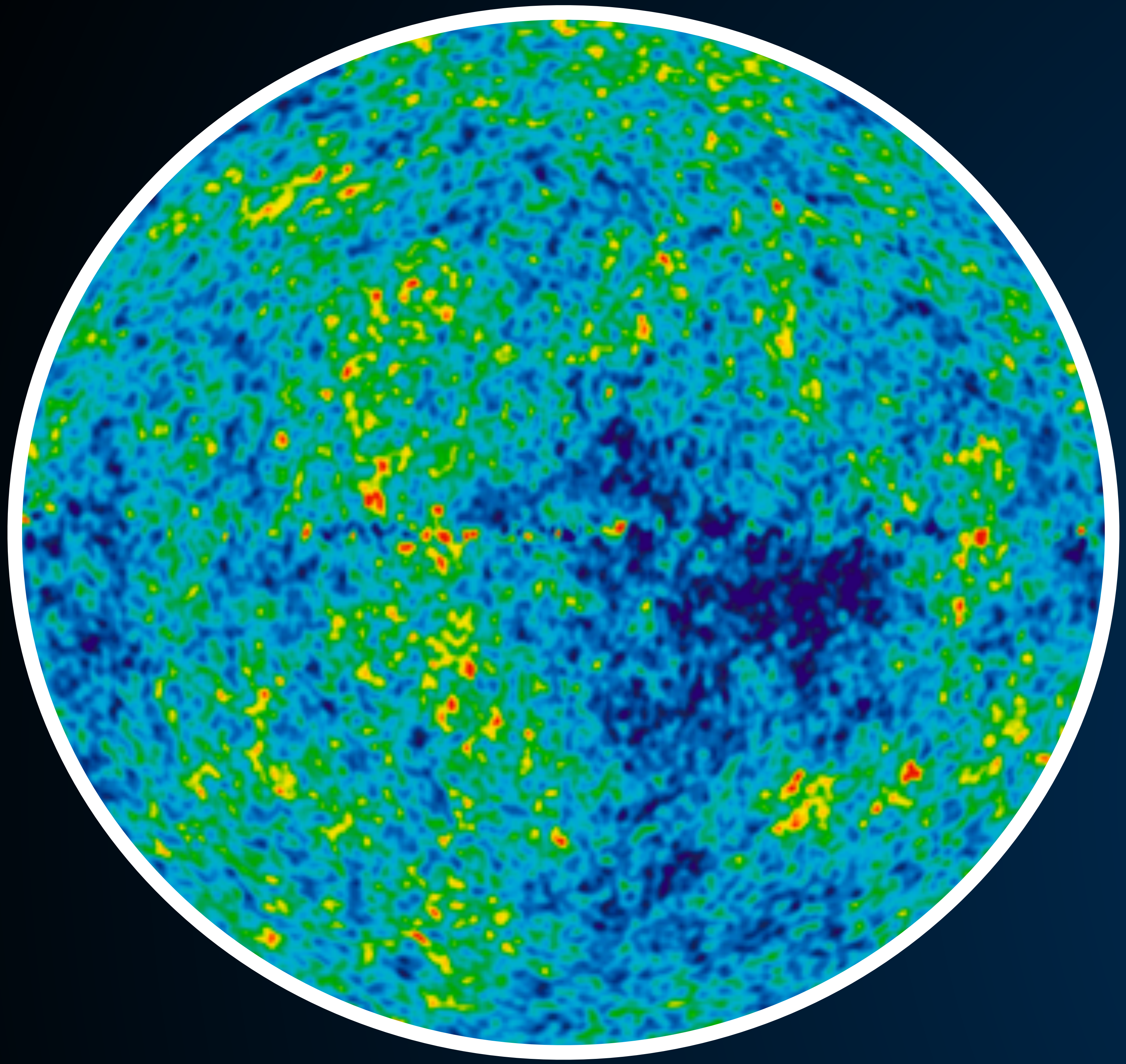
TIM LINDEN

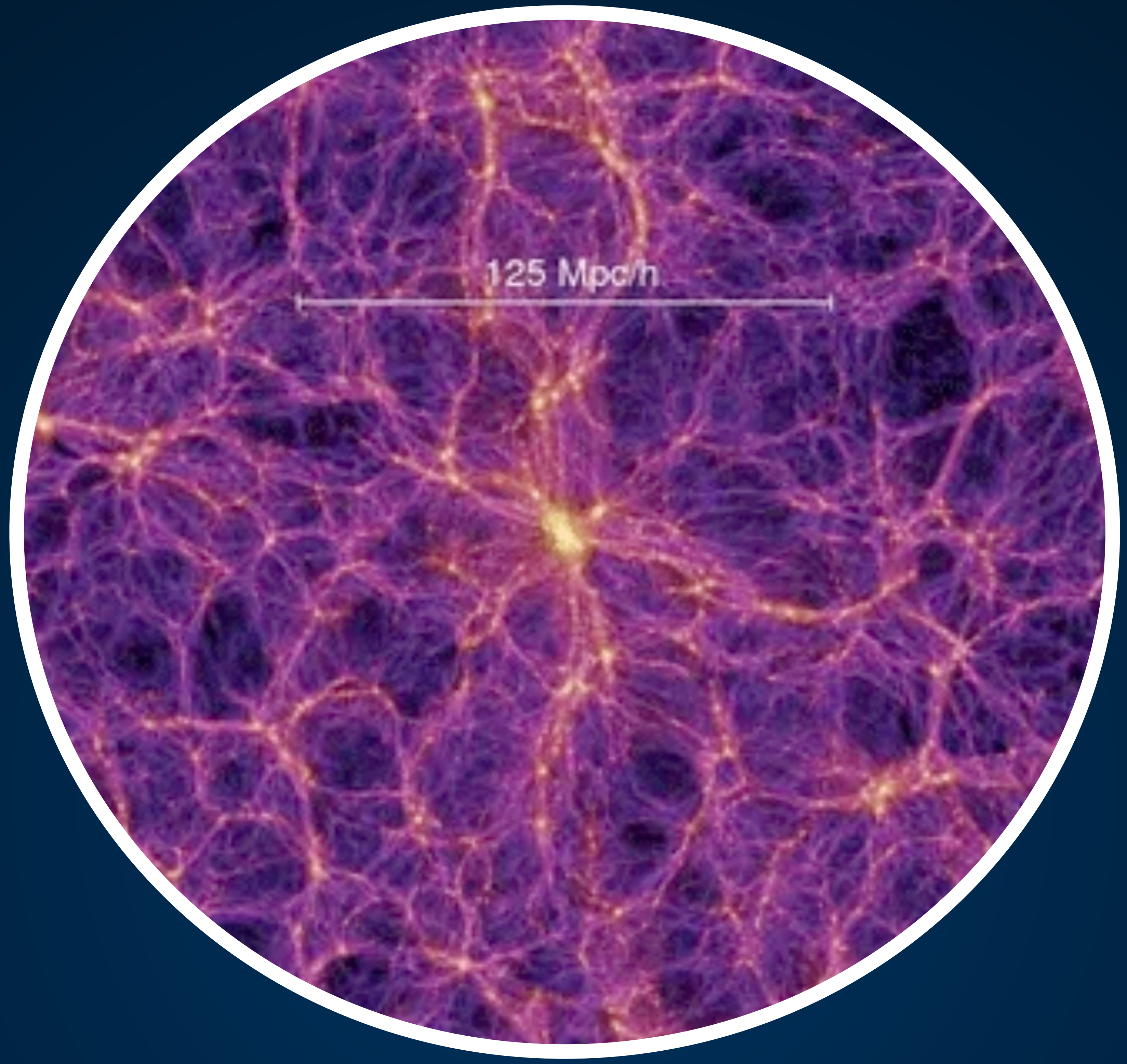
WIMPs on the Brink

Stockholm University BSM Meeting

THE OHIO STATE UNIVERSITY
CENTER FOR COSMOLOGY AND
ASTROPARTICLE PHYSICS

Studying the Dark Matter Particle





~100 GeV

10 GeV (weak force)

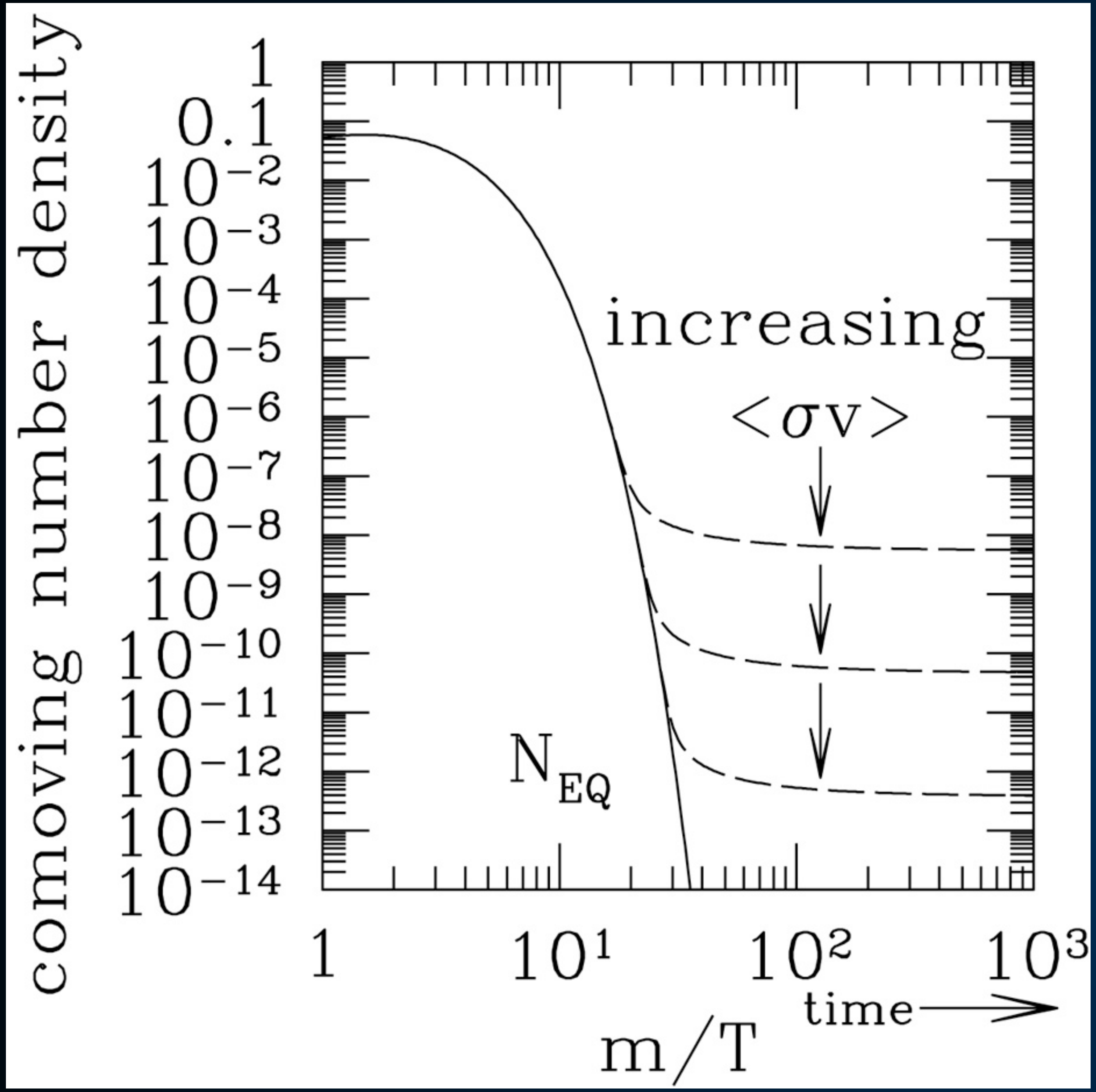
3 MeV (N_{eff})

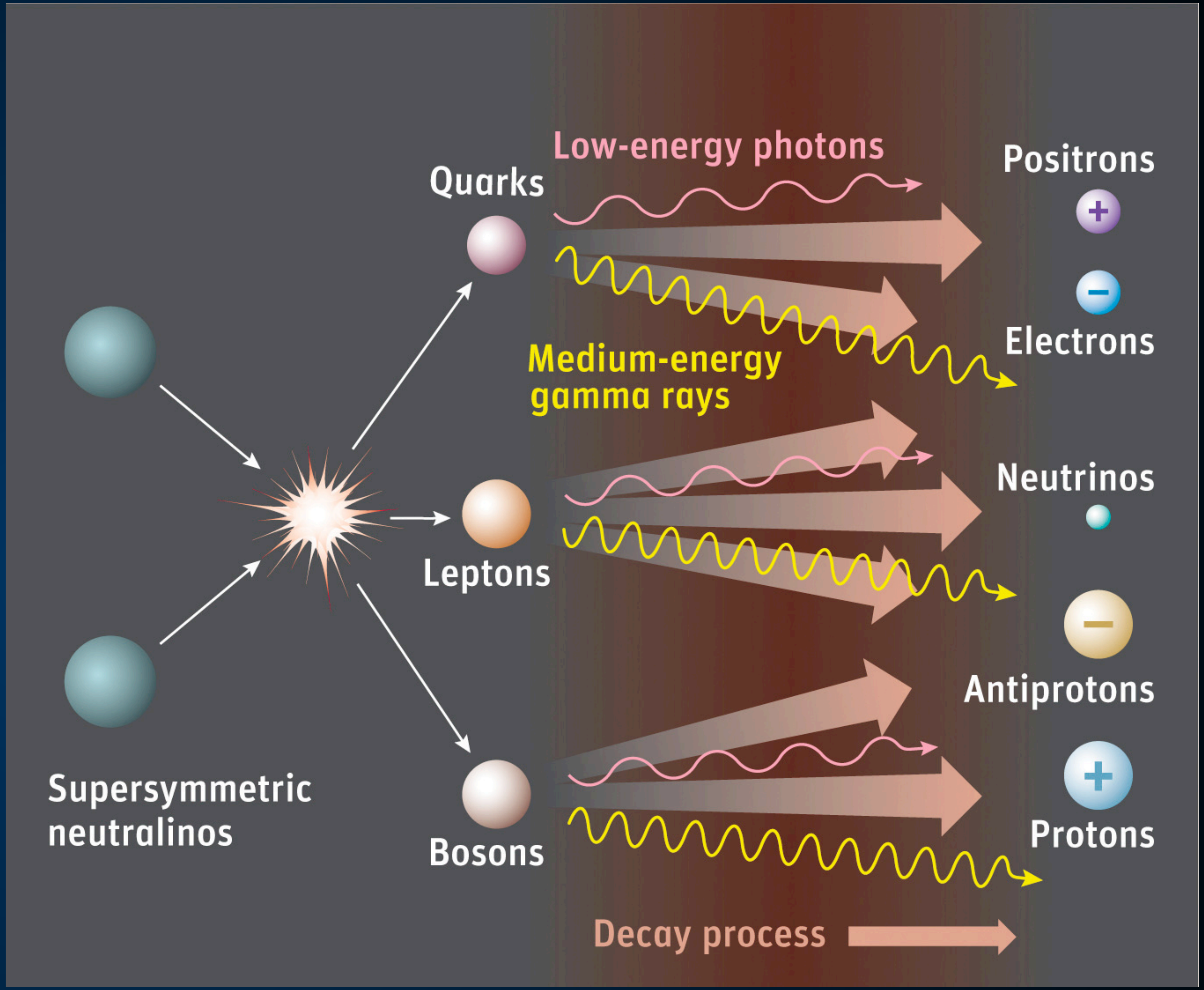
WIMP

Dark Matter

10^5 GeV (unitarity)

WIMP Models Provide a Target





$$\langle \sigma v \rangle \sim 10^{-8}\ \mathrm{GeV}^{-2} \left(3 \times 10^{-28}\ \mathrm{GeV}^2\ \mathrm{cm}^2\right)\ 10^{10}\ \frac{\mathrm{cm}}{\mathrm{s}} = 3 \times 10^{-26}\ \frac{\mathrm{cm}^3}{\mathrm{s}}$$

A Philosophical Debate

REVIEW

https://doi.org/10.1038/s41586-018-0542-z

A new era in the search for dark matter

Gianfranco Bertone[1]* & Tim M. P. Tait[1,2]*

There is a growing sense of 'crisis' in the dark-matter particle community, which arises from the absence of evidence for the most popular candidates for dark-matter particles—such as weakly interacting massive particles, axions and sterile neutrinos—despite the enormous effort that has gone into searching for these particles. Here we discuss what we have learned about the nature of dark matter from past experiments and the implications for planned dark-matter searches in the next decade. We argue that diversifying the experimental effort and incorporating astronomical surveys and gravitational-wave observations is our best hope of making progress on the dark-matter problem.

The fall of natural weakly interacting massive particles

The existence of dark matter has been discussed for more than a cen-

the observed Higgs mass at the weak scale appears highly unnatural, requiring an incredibly fine-tuned cancellation between the individ-

A Philosophical Debate

MIT-CTP/5020

11 Jul 2018

GeV-Scale Thermal WIMPs: Not Even Slightly Dead

Rebecca K. Leane,[1,*] Tracy R. Slatyer,[1,†] John F. Beacom,[2,3,4,‡] and Kenny C. Y. Ng[5,§]

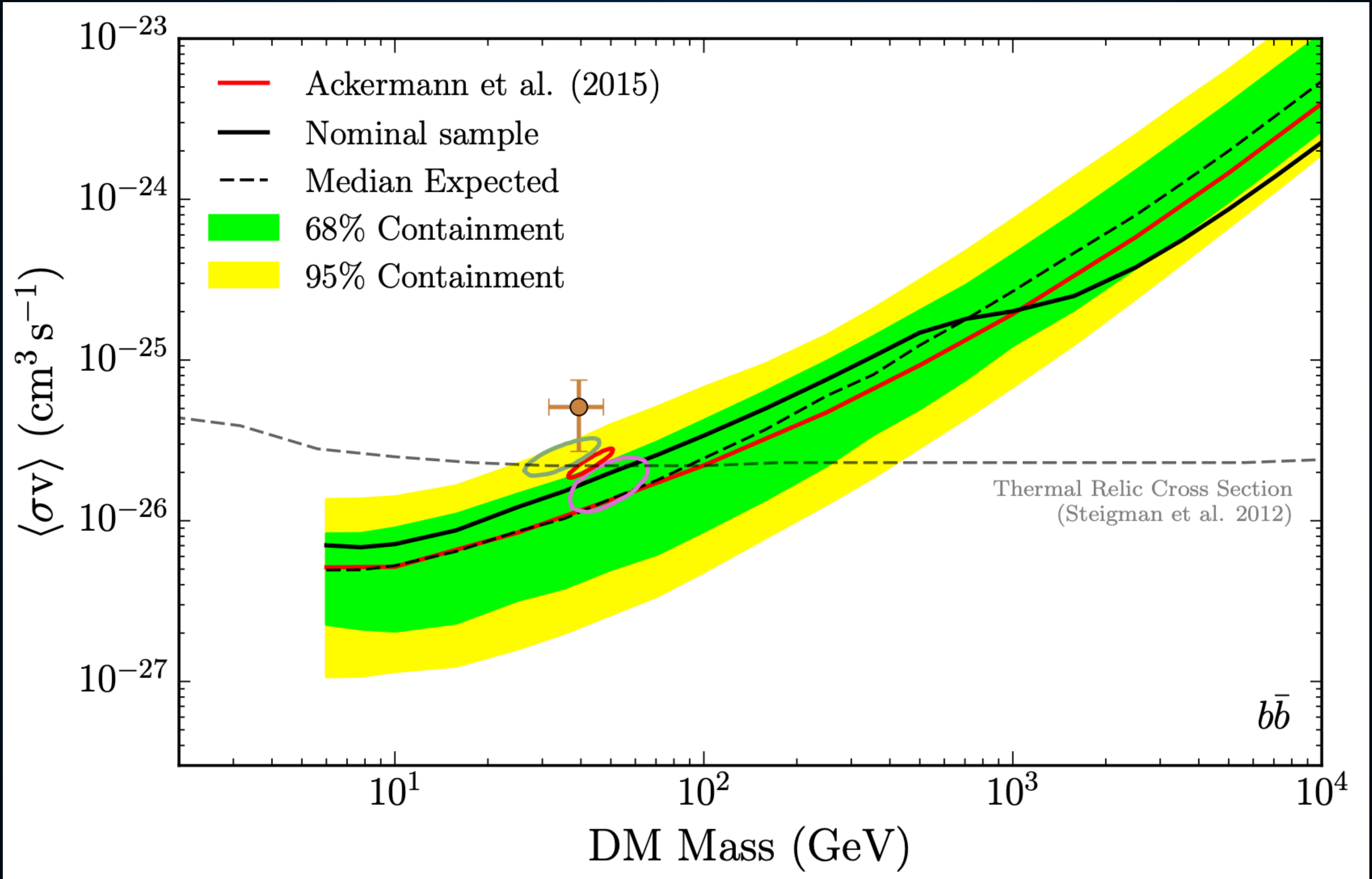
[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2] *Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, OH 43210, USA*
[3] *Department of Physics, Ohio State University, Columbus, OH 43210, USA*
[4] *Department of Astronomy, Ohio State University, Columbus, OH 43210, USA*
[5] *Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 76100, Israel*

(Dated: July 13, 2018)

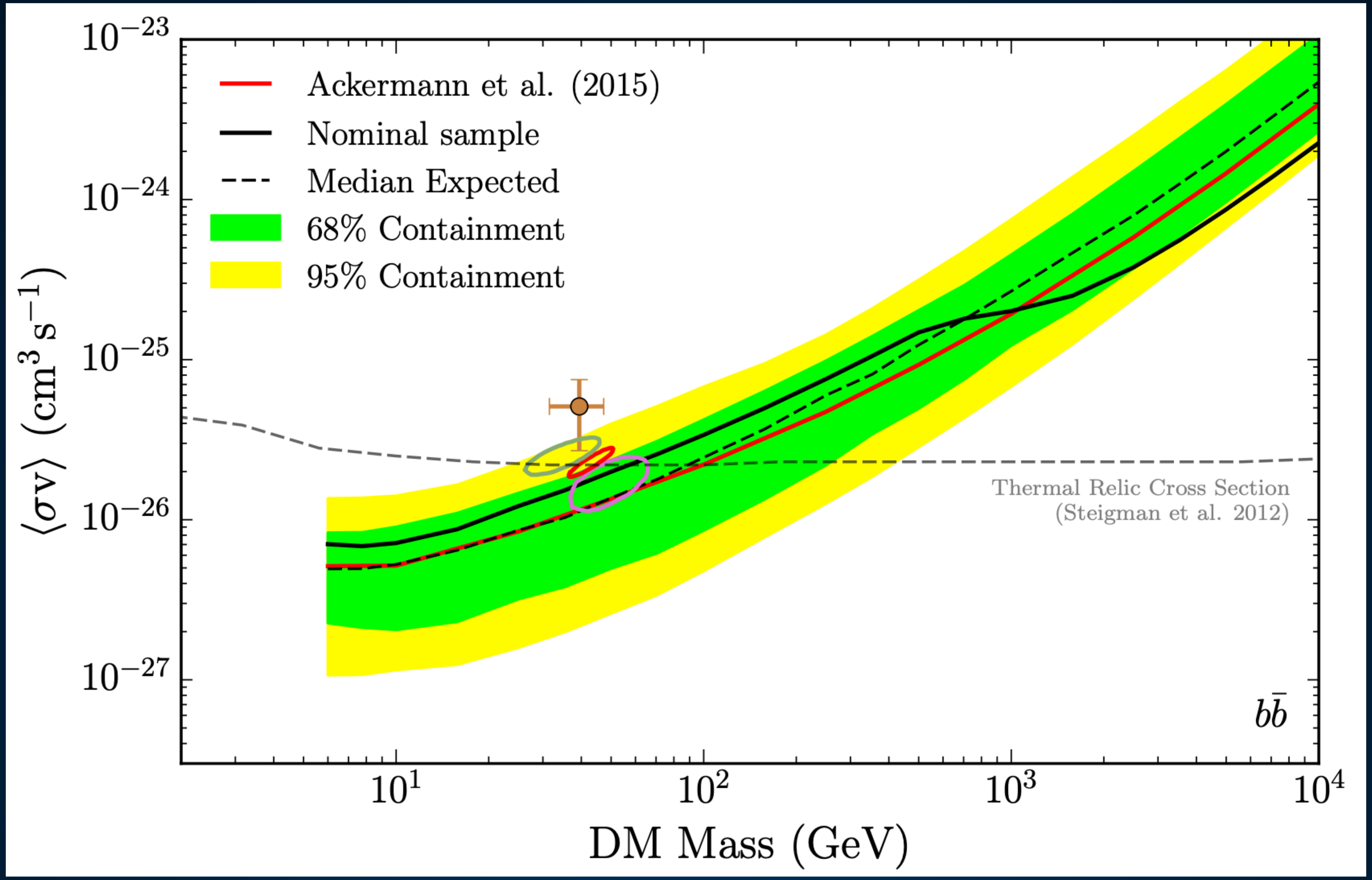
Weakly Interacting Massive Particles (WIMPs) have long reigned as one of the leading classes of dark matter candidates. The observed dark matter abundance can be naturally obtained by freeze-out of weak-scale dark matter annihilations in the early universe. This "thermal WIMP" scenario makes direct predictions for the total annihilation cross section that can be tested in present-day experiments. While the dark matter mass constraint can be as high as $m_\chi \gtrsim 100$ GeV for particular annihilation channels, the constraint on the *total* cross section has not been determined. We construct the first model-independent limit on the WIMP total annihilation cross section, showing that allowed combinations of the annihilation-channel branching ratios considerably weaken the sensitivity. For thermal WIMPs with s-wave $2 \to 2$ annihilation to visible final states, we find the dark matter mass is only known to be $m_\chi \gtrsim 20$ GeV. This is the strongest largely model-independent lower limit on the mass of thermal-relic WIMPs; together with the upper limit on the mass from the unitarity bound ($m_\chi \lesssim 100$ TeV), it defines what we call the "WIMP window". To probe the remaining mass range, we outline ways forward.

Reasons to Stay Optimistic: Lots of Parameter Space Left

Fermi-LAT Collaboration (2017; 1611.03184)



What Does it all Mean?



~100 GeV

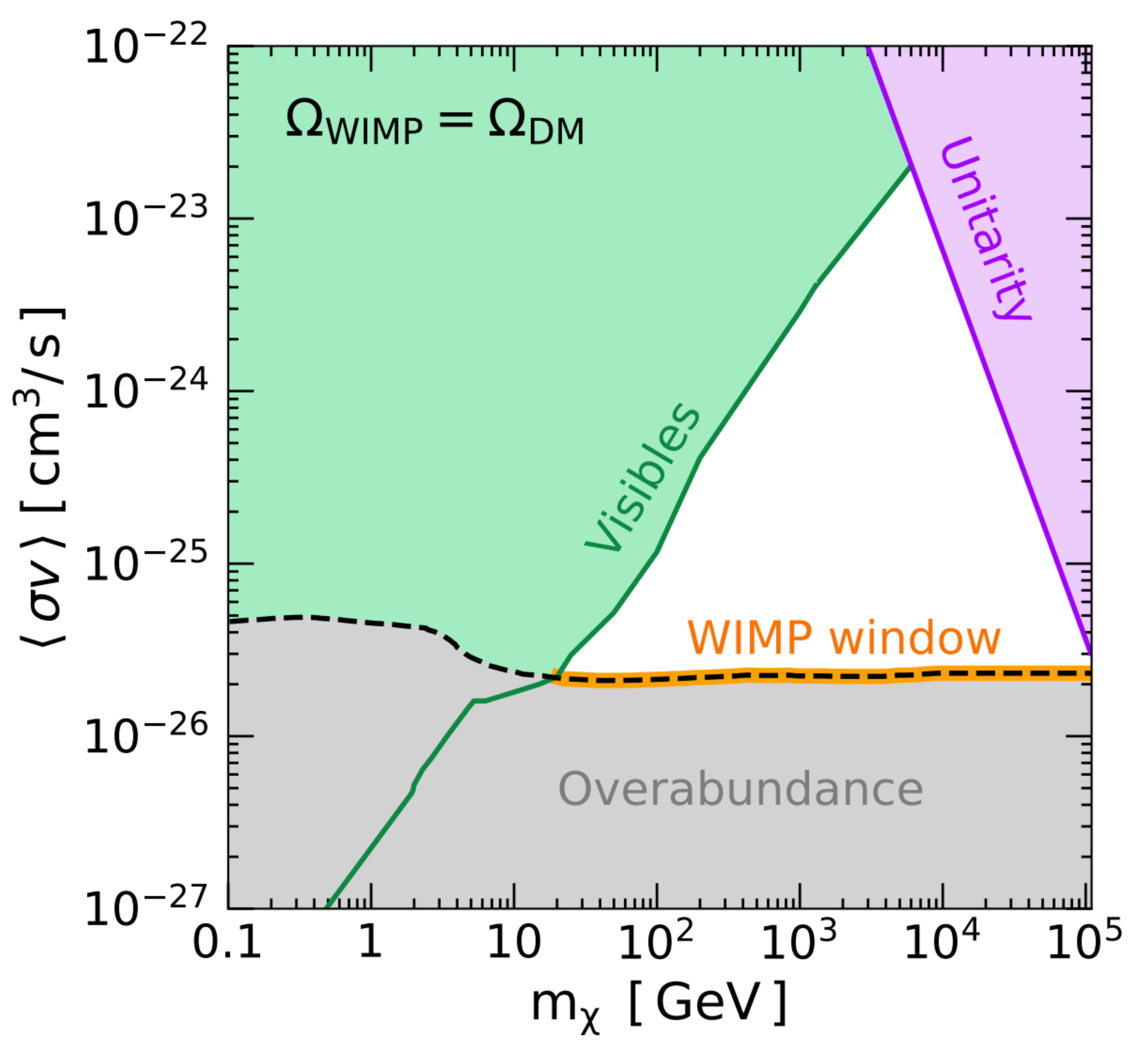
10^{-2} GeV (thermal)
10 GeV (weak force)

WIMP
Dark Matter

10^5 GeV (unitarity)

Reasons to Stay Optimistic: Lots of Parameter Space Left

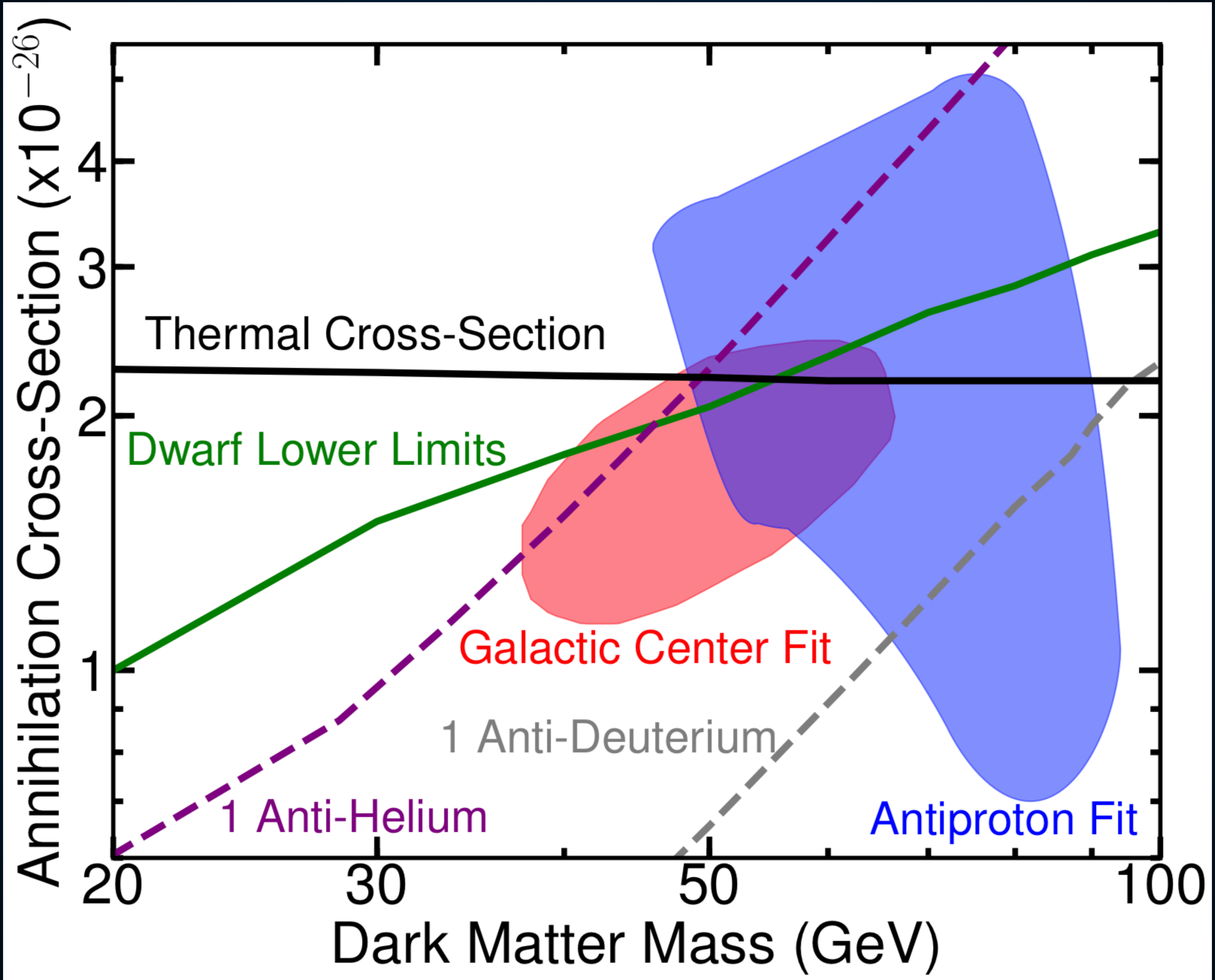
Leane et al. (2018; 1805.10305)



Reasons to Stay Optimistic: Amazing Sensitivity

10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
$<\sigma v>$ (cm^3 s^{-1})
Thermal Annihilation Cross-Section
Produces 1 observed photon from the Galactic Center
10^1
10^2
10^3
10^4
10^5
Dark Matter Mass (GeV)


THE TRUTH IS OUT THERE

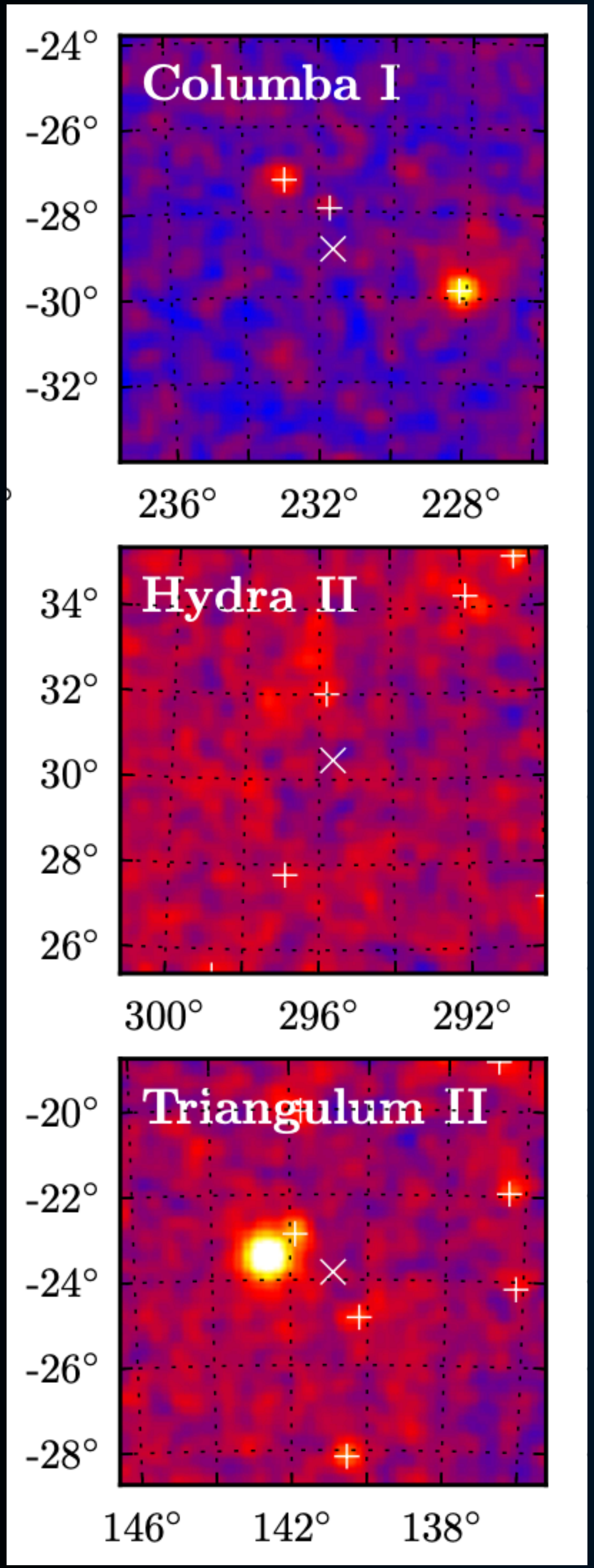


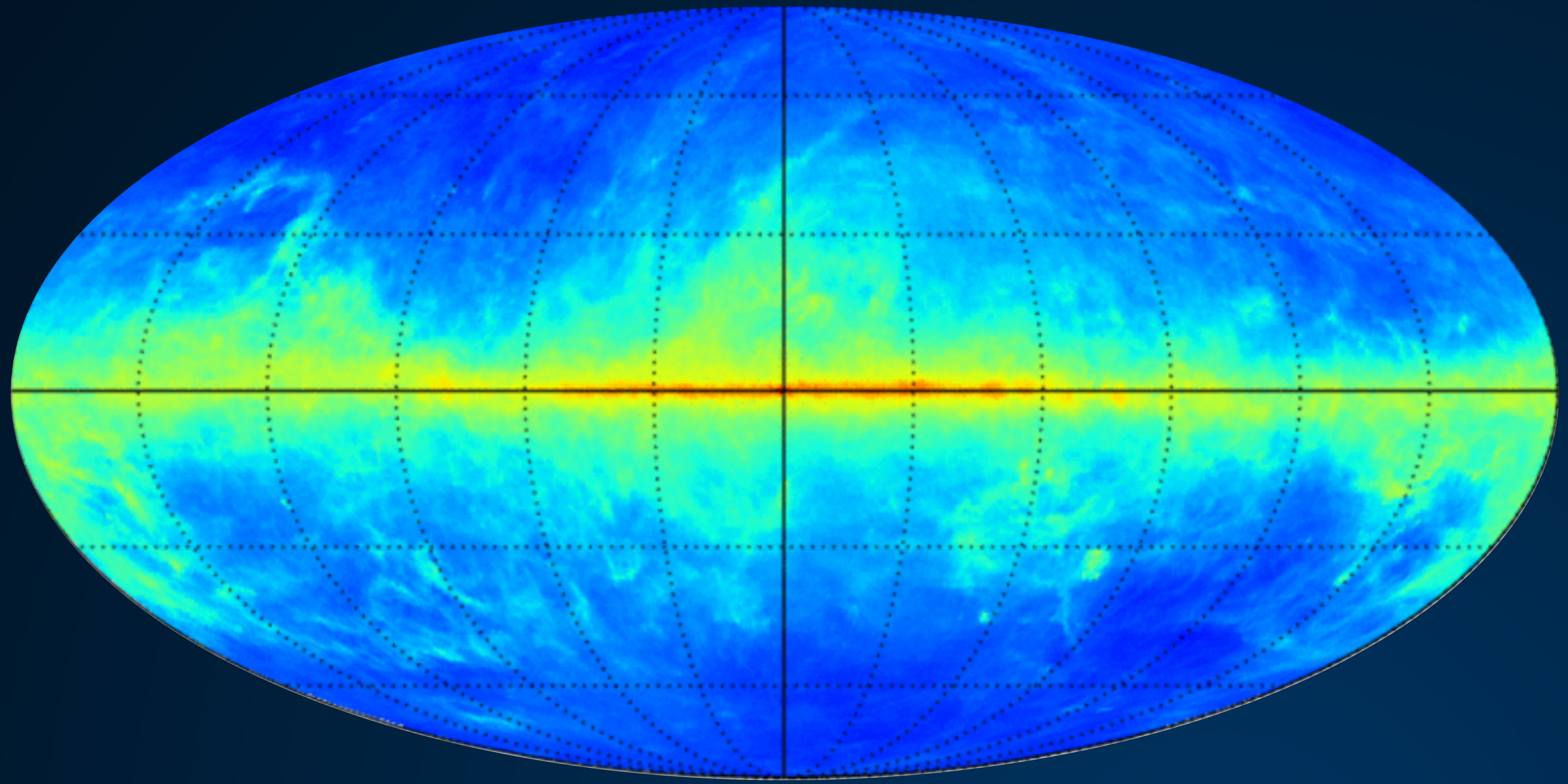
Annihilation Cross-Section (x10^{-26})
4
3
2
1
Thermal Cross-Section
Dwarf Lower Limits
Galactic Center Fit
1 Anti-Deuterium
1 Anti-Helium
Antiproton Fit
20
30
50
100
Dark Matter Mass (GeV)

Dwarf Galaxies in the Milky Way

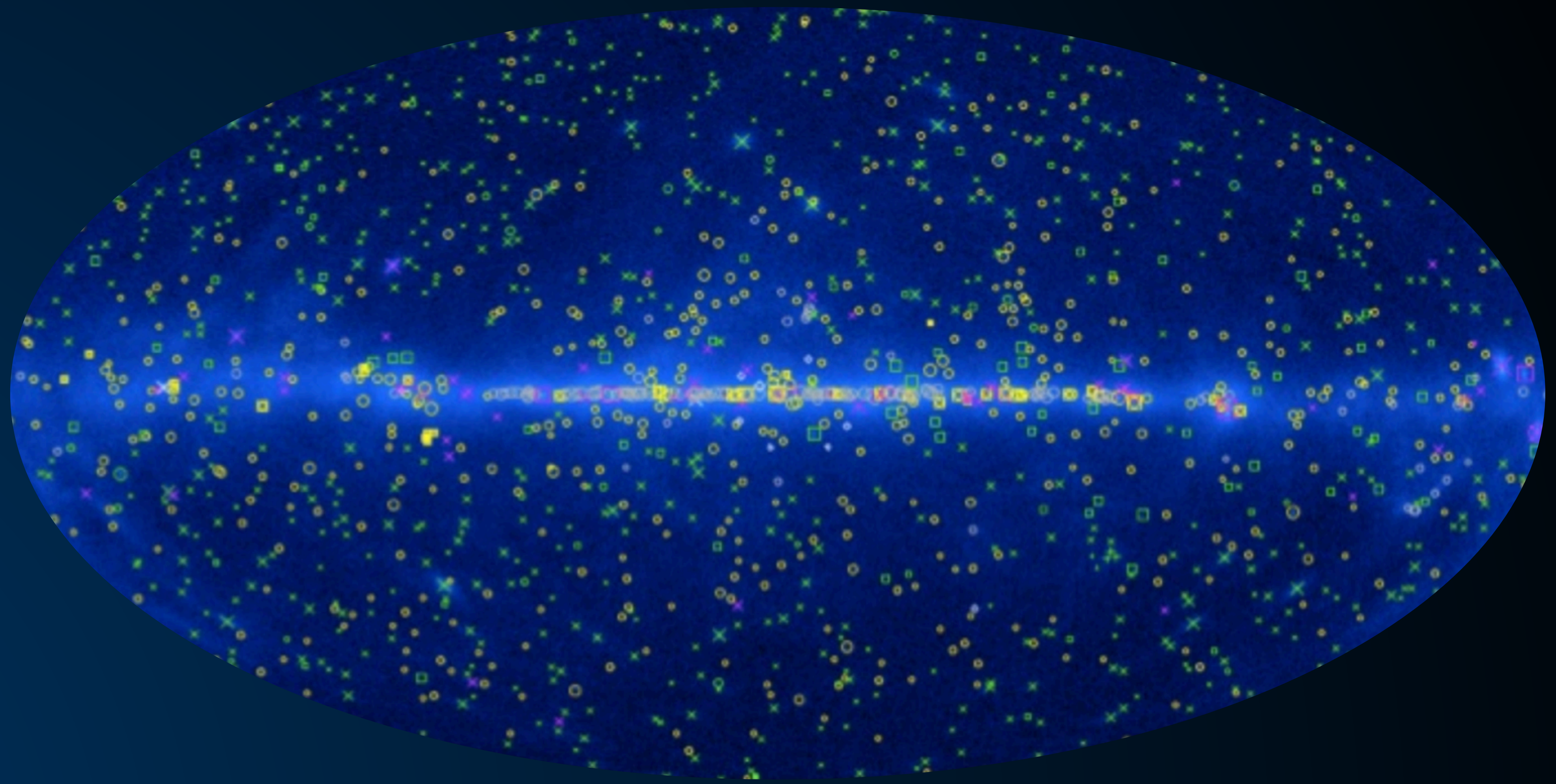
Dwarf Spheroidal Galaxies - Techniques

Fermi-LAT Collaboration (2017; 1611.03184)



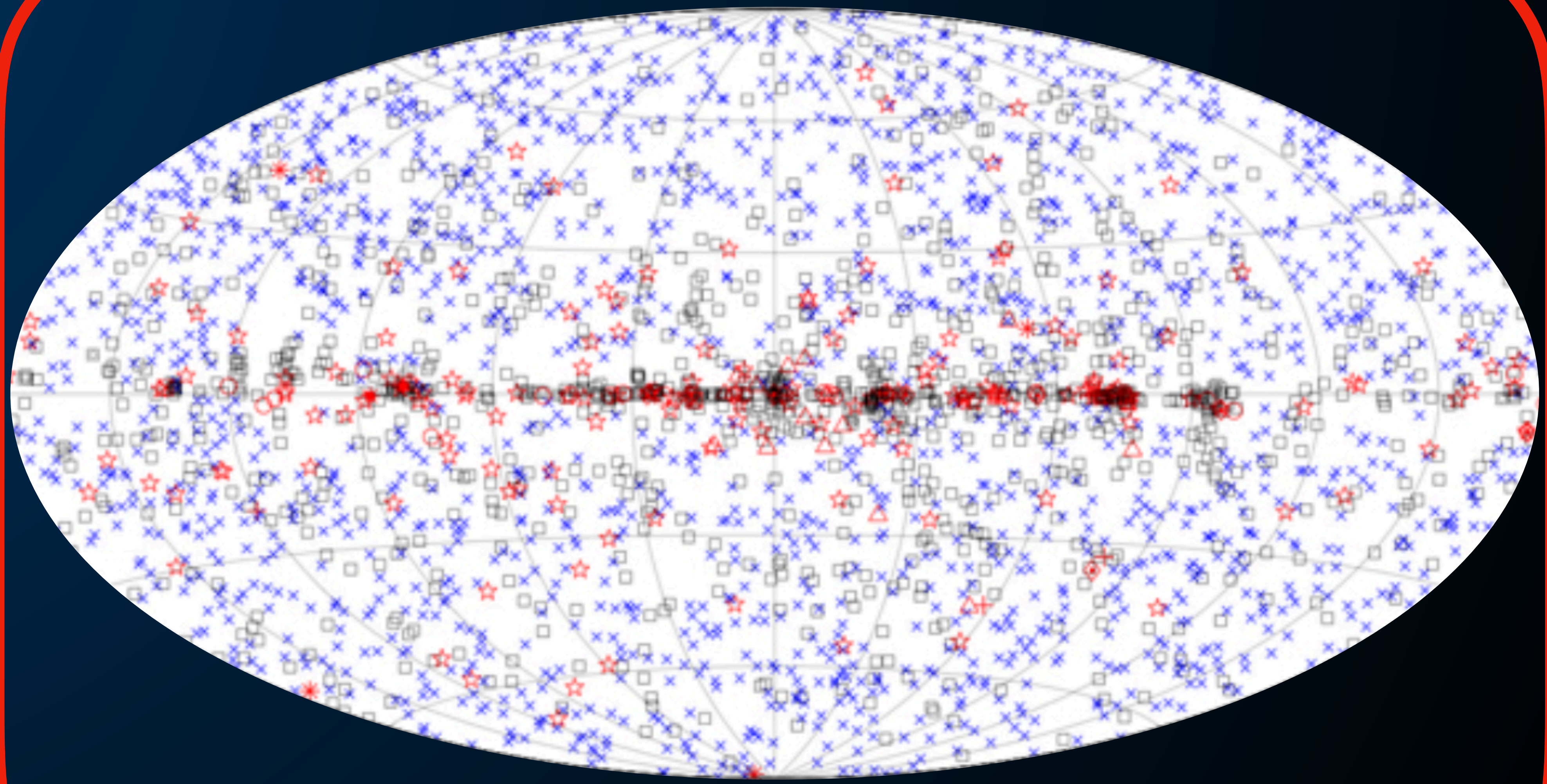


Galactic Diffuse



Point Sources

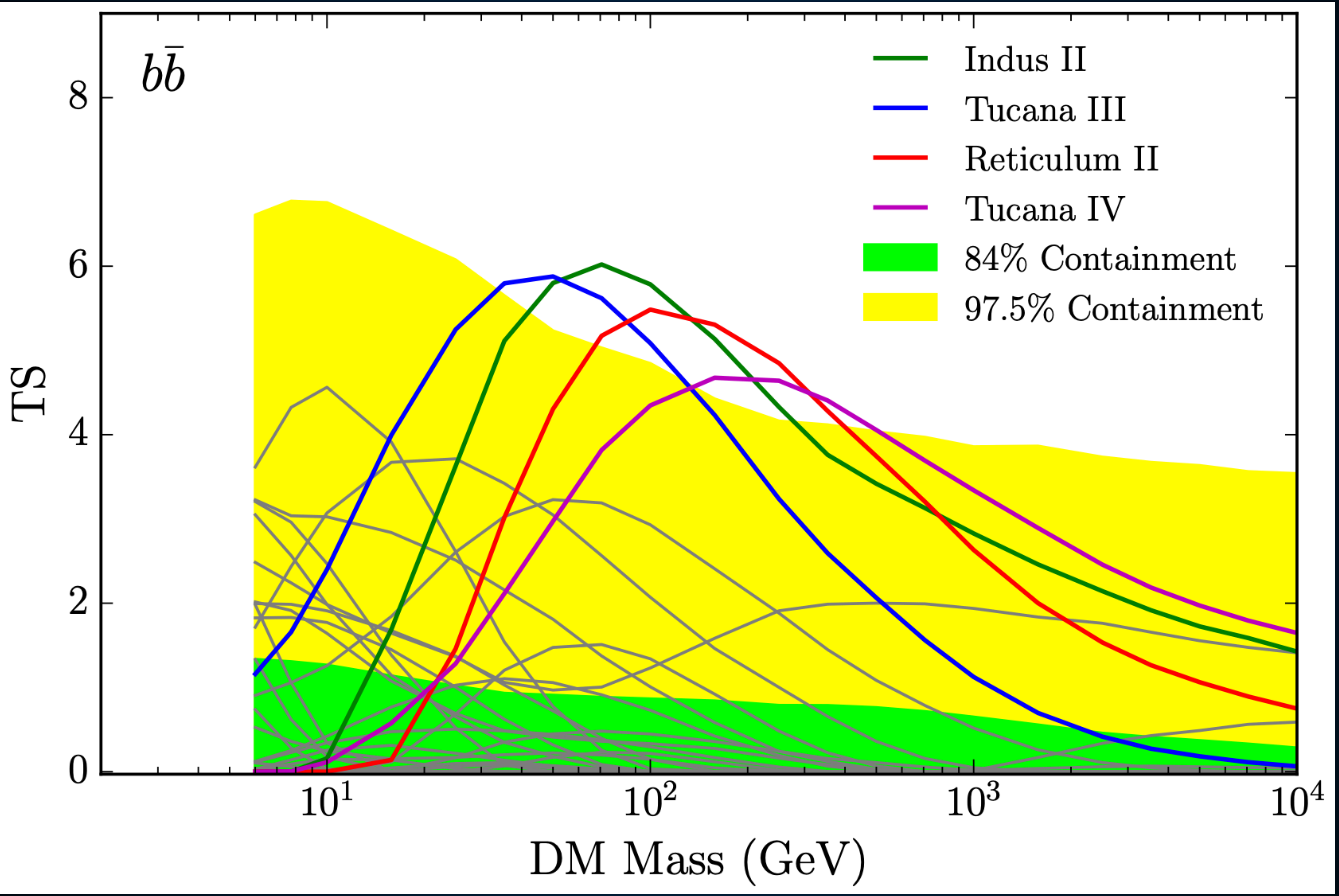
Isotropic Emission



Sub-Threshold Sources

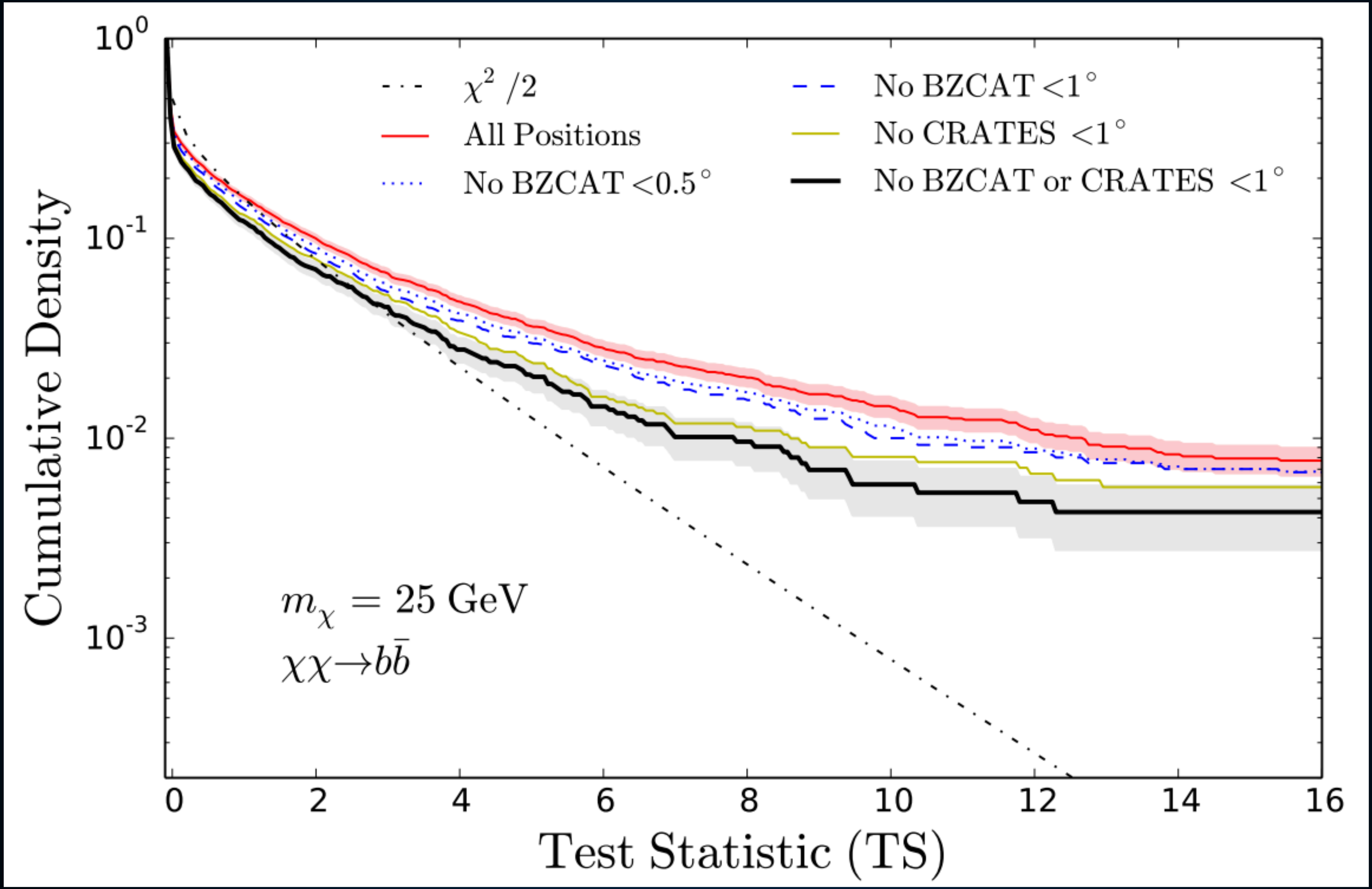
Dwarf Spheroidal Galaxies - Techniques

Fermi-LAT Collaboration (2017; 1611.03184)

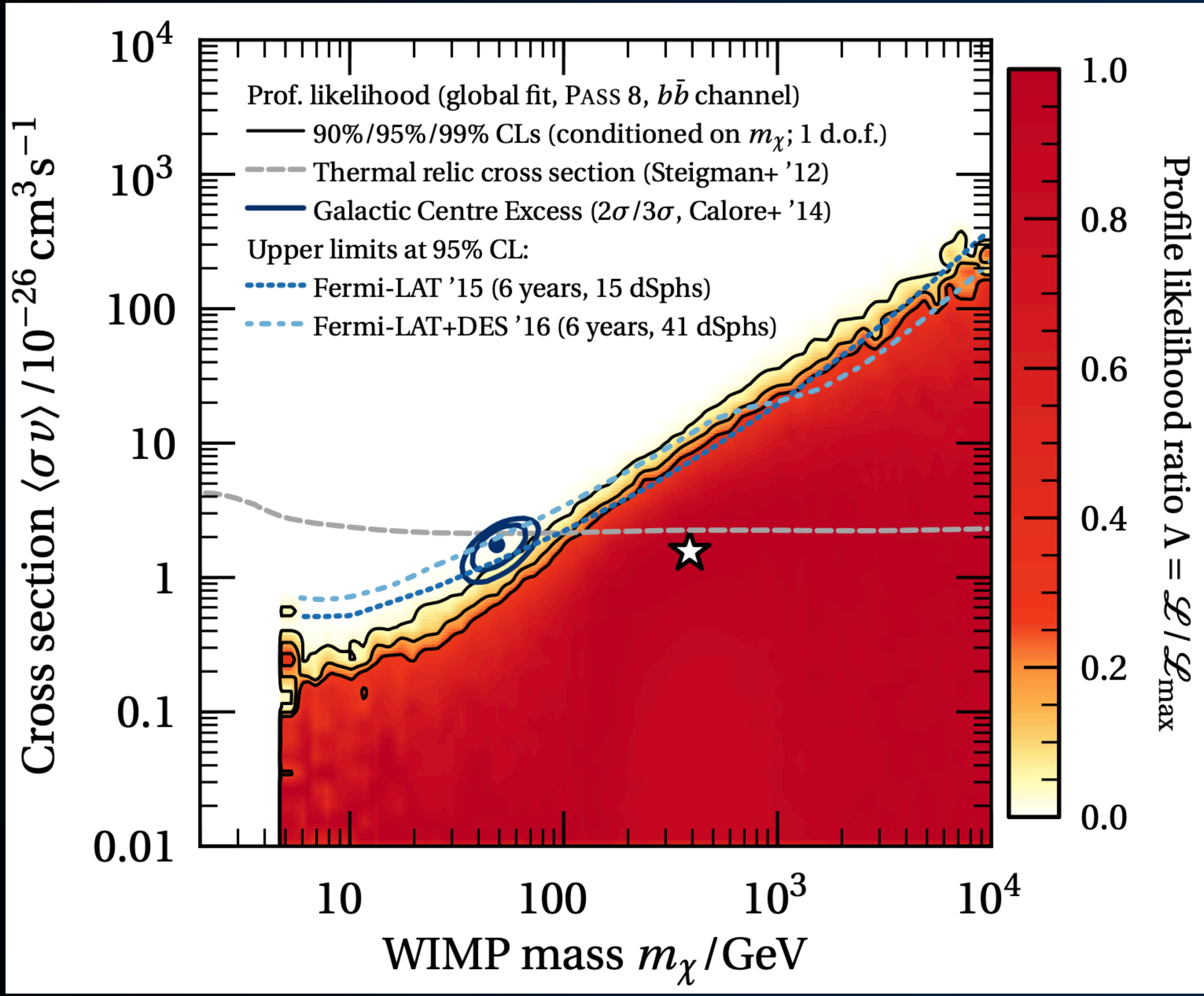


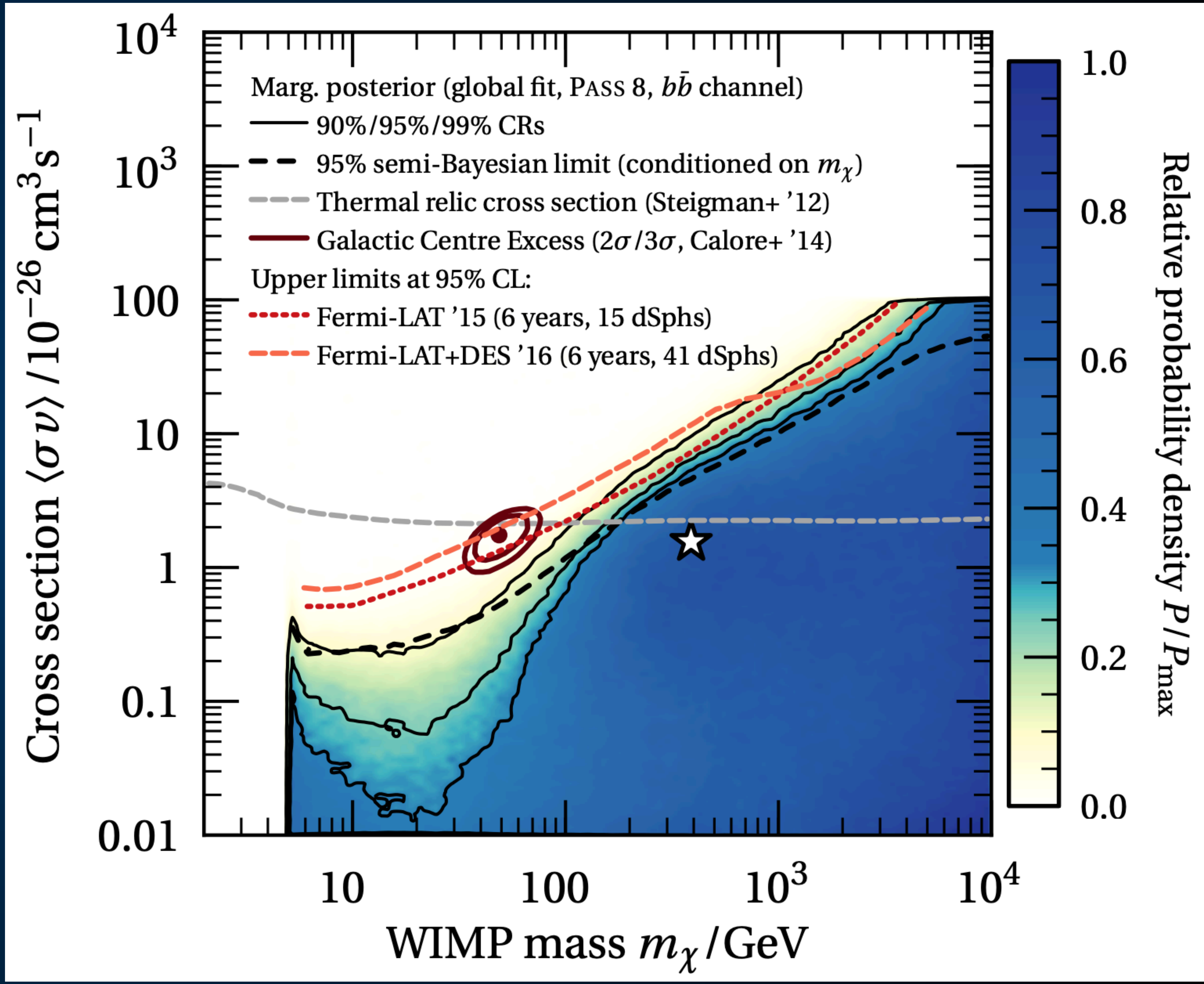
Dwarf Spheroidal Galaxies - Techniques

Carlson, Hooper, Linden (1409.1572)



Hoof, Geringer-Sameth, Trotta (1812.06986)





Frequentist **Bayesian**

Dwarf Spheroidal Galaxies - Techniques

$$P(\langle\sigma v\rangle) = \prod_i \arg\max_{\phi_{s,i}} \int_{-\infty}^{\infty} \mathcal{L}(\phi_{s,i} + \phi_{bg}) P_{bg}(\phi_{bg}) \times \times P_{s,i}\left(\phi_{s,i}, \langle\sigma v\rangle, J_i, \sigma_i\right) \mathrm{d}\phi_{\mathrm{bg}}$$

Dwarf Spheroidal Galaxies - The Future

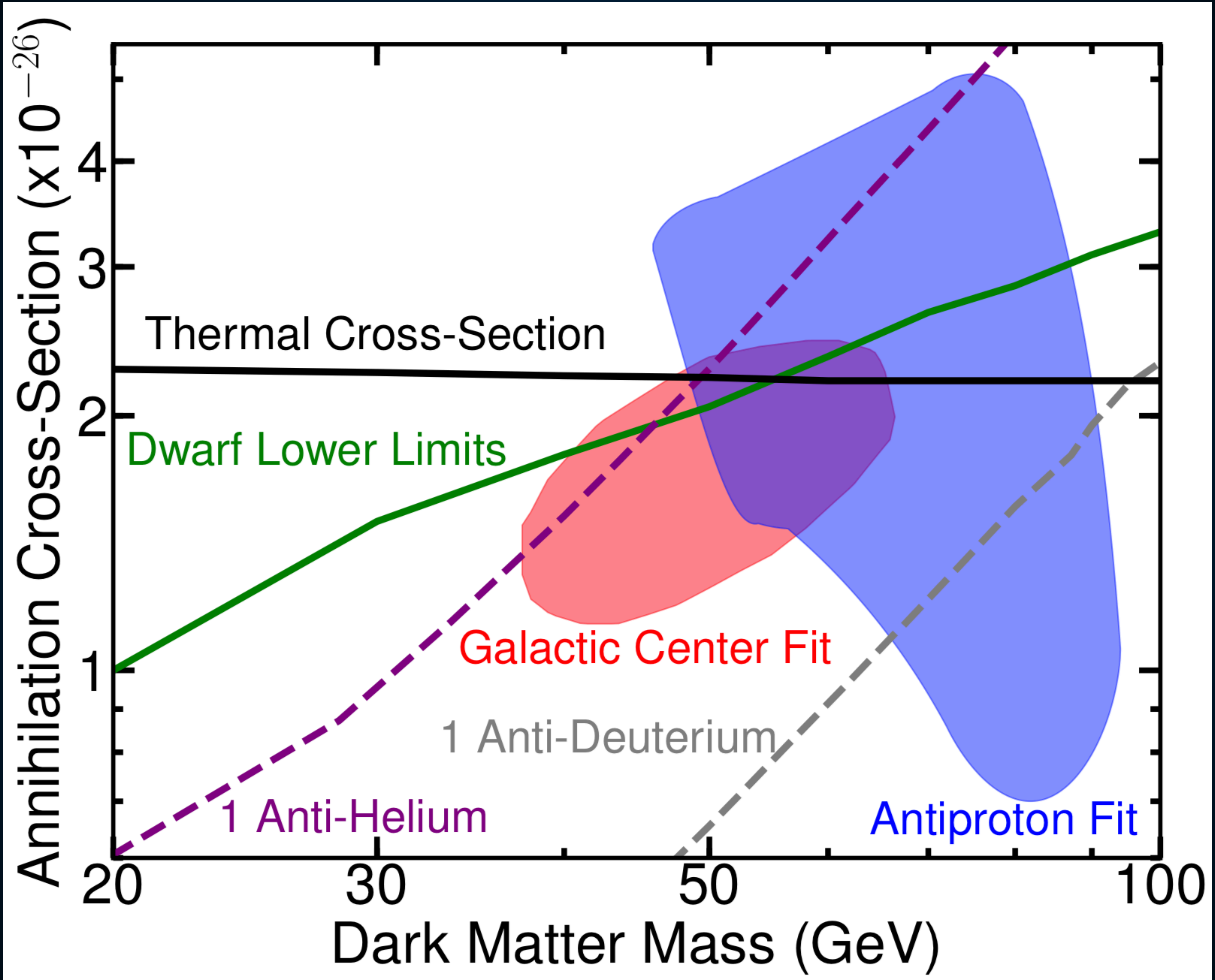
Discovery prospects of dwarf spheroidal galaxies for indirect dark matter searches

Shin'ichiro Ando,[a,b,c] Bradley J. Kavanagh,[a,b] Oscar Macias,[c,a,b] Tiago Alves,[b] Siebren Broersen,[b] Stijn Delnoij,[b] Thomas Goldman,[b] Jim Groefsema,[b] Jorinde Kleverlaan,[b] Jaïr Lenssen,[b] Toon Muskens,[b] Liam X. Palma Visser,[b] Ebo Peerbooms,[b] Bram van der Linden,[b] and Sill Verberne[b]

[a]GRAPPA Institute, University of Amsterdam, 1098 XH Amsterdam, The Netherlands
[b]Institute for Theoretical Physics, University of Amsterdam, 1098 XH Amsterdam, The Netherlands
[c]Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa 277-8583, Japan

E-mail: s.ando@uva.nl, b.j.kavanagh@uva.nl, o.a.maciasramirez@uva.nl

Abstract. We study the prospects for the Large Synoptic Survey Telescope (LSST) to find new dwarf spheroidal galaxies in the Milky Way. Adopting models of Milky-Way halo substructure and phenomenological prescriptions connecting subhalos and satellite galaxies, we obtain surface brightness distributions of V-band magnitude that lead us to predict that LSST will discover tens to hundreds of dwarf spheroidal galaxies above its sensitivity. The soon-to-be-discovered dwarfs will be interesting targets for indirect searches of dark matter annihilation yields. We forecast the distribution function of gamma-ray emission from dark matter annihilation in these objects, and discuss the detectability of these signals at both Fermi Large Area Telescope (LAT) and Cherenkov Telescope Array (CTA). By combining



Annihilation Cross-Section (x10^{-26})
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Thermal Cross-Section
Dwarf Lower Limits
Galactic Center Fit
1 Anti-Deuterium
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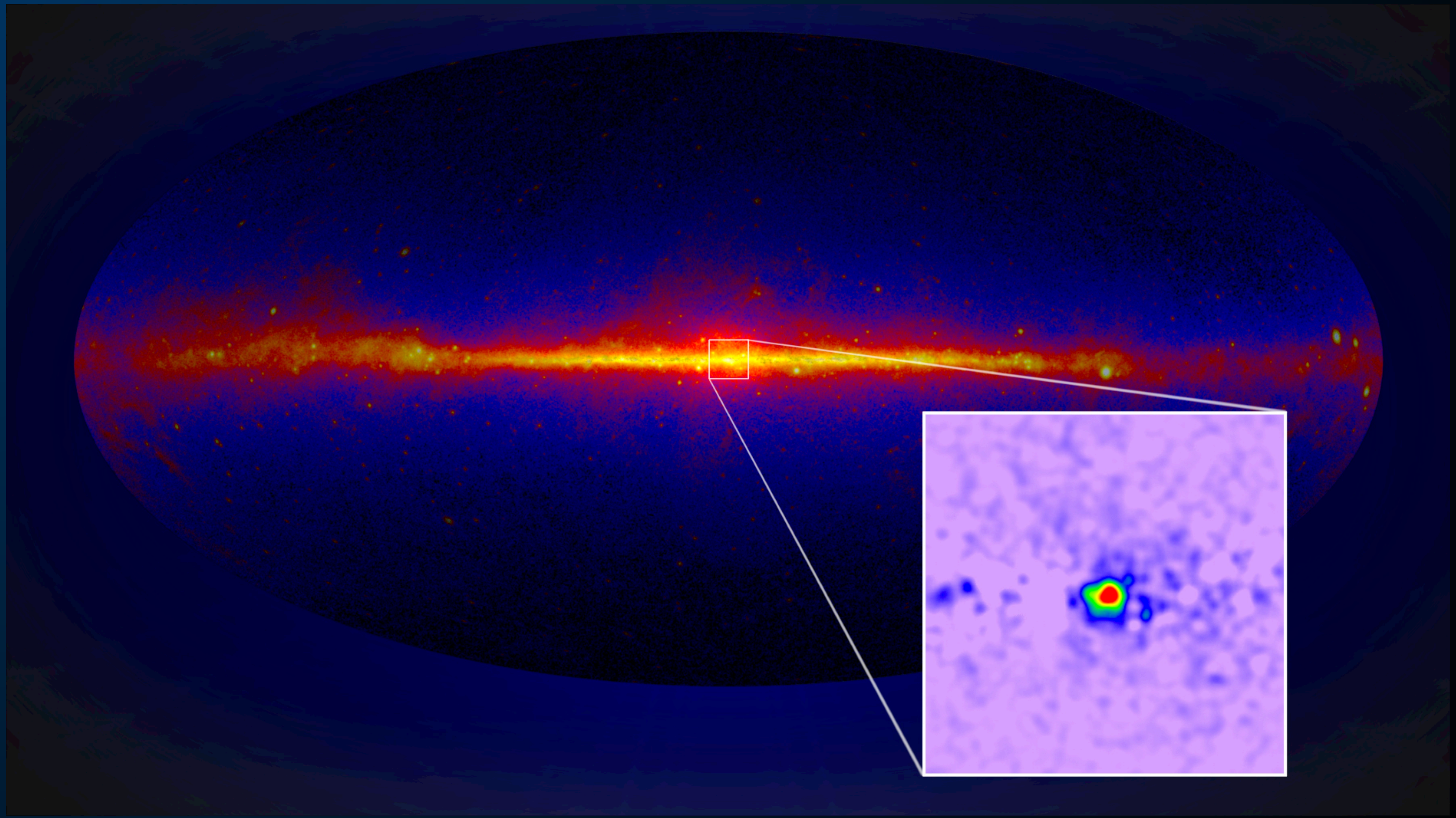
Antiproton Fit
20
30
50
100
Dark Matter Mass (GeV)

The Galactic Center - The Optimal Detection Region

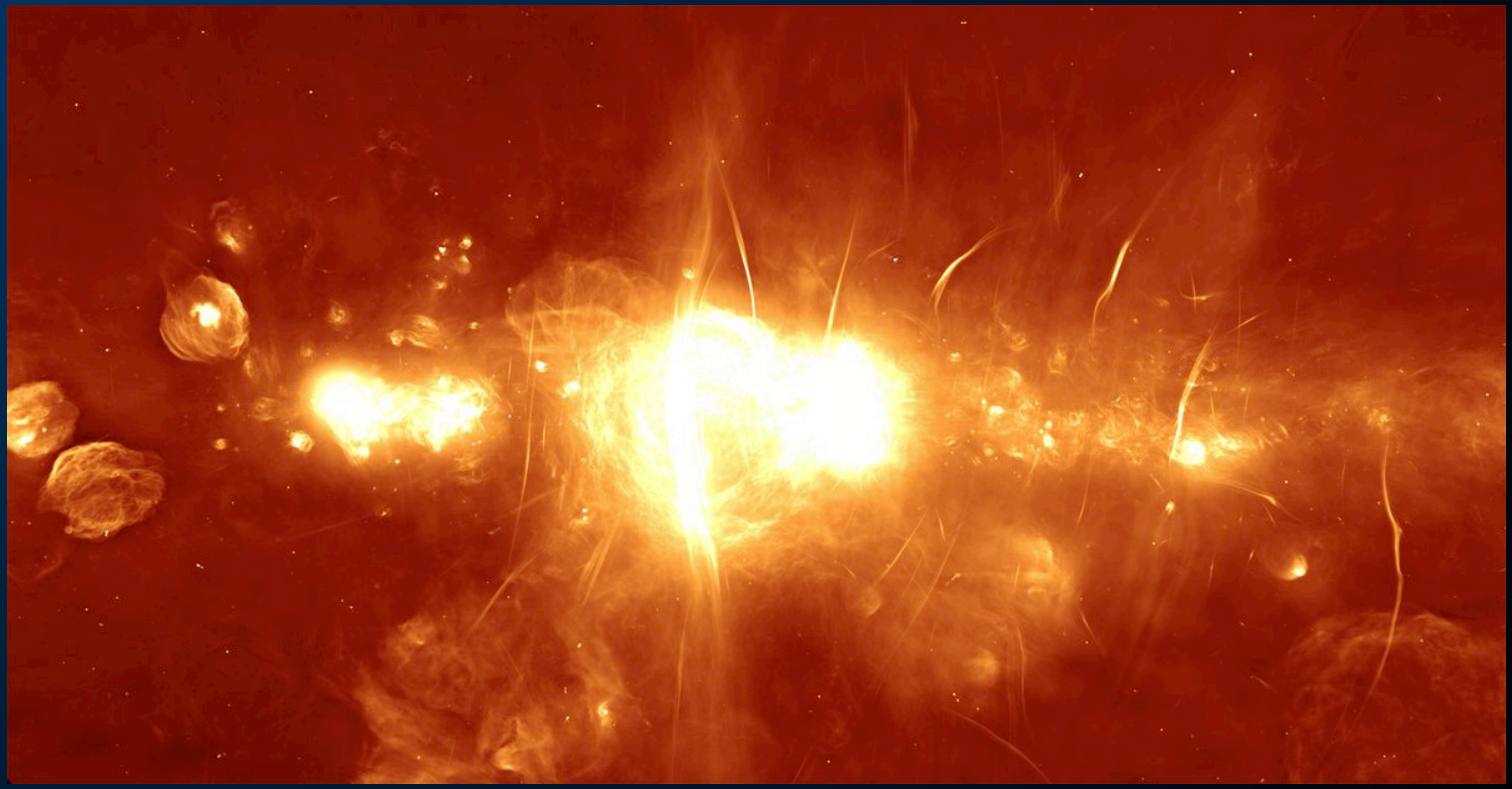
The Galactic Center - The Optimal Detection Region

- **Model:**
  - 100 GeV dark matter particle annihilates to bb
  - Annihilation Rate is Thermal Cross-Section
- **Expected Galactic Center Flux (above 1 GeV):**
  - 2×10^{-11} erg cm^{-2} s^{-1}
- **Observed Flux:**
  - 1×10^{-10} erg cm^{-2} s^{-1}



The Galactic Center - The Optimal Detection Region

- **Model:**
  - 100 GeV dark matter particle annihilates to bb
  - Annihilation Rate is Thermal Cross-Section
- **Expected Galactic Center Flux (above 1 GeV):**
  - 2×10^{-13} erg cm^{-2} s^{-1}
- **Observed Flux:**
  - 5×10^{-10} erg cm^{-2} s^{-1}

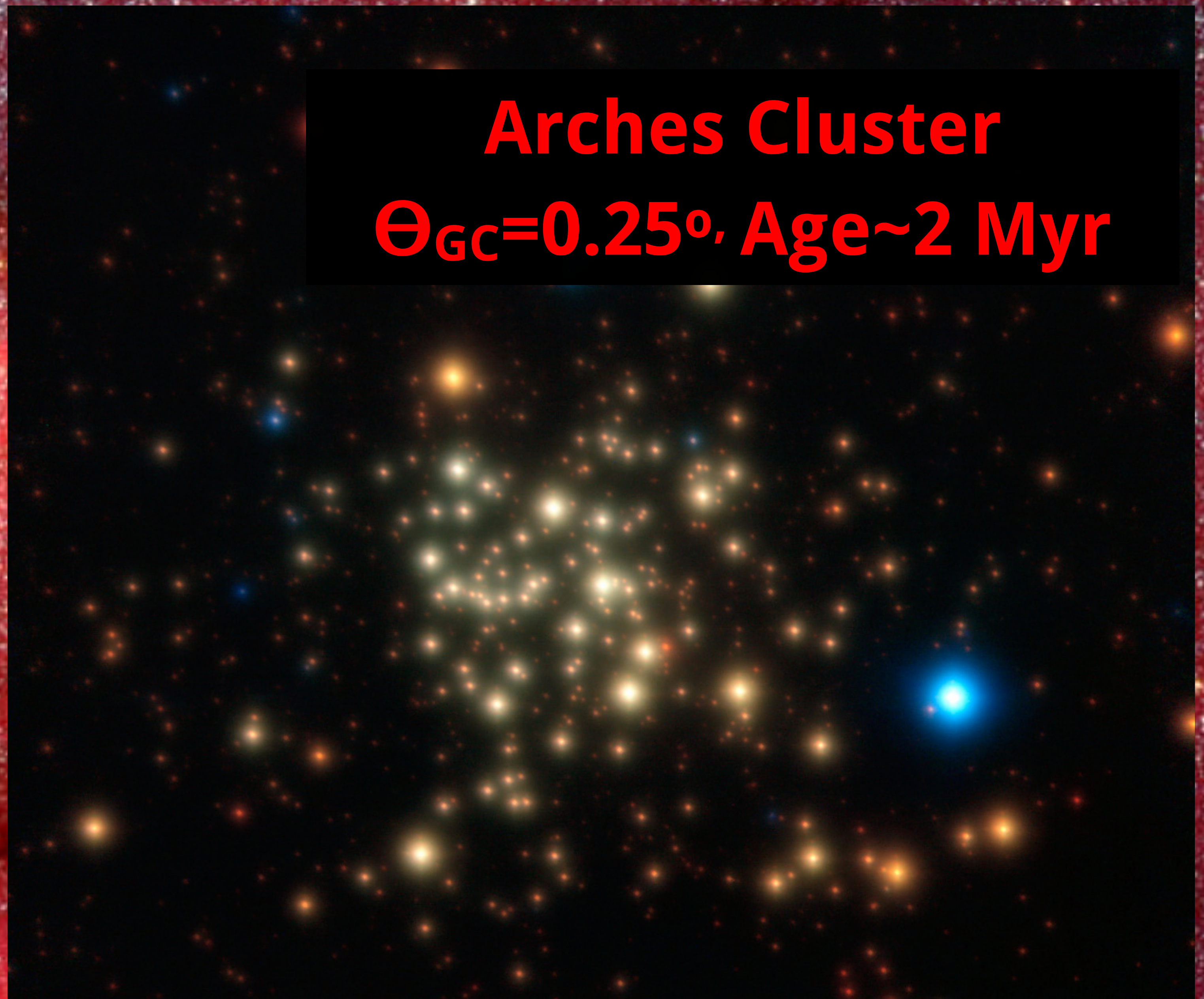


The Galactic Center is Complicated

Galactic Center is a dense star-forming environment.

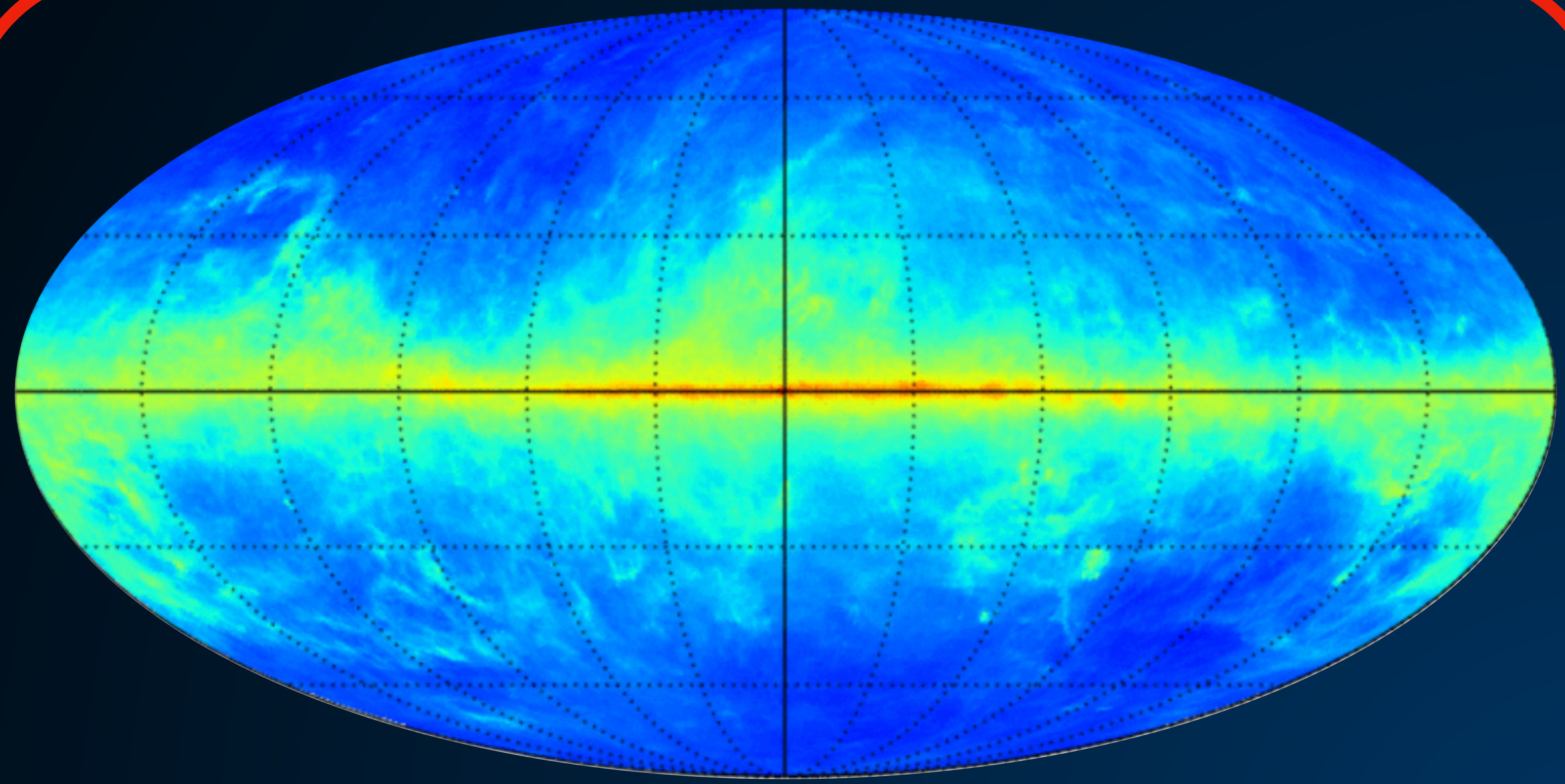
3-20% of total Milky Way Star Formation

- 2-4% - ISOGAL Survey Immer et al. (2012)
- 2.5-5% - Young Stellar Objects Yusef-Zadeh et al. (2009)
- 5-10% - Infrared Flux Longmore et al. (2013)
- 10-20% - Wolf-Rayet Stars Rosslowe & Crowther (2014)
- 2% - Far-IR Flux Thompson et al. (2007)
- 2.5-6% - SN1a Schanne et al. (2007)



The Galactic Center is Complicated

The Galactic Center - Techniques



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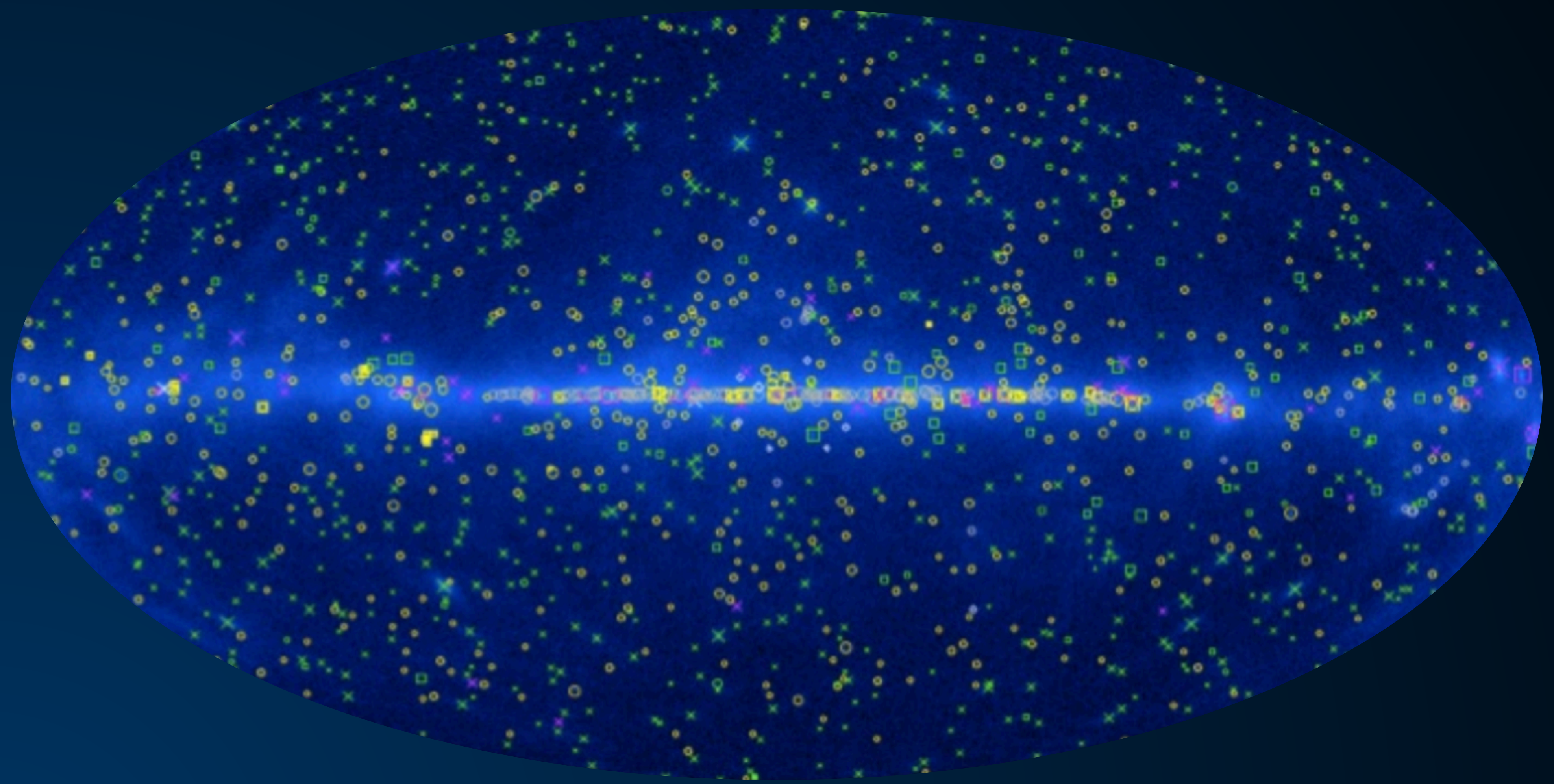

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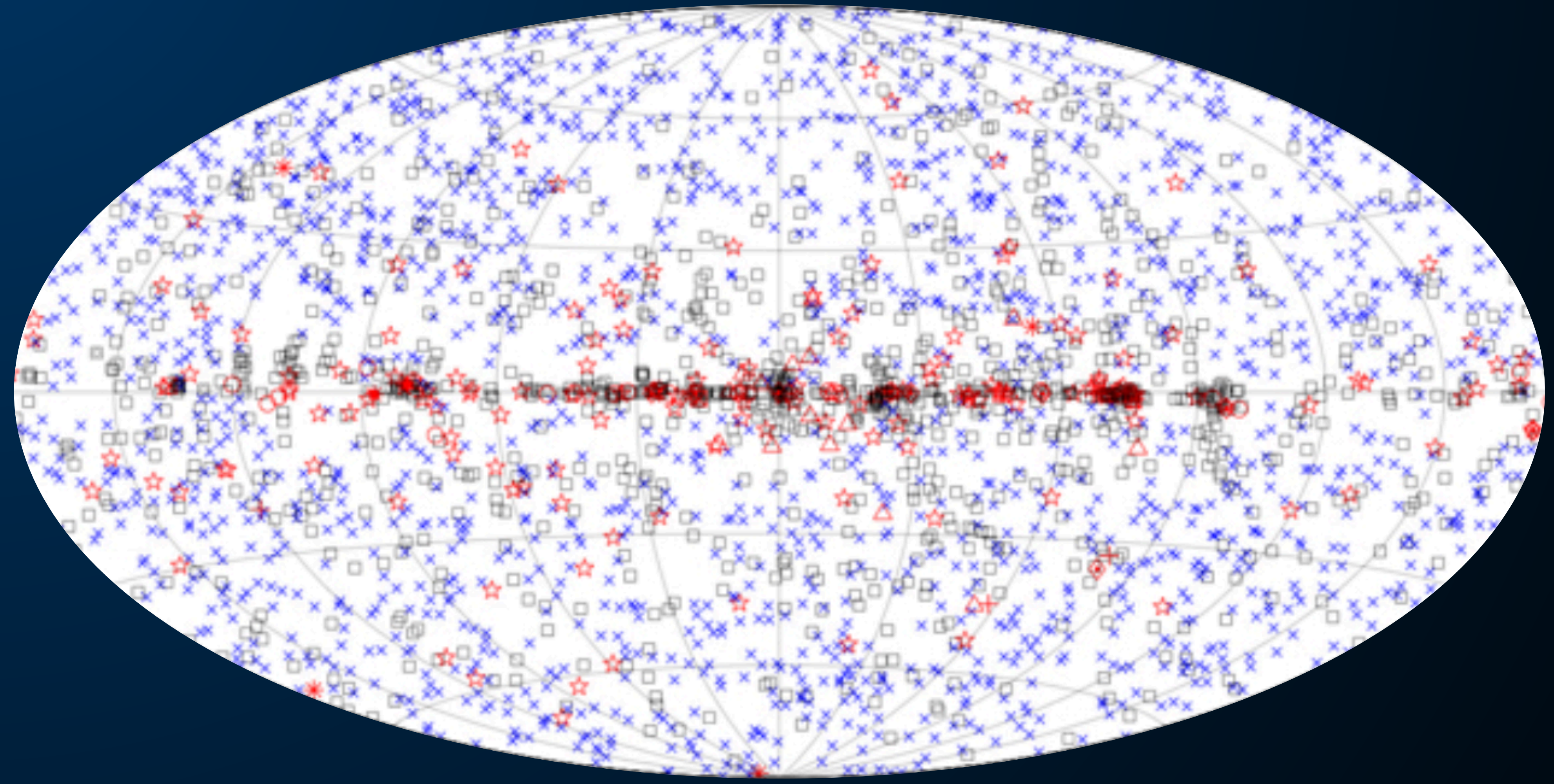
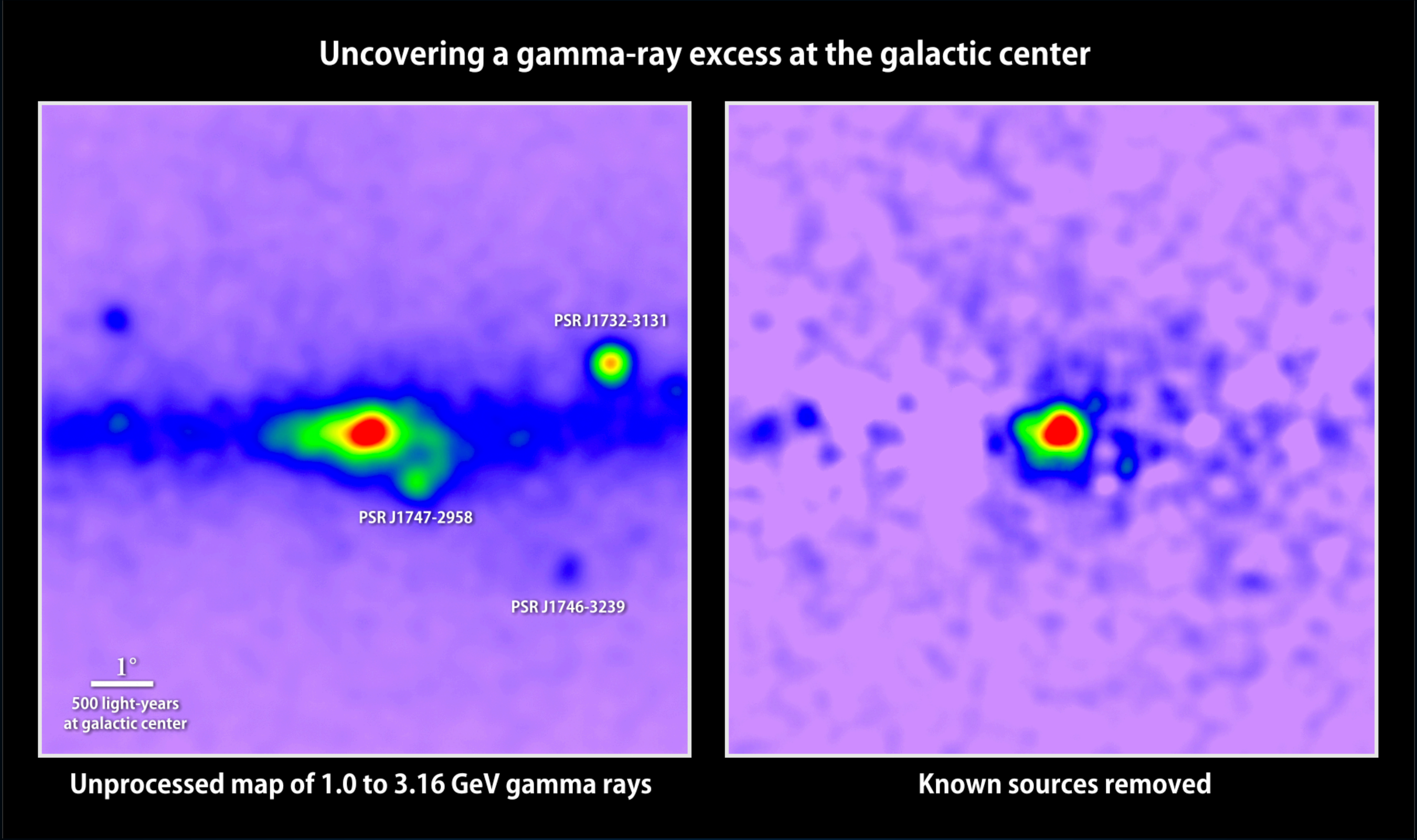
Isotropic Emission



Sub-Threshold Sources

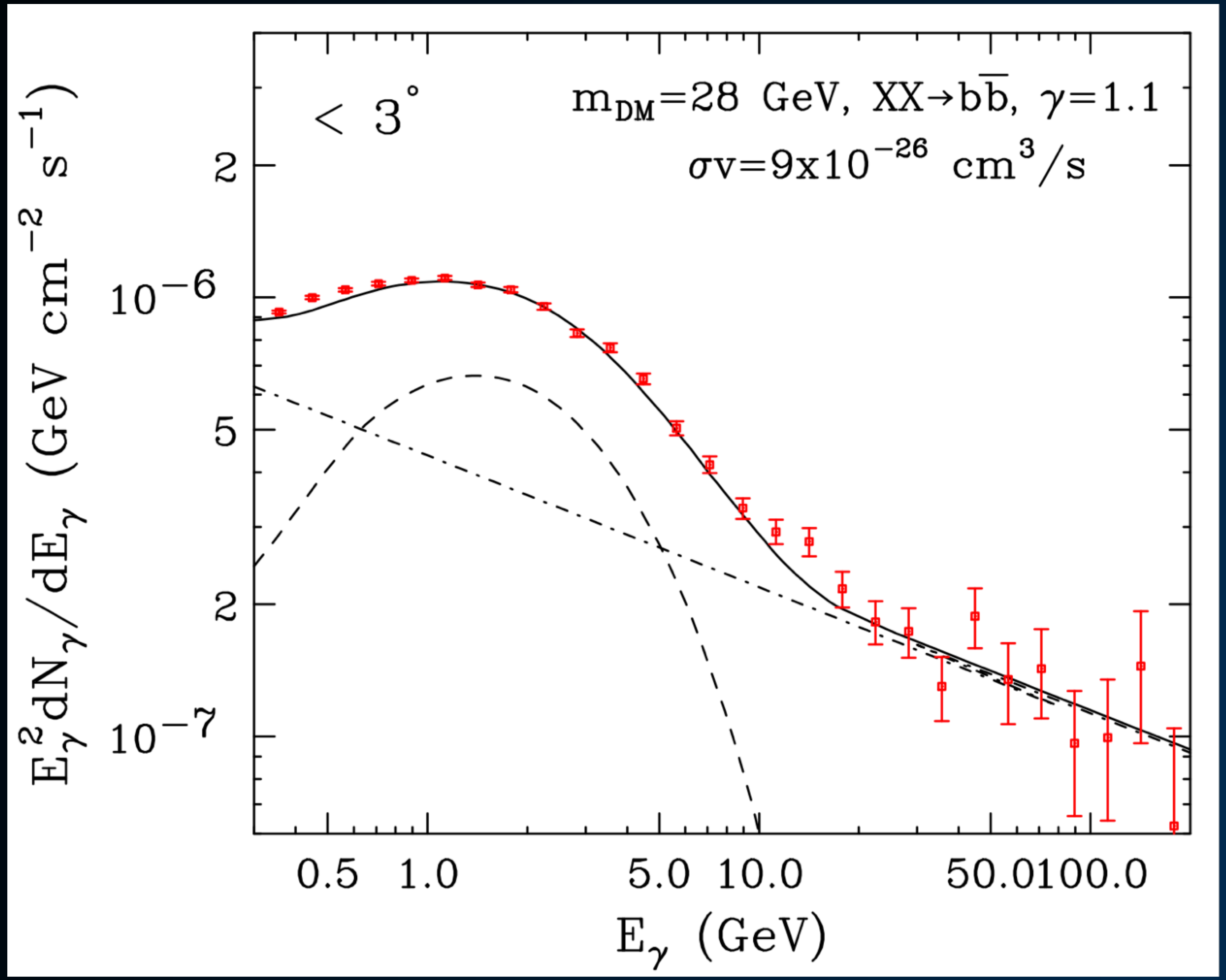
Detections! - The Galactic Center Excess

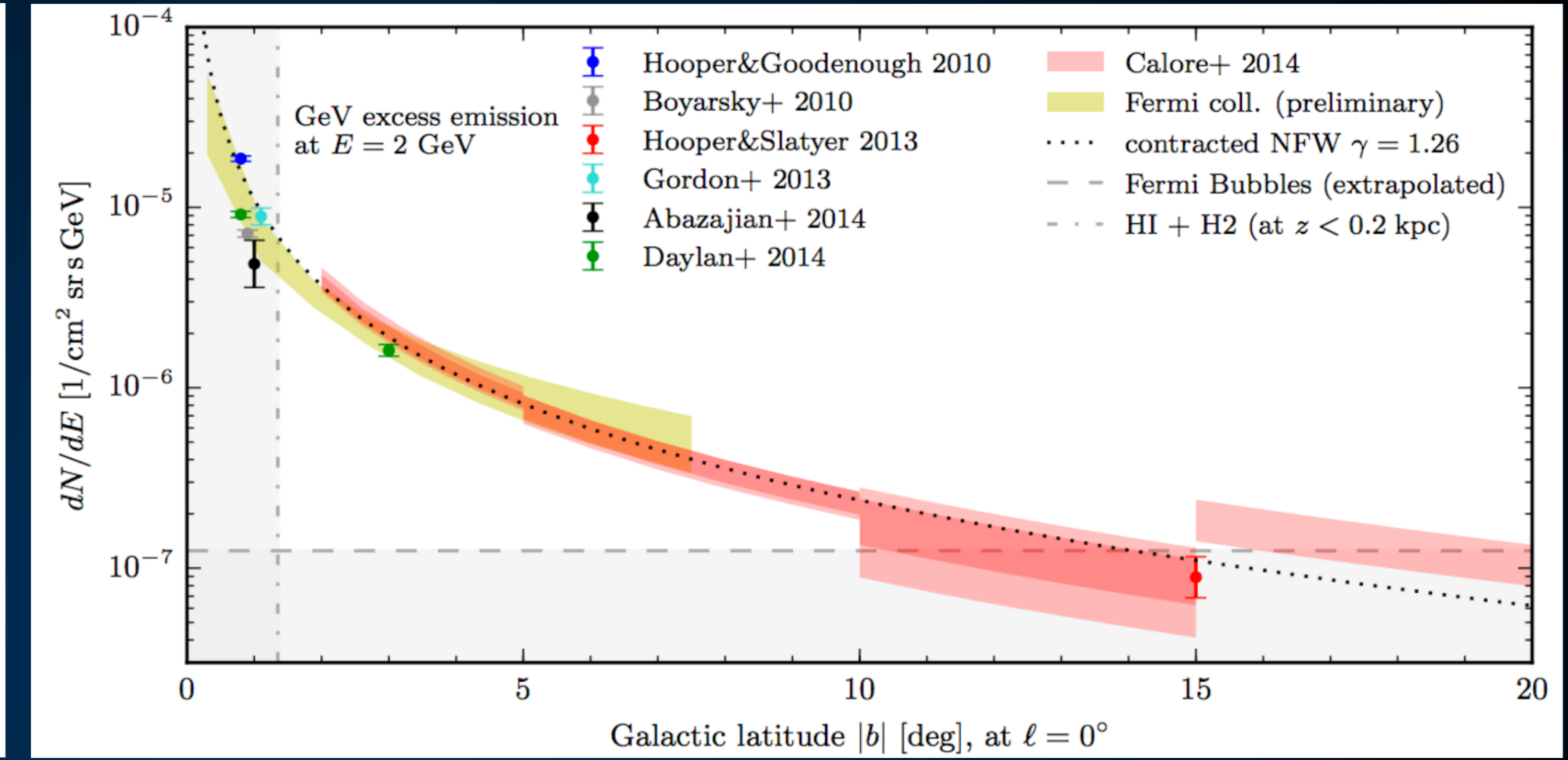
Daylan et al. (2016; 1402.6703)



Detections! - The Galactic Center Excess

Goodenough & Hooper (2009; 0910.2998)





Bright *Detected at >50σ*

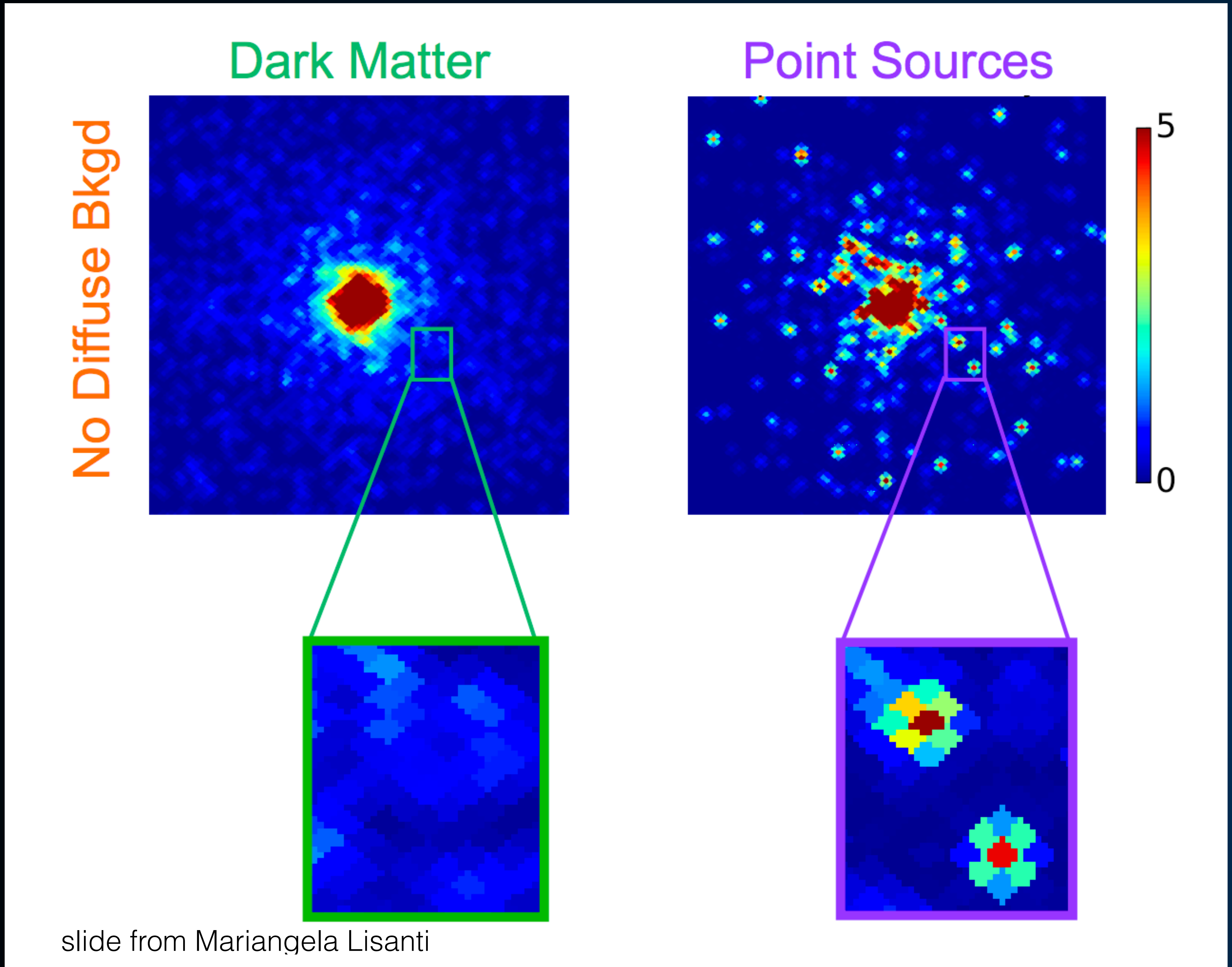
Hard-Spectrum *Incompatible with standard backgrounds*

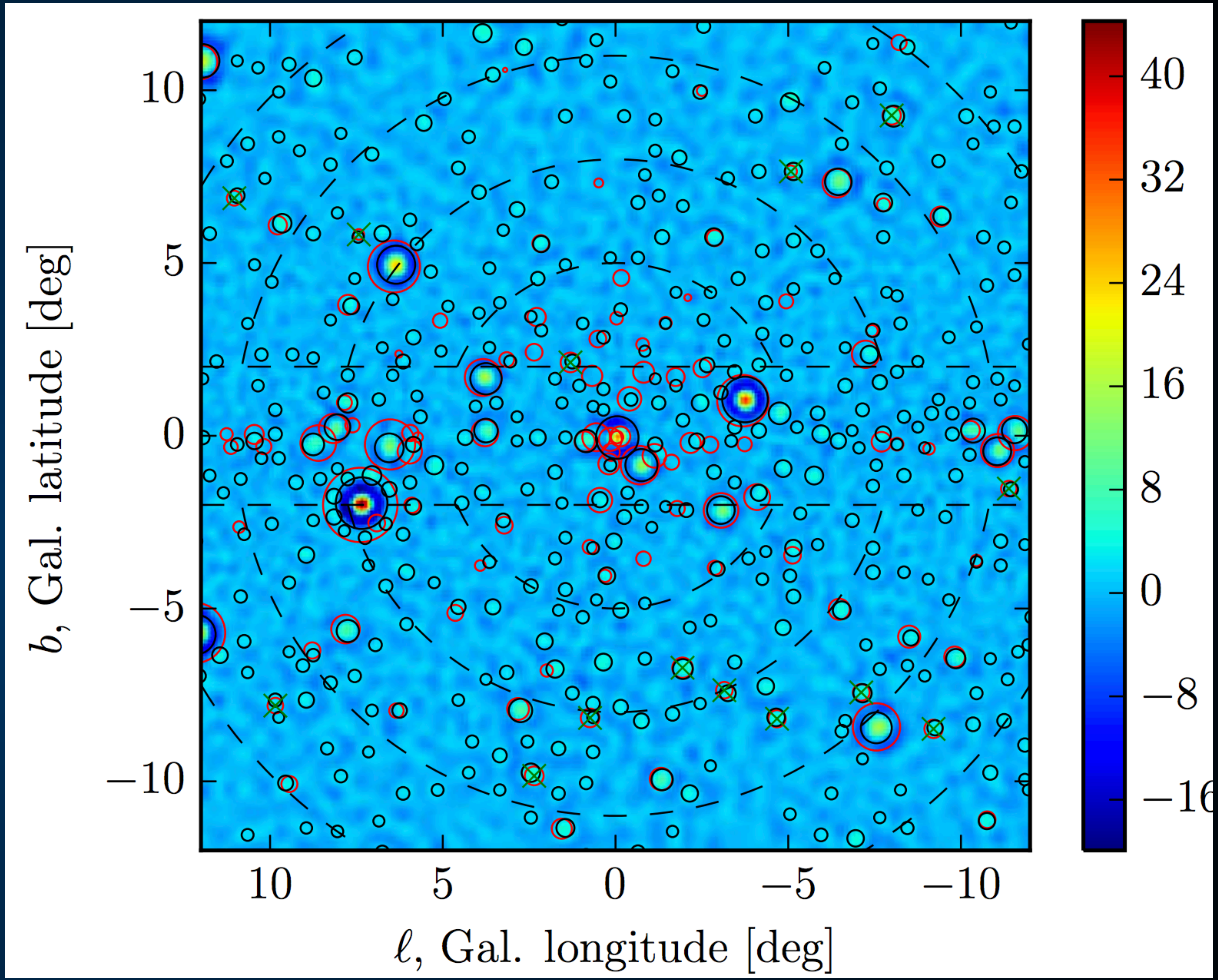
Spherically Symmetric *Expected from Dark Matter*

Spatially Extended *to nearly 15 degrees from Galactic center.*

Detections! - The Galactic Center Excess

Bartels et al. (2015; 1506.05104)
Lee et al. (2015; 1506.05124)





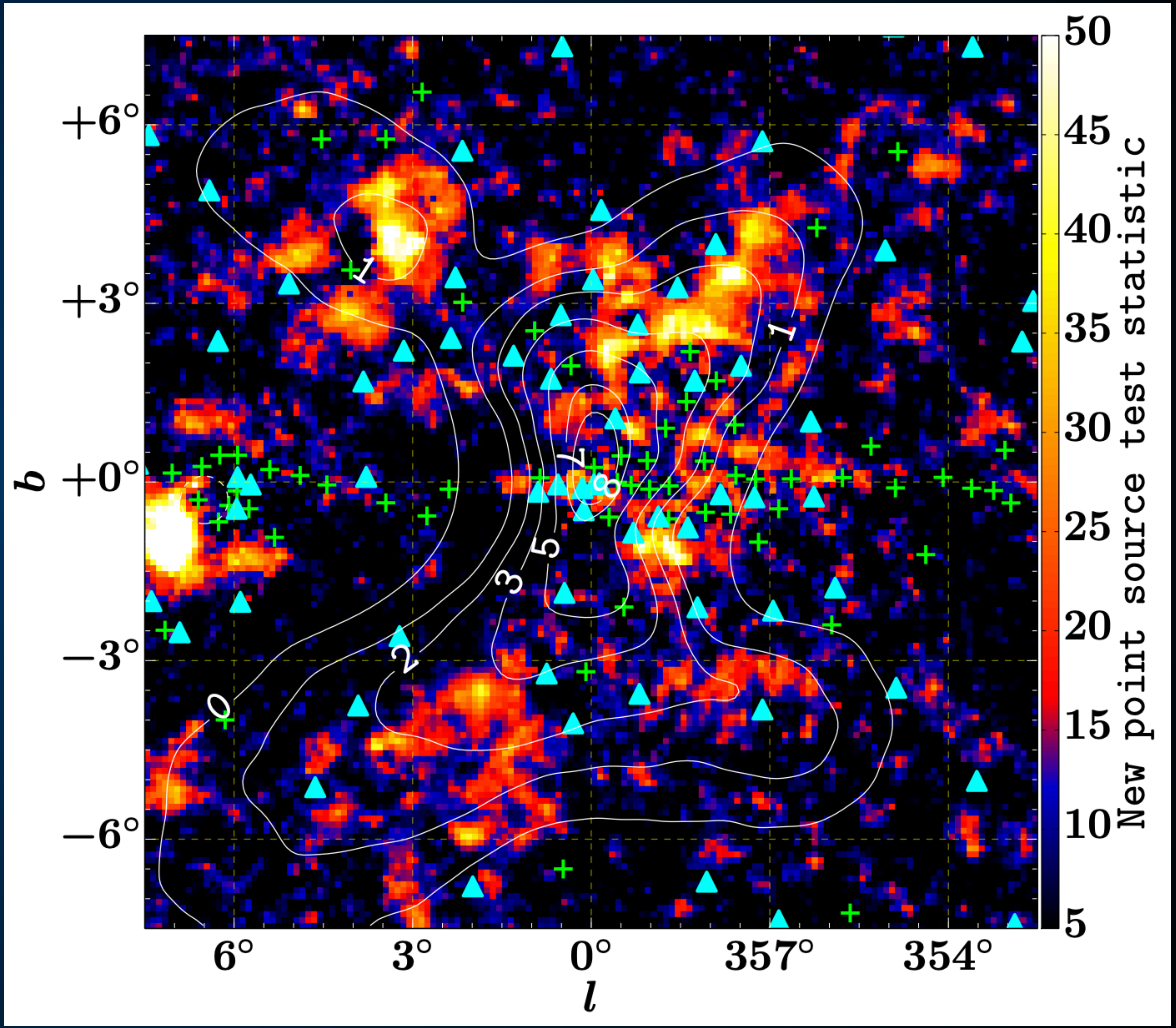
Tentative evidence of sub-threshold fluctuations in the Fermi-LAT data point to pulsar interpretations.

Detections! - The Galactic Center Excess

Macias et al. (2018; 1611.06644)

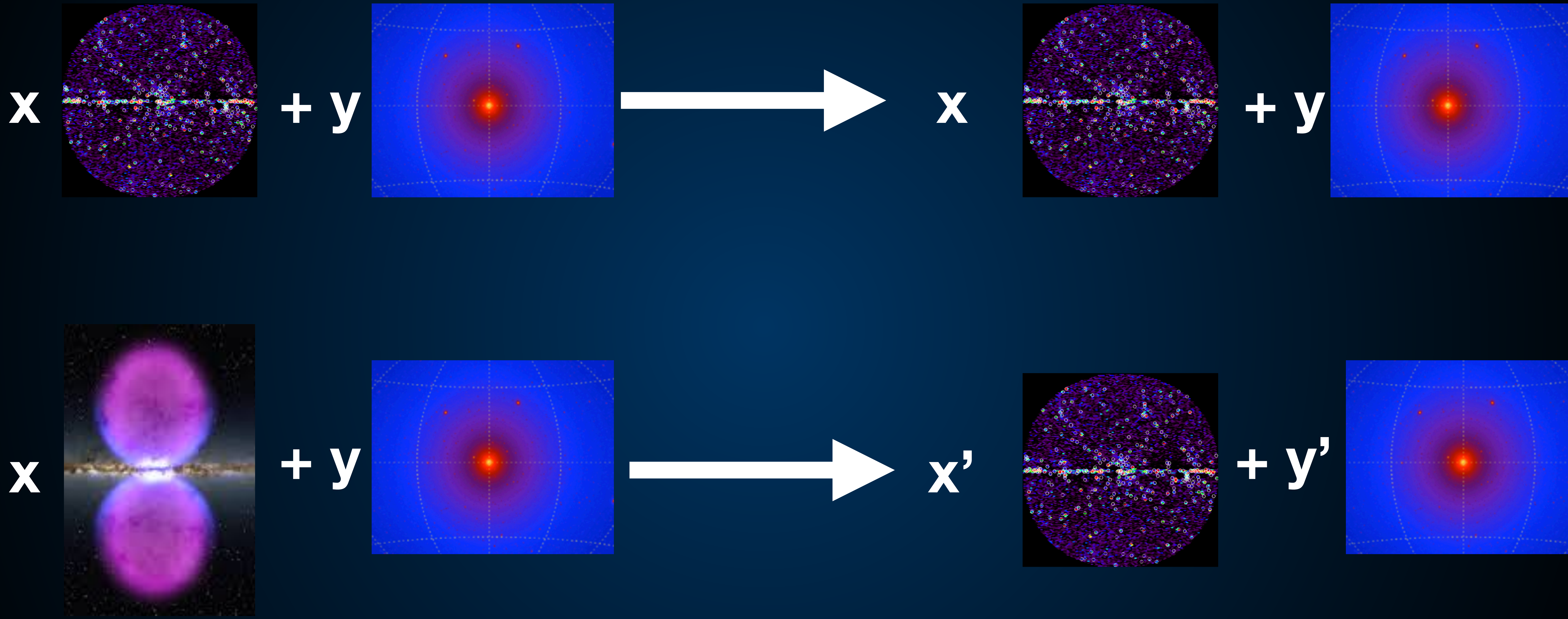
Some evidence that the global distribution of the excess more closely resembles the bulge

Both models of X-shaped, and box-shaped bulges have been advocated in multi-wavelength literature.



Detections! - The Galactic Center Excess

Leane & Slatyer (2019; 1904.08430)



If the point-source model is wrong, then point sources can be found even if they do not exist.

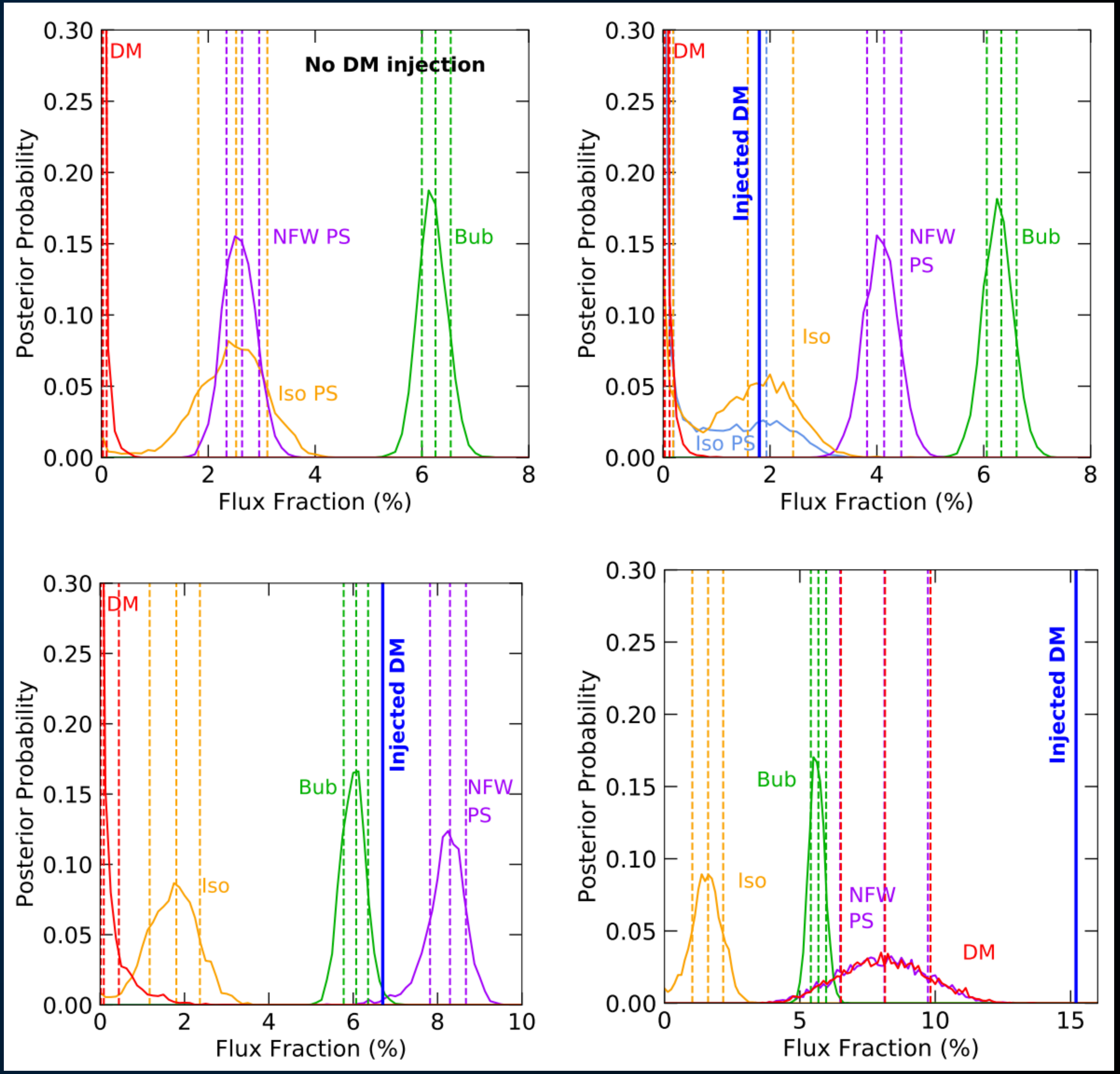
Detections! - The Galactic Center Excess

Leane & Slatyer (2019; 1904.08430)

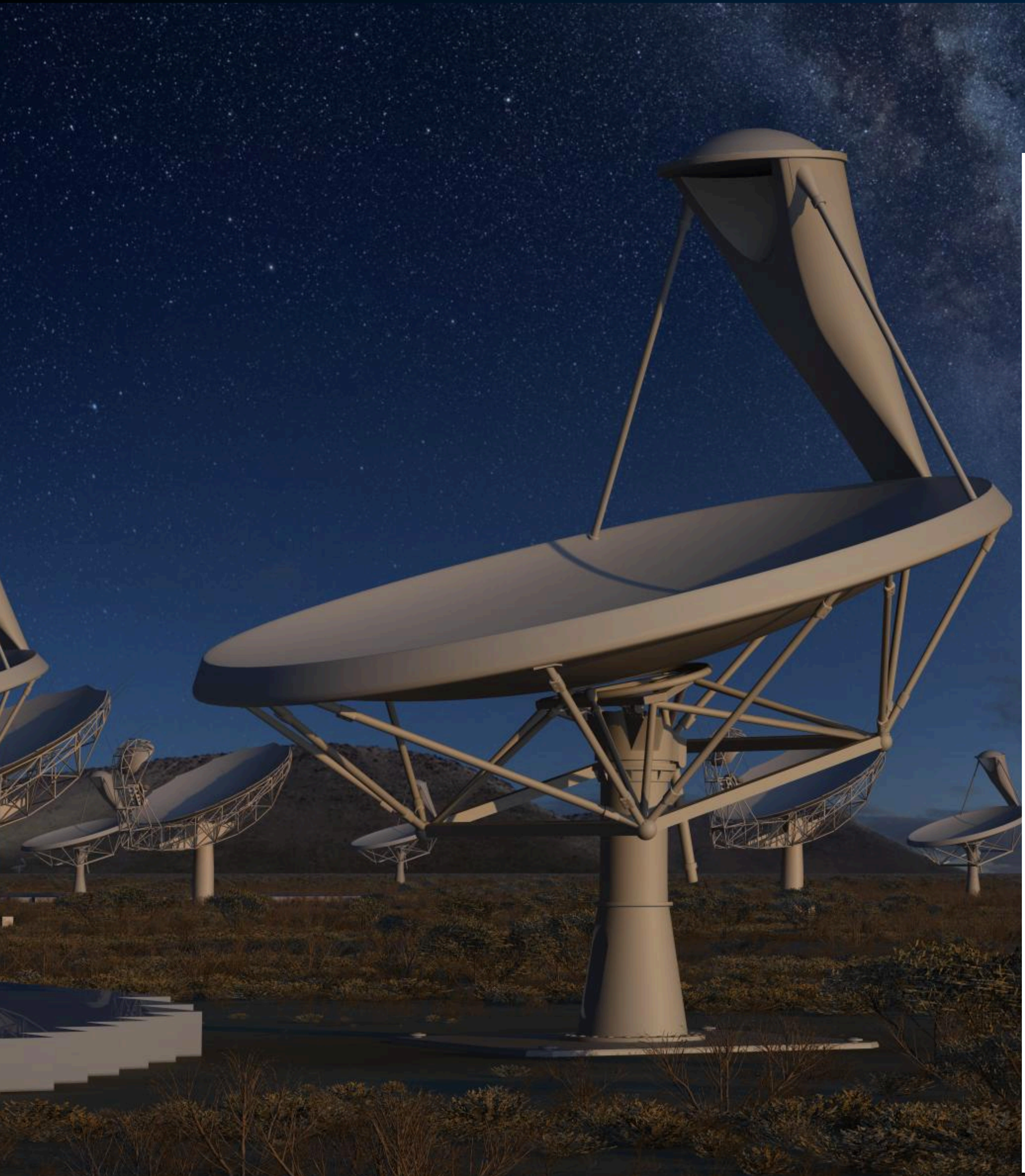
Can Try This in Real Data:

Take Fermi-LAT data, inject a smooth dark matter distribution.

Can you recover what you inject?



The Future: Square Kilometer Array



1512.06825v2 [astro-ph.HE] 12 Sep 2016

RADIO DETECTION PROSPECTS FOR A BULGE POPULATION OF MILLISECOND PULSARS AS SUGGESTED BY FERMI LAT OBSERVATIONS OF THE INNER GALAXY

F. Calore[1,†], M. Di Mauro[2], F. Donato[3,4], J.W.T. Hessels[5,6], C. Weniger[1,‡]

[1]GRAPPA Institute, University of Amsterdam, Science Park 904, 1090 GL Amsterdam, Netherlands
[2] Department of Physics and SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, USA
[3]Physics Department, Torino University, via Giuria 1, 10125 Torino, Italy
[4]Istituto Nazionale di Fisica Nucleare, Sezione di Torino, via Giuria 1, 10125 Torino, Italy
[5] ASTRON, the Netherlands Institute for Radio Astronomy, Postbus 2, 7990 AA, Dwingeloo, The Netherlands
[6] Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands

Draft version September 13, 2016

ABSTRACT

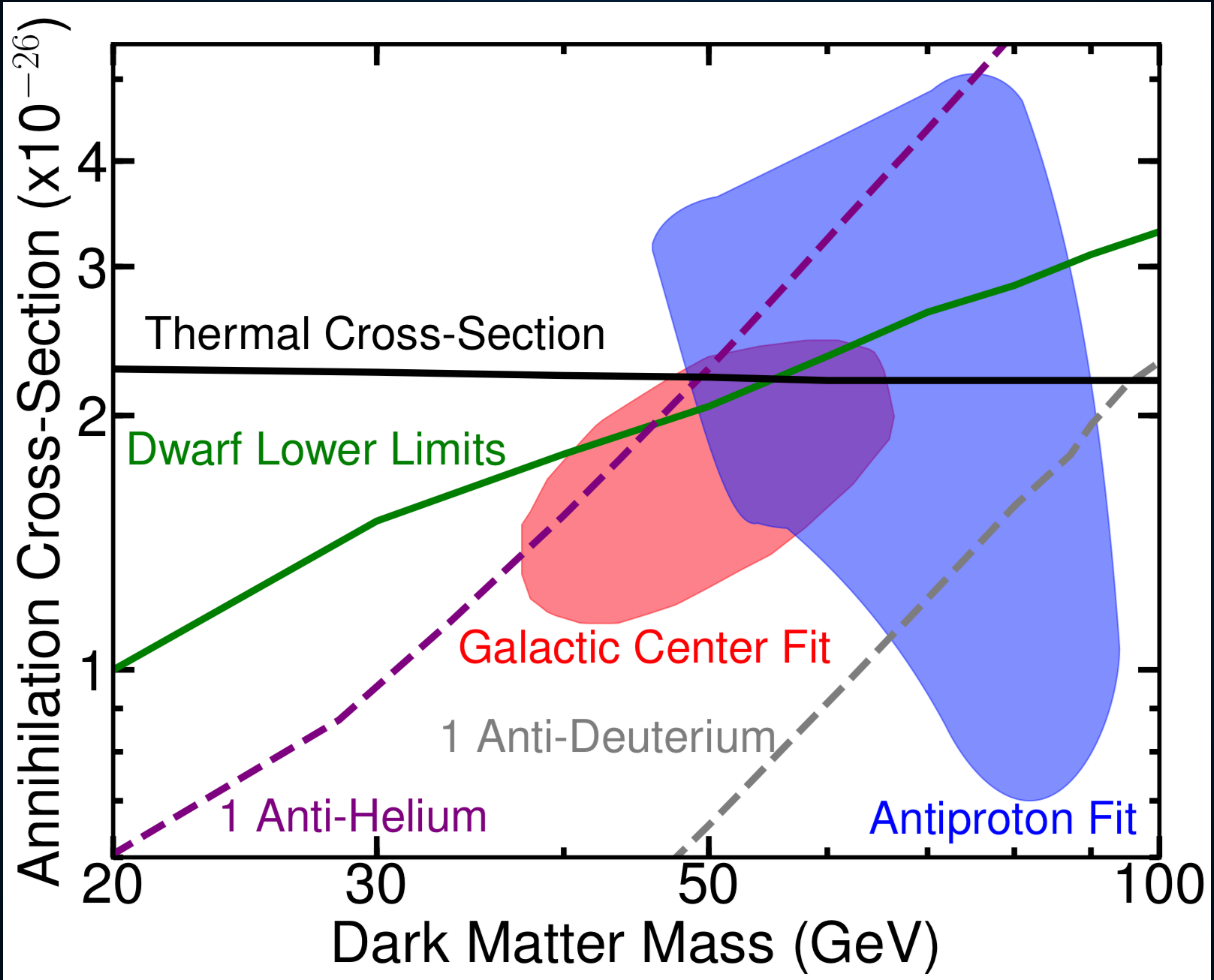
The dense stellar environment of the Galactic center has been proposed to host a large population of as-yet undetected millisecond pulsars (MSPs). Recently, this hypothesis has found support in an analysis of gamma rays detected with the Large Area Telescope onboard the *Fermi* satellite, which revealed an excess of diffuse GeV photons in the inner 15 deg about the Galactic center. The excess can be interpreted as the collective emission of thousands of MSPs in the Galactic bulge, with a spherical distribution strongly peaked towards the Galactic center. In order to fully establish the MSP interpretation, it is essential to find corroborating evidence in multi-wavelength searches, most notably through the detection of radio pulsations from individual bulge MSPs. Based on globular cluster observations and gamma-ray emission from the inner Galaxy, we investigate the prospects for detecting MSPs in the Galactic bulge. While previous pulsar surveys failed to identify this population, we demonstrate that upcoming large-area surveys of this region should lead to the detection of dozens of bulge MSPs. Additionally, we show that deep targeted searches of unassociated *Fermi* sources should be able to detect the first few MSPs in the bulge. The prospects for these deep searches are enhanced by a tentative gamma-ray/radio correlation that we infer from high-latitude gamma-ray MSPs. Such detections would constitute the first clear discoveries of field MSPs in the Galactic bulge, with far-reaching implications for gamma-ray observations, the formation history of the central Milky Way and strategy optimization for future deep radio pulsar surveys.

1. INTRODUCTION

Millisecond pulsars (MSPs) are rapidly spinning neutron stars that produce observable pulsations (mostly in radio, but often also in gamma-rays, and occasionally in X-rays), have short spin periods and low surface magnetic fields (compared to other pulsars) that are loosely in the range $P \leq 30\,\mathrm{ms}$ and $B \leq 10^9\,\mathrm{G}$. MSPs are believed to originate from pulsars in binary systems, in which the companion star transfers material to the pulsar, reducing its magnetic field and increasing its angular momentum. During the accretion phase, and for

ing with the surrounding medium, might be responsible for non-pulsed X-ray emission through synchrotron radiation (Chevalier 2000; Cheng et al. 2004) and for TeV photons through inverse Compton scattering Aharonian et al. (1997). The detailed timing of the multi-wavelength emission provides useful information to study emission models (*e.g.* Kalapotharakos et al. 2014).

About 370 MSPs are currently known at radio frequencies: 237 of them are field MSPs in the Galactic disk,[1] and 133 (with $P \leq 30\,\mathrm{ms}$) are associated with 28 different globular clusters.[2] Historically, the first ~ 35



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Antiproton Fit
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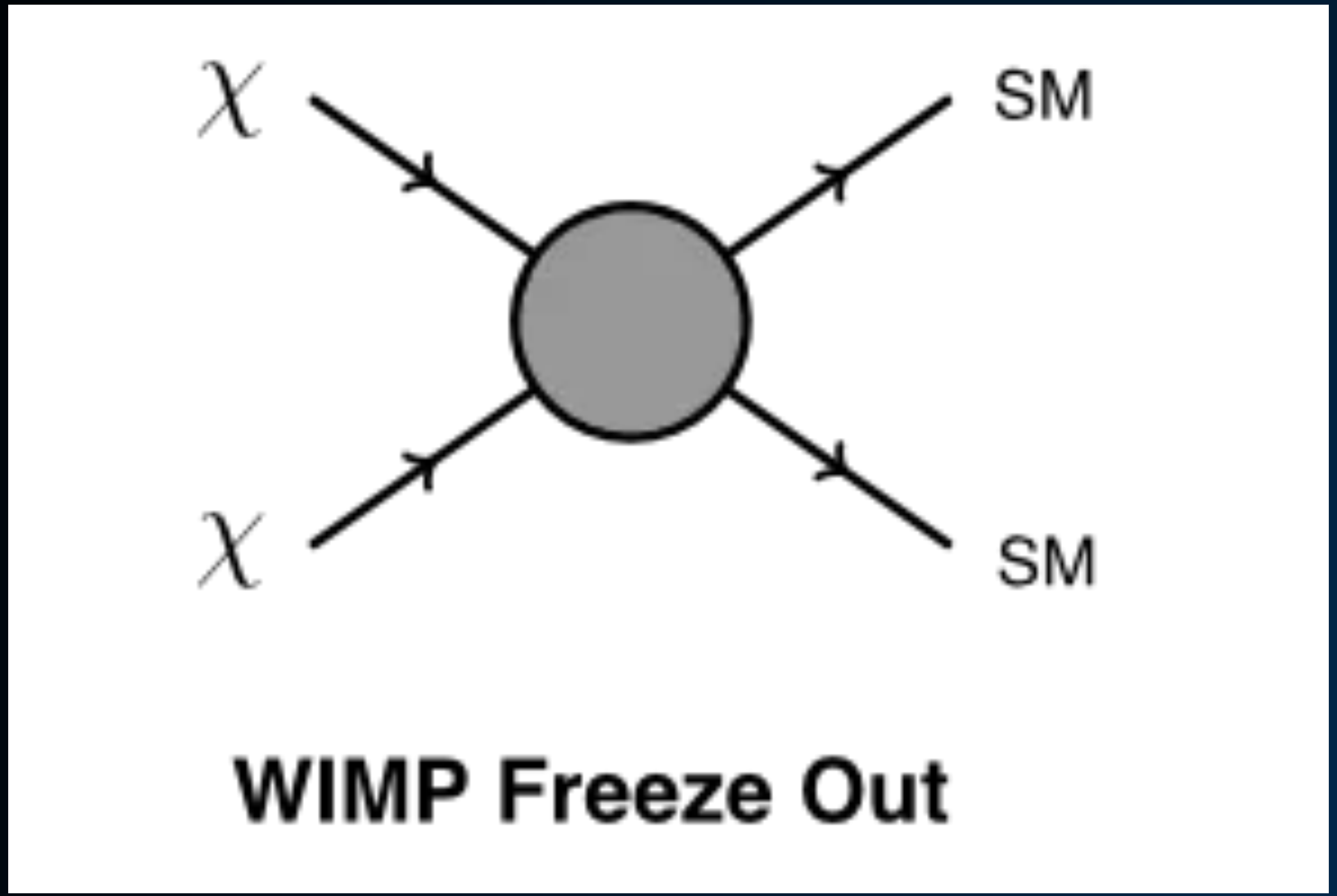
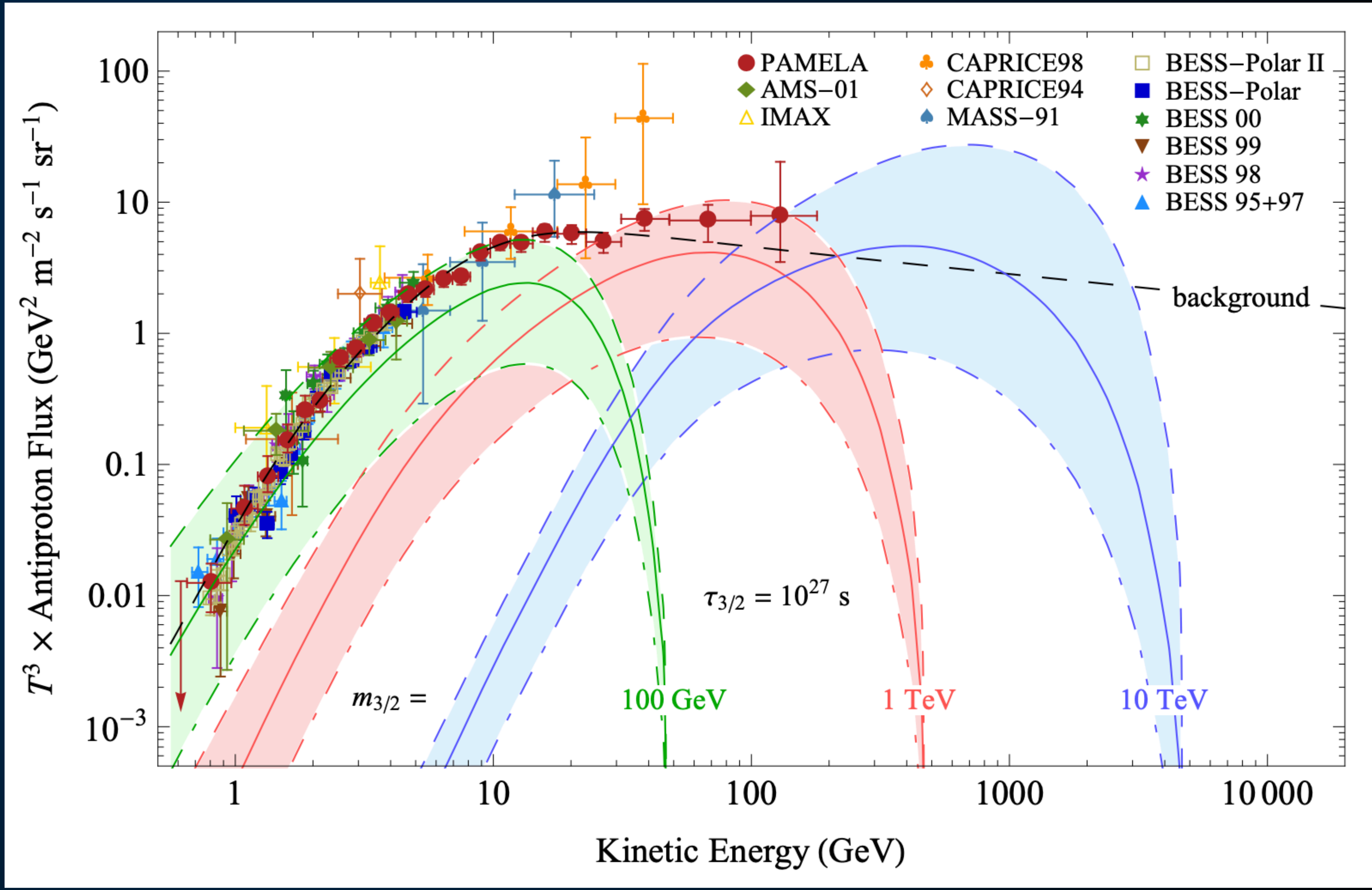
Dark Matter Mass (GeV)

Detecting Dark Matter with Antiprotons

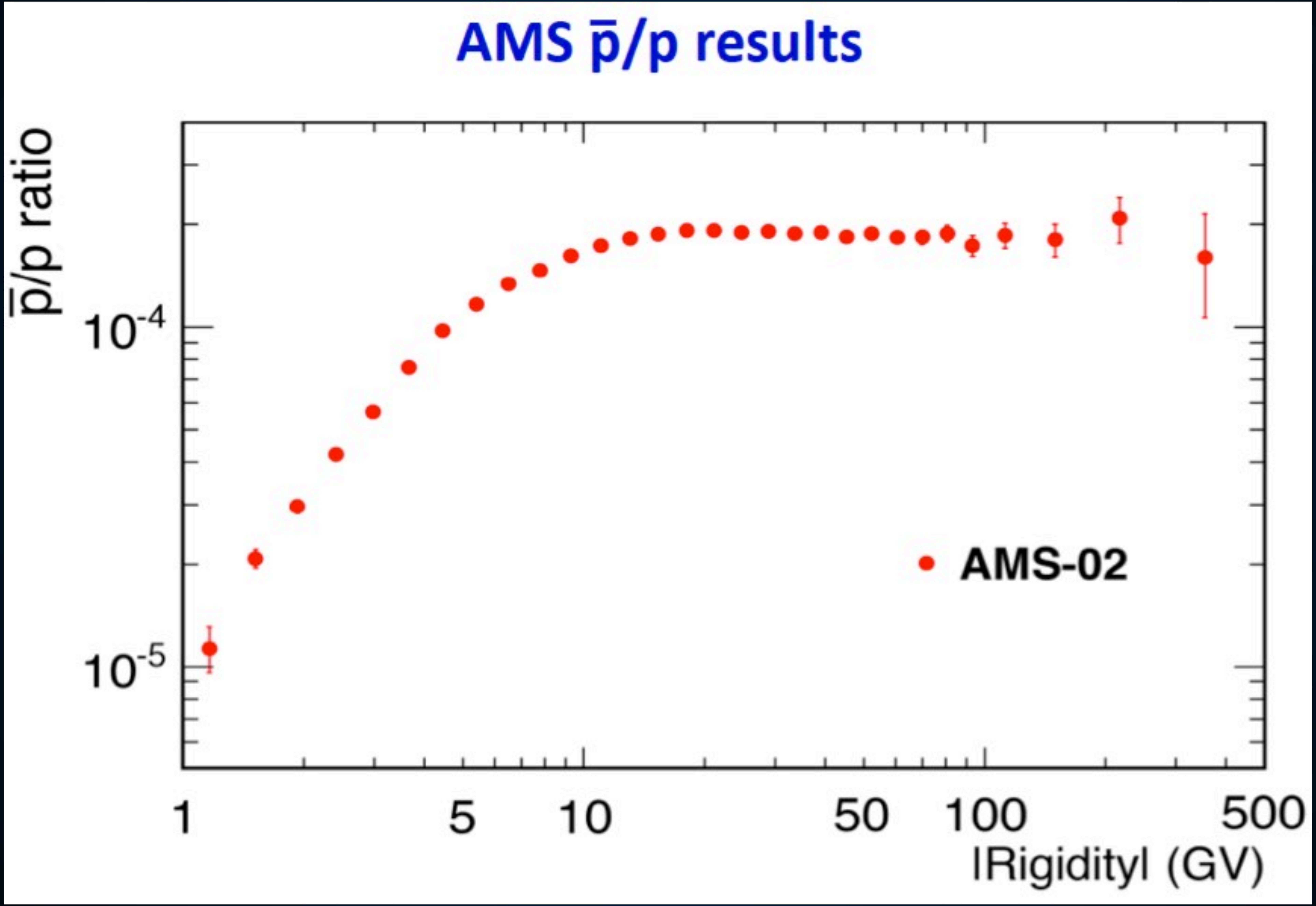
Grefe (2012; 1111.7117)



Exploiting the fact that the universe is mostly matter!

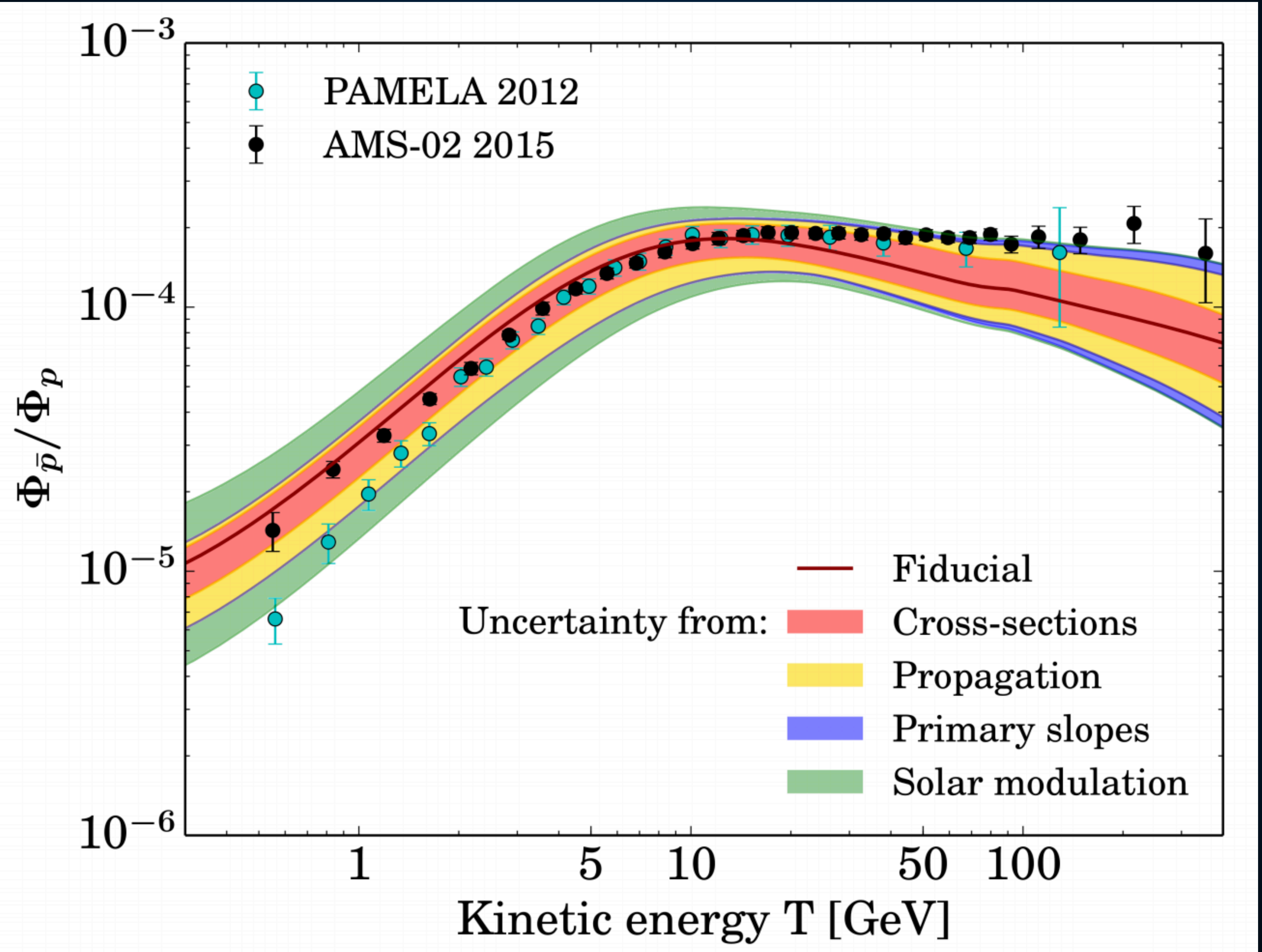


Antiprotons



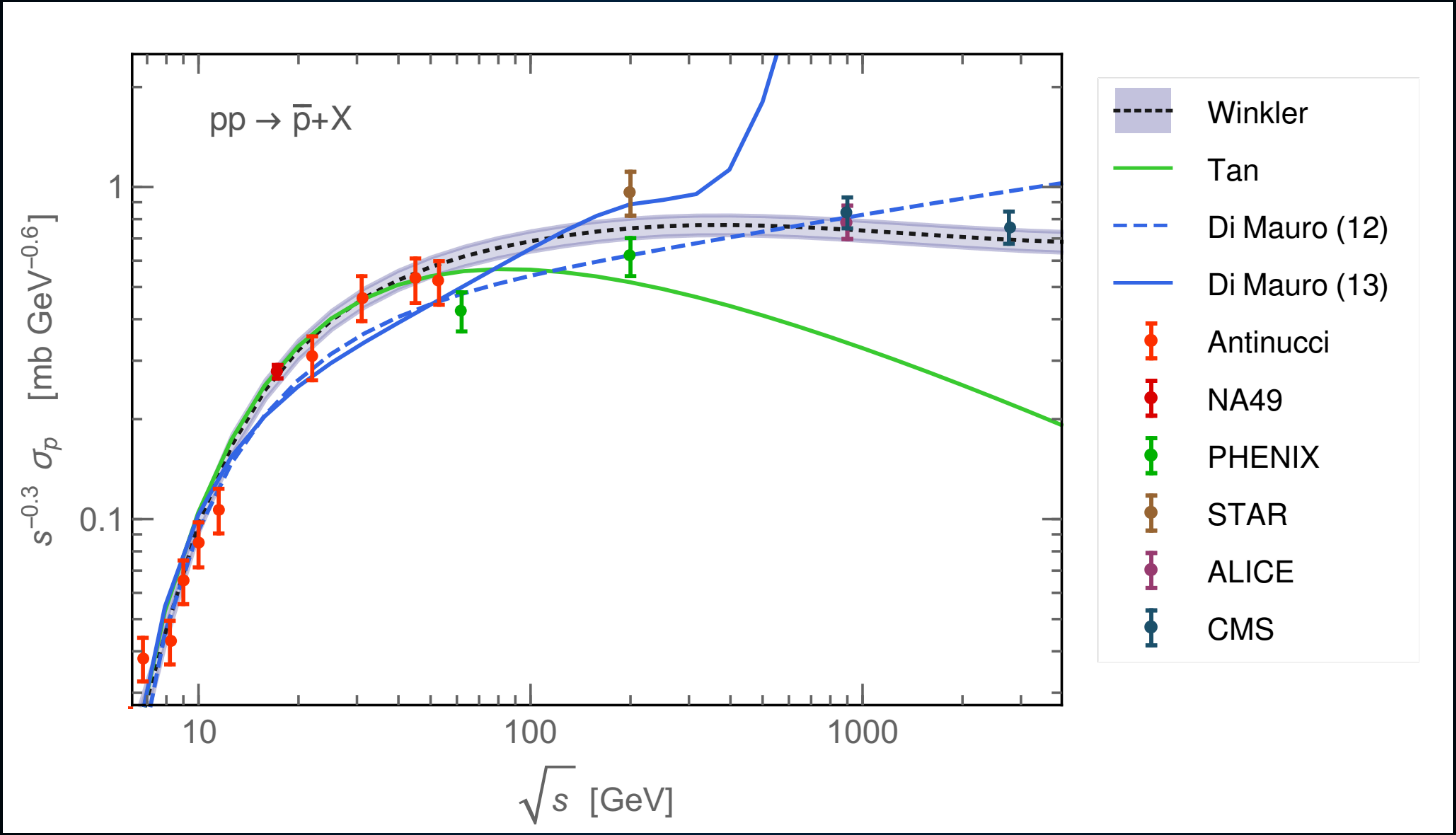
Antiprotons

Giesen et al. (2015; 1504.04276)



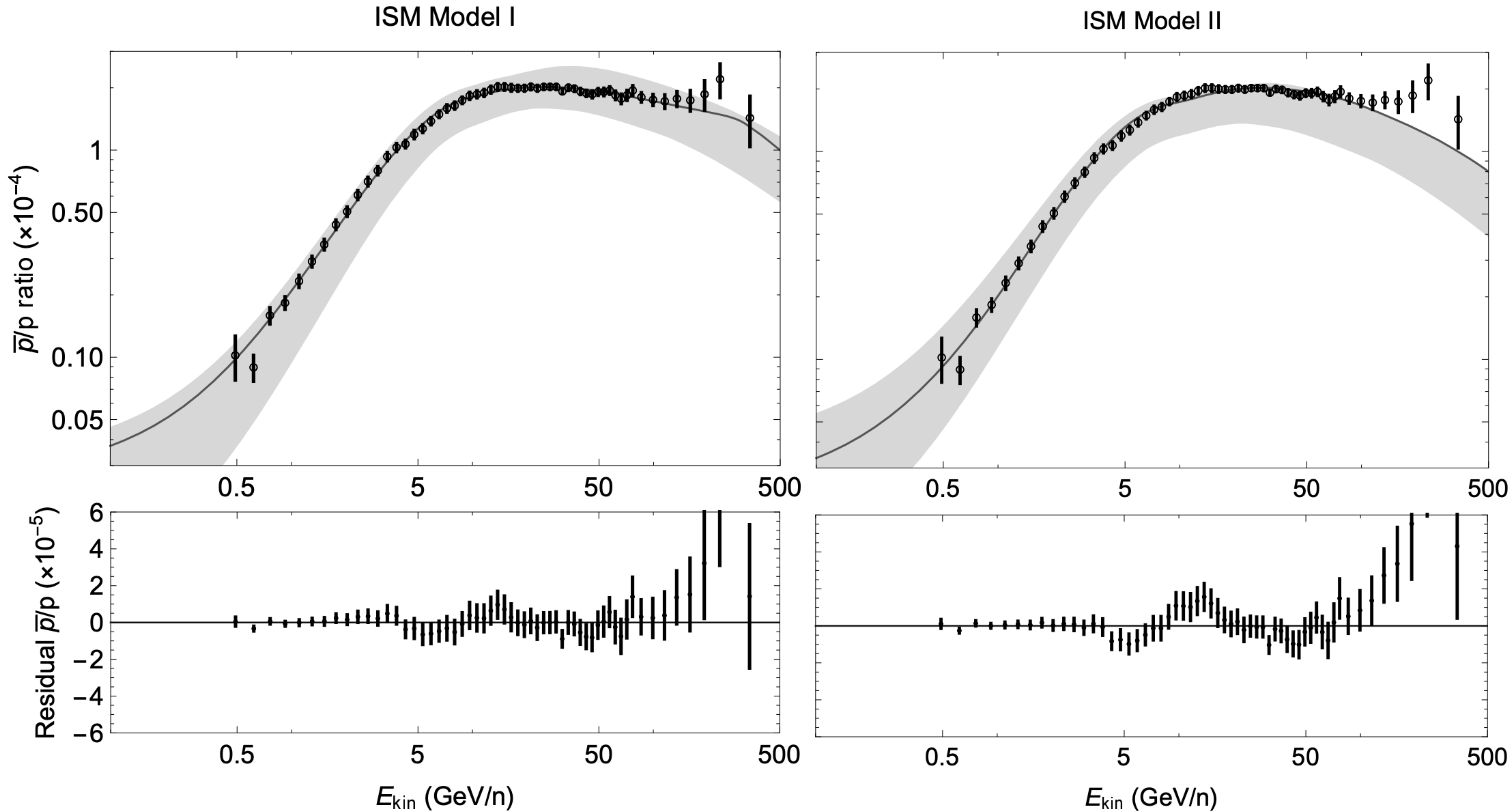
Antiprotons

Reinert & Winkler (2017; 1712.00002)



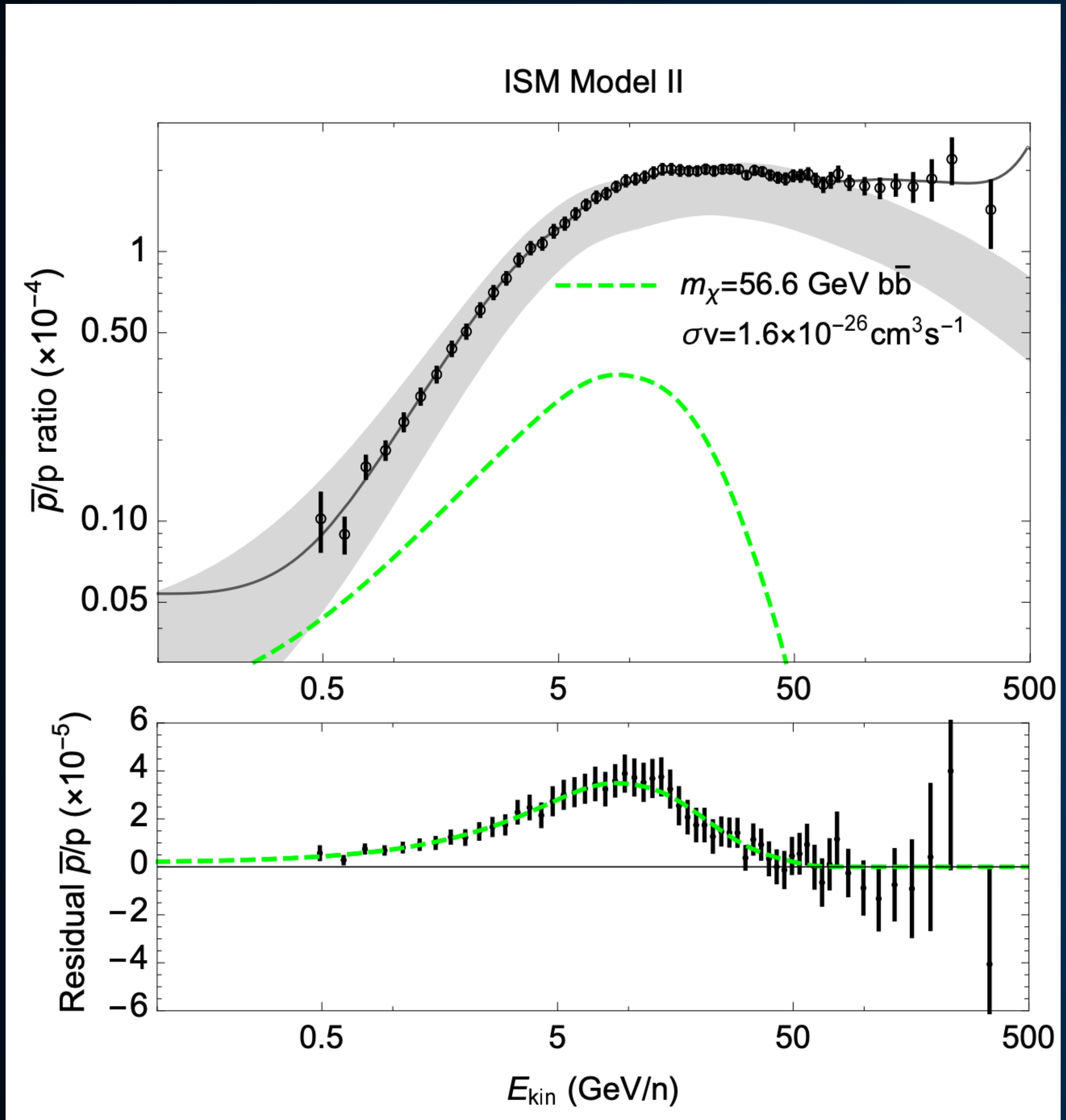
Antiprotons

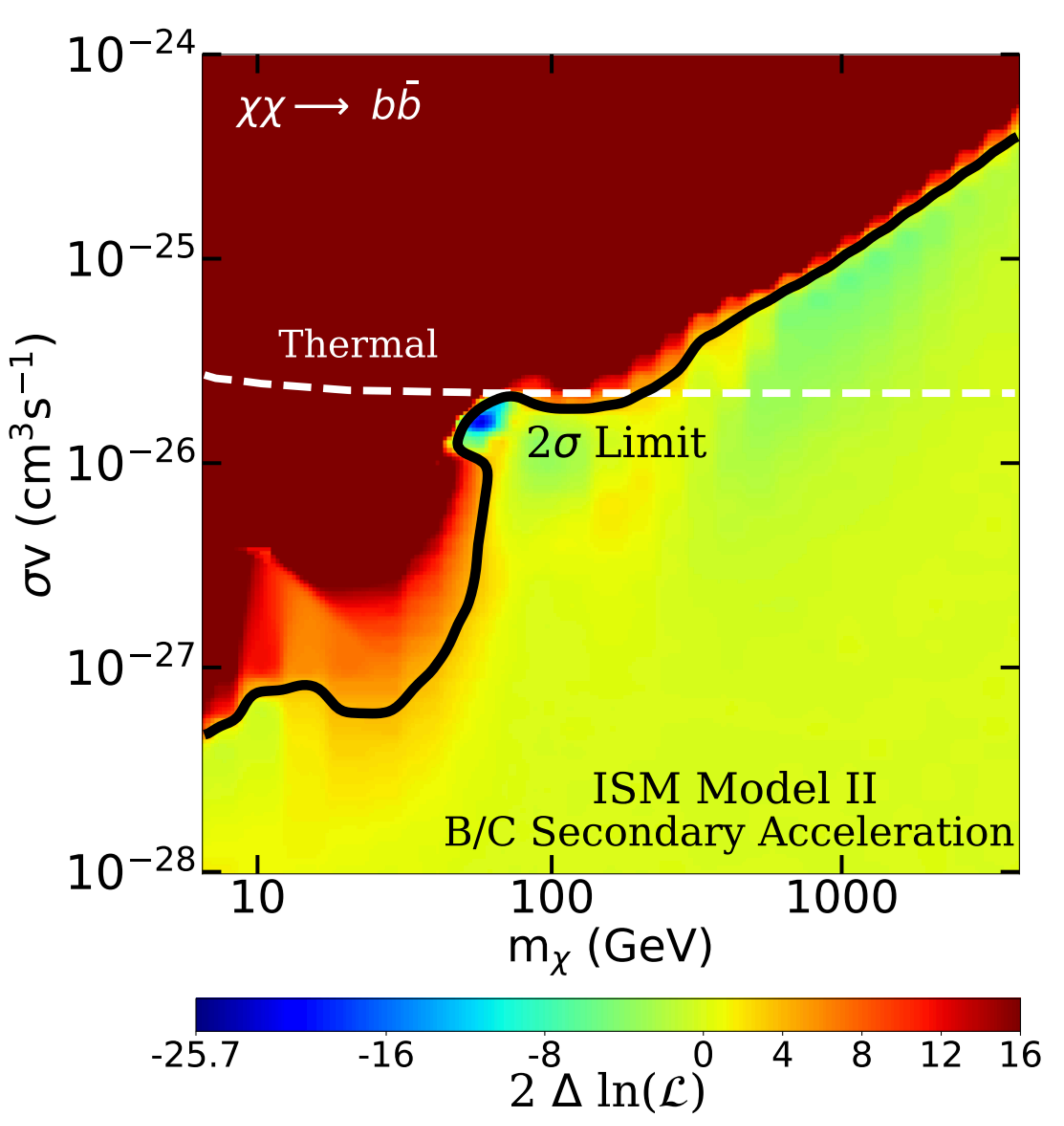
Cholis, Linden, Hooper (2019; 1903.02549)



Antiprotons

Cholis, Linden, Hooper (2019; 1903.02549)

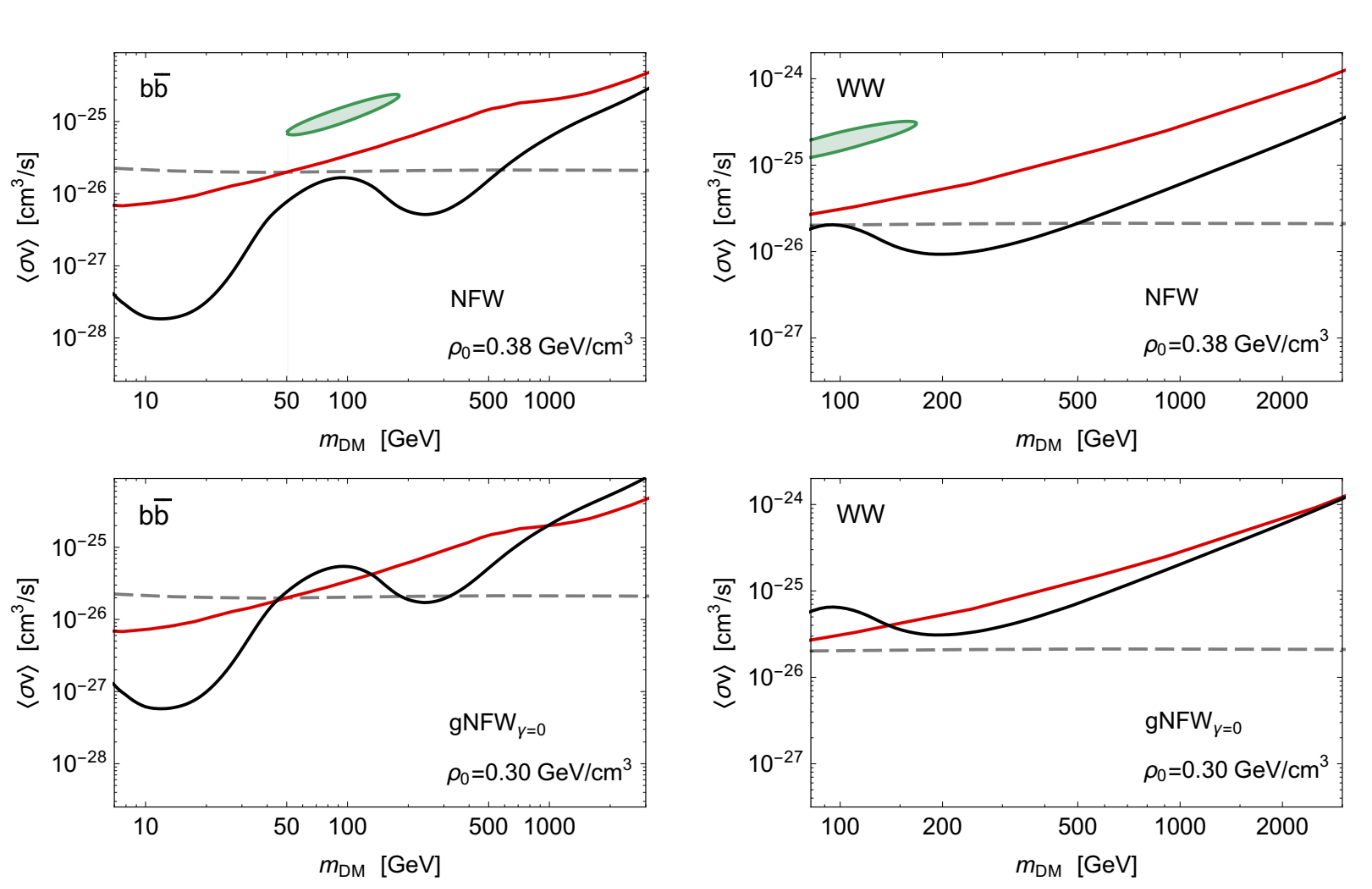




$$N_{CS}(E_{\rm kin}) = a + b\,\ln\left(\frac{E_{\rm kin}}{\rm GeV}\right) + c\left[\ln\left(\frac{E_{\rm kin}}{\rm GeV}\right)\right]^2.$$

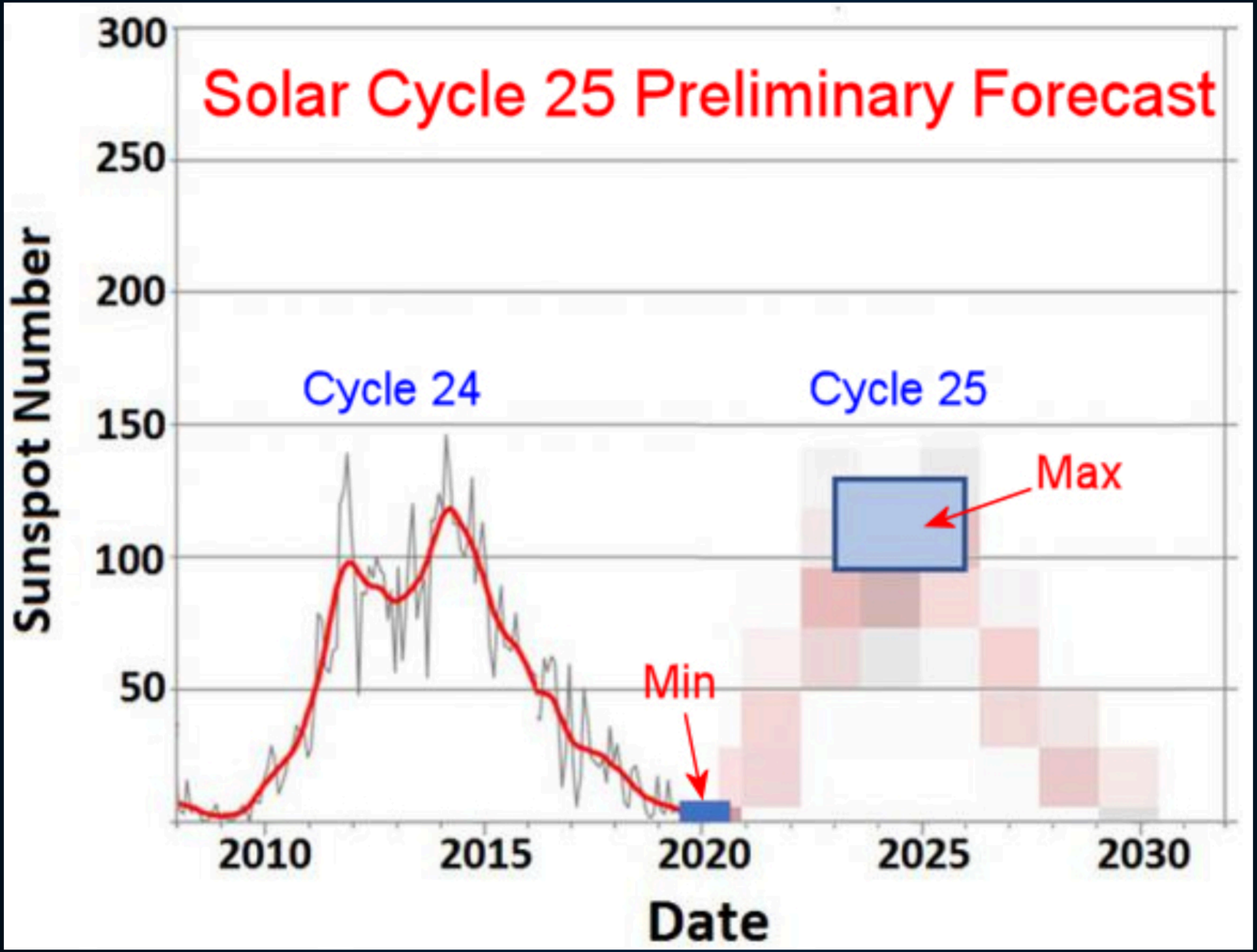
Antiprotons

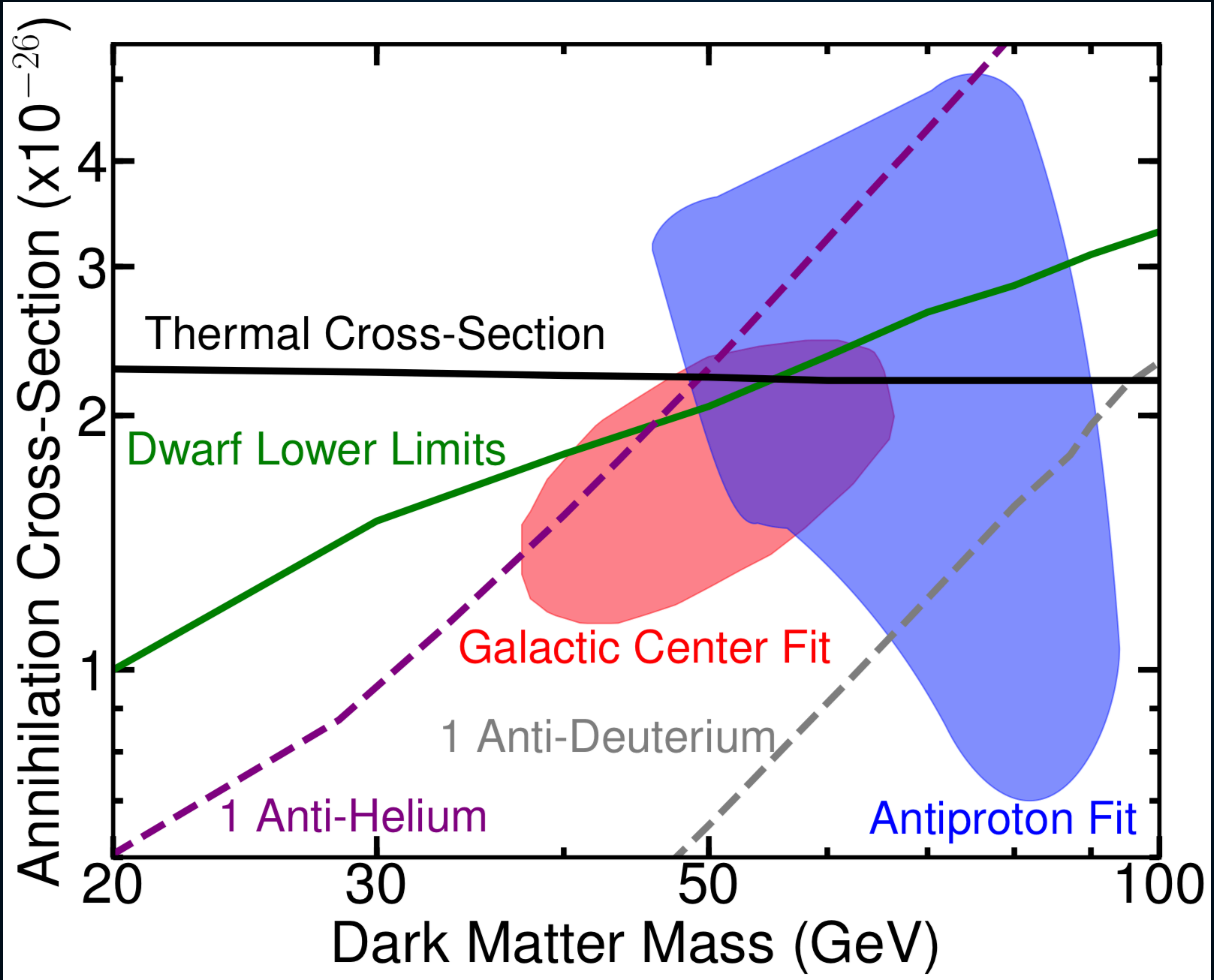
Reinert & Winkler (2017; 1712.00002)



Future Data is Coming

Future Data is Coming

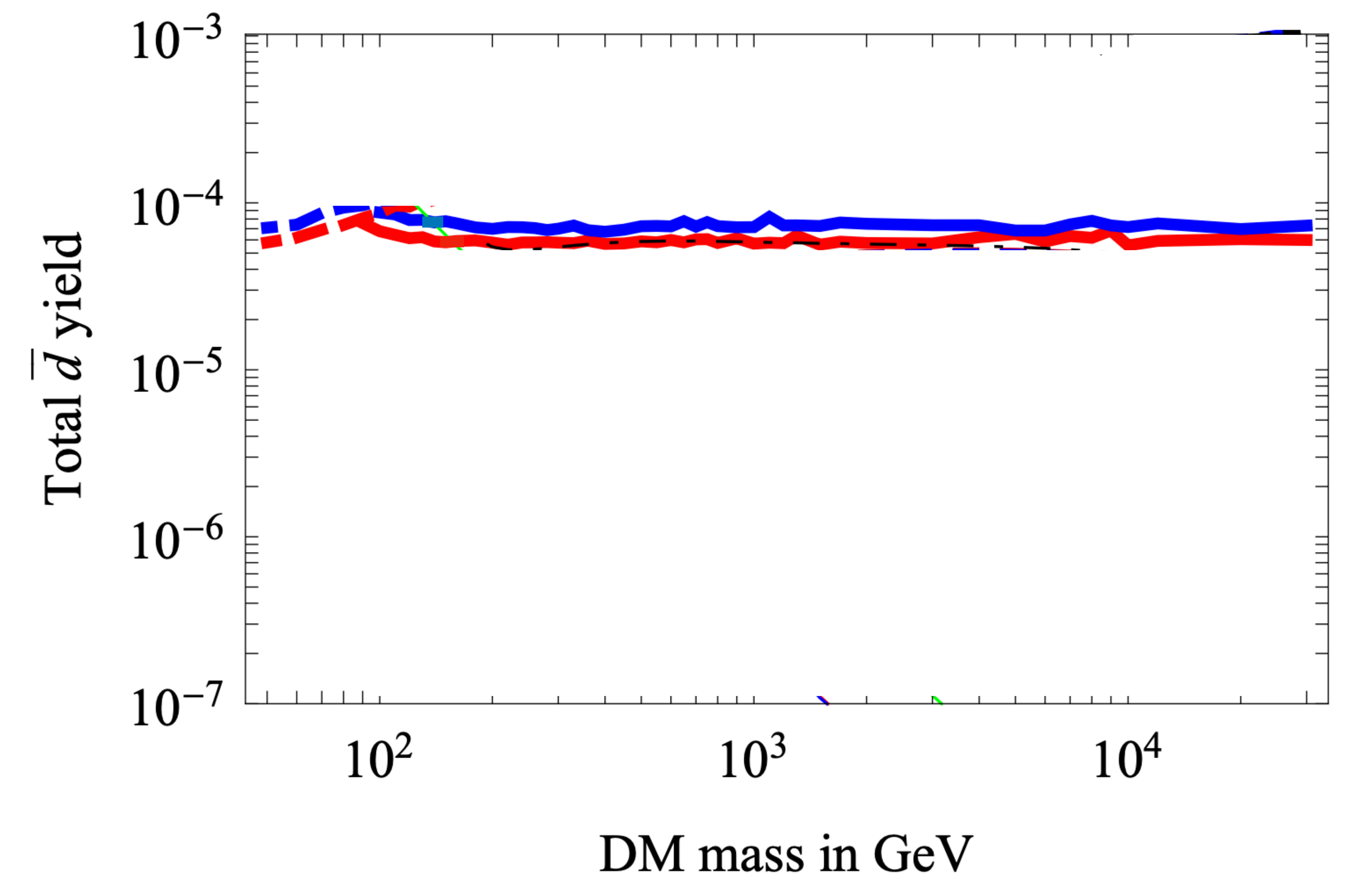




Annihilation Cross-Section (x10^{-26})
4
3
2
1
Thermal Cross-Section
Dwarf Lower Limits
Galactic Center Fit
1 Anti-Deuterium
1 Anti-Helium
Antiproton Fit
20
30
50
100
Dark Matter Mass (GeV)

Anti-Deuterium

$$p + p \longrightarrow p + p + p + \bar{p} + n + \bar{n}$$

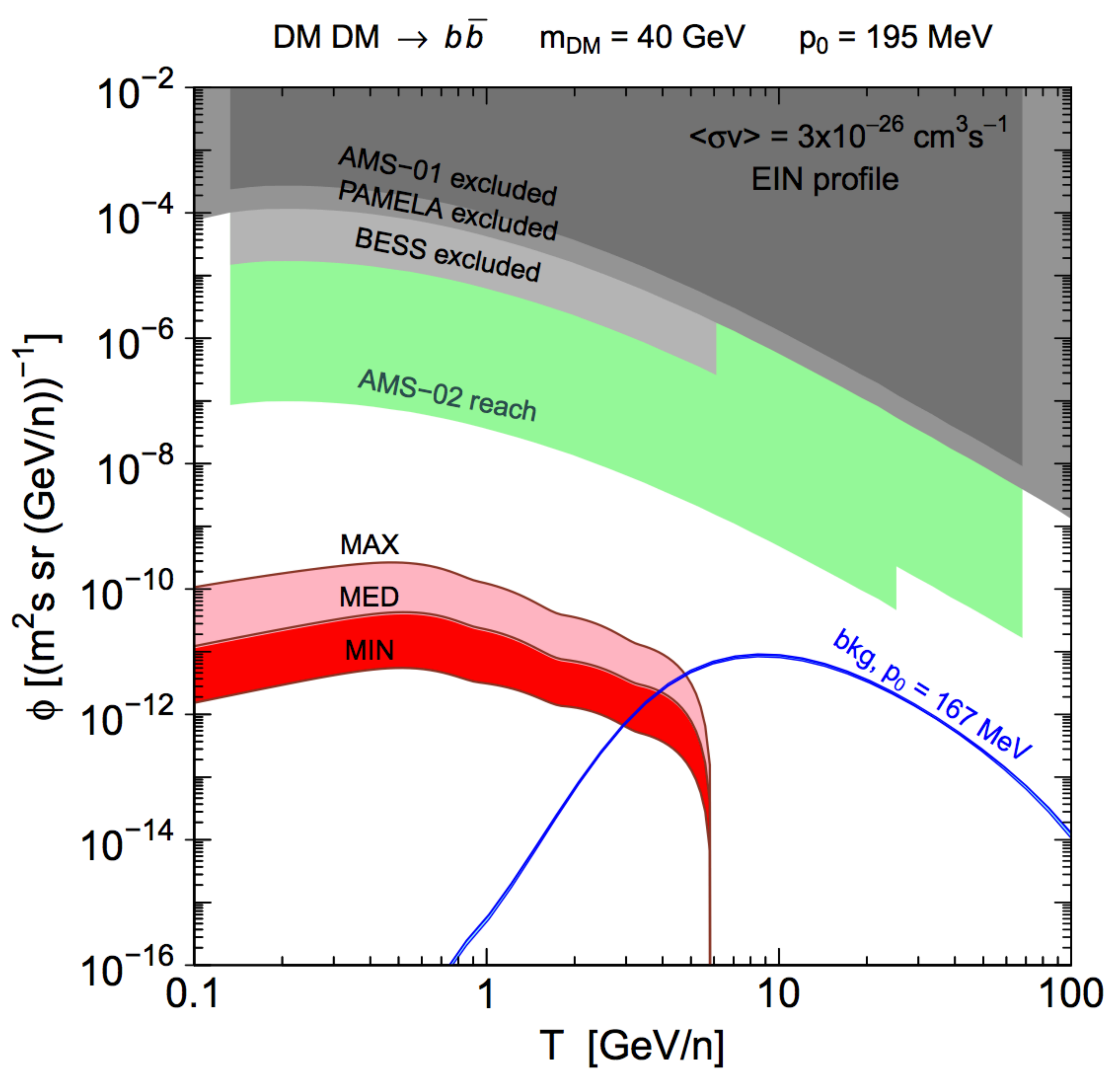


10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
<σv> (cm^3 s^{-1})
Thermal Annihilation Cross-Section
Produces 1 observed photon from the Galactic Center
10^1
10^2
10^3
10^4
10^5
Dark Matter Mass (GeV)

Anti-Deuterium

$$\chi + \chi \longrightarrow p + \bar{p} + n + \bar{n}$$

- **Dark matter annihilation occurs in the lab frame.**
- **Dark matter signal dominate at low energies.**
- **Energies can't change due to propagation!**

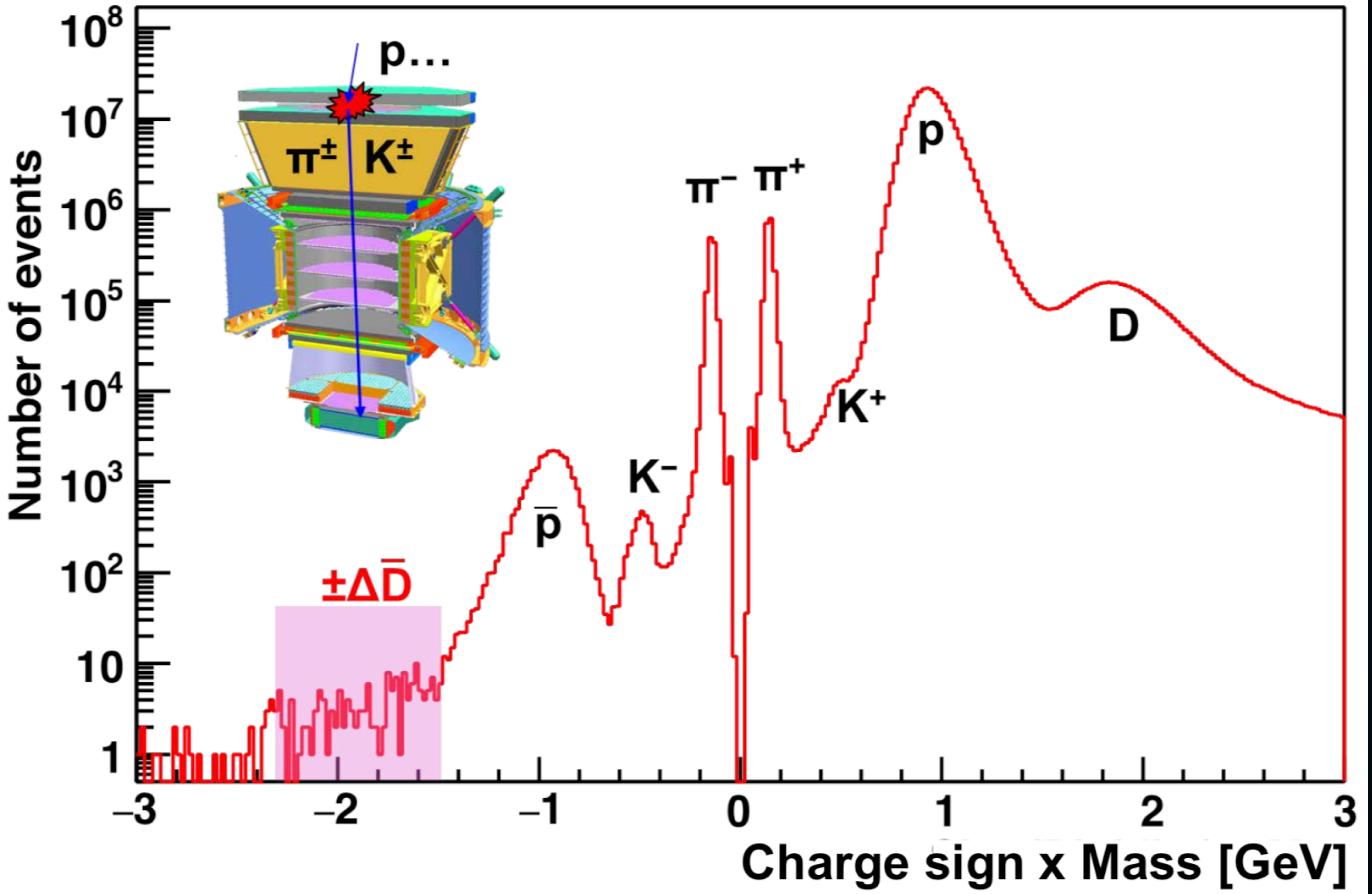


Cirelli et al. (1401.4017)

To date, we have observed eight events in the mass region from 0 to 10 GeV with $Z = -2$. All eight events are in the helium mass region.

Currently (having used 50 million core hours to generate 7 times more simulated events than measured events and having found no background events from the simulation), our best evaluation of the probability of the background origin for the eight $\overline{He}$ events is less than 3×10^{-8}. For the two $^{4}\overline{He}$ events our best evaluation of the probability (upon completion of the current 100 million core hours of simulation) will be less than 3×10^{-3}.

Note that for $^{4}\overline{He}$, projecting based on the statistics we have today, by using an additional 400 million core hours for simulation the background probability would be 10^{-4}. Simultaneously, continuing to run until 2023, which doubles the data sample, the background probability for $^{4}\overline{He}$ would be 2×10^{-7}, i.e., greater than 5-sigma significance.

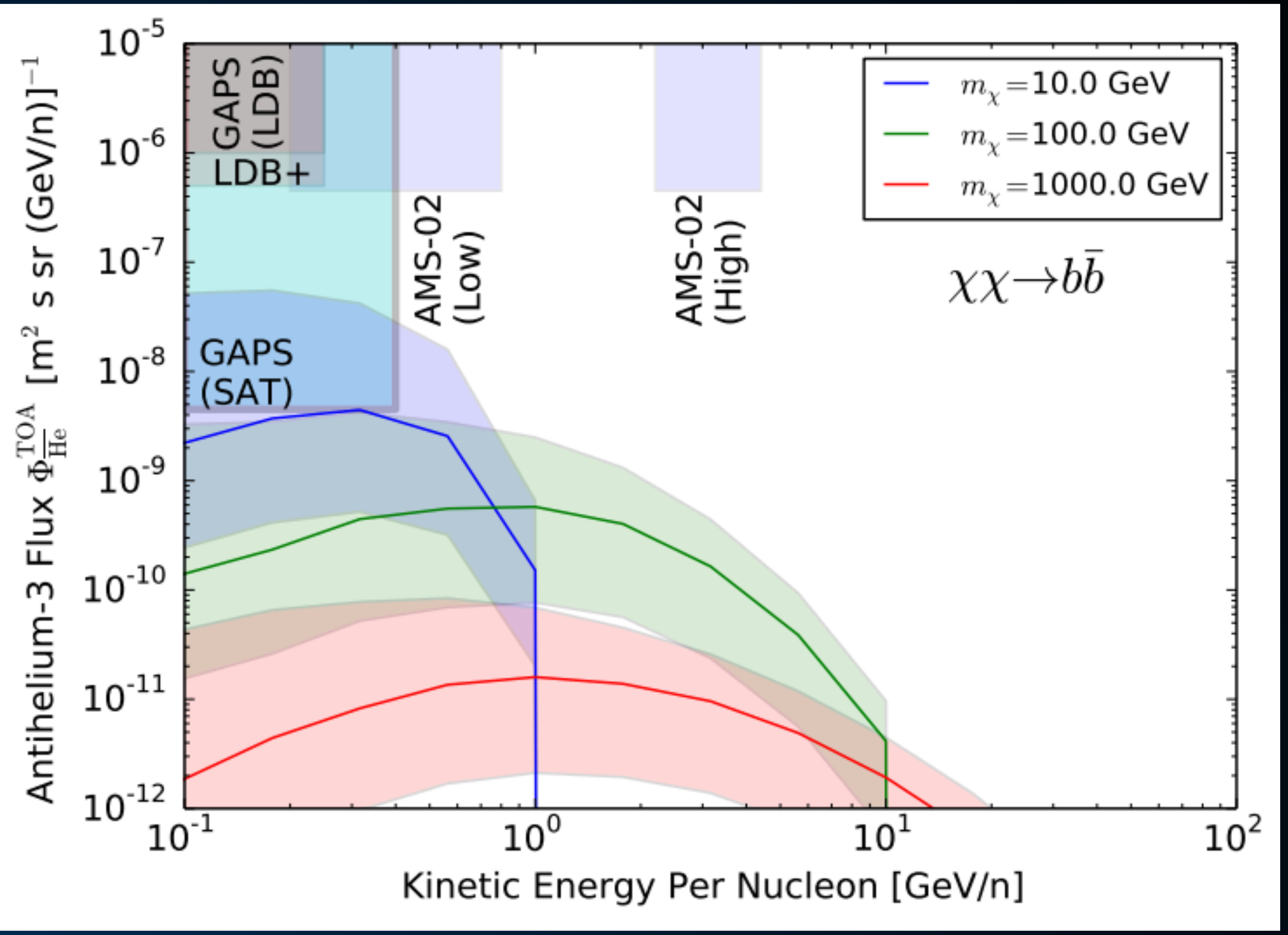


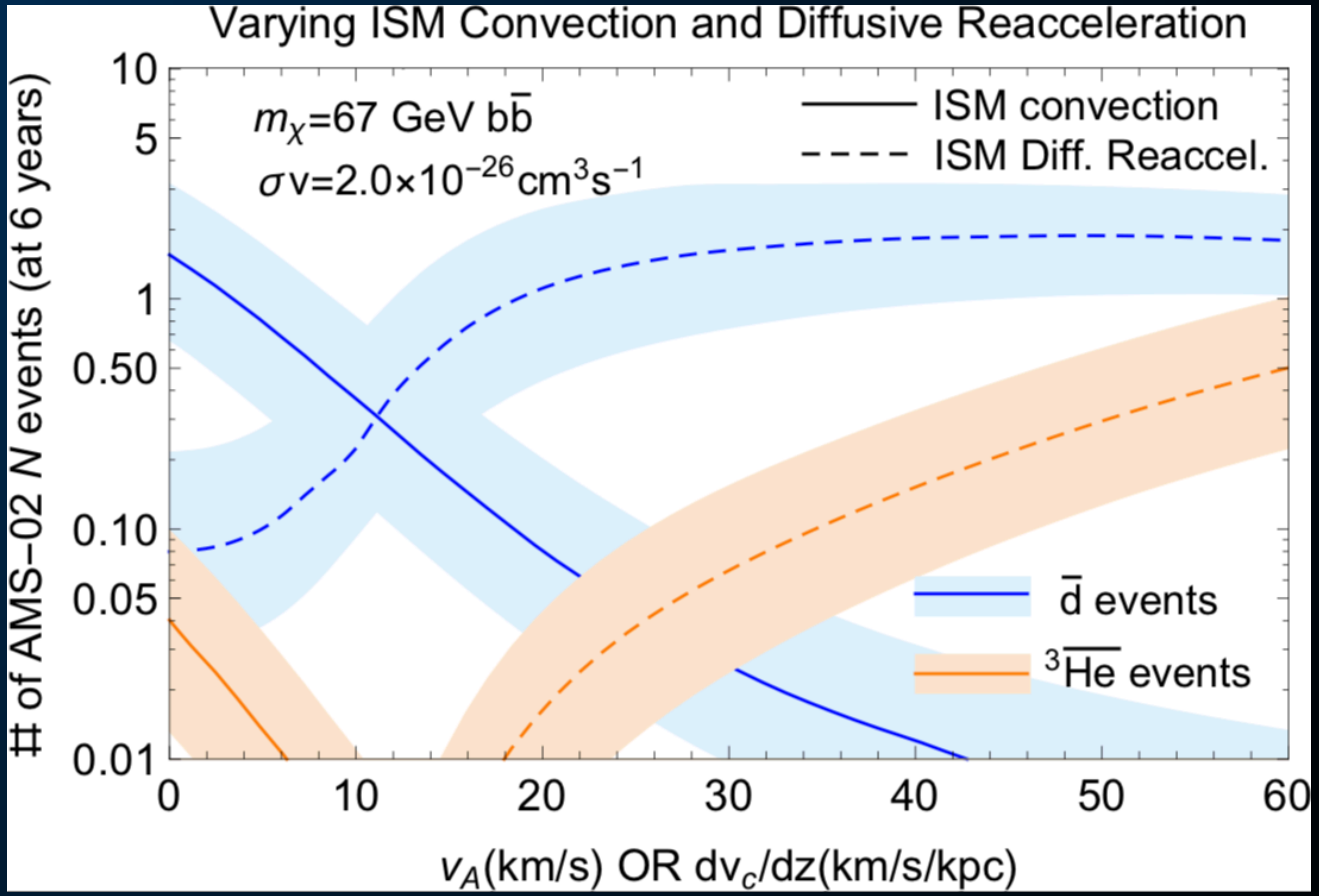
Number of events
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
p…
$\pi^{\pm}$ $K^{\pm}$
p
π^- π^+
K^+
D
K^-
$\bar{p}$
$\pm\Delta\bar{D}$
–3
–2
–1
0
1
2
3
Charge sign x Mass [GeV]

Anti-Helium (?!)

Carlson, Coogan, TL, Profumo, Ibarra & Wild (2014; 1401.2461)

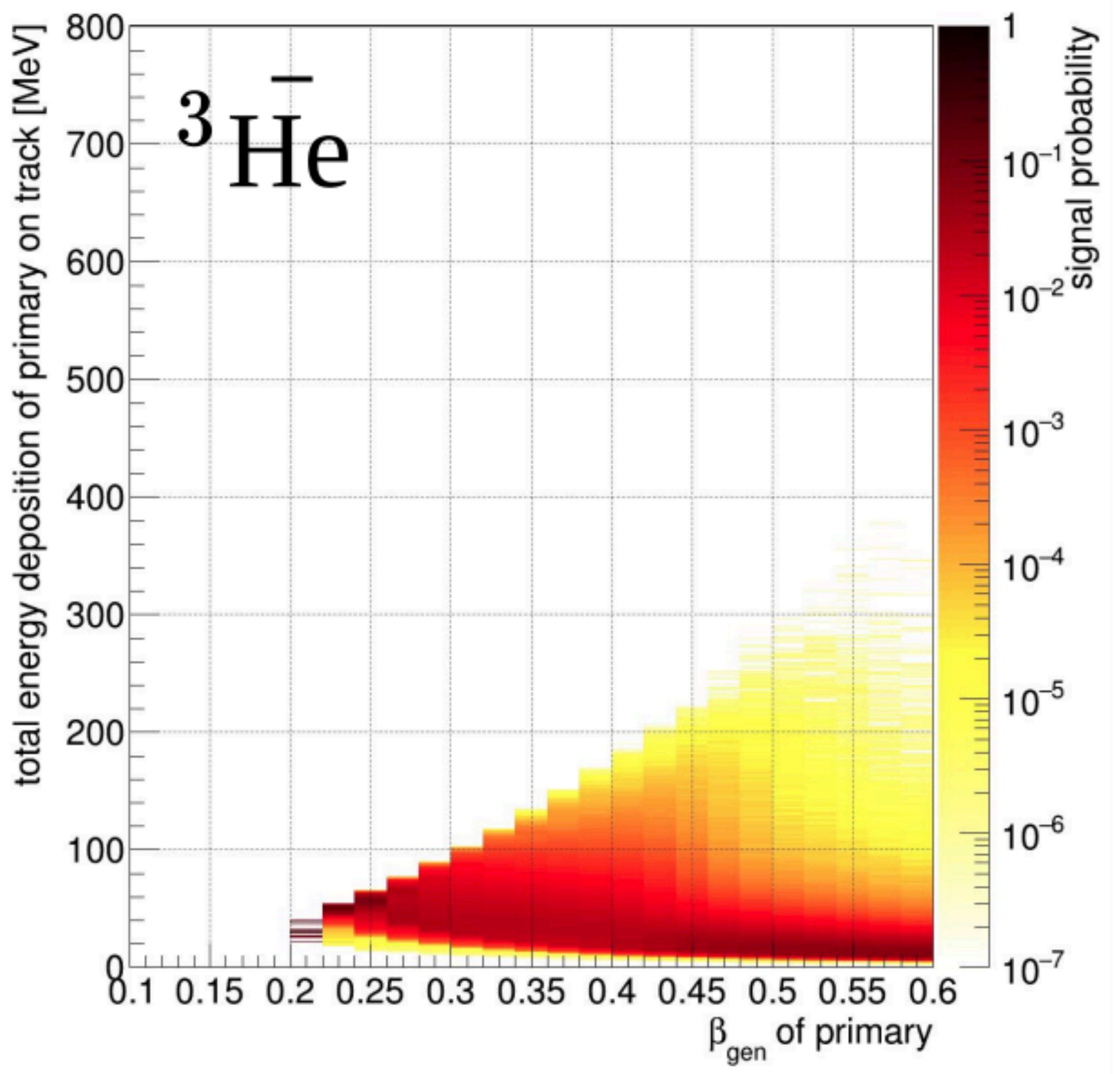
- **Several Ways To Boost Anti-Helium Production:**
  - **Anti-Helium Production Probability (Coalescence Model?)**
  - **Anti-Helium Reacceleration**
  - **Detector Effective Areas**

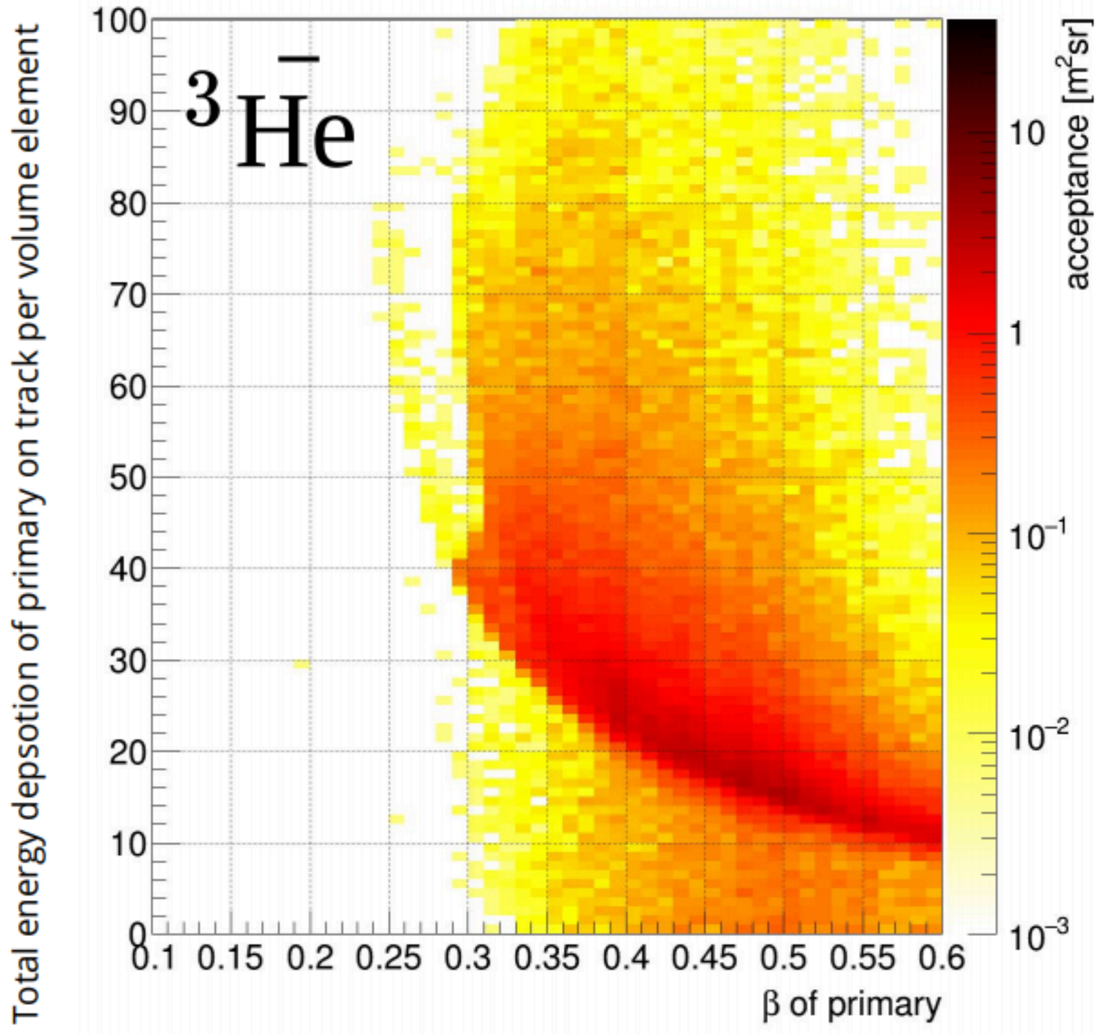




Anti-Helium (?!)

$^3\overline{\text{He}}$ capabilities





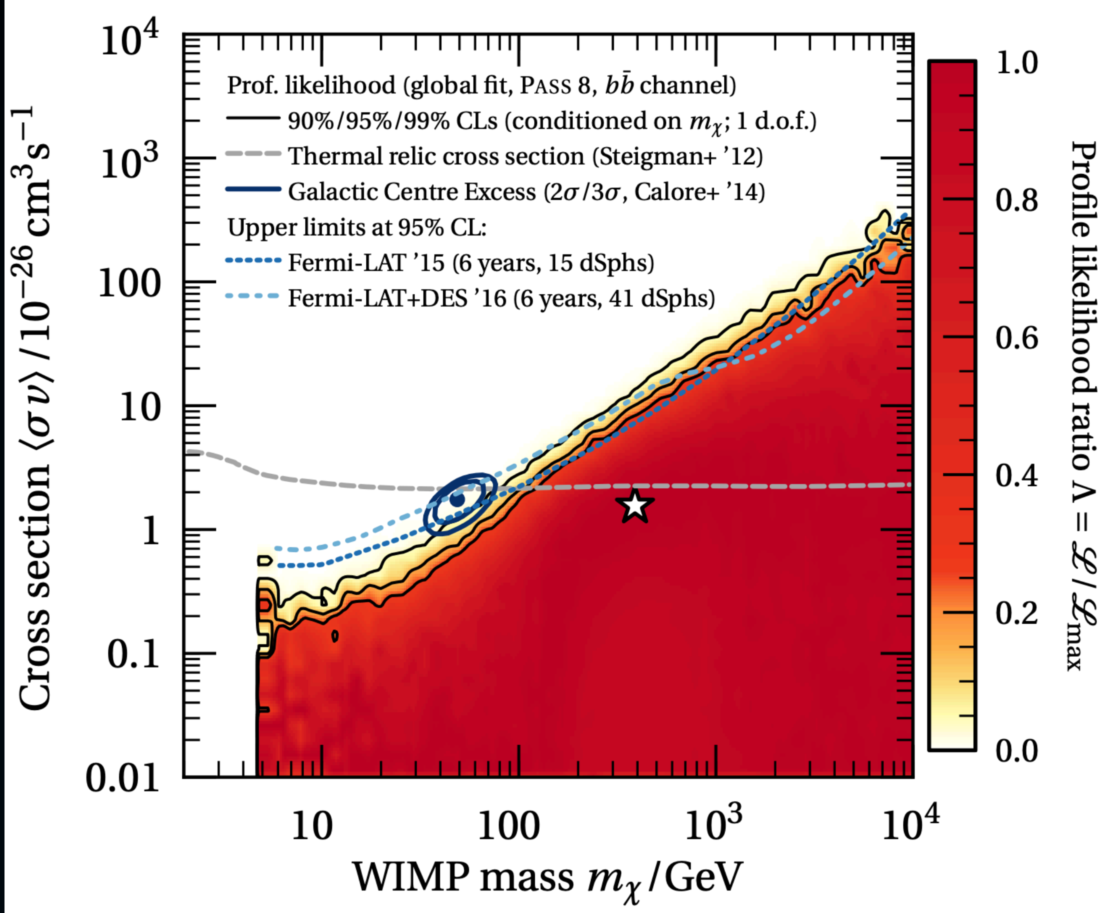
$^3\overline{\text{He}}$ "Hot topic" - AMS-02 reports on candidates [*see talk by* *Alberto Oliva*], however $\bar{d}$ missing yet (as predicted by coalescence models)

$^3\overline{\text{He}}$ identification similar to $\bar{d}$ identification, with $\bar{d}$, & $\bar{p}$ as dominant background

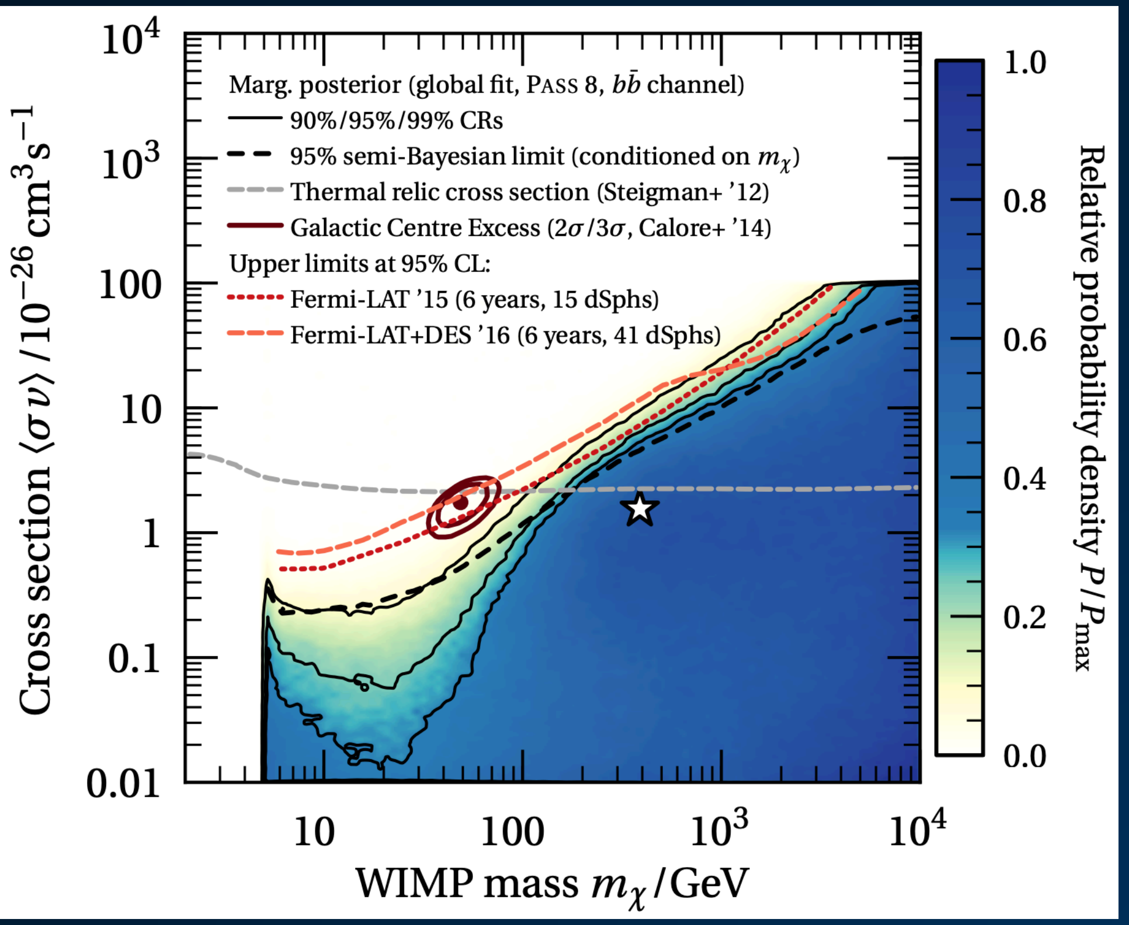
<u>Challenge for GAPS:</u>
High individual energy deposition in the tracker (up to 100 MeV) - high dynamic range required (X-Rays in keV regime!) - GAPS ASIC can do it.

Promises of the Next Decade

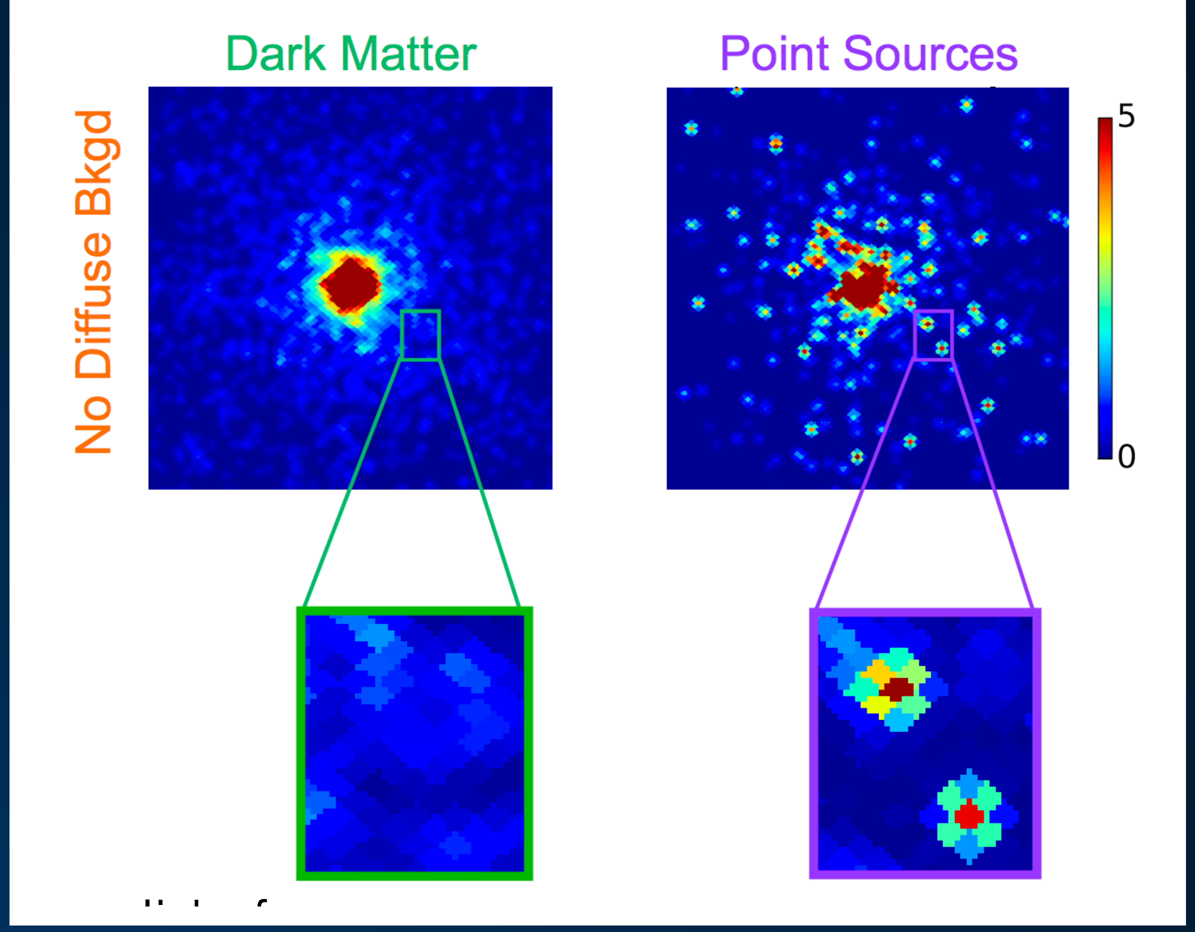
Promises of the Next Decade

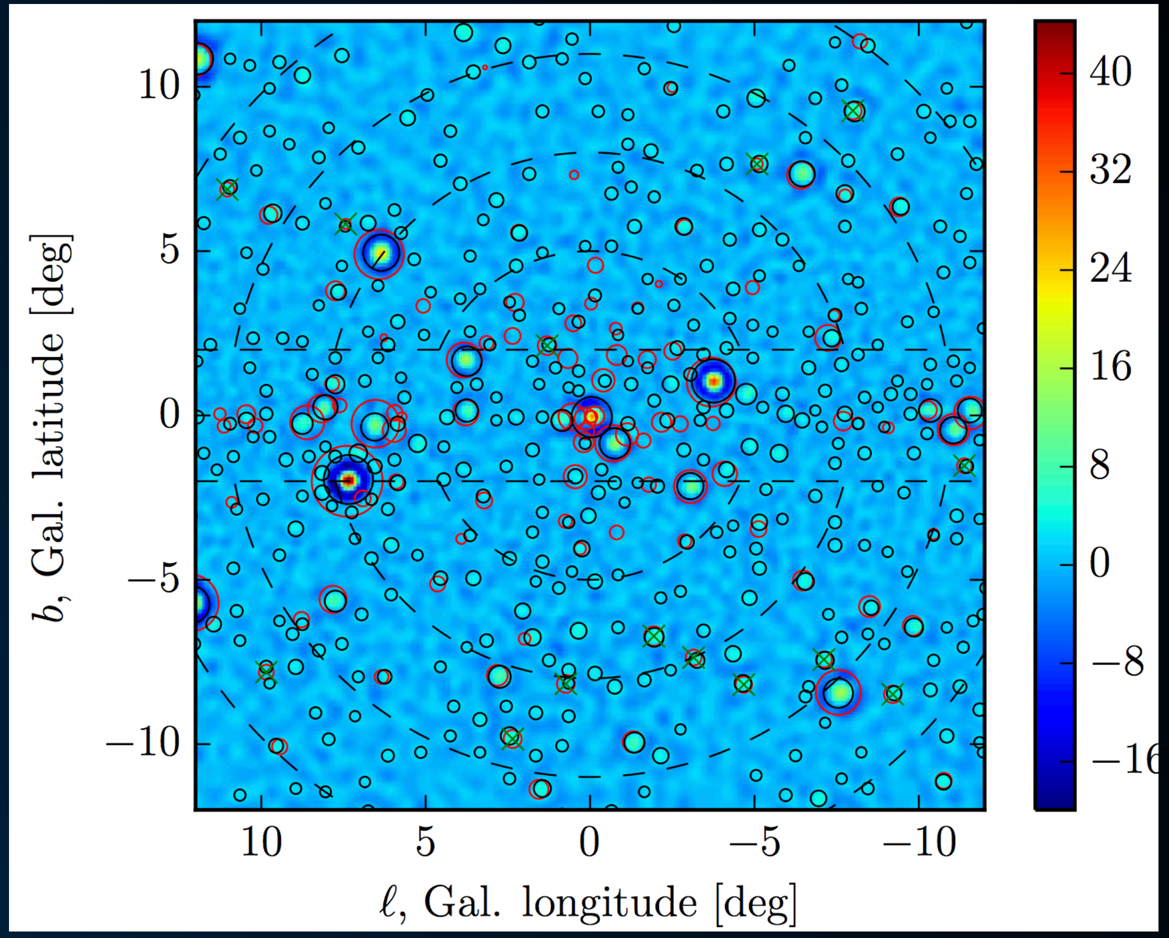


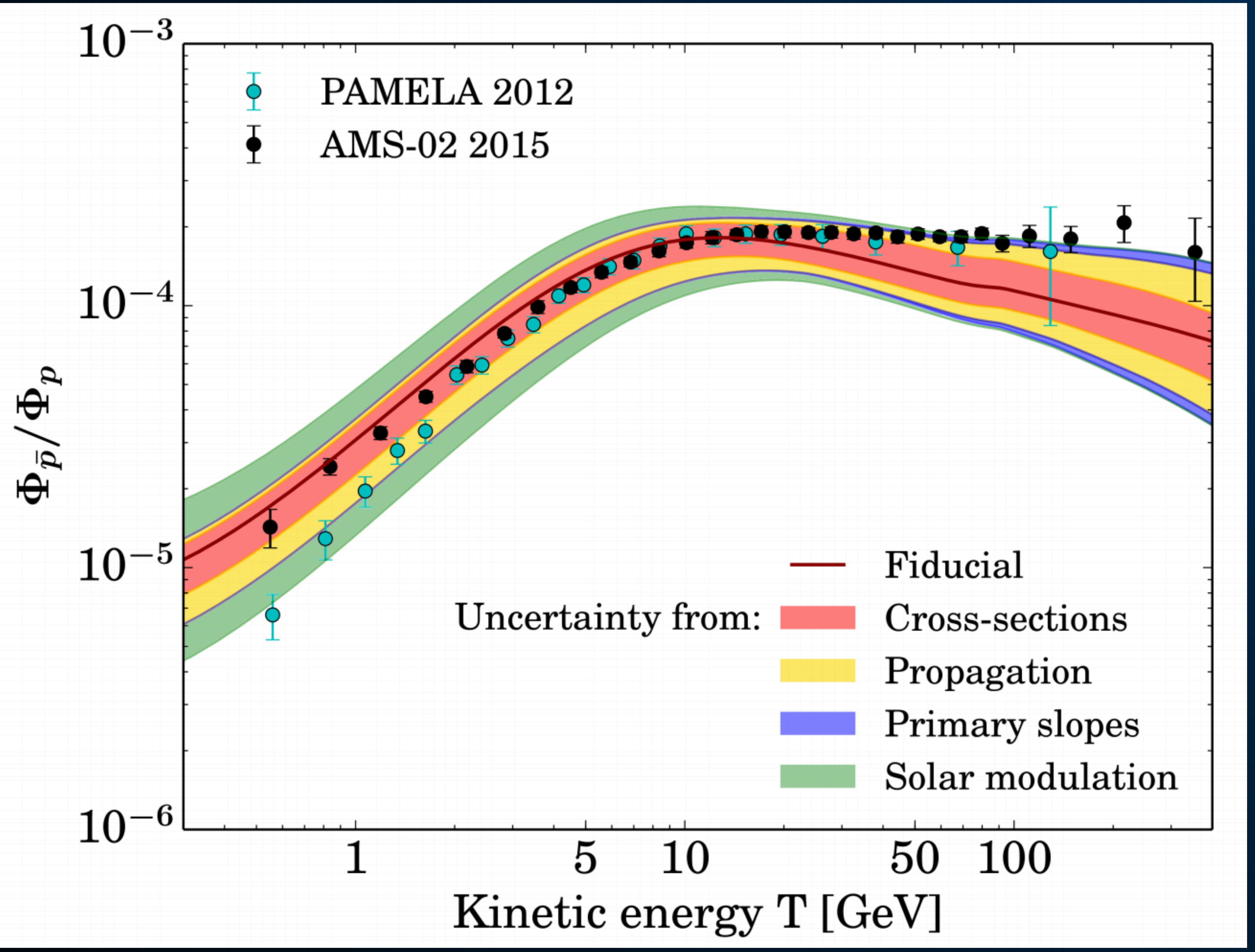
Frequentist



Bayesian







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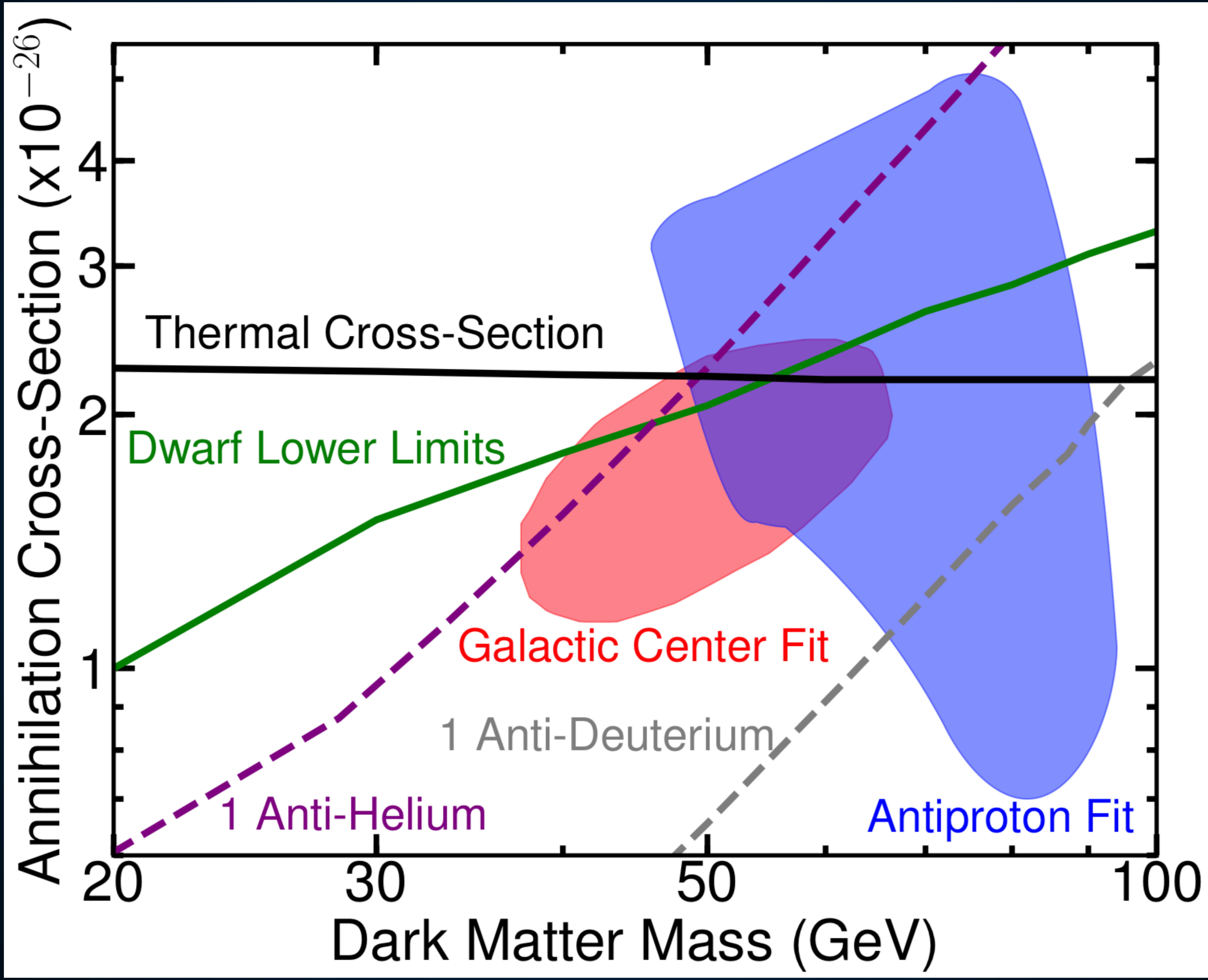
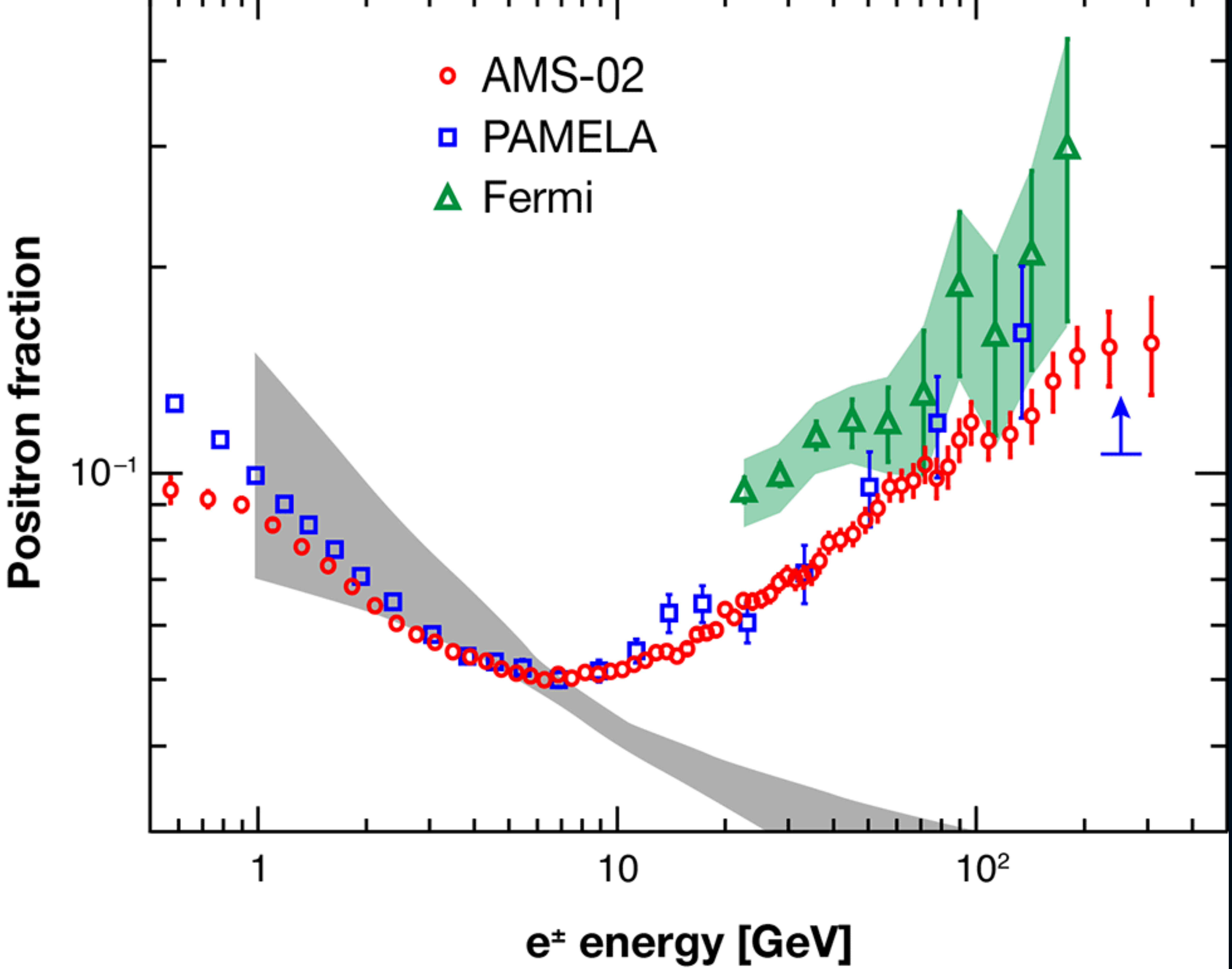
Conclusions



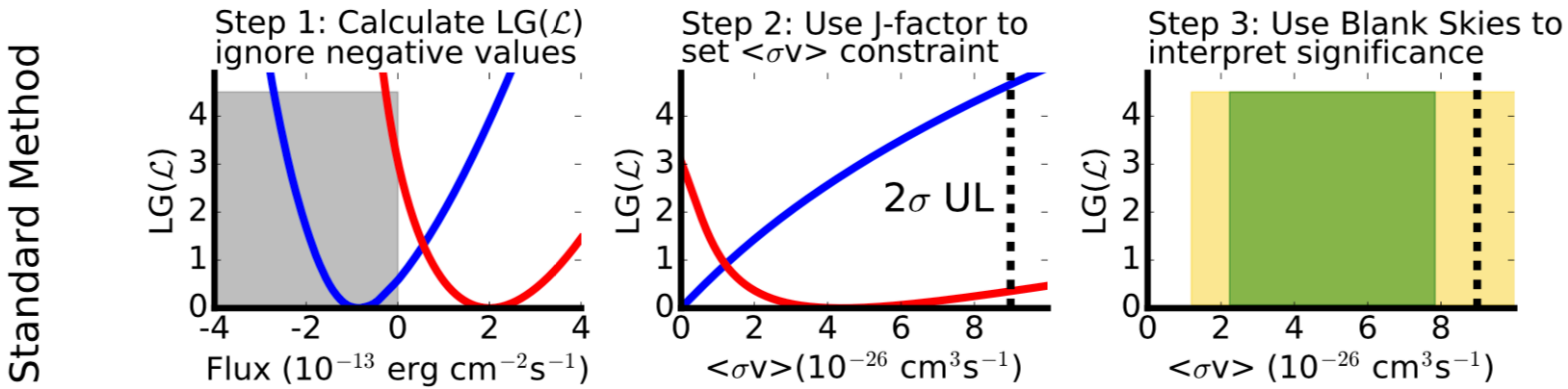
Extra Slides



AMS-02
PAMELA
Fermi
Positron fraction
10^{-1}
1
10
10^2
e± energy [GeV]

Dwarf Spheroidal Galaxies - Techniques

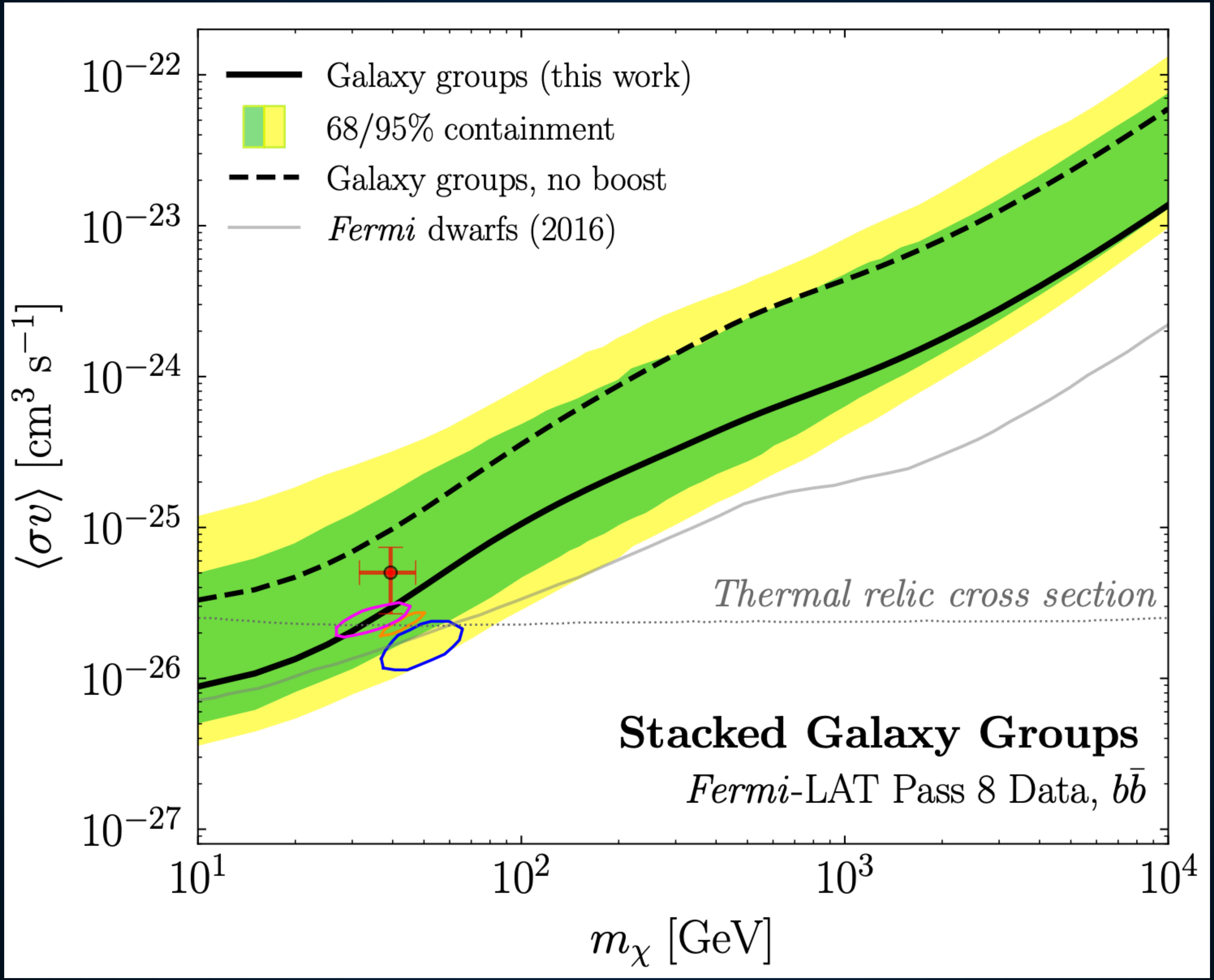
Linden (TBS)



Targets, Targets Everywhere!

Isotropic Gamma-Ray Background - Constraints

Lisanti et al. (2018; 1708.09385)



The Future of Dark Matter Limits - IGRB

Fermi-LAT Collaboration (2015; 1501.05464)

Constraints improve significantly as the background is resolved.

Improvement in limits can proceed faster than $t^{1/2}$.