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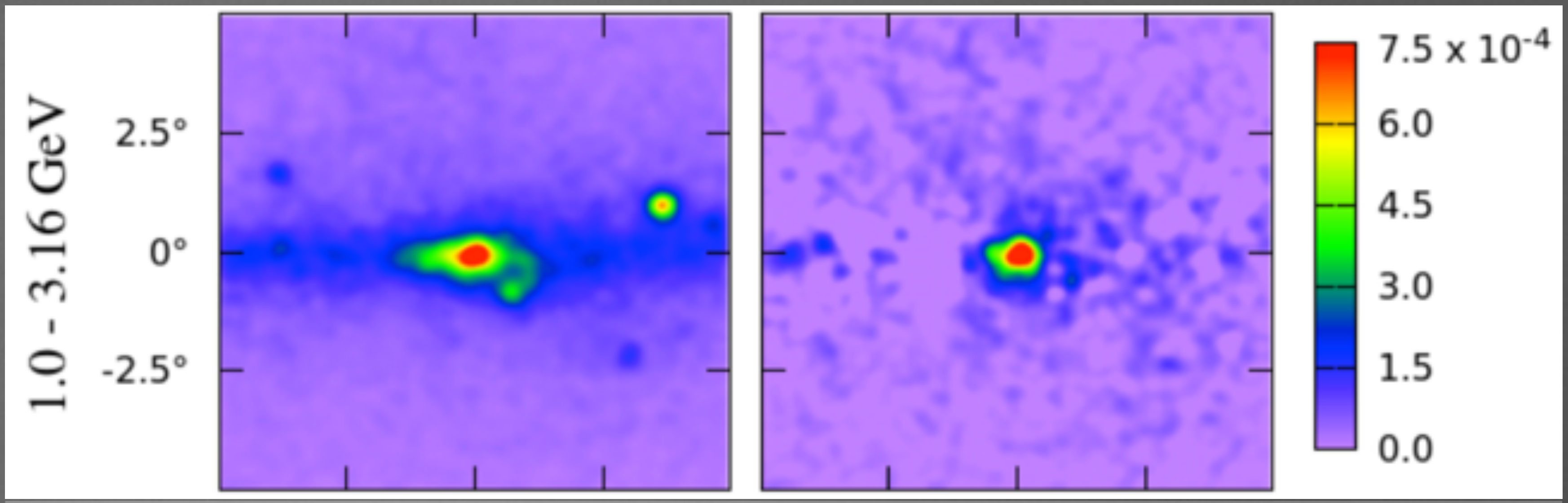


The Characterization of the Gamma-Ray Excess from the Central Milky Way

Tim Linden

along with: Tansu Daylan, Doug Finkbeiner, Dan Hooper,
Stephen Portillo, Tracy Slatyer, Ilias Cholis

1402.6703
1407.5583
1407.5625
1410.1527

Einstein Fellows Symposium - Cambridge, MA - October 29, 2014

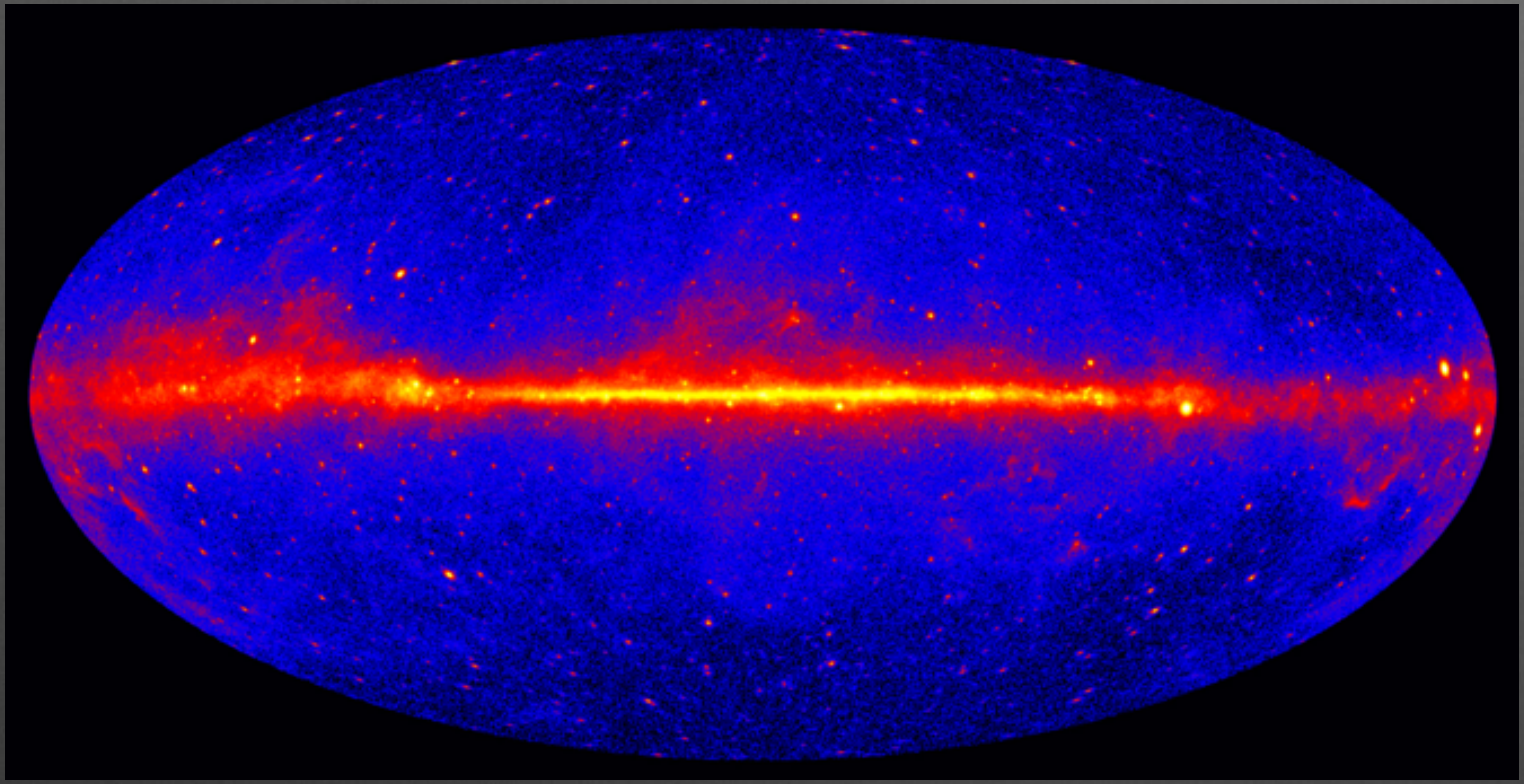
The Galactic Center

- Total Observed Gamma-Ray Flux from 1-3 GeV within 1° of the GC is ~1 x 10^{-10} erg cm^{-2} s^{-1}

- The flux expected from a vanilla dark matter model (100 GeV -> bb with an NFW profile) is ~2 x 10^{-11} erg cm^{-2} s^{-1}

- There's no reason this needs to be true -- the total gamma-ray emission from the Galactic center happens to fall within an order of magnitude of the most naive prediction from dark matter simulations

Gamma-Ray Backgrounds



Point Sources

Pulsars

Blazars/AGN

Star Forming Galaxies

Supernova Remnants

Unidentified

Extragalactic (Isotropic) Background

Galactic Diffuse Emission

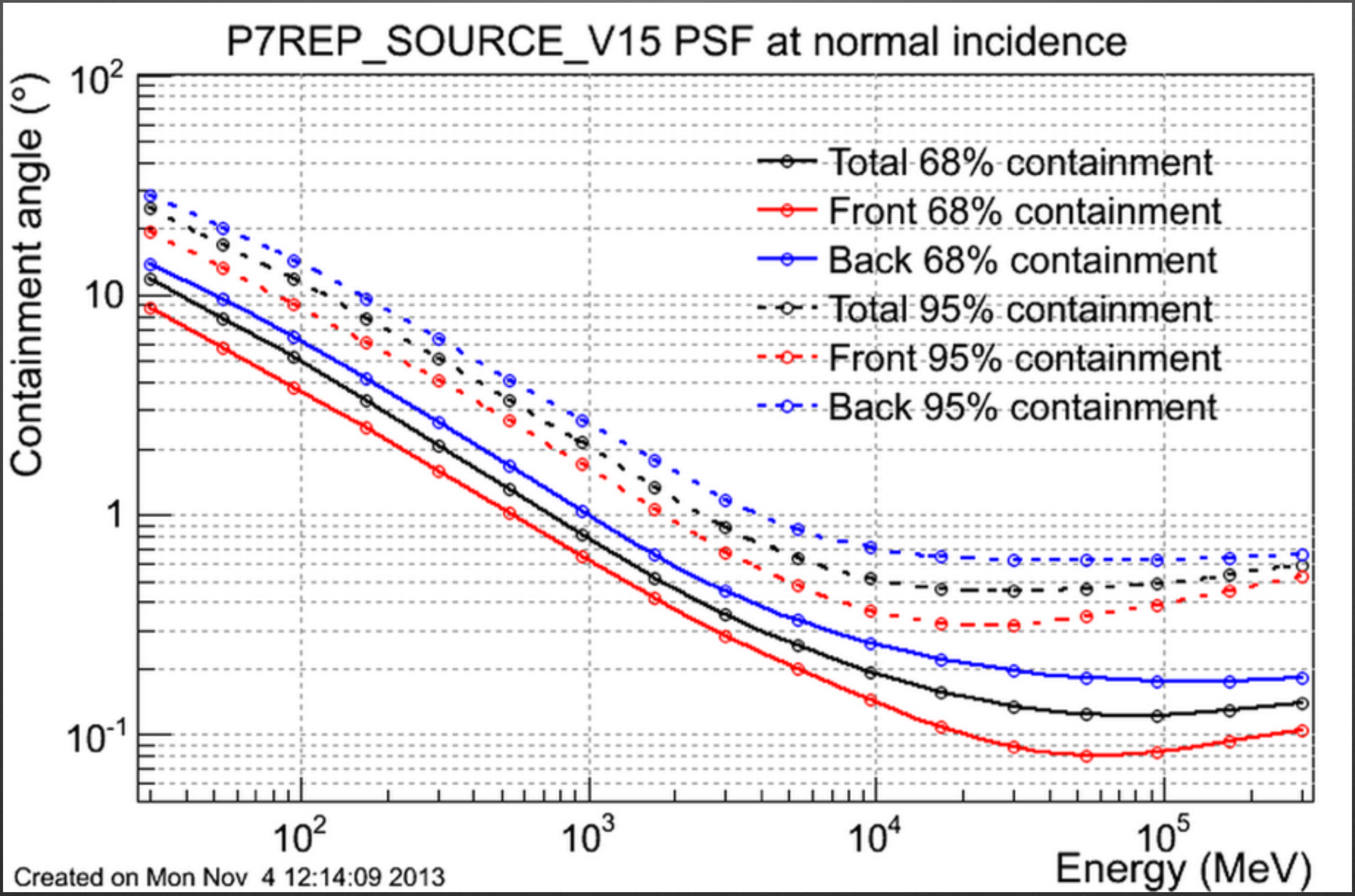
π^0-decay

bremsstrahlung

inverse-Compton

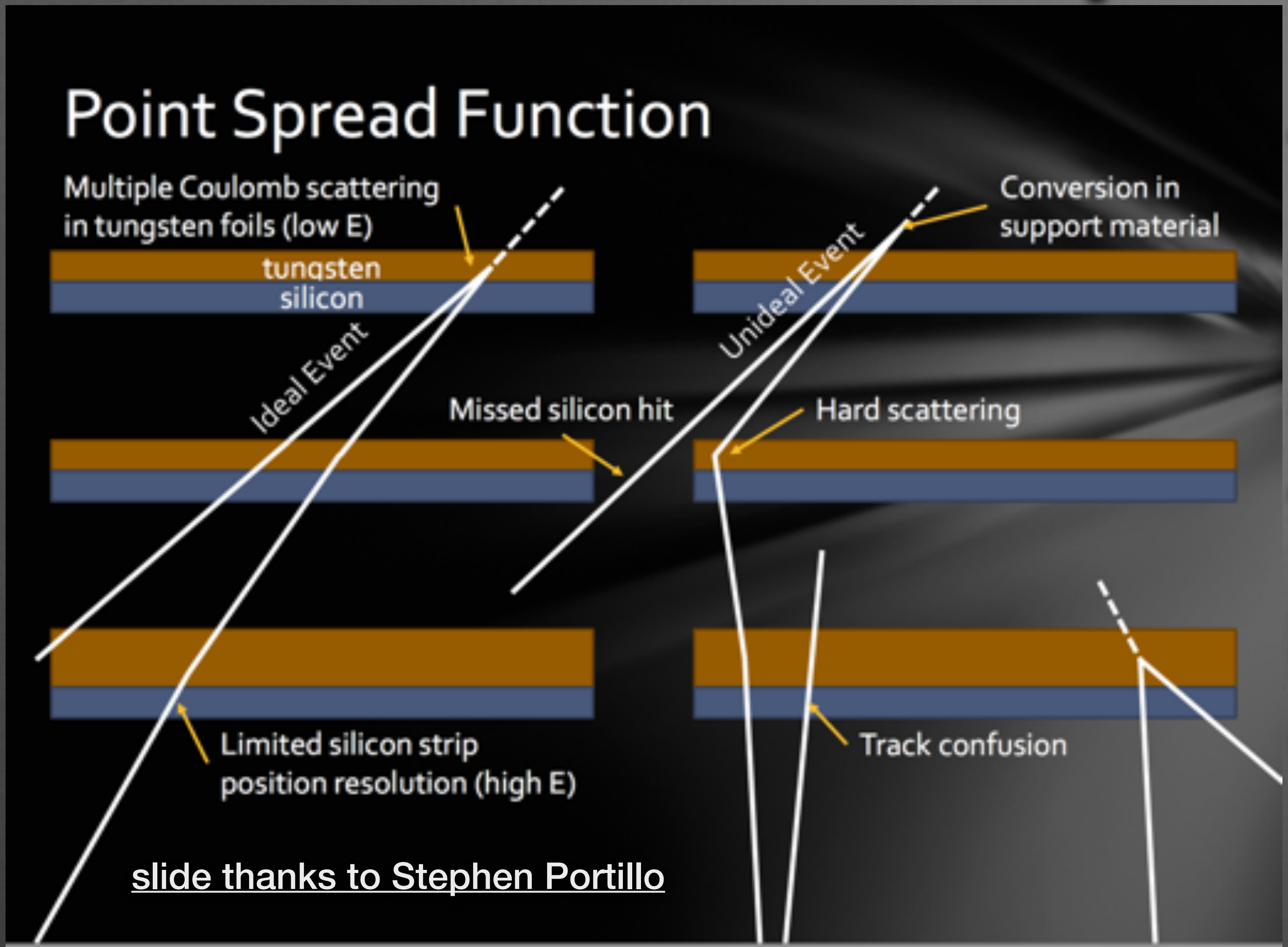
The Galactic Center

CTBCORE

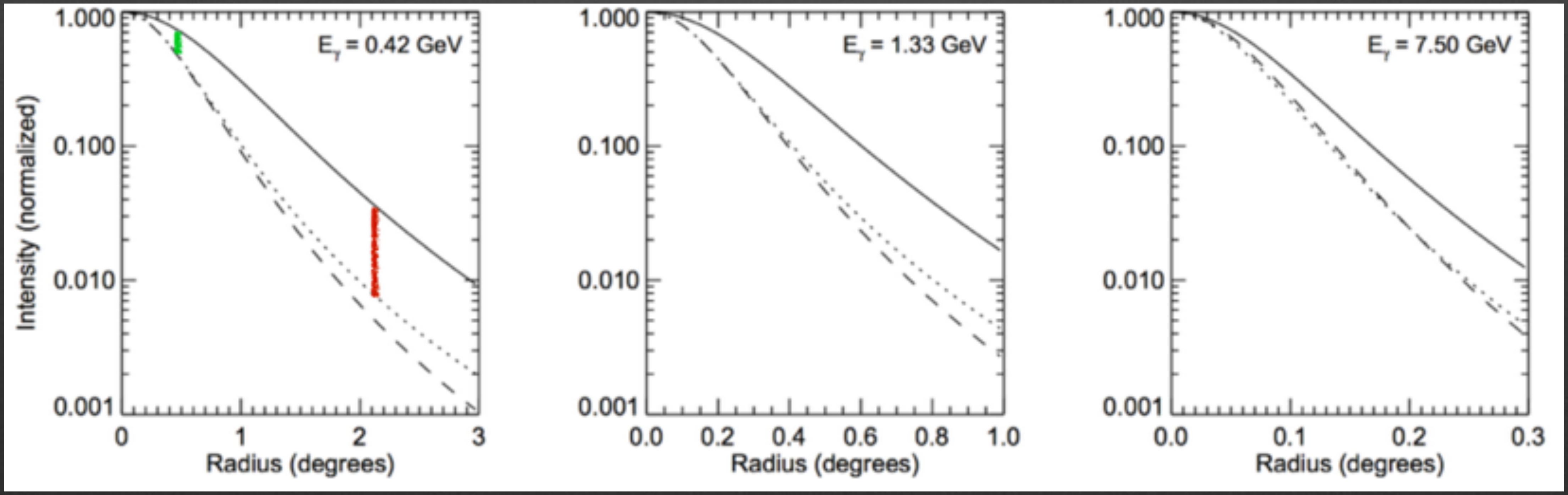


P7REP_SOURCE_V15 PSF at normal incidence
Containment angle (°)
10^2
10
1
10^{-1}
Total 68% containment
Front 68% containment
Back 68% containment
Total 95% containment
Front 95% containment
Back 95% containment
10^2
10^3
10^4
10^5
Energy (MeV)
Created on Mon Nov 4 12:14:09 2013

CTBCORE: Sharper Fermi-LAT Images



The improvement in the PSF is especially important at low energies. Using these cuts, we include all photons down to an energy of 300 MeV



Daylan et al. (2014, 1402.6703)

Portillo & Finkbeiner (2014, 1406.0507)

Two Types of Analyses

Galactic Center

- Examine box around the GC (eg. 10º x 10º)
- Include and model all point sources
- Use likelihood analysis to calculate the spectrum and intensity of each source component
- Calculate log-likelihood to determine significance of component

Inner Galaxy

- Mask galactic plane (e.g. |b| > 1º)
- Bright point sources masked at 2º
- Allow diffuse templates (galactic diffuse, isotropic, Fermi bubbles, dark matter) to float independently in each of 30 energy bins

Two Separate Analyses

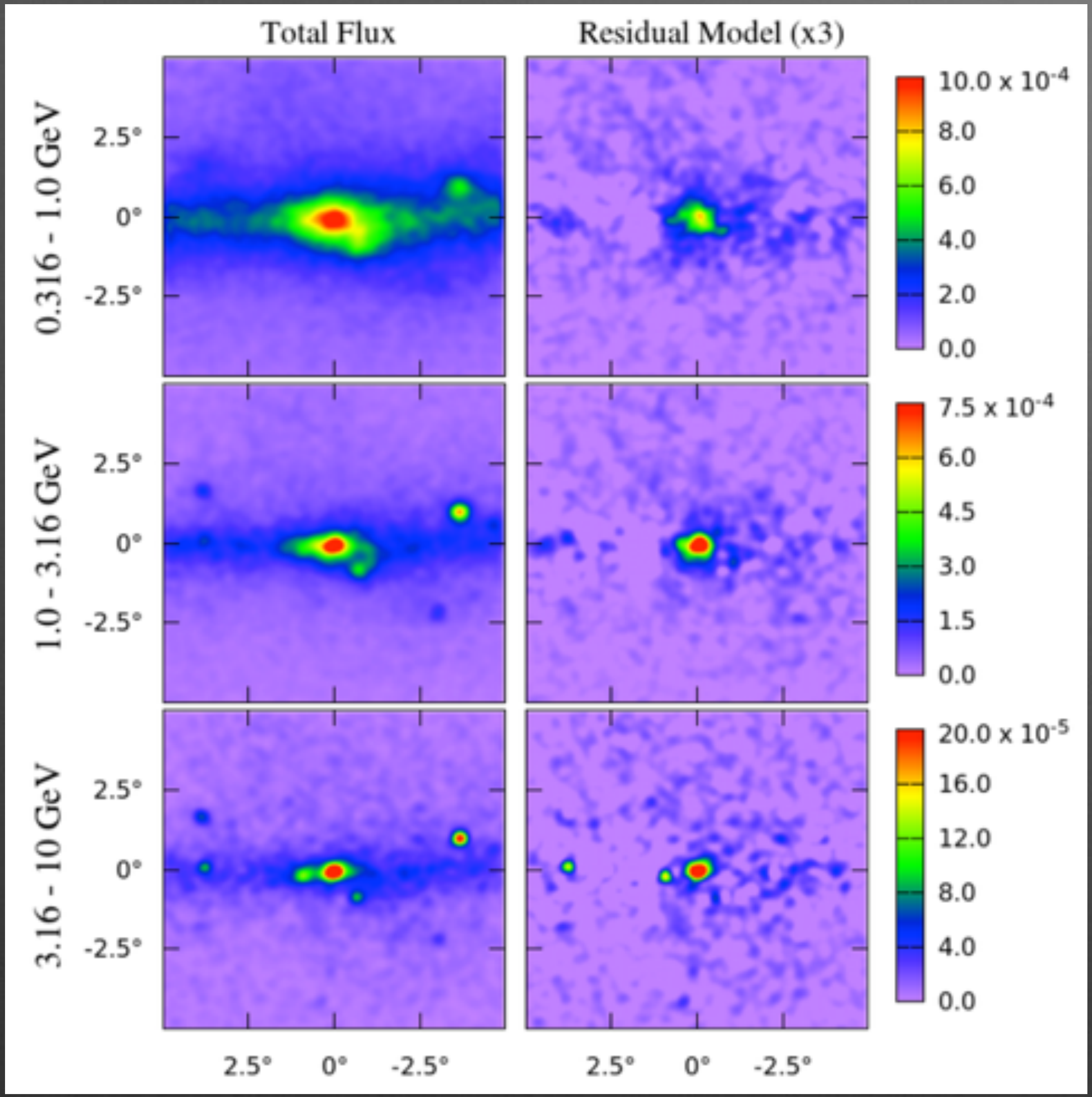
Galactic Center

- **Advantages:**
  - Signal brighter
  - Can test profile in inner regions
- **Disadvantages:**
  - More astrophysical contamination
  - Many free parameters
  - Bin by bin energy analysis is impossible

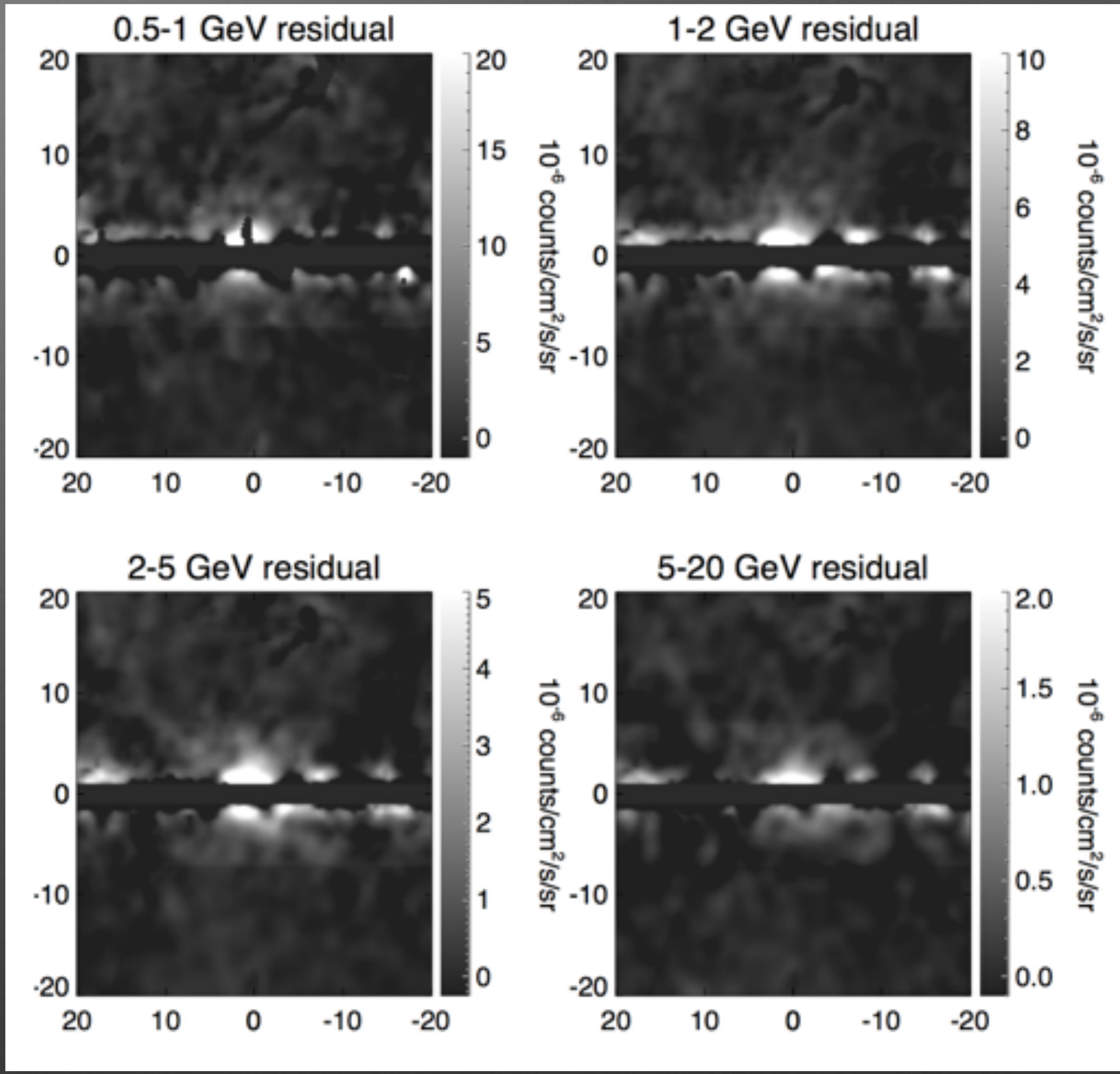
Inner Galaxy

- **Advantages:**
  - Less astrophysical contamination
  - Fewer parameters in fit
  - Instrumental PSF Doesn't Matter
- **Disadvantages:**
  - Signal is dimmer
  - Can't test center profile
  - Fit parameters may be skewed by the entire sky

Consistent Results!



Galactic Center

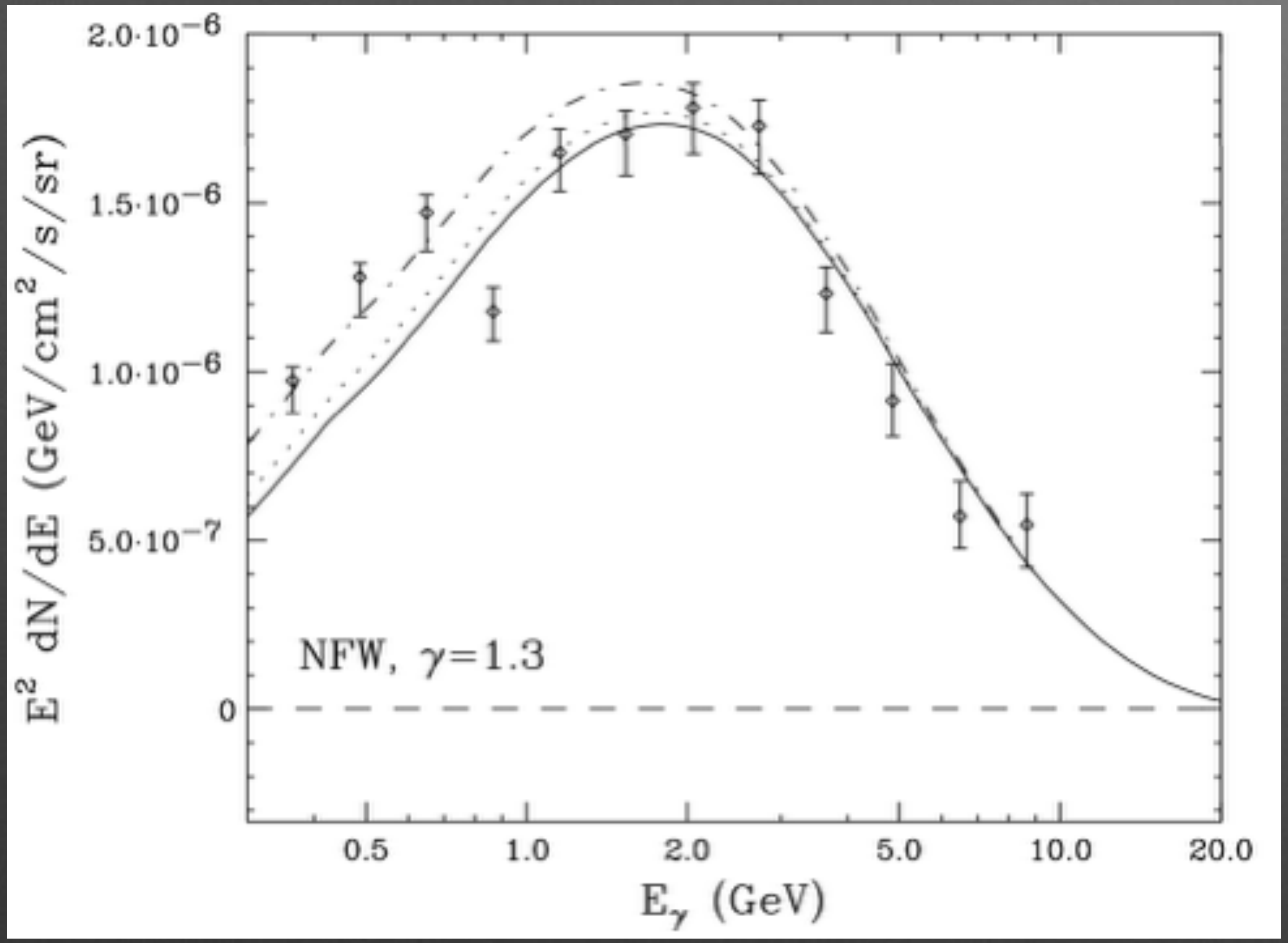


Inner Galaxy

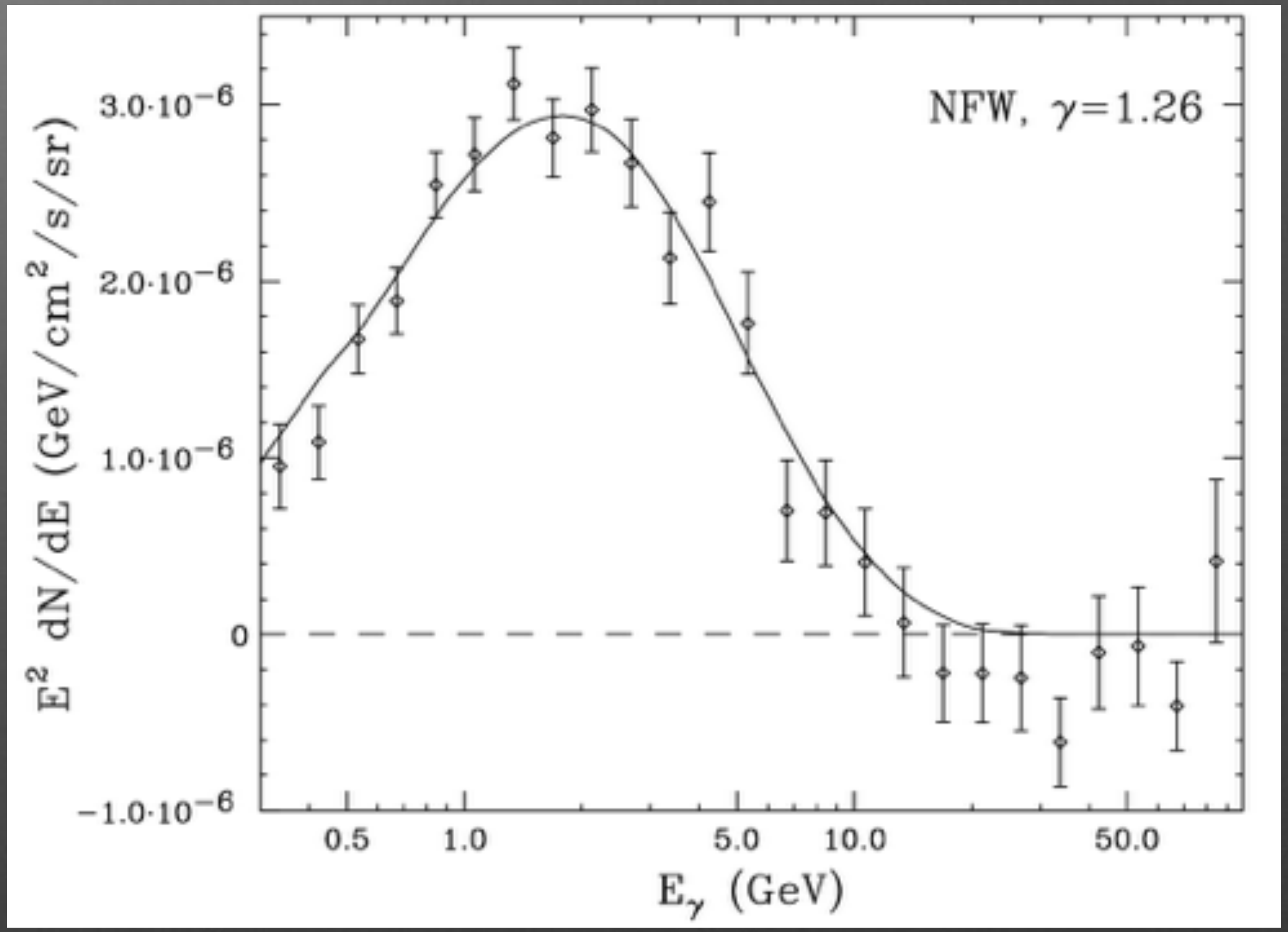
Daylan et al. (2014, 1402.6703)

Consistent Results!

Gamma-Ray Spectrum



Galactic Center

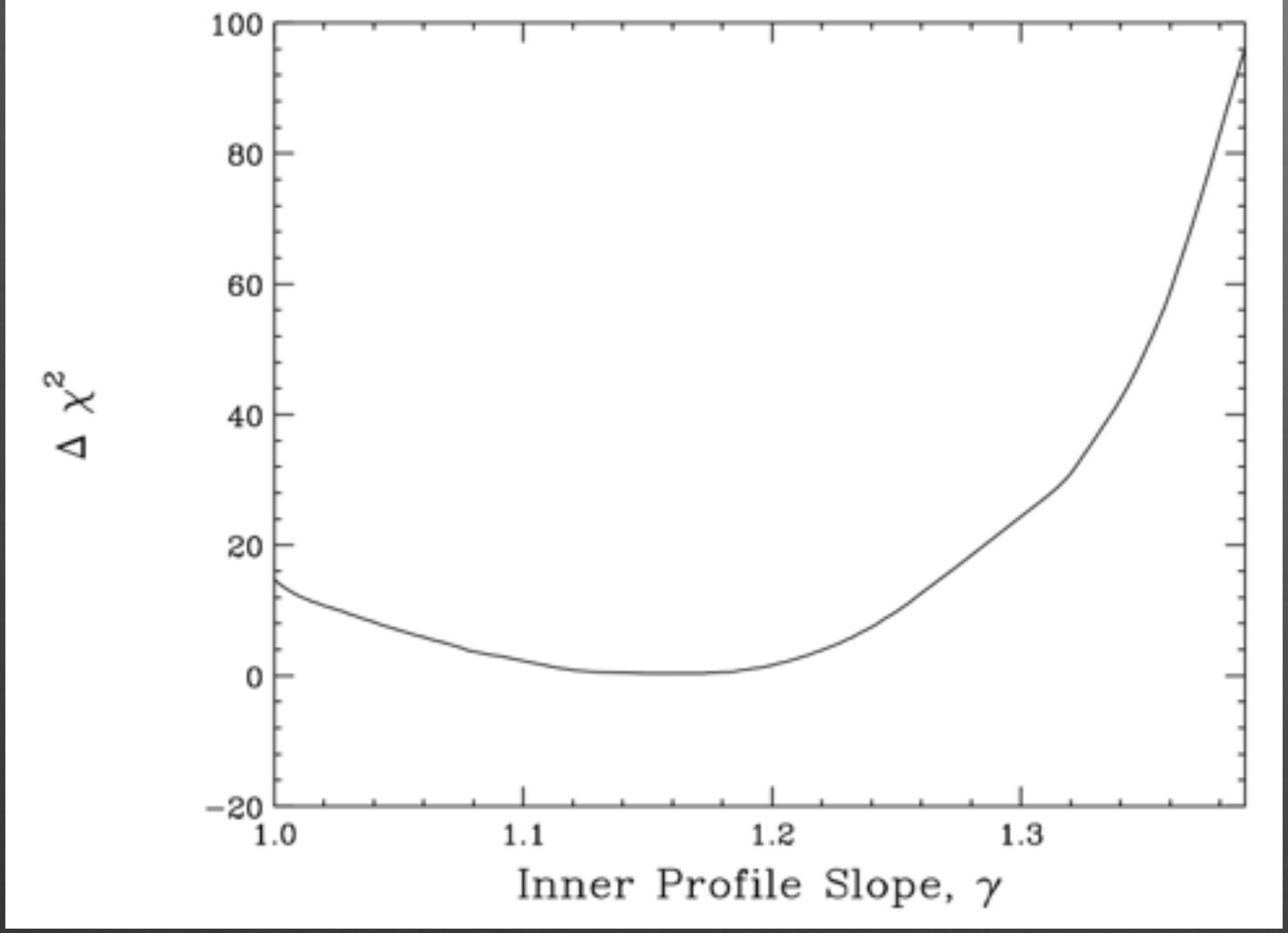


Inner Galaxy

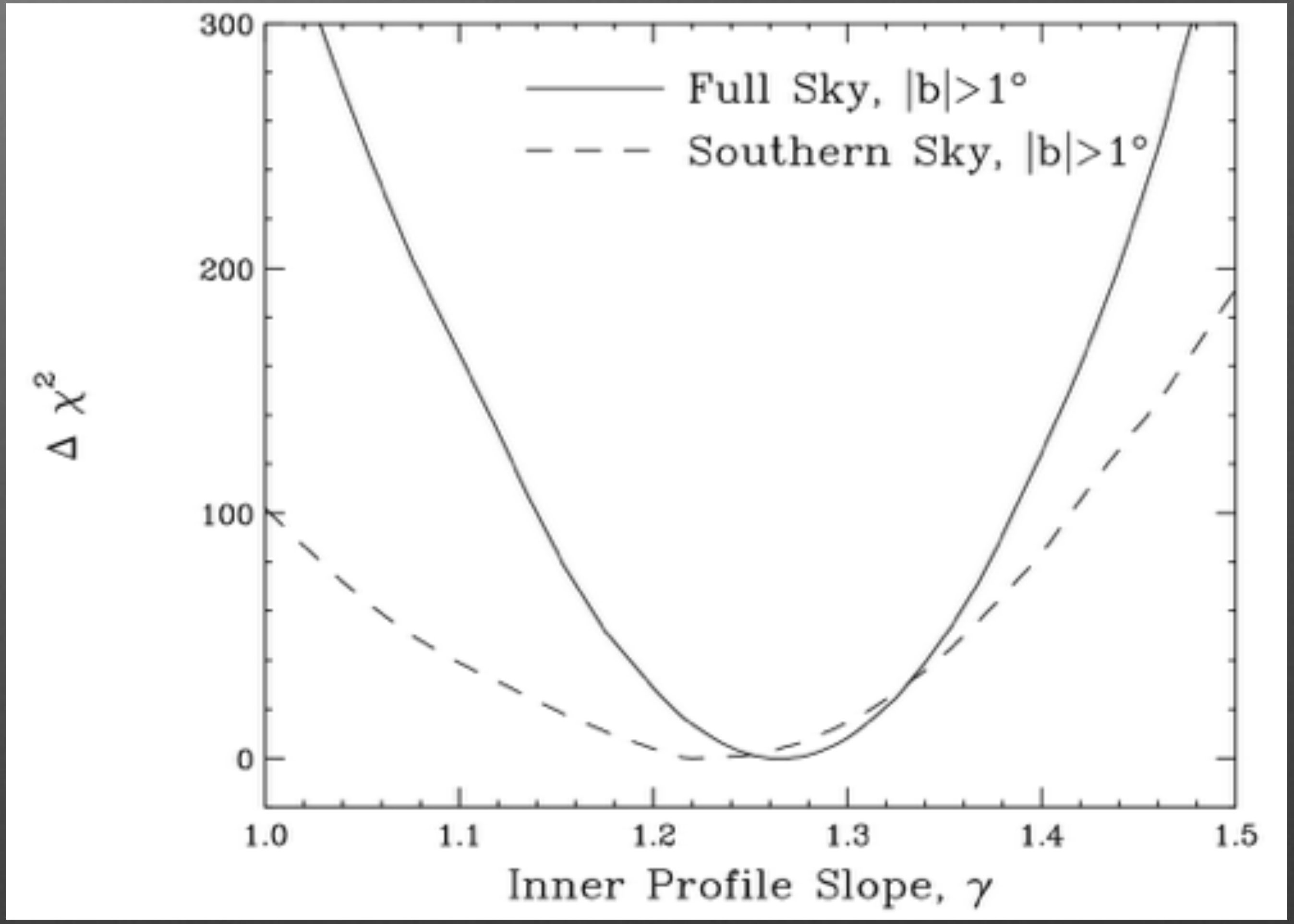
Daylan et al. (2014, 1402.6703)

Consistent Results!

Radial Profile



Galactic Center



Inner Galaxy

Daylan et al. (2014, 1402.6703)

Previous Papers Finding a GC Excess

- Goodenough & Hooper (2009) arXiv:0910.2998
- Hooper & Goodenough (2011, PLB 697 412) arXiv:1010.2752
- Hooper & Linden (2011, PRD 84 12) arXiv:1110.0006
- Abazajian & Kaplinghat (2012, PRD 86 8) arXiv:1207.6047
- Hooper & Slatyer (2013, PDU 2 118) arXiv:1302.6589
- Gordon & Macias (2013, PRD 88 8) arXiv:1306.5725
- Macias & Gordon (2014, PRD 89 6) arXiv:1312.6671
- Abazajian et al. (2014, PRD 90 2) arXiv:1402.4090
- Daylan et al. (2014) arXiv:1402.6703
- Calore et al. (2014) arXiv:1409.0042

Consistent Results!

Note: There is strong agreement on the basic properties of the galactic center excess, among all published (and pre-published) results.

All groups agree:

- The spectrum of the excess is peaked at an energy of ~2 GeV, and falls off at low energies with a spectrum that is harder than expected for astrophysical pion emission

- The excess extends to at least 10º away from the galactic center, following a 3D profile which falls in intensity as $r^{-2.2 \text{ to } -2.8}$

Physically Meaningful Constraints

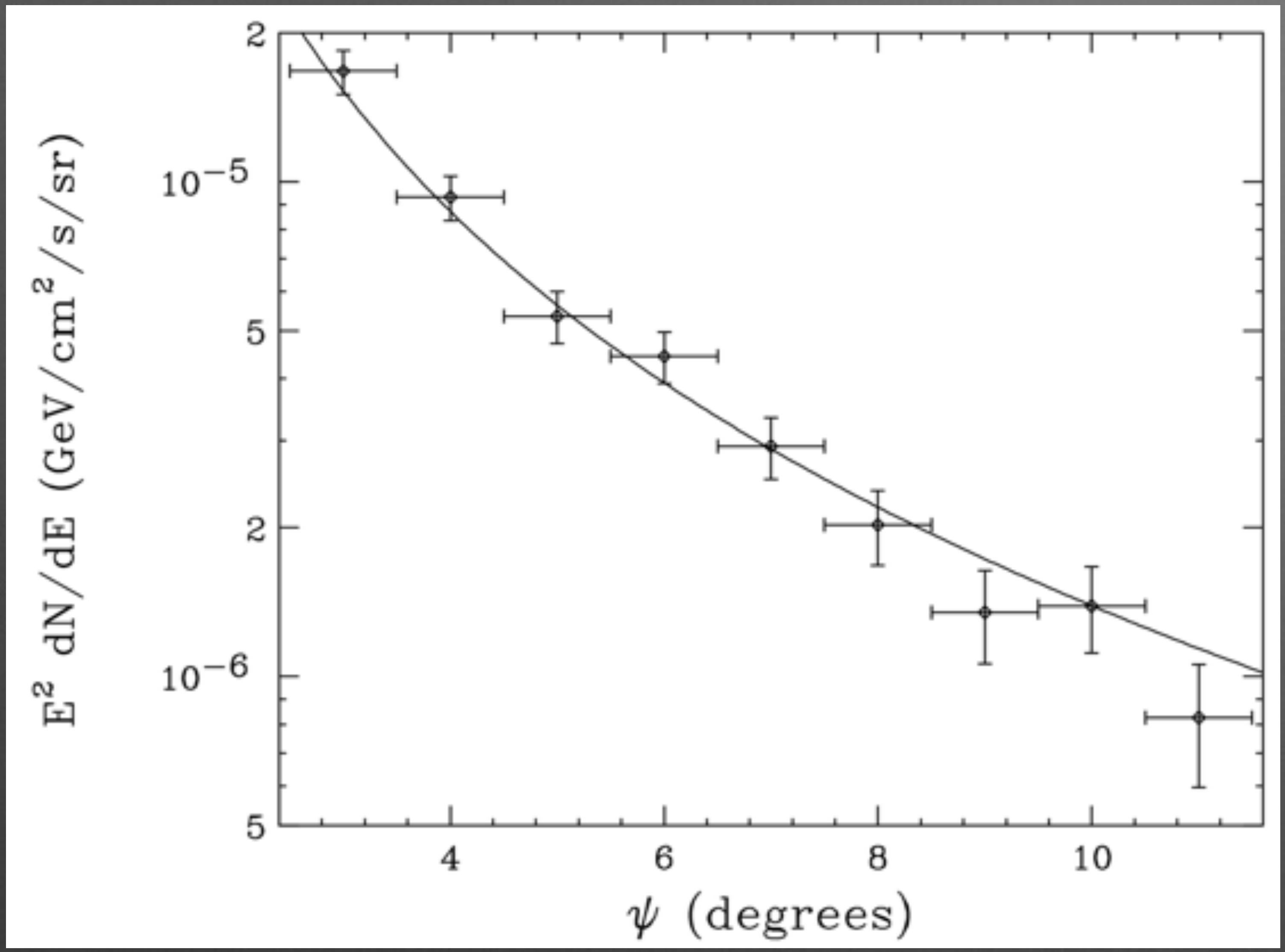
The Combination of:

- 5.5 years of Fermi-LAT data
- Enhanced Photon Selection with CTBCORE
- Two separate analysis techniques

Allow us to produce analyses which are not only highly precise, but also capable of differentiating between sources of the gamma-ray excess

Daylan et al. (2014, 1402.6703)

Extension of the Gamma-Ray Source

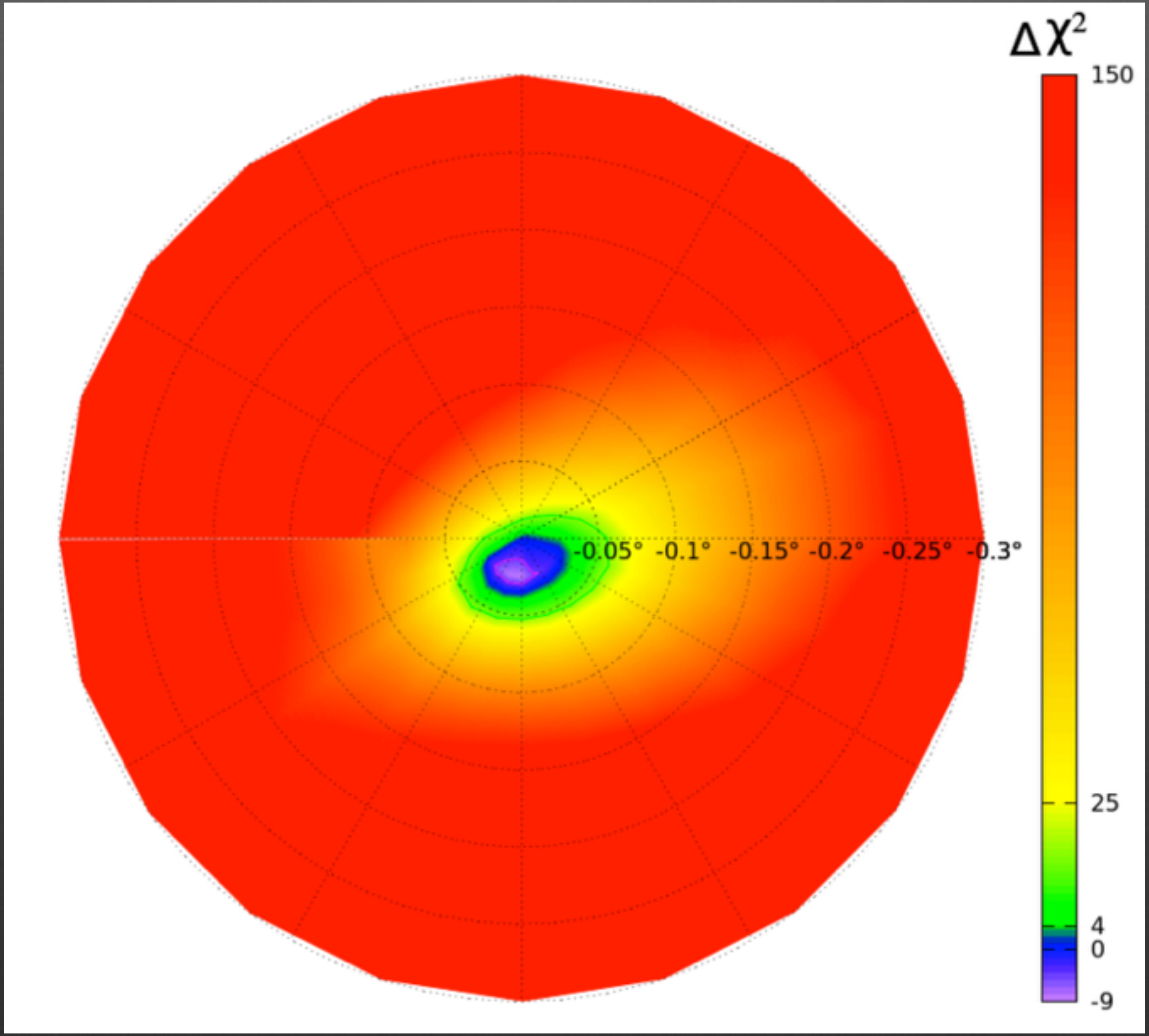


- Fix the spectra of each component in the inner galaxy analysis to its best fit value
- Allow the normalization of the dark matter component to float independently in each galactocentric bin

- The data show clear spatial extension out to at least 10º from the galactic center
- The consistency in the radial fall-off is clear on a bin to bin basis

Daylan et al. (2014, 1402.6703)

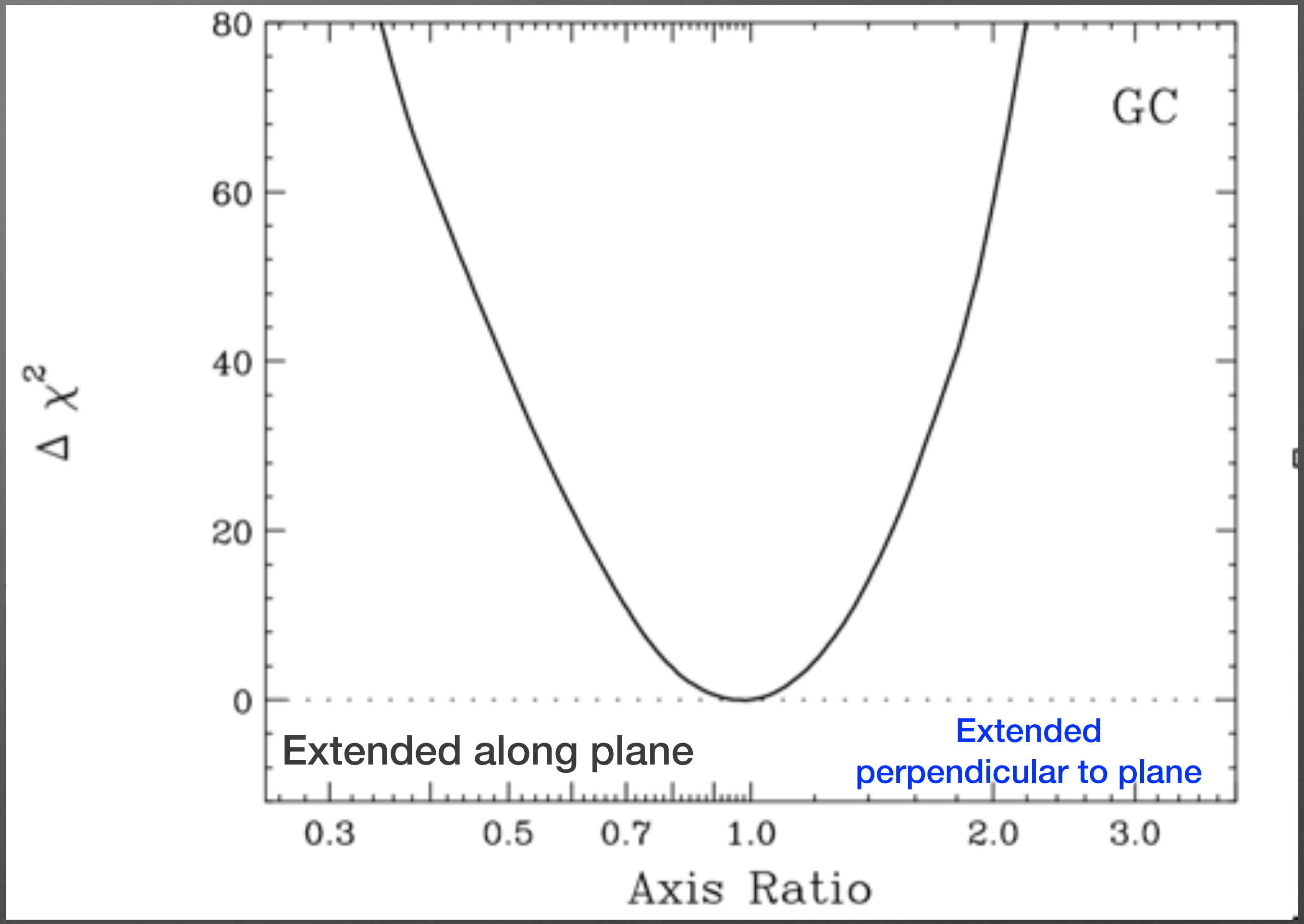
Center of the Gamma-Ray Source



Daylan et al. (2014, 1402.6703)

Sphericity of the Gamma-Ray Source

- Can add in “dark matter” profiles that are not spherically symmetric
- Do these fit the excess as well as a spherically symmetric template?



- The data strongly prefer a template with an axis ratio of unity (+/- 20%)

Daylan et al. (2014, 1402.6703)

Models of the Gamma-Ray Source

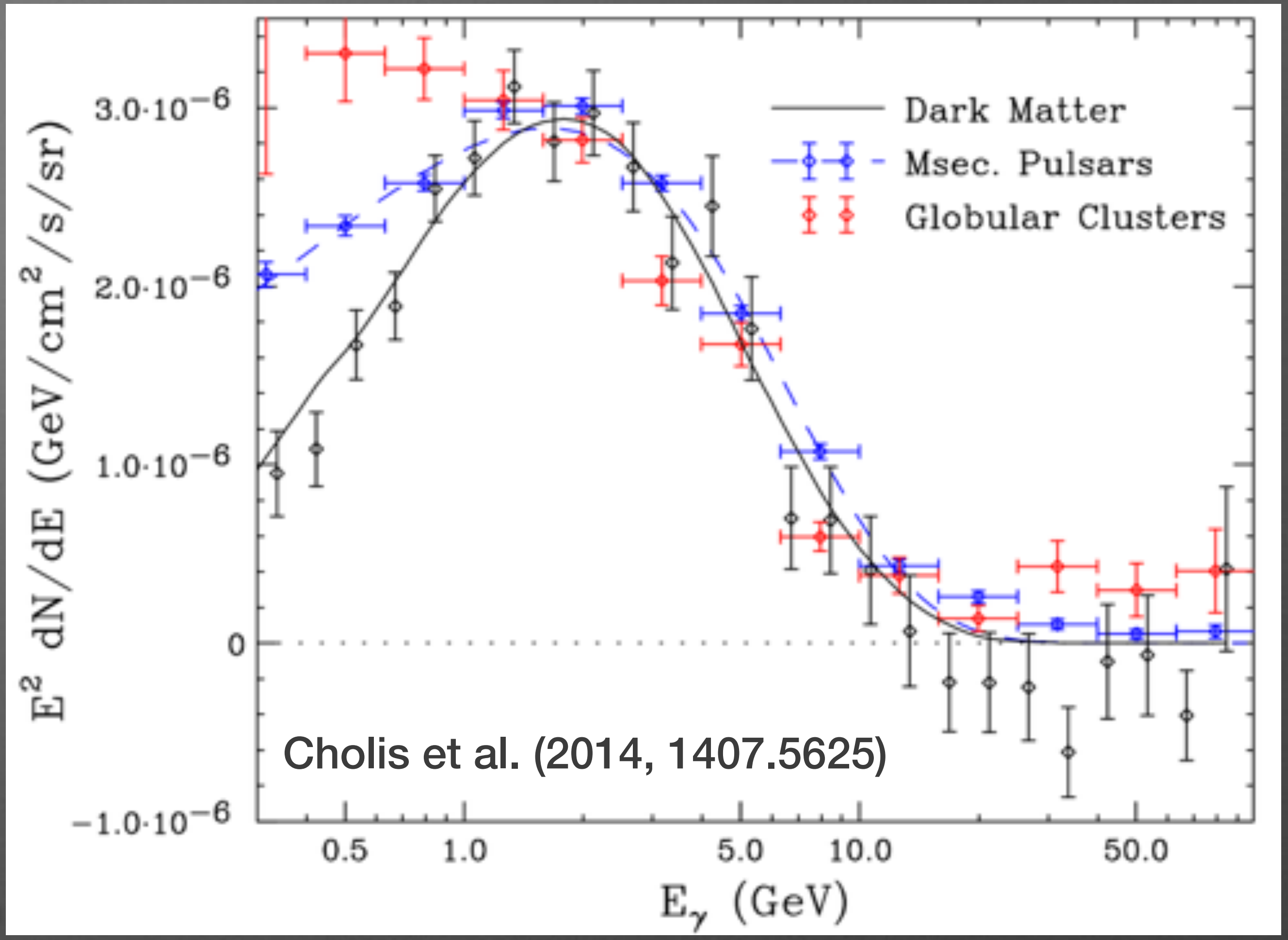
Three Primary Classes of Models for the Gamma-Ray Excess:

1. Millisecond Pulsars
2. Cosmic-Ray Outbursts from the GC
3. Dark Matter Annihilation

Daylan et al. (2014, 1402.6703)

Why: Millisecond Pulsars

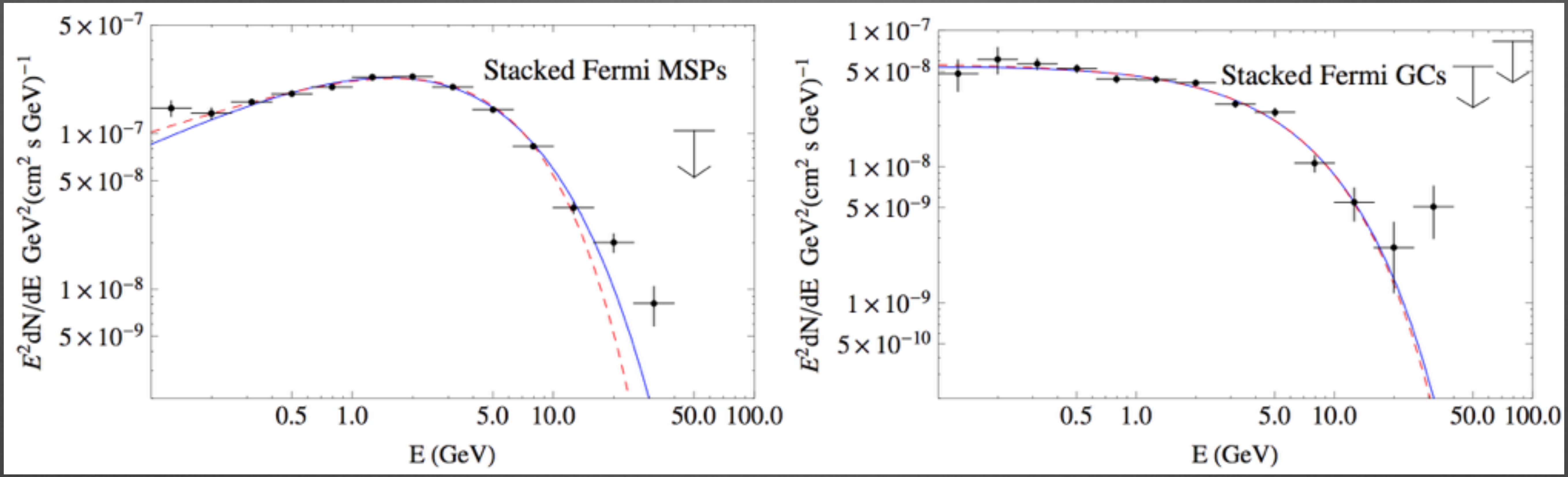
- To first order, the peak of the MSP energy spectrum matches the peak of the observed excess
- MSPs are thought to be overabundant in dense star-forming regions (like globular clusters, and potentially the galactic center)



Abazajian (2011, 1011.4275)

Abazajian & Kaplinghat (2012, 1207.6047)

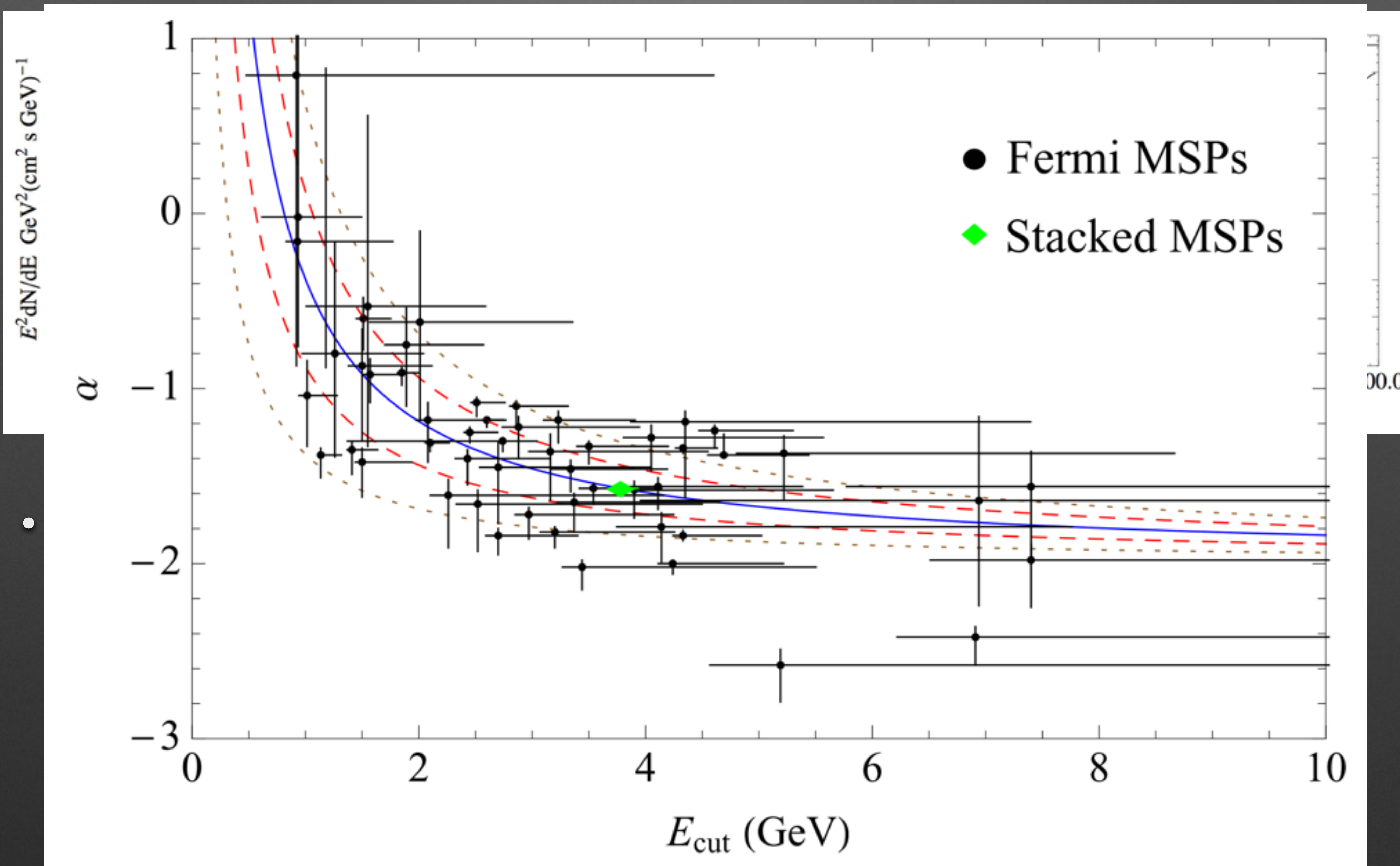
Millisecond Pulsars



- Analyze the average spectrum and luminosity of the Fermi MSP and globular cluster populations:
  - **5.5 years of data**
  - **P7 Reprocessed Photons**
  - **15 energy bins, no spectral model assumed**

Cholis et al. (2014, 1407.5583)
Cholis et al. (2014, 1407.5625)

Millisecond Pulsars



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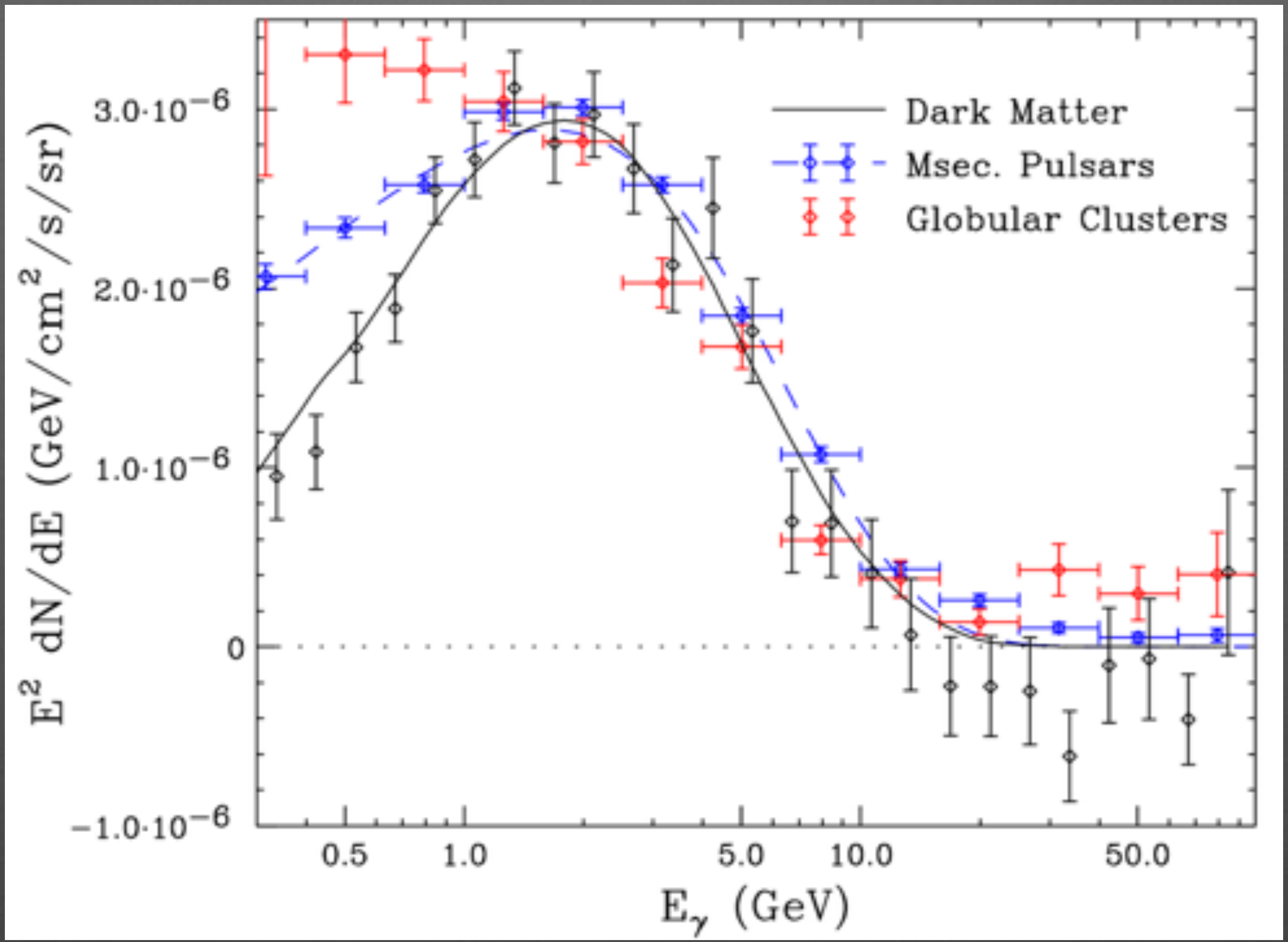
Cholis et al. (2014, 1407.5583)
Cholis et al. (2014, 1407.5625)

Why Not: Millisecond Pulsars

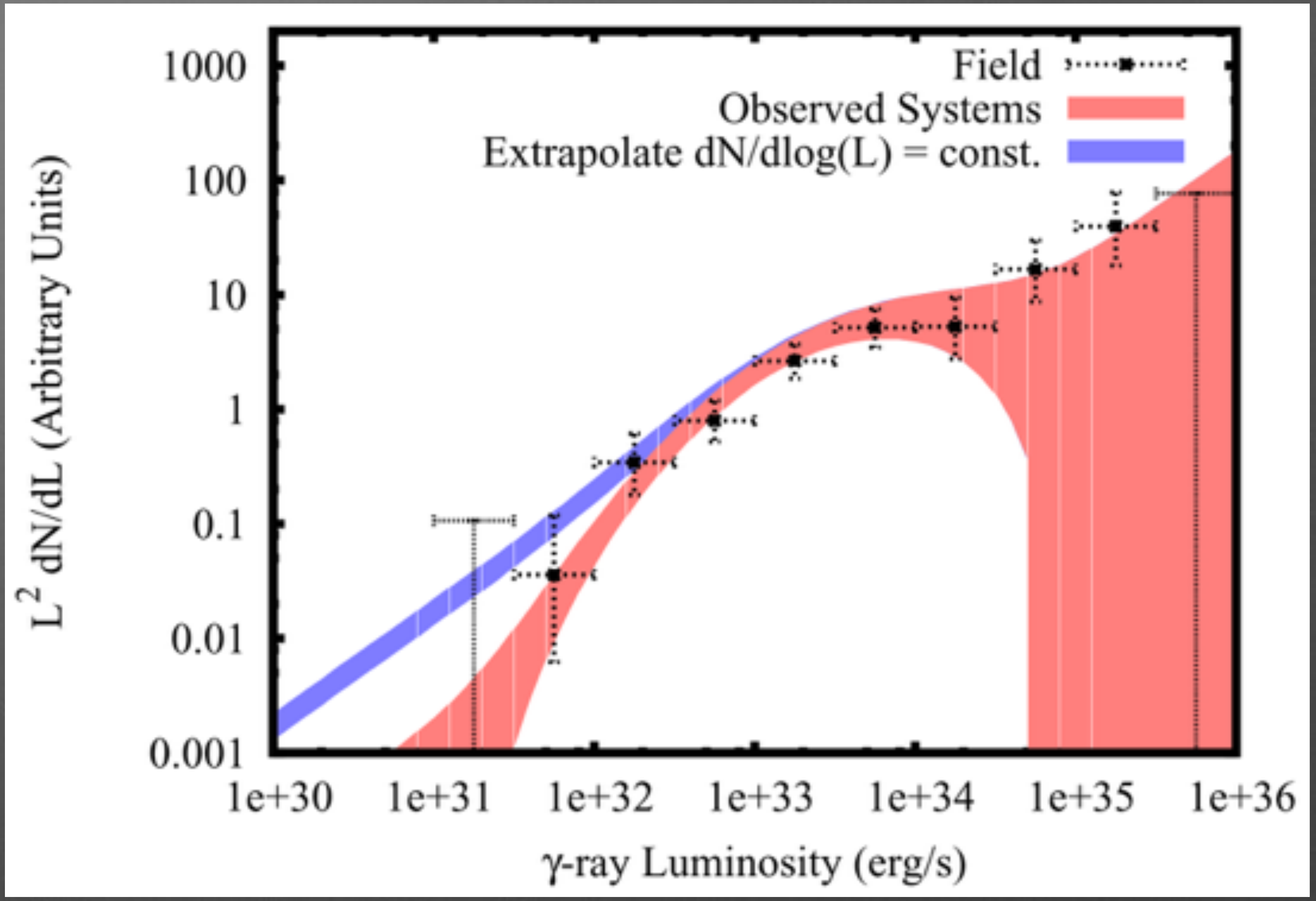


- While the bump of the MSP spectrum is very similar to the GeV excess, the low energy behavior is quite different.
- This is not a death knell to MSP models by itself, but additional constraints on systematic errors could make the offset concerning

Cholis et al. (2014, 1407.5625)

Why Not: Millisecond Pulsars

- There would need to be 226 (+91/-67) MSPs with luminosity > 10^{34} erg s^{-1} in the circular region, and 61.9 (+60/-33.7) with luminosity > 10^{35} erg s^{-1}.



- We can also compare the MSP population to the observed LMXB population. Using the ratio for LMXBs to the MSP luminosity of globular clusters, we predict that the gamma-ray luminosity in the Galactic center would imply a population of 103 (+70/-45) LMXBs in the GC, only 6 are detected

Cholis et al. (2014, 1407.5625)

Why Not: Millisecond Pulsars

- Can also compare the expected gamma-ray emission from globular clusters given the number of INTEGRAL detected LMXBs in these systems

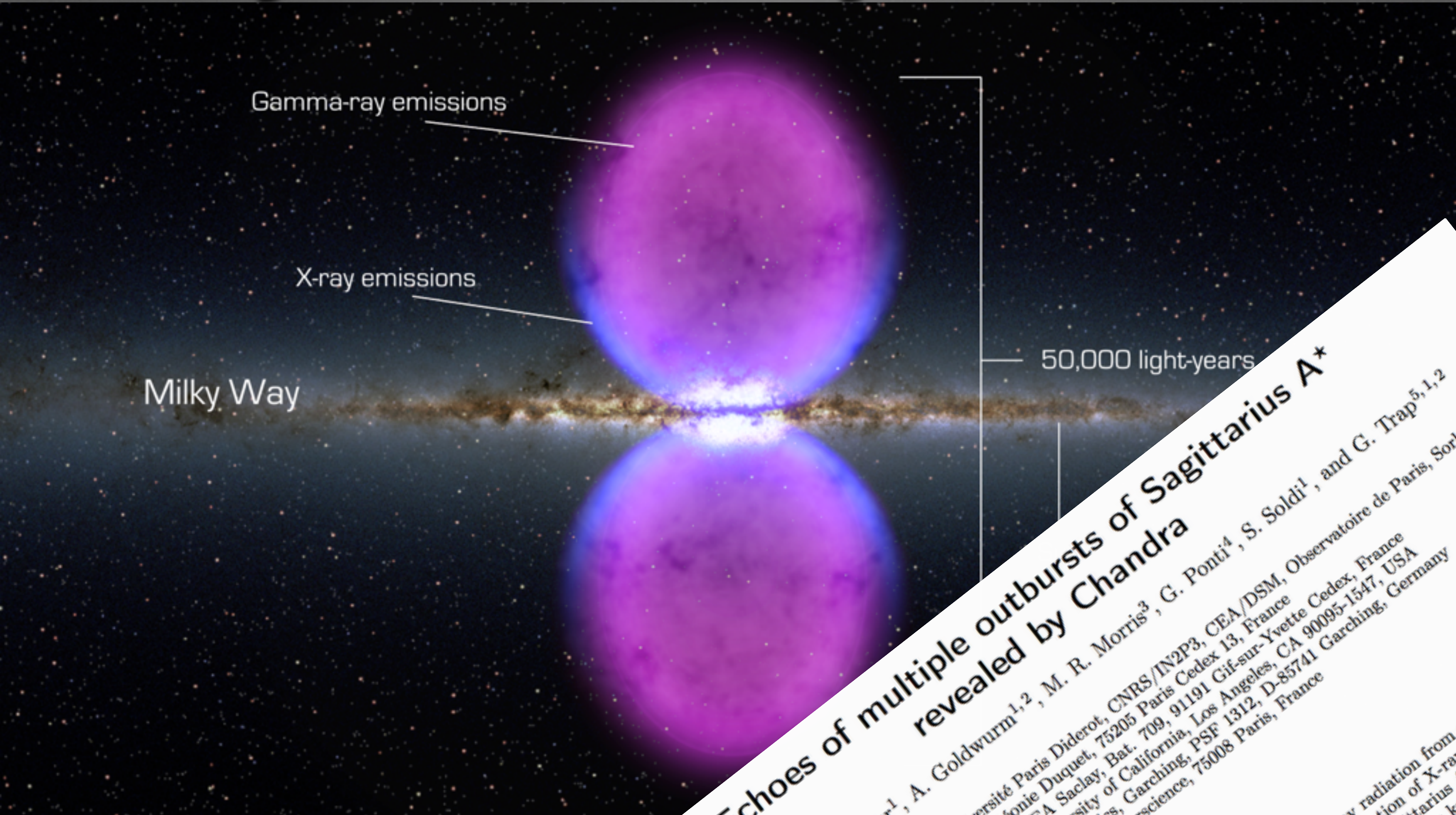
- X-Ray observations of Globular Clusters indicate the existence of 5 bright ($L_x > 10^{36}$ erg/s) LMXBs in globular clusters (12 total), and Fermi observations find a gamma-ray flux of 6.1×10^{35} erg s^{-1}.

- The luminosity of the galactic center (1.3×10^{37} erg s^{-1}) should then correspond to a population of 103 (+70/-44.5) very bright LMXBs in the GC region (luminosities above the INTEGRAL GC threshold)

- Instead only 6 LMXBs with $L_x > 10^{36}$ erg/s are observed, again indicating that MSPs can account for approximately 5% of the total residual flux.

Cholis et al. (2014, 1407.5625)

Why: Cosmic-Ray Outbursts



Echoes of multiple outbursts of Sagittarius A*
revealed by Chandra

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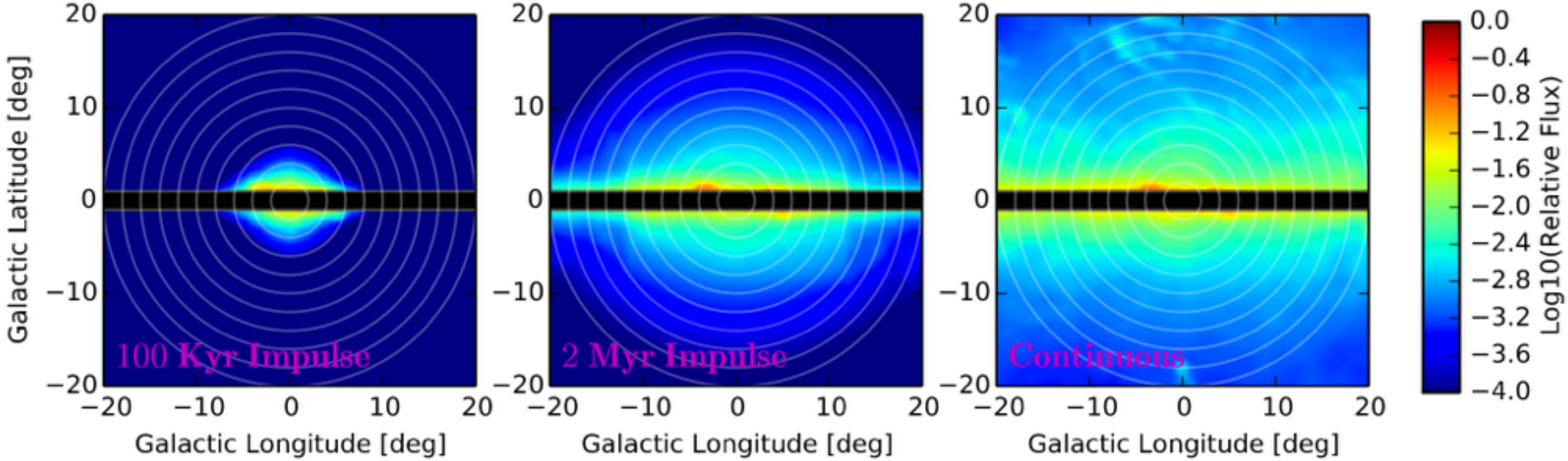
Accepted 12 July 2013

ABSTRACT

Carlson & Profumo (2014, 1405.7685)

Petrovic et al. (2014, 1405.7928)

Why Not: Cosmic-Ray Outbursts



Best Fitting Linear Combination of Hadronic Outburst Models: TS=51 (14 d.o.f)

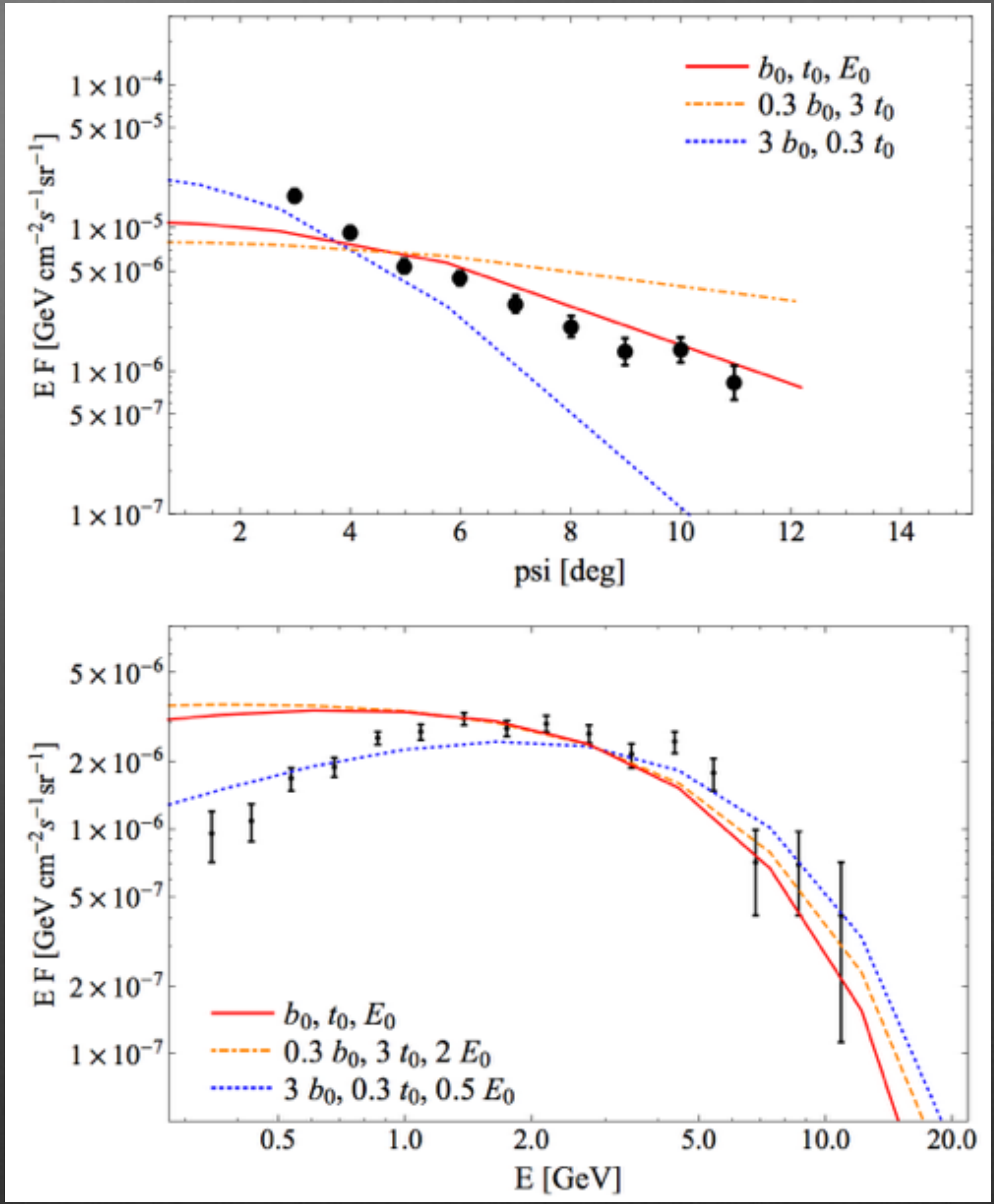
Best Fitting NFW Template TS=315 (5 d.o.f)

Note that the diffuse model includes contributions from gas in the galactic center, which also correlates to the expected bright emission from these sources

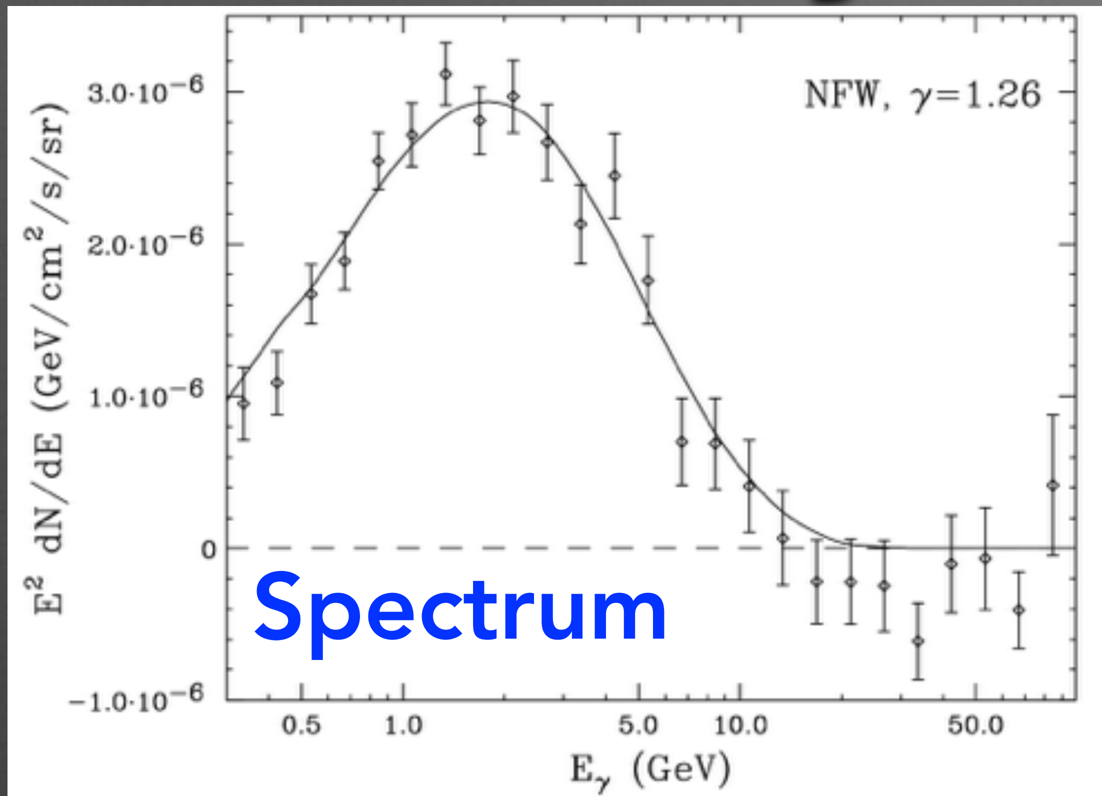
Why Not: Cosmic-Ray Outbursts

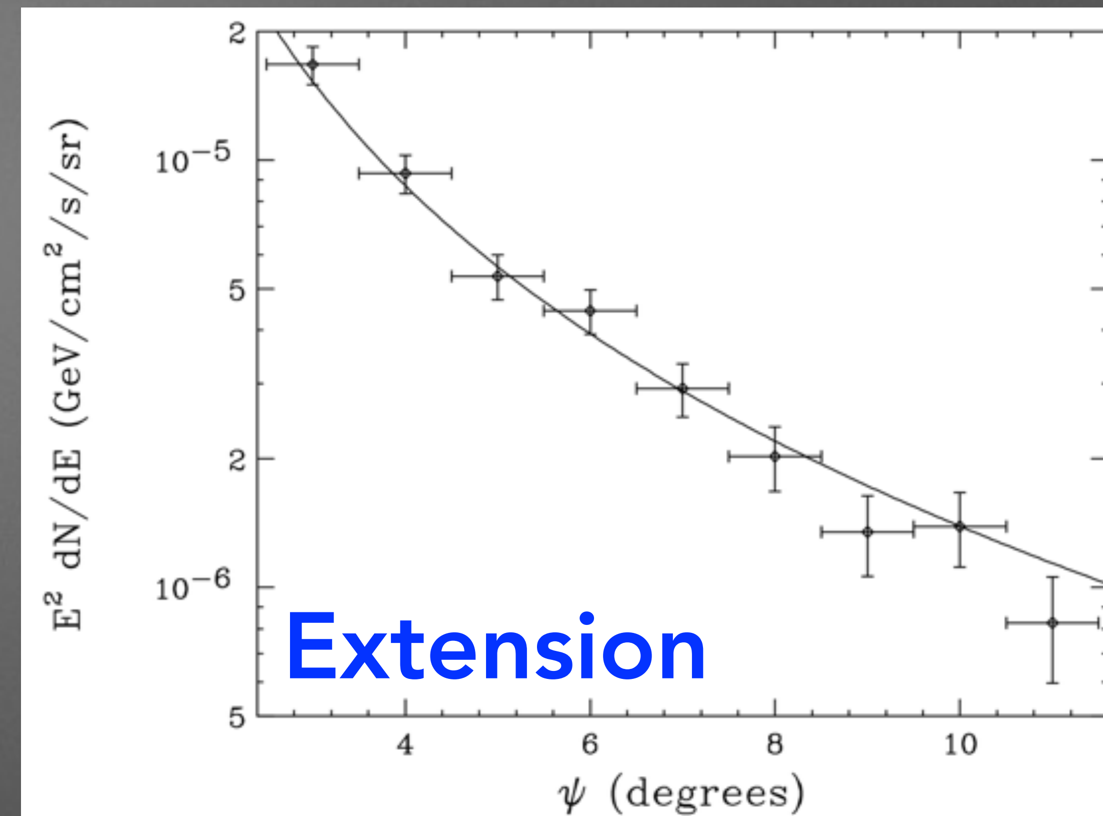
Leptonic models can produce emission by up scattering the ISRF, in addition to producing bremsstrahlung emission in gas

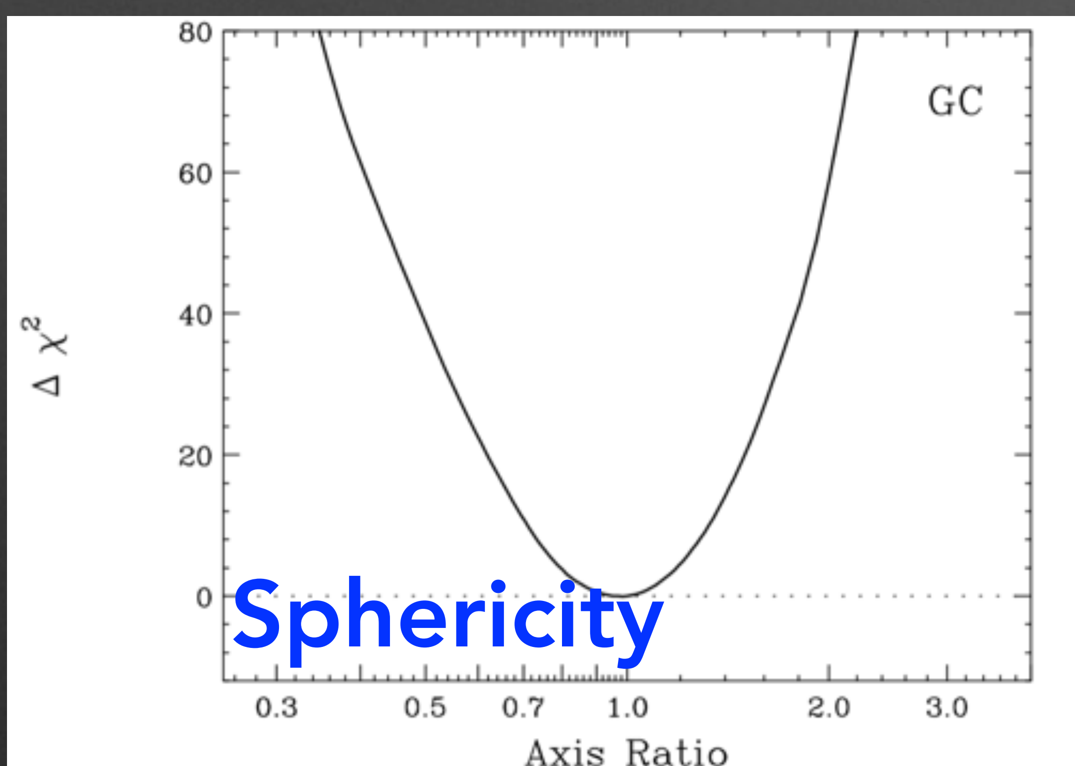
Difficult to explain the spectral consistency of the excess in light of the fact that electrons cool effectively in the GC region

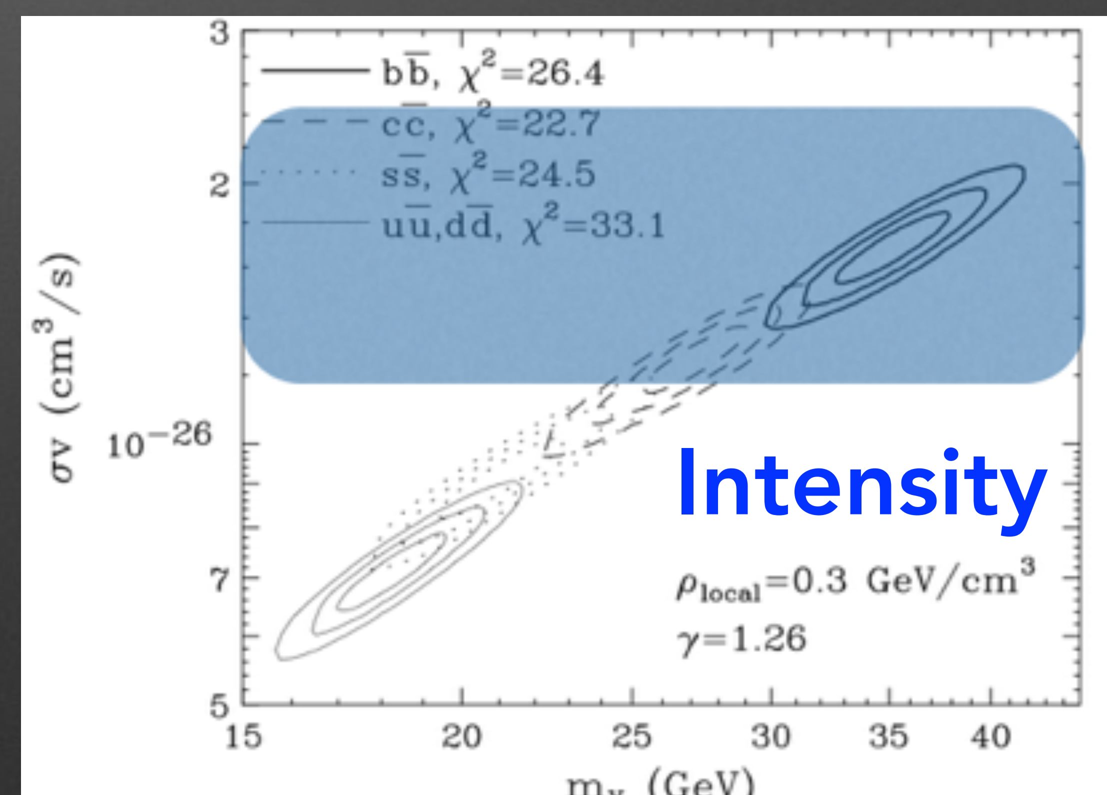


Why: Dark Matter









Daylan et al. (2014, 1402.6703)

Conclusions

- Multiple groups have observed the gamma-ray excess in the galactic center region using different techniques and obtaining *extremely* similar results

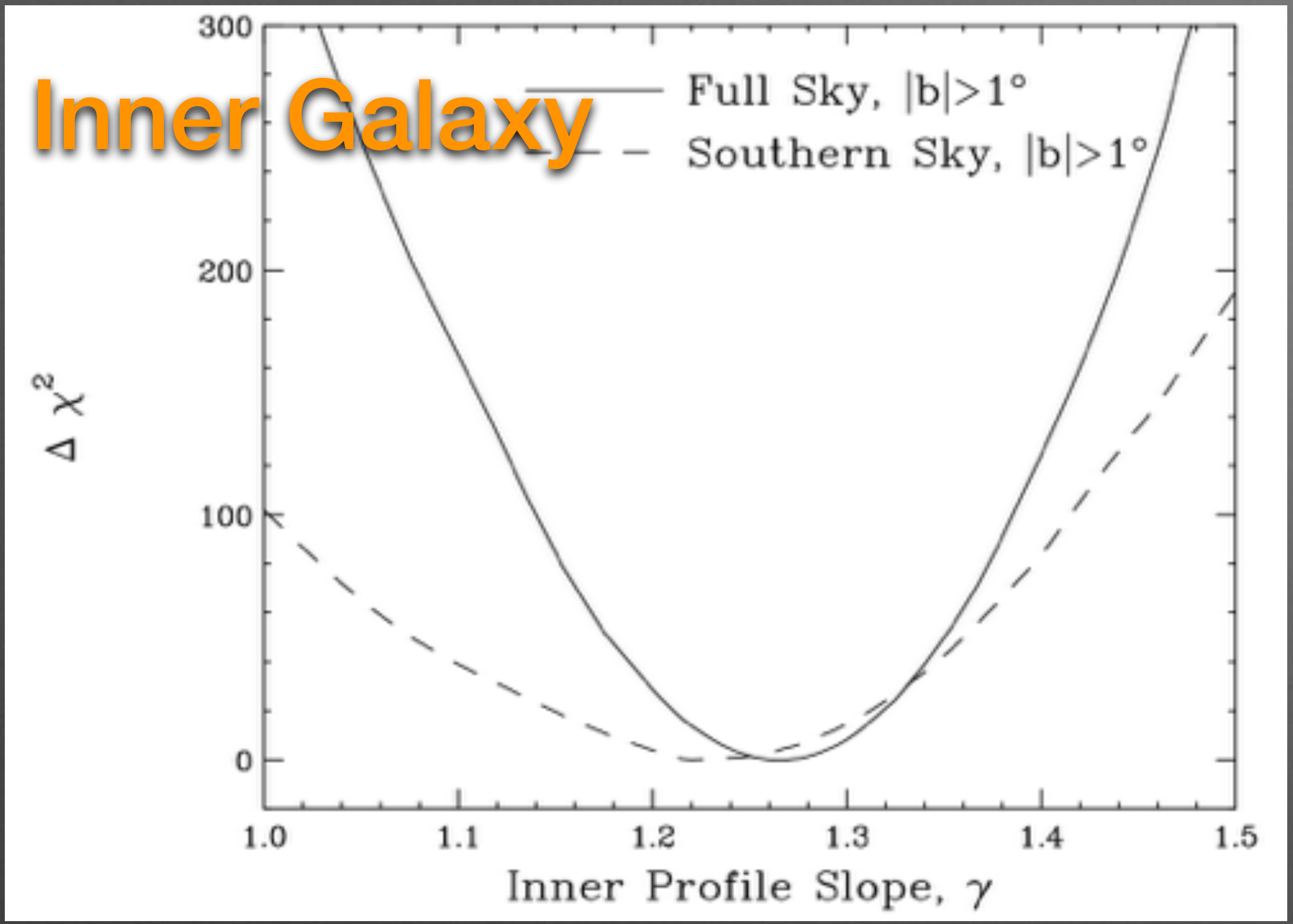
- Current analyses (CTBCORE, 5.5 years of data, 300 MeV energy cut) have produced multiple results which can be used to test dark matter and astrophysical models

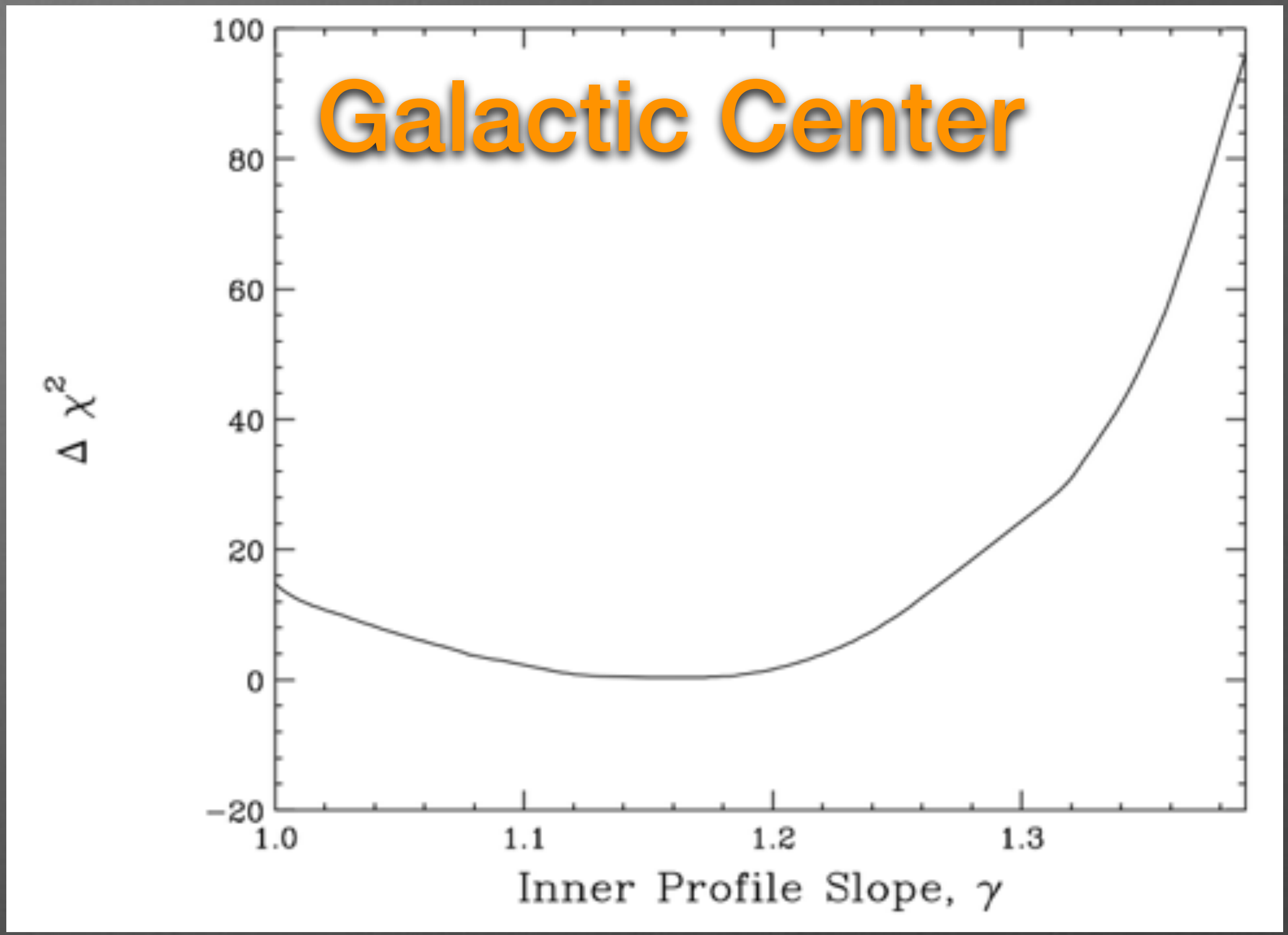
- Recent results have made astrophysical fits to the data difficult, dark matter remains the best statistical fit to the data.

- Stay tuned!

Extra Slides

Some (Very Slight) Evidence for Changes in the Profile?





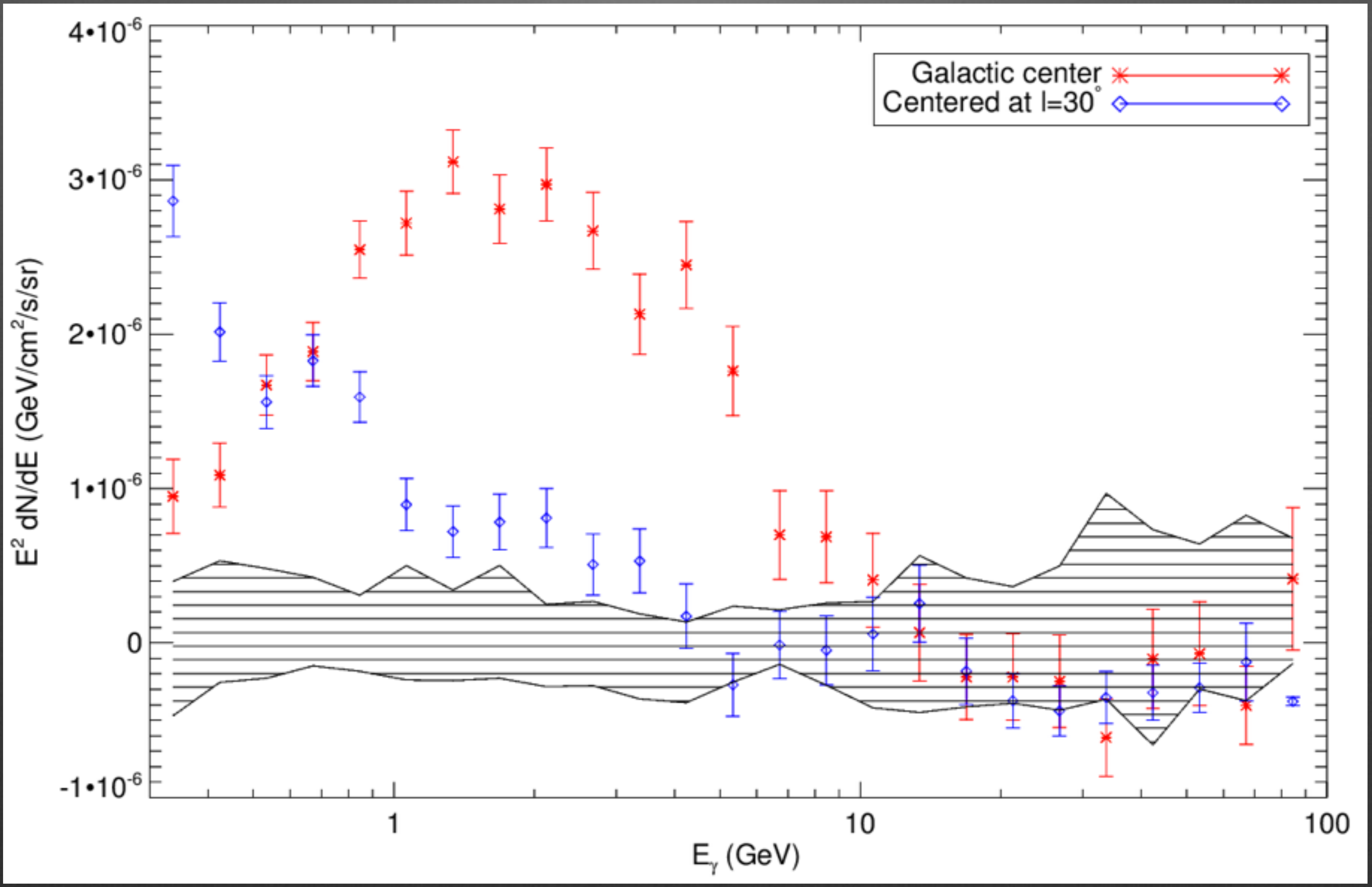
Astrophysical and dark matter interpretations of extended gamma-ray emission from the Galactic Center

Kevork N. Abazajian,* Nicolas Canac,† Shunsaku Horiuchi,‡ and Manoj Kaplinghat§
Center for Cosmology, Department of Physics and Astronomy, University of California, Irvine, Irvine, California 92697 USA

We include point sources from the 2FGL catalog [2] in our ROI, $7° \times 7°$ around the GC centered at $b = 0, \ell = 0$.

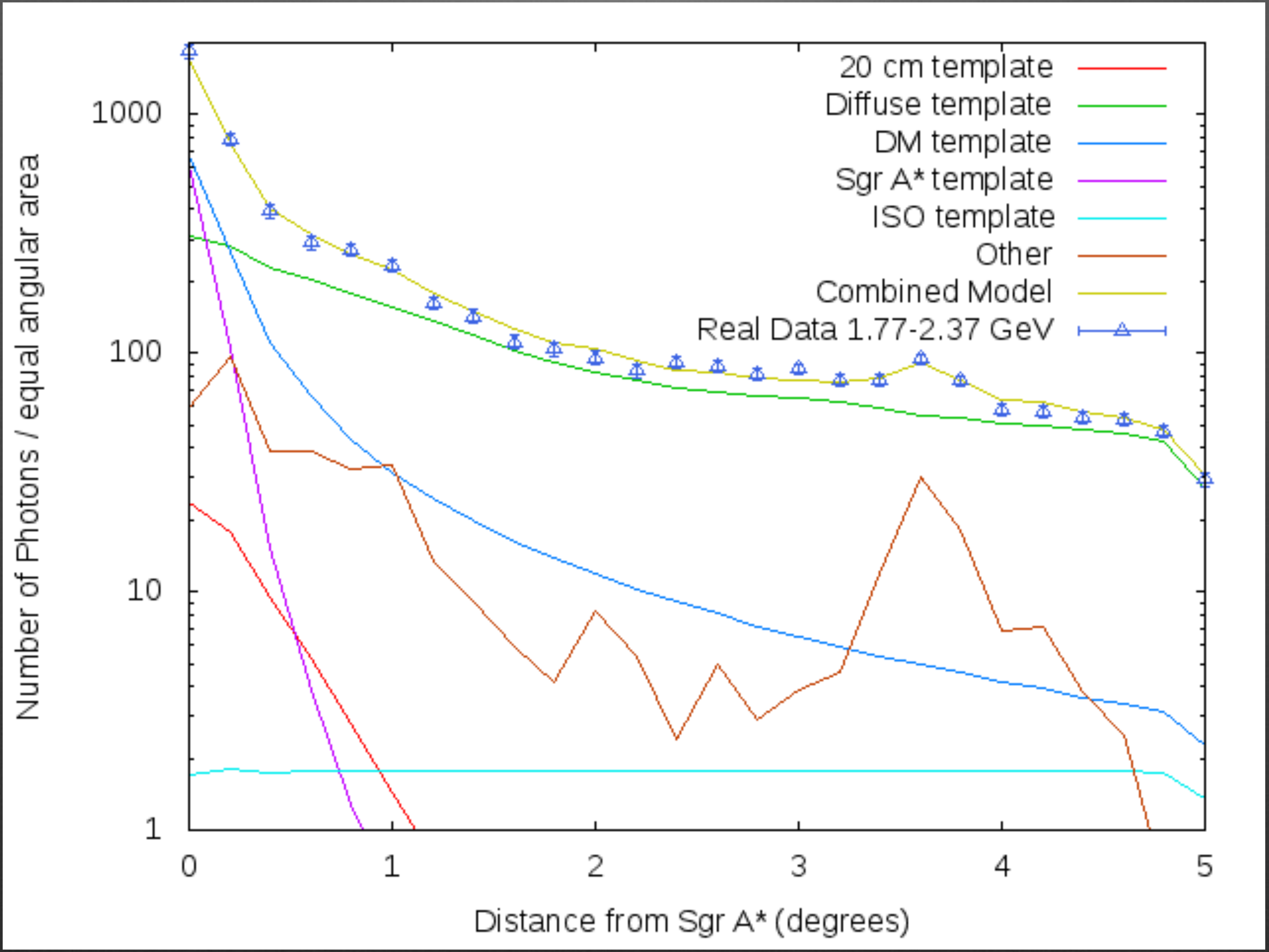
their best fit values. The change for $\Delta\gamma = \pm 0.1$ is larger. Fitting a polynomial to the profile likelihood on the variation of γ, we find $\gamma = 1.12 \pm 0.05$ (statistical errors only).

Comparison To Other Residuals

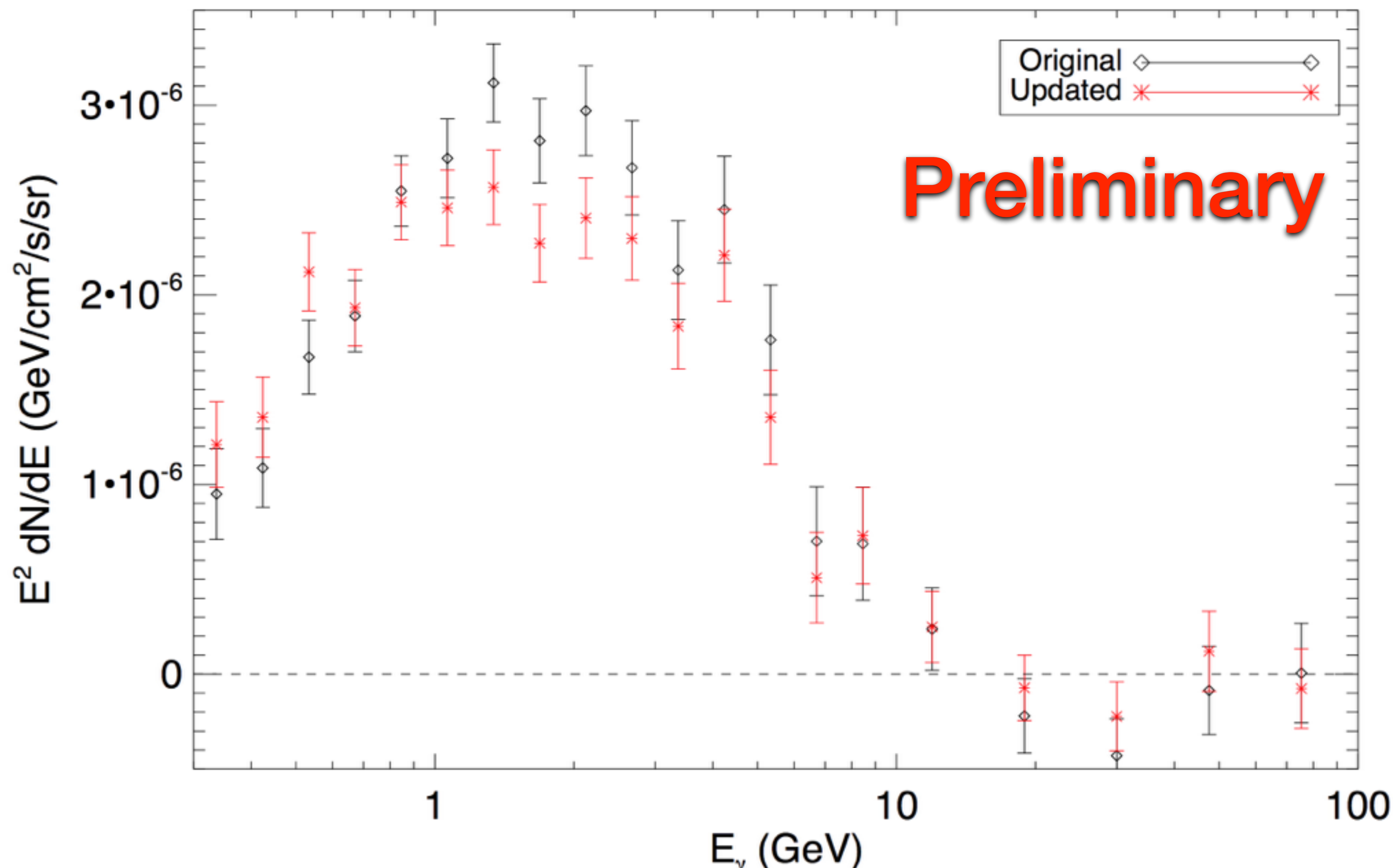


Inner Galaxy

Fractional Intensity of the Signal

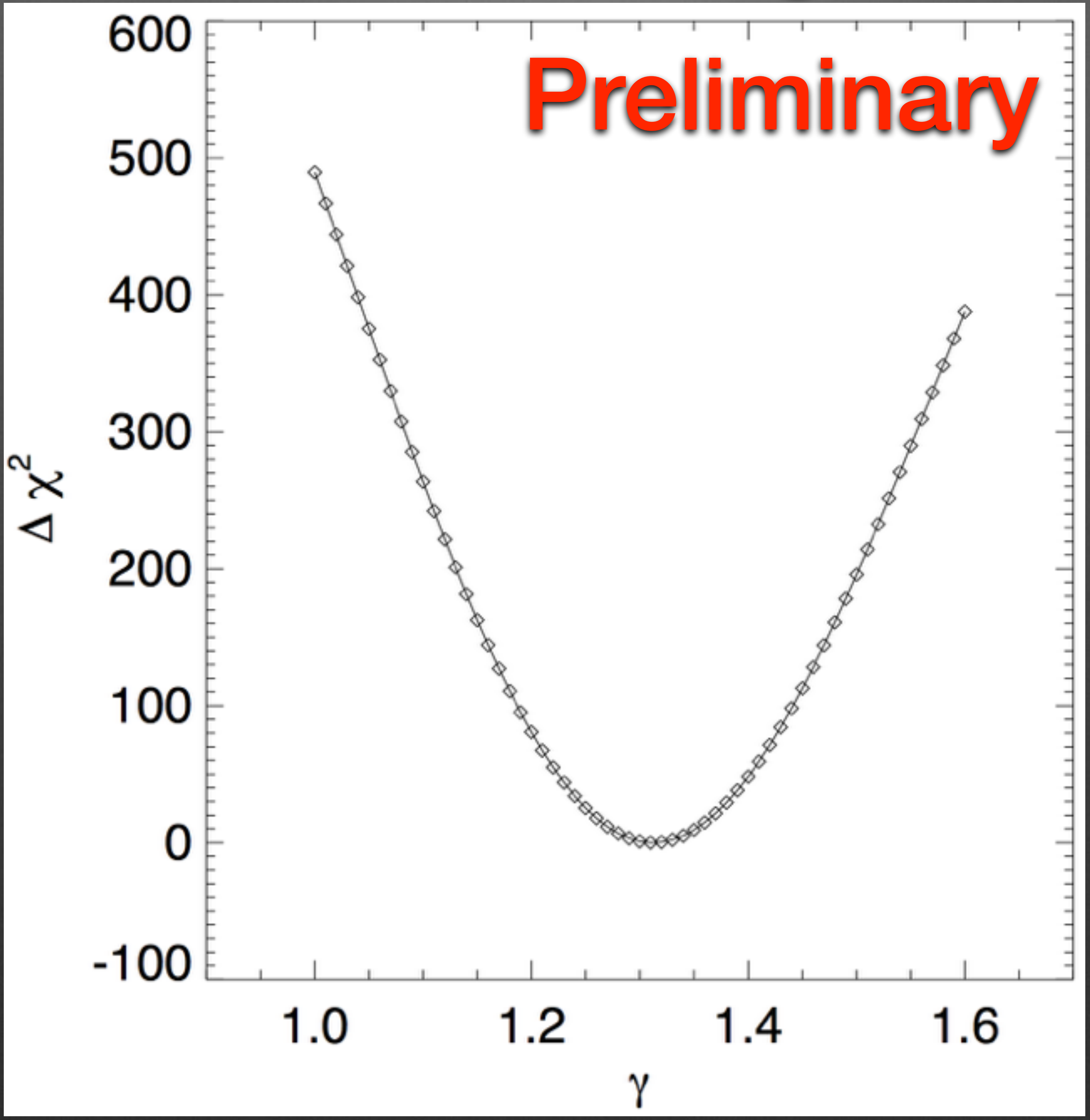


Small Bug



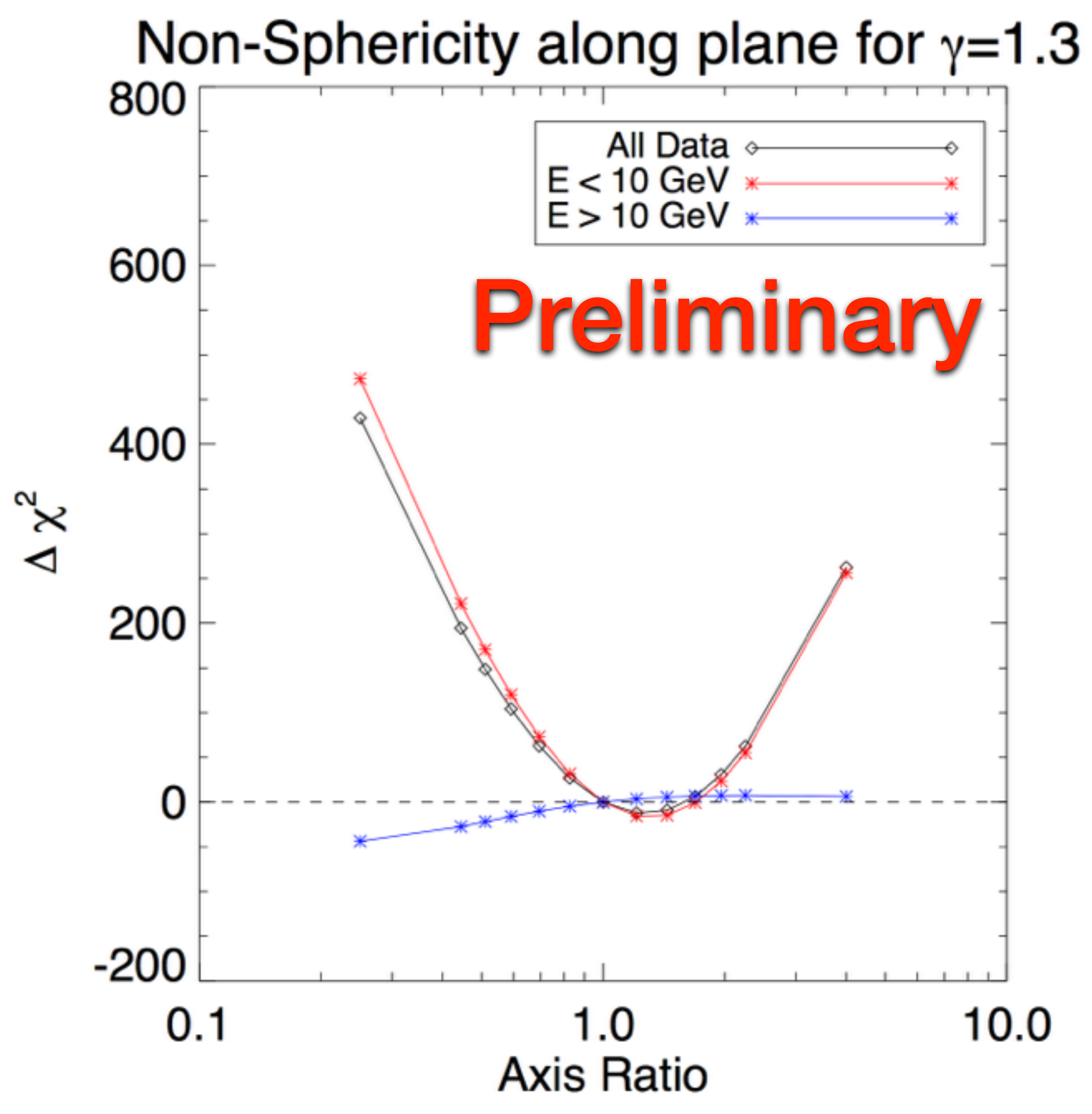
Original
Updated
Preliminary
3•10^-6
2•10^-6
1•10^-6
0
1
10
100
E^2 dN/dE (GeV/cm^2/s/sr)
E_γ (GeV)

Small Bug



600
500
400
300
200
100
0
-100
$\Delta\chi^2$
1.0
1.2
1.4
1.6
γ
Preliminary

Small Bug



Non-Sphericity along plane for γ=1.3
All Data
E < 10 GeV
E > 10 GeV
Preliminary
800
600
400
200
0
-200
Δ χ²
0.1
1.0
10.0
Axis Ratio

Dwarf Constraints