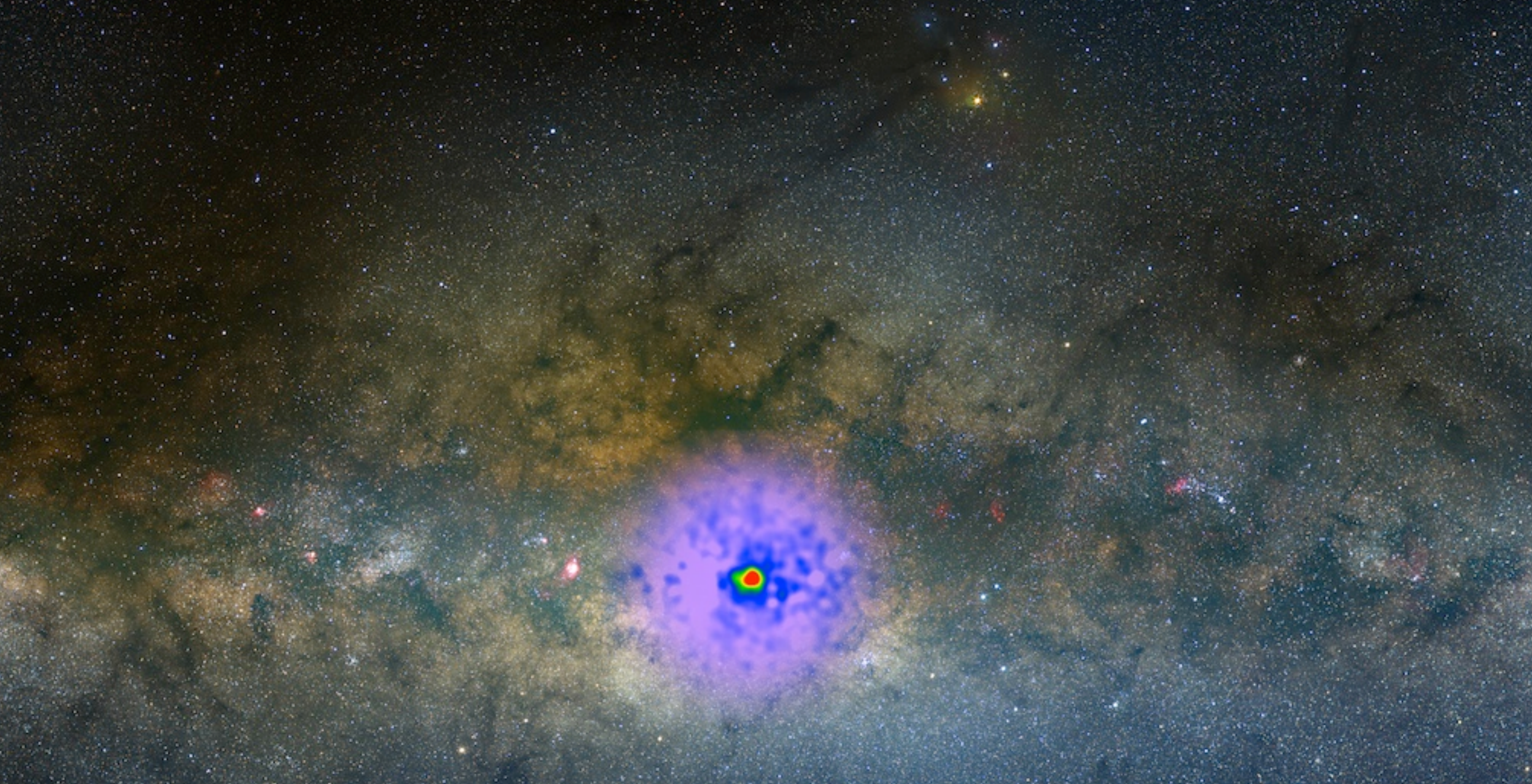

The Status of Indirect Detection Anomalies

Tim Linden

Interplay between Particle and Astroparticle Physics
Cincinnati, OH — October 8, 2018

The Ohio State University
Center for Cosmology and Astroparticle Physics

The Status of Indirect Detection Searches

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

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

The Status of Indirect Detection Searches

MIT-CTP/5020

GeV-Scale Thermal WIMPs: Not Even Slightly Dead

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(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 $2 \rightarrow 2$ 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.

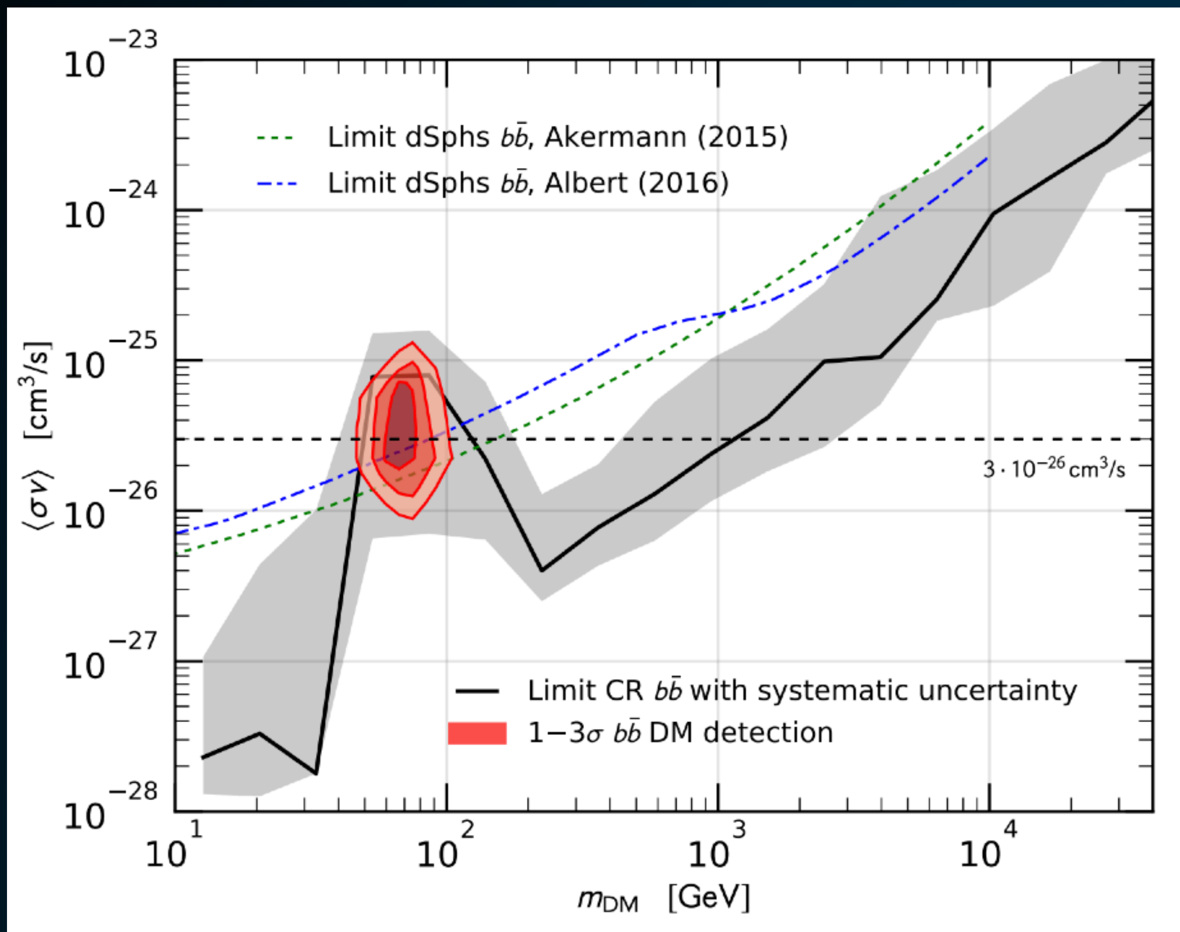
[hep-ph] 11 Jul 2018

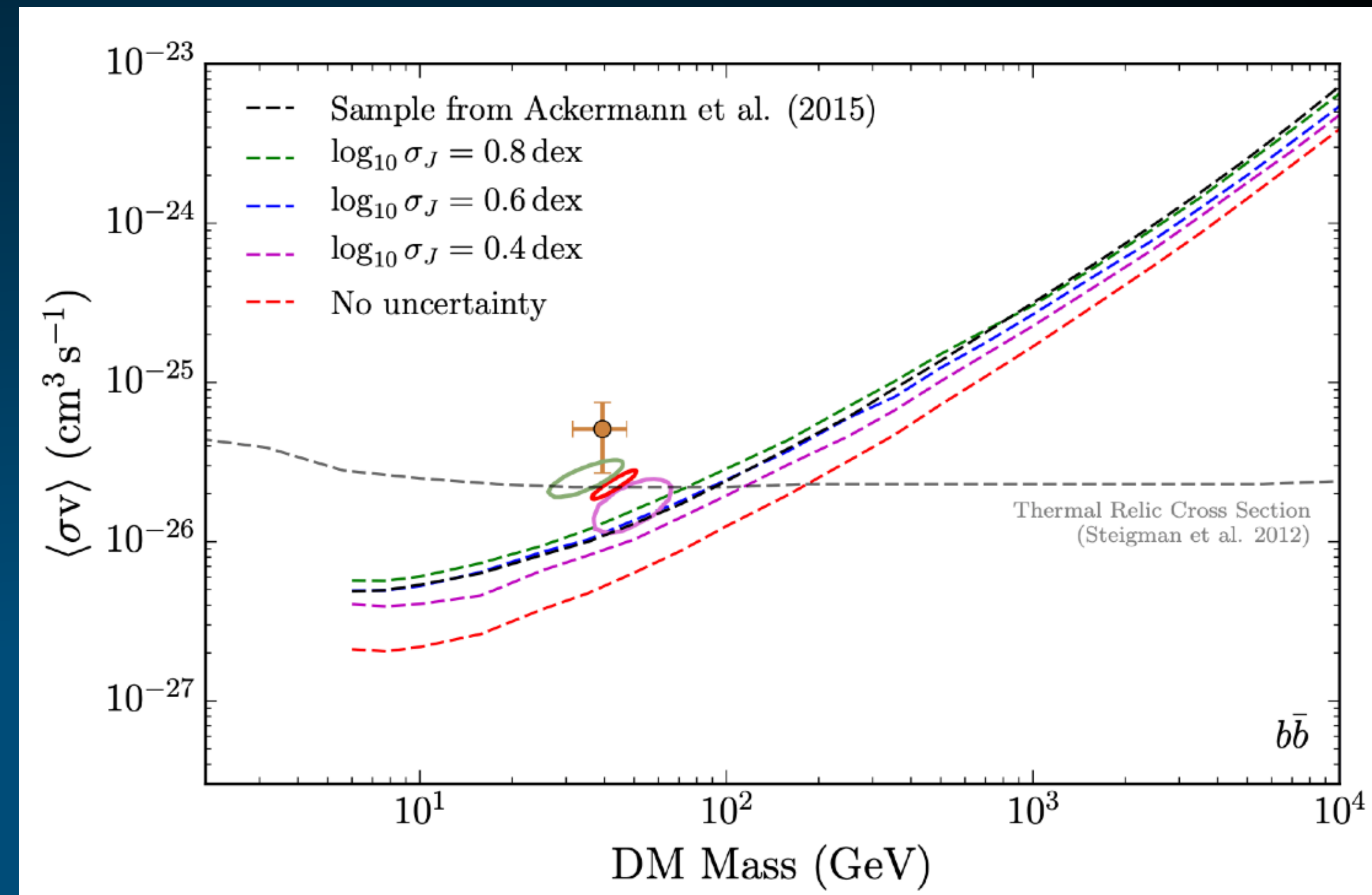
I. INTRODUCTION

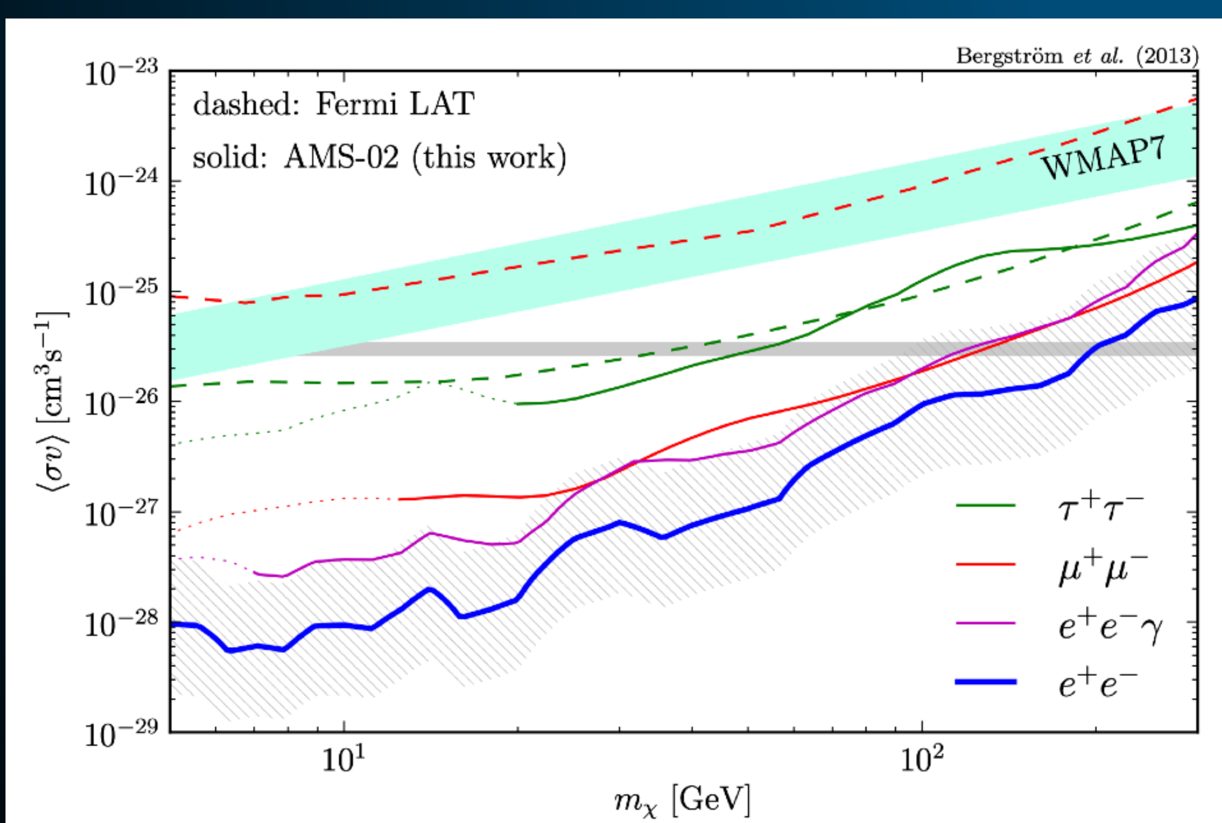
A leading candidate for dark matter (DM) is a Weakly Interacting Massive Particle (WIMP) that is a thermal

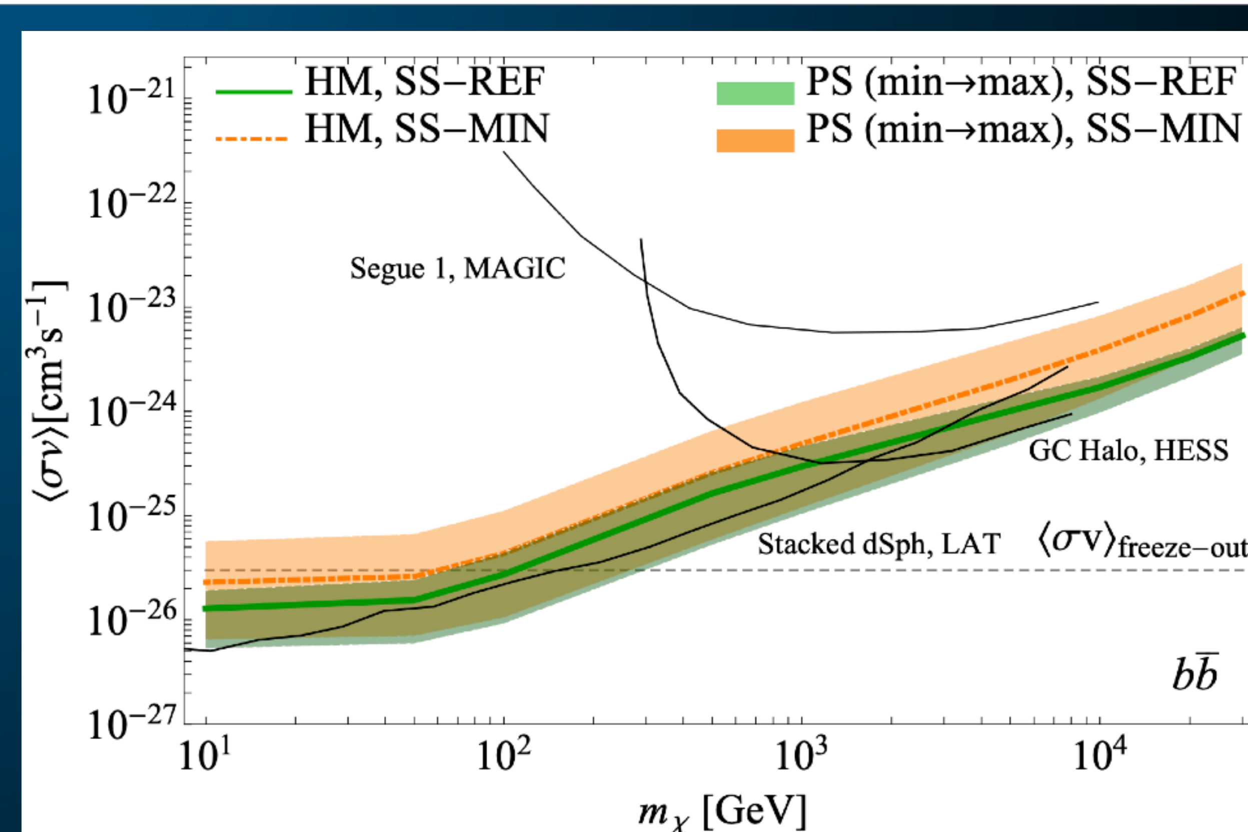
scenarios. The branching ratios, coupling types and signals are model-dependent, and so the lack of observations may just be due to such features. For example, there can be interference effects, momentum suppression, or

The Status of Indirect Detection Searches

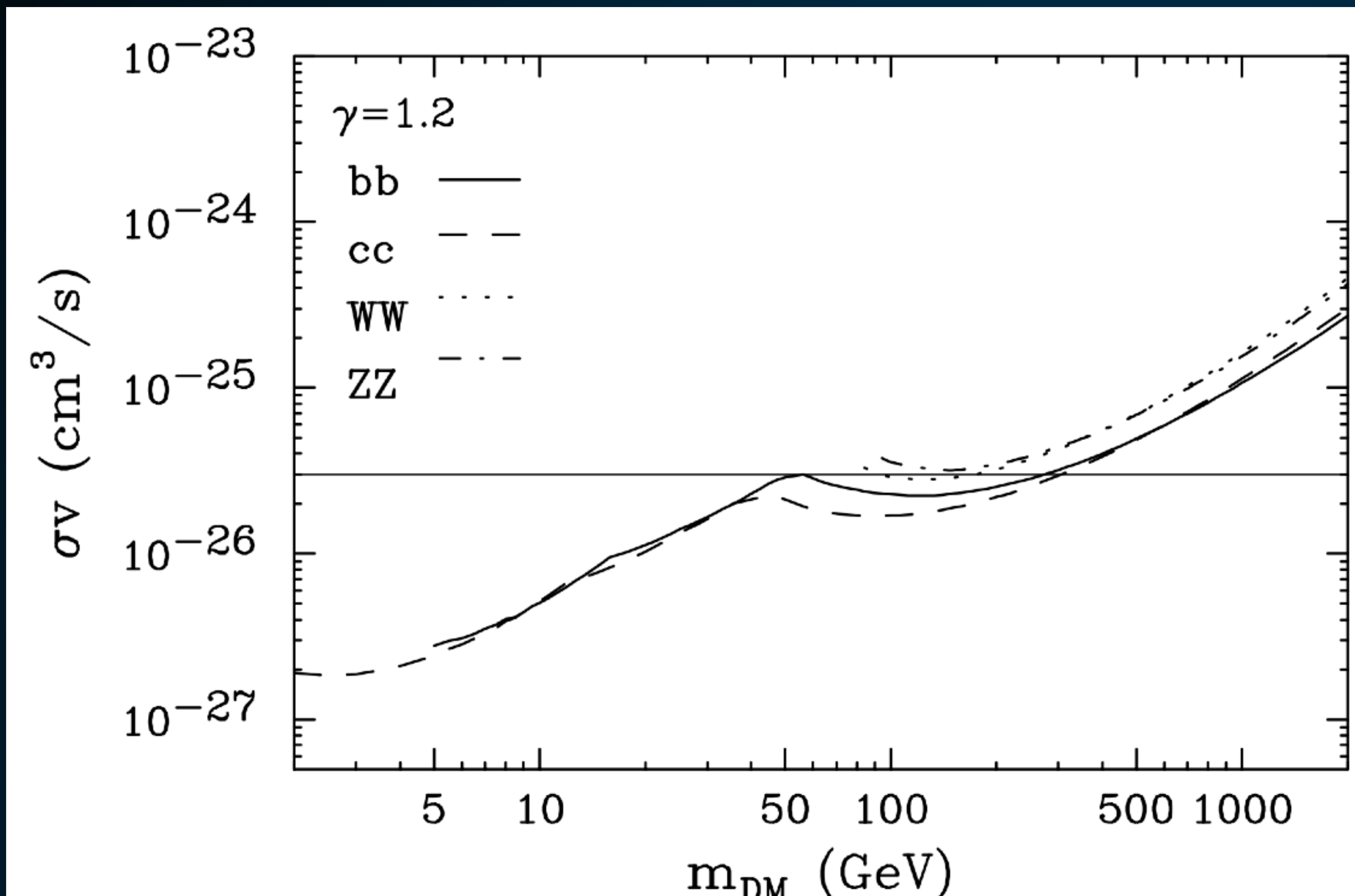


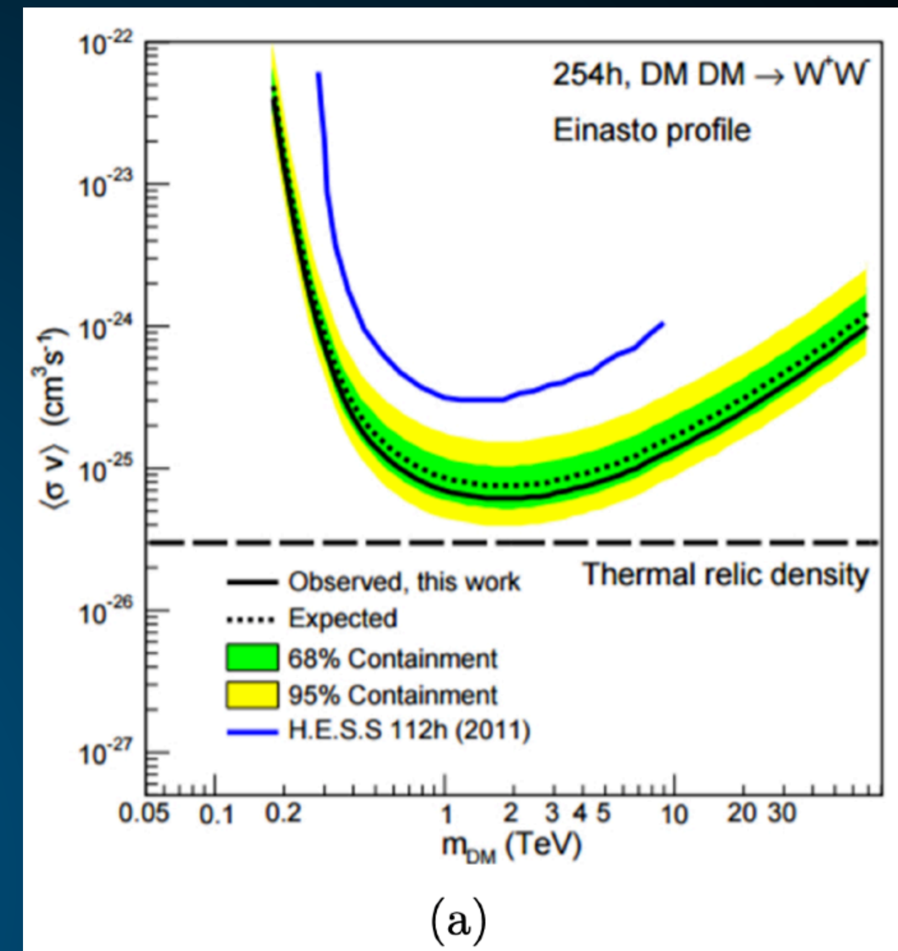


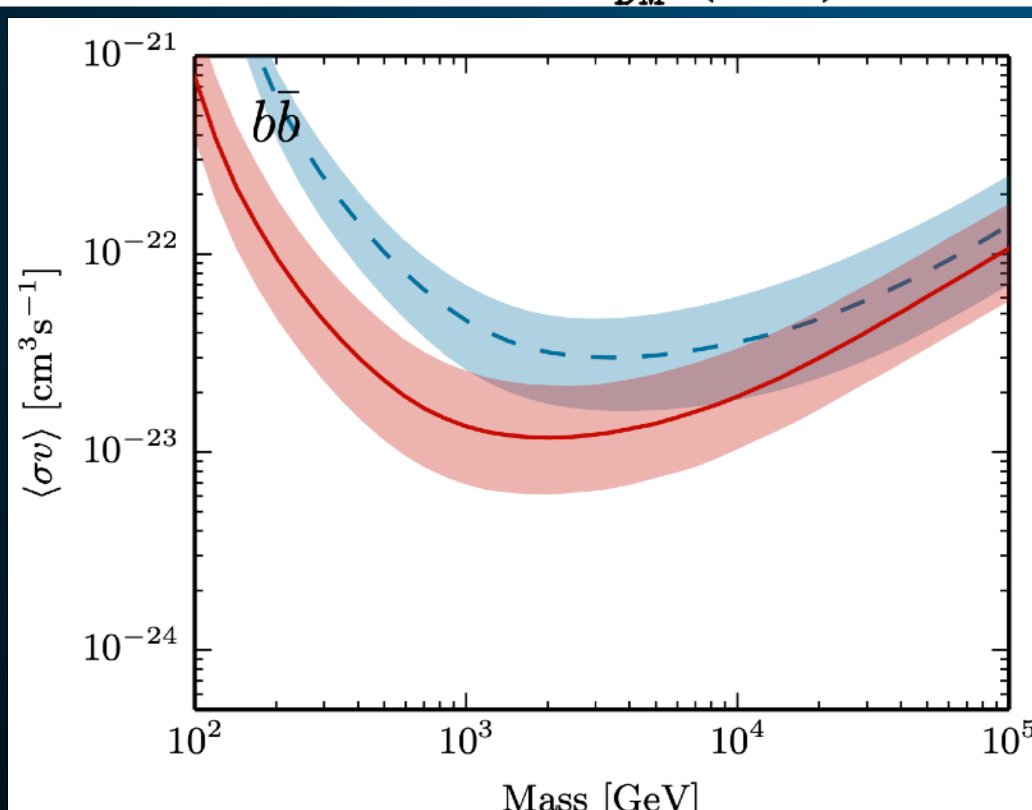


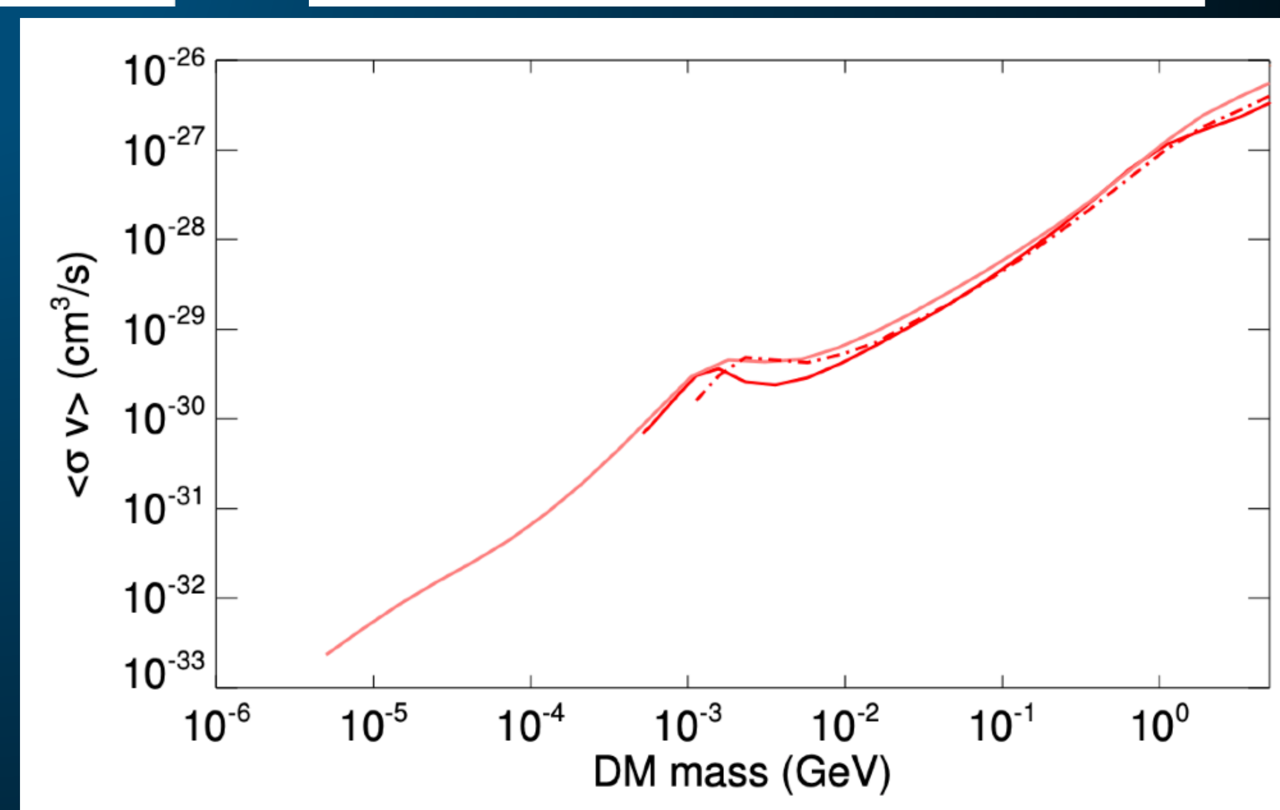


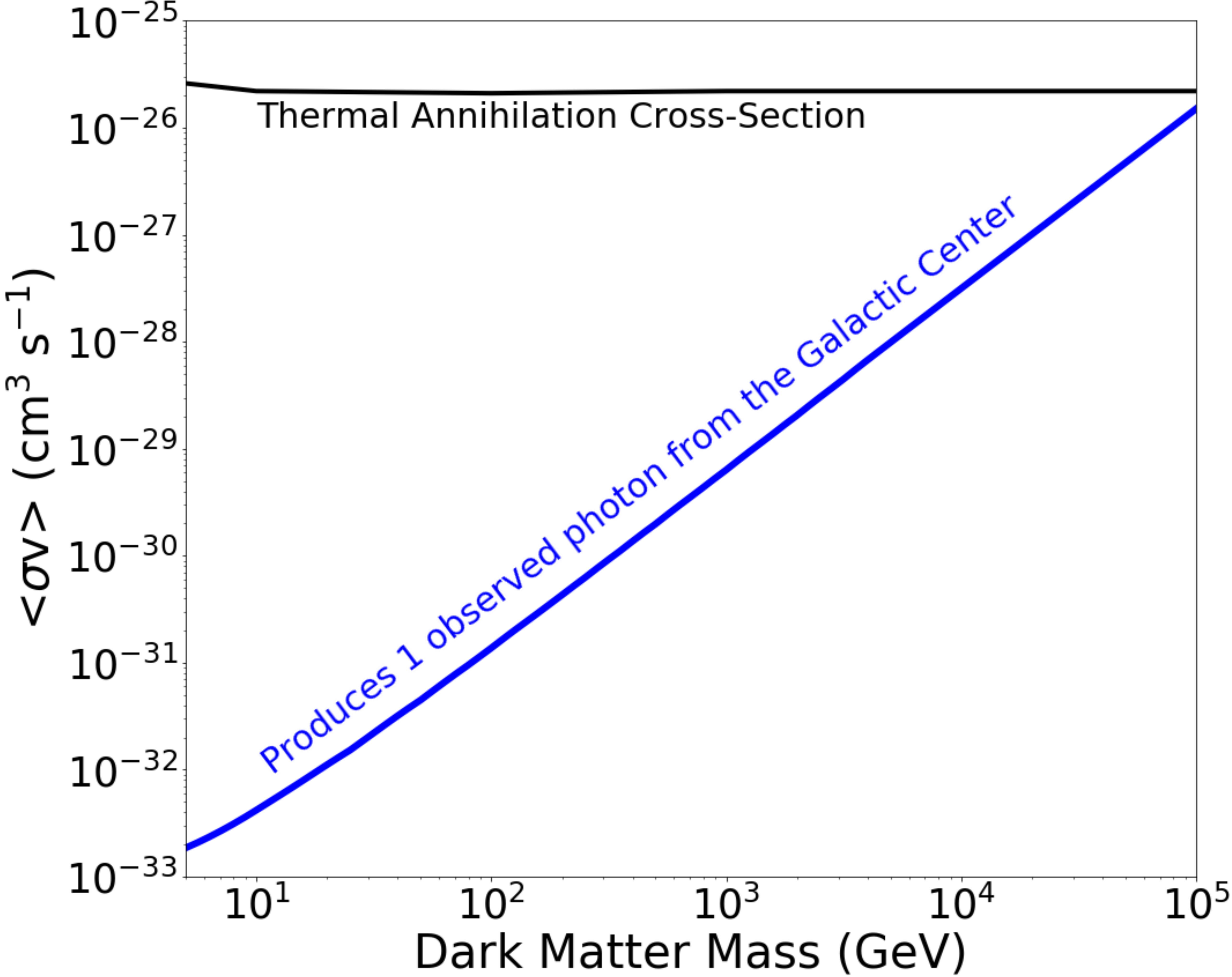
The Status of Indirect Detection Searches



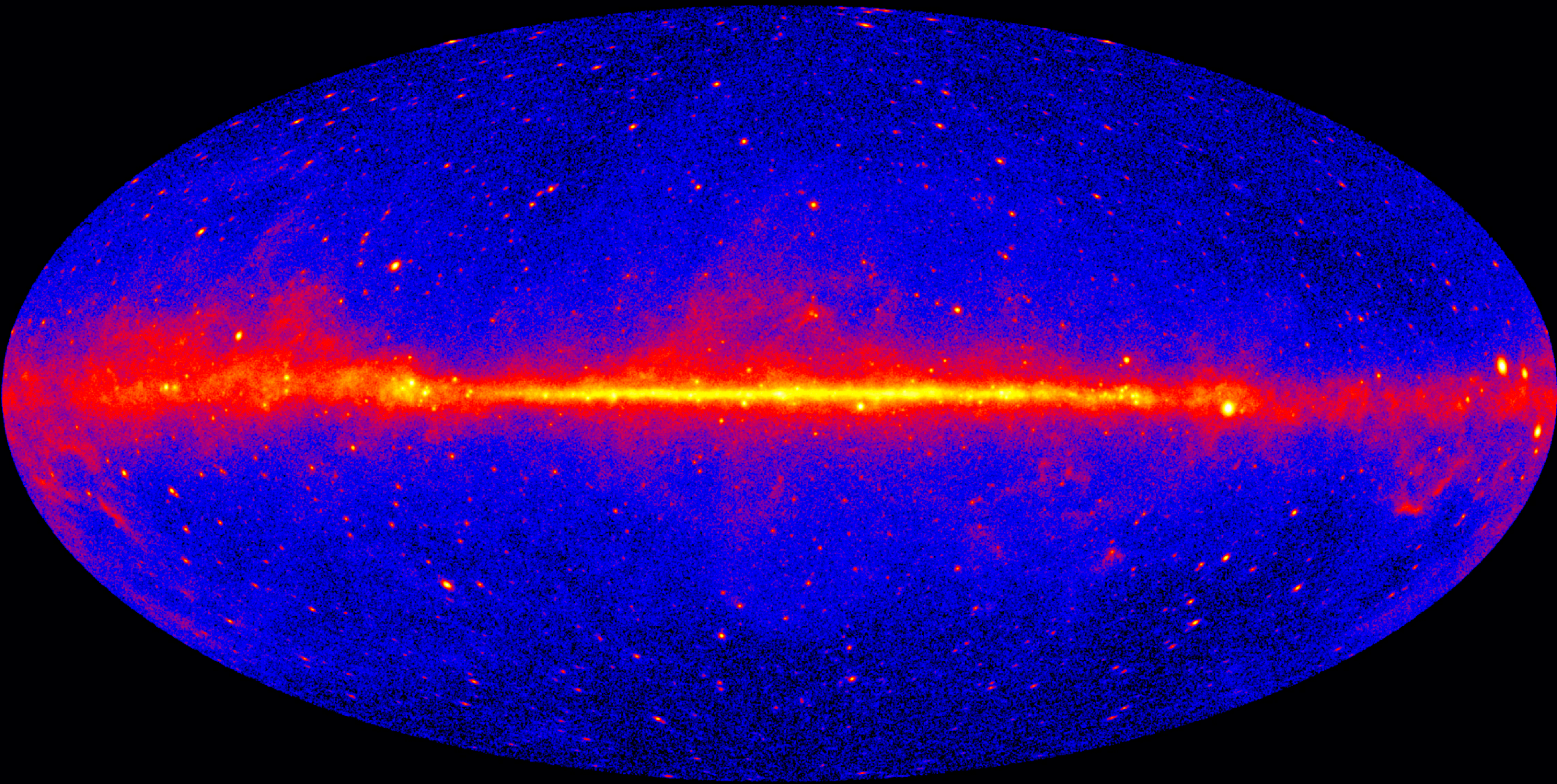


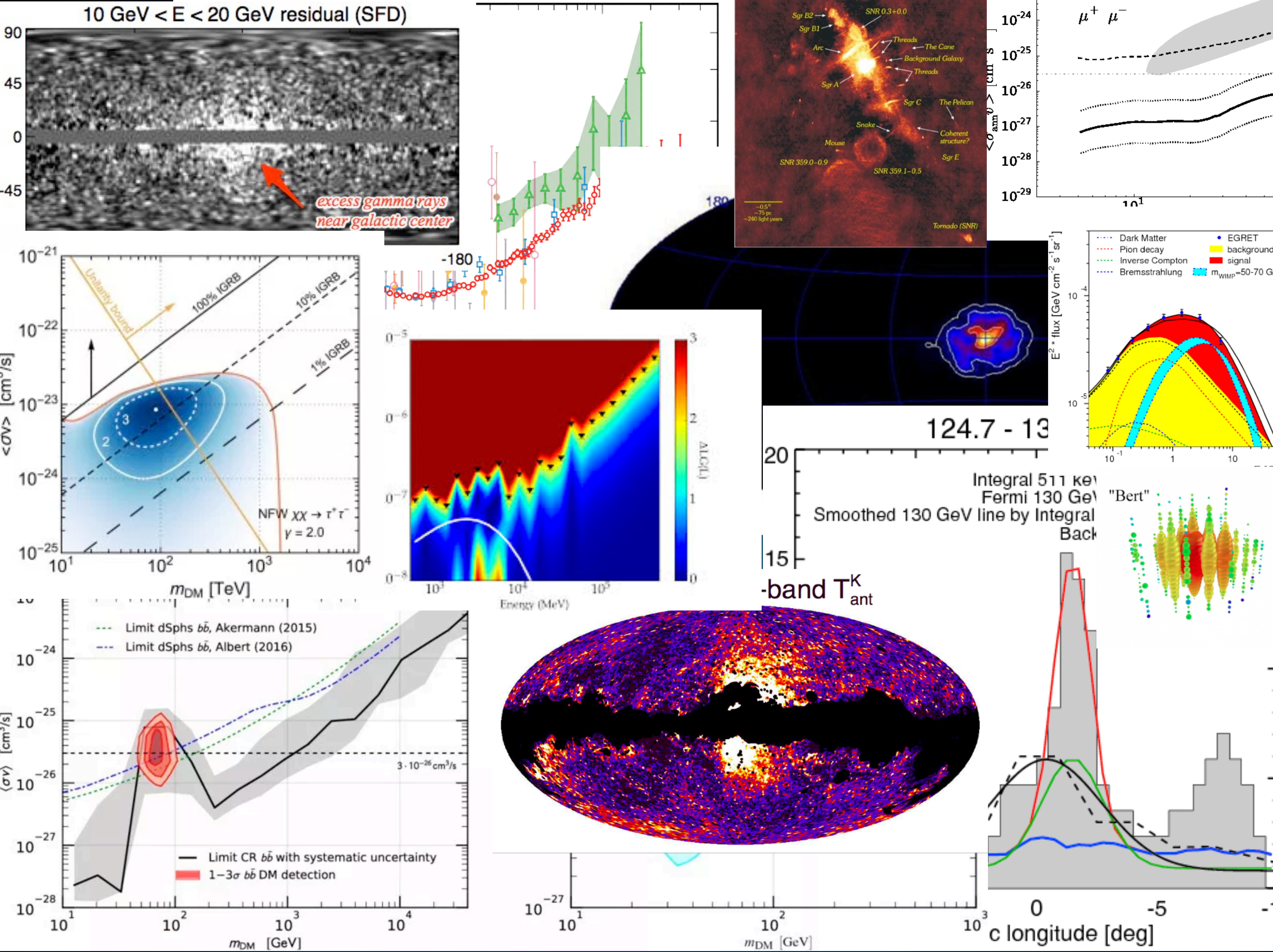






Thermal Annihilation Cross-Section
Produces 1 observed photon from the Galactic Center
<σv> (cm^3 s^{-1})
Dark Matter Mass (GeV)
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^1
10^2
10^3
10^4
10^5




10 GeV < E < 20 GeV residual (SFD)
excess gamma rays near galactic center
Sgr B2
Sgr B1
SNR 0.3+0.0
Arc
Threads
The Cane
Background Galaxy
Sgr A
Sgr C
The Pelican
Snake
Coherent structure?
Mouse
Sgr E
SNR 359.0-0.9
SNR 359.1-0.5
Tornado (SNR)
μ⁺ μ⁻
Dark Matter
Pion decay
Inverse Compton
Bremsstrahlung
EGRET
background
signal
Unitarity bound
100% IGRB
10% IGRB
1% IGRB
NFW χχ → τ⁺τ⁻
γ = 2.0
<σv> [cm³/s]
m_DM [TeV]
ΔLG(L)
Energy (MeV)
124.7 - 13
Integral 511 keV
Fermi 130 GeV
Smoothed 130 GeV line by Integral
Back
"Bert"
-band T^K_ant
Limit dSphs bb̄, Akermann (2015)
Limit dSphs bb̄, Albert (2016)
3·10⁻²⁶ cm³/s
Limit CR bb̄ with systematic uncertainty
1−3σ bb̄ DM detection
⟨σv⟩ [cm³/s]
m_DM [GeV]
c longitude [deg]

Current Anomalies in Indirect Detection

Astrophysics Excesses:

Positron Excess
Galactic Center Excess

Statistical Excesses:

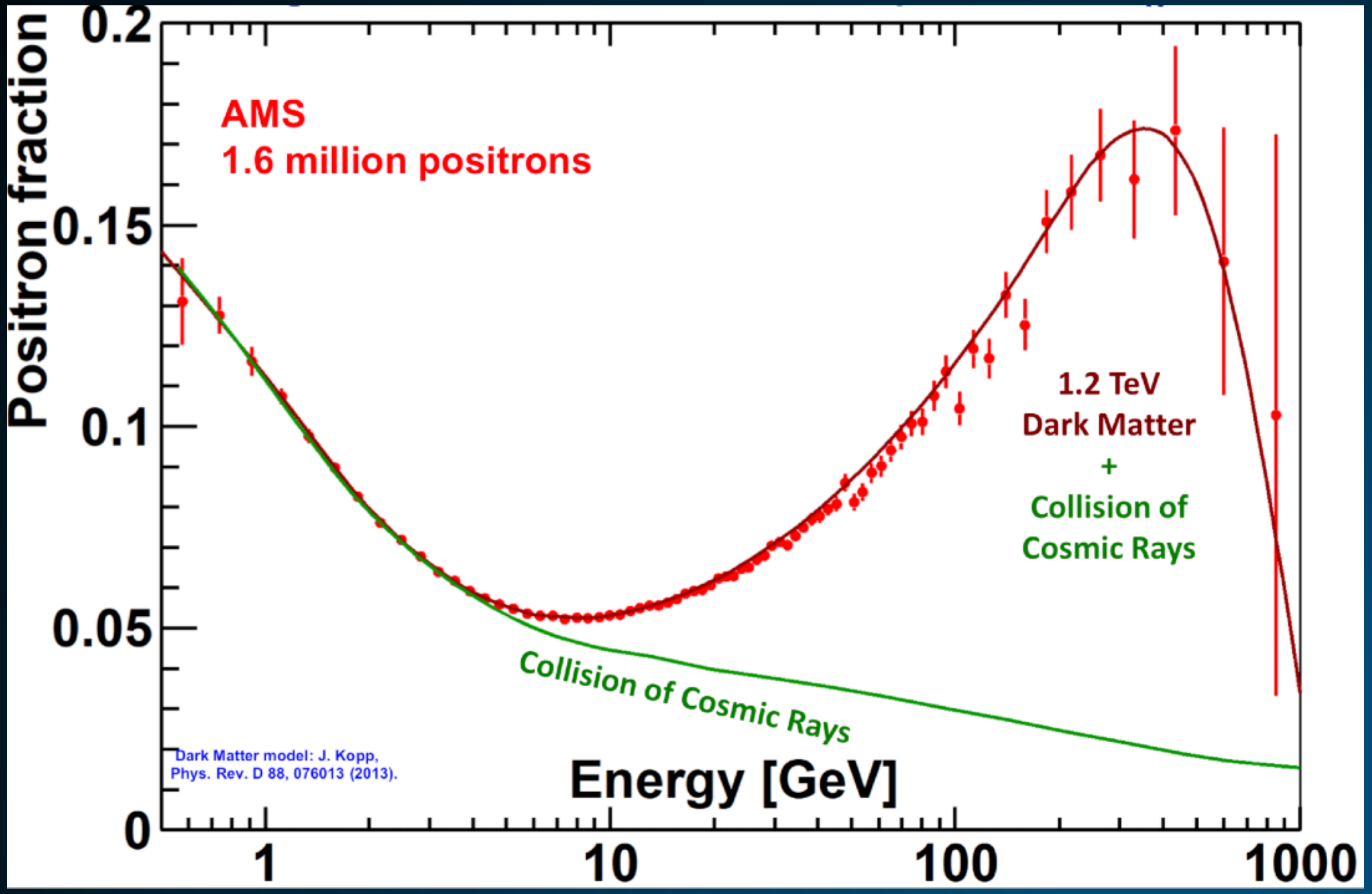
Antiproton Excess
3.5 keV Line

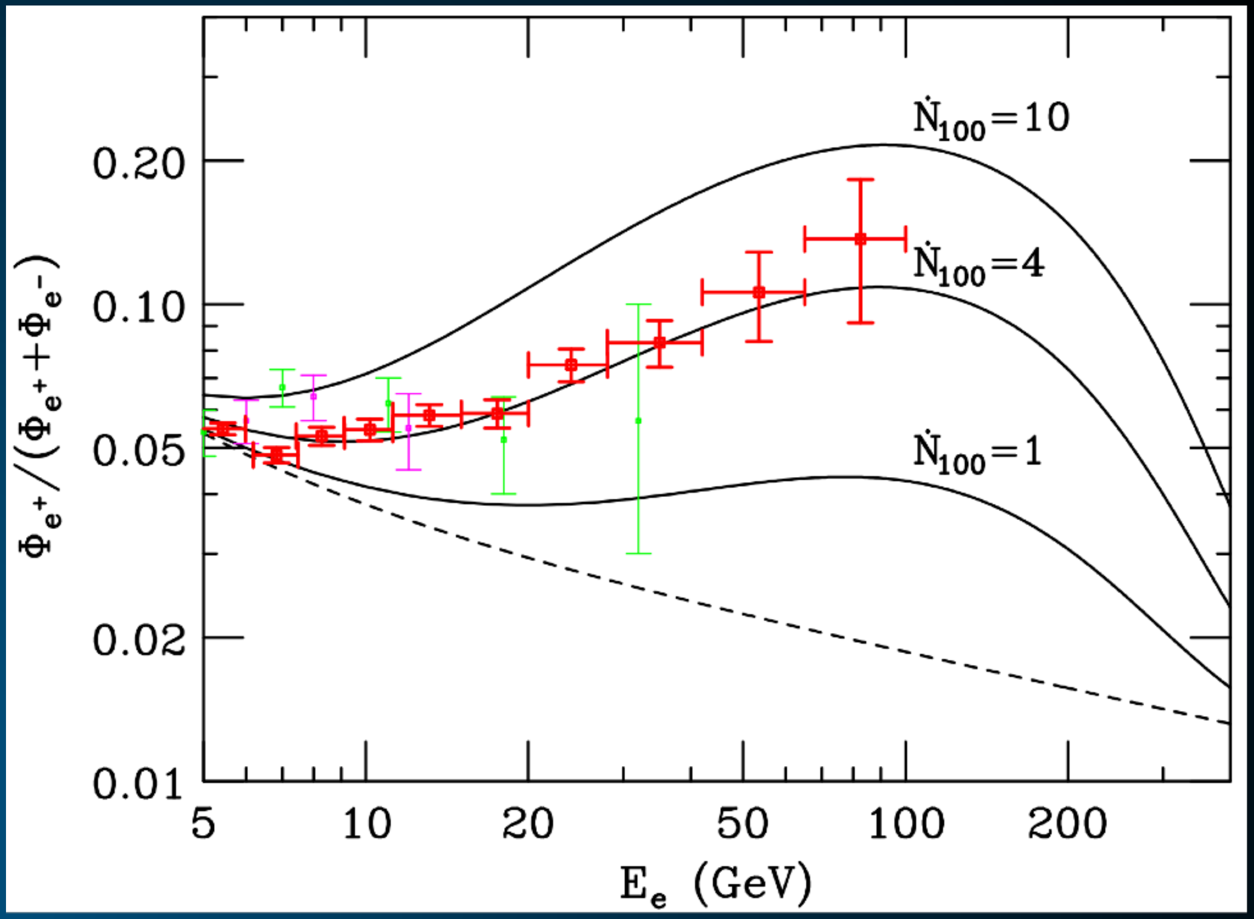
Instrumental Excesses:

Anti-Helium Excess
EDGES/ARCADE II Excesses

The Positron Excess Debate is Over

Pulsars win!





Dark Matter Models

- *Highly Sommerfeld Enhanced*
- *Leptophilic*

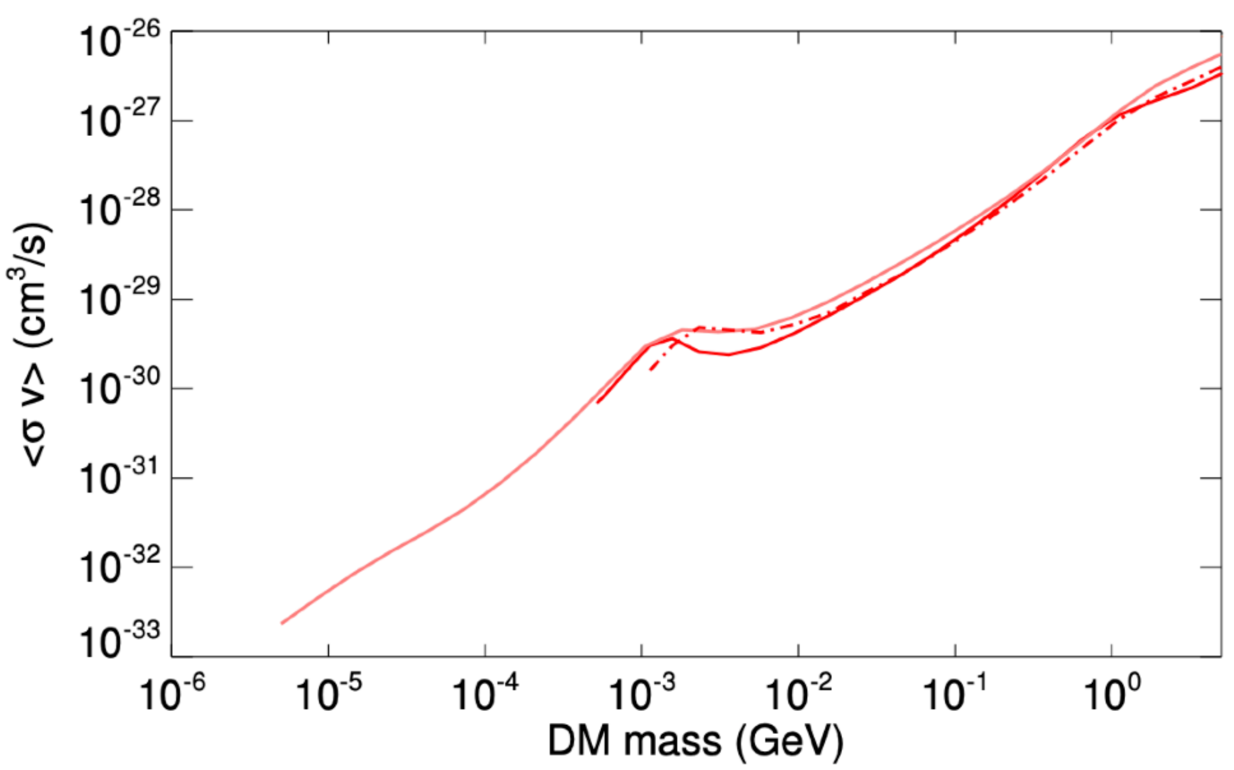
Pulsar Models

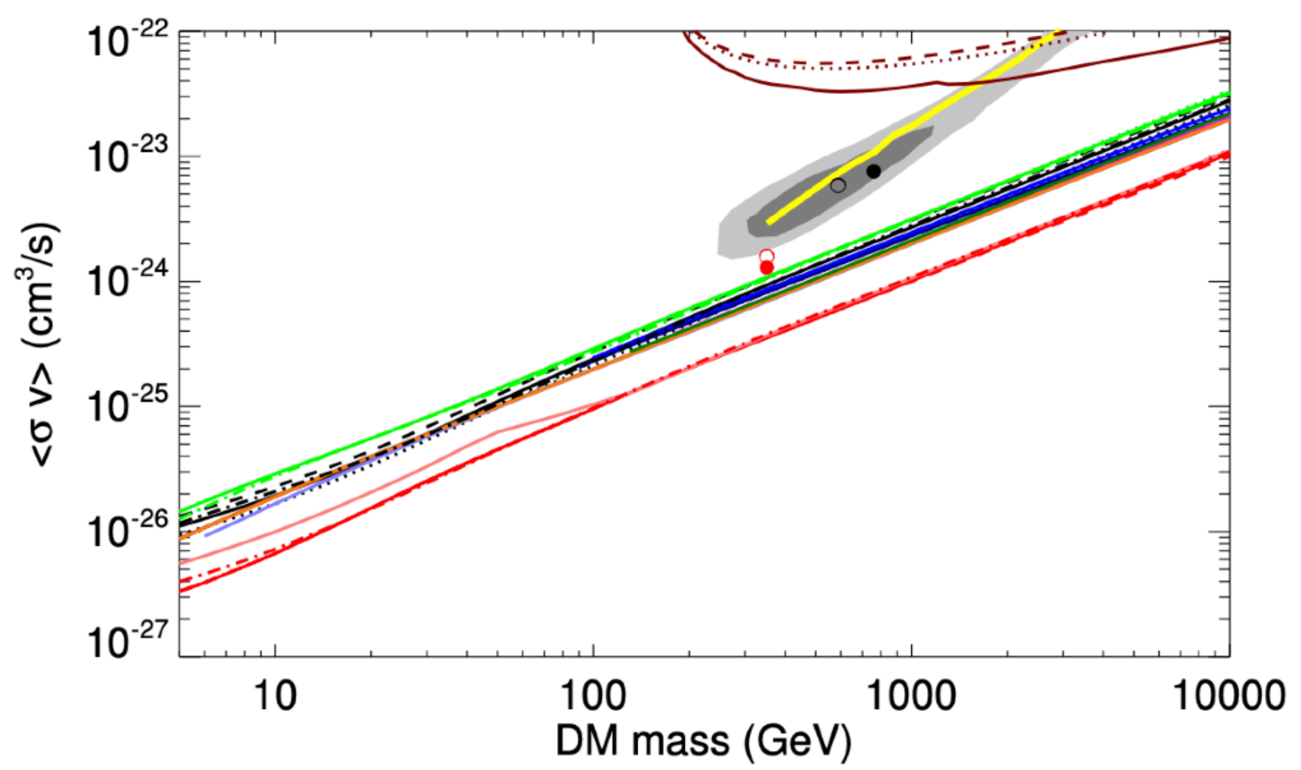
- *Efficient e+e- Production*
- *Hard e+e- Spectrum*

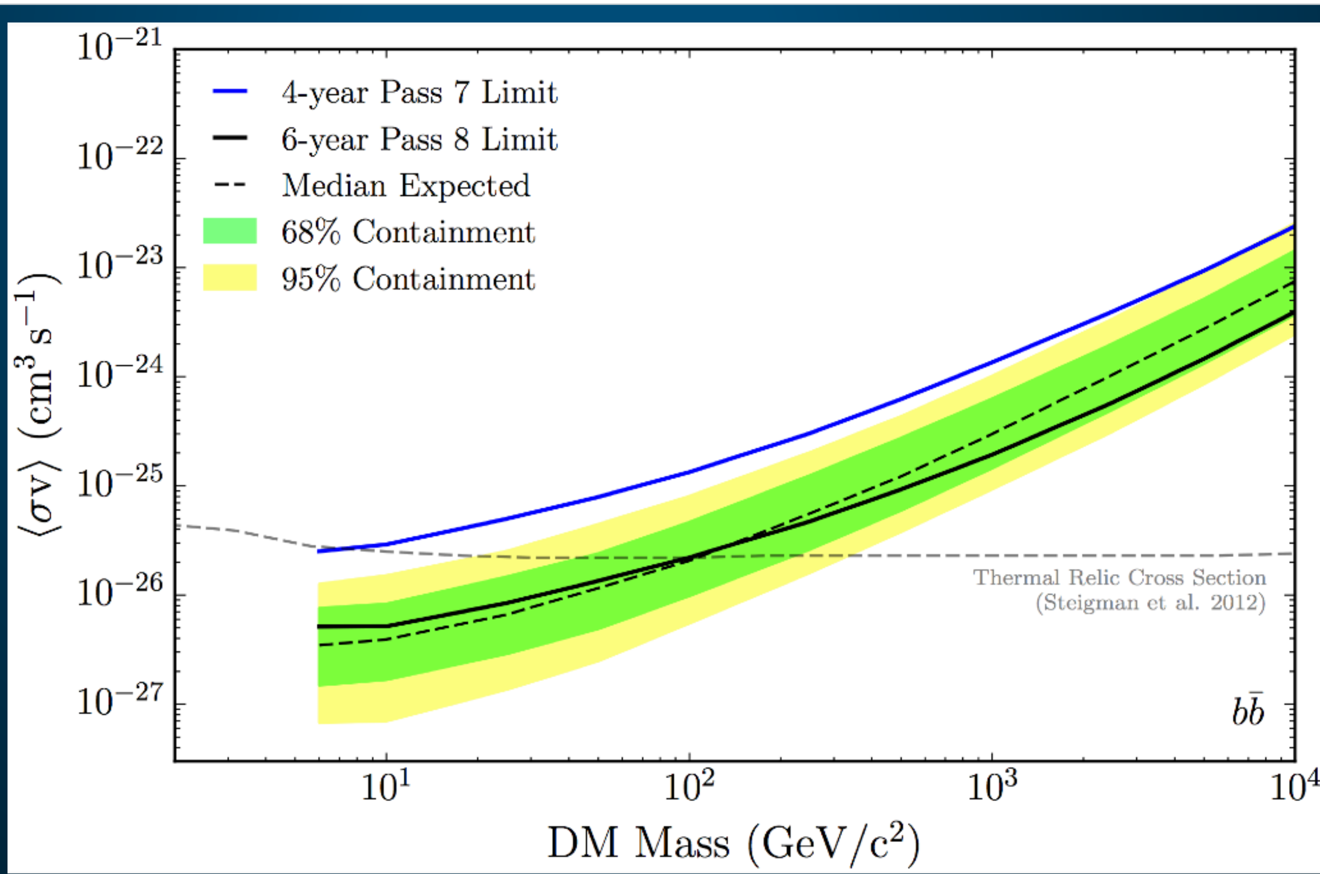
The Positron Excess Debate is Over

Slatyer (2015; 1506.03811)

Pulsars win!







Fermi-LAT Collaboration (2016; 1611.03184)

PULSARS PRODUCE THE POSITRON EXCESS

- **What were the uncertainties in pulsar models?**
  - **I: The e^+e^- production efficiency?**

Profumo (0812.4457); Malyshev et al. (0903.1310)

%. A quantitative discussion of plausible values for $f_{e^\pm}$ was recently given in Ref. [38]. We shall not review their discussion here, but Ref. [38] argues (see in particular their very informative App. B and C) that in the context of a standard model for the pulsar wind nebulae, a reasonable range for $f_{e^\pm}$ falls between 1% and 30%.

  - **II: The e^+e^- spectrum.**
  - **III: The propagation of e^+e^- to Earth.**

PULSARS PRODUCE THE POSITRON EXCESS

- **What were the uncertainties in pulsar models?**
  - **I: The e^+e^- production efficiency?**
  - **II: The e^+e^- spectrum.**

Hooper et al. (0810.1527)

part of their energy adiabatically because of the expansion of the wind. The energy spectrum injected by a single pulsar depends on the environmental parameters of the pulsar, but some attempts to calculate the average spectrum injected by a population of mature pulsars suggest that the spectrum may be relatively hard, having a slope of ~1.5-1.6 [18]. This spectrum, however, results from a complex interplay of individual pulsar spectra, of the spatial and age distributions of pulsars in the Galaxy, and on the assumption that the chief channel for pulsar spin down is magnetic dipole radiation. Due to the related uncertainties, variations from this injection spectra cannot be ruled out. Typically, one concentrates the attention on pulsars of age $\sim 10^5$ years because younger pulsars are likely to still

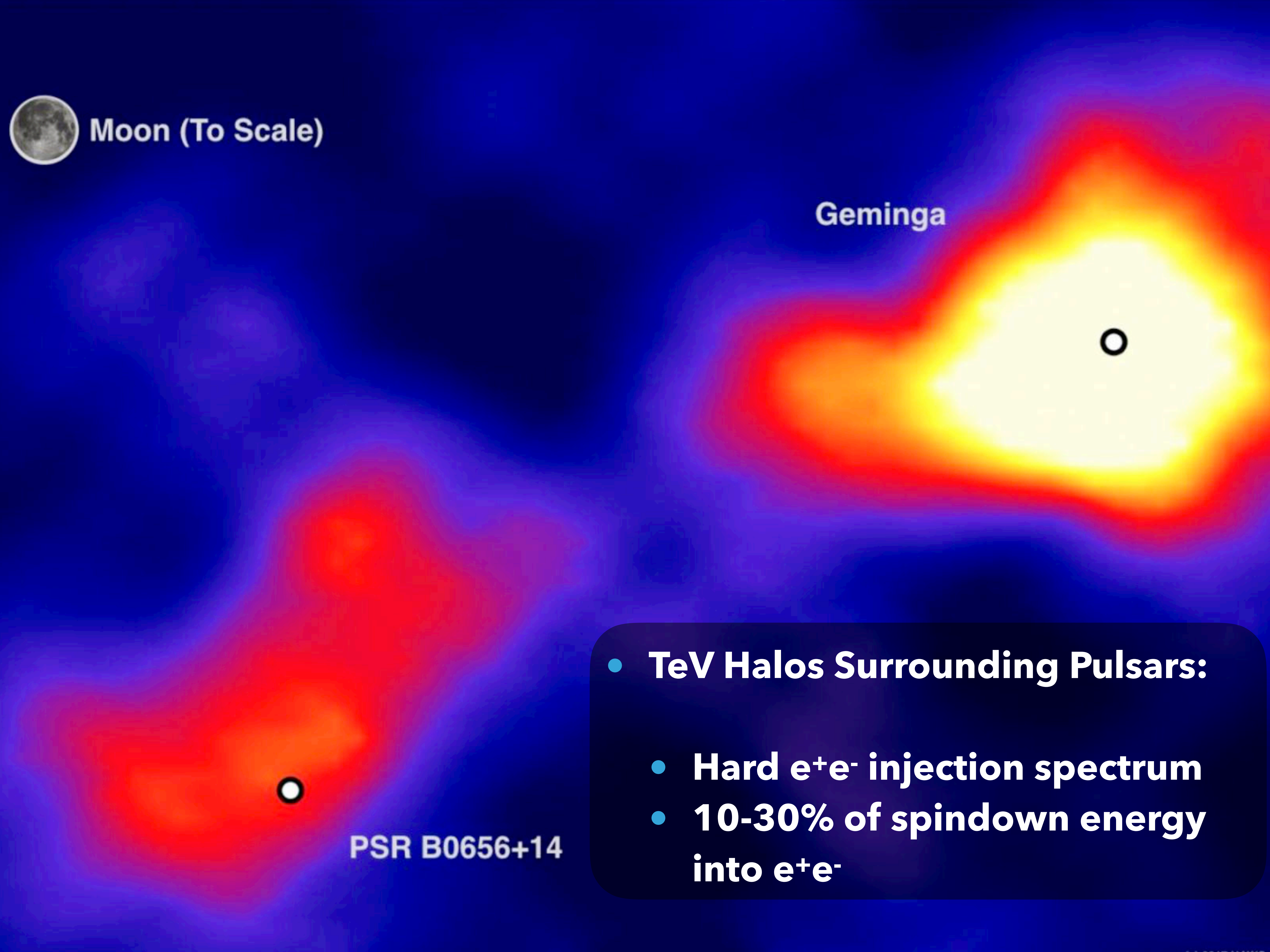
  - **III: The propagation of e^+e^- to Earth.**

PULSARS PRODUCE THE POSITRON EXCESS

- **What were the uncertainties in pulsar models?**
  - **I: The e^+e^- production efficiency?**
  - **II: The e^+e^- spectrum.**
  - **III: The propagation of e^+e^- to Earth.**

Malyshev et al. (0903.1310)

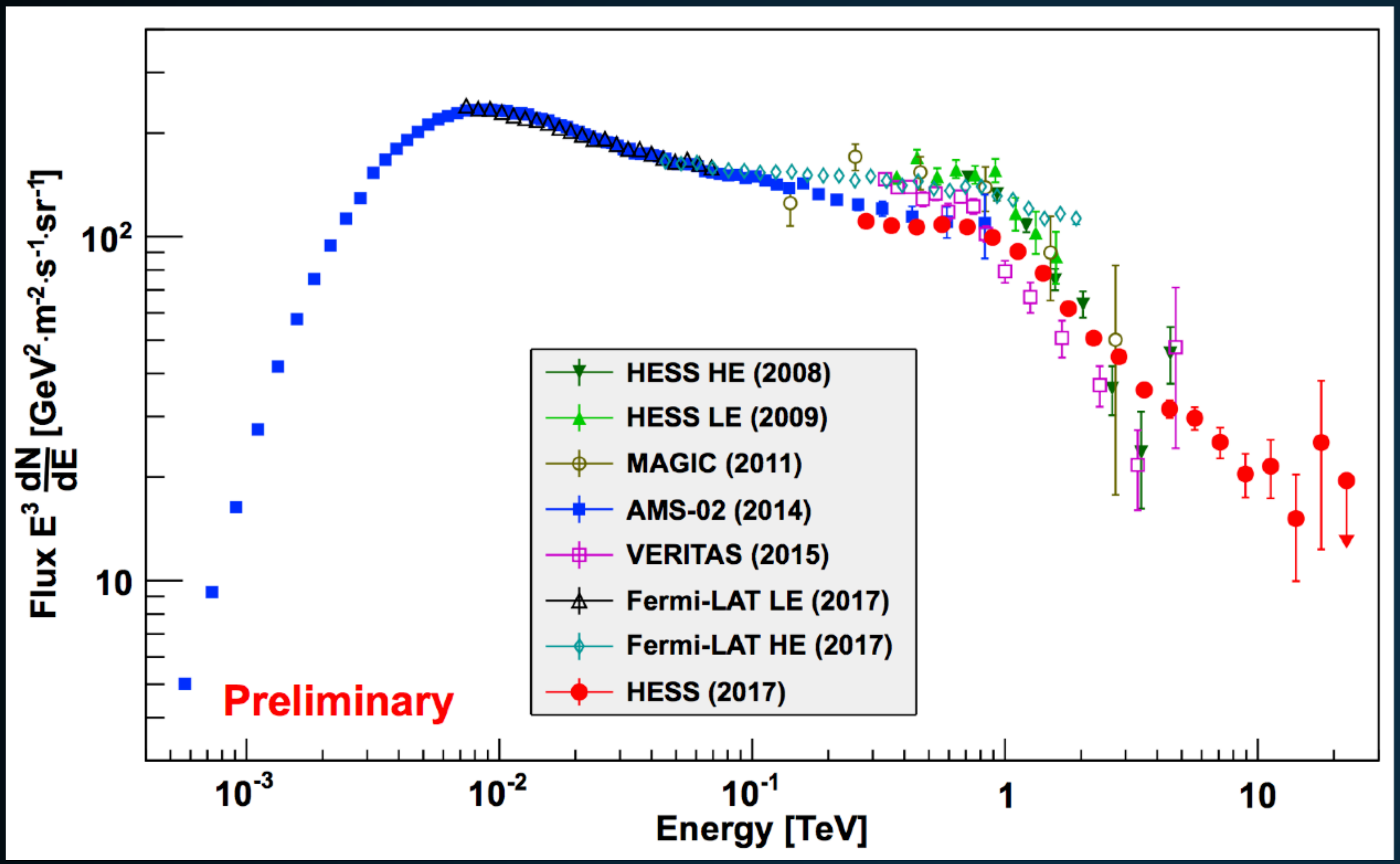
The observed spectrum on Earth of electrons and positrons injected by pulsars is also strongly dependent on propagation effects. In particular, the observed cutoff in the flux of electrons from a pulsar can be much smaller than the injection cutoff due to energy losses ("cooling") during propagation. We define the cooling break, $E_{\rm br}(t)$, as the maximal energy electrons can have after propagating for time t. Since – as stated above – the typical

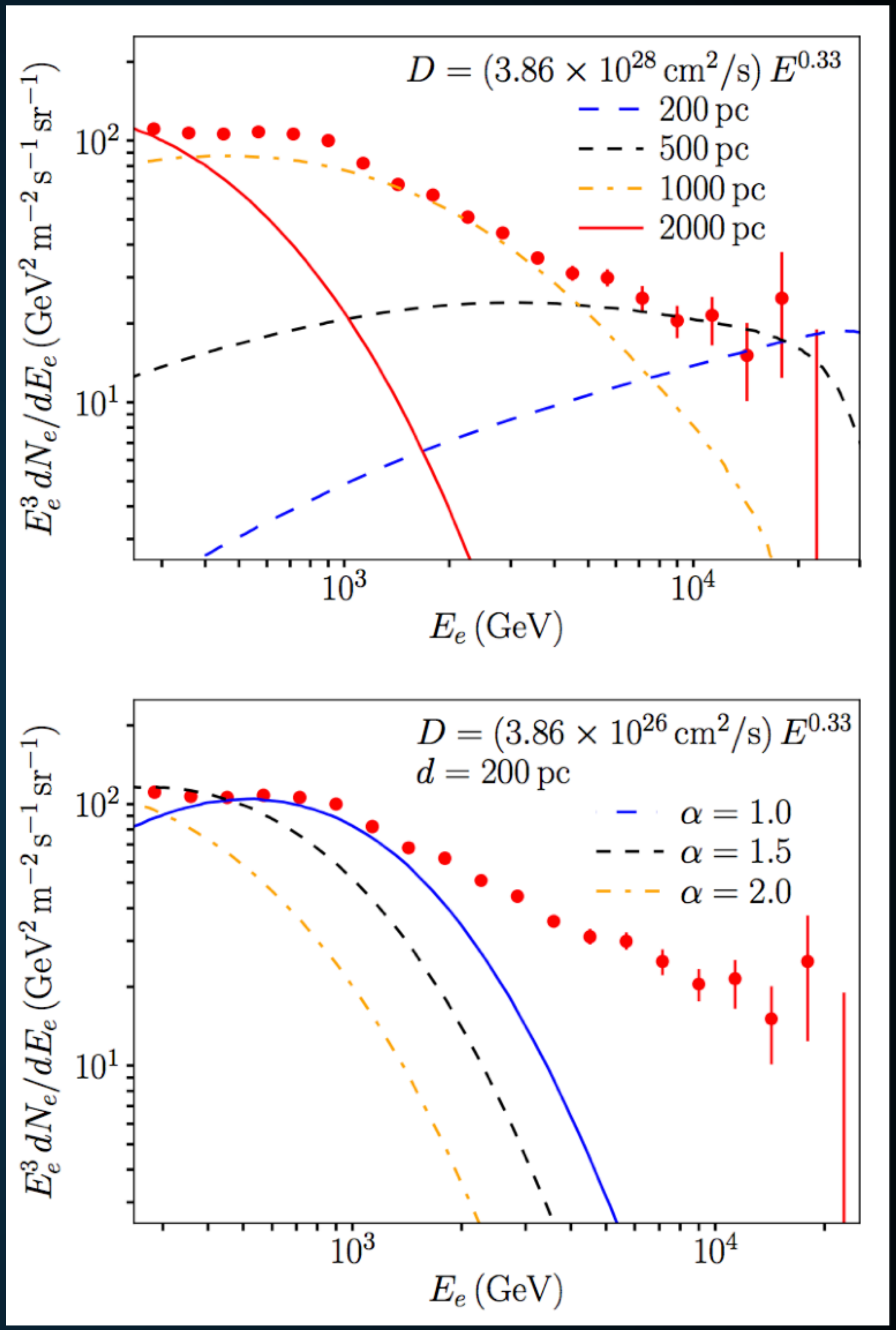


- **TeV Halos Surrounding Pulsars:**
  - **Hard e^+e^- injection spectrum**
  - **10-30% of spindown energy into e^+e^-**

CAN THE LOCAL DIFFUSION CONSTANT BE LOW?

Hooper & Linden (1711.07482)

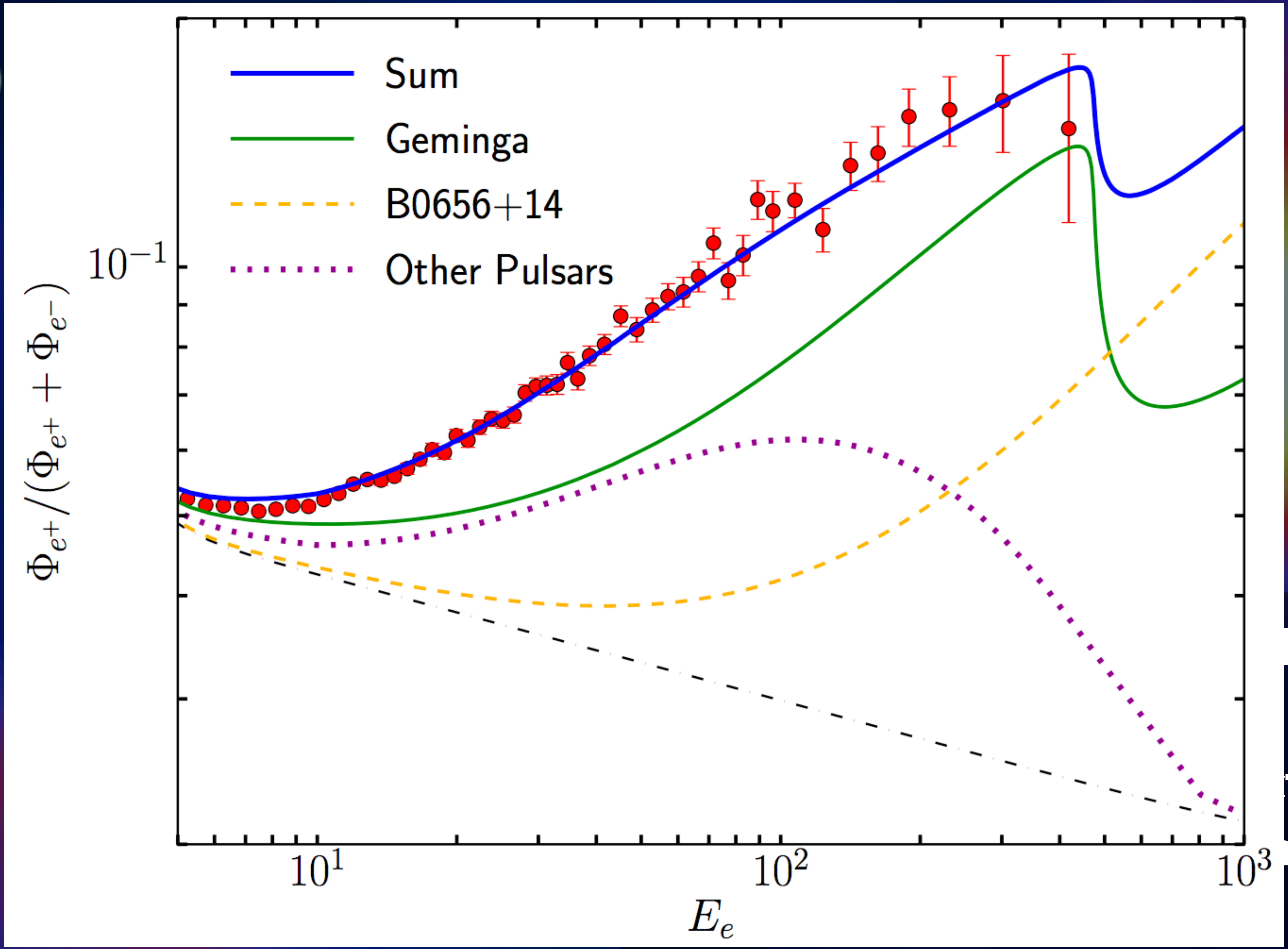




- **HESS Observations of 20 TeV electrons resolve this.**
- **If diffusion near Earth is low, then there is no source for these particles.**

Spectral Features

Part 1: The Positron Excess



lsars:

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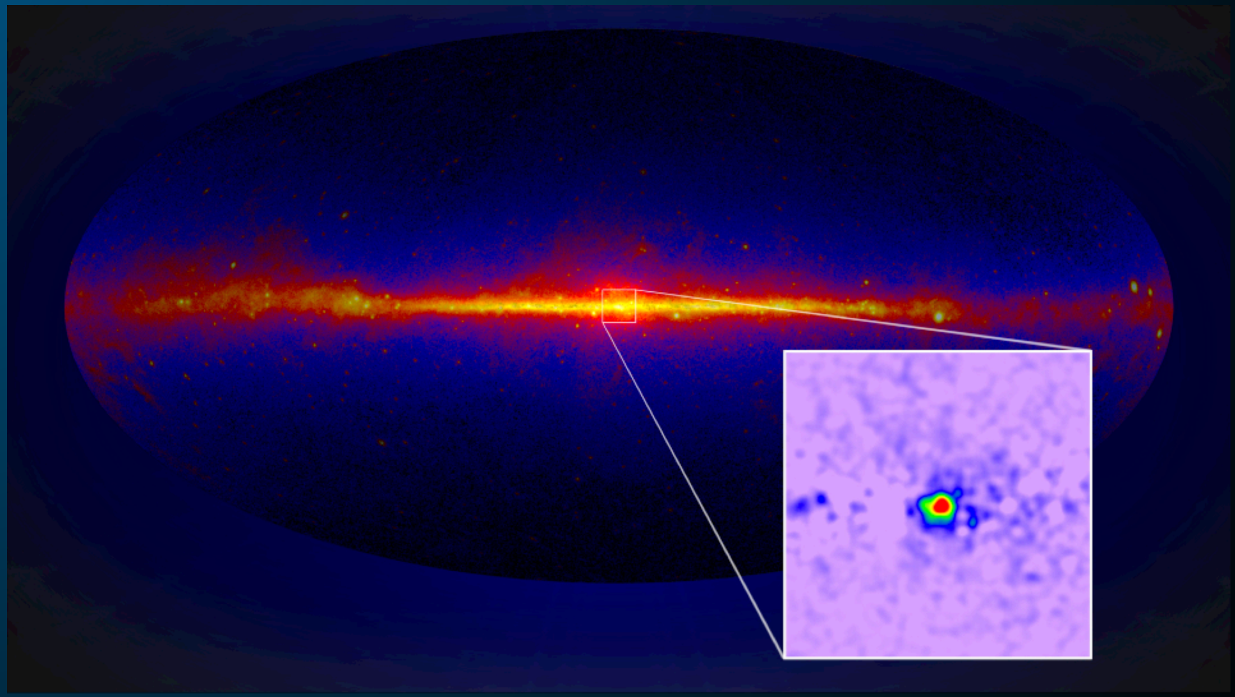
ergy

The Galactic Center Excess Debate is Not Over

Pulsars Up 3 to 1?

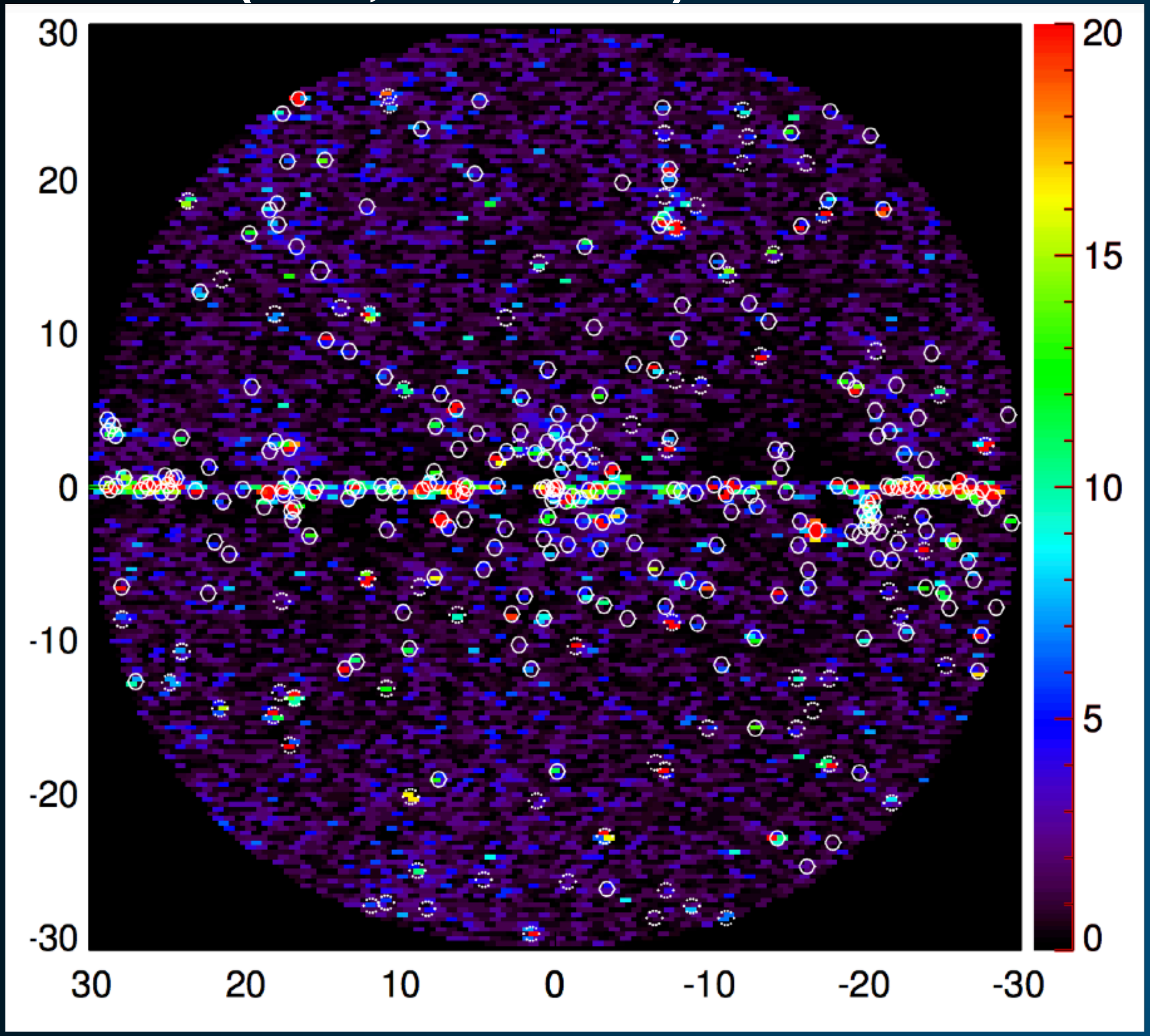
- **Model:**
  - **100 GeV dark matter particle annihilates to bb**
  - **Annihilation Rate is Thermal Cross-Section**
- **Expected Galactic Center Flux (above 1 GeV):**
  - **2×10^{-11} erg cm^{-2} s^{-1}**
- **Observed Flux:**
  - **1×10^{-10} erg cm^{-2} s^{-1}**



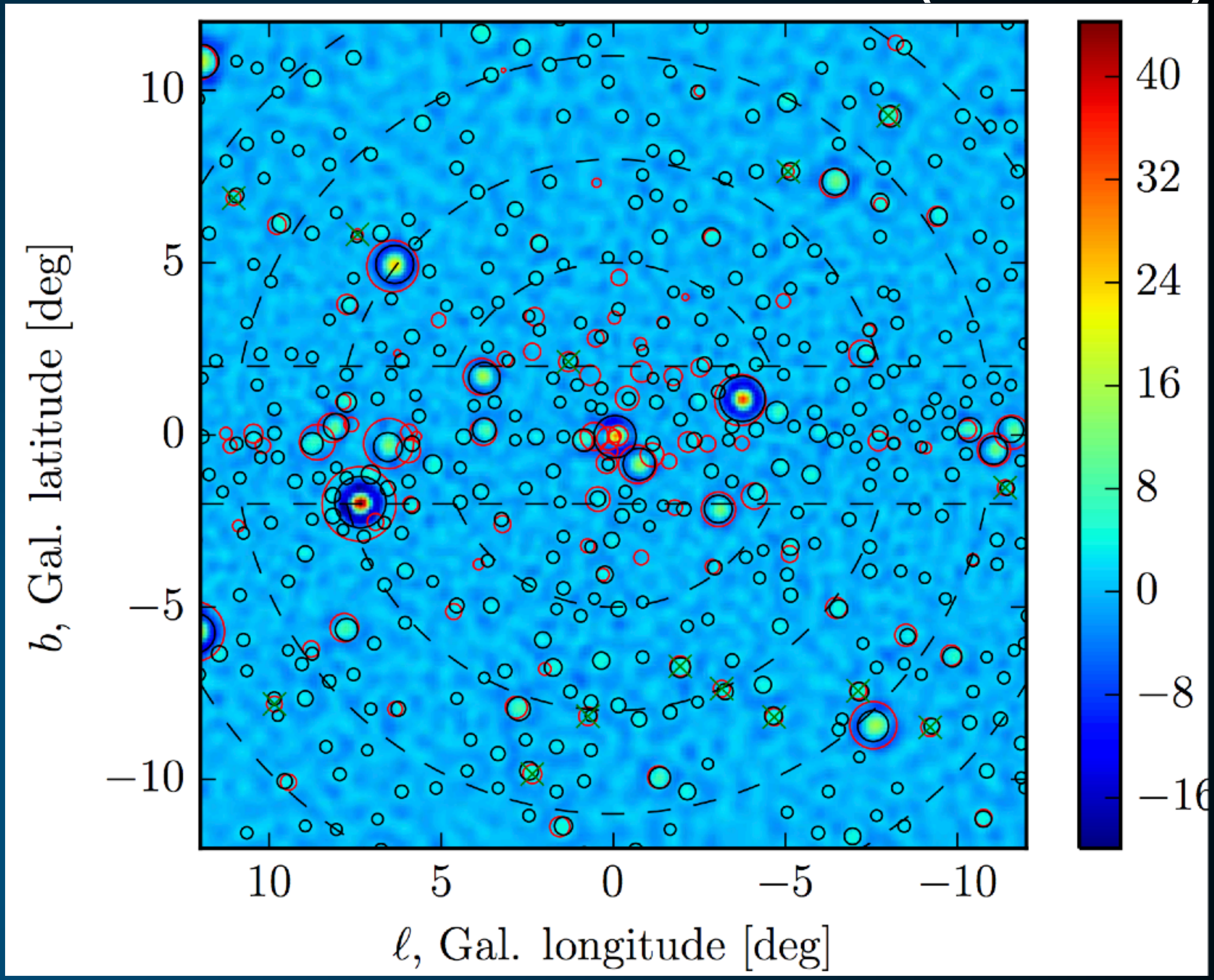
The Galactic Center Excess Debate is Not Over

Pulsars Up 3 to 1?

Lee et al. (2016; 1506.05124)



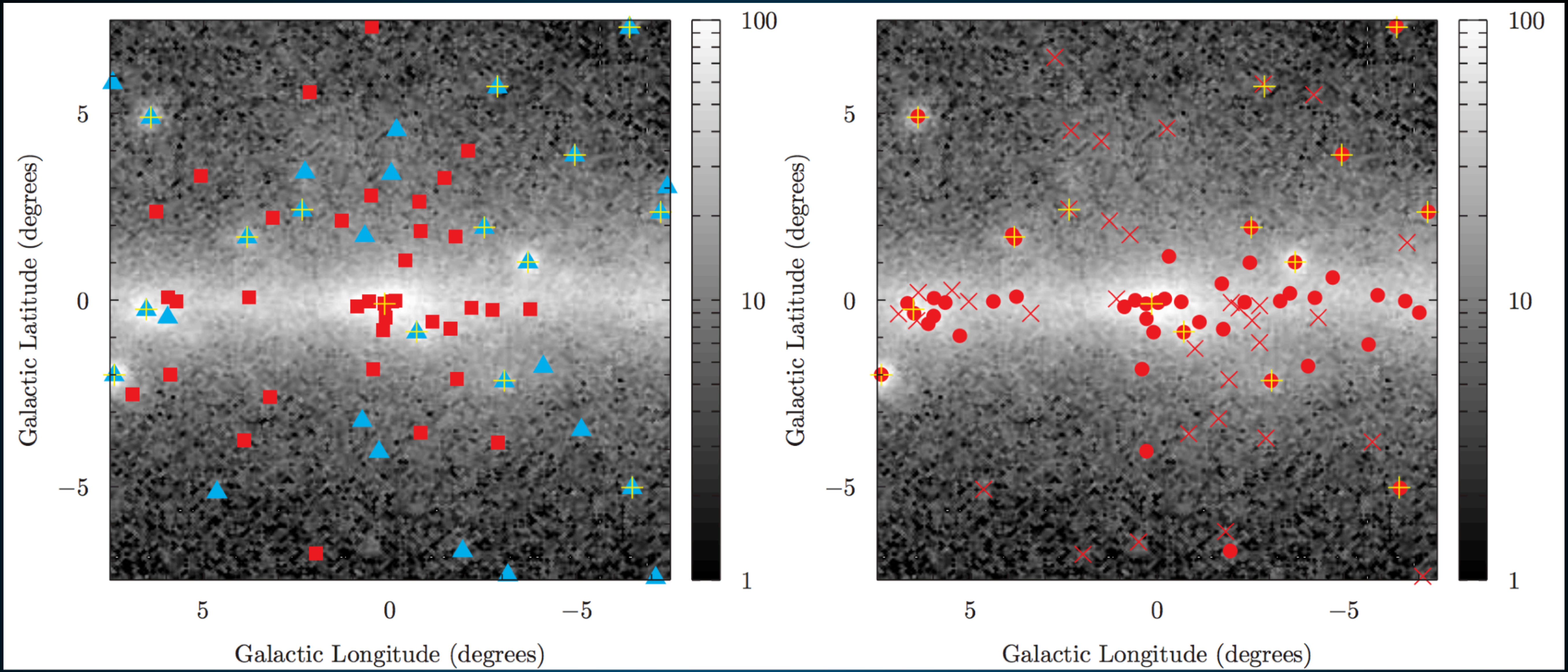
Bartels et al. (1506.05104)



- **The strongest, but most controversial, evidence supporting the pulsar interpretation is the observation of significant fluctuations in the gamma-ray flux, which have a spectrum similar to that of unassociated point sources.**

The Galactic Center Excess Debate is Not Over

Pulsars Up 3 to 1?

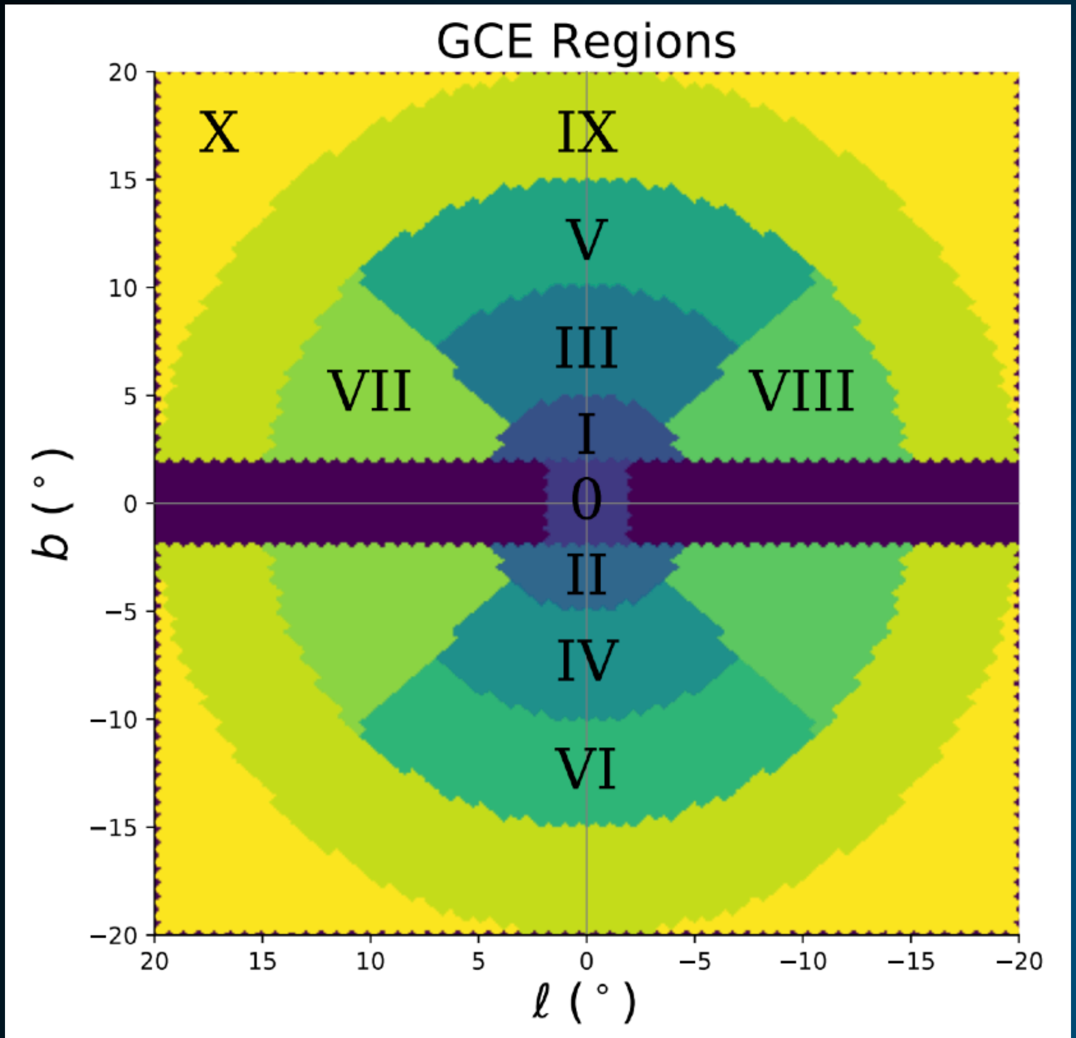


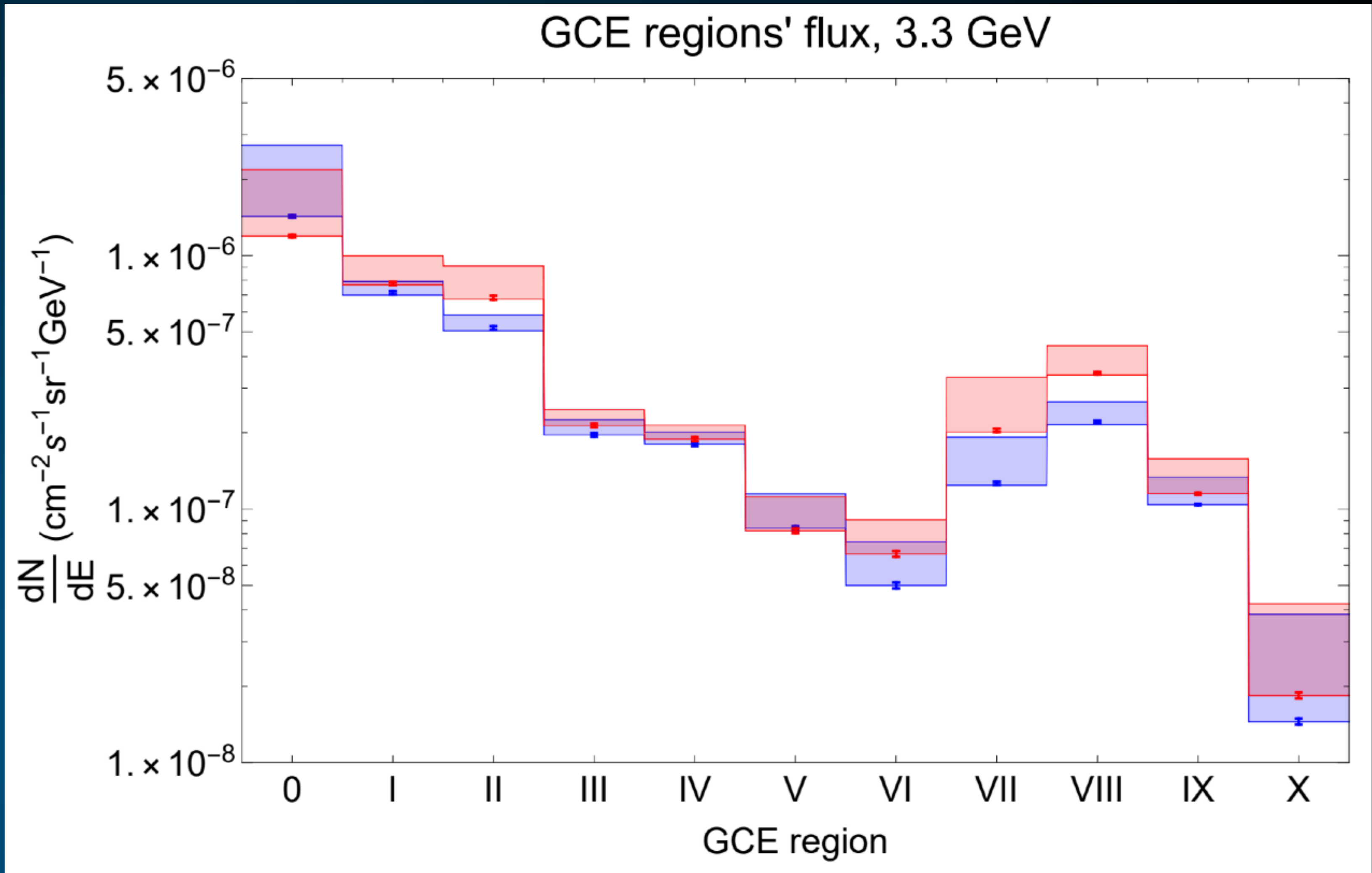
- **Different backgrounds lead to different fluctuations - even among 5σ point sources.**

The Galactic Center Excess Debate is Not Over

Pulsars Up 3 to 1?

Balaji et. al (2018; 1803.01952)





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The Galactic Center Excess Debate is Not Over

Pulsars Up 3 to 1?

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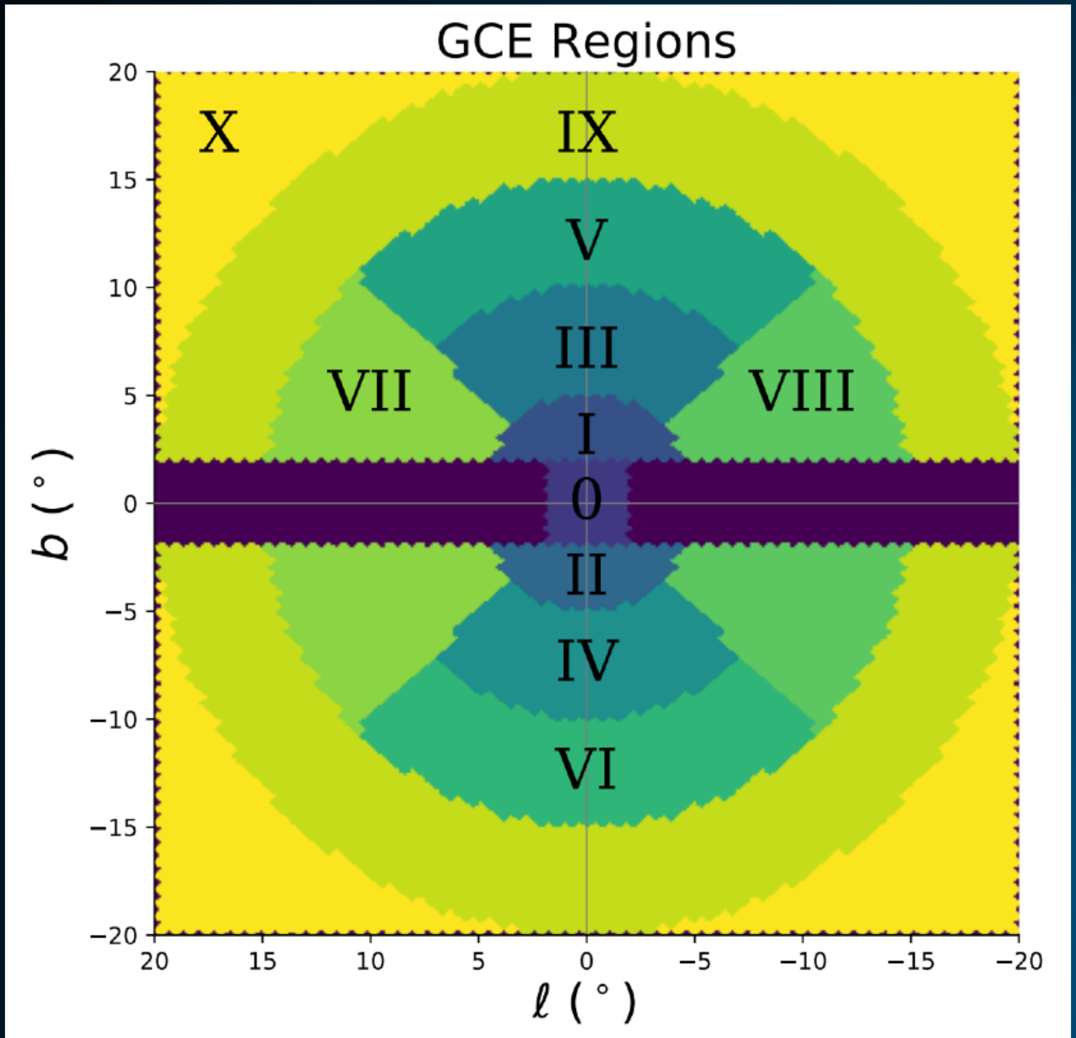
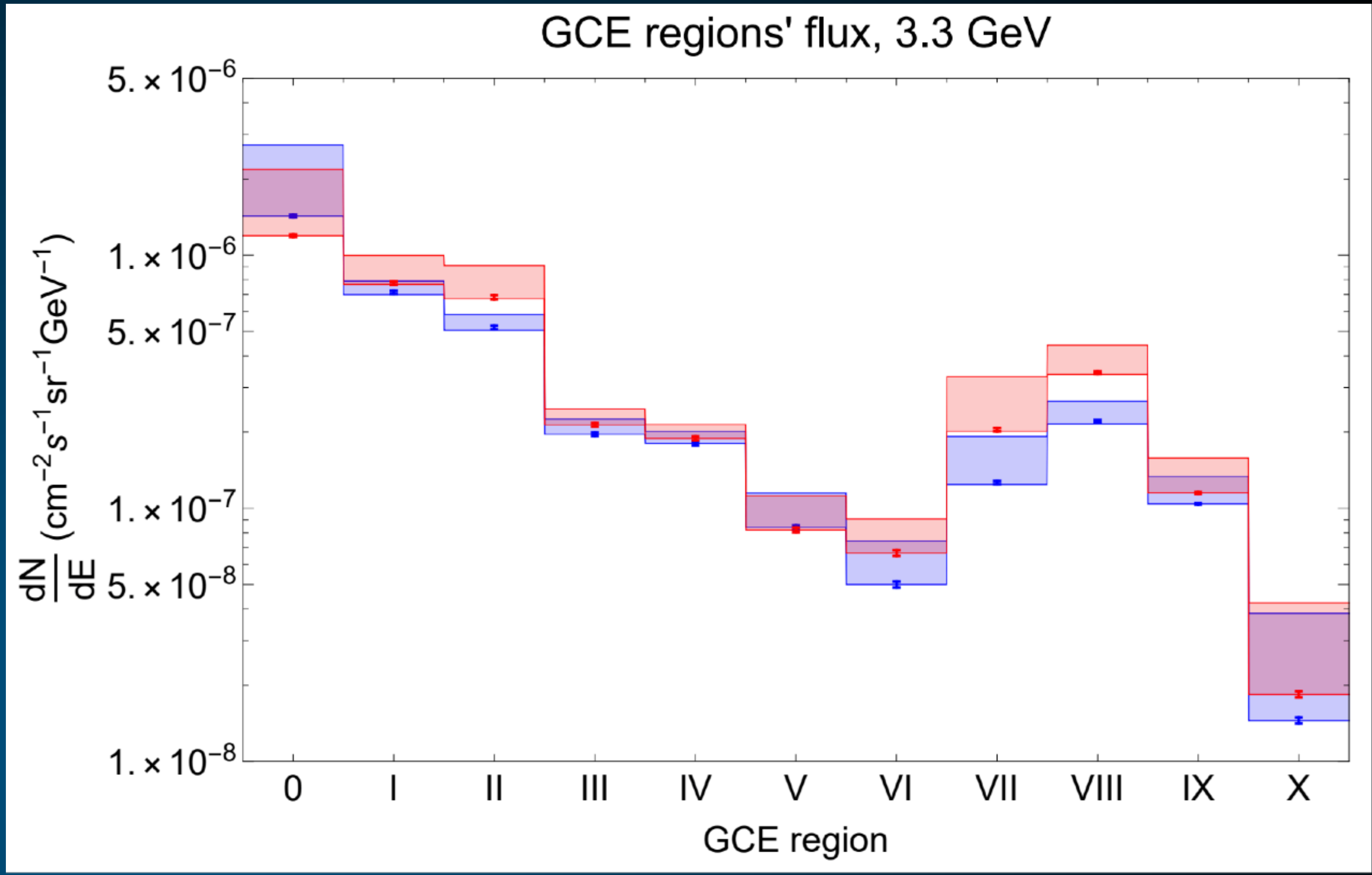


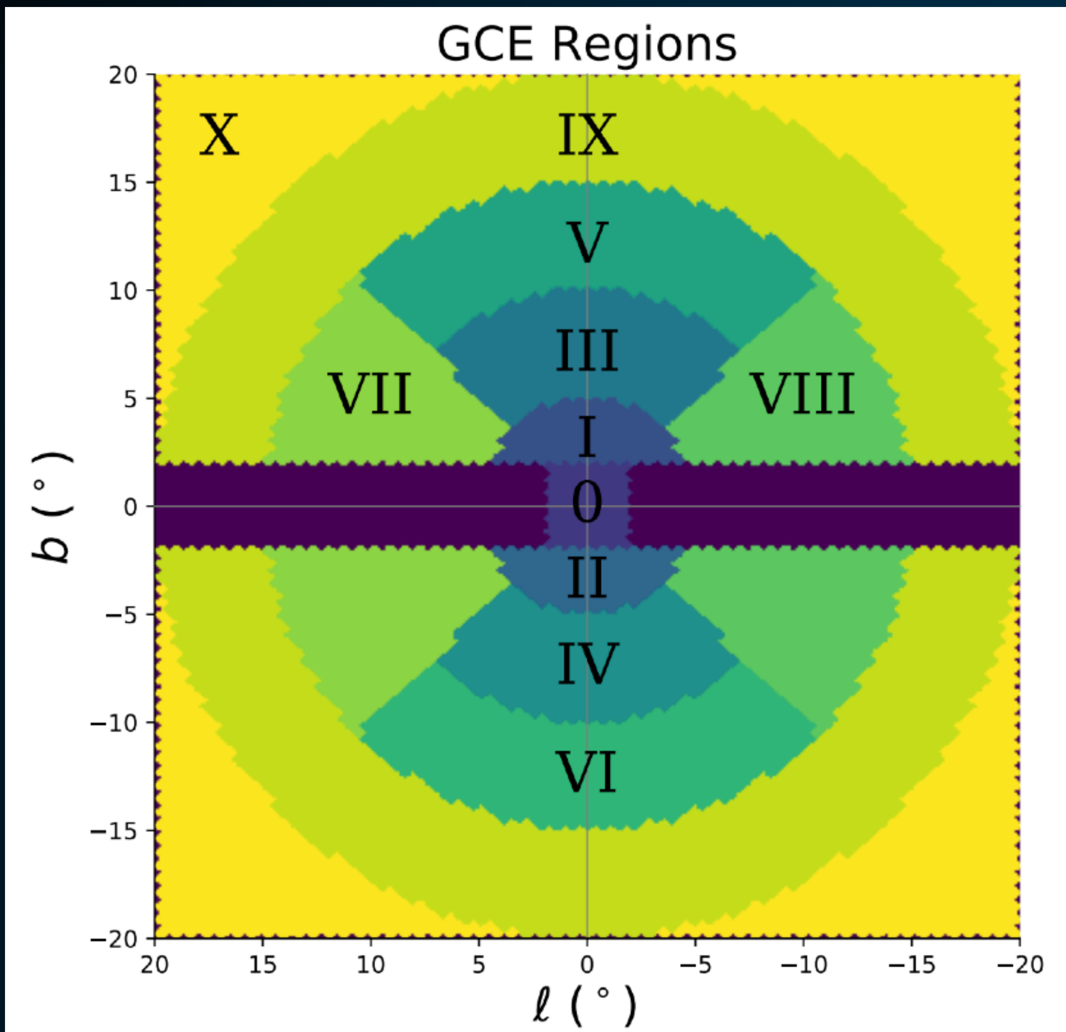


- **A recent analysis by Balaji et al. using wavelets on all angular sizes finds a separate result.**
- **Blue = Total Power in GCE**
- **Red = Total Power on scales larger than 4°.**

The Galactic Center Excess Debate is Not Over

Pulsars Up 3 to 1?

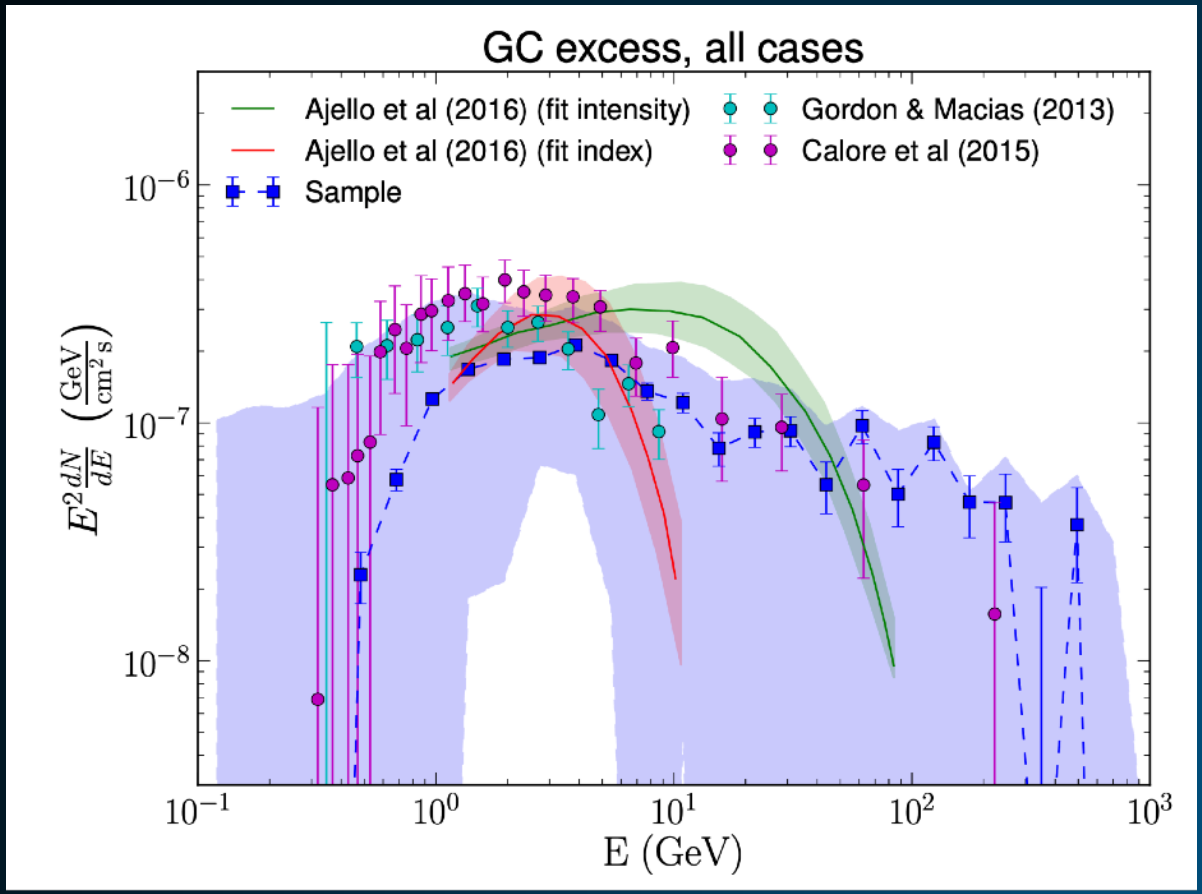
Balaji et. al (2018; 1803.01952)

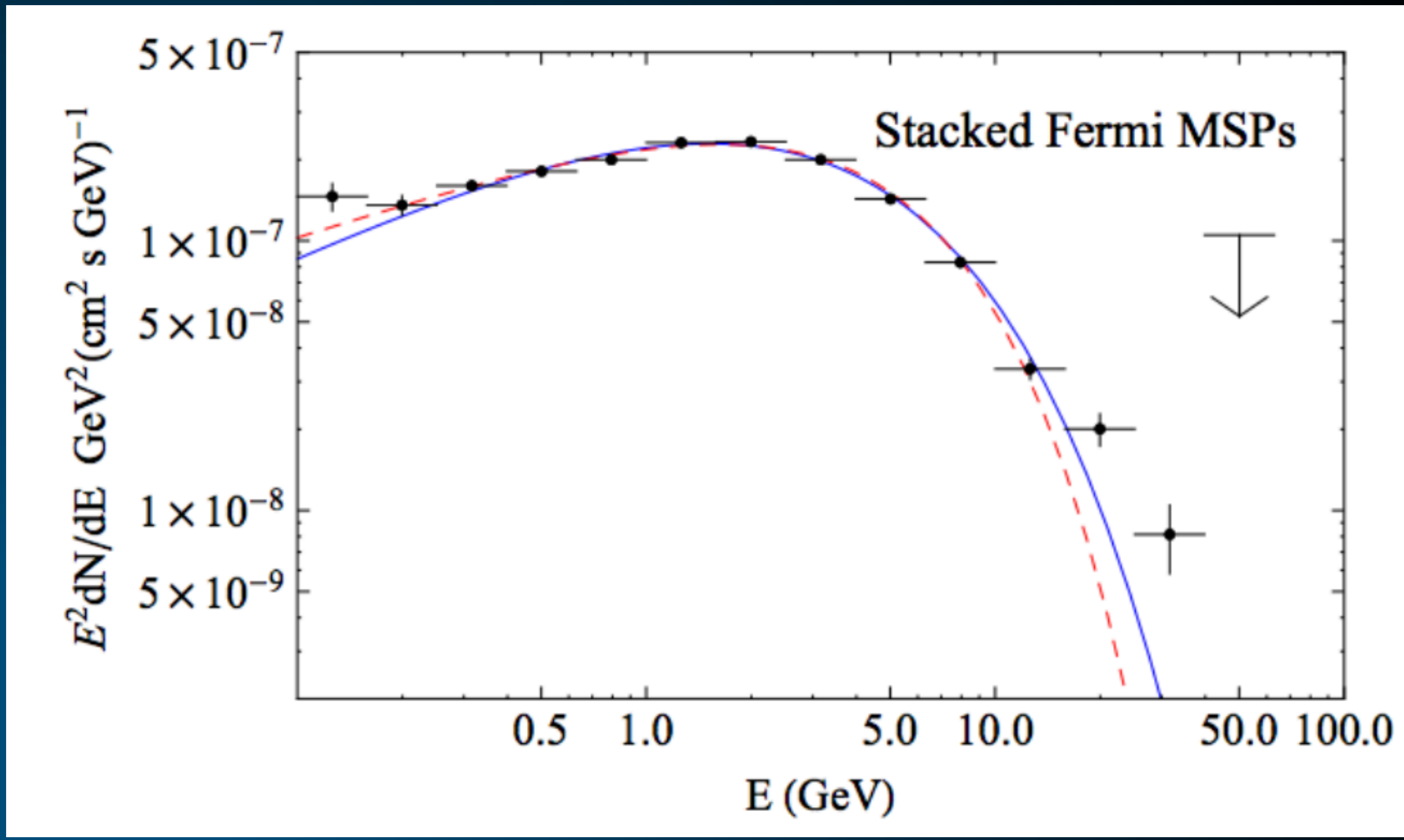


Regions VII and VIII are the easiest to understand and compare to, since they are removed from the center, far from the Bubbles, and in these parts of the sky point sources from the Galactic disk are expected to be relatively most dominant. At 1.5 GeV and above, in these two regions we find that ~30–50% of the total ($1 \leq j \leq 9$) emission is in the first two wavelet scales, and moreover the first two wavelet scales contribute *negatively*. There are 1.2 3FGL point sources per deg^2 on average in these two windows. This is still higher than the average of 1.02 3FGL point sources per deg^2 along the two stripes of $2° \leq |b| \leq 5°$ extending at all longitudes: Regions VII and VIII are rich in detected point sources. Only Regions II and VI have a similar ∼ 30% of their emission in the first two wavelet scales, which is also negative. The magnitude and the sign of this small scale contribution is intriguing. The negative sign in the first two wavelet levels for the regions near the Galactic center and Galactic disk means that unphysical flux has been imparted to the templates on small angular scales at intermediate angular distances from the Galactic center. This is suggestive either of mismodelled bremsstrahlung and pion emission or the inclusion of spurious point sources near the galactic center. We note that Region 0 does not suffer from a similarly large negative contribution at small angular scales. This may be an indication of the large positive contribution from the GCE, or an issue with the procedure to determine the point-source maps.

The Galactic Center Excess Debate is Not Over

Pulsars Up 3 to 1?

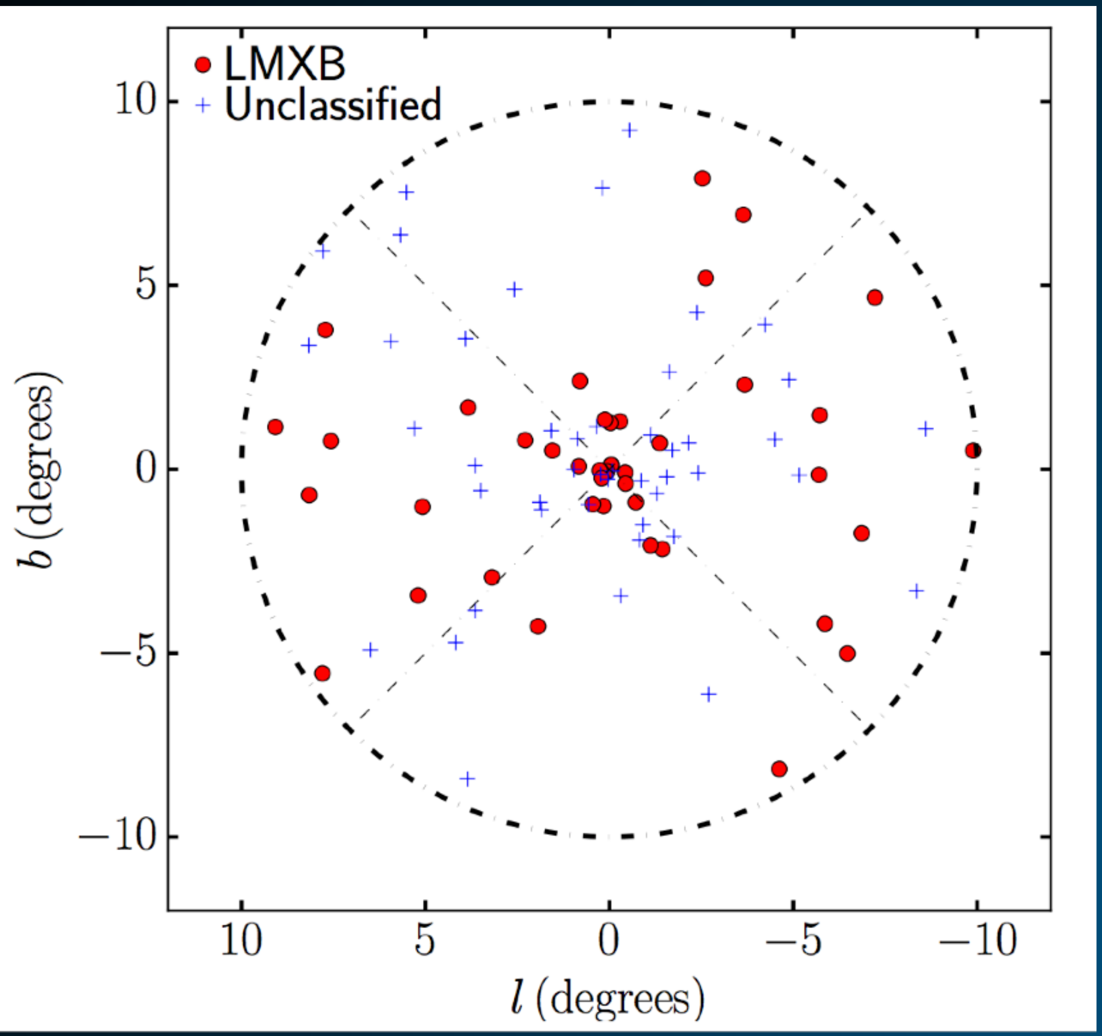


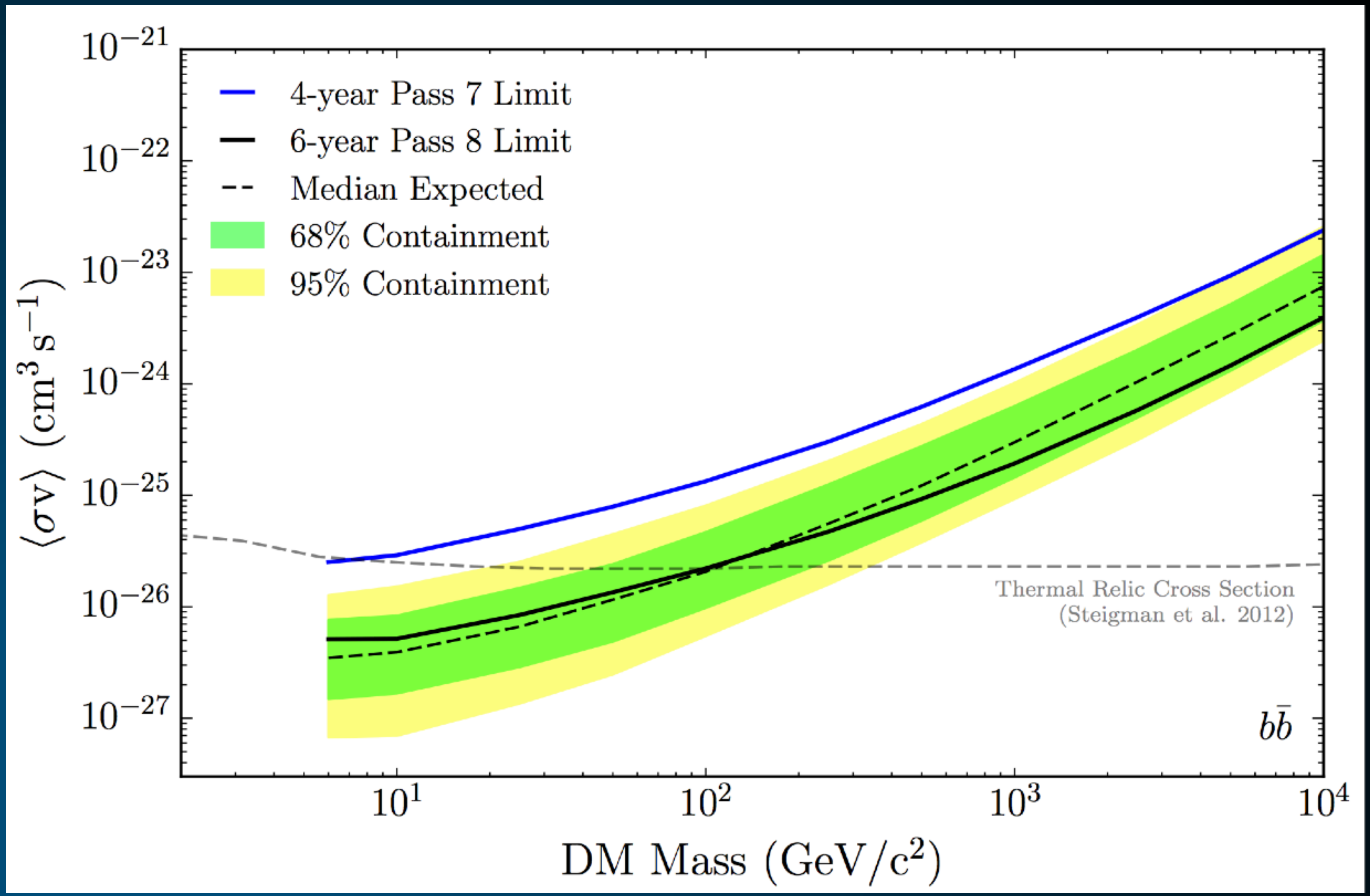


- **Pulsar Spectrum is a slightly poorer fit to the data, but with fewer degrees of freedom.**

The Galactic Center Excess Debate is Not Over

Pulsars Up 3 to 1?

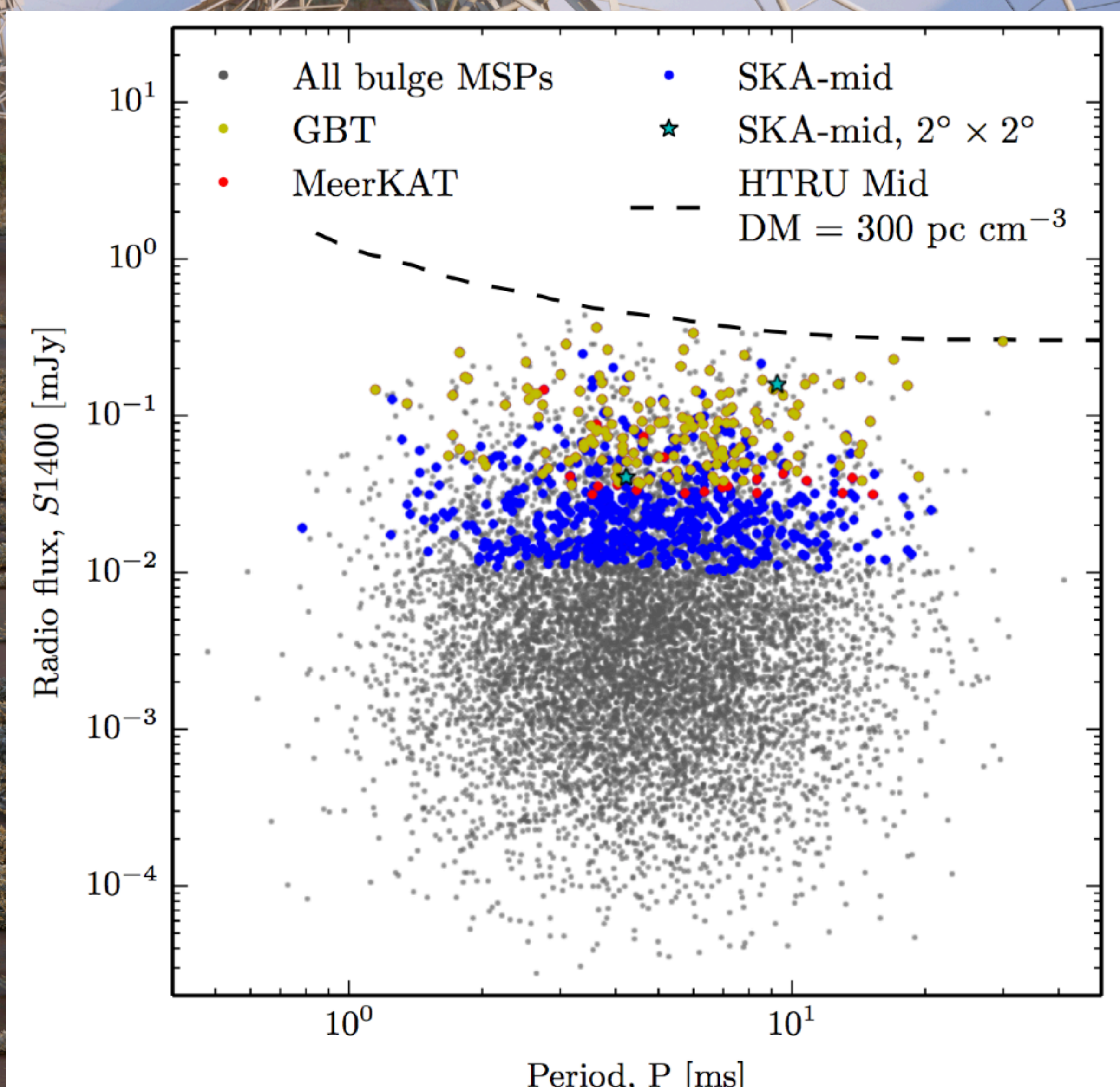




- **Pulsars slightly constrained by lack of observed LMXBs.**
- **Dark Matter slightly constrained by dSph observations.**

The Galactic Center Excess Debate is Not Over

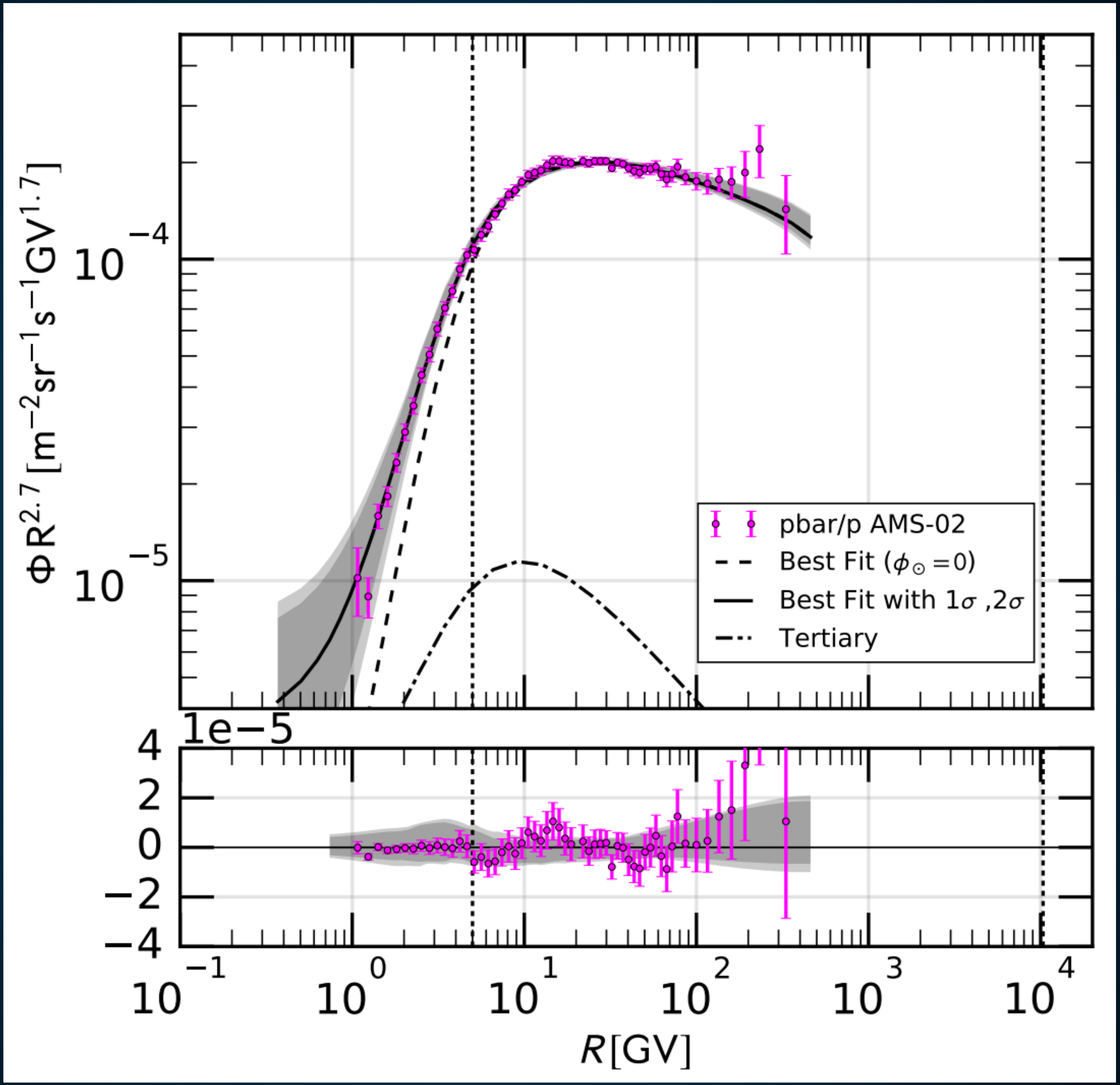
Pulsars Up 3 to 1?



Up and Coming Excesses

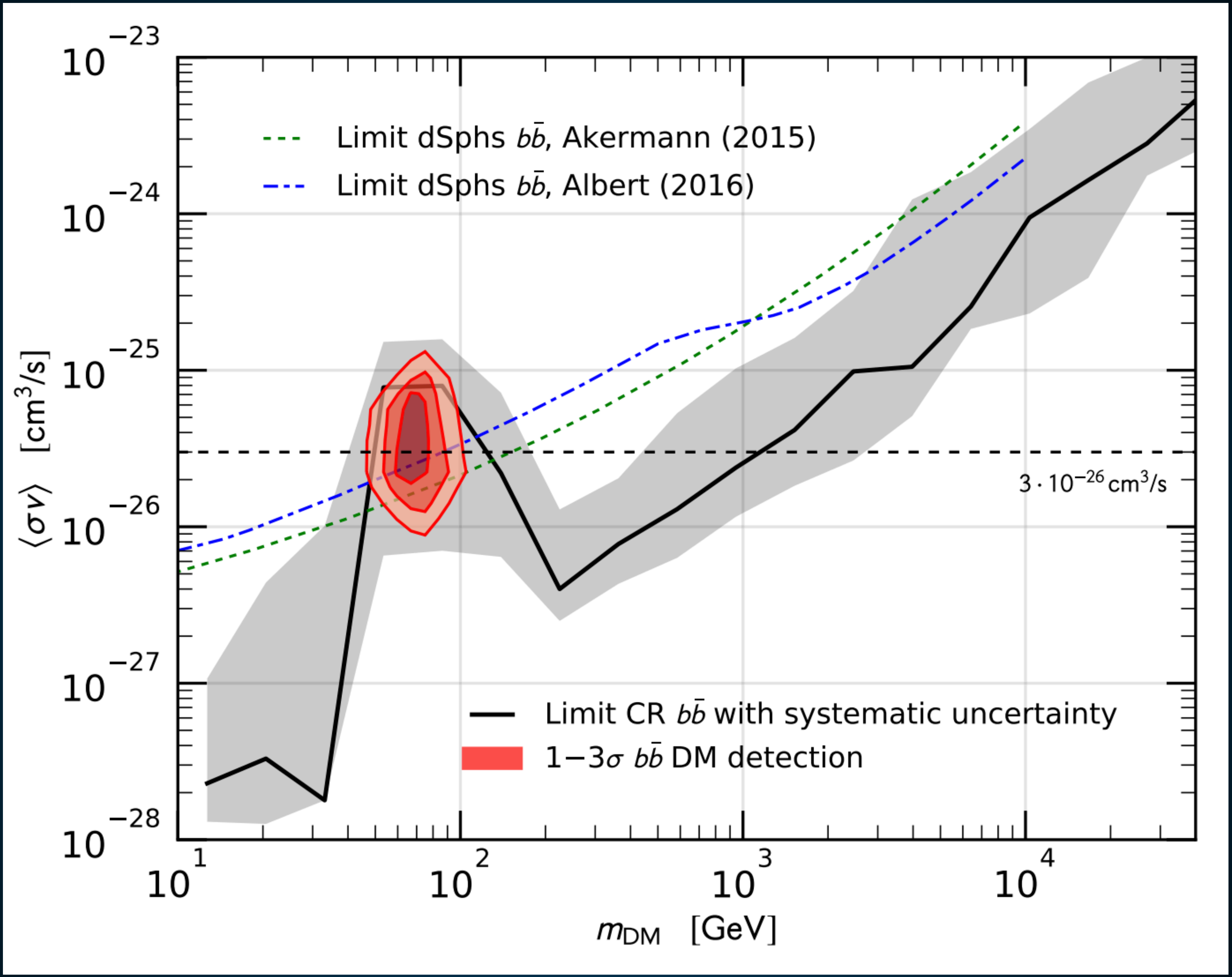
The Antiproton Excess

Cuoco et al. (2016; 1610.03071)



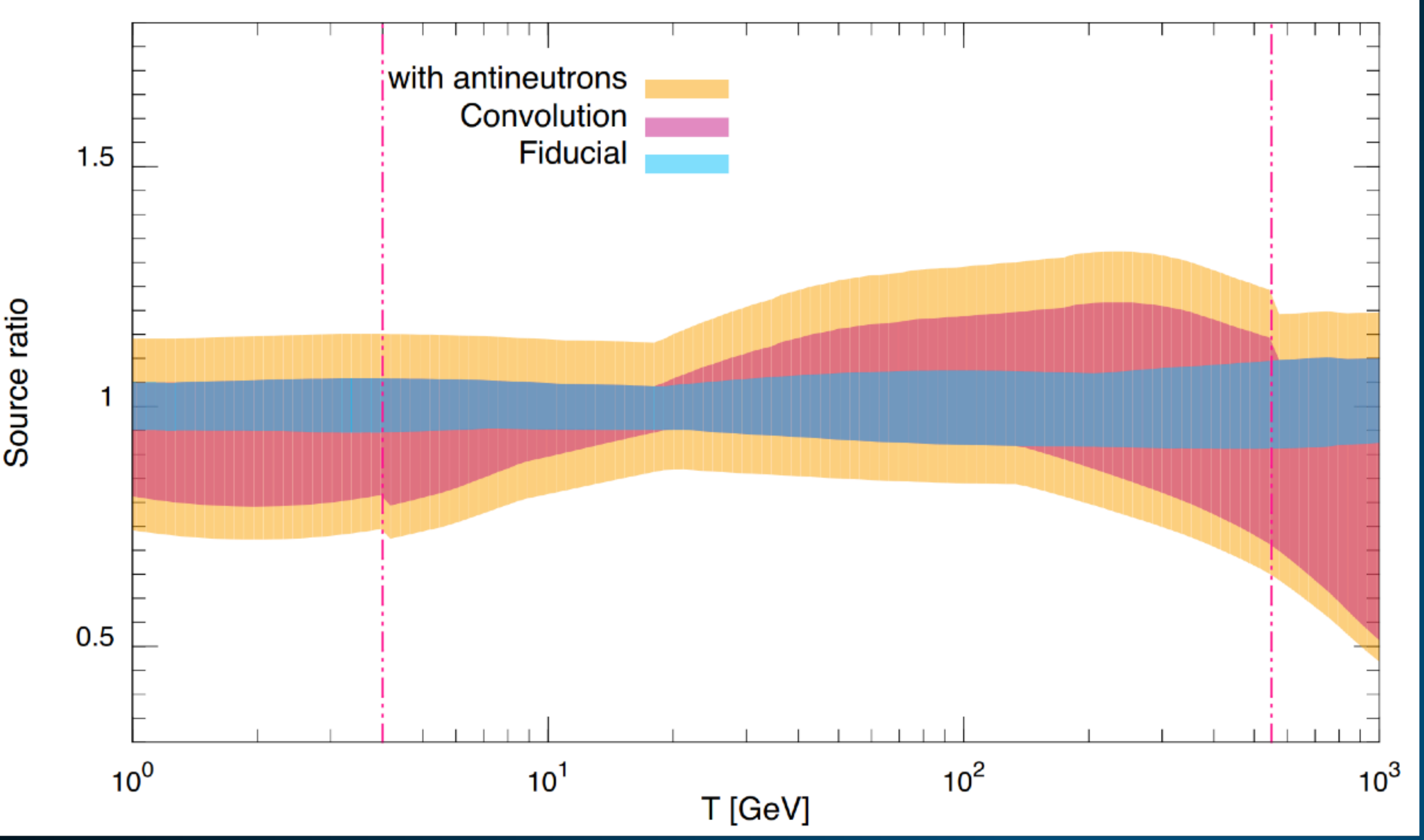
The Antiproton Excess

Cuoco et al. (2016; 1610.03071)

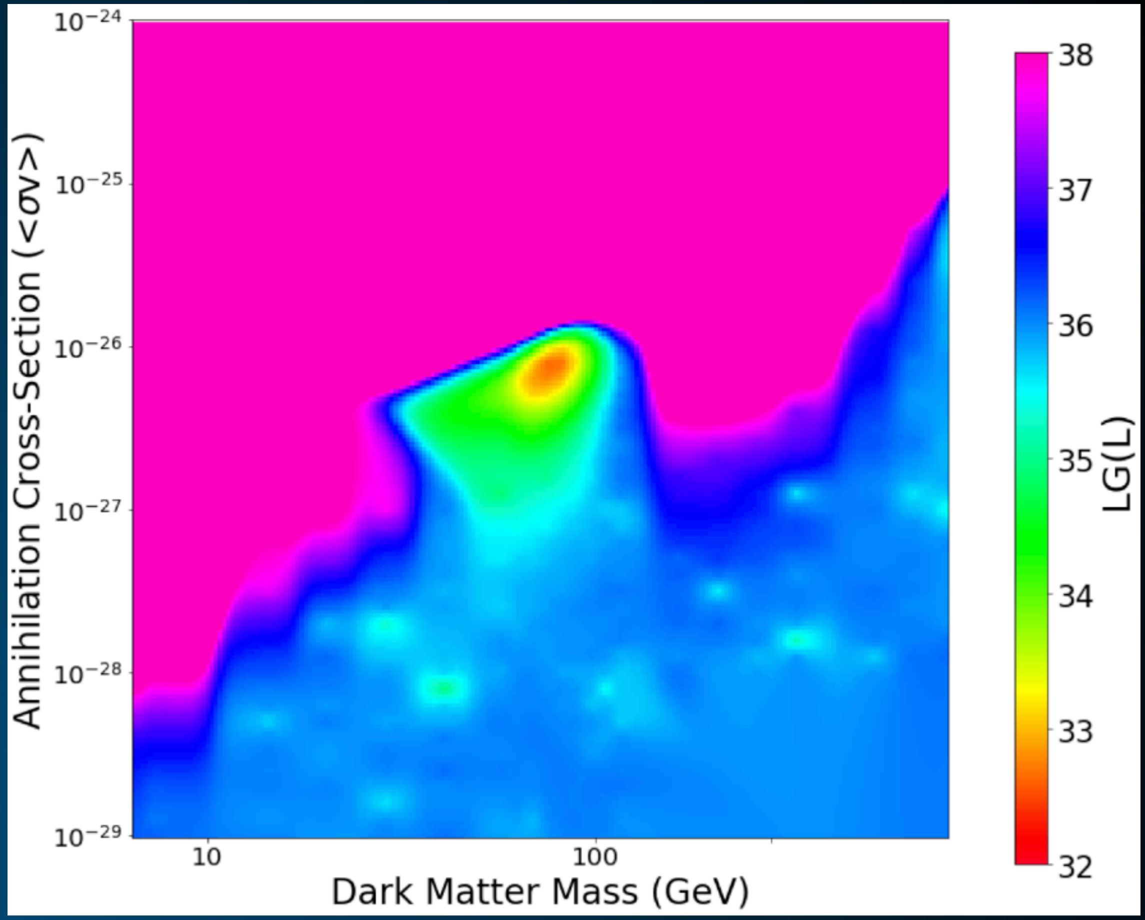


The Antiproton Excess

di Mauro et al. (2014; 1408.0288)

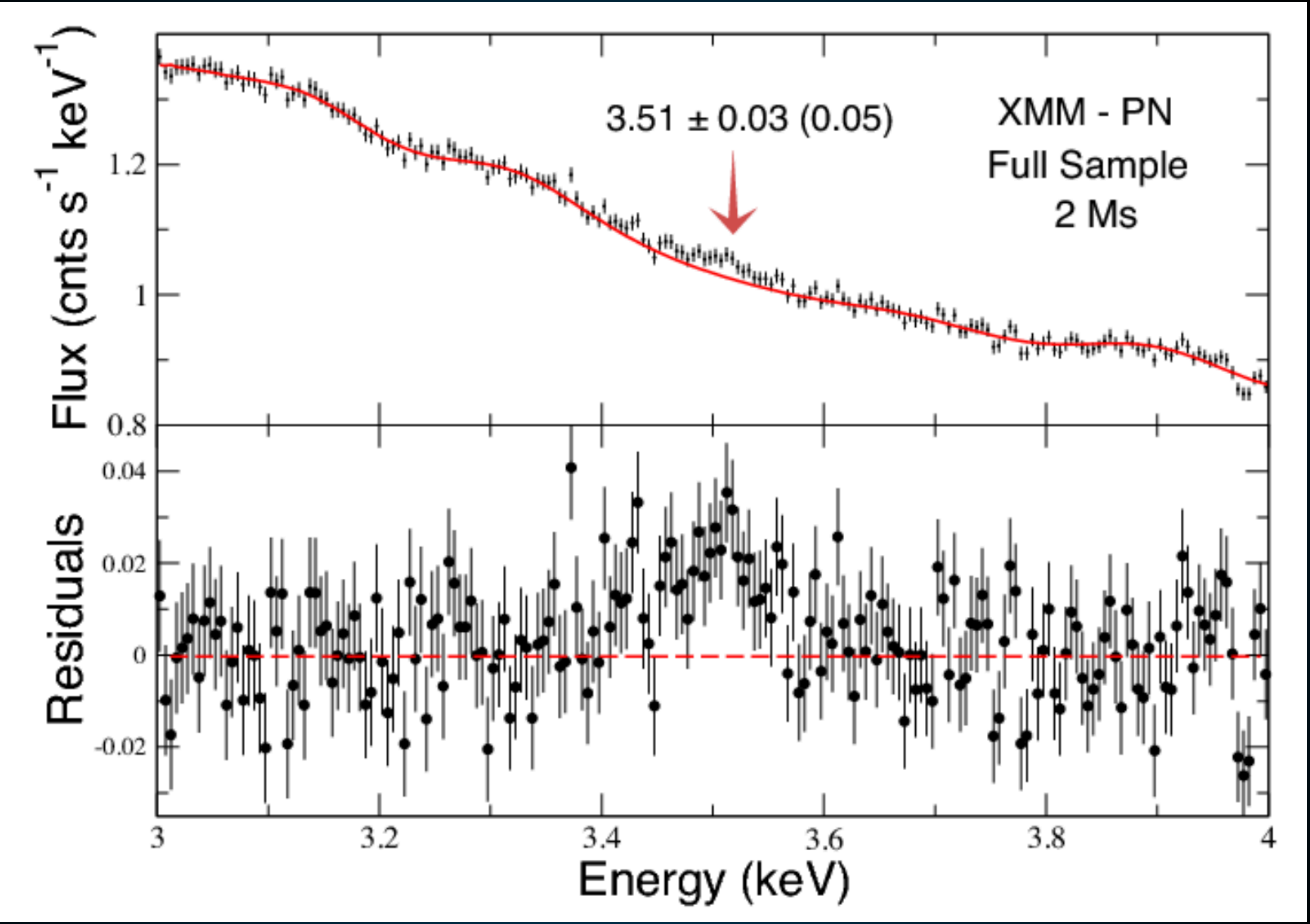


Cholis, Hooper, TL (TBS)

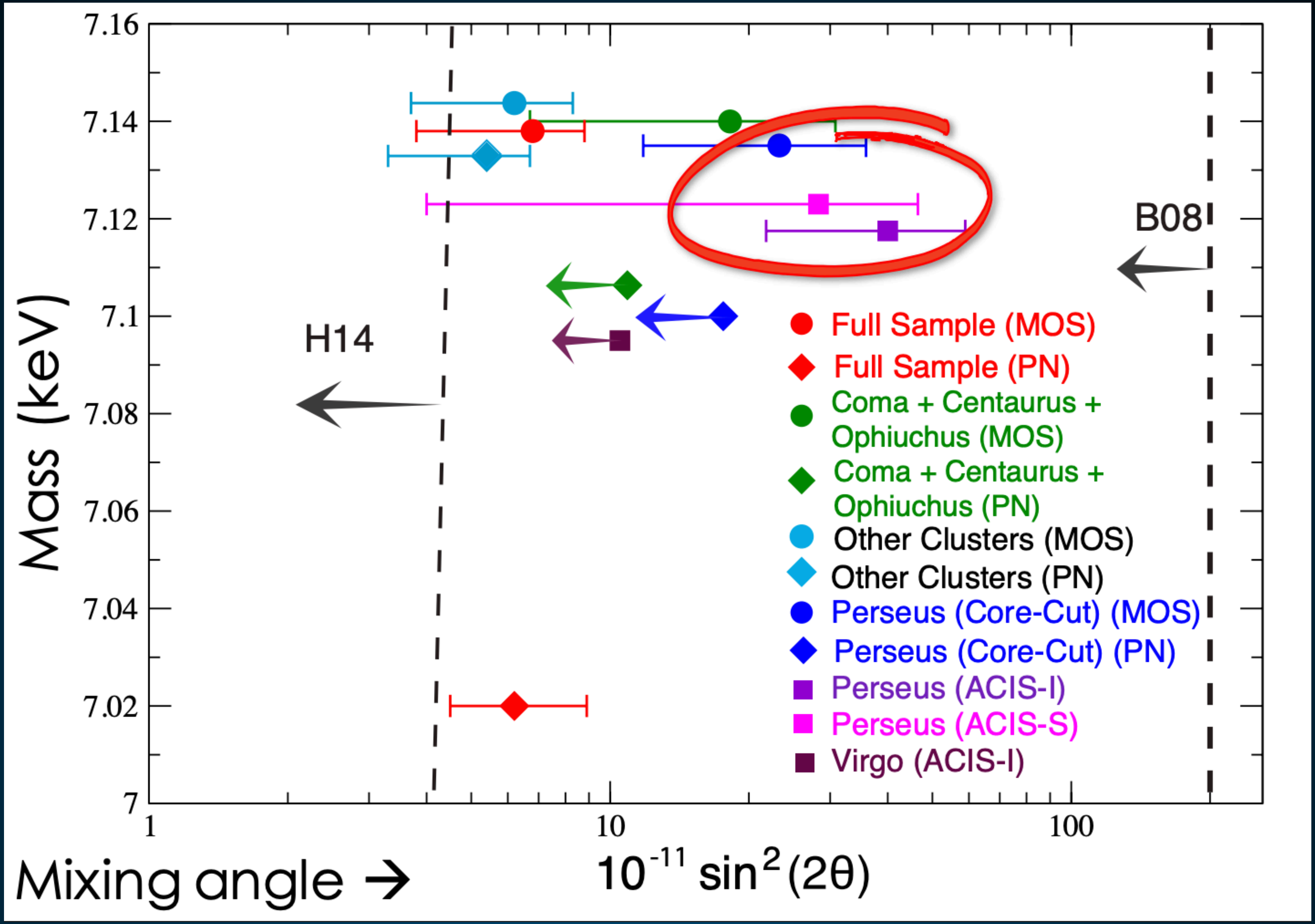


- **Primary uncertainty is the energy dependence of the antiproton production cross-section.**
- **Even very liberal uncertainty models do not eliminate the excess.**

3.5 keV Line


3.51 ± 0.03 (0.05)
XMM - PN
Full Sample
2 Ms
Flux (cnts s^-1 keV^-1)
Residuals
Energy (keV)
0.8
1
1.2
0.04
0.02
0
-0.02
3
3.2
3.4
3.6
3.8
4

3.5 keV Line



- **Observed in multiple targets using multiple instruments.**
- **Observed only after de-Redshifting, appears to rule out instrumental effect.**

3.5 keV Line

Letter to the Editor

A novel scenario for the possible X-ray line feature at ∼3.5 keV:

Charge exchange with bare sulfur ions

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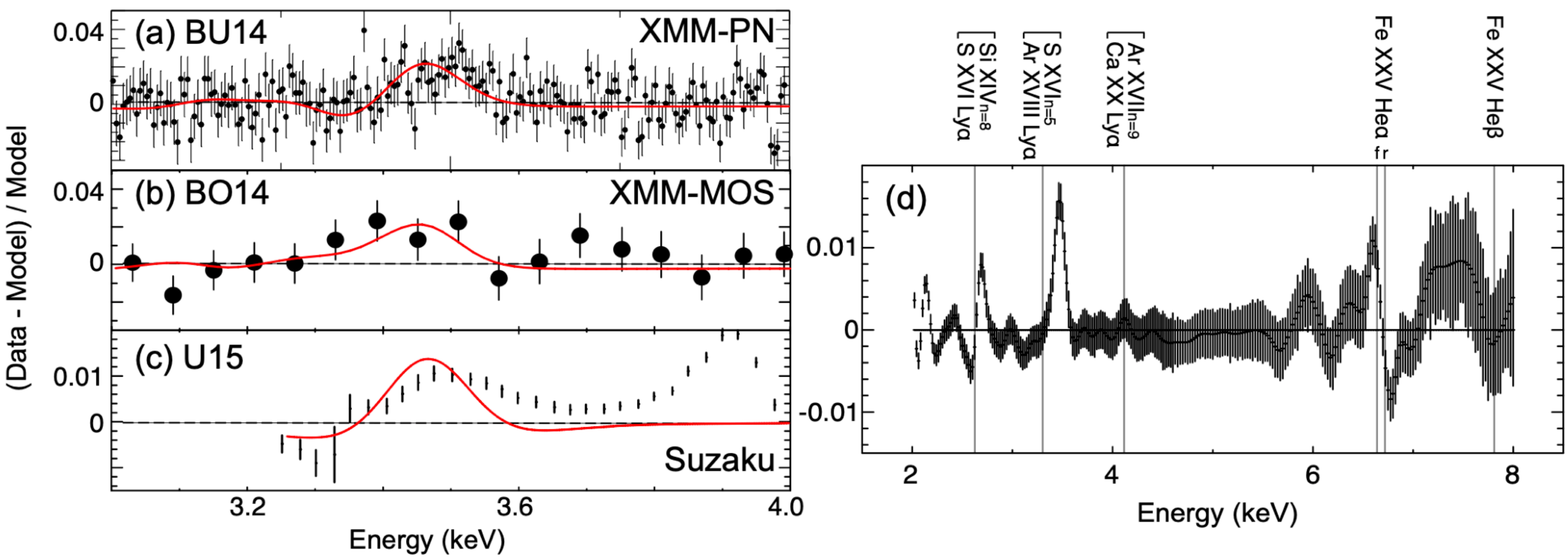
October 8, 2018

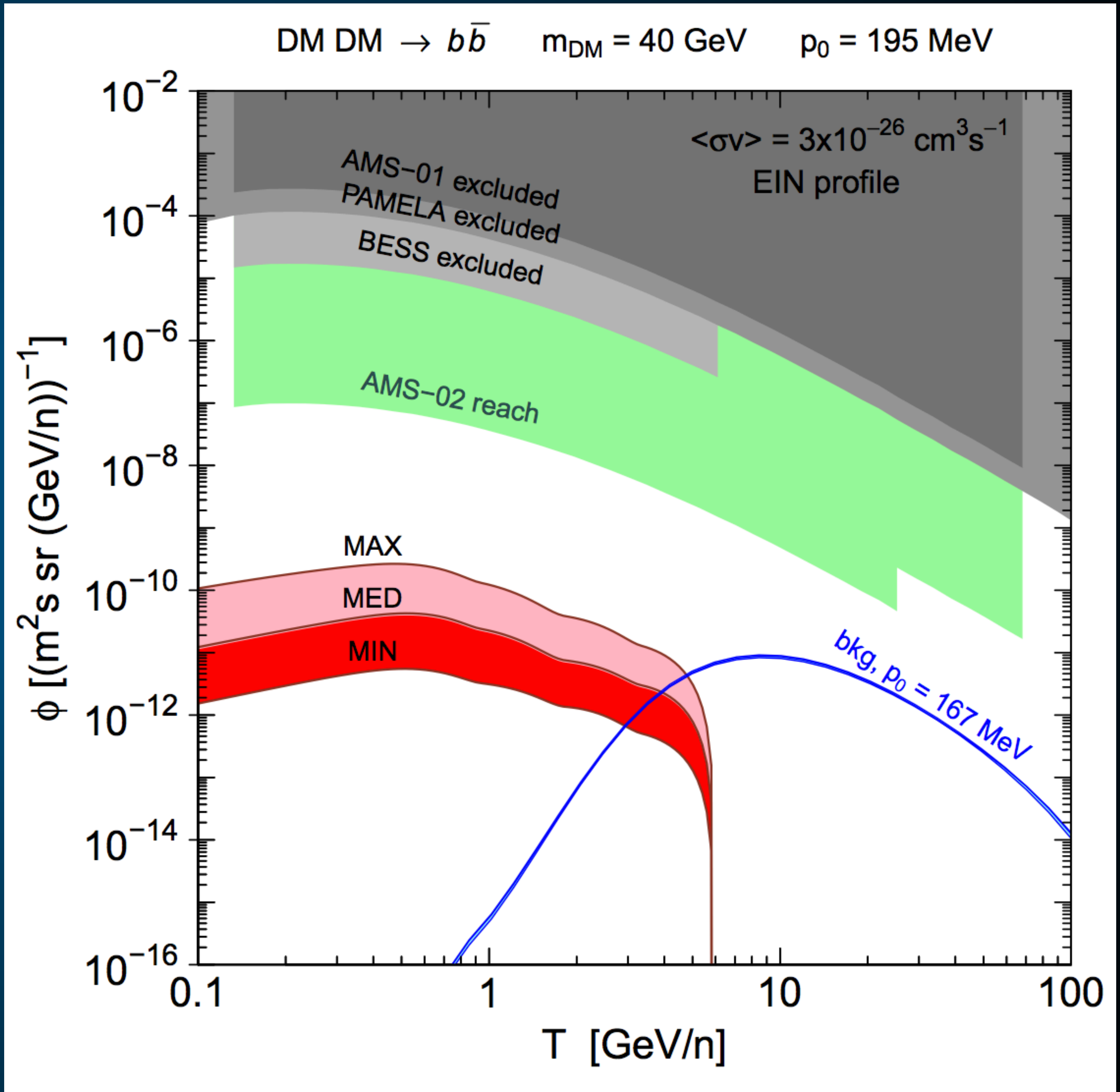


The Antihelium Excess

Can't be Astrophysics – Could be Instrumental Systematics

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

- **Dark matter annihilation occurs in the lab frame.**
- **Dark matter signal dominate at low energies - example, antideutrons.**
- **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.

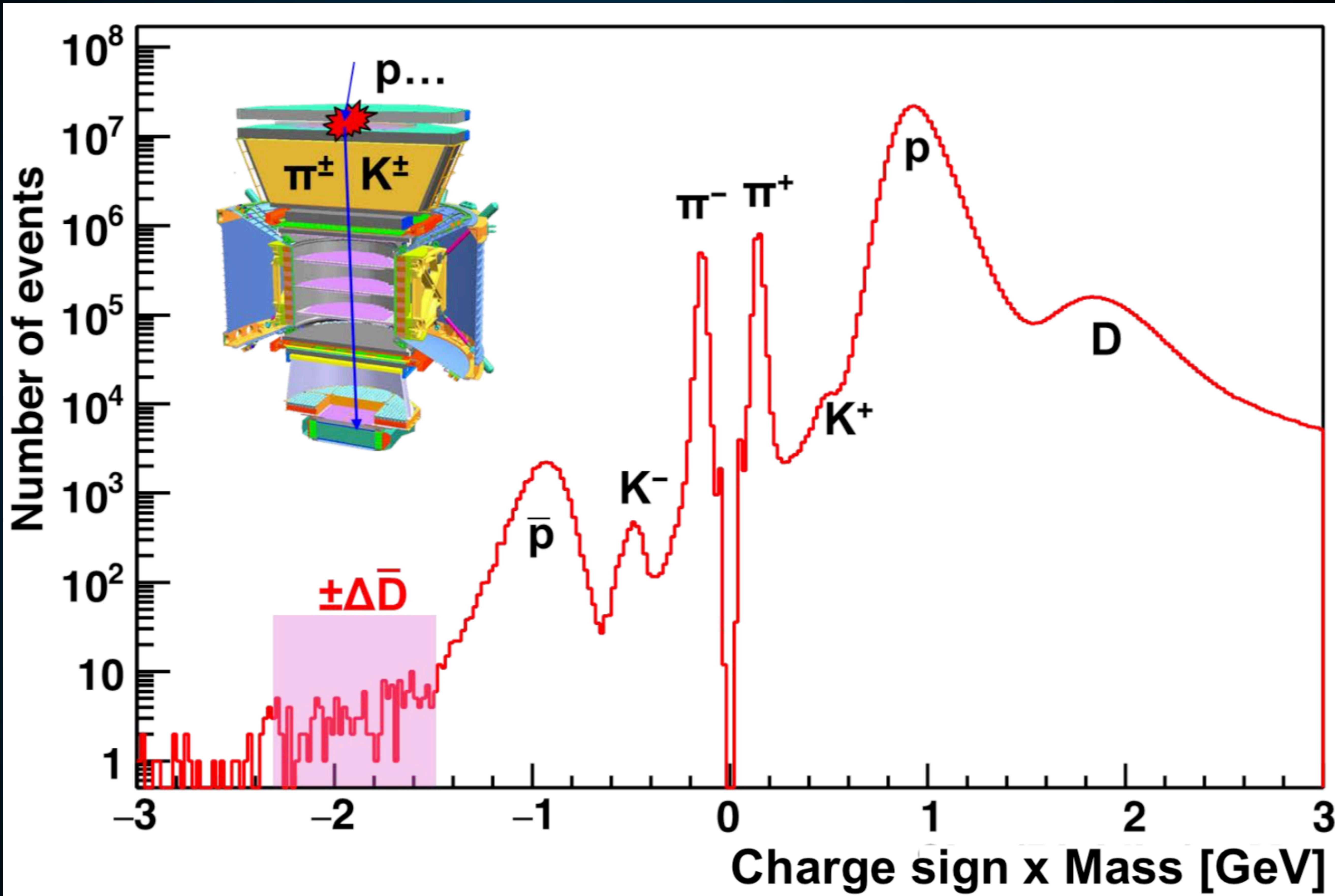
Currently (having used 50 million core hours to generate 7 times more simulated events than measured events and having found no background events from the simulation), our best evaluation of the probability of the background origin for the eight $\overline{He}$ events is less than 3×10^{-8}. For the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

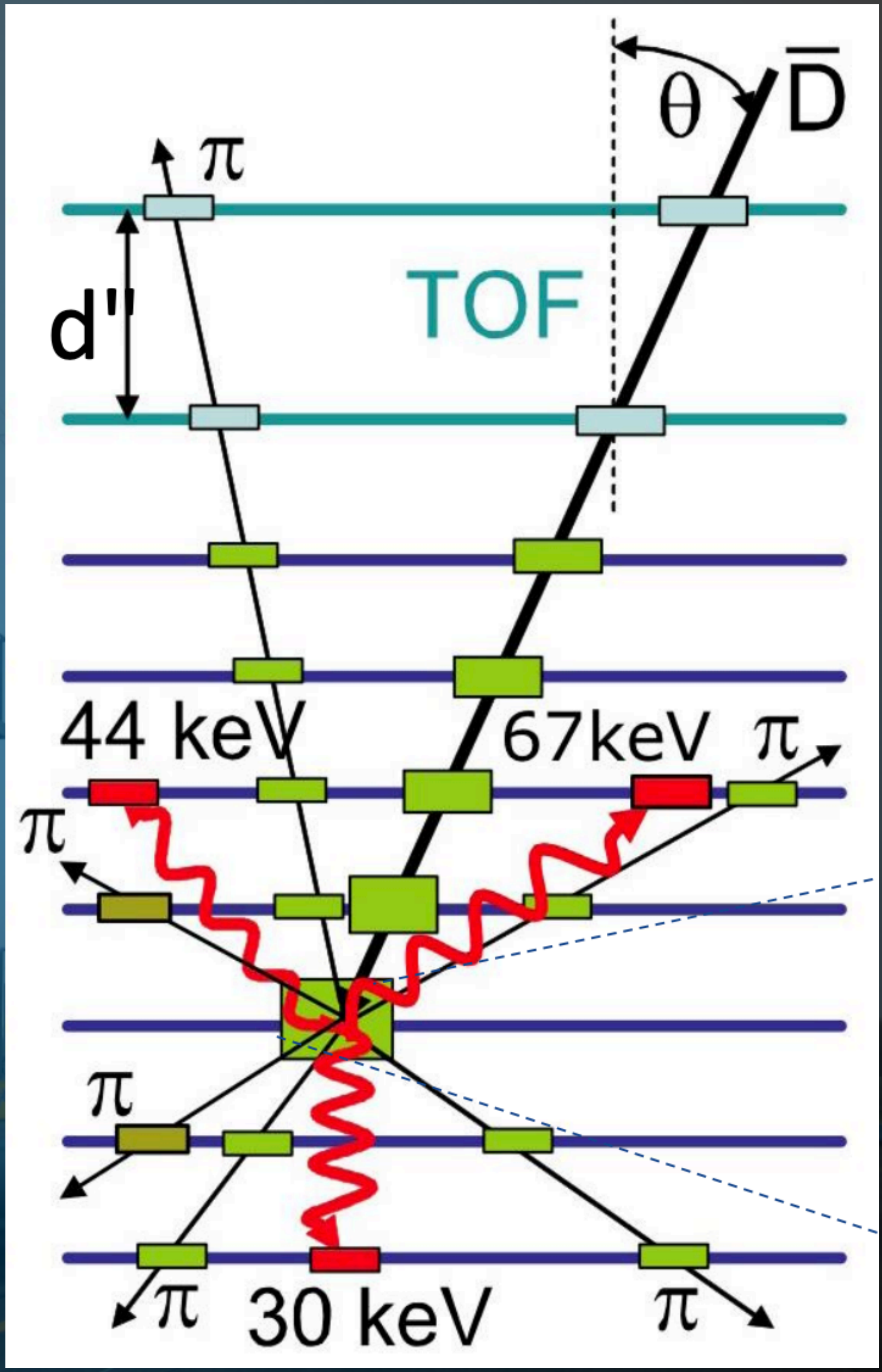
Note that for $^4\overline{He}$, projecting based on the statistics we have today, by using an additional 400 million core hours for simulation the background probability would be 10^{-4}. Simultaneously, continuing to run until 2023, which doubles the data sample, the background probability for $^4\overline{He}$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

slide from Sam Ting

Rare Particle Detection

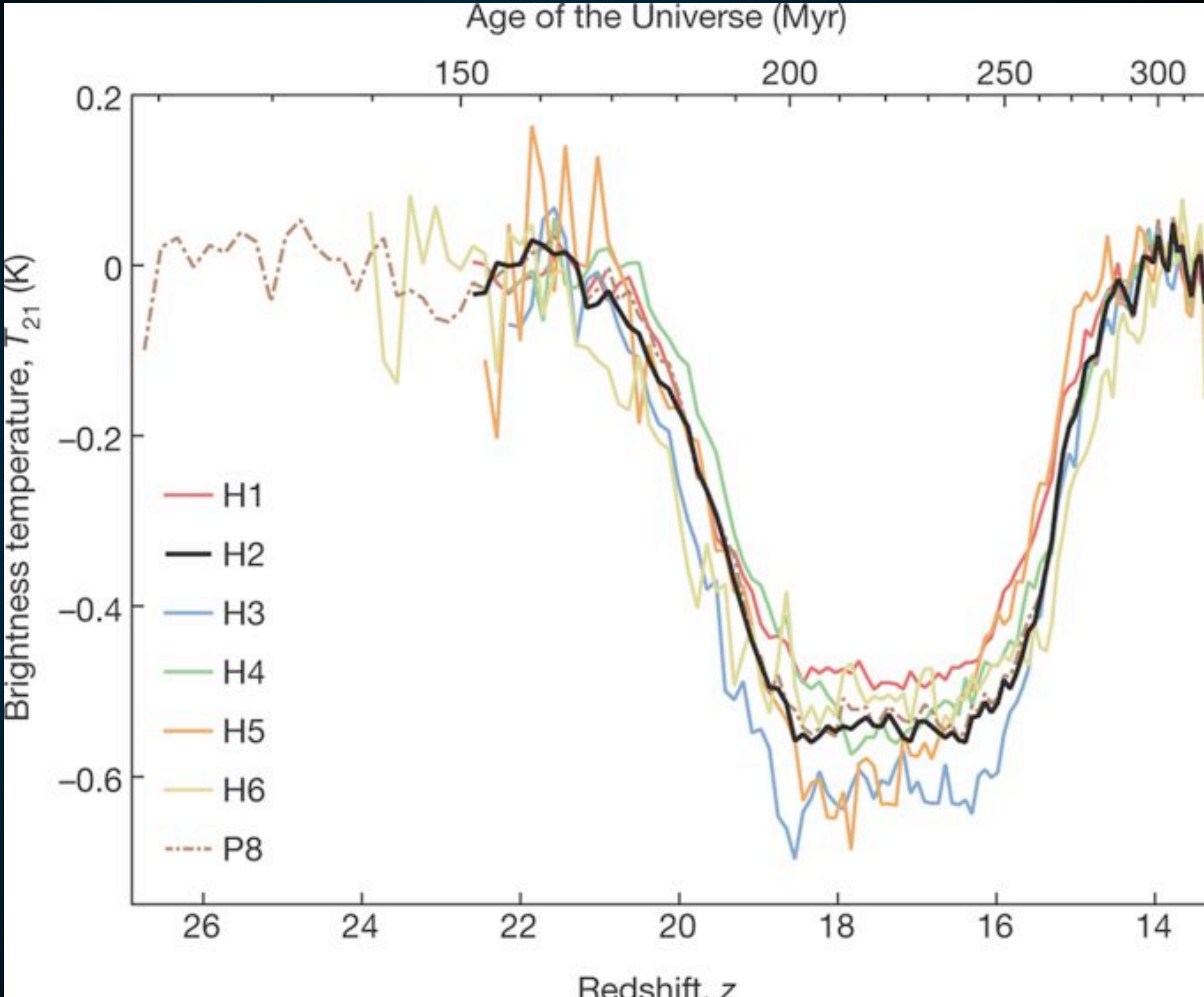
Exploiting the fact that the universe is mostly matter



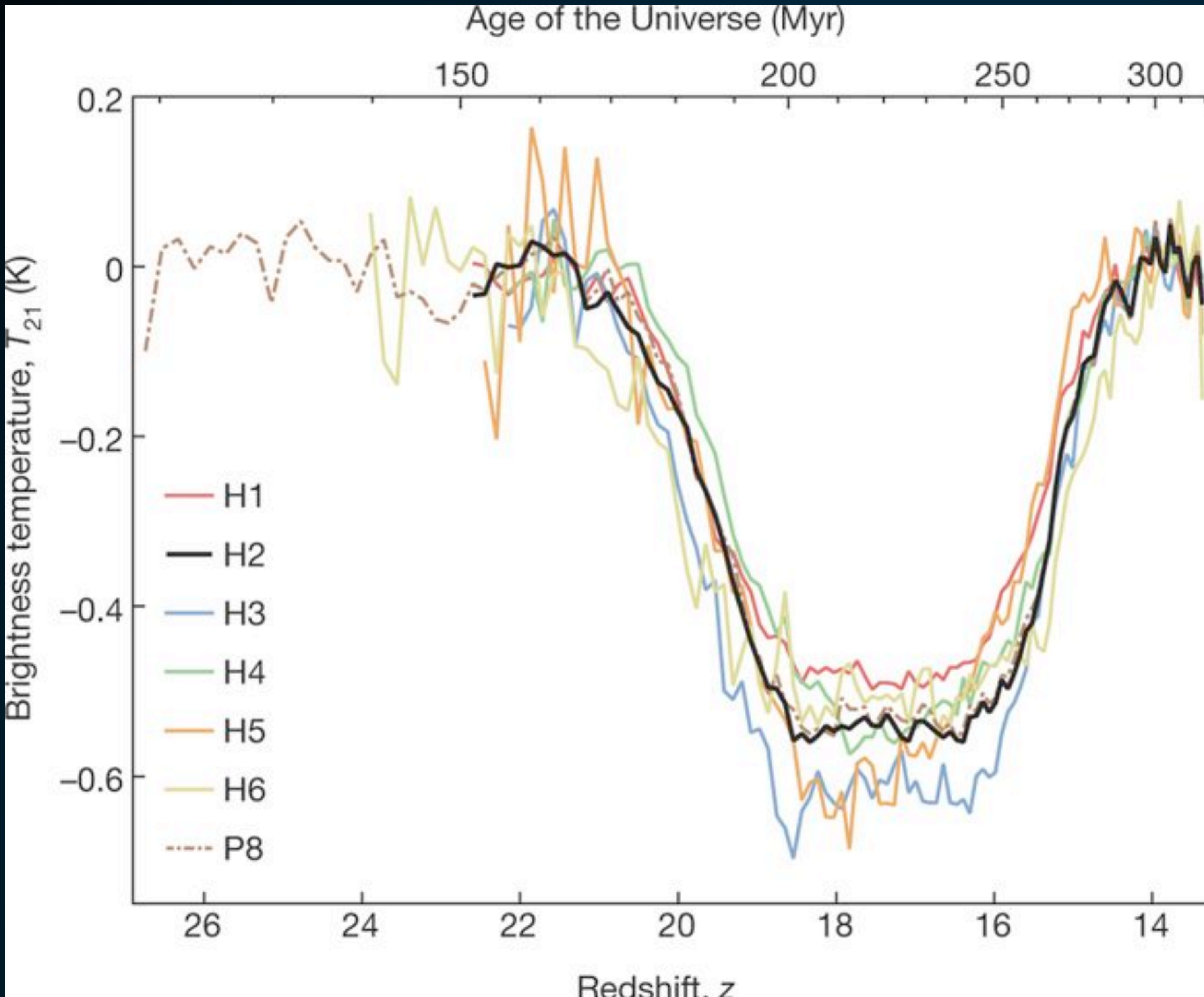

θ
$\bar{D}$
π
TOF
d"
44 keV
67keV
π
π
π
π
30 keV
π

EDGES/21 cm

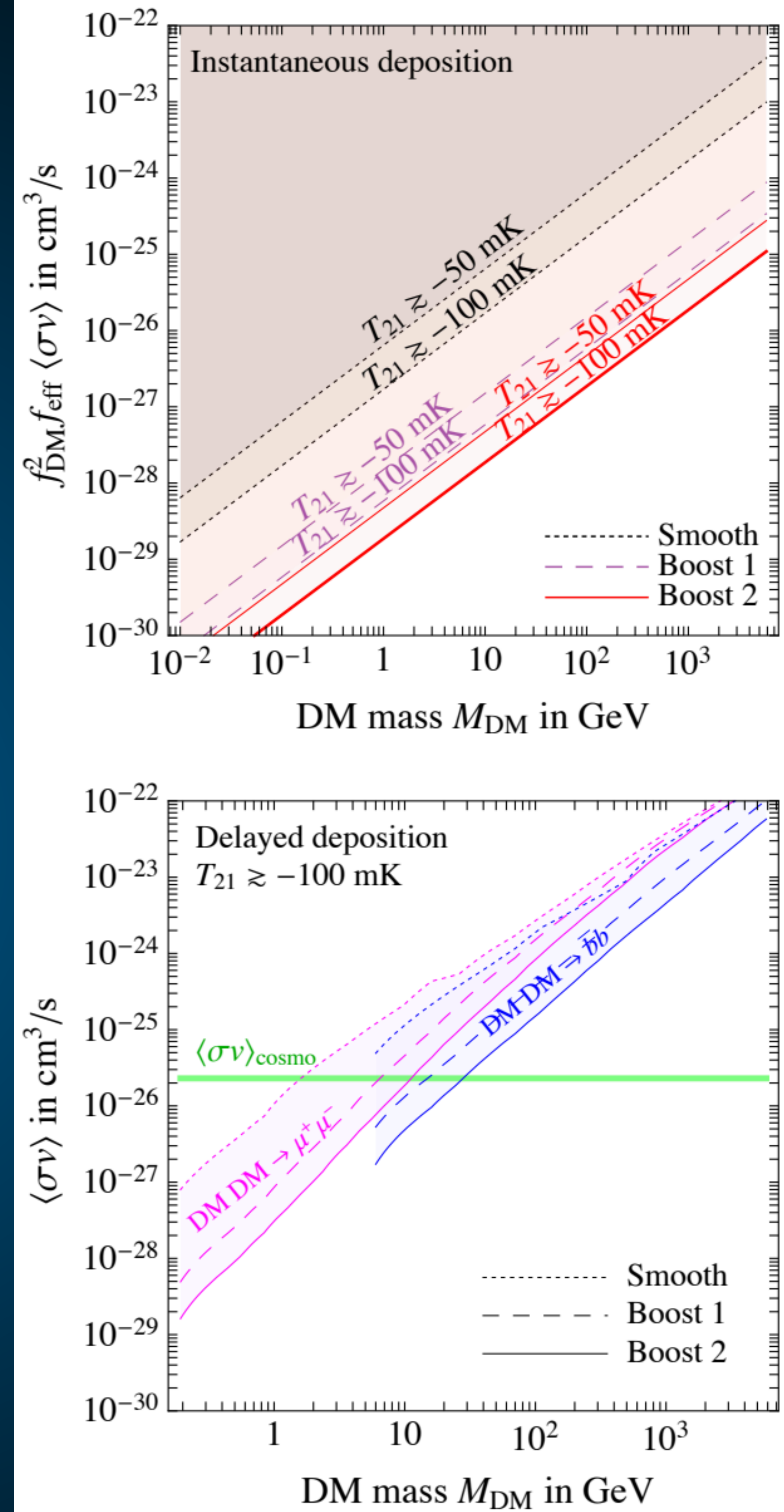
see talk by Jordan Mirocha (Wednesday)



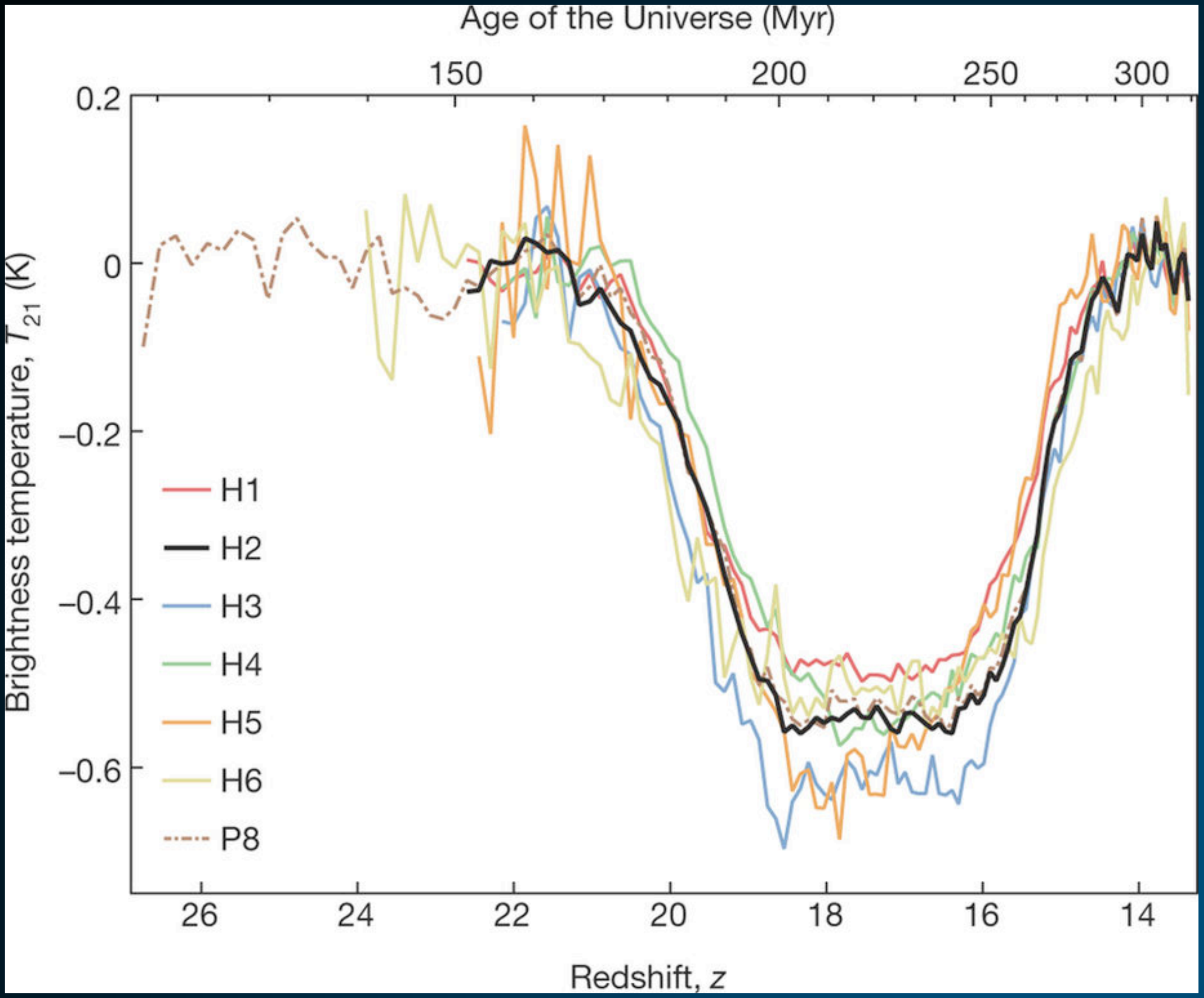
EDGES/21 cm

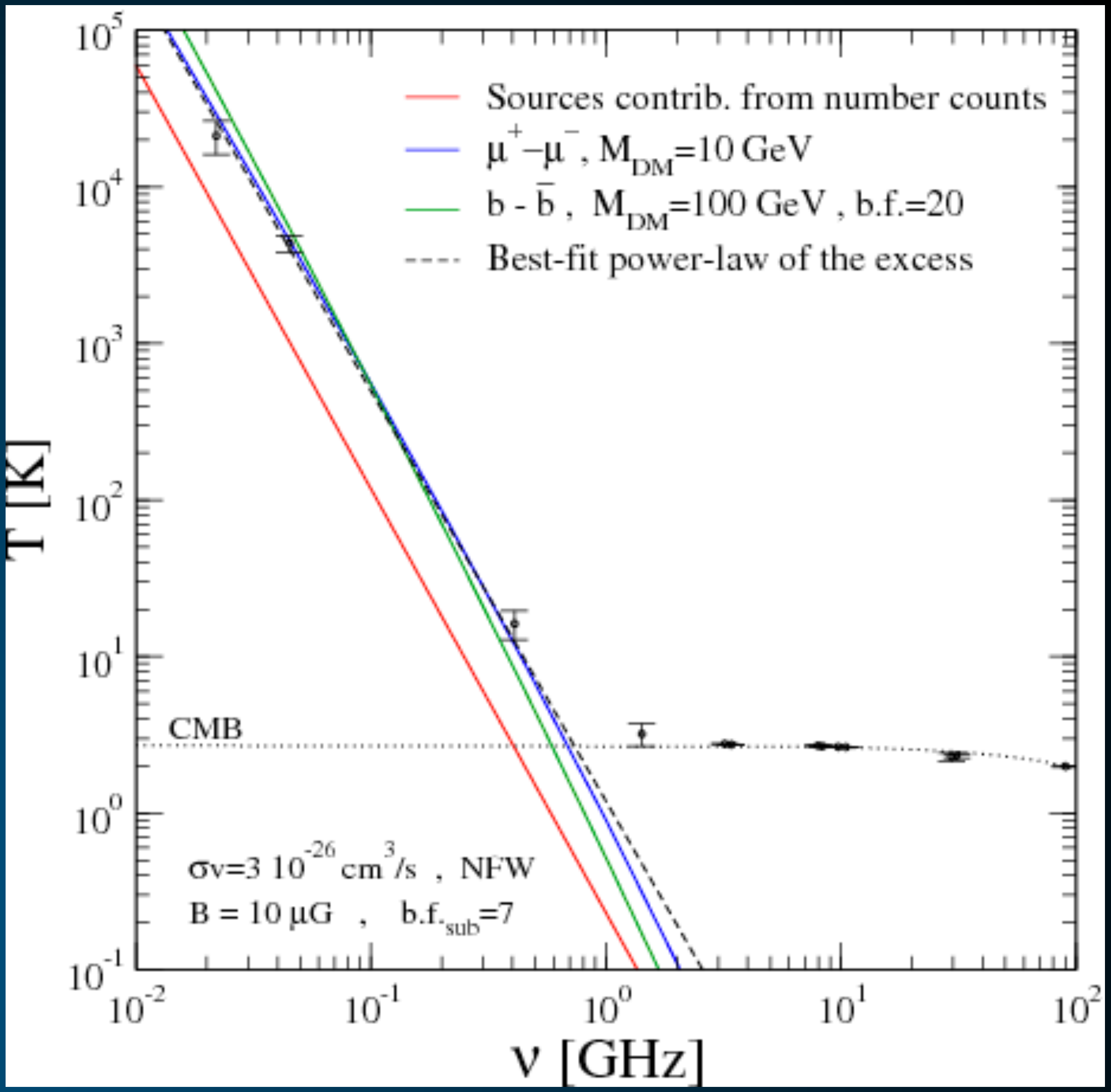


Strong constraint on dark matter even if the feature does not exist.



EDGES/ARCADE Observations





EDGES - Strong constraints

ARCADE - A Possible Signal?

Conclusions

- **Indirect Detection of Thermal Dark Matter is at a critical time — this is not a denouement.**

- **Probes constrained by Systematic/Astrophysical/ Statistical uncertainties have similar sensitivities (?)**

- **Combination of improved modeling and instrumentation will offer order of magnitude improvements in sensitivity.**