Spectrum and Morphology of the Fermi Bubbles

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for the Fermi-LAT Collaboration

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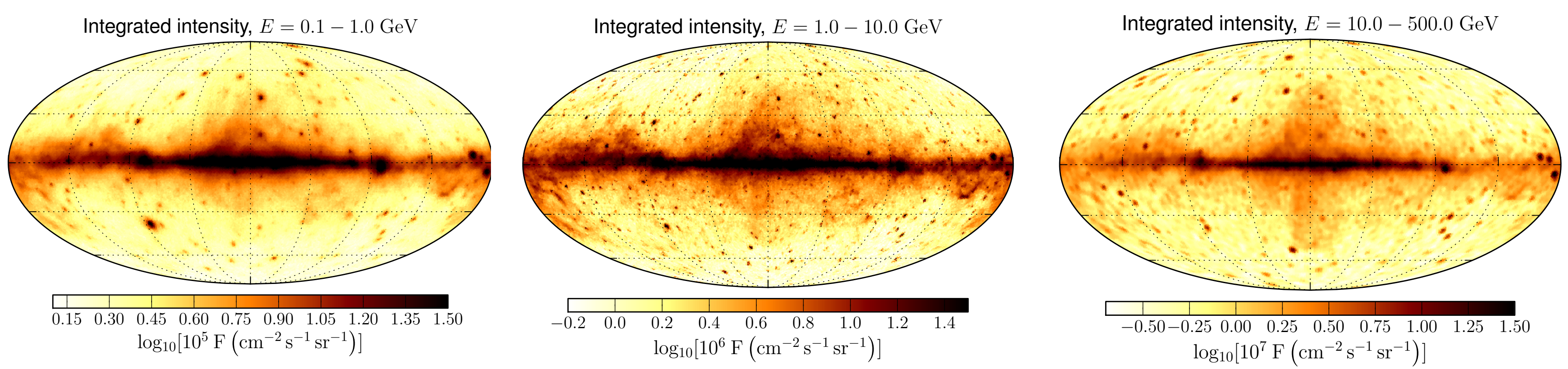
Fermi-LAT Analysis

- **50 months of data**
- **Pass 7 reprocessed data set**
- **Ultraclean class**
- **Galactic plane masked for |b| > 10°**
- **Data are binned**
  - **25 logarithmic energy bins from 100 MeV to 500 GeV**
  - **Spatial binning with HEALPix (0.9° resolution)**



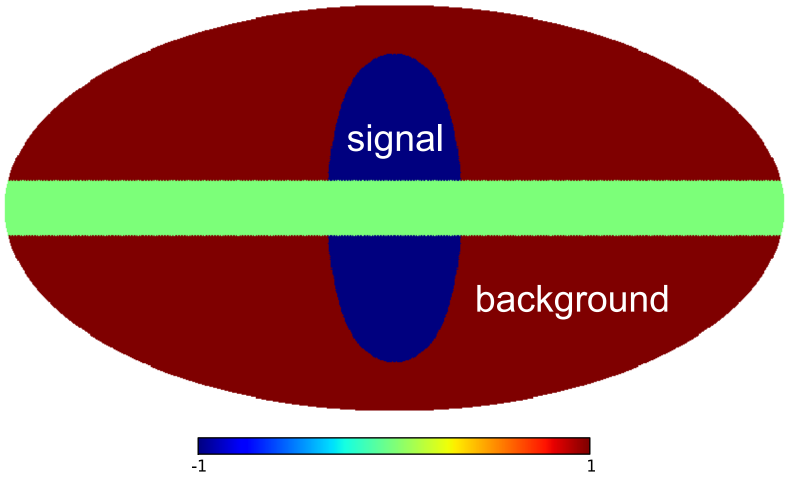
ApJ, 793, 64

Galactic Diffuse Modeling

- Two methods
  - One based on Galactic propagation code GALPROP
    - Assumptions about CR source distribution etc.
  - The other one data driven
    - Does not depend on GALPROP
    - Uses features of gamma-ray data to define templates for Galactic diffuse components
- Combination of both methods gives a handle on systematic uncertainties

Bubble Template

- Fit diffuse model templates to data (signal region masked)
- Define bubble template from residuals (integrated from 6.4 to 300 GeV)



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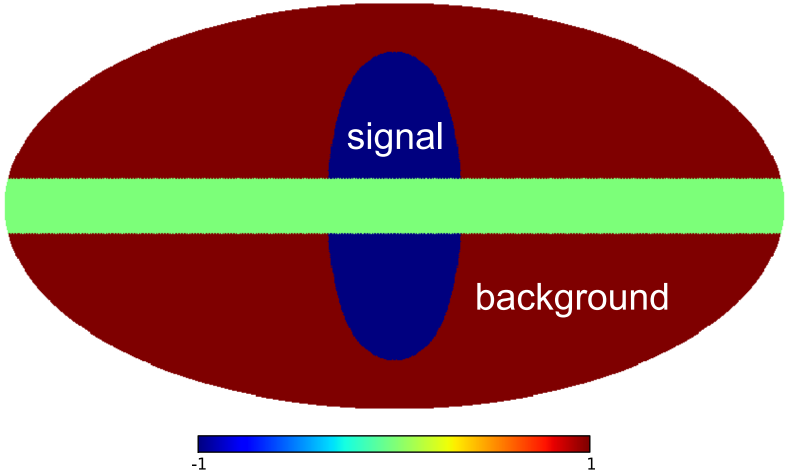

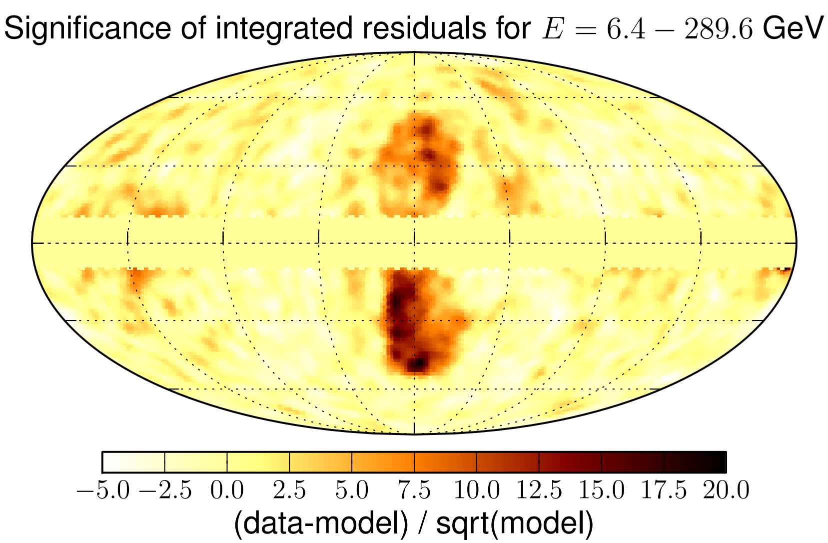

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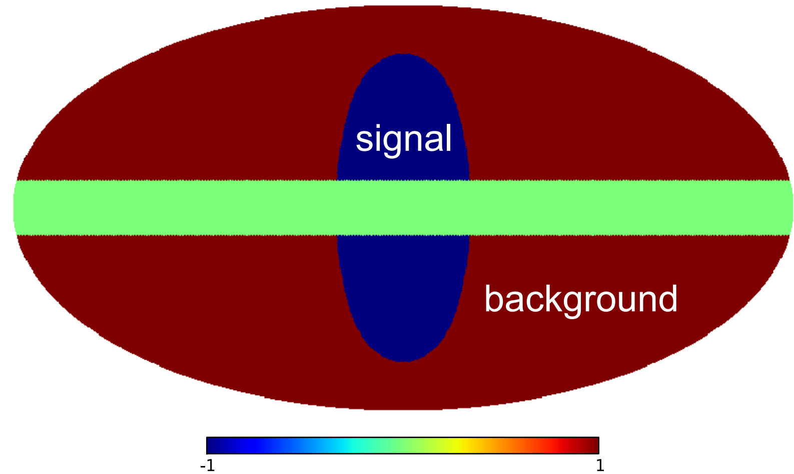
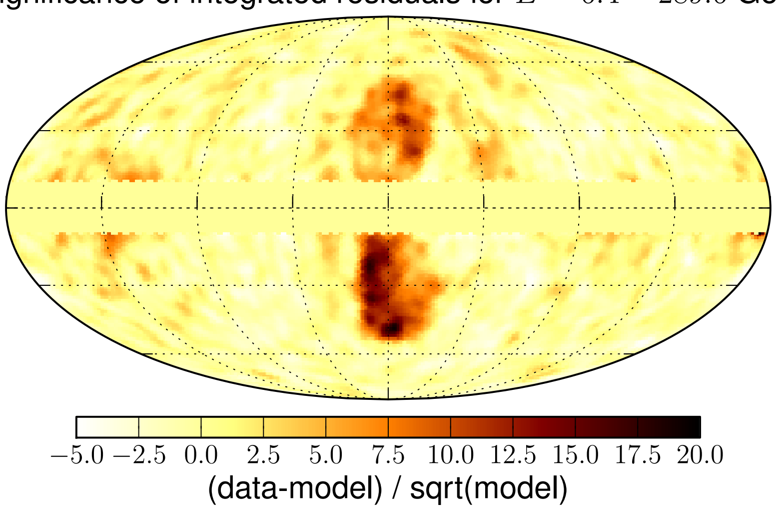
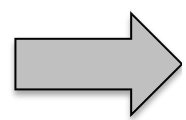


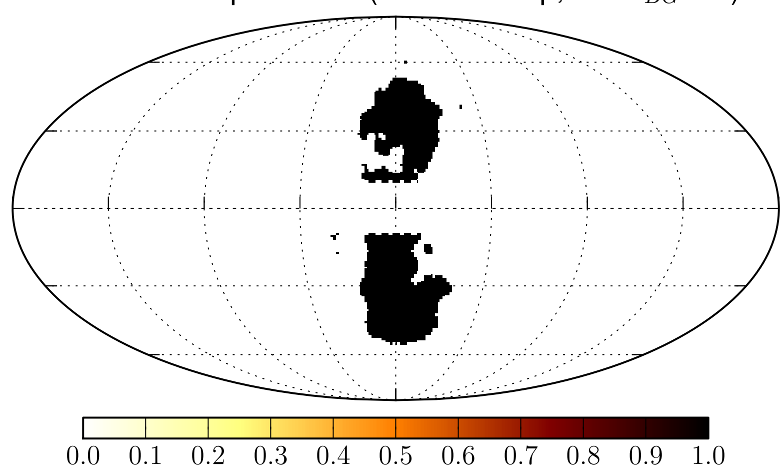
Significance of integrated residuals for $E = 6.4 - 289.6$ GeV



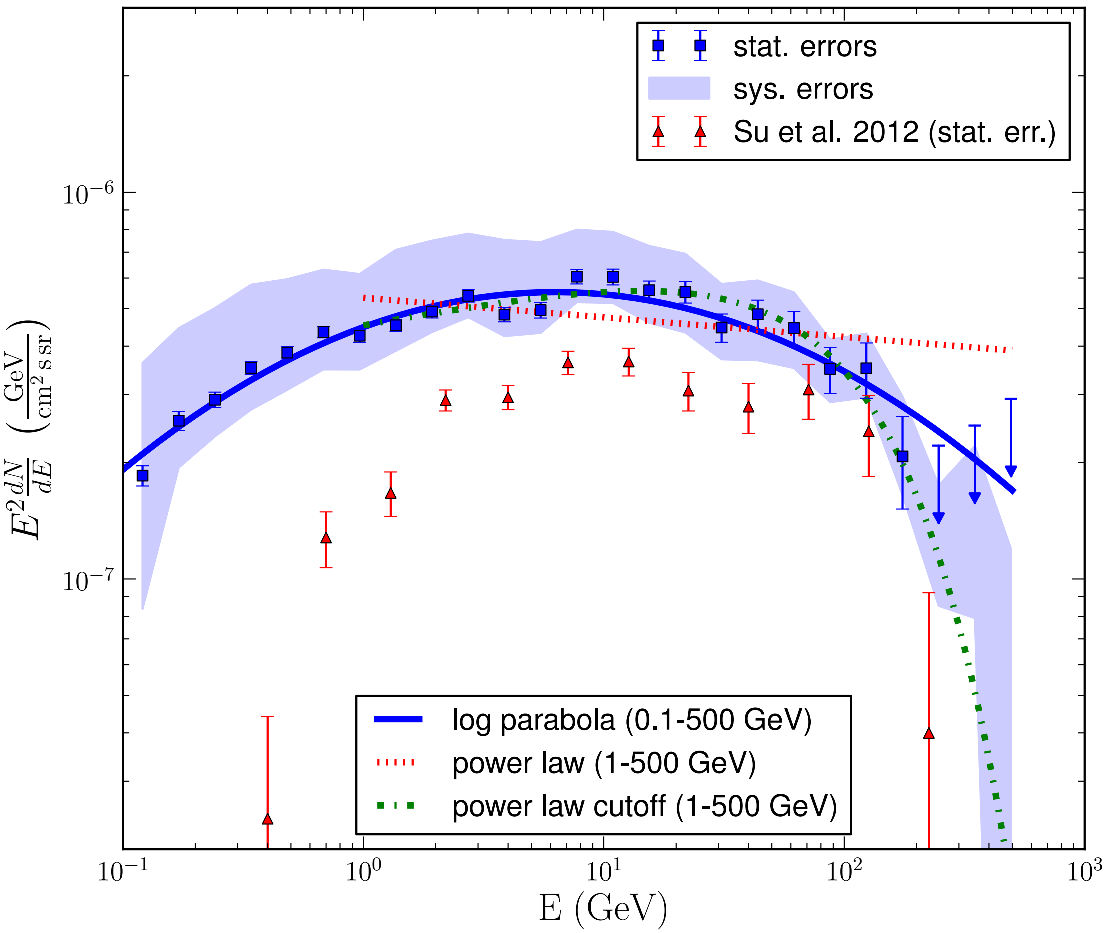
apply threshold



Bubbles Template Flat (residual map, 3.0 σ_{BG} cut)



Spectrum



Spectrum obtained from all-sky fit (excluding |b|<10°) with diffuse and bubble templates free

Shift in normalization can be explained by different:

- foreground modeling
- definition of the bubble template
- mask of Galactic plane

Cut off at:

$$E_{\mathrm{cut}} = 113 \pm 19[\mathrm{stat}]^{+45}_{-53}[\mathrm{syst}]\ \mathrm{GeV}$$

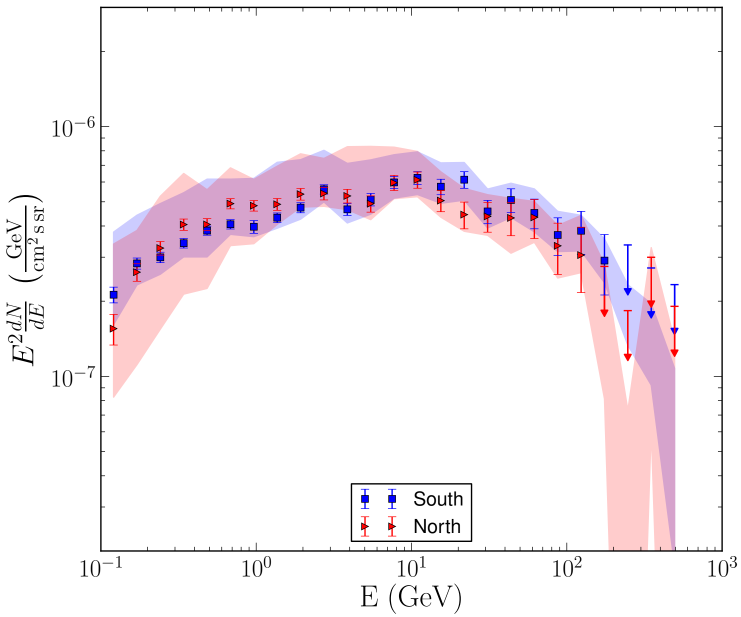
Index:

$$\gamma = 1.87 \pm 0.02[\mathrm{stat}]^{+0.14}_{-0.17}[\mathrm{syst}]$$

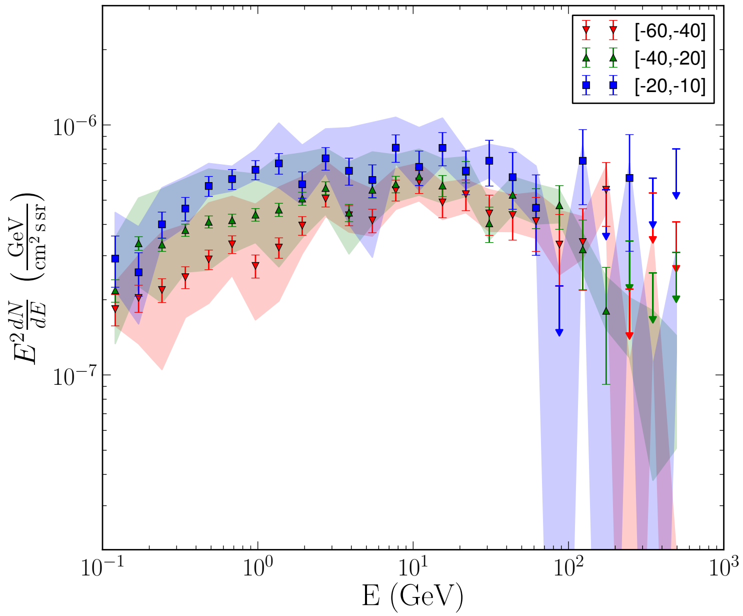
Gamma-ray luminosity: $(4.4 \pm 0.1[\mathrm{stat}]^{+2.4}_{-0.9}[\mathrm{syst}]) \times 10^{37}\ \mathrm{erg\ s^{-1}}$

Spectral Variations

- **North and South Bubble have similar spectrum**

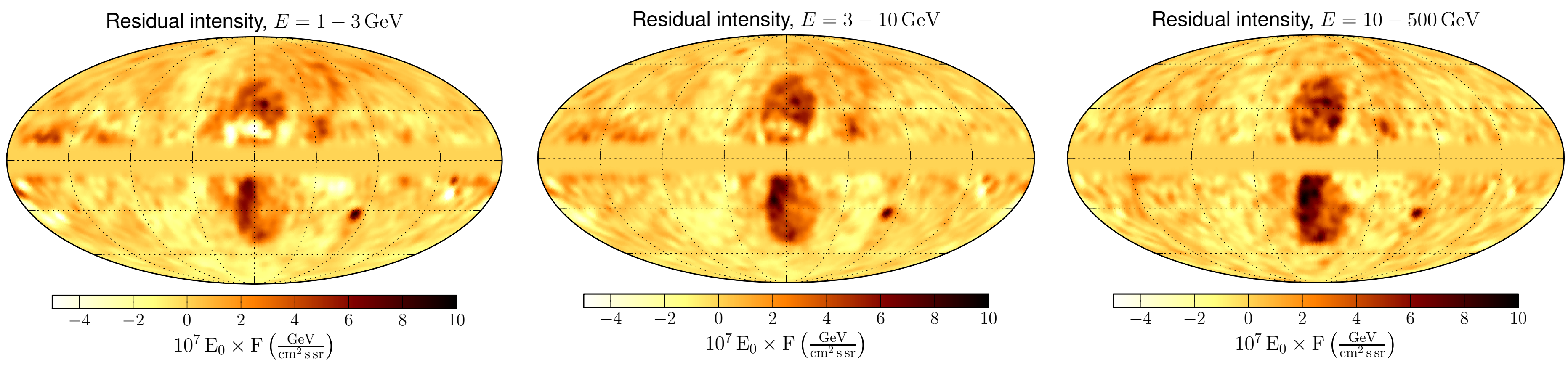


- **All spectral variations within systematic errors**



Shape at Different Energies

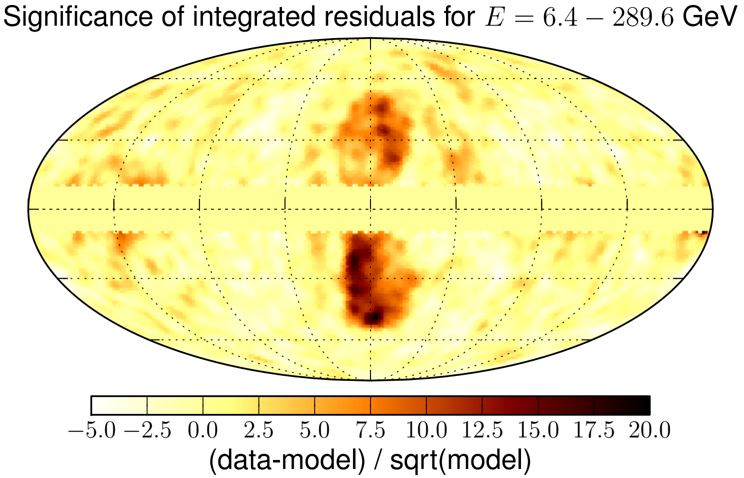
No change in bubble shape with energy found

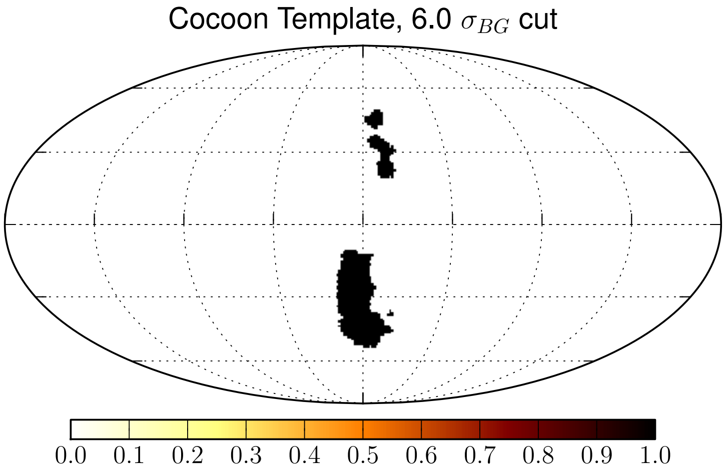


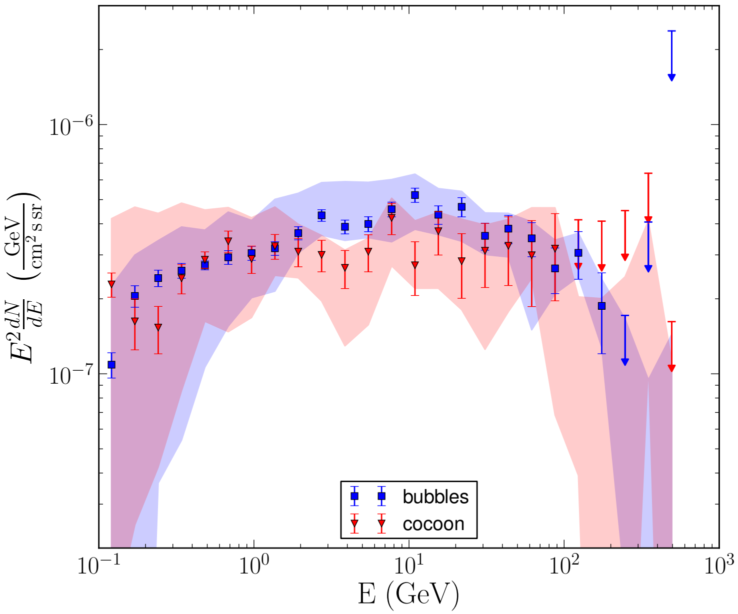
A. Franckowiak

Substructure – "Cocoon"

- Excess emission in South East of the bubbles
- Variation in spectral shape within systematic errors



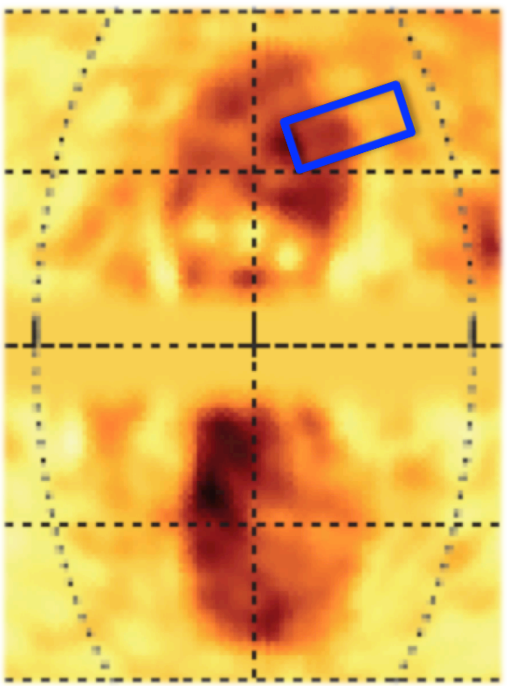


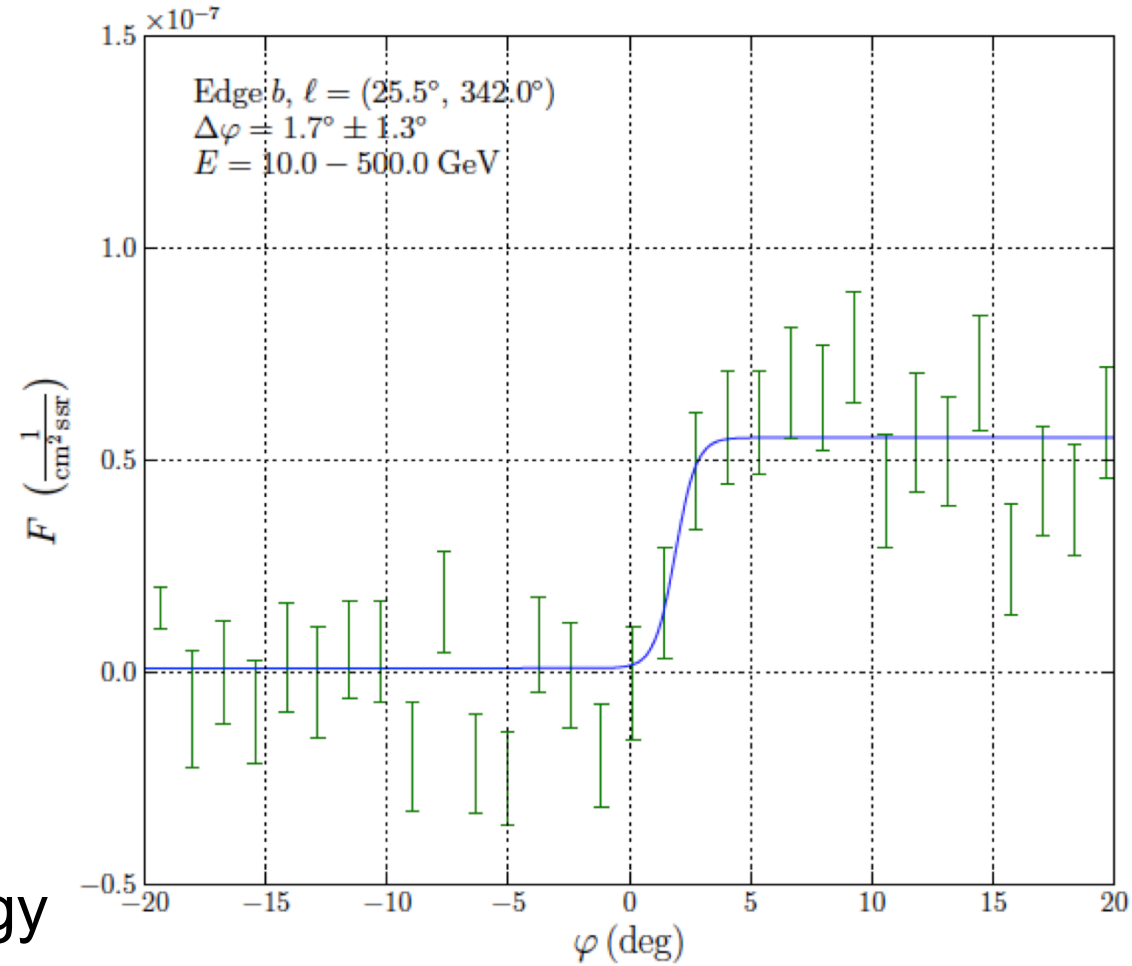


No evidence for a pair of jets as claimed in Su and Finkbeiner (ApJ 753, 2012)

Boundary of the Bubbles

Residual map



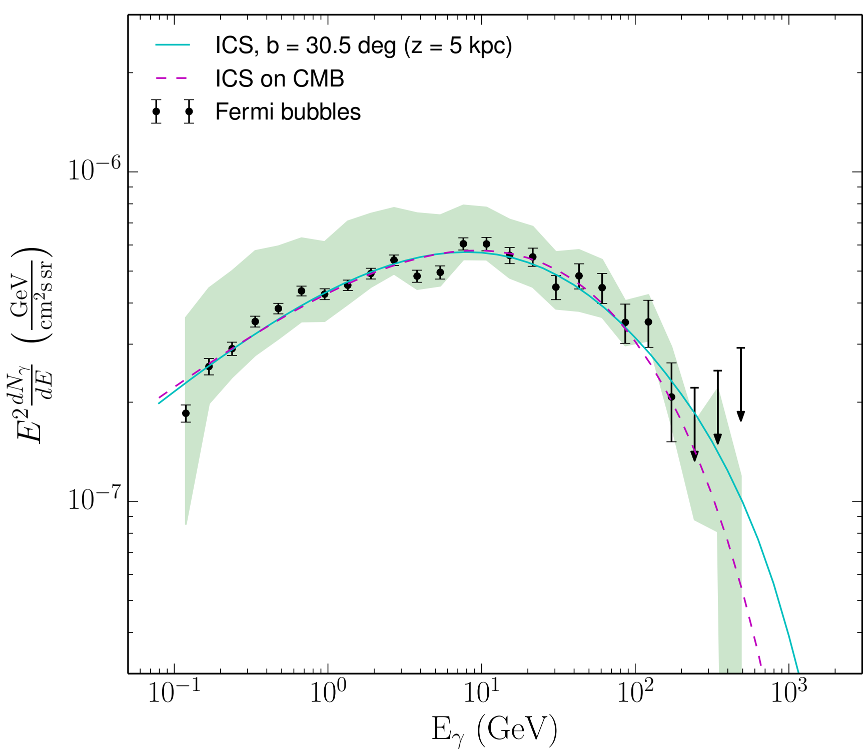


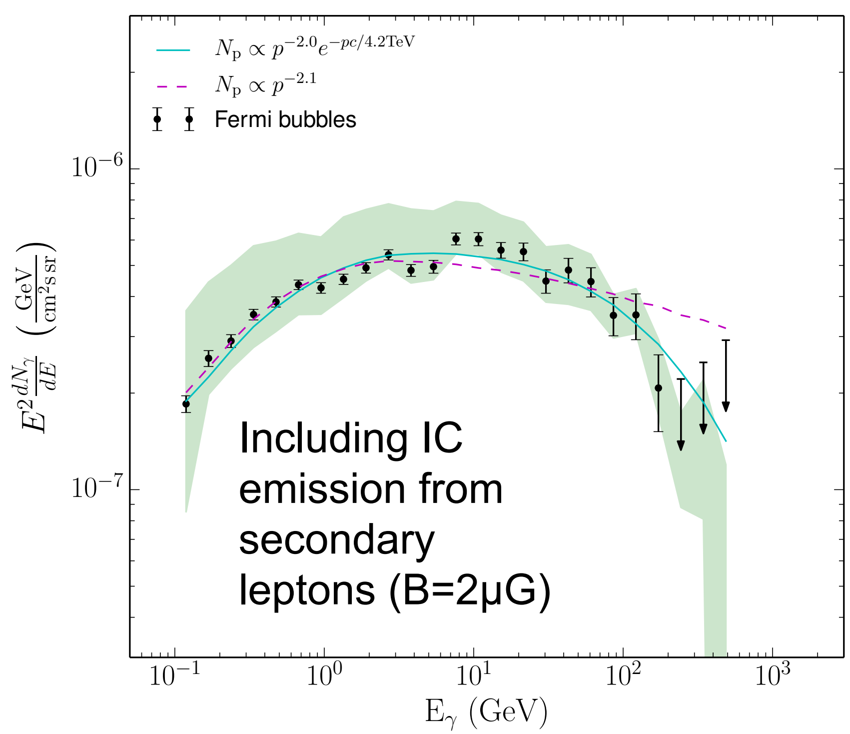
Average width: $3.4^{+3.7}_{-2.6}\,°$

No variation with energy found, but some variation with position

Leptonic, Hadronic, Gin & Tonic?

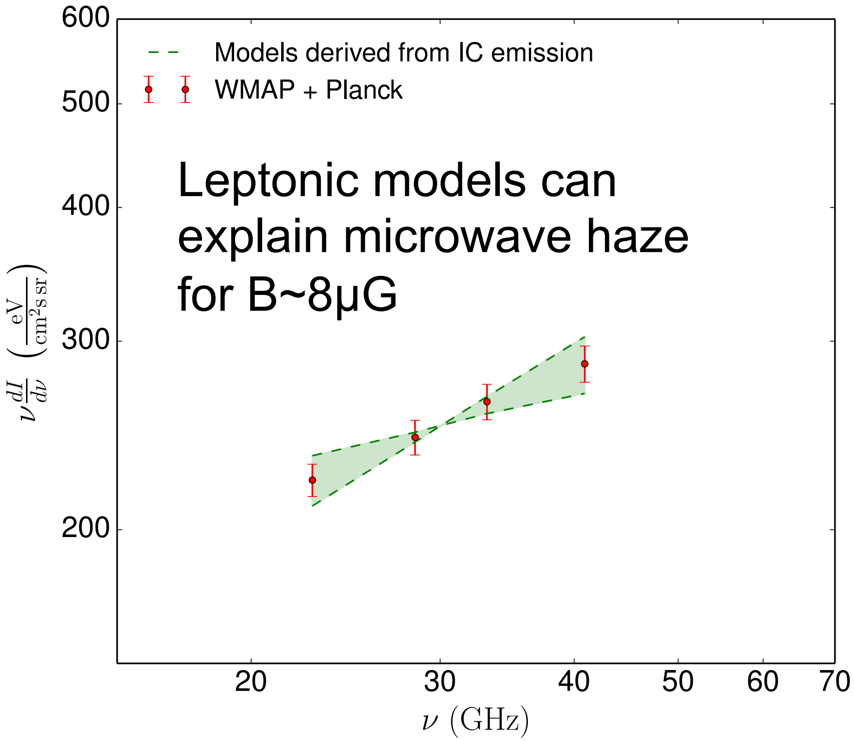
- **Both leptonic and hadronic models describe the gamma-ray spectrum well**

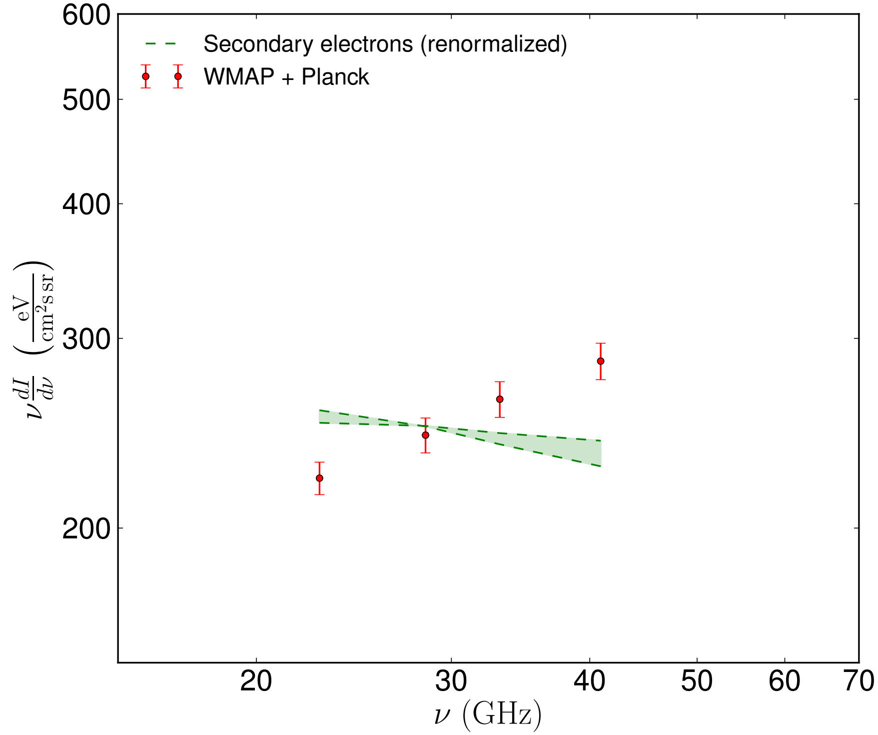




Leptonic, Hadronic, Gin & Tonic?

- **Assuming that the microwave haze and the gamma-ray bubbles are produced by the same population of electrons: hadronic model fails to describe the spectral shape**





Leptonic / Hadronic Summary

	Leptonic	Hadronic
• Gamma-ray spectrum	☺	☺
• Microwave haze	☺	☹
• No spectral changes	☹	☺
• Narrow boundary	☺	☹
• Absence of a visible shock front	☹	☺

Leptonic / Hadronic Summary

	Leptonic	Hadronic
• **Gamma-ray spectrum**	🙂	🙂
• **Microwave haze**	🙂	☹️
• **No spectral changes**	☹️	🙂
• **Narrow boundary**	🙂	☹️
• **Absence of a visible shock front**	☹️	🙂

Possible leptonic scenario: (Mertsch, Sarkar, Guo, Mathews etc.):

- Jets from the black hole create shock front
- Shock front dissipates, but leaves plasma turbulences behind
- Electrons are accelerated on the turbulences with a characteristic time less than the cooling time

Possible hadronic scenario: (Crocker, Aharonian):

- Wind from SNRs produces CR during several billions of years
- Magnetic fields confine the CR in the bubble volume
- WMAP haze produced by ~ 30 GeV electrons in the SNR wind which have a characteristic cooling time ~ 10 Myr


Thank you

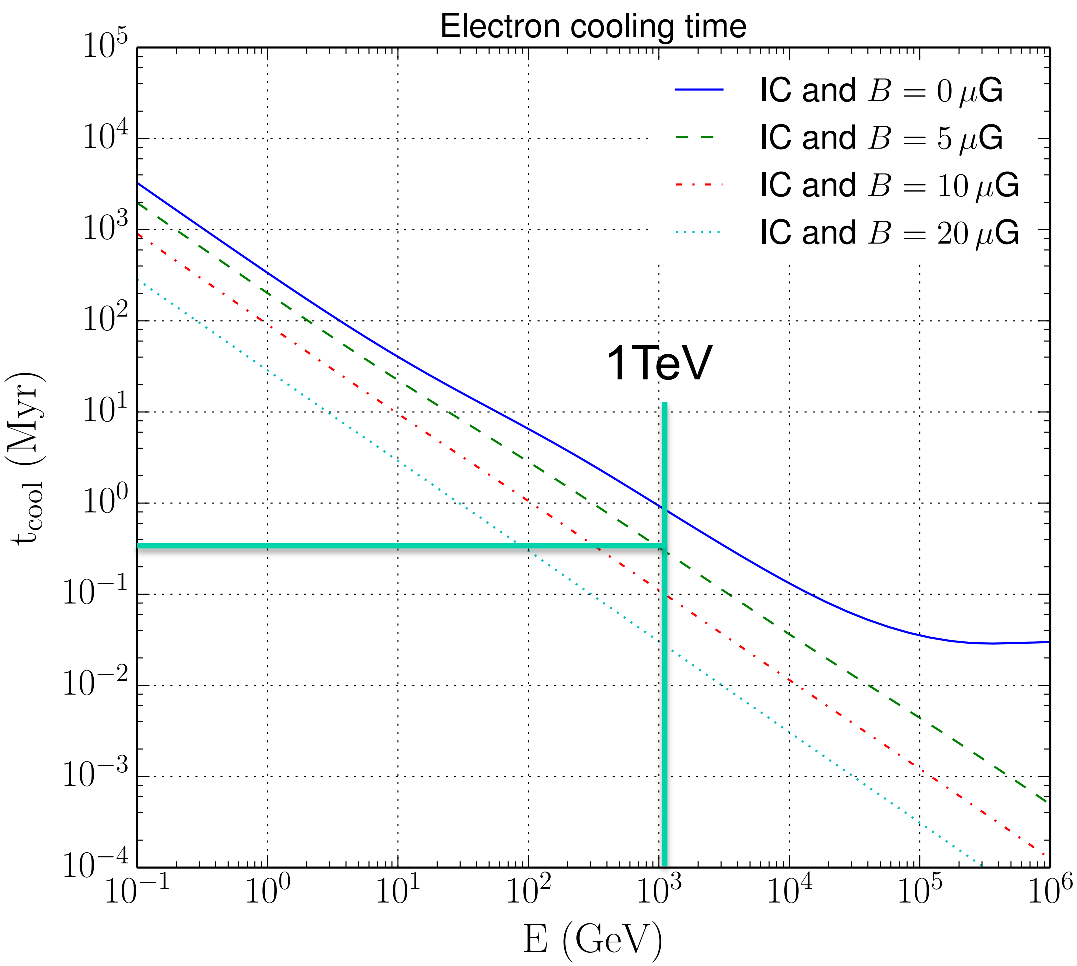
BACKUP

Leptonic Model – Electron Cooling Time

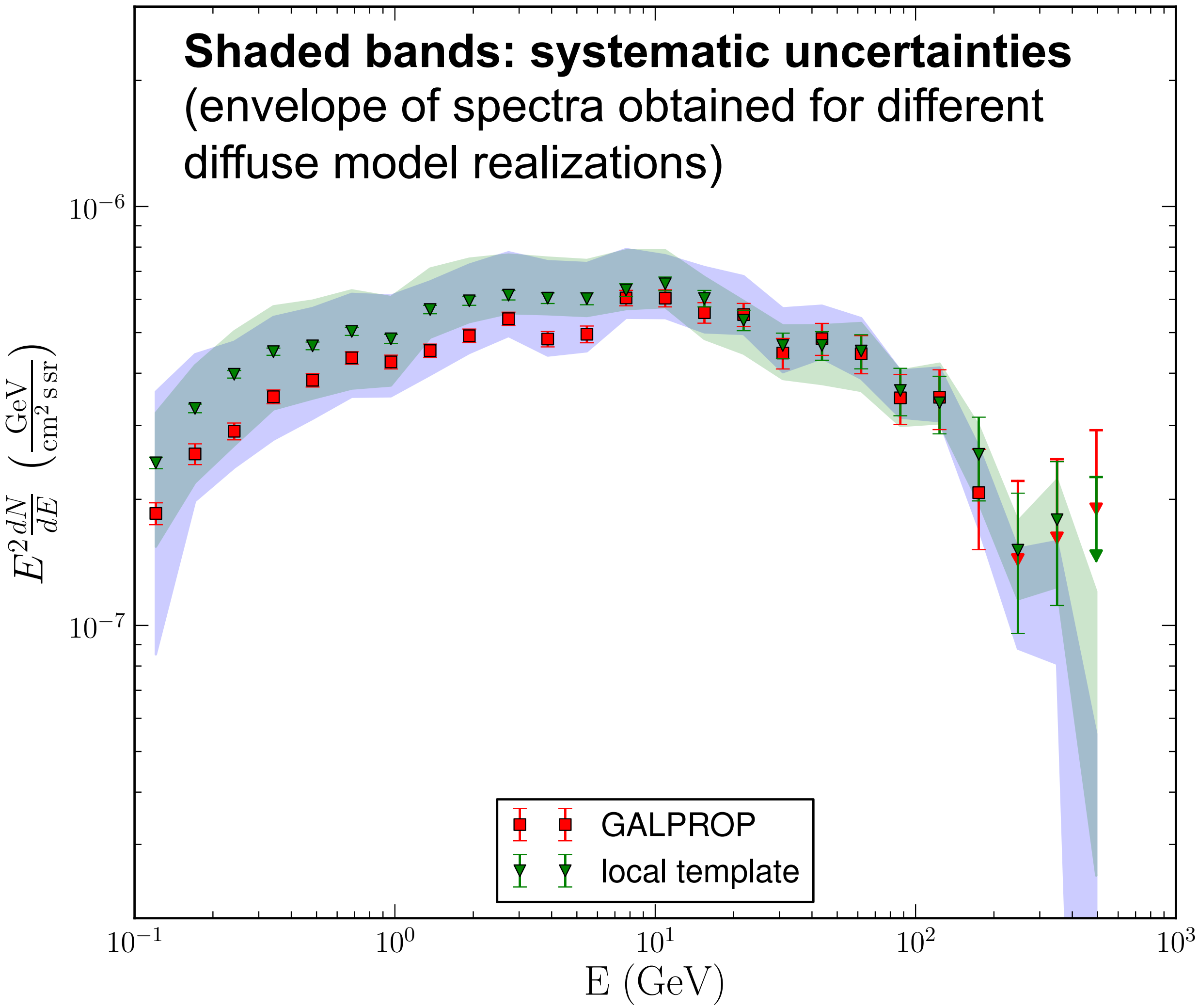
Gamma rays in the bubbles are mainly produced by ~ 1TeV electrons: ~ 0.5 Myr cooling time

$t_{cool} < t_{formation} \rightarrow$ Expansion speed of the bubbles of ~20,000km/s

Reacceleration? E.g. plasma wave turbulences (Mertsch & Sakar, 2011)

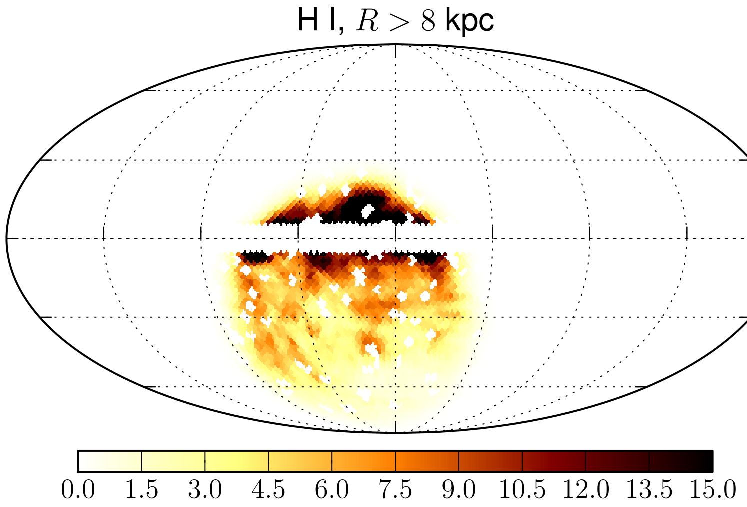


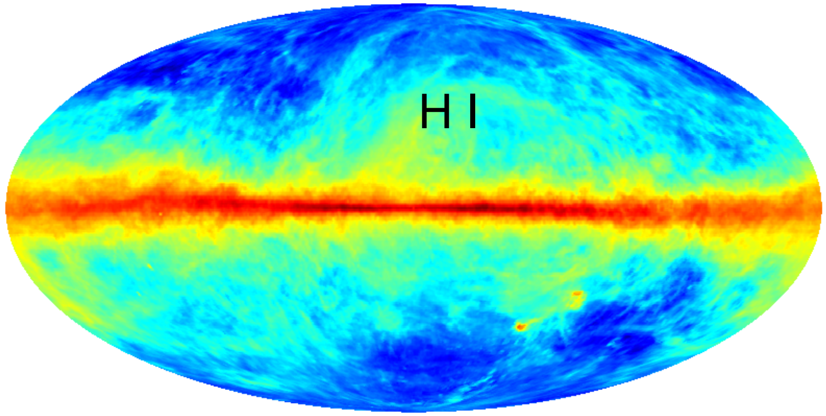
Spectrum – two methods



Alternative Galactic Modeling: Local template Analysis

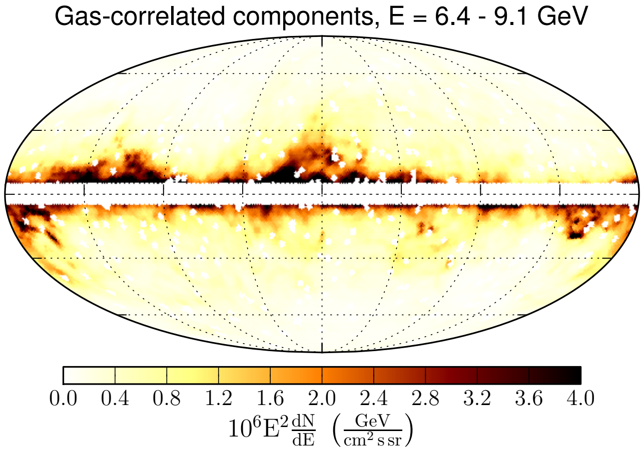
- **Does not depend on GALPROP**
- **Does not assume azimuthal symmetry (e.g. violated for spiral arms)**
- **Gas maps used to trace gamma-ray emission in small patches**
  - **H I and CO survey, SFD dust map**
  - **Scaling factor is proportional to line of sight cosmic-ray density**

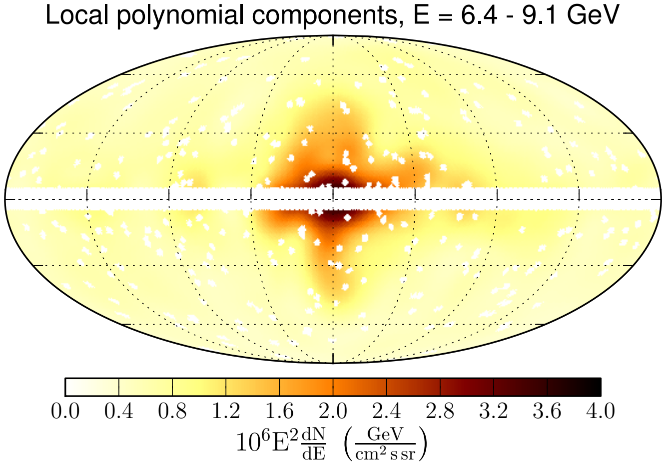




Alternative Galactic Modeling: Local template Analysis

- Does not depend on GALPROP
- Does not assume azimuthal symmetry (e.g. violated for spiral arms)
- Gas maps used to trace gamma-ray emission in small patches
  - H I and CO survey, SFD dust map
  - Other components (IC, bubbles, Loop I) are assumed to be smooth or not correlated with the gas and are modeled by spatial polynomial

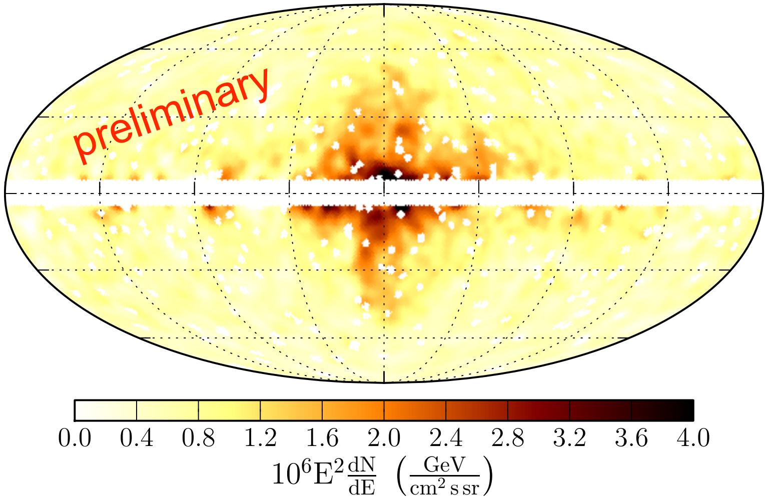




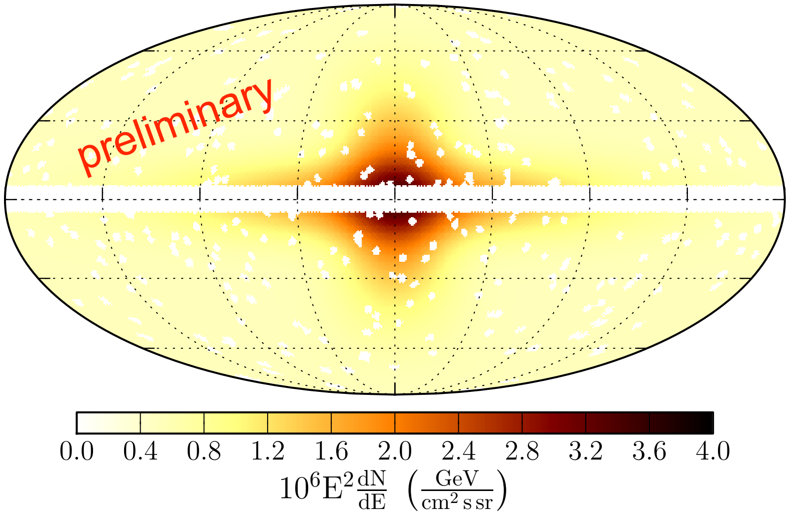
Alternative Galactic Modeling: Local template Analysis

- **After subtraction of the gas component, the IC is modeled with a bivariate Gaussian along the Galactic plane**
- **Other components (Loop I and bubbles) are estimated with Gaussian perpendicular to the plane**

Data minus gas-correlated emission, $E = 6.4 - 9.1\ \mathrm{GeV}$



Gaussian model, $E = 6.4 - 9.1\ \mathrm{GeV}$



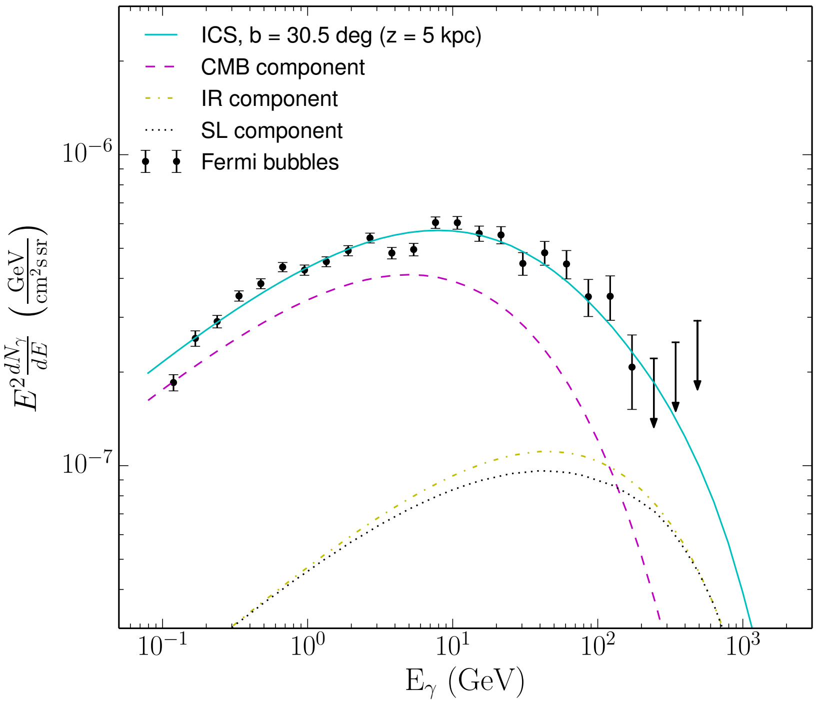
Systematic Uncertainties

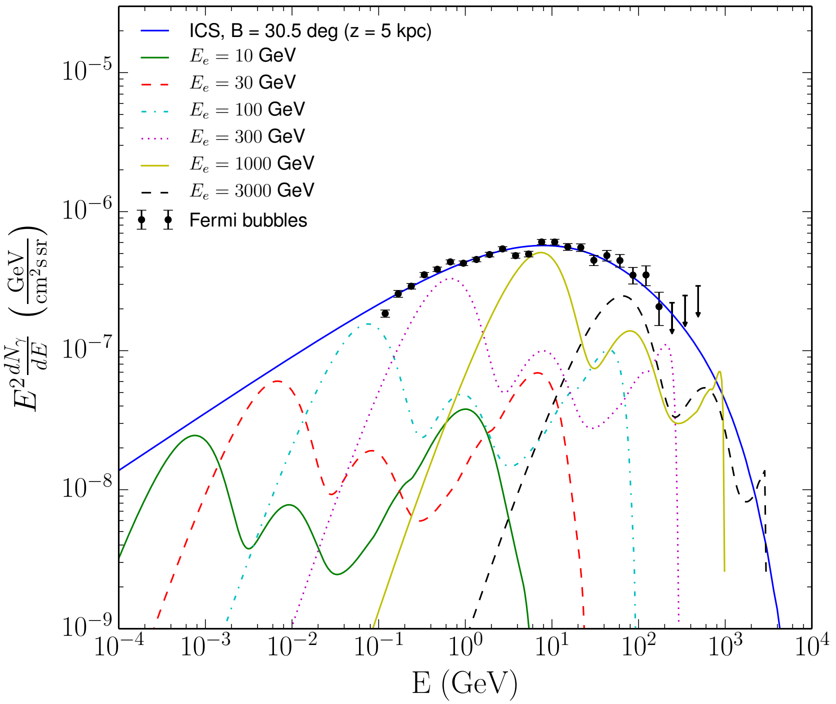
Added in quadrature

- **Instrument related:**
  - **Systematic error in the effective area (2012 ApJS, 203)**

envelope

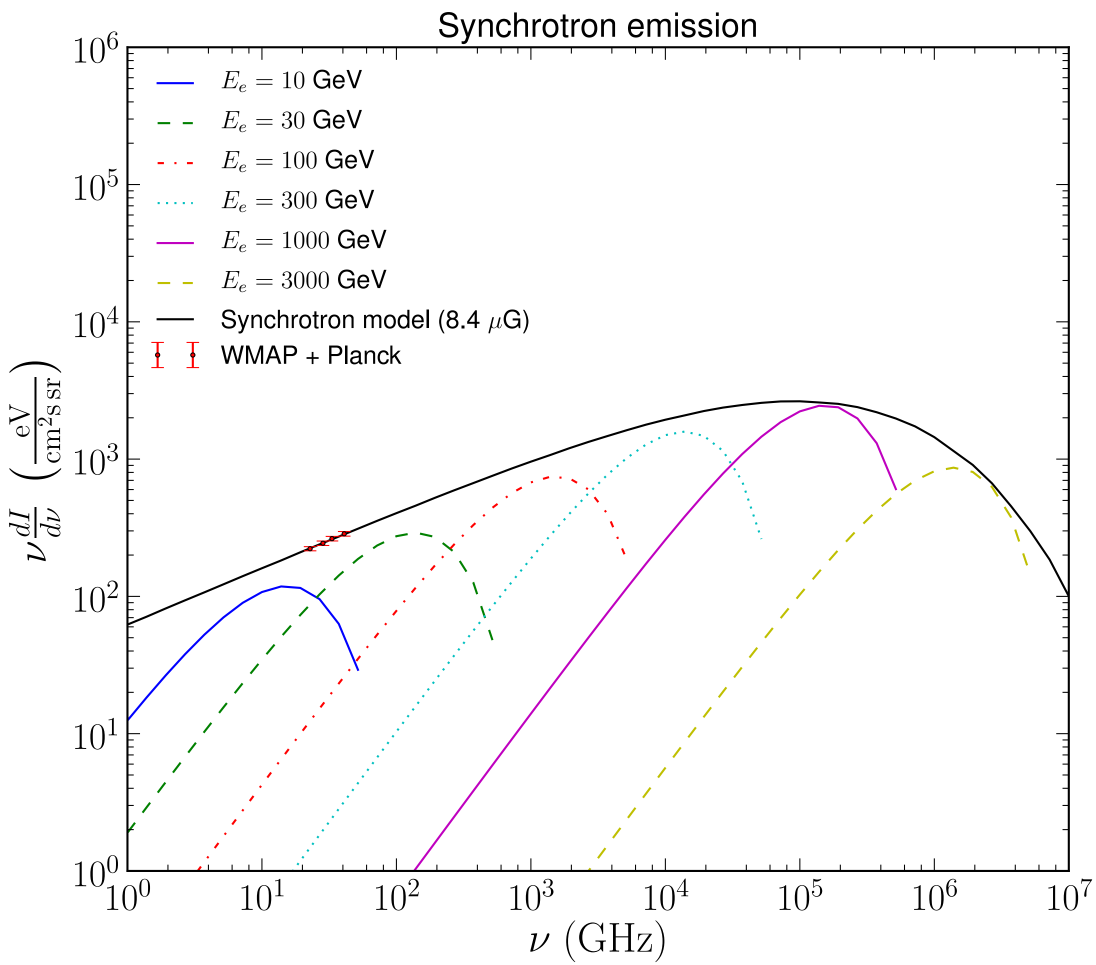
- **Galactic modeling:**
  - **The choice of the input GALPROP configuration might influence the extracted bubble features**
    - **Cosmic-ray source distribution:**
      - **Pulsars, SNR**
    - **Size of cosmic-ray confinement volume (halo size)**
      - **Cylindrical geometry with R = 20, 30 kpc and z = 4,10 kpc**
    - **Spin temperature (optical depth correction of the H I component obtained from 21cm survey)**
      - **T = 150K, optically thin**
  - **Loopl template**
  - **Bubble template**
- **Alternative analysis method based on fits in local patches**



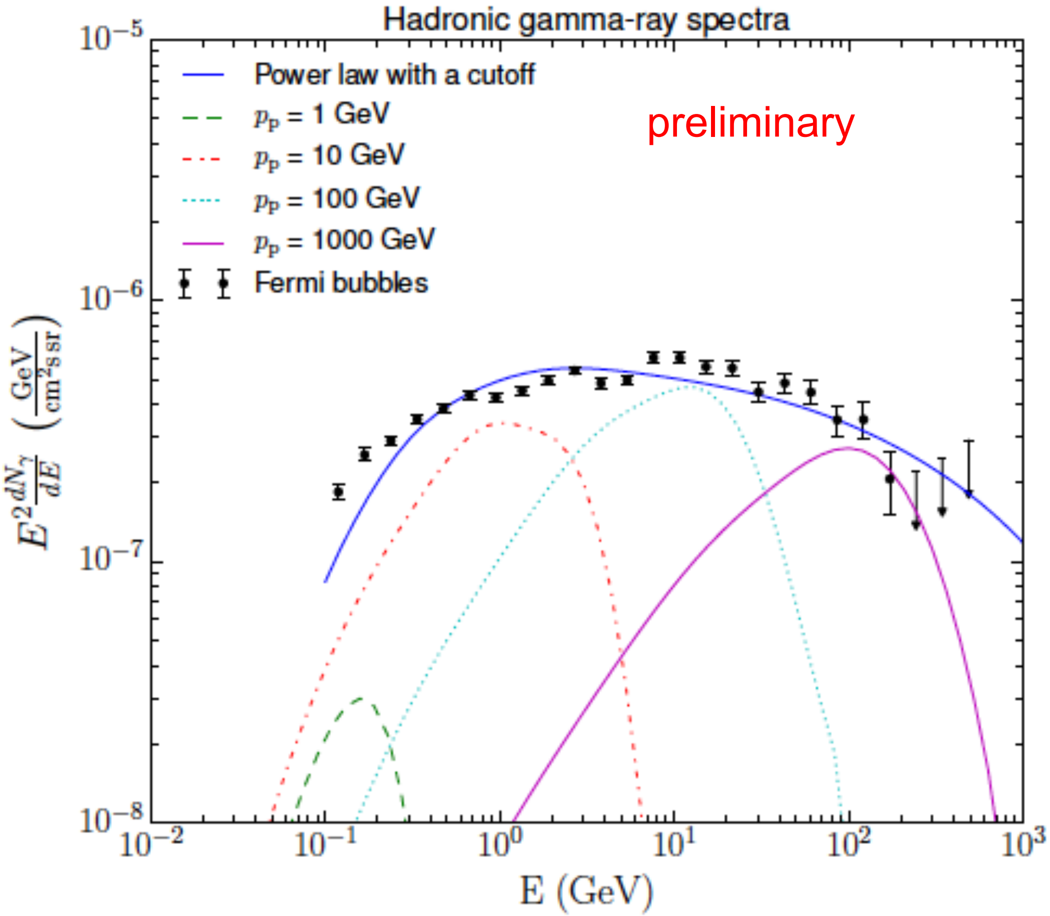


Energy in electrons $(1.0 \pm 0.2[\text{stat}]^{+6.0}_{-1.0}[\text{syst}]) \times 10^{52}$ erg

Synchrotron emission

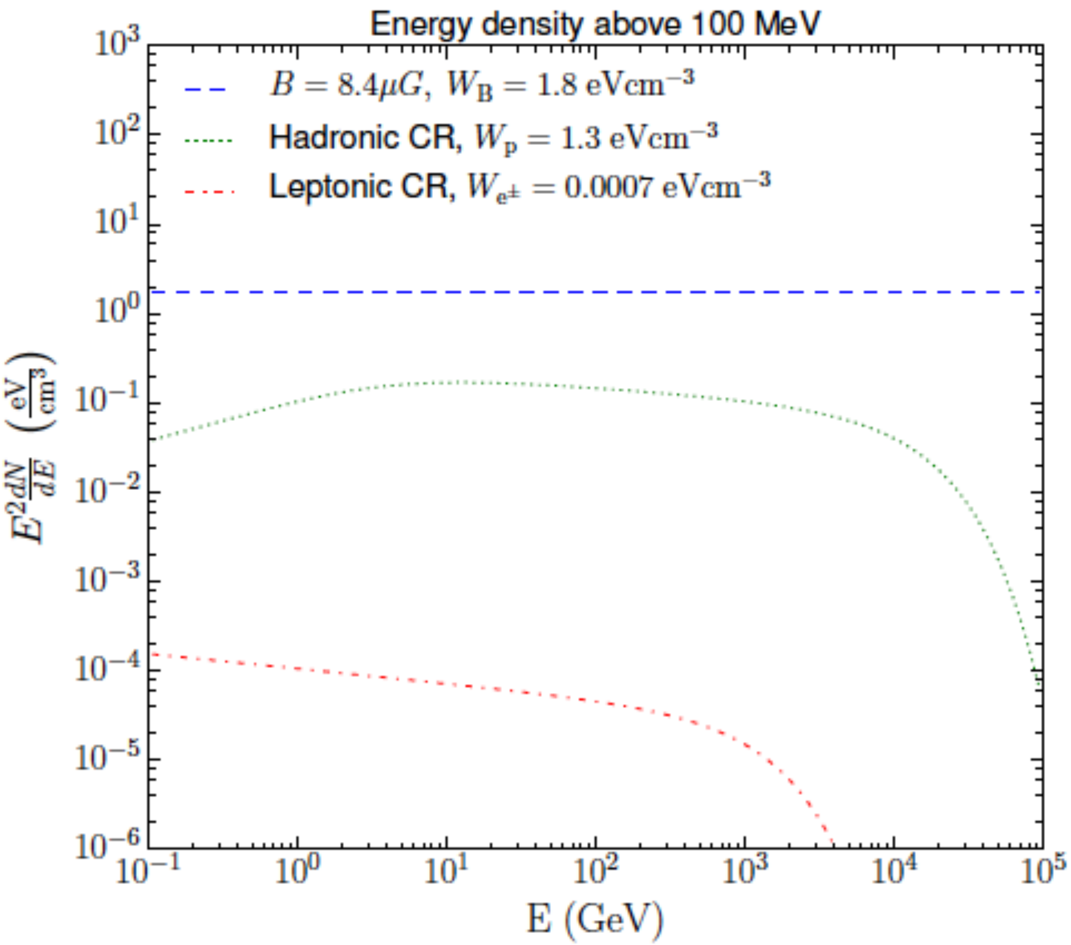


Hadronic gamma-ray spectrum

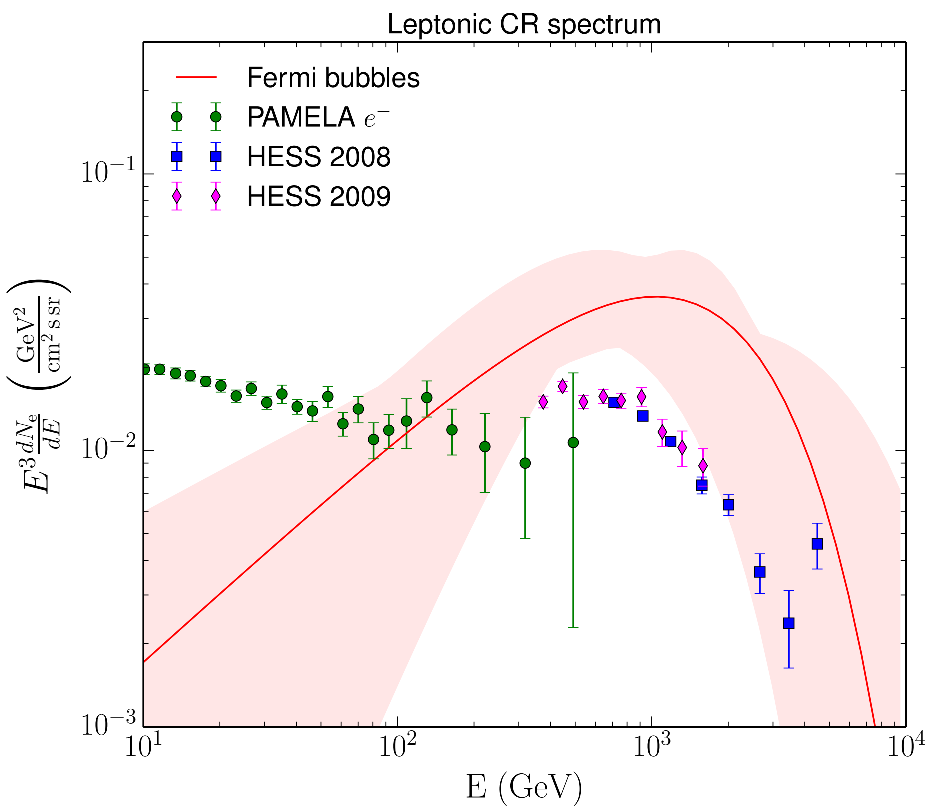


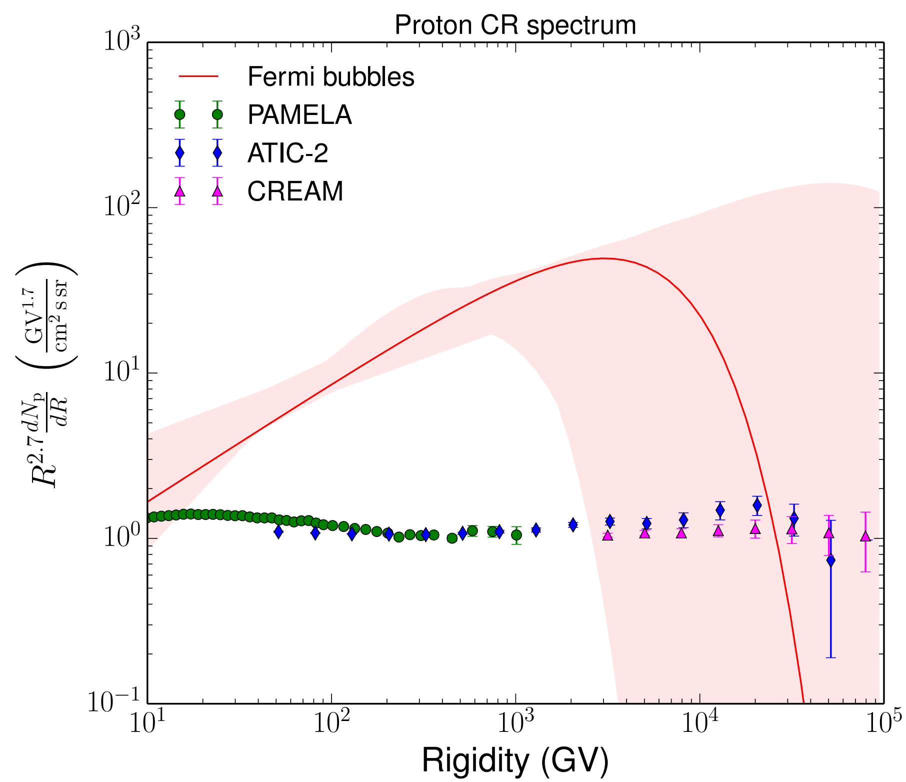
Energy in protons $(3.5 \pm 0.1[\text{stat}]^{+4.7}_{-3.0}[\text{syst}]) \times 10^{55} \left(\frac{0.01\ \text{cm}^{-3}}{n_\text{H}}\right)$ erg

Energy density



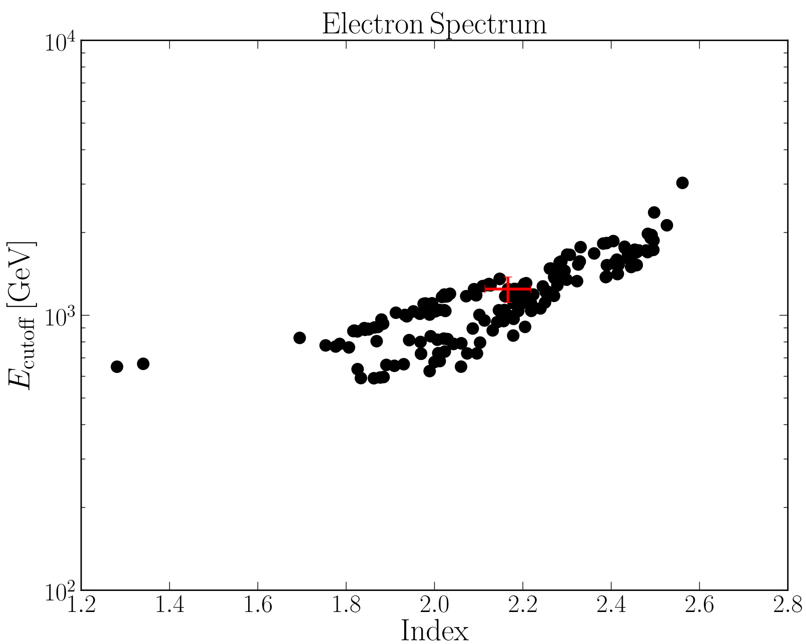
Comparison to local spectra

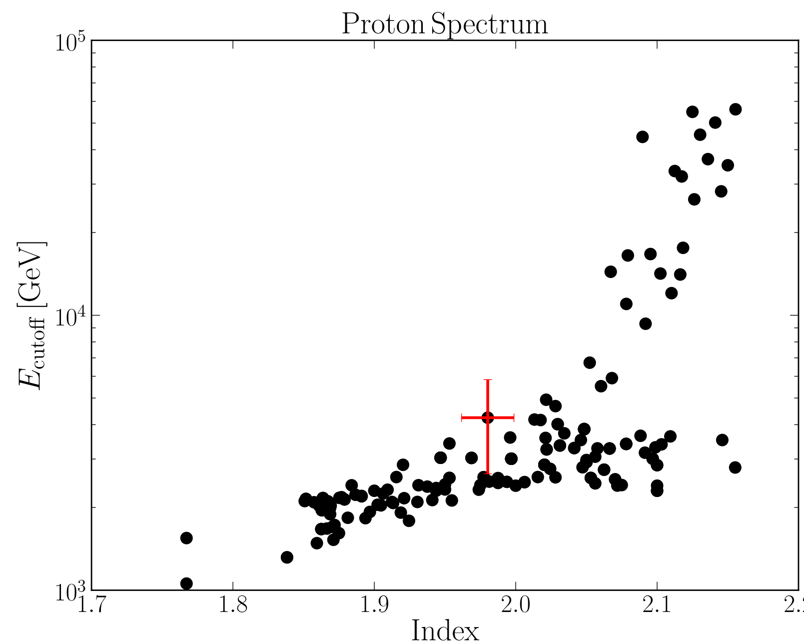




Leptonic, Hadronic, Gin Tonic?

- **Electron and proton spectral parameter**





Energy in electrons

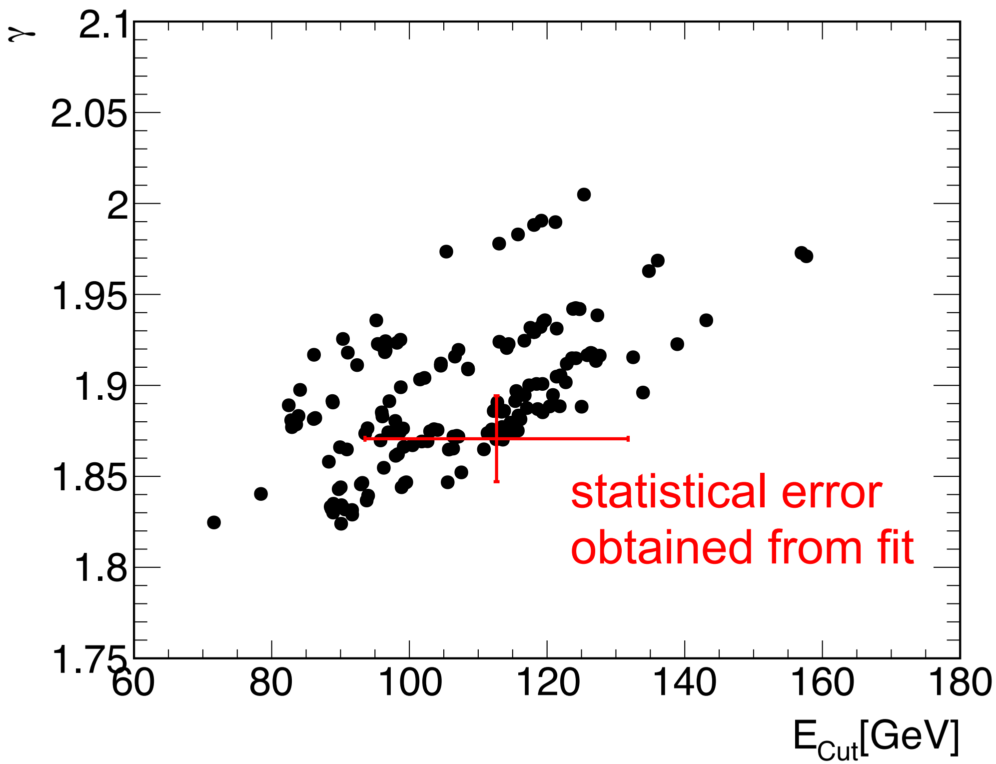
$$(1.0 \pm 0.2[\mathrm{stat}]^{+6.0}_{-1.0}[\mathrm{syst}]) \times 10^{52}\ \mathrm{erg}$$

Energy in protons

$$(3.5 \pm 0.1[\mathrm{stat}]^{+4.7}_{-3.0}[\mathrm{syst}]) \times 10^{55} \left(\frac{0.01\ \mathrm{cm}^{-3}}{n_{\rm H}}\right)\ \mathrm{erg}$$

Spectrum – Cutoff

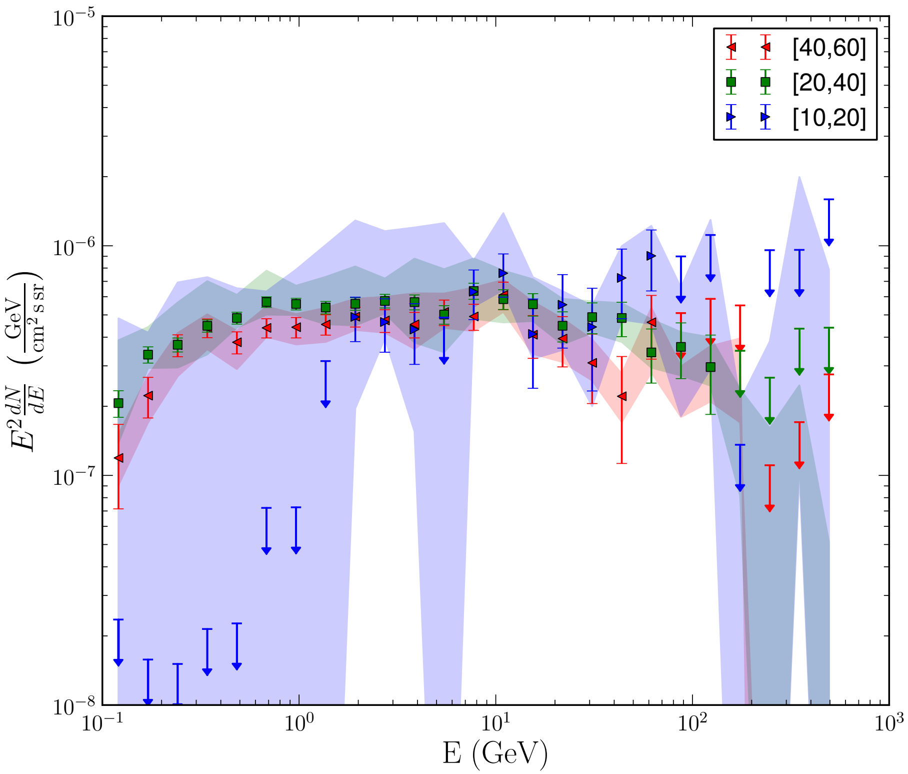
- **Well described by log parabola or power law with exponential cutoff: cutoff at ~110 GeV, index 1.9**

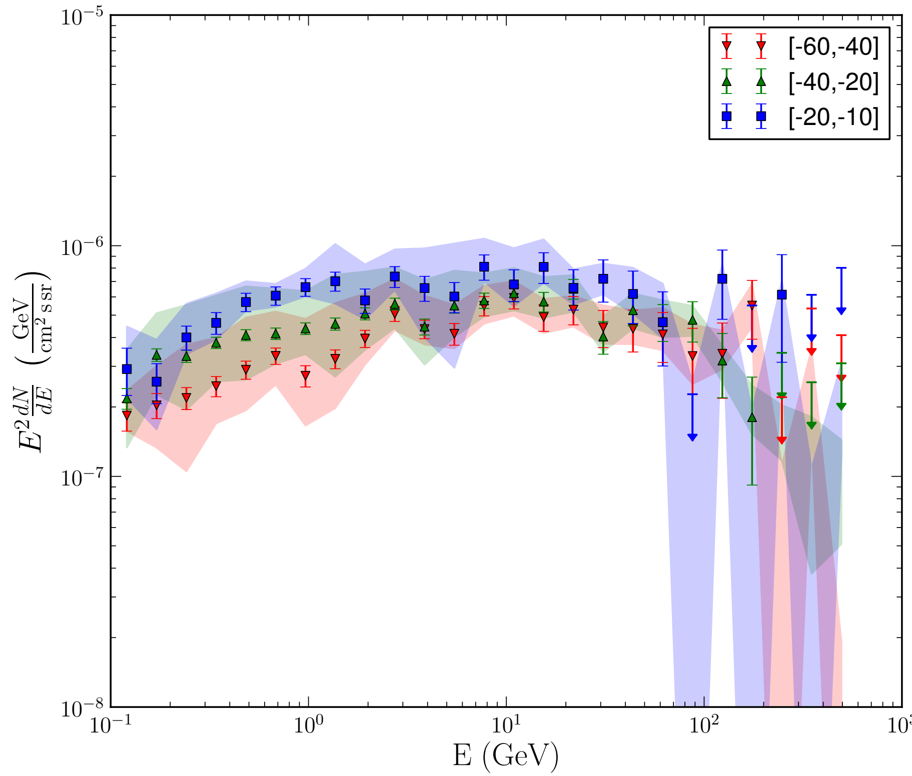


each dot represents a different diffuse model realization

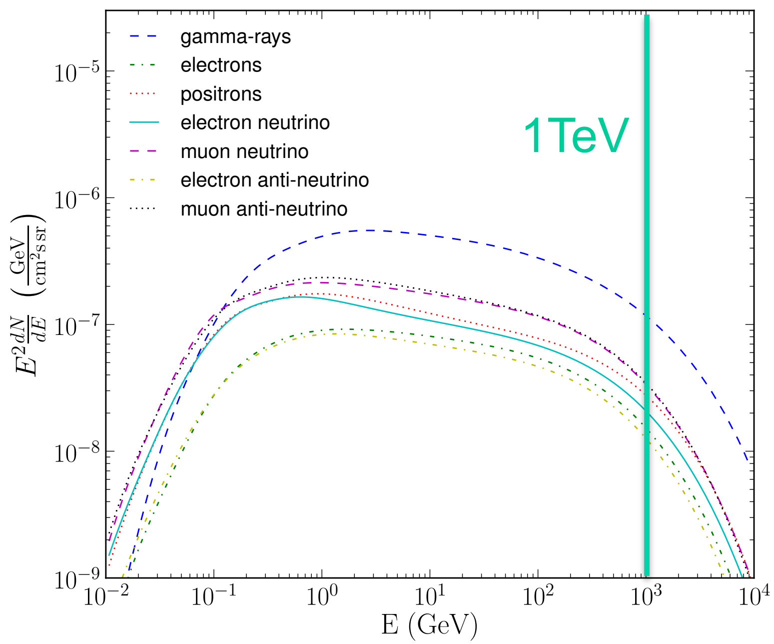
Spectral Variations

- **No spectral variation in latitude stripes within systematic uncertainties**

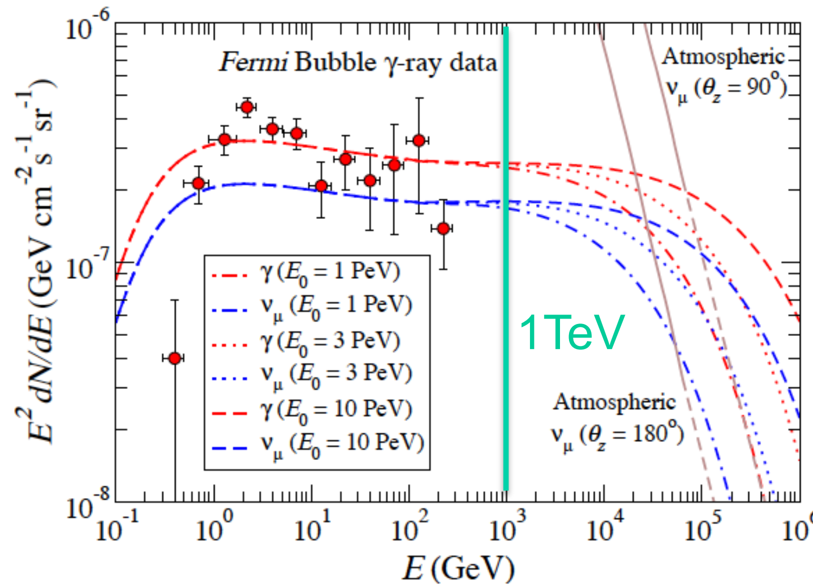




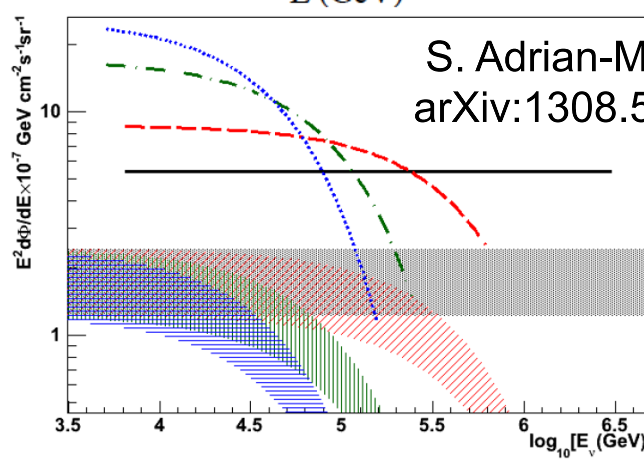
Neutrino from the Fermi Bubbles



Lunardini, Razzaque PRL 108 (2012)



S. Adrian-Martinez et al.
arXiv:1308.5260

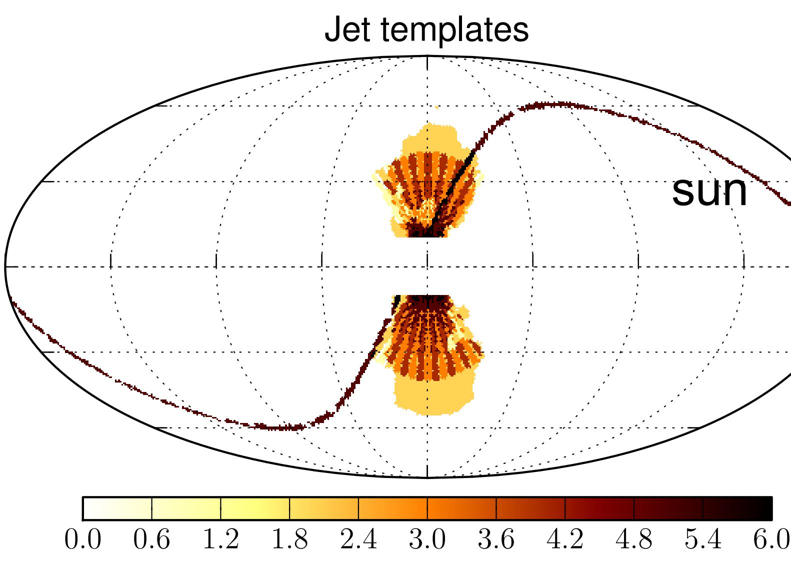


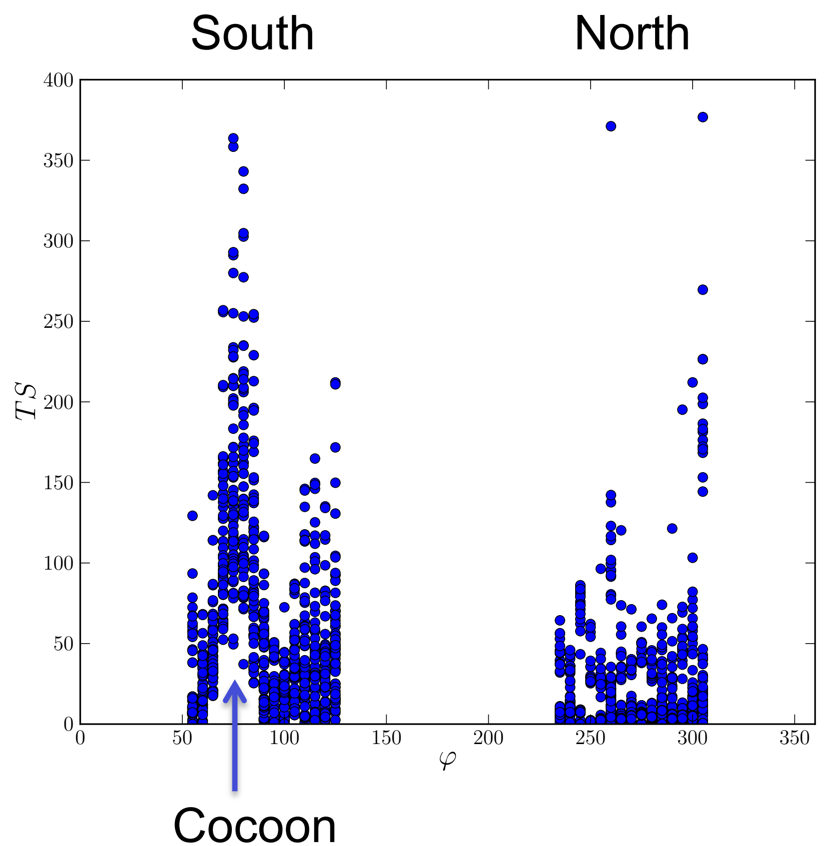
No cutoff
500TeV
100TeV
50TeV

- **Antares data analysis: data from 2008 to 2011**
- **various energy cutoffs tested**
- **no statistically significant excess of events is observed → upper limits on the neutrino flux**

Substructure – Existence of "Jets"

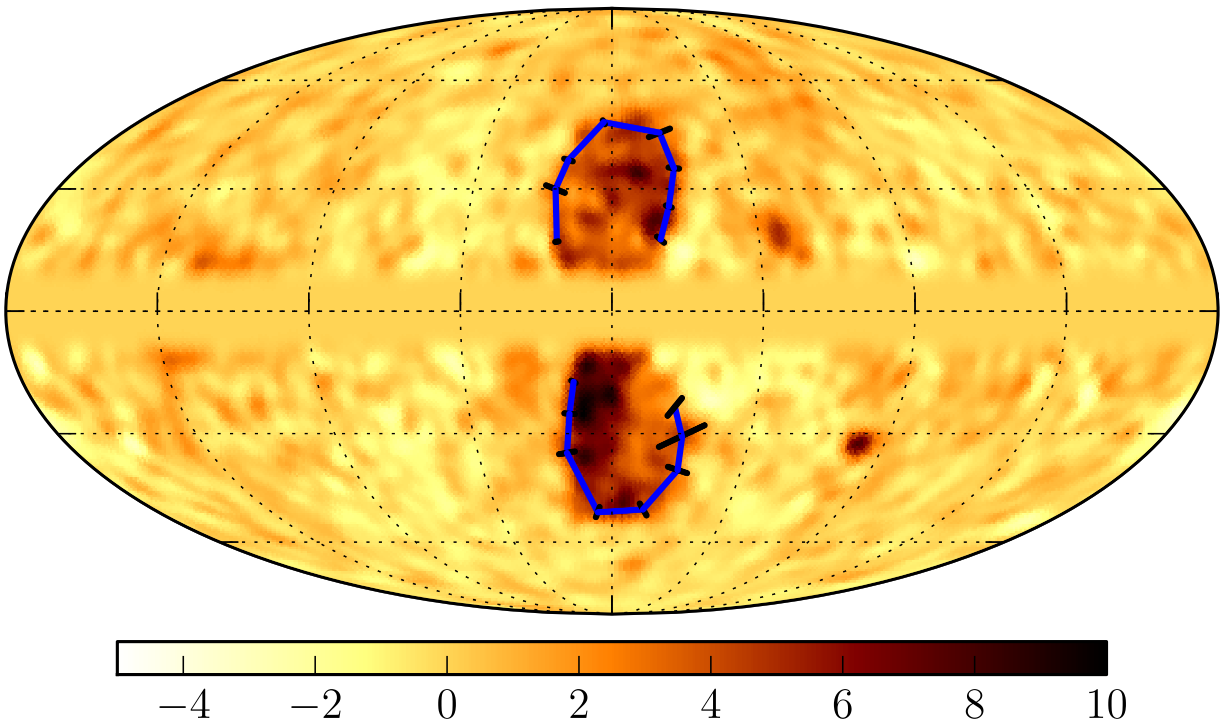
- **No significant residuals found aligned along a specific direction that could be interpreted as a jet**





Boundary of the Bubbles

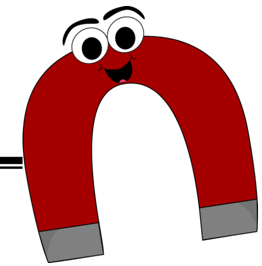
Residual intensity, $E = 10 - 500\,\mathrm{GeV}$



$10^7\,\mathrm{E_0} \times \mathrm{F}\,\left(\frac{\mathrm{GeV}}{\mathrm{cm^2\,s\,sr}}\right)$

No variation with energy found, but some variation with position

Leptonic Models – Magnetic Field



- **Leptonic models can explain microwave haze for B~8μG**
- **Drop in magnetic field at latitudes of |b| ~35° could explain different latitudinal extension**