Dark Matter Searches with Gamma Rays

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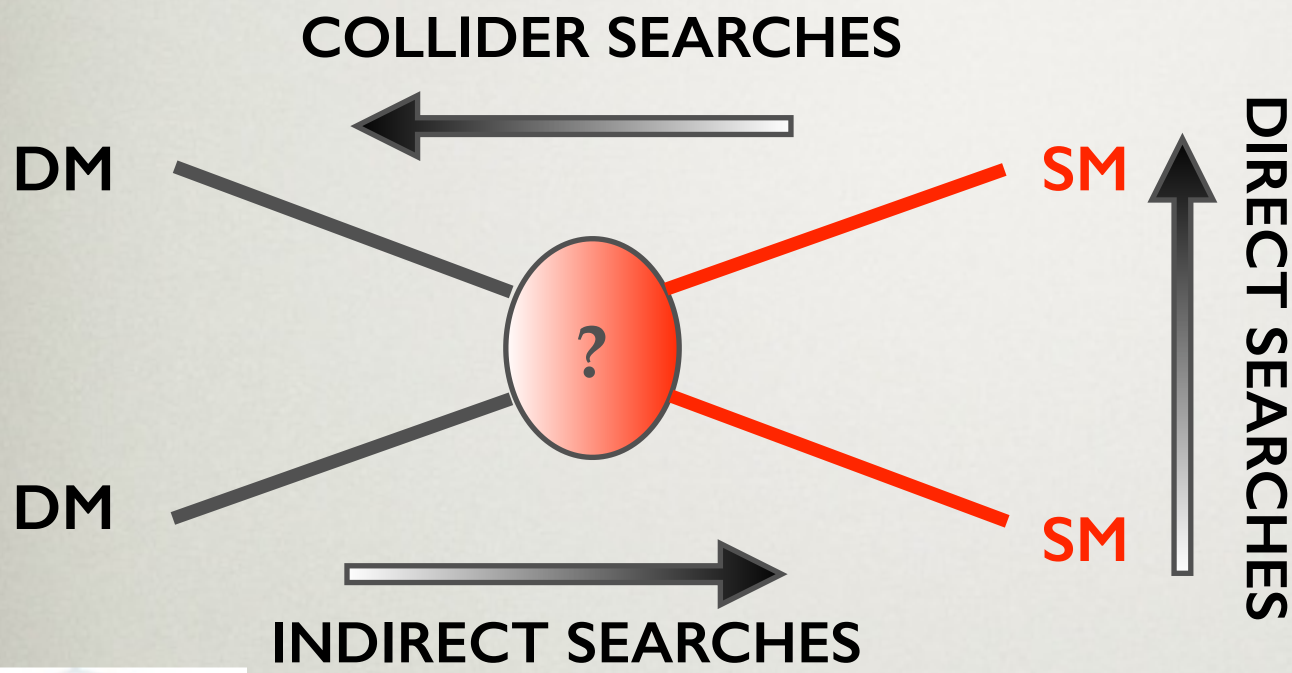
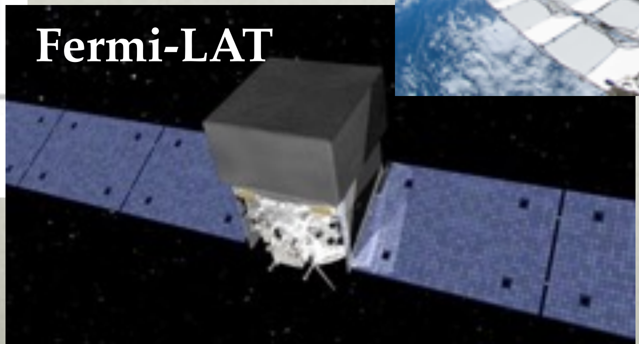
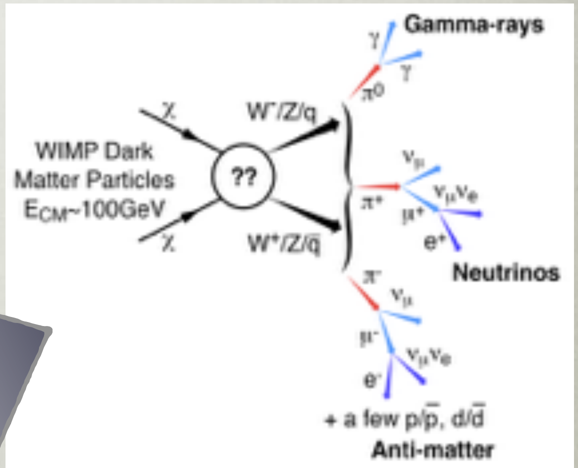
Durham-Kavli-IPMU-KEK-KIAS workshop
Seoul, Korea - 27 October 2016

WIMP Searches







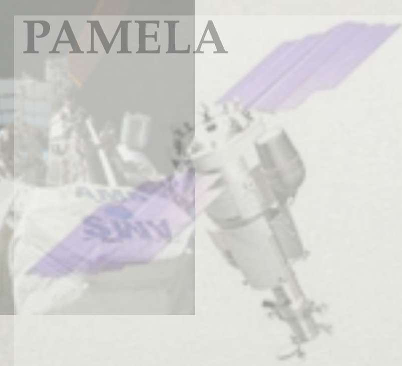
Indirect Detection

- **Gamma rays**
  - VERITAS
  - HESS
  - MAGIC
  - Fermi LAT

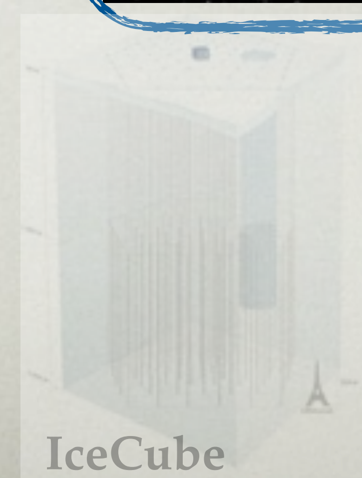
ON THE GROUND

IN SPACE

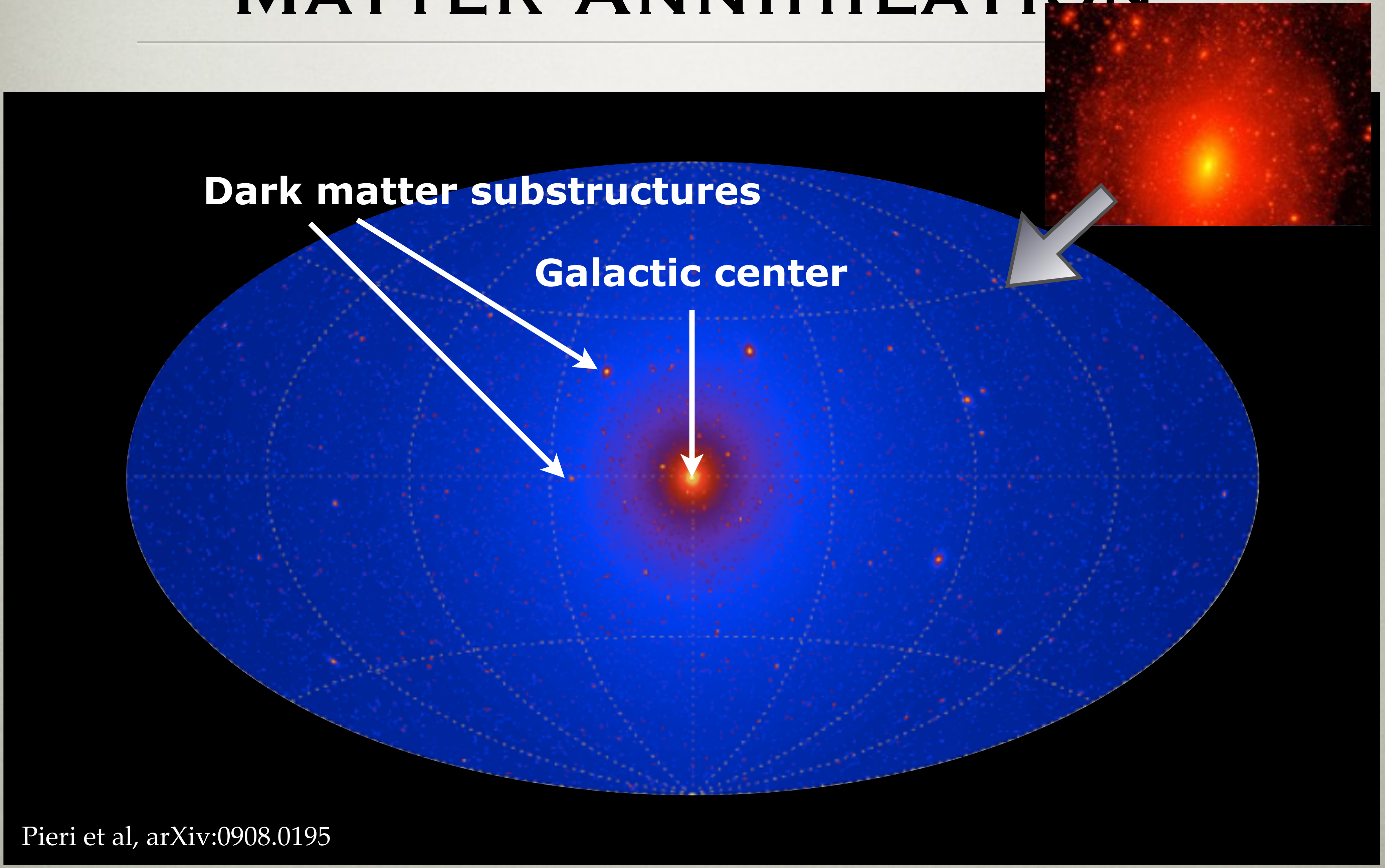
- Cosmic Rays
  - AMS-02
  - PAMELA
  - Fermi LAT



- Neutrinos
  - IceCube



Gamma rays from Dark Matter Annihilation



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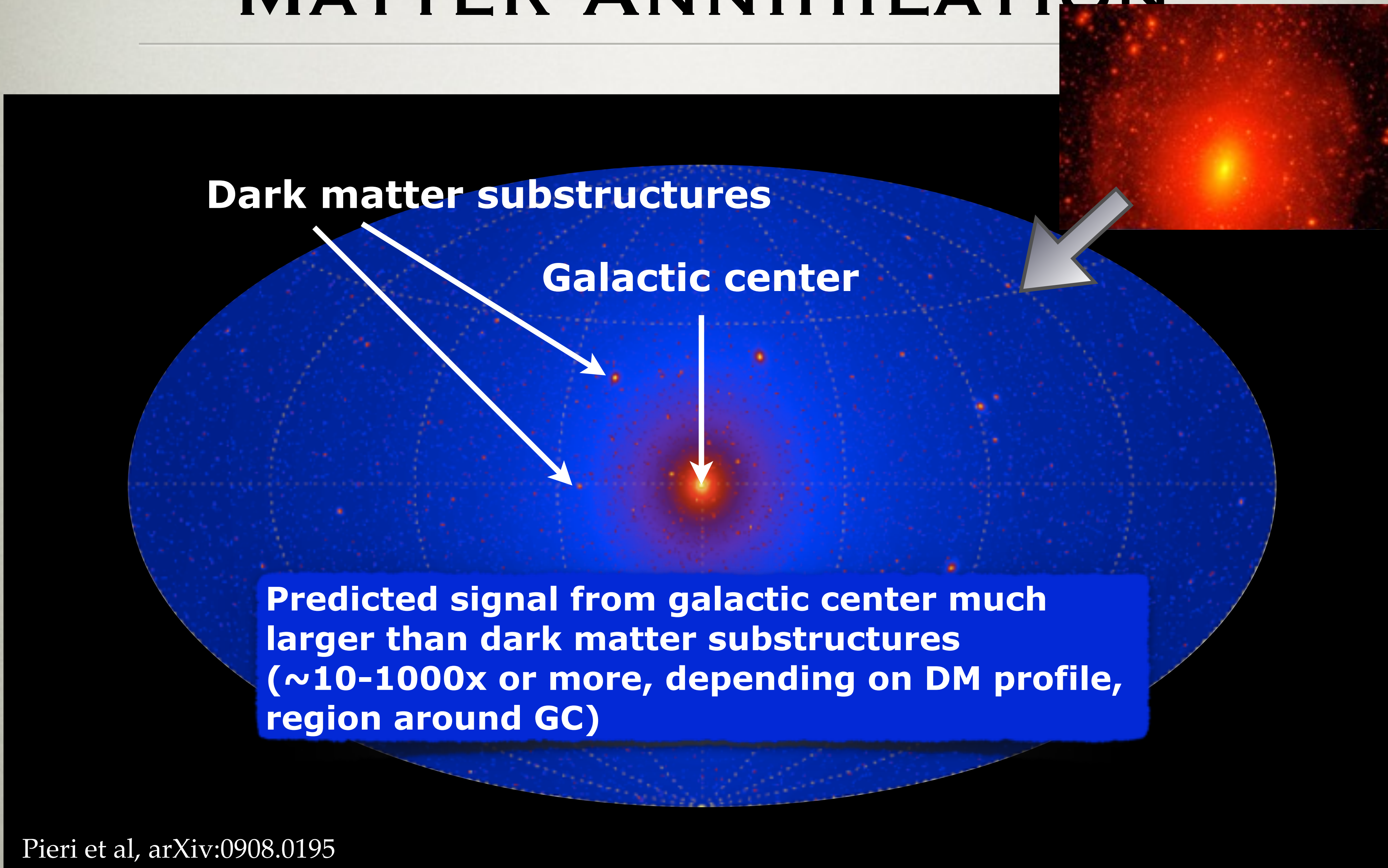
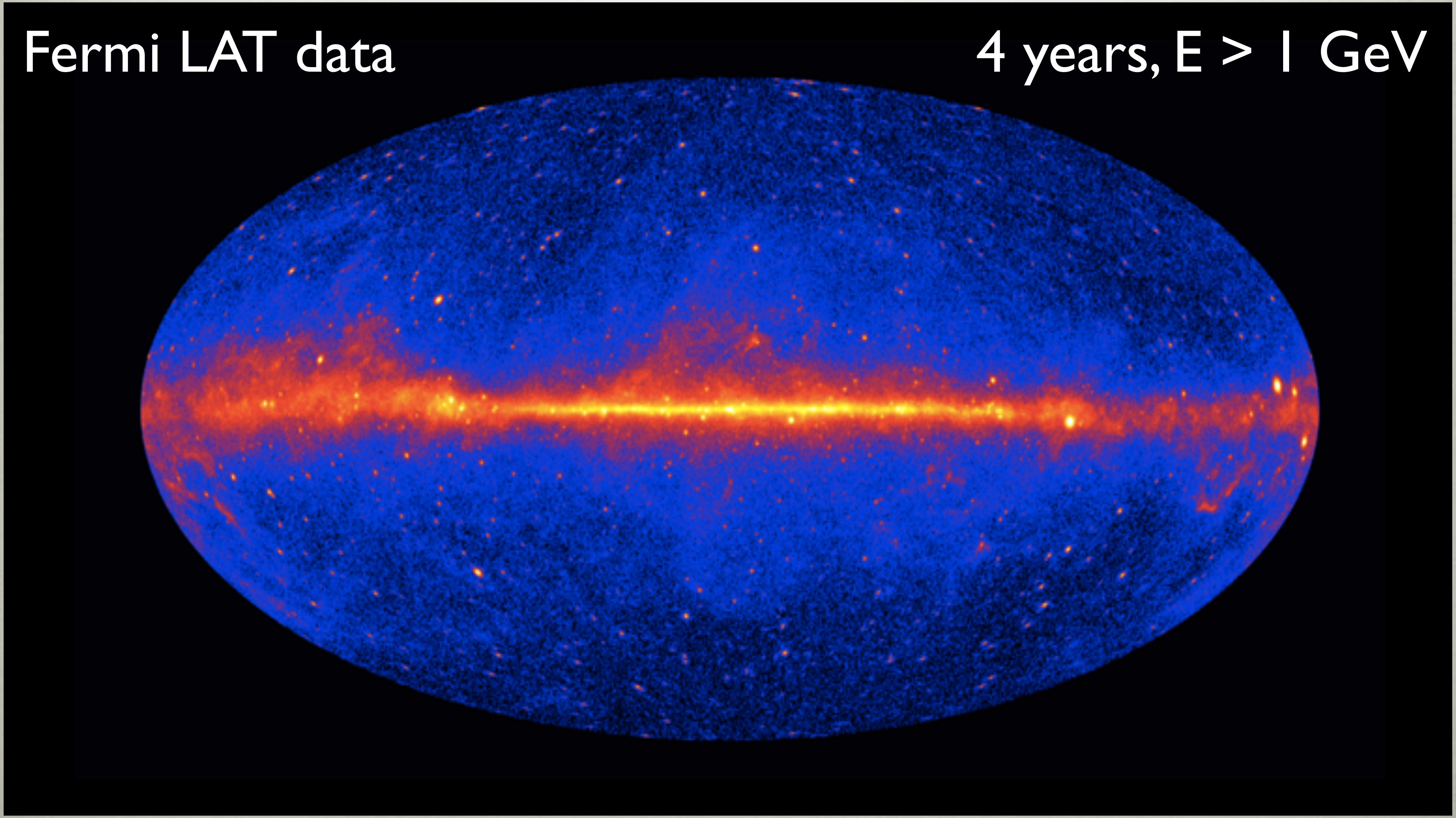
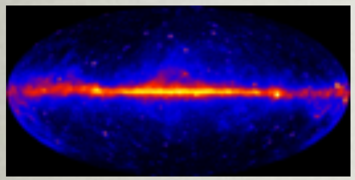


Pieri et al, arXiv:0908.0195

The Fermi Sky



Understanding the Gamma-ray Sky



data

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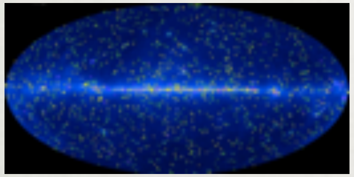
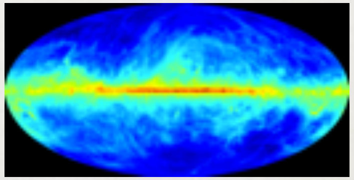


sources

+



galactic interstellar emission

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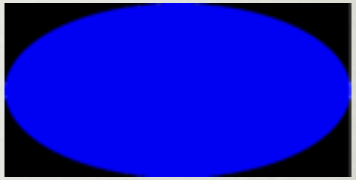

isotropic

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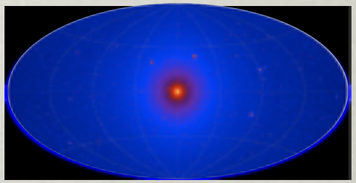
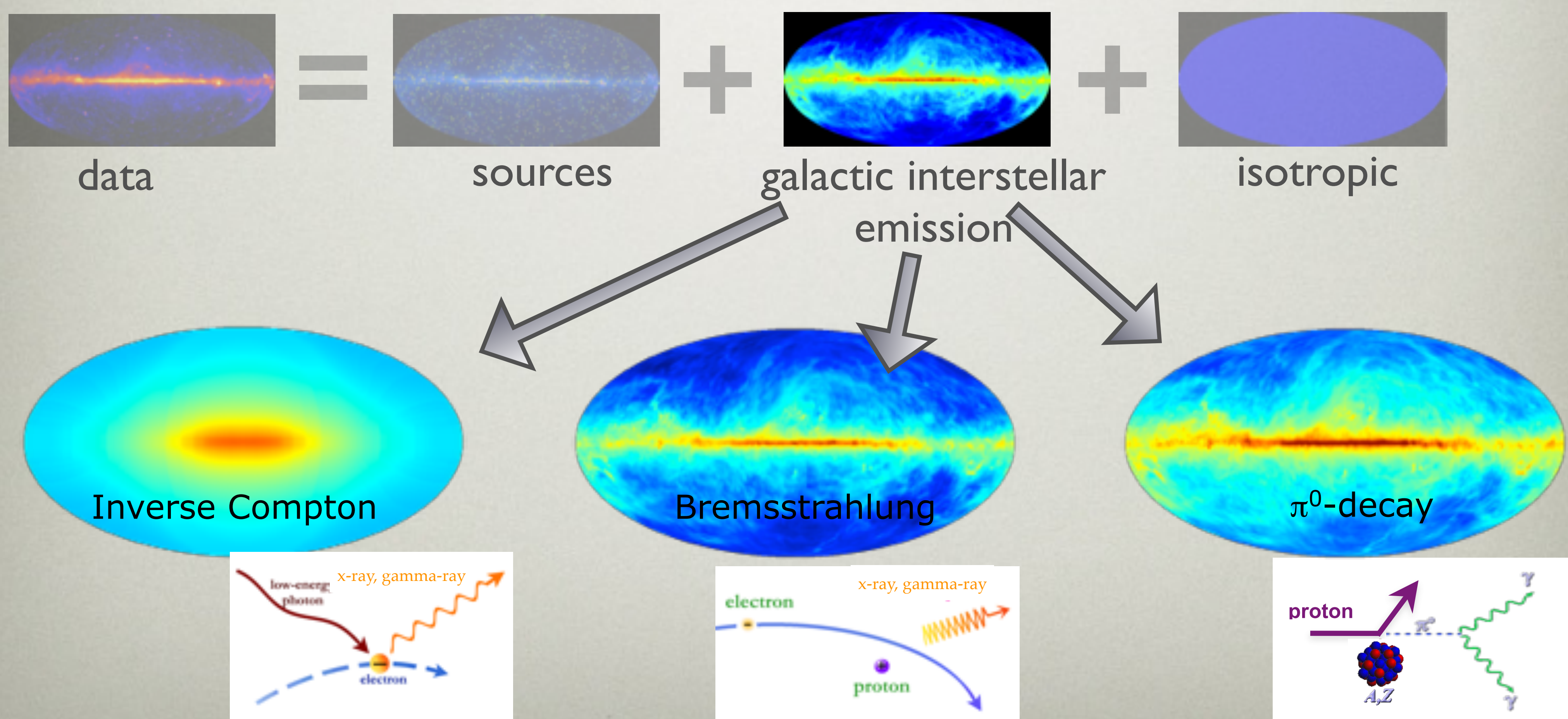


dark matter??

Galactic Gamma-Ray Interstellar Emission

- The interstellar gamma-ray emission in the Milky Way is produced by cosmic rays interacting with the interstellar gas and radiation field

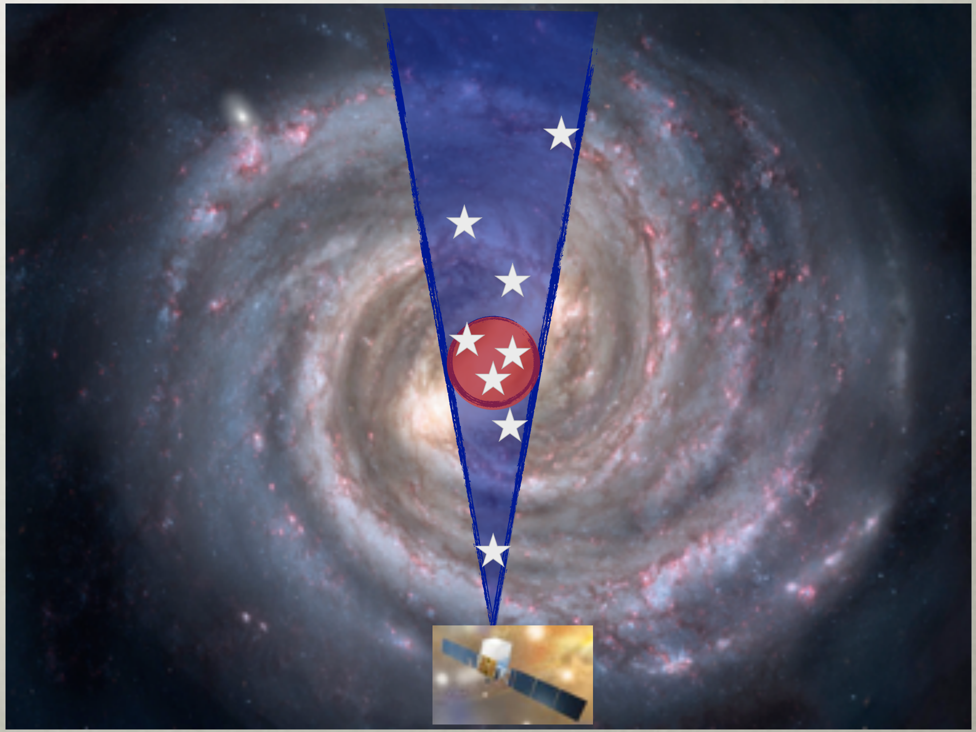


Galactic Center Region

- Complex region: CR intensities, density of radiation fields and gas are highest and most uncertain; significant foreground/background contribution with long integration path over the entire Galactic disc. Large uncertainties modeling the gamma-ray interstellar emission

- 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 predicted to be largest here, where modeling of the interstellar emission+sources is problematic



Galactic Center Excess

- An excess in the Fermi LAT GC data was first claimed by Goodenough and Hooper (arXiv:0910.2998.) More recent analyses also find an excess

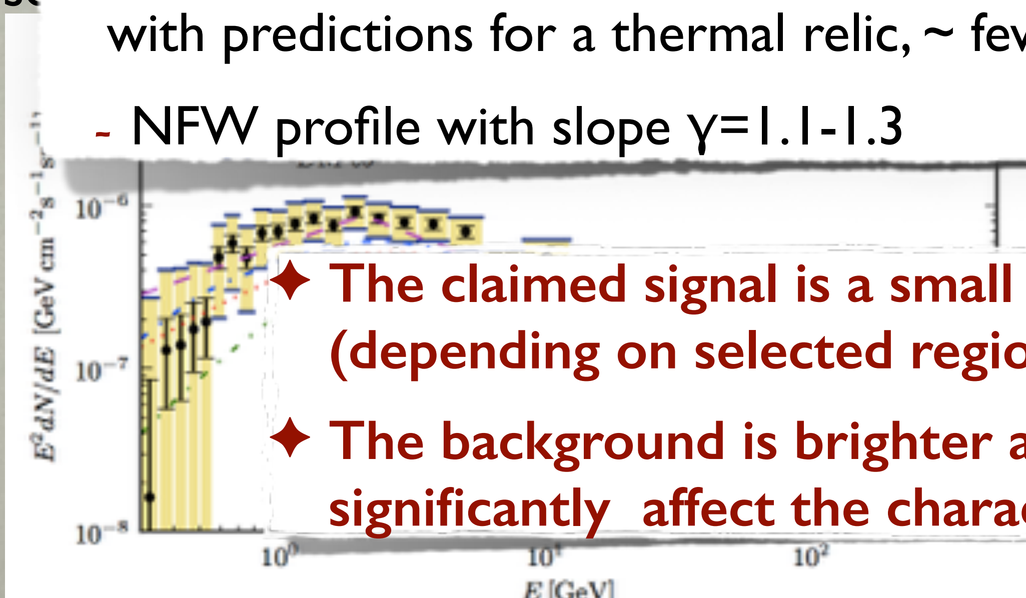
- Generally, two approaches to model the interstellar emission:

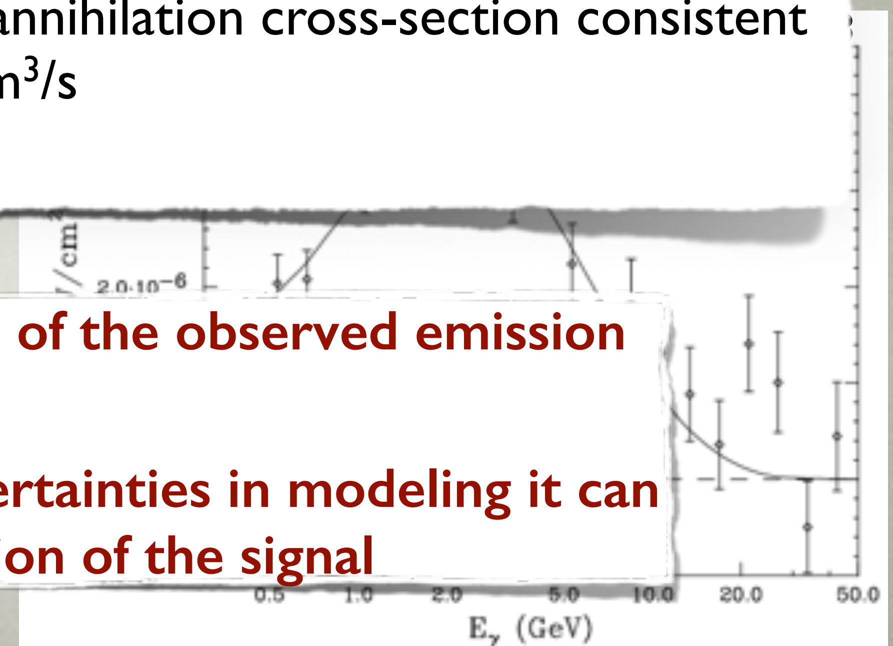
Interstellar emission model (IEM) based on the CR propagation code (GALPROP): physically motivated models, however do not fully capture complexity of the Galaxy

✦ The excess is consistent with a dark matter annihilation signal in spectrum and spatial morphology:

- ~50 GeV mass, annihilating into b-bbar with an annihilation cross-section consistent with predictions for a thermal relic, ~ few10^{-26} cm^3/s

- NFW profile with slope γ=1.1-1.3



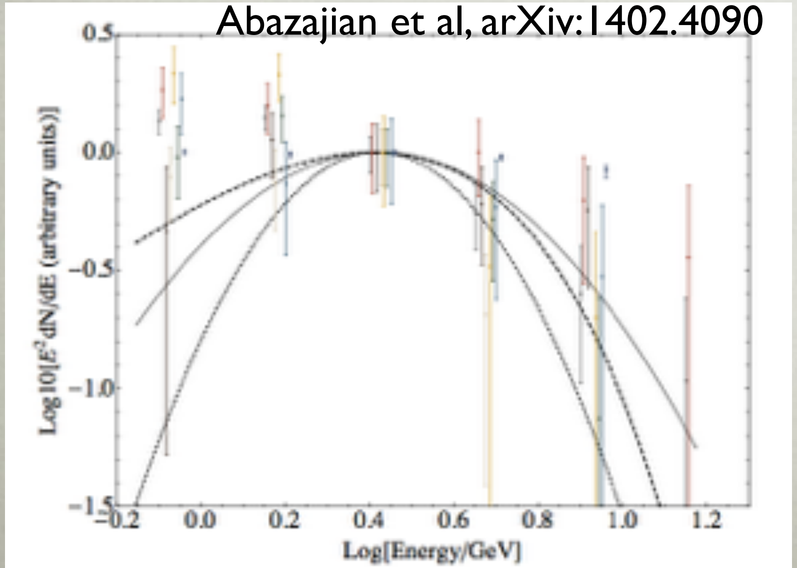


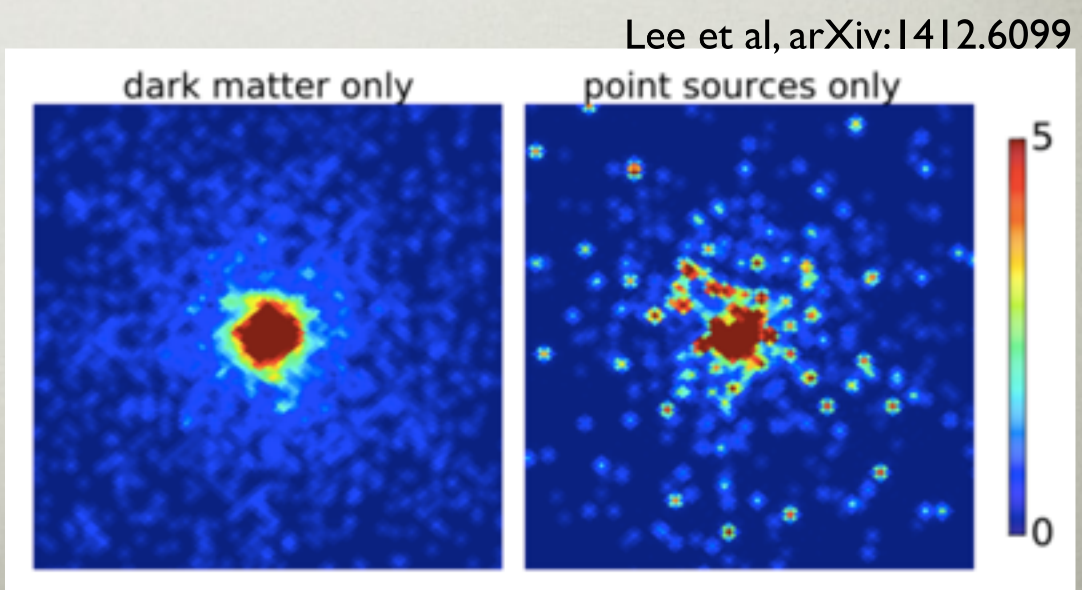
✦ **The claimed signal is a small fraction of the observed emission (depending on selected region)**

✦ **The background is brighter and uncertainties in modeling it can significantly affect the characterization of the signal**

Other Interpretations

- **In addition to DM, unresolved pulsar interpretation is found plausible**
  - Claimed excess is found consistent with O(1000) millisecond pulsars within ~1 kpc of GC (Abazajian et al arXiv:1402.4090), but see also Hooper et al arXiv:1606.09250
  - Very young pulsars might also contribute to the excess (O'Leary et al arXiv:1504.02477)
  - Spherical symmetry? Cuspy distribution? Extend out to 10°? Possibly (e.g. Abazajian et al arXiv:1402.4090, Brandt et al arXiv:1507.05616)
  - Also tested with non-poissonian photon statistics template analysis and wavelet decomposition (Lee et al arXiv:1412.6099, 1506.05124; Bartels et al arXiv:1506.05104)
- **CR proton or electron outbursts interpretations have also been proposed** (e.g. Carlson et al arXiv:1405.7685, Petrovic et al 1405.7928, Cholis et al arXiv:1506.0511



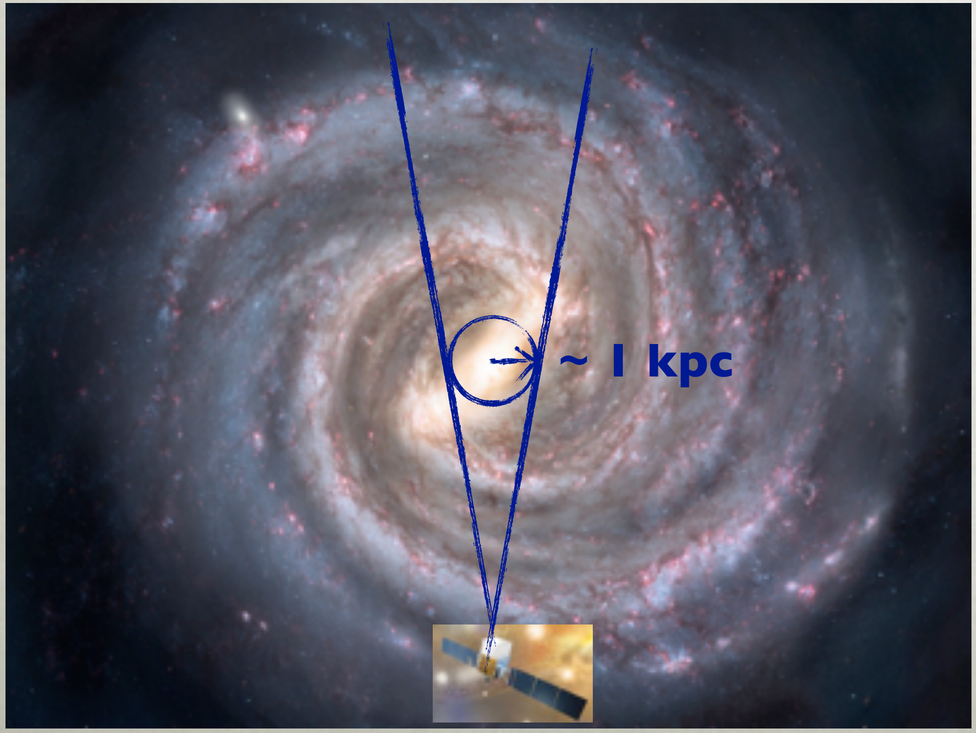


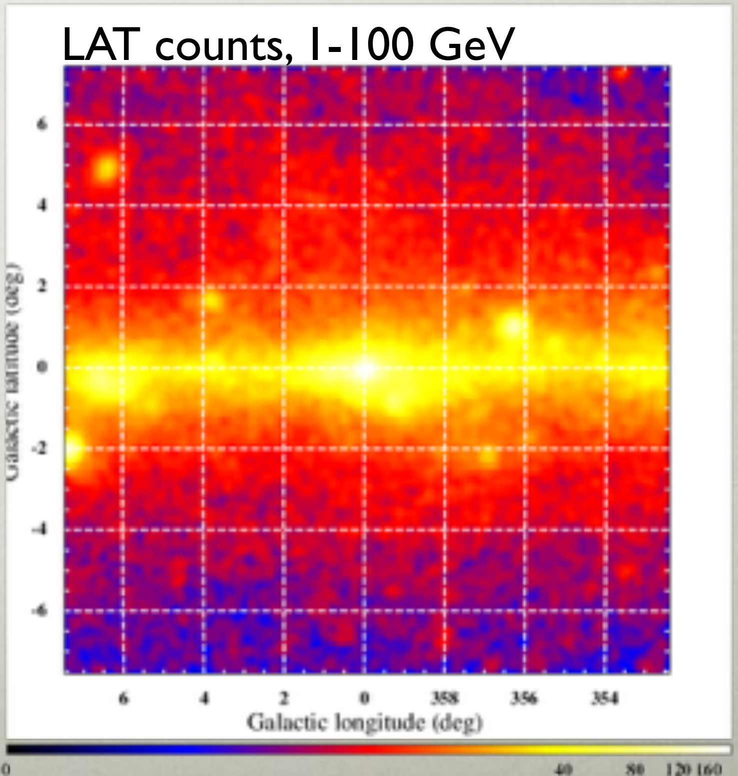
Is the presence of the excess, and its characterization, robust?

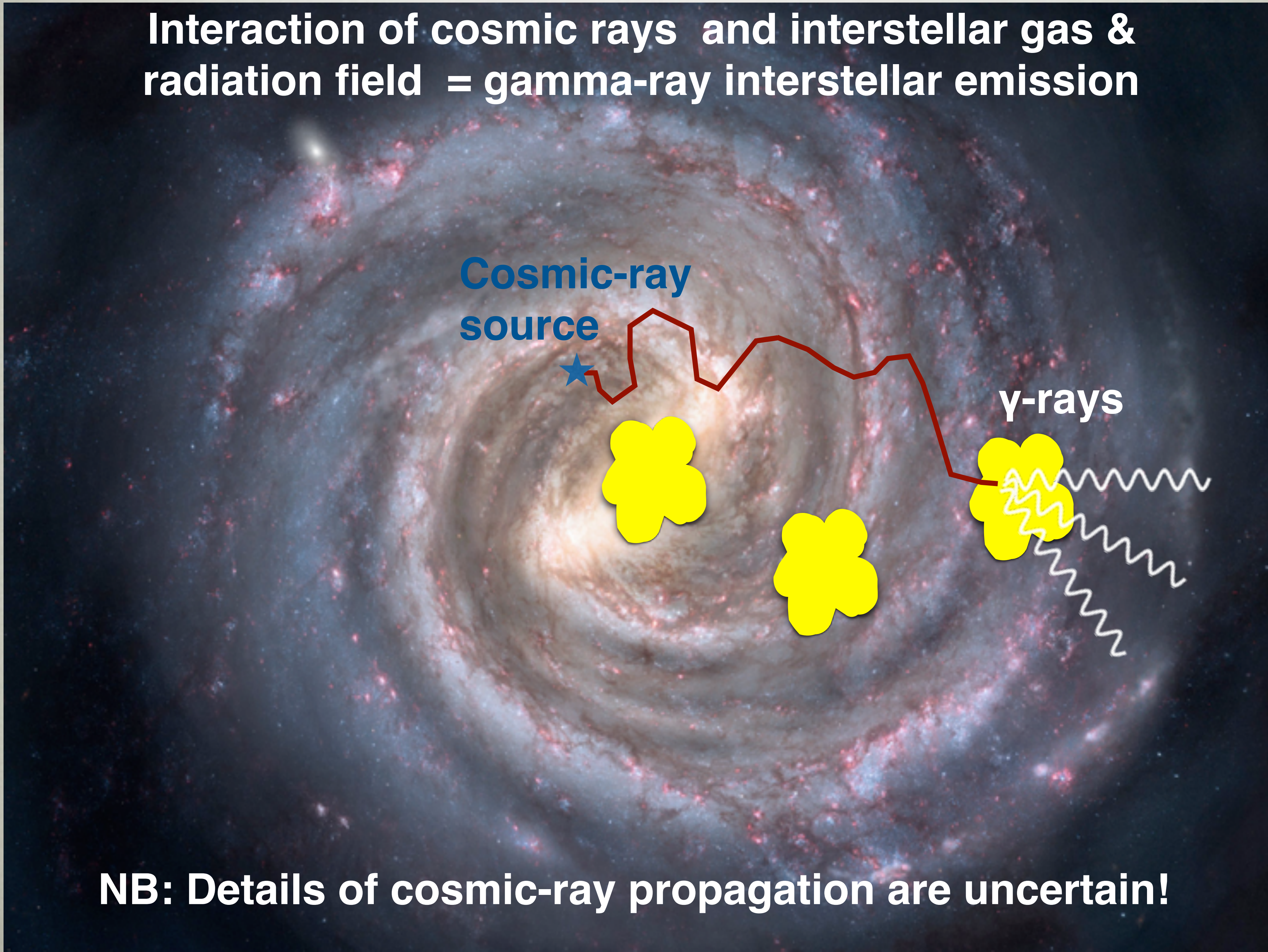
A closer look at the uncertainties in the interstellar gamma-ray emission is crucial to answer these questions

Modeling the Interstellar Emission REVISITED

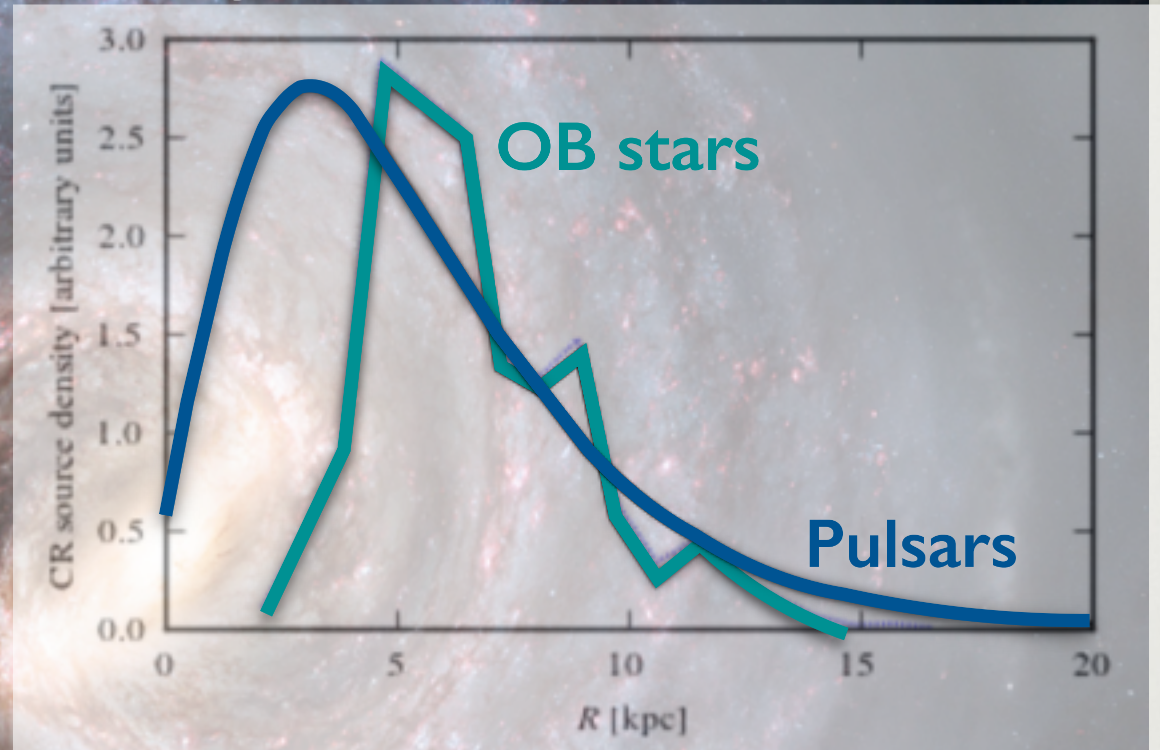
- Alternative approach by Fermi LAT collab. to develop a set of specialized models for the inner 15°x15° to <u>extract the emission from the innermost ~1 kpc</u>
- Determine point sources self-consistently with modeling of the interstellar emission






Interaction of cosmic rays and interstellar gas & radiation field = gamma-ray interstellar emission
Cosmic-ray source
γ-rays
NB: Details of cosmic-ray propagation are uncertain!

Interaction of cosmic rays and interstellar gas & radiation field = gamma-ray interstellar emission



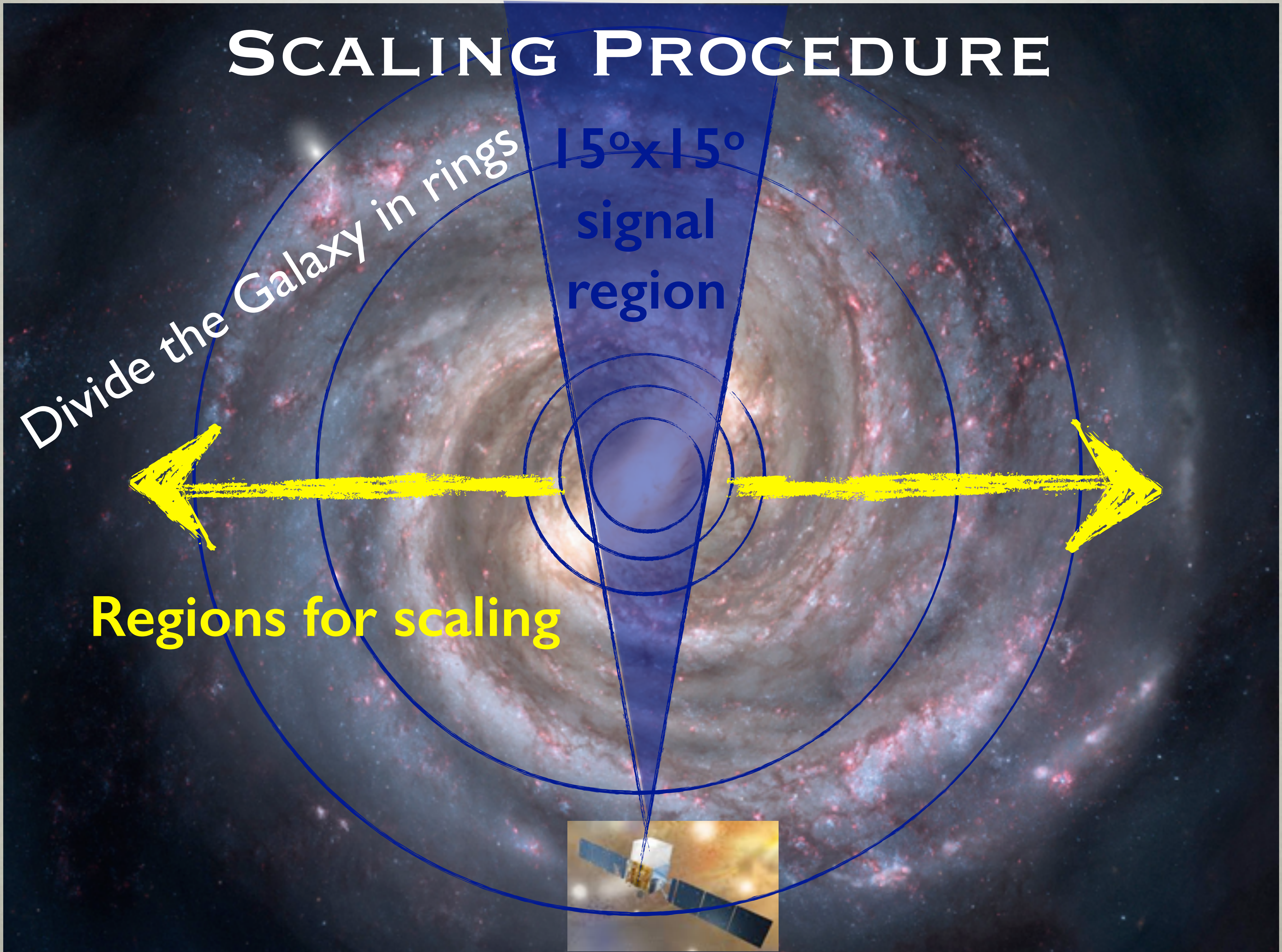
Cosmic-ray source density

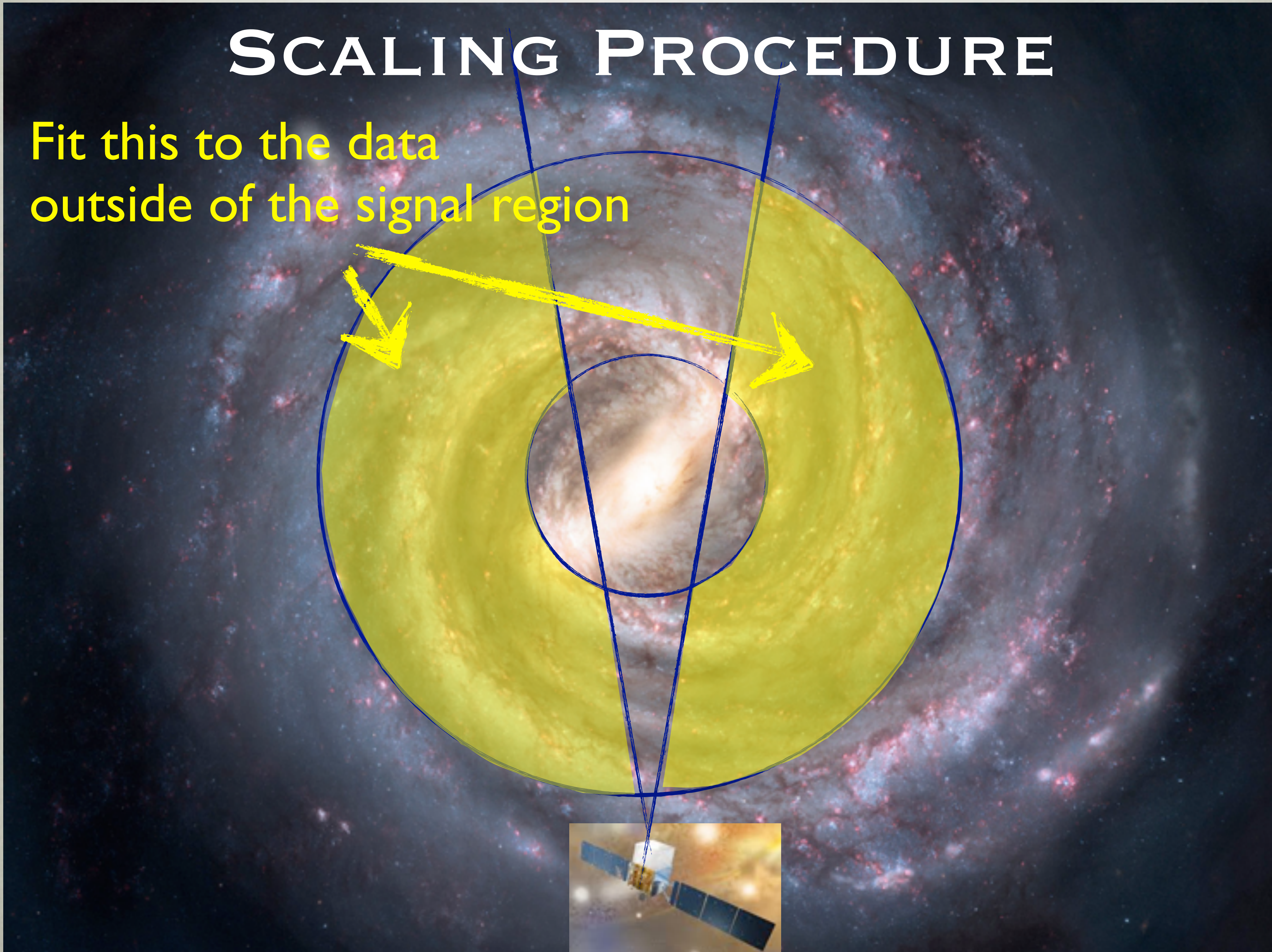
- Start with physically motivated models (GALPROP) as baseline: select two possibilities for the CR source distribution (a major uncertainty; Pulsars, OB stars used as proxies)

➡ Tune the γ-ray intensities (in rings) predicted by baseline models to the gamma-ray data outside of the 15°x15° region to **address some of the shortcomings of the baseline models for improved fore/background determination**

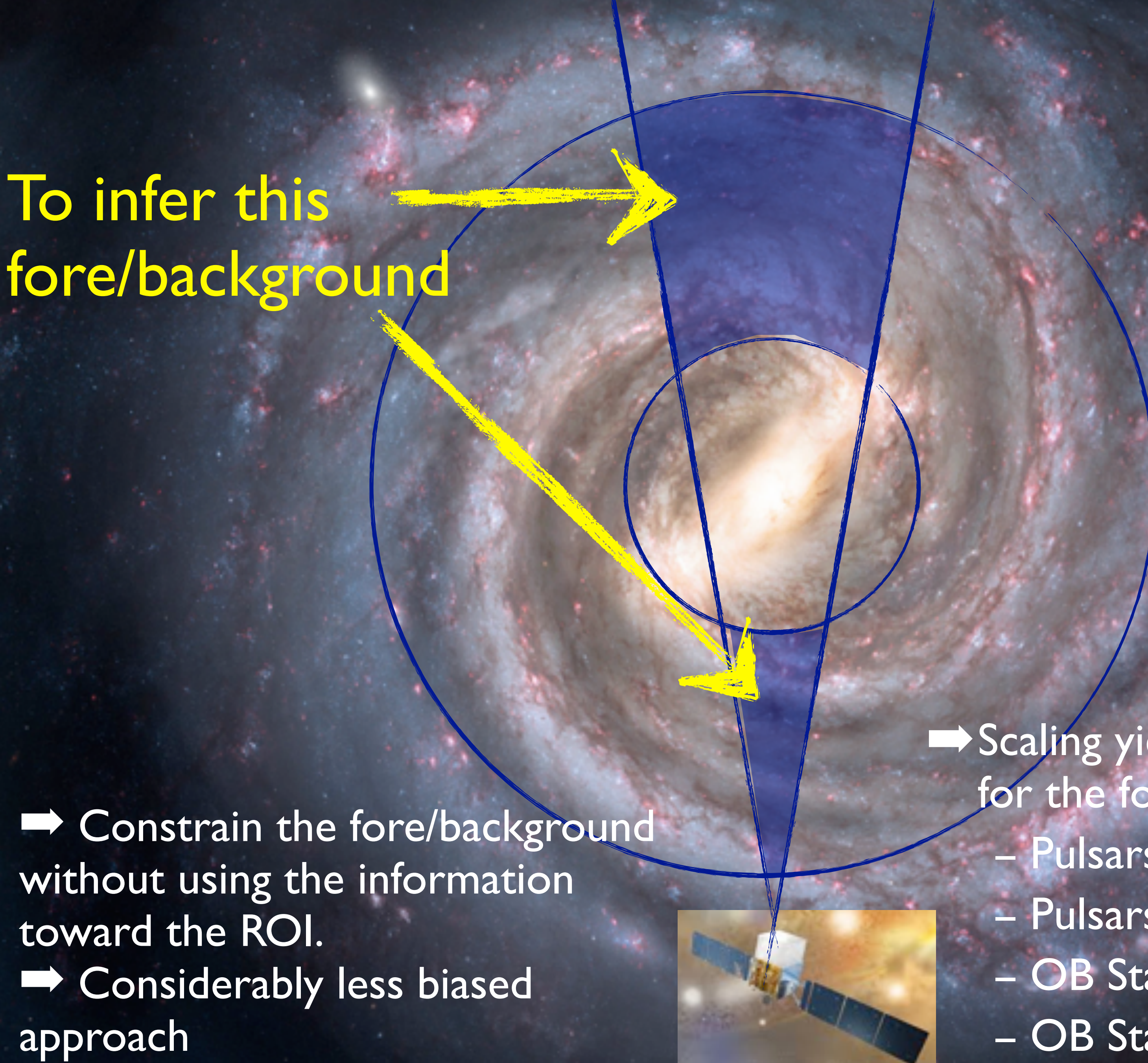
Scaling Procedure

Scaling Procedure




Scaling Procedure
Fit this to the data
outside of the signal region

Scaling Procedure



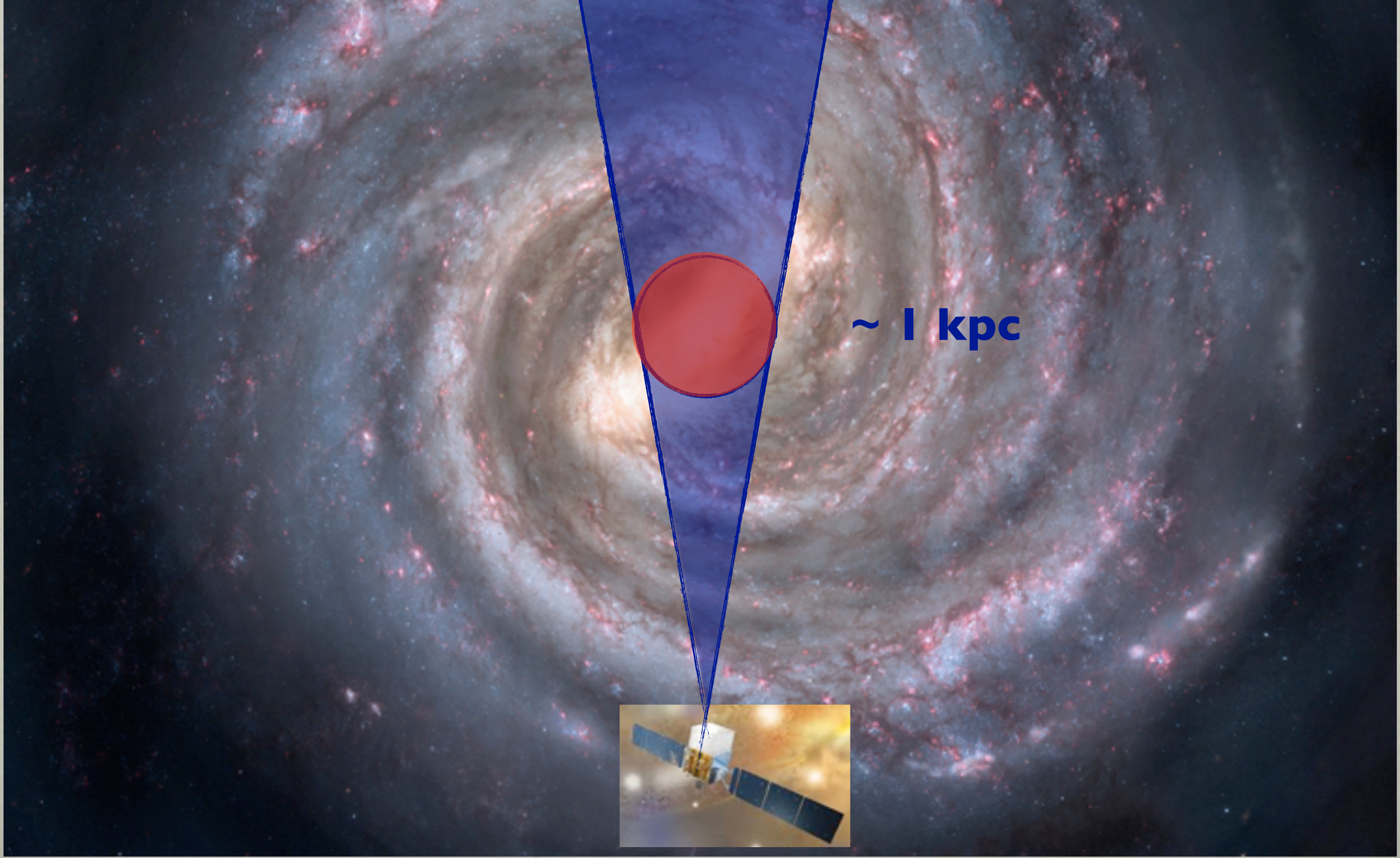
➡ Constrain the fore/background without using the information toward the ROI.

➡ Considerably less biased approach

➡ Scaling yields four variants for the fore/background IEM:

– Pulsars, intensity scaled
– Pulsars, index scaled
– OB Stars, intensity scaled
– OB Stars, index scaled

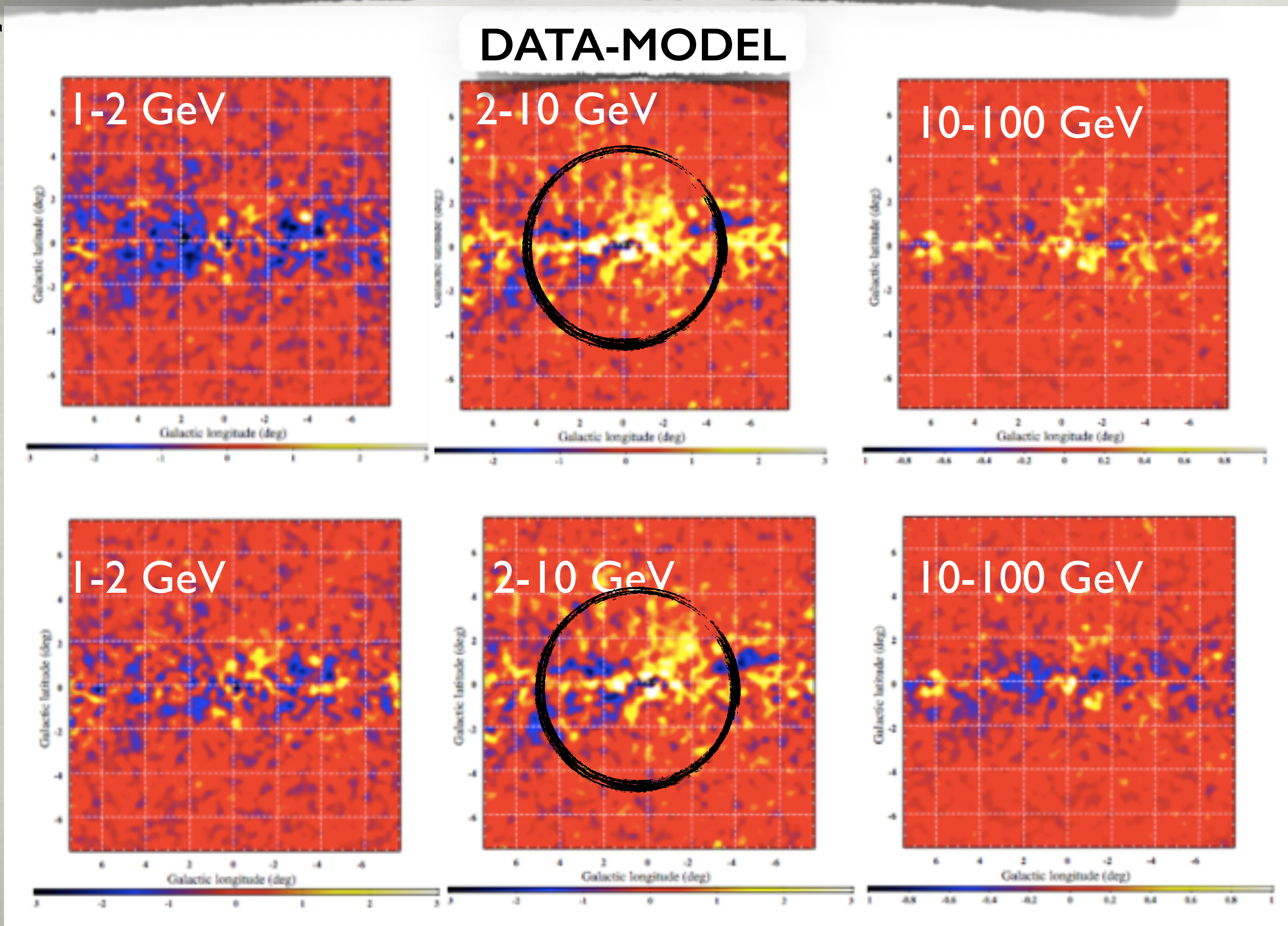
➡ Determine intensities for the **inner ~1 kpc for HI/H_2 π^0, and IC** by fitting the data in the 15°x15° region for each of the four **fore/background models** (held constant in the fit)



Structured excesses and deficits point to imperfectly modeled components and/or <u>un-modeled contributions</u>

Pulsars, tuned-intensity

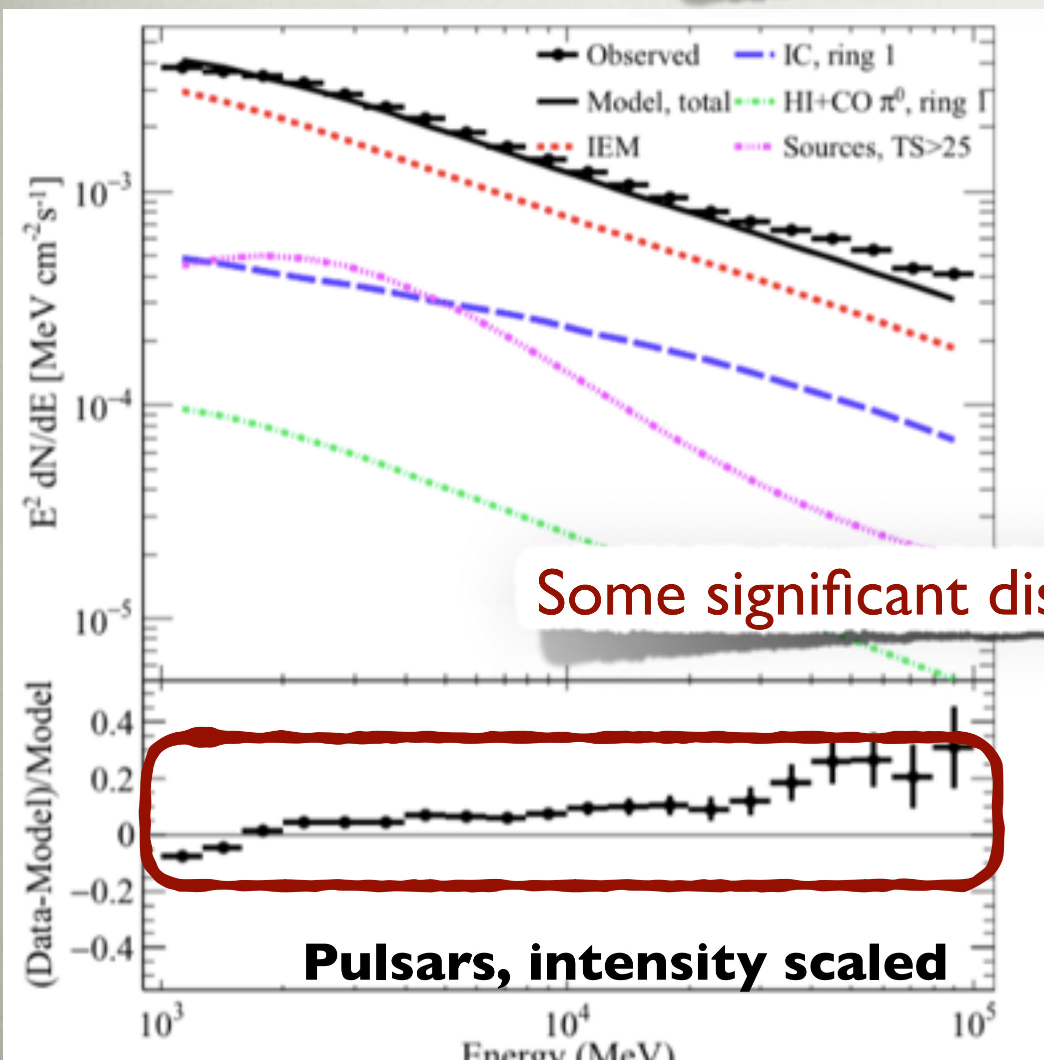
Pulsars, tuned-index

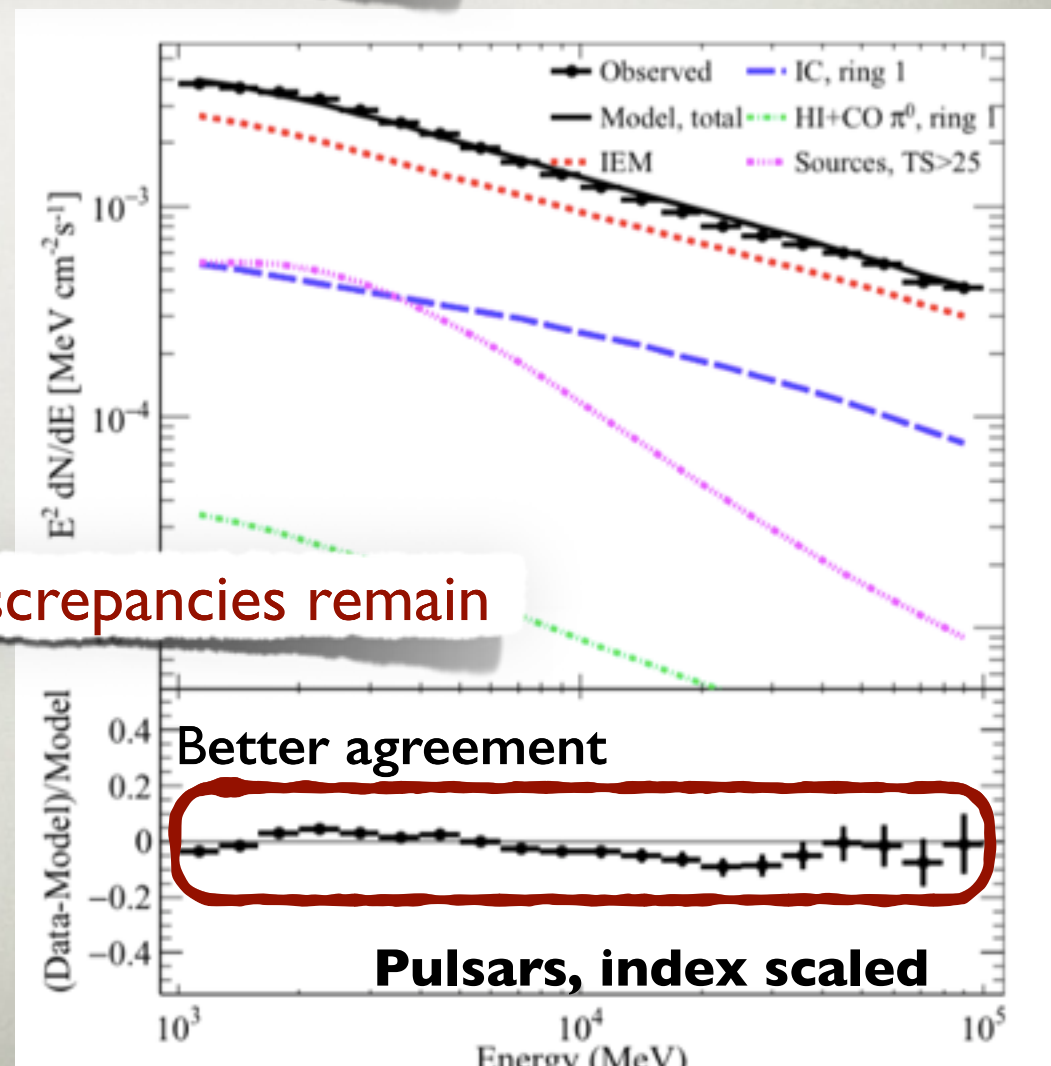


Counts in 0.1°x0.1° pixels, 0.3° radius gaussian smoothing

Results - IEM

Integrated flux in 15°x15° ROI



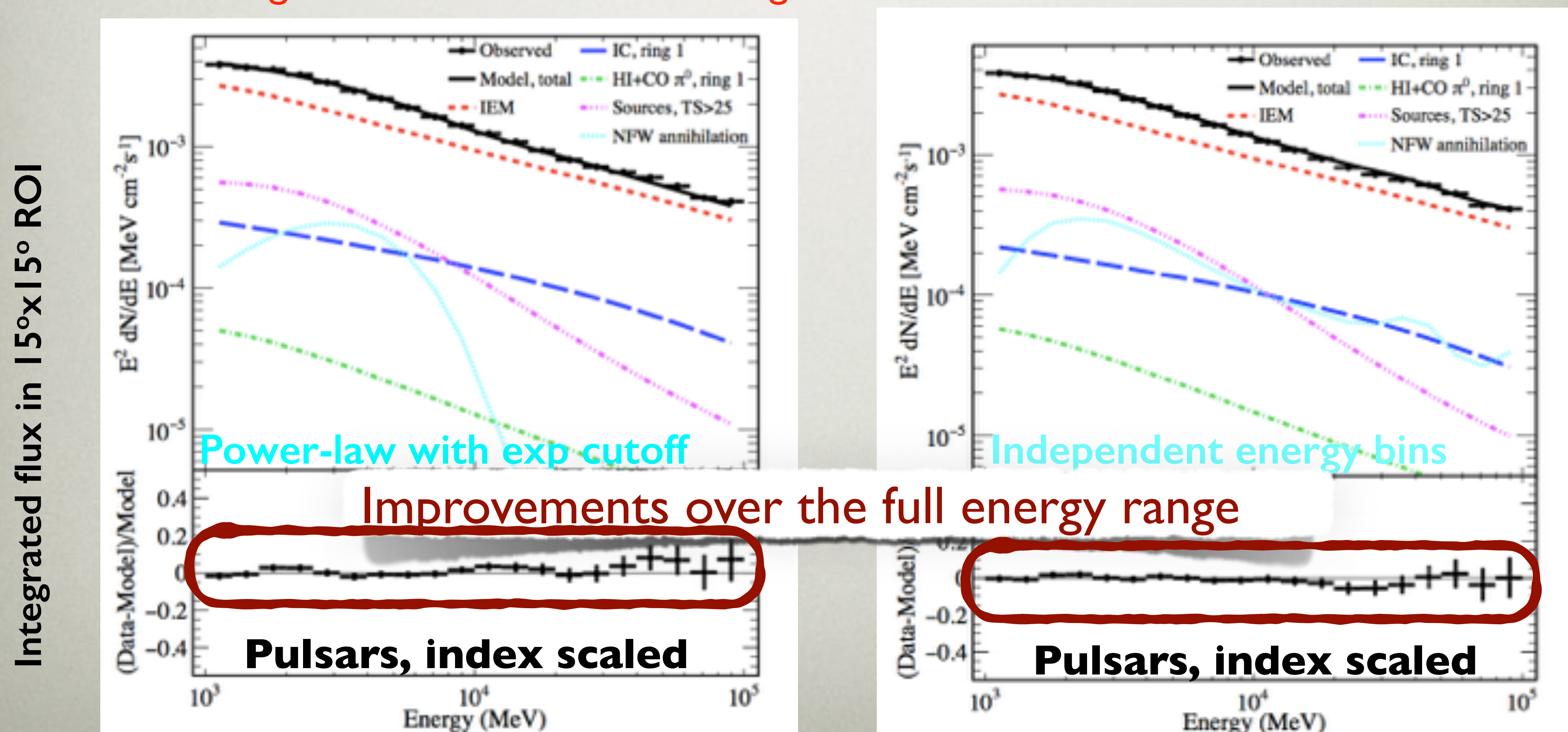


Some significant discrepancies remain

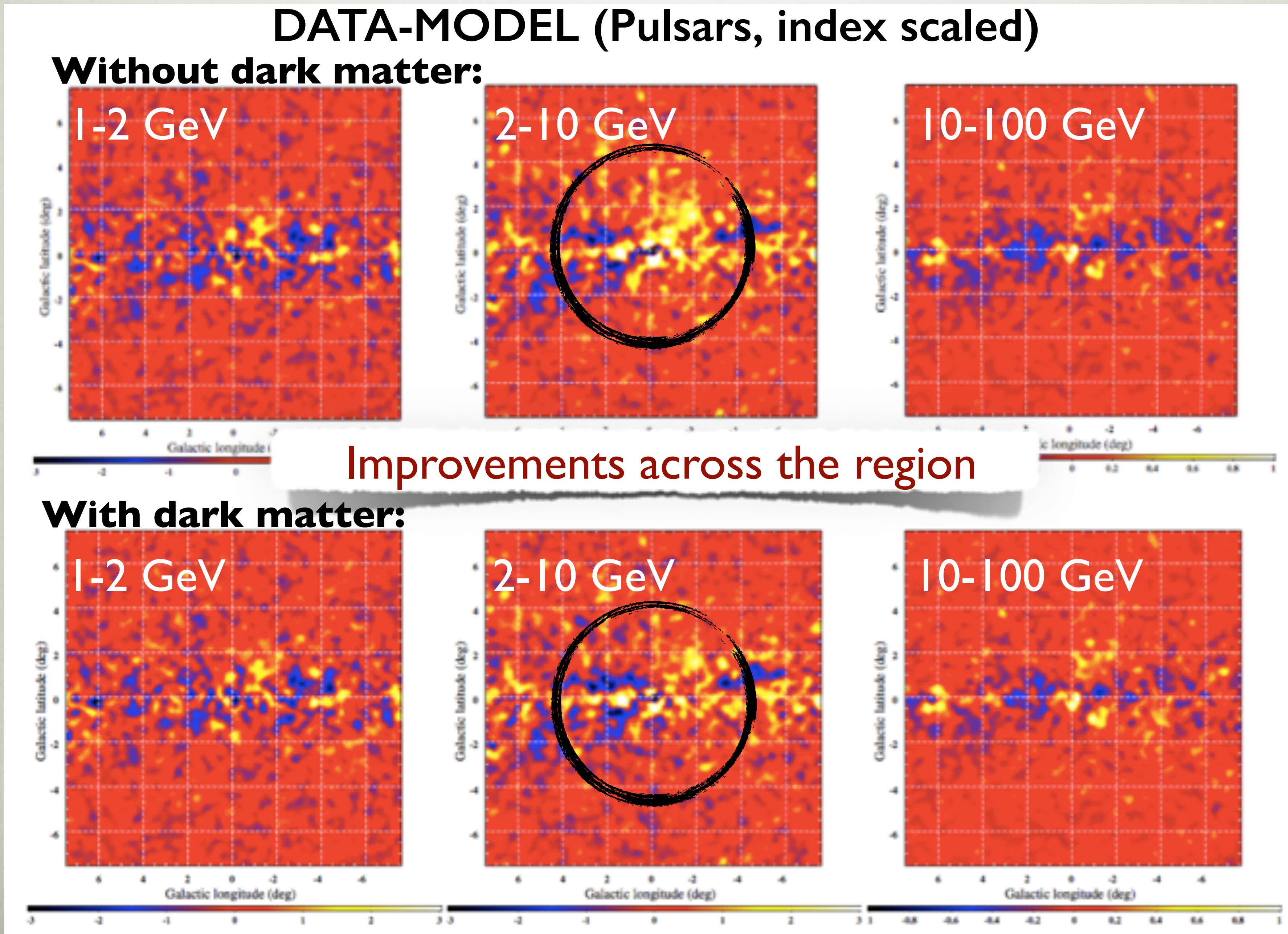
Additional Component

- Spatial morphology: 2D gaussians, dark matter annihilation/decay, or a gas-like as proxy for unresolved source. Spectrum: **exponentially cutoff power law** (motivated by some dark matter and pulsar models); fit in **independent energy bins**

➡ The dark matter annihilation morphology yields the most significant improvements in the data-model agreement for the 4 fore/background IEMs



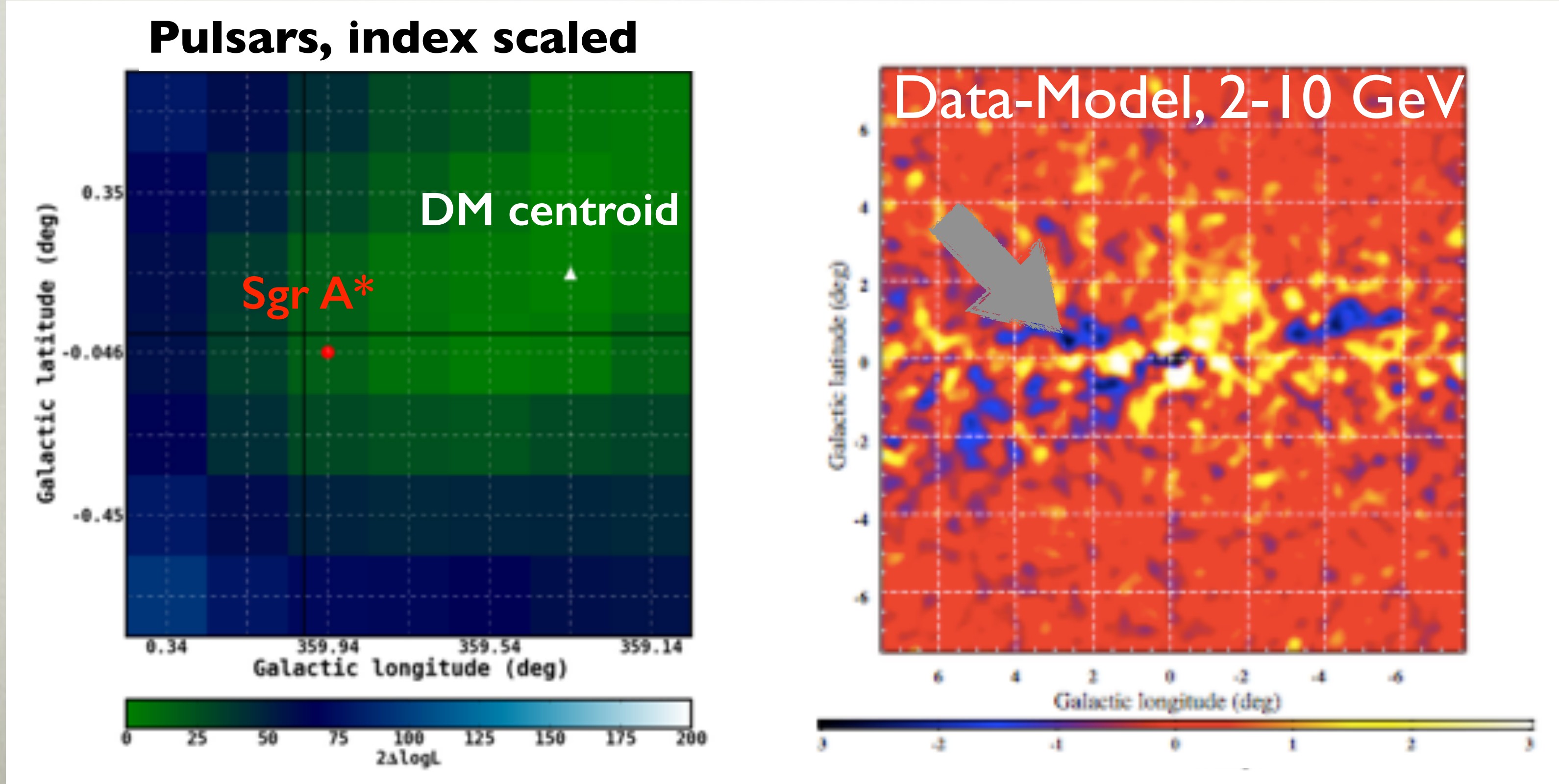
Residual Maps
Dark Matter



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

Dark Matter Component Morphology

- Cuspiness of the DM profile (whether a standard, $\gamma=1$, or cuspier, $\gamma=1.2$, profile is favored) depends on IEM modeling
- Centroid is offset compared to Sgr A* (disfavored at ~90% C.L., C. Karwin et al, in prep), <u>but</u>:
  - ✓ some dependence on IEM (offset ~0.5°-1°)
  - ✓ cannot rule out offset is due to shortcomings in modeling of IEM



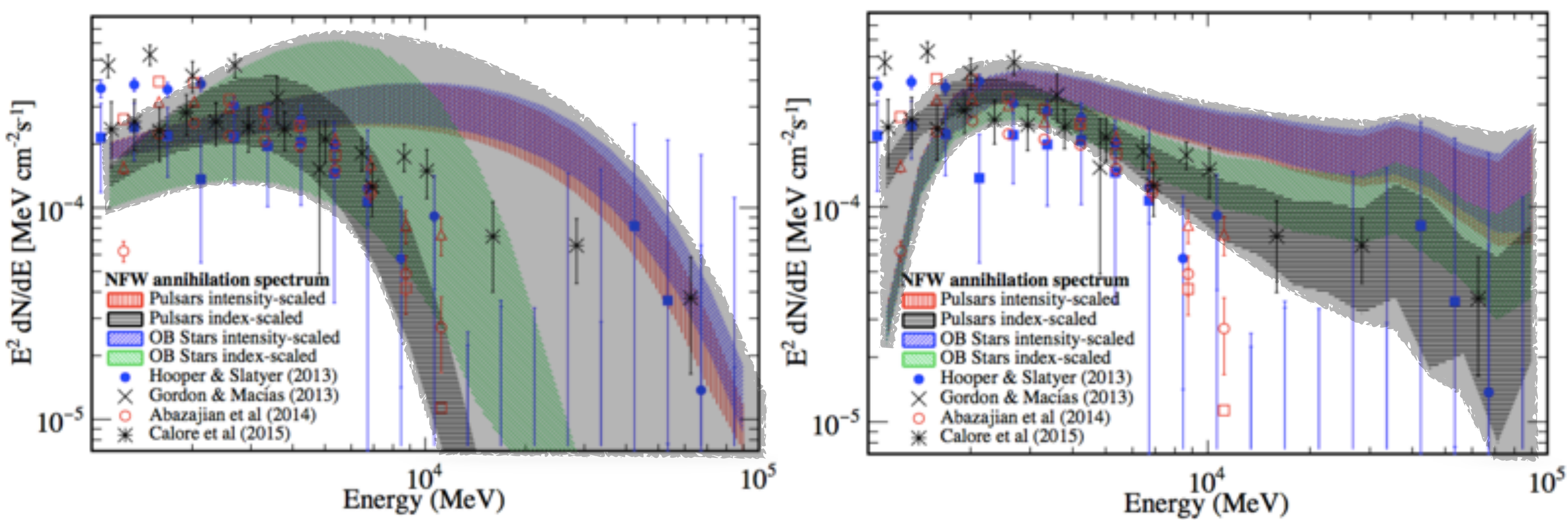
C. Karwin et al, in prep

Dark Matter Component Spectrum

- The dark matter component spectrum depends strongly on the fore/background models.

Grey bands include systematic uncertainties explored by Fermi LAT collab. analysis

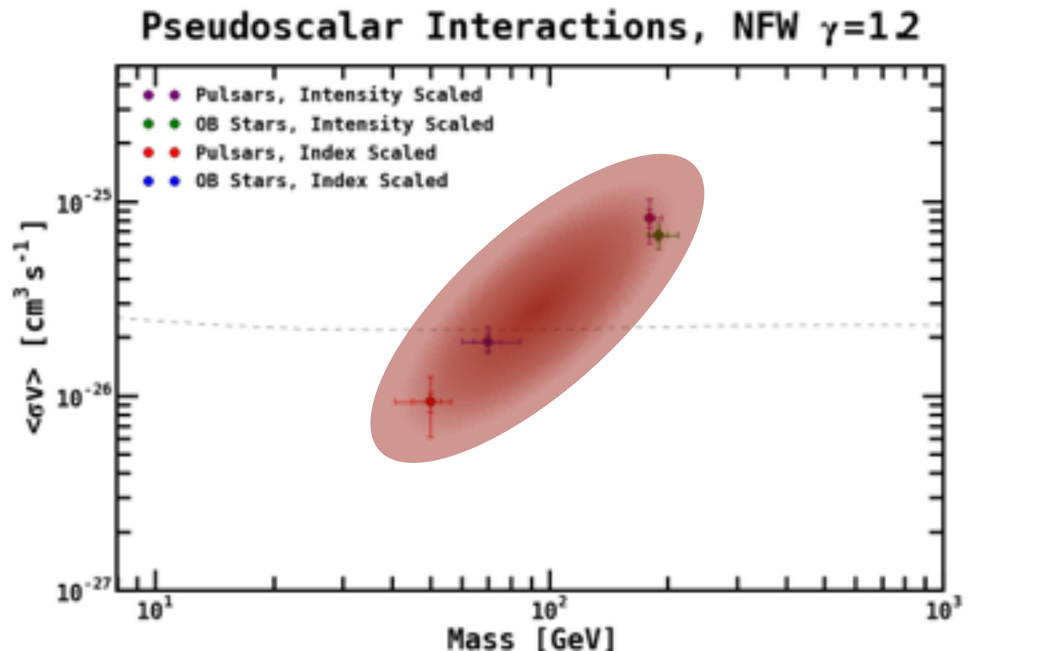
➡ A broader range of interpretations is allowed compared to previous results



Implications for Dark Matter Models

- Consider general models with DM particles annihilating into two-body (fermionic) final states where the interactions between the dark sector and standard model particles occurs via *scalar* or *vector* interactions
  - Scalar interaction proportional to the fermion mass
  - Vector interaction independent of fermion mass
- Fit the relative strengths of couplings to quarks and leptons to the Fermi LAT data with the developed IEMs+point sources

C. Karwin, et al, in prep.



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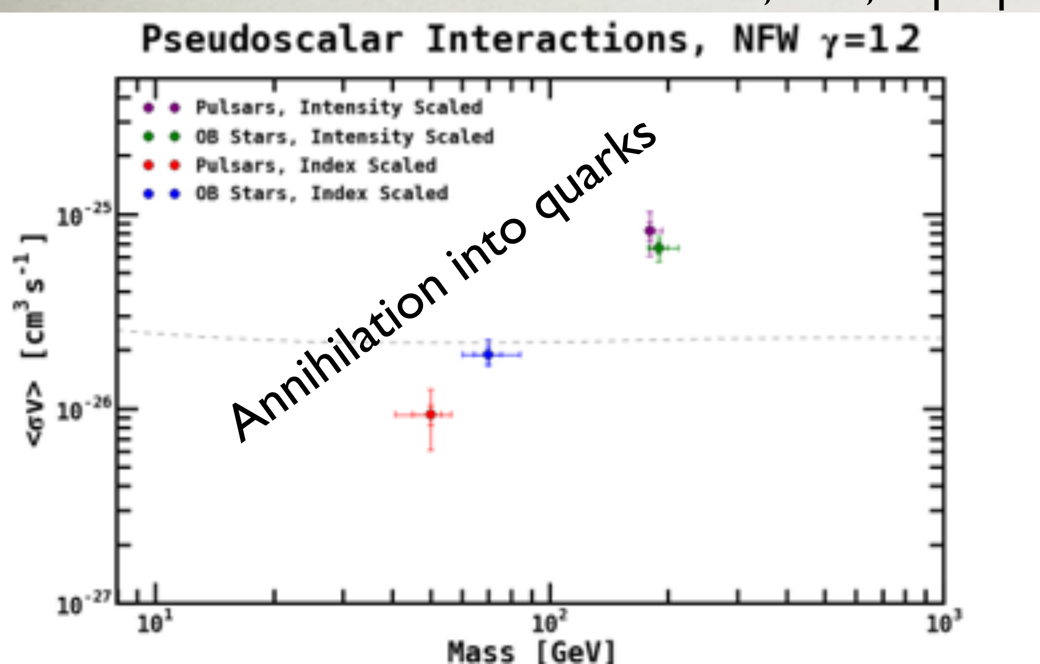

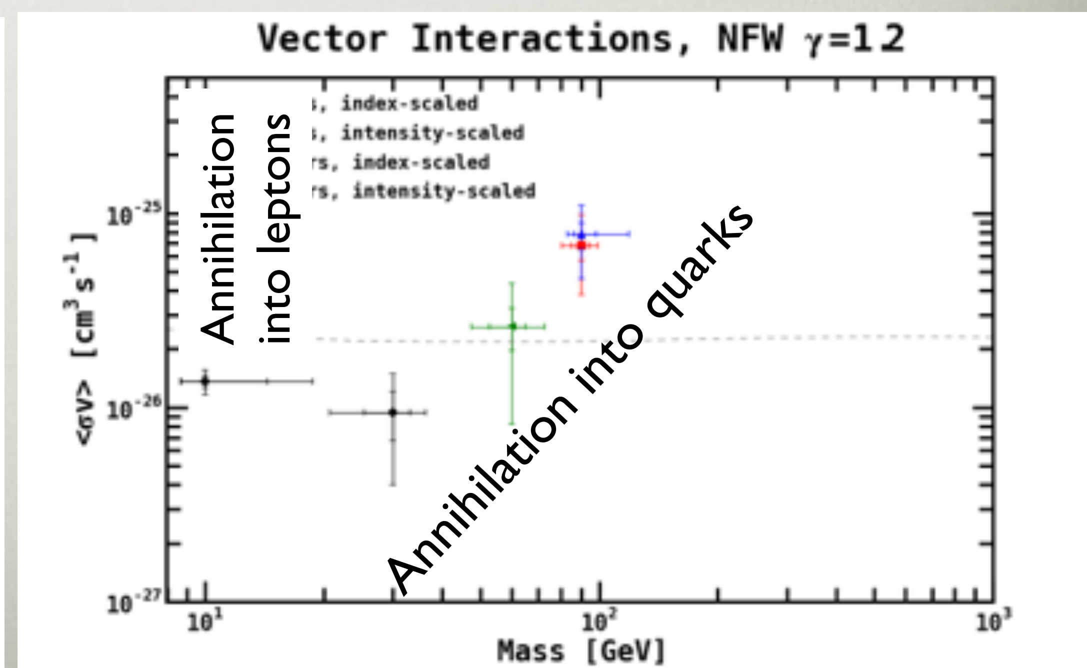

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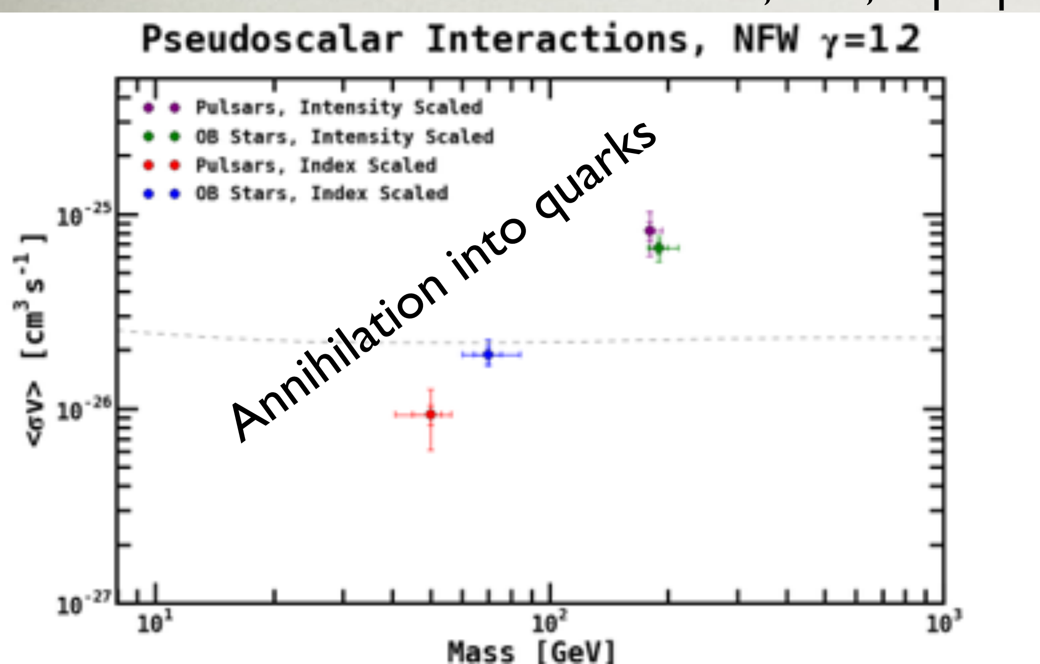
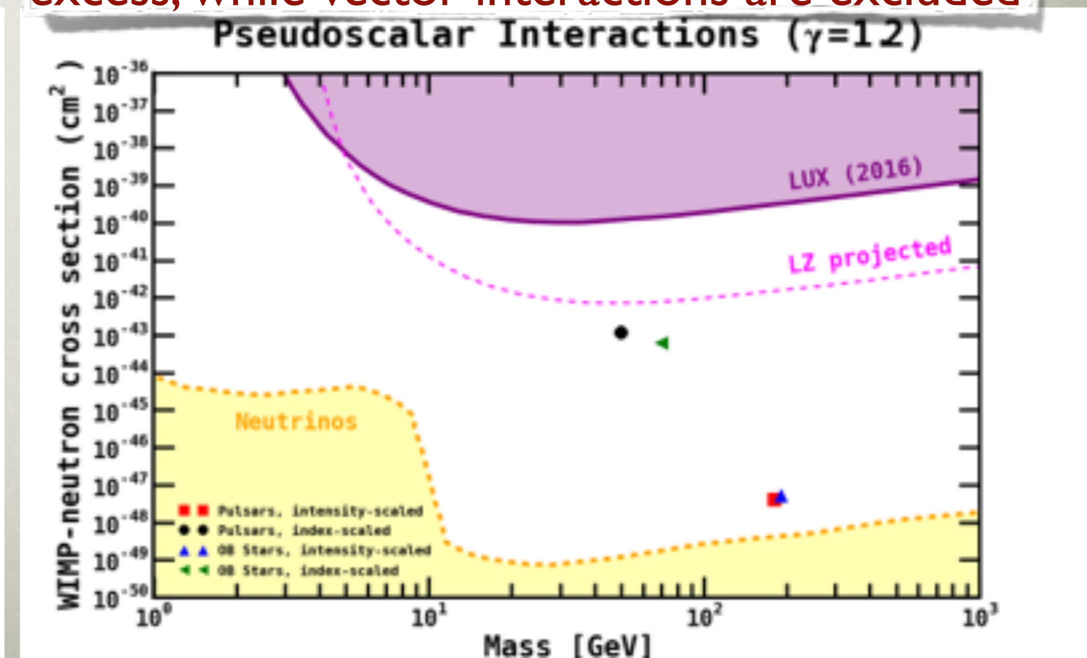
Direct detection doesn't rule out scalar interactions as an interpretation of the GC excess, while vector interactions are excluded

C. Karwin, et al, in prep.

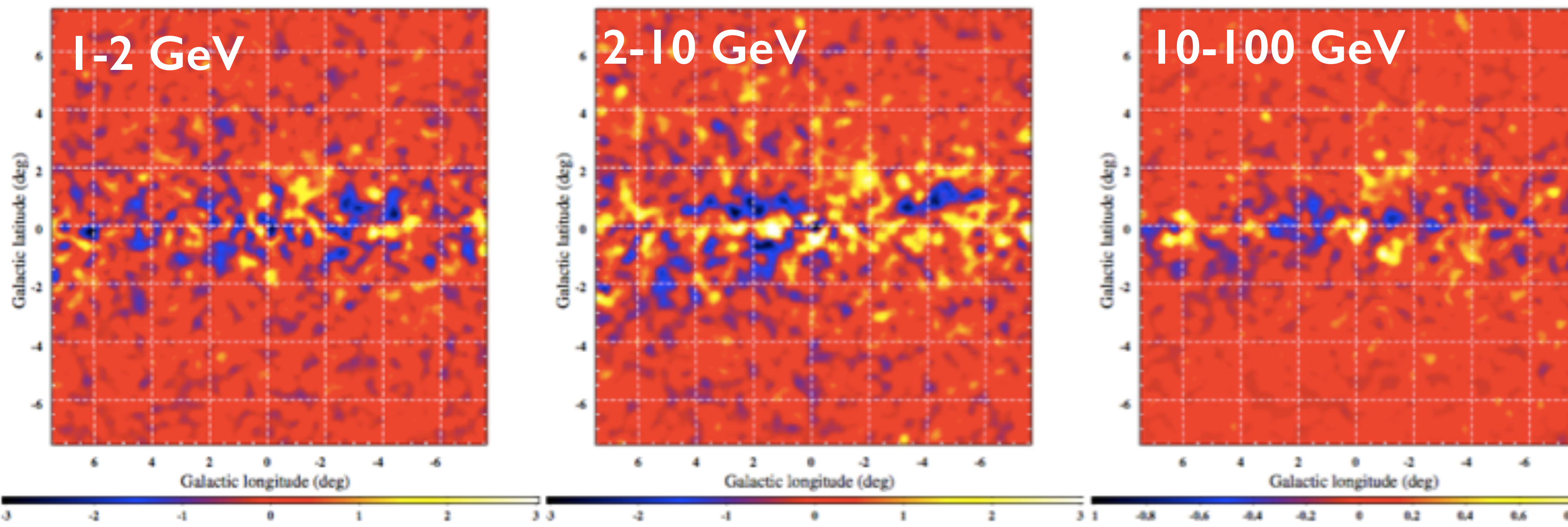




Residual Maps
Dark Matter

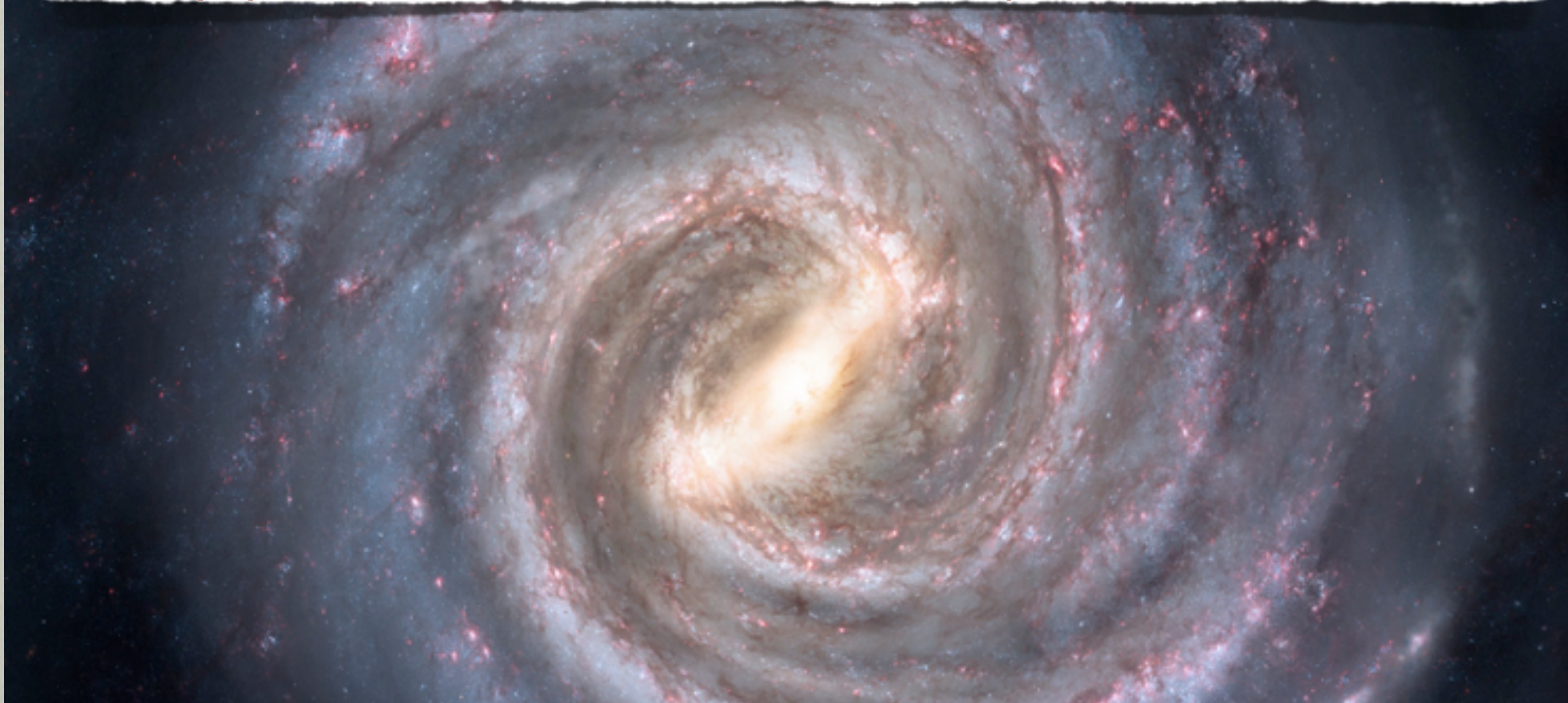
Improvements across the region, but some discrepancies between data and model remain

DATA-MODEL (Pulsars, index scaled - <u>with dark matter</u>)



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

✦ Not surprising… there are limitations in **all** interstellar emission models employed so far, e.g., cylindrical symmetry, the gas distribution, as well as interplay between the interstellar emission and point sources.



The density of cosmic-ray sources and interstellar medium is associated with spiral arms, Galactic bar/bulge, and therefore radially and azimuthally dependent

Currently there are no detailed 3D models for the interstellar gas, radiation field, and cosmic-ray sources

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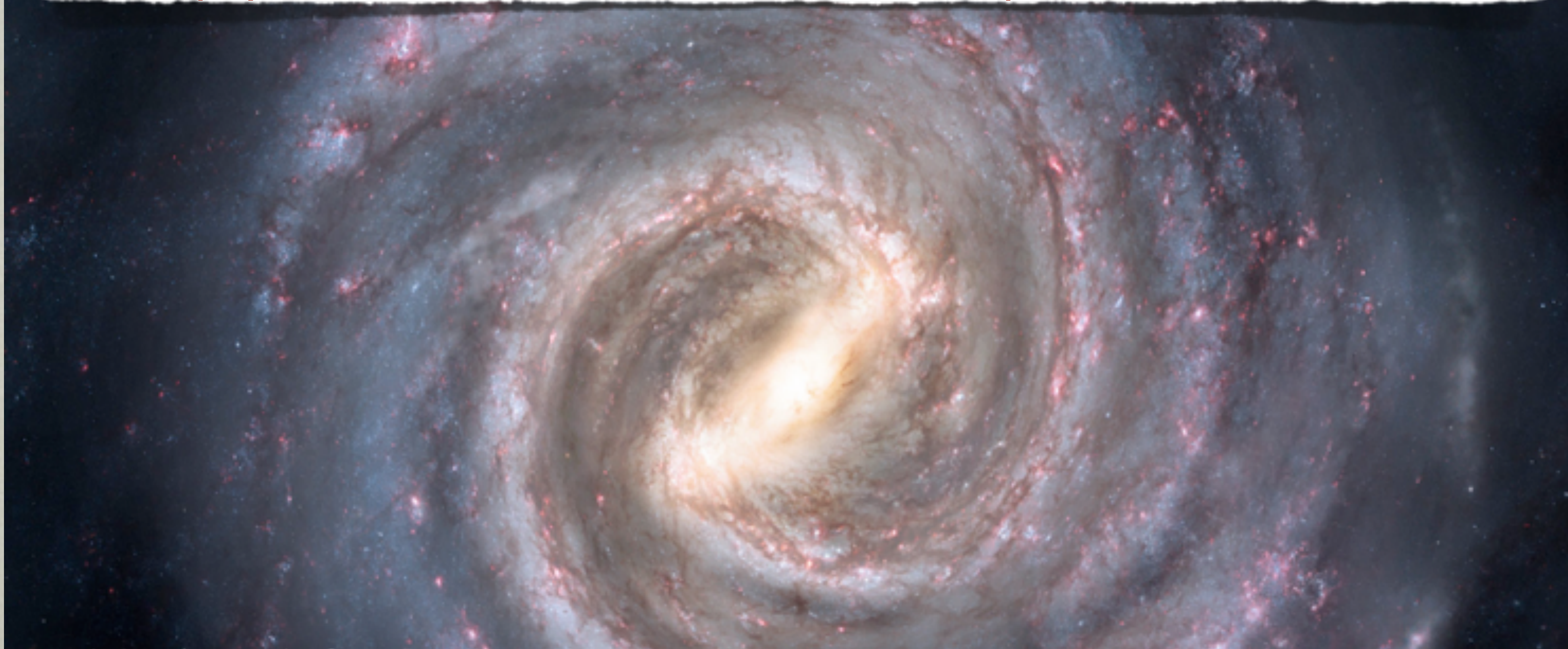


➡ **Understanding these issues and addressing these limitations is crucial to confirm the presence and properties of additional components, <u>dark matter or otherwise!</u>**

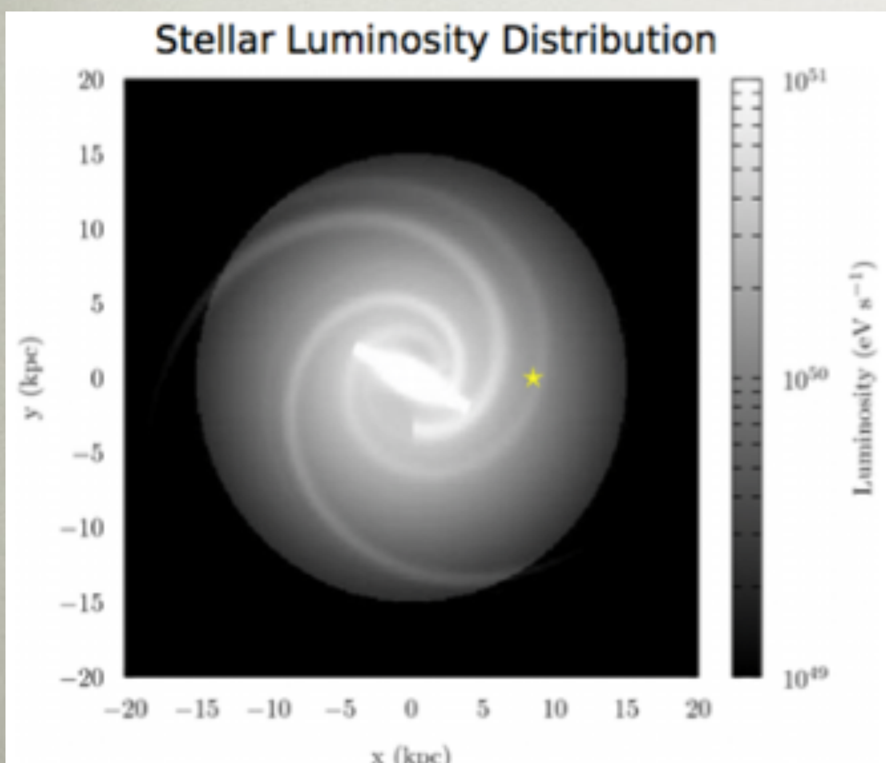
➡ **Work is underway in addressing these limitations**

3D ISRF

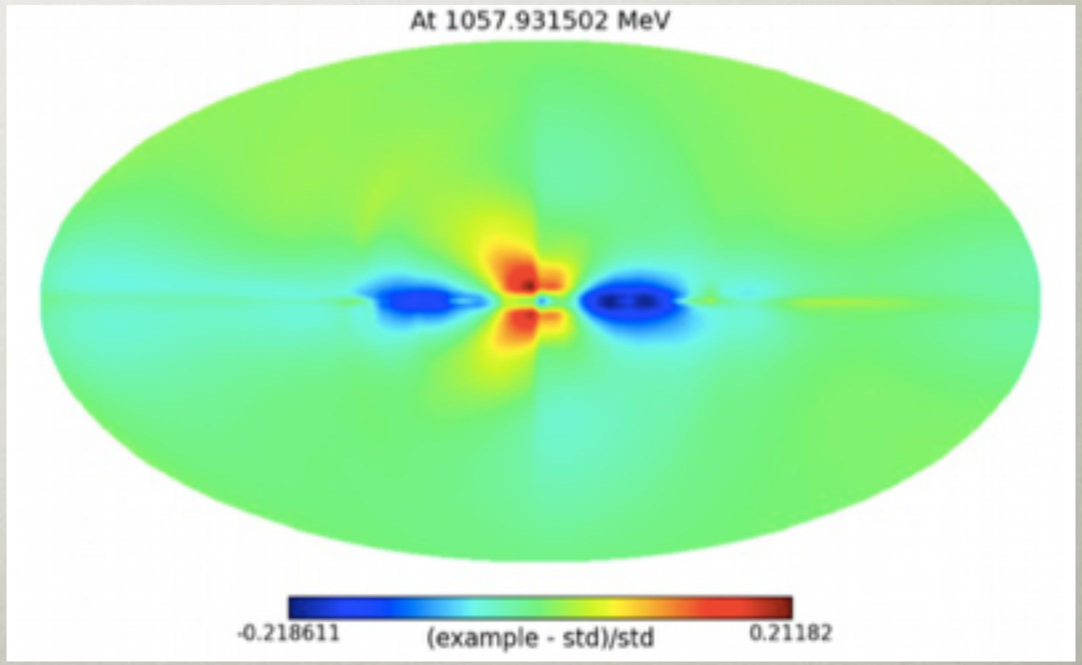
- First steps on 3D modeling of the interstellar radiation fields underway (GALPROP, T. Porter et al)

  Build improved stellar luminosity model tuned to multi-wavelength data (few μm and ~ 100 μm), test case results are shown

IC γ-ray map based on preliminary 3D ISRF is asymmetric (not so for 2D ISRF)! Implications for residual emission and its interpretation

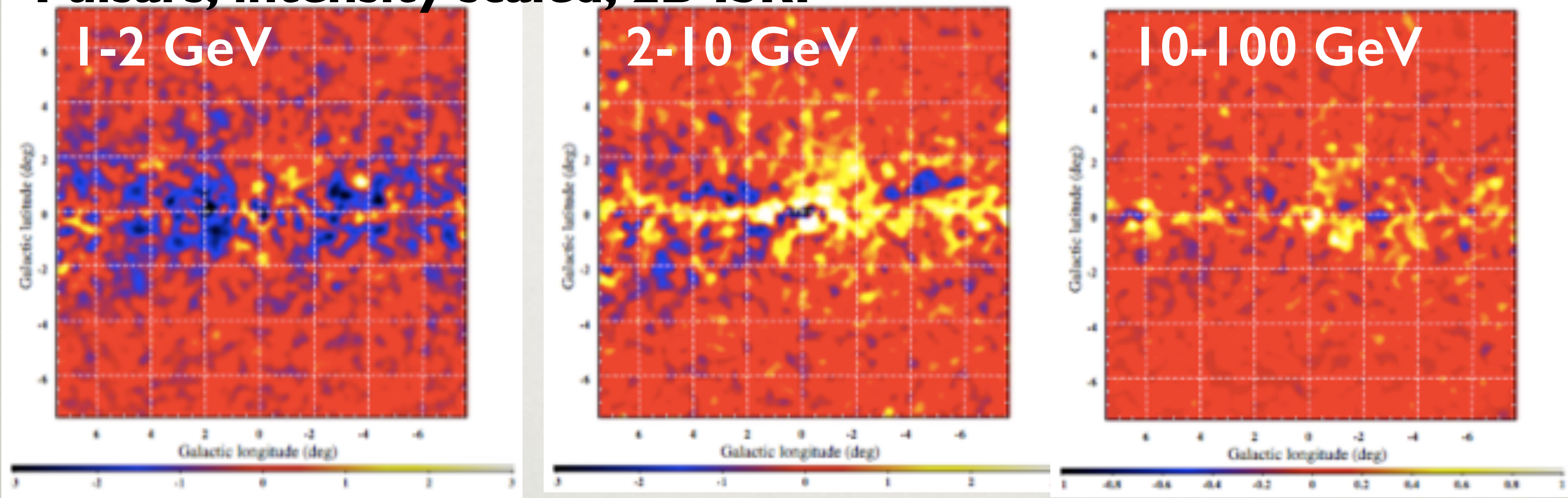


(IC_3D - IC_2D)/IC_2D at ~1 GeV

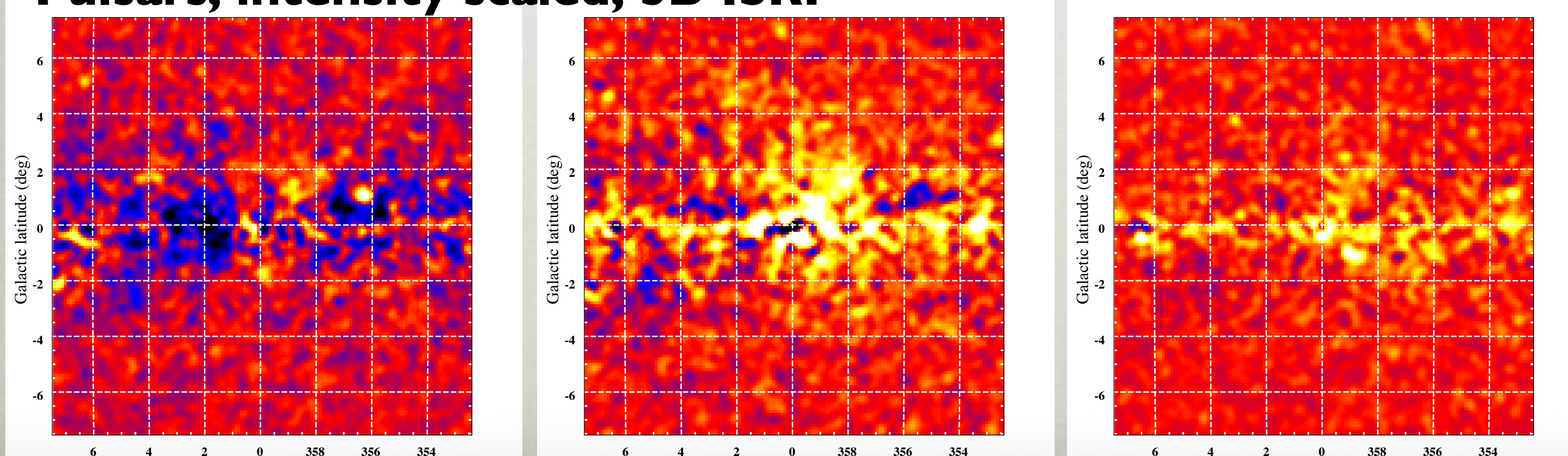


GC Preliminary Results with 3D ISRF

Pulsars, intensity scaled, 2D ISRF



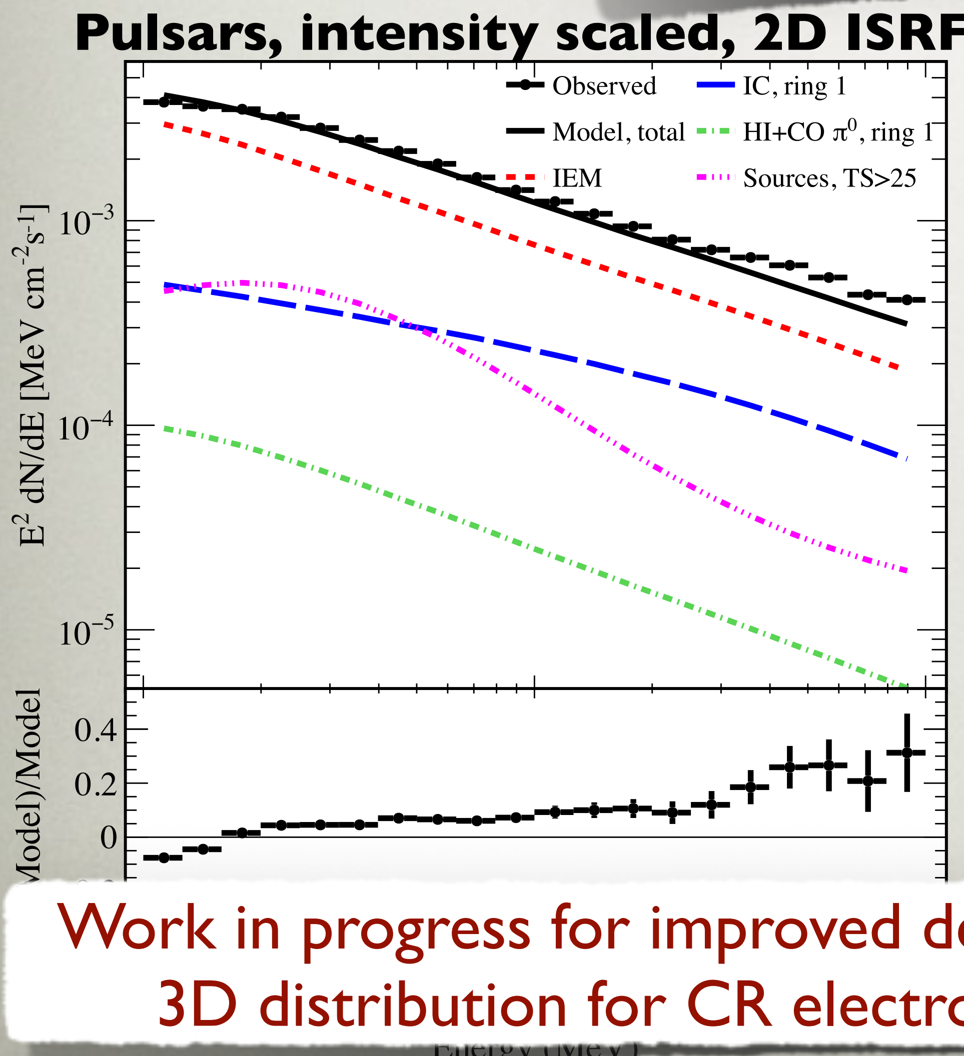
Pulsars, intensity scaled, 3D ISRF

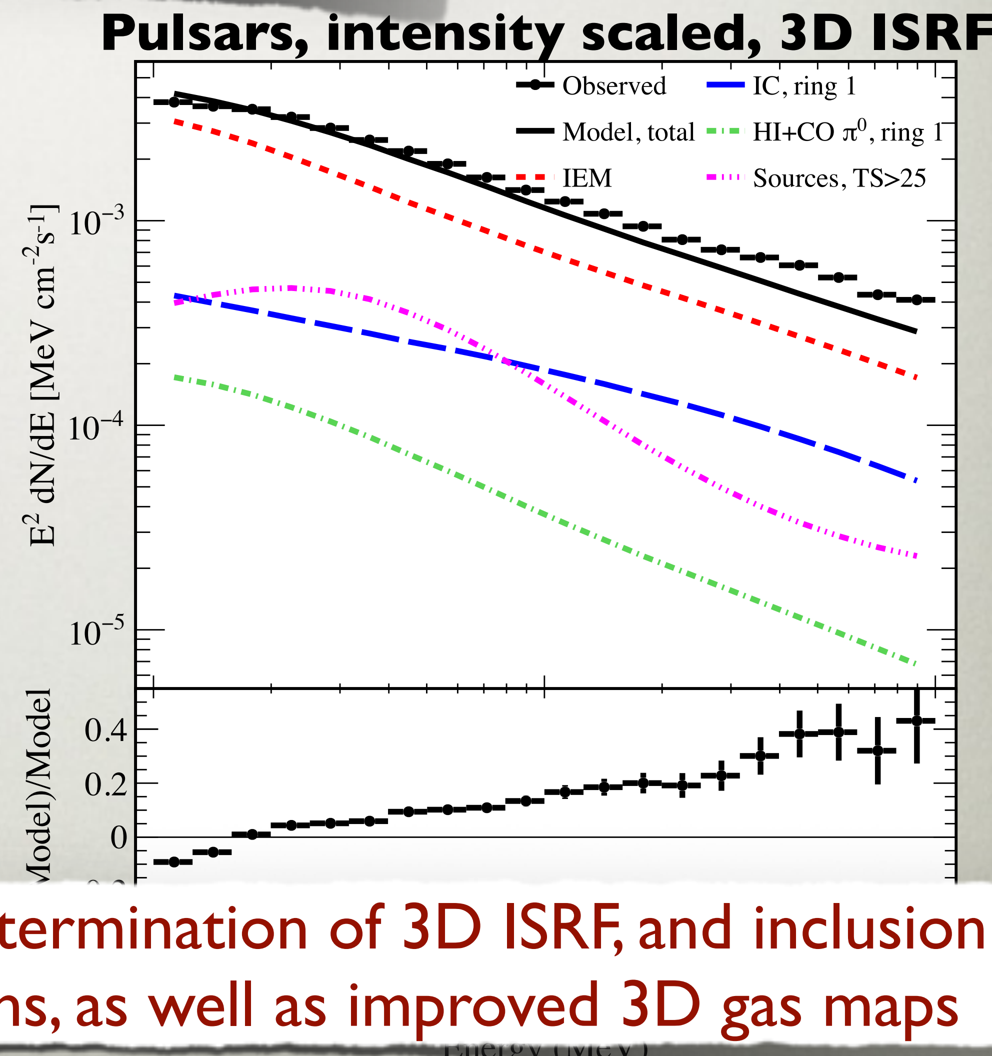


Similar features in residuals as with 2D ISRF, but more enhanced for 3D ISRF

GC Preliminary Results with 3D ISRF

Integrated flux in 15°x15° ROI





Work in progress for improved determination of 3D ISRF, and inclusion of 3D distribution for CR electrons, as well as improved 3D gas maps

Similar features in residuals as with 2D ISRF, but more enhanced for 3D ISRF

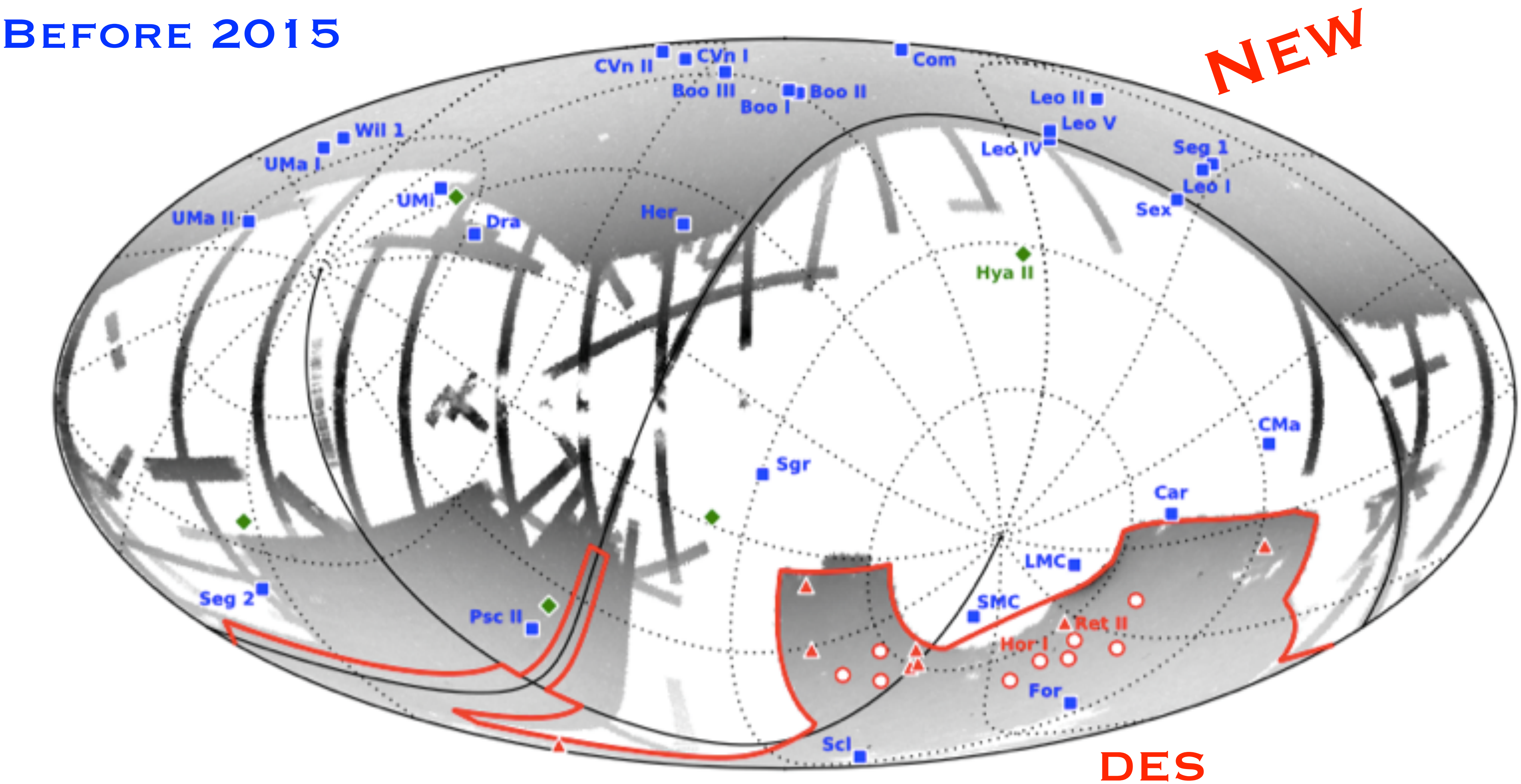
Dwarf Spheroidal Galaxies

- Optically observed dwarf spheroidal galaxies: 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

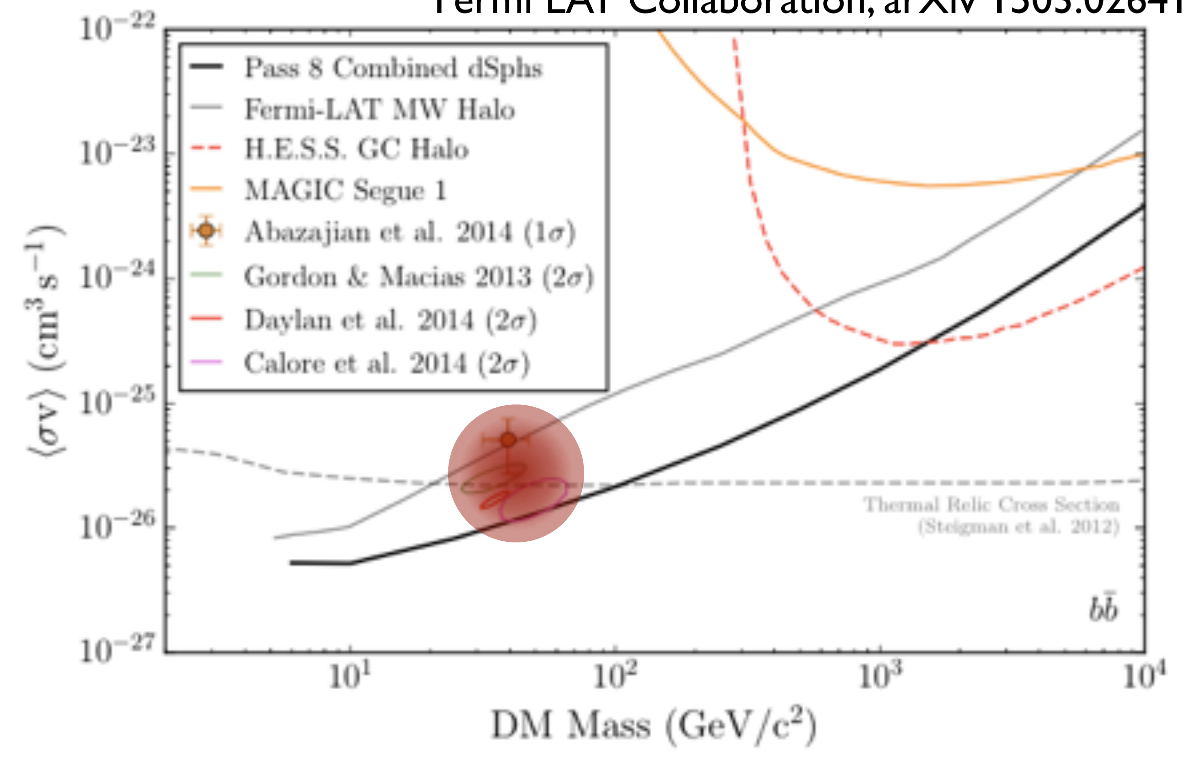
DES Collaboration, arXiv:1508.03622



Dwarf Spheroidal Galaxies

- Search for a signal in 25 dwarf spheroidal galaxies, 6 years of Fermi LAT data
  - ➡ No significant emission is found
- Limits probe DM explanation of the GC excess

Fermi LAT Collaboration, arXiv 1503.02641



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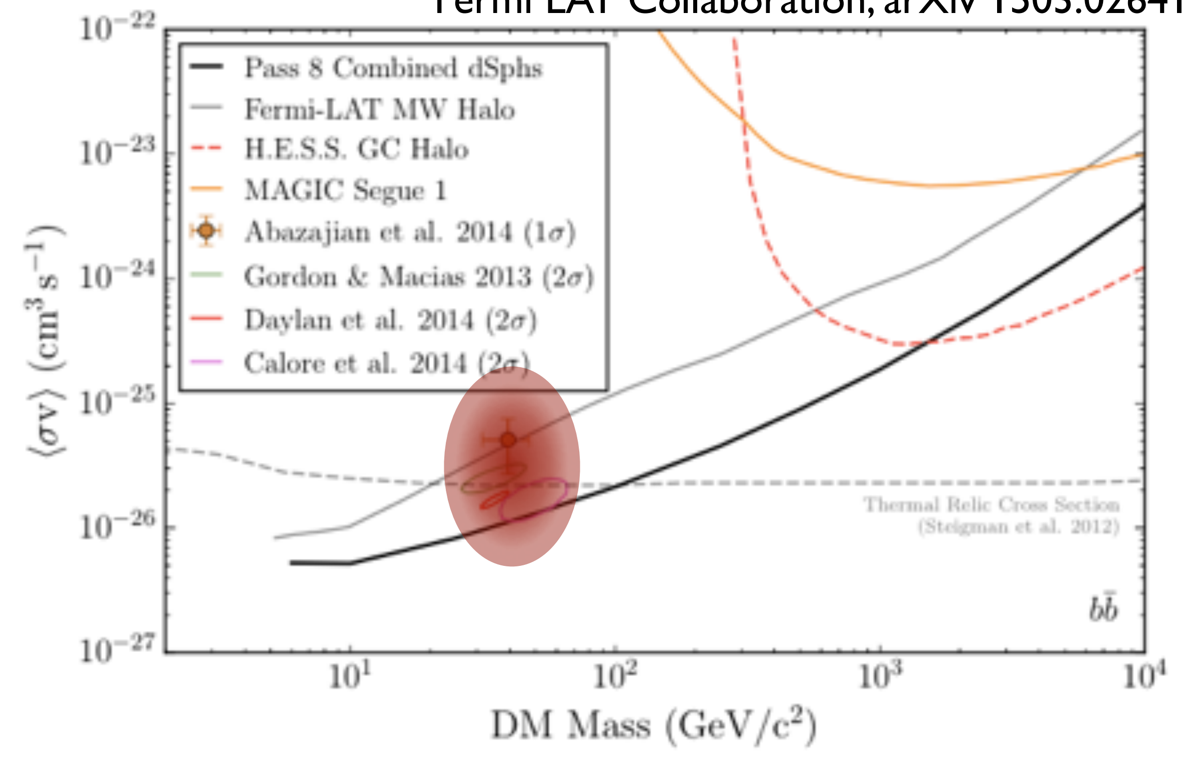
Fermi LAT Collaboration, arXiv 1503.02641

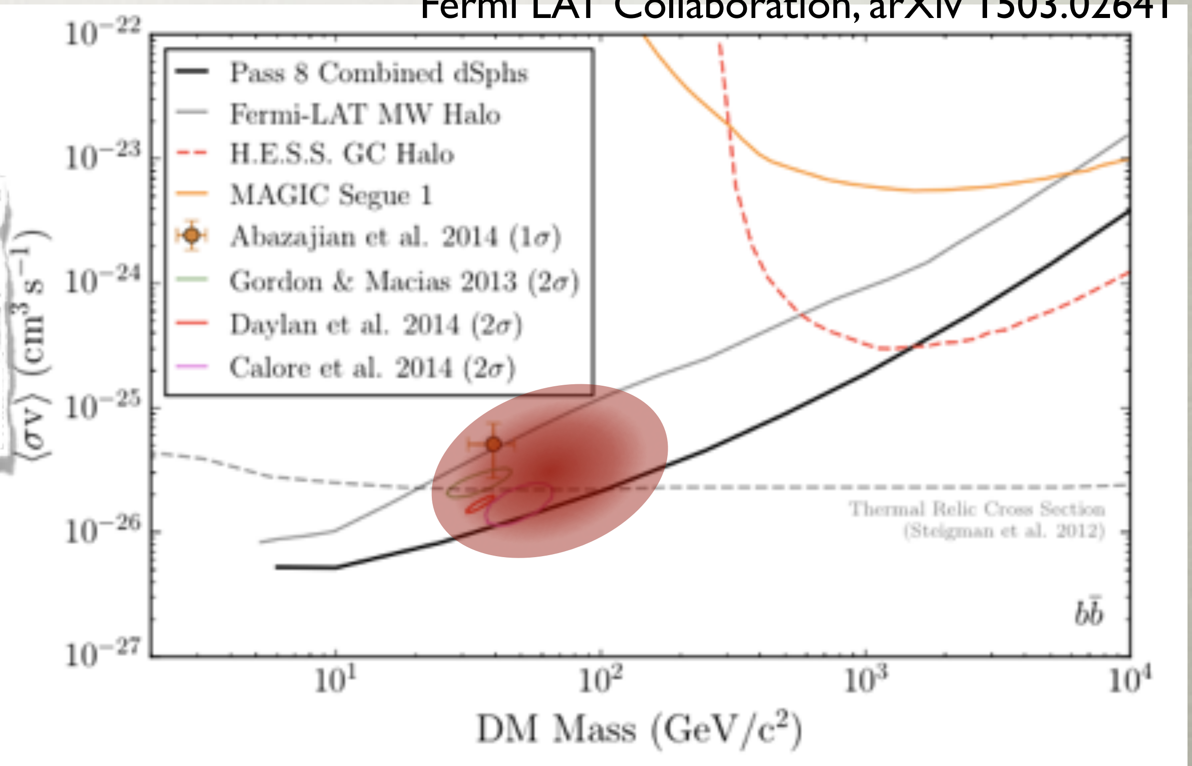


N.B.:
Contours do not fully reflect uncertainties in the DM profile!
(also see Abazajian et al, arXiv:1510.06424)

Dwarf Spheroidal Galaxies

- Search for a signal in 25 dwarf spheroidal galaxies, 6 years of Fermi LAT data
  - ➡ No significant emission is found
- Limits probe DM explanation of the GC excess

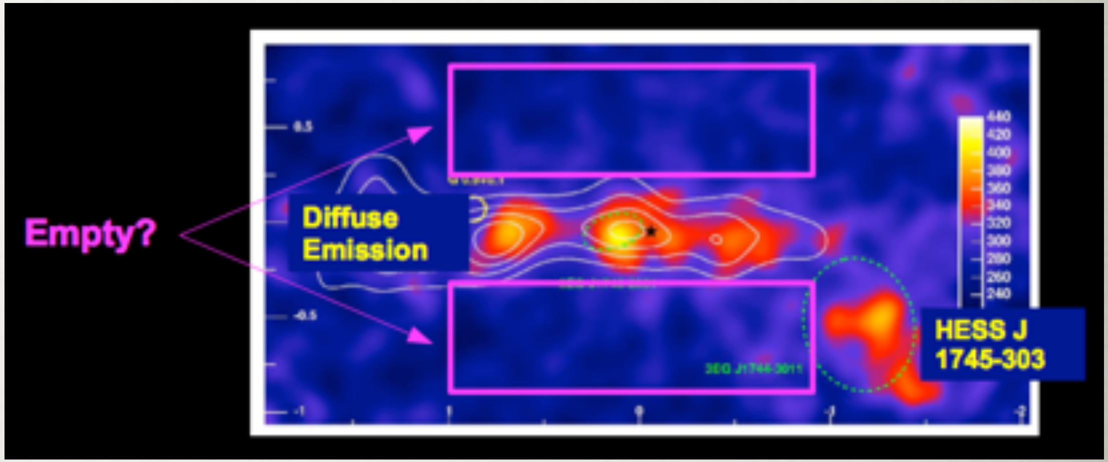
Fermi LAT Collaboration, arXiv 1503.02641



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)

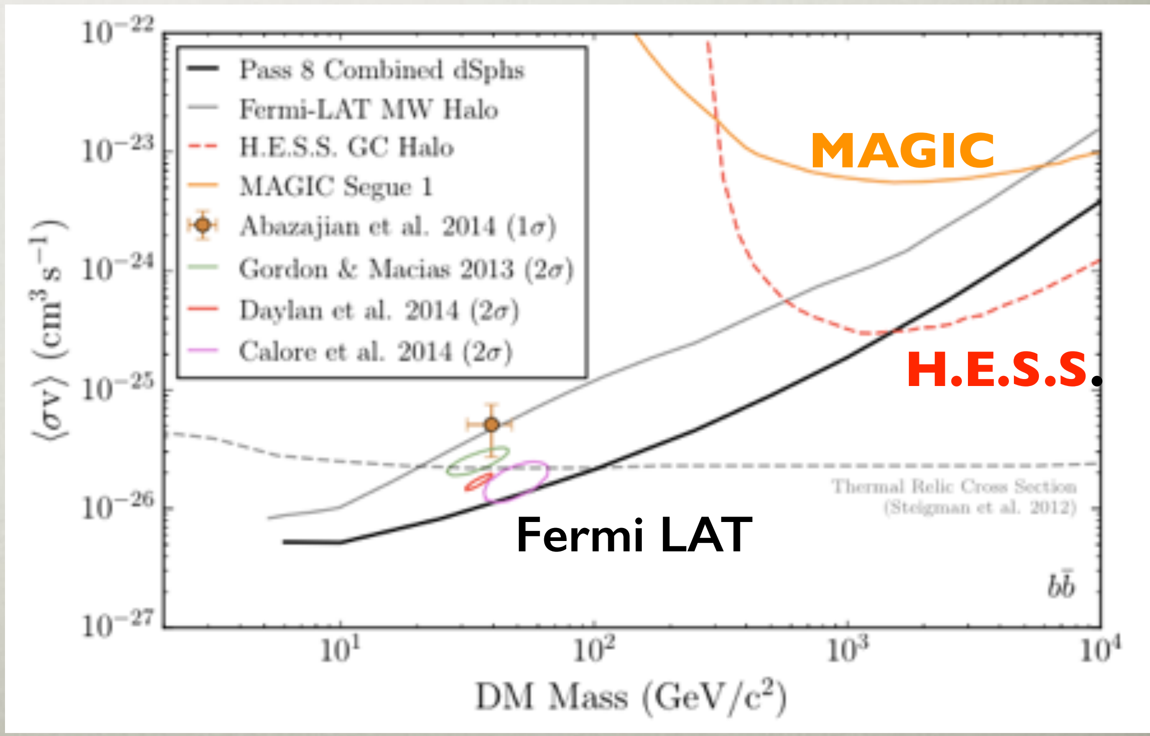
VHE Gamma Rays: H.E.S.S., MAGIC, VERITAS

- Higher energy threshold compared to Fermi LAT
  ➡ Sensitive to higher dark matter masses

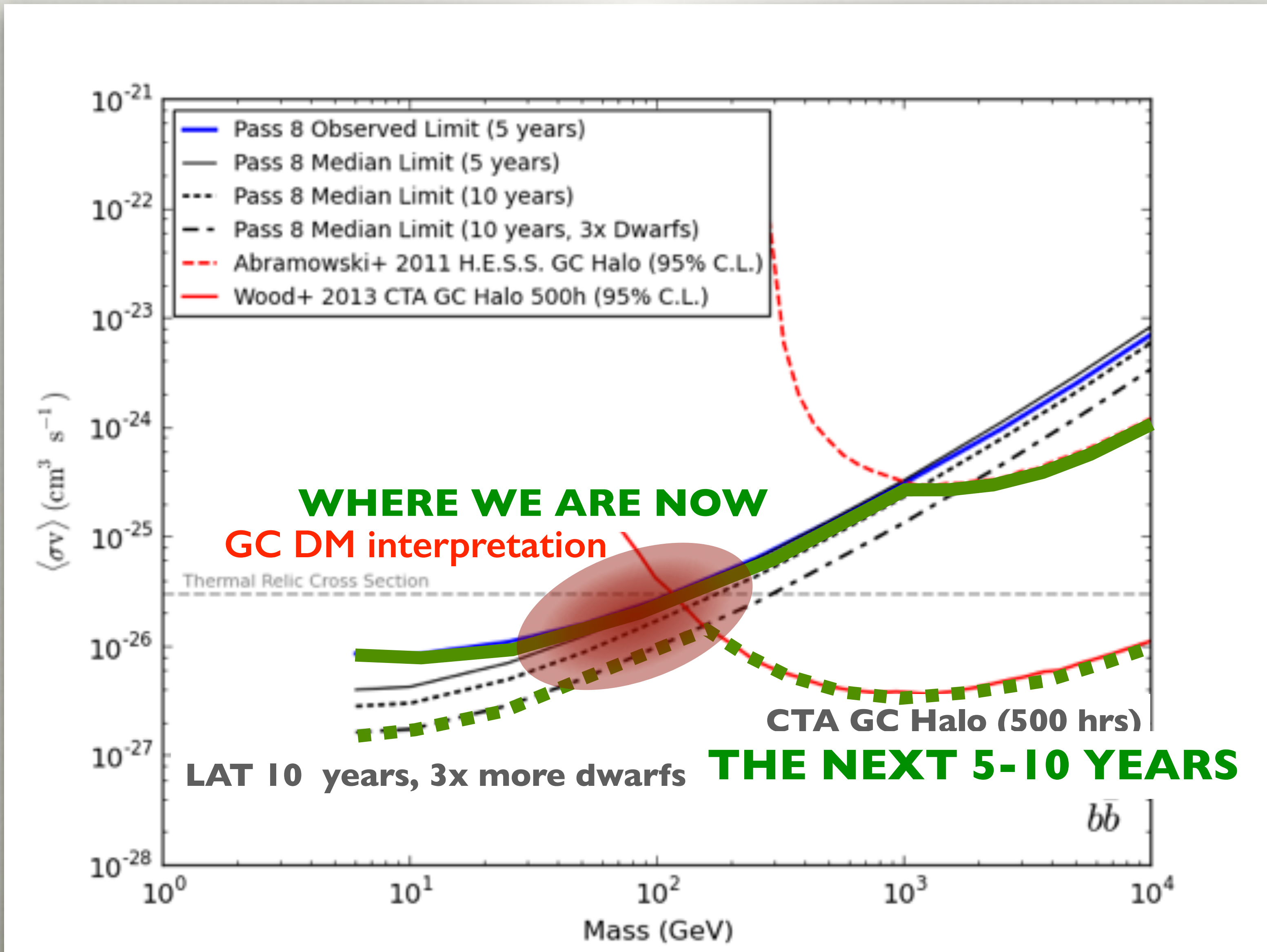


- No dark matter-like emission is observed

- Dark matter constraints are competitive with Fermi LAT for dark matter particle masses above ~1 TeV



Putting it all Together



Conclusions

- An intriguing hint of a potential signal in gamma-ray from the Galactic center has been claimed
  - ➡ However the astrophysical background is currently a limitation. More work is required to better understand the data
  - ➡ A consistent signal from other DM targets/searches would provide the most compelling confirmation of the DM interpretation for this excess
- In the meanwhile, indirect searches continue to set strong constraints on the nature of DM
- Improvements in current experiments as well as upcoming experiments promise more interesting results to come

Thank you!