The Fermi Galactic Center GeV excess
Observational Status and Interpretations

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GRAPPA
GRavitation AstroParticle Physics Amsterdam

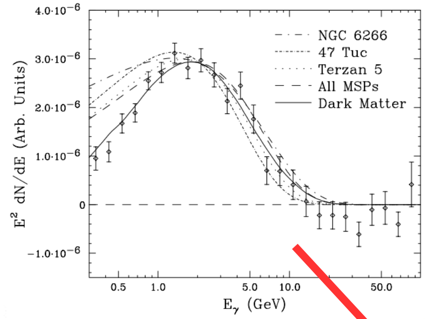
NWO

Observations.

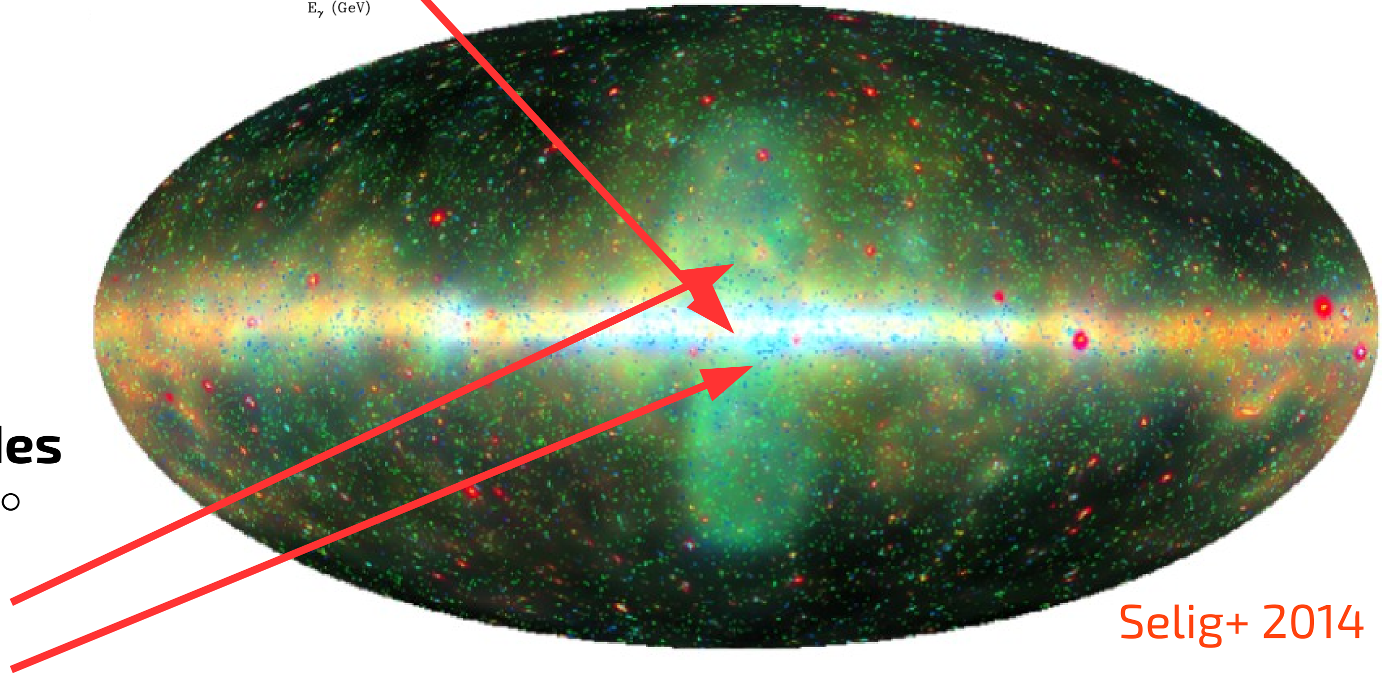
GeV excesses have been claimed since 2009

GeV excess at the Galactic center $|\ell|, |b| \lesssim 2^\circ$

- Goodenough & Hooper 2009
- Vitale & Morselli 2009
- Hooper & Goodenough 2011
- Hooper & Linden 2011
- Boyarsky+ 2011
- Abazajian & Kaplinghat 2012
- Gordon & Macias 2013
- Macias & Gordon 2014
- Abazajian+ 2014
- Daylan+2014
- Huang+ 2015
- Gaggero+ 2015
- Carlson+ 2015
- Ajello+ 2015
- ...



Pseudo-colors: Color depends on where most energy is emitted



GeV excess at mid-latitudes

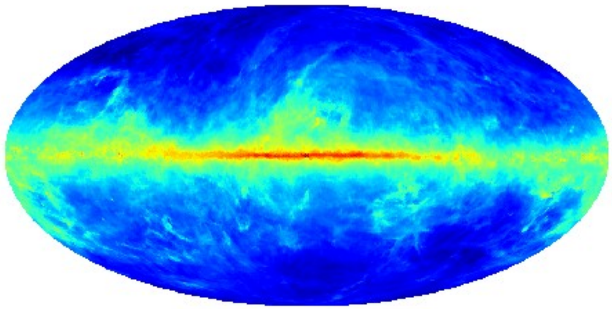
$$|\ell| \lesssim 20^\circ, \quad 2^\circ \lesssim |b| \lesssim 20^\circ$$

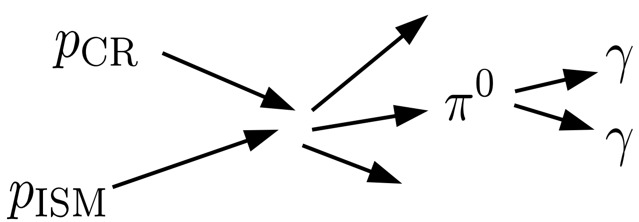
- Hooper & Slatyer 2013
- Huang+ 2013
- Zhou+ 2014
- Daylan+ 2014
- Calore+ 2014
- ...

Selig+ 2014

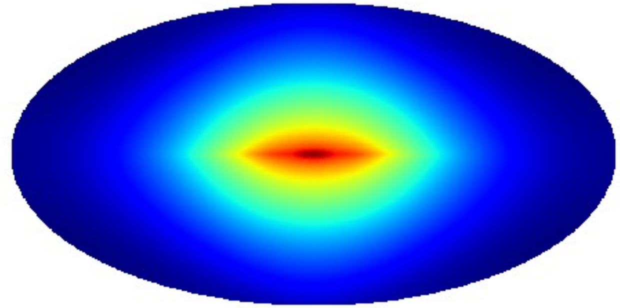
Relevant diffuse emission mechanisms

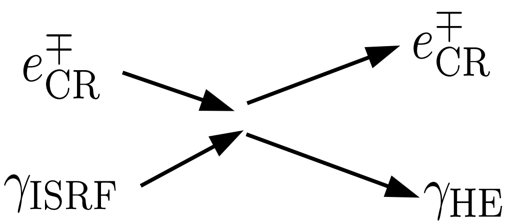
Neutral pions



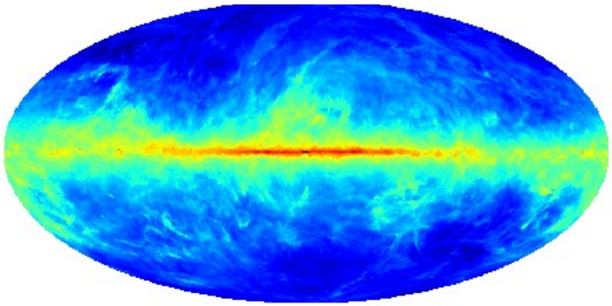


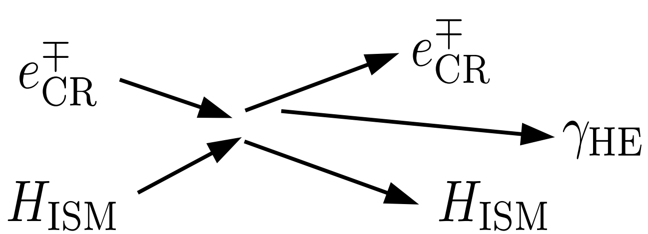
Inverse Compton





Bremsstrahlung





Predictions rely on

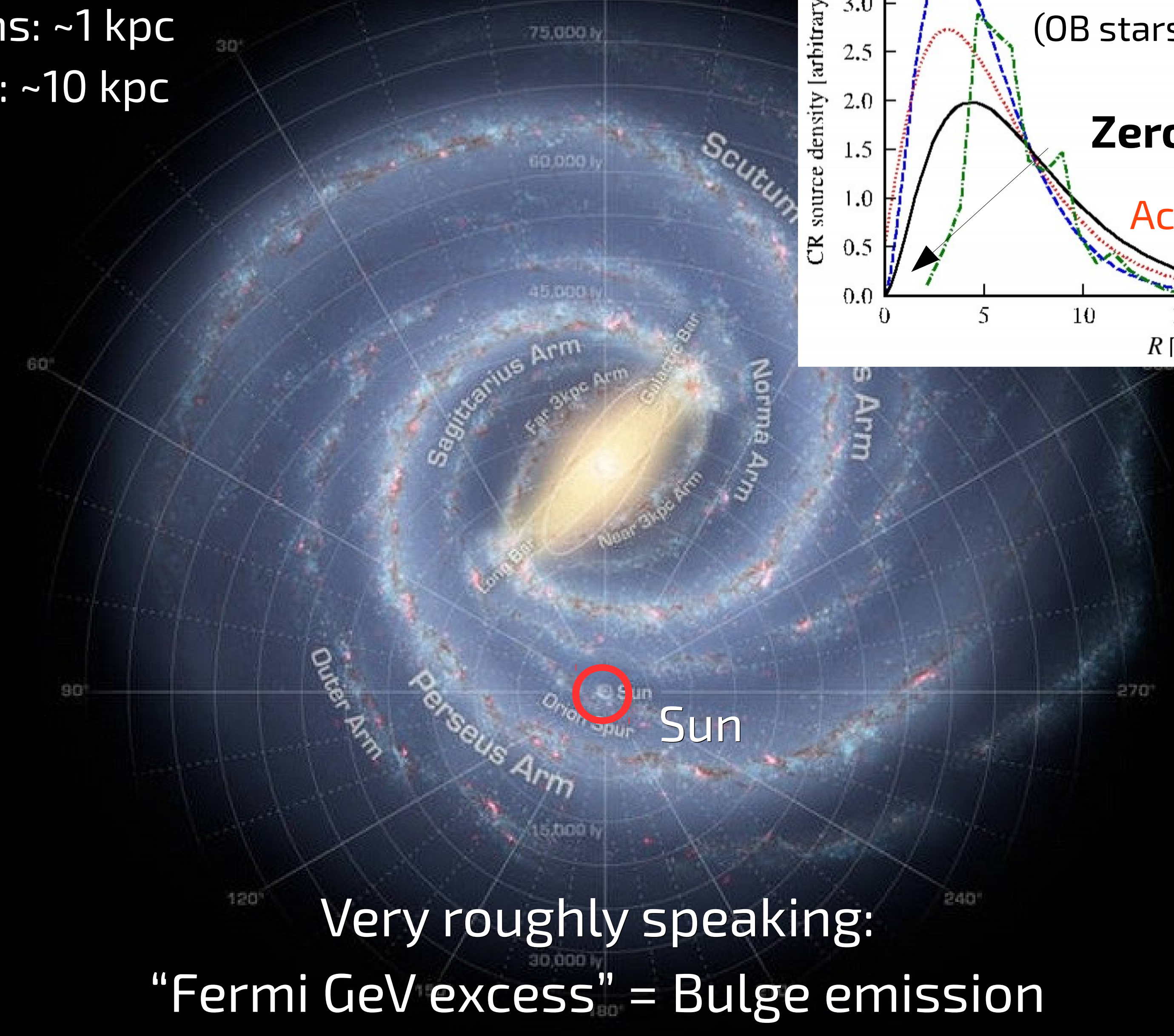
- Distribution and composition of interstellar medium
- Distribution and spectrum of interstellar radiation field
- Distribution and injection spectra of cosmic ray sources
- Regular Galactic magnetic field
- Properties of diffusion halo
- Hadronic scattering cross-sections
- …

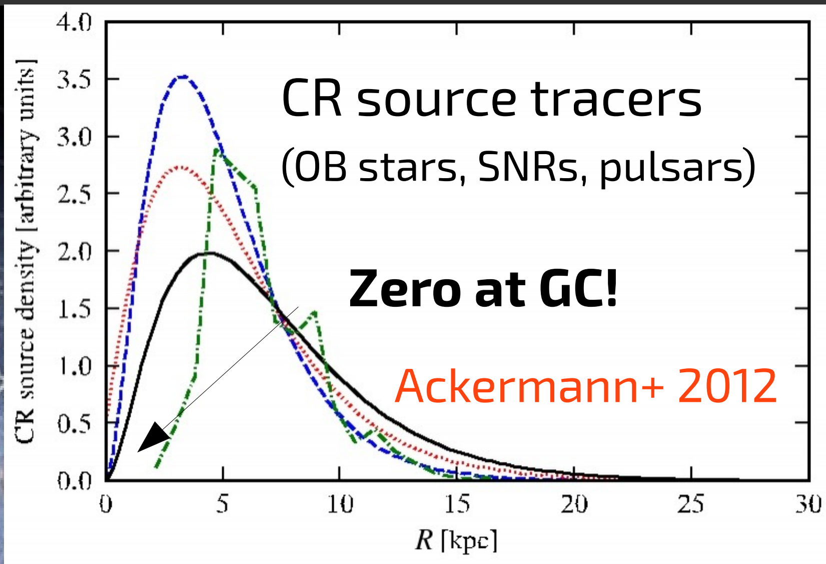
Distribution of cosmic-ray sources

Typical reach (at 1 – 100 GeV)

CR electrons: ~1 kpc

CR protons: ~10 kpc



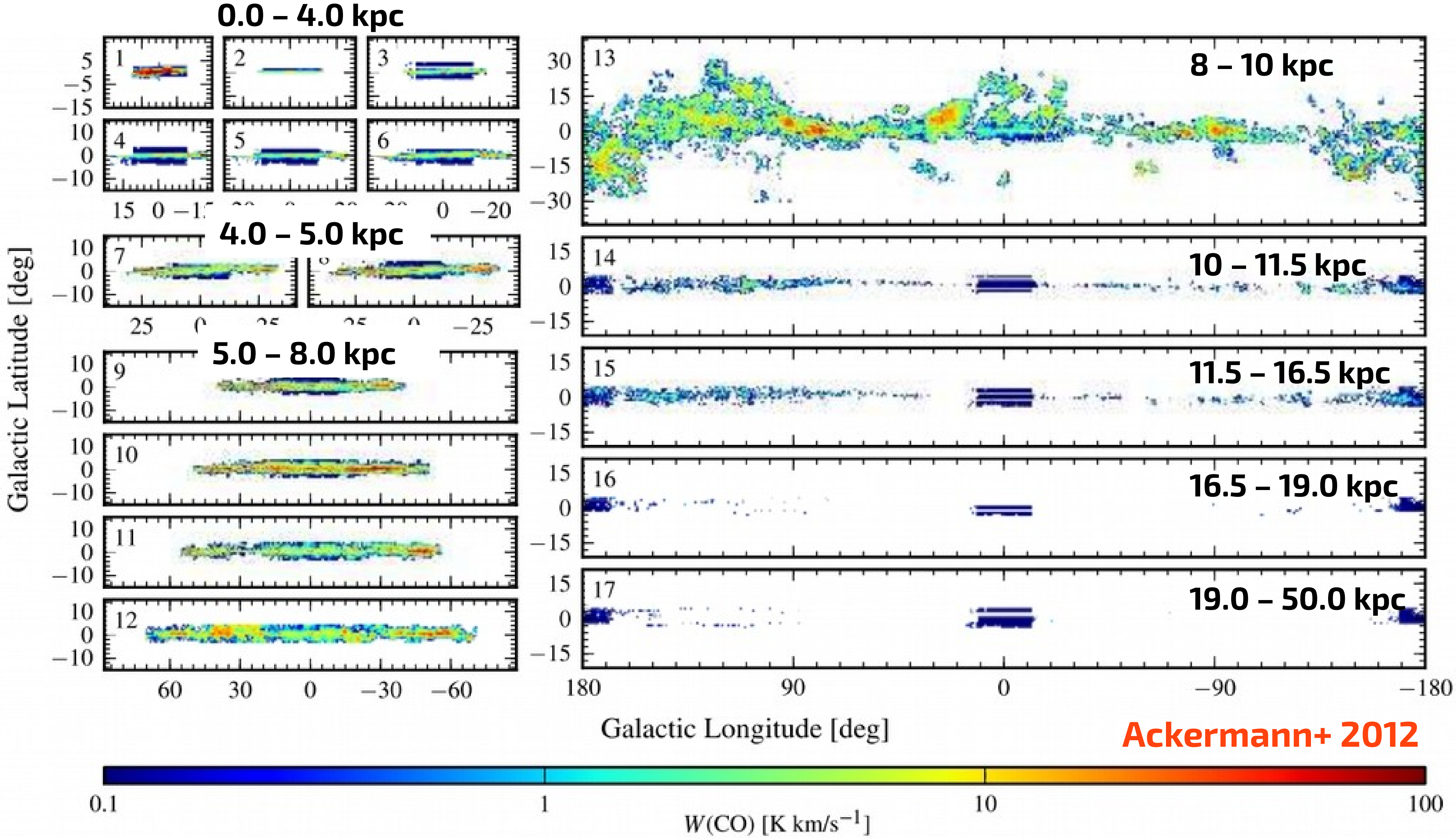


Very roughly speaking:

"Fermi GeV excess" = Bulge emission

http://www.nasa.gov/mission_pages/sunearth/news/gallery/galaxy-location.html

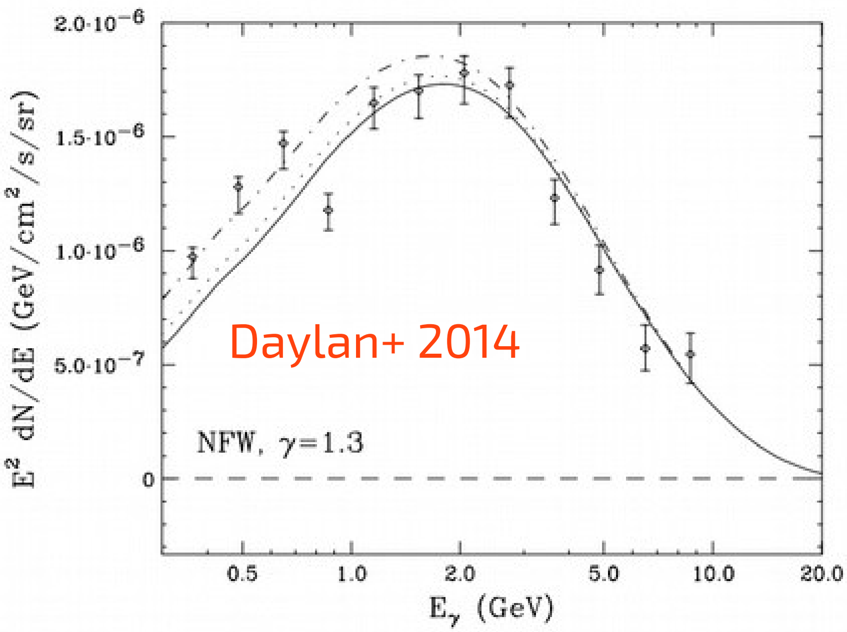
Spatial decomposition of CO line measurements

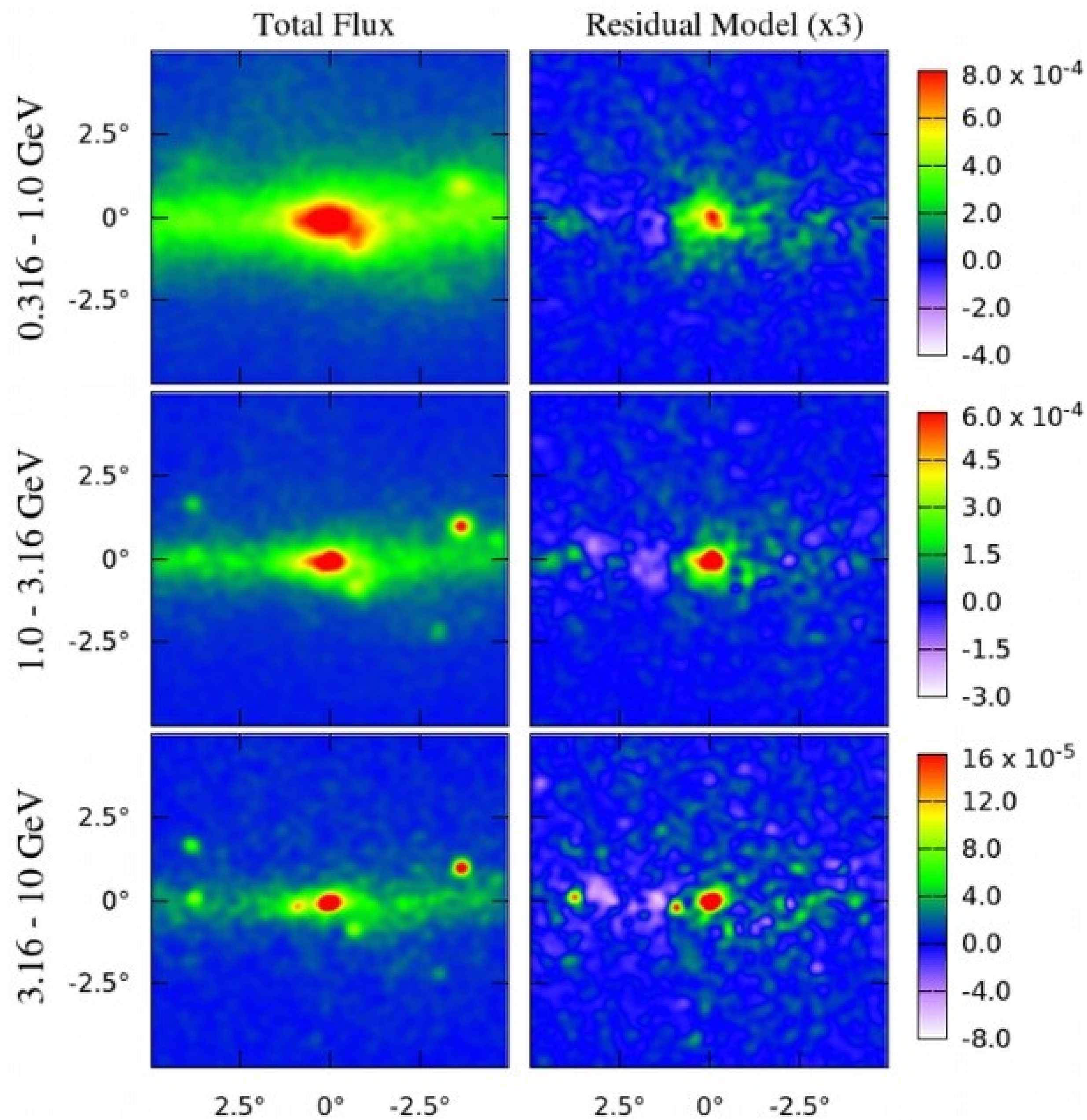


Spatial decomposition

- Significant column densities all the way towards the GC (inner degrees)
- No molecular hydrogen above 5 deg in the inner ~5 kpc

GeV excess from Galactic center region



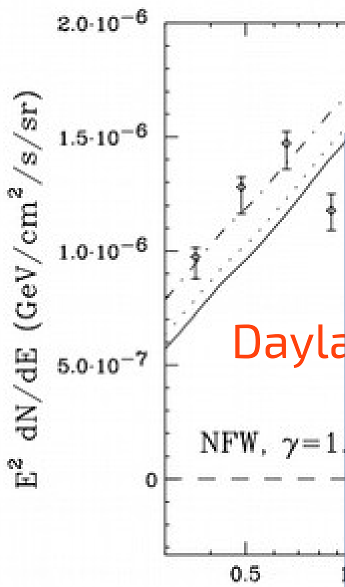


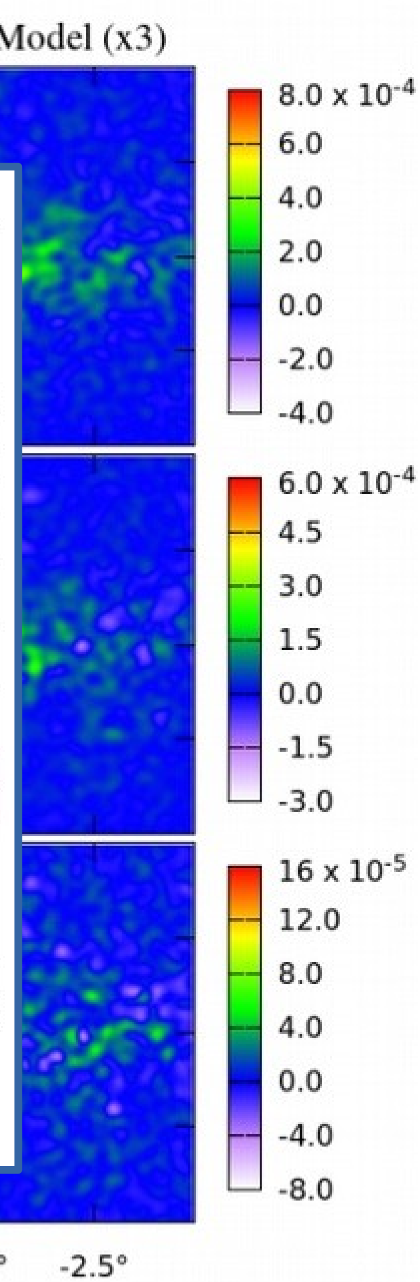
General results

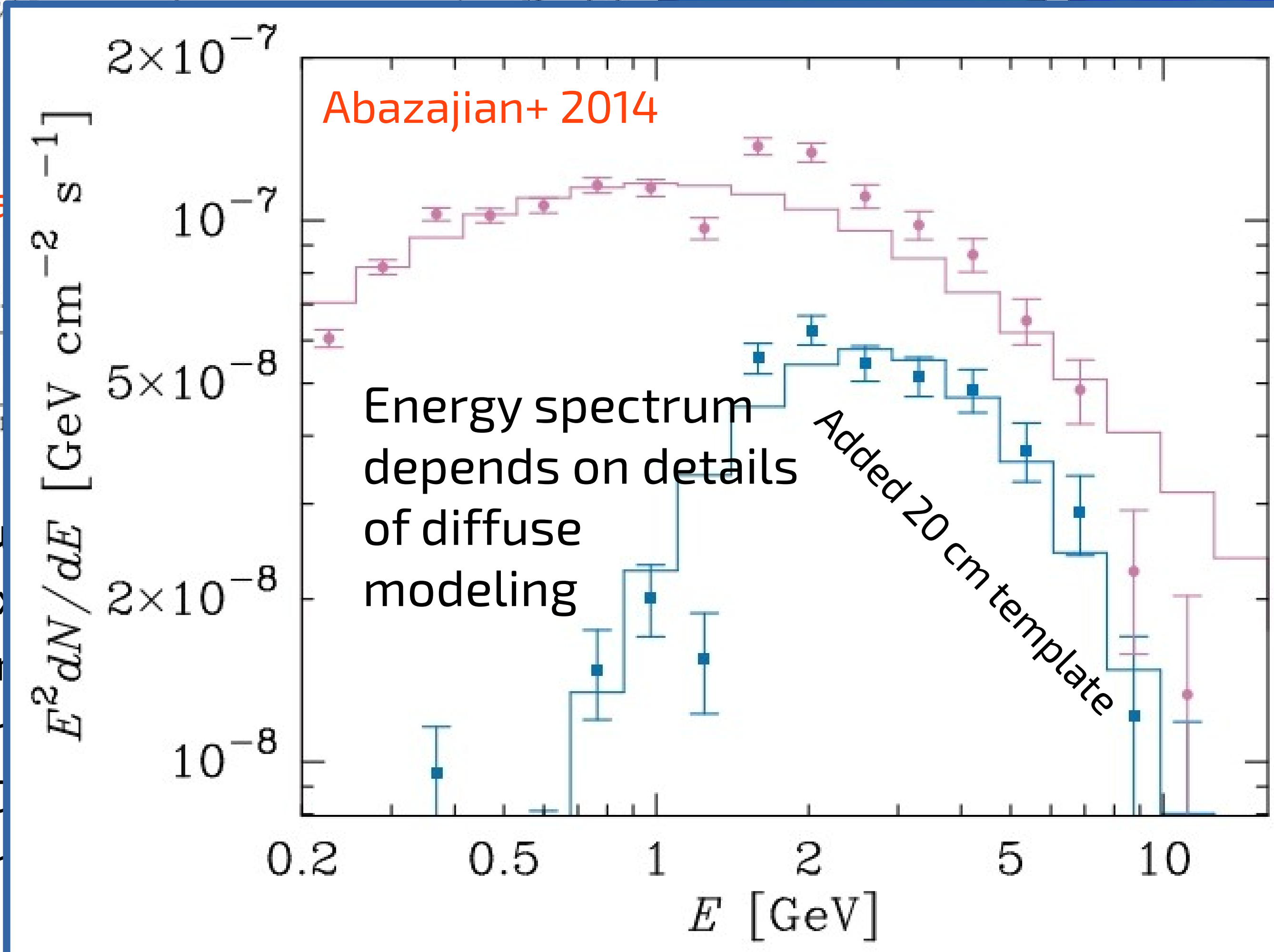
- Extended excess emission above
  - Diffuse emission model
  - Gamma-ray emission at Sgr A*
  - Other 2FGL sources
- Emission profile

$$\frac{dn}{dV} \sim r^{-\Gamma} \qquad \Gamma \sim 2.6$$

GeV excess from Galactic center region







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  - Gamma-r
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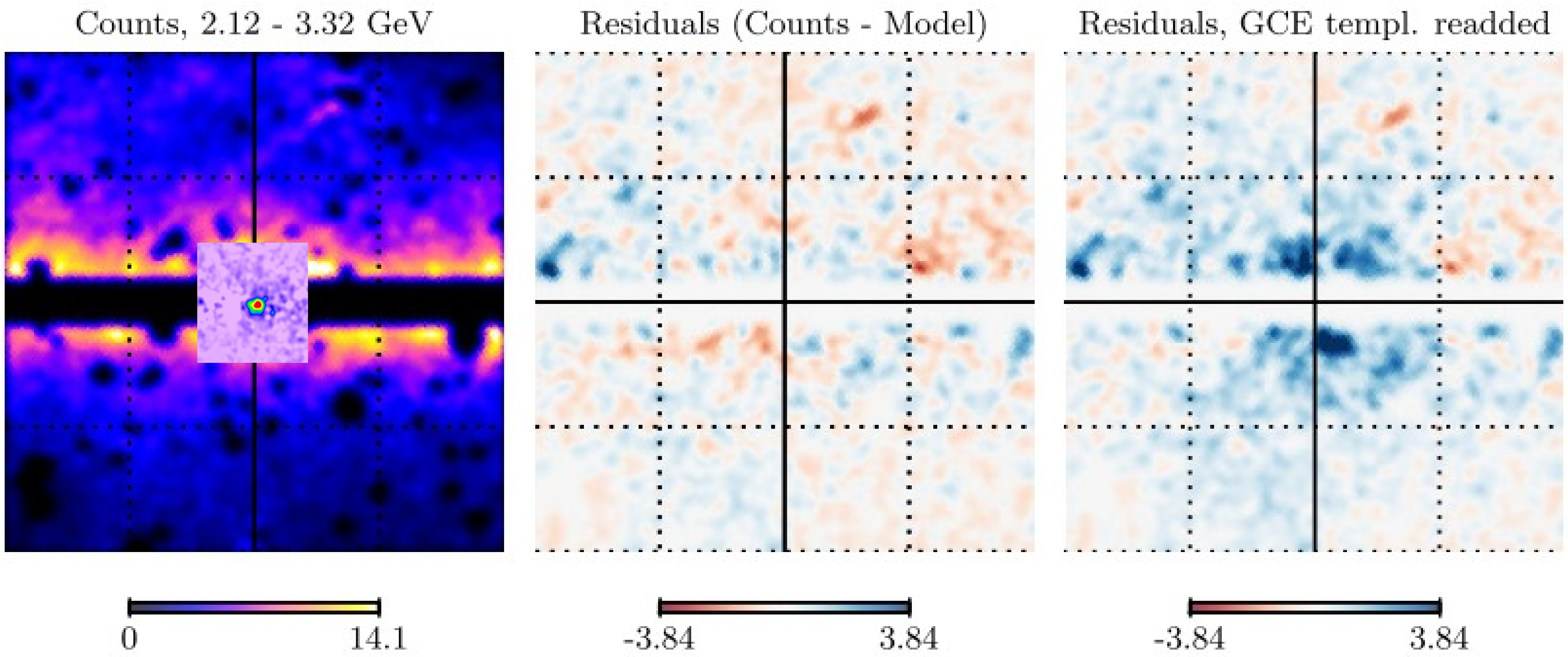
GeV excess at mid-latitudes

Calore+ 2014

40 deg x 40 deg



- Left: Point source mask clearly visible
- Middle: Residuals at the level of <20% are observed
- Right: Re-adding the DM template clearly shows an extended excess around the GC

See also Hooper & Slatyer 2013, Daylan+ 2014

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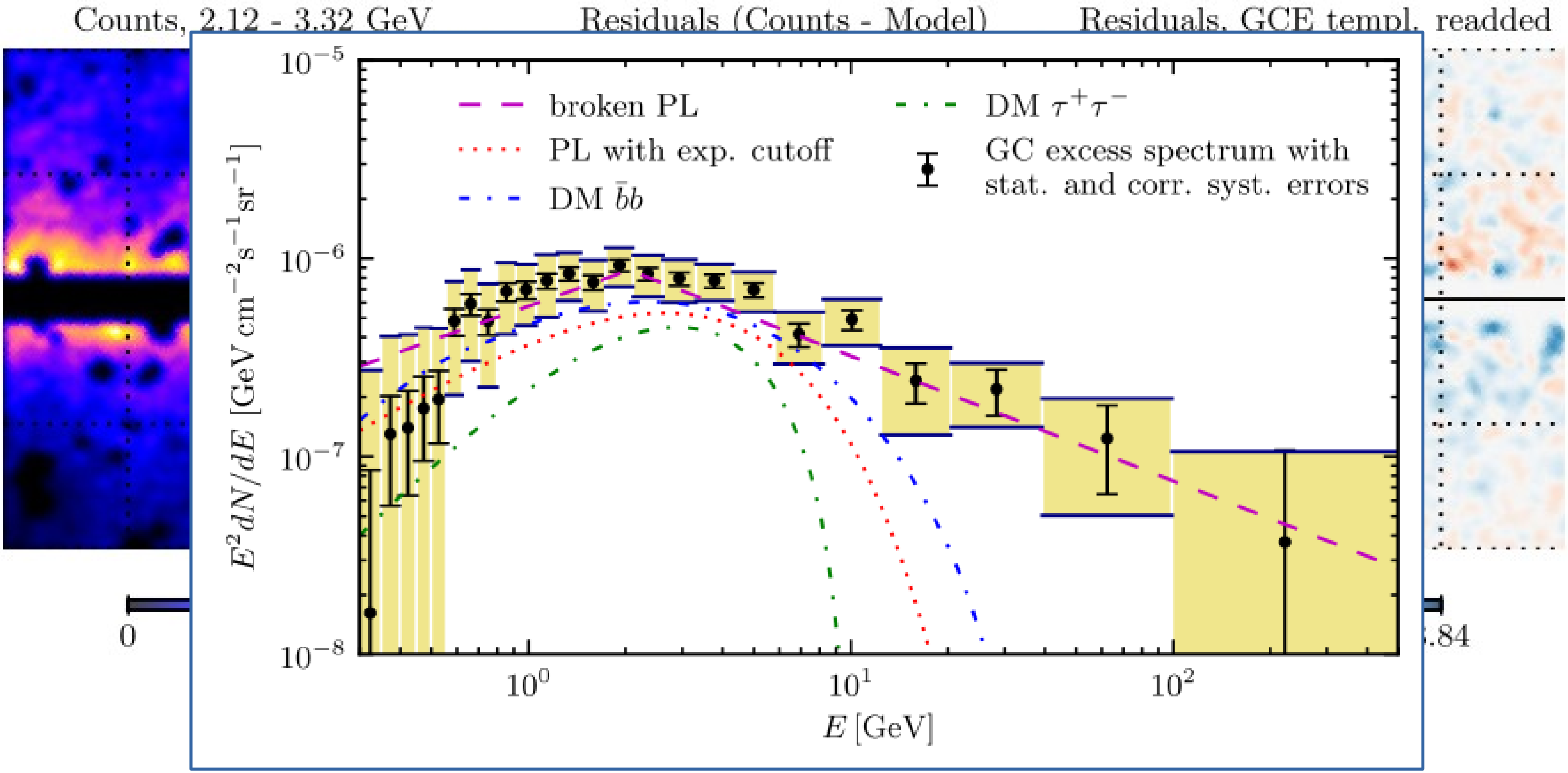

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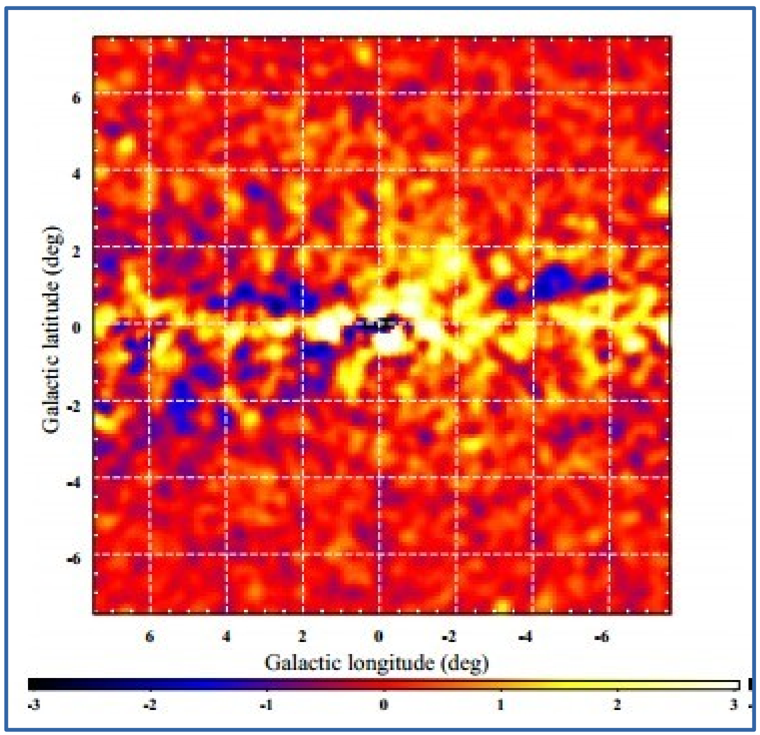
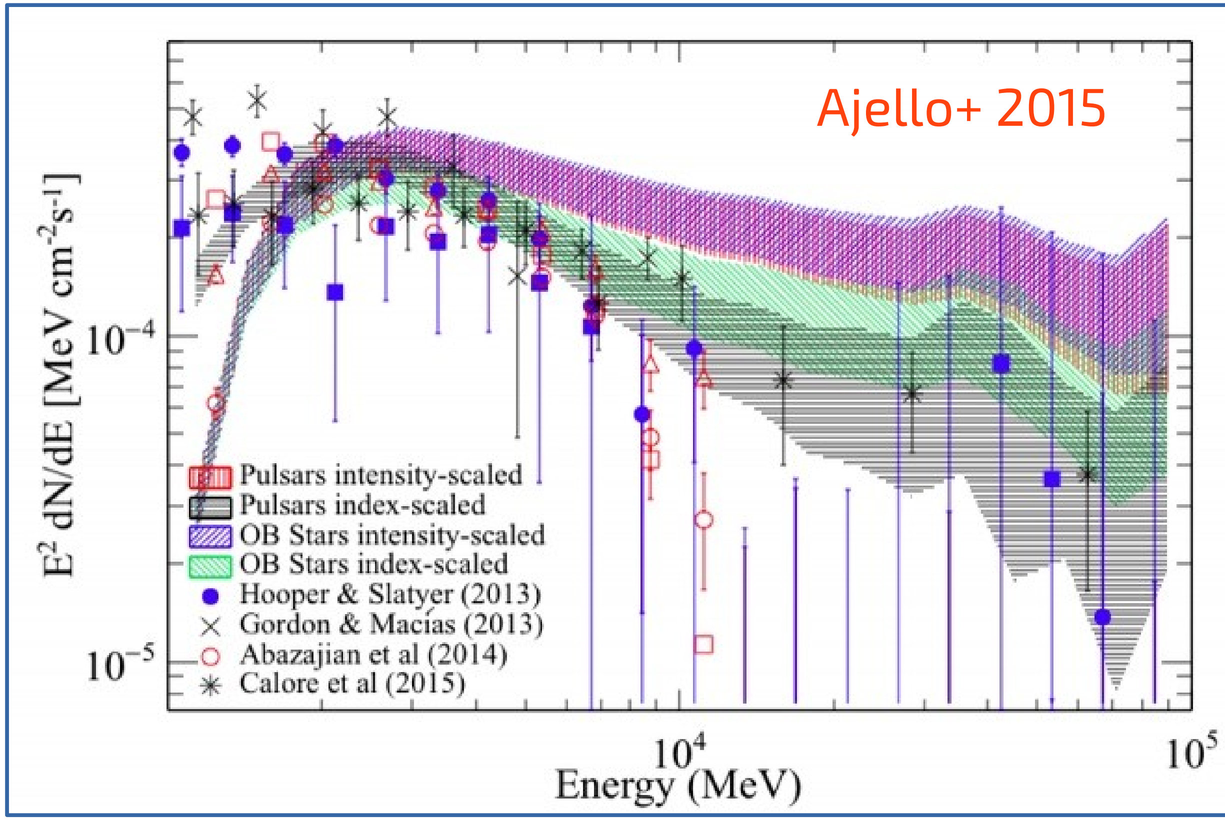
Confirmation in Fermi paper from Wednesday

Fermi–LAT OBSERVATIONS OF HIGH-ENERGY γ-RAY EMISSION TOWARD THE GALACTIC CENTRE

of the interstellar emission and energy ranges used by the respective analyses. Three 1FIG sources are found to spatially overlap with supernova remnants (SNRs) listed in Green's SNR catalog; these SNRs have not previously been associated with high-energy γ-ray sources. Most 3FGL sources with known multi-wavelength counterparts are also found. However, the majority of 1FIG point sources are unassociated. After subtracting the interstellar emission and point-source contributions from the data a residual is found that is a sub-dominant fraction of the total flux. But, it is brighter than the γ-ray emission associated with interstellar gas in the inner $\sim$ 1 kpc derived for the IEMs used in this paper, and comparable to the integrated brightness of the point sources in the region for energies $>$ 3 GeV. If spatial templates that peak toward the GC are used to model the



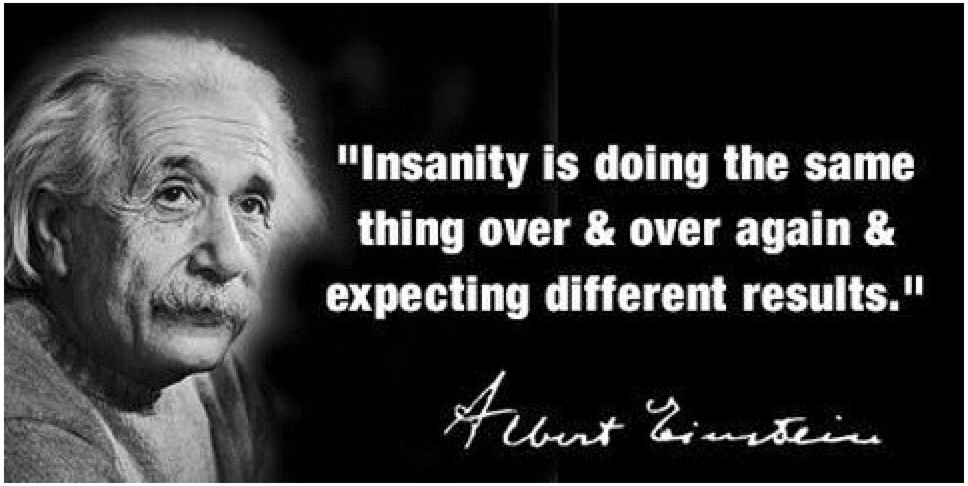


Maybe everybody is just doing the same...

...and hence gets similar results?

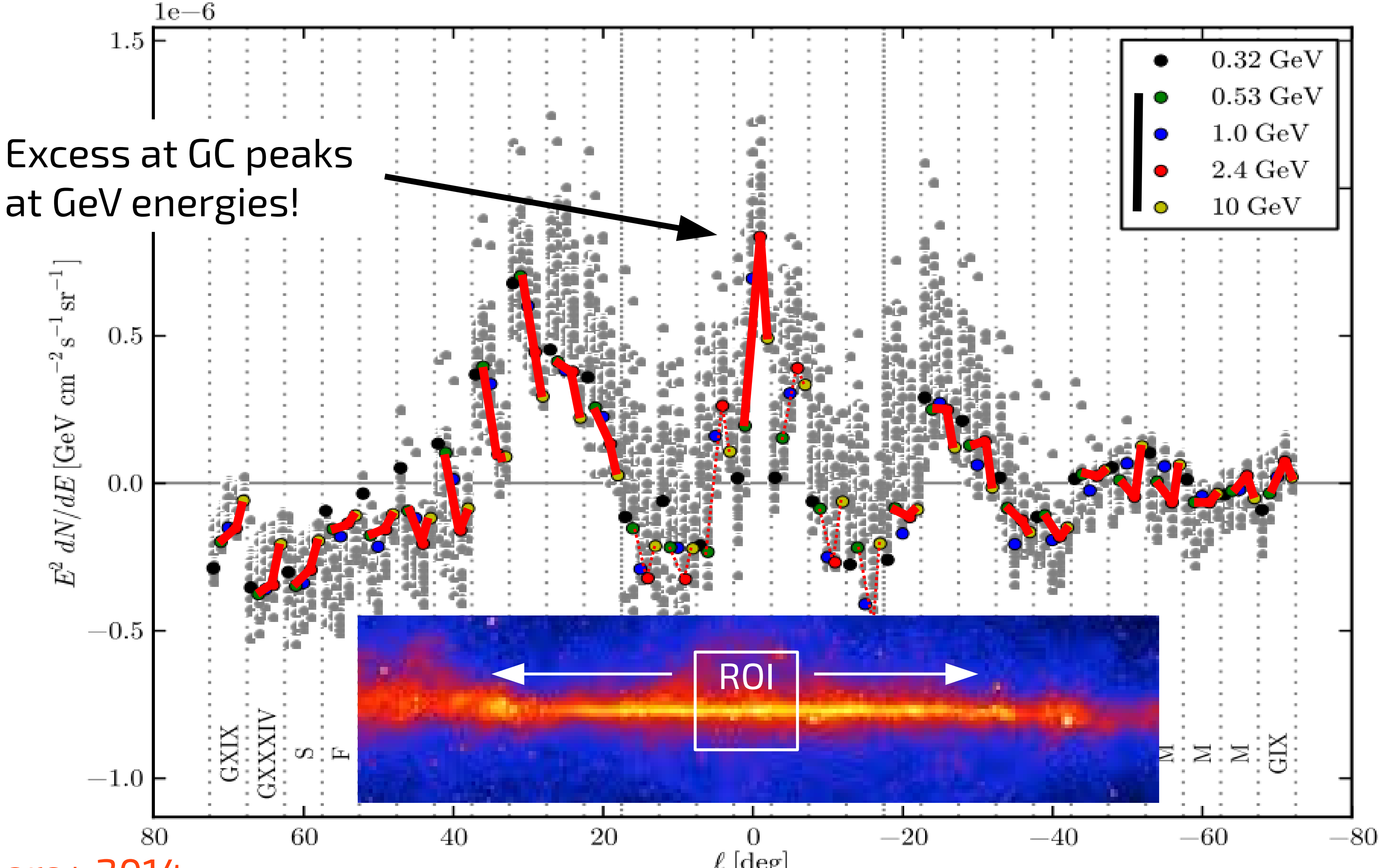
Things that are (usually) not touched:

- No constant CR sources at the Galactic center or in the Galactic bulge
  BUT: Gaggero+ 2014, Carlson+ 2014
- Same gas maps (based on LAB survey and Dame+ 2001)
  BUT: Carlson+ 2014
- Constant diffusion properties throughout the disk
  BUT: Cholis+ 2014
- No notion of spiral arms or local variations in cosmic ray density
- 2FGL/3FGL sources – no new sources searched for
  BUT: Ajello+ 2015
- No episodic CR injection
- ...



Caveats of analyses based on GALPROP

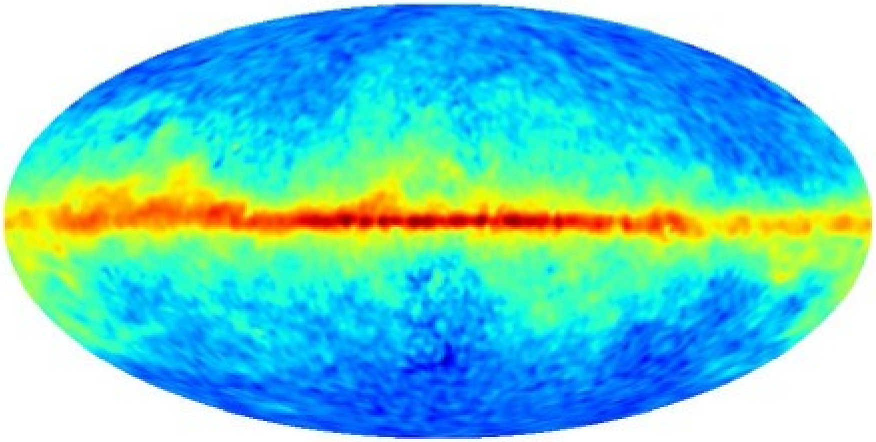
Using GALRPOP to estimate Galactic diffuse foreground produced *many* residuals along the Galactic disk ($p \sim 10^{-300}$). So what is special about the GC?



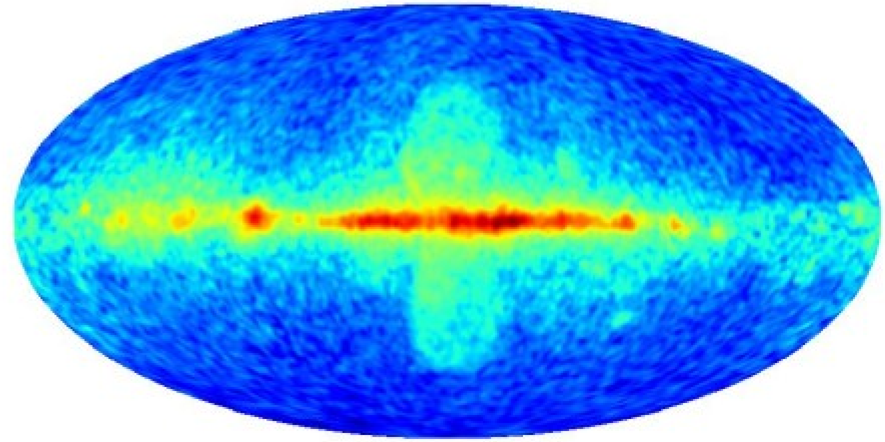
Calore+ 2014

The D³PO version of the GeV excess

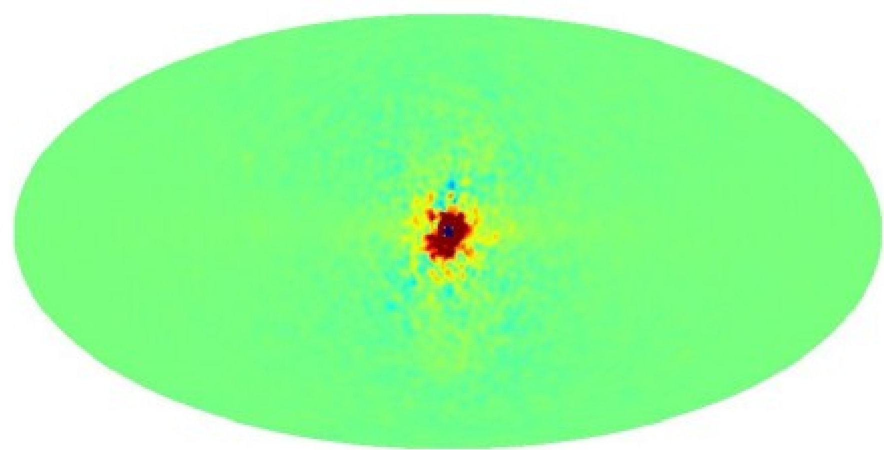
"Cloud-like" component



"Bubble-like" component



"DM-like" component (GeV excess)



Local significance for contribution from bb spectrum

Pixel-by-pixel spectral decomposition:

$$\frac{dN}{dE} = \alpha_1 \left.\frac{dN}{dE}\right|_{\mathrm{Bu}} + \alpha_2 \left.\frac{dN}{dE}\right|_{\mathrm{Cl}} + \alpha_3 \left.\frac{dN}{dE}\right|_{b\bar{b}} + \mathrm{PSC}$$

Huang+ 2015

The poor-man GeV excess

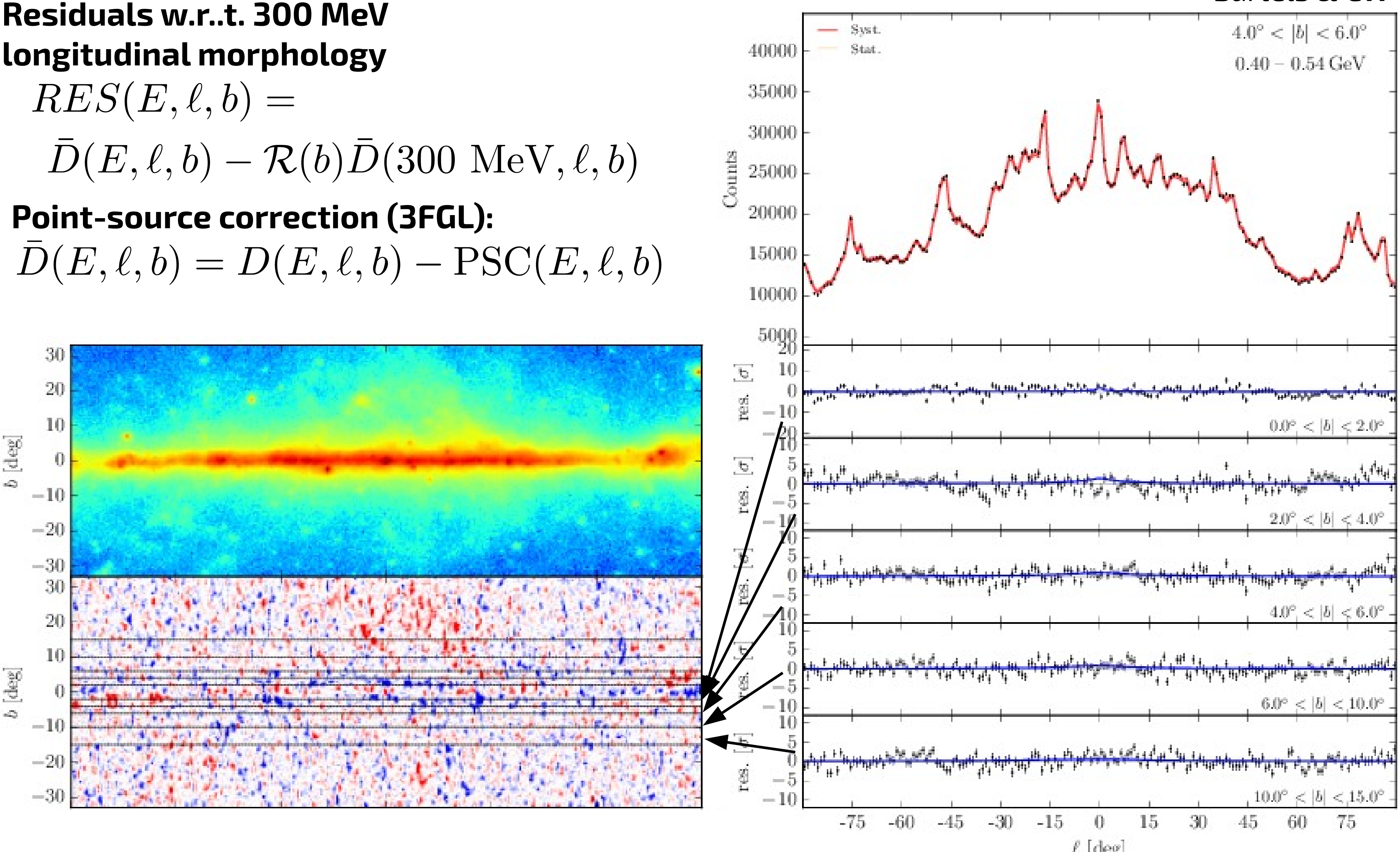
Residuals w.r..t. 300 MeV longitudinal morphology

$$RES(E,\ell,b) = \bar{D}(E,\ell,b) - \mathcal{R}(b)\bar{D}(300\ \mathrm{MeV},\ell,b)$$

Point-source correction (3FGL):

$$\bar{D}(E,\ell,b) = D(E,\ell,b) - \mathrm{PSC}(E,\ell,b)$$

Bartels & CW



Blue: stacked MSP spectrum

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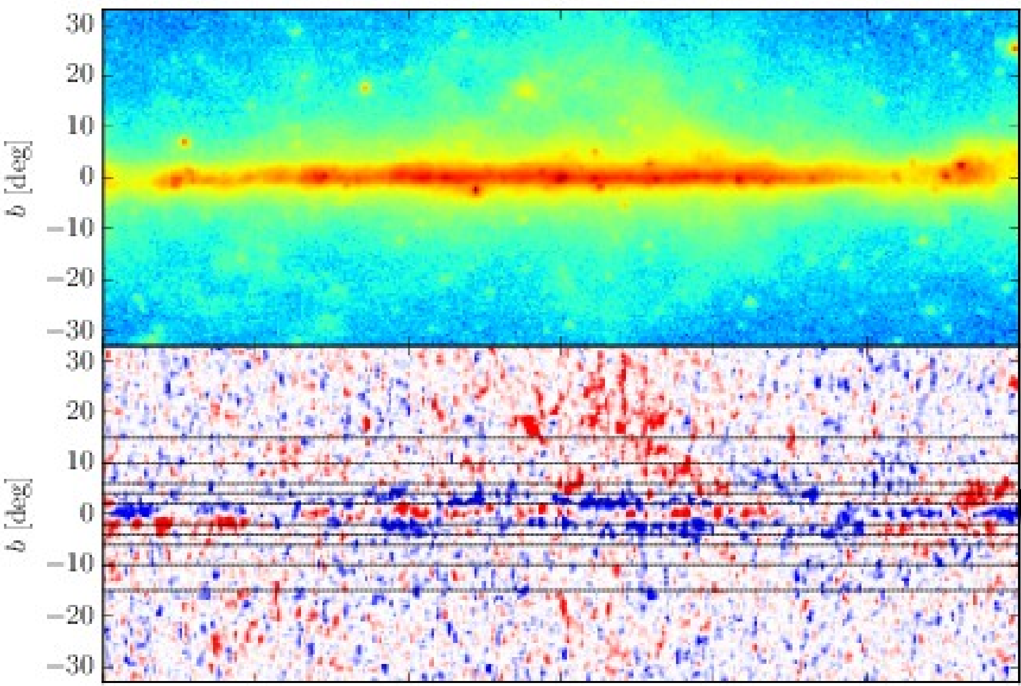

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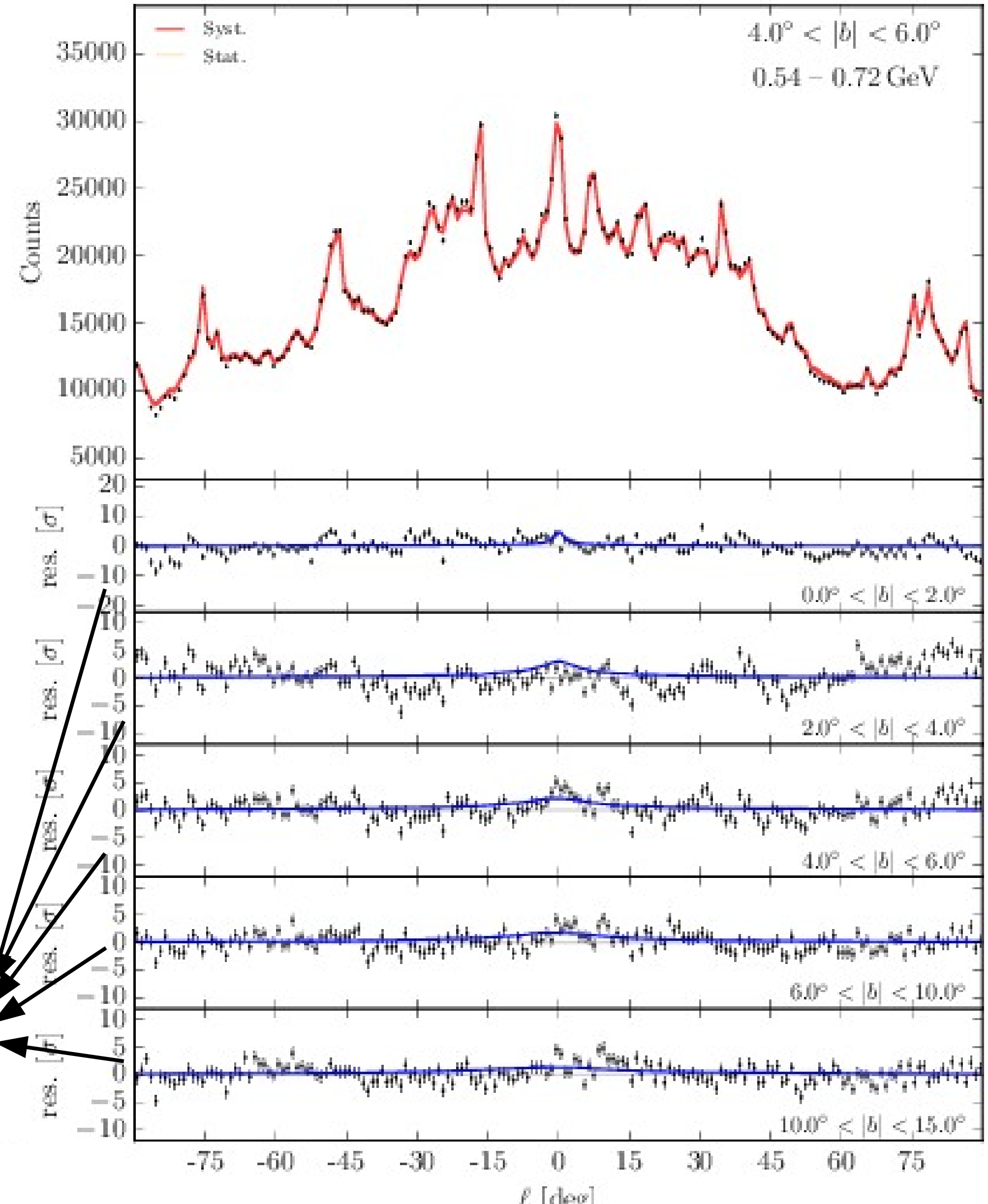

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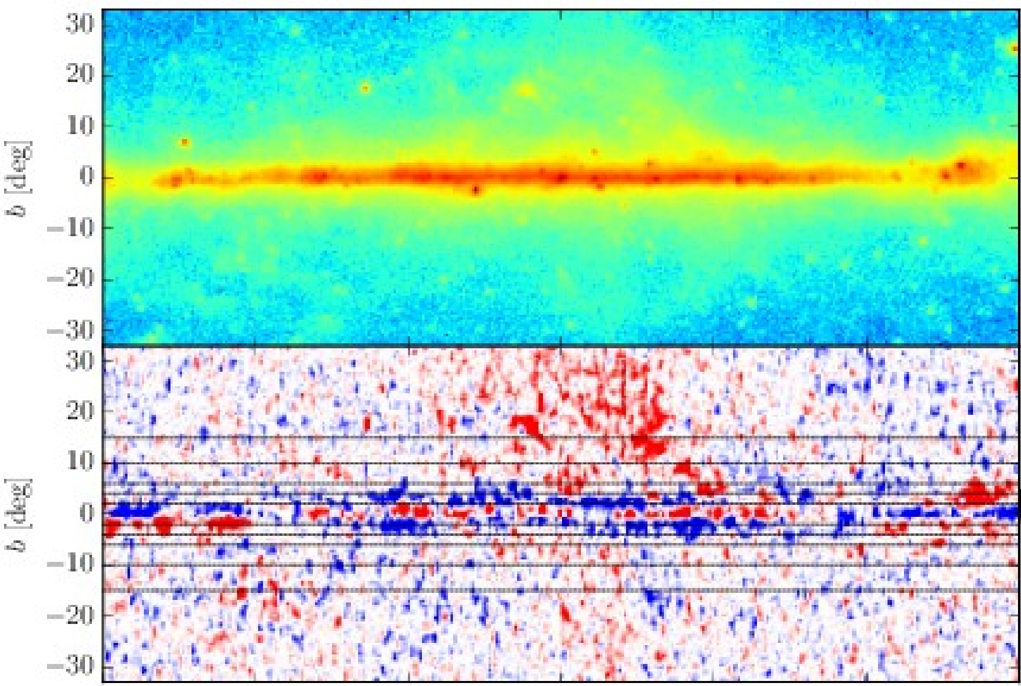

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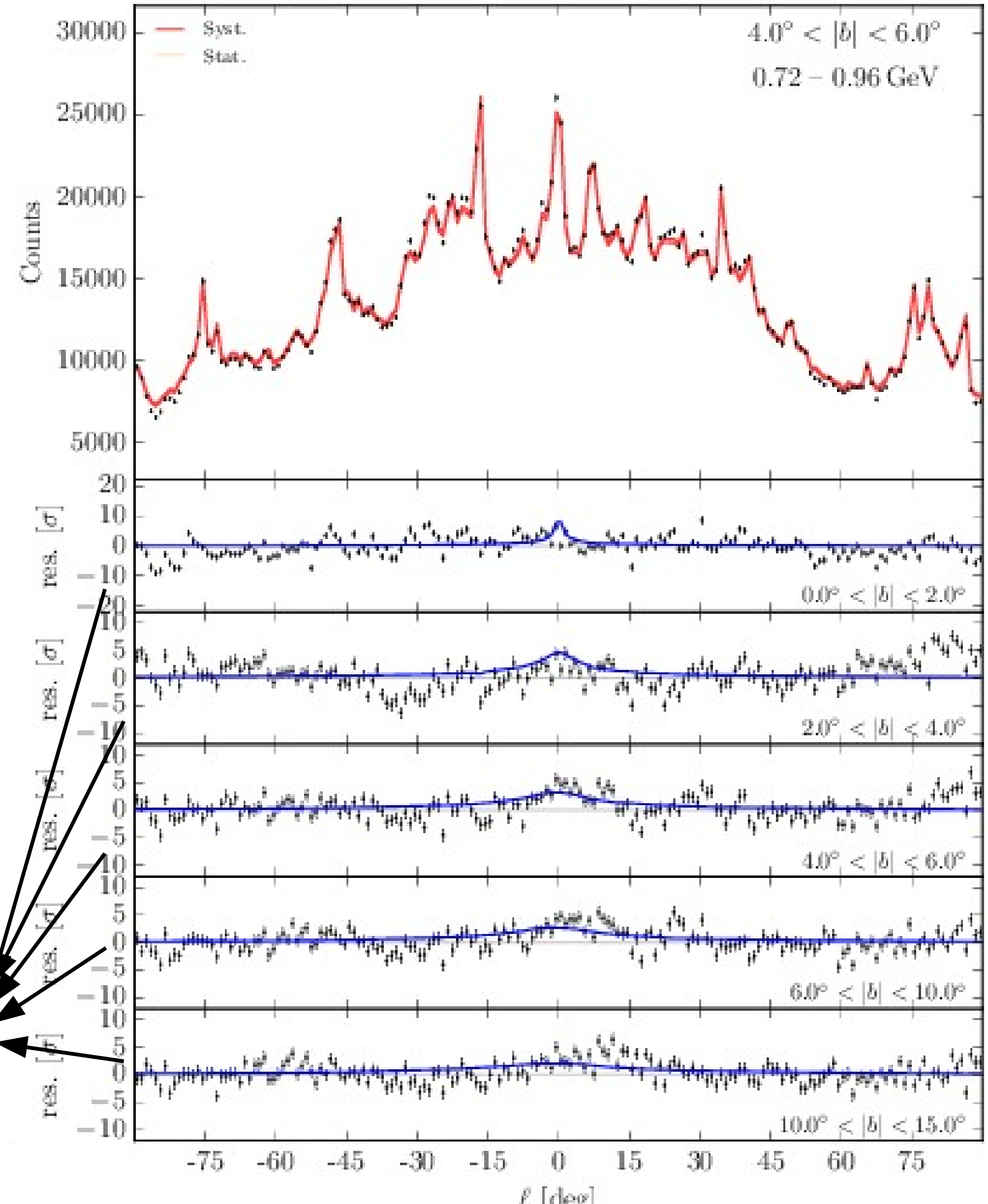

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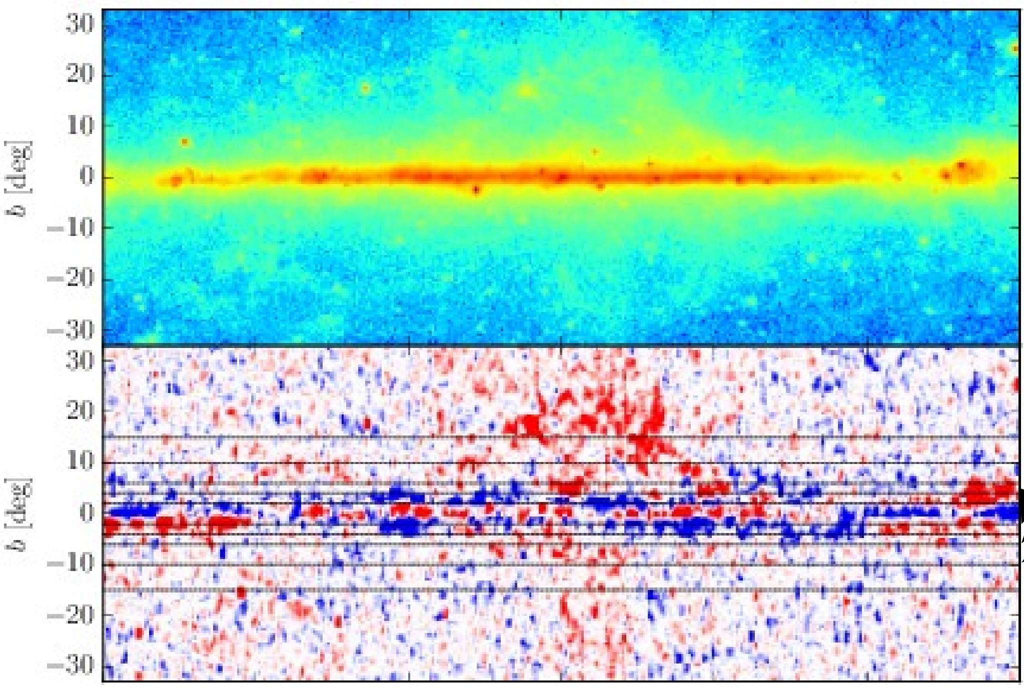

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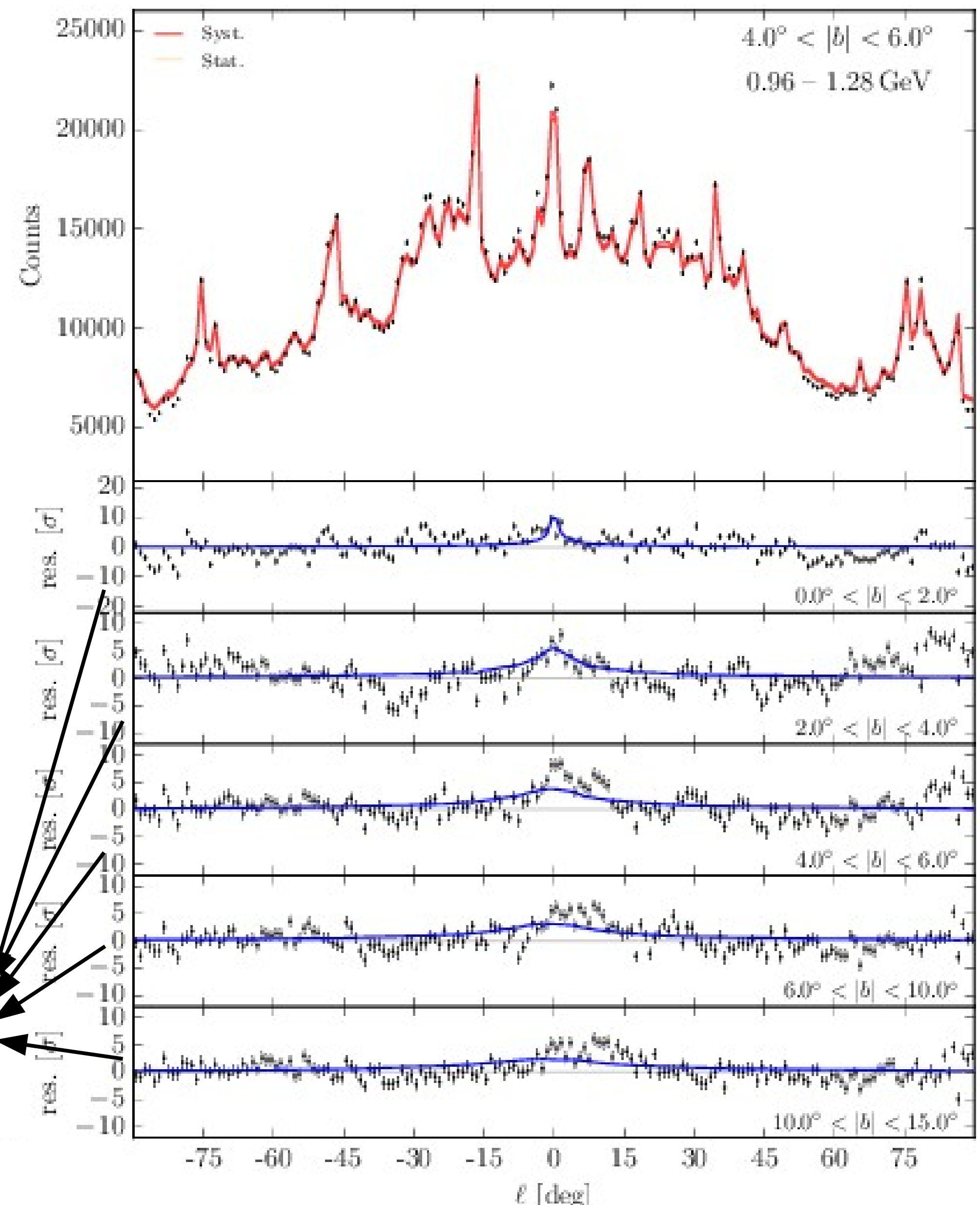

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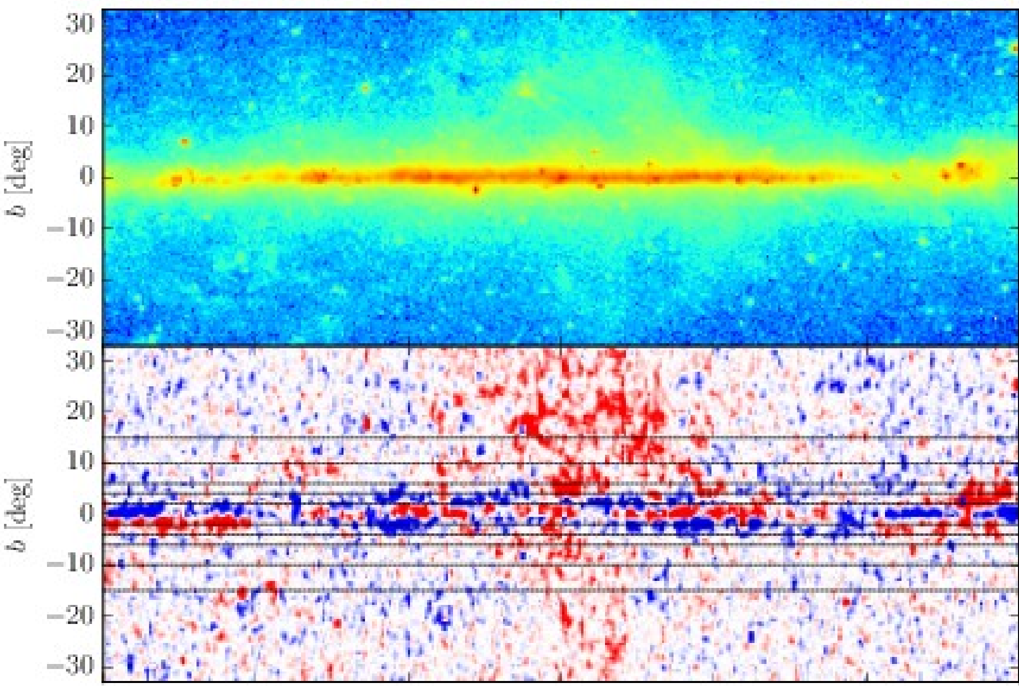

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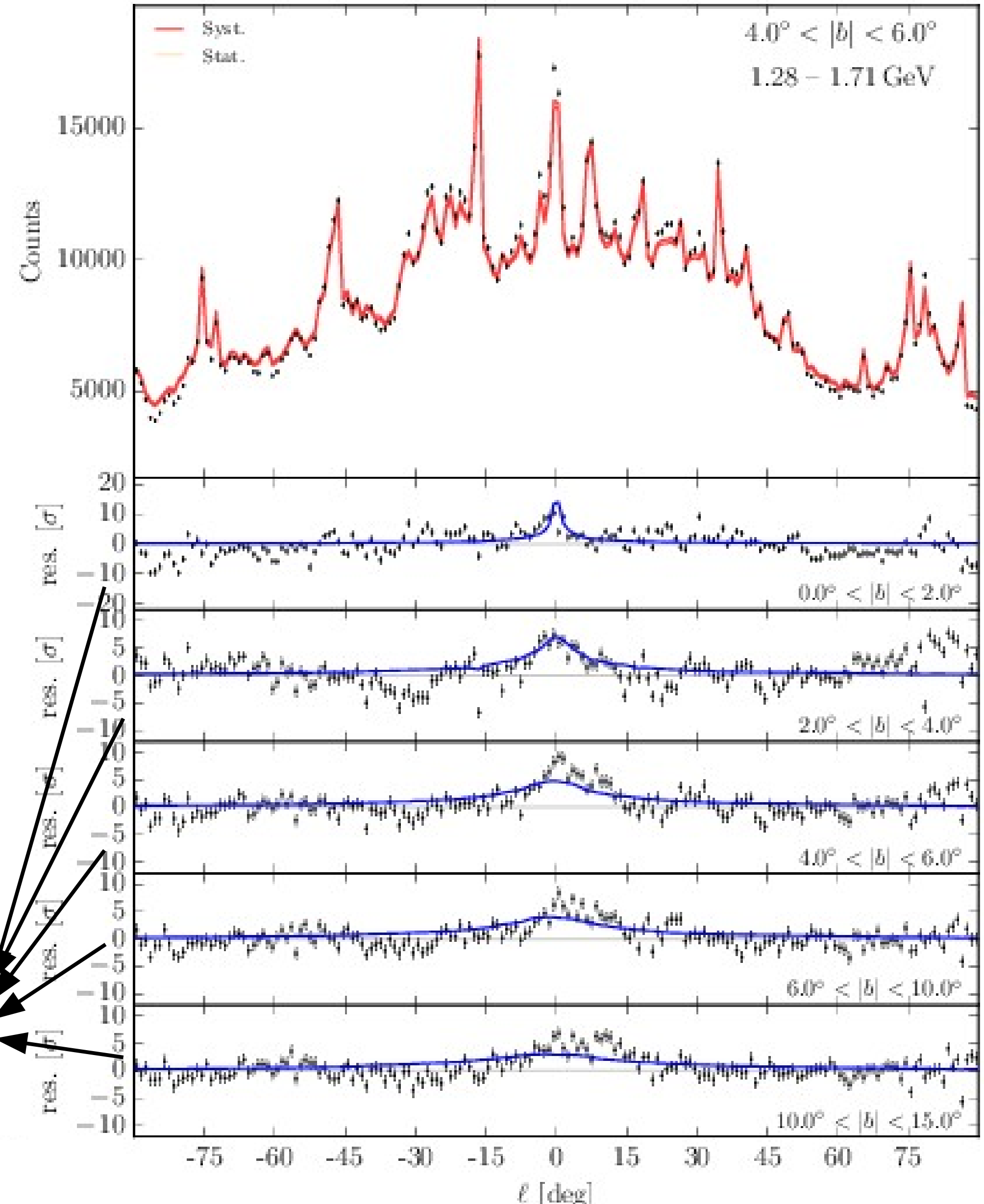

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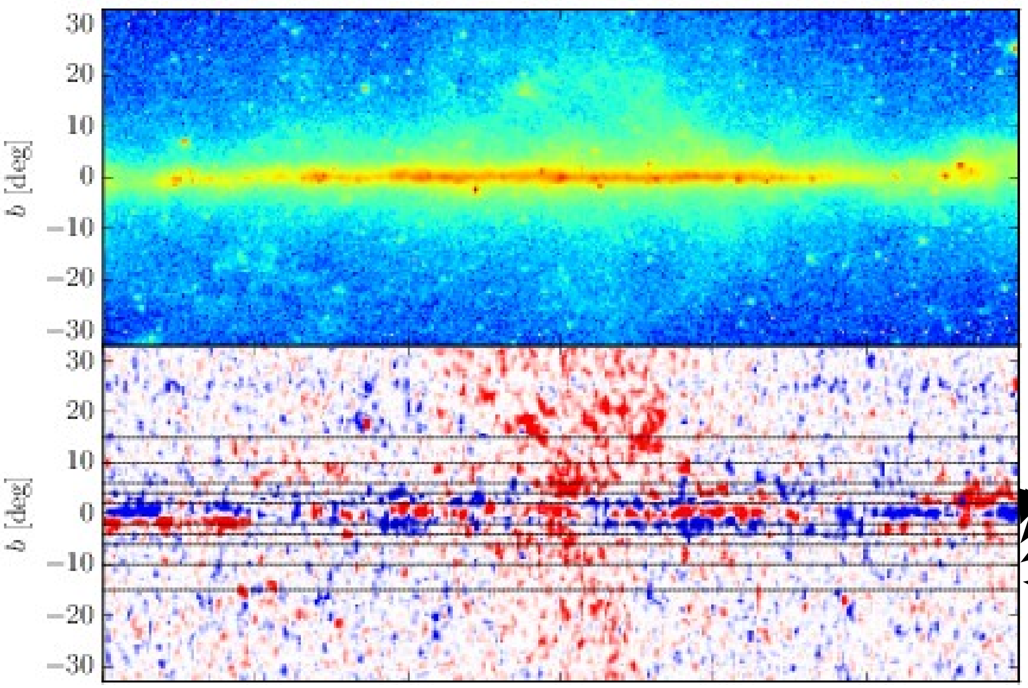

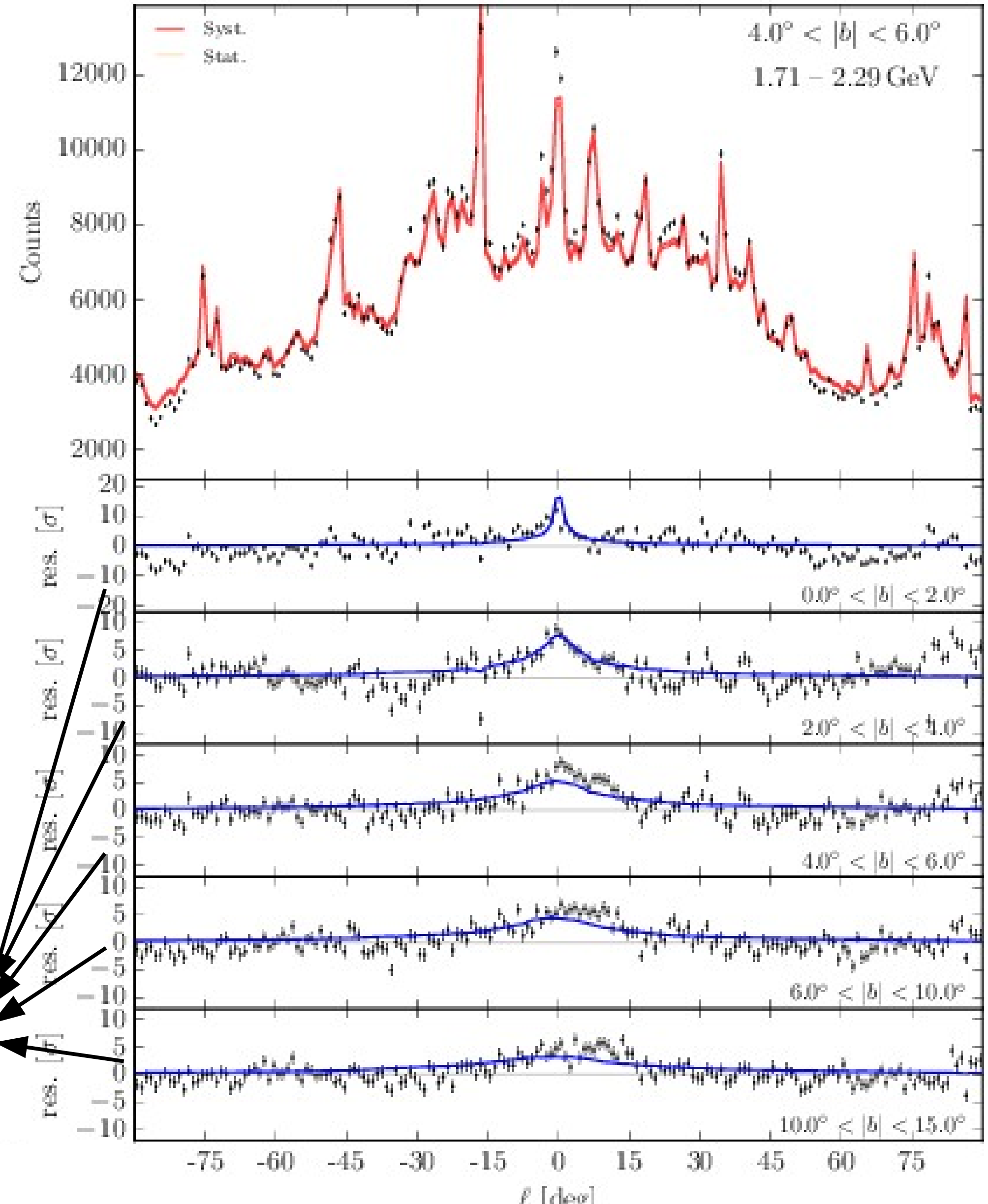

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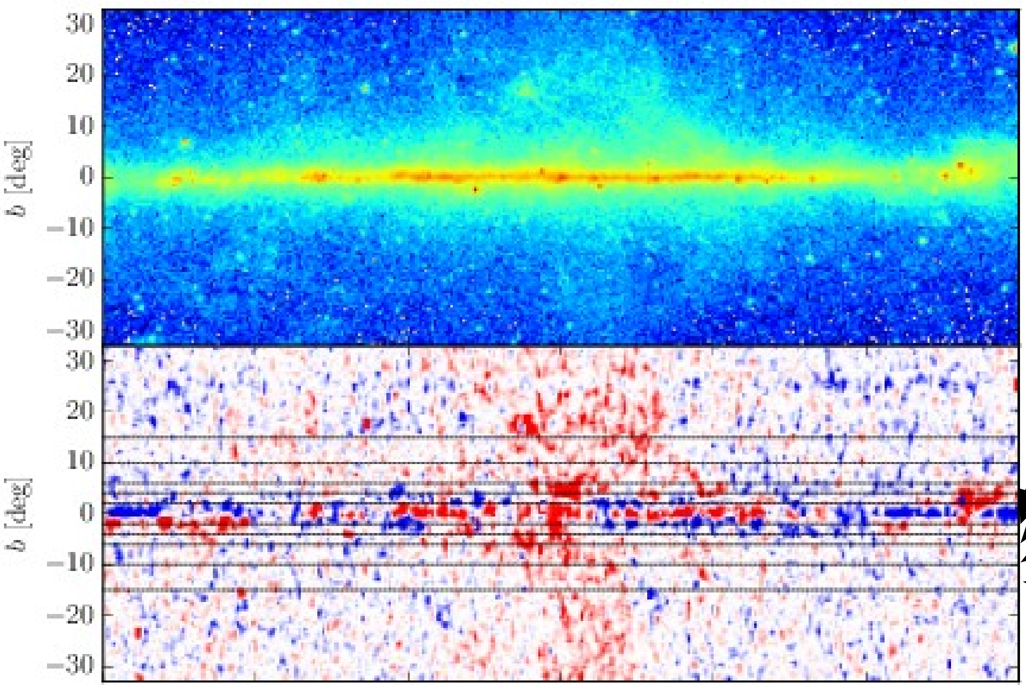

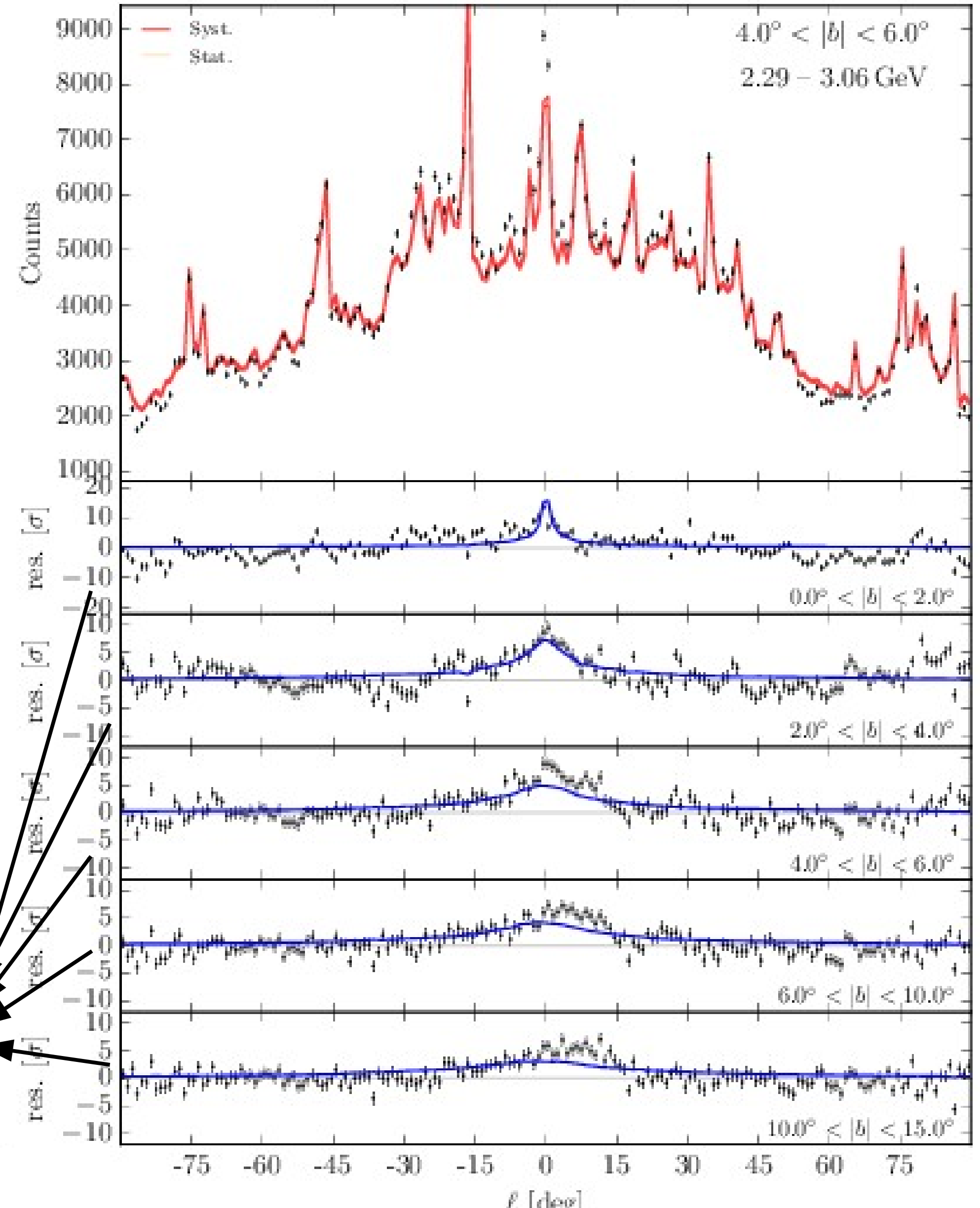

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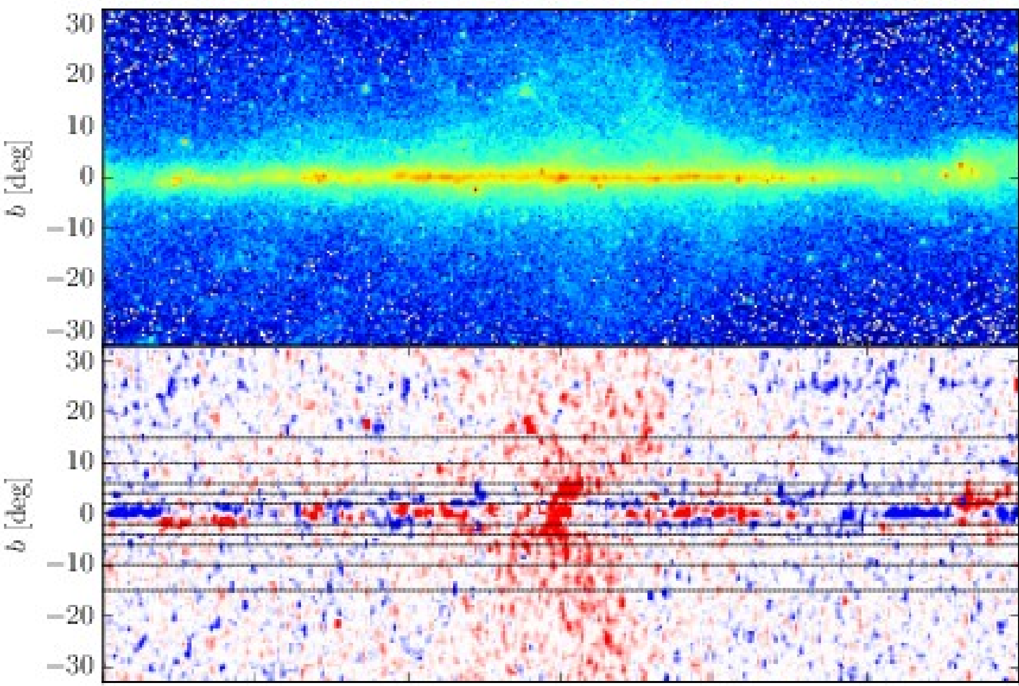

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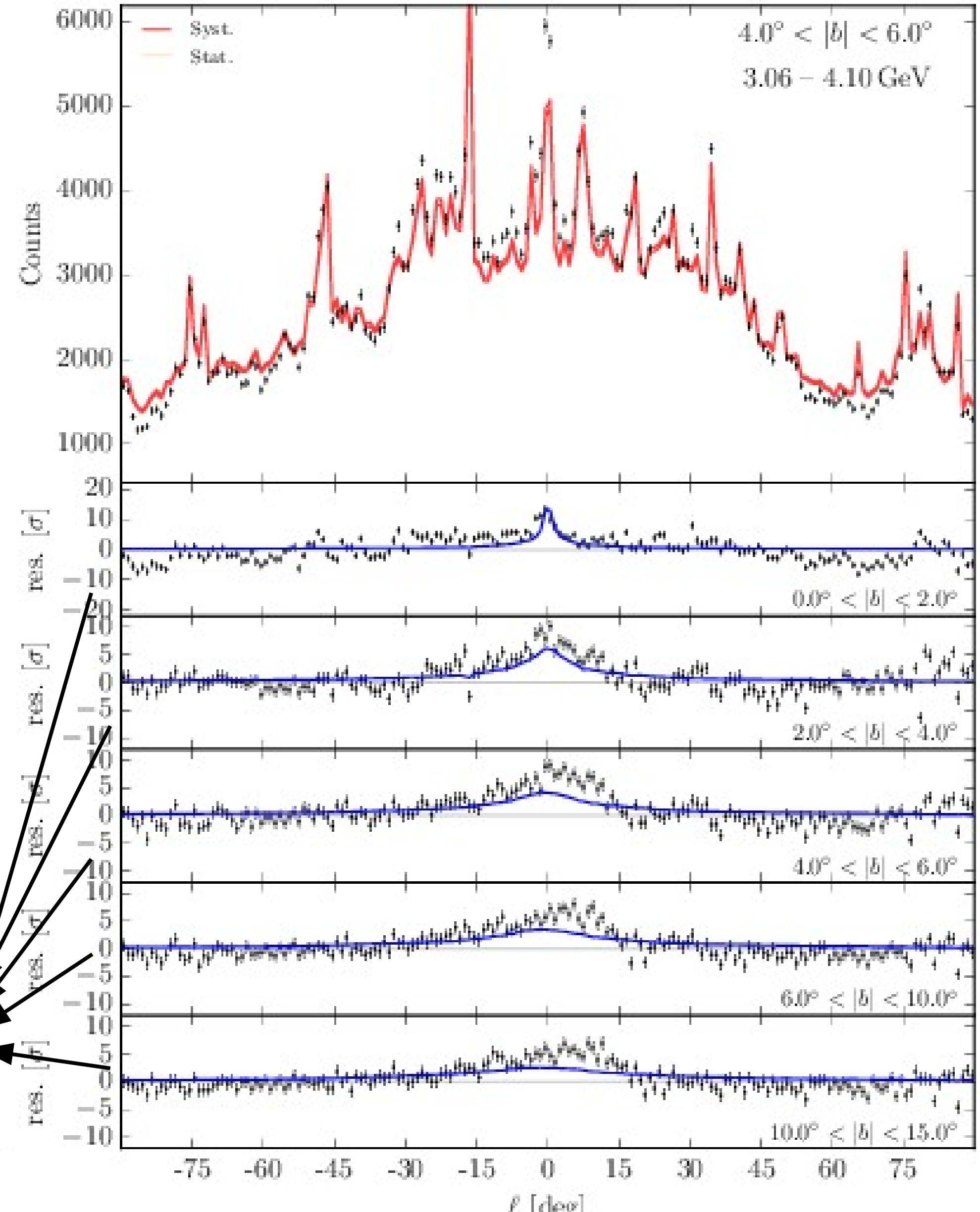

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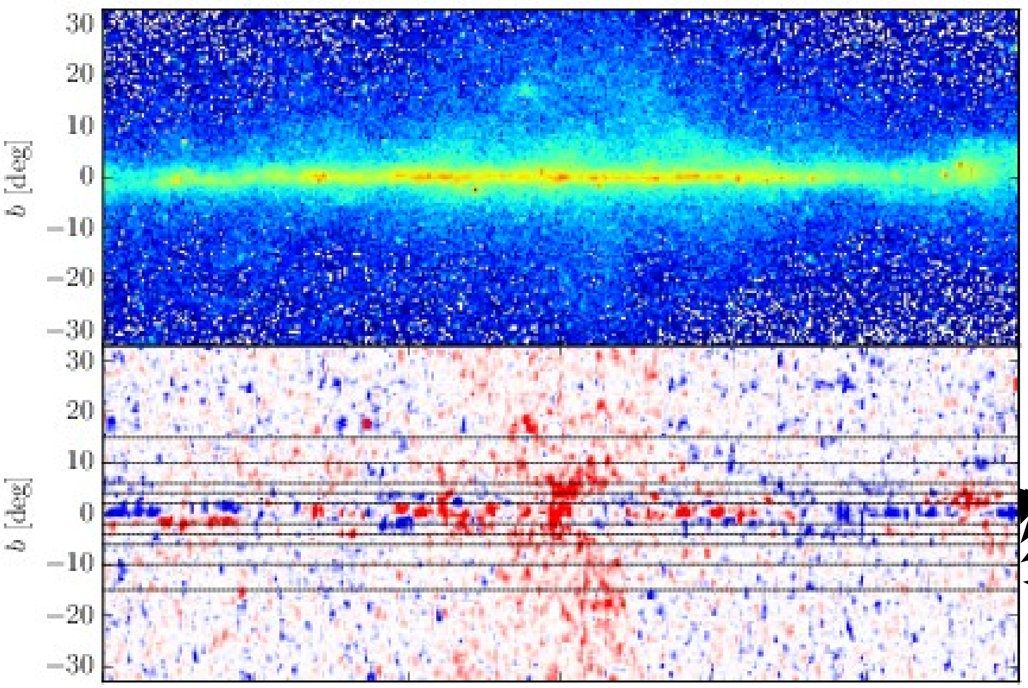

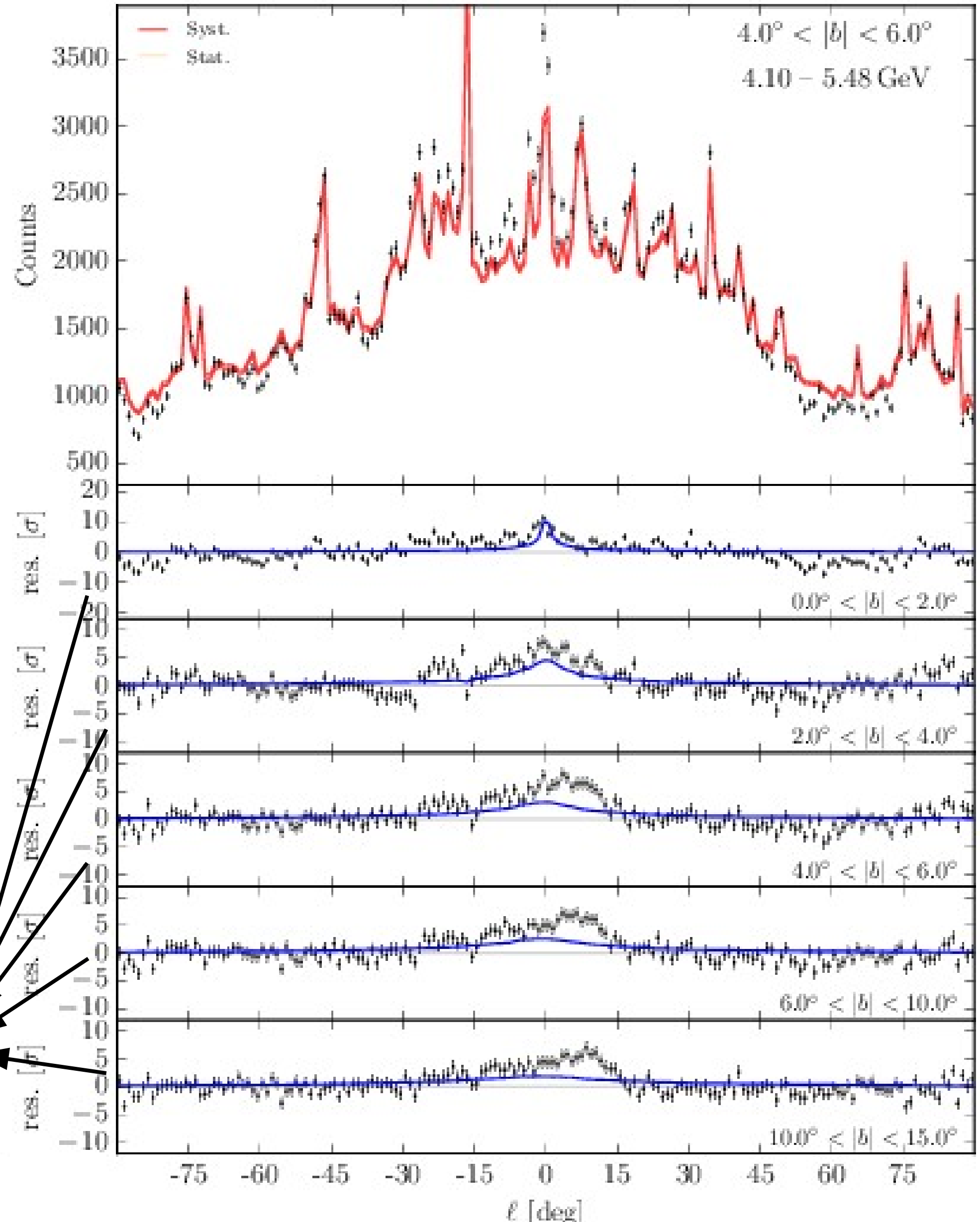

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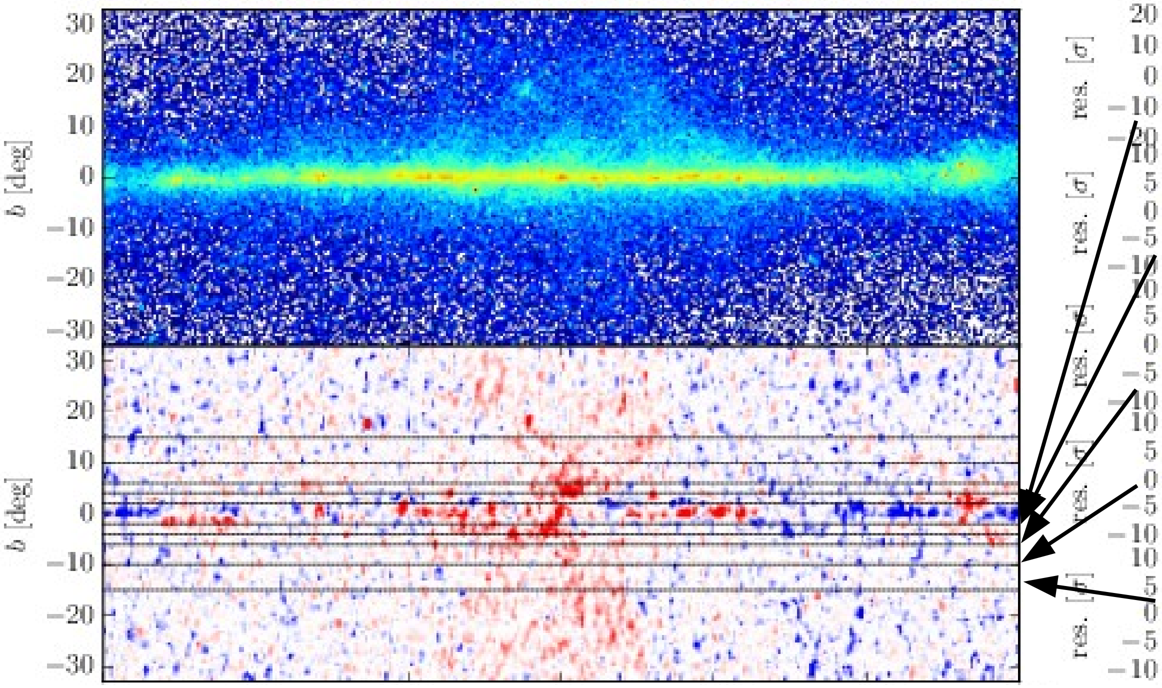

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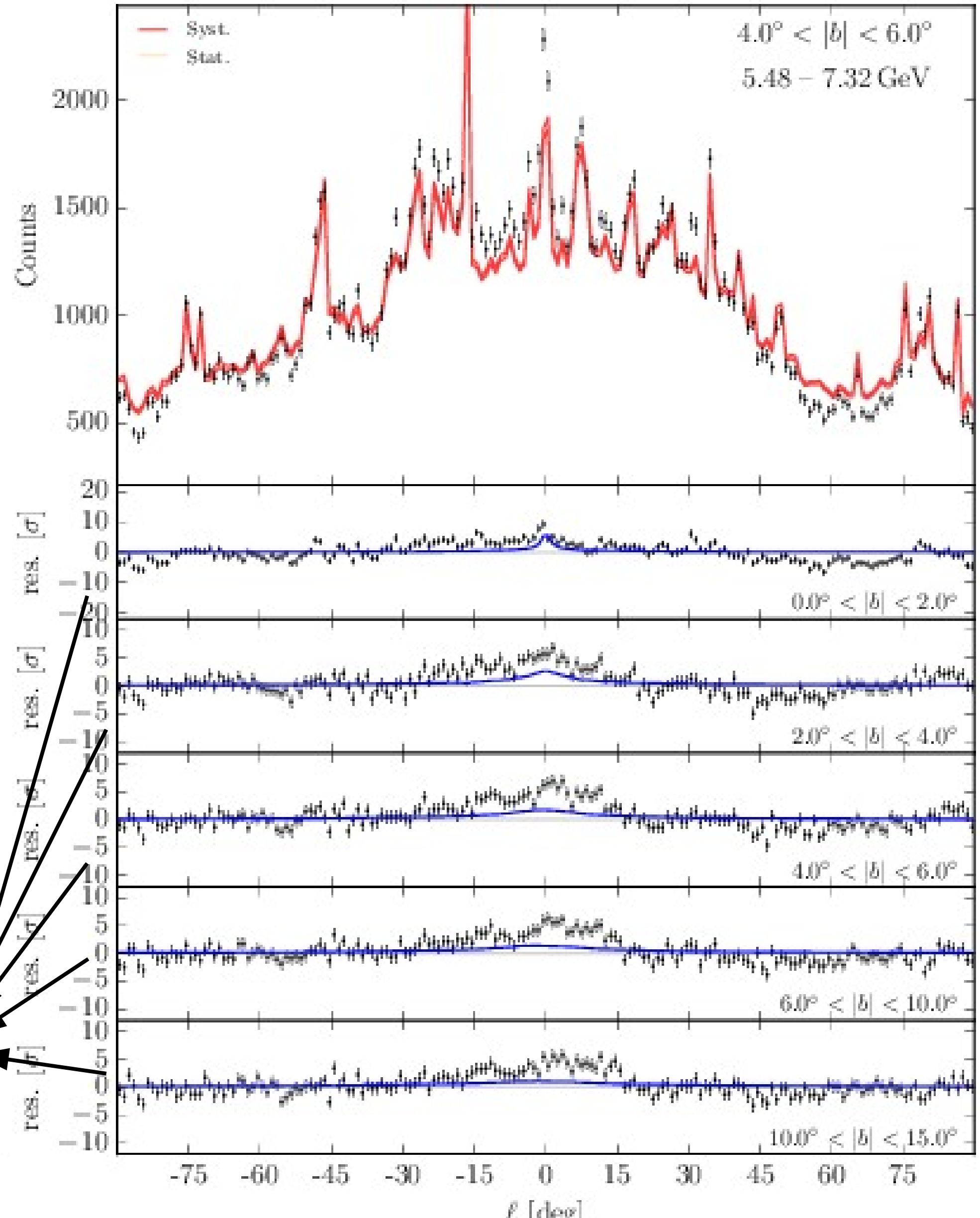

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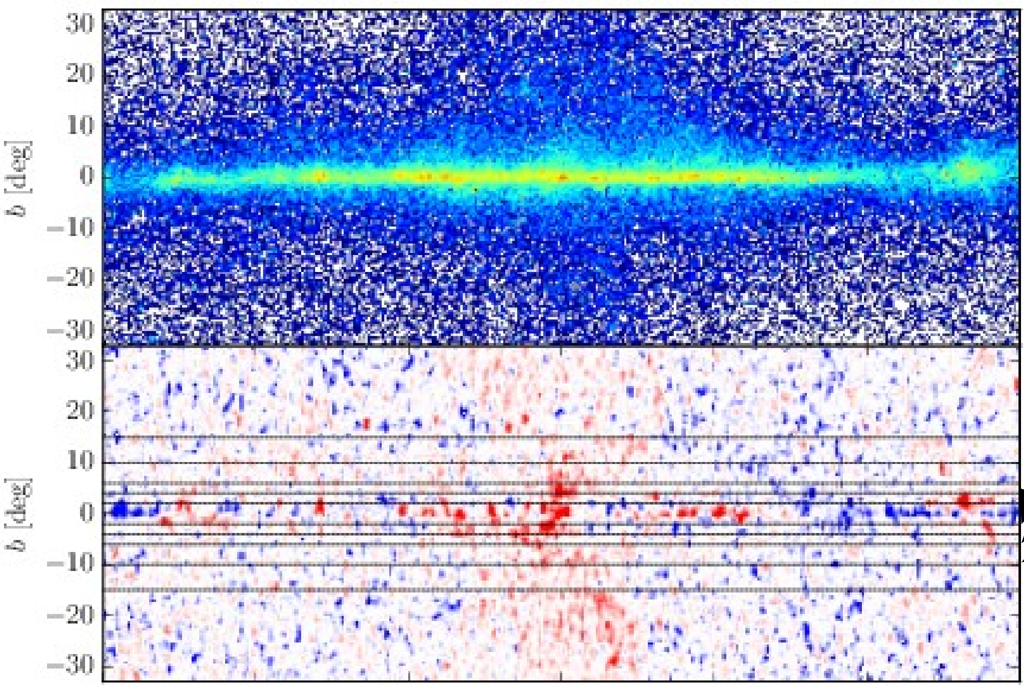

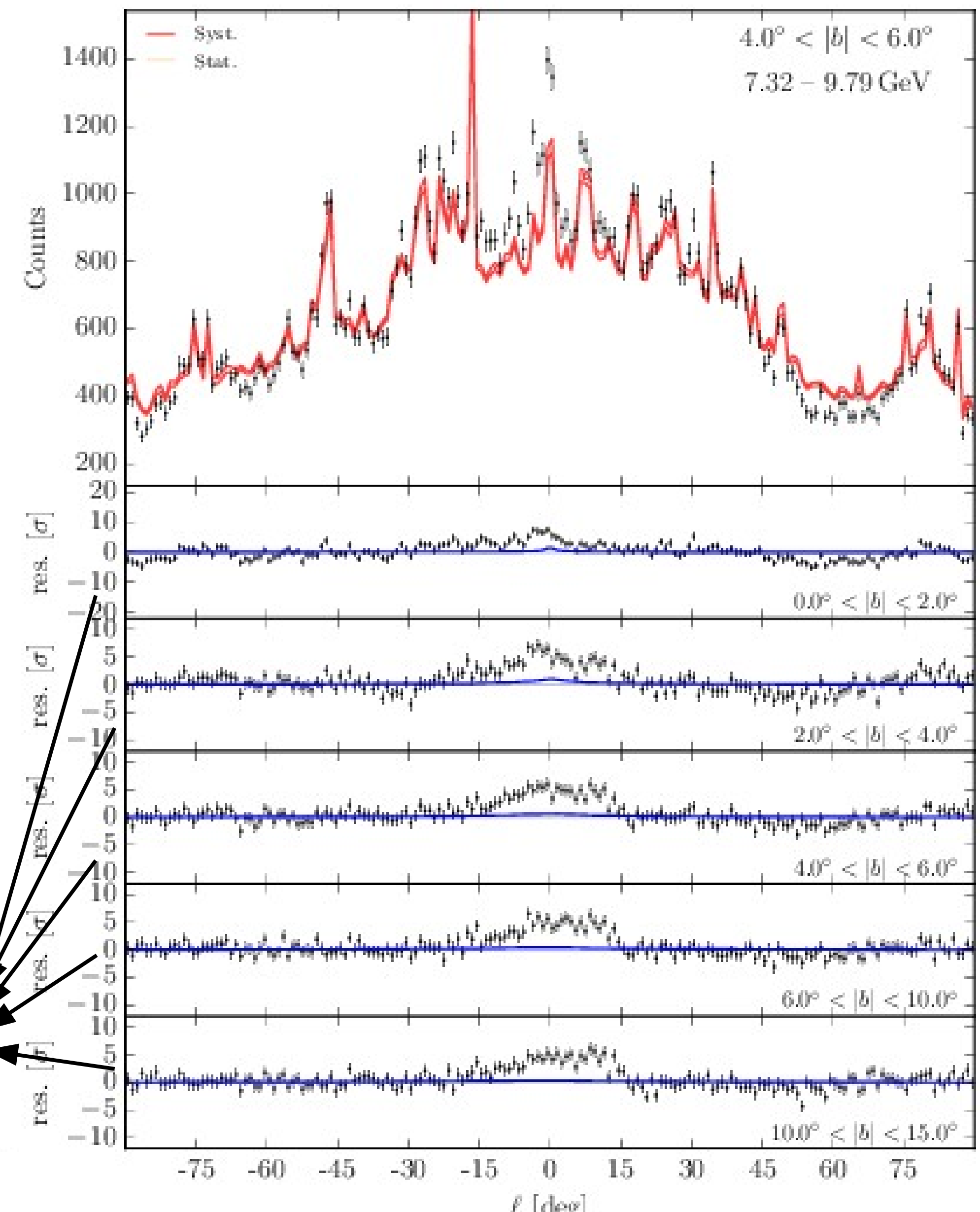

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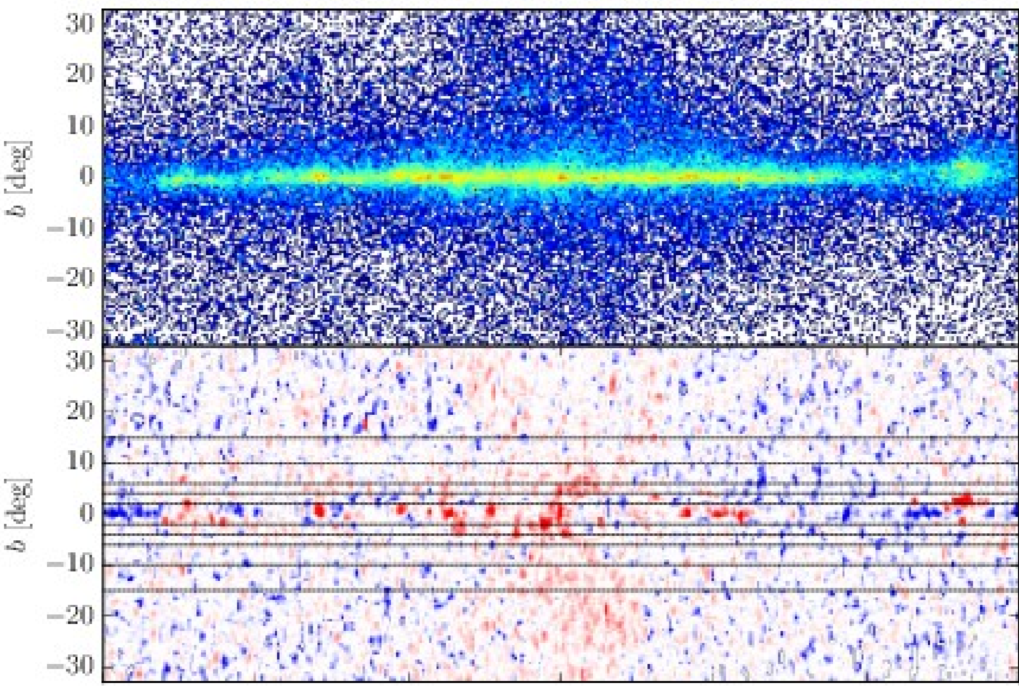

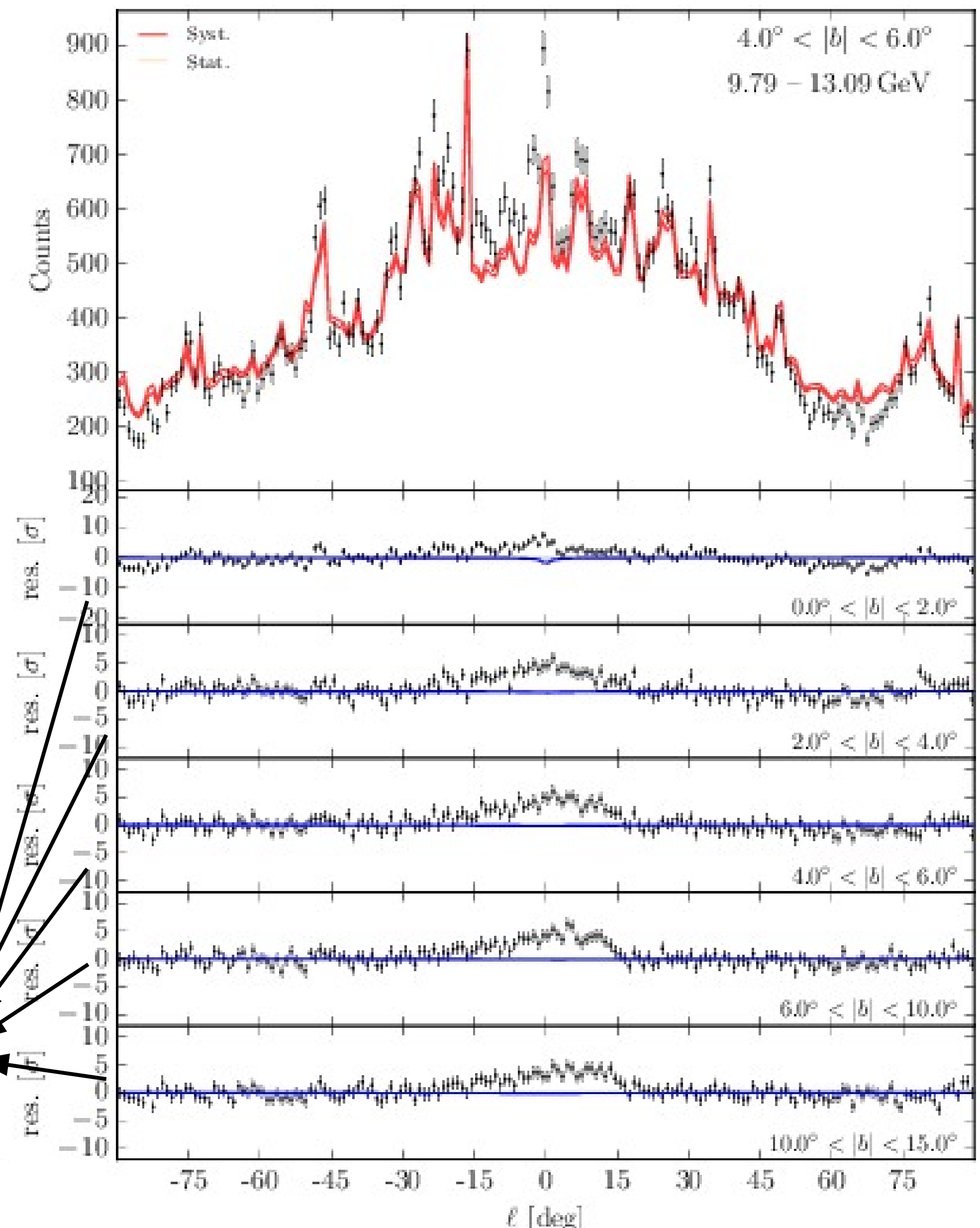

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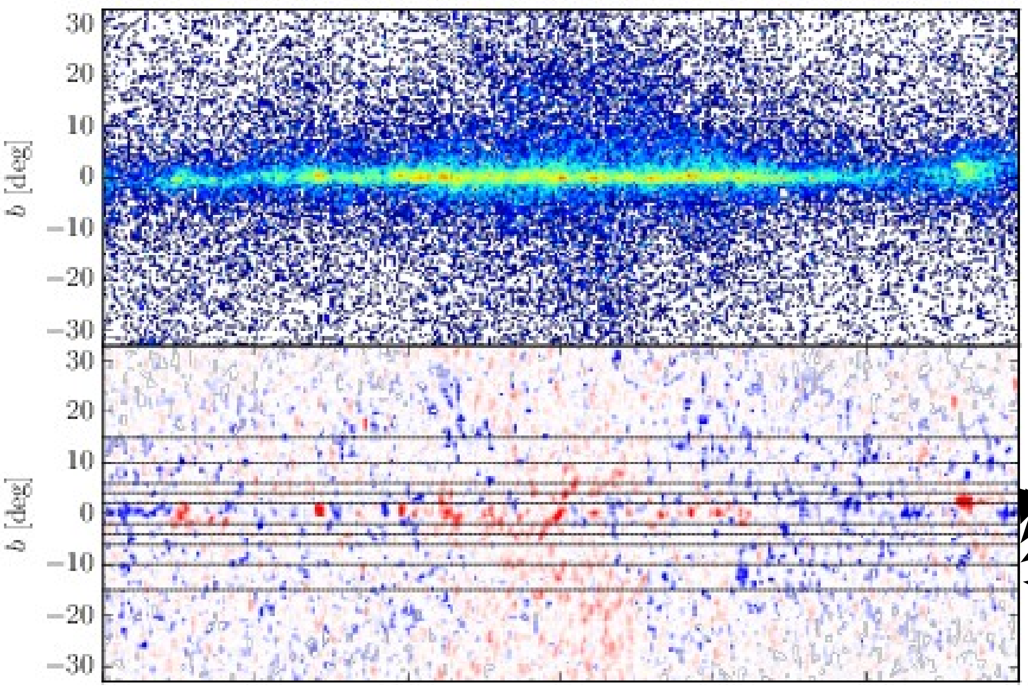
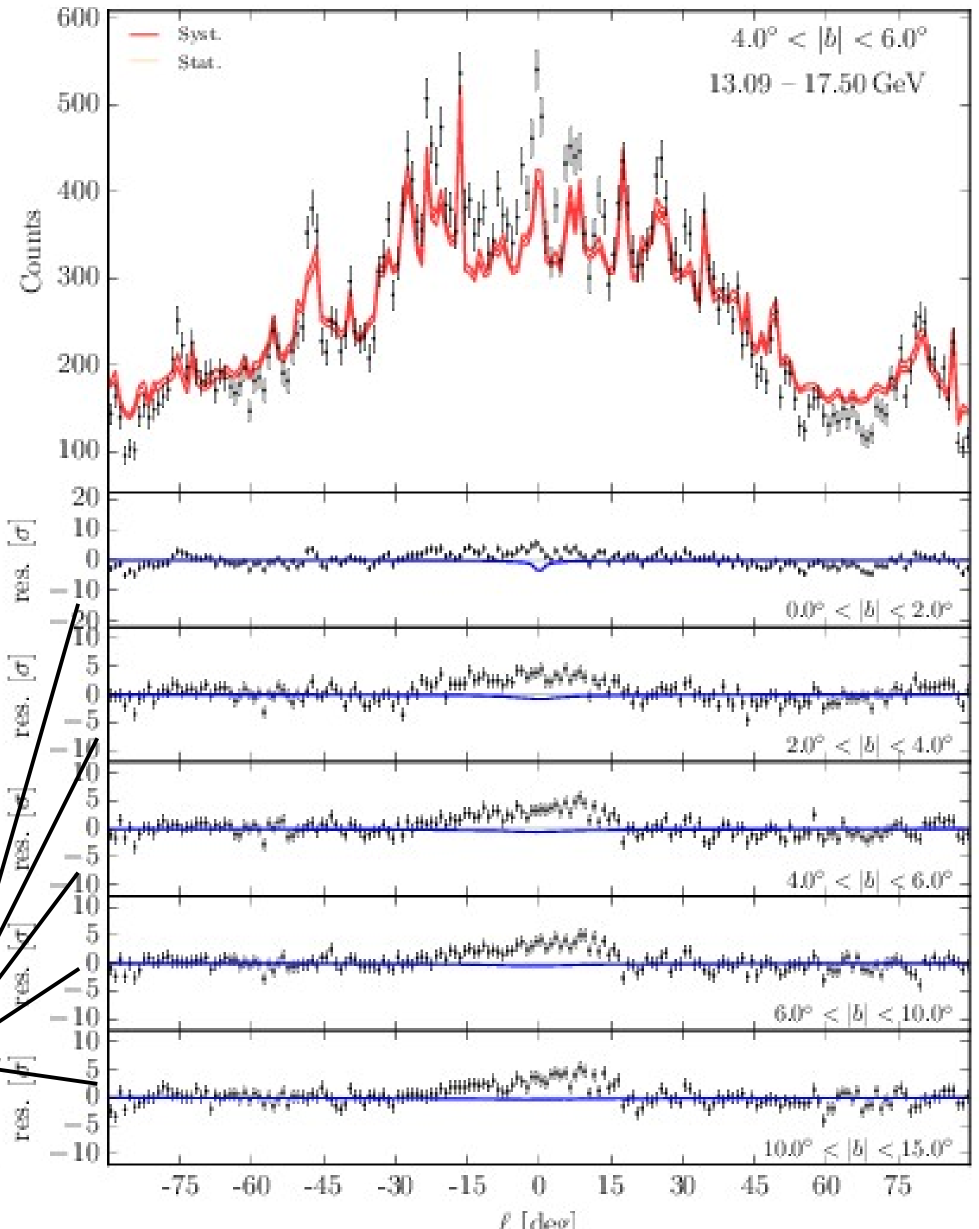


Bartels & CW



Blue: stacked MSP spectrum

The poor man version of the GeV excess

Bartels & CW

Residuals w.r..t. 300 MeV longitudinal morphology

$$RES(E,\ell,b) =$$
$$\bar{D}(E,\ell,b) - \mathcal{R}(b)\bar{D}(300\ \mathrm{MeV},\ell,b)$$

Point-source correction:

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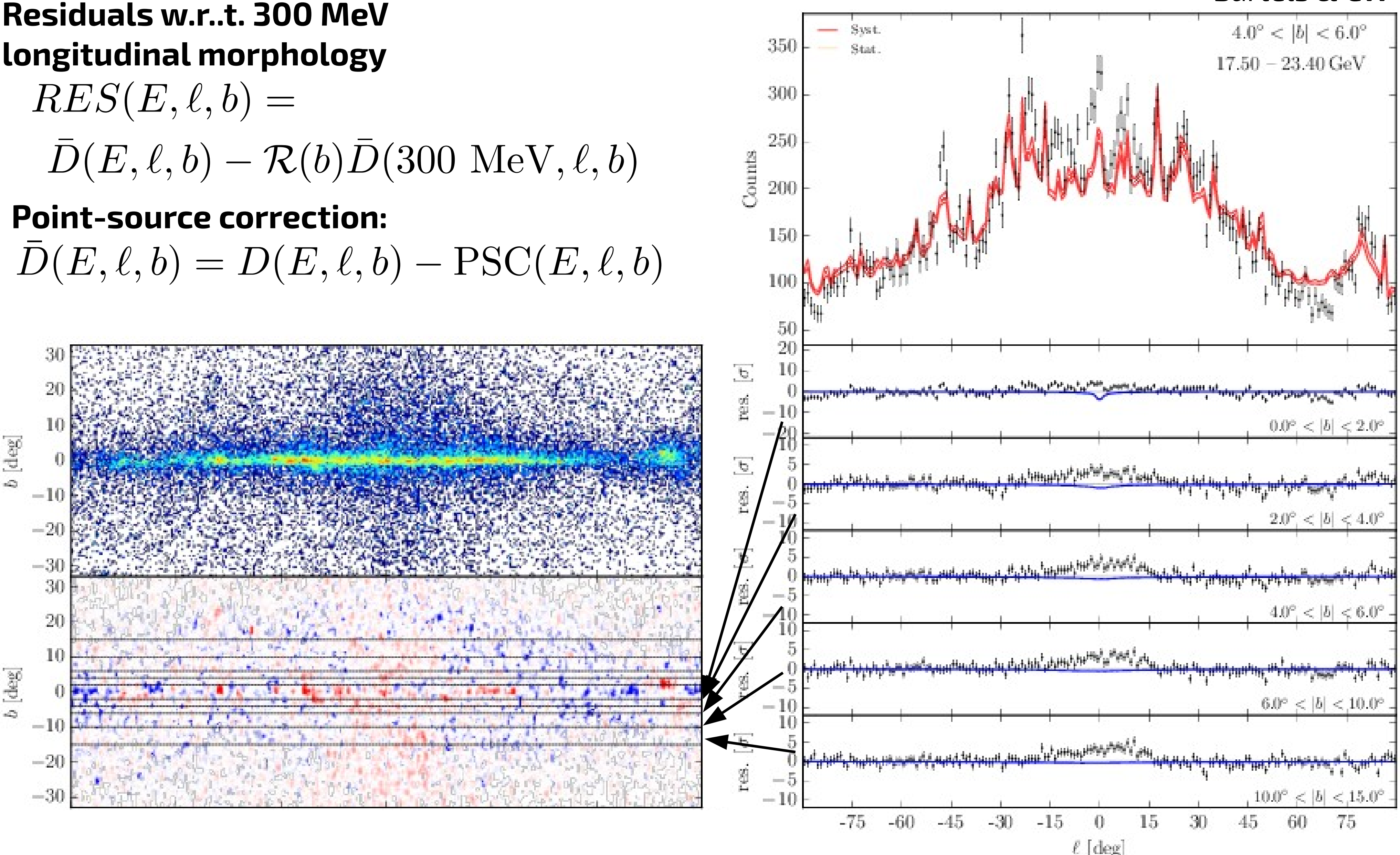

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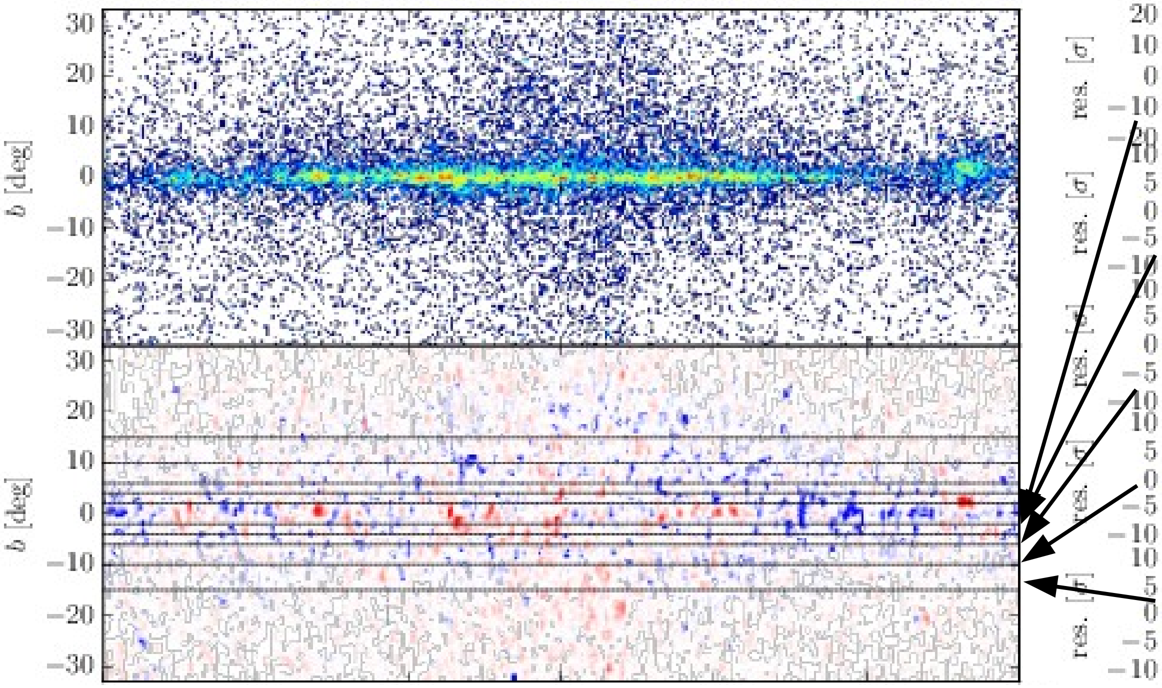

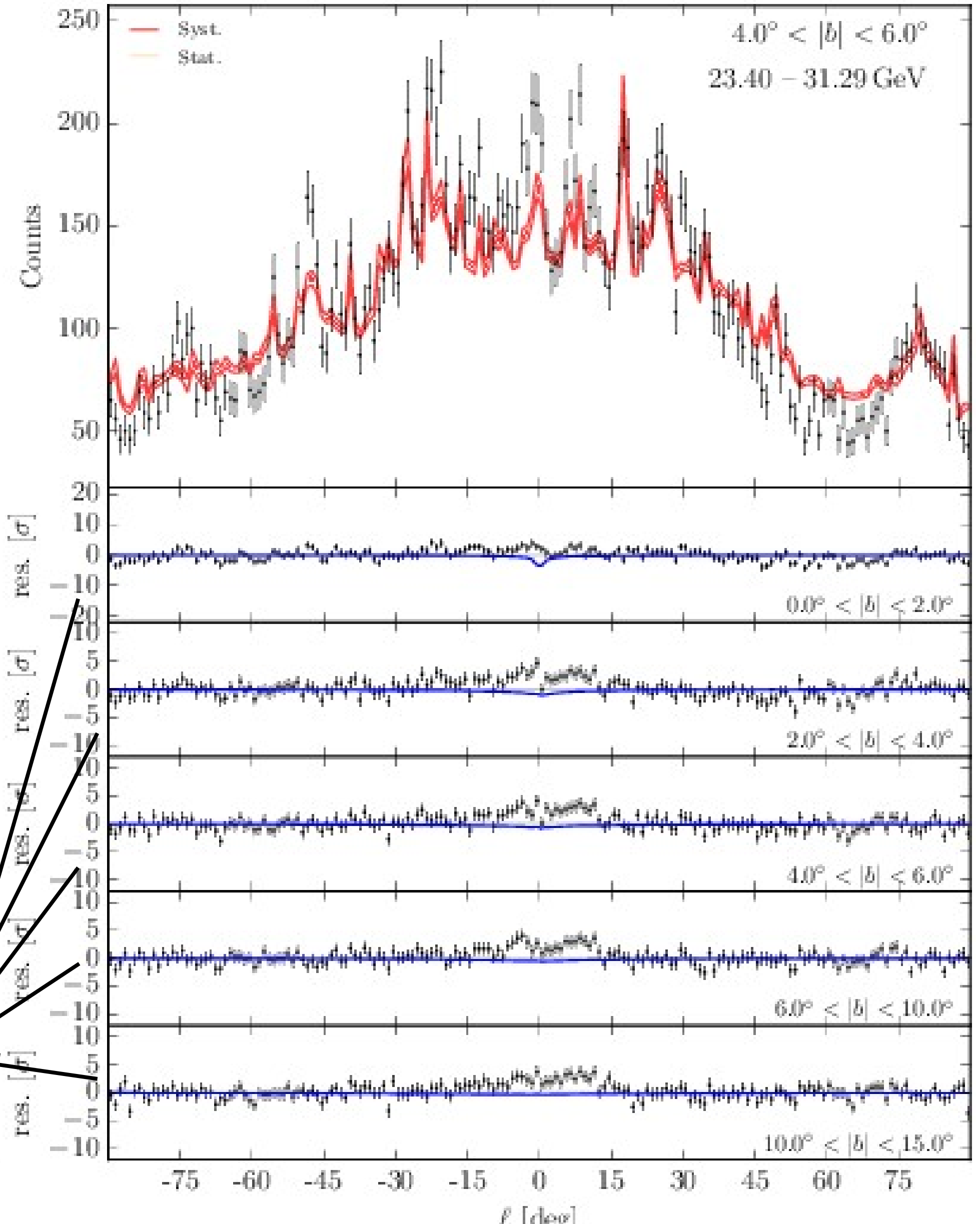

Blue: stacked MSP spectrum

The poor man version of the GeV excess

Bartels & CW

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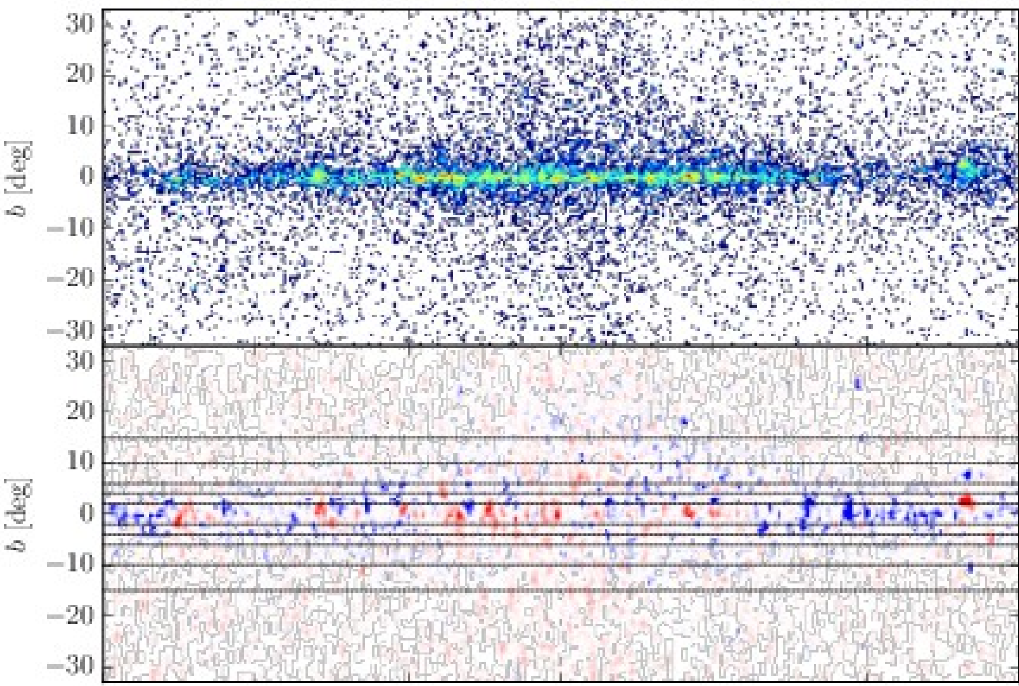

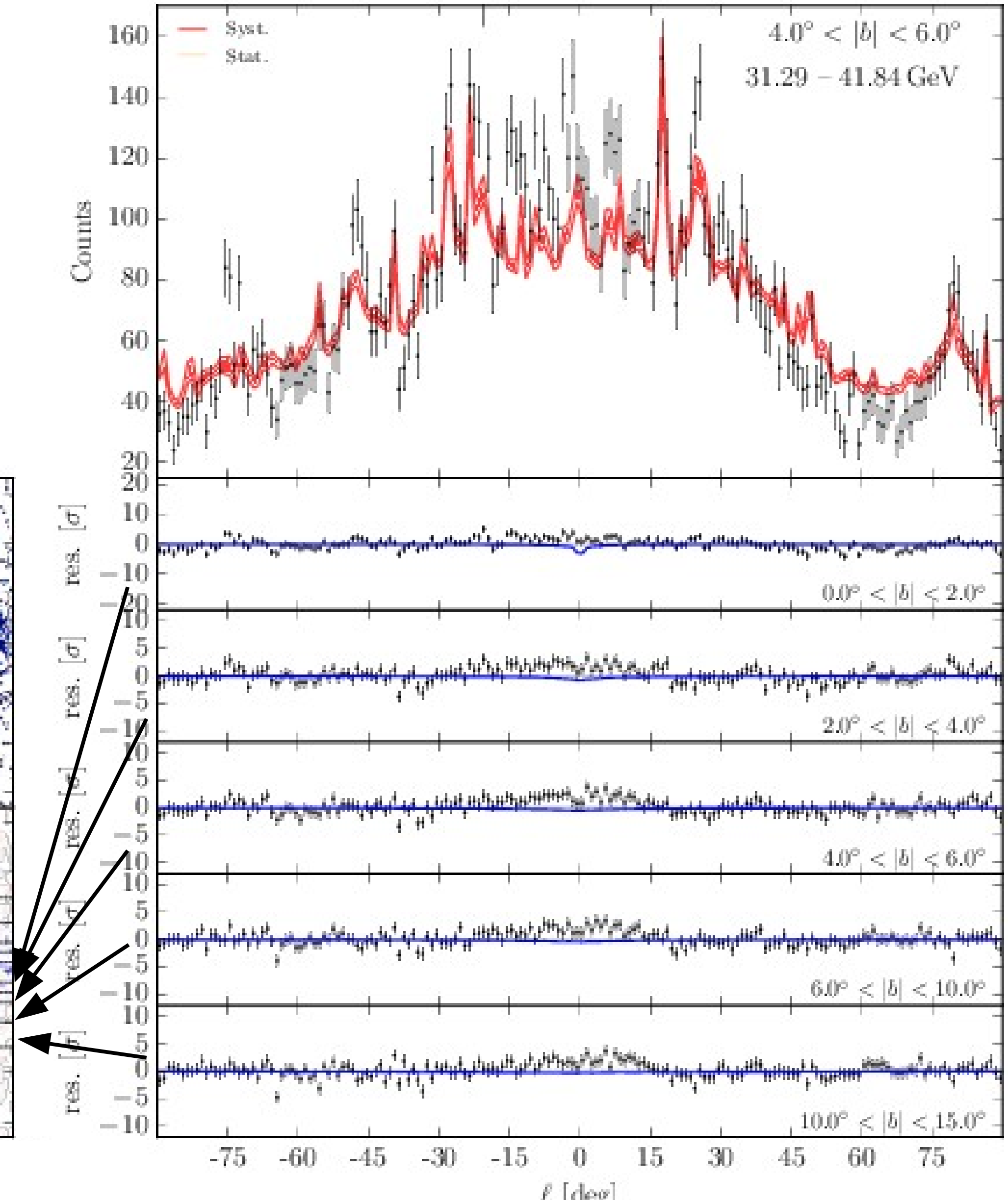

Blue: stacked MSP spectrum

The poor man version of the GeV excess

Residuals w.r..t. 300 MeV longitudinal morphology

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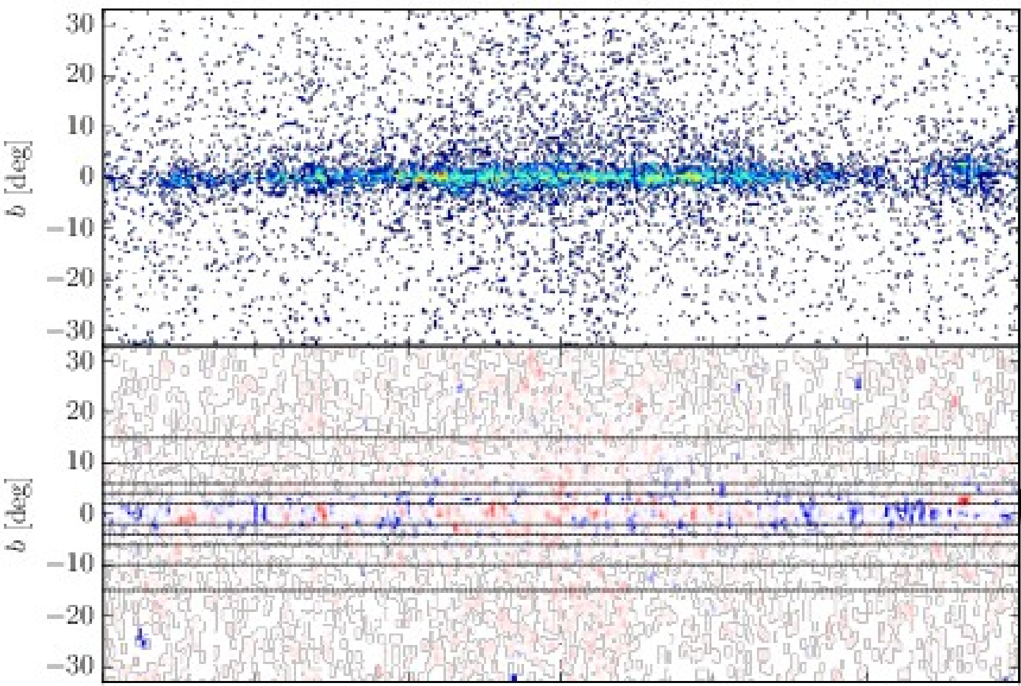
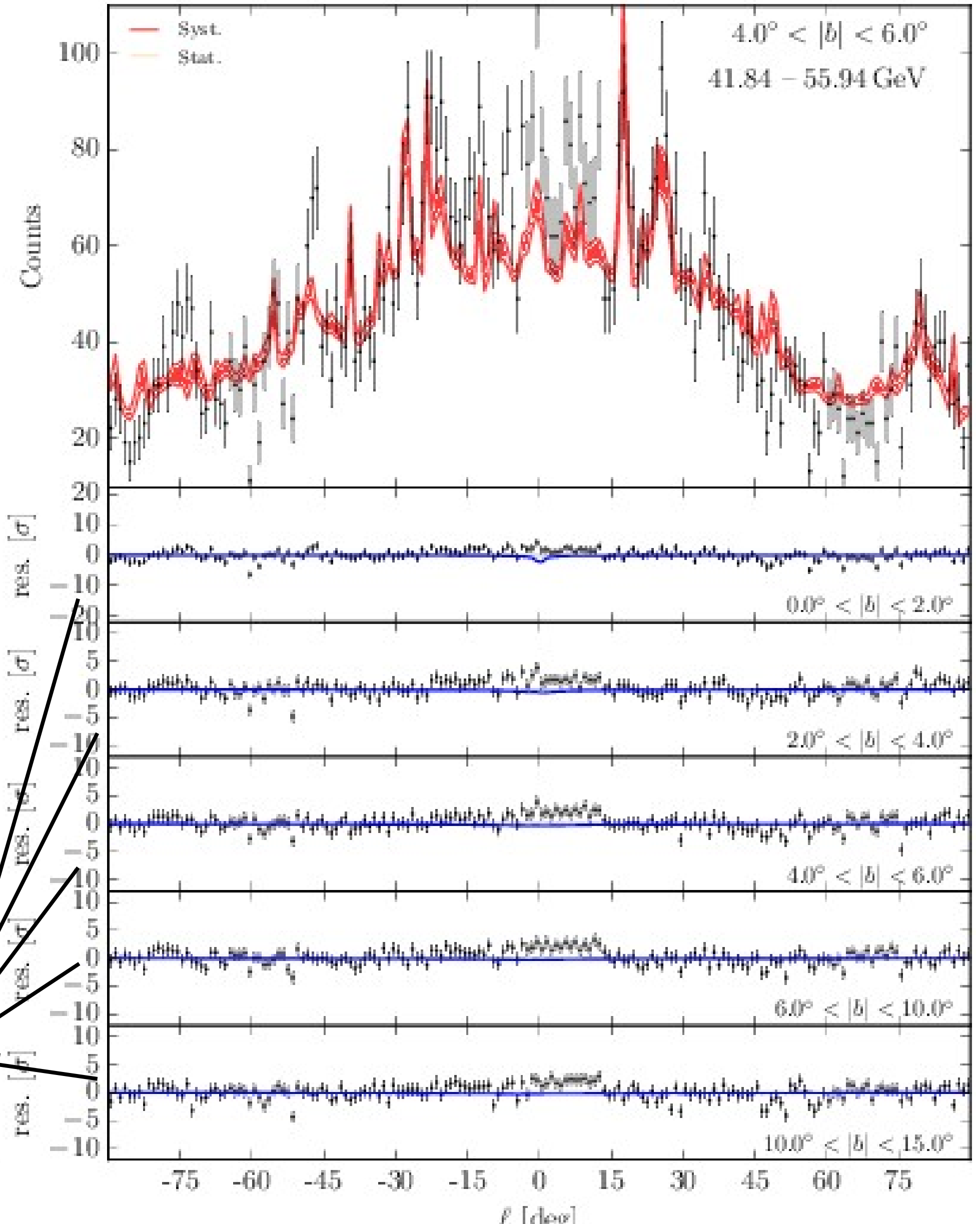
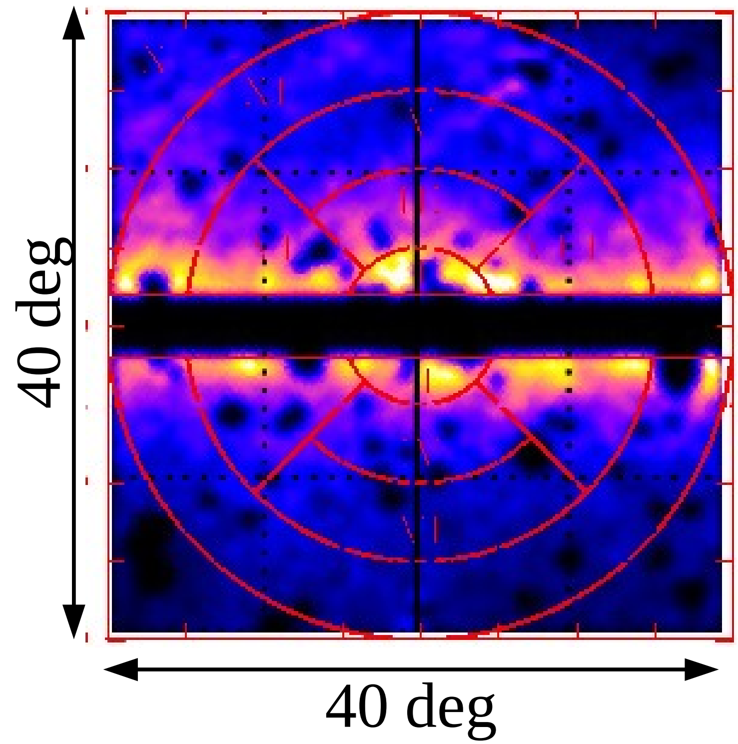


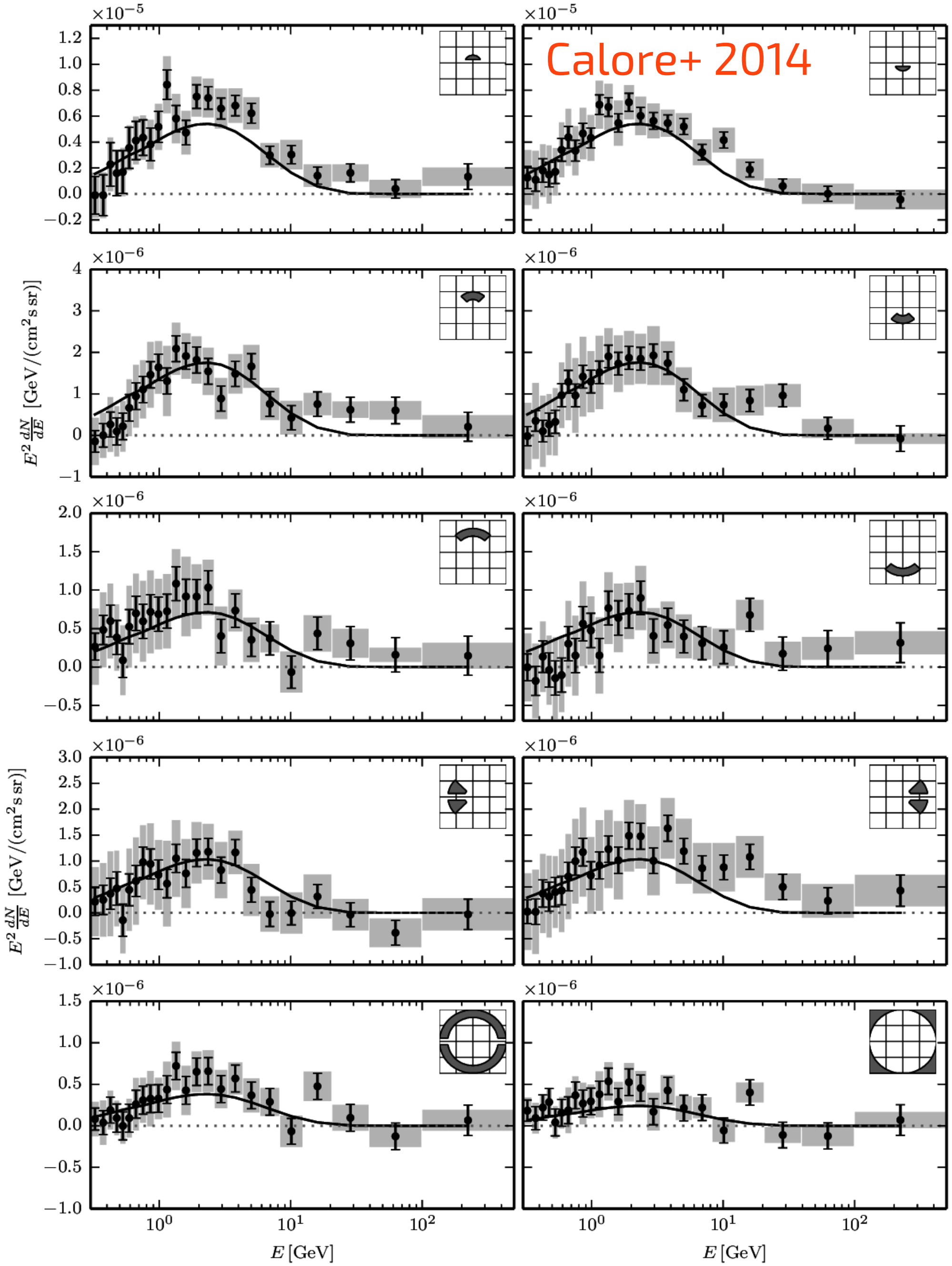
Bartels & CW



Blue: stacked MSP spectrum

The excess at high latitudes



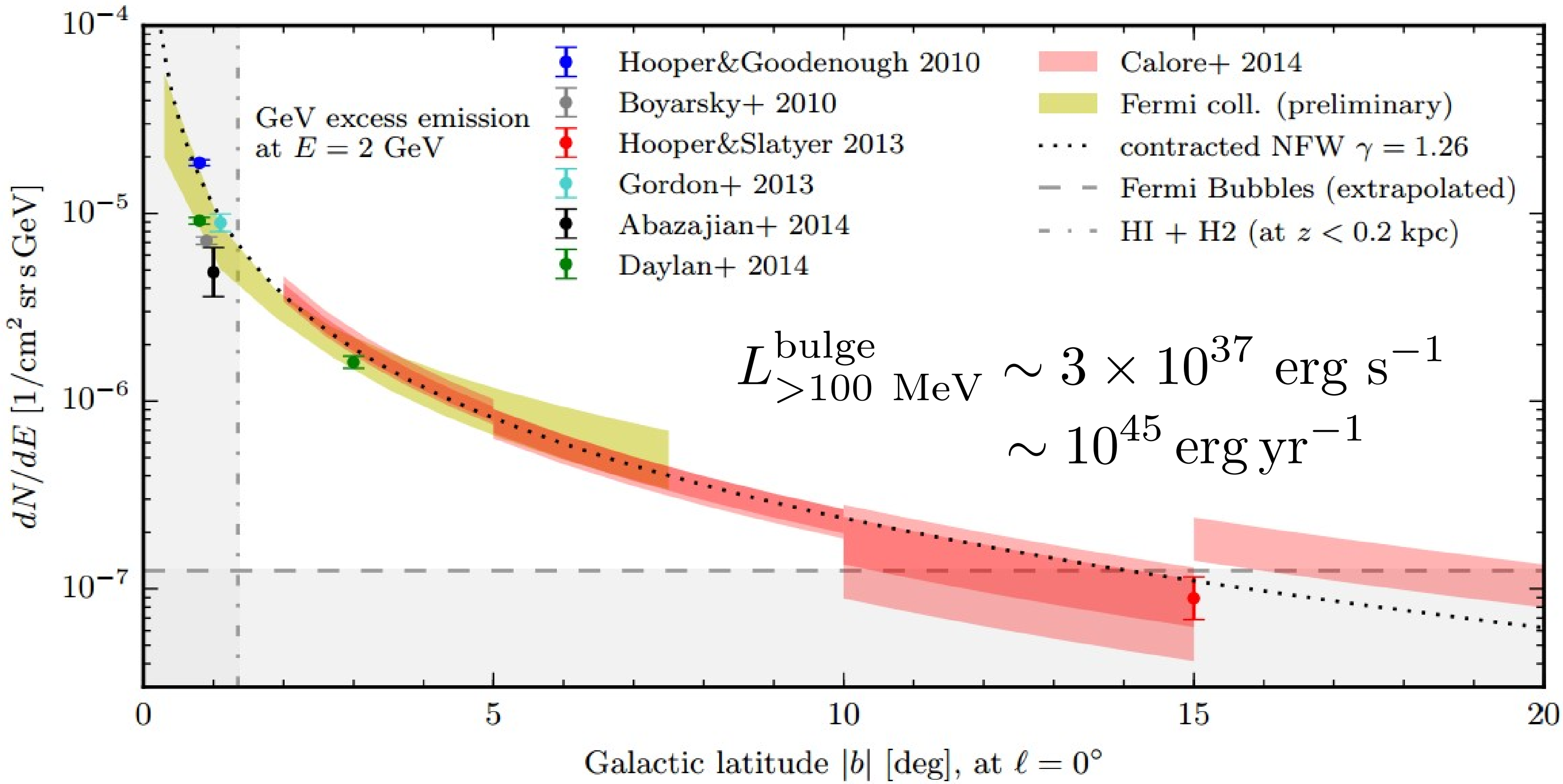


Excess at high latitudes

- The individual excess spectra agree with each other to within two sigma!
- Normalization difference compatible with spherical symmetry and a slope of

$$\frac{dN}{dV} \propto r^{-\Gamma} \qquad \Gamma = 2.52 \pm 0.17$$

Summary slide



Notes

- What we call "excess" is most likely the gamma-ray emission from the Galactic bulge (this component is not included or modeled in most of the diffuse emission models)
- The emission is compatible with a uniform energy spectrum and a spherically symmetric volume emissivity that follows an inverse power-law

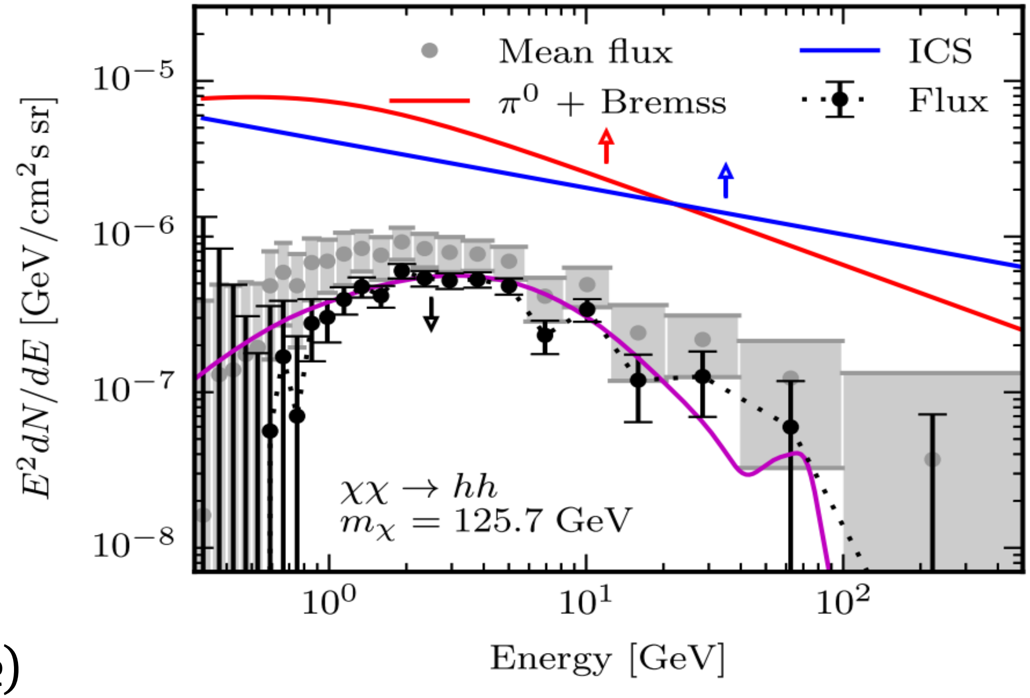
Interpretations.

A signal from Dark Matter Annihilation !?

The similarity with a possible DM annihilation signal is tantalizing!

Dark matter annihilation works

- This is how the GeV excess was first found in Fermi LAT data (Hooper & Goodenough 2009; Vitale & Morselli 2009)
- Slightly steeper profile than NFW
- Typical DM annihilation spectra
- Typical annihilation cross-section
- 200+ papers that contemplate this possibility (1-2% can be blamed on me)



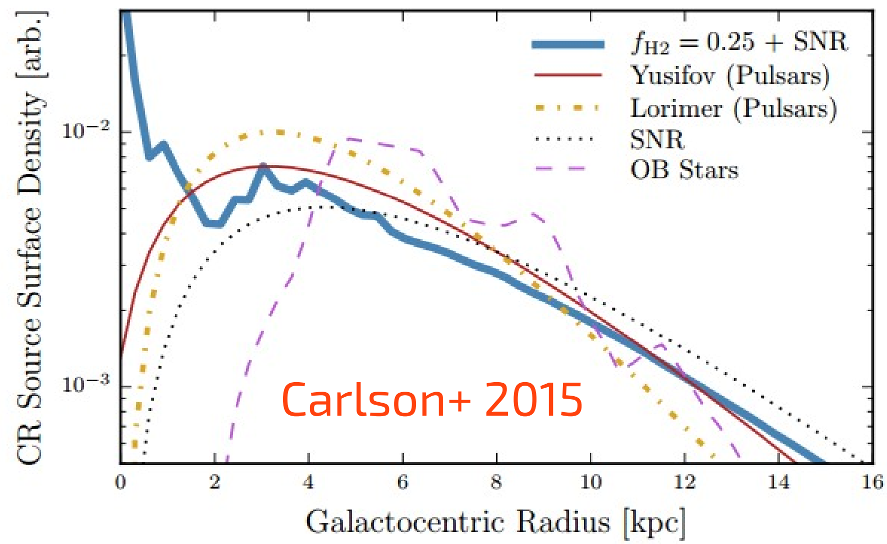
"…when you have eliminated all which is impossible, then whatever remains, however improbable, must be the truth."

Sherlock Holmes, 1854 - ?

Star formation in CMZ I

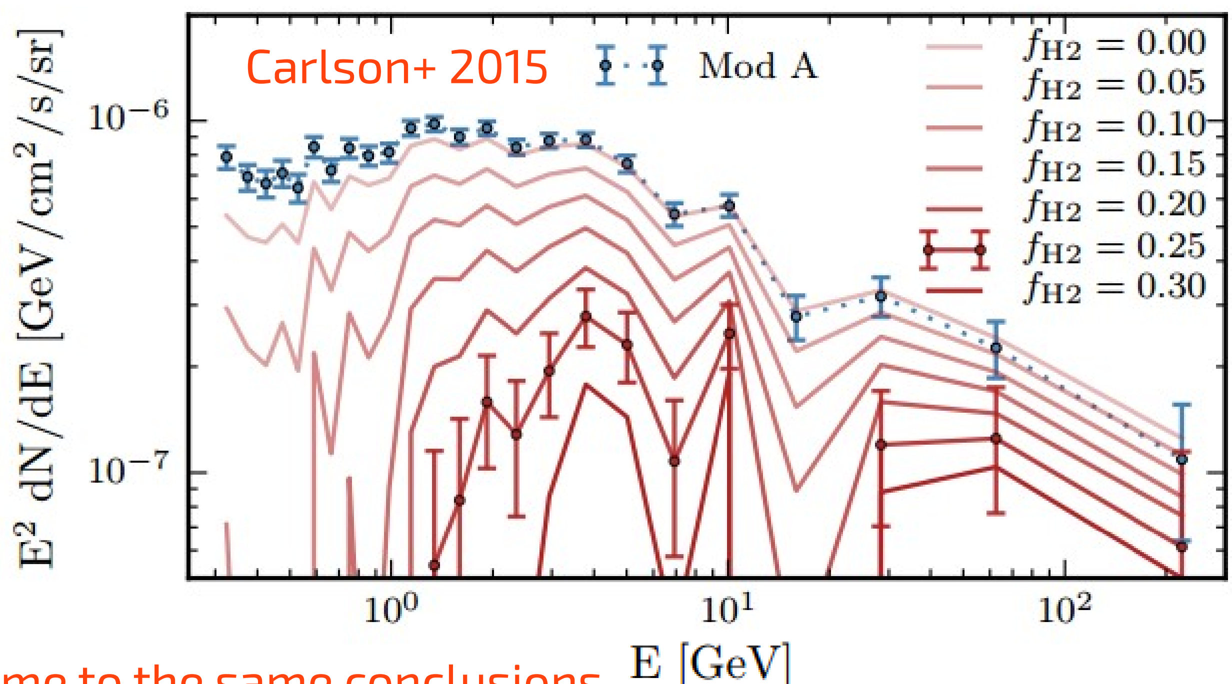
Comments and Caveats

- (Most) previous Galactic diffuse emission models neglected CR injection in the inner Galaxy.
- Inverse Compton emission from electrons accelerated by star formation in CMZ can *energetically* account for all of the observed bulge emission
- ***The predicted spectra appear to be not hard enough below 3 GeV***



Energetics work out:

$$\Gamma_{SN} \sim 10^{-3}\ \mathrm{yr}^{-1}$$
$$E_{SN} \sim 10^{51}\ \mathrm{erg}$$
$$f_{e^\pm} \sim 10^{-3}$$



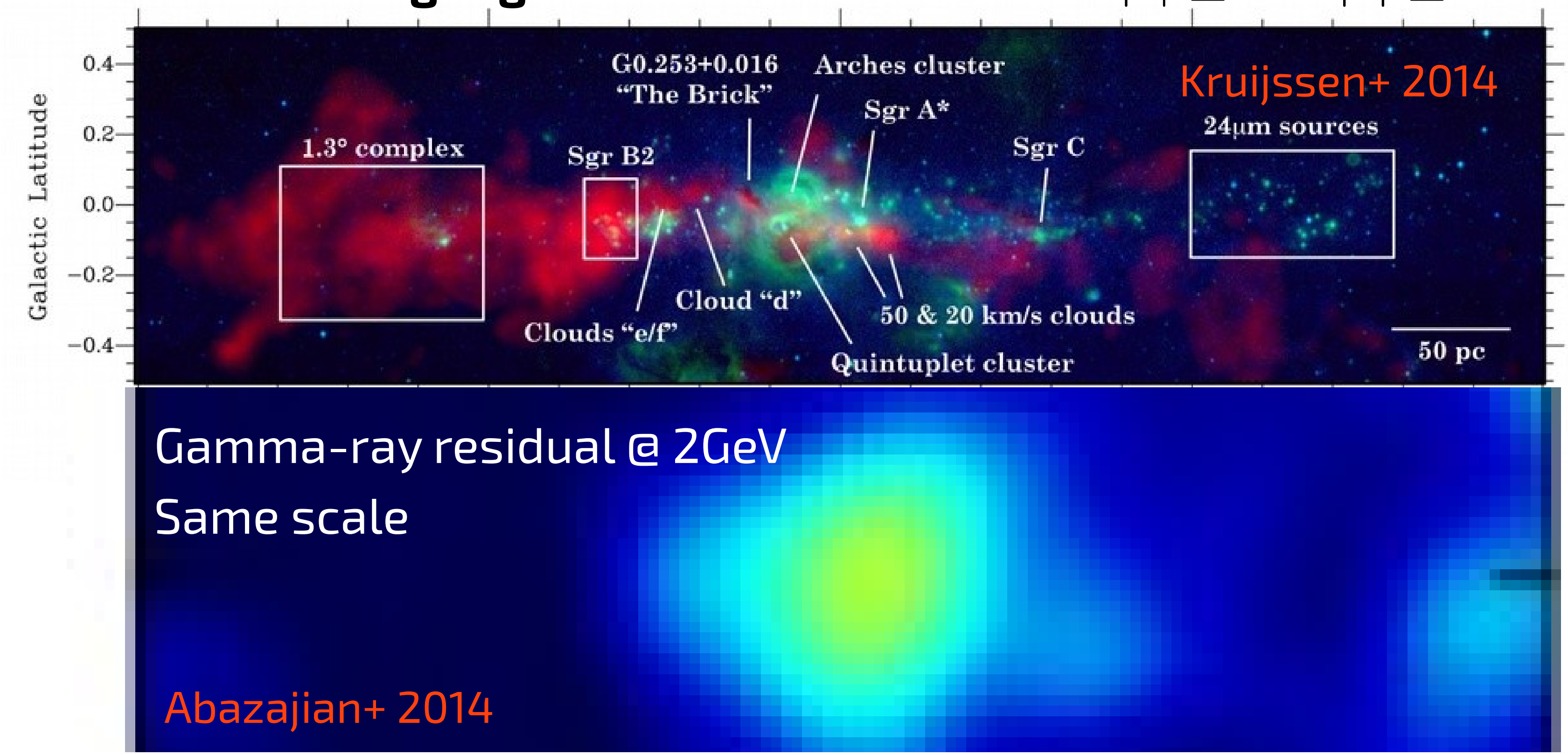
Note: Earlier work by Gaggero+ 2015 came to the same conclusions

Star formation in CMZ II

Cosmic ray injection in the central Galaxy

- Gas in inner 500 pc dominated by central molecular zone (CMZ)
- Contains around ~5% of all current star formation and about 10% of all molecular gas

Star forming regions $|\ell| \leq 2^\circ \quad |b| \leq 0.5^\circ$



Contributions from SF should be there, but probably not dominate GeV excess.

A leptonic outburst from the SMBH?

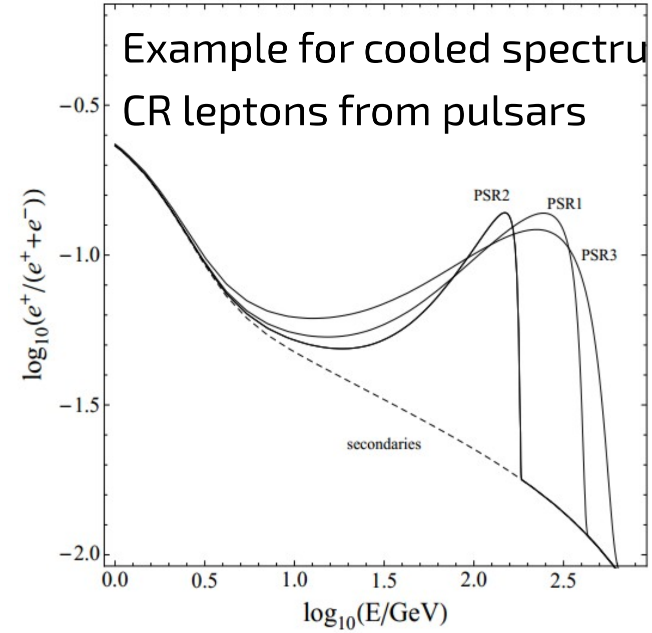
Scenario

- Injection of cosmic-ray electrons/positrons at the SMBH, about ~1 Myr ago

$$E \sim 10^{51}\,\mathrm{erg}$$

- CRs cool and propagate out → peaked propagated spectrum → peaked ICS emission (time-scale of ICS cooling losses again ~Myrs)

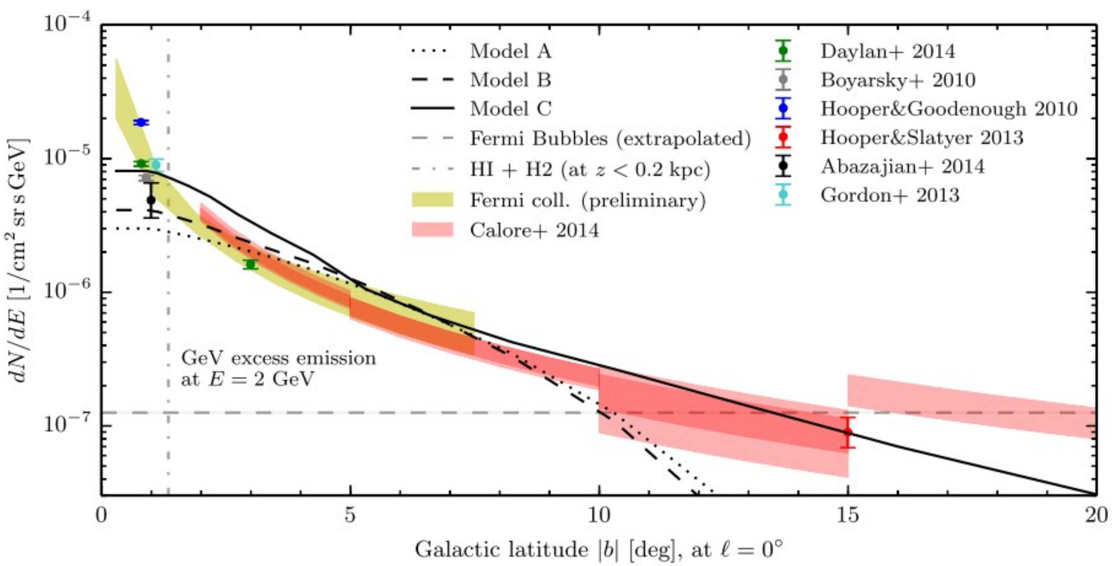
Example for cooled spectrum: CR leptons from pulsars



Features

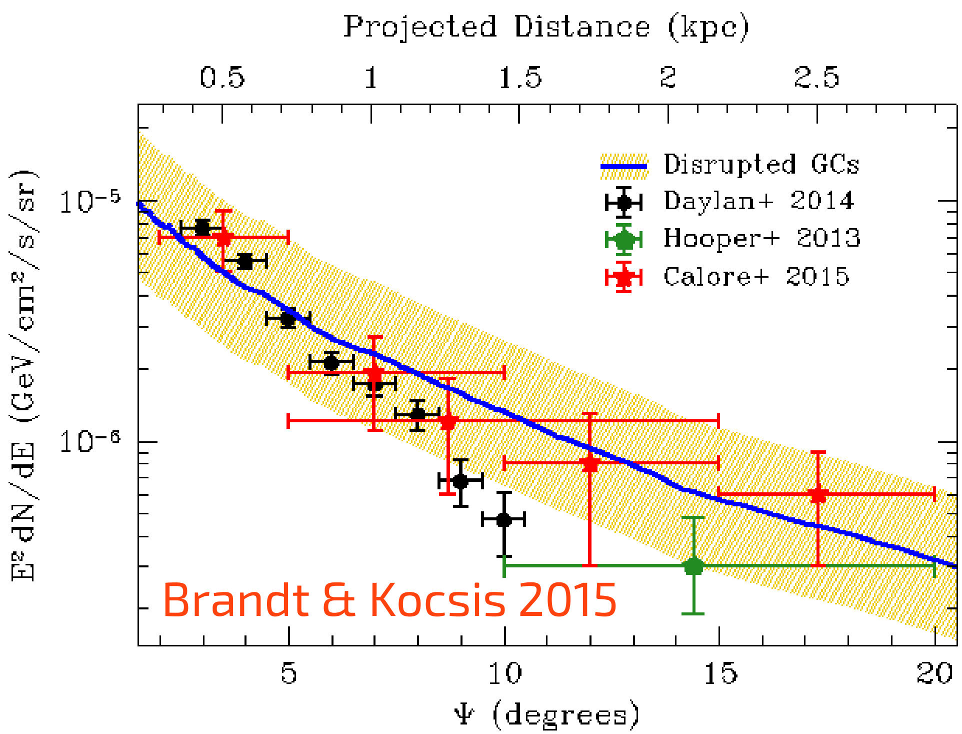
- "GeV excess" spectrum can be reproduced in *some* parts of the sky
- Morphology in general too flat (Gaussian instead of inverse power-law)

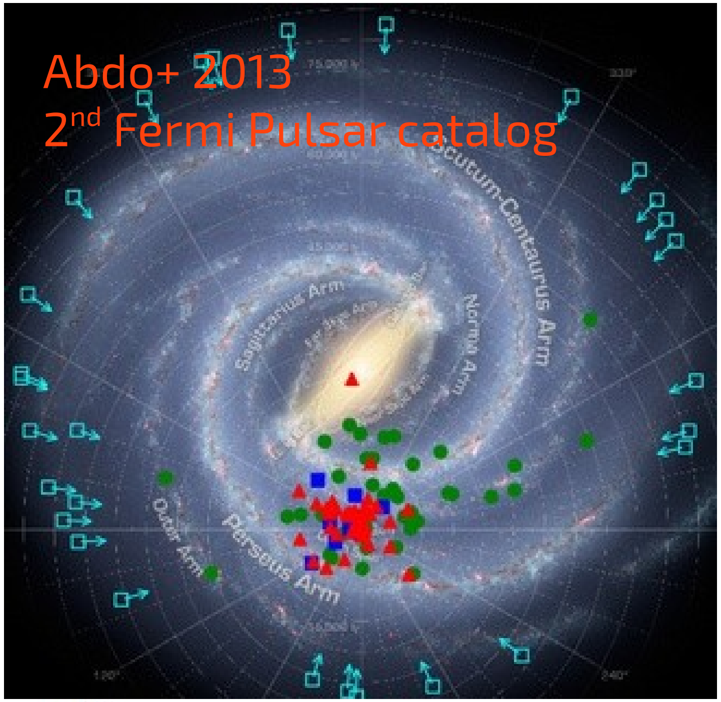
  → Multiple brusts with varying injection indices could do the trick. This seems highly fine-tuned.

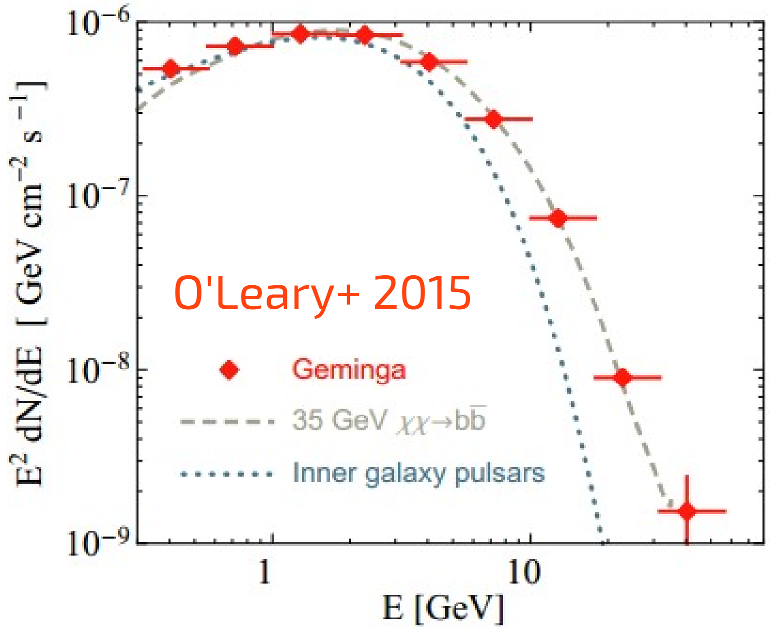


Cholis, Evoli, Calore, Linden, CW, Hooper 2015 (see also Petrovic+ 2013)

Millisecond pulsars







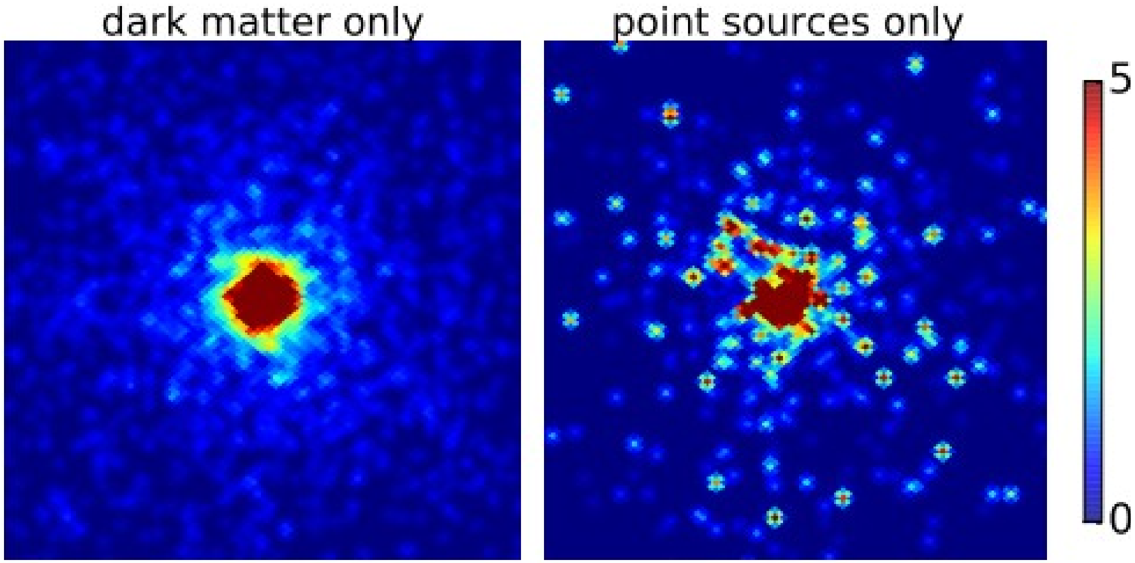
Pulsars work

- Stacked young pulsar or millisecond pulsar spectra are compatible with GeV excess
  (*zero* free parameters)
- Notoriously hard to measure in the bulge region in radio or X-ray
- Possible scenario: MSP form in globular clusters, are then spilled out into the bulge by tidal disruption

An observational challenge

Point sources or diffuse emission?

- A signal composed of point sources would appear more "**speckled**" than a purely diffuse signal



Credit: Lee+ 2014

Wavelet analysis

- *Local maxima of normalized wavelet transform:*
  - "*Wavelet transform*"*:* spatially constrained Fourier transform.
    Filters out structures of a specific size, like point sources. Removes diffuse emission.
  - "*Normalized*"*:* Null hypothesis is equivalent to smoothed Gaussian random field

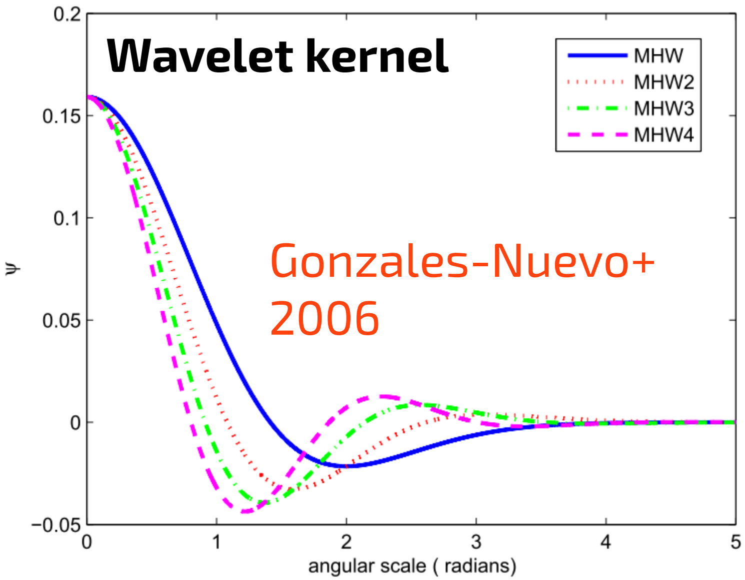
    → Largely independent of modeling of diffuse backgrounds

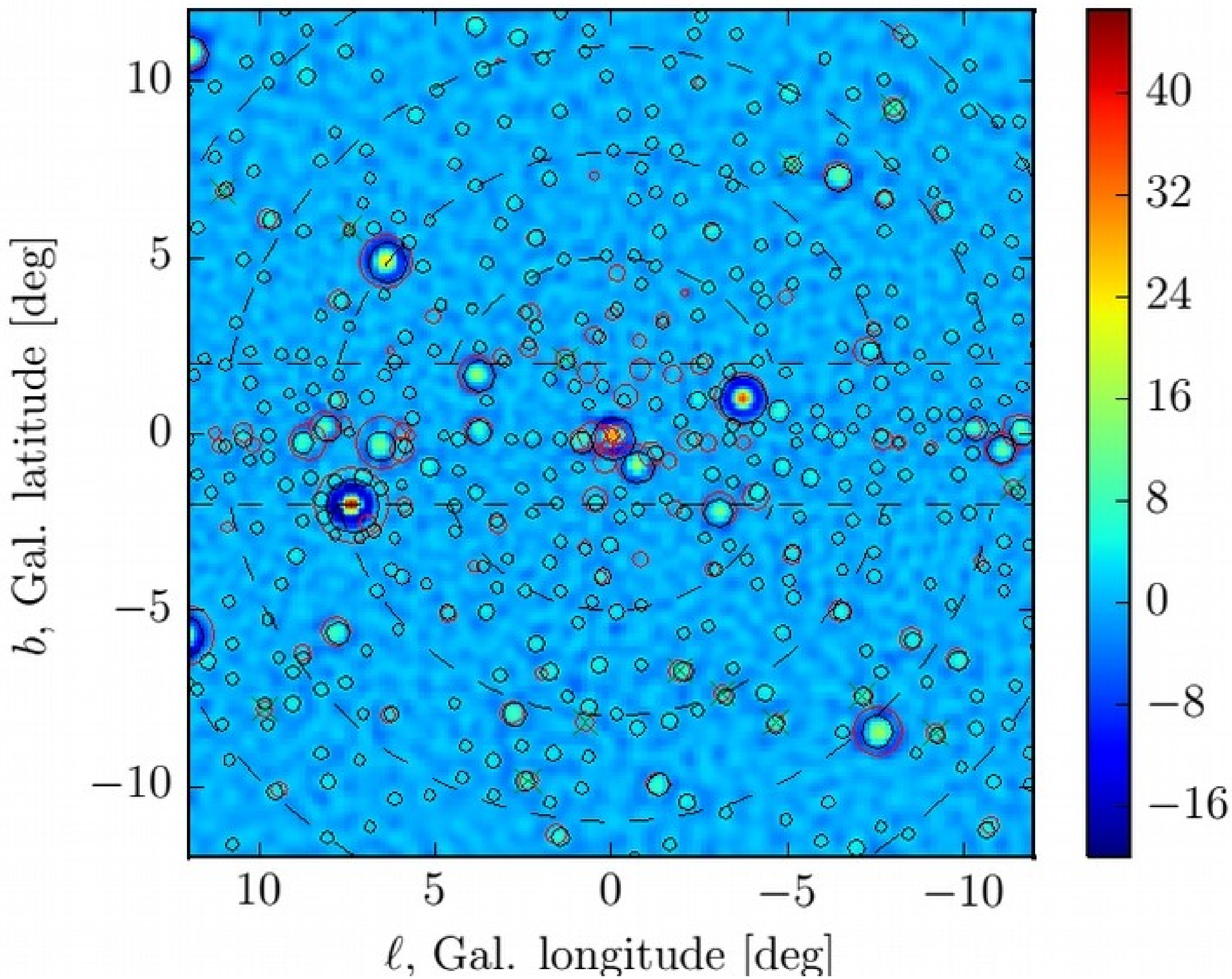
For a similar work based on non-Poissonian template fits see Lee+ 2015

Wavelet transform of 1-4 GeV inner Galaxy

Notes on wavelet results

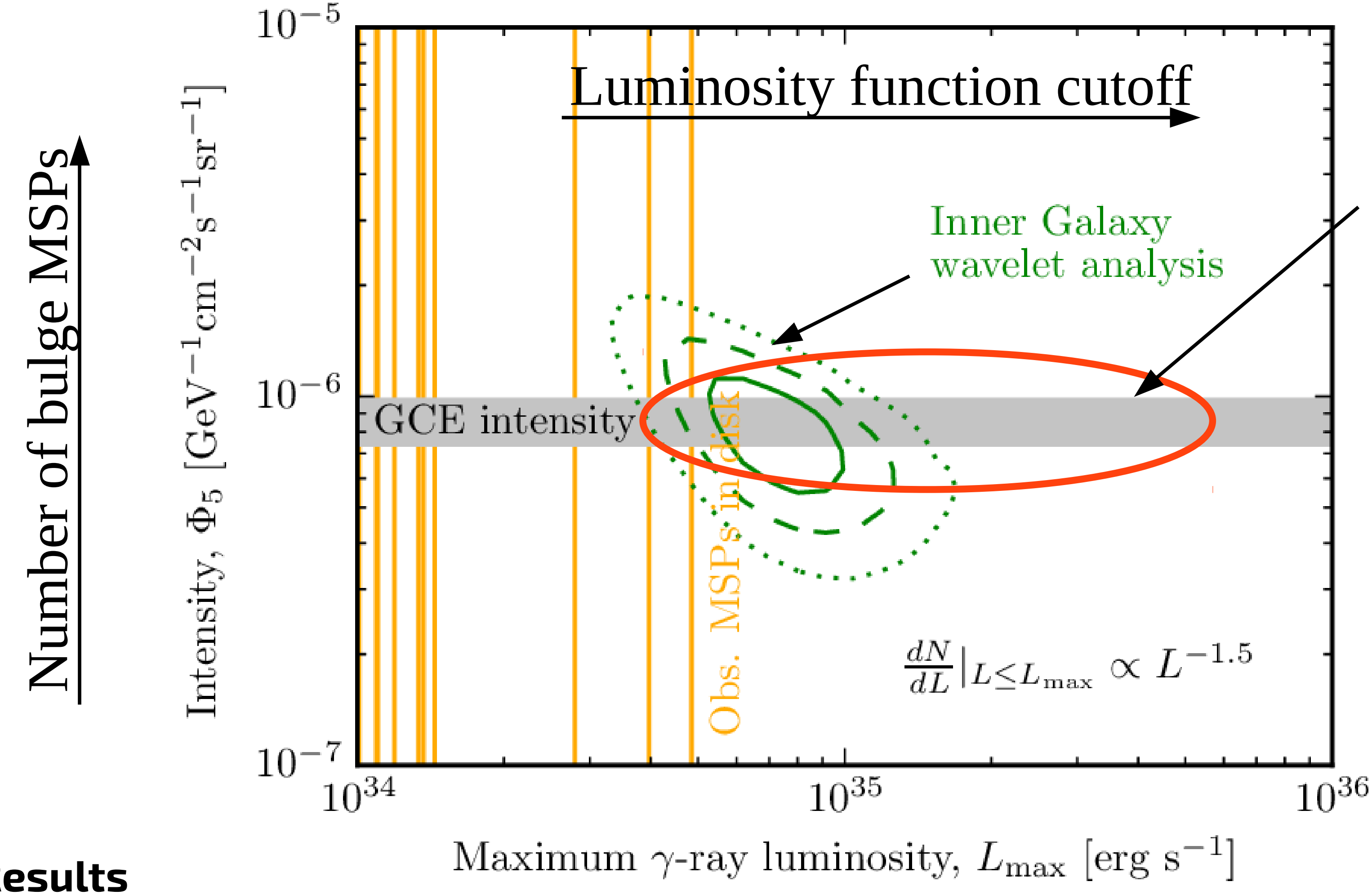
- Already peak density with >1 sigma significance contains information!
- Peaks with >3 sigma significance correspond in many cases to real sources
- Peaks with >>5 sigma are aways in the 3FGL





Bartels, Krishnamurthy, CW 2015

Wavelet results



Results

- For a luminosity function index around 1.5, a MSP population with the best-fit normalization would reproduce 100% of the excess emission
- The best-fit cutoff luminosity is compatible with gamma-ray emission from detected nearby MSPs (beware of large uncertainties due to uncertainties in the distance measure, Petrovic+ 2014, Brandt & Kocsis 2015)

Outlook.

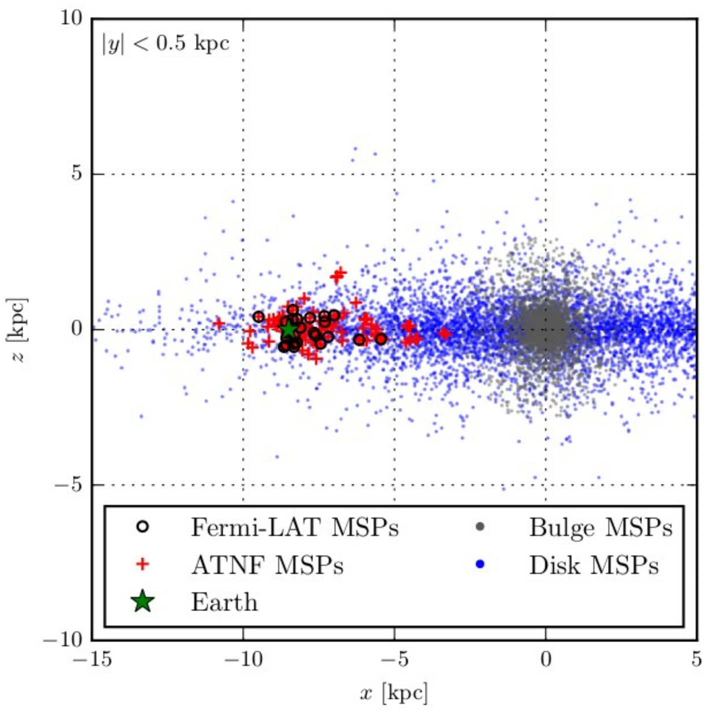
Radio prospects

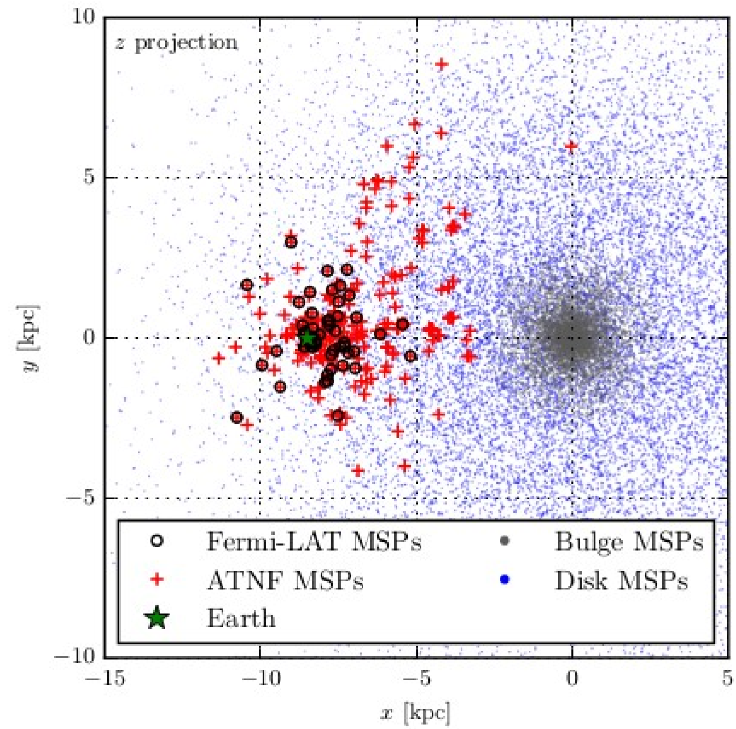
Hypothetical MSP population

- 10000 – 20000 radio MSPs in the Galactic bulge
- Flux densities up to 0.3 mJy @ 1.4 GHz
- Just below detection threshold of current surveys

$$\frac{dn_{\mathrm{MSP}}}{dV} \sim r^{-\Gamma}$$

$$\Gamma \simeq 2.5$$





Radio prospects

Strategy A (short-term)

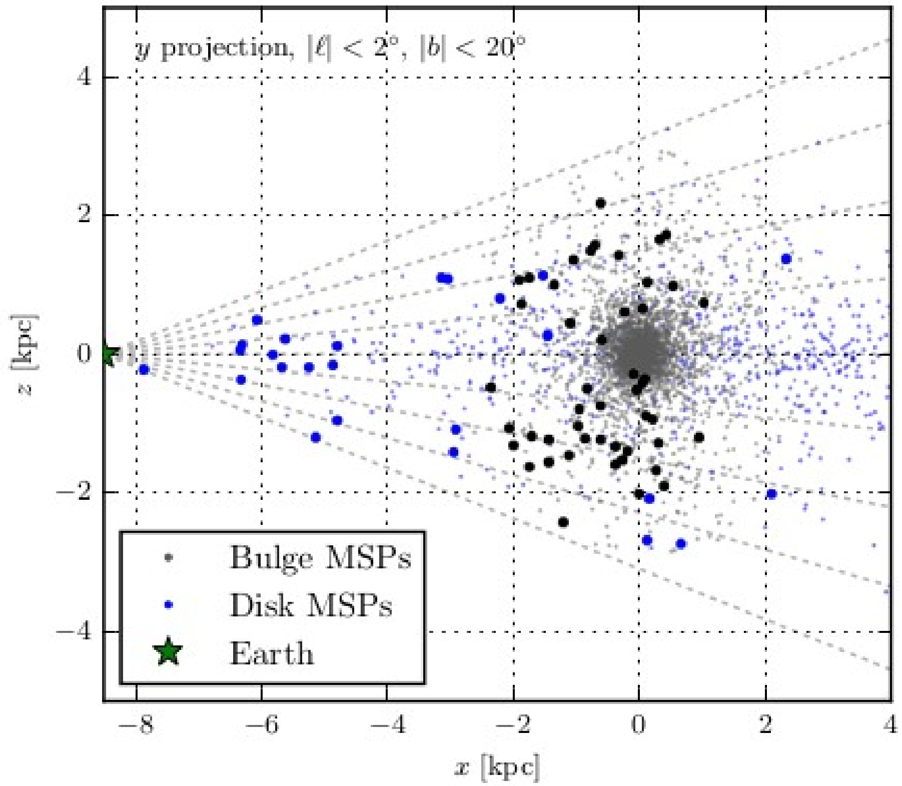
- Follow-up observations of unassociated point sources & wavelet peaks
- Requires careful assessment of source probabilities and instrumental sensitivity

  → Probably most promising strategy for GBT
- Is a bit of gambling, since beaming properties of sources not well known

Strategy B (long-term)

- Deep surveys of the Galactic bulge
- MeerKAT, SKA etc. can likely discover dozens or hundreds of bulge MSPs

Calore, DiMauro, Donato, Hessels, Massaro, CW, soon



Conclusions

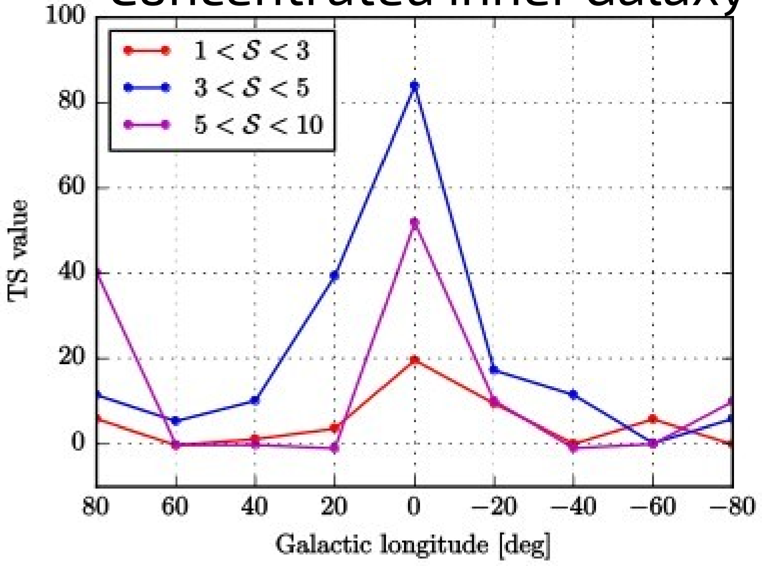
- There *is* an **extended excess of gamma rays** in the inner Galaxy, with **very hard spectrum below ~2 GeV**, and most likely associated with emission from the Galactic bulge and center
- The bulge emission is **likely a sum of different components** (SF, MSPs, DM?, …), with one component peaking around 2—3 GeV and the rest contributing in the low- and high-energy tails
- The component peaking at GeV energies is probably **spherically symmetric**, extended **up to >10 deg** away from the GC, and has a **uniform spectrum** throughout the entire emission region
- The most likely astrophysical explanation are bulge MSPs
- This is **strongly supported by** dedicated searches for sub-threshold point sources (like **wavelet analysis**)
- **Prospects for finding the bulge MSPs in radio** in the near future (deep targeted searches based on e.g. wavelet results) and next 10 yrs (large area surveys) future **are good**

Thank you – and stay tuned!

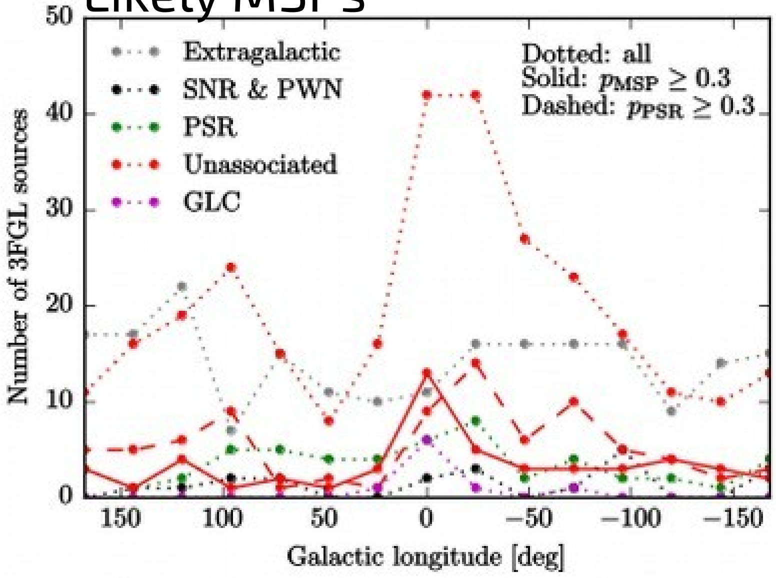
Backup slides.

Details wavelet results

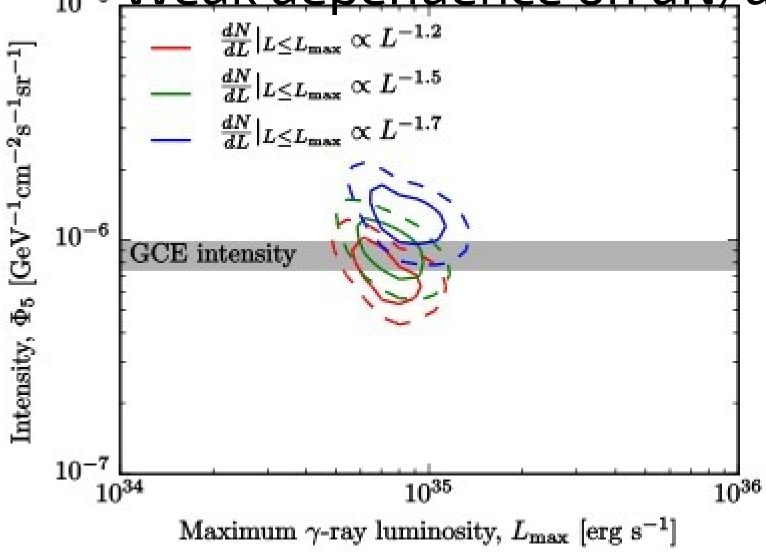
Concentrated inner Galaxy



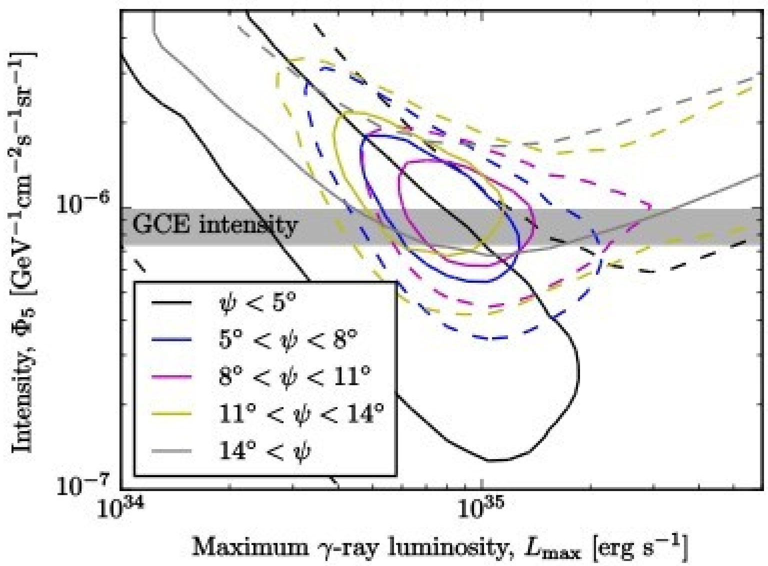
Likely MSPs



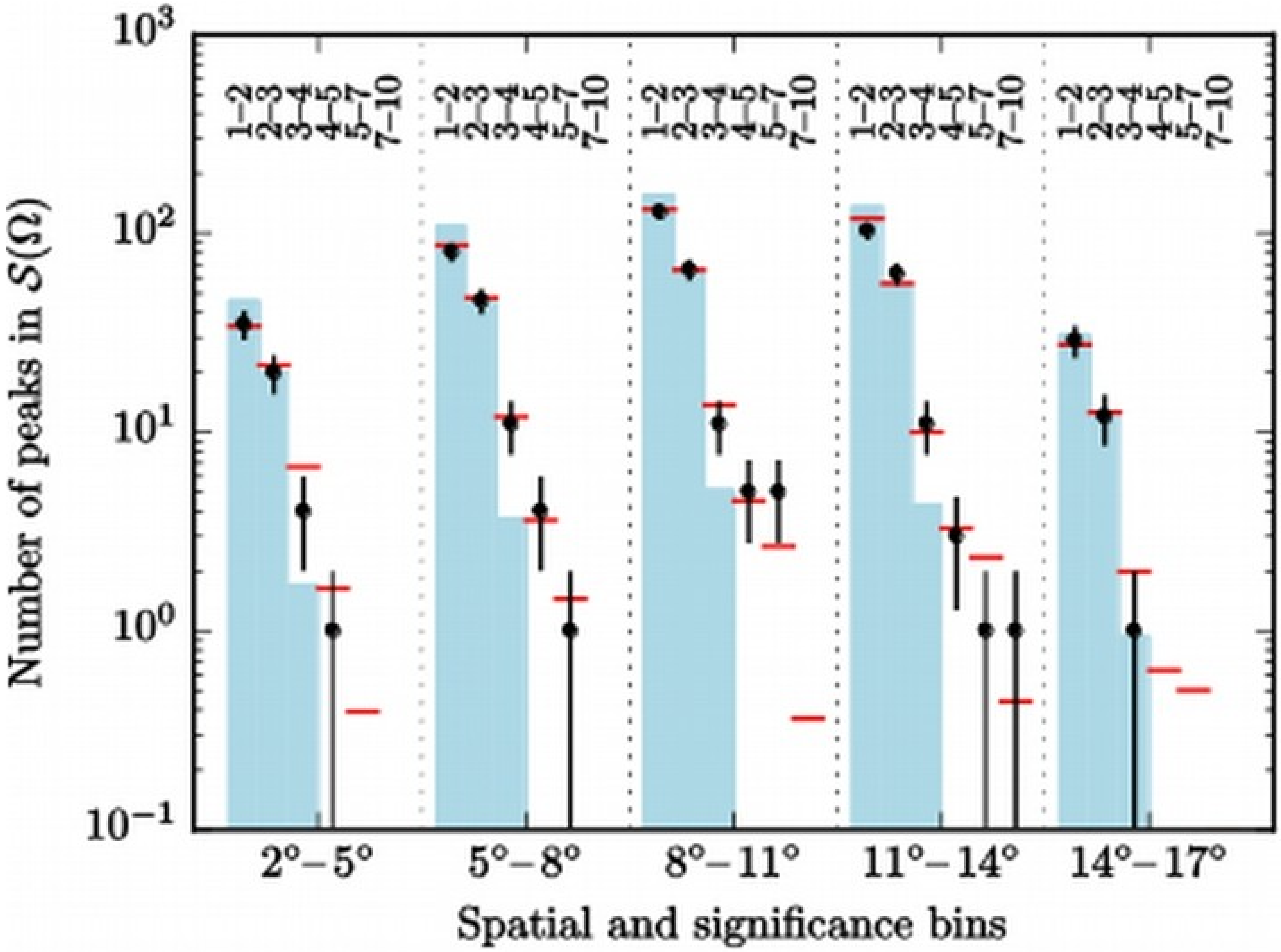
Weak dependence on dN/dL



Self consistent in sub ROIs



Details wavelet results



Histogram

- **Error bars:** inner Galaxy data

Null-hypothesis

- **Red**: null-hypothesis
- **Gray**: Control region results

Fit for norm and Lmax

- **Green**: best-fit

→ 8.3 sigma significance

MC predictions + simple estimates for disk population

We use a common maximum likelihood analysis (assuming that peaks are Poissonian distributed) to perform parameter estimation for the luminosity function.