Fermi measurements of diffuse gamma-ray emission in the outer Galaxy: Cassiopeia, Cepheus and the Perseus arm

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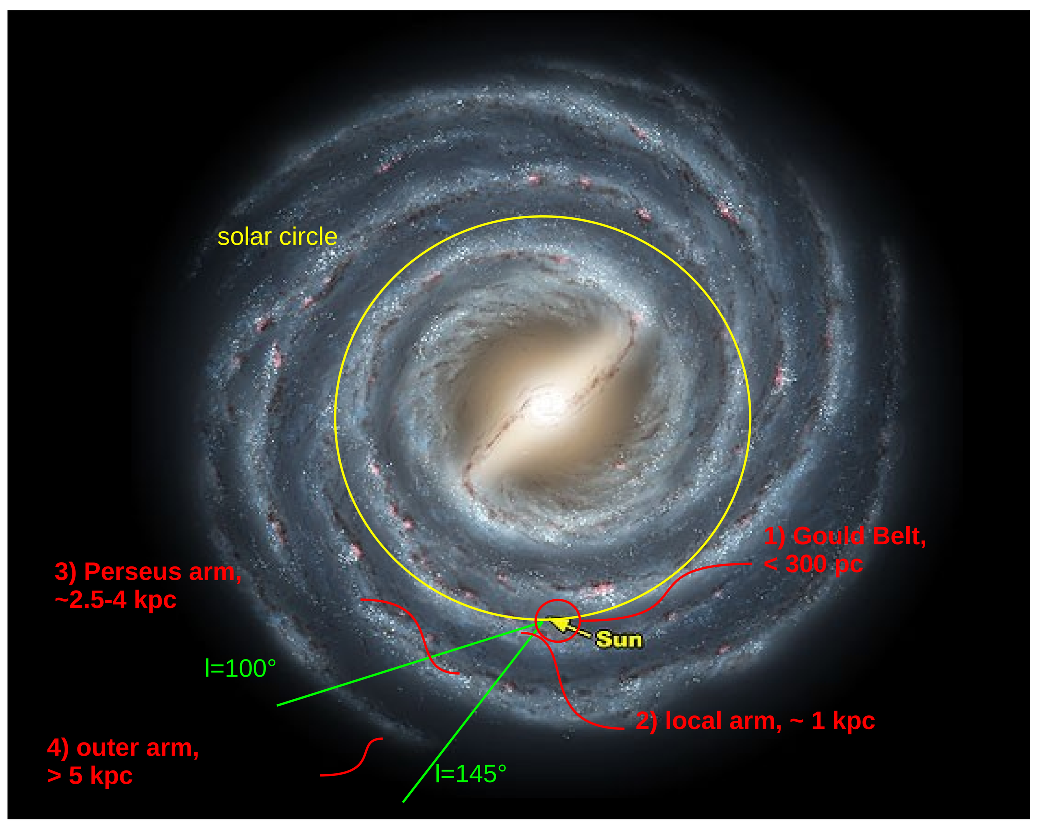
Summary: We report on the gradient of cosmic-ray densities and of X_{CO} =N(H_2)/W_{CO} toward the outer Galaxy in the second Galactic quadrant, derived from measurements of diffuse gamma-ray emission by the *Fermi* Large Area Telescope.

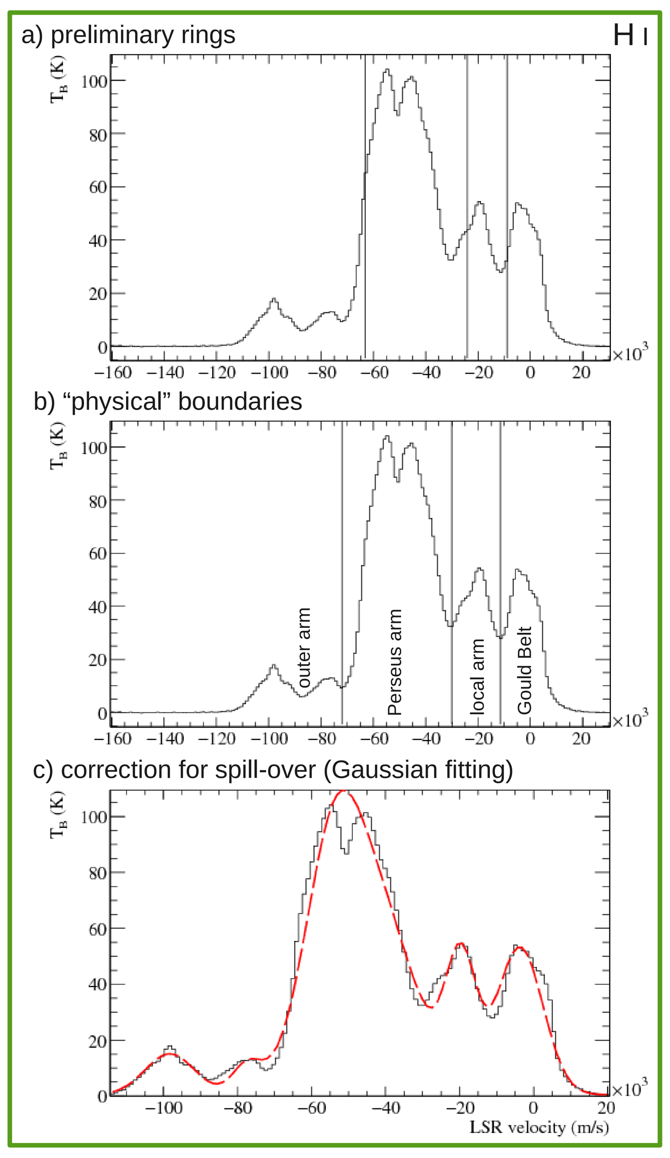
Abstract

We present the analysis of the interstellar gamma-ray emission measured by the Fermi Large Area Telescope (LAT) in the second Galactic quadrant at 100° < l < 145°, -15° < b < +30°. This region encompasses the prominent Gould-Belt clouds of Cassiopeia, Cepheus and the Polaris flare, as well as conspicuous clouds at larger distances in the local and Perseus spiral arms, suitable to probe the cosmic-ray densities and interstellar masses beyond the solar circle. We find that the gamma-ray emissivity spectrum of the local gas is consistent with expectations based on the cosmic-ray spectra measured at Earth. The emissivity decreases from the Gould Belt to the Perseus arm, but the measured gradient is flatter than expectations based on diffusion of cosmic rays from supernova remnant sources with a distribution peaked in the inner Galaxy as suggested by pulsars. The X_{CO} =N(H_2)/W_{CO} conversion factor moderately increases by a factor 2 from the Gould Belt to the Perseus arm. The presence of additional gas not properly traced by H I and CO in the Gould Belt is suggested by the correlation between gamma-ray data and dust detected through its thermal emission.

SCIENTIFIC CASE

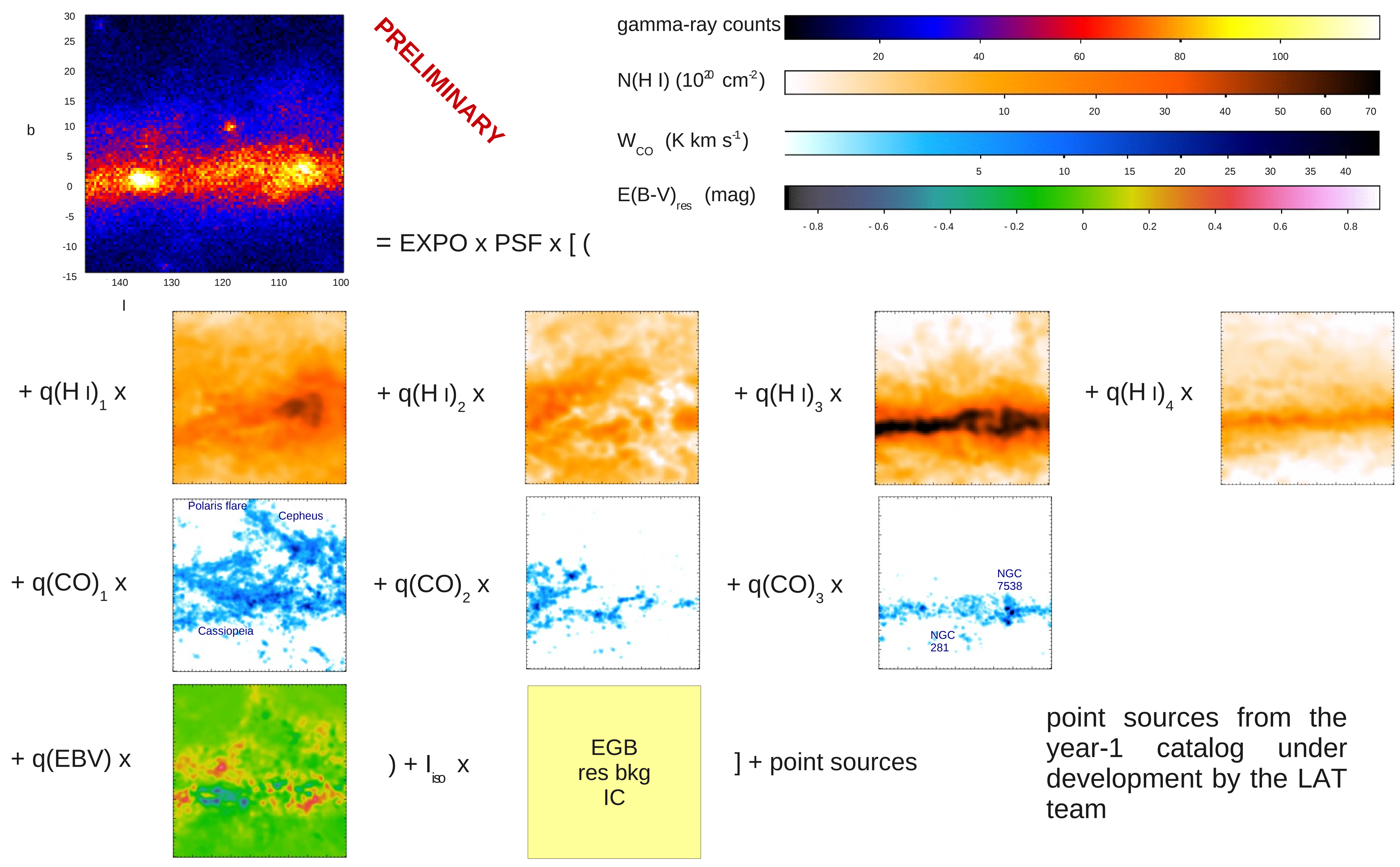
- High energy interstellar gamma-ray emission is produced by interactions of cosmic rays (CRs) with the gas in the interstellar medium (pion production and Bremmstrahlung) and the interstellar radiation field (Inverse Compton, IC, scattering).
- Often interpreted in term of radio/microwave ISM tracers:
  - the 21 cm line of atomic hydrogen (H I) gives the densities of atomic gas;
  - the 2.6 mm line of carbon monoxide (CO) indirectly traces the molecular gas.
- X_{CO} =N(H_2)/W_{CO} is thought to increase in the outer Galaxy; this need to be verified in gamma rays.
- The origin of CRs is still mysterious; supernova remnants are thought to be CR sources in our Galaxy but their distribution is highly uncertain; the gradient of gamma-ray emissivities can provide useful constraints.
- The region of Cassiopeia and Cepheus, at 100° < l < 145° and -15° < b < +30°, is well suited to probe CRs and the ISM beyond the solar circle because of the good kinematic separation and the presence of conspicuous gas complexes.

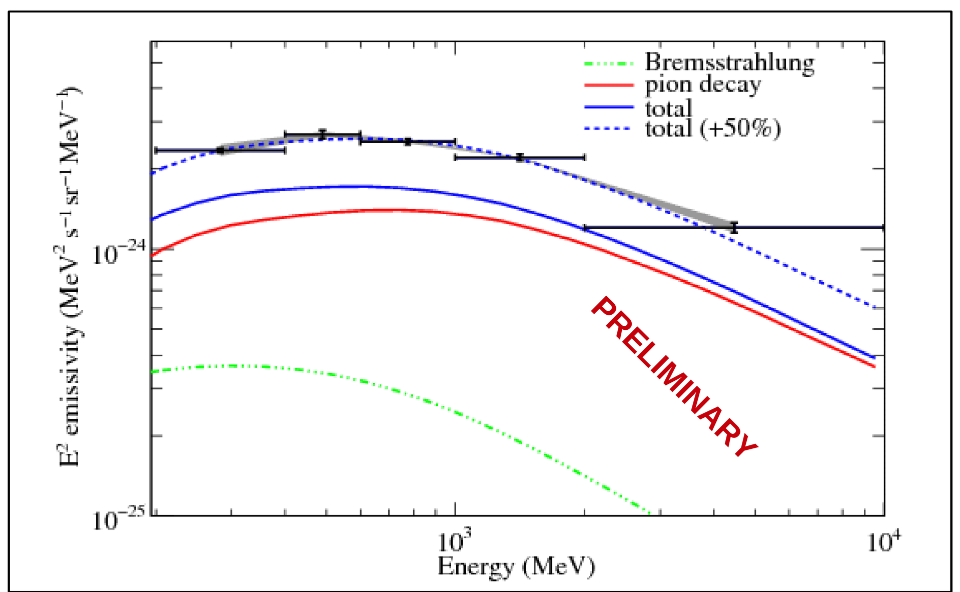




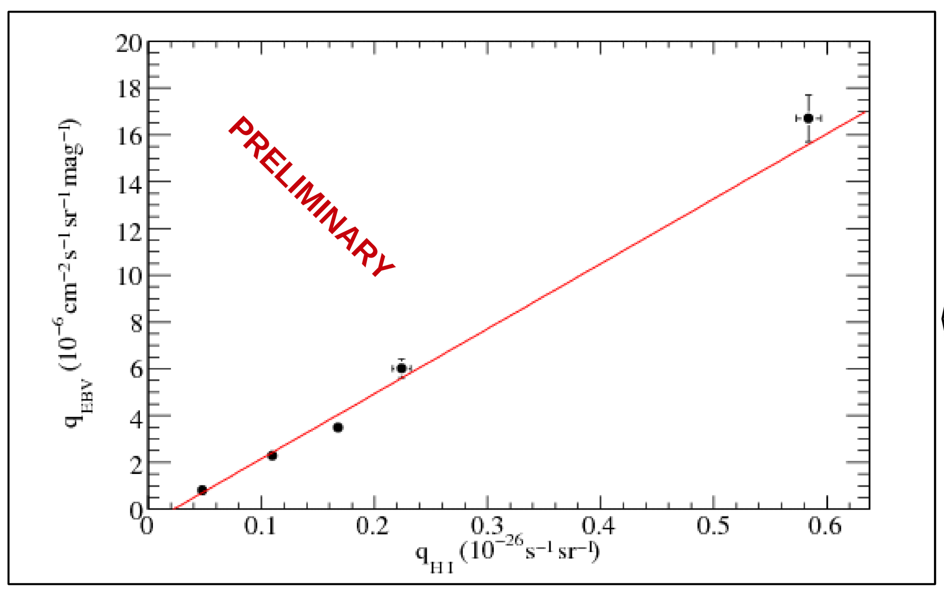
ANALYSIS

- H I (Kalberla et al. 2005) and CO (Dame, Hartmann & Thaddeus 2001) data used to produce maps of N(H I) (uniform spin temperature of 125 K) and W_{CO} in the four regions (kinematic separation of structures ←);
- E(B-V) map tracing total dust column densities (Schlegel, Finkbeiner & Davis 1998) fitted with linear combination of radio maps; residuals can trace additional gas/ compensate for approximations used to handle the radio tracers;
- if the ISM is transparent to gamma rays, CR diffusion lengths are larger than ISM complexes and CRs prenetrate clouds uniformly to their cores, gamma-ray intensities can be modeled as a linear combination of maps (→);
- First 11 months of LAT (Atwood et al. 2009) science data analysed with binned maximum Likelihood procedure with Poisson statistics (post-launch Instrument Response Functions).

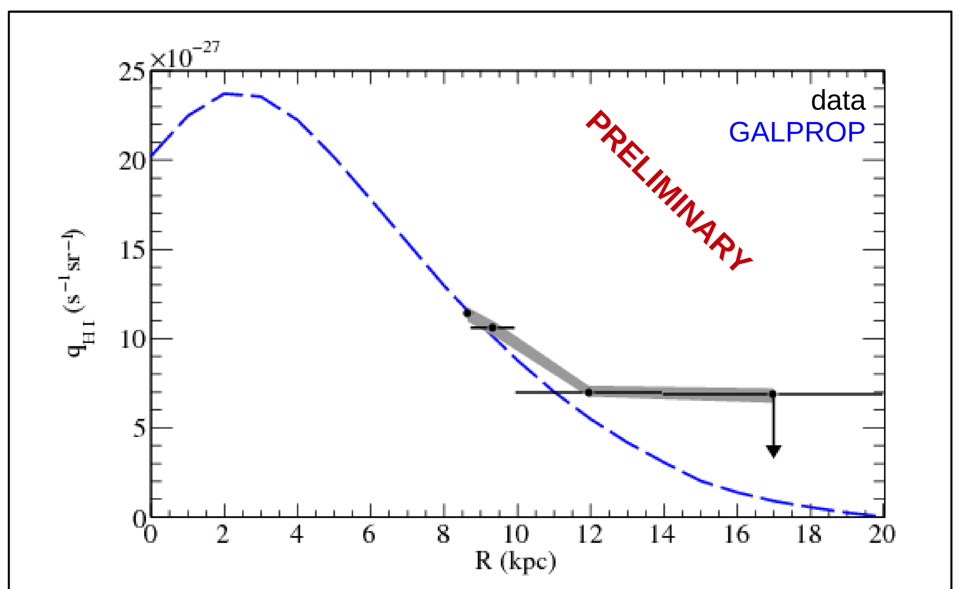




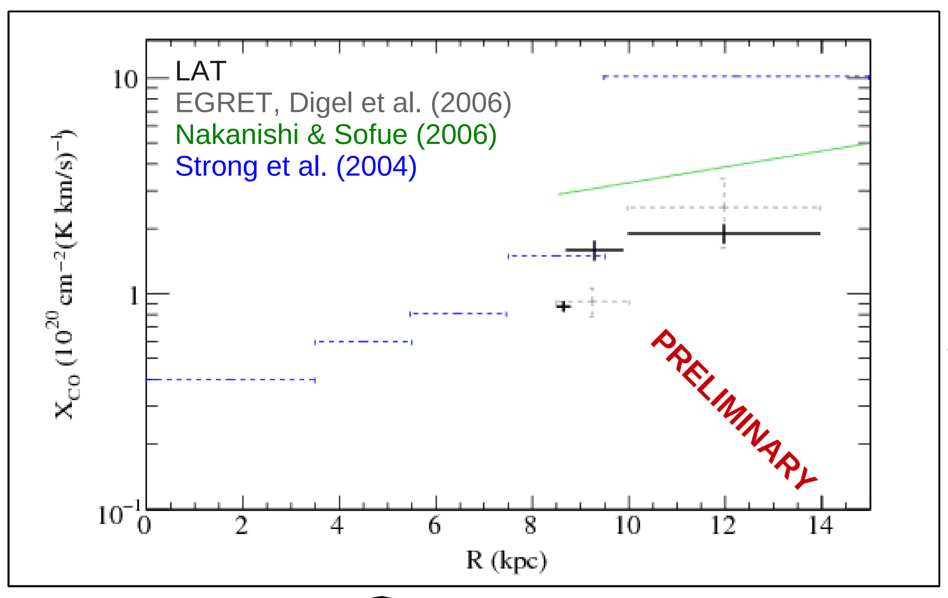
- The **Gould Belt emissivity** spectrum is **consistent with locally measured CR spectra**.
- The **spectral shape** shows good agreement with model.
- **Higher pion-decay contribution** relative to some estimates in the literature (plausibly attributed to uncertainties in the local CR spectra)



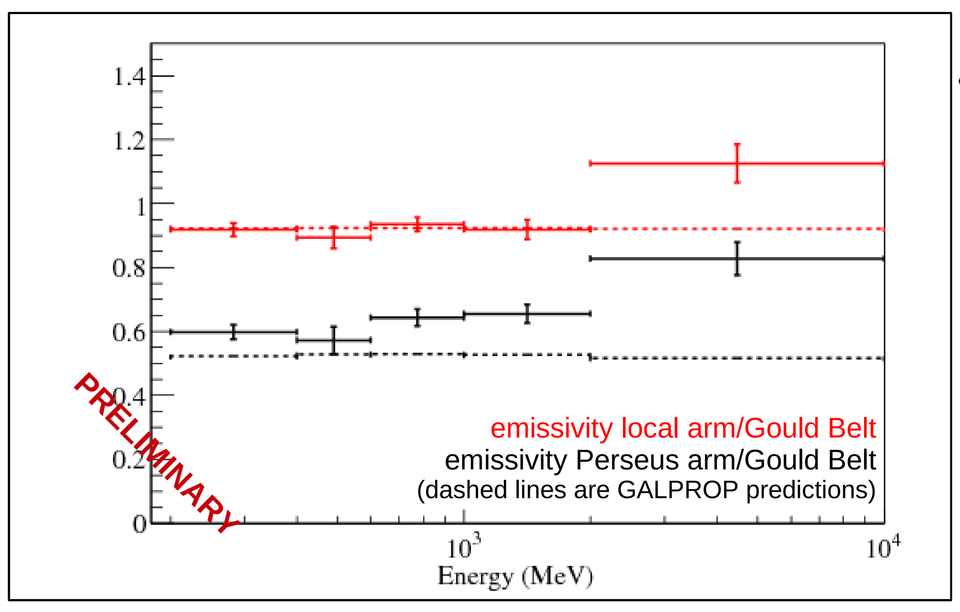
- Reddening residuals are correlated with gamma-ray data at c.l. > 99.9%.
- Good linear **correlation found between emissivities** of H I gas and emission associated with reddening residuals; **additional gas** is required.
- Positive residuals around CO clouds trace **additional mass**, the order of magnitude is **50%** of that traced by CO.



The **emissivity gradient** toward the outer Galaxy is **flatter** than predictions by a GALPROP model assuming that CRs diffuse from supernova remnant sources peaking in the inner Galaxy as suggested by pulsars.

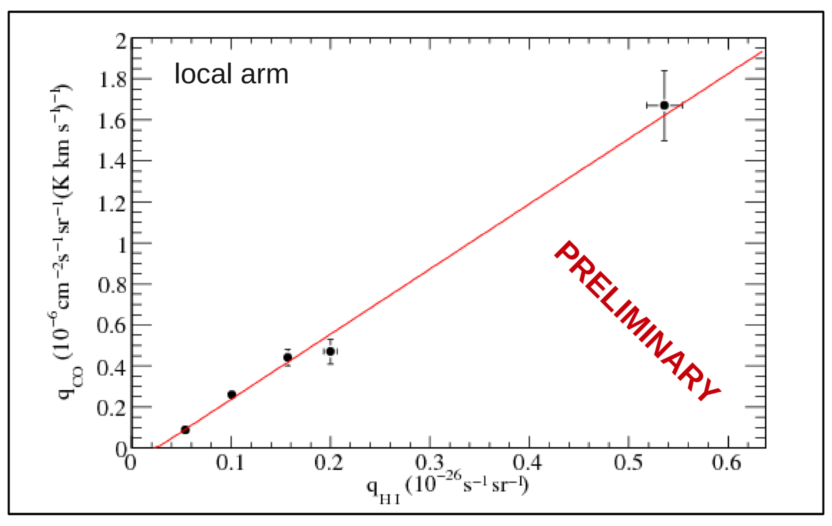


- **X_{CO} : moderate but significant increase** from Gould Belt to Perseus arm (consistent with EGRET results).
- Values **lower** than CO-to-H_2 law by Nakanishi & Sofue (2006), based on **virial masses**.
- A **very large gradient**, as assumed by Strong et al. (2004), is **not confirmed.**



- Emissivity spectrum in the local arm is consistent with that in the Gould Belt.
- **Perseus arm** shows a **harder spectrum** (might hint to diffusion of CRs not far from their sources or to a variation of the CR injection spectra across the Galaxy).

Found good linear correlation between H I and CO emissivities (e.g. local arm on the right). Linear fit used to calculate X_{CO} .



REFERENCES

Kalberla et al. 2005, A&A, **440**, 775
Dame, Hartmann & Thaddeus 2001, ApJ, **547**, 792
Schlegel, Finkbeiner & Davis 1998, ApJ, **500**, 525
Atwood et al. 2009, ApJ, **697**, 1071
Digel et al. 1996, ApJ, **463**, 609
Nakanishi & Sofue 2006, PASJ, **58**, 847
Strong et al. 2004, A&A, **422**, L47