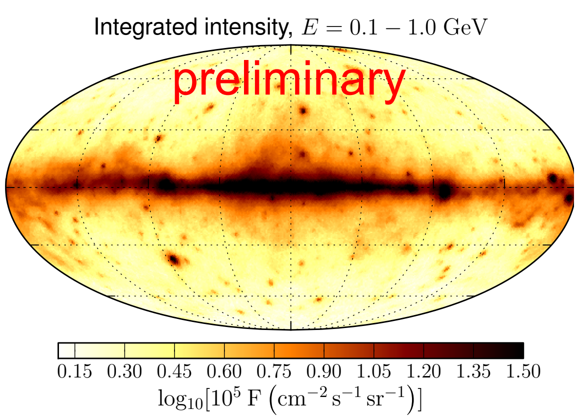
Spectrum and Morphology of the Fermi Bubbles

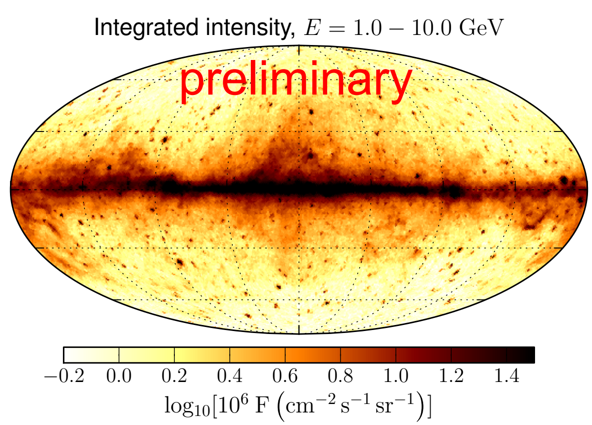
Anna Franckowiak, SLAC/KIPAC
in collaboration with
Dmitry Malyshev and Vahe Petrosian

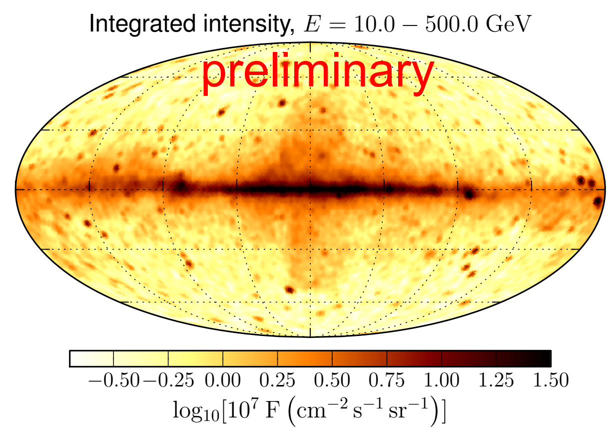
for the Fermi-LAT Collaboration

Fermi-LAT Analysis

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







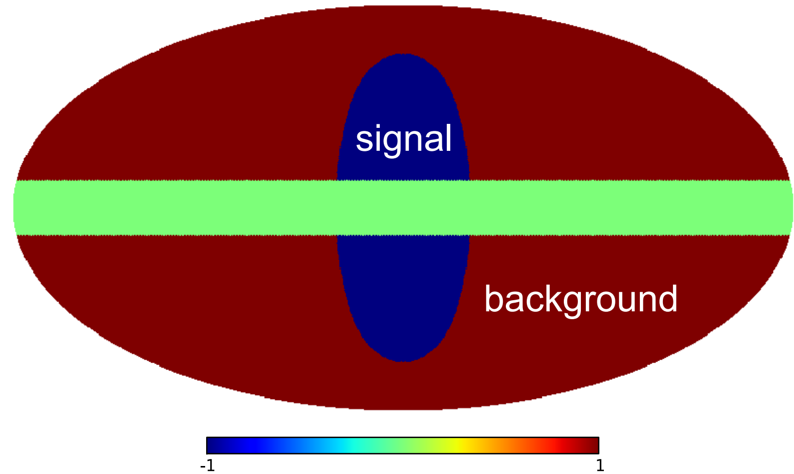
Submitted to ApJ

Galactic Diffuse Modeling

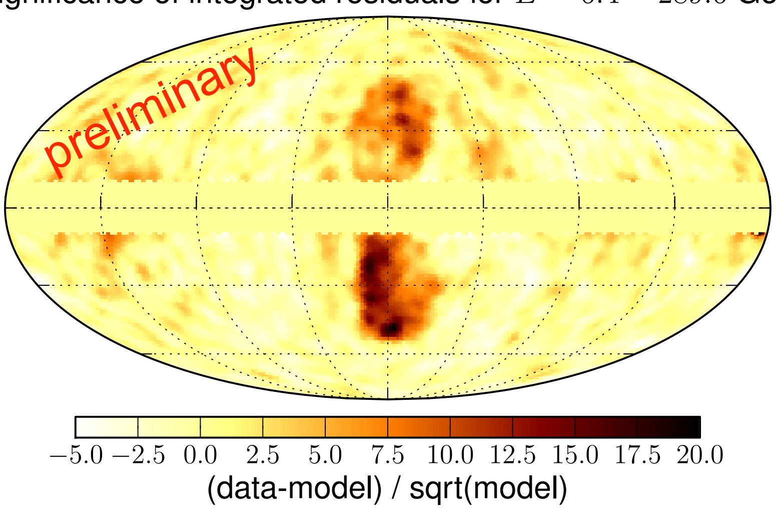
- Two methods
  - Based on GALPROP (see talk by Luigi Tibaldo)
    - Assumptions about CR source distribution etc.
  - Data driven
    - Does not depend on GALPROP
    - Uses features of gamma-ray data to define templates for Galactic diffuse components
- Combination of both methods gives a handle on systematic uncertainties

Bubble Template

- **All-sky fit including all diffuse model templates BUT bubble template, signal region masked**
- **Define bubble template from residuals (integrated from 6.4 to 300 GeV)**

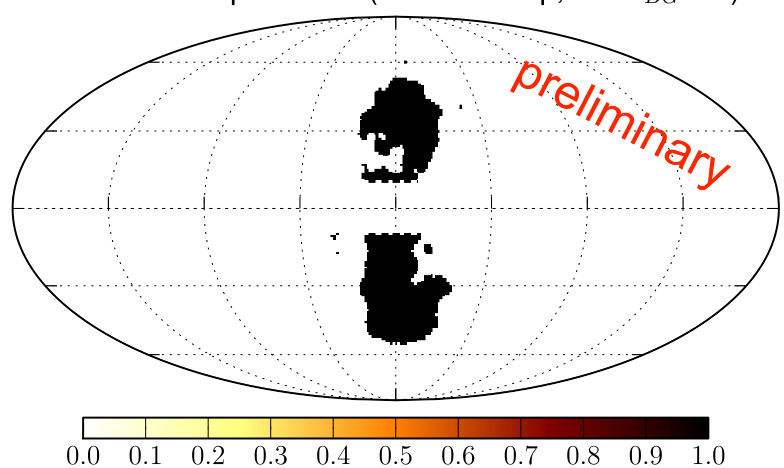


Significance of integrated residuals for $E = 6.4 - 289.6$ GeV

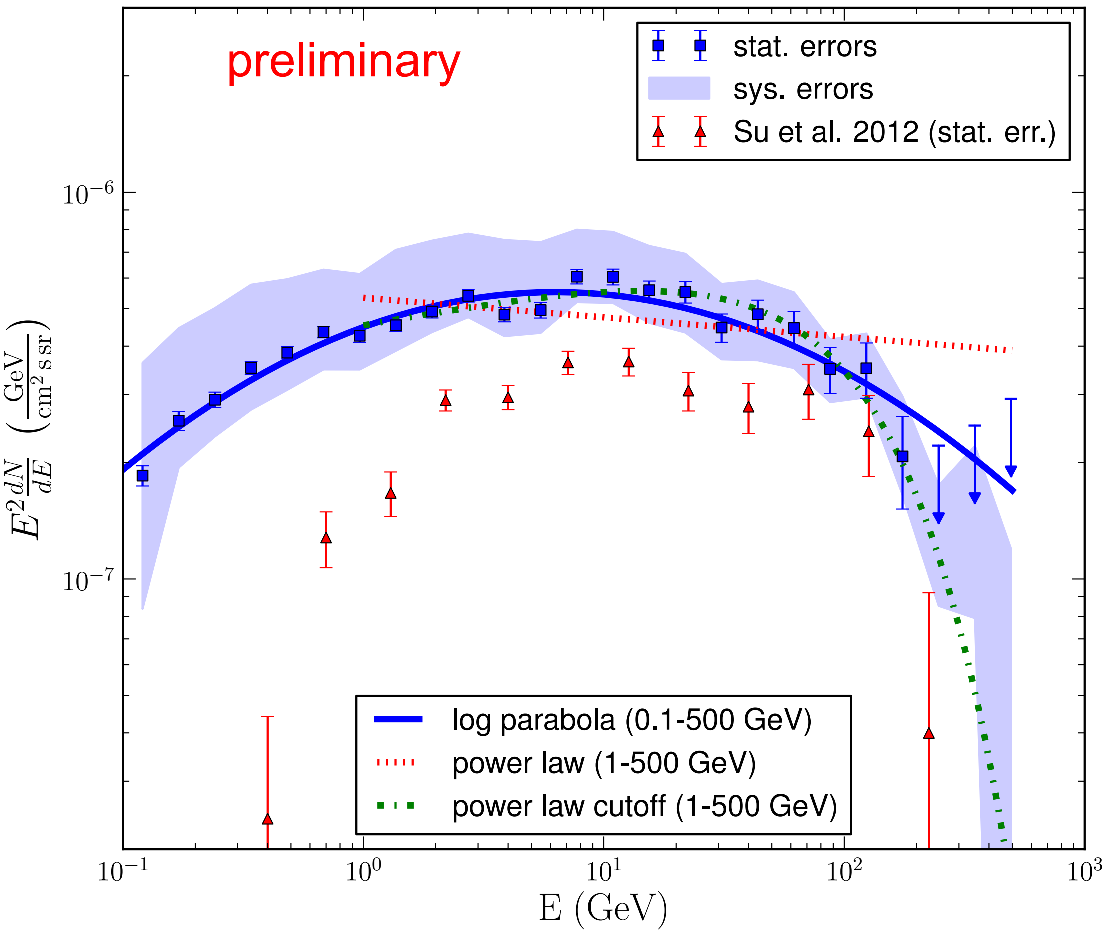


apply threshold

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



Spectrum



Shift in normalization can be explained by:

- Different foreground modeling
- Different definition of the bubble template resulting in different area of the template
- Different mask of Galactic plane

Cut off at:

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

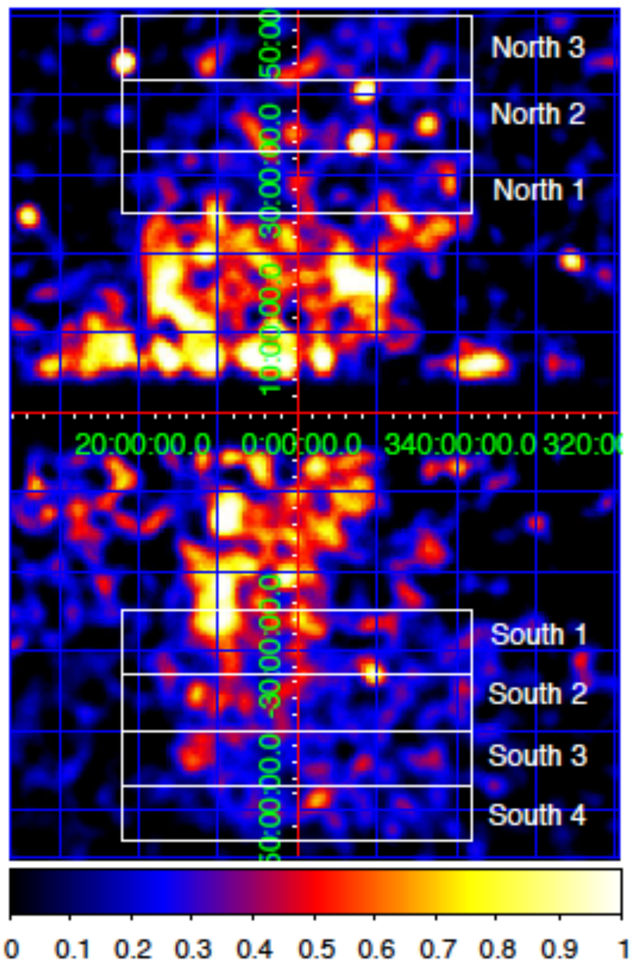
Index:

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

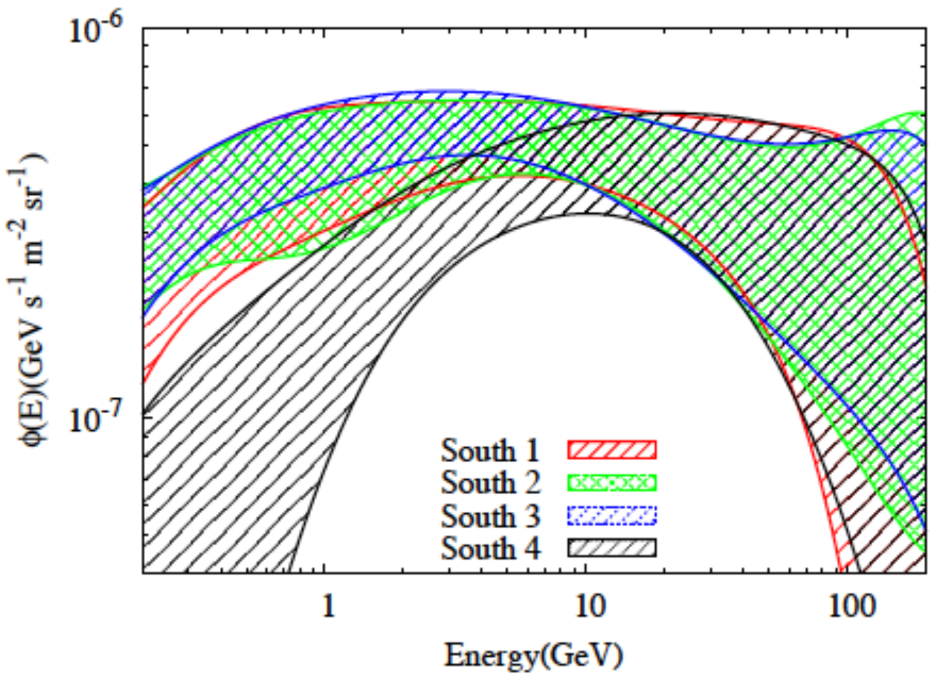
Gamma-ray luminosity: $(4.4 \pm 0.1[\text{stat}]^{+2.4}_{-0.9}[\text{syst}]) \times 10^{37}\ \text{erg s}^{-1}$

Spectral Variations – Previous Results

- Previous claims, Yang et al, arXiv:1402.0403, hardening towards top of South bubble

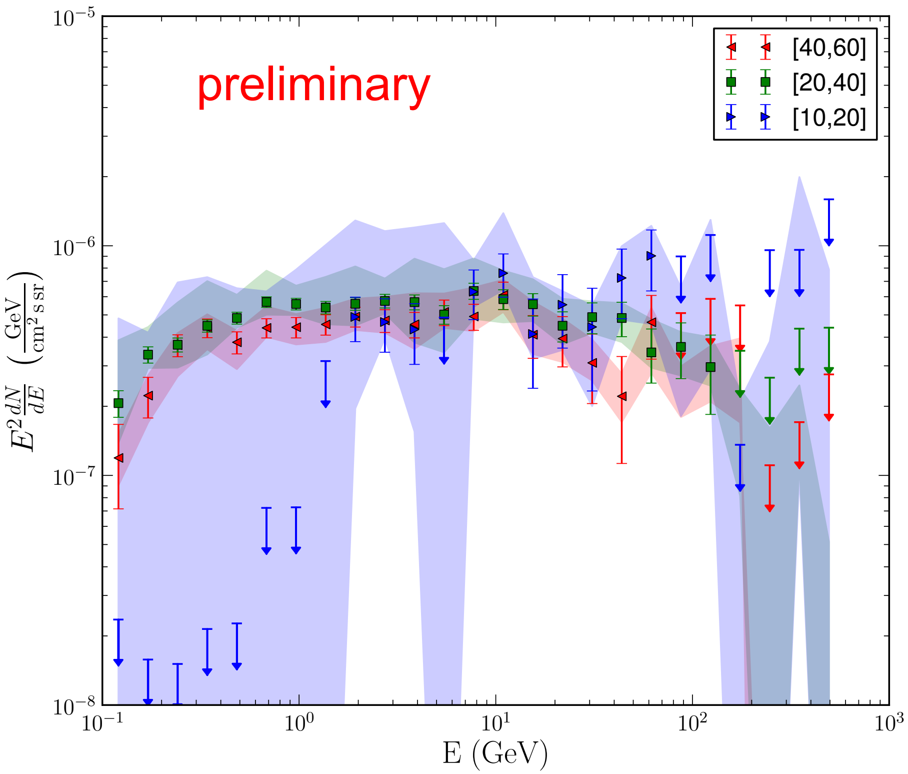


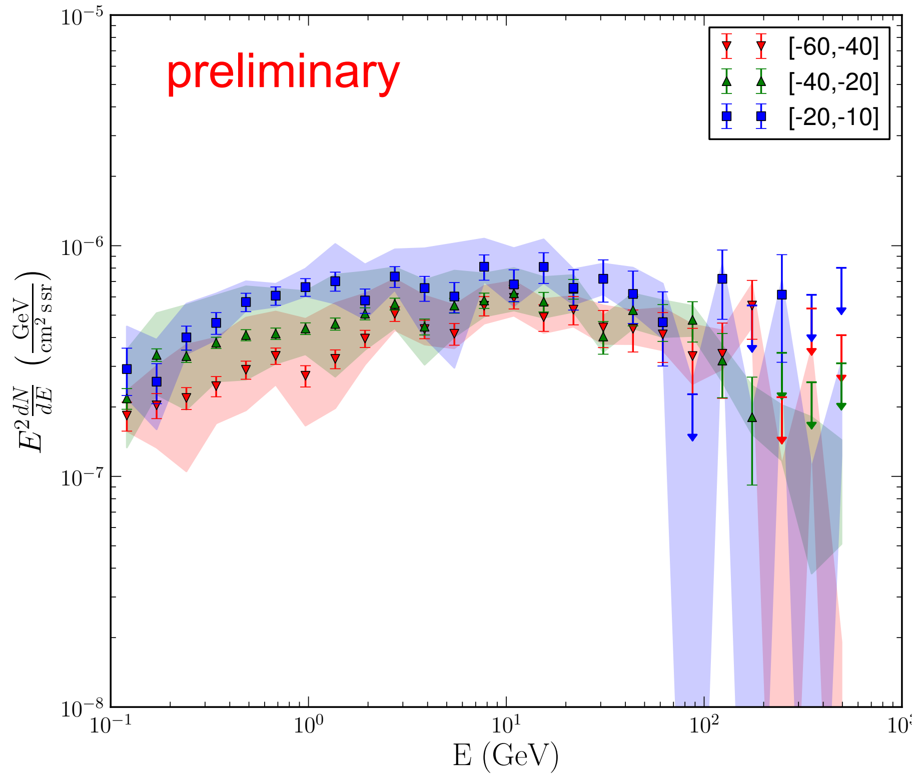
- Explanation: high-energy particles diffuse faster and reach high latitudes above the assumed injection source in the plane first



Spectral Variations

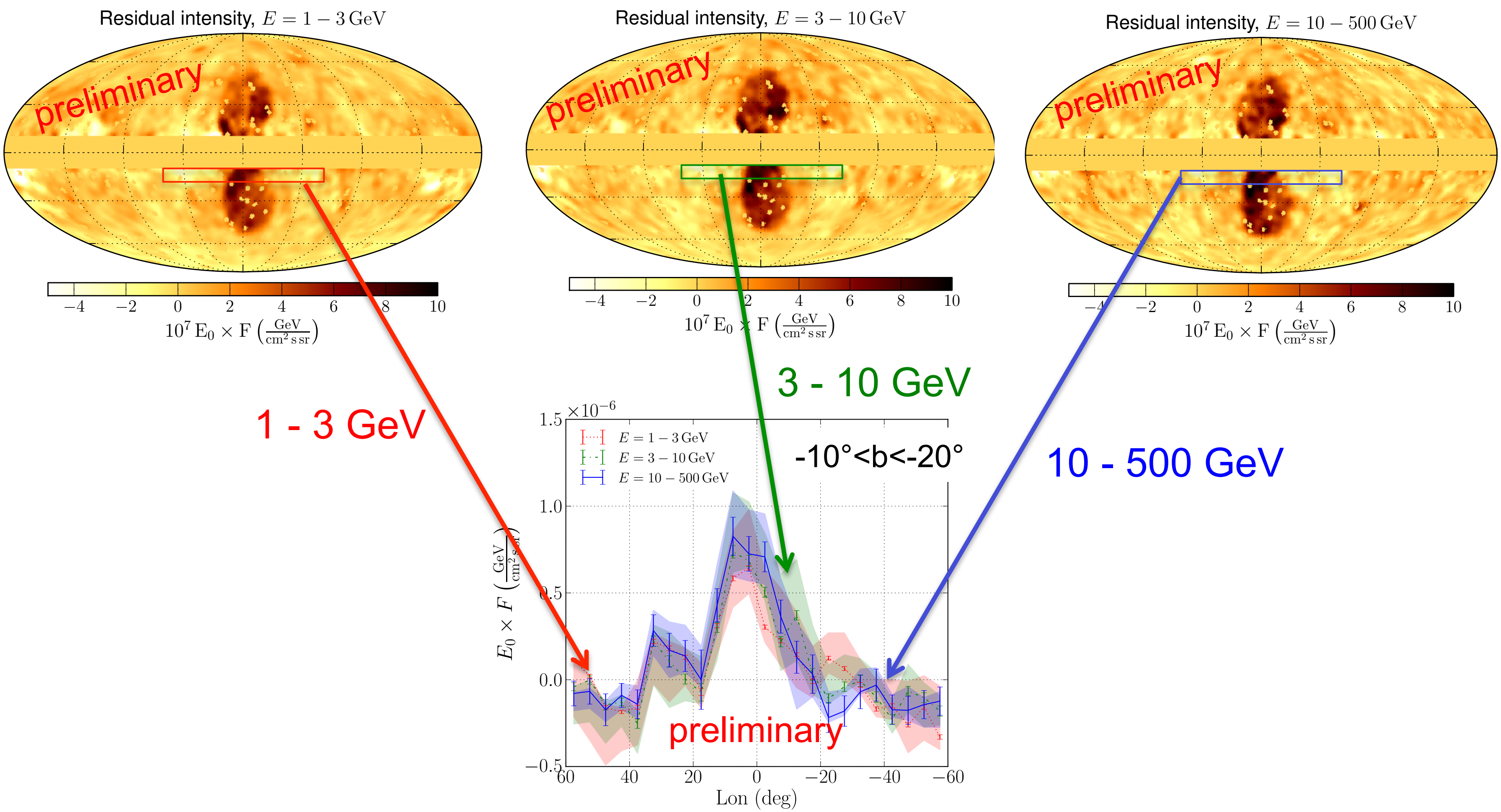
- **No spectral variation in latitude stripes within systematic uncertainties**





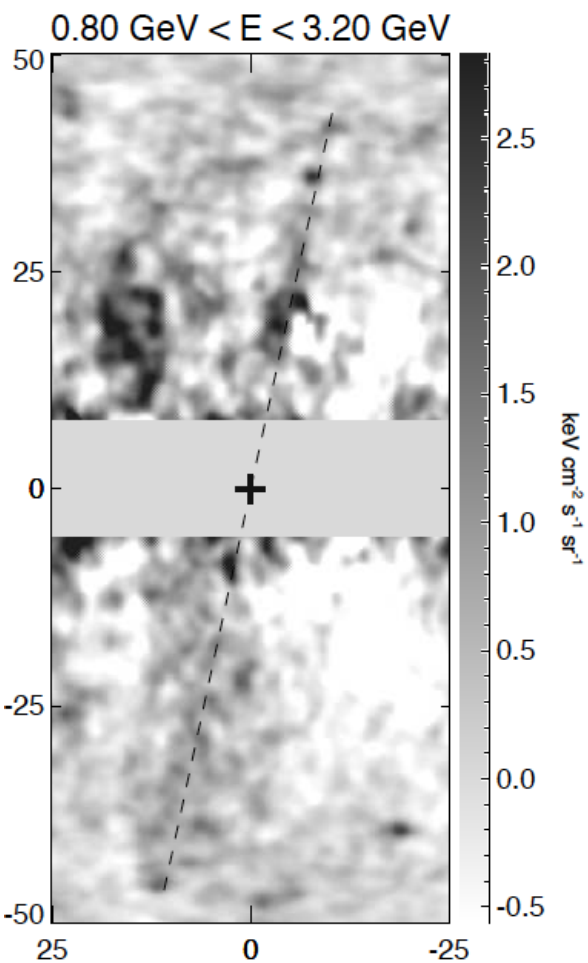
Shape at Different Energies

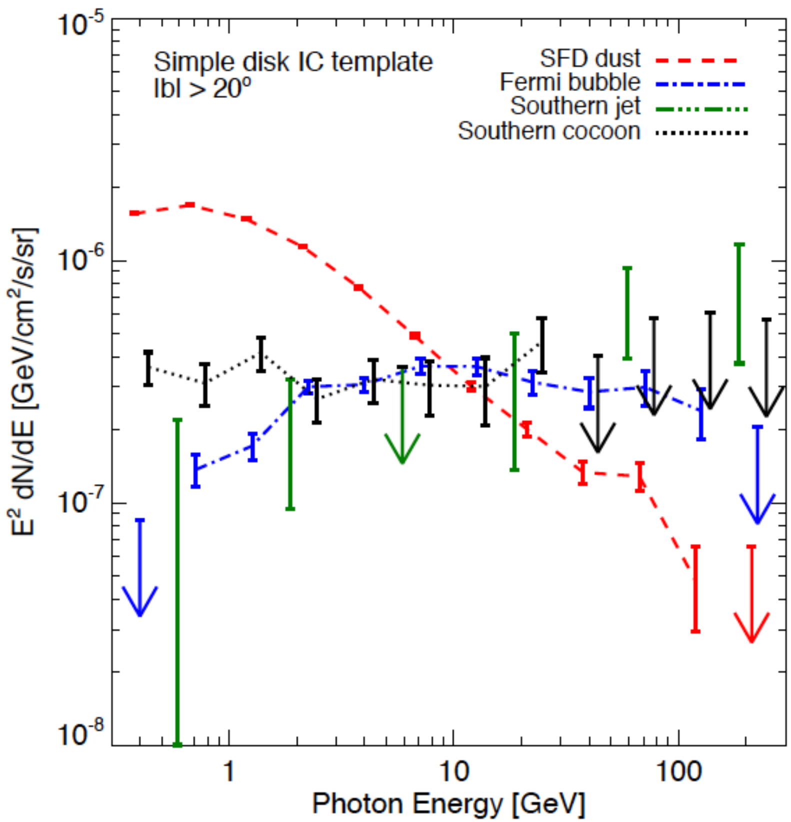
No change in bubble shape with energy found



Substructure – Previous Results

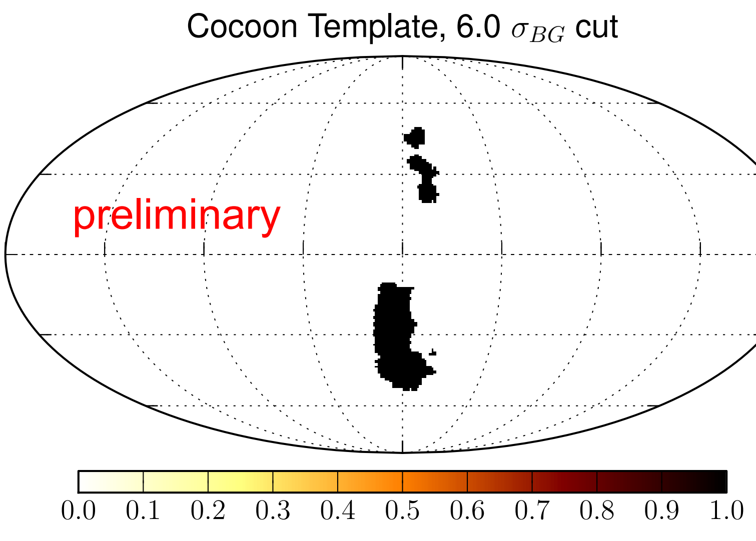
- **Su and Finkbeiner (ApJ 753, 2012): evidence for cocoon and pair of jets with hard spectra**

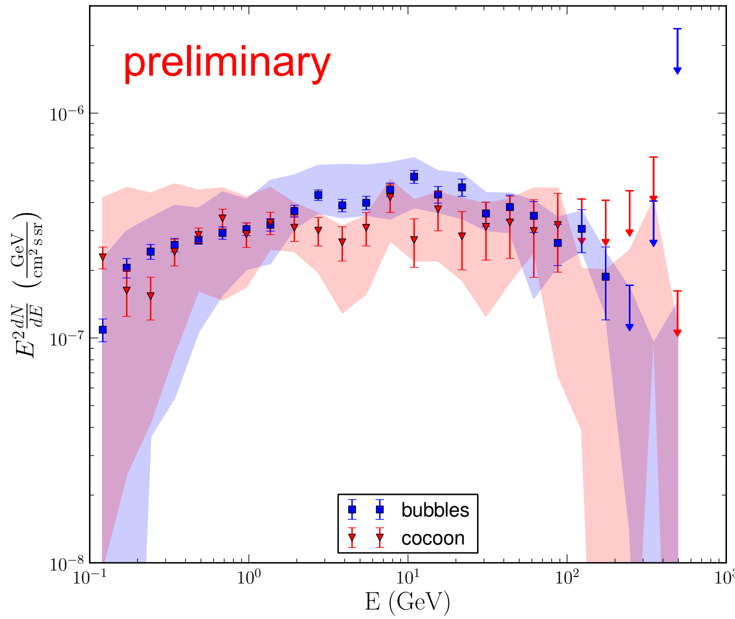




Substructure – "Cocoon"

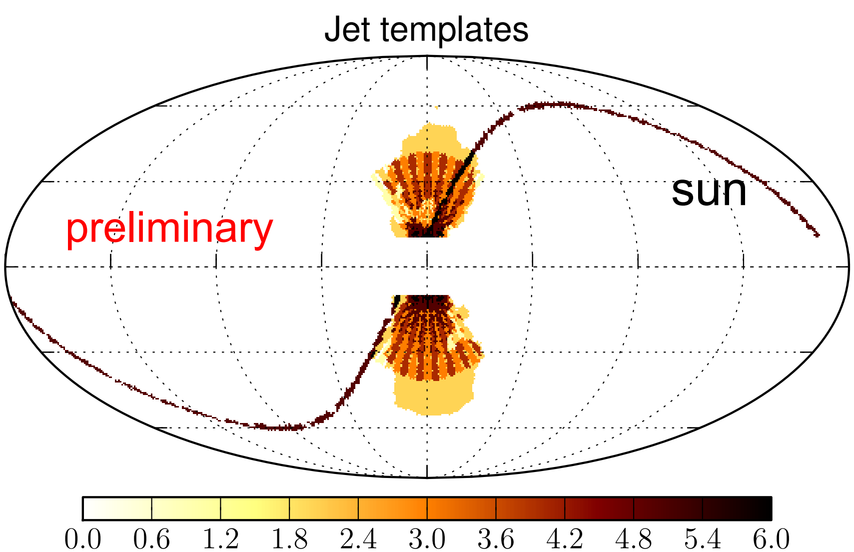
- Excess emission in South East of the bubbles
- Identical spectral shape within systematic errors

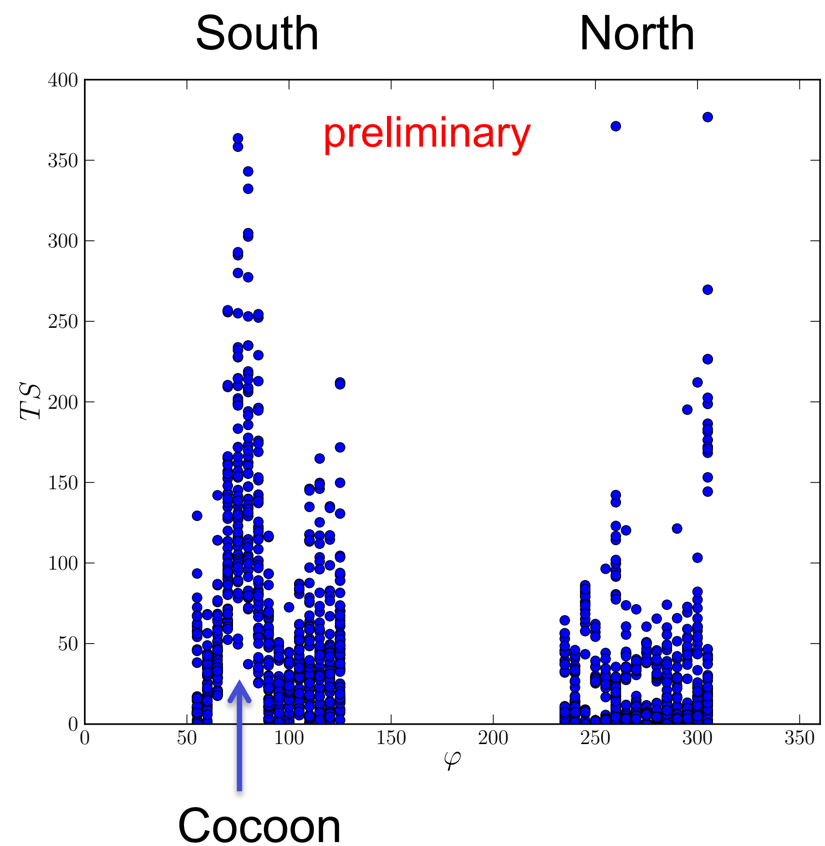




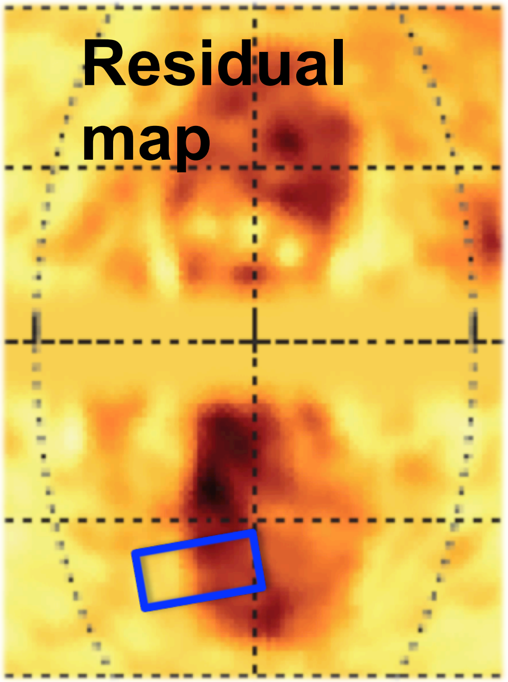
Substructure – Existence of "Jets"

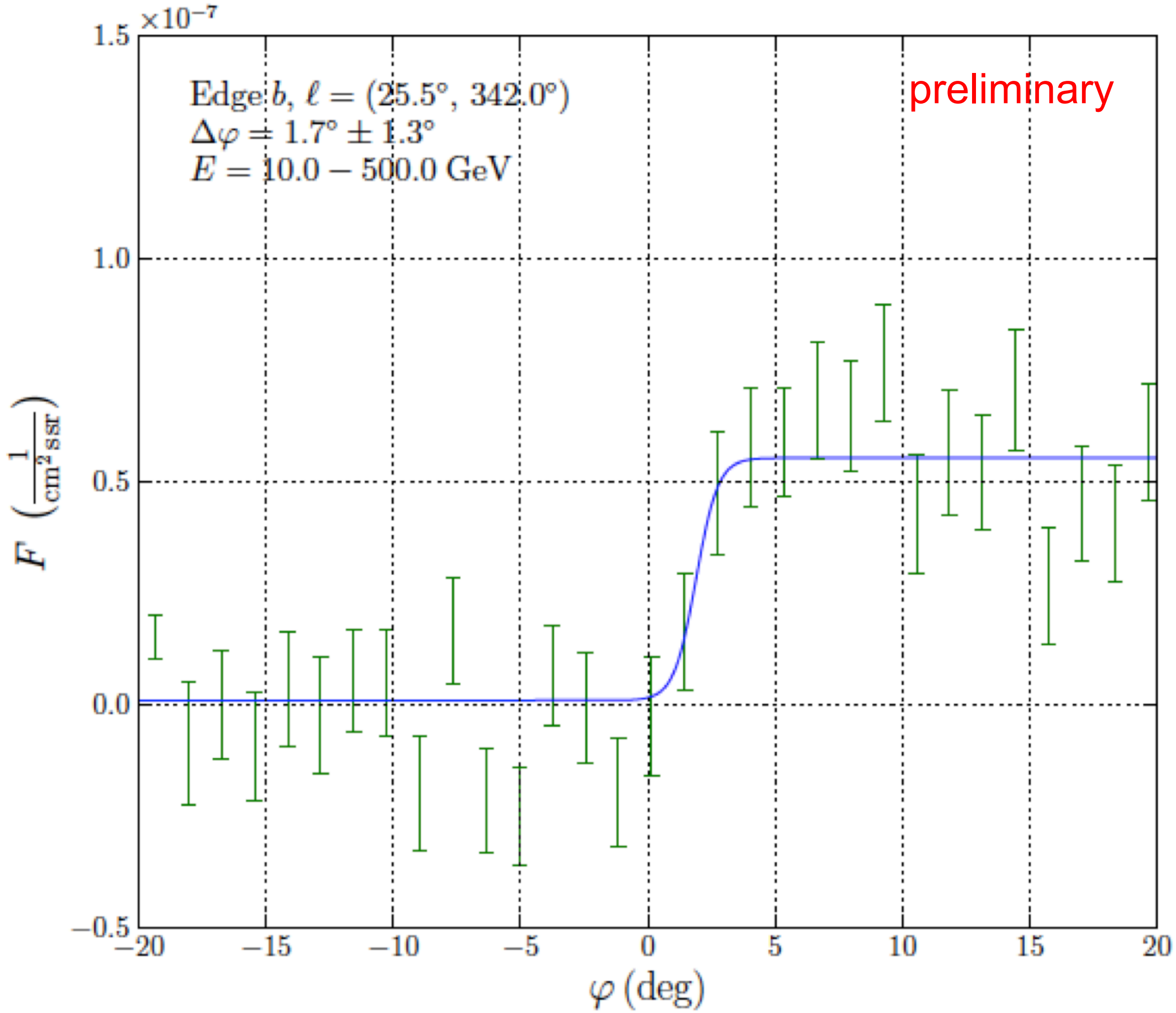
- **No significant residuals found aligned along a specific direction that could be interpreted as a jet**





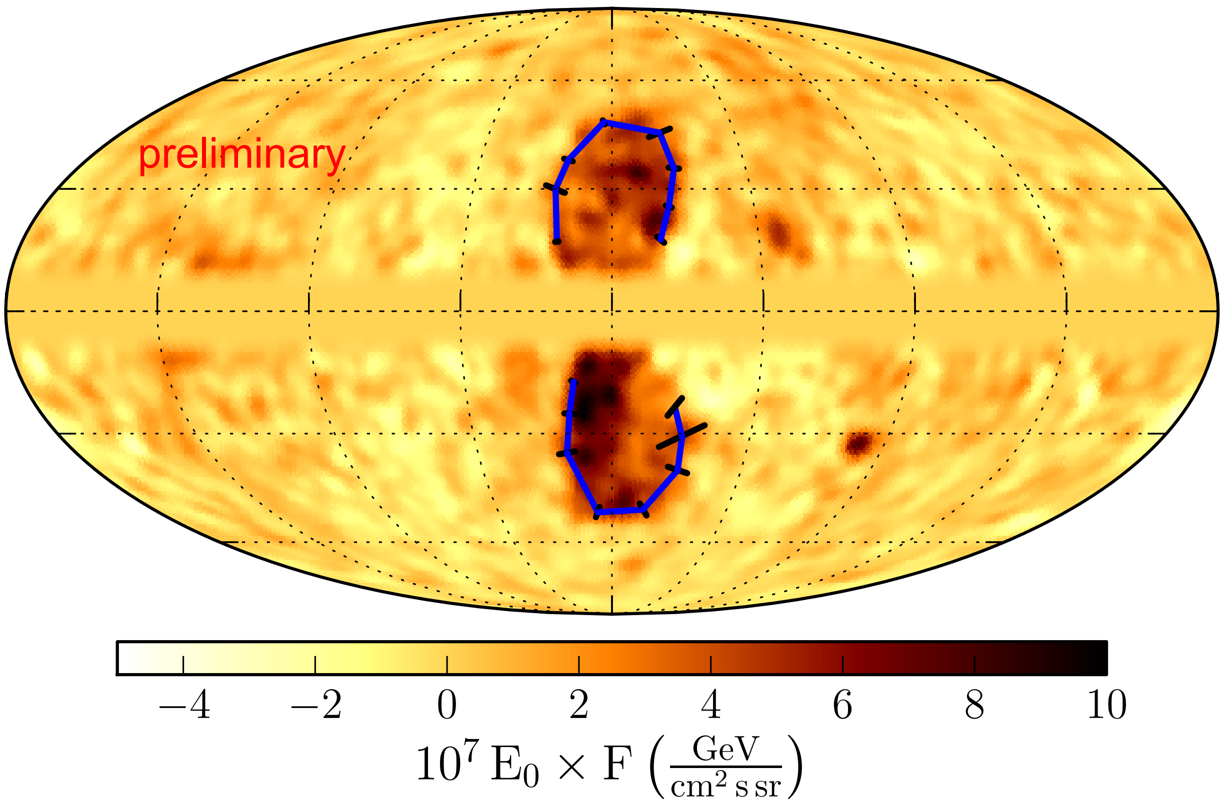
Boundary of the Bubbles





Boundary of the Bubbles

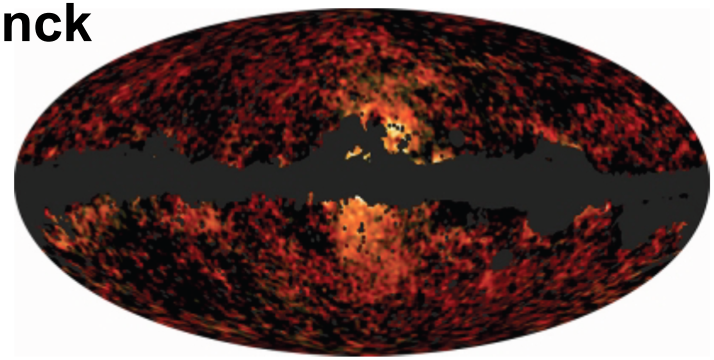
Residual intensity, $E = 10 - 500\,\mathrm{GeV}$



No variation with energy found, but some variation with position

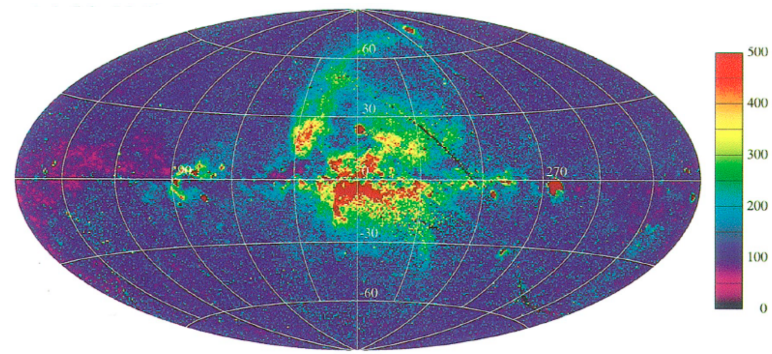
Observations in Other Wavelength

- **Microwave Haze: WMAP/ Planck**



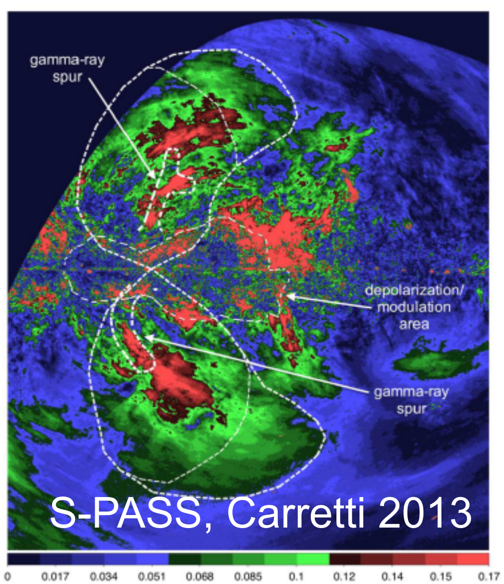
Ade et al., 2012, A&A, 554, A139

- **X-ray: ROSAT**



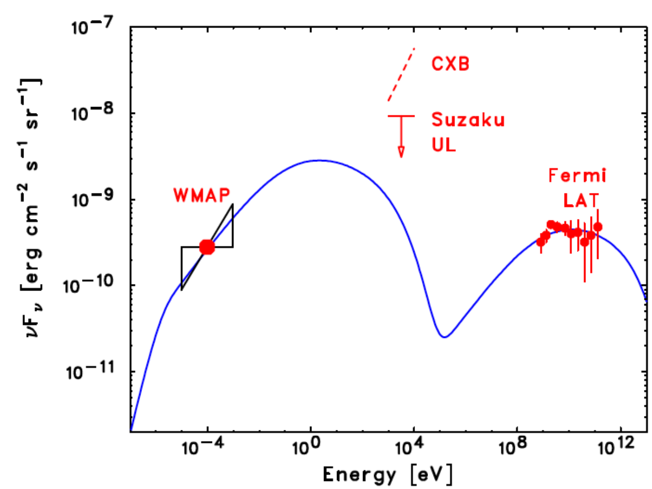
Snowden et al. 1997, ApJ, 485, 125

- **Polarization**



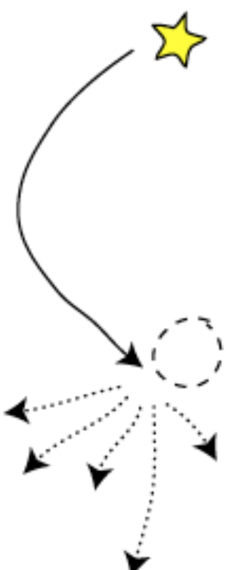
S-PASS, Carretti 2013

- **X-ray: Suzaku**

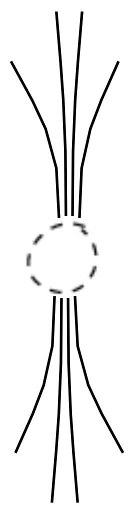


Leptonic Model

- **Electrons accelerated to E^{-2} spectrum by diffusive shock acceleration**
- **Gamma rays by inverse Compton scattering on radiation fields**
- **Microwave haze by synchrotron of same population of electrons**

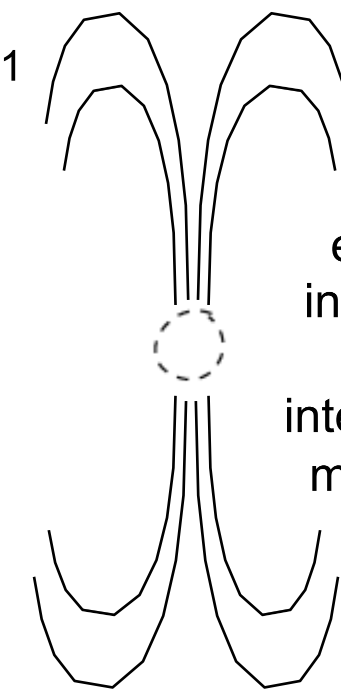


disruption of stars
by central black hole



Guo & Mathews 2012, ApJ, 756, 181
Yang et al. 2012, ApJ, 761, 185

AGN-like jet transports
particles to high latitudes

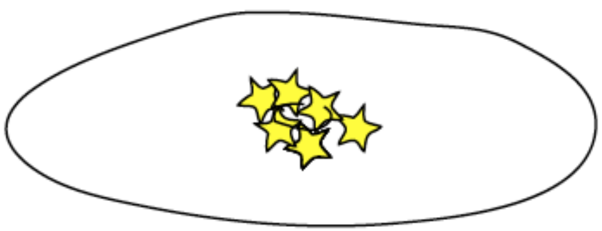


ejecta interacts with interstellar medium

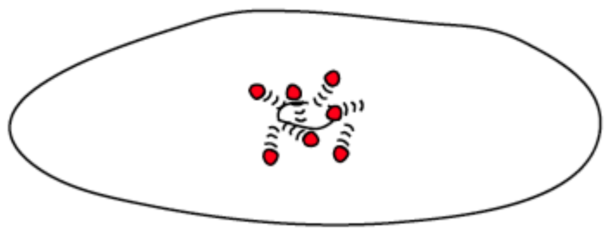
Illustrations by P. Mertsch

Hadronic Model

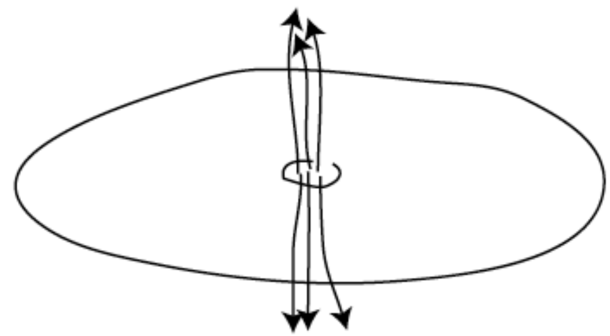
- **Gamma rays by π^0 on thermal gas (density ~ 0.01 cm^{-3})**
- **Secondary e^- produce synchrotron**



increased star formation rate close to GC



acceleration of CR protons and nuclei in SNRs



wind convects CRs away from disk

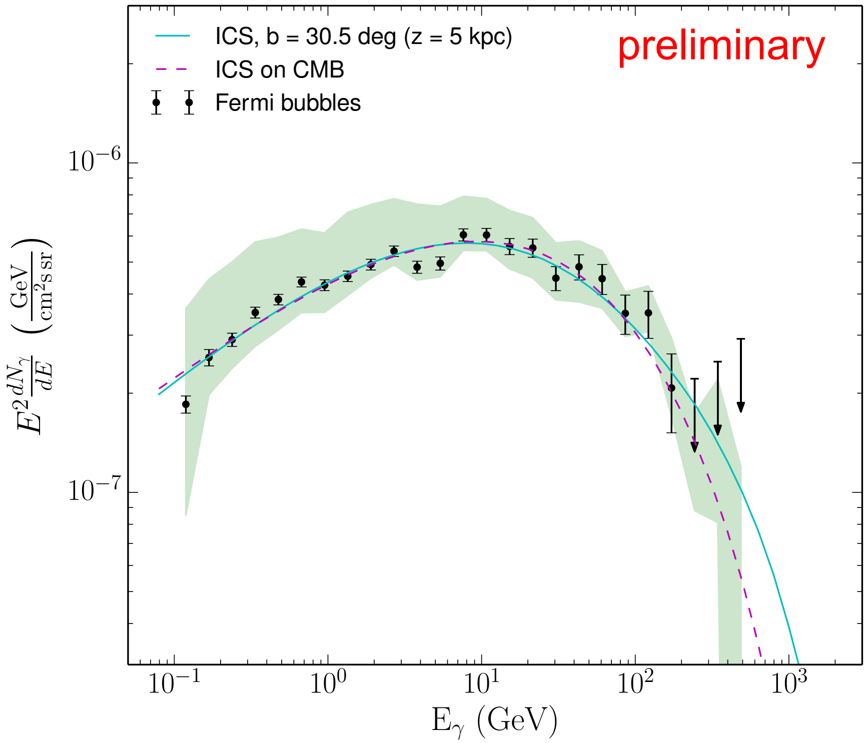
Neutrinos from π^+/π^-

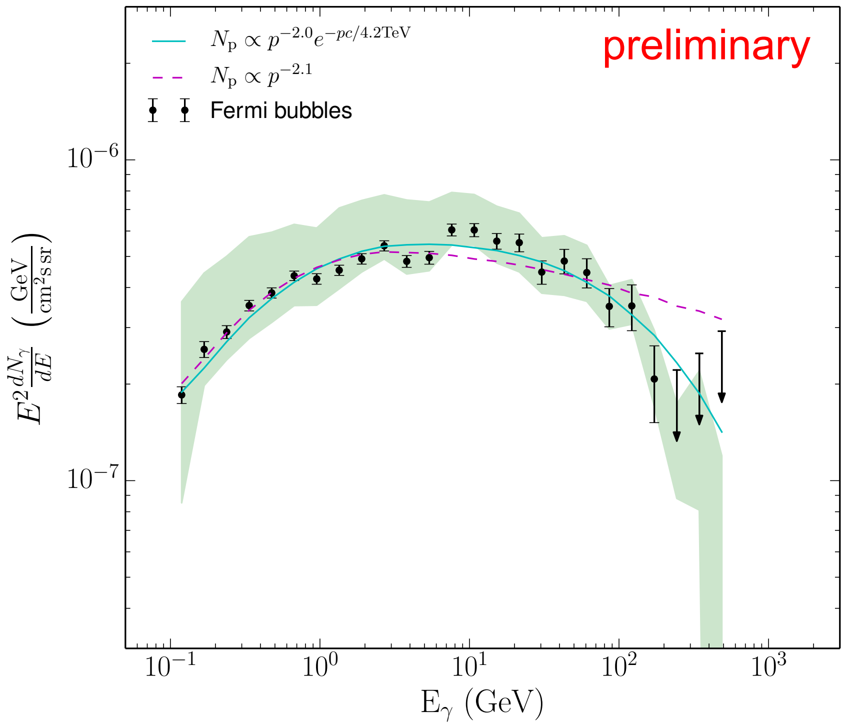
Aharonian & Crocker, PRL, 106 (2011)

Illustrations by P. Mertsch

Leptonic, Hadronic, Gin Tonic?

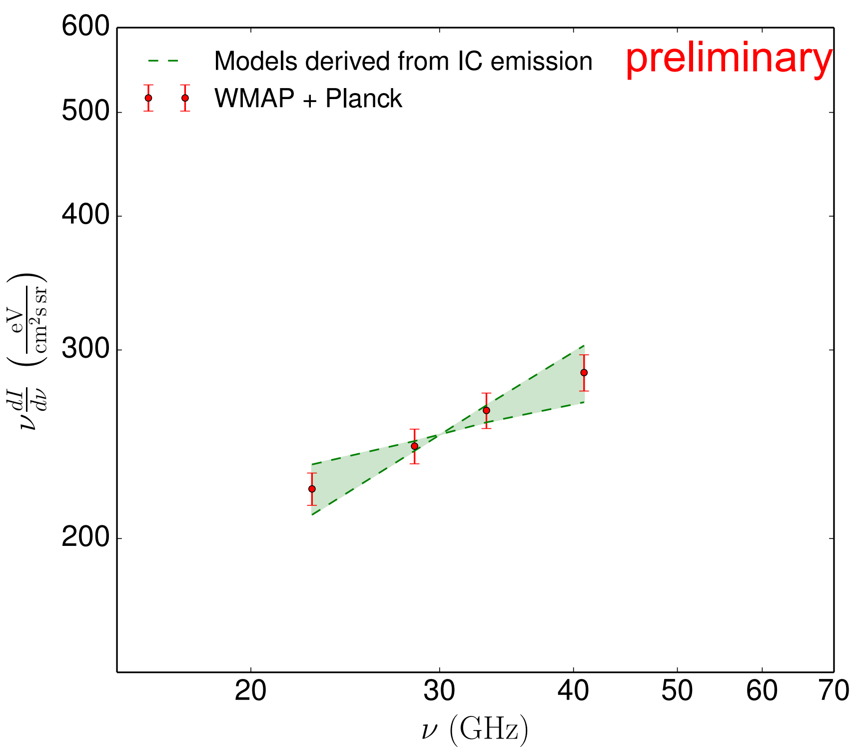
- **Both leptonic and hadronic models describe the gamma-ray spectrum well**

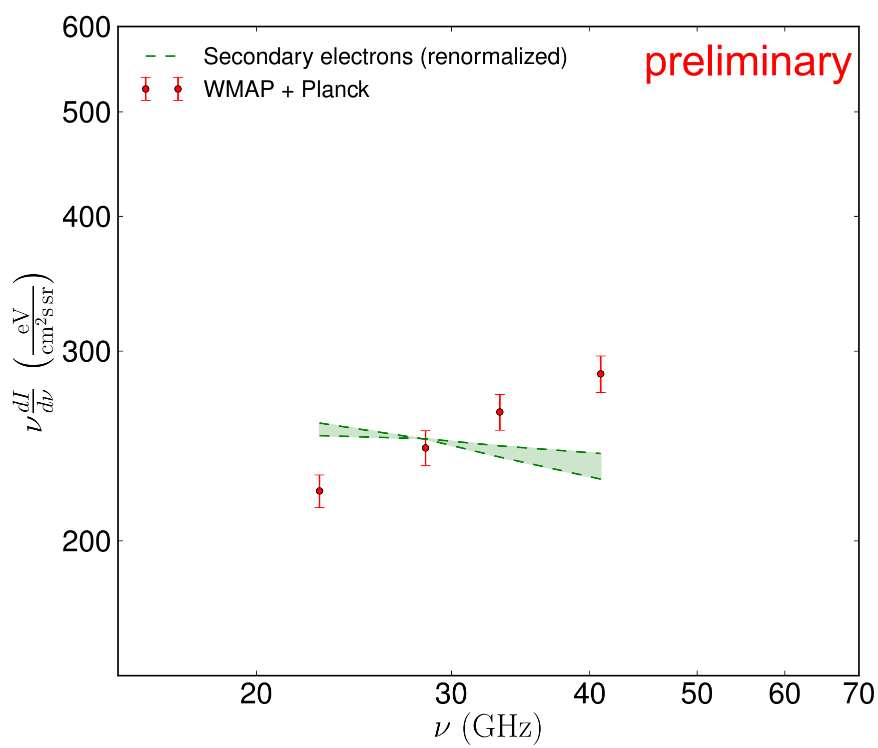




Leptonic, Hadronic, Gin Tonic?

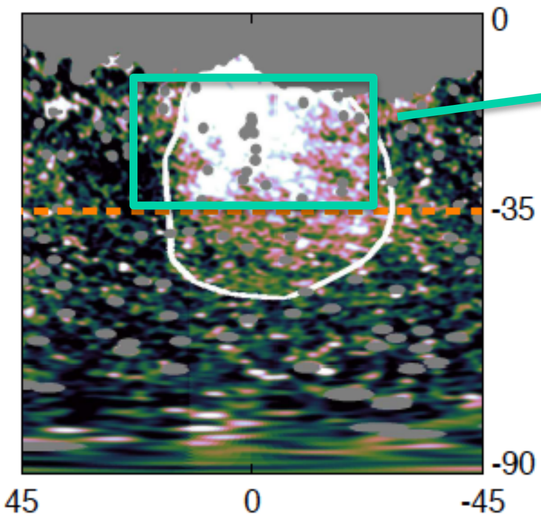
- **Assuming that the microwave haze and the gamma-ray bubbles are produced by the same population of electrons: hadronic model fails to describe the spectral shape**



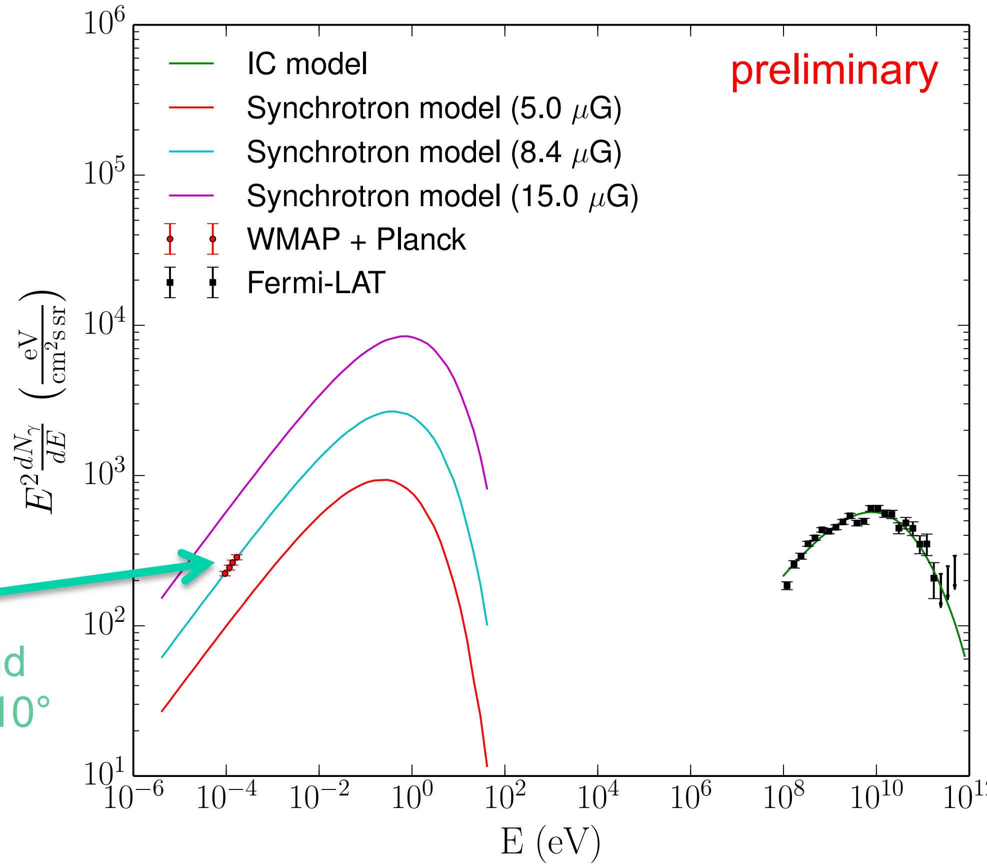


Leptonic Models – Magnetic Field

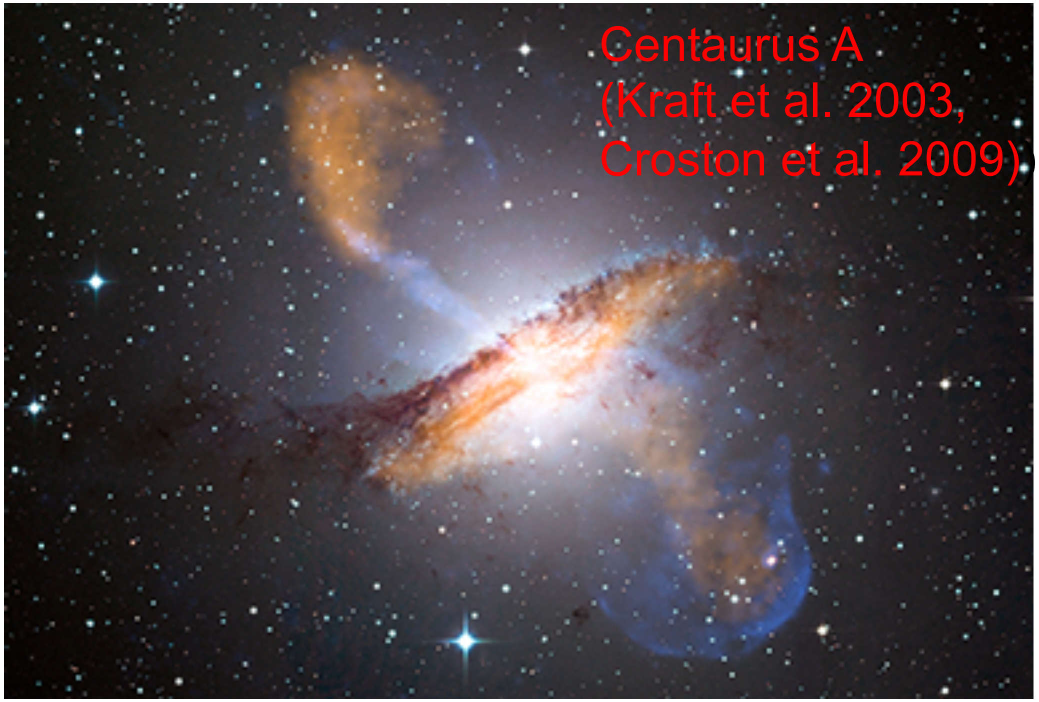
- Leptonic models can explain microwave haze for B~8μG
- Drop in magnetic field at latitudes of |b| ~35° could explain different latitudinal extension



|l| < 25° and
-35° < b < -10°



Shocks and Bubbles are common in other Galaxies



Unlikely that similar structures in gamma rays can be detected in other galaxies due to limited spatial resolution

Unique opportunity to study gamma-ray lobes in our neighborhood

Summary

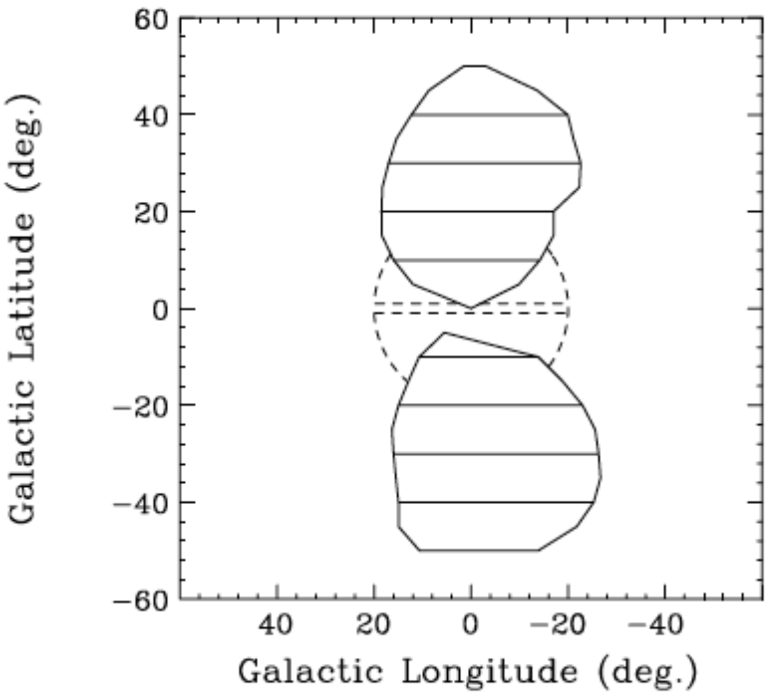
- Fermi Bubbles detected in gamma-ray data
- Hard spectrum with cutoff at ~110GeV
- Possible association with microwave haze and ROSAT data
- Leptonic and hadronic interpretation of gamma-ray data possible, assuming association with microwave haze prefers leptonic models
- Energy injection from GC:
  - Enhanced star formation or jet activity
- Simulation can describe observed features of the bubbles
- More data (radio polarization, X-ray) will help to obtain deeper understanding

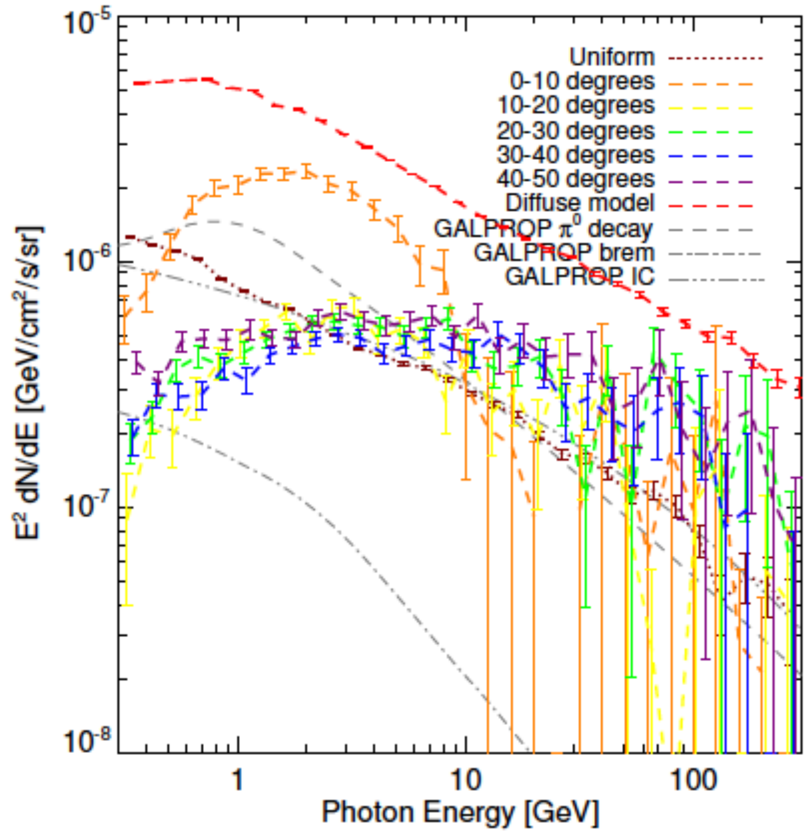
Thank you

BACKUP

Spectral Variations – Previous Results

- **Hooper and Slatyer, arXiv:1302.6589, additional component at low energies**
- **Interpretation: dark matter, millisecond pulsars?**



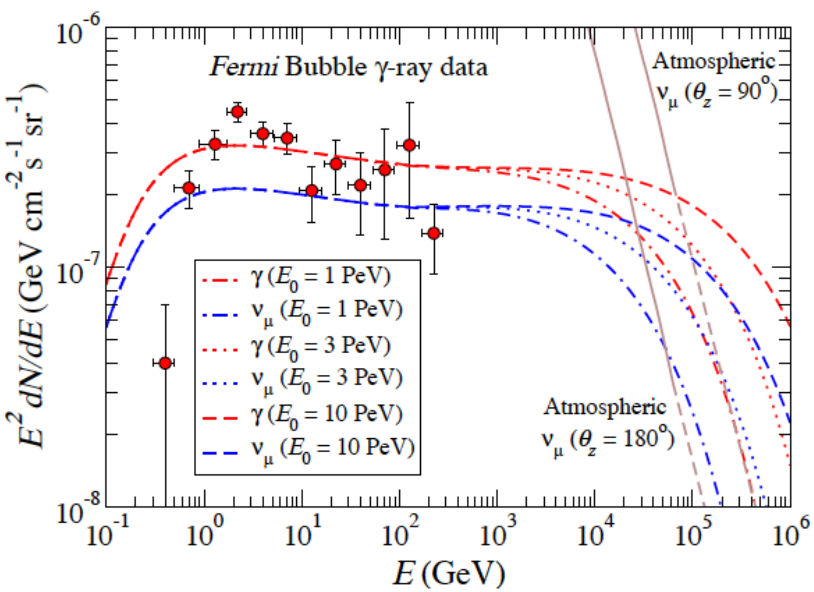


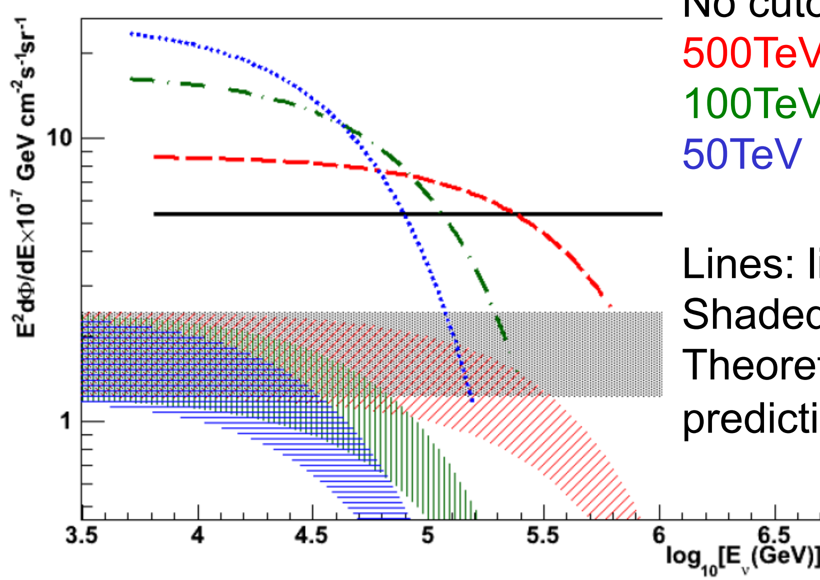
Neutrino Search with ANTARES

S. Adrian-Martinez et al. arXiv:1308.5260

- **data from 2008 to 2011**
- **Test various energy cutoffs of the assumed proton spectrum**
- **no statistically significant excess of events is observed → upper limits on the neutrino flux**

Prediction: Lunardini, Razzaque
Phys.Rev.Lett. 108 (2012) 221102

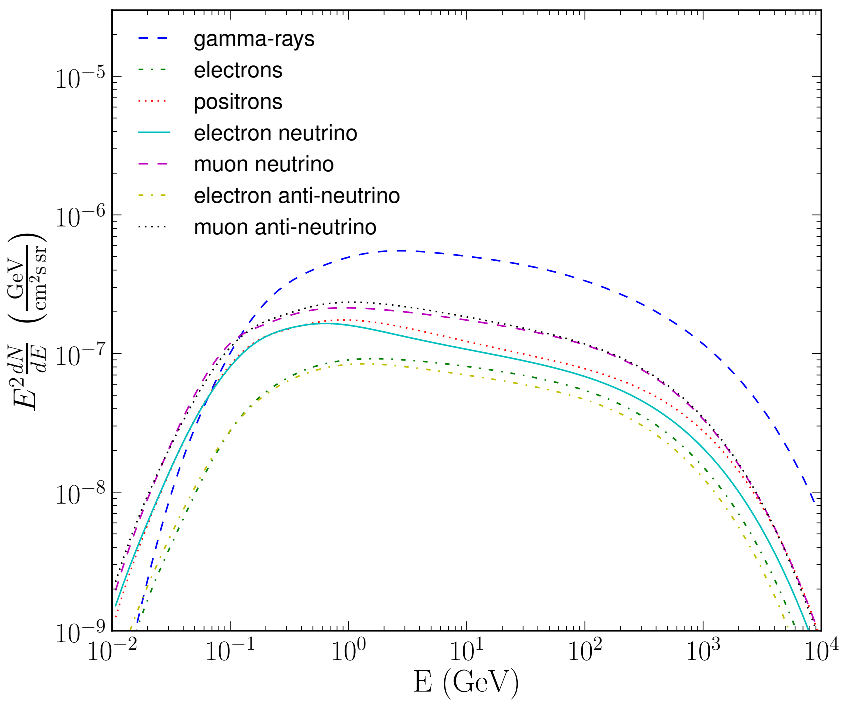




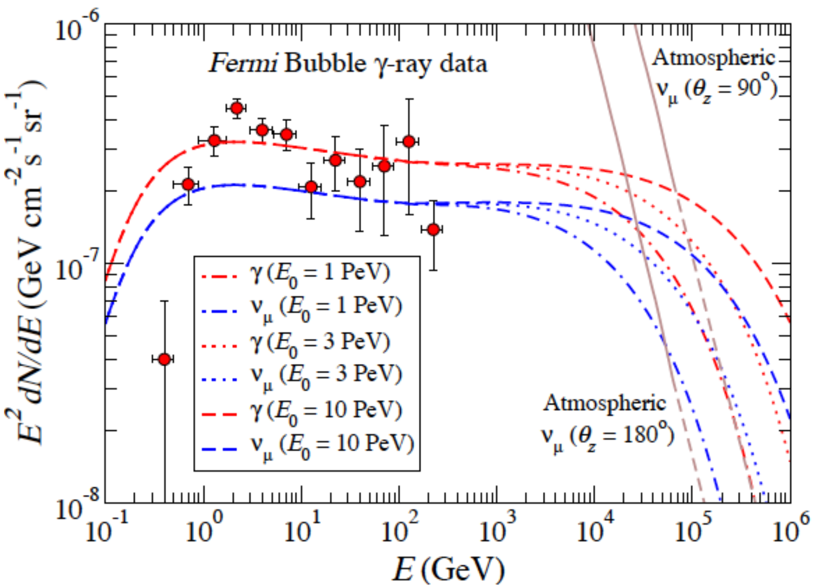
No cutoff
500TeV
100TeV
50TeV

Lines: limits
Shaded regions: Theoretical prediction

Neutrino Flux in Hadronic Models



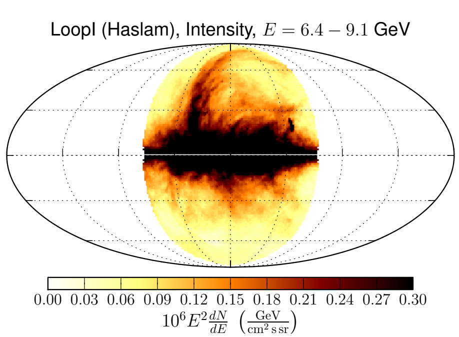
Lunardini, Razzaque Phys.Rev.Lett. 108 (2012) 221102

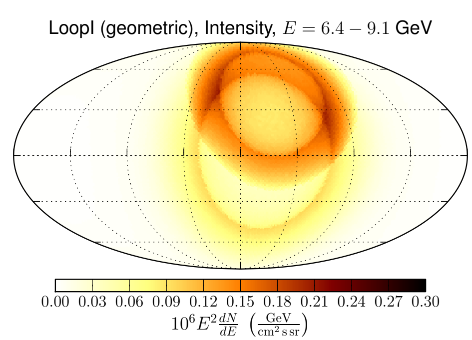


GALPROP Template Fitting

- **Templates (free/fixed):**
  - **Inverse Compton (IC)**
  - **Local hydrogen (HI and HII)**
  - **Non-local hydrogen (HI and HII)**
  - **Molecular hydrogen (H2)**
  - **Loop I (geometric template or Haslam map)**
  - **Bubbles (from residuals)**
  - **Isotropic**
  - **Point sources: 2FGL, bright sources refitted**
- **Fit in individual energy bins**

Haslam et al. 1982, 408MHz survey





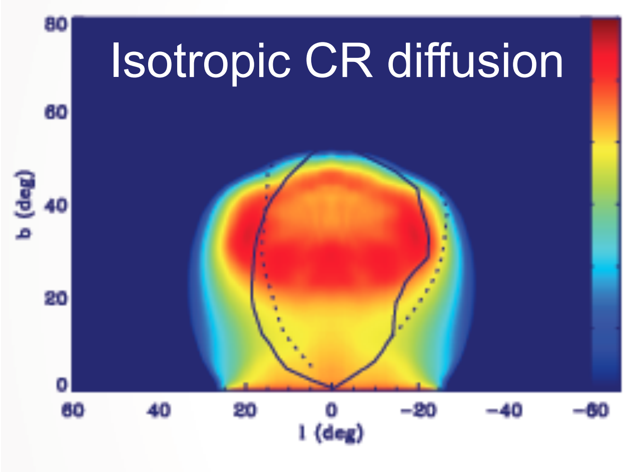
Wolleben, M. et al. 2007, based on polarization surveys at 1.4GHz

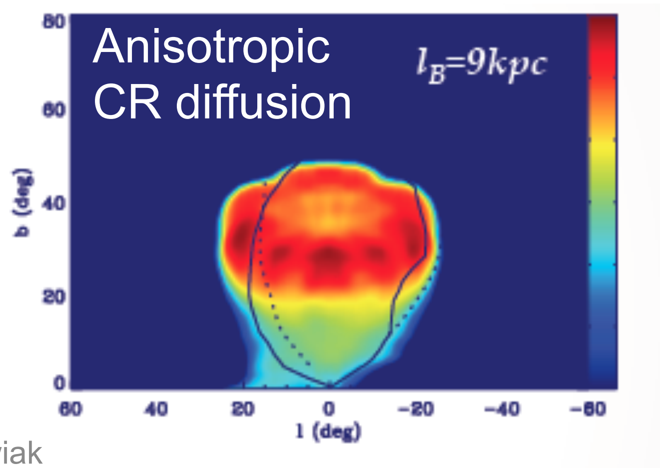
Local Template Fitting

- Template definition, "Peeling the onion":
  - Define gas-correlated component by fitting gas maps in local patches, other smooth components are modeled with local polynomials
  - Subtract gas-correlated component
  - Define IC and isotropic contribution:
    - Gaussian along Gal. plane (to model IC)
      - Gaussian perpendicular to plane (as a proxy for bubbles and Loop I)
    - Isotropic template
  - Subtract IC Gaussian, define bubble template from residuals
- Fit all templates to data in individual energy bins

Simulations

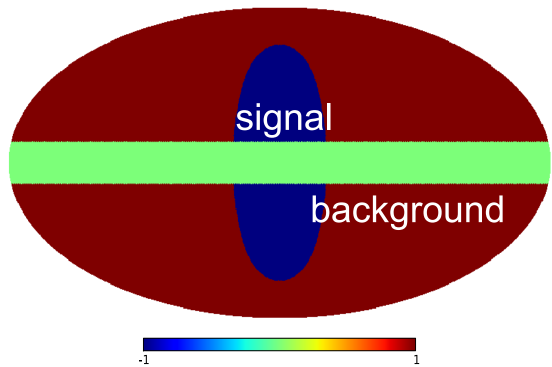
- AGN jets from Galactic center (e.g. Guo & Mathews, Yang 2012/13)
  - CRs accelerated and transported by jets
- Spherical outflow from hot accretion disk (Guobin 2014)
  - Central molecular zone collimates the outflow
- Problems
  - limb darkening → shear viscosity to concentrated CR near edges
  - Edges are not sharp → tangential fields at edges → suppressing CR diffusion across edges causing sharp edges)

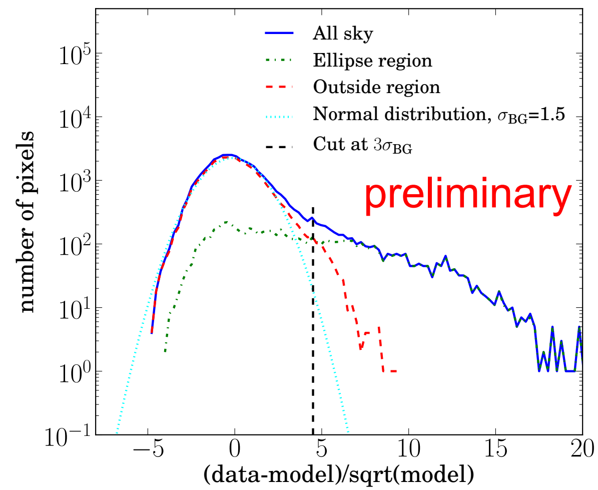


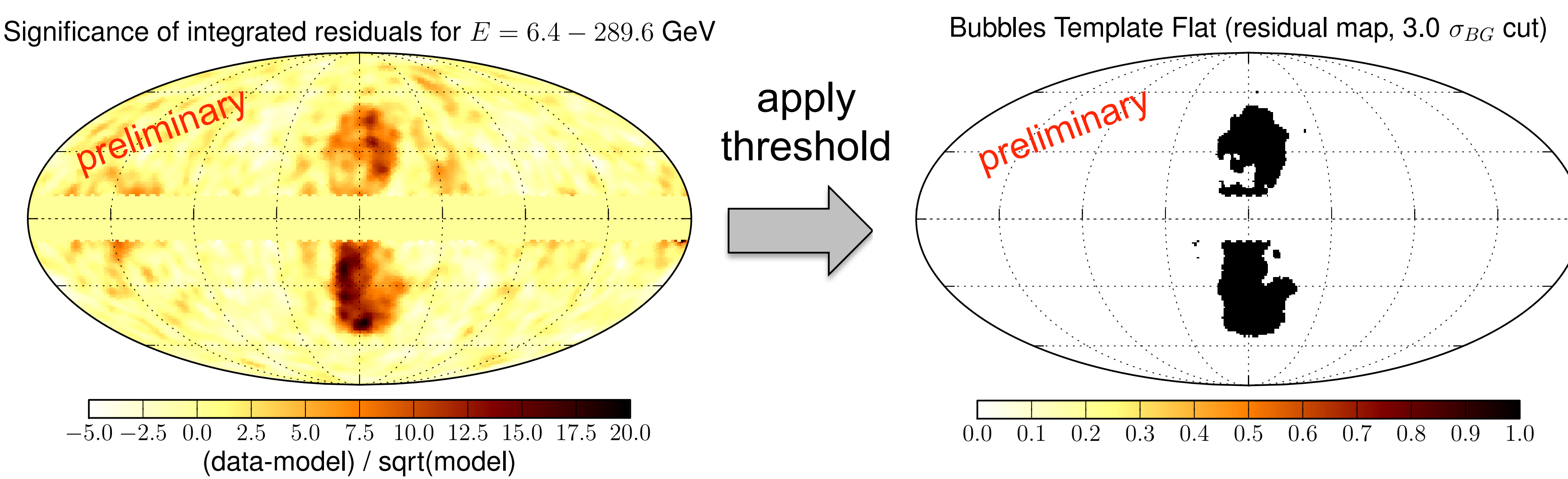


Bubble Template

- **All sky fit including all templates BUT bubble template, signal region masked**
- **Define bubble template from residuals (integrated from 6.4 to 300 GeV)**



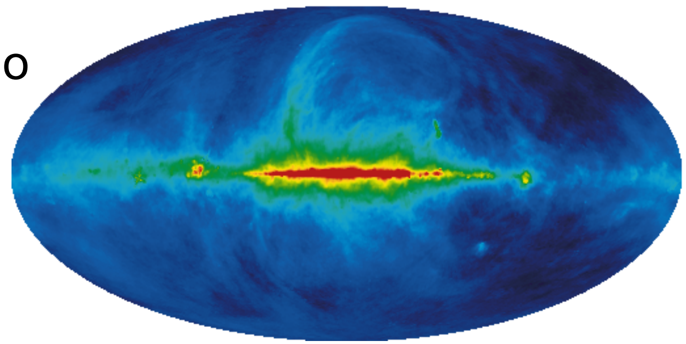


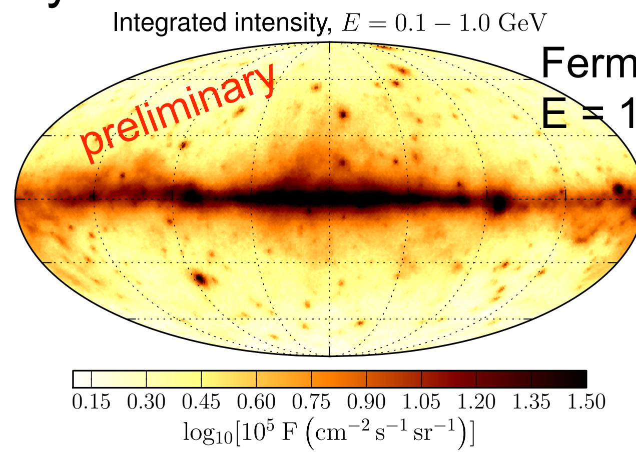


Modeling of Galactic Diffuse Emission
Loop I

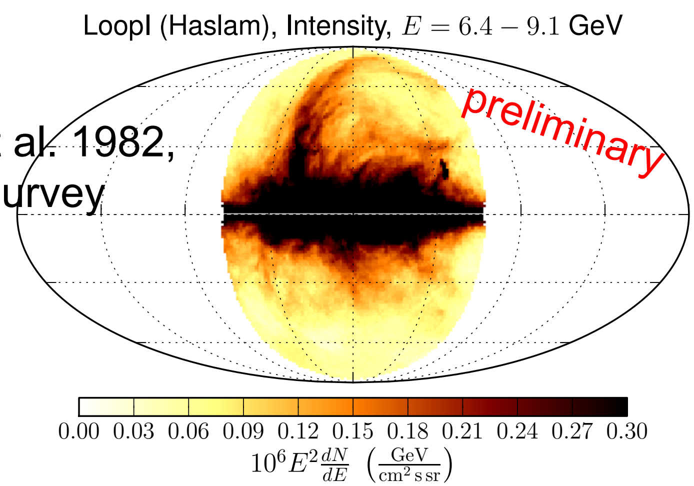
Giant radio loop spanning 100° on the sky

Radio map

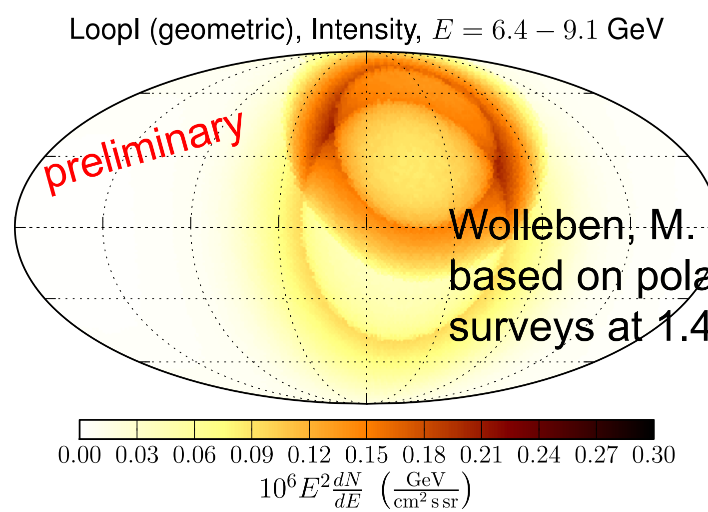




Fermi data
E = 100 Mev – 1GeV



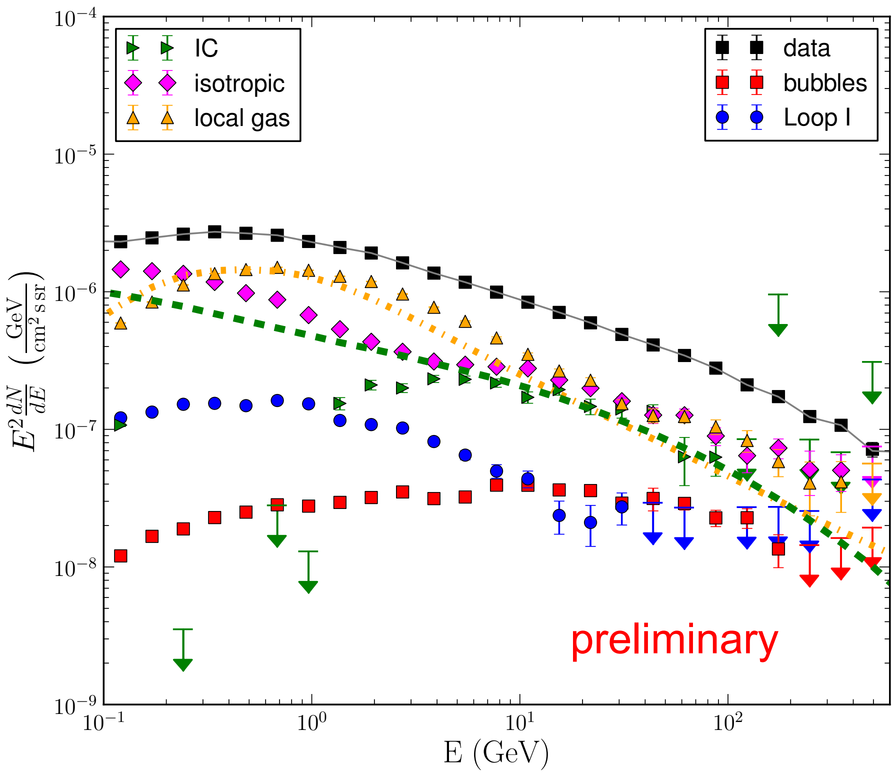
Haslam et al. 1982, 408MHz survey



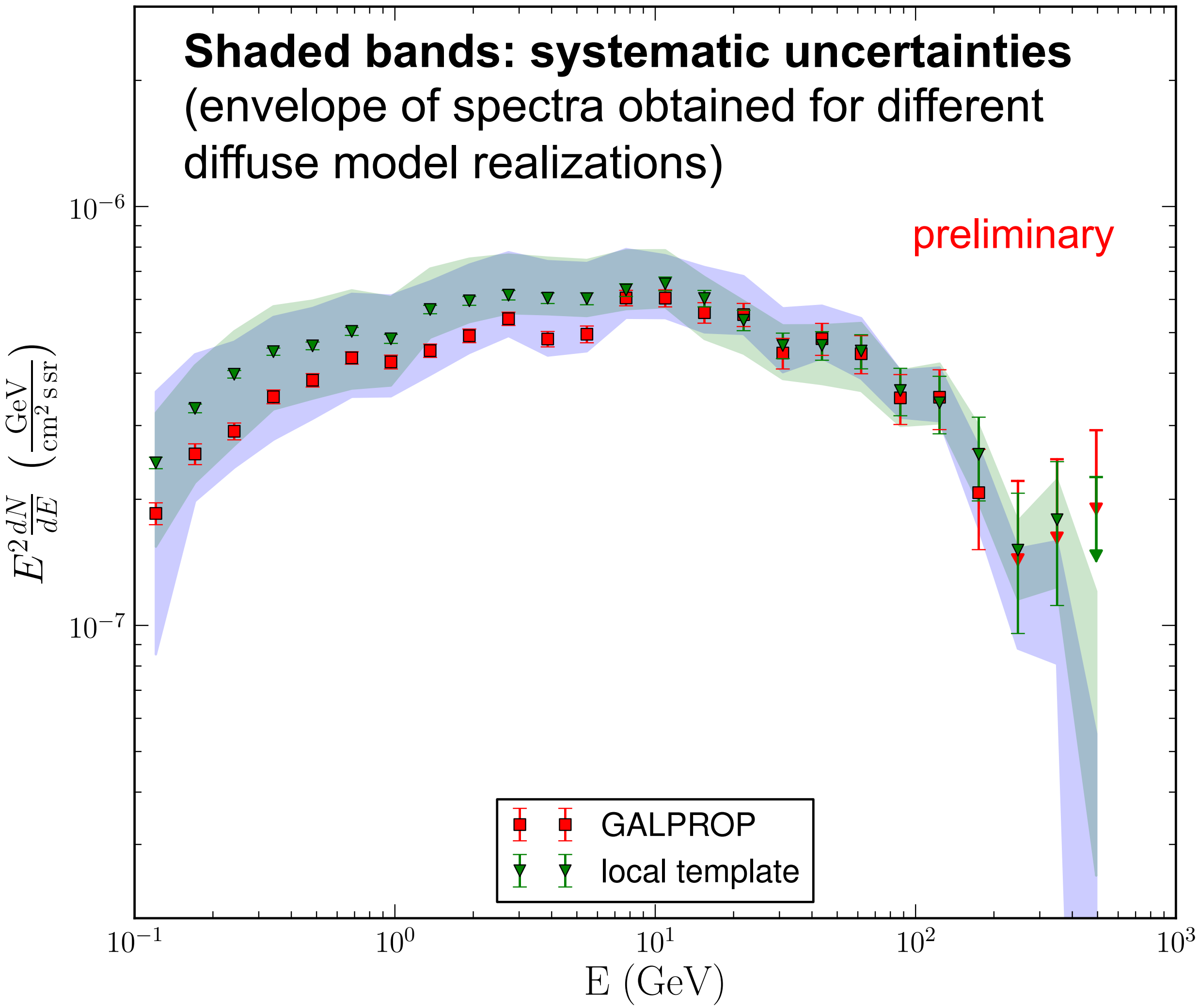
Wolleben, M. et al. 2007, based on polarization surveys at 1.4GHz

All Sky Fit

- Fit all sky (|b|>10°), each energy bin separately
- Templates used in fit: GALPROP templates (gas & IC), Loop I, bubble, point sources, isotropic

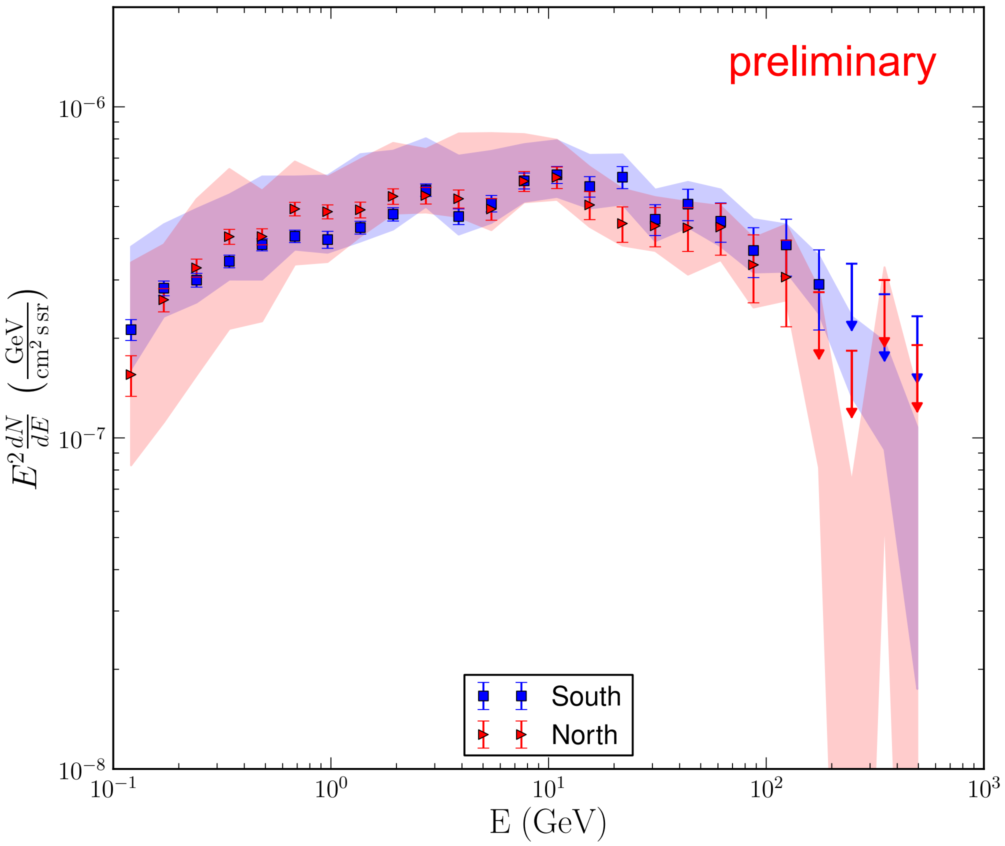


Spectrum – two methods



Spectral Variations

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



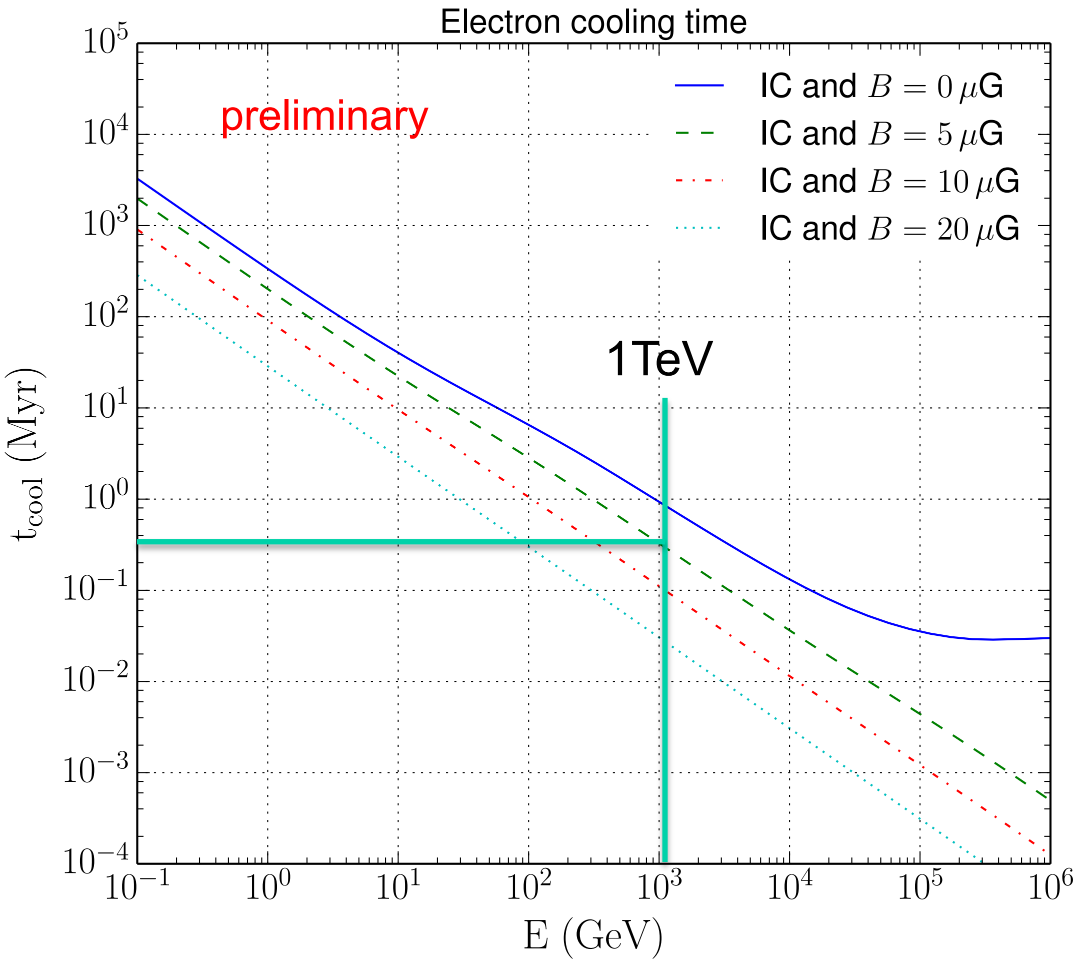
A. Franckowiak

Leptonic Model – Electron Cooling Time

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

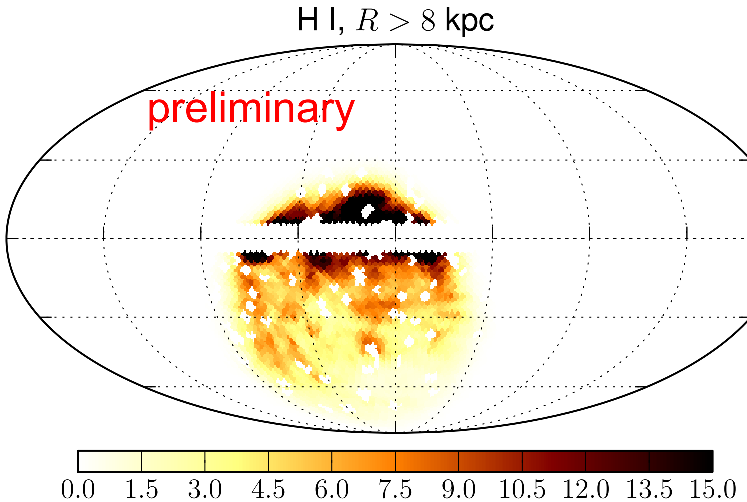
$t_{cool} < t_{formation} \rightarrow$ Expansion speed of the bubbles of ~20,000km/s

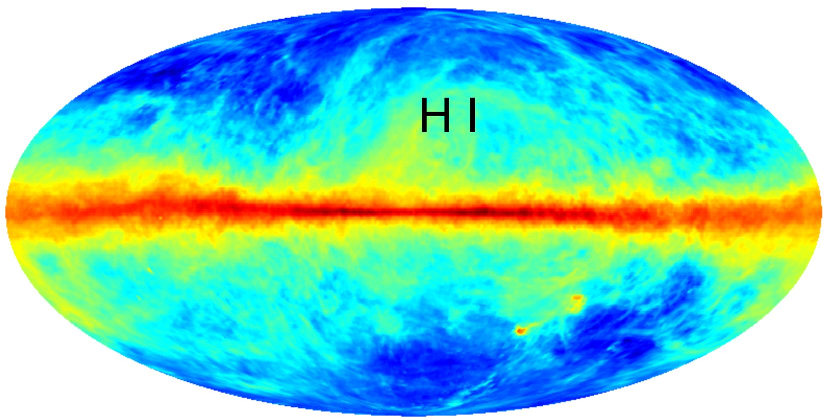
Reacceleration? E.g. plasma wave turbulences (Mertsch & Sakar, 2011)



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

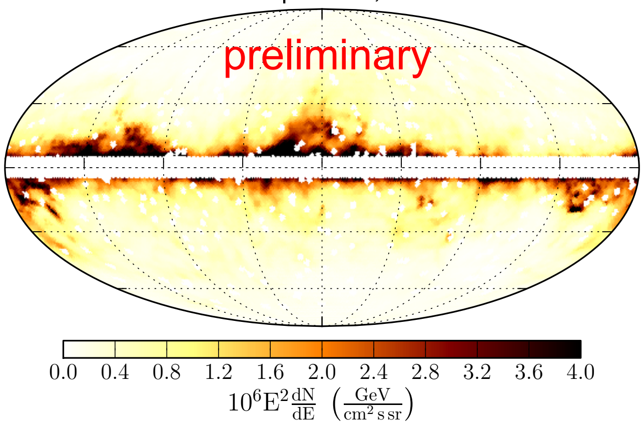




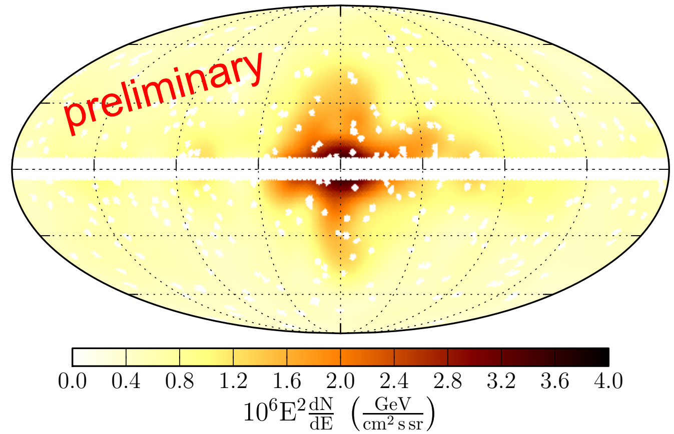
Alternative Galactic Modeling: Local template Analysis

- 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

Gas-correlated components, E = 6.4 - 9.1 GeV

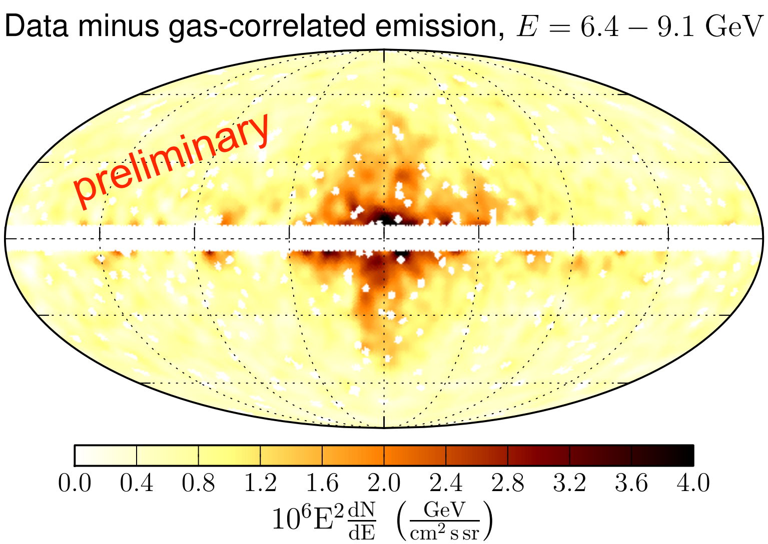


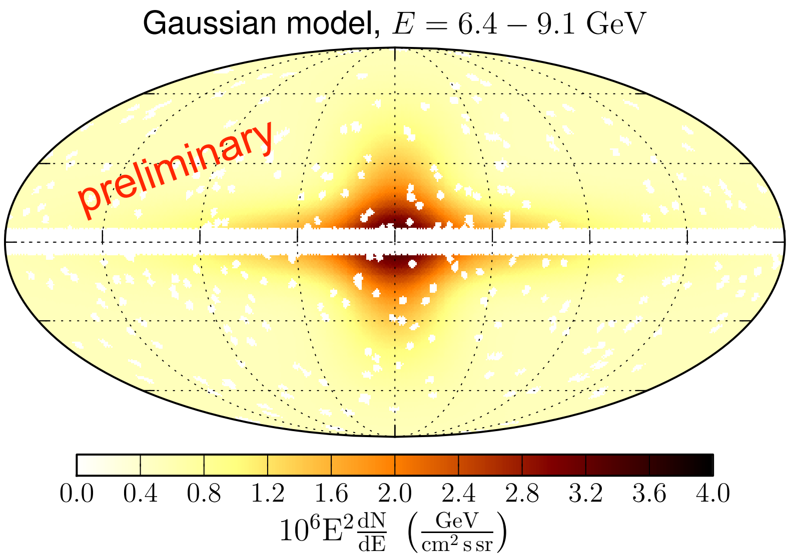
Local polynomial components, E = 6.4 - 9.1 GeV



Alternative Galactic Modeling: Local template Analysis

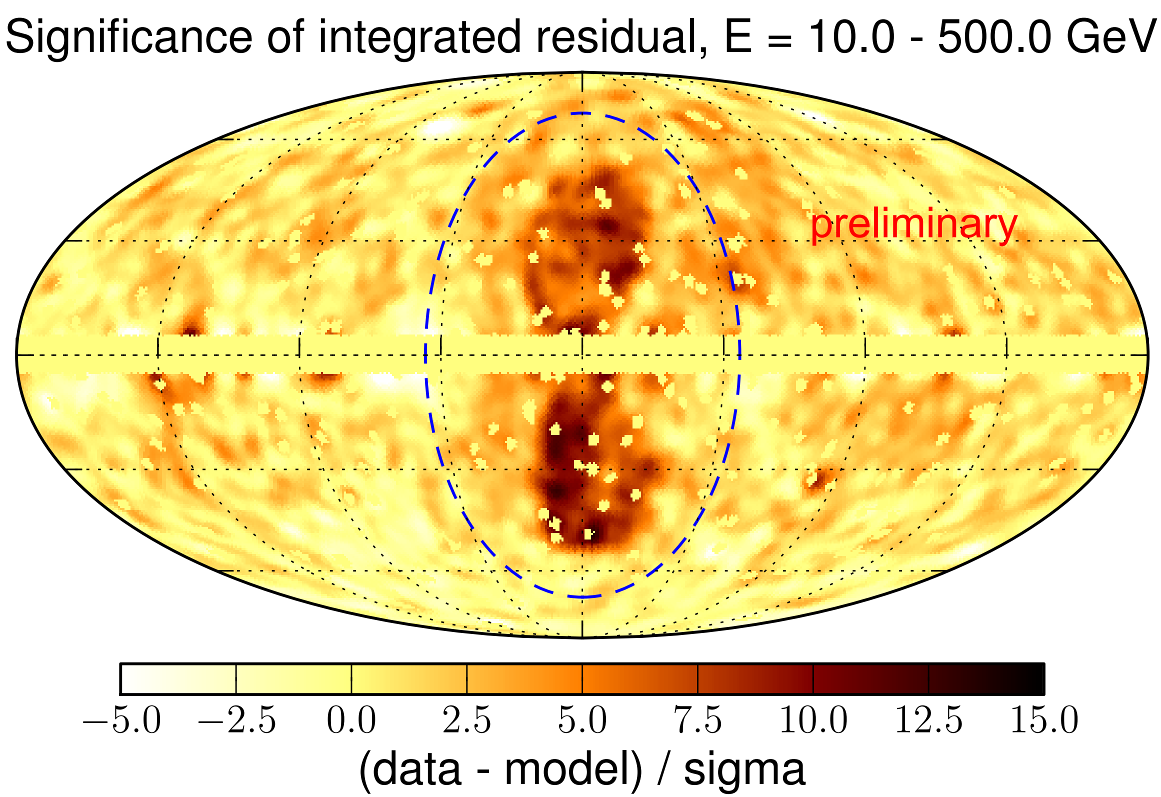
- **After subtraction of the gas component, the IC is modeled with a bivariate Gaussian along the Galactic plane**
- **Other components (Loop I and bubbles) are estimated with Gaussian perpendicular to the plane**





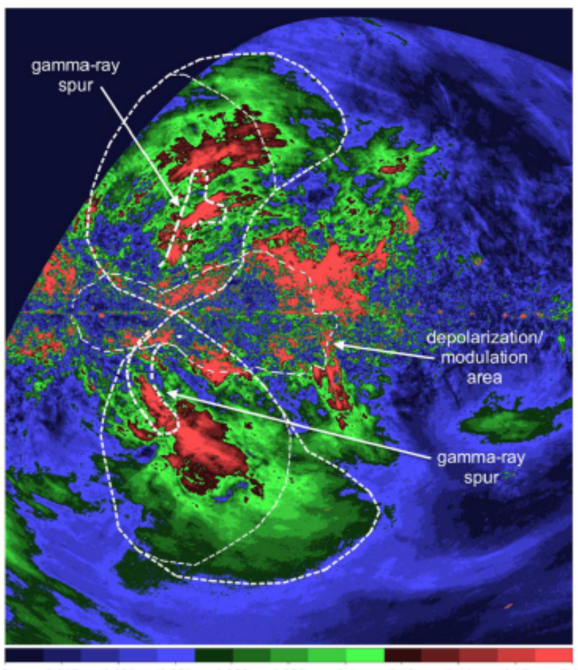
Alternative Galactic Modeling: Local template Analysis

- **Definition of Fermi bubbles template from the residuals using significance threshold (similar to previous method)**

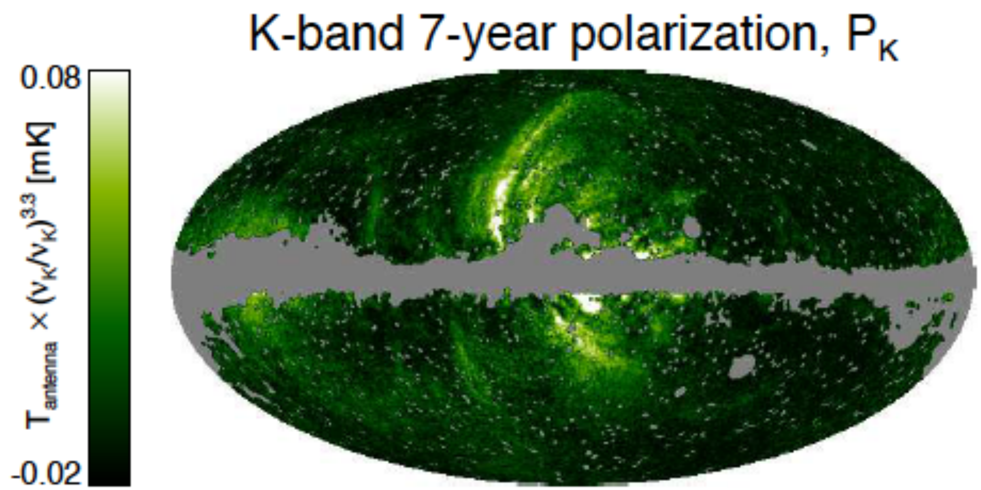


Polarization

- **WMAP data: no evidence for polarization, possibly hidden by noise (small turbulent component in the magnetic field can reduce the polarization amplitude when projecting along the line of sight)**
- **S-PASS data: discovered a high degree of polarized lobe emission at 2.3 GHz: ordered magnetic field lines inside bubbles**



S-PASS, Carretti 2013



WMAP, Dobler 2012

Systematic Uncertainties

Added in quadrature

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

envelope

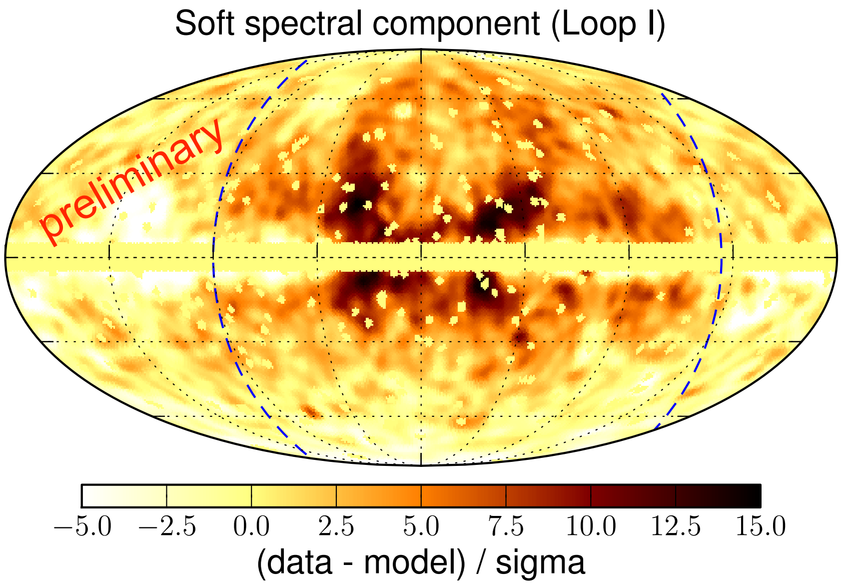
- **Galactic modeling:**
  - The choice of the input GALPROP configuration might influence the extracted bubble features
    - Cosmic-ray source distribution:
      - Pulsars, SNR
    - Size of cosmic-ray confinement volume (halo size)
      - Cylindrical geometry with R = 20, 30 kpc and z = 4,10 kpc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

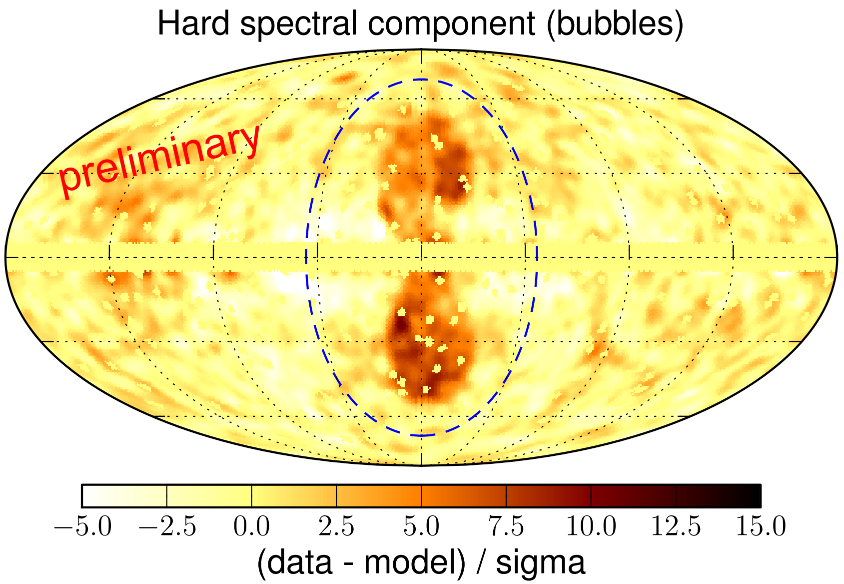
Alternative Galactic Modeling: Local template Analysis

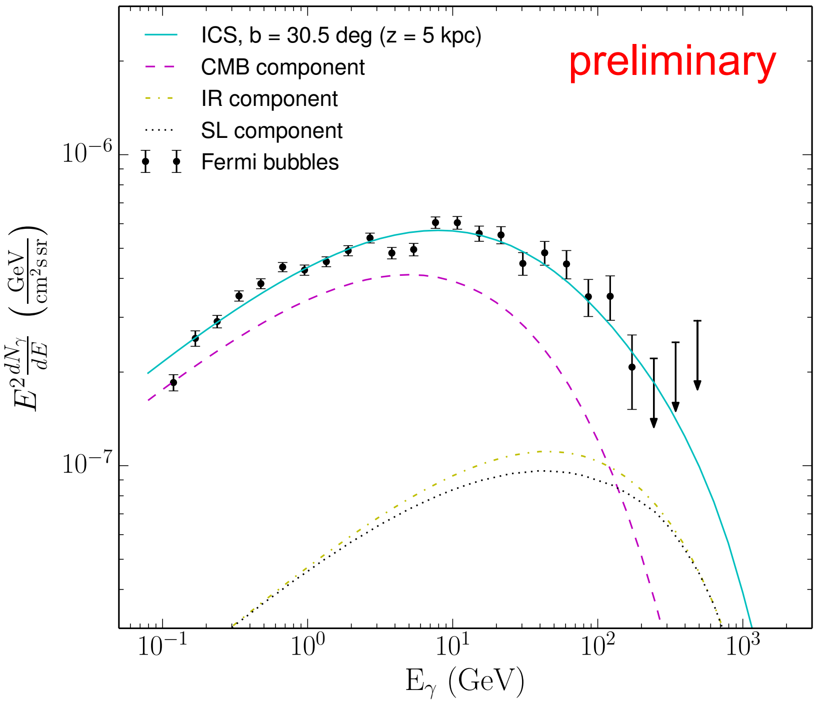
- **Loop I and the bubbles are disentangled from the residuals in a spectral component analysis, assuming a softer spectrum**

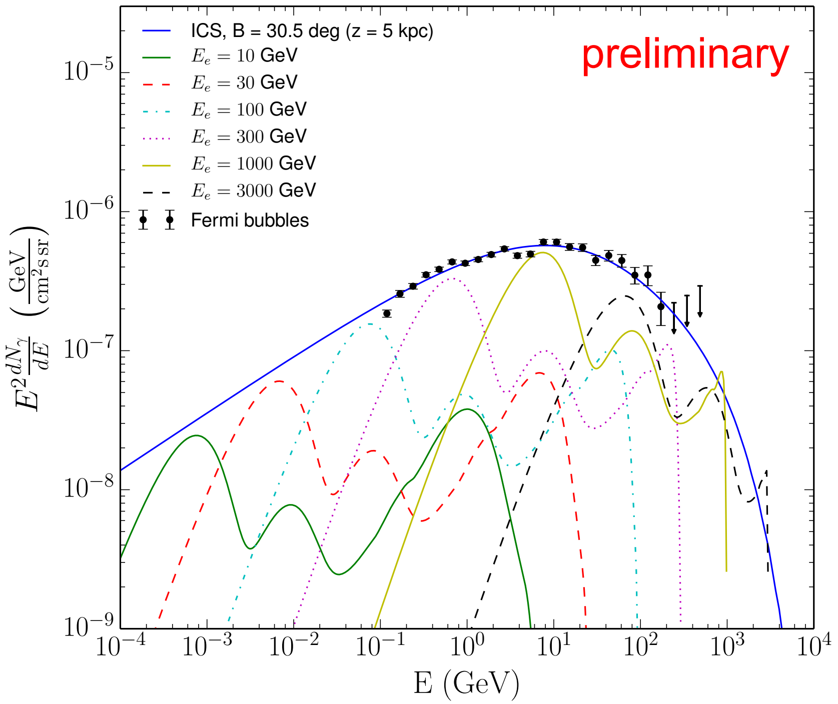
$F_{soft} \sim E^{-2.4}$

$F_{hard} \sim E^{-1.9}$



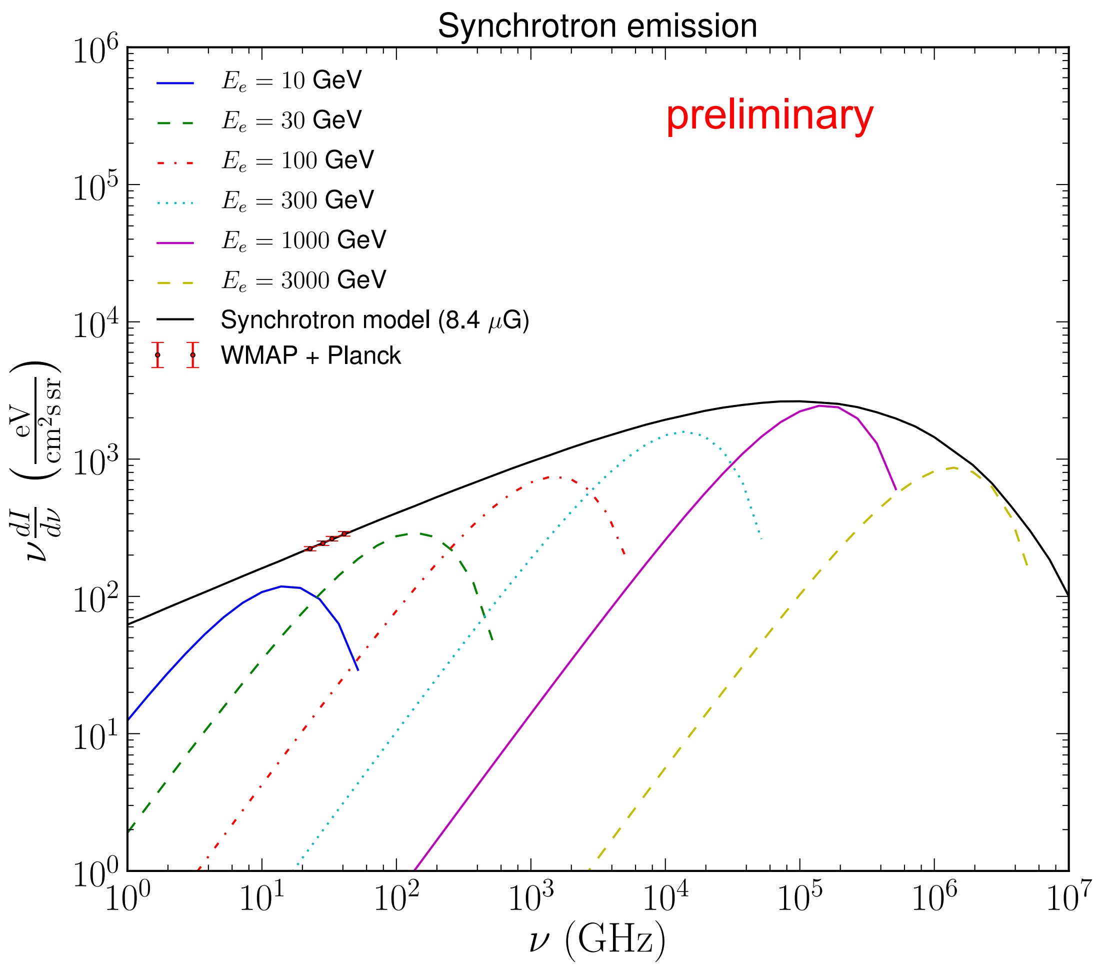




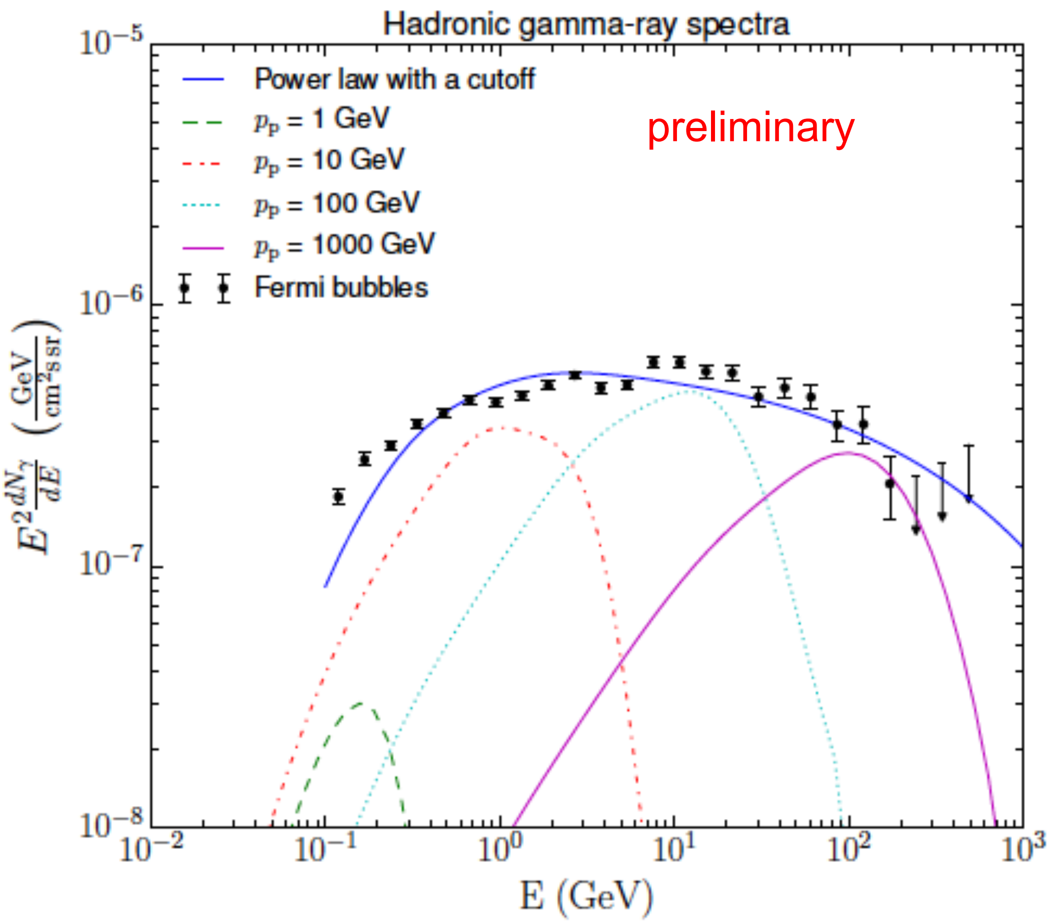


Energy in electrons $(1.0 \pm 0.2[\mathrm{stat}]^{+6.0}_{-1.0}[\mathrm{syst}]) \times 10^{52}$ erg

Synchrotron emission

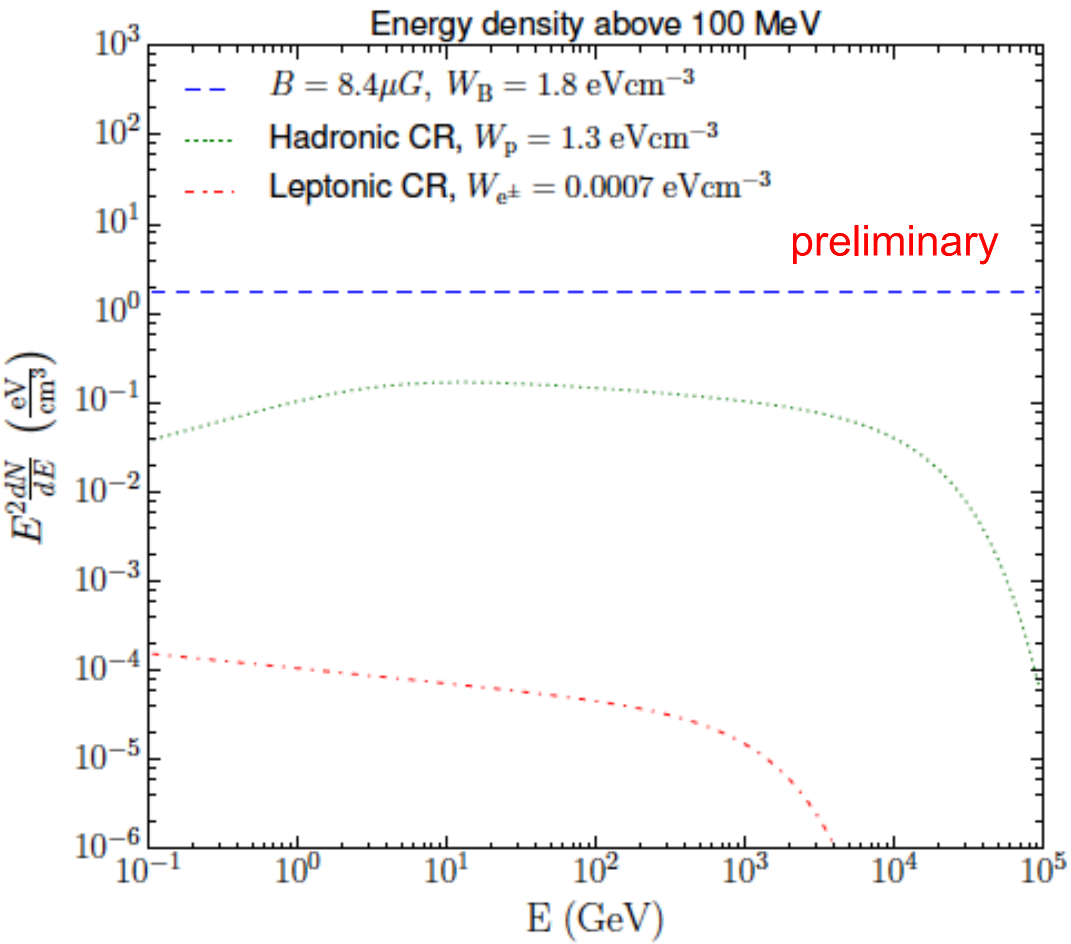


Hadronic gamma-ray spectrum

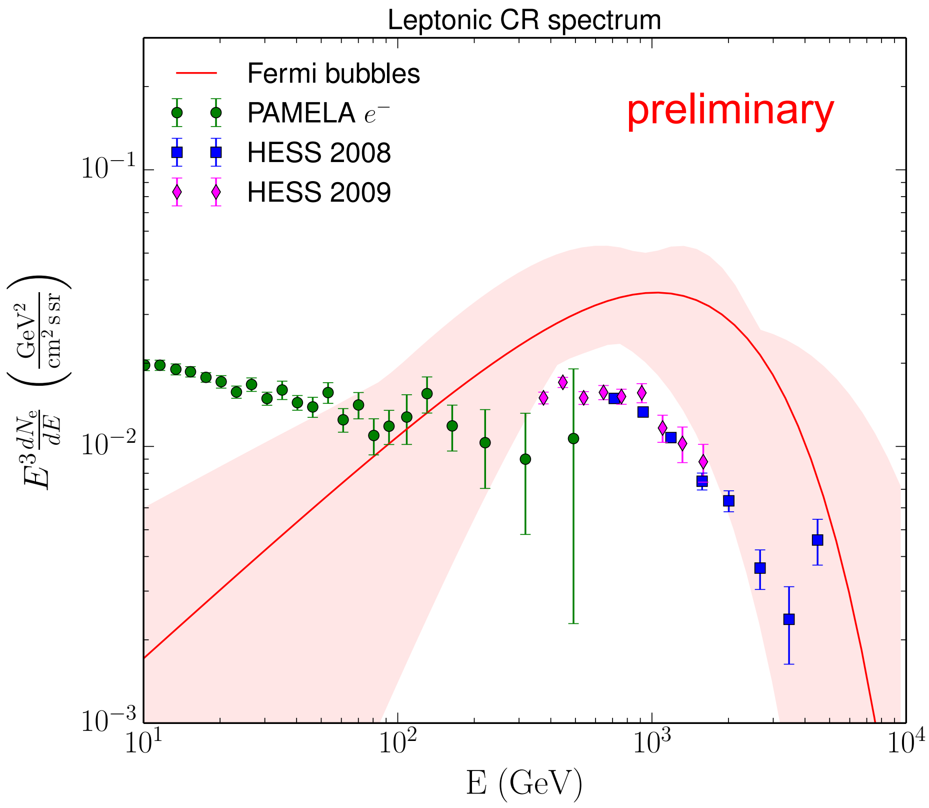


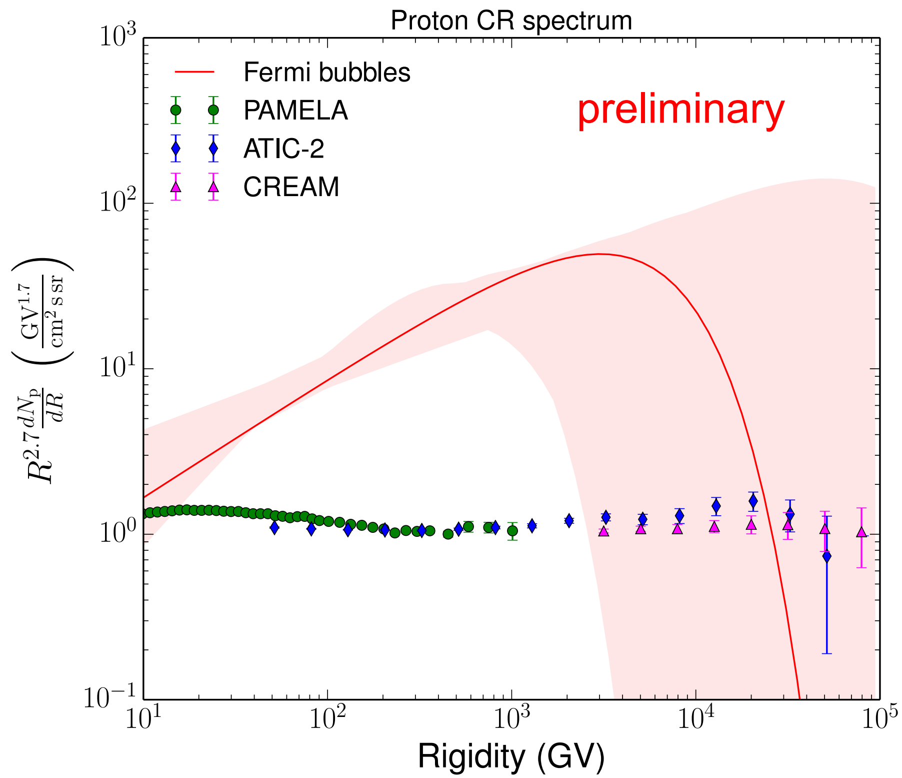
Energy in protons $(3.5 \pm 0.1[\text{stat}]^{+4.7}_{-3.0}[\text{syst}]) \times 10^{55} \left(\frac{0.01\ \text{cm}^{-3}}{n_\text{H}}\right)$ erg

Energy density



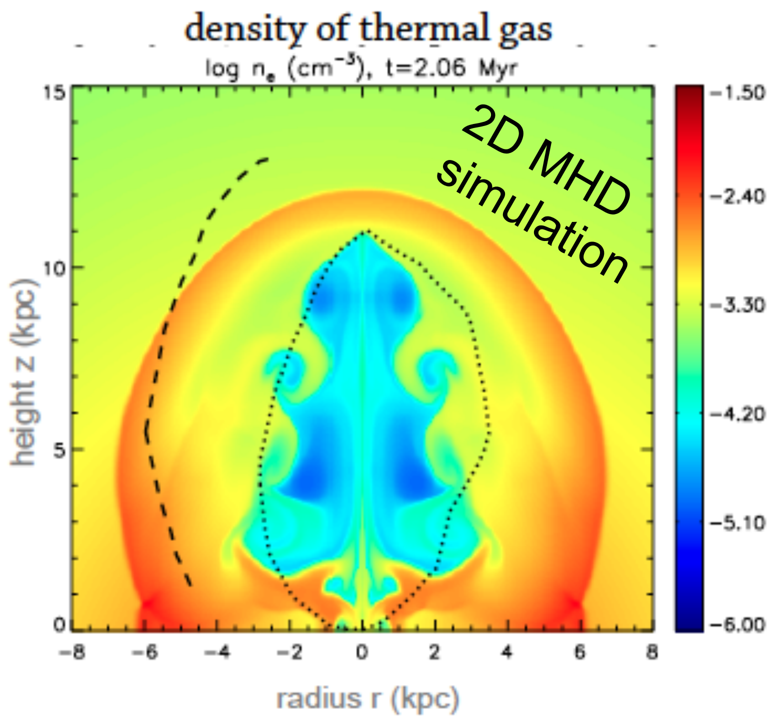
Comparison to local spectra





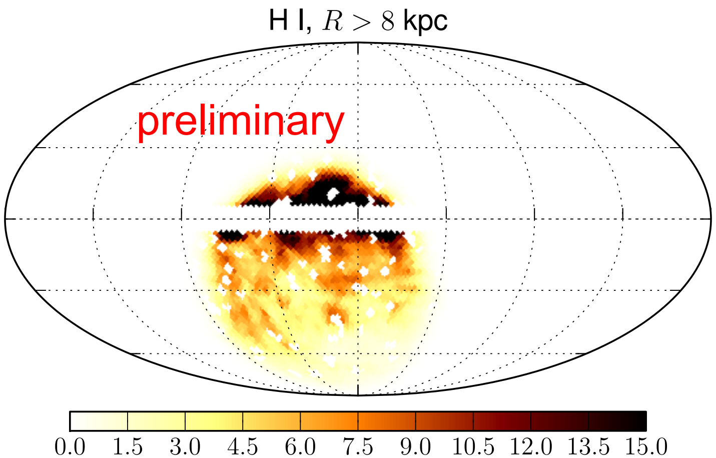
Origin of the Shock

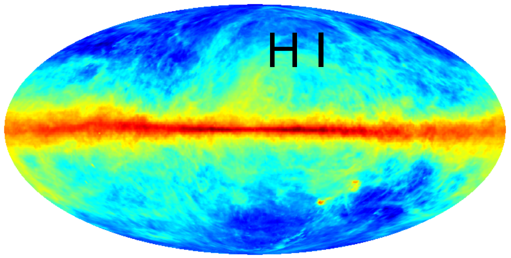
- Guo & Mathews, arXiv:1103.0055
- Jet from Galactic center
  - overpressured but underdense
  - 10 % Eddington luminosity
  - active for 1-2 Myr
  - terminated a Myr ago
- Results are limb darkening
  - Solution: shear viscosity to concentrated CR near edges
- Edges are not sharp
  - Solution: magnetic draping (field lines are draped around jet/ bubble, tangential fields at edges → suppressing CR diffusion across edges causing shard edges)

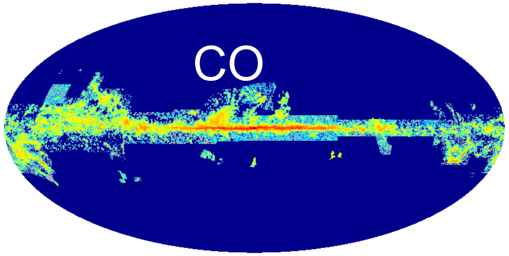


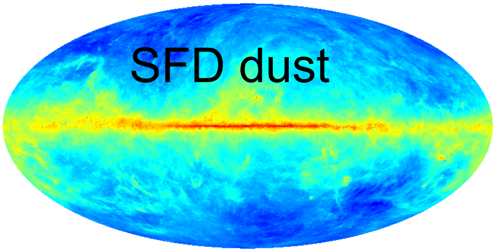
Alternative Galactic Modeling: Local template Analysis

- 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



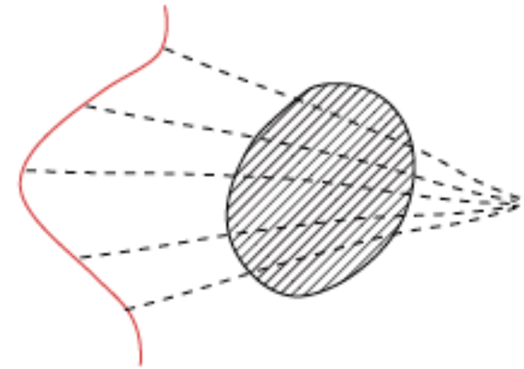




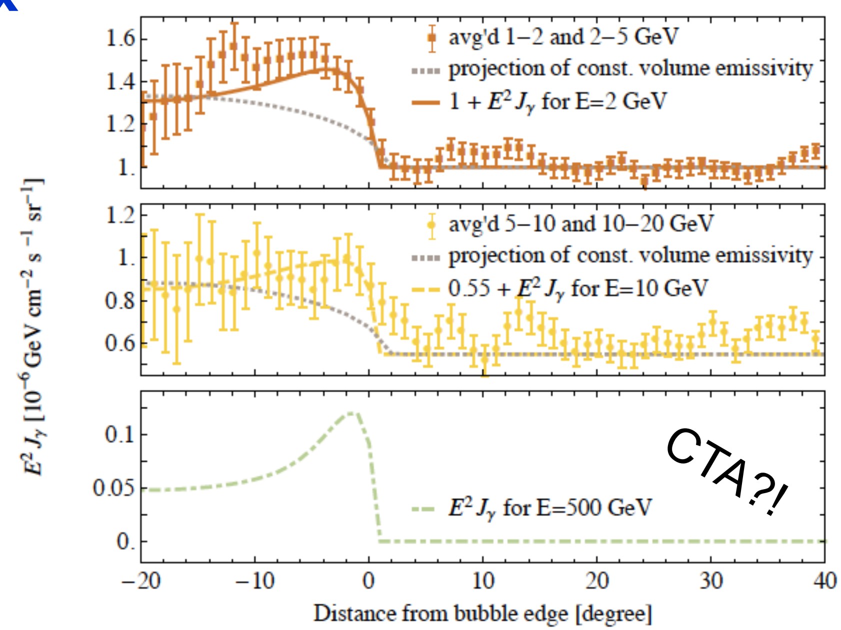


Reacceleration

- Constant volume emissivity → bump-profile in projection
- Evidence for shock only at bubble edges (from ROSAT data)
  - turbulence produced at shock and convected downstream → non trivial spatial variation of electron index



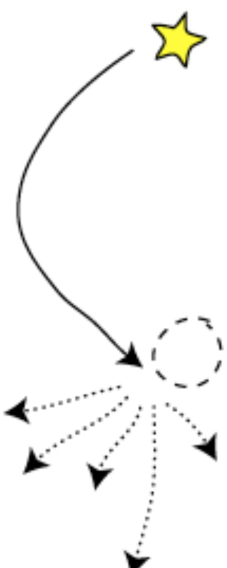
- 2nd order Fermi acceleration by large-scale turbulence → almost constant surface brightness in gamma-rays and sharp edges



(Mertsch &Sarkar, PRL 107 (2011) 091101)

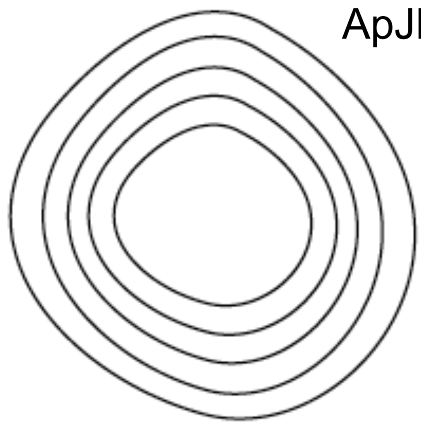
Leptonic Model (multiple shocks)

- Electrons accelerated to E^{-2} spectrum by diffusive shock acceleration
- Gamma rays by inverse Compton scattering on radiation fields
- Microwave haze by synchrotron of same population of electrons

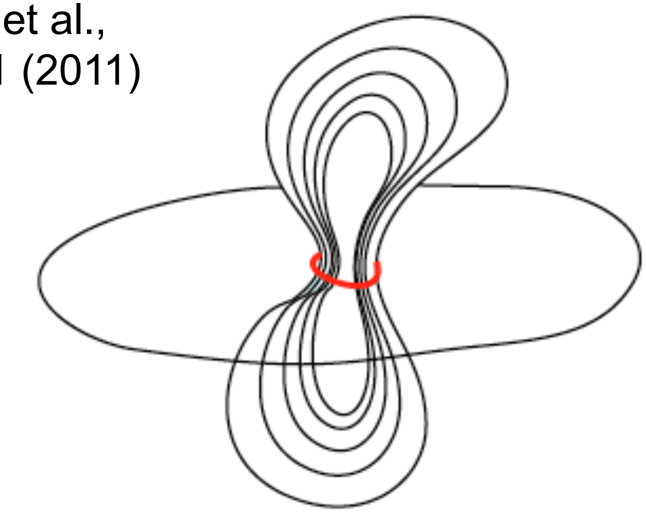


disruption of stars
by central black hole

Cheng et al.,
ApJL 731 (2011)



hundreds of concentric
shock fronts

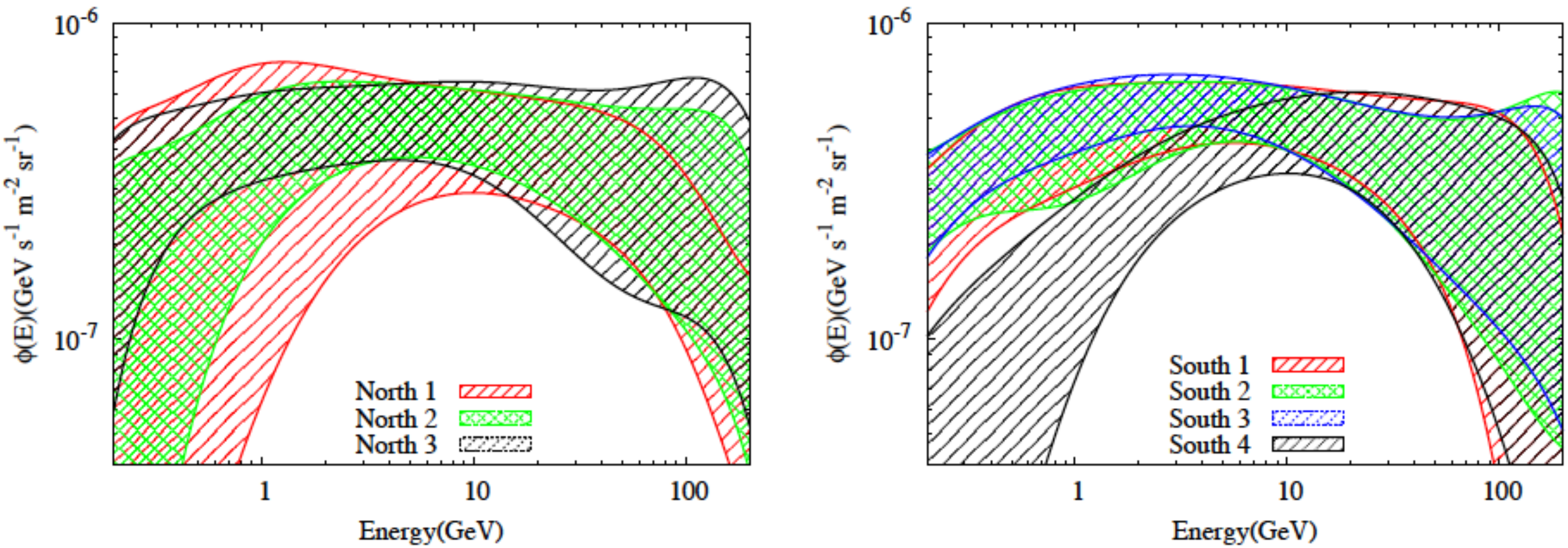


shocks constricted
in galactic disk →
bubble shape

Illustrations by
P. Mertsch

Spectral Variations – Previous Results

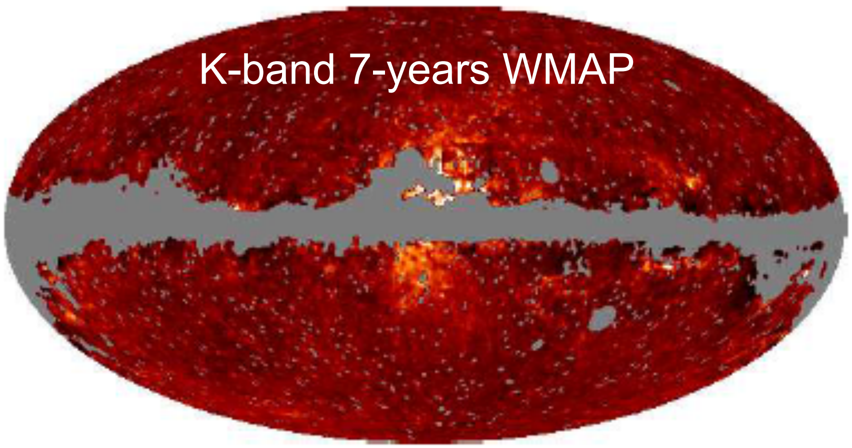
- **Pervious claims, Yang et al., arXiv:1402.0403, hardening towards top of South bubble**
- **Explanation: high energy faster diffuse faster and reach high latitudes above the assumed injection source in the plane first**

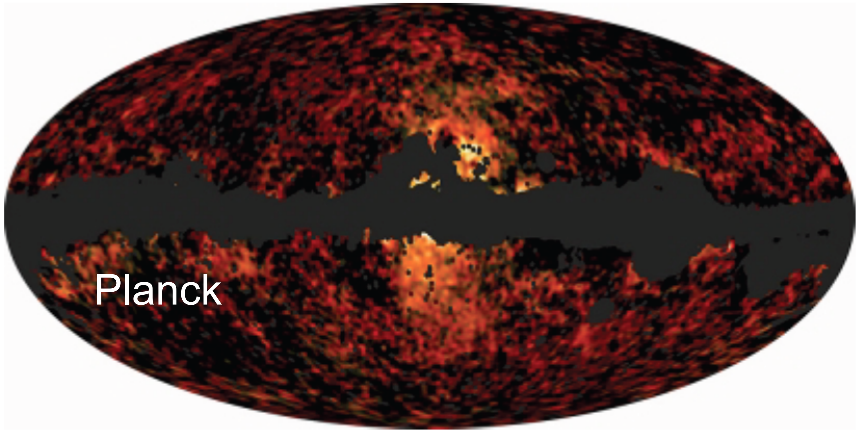


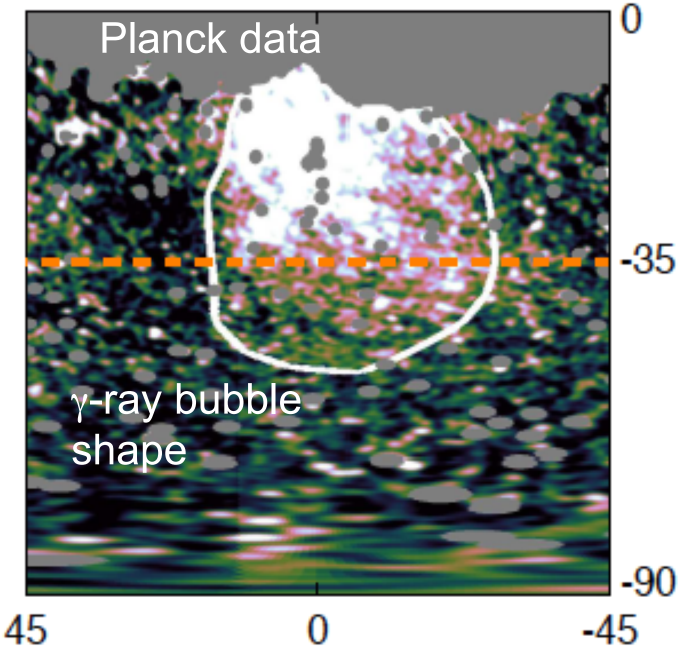
Difference to this work: Yang et al. allow less freedom in diffuse models

Microwave Haze

First detection **in WMAP** data: Finkbeiner, 2004, Astrophys. J., 614, 186
Planck: Ade et al., 2012, A&A, 554, A139

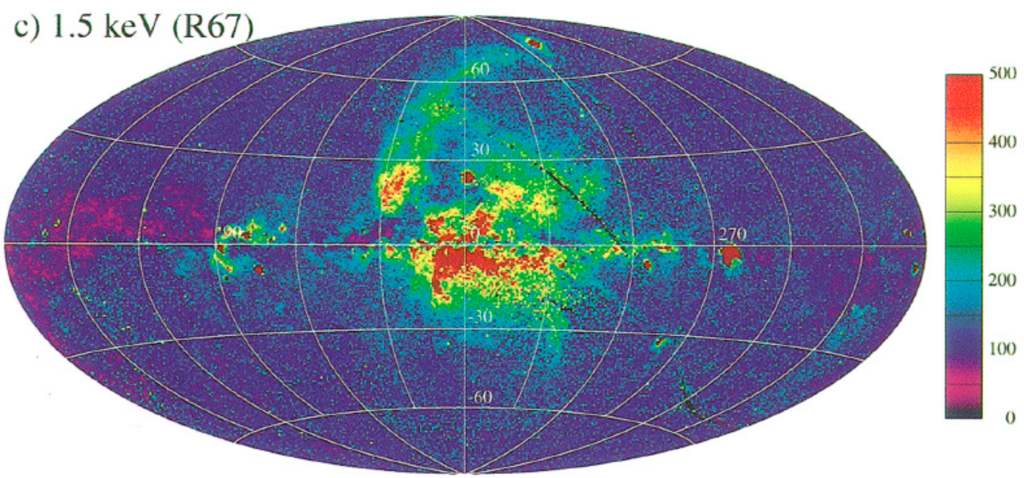


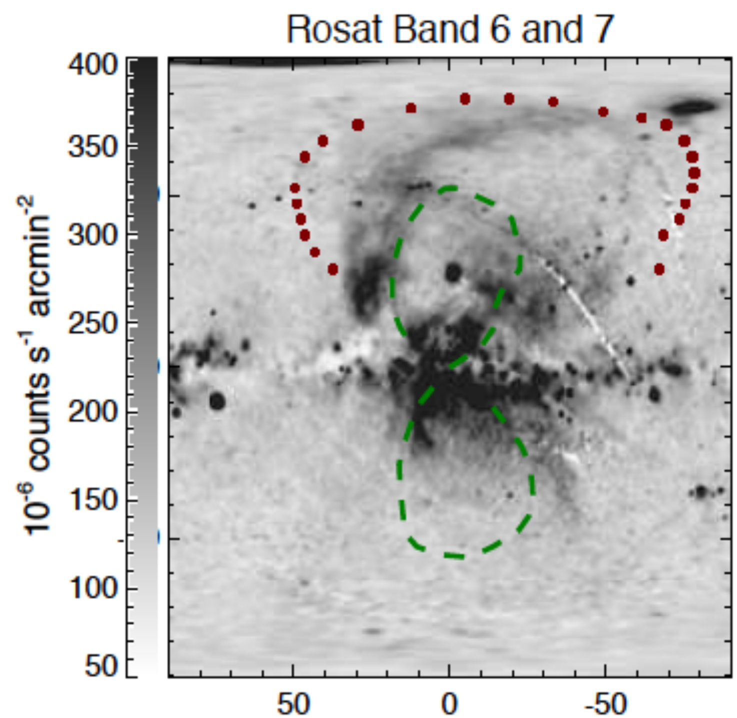




ROSAT

- Snowden, S. L., et al. 1997, ApJ, 485, 125
- Low-latitude bubble edges might line up with features in the ROSAT X-ray maps at 1.5 keV

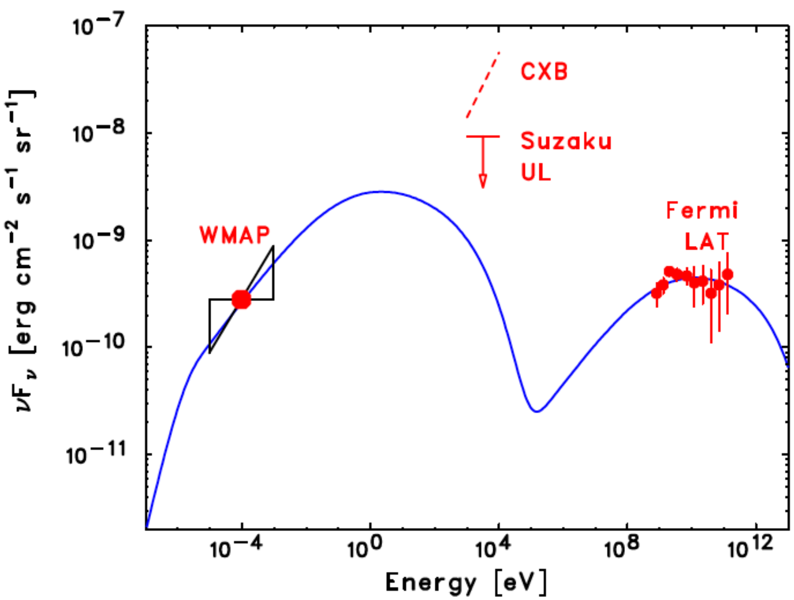


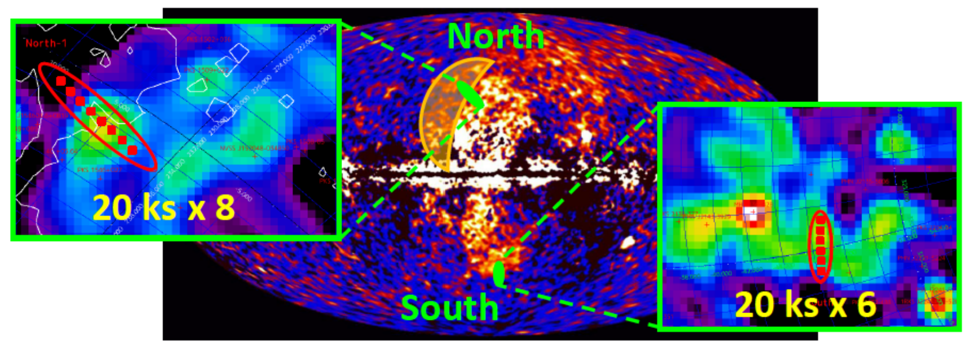


Su, Slatyer, Finkbeiner, ApJ 724 (2010)

Suzaku

- North/South edges bubble in X-ray with 280 ks Suzaku exposure
- No excess in non-thermal X-ray emission found associated with the Fermi bubble





Indications for weak shock driven by the bubbles' expansion at ~300km/s, compressing the surrounding halo gas to form Loop I

Expected non-thermal emission is still about factor of 5-10 lower than present UL.

Kataoka et al., 2013ApJ...779

MODELS AND INTERPRETATION