



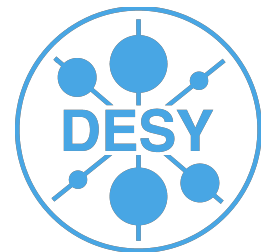
Fermi

Gamma-ray Space Telescope



The Fermi Bubbles

**Anna Franckowiak (DESY Zeuthen),
Dmitry Malyshev (Erlangen),
Vahé Petrosian (Stanford)
for the Fermi-LAT Collaboration**

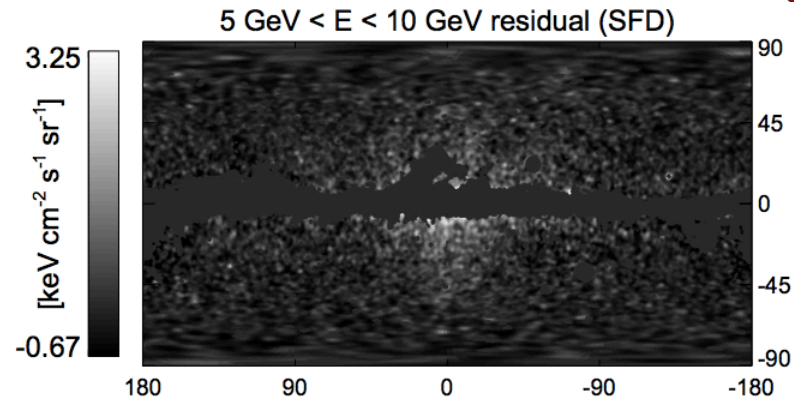


First Discovery



- Dobler et al.: **Fermi Haze**
- 1 year of Fermi-LAT data

Dobler et al. ApJ, 717 (2010)

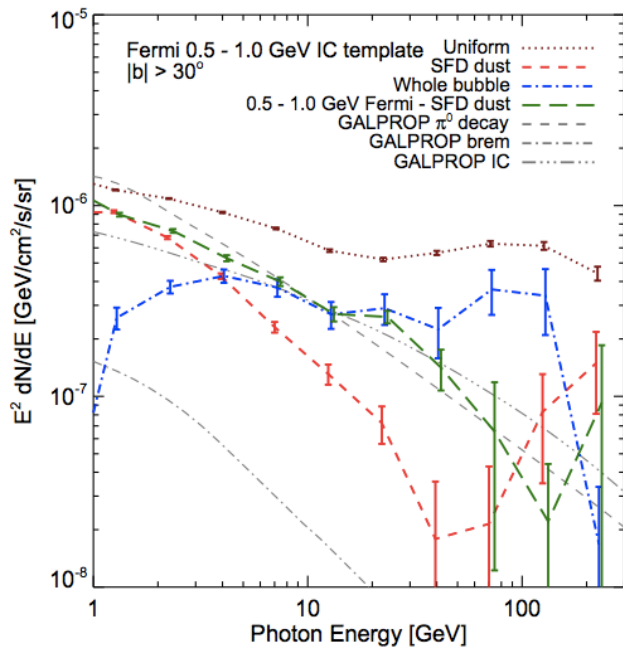
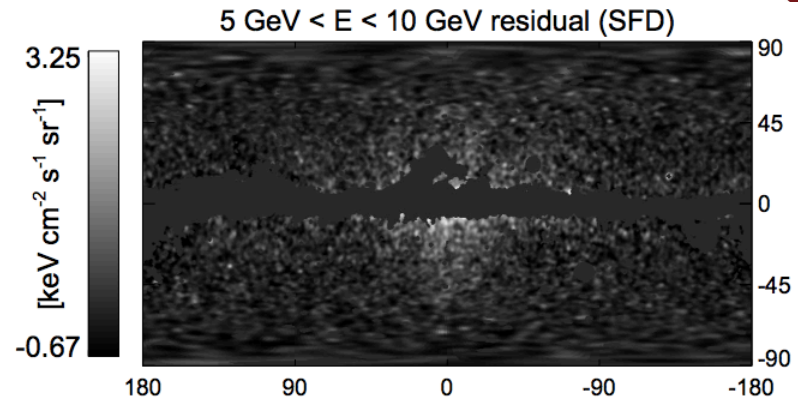


First Discovery

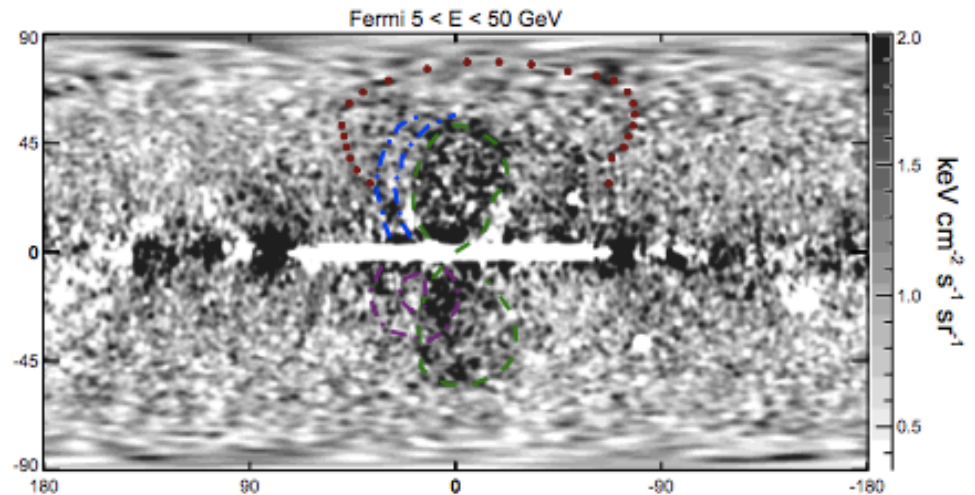


- Dobler et al.: **Fermi Haze**
- 1 year of Fermi-LAT data

Dobler et al. ApJ, 717 (2010)



- Su, Slatyer, Finkbeiner: **Fermi Bubbles**
- 1.66 years of Fermi-LAT data

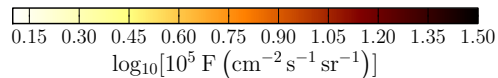
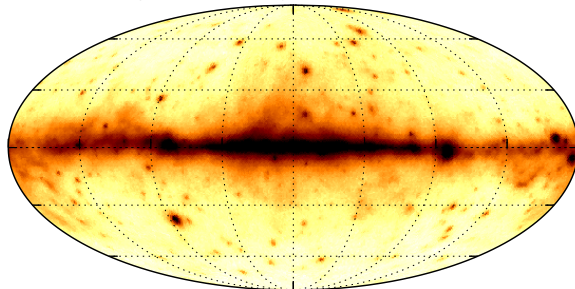


Su et al. ApJ, 724 (2010)

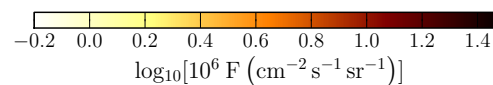
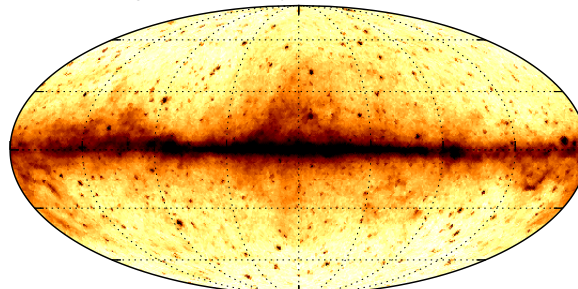


- **50 months of data**
- **Pass 7 reprocessed data set**
- **Ultraclean class**

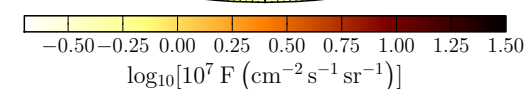
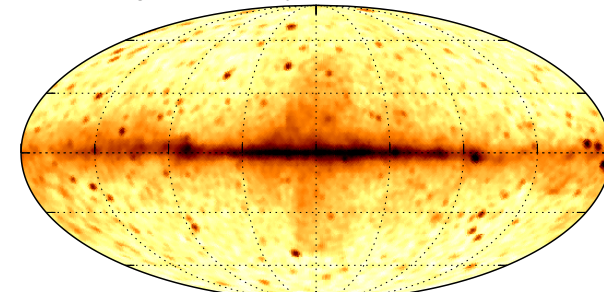
Integrated intensity, $E = 0.1 - 1.0$ GeV



Integrated intensity, $E = 1.0 - 10.0$ GeV



Integrated intensity, $E = 10.0 - 500.0$ GeV

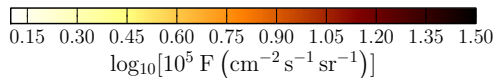
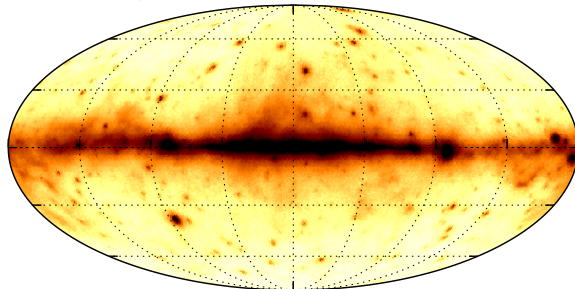


Ackermann et al. (the Fermi-LAT
Collaboration, ApJ, 793 (2014)

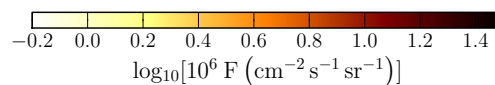
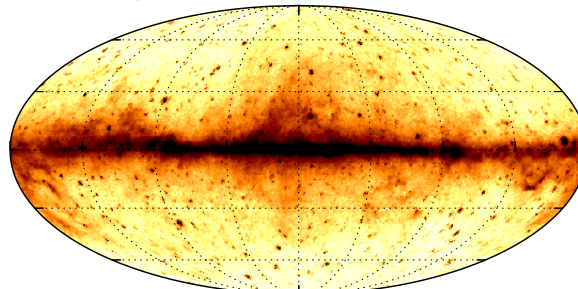


- 50 months of data
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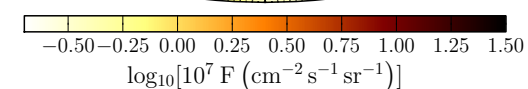
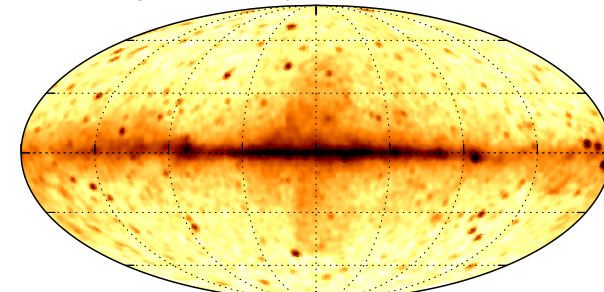
Integrated intensity, $E = 0.1 - 1.0$ GeV



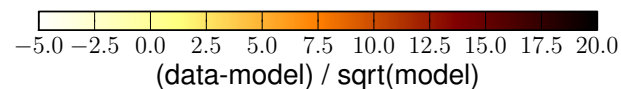
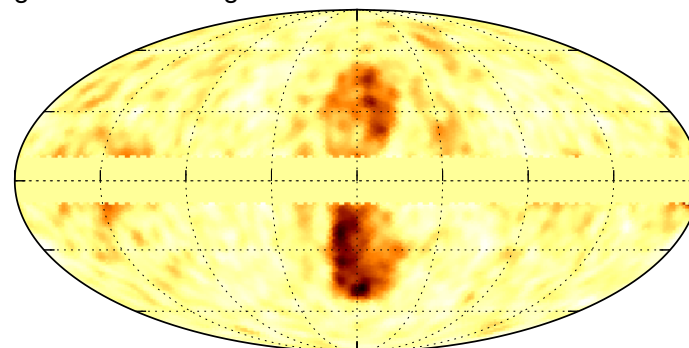
Integrated intensity, $E = 1.0 - 10.0$ GeV



Integrated intensity, $E = 10.0 - 500.0$ GeV



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

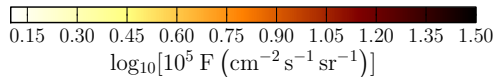
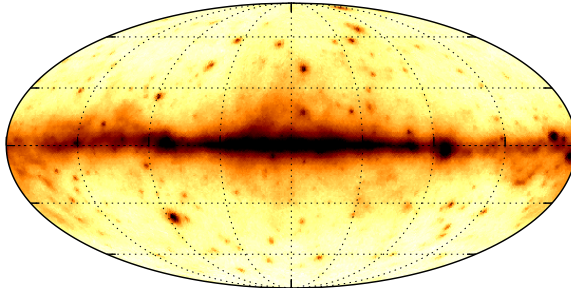


Ackermann et al. (the Fermi-LAT
Collaboration, ApJ, 793 (2014))

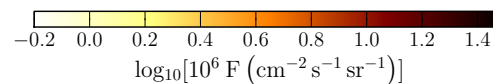
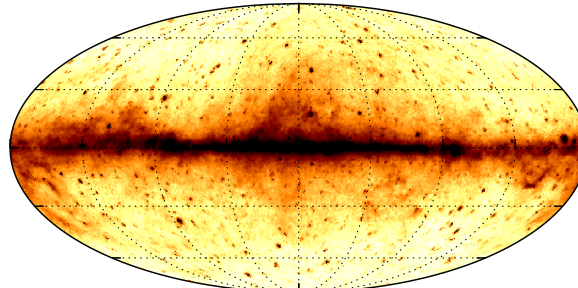


- 50 months of data
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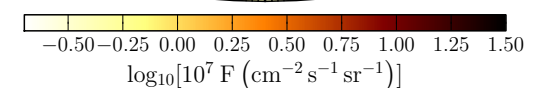
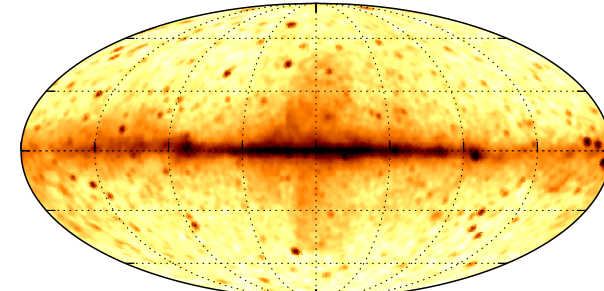
Integrated intensity, $E = 0.1 - 1.0$ GeV



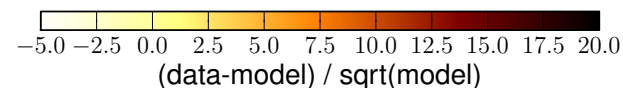
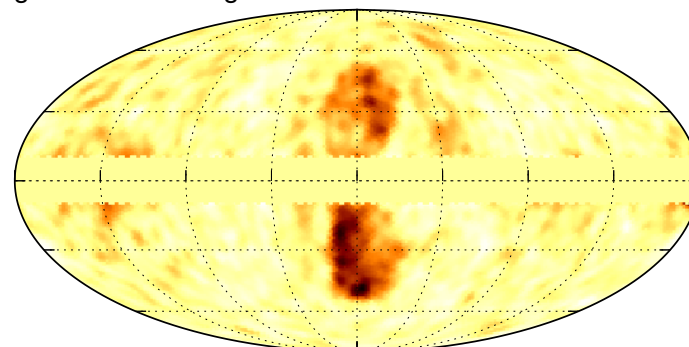
Integrated intensity, $E = 1.0 - 10.0$ GeV



Integrated intensity, $E = 10.0 - 500.0$ GeV

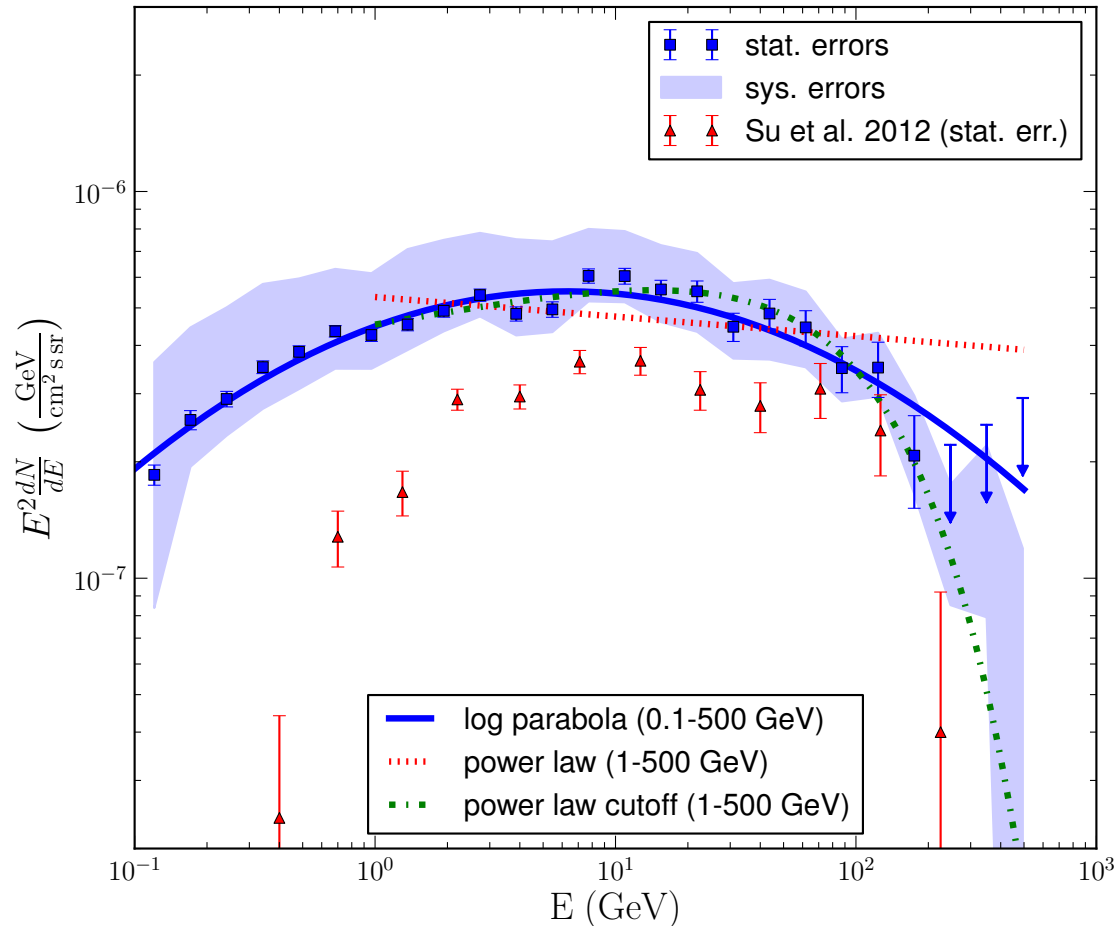


Significance of integrated residuals for $E = 6.4 - 289.6$ GeV



Bubbles template closer to the plane: see talk by Dmitry Malyshev on Monday

Ackermann et al. (the Fermi-LAT Collaboration, ApJ, 793 (2014))



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:

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

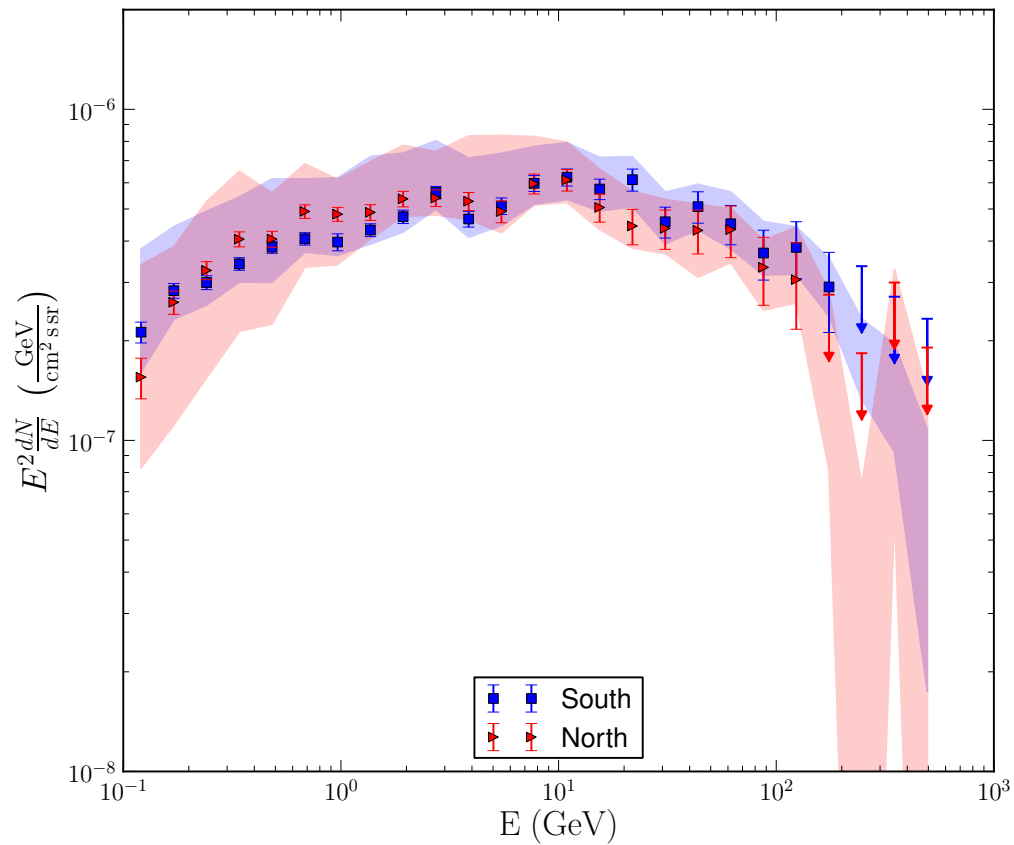
Index:

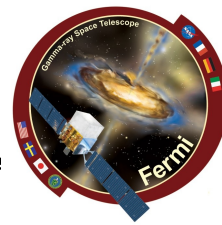
$$\gamma = 1.87 \pm 0.02[\text{stat}]_{-0.17}^{+0.14}[\text{syst}]$$

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

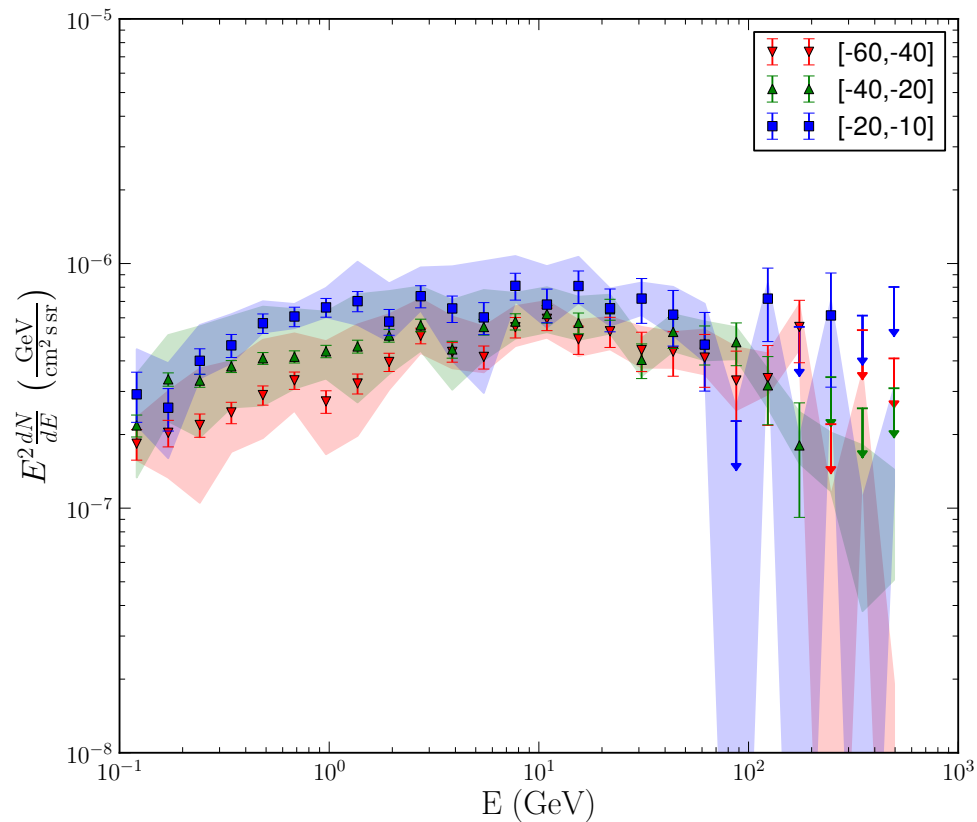


- **North and South Bubble have similar spectrum**



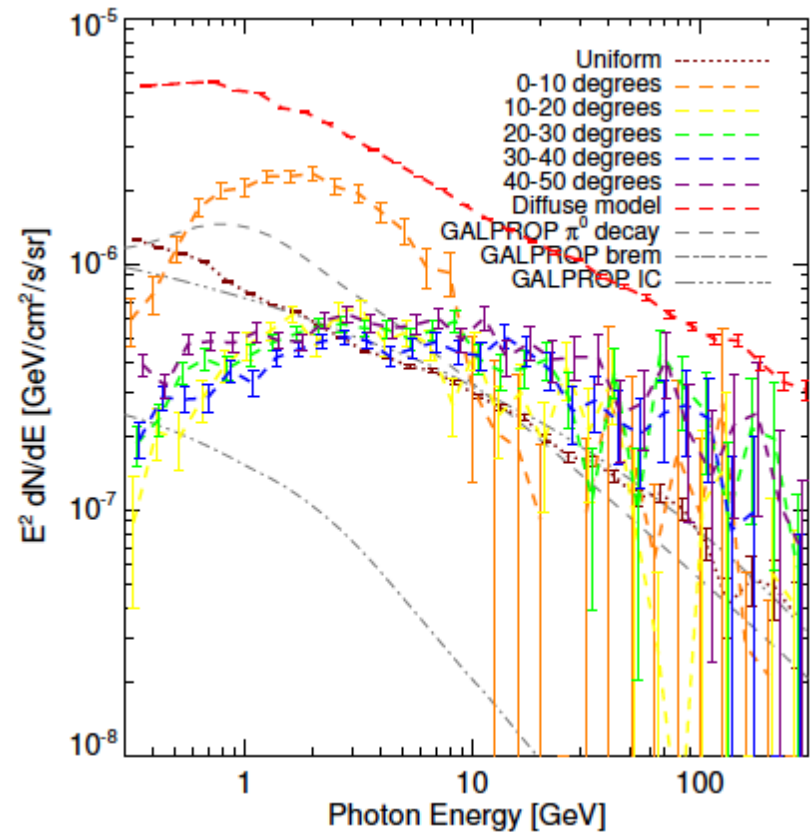
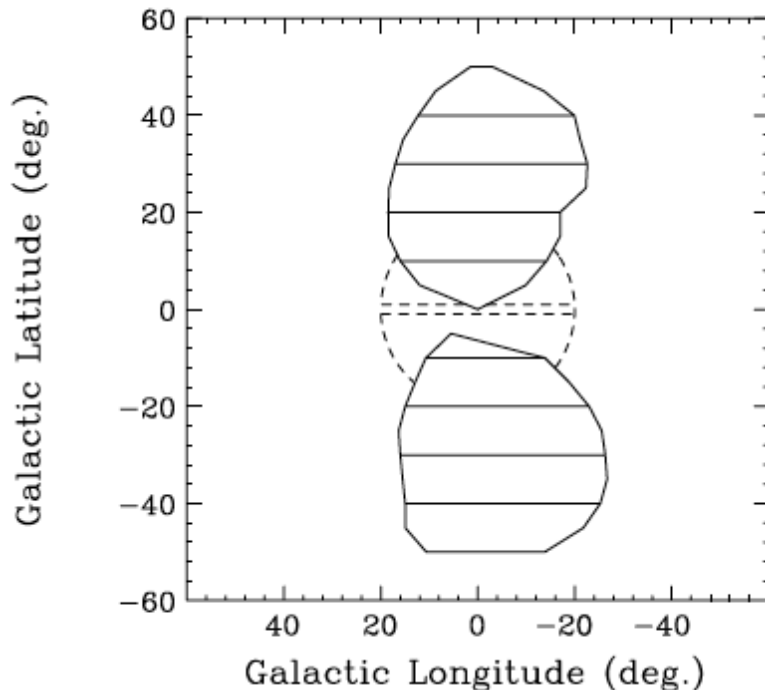


- **Ackermann et al. 2014 : no spectral variation in latitude stripes within systematic uncertainties ($|b| > 10$ deg)**



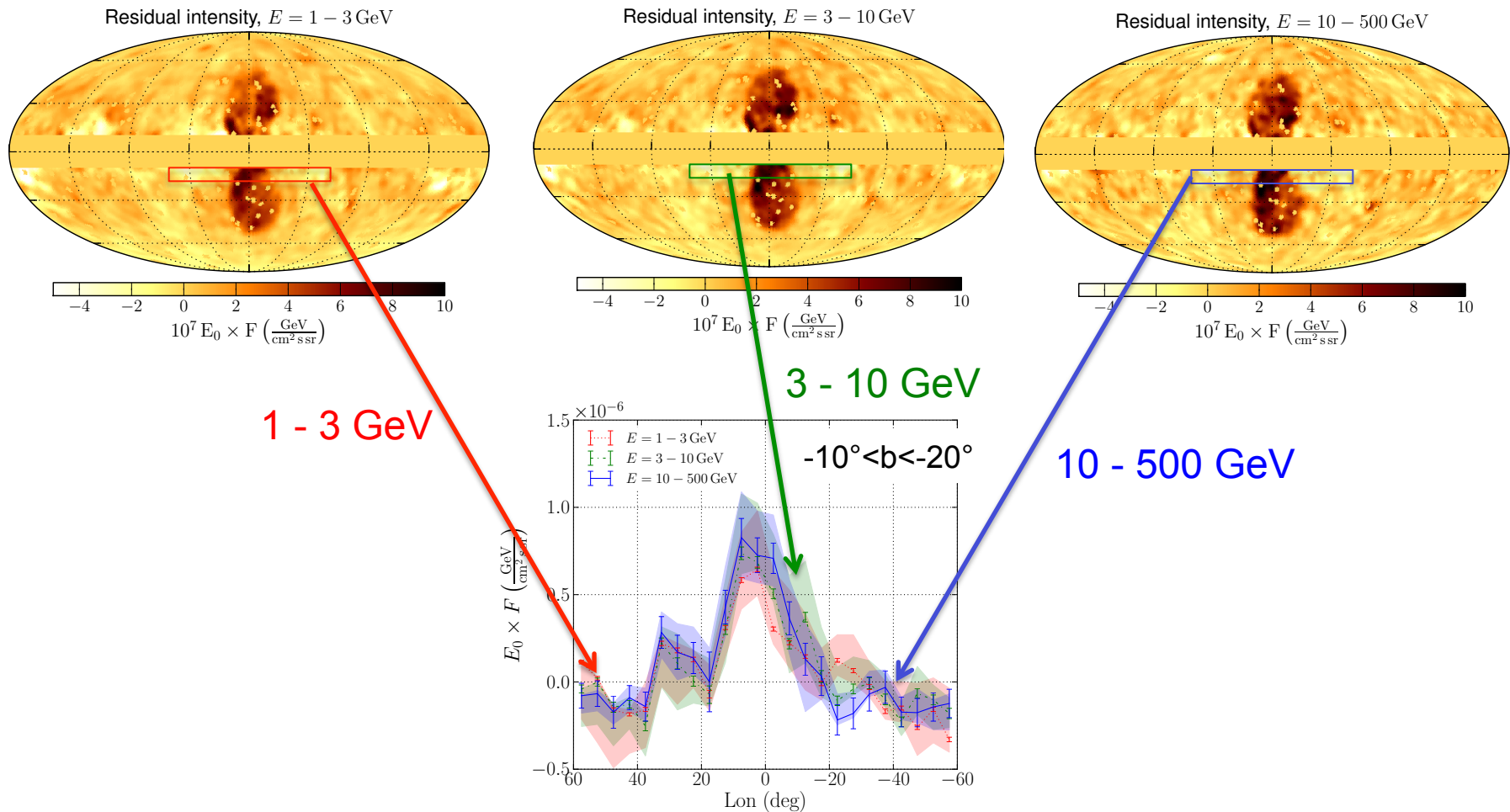


- Hooper and Slatyer, Phys. Dark Univ. 2 (2013): additional component at low energies
- Interpretation: dark matter, millisecond pulsars?



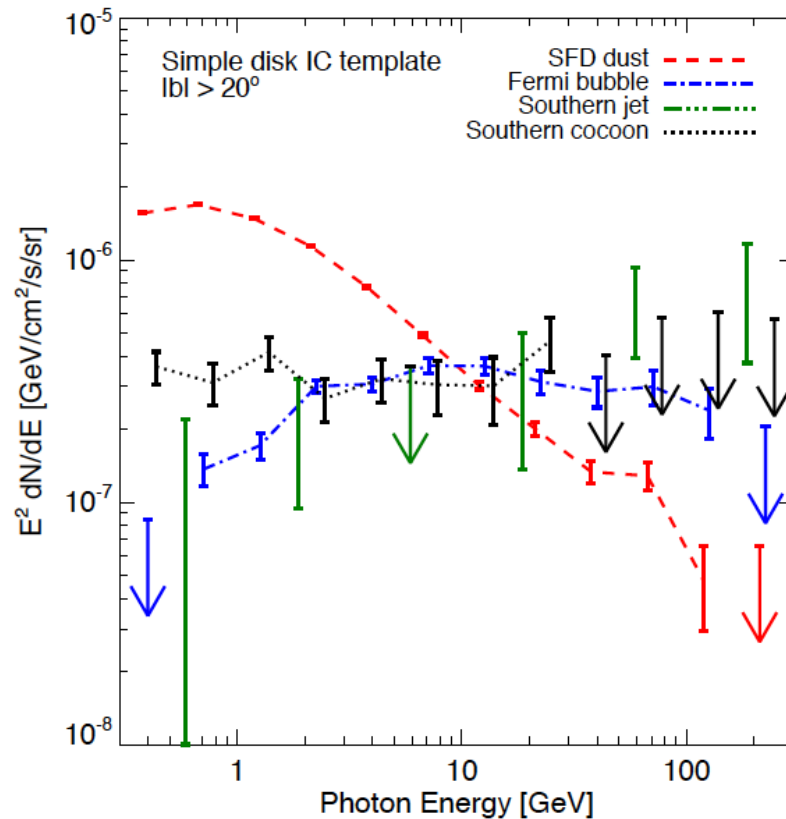
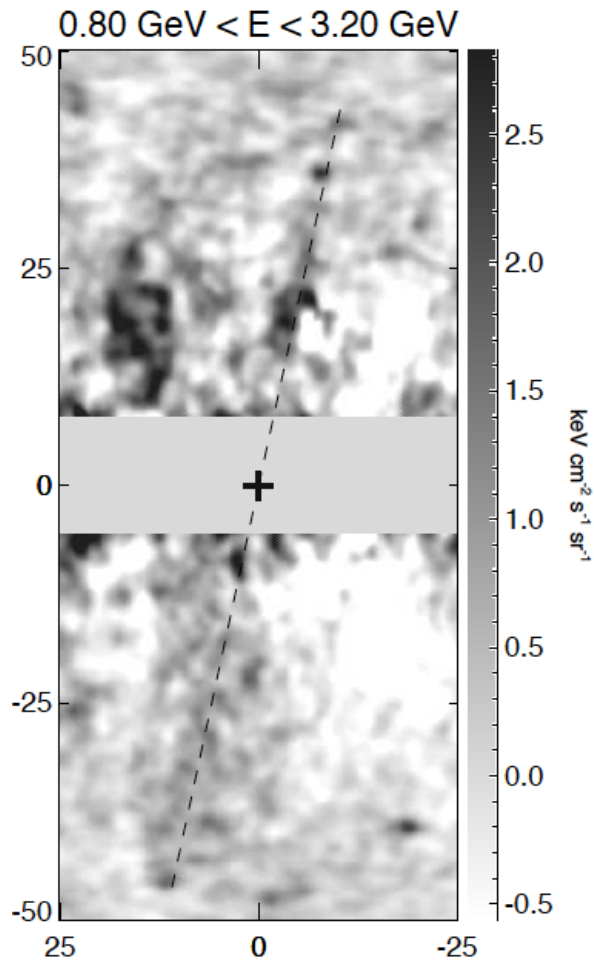


No change in bubble shape with energy found





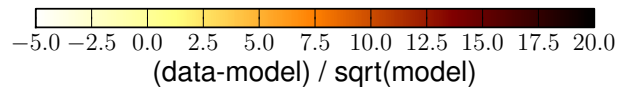
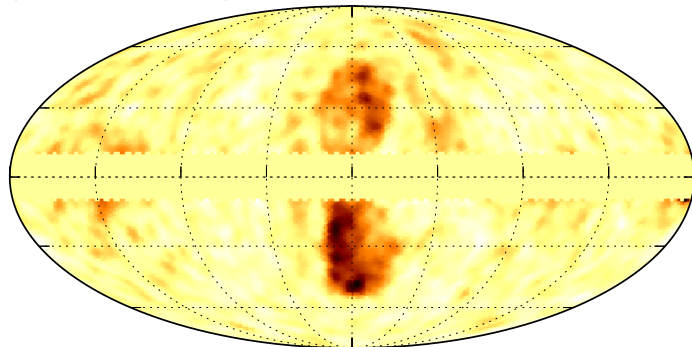
- **Su and Finkbeiner (ApJ 753, 2012): evidence for cocoon and pair of jets with hard spectra**



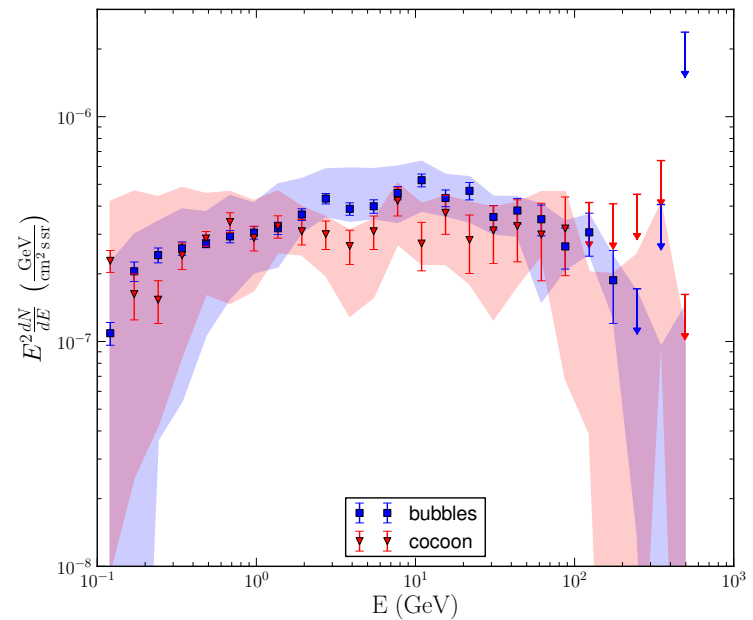
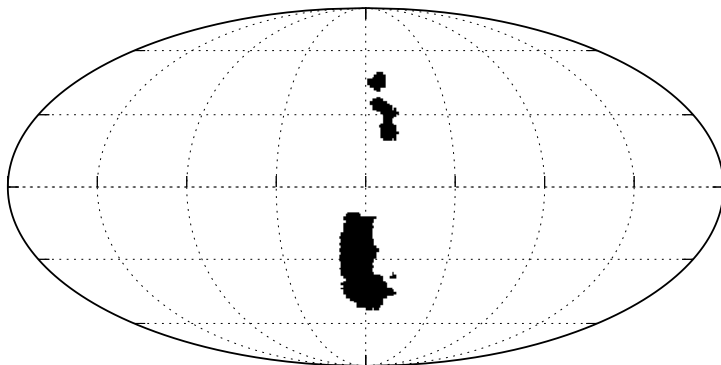


- Excess emission in South East of the bubbles
- Identical spectral shape within systematic errors

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



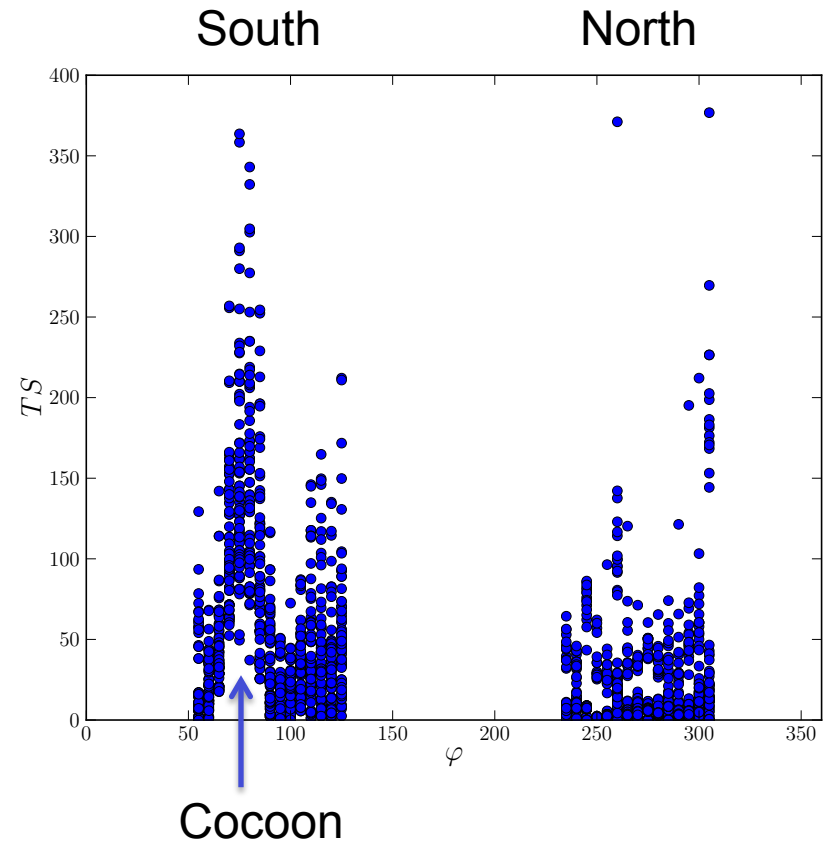
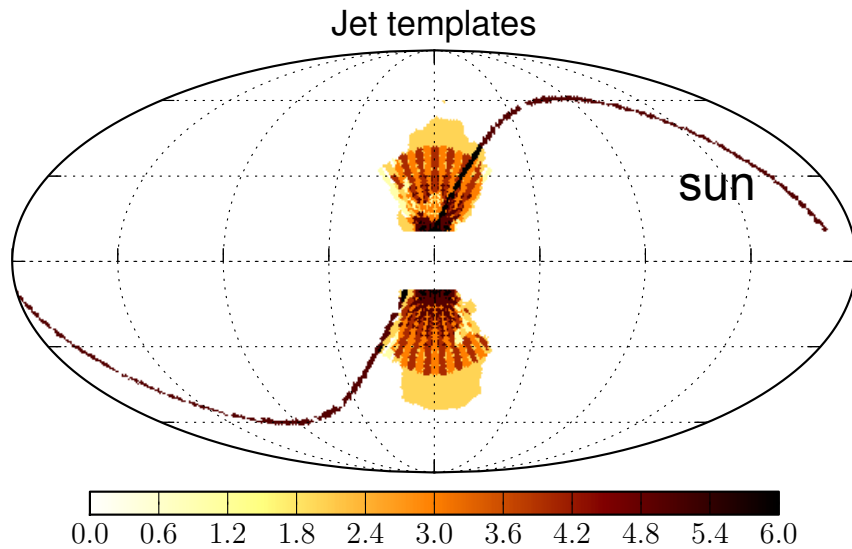
Cocoon Template, $6.0 \sigma_{BG}$ cut



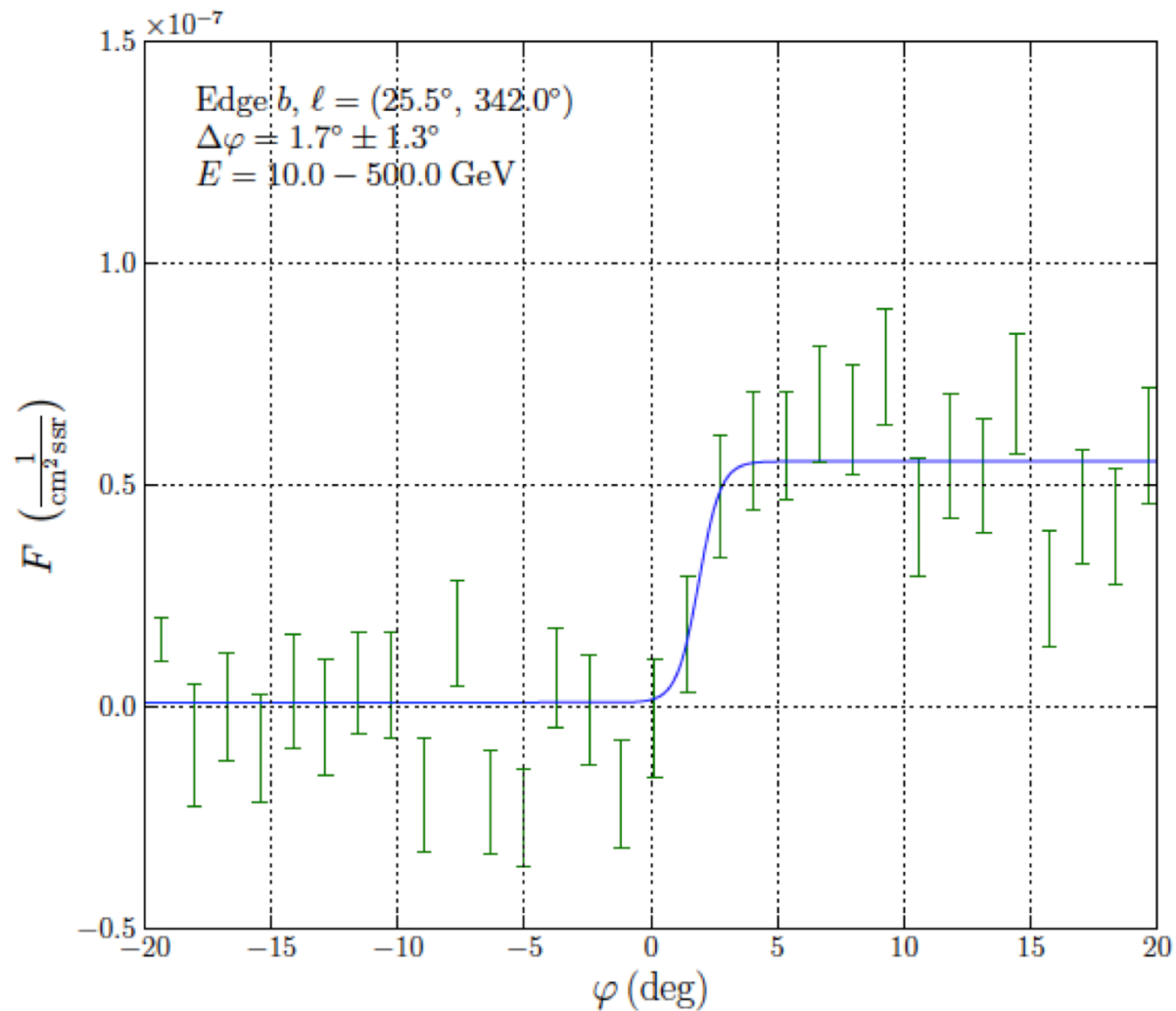
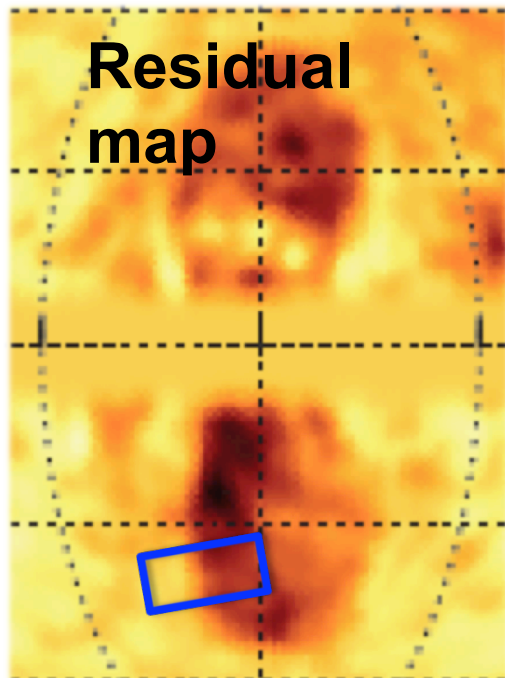
Ackermann et al. 2014



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



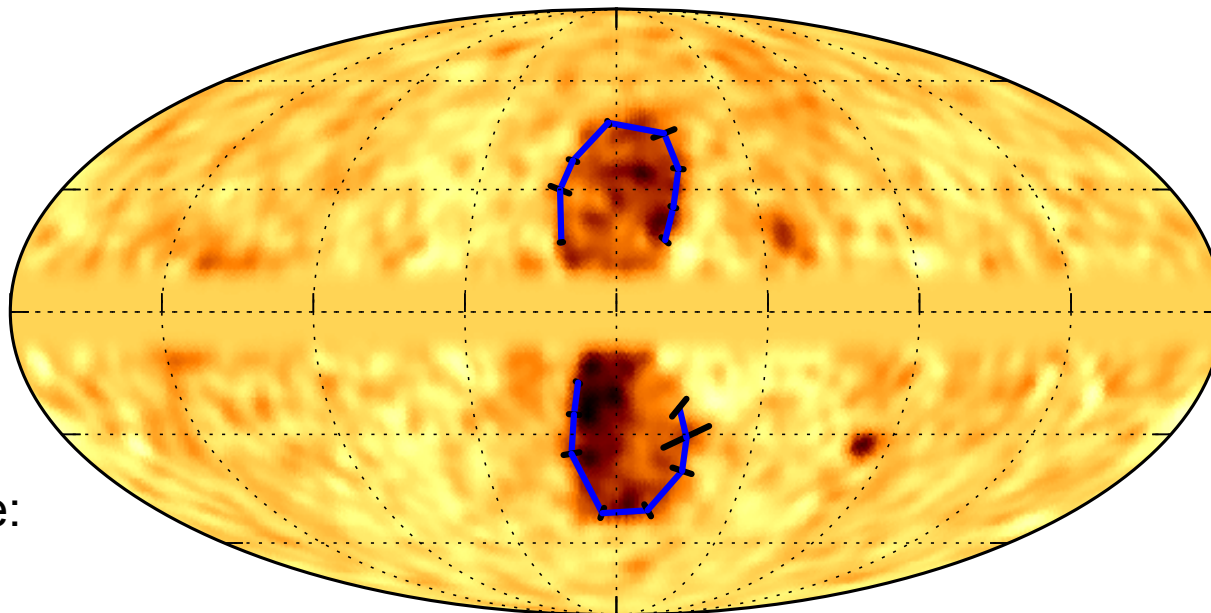
Boundary of the Bubbles



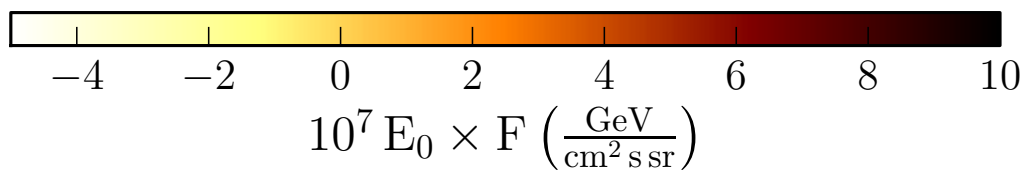
Boundary of the Bubbles



Residual intensity, $E = 10 - 500$ GeV

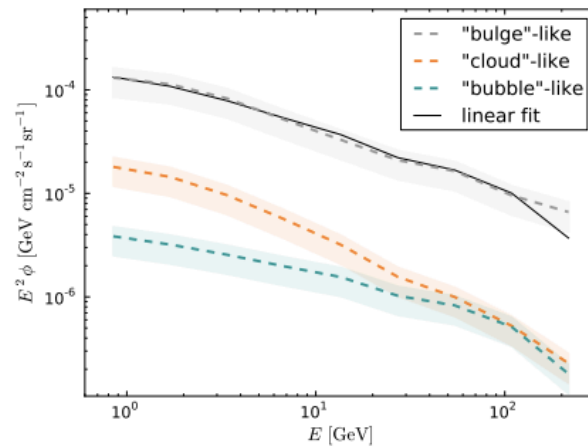
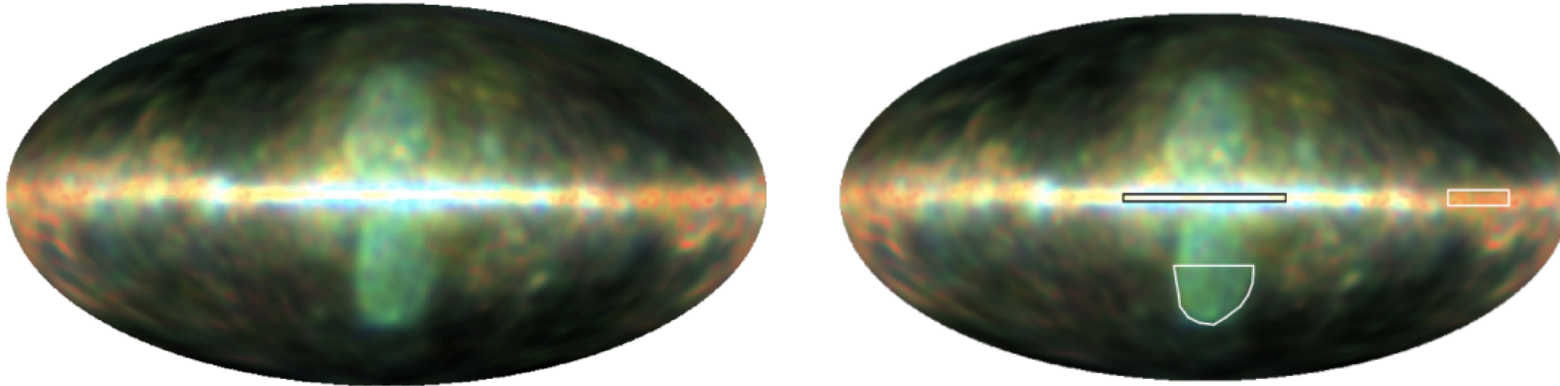


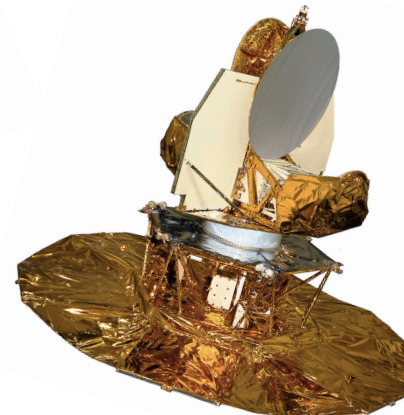
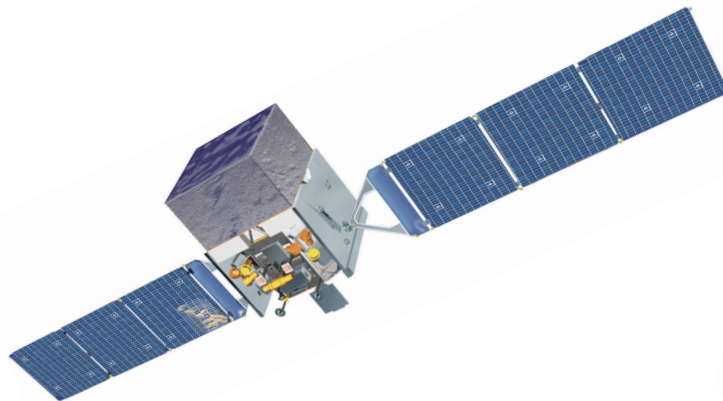
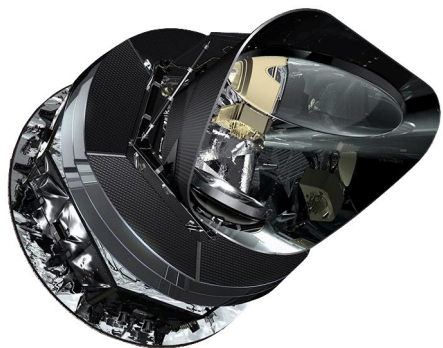
Average value:
 $3.4^{+3.7}_{-2.6}$ deg



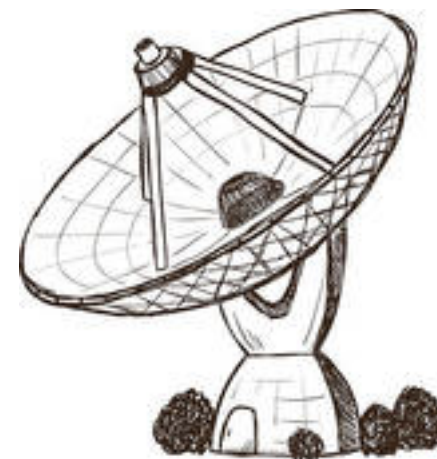
No variation with energy found, but some variation with position along the bubbles' edge

- Use spectral properties for component separation





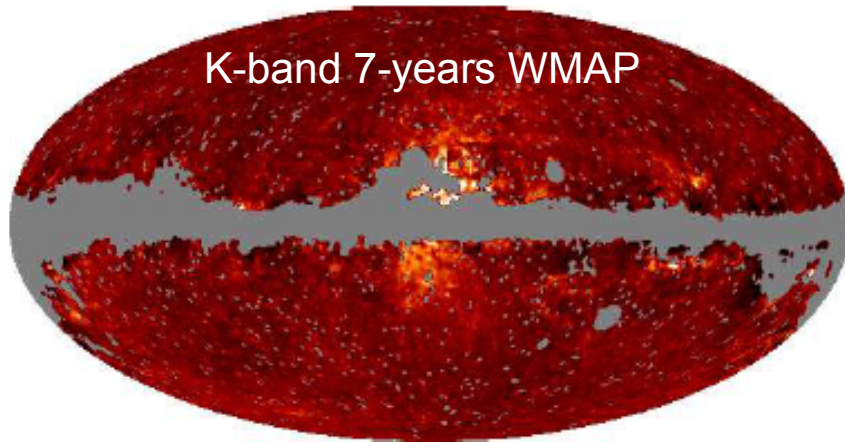
MULTIWAVELENGTH OBSERVATIONS



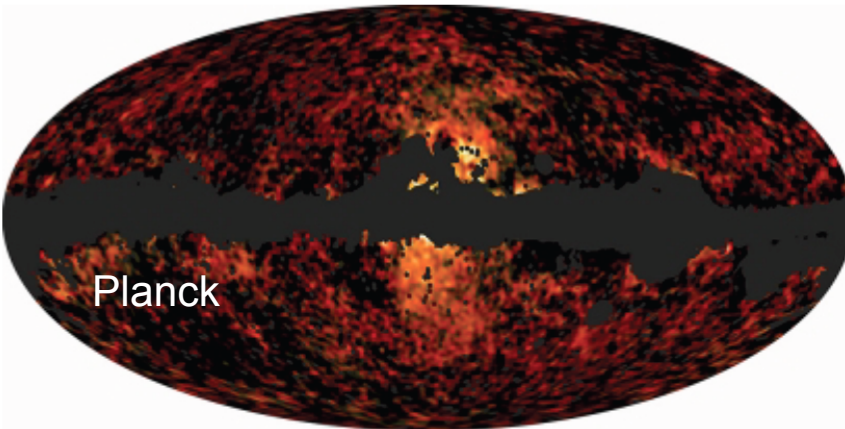
Microwave Haze



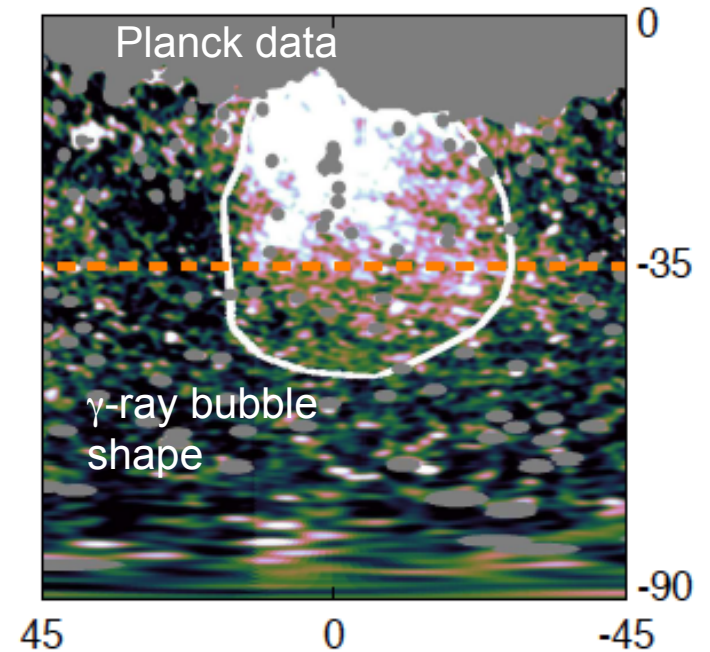
First detection in **WMAP** data: Finkbeiner, 2004, *Astrophys. J.*, 614, 186
Planck: Ade et al., 2012, *A&A*, 554, A139



K-band 7-years WMAP



Planck

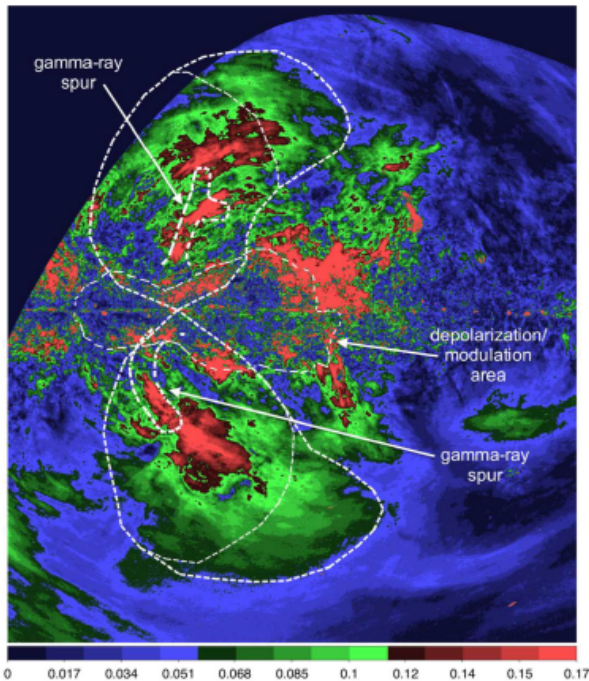


Planck data

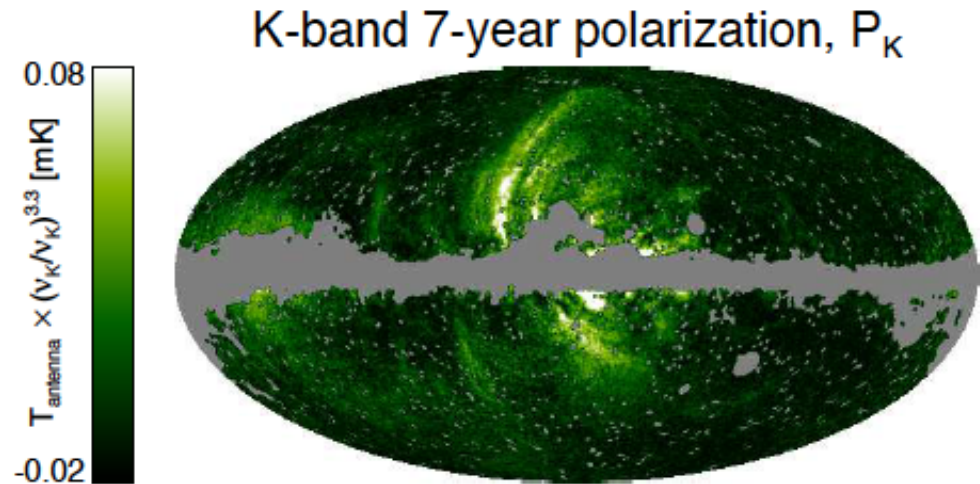
γ -ray bubble
shape



- **WMAP data: no conclusive evidence for polarization related to Fermi bubbles**
- **S-PASS data: polarized radio lobes larger than Fermi bubbles at 2.3 GHz**



S-PASS, Carretti 2013

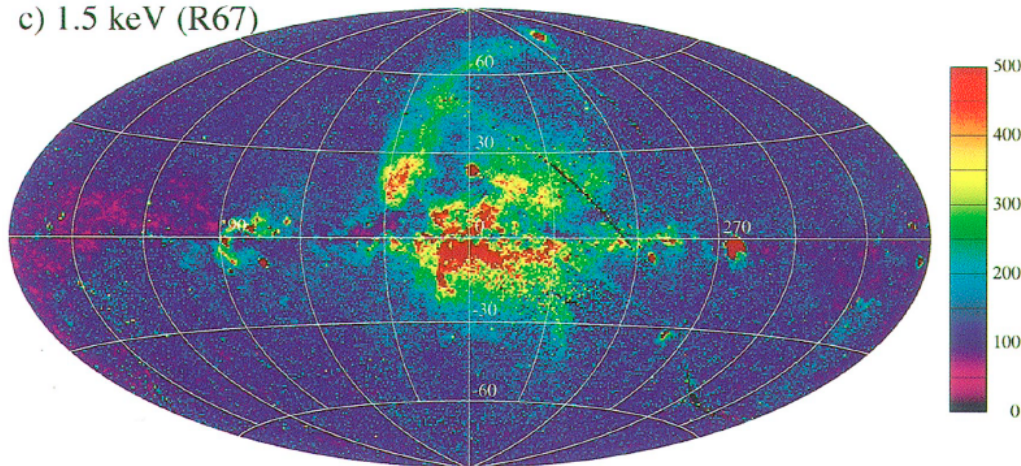


WMAP, Dobler 2012

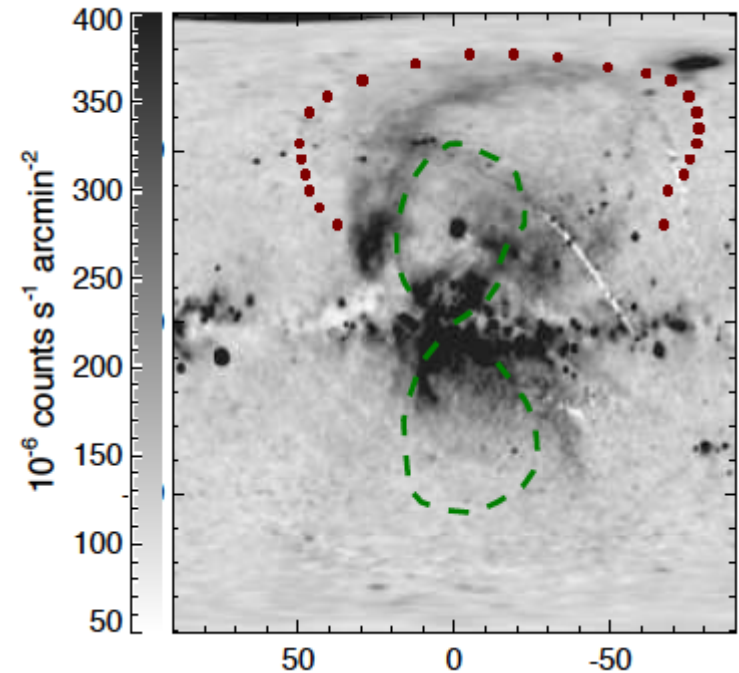


- Snowden, S. L., et al. 1997, ApJ, 485, 125
- Low-latitude bubble edges might line up with features in the ROSAT X-ray maps at 1.5 keV

c) 1.5 keV (R67)



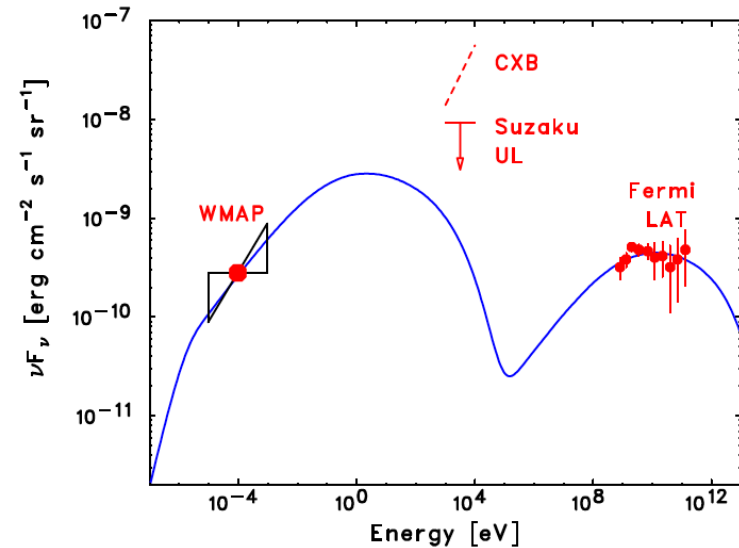
Rosat Band 6 and 7



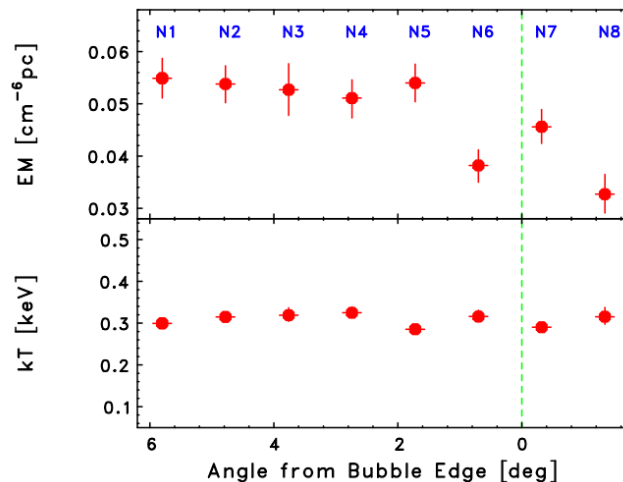
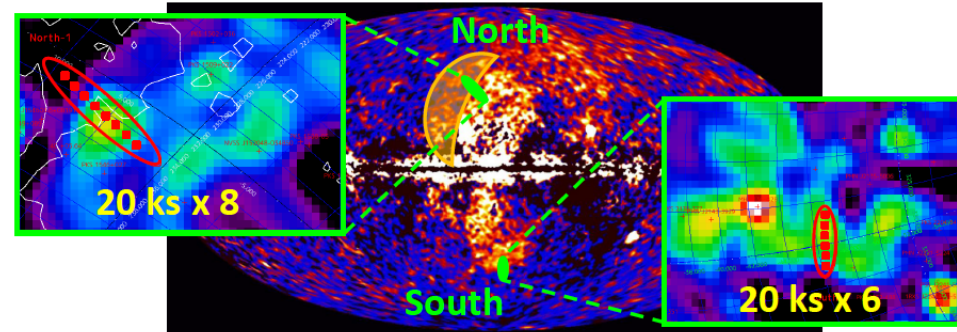
Su, Slatyer, Finkbeiner, ApJ
724 (2010)



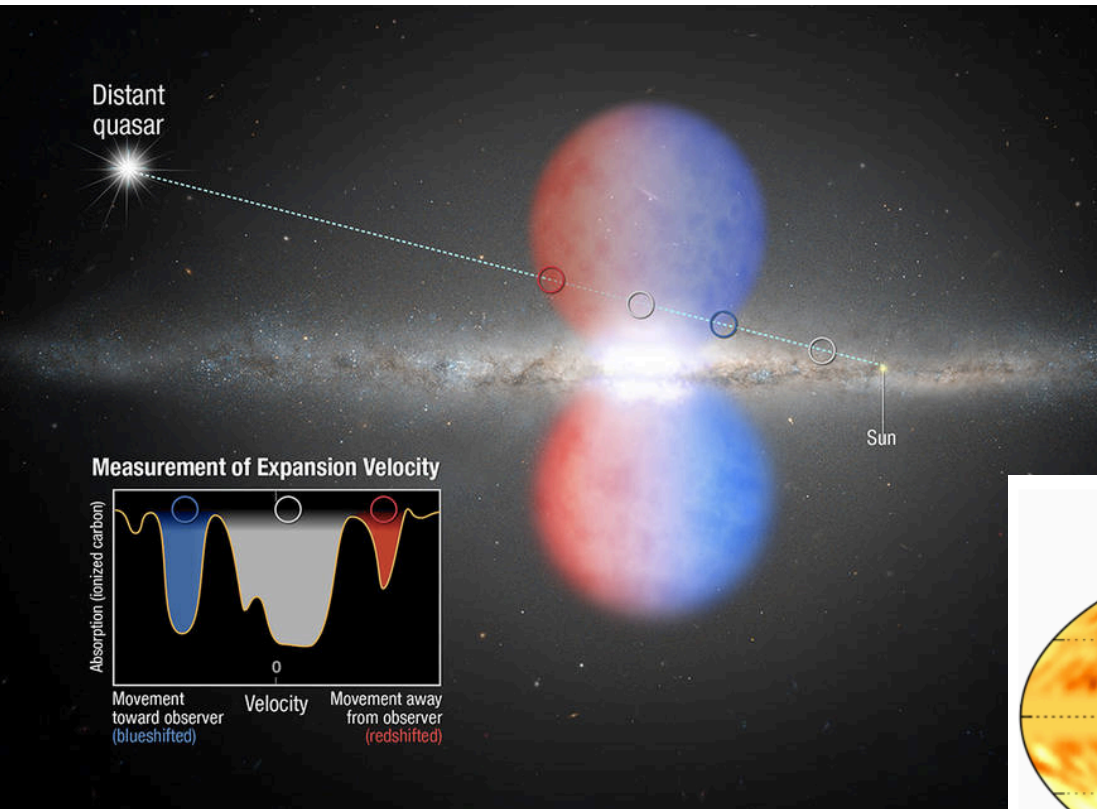
- North/South edges bubble in X-ray with 280 ks Suzaku exposure
- No excess in non-thermal X-ray emission found associated with the Fermi bubble



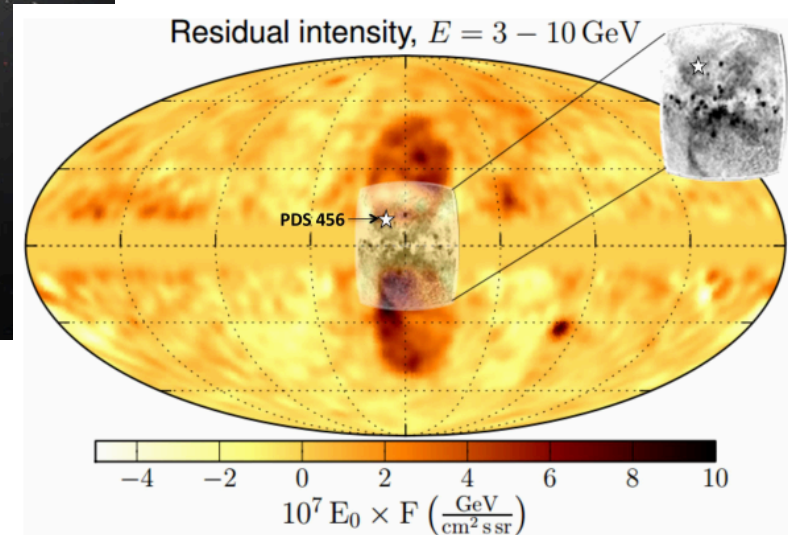
Expected non-thermal emission is still about factor of 5-10 lower than present UL.



compressing the surrounding halo gas to form Loop I: indications for weak shock driven by the bubbles' expansion



Absorption lines indicate outflow velocities of $>900\text{km/s}$

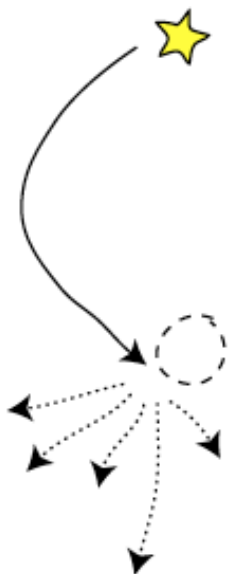


MODELING

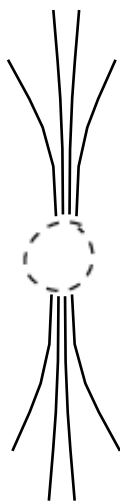




- **Electrons accelerated to E^{-2} spectrum by diffusive shock acceleration**
- **Gamma rays by inverse Compton scattering on radiation fields**
- **Microwave haze by synchrotron of same population of electrons**

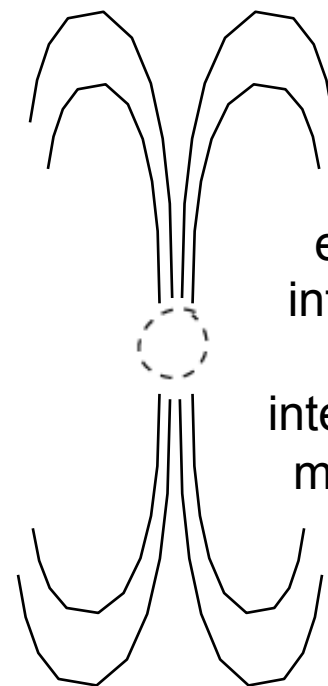


disruption of stars
by central black hole



AGN-like jet transports
particles to high latitudes

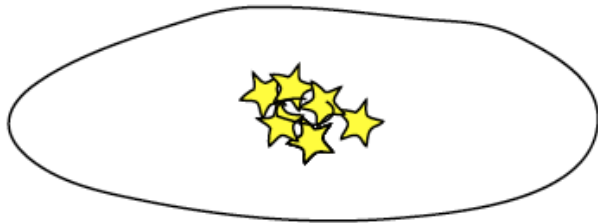
Guo & Mathews
2012, ApJ, 756, 181
Yang et al. 2012,
ApJ, 761, 185



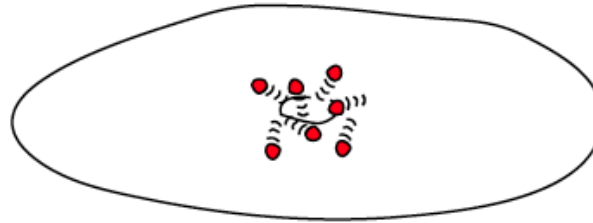
ejecta
interacts
with
interstellar
medium



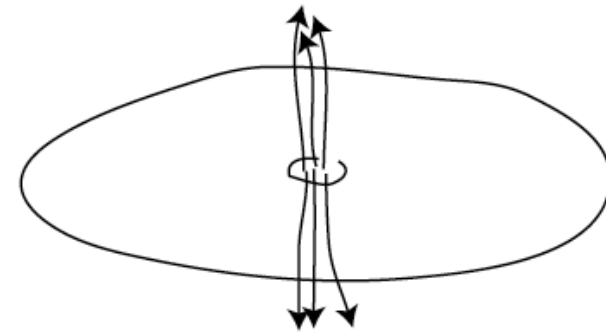
- **Gamma rays by π^0 on thermal gas (density $\sim 0.01 \text{ cm}^{-3}$)**
- **Secondary e^- produce synchrotron**



increased star
formation rate
close to GC



acceleration of CR
protons and nuclei
in SNRs



wind convects CRs
away from disk

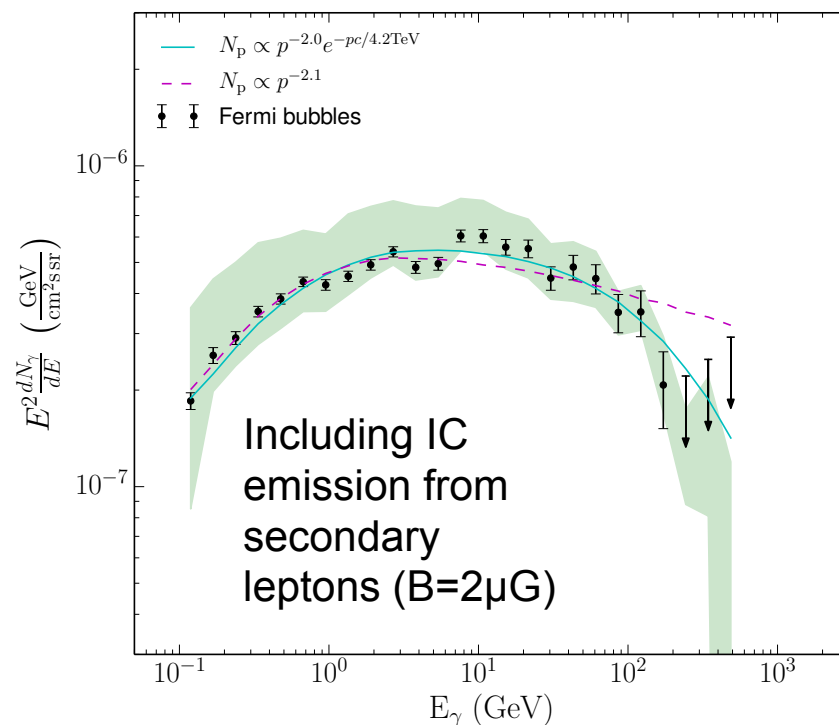
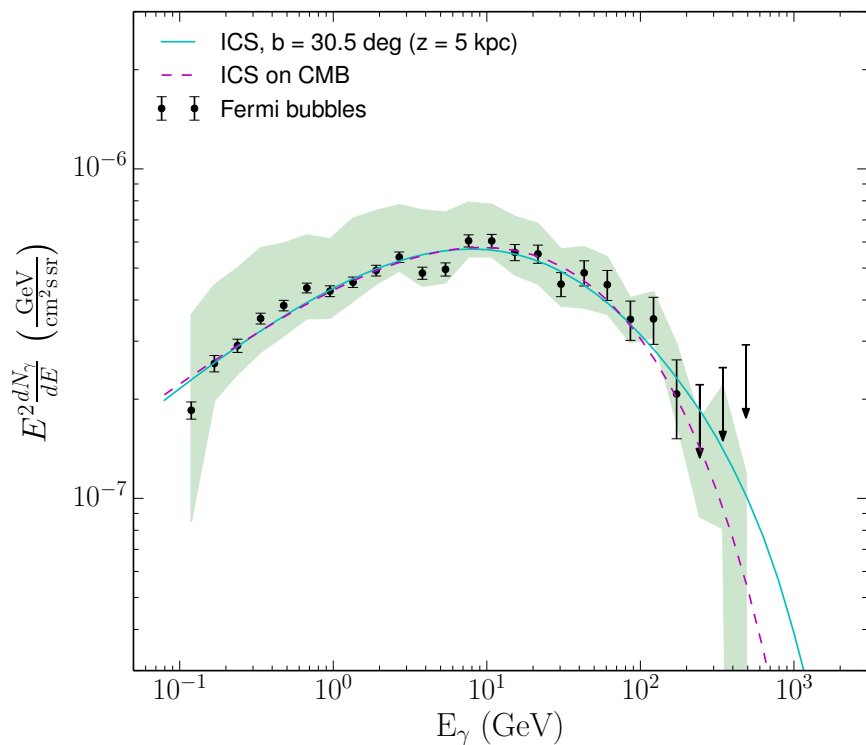
Neutrinos from π^+/π^-

Crocker & Aharonian, PRL, 106 (2011)





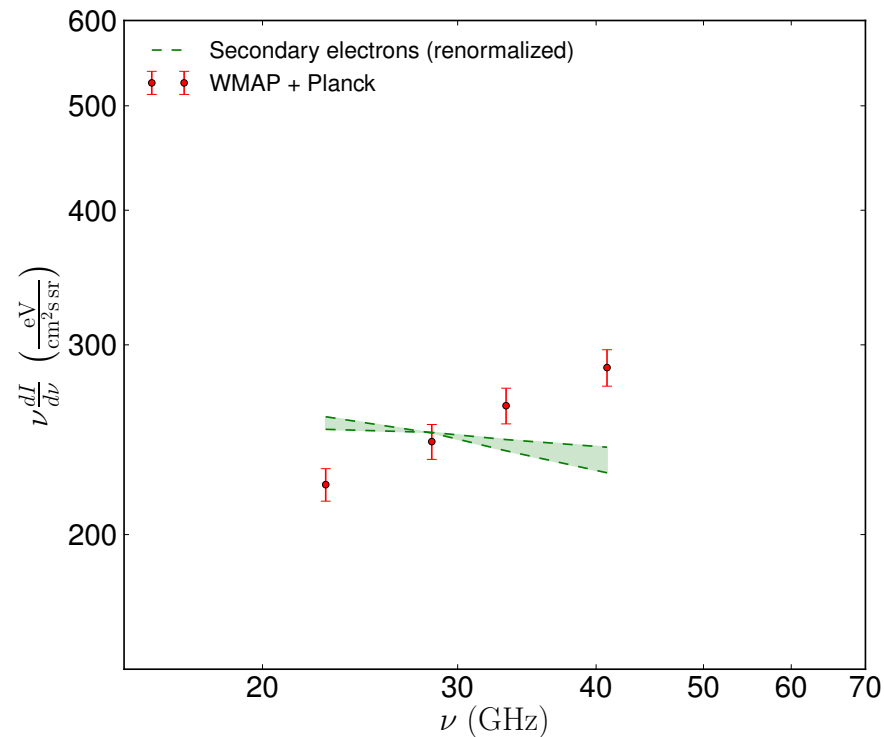
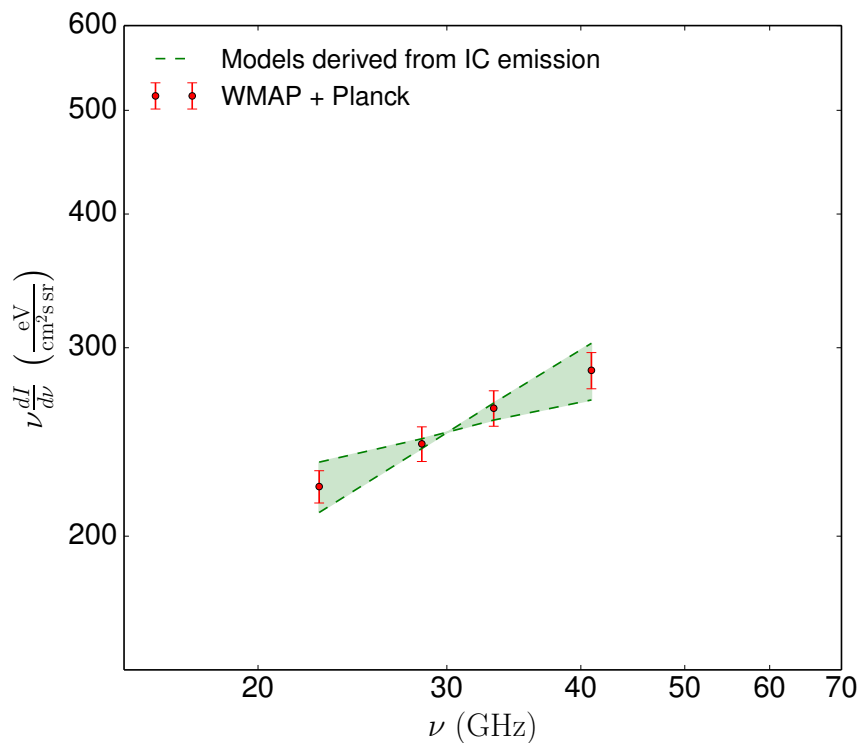
- Both leptonic and hadronic models describe the gamma-ray spectrum well



Leptonic, Hadronic, Gin & Tonic?

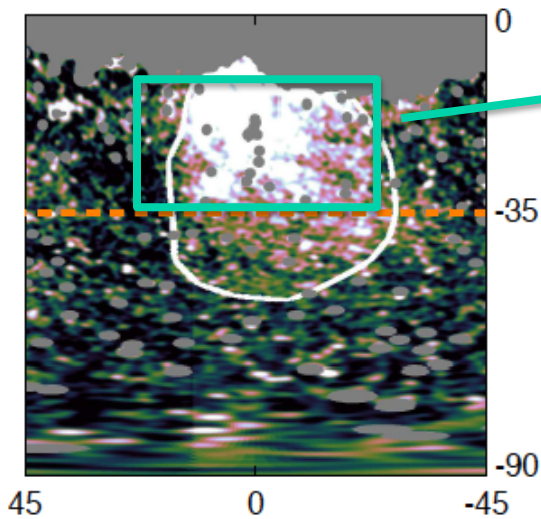
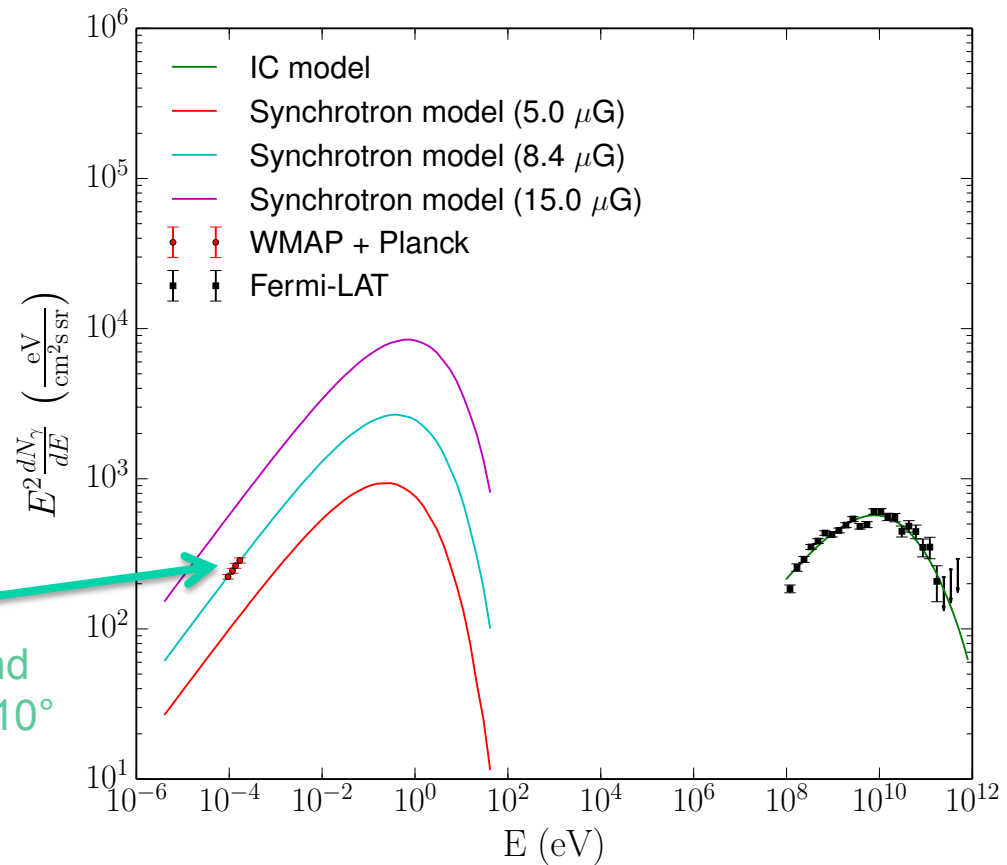


- Assuming that the microwave haze and the gamma-ray bubbles are produced by the same population of electrons: hadronic model fails to describe the spectral shape





- **Leptonic models can explain microwave haze for $B \sim 8 \mu\text{G}$**
- **Drop in magnetic field at latitudes of $|b| \sim 35^\circ$ could explain different latitudinal extension**



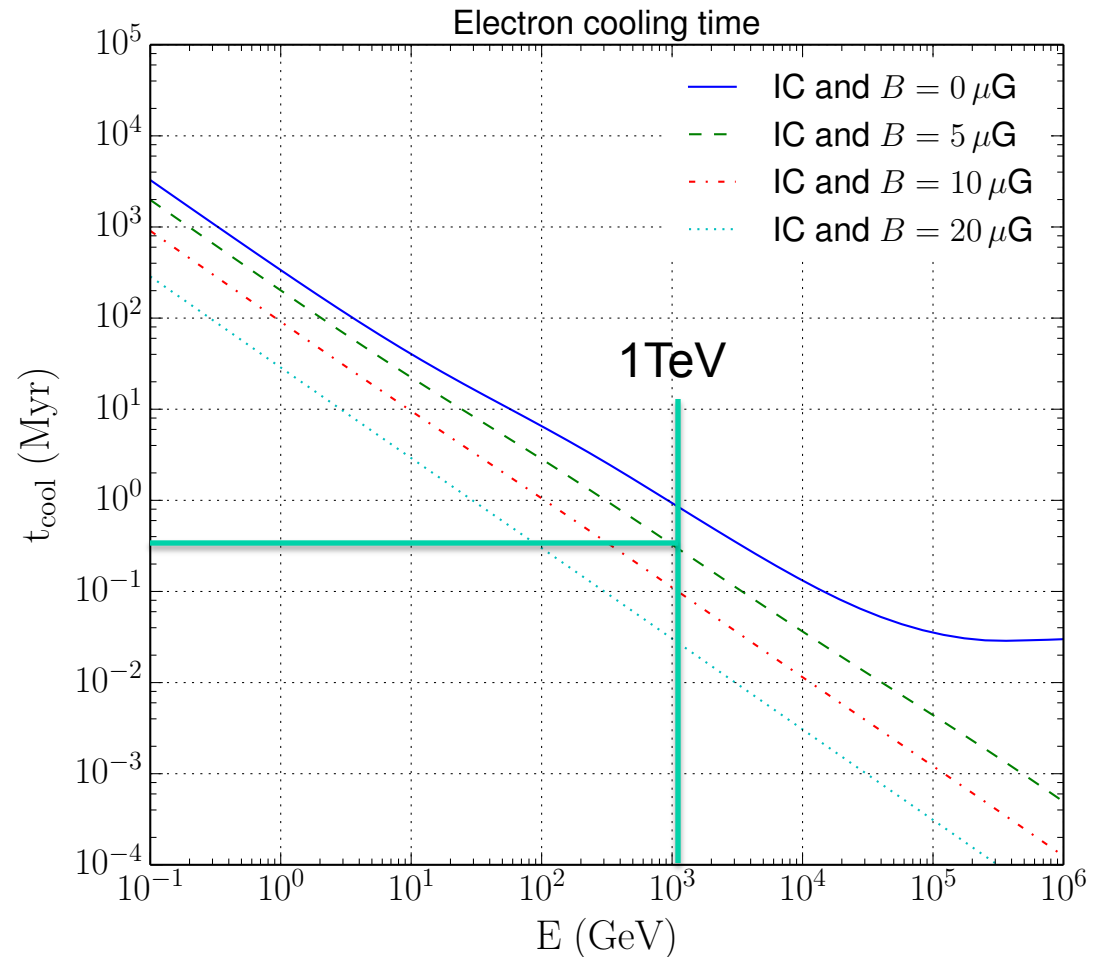
$|l| < 25^\circ$ and
 $-35^\circ < b < -10^\circ$

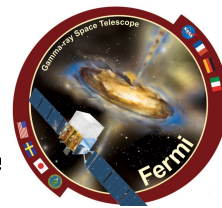


Gamma rays in the bubbles are mainly produced by $\sim 1\text{TeV}$ electrons: $< 0.5\text{ Myr}$ cooling time

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

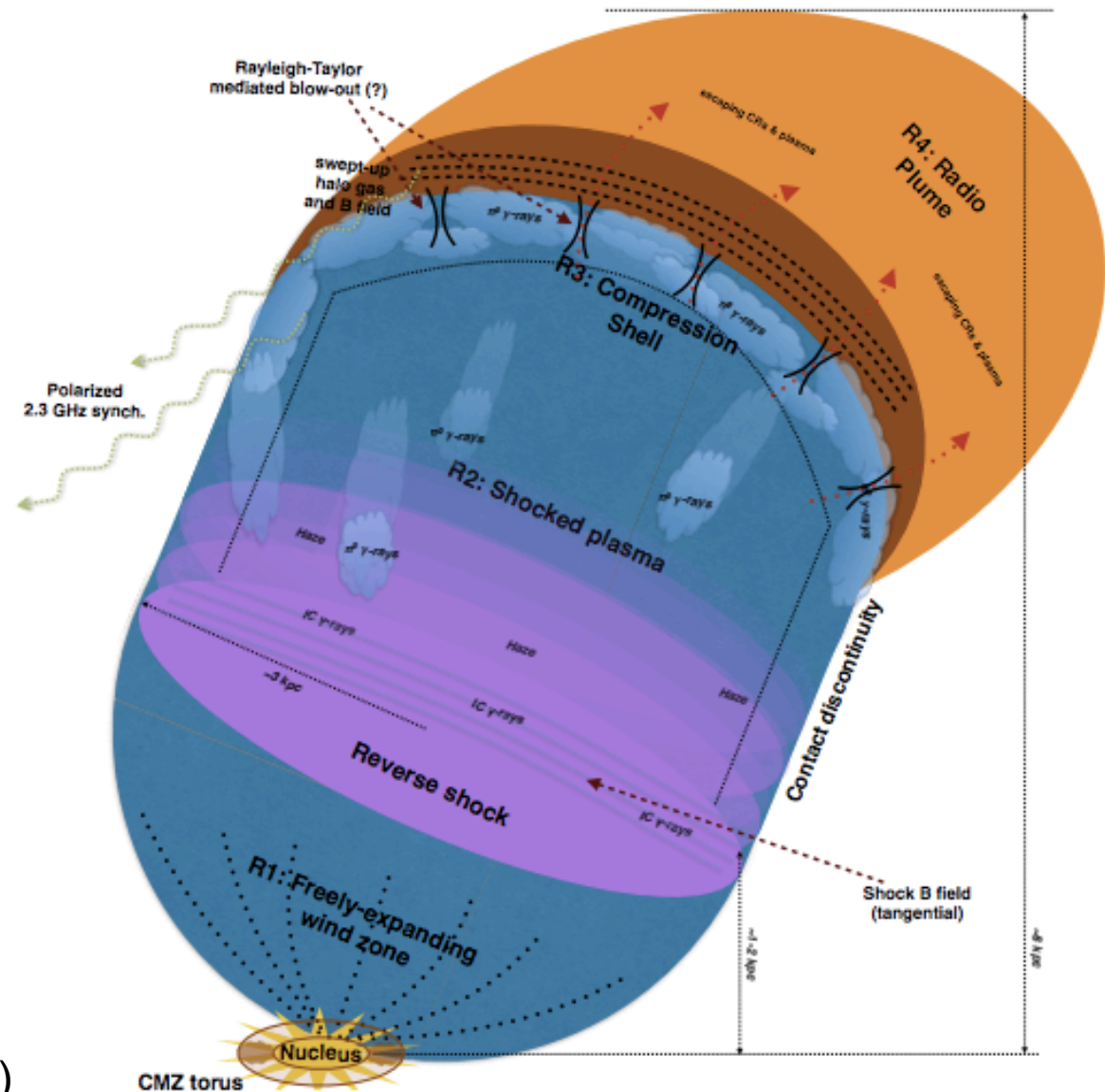
Reacceleration? E.g. plasma wave turbulences (Mertsch & Sakar, PRL 107, 2011)



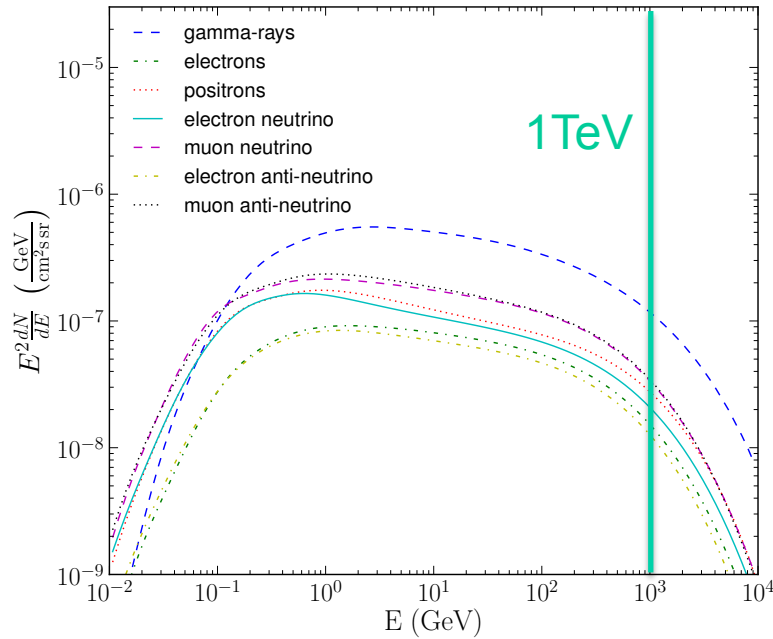


Microwave haze and polarized radio lobes:
Synchrotron emission from shock-reaccelerated cosmic-ray electrons

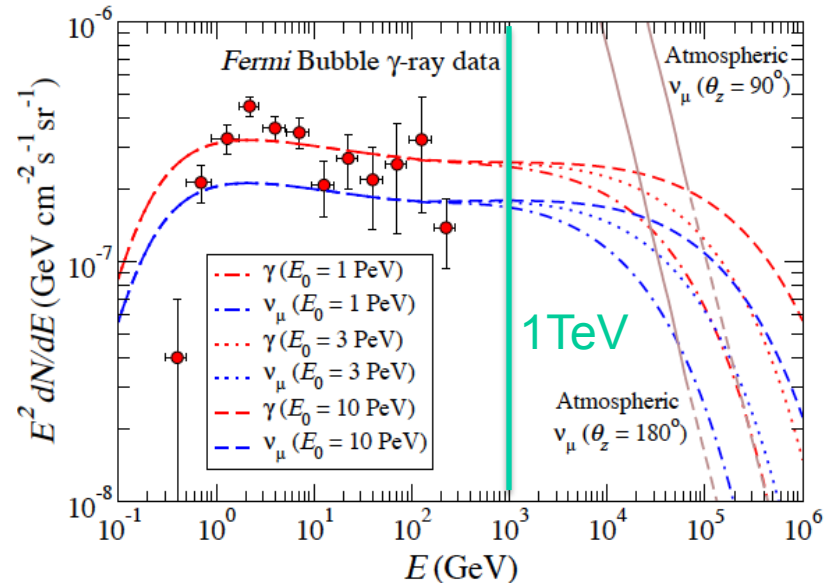
Fermi bubbles:
Collisions between shock-reaccelerated hadrons and denser gas in cooling condensations that form inside the contact discontinuity



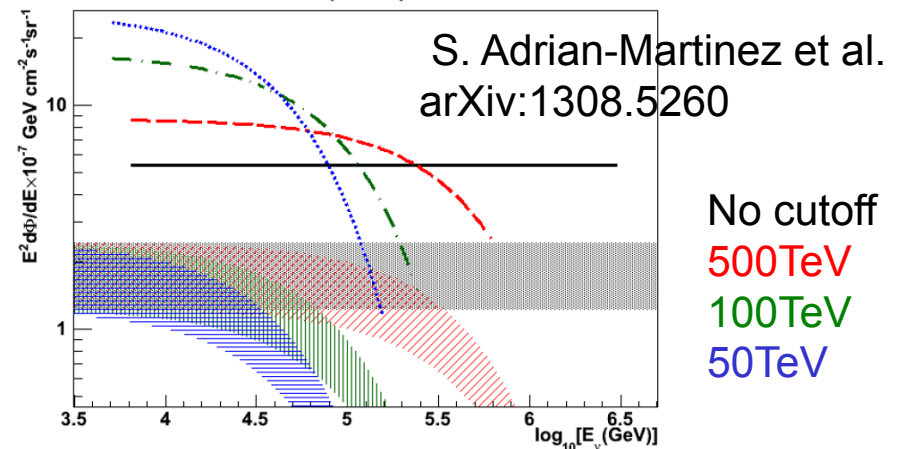
Neutrinos from the Fermi Bubbles



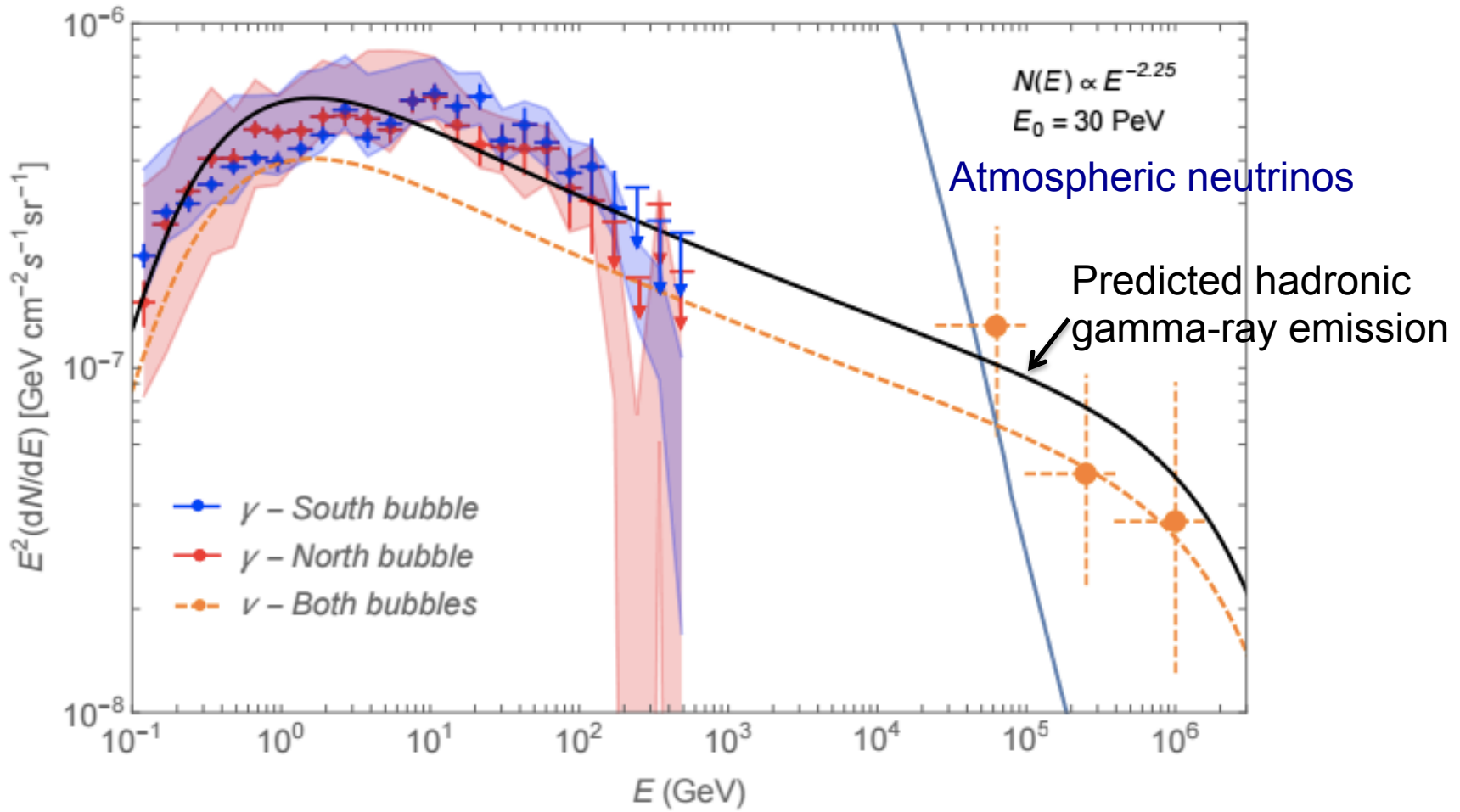
Lunardini, Razzaque PRL 108 (2012)



- **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**



IceCube's Diffuse Neutrinos from the Fermi Bubbles?

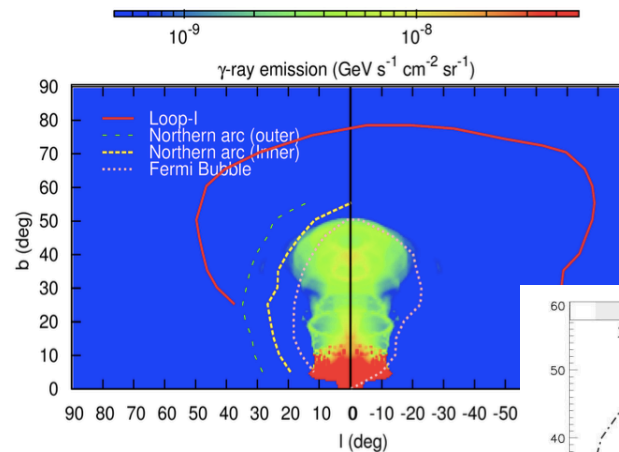


Simulations (some examples)



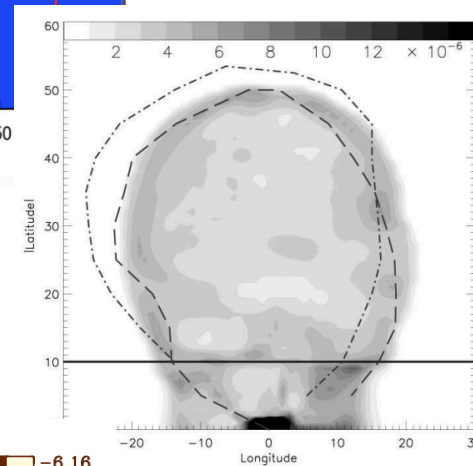
- **Wind scenario and hadronic gamma-ray production**

Sarkar et al. MNRAS, 453 (2015)



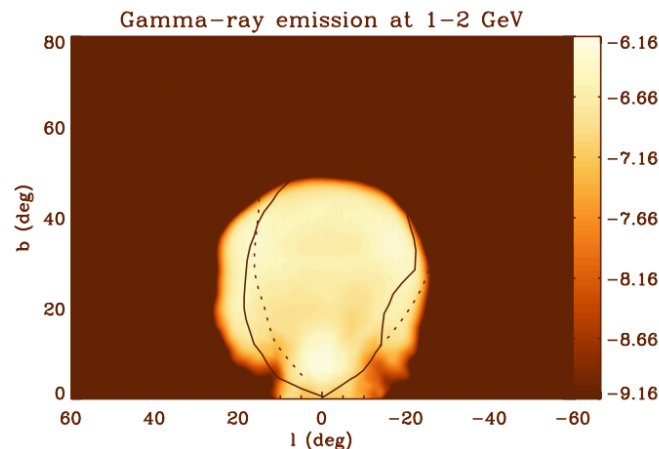
- **Wind from hot accretion flow in Sgr A***

Guobin et al. ApJ, 811 (2014)

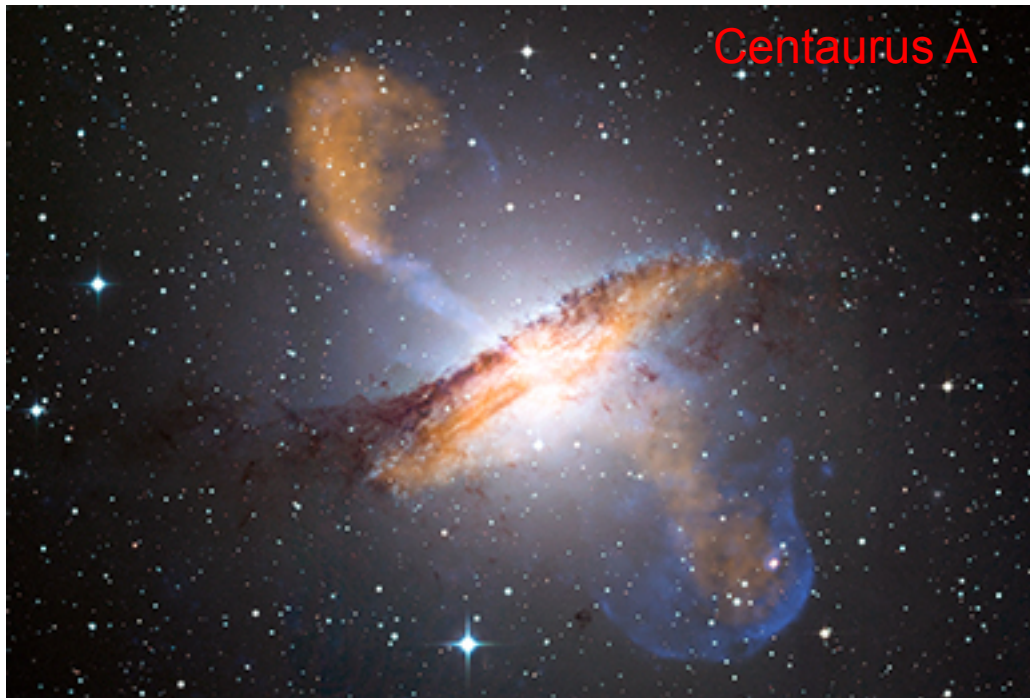


- **Leptonic AGN Jets**

Yang et al. MNRAS 436 (2013)



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



- **Fermi Bubbles firmly detected in gamma-ray data**
- **Hard spectrum with cutoff at ~ 110 GeV**
- **Possible association with microwave haze and ROSAT data**
- **Leptonic and hadronic interpretation of gamma-ray data possible**
- **Energy injection from GC:**
 - **Enhanced star formation or jet activity**
- **Low latitude Fermi bubbles are background for GC excess studies**



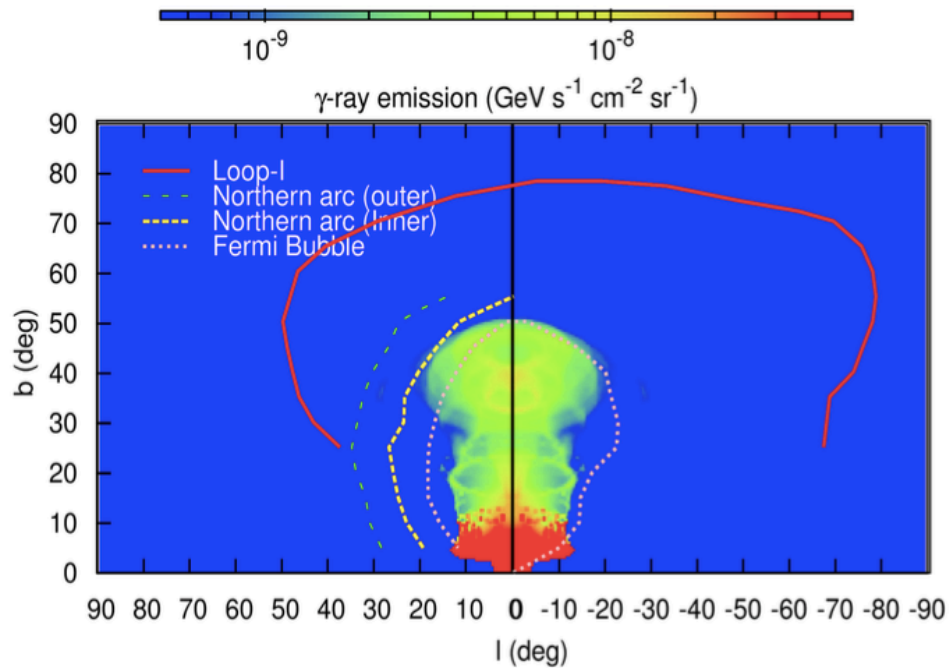
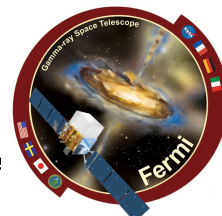
Thank you



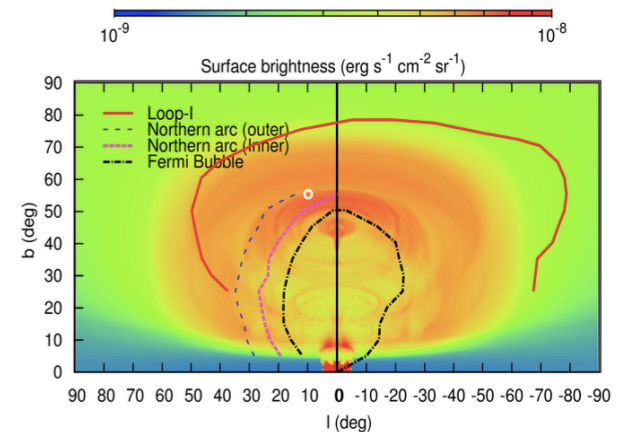
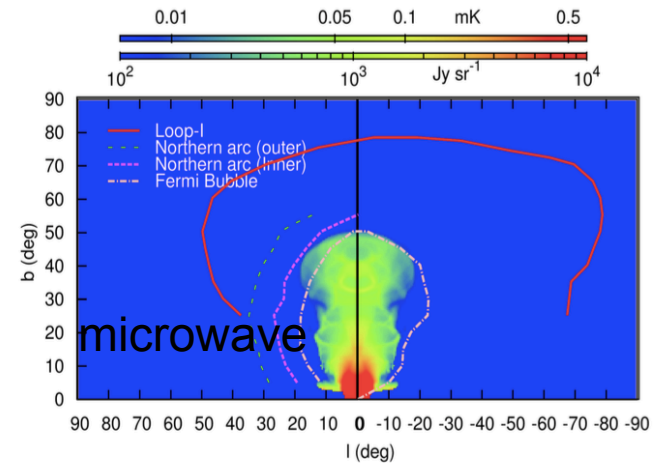


BACKUP

Simulations of Wind Scenario and Hadronic Gamma-ray Emission



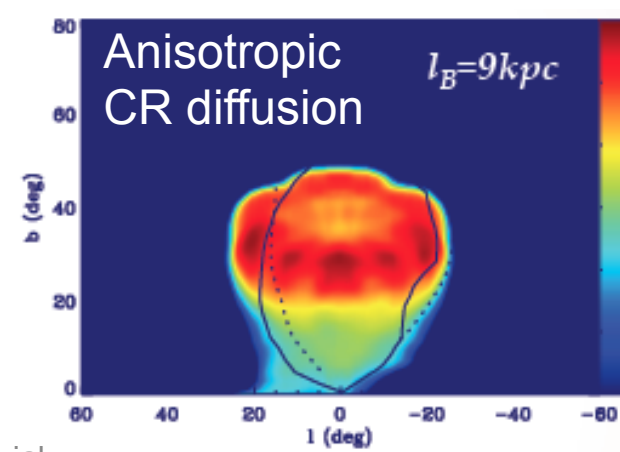
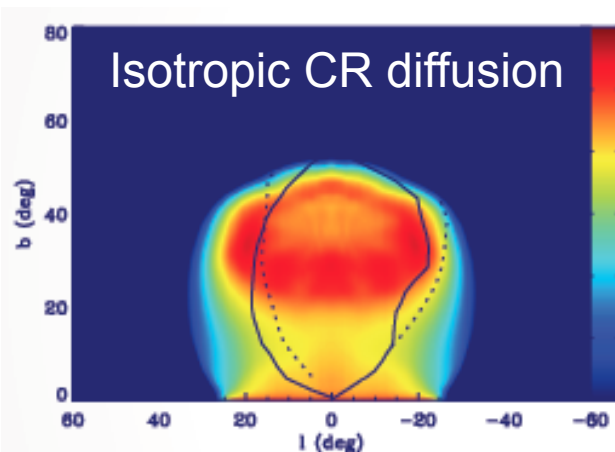
Simulated hadronic gamma-ray emission

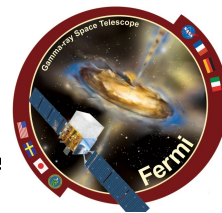


Simulated X-ray emission

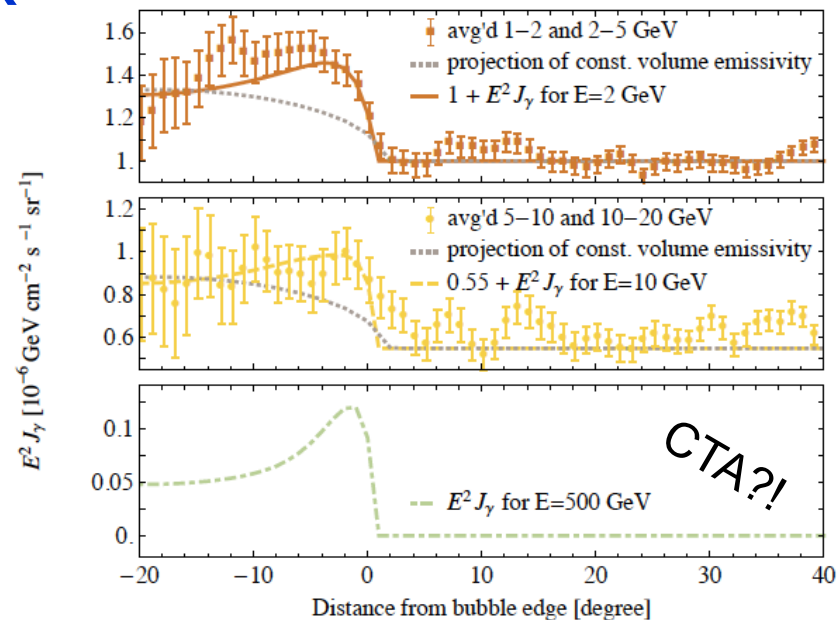
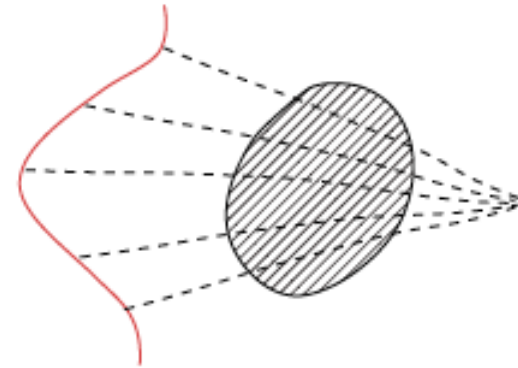


- AGN jets from Galactic center (e.g. Guo & Mathews, Yang 2012/13)
 - CRs accelerated and transported by jets
- Spherical outflow from hot accretion disk (Guobin 2014)
 - Central molecular zone collimates the outflow
- Problems
 - limb darkening → shear viscosity to concentrated CR near edges
 - Edges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





- **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**



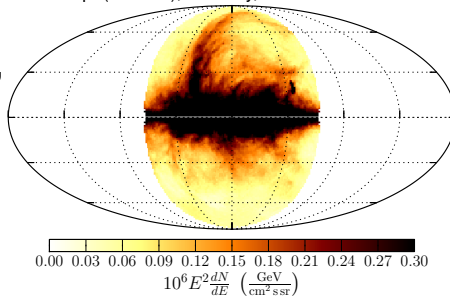
(Mertsch & Sarkar, PRL
107 (2011) 091101)



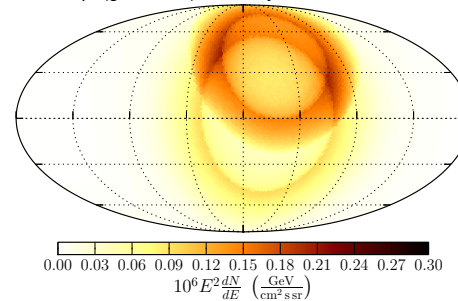
- **Templates (free/fixed):**
 - Inverse Compton (IC)
 - Local hydrogen (HI and HII)
 - Non-local hydrogen (HI and HII)
 - Molecular hydrogen (H₂)
 - Loop I (geometric template or Haslam map)
 - Bubbles (from residuals)
 - Isotropic
 - Point sources: 2FGL, bright sources refitted
- **Fit in individual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



LoopI (Haslam), Intensity, $E = 6.4 - 9.1$ GeV



LoopI (geometric), Intensity, $E = 6.4 - 9.1$ GeV



Haslam et al. 1982,
408MHz survey

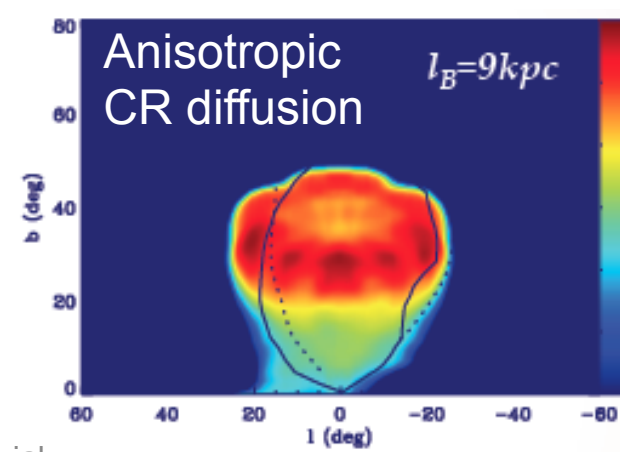
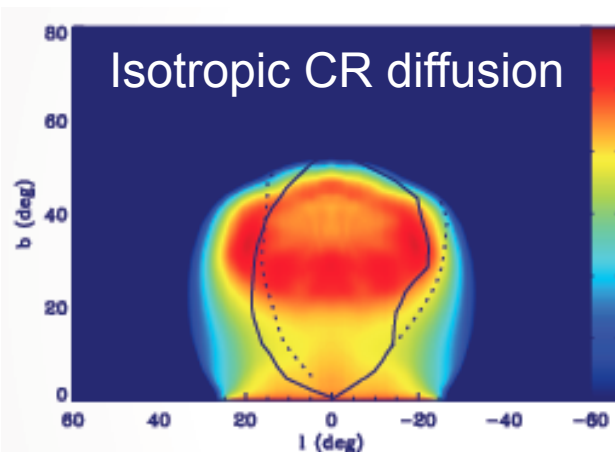
Wolleben, M. et al. 2007,
based on polarization
surveys at 1.4GHz



- **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**

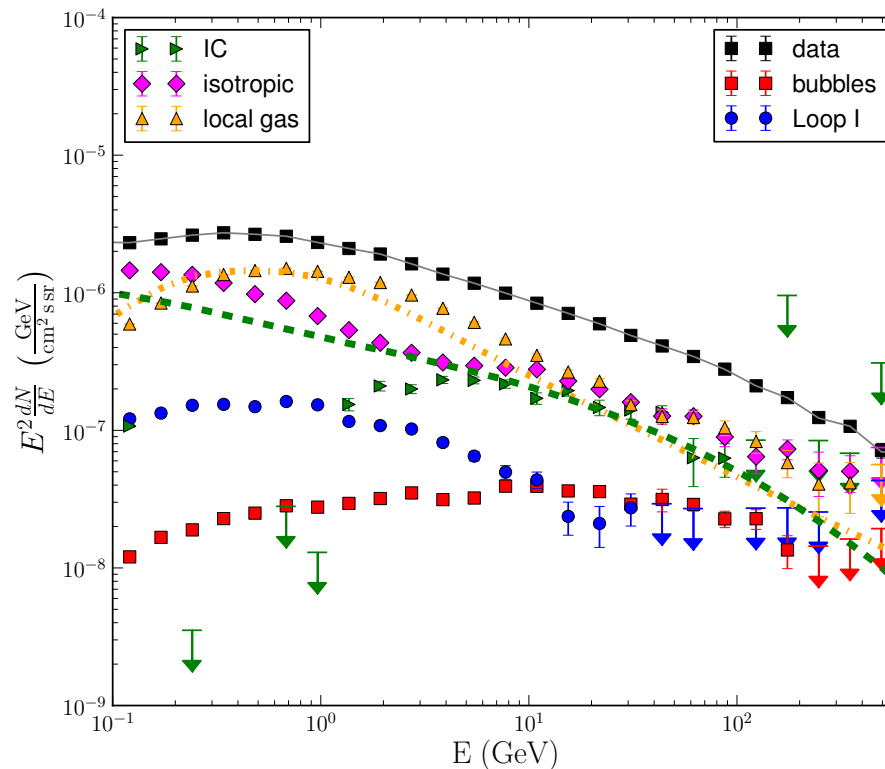


- AGN jets from Galactic center (e.g. Guo & Mathews, Yang 2012/13)
 - CRs accelerated and transported by jets
- Spherical outflow from hot accretion disk (Guobin 2014)
 - Central molecular zone collimates the outflow
- Problems
 - limb darkening → shear viscosity to concentrated CR near edges
 - Edges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

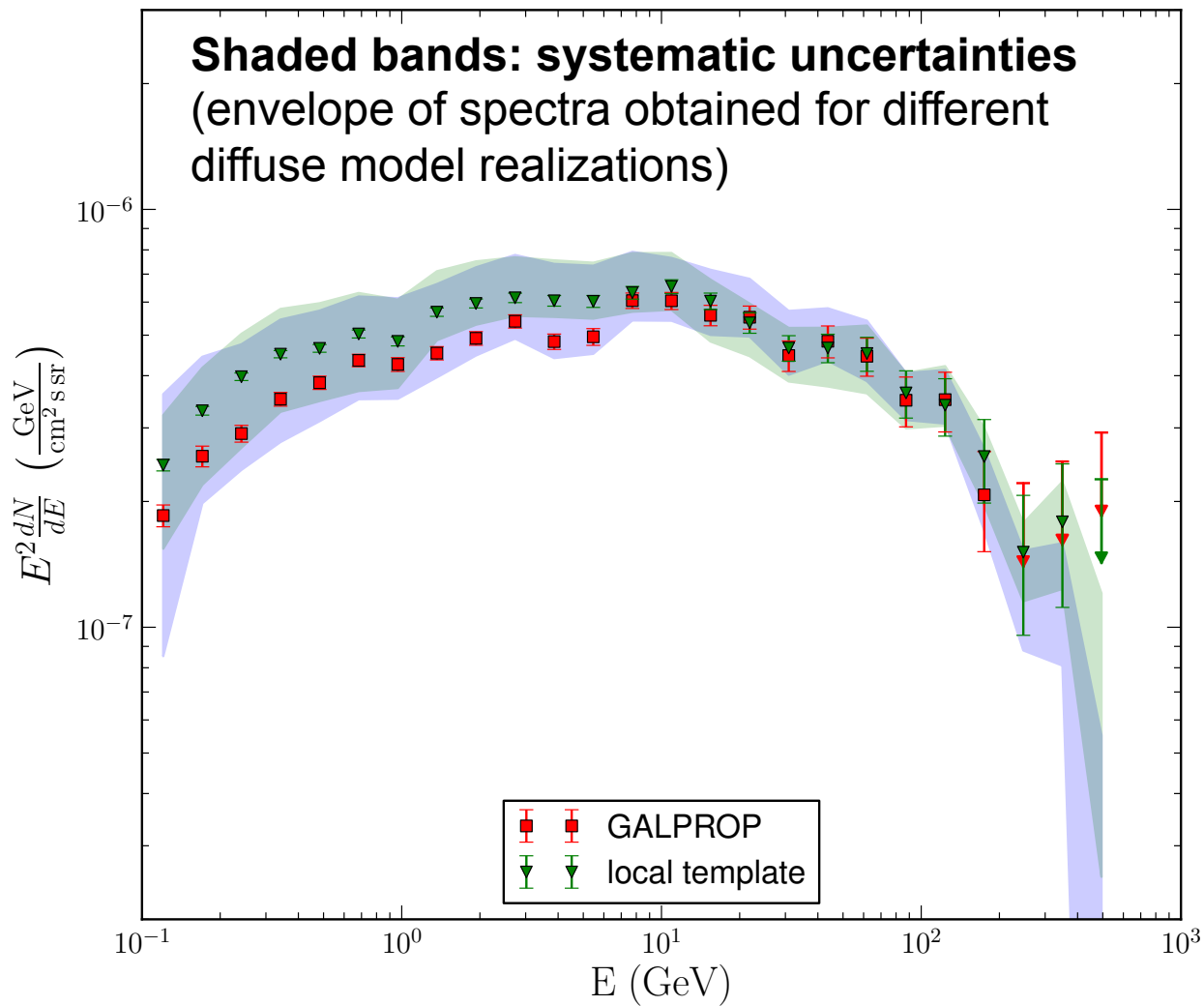




- Fit all sky ($|b| > 10^\circ$), each energy bin separately
- Templates used in fit: GALPROP templates (gas & IC), Loop I, bubble, point sources, isotropic

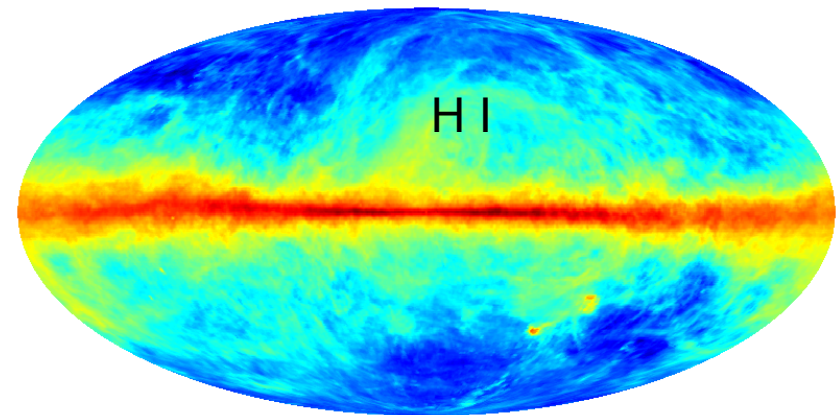
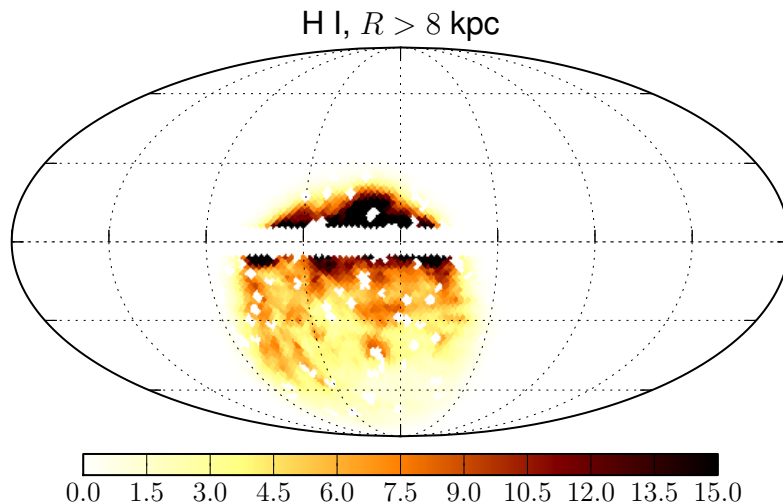


Spectrum – two methods





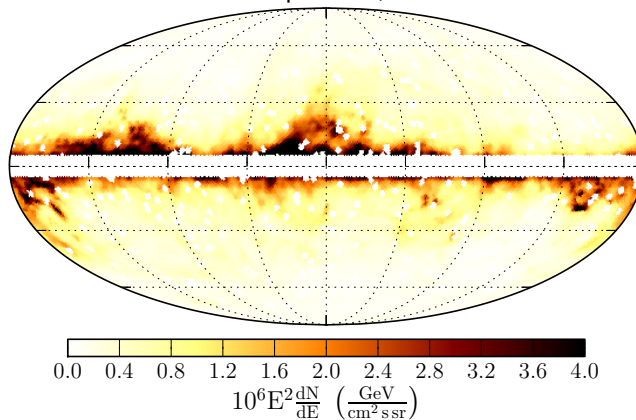
- Does not depend on GALPROP
- Does not assume azimuthal symmetry (e.g. violated for spiral arms)
- Gas maps used to trace gamma-ray emission in small patches
 - H I and CO survey, SFD dust map
 - Scaling factor is proportional to line of sight cosmic-ray density



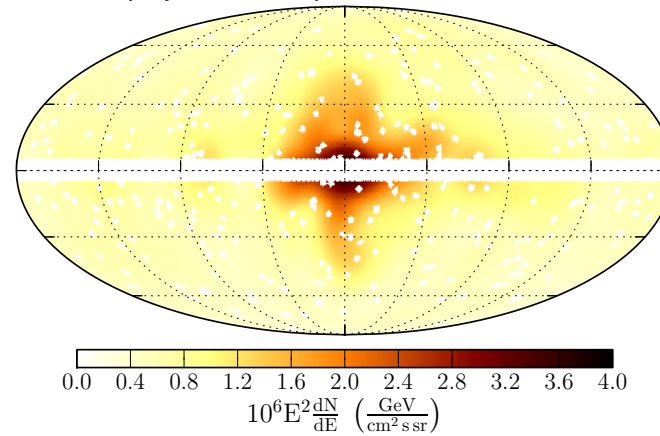


- Does not depend on GALPROP
- Does not assume azimuthal symmetry (e.g. violated for spiral arms)
- Gas maps used to trace gamma-ray emission in small patches
 - H I and CO survey, SFD dust map
 - Other components (IC, bubbles, Loop I) are assumed to be smooth or not correlated with the gas and are modeled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

Gas-correlated components, E = 6.4 - 9.1 GeV



Local polynomial components, E = 6.4 - 9.1 GeV

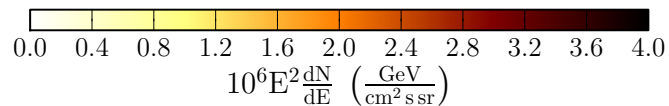
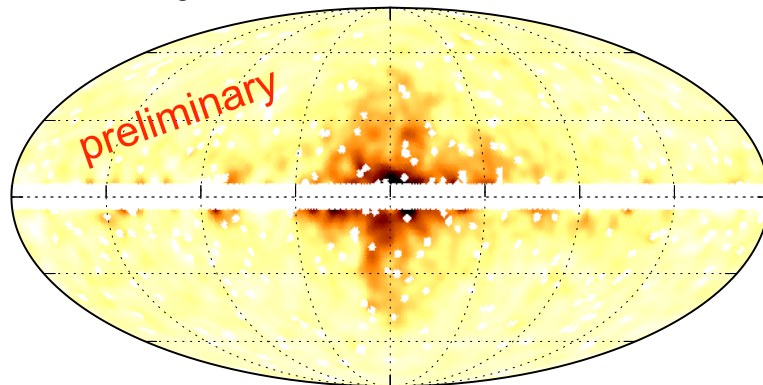


Alternative Galactic Modeling: Local template Analysis

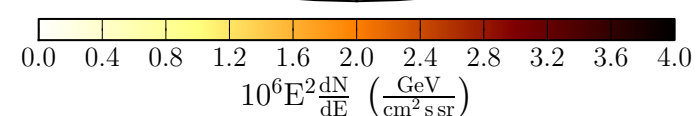
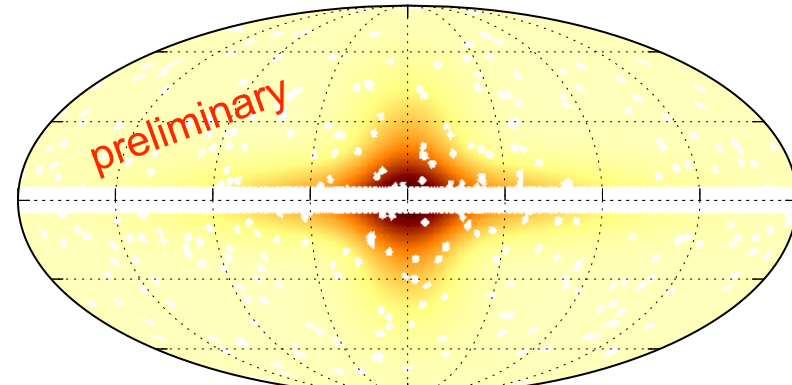


- After subtraction of the gas component, the IC is modeled with a bivariate Gaussian along the Galactic plane
- Other components (Loop I and bubbles) are estimated with Gaussian perpendicular to the plane

Data minus gas-correlated emission, $E = 6.4 - 9.1$ GeV



Gaussian model, $E = 6.4 - 9.1$ GeV

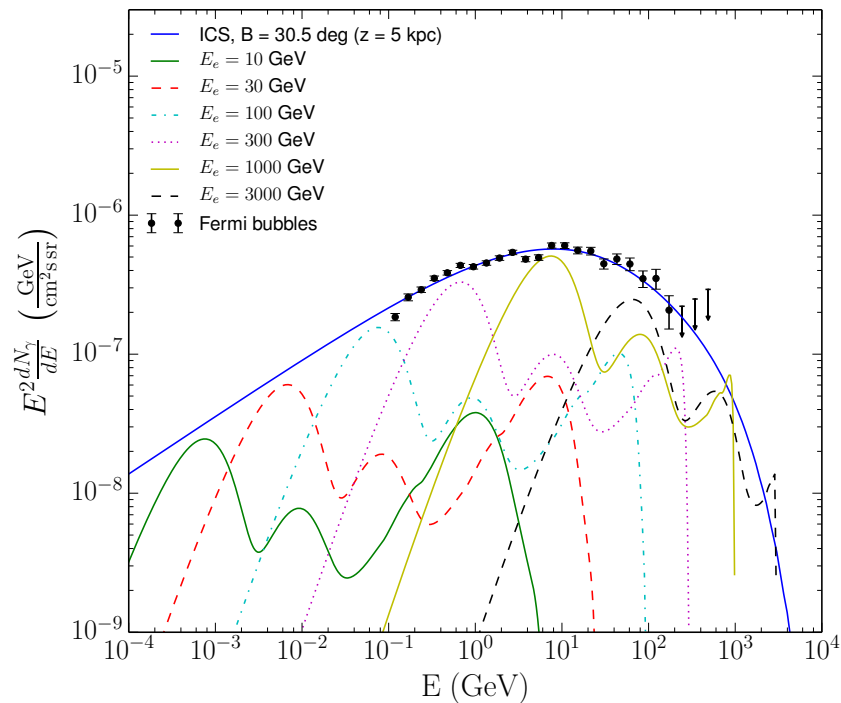
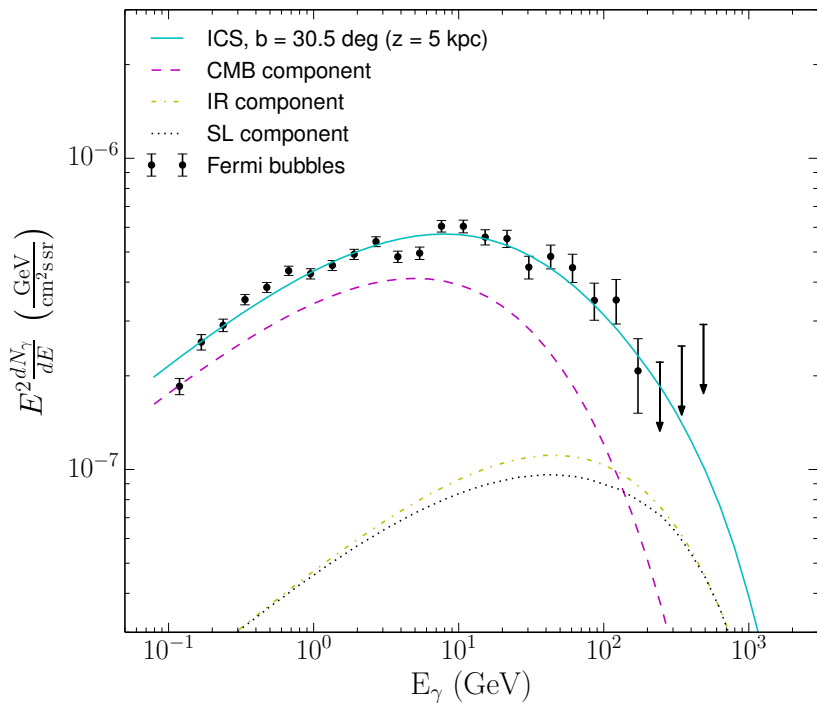




Added in
quadrature

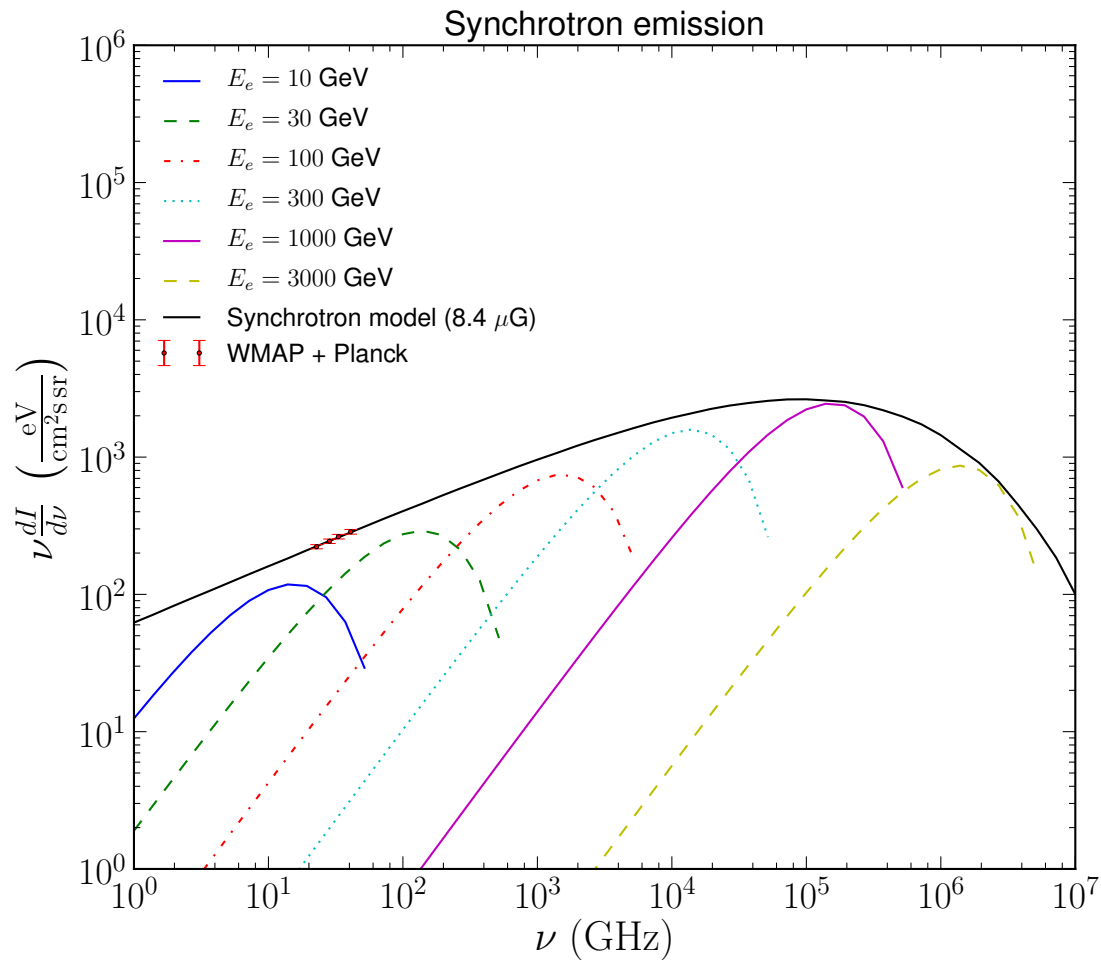
- **Instrument related:**
 - **Systematic error in the effective area (2012 ApJS, 203)**
- **Galactic modeling:**
 - **The choice of the input GALPROP configuration might influence the extracted bubble features**
 - **Cosmic-ray source distribution:**
 - Pulsars, SNR
 - **Size of cosmic-ray confinement 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)**
 - $T = 150\text{K}$, optically thin
 - **Loopl template**
 - **Bubble template**
- **Alternative analysis method based on fits in local patches**

envelope

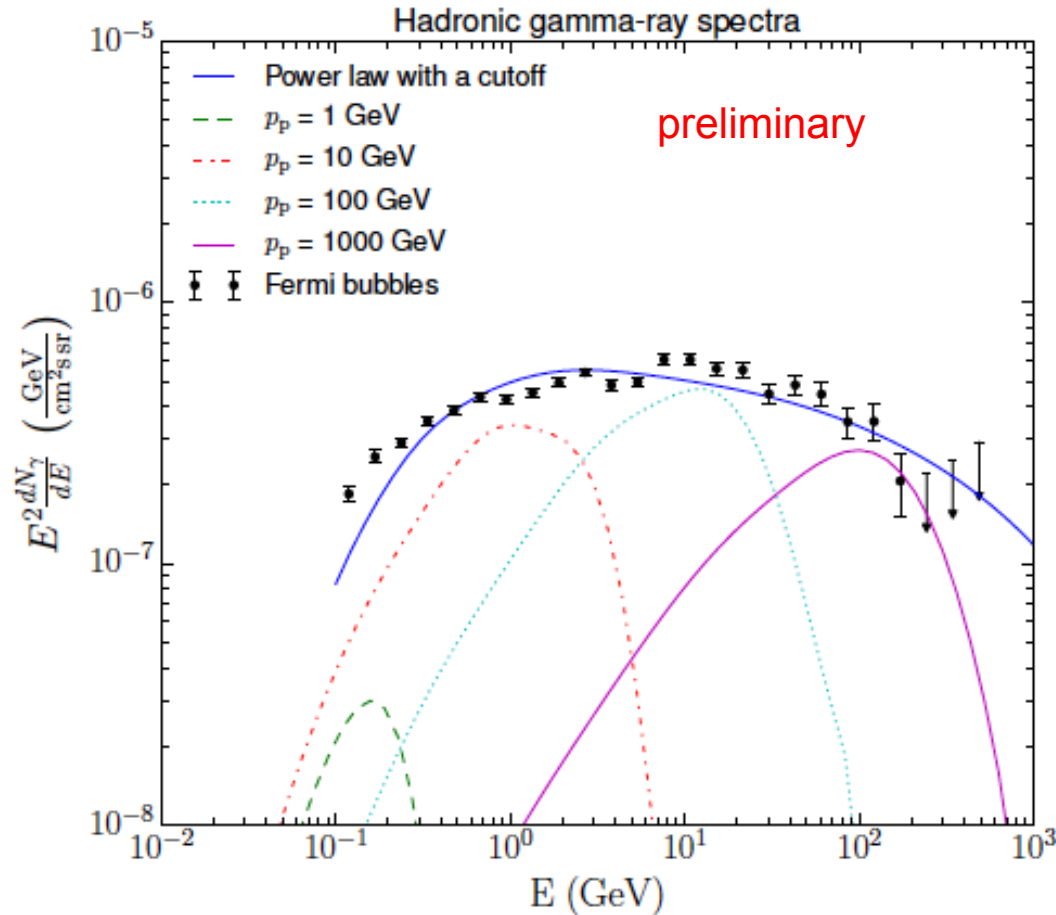


Energy in electrons $(1.0 \pm 0.2[\text{stat}]_{-1.0}^{+6.0}[\text{syst}]) \times 10^{52} \text{ erg}$

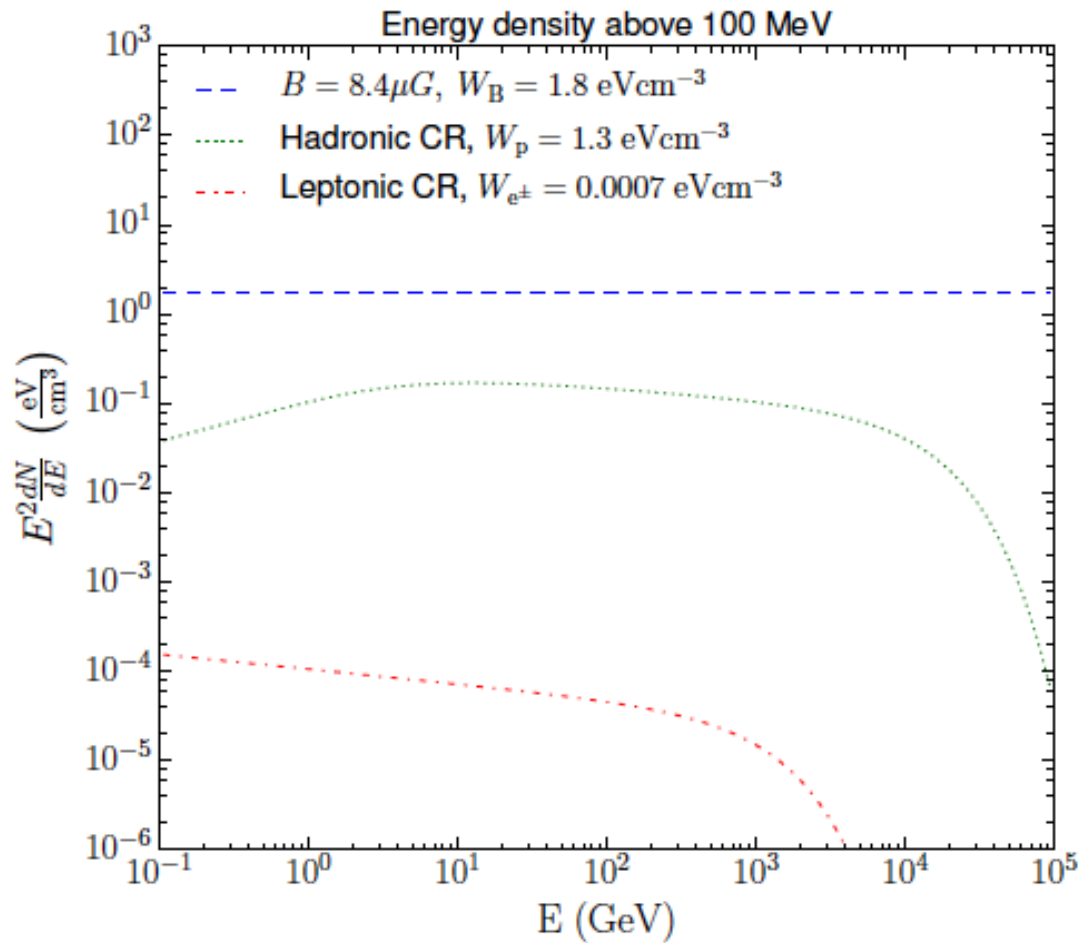
Synchrotron emission



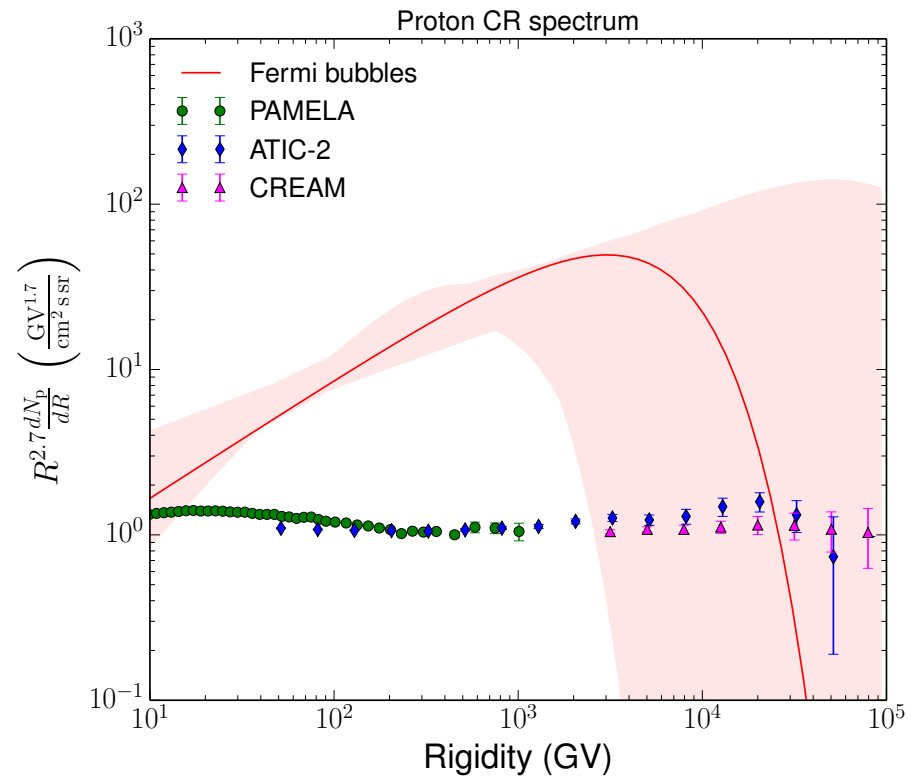
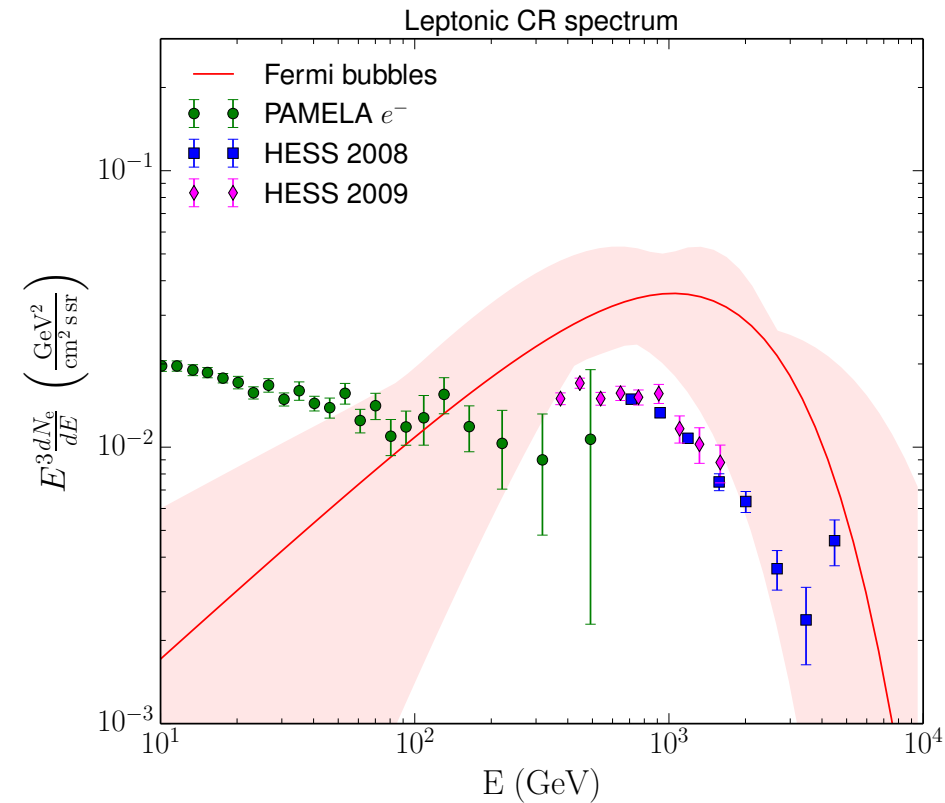
Hadronic gamma-ray spectrum



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

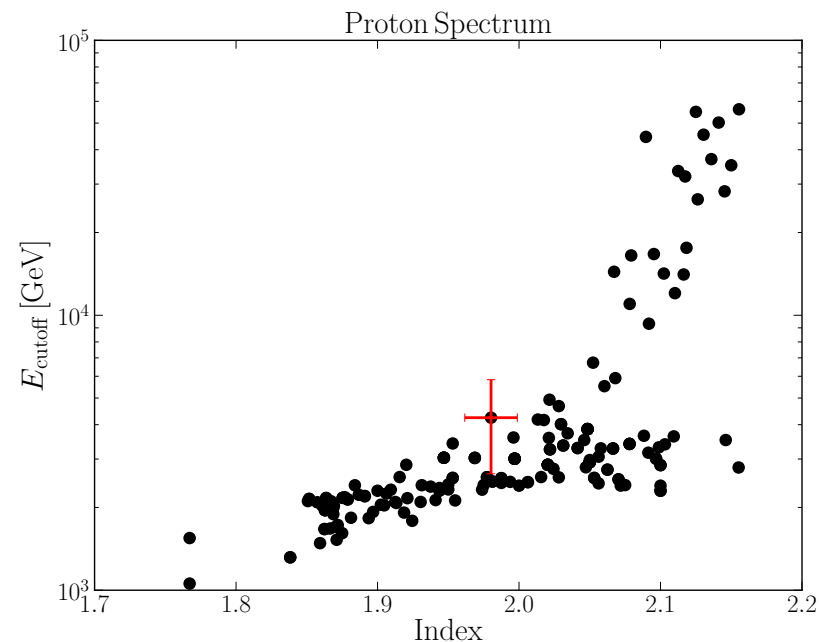
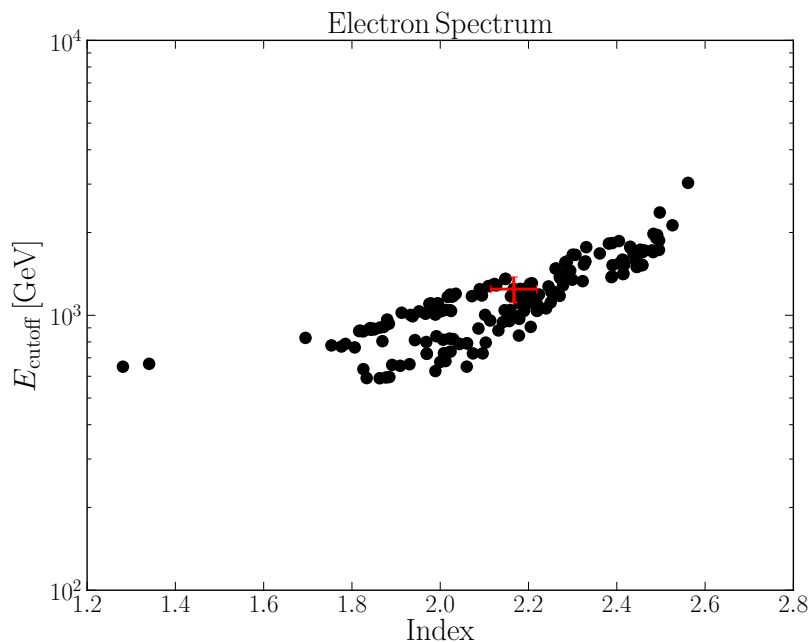


Comparison to local spectra





- **Electron and proton spectral parameter**



Energy in electrons

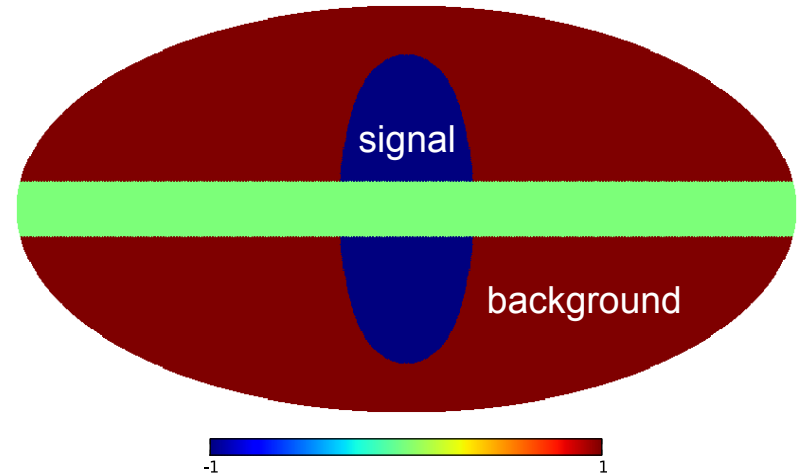
$$(1.0 \pm 0.2[\text{stat}]_{-1.0}^{+6.0}[\text{syst}]) \times 10^{52} \text{ erg}$$

Energy in protons

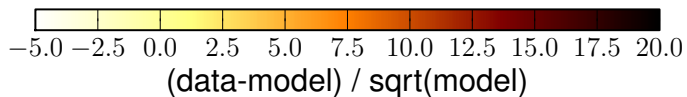
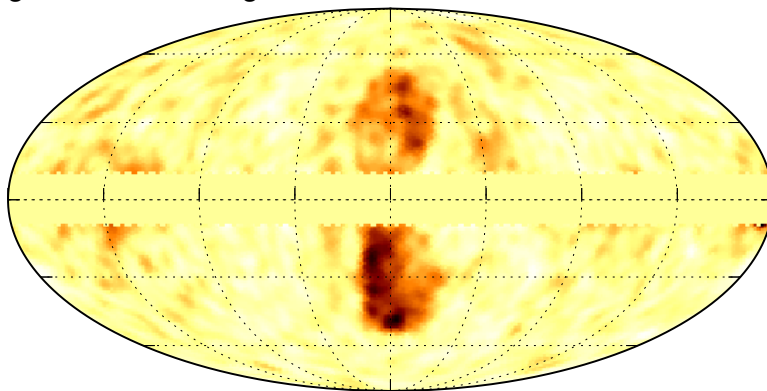
$$(3.5 \pm 0.1[\text{stat}]_{-3.0}^{+4.7}[\text{syst}]) \times 10^{55} \left(\frac{0.01 \text{ cm}^{-3}}{n_{\text{H}}} \right) \text{ erg}$$



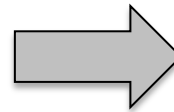
- All-sky fit including all diffuse model templates BUT bubble template, signal region masked
- Define bubble template from residuals (integrated from 6.4 to 300 GeV)



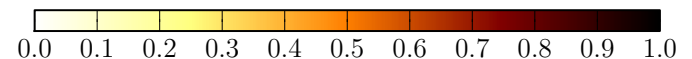
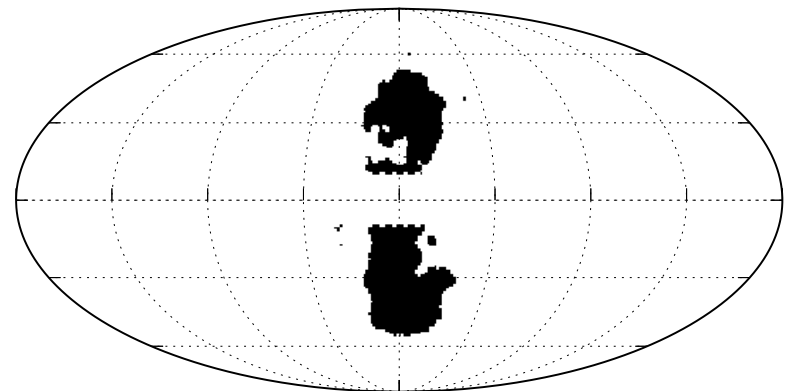
Significance of integrated residuals for $E = 6.4 - 289.6$ GeV

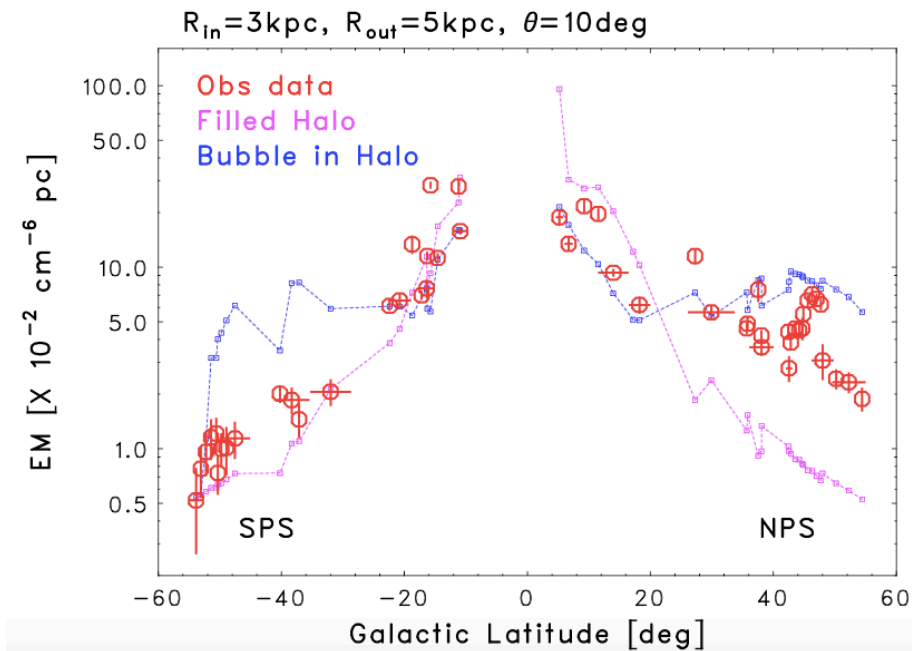
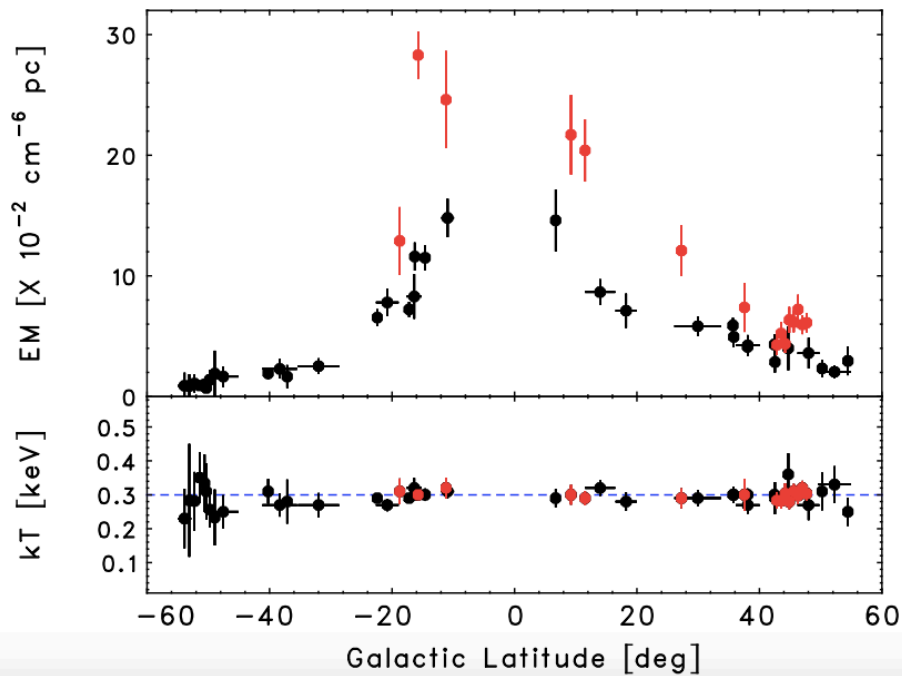


apply
threshold



Bubbles Template Flat (residual map, $3.0 \sigma_{BG}$ cut)

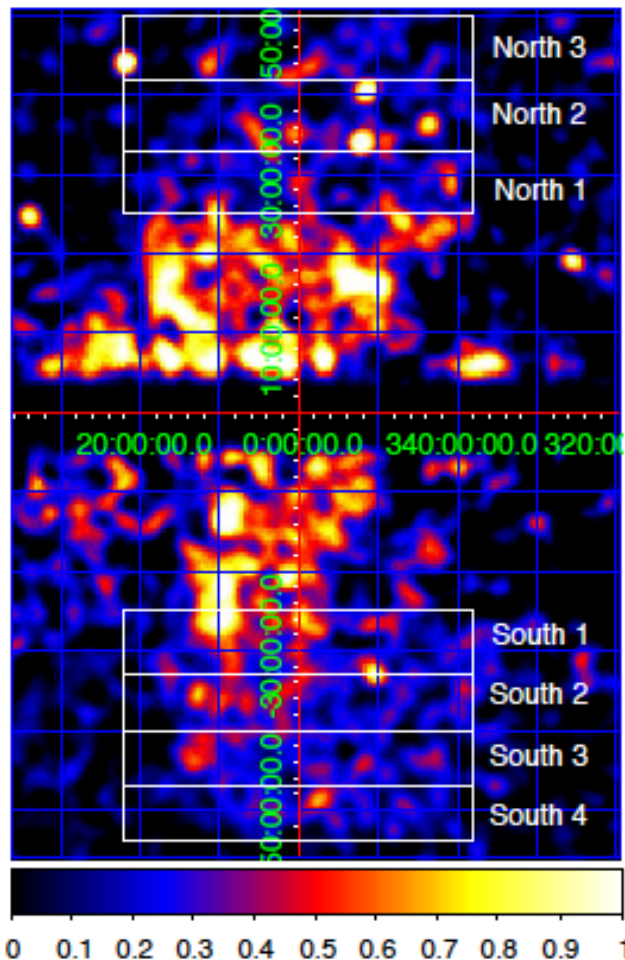




Kataoka et al. 2015



- Yang et al. A&A 567 (2014) claim 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

