The Fermi LAT view of cosmic rays and interstellar gas in the Cygnus X region: a not so special spot of the Local Arm

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Cygnus X is a conspicuous star-forming region, embedded in a giant molecular cloud complex. The properties of the interstellar medium and the cosmic-ray population over a scale of a few hundred parsecs are similar to those of other segments of the Local Arm.

We present an analysis of the Fermi LAT observations of Cygnus X intended to probe the cosmic-ray and interstellar-matter content of the region. From gamma-ray data we estimate a total of $8^{+5}_{-1} \times 10^6$ $M_\odot$ of interstellar gas in the complex at a distance of 1.4 kpc. The gamma-ray emission from atomic gas supports an average H I spin temperature of a few hundreds K as derived from radio absorption/emission pairs to estimate its column-densities. The $X_{CO}=N(H_2)/W_{CO}$ ratio derived in the massive Cygnus complex, $[1.68 \pm 0.05(\text{stat.})^{+0.87}_{-0.10}(\text{H I opacity})] \times 10^{20}$ cm^{-2} $(K\ km\ s^{-1})^{-1}$, is consistent with other LAT estimates for clouds in the Local and Perseus arms. The mass of dark gas, escaping H I and CO observations but traced by dust and gamma rays, amounts to ~40% of the CO-bright molecular gas. We find an average gamma-ray emissivity per interstellar H atom in the 0.1-100 GeV energy band in good agreement with measurements in other segments of the Local Arm. We infer that the cosmic-ray population averaged over a few hundred parsecs is fairly uniform in density and spectrum along the Local Arm. Despite the presence of potential accelerators and much larger interstellar densities in Cygnus X compared to the solar neighborhood, their cosmic-ray populations are similar on such a scale.

Analysis

- Region at 72° < l < 88°, -15° < b < +15°.
- 2-year LAT data, tight background-rejection criteria.
- Bright pulsars (see poster by M. Razzano) dimmed by selecting off-pulse phase intervals.
- Emission from interstellar gas modeled by linear combination of cloud complexes along the line of sight; tracer maps:
  - H I 21-cm line → **N(H I)**; approximation of uniform spin temperature;
  - CO 2.6-mm line → $\mathbf{W_{CO}}$; assume $N(H_2) = X_{CO} \cdot W_{CO}$;
  - A_V (2MASS Catalog) → $\mathbf{A_{V,exc}} = A_V - \sum_i [a_i \cdot N(H\ I)_{,i} + b_i \cdot W_{CO,i}] \propto$ dark gas;
- Likelihood fit with Poisson statistics over angular grid of 1/8°, 10 independent energy bands from 100 MeV to 100 GeV.

H I spin temperature

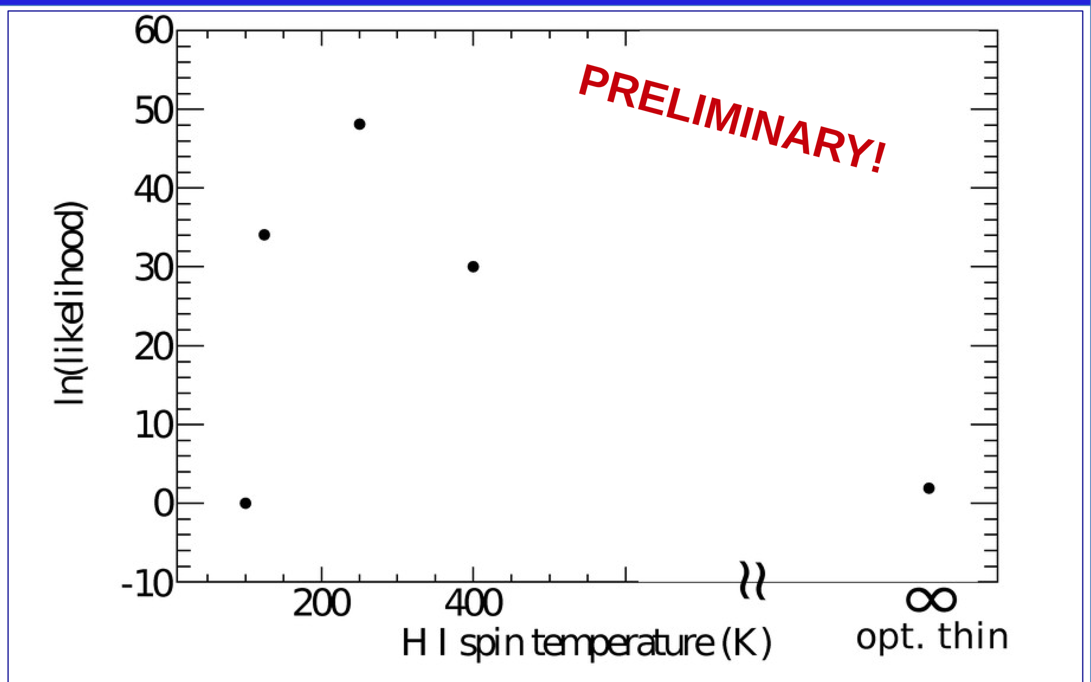

Figure 1: *Log-likelihood as a function of uniform spin temperature assumed for the optical depth correction of H I maps.*

Consistent with radio emission-absorption pairs: < 25% cold H I and > 75% warm (Dickey et al. 2009).

H I emissivity spectrum

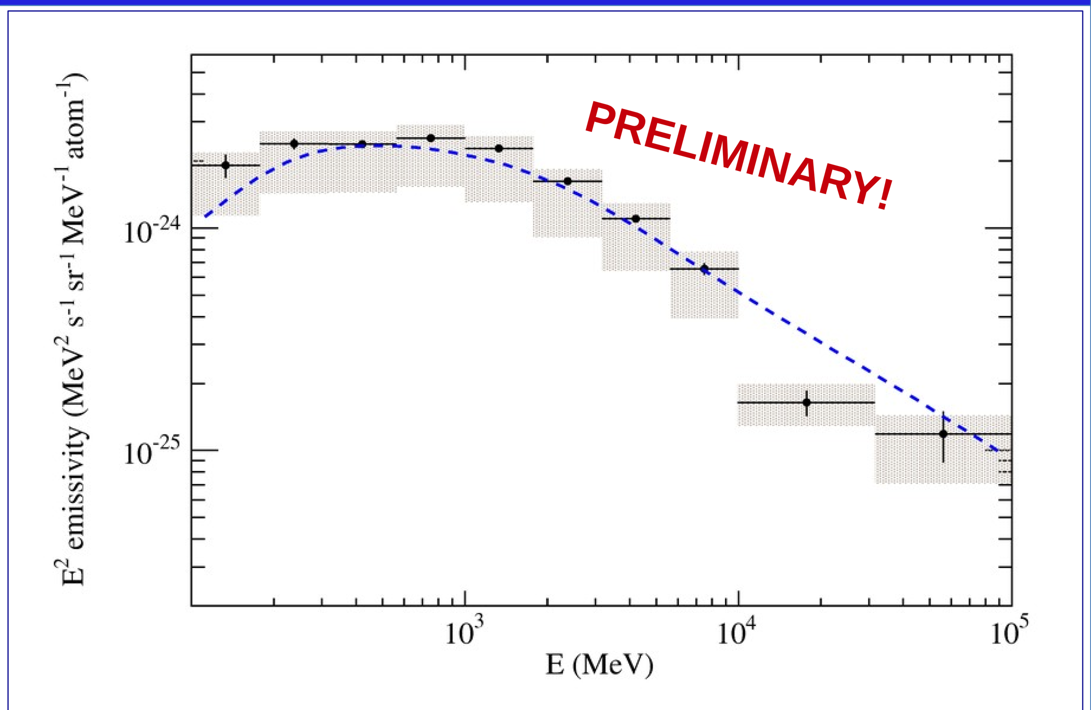

Figure 2: *Gamma-ray emissivity per hydrogen atom compared with expectations for solar neighborhood (blue line).*

Consistent with expectations from directly measured cosmic-ray spectrum.

Calibration of interstellar masses

- H I: at 1.4 kpc $5^{+4}_{-1} \times 10^6$ $M_\odot$.
- Emissivity per W_{CO} and $A_{V,exc}$ unit linearly scale with H I emissivity → good mass tracers.
- CO-bright gas:
  - $X_{CO}=N(H_2)/W_{CO}=[1.68 \pm 0.05(\text{stat.})^{+0.87}_{-0.10}(\text{H I opacity})] \times 10^{20}$ cm^{-2} $(K\ km\ s^{-1})^{-1}$
  - $2.3^{+1.2}_{-0.9} \times 10^6$ $M_\odot$.
- Dark gas:
  - $X_{av}=N(H)/A_{V,exc}=[28 \pm 2(\text{stat.})^{+20}_{-1}(\text{H I opacity})] \times 10^{20}$ cm^{-2} $(K\ km\ s^{-1})^{-1}$
  - $0.9^{+0.4}_{-0.1} \times 10^6$ $M_\odot$, 40% of CO-bright mass.
- Total: $8^{+5}_{-1} \times 10^6$ $M_\odot$.

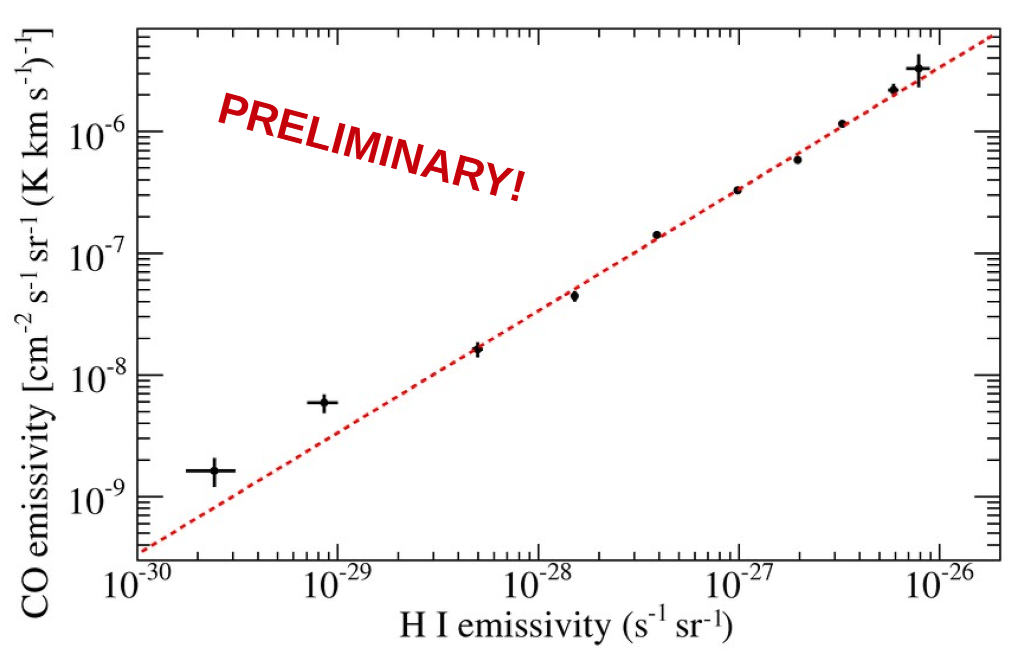

Figure 3: *Gamma-ray emissivity per W_{CO} unit vs. per hydrogen atom with best-fit linear relation (red line); T_S =250 K.*

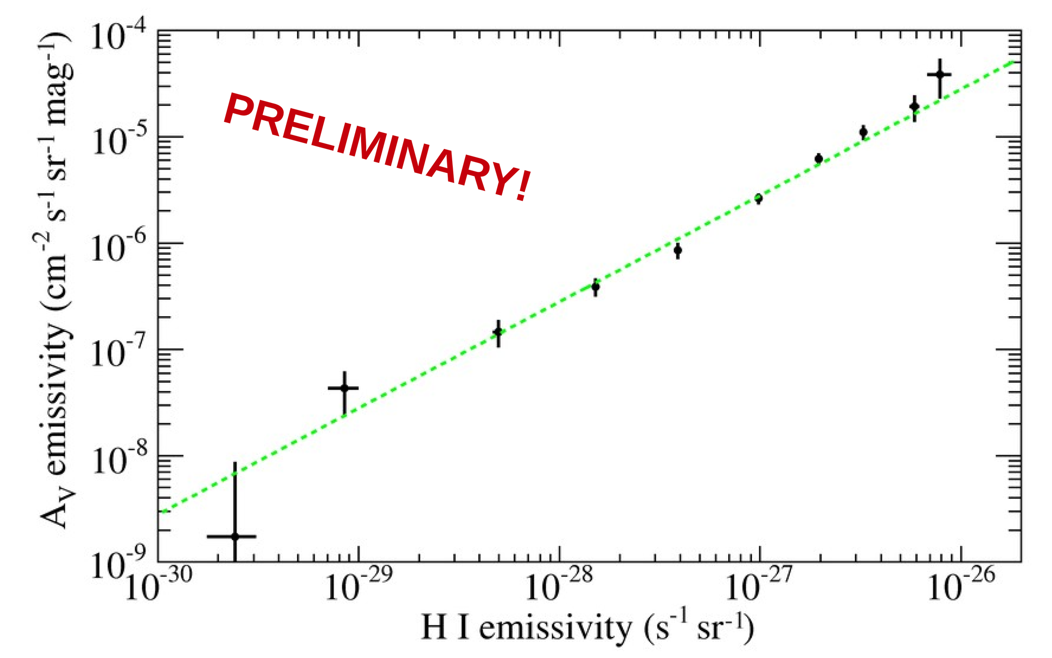

Figure 4: *Gamma-ray emissivity per A_V excess unit vs. per hydrogen atom with best-fit linear relation (green line); T_S = 250 K.*

The X_{CO} conversion factor

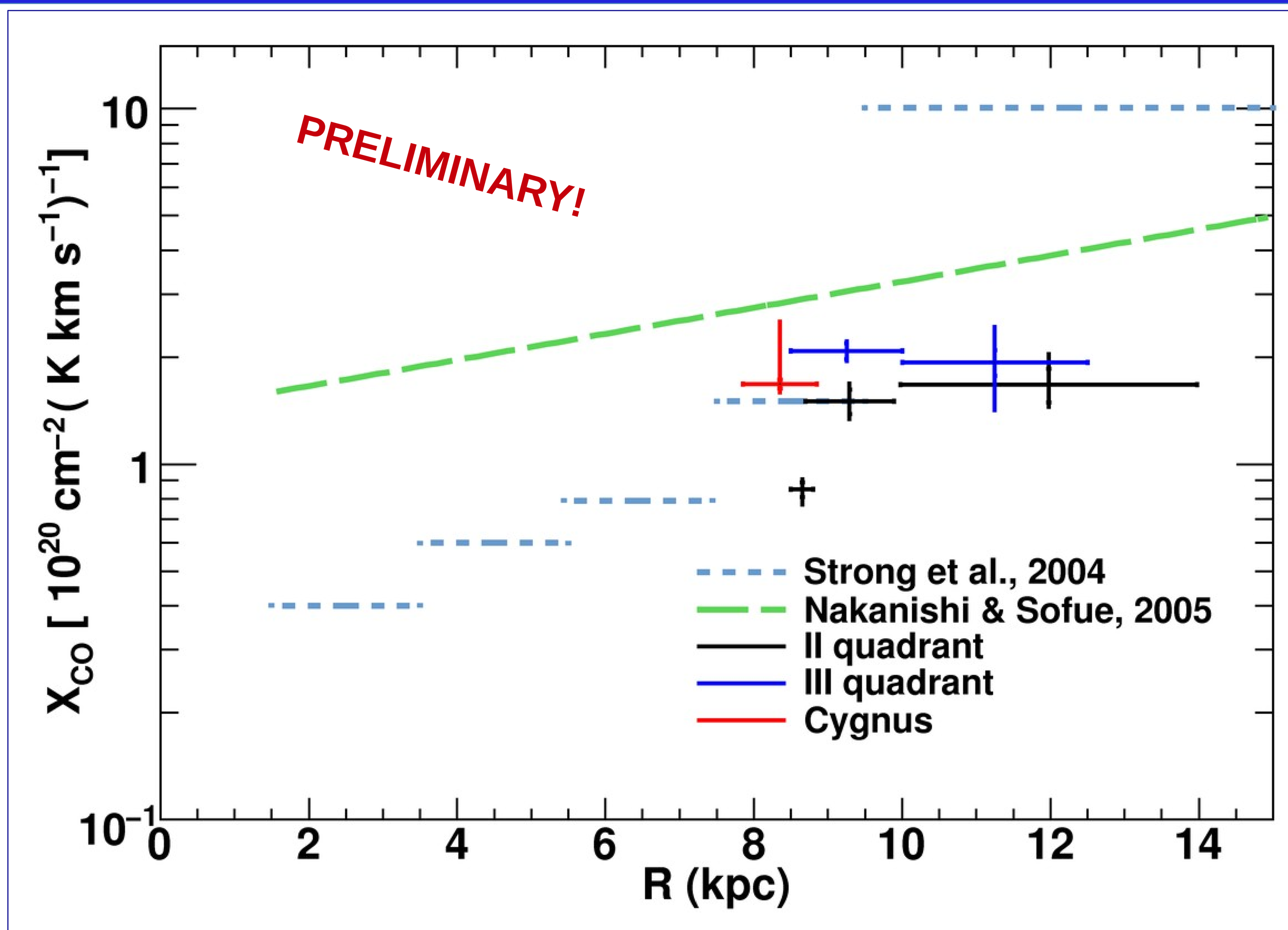

Figure 5: *$X_{CO}=N(H_2)/W_{CO}$ as a function of Galactocentric radius, including estimates based on LAT data for second Galactic quadrant (Abdo et al. 2010), third quadrant (Ackermann et al. 2011) and Cygnus.*

Uniform X_{CO} along Local Arm and toward outer Galaxy
- Significant difference between complexes sampled as a whole and clouds sampled at pc scale → cause to be investigated.

The distribution of cosmic-ray densities

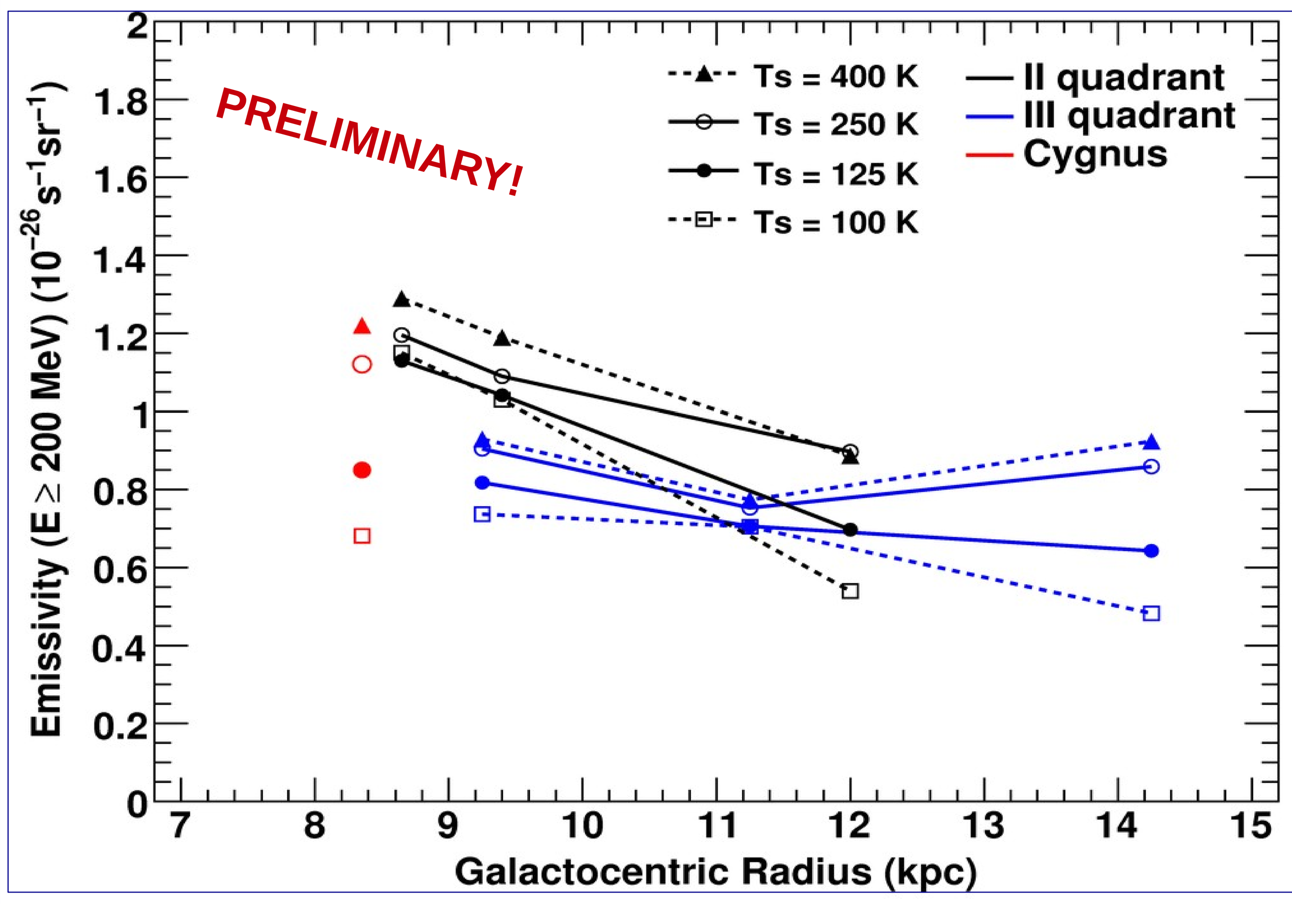

Figure 6: *Gamma-ray emissivity per hydrogen atom as a function of Galactocentric radius, including second Galactic quadrant (Abdo et al. 2010), third quadrant (Ackermann et al. 2011) and Cygnus.*

Uniform H I emissivity (cosmic-ray densities) along the Local Arm and mild gradient toward the outer Galaxy:
- variations of a factor 2 in gas surface densities → no indication of cosmic-ray matter coupling;
- potential accelerators in Cygnus X → the cosmic-ray population is 'normal' over a few hundred parsecs.