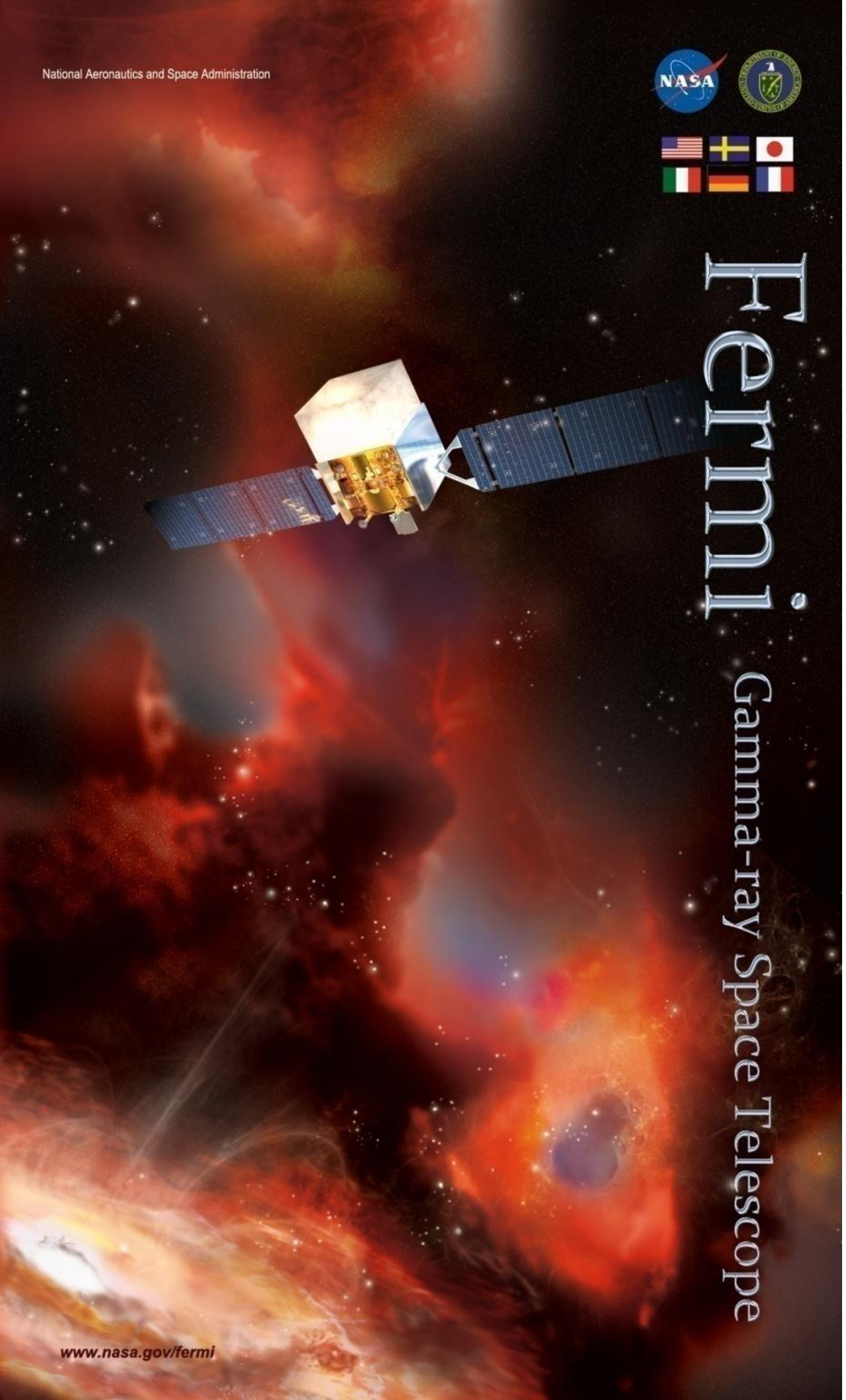


Los Alamos NATIONAL LABORATORY EST. 1943

Fermi Gamma-ray Space Telescope

Characterization of the Fermi Bubbles and the GeV Excess

Andrea Albert
(Los Alamos Ntl. Lab)
Dmitry Malyshev, Anna Franckowiak, Luigi Tibaldo, Eric Charles
On behalf of the Fermi-LAT Collaboration

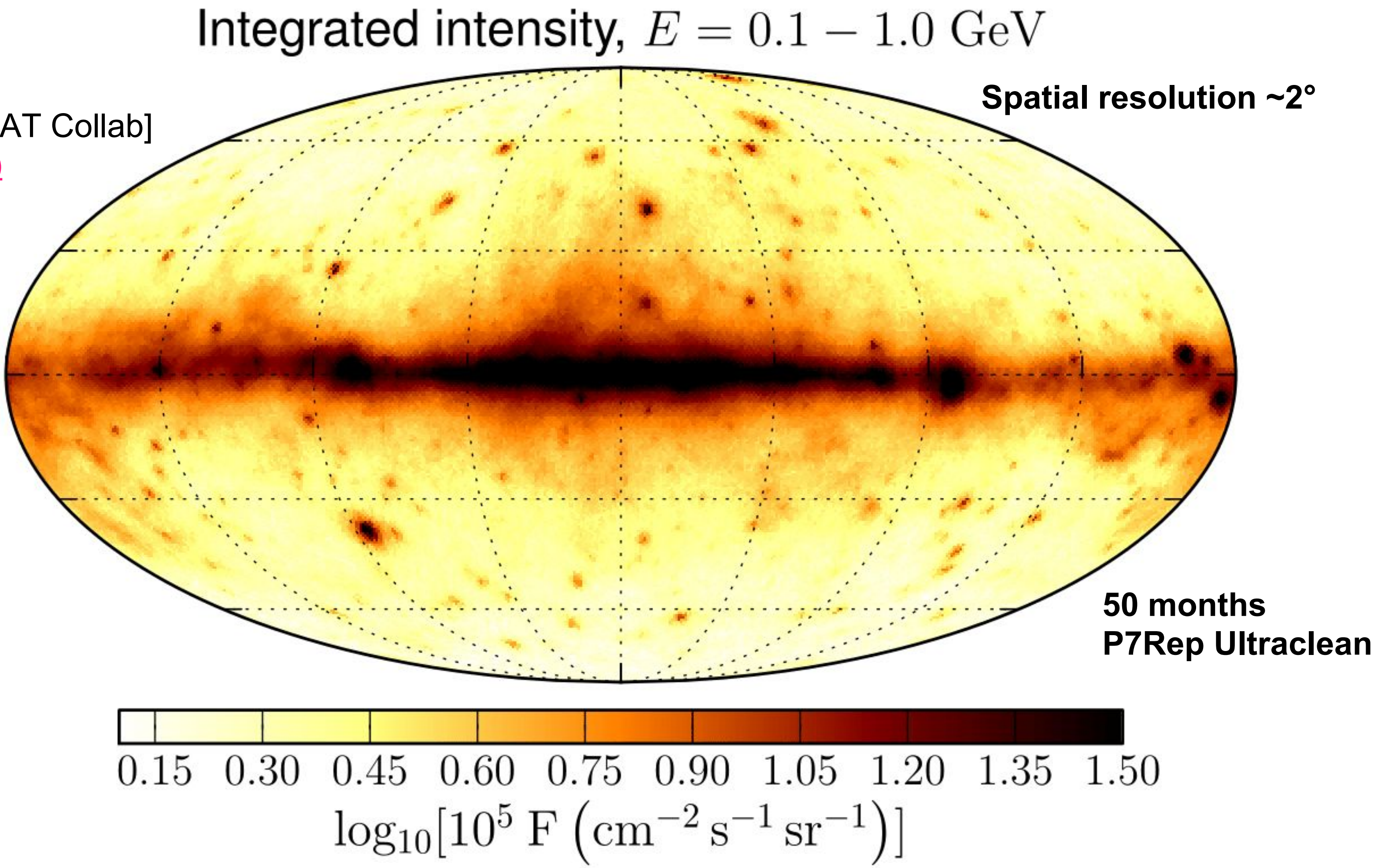
IAU Symposium 322

The Multi-Messenger Astrophysics of the Galactic Center

Thursday July 21, 2016

The GeV Sky

Ackermann+ [LAT Collab]
ApJ 793 (2014)

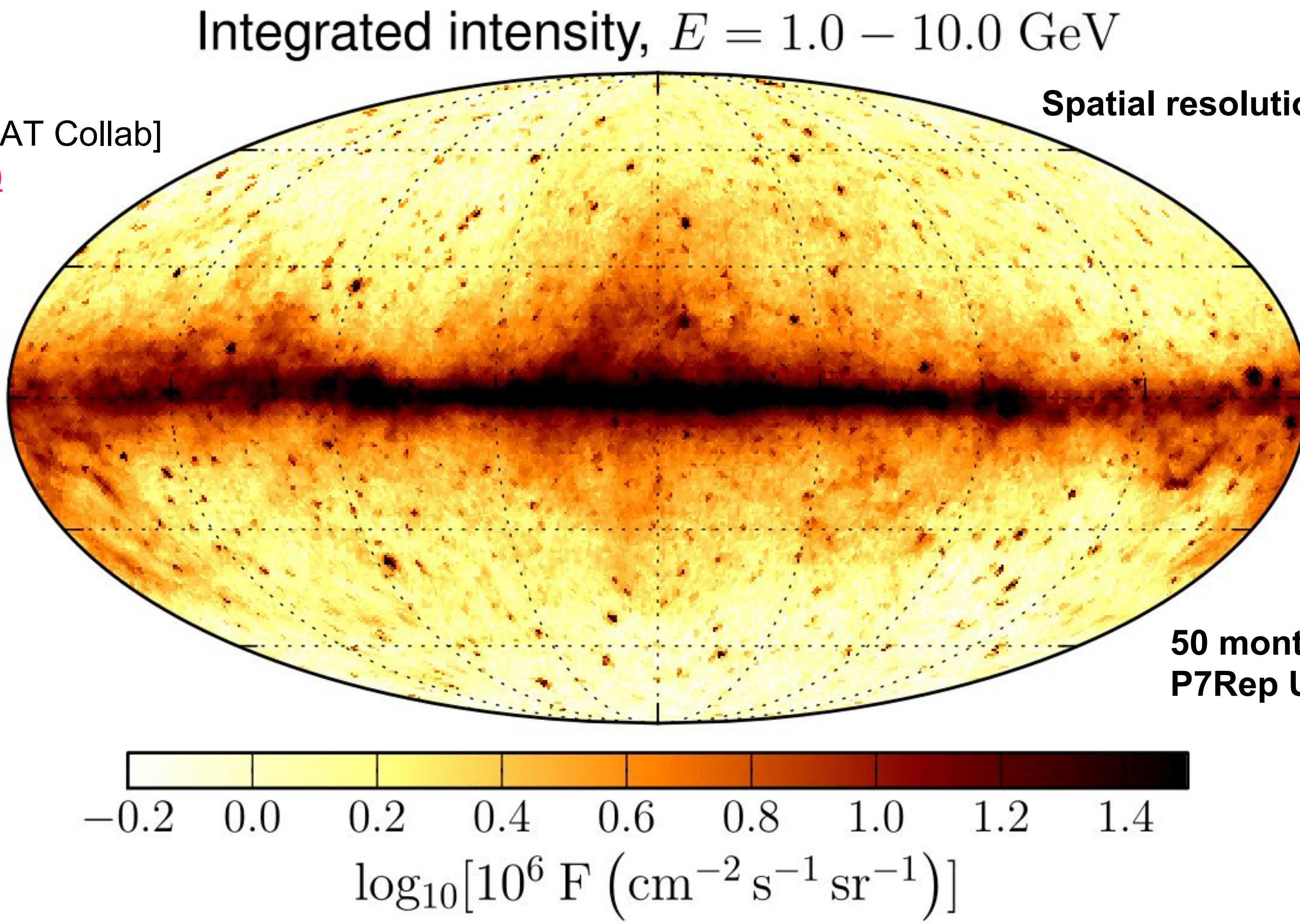


- **The Fermi Large Area Telescope has been observing the gamma-sky from 20 MeV to >300 GeV for over 8 years**
- **Large field of view + survey mode has revealed the entire GeV sky with unprecedented sensitivity**

The GeV Sky

Ackermann+ [LAT Collab]
[ApJ 793 (2014)]

Spatial resolution ~0.4°



50 months
P7Rep Ultraclean

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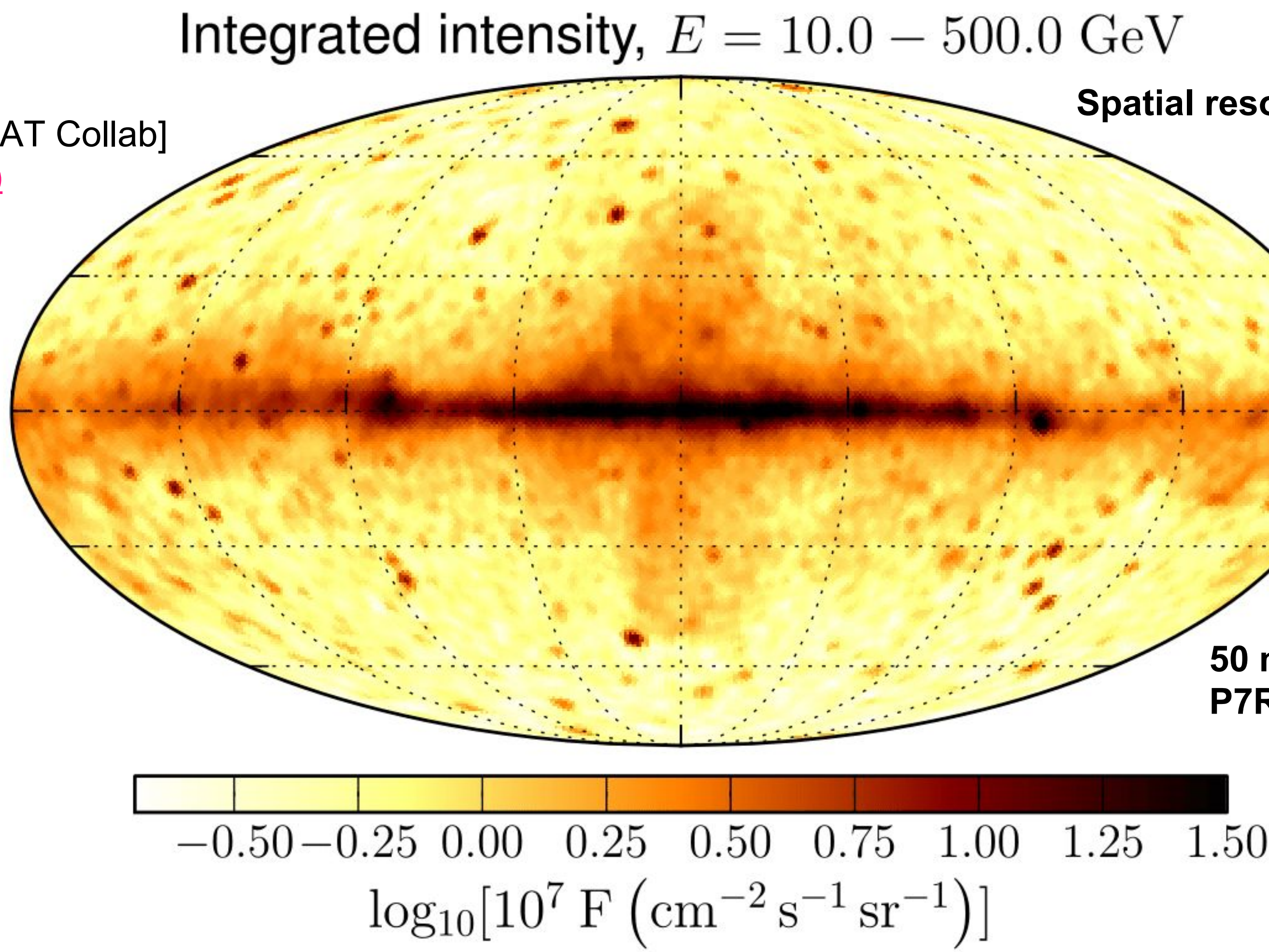

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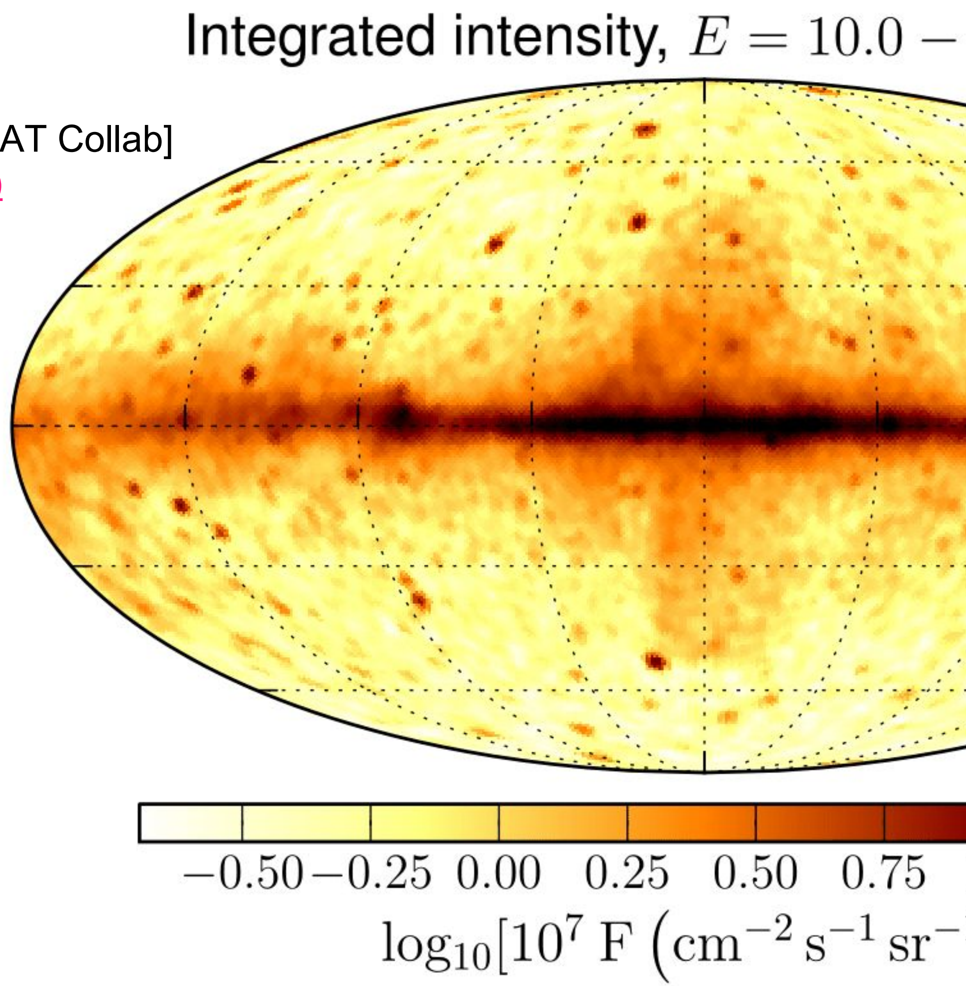
Fermi Bubbles: The Elephant in the Room/Sky

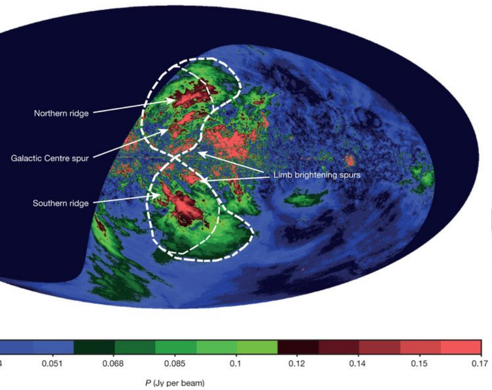
Ackermann+ [LAT Collab]
ApJ 793 (2014)

50 months
P7Rep Ultraclean

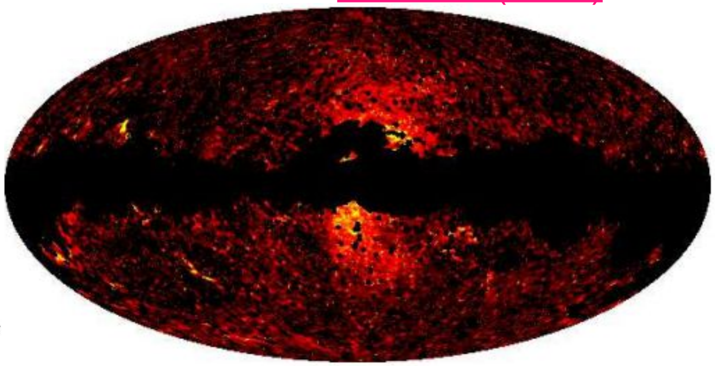


- **Above 10 GeV, a large, unexpected excess is apparent**
  - **Discovery reported in Su, Slatyer, Finkbeiner ApJ 724 (2010)**
- **Bubbles' solid angle is comparable to an elephant viewed at 3 meters**

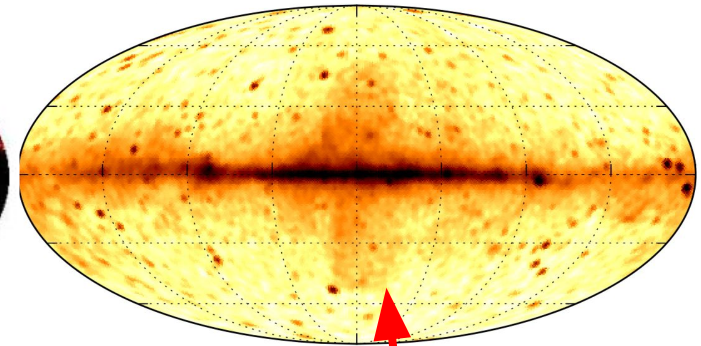
Multiwavelength Evidence of Galactic Haze



Planck Collab A&A 554 (2010)



LAT Collab ApJ 793 (2014)



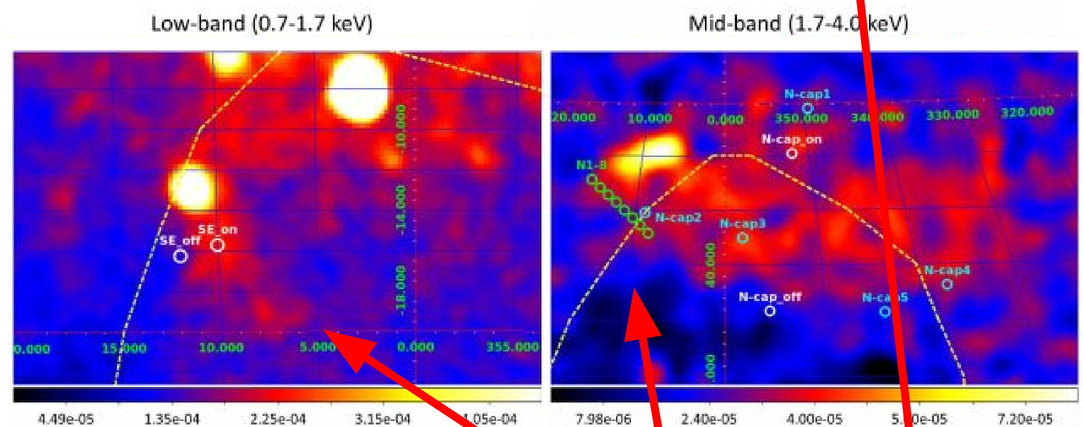
S-PASS 2.3 GHz polarized lobes

Carretti+ Nature 493 (2013)

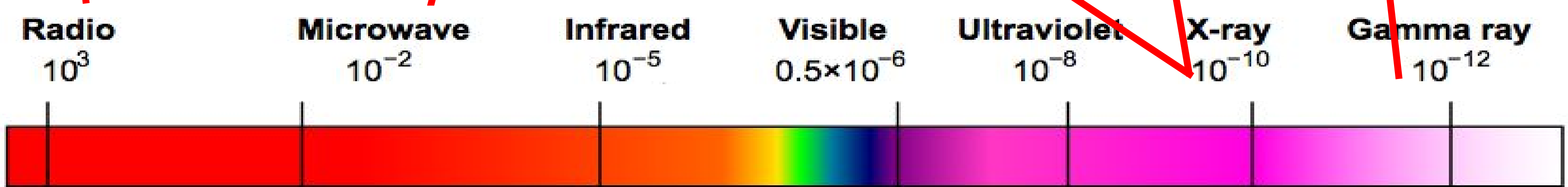
Microwave Haze detected by WMAP and Planck

Fermi Gamma-ray Bubbles

Possible X-ray counterparts seen with Suzaku to northern and southern edges (southern edge possibly seen by ROSAT)



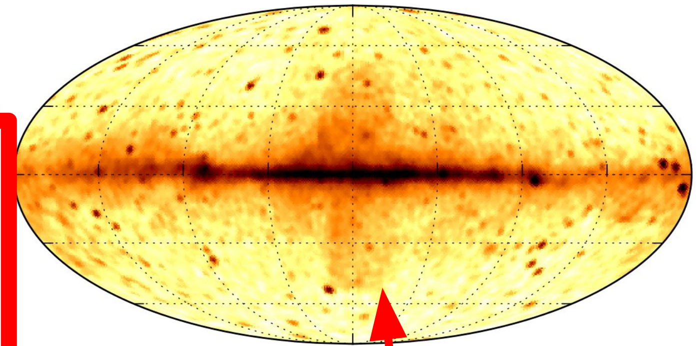
Tahara+ ApJ 802 (2015)



Multiwavelength Evidence of Galactic Haze

Planck Collab A&A 554 (2010)

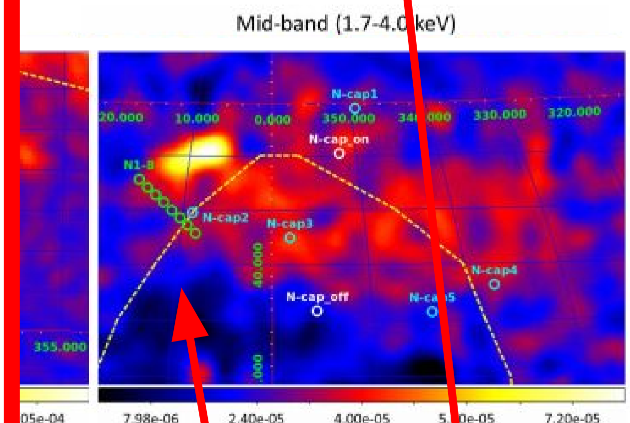
LAT Collab ApJ 793 (2014)



Fermi Gamma-ray Bubbles

- I will focus on a detailed study performed by the LAT Collaboration ApJ 793 (2014)
  - Characterize the spectrum and morphology given diffuse emission modeling uncertainties
  - Explore modeling uncertainties with GALPROP and local template analysis

- Other independent studies of gamma-ray bubbles have also been performed e.g.
  - Su, Slatyer, Finkbeiner ApJ 724 (2010)
  - Hooper & Slatyer Phys. Dark Uni. 2 (2013)
  - Yang, Aharonian, Crocker A&A 567 (2014)



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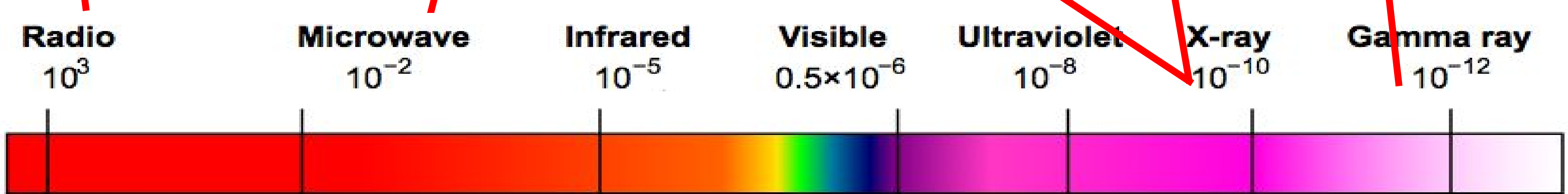
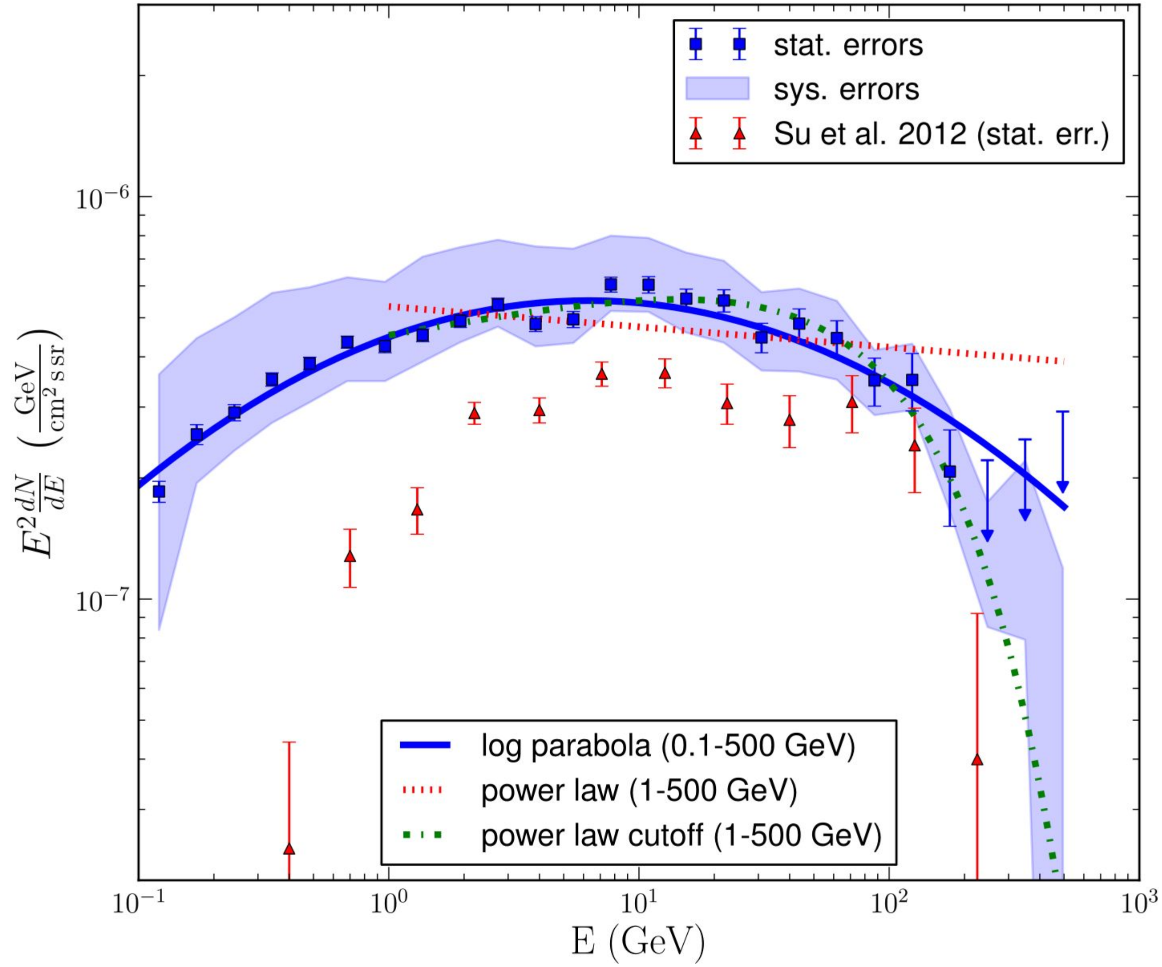
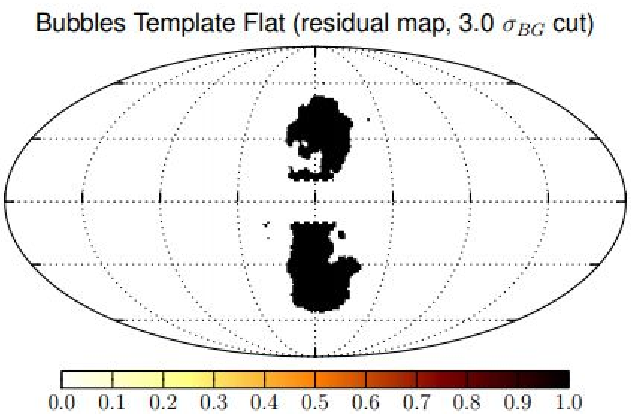


Fermi Bubbles: Spectrum



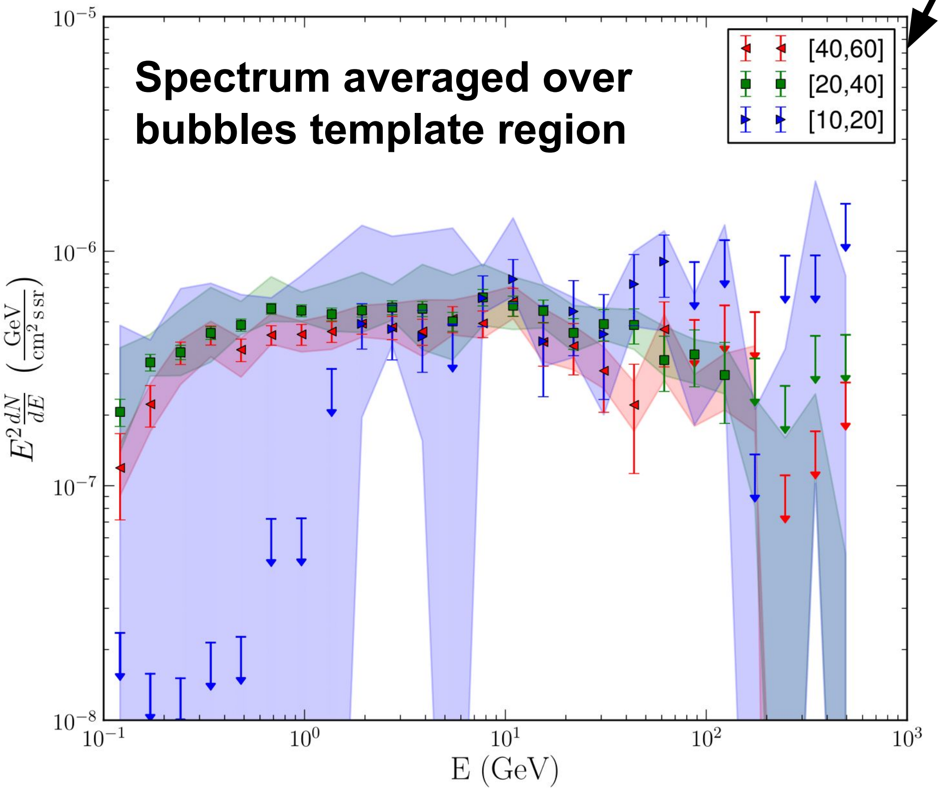
Spectrum averaged over bubbles template region

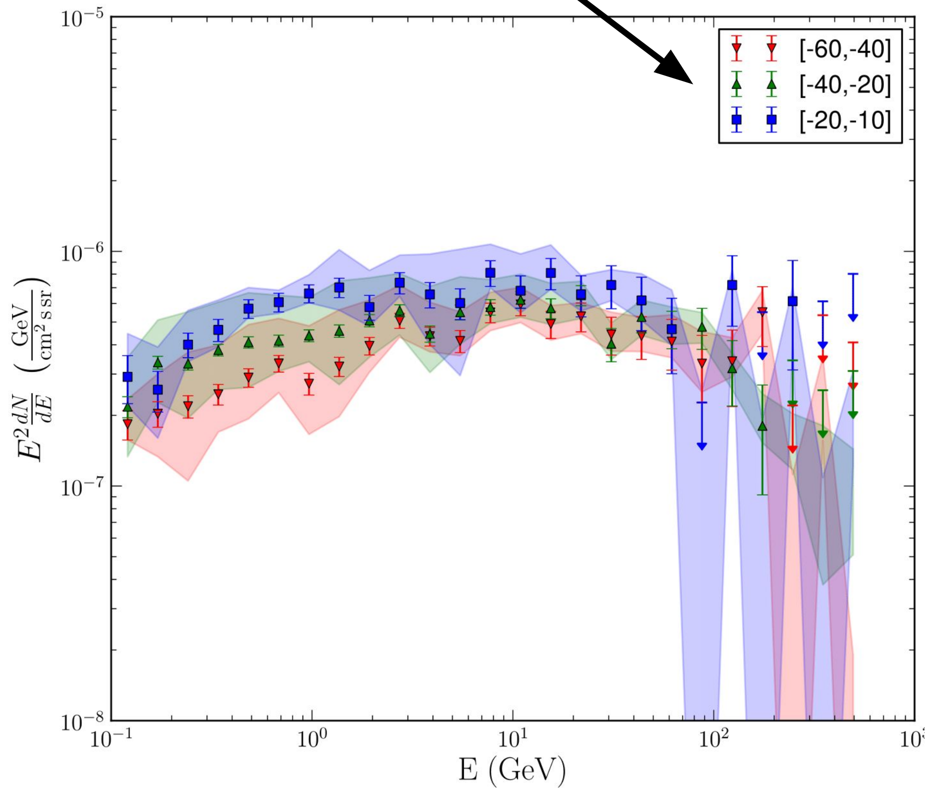


- **Luminosity** $(4.4 \pm 0.1[\mathrm{stat}]^{+2.4}_{-0.9}[\mathrm{syst}]) \times 10^{37}\ \mathrm{erg\ s^{-1}}$
- **Index** $\gamma = 1.87 \pm 0.02[\mathrm{stat}]^{+0.14}_{-0.17}[\mathrm{syst}]$
- **Cutoff Energy** $E_{\mathrm{cut}} = 113 \pm 19[\mathrm{stat}]^{+45}_{-53}[\mathrm{syst}]$ GeV

Fermi Bubbles: Spectrum

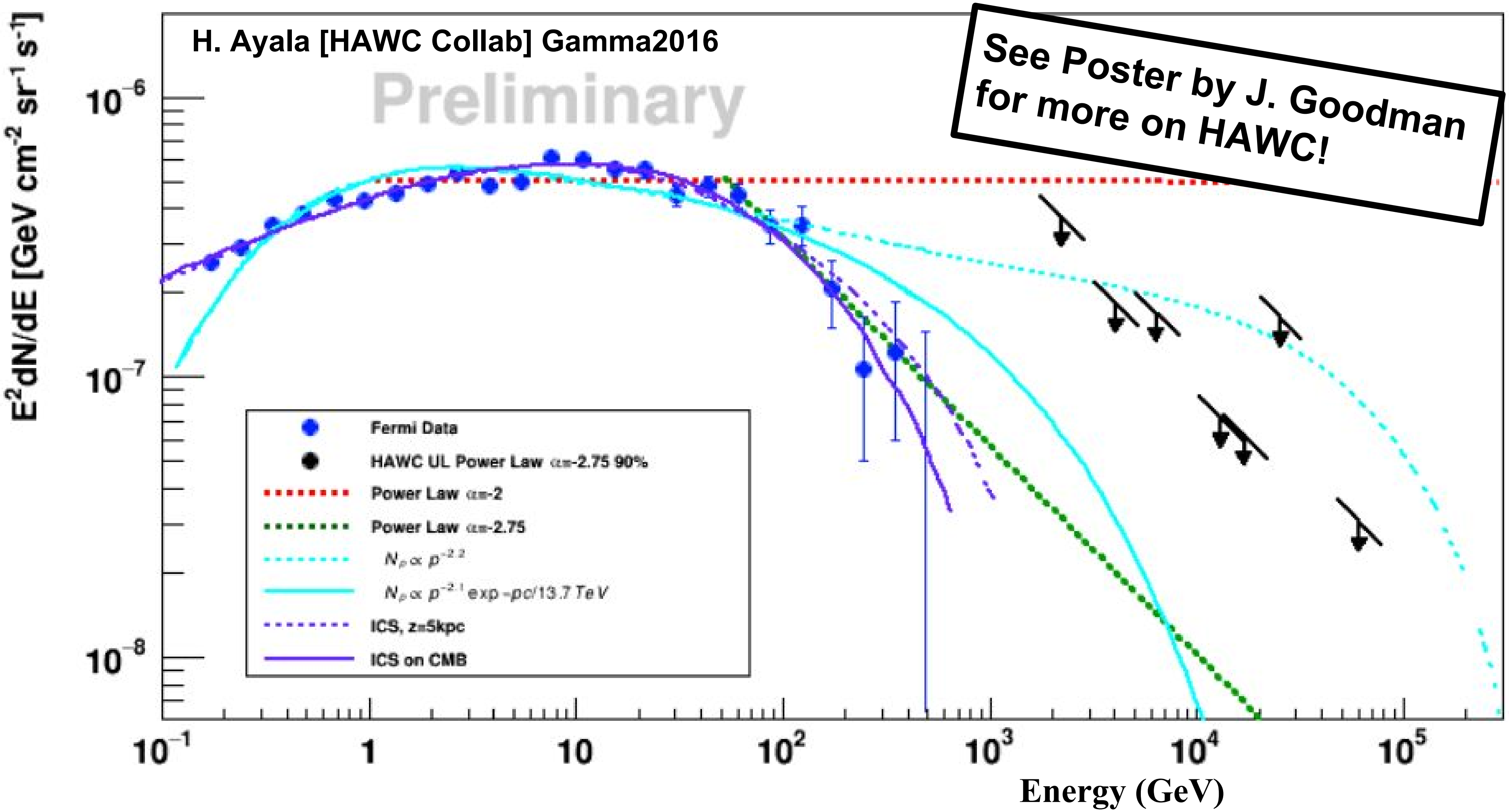
Latitude bins in degrees





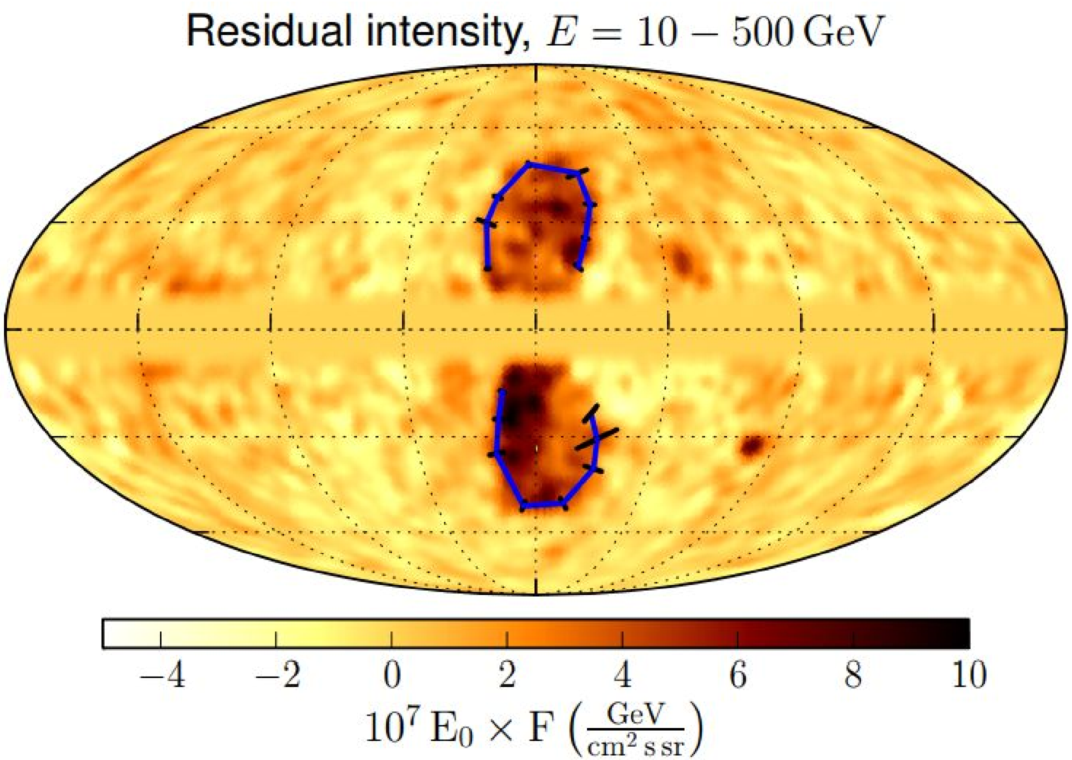
- **No significant spectral variations with latitude at |b| > 10°**

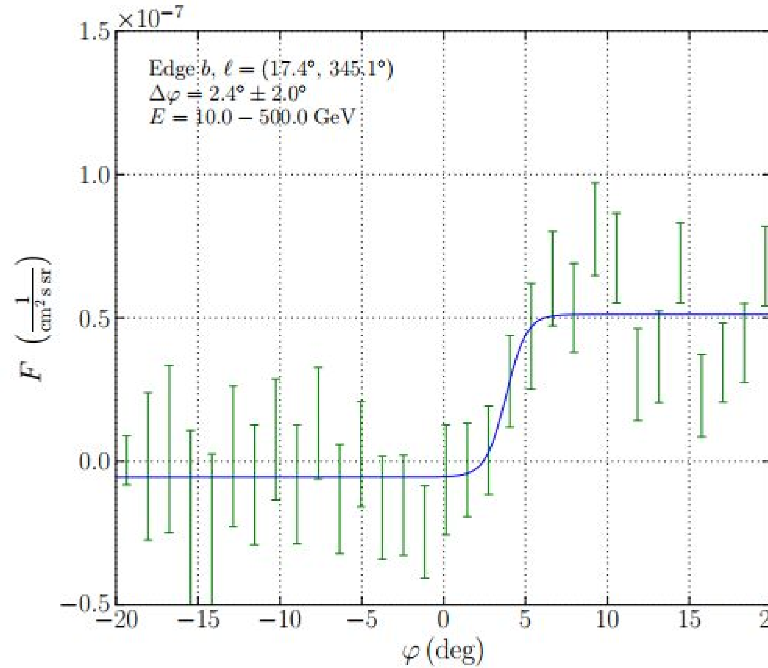
Search for TeV Fermi Bubbles with HAWC



- Search for TeV emission with High Altitude Water Cherenkov Obs
  - Large FoV (~2 sr) and ~100% duty cycle
  - Ideal for large, extended gamma-ray sources

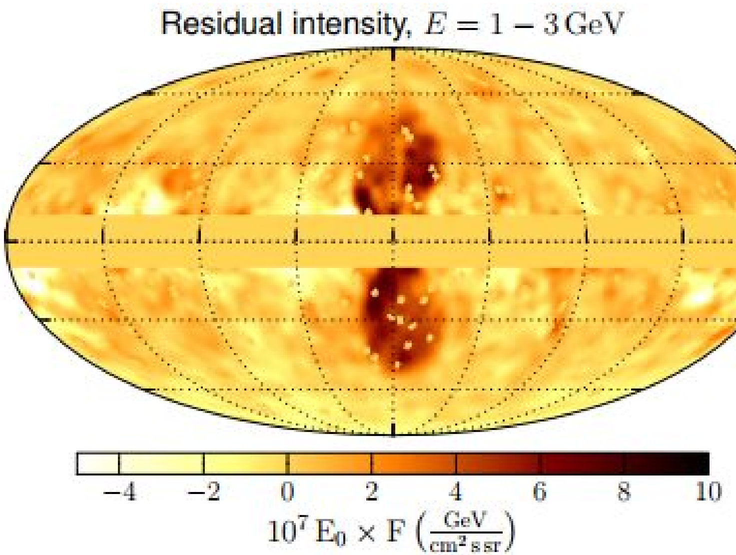
Fermi Bubbles: Morphology

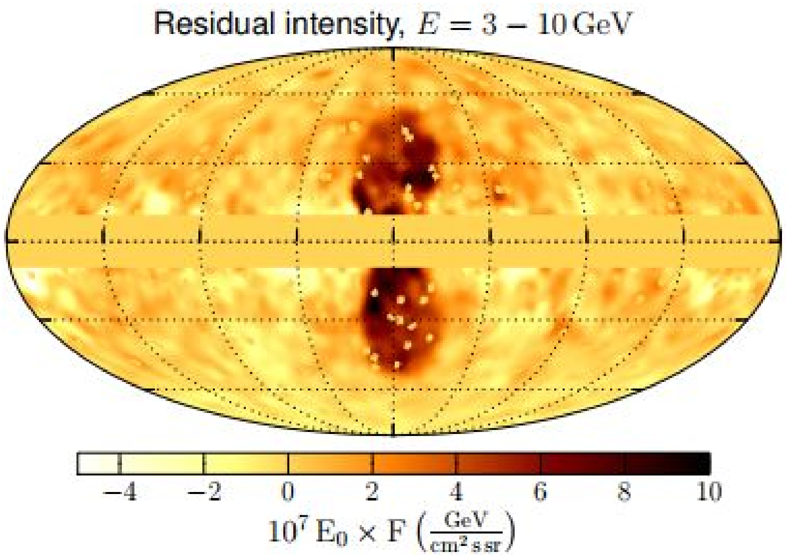


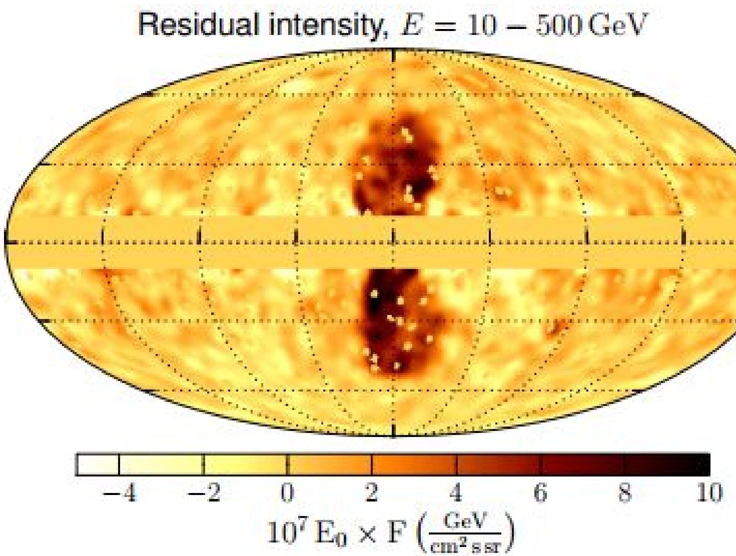


- Both northern and southern lobes have sharp edges
  - Width is 3.4°+3.7°-2.6°
- Southern lobe has brighter "cocoon"
  - Cocoon has similar spectrum to the rest of the bubbles
  - No evidence of jets found

Fermi Bubbles: Morphology



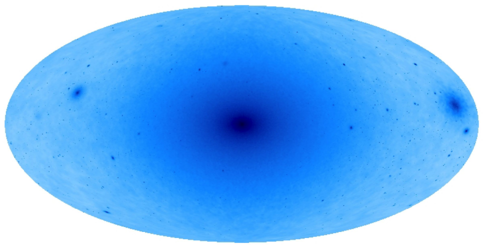




- **No change in morphology observed at different energies**

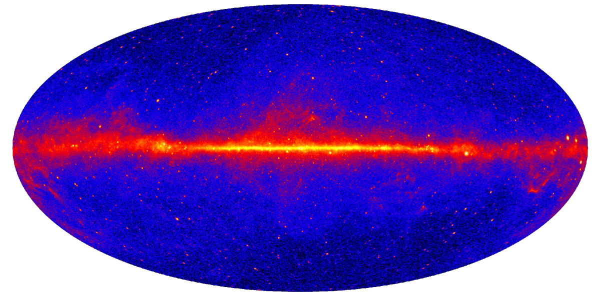
Now for another interesting excess

Dark matter annihilation in the Galactic center?



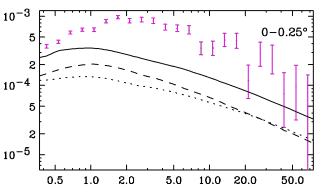
Via Lactea II, Kuhlen et al., Science 325:970-973,2009

?

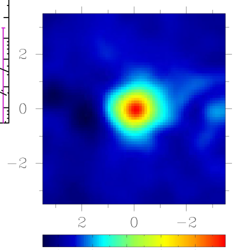


Fermi LAT >1 GeV, 6 years, Pass 8 data

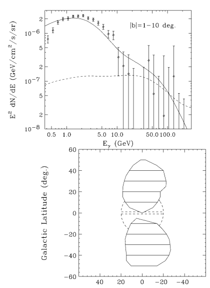
Excess emission spectrum peaks around 3 GeV



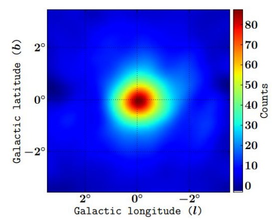
Goodenough & Hooper Phys.Lett. B697 (2011)



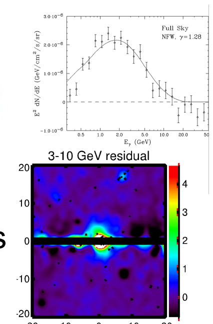
Abazajian & Kaplinghat PRD 87 129902 (2012)



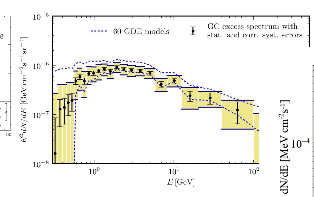
Hooper & Slatyer Phys.Dark Univ. 2 (2013)



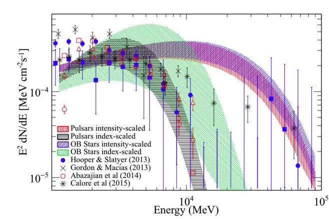
Gordon & Macias PRD 88, 083521 (2013)



Daylan et al. Phys. Dark Univ. 12 (2016)



Calore et al. JCAP 1503 (2015)



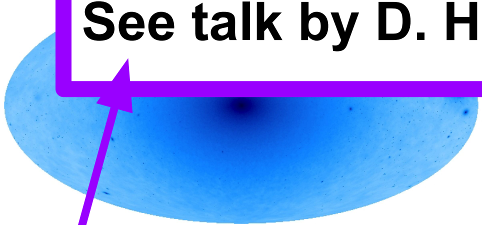
Ajello et al. (The Fermi-LAT Collaboration) ApJ 819 1 44 (2016)

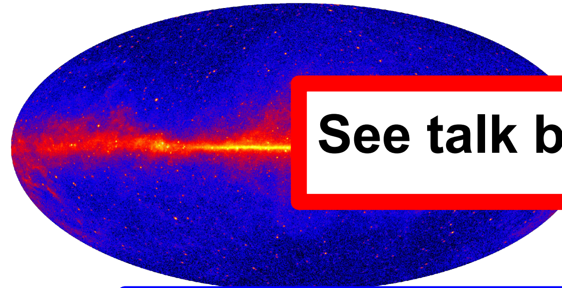
Dark matter annihilation, unresolved sources, CR electrons?

- **Mirabal** (MNRAS 436 (2013) 2461), **Petrovic et al.** (JCAP 1502 (2015) 02,023), **Cholis et al.** (JCAP 1512 (2015) 12, 005), **Lee et al.** (PRL 116 051103 (2016)), **Bartels et al.** (PRL 116 051102 (2016)), **Brandt & Kocsis** (ApJ 812 (2015) 1, 15), **Carlson et al.** (arXiv:1510.04698) **etc.**

Dark matter annihilation in the Galactic center?

See talk by D. Hooper





See talk by S. Murgia

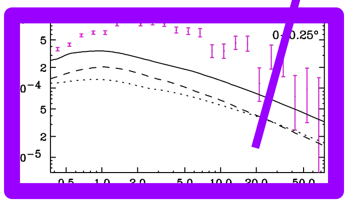
Via Lactea II, Kuhlen et al., Science

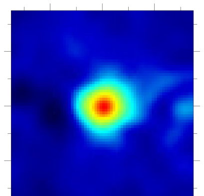
See talk by C. Gordon

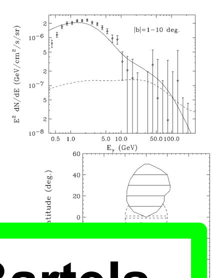
Ferr data

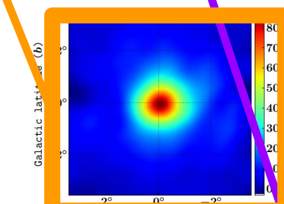
See talk by F. Calore

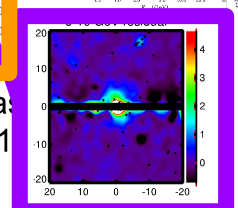
Excess emiss... nd 3 GeV

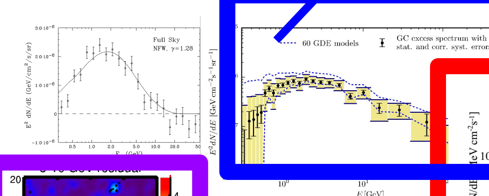


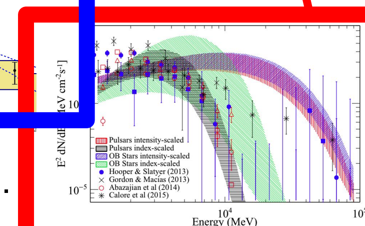












Goodenough & Hooper Phys.Le (2011)

See talk by R. Bartels

PRD 87 129902 (2012)

atyer Phys.Dark Univ. 2 (2013)

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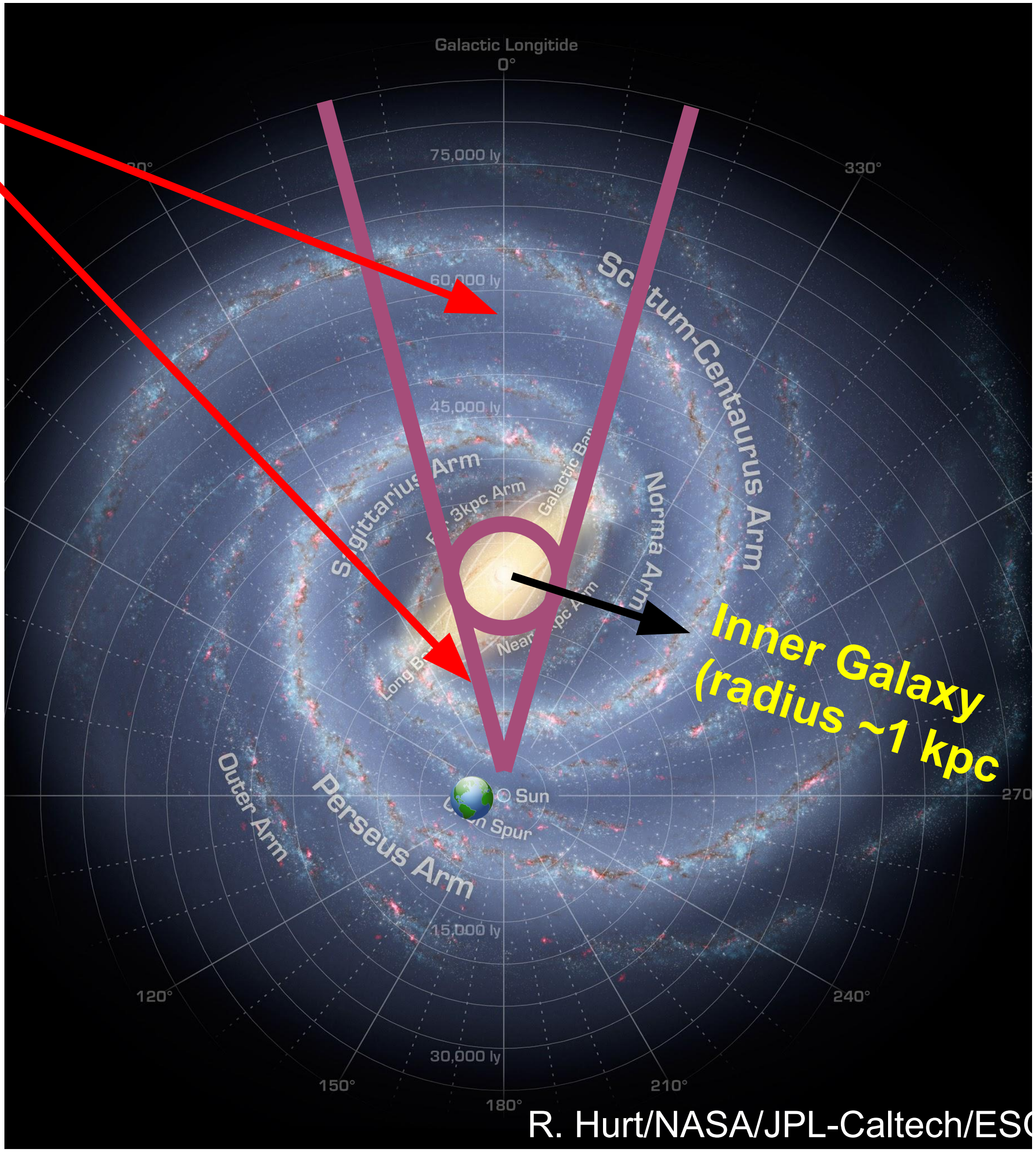
Diffuse Emission Toward the Inner Galaxy is Uncertain

- **Fore/background modeling is critical to studying IG**
  - **~80% of the emission (1-100 GeV in 15°x15° ROI) in the line of sight is from fore/background interstellar emission**
- **Goal: study the effects of varying diffuse emission modeling on the GeV excess**
- **6.5 years of Pass 8 data Ultracleanveto Class zenith angle < 90°**
- **100 MeV – 1 TeV**
  - **27 bins in log energy**
- **Binned into HEALPix maps of order 6 / 7 (1° / 0.5°)**
- **All-sky template fitting**



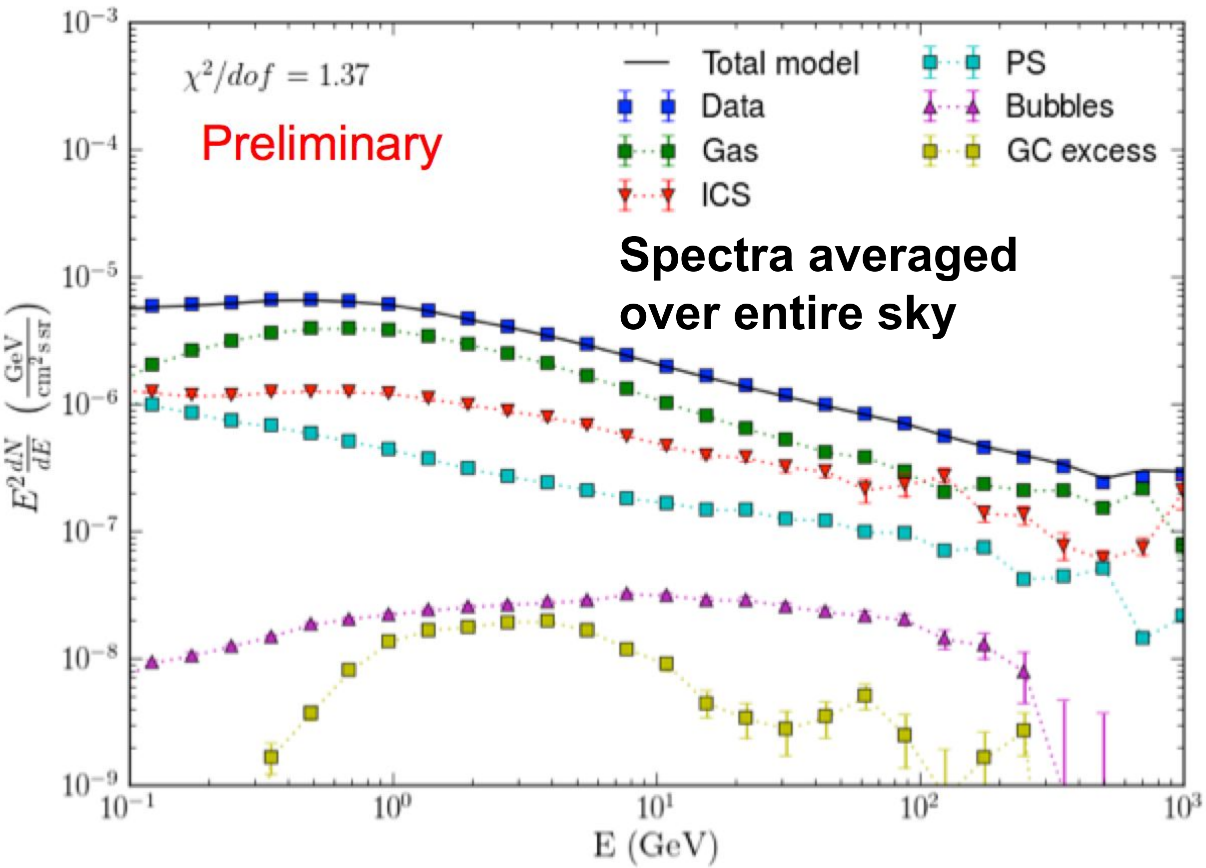
Reference model templates

- Reference (sample) templates:
  - Gas correlated (π^0 decay, bremsstrahlung)
    - Separate H I and CO templates (trace atomic and molecular hydrogen)
      - H I augmented to incorporate dark gas similar to Ackermann et al. 2012, ApJ, 750, 3. Uses Schlegel et al. (1998)
  - Inverse Compton (starlight, IR, CMB)
    - http://galprop.stanford.edu
  - Loop I (Wolleben, ApJ 664 (2007) 349-356)
  - Isotropic
  - Fermi Bubbles (The Fermi-LAT Collaboration, Ackerman et al. ApJ 793 (2014) 1, 64)
  - Point Sources (preliminary 6.5 year list)
    - Derived with 6 years of Pass 8 data
    - The cores of 300 brightest PS are masked
  - Sun / Moon (Fermi-LAT Science Tool gtsuntemp etc.)

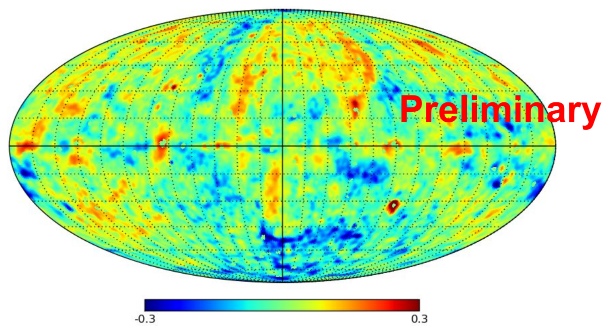
- Excess template:
  - Model as for DM annihilation, generalized NFW profile (gNFW), index 1.25 (slightly contracted)

Reference model templates

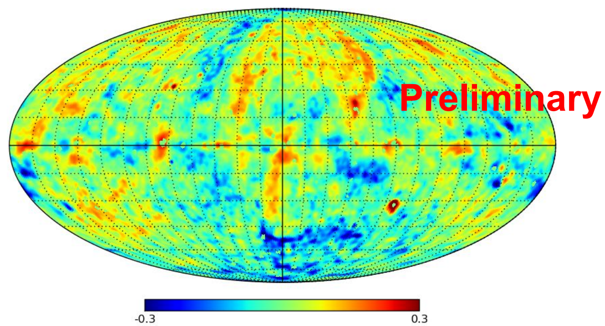
- **Reference (sample) templates:**



Fractional residual, 1.1 – 6.5 GeV



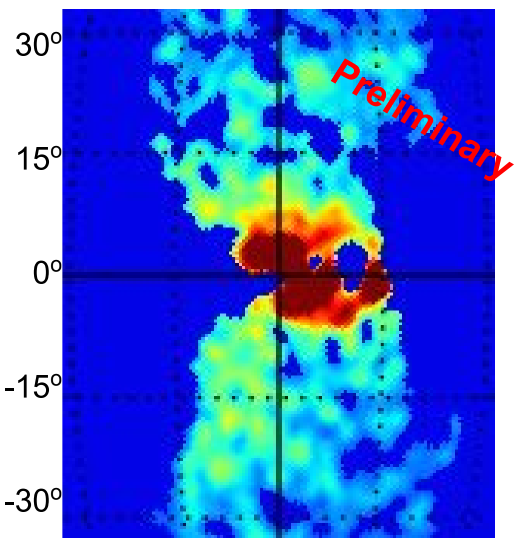
Fractional residual, excess Cusp template added back into residuals

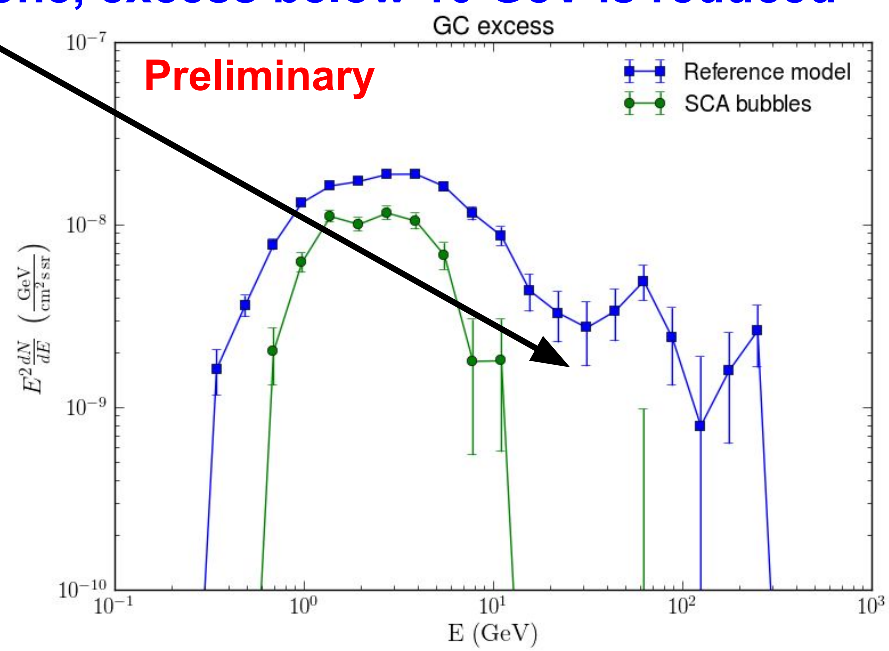


- **Excess template:**
  - **Model as for DM annihilation, generalized NFW profile (gNFW), index 1.25 (slightly contracted)**

Additional & Alternative Templates

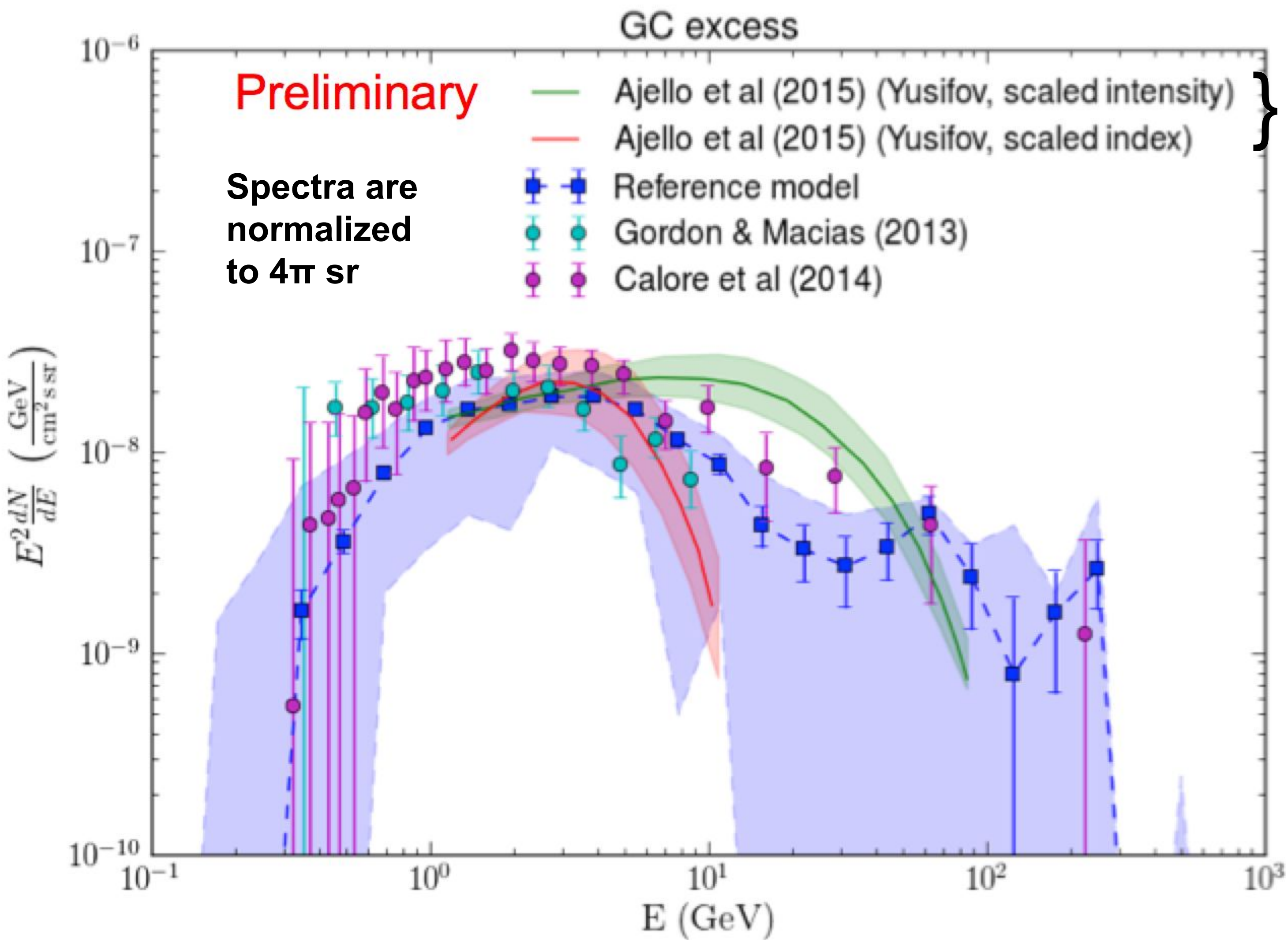
- **Variation of GALPROP model parameters**
  - **Only small effect on spectrum of the GeV excess**
- **Alternative gas maps from 3D dust extinction model** → **Schultheis+ A&A 566 2014**
  - **Softer excess spectrum at low energies (< 1 GeV)**
- **Include additional sources of cosmic-ray electrons in the GC**
  - **Excess flux is reduced**
- **Add data-driven template for low-latitude Fermi Bubbles**
  - **Excess above 10 GeV is gone, excess below 10 GeV is reduced**





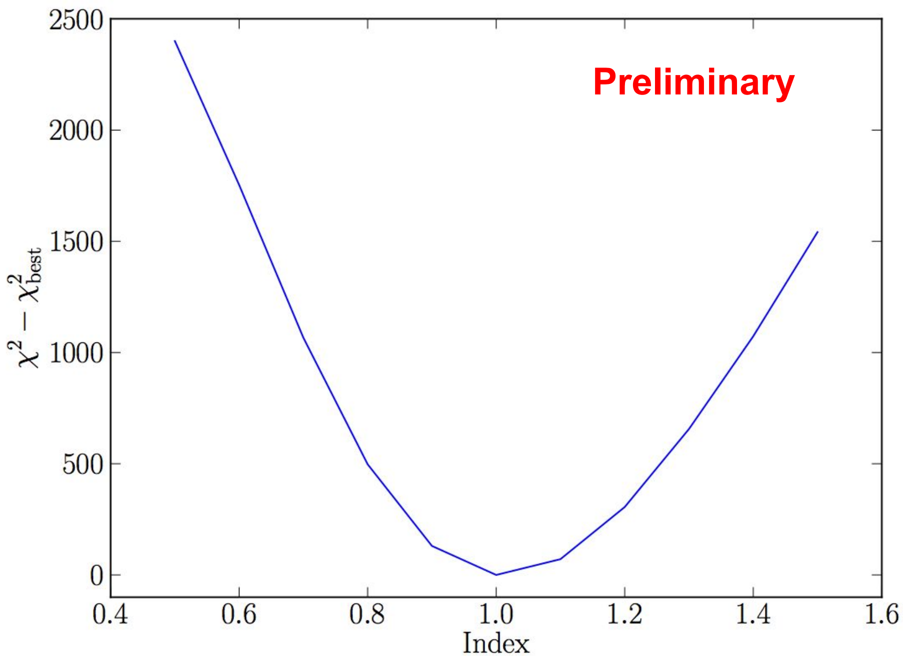
Band of GC excess fluxes

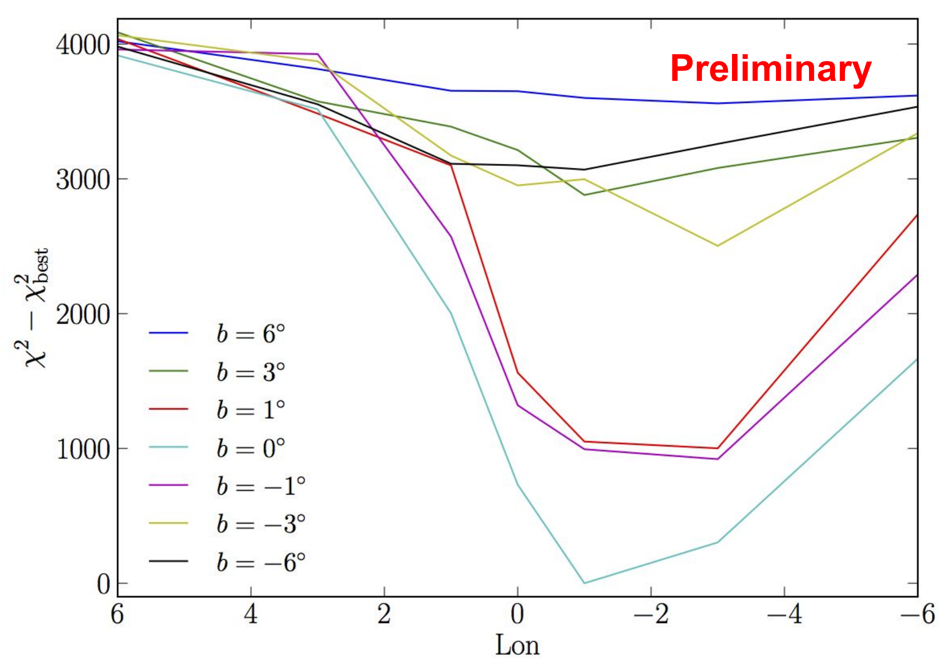
- **The spectrum uncertainty band comes from additions/variations described on previous slide**



Ajello et al.
(The Fermi-LAT Collaboration)
ApJ 819 1 44 (2016)

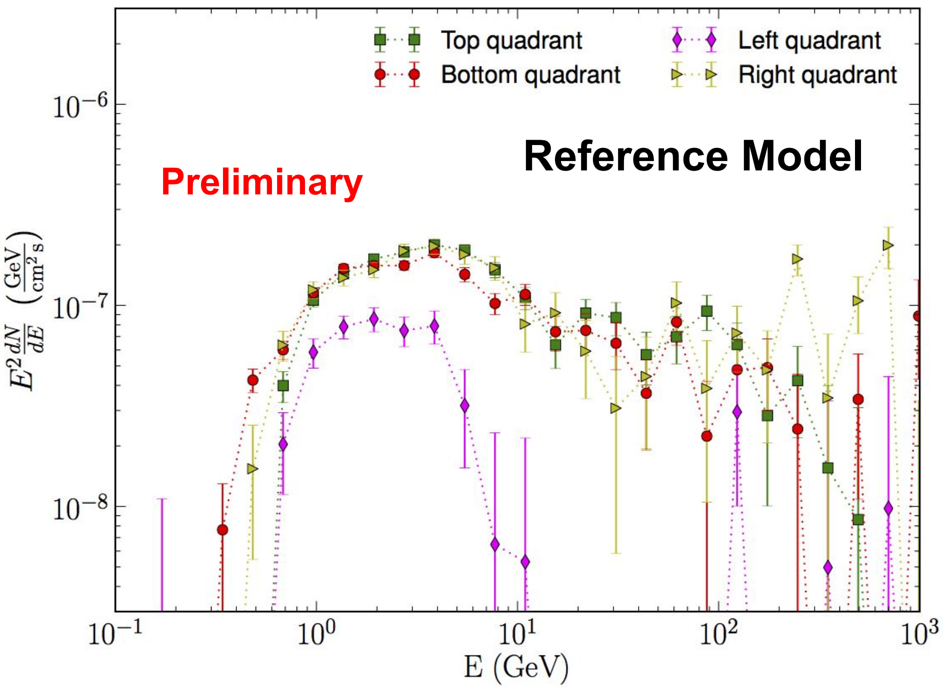
Varying the Cusp Template

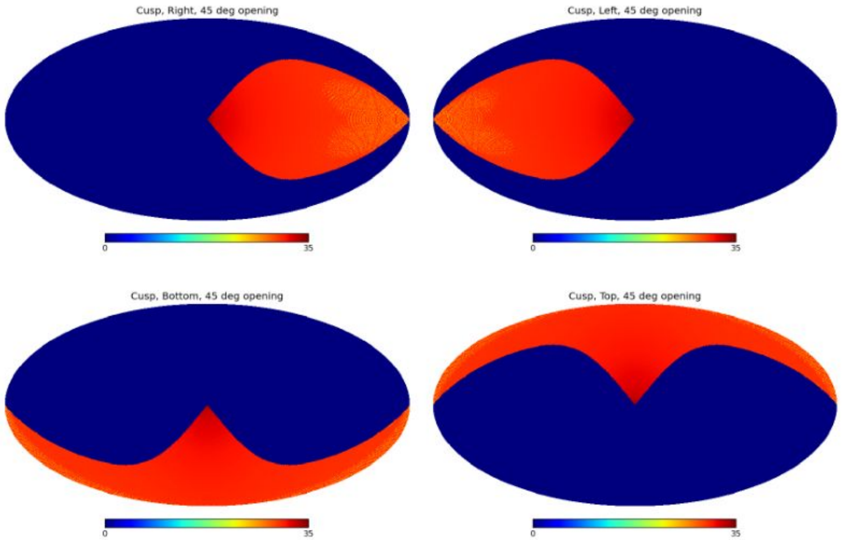




- **All-sky fit using reference model background templates**
- **Fit prefers a standard NFW**
- **Fit prefers Cusp centered in latitude and slightly off-center in longitude**
- **Caution -- χ^2 profiles not marginalized over all background model scenarios**

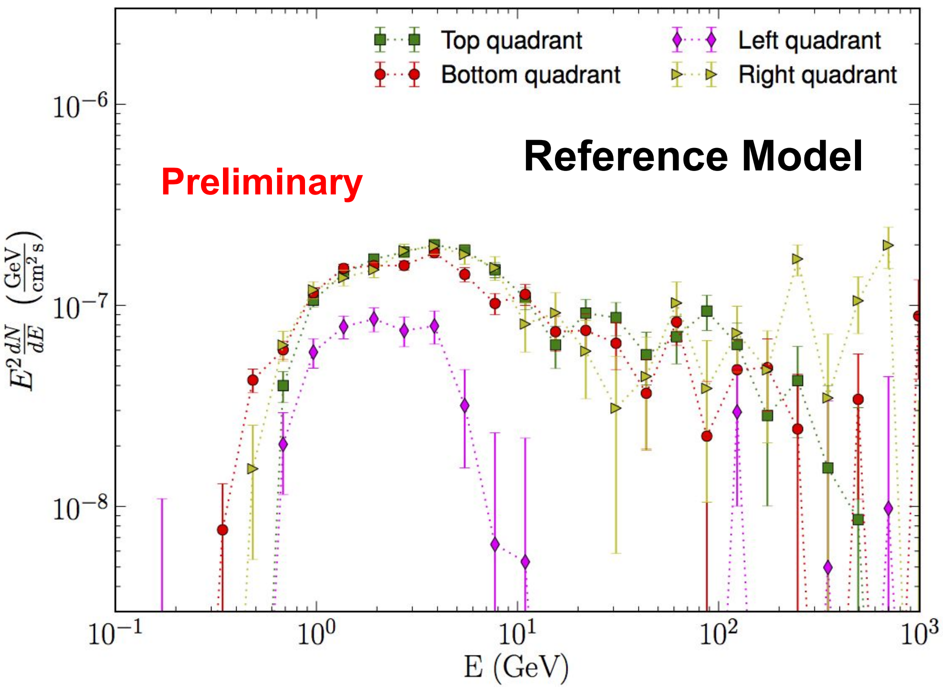
Dividing Cusp Template into Quadrants

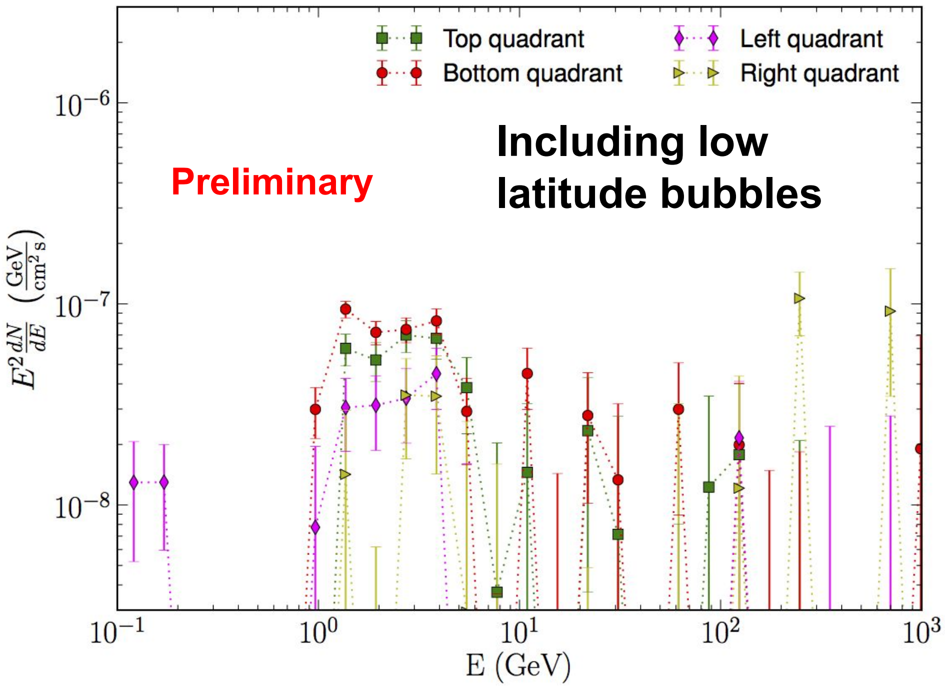




- **All-sky fits using gNFW (index = 1.25) cusp template**
- **In reference model, left quadrant excess spectrum is different**
  - **No high energy tail**
- **When including low latitude bubbles, cusp excess spectrum is similar in all quadrants**

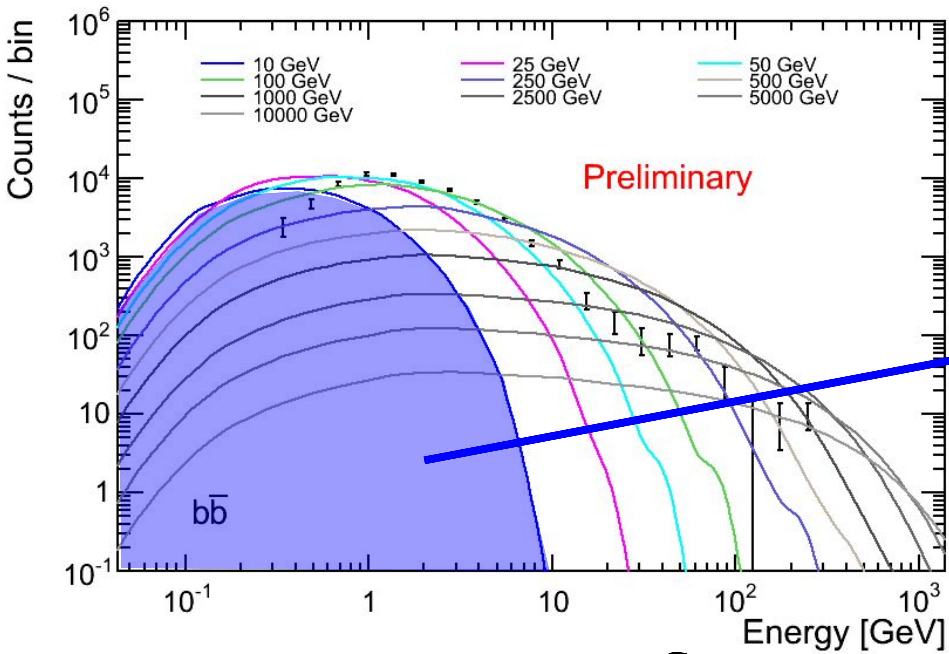
Dividing Cusp Template into Quadrants

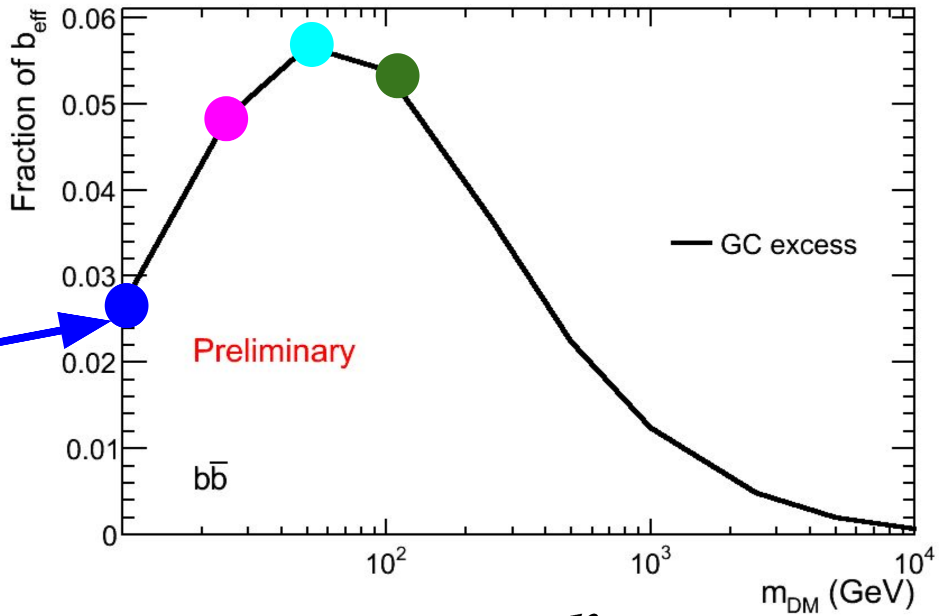




- **All-sky fits using gNFW (index = 1.25) cusp template**
- **In reference model, left quadrant excess spectrum is different**
  - **No high energy tail**
- **When including low latitude bubbles, cusp excess spectrum is similar in all quadrants**

GC Excess -- Fractional Signal

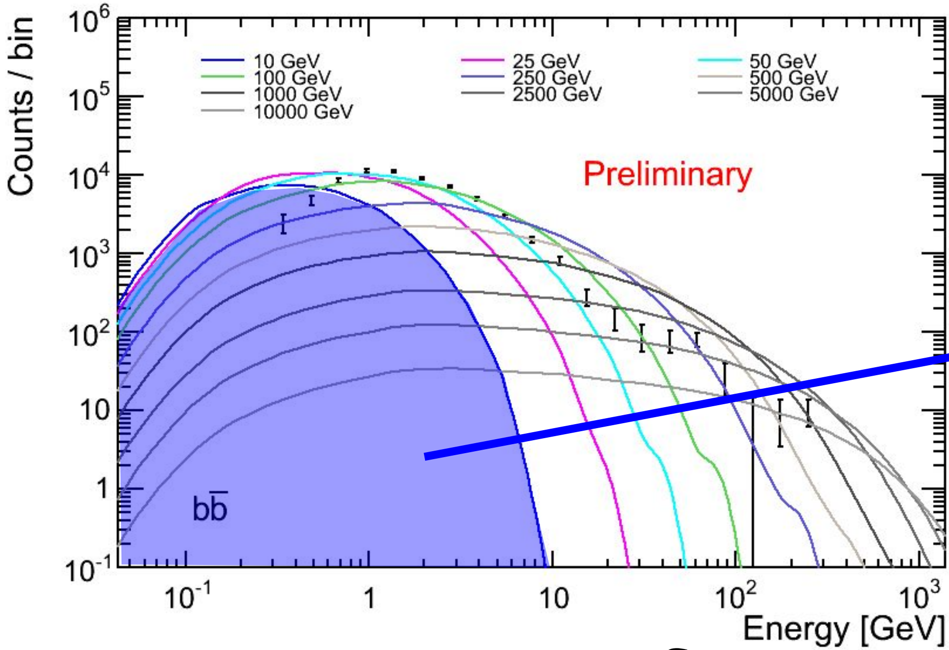


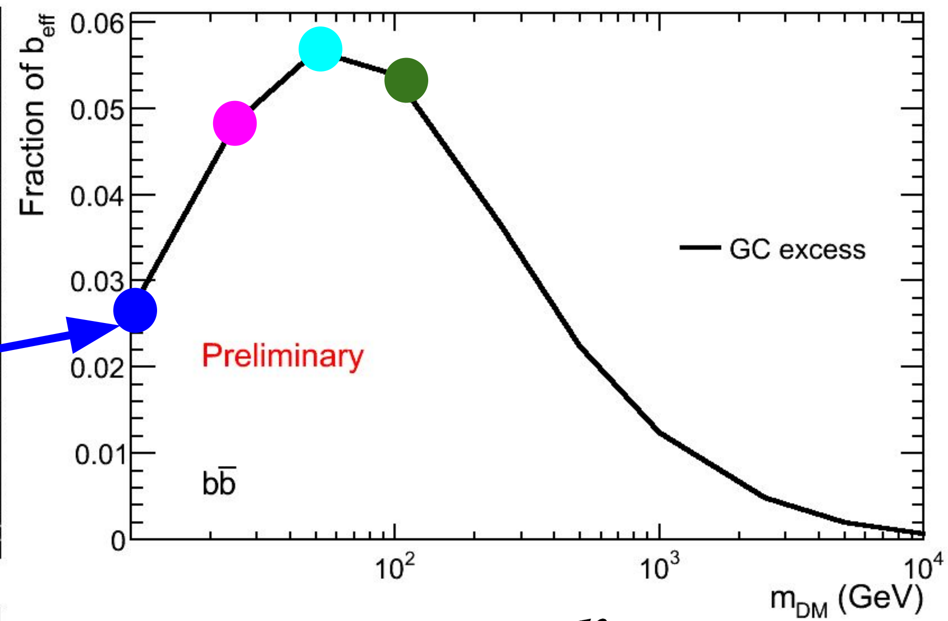


$$f = n_{sig} / b_{eff} \qquad signif \approx \frac{n_{sig}}{\sqrt{b_{eff}}}$$

- **We evaluate the strength of dark-matter-like signals relative to the effective background (b_{eff})**
  - **b_{eff} is the "counts under the signal"**
  - **see backup slide for details on b_{eff}**
    - **also see Buckley et al. PRD 91 10 1020001 (2015) and Ackermann et al. PRD 91 12 122002 (2015)**

GC Excess -- Fractional Signal

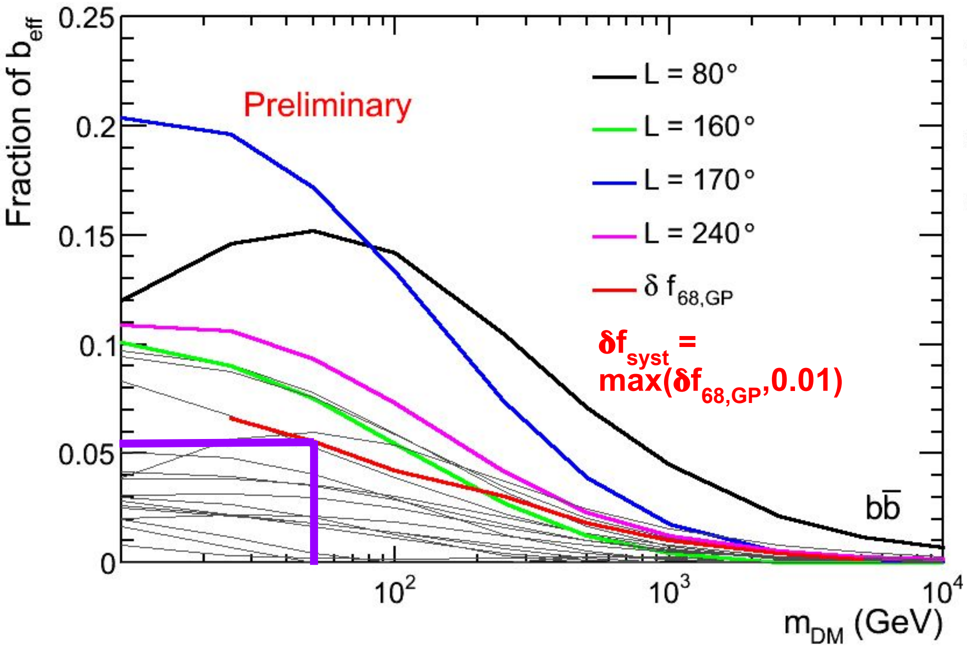


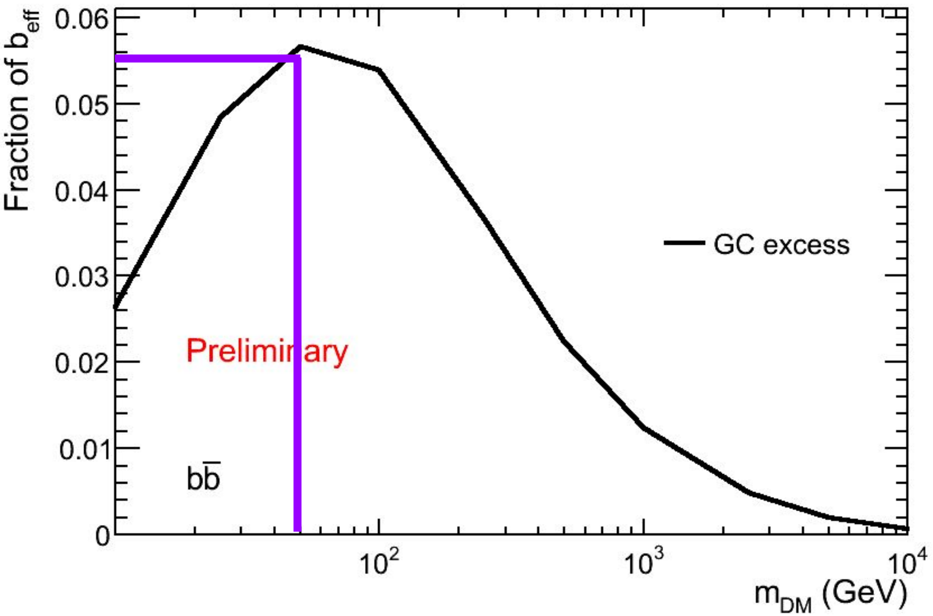


$$f = n_{sig} / b_{eff} \qquad signif \approx \frac{n_{sig}}{\sqrt{b_{eff}}}$$

- **Fit gNFW template in each energy bin independently**
  - **DM models do not provide a good fit to entire excesses**
- **For a specific annihilation channel (e.g. $\chi\chi \rightarrow b\bar{b}$) and DM mass, we find the best fit to the NFWc template spectrum**
  - **Integrate over energy to get total n_{sig}**
- **Galactic Center excess is only a small fraction of b_{eff}**

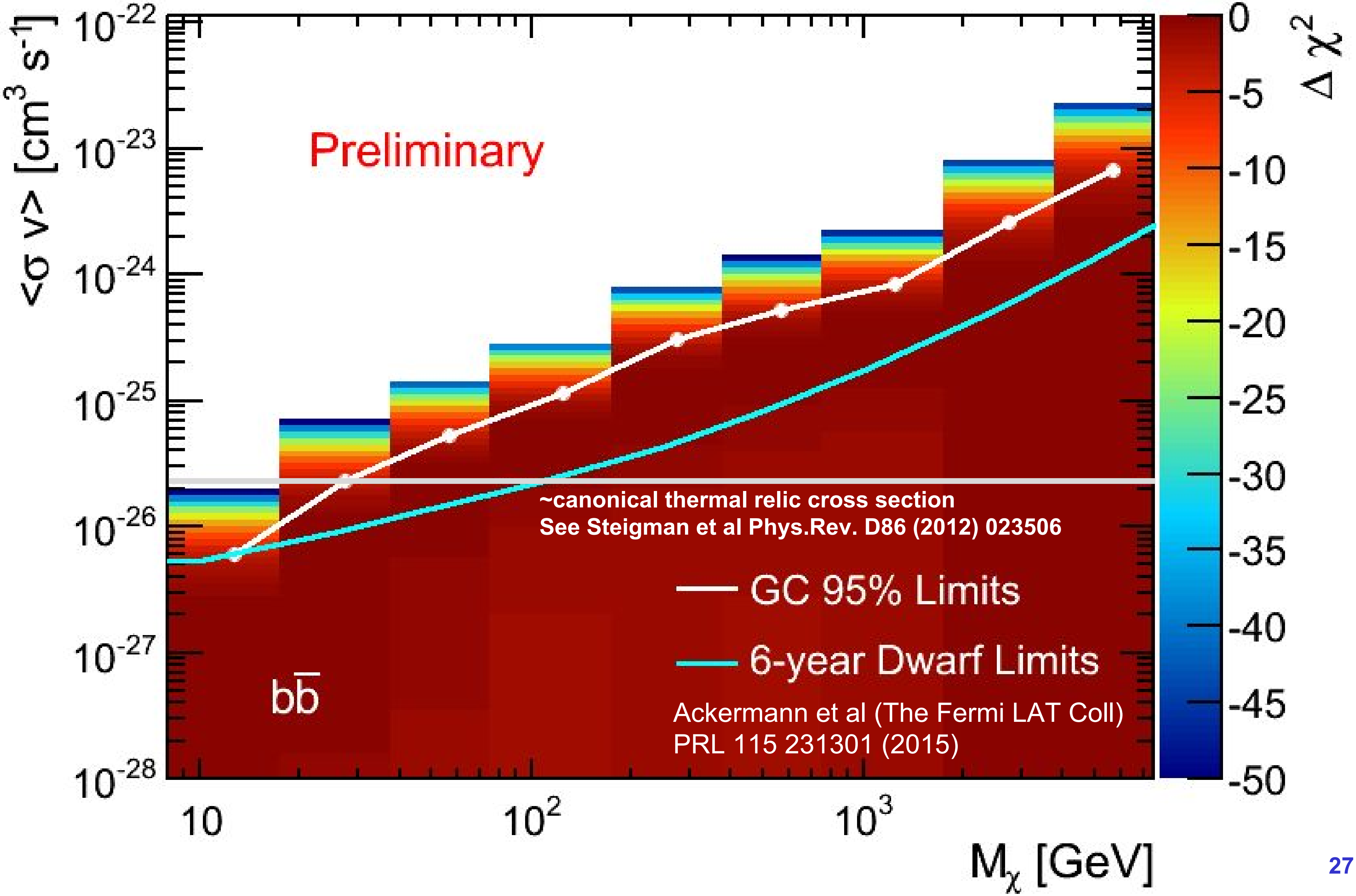
Galactic Plane Scan





- **Perform same fitting with the NFWc template centered along the Galactic Plane, but excluding the center**
  - **Off-center GP is a control region where very little dark matter is expected**
  - **Use 68% containment from GP scan as an estimate of the level of dark-matter-like residuals**
- **Size of dark-matter-like residuals at other longitudes is comparable to the fractional signal in the Galactic Center**

Results -- bb



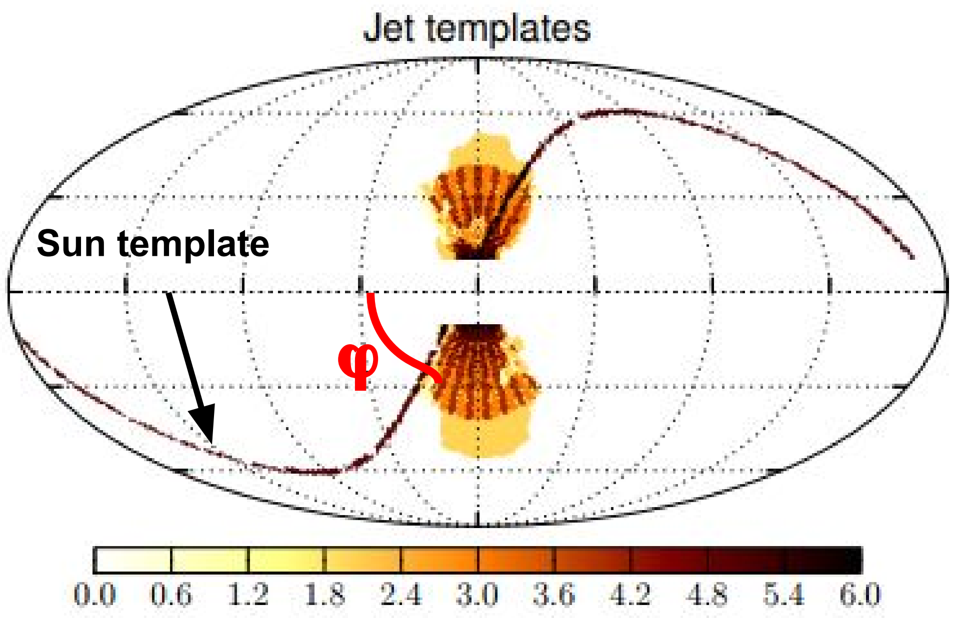
$\langle\sigma v\rangle$ [cm^3 s^{-1}]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
Preliminary
~canonical thermal relic cross section
See Steigman et al Phys.Rev. D86 (2012) 023506
GC 95% Limits
6-year Dwarf Limits
$b\bar{b}$
Ackermann et al (The Fermi LAT Coll)
PRL 115 231301 (2015)
10
10^2
10^3
M_χ [GeV]
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
$\Delta\chi^2$

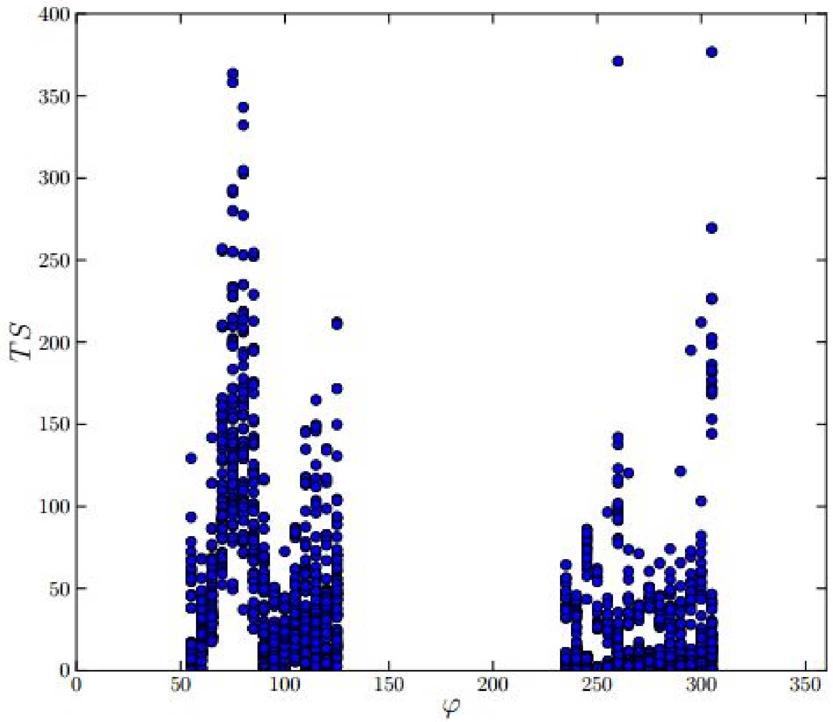
Summary

- Two unexpected, extended features have been detected in the Fermi LAT Data towards the central part of the Galaxy
  - The Fermi Bubbles and the GC GeV Excess
- Fermi Bubbles show no significant spectral variation with latitude (|b| > 10°)
  - Some evidence of a pinched component with E^{-2} spectrum at low latitudes, but largely degenerate with Cusp template
    - Challenging to disentangle the two
- The Fermi Bubbles have sharp edges and morphology does not significantly vary with energy
- Significant sources of uncertainty for GeV excess include
  - Fermi bubbles morphology at low latitudes
  - Possible sources of CR electrons near the GC
- DM fits to of GeV excess spectrum are not significant after including modeling uncertainties estimated from DM fits in the Galactic plane
  - Extended, cusp-like residuals are seen in Galactic plane that can be fit with DM annihilation spectra
  - The size relative to the effective background of the GeV excess in the Galactic Center is comparable to similar residuals at other longitudes along the Galactic Plane

Backup Slides

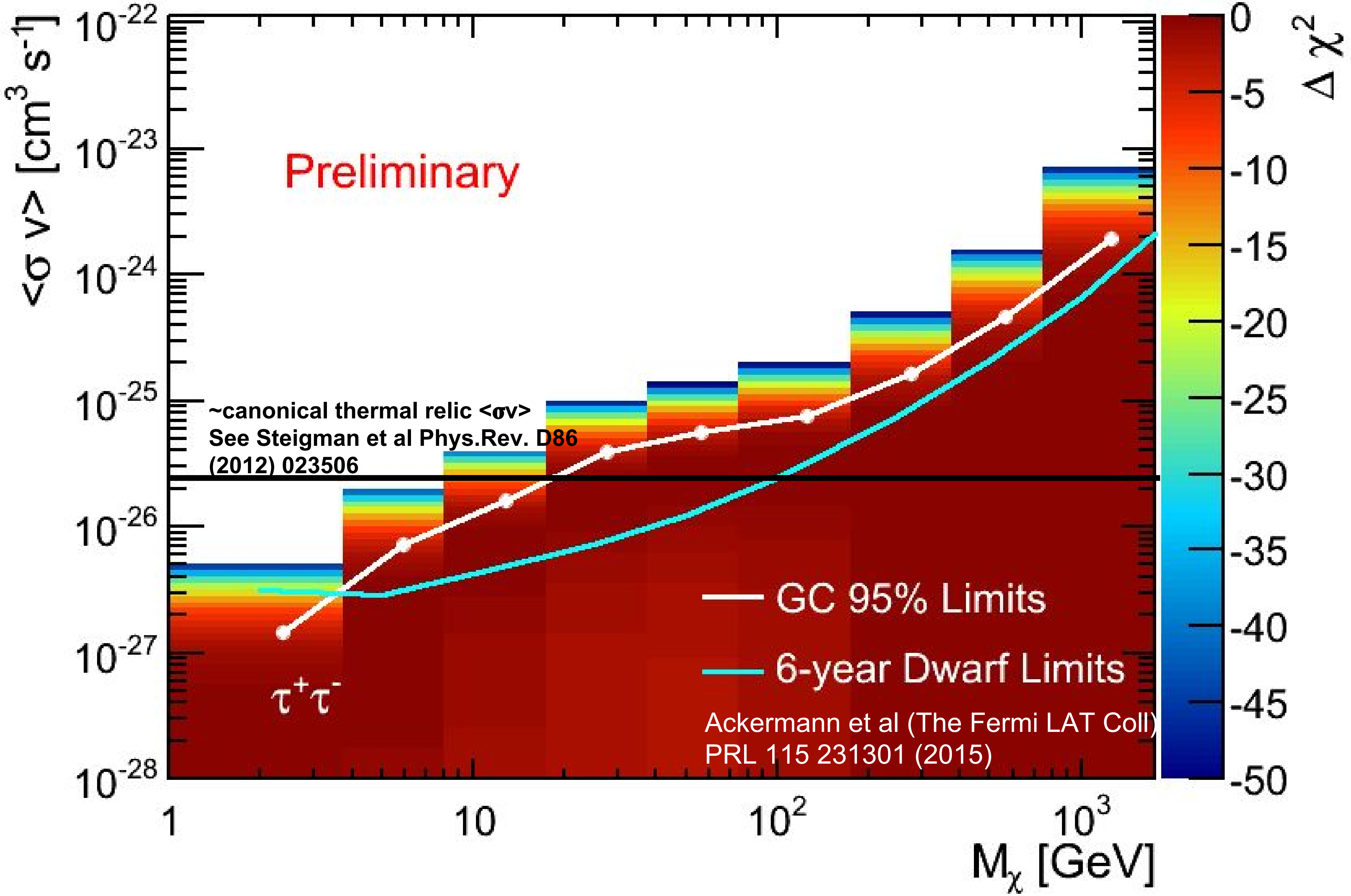
Fermi Bubbles: Check for Jets





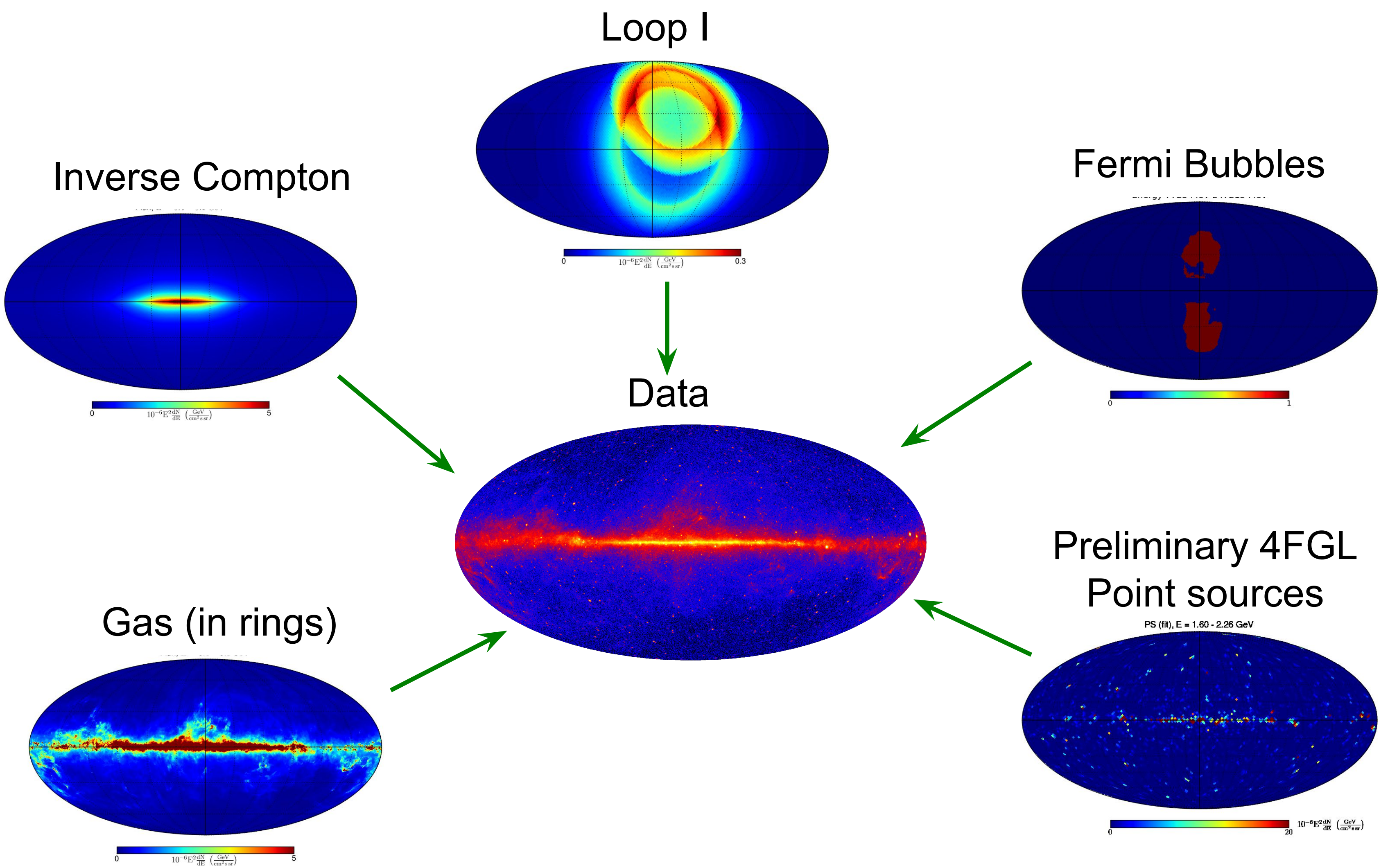
- Fit with various jet templates
  - TS points at each φ corresponds to fit with different diffuse model
  - Some enhancement at location of southern cocoon
- No evidence of symmetric jets found

Results -- $\tau^+\tau^-$



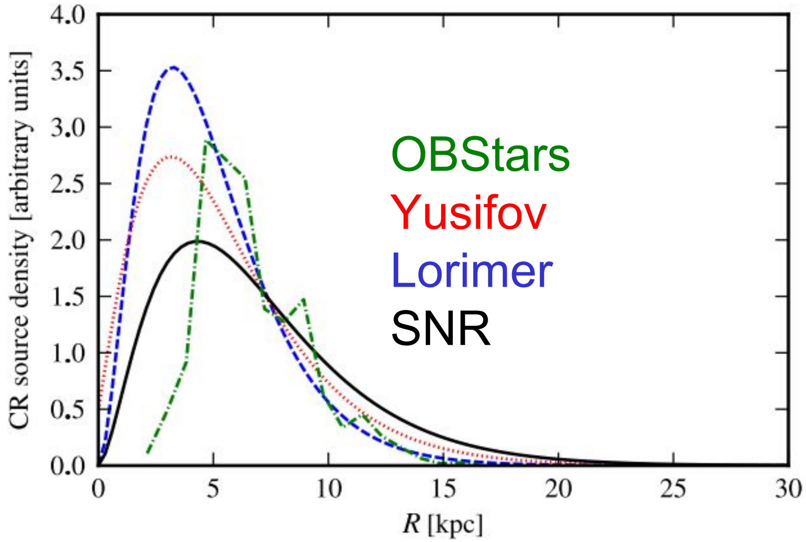
Template fitting

- **Fit templates to the data in energy bins (bin by bin fitting)**



GALPROP parameters

- Use models from Fermi LAT diffuse analysis (Ackerman et al. ApJ 793 (2014) 1, 64)
- Cosmic-ray source distribution:
  - Pulsars (Lorimer et al., MNRAS 372 (2006) 777-800)
  - SNR (Case & Bhattacharya, ApJ 504 (1998) 761)
  - Pulsars (Yusifov & Kucuk, A&A 422 (2004) 545-553)
  - OBStars (Bronfman et al., A&A 358 (2000) 521)
- CR propagation volume
  - Radius: **20**/30 kpc
  - Height: 4/**10** kpc
- Spin Temperature
  - **150K**/optically thin

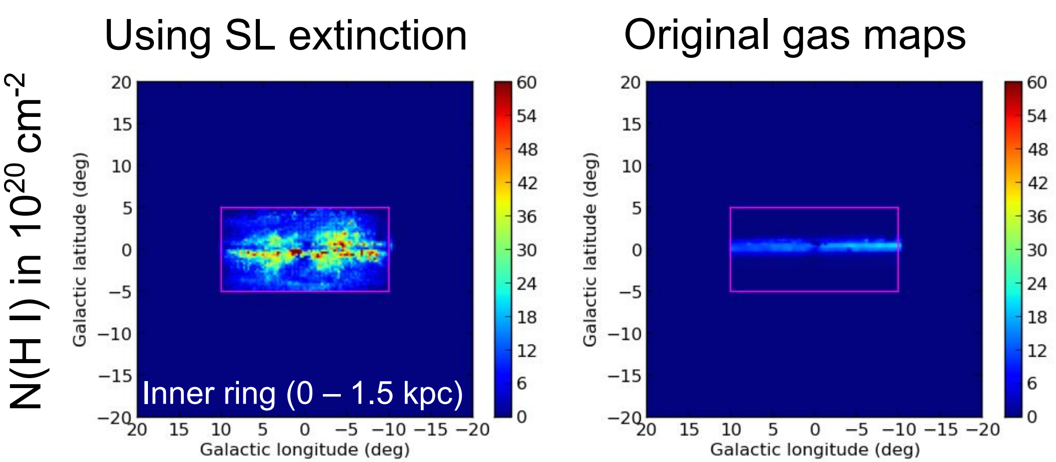


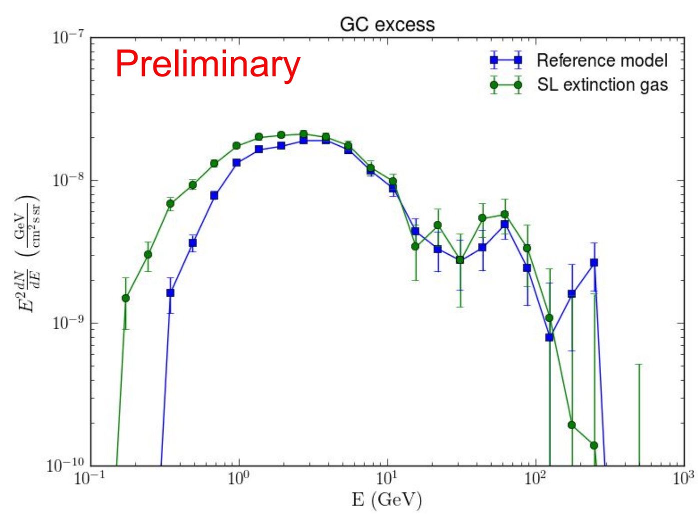
Reference model parameters shown in blue

	R [kpc]
Inner	0 – 1.5
Inner	1.5 – 3.5
Inner	3.5 – 8
Local	8 – 10
Outer	10 – 50

Alternative Gas Maps

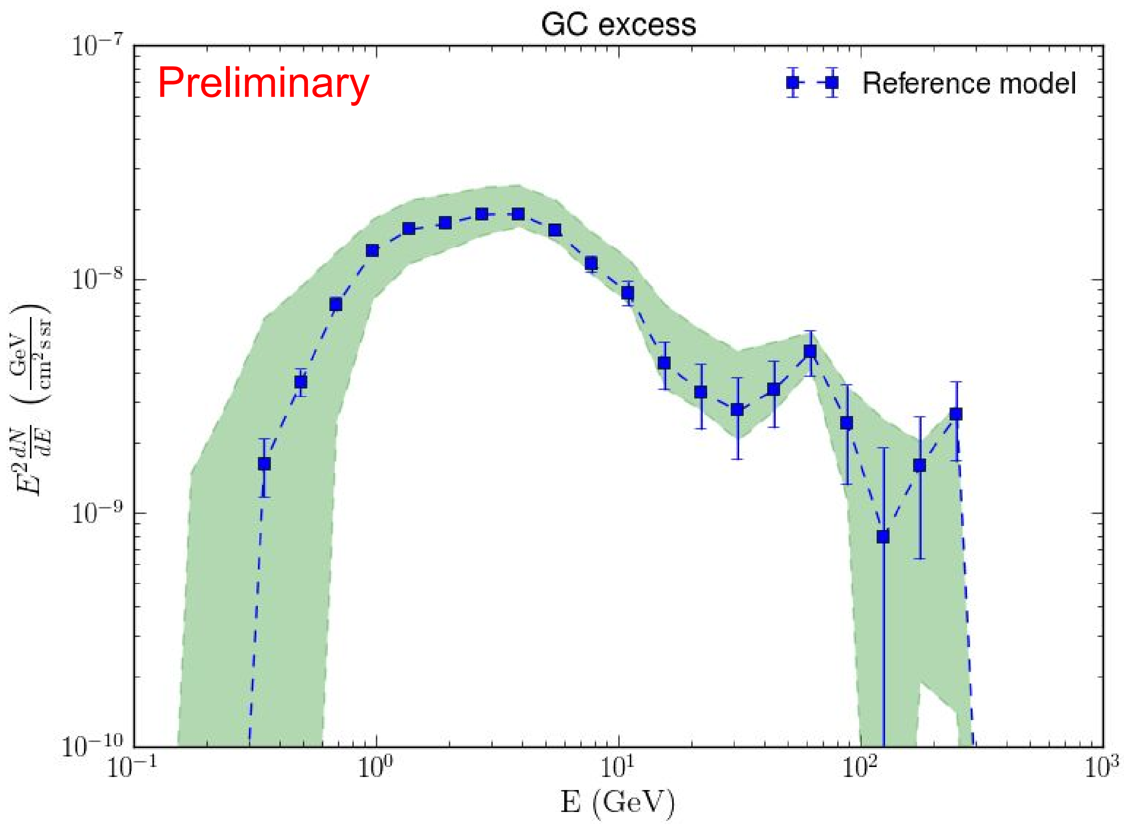
- Hard to model distribution of gas towards the GC due to **lack of Doppler shift** information
  - Gas distribution is interpolated from |Lon| > 10°
- **Use starlight (SL) extinction** (Schultheis et al., A&A 556 (2014) 120S) to find the distribution of dust along the LOS towards the GC
  - Derive the distribution of gas assuming homogeneous mixing of dust and gas
- Not suitable to be a substitution for the current gas maps
  - useful for estimation of modeling uncertainties





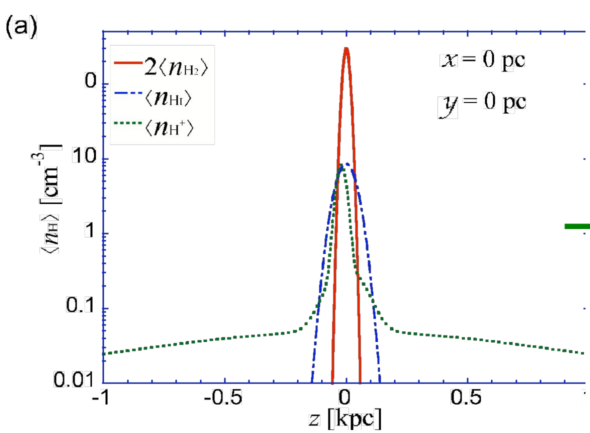
GALPROP parameters and alternative gas distribution

- **Variation of GALPROP parameters and the distribution of gas along the line of sight**

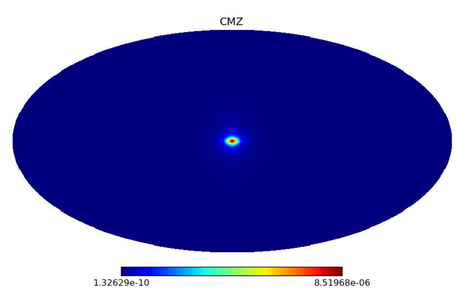


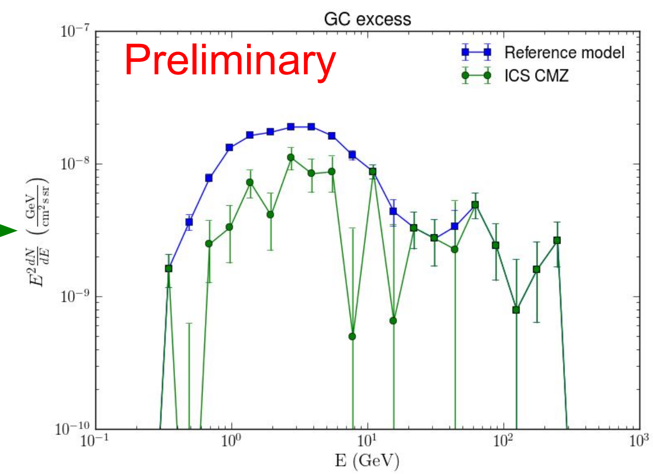
Sources of CR electrons near the GC

- **CR electron sources in the bulge** **(Petrovic et al. JCAP 1502 (2015) 02, 023)**
  - **Electrons are produced by MSPs in the bulge**
- **Starbursts in molecular clouds near the GC**
  - **Burst-like emission from the GC nucleus**
    (Cholis et al. JCAP 1512 (2015) 12, 005)
  - **Stationary CR production traced by molecular clouds**
    (Carlson et al. arXiv:1510.04698)
- **Similar to Carlson et al. (2015), we find that a source of CR electrons in the central molecular zone (CMZ) region can reduce the flux associated with NFWc template:**



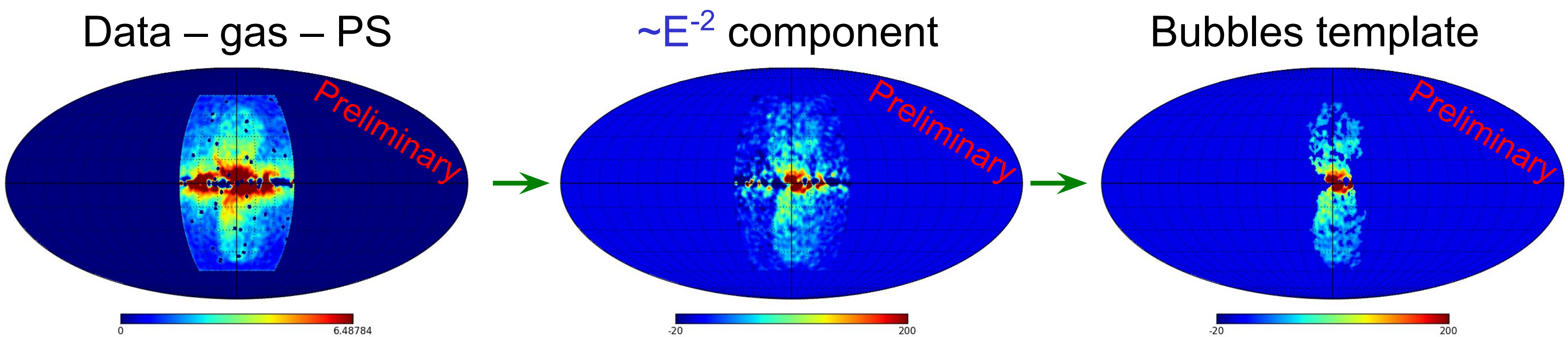
Ferriere et al., A&A 467 (2007) 611-627



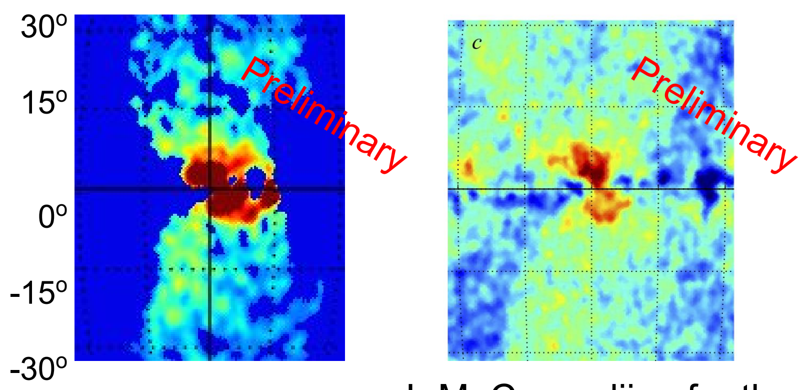


Bubbles template

- **Assume that the bubbles have the same spectrum near the GC as at high latitudes ~E^{-2} between 1 and 10 GeV**
- **Cut on significance to obtain the bubbles template**



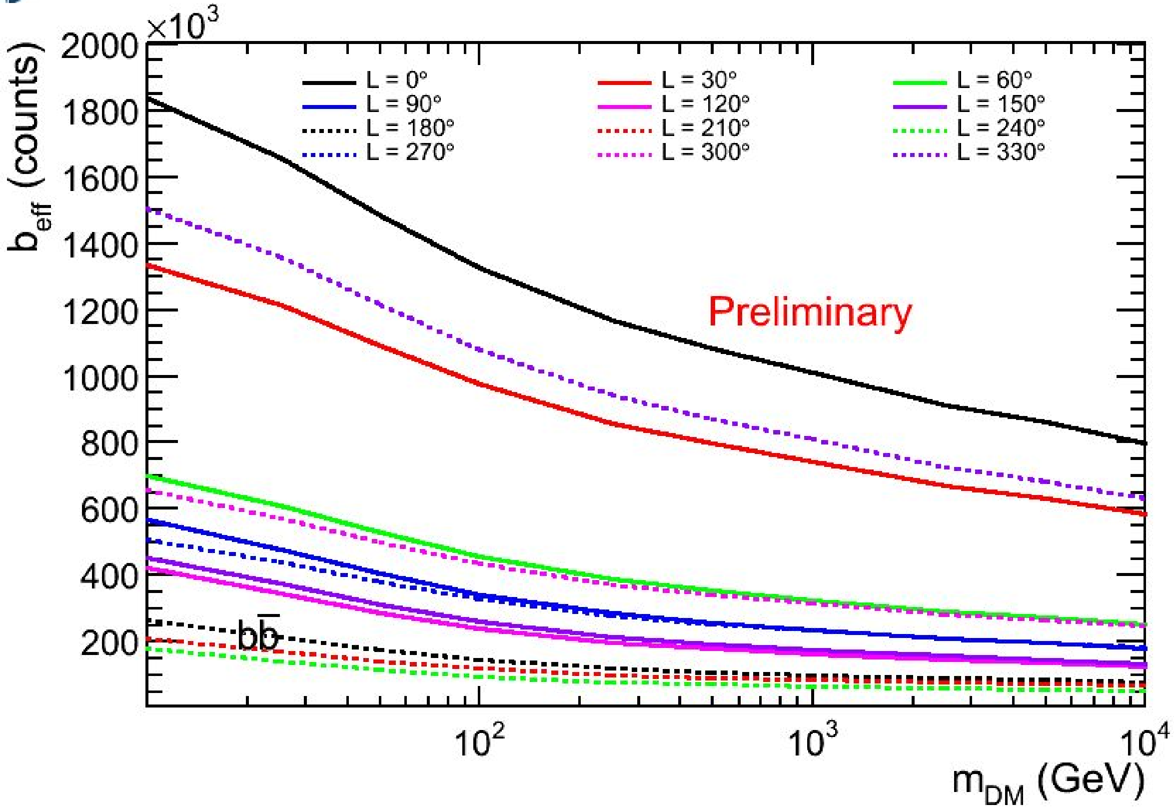
- **Fermi bubbles template in the inner Galaxy looks similar to the template found in Casandjian (2015)**
- **But beware of modeling uncertainties**



This work

J.-M. Casandjian for the Fermi-LAT collaboration, arXiv:1502.07210

Effective Background



$$b_{\rm eff} = \frac{N}{\left(\sum_k \frac{P^2_{{\rm sig},k}(\mu)}{P_{{\rm bkg},k}(\theta)}\right) - 1}$$

sum over spatial and energy bins

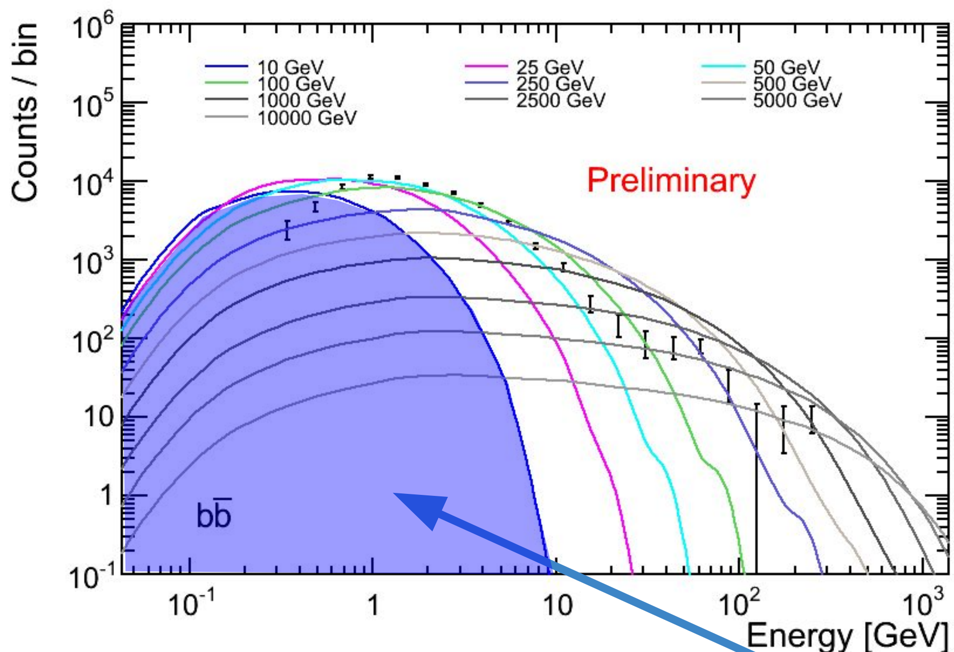
N = total counts

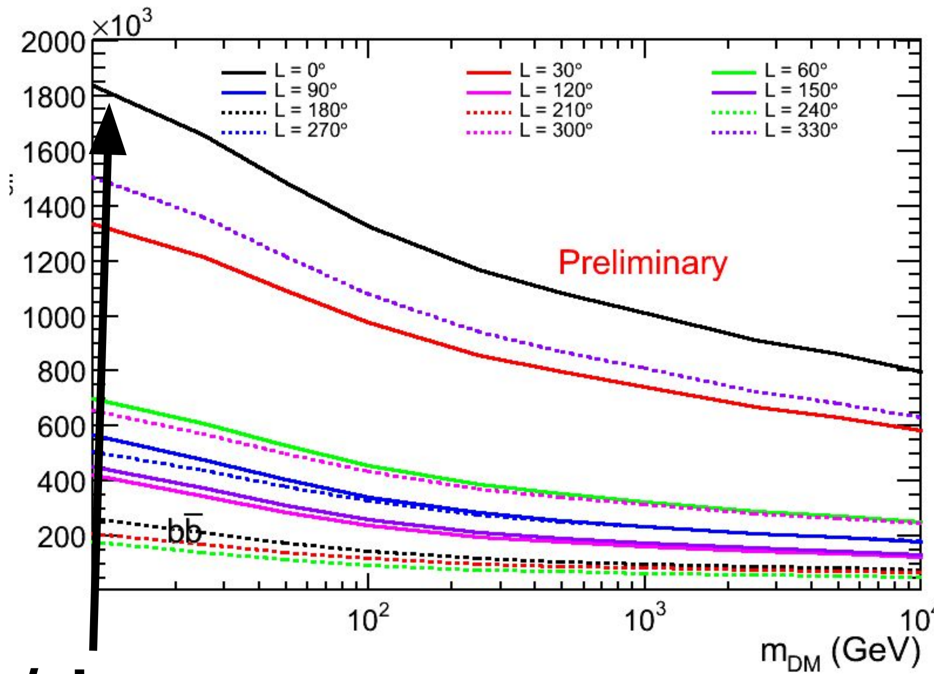
$$f = \frac{n_{sig}}{b_{eff}}$$

$$signif \approx \frac{n_{sig}}{\sqrt{b_{eff}}}$$

- b_{eff} is the weighted "number of counts under the signal"
  - Background Model (P_{bkg}) = adopted Reference Model
  - Signal Model (P_{sig}) = NFWc (γ = 1.25) centered on B = 0°
- If signal model and background model overlap more, the effective background is higher
- Expect systematics that mask/mimic DM signal to scale with b_{eff}

GC Excess -- Fractional Signal





$$f = n_{sig} / b_{eff}$$

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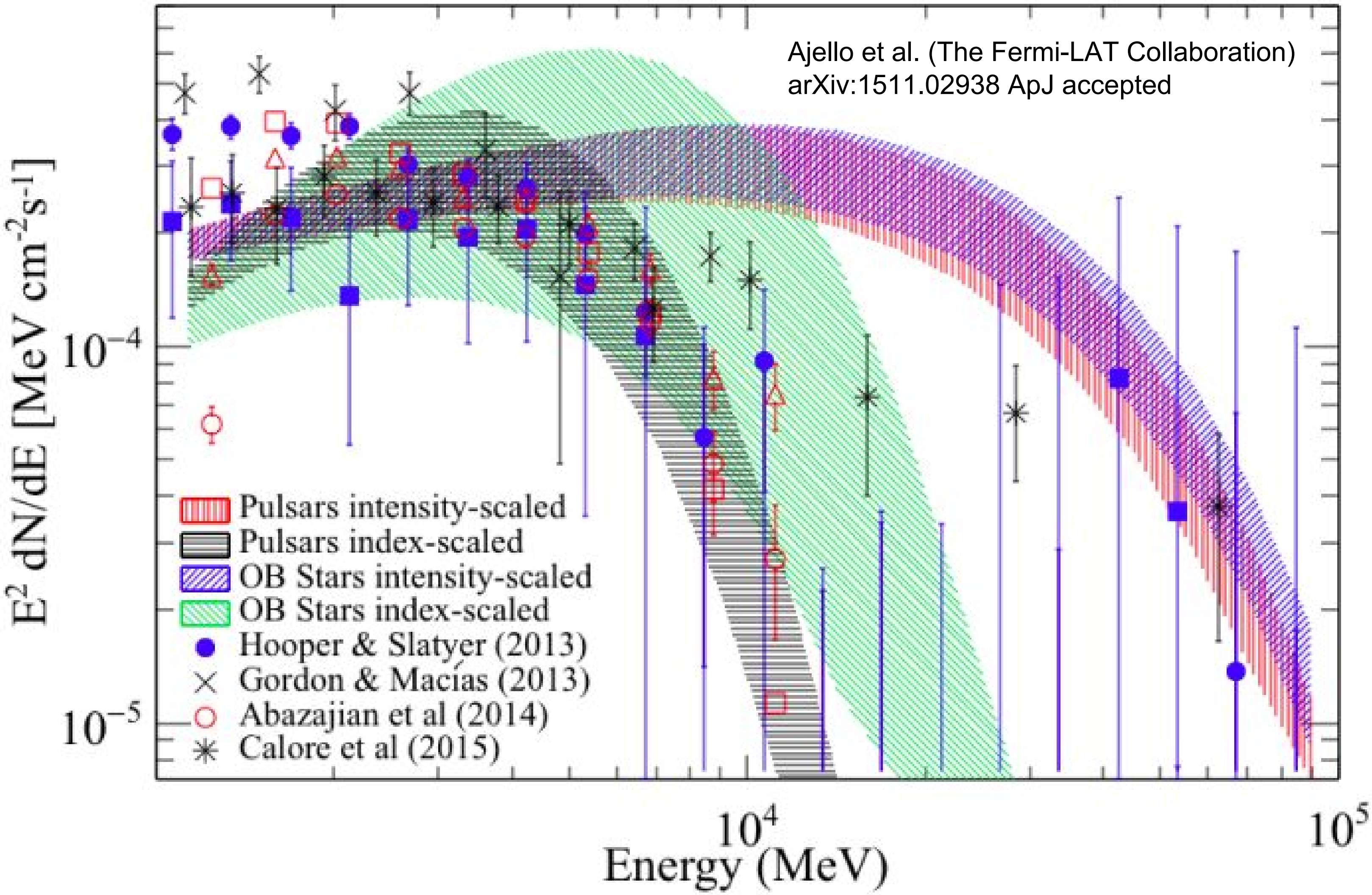
- **Galactic Center excess is only a small fraction of b_{eff}**

Fitting Including δf_{syst}

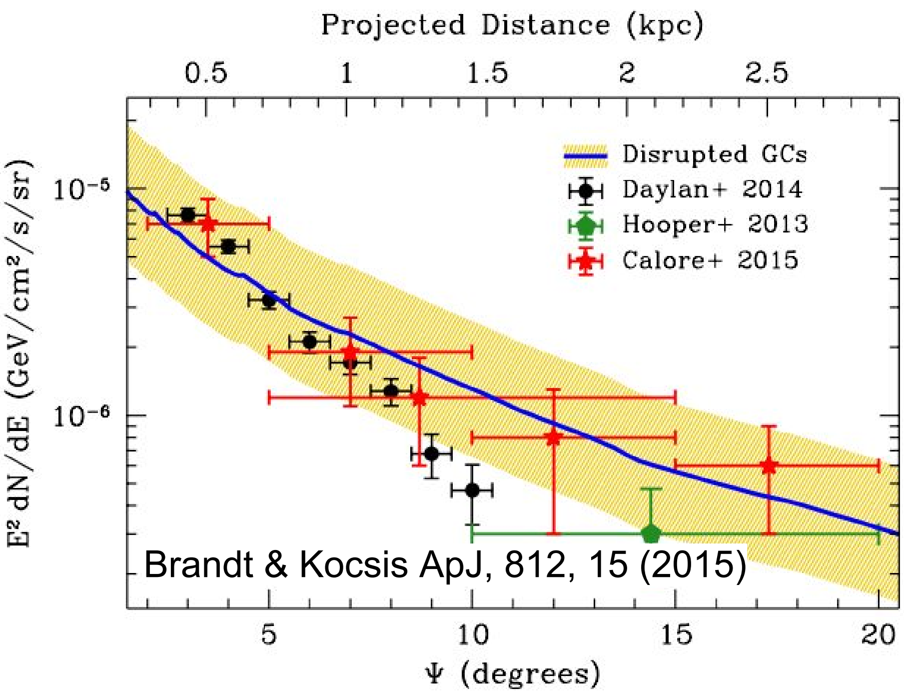
- It is useful to define $\delta f_{syst} = \delta n_{syst} / b_{eff}$ since b_{eff} and n_{syst} both scale with the total number of counts in the fit
  - We define $\delta f_{syst} = \max(\delta f_{68,GP}, 0.01)$
- Separate best fit "apparent signal" into n_{syst} and n_{sig} using a nuisance parameter
  - Constrain n_{syst} with a gaussian prior with width $\delta n_{syst} = \delta f_{syst} * b_{eff}$
  - Can only observe a signal when $n_{sig} > n_{syst}$
    - We are only sensitive to dark matter signals larger than the dark-matter-like signals seen in control regions
- Similar to technique used in LAT-Collaboration P8 Line Search and Search for Dark Matter in the LMC
  - Ackermann, M. et al. 2015, Phys. Rev. D, D91, 122002
  - Buckley, M. R. et al. 2015, Phys. Rev. D, 91, 105004

LAT Inner Galaxy Results



Results from complementary LAT-team work exploring the Galactic Center Excess template used was standard NFW, excess spectrum modeled with exponential cut-off power-law

Unresolved Millisecond Pulsars



- Challenging to predict the number and luminosity function of unresolved MSPs
  - need to extrapolate properties of fainter MSPs from observed MSPs
  - Soft MSP luminosity functions can account for GeV excess
    - e.g. Yuan and Zhang (2014), Petrovic et. al. (2015)
- Derived templates from unresolved point sources can account for the excess
  - Bartels et al. (2015), Lee el al (2015)
- Galactic Bulge may contain MSPs from dissolved Globular Clusters
  - Brandt and Kocsis (2015)

- Even though dark-matter-like part of GC excess comparable to those seen along the Galactic Plane, an excess persists
- Many have shown a population of unresolved MSPs can account for the excess
  - currently we do not include MSP template in our fit
  - including a MSP template would likely improve our limits