TIM LINDEN

WIMPs on the Brink

Fermilab Astroparticle Seminar

THE OHIO STATE UNIVERSITY
CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

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 century[1,2]. In the 1970s, astronomers and cosmologists began to build what is today a compelling body of evidence for this elusive component of the Universe, based on a variety of observations, including temperature anisotropies of the cosmic microwave background, baryonic acoustic oscillations, type Ia supernovae, gravitational lensing of galaxy clusters and rotation curves of galaxies[3,4]. The standard model of particle physics contains no suitable particle to explain these observations, and thus dark matter arguably represents a glimpse of physics beyond the standard model. Proposed candidates for dark matter span 90 orders

the observed Higgs mass at the weak scale appears highly unnatural, requiring an incredibly fine-tuned cancellation between the individually much larger intrinsic contribution and the correction terms, such that their sum is the value observed at the Large Hadron Collider (LHC). Natural theories introduce additional particles and symmetries, which are arranged so that these large corrections cancel each other out, protecting the Higgs mass from the influence of heavy mass scales.

The prototypical natural theory is the minimal supersymmetric (SUSY) standard model, which introduces an additional partner for each standard-model particle. In addition, the partners of electroweak bosons are predicted to be WIMPs and thus are natural dark-matter

A Philosophical Debate

MIT-CTP/5020

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.

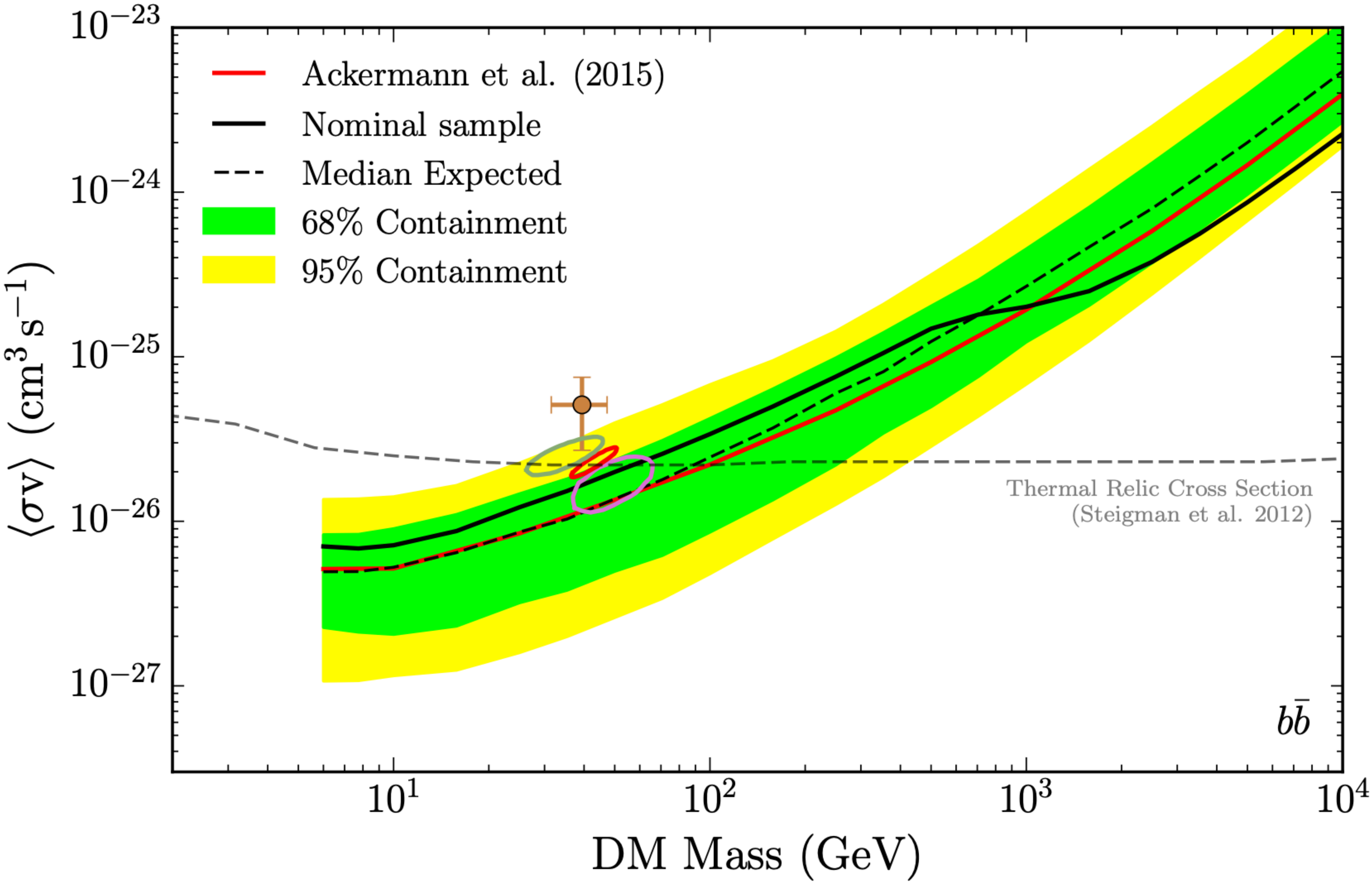
I. INTRODUCTION

A leading candidate for dark matter (DM) is a Weakly Interacting Massive Particle (WIMP) that is a thermal

scenarios. The branching ratios, coupling types and signals are model-dependent, and so the lack of observations may just be due to such features. For example, there can be interference effects, momentum suppression, or

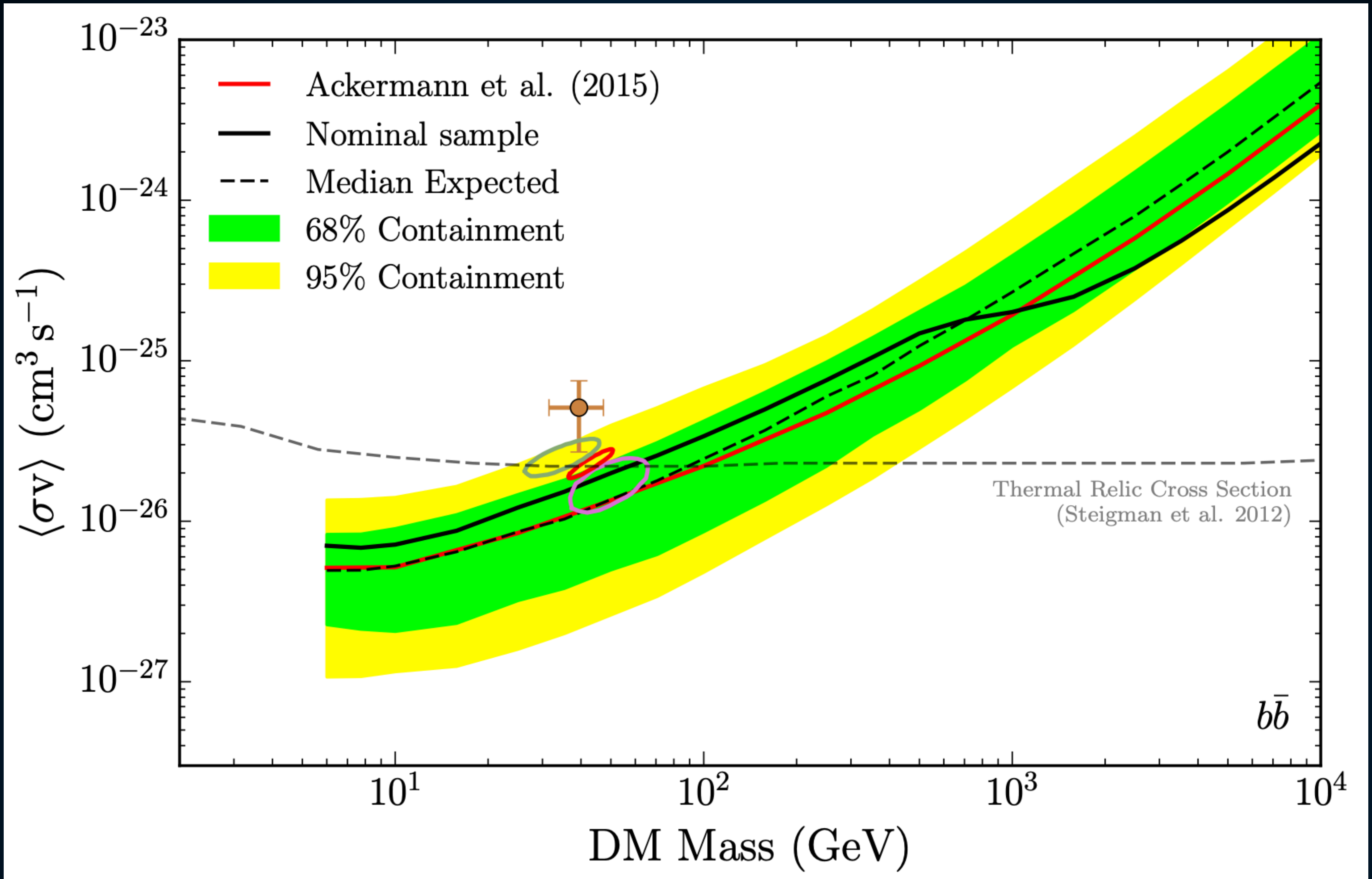
Current Parameter Space

Fermi-LAT Collaboration (2017; 1611.03184)



Current Parameter Space

Fermi-LAT Collaboration (2017; 1611.03184)



~100 GeV

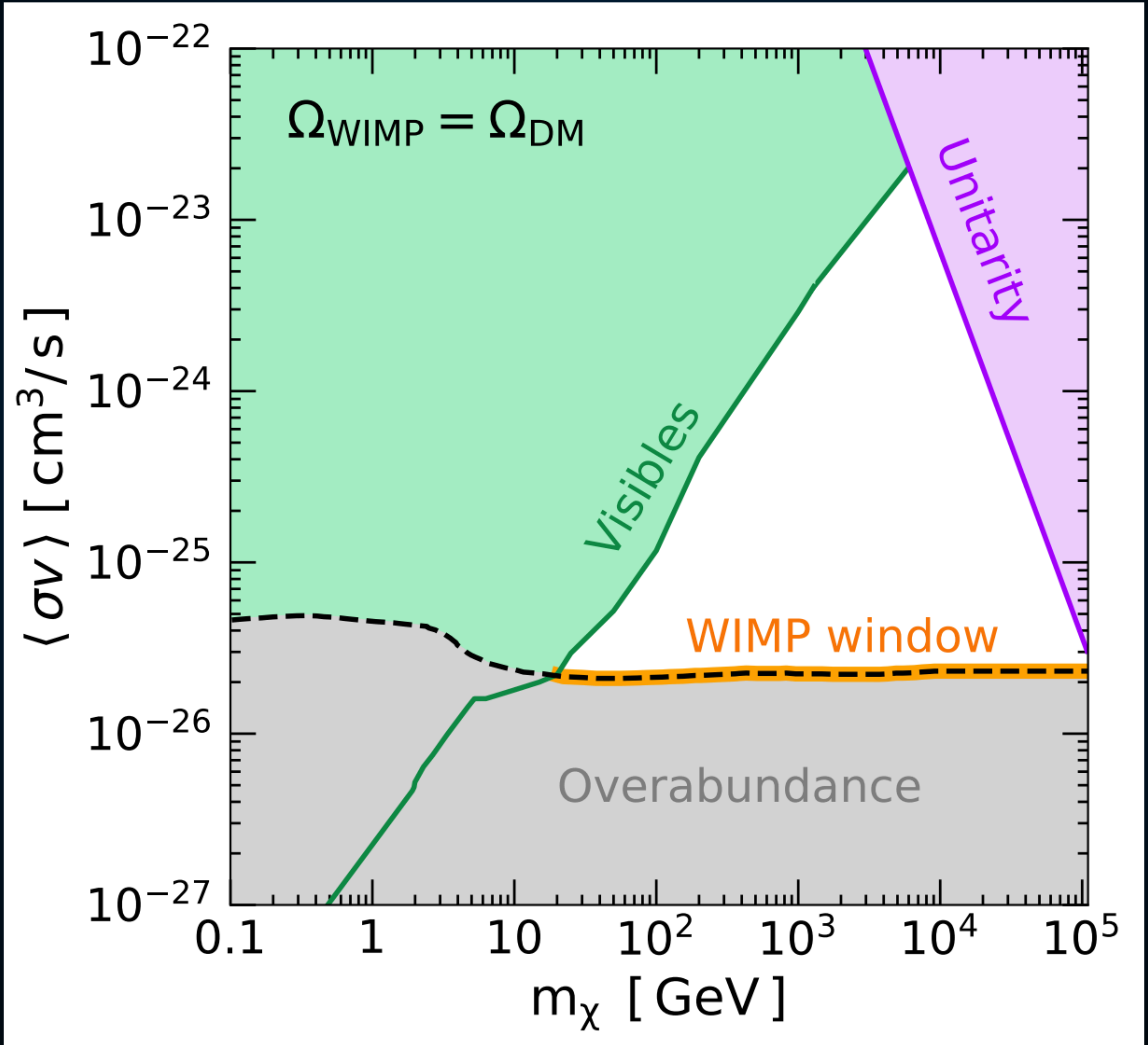
10^{-2} GeV (thermal)

WIMP Dark Matter

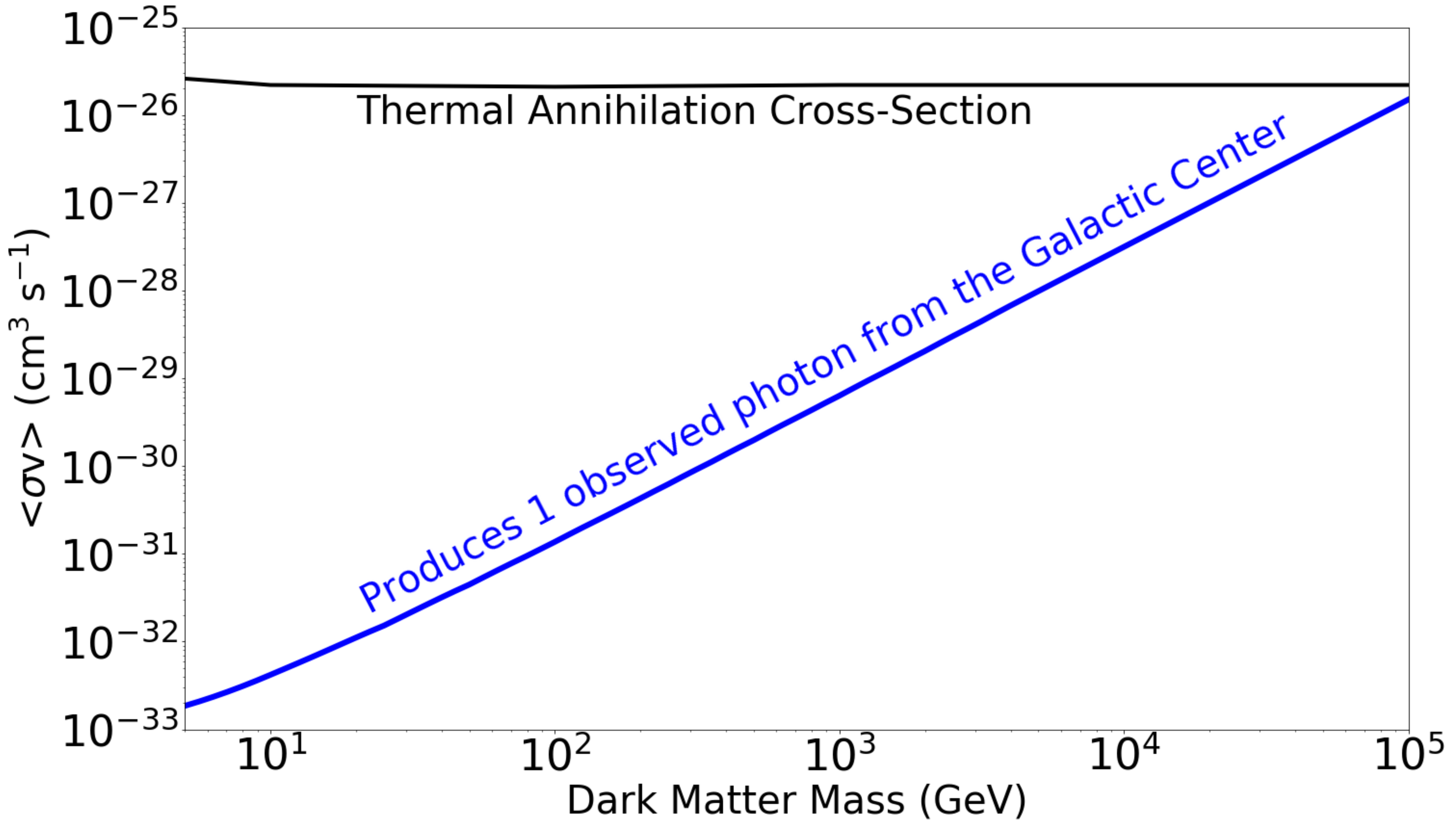
10^5 GeV (unitarity)

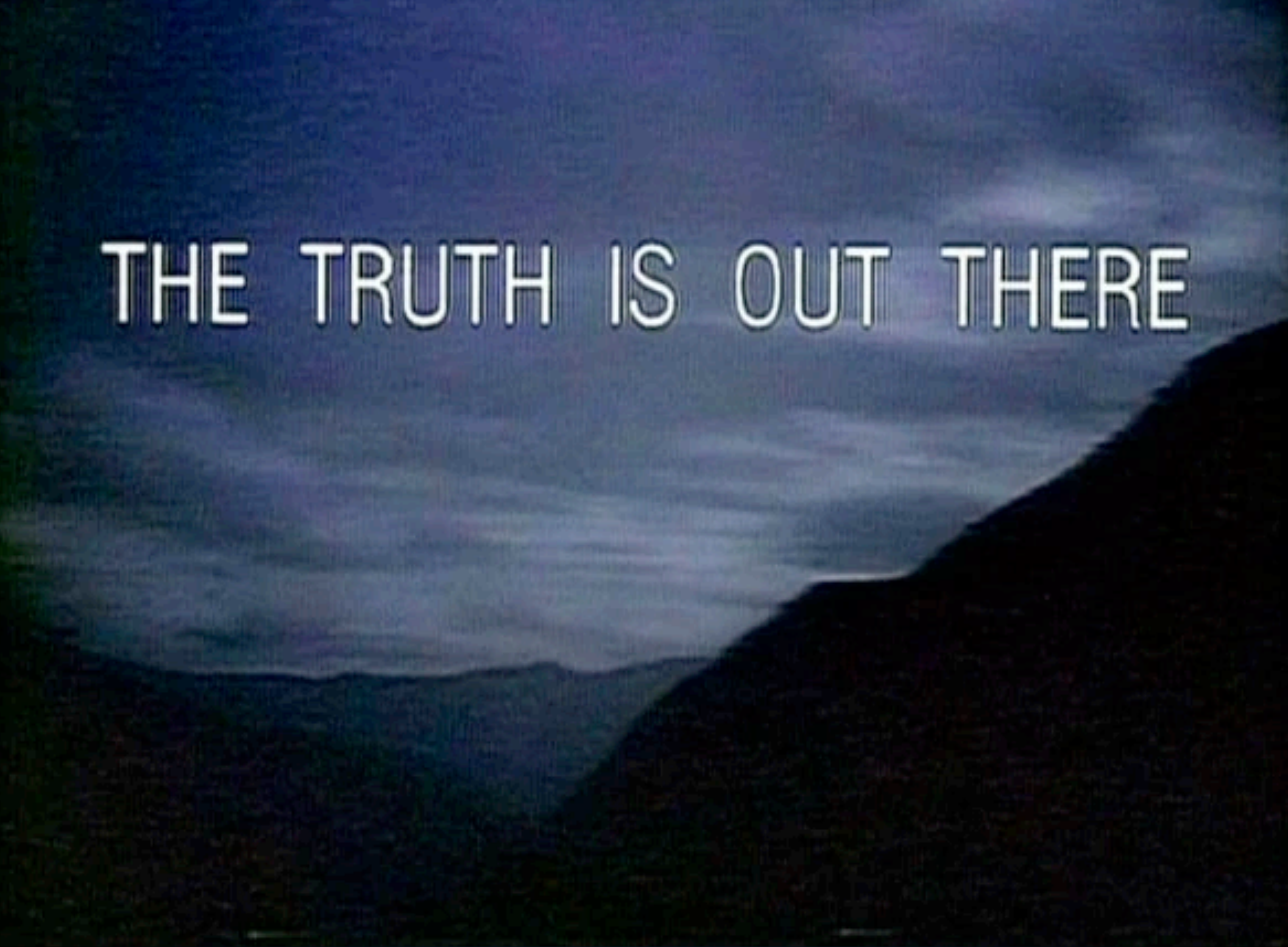
Current Parameter Space

Leane et al. (2018; 1805.10305)



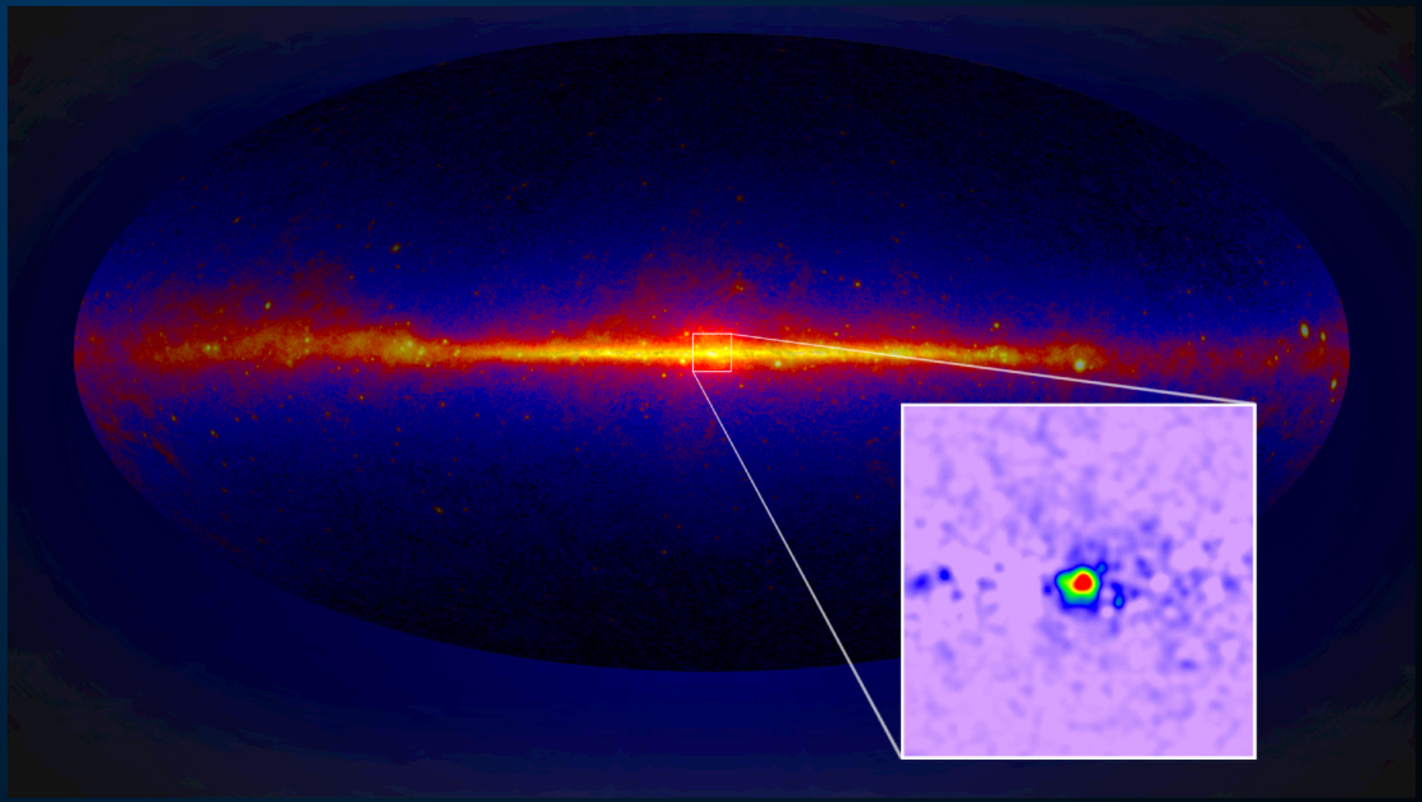
Reasons to Stay Optimistic




THE TRUTH IS OUT THERE

Reasons to Stay Optimistic

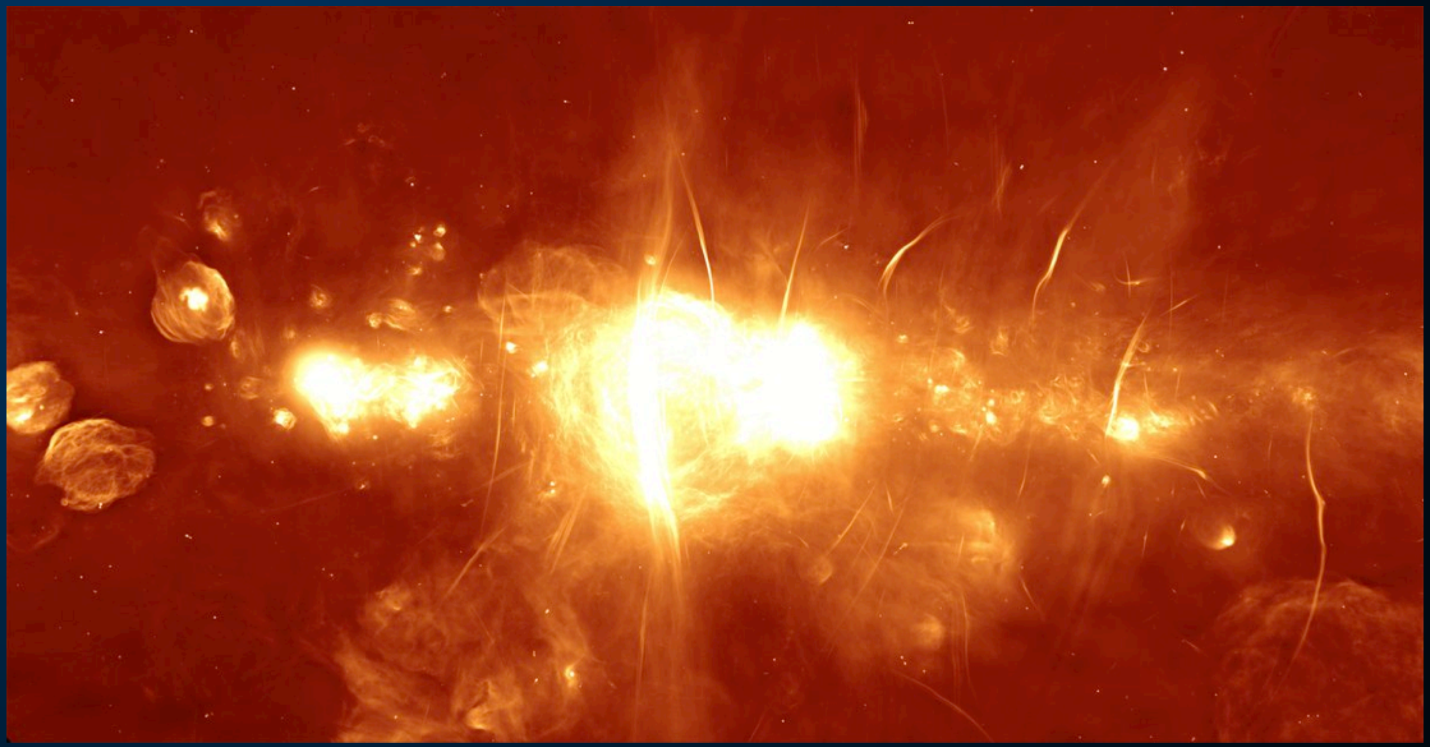
- **Model:**
  - 100 GeV dark matter particle annihilates to bb
  - Annihilation Rate is Thermal Cross-Section
- **Expected Galactic Center Flux (above 1 GeV):**
  - 2×10^{-11} erg cm^{-2} s^{-1}
- **Observed Flux:**
  - 1×10^{-10} erg cm^{-2} s^{-1}



Reasons to Stay Optimistic

- **Model:**
  - **100 GeV dark matter particle annihilates to bb**
  - **Annihilation Rate is Thermal Cross-Section**

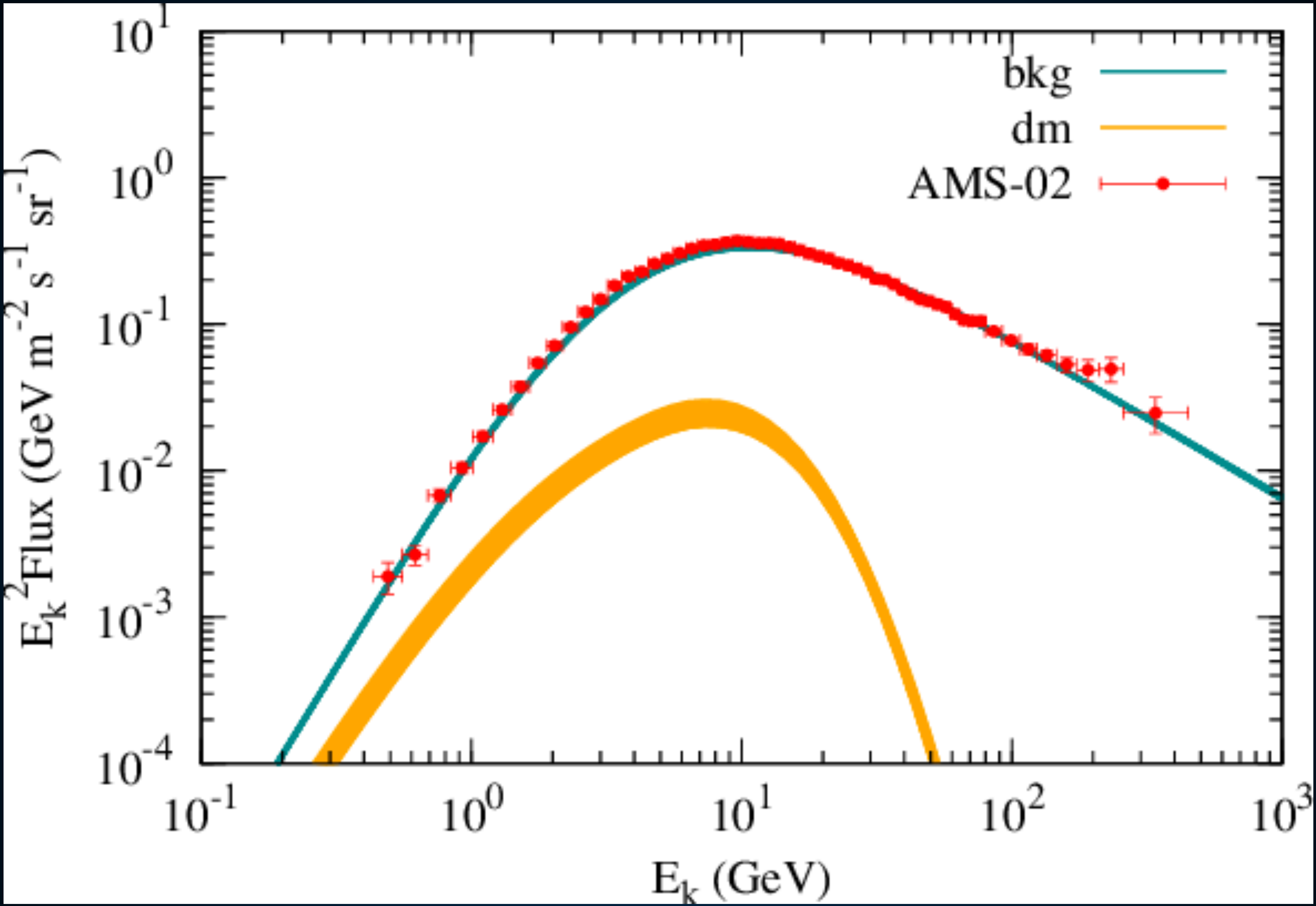
- **Expected Galactic Center Flux (above 1 GeV):**
  - **2×10^{-13} erg cm^{-2} s^{-1}**



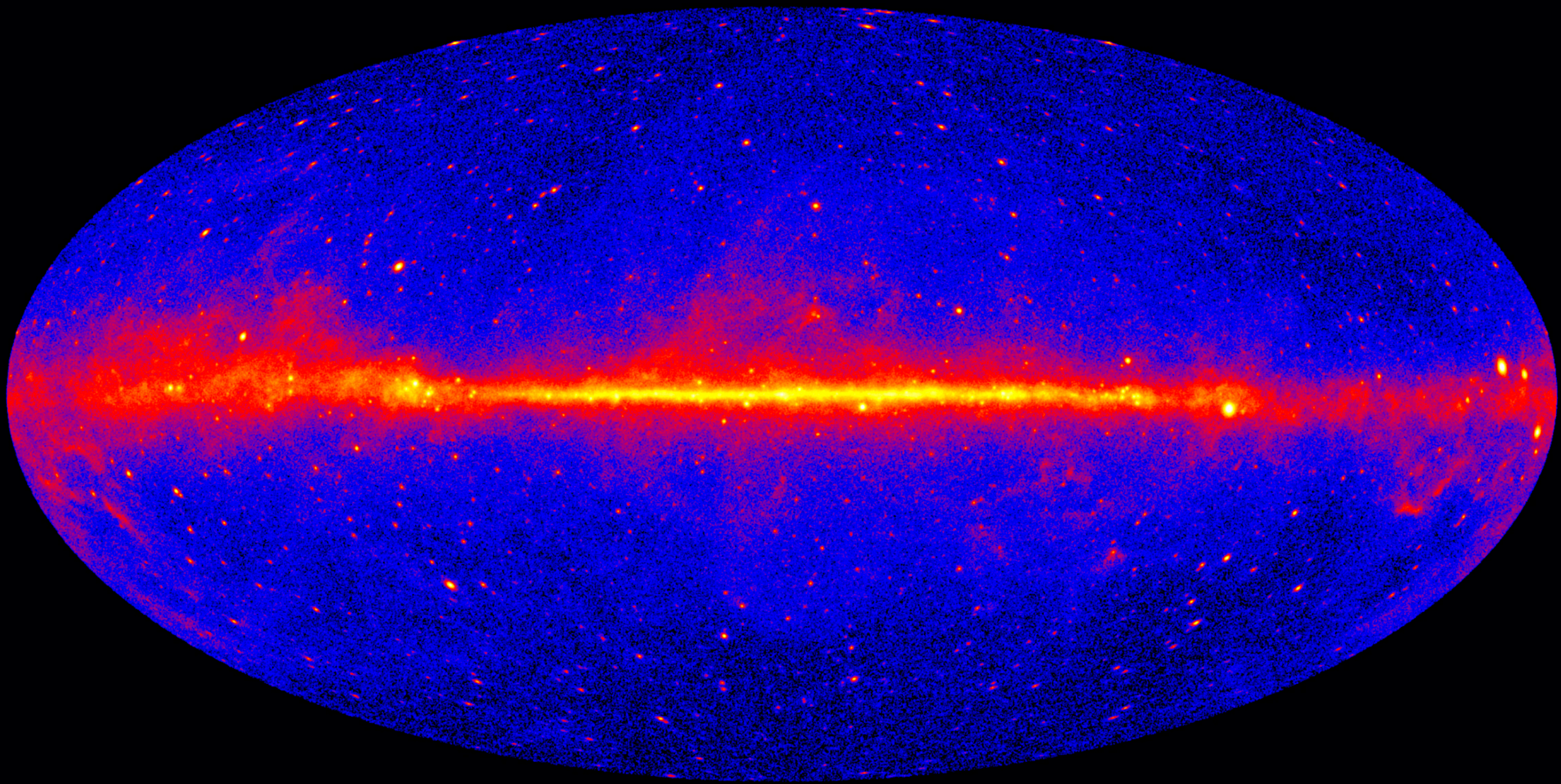
- **Observed Flux:**
  - **5×10^{-10} erg cm^{-2} s^{-1}**

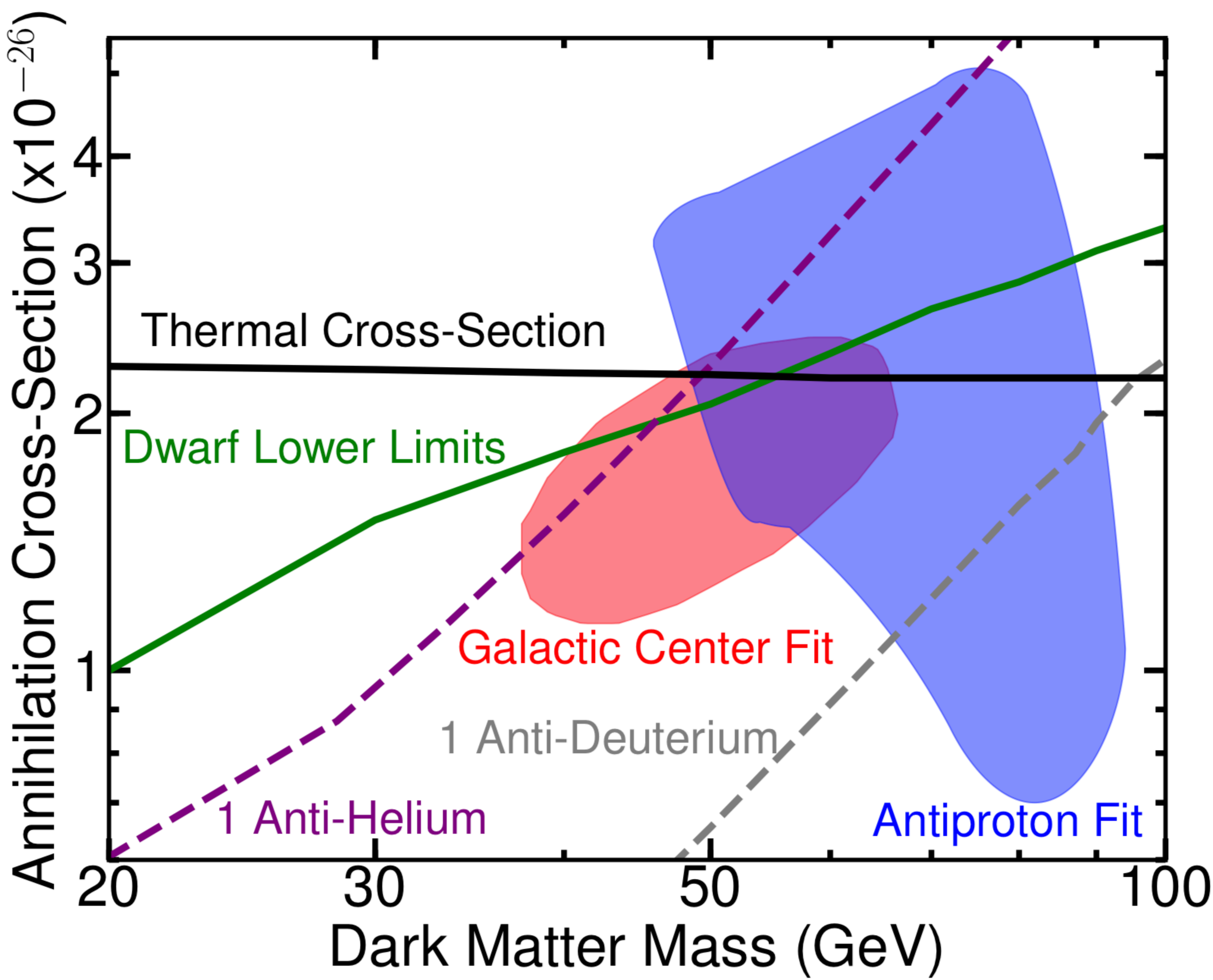
Similar in Cosmic-Rays

Cui et al. (2017; 1610.03840)



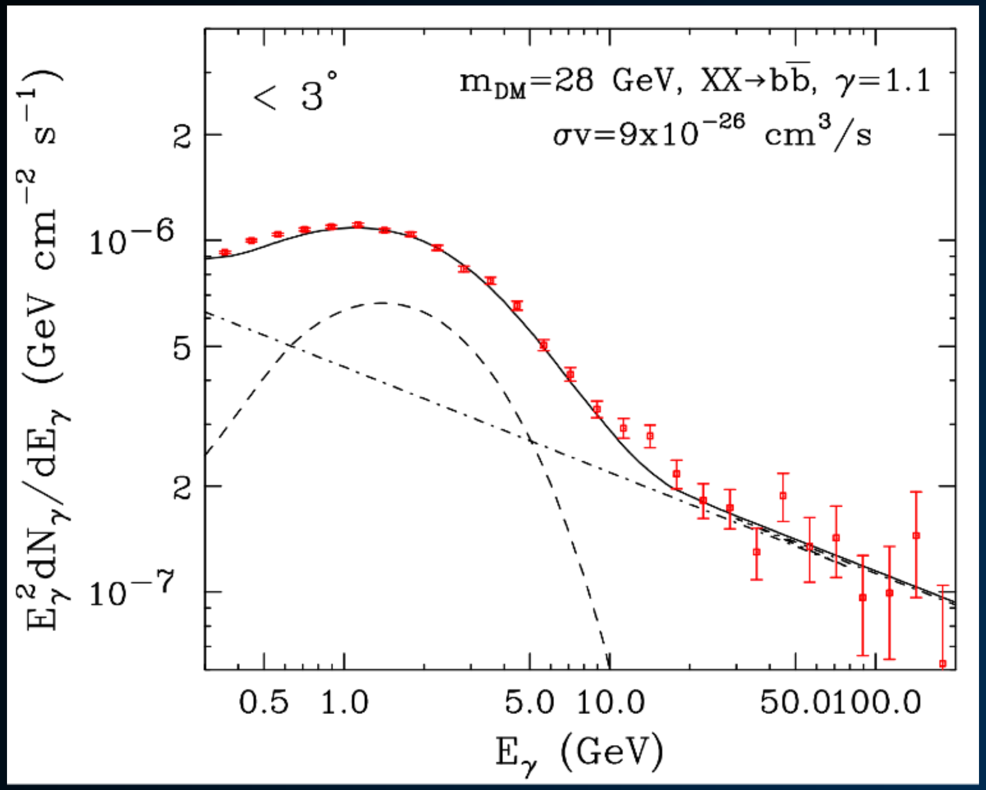
A Beautiful View of Not Dark Matter

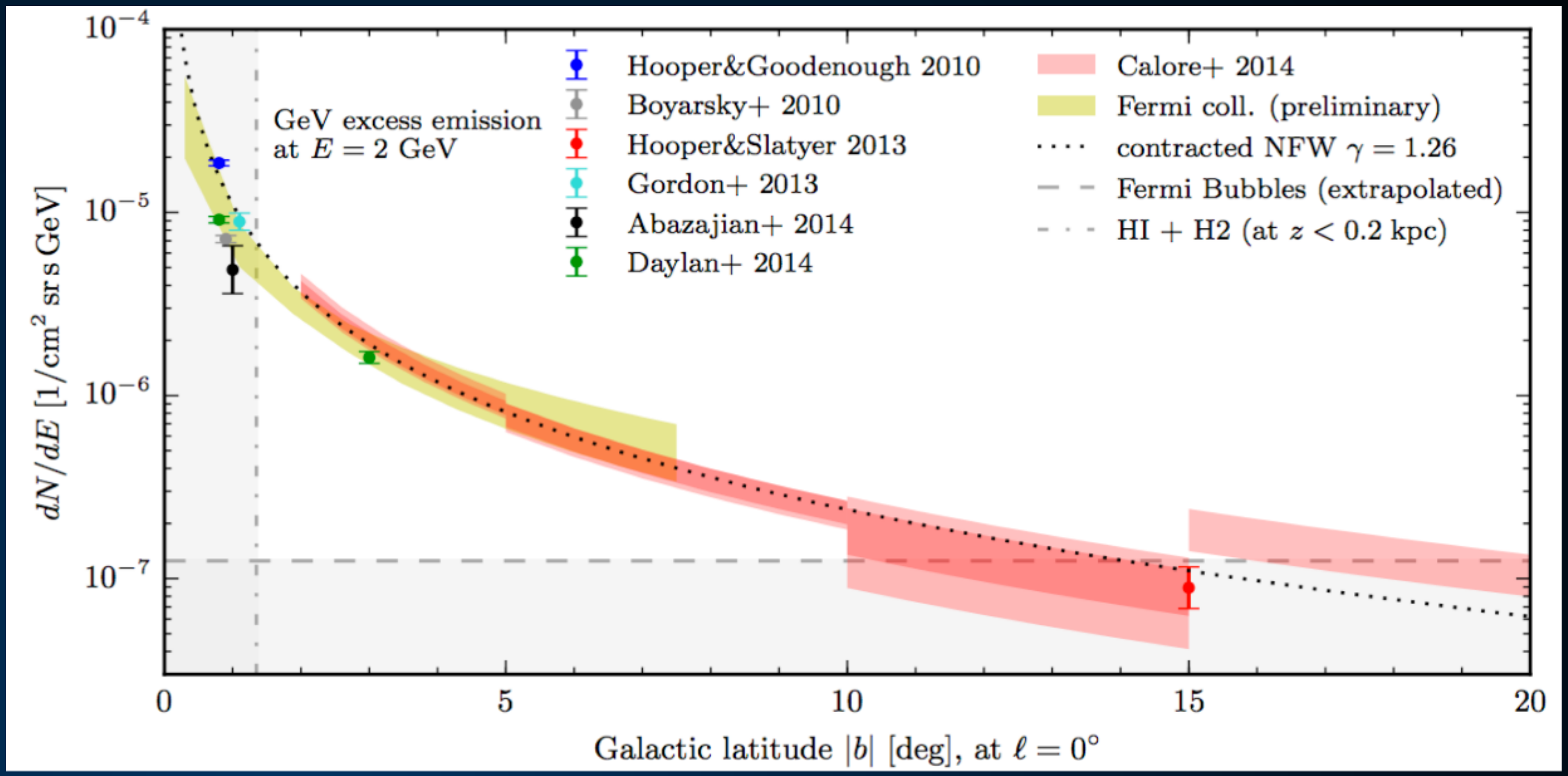



Annihilation Cross-Section (x10^{-26})
4
3
2
1
Thermal Cross-Section
Dwarf Lower Limits
Galactic Center Fit
1 Anti-Deuterium
1 Anti-Helium
Antiproton Fit
20
30
50
100
Dark Matter Mass (GeV)

Status: Galactic Center Excess

Goodenough & Hooper (2009; 0910.2998)





Bright *Detected at >50σ*

Hard-Spectrum *Incompatible with standard backgrounds*

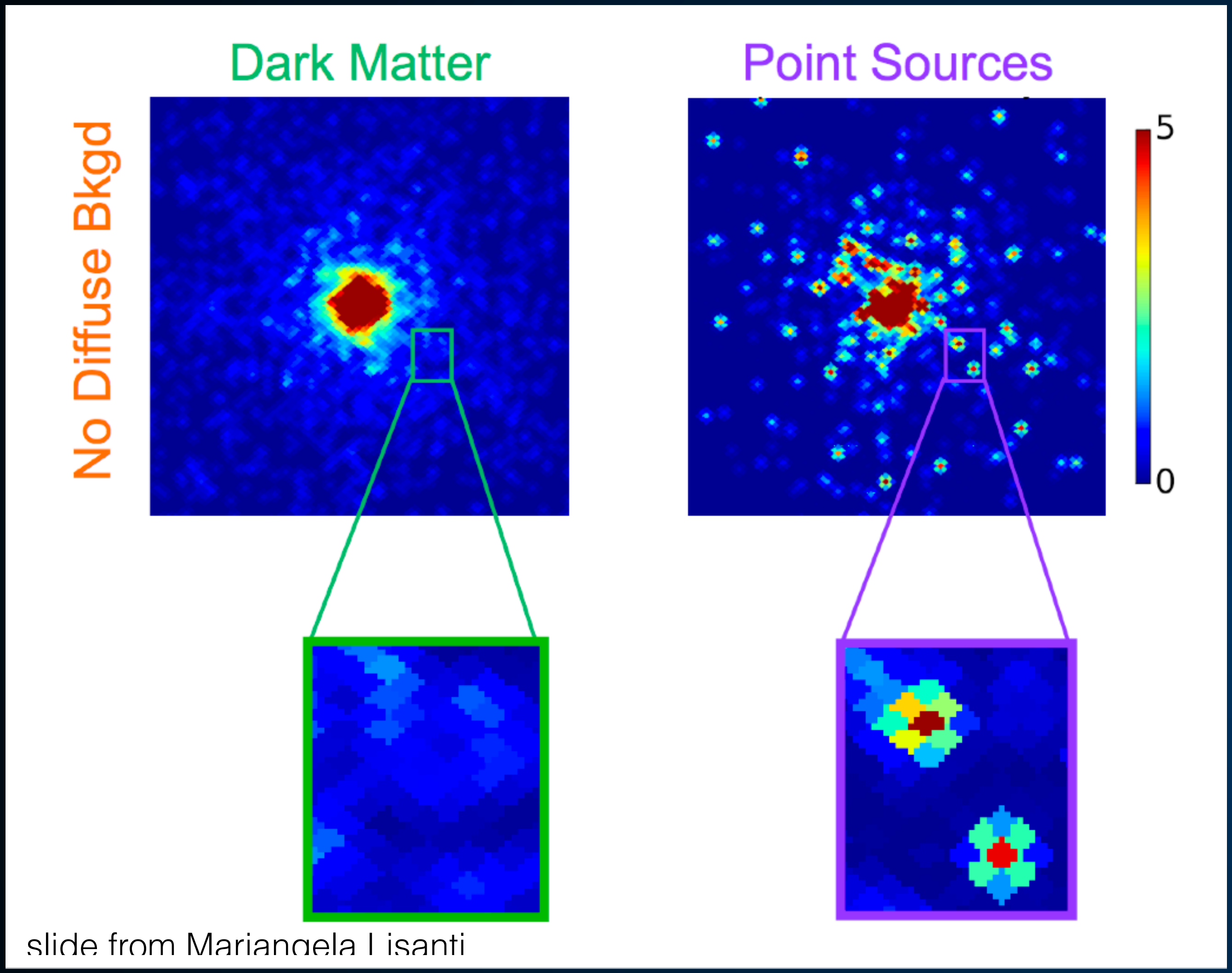
Spherically Symmetric *Expected from Dark Matter*

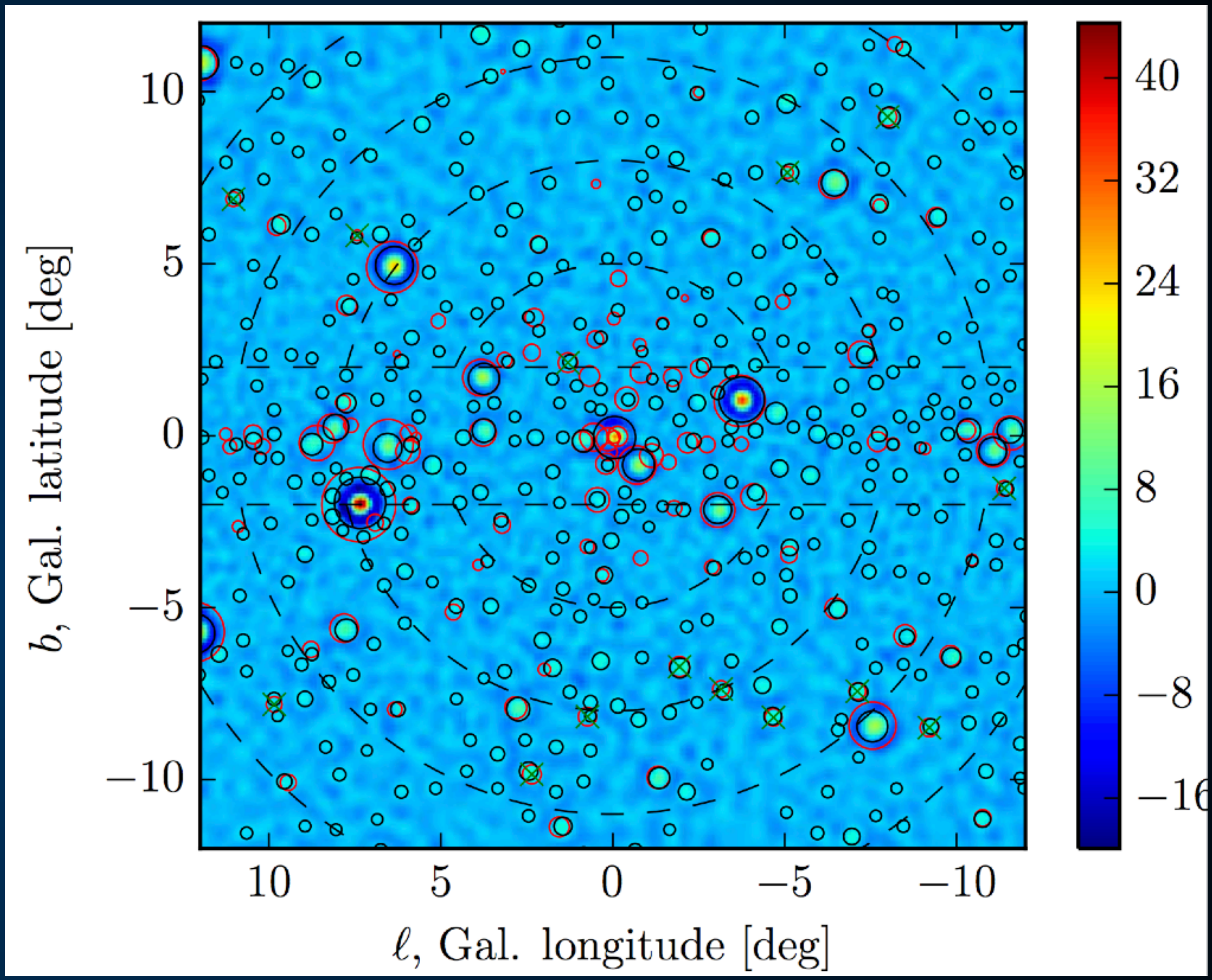
Spatially Extended *to nearly 15 degrees from Galactic center.*

Status: Galactic Center Excess

Lee et al. (2015; 1506.05124)

Bartels et al. (2015; 1506.05104)





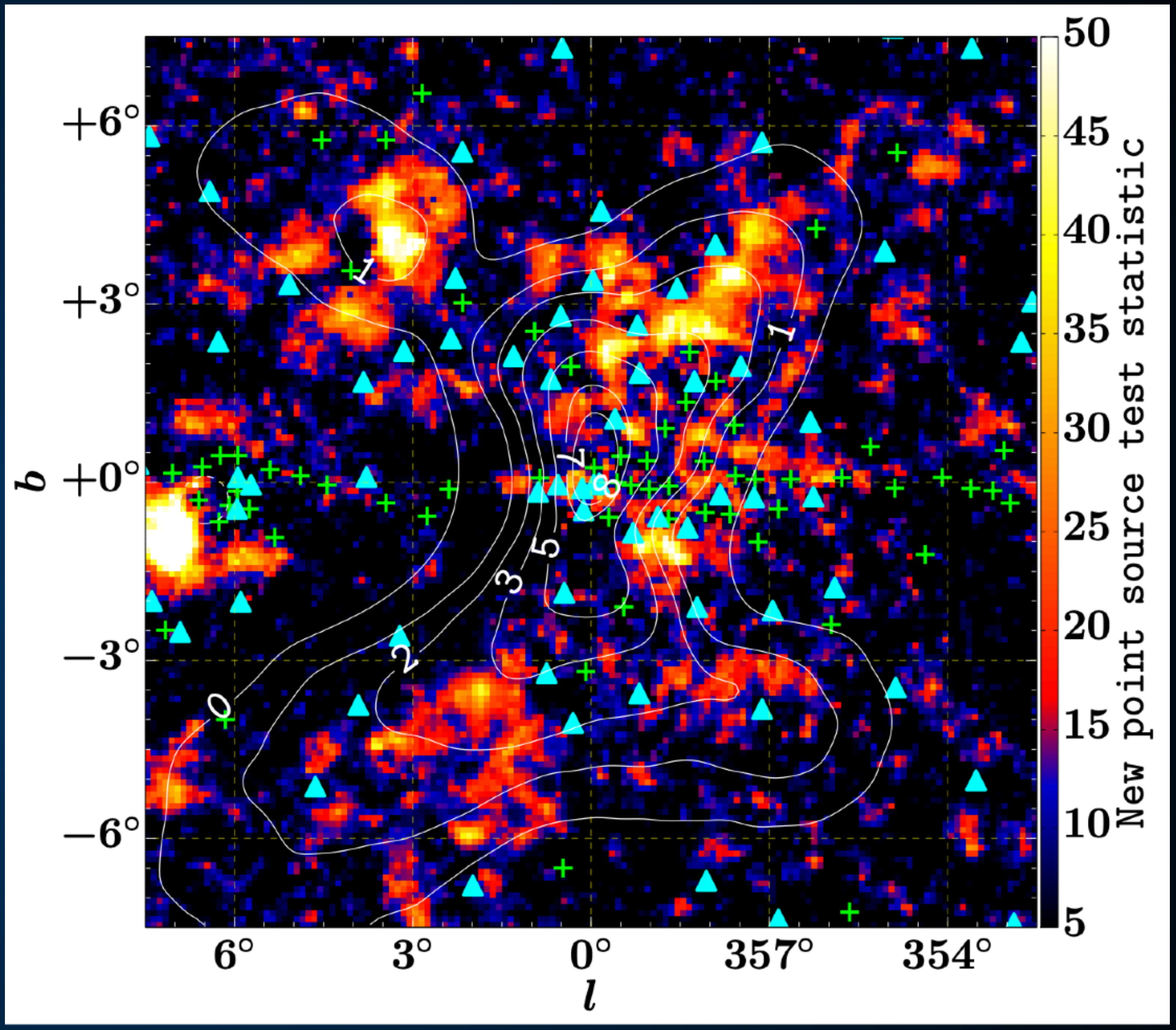
Tentative evidence of sub-threshold fluctuations in the Fermi-LAT data point to pulsar interpretations.

Status: Galactic Center Excess

Macias et al. (2018; 1611.06644)

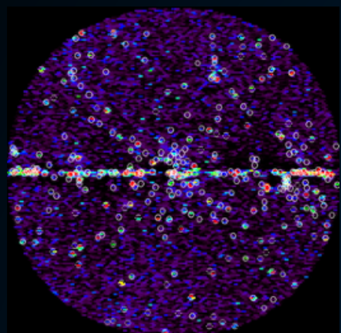
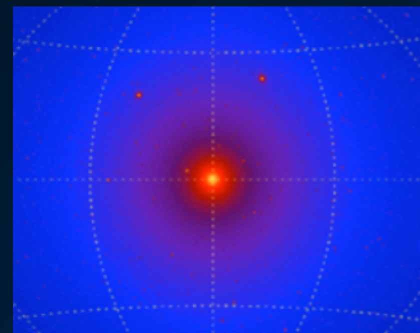
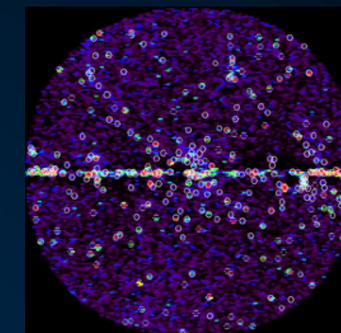
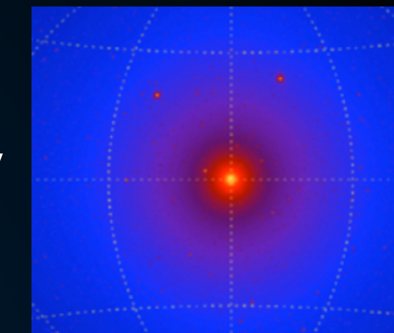
Some evidence that the global distribution of the excess more closely resembles the bulge

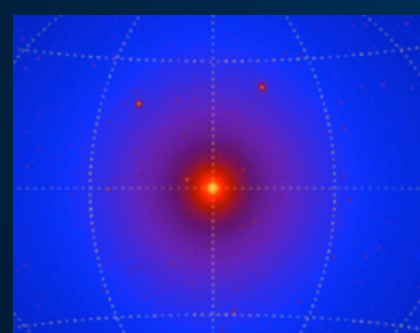
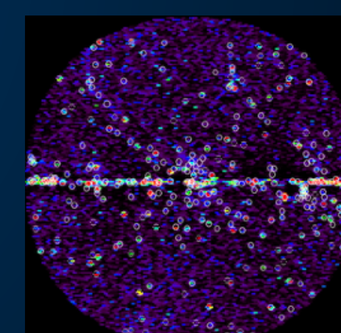
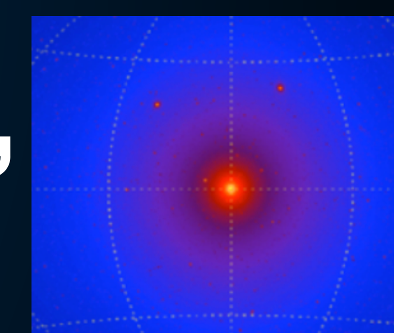
Both models of X-shaped, and box-shaped bulges have been advocated in multi-wavelength literature.



Status: Galactic Center Excess

Leane & Slatyer (2019; 1904.08430)

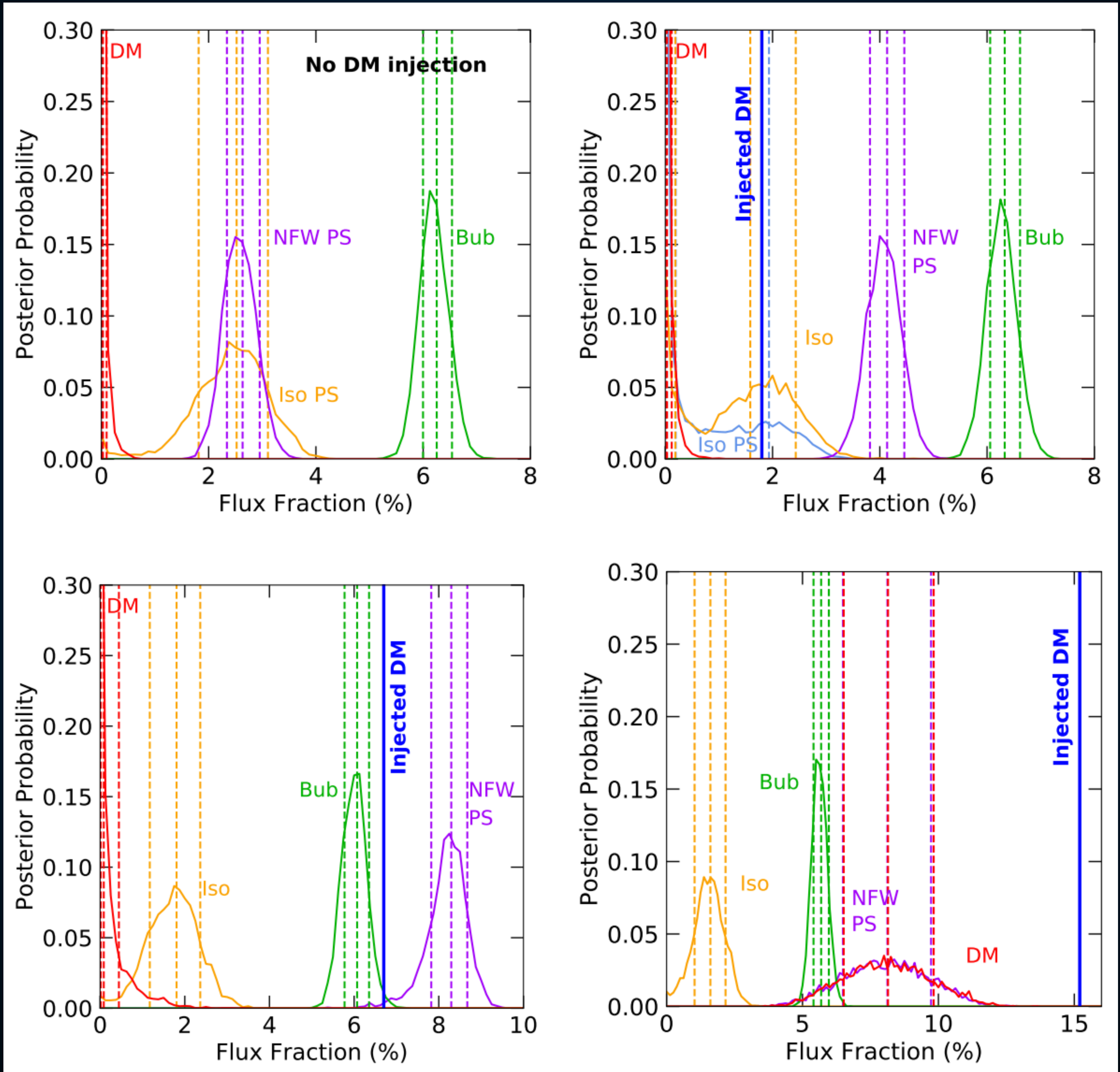
x  + y  → x  + y 

x  + y  → x’  + y’ 

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

Status: Galactic Center Excess

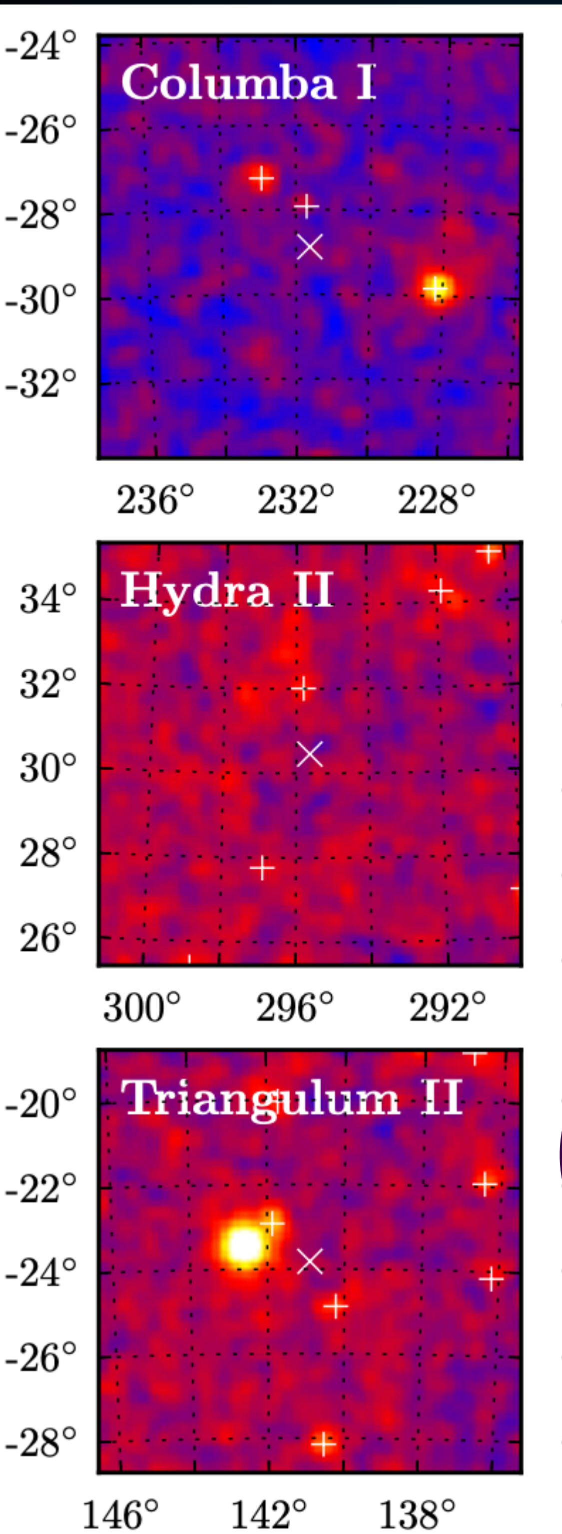
Leane & Slatyer (2019; 1904.08430)

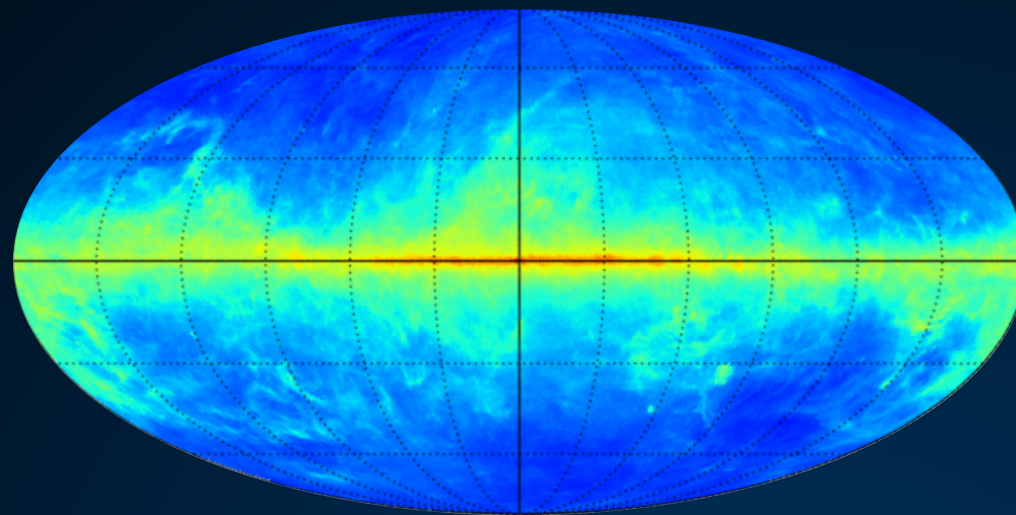


Status: Dwarf Spheroidal Galaxies

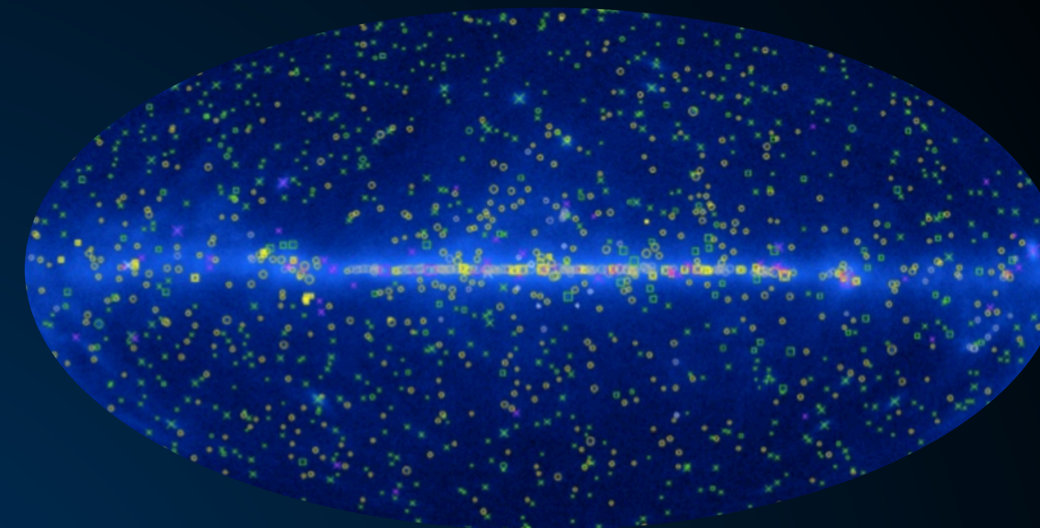
Status: Dwarf Spheroidal Galaxies

Fermi-LAT Collaboration (2017; 1611.03184)



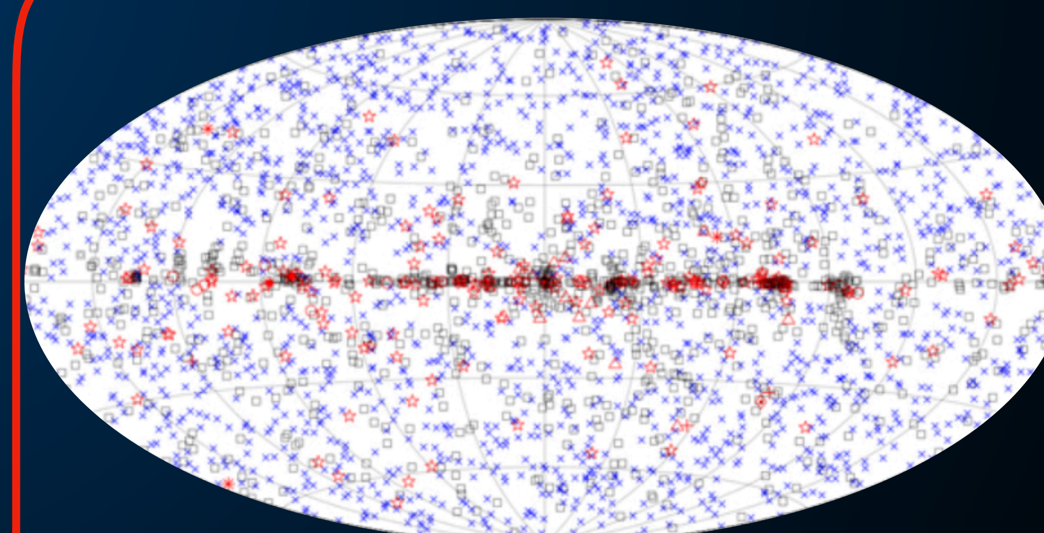


Galactic Diffuse



Point Sources

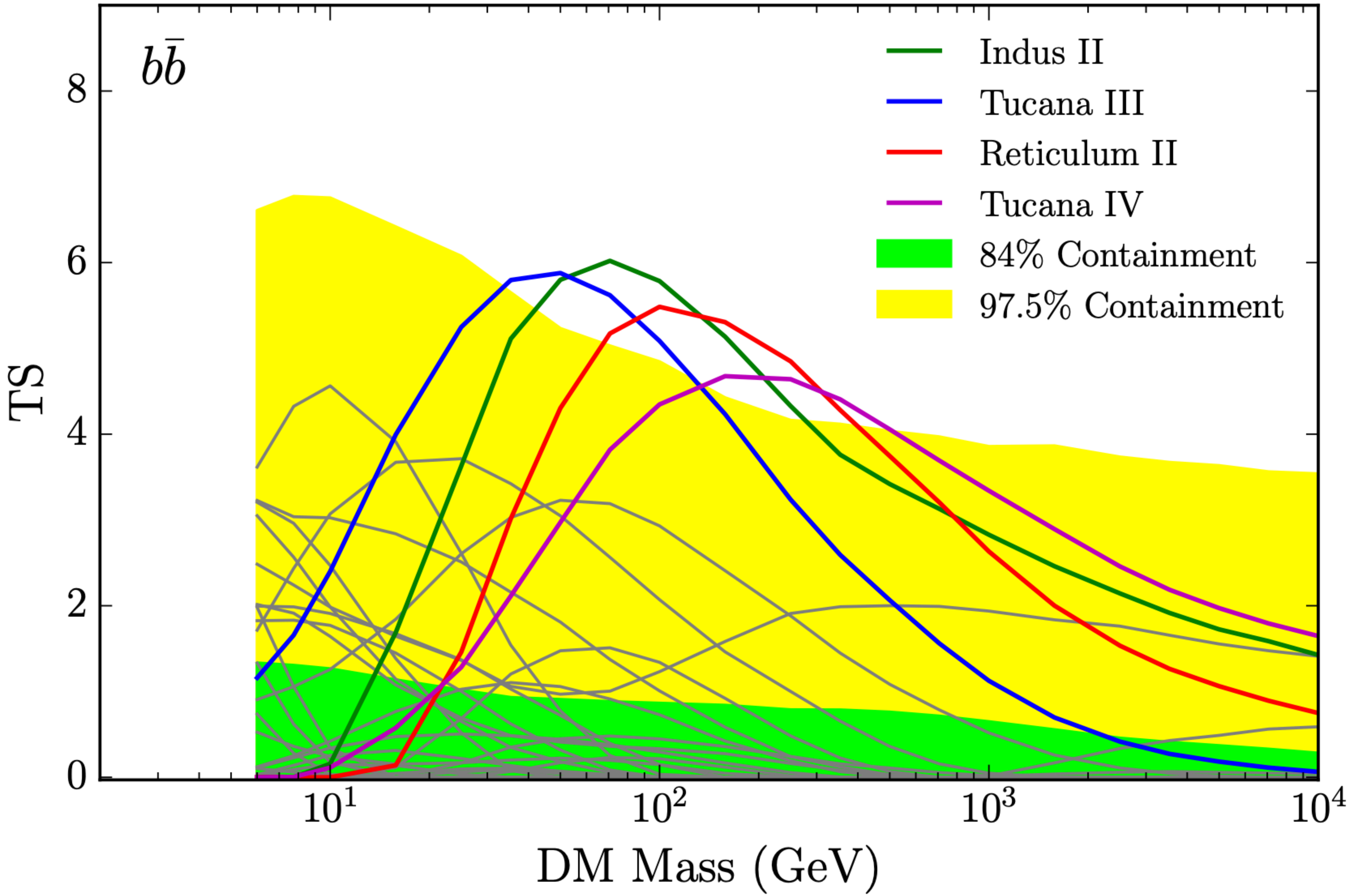
Isotropic Emission



Sub-Threshold Sources

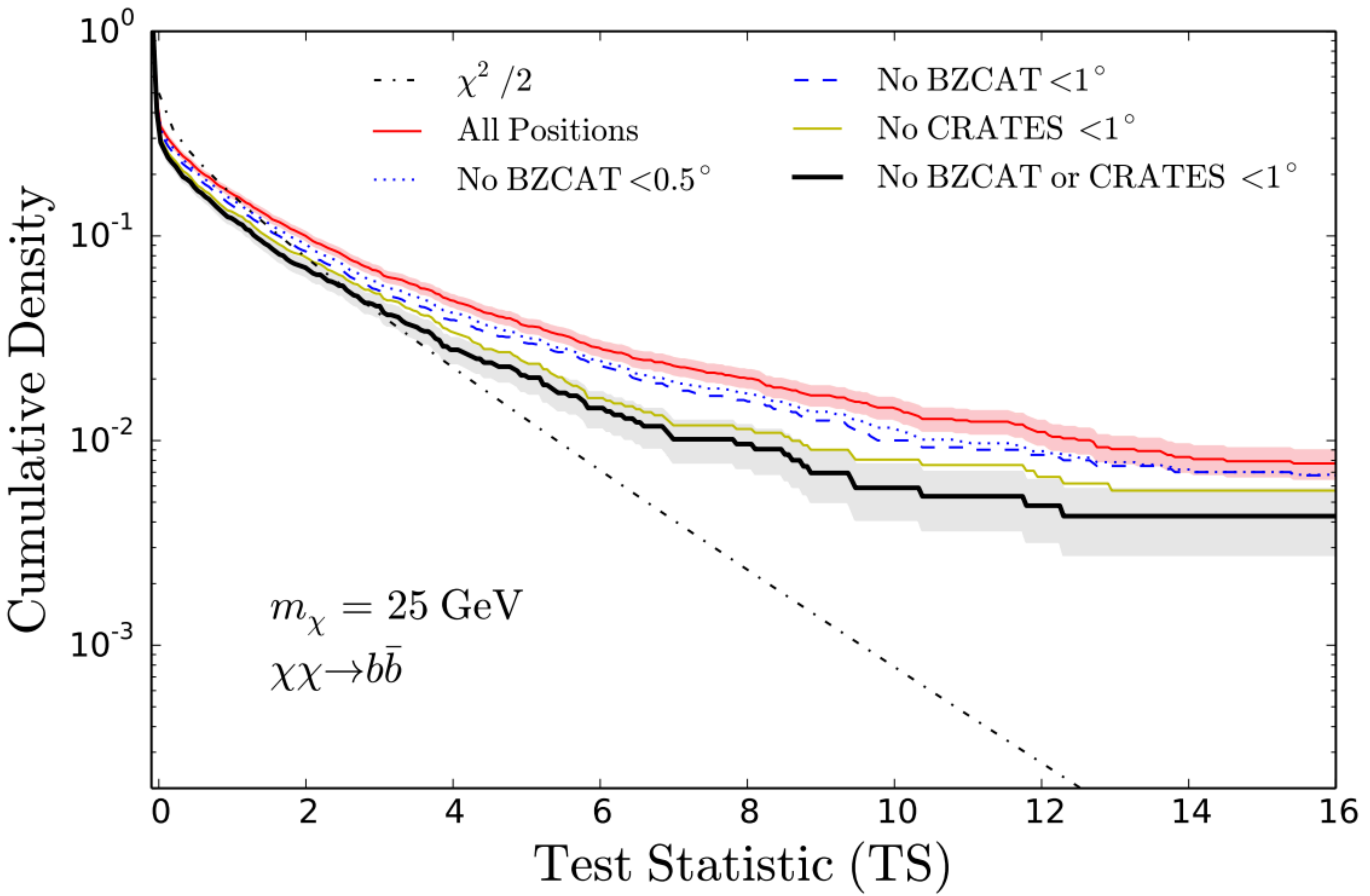
Status: Dwarf Spheroidal Galaxies

Fermi-LAT Collaboration (2017; 1611.03184)



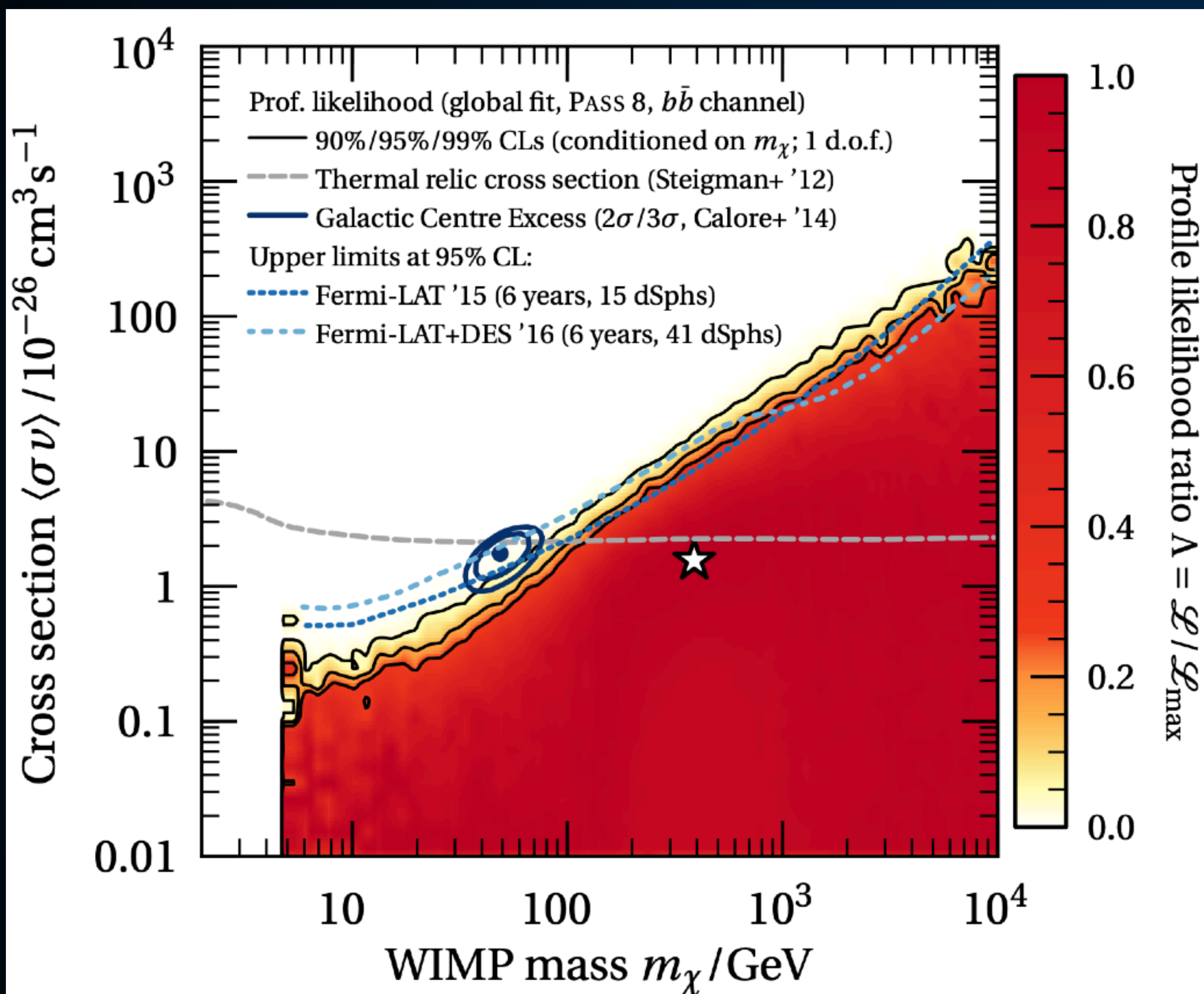
Status: Dwarf Spheroidal Galaxies

Carlson, Hooper, Linden (1409.1572)

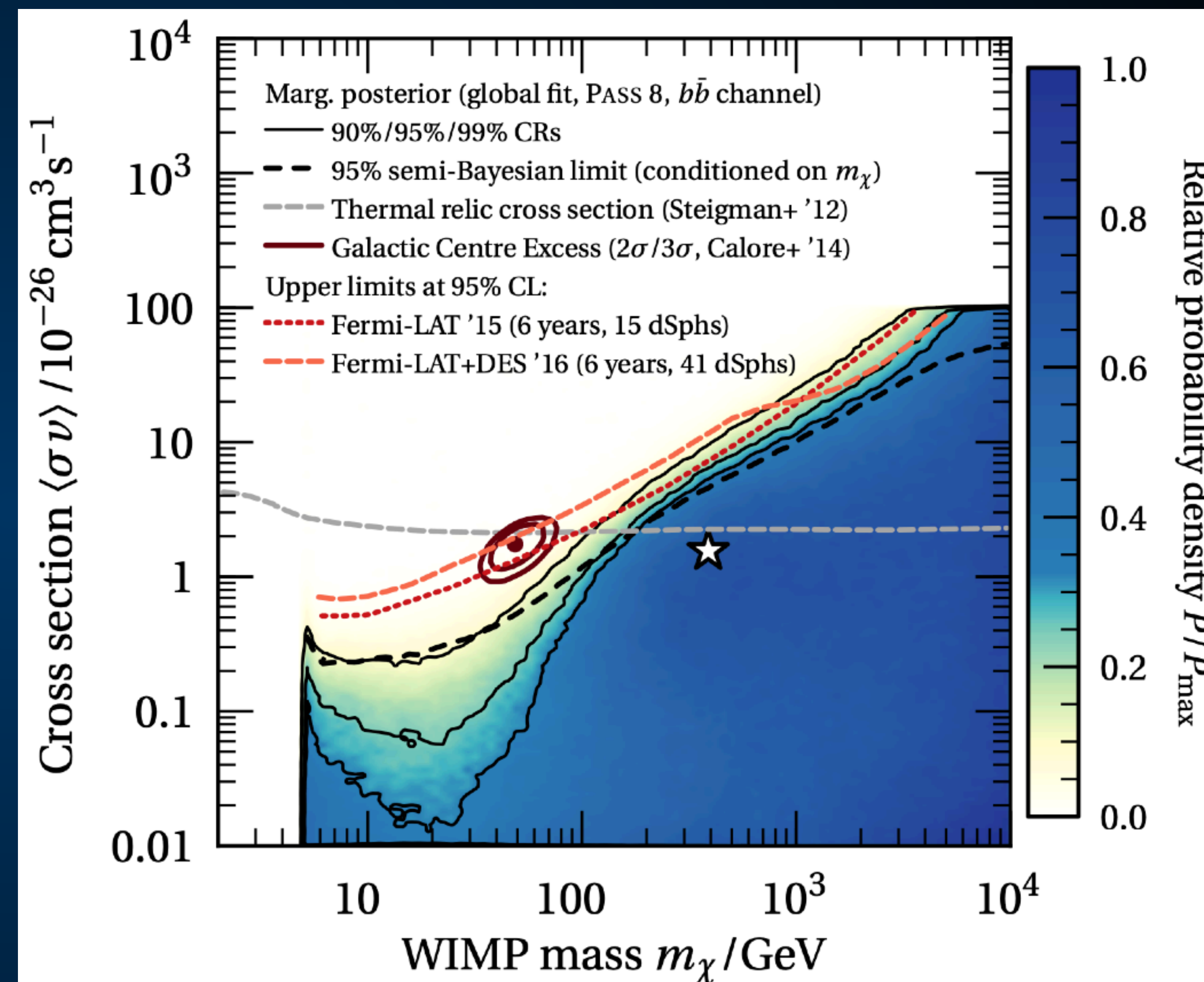


Status: Dwarf Spheroidal Galaxies

Hoof, Geringer-Sameth, Trotta (1812.06986)

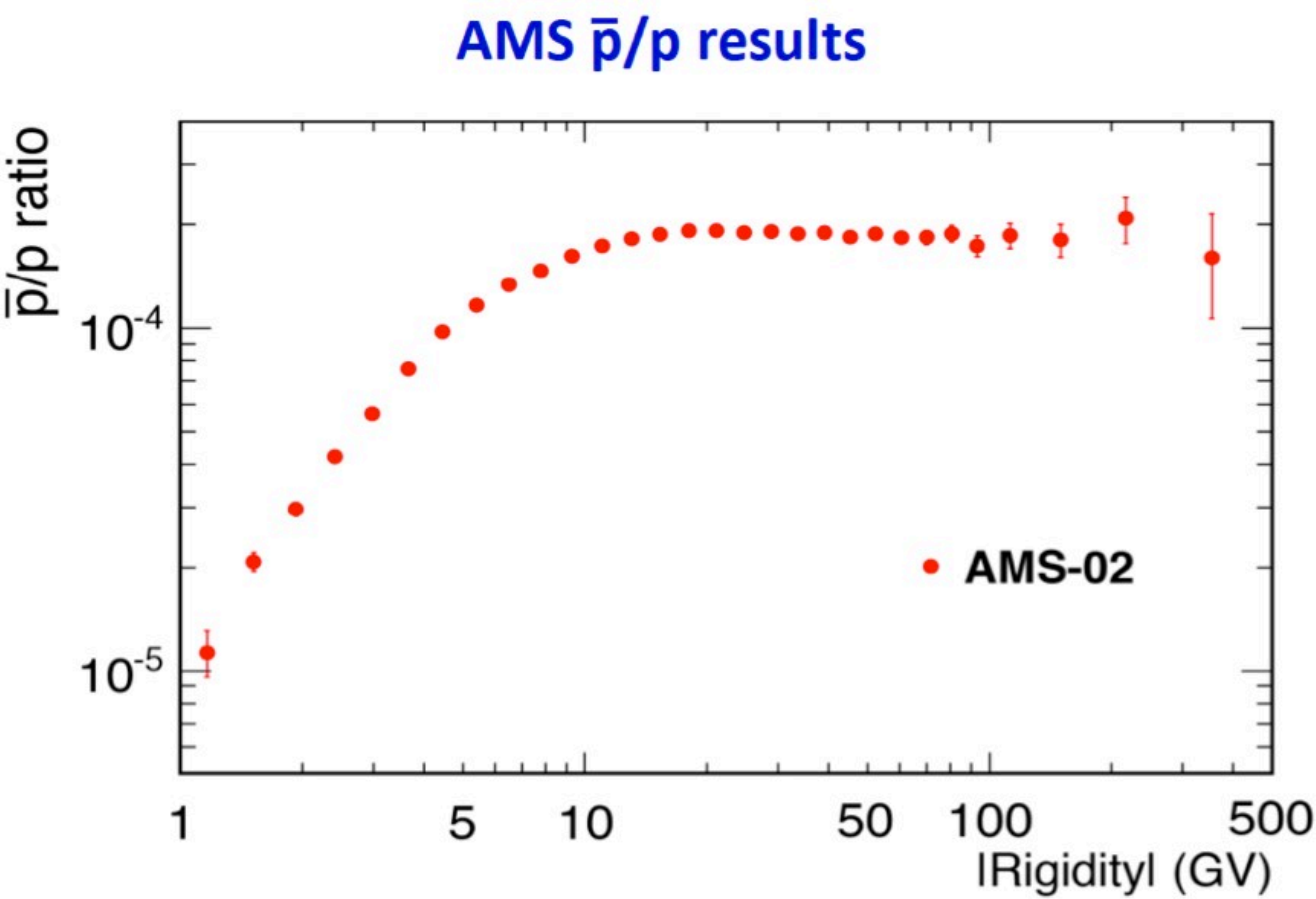


Frequentist



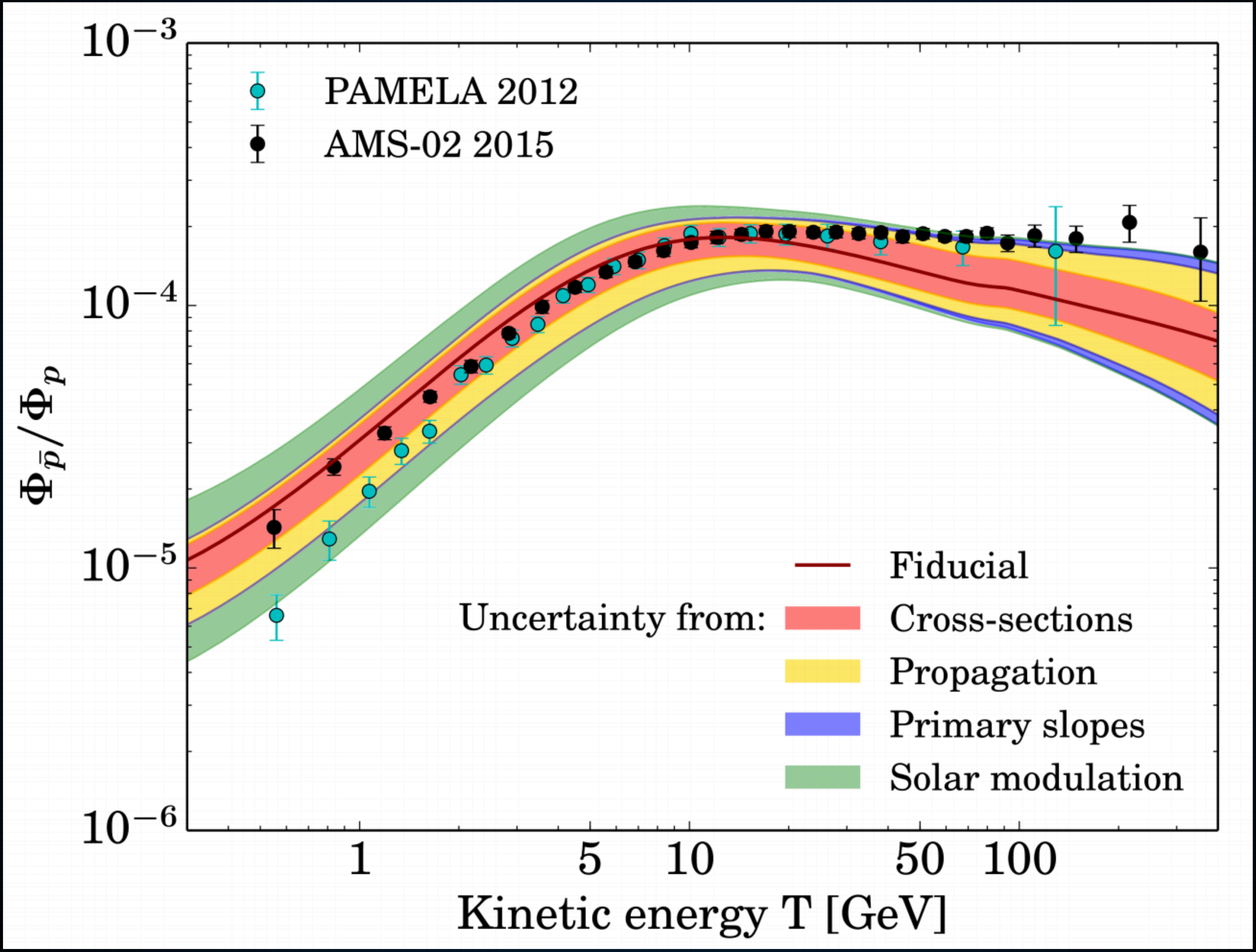
Bayesian

Status: Antiprotons



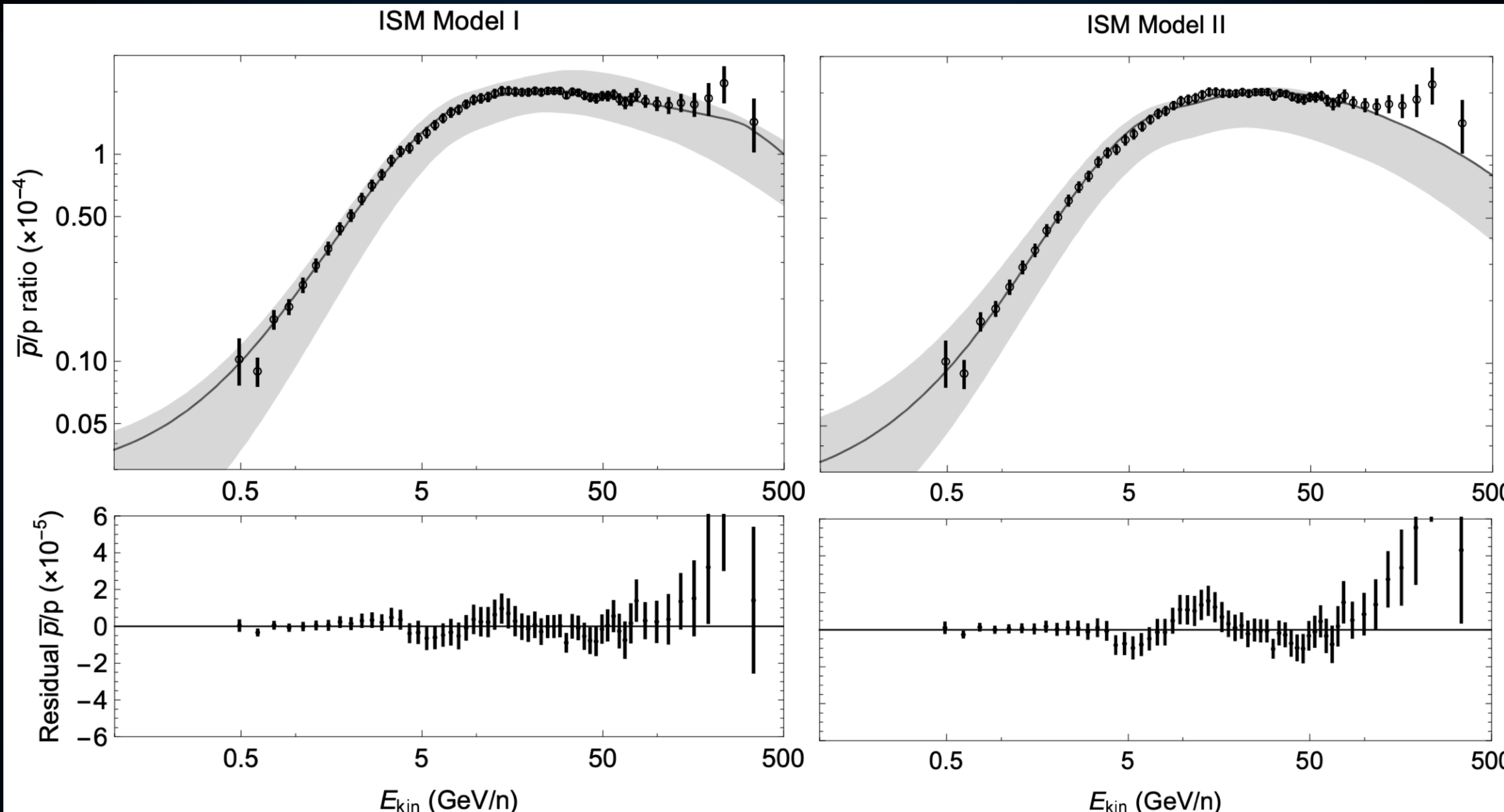
Status: Antiprotons

Giesen et al. (2015; 1504.04276)



Status: Antiprotons

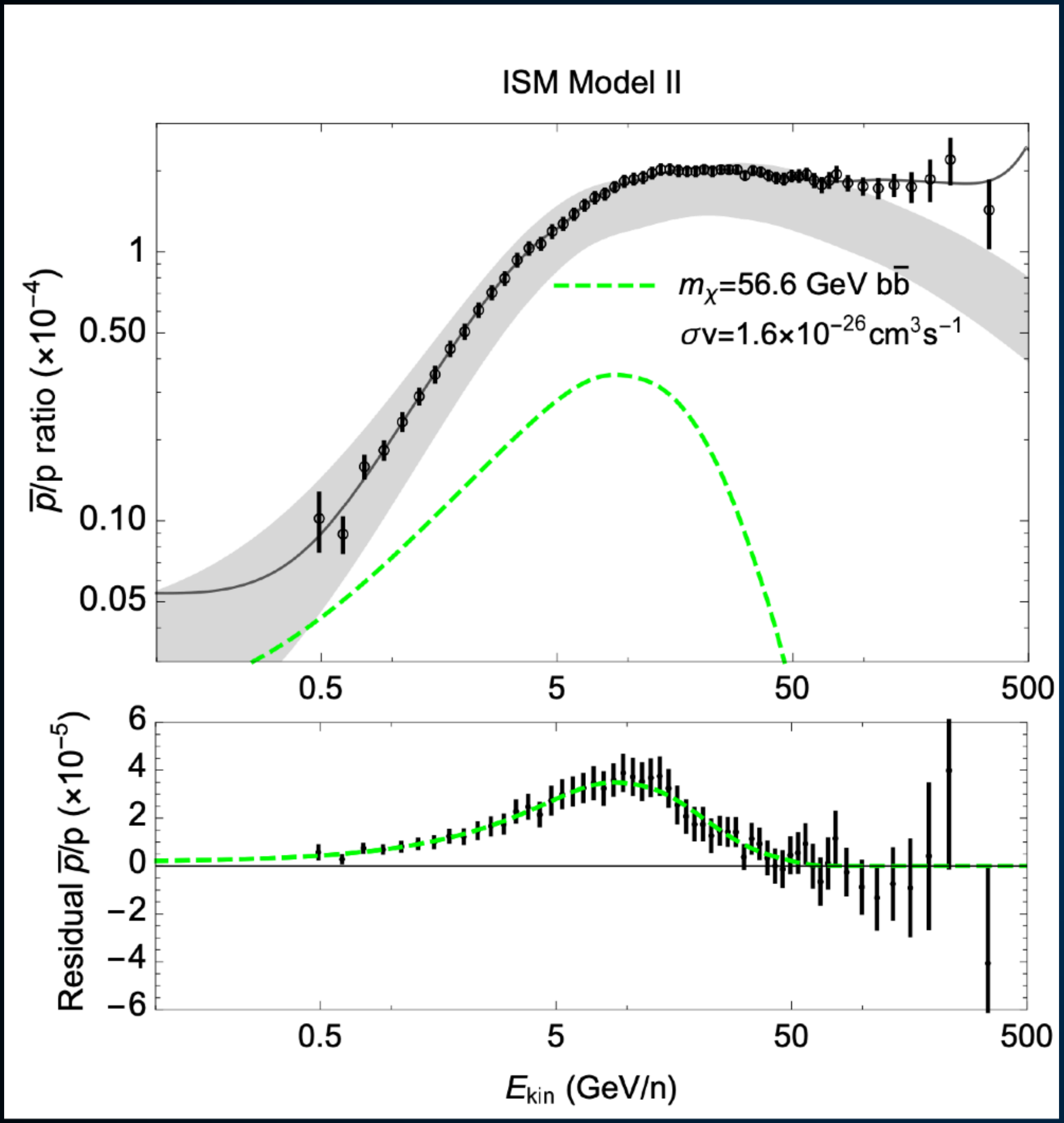
Cholis, Linden, Hooper (2019; 1903.02549)

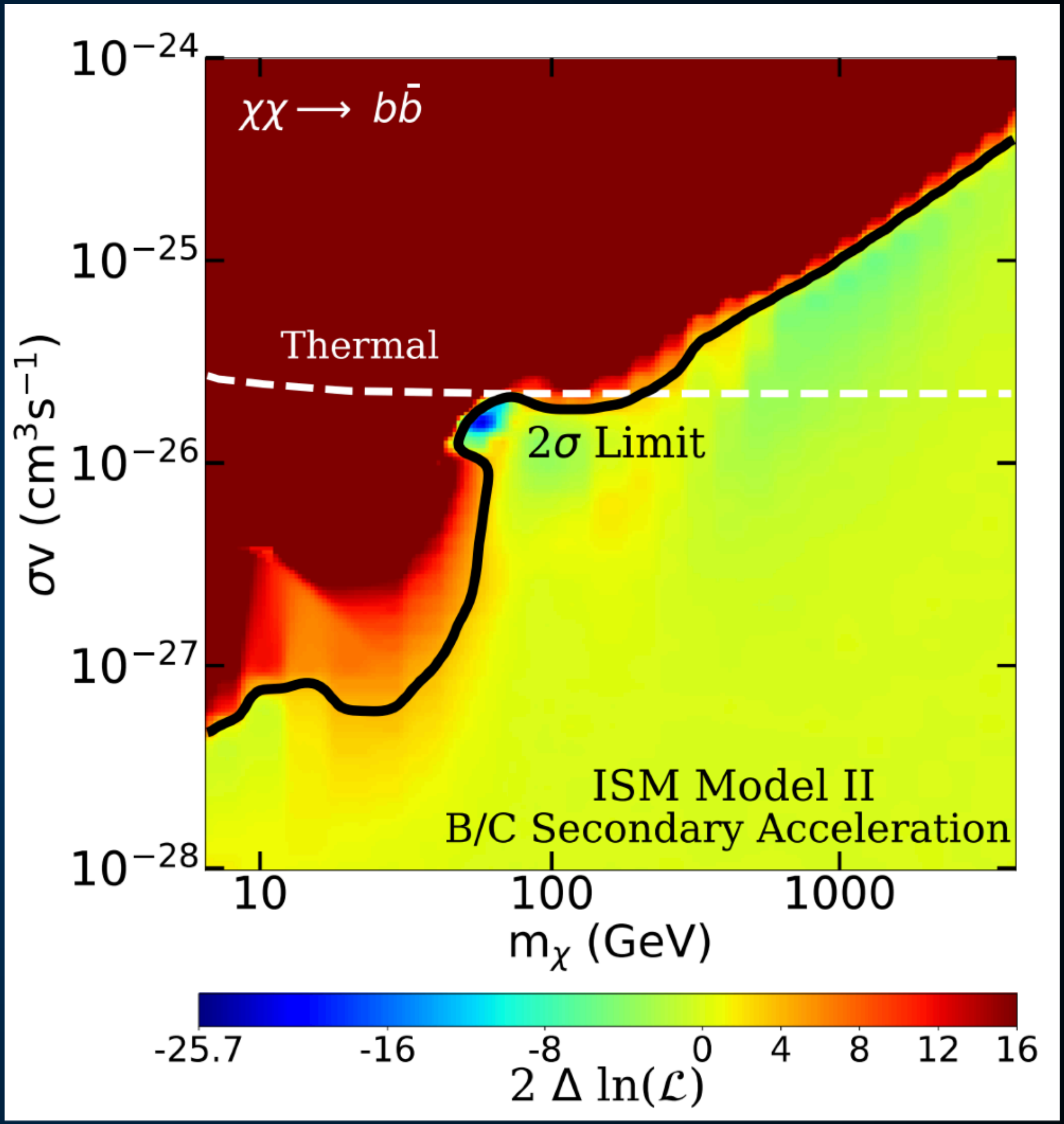


- The energy spectrum of the background is well known, can find small excesses.

Status: Antiprotons

Cholis, Linden, Hooper (2019; 1903.02549)

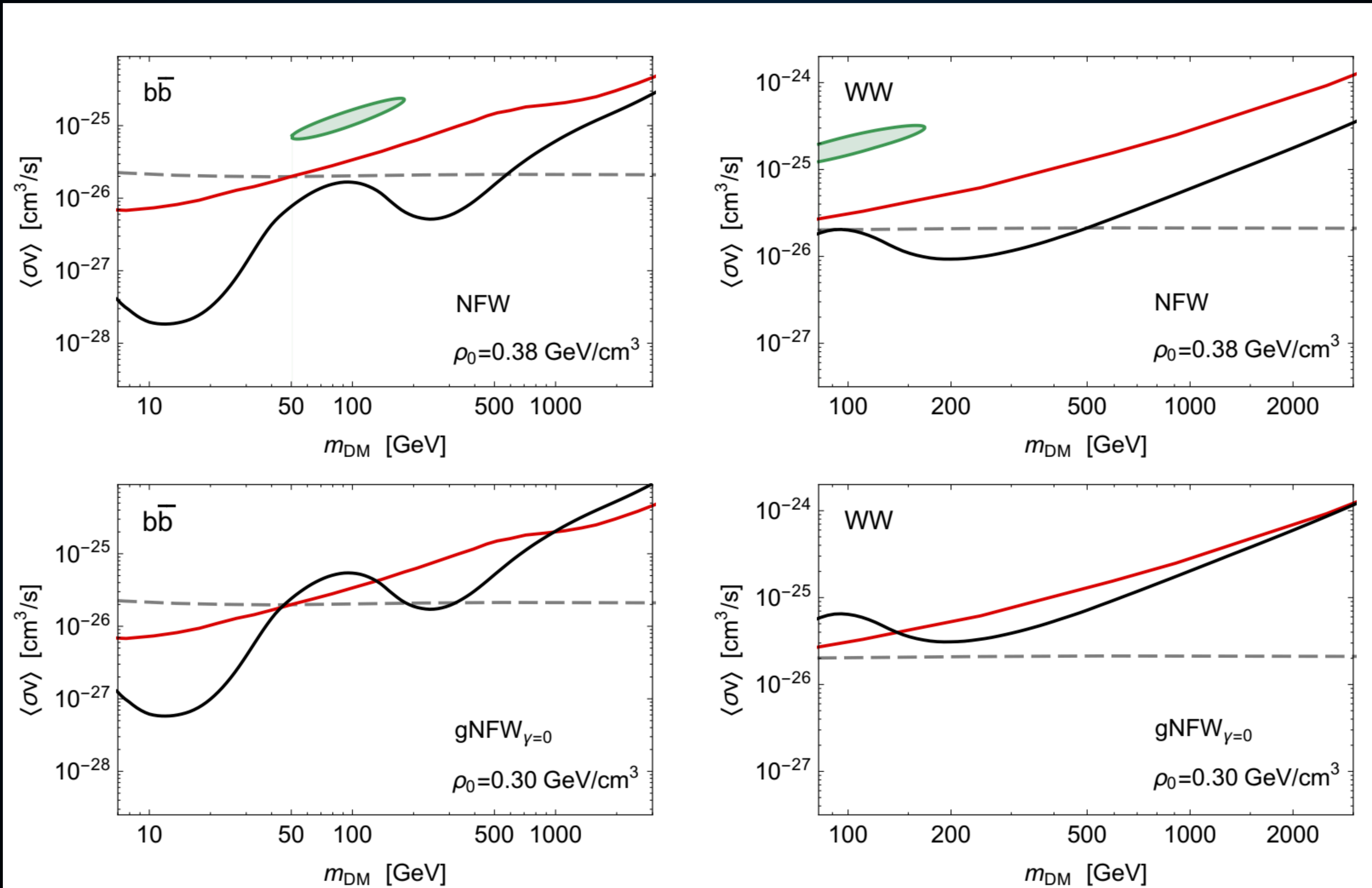




- **The error bars are very small, can get interesting behavior in the limits.**

Status: Antiprotons

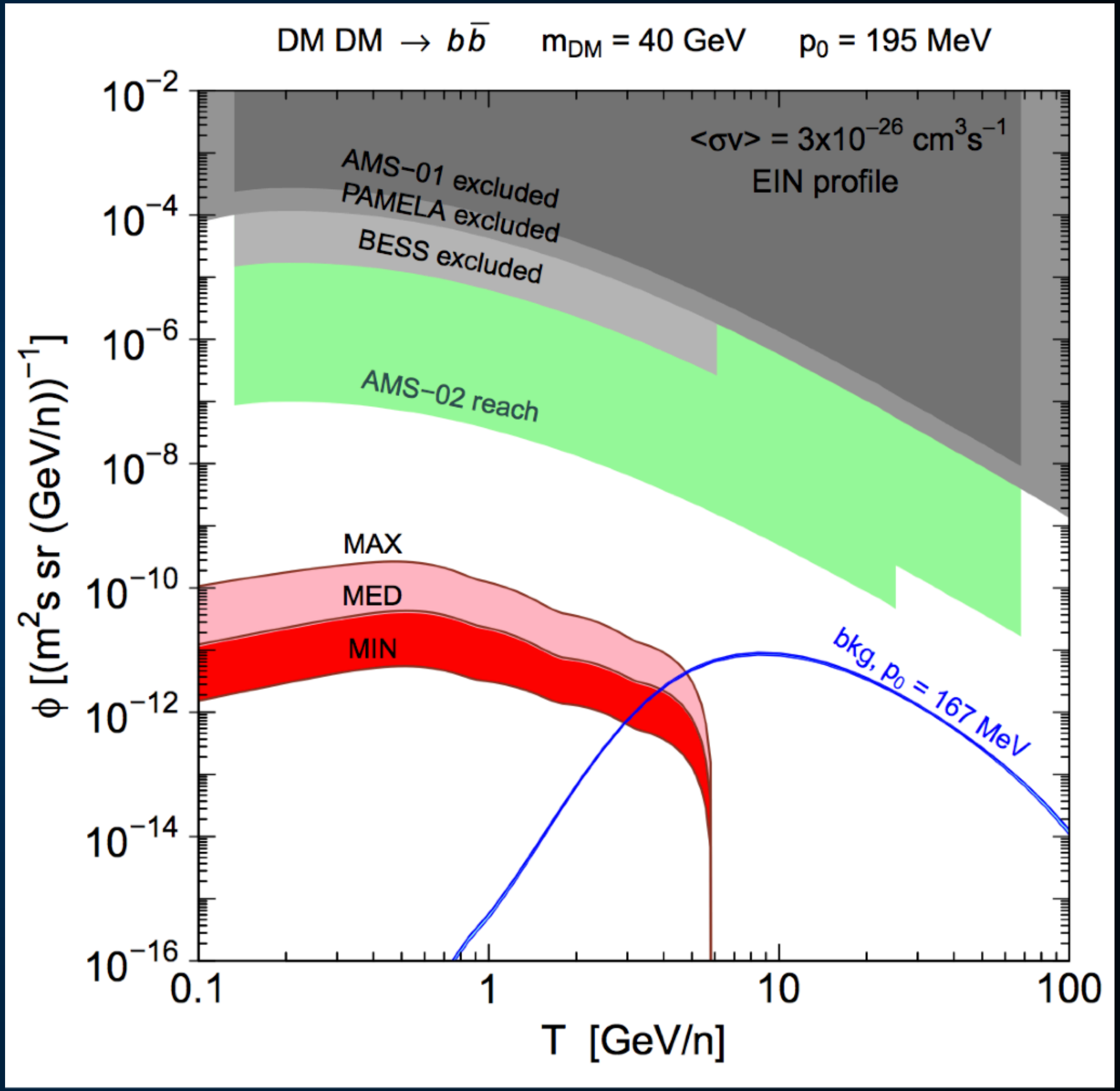
Reinert & Winkler (2017; 1712.00002)



Status: Anti-Nuclei

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

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

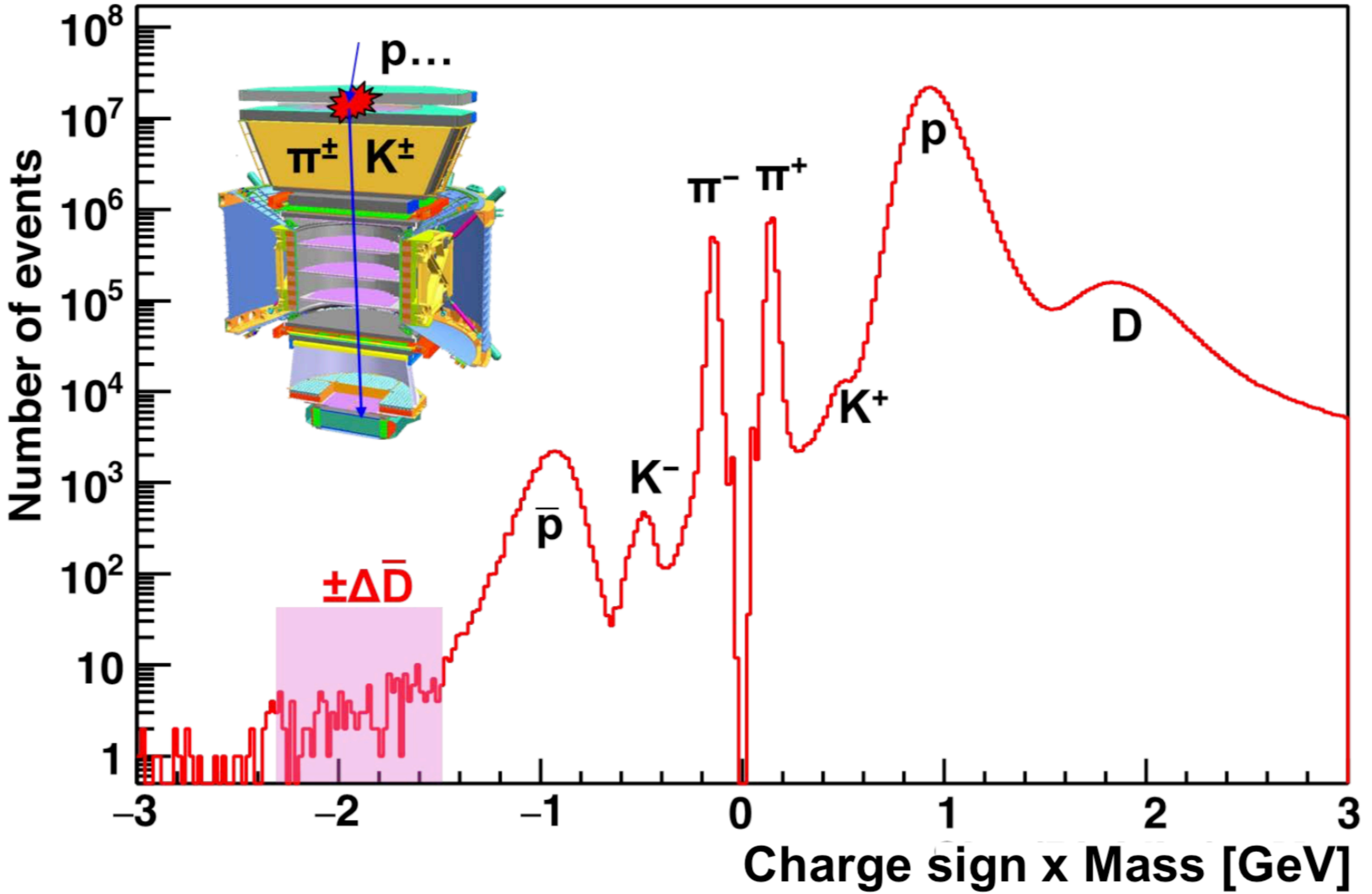


Cirelli et al. (1401.4017)

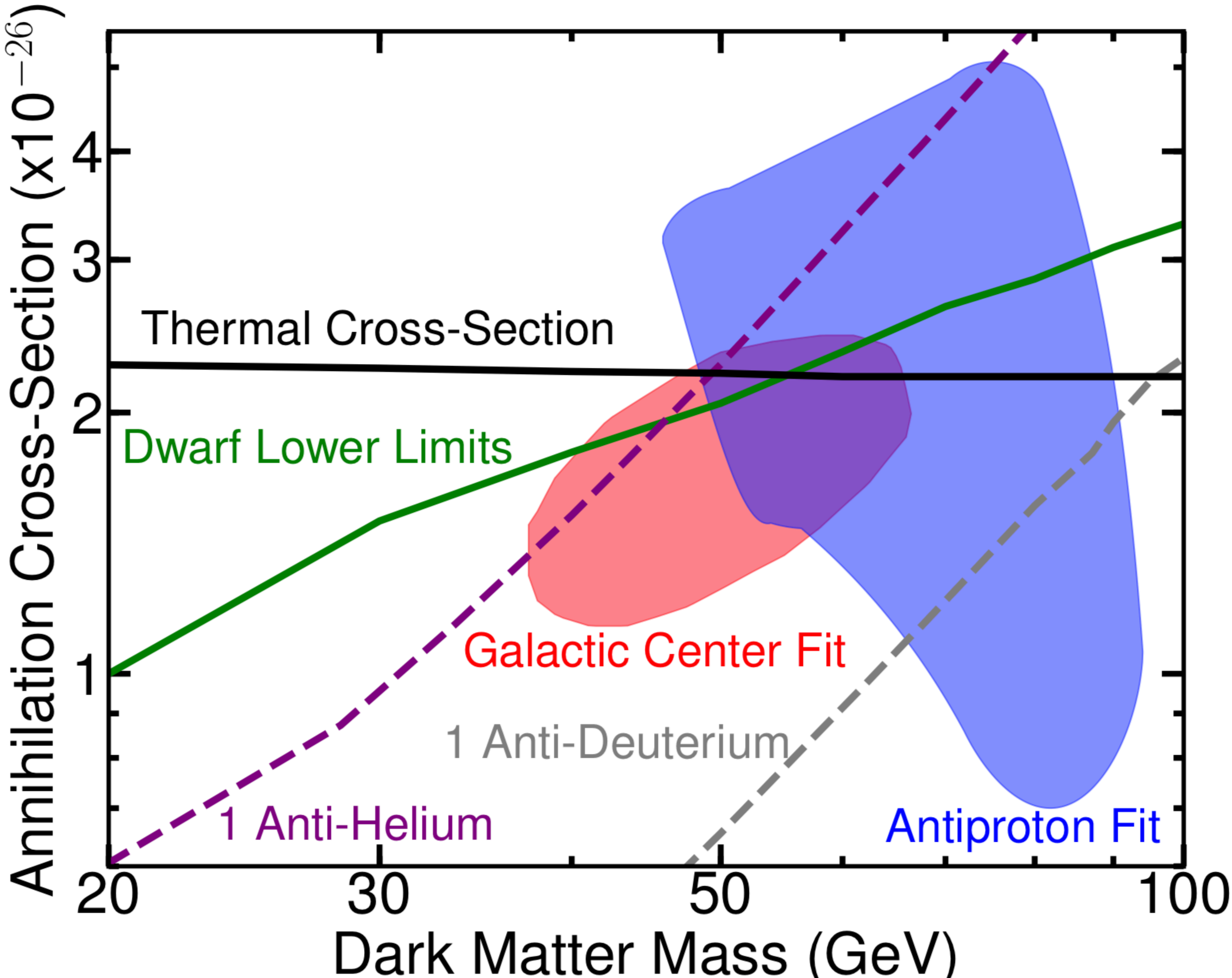
To date, we have observed eight events in the mass region from 0 to 10 GeV with Z= –2. All eight events are in the helium mass region.

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 $\overline{\mathrm{He}}$ events is less than 3×10^{-8}. For the two $^{4}\overline{\mathrm{He}}$ 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}.

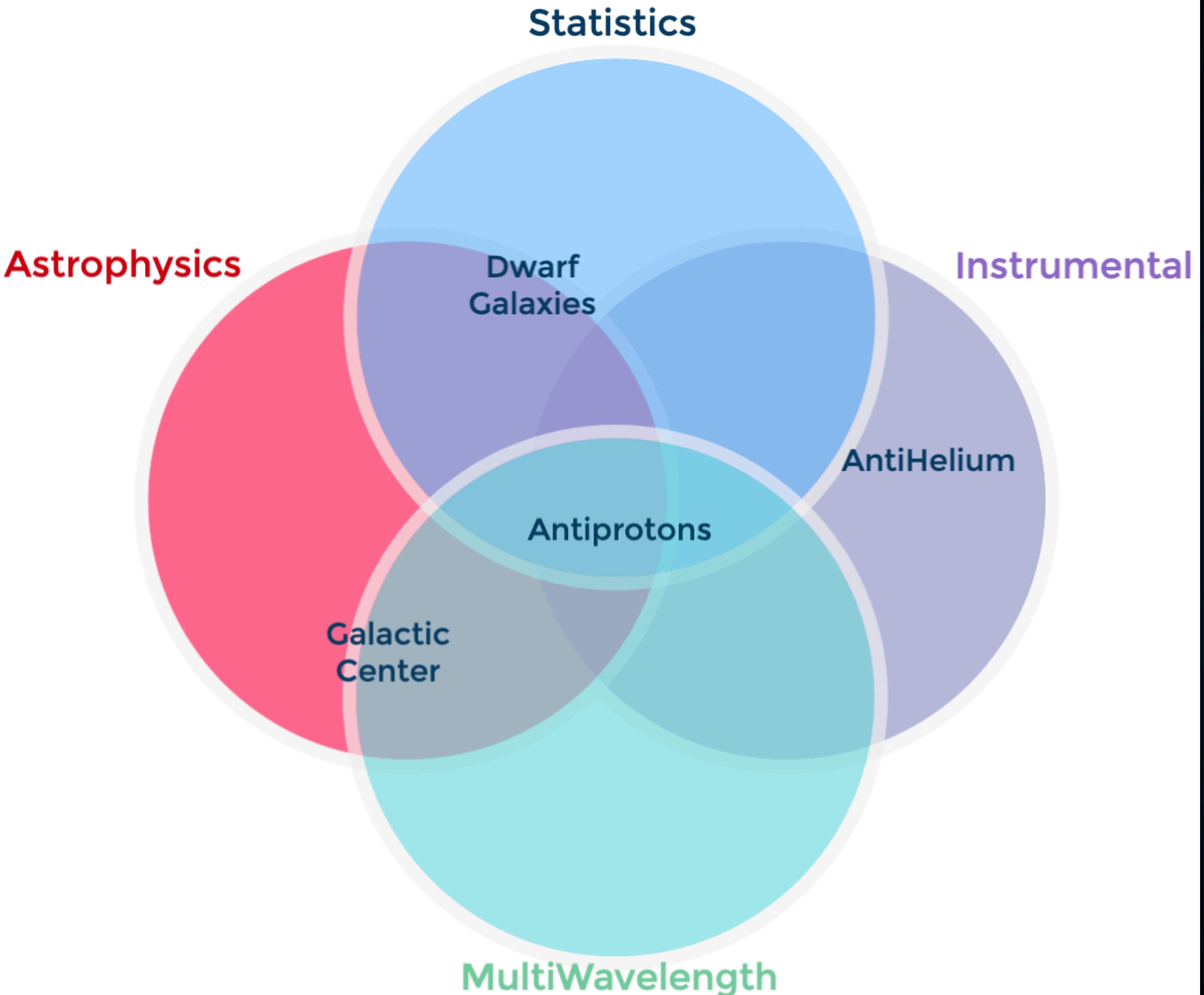
Note that for $^{4}\overline{\mathrm{He}}$, projecting based on the statistics we have today, by using an additional 400 million core hours for simulation the background probability would be 10^{-4}. Simultaneously, continuing to run until 2023, which doubles the data sample, the background probability for $^{4}\overline{\mathrm{He}}$ 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…
$\pi^\pm$ $K^\pm$
π^- π^+
p
D
K^+
K^-
$\bar{p}$
$\pm\Delta\bar{D}$
–3
–2
–1
0
1
2
3
Charge sign x Mass [GeV]


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)

The Future


Statistics
Astrophysics
Instrumental
Dwarf Galaxies
AntiHelium
Antiprotons
Galactic Center
MultiWavelength

Future: Galactic Center

Analyzing the Gamma-ray Sky with Wavelets

Bhaskaran Balaji,[1,*] Ilias Cholis,[1] Patrick J. Fox,[2] and Samuel D. McDermott[3]

[1] *Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, Maryland, 21218, USA*
[2] *Theoretical Physics Department, Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA*
[3] *Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA*
(Dated: March 7, 2018)

We analyze the gamma-ray sky at energies of 0.5 to 50 GeV using the undecimated wavelet transform on the sphere. Focusing on the inner $60^\circ \times 60^\circ$ of the sky, we identify and characterize four separate residuals beyond the expected Milky Way diffuse emission. We detect the *Fermi* Bubbles, finding compelling evidence that they are diffuse in nature and contain very little small-scale structure. We detect the "cocoon" inside the Southern Bubble, and we also identify its northern counterpart above 2 GeV. The Northern Cocoon lies along the same axis but is $\sim 30\%$ dimmer than the southern one. We characterize the Galactic center excess, which we find extends up to 20° in $|b|$. At latitudes $|b| \leq 5^\circ$ we find evidence for power in small angular scales that could be the result of point-source contributions, but for $|b| \geq 5^\circ$ the Galactic center excess is dominantly diffuse in its nature. Our findings show that either the Galactic center excess and *Fermi* Bubbles connect smoothly or that the Bubbles brighten significantly below 15° in latitude. We find that the Galactic center excess appears off-center by a few degrees towards negative ℓ. Additionally, we find and characterize two emissions along the Galactic disk centered at $\ell \simeq +25^\circ$ and -20°. These emissions are significantly more elongated along the Galactic disk than the Galactic center excess.

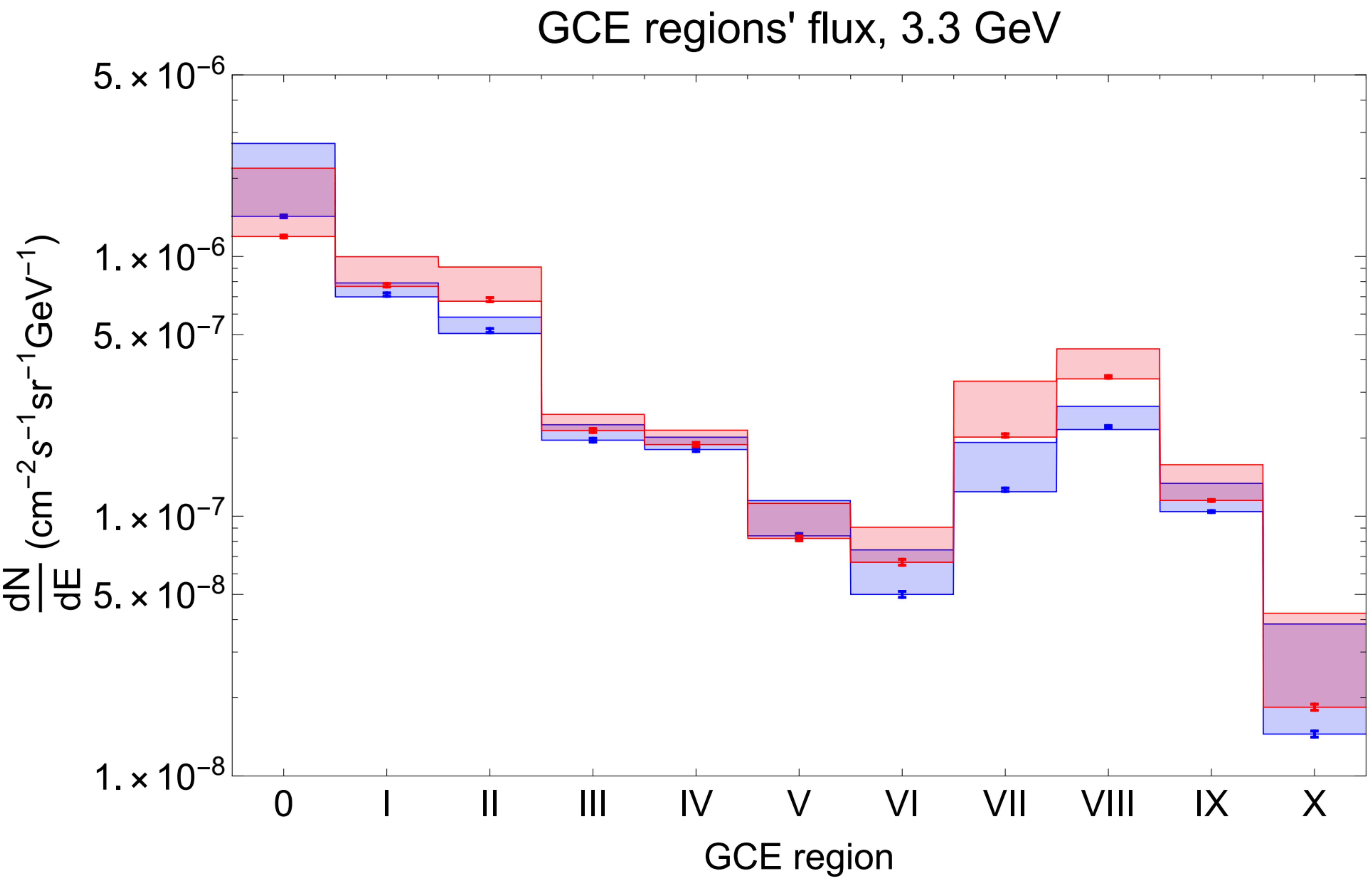
v1 [astro-ph.HE] 5 Mar 2018

I. INTRODUCTION

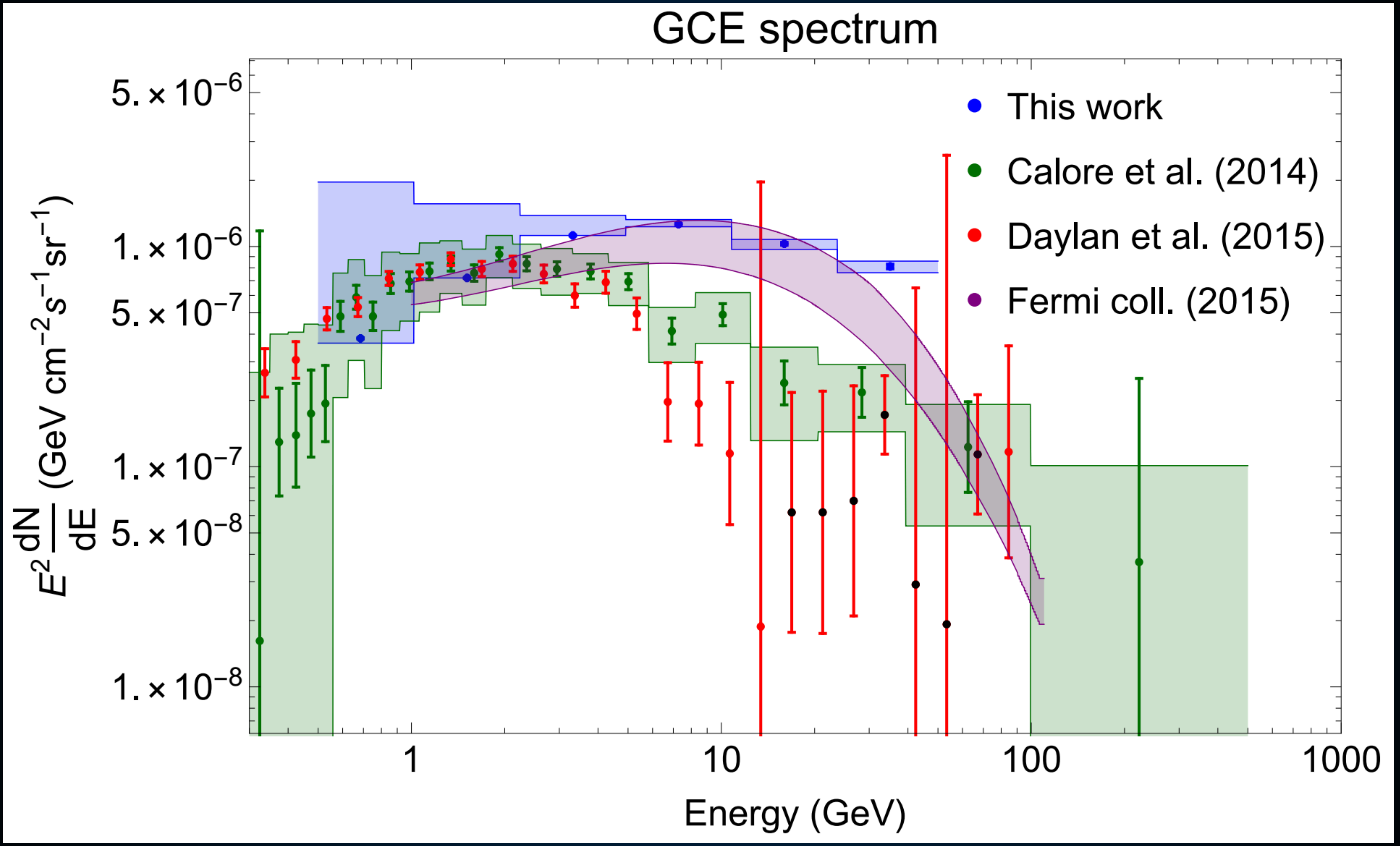
Electromagnetic radiation has allowed us a gateway to the mysteries of the Universe since time immemorial. Over the ages, we have become sensitive to radiation of increasingly higher energy. The highest energy photons are classified as gamma rays. Gamma-ray astronomy started in 1961 with 22 events observed by *Explorer 11* [1]. This was followed by *OSO-3*, which observed 621 photons and provided the first proof of emission from our own Milky Way [2]. Observations ensued with the *SAS-2*

cosmic rays (CRs) propagating in the Galaxy and interacting with the interstellar medium (ISM). The mechanism of diffuse emission is conventionally broken down into three classes, depending on the type of CR and the type of target it impinges upon. The dominant contribution to diffuse emission is from inelastic collisions of CR *nuclei* with ISM gas; these collisions produce neutral particles, predominantly π^0 and η mesons, whose decay products include photons. This emission is conventionally referred to as π^0-emission [14, 15]. CR *electrons* can also interact with the ISM gas [16]. The resulting photons

Future: Galactic Center

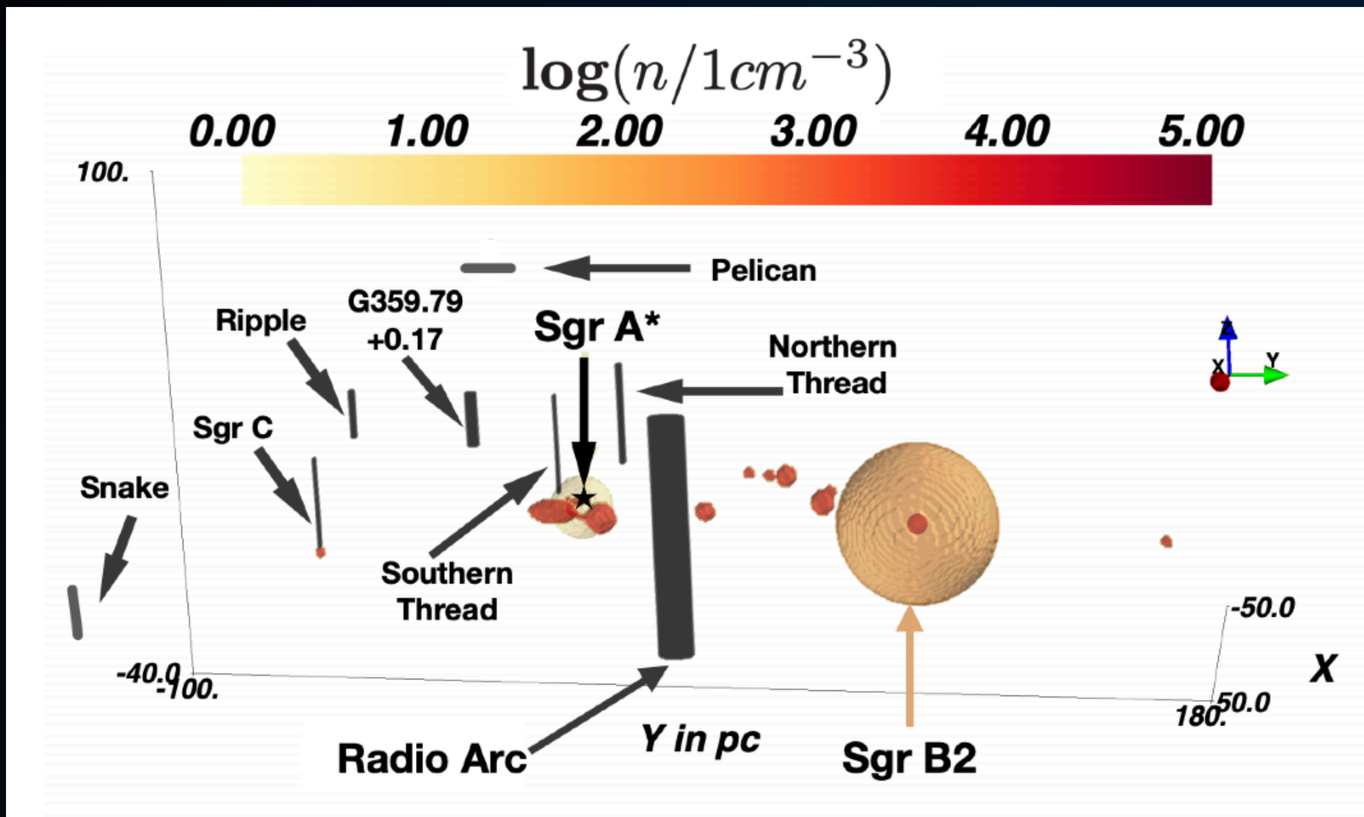


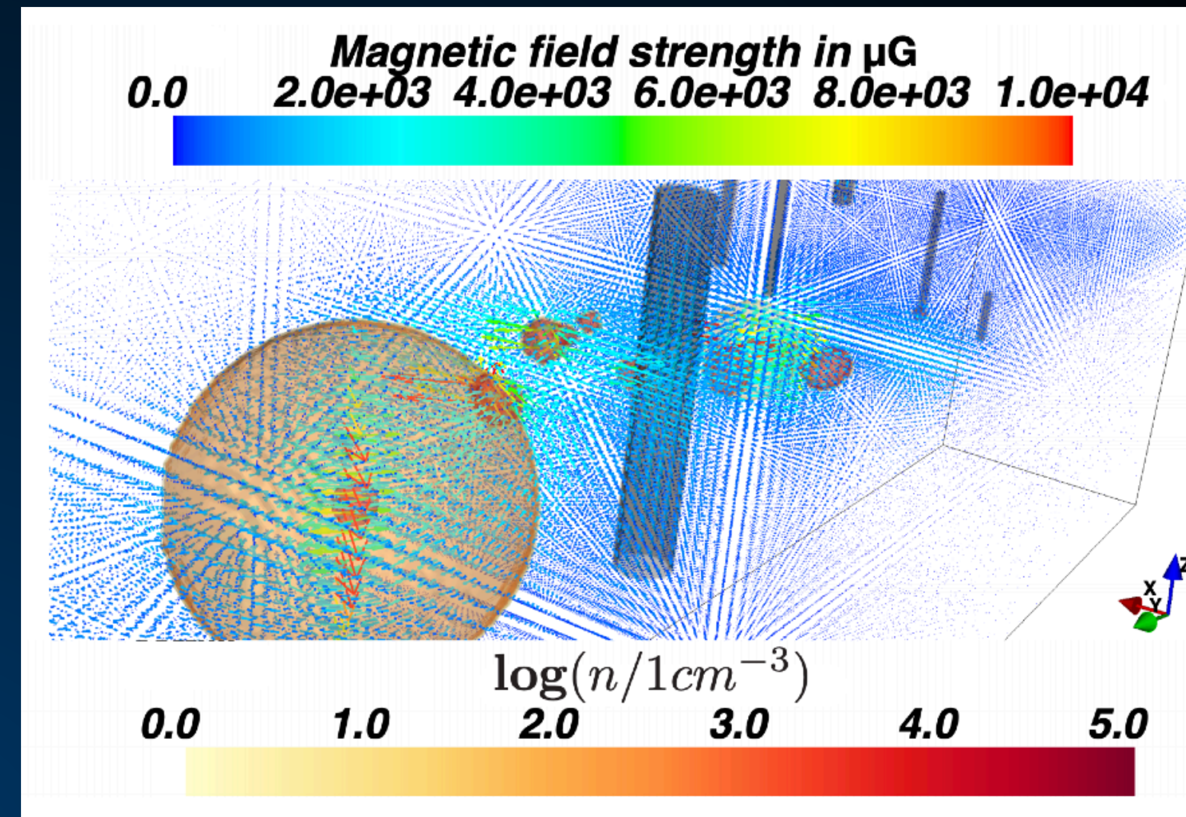
Future: Galactic Center



Future: Galactic Center

Guenduez et al. (2019; 1906.05211)



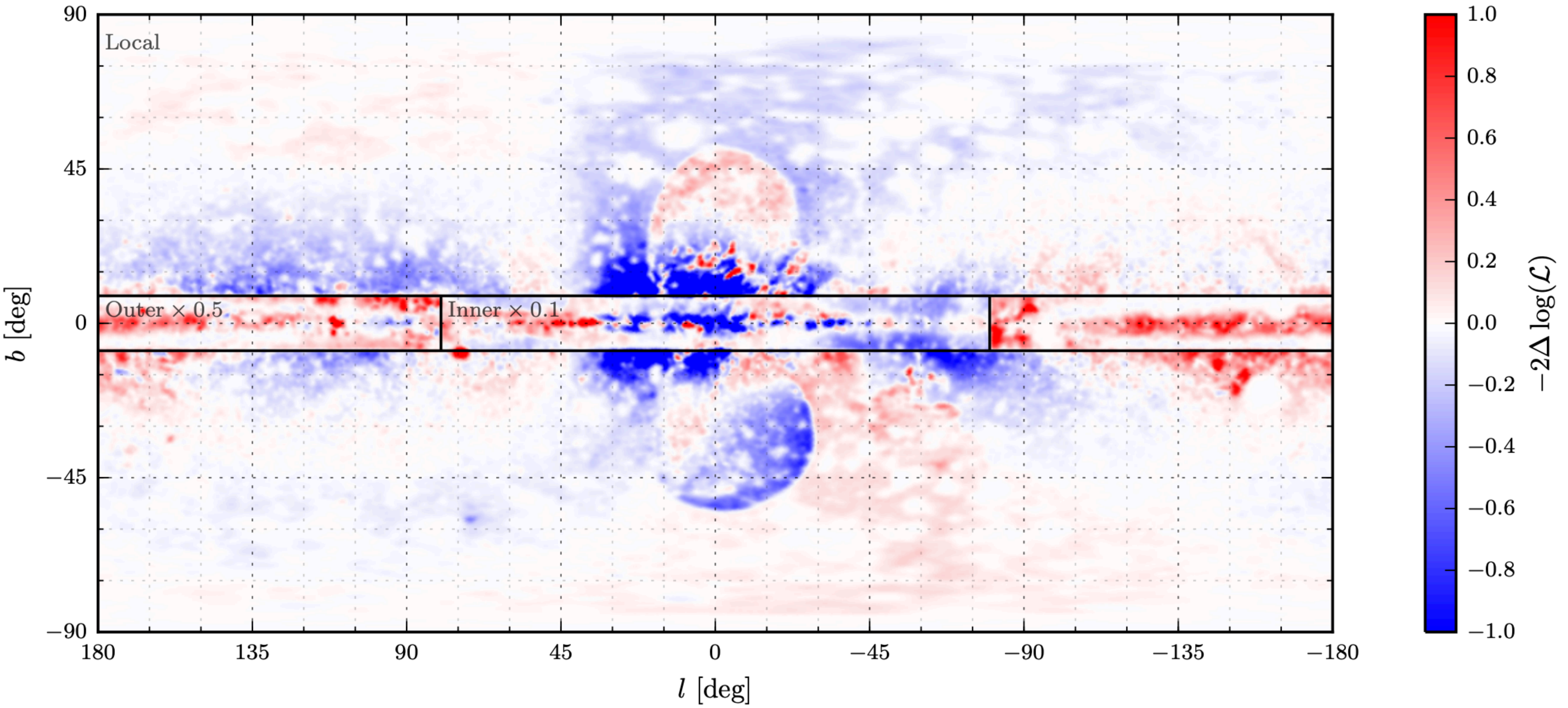


- **New models of Milky Way Gas and Magnetic fields.**

- **Can use multi wavelength observations to constrain cosmic-ray propagation.**

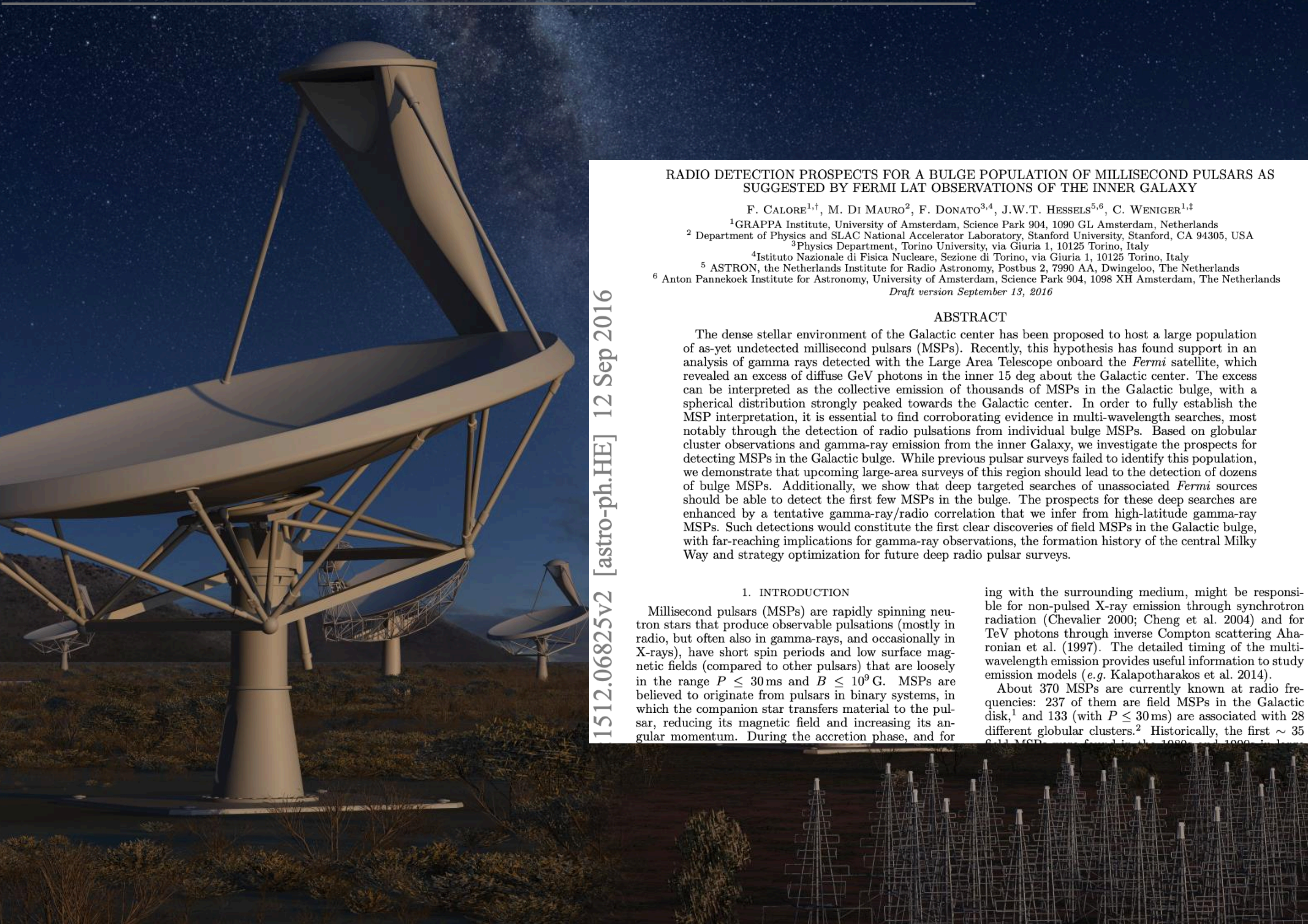
Future: Galactic Center

Carlson, TL, Profumo (2016; 1603.06584)



- **Changing diffusion parameters near the Galactic center can significant affect the fit of the diffuse background model.**

Future: Galactic Center



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

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

ABSTRACT

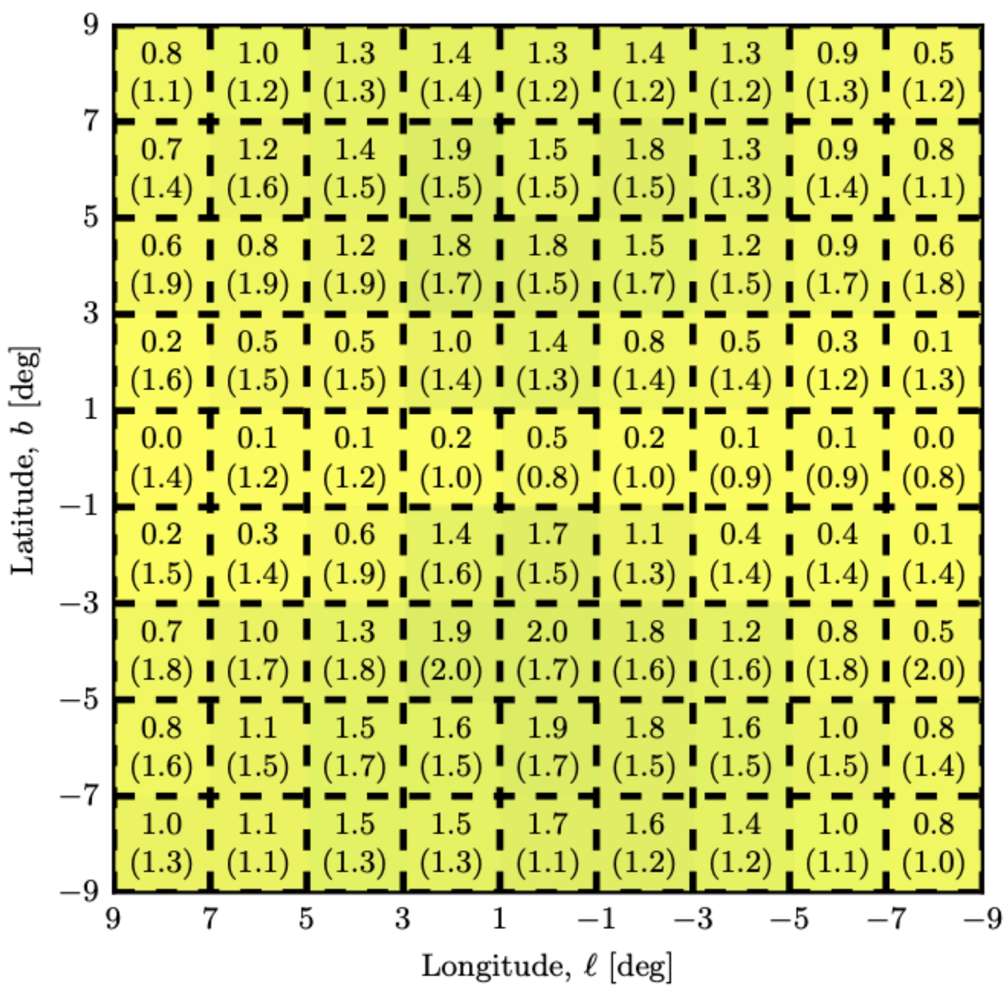
The dense stellar environment of the Galactic center has been proposed to host a large population of as-yet undetected millisecond pulsars (MSPs). Recently, this hypothesis has found support in an analysis of gamma rays detected with the Large Area Telescope onboard the *Fermi* satellite, which revealed 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.

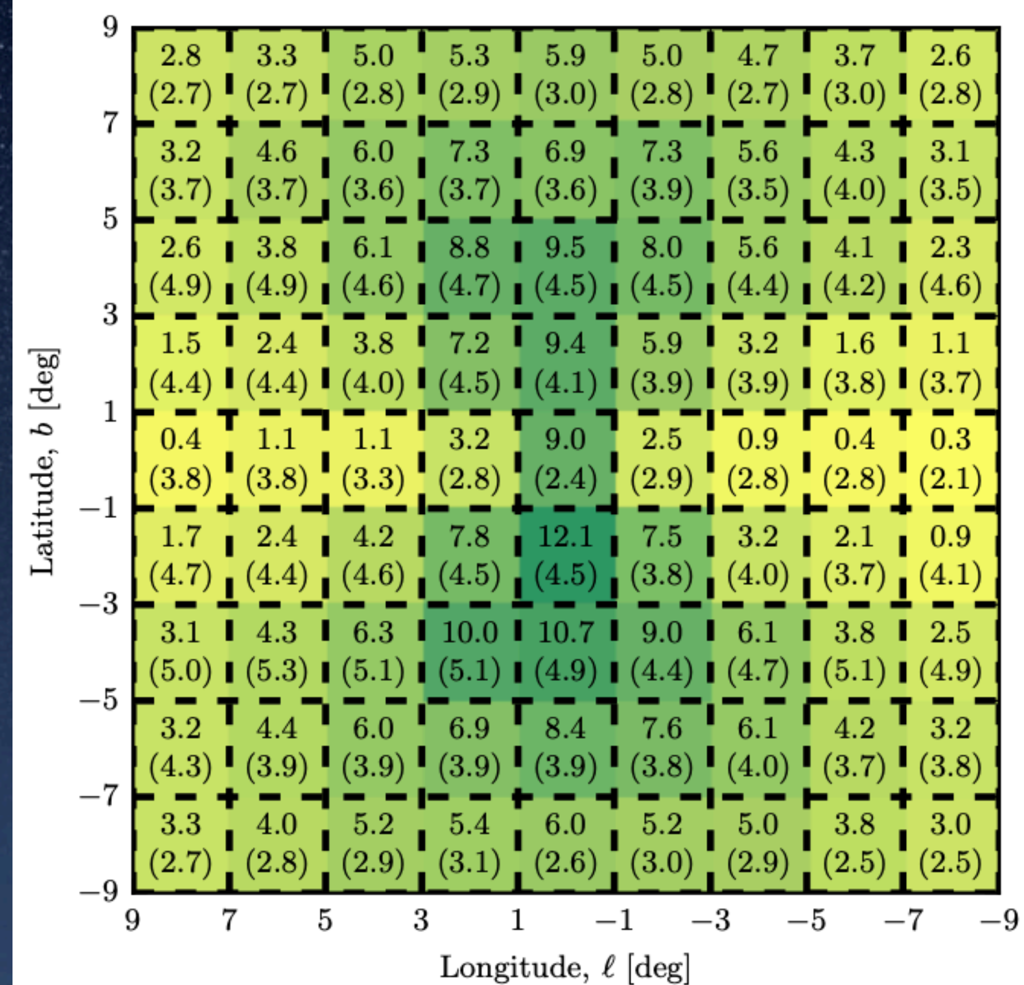
1. INTRODUCTION

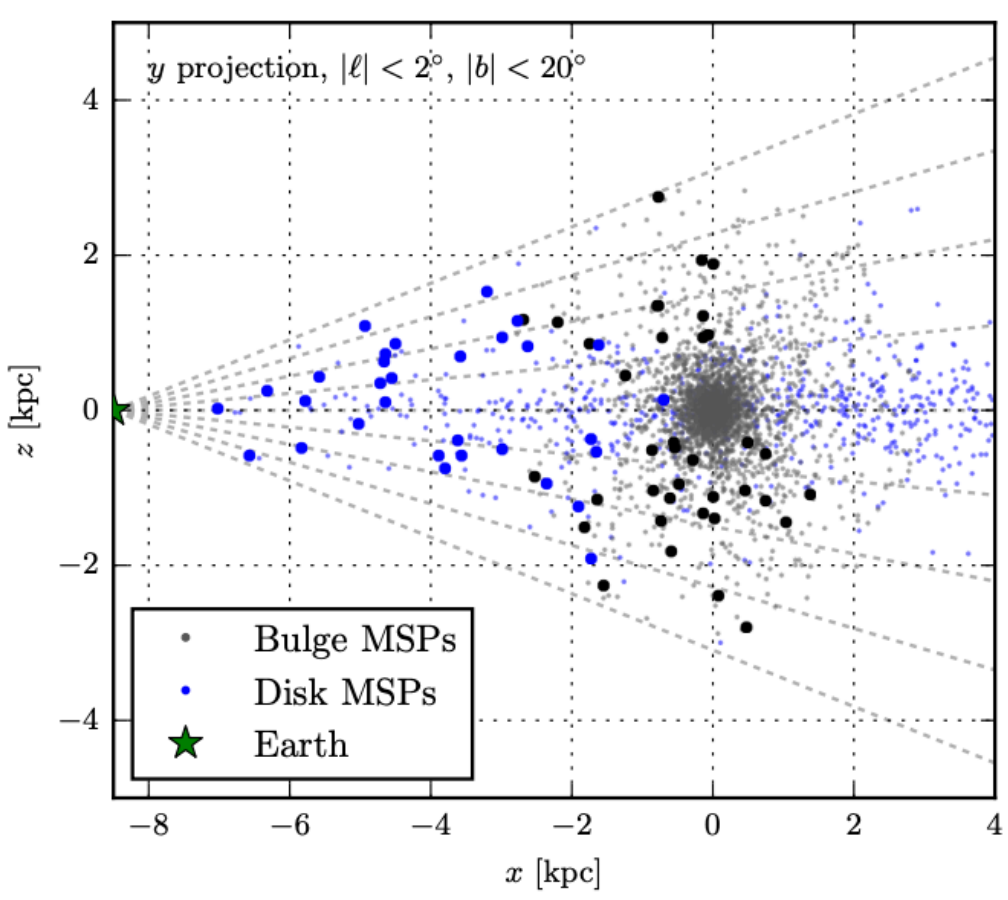
Millisecond pulsars (MSPs) are rapidly spinning neutron stars that produce observable pulsations (mostly in radio, but often also in gamma-rays, and occasionally in X-rays), have short spin periods and low surface magnetic fields (compared to other pulsars) that are loosely in the range $P \leq 30\,\mathrm{ms}$ 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).

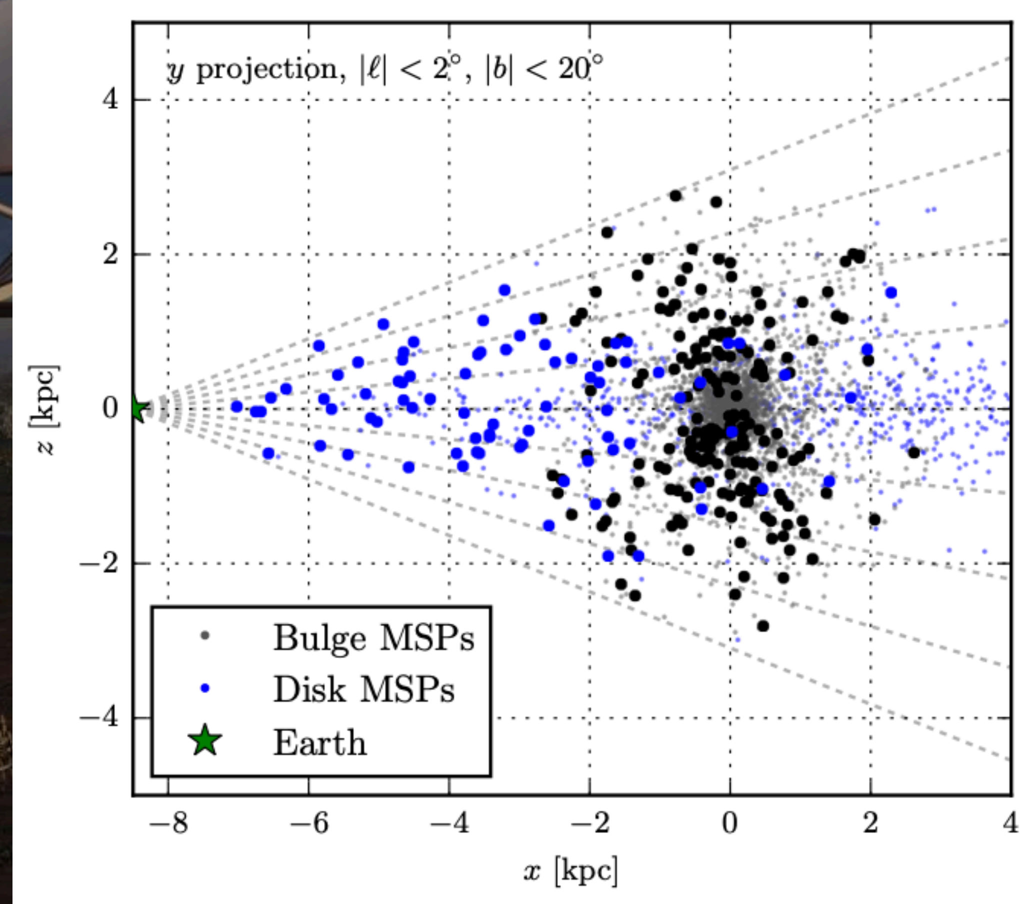
About 370 MSPs are currently known at radio frequencies: 237 of them are field MSPs in the Galactic disk,[1] and 133 (with $P \leq 30\,\mathrm{ms}$) are associated with 28 different globular clusters.[2] Historically, the first $\sim$ 35

Future: Galactic Center









Future: Dwarf Spheroidal Galaxies

Probing the Fundamental Nature of Dark Matter with the Large Synoptic Survey Telescope

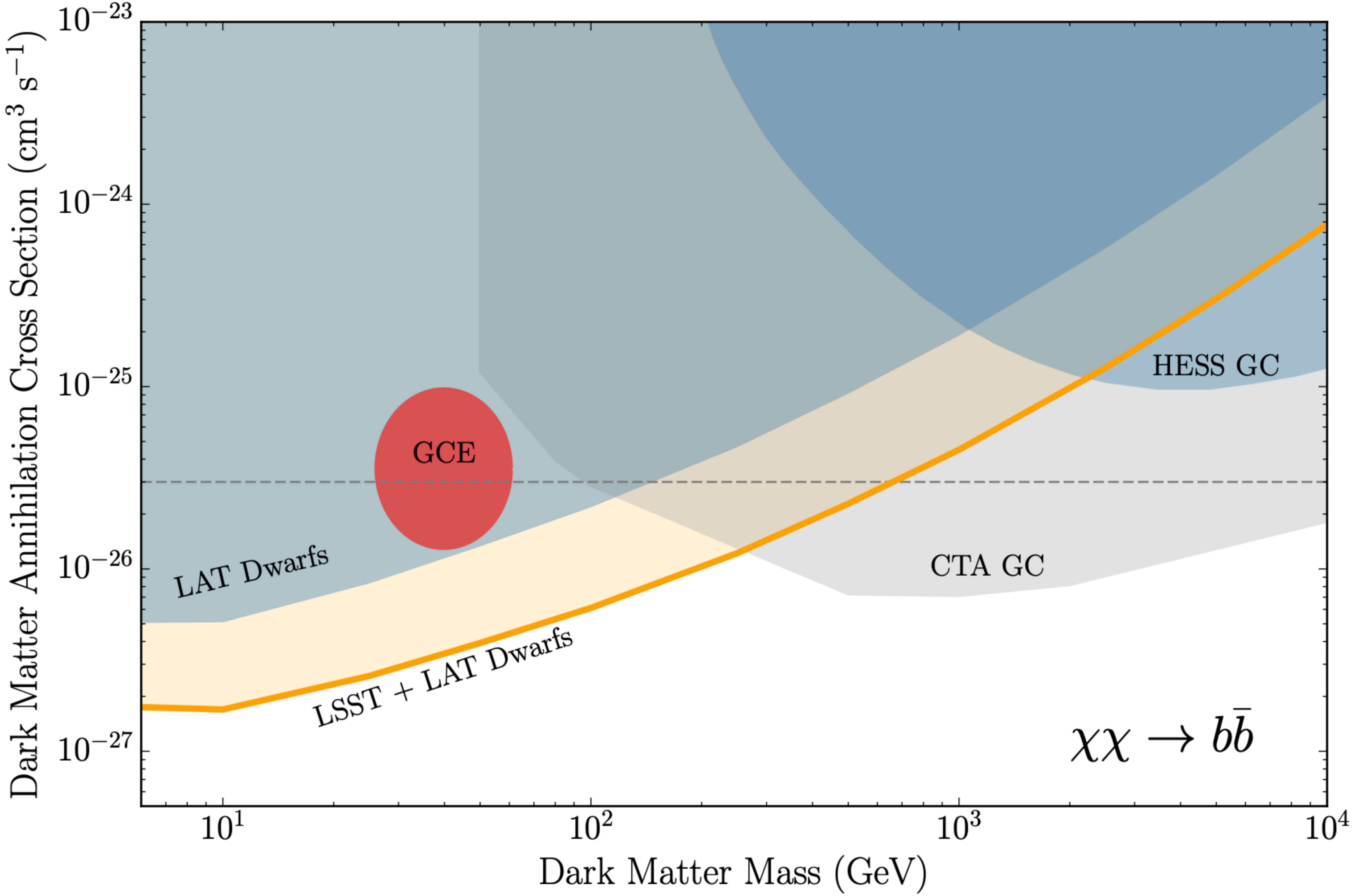
LSST Dark Matter Group

April 25, 2019

v1.1

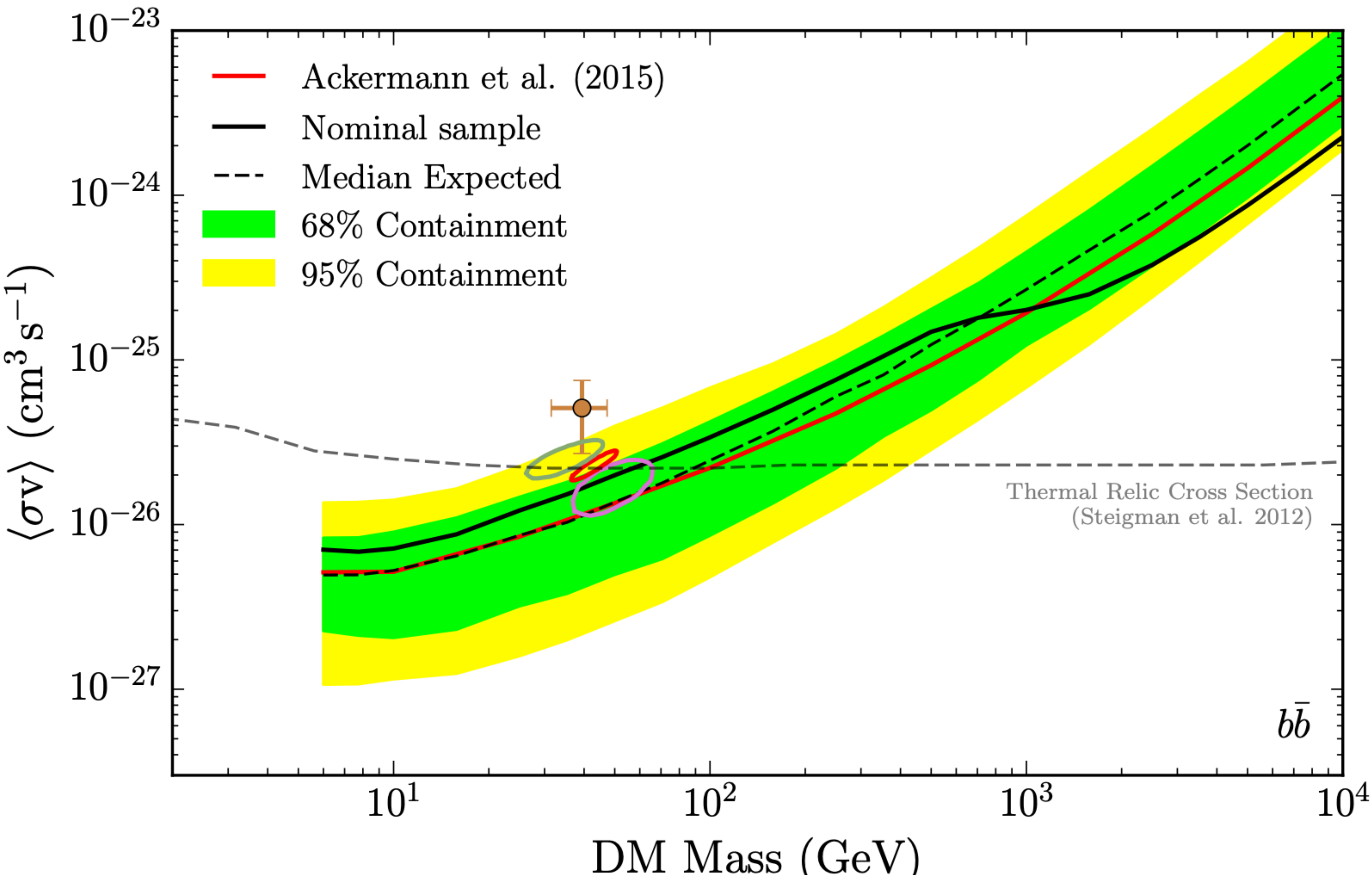
arXiv:1902.01055v2 [astro-ph.CO] 24 Apr 2019

Future: Dwarf Spheroidal Galaxies



Future: Dwarf Spheroidal Galaxies

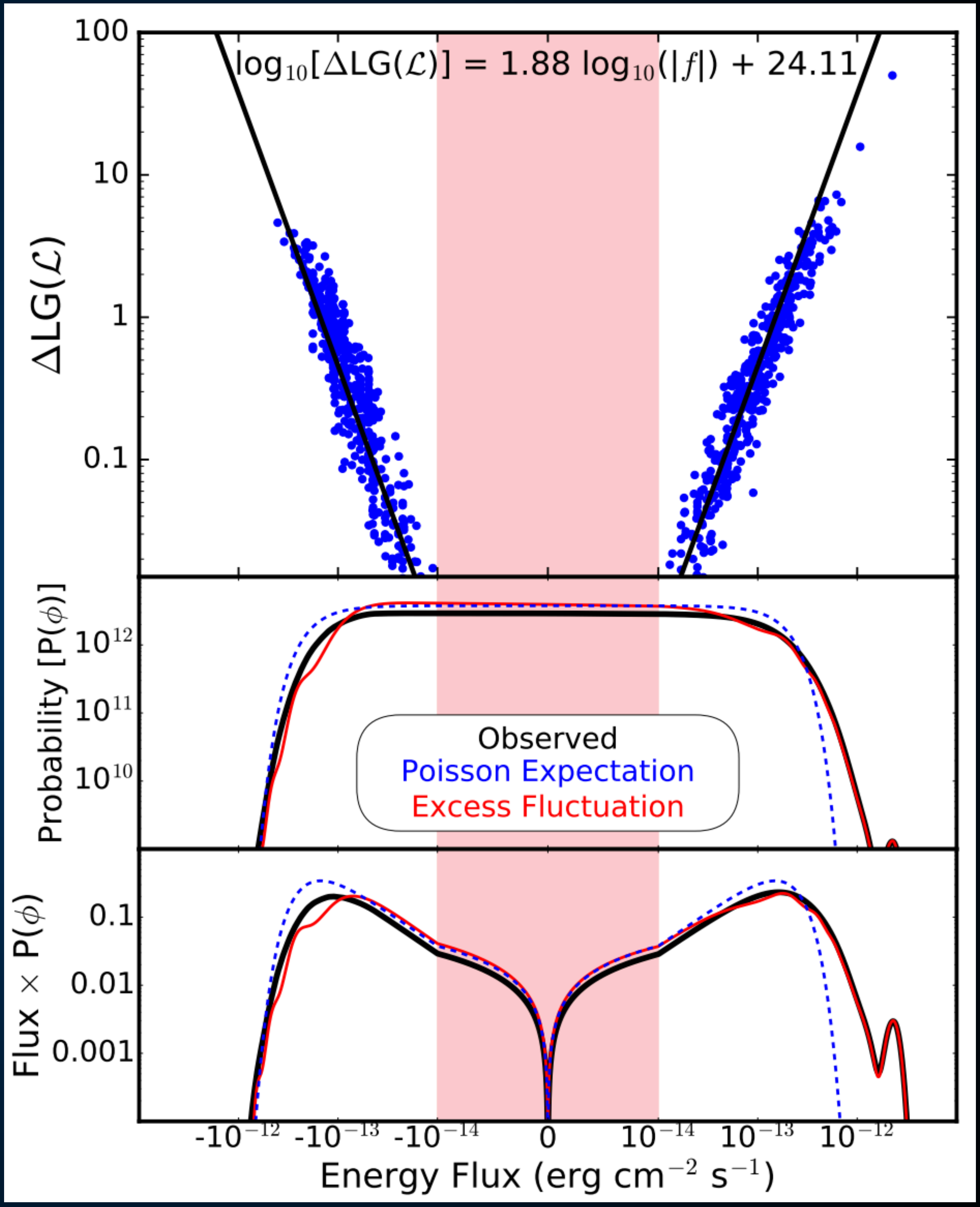
Fermi-LAT Collaboration (2016; 1611.03184)



Future: Dwarf Spheroidal Galaxies

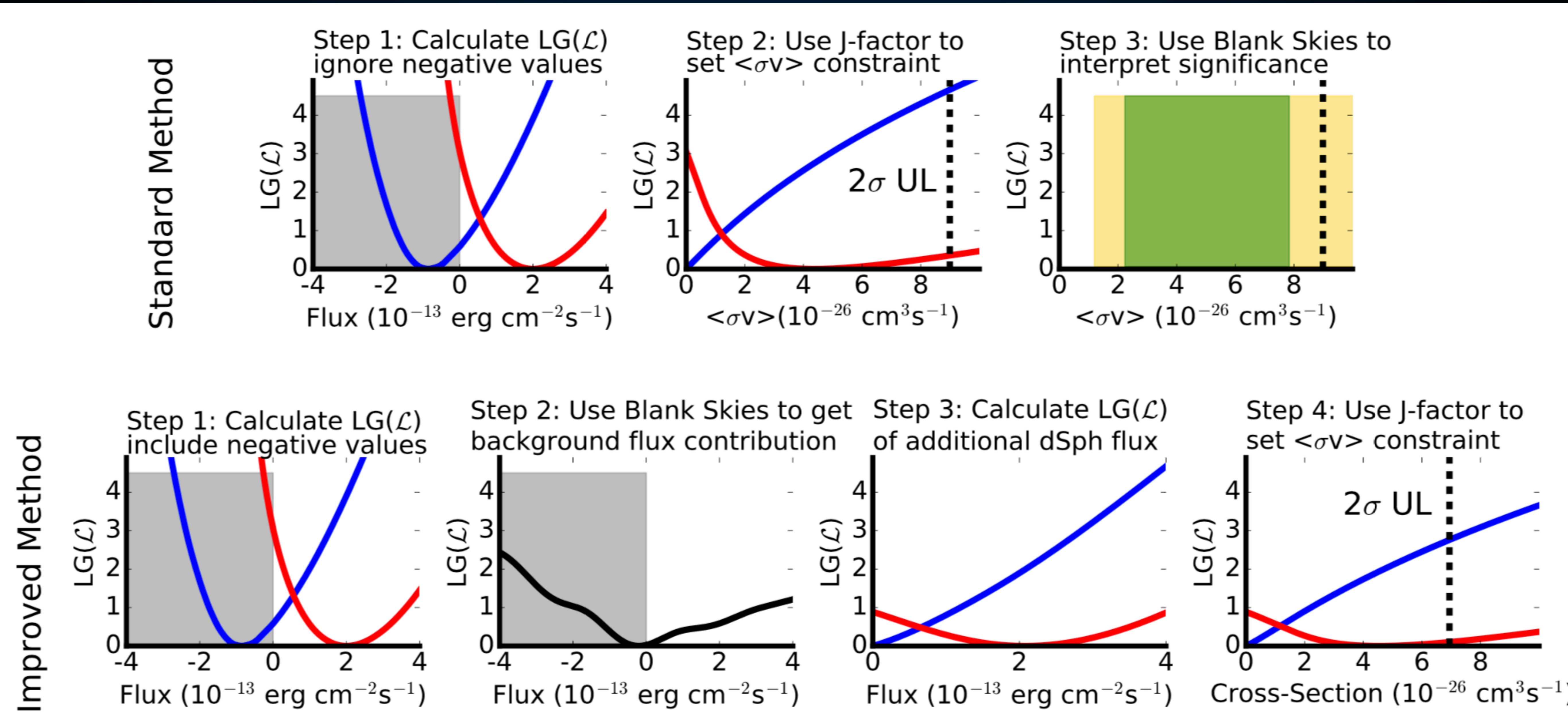
Linden (2019; 1905.11992)

- <u>Problem:</u> Random sky positions have a much higher probability of having 2-sigma fluctuations than expected from Poisson statistics.
- Fluctuations can be upward or downward.
- Separating these from dark matter is hard.



Future: Dwarf Spheroidal Galaxies

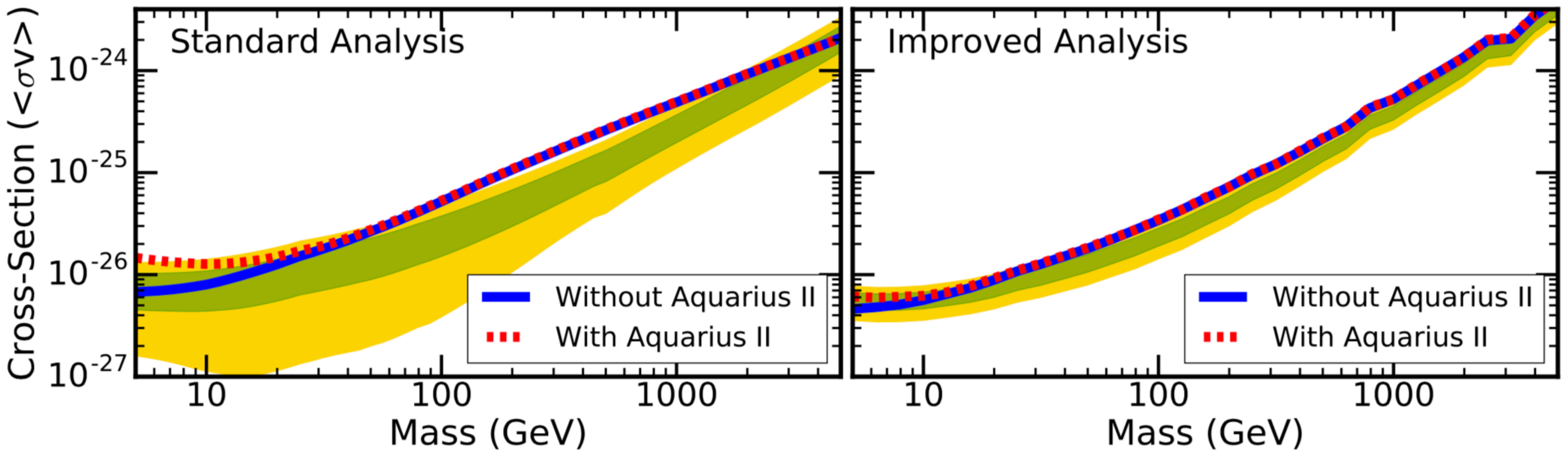
Linden (2019; 1905.11992)



- **<u>Solution:</u> Calculate the dwarf flux as the sum of a true dark matter flux and a “mismodeling” flux, and marginalize over the probability distribution of the background fluctuation.**

Future: Dwarf Spheroidal Galaxies

Linden (2019; 1905.11992)

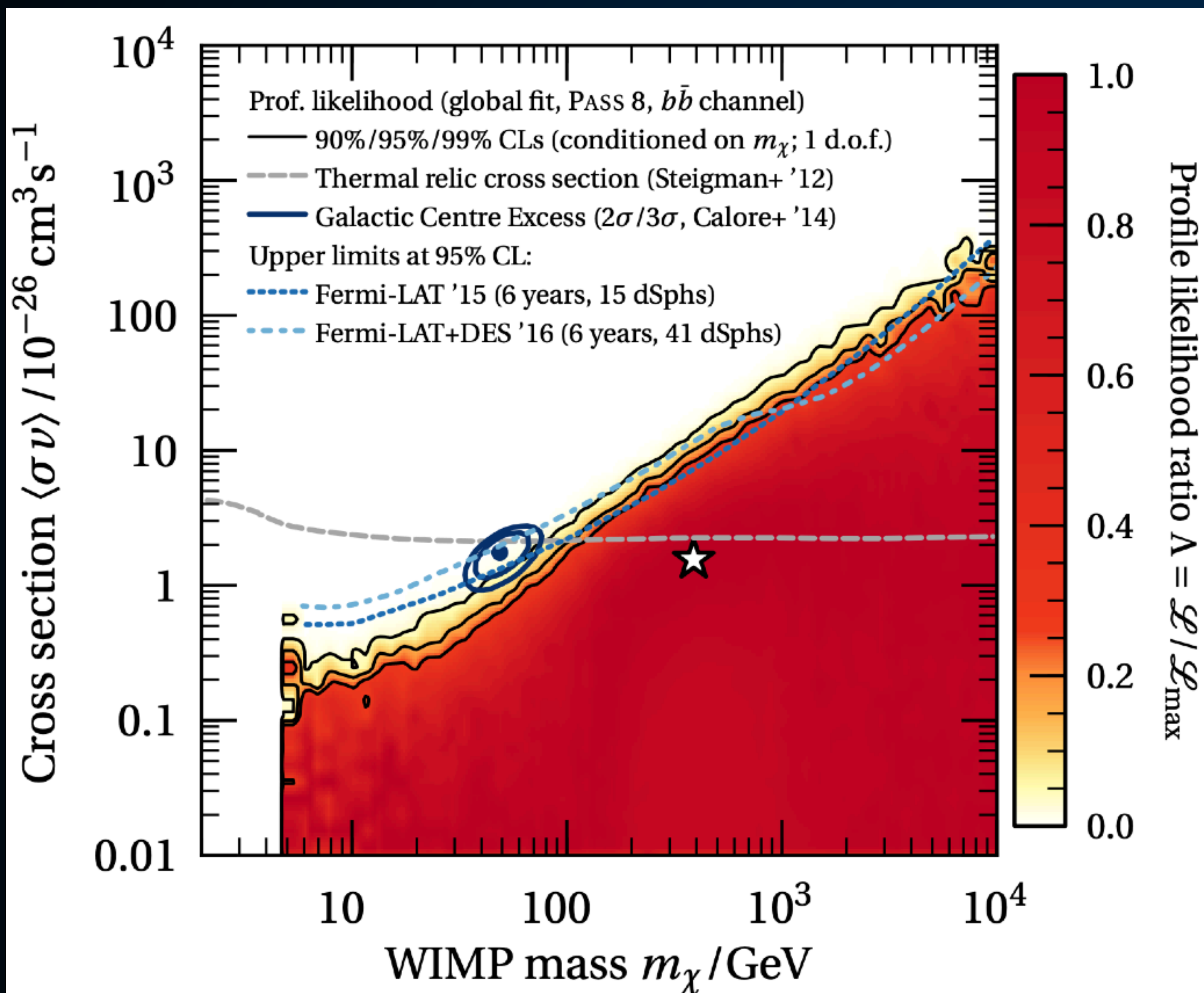


$$P(\langle\sigma v\rangle) = \prod_i \arg\max_{\phi_{s,i}} \int_{-\infty}^{\infty} \mathcal{L}(\phi_{s,i} + \phi_{bg}) P_{bg}(\phi_{bg}) \times$$
$$\times P_{s,i}\left(\phi_{s,i}, \langle\sigma v\rangle, J_i, \sigma_i\right) \mathrm{d}\phi_{\mathrm{bg}}$$

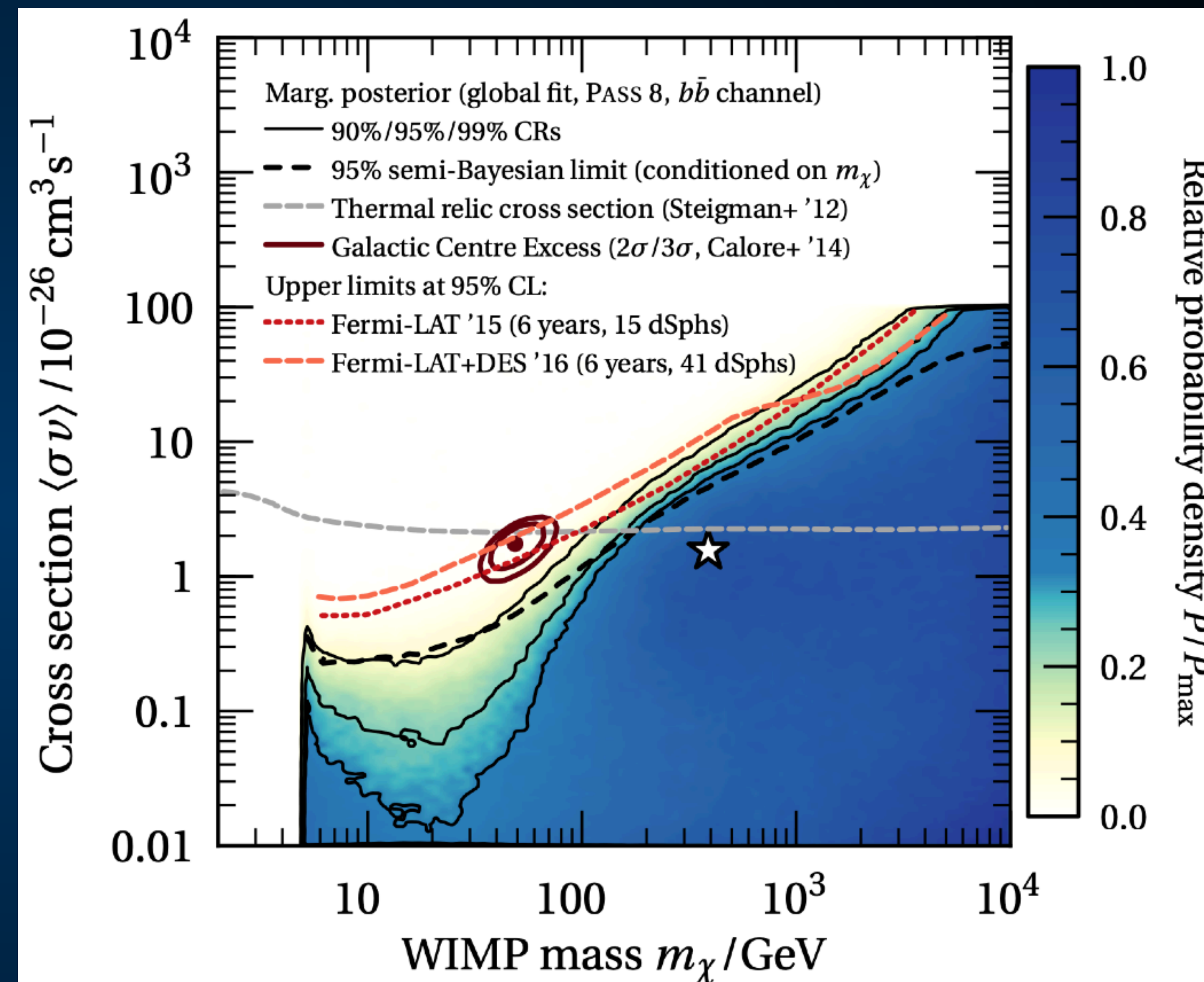
- **Solution: Produces a much tighter constraint (with smaller uncertainties) on the dark matter annihilation cross-section.**

Future: Statistical Techniques

Hoof, Geringer-Sameth, Trotta (1812.06986)



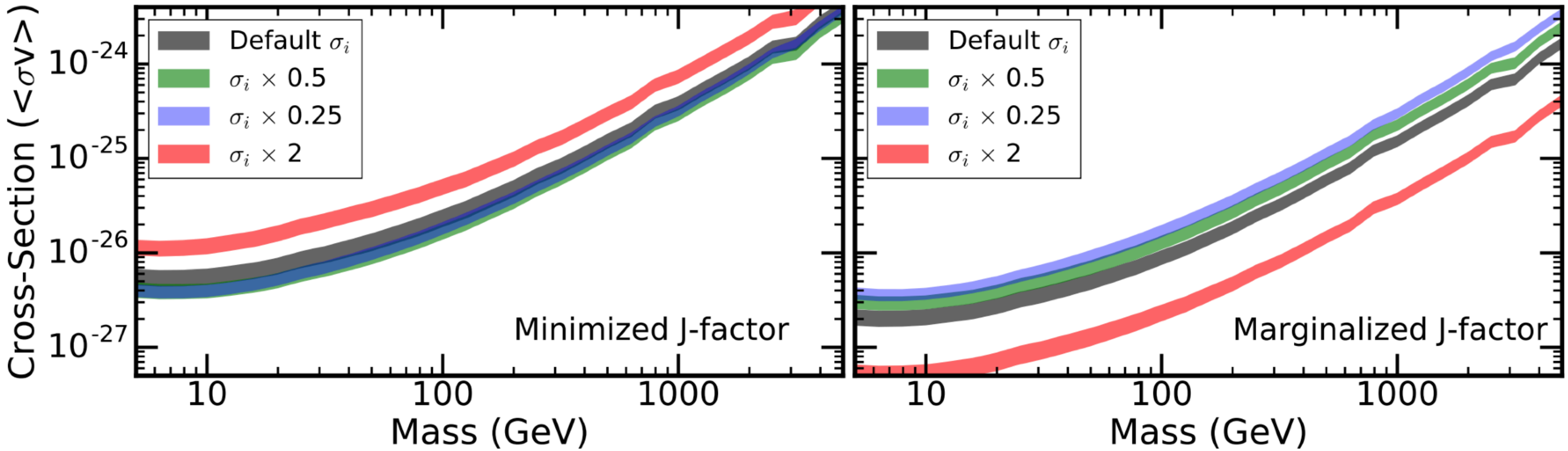
Frequentist



Bayesian

Future: Statistical Techniques

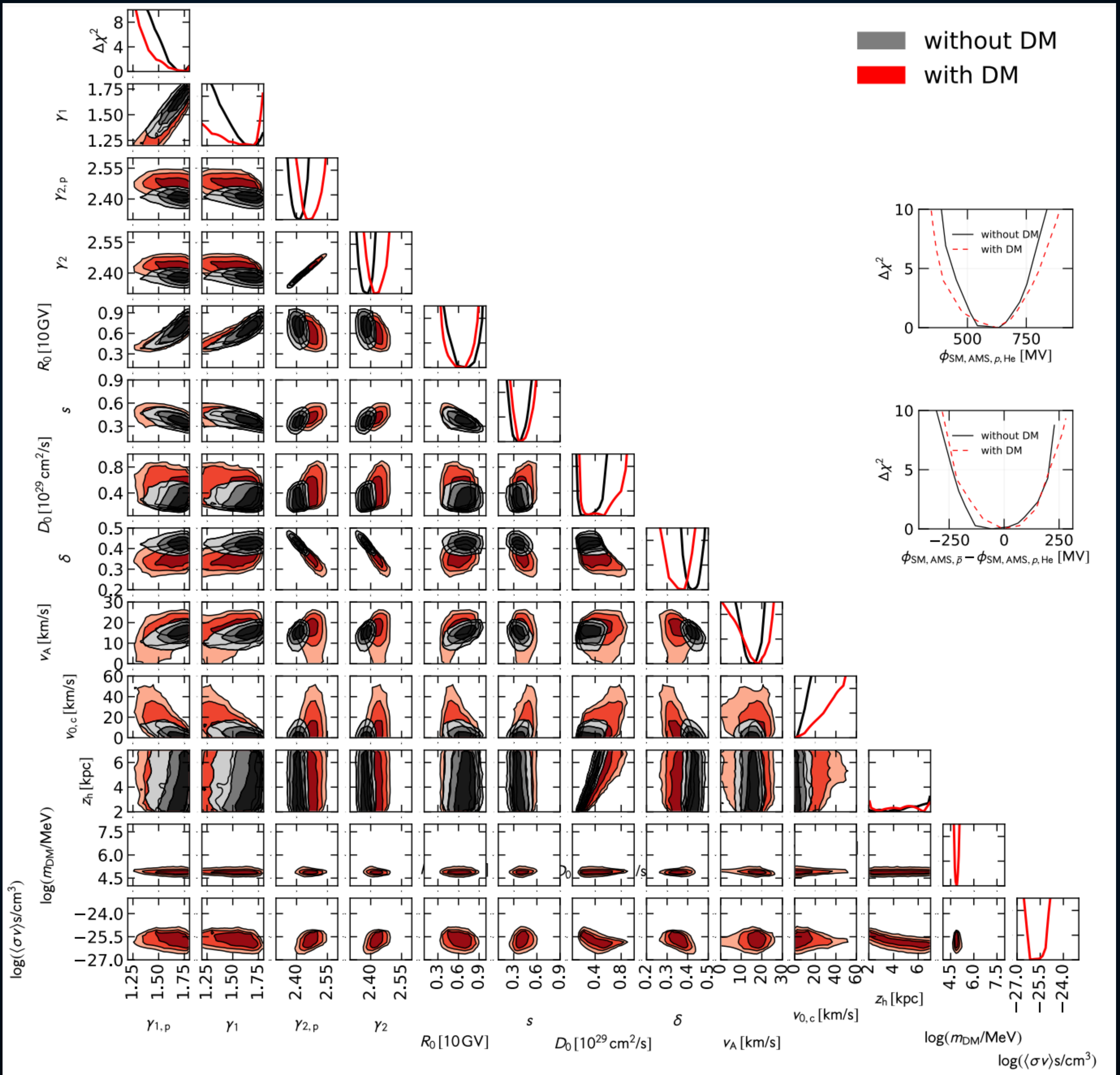
Linden (2019; 1905.11992)



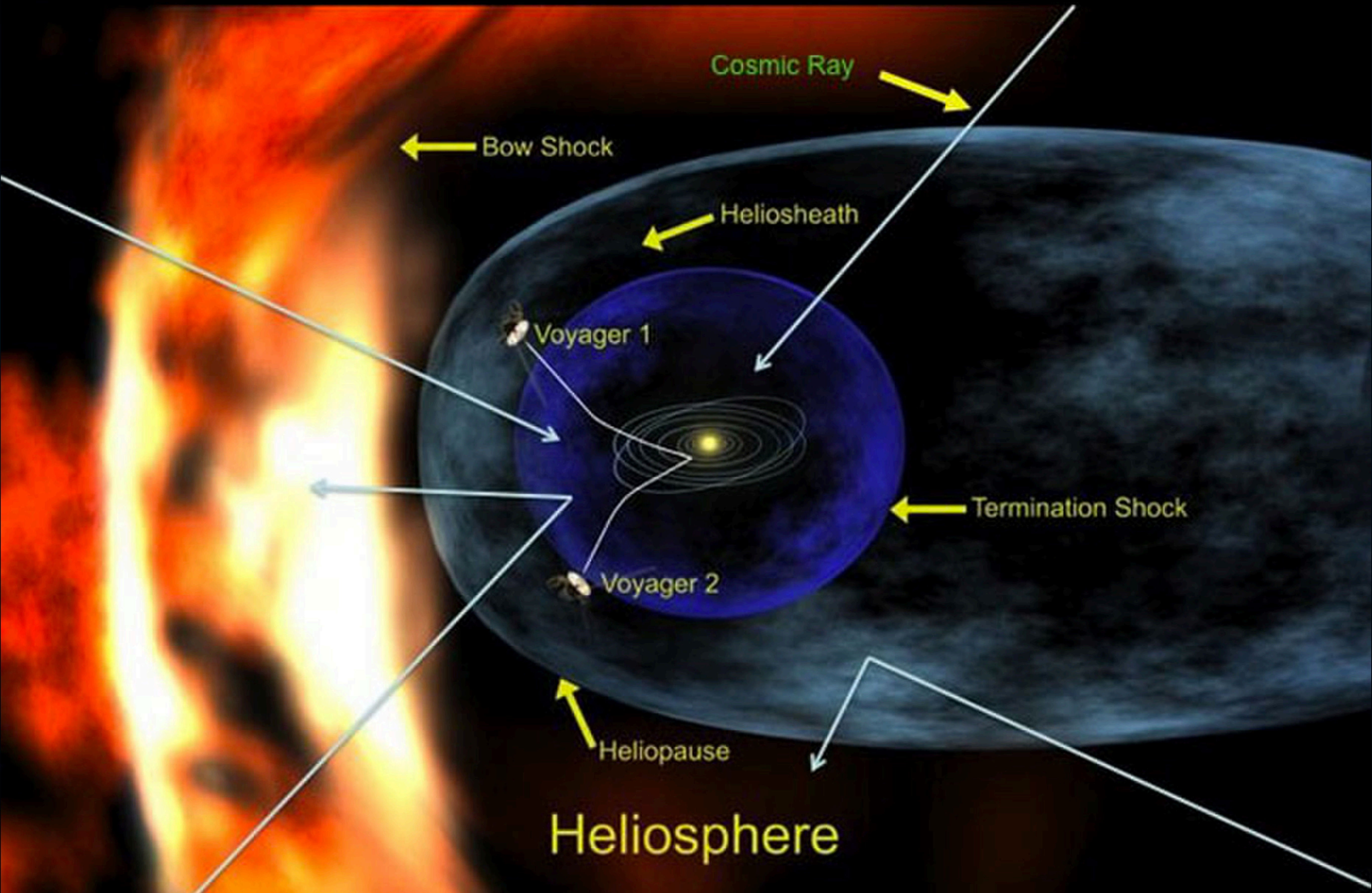
- **Marginalizing over the J-factor uncertainties produces odd behavior in the stacked limit.**
- **Due to logarithmic-uncertainty in the J-factor estimation.**

Future: Antiprotons

Cuoco et al. (2019; 1903.01472)

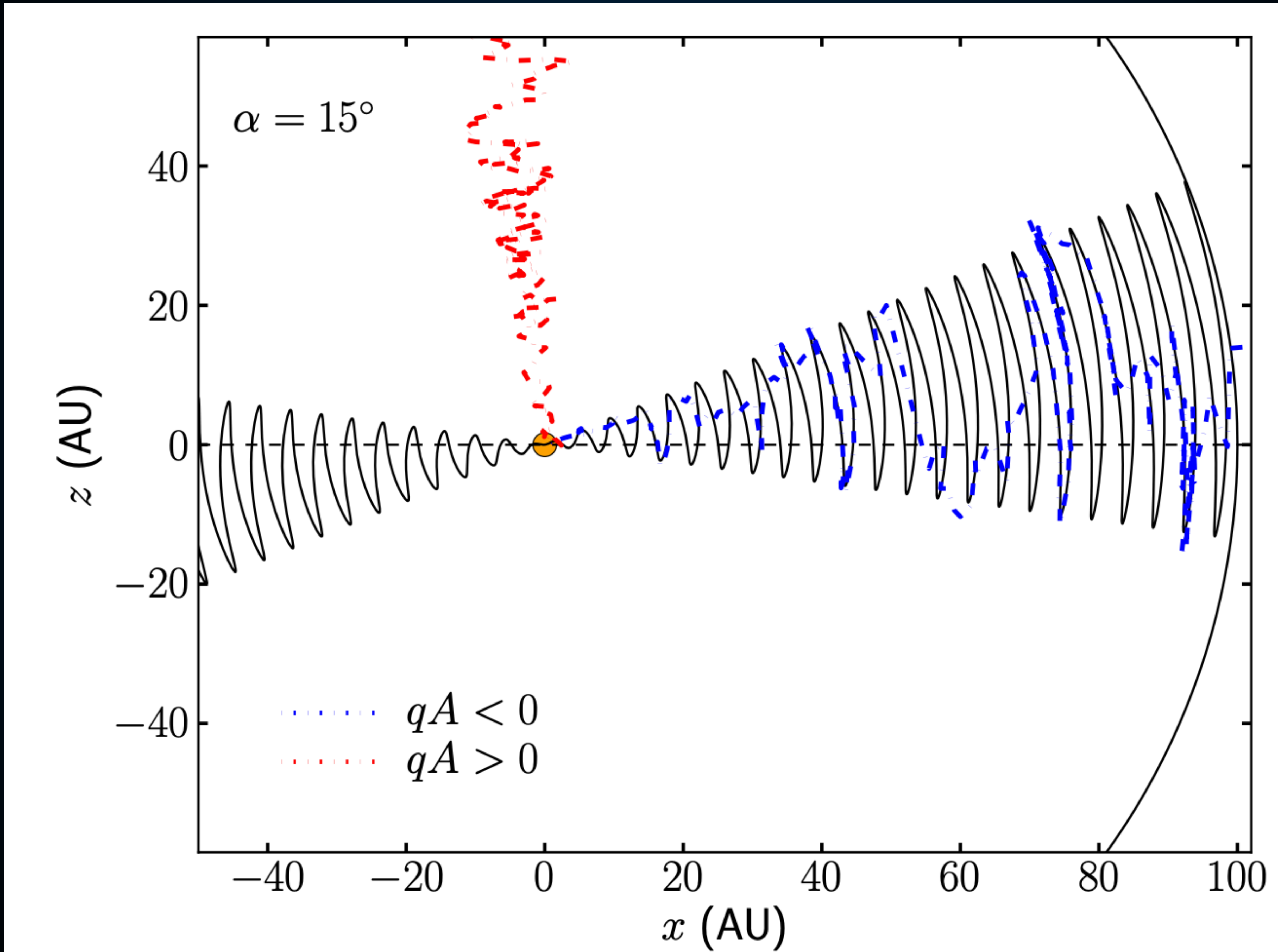


Future: Antiprotons



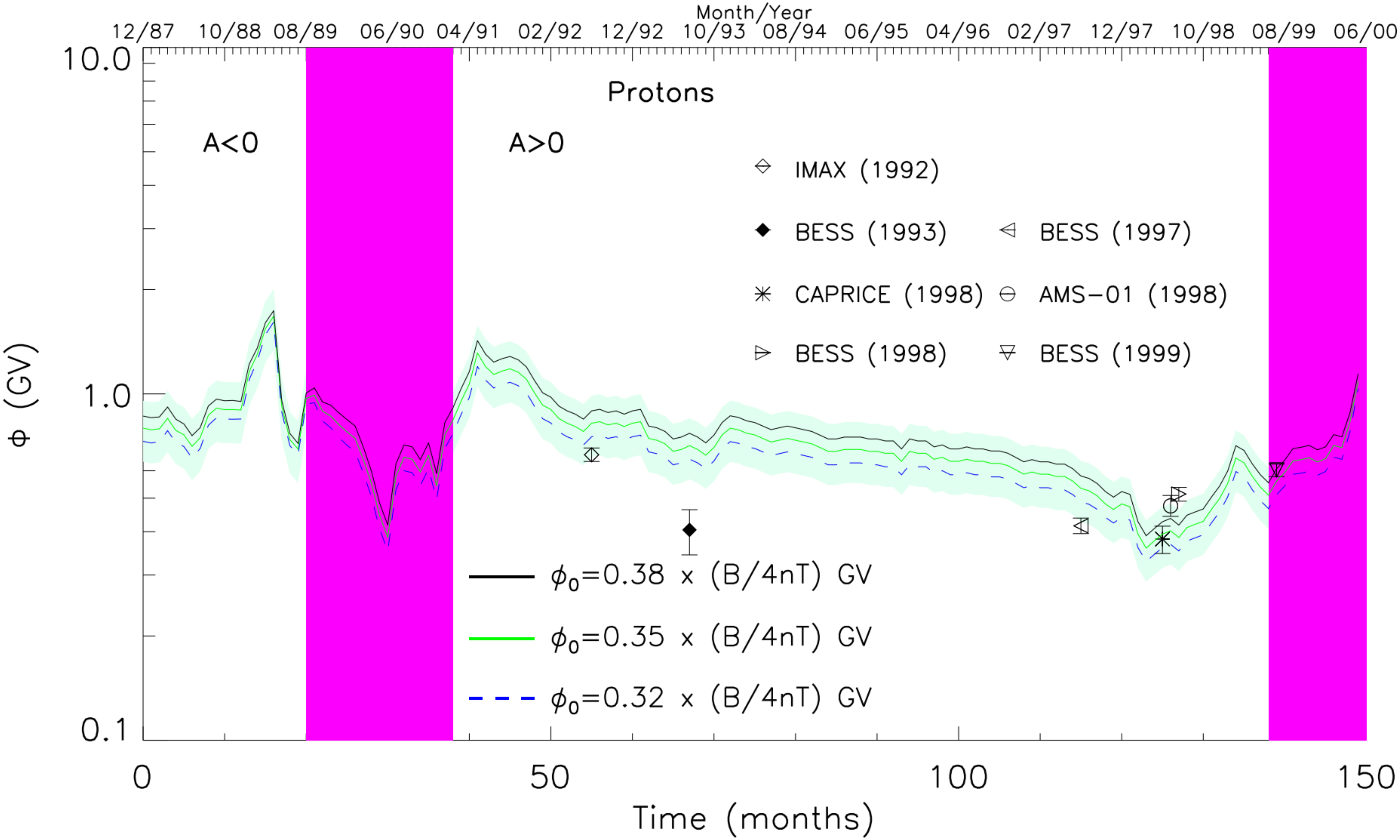
Future: Antiprotons

Cholis, Hooper, TL (2016; 1511.01507)

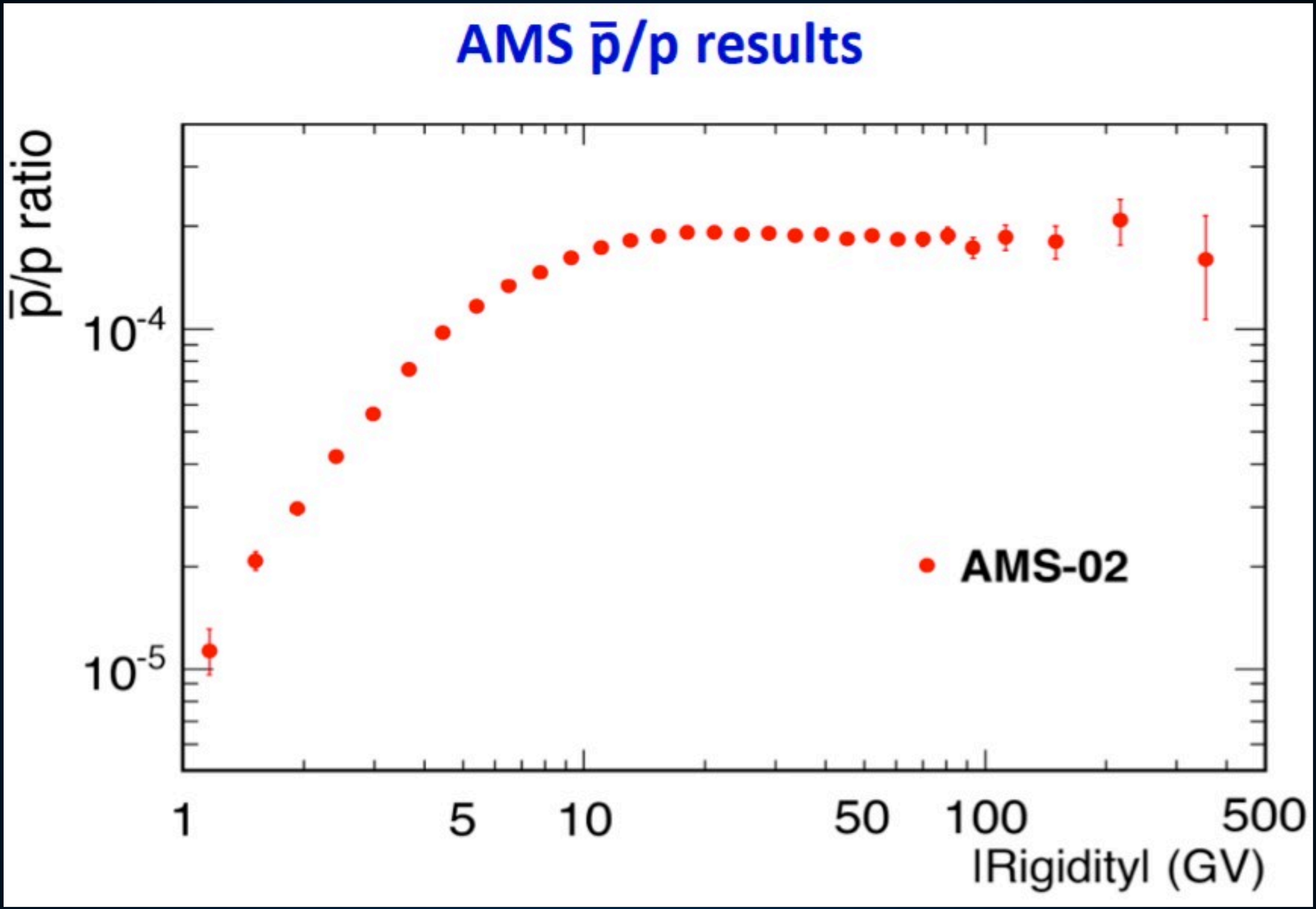


Future: Antiprotons

Cholis, Hooper, TL (2016; 1511.01507)

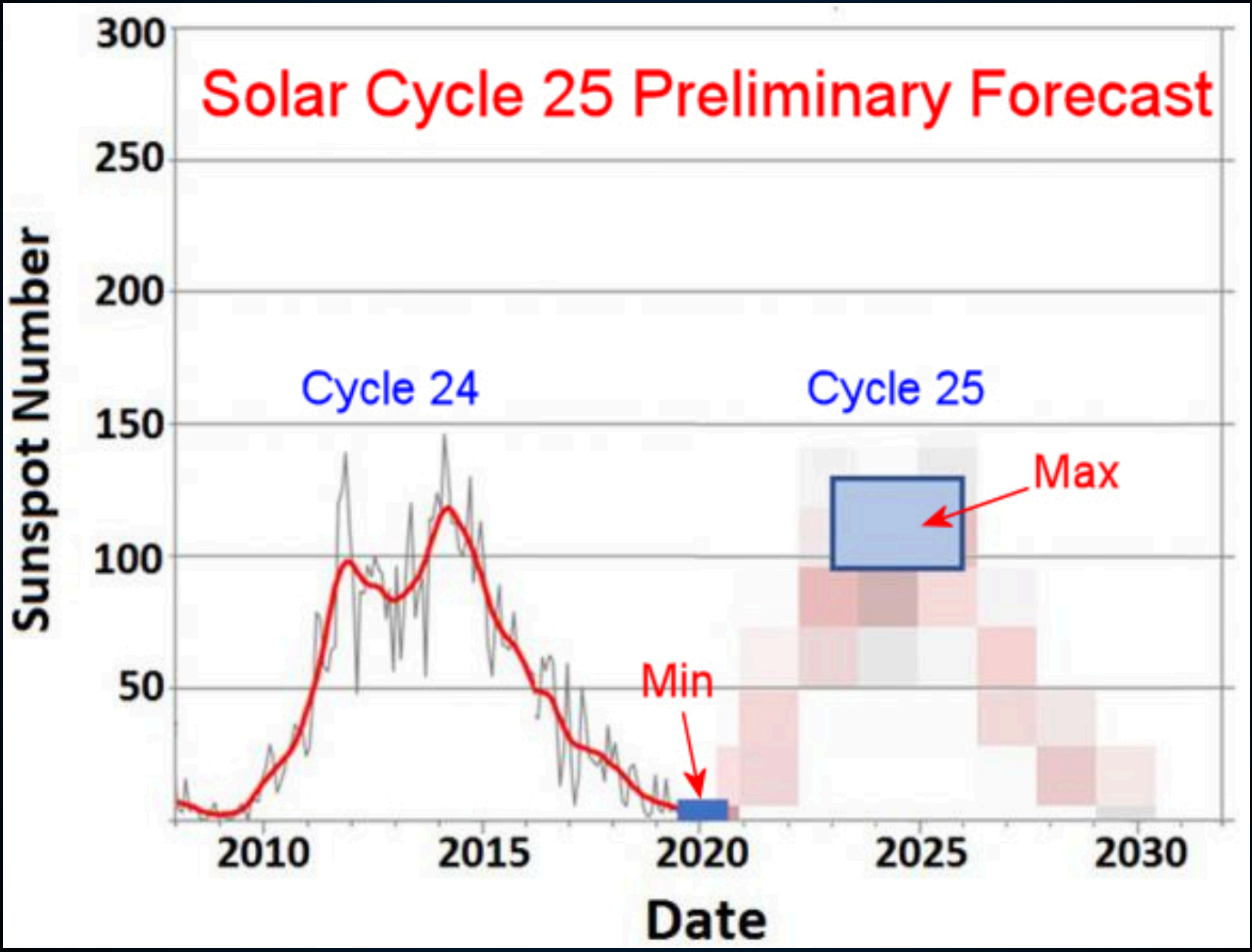


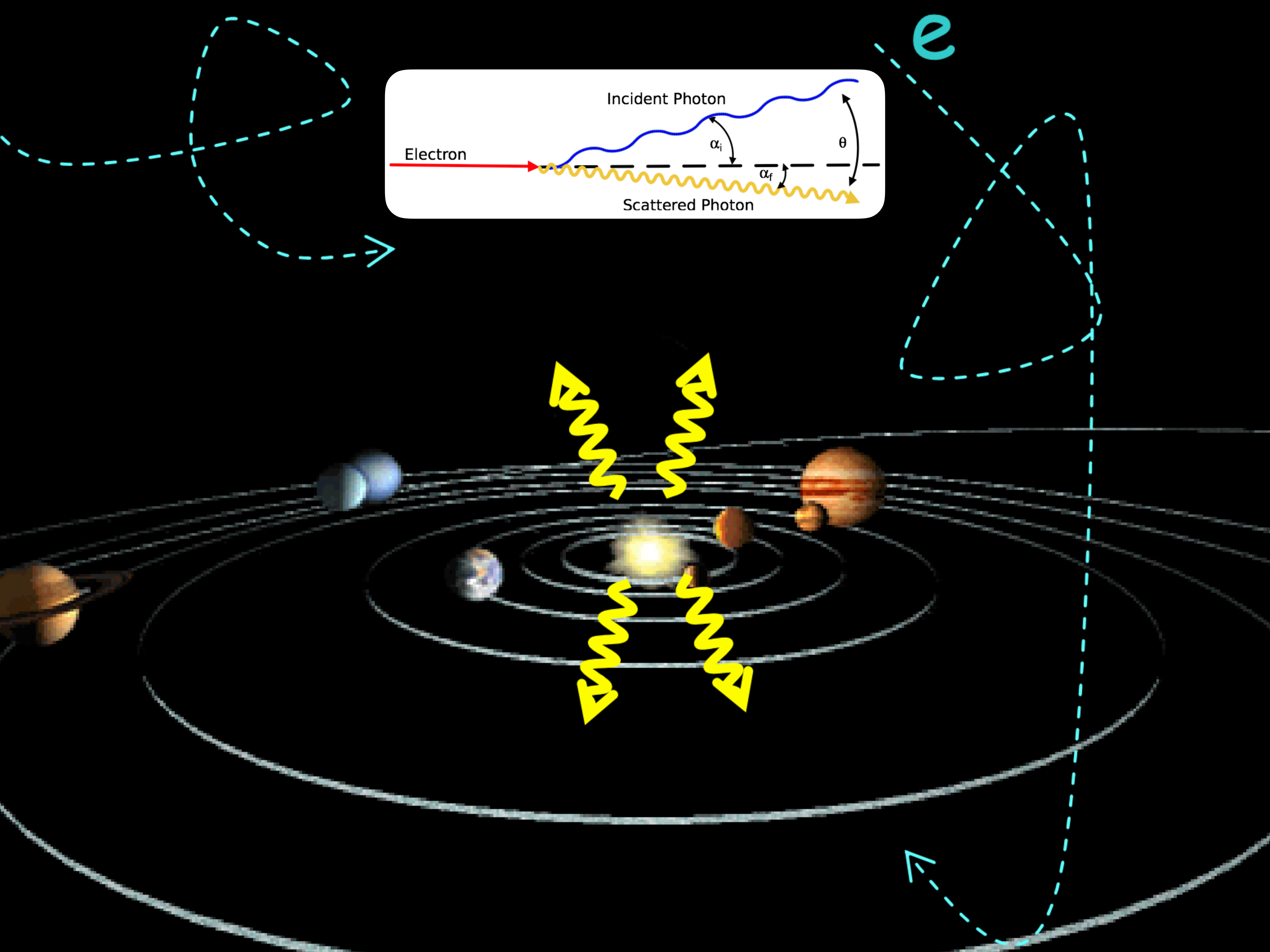
Future: Antiprotons



Publicly available AMS-02 data covers only 2011-2015.

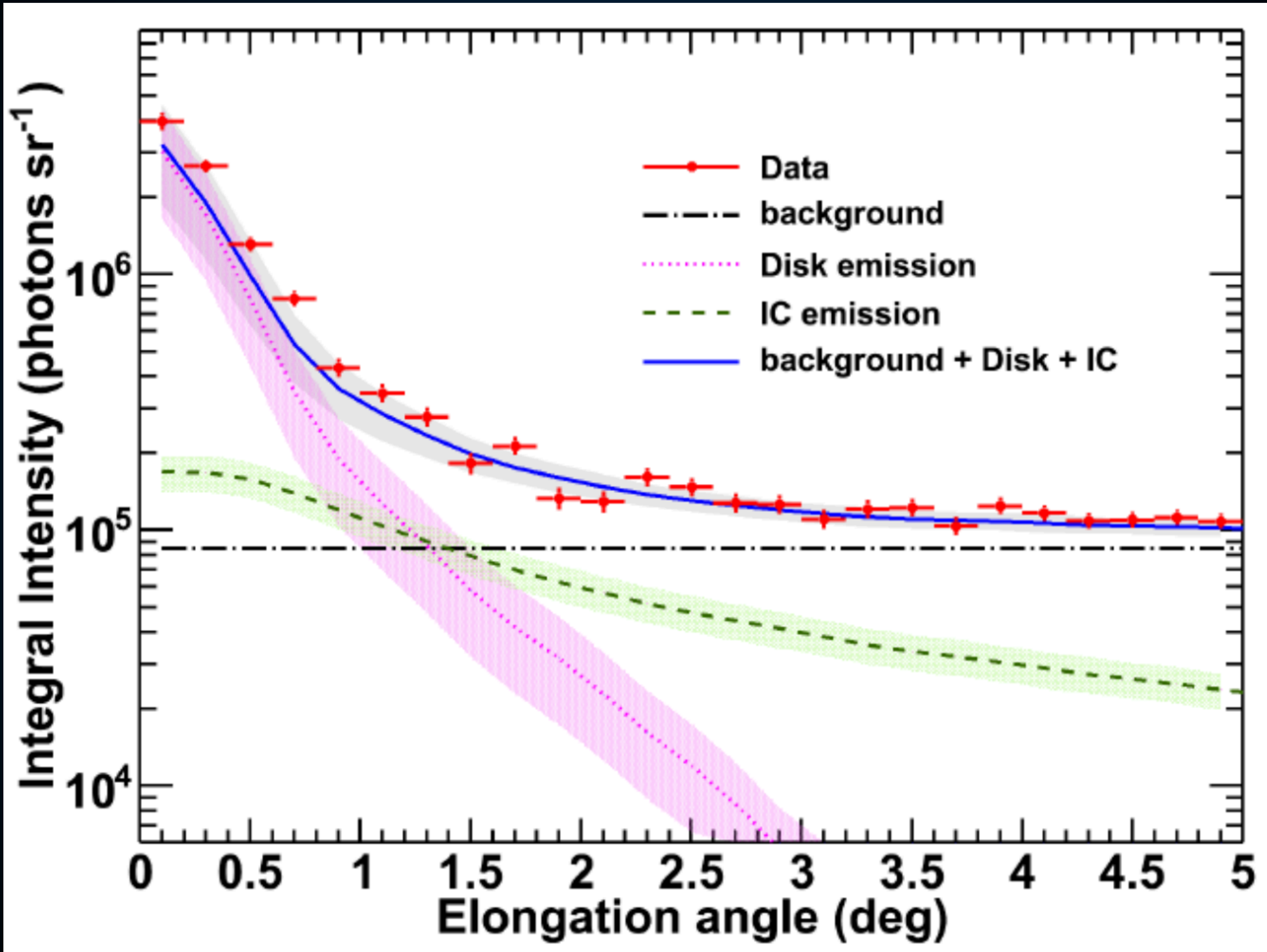
Future: Antiprotons



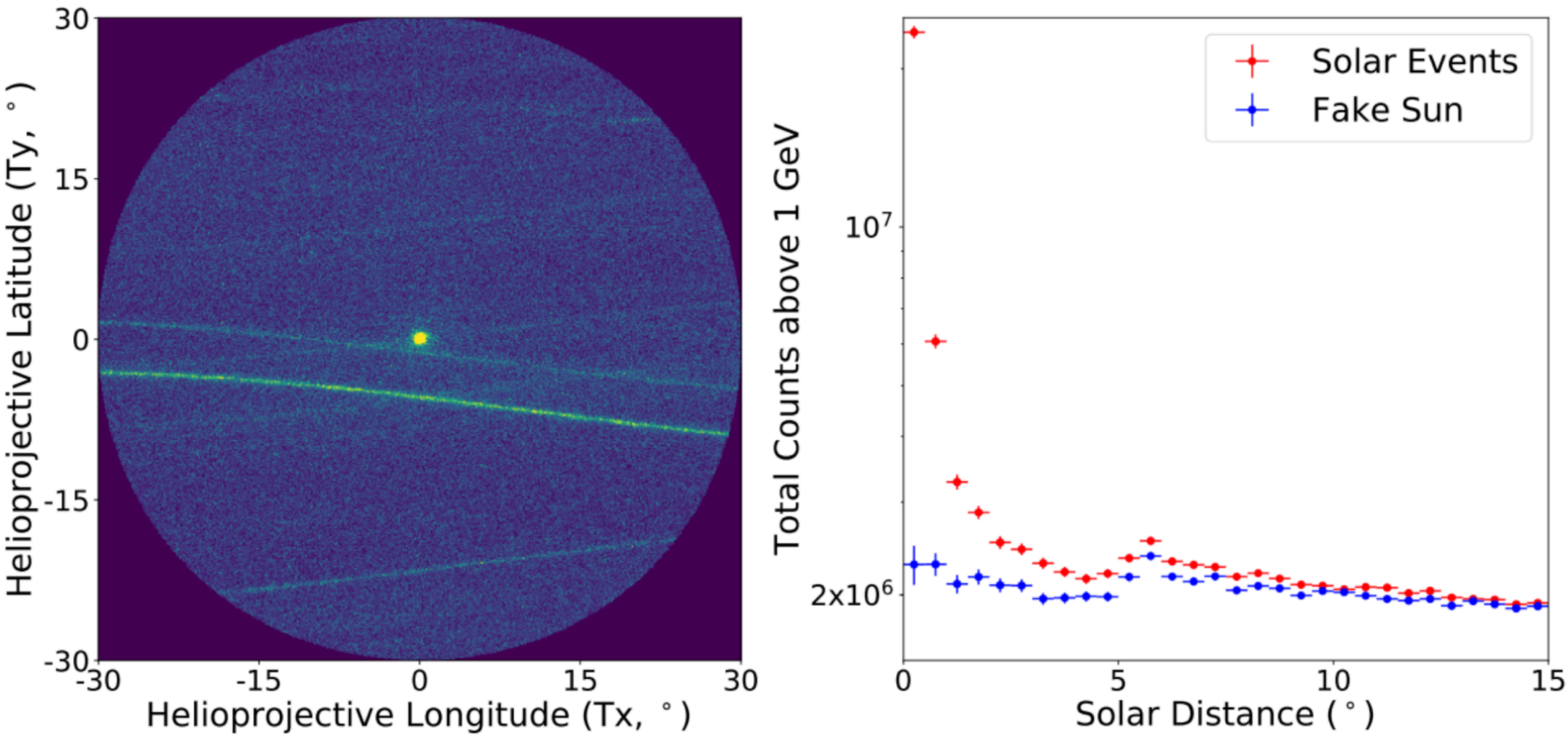

e
Incident Photon
Electron
α_i
θ
α_f
Scattered Photon

Future: Antiprotons

Abdo et al. (2011; 1104.2093)



Future: Antiprotons

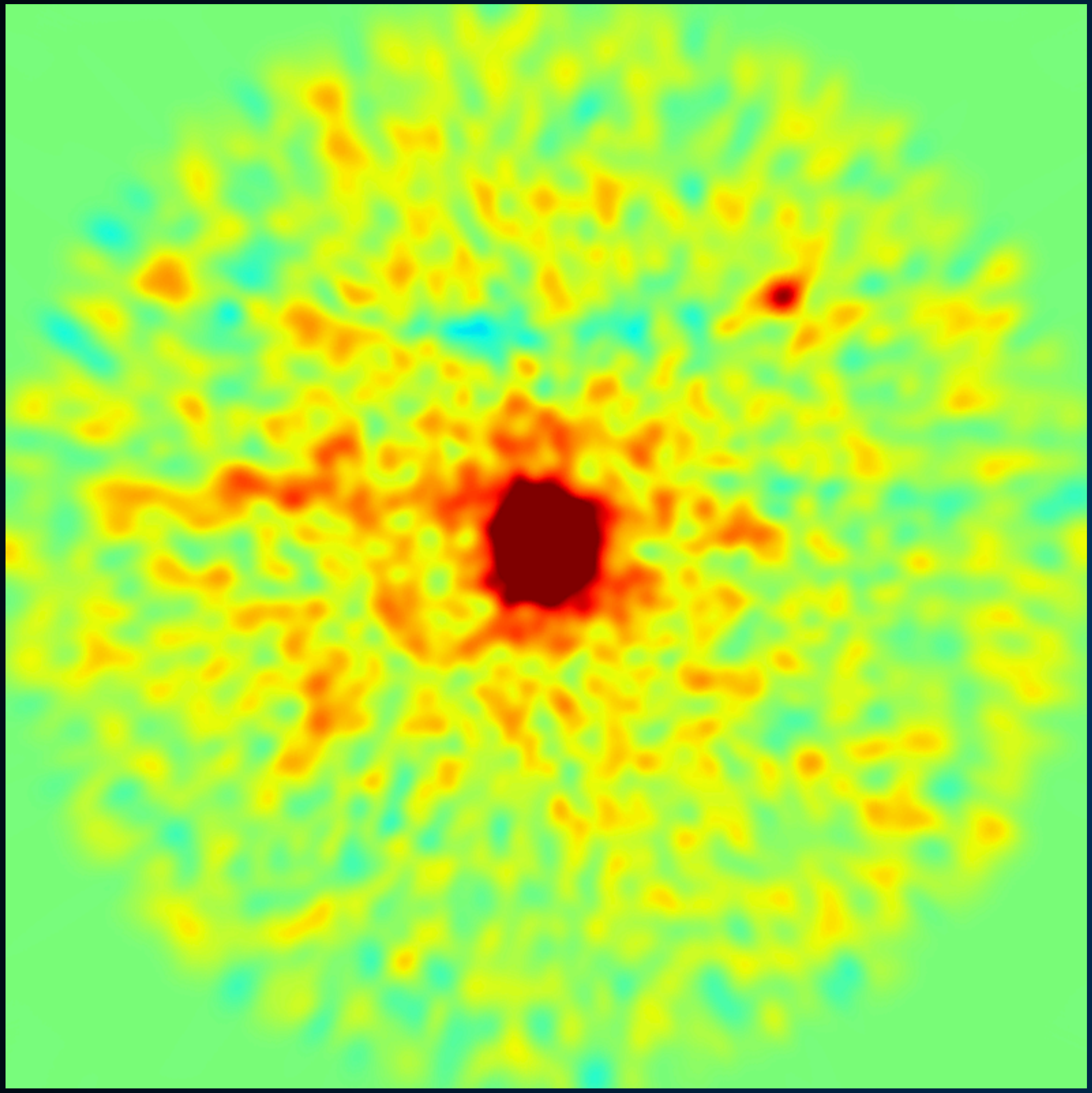


Can Return to this Problem:

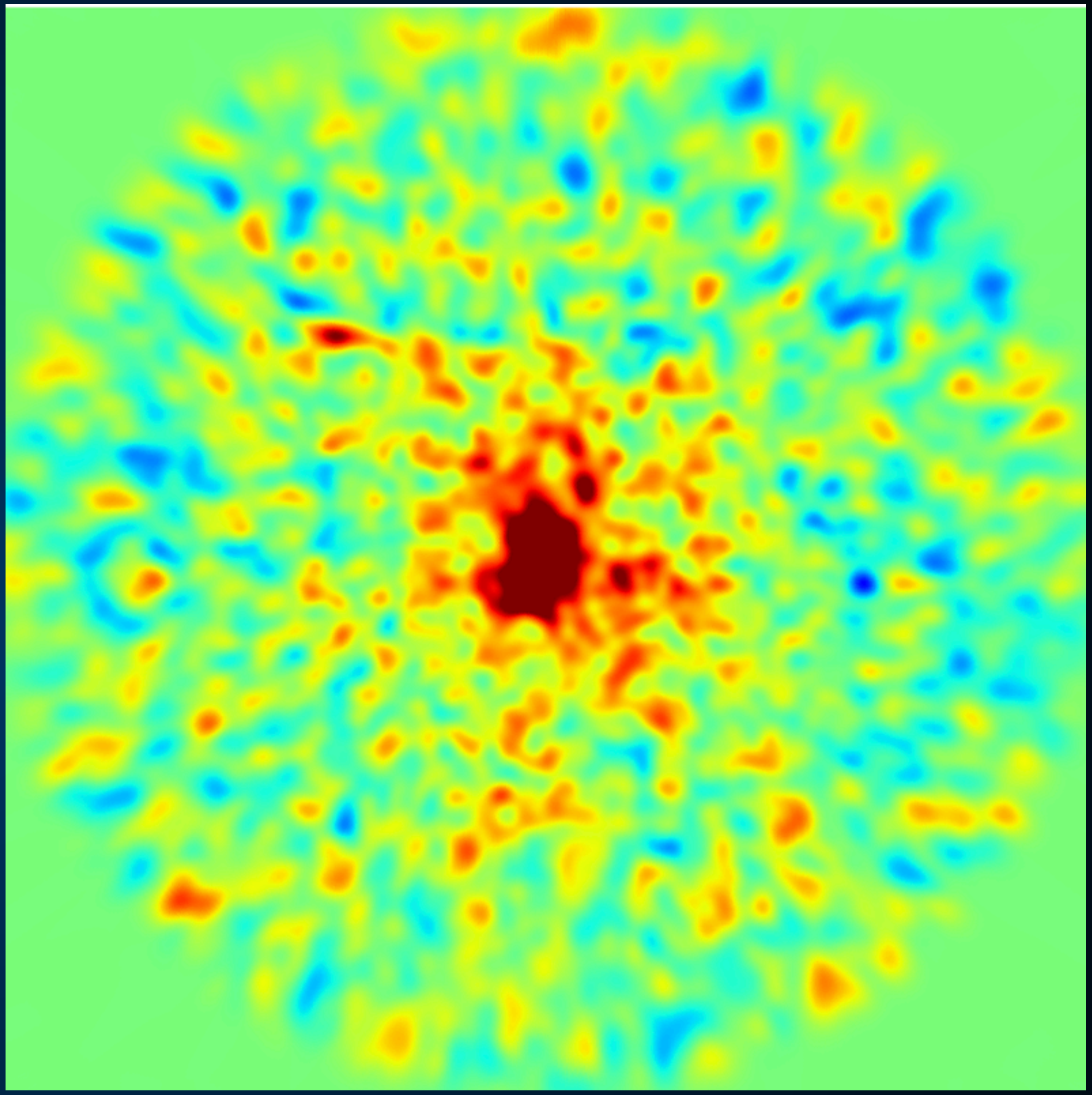
- 10 years of data
- Better Diffuse Background Subtraction
- Less Stringent Temporal Cuts

Future: Antiprotons

133 - 562 MeV



1-3.1 GeV



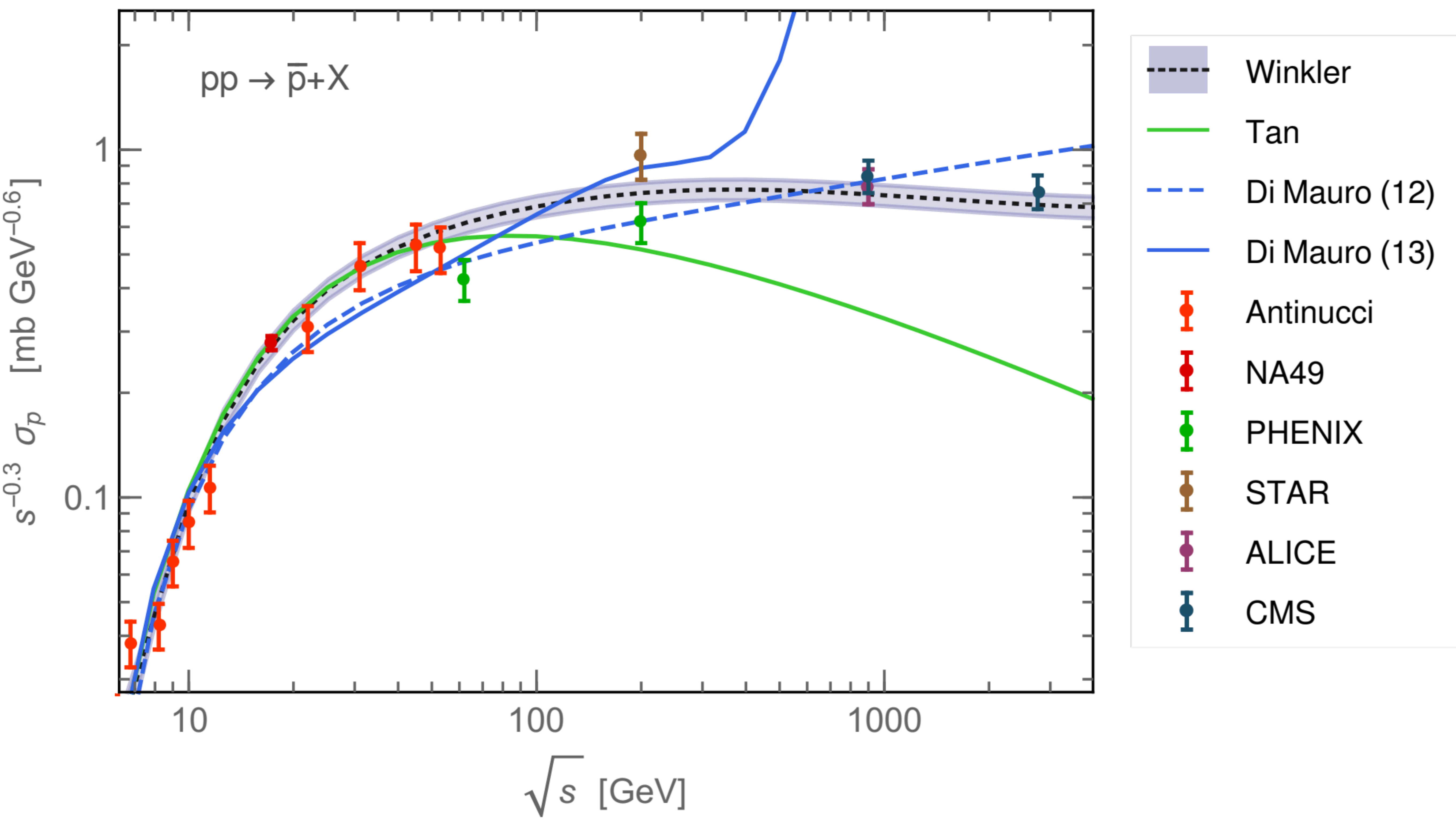
Preliminary

Spatial Extension to more than 15 degrees from Solar Center

Can study temporal and energy dependence of ICS morphology.

Future: Antiprotons

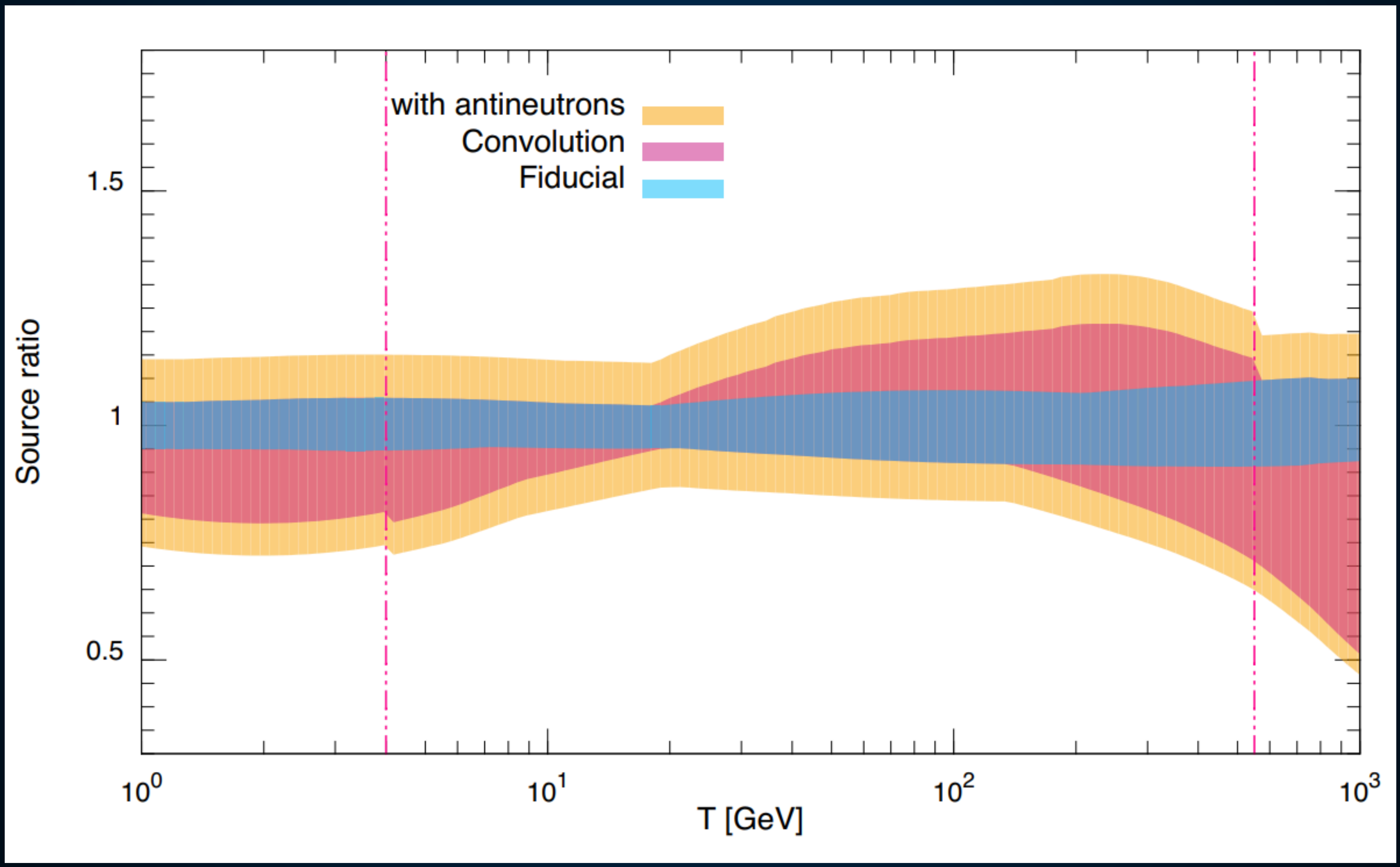
Reinert & Winkler (2017; 1712.00002)



Future: Antiprotons

Cholis, Linden, Hooper (2019; 1903.02549)

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

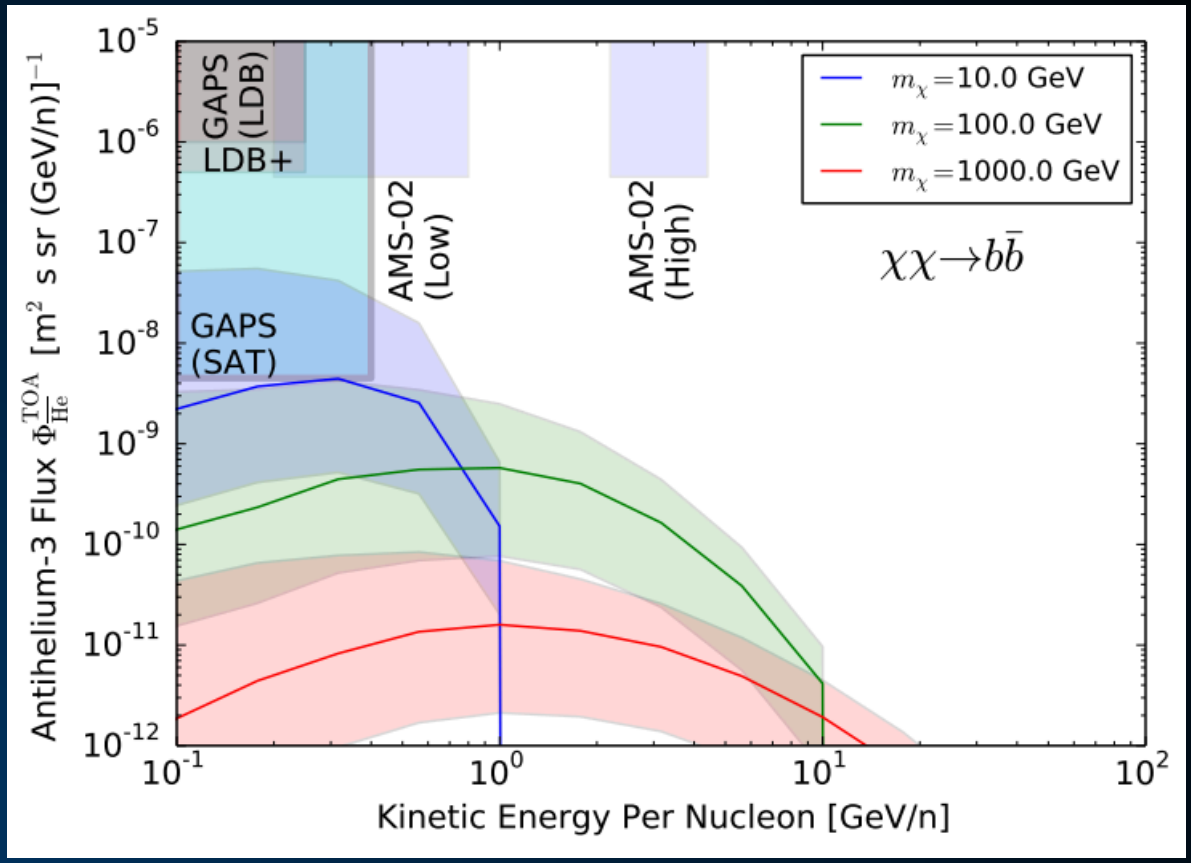


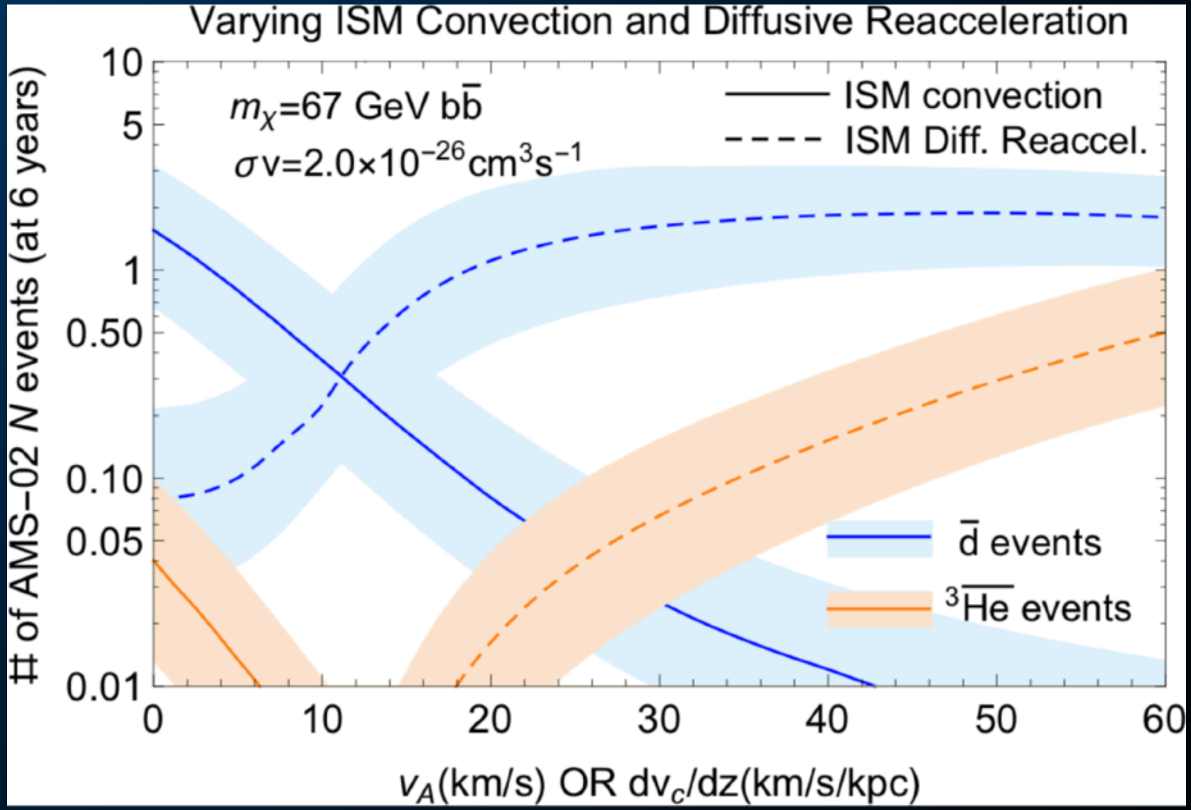
di Mauro et al. (2014; 1408.0288)

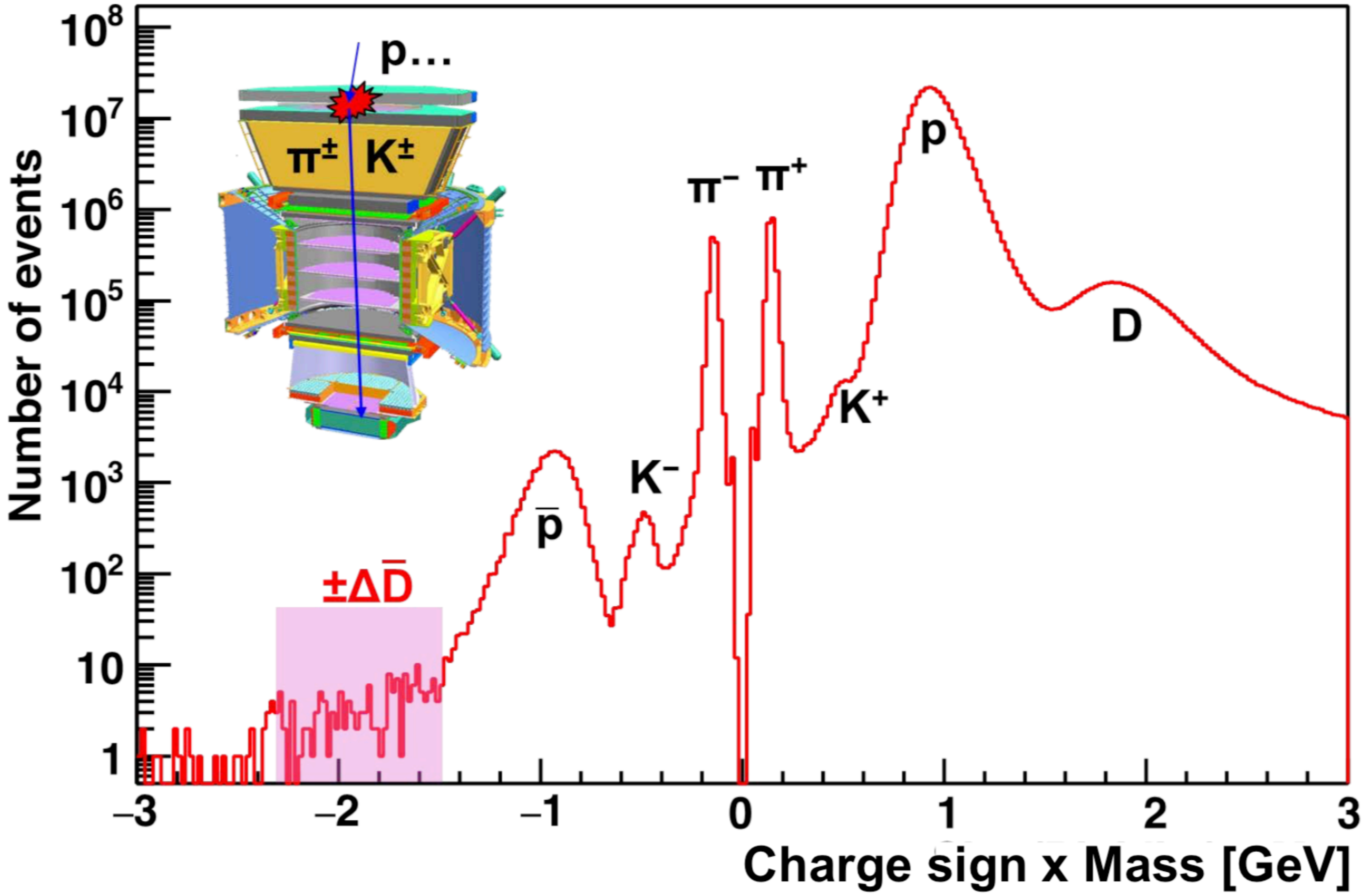
Future: Anti-Nuclei

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**



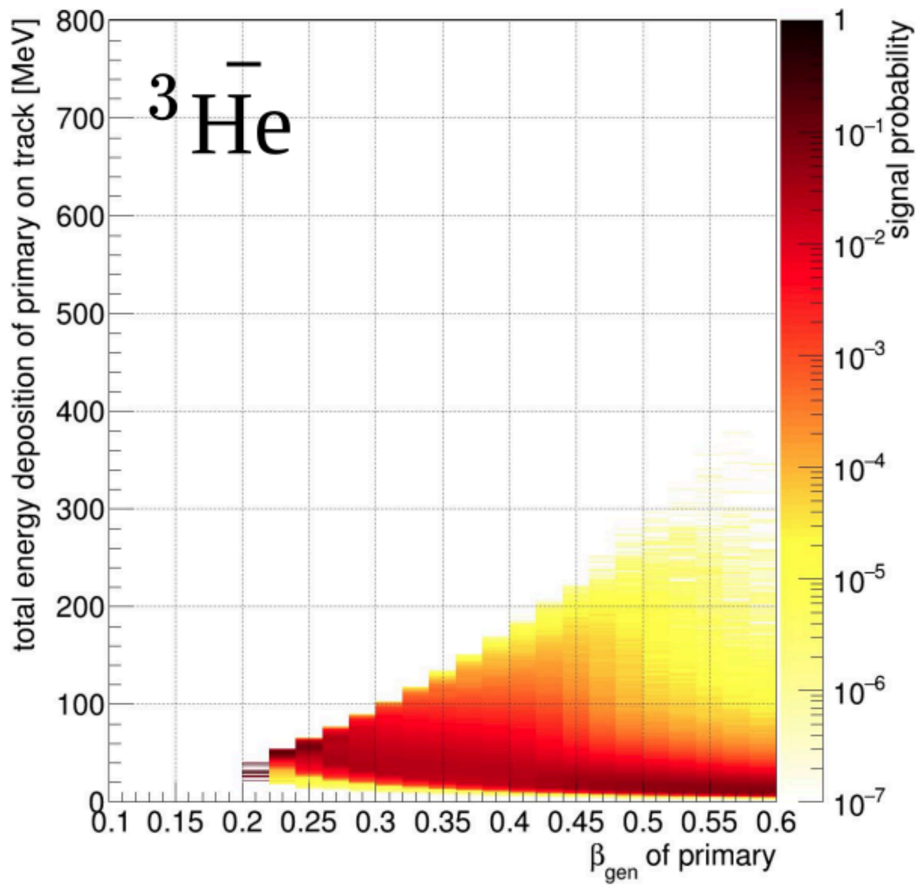


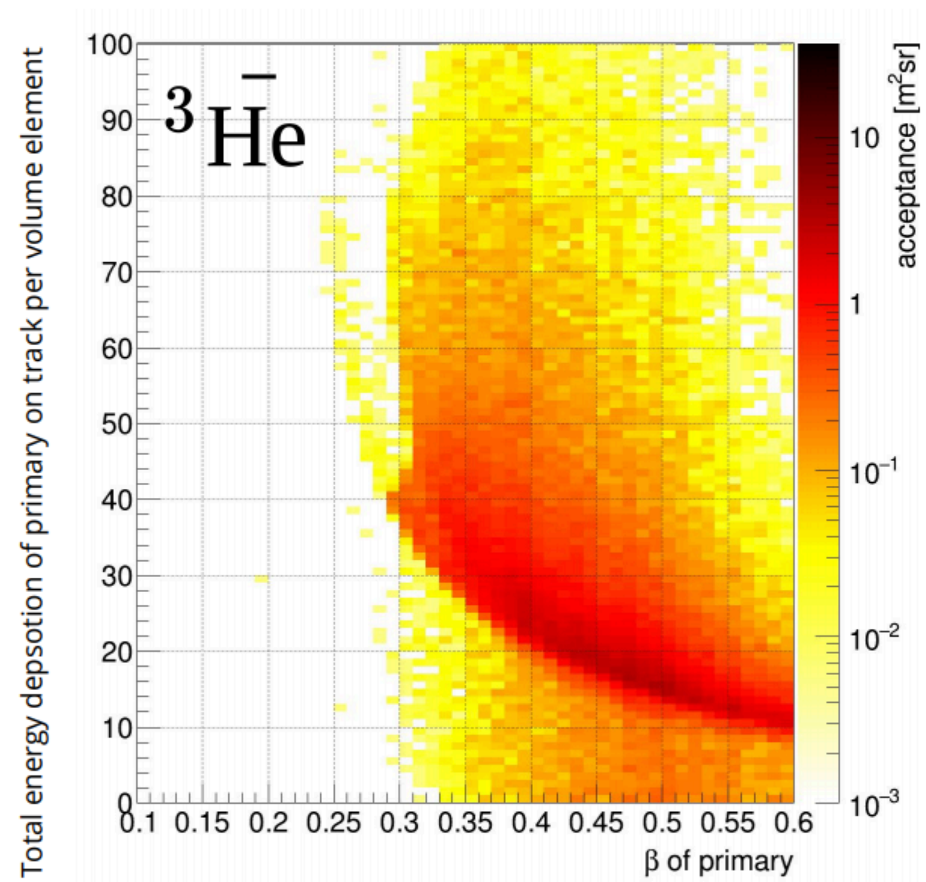


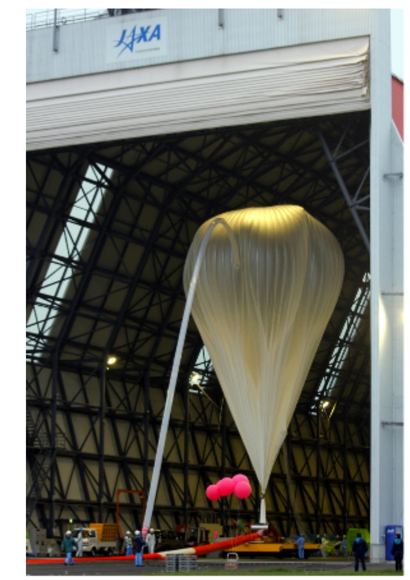
Number of events
p...
π± K±
π− π+
p
D
K+
K−
p̄
±ΔD̄
Charge sign x Mass [GeV]

Future: Anti-Nuclei

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



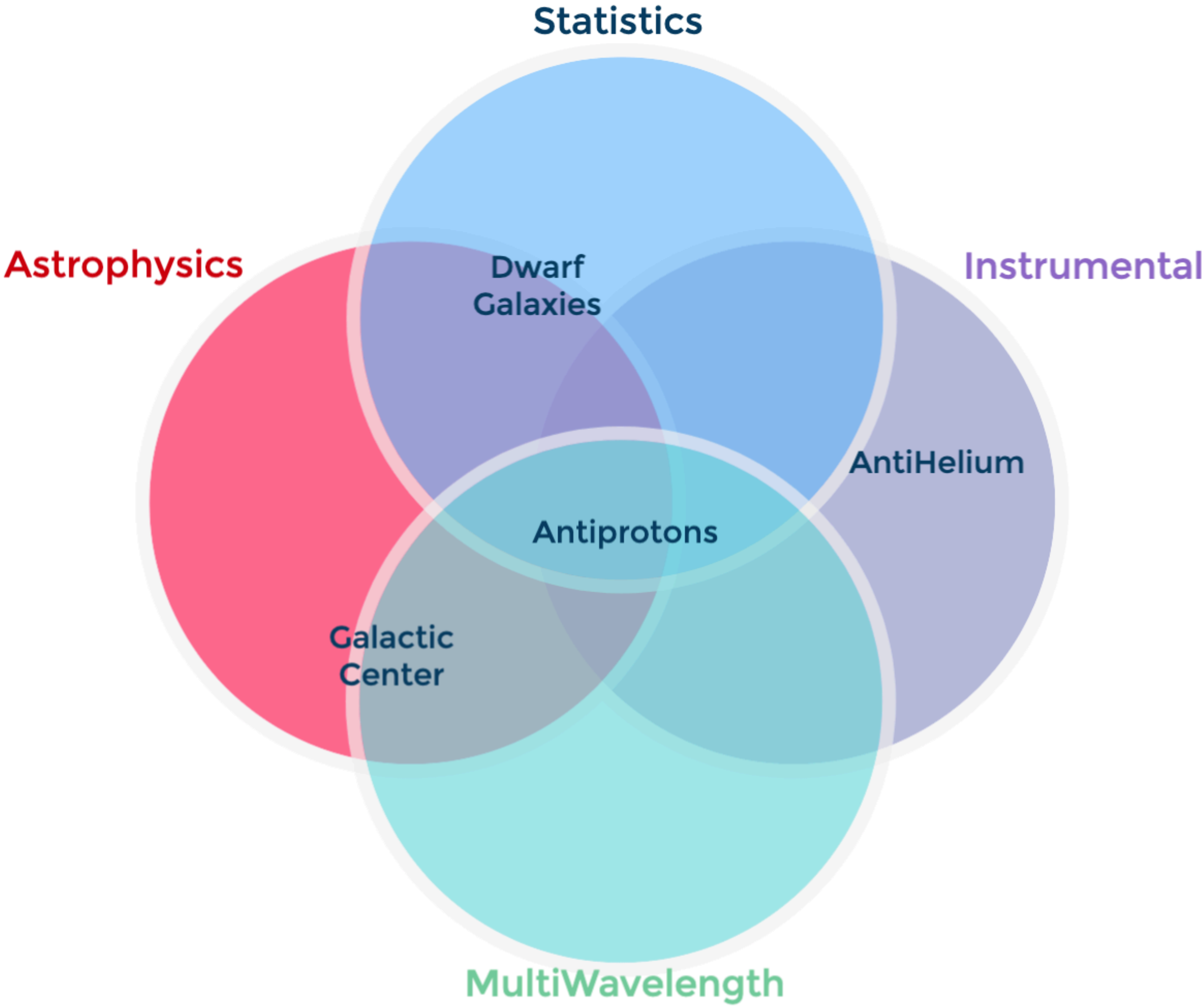




$^3\overline{\text{He}}$ "Hot topic" - AMS-02 reports on candidates [*see talk by Alberto Oliva*], however $\bar{d}$ missing yet (as predicted by coalescence models)

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

Challenge for GAPS:
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.


Statistics
Astrophysics
Instrumental
Dwarf Galaxies
AntiHelium
Antiprotons
Galactic Center
MultiWavelength