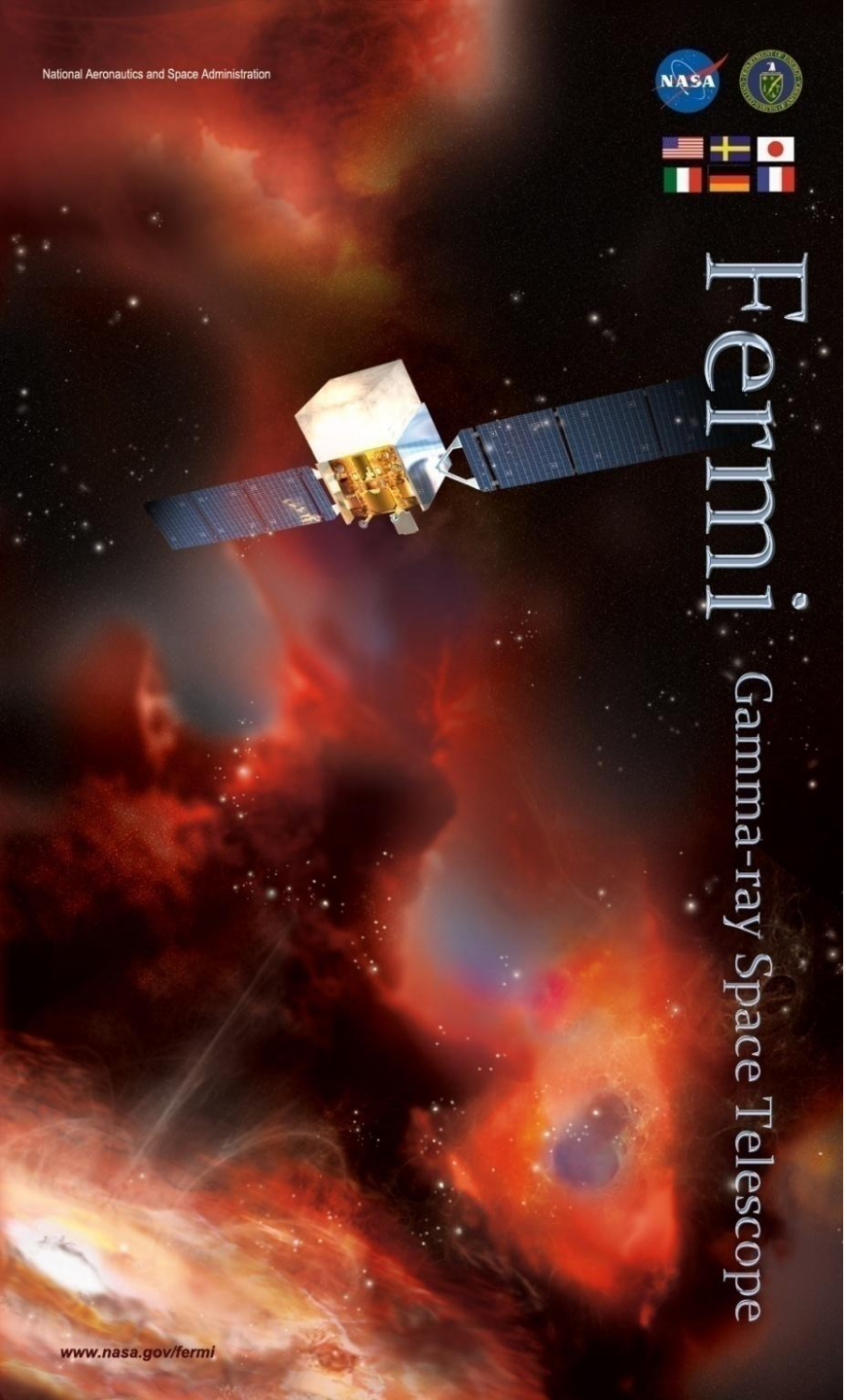

Fermi LAT study of cosmic-rays and the interstellar medium in nearby molecular clouds

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On behalf of the *Fermi*-LAT Collaboration

JPS meeting @Kyoto Sangyo Univ.
Sep 14, 2012

Giant Molecular Clouds

- **Temperature ~10K, Mass ~$10^{4\text{-}6}M_{solar}$, density ~10^{2}-10^{3} cm^{-3}**
- **Some GMCs close to the solar system (Orion, etc)**
- **Emission/absorption mechanism**
  - rotational transition of molecule → microwaves
  - extinction/emission by dust → optical, infrared
  - **interaction with CR → gamma-ray**

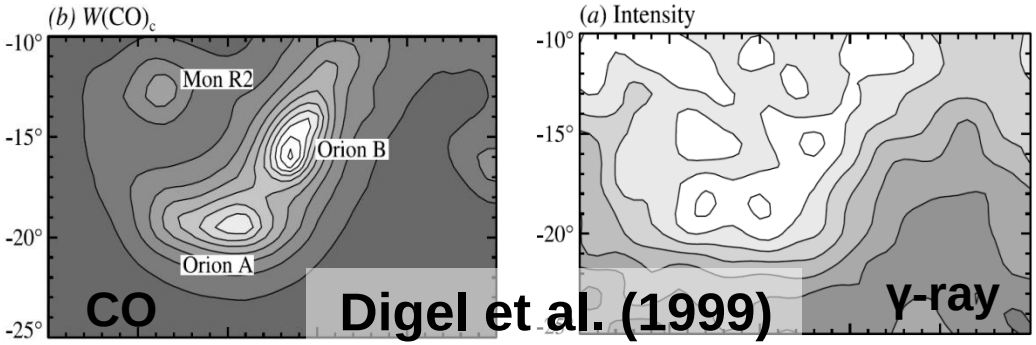
H_2 (main component of molecular gas) is not detectable in emission in interstellar conditions

$$p + p \longrightarrow \pi^+, \pi^-$$
$$\pi^0 \longrightarrow \gamma + \gamma$$

Gamma-ray emissivity does not depend on the gas temperature, phase, etc.
→ Study of CR spectrum and matter distribution by gamma-rays

Observation by EGRET (in 90')

Study of CR and matter distribution limited by sensitivity and angular resolution.



Motivation

***Fermi* Gamma-ray Space Telescope** (2008-) enables studying the diffuse gamma-ray emission with unprecedented sensitivity.

Detect gamma-rays from small GMCs (M <10^4 M_{solar})

→ **We can study CR and matter distribution in wide-ranging samples.**

Reveal the CR and matter distribution in the vicinity of the solar system (<~300pc).

- ***Cosmic rays***

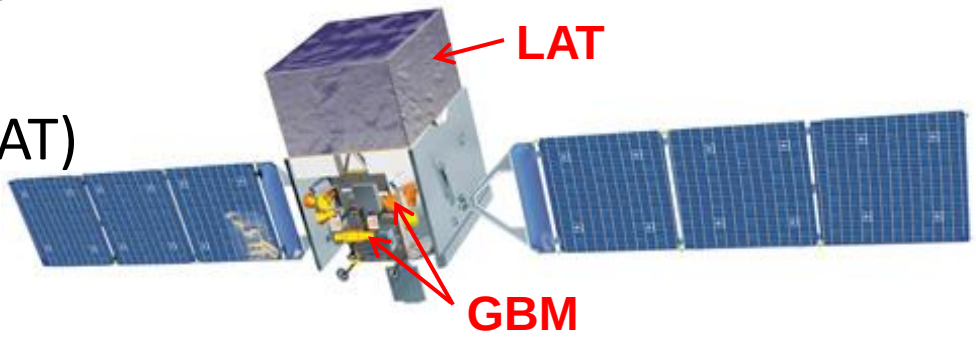
  local interstellar CR densities?

- ***Matter distribution***
  - Molecular mass calibration ratio

    Xco = $N(H_2)/W$co ~(1-2) x 10^{20} cm^{-2}/(K km/s) is highly uncertain.
  - How is the gas not traced by HI and CO surveys (“dark gas”) spread?

Fermi Gamma-ray Space Telescope

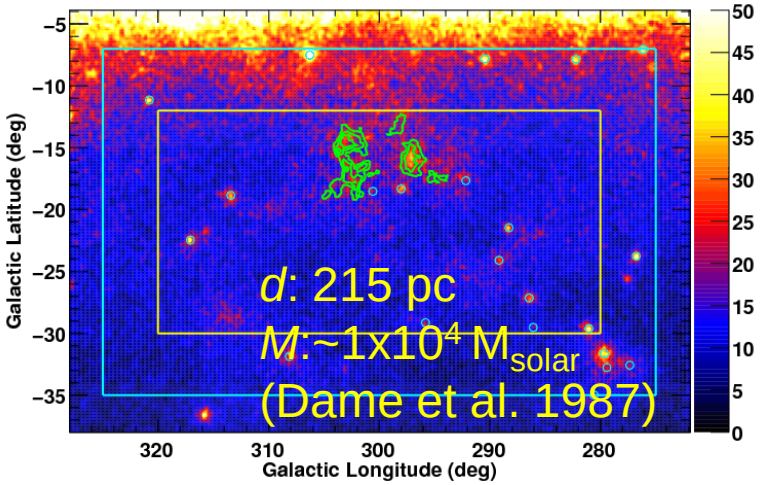
- Launched on June 11, 2008
- Two instruments:
  - Large Area Telescope (LAT)
    e+/e- pair-conversion
    with silicon detectors
  - Gamma-ray Burst Monitor (GBM)



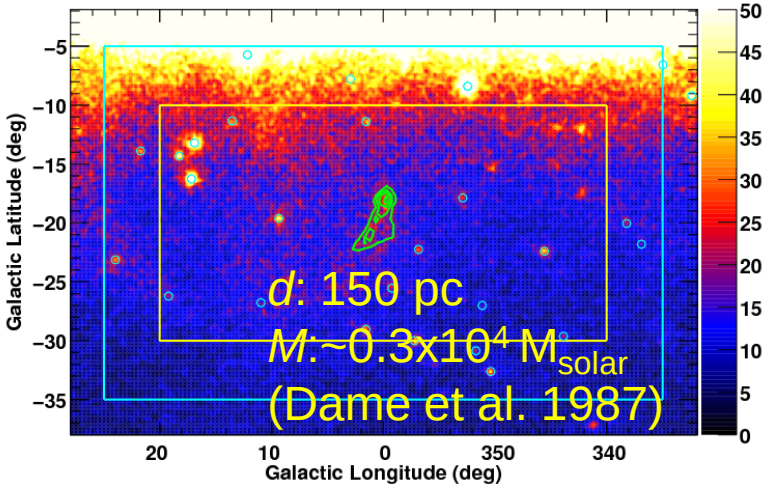
	CGRO-EGRET	Fermi-LAT
Energy range	20 MeV – 30 GeV	20 MeV – >300 GeV
Effective area	1500 cm^2	>8000 cm^2
PSF (68%) @ 1GeV	1.7 deg	0.8 deg
Field of view	0.5 str	2.4 str
Detected sources (>5σ)	271 (9 years)	1873 (2 years)

Target Molecular Clouds

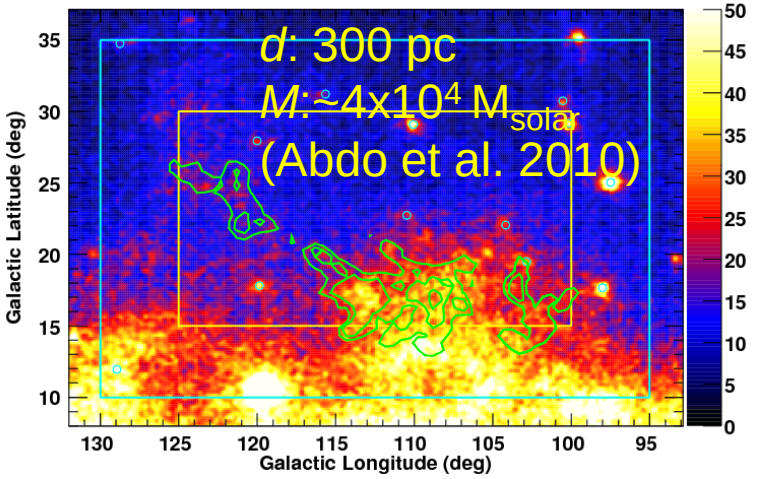
Chamaeleon



R CrA



Cepheus & Polaris



γ-ray data count map (*E*>250 MeV)

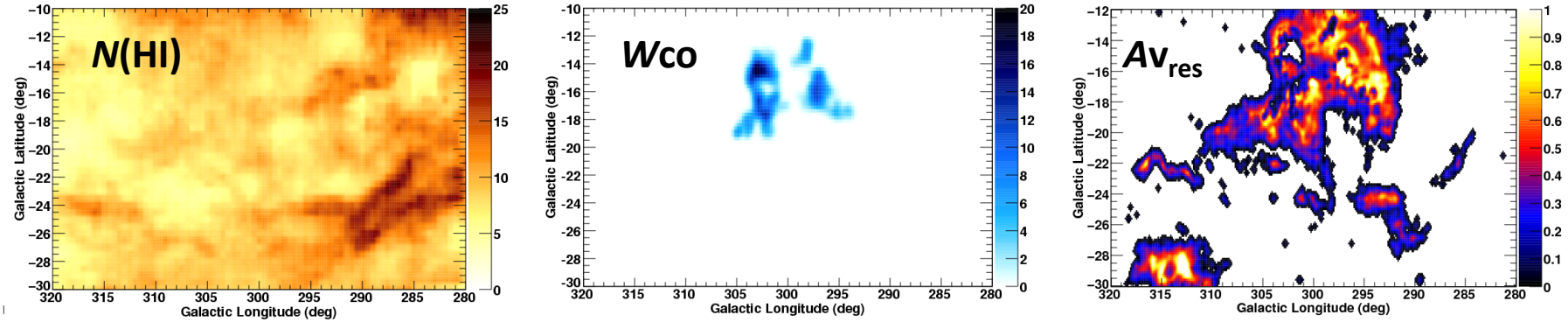
- Low-background event selection data (P6 Diffuse class) from Aug 2008 to May 2010
- Contour: intensity of CO 2.6mm line
- Cyan circles: point sources in 1FGL catalog (TS > 50)
- Yellow rectangle: region of interest
- Cyan rectangle: region in which point sources are taken into account in the analysis

Analysis Procedure (1)

Prepare template gas maps (HI, CO and dark gas) for each region

- ***N*(HI): LAB survey by Kalberla et al. (2005)**
  - **HI optical depth correction; spin temperature (*T*s) = 125 K**
  - **We examined maps with *T*s = (100K and optically-thin approximation) → evaluate the systematic uncertainty**
- ***W*co: composite survey by Dame et al. (2001)**
- **dark gas (Av_{res}): Derived from visual extinction (*A*v) map**
  - **Fitting with a linear combination of the *N*(HI) and *W*co maps**
  - **Av_{res} traces the gas that HI and CO collectively do not**

Gas maps for the Chamaeleon region



→ **Different spatial structures could be seen**

Analysis Procedure (2)

Fit the γ-ray data and obtained each gas emissivity (q_{HI}, q_{CO} and q_{Avres})

- **8 logarithmically spaced energy bins (250MeV--10GeV)**
- **Assuming that gas components are separable**

$$I(l,b,E) = \sum_{i=1}^{2} q_{HI} \times N(HI)(l,b) + q_{CO} \times Wco(l,b)$$
$$+ q_{Av_{res}} \times Av_{res}(l,b)$$
$$+ c_{IC} \times I_{IC}(l,b) + I_{iso} + \sum_{j} PS_j$$

- local (~<300 pc)
- the rest

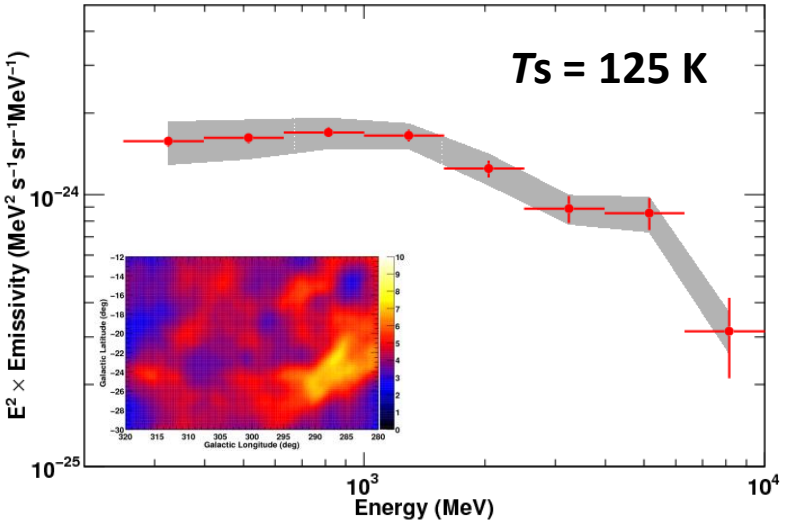
- **IC model (GALPROP model) :** the normalization is fitted
  Systematic uncertainty is examined by using several IC models

- **Isotropic component (Extra galactic diffuse + BGD) :** fixed
  Systematic uncertainty is examined by changing the intensity +/-10%

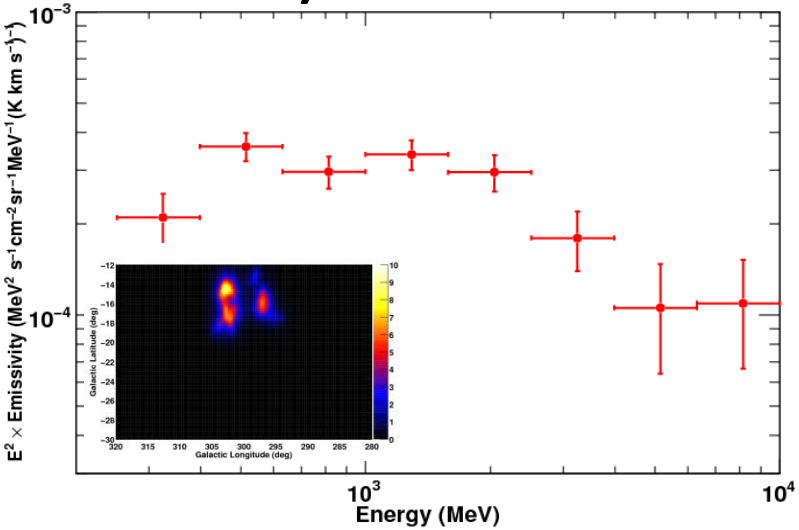
- **Point sources**: 1FGL catalog (TS>50)

γ-ray Emissivity Spectra and Maps (Chamaeleon region)

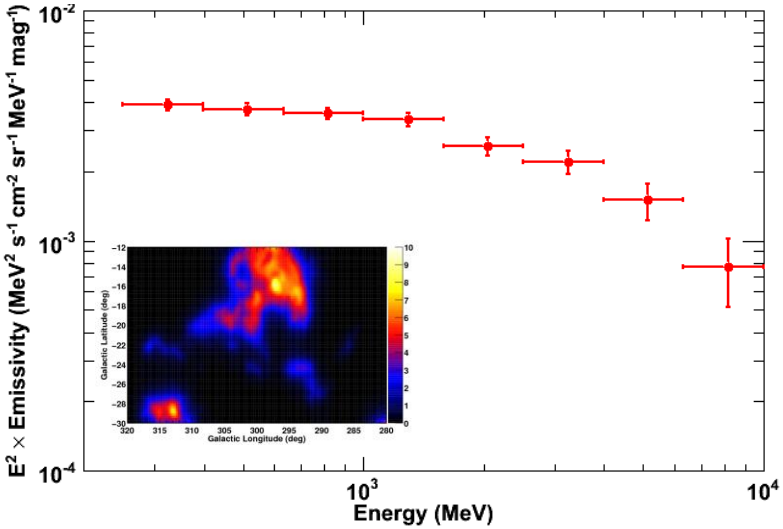
HI emissivity



CO emissivity

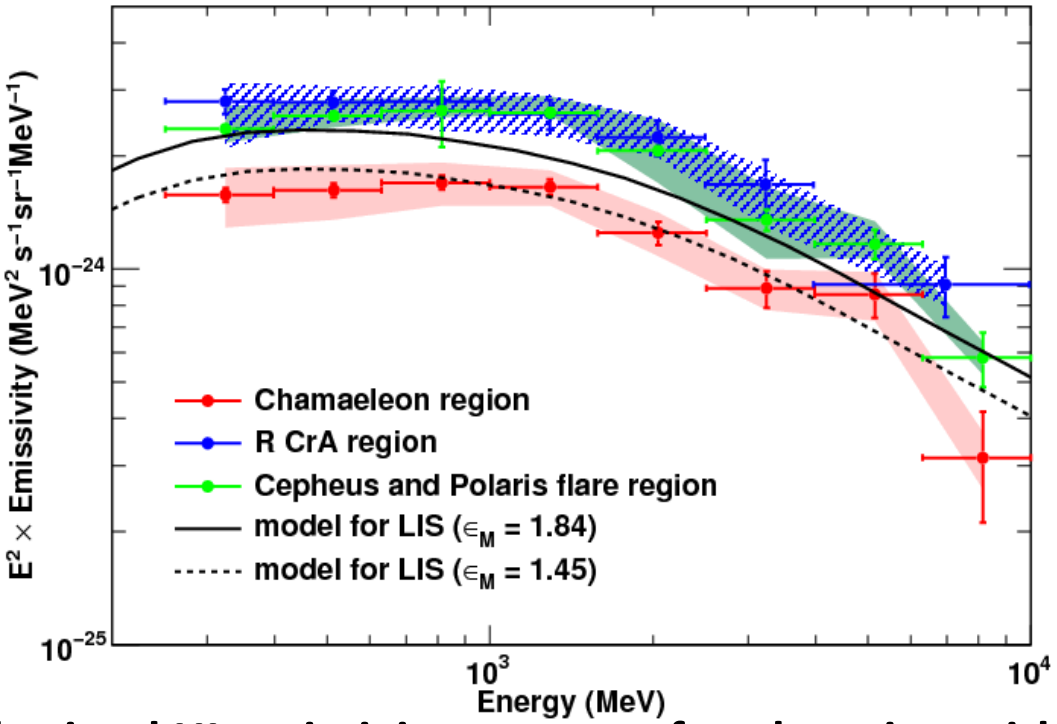


Av_{res} emissivity



- Shaded region: combined systematic uncertainty (~20%) due to the spin temperature, isotropic component, and IC model.
- Systematic uncertainties of the CO and Av_{res} emissivity spectra are smaller than the statistical error even if we take account of the systematic uncertainties described above.

CR Spectrum Close to the Solar System

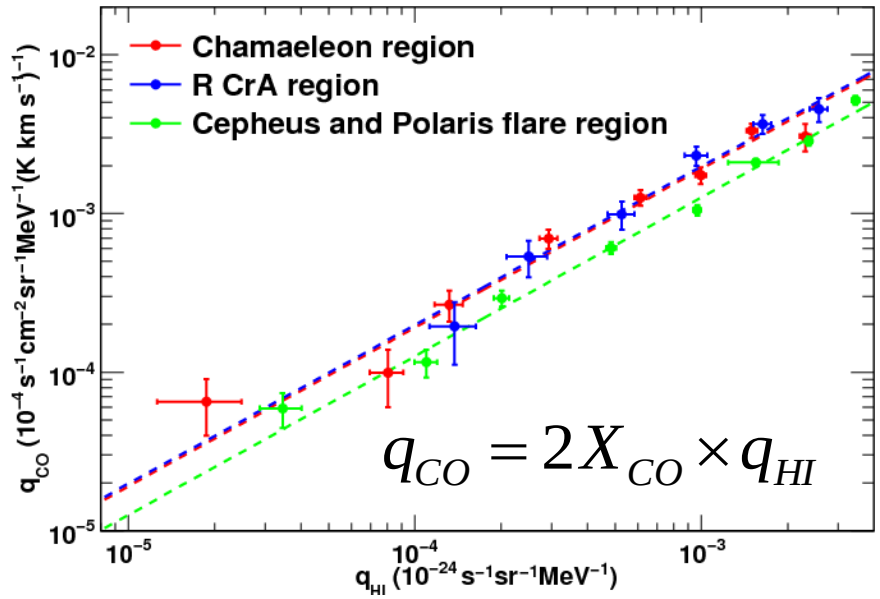


Compare the obtained HI emissivity spectra of each region with the LIS model (calculated from observed local interstellar spectrum assuming different nuclear enhancement factors (ε_M))

- **Spectral shapes are similar among them.**
- **Emissivities differ by ~20% even if we consider the systematic uncertainties.**

→ Small (<20%) variation in local interstellar CR densities (if we assume uniform CR composition)

*X*co and molecular cloud mass



	*X*co ($\times 10^{20}$cm^{-2}(K km s^{-1})$^{-1}$)
Chamaeleon	$0.96 \pm 0.06_{(stat)} \pm 0.13_{(sys)}$
R CrA	$0.99 \pm 0.08_{(stat)} \pm 0.14_{(sys)}$
Cepheus & Polaris	$0.63 \pm 0.02_{(stat)} \pm 0.08_{(sys)}$

	*M*co (M_{solar})	M_{Avres} (M_{solar})
Chamaeleon	~5×10^3	~2.0×10^4
R CrA	~10^3	~10^3
Cepheus & Polaris	~3.3×10^4	~1.3×10^4

$$M = 2\mu m_H d^2 Xco \int Wco(l,b) d\Omega$$

- LAT data suggest a variation of *X*co close to the solar system.
- Relation between the q_{HI} and q_{Avres} (X_{Avres}) is also calculated.
- Gas mass traced by CO and Av_{res} can be calculated with the *X*co and X_{Avres}.
- Dark gas mass estimated to be comparable or greater to gas mass traced by CO.

Conclusion

- We have studied the interstellar γ-ray emission from the molecular clouds of Chamaeleon, R CrA and Cepheus & Polaris regions close to the solar system using *Fermi* LAT data.
- We compared obtained γ-ray emissivity spectra among the regions and the LIS model, and obtained *X*co values.
  - → Small (< 20%) variation in local interstellar CR densities (assuming the uniform CR composition)
  - → Variation of *X*co close to the solar system and dark gas mass estimated to be comparable or greater to gas mass traced by CO.

To Do:

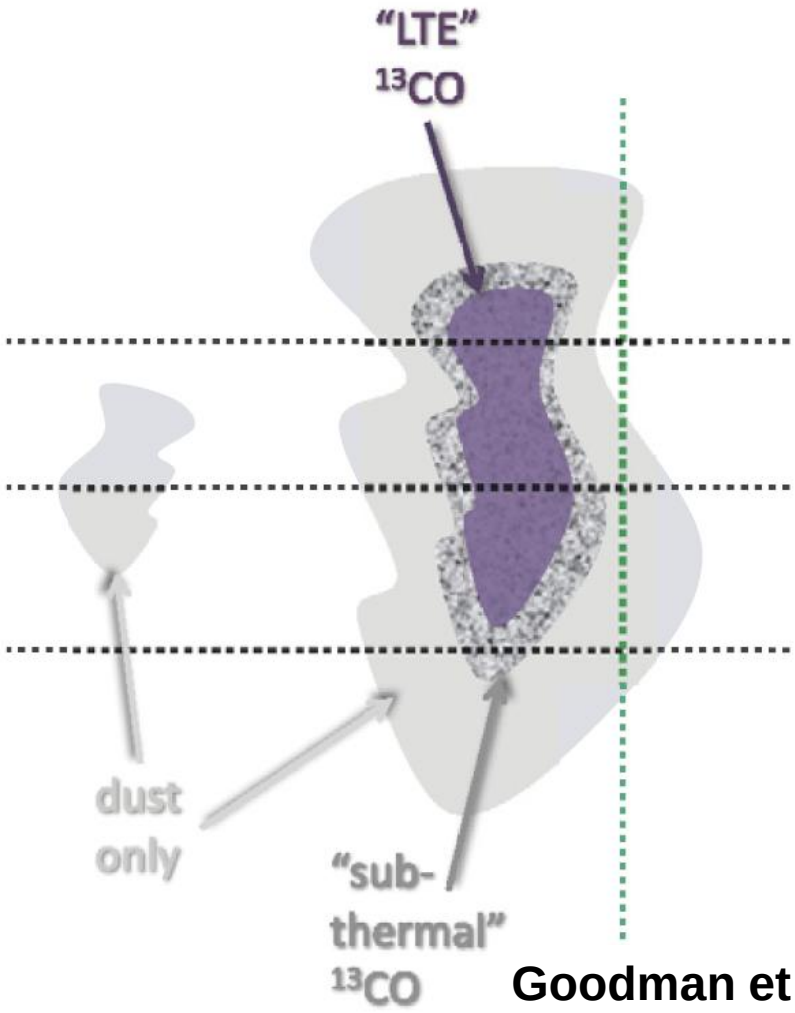
- Further investigation of the systematic uncertainty
  - Effects by the assumption that gas structures are separable
  - → Test by varying *X*co and gas-to-dust ratio (Av_{res} map)
- Investigate potential causes of the emissivity differences
  - e.g., relation with an evolutionary process of the Gould Belt

Back up

Gas of traced by Av_{res}

- Some fraction of gas is not detectable by 21 cm line (atomic hydrogen) and CO line (e,g., Grenier et al. 2005, Goodman et al. 2009)

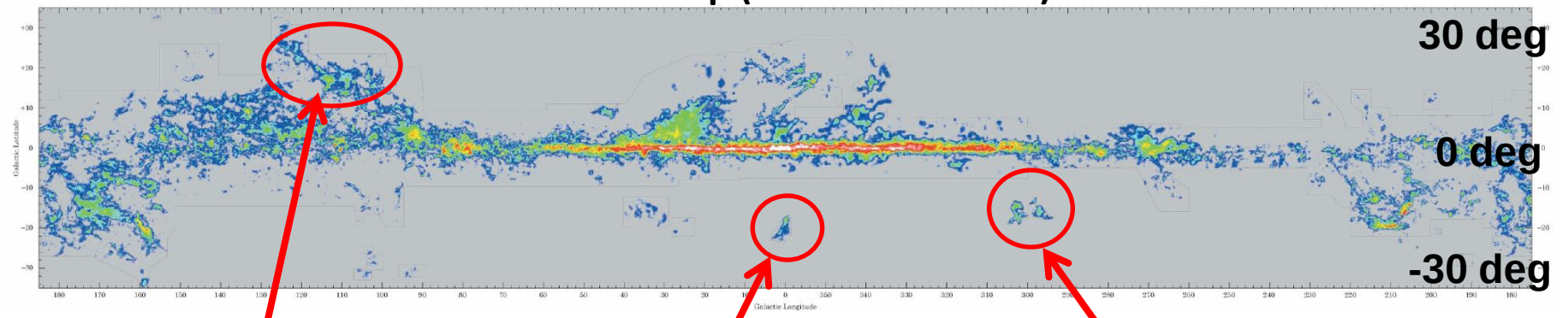
- We estimated their contribution from the emission of dust.

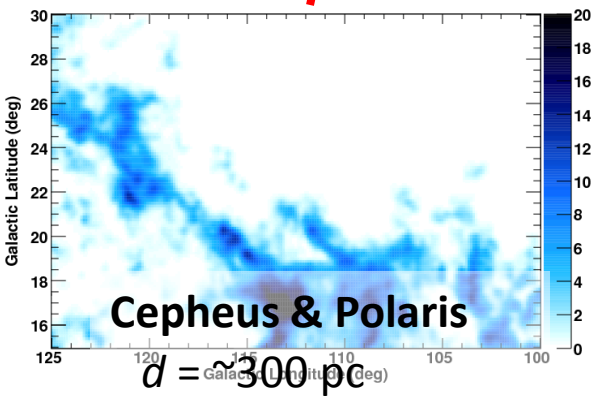


Goodman et al. 2009

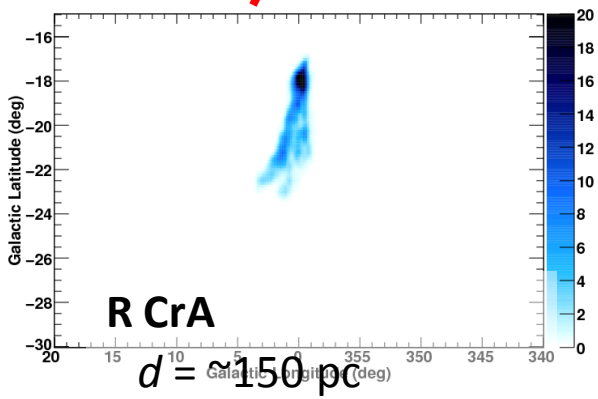
Target Molecular Clouds

2.6 mm CO map (Dame et al. 2001)

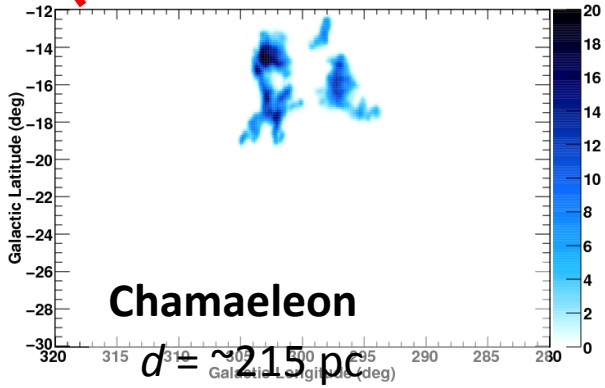




d = ~300 pc
M = ~40,000 M_{solar}
(Abdo et al. 2010)



d = ~150 pc
M = ~3,000 M_{solar}
(Dame et al. 1987)



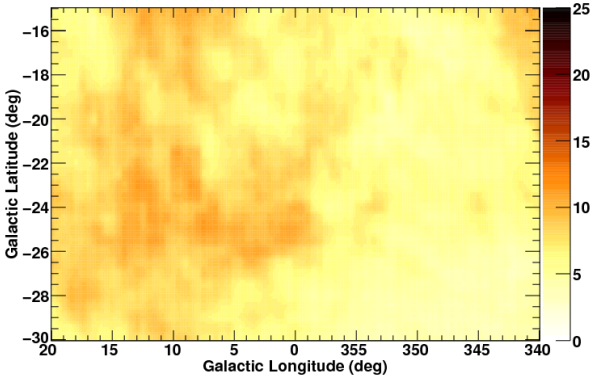
d = ~215 pc
M = ~10,000 M_{solar}
(Dame et al. 1987)

high latitude position → avoid confusion with the strong emission from the Galactic plane

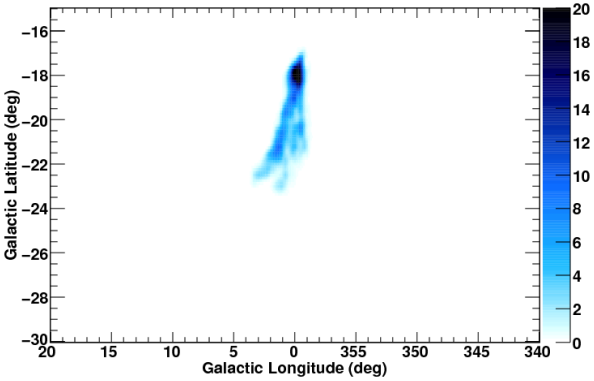
Template Gas Maps

R CrA region

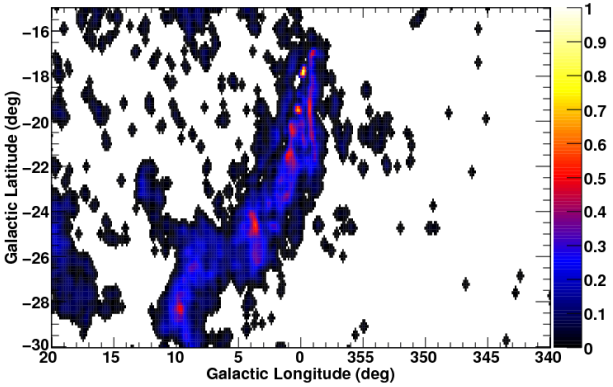
N(HI)



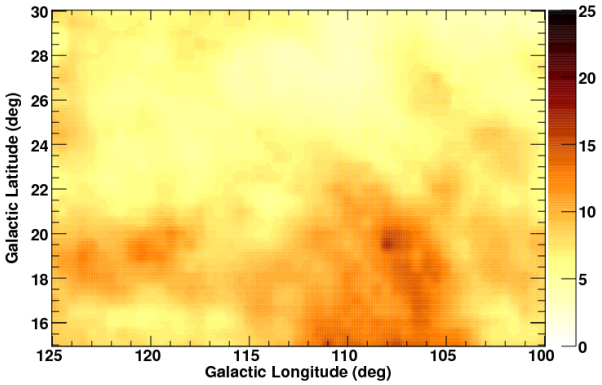
*W*co

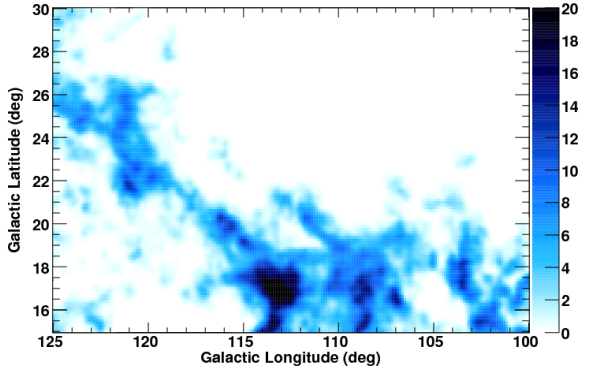


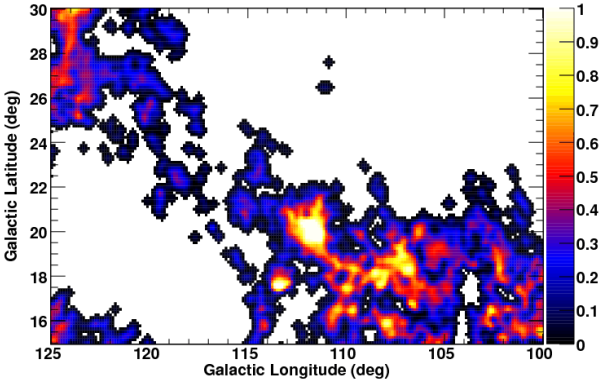
Av_{res}



Cepheus & Polaris region

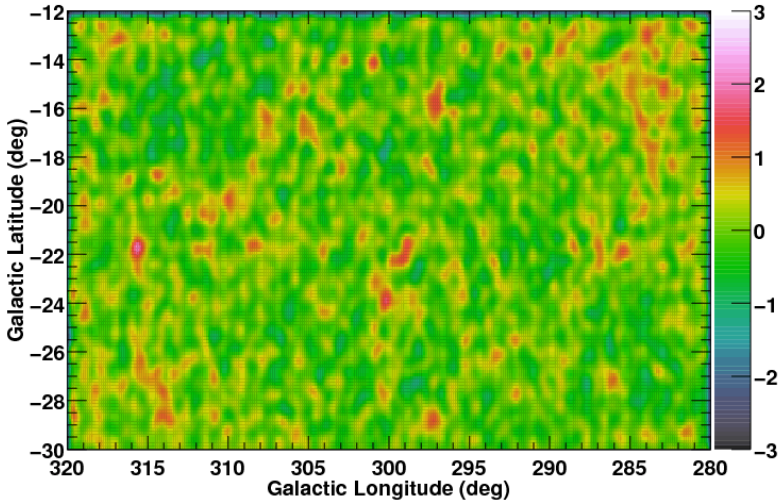




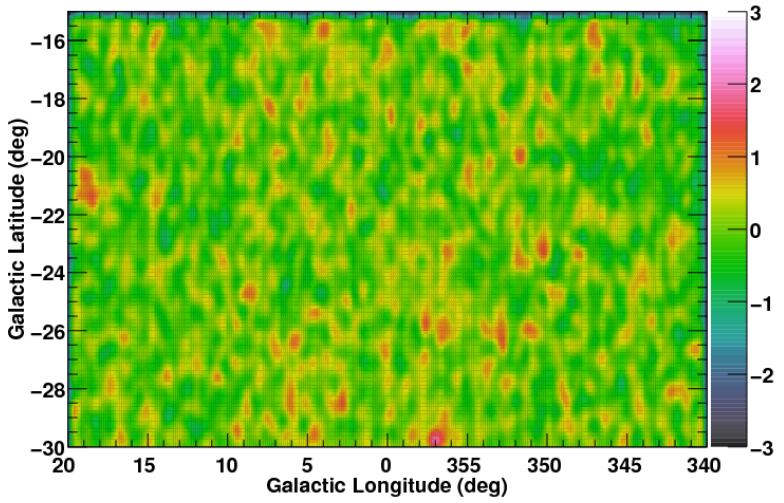


Residual Map

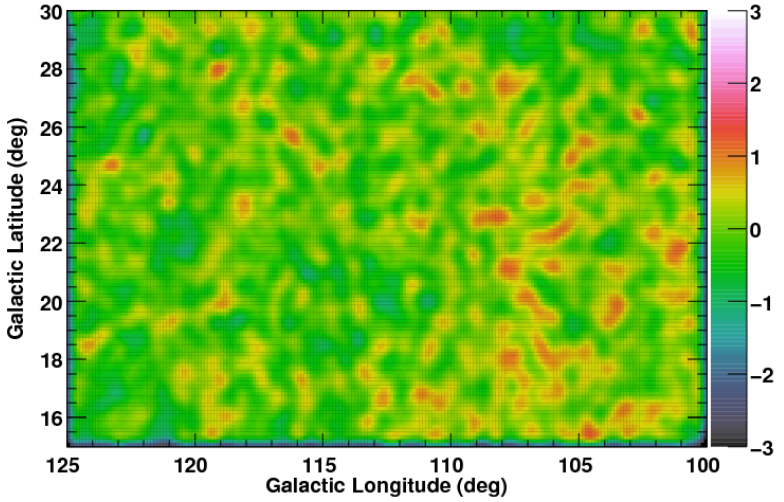
Chamaeleon



R CrA



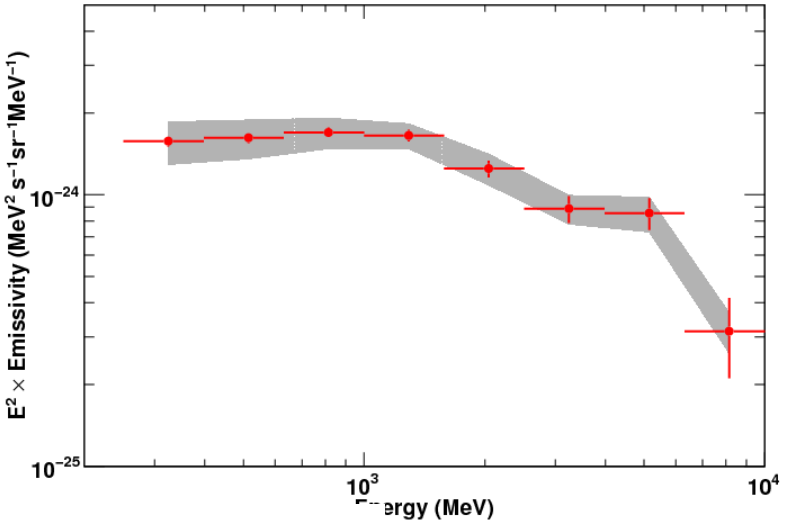
Cepheus & Polaris



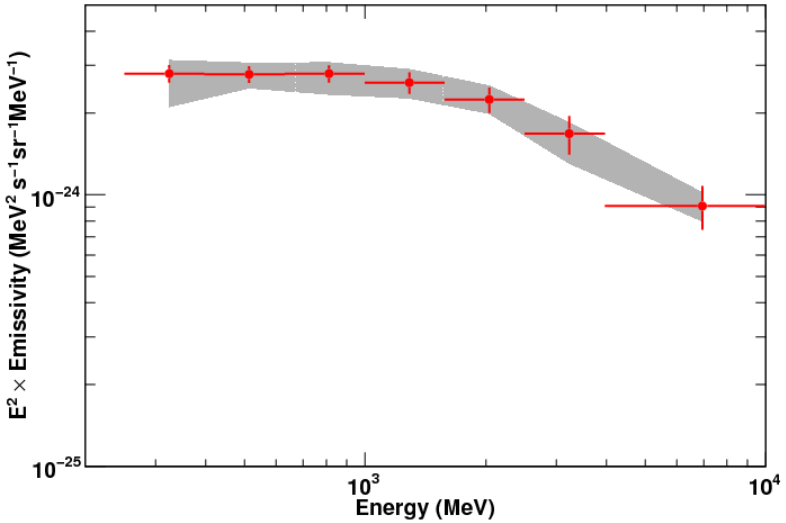
- No conspicuous structures → Our model reasonably reproduces the data, particularly the diffuse emission.

HI Emissivity Spectrum

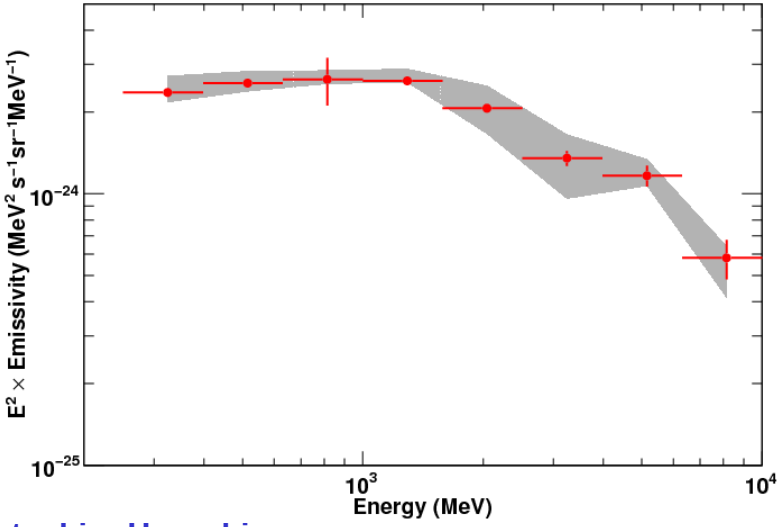
Chamaeleon



R CrA



Cepheus & Polaris



- γ-ray emissivity spectra with (*Ts*) = 125 K.
- The combined systematic uncertainty due to the spin temperature, isotropic component, and IC model is ~20%.
- Systematic uncertainty of the effective area does not affect the relative value of emissivities among three regions.

Derivation of CR density and *X*co

$$I(l,b,E) = q_{HI} \times N(HI)(l,b) + q_{CO} \times Wco(l,b) + \ldots$$

Gamma-ray flux

Emissivity of HI gas
→ CR density

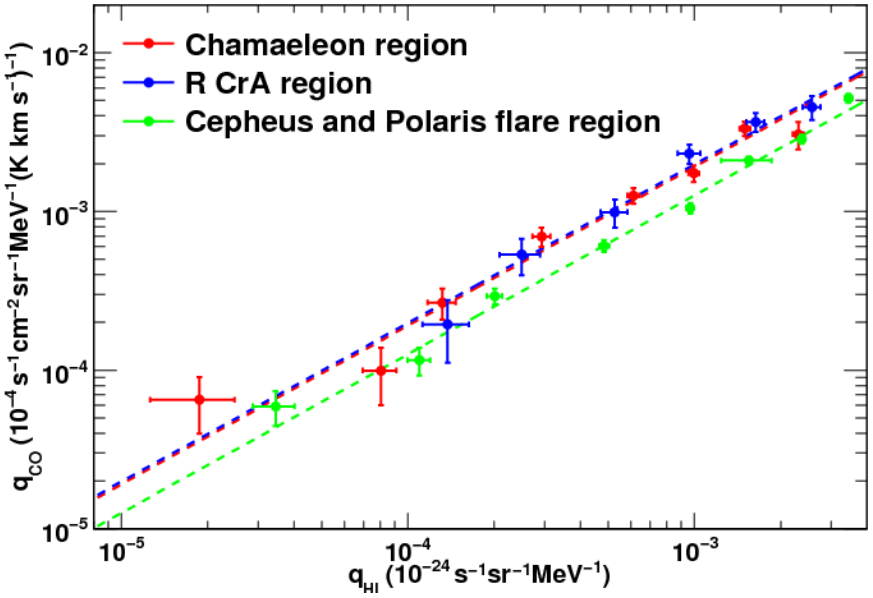
- **emissivity of H_2 gas (in unit of *W*co)**
- **emissivity of H_2 is 2 × emissivity of HI**

$$= q_{HI} \times N(HI)(l,b) + \underline{2 \times q_{HI} \times N(H_2)(l,b)} + \ldots$$

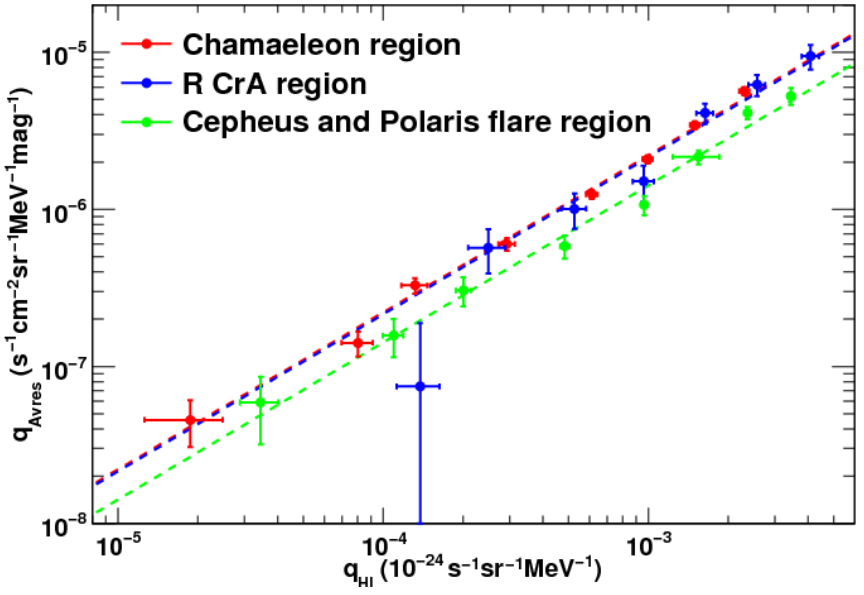
$$\therefore Xco \equiv \frac{N(H_2)}{Wco} = \frac{q_{CO}}{2 \times q_{HI}}$$

Relation of Gas Emissivities

q_{HI} vs. q_{CO}



q_{HI} vs. q_{Avres}



The linear relation supports that the GCRs penetrate molecular clouds uniformly to their cores.