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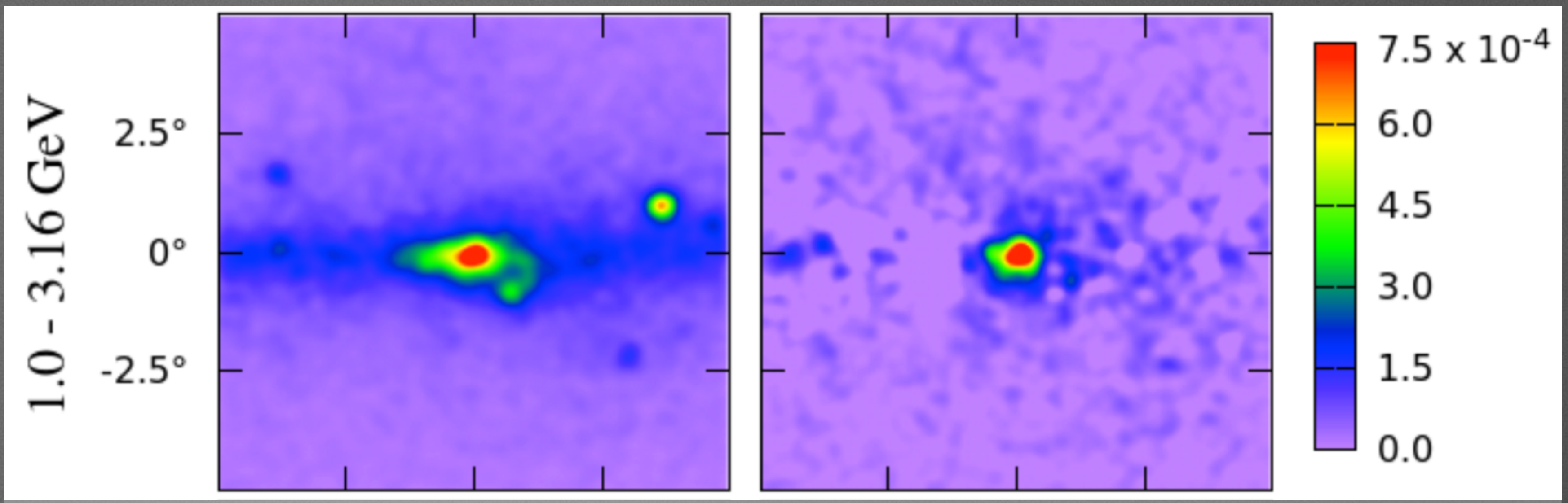



# The Characterization of the Gamma-Ray Excess from the Central Milky Way

Tim Linden

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

1402.6703
1407.5583
1407.5625
1410.1527

5th International Fermi Symposium, Nagoya Japan, October 22, 2014

# Two Types of Analyses

## Galactic Center

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

## Inner Galaxy

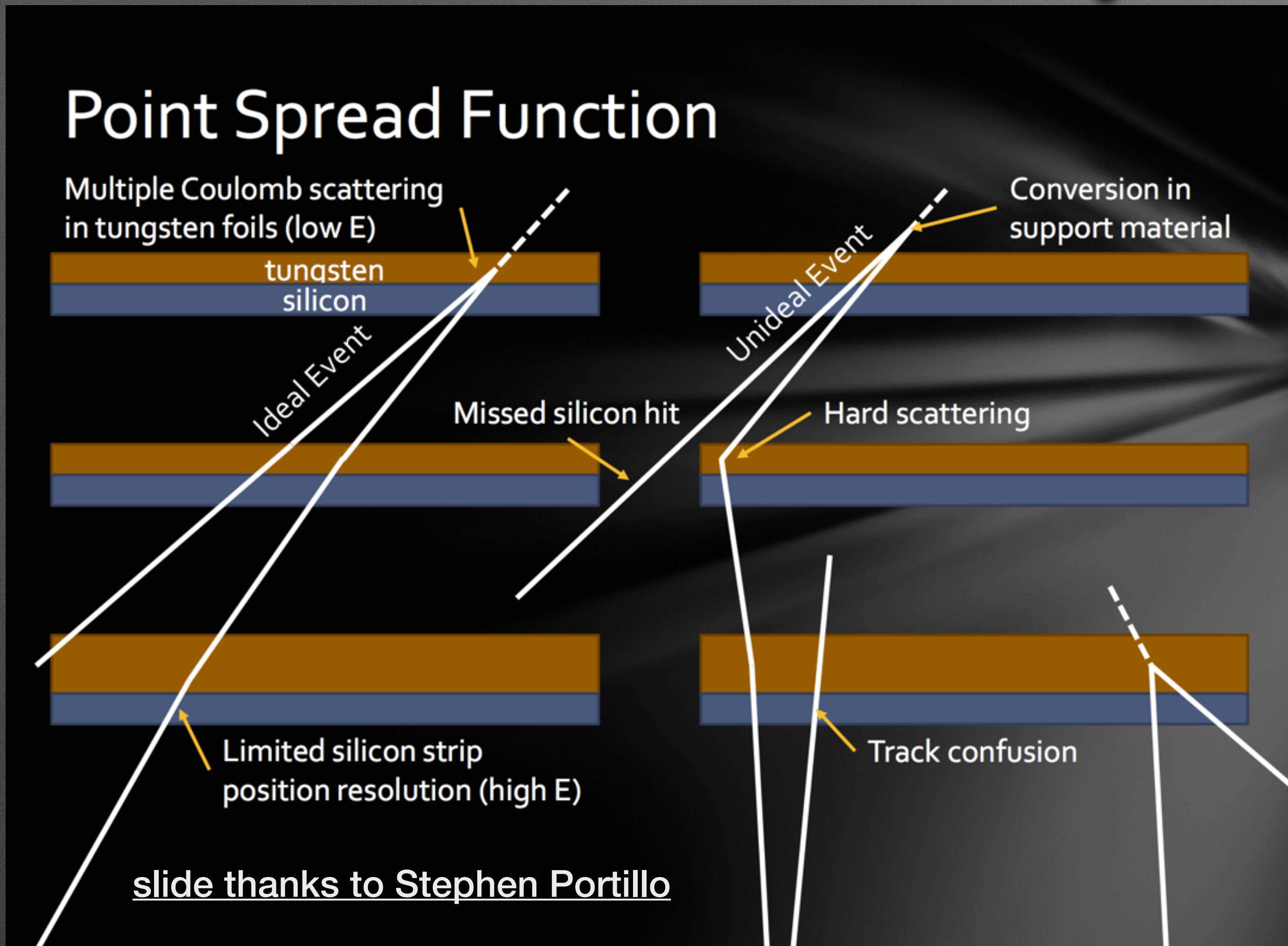
- Mask galactic plane (e.g. $|b| > 1^o$)
- Mask bright point sources at $2^o$
- Allow diffuse templates (galactic diffuse, isotropic, Fermi bubbles, dark matter) to float independently in each of 30 energy bins
- Calculate log-likelihood to determine the significance of the excess component

# Previous Papers Finding a GC Excess

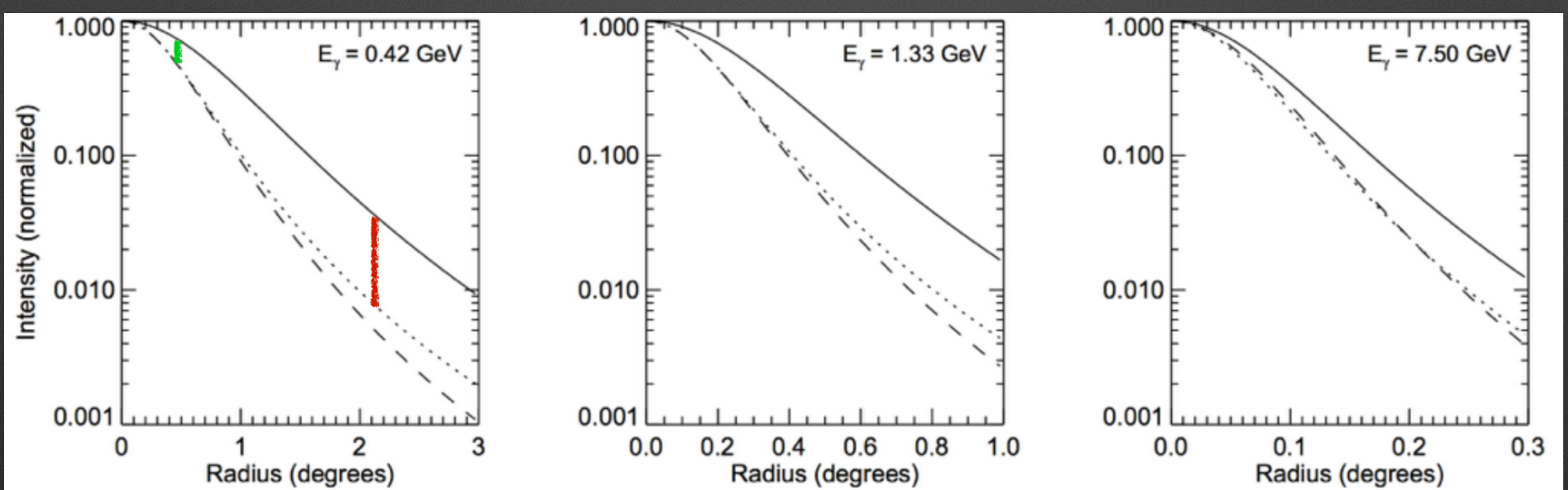
- Goodenough & Hooper (2009) arXiv:0910.2998
- Hooper & Goodenough (2011, PLB 697 412) arXiv:1010.2752
- Hooper & Linden (2011, PRD 84 12) arXiv:1110.0006
- Abazajian & Kaplinghat (2012, PRD 86 8) arXiv:1207.6047
- Hooper & Slatyer (2013, PDU 2 118) arXiv:1302.6589
- Gordon & Macias (2013, PRD 88 8)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

# CTBCORE: Sharper Fermi-LAT Images

see talk by Stephen Portillo



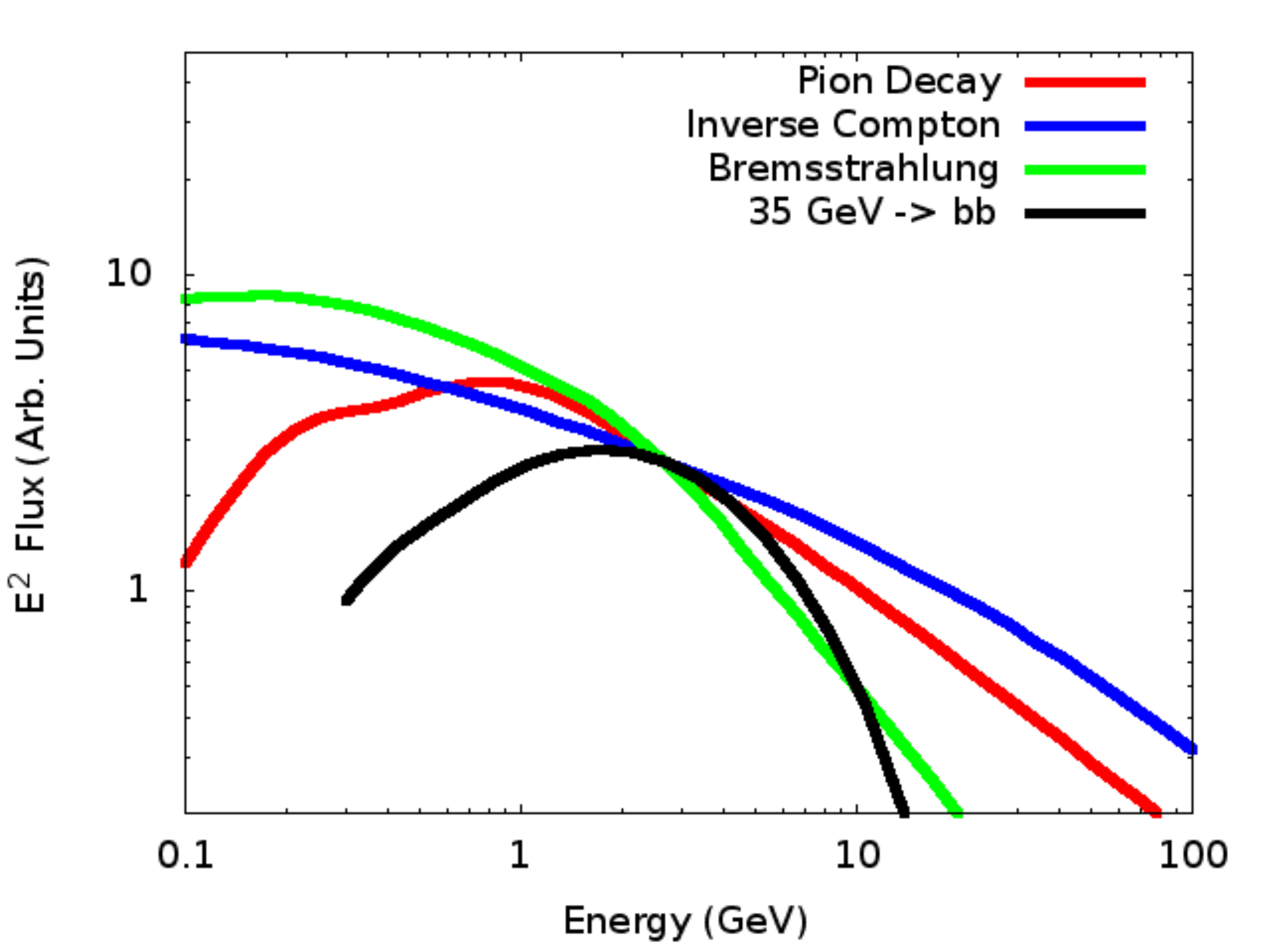

The improvement in the PSF is especially important at low energies. Using these cuts, we include all photons down to an energy of 300 MeV




Daylan et al. (2014, 1402.6703)

Portillo & Finkbeiner (2014, 1406.0507)

# The Importance of Low-Energy Photons

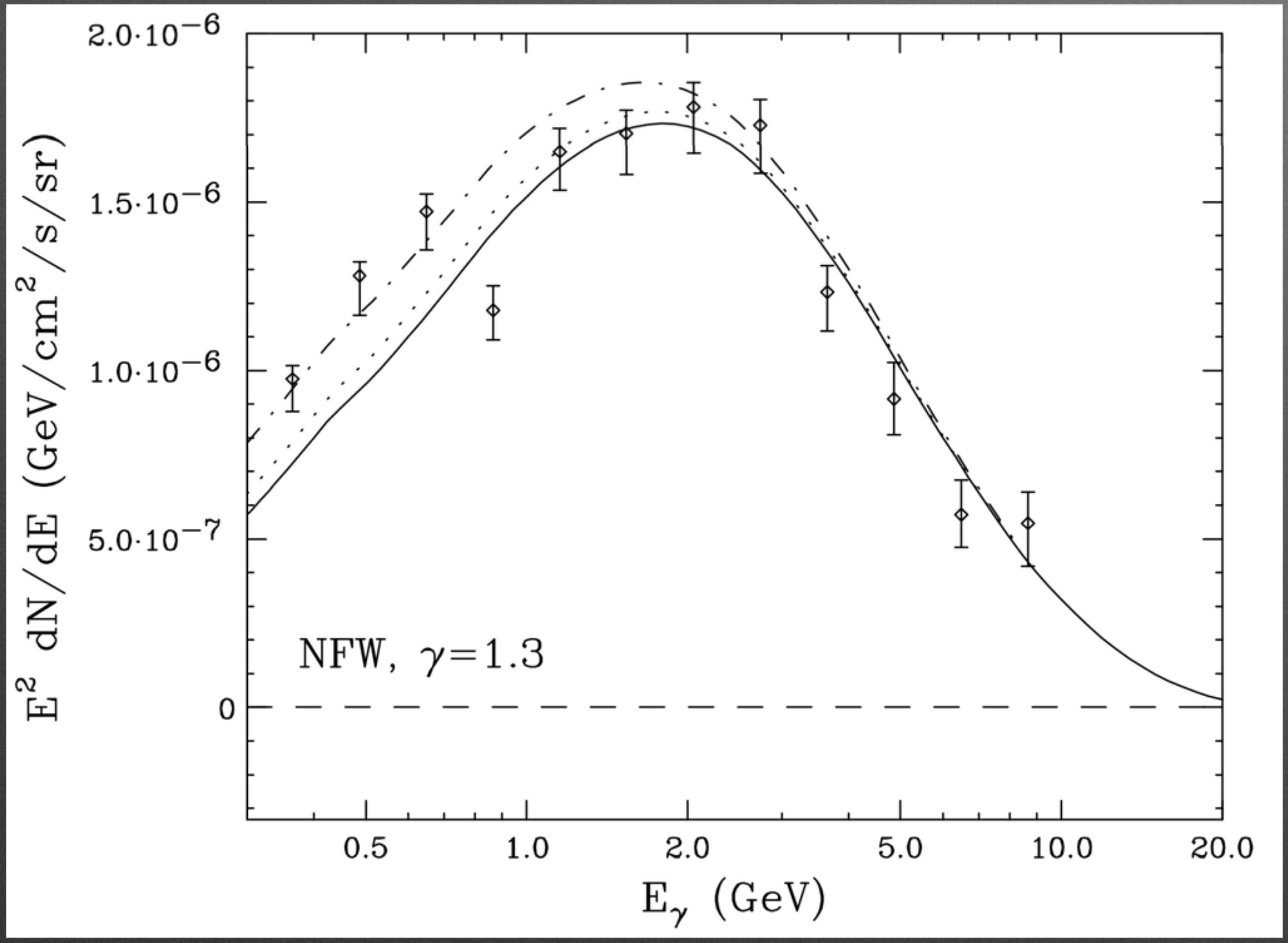



The usage of low-energy photons is critical for differentiating possible dark matter signals from astrophysical backgrounds

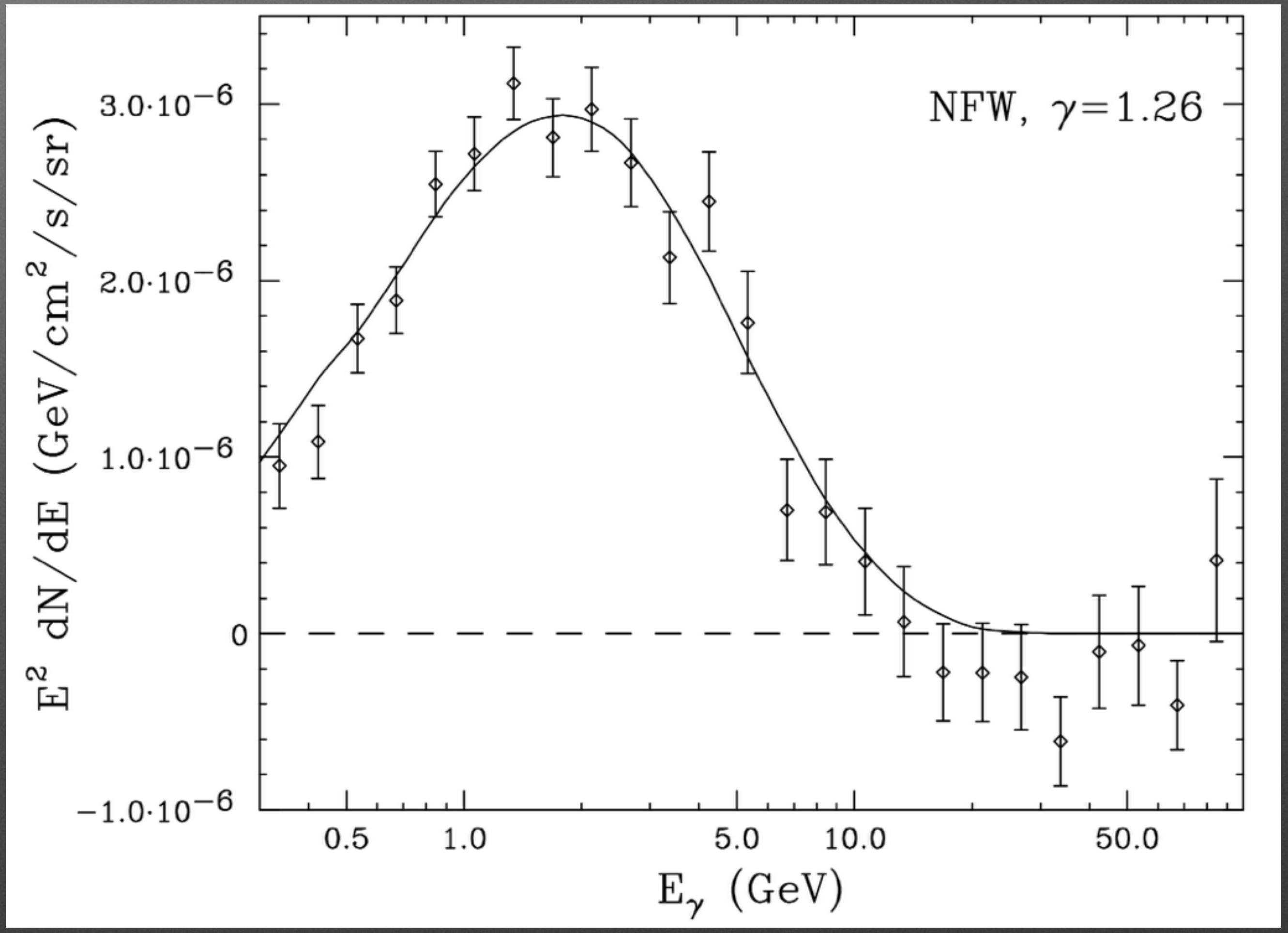
Galprop Generated astrophysical backgrounds in 20°x20° box around the GC

# Consistent Results!

## Gamma-Ray Spectrum




Galactic Center

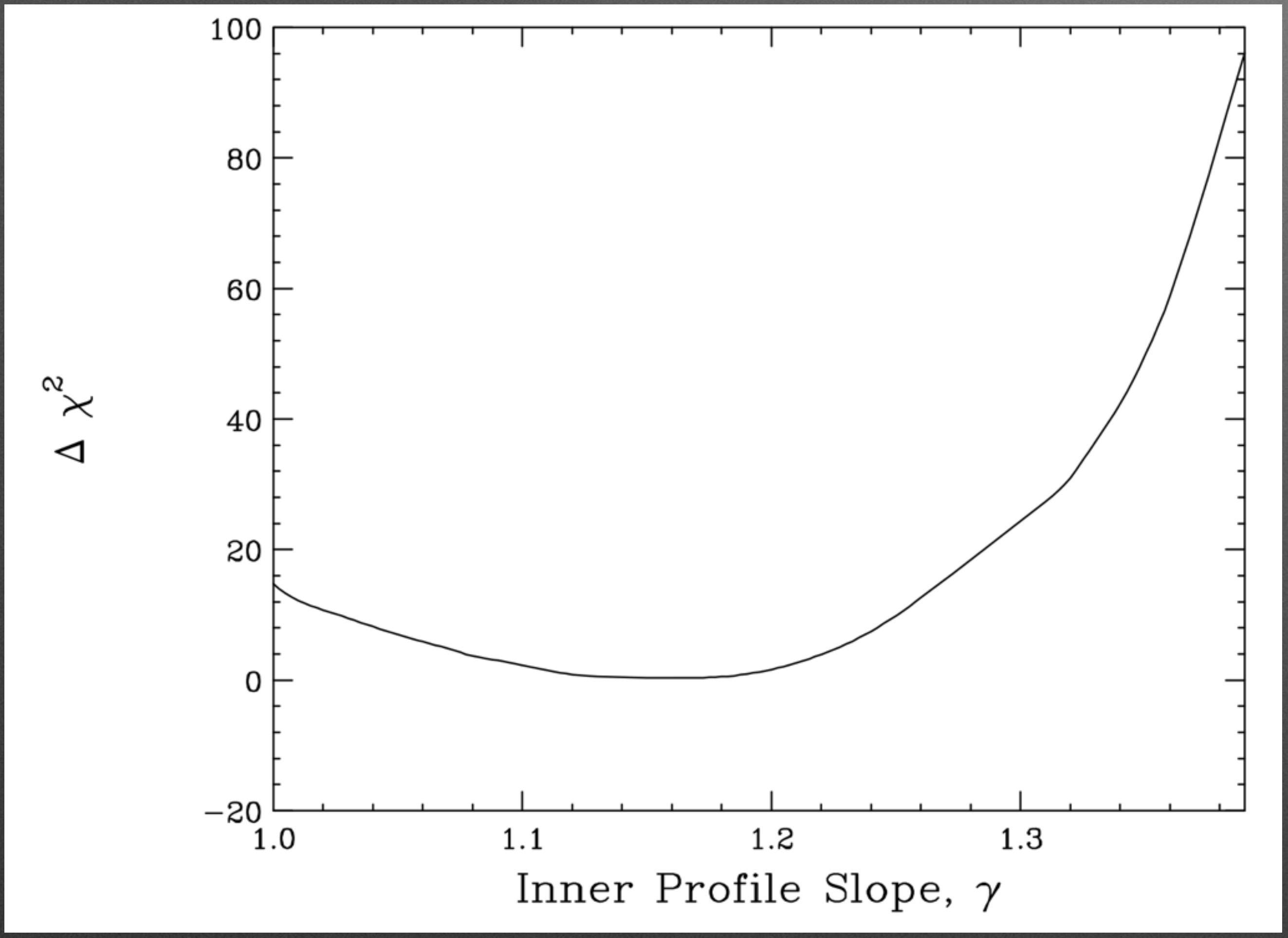



Inner Galaxy

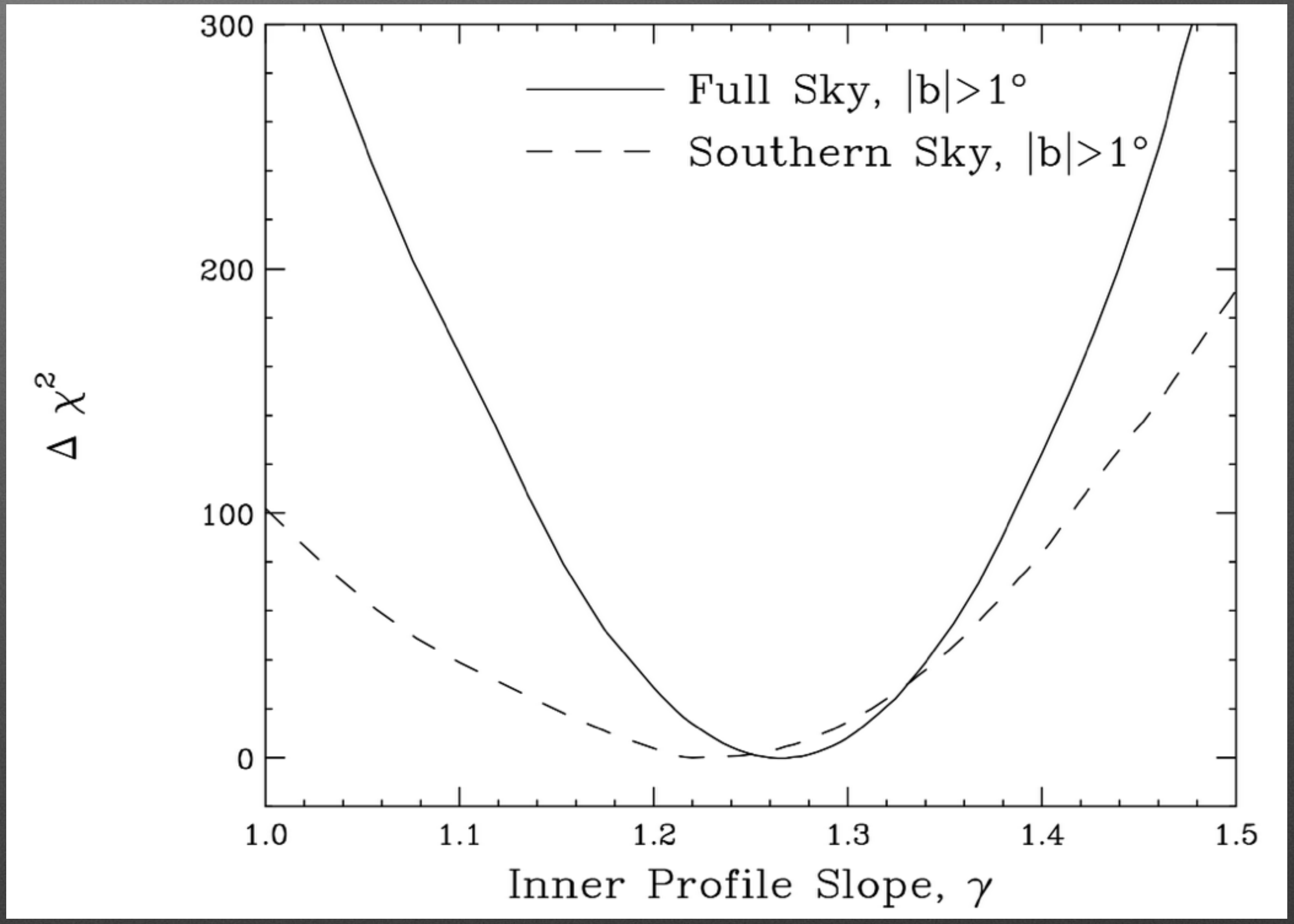
Daylan et al. (2014, 1402.6703)

# Consistent Results!

## Radial Profile




Galactic Center




Inner Galaxy

Daylan et al. (2014, 1402.6703)

# 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 $r^{-2.0 \text{ to } -2.8}$

# Physically Meaningful Constraints

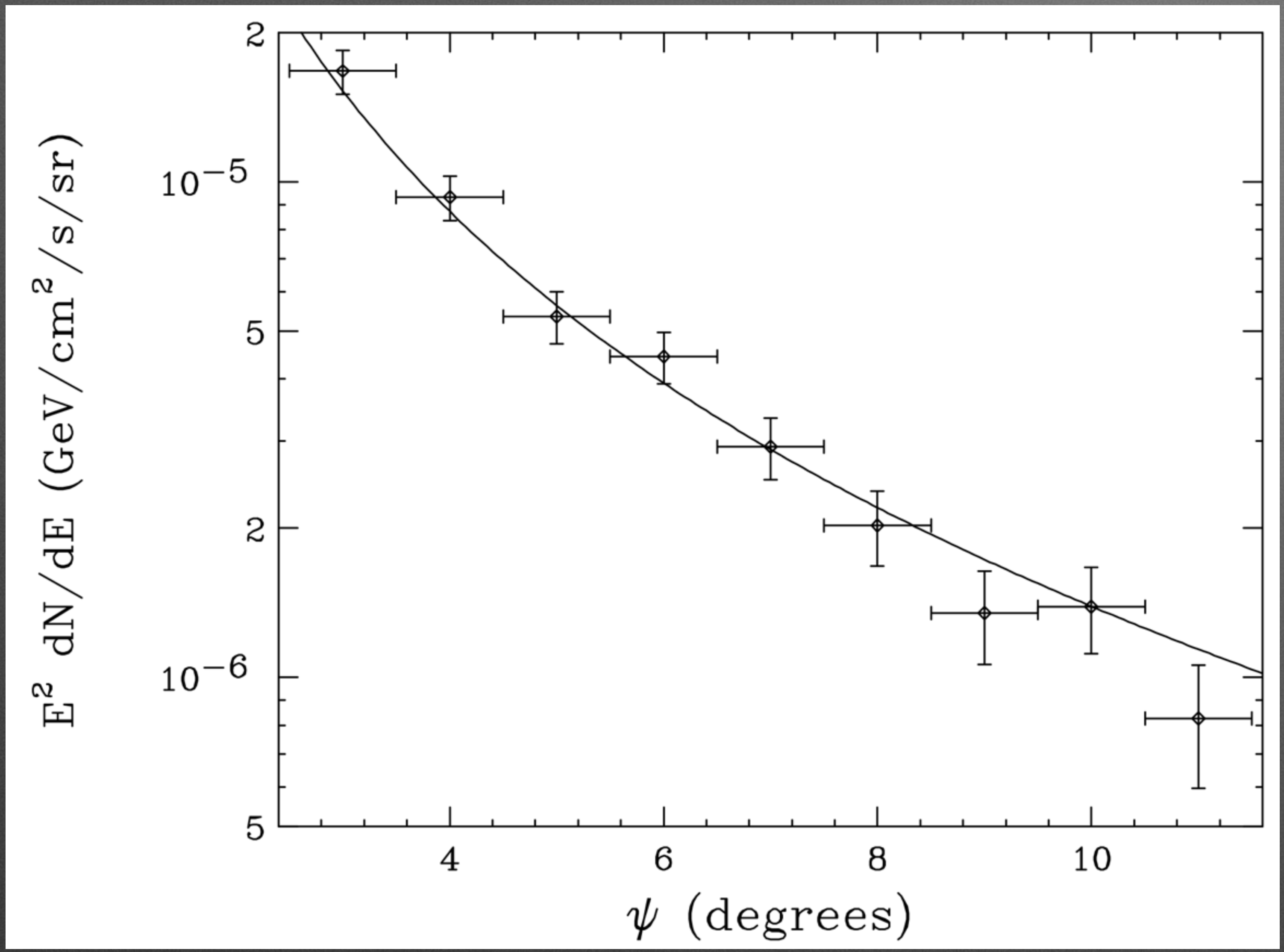
The Combination of:

- 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

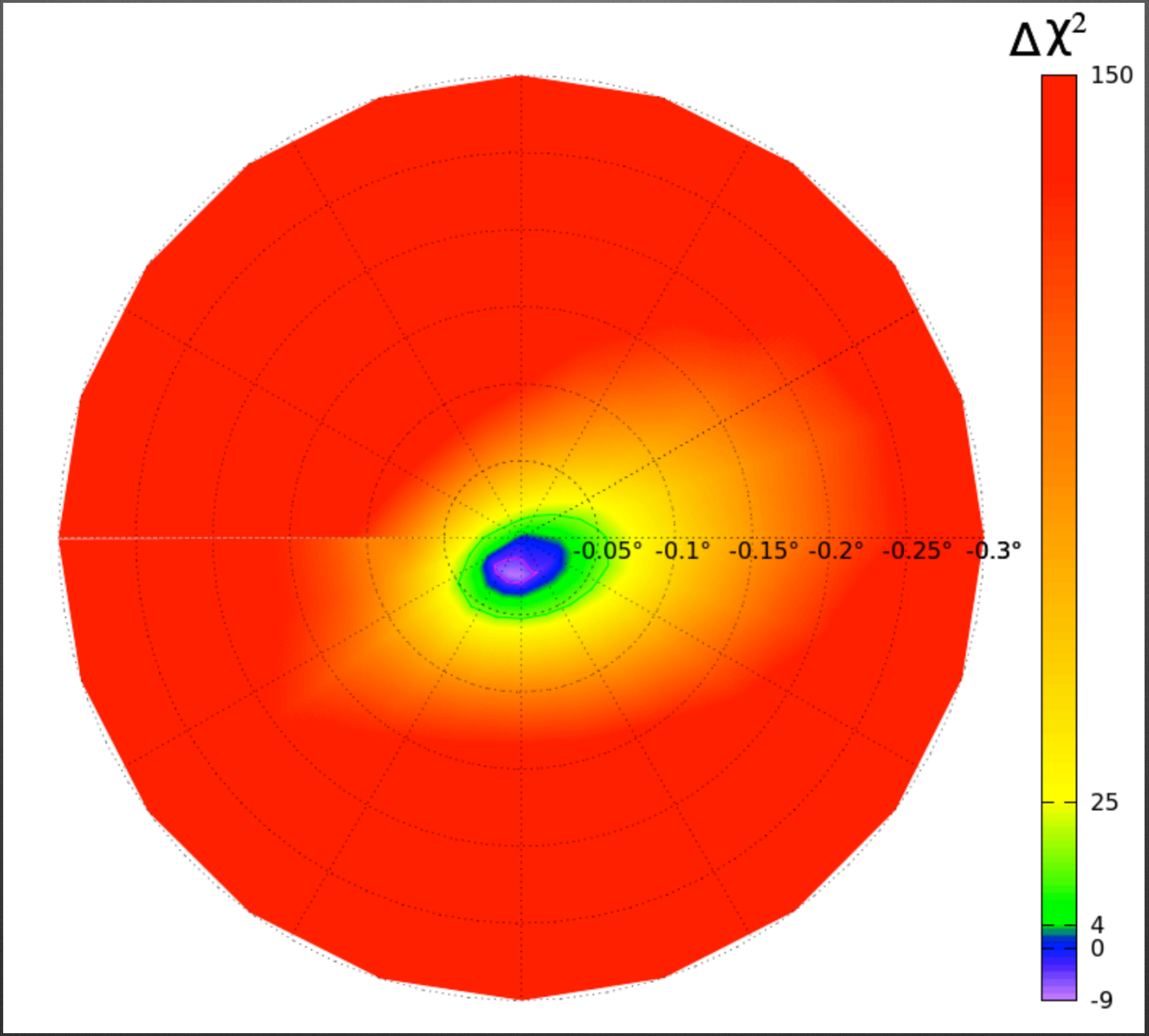



- Fix the spectra of each component in the inner galaxy analysis to its best fit value
- Allow the normalization of the dark matter component to float independently in each galactocentric bin

- 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

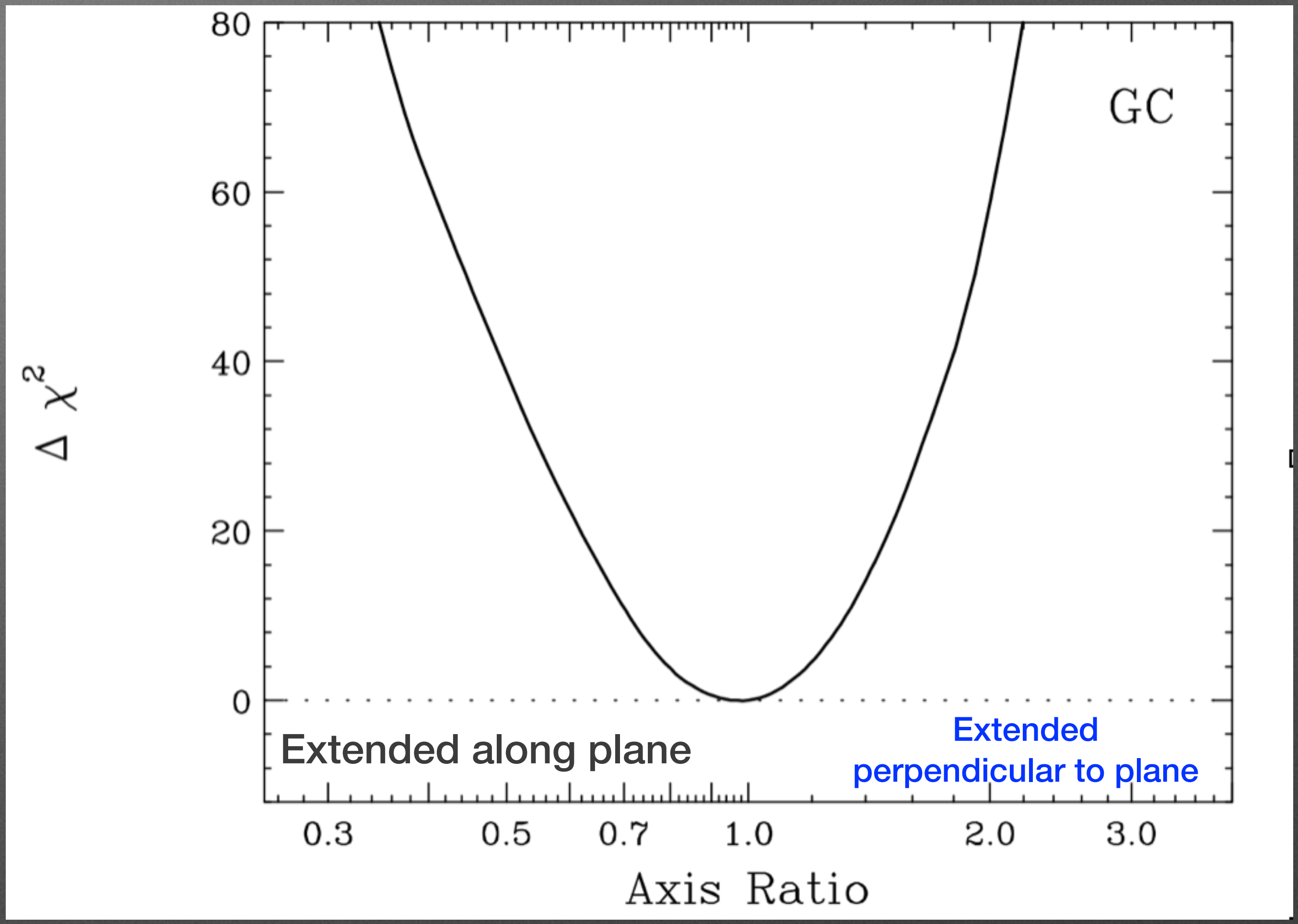



Daylan et al. (2014, 1402.6703)

# 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?




Galactic Center

- 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

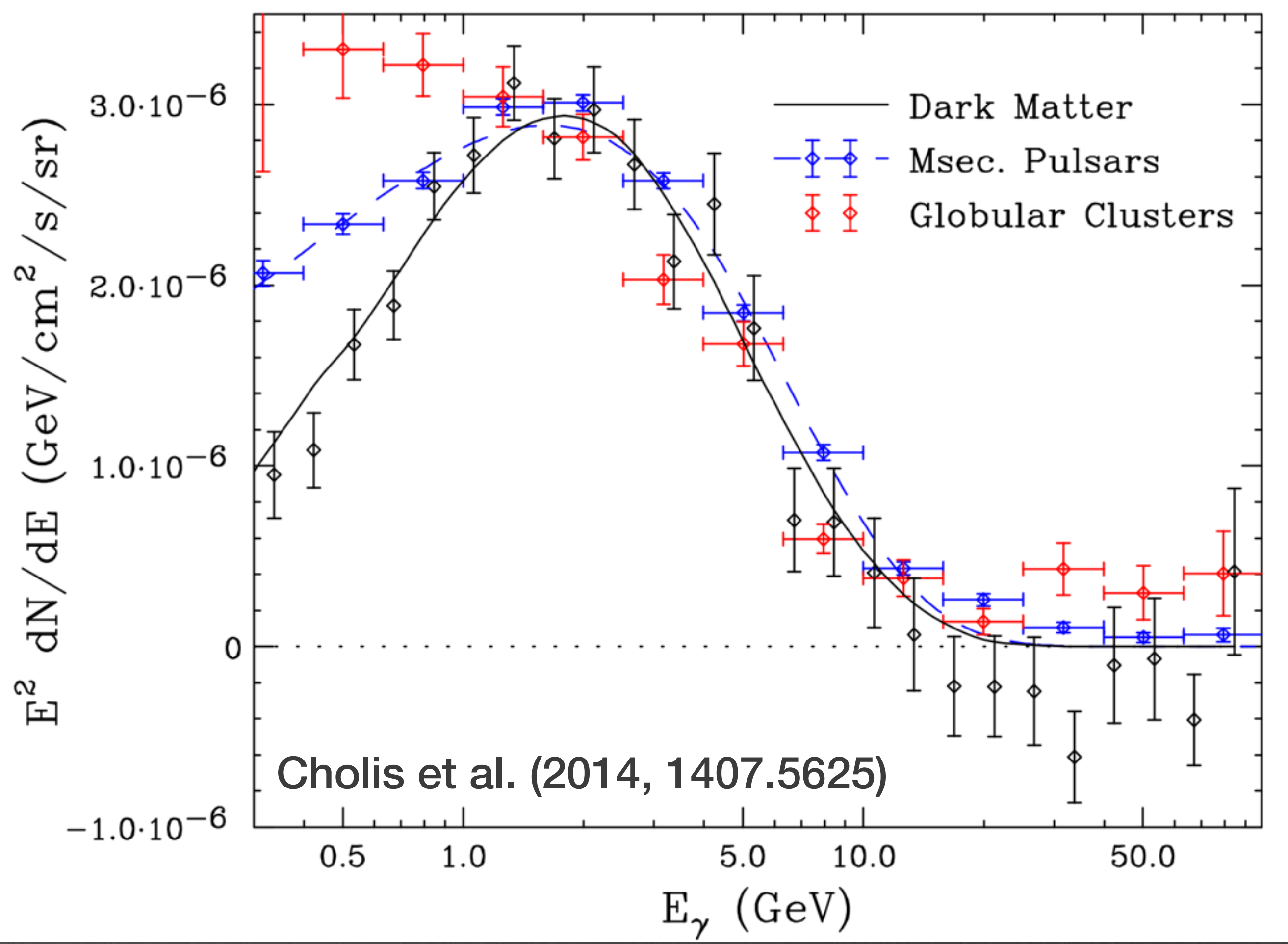
Three Primary Classes of Models for the Gamma-Ray Excess:

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

Daylan et al. (2014, 1402.6703)

# Why: Millisecond Pulsars

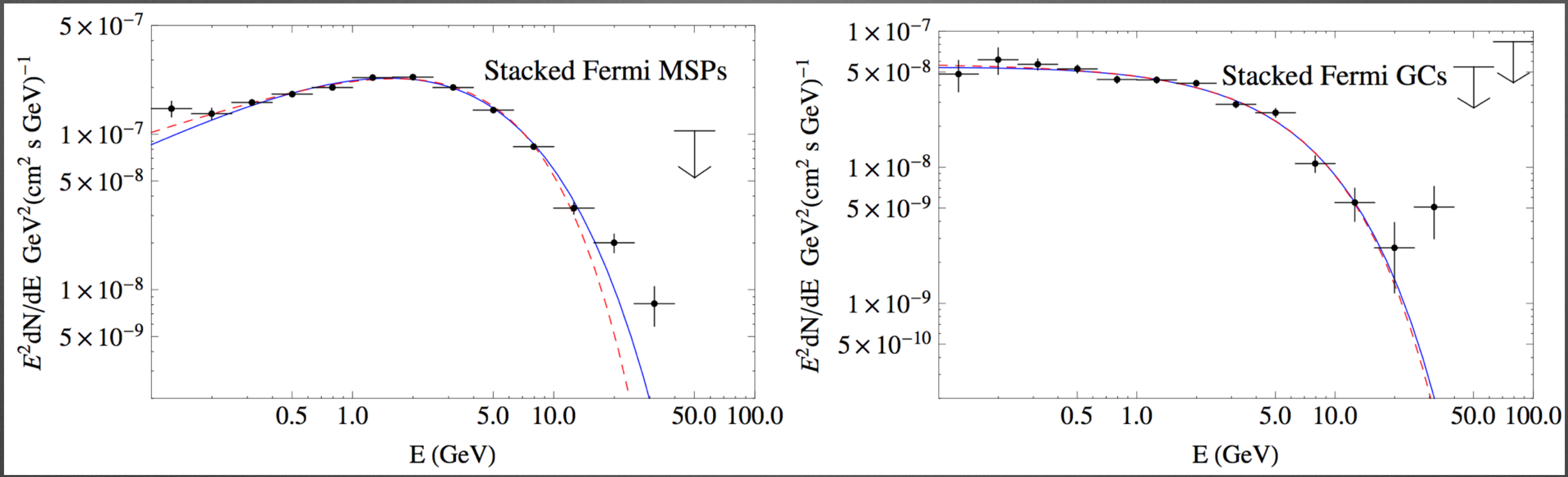
- To first order, the peak of the MSP energy spectrum matches the peak of the observed excess




- 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)

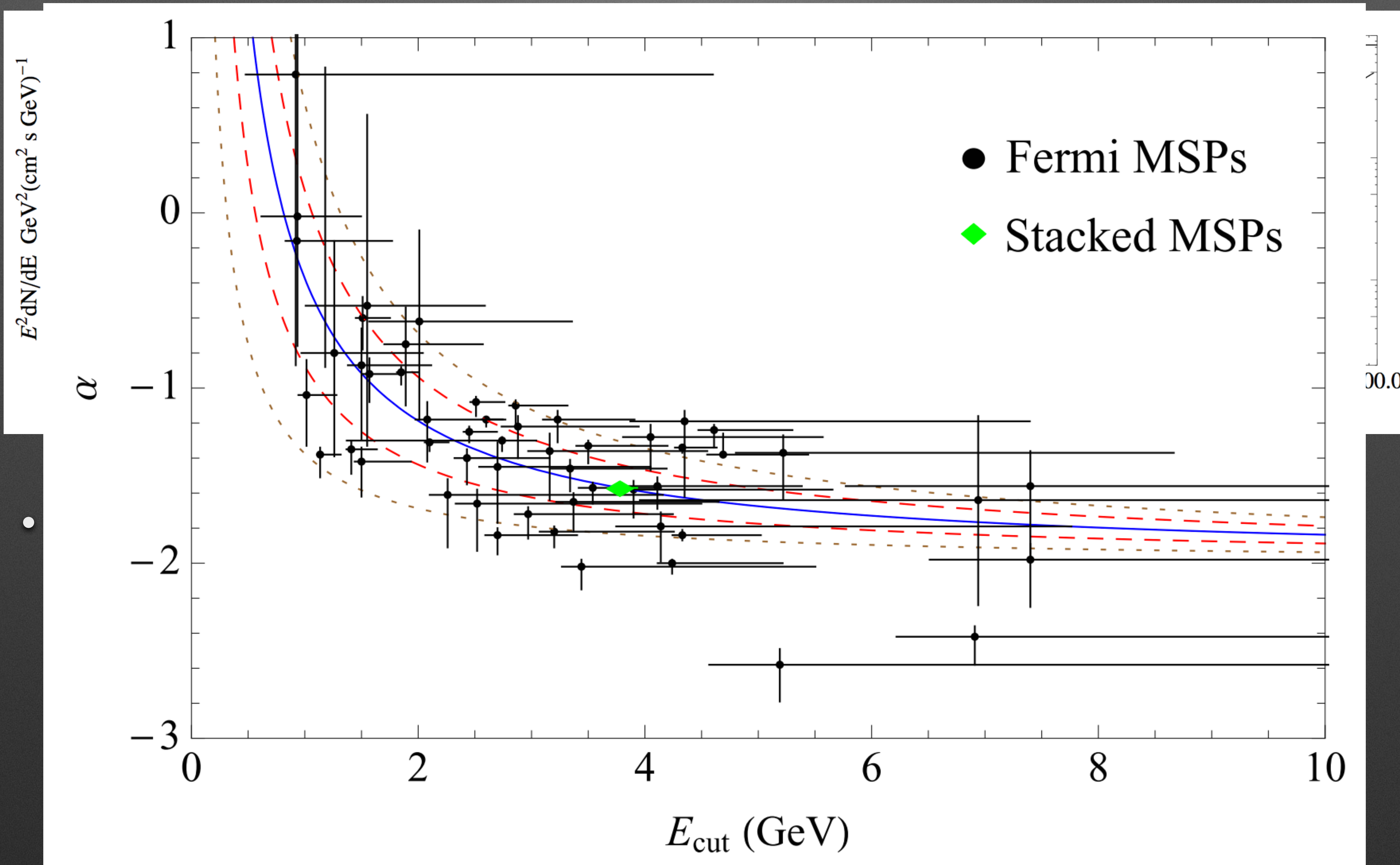
# Millisecond Pulsars




- 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)

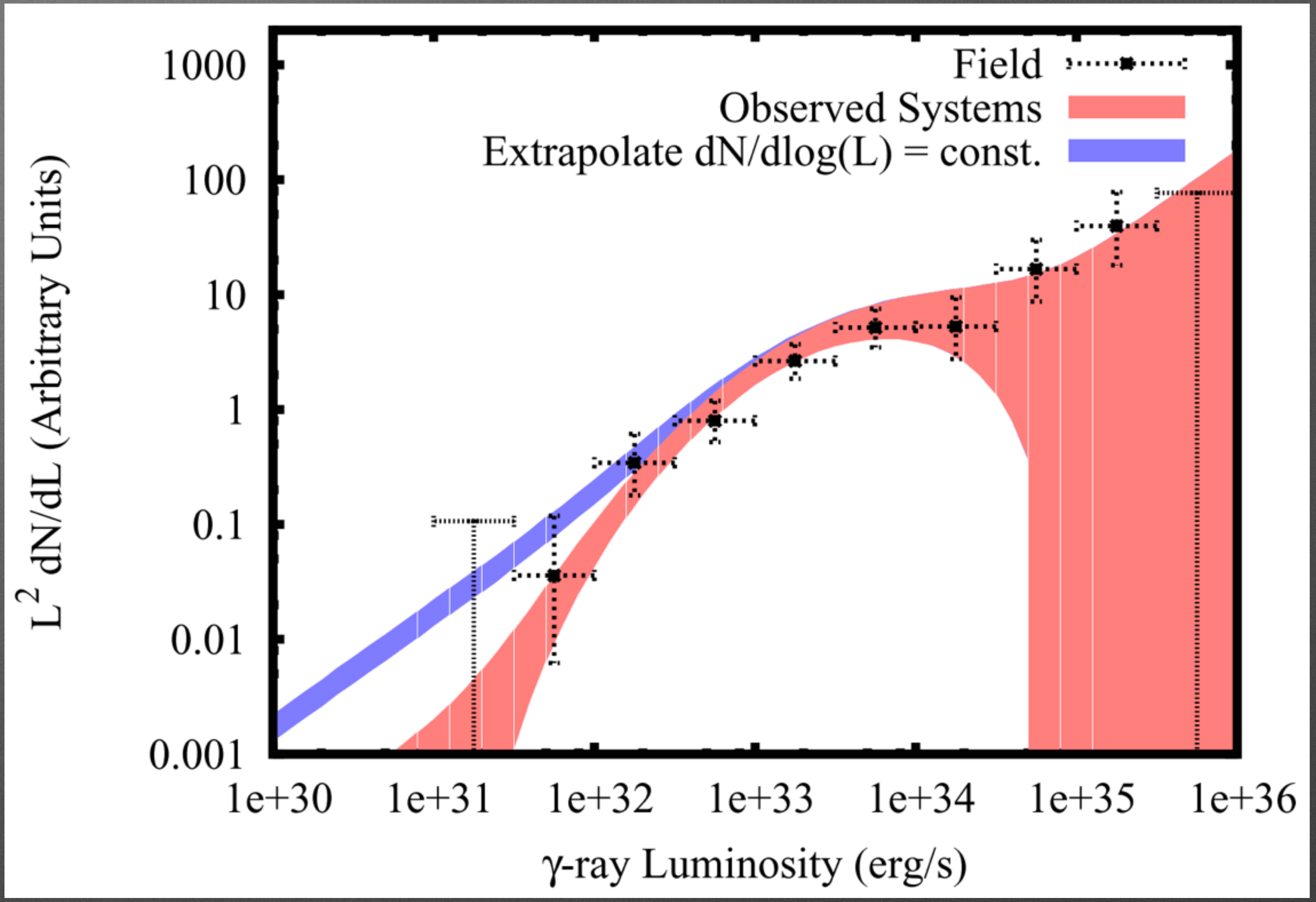
# Millisecond Pulsars




Cholis et al. (2014, 1407.5583)
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

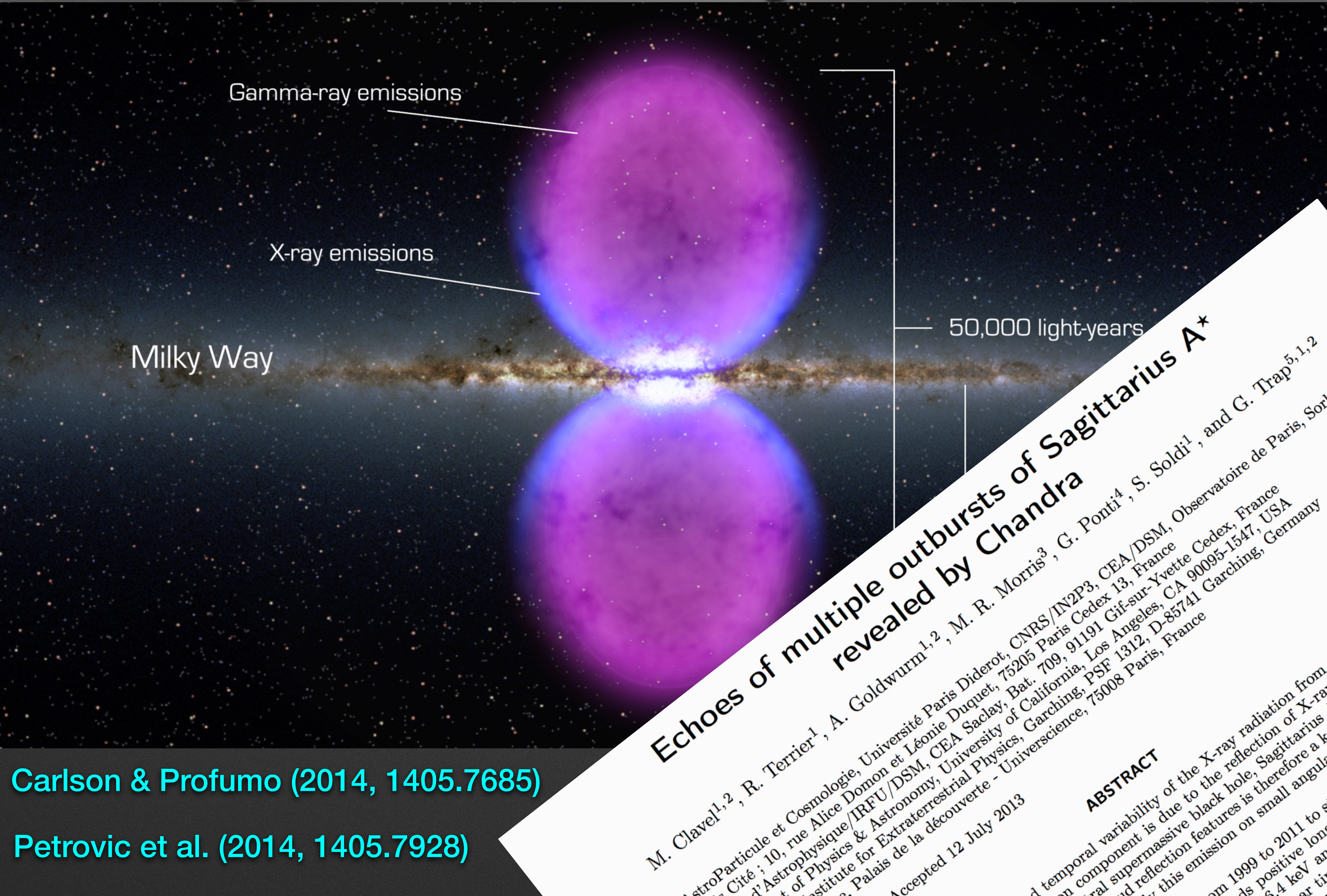
- X-Ray observations of Globular Clusters indicate the existence of 5 bright ($L_x > 10^{36}$ erg/s) LMXBs in globular clusters (12 total), and Fermi observations find a gamma-ray flux of $6.1 \times 10^{35}$ erg $s^{-1}$.

- The luminosity of the galactic center ($1.3 \times 10^{37}$ 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


M. Clavel[1,2], R. Terrier[1], A. Goldwurm[1,2], M. R. Morris[3], G. Ponti[4], S. Soldi[1], and G. Trap[5,1,2]

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…Accepted 12 July 2013


ABSTRACT


…d temporal variability of the X-ray radiation from…
…n component is due to the reflection of X-ra…
…ral supermassive black hole, Sagittarius…
…d reflection features is therefore a k…
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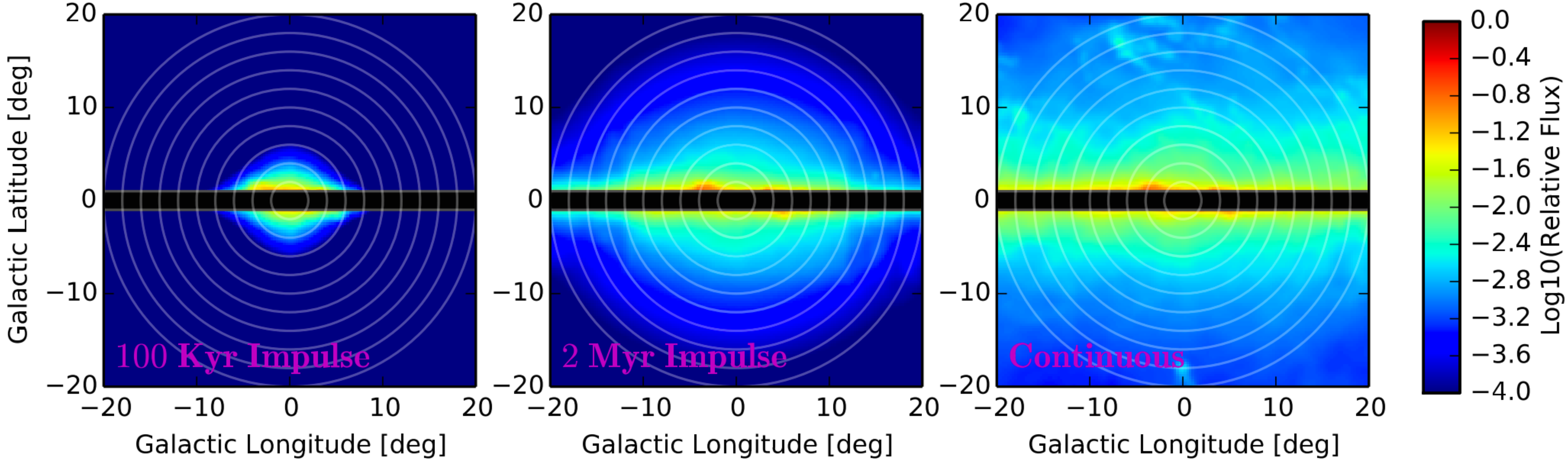
Carlson & Profumo (2014, 1405.7685)

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)

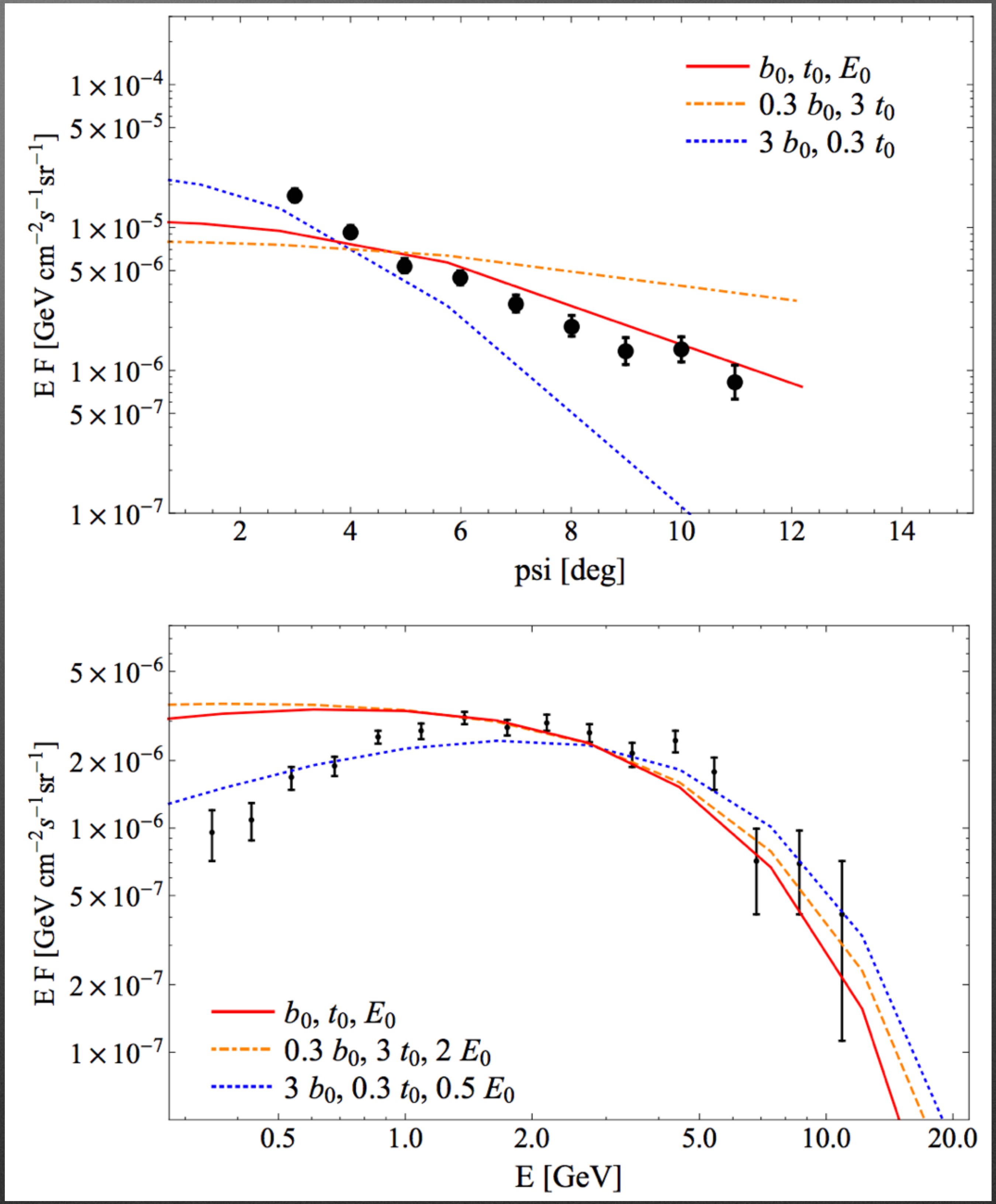
Best Fitting NFW Template TS=315 (5 d.o.f)

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

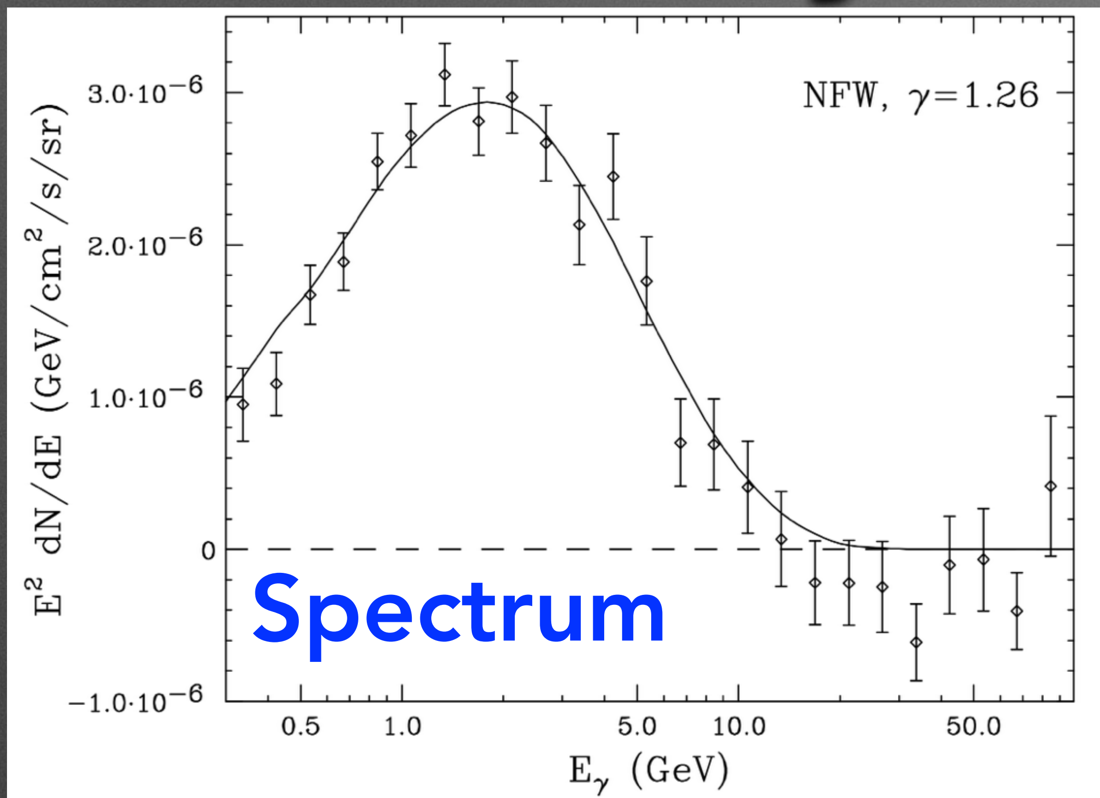
# Why Not: Cosmic-Ray Outbursts

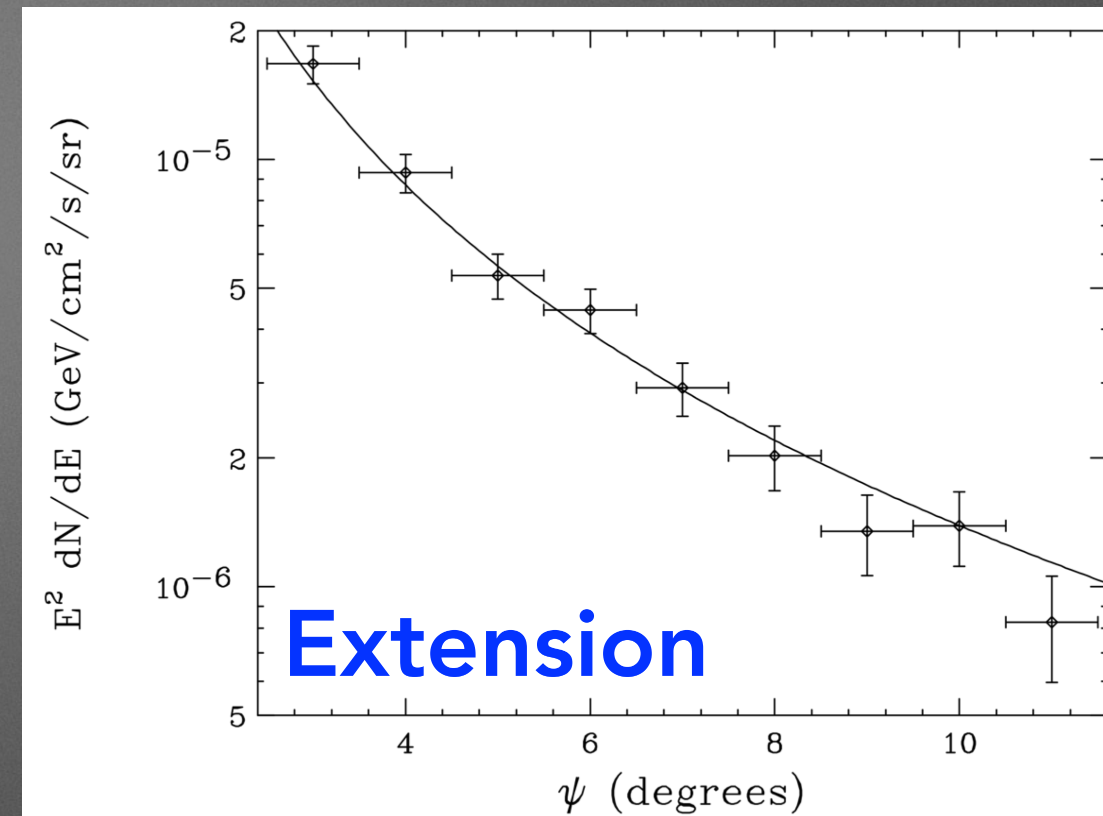
Leptonic models can produce emission by up scattering the ISRF, in addition to producing bremsstrahlung emission in gas

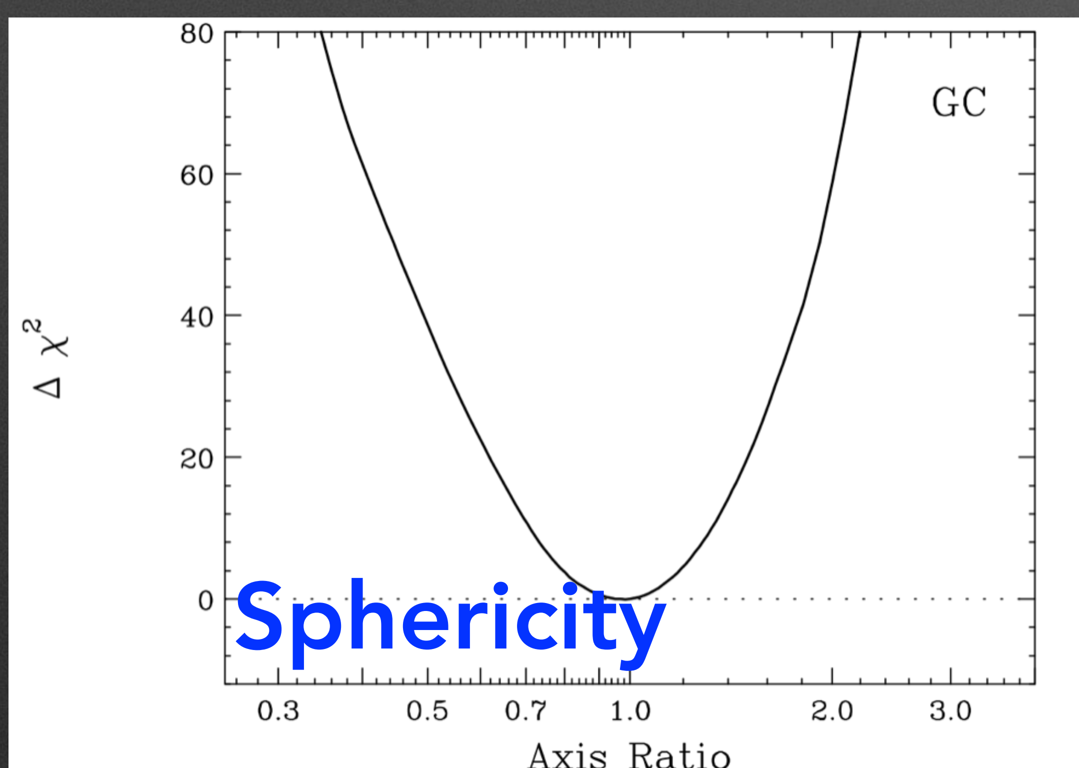
Difficult to explain the spectral consistency of the excess in light of the fact that electrons cool effectively in the GC region

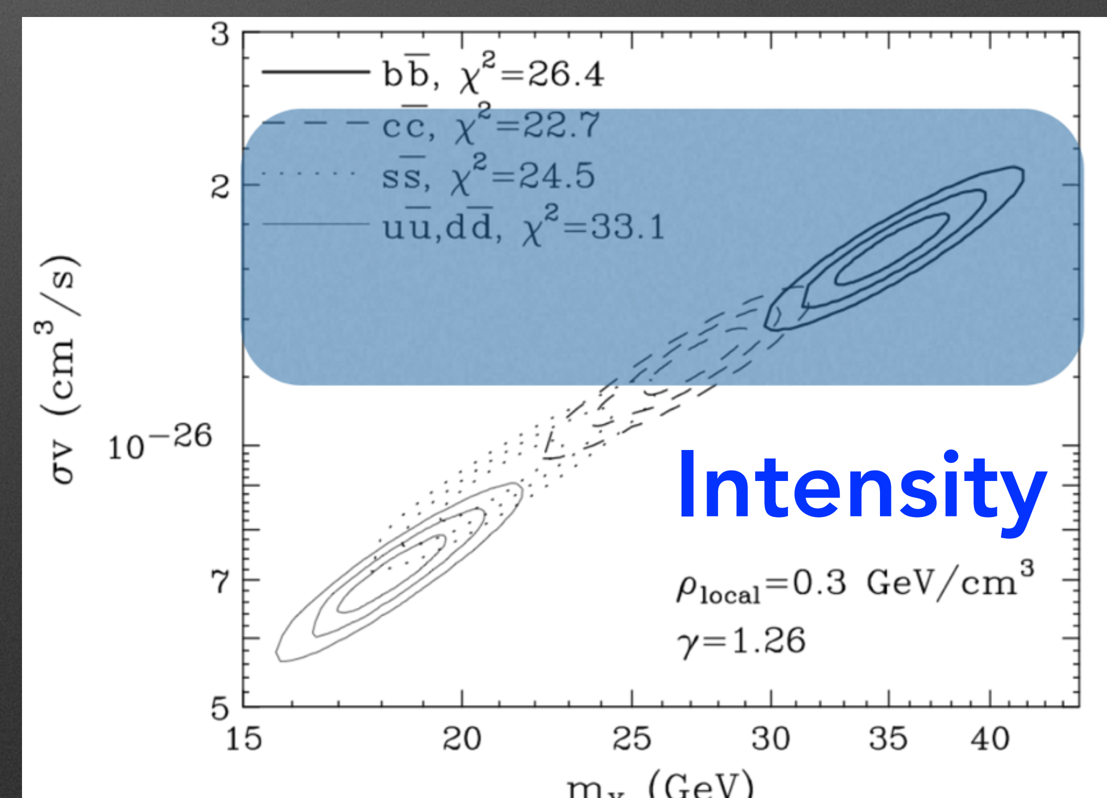


# Why: Dark Matter




Daylan et al. (2014, 1402.6703)

see talk by Dan Hooper

# Conclusions

- Multiple groups have observed the gamma-ray excess in the galactic center region using different techniques and obtaining *extremely* similar results
    - see talks by: Calore, Kwa, Portillo, Weniger)
- 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.
    - see interpretation talks: Hooper, Zaharijas
- Stay tuned!