

# Tenth International Fermi Symposium

9th-15th October 2022



## Indirect Dark Matter Searches with *Fermi*-LAT

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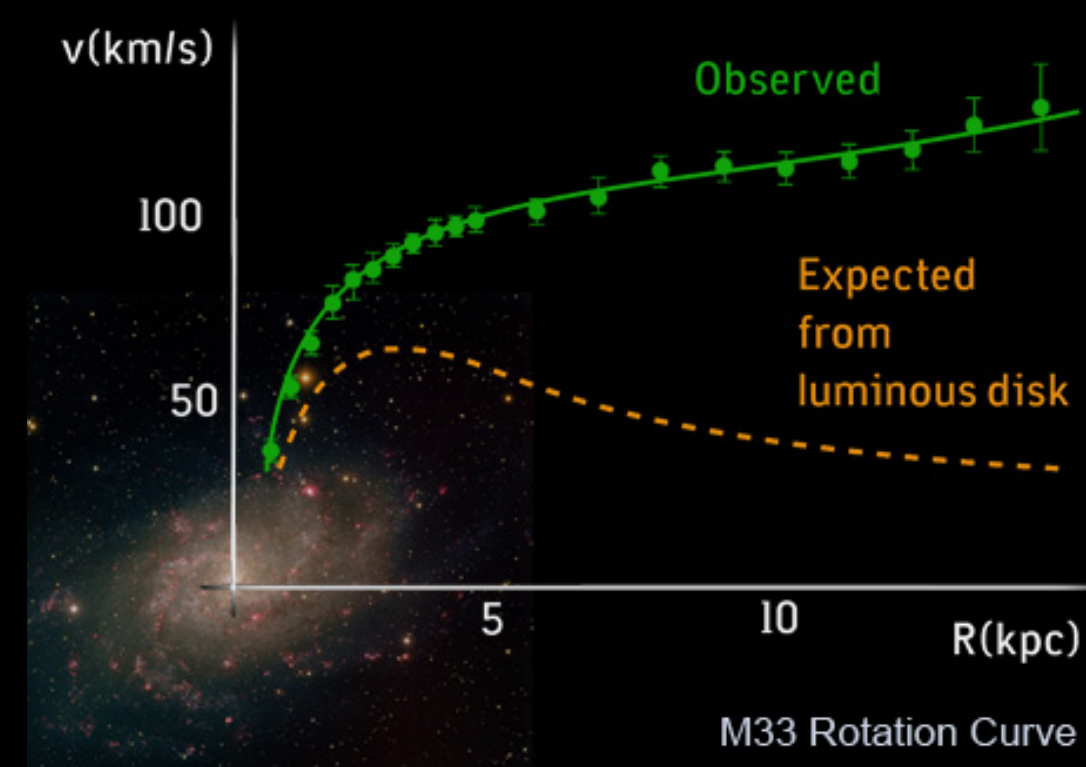
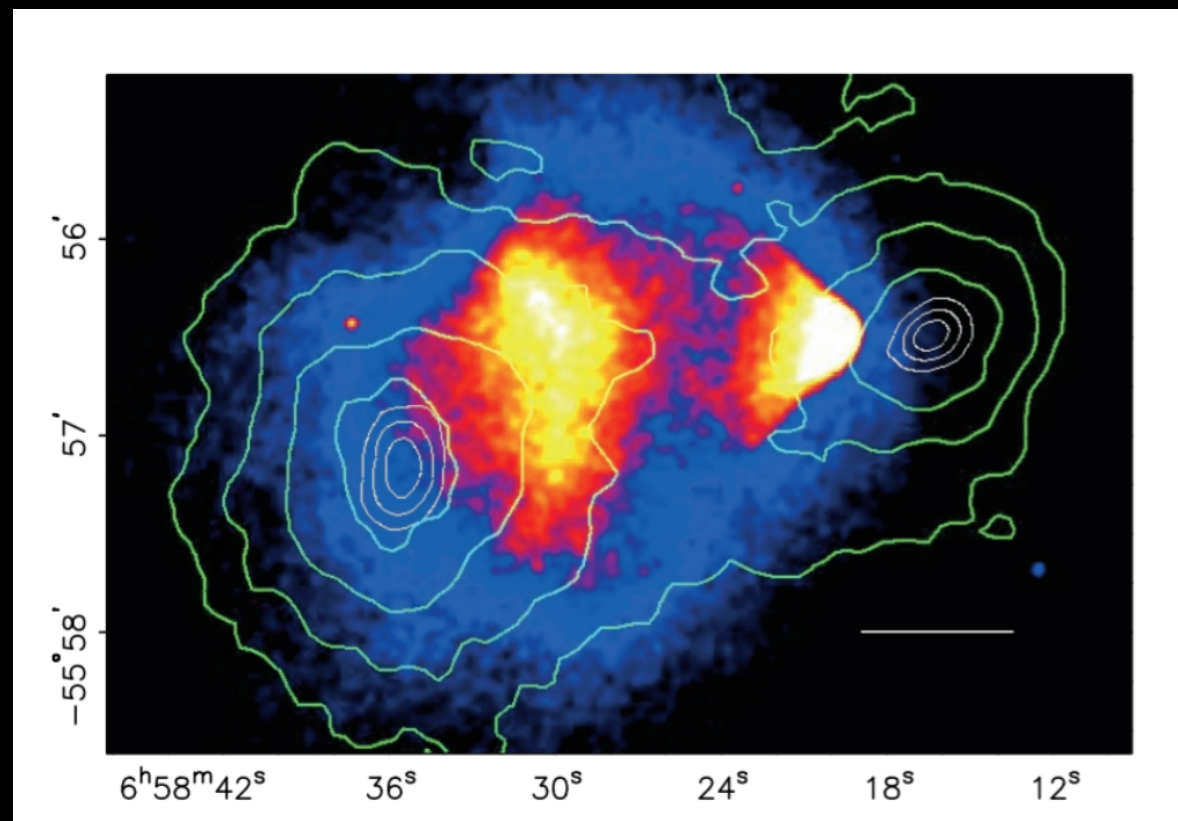
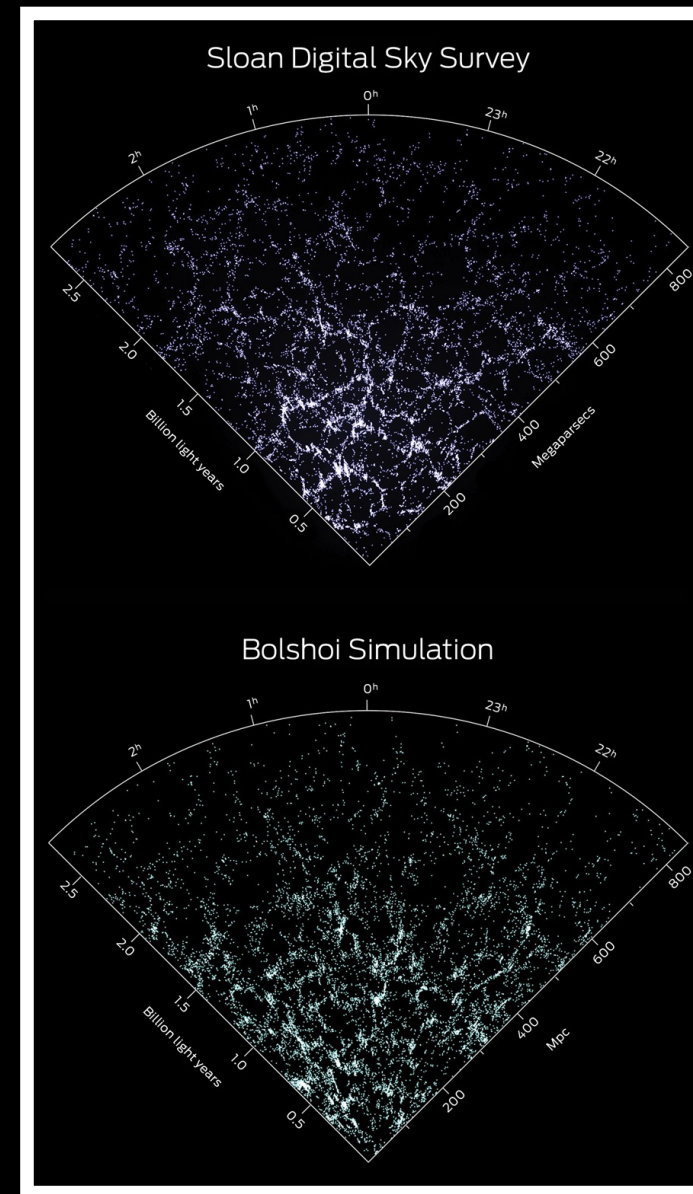
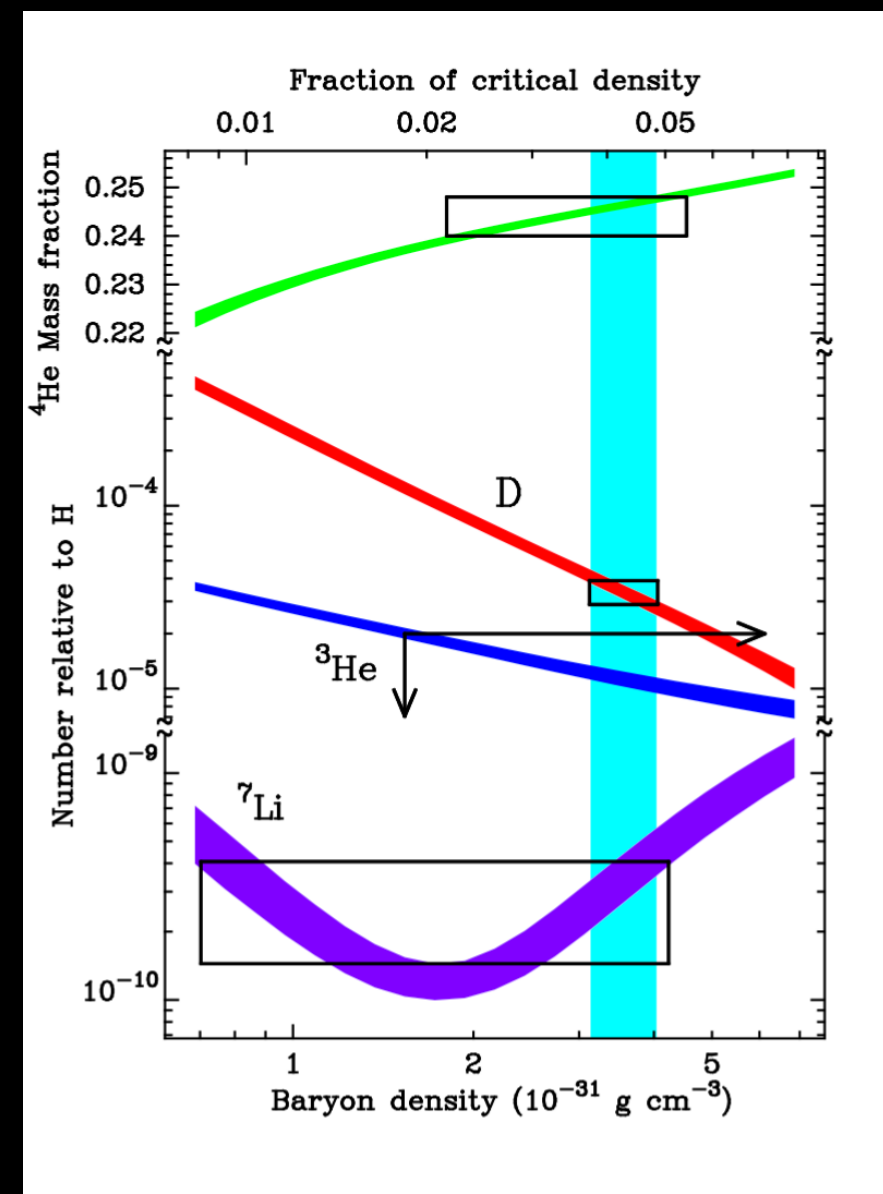
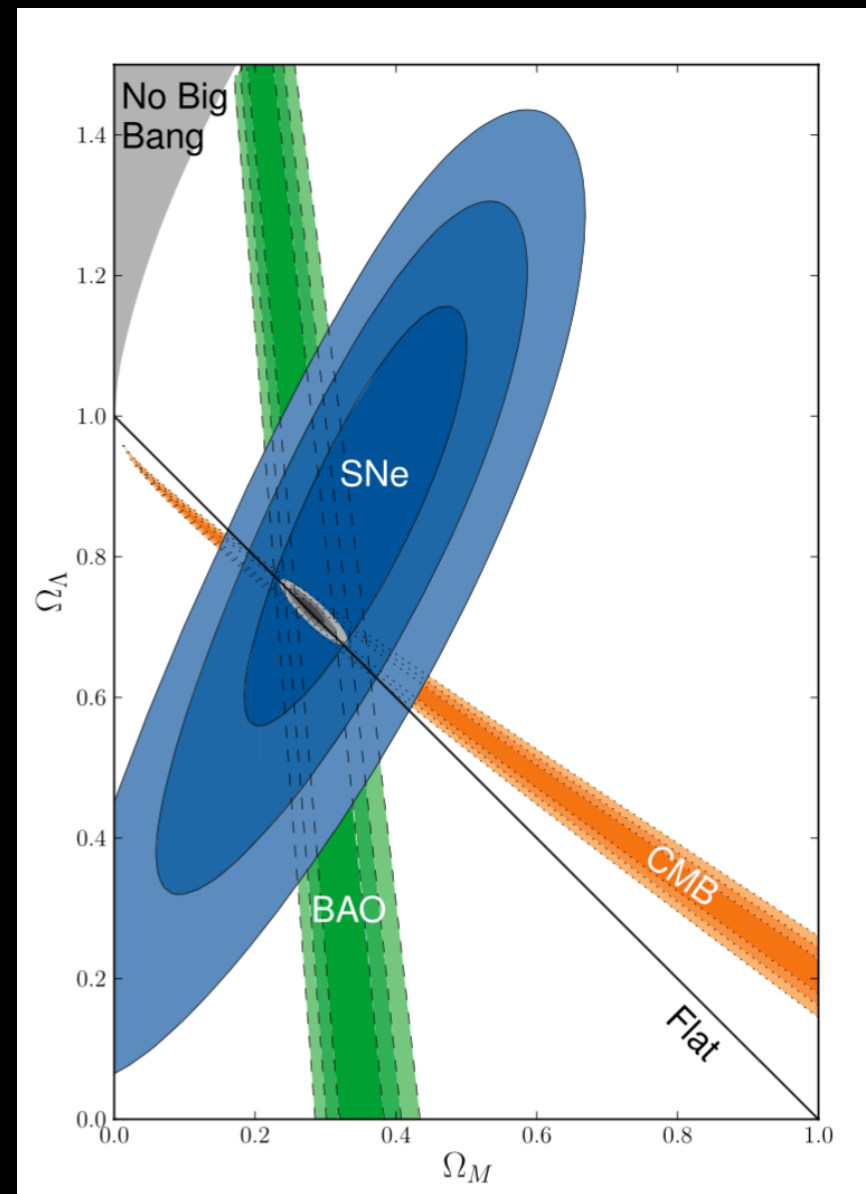
[\\*christopher.m.karwin@nasa.gov](mailto:christopher.m.karwin@nasa.gov)

# Outline

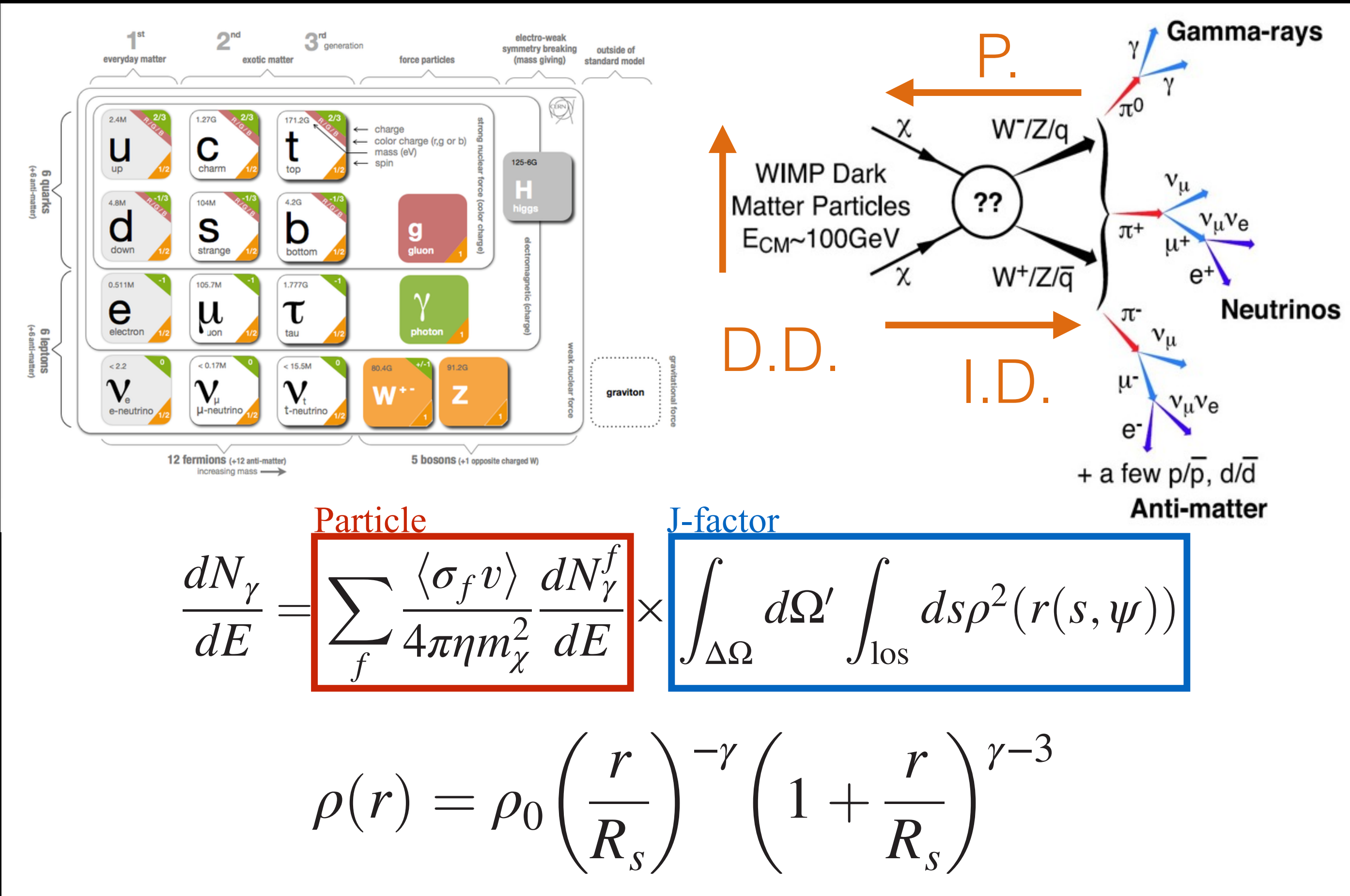
- Dark Matter (DM)
- The GC excess
- The Milky Way Dwarf Spheroidal Galaxies
- The Andromeda Galaxy
- Additional Searches
- Future Directions
- Summary and Conclusions

# The Dark Matter Paradigm

- Evidence for DM is found at all cosmological scales.
- Matter-energy density of the Universe:
  - Baryons: 4%
  - Dark Matter: 26%
  - Dark Energy: 70%

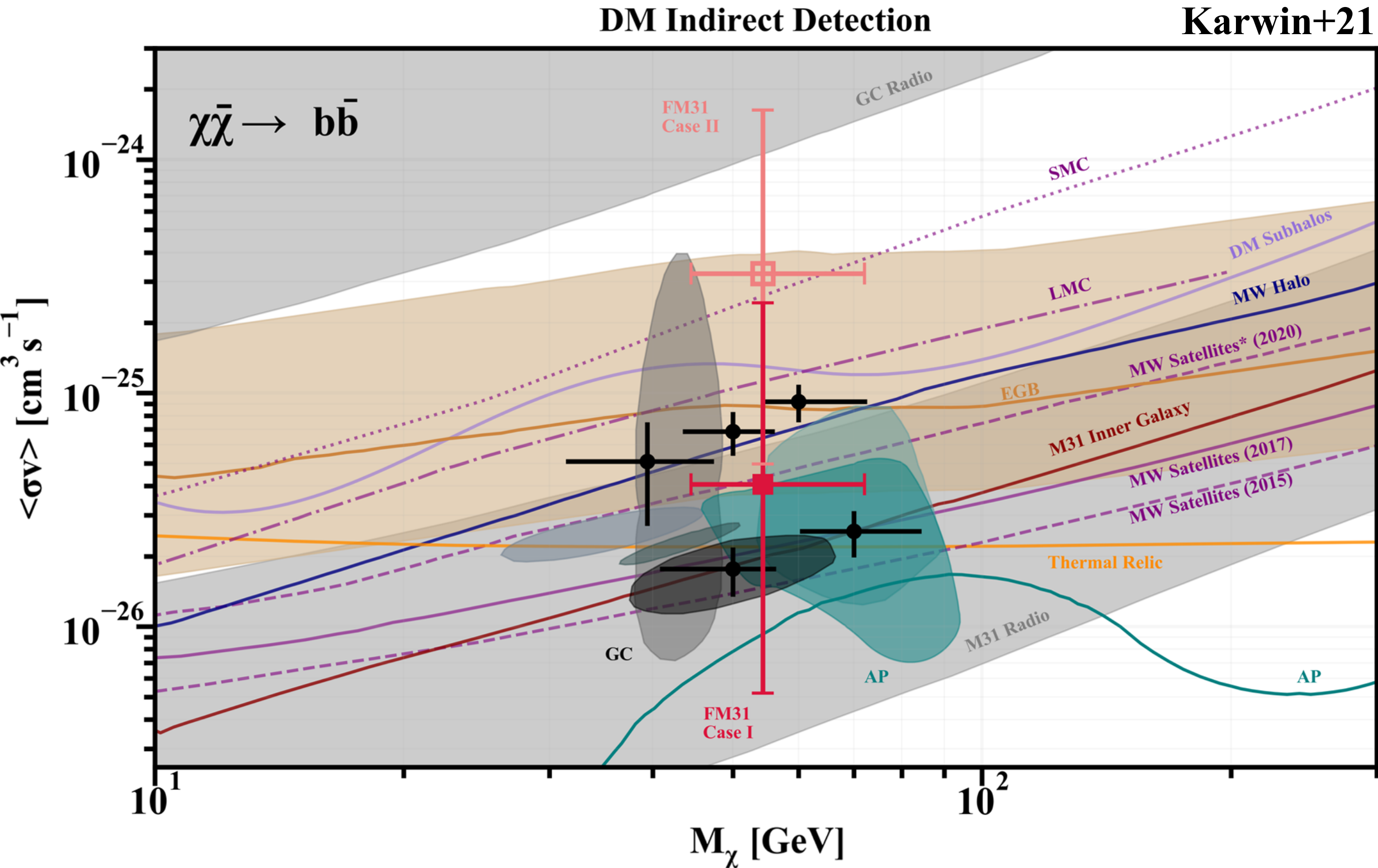


# Detecting Dark Matter



- Historically, DM has been thought to likely be a particle.
- Discovering DM will require complementarity between different search methods and targets.

# Overview of Dark Matter Searches

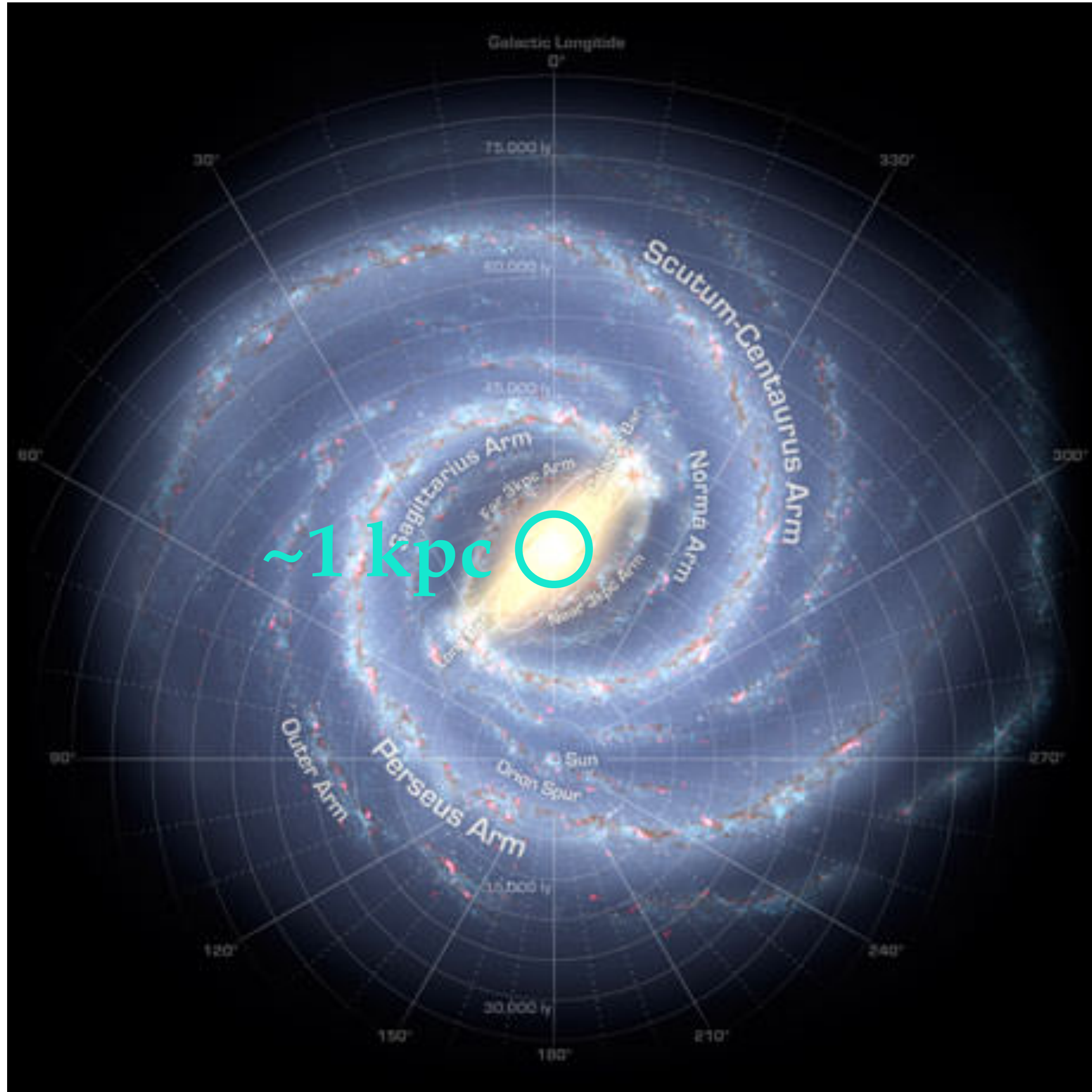


Numerous dark matter searches with the LAT:

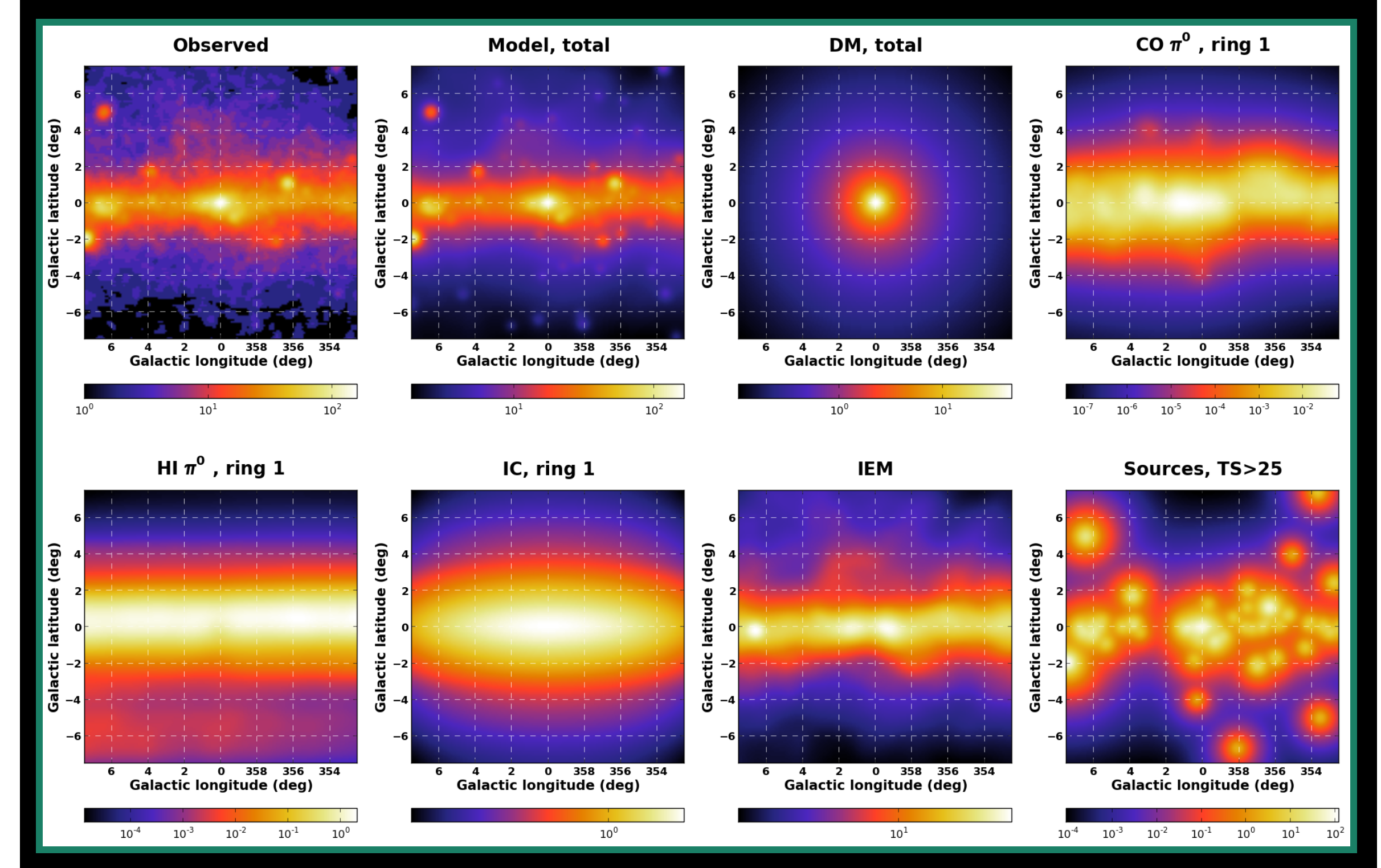
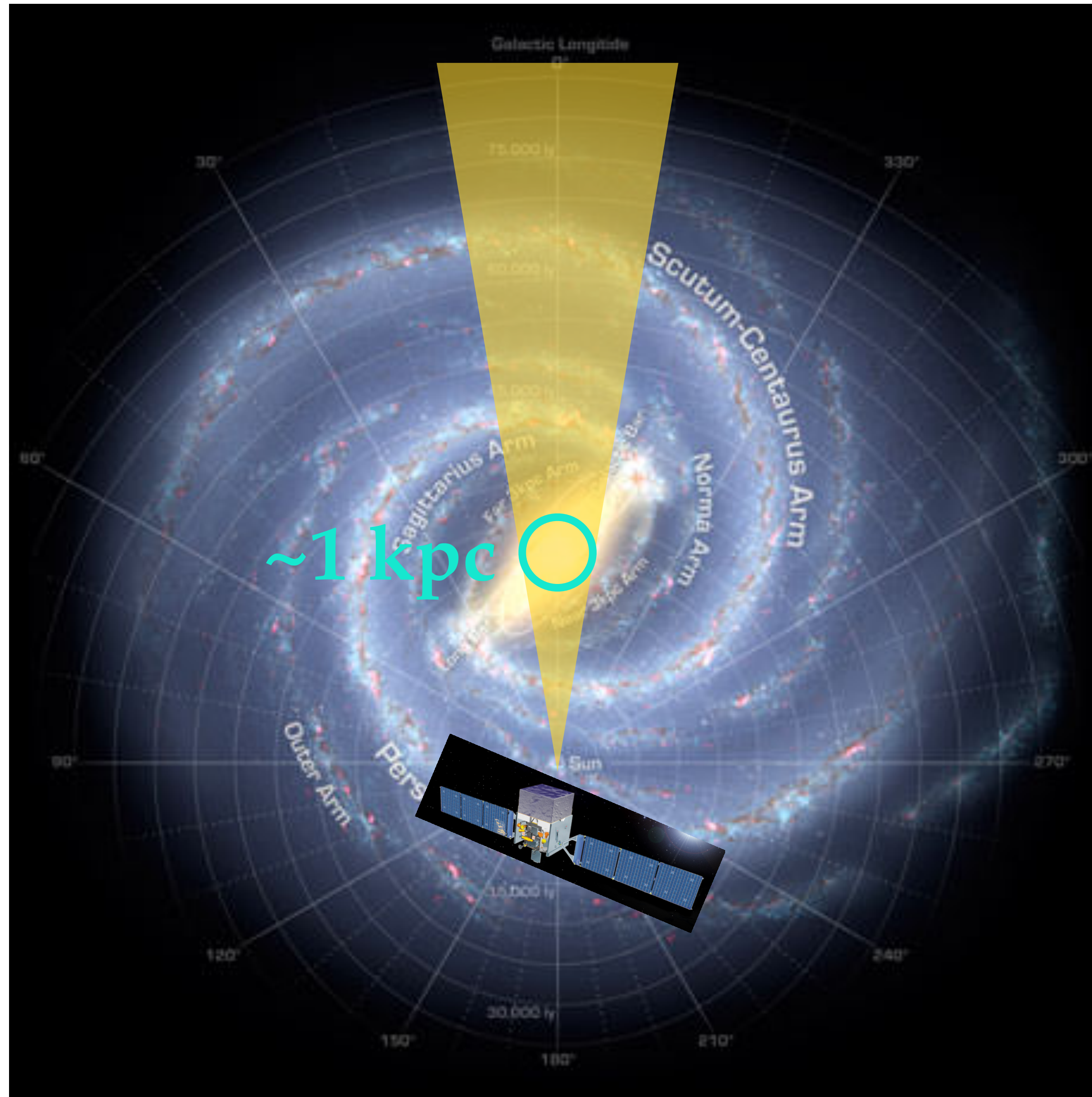
- Galactic center
- MW dwarf spheroidal galaxies
- LMC and SMC
- Dark matter sub-halos
- Milky Way halo
- M31 (center and halo)
- Extragalactic gamma-ray background



# Observing the GC



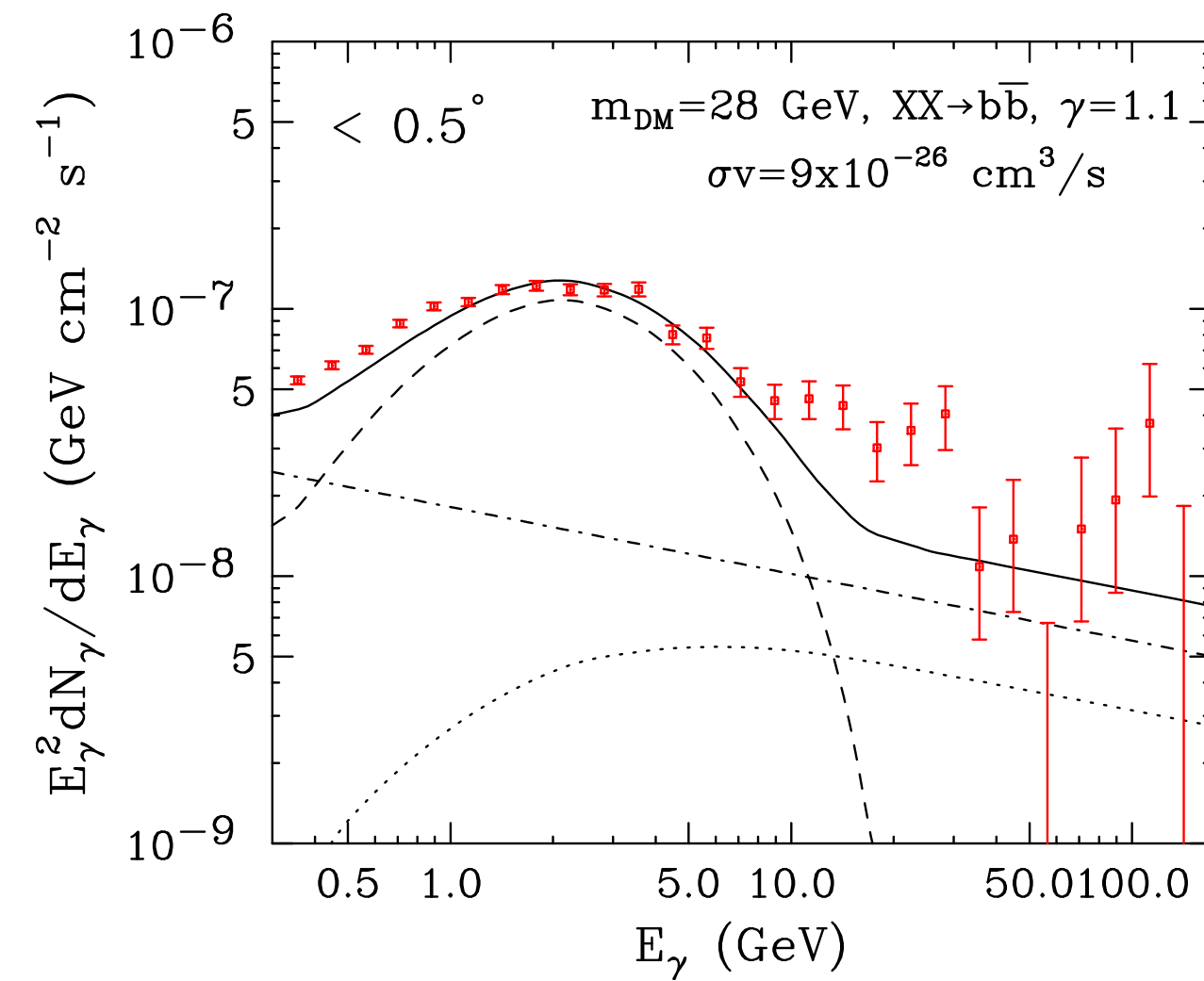
# Observing the GC



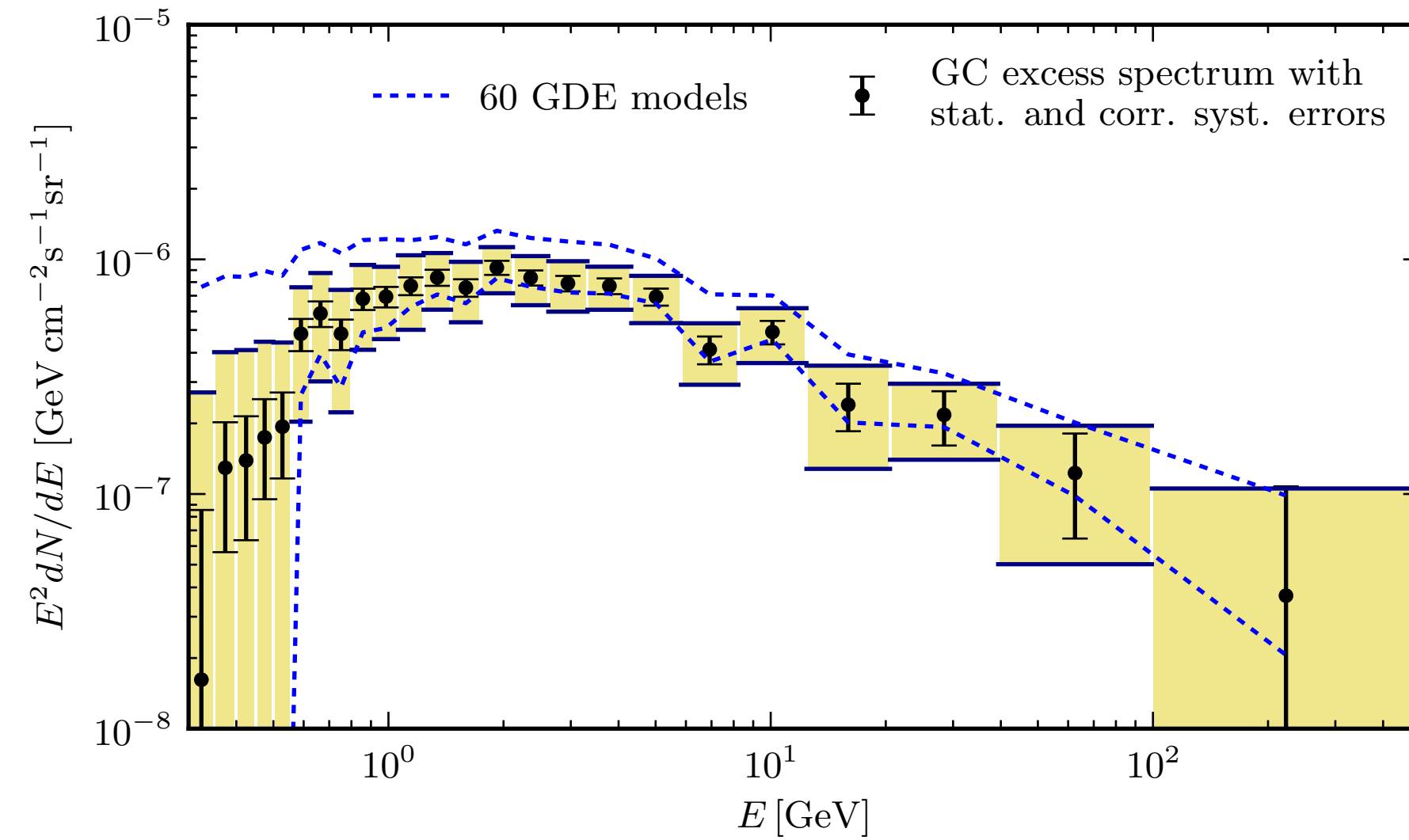
- An excess above model predictions has been observed, although with significant systematic uncertainties.
- Leading explanations include:
  1. Mid-modelling of the Galactic diffuse along the line of sight.
  2. An unresolved point source population, i.e. millisecond pulsars.
  3. DM annihilation.

# The GC Excess Spectrum

**Goodenough & Hooper 2009**

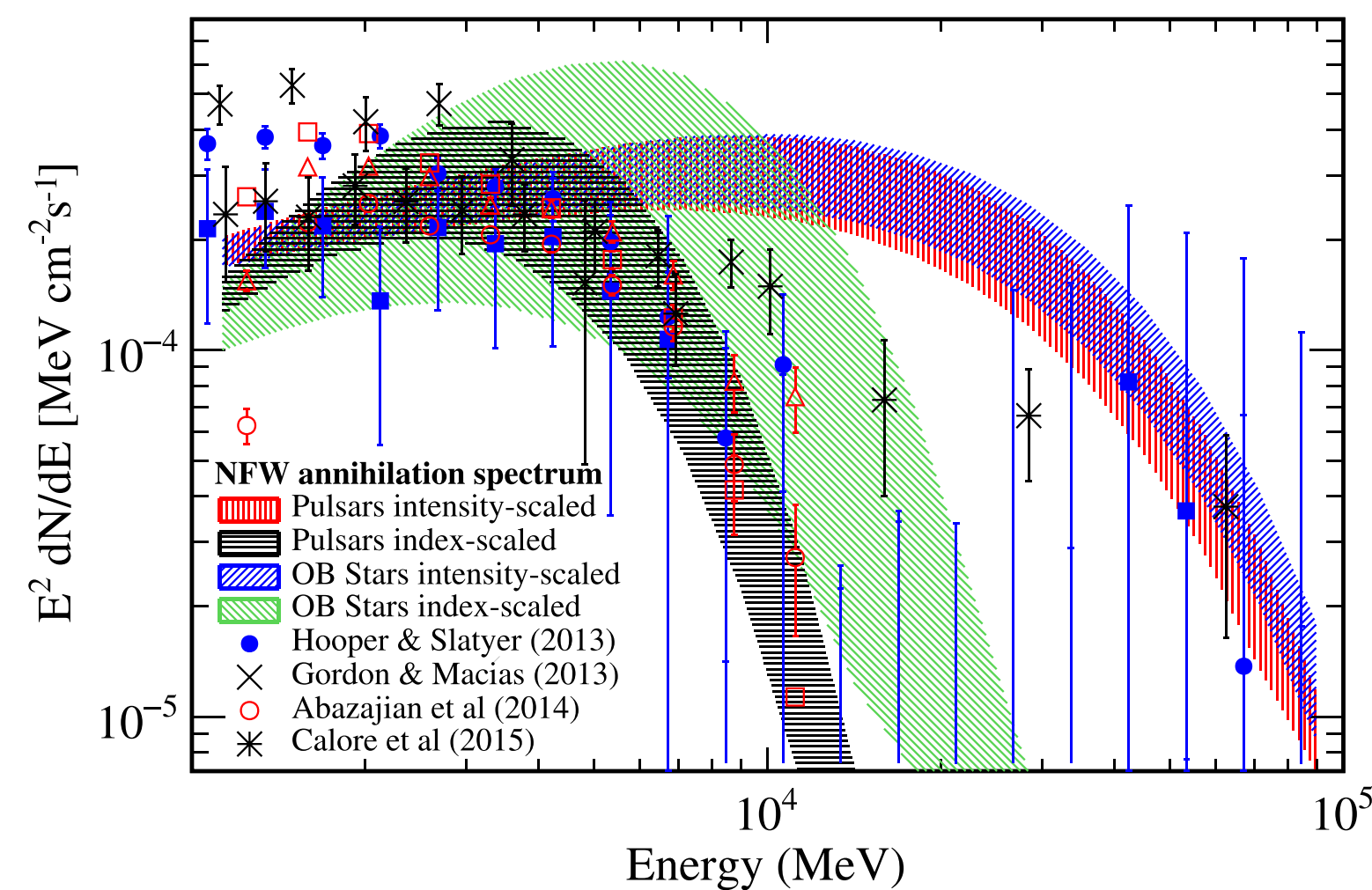


**Calore+2015**

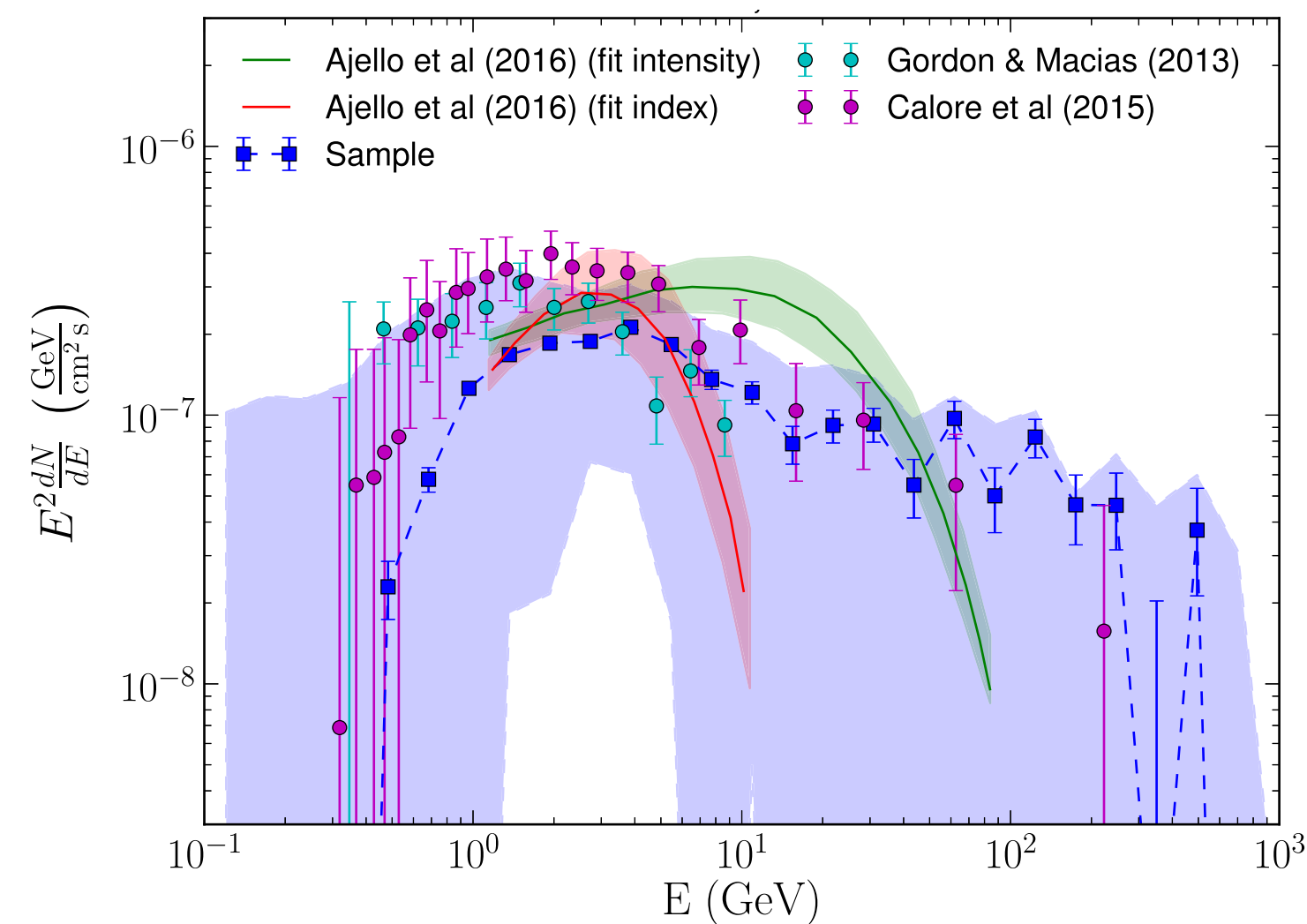


- It's generally agreed that there exists a systematic excess towards the GC.
- The uncertainty in the spectrum is dominated by systematics relating to the Galactic diffuse model.

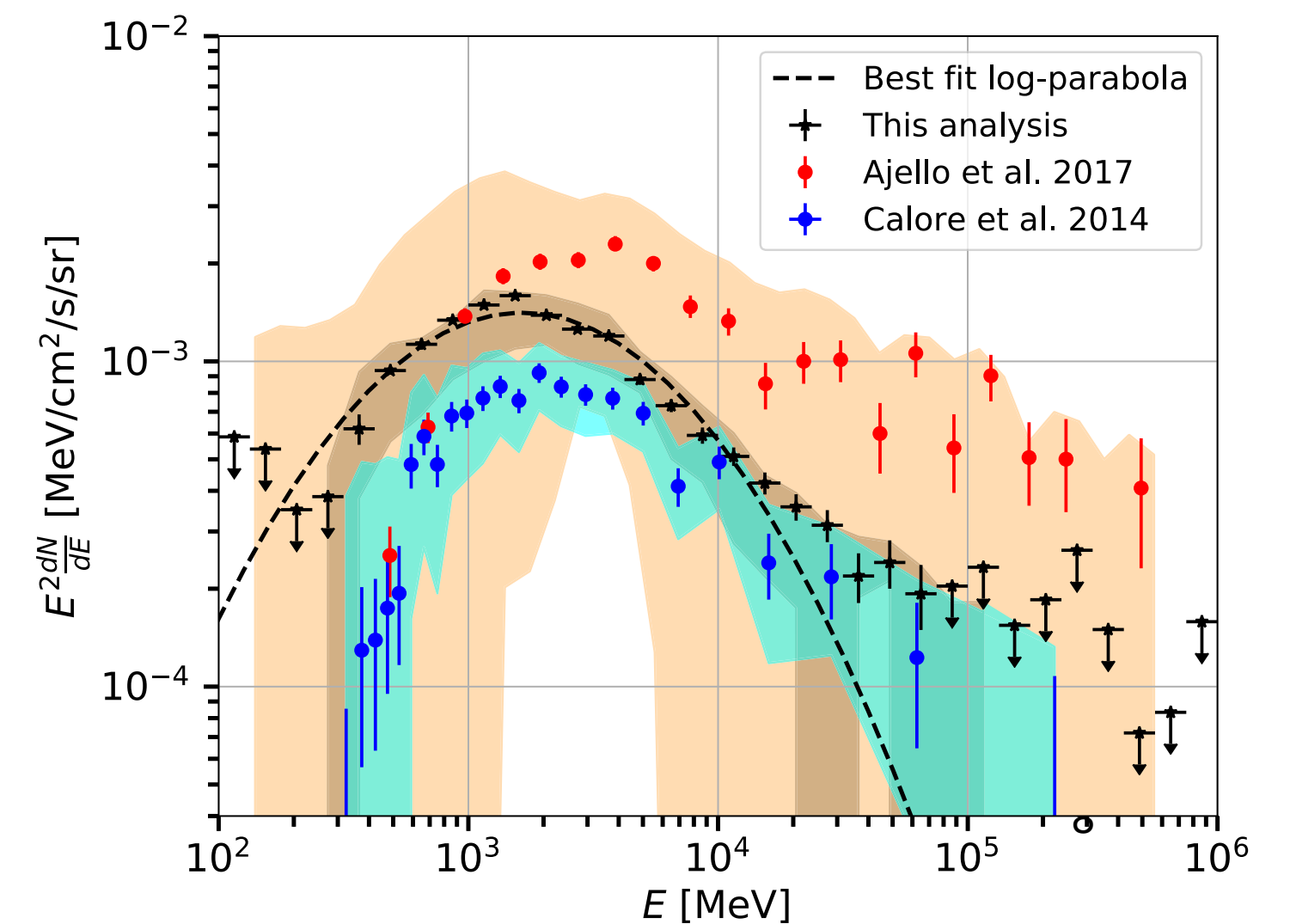
**Ajello+16**



**Ackermann+17**

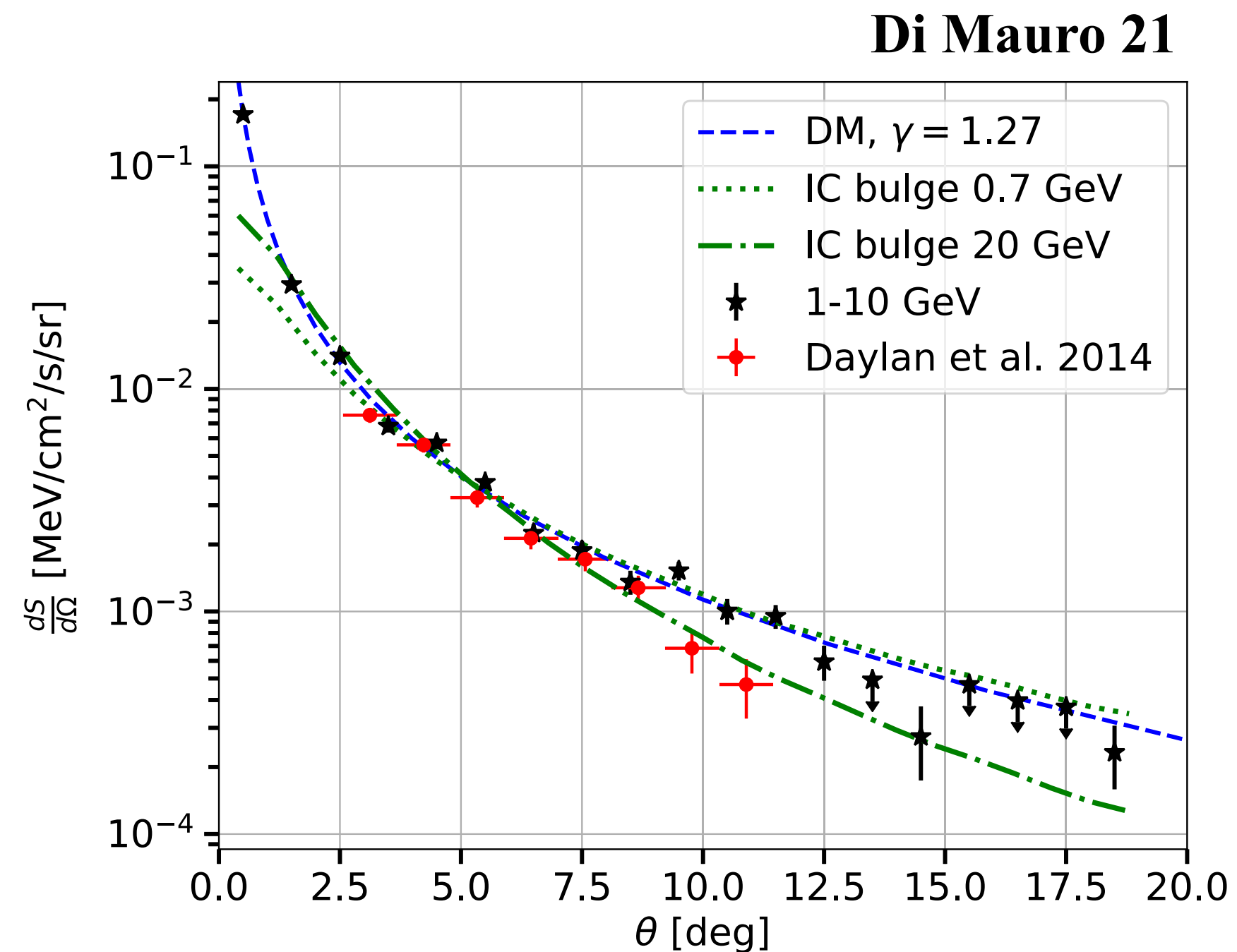


**Di Mauro 21**



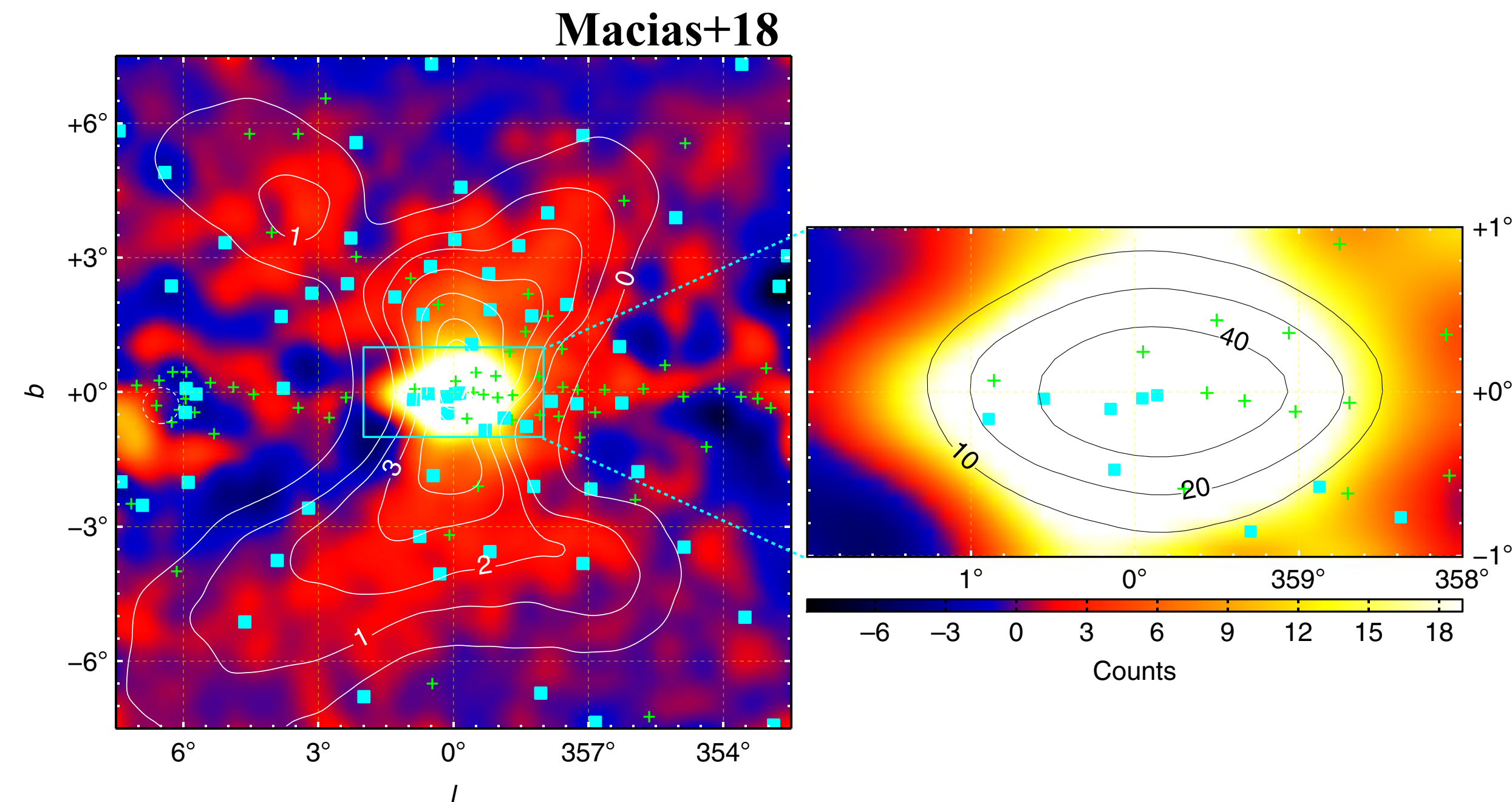
# Spherically Symmetric or Tracing Stellar Populations??

## Spherically Symmetric



- Consistent with an NFW profile with an inner slope of  $\sim 1.1-1.3$
- Centroid is consistent with dynamical center of Galaxy, although may be slightly offset.

## Tracing Stellar Populations



- Traces stellar populations in the X-shaped bulge, boxy bulge, and nuclear bulge.

# Spherically Symmetric or Tracing Stellar Populations?

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope

Lisa Goodenough<sup>1</sup> and Dan Hooper<sup>2,3</sup>

Oct 2009: <https://arxiv.org/abs/0910.2998>

## Background model systematics for the Fermi GeV excess

Francesca Calore,<sup>a</sup> Ilias Cholis<sup>b</sup> and Christoph Weniger<sup>a</sup>

Mar 2015: <https://arxiv.org/abs/1409.0042>

Dark matter interpretation of the *Fermi*-LAT observation toward the Galactic Center

Christopher Karwin,<sup>\*</sup> Simona Murgia,<sup>†</sup> and Tim M. P. Tait<sup>‡</sup>

May 2017: <https://arxiv.org/abs/1612.05687>

## The Fermi-LAT GeV excess as a tracer of stellar mass in the Galactic bulge

Richard Bartels<sup>1\*</sup>, Emma Storm<sup>1</sup>, Christoph Weniger<sup>1</sup> and Francesca Calore<sup>2</sup>

Oct 2018: <https://arxiv.org/abs/1711.04778>

## Galactic bulge preferred over dark matter for the Galactic centre gamma-ray excess

Oscar Macias<sup>1\*</sup>, Chris Gordon<sup>2</sup>, Roland M. Crocker<sup>3</sup>, Brendan Coleman<sup>2</sup>, Dylan Paterson<sup>2</sup>, Shunsaku Horiuchi<sup>1</sup> and Martin Pohl<sup>4,5</sup>

May 2018: <https://arxiv.org/abs/1611.06644>

## Strong evidence that the galactic bulge is shining in gamma rays

Oscar Macias,<sup>a,b,c</sup> Shunsaku Horiuchi,<sup>a</sup> Manoj Kaplinghat,<sup>d</sup> Chris Gordon,<sup>e</sup> Roland M. Crocker<sup>f</sup> and David M. Nataf<sup>g</sup>

Sep 2019: <https://arxiv.org/abs/1901.03822>

## Characteristics of the Galactic Center excess measured with 11 years of *Fermi*-LAT data

Mattia Di Mauro<sup>1\*</sup>

March 2021: <https://arxiv.org/abs/2101.04694>

## Assessing the Impact of Hydrogen Absorption on the Characteristics of the Galactic Center Excess

Martin Pohl<sup>1,2</sup>, Oscar Macias<sup>3,4</sup>, Phaedra Coleman<sup>5</sup>, and Chris Gordon<sup>5</sup>

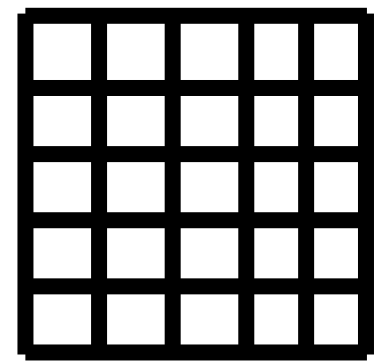
April 2022: <https://arxiv.org/abs/2203.11626>

## A Phantom Menace: On the Morphology of the Galactic Center Excess

Samuel D. McDermott,<sup>1</sup> Yi-Ming Zhong,<sup>2</sup> and Ilias Cholis<sup>3</sup>

Sep 2022: <https://arxiv.org/abs/2209.00006>

# Point-like (i.e. millisecond pulsars) or Smooth (i.e. DM)??



Spatial Pixels

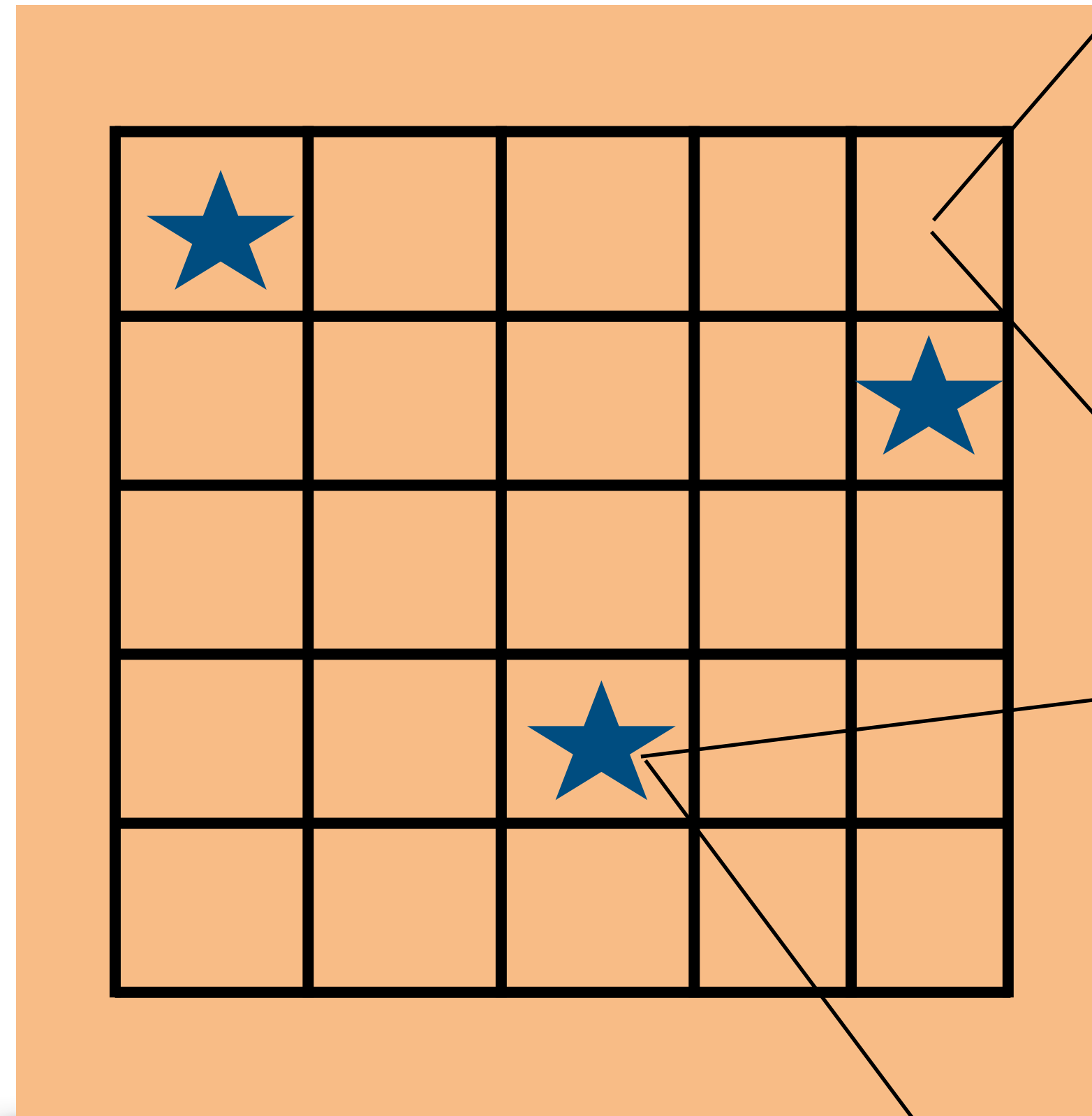


Smooth Emission Template

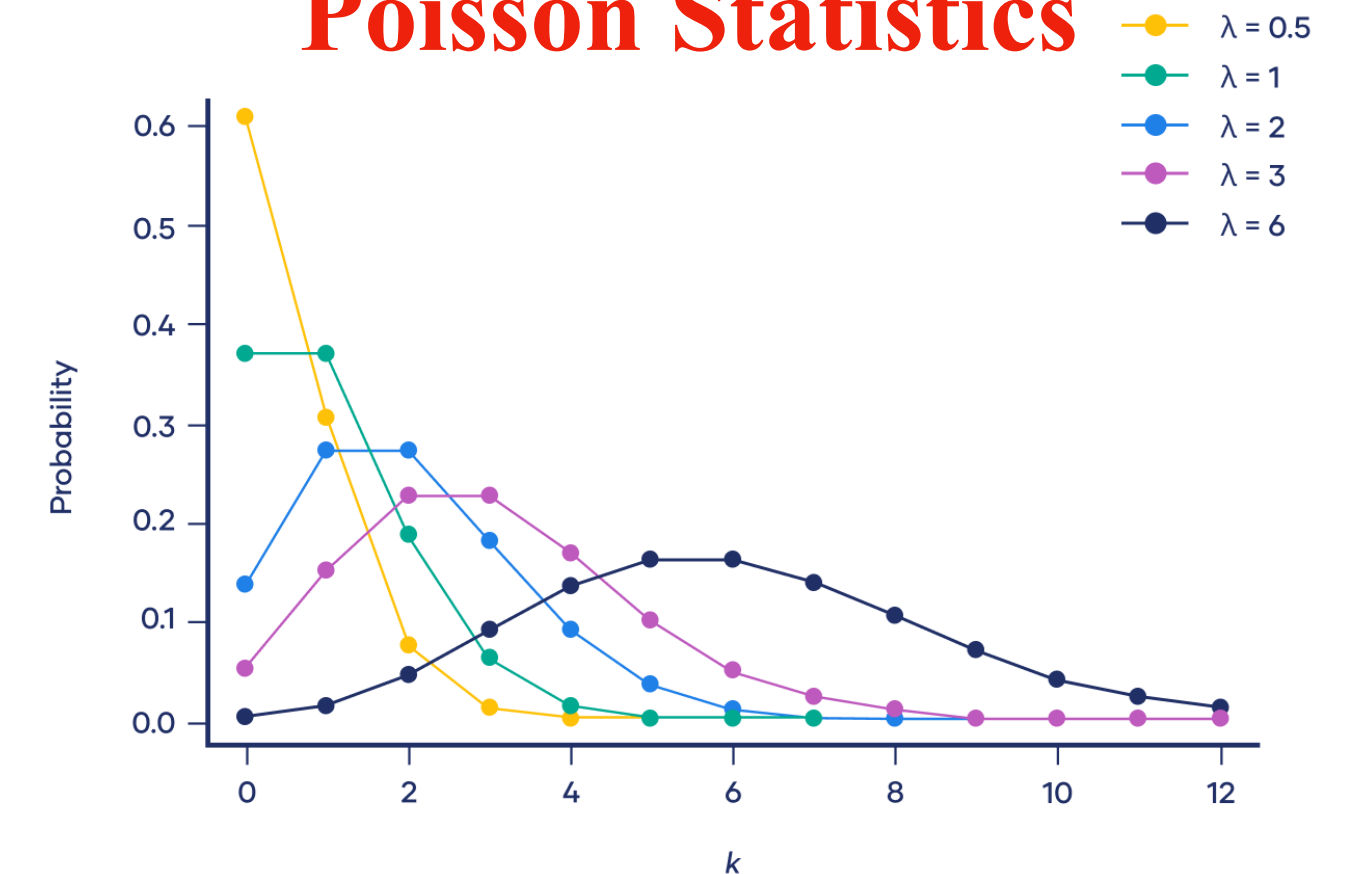


Unresolved point source

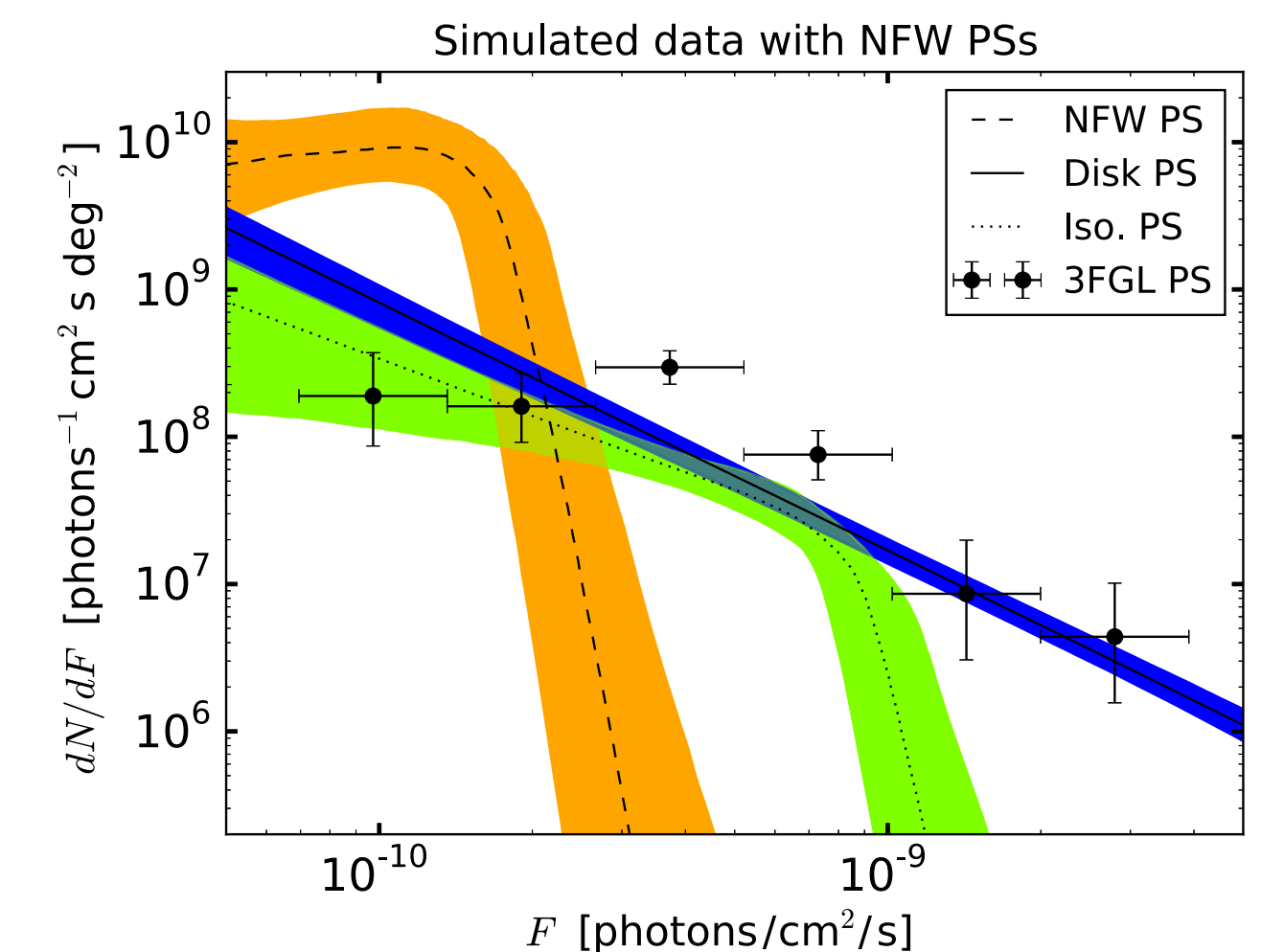
Counts Space



Poisson Statistics



non-Poissonian Statistics



- Lee+16 developed a method to test for non-Poissonian photon statistics.
- They concluded that the GC excess favors a point-like interpretation.

# Point-like (i.e. millisecond pulsars) or Smooth (i.e. DM)??

## Evidence for Unresolved $\gamma$ -Ray Point Sources in the Inner Galaxy

Samuel K. Lee,<sup>1,2</sup> Mariangela Lisanti,<sup>3</sup> Benjamin R. Safdi,<sup>4</sup> Tracy R. Slatyer,<sup>4</sup> and Wei Xue<sup>4</sup>

**Feb 2016:** <https://arxiv.org/abs/1506.05124>

## Strong Support for the Millisecond Pulsar Origin of the Galactic Center GeV Excess

Richard Bartels,<sup>\*</sup> Suraj Krishnamurthy,<sup>†</sup> and Christoph Weniger<sup>‡</sup>

**Feb 2016:** <https://arxiv.org/abs/1506.05104>

## Revival of the Dark Matter Hypothesis for the Galactic Center Gamma-Ray Excess

Rebecca K. Leane<sup>1,\*</sup> and Tracy R. Slatyer<sup>1,2,†</sup>

**Dec 2019:** <https://arxiv.org/abs/1904.08430>

## Characterizing the nature of the unresolved point sources in the Galactic Center: An assessment of systematic uncertainties

Laura J. Chang<sup>1</sup>, Siddharth Mishra-Sharma,<sup>2</sup> Mariangela Lisanti,<sup>1</sup> Malte Buschmann,<sup>3</sup>  
Nicholas L. Rodd,<sup>4,5</sup> and Benjamin R. Safdi<sup>3</sup>

**Jan 2020:** <https://arxiv.org/abs/1908.10874>

## Testing the Sensitivity of the Galactic Center Excess to the Point Source Mask

Yi-Ming Zhong<sup>1</sup>, Samuel D. McDermott<sup>2</sup>, Ilias Cholis,<sup>3</sup> and Patrick J. Fox<sup>2</sup>

**June 2020:** <https://arxiv.org/abs/1911.12369>

## Foreground mismodeling and the point source explanation of the Fermi Galactic Center excess

Malte Buschmann,<sup>1</sup> Nicholas L. Rodd<sup>2,3</sup>, Benjamin R. Safdi,<sup>1</sup> Laura J. Chang,<sup>4</sup>  
Siddharth Mishra-Sharma<sup>5</sup>, Mariangela Lisanti,<sup>4</sup> and Oscar Macias<sup>6,7</sup>

**July 2020:** <https://arxiv.org/abs/2002.12373>

## The enigmatic Galactic Center excess: Spurious point sources and signal mismodeling

Rebecca K. Leane<sup>1,\*</sup> and Tracy R. Slatyer<sup>†</sup>

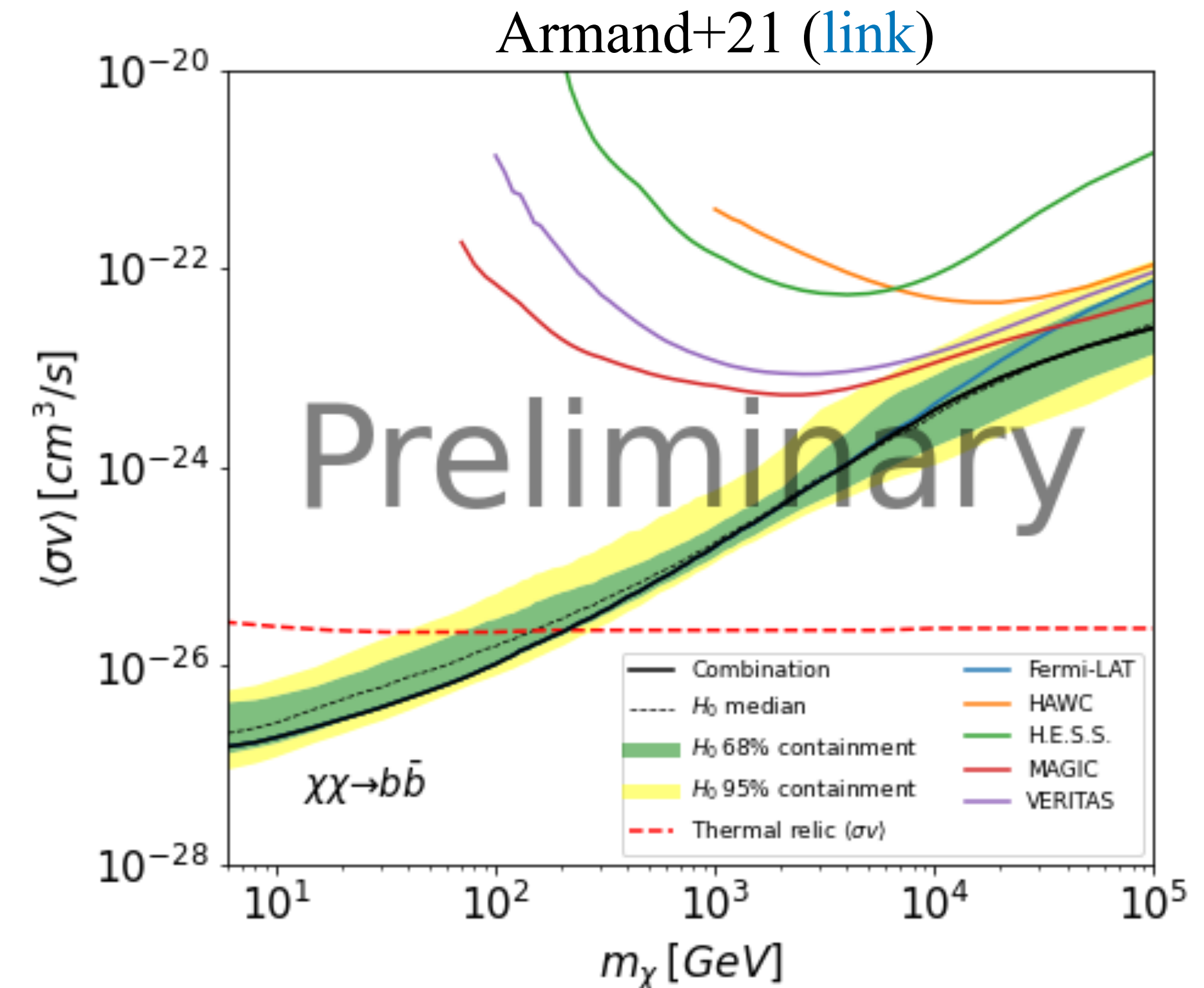
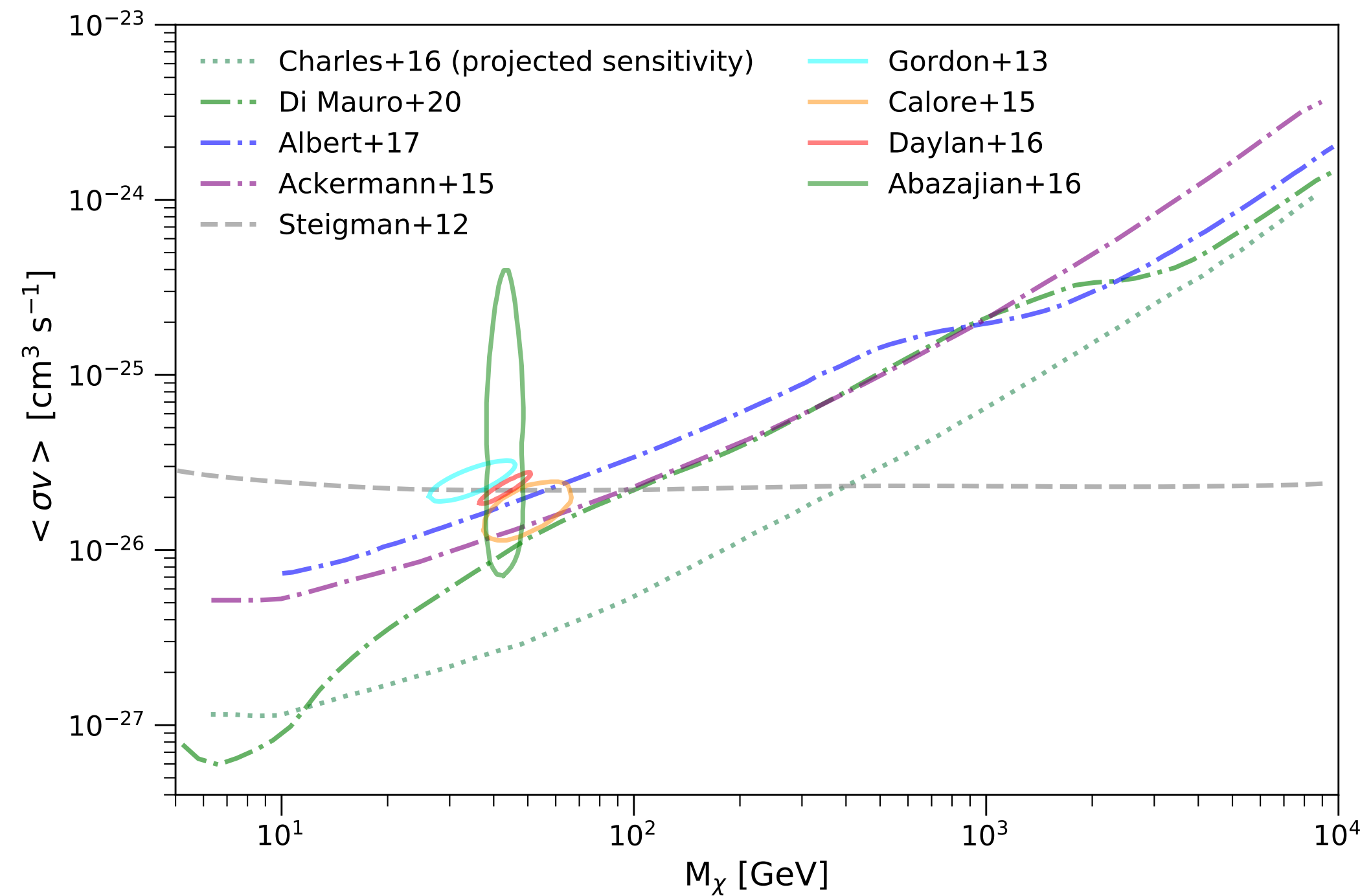
**Sep 2020:** <https://arxiv.org/abs/2002.12371>

## The Status of the Galactic Center Gamma-Ray Excess

Dan Hooper

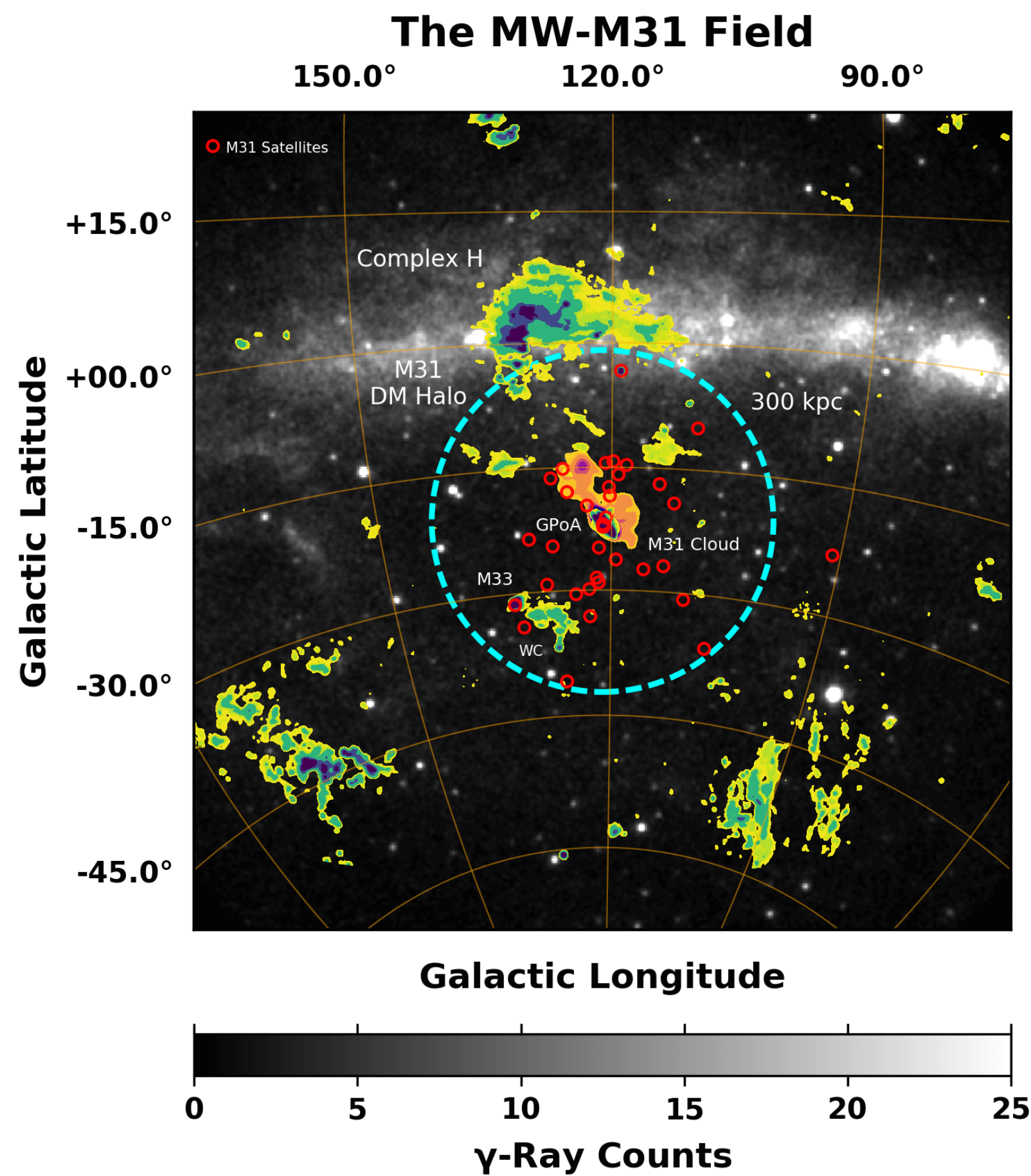
**Sep 2022:** <https://arxiv.org/pdf/2209.14370.pdf>

# The Milky Way Dwarf Spheroidal Galaxies



- Projected sensitivity is for 60 dwarfs and 15 years.
- Combined search in production with LAT, HAWC, HESS, MAGIC, and VERITAS.
- Also working on updated comprehensive dwarf analysis (following Albert+17) within LAT DMNP working group (led by myself, Alex McDaniel, and Marco Ajello), which will include:
  - More data
  - Most recent dwarf census
  - Improved handling of astrophysical mis-modeling
  - J-factor systematic uncertainty

# The Andromeda Galaxy

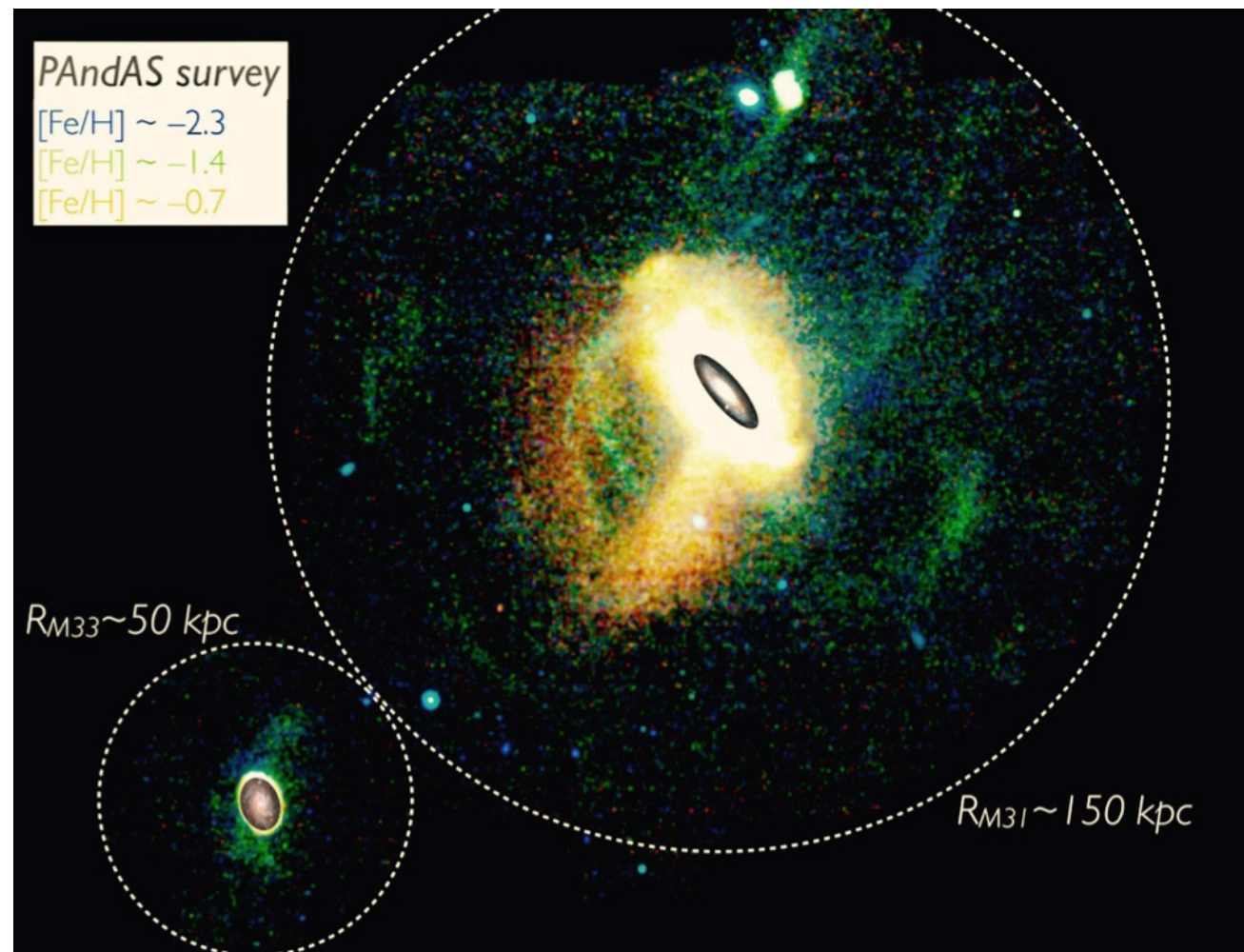


- Reported excesses towards inner galaxy and outer halo.
- See extra slides for recent papers.

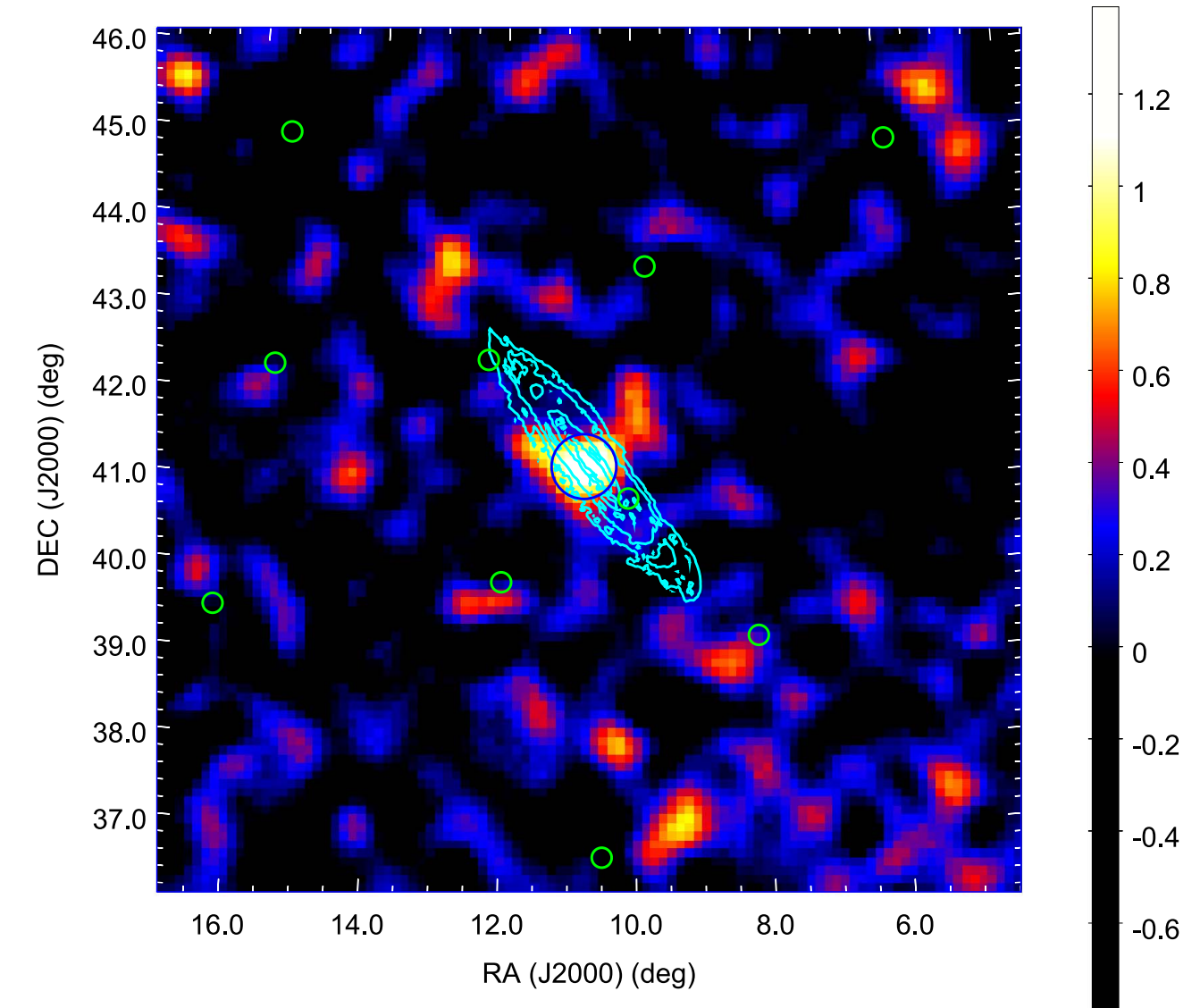
Inner galaxy



Outer halo

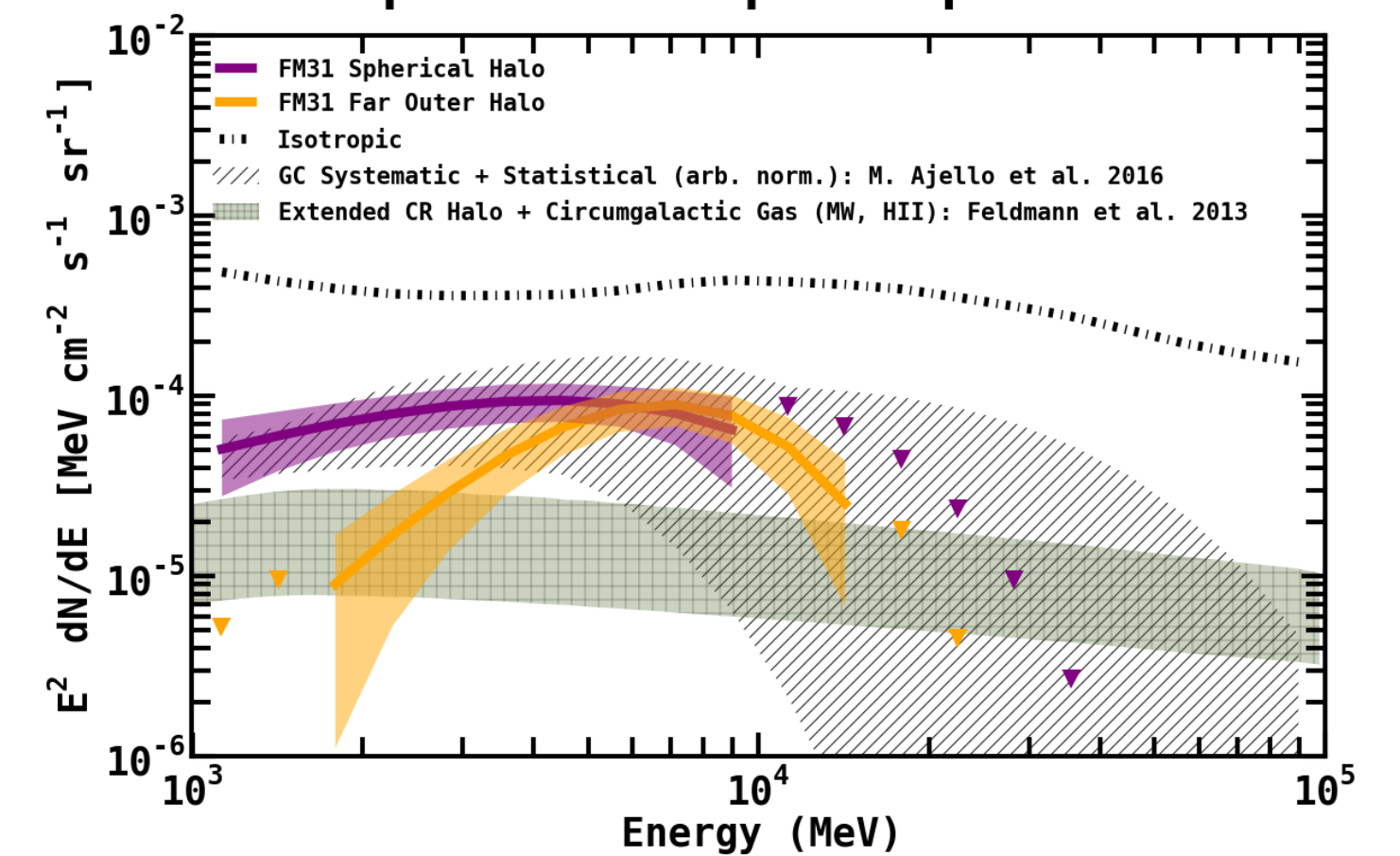


Ackermann+17



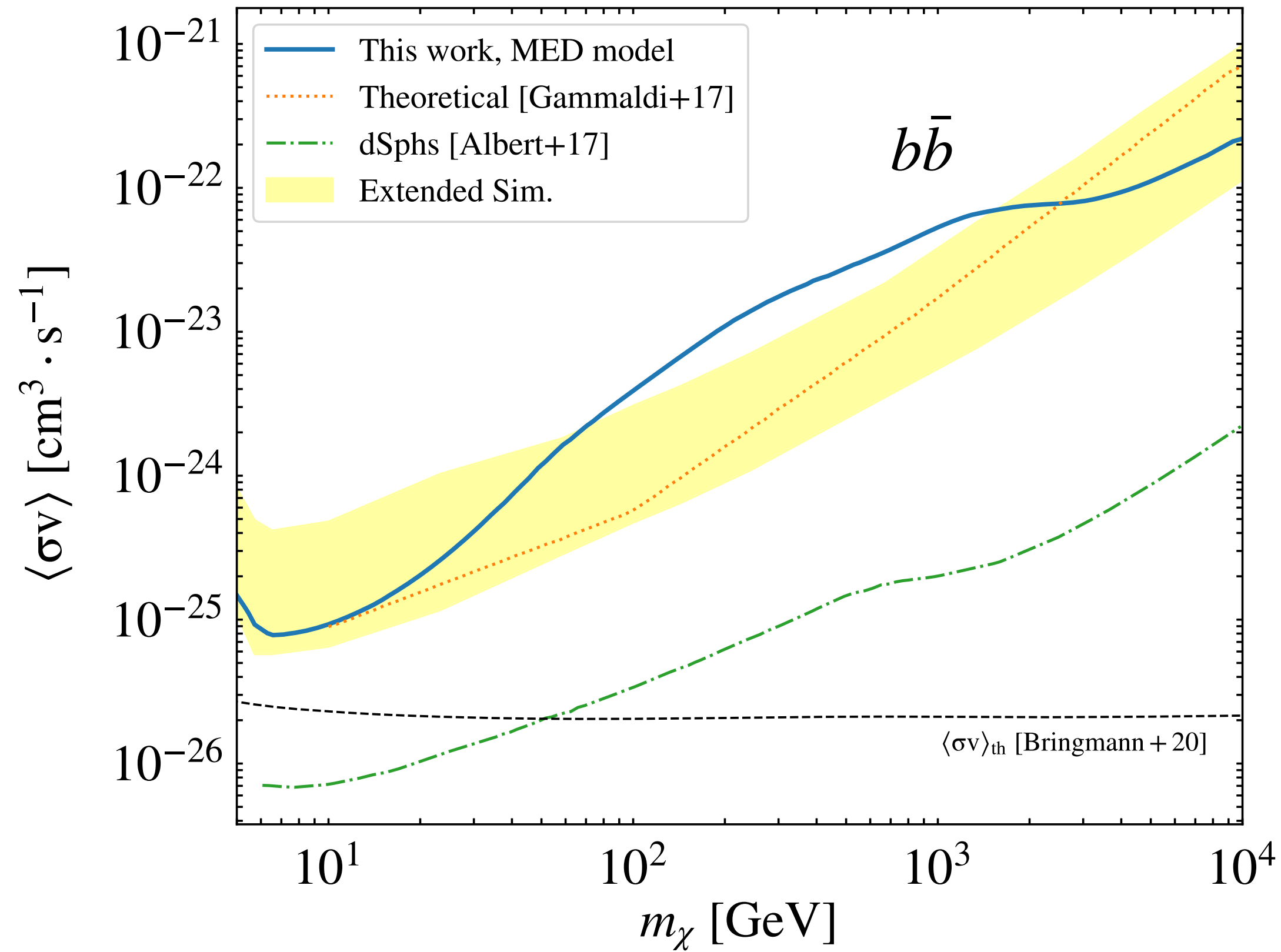
Karwin+19

Spectral Shape Comparison



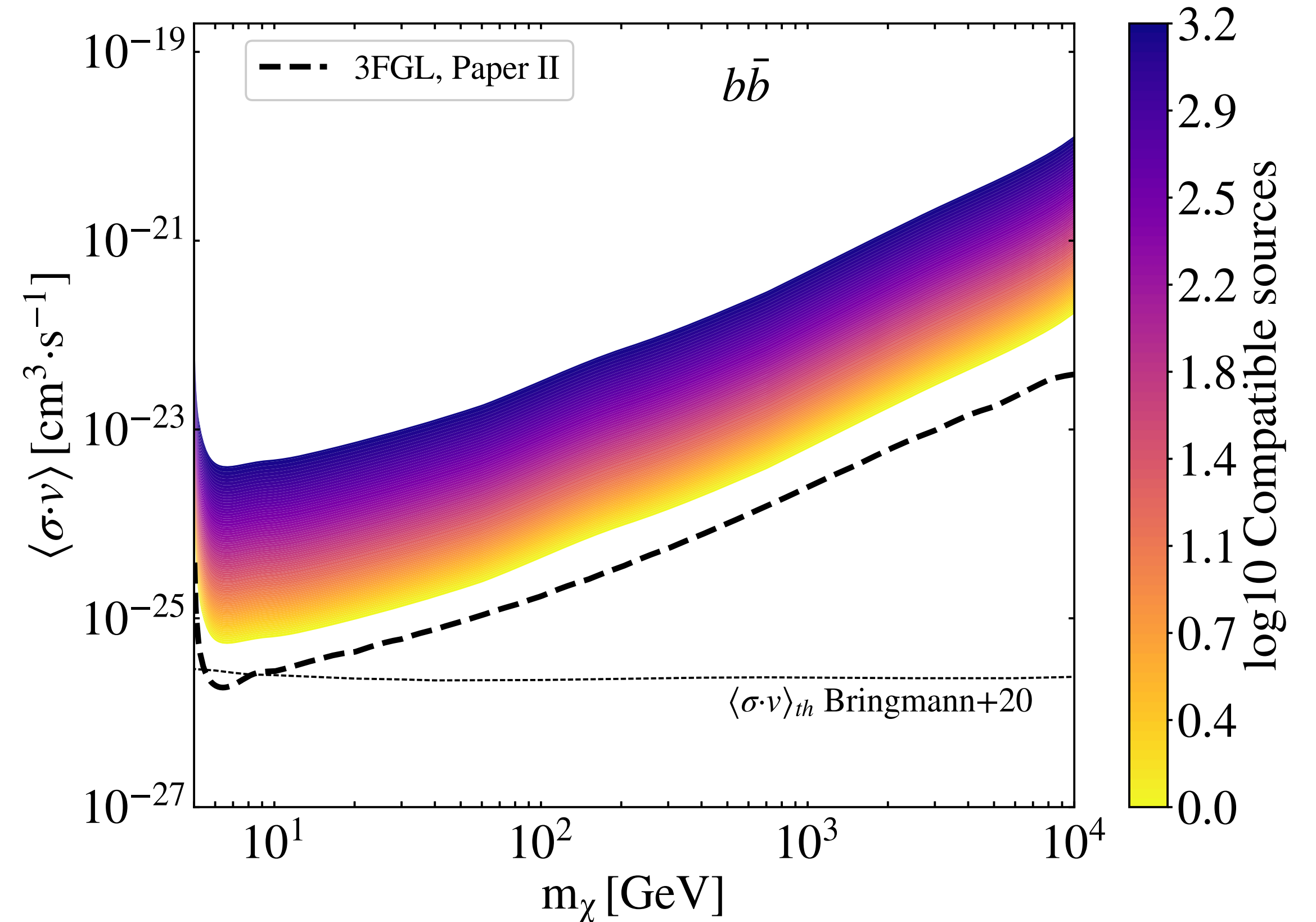
# Additional Searches

## Dwarf Irregular Galaxies



- Dark Matter Search in Dwarf Irregular Galaxies with the Fermi Large Area Telescope ([link](#)).
- Oct 2021
- Gammaldi et al.

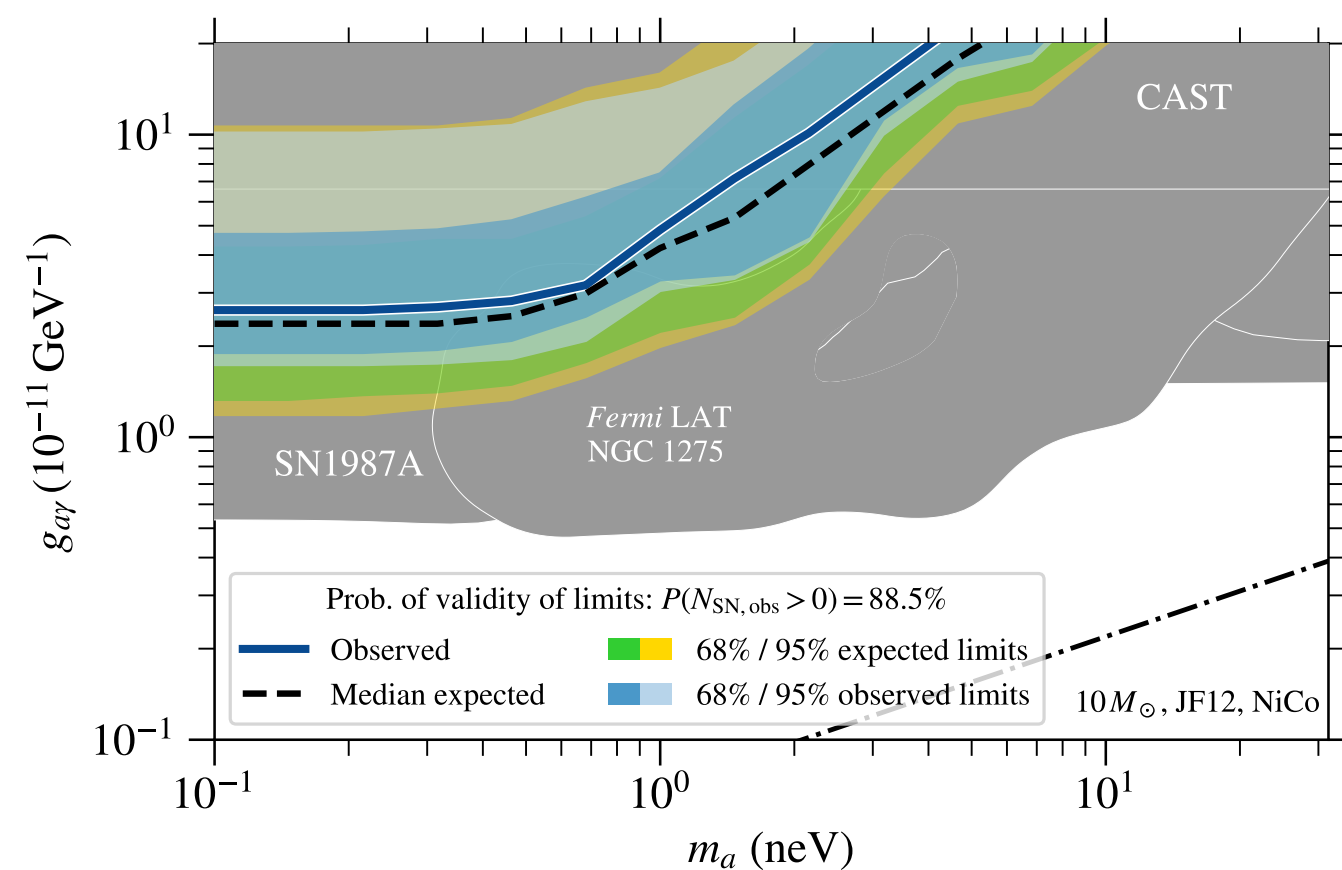
## Dark Subhalos



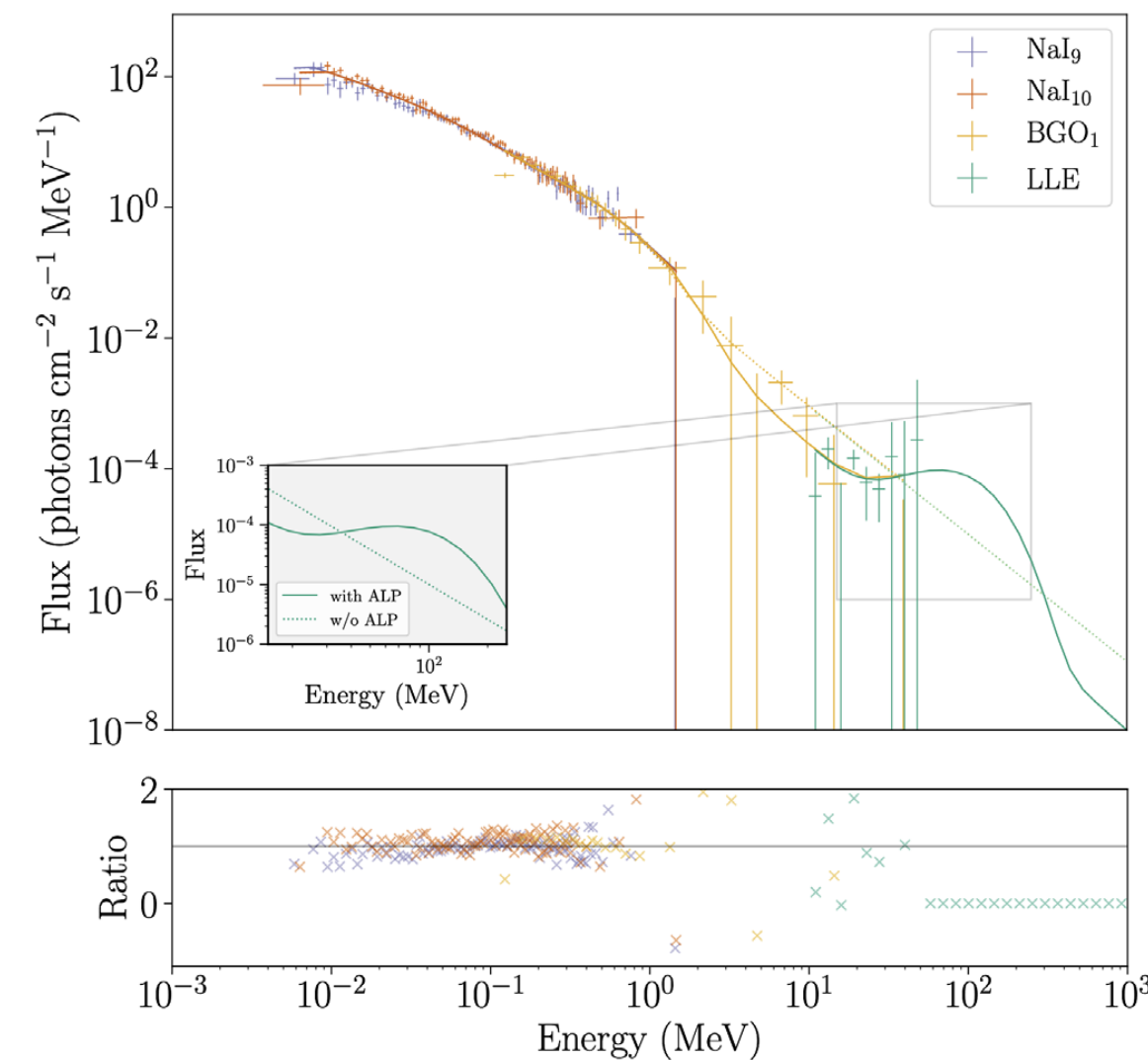
- Spatial Extension of Dark Subhalos as Seen by the Fermi-LAT and Implications for WIMP Constraints ([link](#)).
- April 2022
- Coronado-Blazques et al.

# Additional Searches

## Axionlike Particles

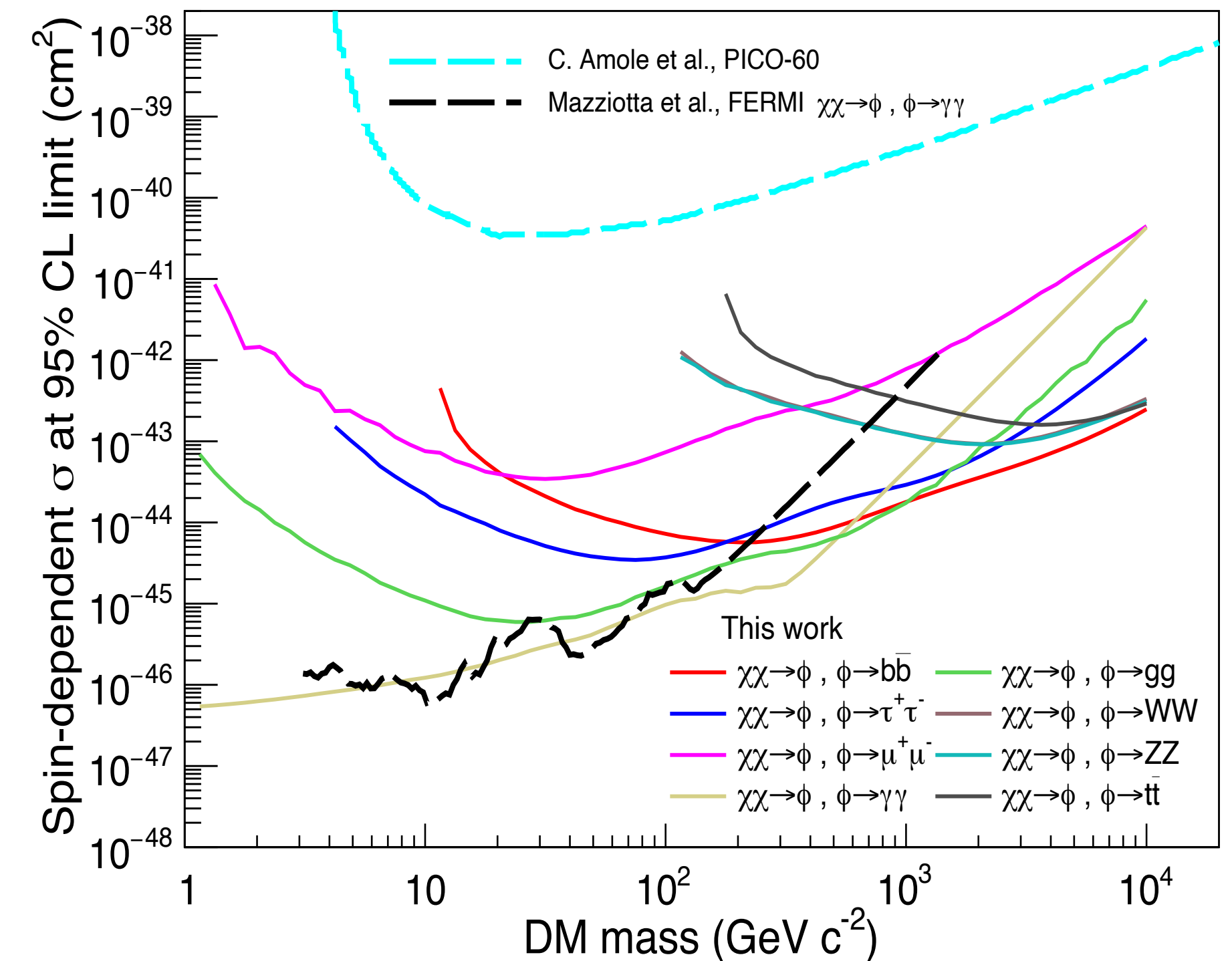


- Search for Axionlike-Particle-Induced Prompt Gamma-Ray Emission from Extragalactic Core-Collapse Supernovae with the Fermi Large Area Telescope ([link](#)).
- June 2020
- Meyer et al.



- Searching for Axionlike Particles from Core-collapse Supernovae with Fermi LAT's Low-Energy Technique ([link](#)).
- Nov 2021
- Crnogocevic et al.

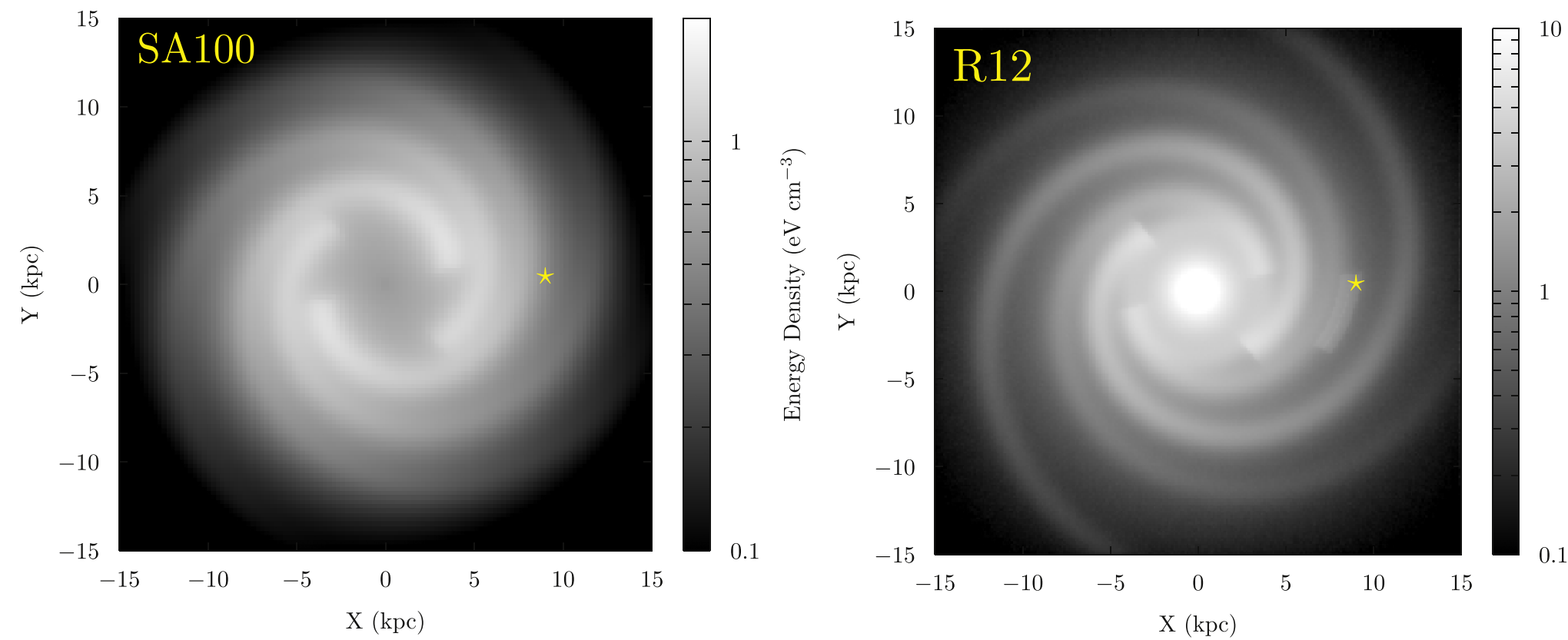
## Long Lived Mediators from the Sun



- Constraints on Dark Matter Scattering with Long Lived Mediators from Observations of the Sun with the Fermi Large Area Telescope ([link](#)).
- August 2022
- Serini et al.
- See talk at Parallel 7!

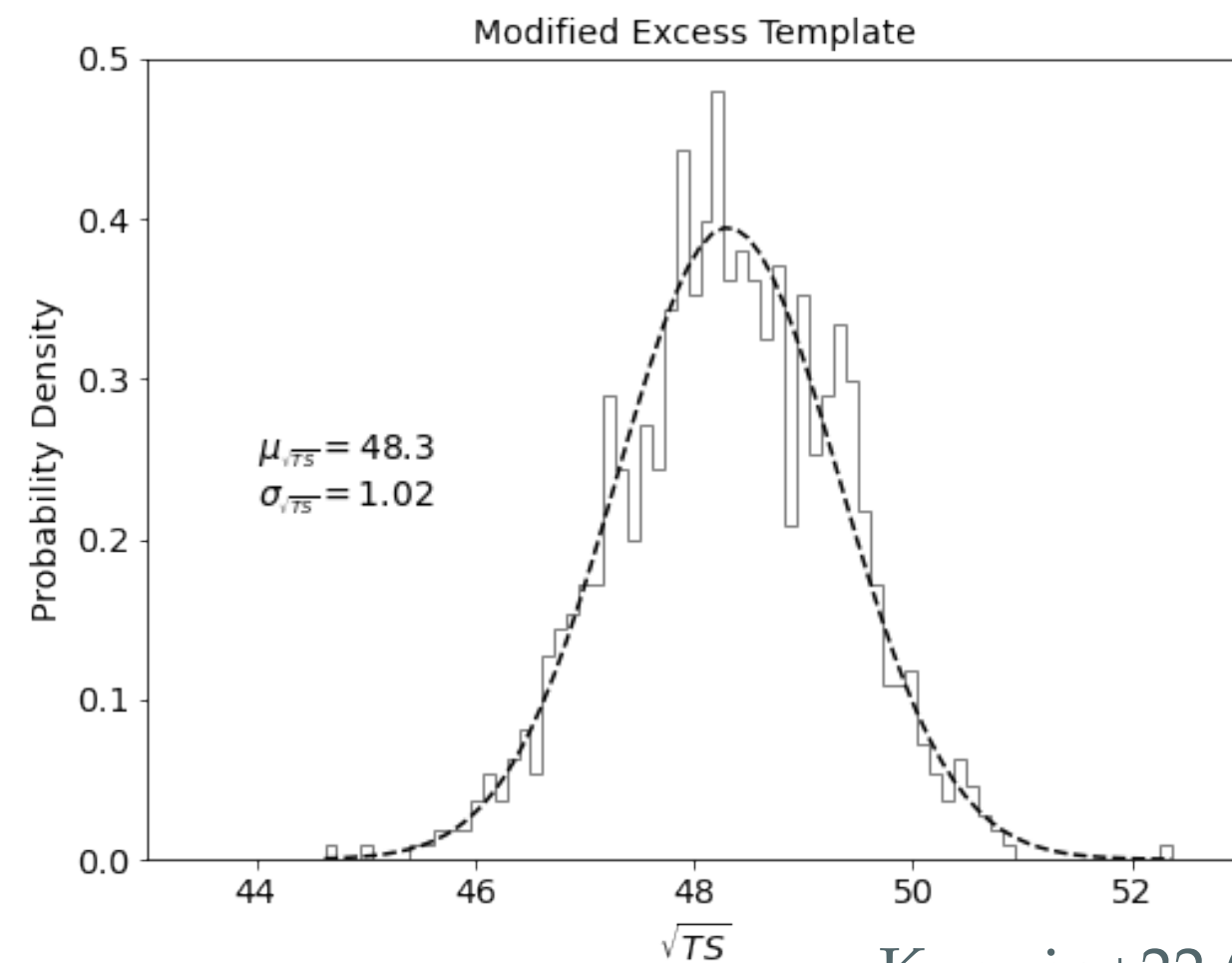
# Future Directions: Galactic Diffuse Models

## Three-dimensional spatial models for the cosmic ray and radiation field densities in the Milky Way



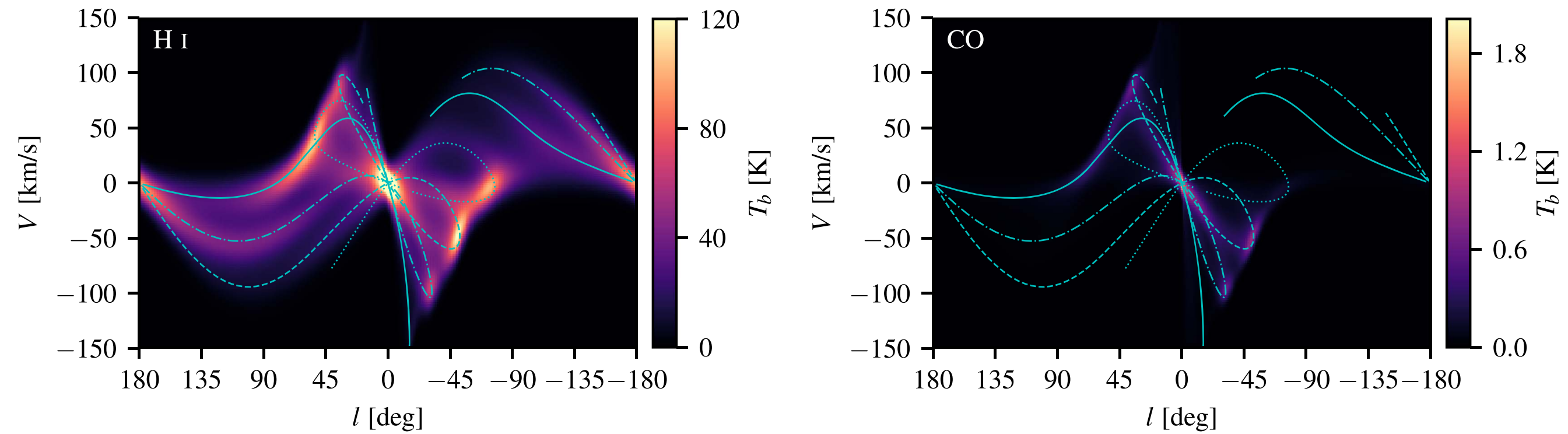
Porter+17 ([link](#))

## Improved models of the small-scale structure relating to the underlying gas distributions



Karwin+22 ([link](#))

## Three-dimensional spatial distribution of Interstellar gas in the Milky Way



Johannesson+18 ([link](#))

## Improvements to the Galactic Diffuse model:

- 3D models for the CR and ISRF densities.
- 3D models for the gas distributions.
- Improved modeling of the small-scale structure in the gas.

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# The Magellanic System

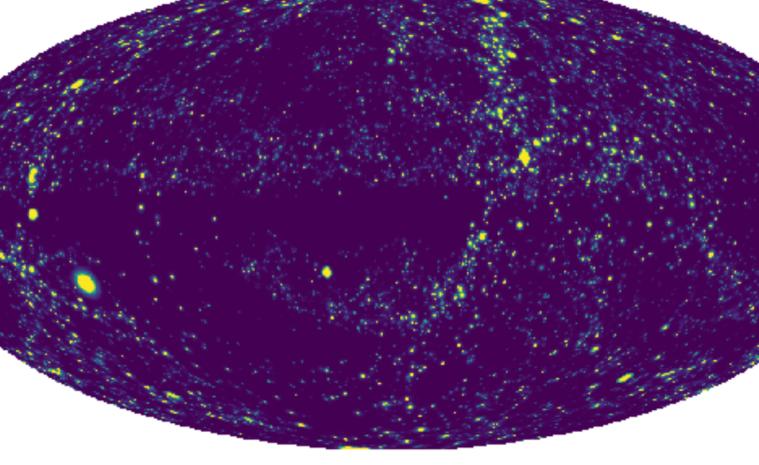


Figure 1 is a color map of the radio continuum emission from the SNR G1.9-0.7. The map shows a complex, multi-peaked structure with a color scale from 0 to 30 Jy/beam. A dashed white circle indicates the 1.4-GHz radio position of the SNR. A white diamond marks the position of the SNR remnant, and a red circle highlights the region of the remnant. The axes are labeled RA---STG and DEC--STG.

# The M31 System



Galaxy Group  $J$ -factors



0  $\text{GeV}^2 \text{cm}^{-5} \text{sr}$   $1\text{e}+15$

# All-Sky Analysis

- Galactic Center
- Milky Way Dwarfs
- Magellanic System
- Milky Way Halo
- M31 System
- Galaxy Clusters
- Galaxy Groups
- EGB

# Future Directions: New Missions and Synergies

## Synergies with other Search Methods, Messengers, and Wavelengths:

- Complementarity with direct detection.
- Complementarity with other indirect searches, e.g. cosmic rays (i.e. anti-protons, anti-deuterons, and anti-helium) and radio (i.e. dwarfs and M31).

## Deep Radio Surveys and Very-High Energy Observations with CTA:

- Search for milli-second pulsars in the GC.

## The MeV Band with COSI (and future prospects for AMEGO-X, GECCO, and others):

- Measure the IC and Bremsstrahlung between 200 keV - 5 MeV.
- Conduct multi-wavelength analysis of the Galactic diffuse, including radio, MeV, and LAT bands.
- Search for unresolved point-source population in the GC.
- Explore possible connections between the LAT GC excess and the MeV GC excess measured by COMPTEL and INTEGRAL.

## New Instrument Designs:

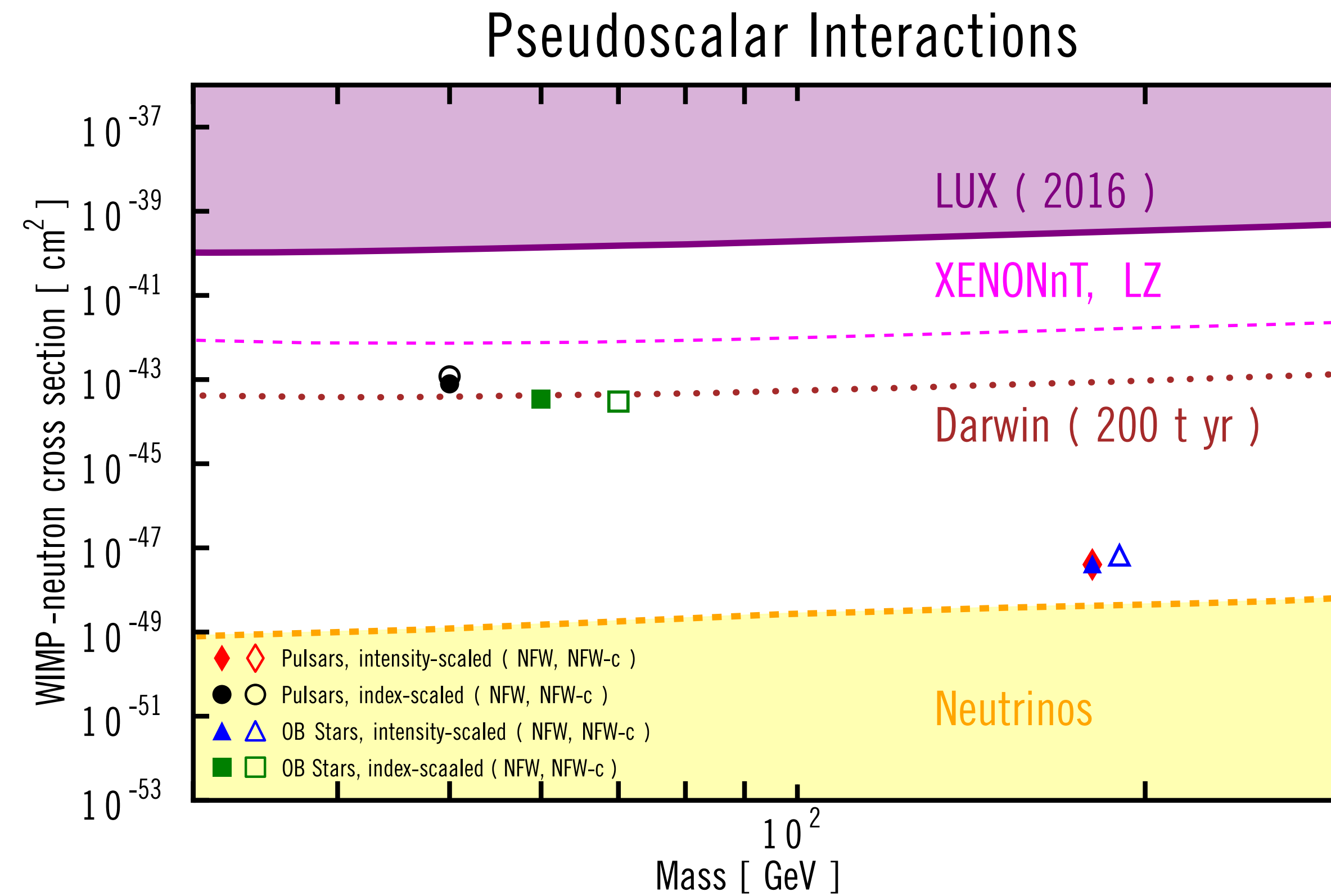
- A wide FOV gamma-ray instrument with high sensitivity and improved angular resolution between 1-100 GeV, in order to resolve possible gamma-ray point sources in the Galactic center.

# Summary and Conclusions

- There is an excess towards GC, possibly from mis-modeling of the foreground/background, unresolved point source population, and/or DM annihilation. However, interpretations are limited by systematic uncertainties relating to the Galactic diffuse.
- The Milky Way dwarfs remain a key constraint on DM interpretations of the GC Excess.
- Many other targets serve as complementary probes, as well as alternative possibilities.
- Future directions include improvements to the Galactic diffuse model, different targets, and synergies with other wavelengths and search methods (see previous three slides).

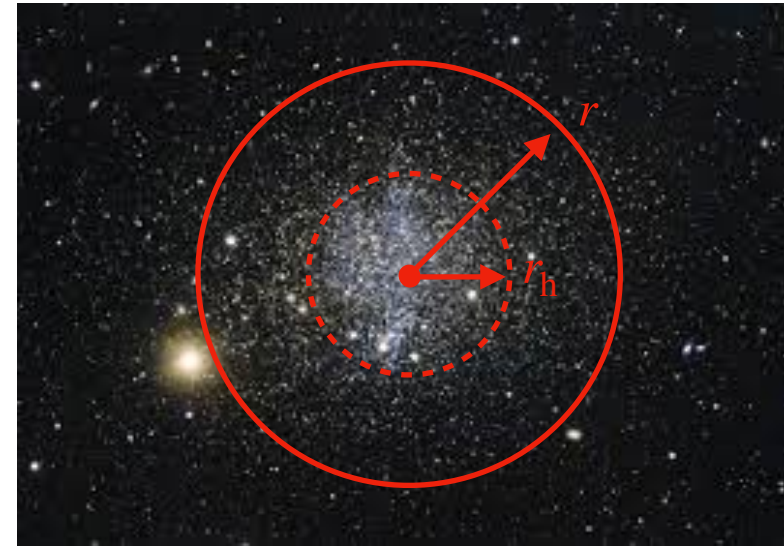
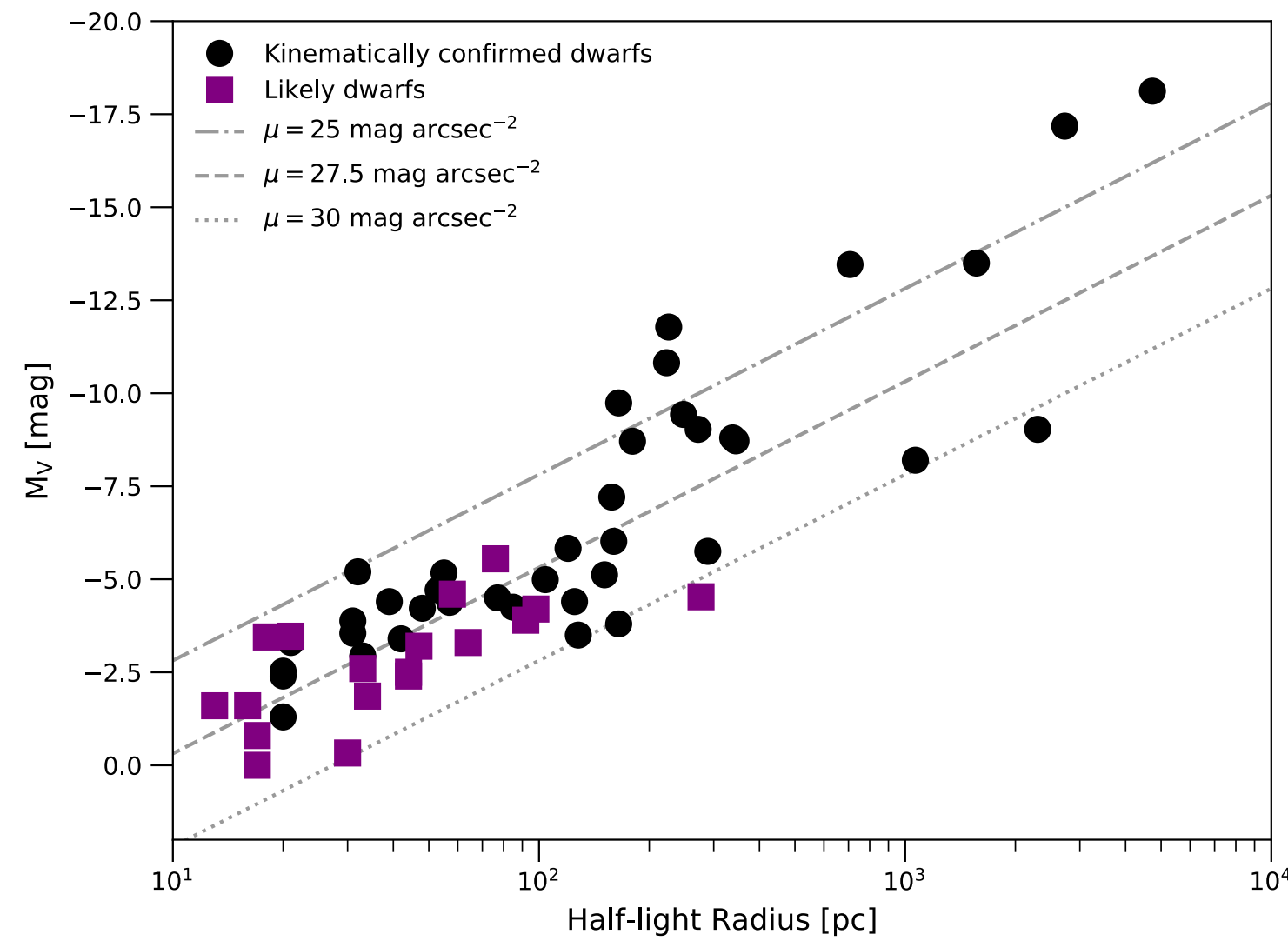
**Thank you for your attention!**

# Extra: GC Excess



- Direct detection parameter space corresponding to the GC excess from Karwin+17

# Extra: The Milky Way Dwarfs



kinematic scaling:

$$\frac{J(0.5)}{\text{GeV}^2 \text{ cm}^{-5}} \approx 10^{17.87} \left( \frac{\sigma_{\text{los}}}{5 \text{ km s}^{-1}} \right)^4 \left( \frac{d}{100 \text{ kpc}} \right)^{-2} \left( \frac{r_{1/2}}{100 \text{ pc}} \right)^{-1}$$

photometric scaling:

$$\frac{J(0.5)}{\text{GeV}^2 \text{ cm}^{-5}} \approx 10^{18.17} \left( \frac{L_V}{10^4 L_{\odot}} \right)^{0.23} \left( \frac{d}{100 \text{ kpc}} \right)^{-2} \left( \frac{r_{1/2}}{100 \text{ pc}} \right)^{-0.5}$$

Pace and Strigari 19.

- Ackermann+15: 15 kinematically confirmed srcs
- Albert+17: 28 kinematically confirmed srcs, 17 candidate galaxies
- Updated analysis (Karwin et al. in prep): 37 kinematically confirmed srcs, 17 candidate galaxies
- J-factor determination: 1) calculated, 2) kinematic scaling relation, 3) photometric scaling relation

# Extra: The Andromeda Galaxy

## Recent Papers:

- June 2019: Search for Gamma-Ray Emission from Dark Matter Particle Interactions from the Andromeda and Triangulum Galaxies with the Fermi Large Area Telescope ([link](#))
- July 2019: Fermi-LAT Observations of Gamma-Ray Emission Toward the Outer Halo of M31 ([link](#))
- October 2020: GeV Gamma-ray Emission from M33 and Arp 299 ([link](#))
- May 2020: The Gamma-ray Emission of Star-Forming Galaxies ([link](#))
- Jan 2021: Dark Matter Interpretation of the Fermi-LAT Observations Toward the Outer Halo of M31 ([link](#))
- April 2021: Gamma-Ray Image Reconstruction of the Andromeda Galaxy ([link](#))
- June 2021: Giant Cosmic-Ray Halos Around M31 and the Milky Way ([link](#))
- Sep 2022: The Android Gamma-ray Excess: Background Systematics of the Millisecond Pulsars and Dark Matter Interpretations ([link](#))