Challenges for identification of dark matter in the diffuse gamma-ray emission

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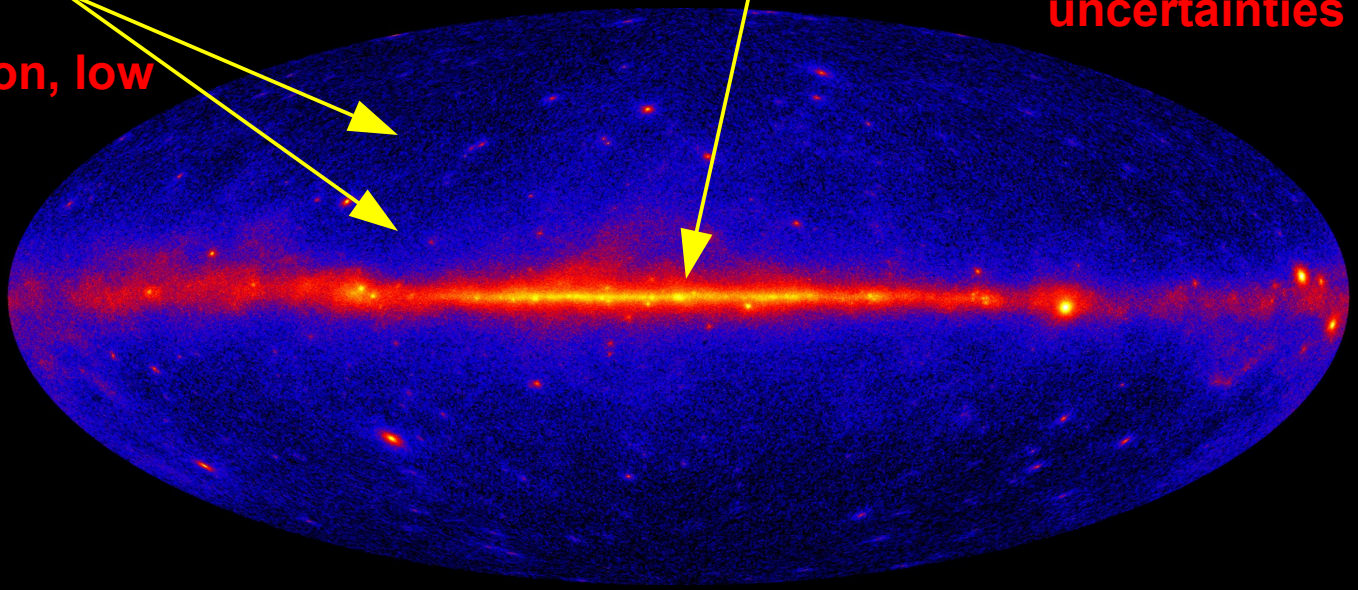
Where to look for gamma-ray signatures of dark matter?

Galactic Centre: good statistics, strong background/foreground + source confusion

Satellites: low background + good source identification, low statistics,

Halo: large statistics, diffuse Galactic emission uncertainties



Spectral lines: no astrophysical uncertainties, low statistics

Extragalactic diffuse: large statistics, foreground subtraction + astrophysical source populations

Galaxy clusters: low background, low statistics

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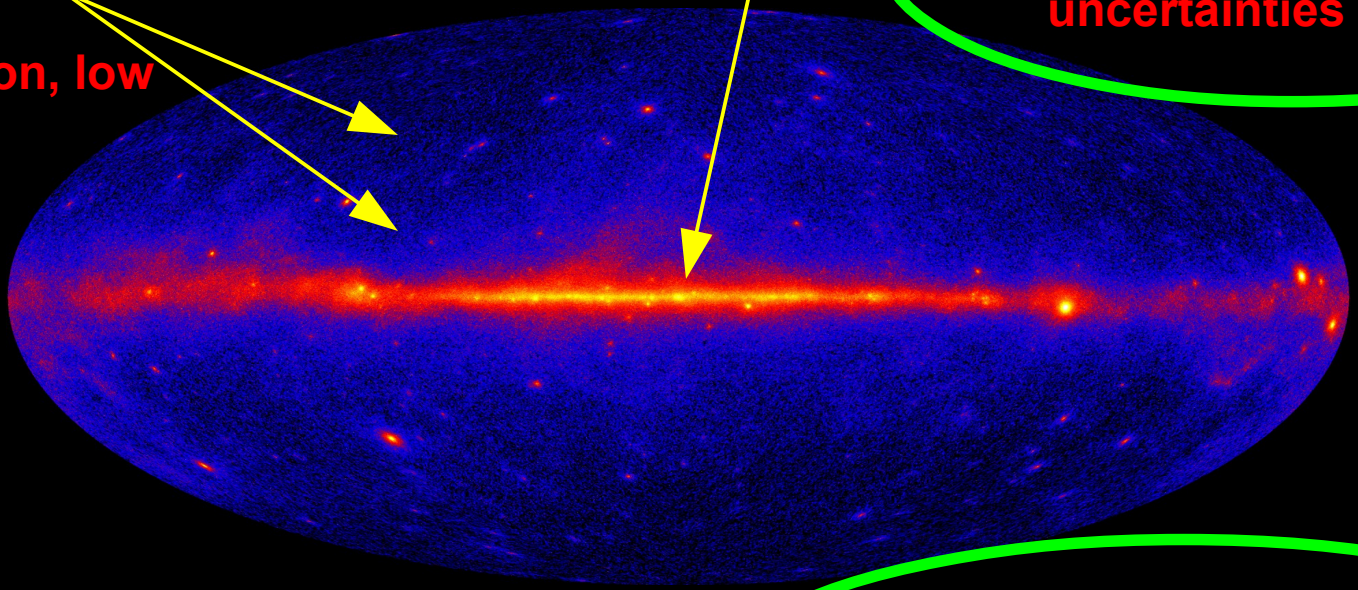

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Why study the Diffuse Emission?

The Milky Way and its Structure

→ 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.

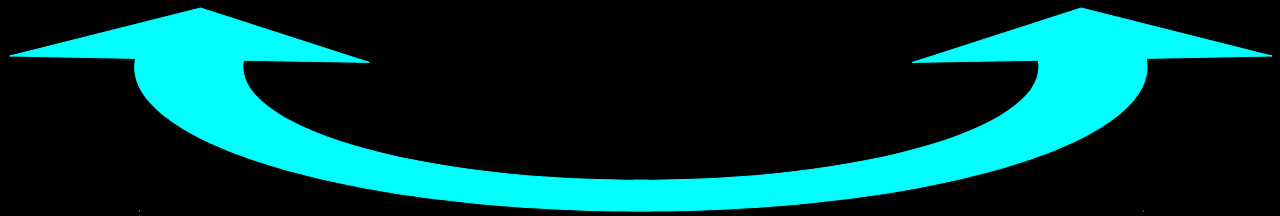
→ Interstellar Medium
Distribution of HI, H_2, HII gas
Nature of X_{CO} relation in Galaxy
Distribution and intensity of interstellar radiation field ↔ formation of H_2
etc.

As a Foreground

→ The diffuse emission is the foreground against which sources are detected
Point sources : limitation on sensitivity
Extended sources : disentanglement

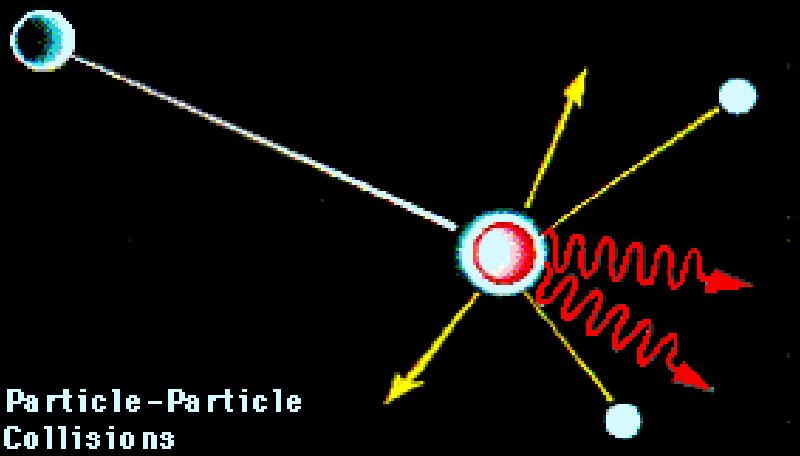
→ Indirect dark matter detection
Predicted gamma-ray/cosmic-ray signals rely on accurate subtraction of standard astrophysical sources

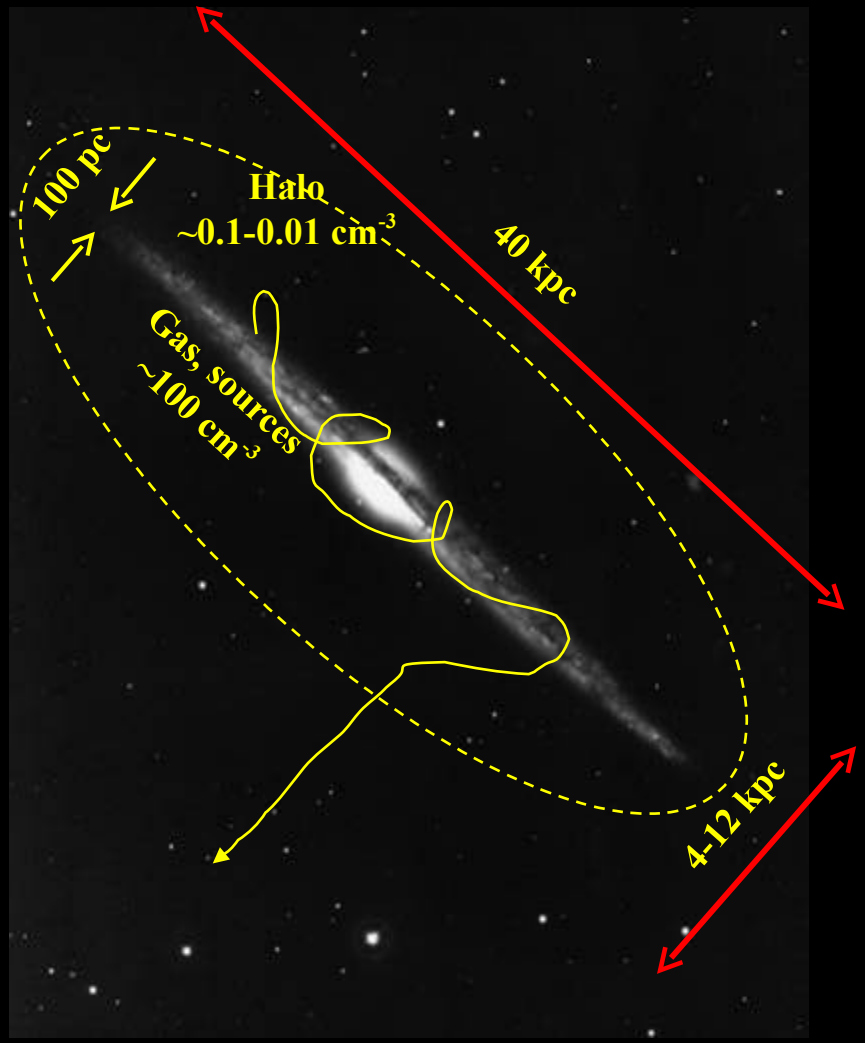
→ Foreground for isotropic diffuse background
Whatever its nature



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.)

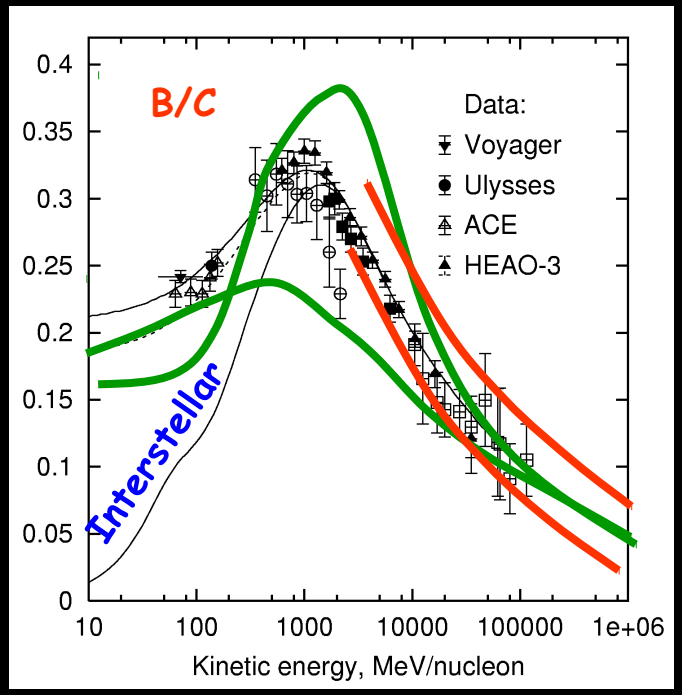




Components of realistic CR propagation model

- Detailed gas distributions (fragmentation, energy losses: π^0-decay, brem)
- Interstellar radiation field ($e^{\pm}$ energy losses: IC)
- Nuclear & particle production cross sections + reaction network
- Secondary particle production ($pX \rightarrow \pi^0\pi^{\pm} \rightarrow \gamma, e^{\pm}, \nu$)
- Energy losses: ionisation, Coulomb, brem, IC, synchrotron $\rightarrow$ ISM heating, γ-rays and other diffuse emissions
- Spatial distribution of cosmic-ray sources, injection spectrum
- Solve propagation equations for all CR species
- Derive propagation parameters

Determining propagation parameters



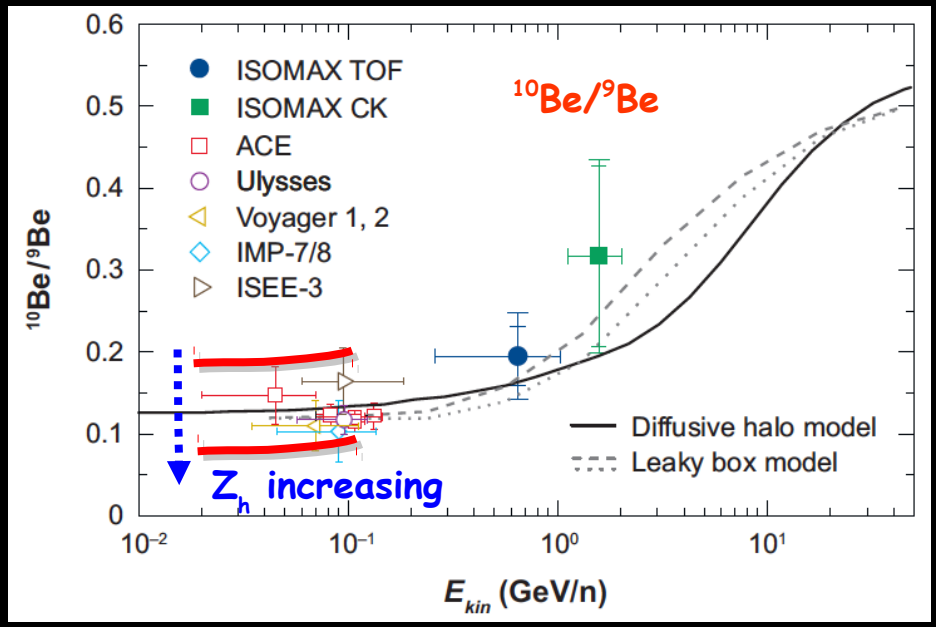
Typical Parameters (model dependent):

$D \sim 10^{28}\ (\rho/1\ GV)^{\delta}\ cm^2/s$

$\delta \approx 0.3\text{-}0.6$

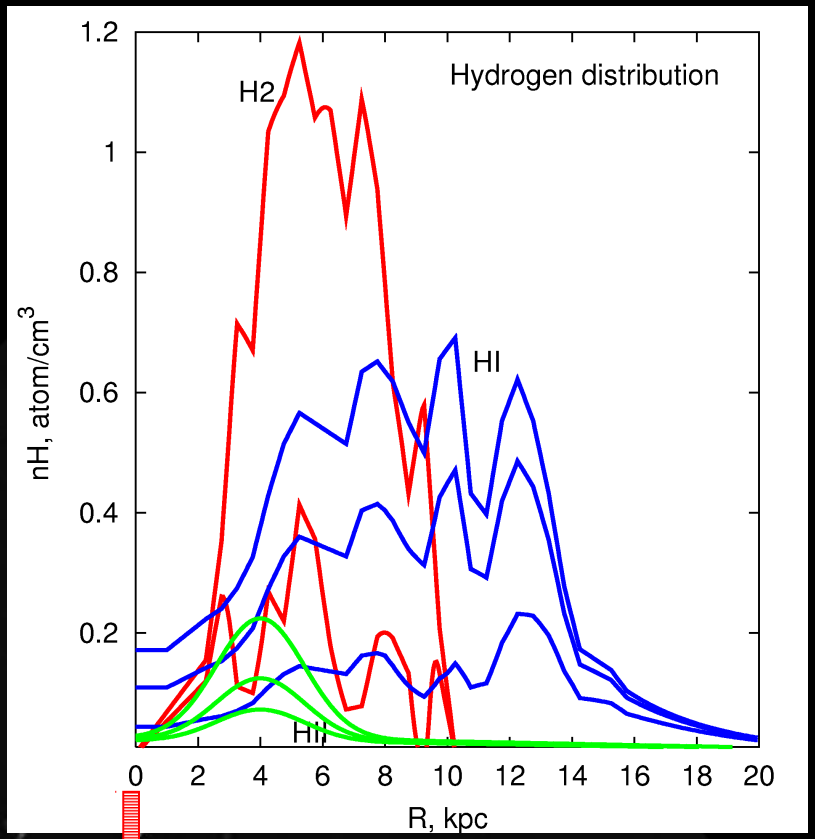
$Z_h \sim 4\text{-}6$ kpc

$(V_A \sim 30$ km/s)



- **Using secondary/primary and flux:**
  - **Diffusion coefficient and index**
  - **Propagation mode and parameters (e.g., convective velocity, etc.)**
  - **Parameters are model dependent**

Gas distribution in the Milky Way

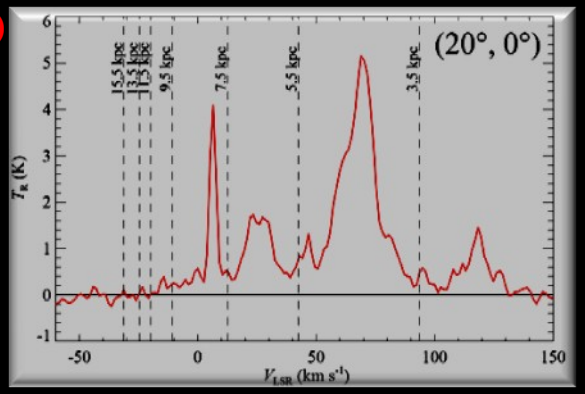


- Molecular hydrogen (H_2) traced using CO J=1→0 transition, concentrated in clouds near Galactic plane (z_{scale} ~ 70 pc)
- Atomic hydrogen (HI) ~smoother and wider distribution out to ~30 kpc (z_{scale} ~ 0.5 kpc)
- Ionised hydrogen (HII) also contributes with lower density but exists out into halo (z_{scale} ~ 1 kpc)

Distribution of interstellar gas

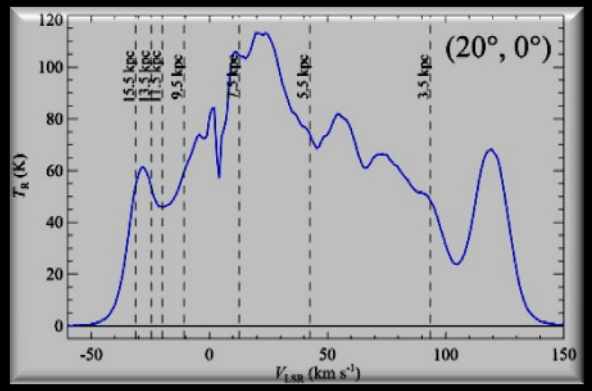
- Neutral interstellar medium – most of the interstellar gas mass
  - 21-cm H I & 2.6-mm CO (surrogate for H_2)
  - Differential rotation of the Milky Way – plus random motions, streaming, and internal velocity dispersions – is largely responsible for the spectrum
  - Rotation curve $V(R)$ →unique line-of-sight velocity-Galactocentric distance relationship
  - This is the best – but far from perfect – distance measure available
- Column densities: $N(H_2)/W_{CO}$ ratio assumed; a simple approximate correction for optical depth is made for N(H I); self-absorption of H I remains

CO



Dame et al. (2001)

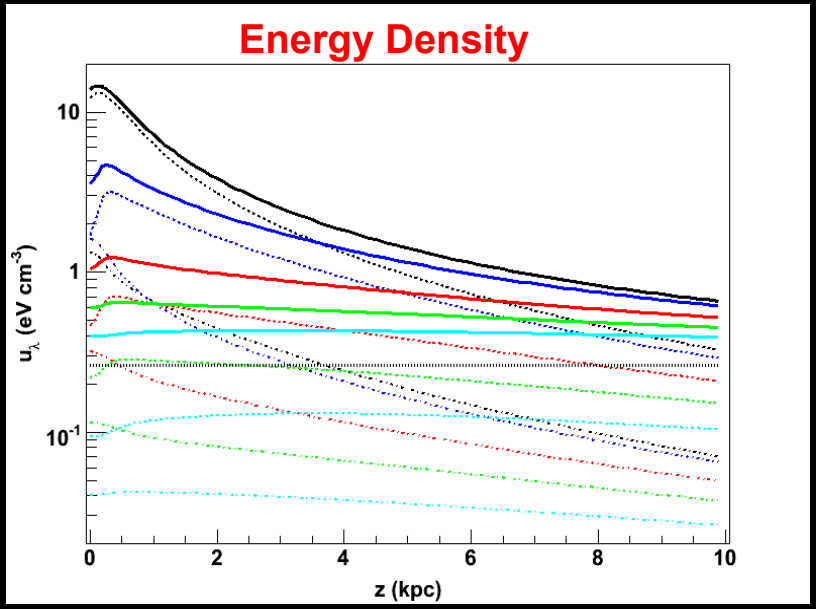
H I

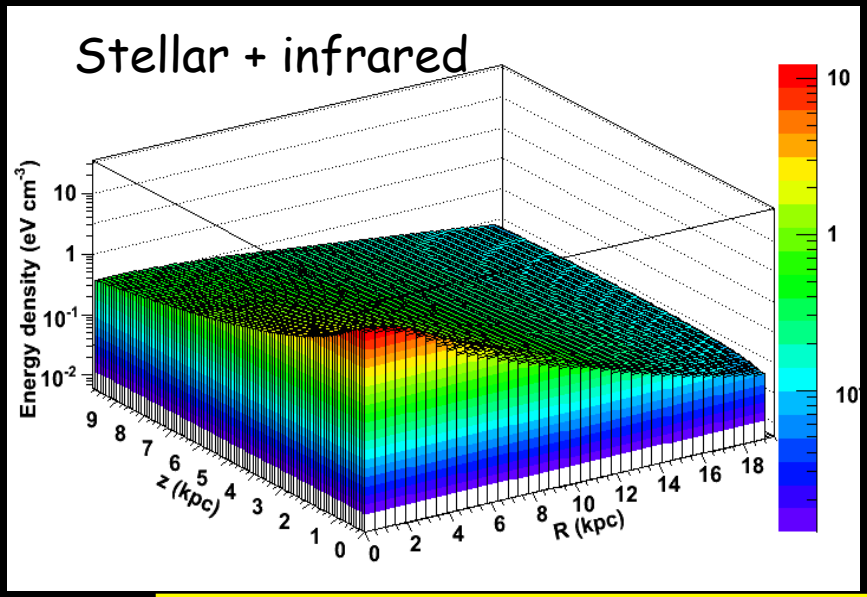


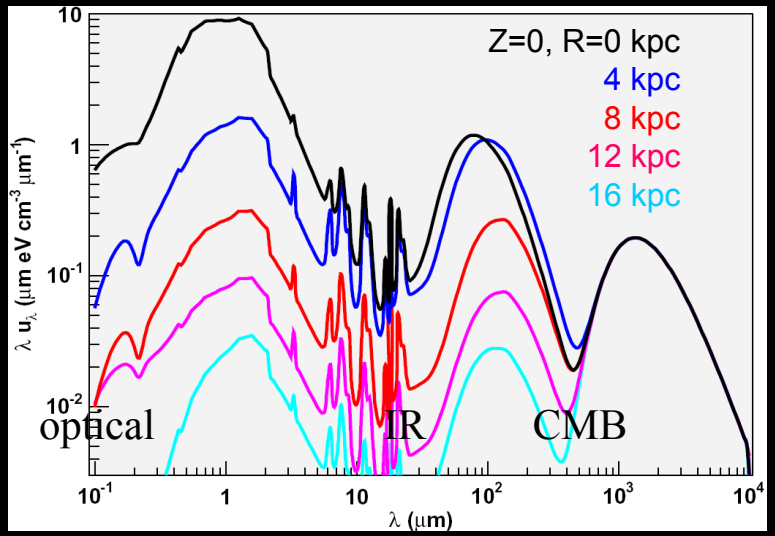
Kalberla et al. (2005)

Interstellar Radiation Field

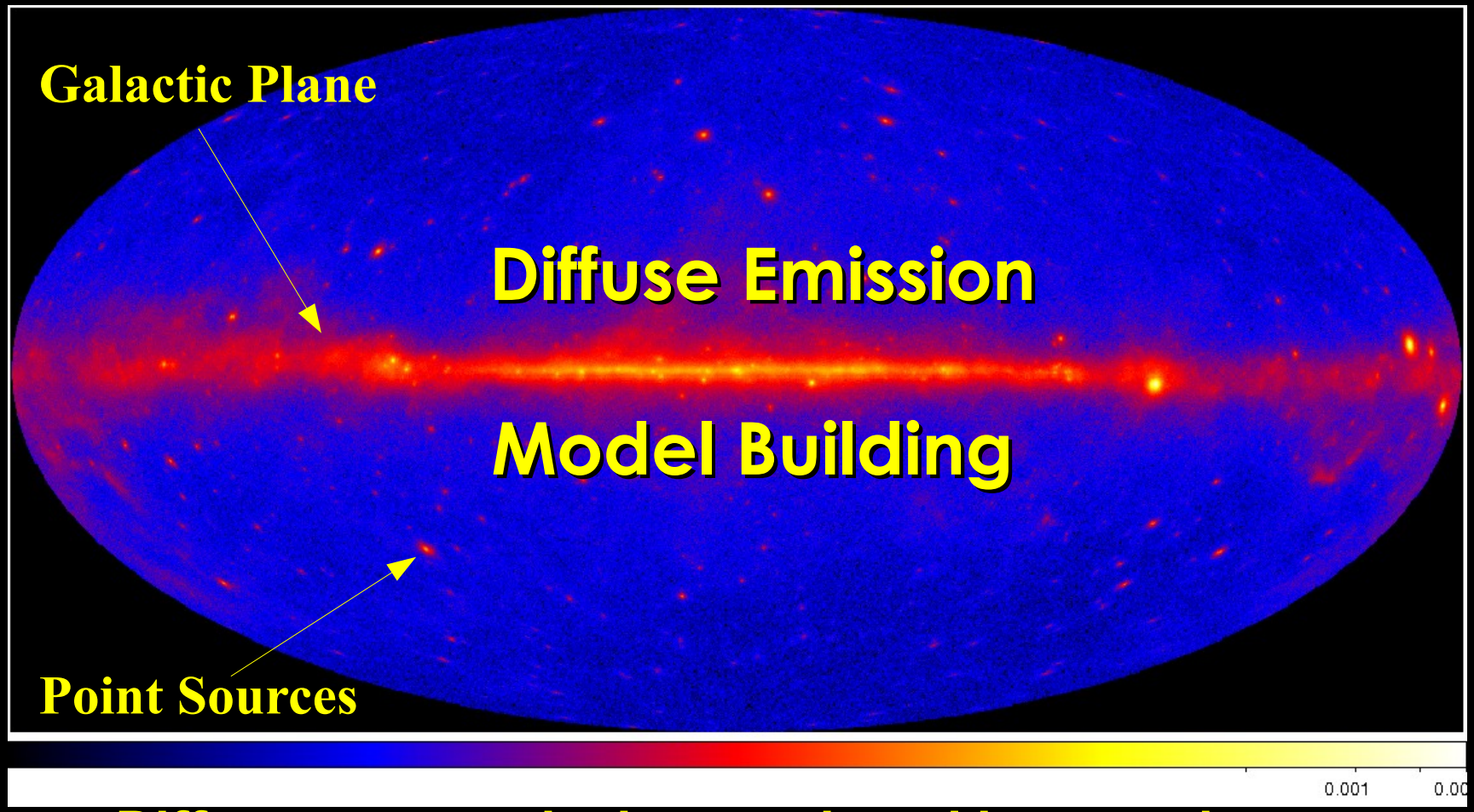
- Detailed modelling
  - Stellar distributions throughout Galaxy
  - Dust emission
  - Radiative transfer calculation
- ISRF ~ CMB 10s kpc above Galactic plane







Fermi LAT 1-Year Sky Map

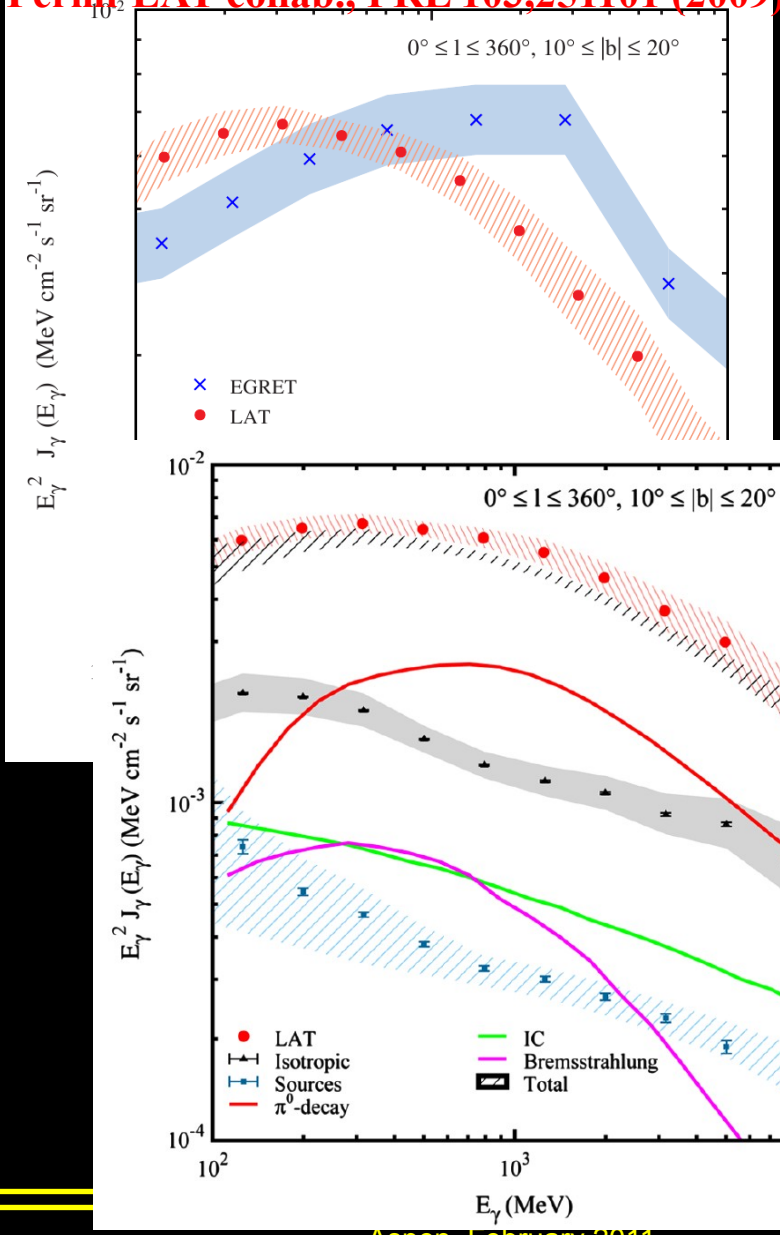


Diffuse γ-ray emission produced by cosmic rays interacting with interstellar gas and radiation fields. Comprises > 80% of the total γ-ray flux!

Testing the ``EGRET GeV Excess''

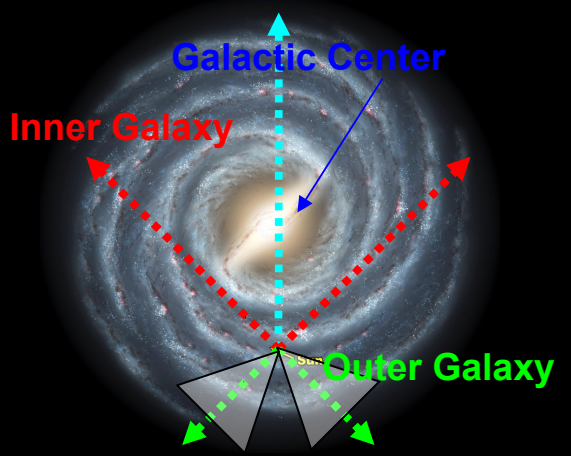
- Observations with the EGRET instrument showed excess emission above a few GeV when compared to conventional diffuse emission models
  - `Conventional' means based on local CR measurements
- Possible hint for
  - Dark matter
  - Local CR bubble
  - Unresolved sources
  - ...
- Not seen in Fermi LAT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

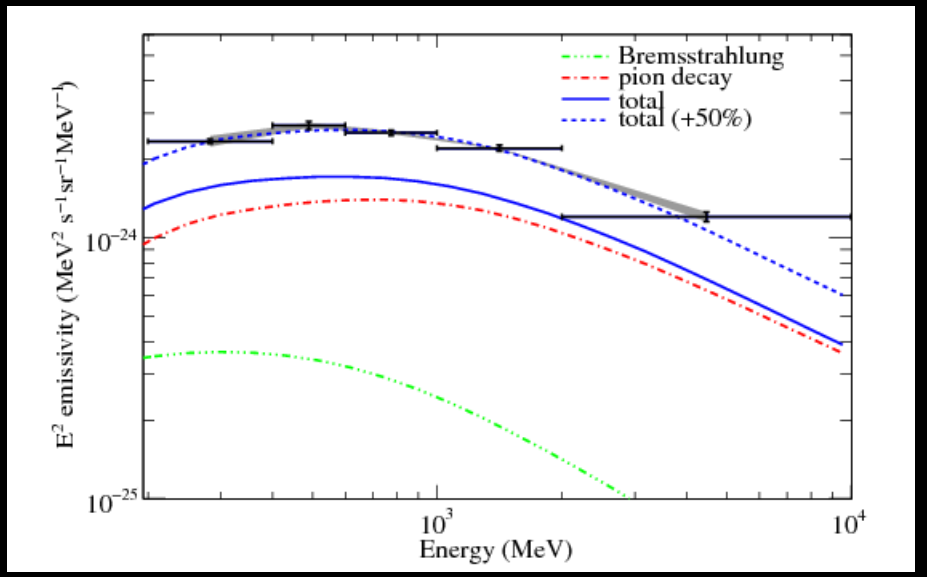
Fermi-LAT collab., PRL 103,251101 (2009)



Nearby Diffuse Emission – Local Gas

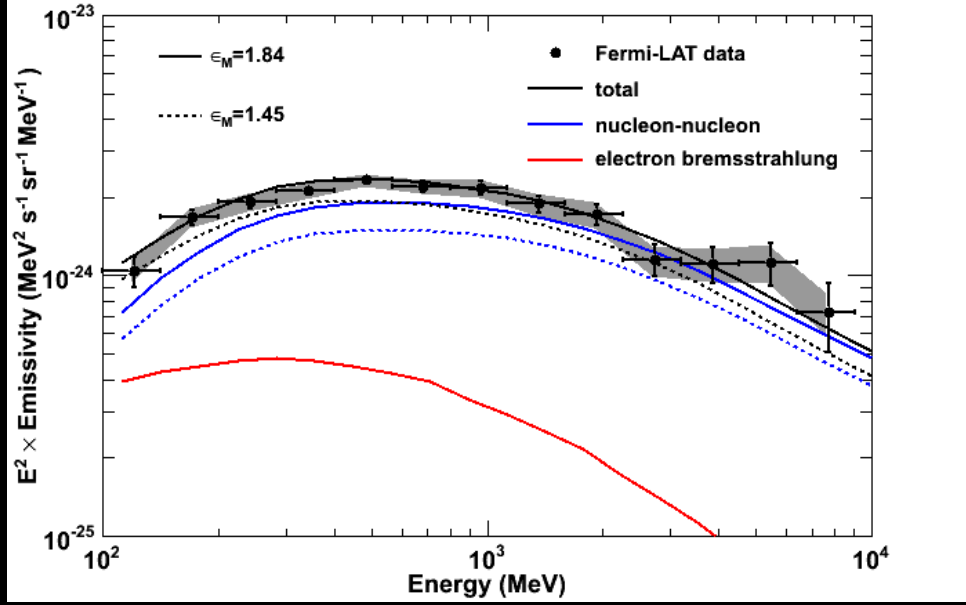
- Selected region with good radial resolution
- Two independent analysis show agreement with local observations of CRs
- Hints for an increased nuclear enhancement factor (effects of high Z nuclei)





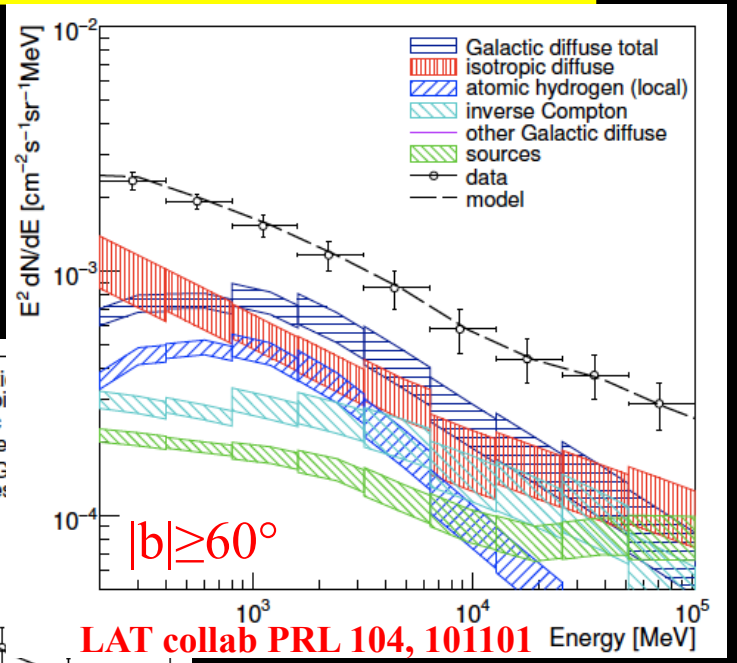
Fermi-LAT collab. ApJ 710,133 (2010)

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

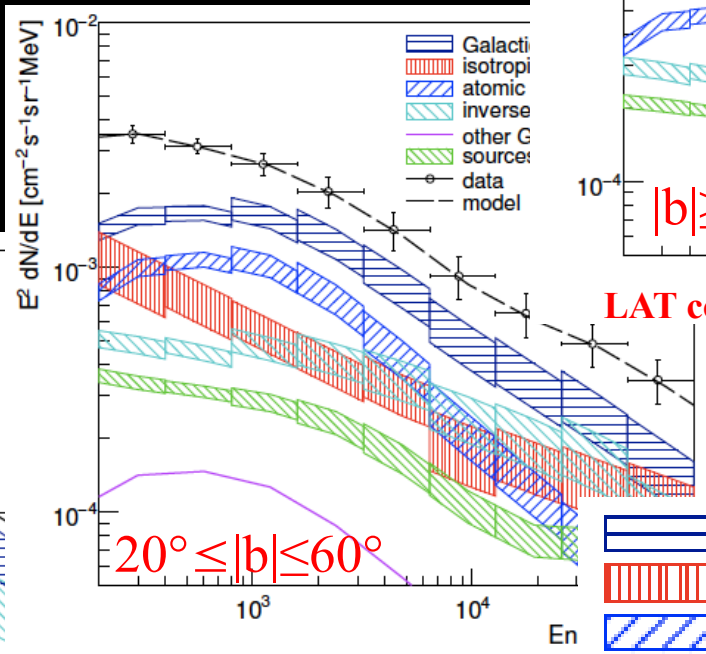


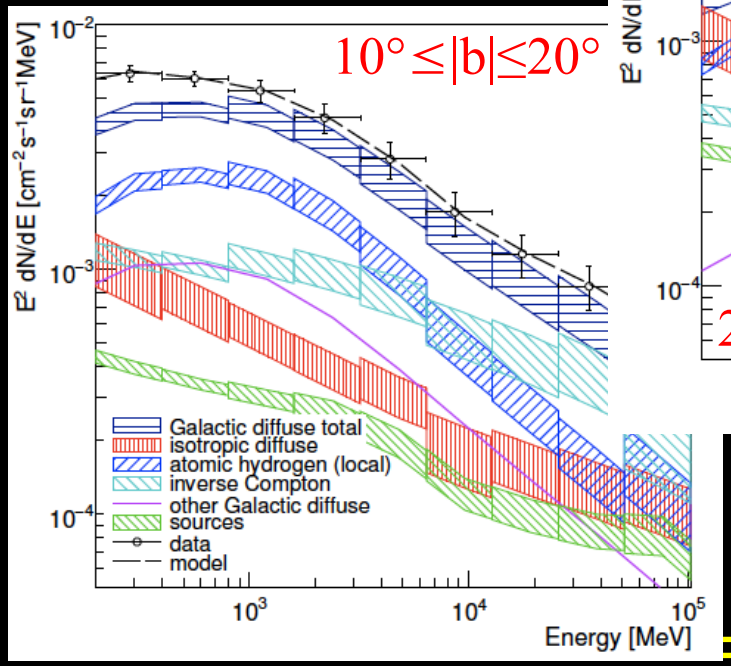
Diffuse Emission Outside Galactic Plane

- Pion-decay and IC dominant components outside plane
- Agreement between model and data is good outside plane
- Uncertainties in model components come from data fit

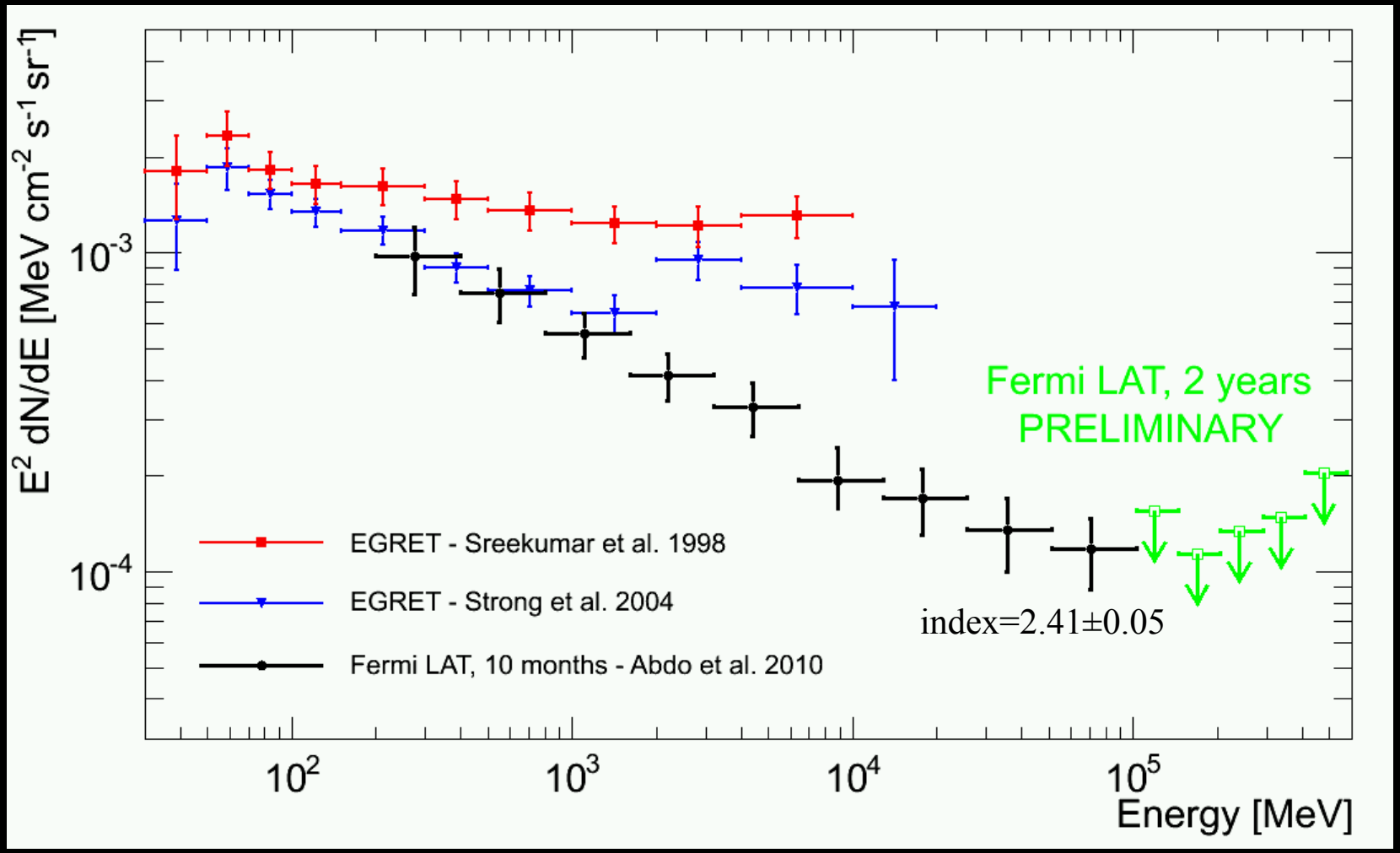


LAT collab PRL 104, 101101





Spectrum of isotropic diffuse γ-ray emission



- Assessed every 6 years (1998, 2004, 2010, … so far)
- Time-dependent: more resolved sources steepens spectrum

Systematic Large-Scale Study: 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**

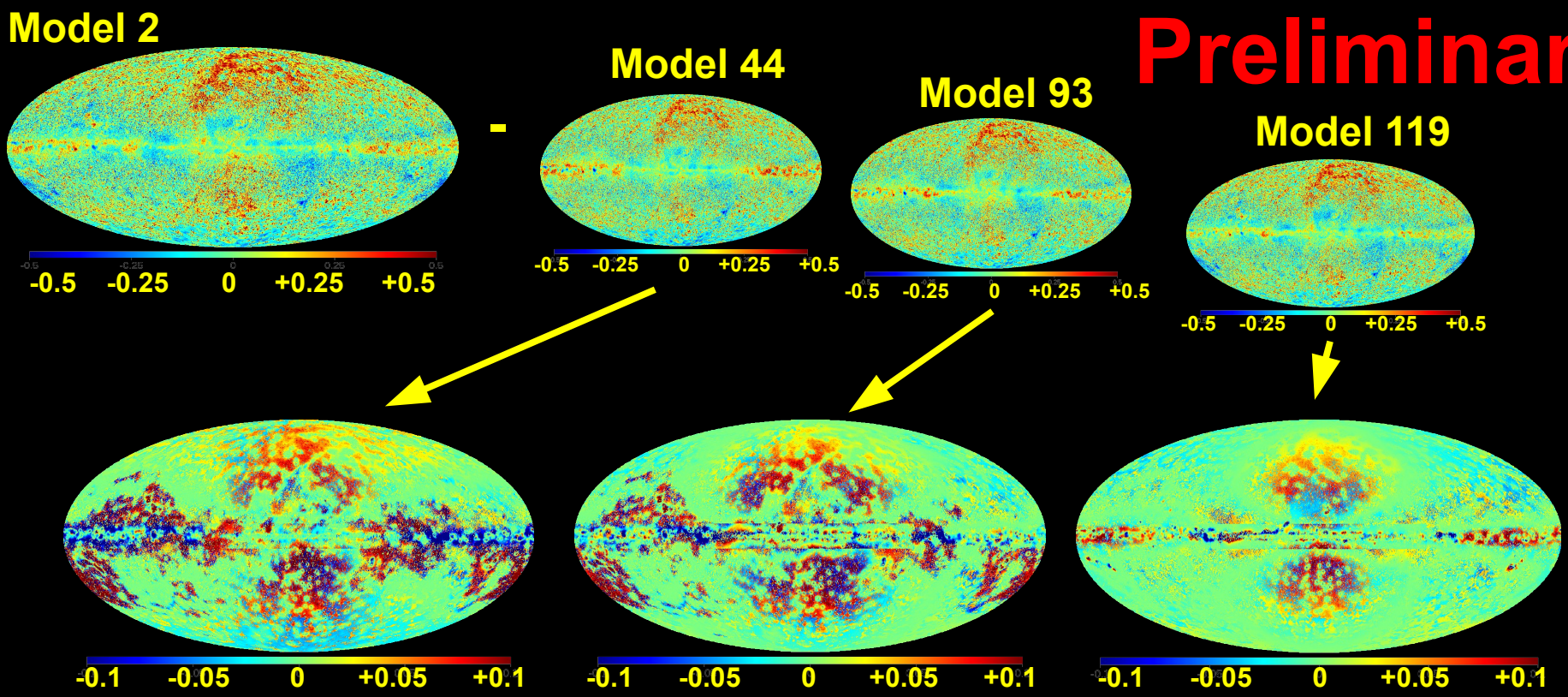
* 10^{28} cm^2 s^{-1}

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

*** km s^{-1}

Systematic Large-Scale Study: Residuals

Preliminary



- 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

Cosmic-ray Propagation Model Constraints from Global Parameter Scans

- Bayesian method (Q – parameter vector, D – observations):

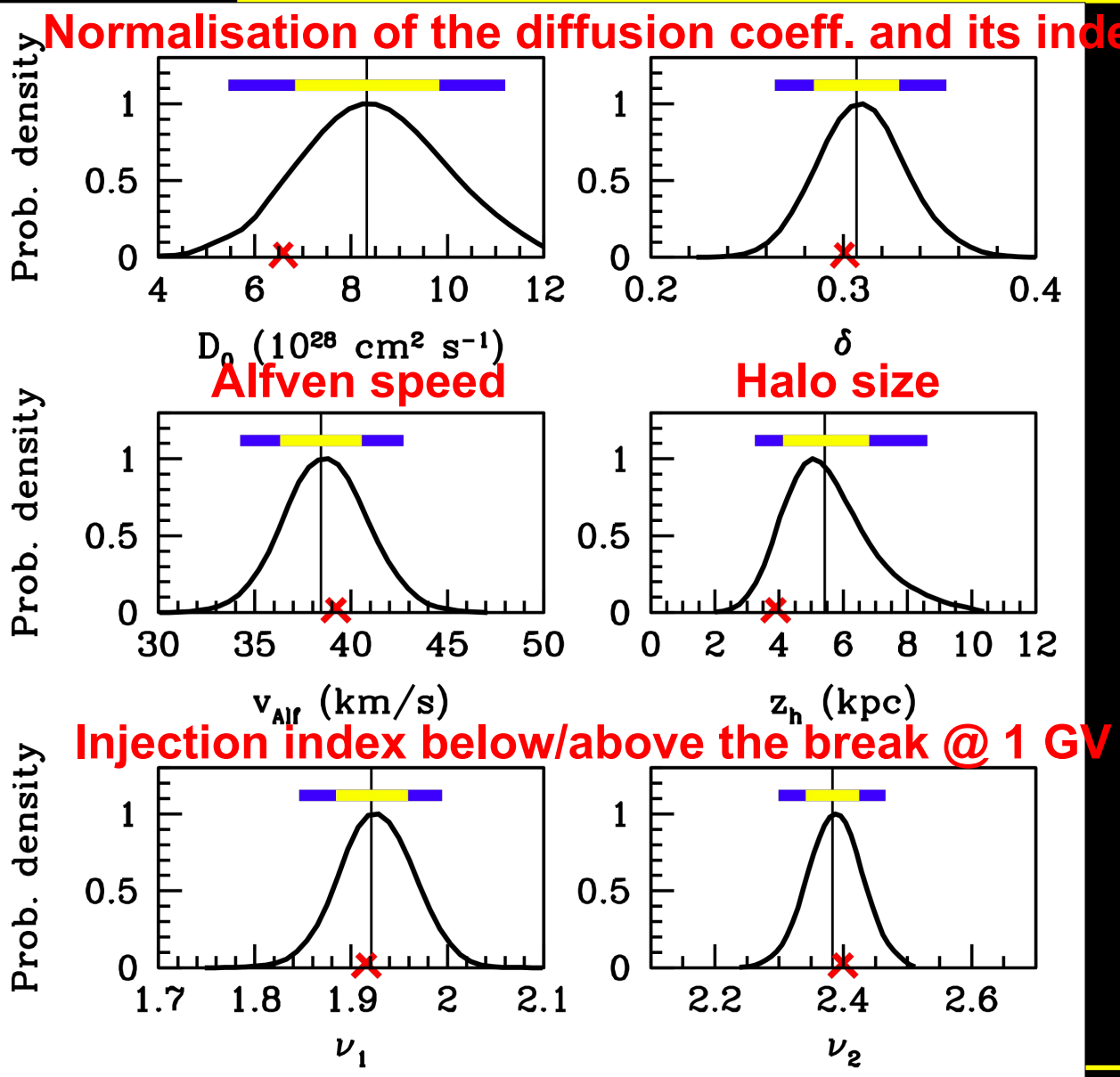
$$P(\mathrm{Q}\,|\,D) = \frac{P(D\,|\,\mathrm{Q})P(\mathrm{Q})}{P(D)}$$

  P(Q|D) – posterior distribution
  P(D|Q) – likelihood function (for fixed D)
  P(Q) – prior distribution
  P(D) – Bayesian evidence

- Allows for more sophisticated treatment of systematics
- Nested sampling (Skilling '04,'06) and MultiNest (Feroz&Hobson '08) in SuperBayeS ↔ GALPROP
- > 10^5 samples, ~ 13 CPU years
- Tested posterior distribution agrees very well with MCMC-derived distribution
- Used representative data from ACE, ISOMAX, HEAO-3, ATIC-2, CREAM
- Total of 17 parameters fitted, best-fit χ^2/dof ~ 1

Trotta et al., ApJ in press (2011), arXiv:1011.0037

Posterior Probability Distributions



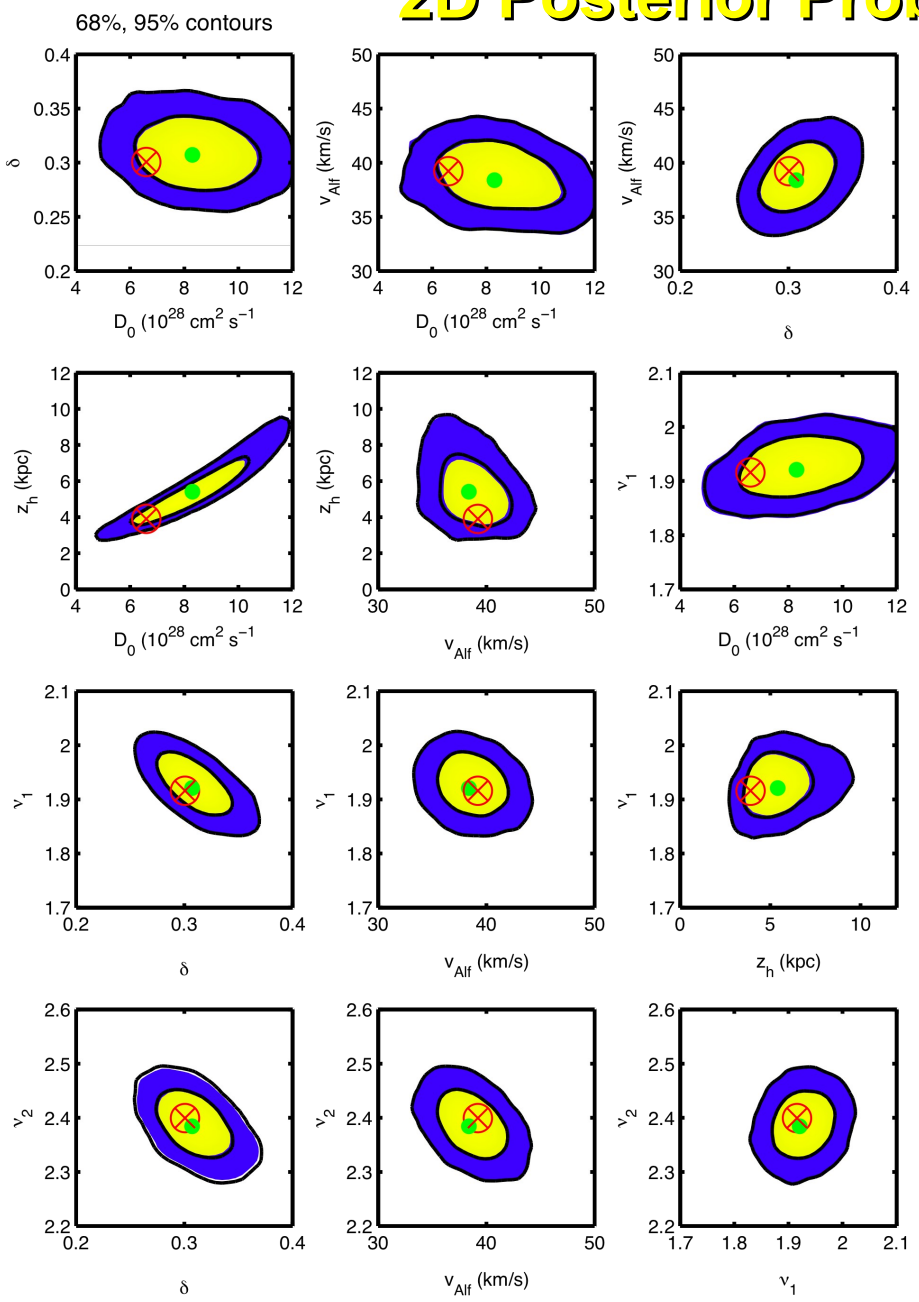
X – best fit

Vertical line – posterior mean

Colour bar – 68/95% range

- Reacceleration model
- Parameters very close to those derived by `chi-by-eye'

2D Posterior Probability Distributions

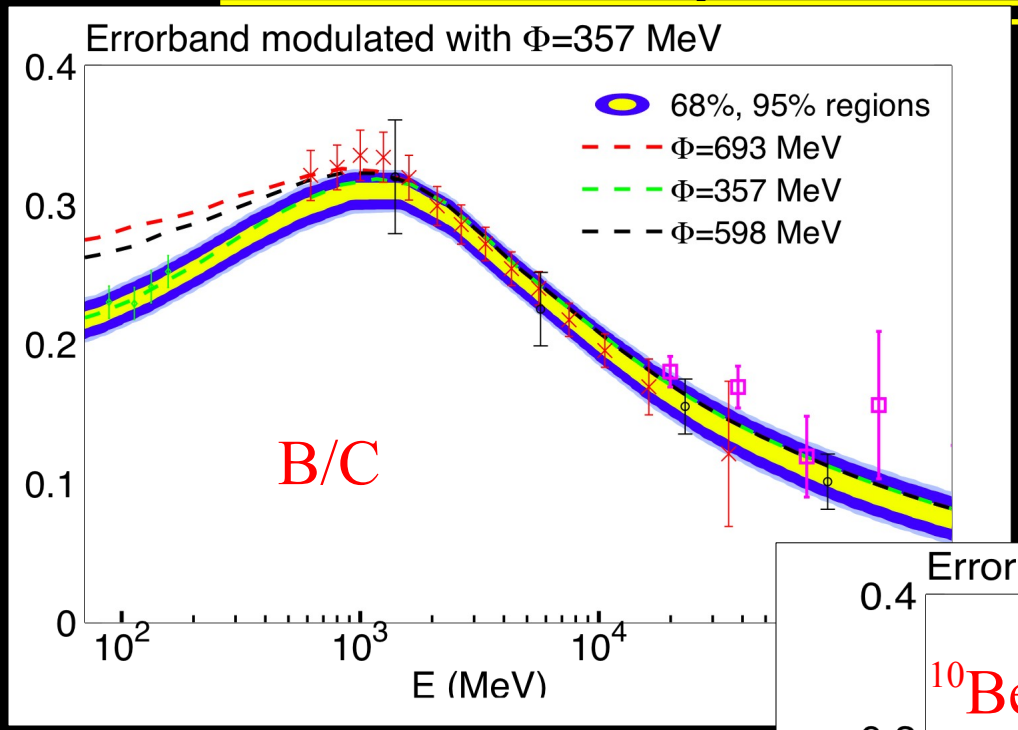


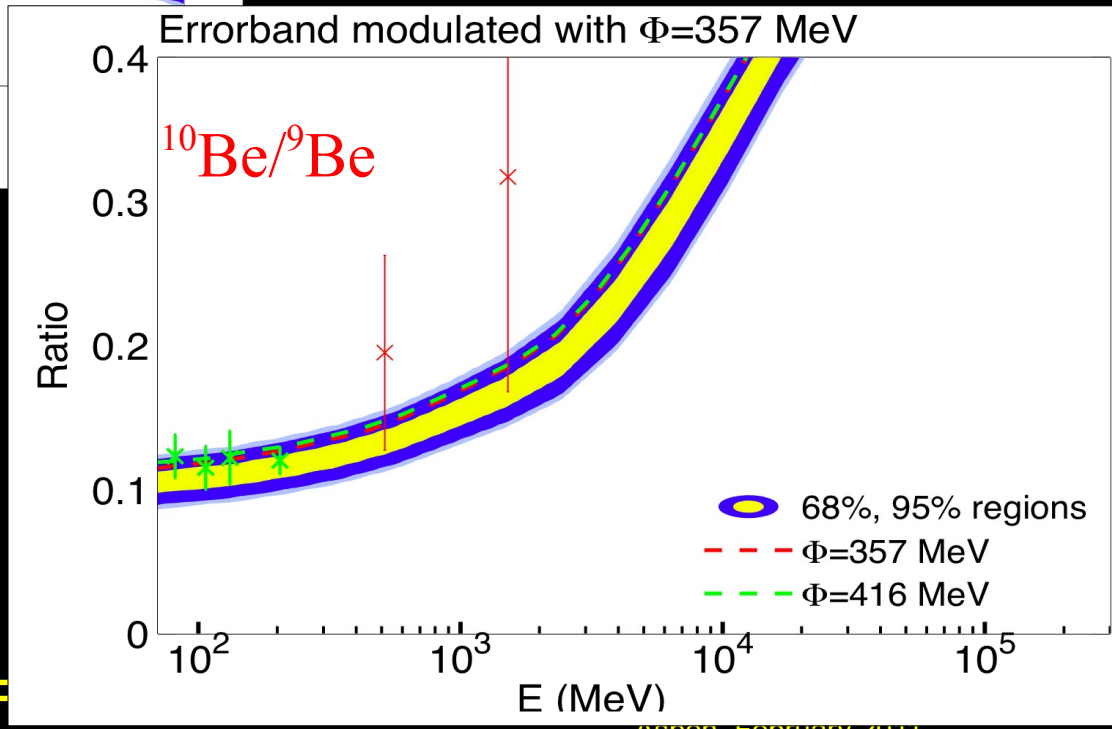
- Contours enclose 68% and 95% probability regions

⊗ - best fit

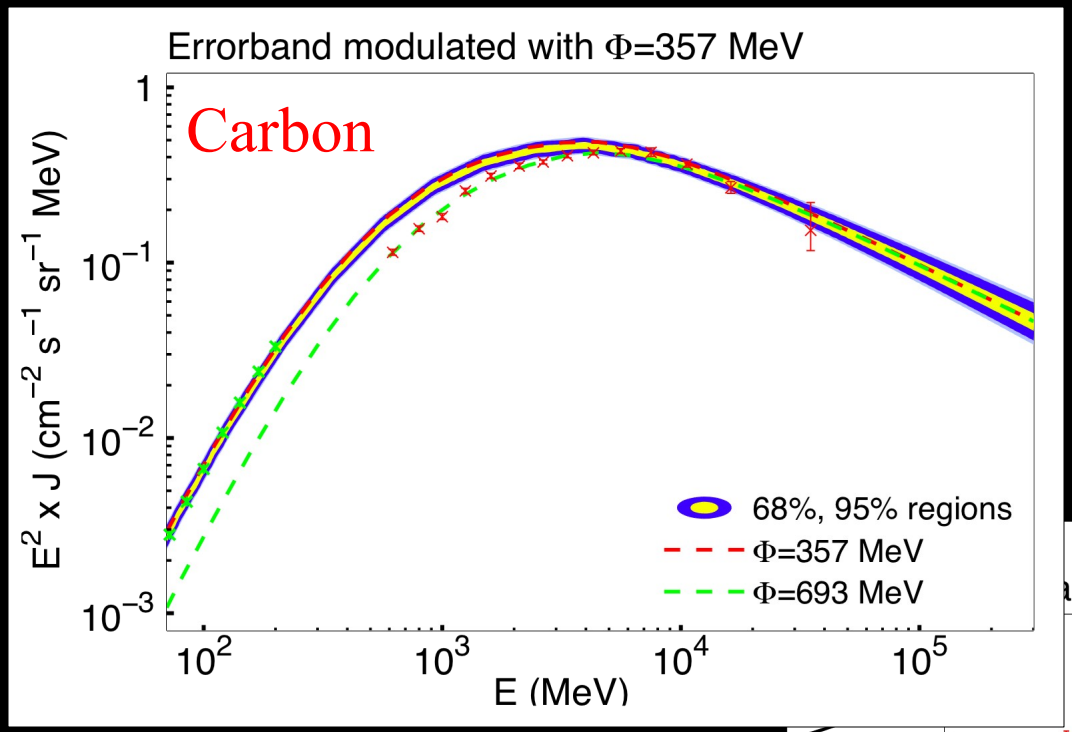
- posterior mean

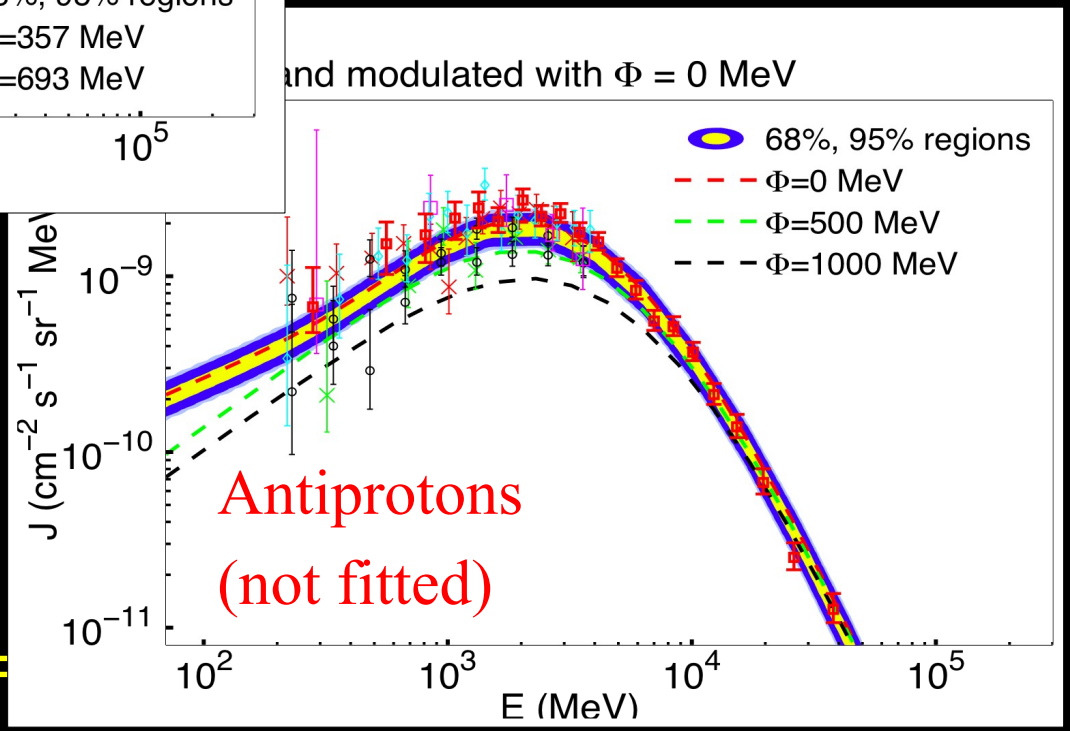
Examples: B/C and Be ratios





Examples: Carbon and Antiprotons



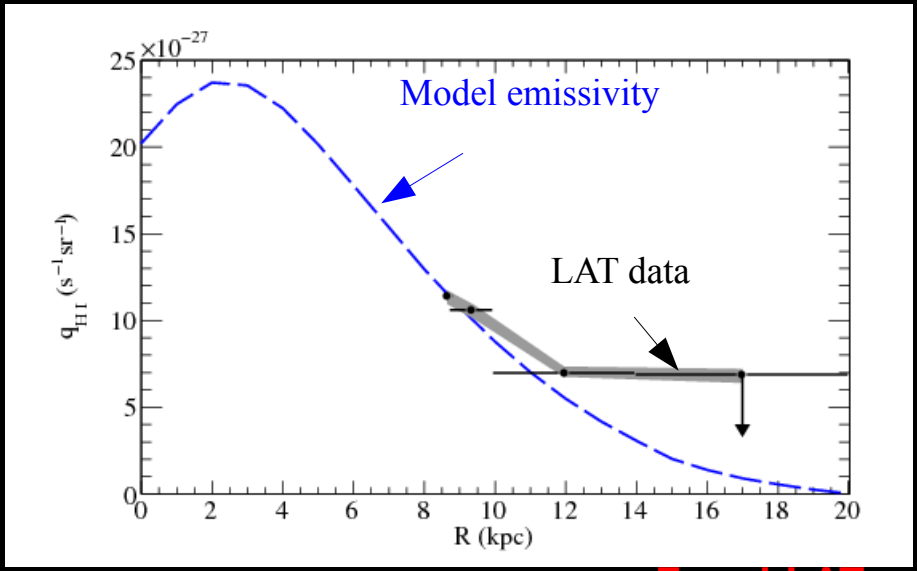


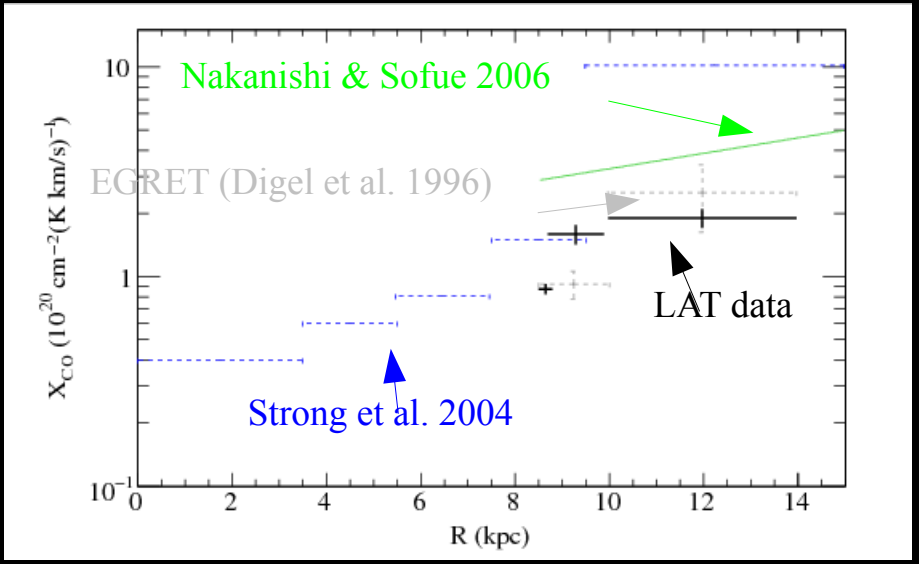
Summary

- The diffuse gamma-ray emission presents the highest statistical sample for the potential identification of a dark matter signal but …
- Understanding systematic effects in astrophysical foreground are now crucial
- Large scale residuals in diffuse emission compared to models show improvement required
- Analysis of cosmic-ray propagation models using Bayesian methods provides well-defined model uncertainty compared with data
- Work is still required to understand the astrophysical uncertainties

Cosmic Ray 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)