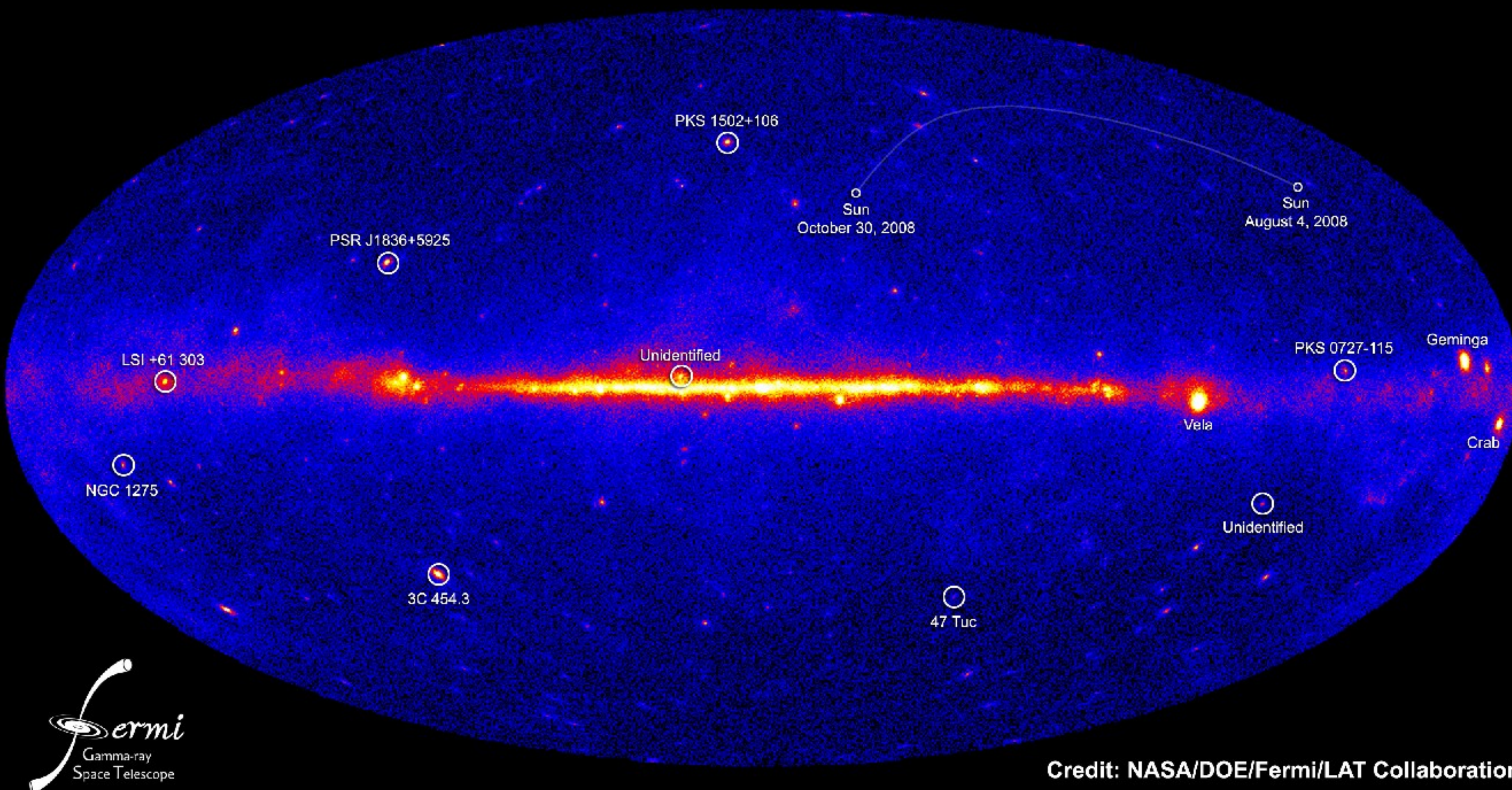
Results from the Fermi-LAT Mission: Cosmic Rays and the Interstellar Medium of the Milky Way and Other Galaxies

Troy A. Porter
Stanford University

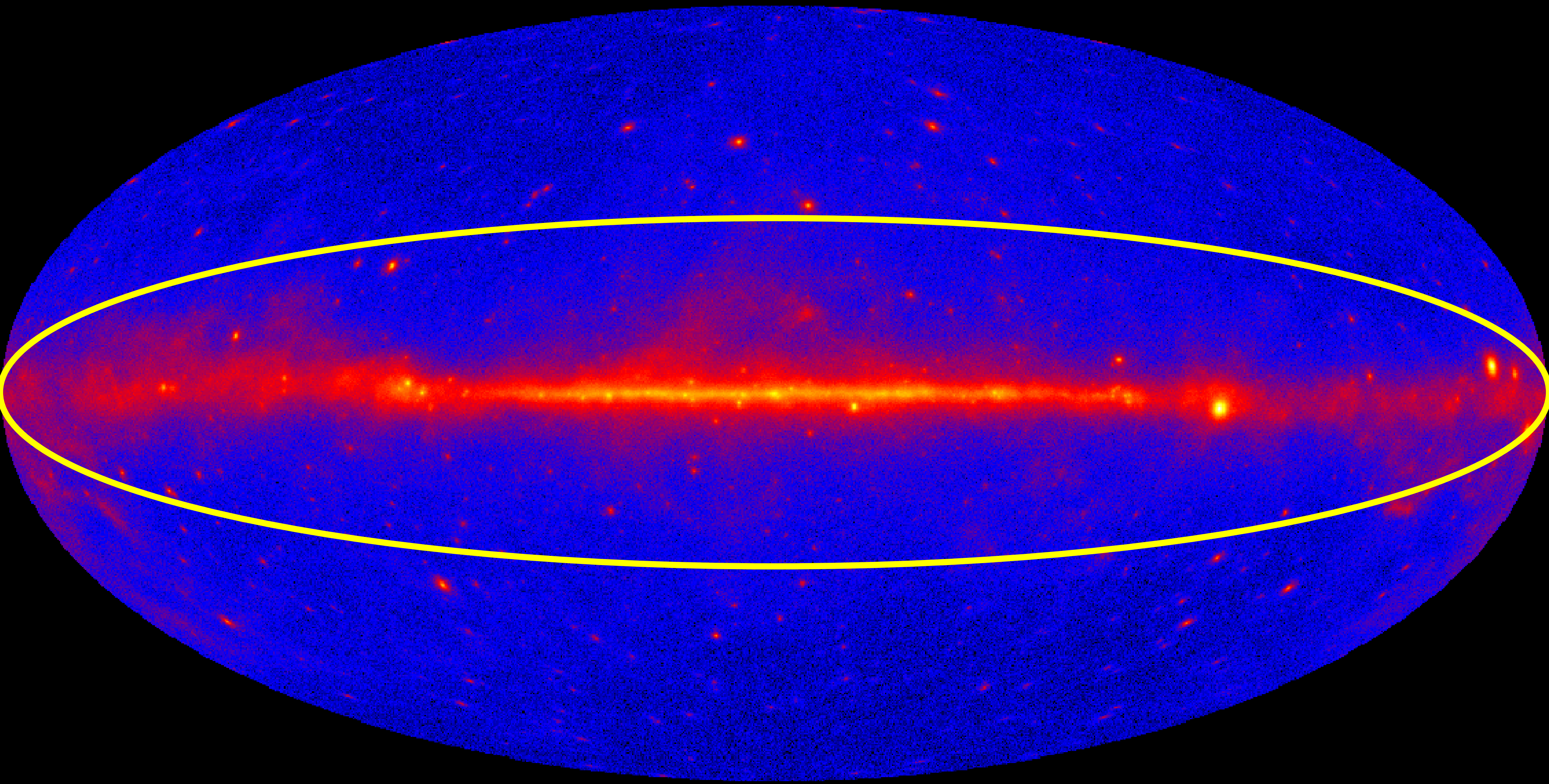
On behalf of the Fermi-LAT Collaboration

NASA's Fermi telescope reveals best-ever view of the gamma-ray sky



Credit: NASA/DOE/Fermi/LAT Collaboration

Count Map > 200 MeV



Why study the Diffuse Emission?

<u>The Milky Way and its Structure</u>

→ Origin and propagation of cosmic rays

Nature and distribution of sources
The propagation mode itself ↔ relationship to magnetic turbulence in the ISM
Relative proportions of primary species
Production of secondary species
etc.

→ Interstellar Medium

Distribution of HI, H_2, HII gas
Nature of X_{CO} relation in Galaxy
Distribution and intensity of interstellar radiation field ↔ formation of H_2
etc.

<u>As a Foreground</u>

→ The diffuse emission is the foreground against which sources are detected

Point sources : limitation on sensitivity
Extended sources : disentanglement

→ Indirect dark matter detection

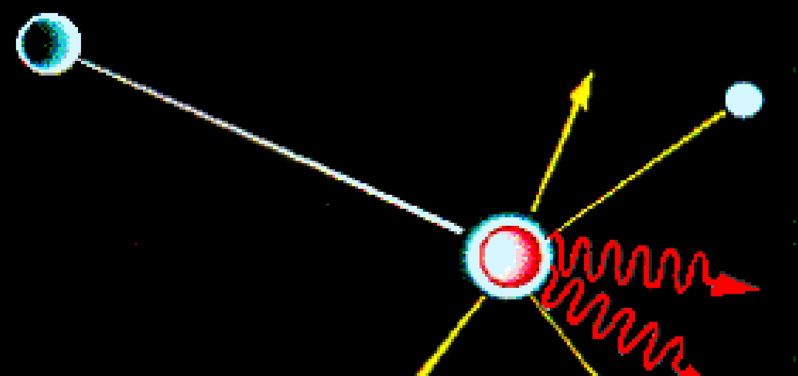
Predicted gamma-ray/cosmic-ray signals rely on accurate subtraction of standard astrophysical sources

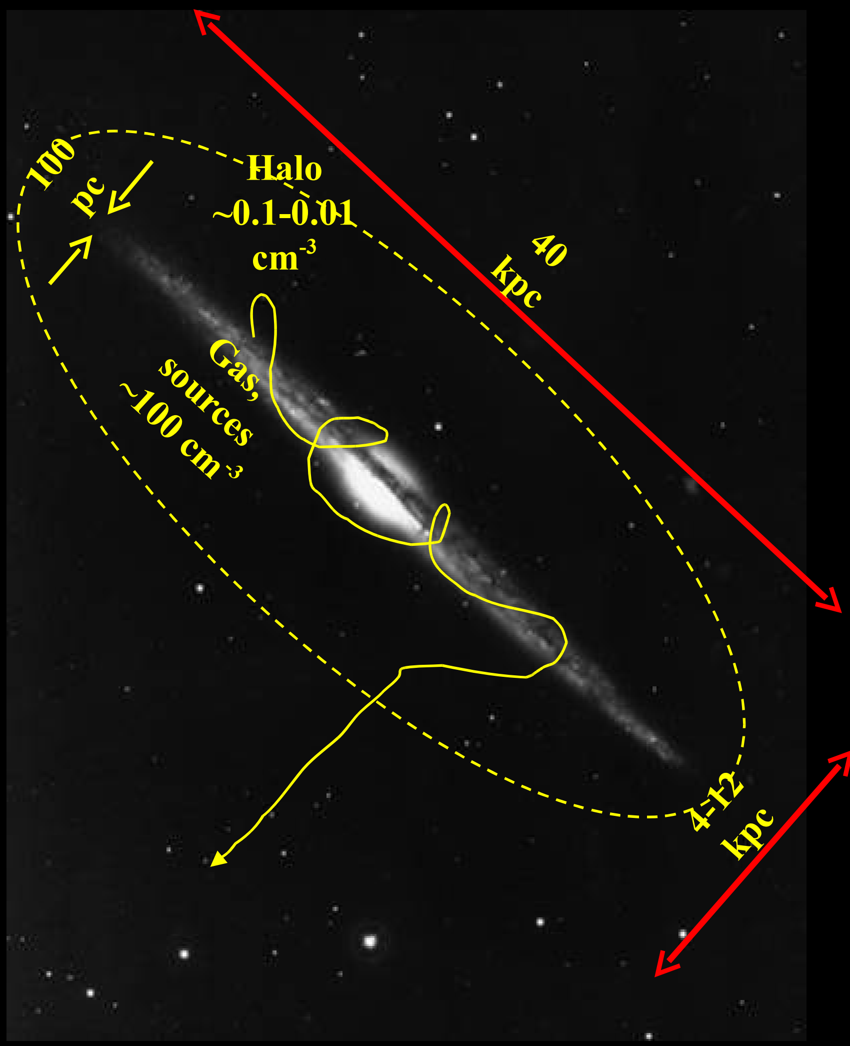
→ Foreground for isotropic diffuse background

Whatever its nature

Connection Between Cosmic Rays and Diffuse Emission

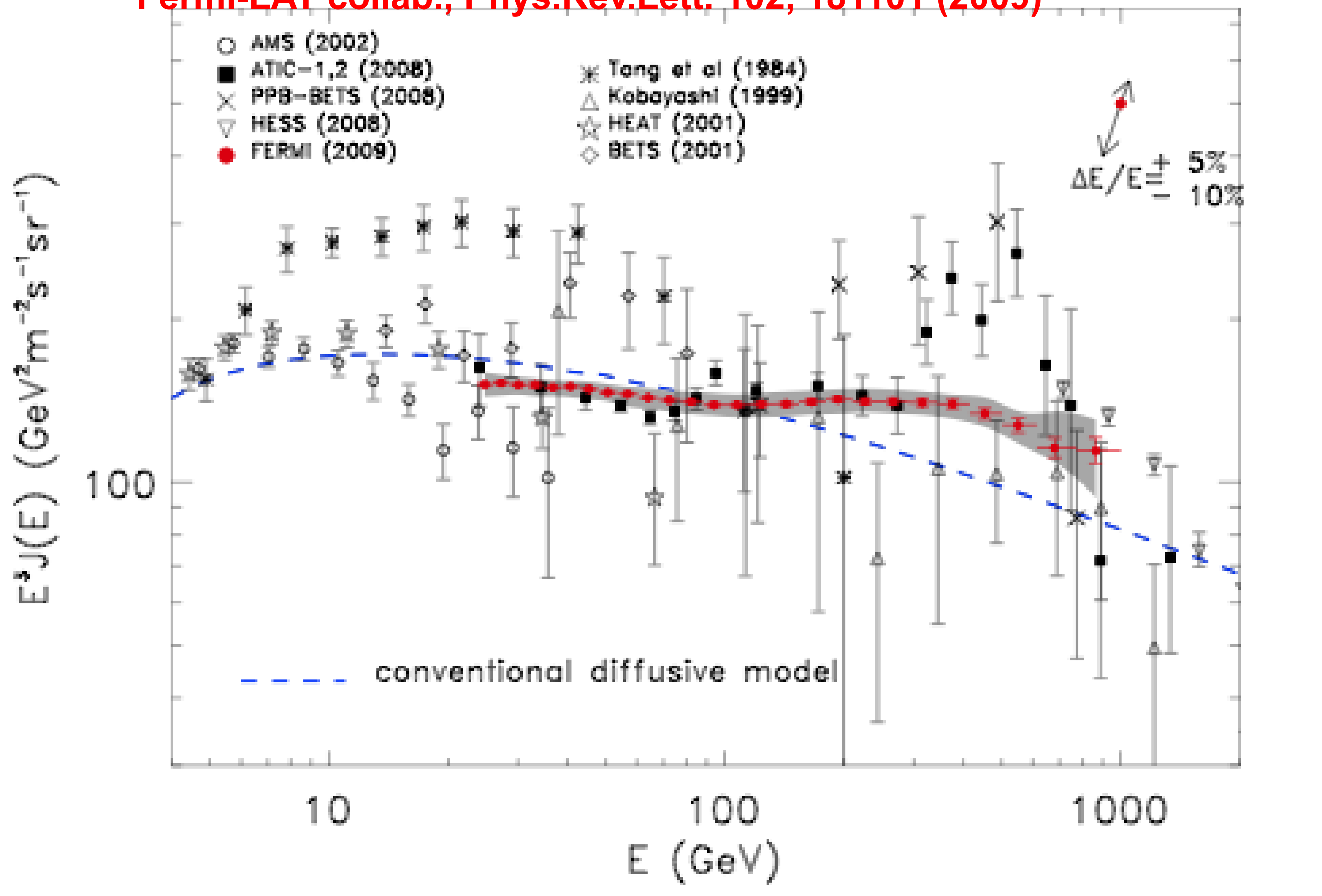
- **Cosmic rays injected into ISM propagate for millions of years before escape to intergalactic space**
- **Particle interactions with interstellar gas, radiation and magnetic fields produce EM radiation from radio to gamma rays, and other secondaries ($e^{\pm}$, ν, etc.)**



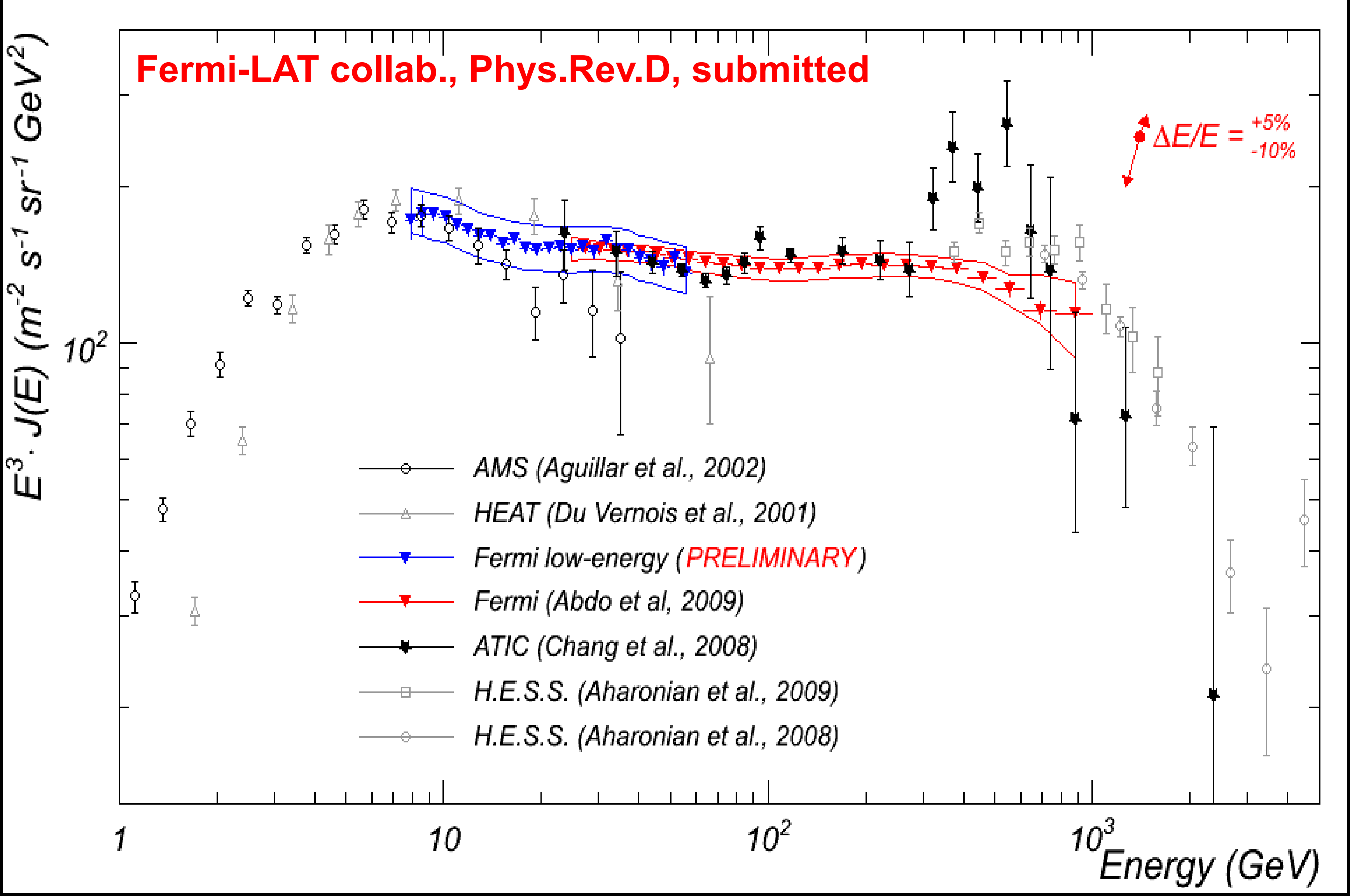


Cosmic-Ray Electron Spectrum #1

Fermi-LAT collab., Phys.Rev.Lett. 102, 181101 (2009)



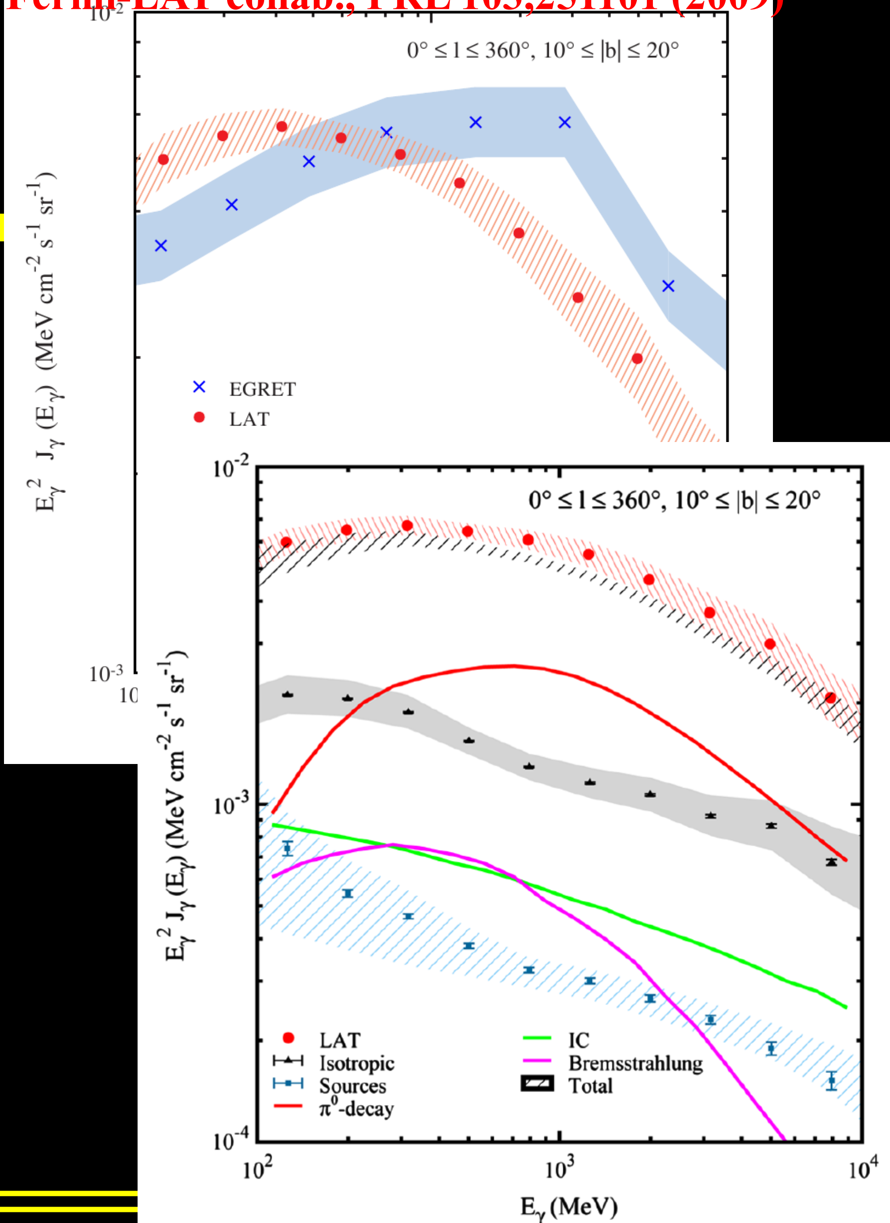
Cosmic-Ray Electron Spectrum #2



No GeV excess

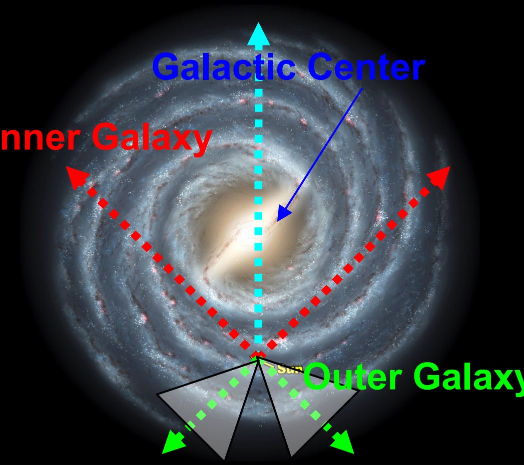
- Observations with the EGRET instrument showed excess emission above a few GeV when compared to convention[al] diffuse emission models
  - `Conventional' means based on local CR measurements
- Possible hint for
  - Dark matter
  - Local CR bubble
  - Unresolved sources
  - ...
- Not seen in Fermi LAT data
- Instrumental origin: similar discrepancy seen between EGRET and LAT Vela pulsar spectra

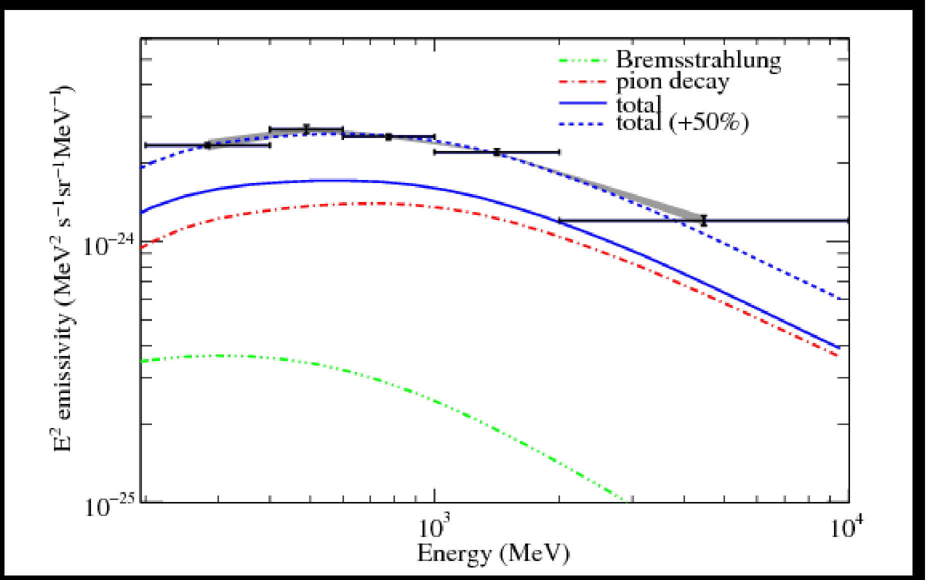
Fermi-LAT collab., PRL 103,251101 (2009)



Nearby Diffuse Emission – Local Gas

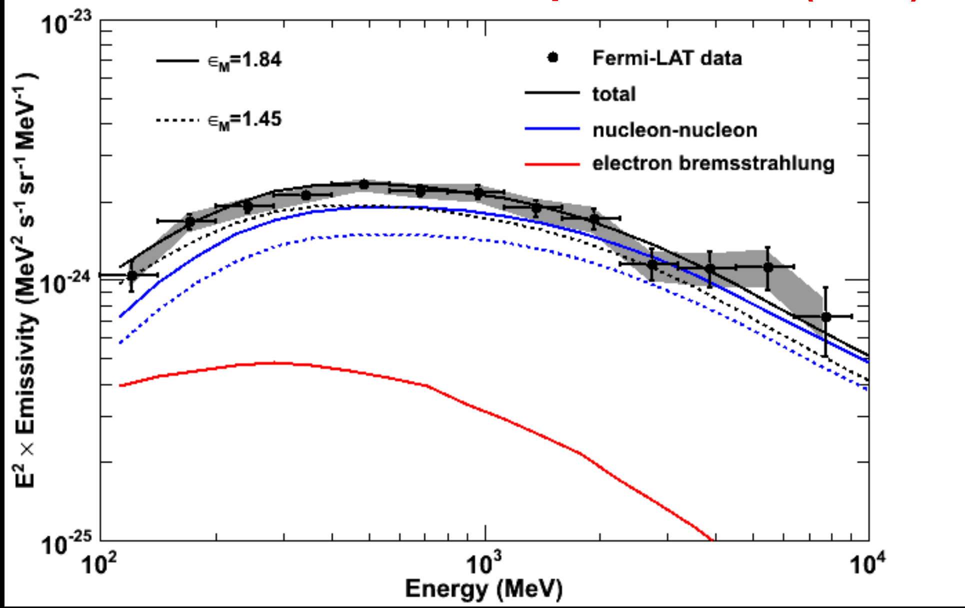
- Selected region with good radial resolution
- Two independent analysis show agreement with local observations of CRs
- Hints for an increased nuclear enhancement factor (effects of high Z nuclei)





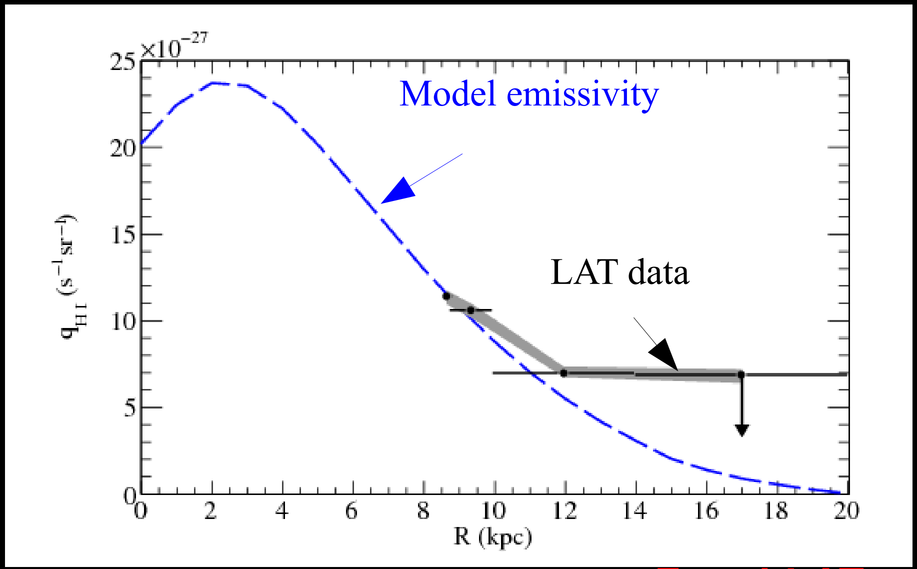
Fermi-LAT collab. ApJ 710,133 (2010)

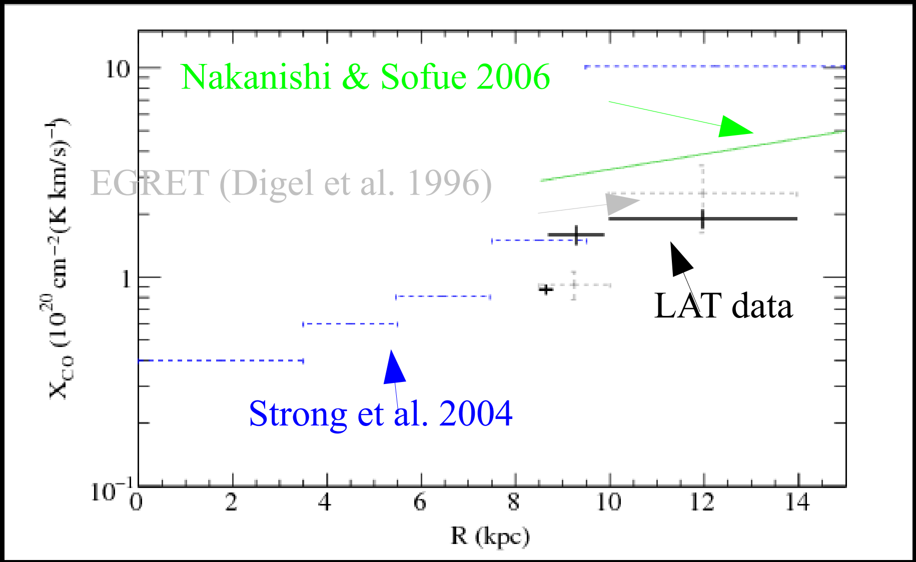
Fermi-LAT collab., ApJ 703,1249 (2009)



CR Flux and X_{CO} factor in outer Galaxy

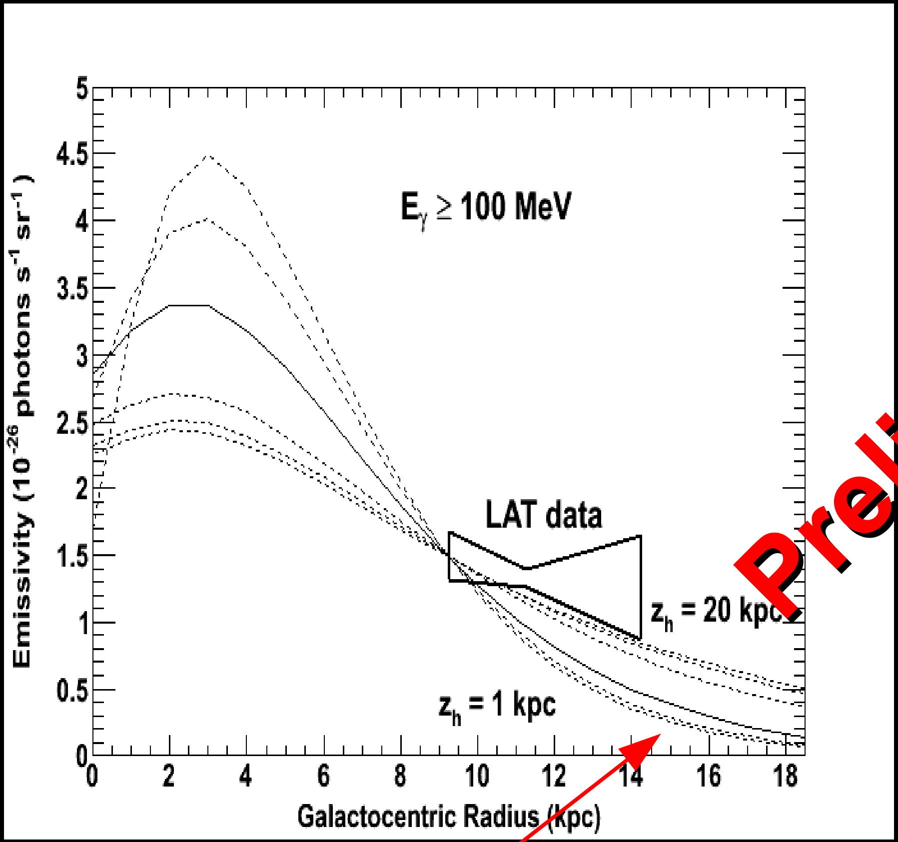
- CR emissivity higher than predicted by some conventional propagation models
  - Conventional models are consistent with local observations of CRs but still have some freedom.
  - A hint for a different halo size or CR source distribution
- X_{CO} factor doesn't rise as steeply as older predictions

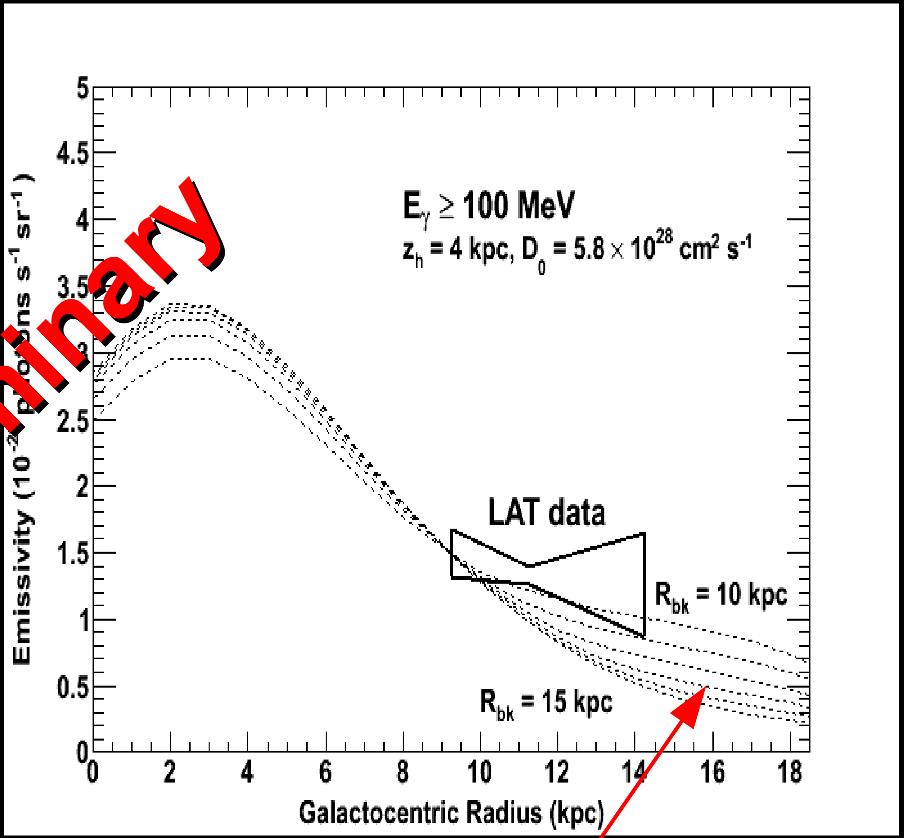




Fermi-LAT collab., ApJ 710, 133 (2010)

Emissivity Distribution in Outer Galaxy: 3rd Quadrant





Preliminary

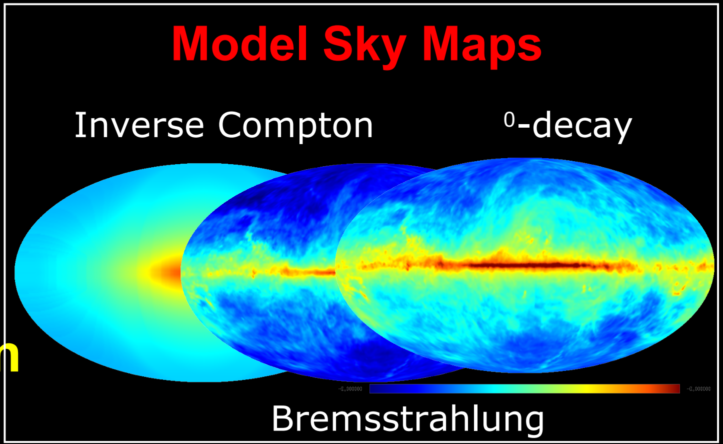
Halo size varies from 1 to 20 kpc

Source density constant outside R_{bk}

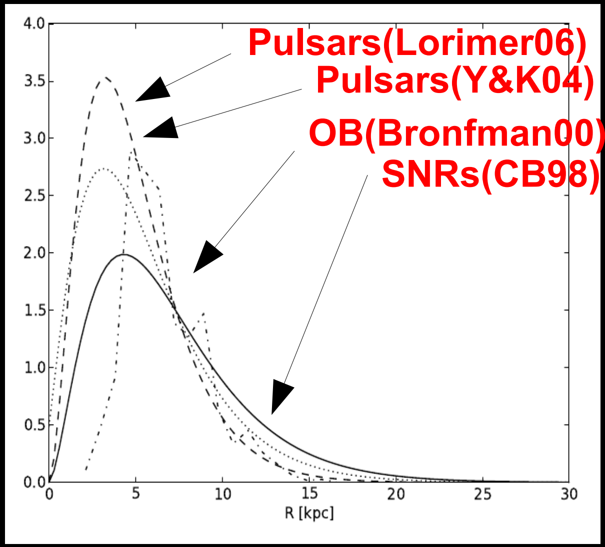
Fermi-LAT collab., ApJ submitted

Large-Scale Study of Diffuse Emission

- Starting point for our studies: the cosmic-ray spectra consistent with local observations (cosmic-ray nuclei, Fermi LAT electrons) ➔ `conventional model'
- Use GALPROP code with diffusion-reacceleration model for CR propagation ➔ propagation parameters found using CR data
- Grid of 128 models covering plausible confinement volume, CR source distributions, etc.
- Corresponding model sky maps compared with data using maximum likelihood
- Iterative process since the model parameters depend on outcome of fits



CR sources



Cosmic Ray Propagation

- **Main result: propagation parameters depend on**

Preliminary

  - **Assumed source distribution**
    (Z_{max} = 6 kpc, R_{max} = 20 kpc, T_S = 150 K, mag = 5)

Parameter	SNR	Lorimer	Yusifov	OBstars
$D_{0,xx}$ *	7.08 +/- 0.12	7.40 +/- 0.11	7.30 +/- 0.12	6.51 +/- 0.12
p $norm_{100GeV}$ **	4.06 +/- 0.05	3.98 +/- 0.05	4.02 +/- 0.05	4.22 +/- 0.05

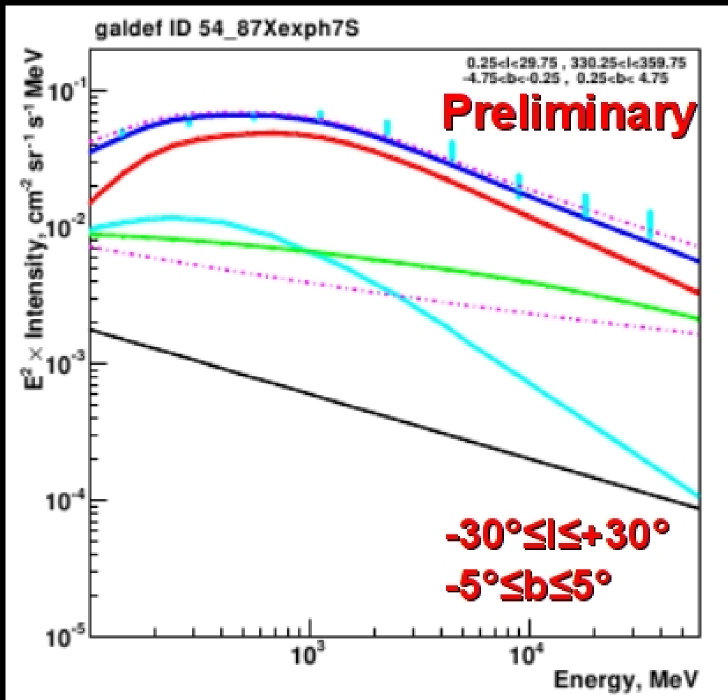
  - **Distribution of gas in Galaxy**
    (SNR, Z_{max} = 6 kpc, R_{max} = 20 kpc, mag = 5)

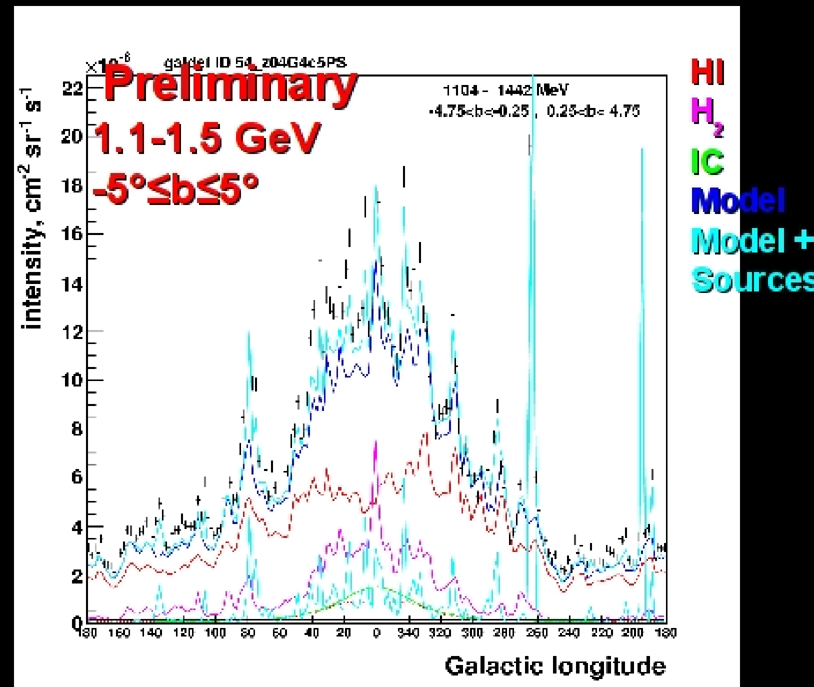
Parameter	HI, T_S = 150 K	HI, optically thin
v_{Alfven} ***	31.9 +/- 0.9	35.6 +/- 1.0
$D_{0,xx}$ *	7.08 +/- 0.12	7.88 +/- 0.14

  - **Still within systematic uncertainties of CR data**

* 10^{28} cm^2 s^{-1}
** 10^{-9} cm^{-2} s^{-1} sr^{-1} MeV^{-1}
*** km s^{-1}

Example Spectra and Profiles





IC:
Total
OPT
IR
CMB

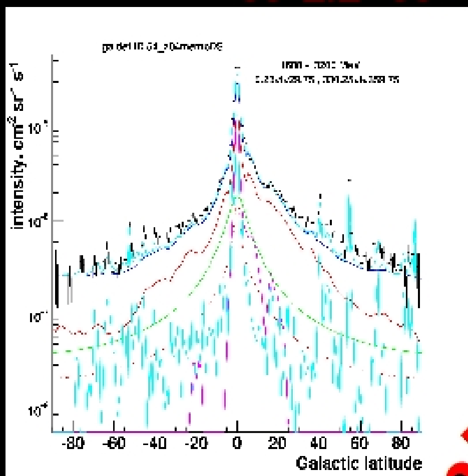
Brem
π^0-decay
Catalogue sources
Model total

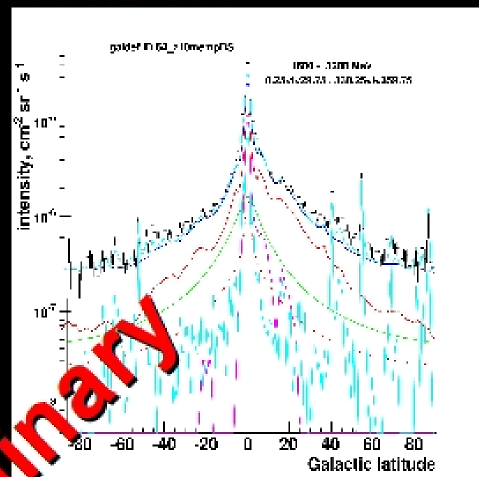
Overall agreement for spectra and profiles of models is good given the limited parameters that can be adjusted

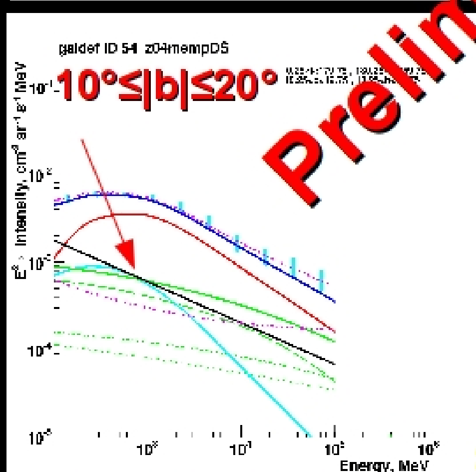
Extended Cosmic-Ray Halo

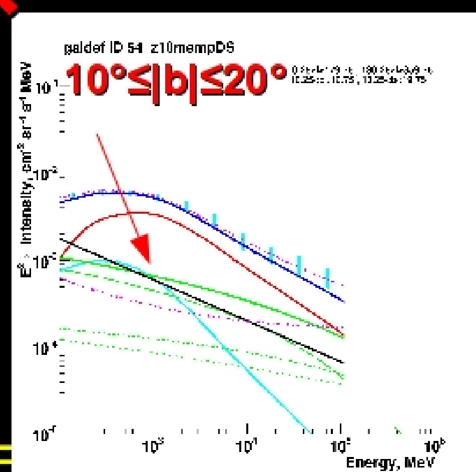
Halo = 4 kpc **Halo = 10 kpc** **Study of 3rd Quadrant**

-30°≤l≤+30° 1.6-3.2 GeV

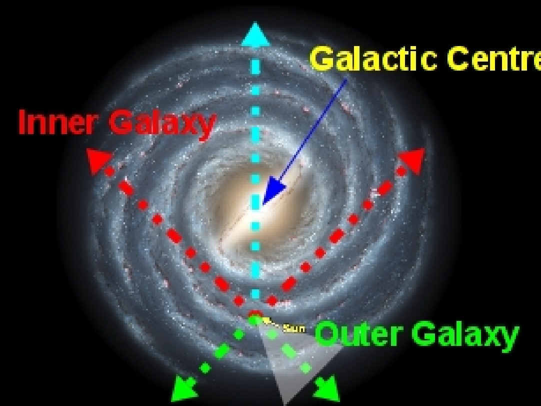


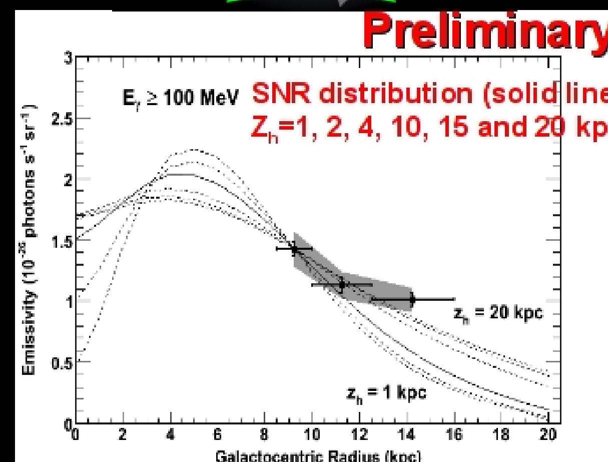




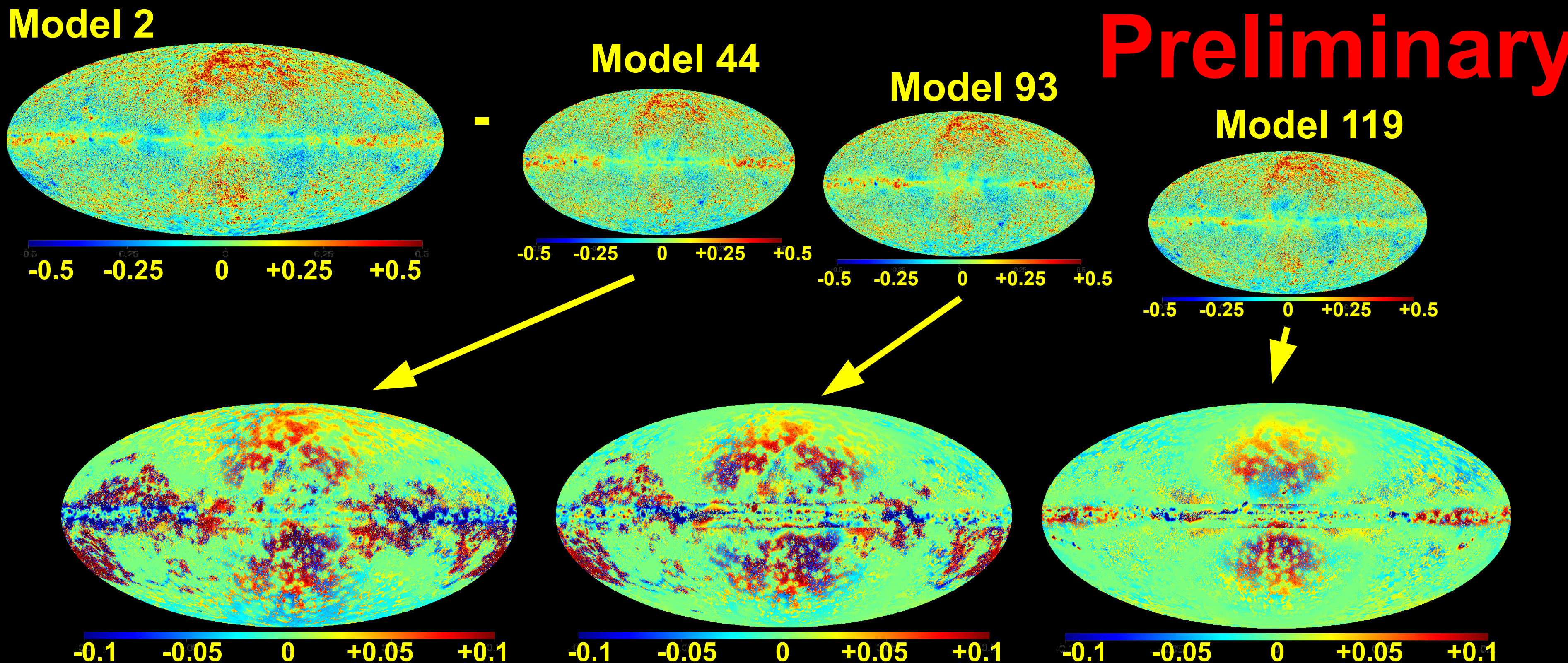


Preliminary





Fractional Count Residuals



- Agreement for models is overall good but features are visible in residuals at ~ % level
- Difference between illustrative models shown in lower maps: structure due to variations of model parameters

Model details →

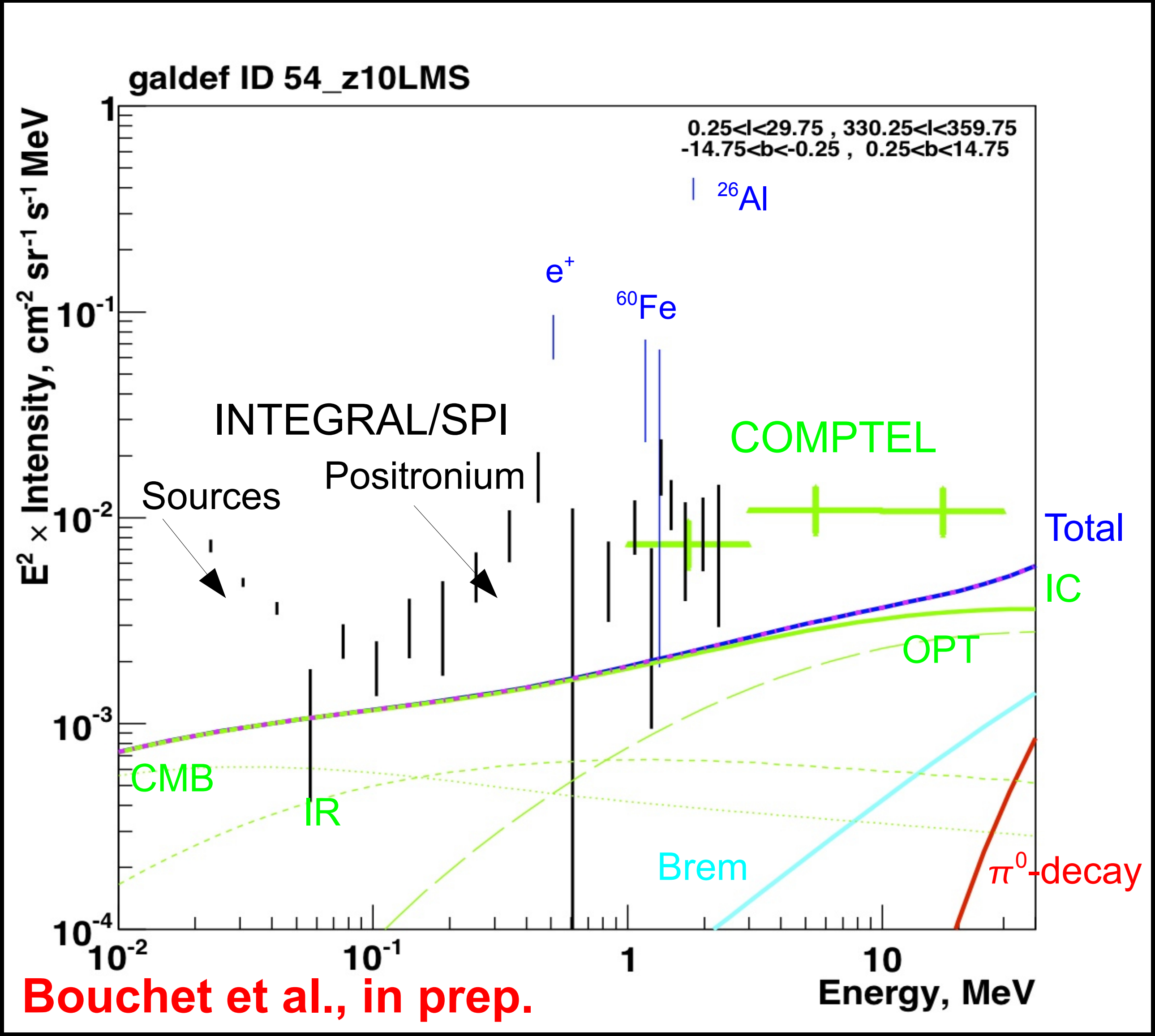
2: SNR, Z_h=4kpc, R_{max}=20kpc, T_S=150K, mag=5

44: Lorimer, Z_h=6kpc, R_{max}=20kpc, mag=5, optically thin HI

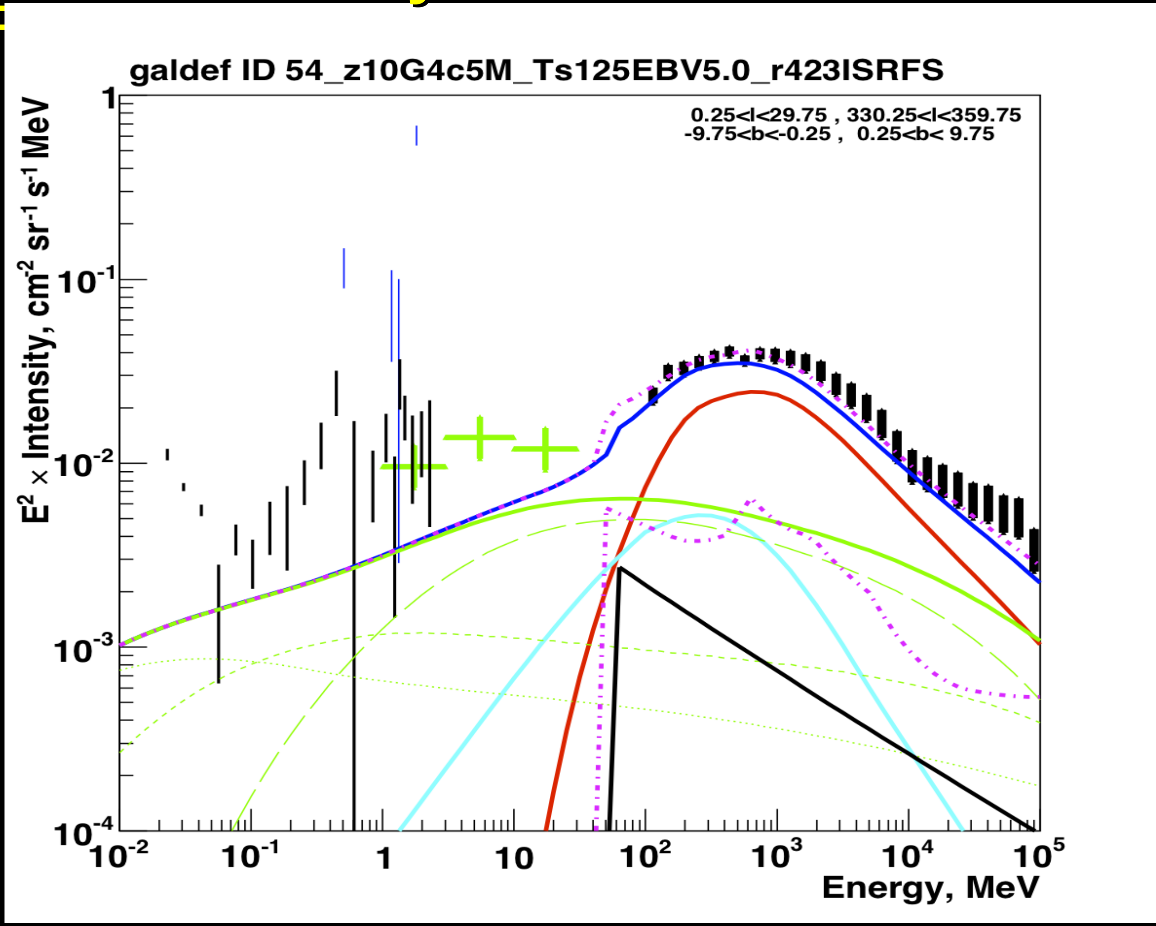
93: Yusifov, Z_h=10kpc, R_{max}=30kpc, T_S=150K, mag=2

119: OB, Z_h=8kpc, R_{max}=30kpc, mag=2, optically thin HI

Complementary Information: INTEGRAL/SPI Spectrum of Inner Galaxy



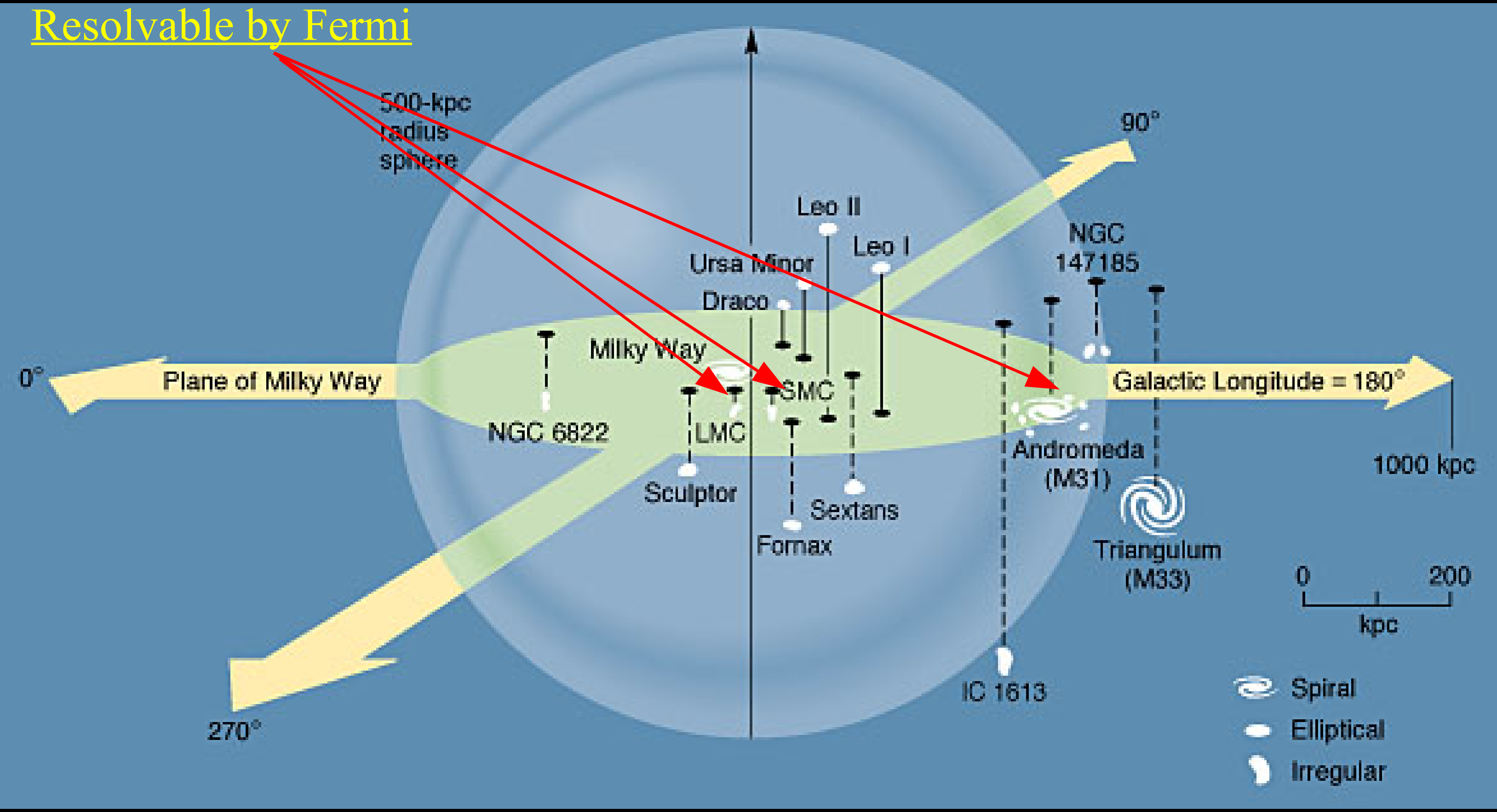
Inner Galaxy from 10 keV to 100 GeV



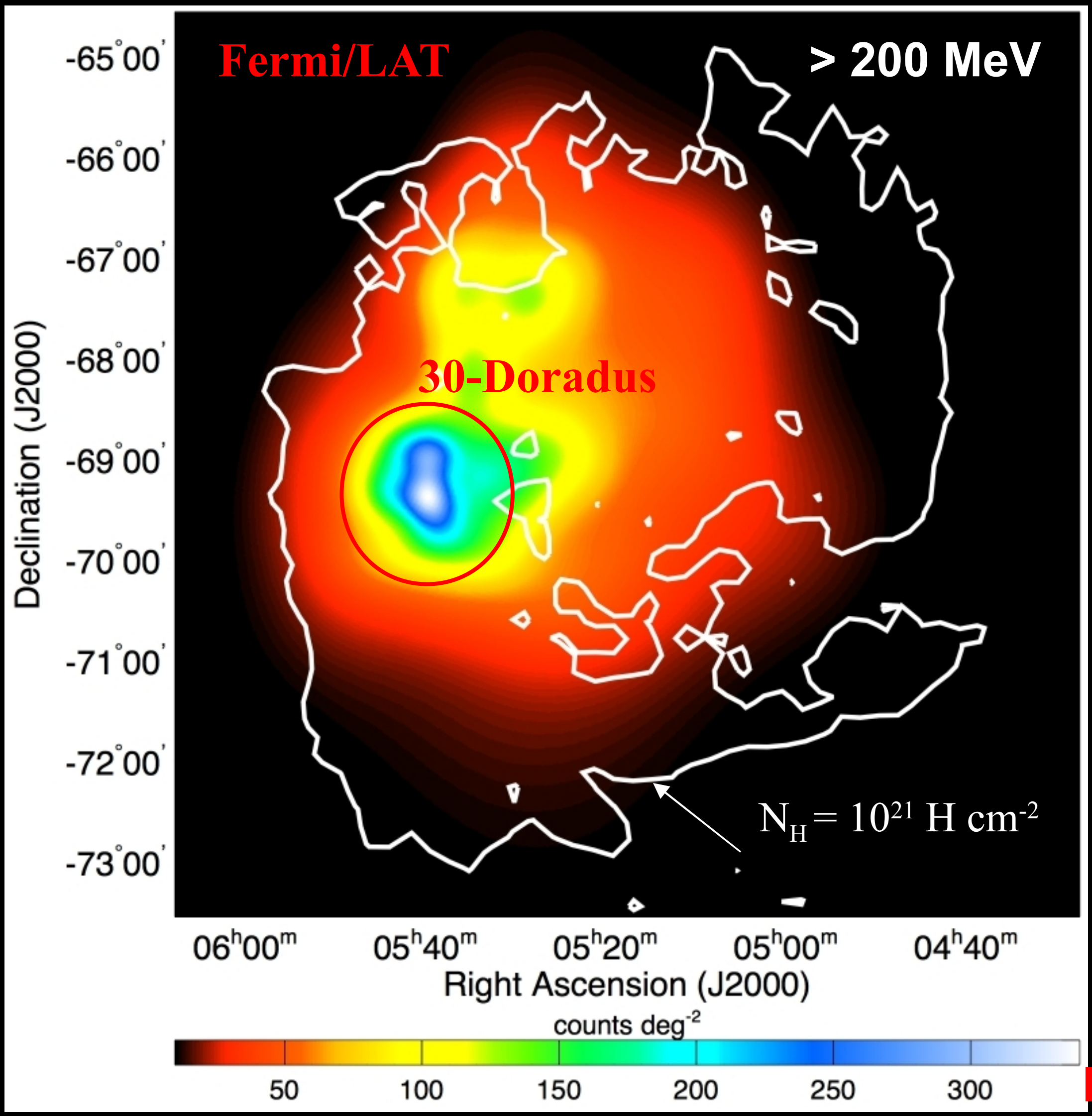
- Spectrum from 10 keV to 100 GeV can be described by single model with sources + isotropic component
- Note: only one model is shown → `systematic' band of models in progress

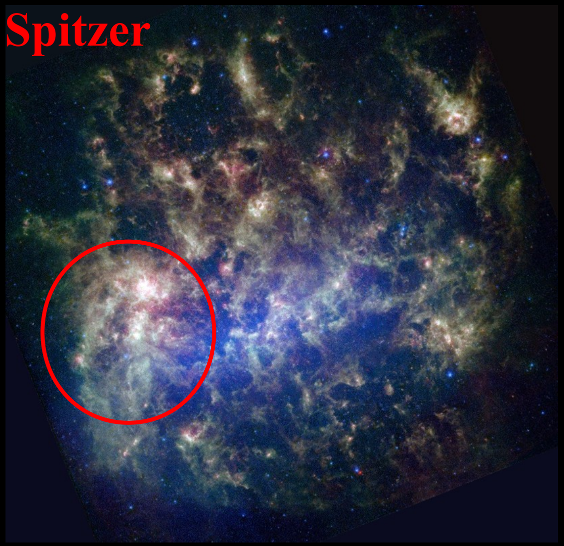
Preliminary

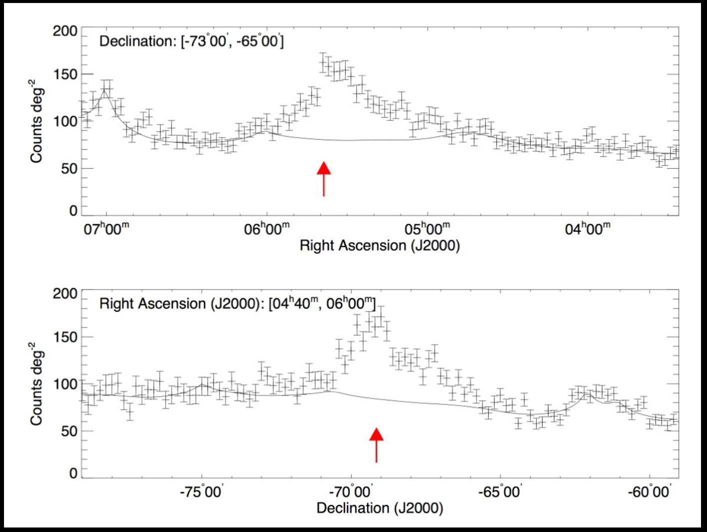
Diffuse Gamma-Ray Emission in Nearby Galaxies



Resolving the LMC in gamma rays



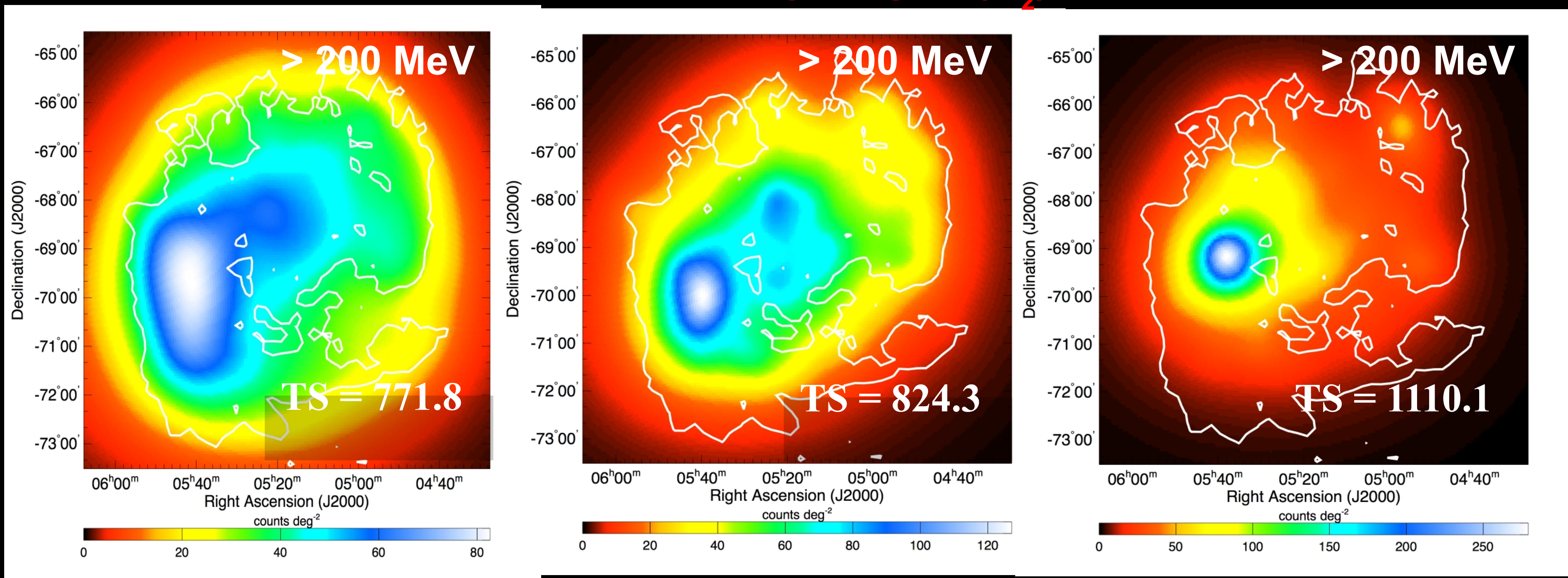




Fermi-LAT collab., A&A 512, 7 (2010)

Modelling the Spatial Distribution

Neutral Hydrogen (HI) Molecular Hydrogen (H_2) Ionised Hydrogen (Hα)



Neutral & molecular hydrogen templates poorly fit the data

Ionised hydrogen template provides highest likelihood

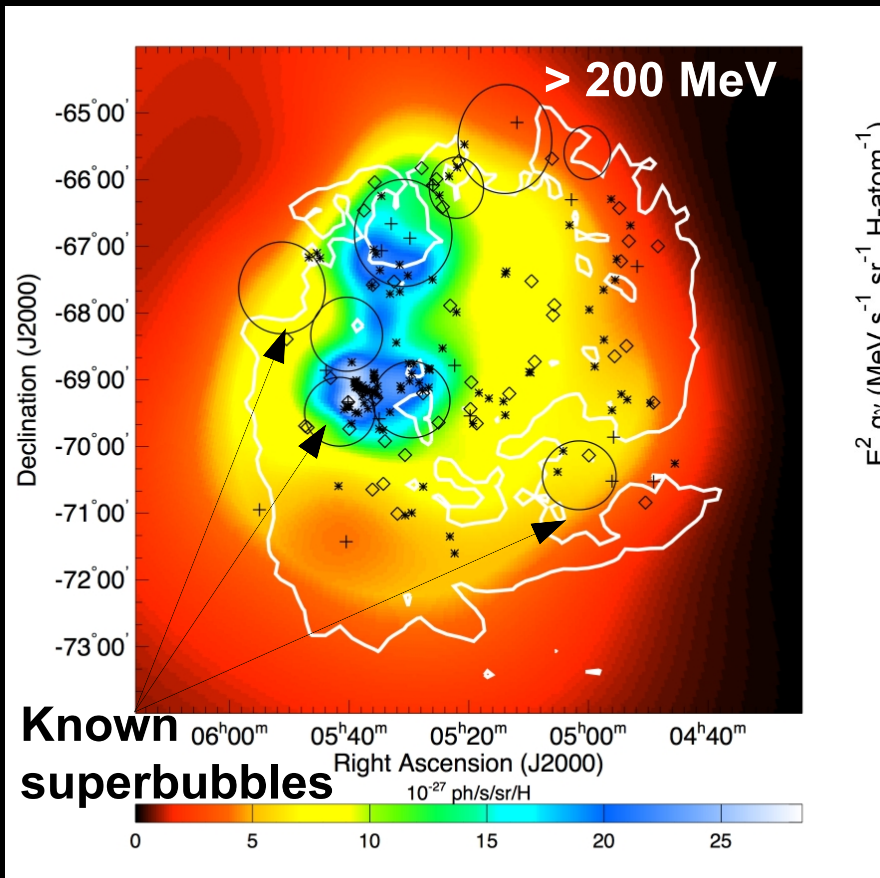
Gamma-ray emission correlates little with gas
(90-95% (atomic), 5-10% (molecular), 1% (ionised))

Exclusion of 30 Doradus region from fit does not change these findings

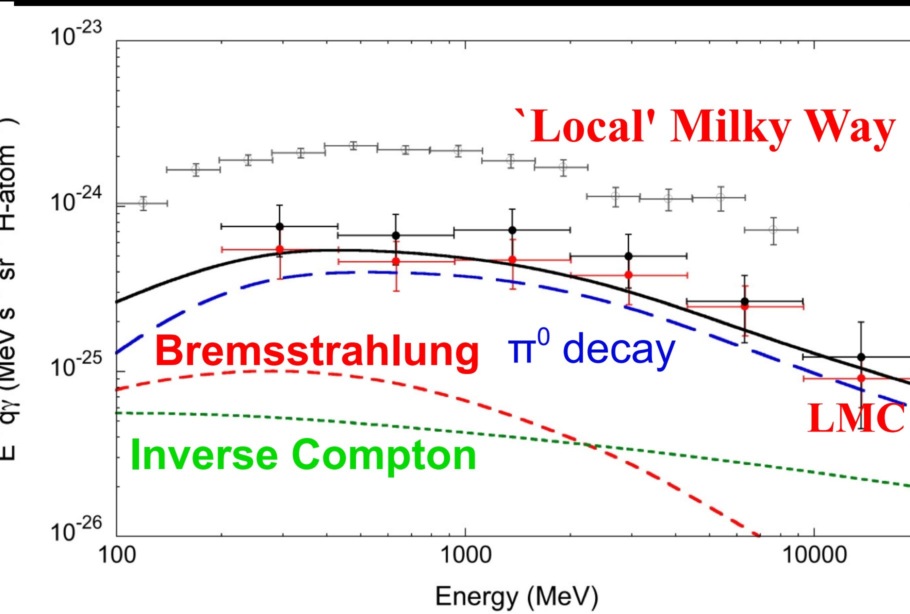
Fermi-LAT collab., A&A 512, 7 (2010)

Cosmic-ray Density

LMC emissivity map



Average emissivity spectrum



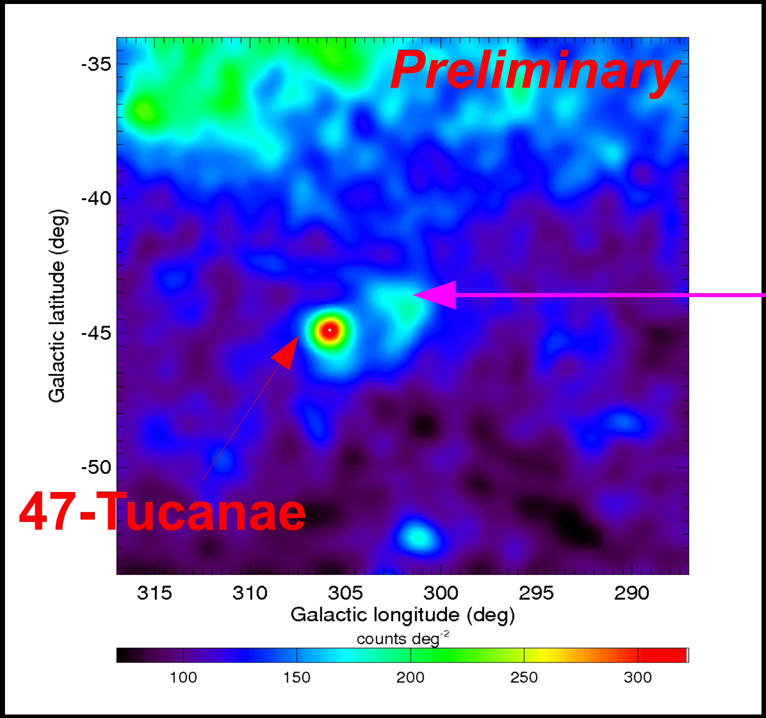
- Considerable cosmic-ray density variations
- Small GeV proton diffusion length

- Spectrum consistent with expectations from π^0 decay (using local galactic p, e^-, e^+ spectral shapes)
- Average cosmic-ray density about 0.2-0.3 times that in solar vicinity (consistent with difference between Galactic and LMC SN rate)

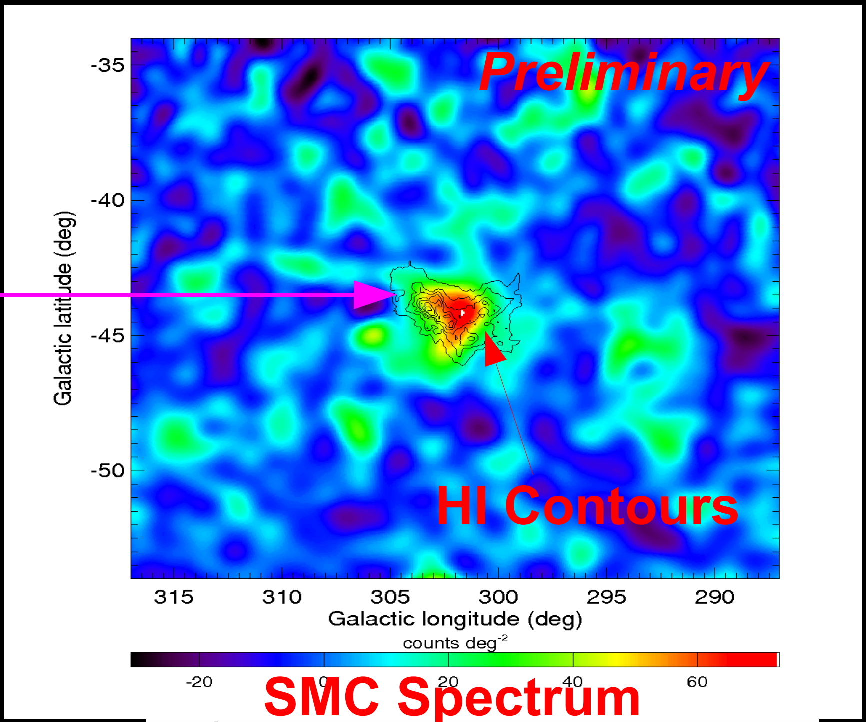
Fermi-LAT collab., A&A 512, 7 (2010)

Detection and Resolving of SMC in Gamma Rays

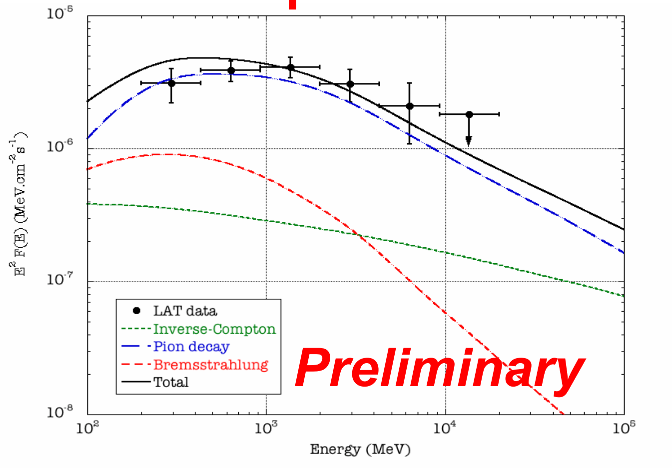
SMC region counts map



Counts map (47-Tuc removed)



SMC Spectrum



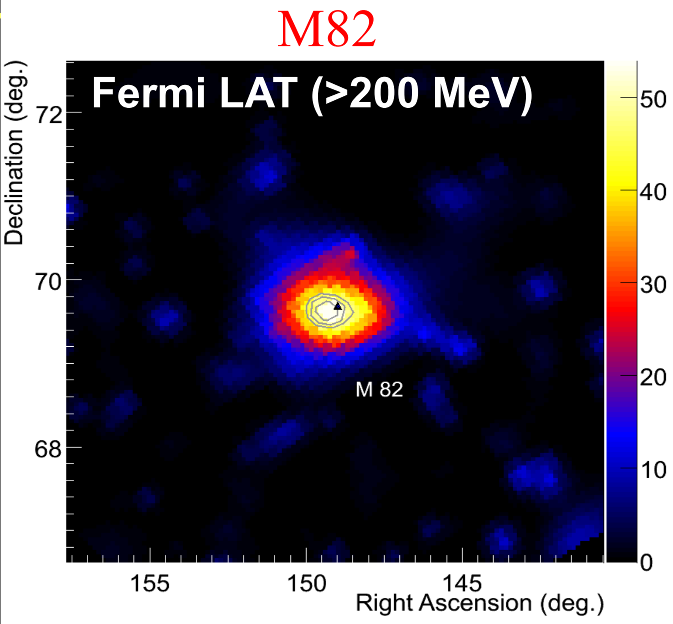
- First detection of SMC after 1+ year of data
- Subtraction of 47-Tuc and Galactic diffuse emission shows extended object coincident with SMC (no flux variations)

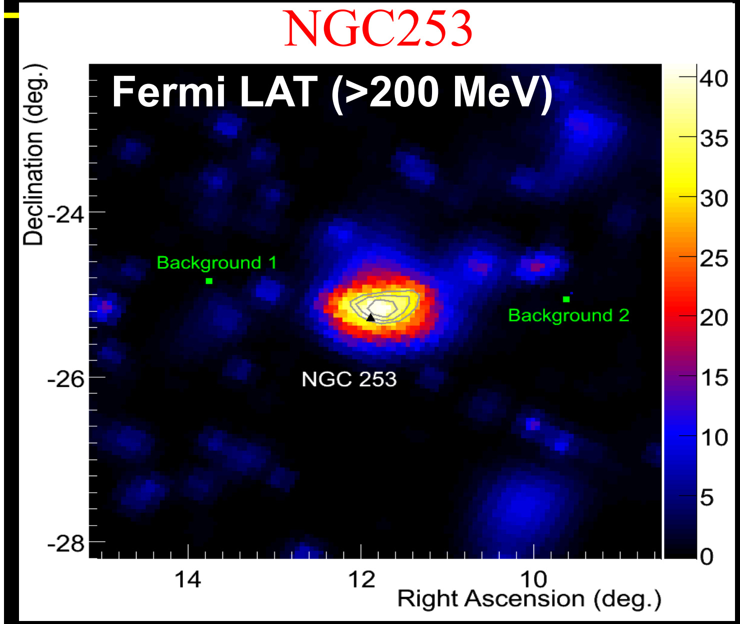
Fermi-LAT collab., A&A submitted

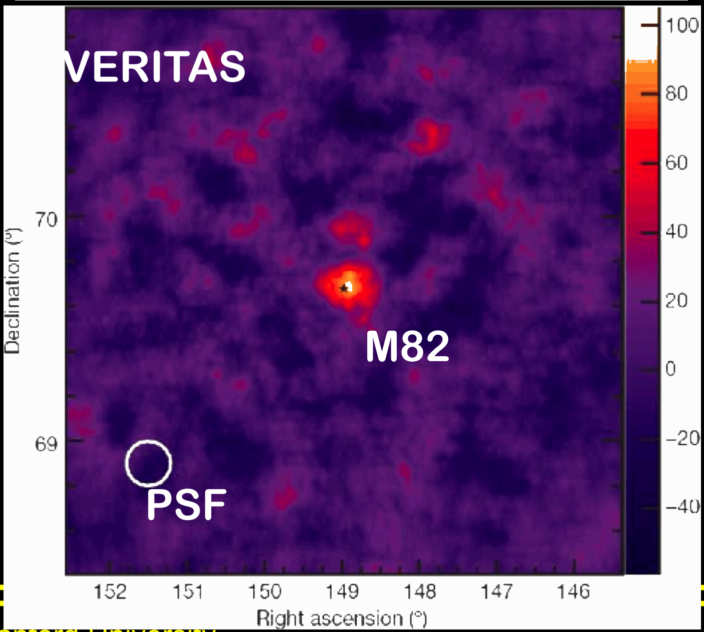
Star-Burst Galaxies Detected in Gamma Rays

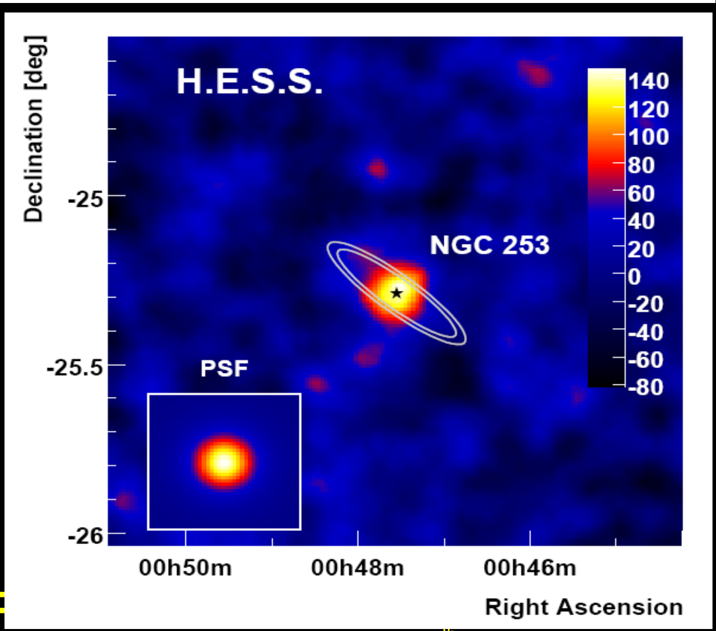
- ' 09 detections of starburst galaxies NGC253 and M82 in HE and VHE gamma rays
- Galaxies are not resolved by any of the instruments so appear as point sources

Note: angular scales not the same!

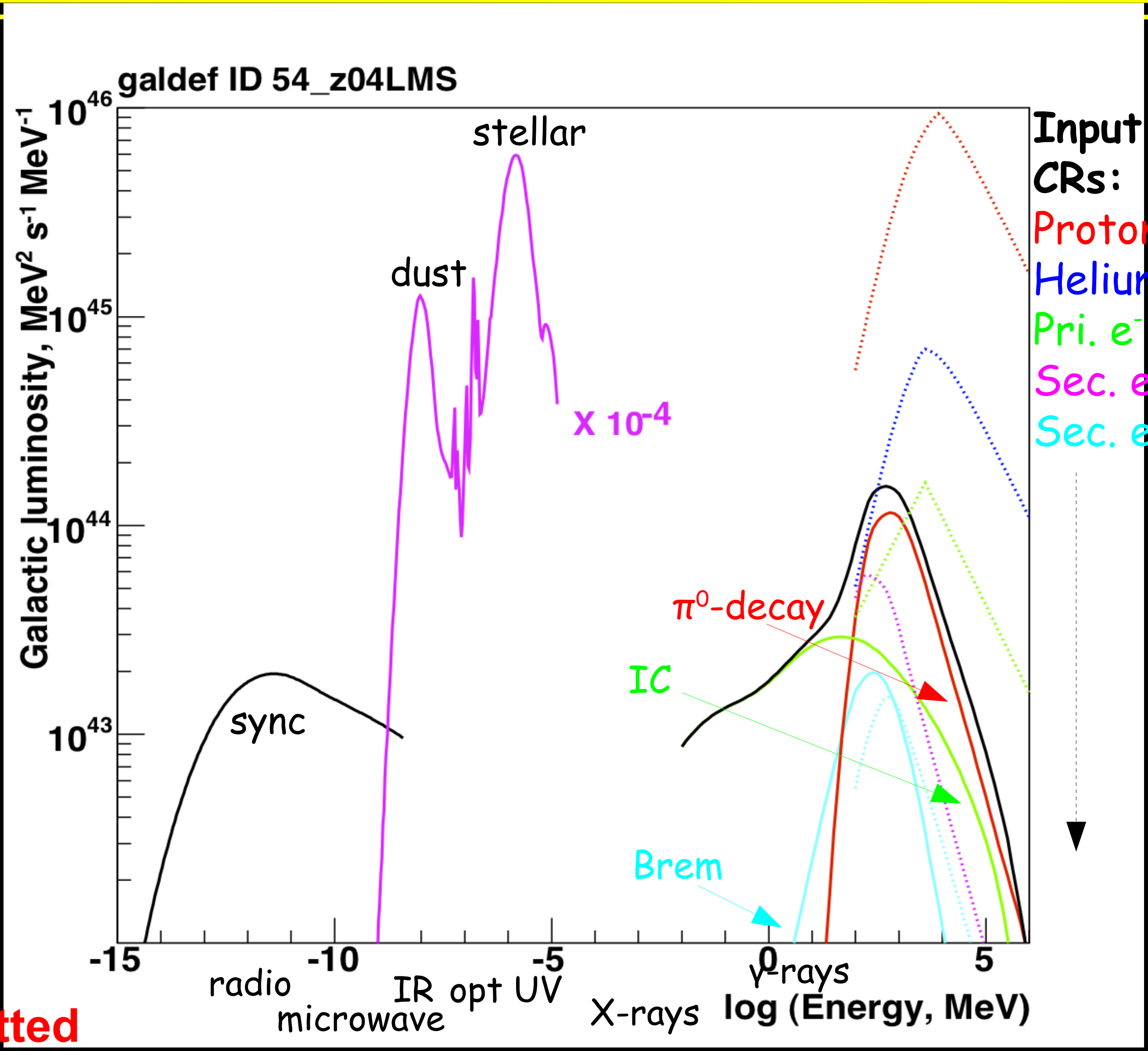






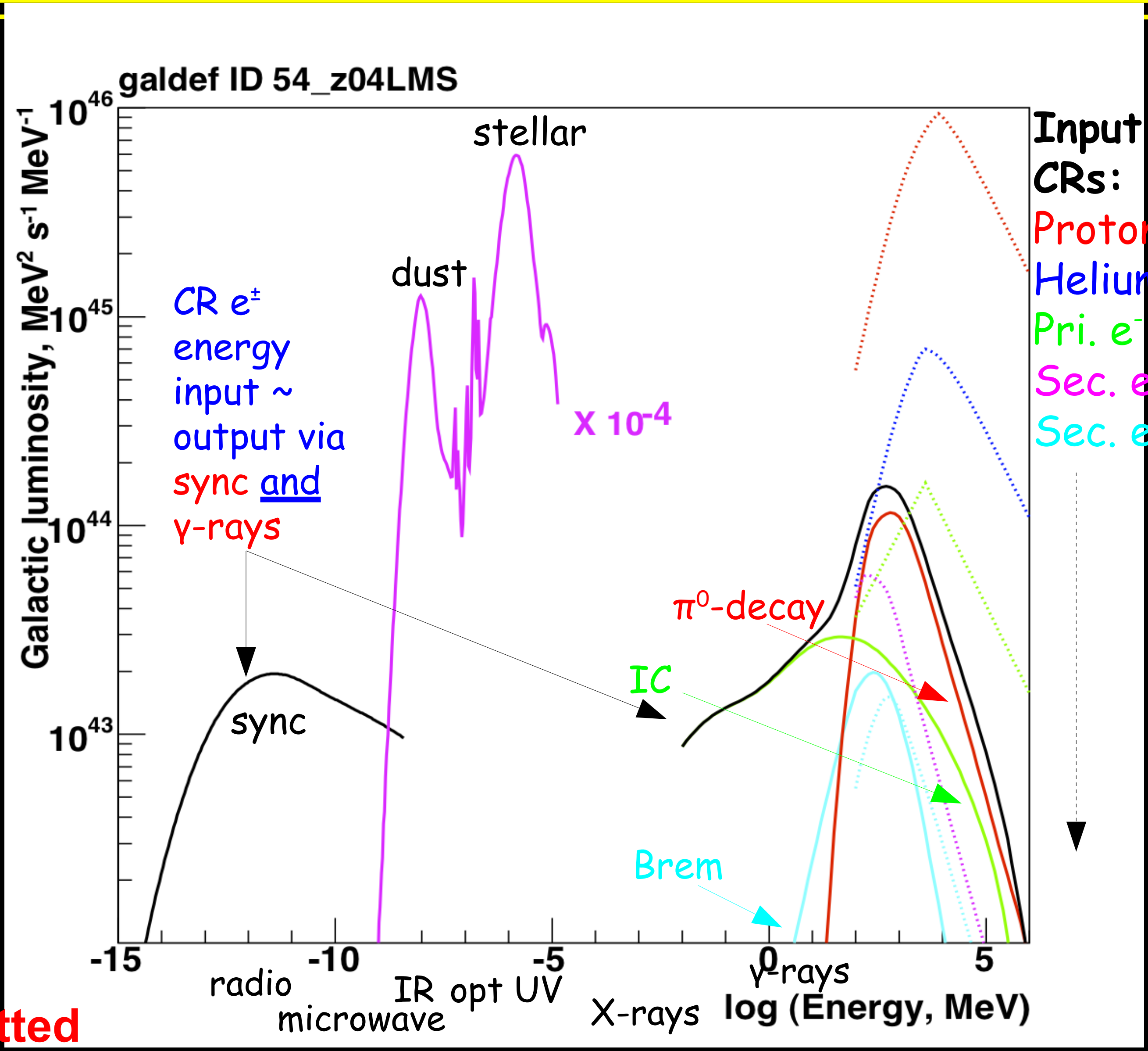


Multi-Frequency Spectrum of Milky Way



Strong et al. ApJL, submitted

Multi-Frequency Spectrum of Milky Way



Strong et al. ApJL, submitted

Open Questions

- How does cosmic-ray propagation work? How are the sources of cosmic rays in the Galaxy distributed?
- Are protons and electrons confined in the same way?
- What combination of star formation, propagation, confinement, sources, X_{CO}, ..., are we seeing in these nearby galaxies? Can we use this information to resolve issues interpreting the Milky Way diffuse emission?
- What will a detection (and resolved image) of M31 reveal? Expected in a few years ...
- How to interpret the radio-FIR-gamma relationship? Intrinsic connection between these wavebands because electrons/positrons produced by protons interacting with the interstellar gas
- Extension to other galactic types – how does the physics affect the multi-frequency emission?
    - Required to predict the contribution by different sub-classes of star forming galaxies to the radio → gamma extragalactic diffuse background

GALPROP v54 and WebRun available July 2010

WebRun: GALPROP without installation

A new feature of this Project, the **WebRun service**, allows you to configure and run GALPROP calculations on a **dedicated high perfomance computing cluster** using only your web browser (i.e., you do not need to download, install and run the code on your computer).

This feature is **only available to registered users**. If you wish to use it, please register at the forum first or just log in if you already have an account at the GALROP forum.

Note: the interface of WebRun requires the following features enabled in your web browser: cookies, JavaScript and iframe support. Any modern major browser will do.

- Run GALPROP from browser on dedicated cluster
- No user installation: latest release version available together with earlier versions for easy comparison of results
- Provides parameter and configuration checking, availability of latest supporting data sets (gas, ISRF, etc.), plotting of results via browser
- Requires user registration (access to forums, updates, etc.)
- Source code still available for registered users

GALPROP website: http://galprop.stanford.edu

Supplementary Slides

Modified Model: Including Residual Gas

- Increasing intensity of cosmic-ray spectra improves agreement but profiles show residuals
- Gamma rays → gas not traced by usual methods
- Noted by Grenier & Casandjian (2005)
- A way of incorporating this is into the model is to modify HI with a correction for `local' gas based on dust emission (SFD99)