A *Herschel* Galactic Plane Survey of [NII] Emission:

Preliminary Results

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Unraveling the Structure of the Interstellar Medium

There are multiple components having 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?

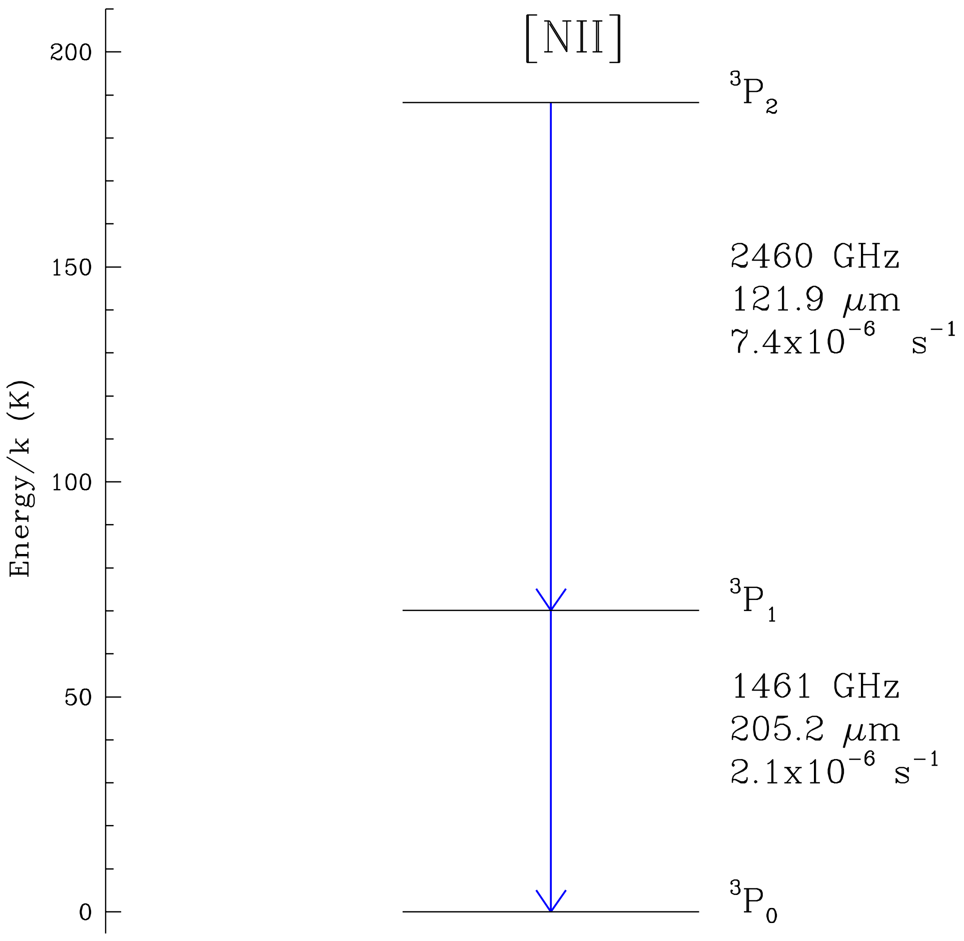
N^+ Fine Structure Levels & Lines

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

Two allowed transitions at 122 microns and 205 microns wavelength

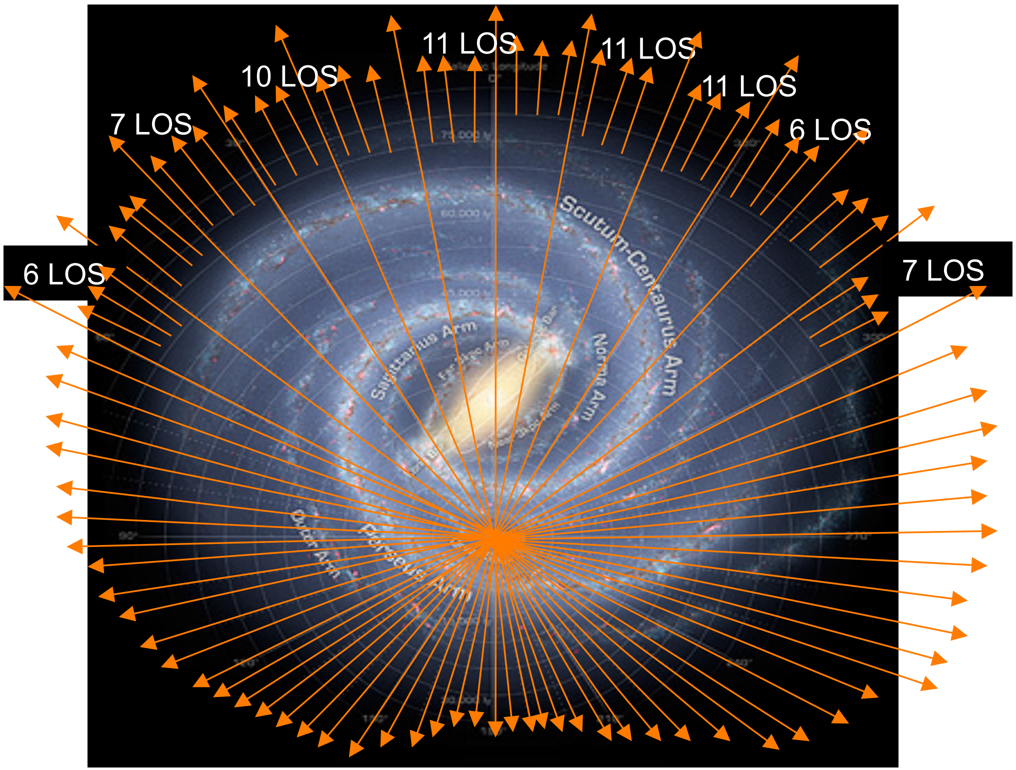
Nitrogen IP is 14.5 eV so found **only** in regions where H completely ionized. Electron collisions dominate (rates calculated by Hudson & Bell 1994)

Transition	n_{cr} $\lvert\Delta J\rvert = 1$	n_{cr} All ΔJ
$^3P_2 - {}^3P_1$ (3 – 2)	345	263
$^3P_1 - {}^3P_0$ (2 – 1)	155	73



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)



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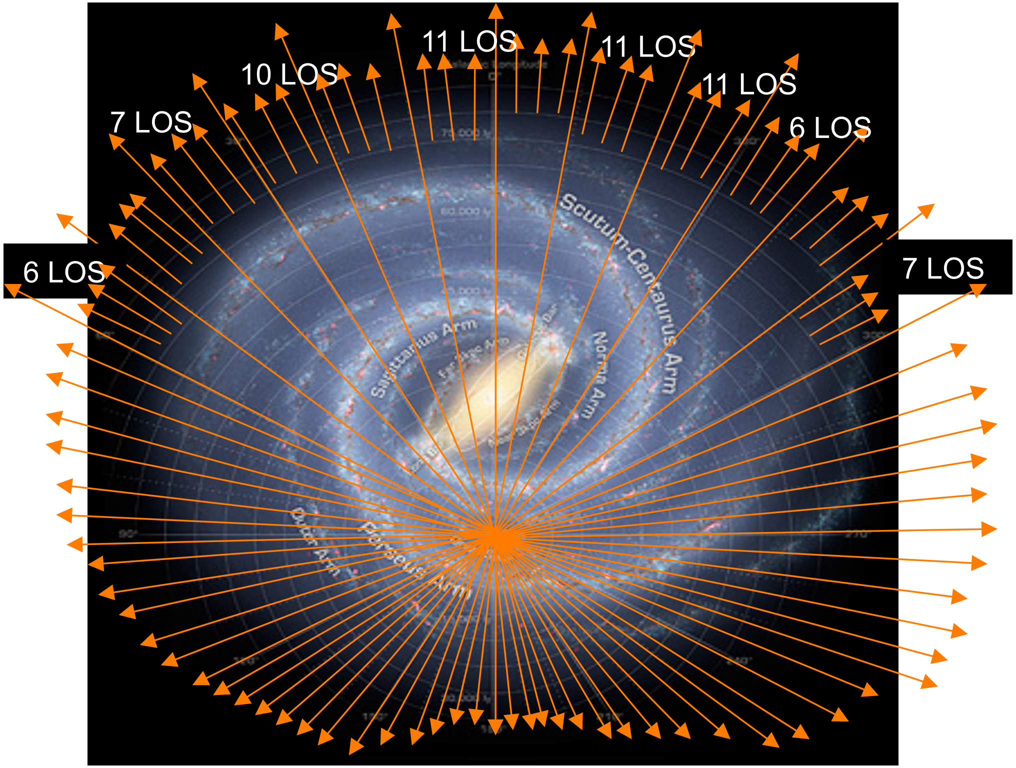
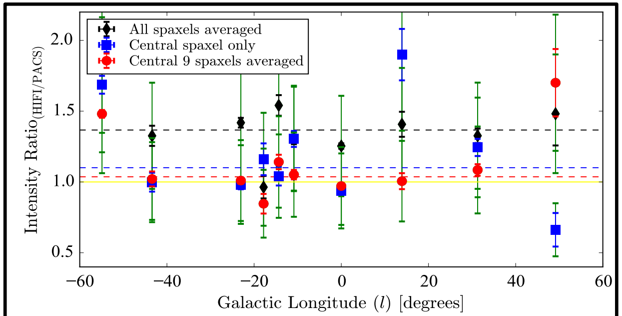
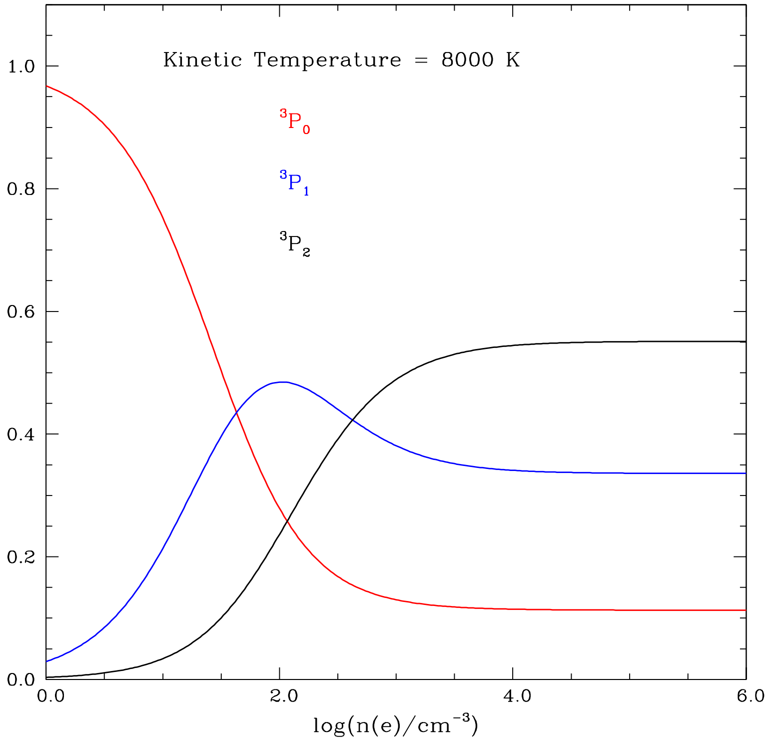
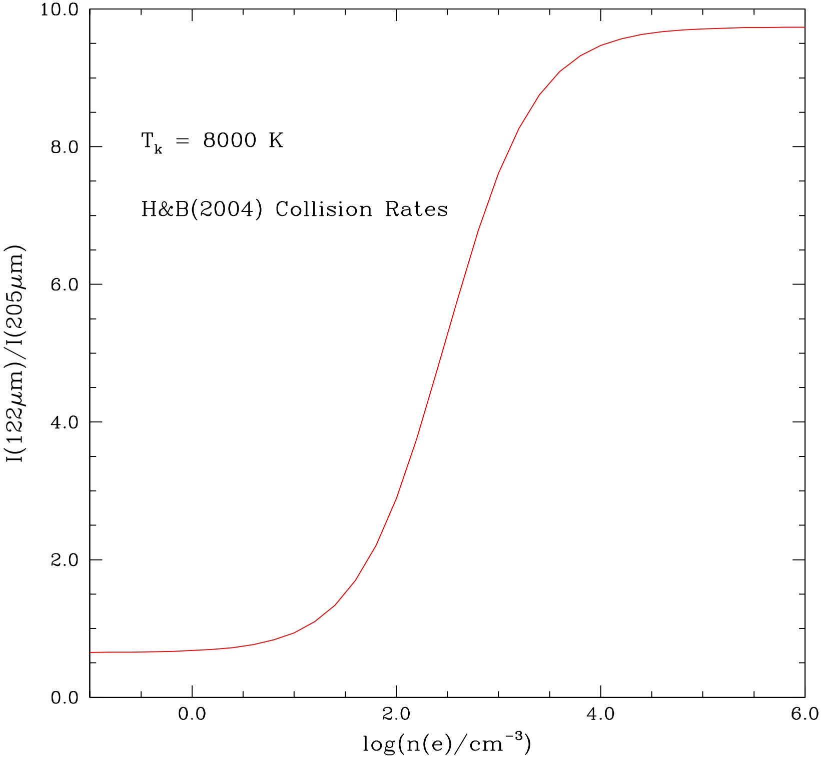




PACS 205 μm intensities agree well with integrated intensities from HIFI

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

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

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

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

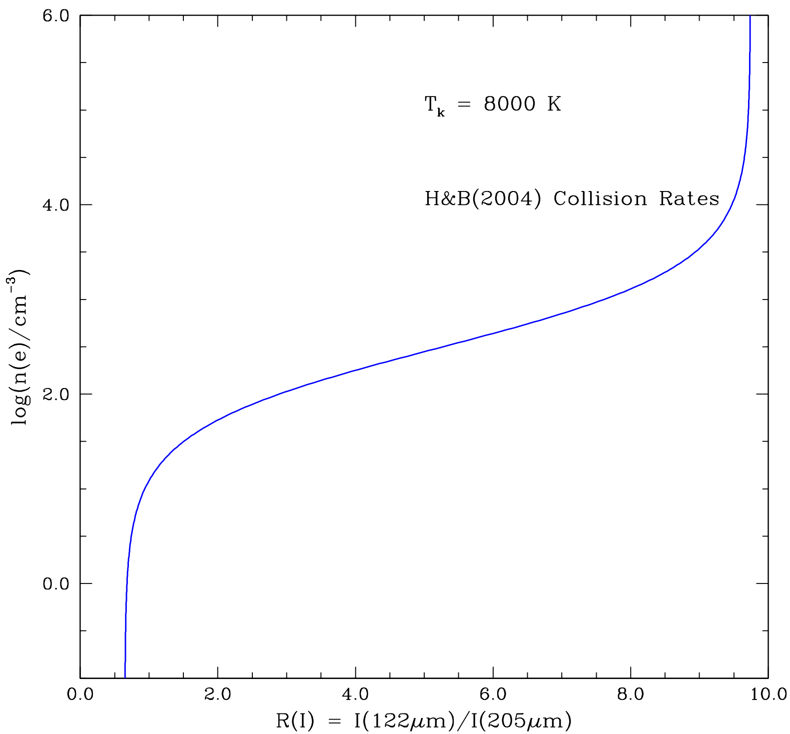
and

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

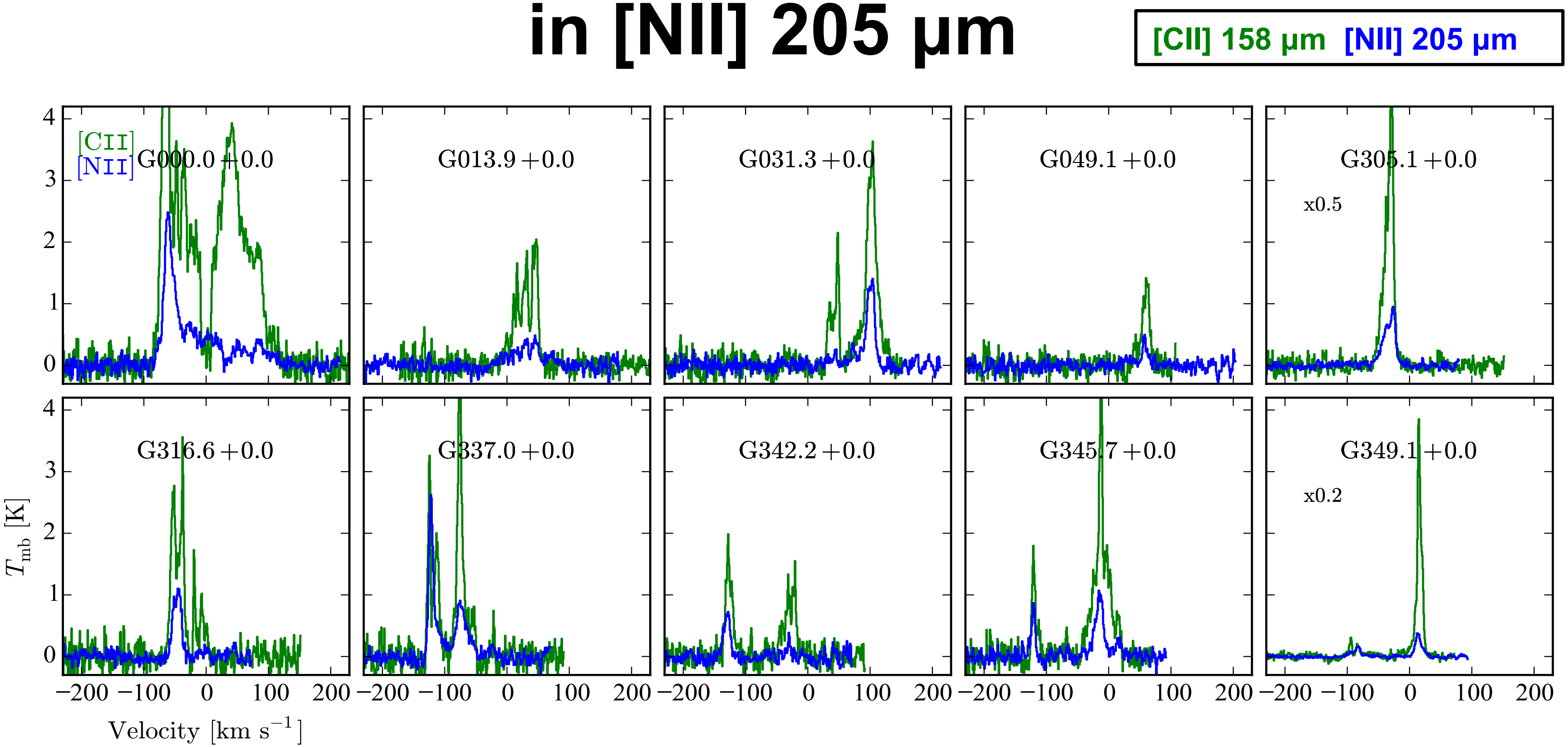
$$R_{min} = b/d$$

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

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

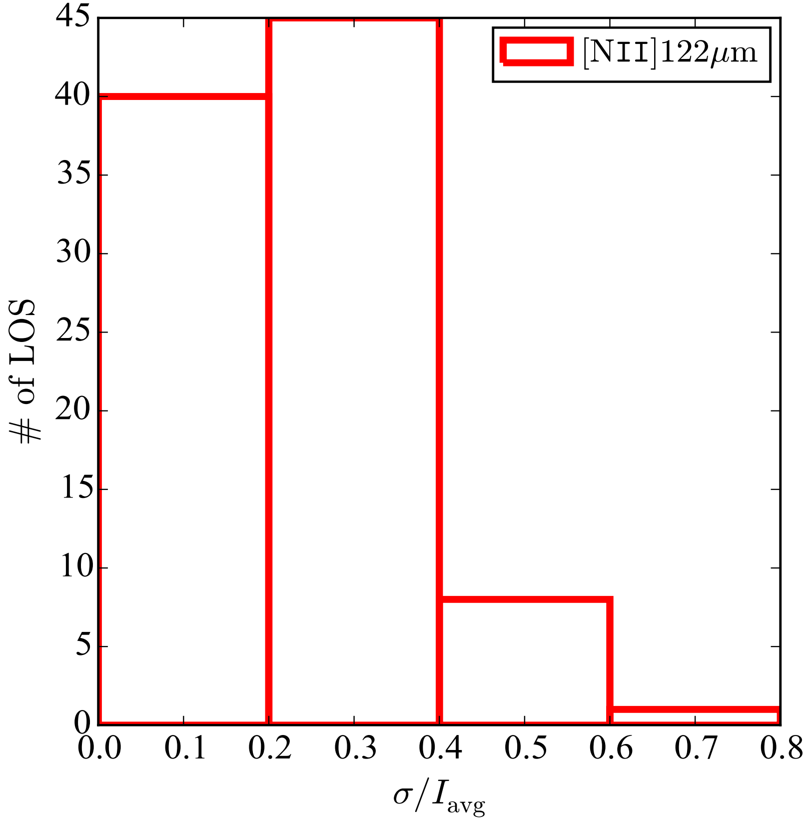


10 LoS in Inner Galaxy Observed with HIFI in [NII] 205 µm



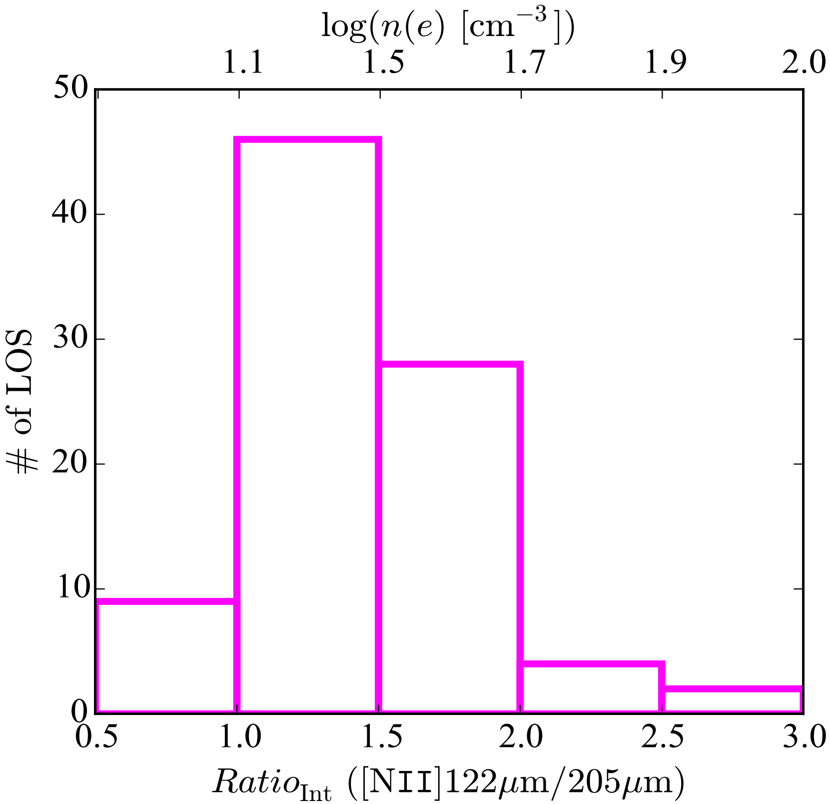
Multiple velocity components are common – typically 2 to 4 per LoS
[NII] and [CII] components at same velocities but ratio highly variable

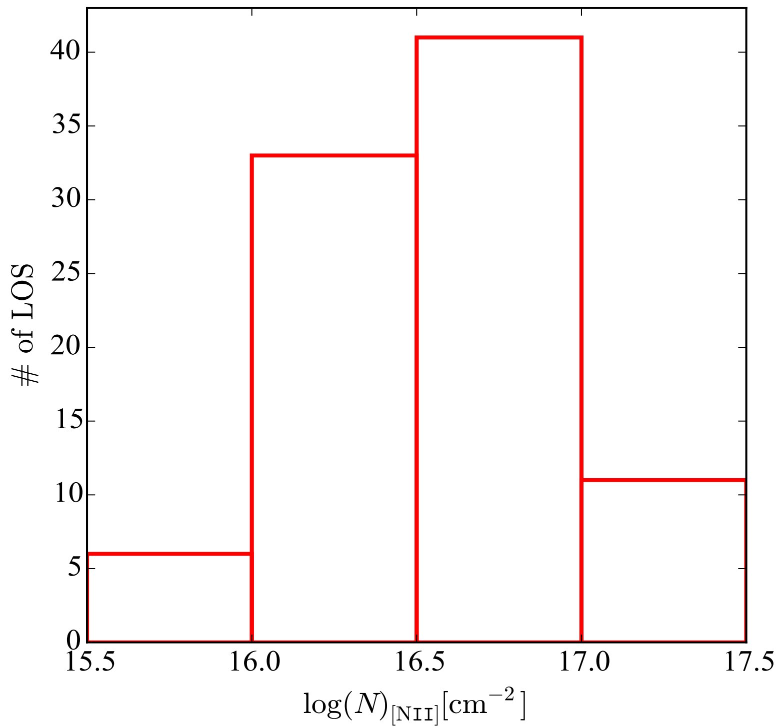
Fractional Variation of Intensity at 122 μm is Relatively Small



We can treat [NII] emission as **extended and relatively uniform**
It is **not** dominated by quasi-isolated point sources

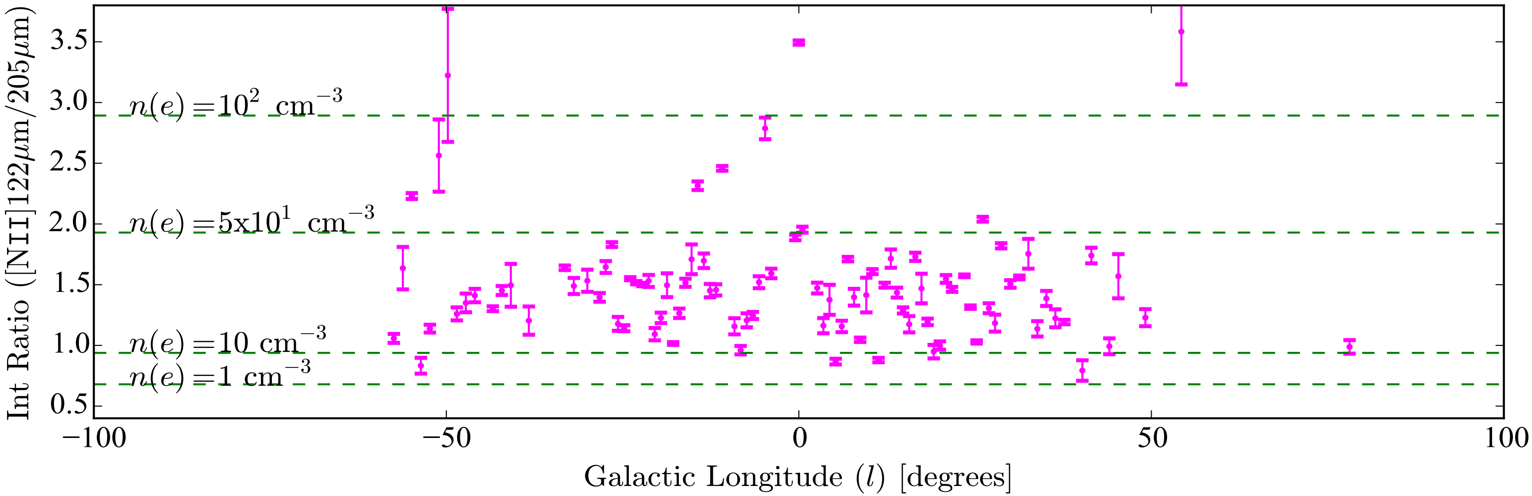
The Essential Results – n(e) and N(N⁺)





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

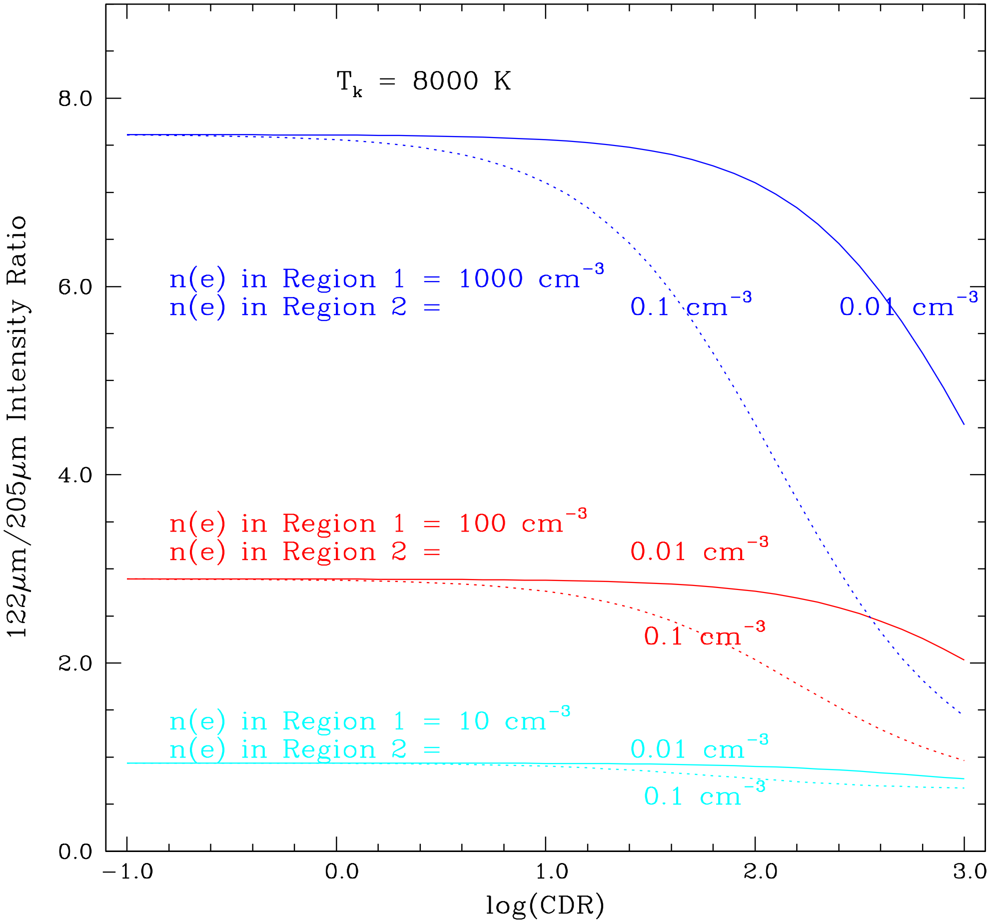
Distribution of Electron Densities as Function of Galactic longitude



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 *l*

Question: Can a Combination of Low and High n(e) Regions Fool us?



CDR = column density ratio = N(low dens)/N(high dens)

For n(high) = 100 cm^{-3}, we require CDR ≥ 100 to significantly change intensity ratio and thus derived n(e)

Very low n(e) puts so little population in EITHER excited state that huge total N(N^+) needed to perturb the observed ratio.

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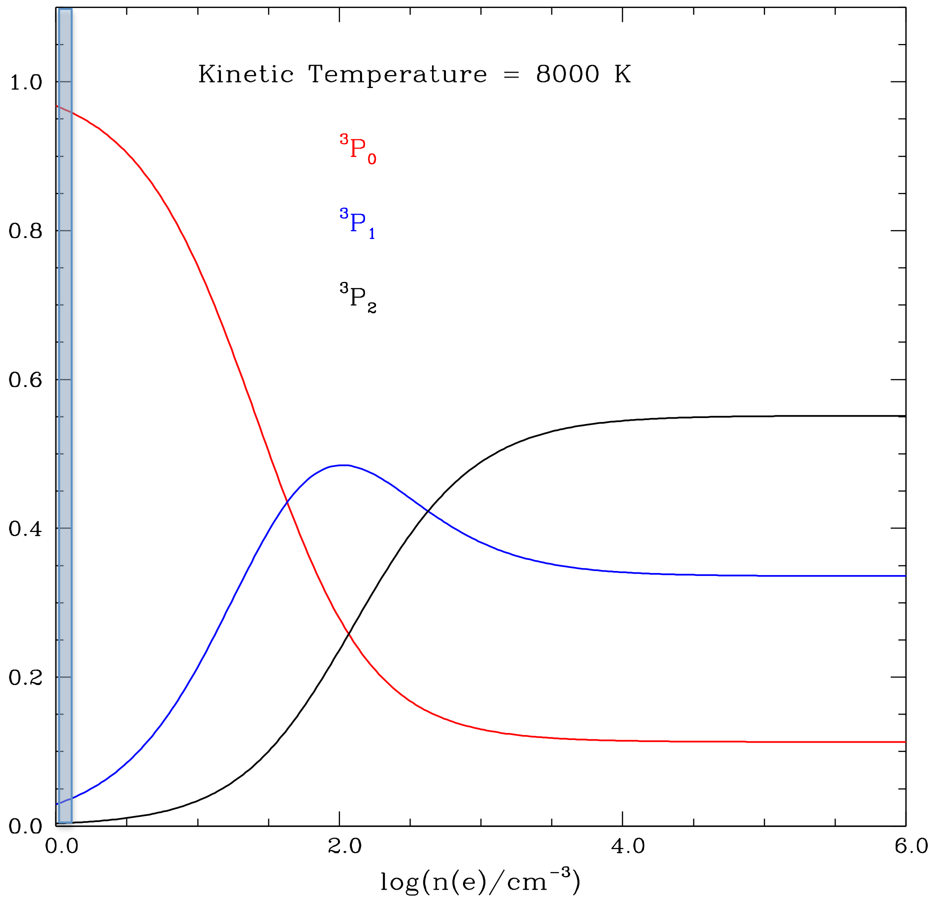


CDR = column density ratio = N(low dens)/N(high dens)

As long as CDR < 100, the derived n(e) will be correct or only slightly less than correct value

The total column density of WIM relative to our derived N(N^+) makes such a large CDR very unlikely

Answer: The derived n(e) should be dominated by that of the high density region

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

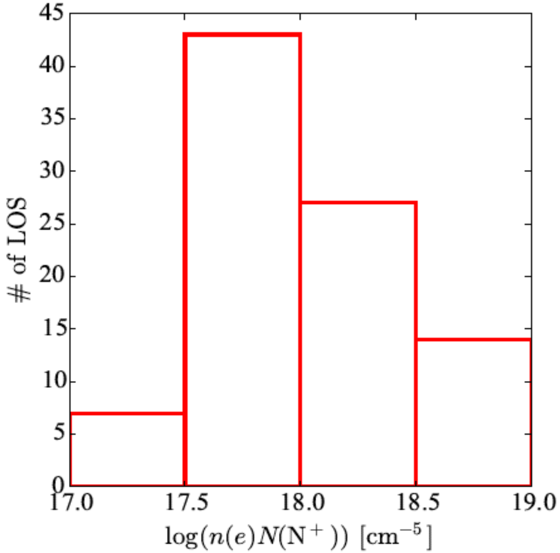
- Assume N is ionized by charge exchange with H^+; rate is moderately rapid at T ≥ 8000 K (Lin et al. 2005)
- The key question is then: what photon flux is required to maintain a specified column of H^+?
- Adopt model from Davidson & Netzer (1979): all photons are absorbed in length L of density n = 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 $X(N^+) = 1 \times 10^{-4}$ (scaled to central portion of galaxy)

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



Typical $N(N^+)n(e) = 1x10^{18}$ cm^{-5} total along LOS

but from HIFI spectra, we have on avg. 5 surfaces/LOS

This leads to Nn = $2x10^{17}$ cm^{-5} per surface & **F = $6x10^8$ ionizing phot/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)

H^+ column density ~ $7x10^{19}$ cm^{-2} for n(e) = 30 cm^{-3} (not unreasonable)

Extended Low-Density (ELD) HII Region Envelopes

A long history of **extended** “low/modest” densities in central region of Milky Way – from low-freq. radio recombination line data: **$n(e) = 3$ to $10\ cm^{-3}$** [Shaver (1976), Mezger (1978), Anantharamaiah (1985, 1986), McKee & Williams(1997), Roshi+ (2001)]

We could be seeing the “intermediate density” envelopes between ELD HII and the HII regions themselves

We see a weak correlation of n(e) with N(e). This could result from LoS passing through more central portion of HII region where density and column density are both higher.

SUMMARY

- We have carried out a survey of the Galactic plane in 205 μm and 122 μm [NII] fine structure transitions
- Both lines 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
- HIFI spectra indicate component-by-component correlation with [CII] but with highly variable ratio
- Large column density of ionized nitrogen at high density suggests that “traditional” WIM is not the origin of [NII] emission
- Ionized Boundary Layers (IBL) and extended intermediate density envelopes of HII regions are possible explanations