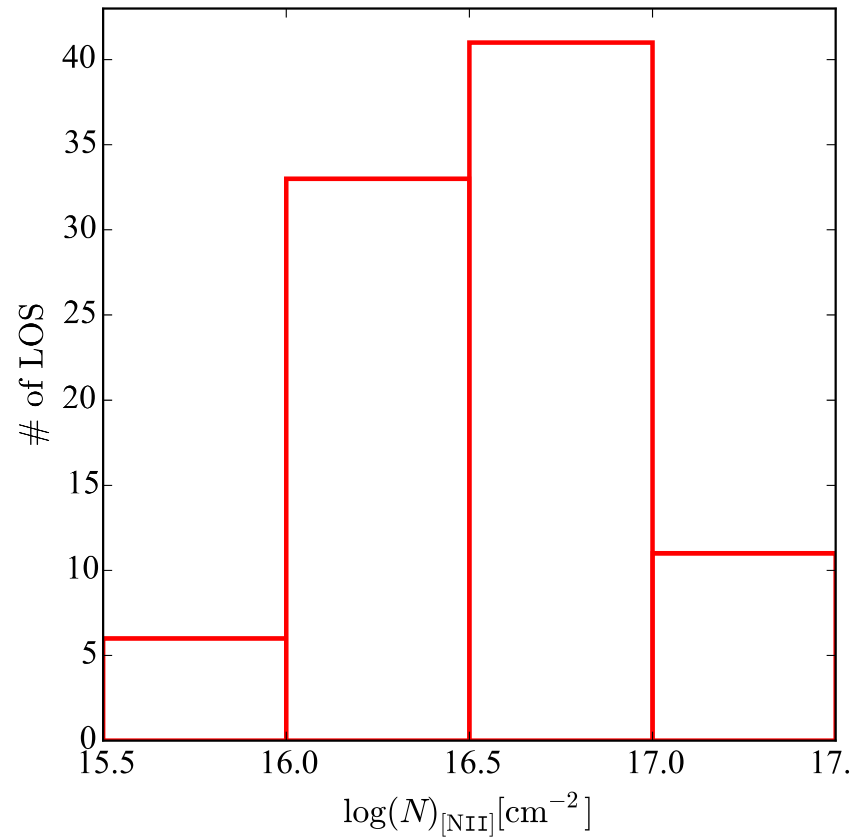


We can treat [NII] emission as **extended and relatively uniform**

It is **not** dominated by quasi-isolated point sources

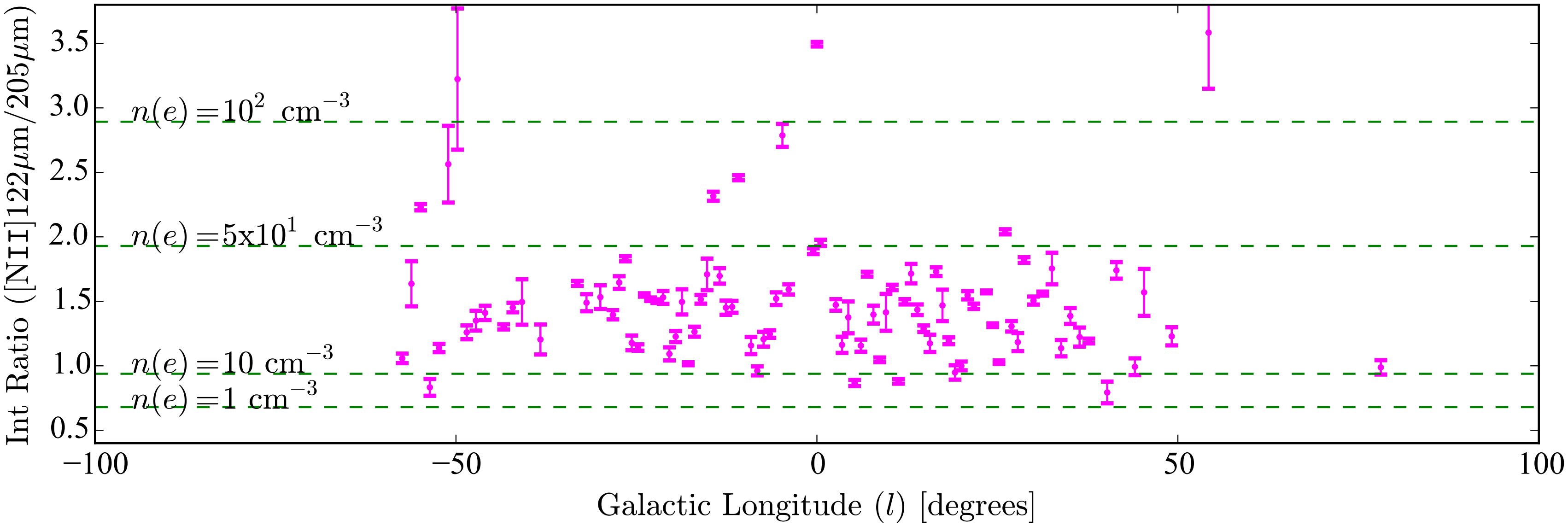
The Essential Results – n(e) and N(N^+)





<n(e)> = 33 cm^{-3} <N(N^+)> = 5.3x10^{16} cm^{-2}

Distribution of Electron Densities as Function of Galactic longitude



A few positions near Galactic Center have n(e) > 50 cm^{-3} and up to 200 cm^{-3}

Vast majority of LOSs have 10 cm^{-3} ≤ n(e) ≤ 50 cm^{-3}; no clear trend with Galactic longitude

Implications of [NII] Analysis

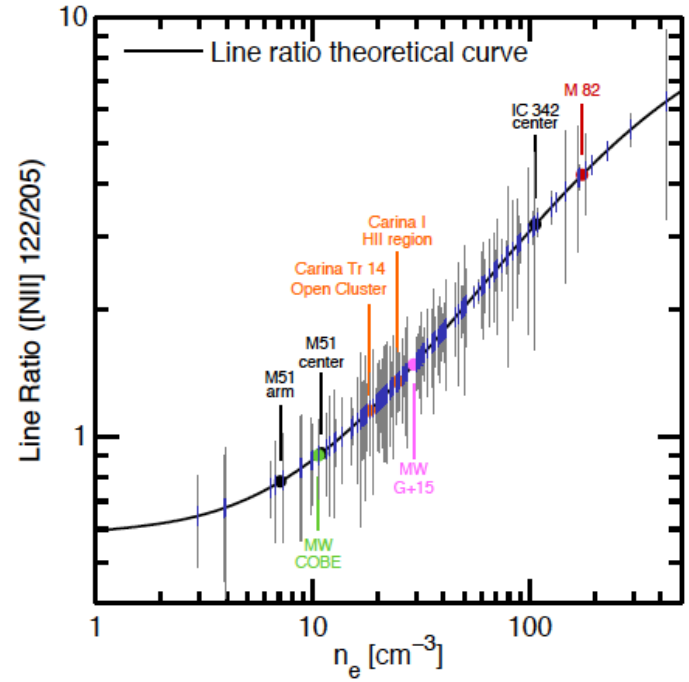
- N^+ column density ~3x10^{16} cm^{-2}
- H^+ column density ~ 1x10^{20} cm^{-2}
- Typically 3 "features/LOS => $N(H^+)$ ~ 3x10^{19} cm^{-2} each
- Characteristic Size ~ 10^{18} cm, << LOS size => VERY small filling factor

PERPLEXING – IF HAVE SUCH A SMALL FILLING FACTOR, WHY DO WE DETECT THIS [NII] EMISSION EVERYHWERE?

The same density is found by an [NII] survey of galaxies
(Herera-Camus et al. 2016)

[NII] NOT from WIM but from
10 < n(e) < 100 cm^{-3} gas

Also conclude that significant fraction of [CII] comes from ionized gas



Possible Explanations for the Results of [NII] Galactic Plane Survey

- **Warm Ionized Medium**
  - Although there may be multiple components (Reynolds WIM, McKee-Ostriker WIM, ELDWIM) they all have <n(e)> well below 1 cm^{-3}. This is **vastly less** than our result <n(e)> = 33 cm^{-3}.

A more likely scenario is the boundary layers of cloud surfaces -the outermost layers beyond PDR

- **Ionized Boundary Layers** (IBL, Bennett et al. (1994)

Modeling N^+ in Ionized Boundary Layer

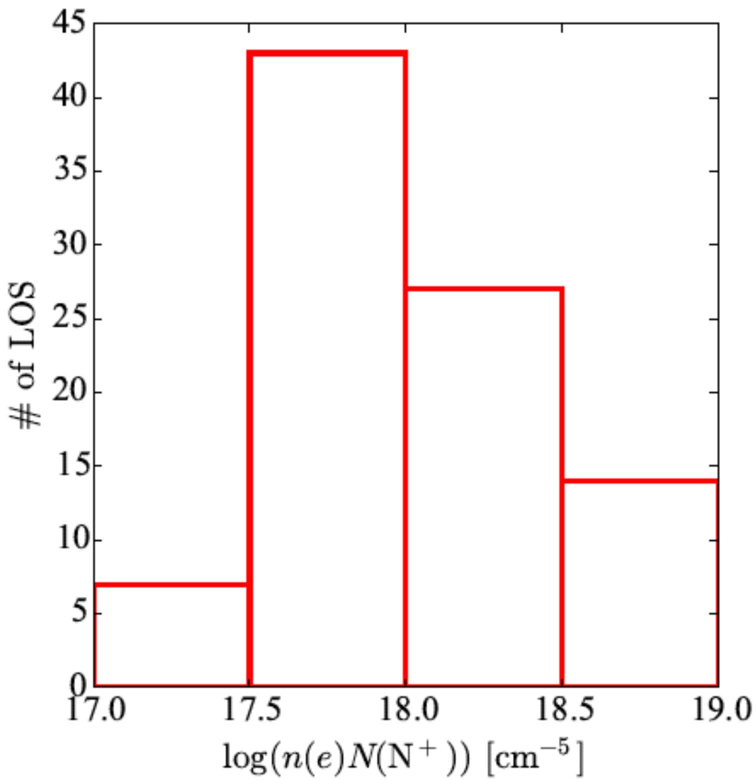
- Assume N is ionized by charge exchange with H^+; rate is moderately rapid at T ≥ 8000 K (Lin et al. 2005)
- The key question is then: what photon flux is required to maintain a specified column of H^+?
- Adopt model from Davidson & Netzer (1979): all photons are absorbed in length L of density n = n(e) = n(H^+) and are balanced by recombinations

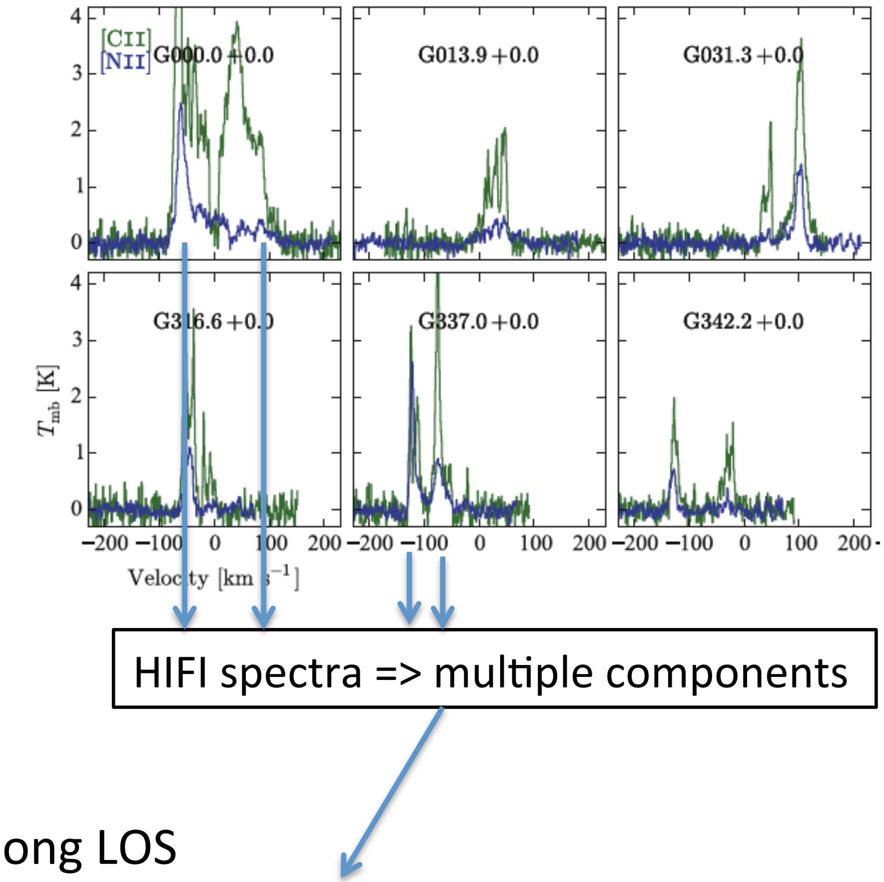
$$F = \alpha n^2 L$$

$$F = \frac{\alpha}{X(\mathrm{N}^+)} n(e) N(\mathrm{N}^+)$$

Assuming $X(N^+) = 1\times10^{-4}$ (scaled to central portion of galaxy)

$$F = 3 \times 10^{-9} n(e) N(\mathrm{N}^+)$$





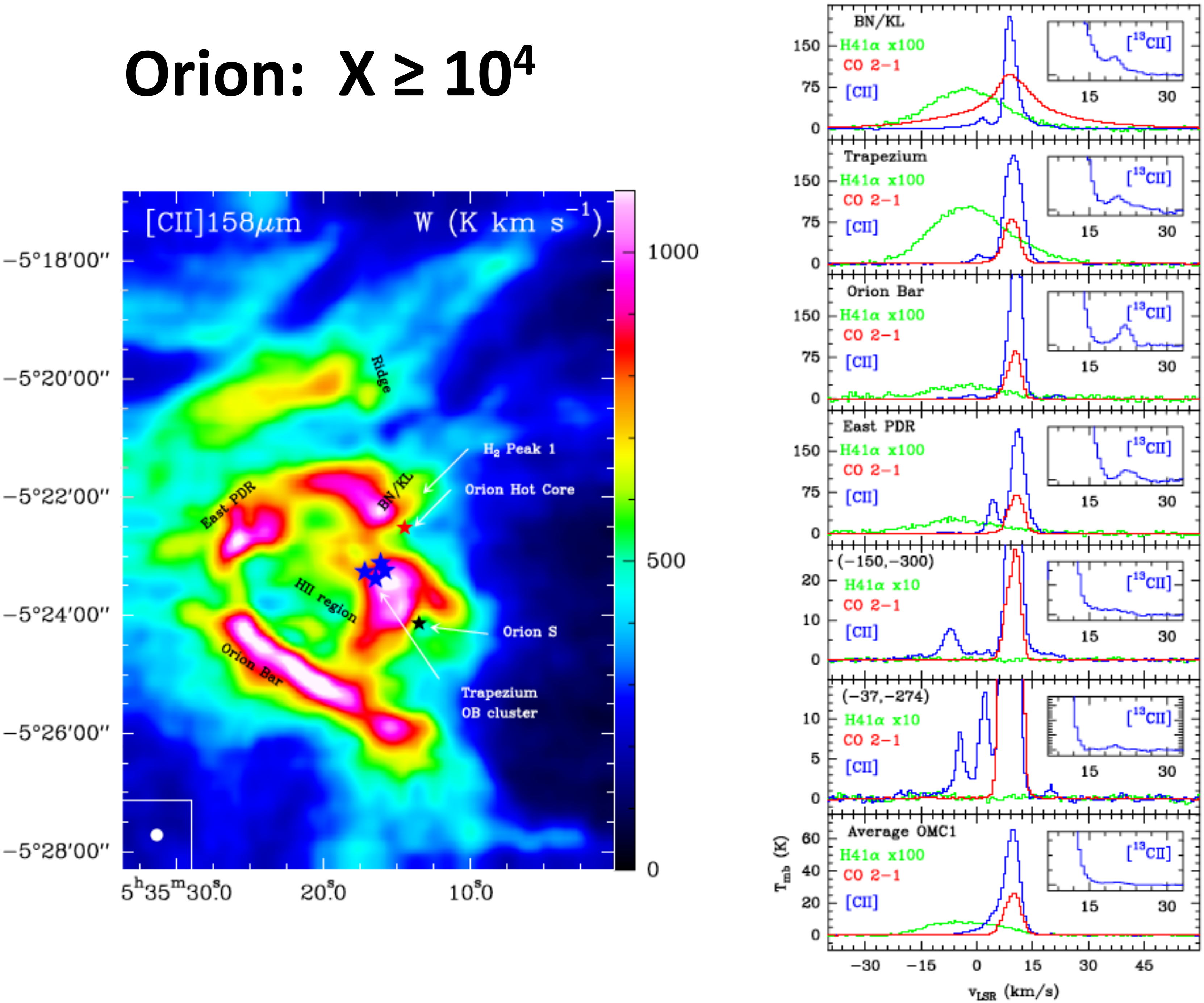
Typical $N(N^+)n(e) = 1 \times 10^{18}$ cm^{-5} total along LOS
but from HIFI spectra, we have 5 - 6 surfaces/LOS
This leads to $N(N^+)n(e) = 2 \times 10^{17}$ cm^{-5} per surface and
F = 6x10^{8} ionizing photons/cm^{2}/s – a large flux!
Massive star cluster produces ~ 10^{49} H-ionizing photons/s (Kaufman 2006)
This will provide required F at distance of ~ 12 pc (w/o any absorption)
Possible, but everywhere in inner galaxy??

Summary of [NII] Survey Results

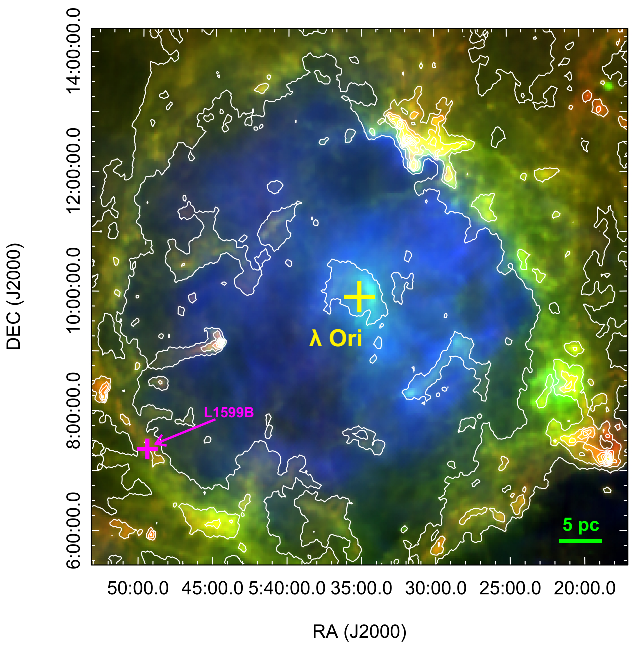
- Both FSLs clearly detected in central 120^{o} sector of Galaxy
- Line ratio indicates $\langle n(e) \rangle = 33\ cm^{-3}$ and $\langle N(N^{+}) \rangle = 5x10^{16}\ cm^{-2}$
- Imaging by PACS indicates that emission is **extended** and relatively smoothly distributed
- Significant column density of ionized nitrogen at high density suggests that “traditional” WIM is not the origin of [NII] emission
- Line of sight filling factor of this “dense” ionized gas is very small, only ~1/6000, so it is likely “concentrated” rather than “diffuse”, but why do we see it everywhere?
- Ionized Boundary Layers (IBL) and extended intermediate density envelopes of HII regions are possible explanations

Case Studies: Individual Regions in Different Environments

Orion: $X \geq 10^4$



L1599B in the Lambda Orionis Ring: A Molecular Cloud in a Highly Asymmetric Radiation Field

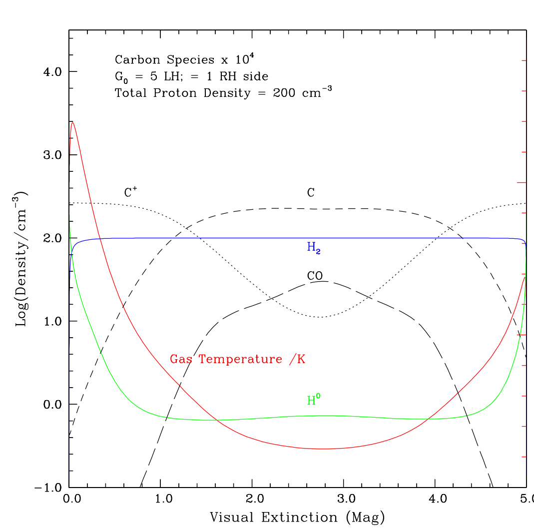


Composite image from Planck 857 GHz (red), IRAS 100 μm (green), Hα (blue)
From Goldsmith et al. (2016, ApJ)

Λ Ori is an O8 III Star; Distance ≅ 425 pc
A ring containing ionized gas (but not much atomic hydrogen or dust) surrounds it

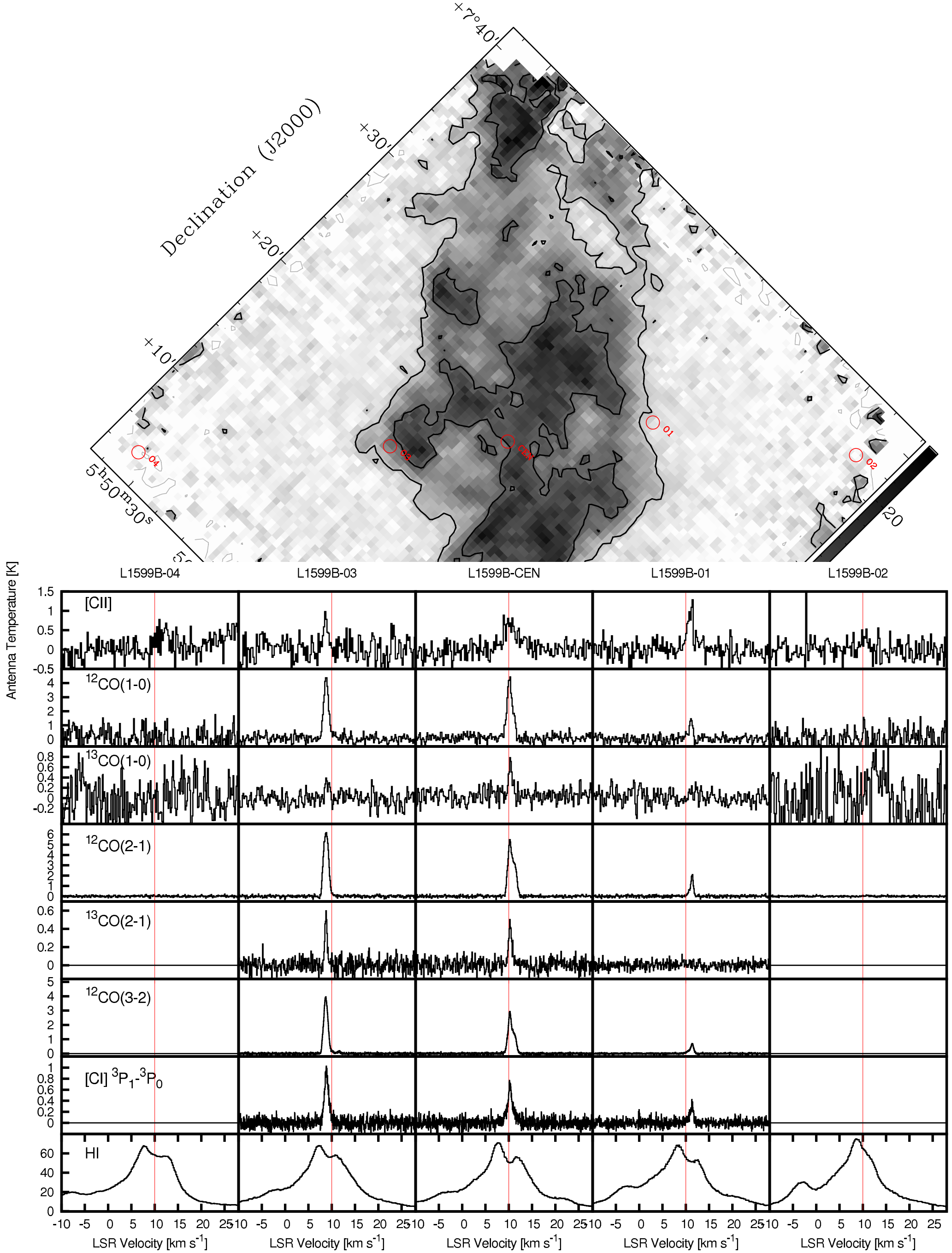
It is not certain that Λ Ori produced this ring, but it is almost at its center
L1599B is ~ 30 pc from the star and produces a radiation field 2-5x standard ISRF (2≤X≤5) on the side facing the star

To Λ Ori



Std. ISRF

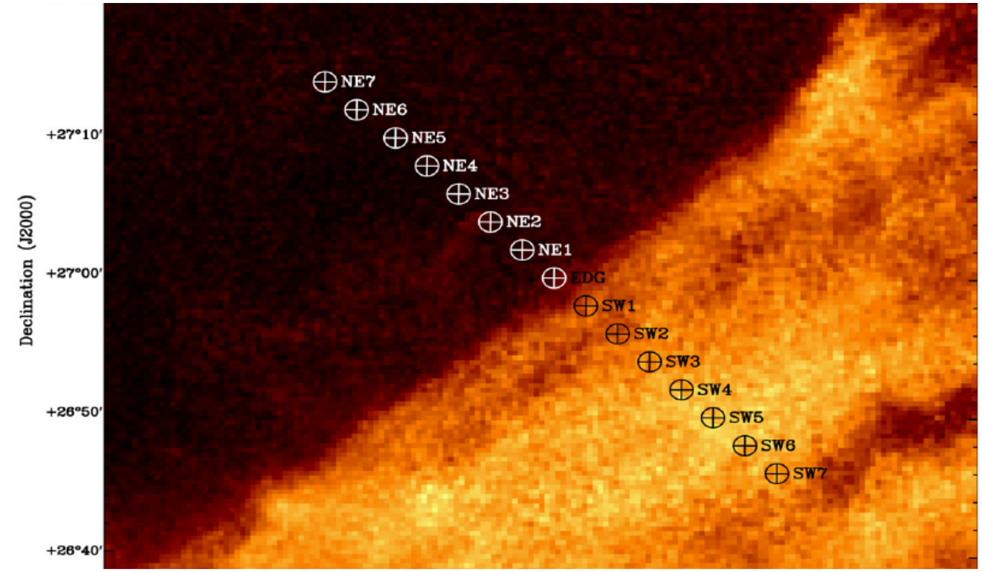
The difference in temperature is significant relative to hf/k = 91.5K for [CII]



Declination (J2000)
+7°40'
+30'
+20'
+10'
5h50m30s
04
03
CEN
01
02
20
L1599B-04
L1599B-03
L1599B-CEN
L1599B-01
L1599B-02
Antenna Temperature [K]
[CII]
12CO(1-0)
13CO(1-0)
12CO(2-1)
13CO(2-1)
12CO(3-2)
[CI] 3P1-3P0
HI
LSR Velocity [km s-1]

To Λ Ori

A Boundary Region in the Taurus Molecular Cloud



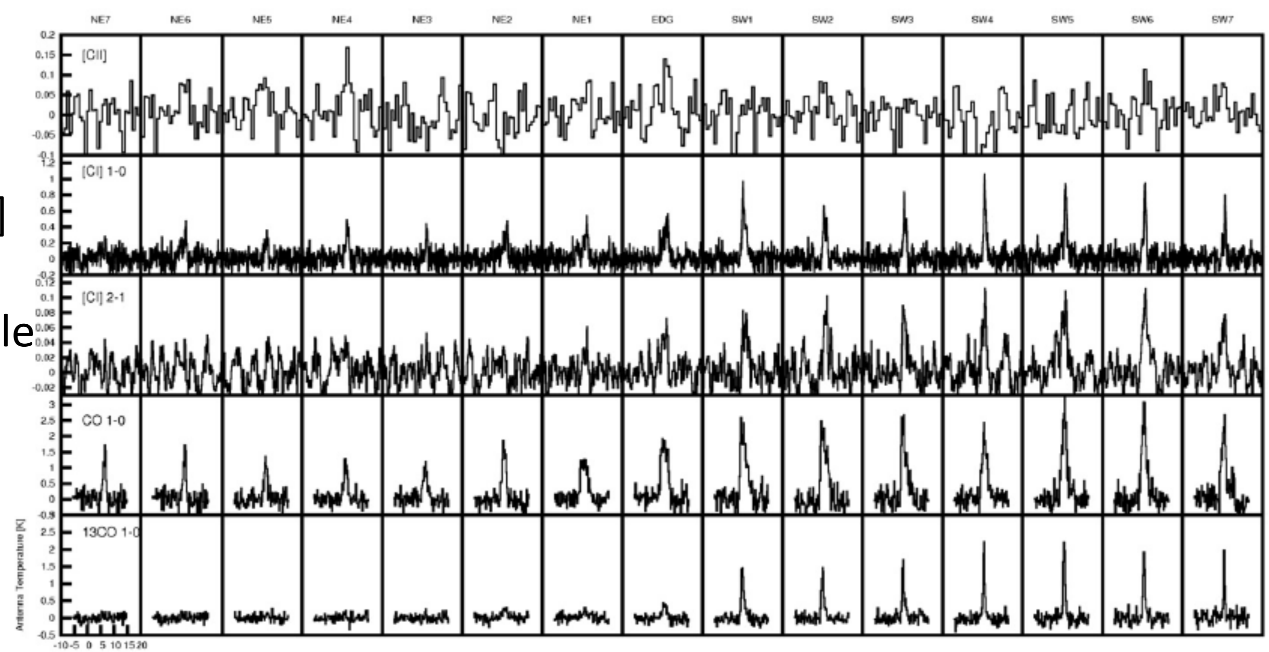
(Orr et al. 2014, ApJ 795)

Low Radiation Field Environment Based on dust temperature at cloud edge (Flagey et al. 2009, ApJ 701) possibly due to extended, absorbing dust envelope

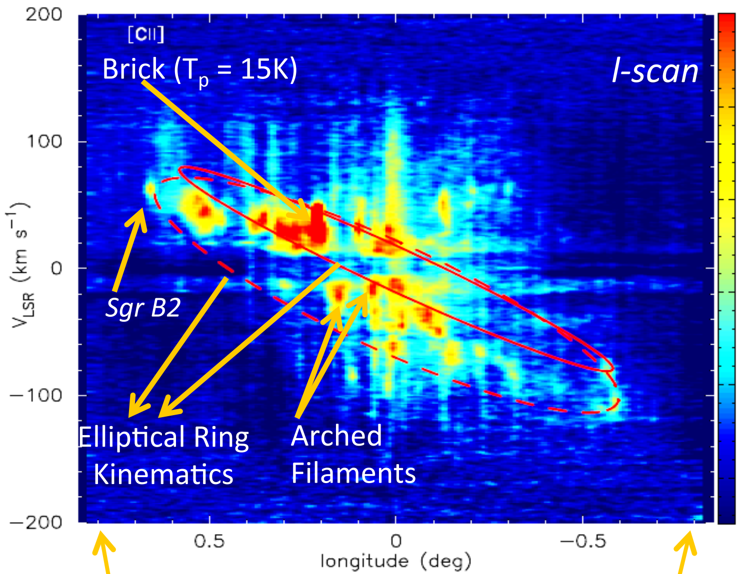
J = 1-0 CO & ^{13}CO, and two [CI] lines allow determination of density and temperature profile

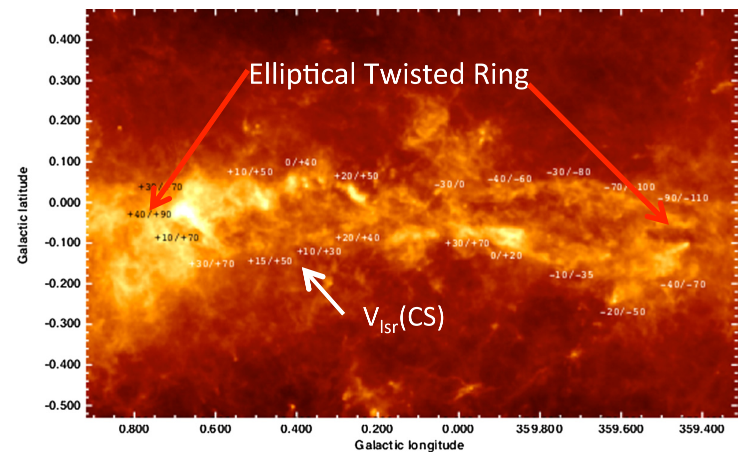
Very weak [CII] marginally detected
Limit: $\chi < 0.2$

← OUTSIDE the Cloud EDGE Cloud Interior →

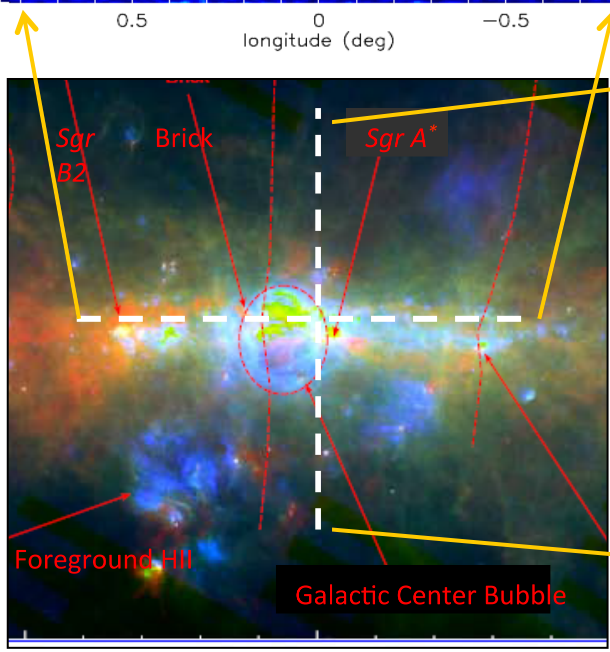


Herschel HIFI [C II] OTF Longitude-Latitude Scans (1.6°X1.6°)

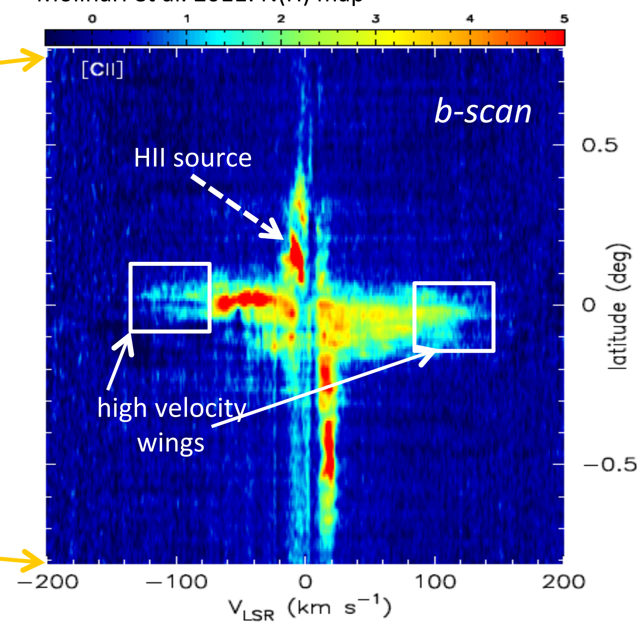




Molinari et al. 2011: N(H) map



Molinari et al. 2014: Composite 24, 70, 500 µm



Langer et al. (2016 – in preparation)

Issues With Interpretation of Fine Structure Line Emission

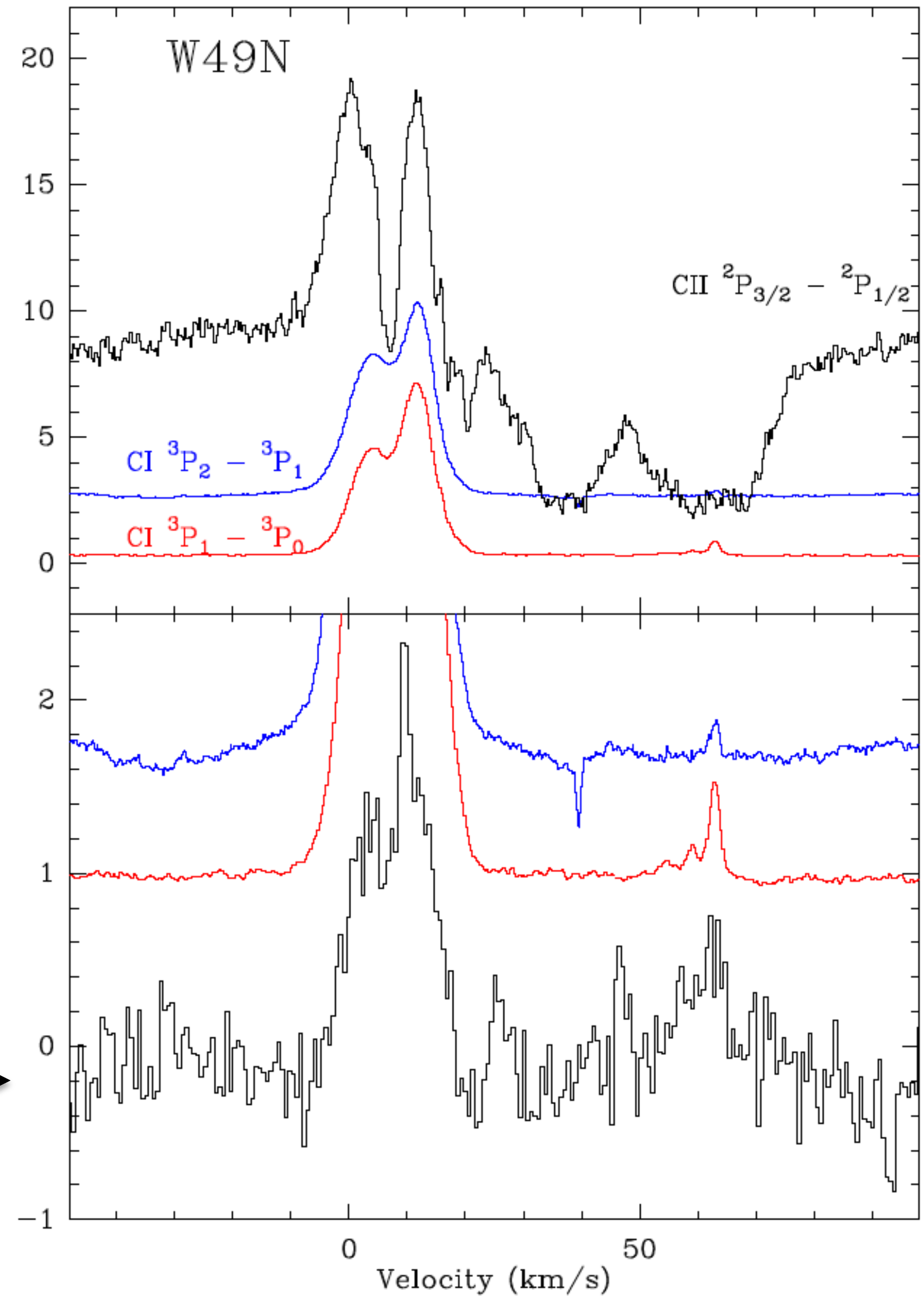
- Absorption due to low-excitation ("foreground") material
- "Self-absorption" from low excitation material within the source itself

Foreground Absorption W49N

[CII] 1900 GHz
[CI] 809 GHz
[CI] 492 GHz

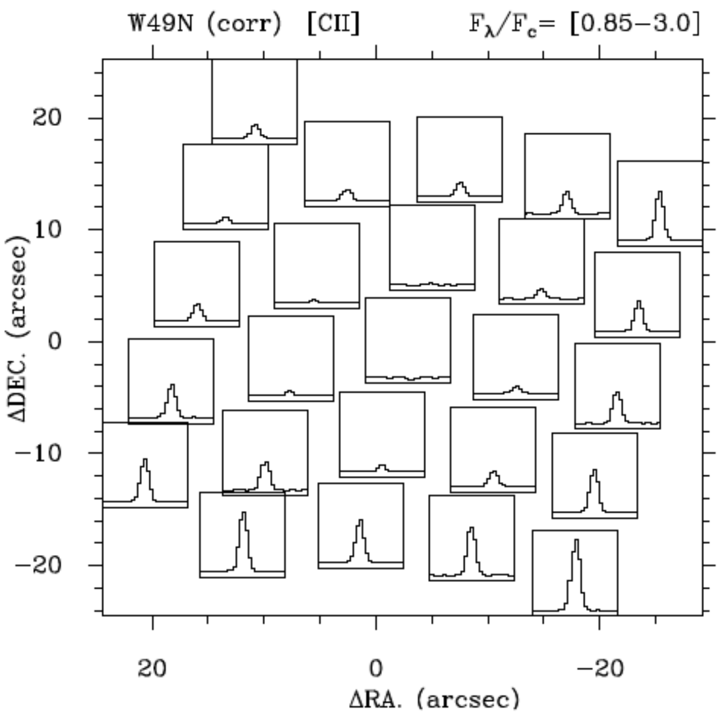
Gerin et al. (A&A 2014)

Average of reference positions
(expanded scale)
(continuum shifted)

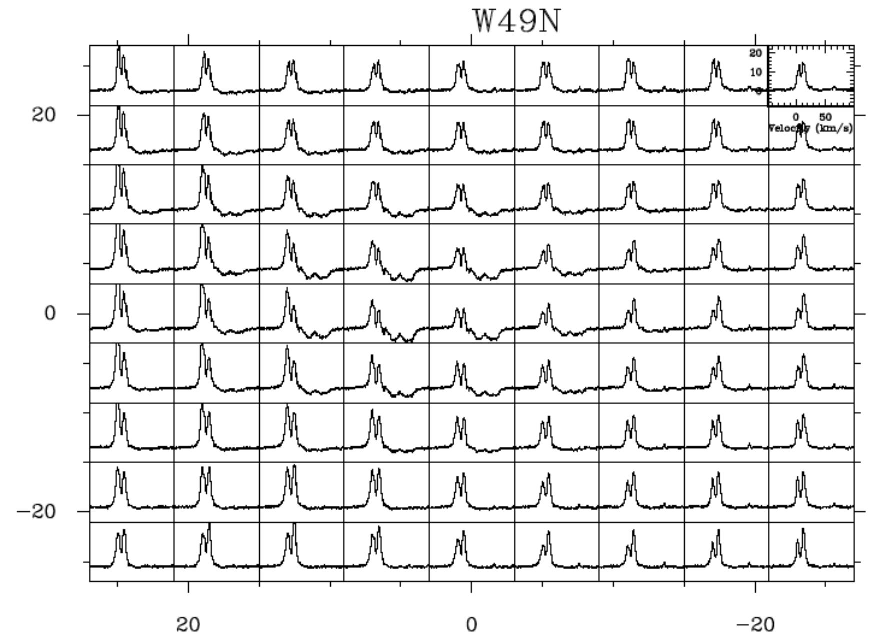


Warning: Unresolved Spectra Can Conceal Serious Problems

PACS

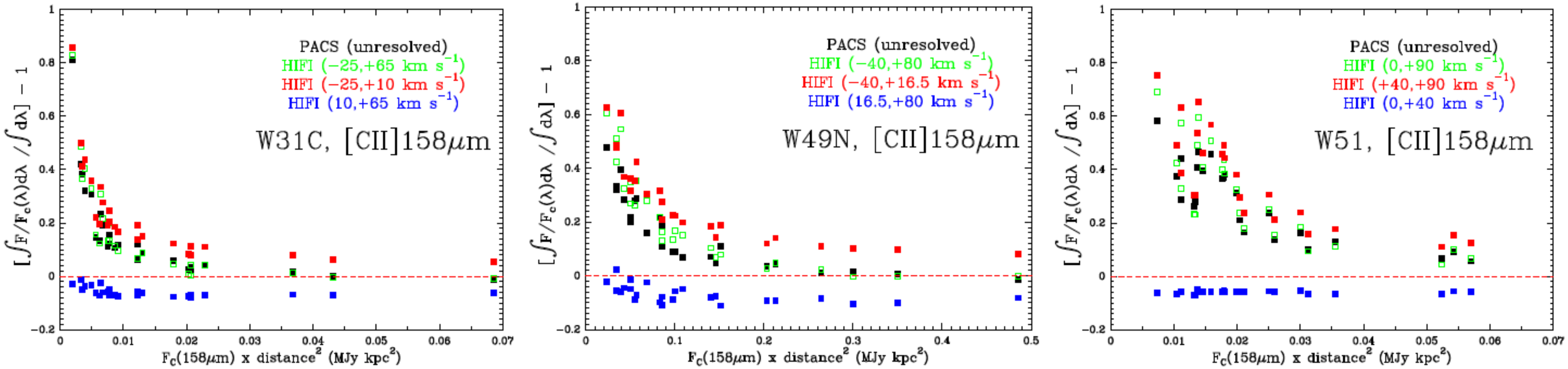


HIFI



PRISMAS GT Project; M. Gerin et al. 2014 in preparation

Line/Continuum ratio drops dramatically as continuum gets stronger IF YOU ARE NOT SPECTRALLY RESOLVING THE LINE !



Velocity-Integrated HIFI spectra and PACS results agree very well
Unresolved lines dramatically weaker for stronger continuum flux

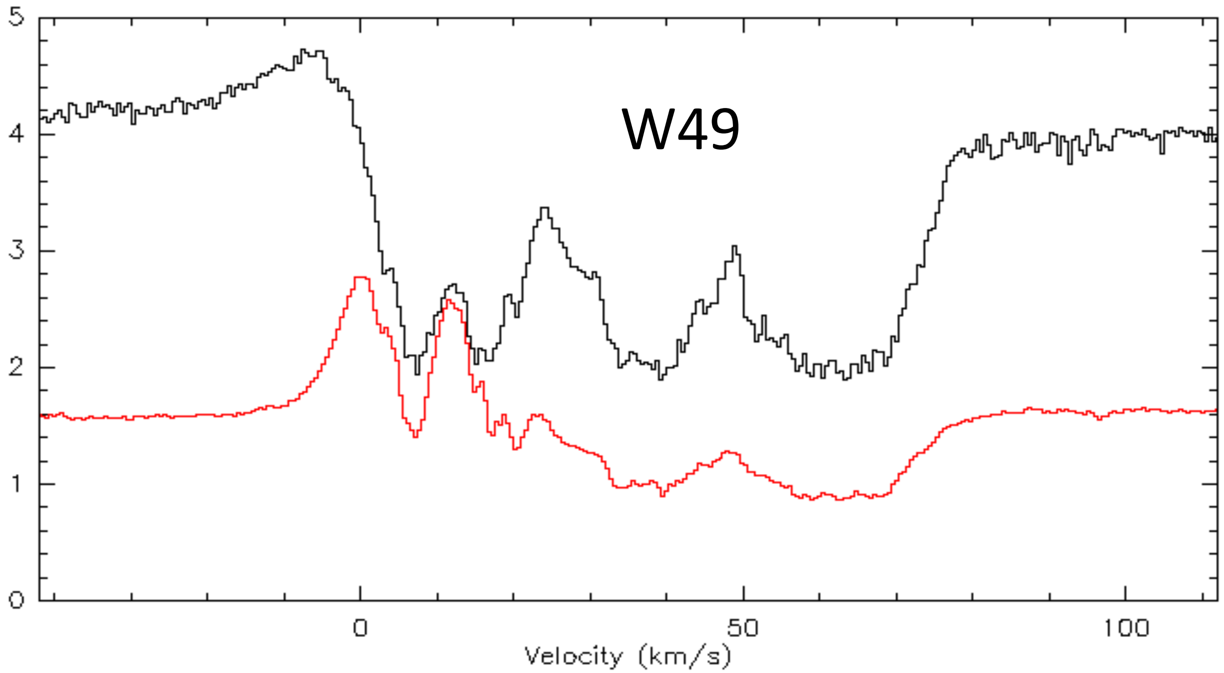
Does this point to a problem, especially for dust & gas-rich galaxies, or central regions of galaxies in which unrecognized absorption may be significant?

With an ensemble of massive star forming regions at different velocities, the absorption may not even be spatially or spectrally evident.

This issue may be contributing to “C^+ deficit” in ULIRGs

Self-Absorption

Can in some cases be obvious, but not always



[OI] 63 μm

[CII] 158 μm

Thanks to R. Güsten

The emission is being affected by very strong self-absorption feature at 8 km/s seen in both [CII] and [OI]. But source emission in [OI] at lower and higher velocities is being dramatically reduced by low-excitation material likely associated with the source

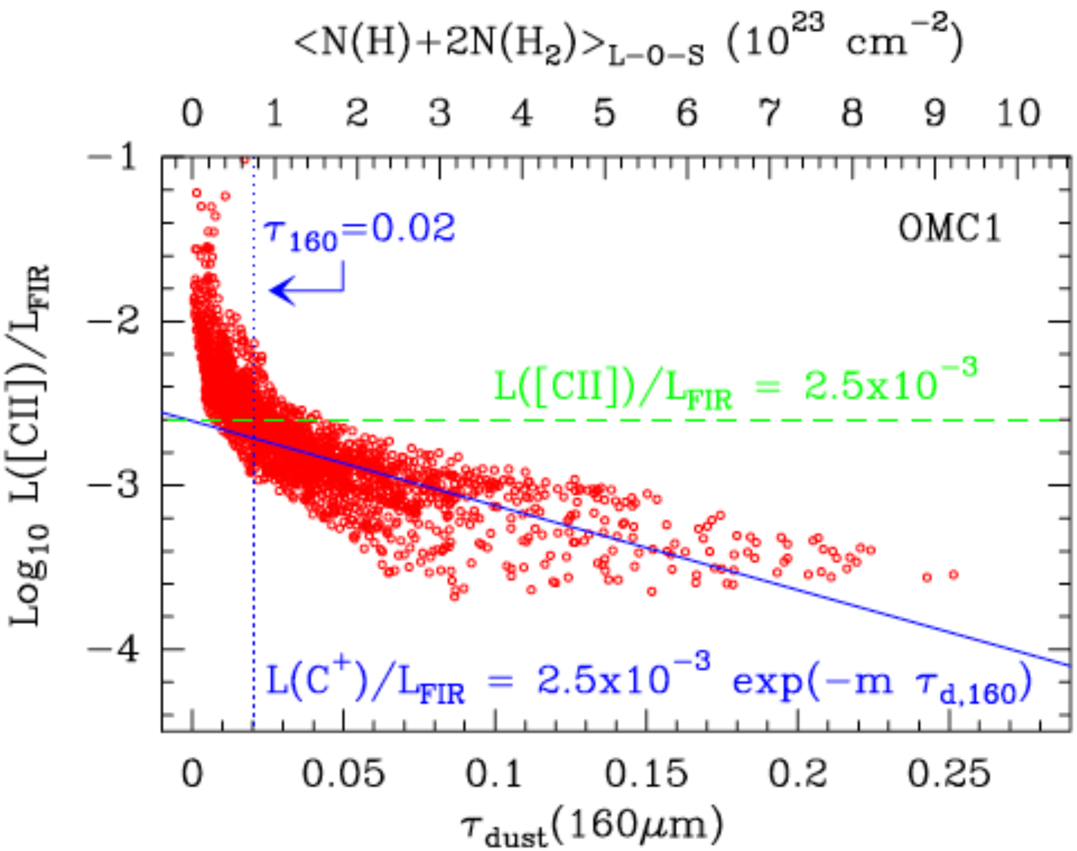
Issues With Interpretation of Fine Structure Line Emission

- Absorption due to low-excitation ("foreground") material
- "Self-absorption" from low excitation material within the source itself
- Is there really a "[CII] Deficit" or is there in fact a "Dust Emission Excess"?

Goicoechea et al. (2015) analyzed [CII] emission as function of the derived dust optical depth derived from FIR emission in Orion

They derived I[CII]/L(FIR) as function of τ(160 μm)

Comparing [CII] and FIR as Function of 160 µm Optical Depth



Goicoechea et al. 2015, ApJ

OBSERVATION

- Extremely high [CII]/FIR for $A_v < 0.5$
- [CII]/FIR drops systematically for LOS with large A_v

EXPLANATION

- For ISRF enhanced by 10^5, $X(C^+)$ flat for $A_v \leq$ but drops precipitously for $A_v > 5$
- Dust temperature distribution is very flat

The [CII] ``Deficit'' May Really Reflect Large Column Densities in Star-Forming Regions

When we encounter strongly-illuminated regions with different LOS column densities

1. [CII] emission is limited to surface layer
2. Warm dust => increasing FIR emission even for very large extinctions
3. L[CII]/LFIR reflects external heating AND column density of region

Low col. density (A_v < few) regions have "high" I([CII])/I(FIR) as long as $\chi \geq 100$ – sufficient to populate [CII] upper level ($^2P_{3/2}$)

If ultraluminous galaxies have typically larger column densities even if larger χ, then they will have smaller [CII]/FIR ratios, like the central portion of Orion

Conclusions

- Fine structure lines are now firmly established as important probes of the ISM
- [CII] is a good probe of star formation for "normal" galaxies.
- [CII] survey has revealed a new phase of the ISM – the "CO Dark Molecular Gas" adding ~30% to the molecular mass of the Milky Way
- [NII] survey has revealed a widespread component of ionized gas in the inner Milky Way having n(e-)~ 33 cm^{-3}; its origin is not yet clear
- LOS absorption and self-absorption can affect the interpretation of FSL emission in particular when the lines are not resolved in velocity.