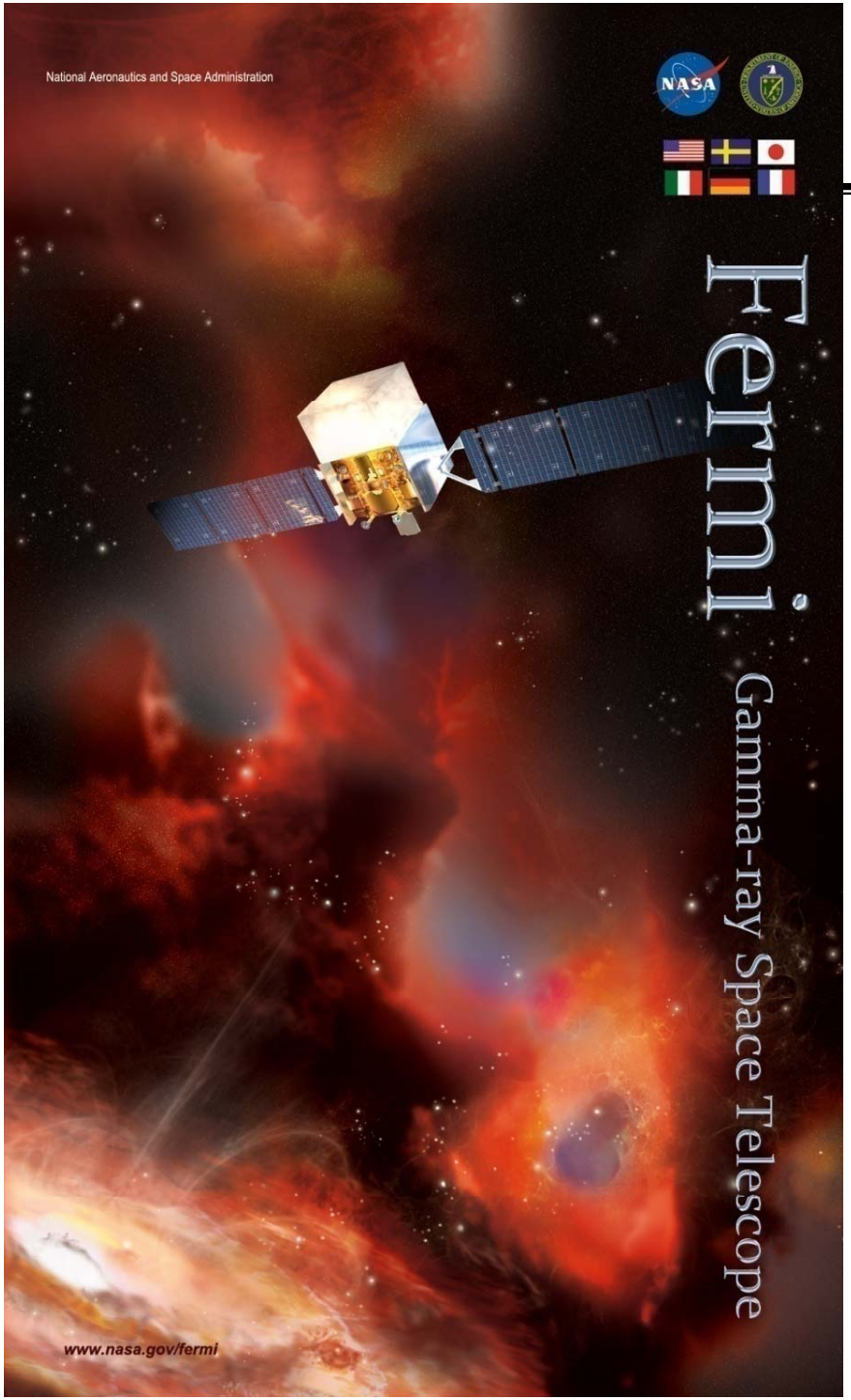


Diffuse Gamma-Rays seen by Fermi-LAT and Cosmic-Ray Distributions

Tsunefumi Mizuno
Hiroshima Univ.
on behalf of the Fermi-LAT Collaboration

18 March 2009, Ehime, Japan

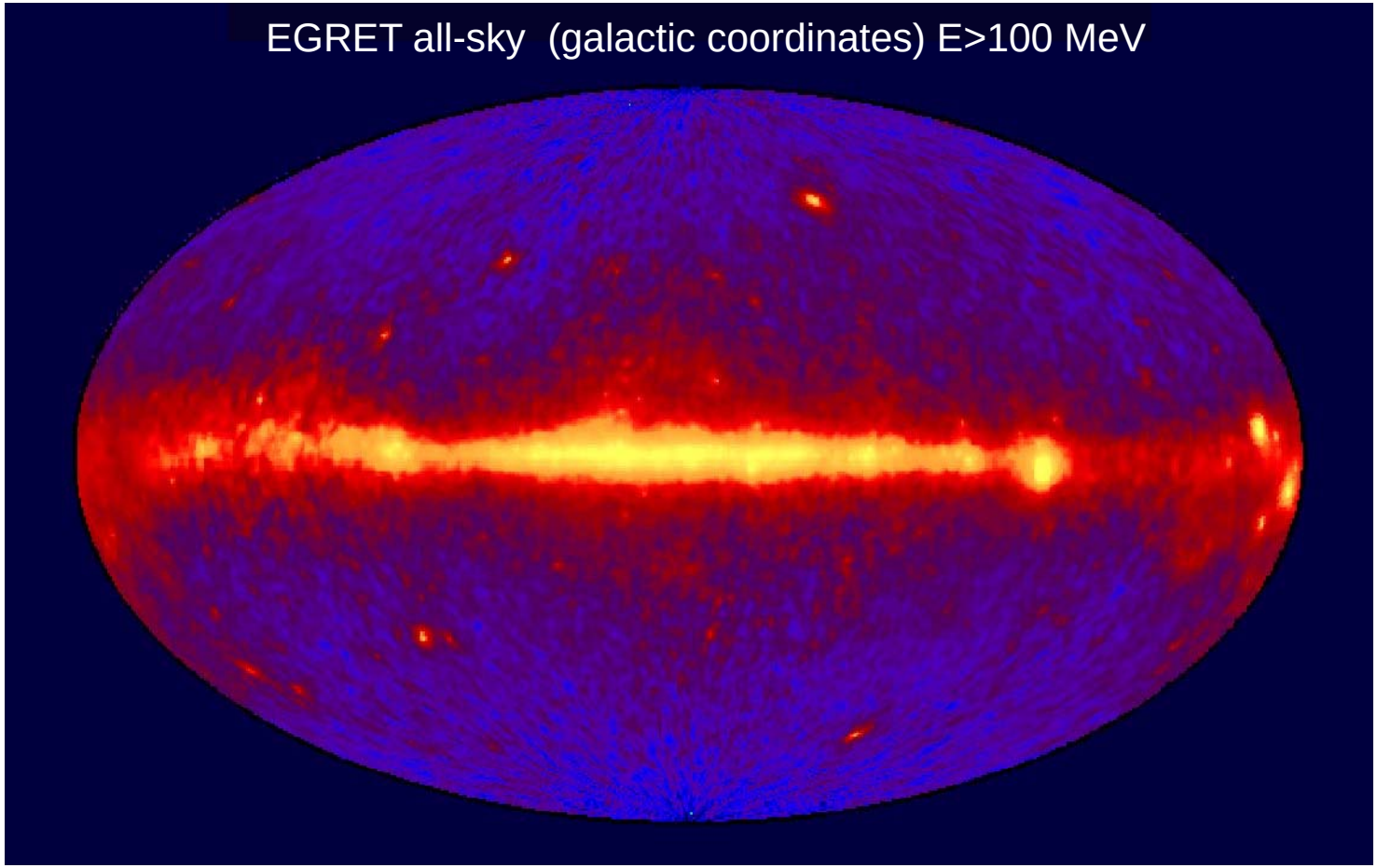
Short History of Gamma-ray Astronomy

- **Prediction of Gamma-rays**
  - ➢ **Feenberg & Primakoff (1948): inverse Compton scattering (photon & CR electron)**
  - ➢ **Hayakawa (1952): π^0-decay (matter & CR nucleon)**
  - ➢ **Hutchinson (1952): bremsstrahlung (matter & CR electron)**
  - ➢ **Morrison (1958)**
- **Early Observations**
  - ➢ **OSO-3 (1967-1968): First detection of gamma-rays from Gal. plane**
  - ➢ **SAS-2 (1972-1973)**] **map of the Gal. plane**
  - ➢ **COS-B (1975-1982)**] **study CR and matter distribution**

- **<u>Diffuse gamma-rays</u> has been one of main topics of gamma-ray astronomy since the beginning of its history**

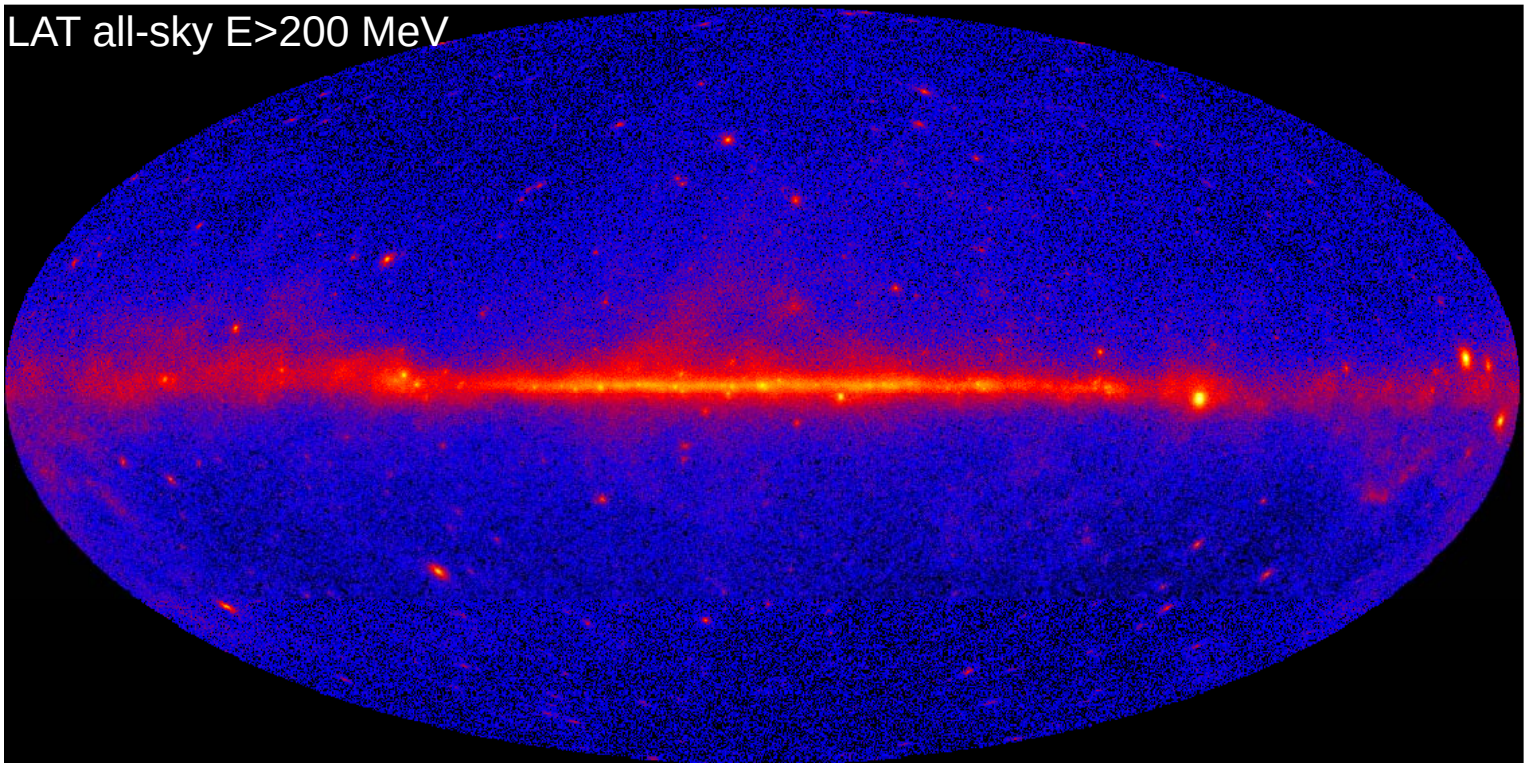
A powerful probe to study <u>cosmic-rays (CRs)</u> and the interstellar medium

EGRET, the Predecessor Instrument



- **1991-2000, 30 MeV-30 GeV**
  - ➢**resolved 271 gamma-ray sources (Hartman et al. 1999)**
  - ➢**detailed study of Galactic diffuse emission (Hunter et al. 1997) and extragalactic diffuse emission (Sreekumar et al. 1998)**

The LAT 3 Month All-Sky Map



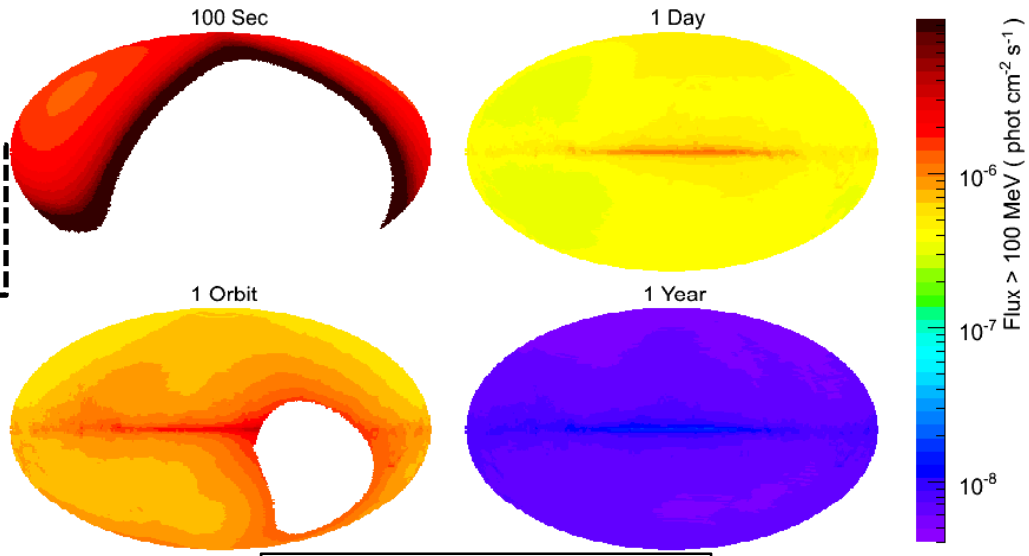
Diffuse emission ~80% total gamma-ray flux

- **The Fermi-LAT has already surpassed the EGRET in many aspects**
  - **More than 3 dozen pulsars (6 by EGRET)**
  - **205 bright sources and 444 above 5 σ (271 by EGRET) arXiv:0902.1340**
  - **exciting results on individual targets**
    CTA1, GRB080916C, Vela Pulsar, etc.

Performance of the Fermi LAT

- **Primary observing mode is Sky Survey**
  - **Full sky every 2 orbits (3 hours)**
  - **Uniform exposure, with each region viewed for ~30 minutes every 2 orbits**
  - **Best serves majority of science, facilitates multiwavelength observation planning**
  - **Exposure intervals commensurate with typical instrument integration times for sources**
  - **EGRET sensitivity reached in days**

sensitivity to point sources

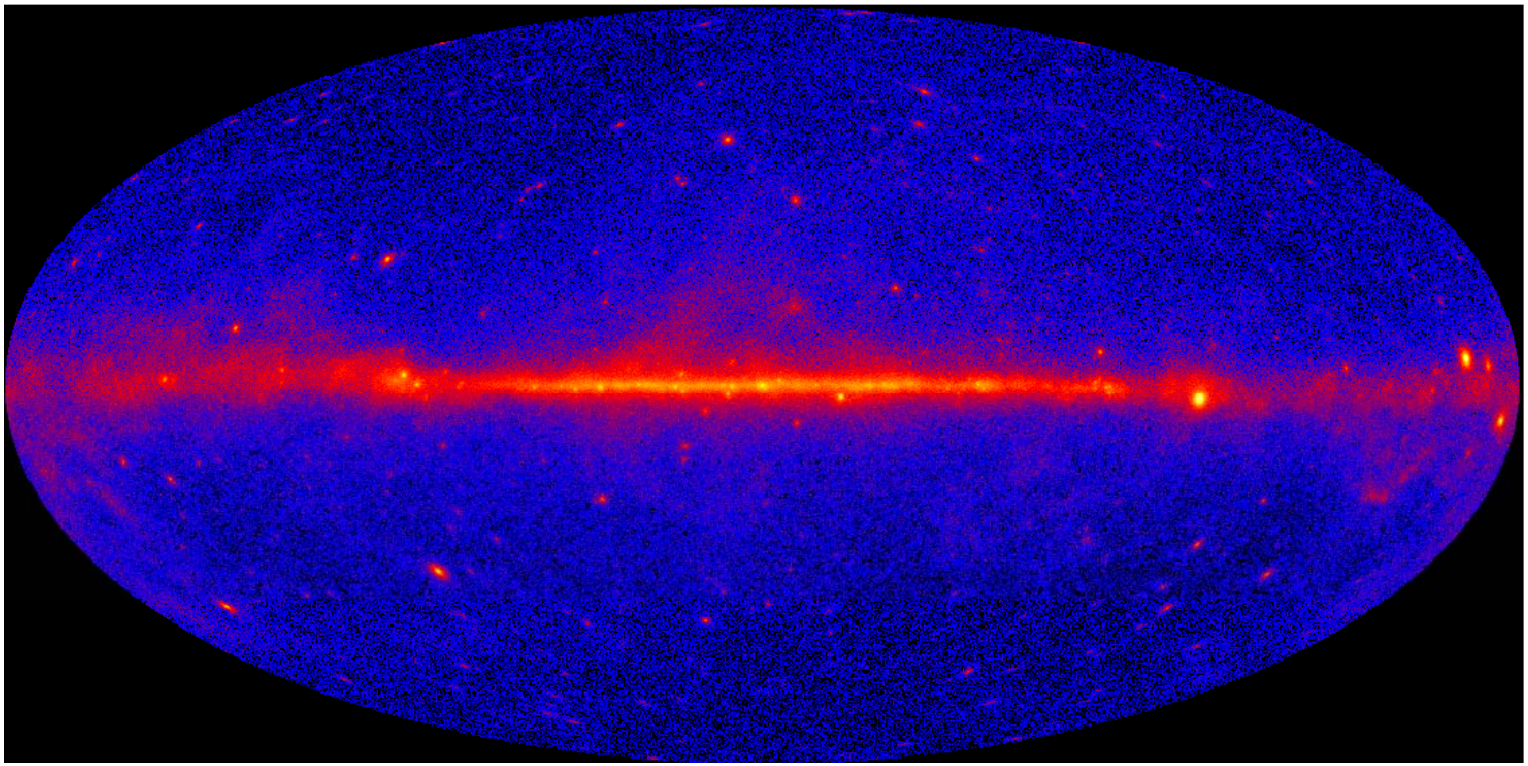


Atwood et al. (arXiv:0902.1089)

- **Large Field of View (2.4 sr)**
- **Large Effective Area (>=8000 cm^2 in 1-10 GeV)**
- **Good Angular Resolution (3.5deg@100 MeV and 0.6deg@1 GeV; 68% contaminant radii, best event class)**

Large FOV and uniform exposure: ideal for the study of diffuse gamma-rays

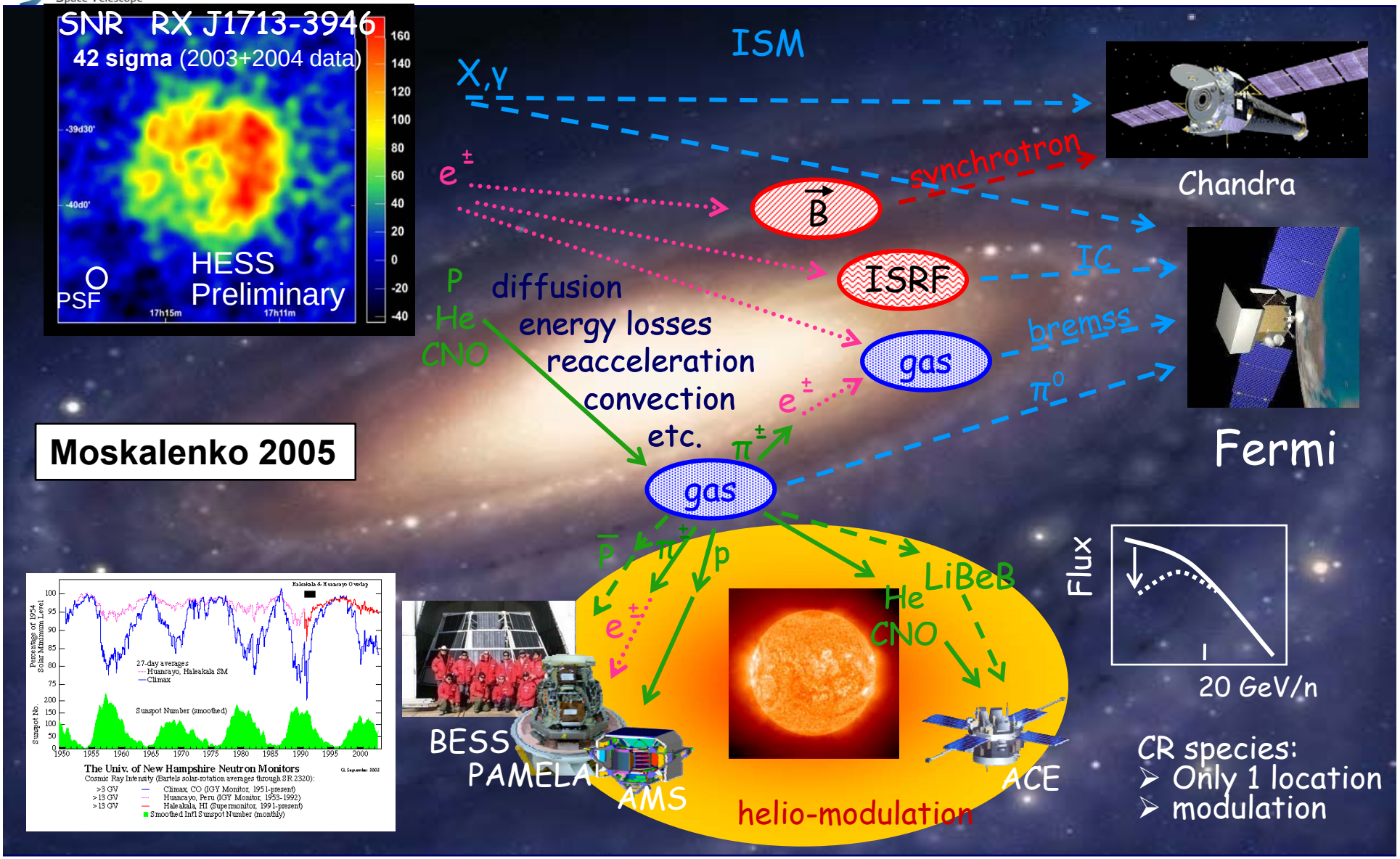
Plan of this Talk



1. Models to study diffuse gamma-rays
2. Mid-latitude region (GeV-excess)
3. Mid/high-latitude region (local CR flux and spectrum)
4. LMC (local group galaxy)

Models to Study Diffuse Gamma-rays: CR Propagation, Maps of Gas and ISRF

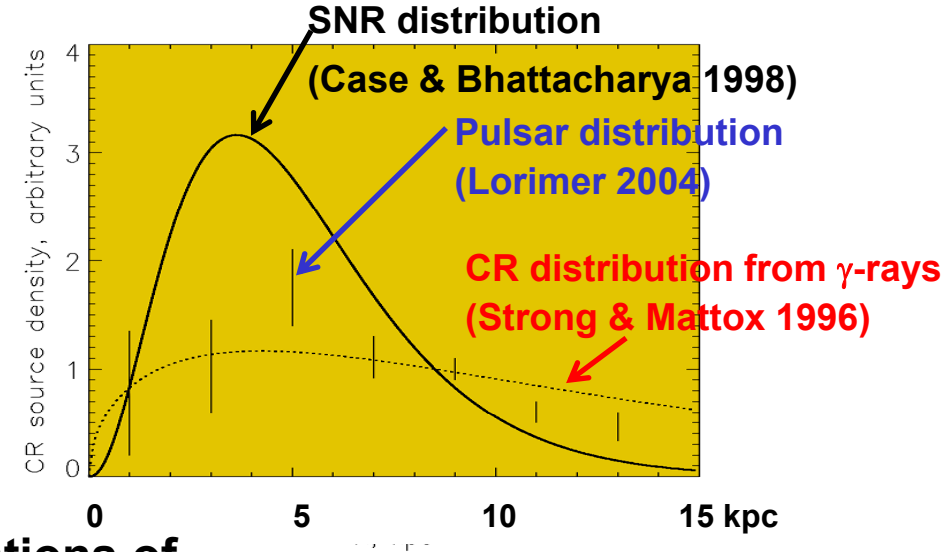
CR Interactions with the Interstellar Medium

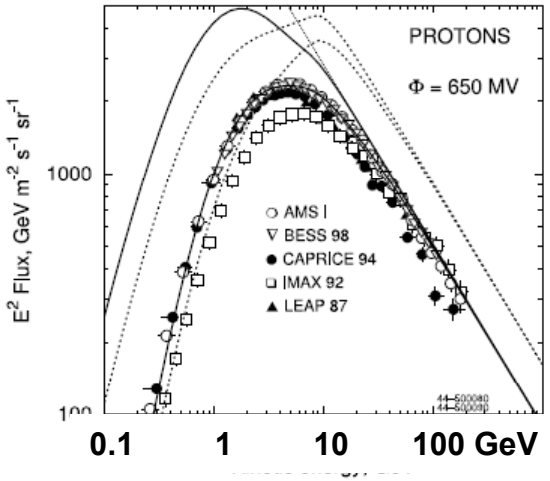


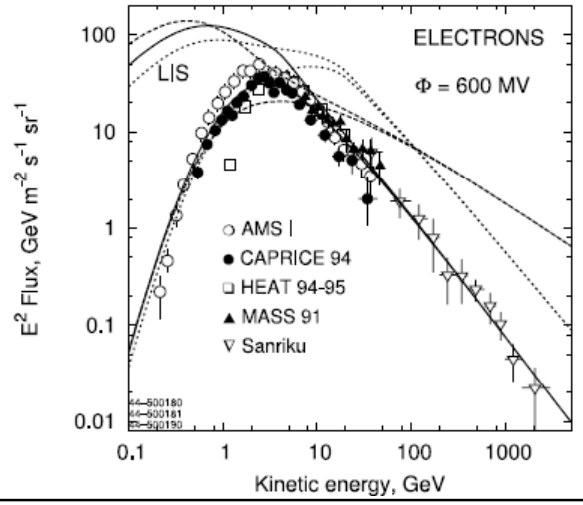
We need models of CR injection, CR propagation, ISRF, gas distribution and gamma-ray production

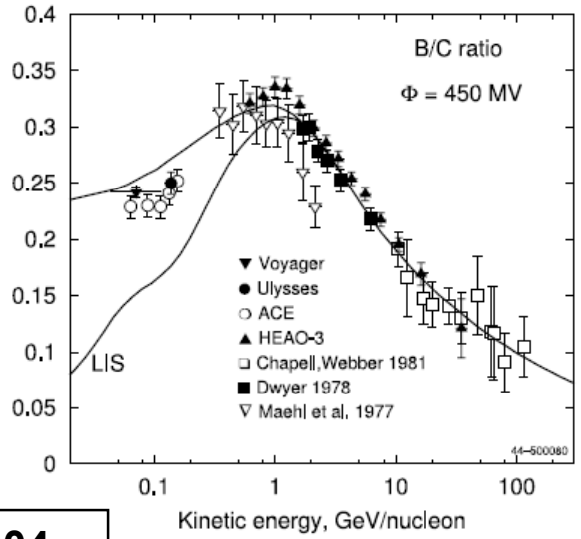
CR Injection/Propagation by GALPROP

- The cosmic-rays have to be accelerated
  - ➢ What are the accelerator?
    - ✓ SNR, pulsars, … ?
    - ✓ Affects the spatial distribution and spectra
- Propagation through the galaxy
  - ➢ Diffusion coefficients, secondary production, energy losses, …
    - ✓ Determined from local observations of cosmic-rays





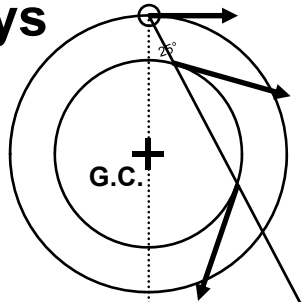




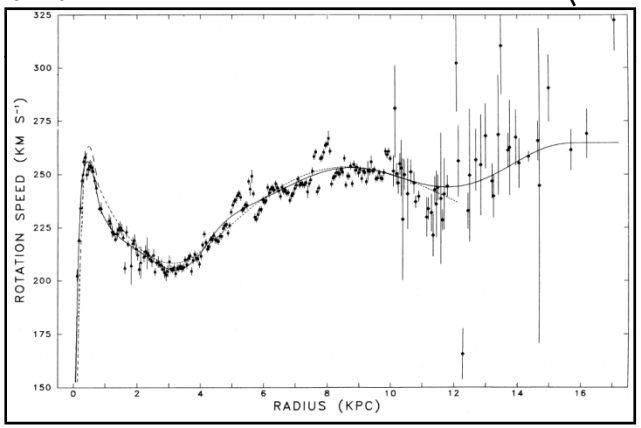
Strong, Moskalenko & Reimter, 2004

Model Gas Maps

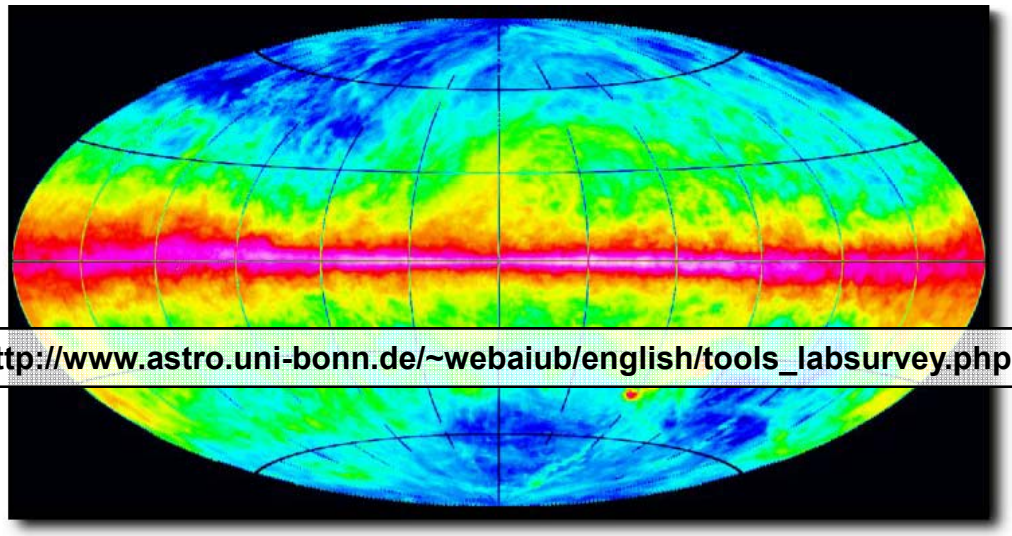
- **Gas distribution determined from radio surveys**
  - ➢**velocity => distance through a rotation curve**



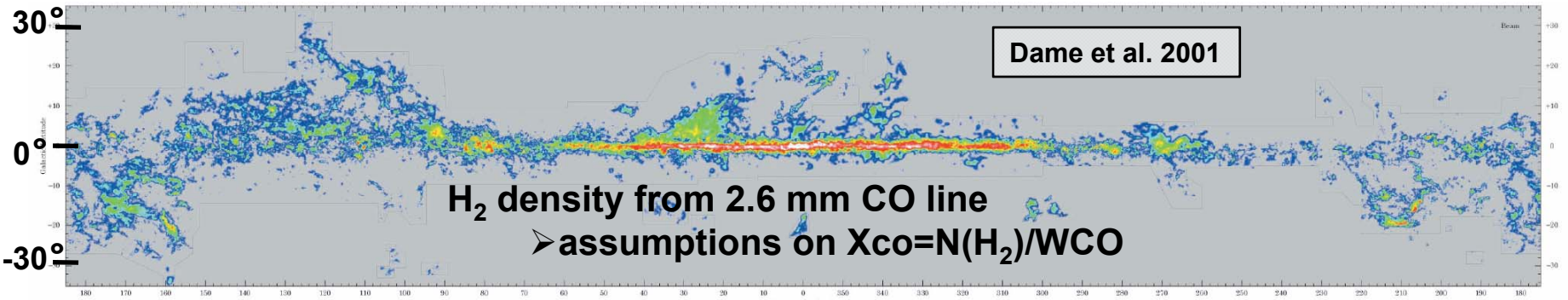
Clements(1985)
(R_0,v_0)=(8.5 kpc, 220 km/s)



HI density from LAB survey
- ➢**Opacity correction needed especially close to Gal. plane**



http://www.astro.uni-bonn.de/~webaiub/english/tools_labsurvey.php



Dame et al. 2001

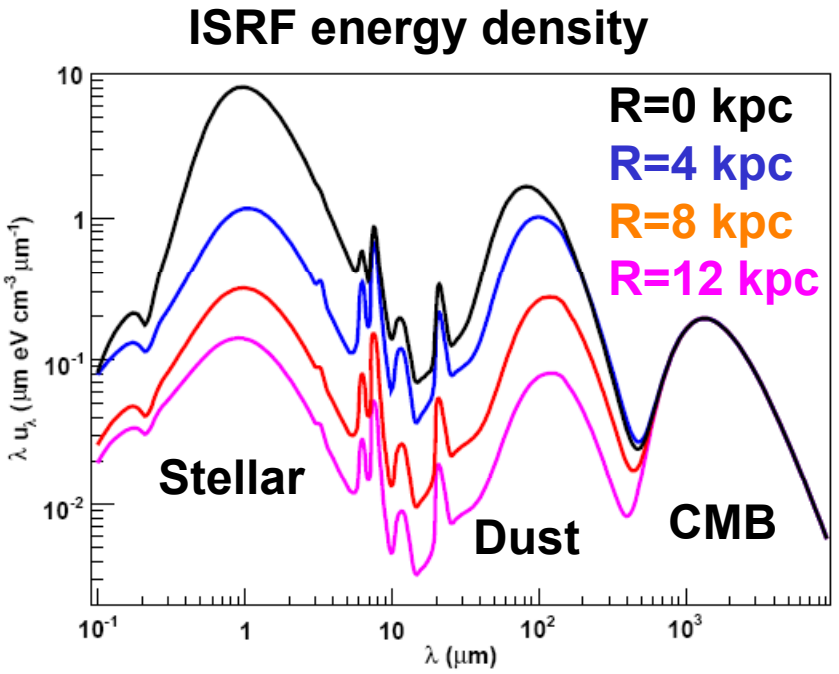
H_2 density from 2.6 mm CO line
- ➢**assumptions on Xco=N(H_2)/WCO**

target for producing gamma-rays through π^0-decay and electron bremsstrahlung

InterStellar Radiation Field

- CR e^+/e^- need targets to create g-rays
  - Interstellar radiation field determined from a realistic model taking into account stellar and dust distribution
    - ✓Starlight (~ 0.1 μm – 10 μm)
    - ✓Dust (~ 10 μm – 300 μm)
    - ✓CMB (>300 μm)

There are systematic uncertainties associated with gas and ISRF!



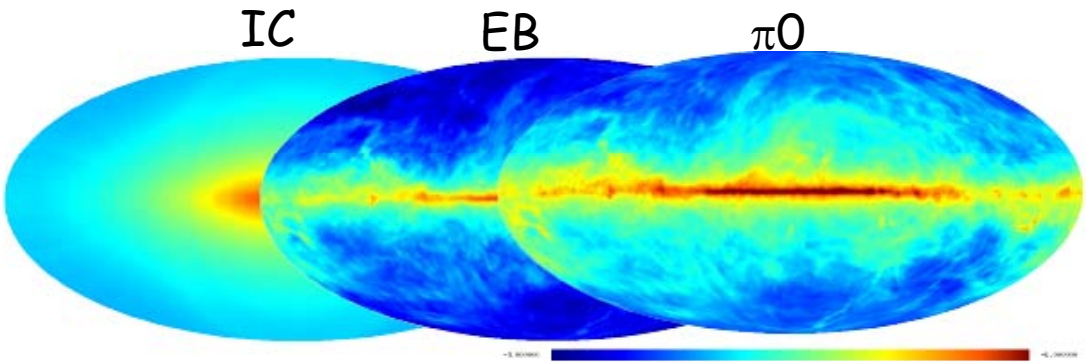
Porter et al. 2008

Fermi-LAT Diffuse Analysis

Distribution of ISM
HI/CO surveys, ISRF model
+ spatial mapping of ISM
+ conversion to HI/H_2 column density

Galactic gamma-ray emissivities
• from GALPROP cosmic-ray propagation
• derived from data for special regions

Line-of-sight integration (by GALPROP) to create gamma-ray flux map for indivicual



- emission processes
- ISM components
- galactocentric annuli

γ-ray model map has been used for point source and diffuse analyses

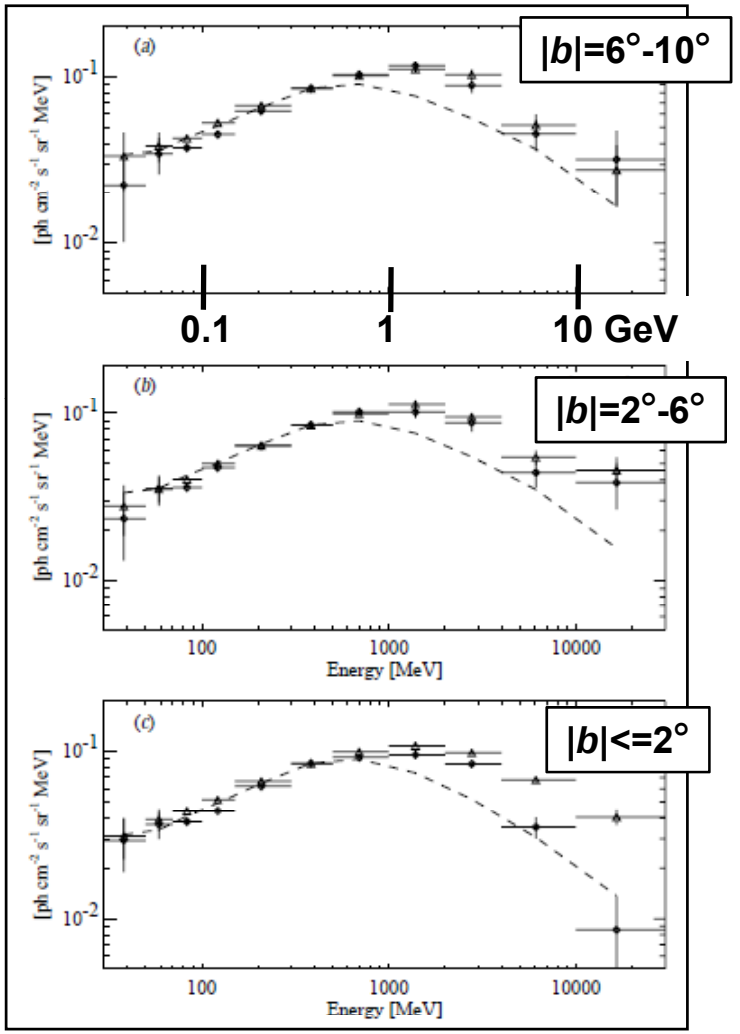
- already provided lots of exciting results on individual targets
- possible uncertainties (or improvement)
  - ➢CR source distrubution, CR propagation
  - ➢optical depth correction (HI), Xco (H_2), ISRF
  - ➢dark gas (Grenier et al. 2005)

} Deviations from input model used to iteratively improve the diffuse model

Mid-Latitude Region (|*b*|=10°-20°): GeV Excess?

EGRET GeV Excess (1)

- EGRET observations showed **excess** emission > 1 GeV when compared with cosmic-ray propagation models based on local cosmic-ray nuclei and electron spectra
- Variety of possible explanations
  - Variations in cosmic-ray spectra over Galaxy
  - Unresolved sources (pulsars, SNRs, …)
  - Dark matter
  - Instrumental

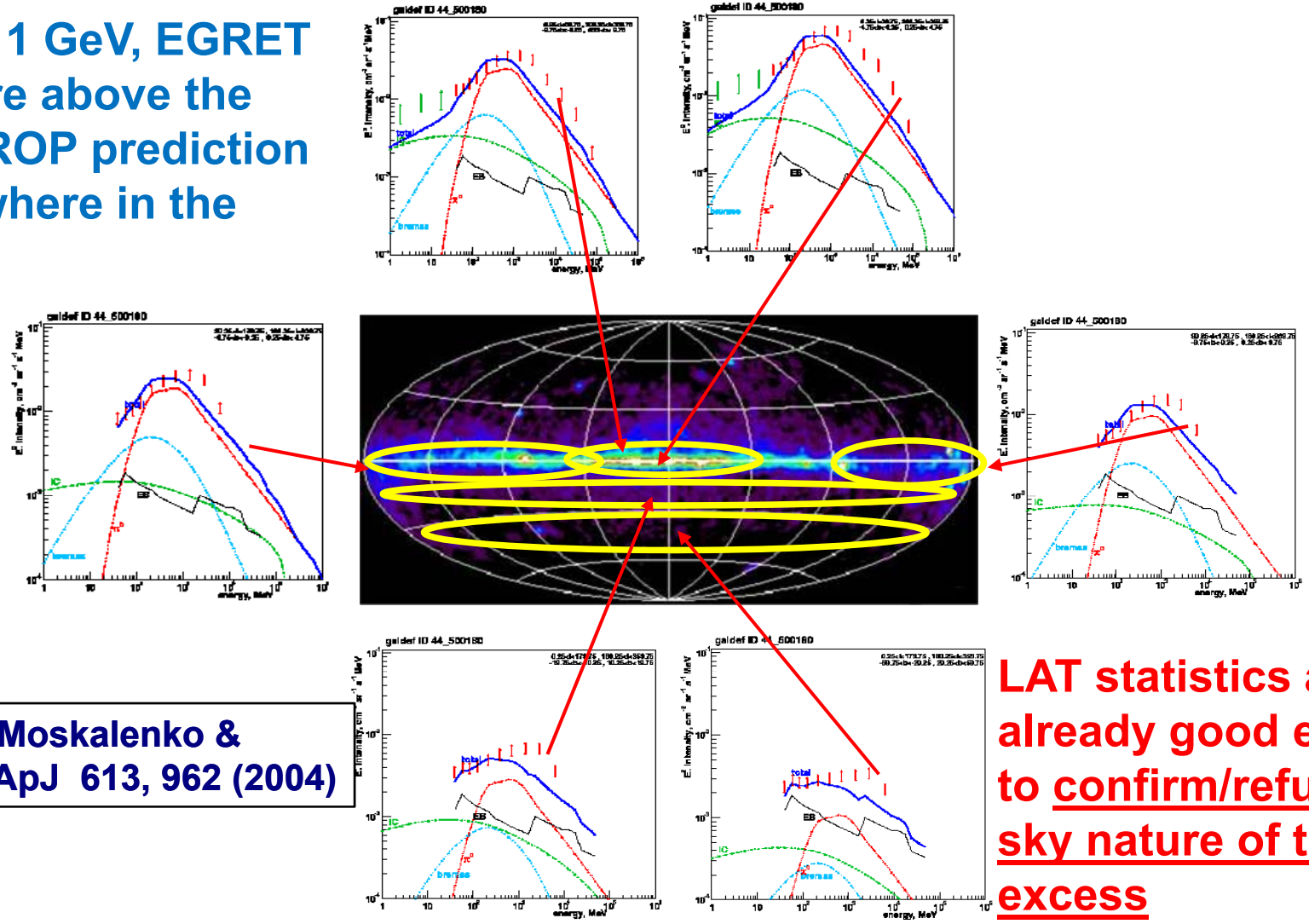


~100% difference above 1 GeV

Hunter et al. 1997

EGRET GeV Excess (2)

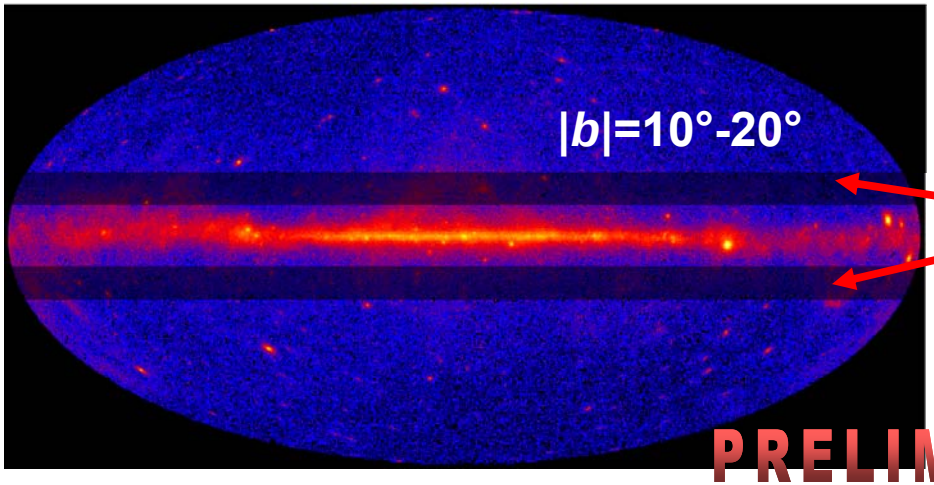
Above 1 GeV, EGRET data are above the GALPROP prediction everywhere in the sky

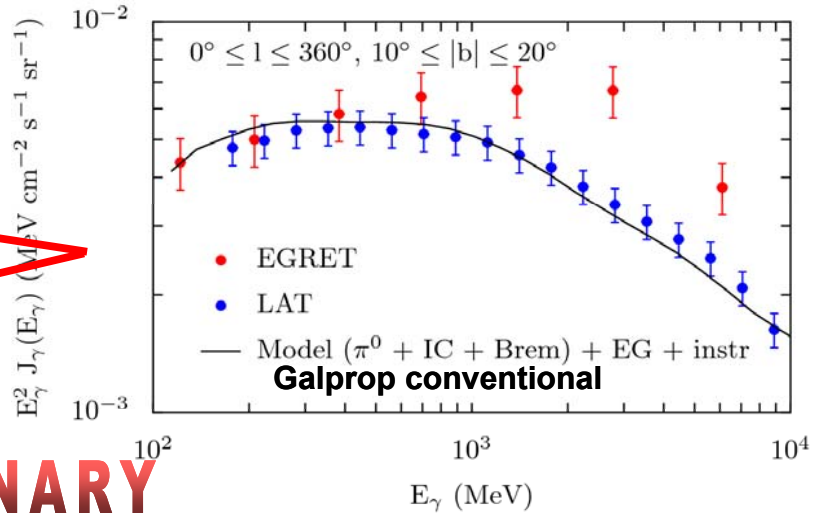


Strong, Moskalenko & Reimer ApJ 613, 962 (2004)

LAT statistics are already good enough to confirm/refute all-sky nature of this excess

The Fermi LAT View (1)





PRELIMINARY

- Spectra shown for mid-latitude range => GeV excess in this region of the sky is not confirmed.
- Sources are not subtracted but are a minor component.
- LAT errors are dominated by systematic uncertainties and are currently estimated to be ~10% -> this is preliminary
- EGRET data is prepared as in Strong, et al. 2004 with a 15% systematic error assumed to dominate (Esposito, et al. 1999)
- EG+instrumental is assumed to be isotropic and determined from fitting the data at at $|b| > 10°$.

Fermi-LAT View (2)

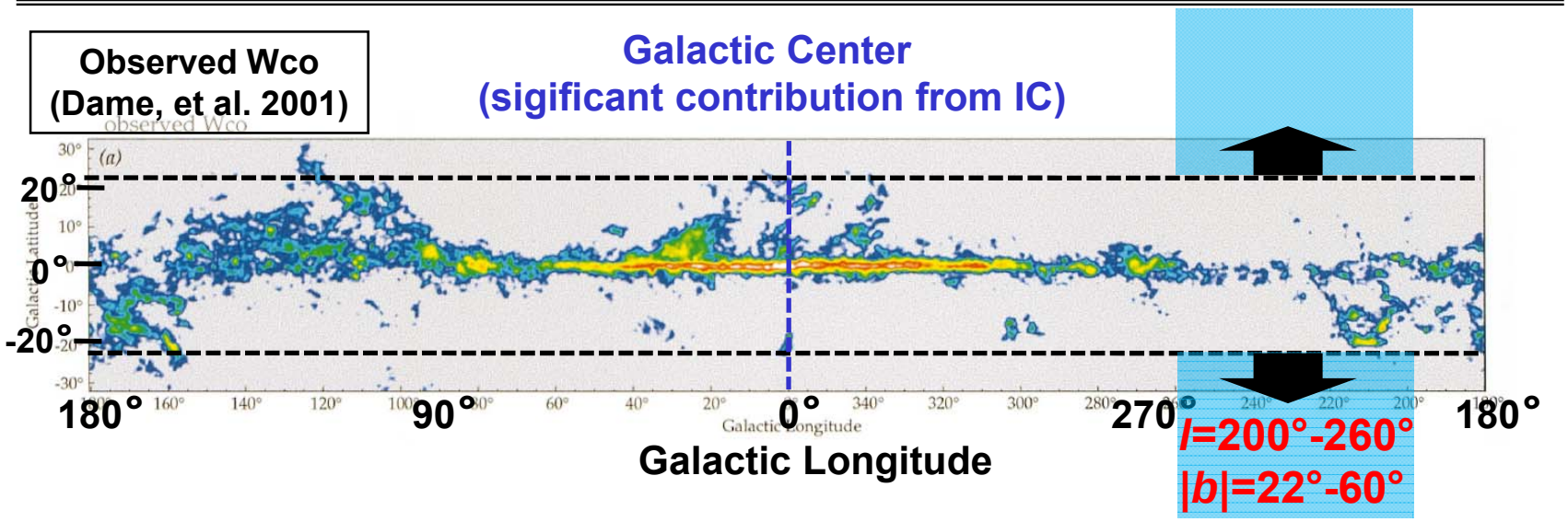
- **Intermediate latitude gamma-ray spectra can be explained by cosmic-ray propagation model consistent with locally measured cosmic-ray nuclei and electron spectra. The EGRET GeV excess is not seen in this region of the sky (|*b*|=10°-20°) with the LAT.**

- **LAT spectrum of Vela (Abdo et al. arXiv:0812.2960) also confirms that the EGRET GeV excess is instrumental.**

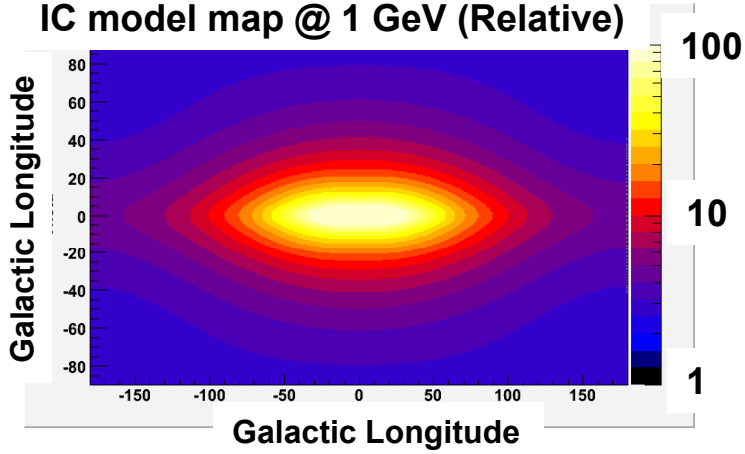
- **Work to analyze and understand diffuse emission over the entire sky is in progress.**

Mid/High-Latitude Region (|*b*|=22°-60° in Third Quadrant): Local CR Flux and the Spectrum

Study of Local CRs using HI



- **Away from the Galactic Center and the Plane:**
  - ➢Small contribution from IC and point sources
  - ➢Less affected by H_2 (uncertainty of Wco)
  - ➢Small optical depth correction
  - ➢Most of HI gas is close to solar system

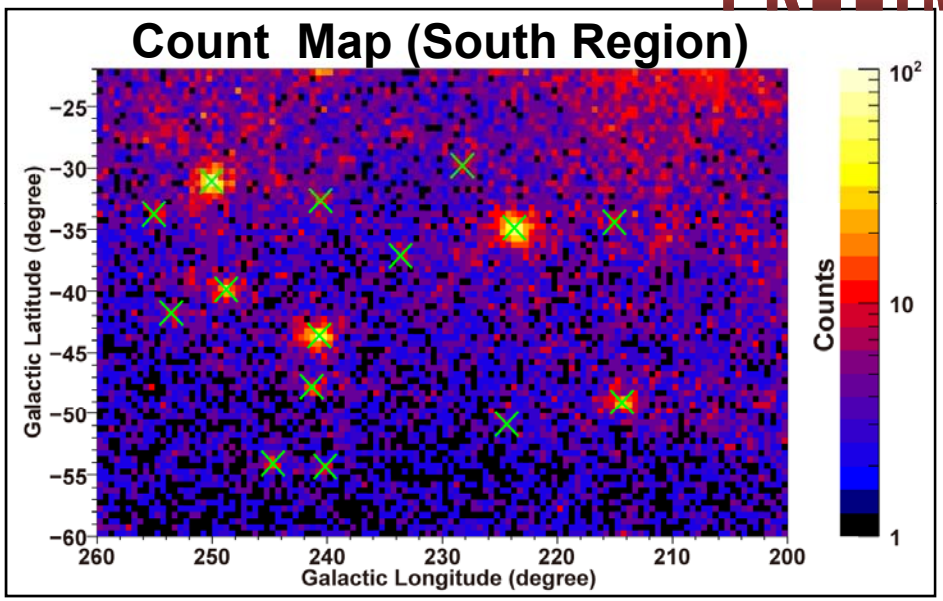


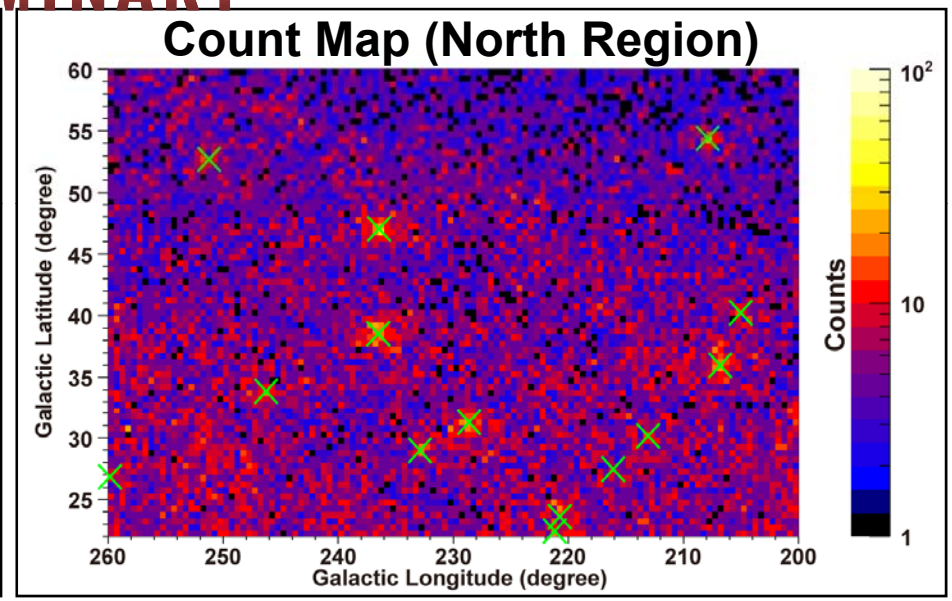
Measurement of HI emissivity <u>constrains the local CR flux and the spectrum</u>

Gamma-ray Count Maps

Count maps in E>=200 MeV, accumulated from Aug. 4 to Oct. 30

PRELIMINARY

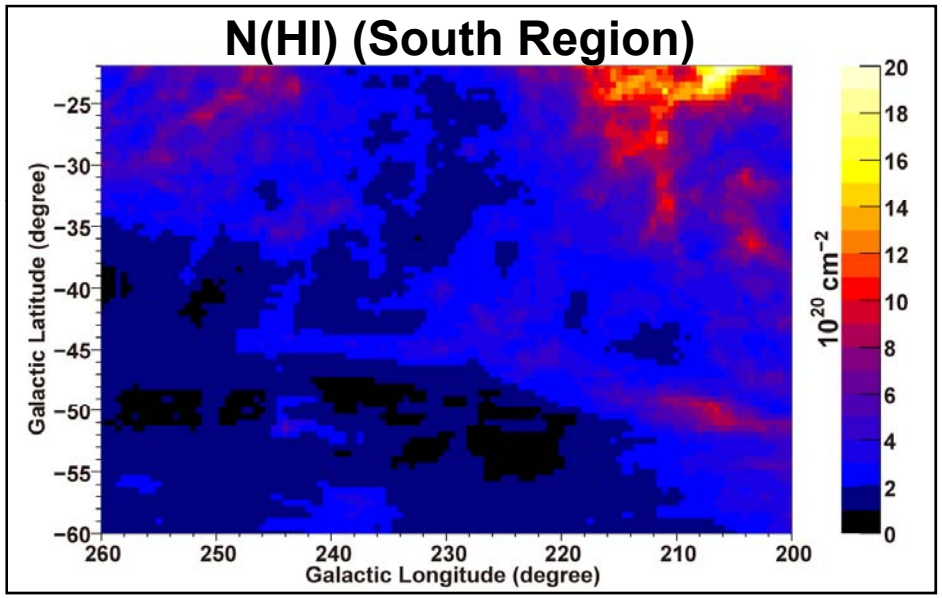


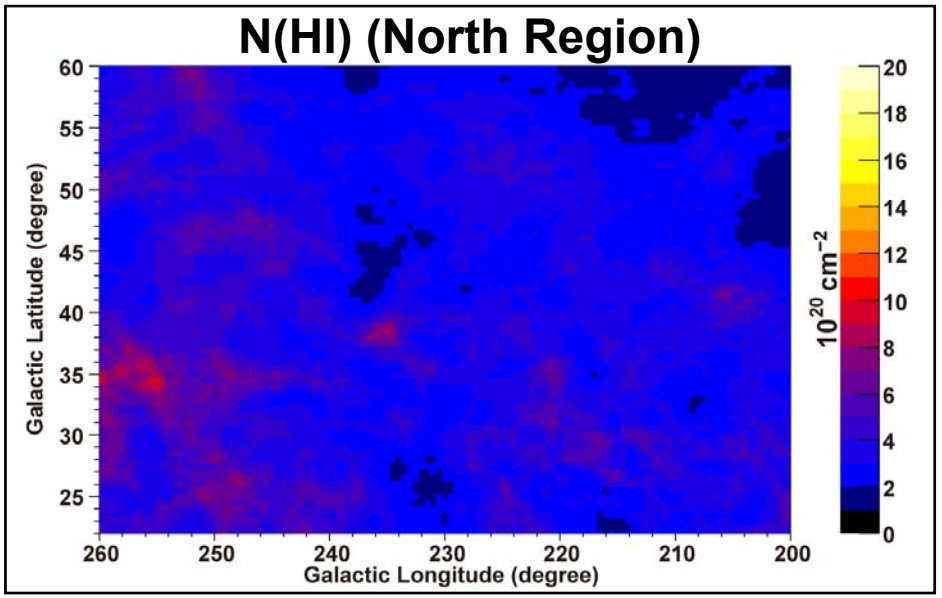


- **The Fermi-LAT has already tripled the number of known gamma-ray sources (29 by LAT three month catalog and 9 in EGRET 3rd catalog).**
  - **The diffuse spectrum by Fermi-LAT is less affected by unresolved sources than early missions.**

Column Density of Atomic Hydrogen

Column density maps of HI gas (w/ optical depth correction)

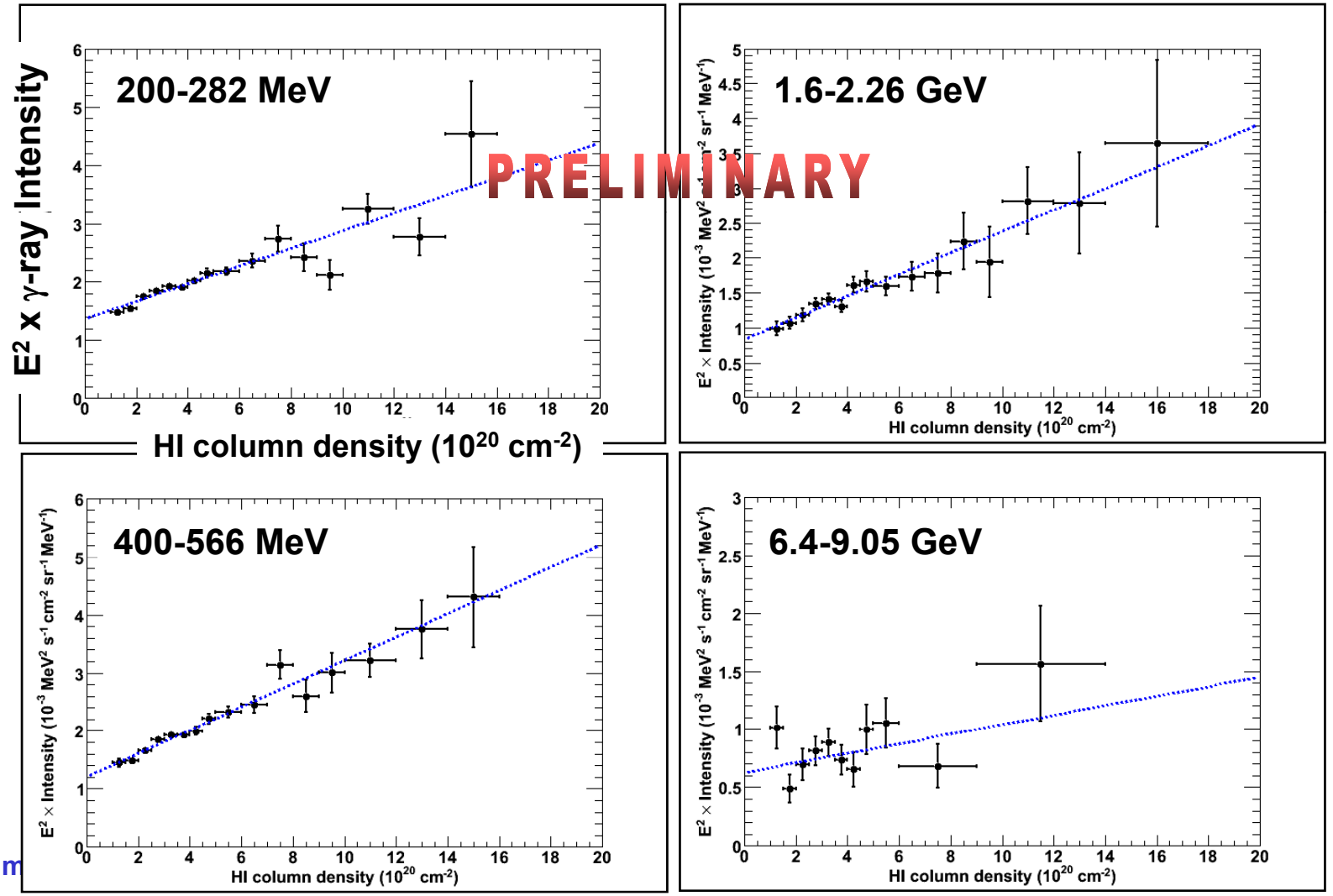




- N(HI) is small, less than 18x10^{20} cm^{-2} throughout the region
  - ➢Small uncertainty of the optical depth correction
- We see a correlation between diffuse gamma-ray counts and N(HI)

Correlation with the HI Column Density

- Point sources are masked (1° radius). IC and residual point source contributions are subtracted.
- Correlation from 200 MeV to 10 GeV. The slope gives the γ-ray emissivity of HI gas.

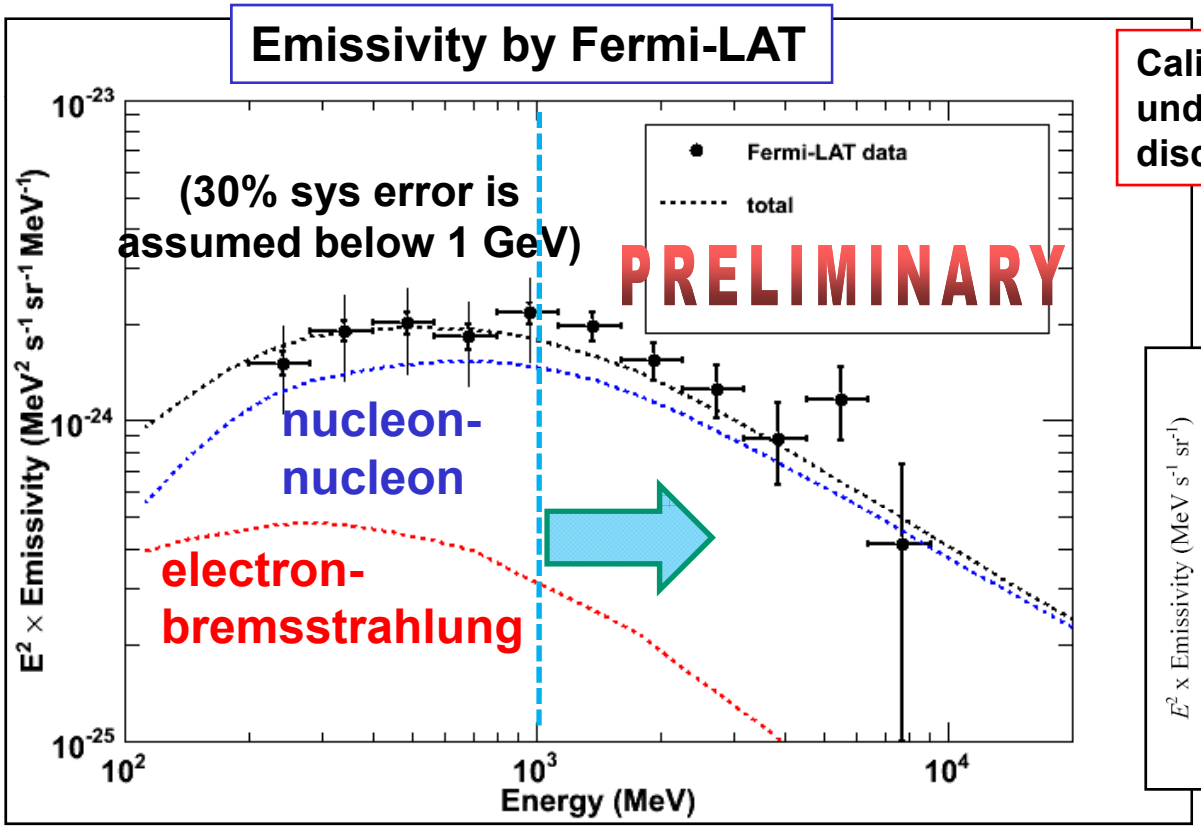


Emissivity of Local Atomic Hydrogen

- Similar to previous works but with much better statistics especially above 1 GeV.
- Agree with the model prediction from the local interstellar spectrum consistent with measurements at Earth.

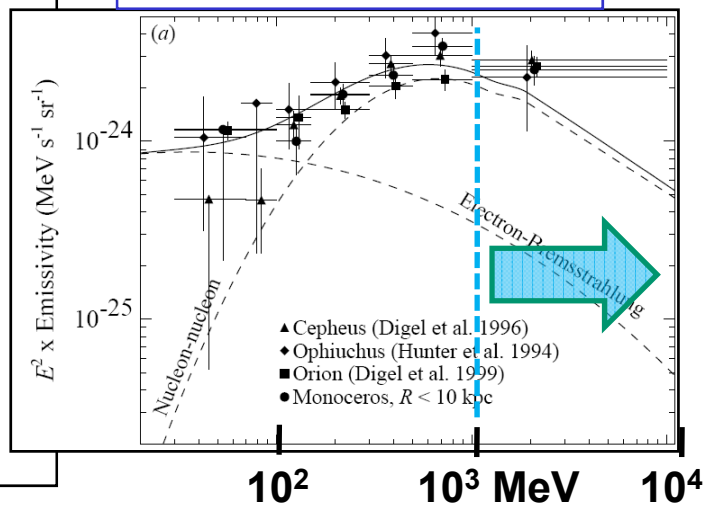
Local CR nucleon spectrum is close to that directly measured at Earth

Emissivity by Fermi-LAT



Calibration below 200 MeV is underway and will allow us to discuss CR electron spectrum

EGRET (Digel et al. 2001)



(assumed electron spectra differ below a few 100s MeV)

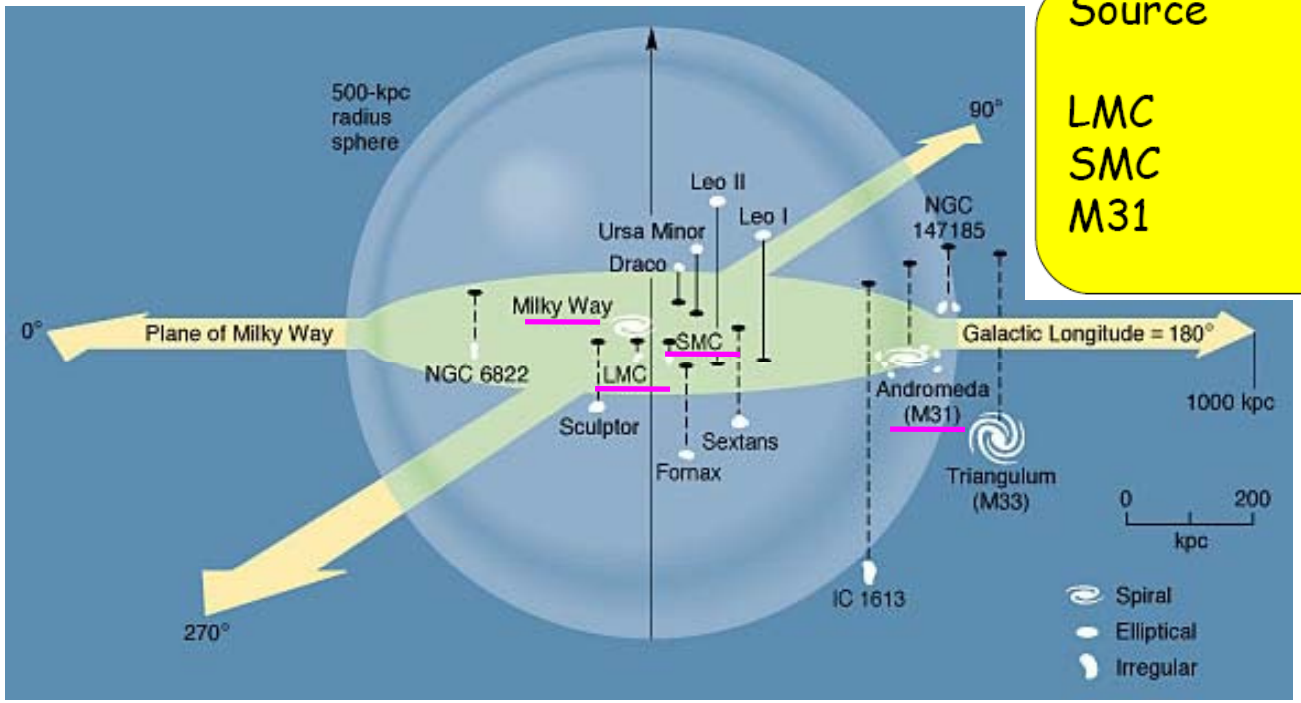
Large Magellanic Cloud (Local Group Galaxy)

Local Group Galaxies

EGRET Observation Summary:

- **LMC detection: CR density is similar to MW**
- **SMC non-detection: CR density is smaller than in the MW**
- **First direct evidence: CRs are galactic and not universal**

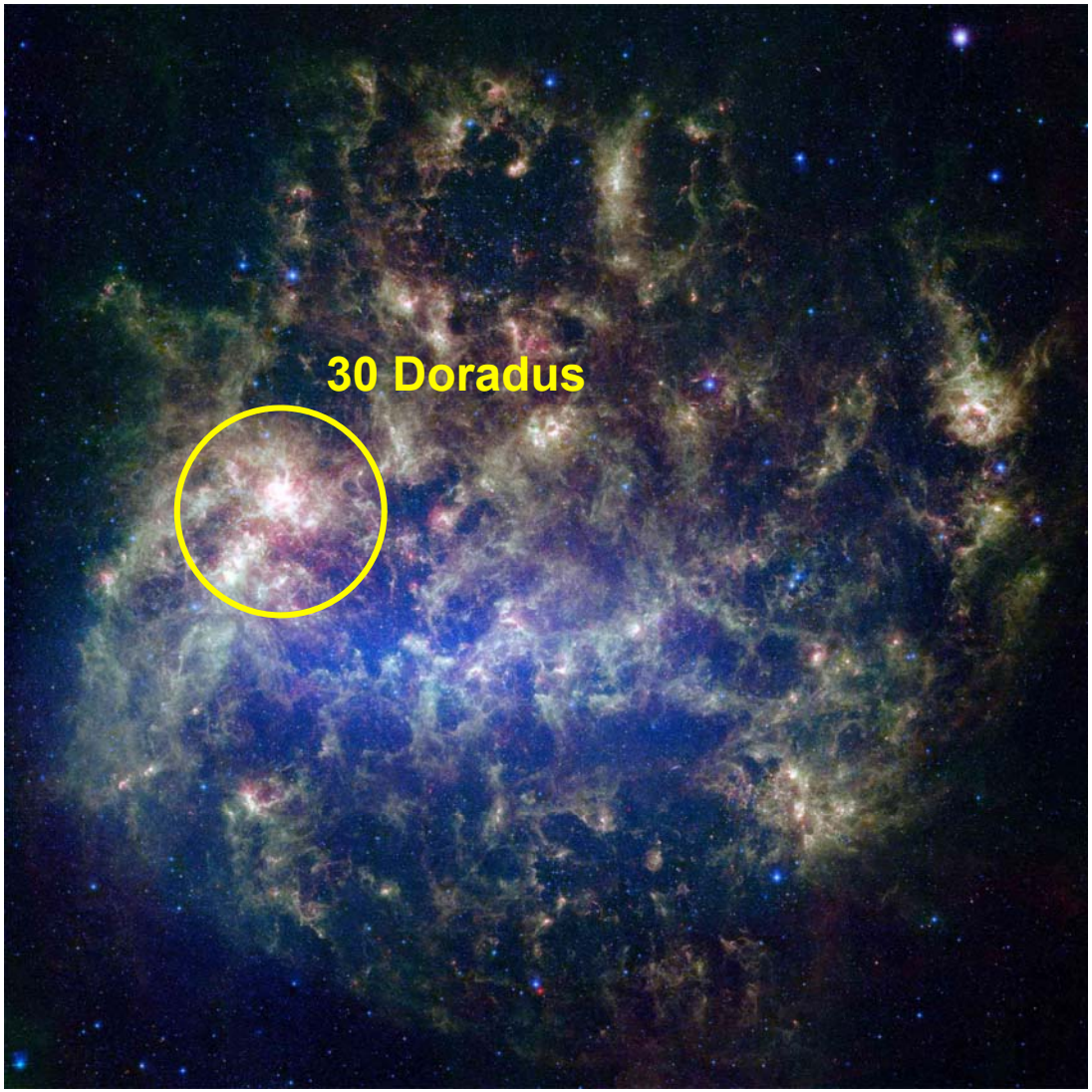
- **M31 non-detection: has to have smaller CR density than the MW (size M31>MW)**



Source	F(>100 MeV), cm^{-2} s^{-1}
LMC	$(1.9\pm0.4)\times10^{-7}$
SMC	$<0.5\times10^{-7}$
M31	$<0.8\times10^{-7}$

Sreekumar et al.(1992-94)

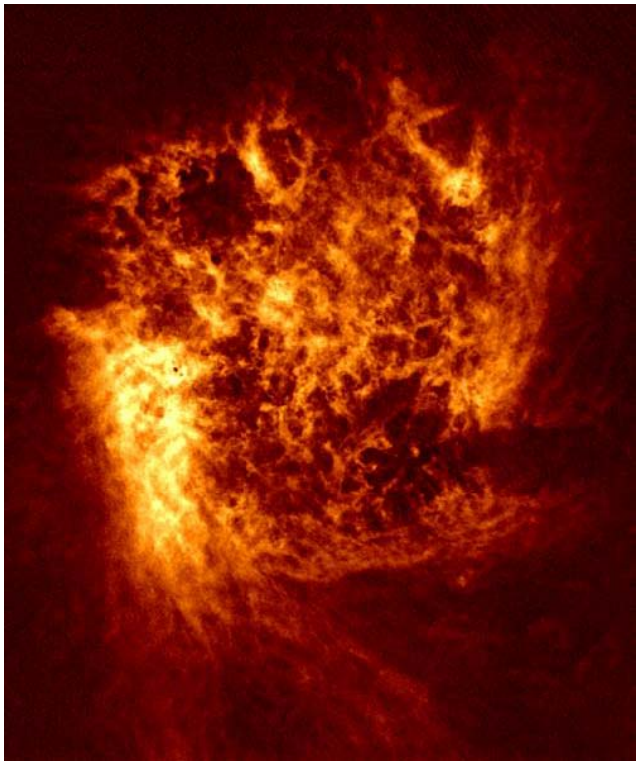
Why Study the Large Magellanic Clouds?



NASA/JPL-Caltech/M. Meixner (STScI) & the SAGE Legacy Team

LMC is

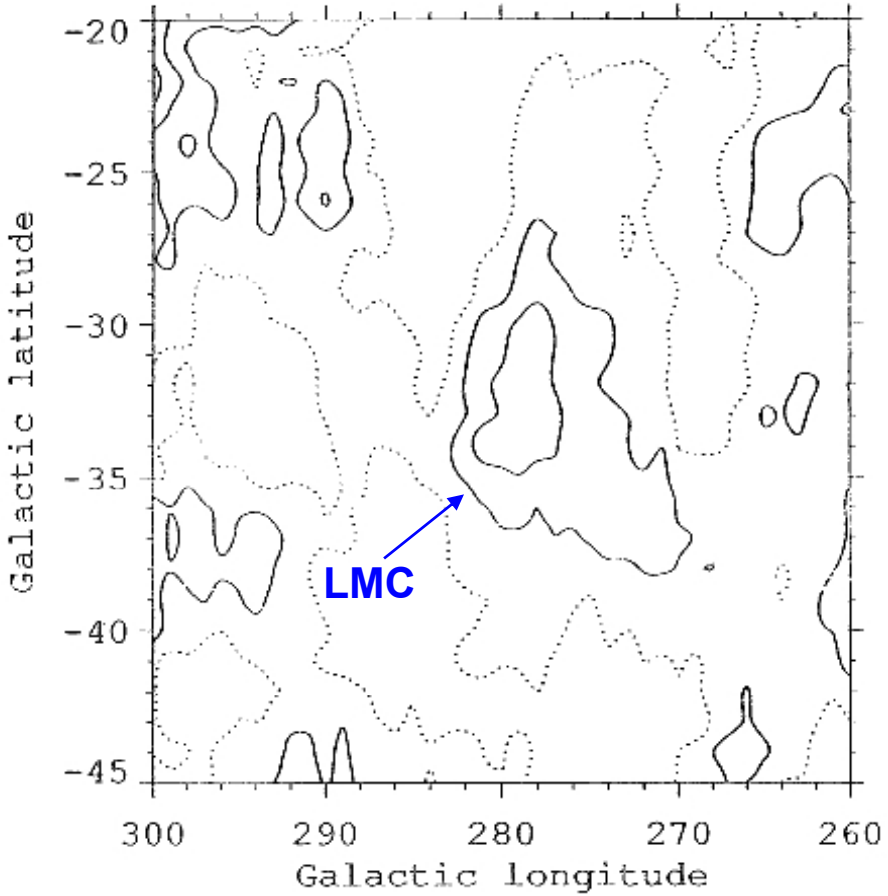
- seen ~ face-on (i ≈ 27°)
- nearby (~ 50 kpc)
- active (many massive star forming regions)

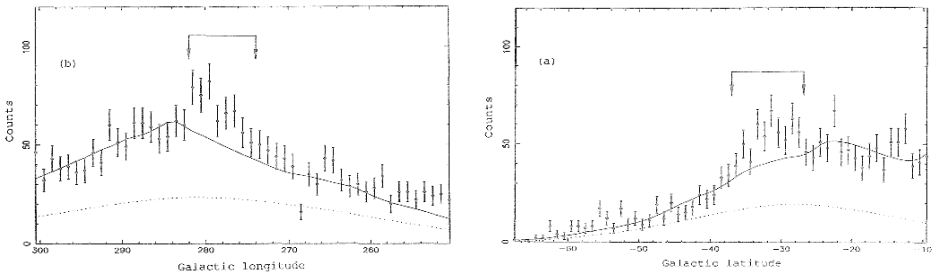


ATCA+Parkes H I (Kim et al. 2003)

EGRET View of the LMC

EGRET maps and profiles of LMC





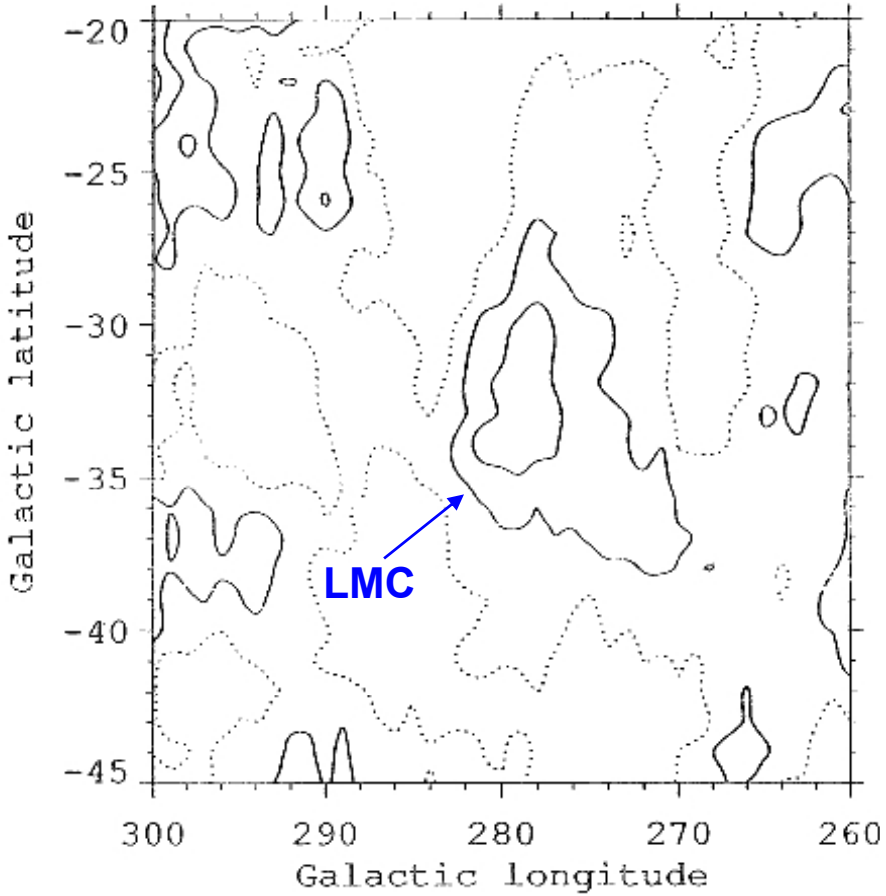
Sreekumar et al. (1992)

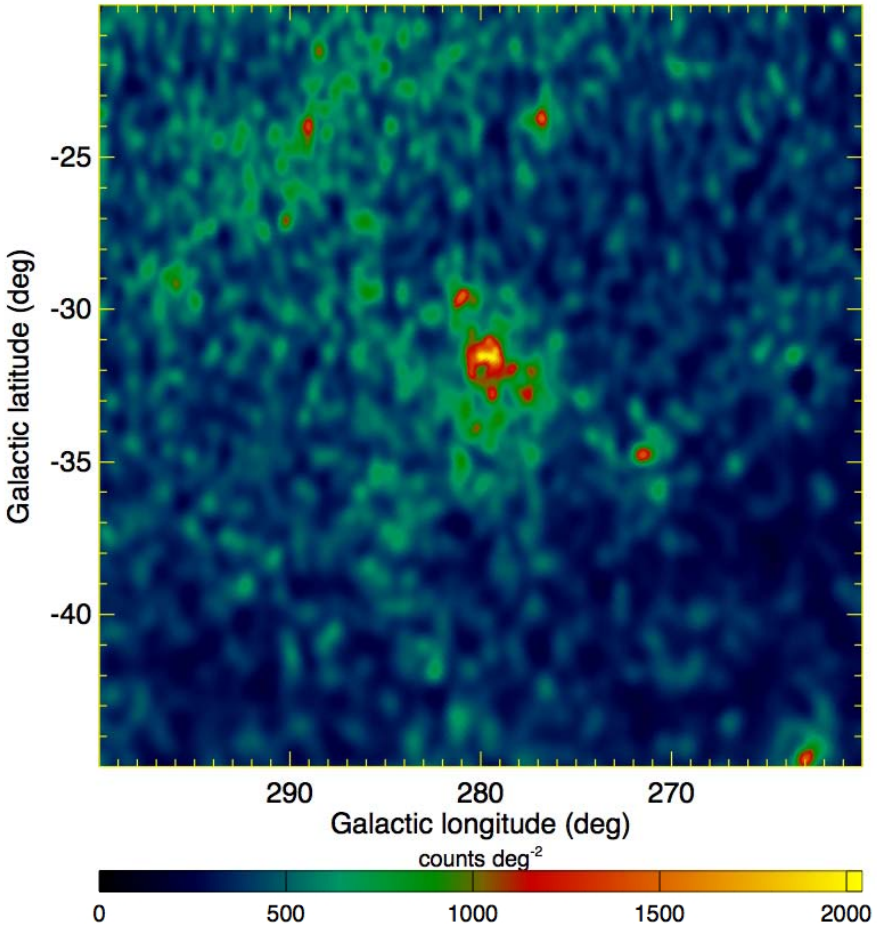
EGRET achievements

- first detection of LMC
- morphology consistent with radio data (yet no real spatial resolution of the emission)
- flux >100 MeV: $(1.9 \pm 0.4)\ 10^{-7}$ ph cm^{-2} s^{-1}
- flux consistent with either:
  - dynamic balance model
  - uniform CR density equal to that in solar neighborhood

EGRET vs. Fermi-LAT View of LMC

PRELIMINARY

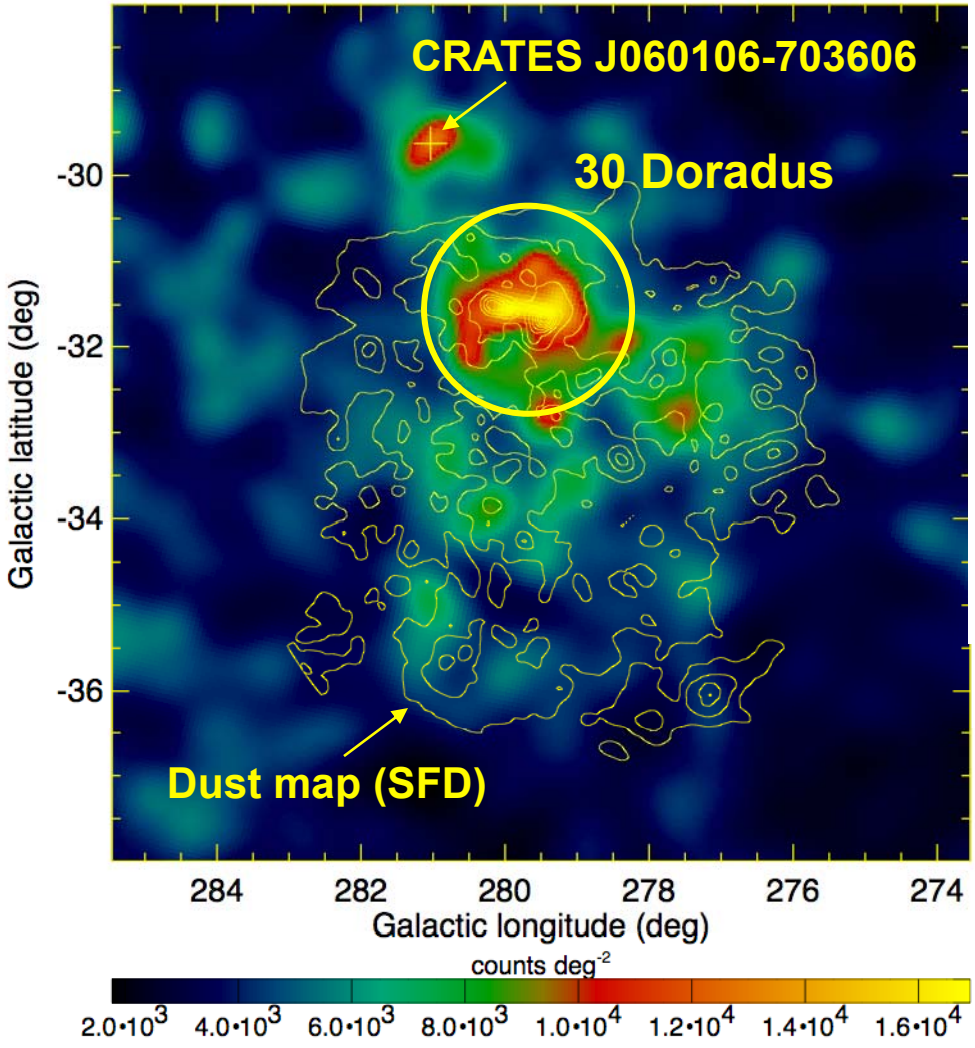


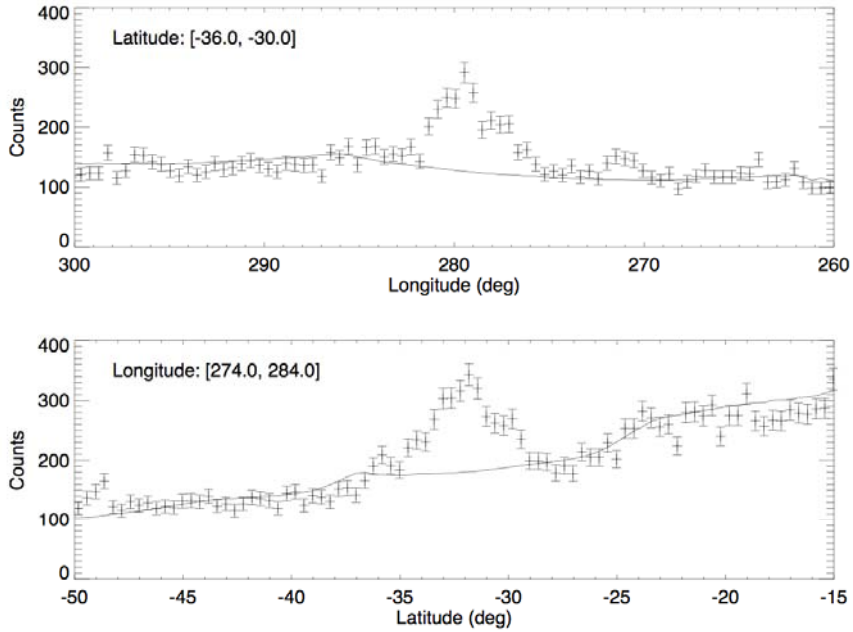


adaptively smoothed counts map (s.n.r. = 5)

Fermi-LAT Image of the LMC

PRELIMINARY





161 days of survey data
~ 1300 events above 100 MeV
Location (assuming point source):
a = 84.6 ± 0.2 (95%)
d = -69.1 ± 0.1 (95%)

Consistent with 30 Doradus / R136 location (a=84.67, d=-69.10)

adaptively smoothed 100 MeV - 10 GeV counts map (s.n.r. = 5)

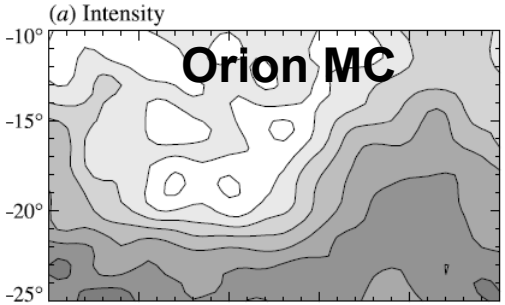
Summary

- Fermi-LAT is a superb instrument for diffuse emission studies
  - ➢uniform and deep coverage of the sky
- CR propagation model and gas/ISRF maps have been developed
  - ➢already provided many exciting results of individual sources
- First results on mid latitude Galactic emission show no evidence for EGRET feature > 1 GeV seen in the same region of the sky
- Mid-high latitude observation indicates the local CR nucleon spectrum is close to that measured at Earth
- Easily detected diffuse emission from LMC
  - ➢Emission resolved => 30-Doradus, host galaxy
  - ➢More results very soon

And More to Come

Contributions to ICRC 2009 (http://icrc2009.uni.lodz.pl/)

- GeV-non-excess
- Large-scale diffuse
- The Galactic-Center
- Extragalactic gamma-ray background
- Orion/Monoceros molecular clouds
- LMC
- Diffuse gamma-rays from Cassiopeia region



Digel et al. 1999

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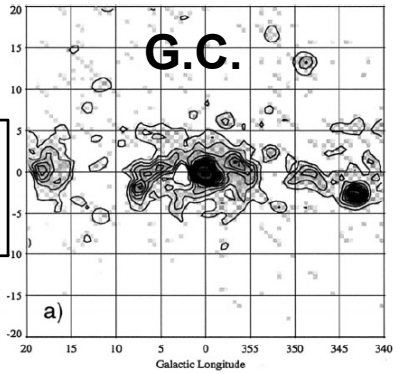
Mayer-Hasselwander et al. 1998



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Stay tuned for further results on diffuse gamma-ray emission by Fermi-LAT