Dark Matter Indirect Detection

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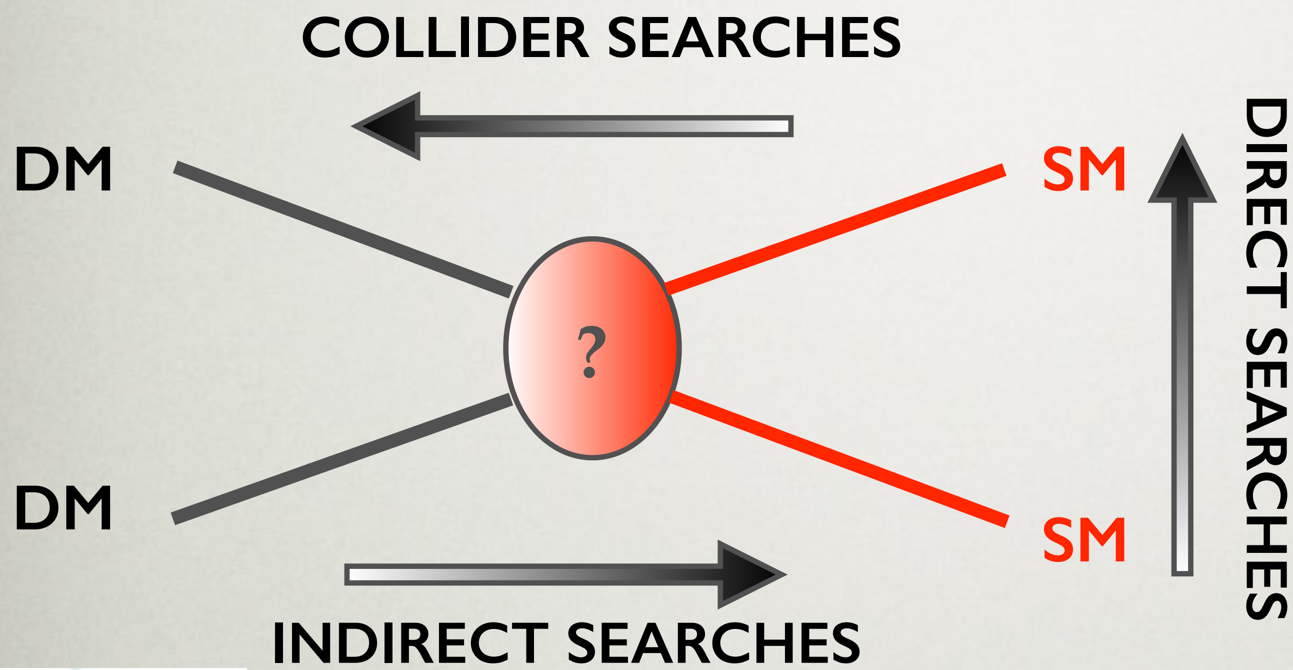
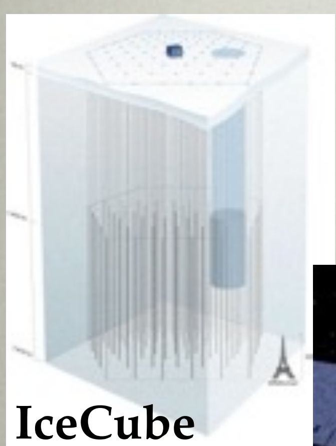
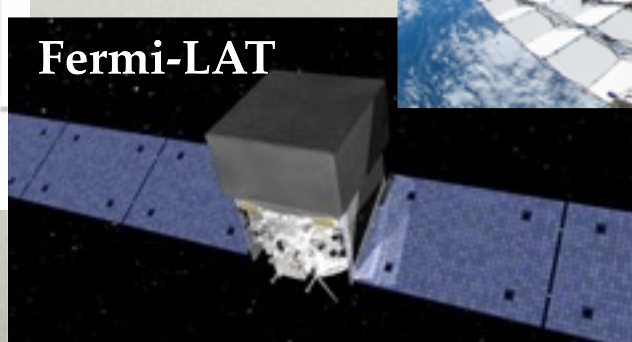
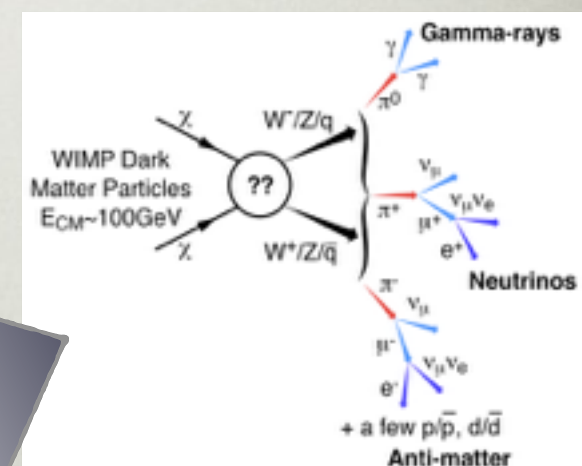
WIMP Searches



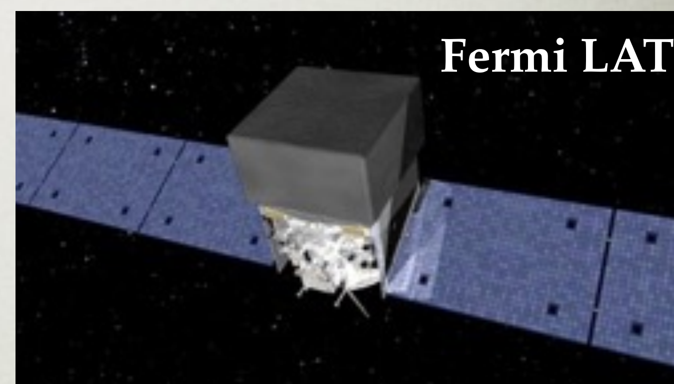


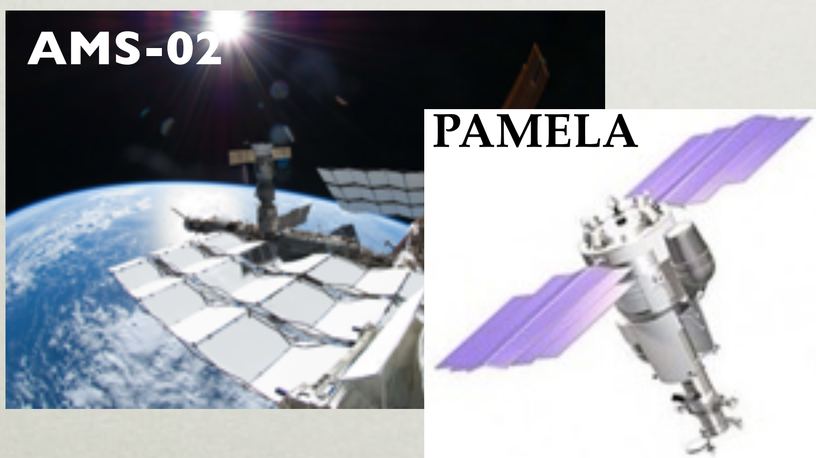


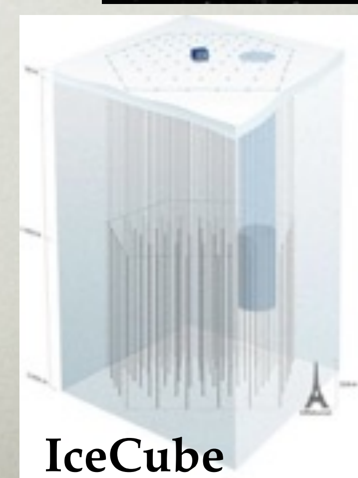


EXPERIMENTS

- Gamma rays
  - VERITAS
  - HESS
  - MAGIC
  - Fermi LAT
- Cosmic Rays
  - AMS-02
  - PAMELA
  - Fermi LAT
- Neutrinos
  - IceCube







EXPERIMENTS

- **Gamma rays**
  - VERITAS
  - HESS
  - MAGIC
  - Fermi LAT
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  - AMS-02
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  - Fermi LAT
- Neutrinos
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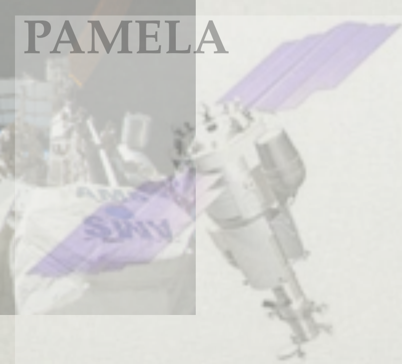
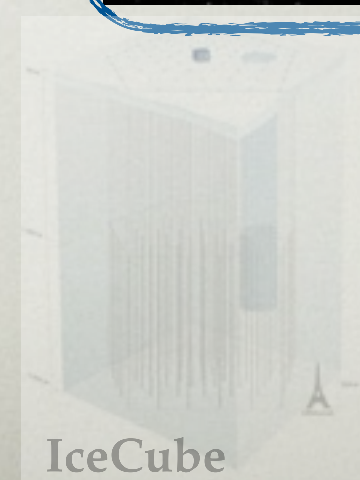
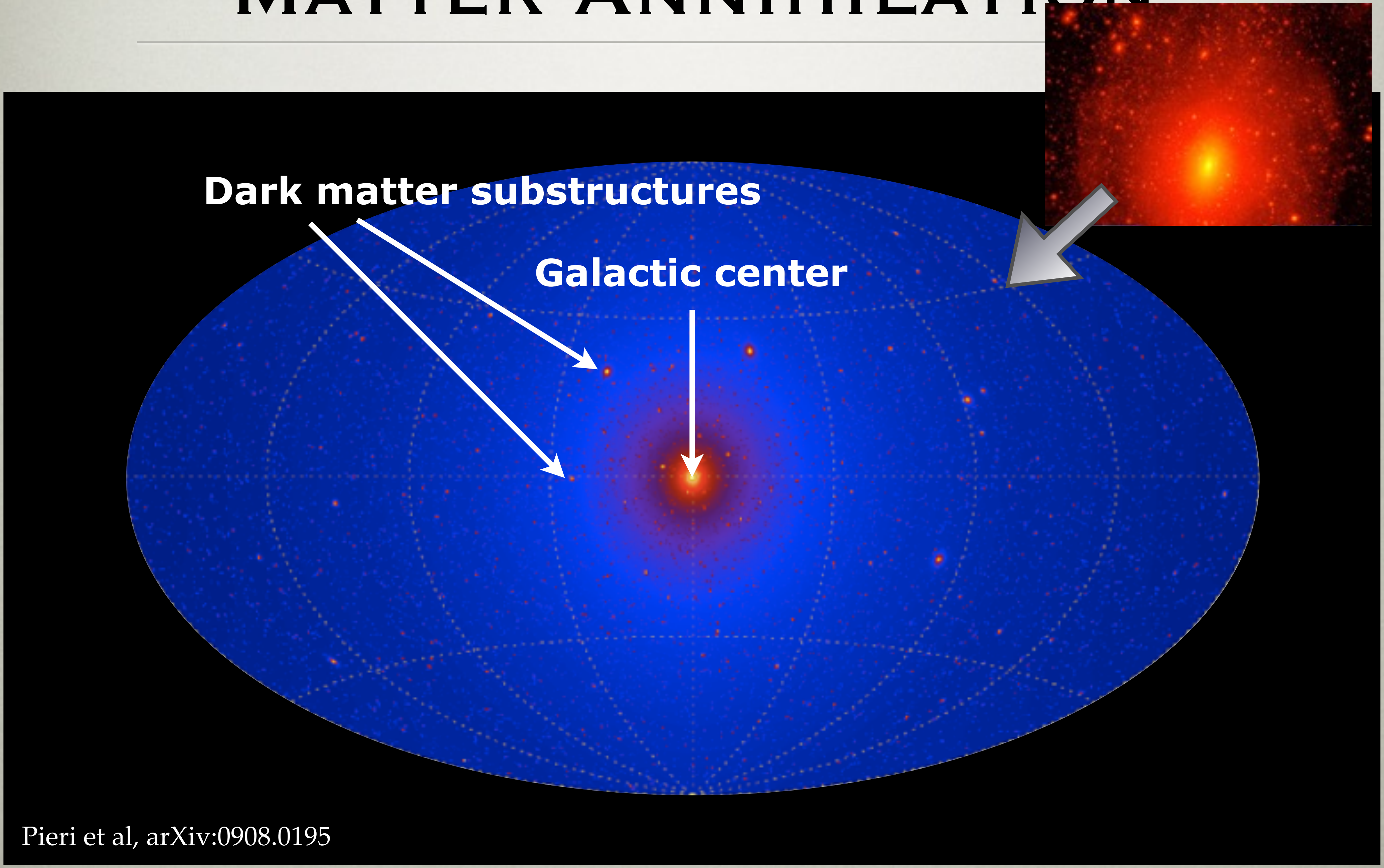
ON THE GROUND

IN SPACE

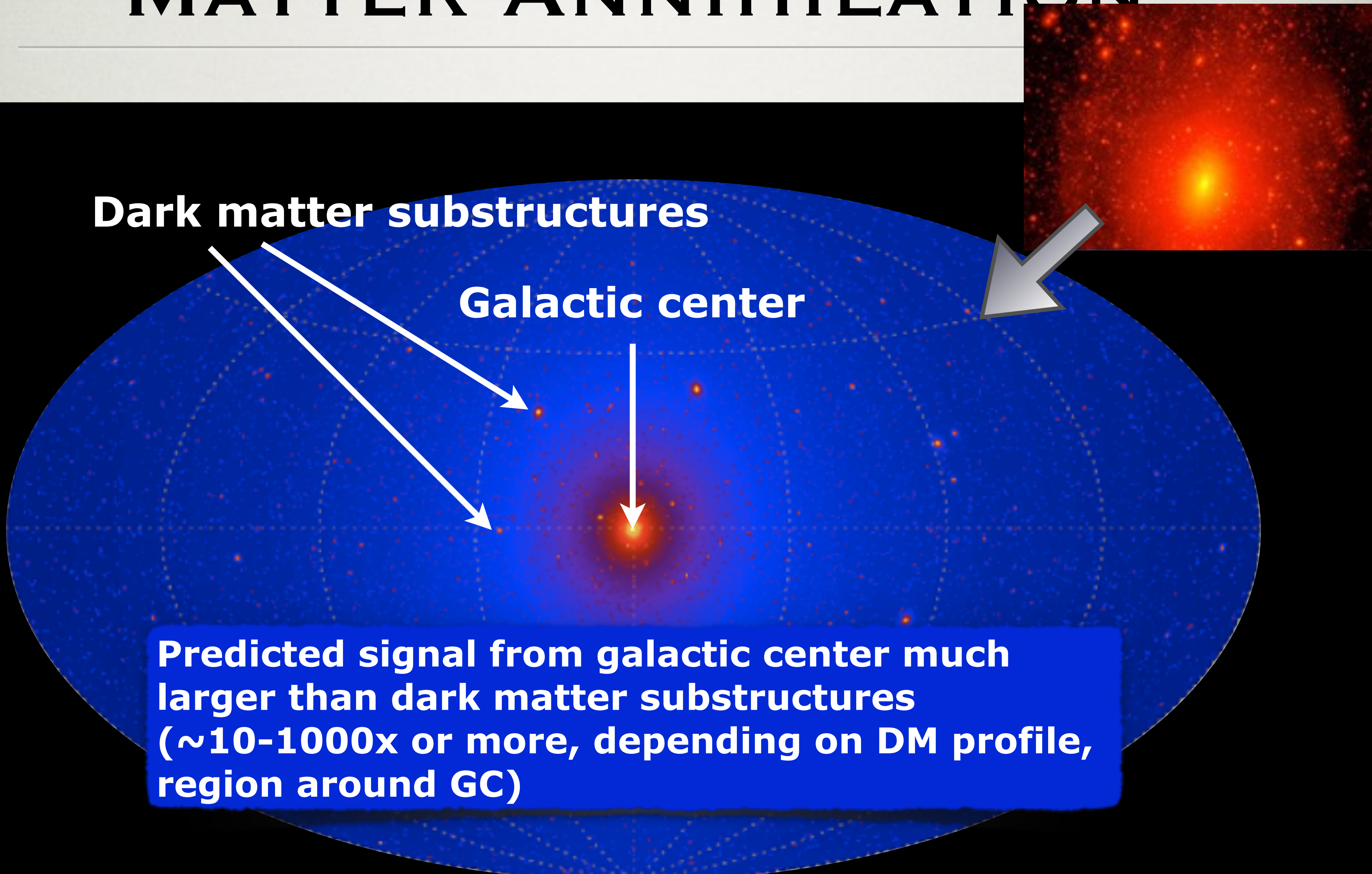




Gamma rays from Dark Matter Annihilation



Gamma rays from Dark Matter Annihilation



Pieri et al, arXiv:0908.0195

WIMP Signal

- Gamma rays from dark matter annihilation:

particle physics

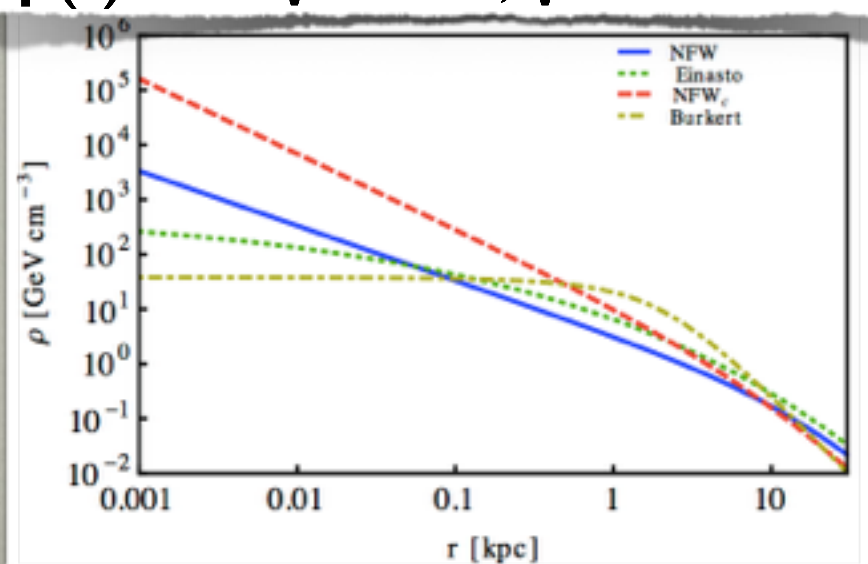
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) \quad = \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f}$$

$$\times \boxed{\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')}$$

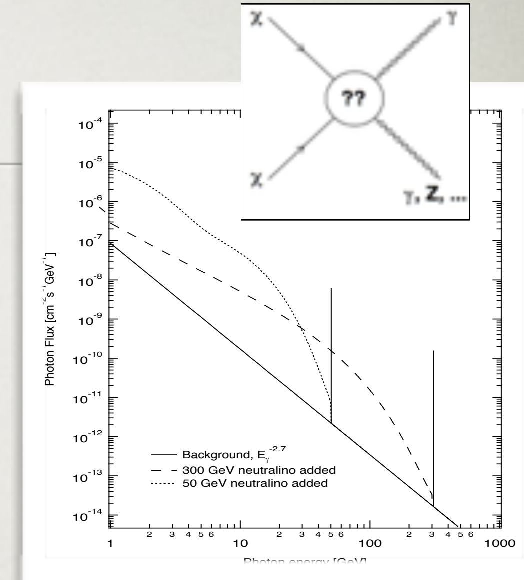
DM distribution

For the central dark matter density:

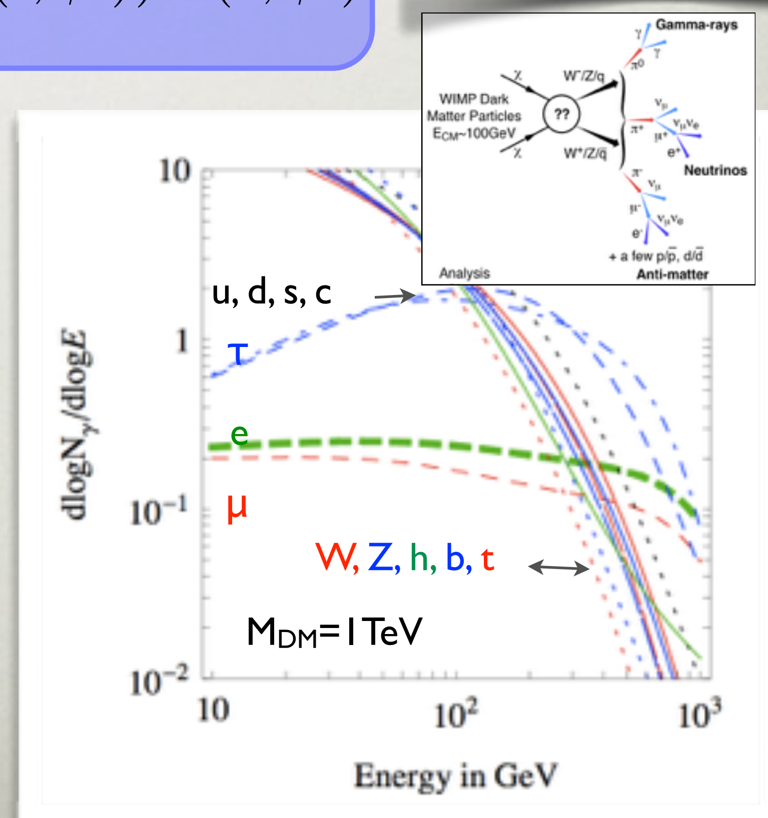
$\rho(r) \sim r^{-\gamma}$ $\gamma=0$ core, $\gamma=1$ NFW/cusp



Gomez-Vargas et al, arXiv:1308.3515

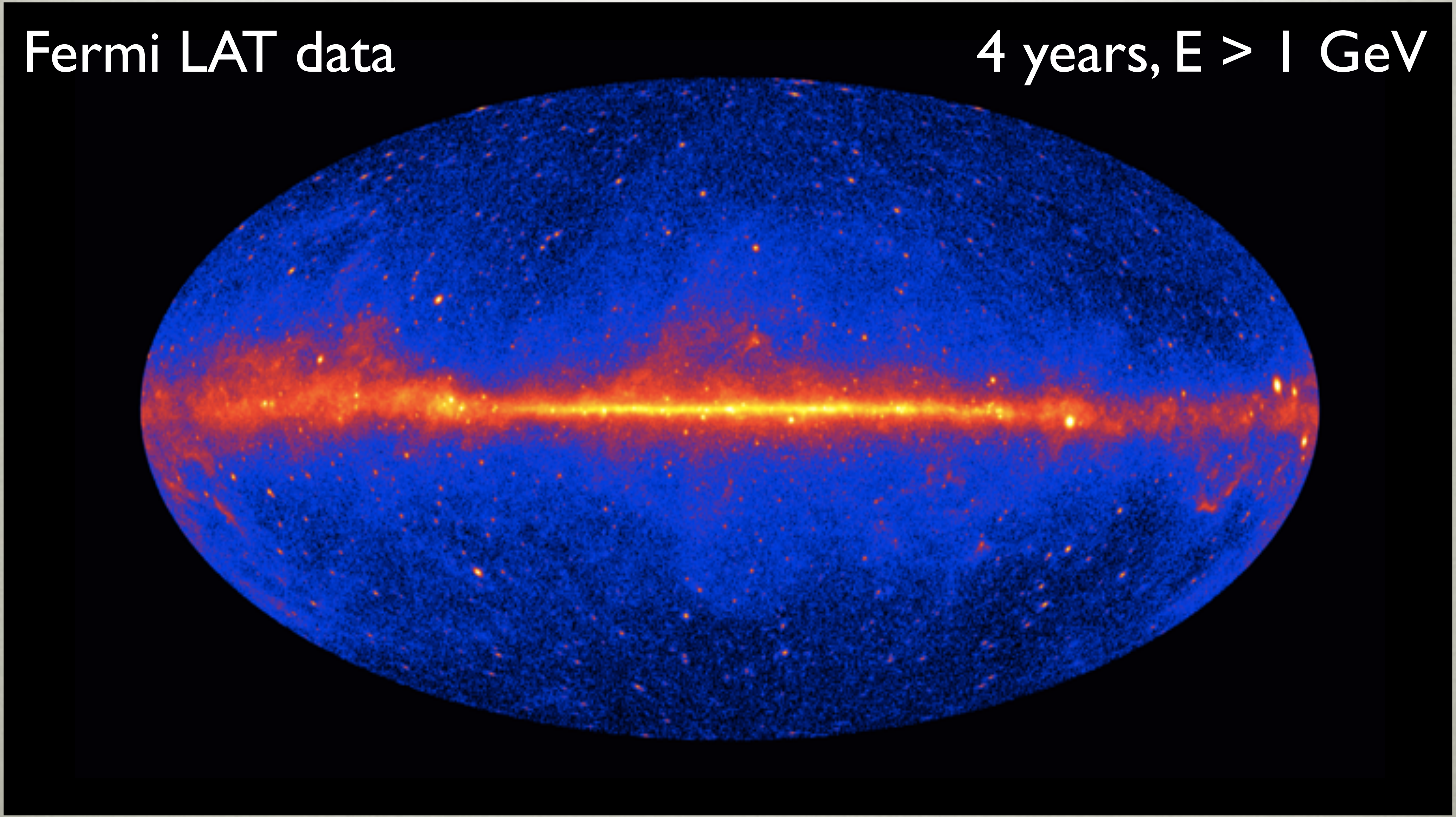


Bergstrom, Ullio, Buckley

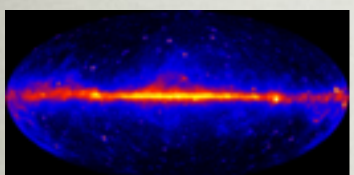


Cirelli et al, arXiv:0809.2409

The Fermi Sky



Understanding the Gamma-ray Sky



data

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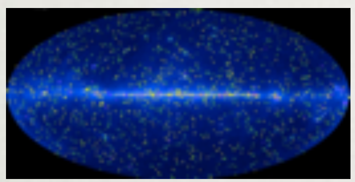
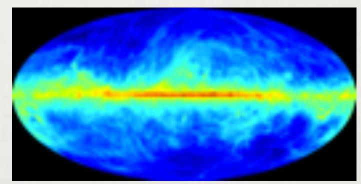


sources

+



galactic interstellar emission

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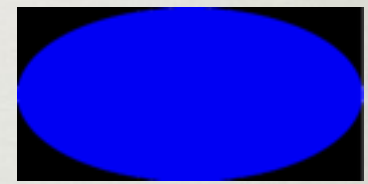
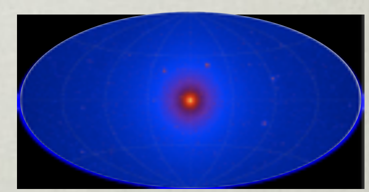


isotropic

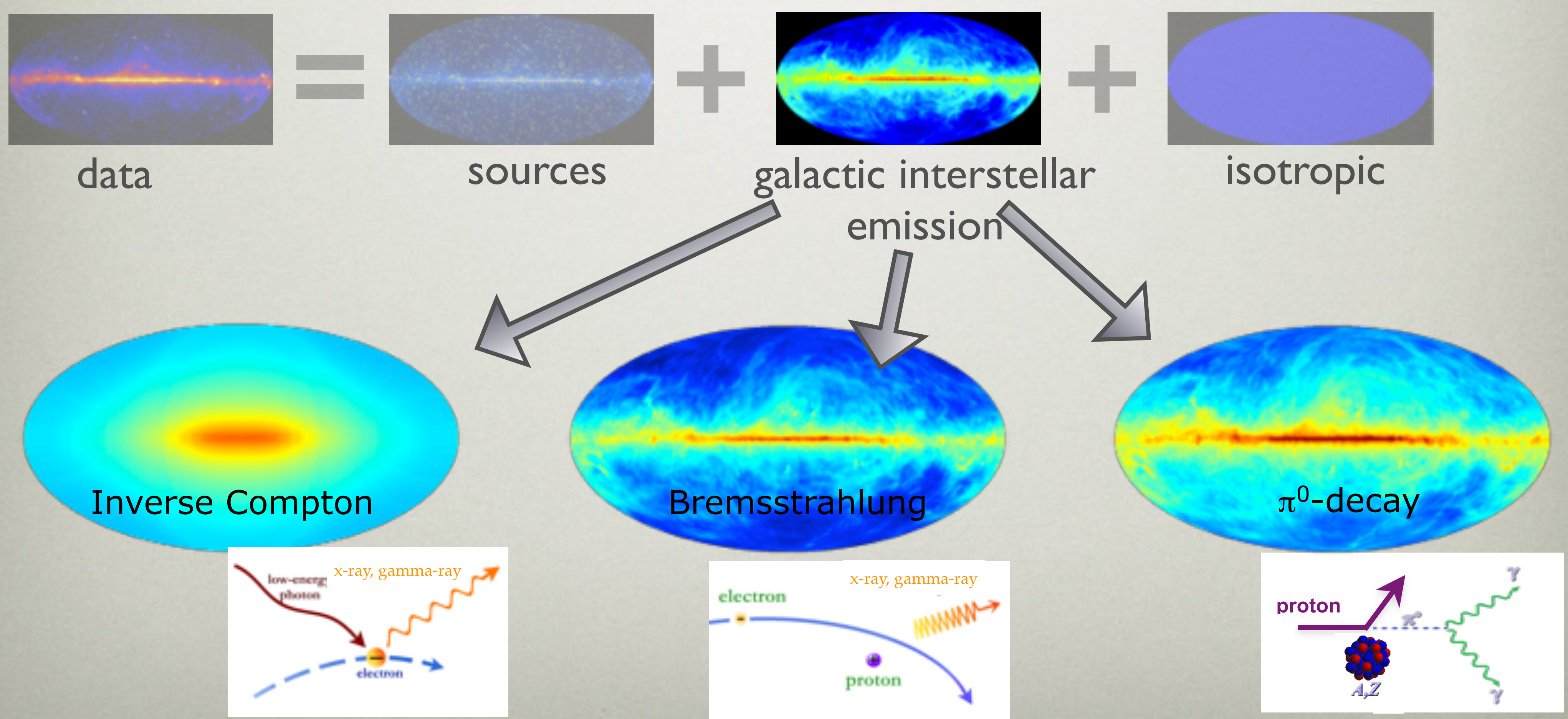
+



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

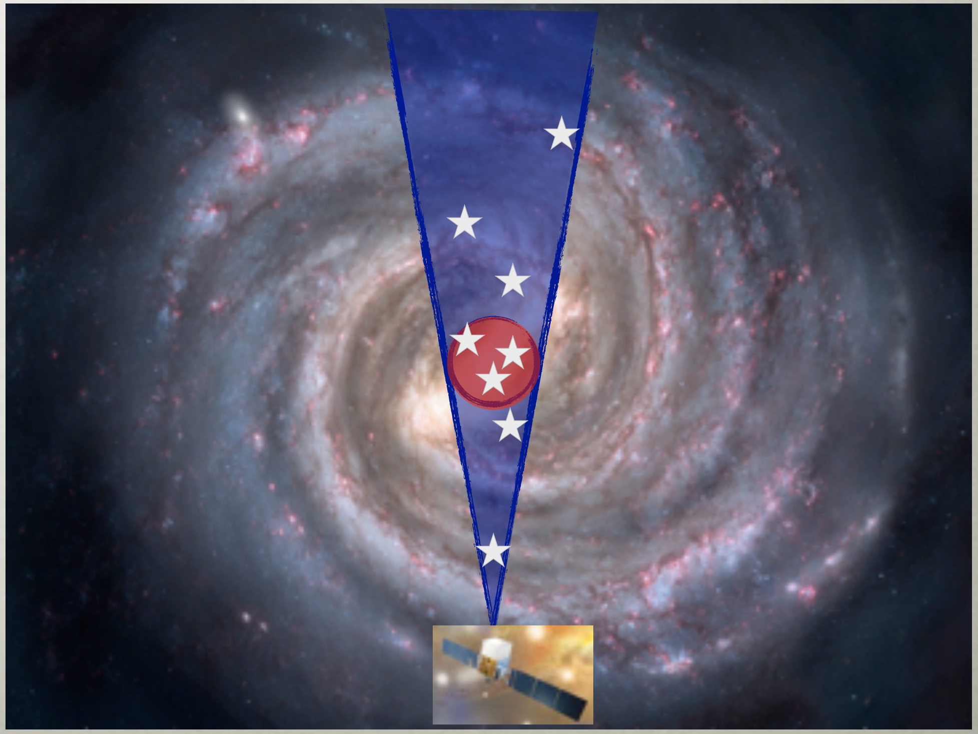


Galactic Center Region

- 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



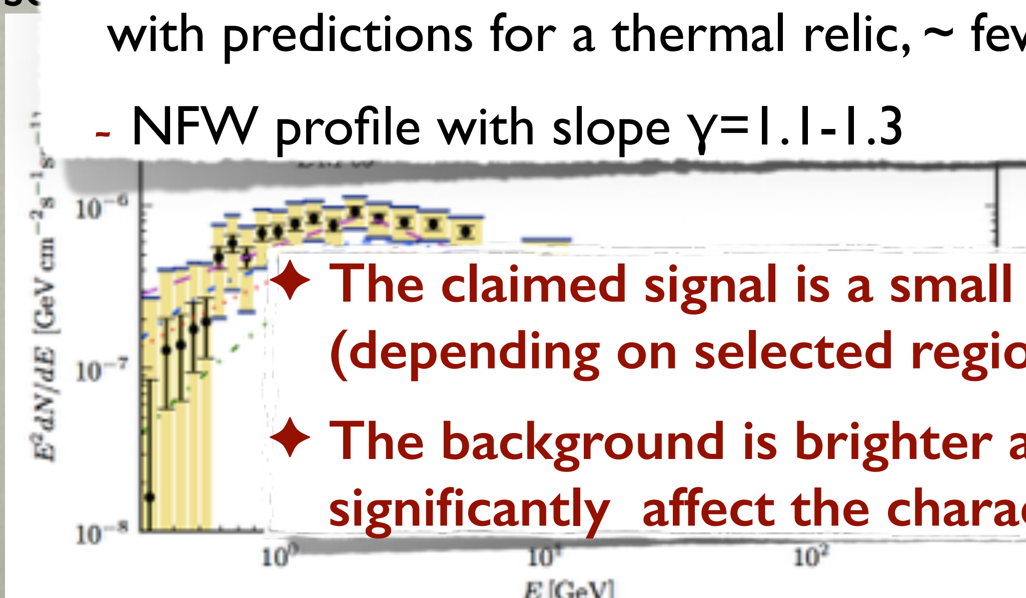
Galactic Center Excess

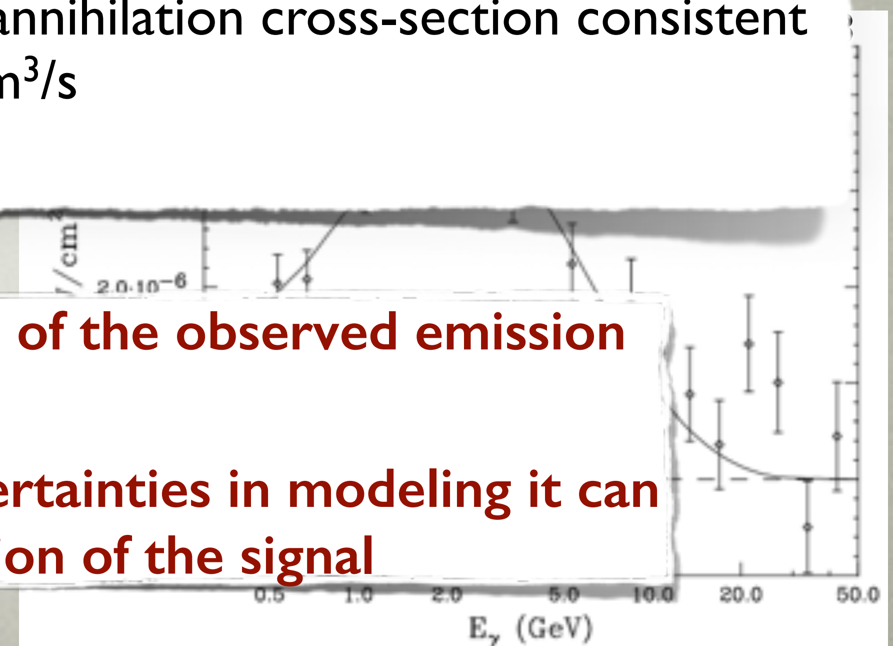
- An excess in the Fermi LAT GC data was first claimed by Goodenough and Hooper (arXiv:0910.2998.) More recent analyses also find an excess
- Generally, two approaches to model the interstellar emission:

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





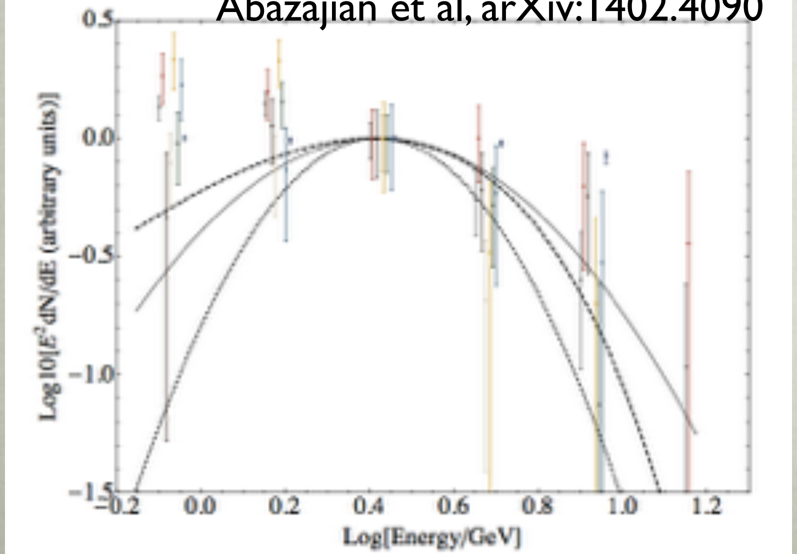
✦ The claimed signal is a small fraction of the observed emission (depending on selected region)

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

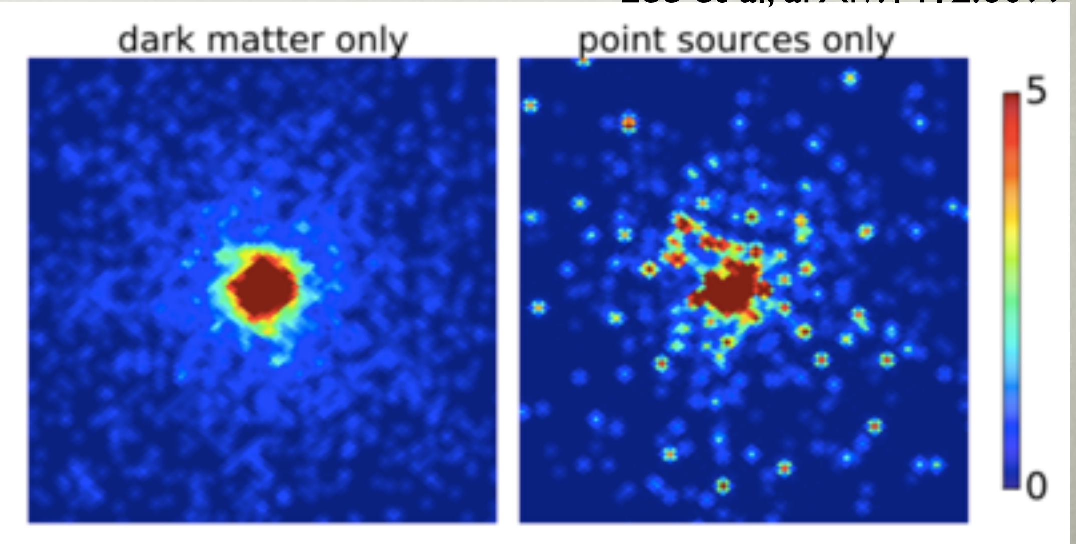
Other Interpretations

- **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

Abazajian et al, arXiv:1402.4090



Lee et al, arXiv:1412.6099

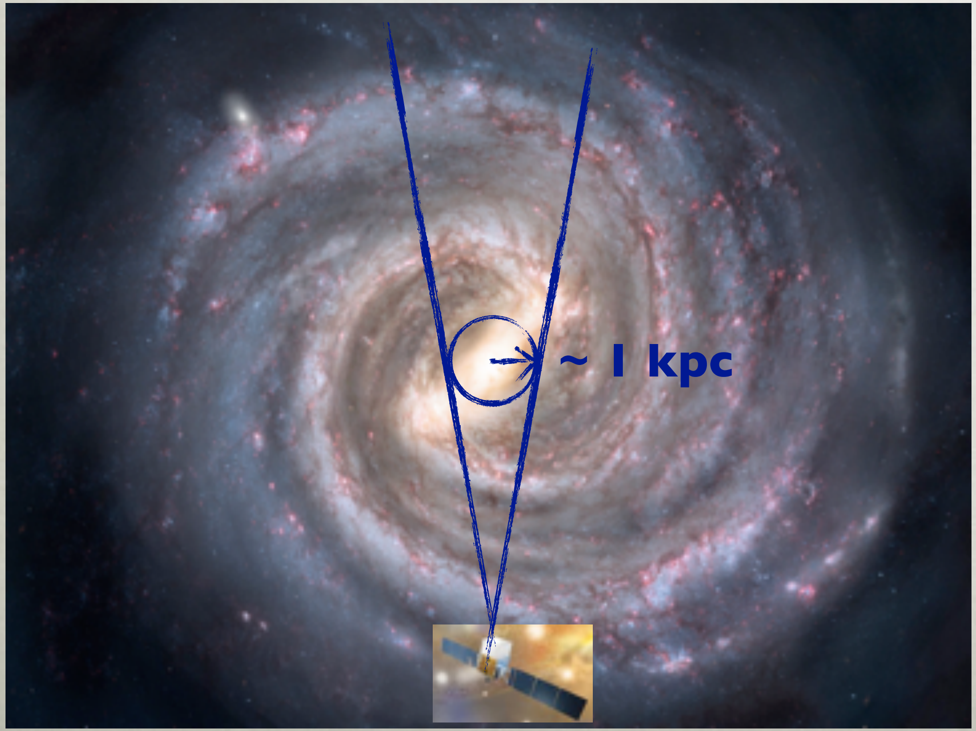


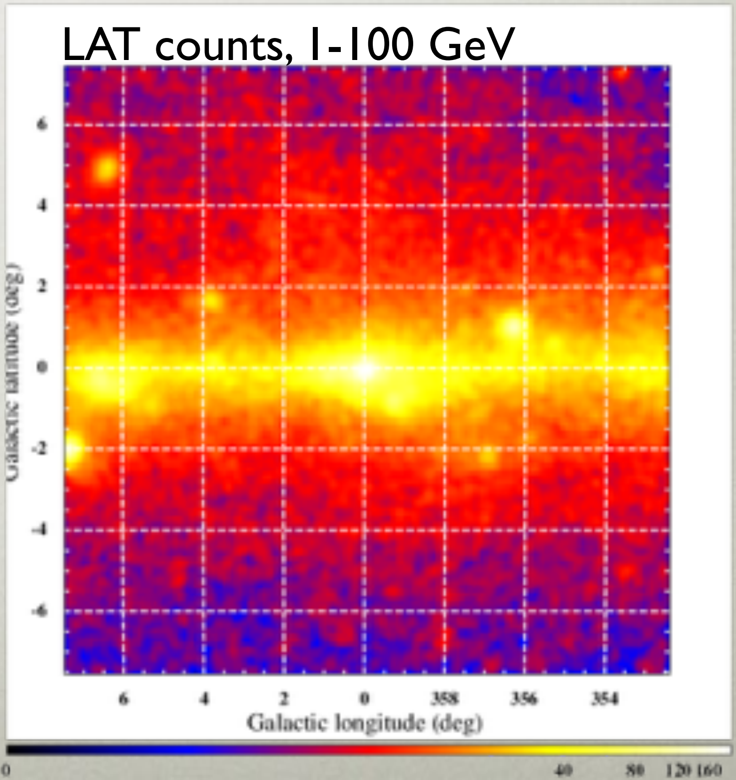
Is the presence of the excess, and its characterization, robust?

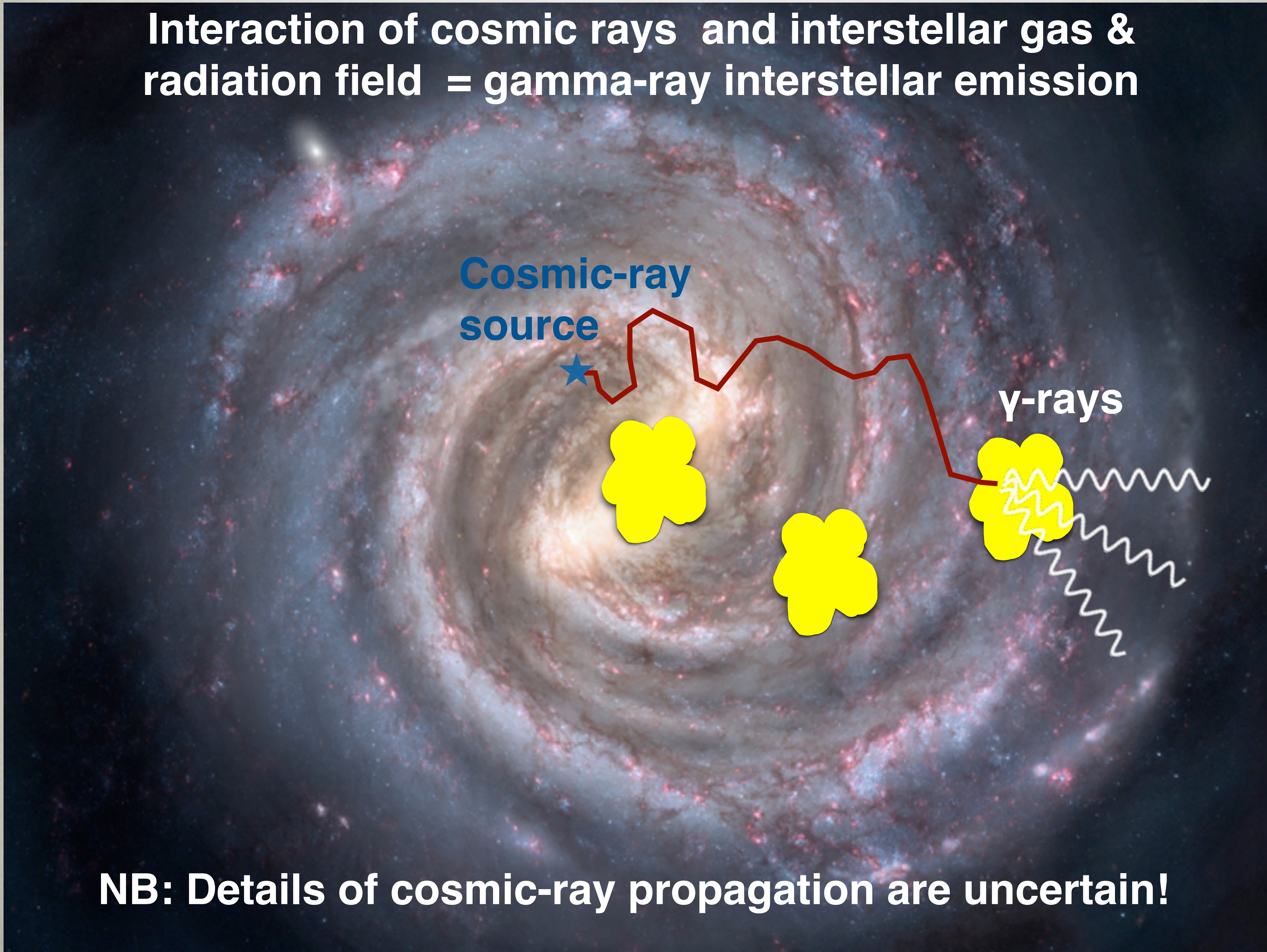
A closer look at the uncertainties in the interstellar gamma-ray emission is crucial to answer these questions

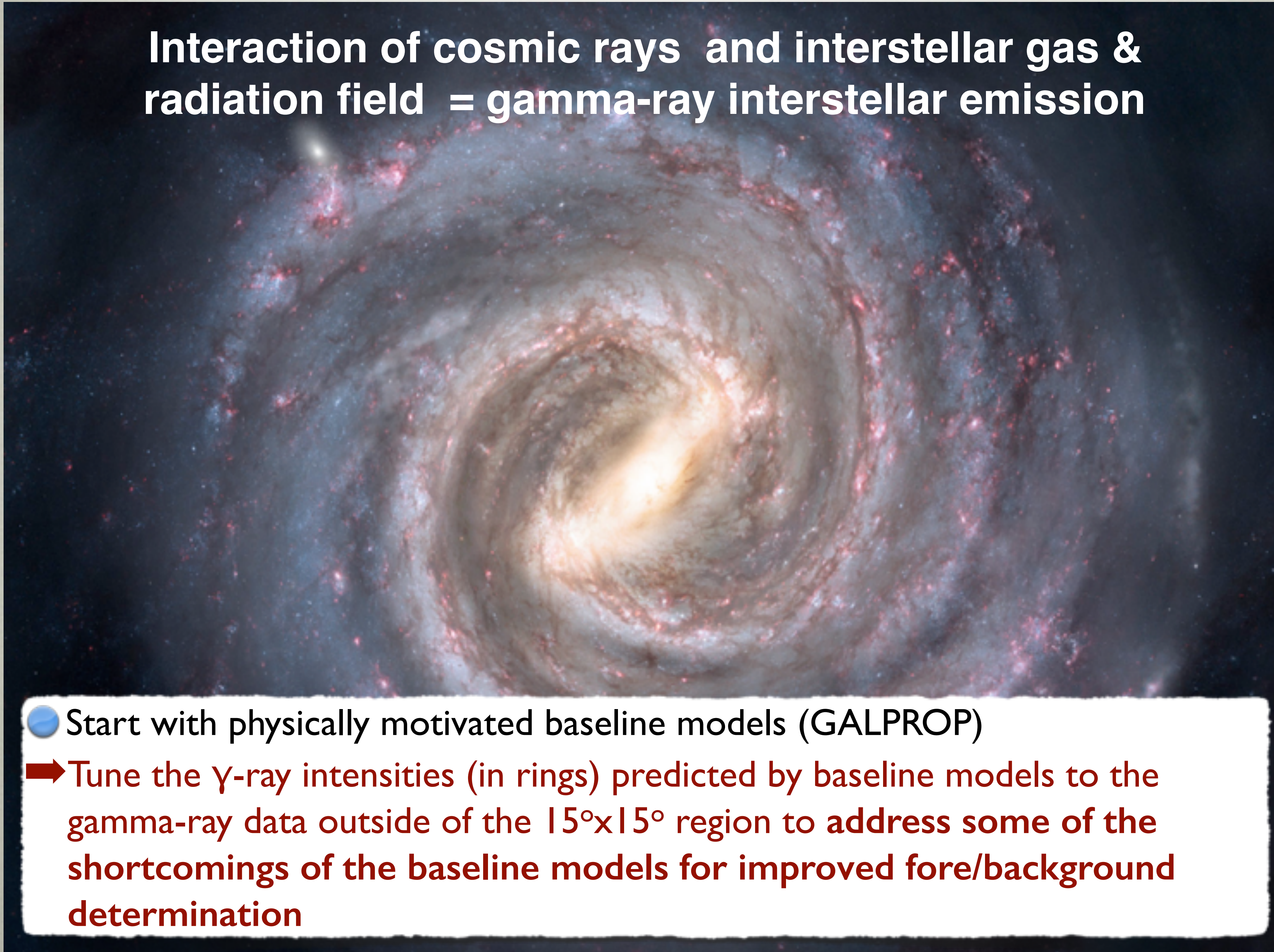
Modeling the Interstellar Emission Revisited

- 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!



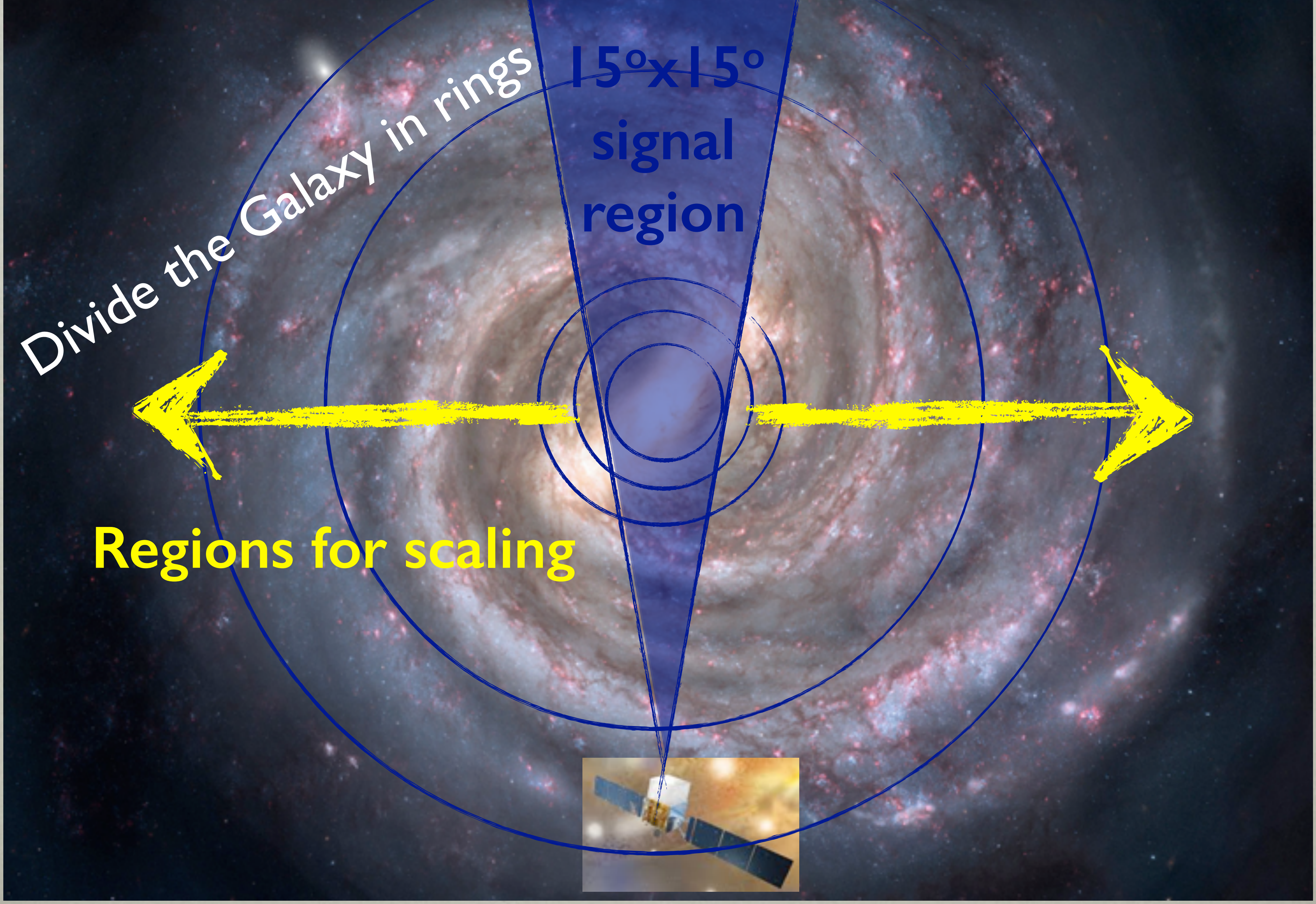
Interaction of cosmic rays and interstellar gas & radiation field = gamma-ray interstellar emission

- Start with physically motivated baseline models (GALPROP)

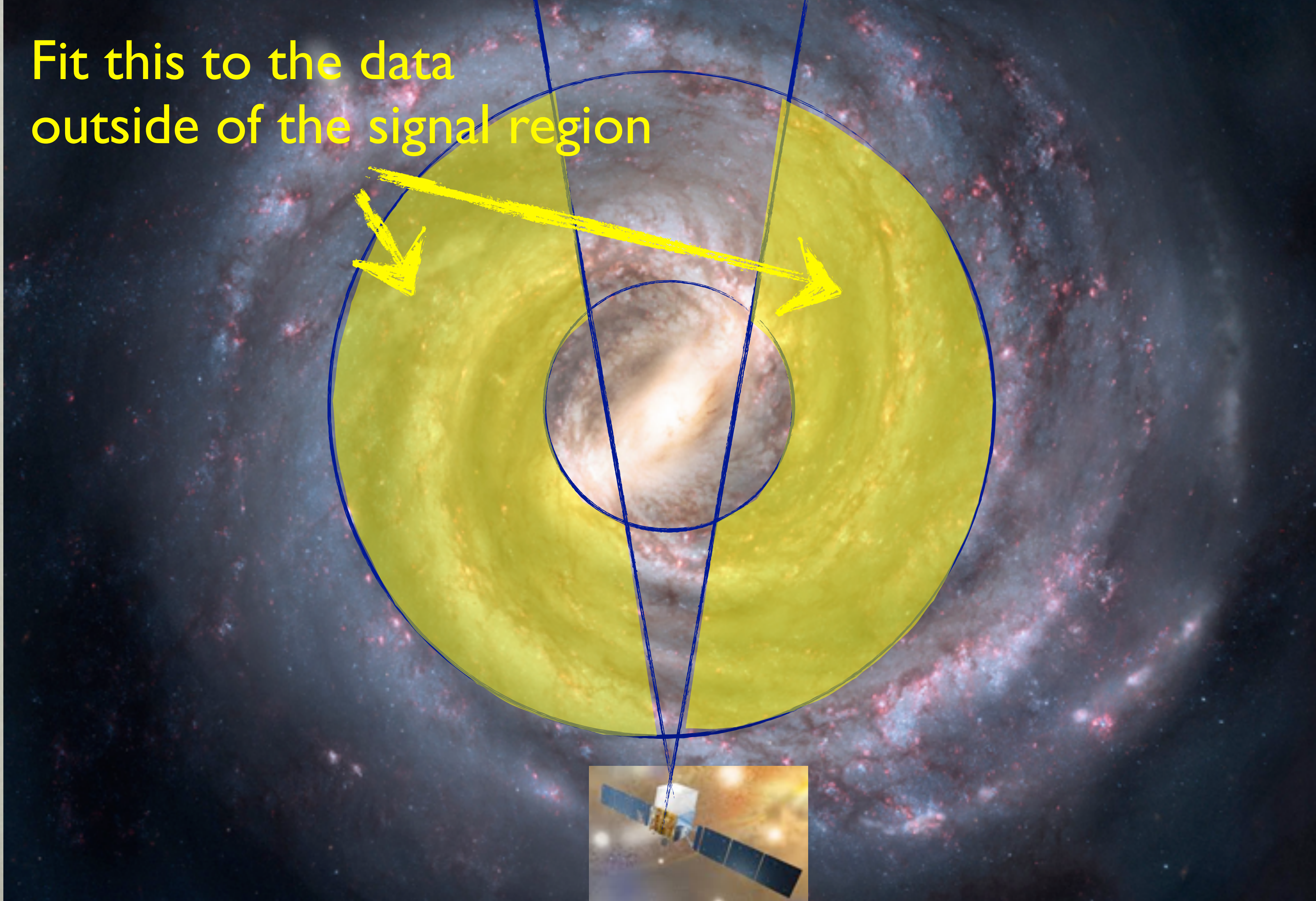
➡ Tune the γ-ray intensities (in rings) predicted by baseline models to the gamma-ray data outside of the 15°x15° region to **address some of the shortcomings of the baseline models for improved fore/background determination**

Scaling Procedure

Scaling Procedure

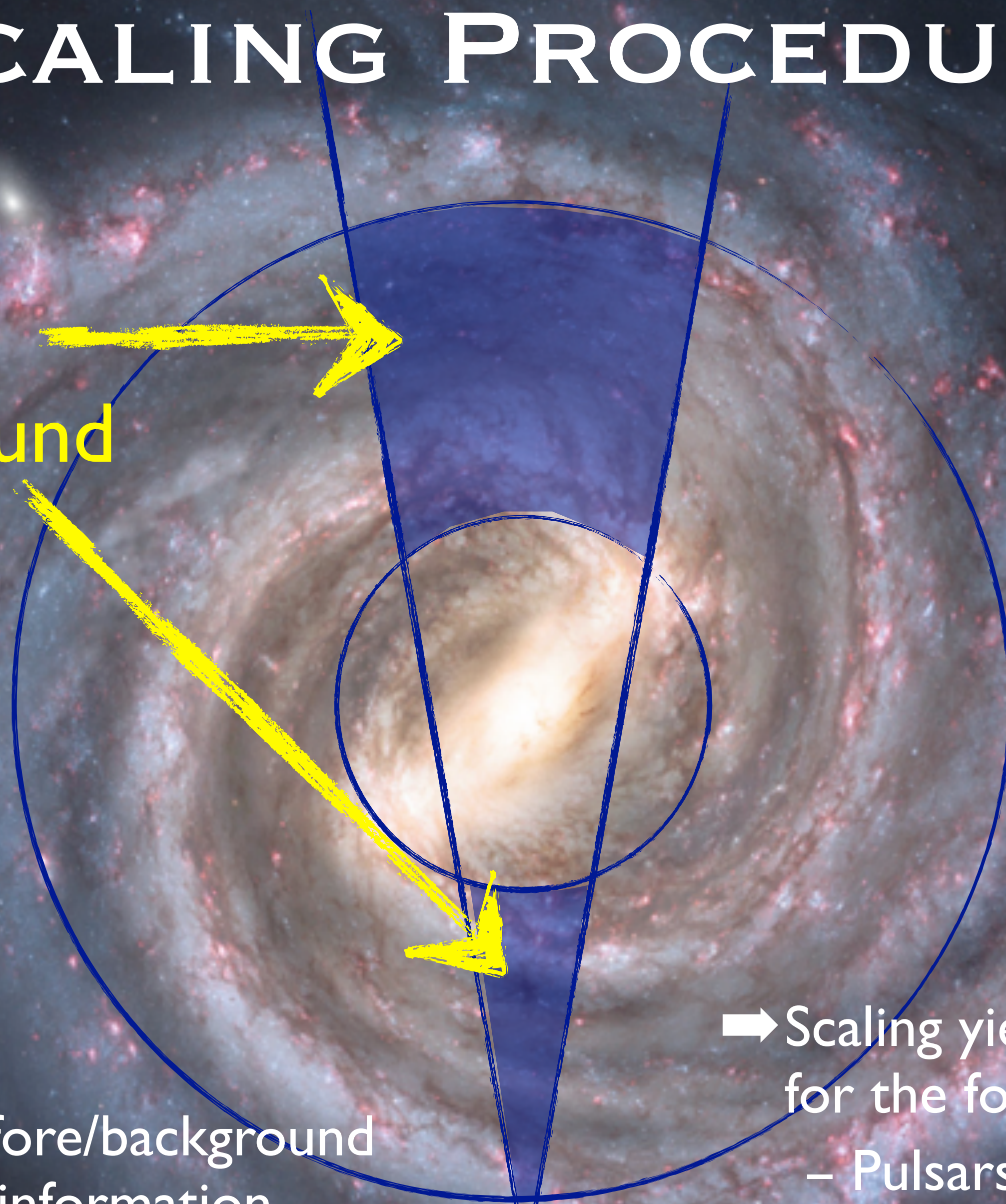


Scaling Procedure



Scaling Procedure

To infer this fore/background

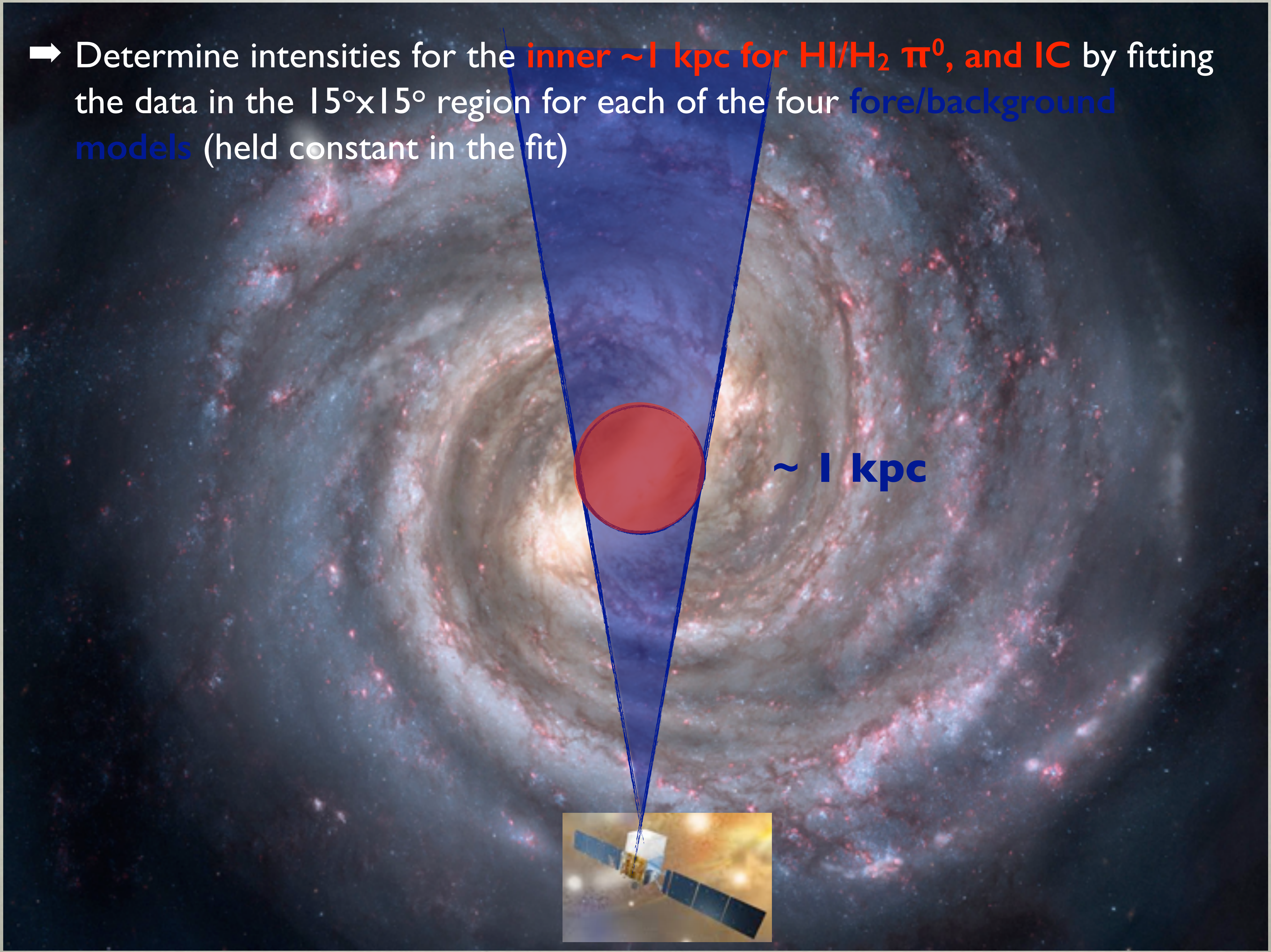


➡ Constrain the fore/background without using the information toward the ROI.
➡ Considerably less biased approach

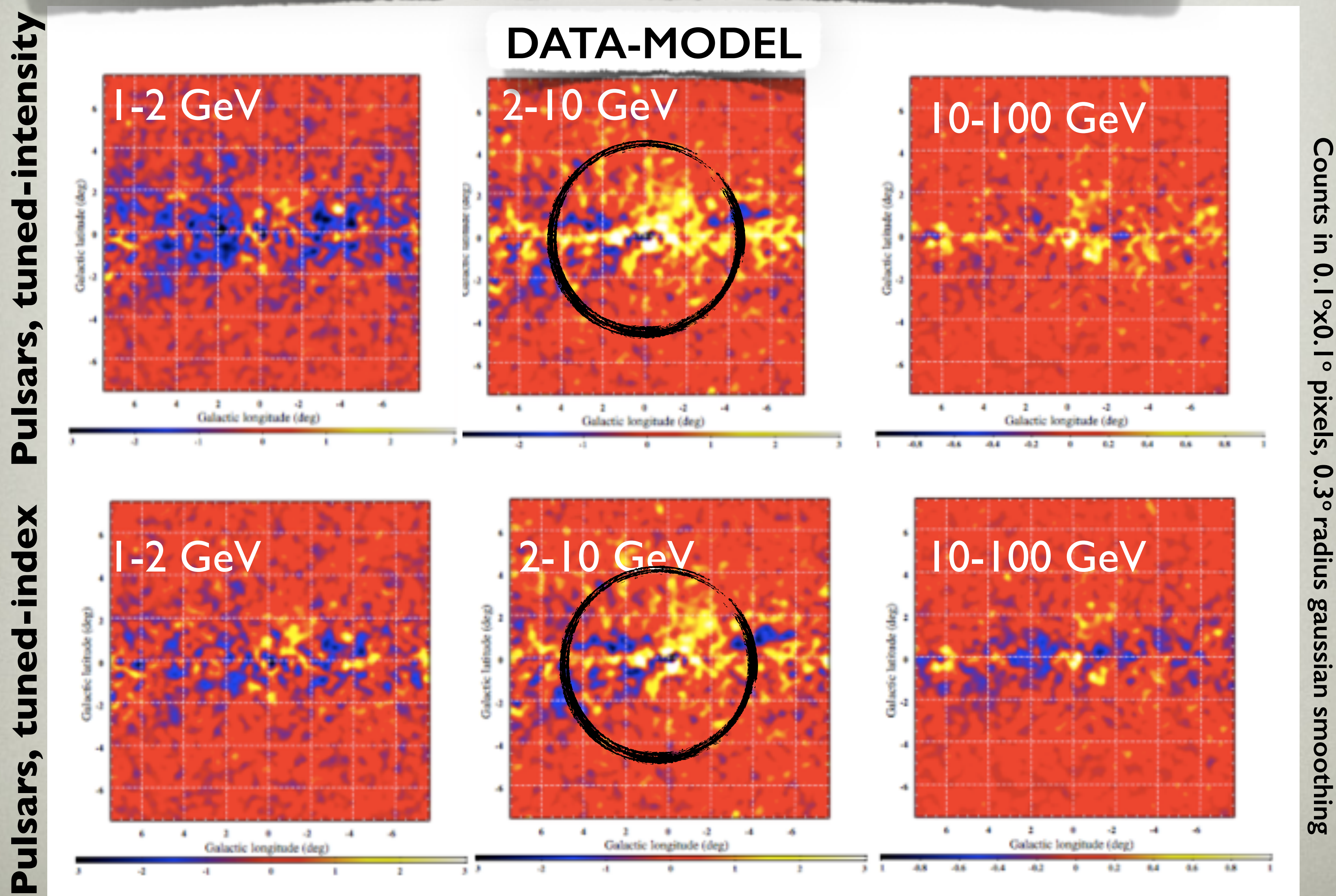
➡ Scaling yields four variants for the fore/background IEM:

- 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)

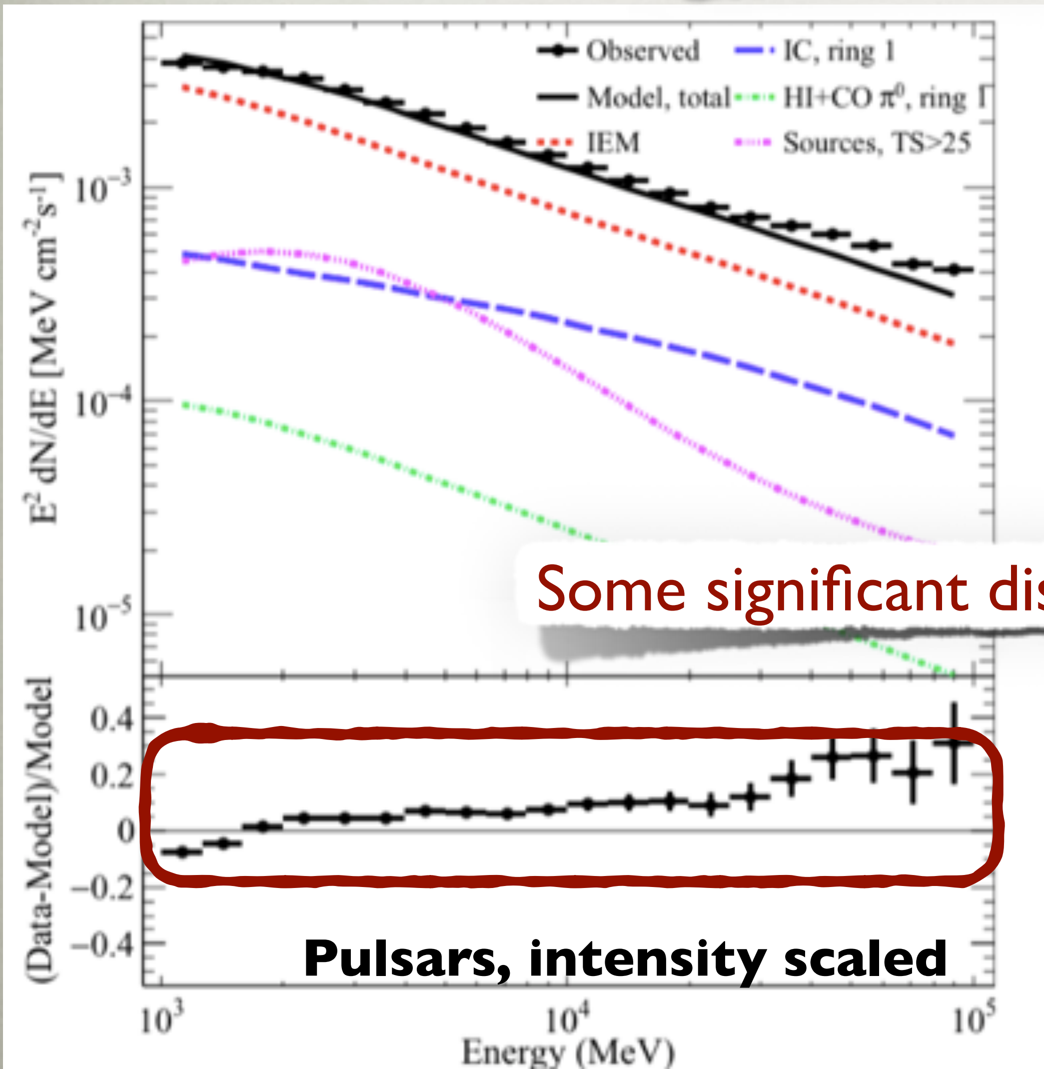


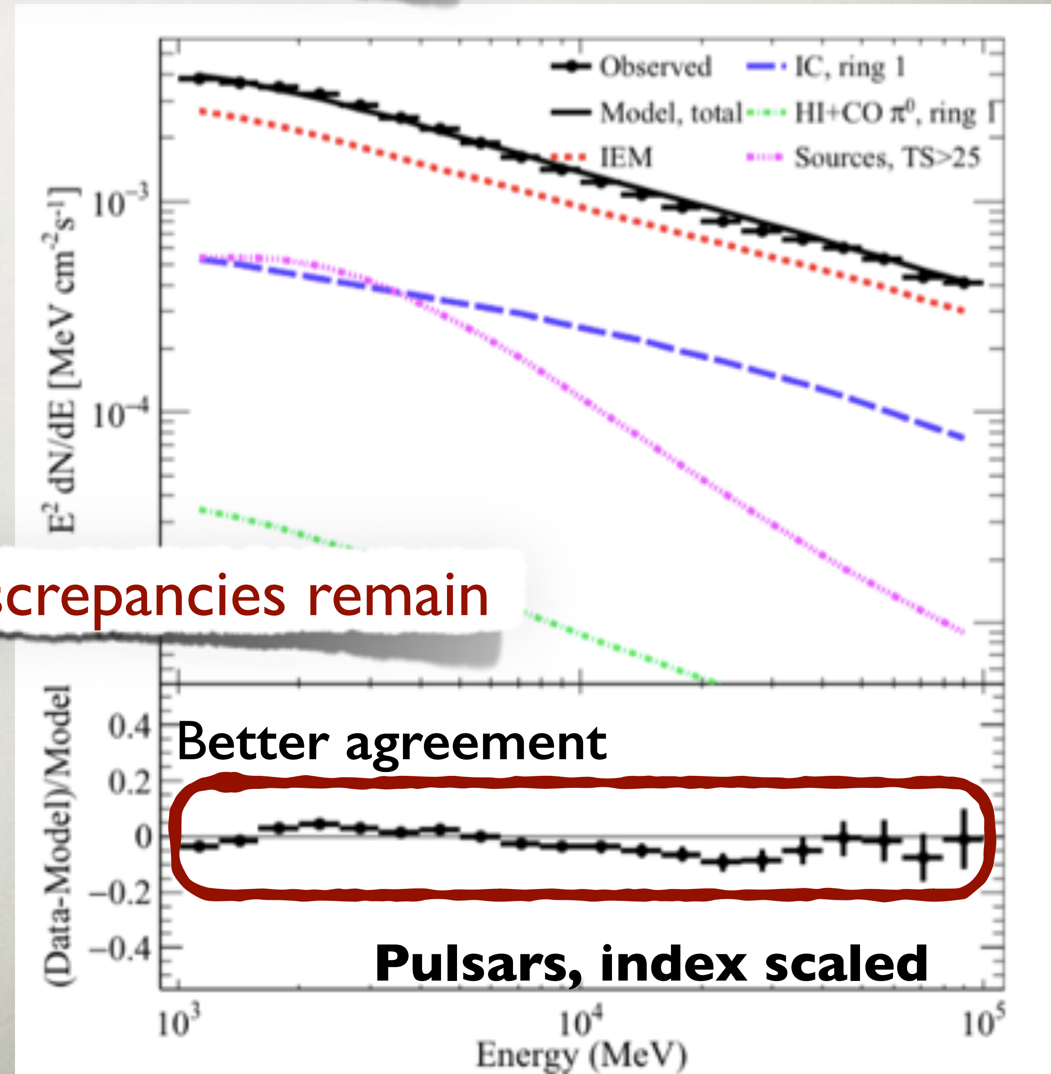
Structured excesses and deficits point to imperfectly modeled components and/or un-modeled contributions



Results - IEM

Integrated flux in 15°x15° ROI





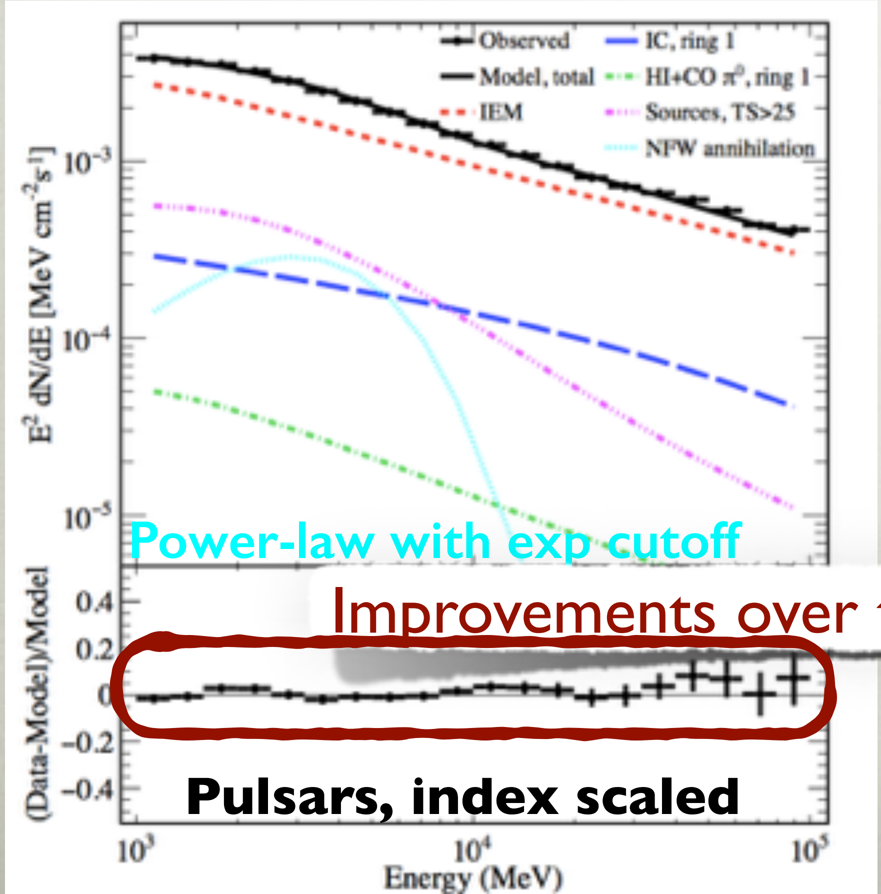
Some significant discrepancies remain

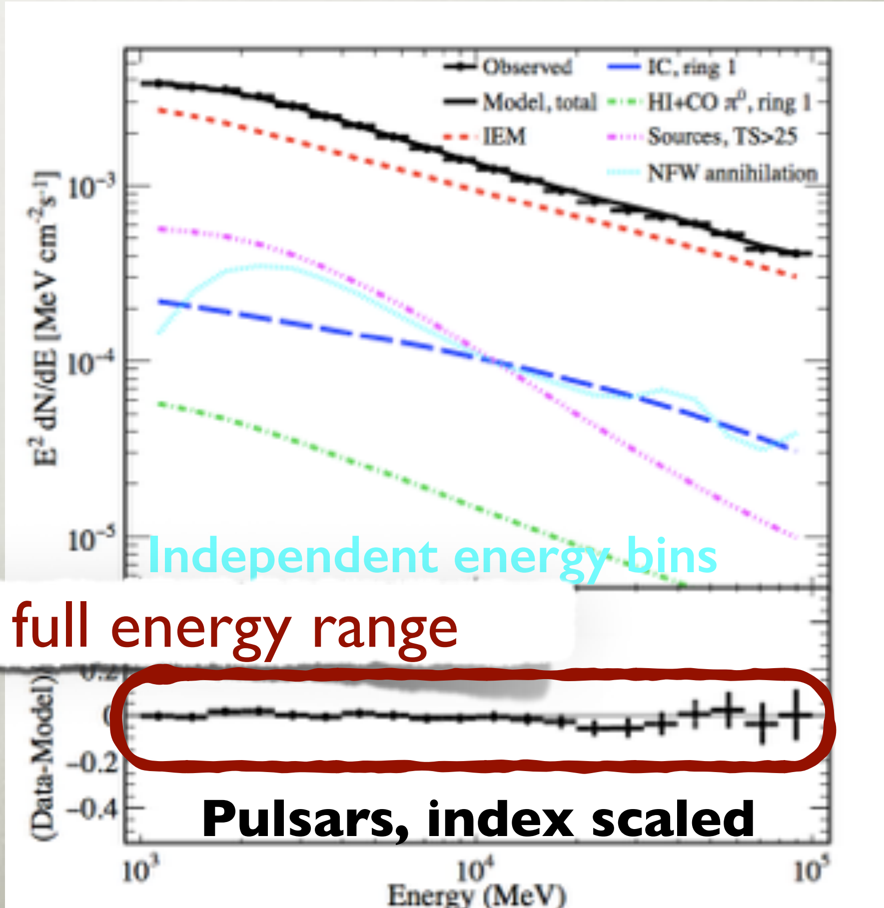
Additional Component

- 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

Integrated flux in 15°x15° ROI

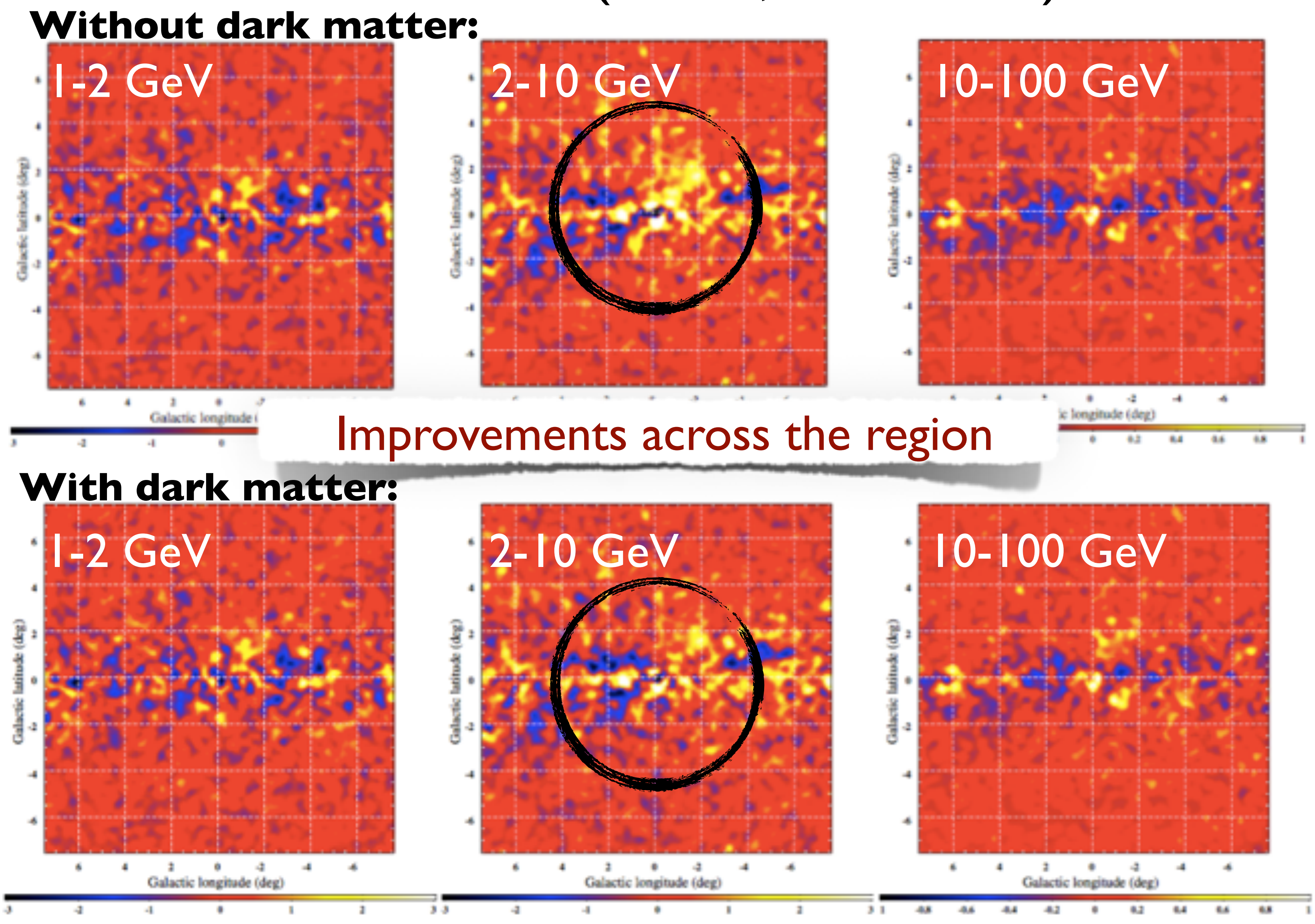




Improvements over the full energy range

Residual Maps Dark Matter

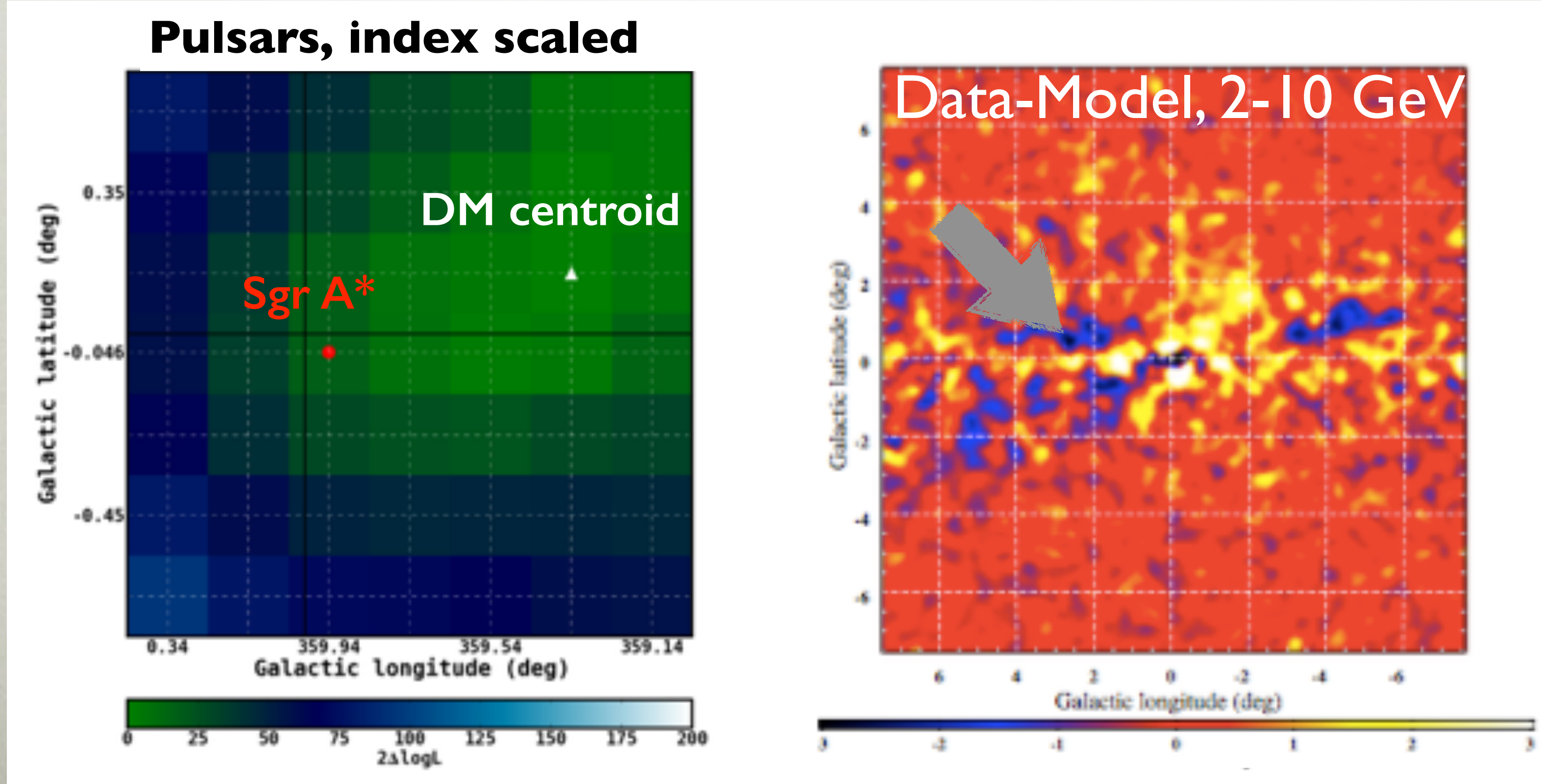
DATA-MODEL (Pulsars, index scaled)



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

Dark Matter Component Morphology

- Cuspiness of the DM profile (whether a standard, **γ=1**, or cuspier, **γ=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), but:
  - ✓ some dependence on IEM (offset ~0.5°-1°)
  - ✓ cannot rule out offset is due to shortcomings in modeling of IEM



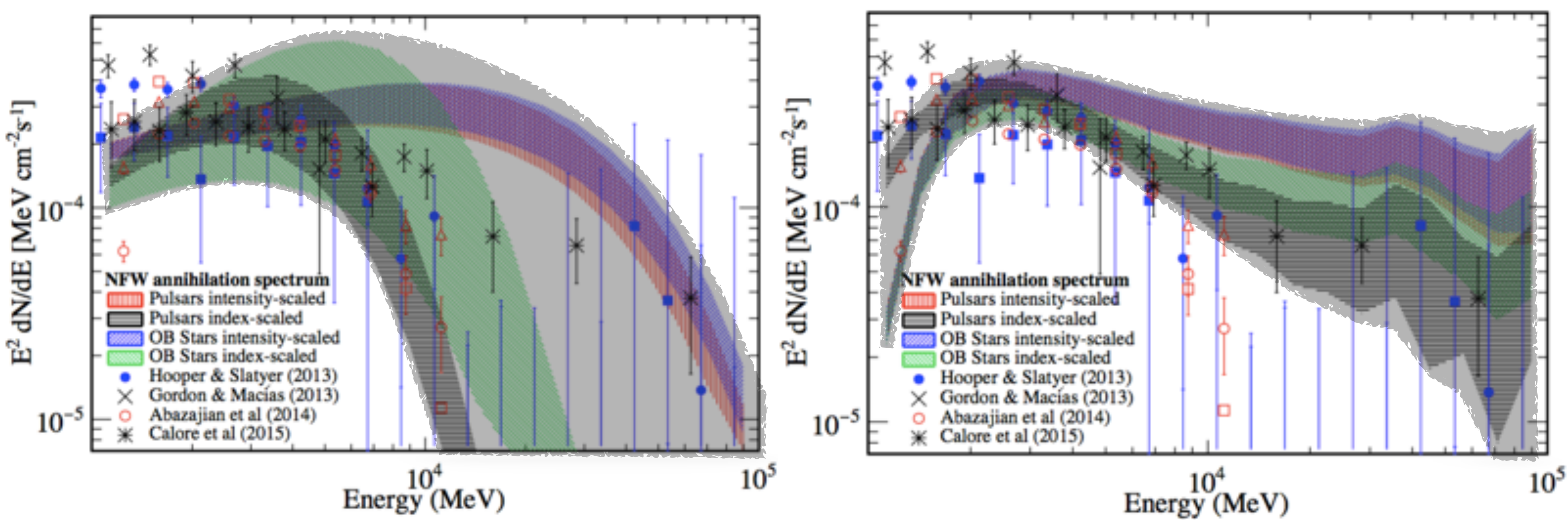
C. Karwin et al, in prep

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

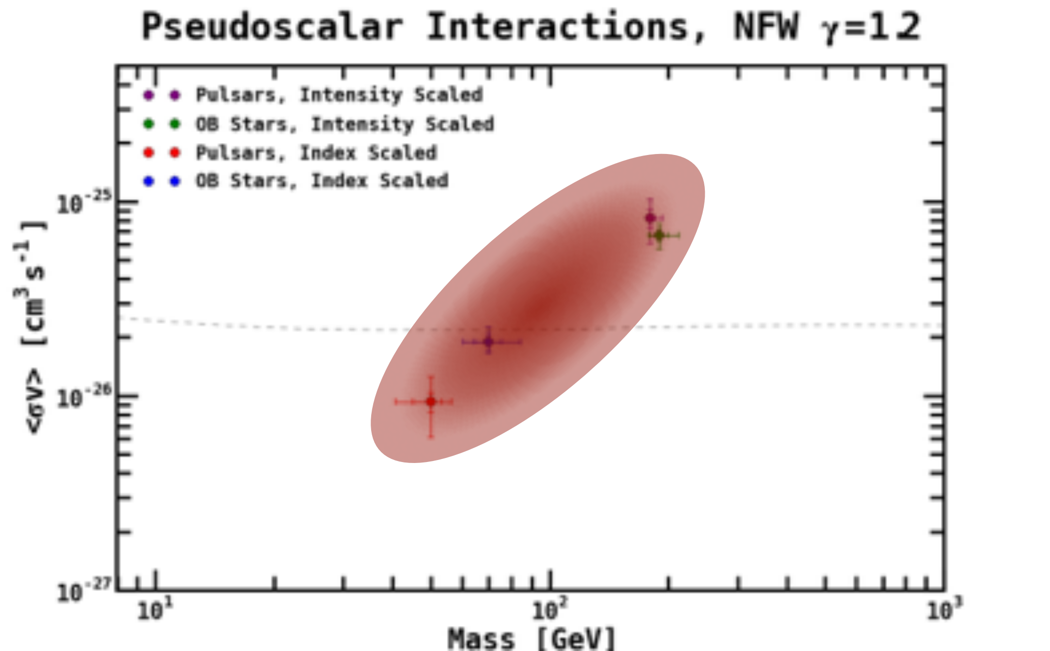
➡A broader range of interpretations is allowed compared to previous results



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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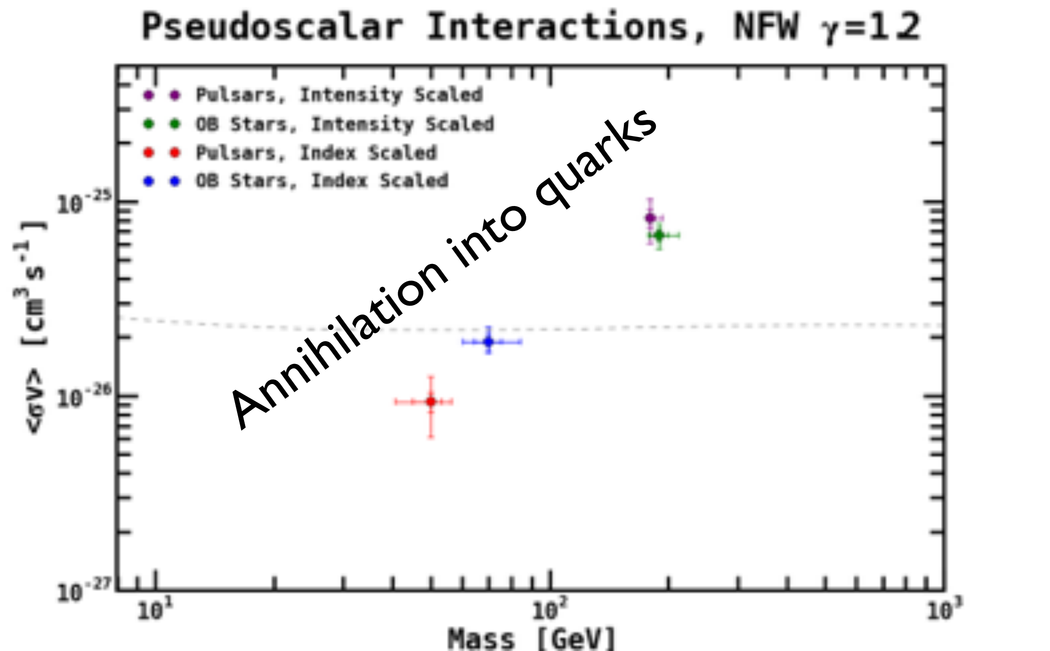
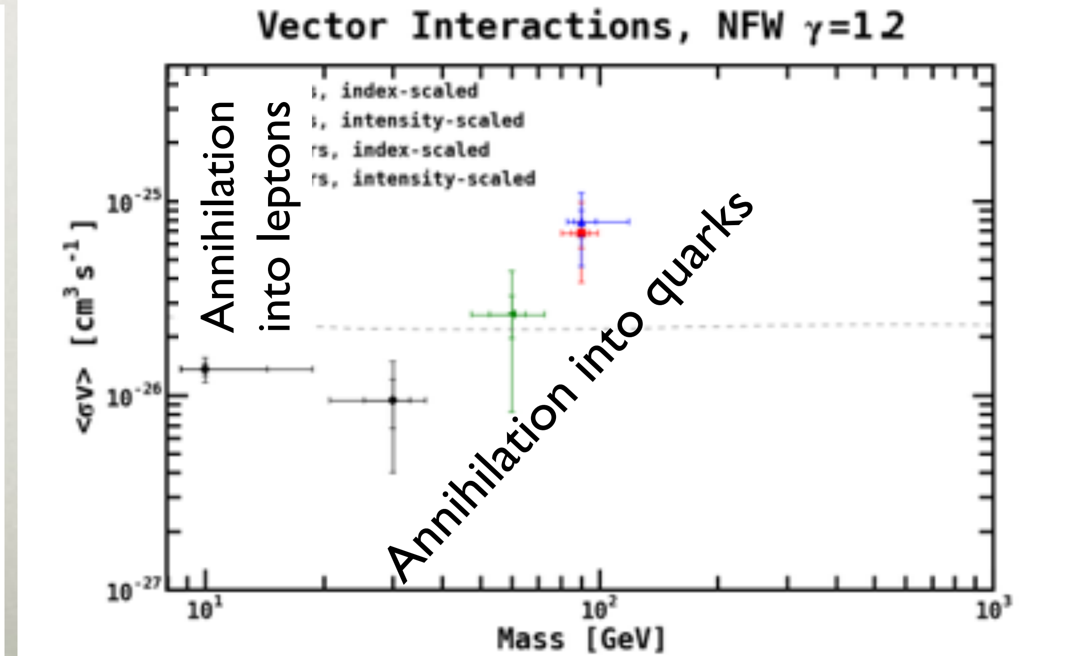
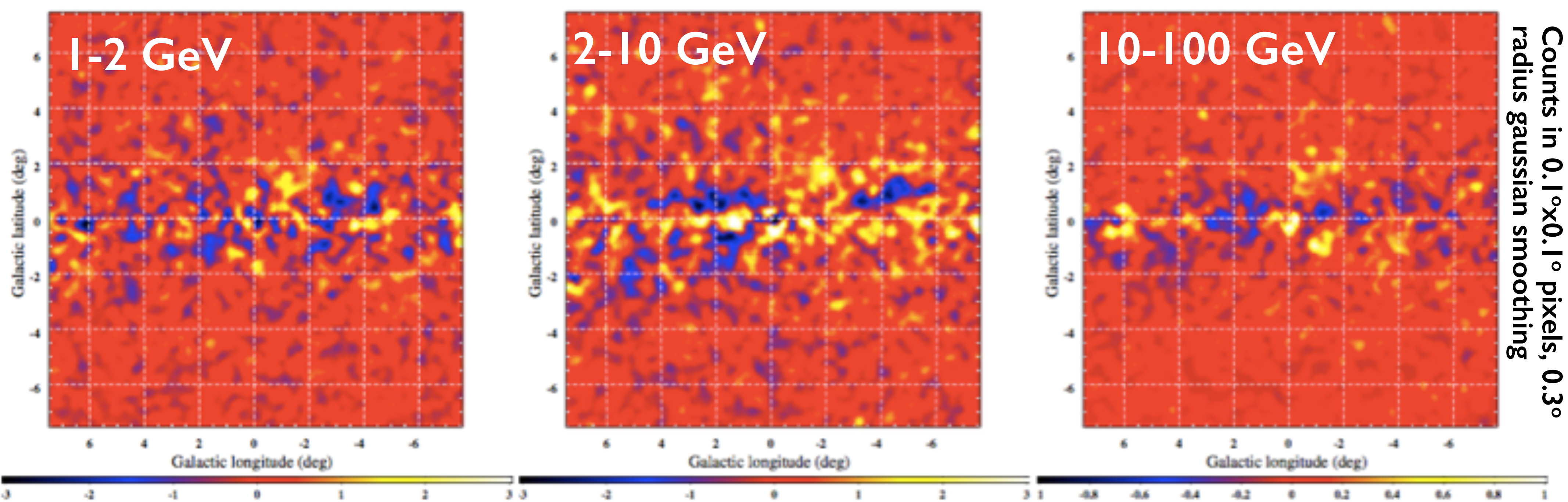


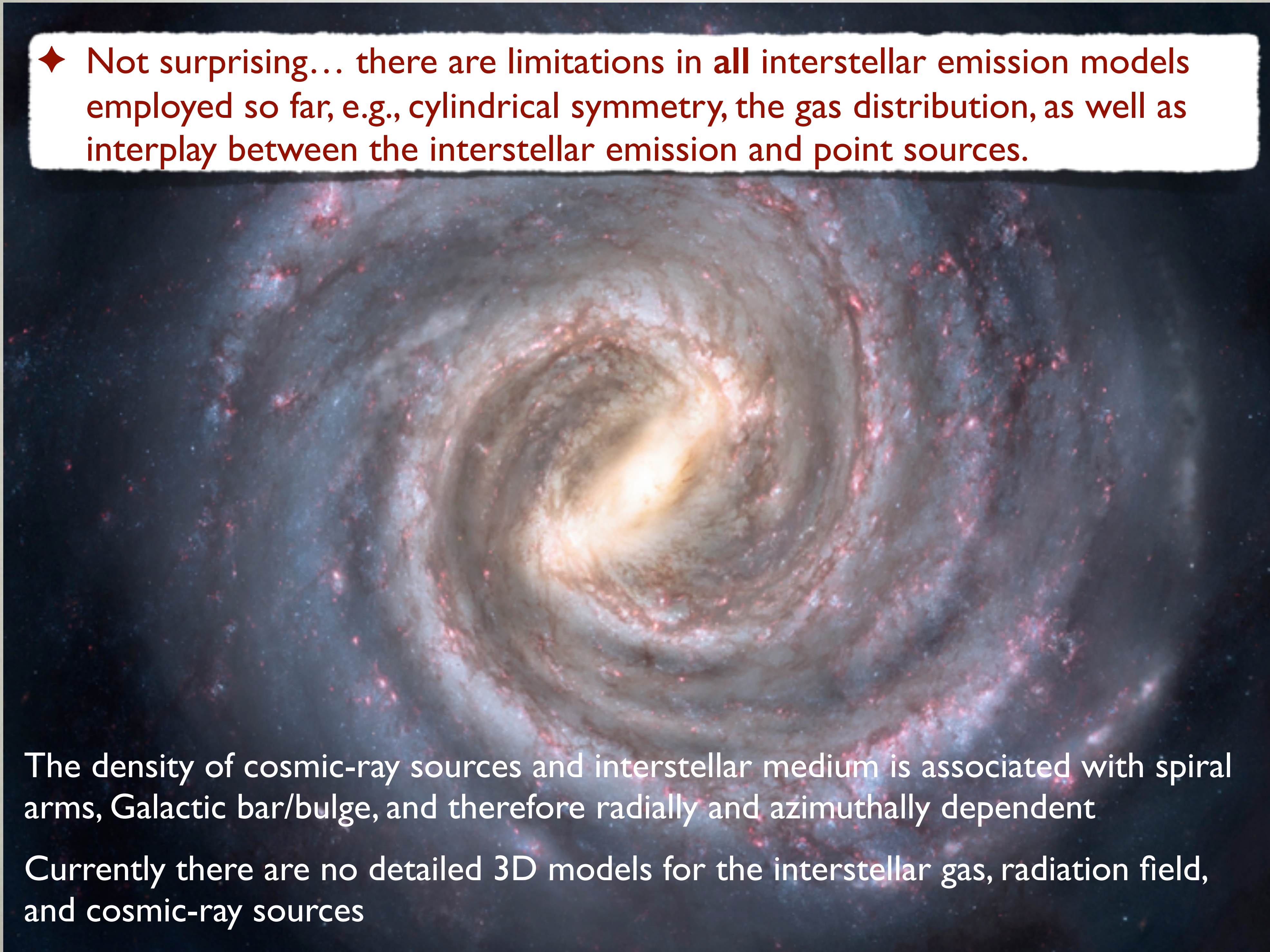


Residual Maps
Dark Matter

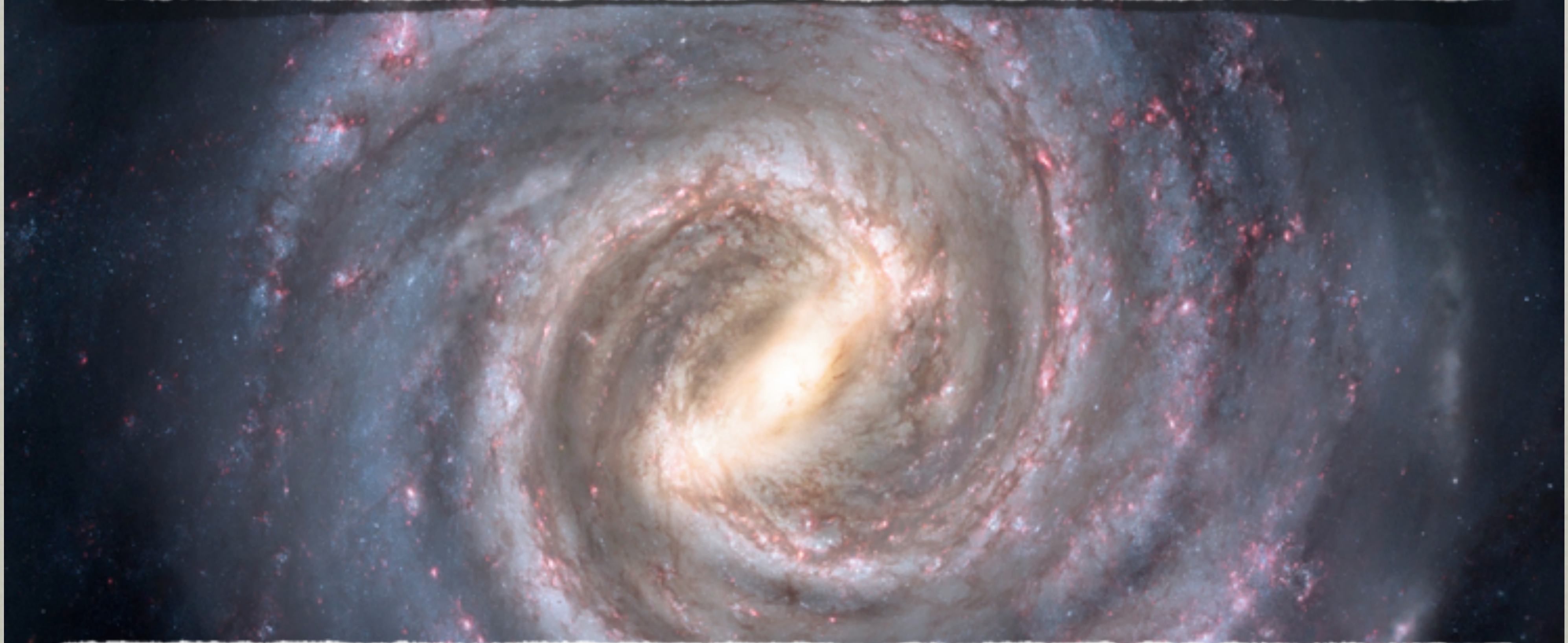
Improvements across the region, but some discrepancies between data and model remain

DATA-MODEL (Pulsars, index scaled - with dark matter)




✦ 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

- ✦ 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.



- ➡ **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**

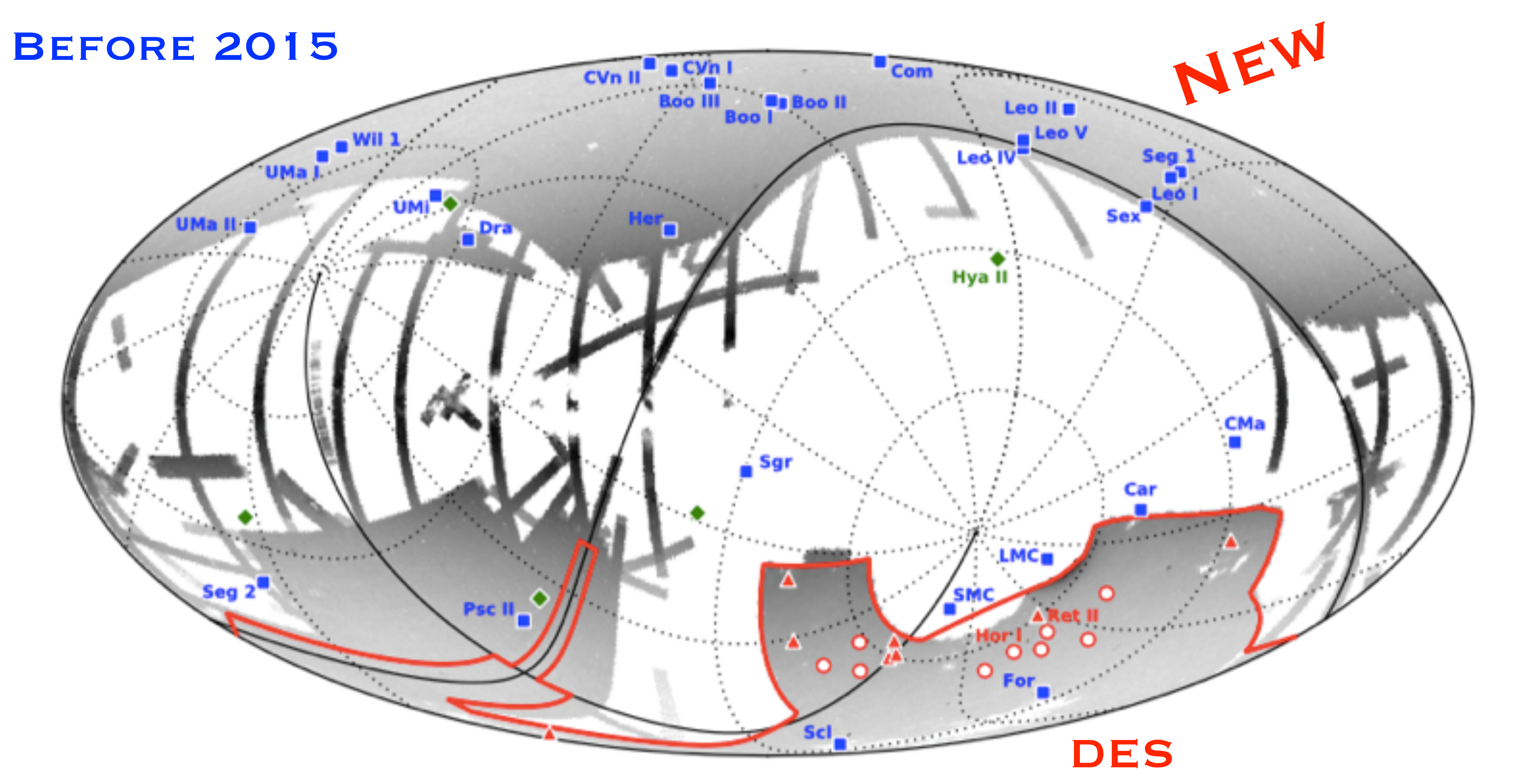
Dwarf Spheroidal Galaxies

- 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

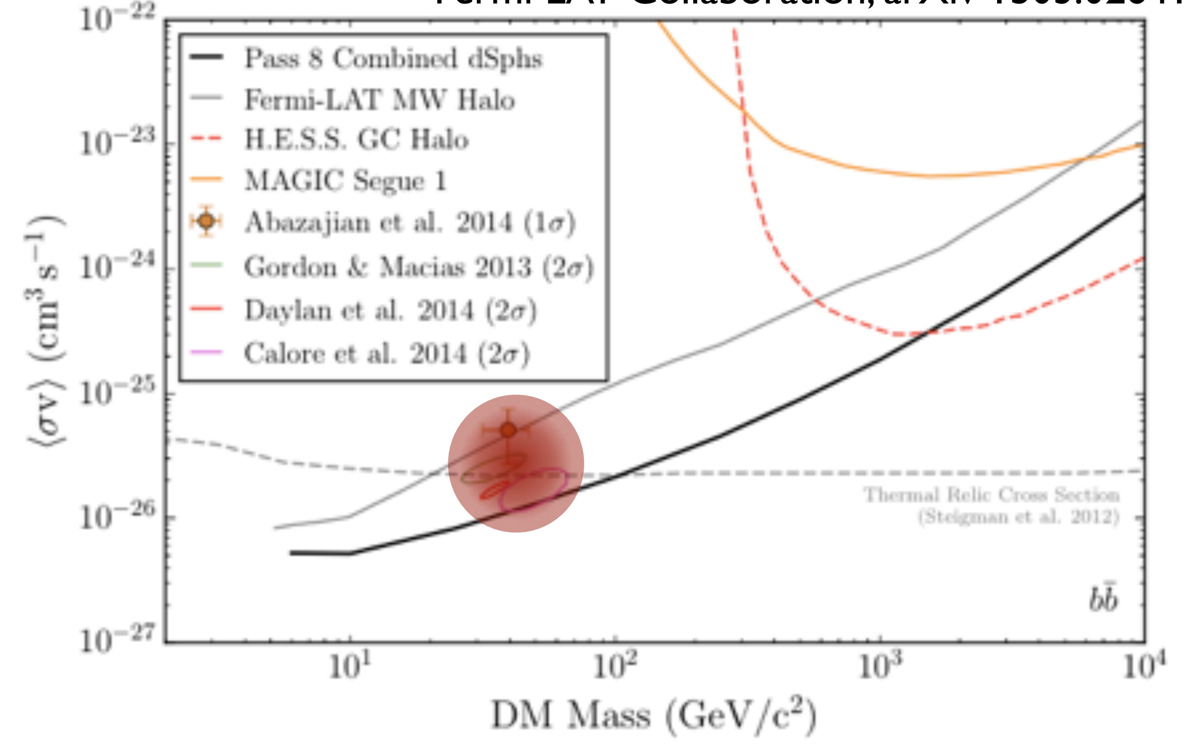
DES Collaboration, arXiv:1508.03622



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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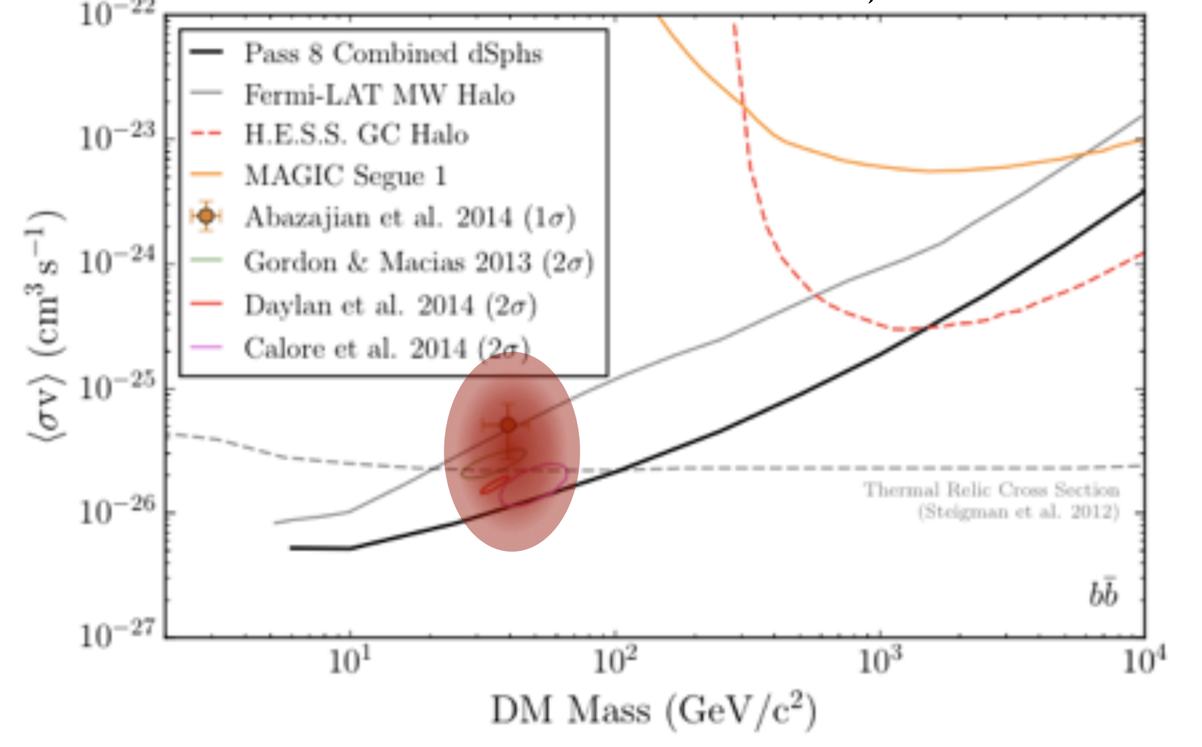

N.B.:
Contours do not fully reflect uncertainties in the DM profile!
(also see Abazajian et al, arXiv:1510.06424)

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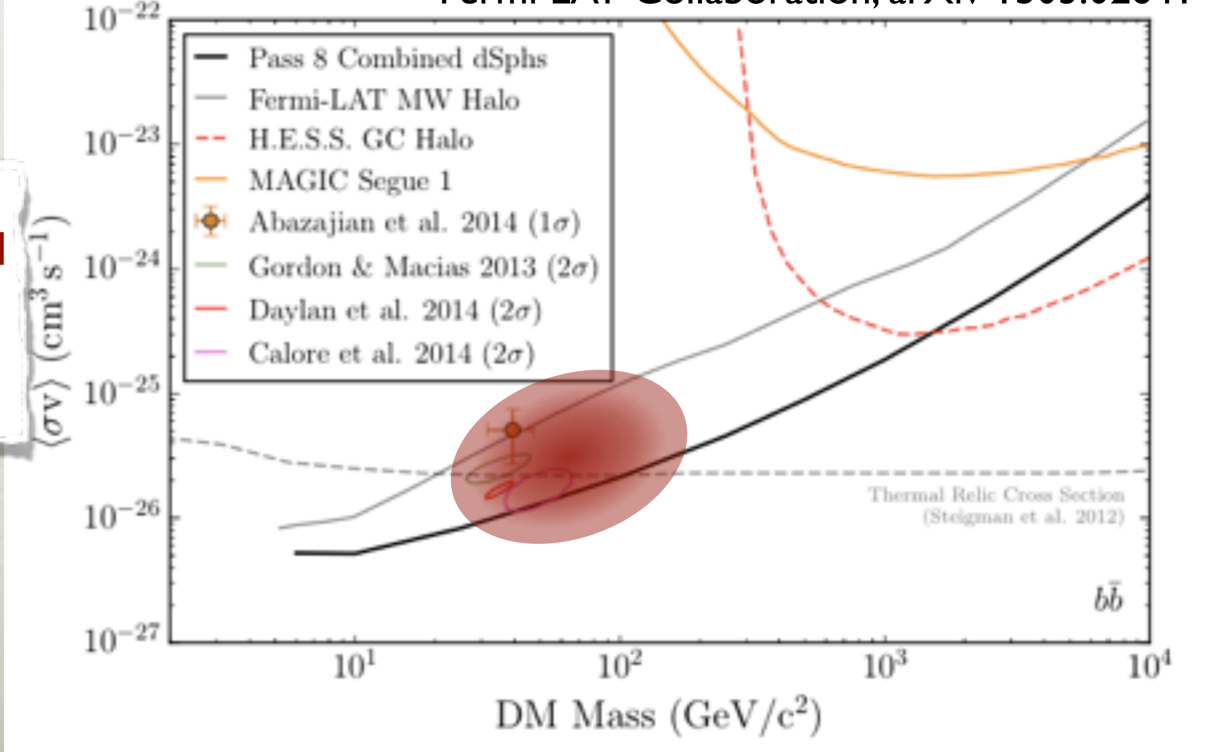
- Limits probe DM explanation of the GC excess

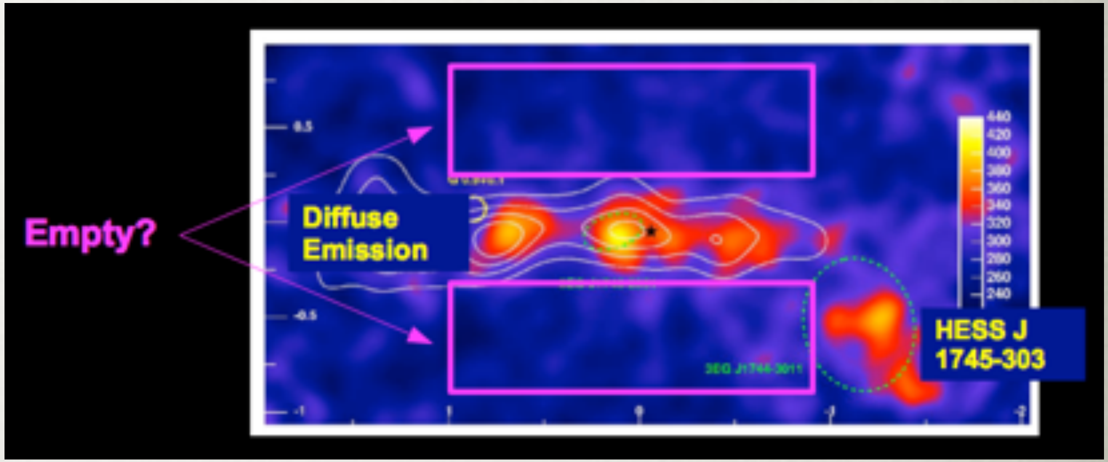
Fermi LAT Collaboration, arXiv 1503.02641

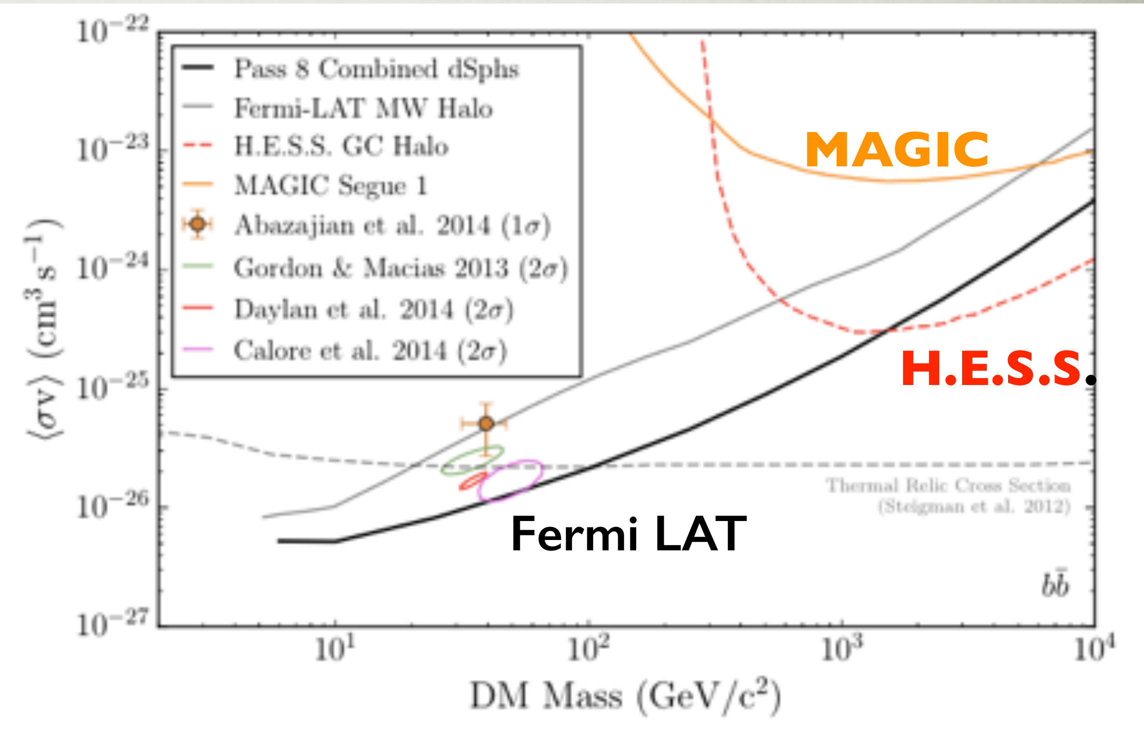


N.B.:
Uncertainties in the astrophysical background model also allow for a broader range of DM masses and annihilation channels
(see e.g. Agrawal et al, arXiv:1411.2592)

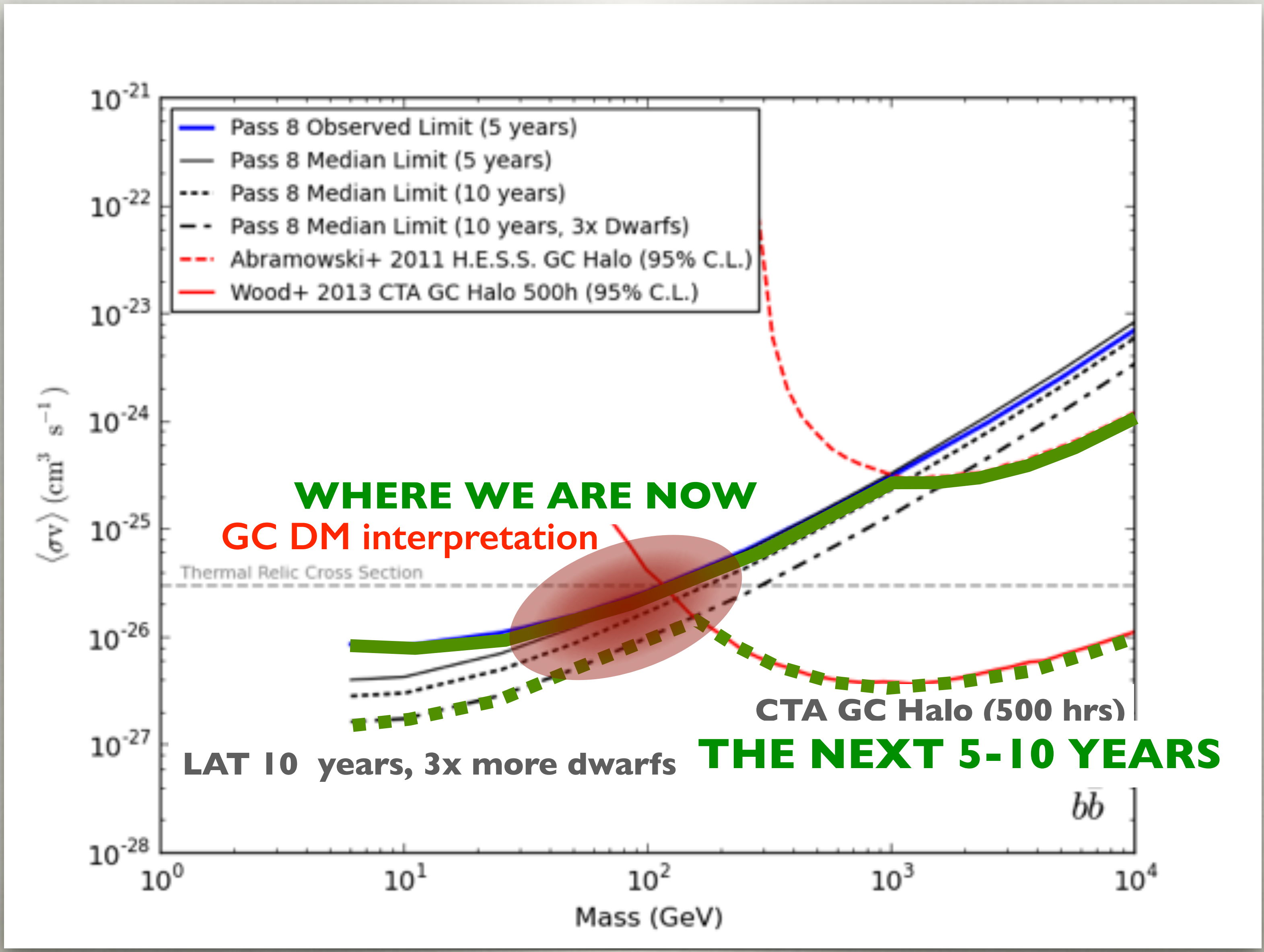
VHE Gamma Rays: H.E.S.S., MAGIC, VERITAS

- 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

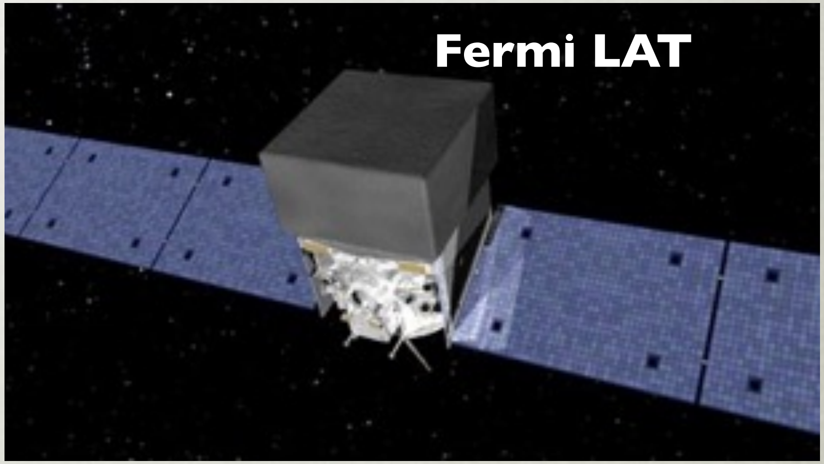




Putting it all Together

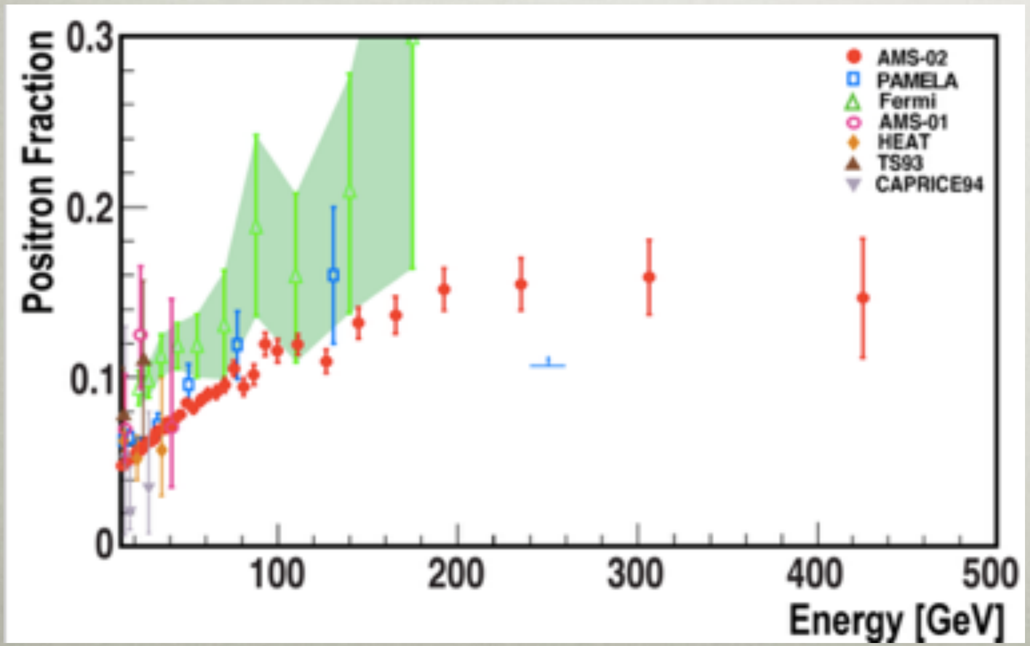


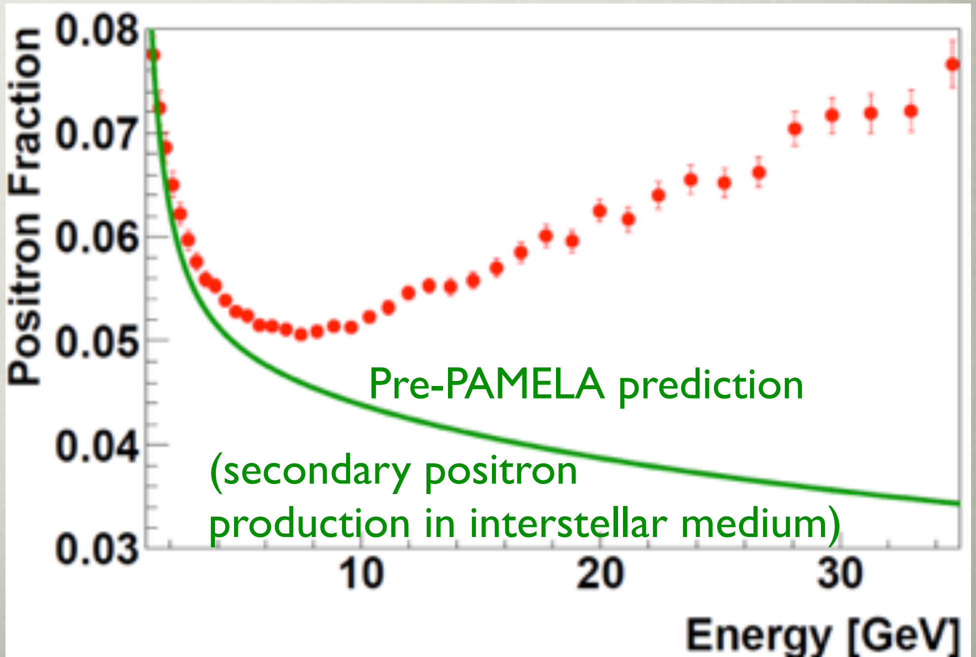
Cosmic rays



Positrons

- Positron fraction measured up to 500 GeV (AMS-02). Rises at high energy, up to ~250 GeV

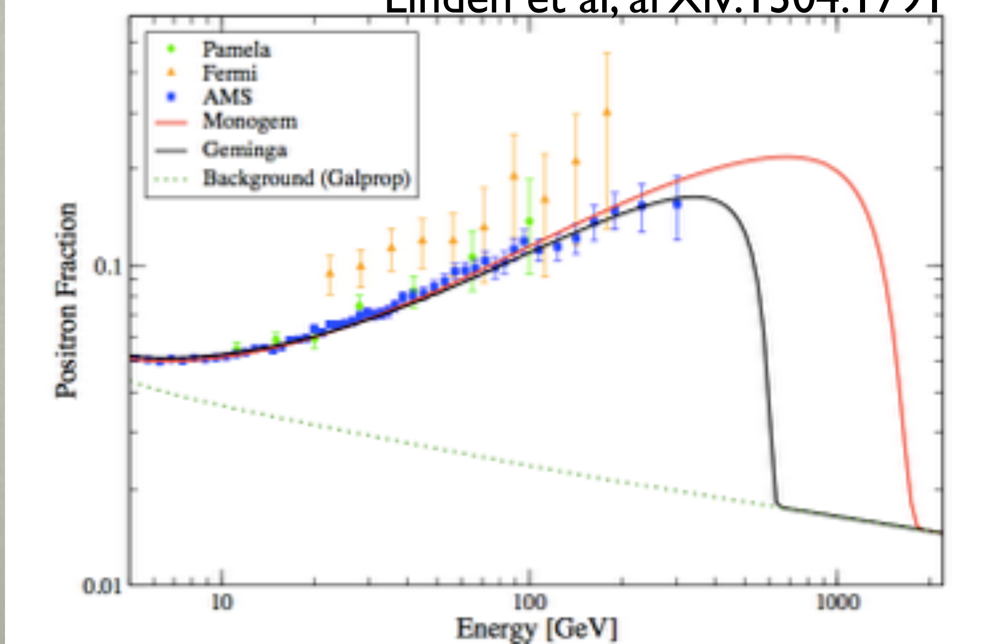




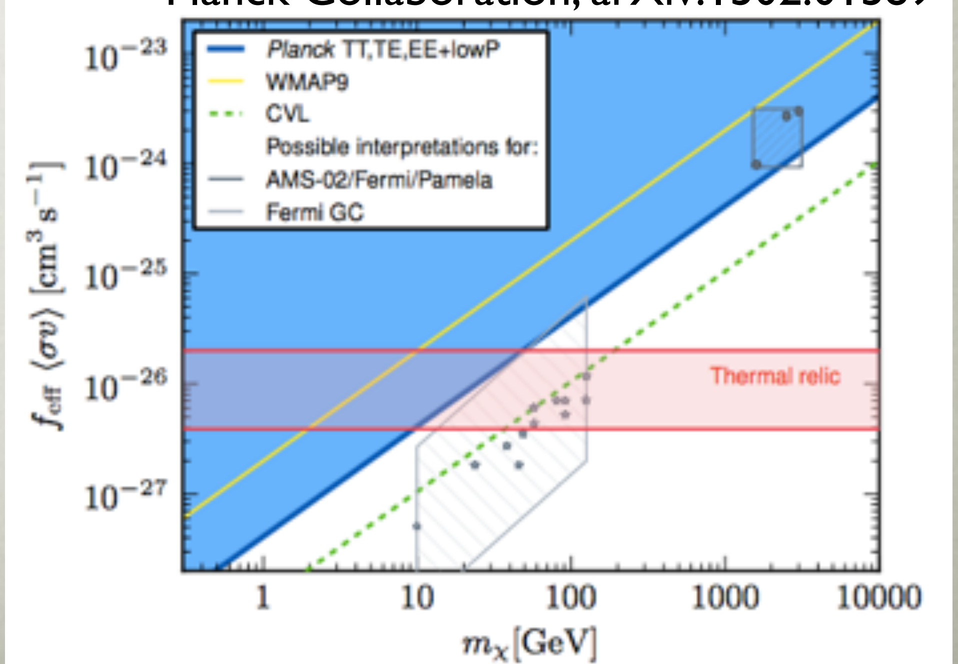
Positrons

- Positron fraction measured up to 500 GeV (AMS-02). Rises at high energy, up to ~250 GeV
- Dark matter can reproduce the rise, but it is disfavored by other searches (gamma rays, CMB, …)
- Other plausible interpretations (**nearby single source**, population of sources, production of secondaries at source, …)
  - ➡ Anisotropy in the e+e- data could confirm the nearby source hypothesis. Predicted anisotropy is consistent with current bounds (Fermi LAT, AMS-02)

Linden et al, arXiv:1304.1791

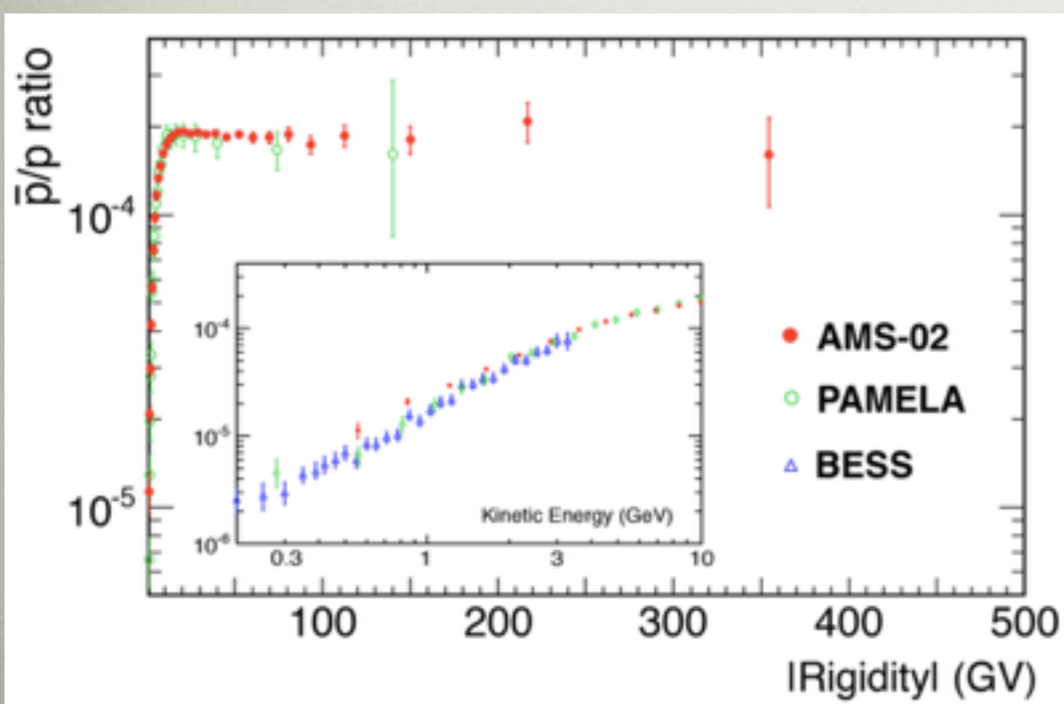


Planck Collaboration, arXiv:1502.01589

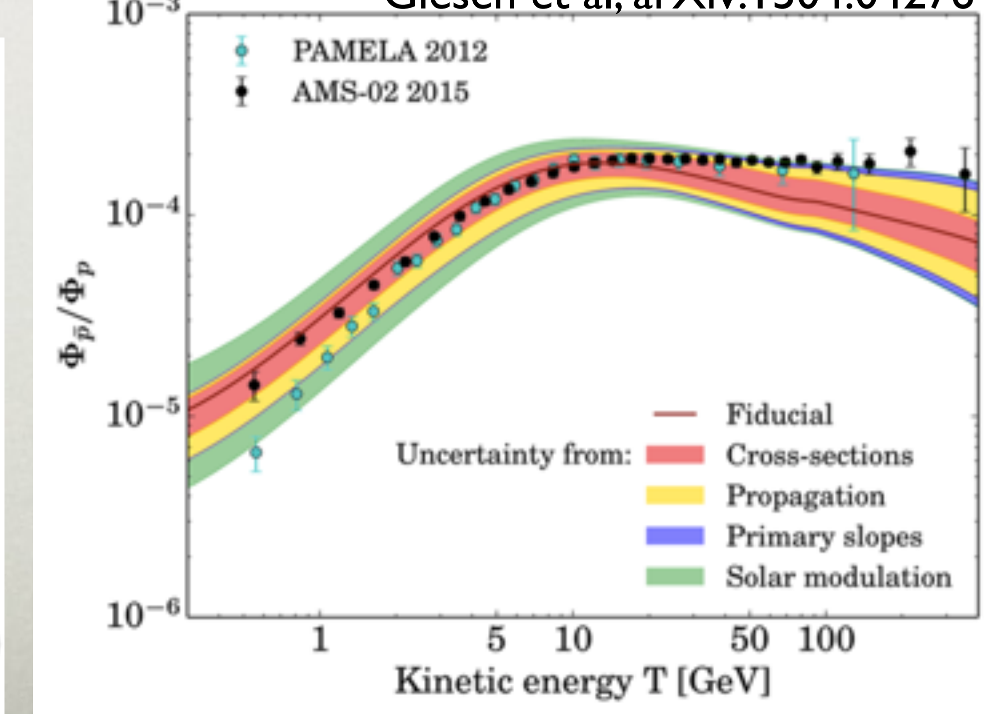


Antiprotons

- Measurement of the antiproton fraction up to 450 GeV
- In agreement with secondary production predictions (based on B/C measurements and antiprotons produced by CR interactions in the interstellar medium); consistent with primary source to explain positron fraction

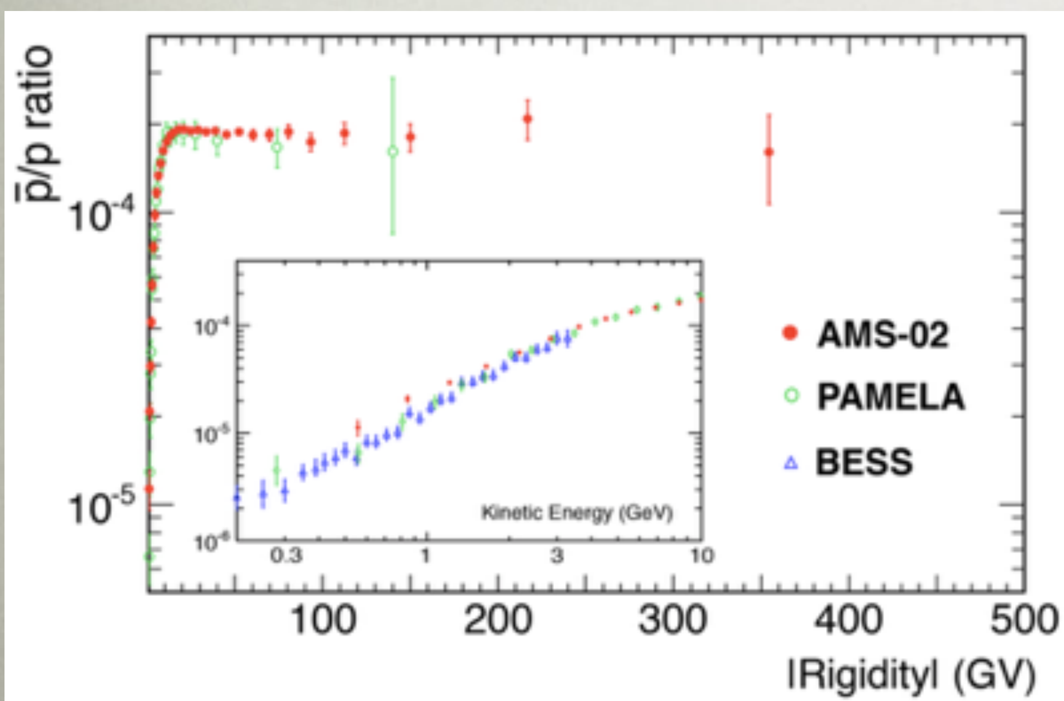


Giesen et al, arXiv:1504.04276

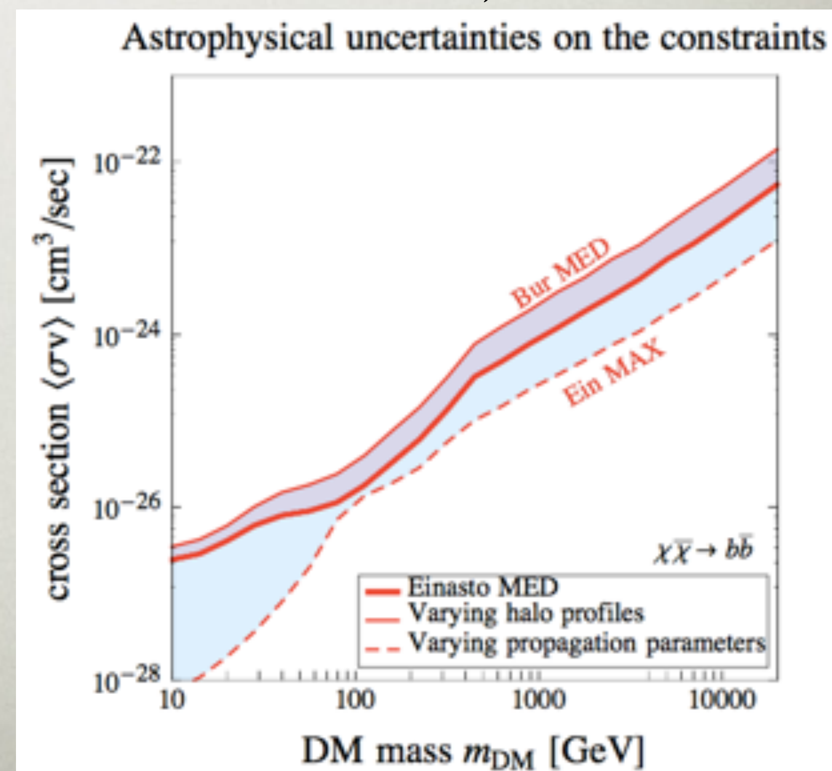


Antiprotons

- Measurement of the antiproton fraction up to 450 GeV
- In agreement with secondary production predictions (based on B/C measurements and antiprotons produced by CR interactions in the interstellar medium); consistent with primary source to explain positron fraction
- DM constraints can be derived with assumptions on CR production and propagation



Giesen et al, arXiv:1504.04276



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 most compelling confirmation of the DM interpretation for this excess
- The rise in the CR positron fraction continues to be investigated. Many viable interpretations other than DM exist
- In the meanwhile, indirect dark matter 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!