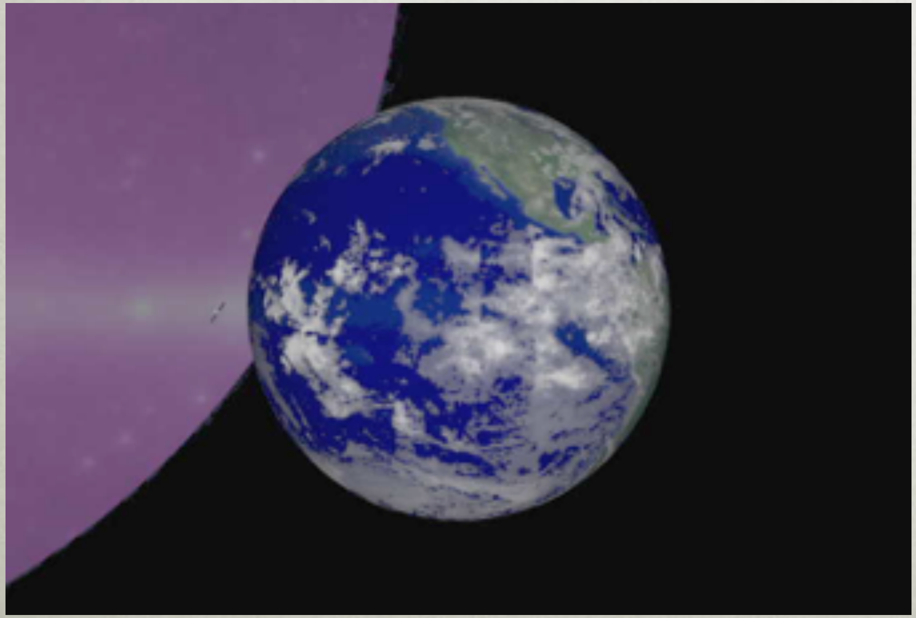
# Searching for Dark Matter in the Galactic Center with Gamma Rays

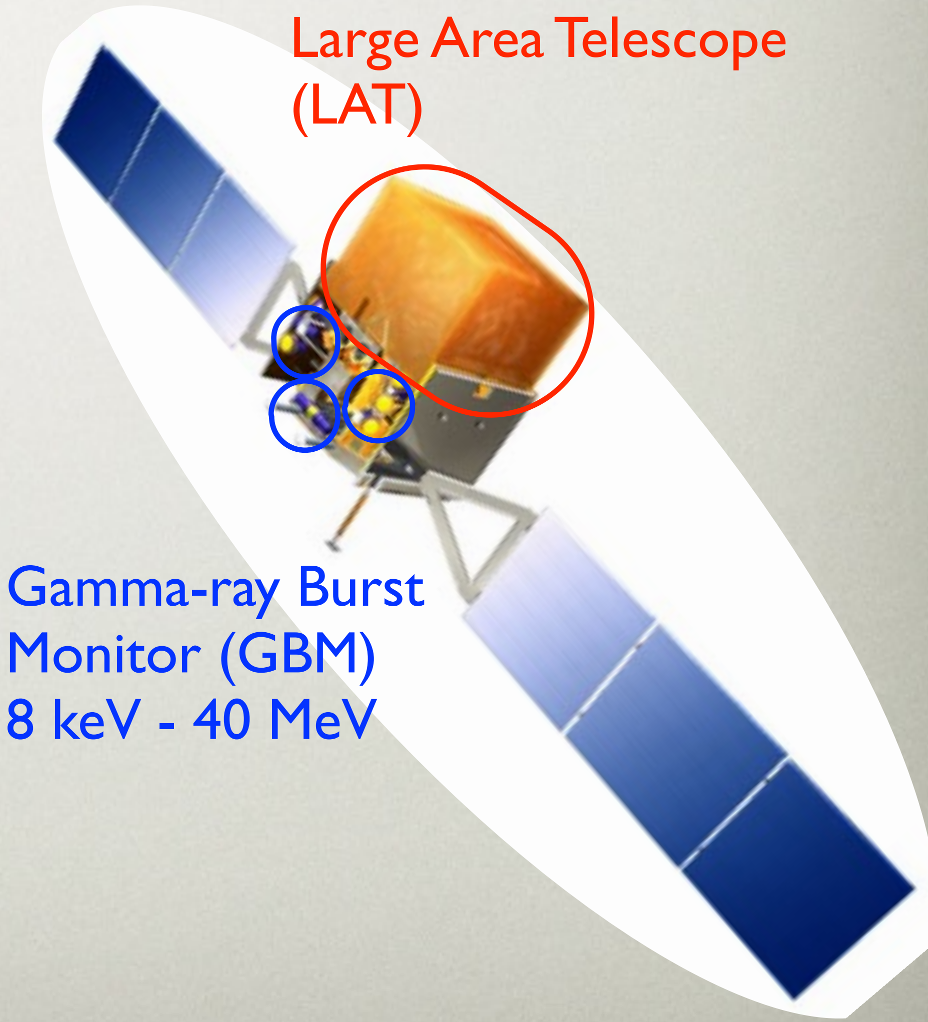
Simona Murgia
University of California, Irvine

LLNL Lattice BSM Workshop
24 April 2015

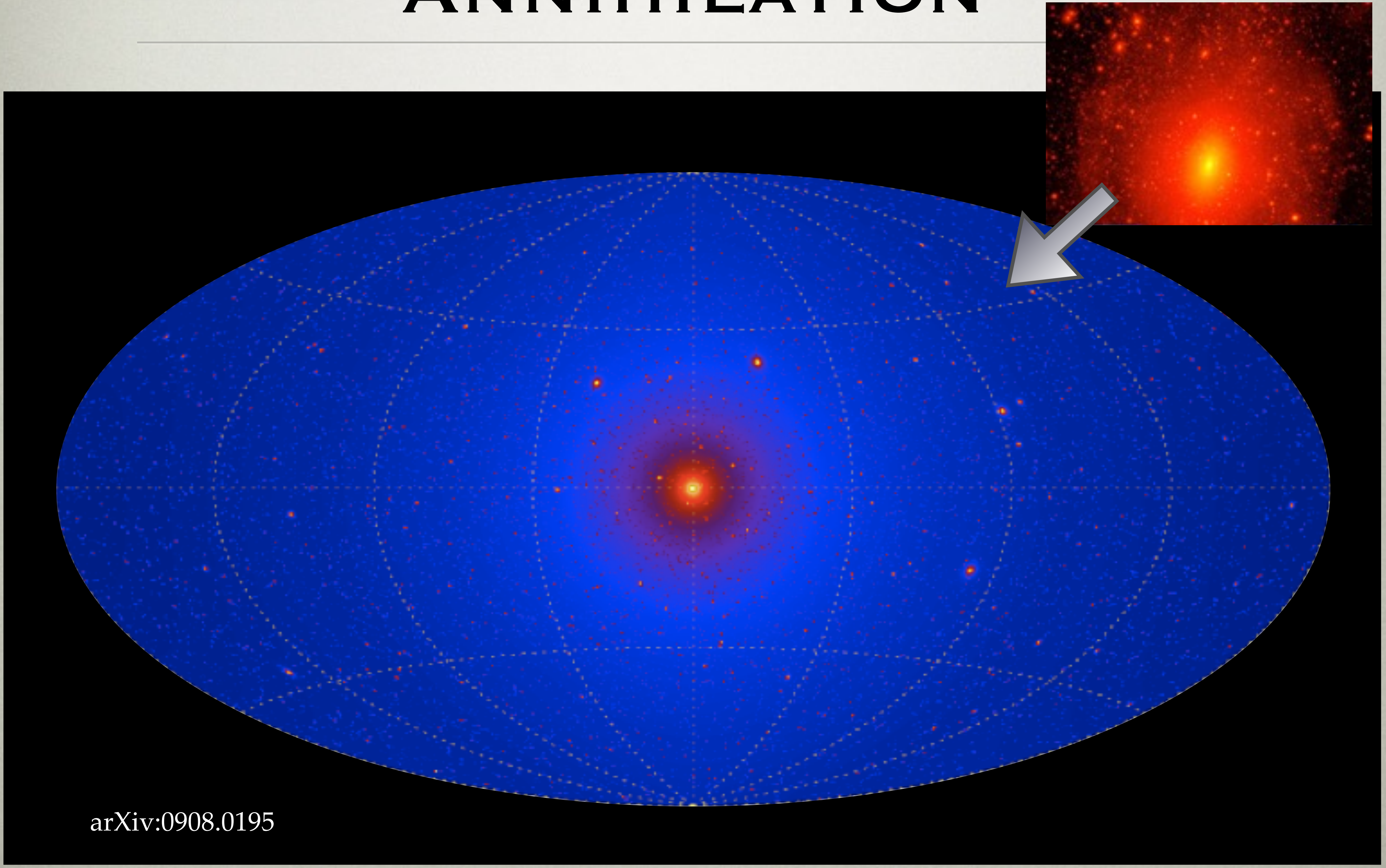
# Fermi Mission
# The Large Area telescope

- The Fermi Large Area Telescope observes the gamma-ray sky in the 20 MeV to >300 GeV energy range with unprecedented sensitivity
- Orbit: 565 km, 25.6° inclination, circular. The LAT observes the entire sky every ~3 hrs (2 orbits)

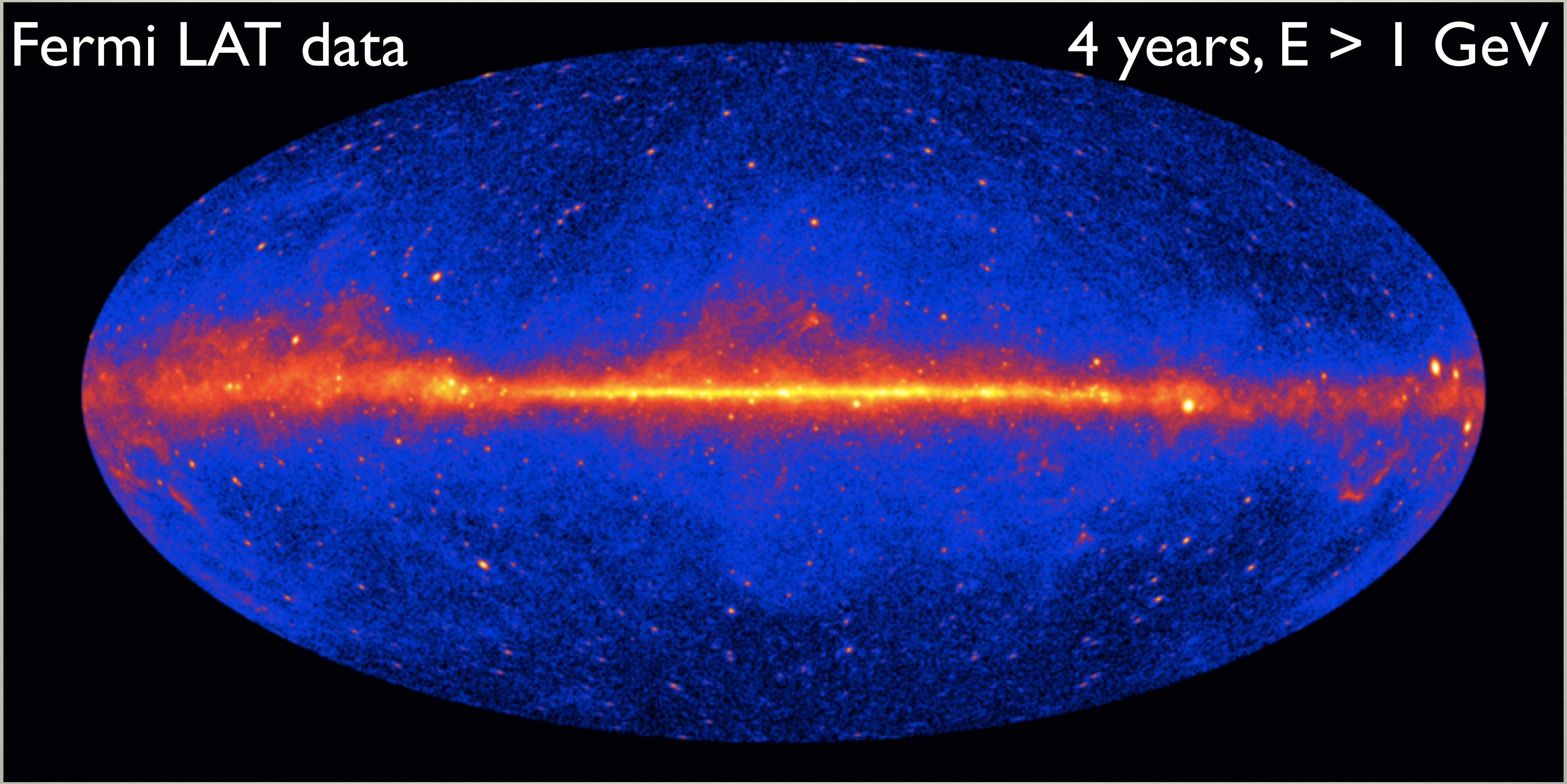




# Gamma rays from DM Annihilation

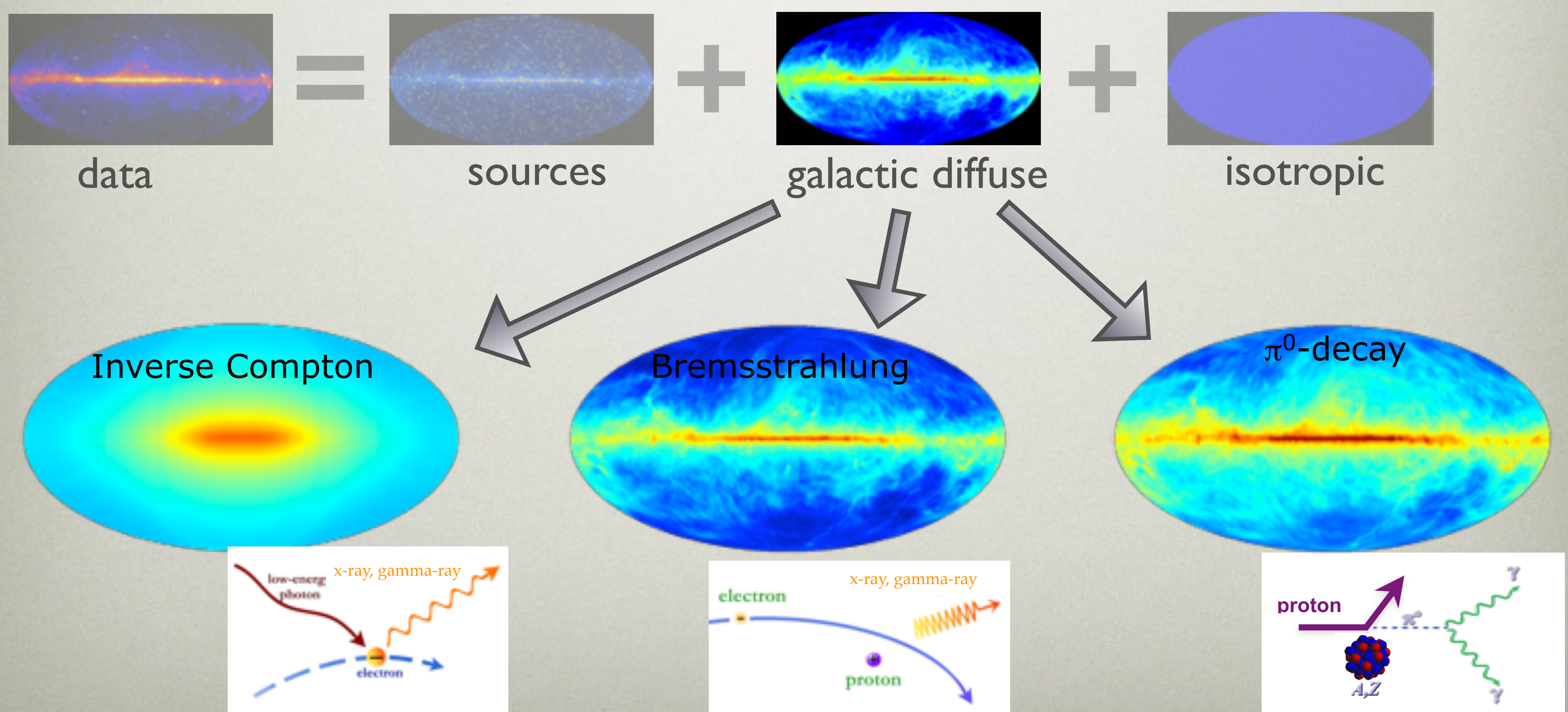


# The Fermi Sky



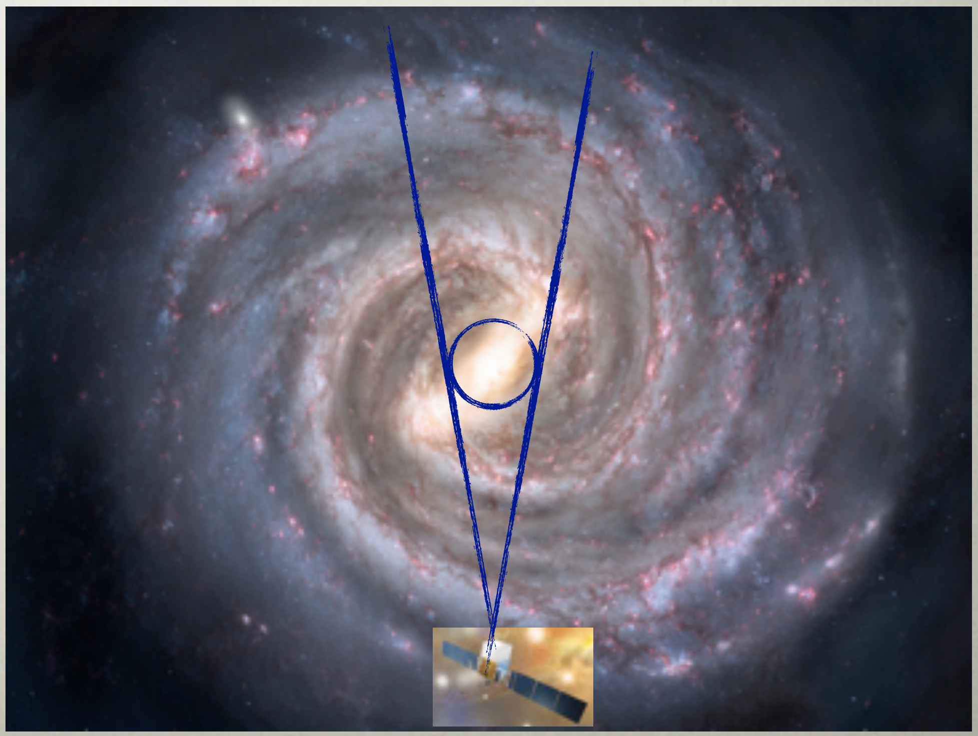
# Galactic Gamma-Ray Interstellar Emission

- The diffuse gamma-ray emission from the Milky Way is produced by cosmic rays interacting with the interstellar gas and radiation field and carries important information on the acceleration, distribution, and propagation of cosmic rays.



# Galactic Center Region

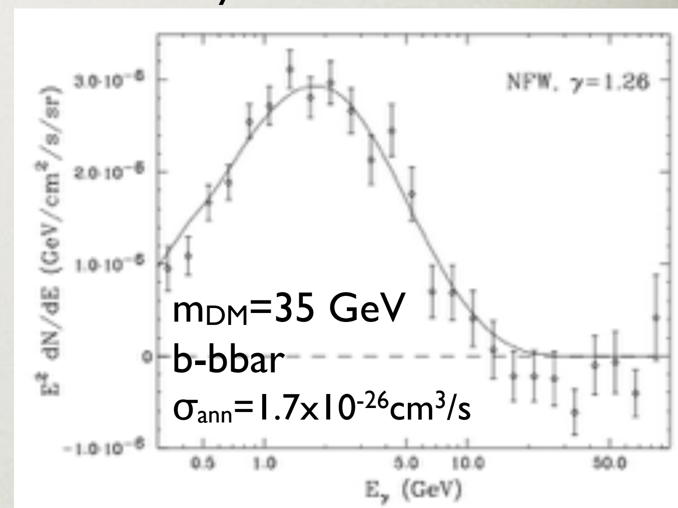
- Complex region: CR intensities, density of radiation fields and gas are highest; large uncertainties modeling the gamma-ray interstellar emission,  significant foreground/ background contribution with long integration path over the entire Galactic disc
- Large density of gamma-ray sources: many energetic sources near to or in the line of sight of the GC, difficult to disentangle from interstellar emission
- A signal of new physics (dark matter annihilation/ decay) is also predicted to be largest here
- An excess in the Fermi LAT GC data was first cautiously claimed by Goodenough and Hooper (arXiv:0910.2998) consistent with a 25-30 GeV WIMP annihilating into b-bbar with an annihilation cross-section a few times larger than expected from an s-wave thermal relic ($9\times10^{-26}cm^3/s$)



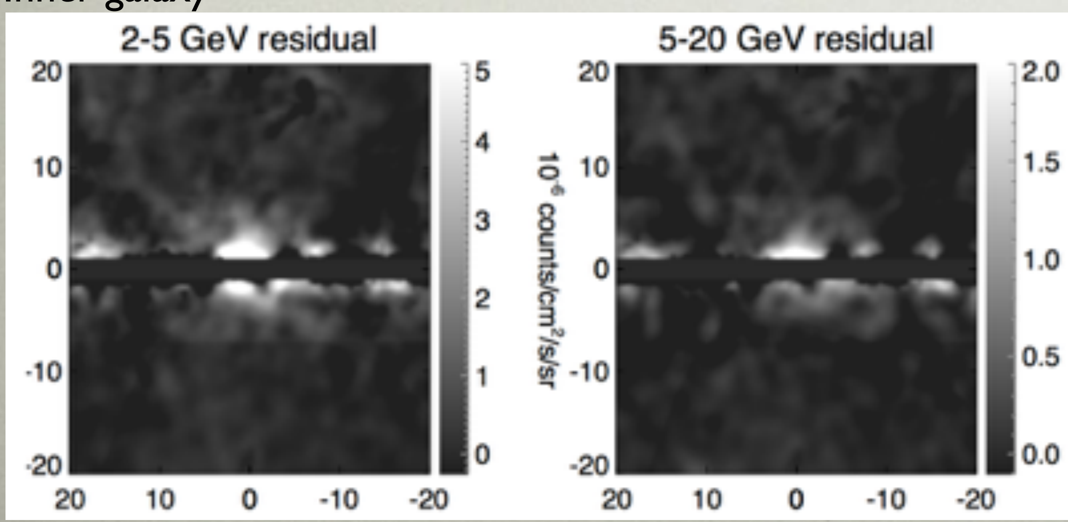
# Galactic Center Dark Matter Searches

- A re-analysis of the Fermi LAT data by Daylan et al (with more statistics, over 5 years, and improved event selection aimed at reducing background leakage in the search region) confirms the presence of an excess on top of the adopted background models
- The addition of the DM component improves the data-model agreement very significantly
- The signal can be modeled by DM annihilating into b-bbar with a mass of 31-40 GeV and $\sigma_{ann}=(1.4\text{-}2)\times10^{-26}\,cm^3/s$

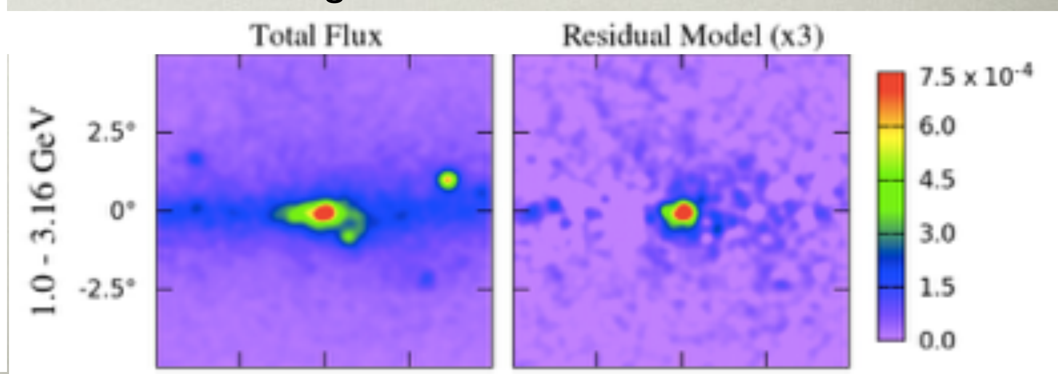
Daylan et al, arXiv:1402.6703




Inner galaxy



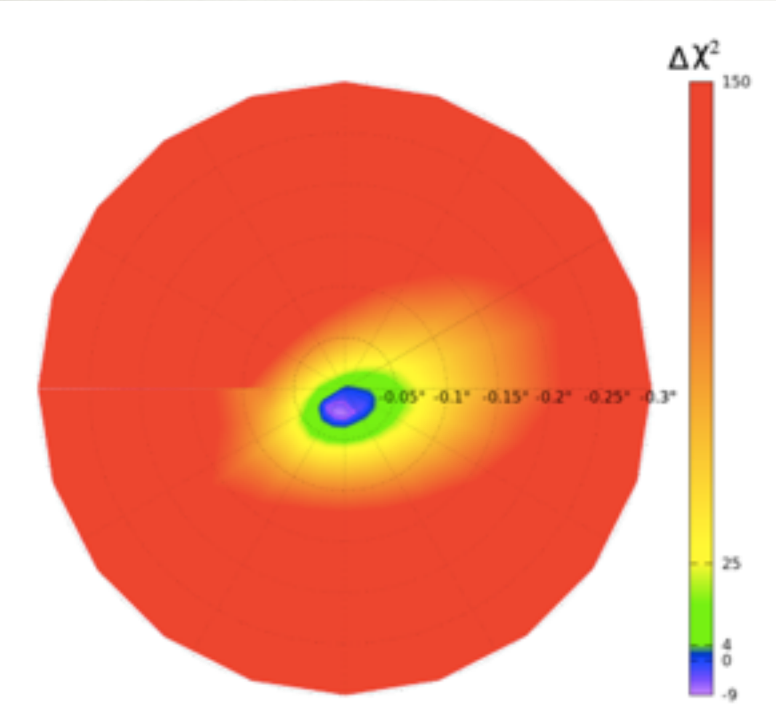

Galactic center region

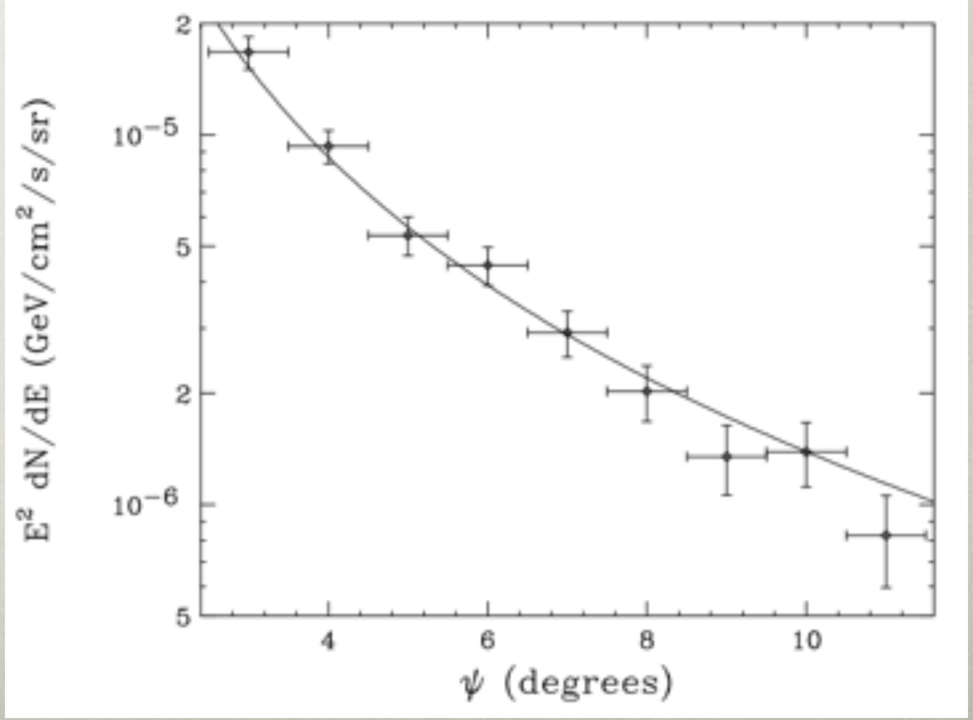


# Galactic Center Dark Matter Searches

- The morphology of the excess in Daylan et al is consistent with an NFW profile with slope γ=1.1-1.3 centered within 0.05° of Sgr A*. Deviations from the spherically symmetric morphology are disfavored
- Independent fits in annuli about the direction of the GC confirm the excess up to at least 10° from the Galactic plane following a steep NFW profile

Daylan et al, arXiv:1402.6703

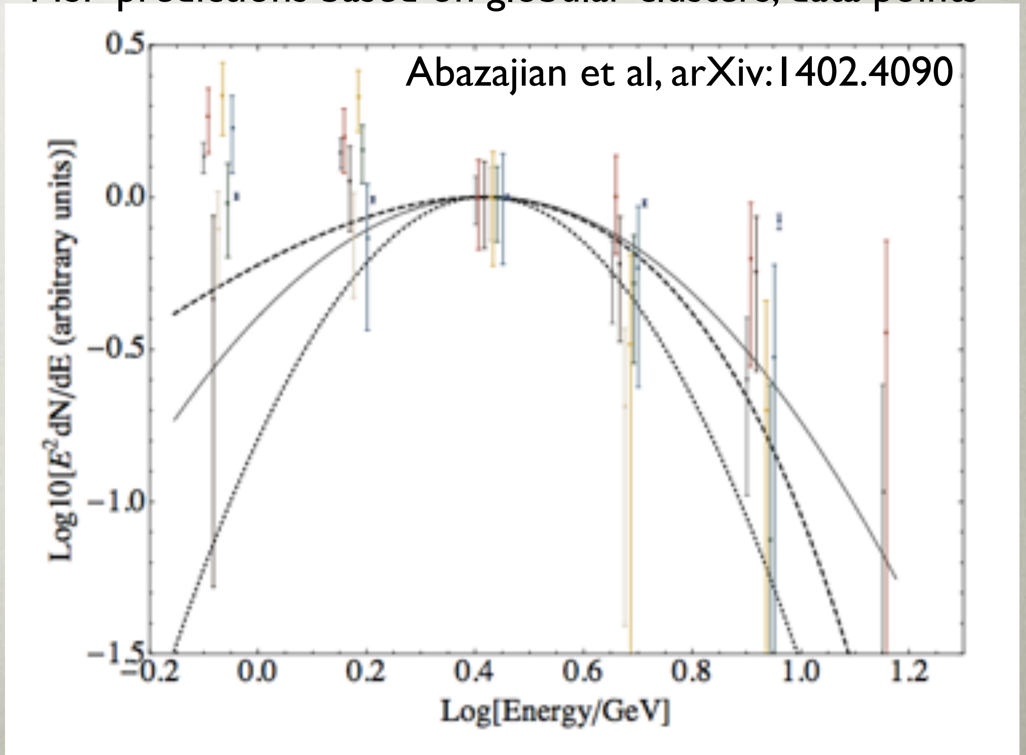


# Galactic Center Dark Matter Searches

- A similar excess has been found by the work of Abazajian et al, focused on a 7°x7° region centered at the GC. In addition to DM, an unresolved pulsar interpretation is found plausible
- Based on globular clusters observations, observed signal is found to be consistent with 3000-5000 millisecond pulsars in a 1 kpc x 1 kpc region
- Morphology? Can MSPs extend out to 10°? Spherical symmetry?

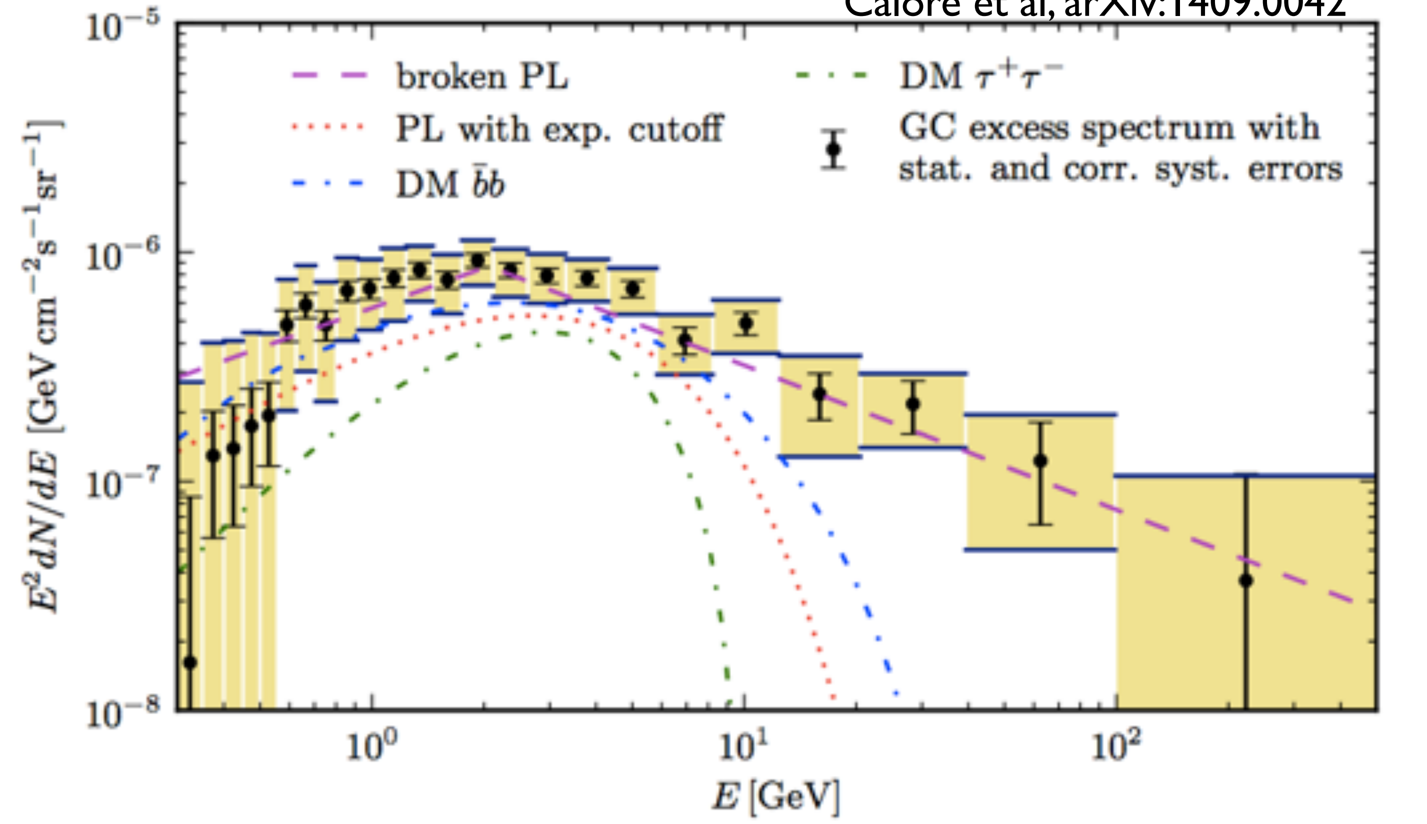
GC extended excess, lines
MSP predictions based on globular clusters, data points



# Galactic Center Dark Matter Searches

- More extensive study of the background model systematics
- Broad range of interstellar emission models
- Results compatible with dark matter annihilation into b-bbar and a mass of ~50 GeV

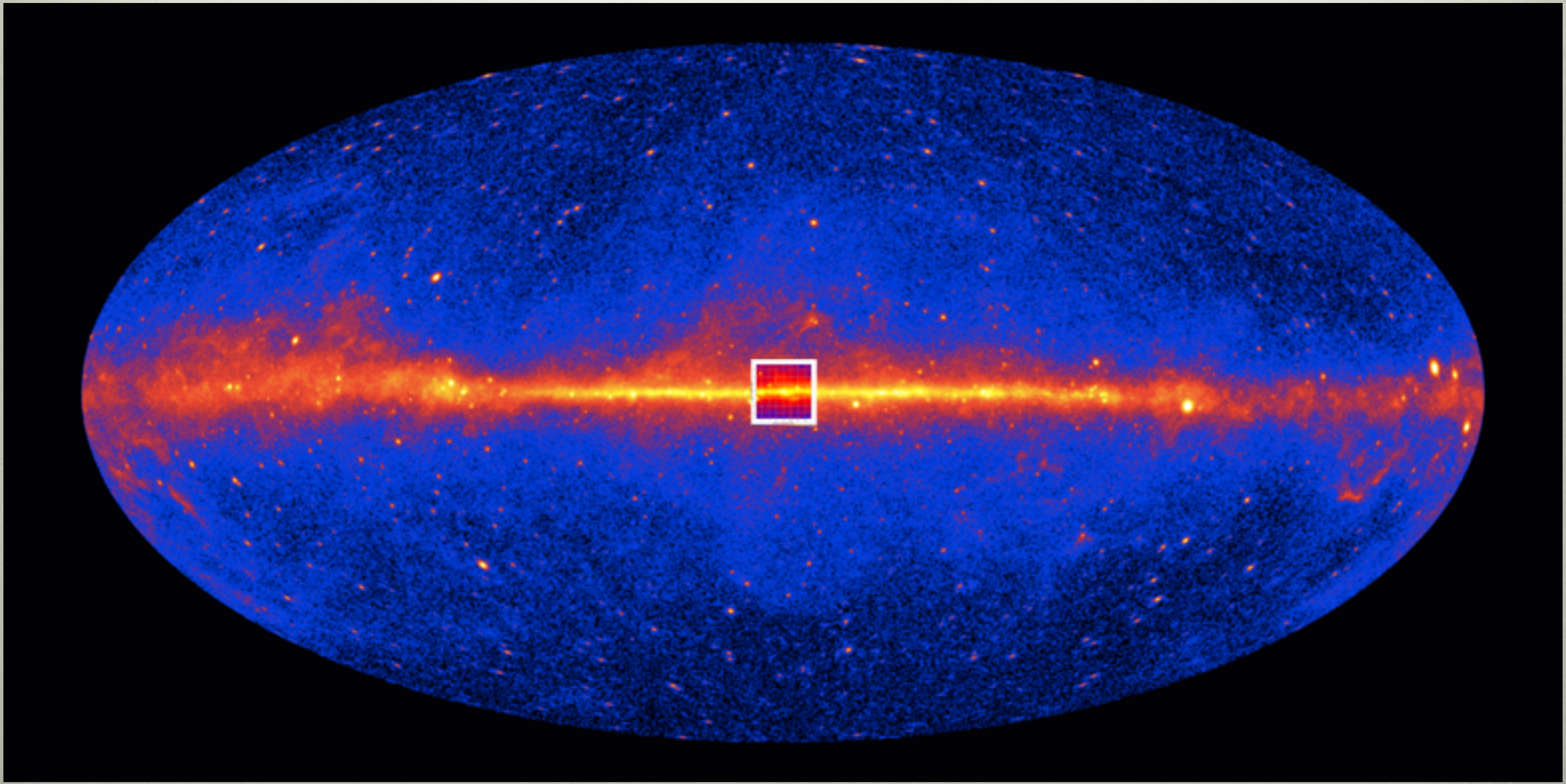
Calore et al, arXiv:1409.0042



# Galactic Center Region

Fermi LAT Collaboration

- Focus on a 15°x15° region (~ 1 kpc) around Galactic center



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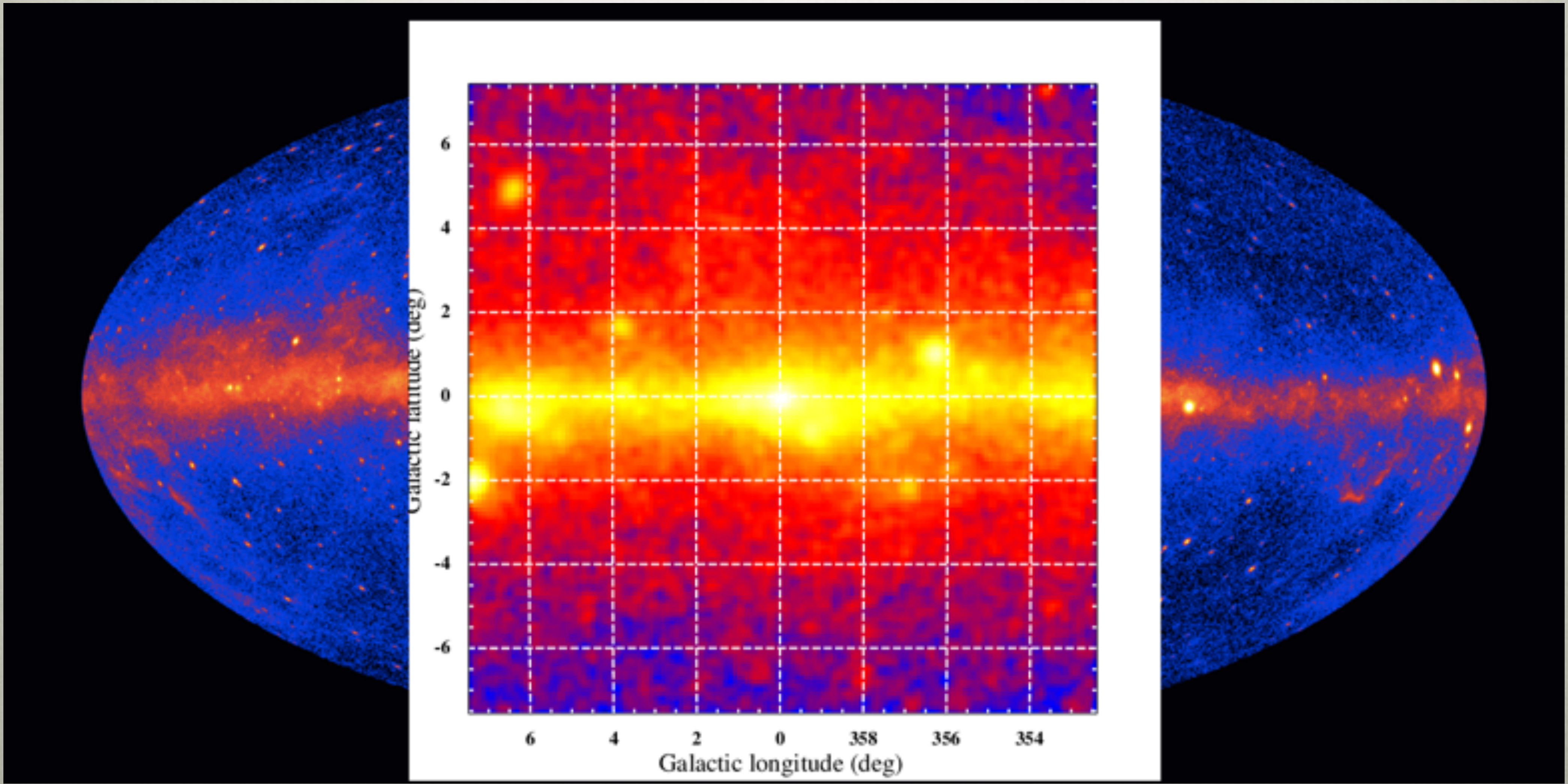
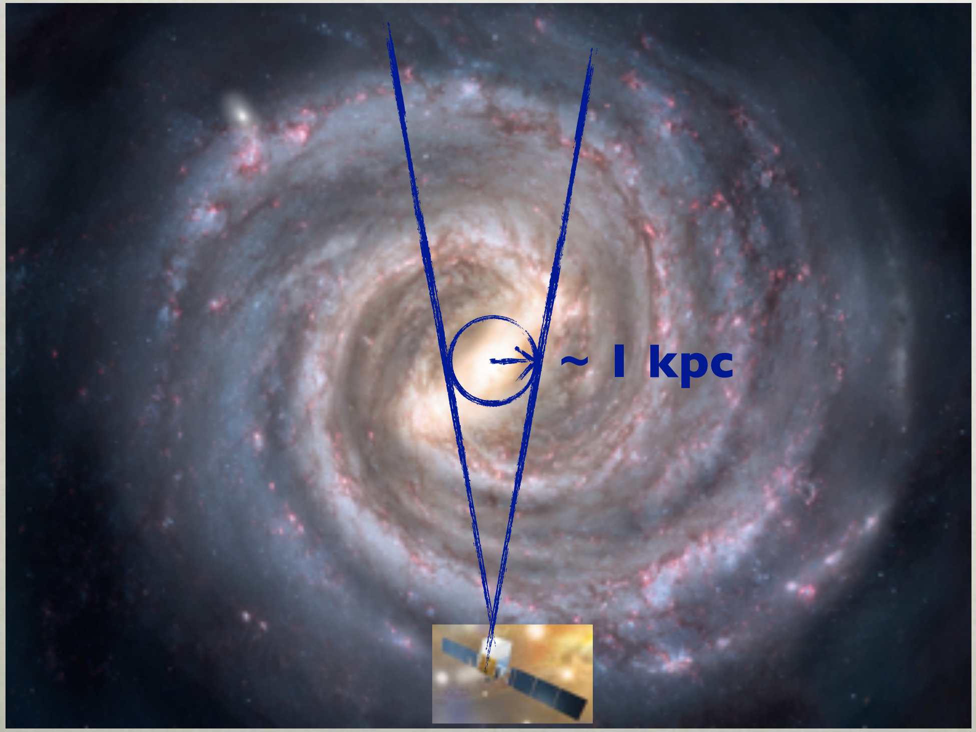
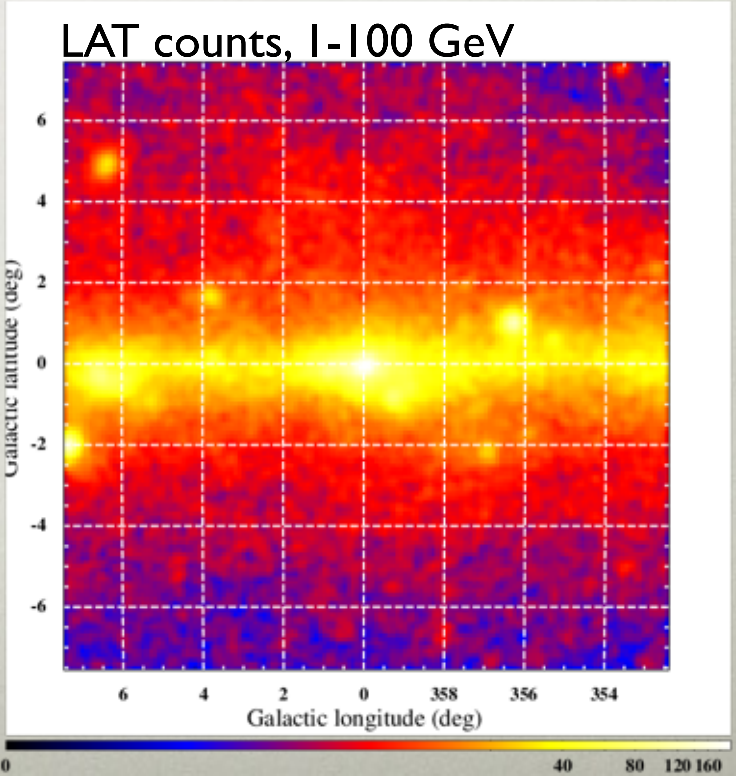


# Galactic Center Region

Fermi LAT Collaboration

- Focus on a 15°x15° region (~ 1 kpc) around Galactic center
- Data selection: 1-100 GeV, CLEAN class, FRONT converting events (large effective area and narrow PSF); PASS 7 reprocessed; 62 months.

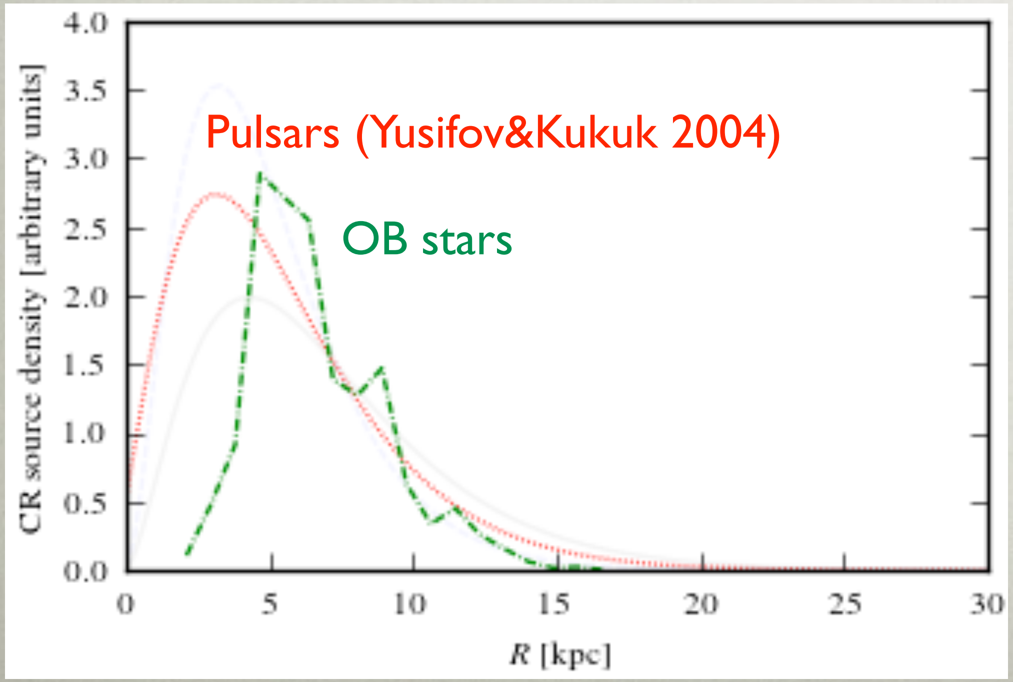


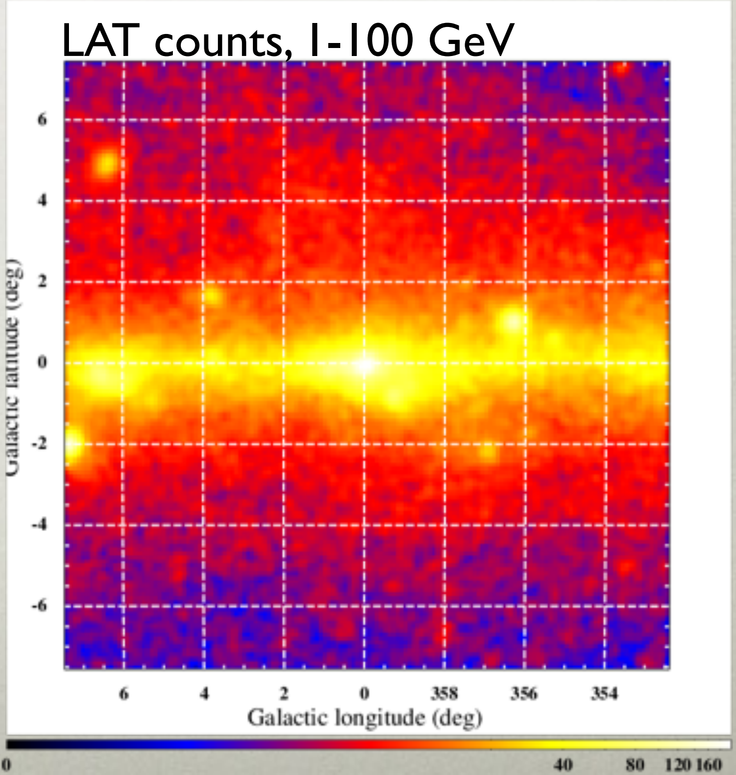



# Modeling the Interstellar Emission

Fermi LAT Collaboration

- Interstellar emission models: use GALPROP models with prop. parameters consistent with CR data and in good agreement with all-sky gamma-ray data, from *Ackermann et al, 2012, ApJ 750*. Select two models with broad range in the radial extent of the CR source distribution (Pulsars, OB stars) as baseline
- Tune the baseline models to gamma-ray data outside of the ROI for improved foreground/ background determination



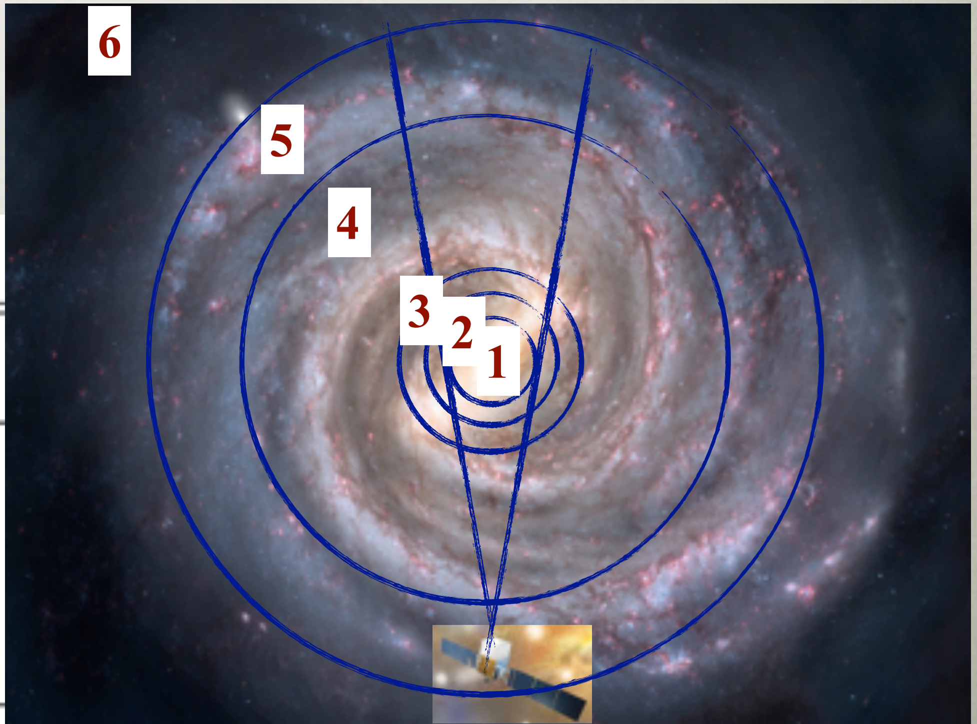
# Background Tuning Procedure

Fermi LAT Collaboration

- Determine intensity for $\pi^0$ (from HI and $H_2$ gas) and IC contributions in galactocentric rings,
  - IC component divided in rings (dev. version of GALPROP), same boundaries as the gas: these additional degrees of freedom can compensate for uncertainies in the GALPROP model of the electron spectrum or ISRF used to calculate the IC templates
- Isotropic and Loop I (*Wolleben, 2007, ApJ 664*) emissions also fitted to the data
- Different sky regions are employed based on where the components that are fitted contribute most. Point source locations and spectra taken from the preliminary 3FGL.

Galactocentric ring boundaries.

| Ring # | $R_{min}$ [kpc] | $R_{max}$ [kpc] | Longitude Range (Full) |
|---|---|---|---|
| 1 | 0 | 1.5 | $-10° \leq l \leq 10°$ |
| 2 | 1.5 | 2.5 | $-17° \leq l \leq 17°$ |
| 3 | 2.5 | 3.5 | $-24° \leq l \leq 24°$ |
| 4 | 3.5 | 8.0 | $-70° \leq l \leq 70°$ |
| 5 | 8.0 | 10.0 | $-180 \leq l \leq 180°$ |
| 6 | 10.0 | 50.0 | $-180 \leq l \leq 180°$ |



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- Isotropic and Loop I (*Wolleben, 2007, ApJ 664*) emissions also fitted to the data
- Different sky regions are employed based on where the components that are fitted contribute most. Point source locations and spectra taken from the preliminary 3FGL.
- Regions containing structures not modeled or that might bias the fit results are not used to tune the IEM (Fermi bubbles, Cygnus region.) The 15°x15° region is also excluded

➡ Two tuning procedures: one adjusting intensity only, the other also allowing spectral adjustment (broken power law, break at ~2 GeV) for $\pi^0$ production within the solar circle. No freedom in IC spectrum

➡ Four variants for the foreground/background IEM: Pulsars/OB Stars, tuned intensity/index

Galactocentric ring boundaries.

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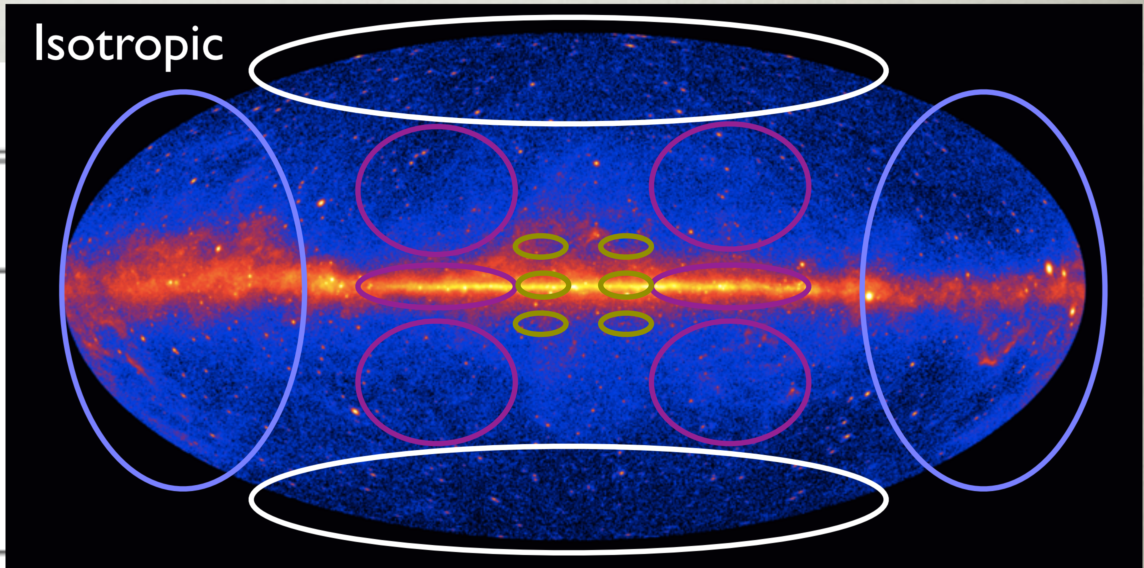


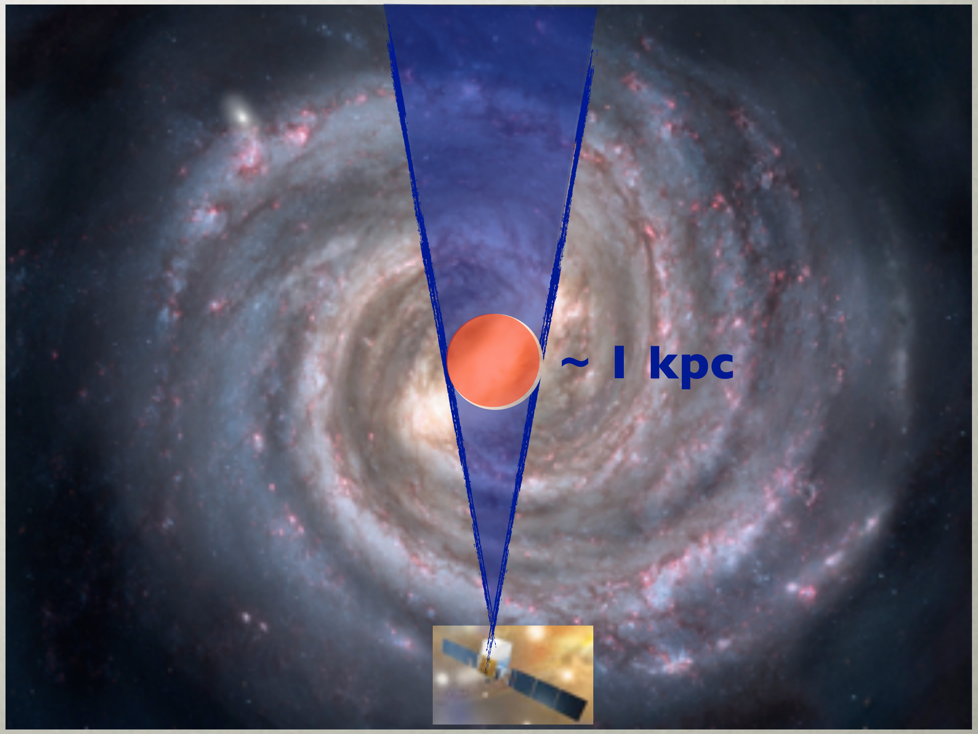
# Modeling the 15°x15° ROI

Fermi LAT Collaboration

- Model the emission from the 15°x15° ROI for each of the 4 foreground/background models
- Point sources in the region are determined consistently with these models - we do not use existing catalogs
  - identify preliminary locations of point source candidates by applying *PGWave* (*Damiani et al. 1997, ApJ, 483* wavelet algorithm, assumes flat background) to the data in 4 equally spaced LogE bins in the1-100 GeV range
  - for each of the (fixed) models, determine position and initial values of the spectra of the point source candidates (*Pointlike*)
  - obtain list of point source candidates with TS>9 for the analysis of the 15°x15° ROI

➡ Intensities for the innermost ring for HI/$H_2$ $\pi^0$, and IC are determined by fitting the data in this region concurrently with the point source candidates. Fore/background models held fixed

- Repeat procedure twice, until no significant point-like excesses are left in the residuals
- Bremsstrahlung and HII $\pi^0$ emissions are subdominant and are fixed to GALPROP prediction

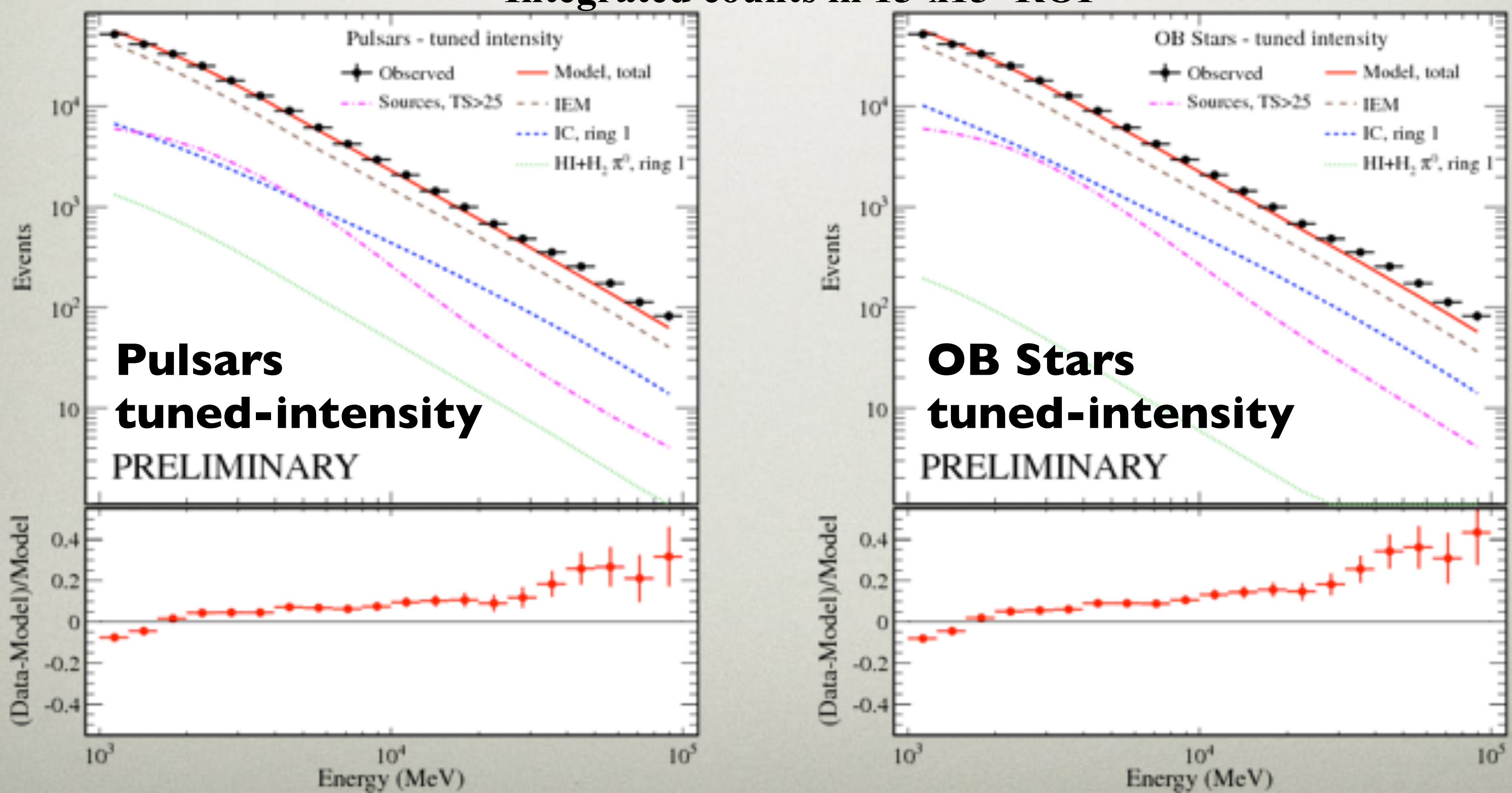


# Results

Fermi LAT Collaboration

- The data-model agreement is within 5-10% averaged over the 15°x15° ROI up to ~ 10 GeV. The models are too bright below ~2 GeV, and too dim above
- The foreground/background accounts for most of the emission in the region.

**Integrated counts in 15°x15° ROI**



# Results

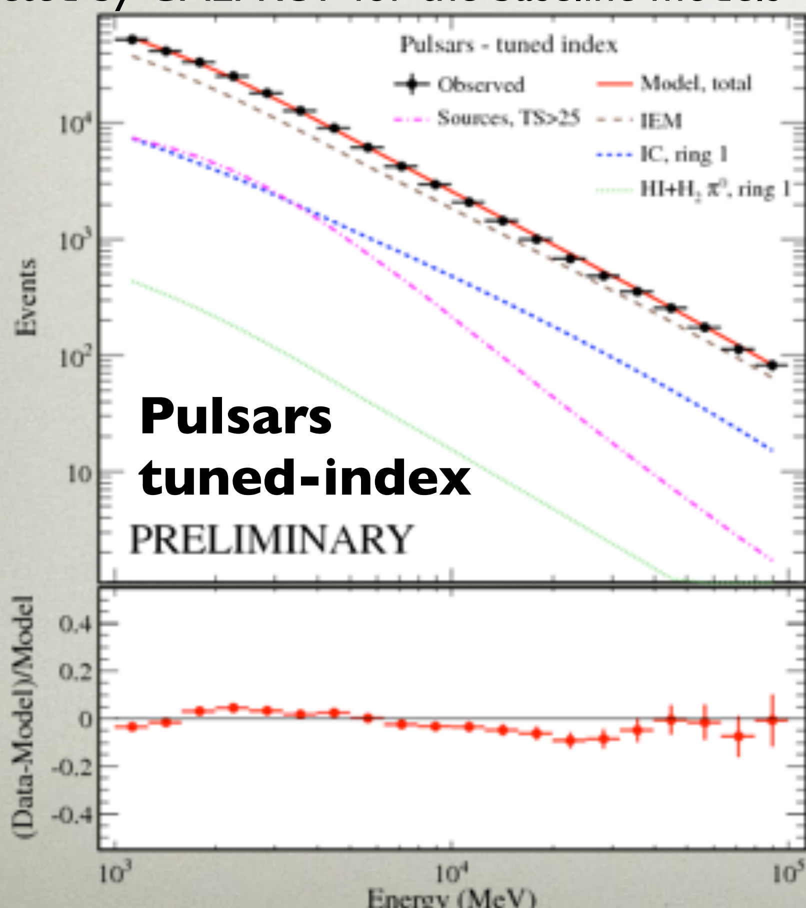
Fermi LAT Collaboration

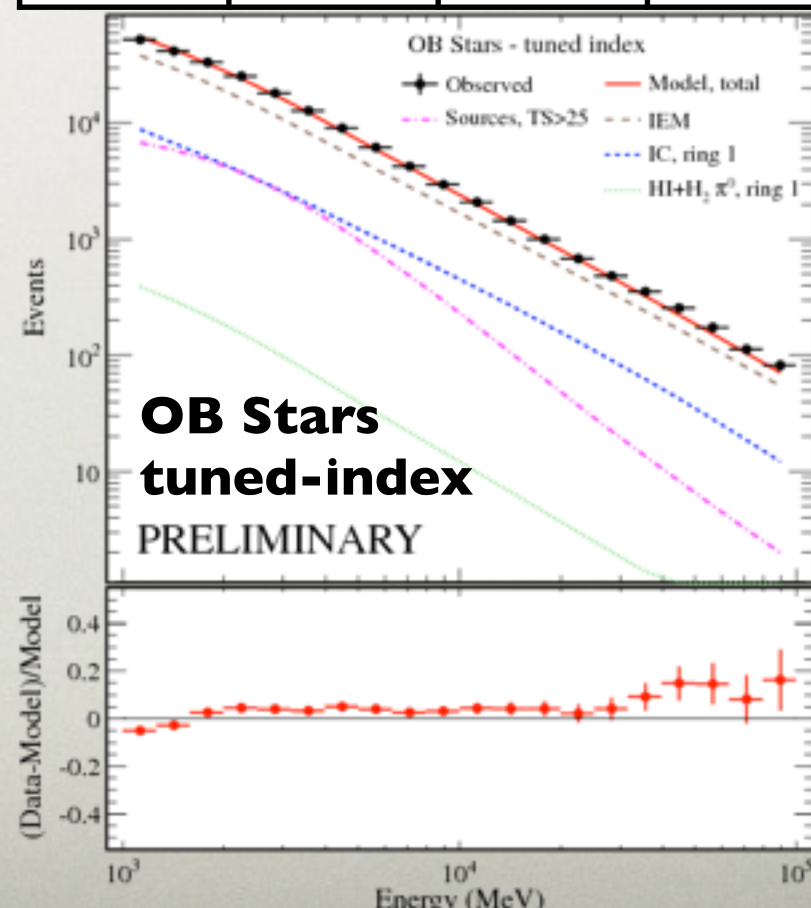
- Agreement is better for tuned index models

➡ For all foreground/background models, the fitted IC emission for ring 1 is brighter than the gas emission and larger (7-30x) than predicted from GALPROP for the baseline models. This could be due to higher intensity of ISRF and/or higher CR lepton intensities than assumed

- Point source contribution comparable to IC
- HI/$H_2$ pi0 intensities are subdominant and less than predicted by GALPROP for the baseline models

| Integrated flux in 15°x15° ROI, E>1GeV, $10^{-8}$ ph cm$^{-2}$ s$^{-1}$ | | | |
|---|---|---|---|
| IC, Ring 1 | $\pi^0$, Ring 1 | IC, IEM | $\pi^0$, IEM |
| **41-59** | 1-8 | **24-33** | 151-164 |



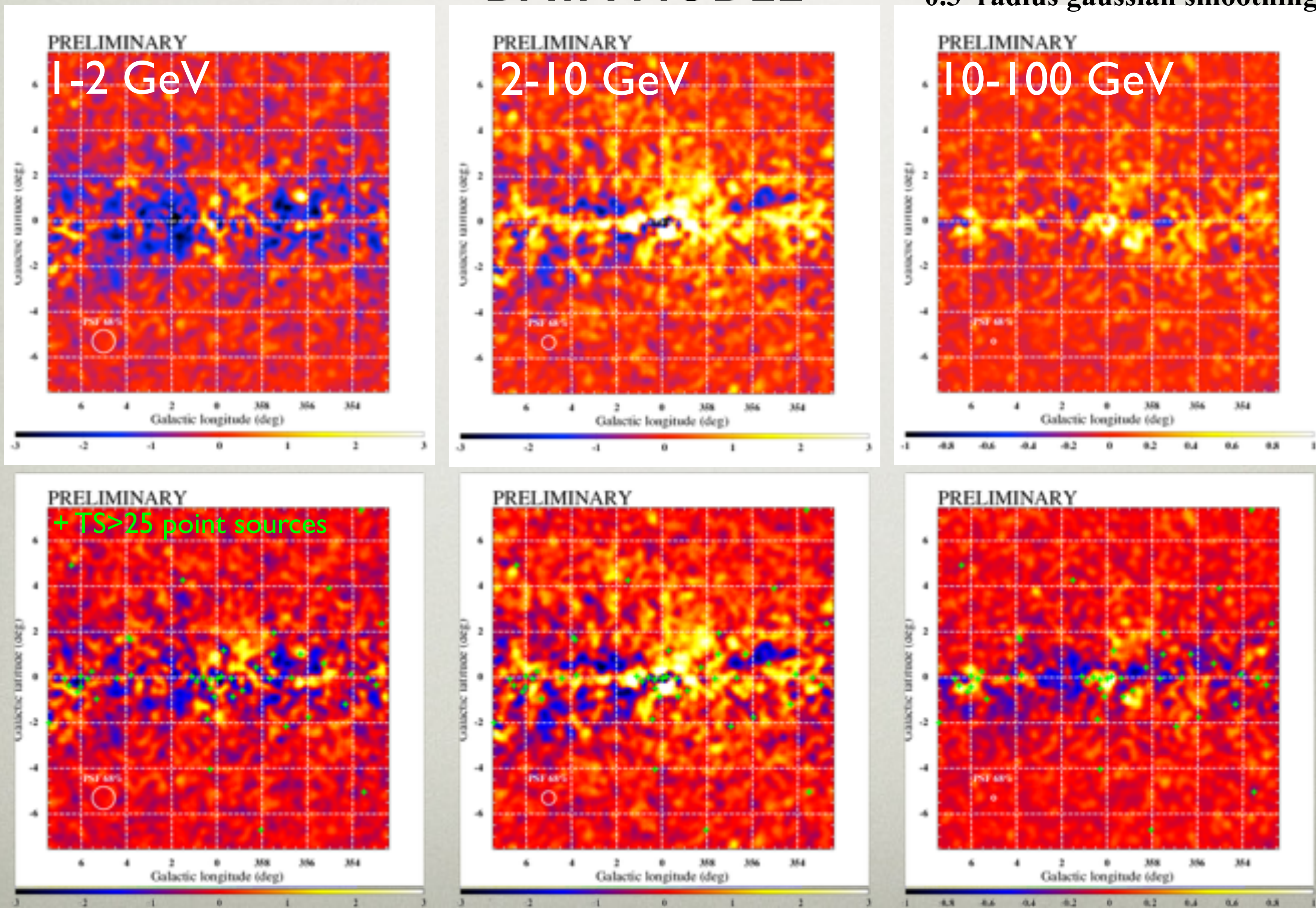



# Results - Residual Maps

Fermi LAT Collaboration

Counts in $0.1^o$x$0.1^o$ pixels
$0.3^o$ radius gaussian smoothing

DATA-MODEL

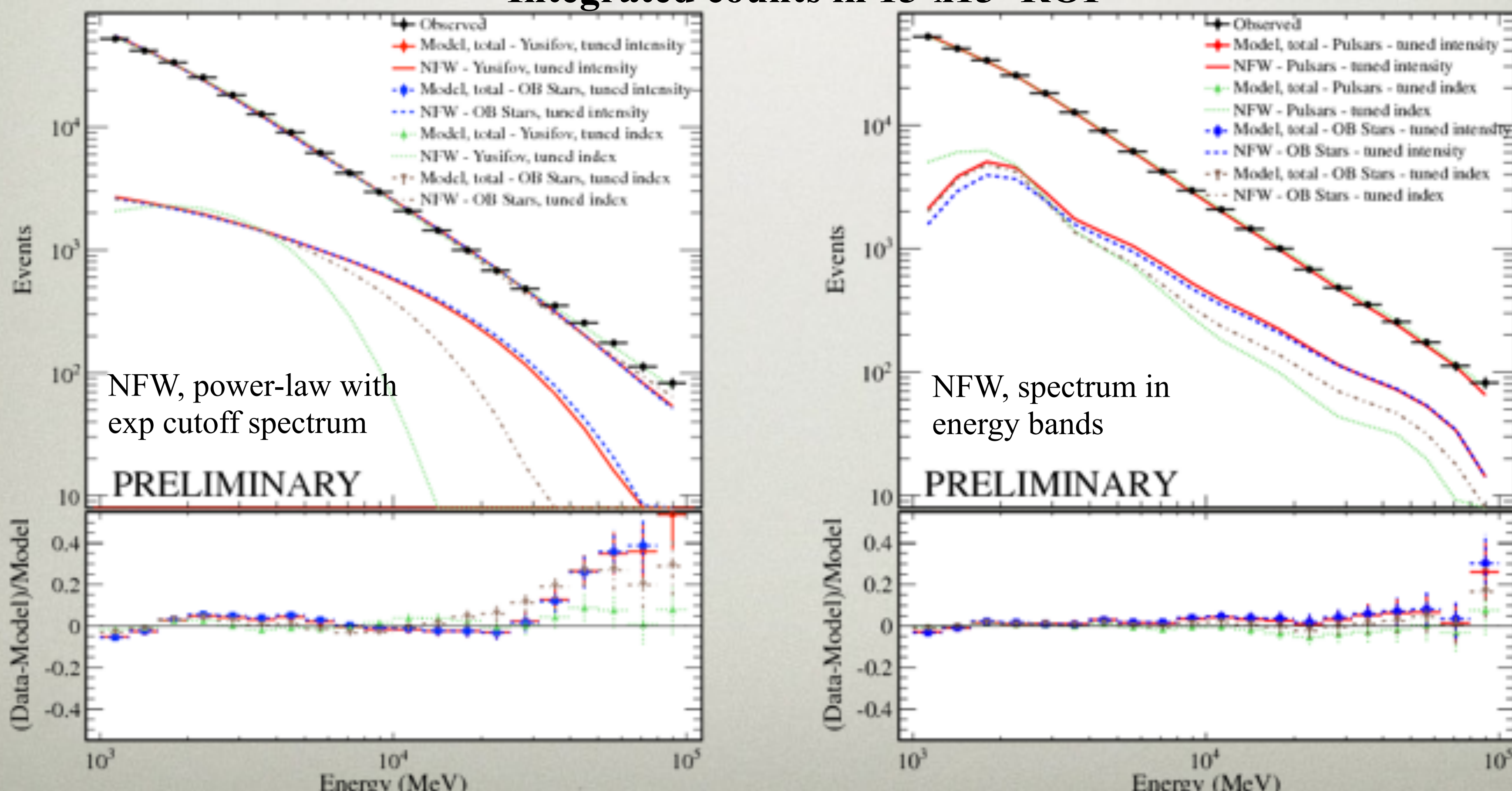


# Additional Templates

Fermi LAT Collaboration

- We test the possibility that an additional component centered at the GC contributes to the data (2D gaussians, Navarro-Frenk-White, or a gas-like distribution as proxy for unresolved sources)
- Peaked profiles with long tails (NFW, NFW contracted) yield the most significant improvements in the data-model agreement for the four variants of the foreground/background models. IC ring 1 contribution ~2-3x smaller than without additional component and HI ring 1 contribution is ~2-5x larger
- ➡ The predicted spectrum depends on the foreground/background models.

**Integrated counts in 15$^o$x15$^o$ ROI**



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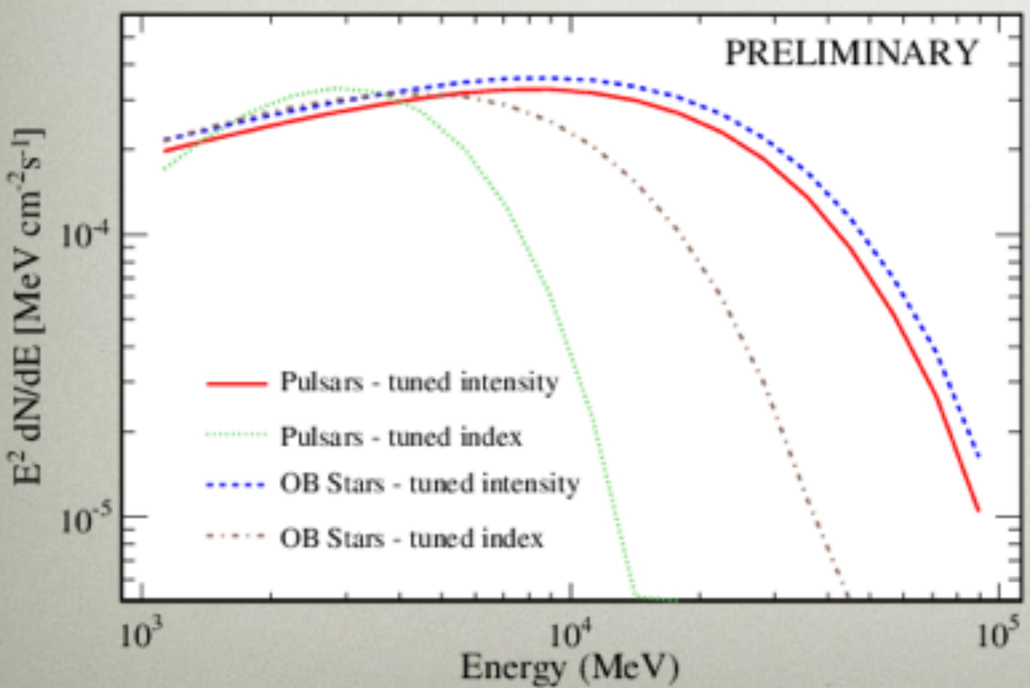
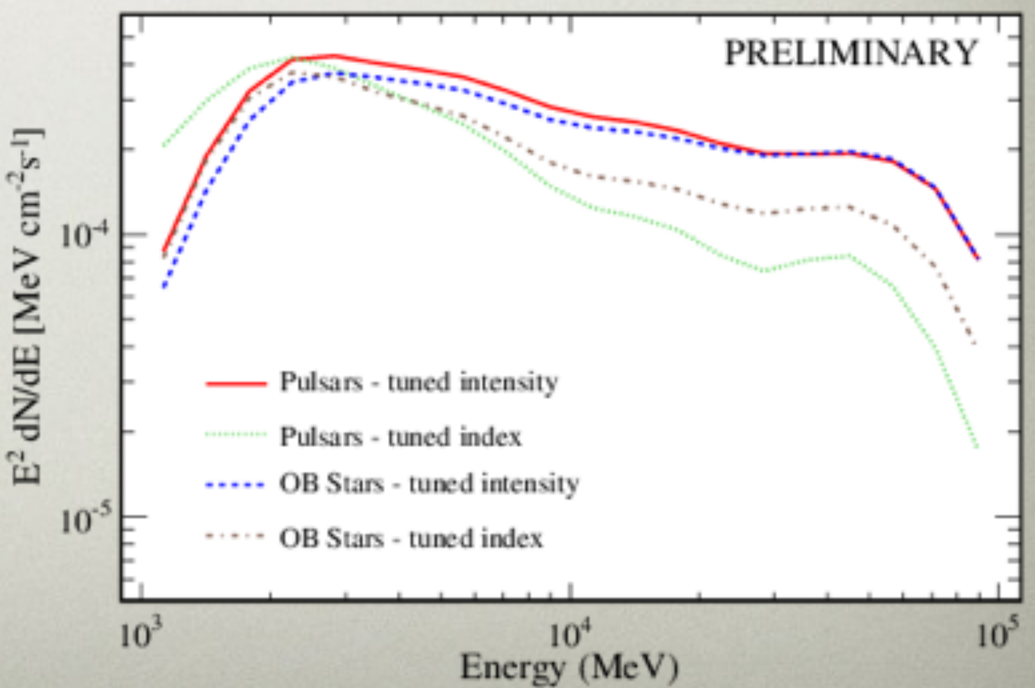
➡ The predicted spectrum depends on the foreground/background models.

**Integrated flux in 15°x15° ROI, NFW component**



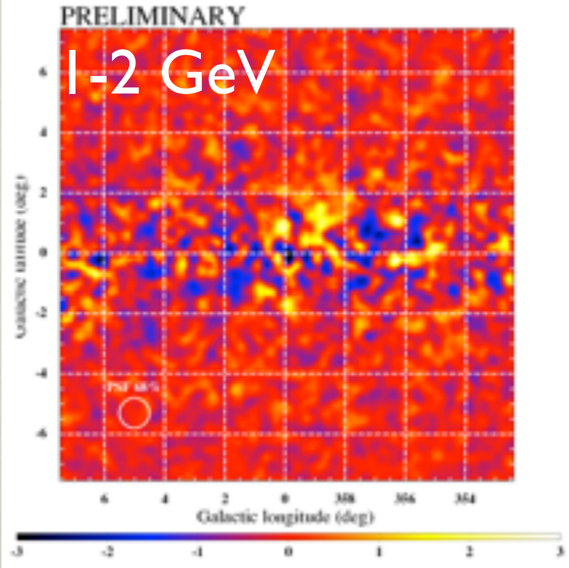
# Additional Templates

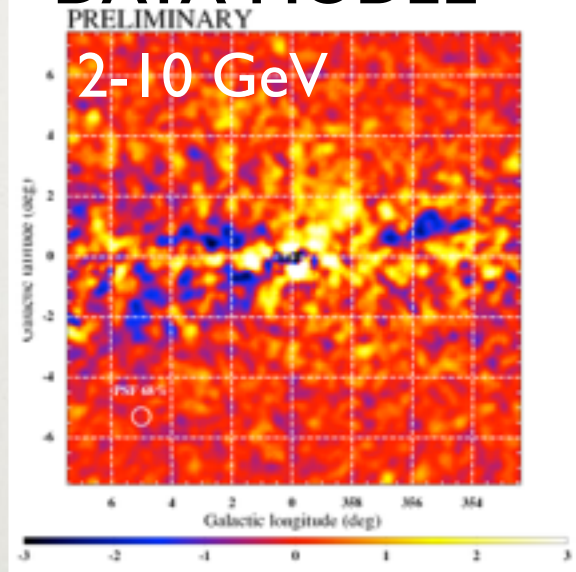
Counts in 0.1°x0.1° pixels
0.3° radius gaussian smoothing

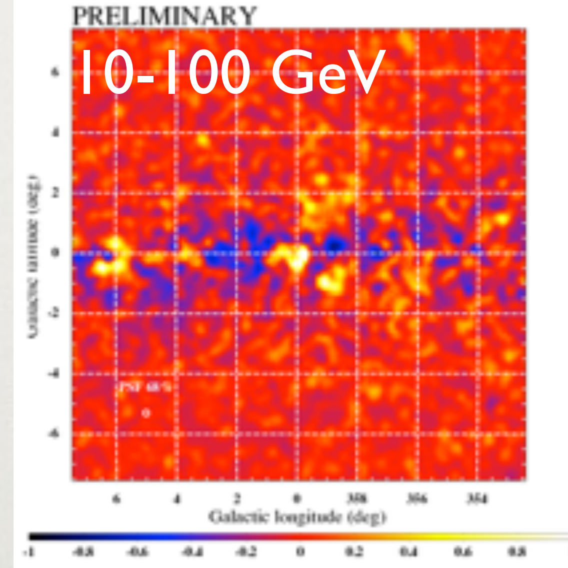
**Without NFW:**

**DATA-MODEL**

**Pulsars, tuned-index**

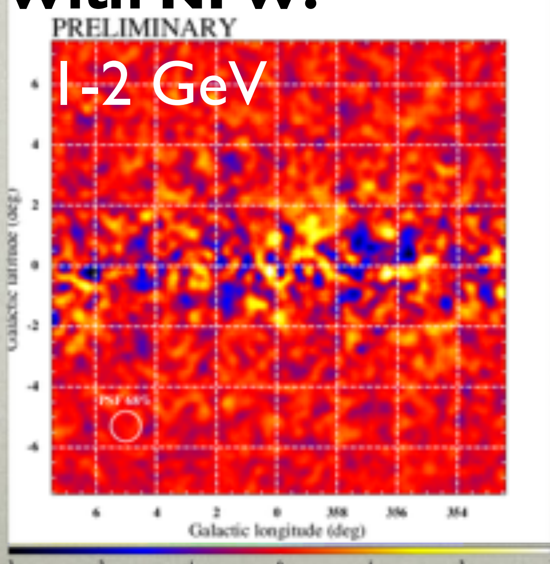


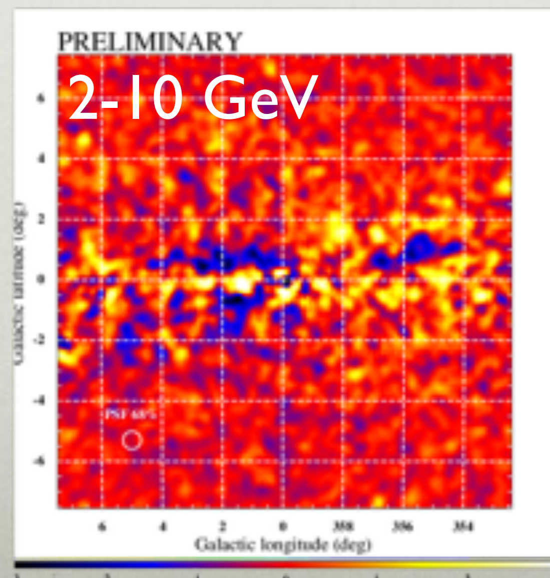



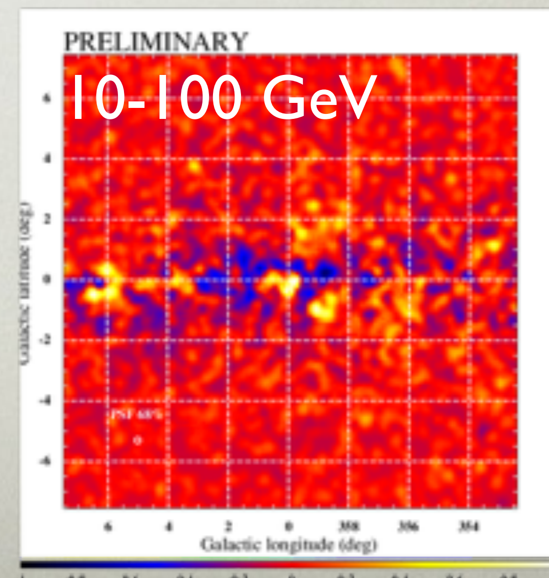




**With NFW:**

**Pulsars, tuned-index**

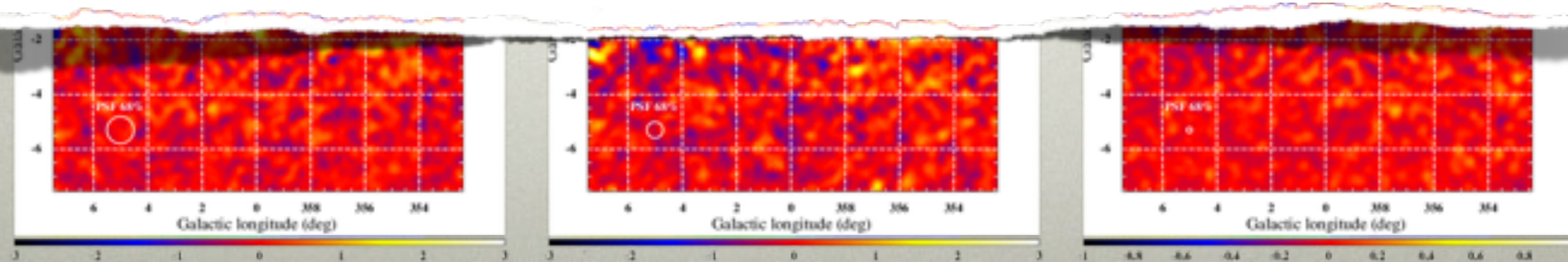


- We have systematically developed a set of models for the diffuse emission in the inner $15^{\circ}$x$15^{\circ}$ of the Milky Way, by fitting GALPROP-derived templates in a way not done before
- We determined the point sources as part of the development of this model
- We employ all sky data to constrain the foreground/background emission, excluding the $15^{\circ}$x$15^{\circ}$ region, for different assumptions on the CR source distribution, gas intensity and spectral index, and IC intensity across galactocentric rings
- We find:
  - We find an excess approximately centered the Galactic center with a spectrum that peaks in the GeV range,  that persist across the models we have employed. The spectral properties vary widely depending on the modeling of the interstellar emission
  - IC emission from inner kpc is higher than predicted and is the dominant interstellar emission component in this region. We are exploring the origin of the enhanced IC in the IG to see what combination of ISRF and CR leptons best explains the data.
  - Foreground/background accounts for most of the emission. Its determination is crucial in extracting the contribution from the Galactic center region

➡ We are further exploring the systematic uncertainties in the IEM, e.g. gas distribution, ISRF, cylindrical symmetry. This is crucial in determining properties of the IEM in the innermost kpc and to confirm the presence and properties of an additional component



# Dwarf Spheroidal Galaxies

- Optically observed dwarf spheroidal galaxies (dSph): largest clumps predicted by N-body simulation.
- Excellent targets for gamma-ray DM searches
  - Very large M/L ratio: 10 to ~> 1000 (M/L ~10 for Milky Way)
  - DM density inferred from the stellar data! Data so far cannot discriminate, in most cases, between cusped or cored dark matter profiles.

    However, Fermi's DM constraints with dSph do not have a strong dependence on the inner profile
  - Expected to be free from other gamma ray sources and have low dust/gas content, very few stars

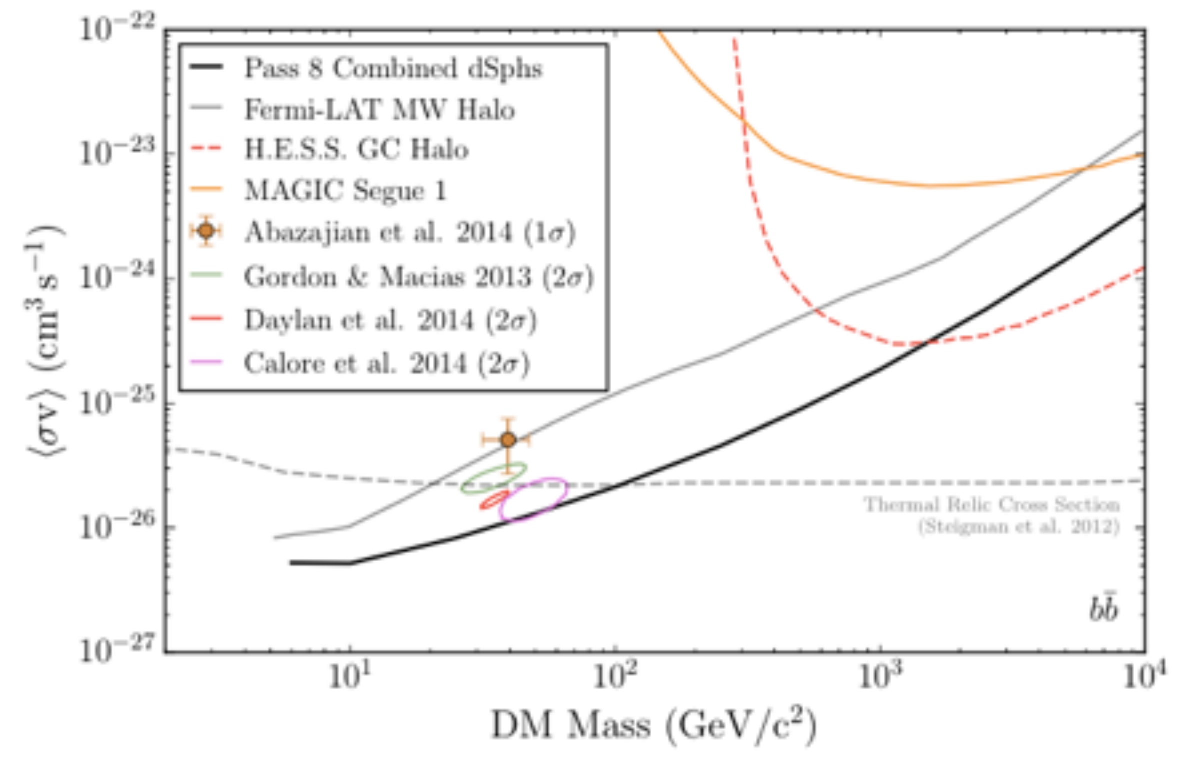
# Dwarf Spheroidal Galaxies

Fermi LAT Collaboration, arXiv 1503.02641

- Search for a signal in 25 dSphs
- 6 years of data, Pass 8, 500 MeV to 500 GeV

➡ No significant emission is found

- Limits begin to probe DM explanation of the GC excess



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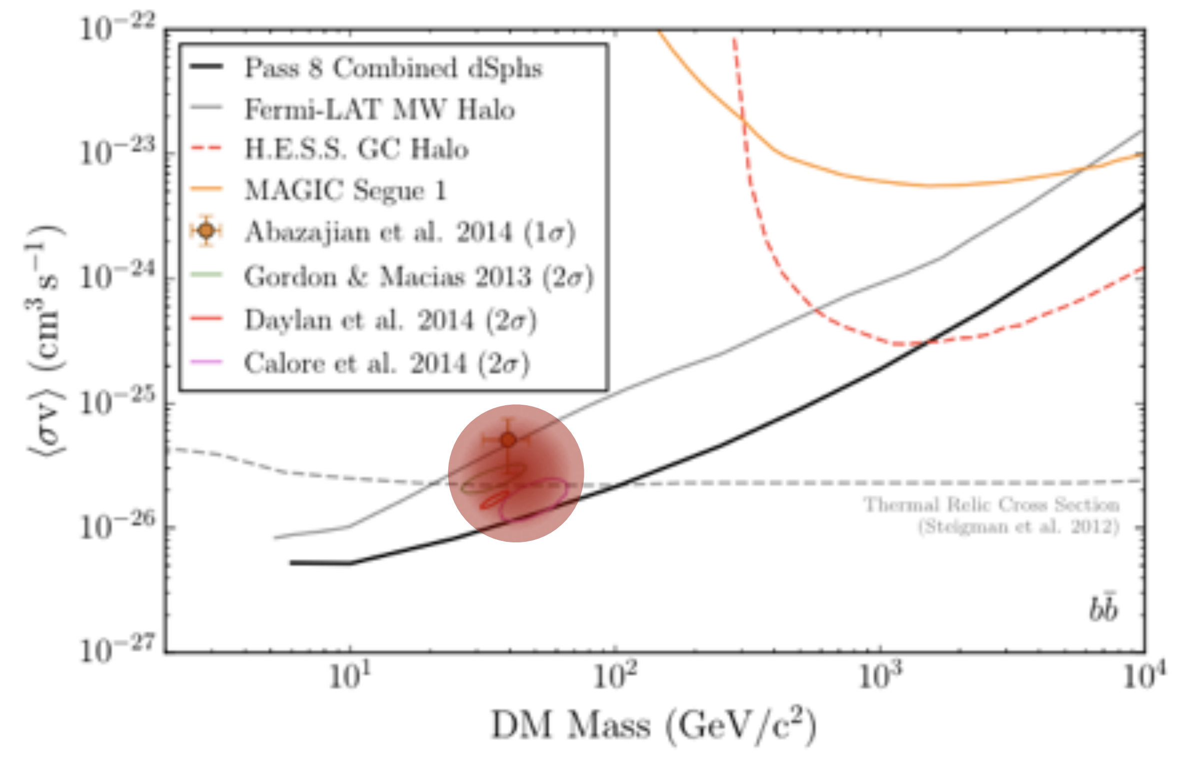

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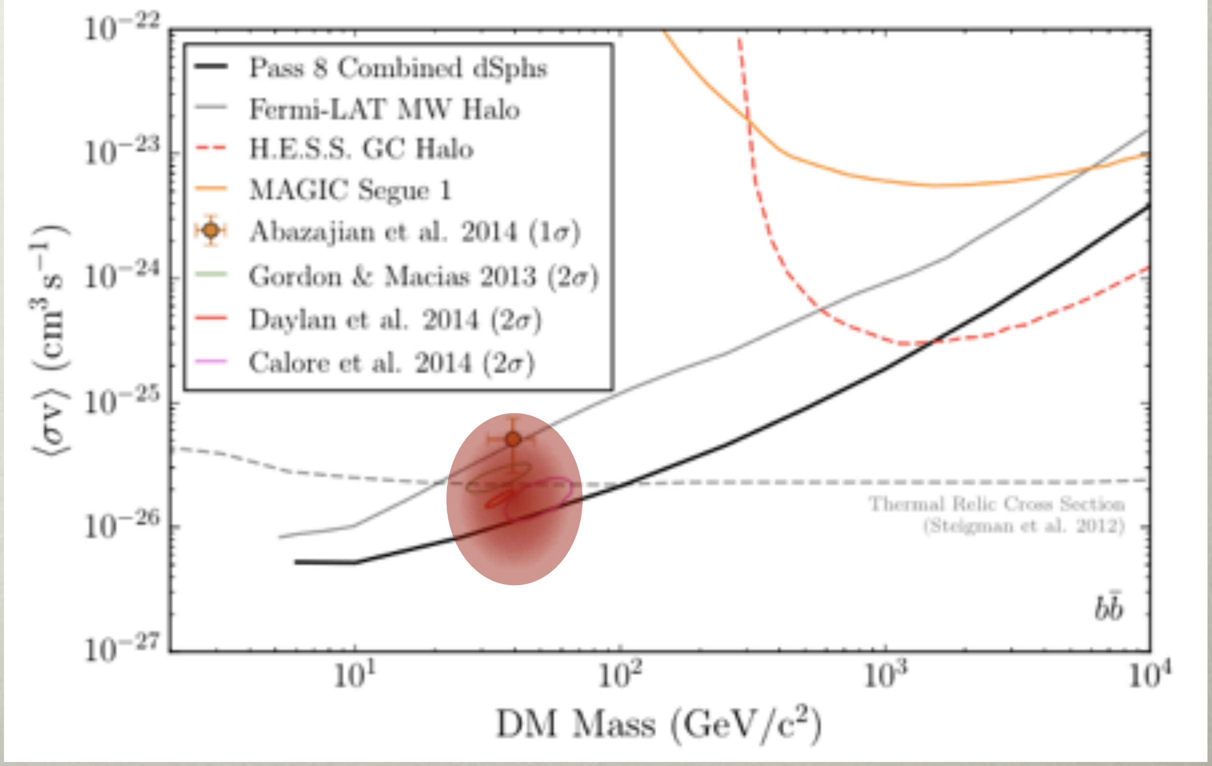
**N.B.:**
Contours do not fully reflect uncertainties in the DM profile!



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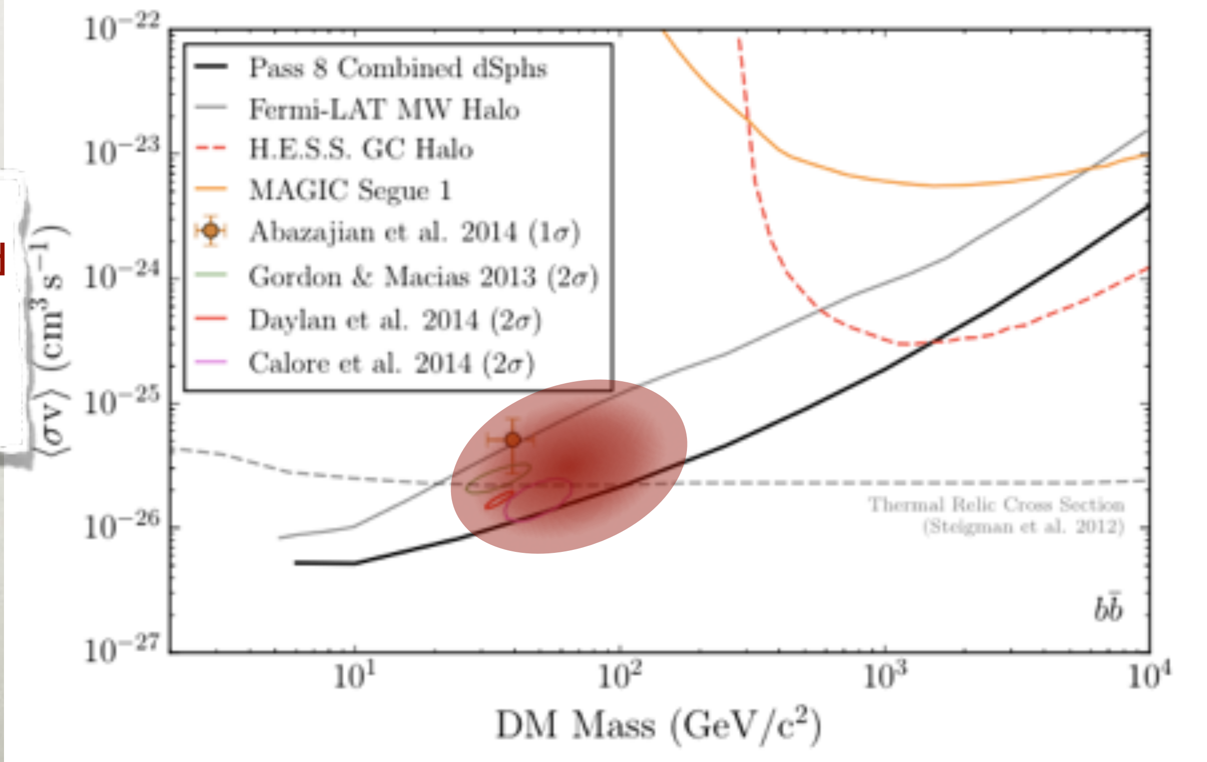
**N.B.:**
Uncertainties in the astrophysical background model also allow for a broader range of DM masses and annihilation channels
(see e.g. Agrawal et al, arXiv:1411.2592)



# Summary/Outlook

- The excess peaked at a few GeV in the Galactic center persists, so far. This is where a dark matter signal is predicted to be brightest

➡ However the astrophysical background is currently a limitation. More work is on the way to better model it. This is crucial to confirm the presence and to determine the properties of this potential signal

- Limits from dwarf spheroidals begin to probe DM explanation of the GC excess

**Thank you!**