

Tim Linden

Thermal WIMP Dark Matter on the Brink

Stockholms universitet

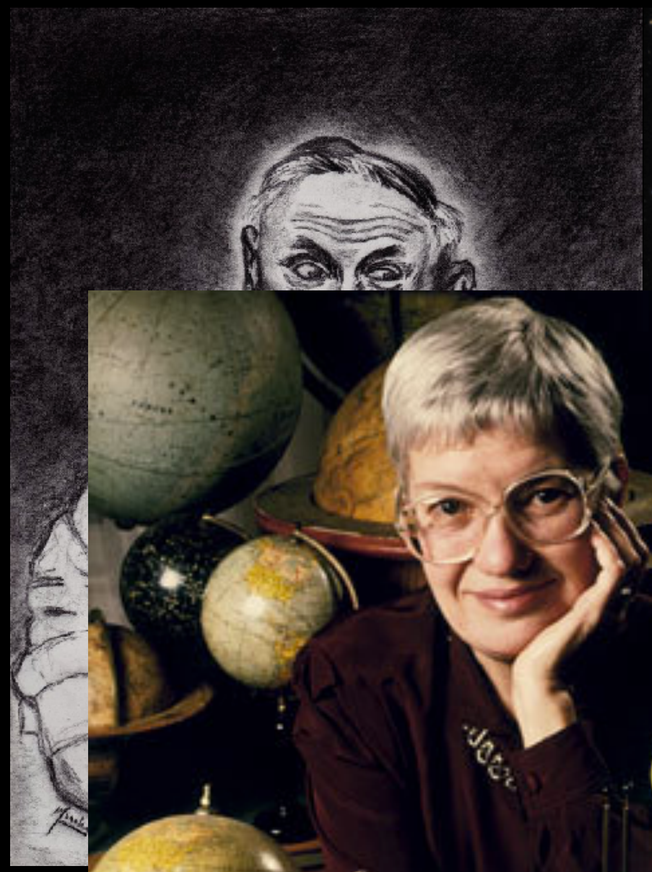
Gravitational Dark Matter



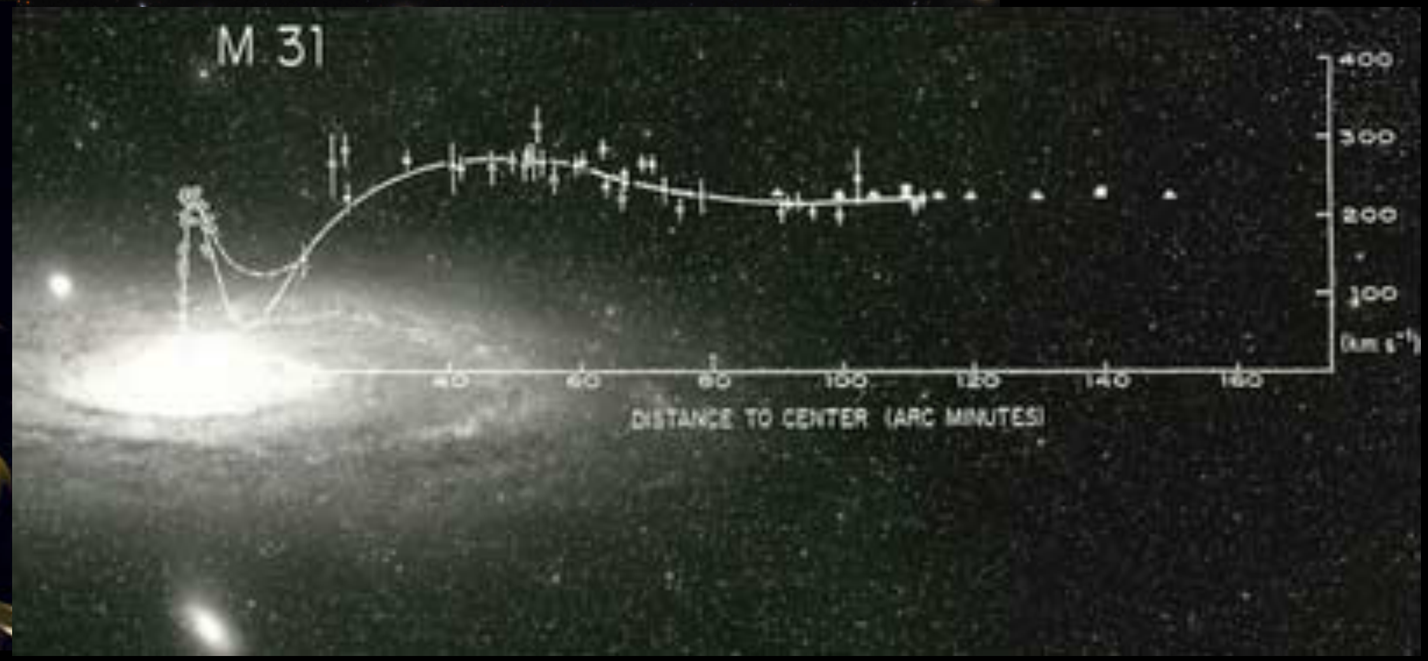


1933: Zwicky observers dark matter in Coma Cluster

Gravitational Dark Matter

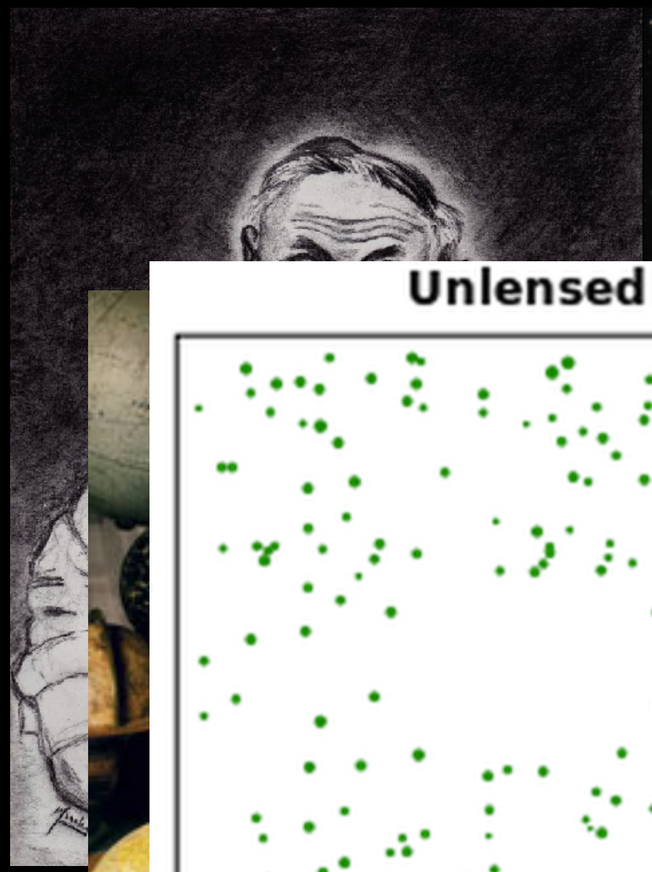


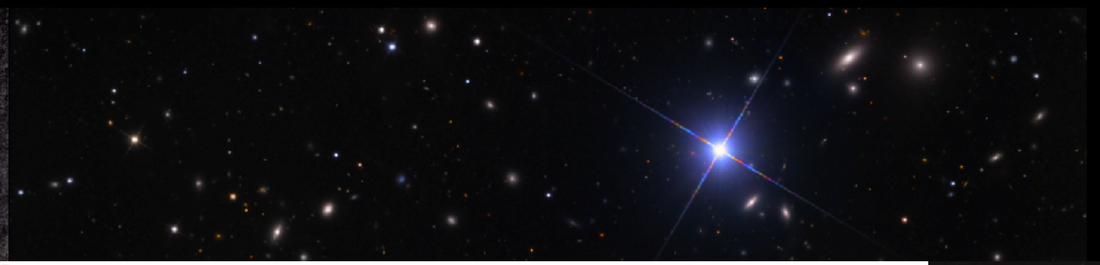




1970s: Vera Rubin observes anomalous rotation velocities in M31

Gravitational Dark Matter

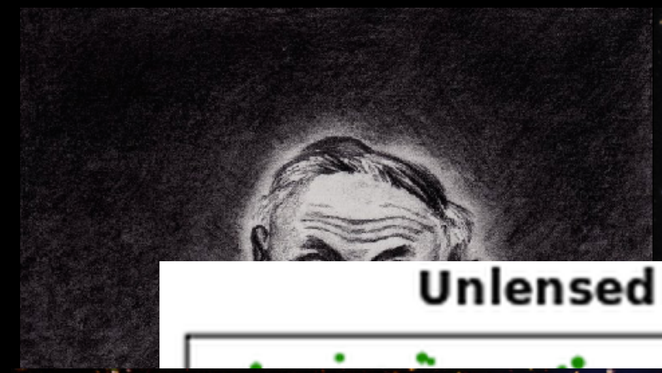


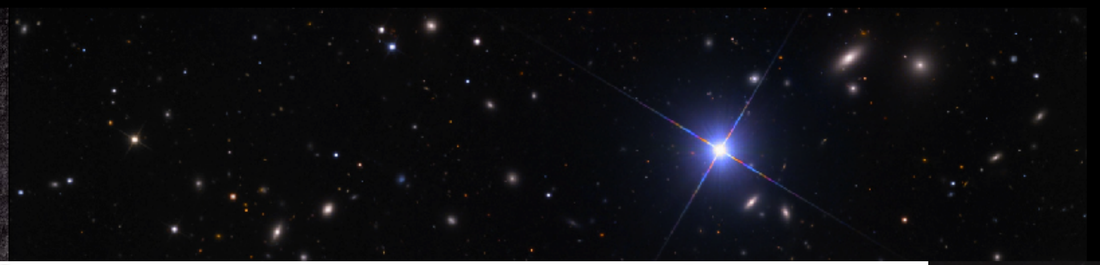


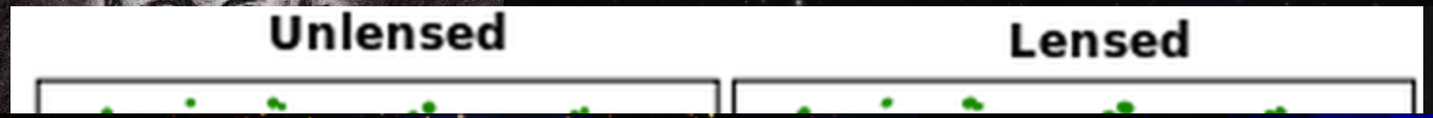


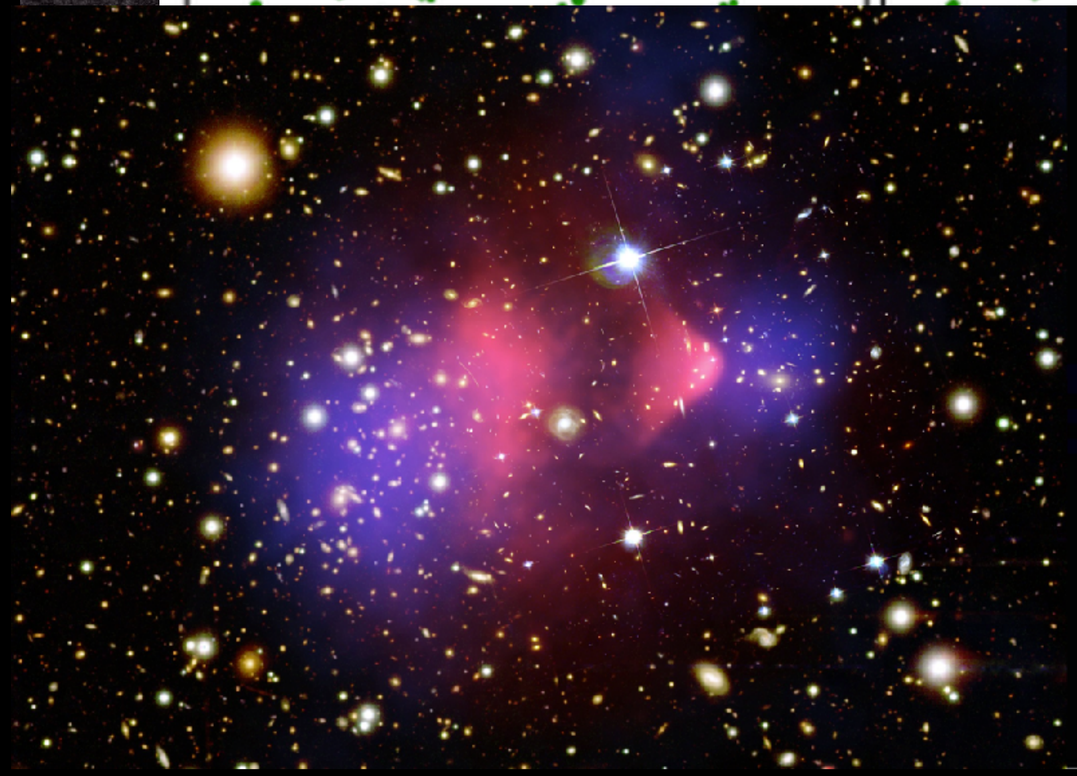
1996: Weak Gravitational Lensing Observed from Dark Matter Halos

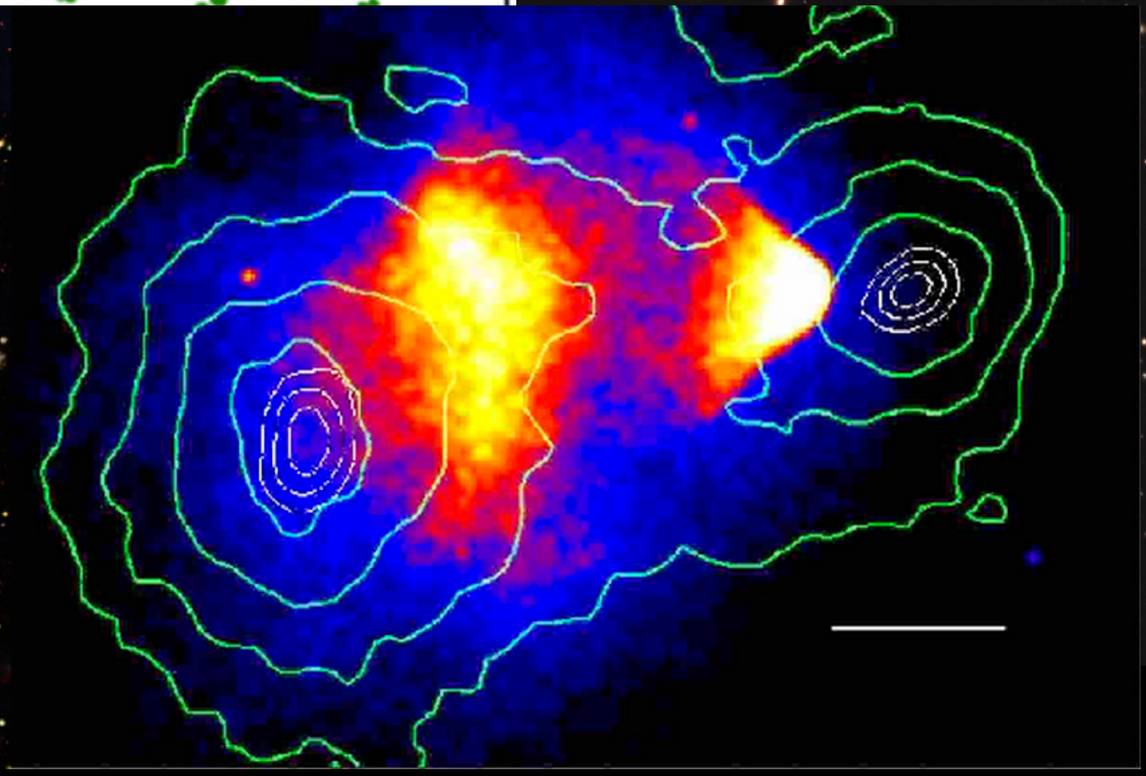
Gravitational Dark Matter











2006: Bullet Cluster Observations Show Offset Between Mass and Hot Gas

Gravitational Dark Matter

WMAP

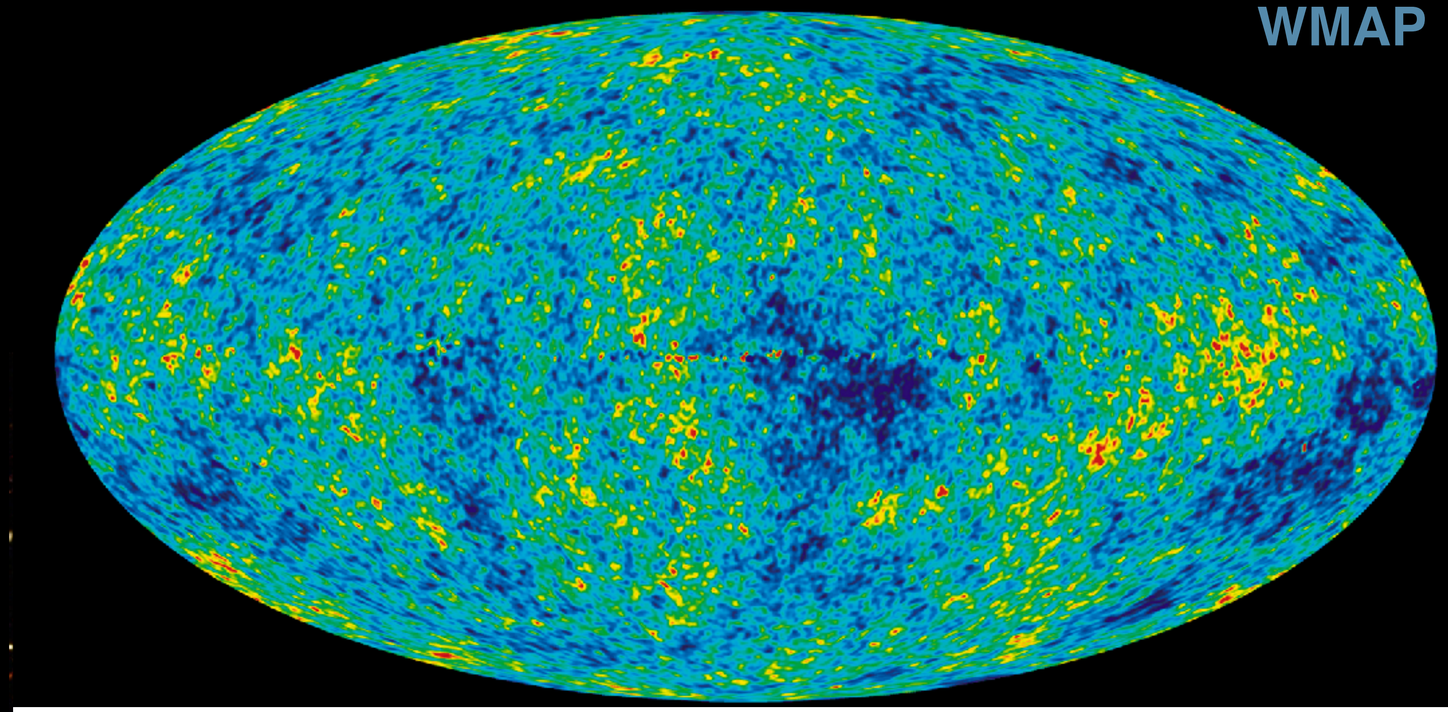
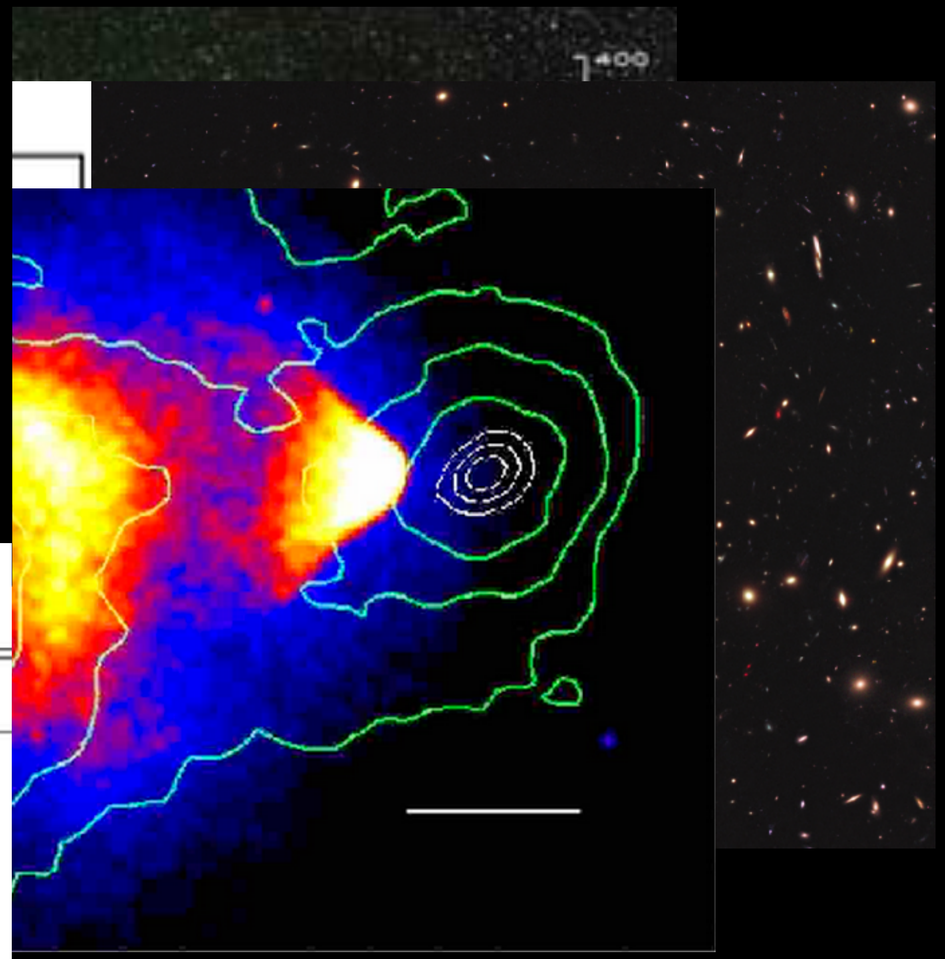


Table 6. Cosmological Parameter Summary

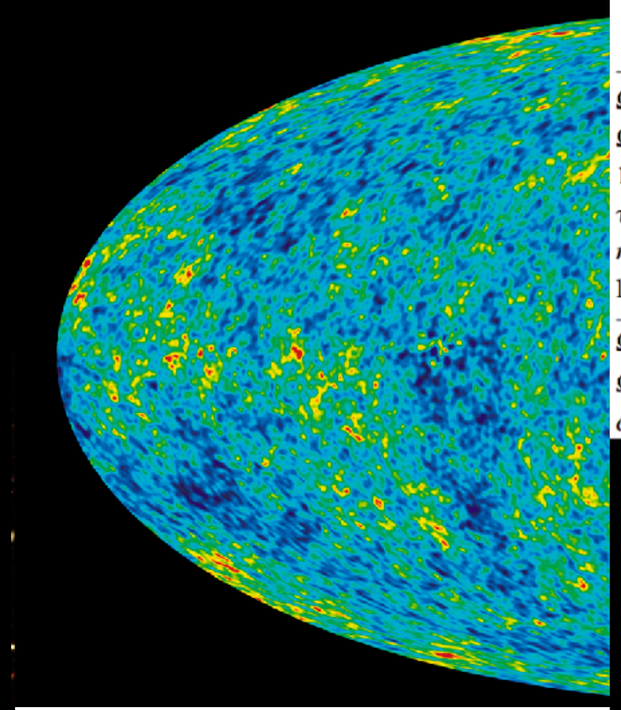
Description	Symbol	*WMAP*-only
Parameters for Standard ΛCDM Model [a]		
Age of universe	t_0	13.69 ± 0.13 Gyr
Hubble constant	H_0	$71.9^{+2.6}_{-2.7}$ km/s/Mpc
Baryon density	Ω_b	0.0441 ± 0.0030
Physical baryon density	$\Omega_b h^2$	0.02273 ± 0.00062
Dark matter density	Ω_c	0.214 ± 0.027



nd Hot Gas

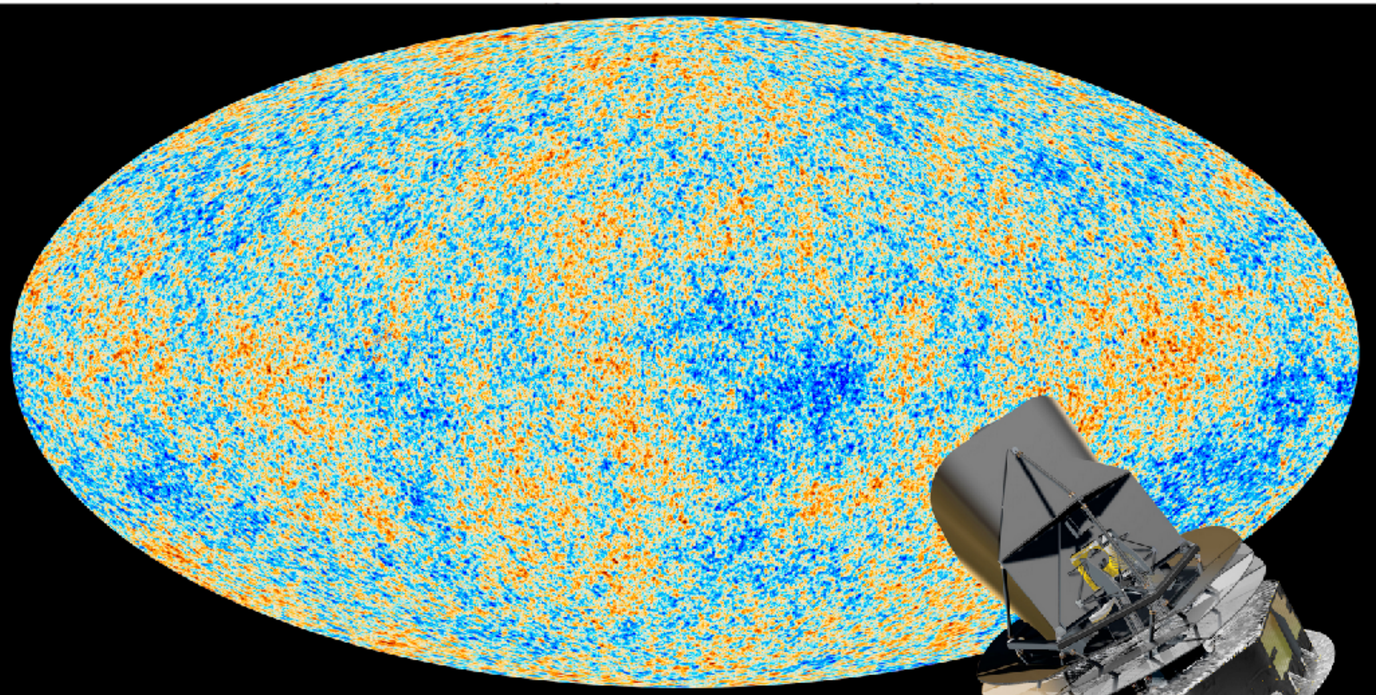
Gravitational Dark Matter

Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012

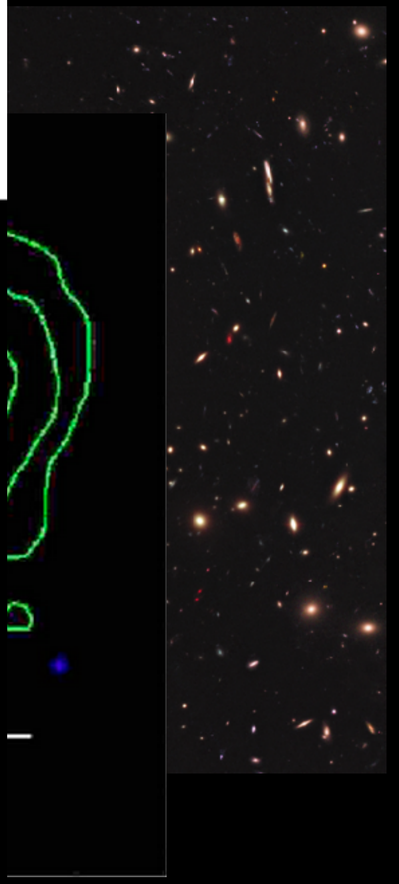


Tabl

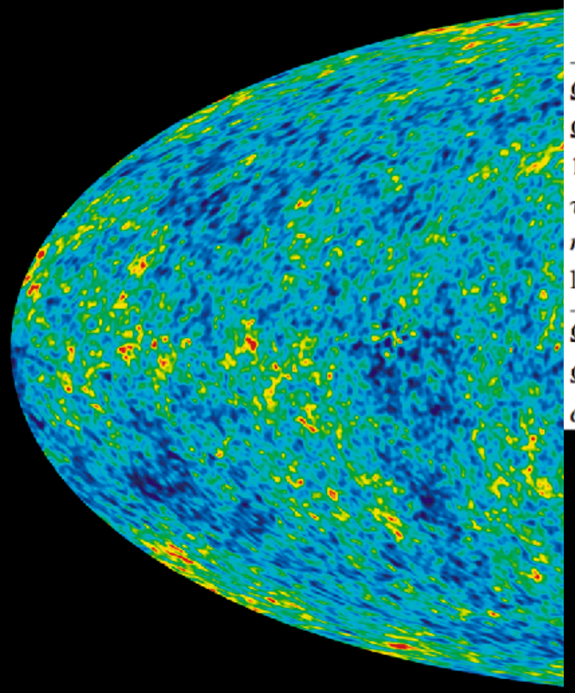
Description
Age of universe
Hubble constant
Baryon density
Physical baryon density
Dark matter density



PLANCK



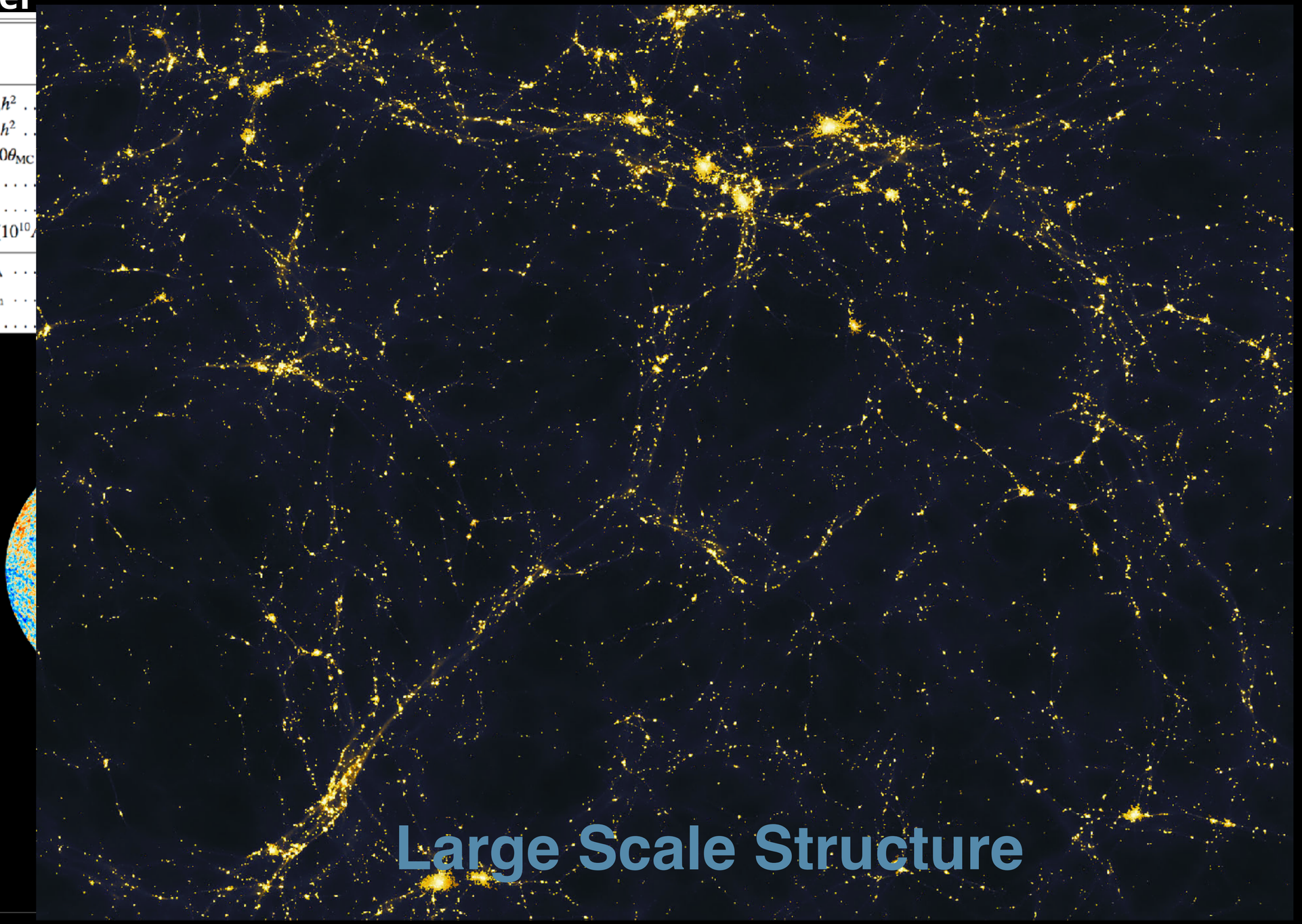
Gravitational Dark Matter



$\Omega_b h^2$ . .
$\Omega_c h^2$ . .
$100\theta_{MC}$
τ . . . .
n_s . . . .
$\ln(10^{10}$
Ω_Λ . . .
Ω_m . . .
σ_8 . . .

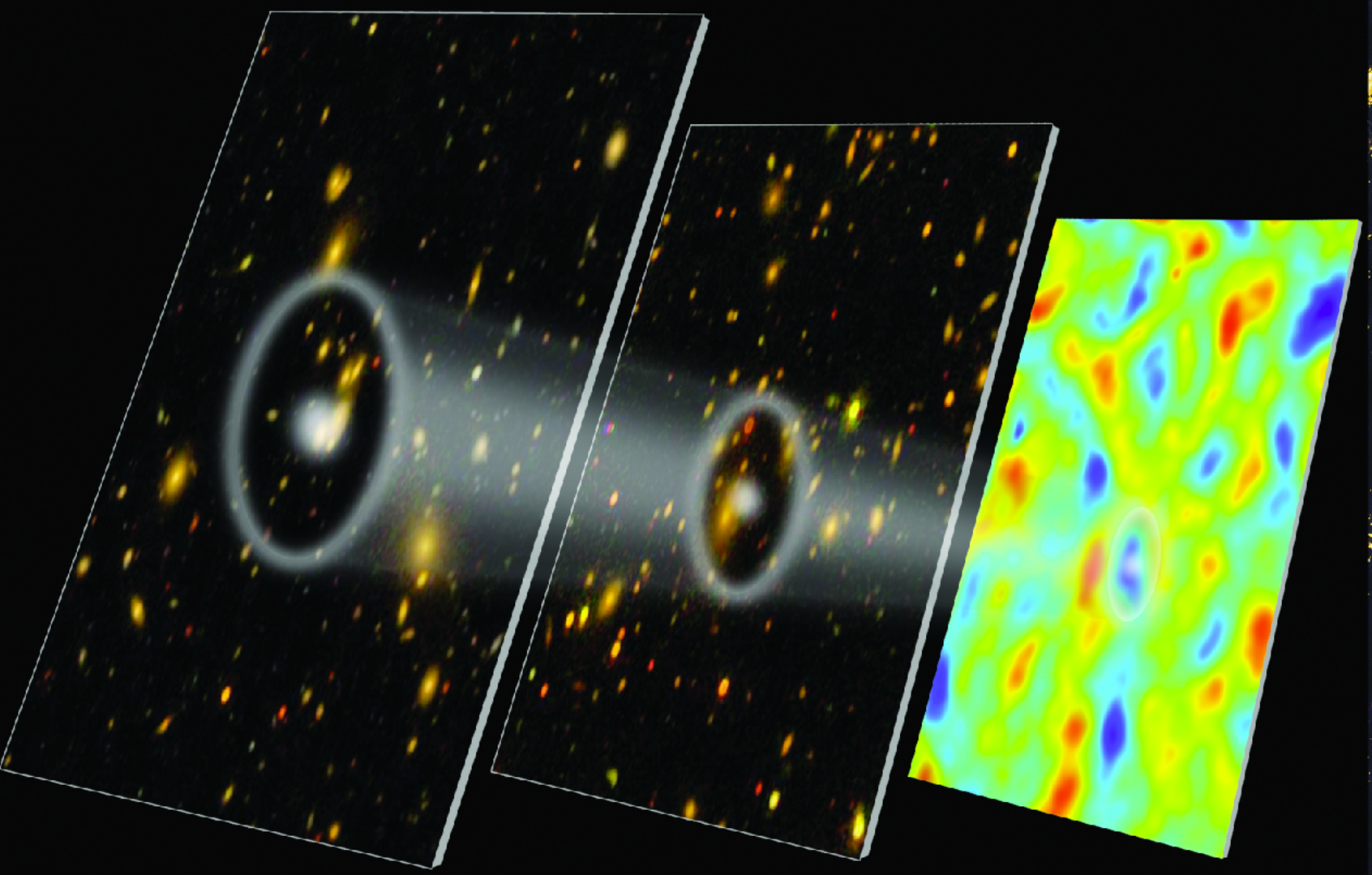
Tabl

	Description
Age of universe	
Hubble constant	
Baryon density	
Physical baryon density	
Dark matter density	



Gravitational Dark Matter

Baryonic Acoustic Oscillations



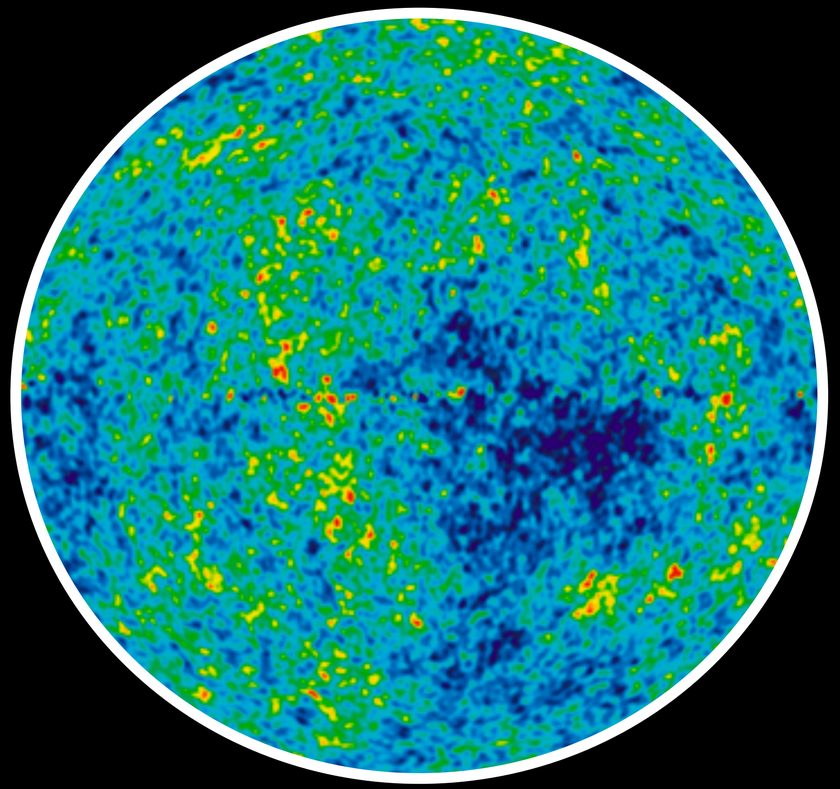
Galaxy map 3.8 billion years ago

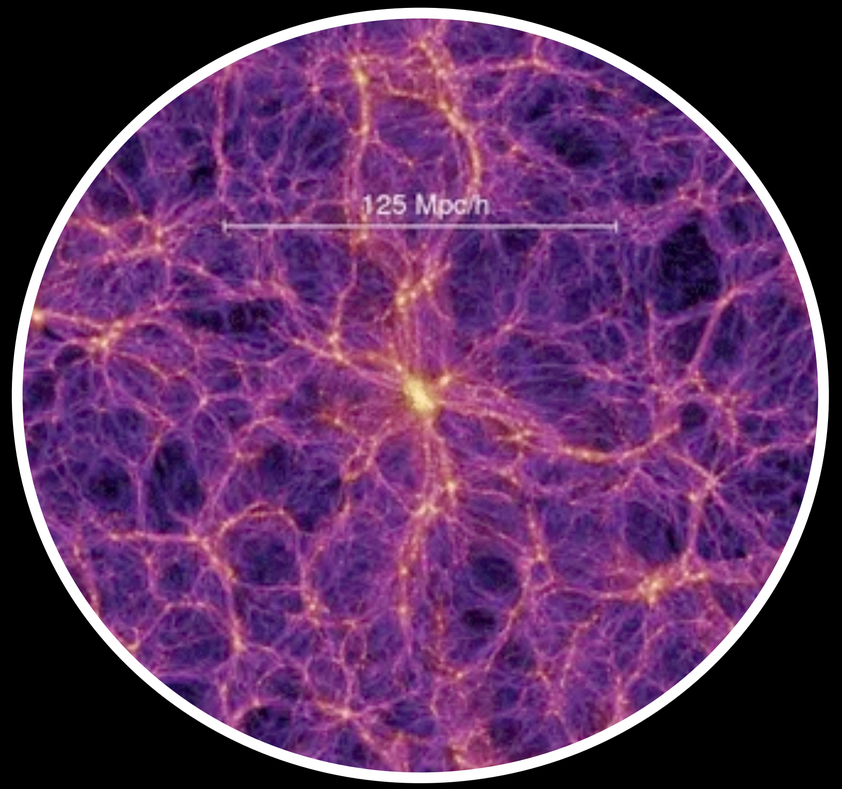
Galaxy map 5.5 billion years ago

CMB 13.7 billion years ago

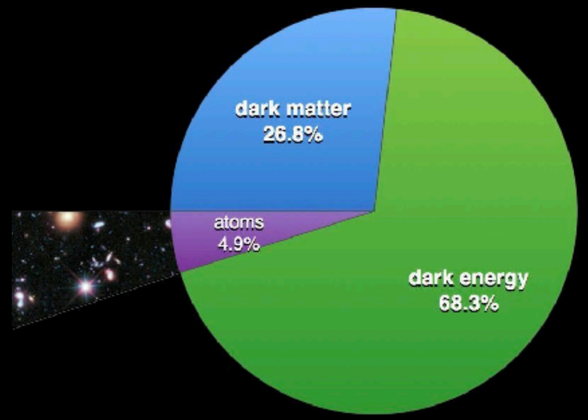
e Structure

Gravitational Dark Matter - The Present

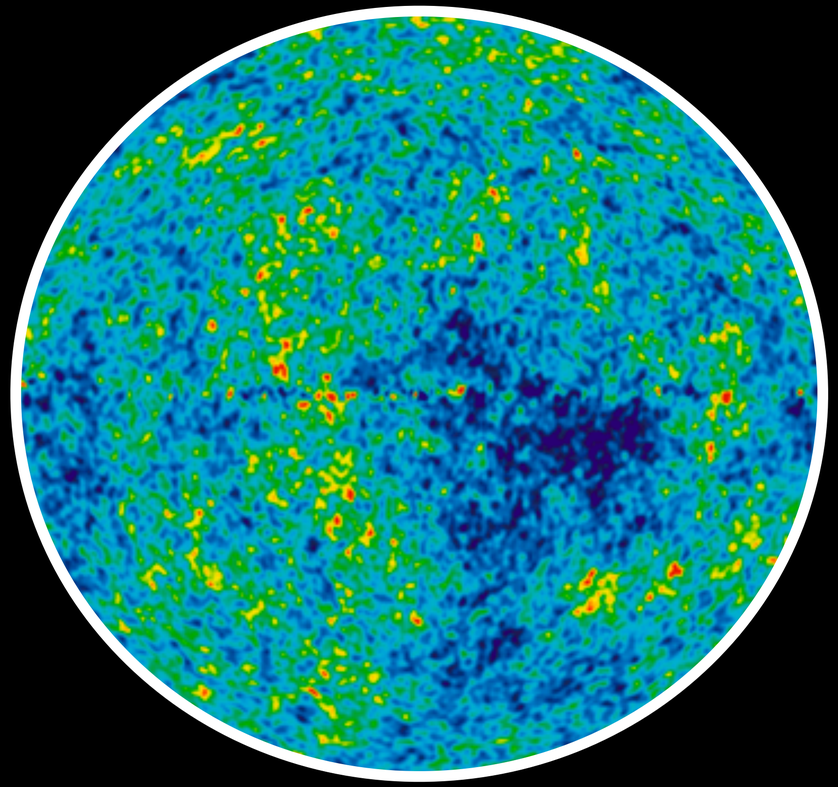


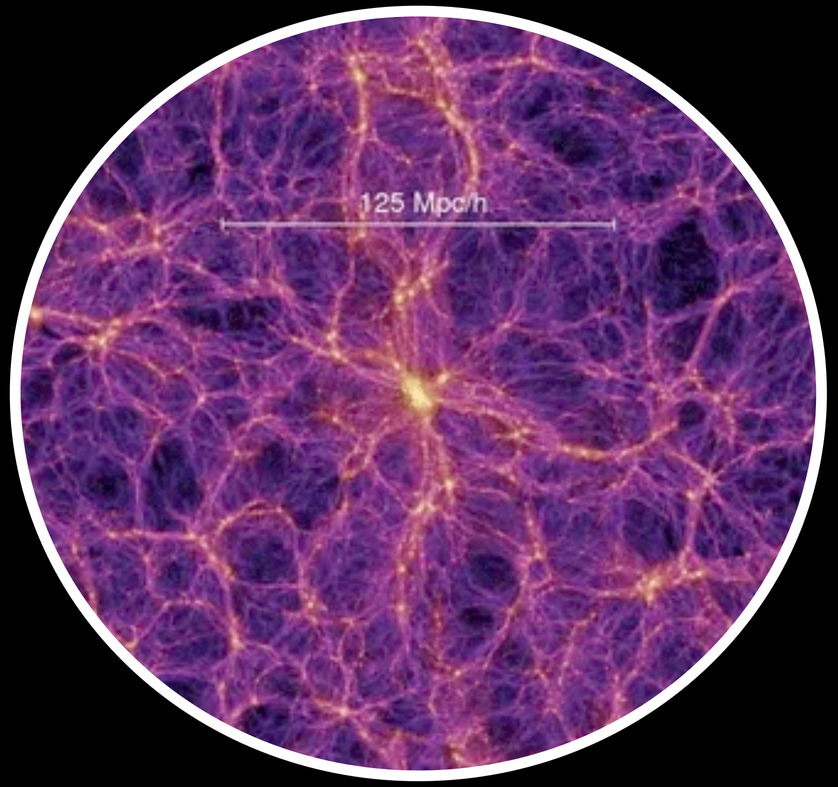






Particle Dark Matter - The Present







10^{-25} GeV

$R_{DM} > R_{UFD}$

slide concept courtesy of Asher Berlin

10^{62} GeV

$M_{DM} > M_{UFD}$

The Present



10^{-25} GeV

$R_{DM} > R_{UFD}$

slide concept courtesy of Asher Berlin

10^{62} GeV

$M_{DM} > M_{UFD}$



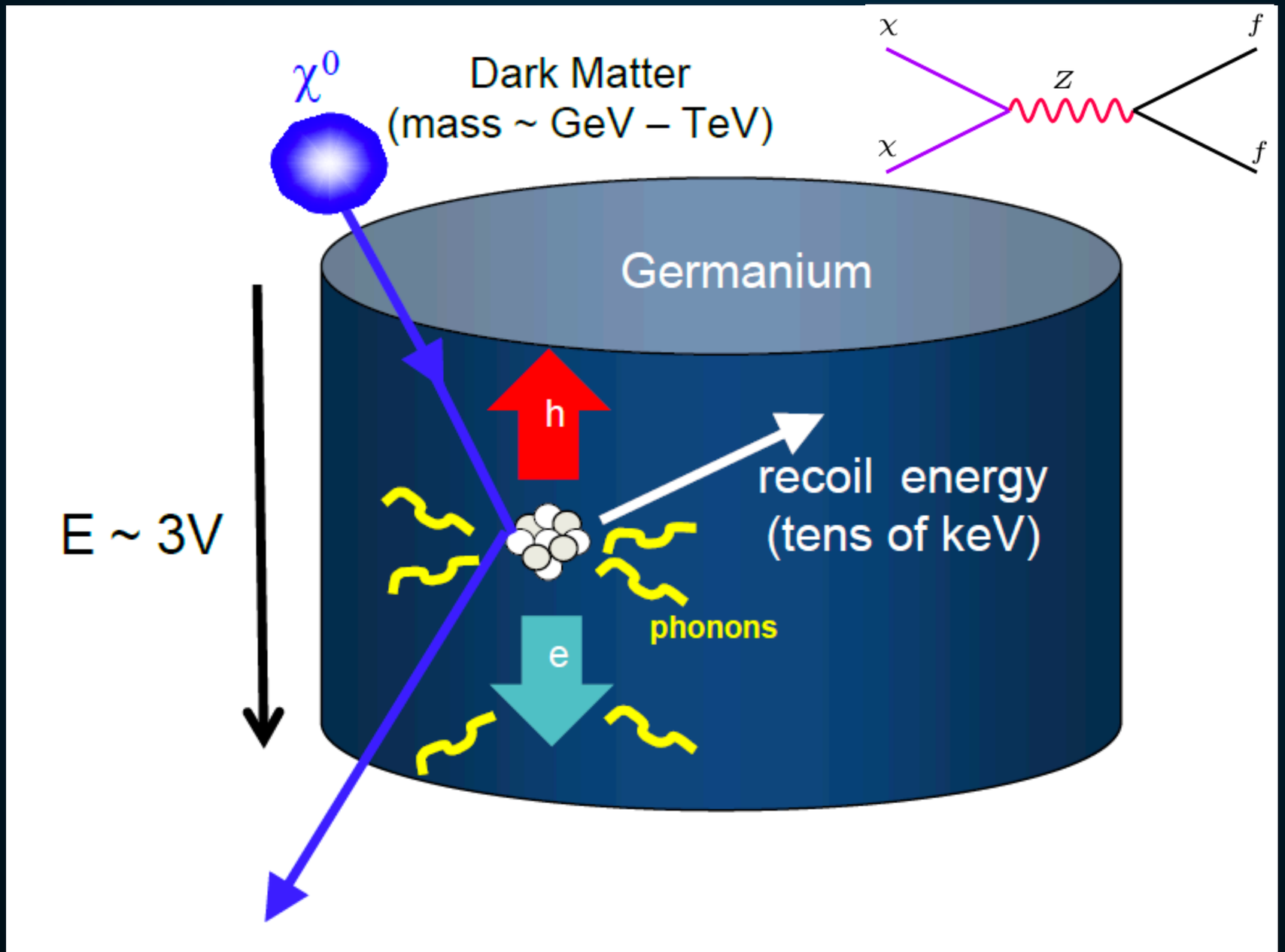
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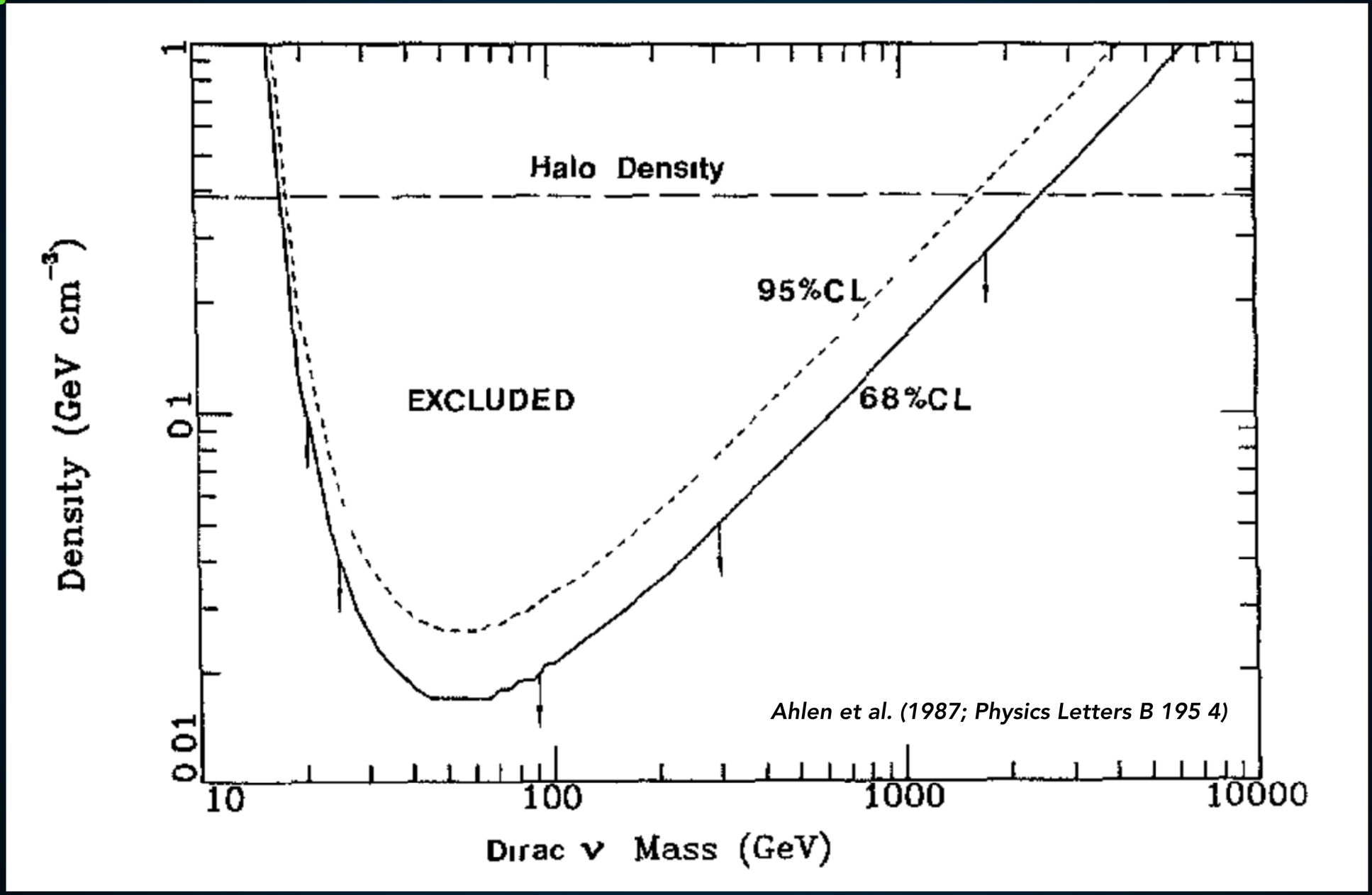
Can We Eliminate Classes of Dark Matter Models?

Yes!



Can We Eliminate Classes of Dark Matter Models?

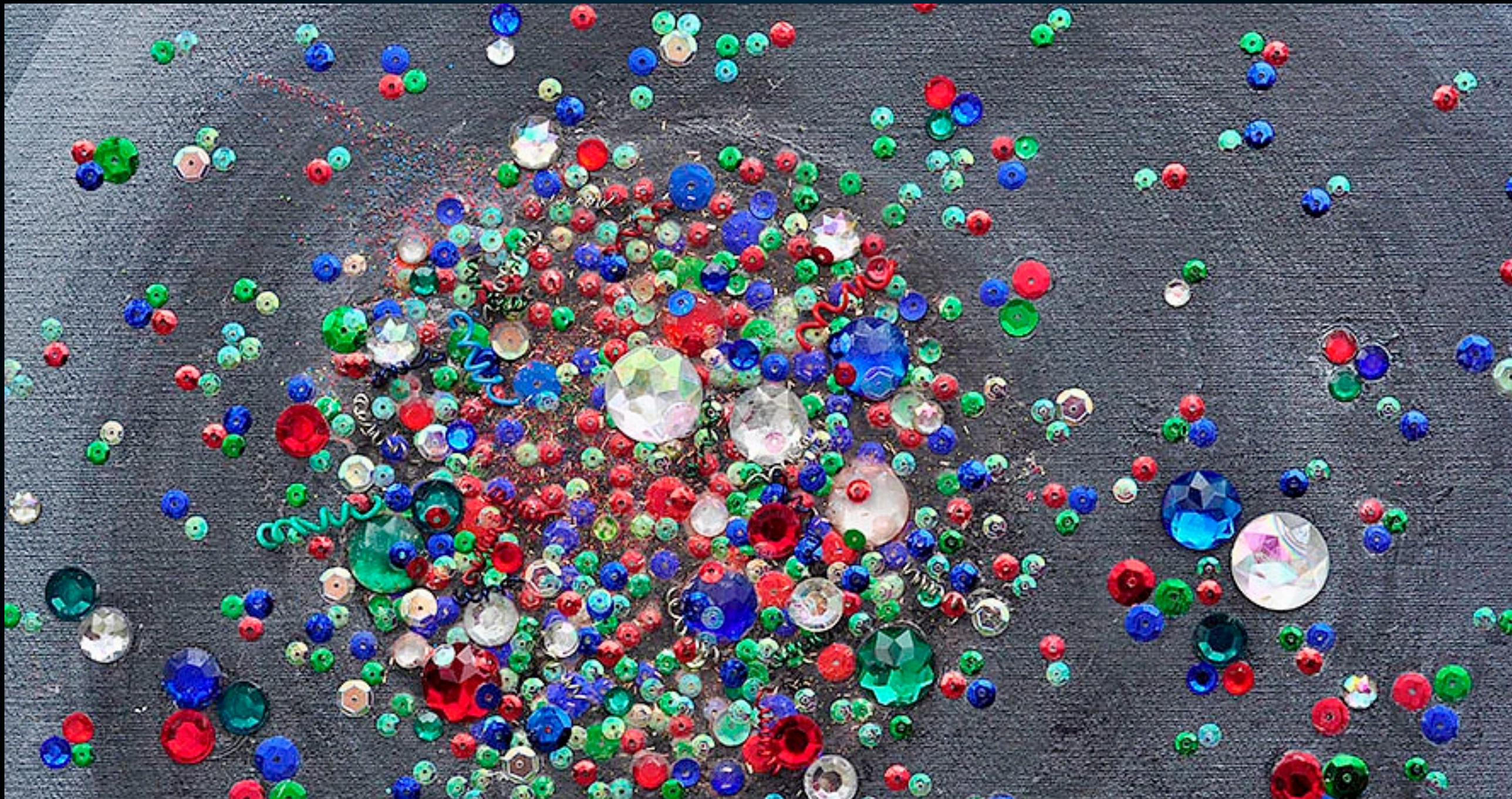
Yes!

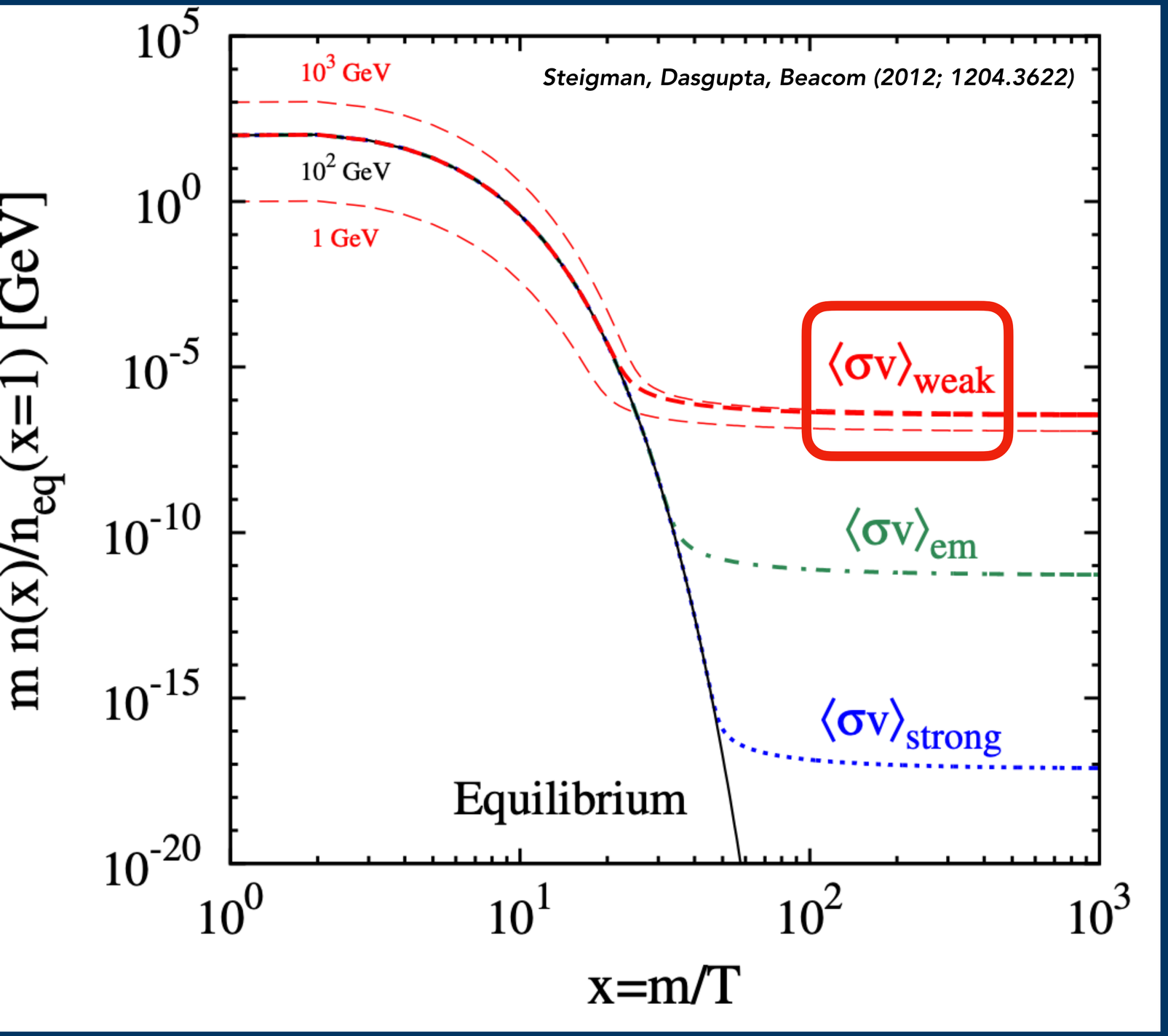


Ahlen et al. (1987; Physics Letters B 195 4)

Thermal Dark Matter

artist: Sarah Szabo



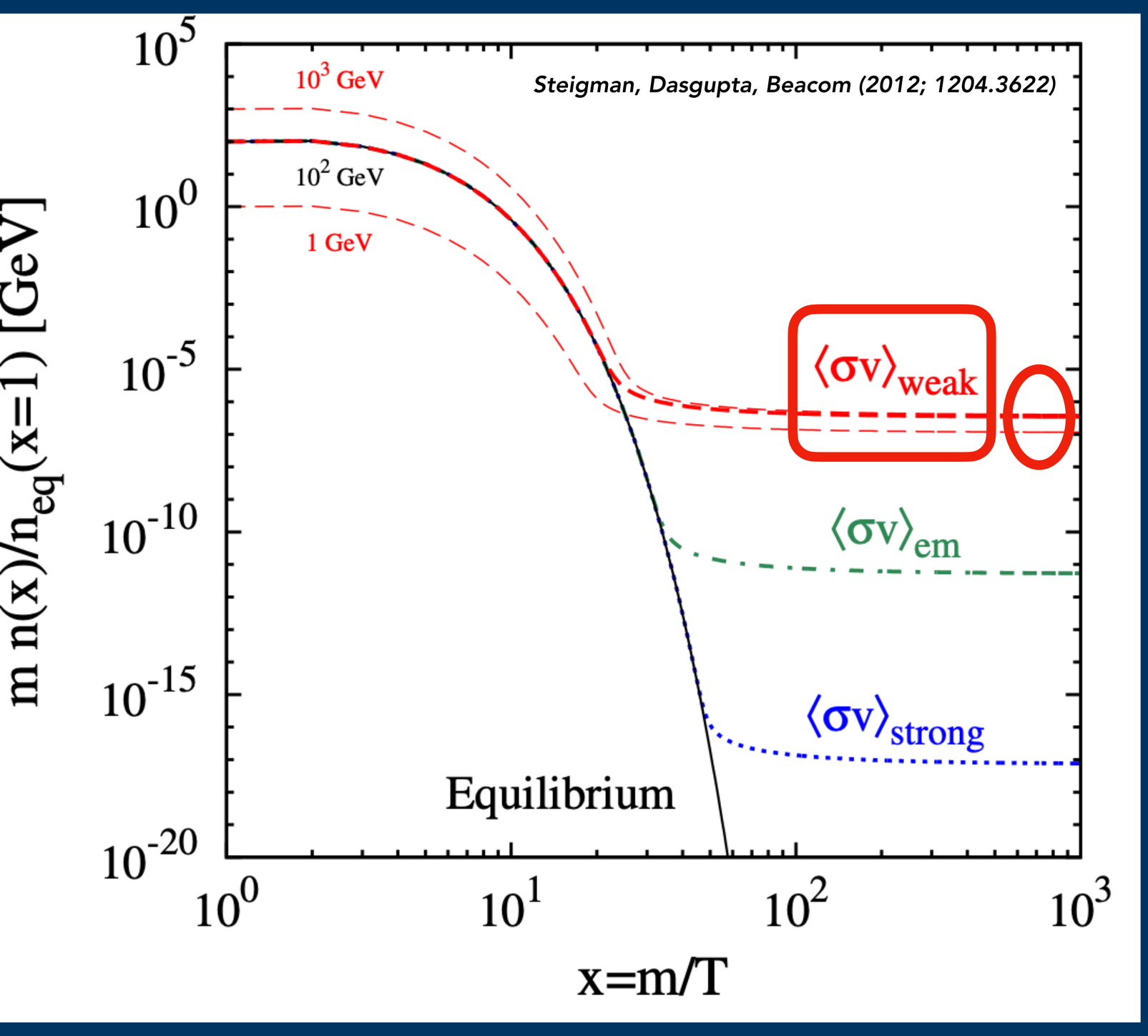


Thermal Dark Matter Density

Present density inversely proportional to the strength of the interaction.

Almost independent of particle mass.

Weak-Interaction Produces the right density!



Thermal Dark Matter Density

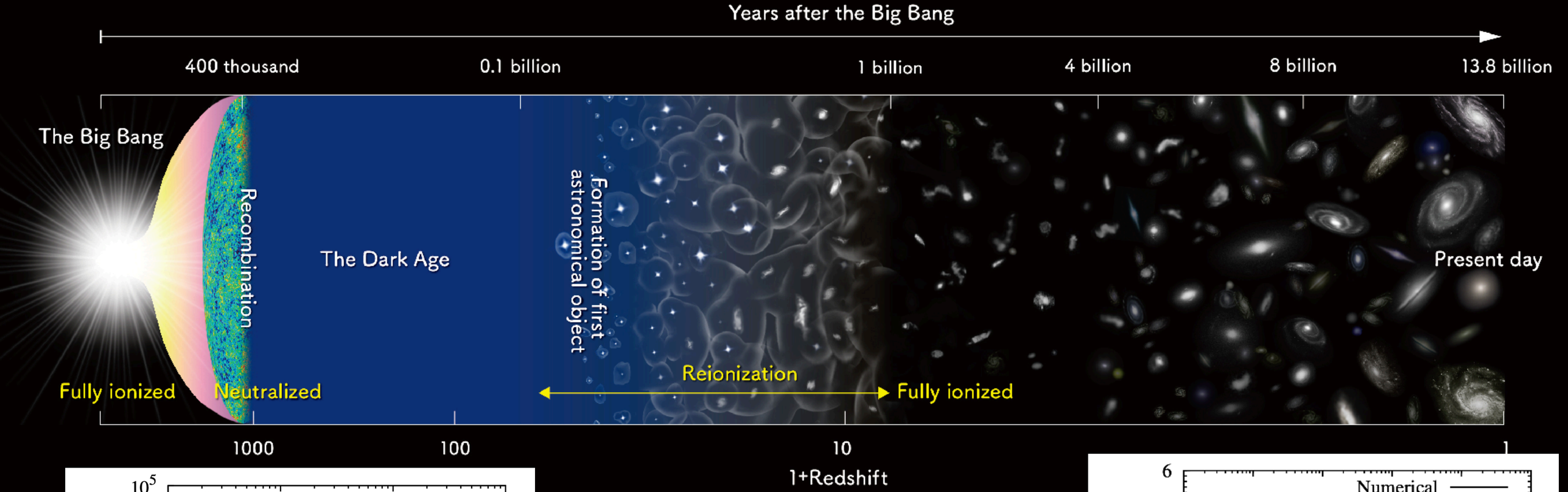
Present density inversely proportional to the strength of the interaction.

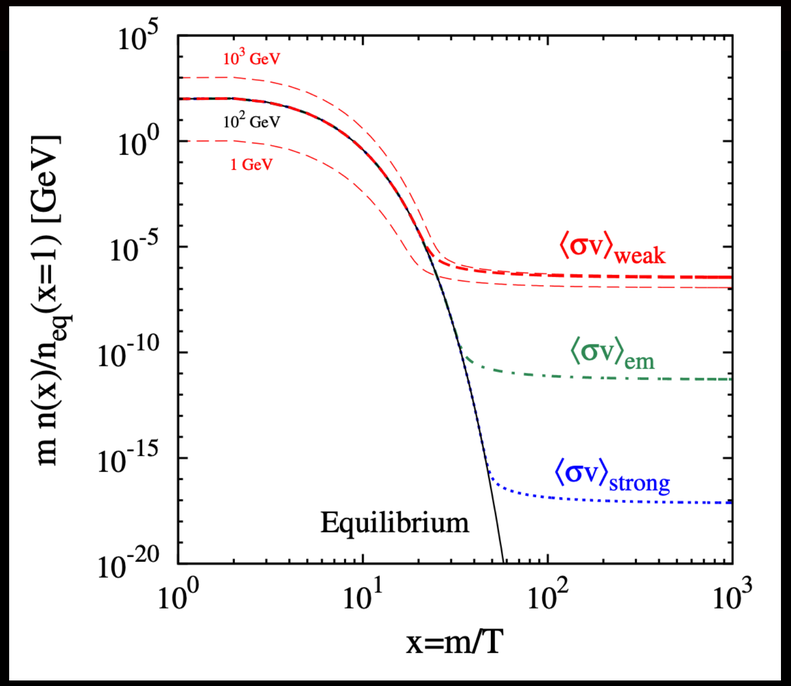
Almost independent of particle mass.

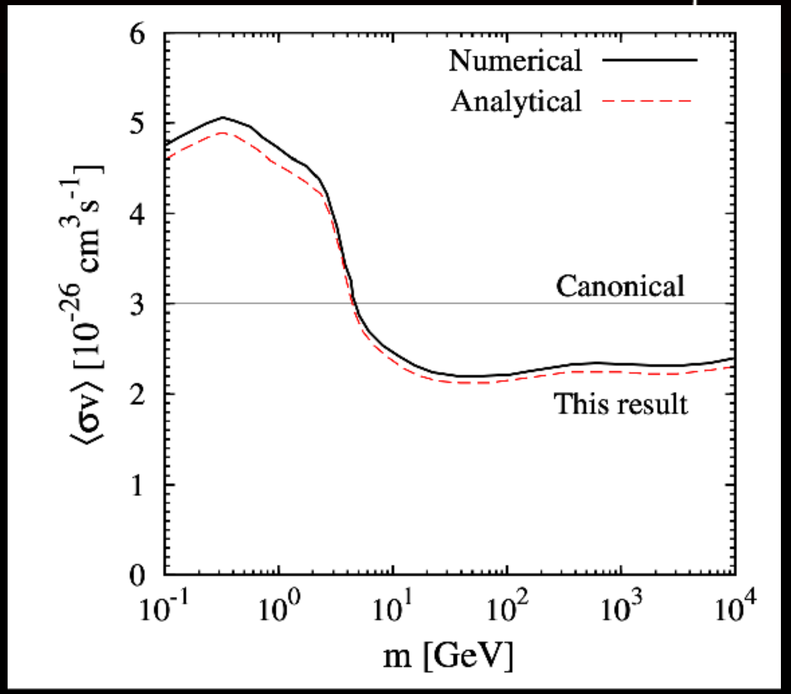
Weak-Interaction Produces the right density!

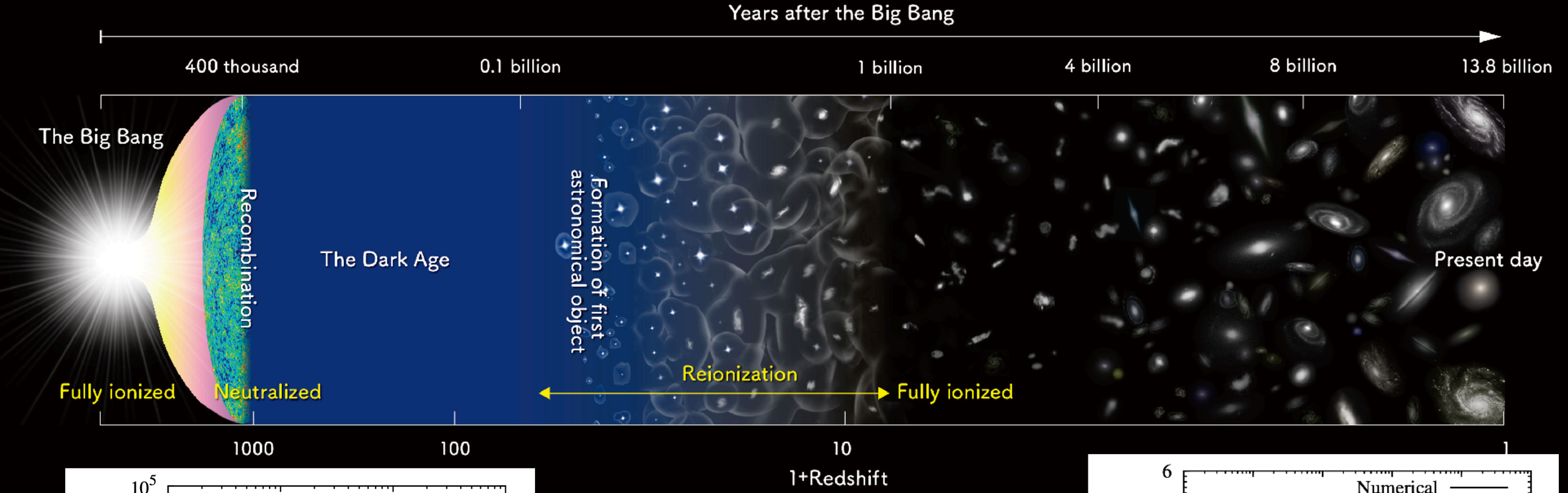
10 MeV - 100 TeV !

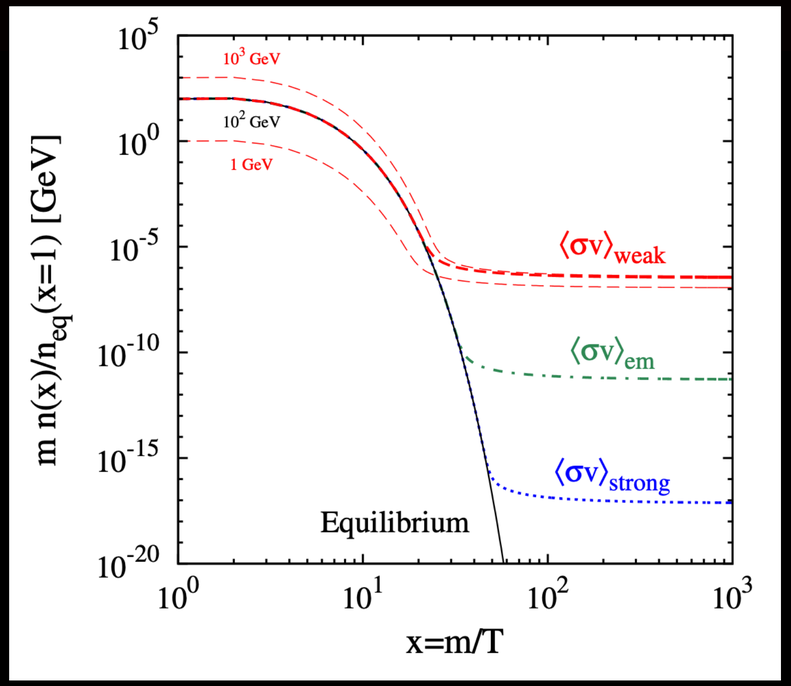
Lee, Weinberg (1977; PRL 39 4)
Ho, Scherrer (2012; 1208.4347)


Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Age
Formation of first astronomical object
Reionization
Present day
Fully ionized
Neutralized
Fully ionized
1000
100
10
1
1+Redshift


10^5
10^0
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^3 GeV
10^2 GeV
1 GeV
$\langle\sigma v\rangle_{weak}$
$\langle\sigma v\rangle_{em}$
$\langle\sigma v\rangle_{strong}$
Equilibrium
$m\, n(x)/n_{eq}(x=1)$ [GeV]
10^0
10^1
10^2
10^3
x=m/T

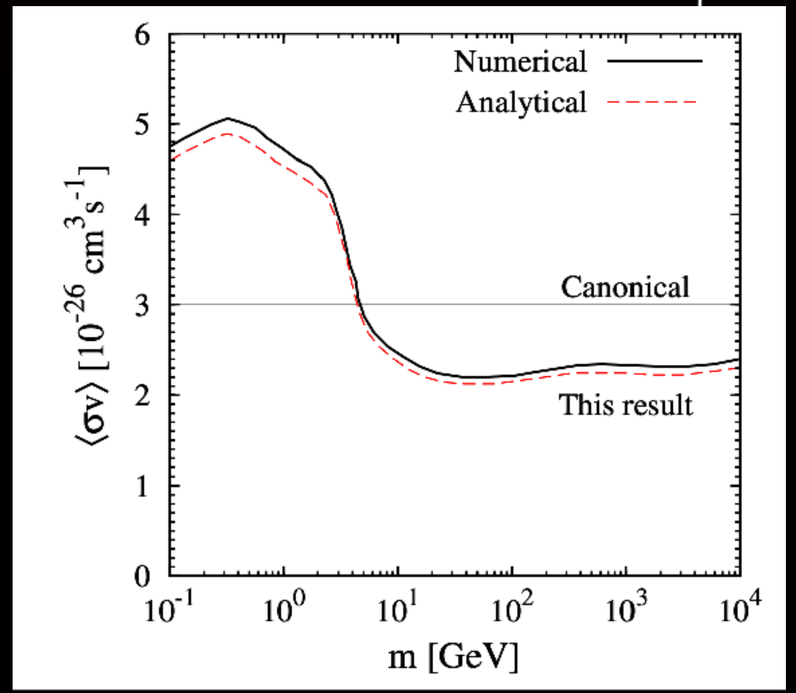

Numerical
Analytical
Canonical
This result
$\langle\sigma v\rangle$ [10^{-26} cm^3 s^{-1}]
0
1
2
3
4
5
6
10^{-1}
10^0
10^1
10^2
10^3
10^4
m [GeV]

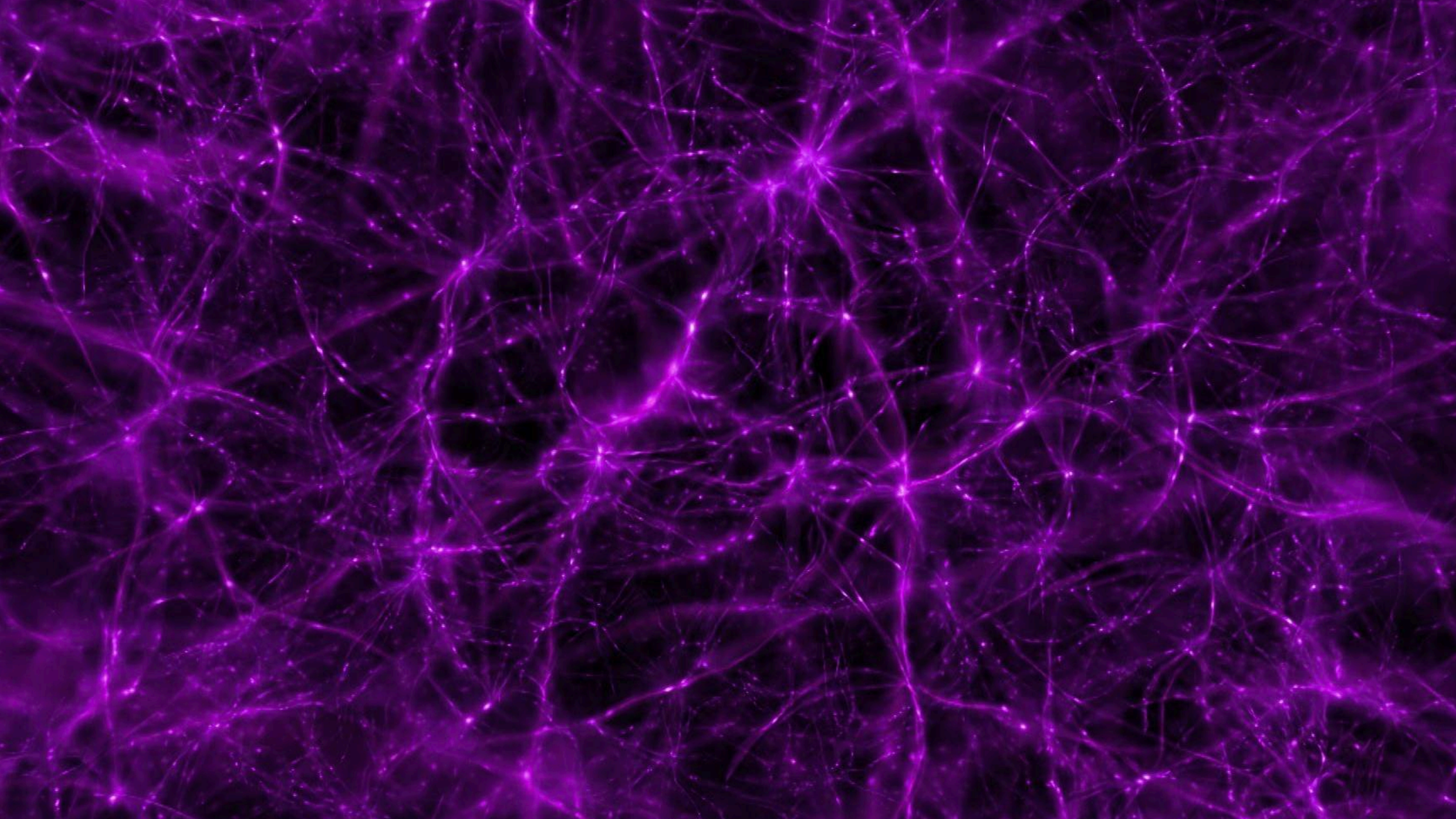


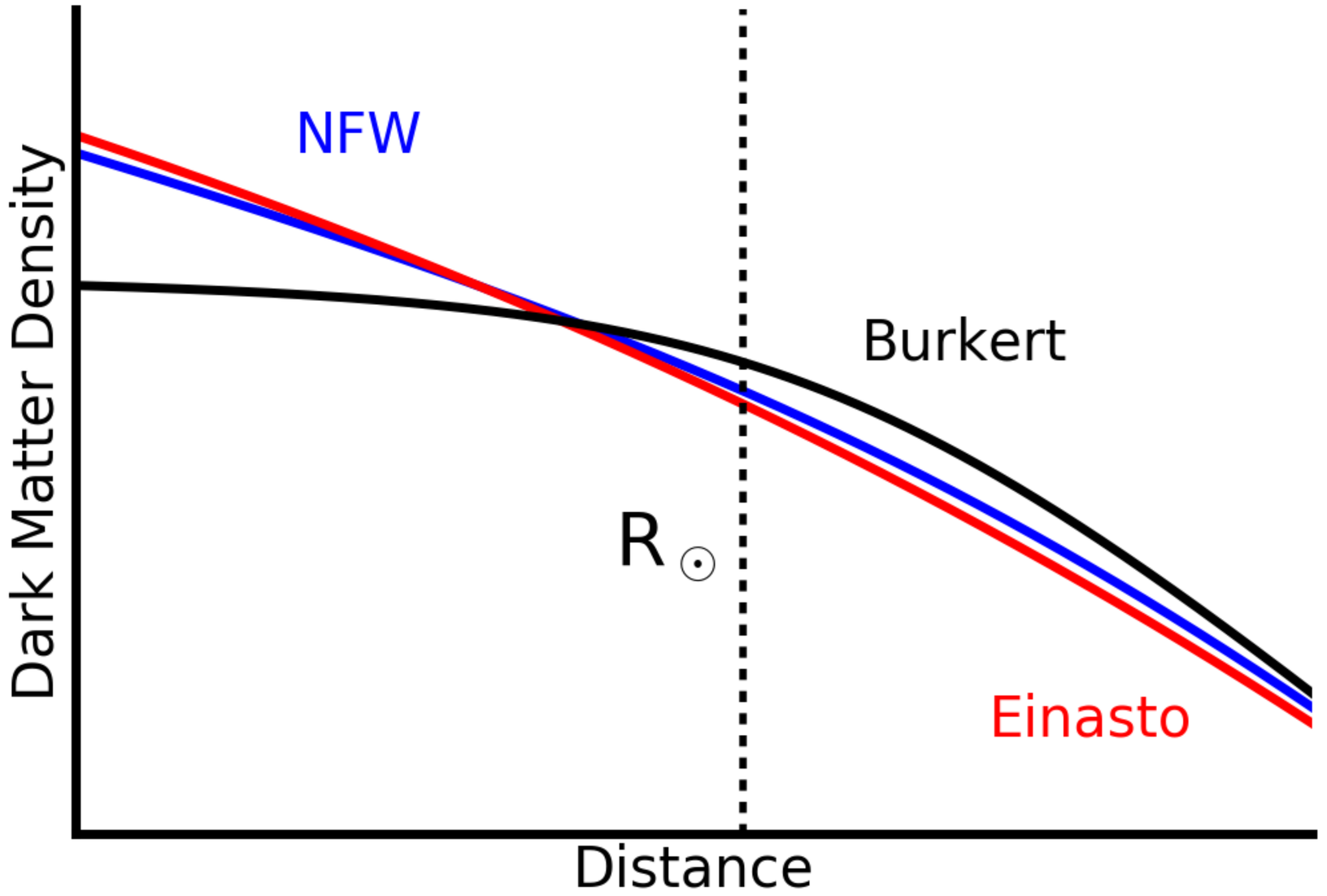


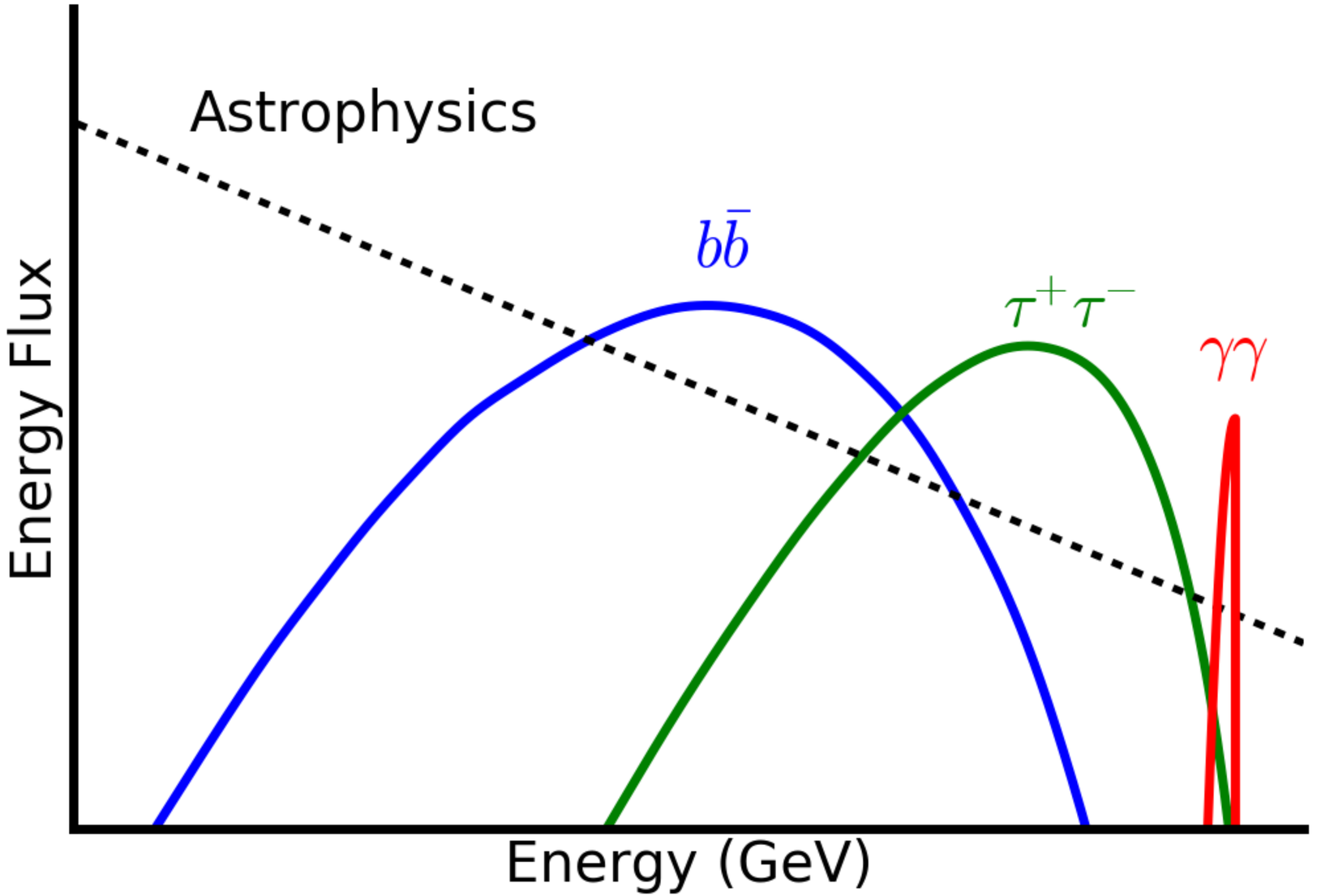
Philosophy:

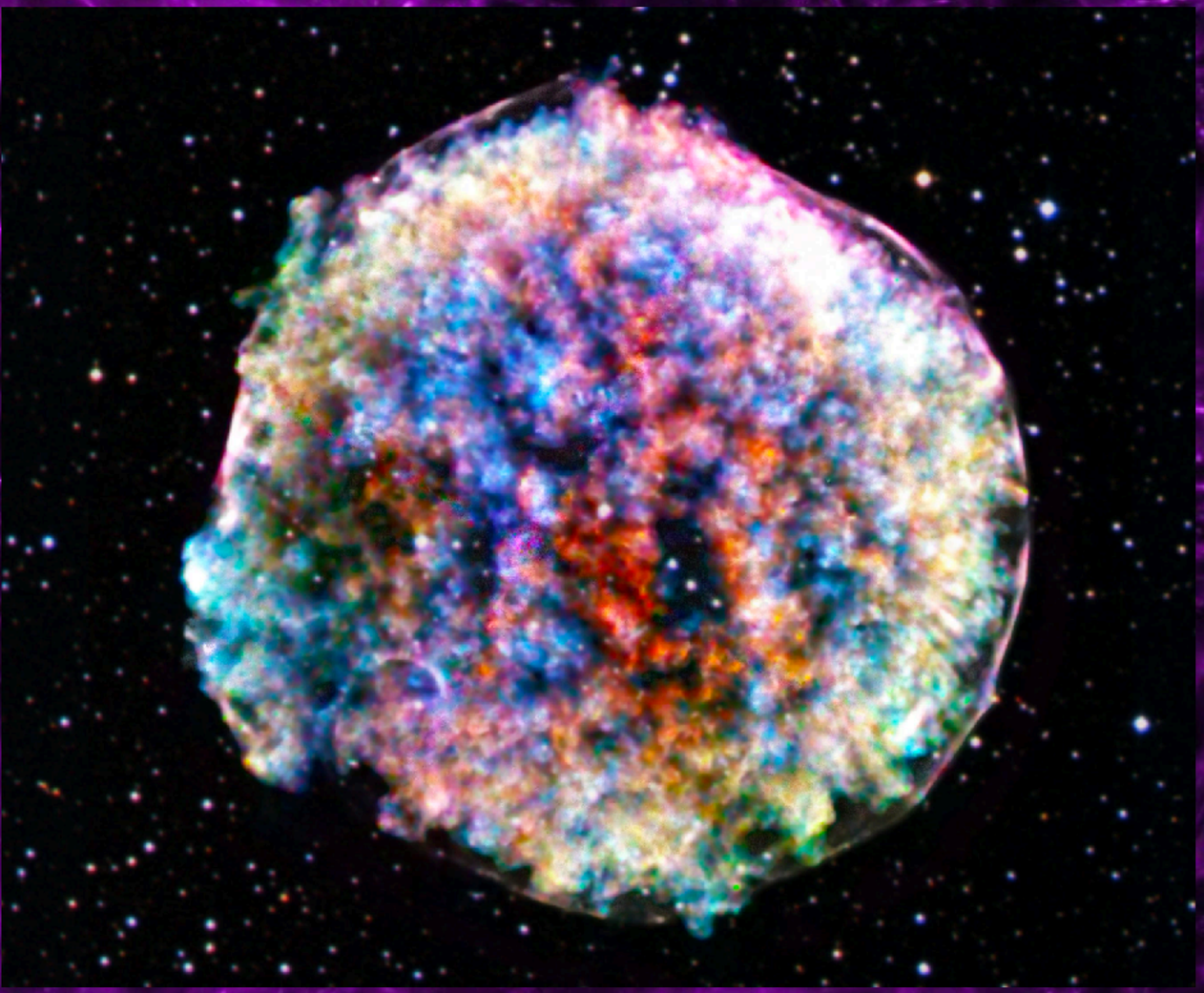
Constrain the simplest model first

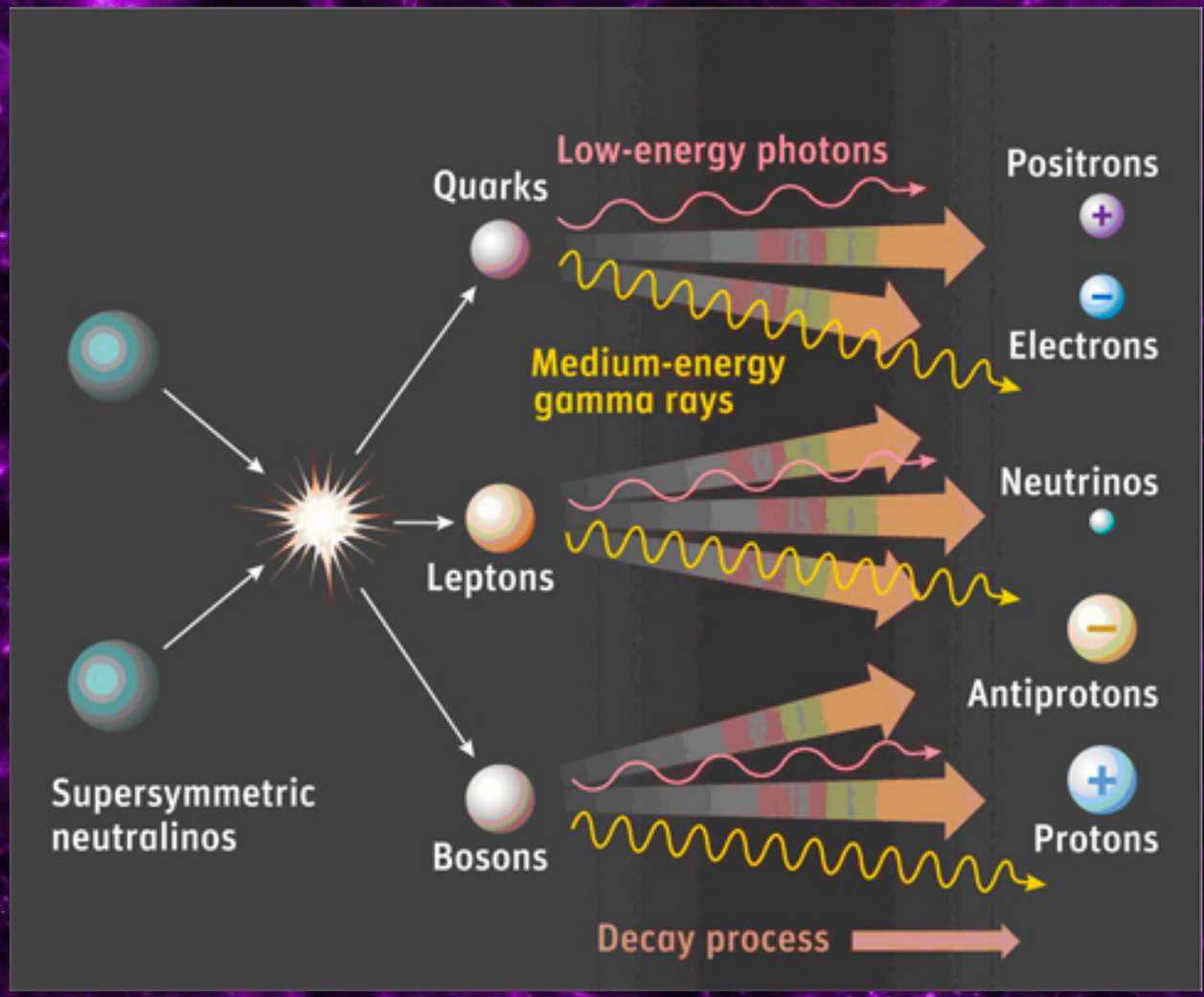




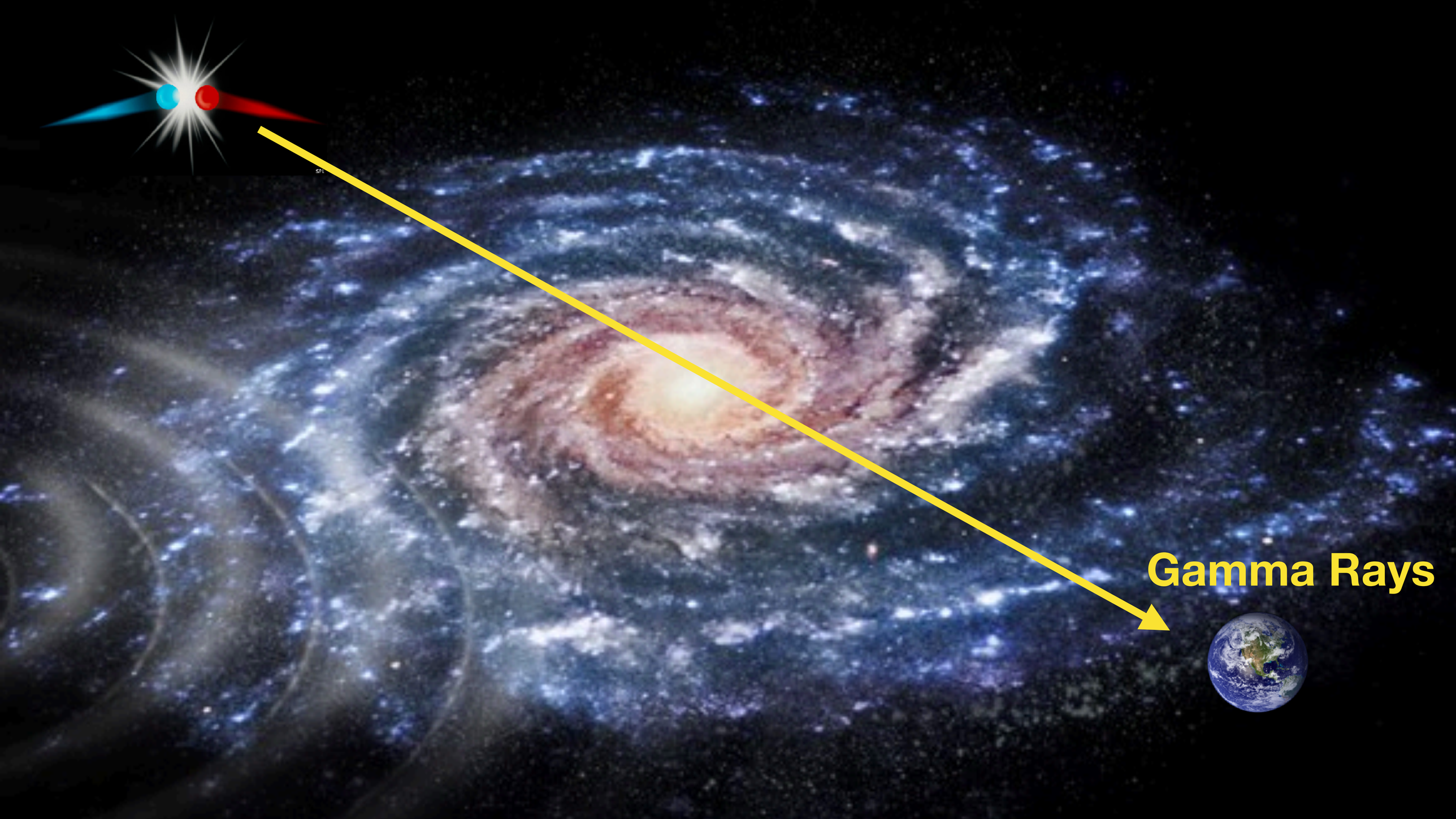

NFW
Burkert
Einasto
R⊙
Dark Matter Density
Distance


Astrophysics
$b\bar{b}$
$\tau^+\tau^-$
$\gamma\gamma$
Energy Flux
Energy (GeV)

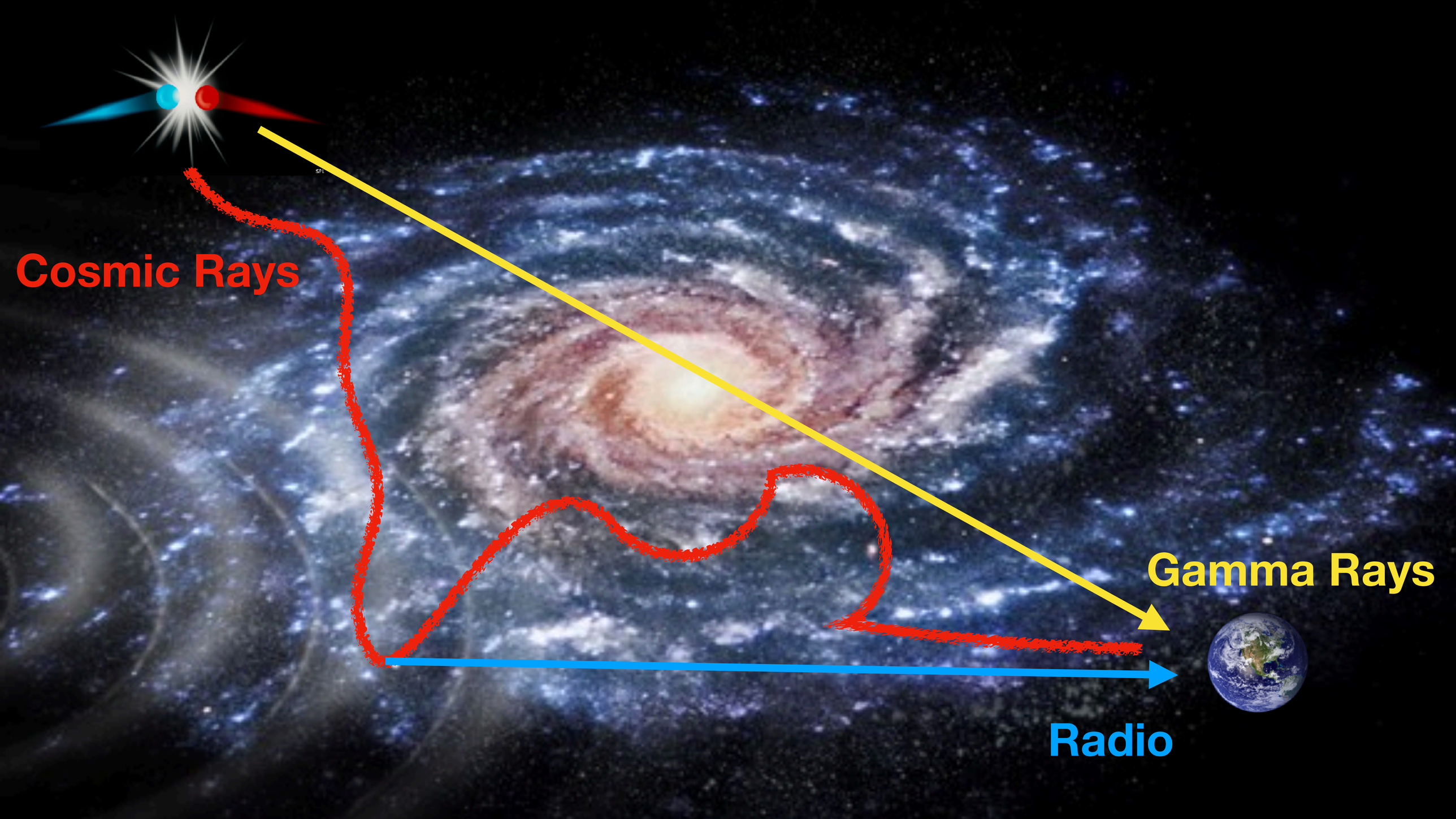



Low-energy photons
Quarks
Positrons
Electrons
Medium-energy
gamma rays
Neutrinos
Leptons
Antiprotons
Supersymmetric
neutralinos
Bosons
Protons
Decay process




Gamma Rays


Cosmic Rays
Gamma Rays


Cosmic Rays
Gamma Rays
Radio

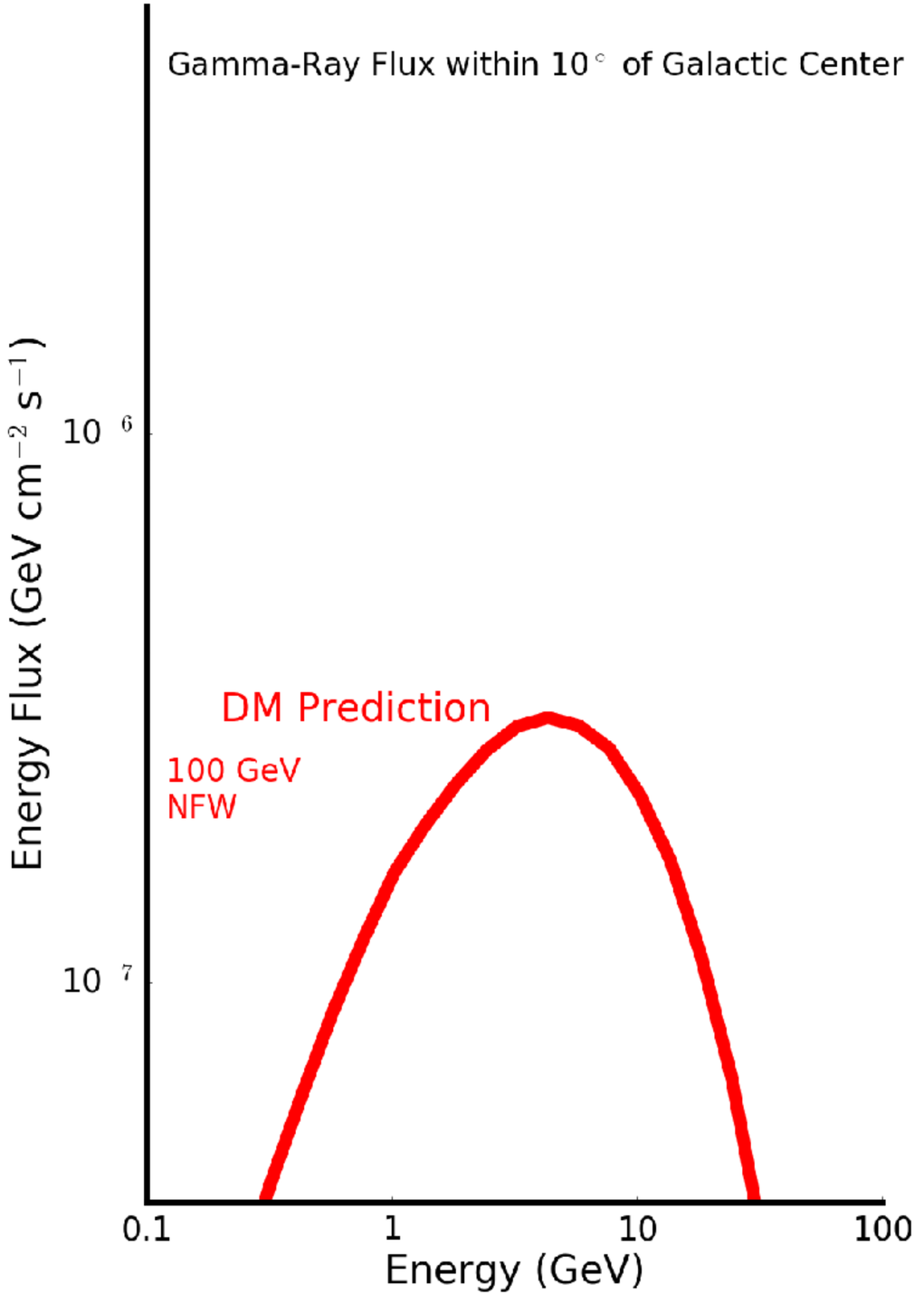
Thermal WIMPs and the Story of Tantalus

NFW Profile (Mass of Milky Way)

Thermal Cross-Section (Early Universe)

Dark Matter Mass (?)

Annihilation Final State (?)



Thermal WIMPs and the Story of Tantalus

NFW Profile (Mass of Milky Way)

Thermal Cross-Section (Early Universe)

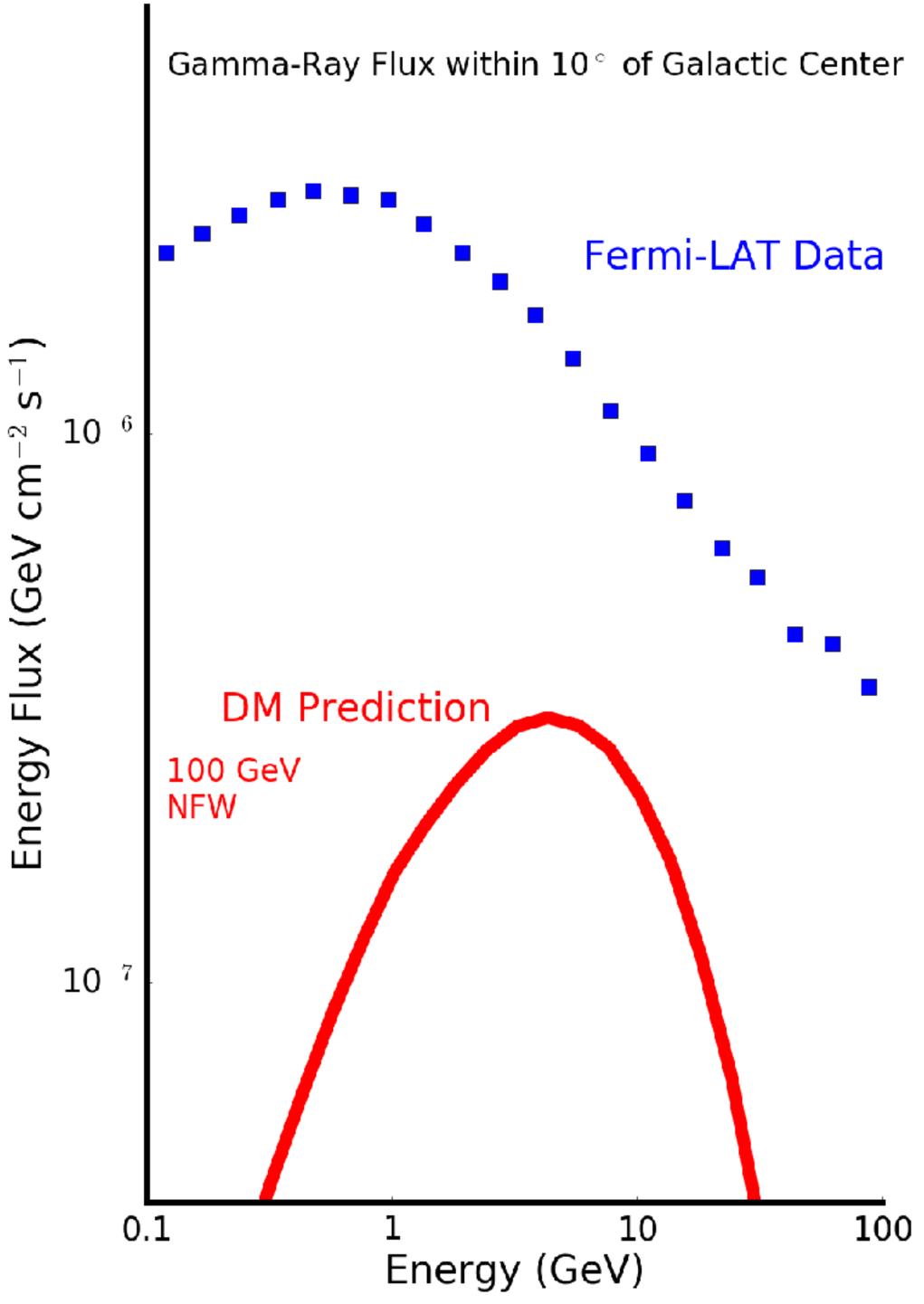
Dark Matter Mass (?)

Annihilation Final State (?)

Milky Way Star-Formation Rate (Galactic Dynamics)

Diffusion Constant in Galactic Center (Hydrodyanmics)

Activity of Supermassive Blackhole (?)



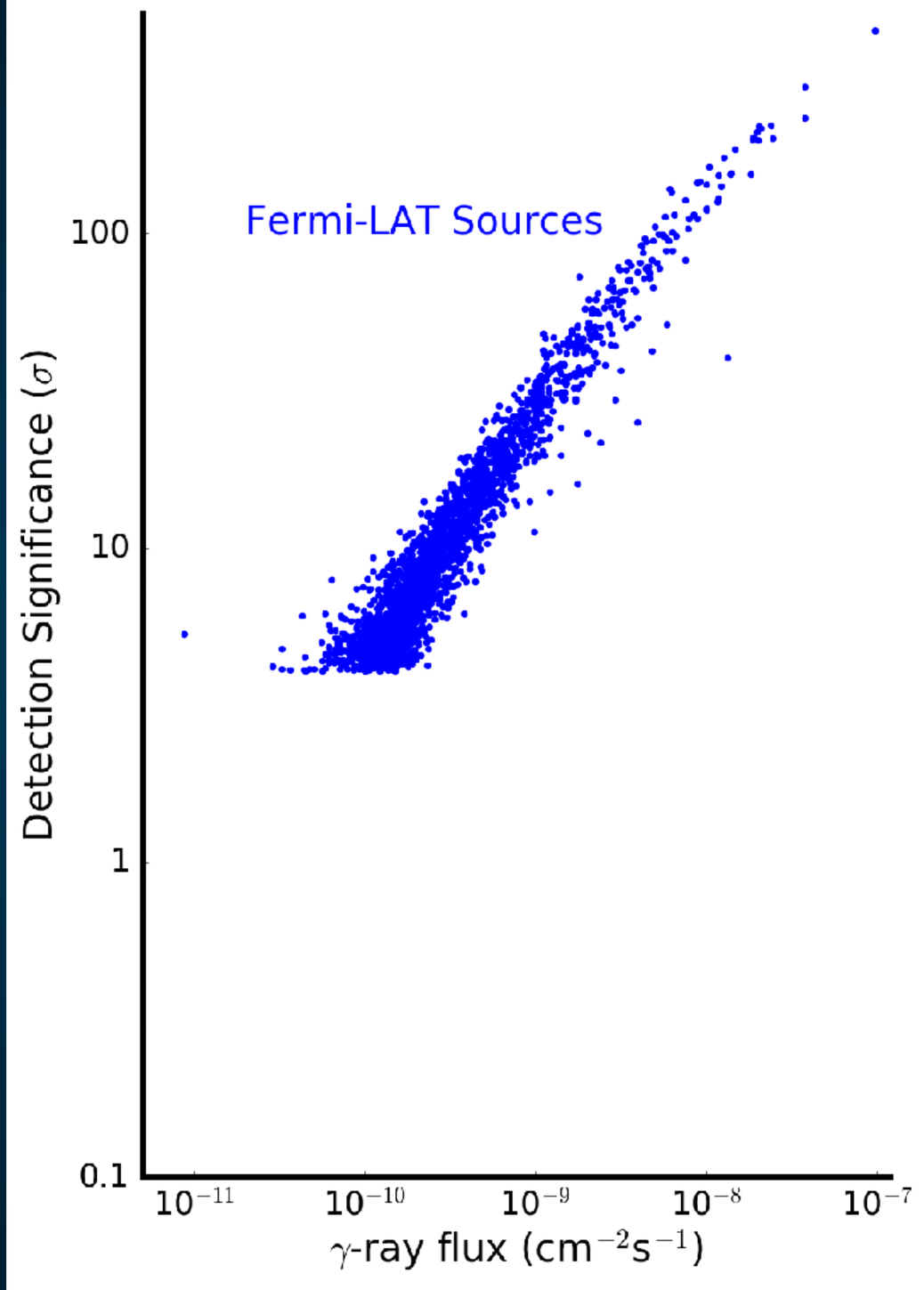
Thermal WIMPs and the Story of Tantalus

SMBH Accretion Efficiency (Magnetohydrodynamics)

Blazar Acceleration Mechanisms (Leptonic? Hadronic?)

Radio Galaxy Emission Models

Star-Formation Rates in Starburst Galaxies



Thermal WIMPs and the Story of Tantalus

SMBH Accretion Efficiency (Magnetohydrodynamics)

Blazar Acceleration Mechanisms (Leptonic? Hadronic?)

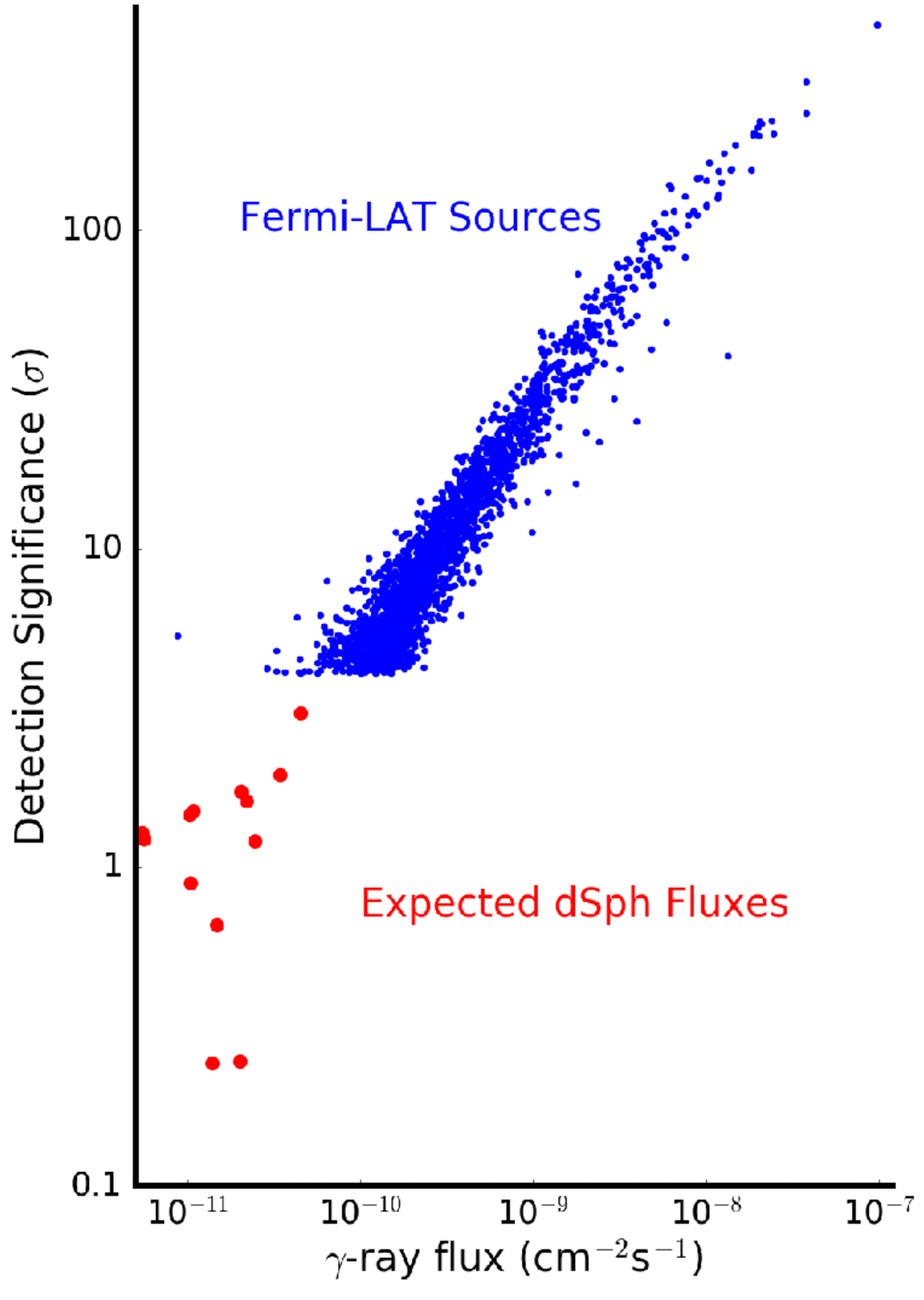
Radio Galaxy Emission Models

Star-Formation Rates in Starburst Galaxies

dSph Proximity

Substructure Models

Milky Way Merger History



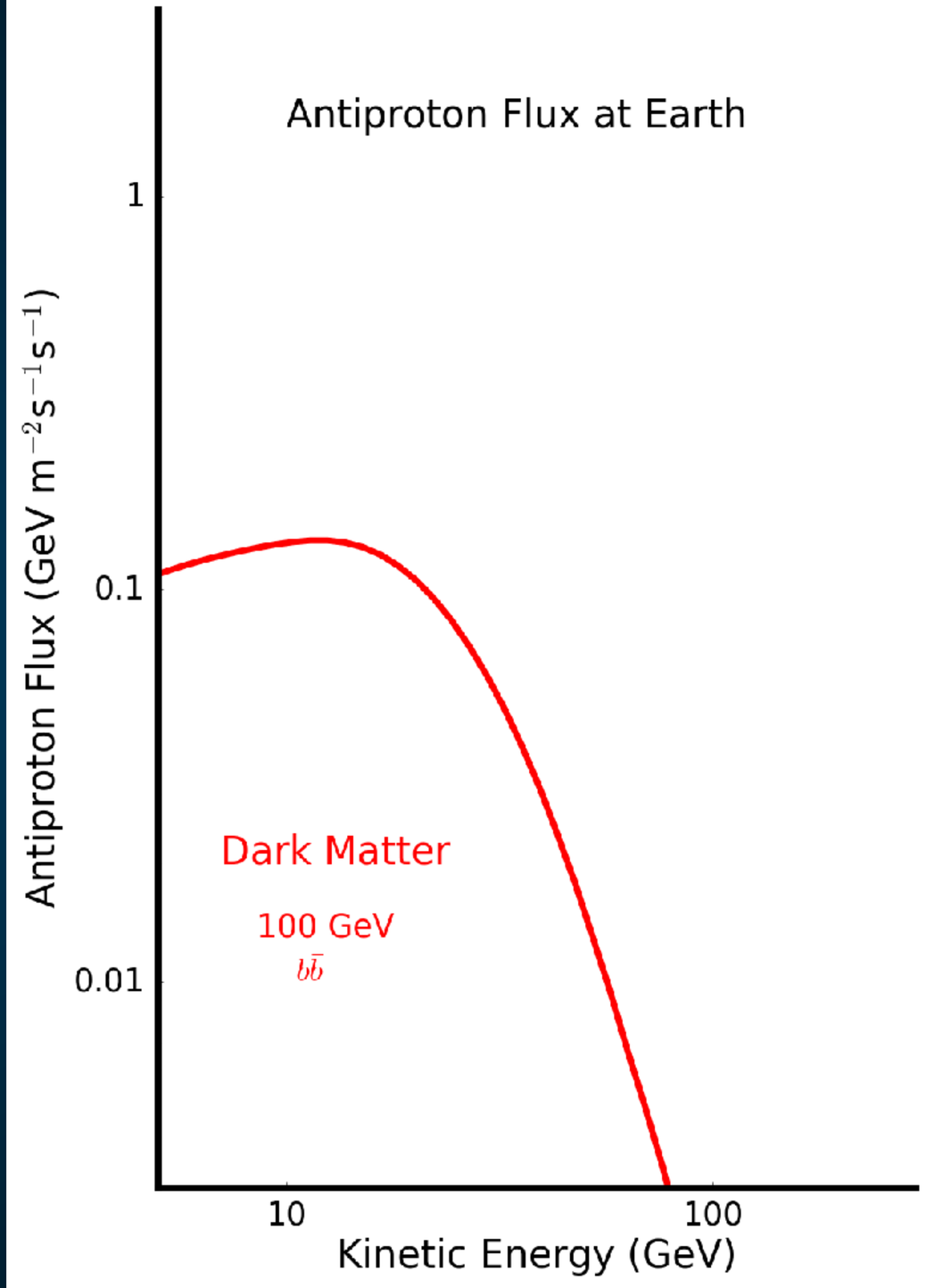
Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

Thermal Cross-Section (Early Universe)

Dark Matter Mass (?)

Convection of Annihilation Products from GC (Winds?)



Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

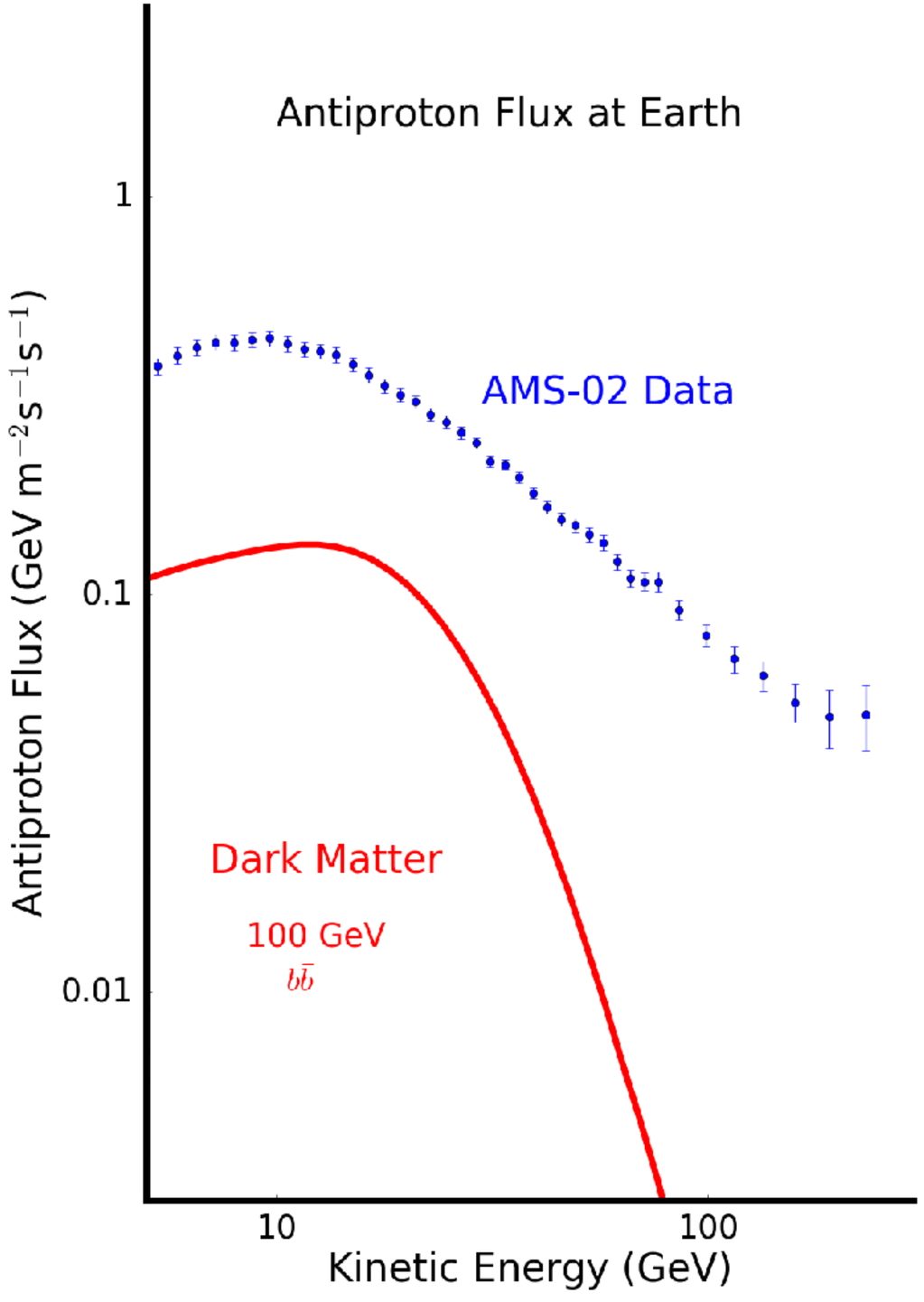
Thermal Cross-Section (Early Universe)

Hadronic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Local Gas Density

Local Supernova Rate



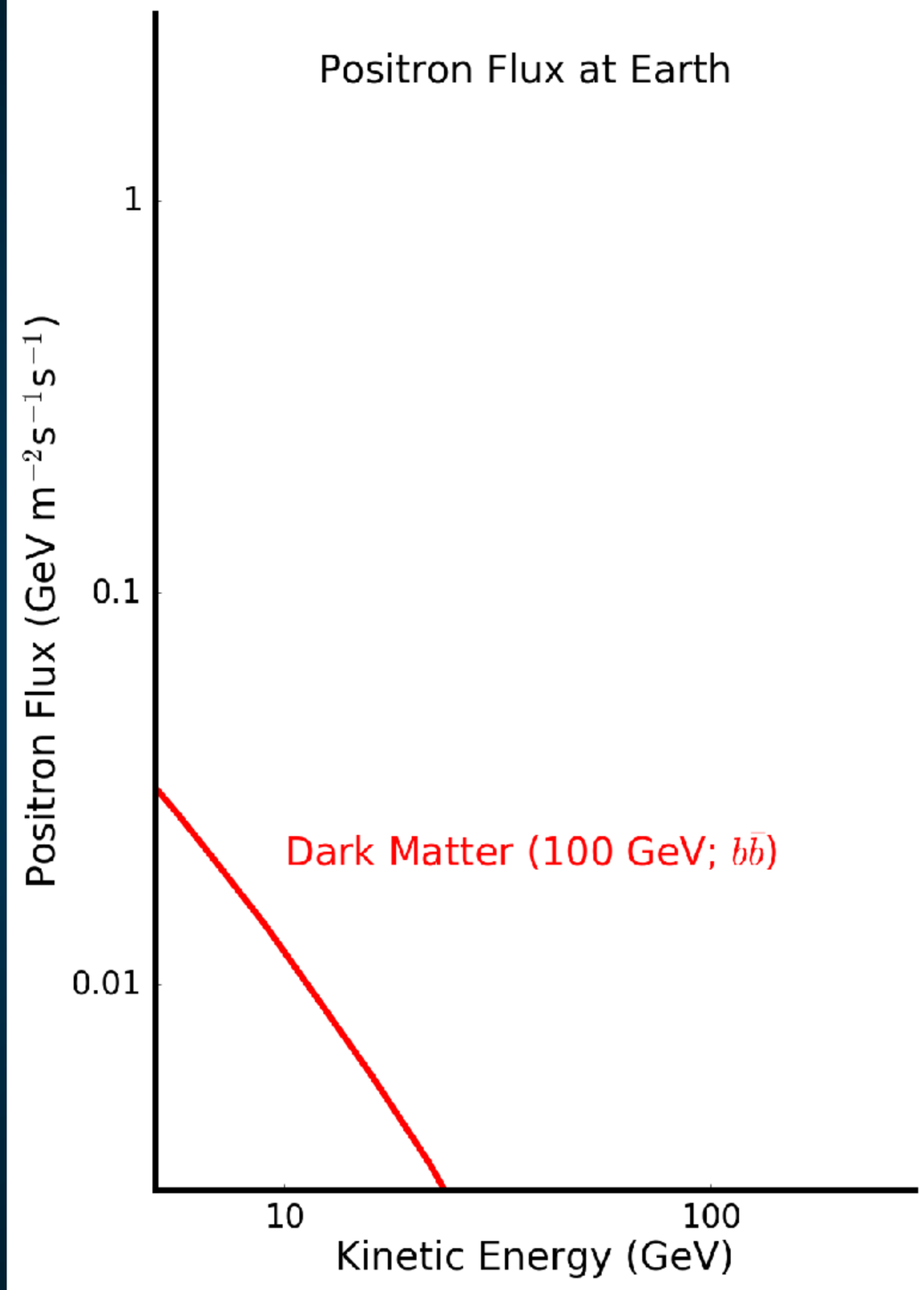
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Local Dark Matter Density

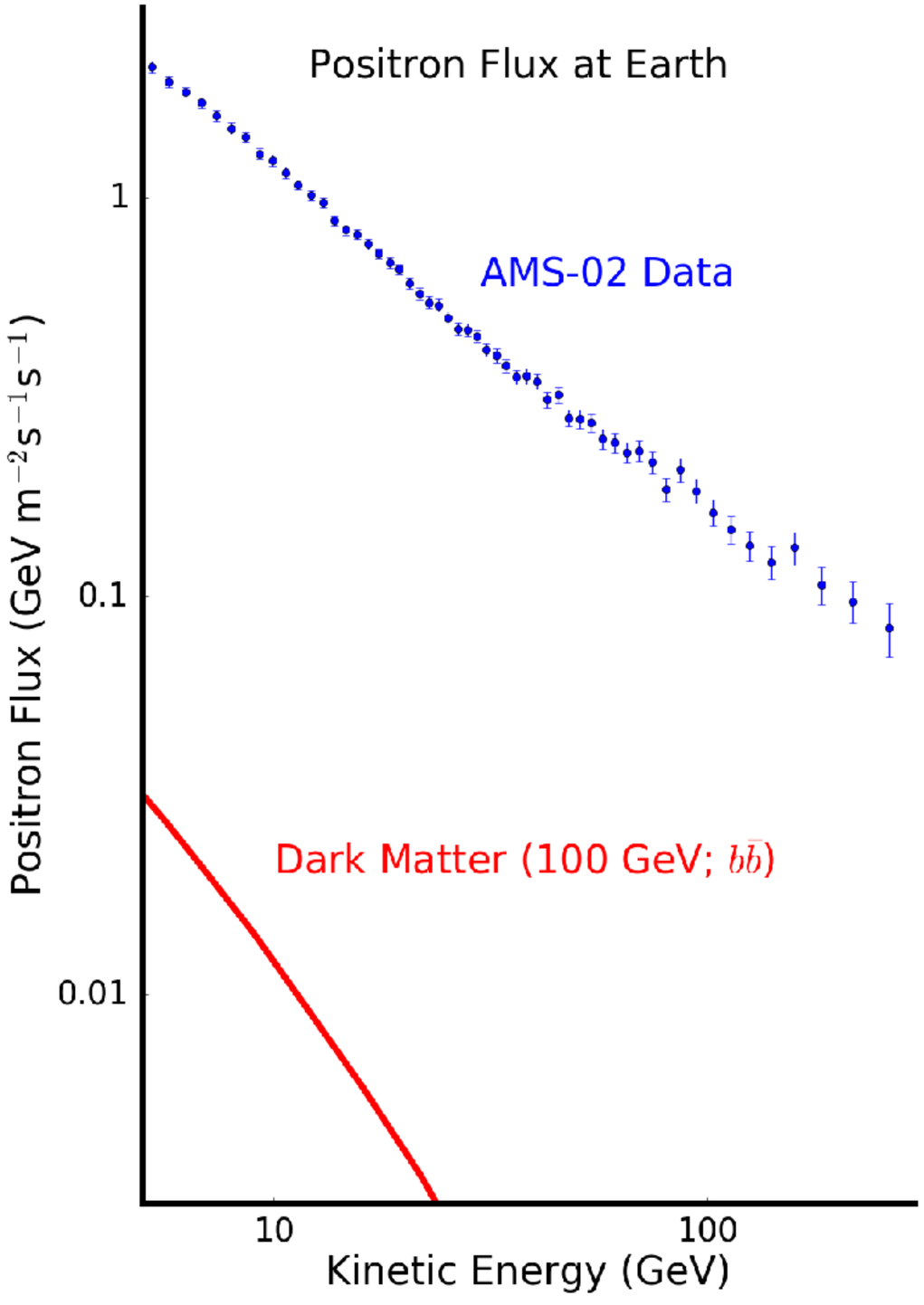
Thermal Cross-Section (Early Universe)

Leptonic Component of Dark Matter Final State

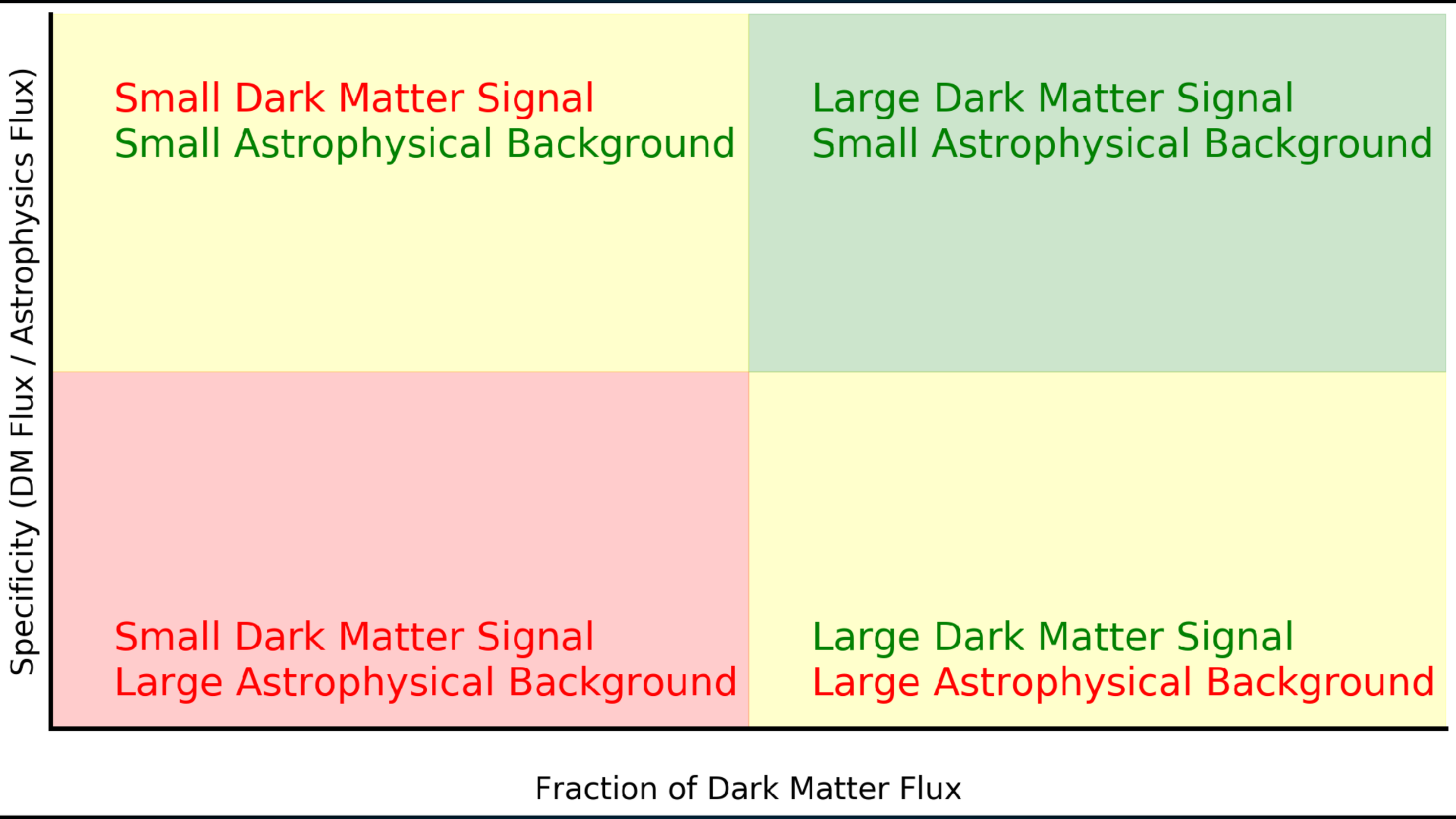
Convection of Annihilation Products from GC (Winds?)

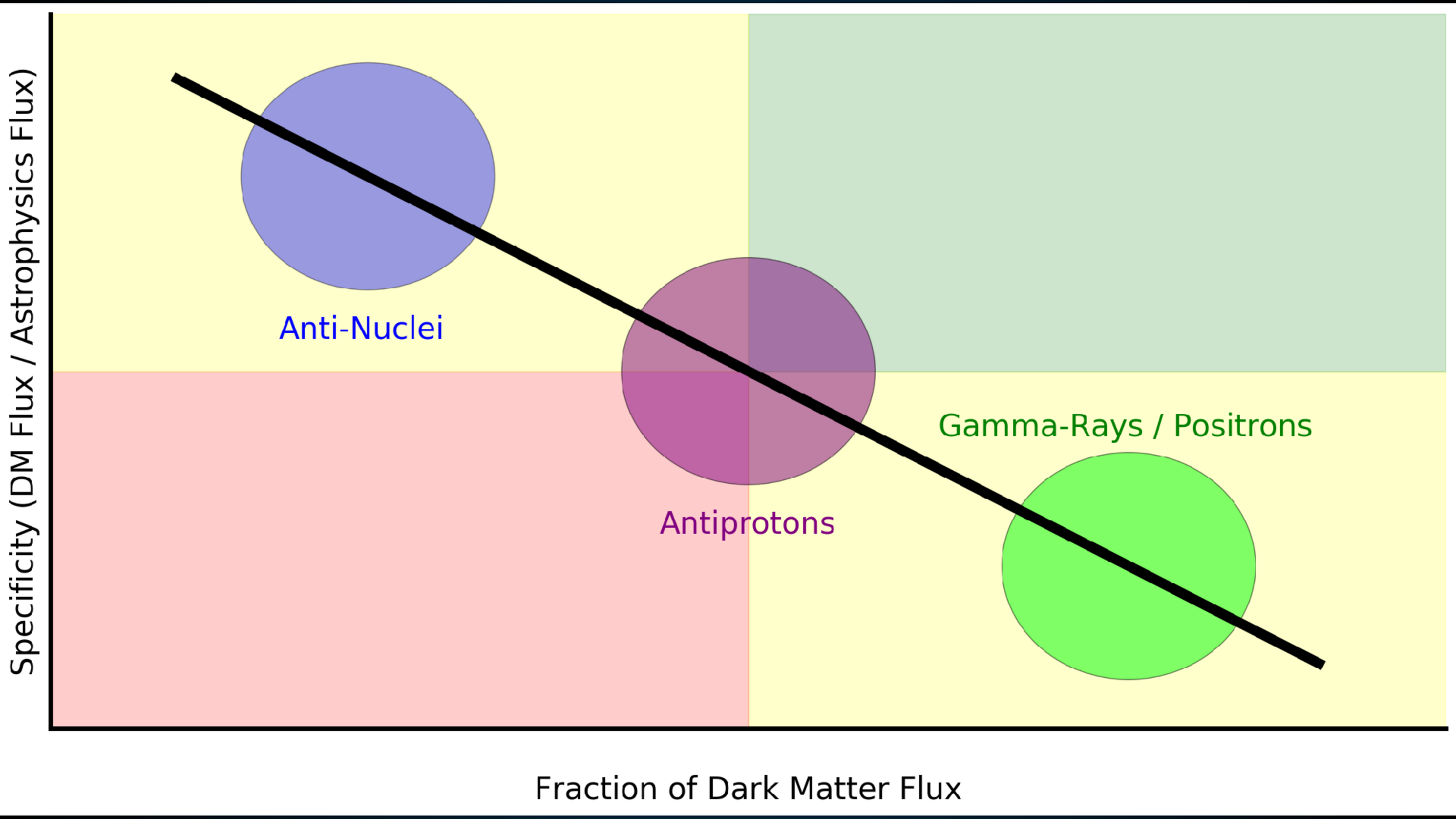
Pulsar Birth Rate

e^+e^- Acceleration Efficiency in Pulsar Magnetospheres






Small Dark Matter Signal
Small Astrophysical Background
Large Dark Matter Signal
Small Astrophysical Background
Small Dark Matter Signal
Large Astrophysical Background
Large Dark Matter Signal
Large Astrophysical Background
Specificity (DM Flux / Astrophysics Flux)
Fraction of Dark Matter Flux


Specificity (DM Flux / Astrophysics Flux)
Anti-Nuclei
Antiprotons
Gamma-Rays / Positrons
Fraction of Dark Matter Flux

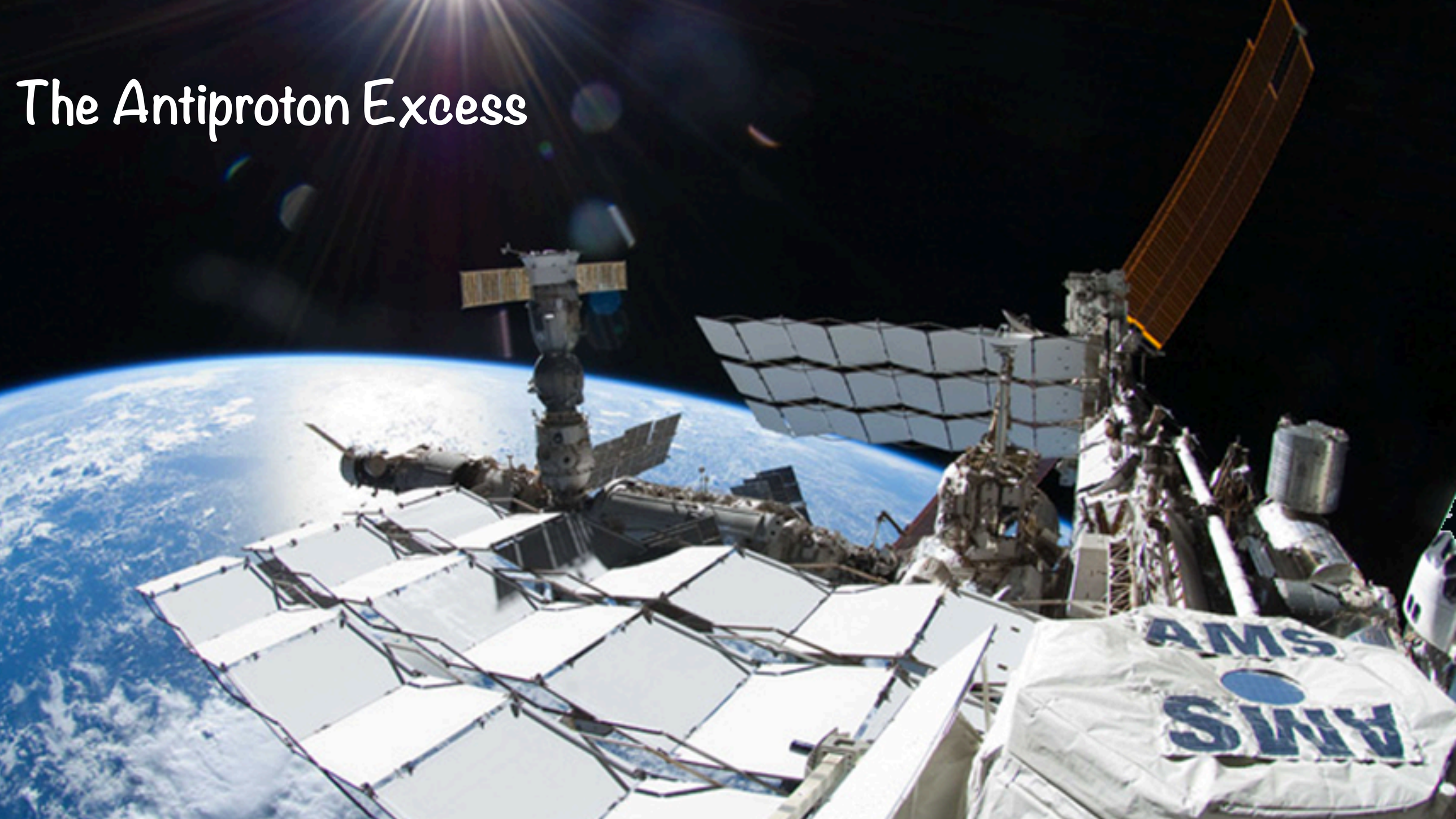
Thermal WIMPs and the Story of Tantalus



Thermal WIMPs and the Story of Tantalus



The Antiproton Excess



The Antiproton Excess

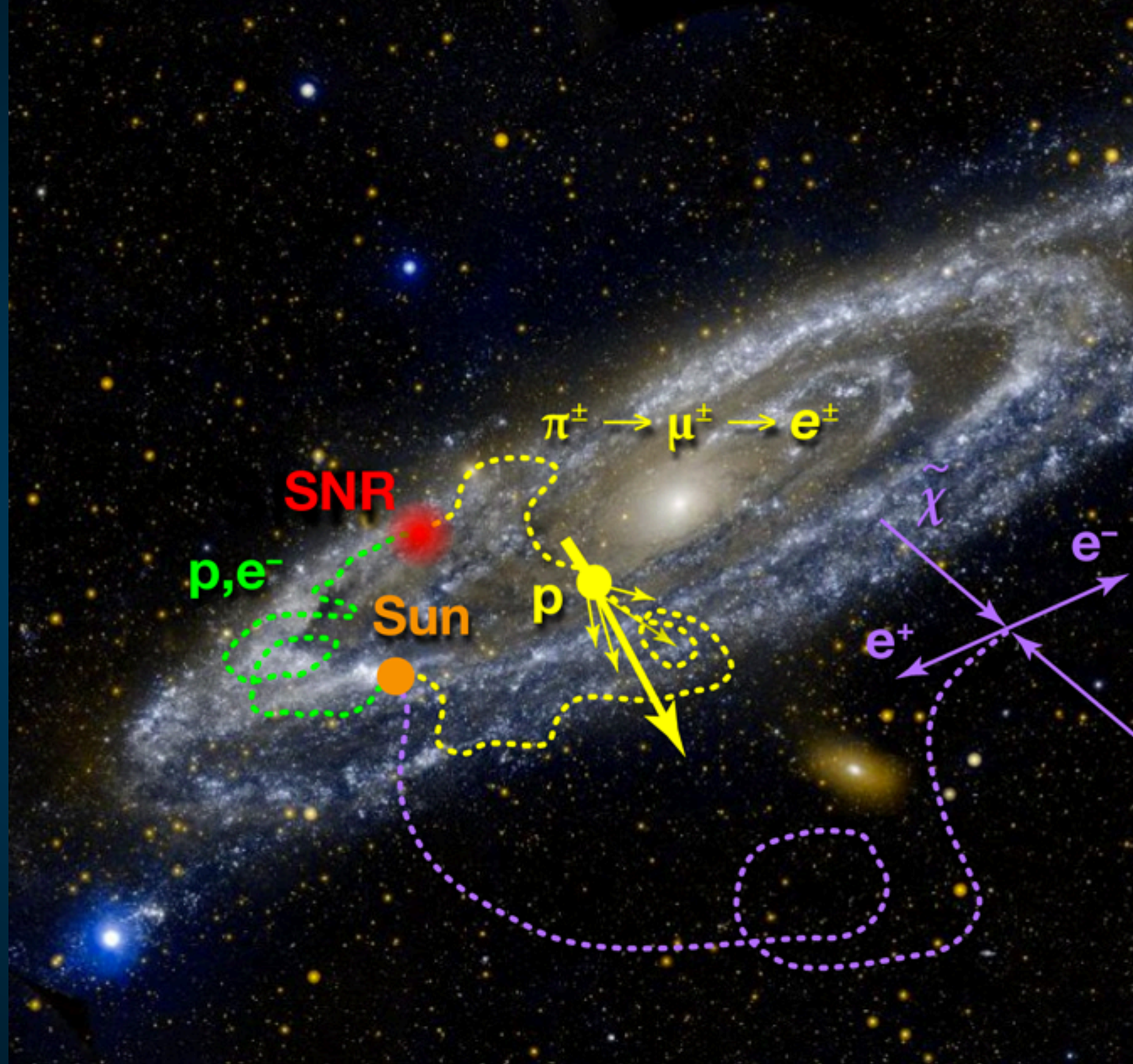
Investigate the Antiproton Fraction!

$$\frac{\phi_{\bar{p}}}{\phi_p}$$

Two Changes:

Ratio is much smaller (don't need to add antiprotons into denominator).

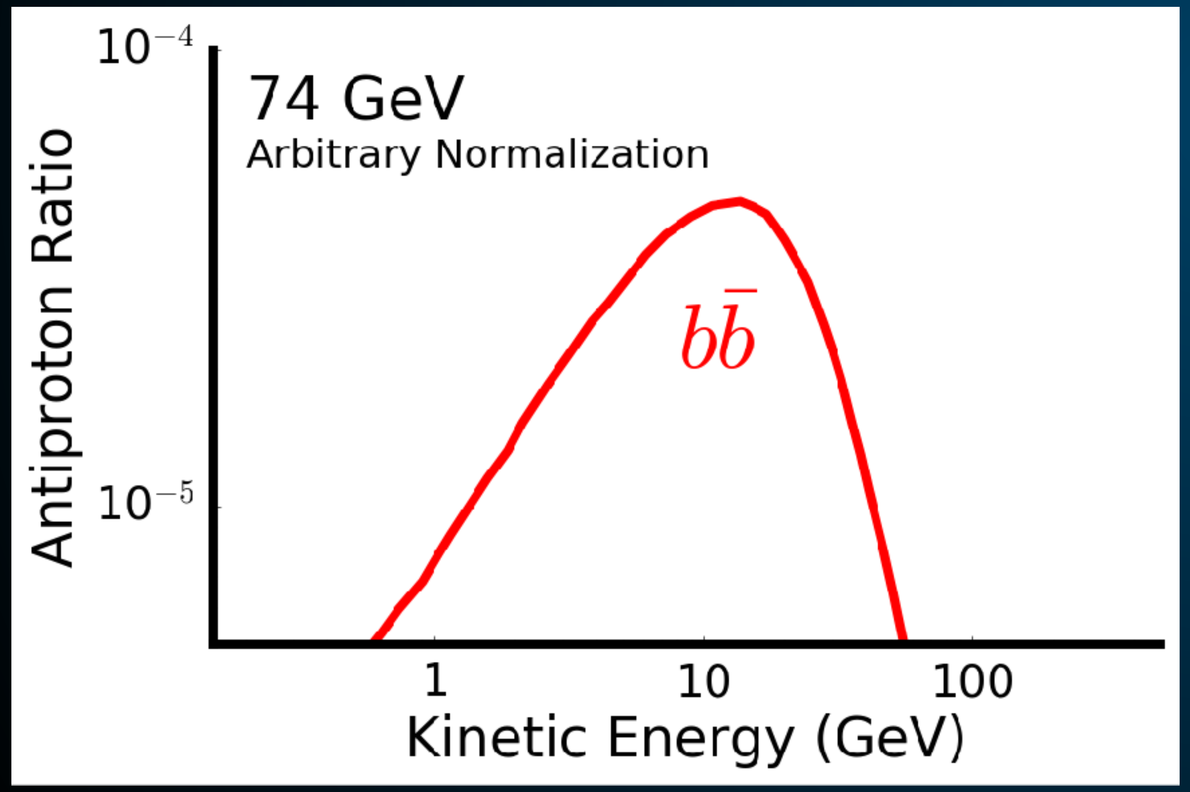
Hadronic Energy losses are slower (sensitive to antiproton production throughout the Galaxy)

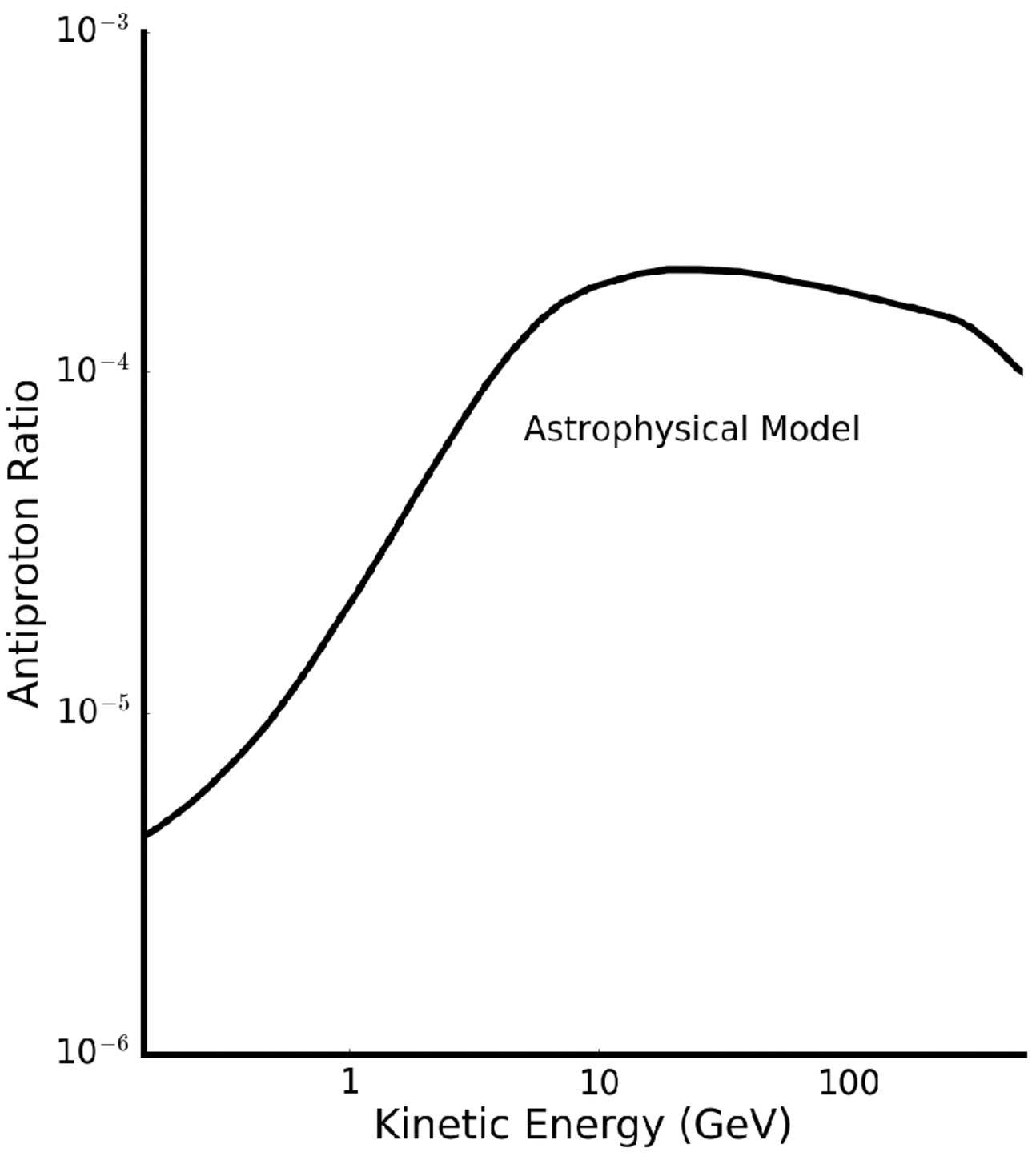


The Antiproton Excess

Astrophysics - Smooth Profile

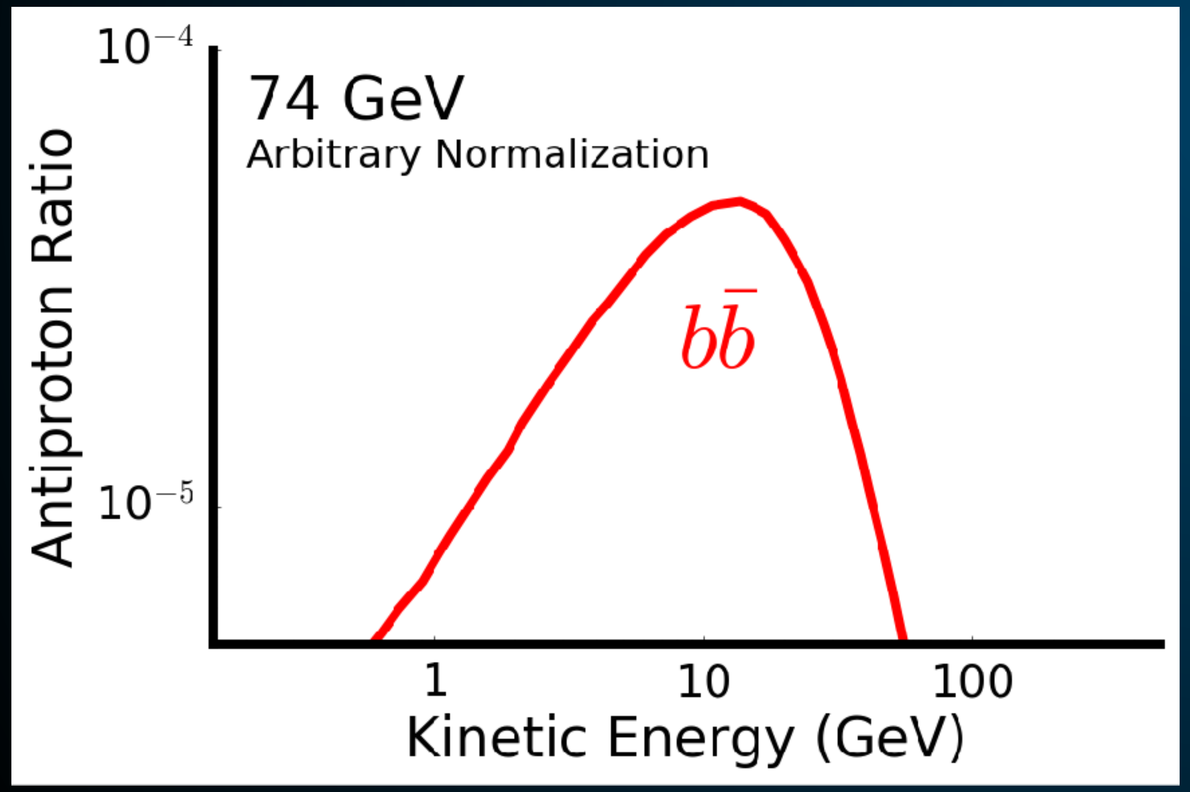
Dark Matter - Sharp Bump!



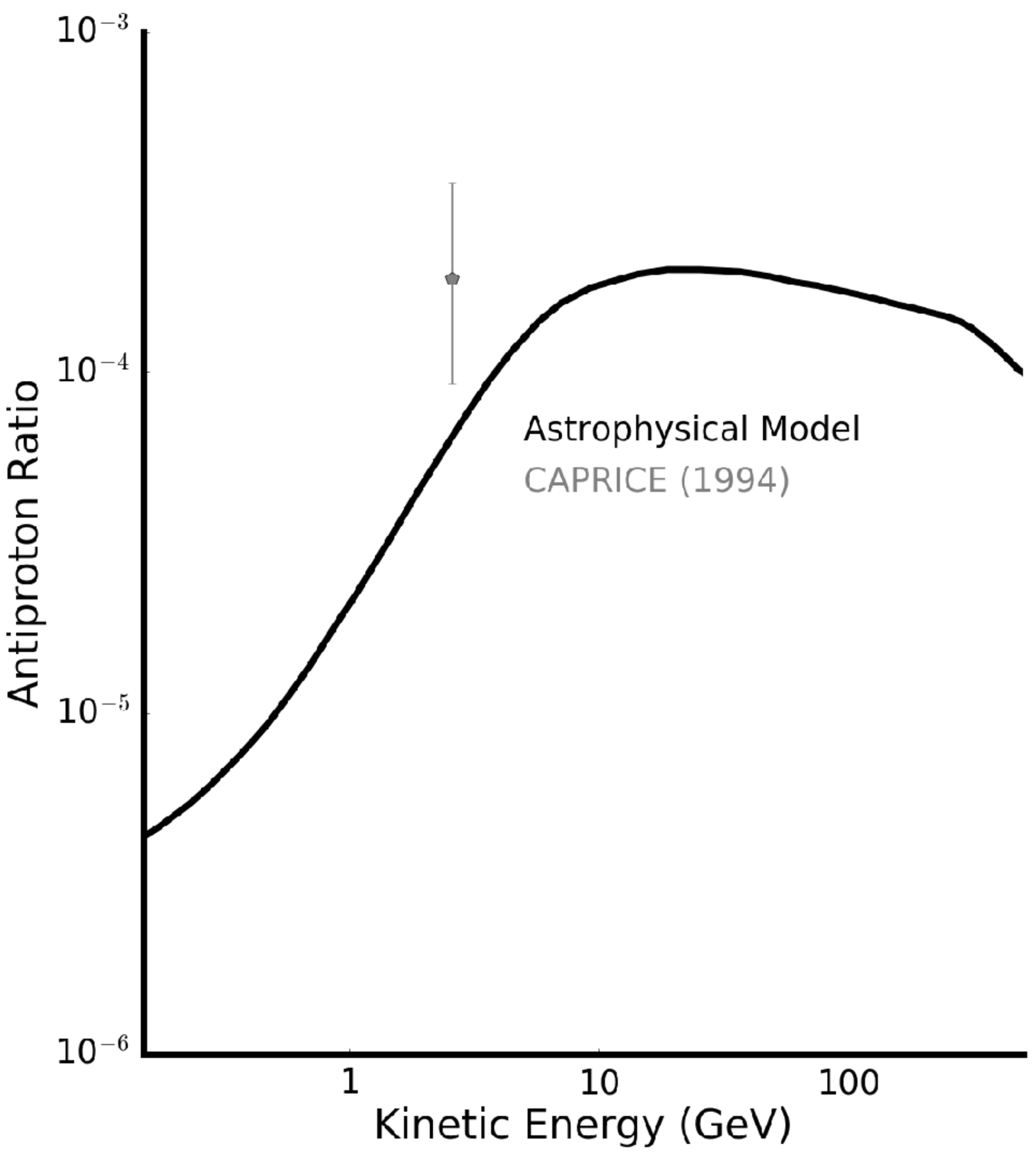


The Antiproton Excess

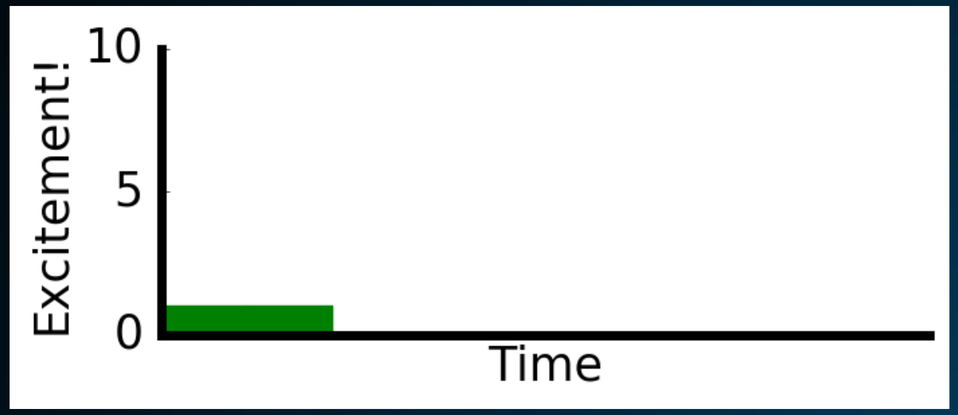


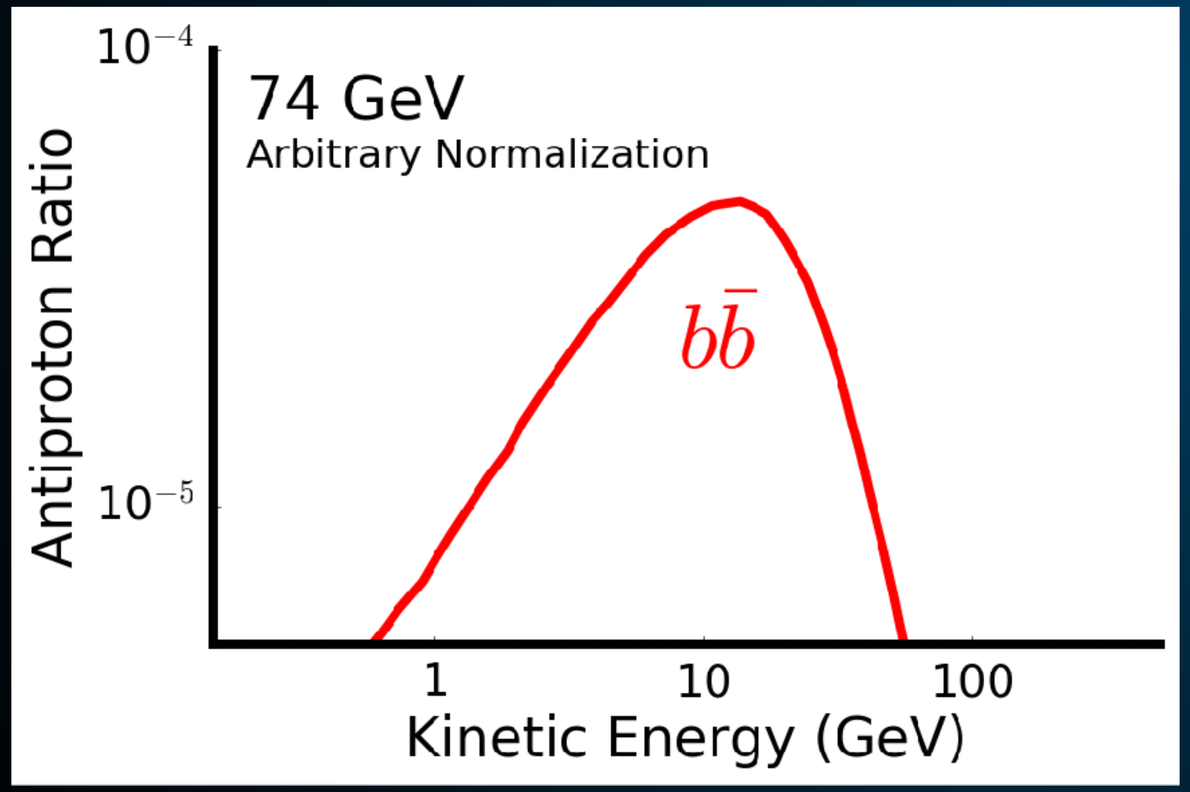


(Not an exhaustive list of observations)

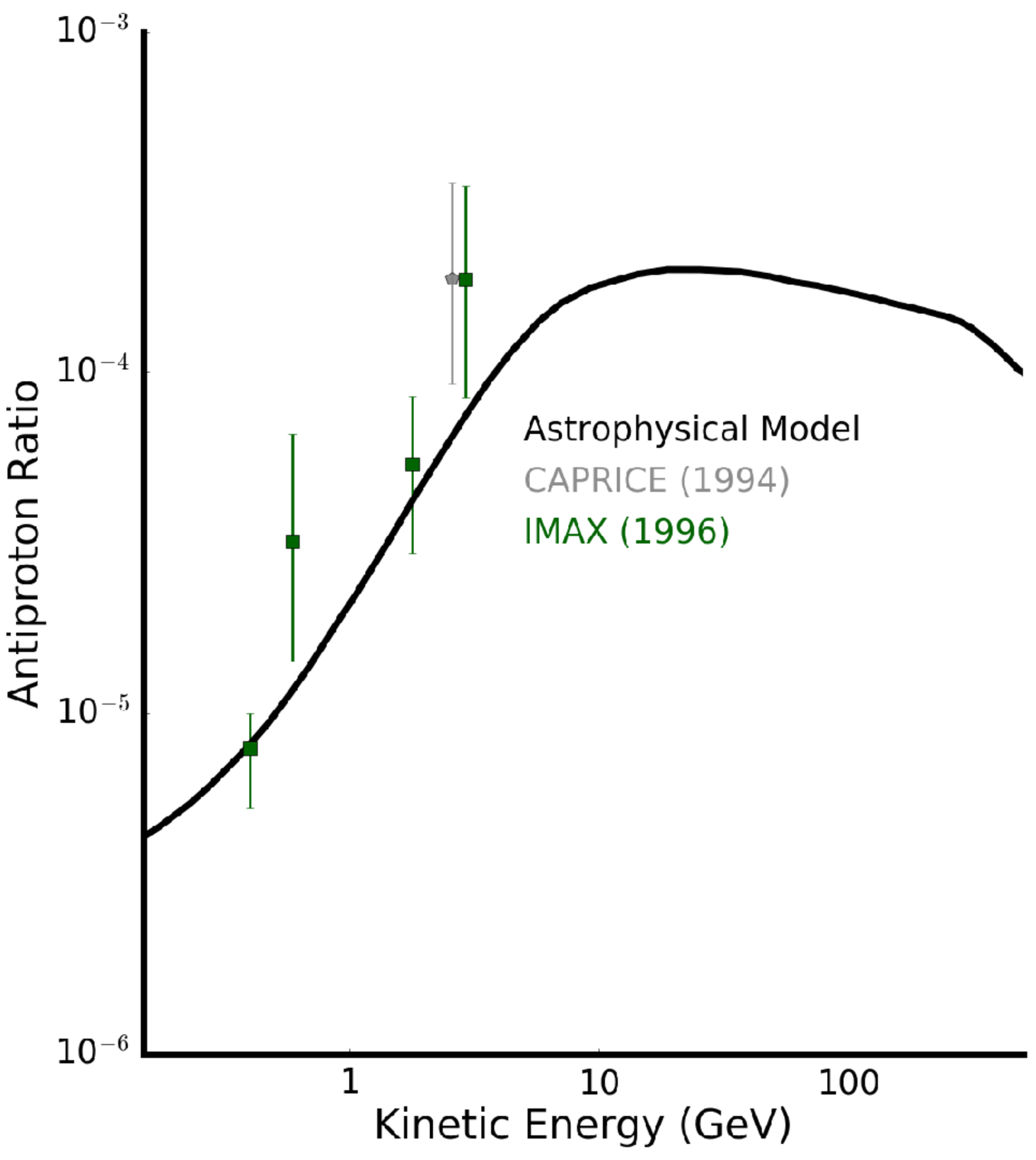


The Antiproton Excess

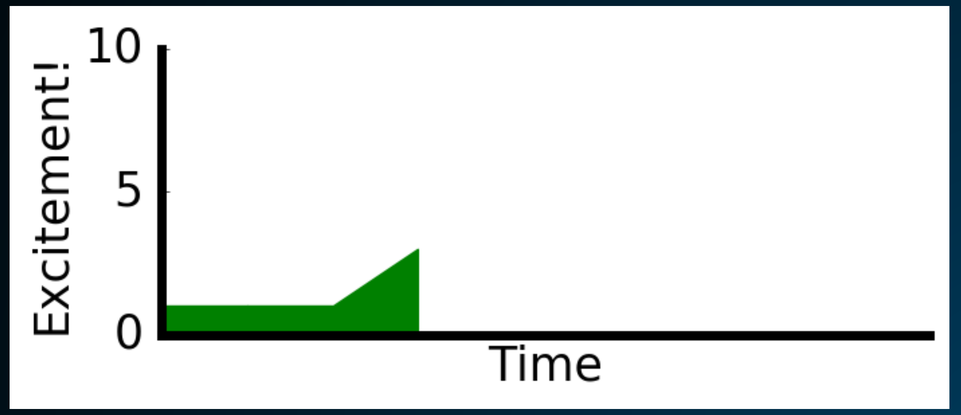


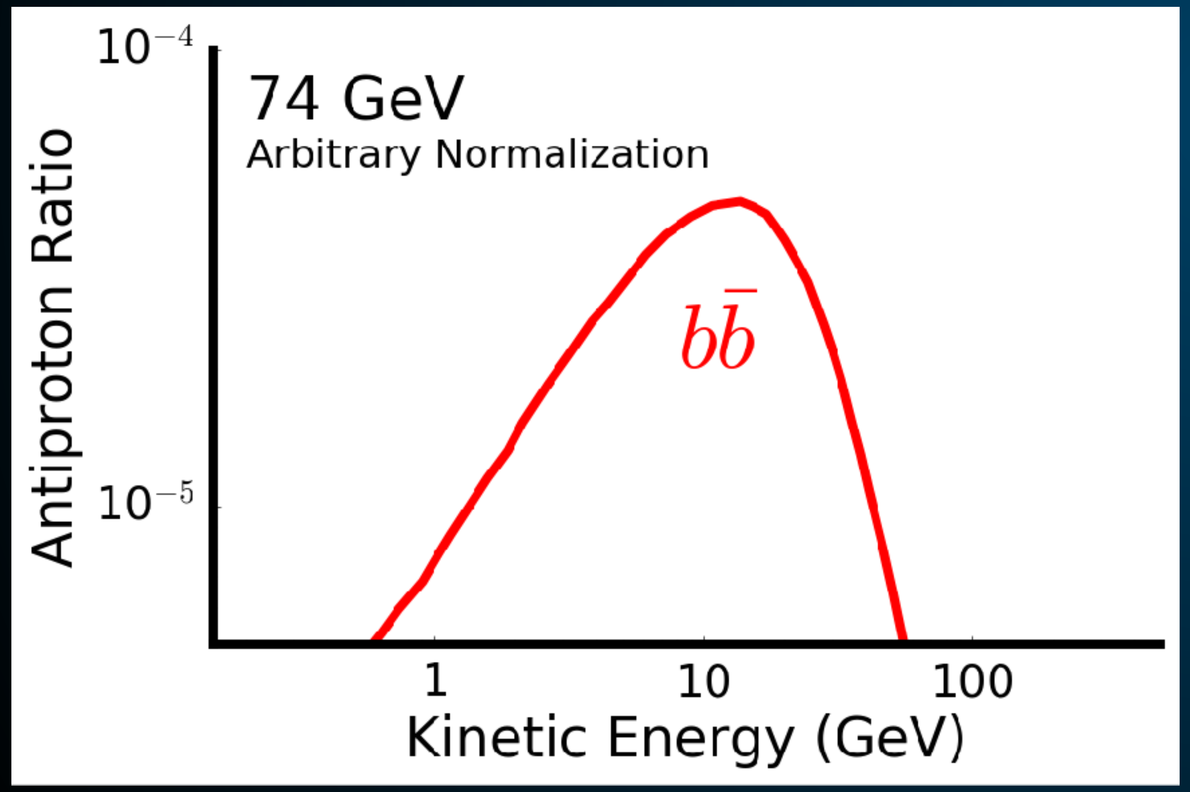


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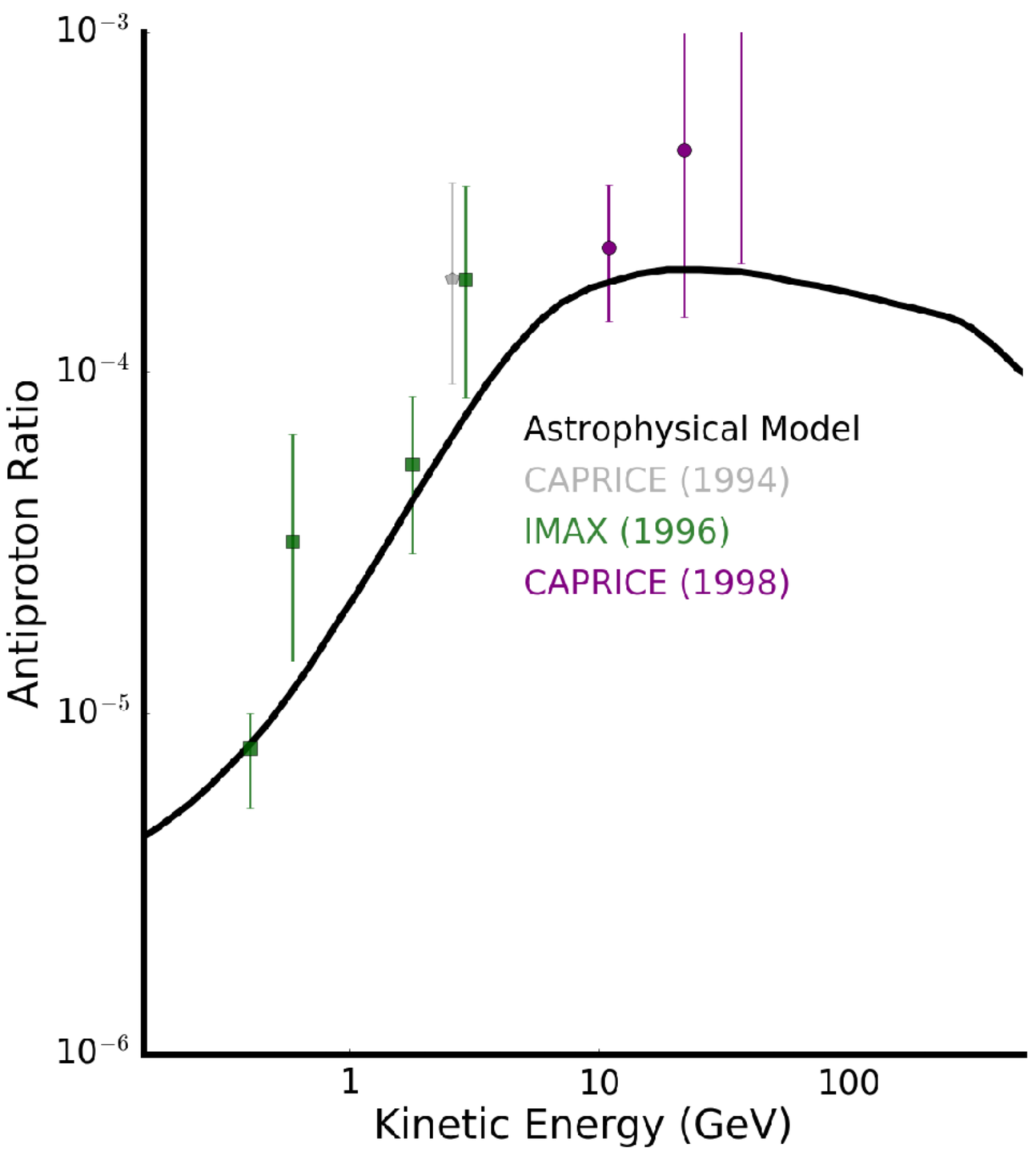


The Antiproton Excess

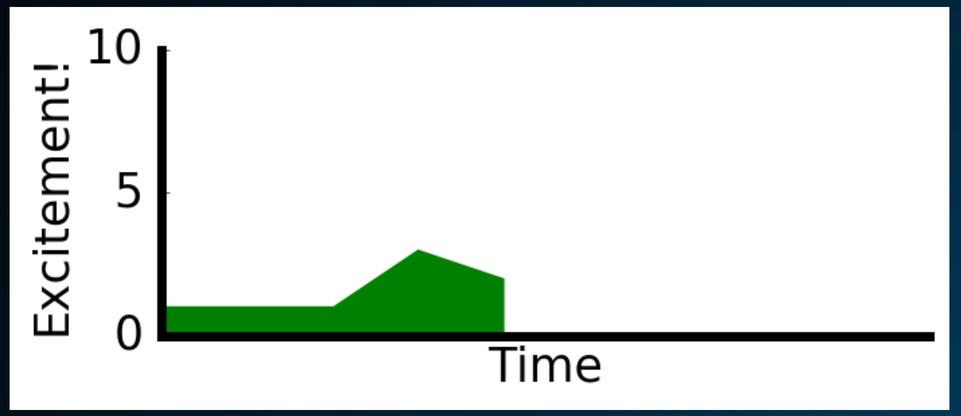


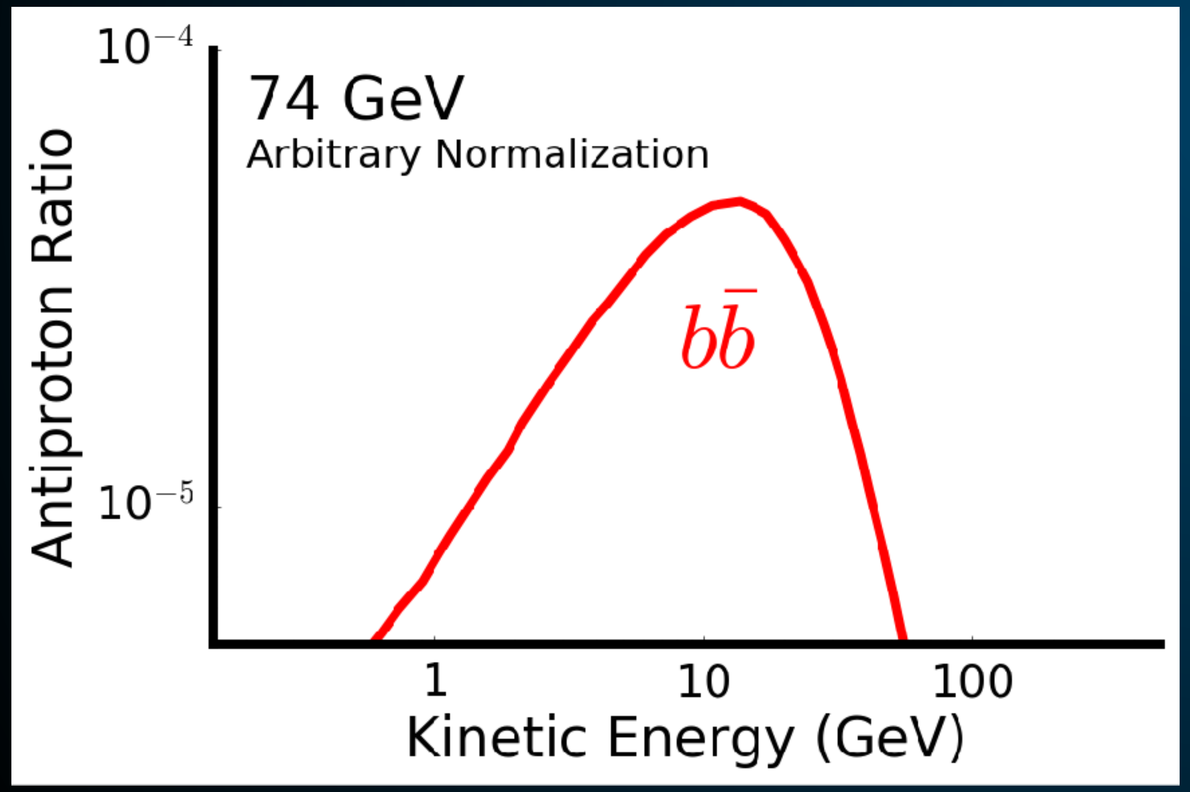


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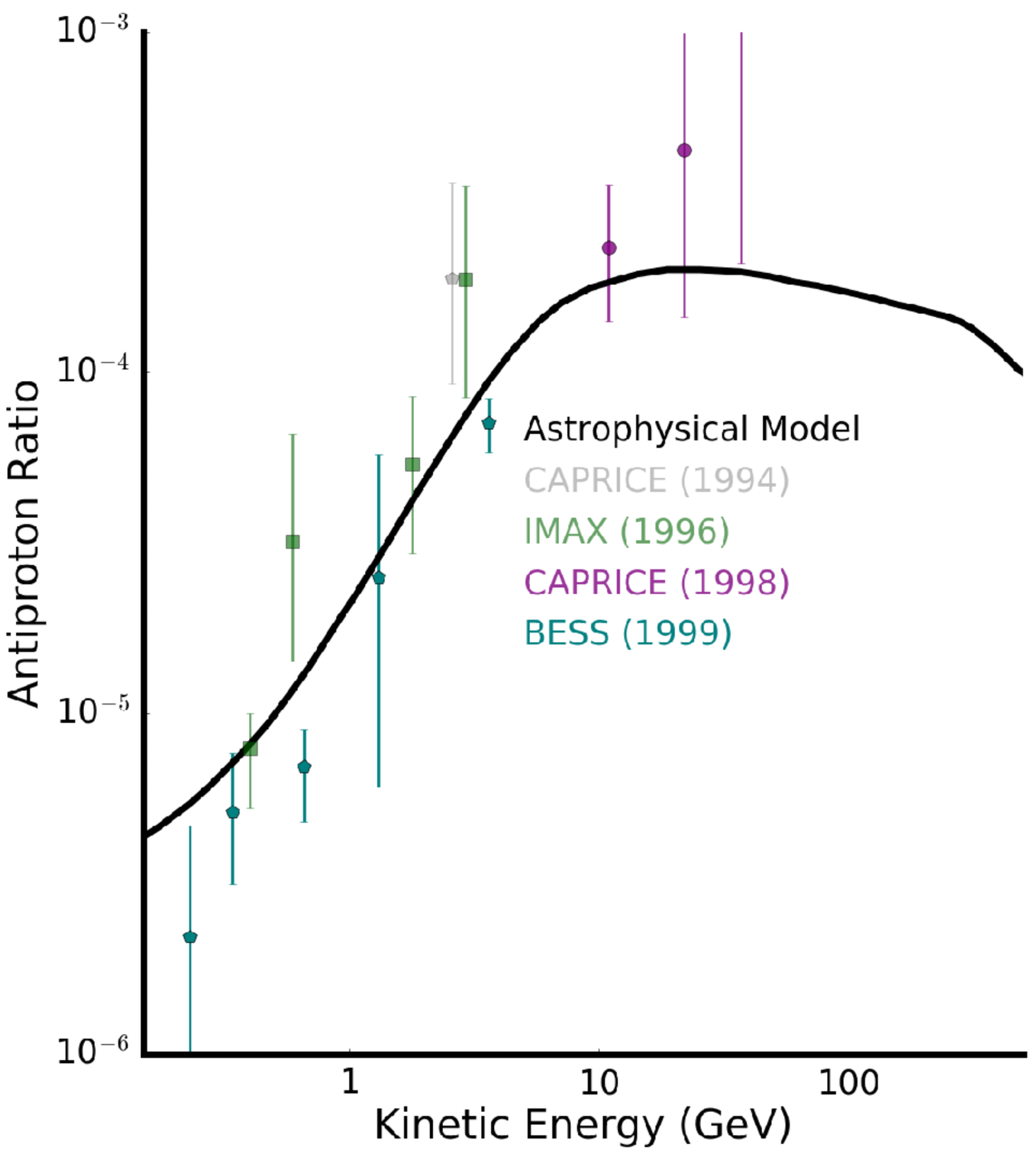


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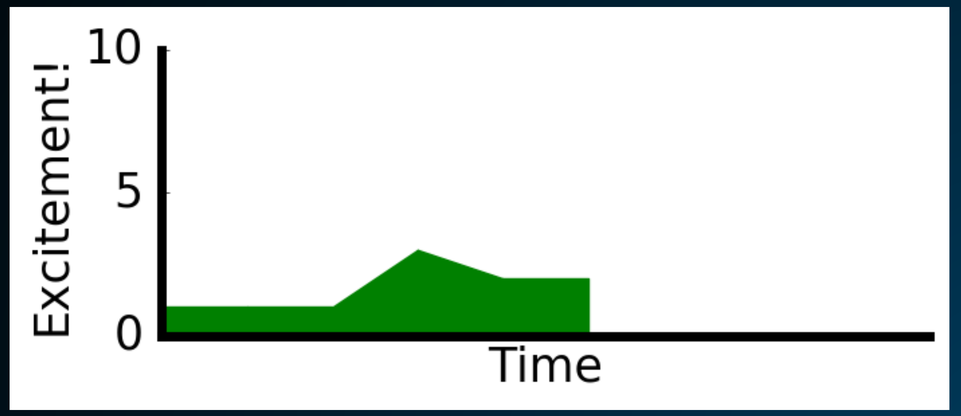


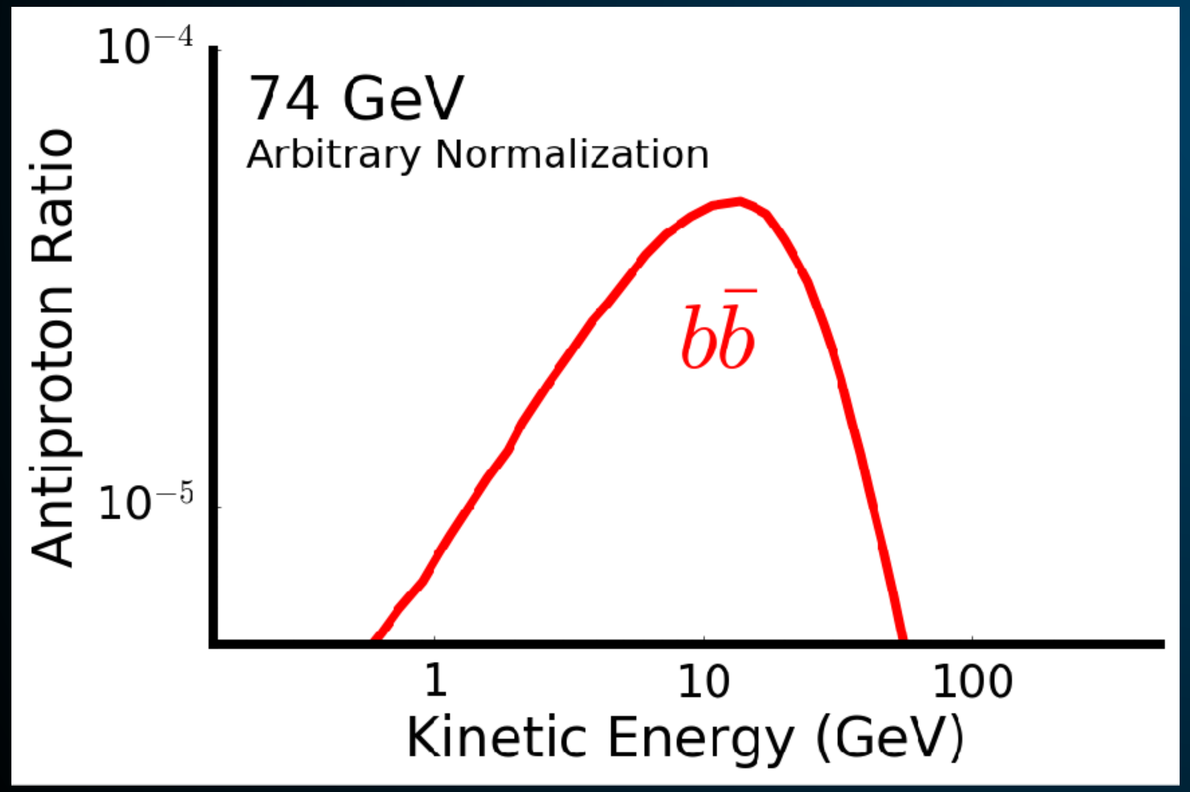


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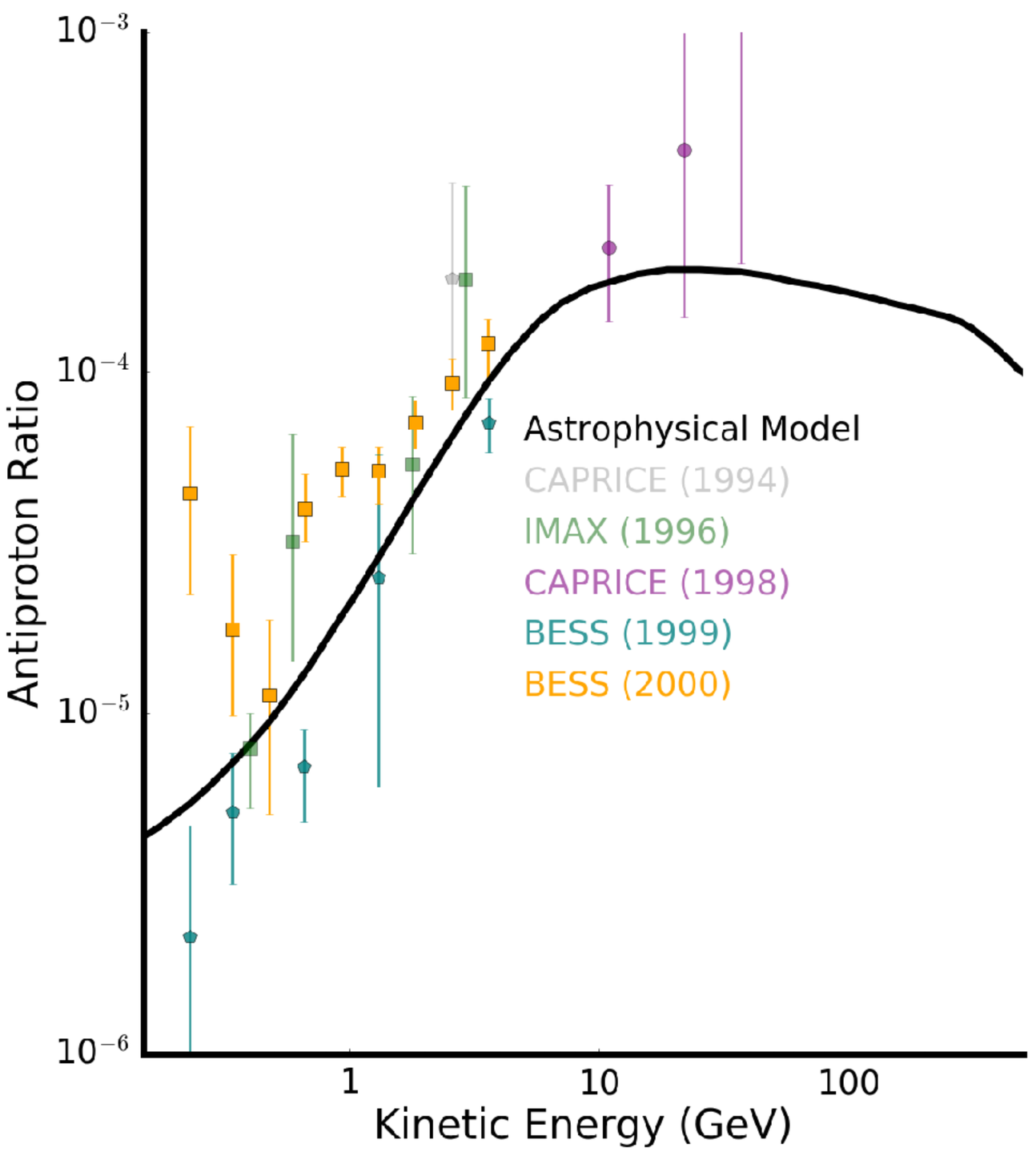


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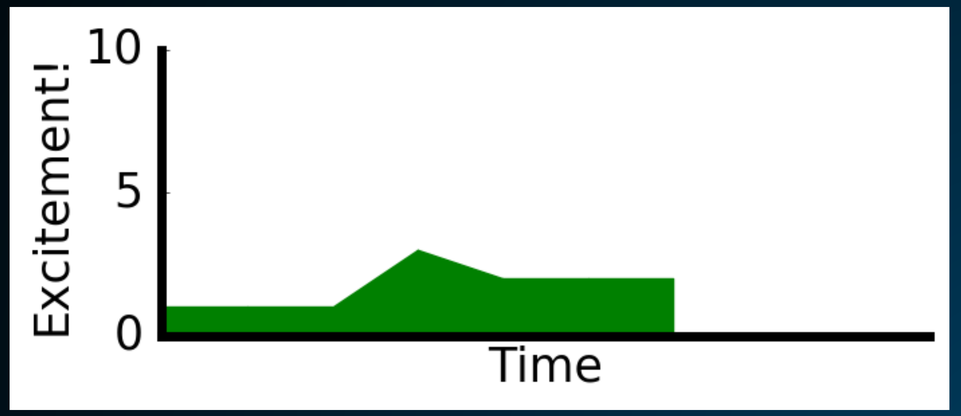


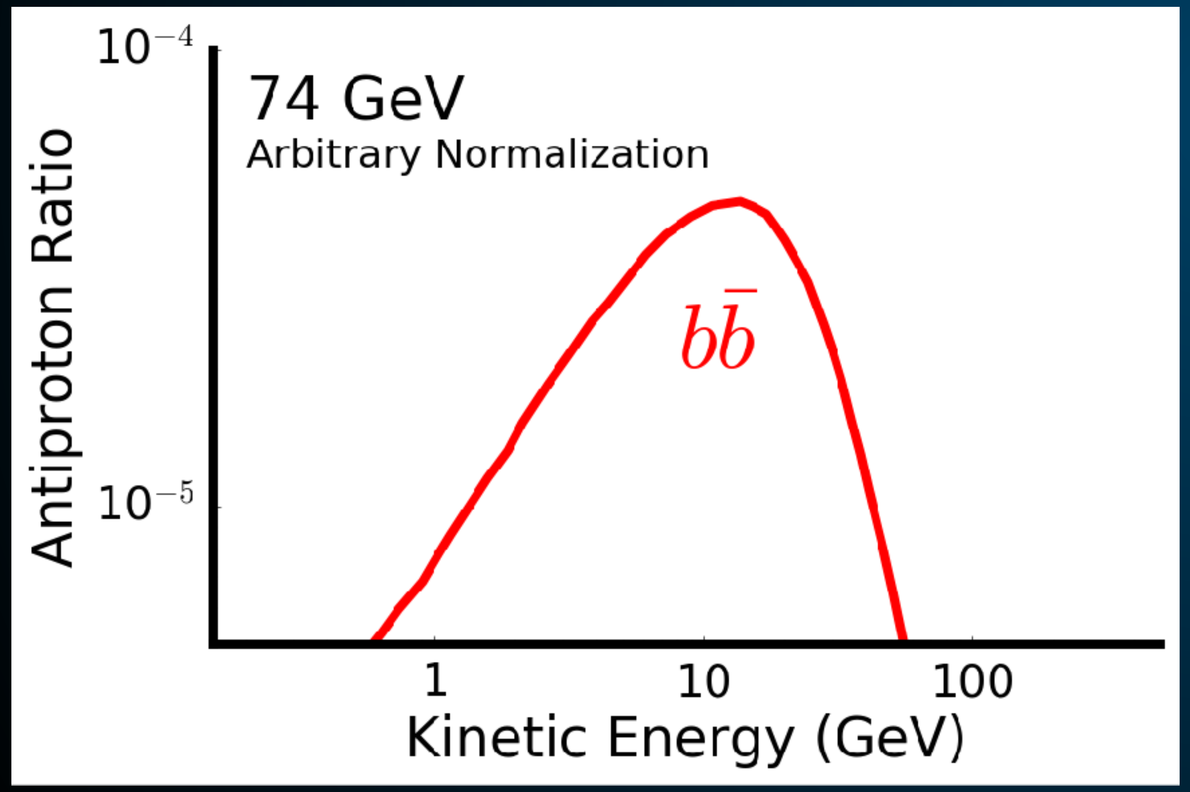


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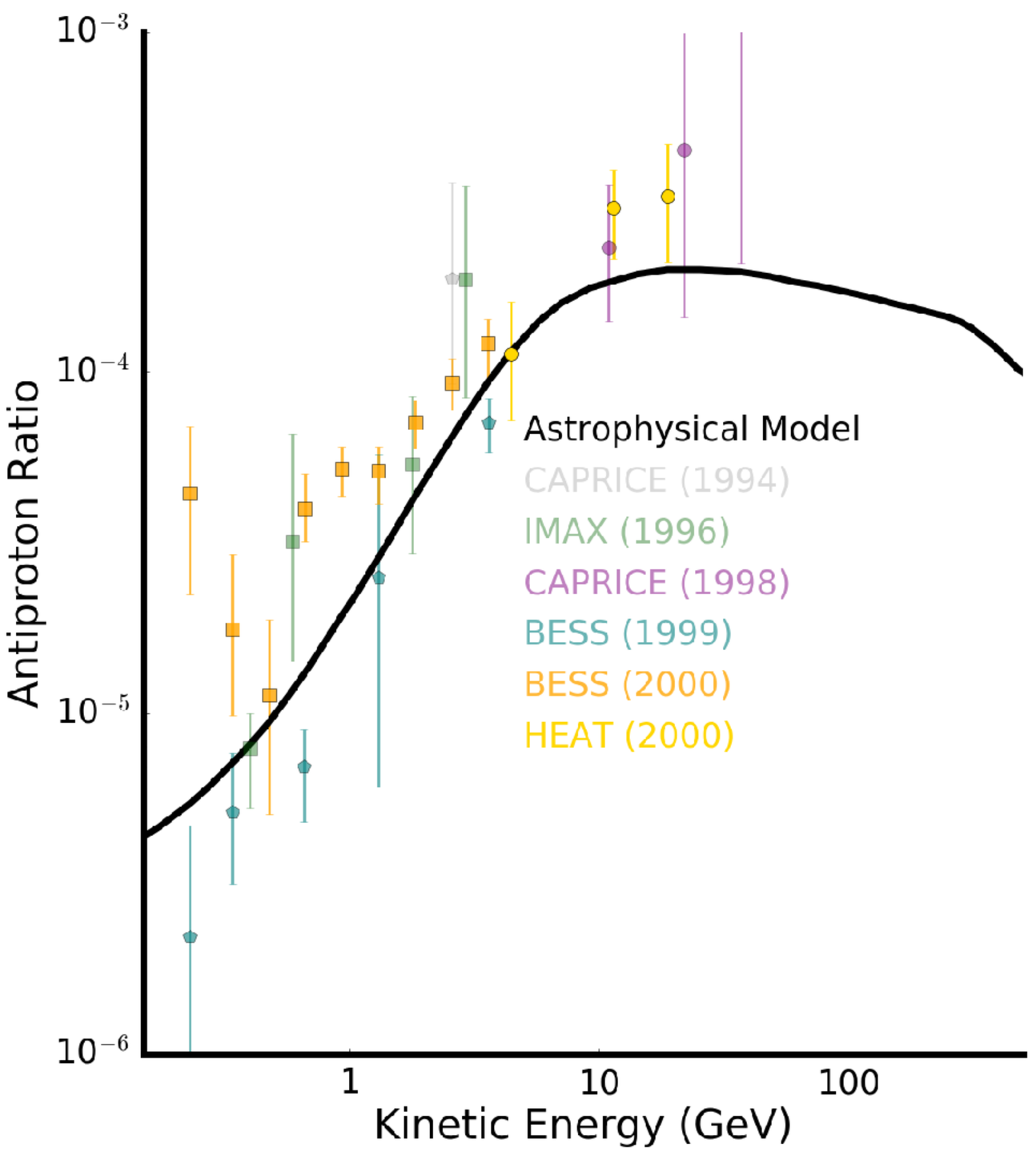


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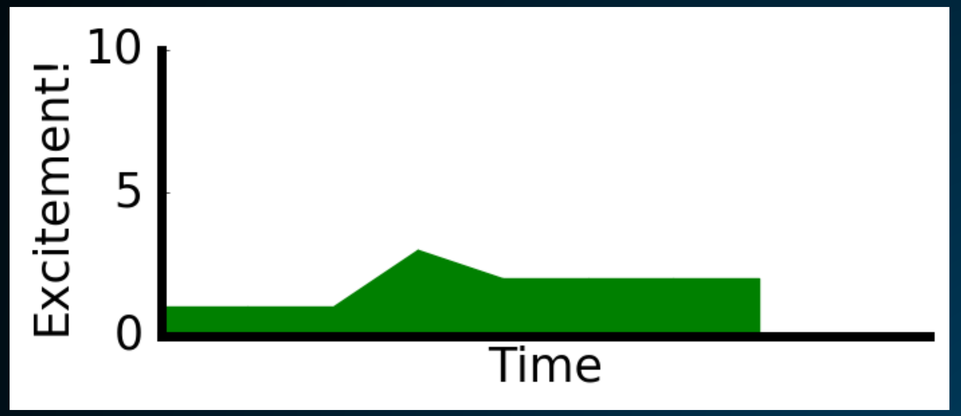


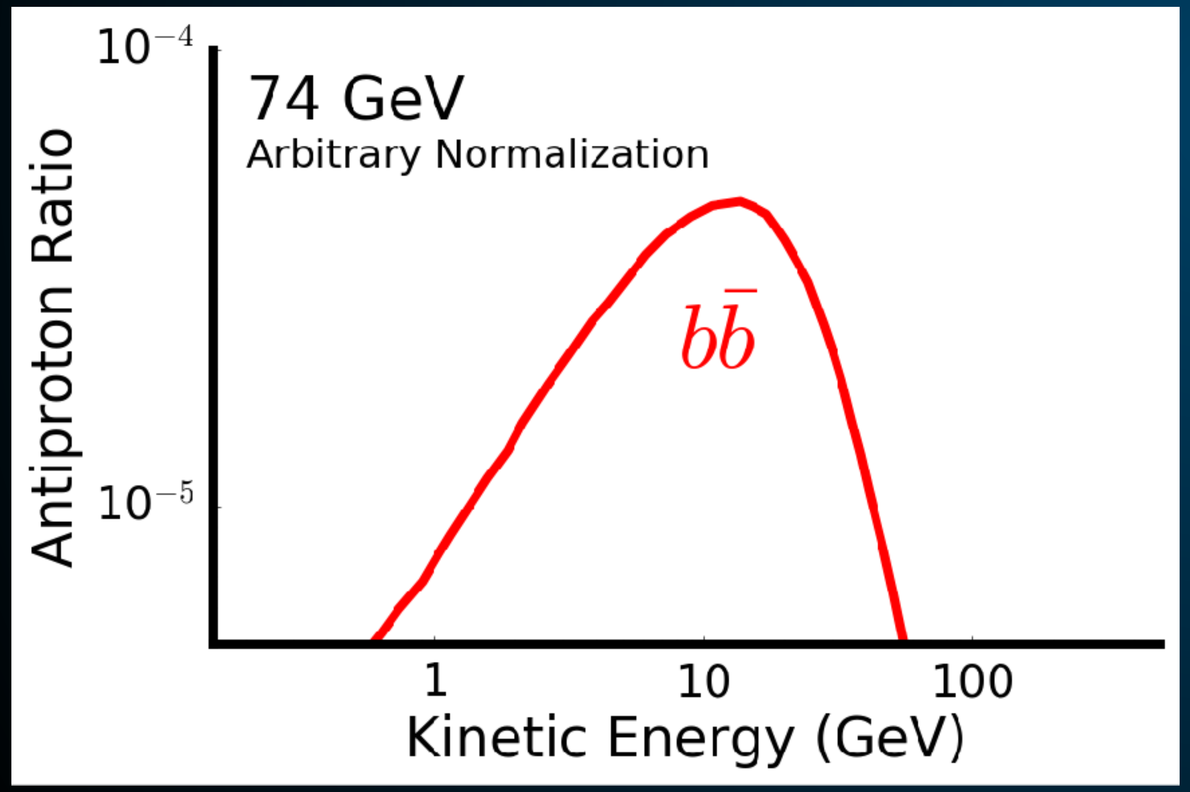


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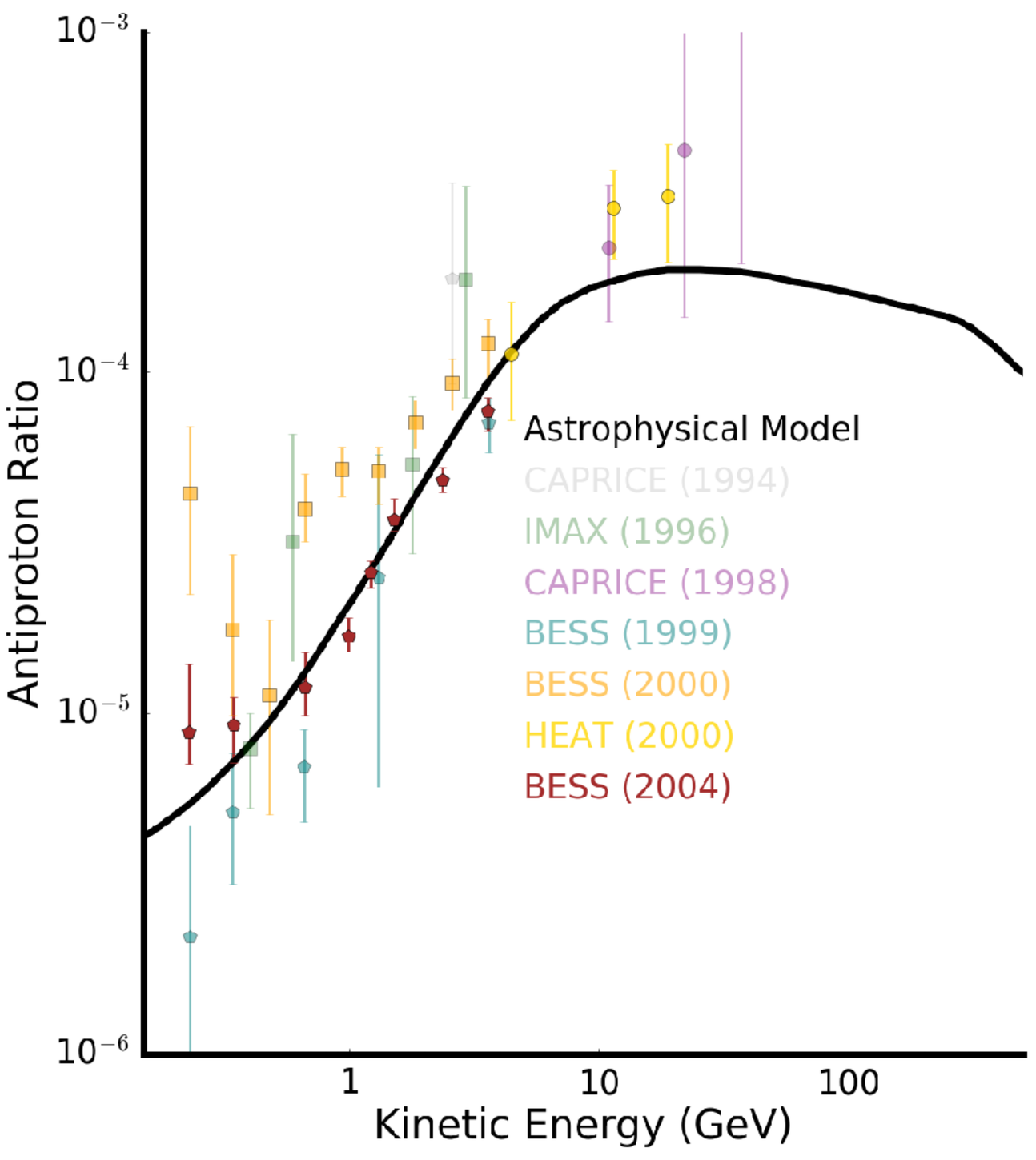


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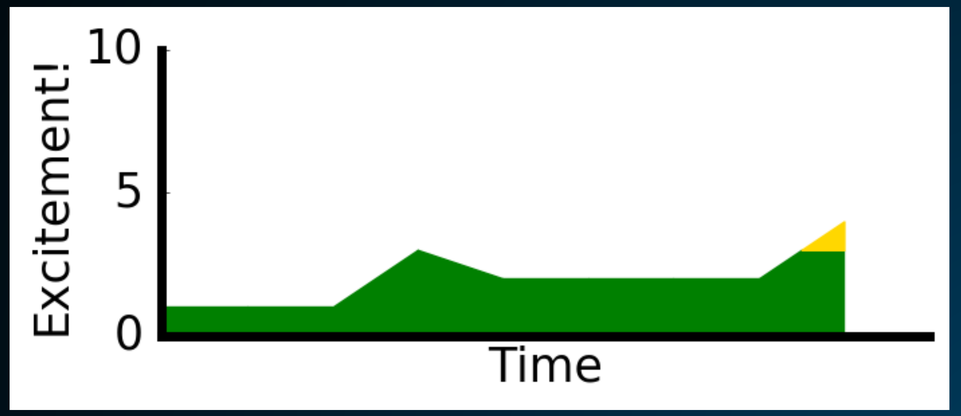


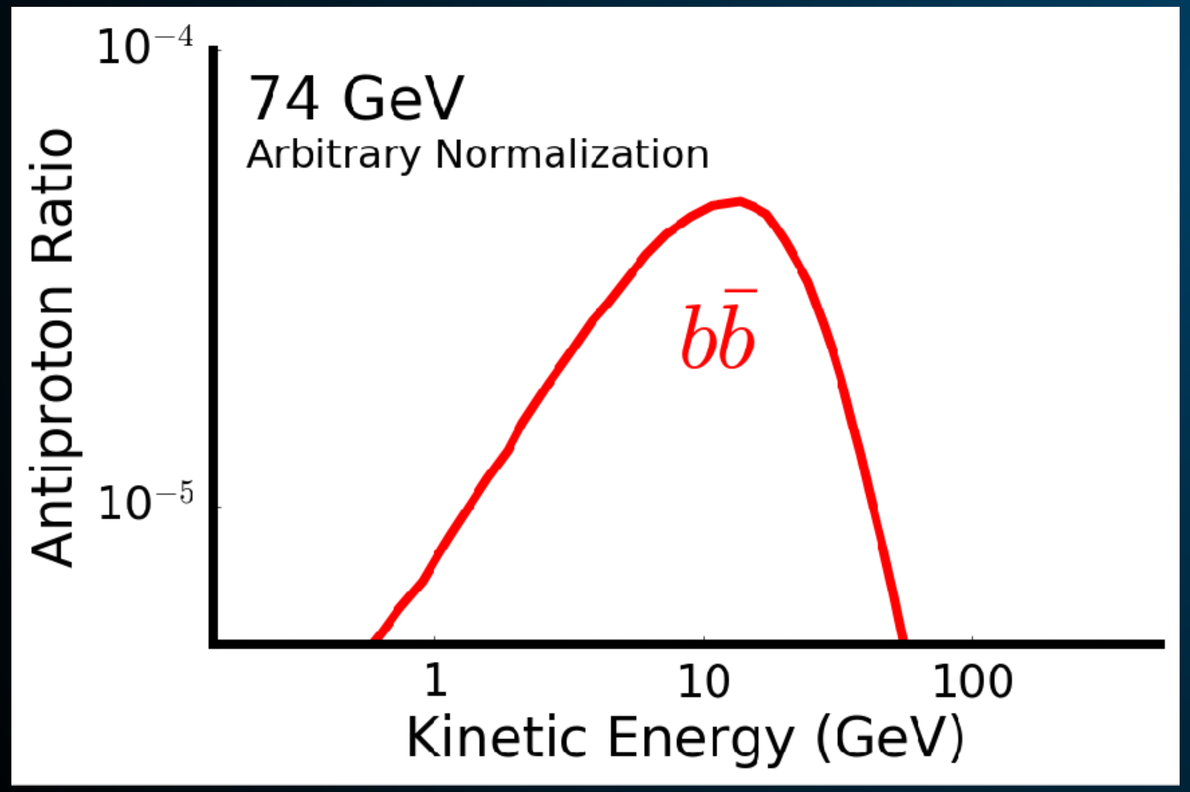


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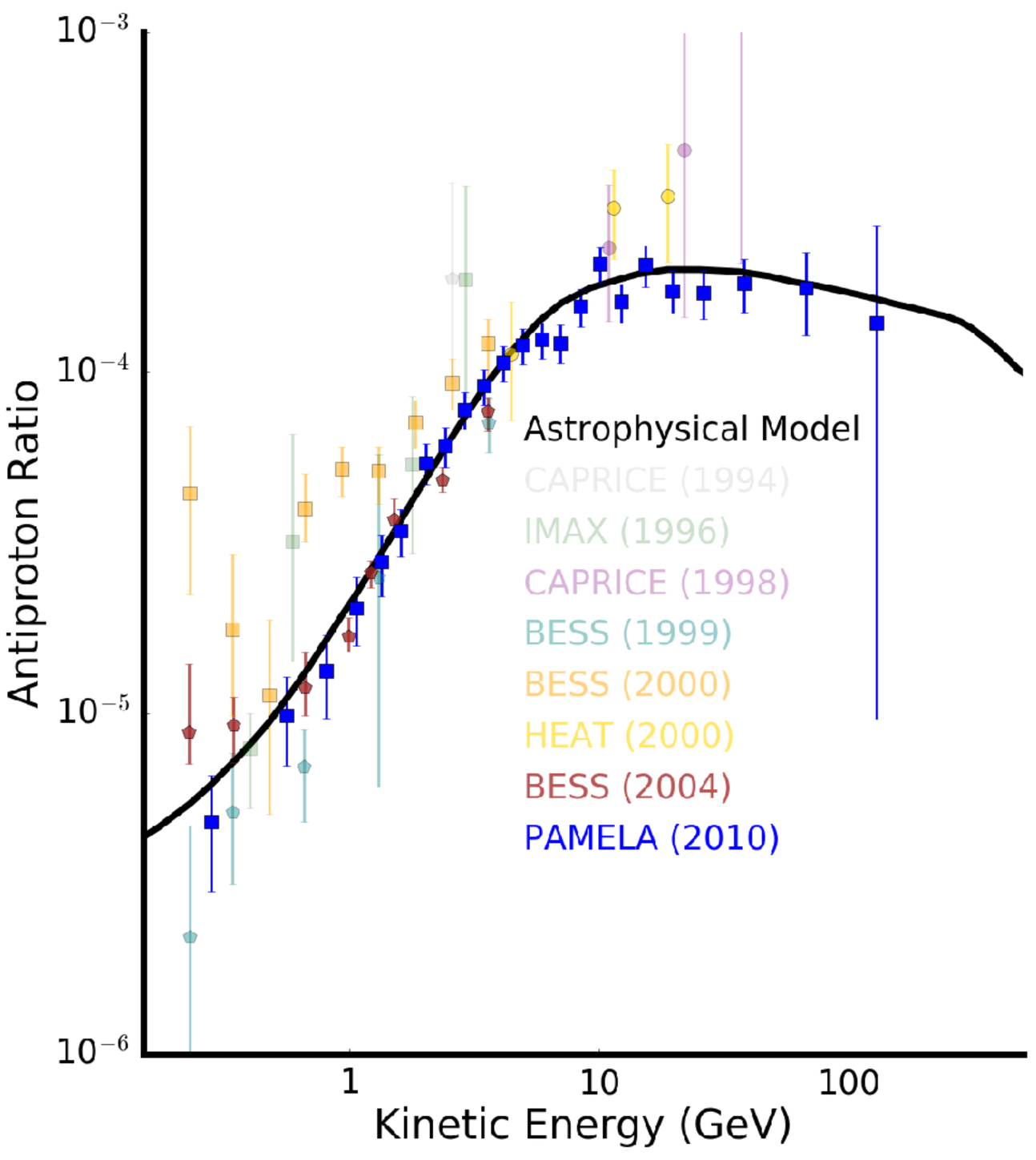


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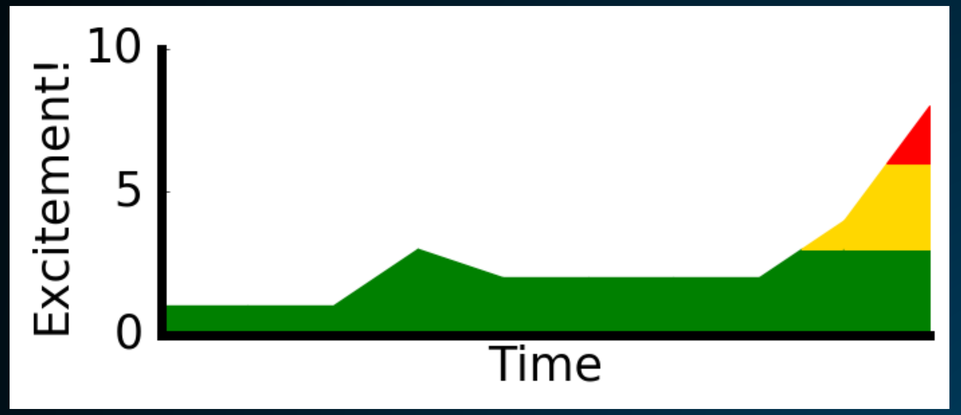


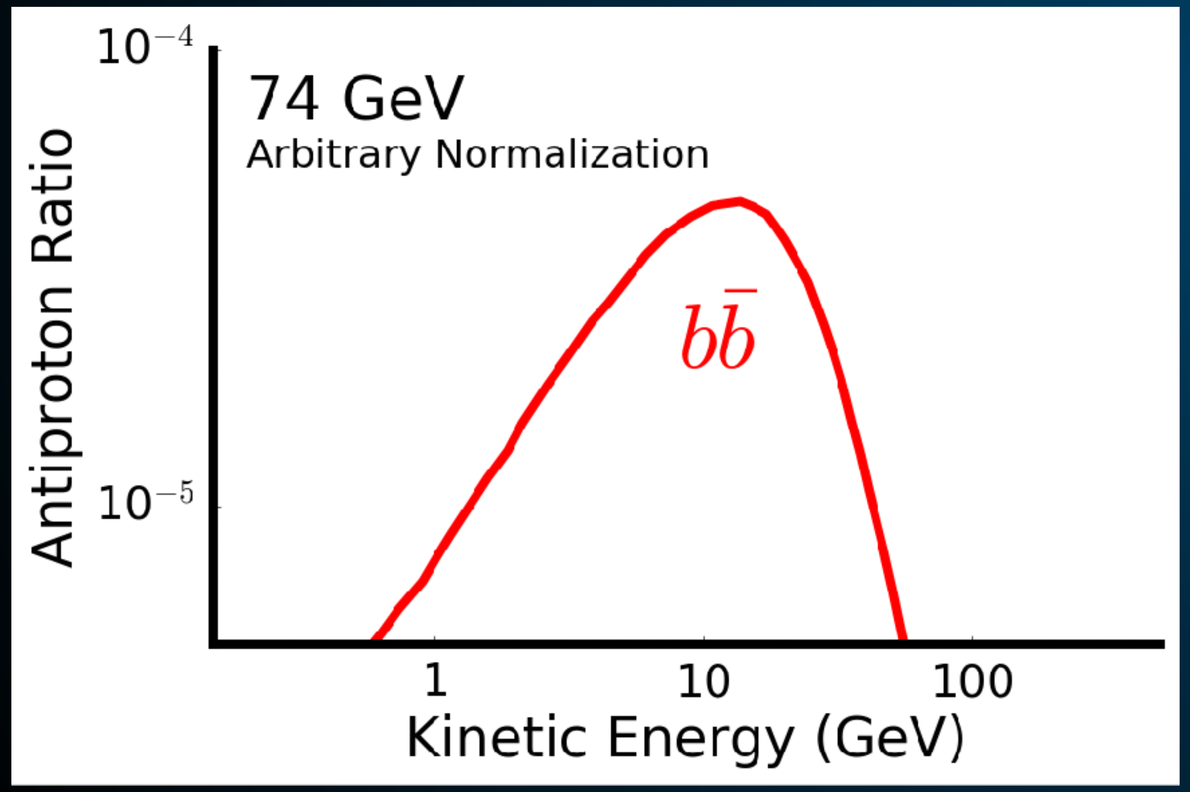


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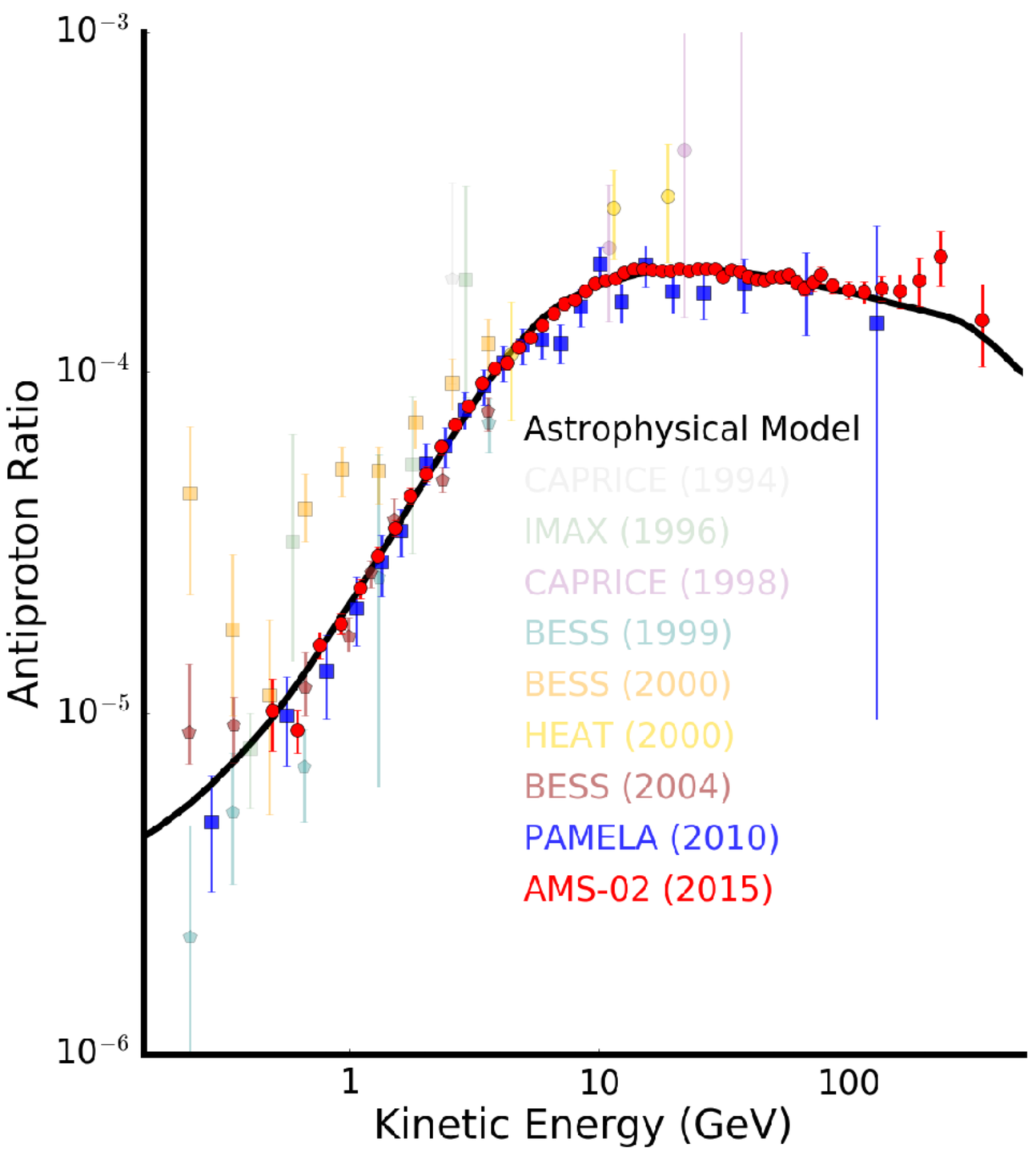


The Antiproton Excess

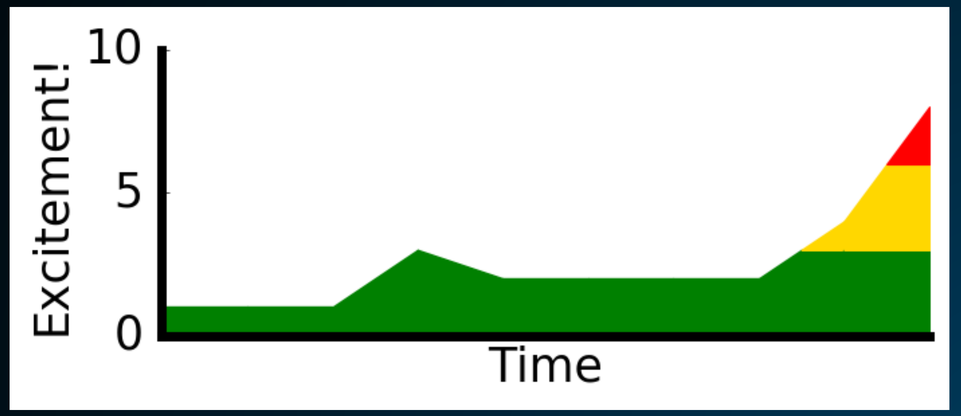


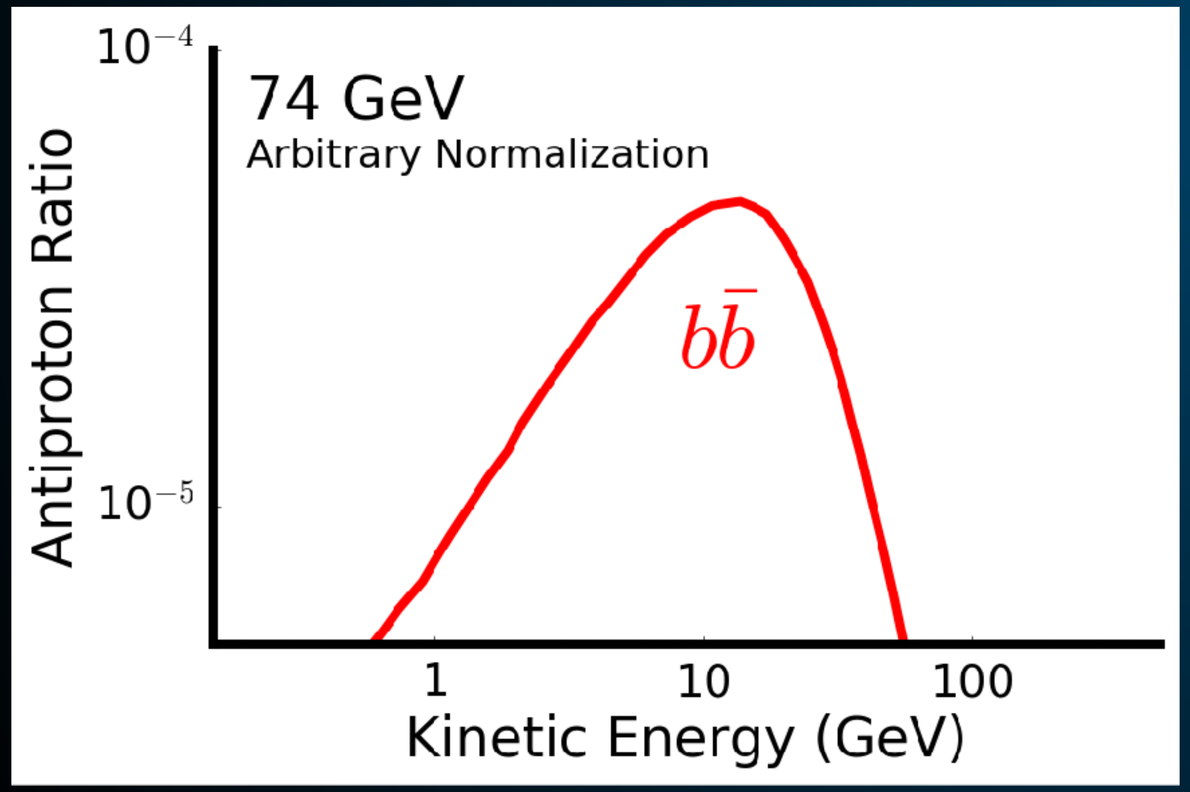


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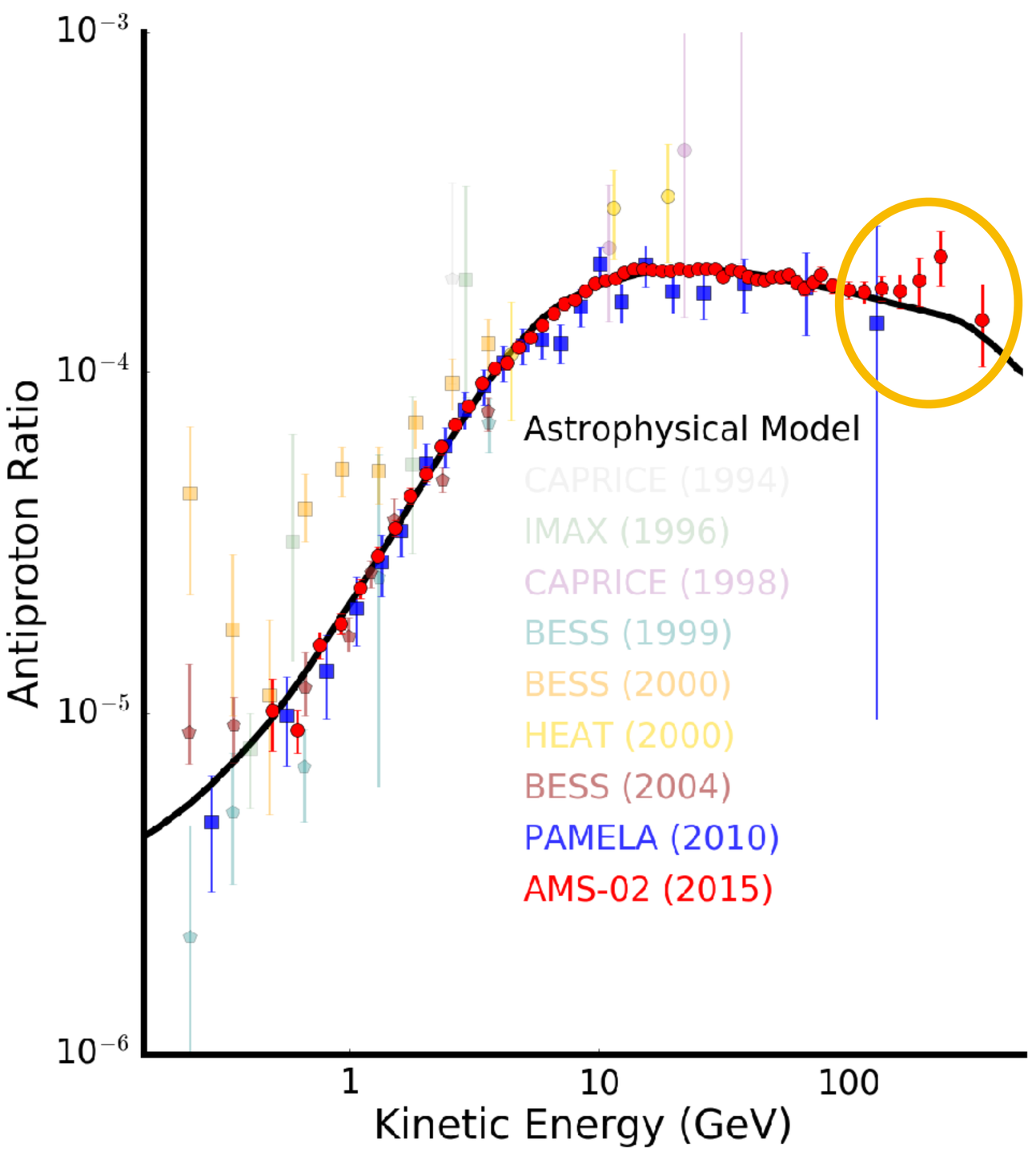


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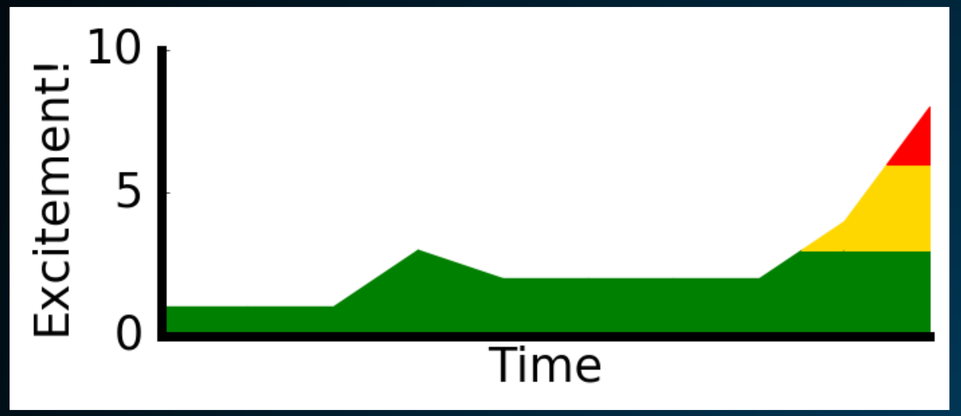


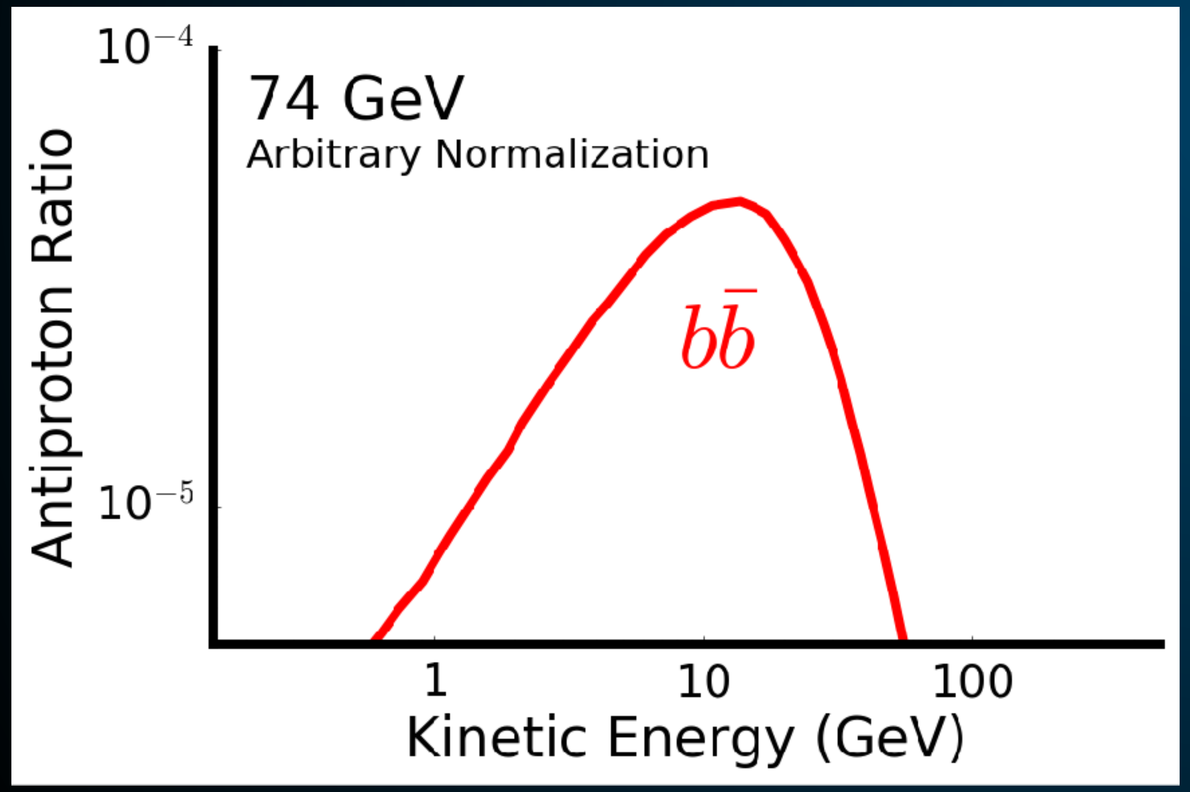


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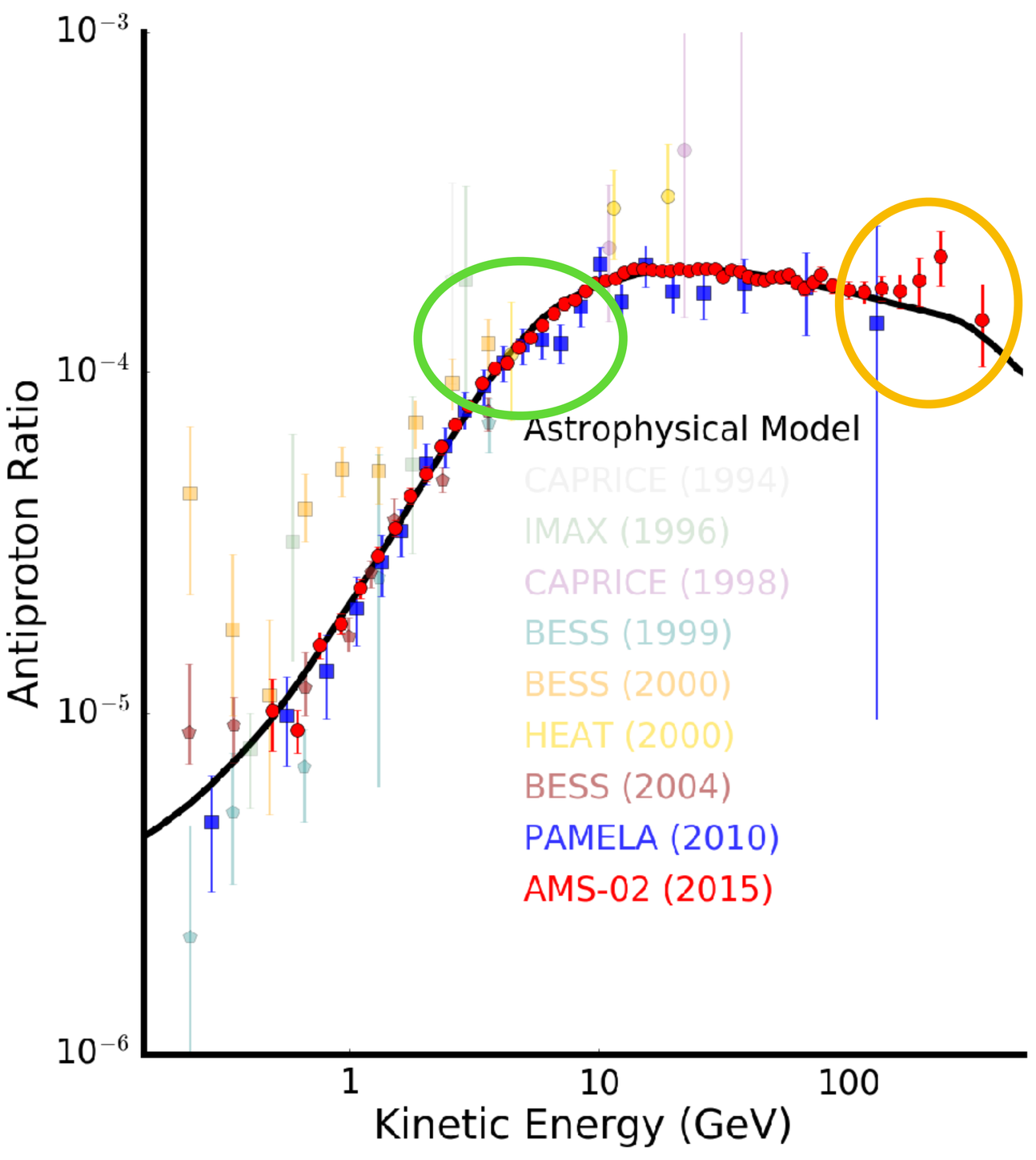


The Antiproton Excess





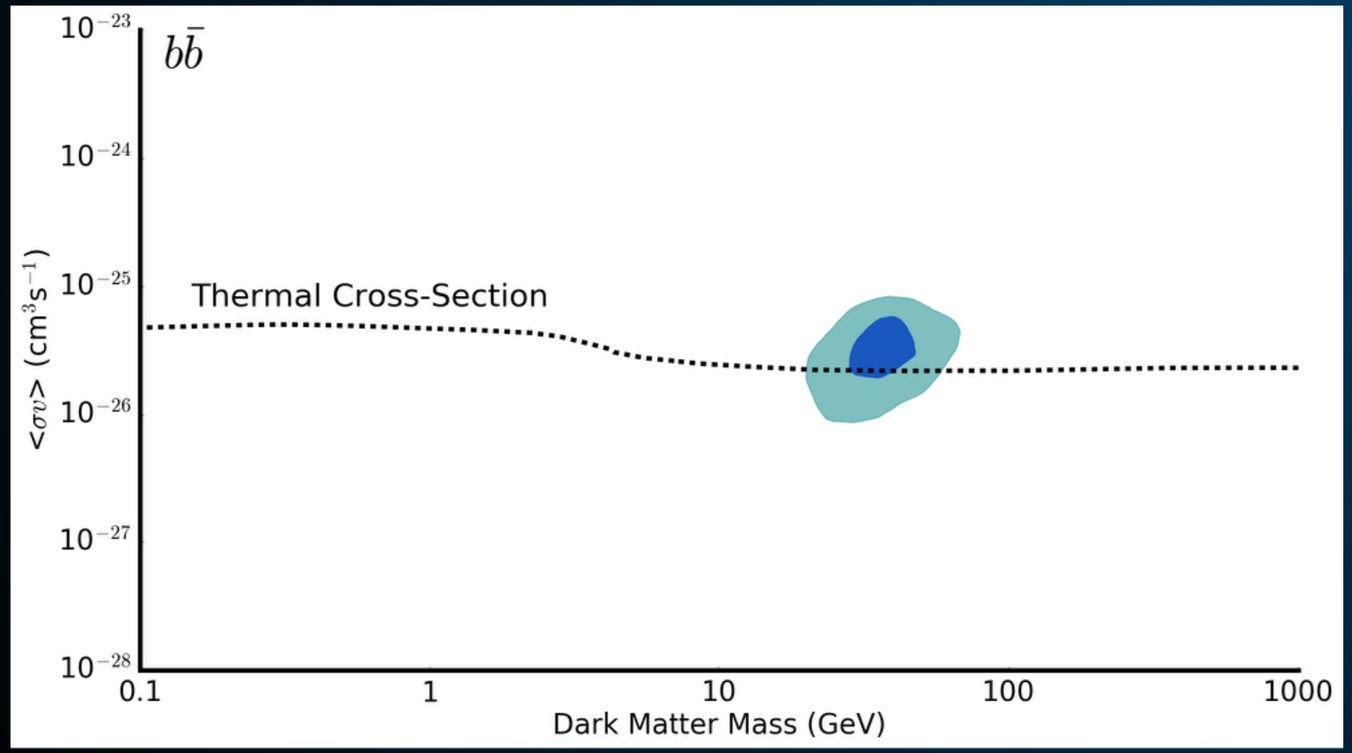
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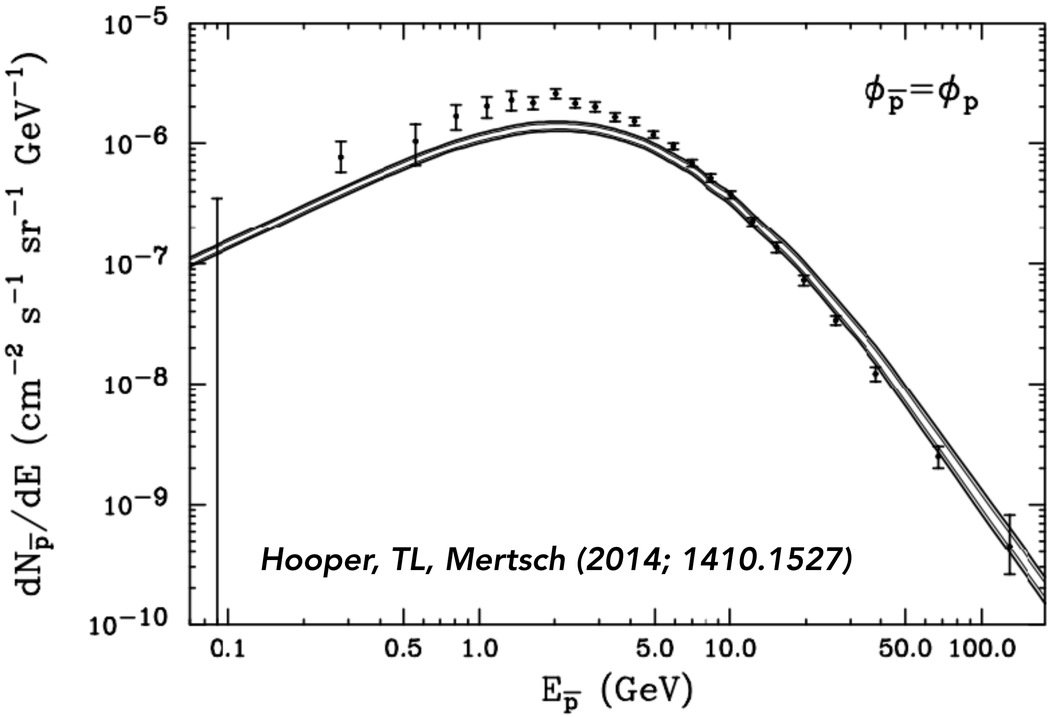


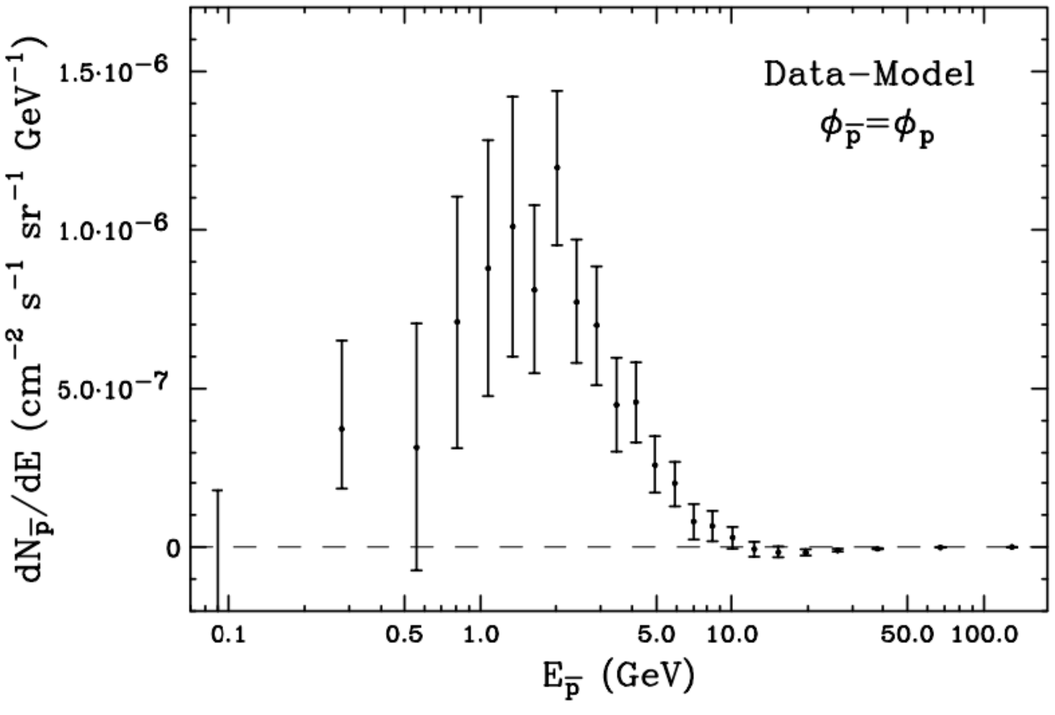
The Antiproton Excess

Hint of Excess in ~5 GeV antiprotons!

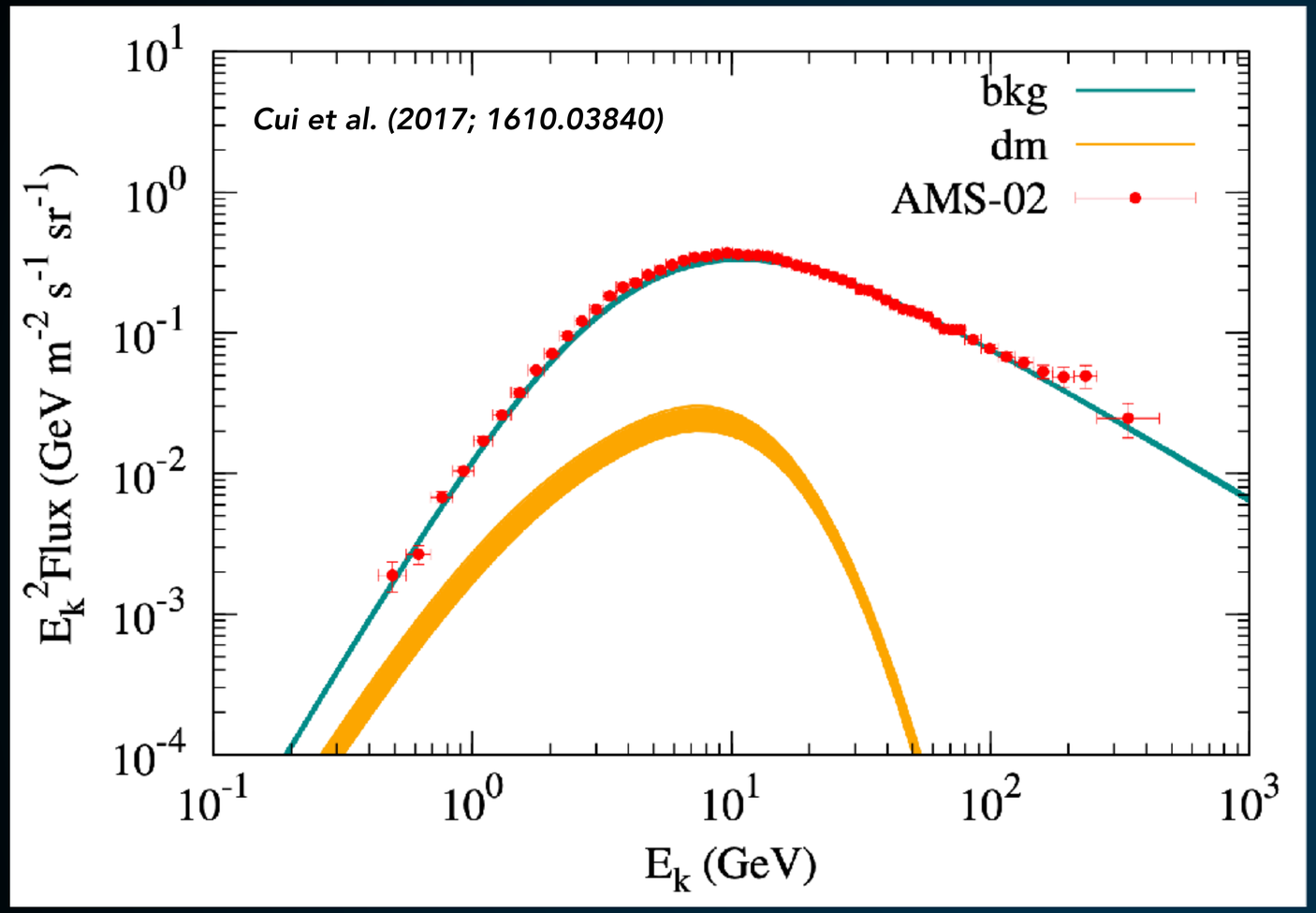
Astrophysical Uncertainties can significantly affect the signal.

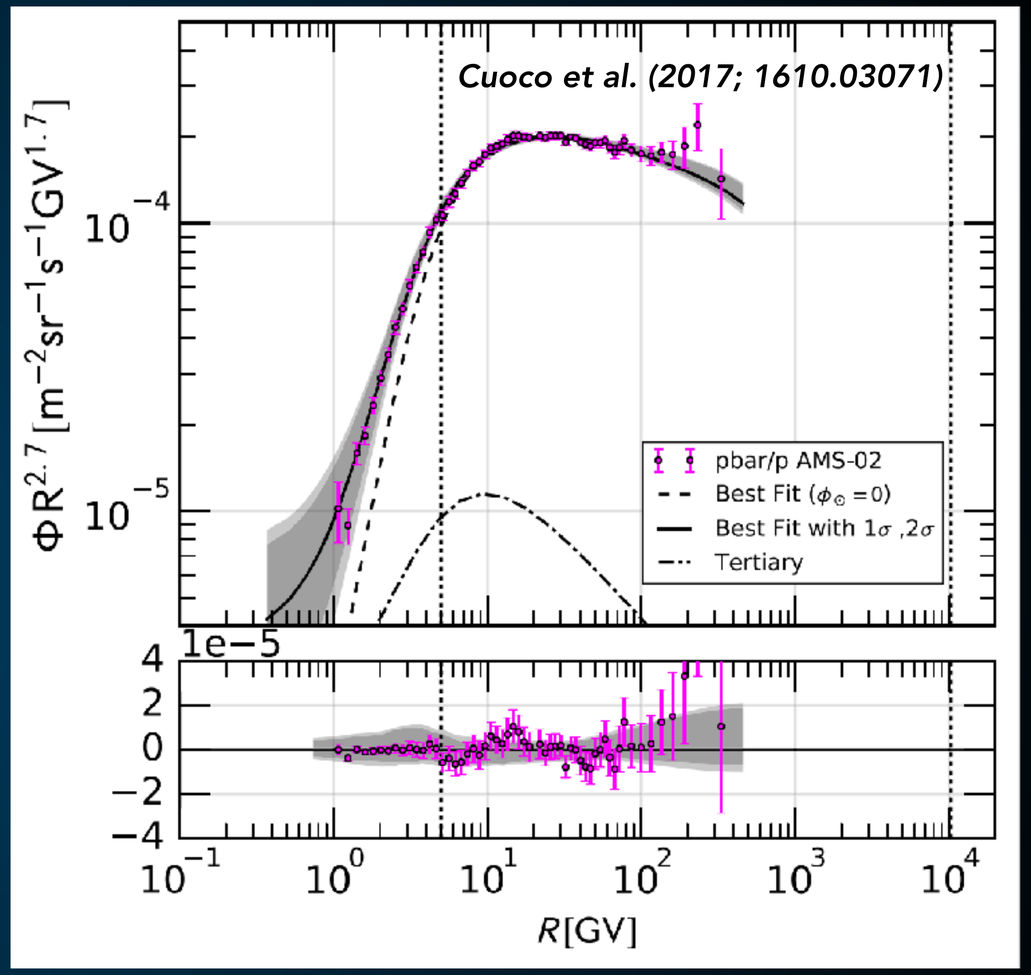






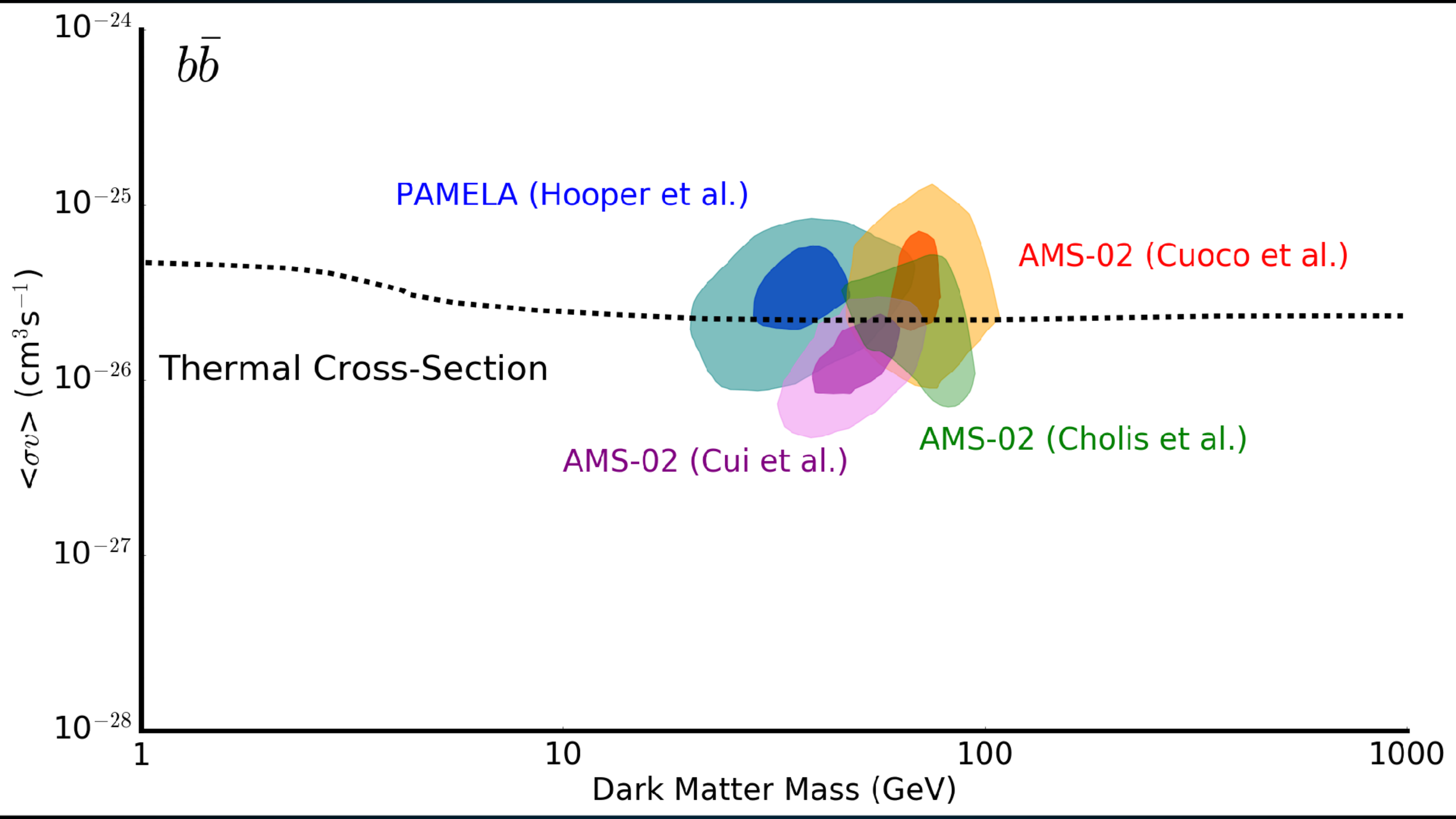
The Antiproton Excess





Two papers simultaneously find an excess in the AMS-02 Antiproton Data!

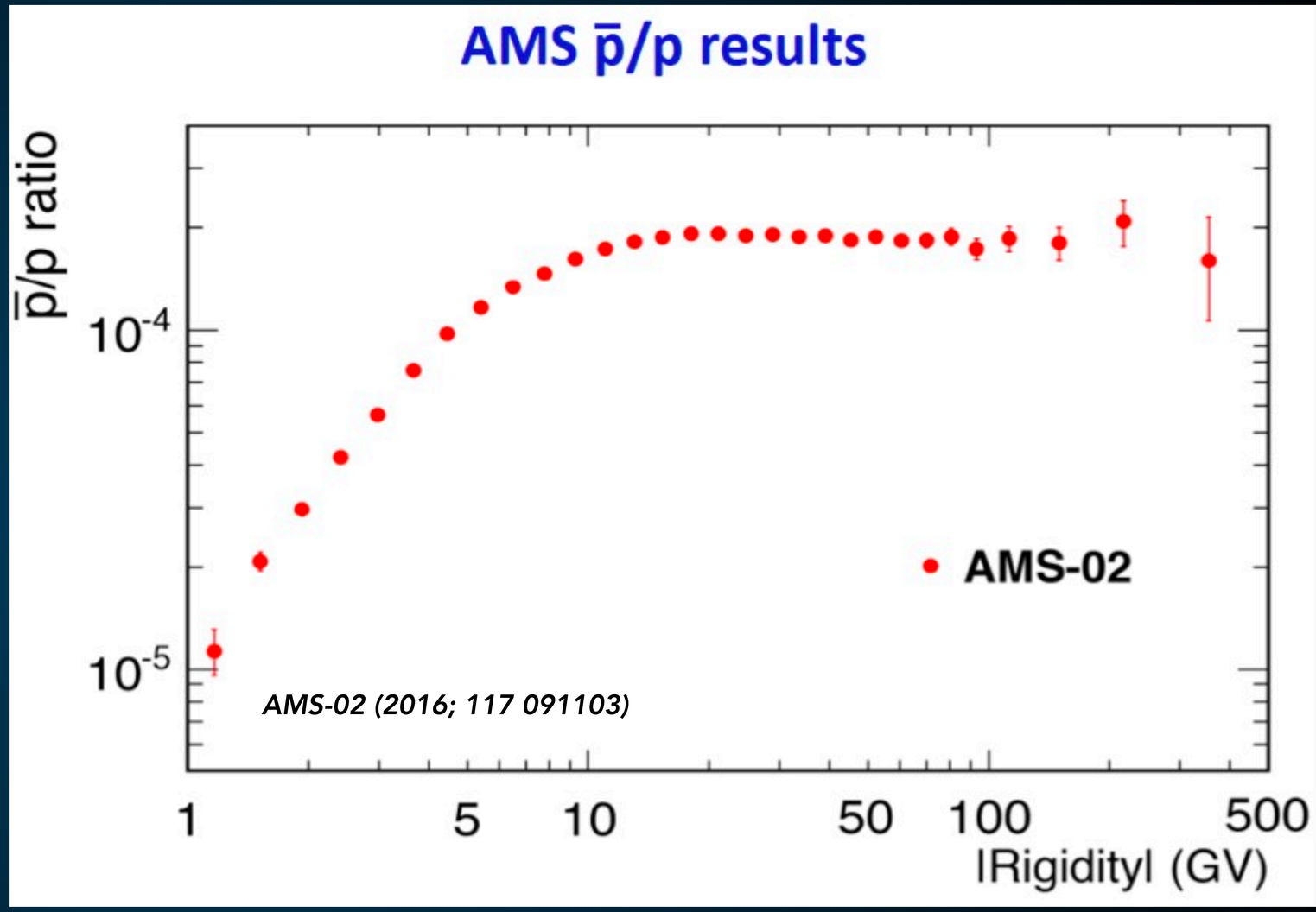
Significance approaching (or past) 5σ !

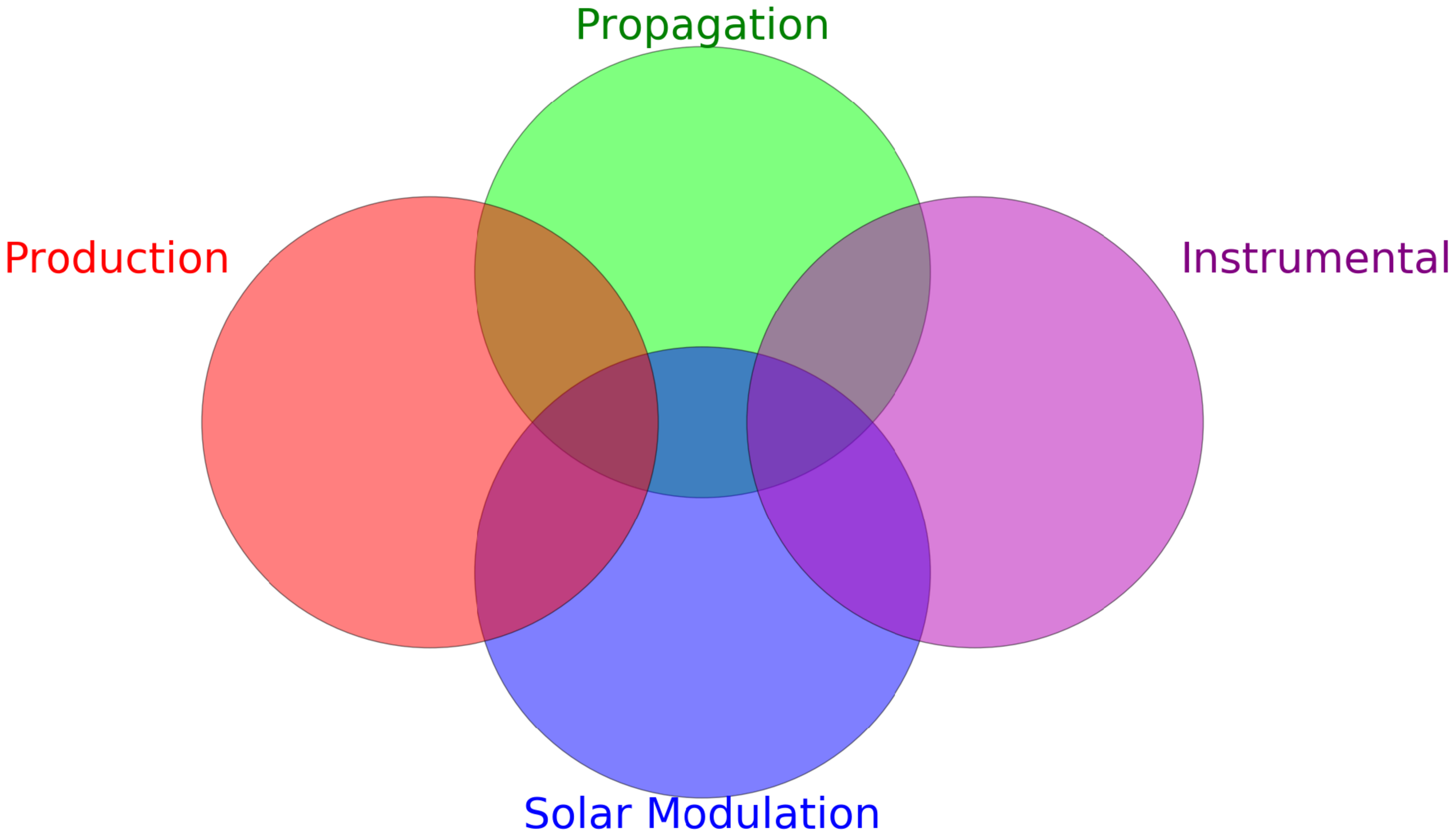

$b\bar{b}$
PAMELA (Hooper et al.)
AMS-02 (Cuoco et al.)
AMS-02 (Cholis et al.)
AMS-02 (Cui et al.)
Thermal Cross-Section
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ ($cm^3 s^{-1}$)
1
10
100
1000
Dark Matter Mass (GeV)

The Antiproton Excess

With great precision comes great responsibility:

- Antiproton Production Cross-Section
- Galactic Primary to Secondary Ratios
- Inhomogeneous Diffusion
- Solar Modulation
- Instrumental Uncertainties



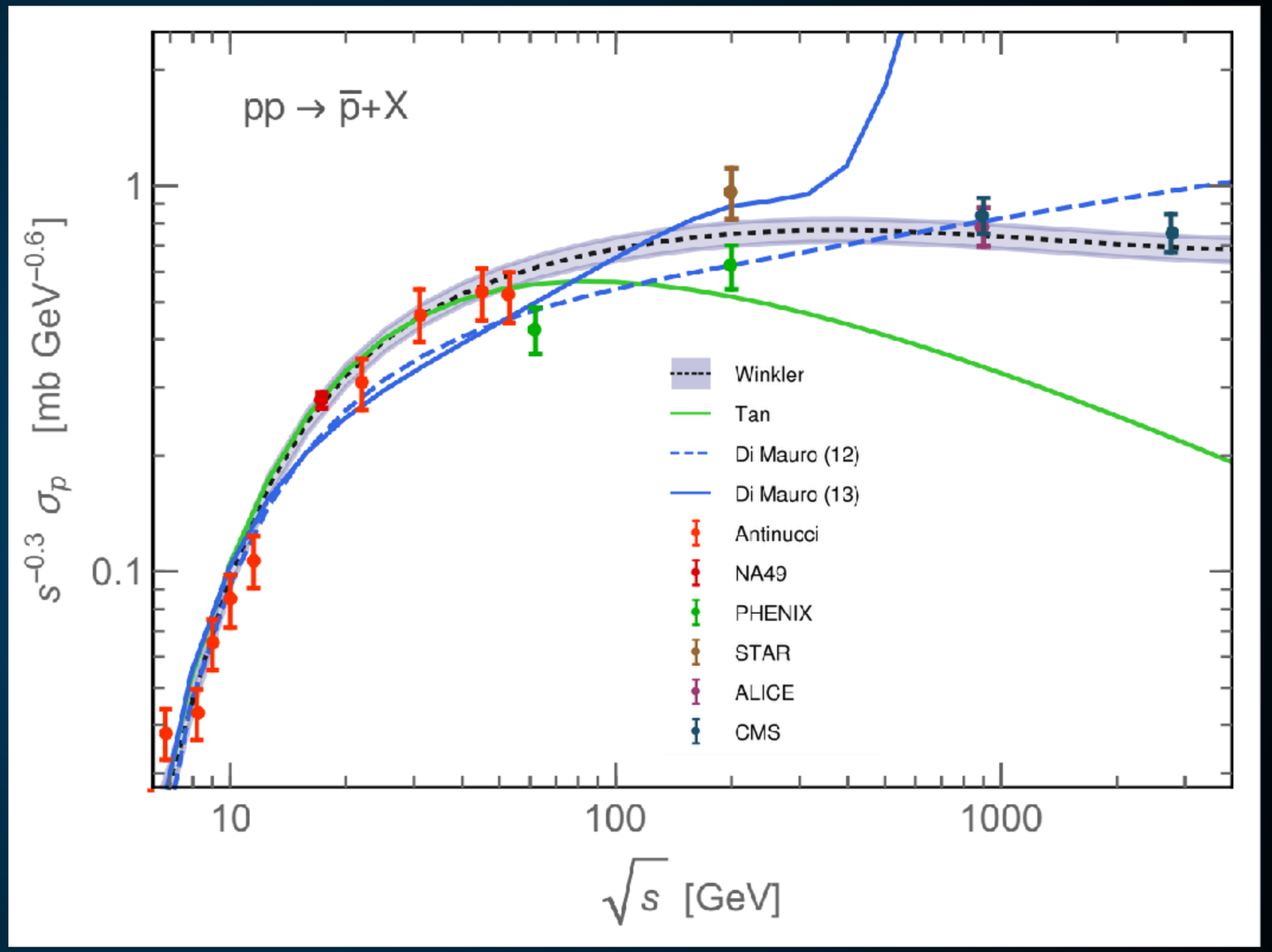

Propagation
Production
Instrumental
Solar Modulation

The Antiproton Excess

Winkler (2017; 1701.04866)
Reinert, Winkler (2018; 1712.00002)

With great precision comes great responsibility:

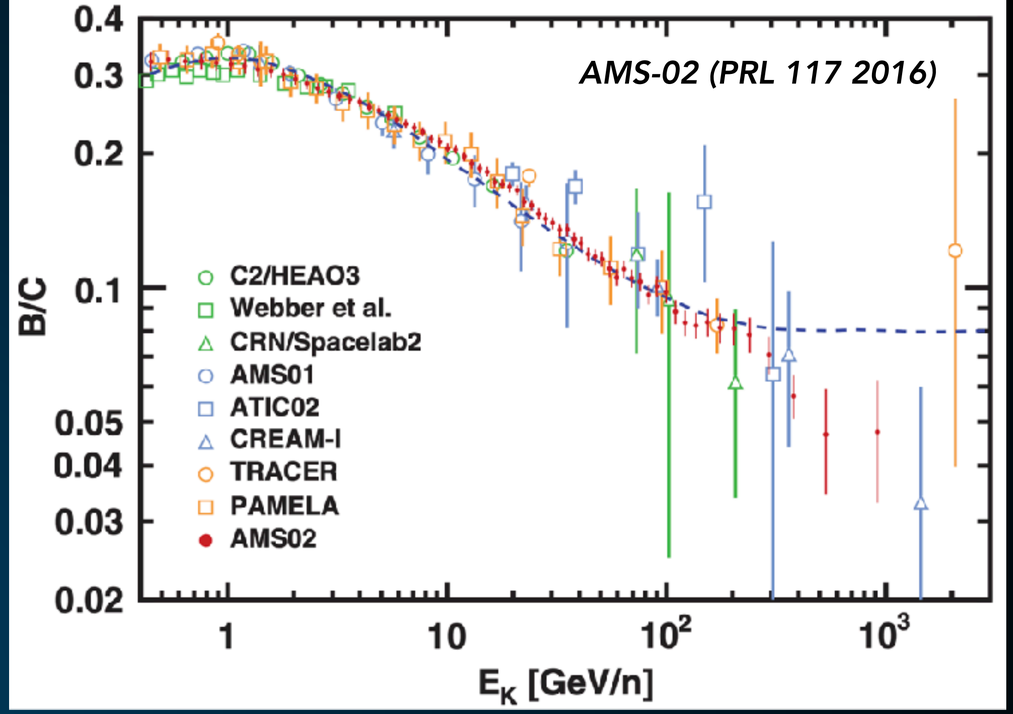
- **Antiproton Production Cross-Section**
- **Galactic Primary to Secondary Ratios**
- **Inhomogeneous Diffusion**
- **Solar Modulation**
- **Instrumental Uncertainties**

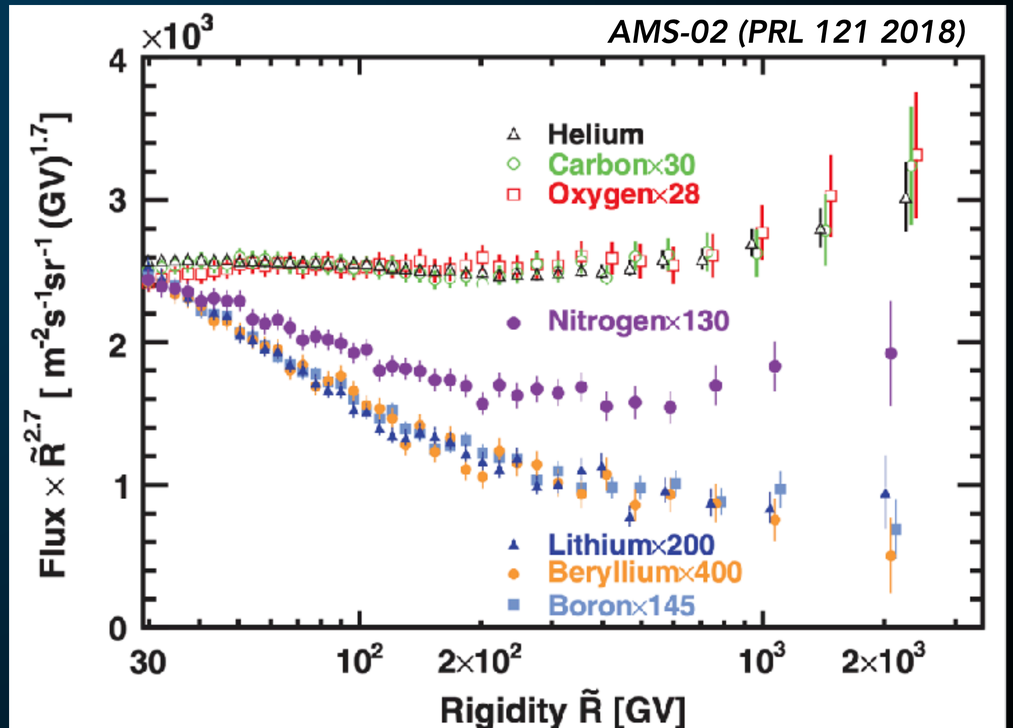


The Antiproton Excess

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- Antiproton Production Cross-Section
- **Galactic Primary to Secondary Ratios**
- Inhomogeneous Diffusion
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- Instrumental Uncertainties



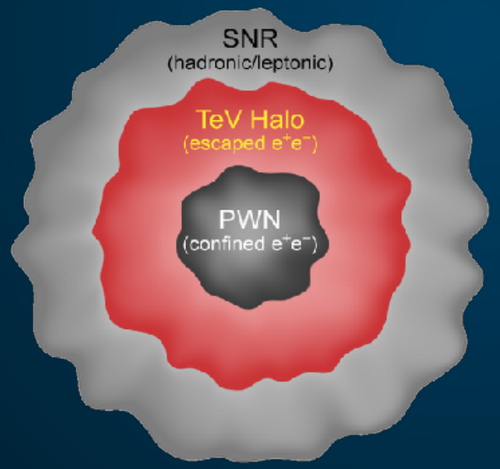


See e.g., Weinrich et al. (2002; 2002.11406)

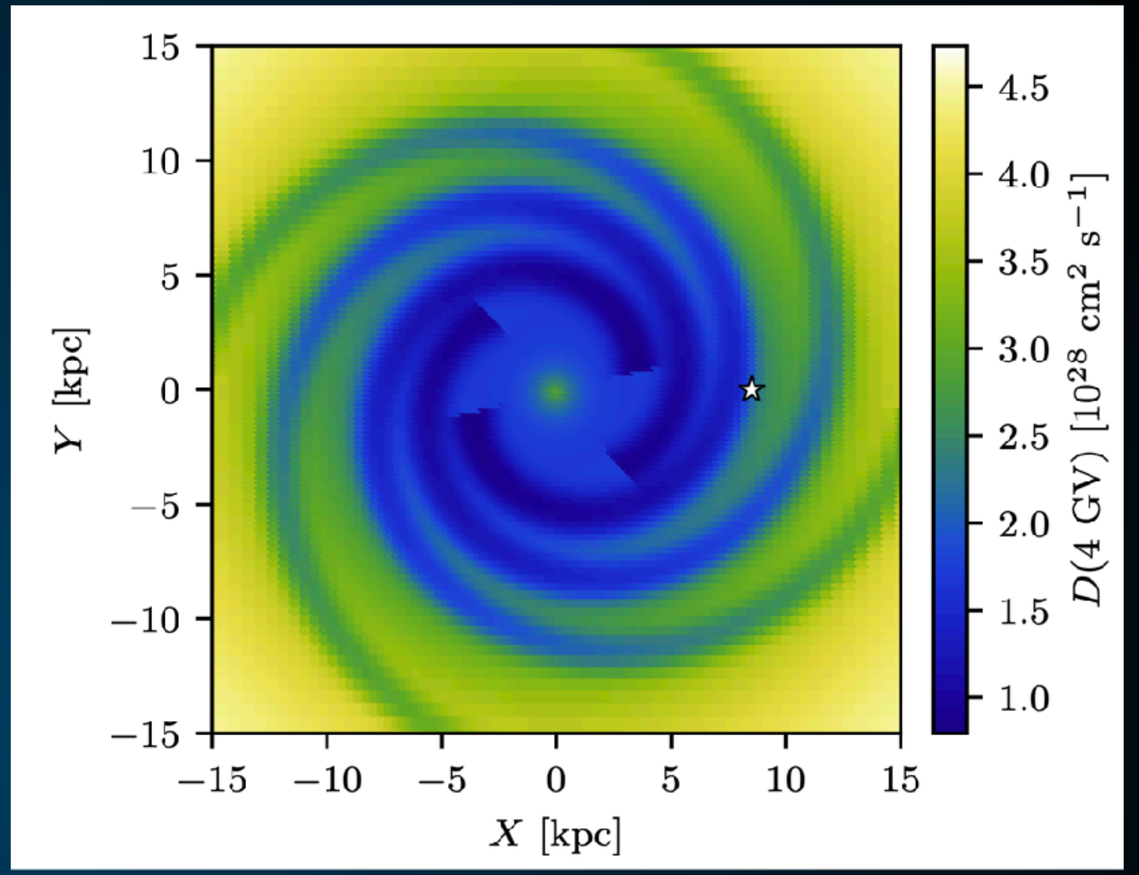
The Antiproton Excess

With great precision comes great responsibility:

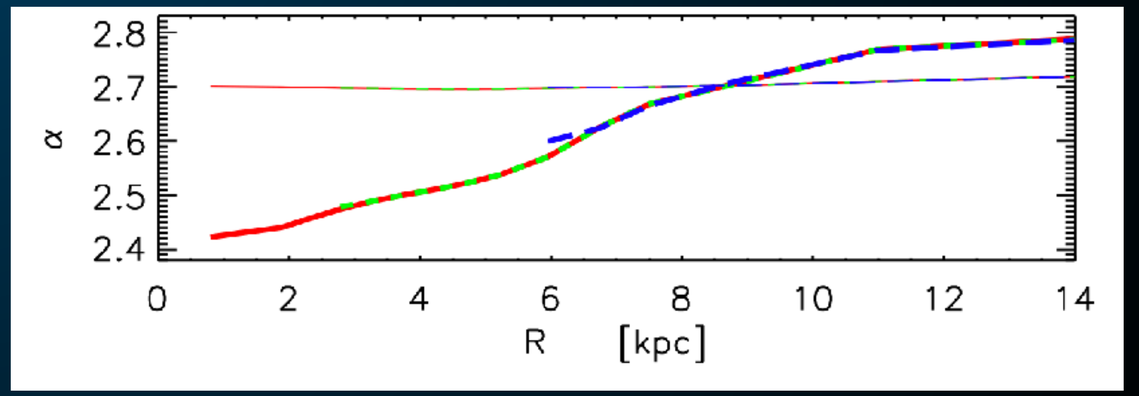
- Antiproton Production Cross-Section
- Galactic Primary to Secondary Ratios
- **Inhomogeneous Diffusion**
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- Instrumental Uncertainties



Johannesson et al. (1903.05509)



Evoli et al. (2014; 1411.7623)

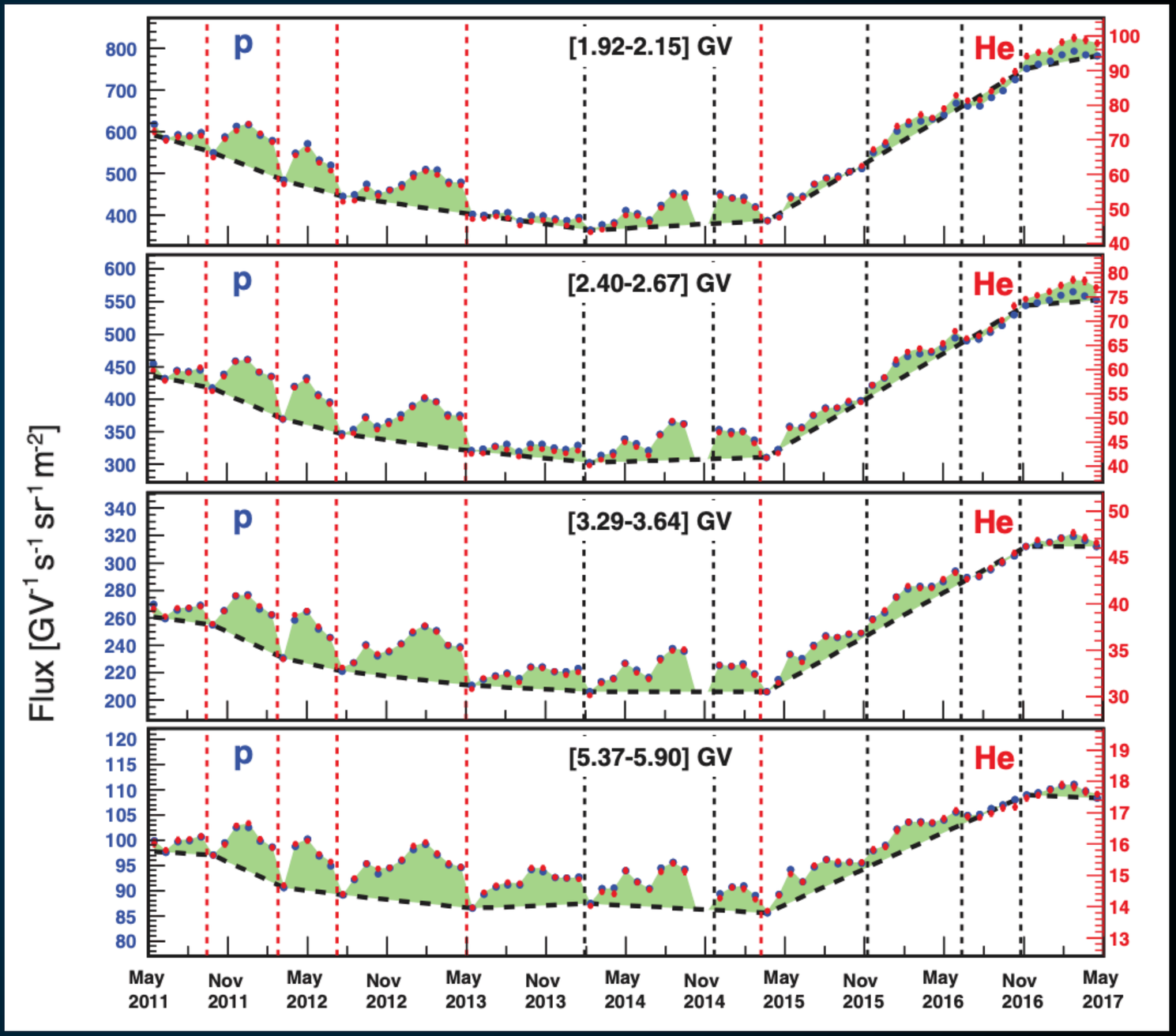


The Antiproton Excess

AMS-02 (PRL 121 2018)

With great precision comes great responsibility:

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- Galactic Primary to Secondary Ratios
- Inhomogeneous Diffusion
- **Solar Modulation**
- Instrumental Uncertainties

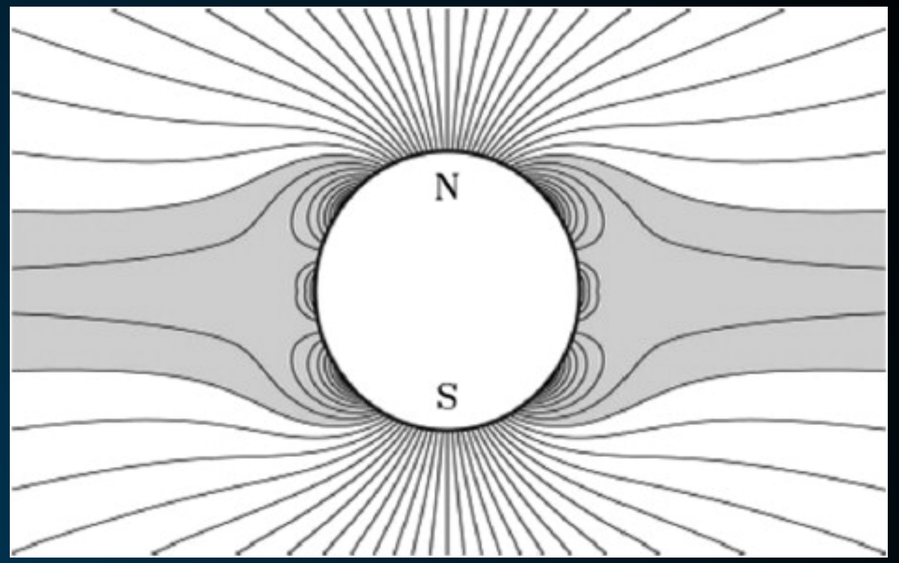


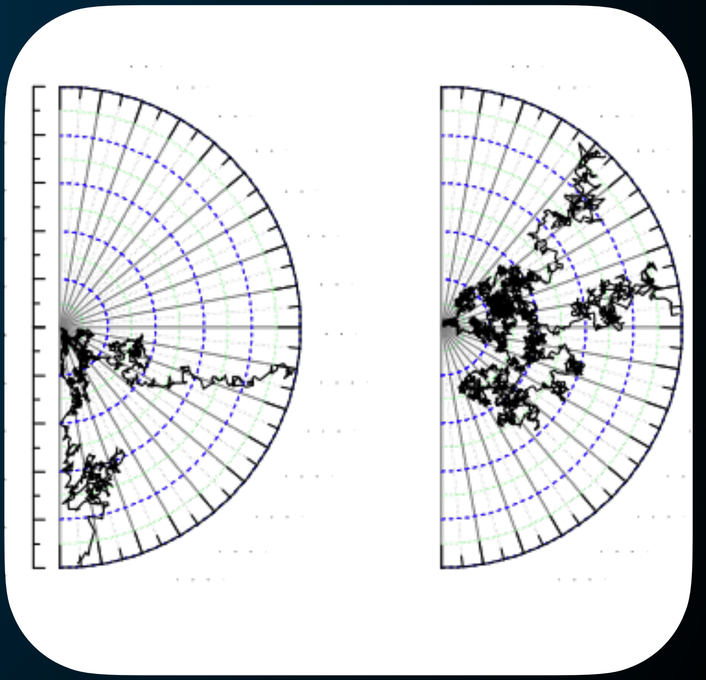
The Antiproton Excess

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Fisk Potential



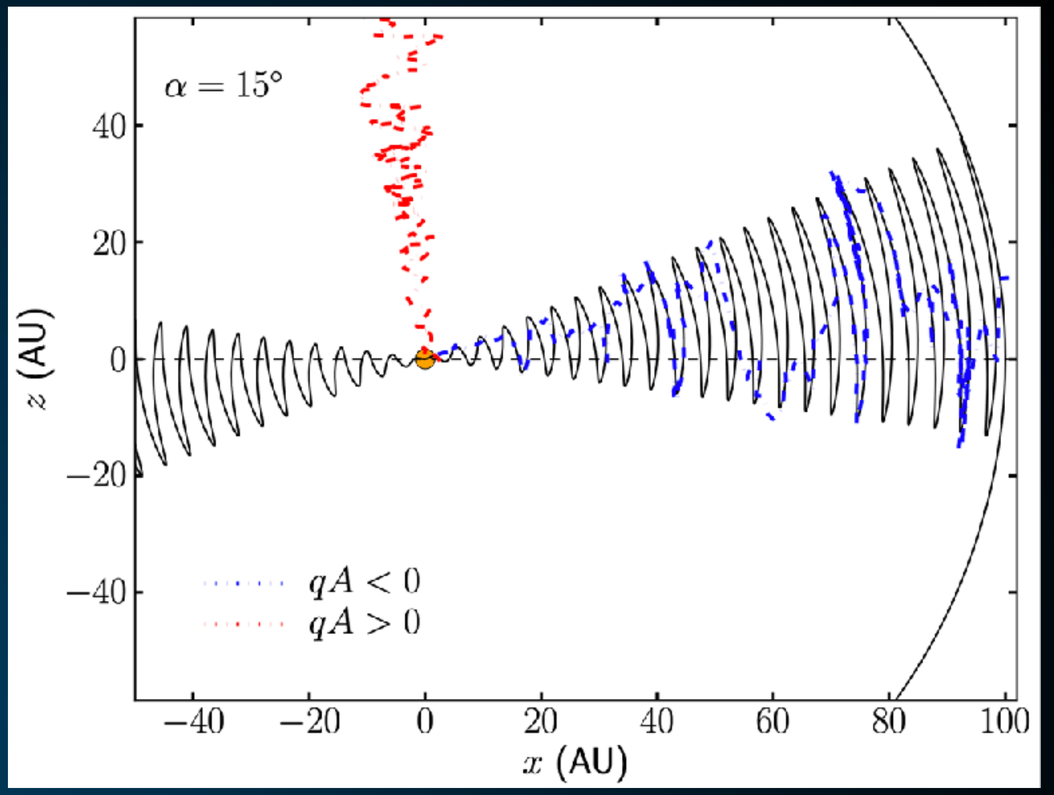


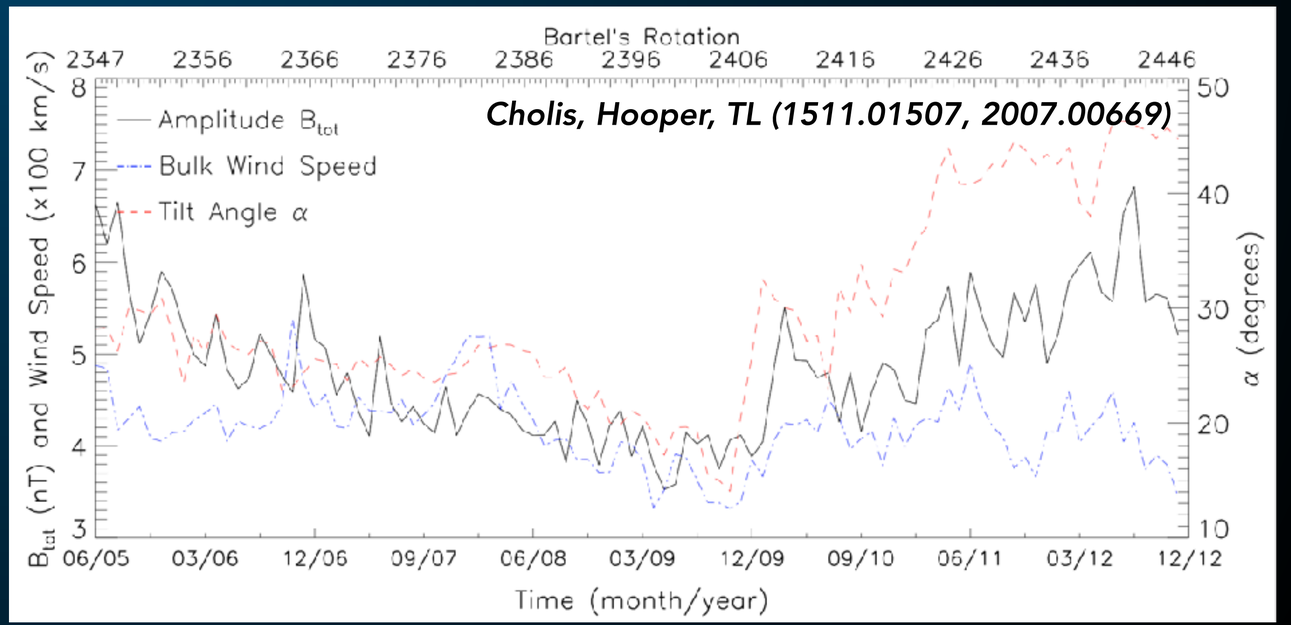
HELMOD Collaboration (2011, 1110.4315)

The Antiproton Excess

With great precision comes great responsibility:

- Antiproton Production Cross-Section
- Galactic Primary to Secondary Ratios
- Inhomogeneous Diffusion
- **Solar Modulation**
- Instrumental Uncertainties





The Antiproton Excess

With great precision comes great responsibility:

Antiproton Production Cross-Section

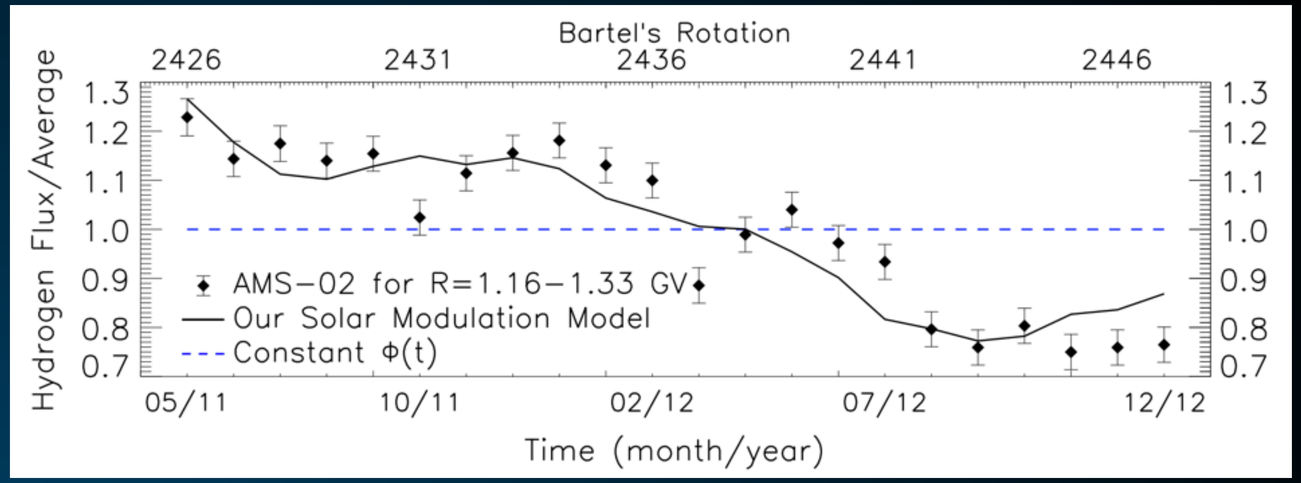
Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

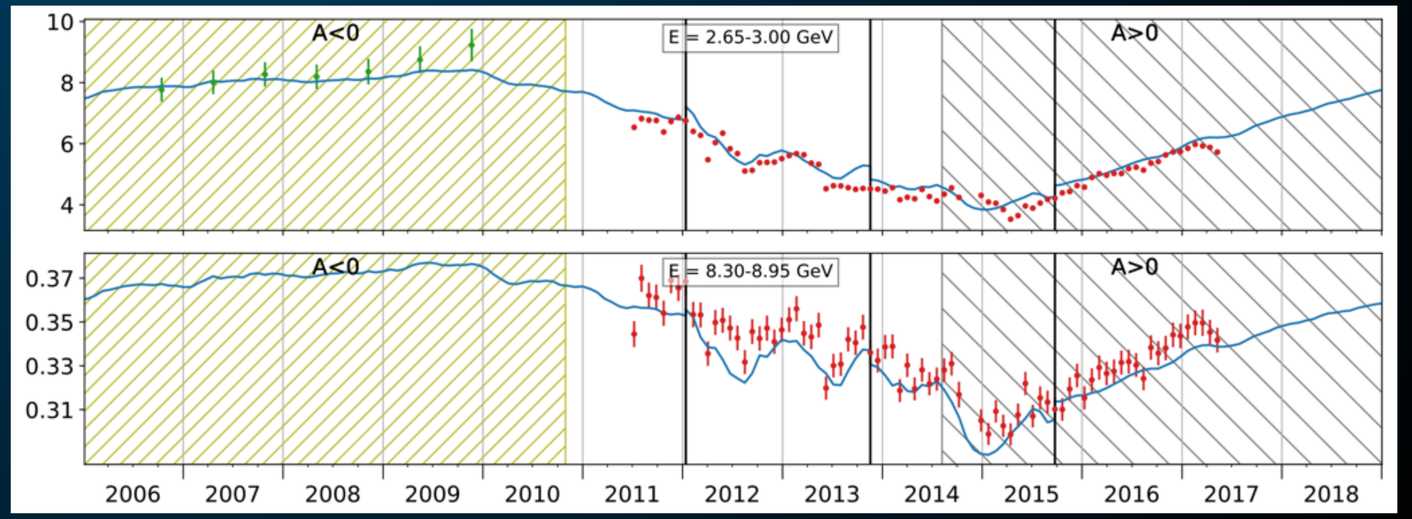
Solar Modulation

Instrumental Uncertainties

Cholis, Hooper, TL (2007.00669)



Kuhlen, Mertsch (1909.01154)



The Antiproton Excess

With great precision comes great responsibility:

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- Inhomogeneous Diffusion
- Solar Modulation
- **Instrumental Uncertainties**

AMS-02 (PRL 117 2016)

Rigidity [GV]	$\bar{N}^{\bar{p}}$	$\Phi^{\bar{p}}$ σ_{stat} σ_{syst}	$\Phi^{\bar{p}}/\Phi^{p}$ σ_{stat} σ_{syst}
1.00 – 1.16	21	$(5.94\ 1.31\ 0.58)\times10^{-3}$	$(1.02\ 0.23\ 0.08)\times10^{-5}$
1.16 – 1.33	74	$(5.57\ 0.68\ 0.51)\times10^{-3}$	$(8.93\ 1.09\ 0.66)\times10^{-6}$
1.33 – 1.51	233	$(9.75\ 0.68\ 0.68)\times10^{-3}$	$(1.59\ 0.11\ 0.09)\times10^{-5}$
1.51 – 1.71	502	$(1.06\ 0.05\ 0.07)\times10^{-2}$	$(1.83\ 0.09\ 0.09)\times10^{-5}$
1.71 – 1.92	888	$(1.25\ 0.05\ 0.08)\times10^{-2}$	$(2.33\ 0.10\ 0.12)\times10^{-5}$
1.92 – 2.15	1449	$(1.40\ 0.05\ 0.08)\times10^{-2}$	$(2.90\ 0.10\ 0.14)\times10^{-5}$
2.15 – 2.40	2192	$(1.50\ 0.05\ 0.09)\times10^{-2}$	$(3.50\ 0.11\ 0.17)\times10^{-5}$
2.40 – 2.67	3366	$(1.64\ 0.04\ 0.09)\times10^{-2}$	$(4.36\ 0.11\ 0.20)\times10^{-5}$
2.67 – 2.97	4474	$(1.64\ 0.04\ 0.09)\times10^{-2}$	$(5.05\ 0.12\ 0.23)\times10^{-5}$
2.97 – 3.29	6028	$(1.69\ 0.04\ 0.09)\times10^{-2}$	$(6.07\ 0.13\ 0.27)\times10^{-5}$
3.29 – 3.64	7321	$(1.67\ 0.03\ 0.09)\times10^{-2}$	$(7.05\ 0.14\ 0.30)\times10^{-5}$
3.64 – 4.02	8592	$(1.59\ 0.03\ 0.08)\times10^{-2}$	$(7.96\ 0.15\ 0.32)\times10^{-5}$
4.02 – 4.43	1932	$(1.56\ 0.04\ 0.08)\times10^{-2}$	$(9.31\ 0.21\ 0.37)\times10^{-5}$
4.43 – 4.88	3083	$(1.43\ 0.03\ 0.07)\times10^{-2}$	$(1.03\ 0.02\ 0.04)\times10^{-4}$
4.88 – 5.37	3880	$(1.23\ 0.02\ 0.06)\times10^{-2}$	$(1.07\ 0.02\ 0.04)\times10^{-4}$
5.37 – 5.90	4780	$(1.12\ 0.02\ 0.05)\times10^{-2}$	$(1.19\ 0.02\ 0.05)\times10^{-4}$
5.90 – 6.47	5472	$(9.80\ 0.13\ 0.45)\times10^{-3}$	$(1.27\ 0.02\ 0.05)\times10^{-4}$
6.47 – 7.09	6538	$(8.69\ 0.11\ 0.39)\times10^{-3}$	$(1.38\ 0.02\ 0.05)\times10^{-4}$
7.09 – 7.76	7369	$(7.59\ 0.09\ 0.34)\times10^{-3}$	$(1.49\ 0.02\ 0.05)\times10^{-4}$
7.76 – 8.48	7818	$(6.54\ 0.08\ 0.29)\times10^{-3}$	$(1.59\ 0.02\ 0.06)\times10^{-4}$
8.48 – 9.26	7821	$(5.46\ 0.06\ 0.24)\times10^{-3}$	$(1.64\ 0.02\ 0.06)\times10^{-4}$
9.26 – 10.1	20382	$(4.67\ 0.03\ 0.20)\times10^{-3}$	$(1.74\ 0.01\ 0.06)\times10^{-4}$
10.1 – 11.0	19445	$(3.96\ 0.03\ 0.17)\times10^{-3}$	$(1.83\ 0.01\ 0.07)\times10^{-4}$
11.0 – 12.0	18769	$(3.23\ 0.02\ 0.14)\times10^{-3}$	$(1.86\ 0.01\ 0.07)\times10^{-4}$
12.0 – 13.0	16372	$(2.65\ 0.02\ 0.11)\times10^{-3}$	$(1.89\ 0.02\ 0.07)\times10^{-4}$
13.0 – 14.1	16076	$(2.23\ 0.02\ 0.09)\times10^{-3}$	$(1.96\ 0.02\ 0.07)\times10^{-4}$
14.1 – 15.3	15578	$(1.85\ 0.02\ 0.08)\times10^{-3}$	$(2.02\ 0.02\ 0.07)\times10^{-4}$
15.3 – 16.6	14734	$(1.49\ 0.01\ 0.06)\times10^{-3}$	$(2.02\ 0.02\ 0.07)\times10^{-4}$
16.6 – 18.0	15816	$(1.19\ 0.01\ 0.05)\times10^{-3}$	$(2.00\ 0.02\ 0.07)\times10^{-4}$
18.0 – 19.5	15049	$(9.53\ 0.08\ 0.37)\times10^{-4}$	$(1.99\ 0.02\ 0.06)\times10^{-4}$
19.5 – 21.1	14426	$(7.72\ 0.07\ 0.29)\times10^{-4}$	$(1.99\ 0.02\ 0.06)\times10^{-4}$
21.1 – 22.8	13511	$(6.33\ 0.06\ 0.23)\times10^{-4}$	$(2.02\ 0.02\ 0.06)\times10^{-4}$
22.8 – 24.7	12943	$(5.02\ 0.05\ 0.18)\times10^{-4}$	$(1.99\ 0.02\ 0.06)\times10^{-4}$
24.7 – 26.7	11723	$(4.11\ 0.04\ 0.14)\times10^{-4}$	$(2.02\ 0.02\ 0.05)\times10^{-4}$
26.7 – 28.8	10411	$(3.32\ 0.04\ 0.11)\times10^{-4}$	$(2.02\ 0.02\ 0.05)\times10^{-4}$
28.8 – 31.1	9508	$(2.68\ 0.03\ 0.08)\times10^{-4}$	$(2.02\ 0.02\ 0.05)\times10^{-4}$
31.1 – 33.5	7876	$(2.07\ 0.03\ 0.06)\times10^{-4}$	$(1.92\ 0.02\ 0.04)\times10^{-4}$
33.5 – 36.1	7212	$(1.75\ 0.02\ 0.05)\times10^{-4}$	$(2.00\ 0.03\ 0.05)\times10^{-4}$

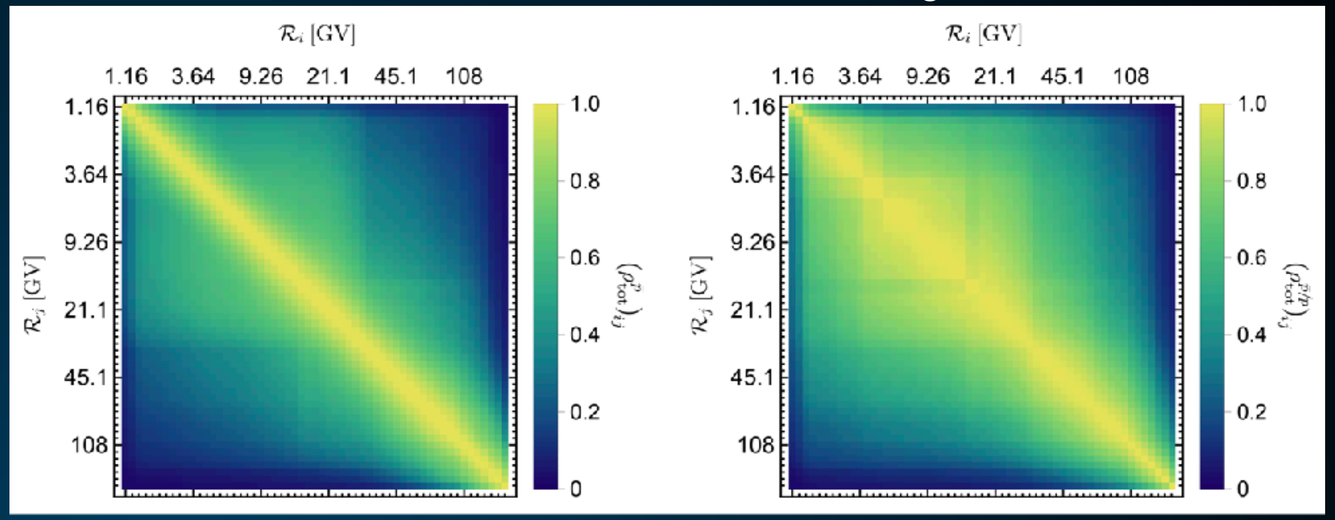
(Table continued)

The Antiproton Excess

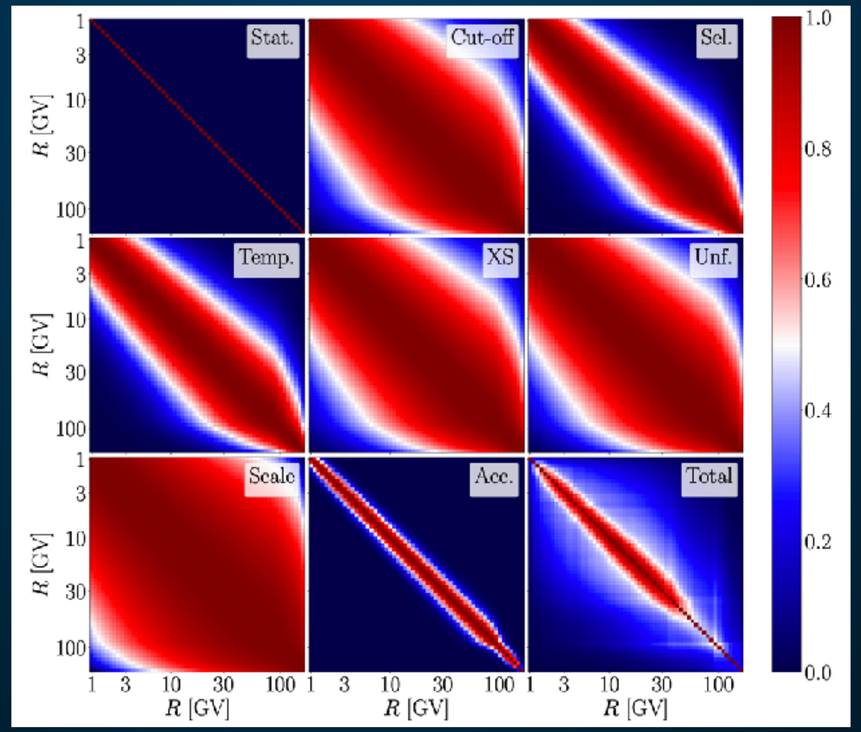
With great precision comes great responsibility:

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- **Instrumental Uncertainties**

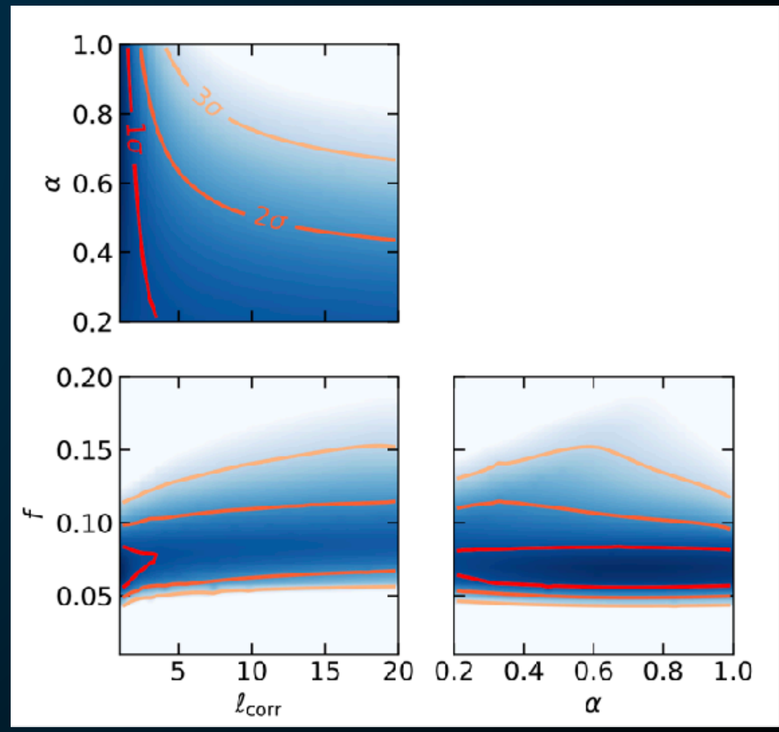
Heisig et al. (2020; 2005.04237)



Boudaud et al. (2019; 1906.07119)



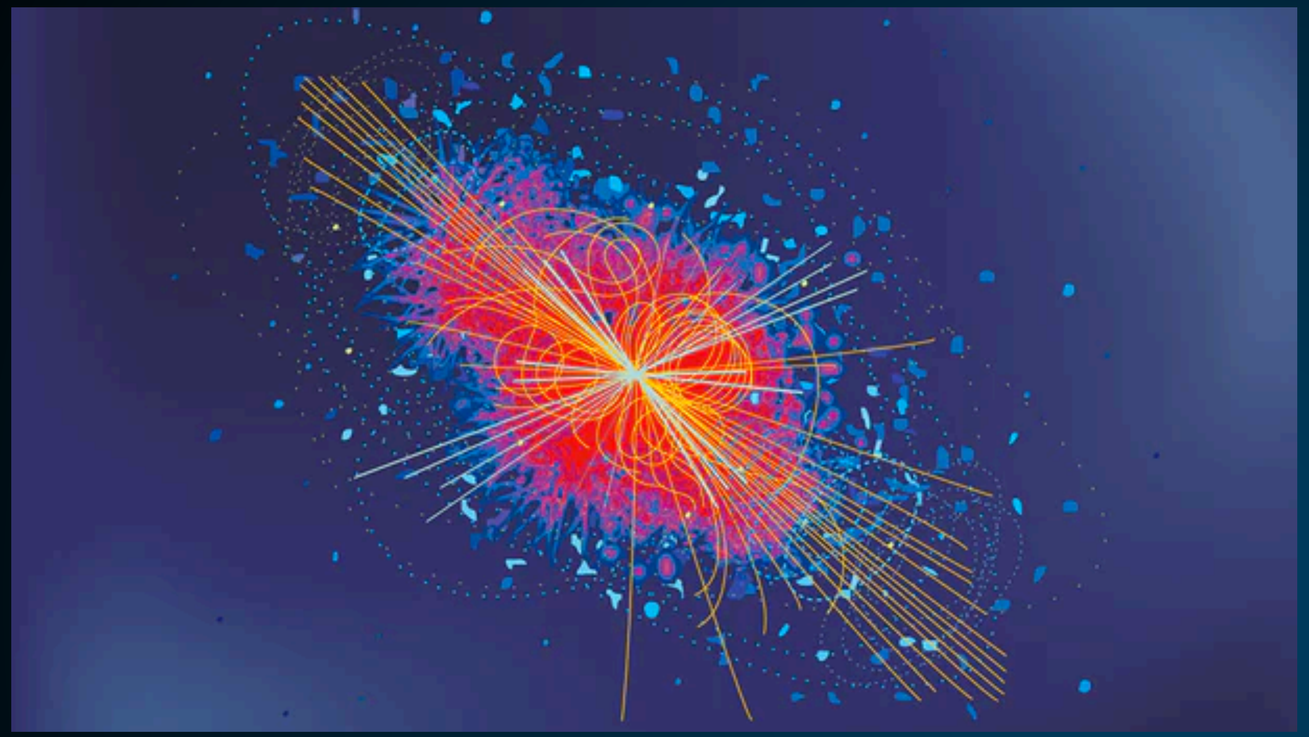
Cuoco et. al. (2019; 1903.01472)



Antinuclei !?



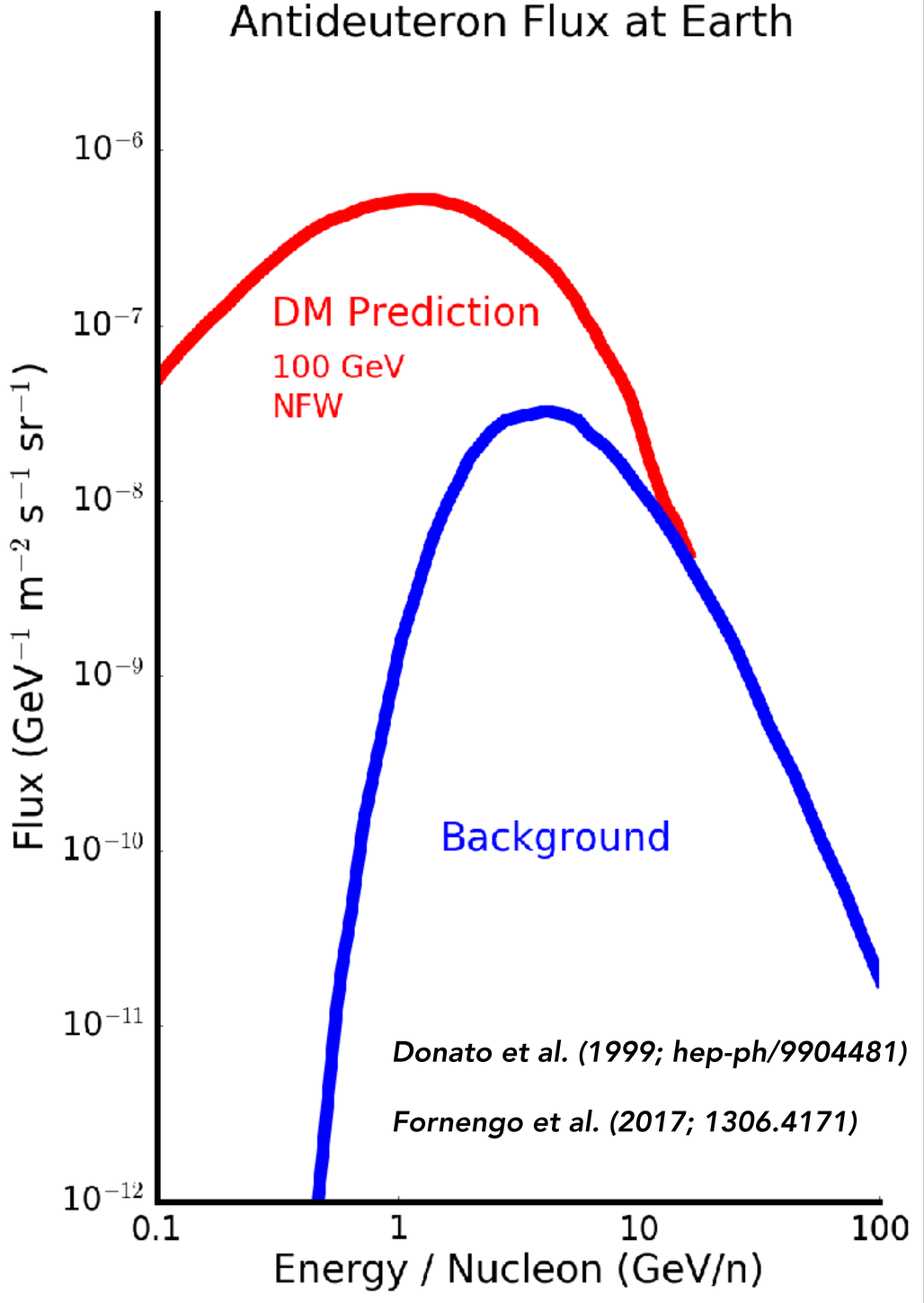
AntiNuclei - A Clean Search Strategy ?



Antinuclei carry away a significant fraction of the total momentum in a particle collision.

Astrophysical Antinuclei - Most be moving relativistically!

Dark Matter Antinuclei - Can be slow!



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

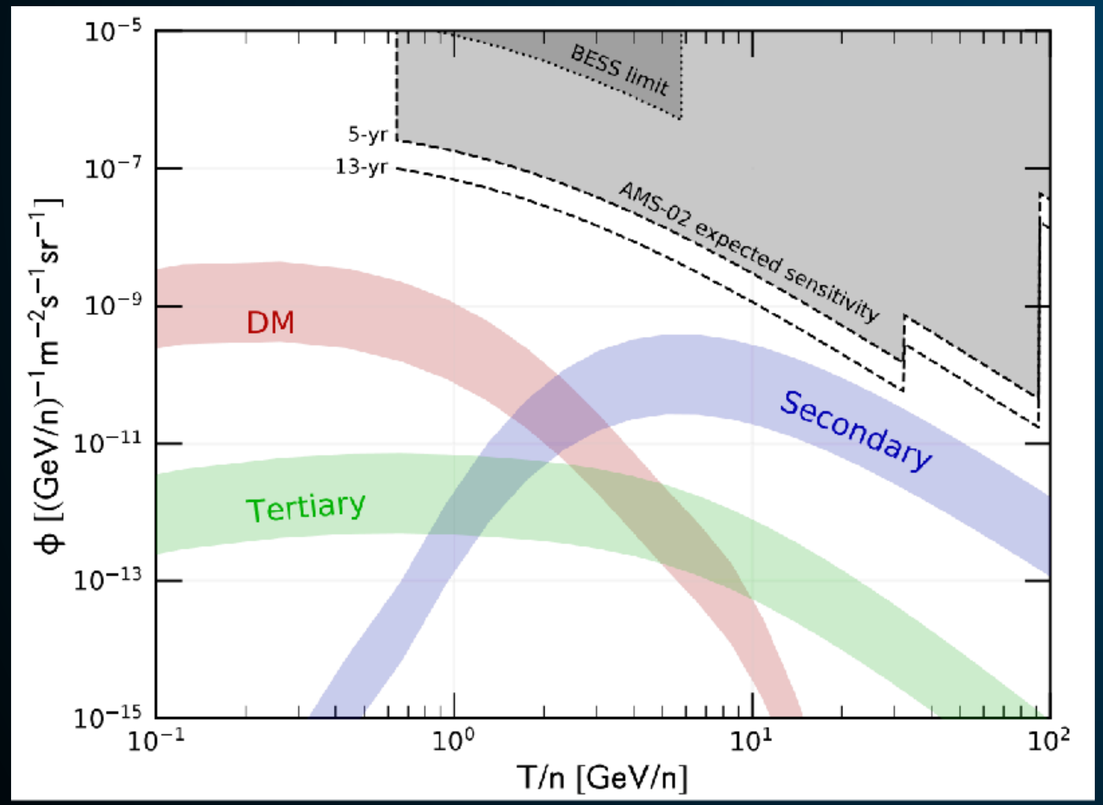
Note that for $^4\bar{He}$, projecting based on the statistics we have today, by using an additional 400 million core hours for simulation the background probability would be 10^{-4}. Simultaneously, continuing to run until 2023, which doubles the data sample, the background probability for $^4\bar{He}$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

slide from Sam Ting (La Palma Conference, April 9 2018)

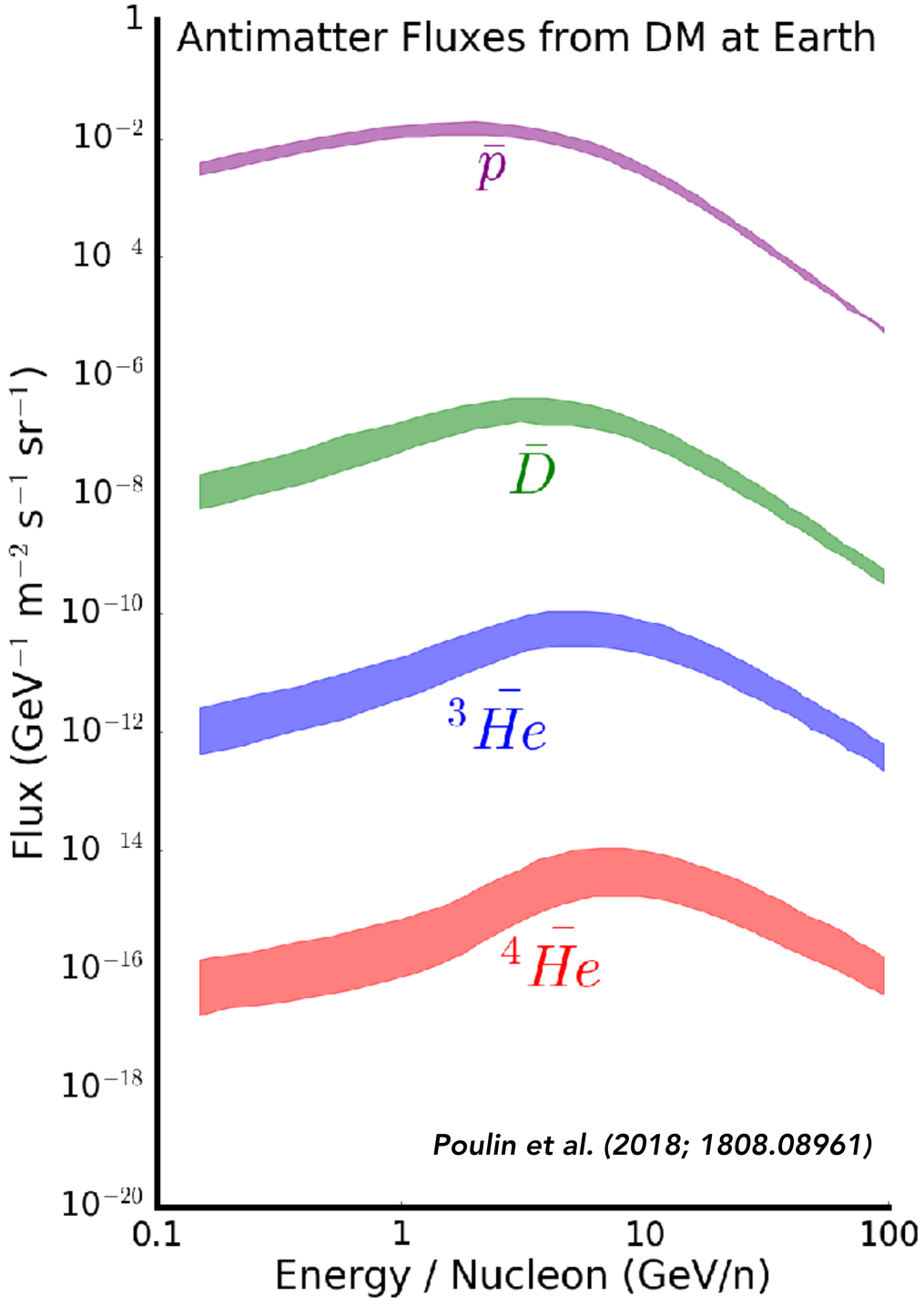
AntiNuclei - A Clean Search Strategy ?

Antihelium background even cleaner than antideuterons

But the flux is supposed to be <u>much</u> smaller.



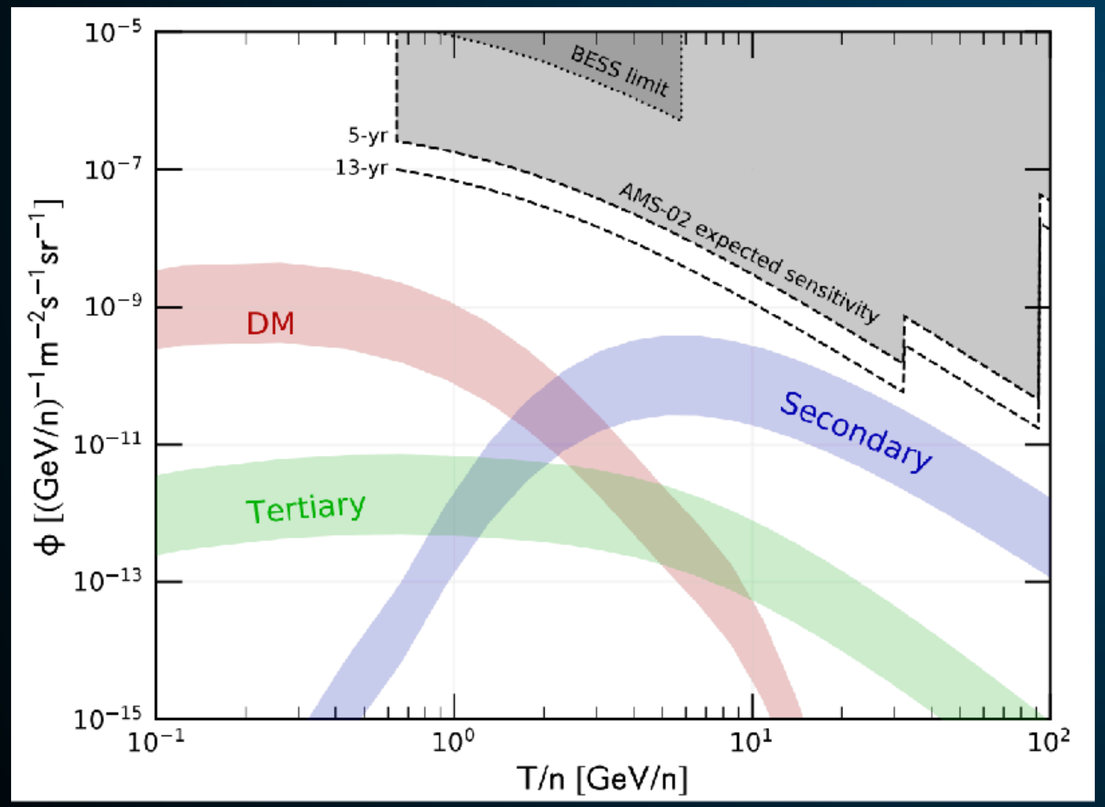
Korsmeier (2017; 1711.08465)



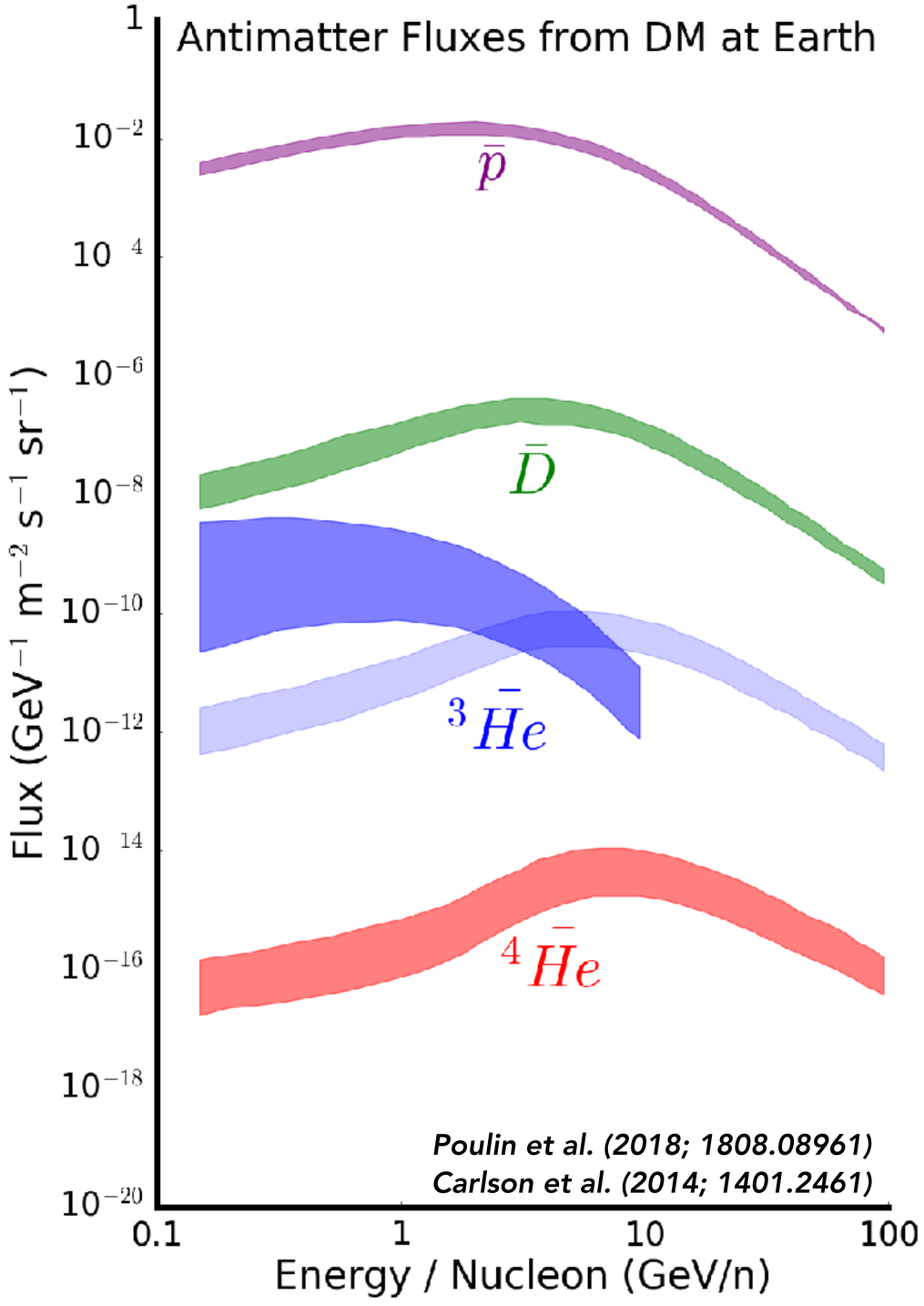
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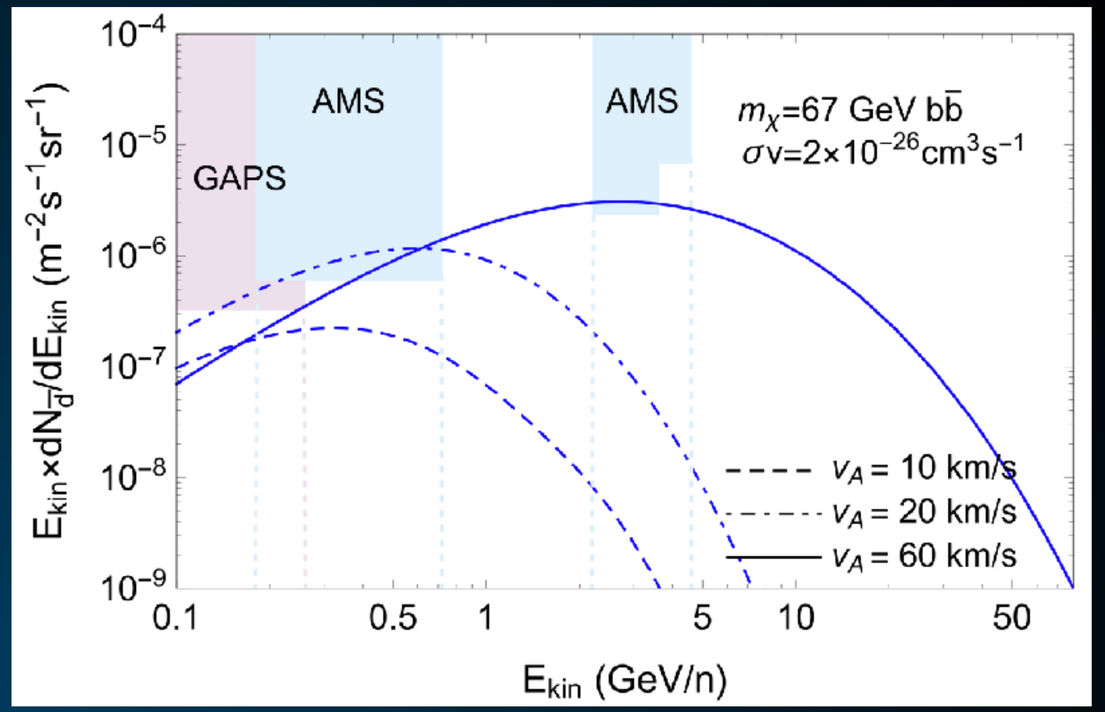
Poulin et al. (2018; 1808.08961)
Carlson et al. (2014; 1401.2461)

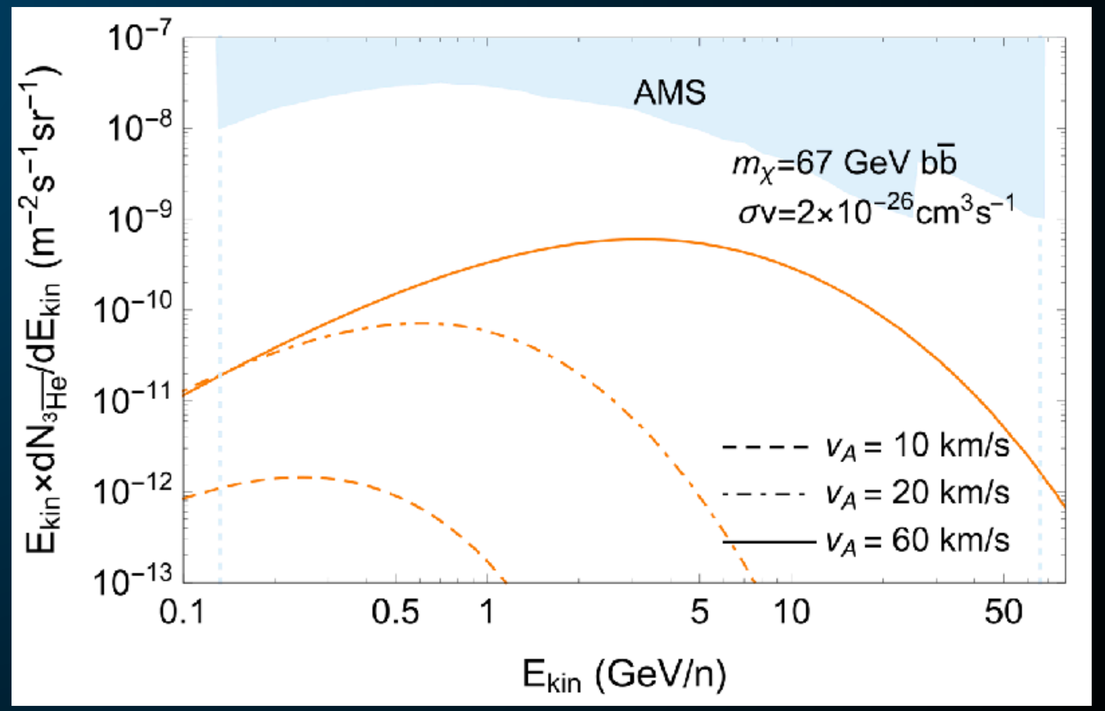
Astrophysical Enhancements!

The current event rates depend on the detector sensitivity to anti-Helium.

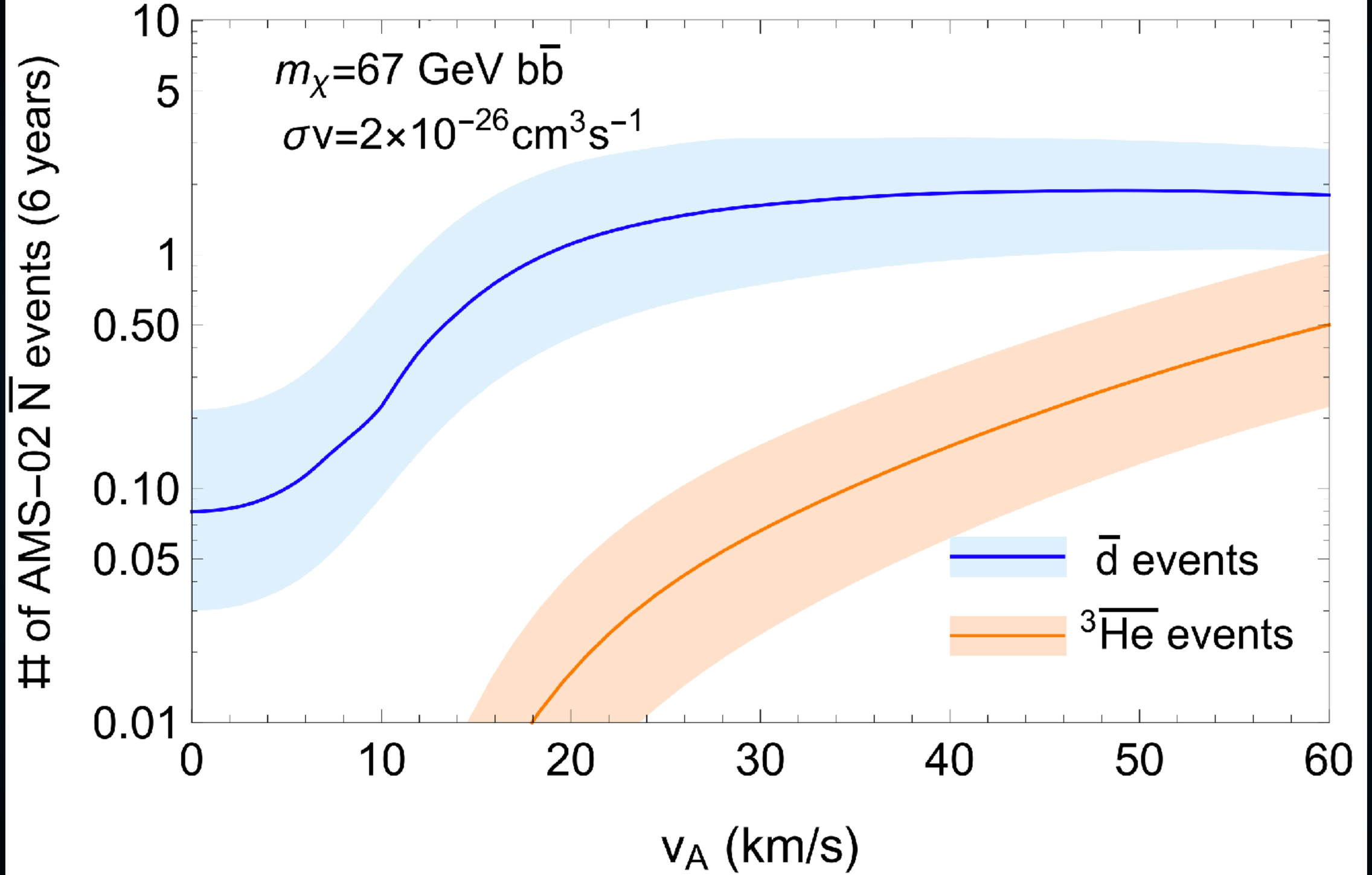
We lose many events because most anti-He are produced at energies that are too small to be detected.

Use re-acceleration to boost the anti-He energies into the detectable range!





Cholis, Linden, Hooper (2020; 2001.08749)


m_χ=67 GeV $b\bar{b}$
$\sigma v = 2\times10^{-26} cm^3 s^{-1}$
# of AMS-02 $\bar{N}$ events (6 years)
10
5
1
0.50
0.10
0.05
0.01
0
10
20
30
40
50
60
v_A (km/s)
$\bar{d}$ events
$^3\bar{He}$ events

Particle Physics Enhancements!

Dark Matter Annihilation Can Produce a Detectable Antihelium Flux through $\bar{\Lambda}_b$ Decays

Martin Wolfgang Winkler[1, *] and Tim Linden[1, †]

[1] *Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden*

Recent observations by the Alpha Magnetic Spectrometer (AMS-02) have tentatively detected a handful of cosmic-ray antihelium events. Such events have long been considered as smoking-gun evidence for new physics, because astrophysical antihelium production is expected to be negligible. However, the dark-matter-induced antihelium flux is also expected to fall below current sensitivities, particularly in light of existing antiproton constraints. Here, we demonstrate that a previously neglected standard model process — the production of antihelium through the displaced-vertex decay of $\bar{\Lambda}_b$-baryons — can significantly boost the dark matter induced antihelium flux. This process can triple the standard prompt-production of antihelium, and more importantly, entirely dominate the production of the high-energy antihelium nuclei reported by AMS-02.

[hep-ph] 29 Jun 2020

I. INTRODUCTION

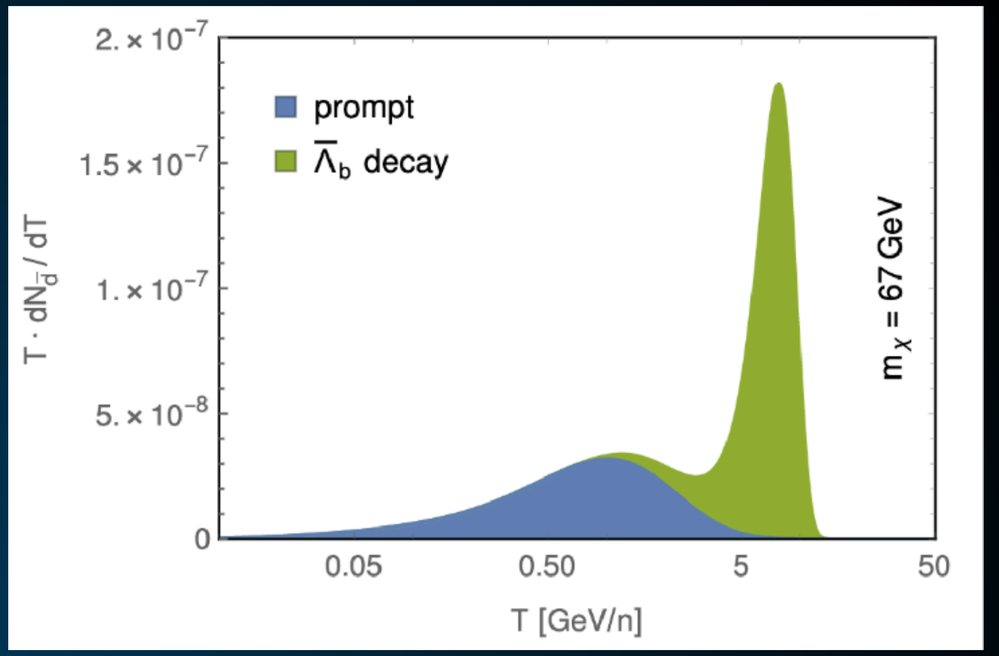
The detection of massive cosmic-ray antinuclei has long been considered a holy grail in searches for WIMP dark matter [1, 2]. Primary cosmic-rays from astrophysical sources are matter-dominated, accelerated by nearby supernova, pulsars, and other extreme objects. The secondary cosmic-rays produced by the hadronic interactions of primary cosmic-rays can include an antinuclei component, but the flux is highly suppressed by baryon number conservation and kinematic constraints [3, 4]. Dark matter annihilation, on the other hand, occurs within the rest frame of the Milky Way and produces equal baryon and antibaryon fluxes [1, 5–7]

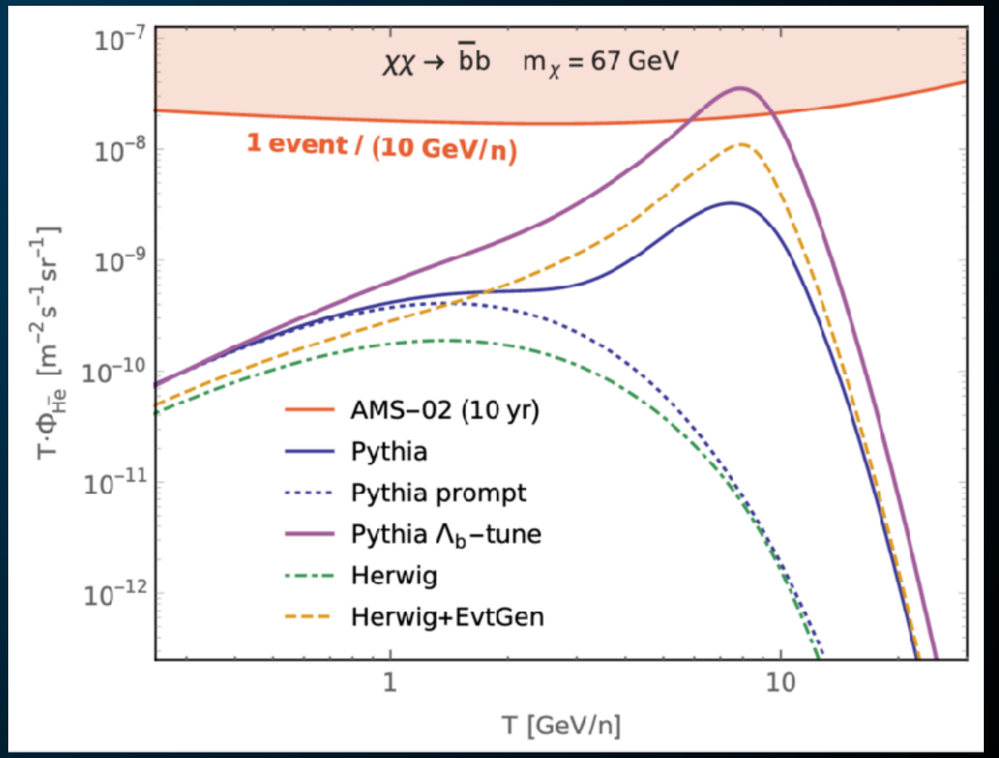
In this *letter*, we challenge the current understanding that standard dark matter annihilation models cannot produce a measurable antihelium flux. Our analysis examines a known, and potentially dominant, antinuclei production mode which has been neglected by previous literature – the production of antihelium through the off-vertex decays of the $\bar{\Lambda}_b$. Such bottom baryons are generically produced in dark matter annihilation channels involving b quarks. Their decays efficiently produce heavy antinuclei due to their antibaryon number and 5.6 GeV rest-mass, which effectively decays to multi-nucleon states with small relative momenta. Intriguingly, because any $^3\overline{\text{He}}$ produced by $\bar{\Lambda}_b$ inherits its boost factor, these nuclei can obtain the large center-of-mass momenta necessary to fit AMS-02 data [13].

Particle Physics Enhancements!

Previous analyses have missed the (potentially) dominant contribution to anti-Helium production.

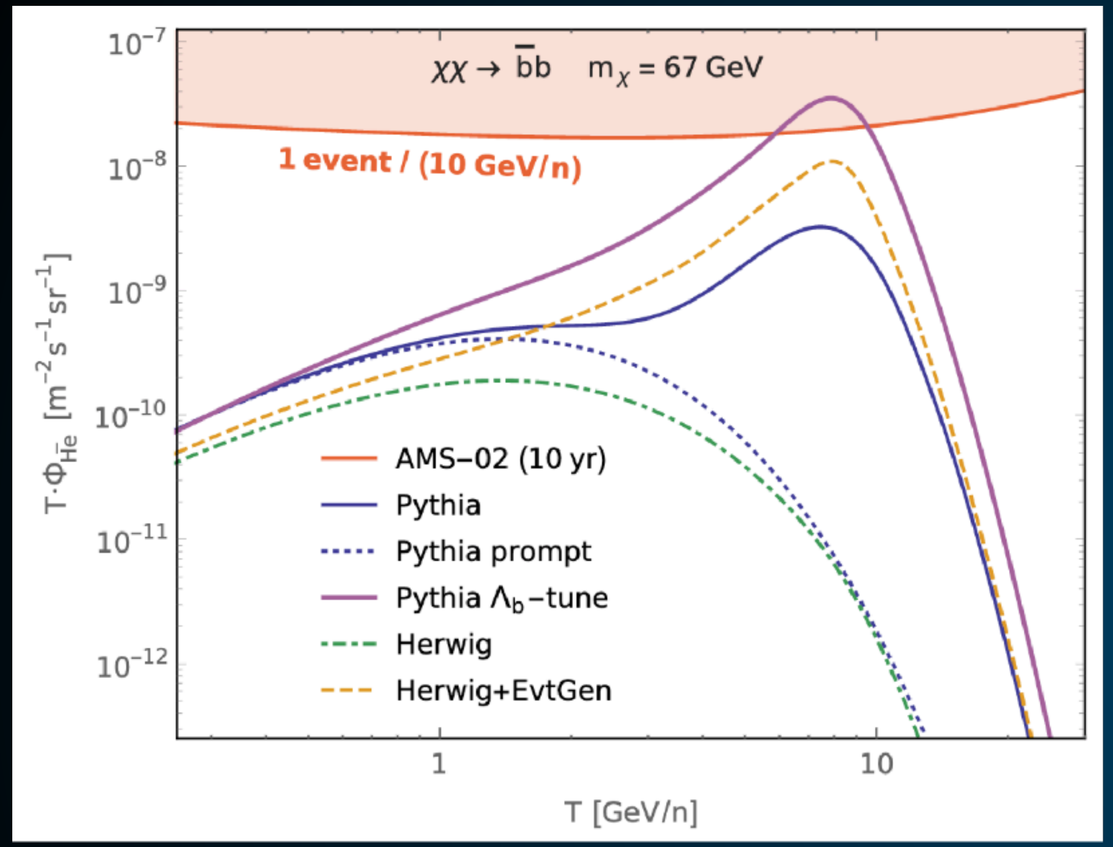
The displaced-vertex decays of Lambda_b baryons potentially boosts the detectable AMS-02 signal by orders of magnitude!

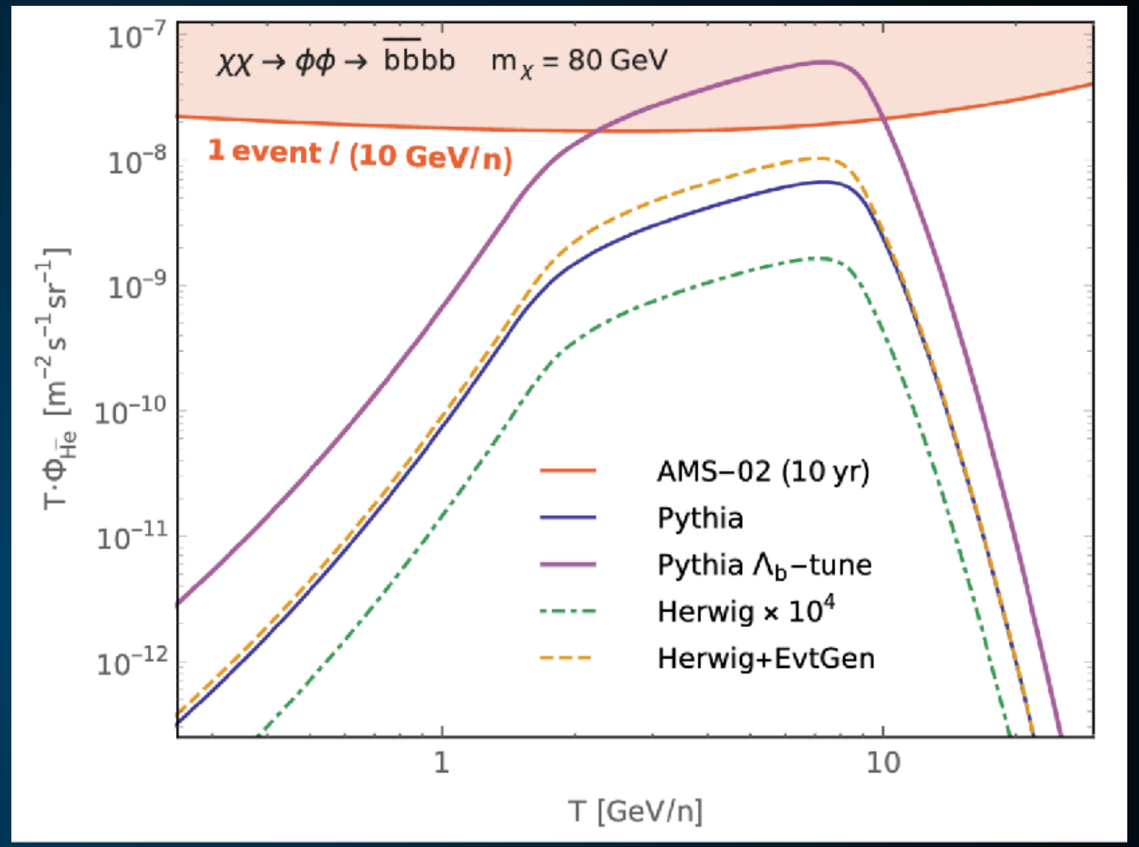




Winkler & Linden (2020; 2020.16251)

Particle Physics Enhancements!

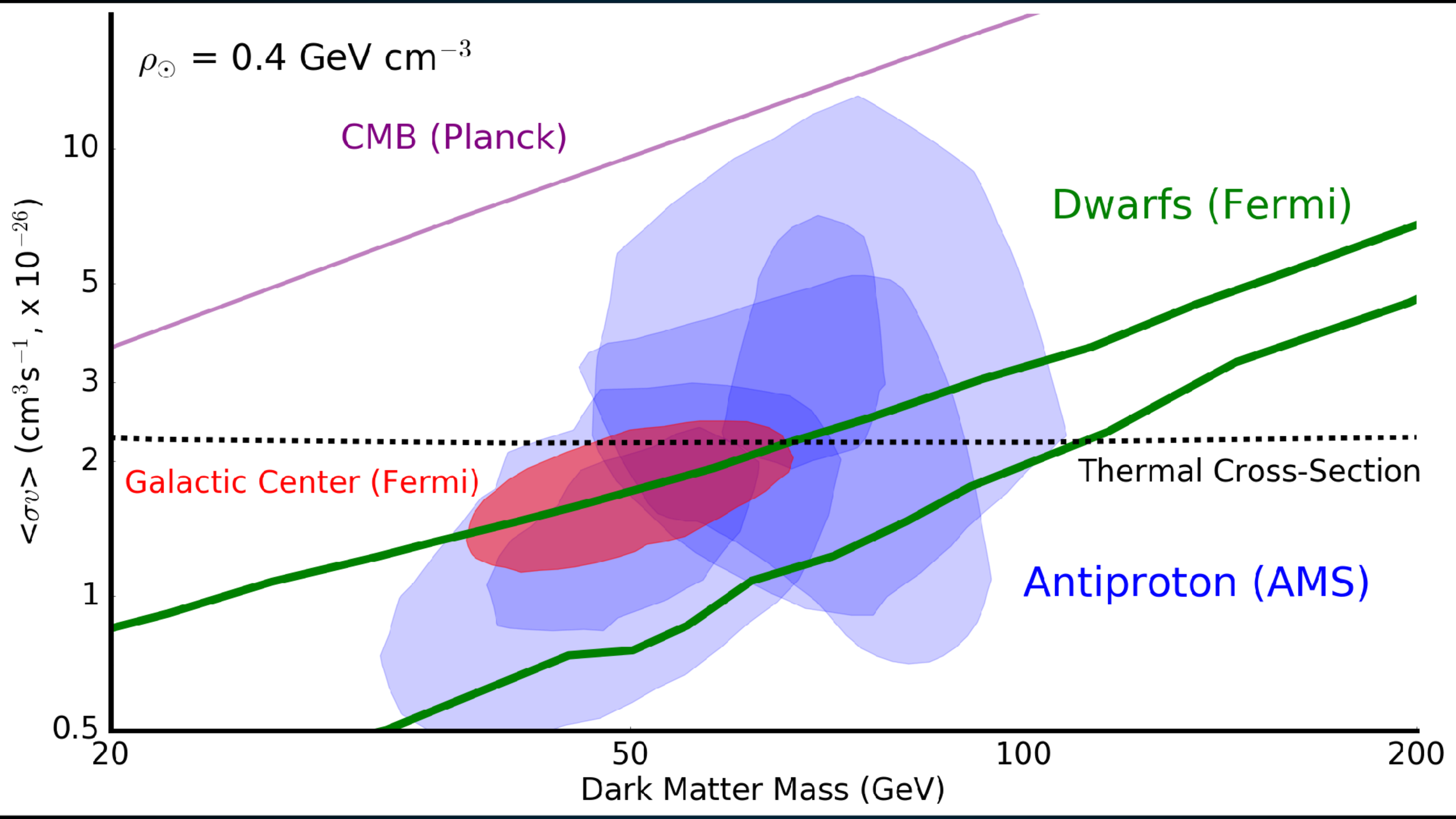




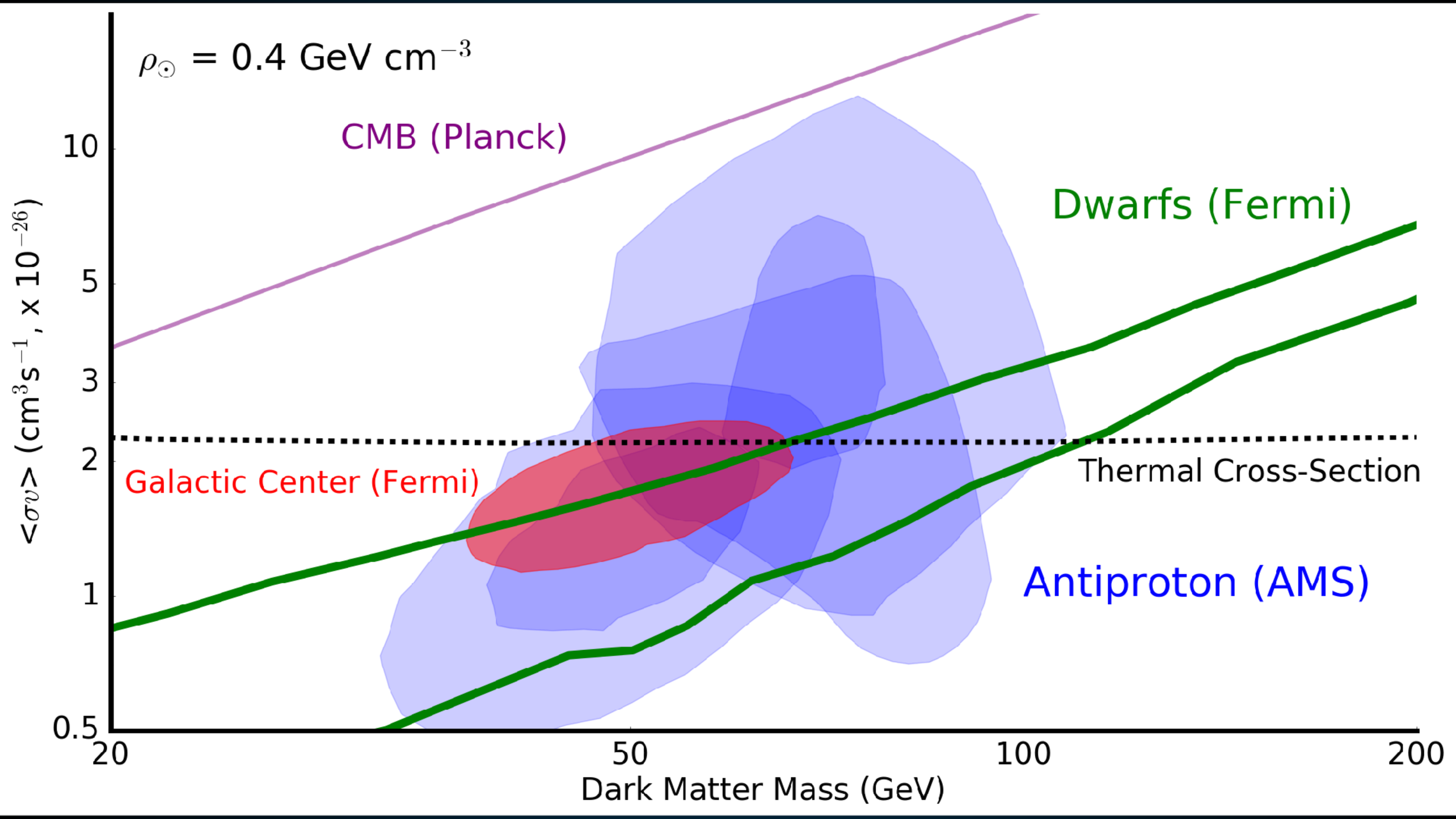
Generator	P	P [Λ_b-tune]	H	H+EvtGen
$^3\overline{\text{He}}$ events	0.1 (0.007)	0.9	0.003	0.3
$\bar{d}$ events	3.7 (3.5)	4.2	1.7	2.1

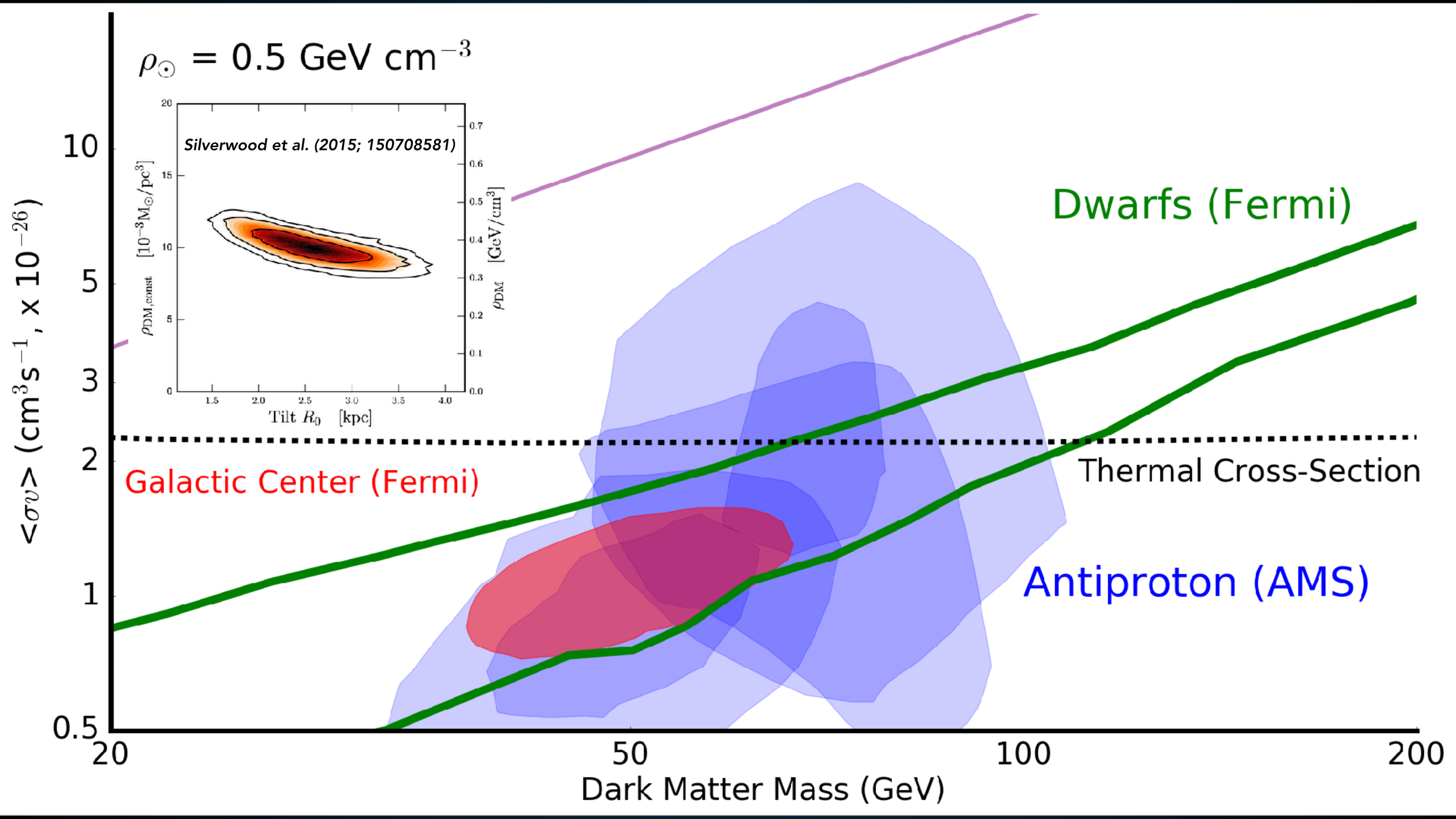
Winkler & Linden (2020; 2020.16251)

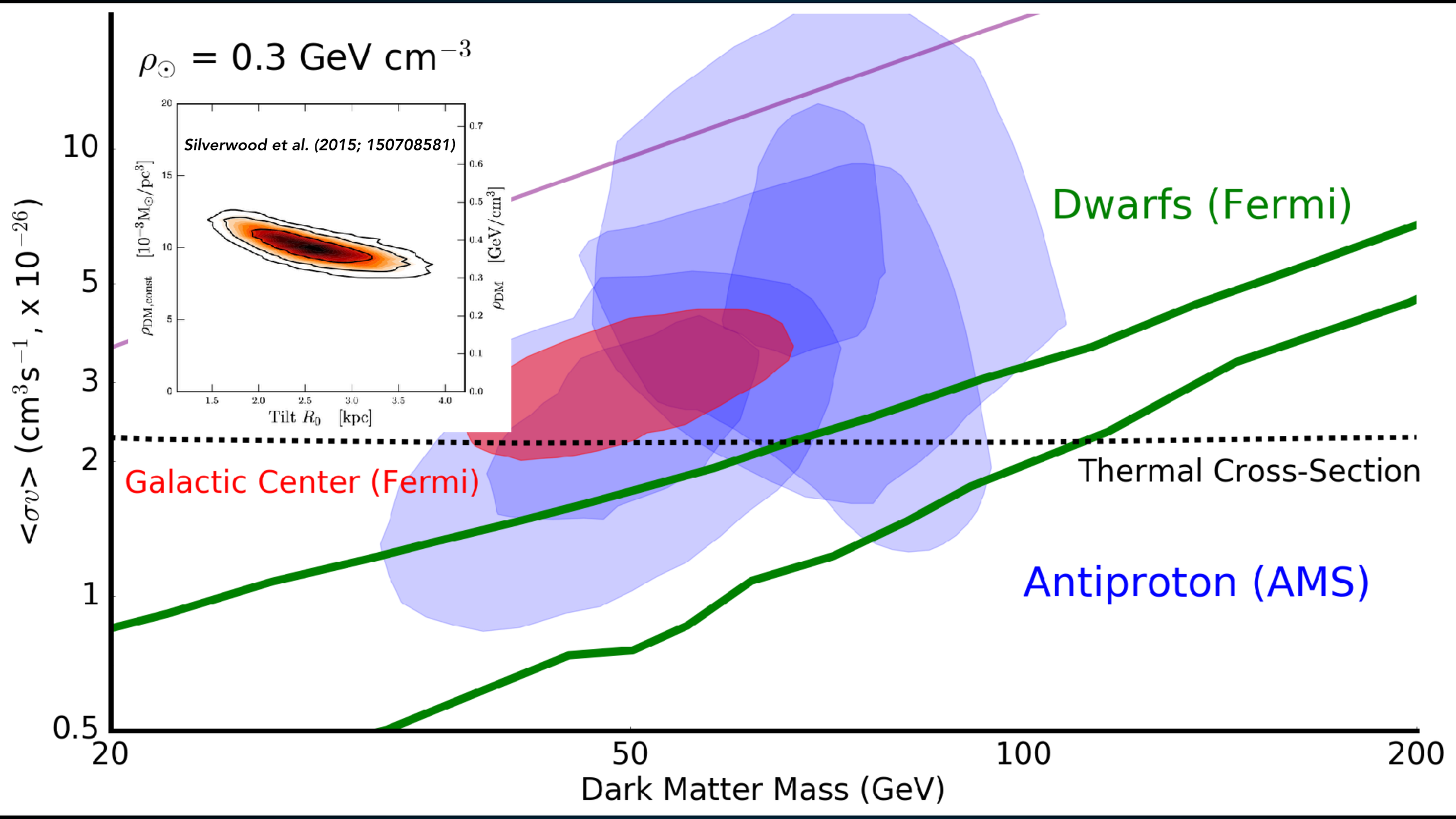

WHERE
ARE
WE NOW?

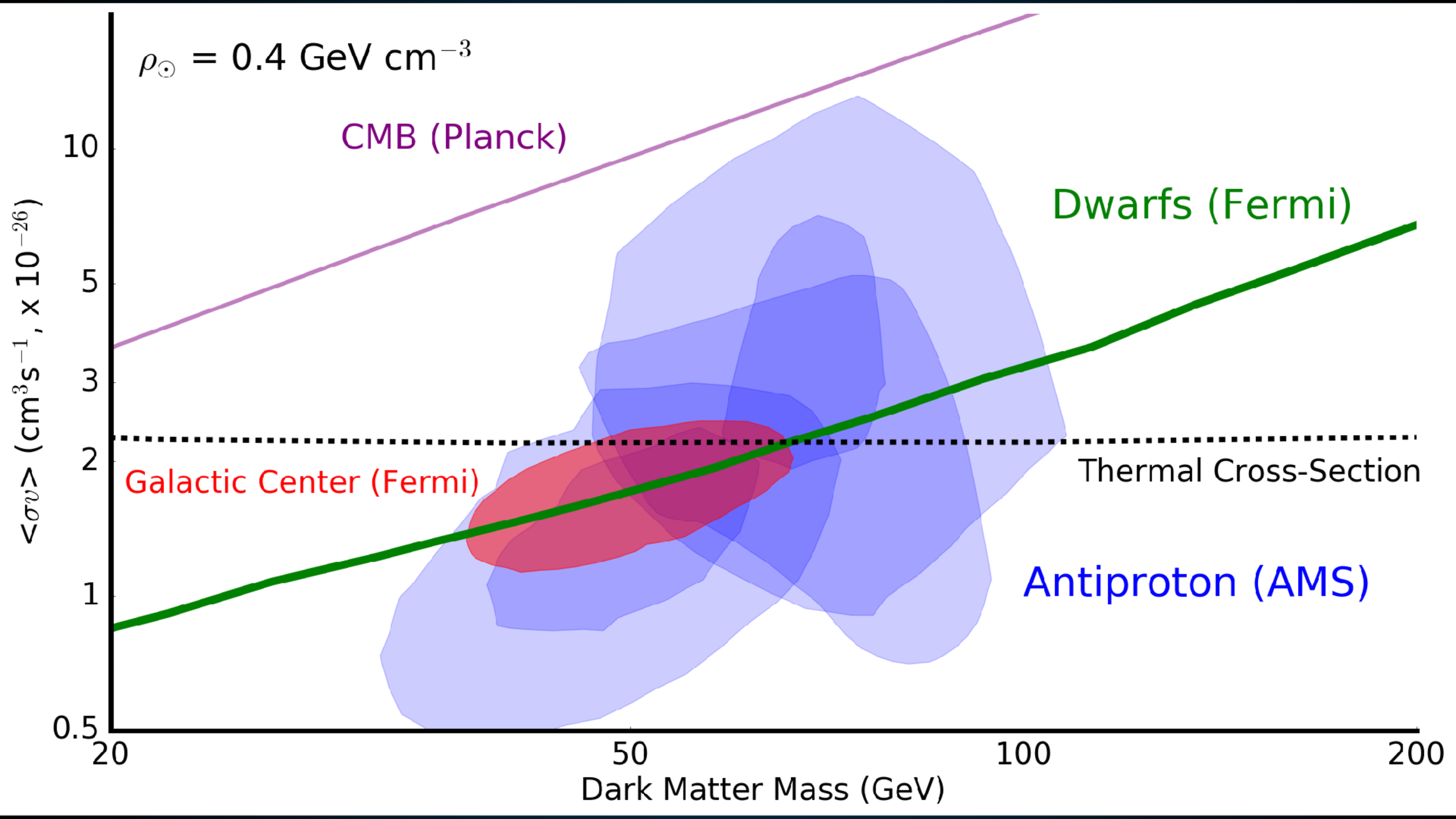

$\rho_\odot$ = 0.4 GeV cm^{-3}
CMB (Planck)
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
10
5
3
2
1
0.5
20
50
100
200
Dark Matter Mass (GeV)

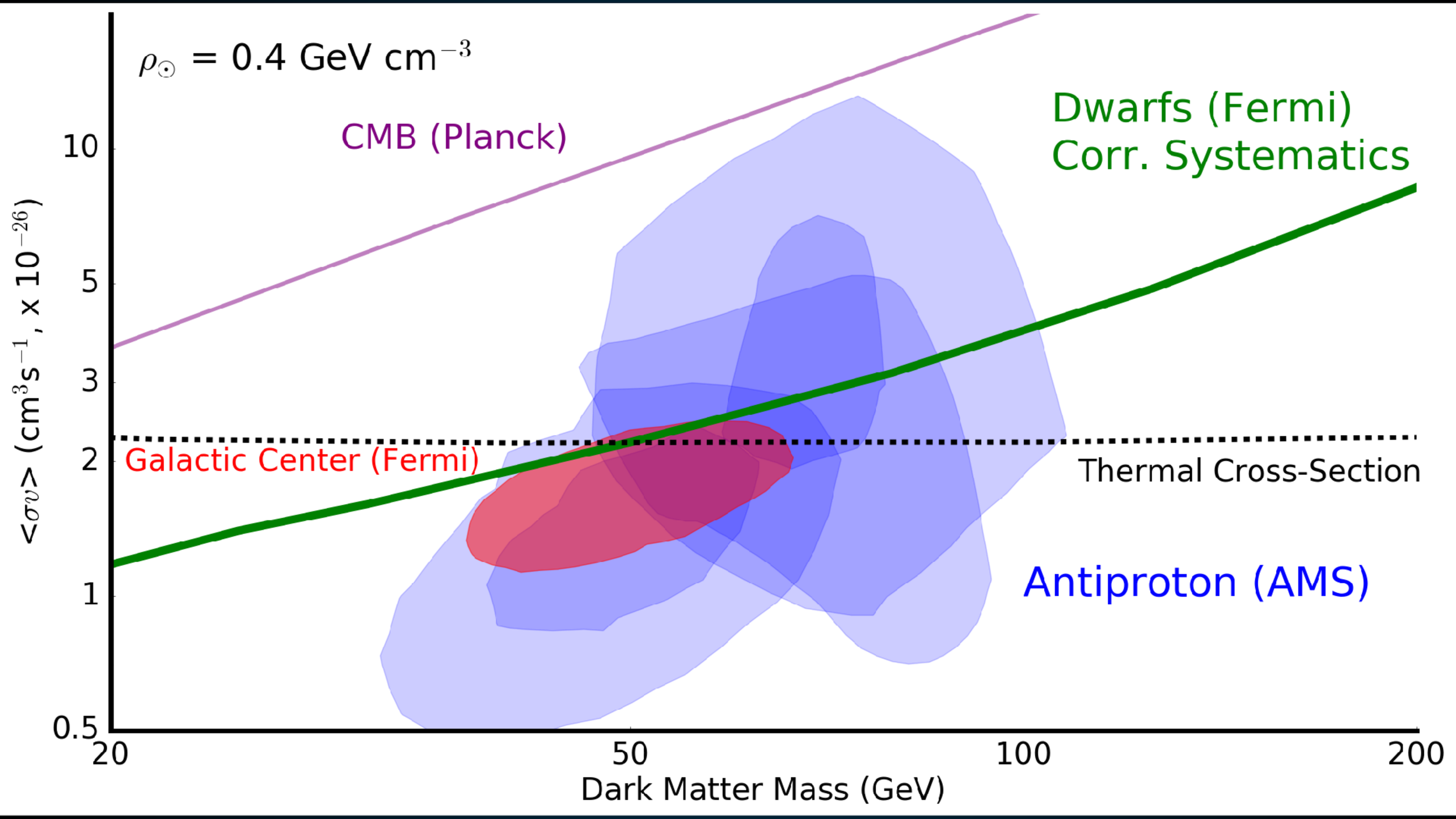


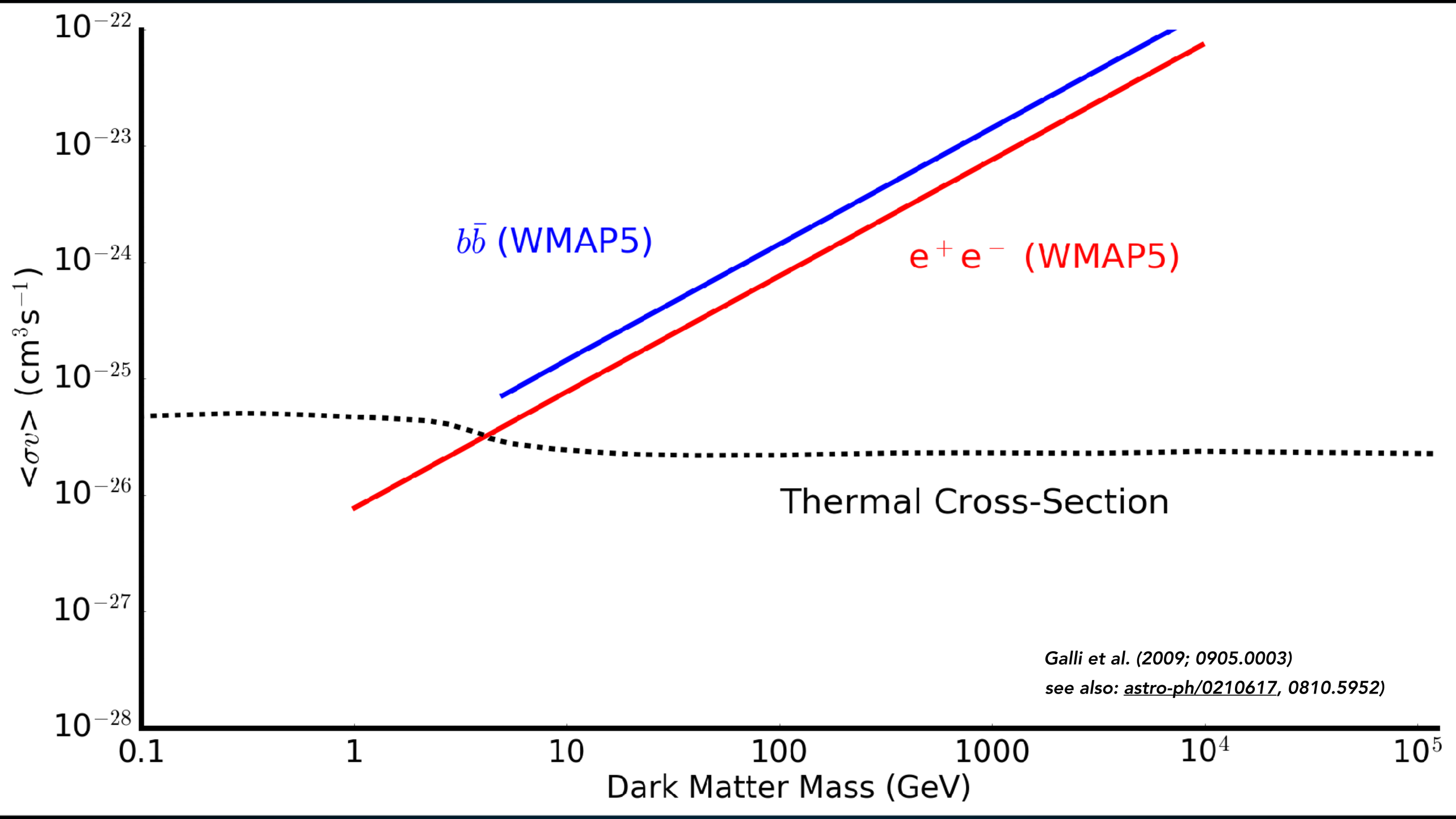

$\rho_\odot$ = 0.4 GeV cm^{-3}
CMB (Planck)
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
10
5
3
2
1
0.5
20
50
100
200
Dark Matter Mass (GeV)


$\rho_\odot$ = 0.5 GeV cm^{-3}
Silverwood et al. (2015; 150708581)
$\rho_{\rm DM,const}$ [10^{-3}M$_\odot$/pc^3]
$\rho_{\rm DM}$ [GeV/cm^3]
Tilt R_0 [kpc]
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
Dark Matter Mass (GeV)
10
5
3
2
1
0.5
20
50
100
200


$\rho_\odot$ = 0.3 GeV cm^{-3}
Silverwood et al. (2015; 150708581)
$\rho_{\rm DM,const}$ [10^{-3}M$_\odot$/pc^3]
$\rho_{\rm DM}$ [GeV/cm^3]
Tilt R_0 [kpc]
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
Dark Matter Mass (GeV)

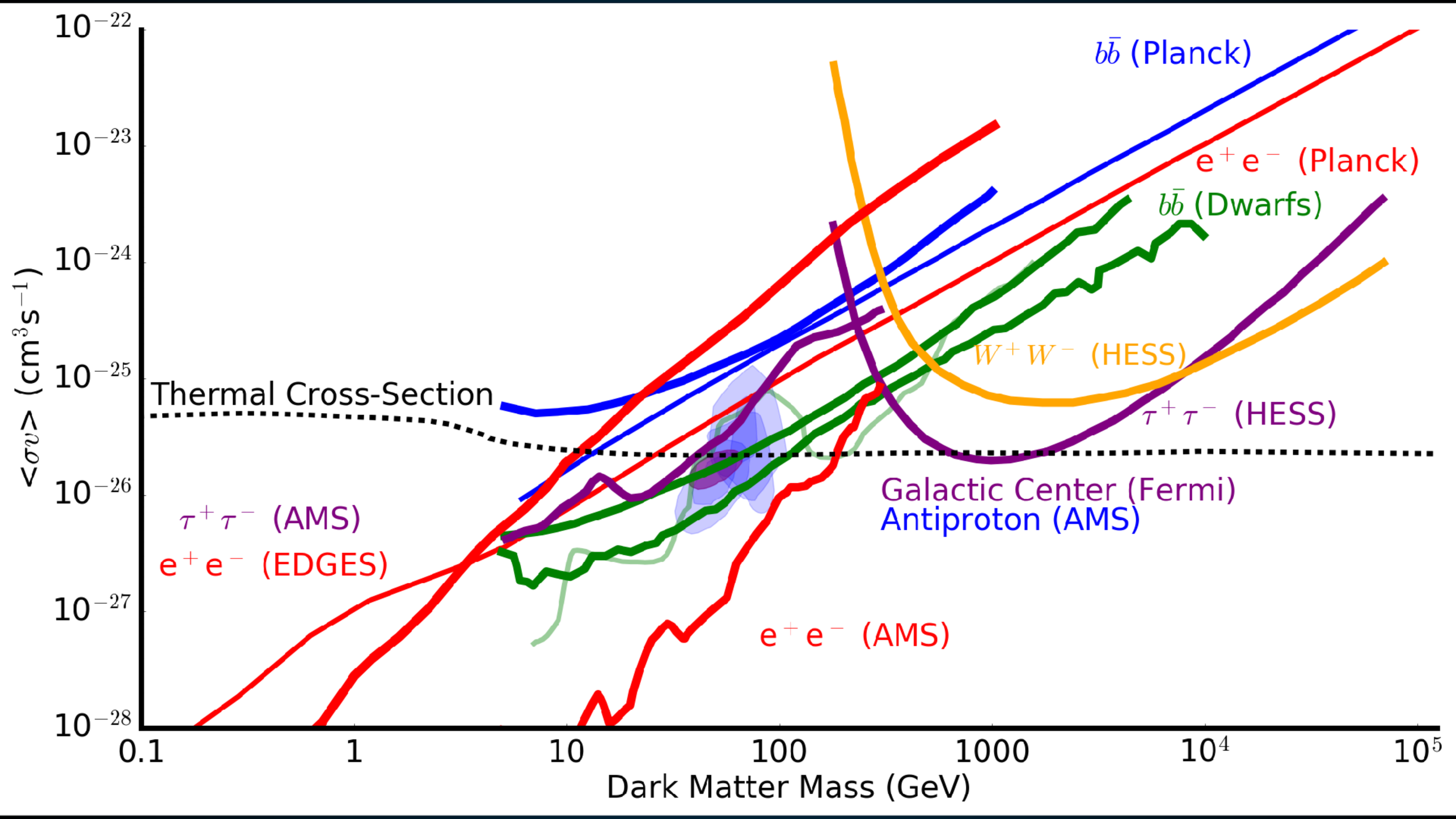

$\rho_\odot$ = 0.4 GeV cm^{-3}
CMB (Planck)
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
10
5
3
2
1
0.5
20
50
100
200
Dark Matter Mass (GeV)


$\rho_\odot$ = 0.4 GeV cm^{-3}
CMB (Planck)
Dwarfs (Fermi)
Corr. Systematics
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
$<\sigma v>$ (cm^{3}s^{-1}, x 10^{-26})
10
5
3
2
1
0.5
20
50
100
200
Dark Matter Mass (GeV)



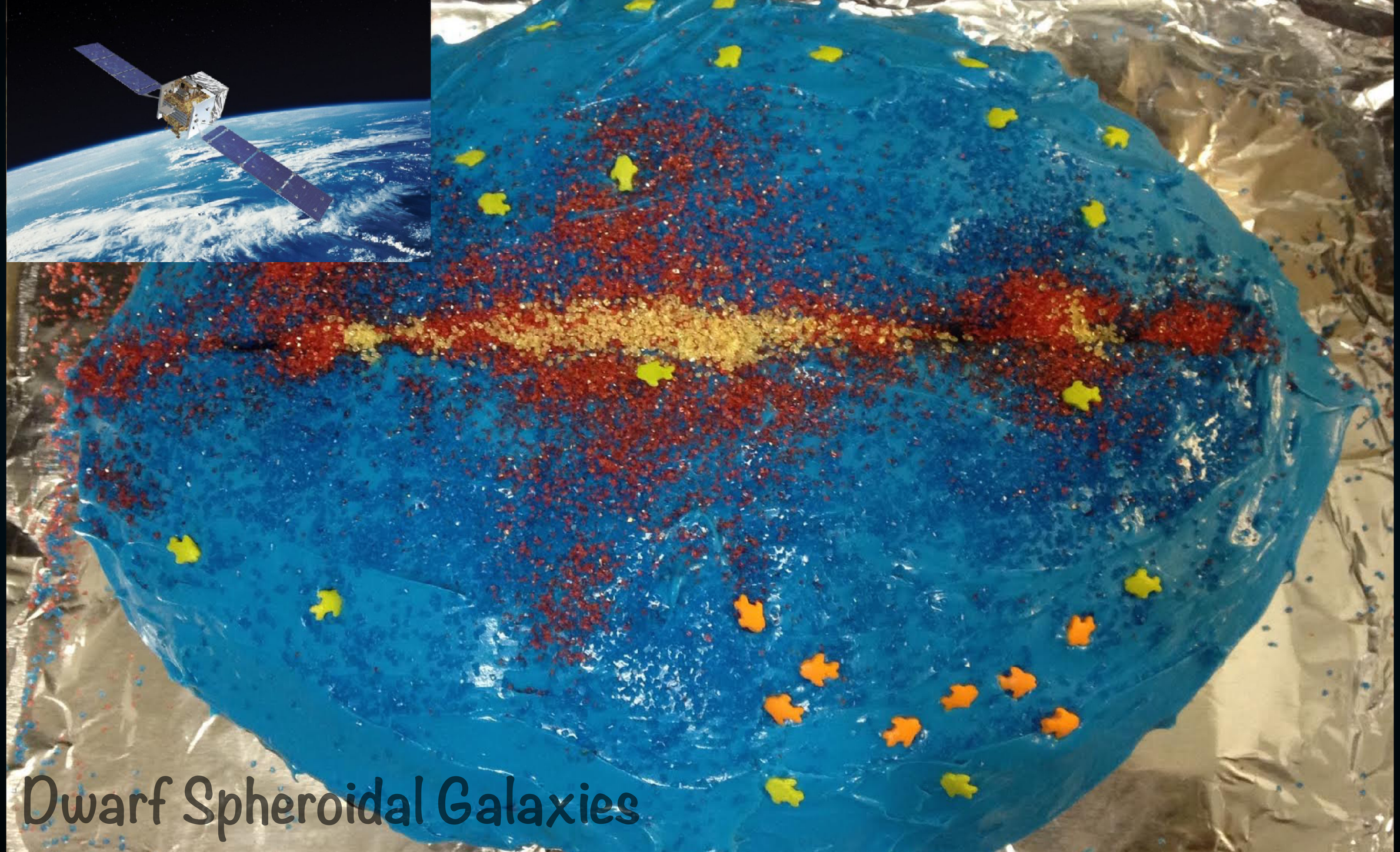
Galli et al. (2009; 0905.0003)

see also: astro-ph/0210617, 0810.5952)

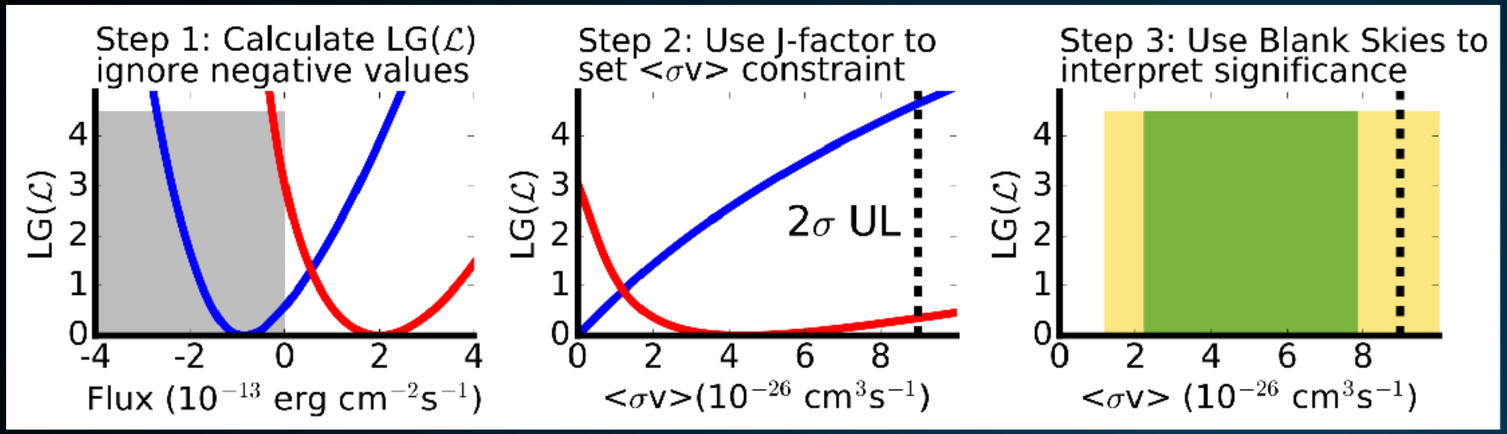

10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ ($cm^3 s^{-1}$)
0.1
1
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)
$b\bar{b}$ (Planck)
e^+e^- (Planck)
$b\bar{b}$ (Dwarfs)
W^+W^- (HESS)
$\tau^+\tau^-$ (HESS)
Thermal Cross-Section
Galactic Center (Fermi)
Antiproton (AMS)
$\tau^+\tau^-$ (AMS)
e^+e^- (EDGES)
e^+e^- (AMS)



Extra Slides


Dwarf Spheroidal Galaxies

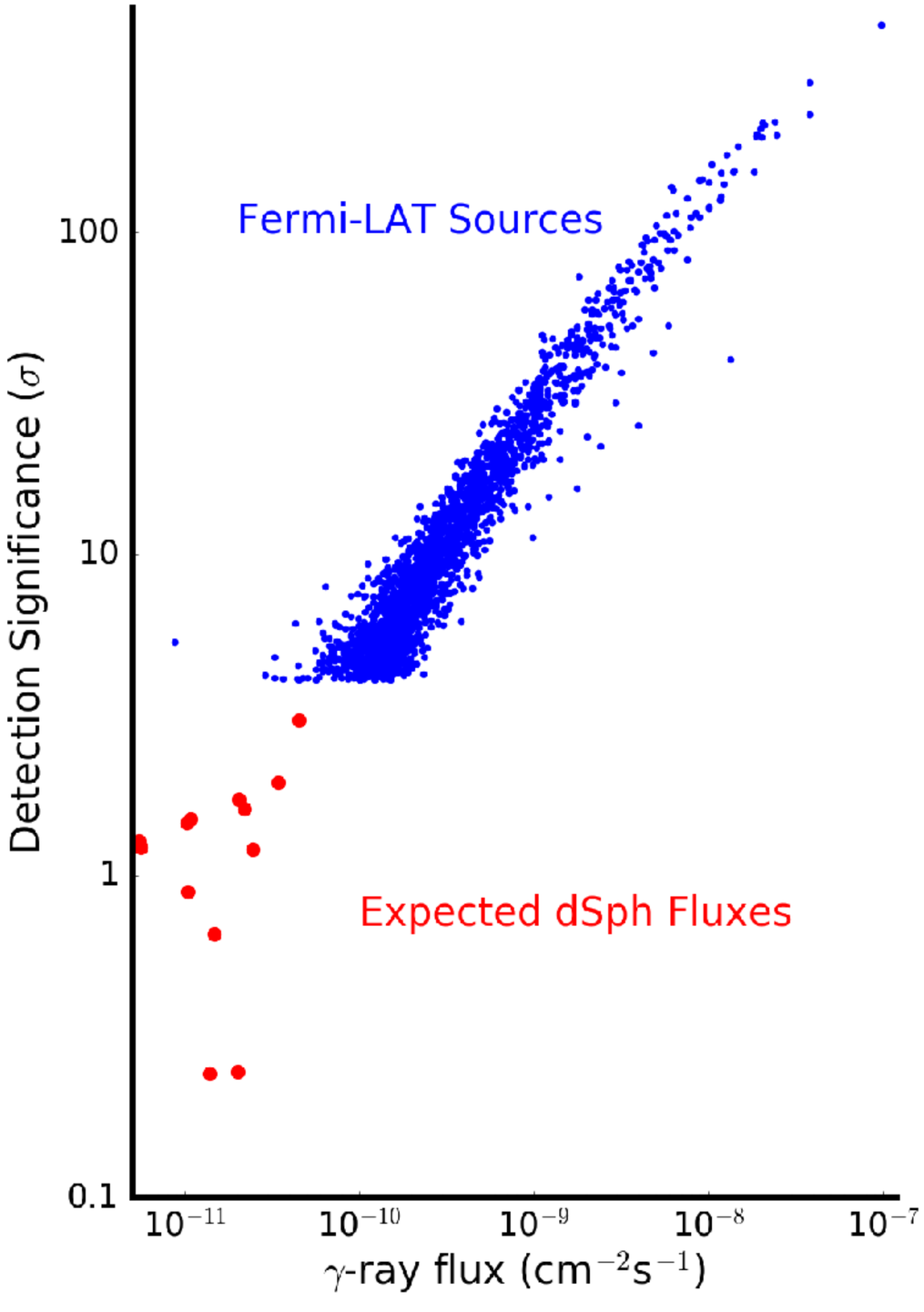
Dwarf Spheroidal Galaxies

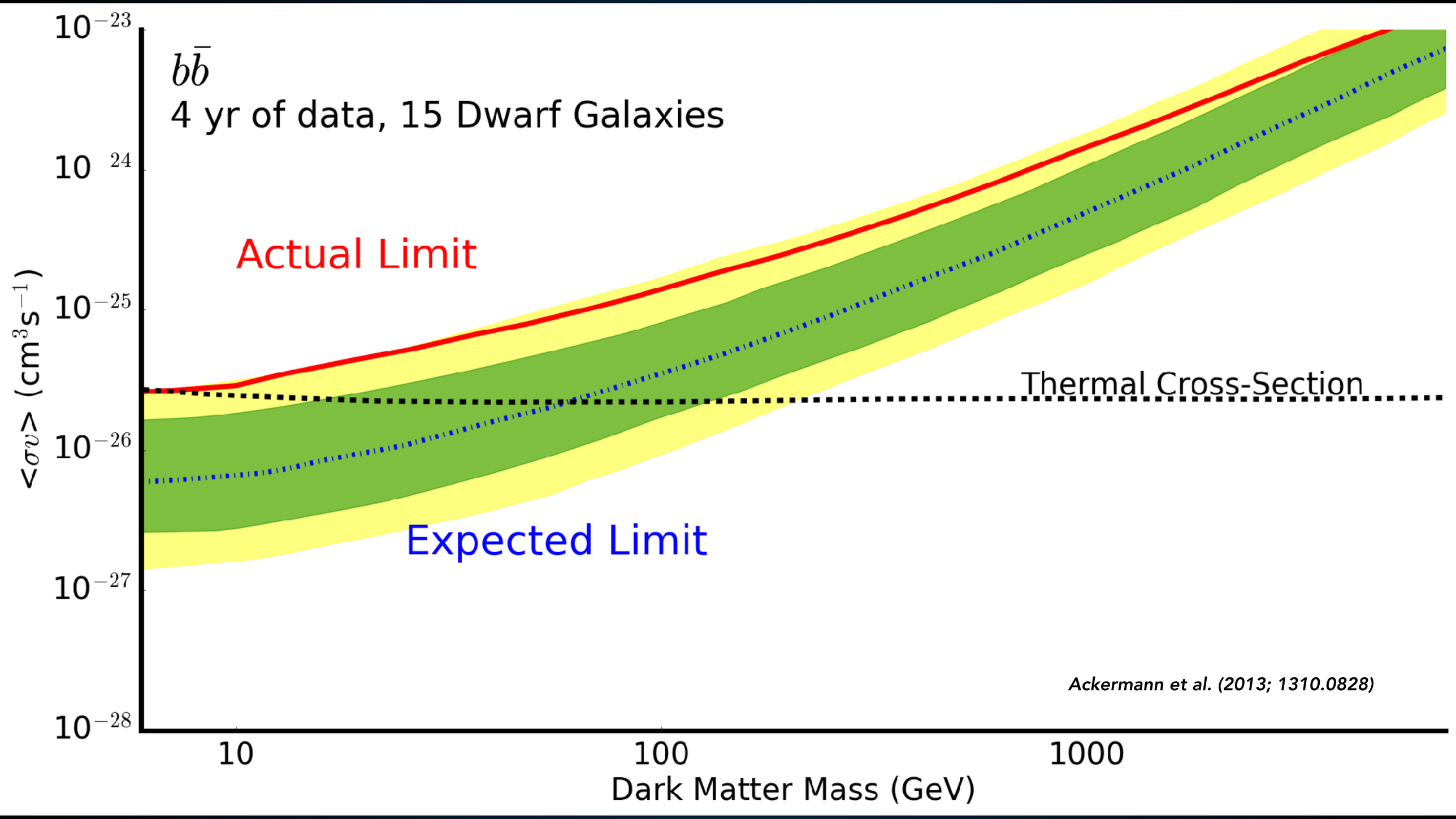


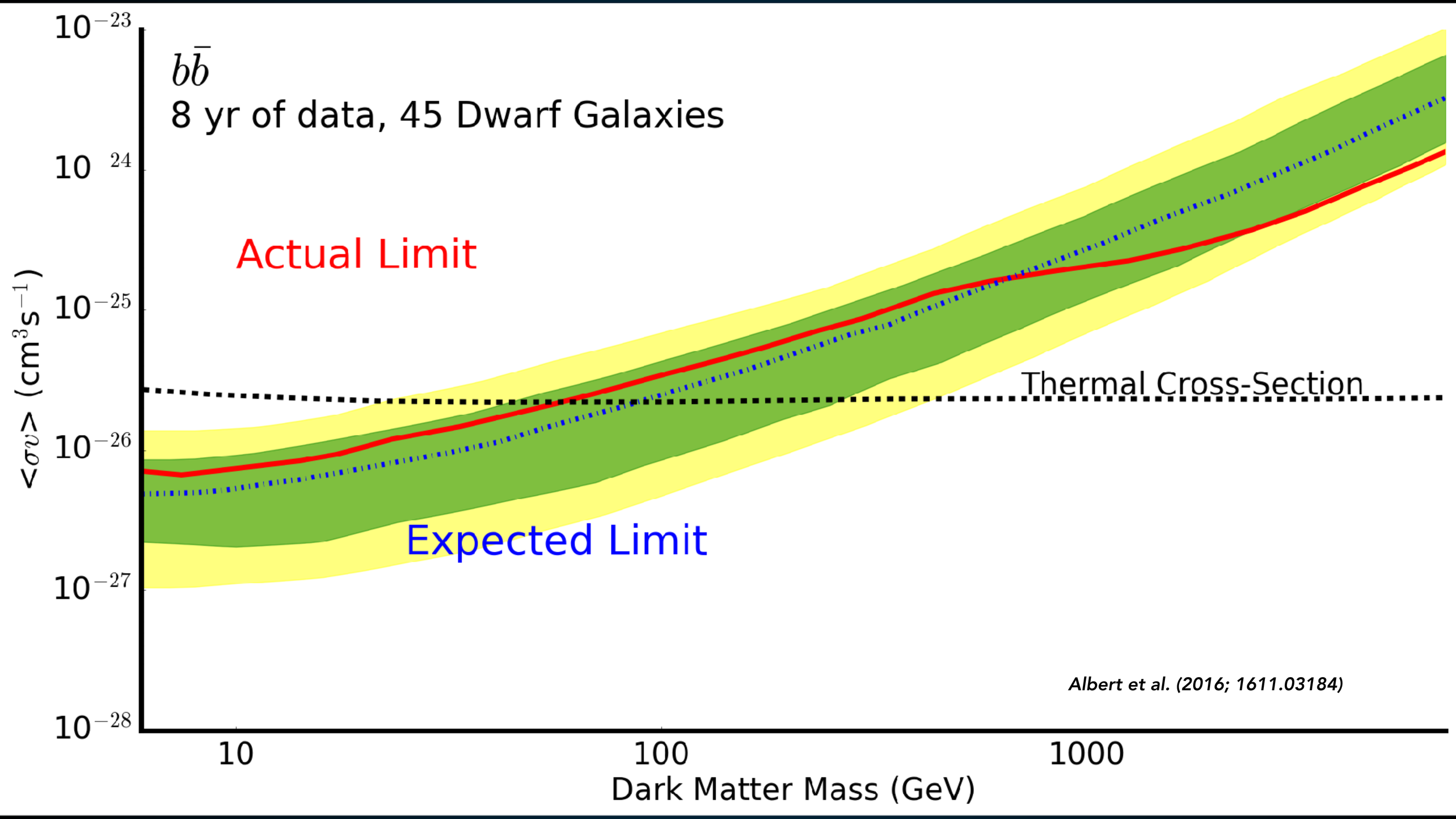
No Astrophysical Background from Dwarfs!

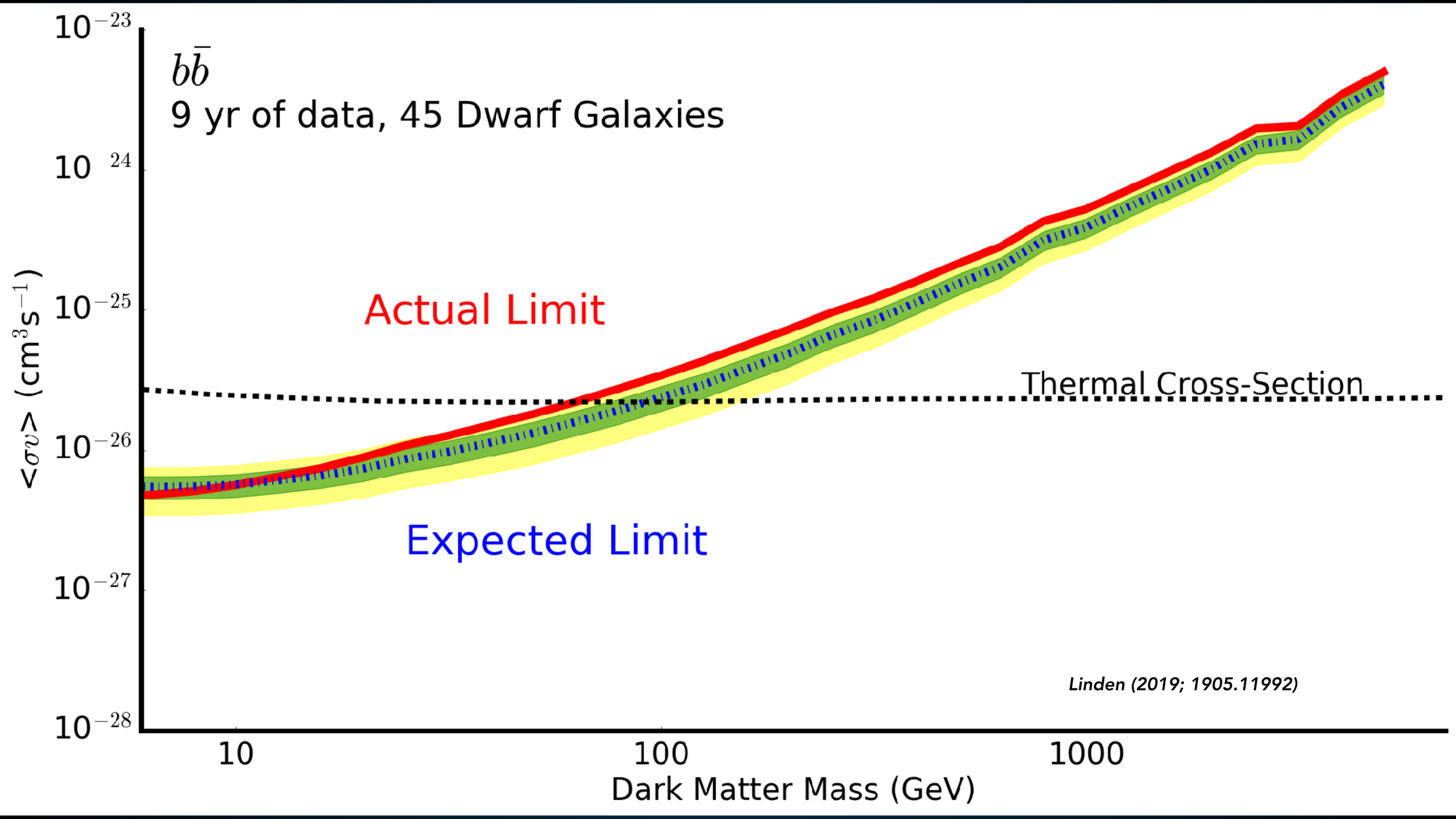
Individual dwarfs are dim

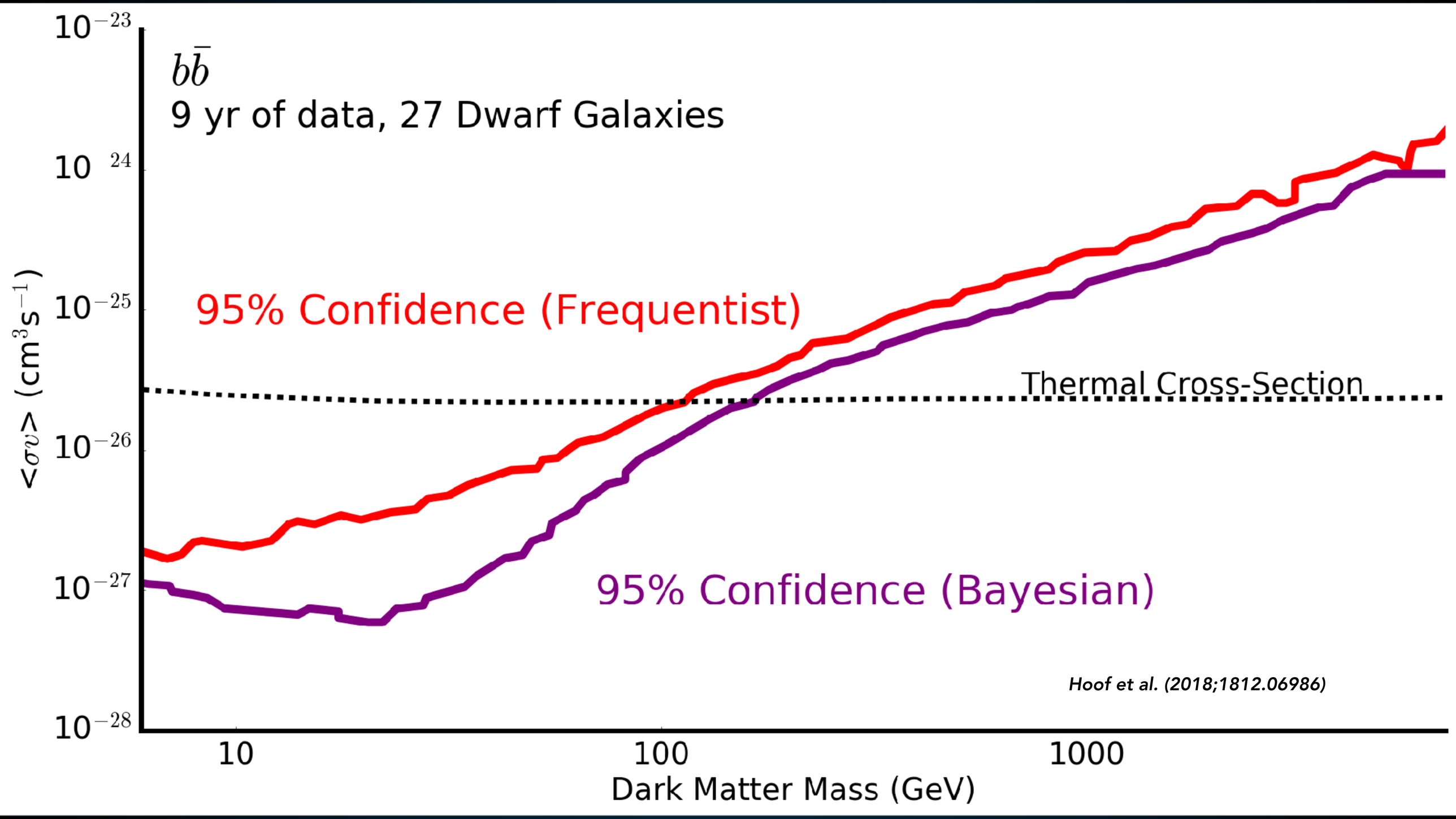
Need to combine observations of multiple dwarfs to constrain thermal cross-section

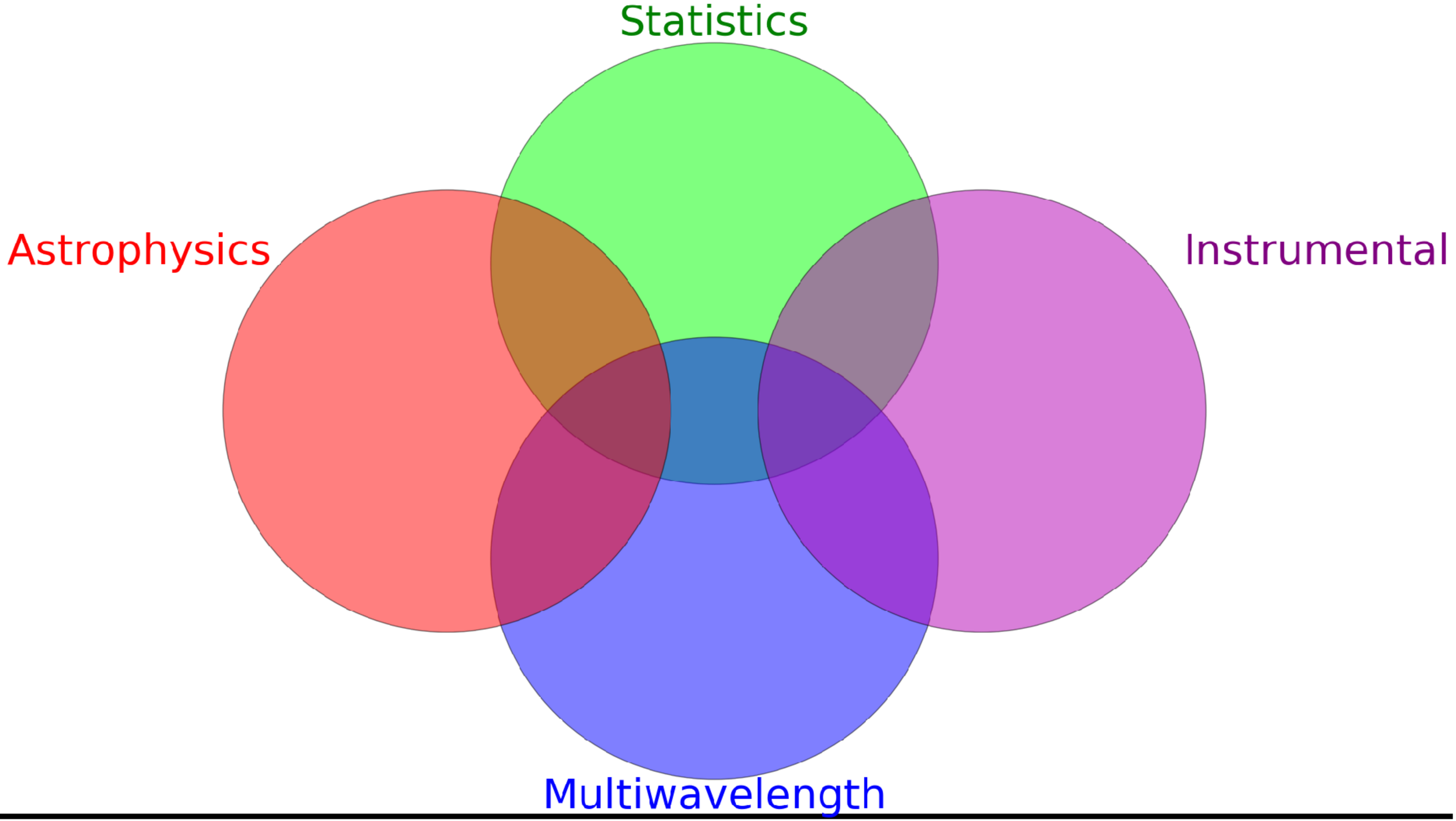


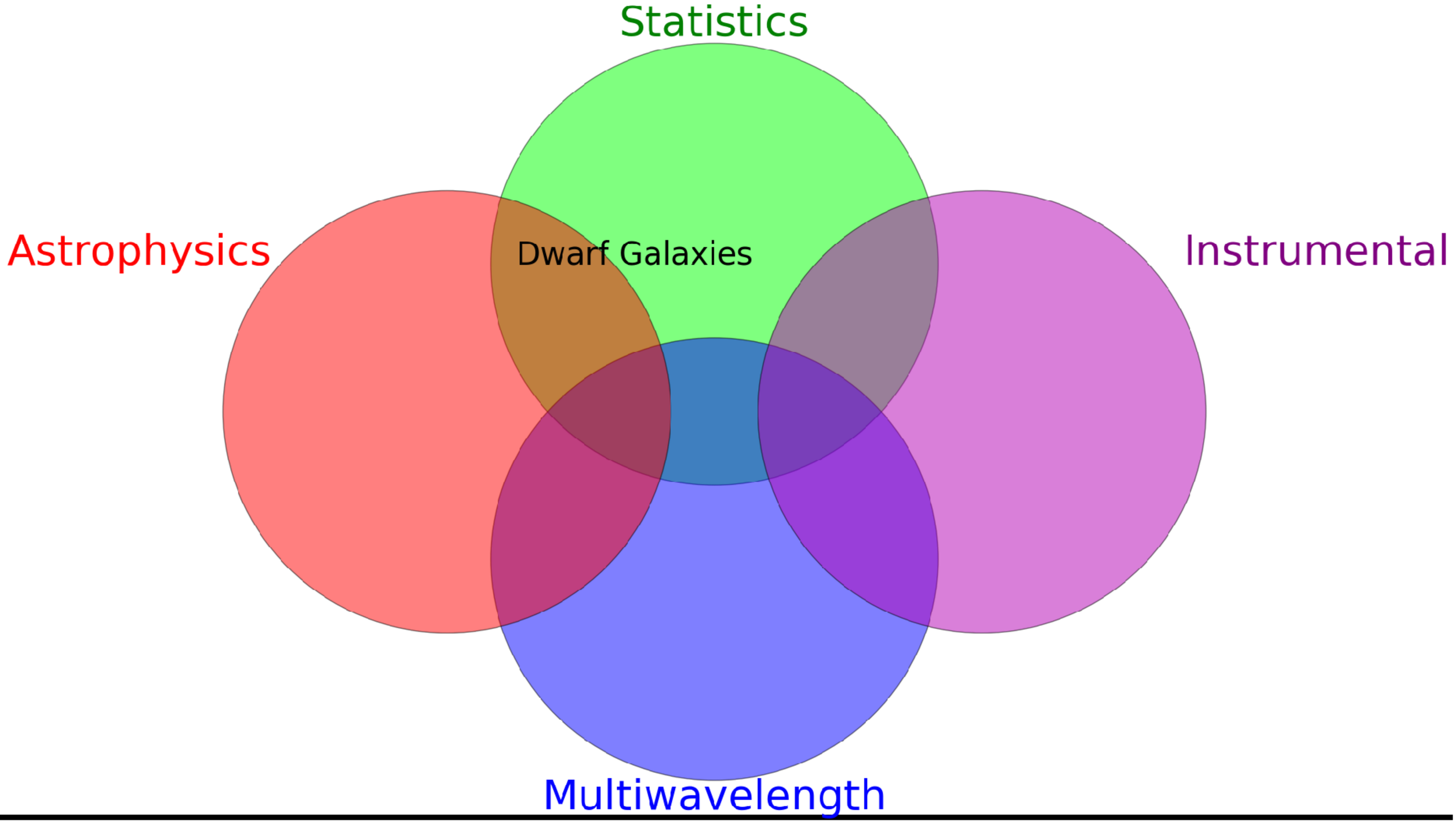

$b\bar{b}$
4 yr of data, 15 Dwarf Galaxies
Actual Limit
Expected Limit
Thermal Cross-Section
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ ($cm^3 s^{-1}$)
10
100
1000
Dark Matter Mass (GeV)
Ackermann et al. (2013; 1310.0828)

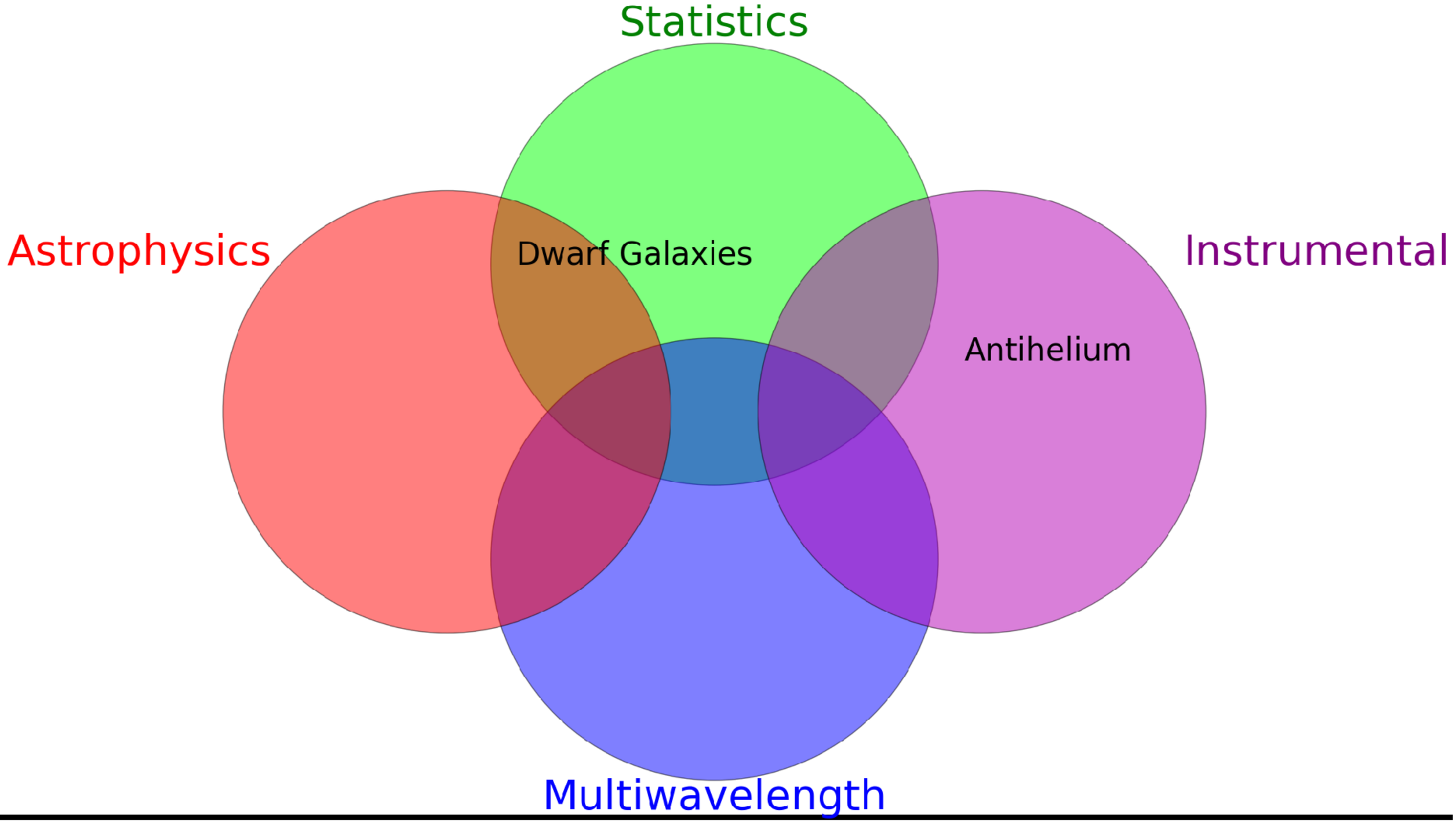

$b\bar{b}$
8 yr of data, 45 Dwarf Galaxies
Actual Limit
Expected Limit
Thermal Cross-Section
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ ($cm^3 s^{-1}$)
10
100
1000
Dark Matter Mass (GeV)
Albert et al. (2016; 1611.03184)

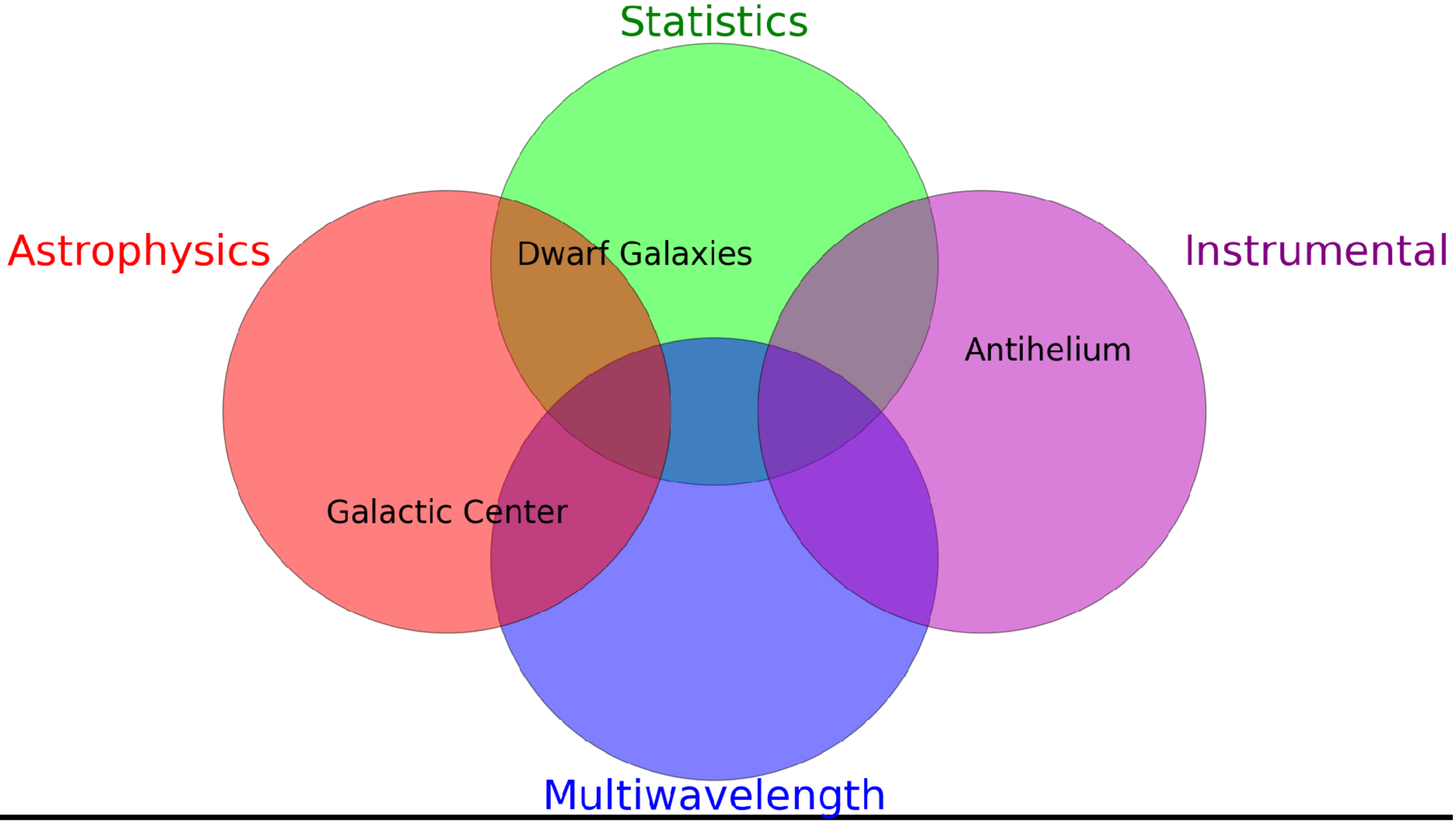

$b\bar{b}$
9 yr of data, 45 Dwarf Galaxies
Actual Limit
Thermal Cross-Section
Expected Limit
Linden (2019; 1905.11992)
10^{-23}
10^{24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ ($cm^3 s^{-1}$)
10
100
1000
Dark Matter Mass (GeV)

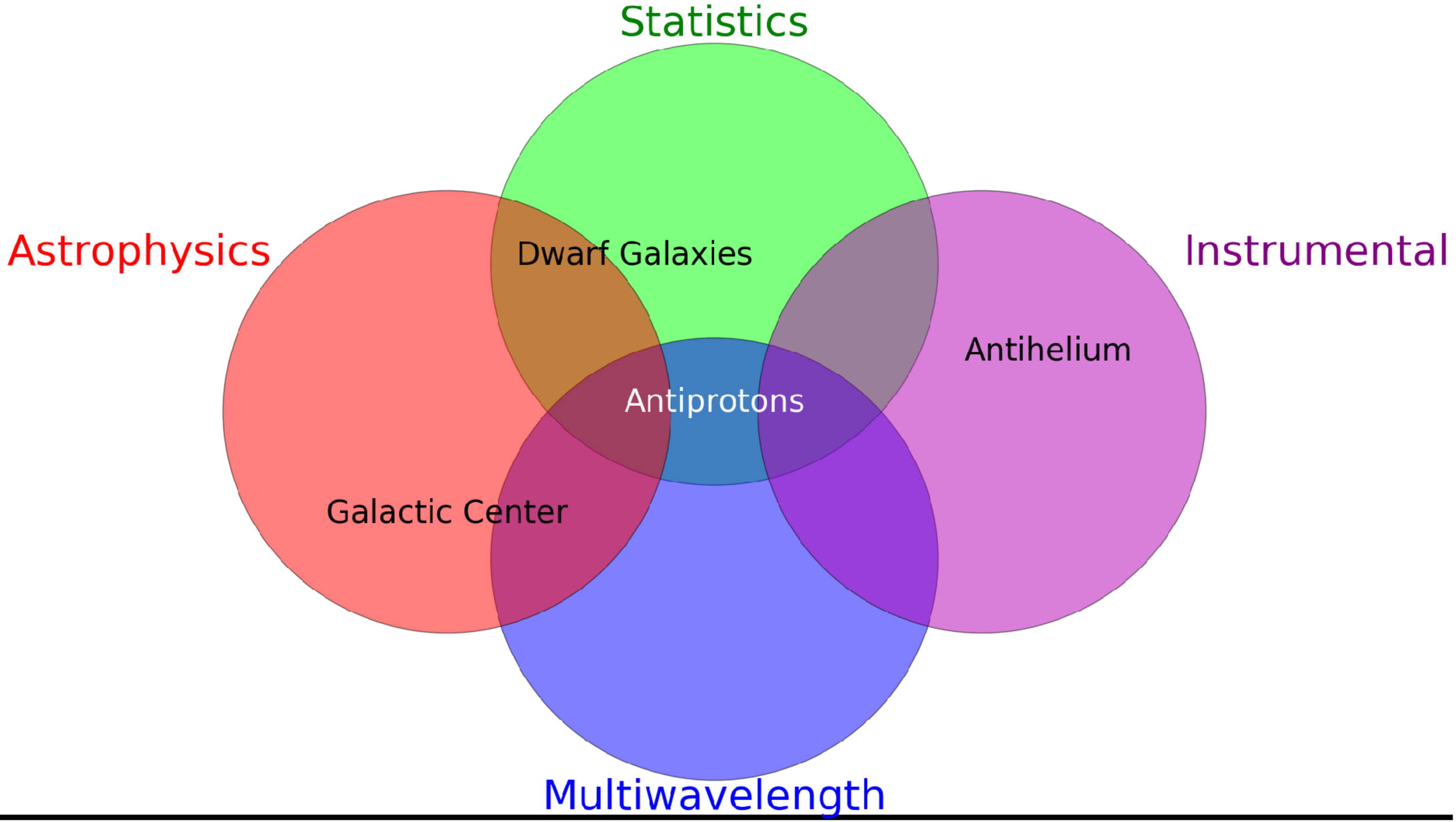

$b\bar{b}$
9 yr of data, 27 Dwarf Galaxies
95% Confidence (Frequentist)
Thermal Cross-Section
95% Confidence (Bayesian)
Hoof et al. (2018;1812.06986)
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ ($cm^3 s^{-1}$)
10
100
1000
Dark Matter Mass (GeV)


Statistics
Astrophysics
Instrumental
Multiwavelength

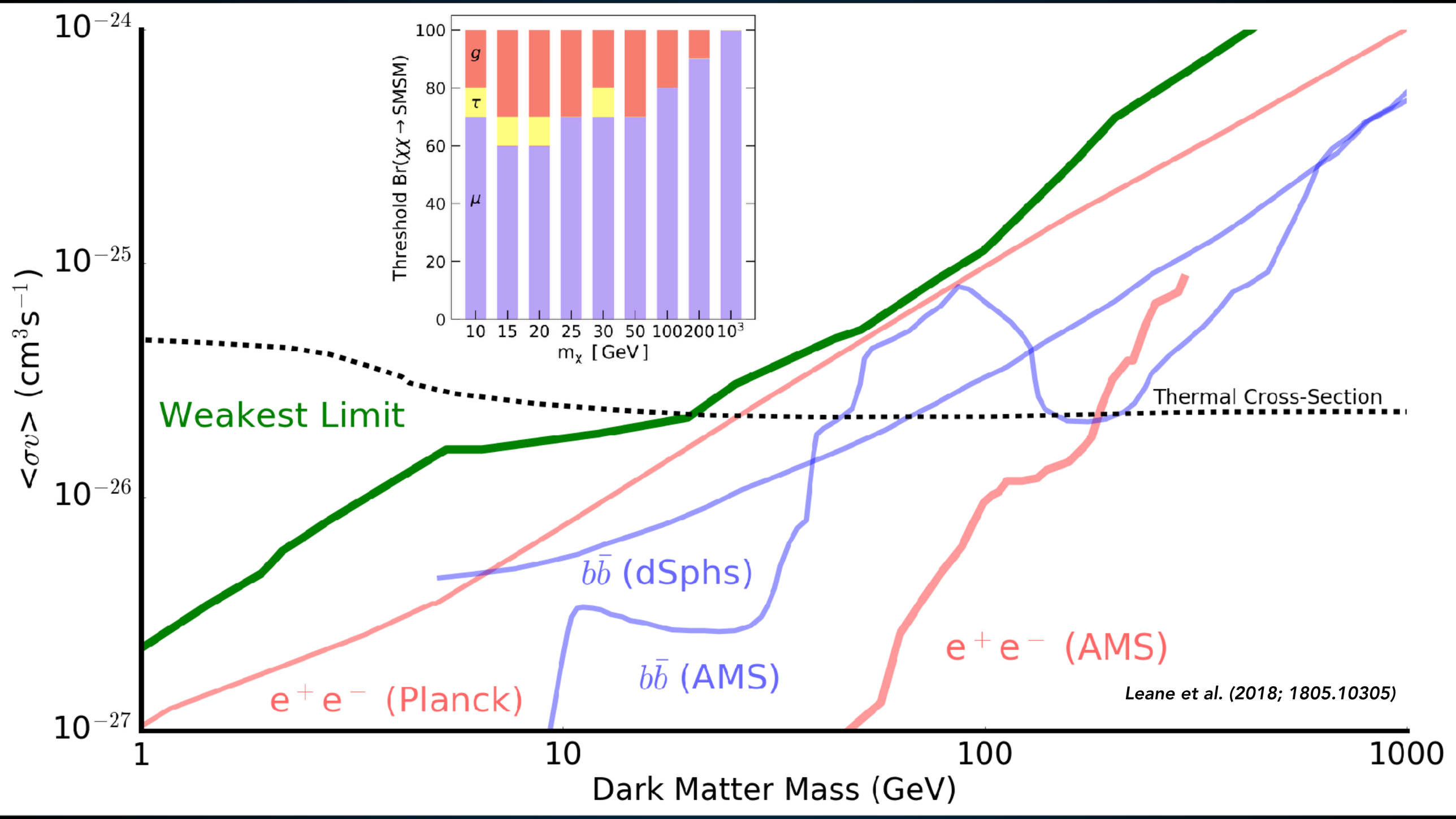

Statistics
Astrophysics
Dwarf Galaxies
Instrumental
Multiwavelength

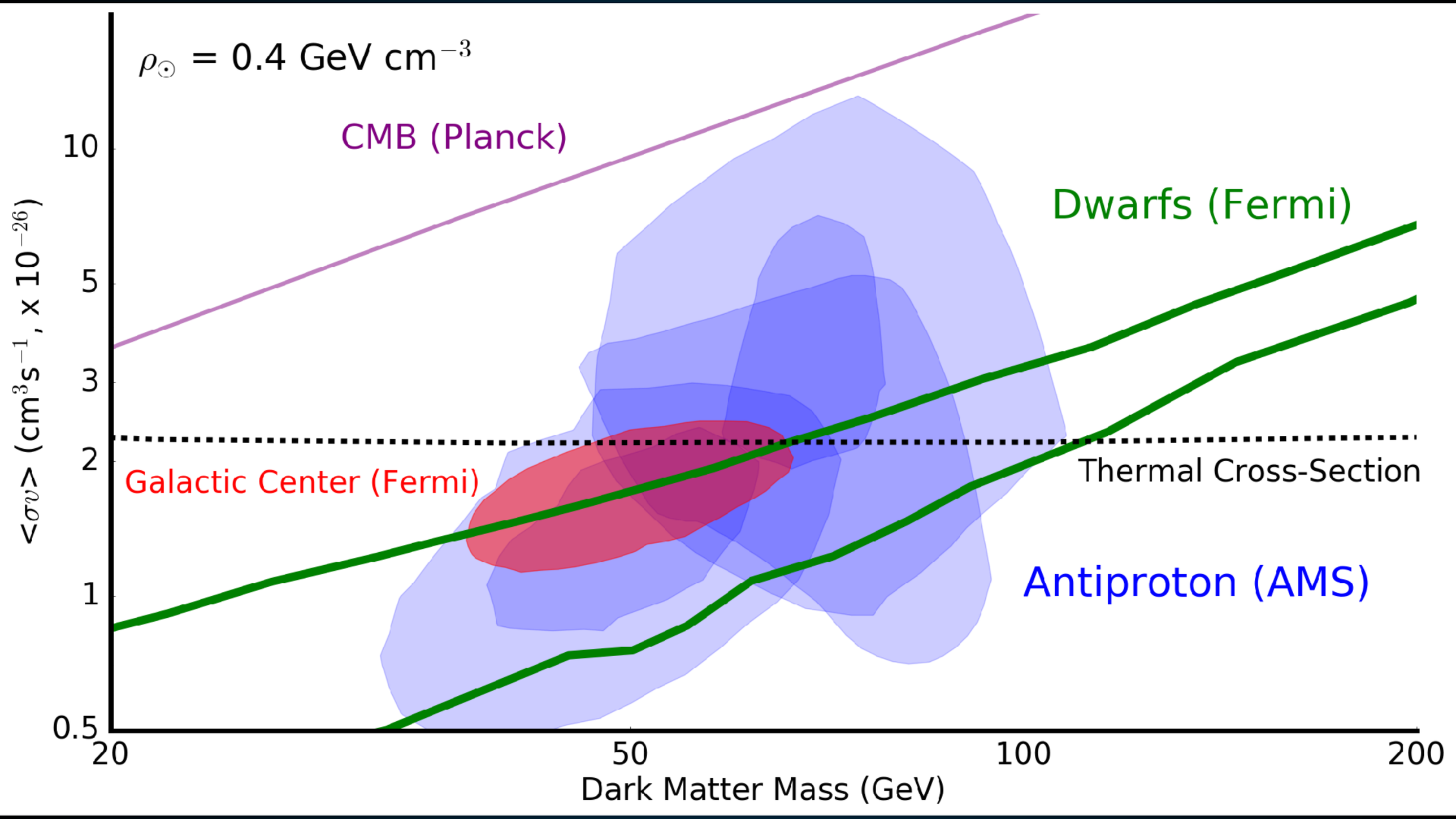

Statistics
Astrophysics
Dwarf Galaxies
Instrumental
Antihelium
Multiwavelength


Statistics
Astrophysics
Instrumental
Multiwavelength
Dwarf Galaxies
Antihelium
Galactic Center

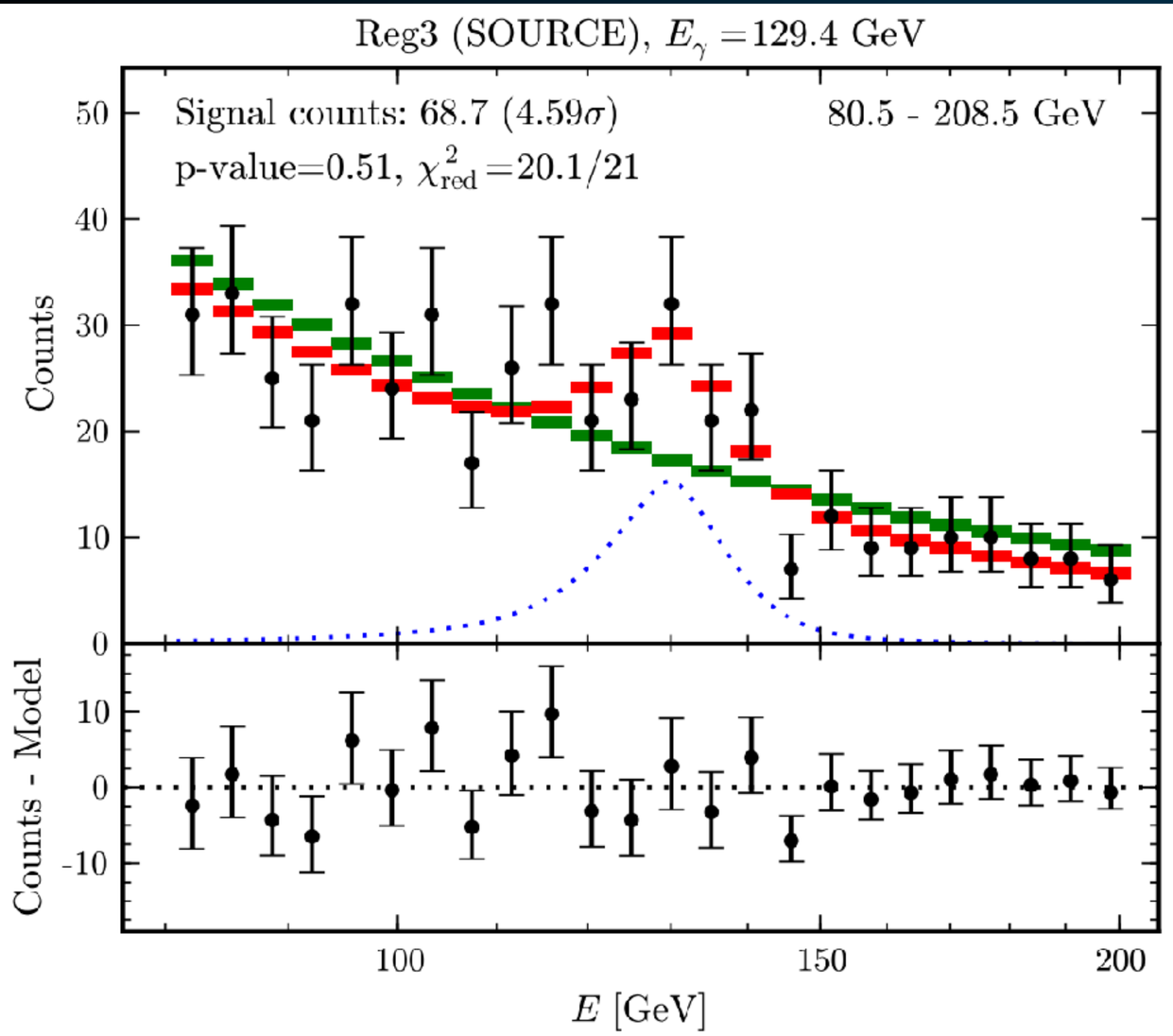

Statistics
Astrophysics
Instrumental
Multiwavelength
Dwarf Galaxies
Antihelium
Antiprotons
Galactic Center

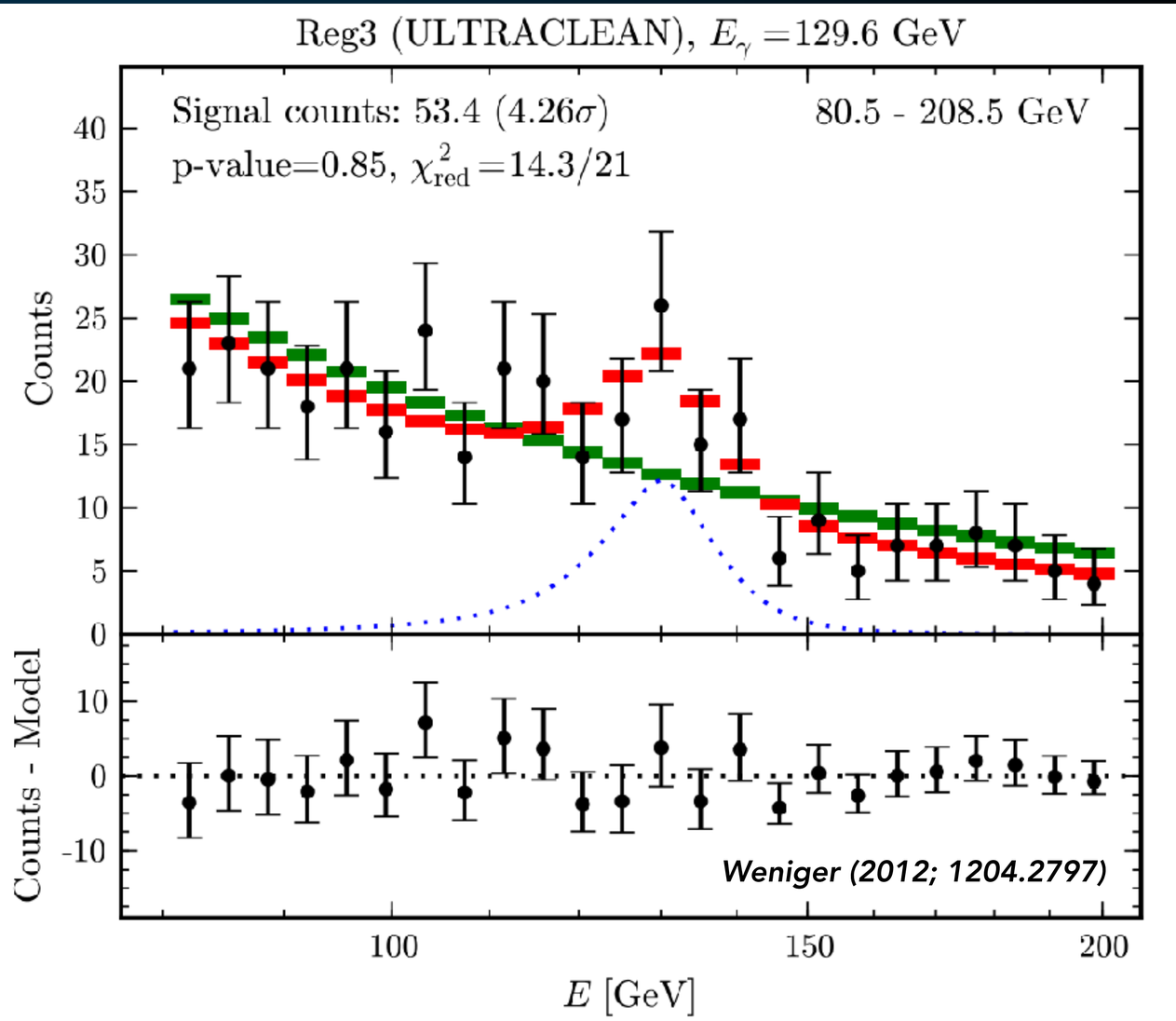



10^{-24}
10^{-25}
10^{-26}
10^{-27}
<σv> (cm³s⁻¹)
Weakest Limit
Thermal Cross-Section
$b\bar{b}$ (dSphs)
$b\bar{b}$ (AMS)
e⁺e⁻ (Planck)
e⁺e⁻ (AMS)
Leane et al. (2018; 1805.10305)
1
10
100
1000
Dark Matter Mass (GeV)
Threshold Br(χχ → SMSM)
g
τ
μ
0
20
40
60
80
100
10 15 20 25 30 50 100 200 10³
m_χ [GeV]

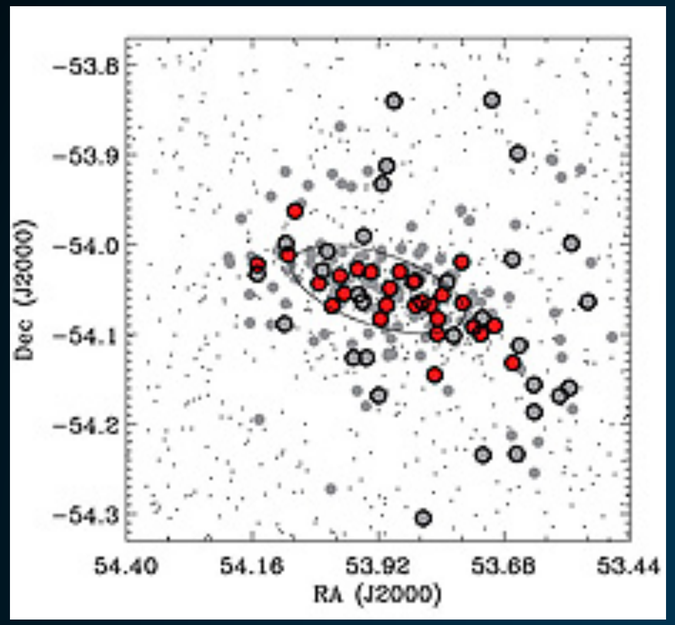

$\rho_\odot$ = 0.4 GeV cm^{-3}
CMB (Planck)
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
10
5
3
2
1
0.5
20
50
100
200
Dark Matter Mass (GeV)

Or Maybe A Surprise !





Reticulum II - The Story of 2015



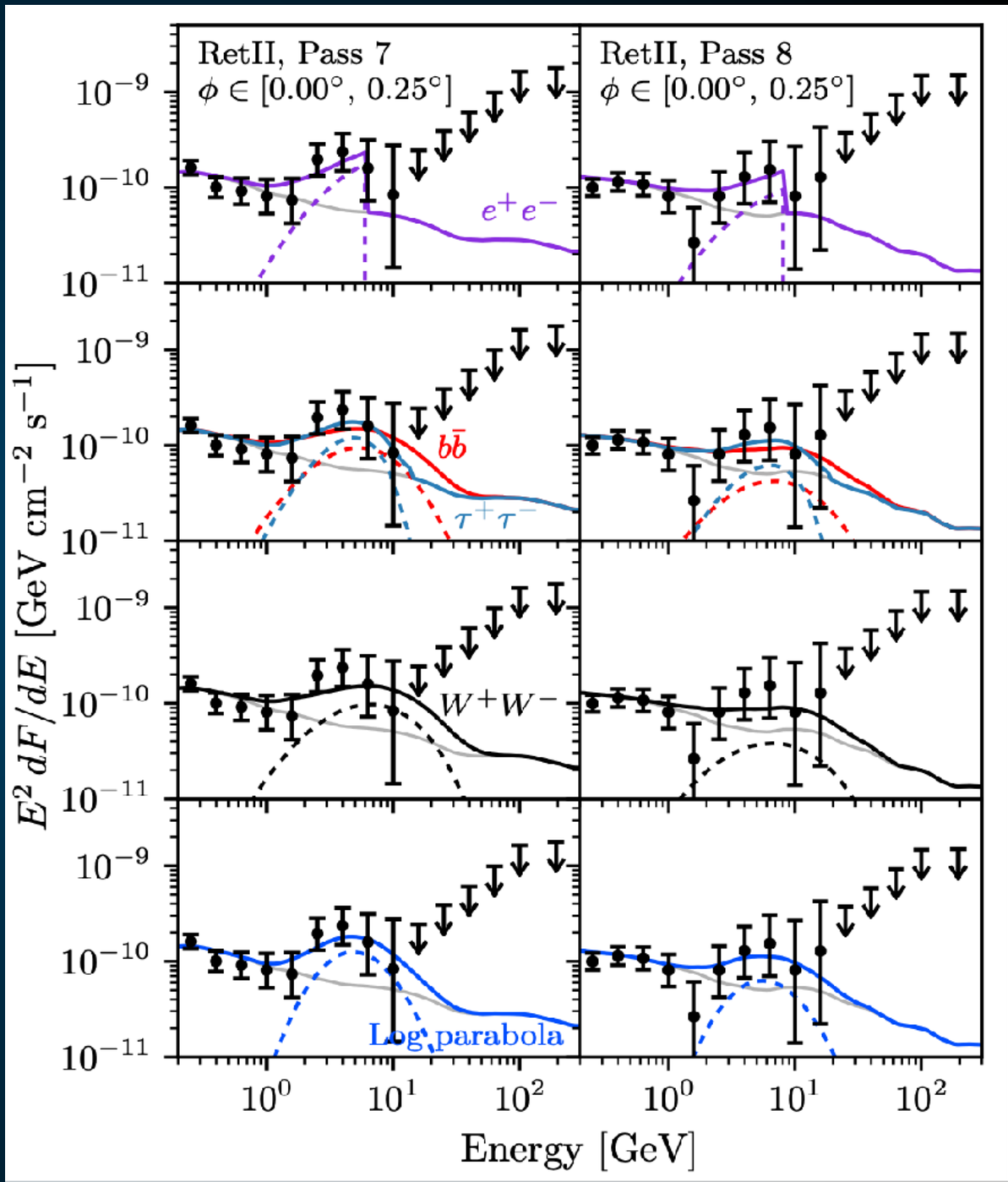
Dense and Nearby dSph!

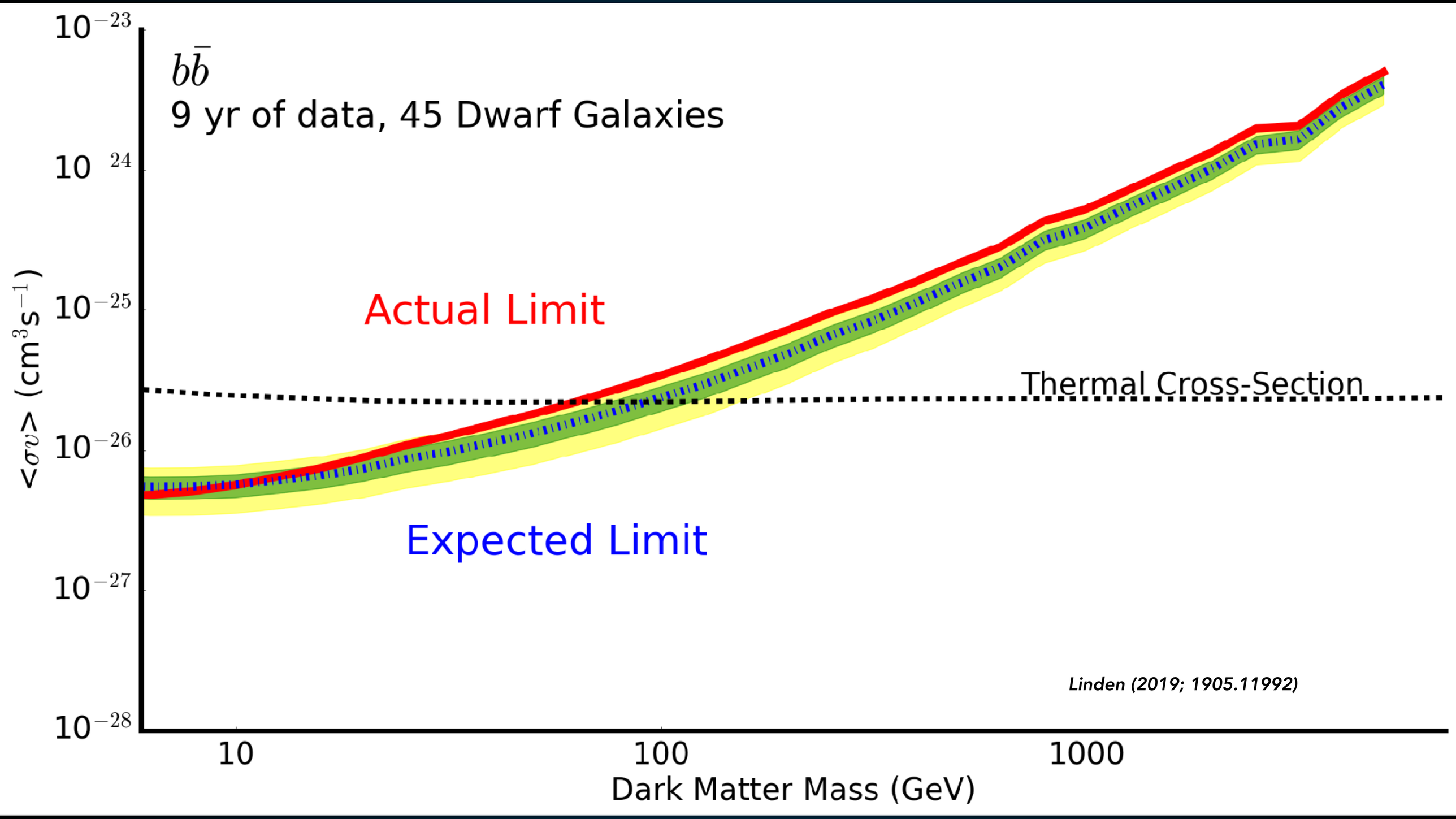
Gamma-Ray Excess!

Significance has decreased from ~3.2σ to ~2.5σ in updated datasets.

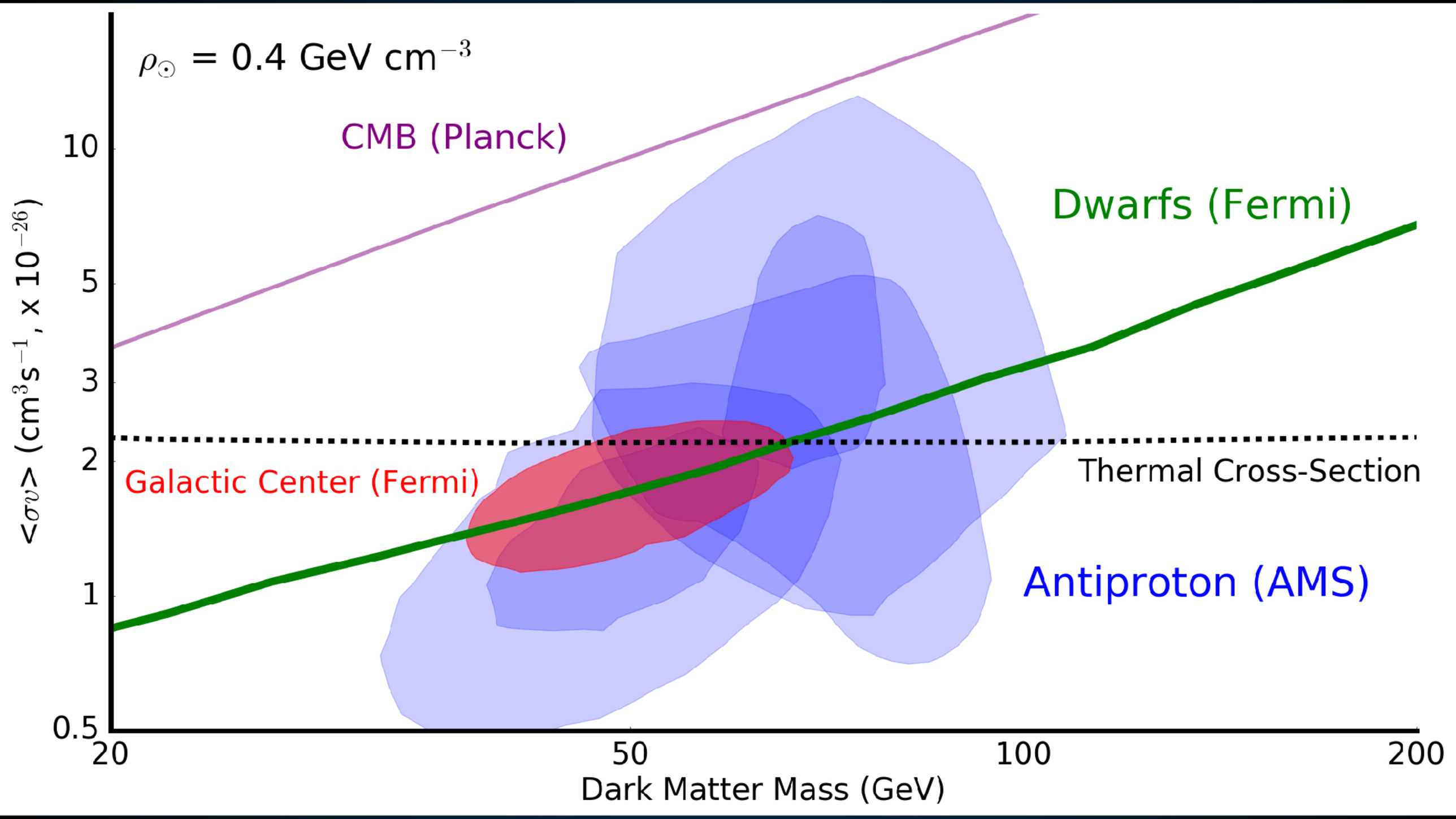
Still interesting!

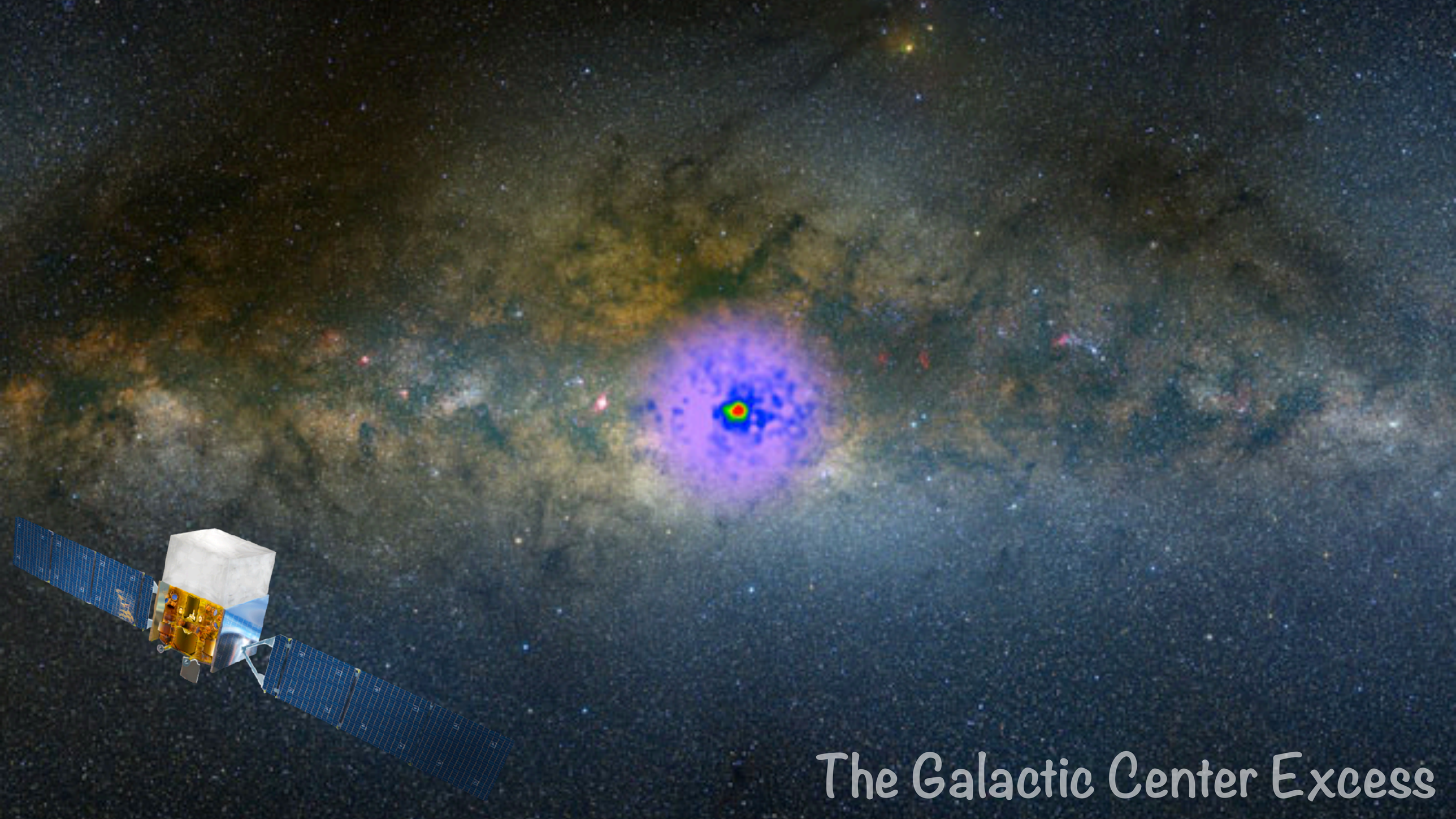
Geringer-Sameth et al. (2018; 1807.08740)

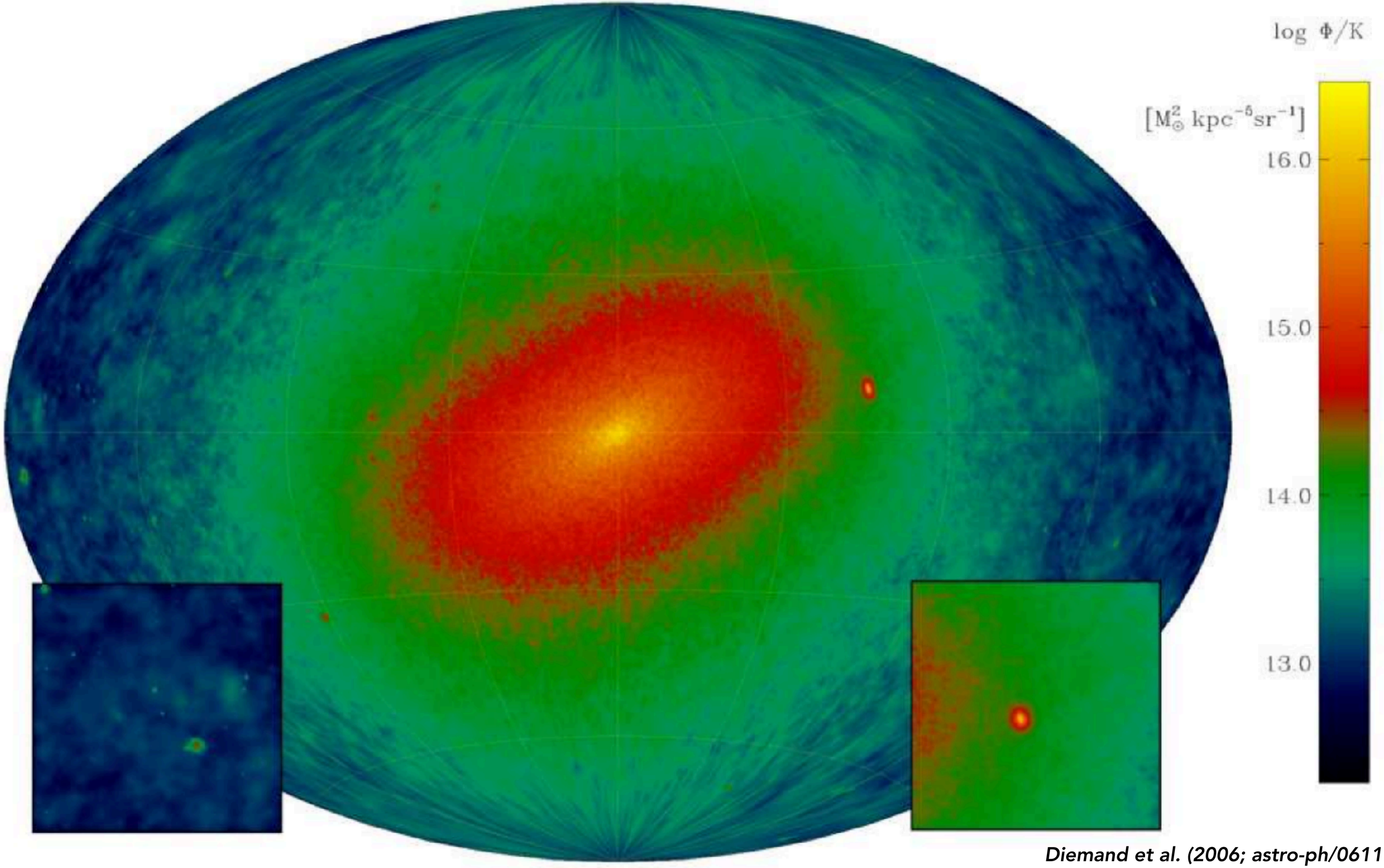



$b\bar{b}$
9 yr of data, 45 Dwarf Galaxies
Actual Limit
Thermal Cross-Section
Expected Limit
Linden (2019; 1905.11992)
10^{-23}
10^{24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ ($cm^3 s^{-1}$)
10
100
1000
Dark Matter Mass (GeV)



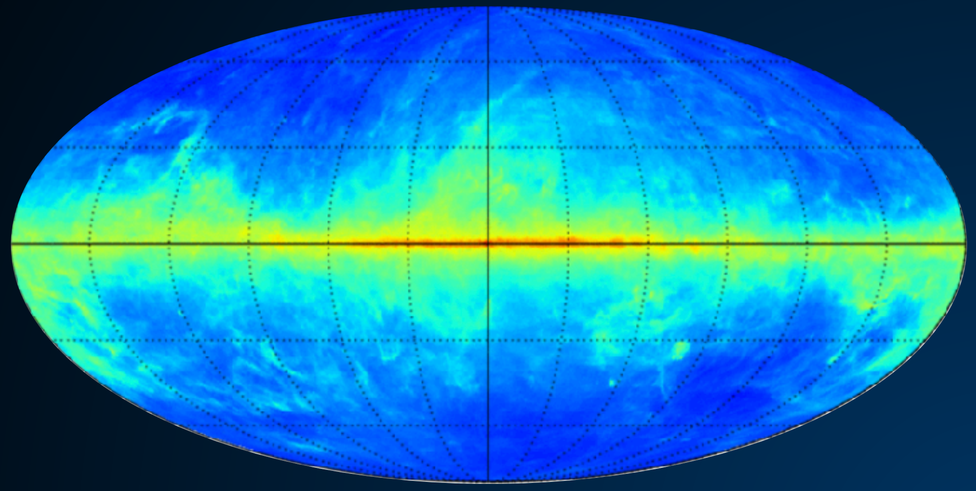

$\rho_\odot$ = 0.4 GeV cm^{-3}
CMB (Planck)
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
10
5
3
2
1
0.5
20
50
100
200
Dark Matter Mass (GeV)


The Galactic Center Excess

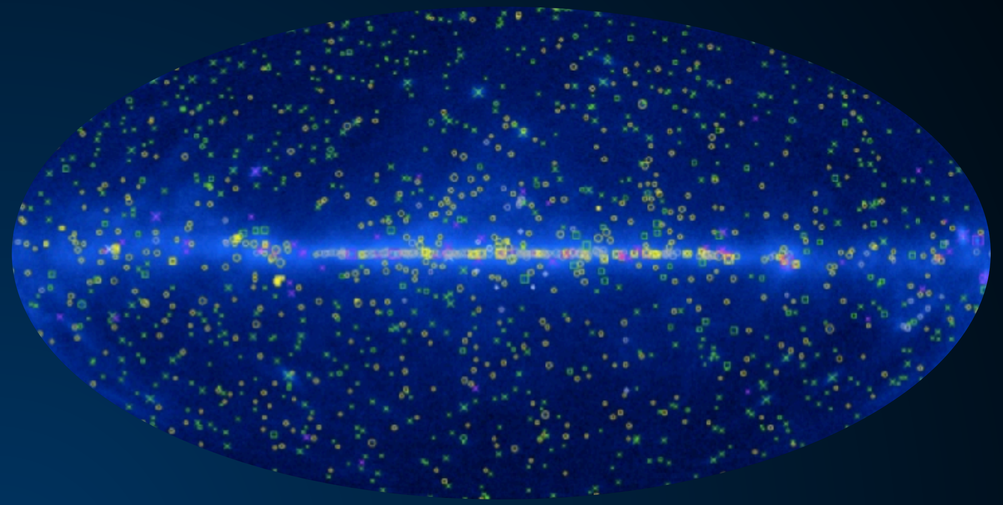


Diemand et al. (2006; astro-ph/0611370)

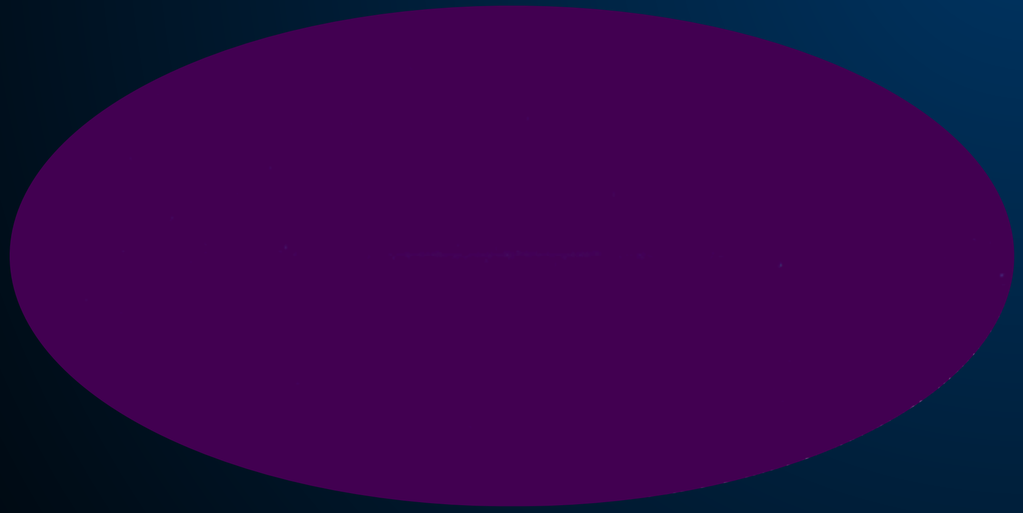
The Galactic Center - Techniques



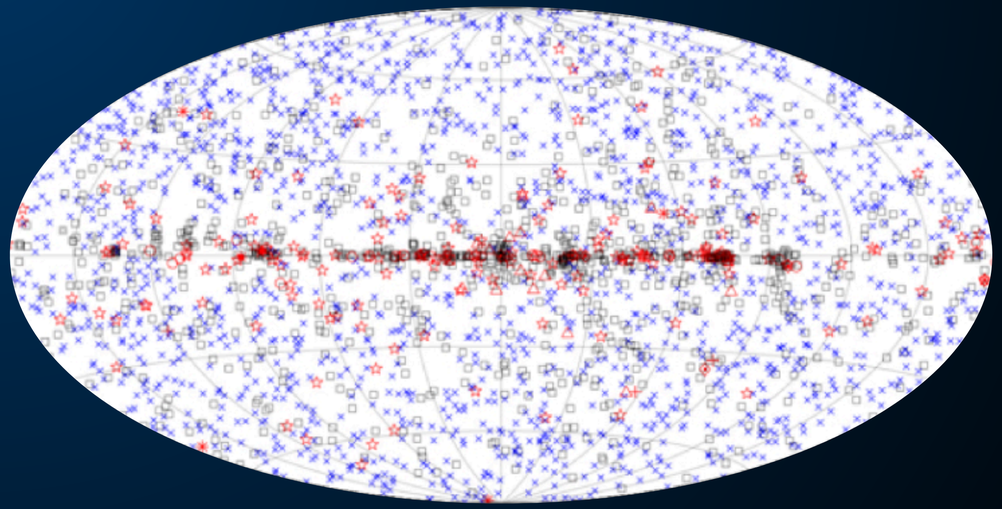
Galactic Diffuse



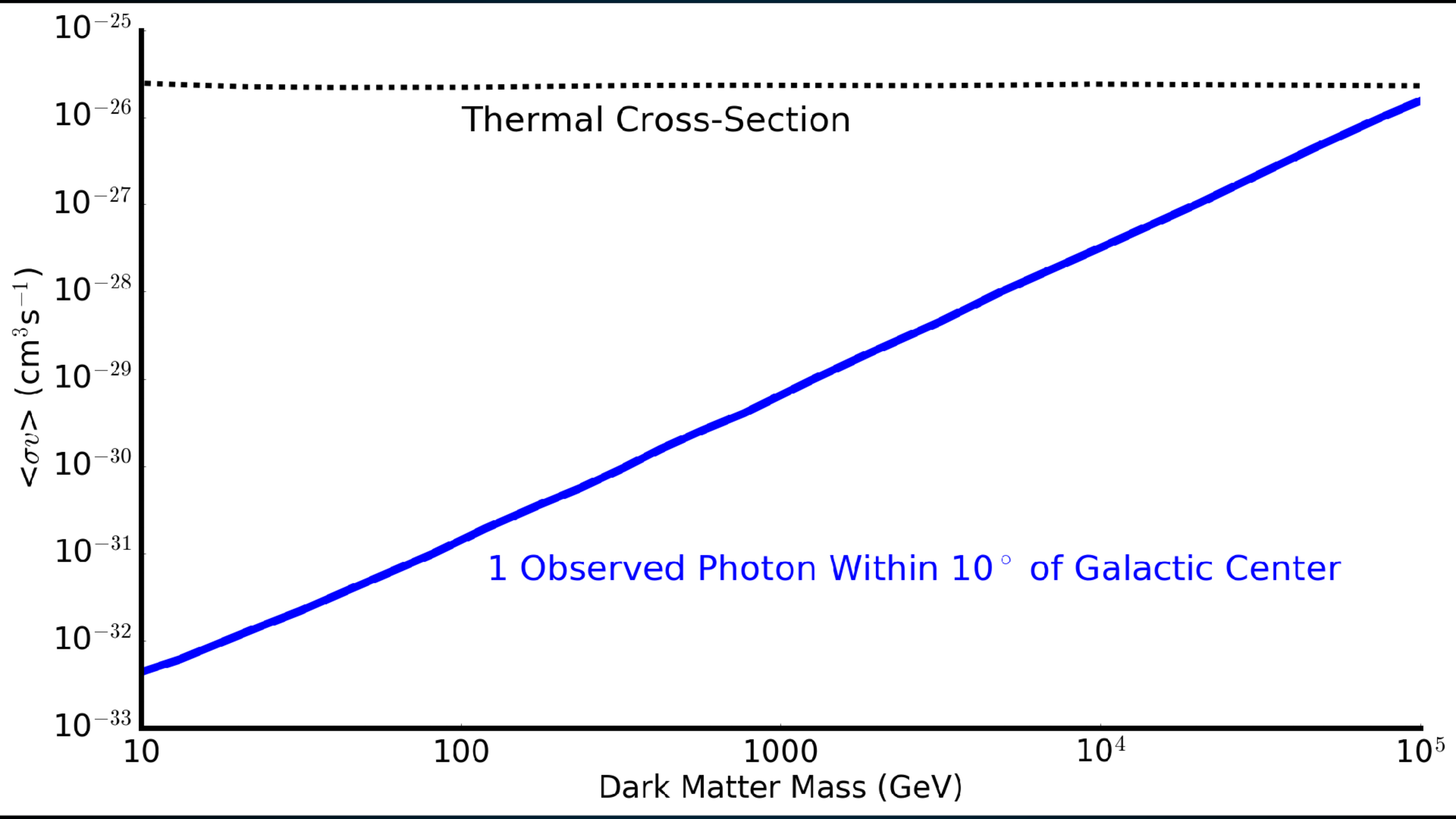
Point Sources



Isotropic Emission

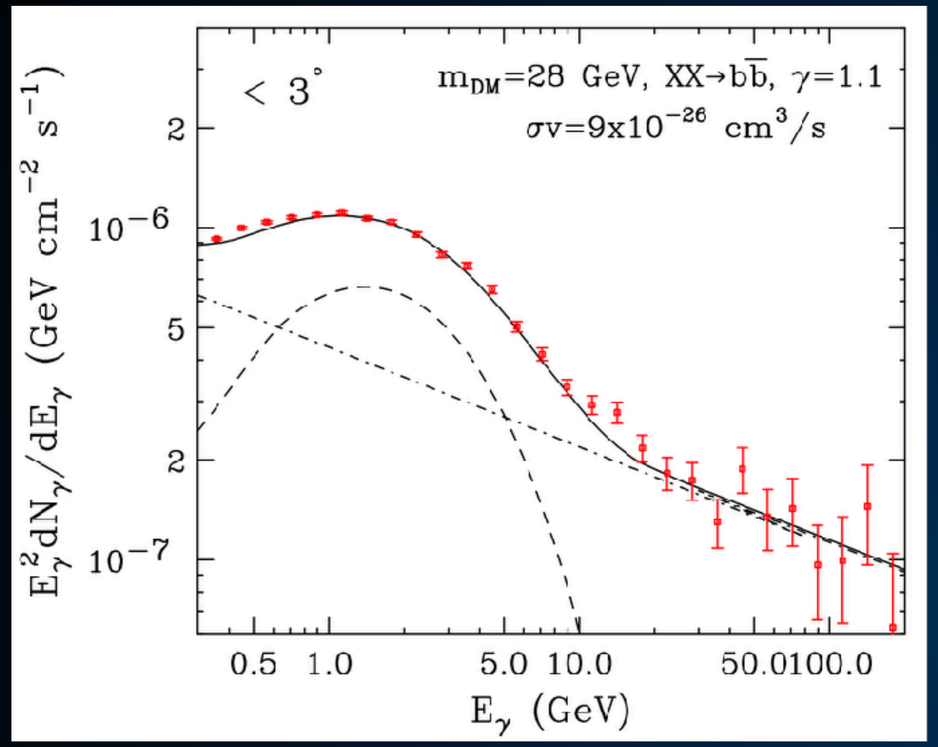


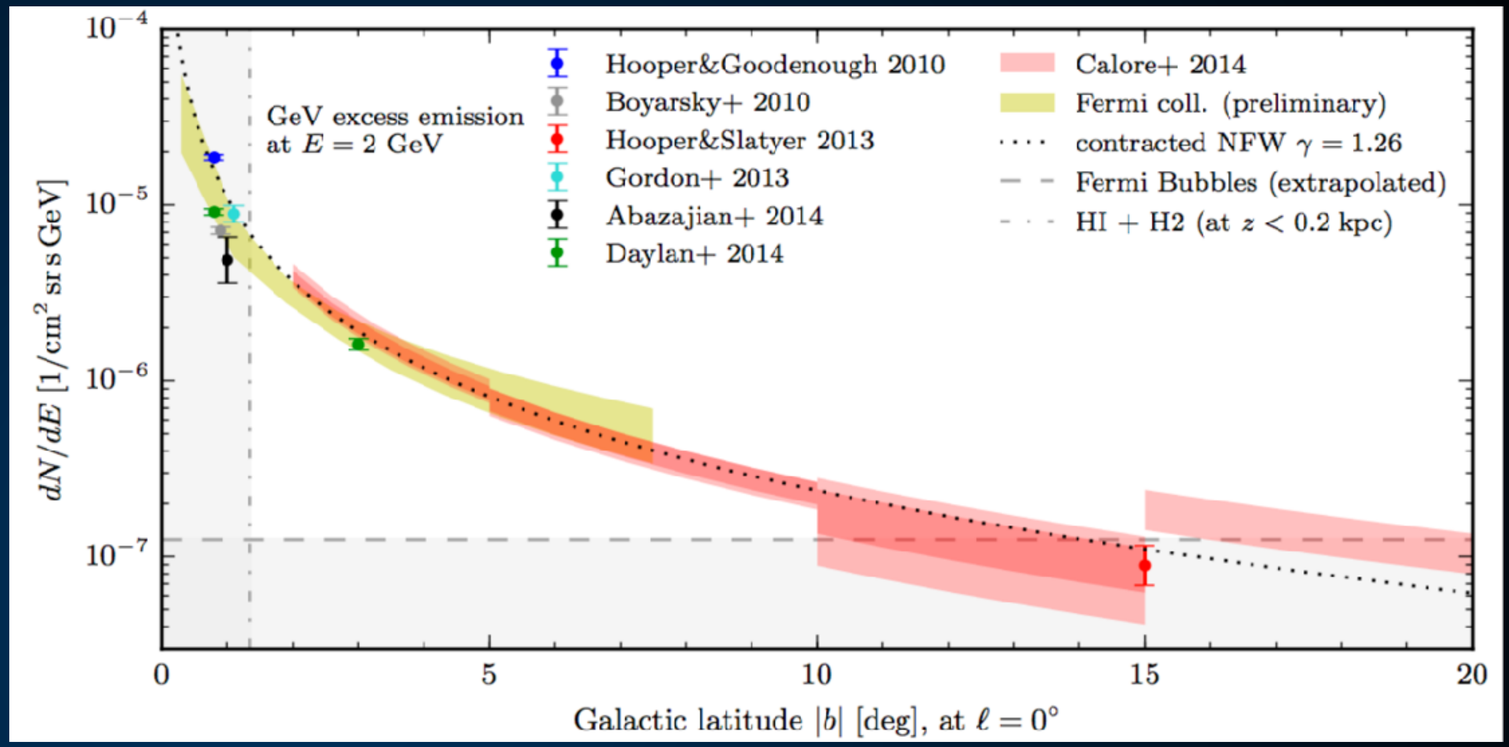
Sub-Threshold Sources


Thermal Cross-Section
1 Observed Photon Within 10° of Galactic Center
$<\sigma v>$ ($cm^3 s^{-1}$)
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

The Galactic Center Excess

Goodenough & Hooper (2009; 0910.2998)



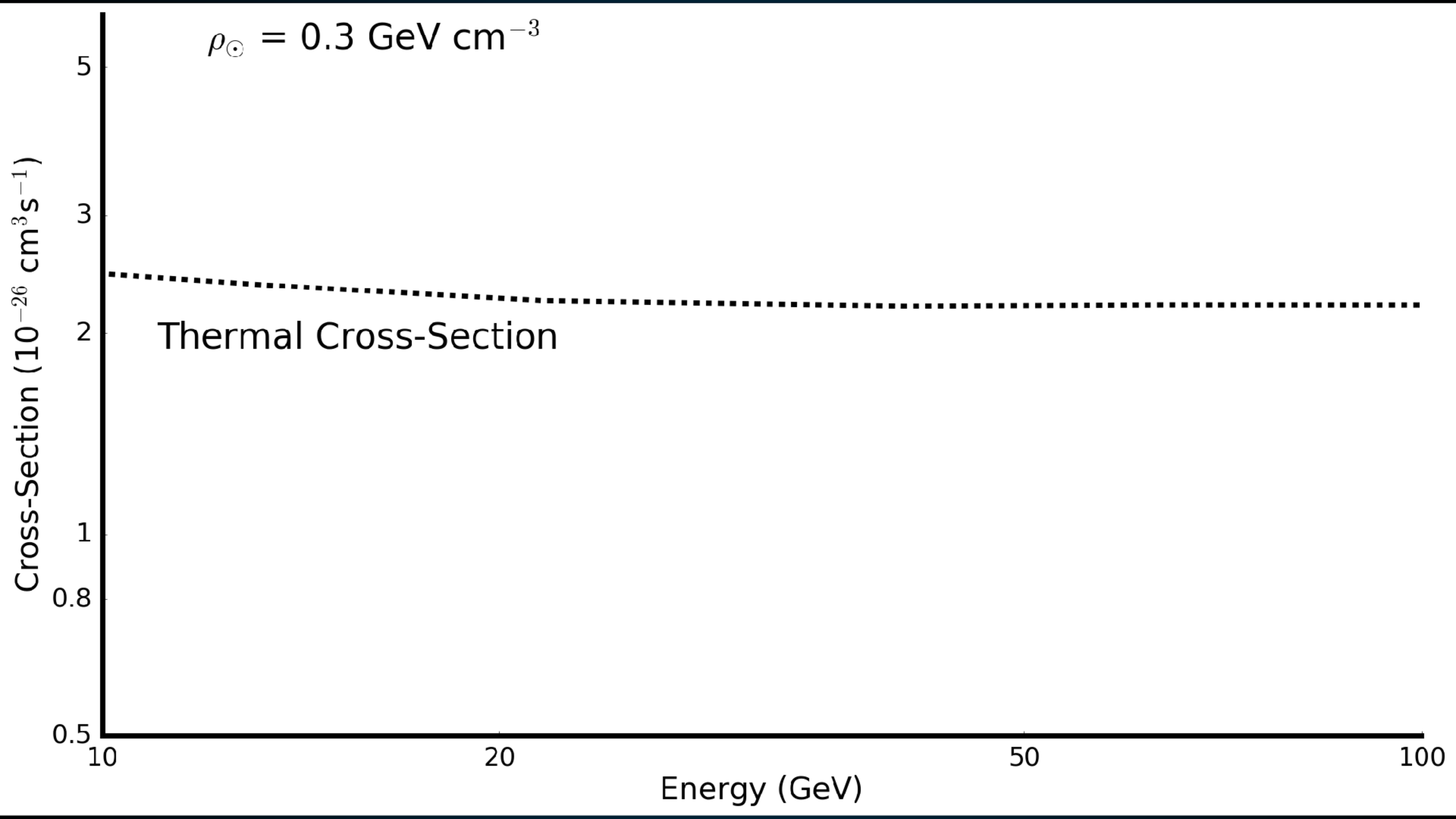


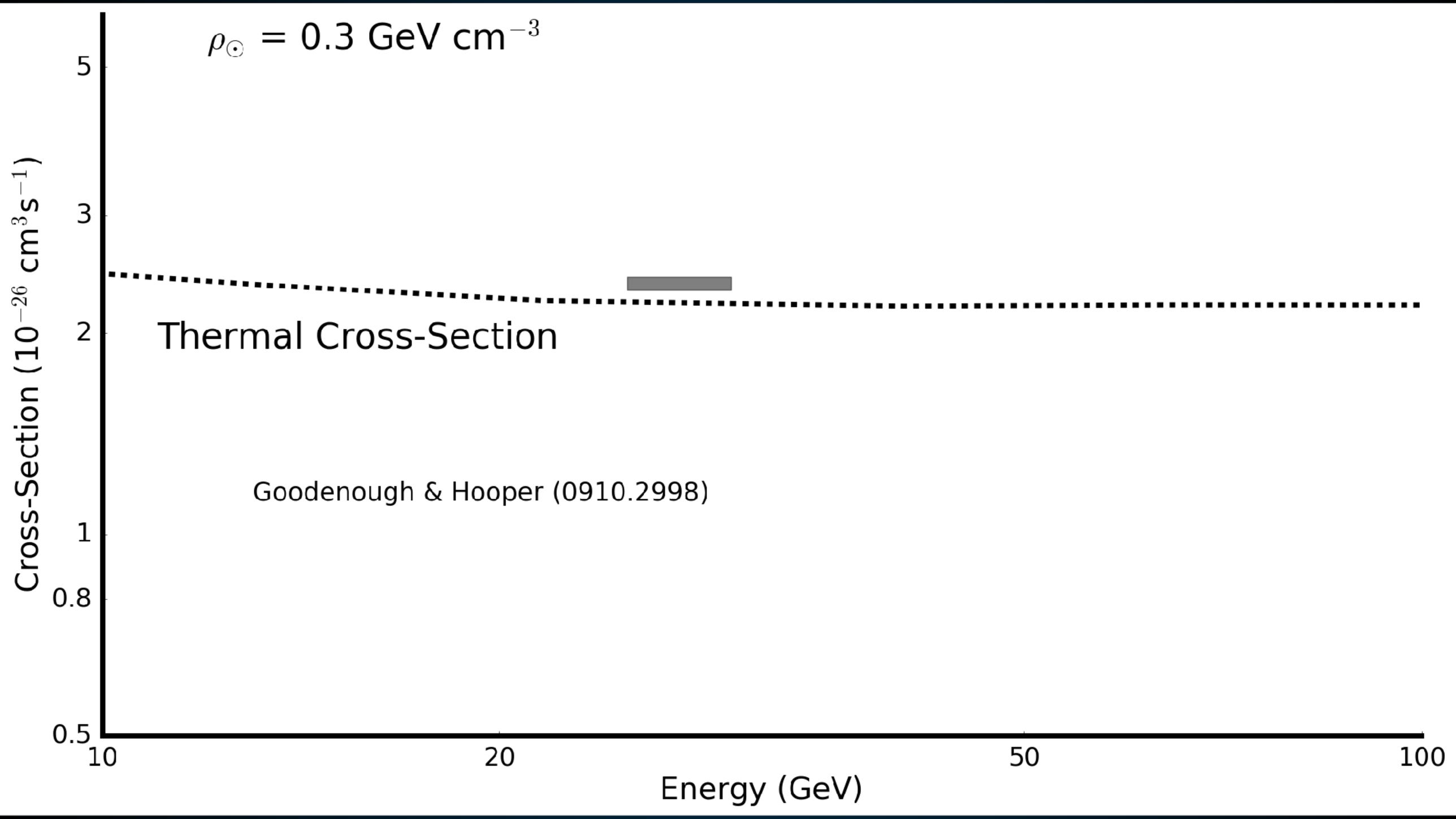
Bright *Detected at >50σ*

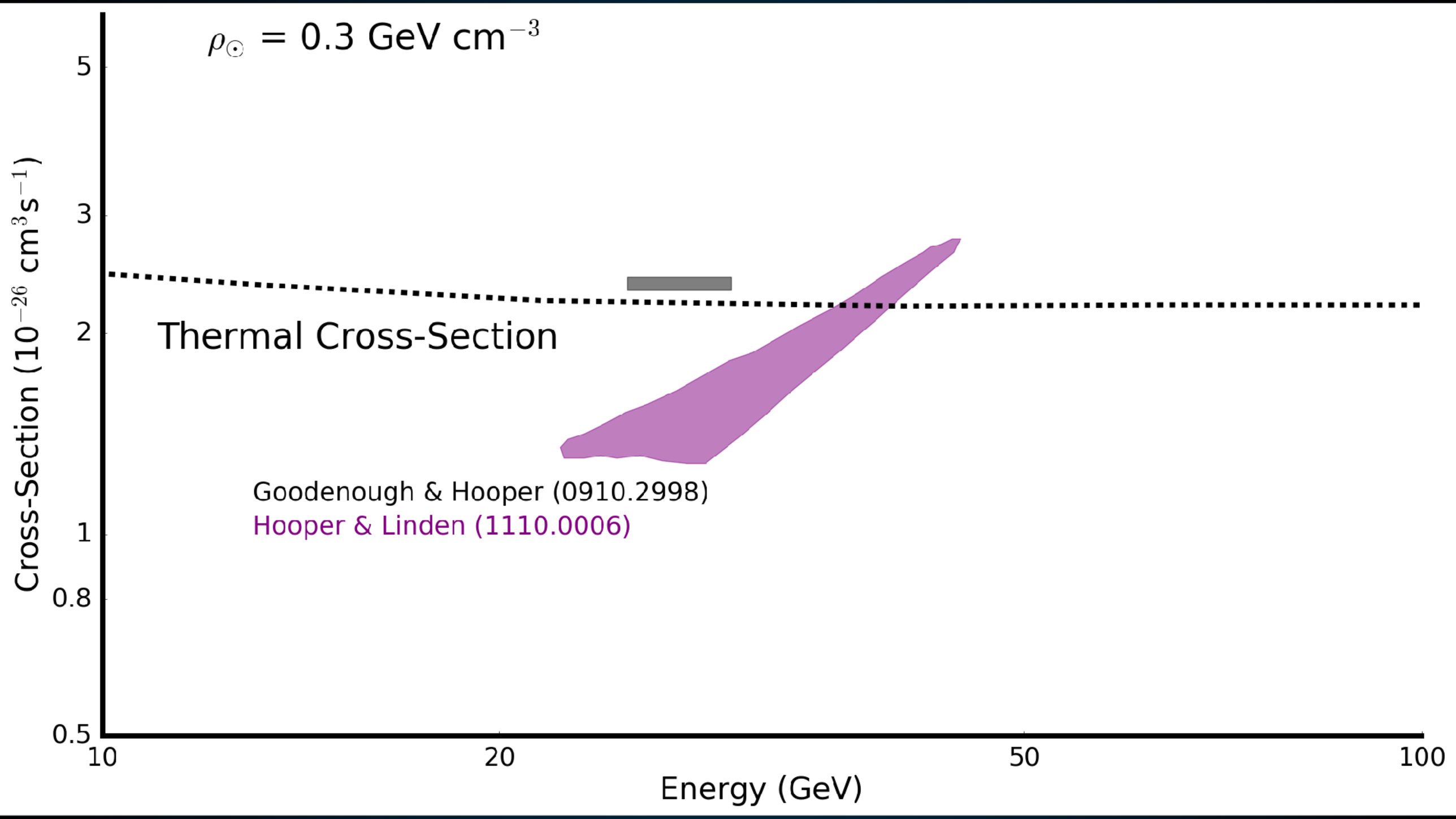
Hard-Spectrum *Incompatible with standard backgrounds*

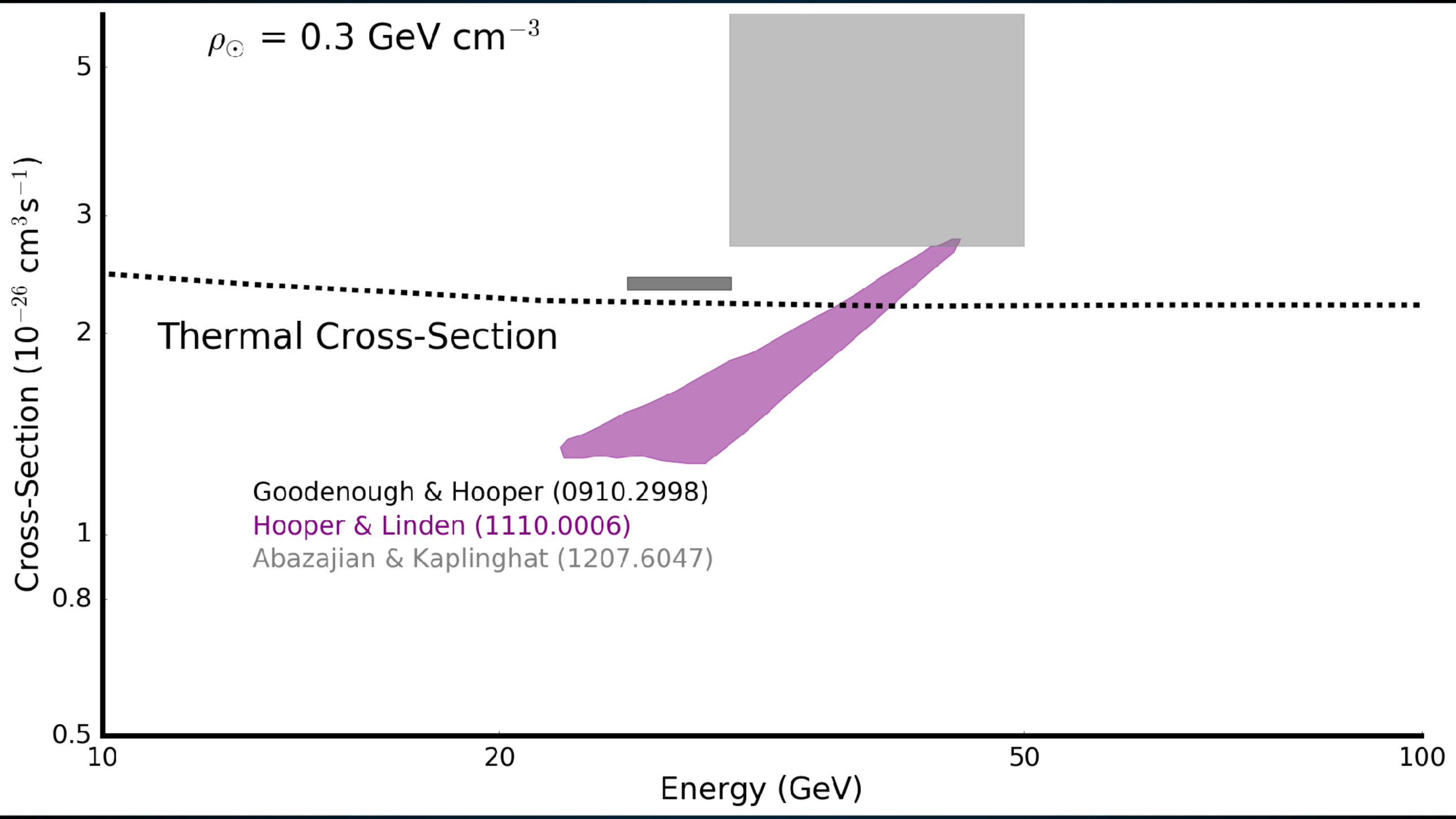
Spherically Symmetric *Expected from Dark Matter*

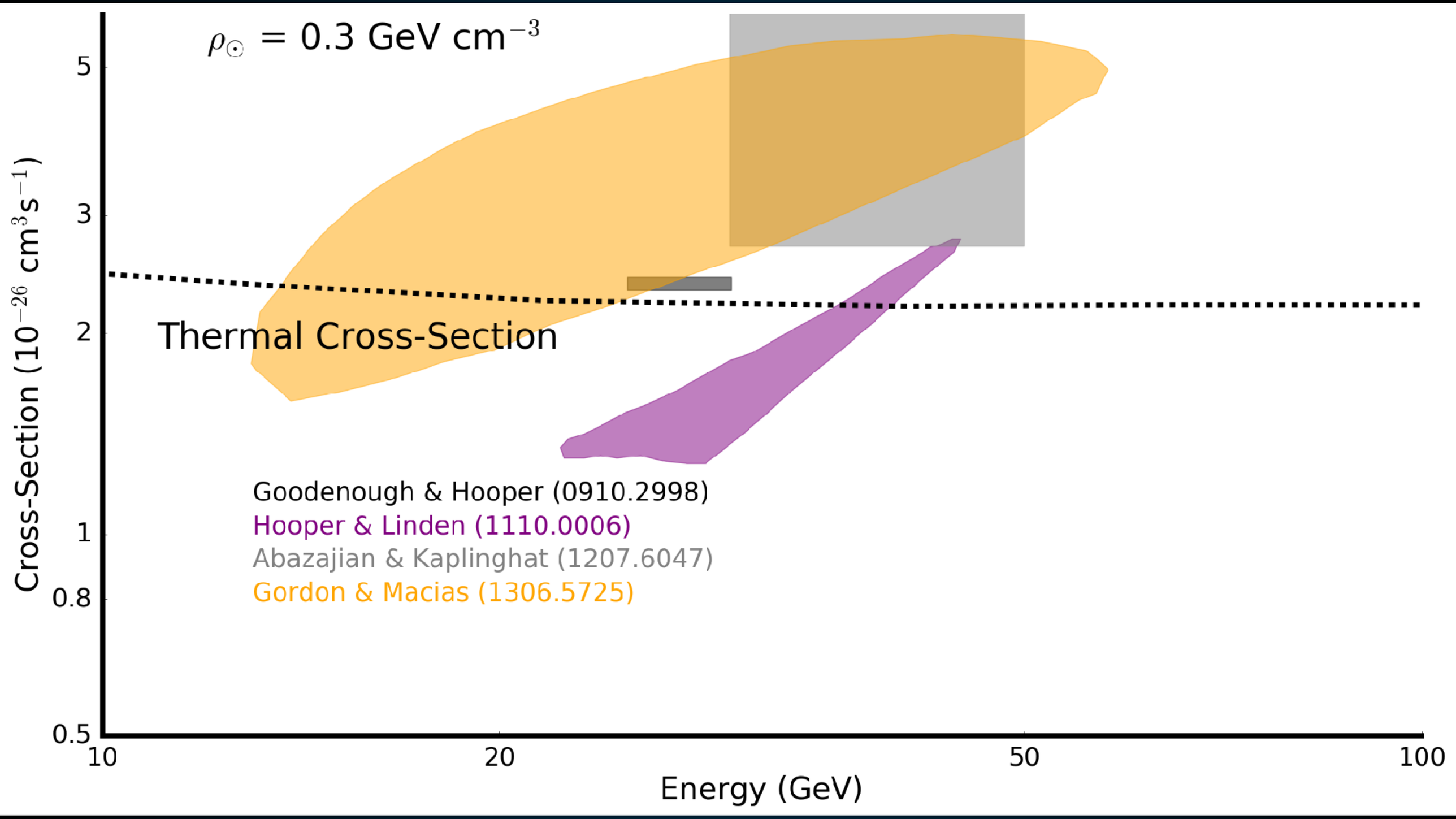
Spatially Extended *to nearly 15 degrees from Galactic center.*

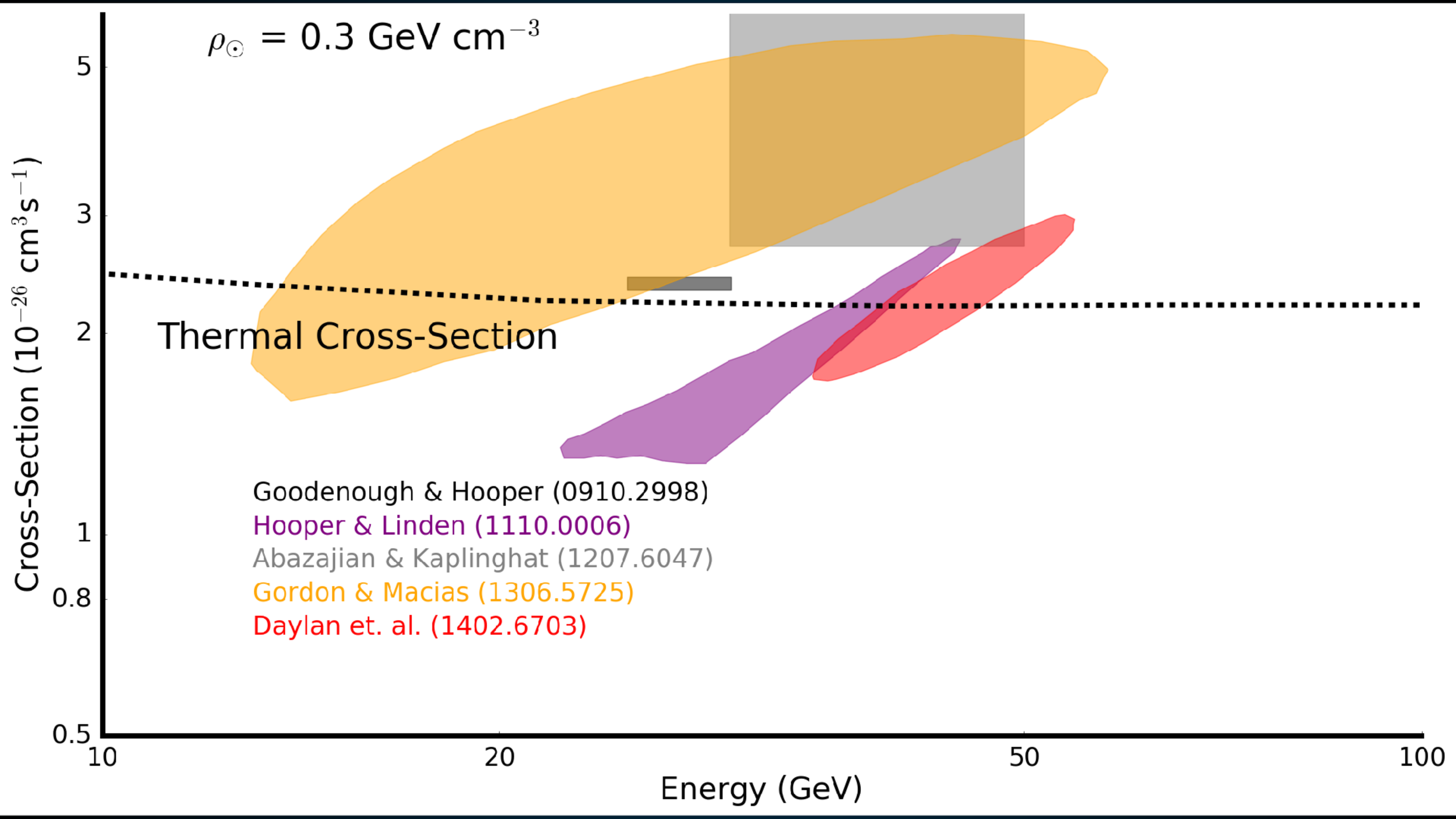

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Cross-Section (10^{-26} cm^{3}s^{-1})
5
3
2
1
0.8
0.5
10
20
50
100
Energy (GeV)

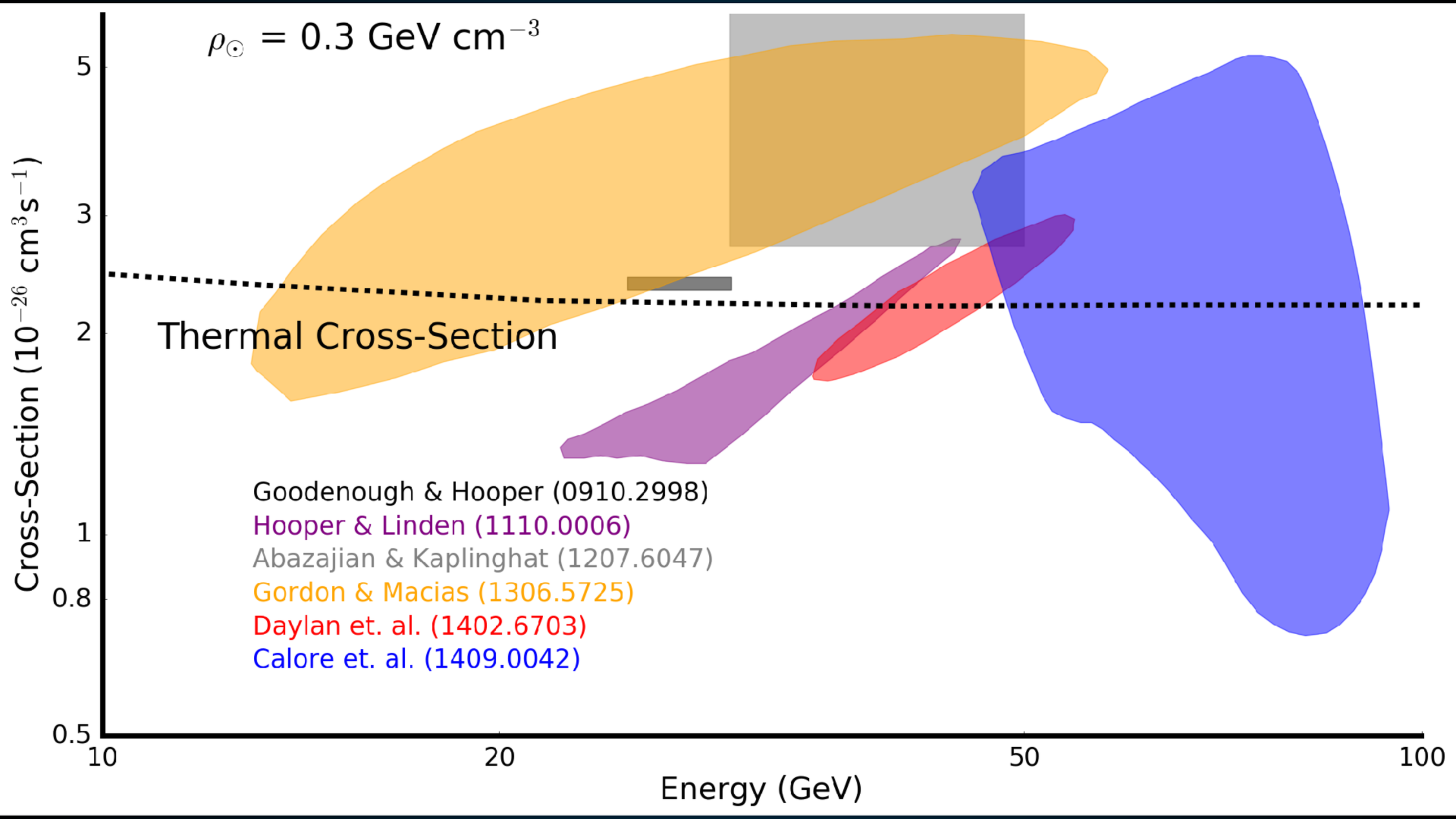

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Cross-Section (10^{-26} cm^{3}s^{-1})
5
3
2
1
0.8
0.5
10
20
50
100
Energy (GeV)

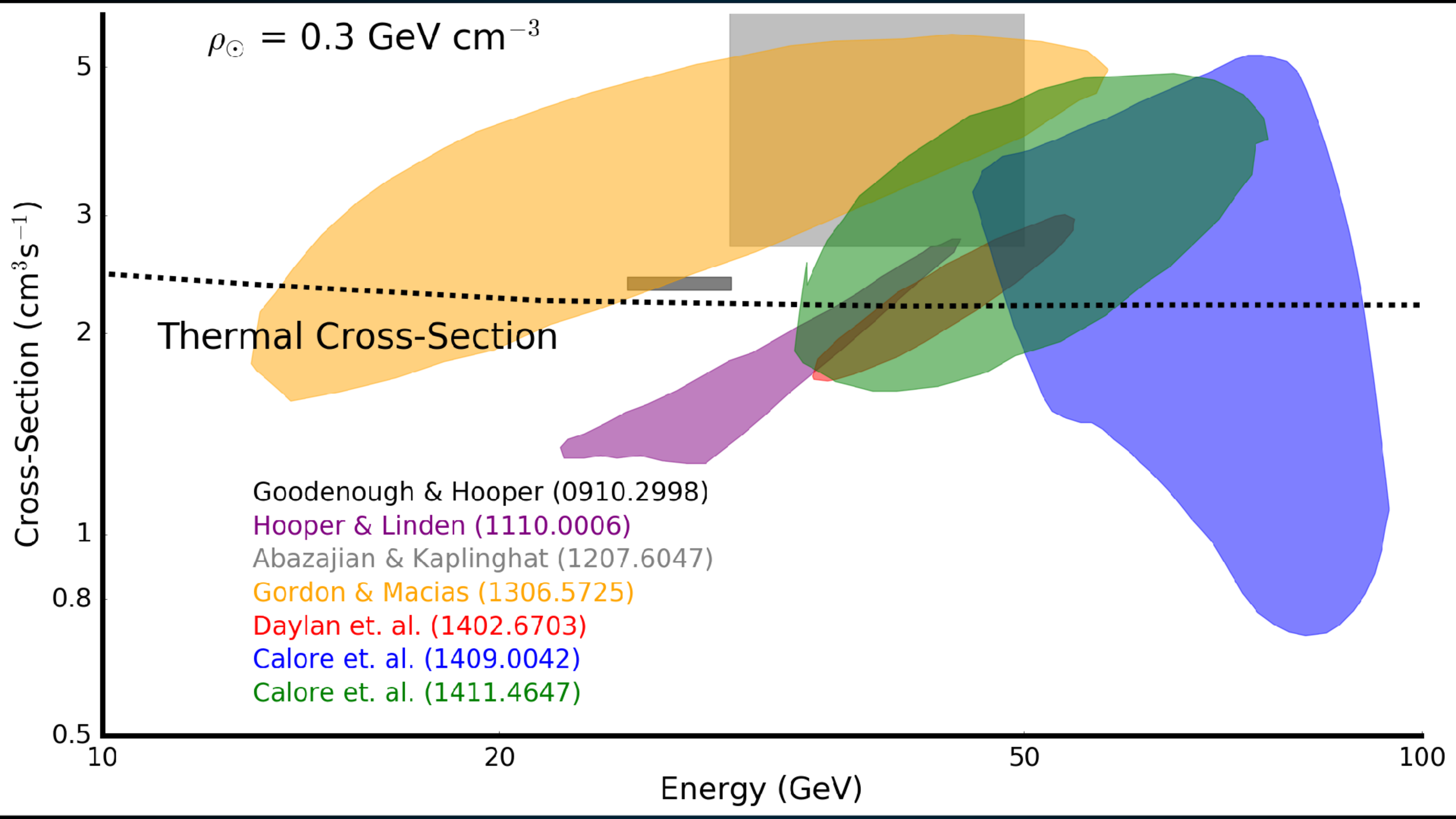

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Cross-Section (10^{-26} cm^{3}s^{-1})
Energy (GeV)
5
3
2
1
0.8
0.5
10
20
50
100

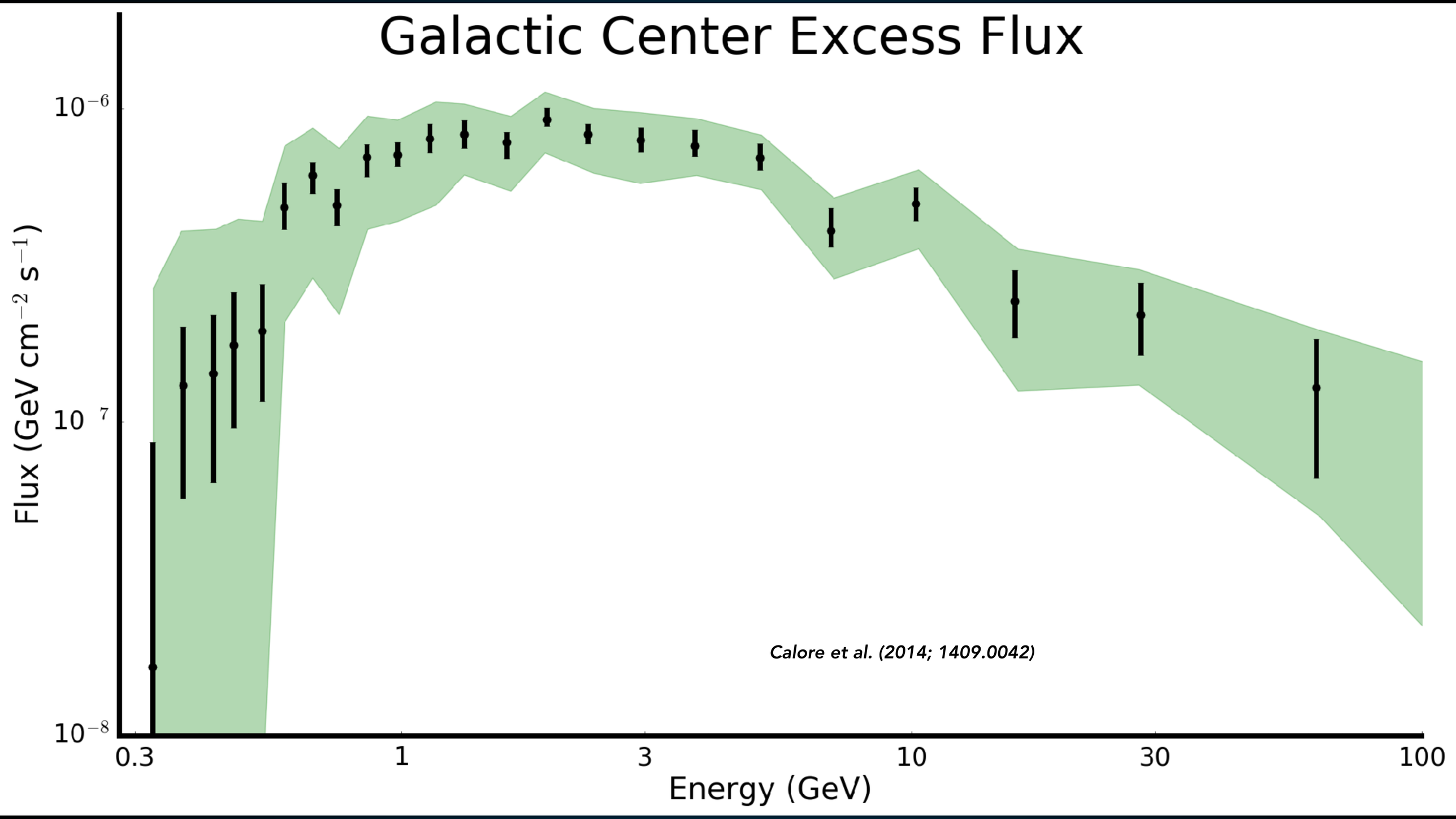

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Abazajian & Kaplinghat (1207.6047)
Cross-Section (10^{-26} cm^{3}s^{-1})
5
3
2
1
0.8
0.5
10
20
50
100
Energy (GeV)

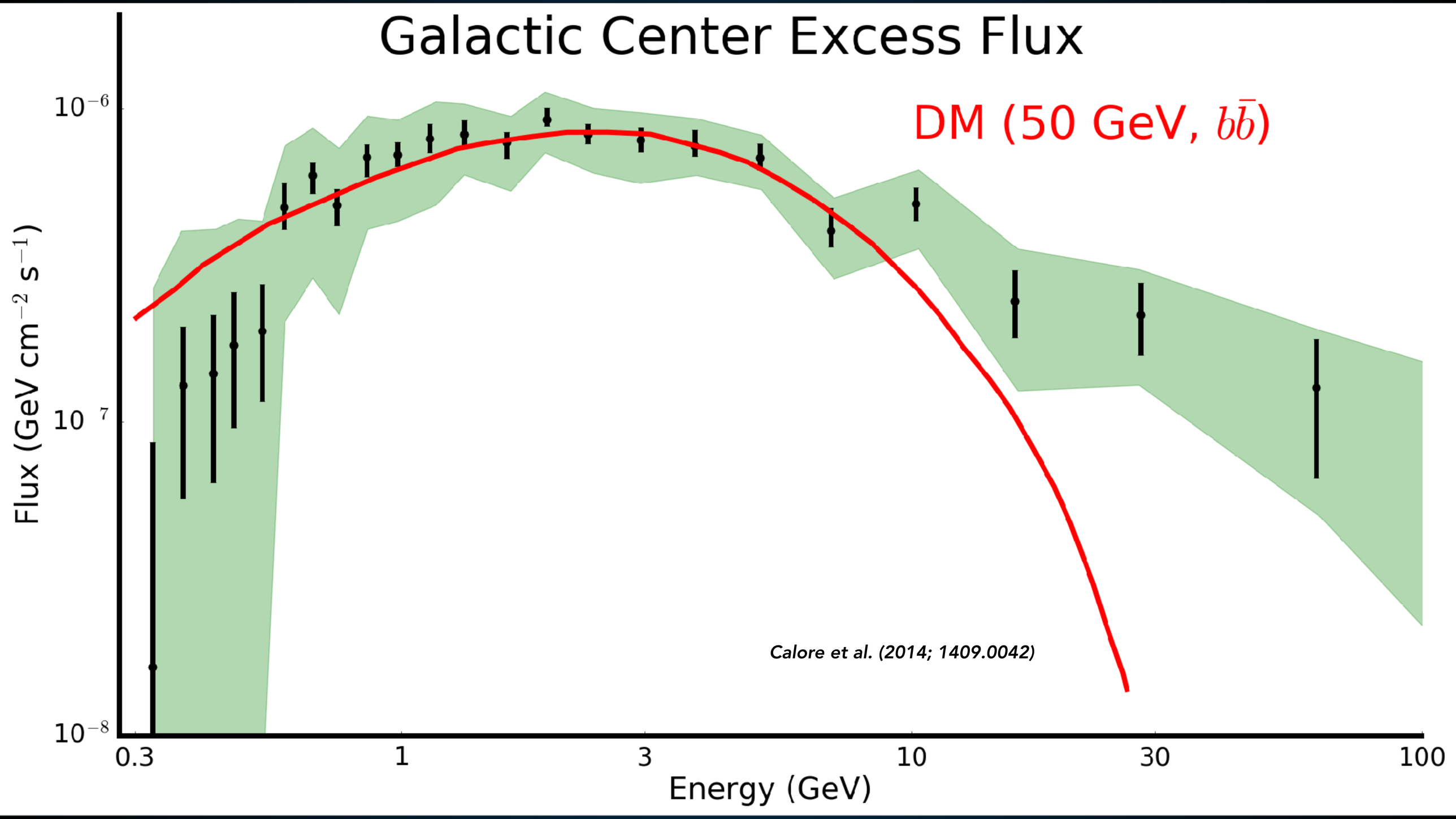

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Abazajian & Kaplinghat (1207.6047)
Gordon & Macias (1306.5725)
Cross-Section (10^{-26} cm^{3}s^{-1})
5
3
2
1
0.8
0.5
10
20
50
100
Energy (GeV)

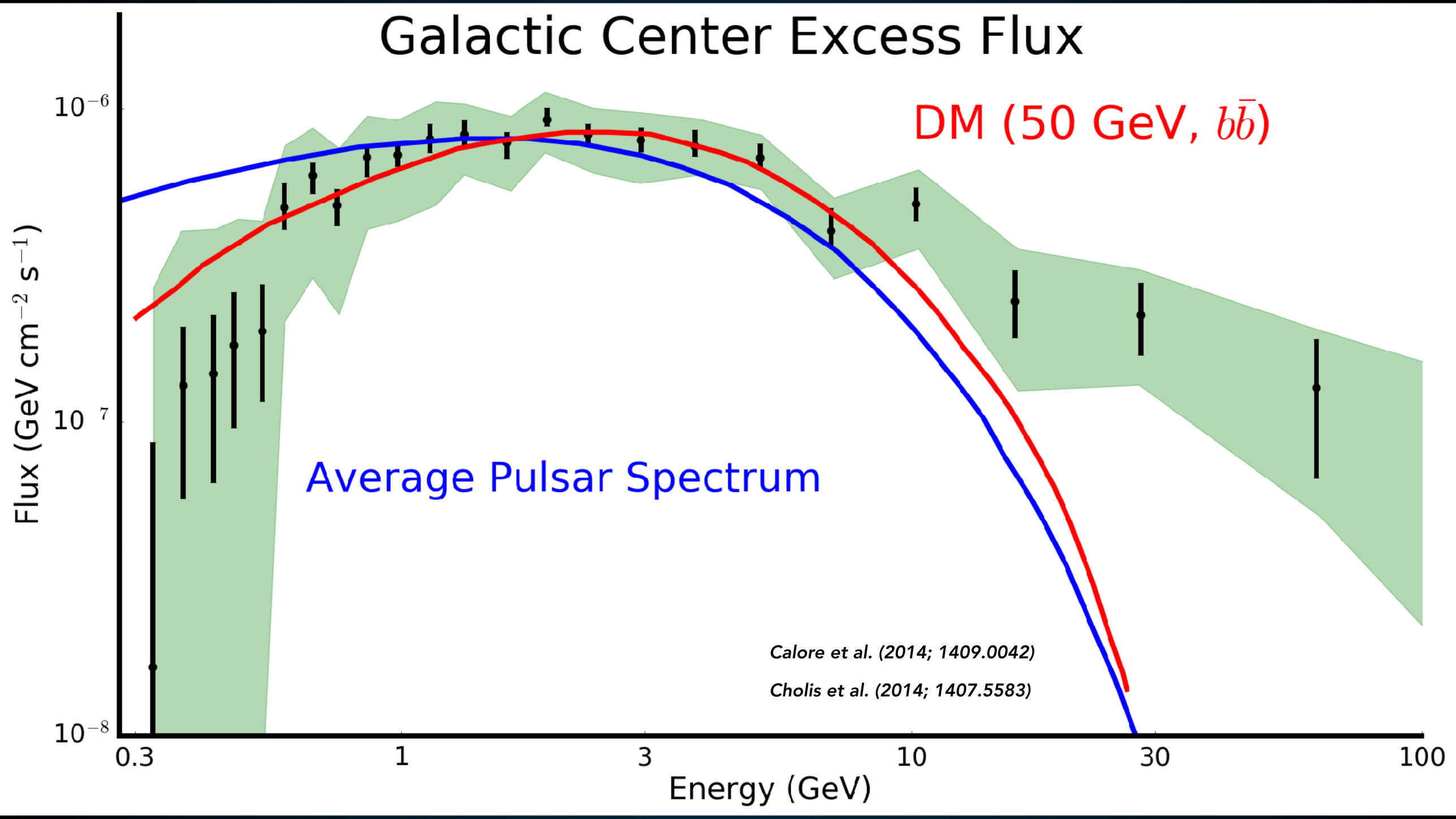

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Abazajian & Kaplinghat (1207.6047)
Gordon & Macias (1306.5725)
Daylan et. al. (1402.6703)
Cross-Section (10^{-26} cm^{3}s^{-1})
5
3
2
1
0.8
0.5
10
20
50
100
Energy (GeV)

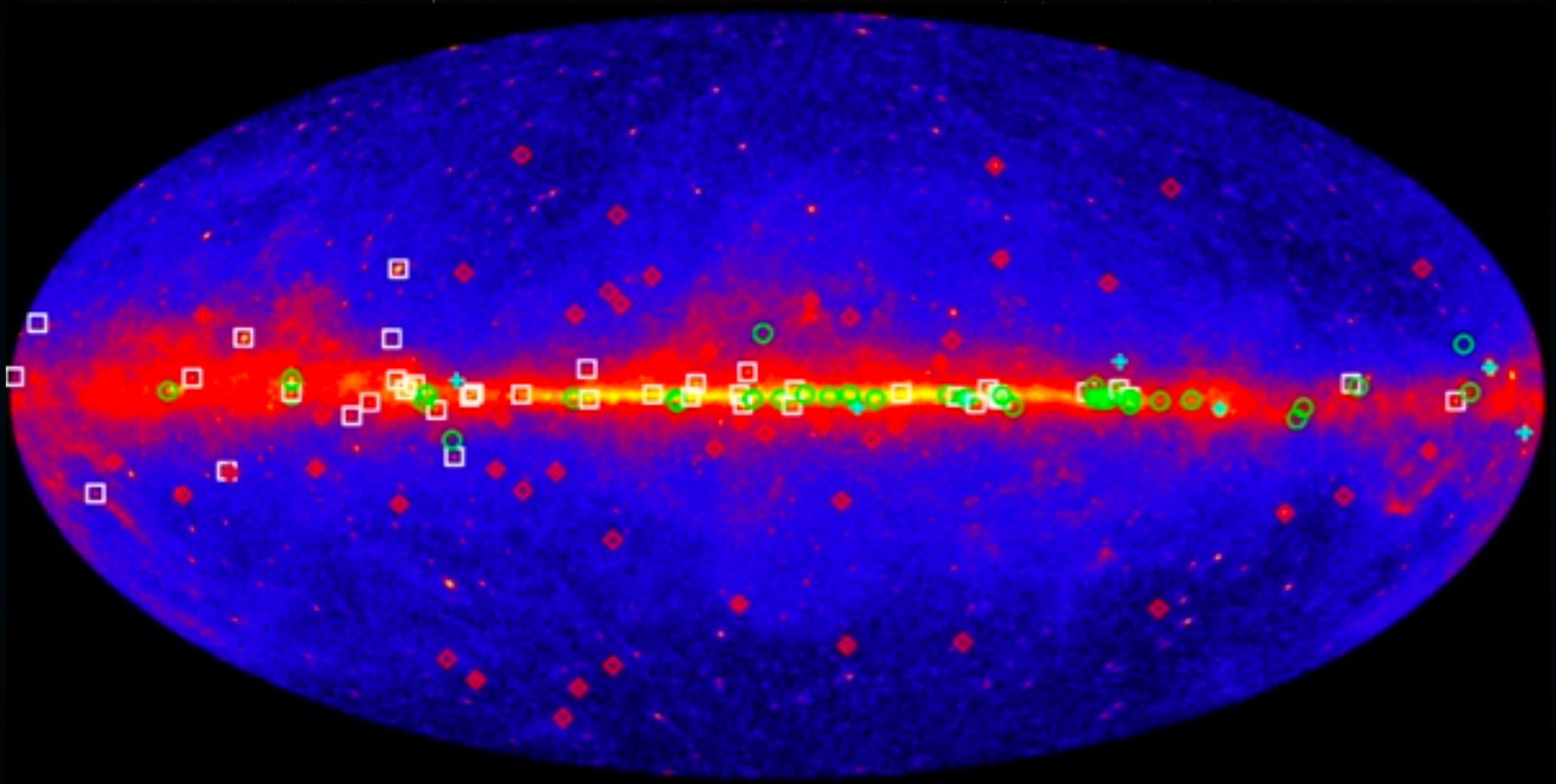

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Abazajian & Kaplinghat (1207.6047)
Gordon & Macias (1306.5725)
Daylan et. al. (1402.6703)
Calore et. al. (1409.0042)
Cross-Section (10^{-26} cm^{3}s^{-1})
5
3
2
1
0.8
0.5
10
20
50
100
Energy (GeV)

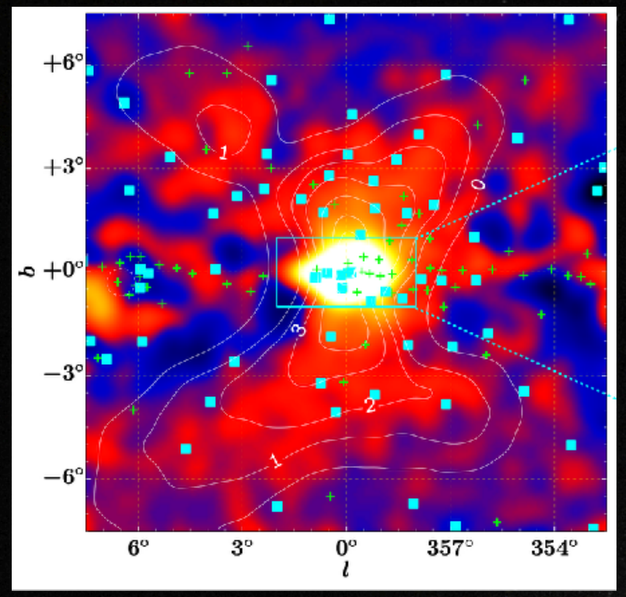

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Abazajian & Kaplinghat (1207.6047)
Gordon & Macias (1306.5725)
Daylan et. al. (1402.6703)
Calore et. al. (1409.0042)
Calore et. al. (1411.4647)
Cross-Section (cm^{3}s^{-1})
5
3
2
1
0.8
0.5
10
20
50
100
Energy (GeV)


Galactic Center Excess Flux
10^{-6}
10^{-7}
10^{-8}
Flux (GeV cm^{-2} s^{-1})
0.3
1
3
10
30
100
Energy (GeV)
Calore et al. (2014; 1409.0042)


Galactic Center Excess Flux
DM (50 GeV, $b\bar{b}$)
Calore et al. (2014; 1409.0042)
Flux (GeV cm^{-2} s^{-1})
10^{-6}
10^{-7}
10^{-8}
0.3
1
3
10
30
100
Energy (GeV)


Galactic Center Excess Flux
DM (50 GeV, $b\bar{b}$)
Average Pulsar Spectrum
Calore et al. (2014; 1409.0042)
Cholis et al. (2014; 1407.5583)
Flux (GeV cm^{-2} s^{-1})
10^{-6}
10^{-7}
10^{-8}
0.3
1
3
10
30
100
Energy (GeV)





Macias et al. (2016; 1611.06644)

Bartels et al. (2017; 1711.04778)

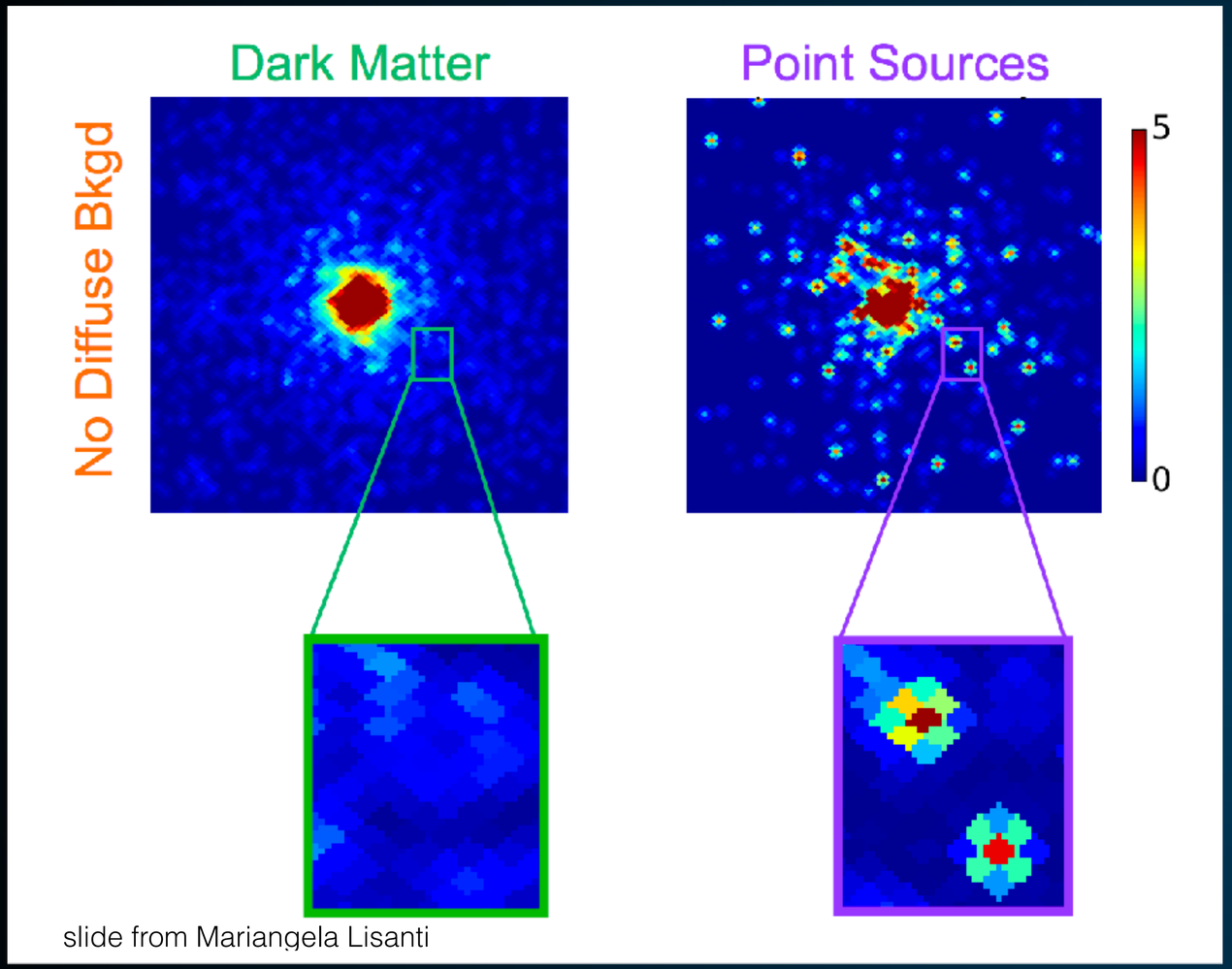
Bartels et al. (2018; 1803.04370)

Macias et al. (2019; 1901.03822)

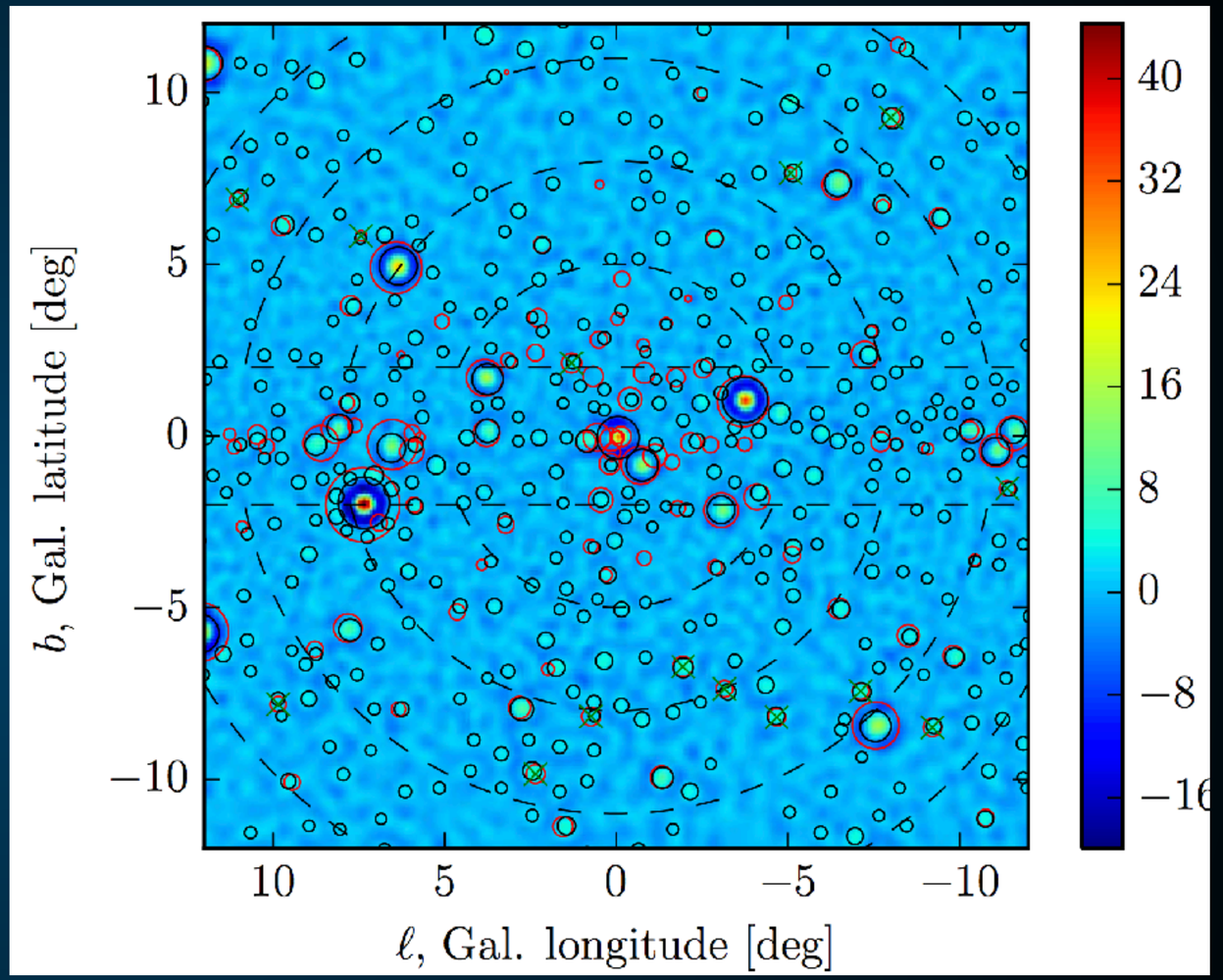
The Galactic Center Excess

Bartels et al. (2015; 1506.05104)

Lee et al. (2015; 1506.05124)



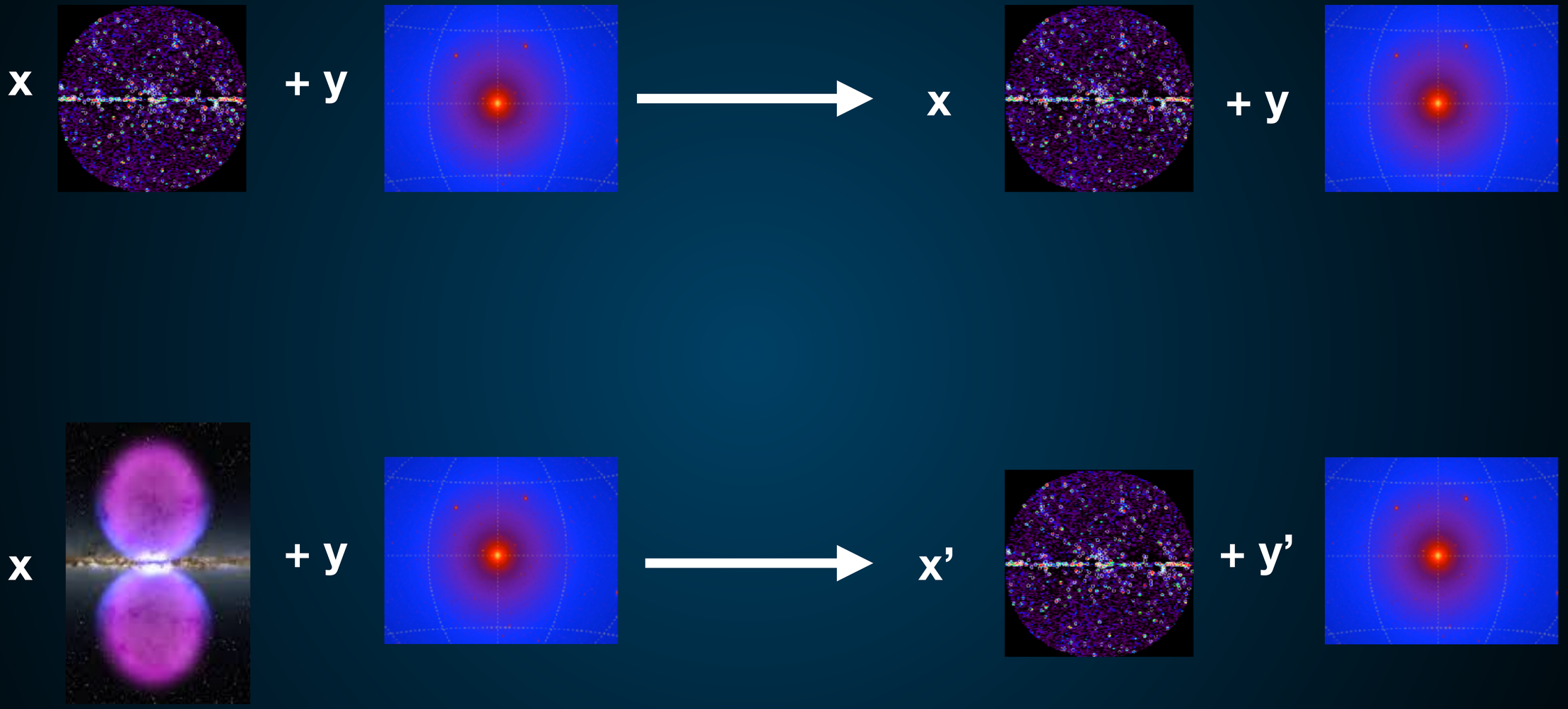
slide from Mariangela Lisanti



Bulletproof evidence for pulsars?

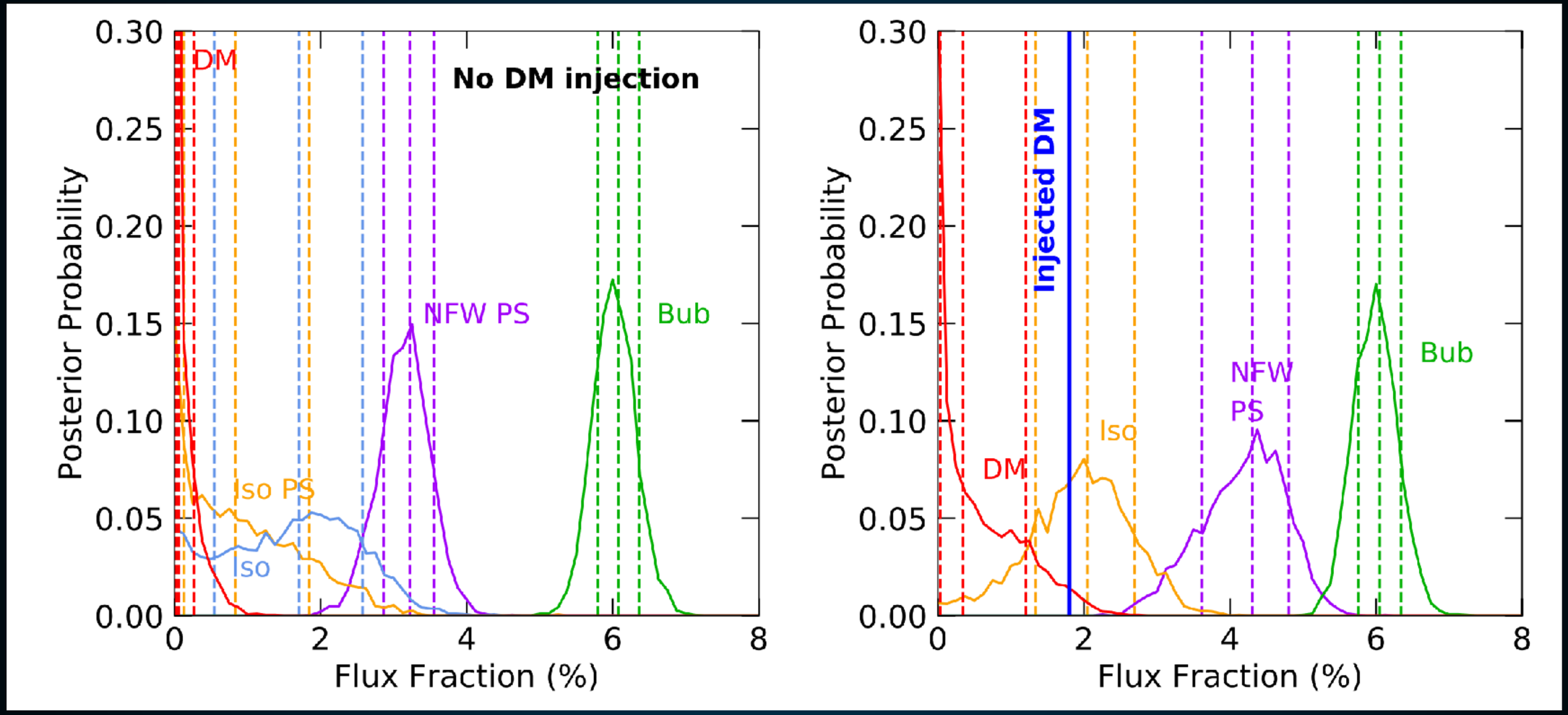
The Galactic Center Excess

Leane & Slatyer (2019; 1904.08430)



The Galactic Center Excess

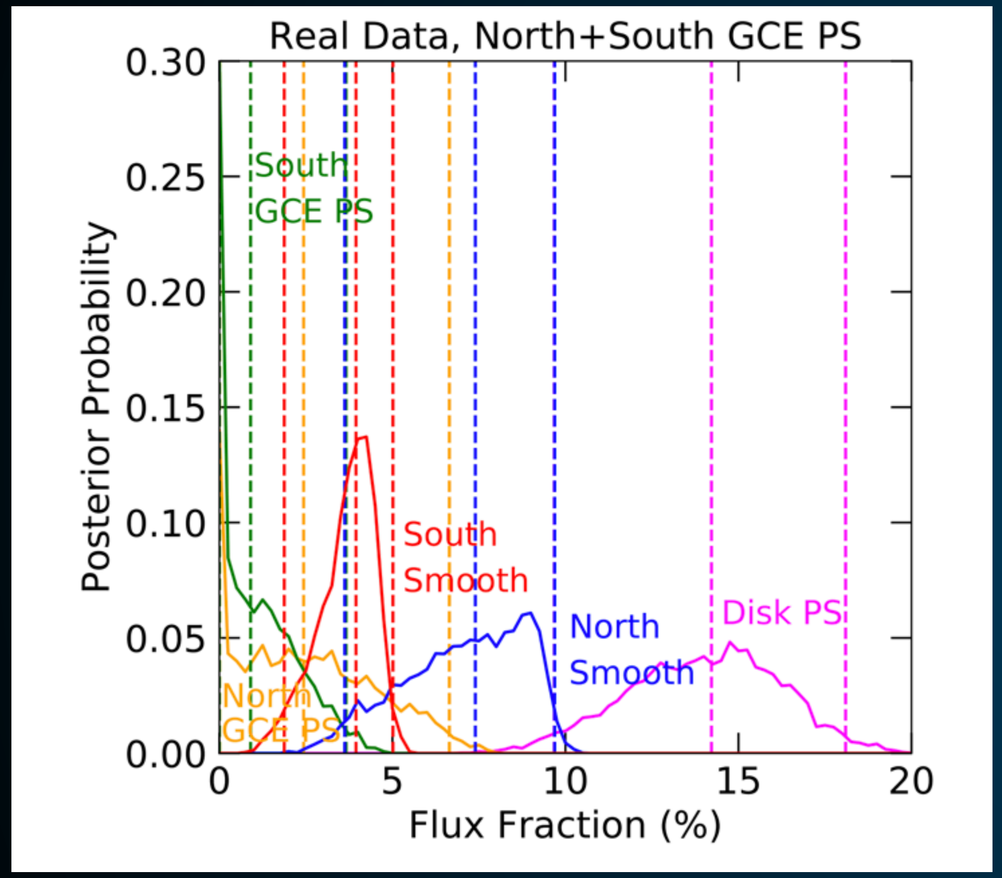
Leane & Slatyer (2019; 1904.08430)



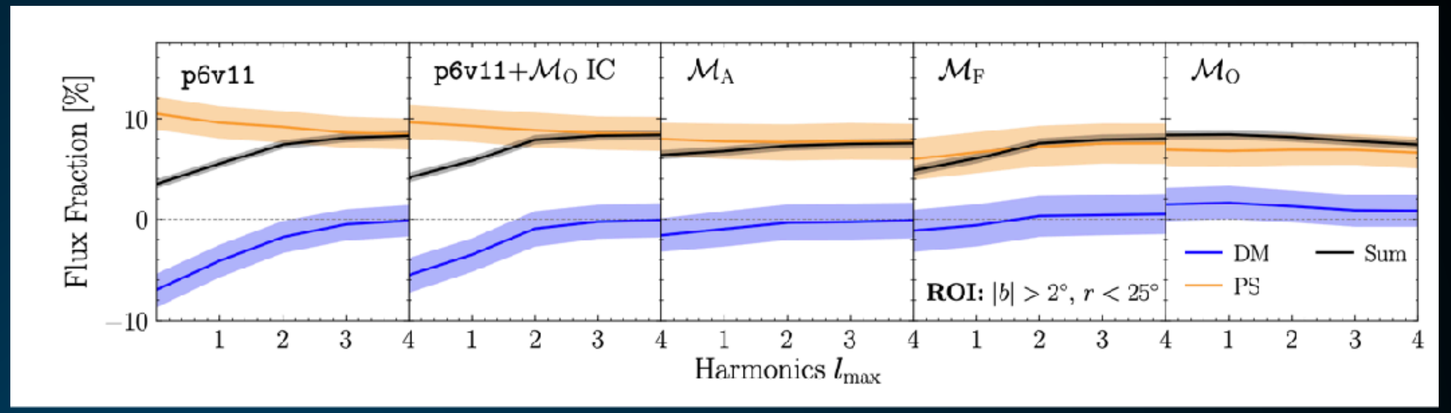
Dark Matter Strikes Back at the Galactic Center

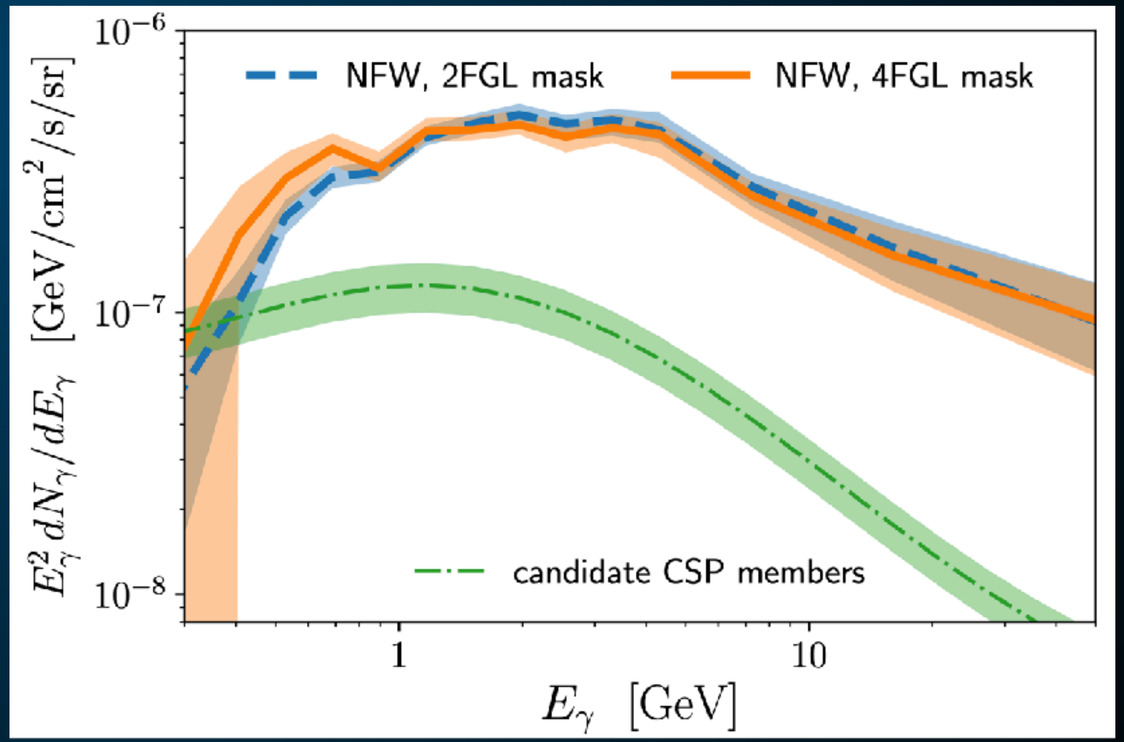
The Galactic Center Excess

Leane & Slatyer (2020; 2002.12370)
Leane & Slatyer (2020; 2002.12371)

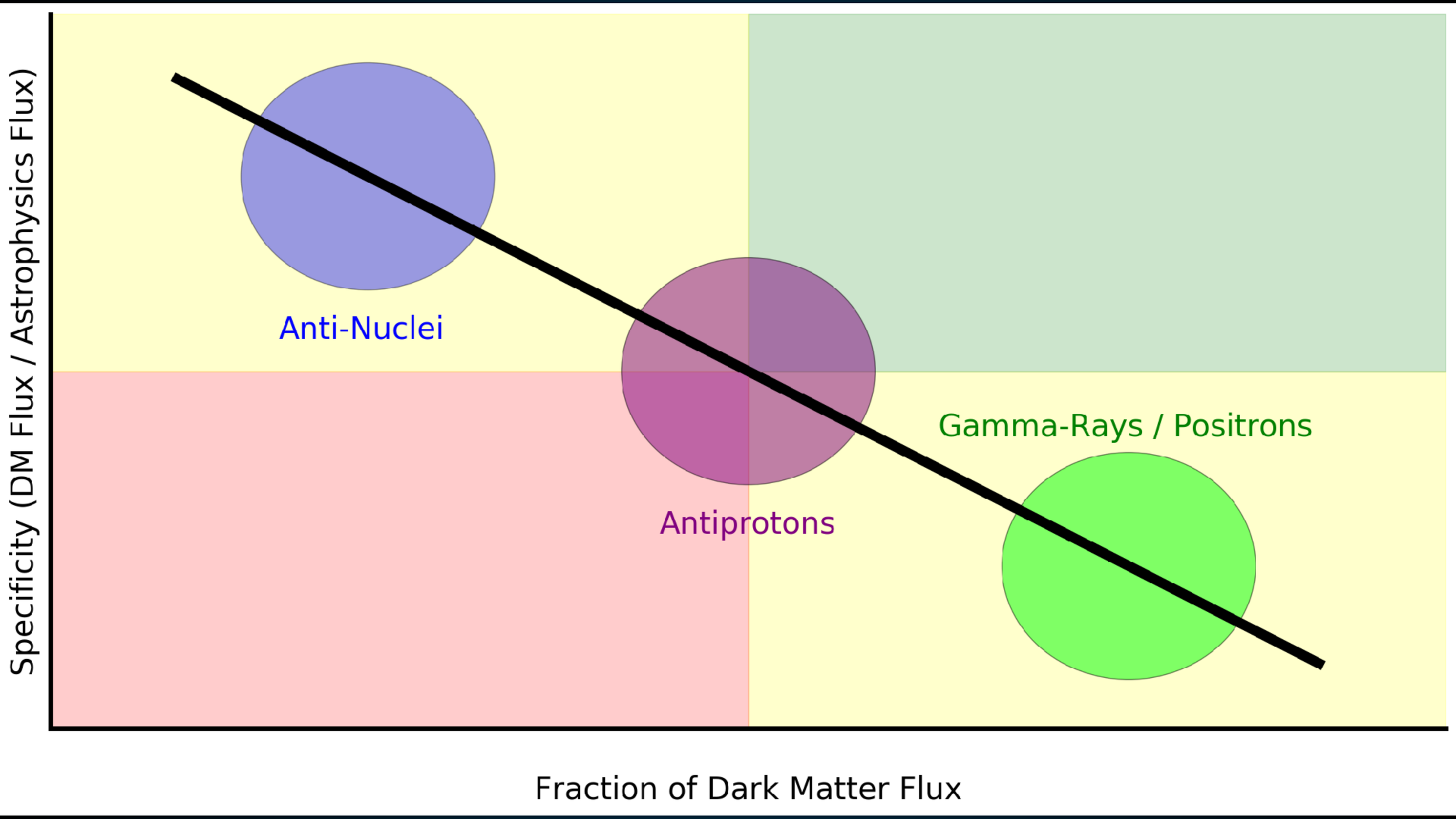


Chang et al. (2019, 1908.10874)
Buschmann et al. (2020, 2002.12373)



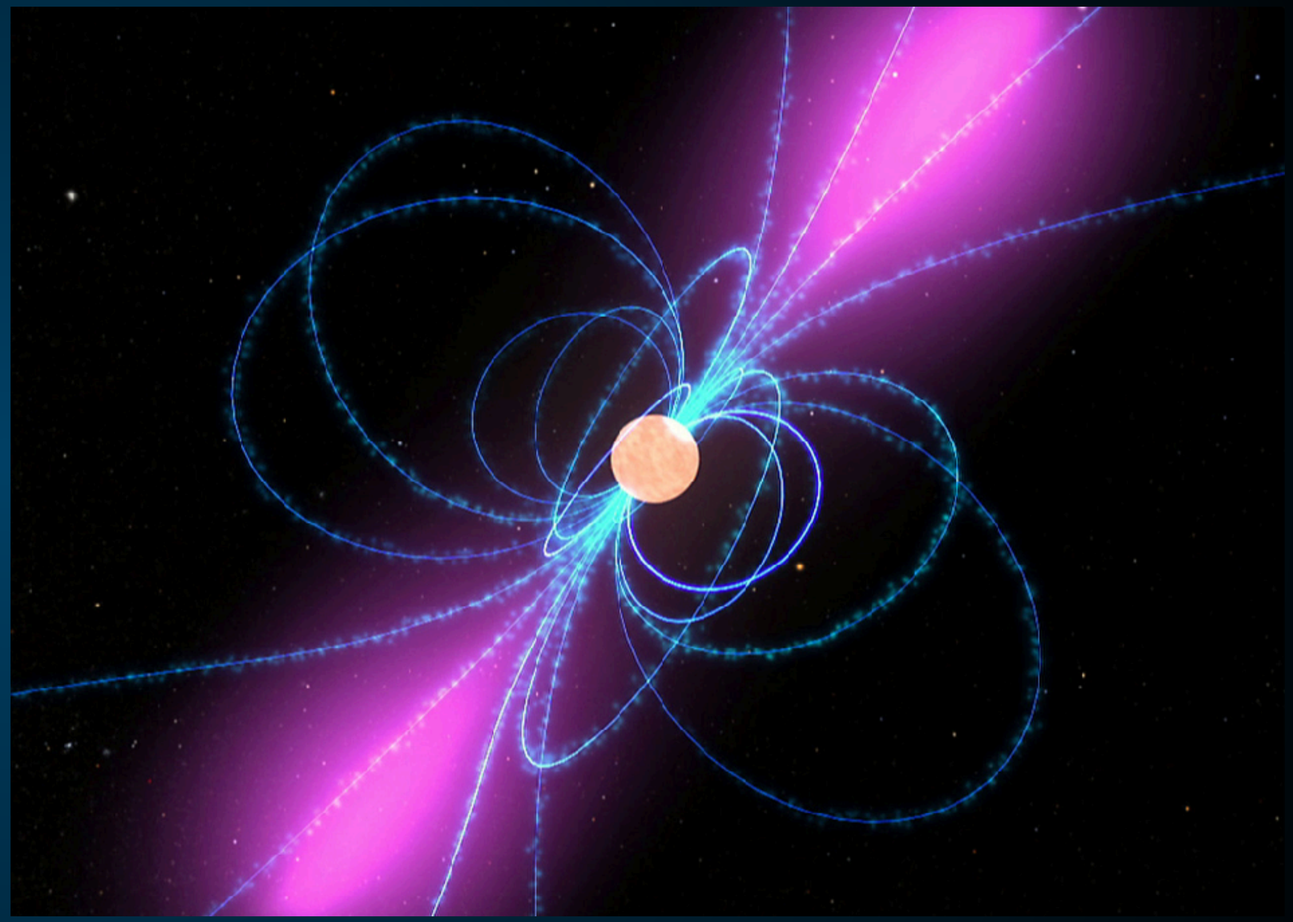


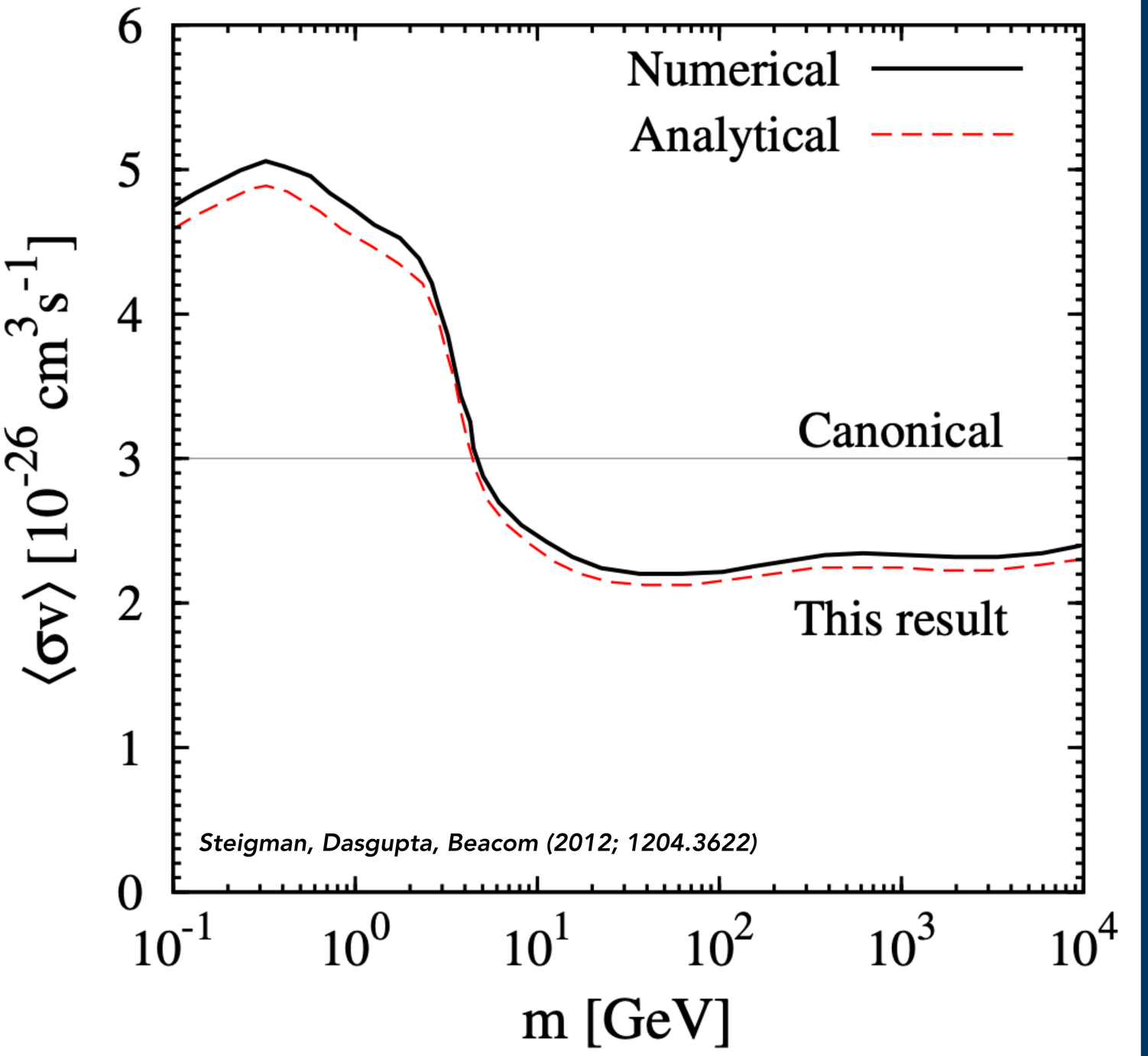
Zhong et al. (2019; 1911.12369)


Specificity (DM Flux / Astrophysics Flux)
Anti-Nuclei
Antiprotons
Gamma-Rays / Positrons
Fraction of Dark Matter Flux



The Galactic Center: The Easiest Place to Find Dark Matter





Thermal Dark Matter Density

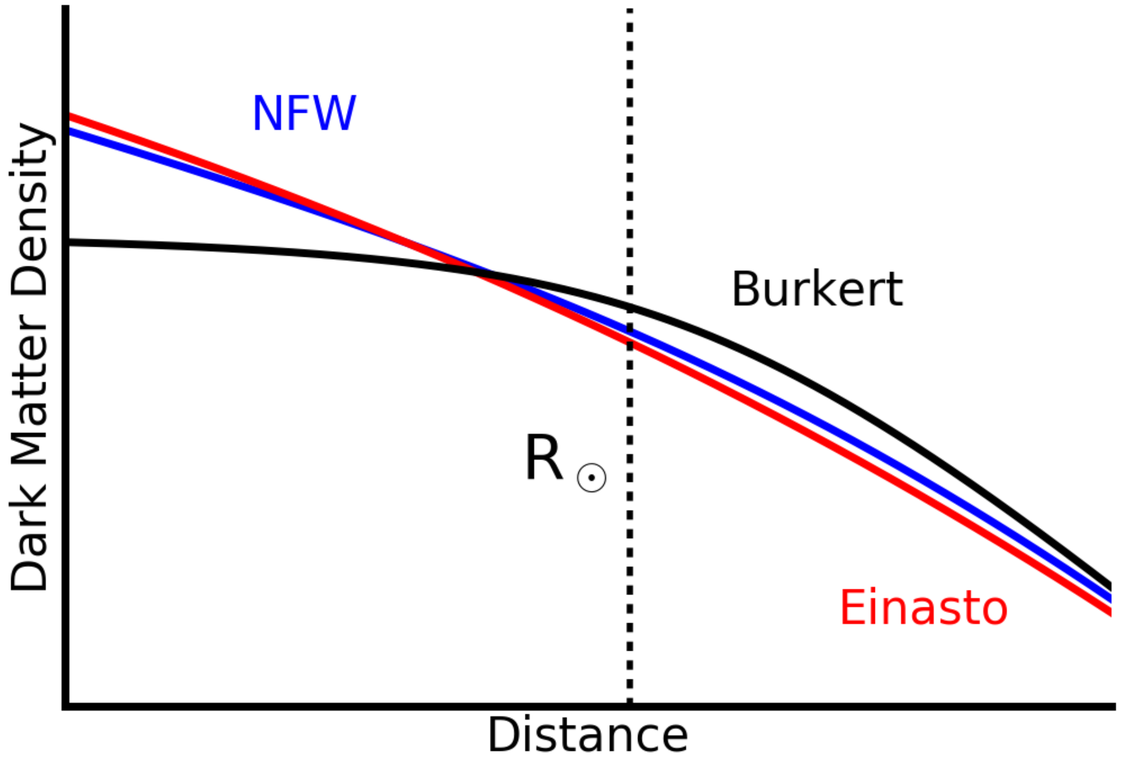
Simplest model has a known cross-section!

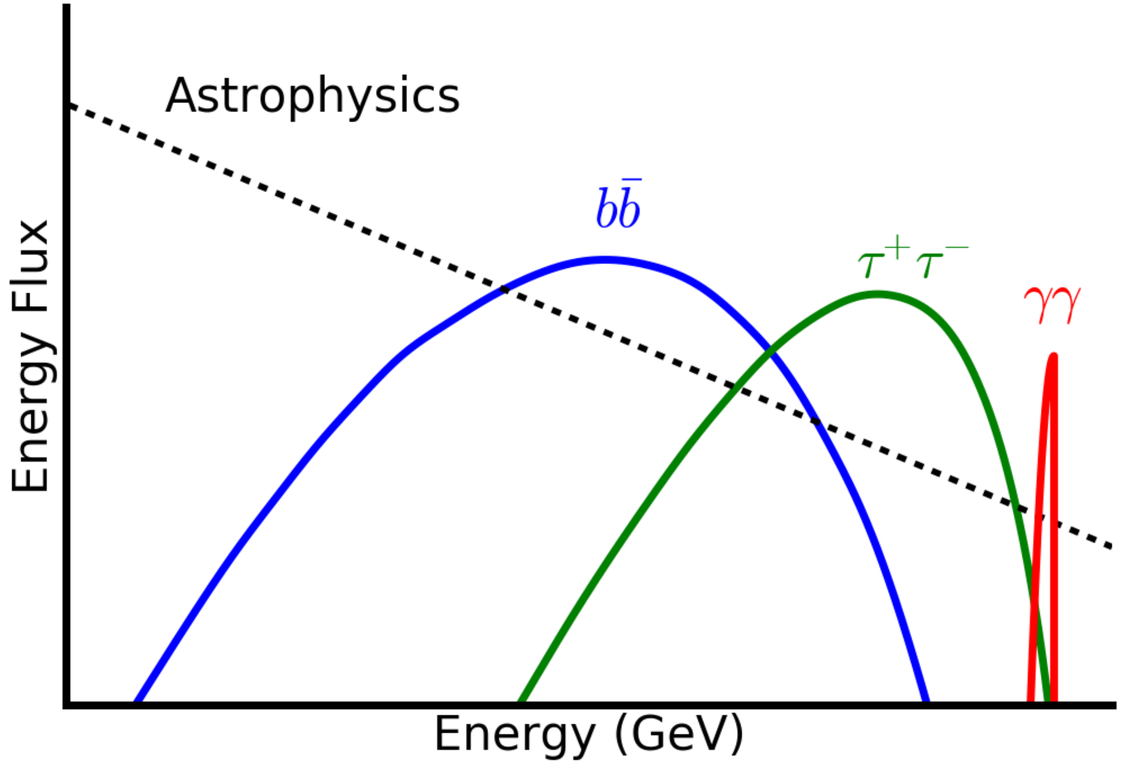
Deviations from this cross-section include complicating effects.

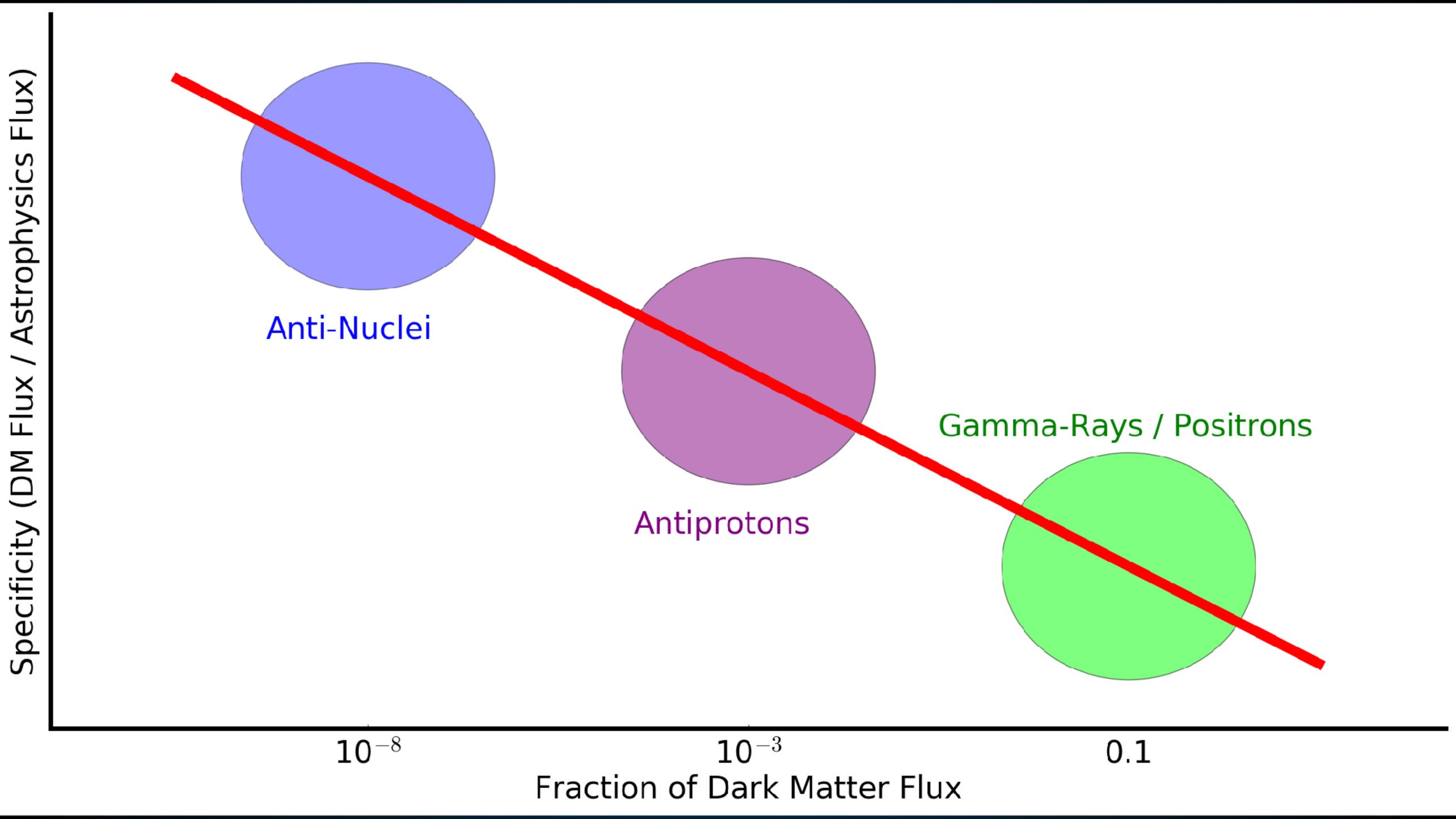
Philosophy:

Constrain the simplest model first

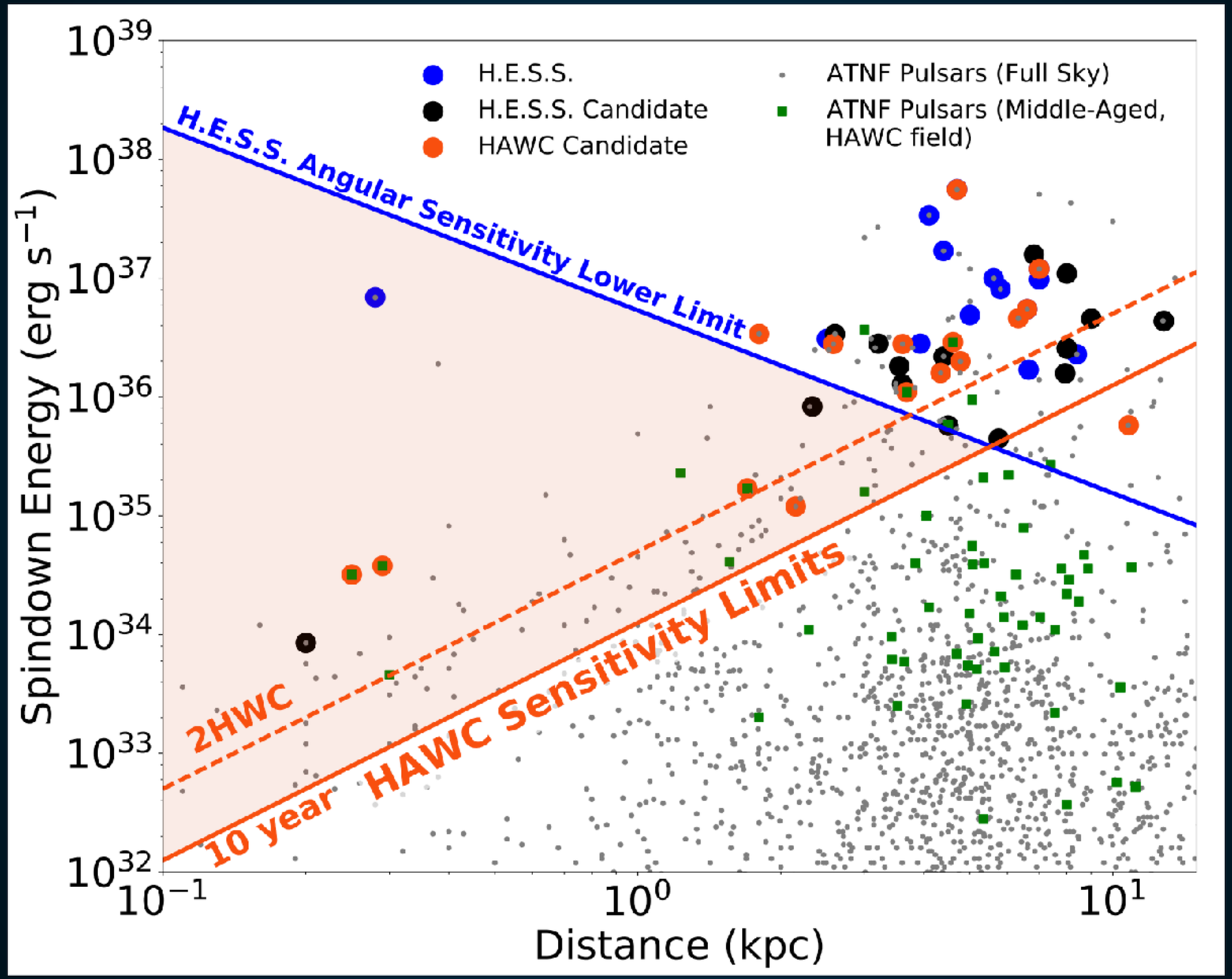



NFW
Burkert
Einasto
R ⊙
Dark Matter Density
Distance

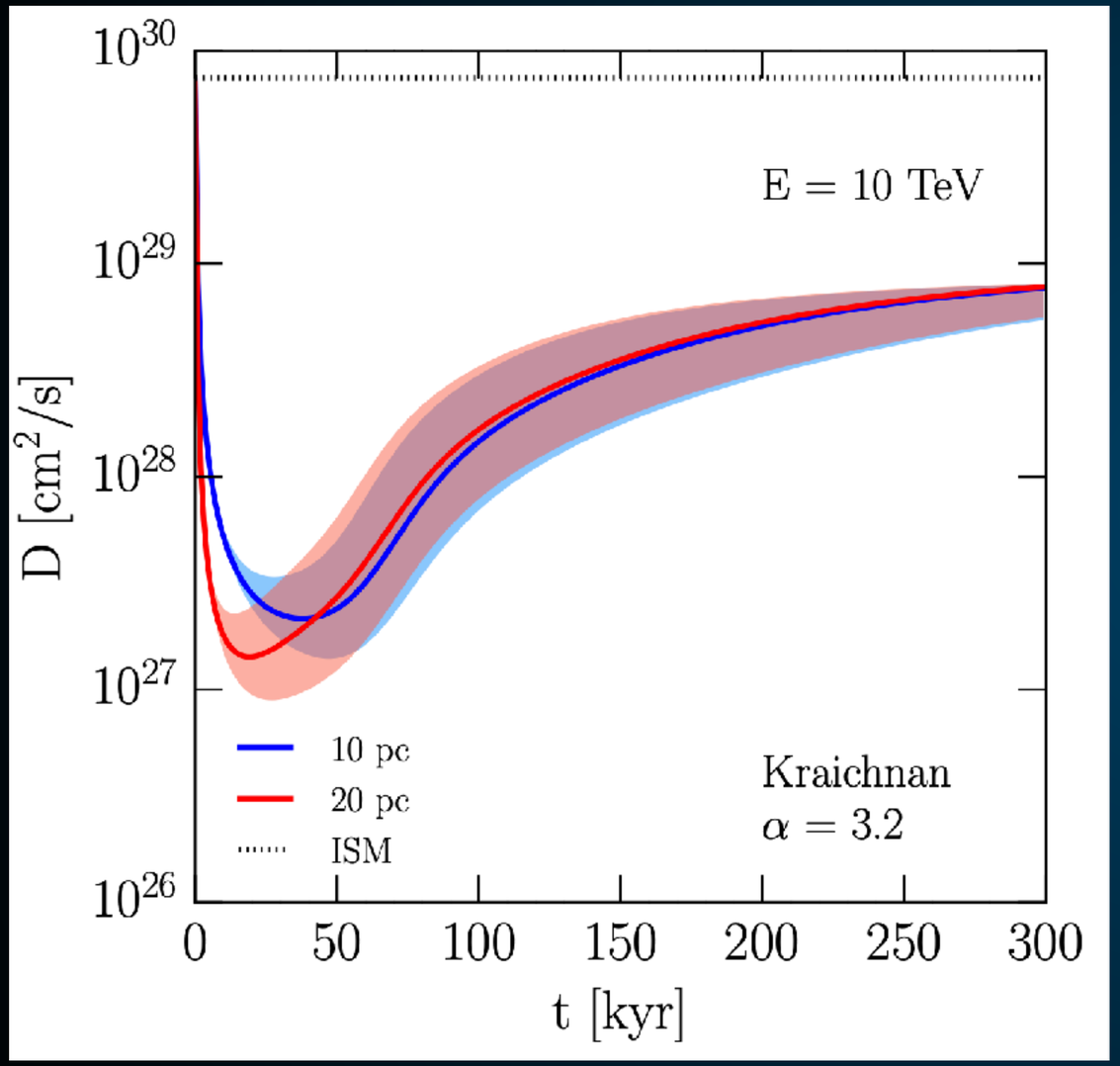

Astrophysics
$b\bar{b}$
$\tau^+\tau^-$
$\gamma\gamma$
Energy Flux
Energy (GeV)

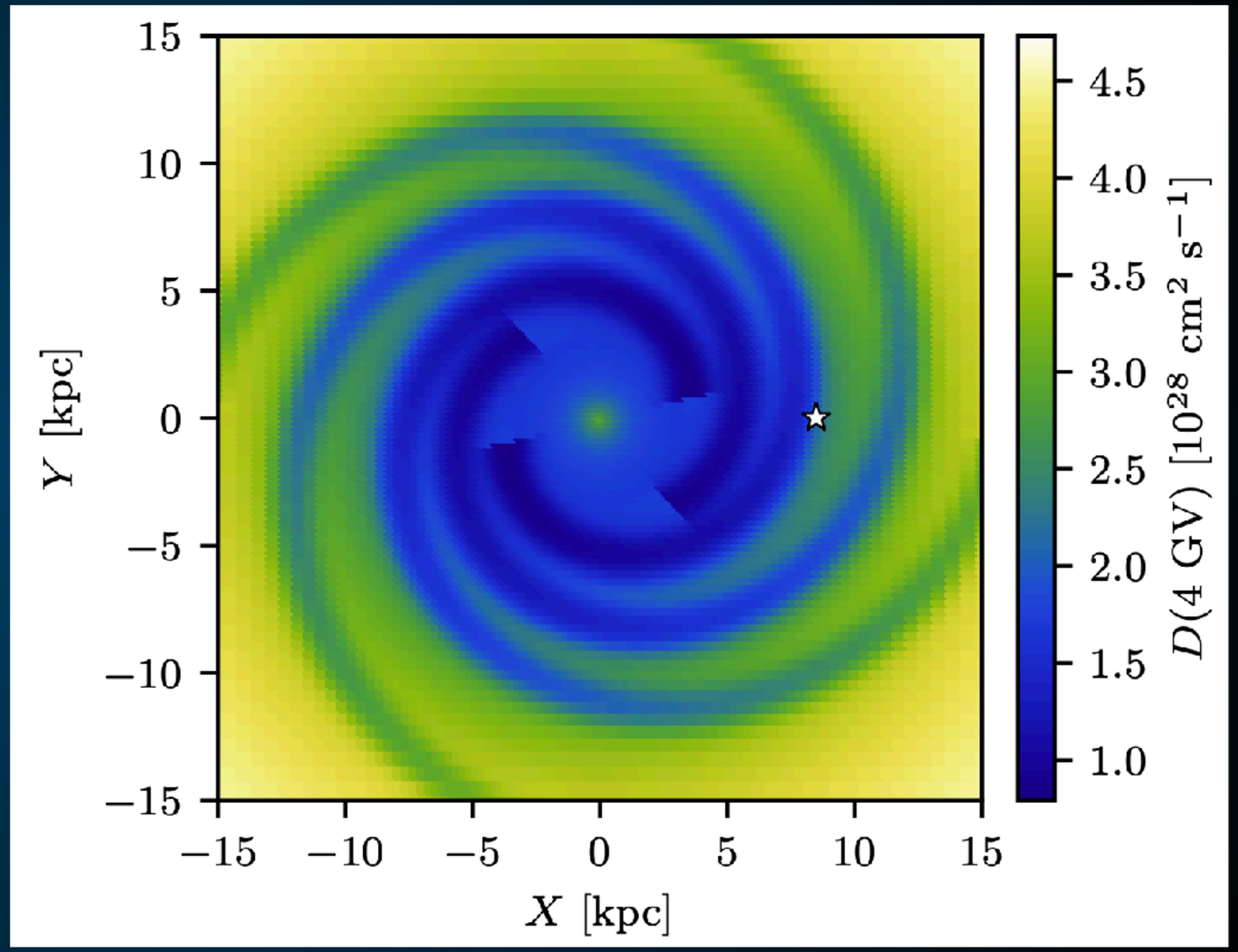

Specificity (DM Flux / Astrophysics Flux)
Anti-Nuclei
Antiprotons
Gamma-Rays / Positrons
10^{-8}
10^{-3}
0.1
Fraction of Dark Matter Flux

New Discoveries!

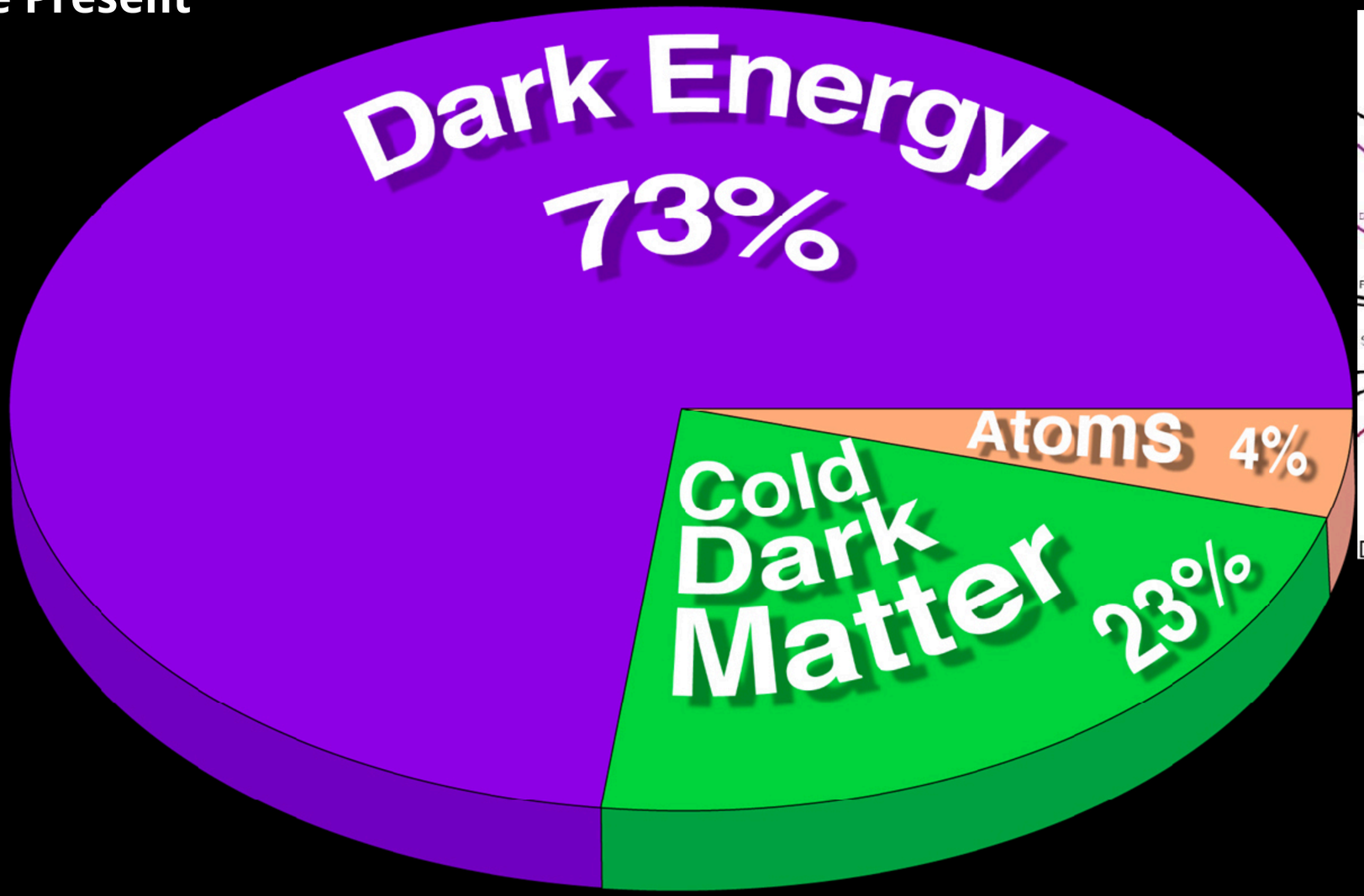


New Discoveries!

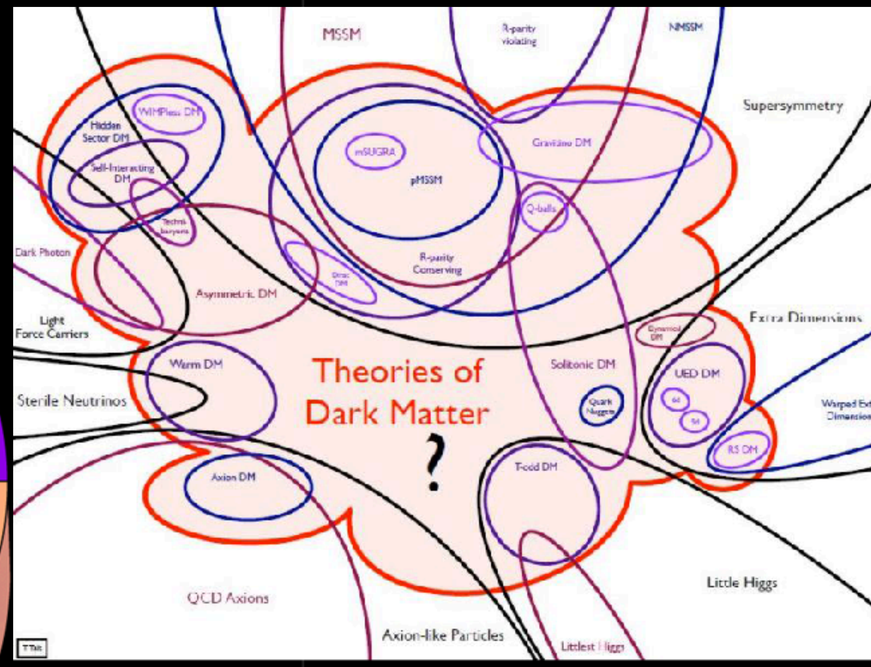




The Present



courtesy: Tim Tait

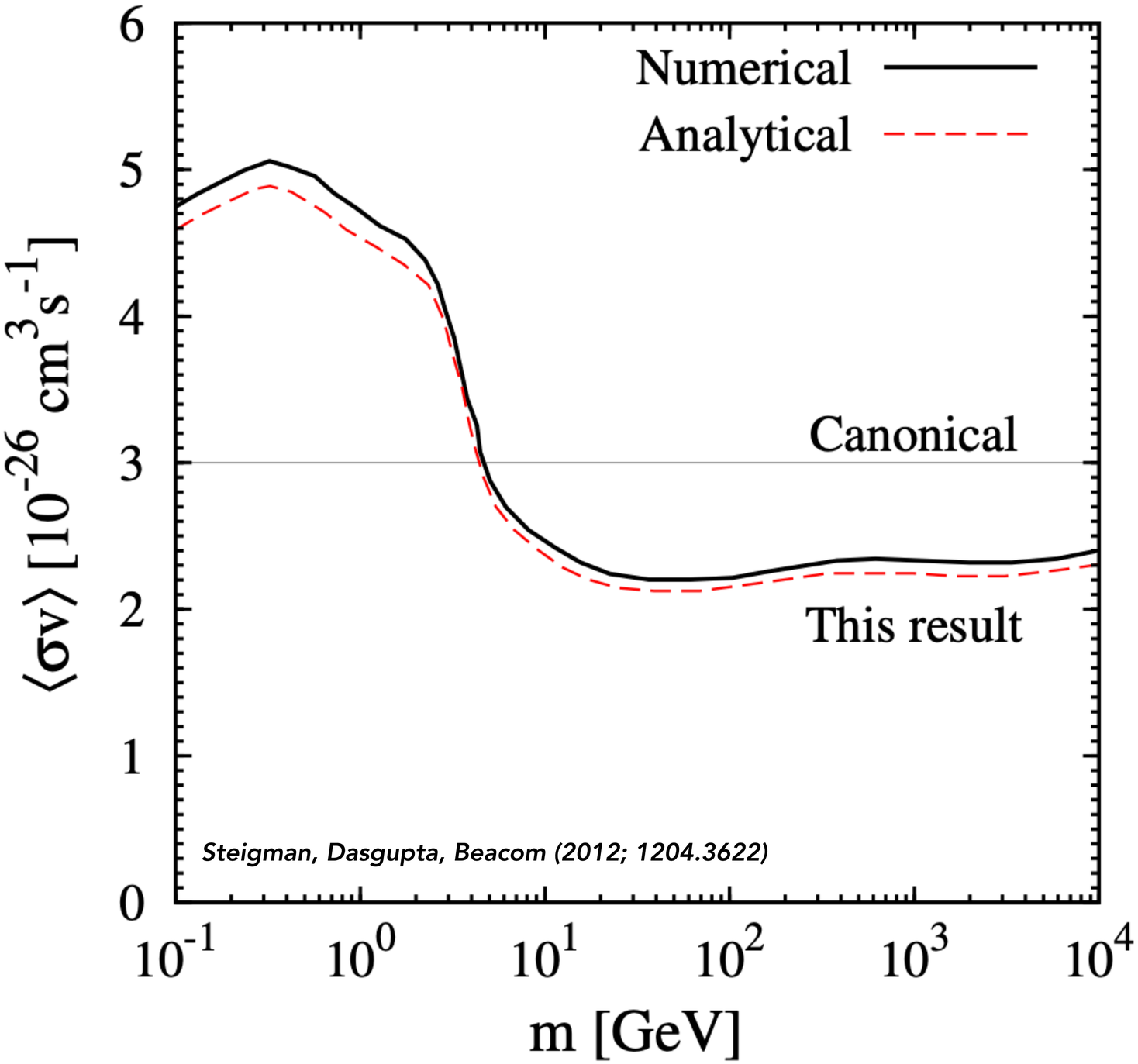


10^{-25} GeV

$R_{DM} > R_{UFD}$

10^{62} GeV

$M_{DM} > M_{UFD}$

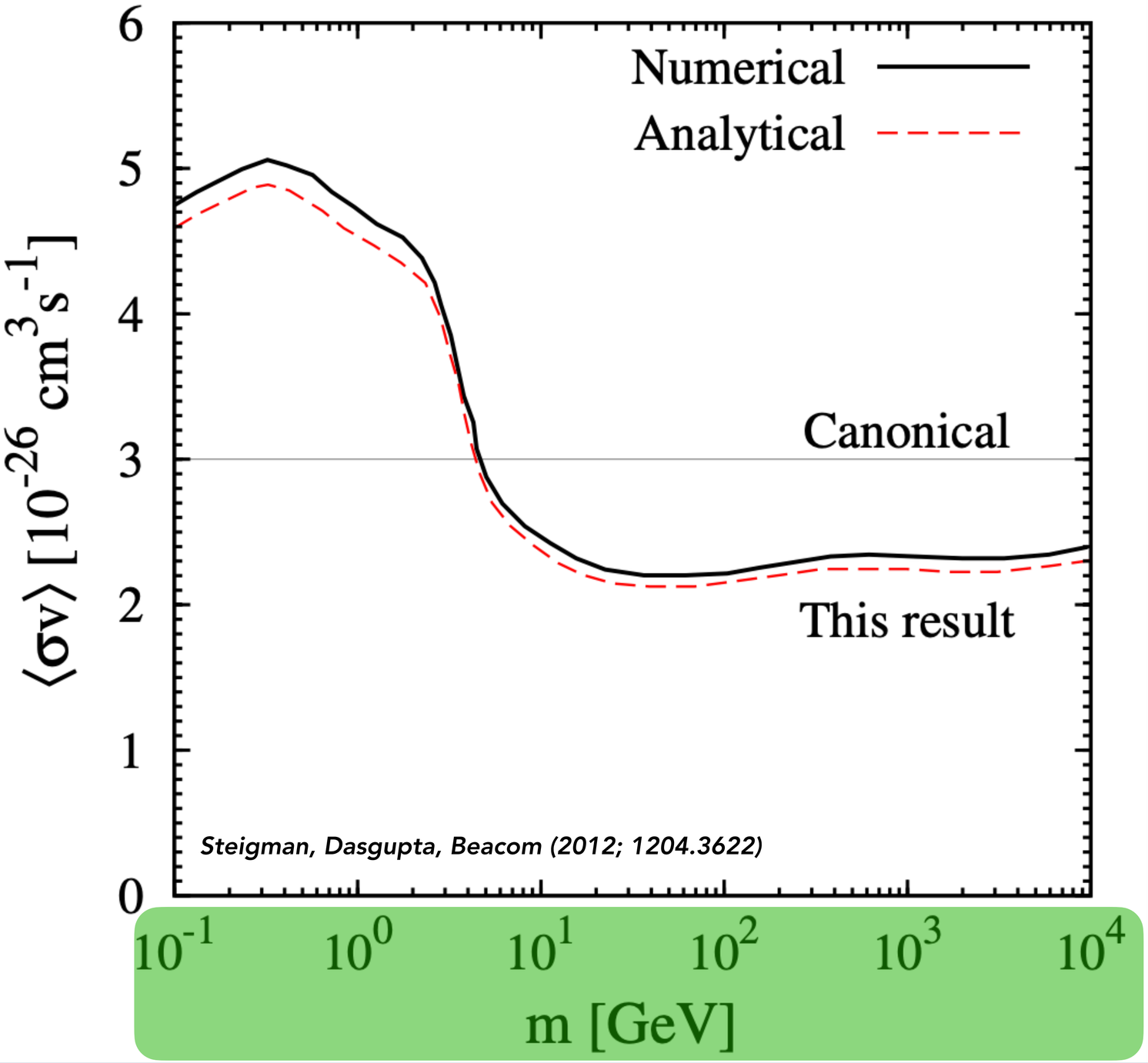


Steigman, Dasgupta, Beacom (2012; 1204.3622)

Thermal Dark Matter Density

Simplest model has a known cross-section!

Deviations from this cross-section include complicating effects.

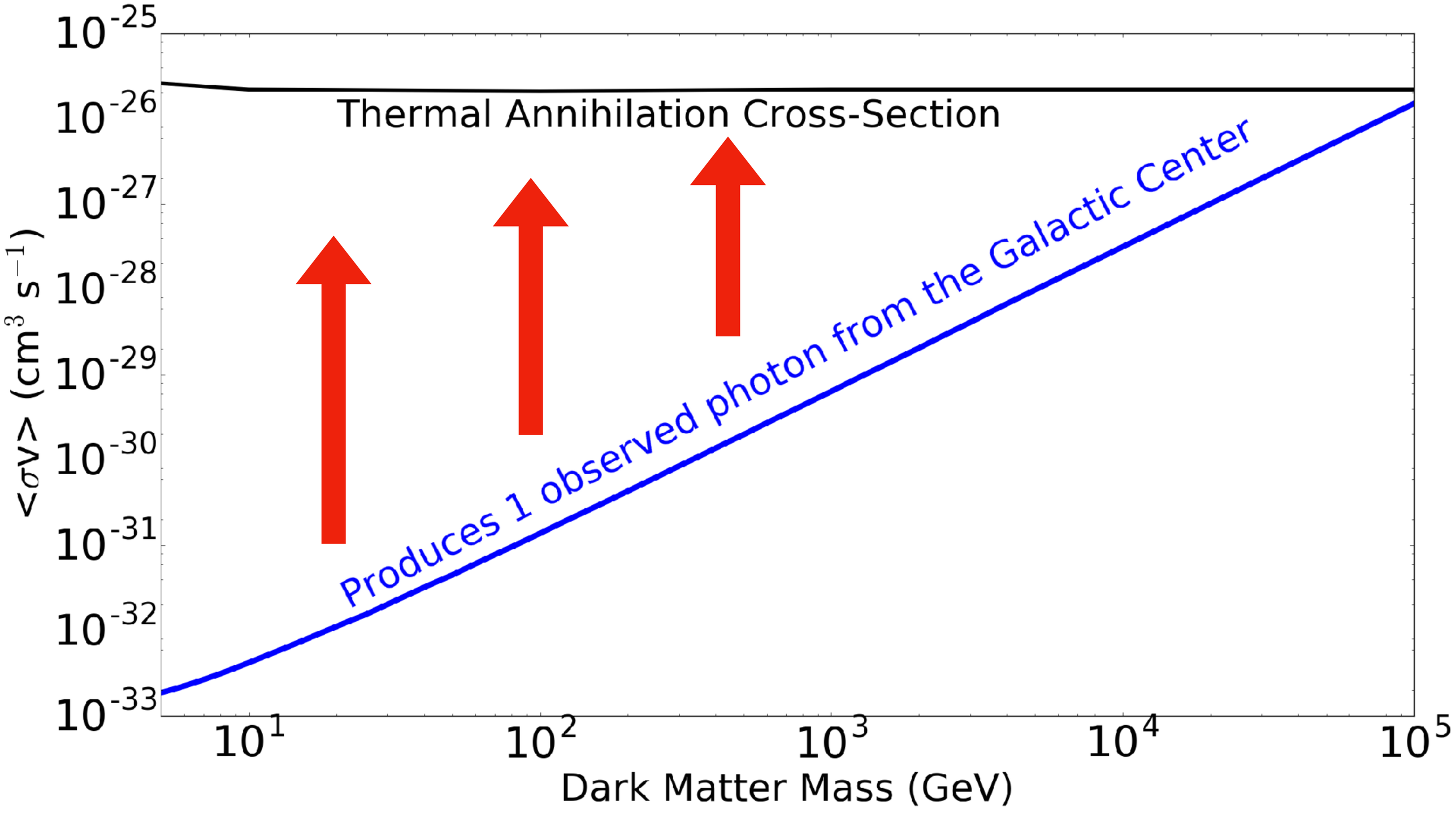


Thermal Dark Matter Density

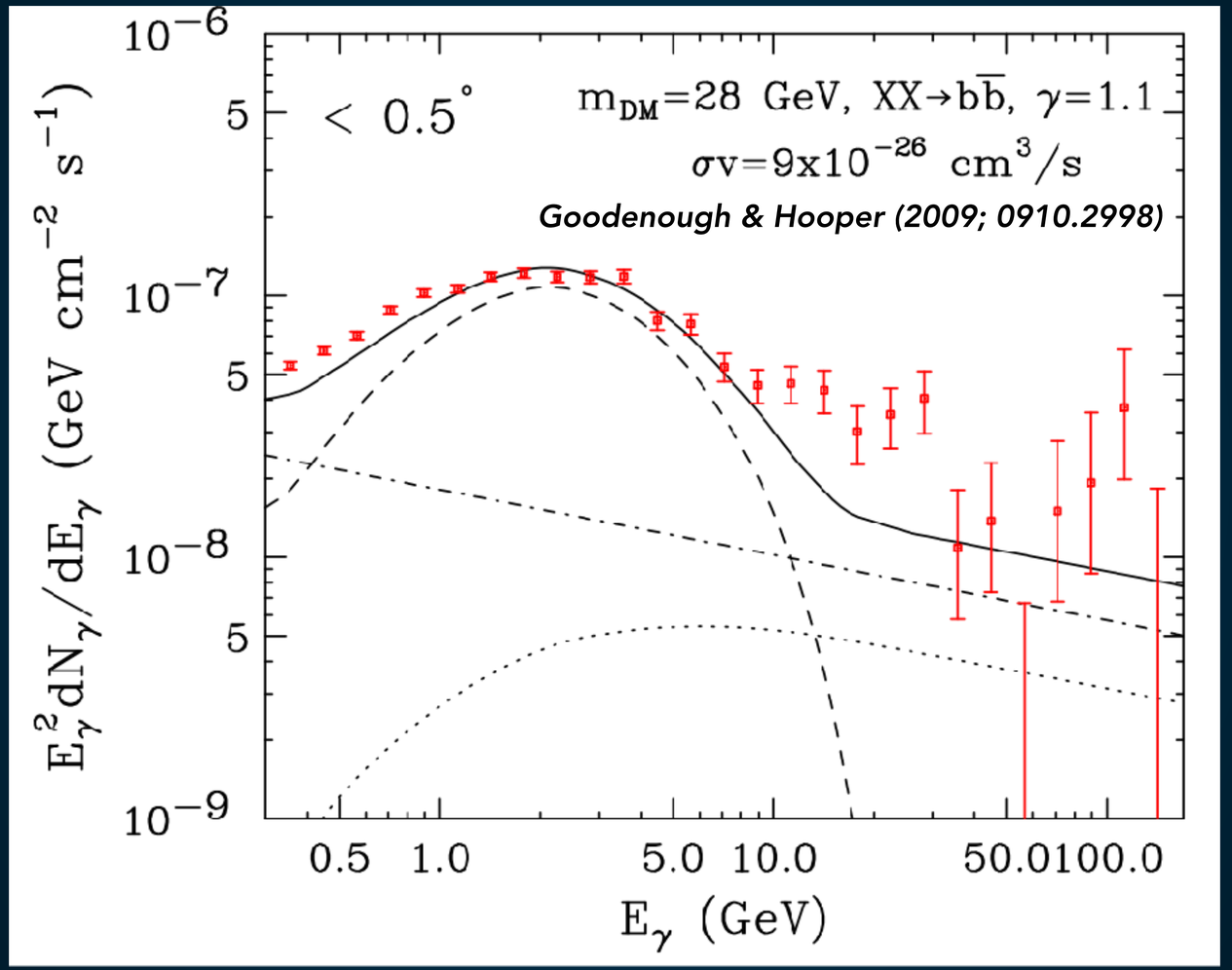
Simplest model has a known cross-section!

Deviations from this cross-section include complicating effects.

A Mass Scale!

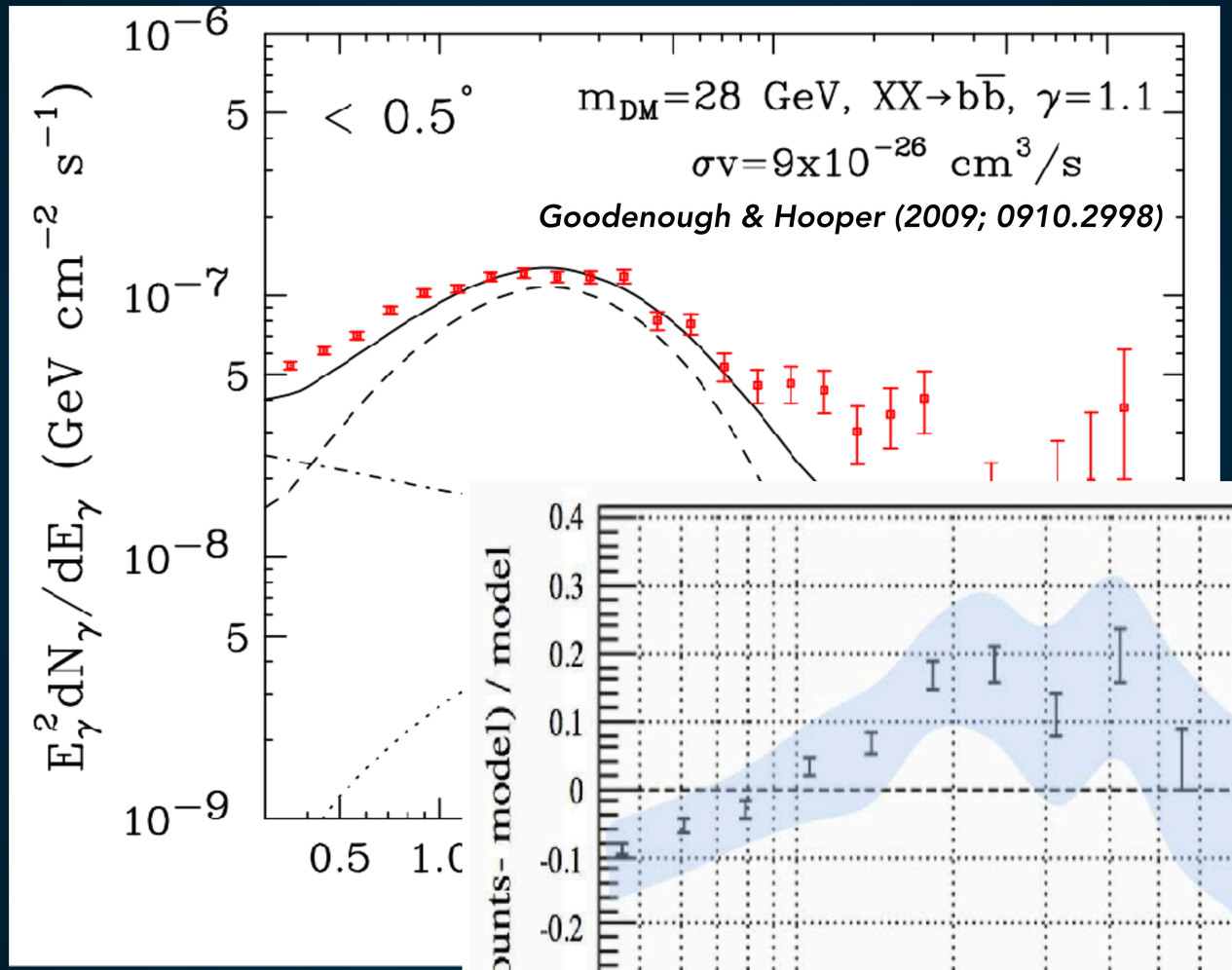

Thermal Annihilation Cross-Section
Produces 1 observed photon from the Galactic Center
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
$<\sigma v>$ (cm^3 s^{-1})
10^1
10^2
10^3
10^4
10^5
Dark Matter Mass (GeV)

The Galactic Center: The Easiest Place to Find Dark Matter

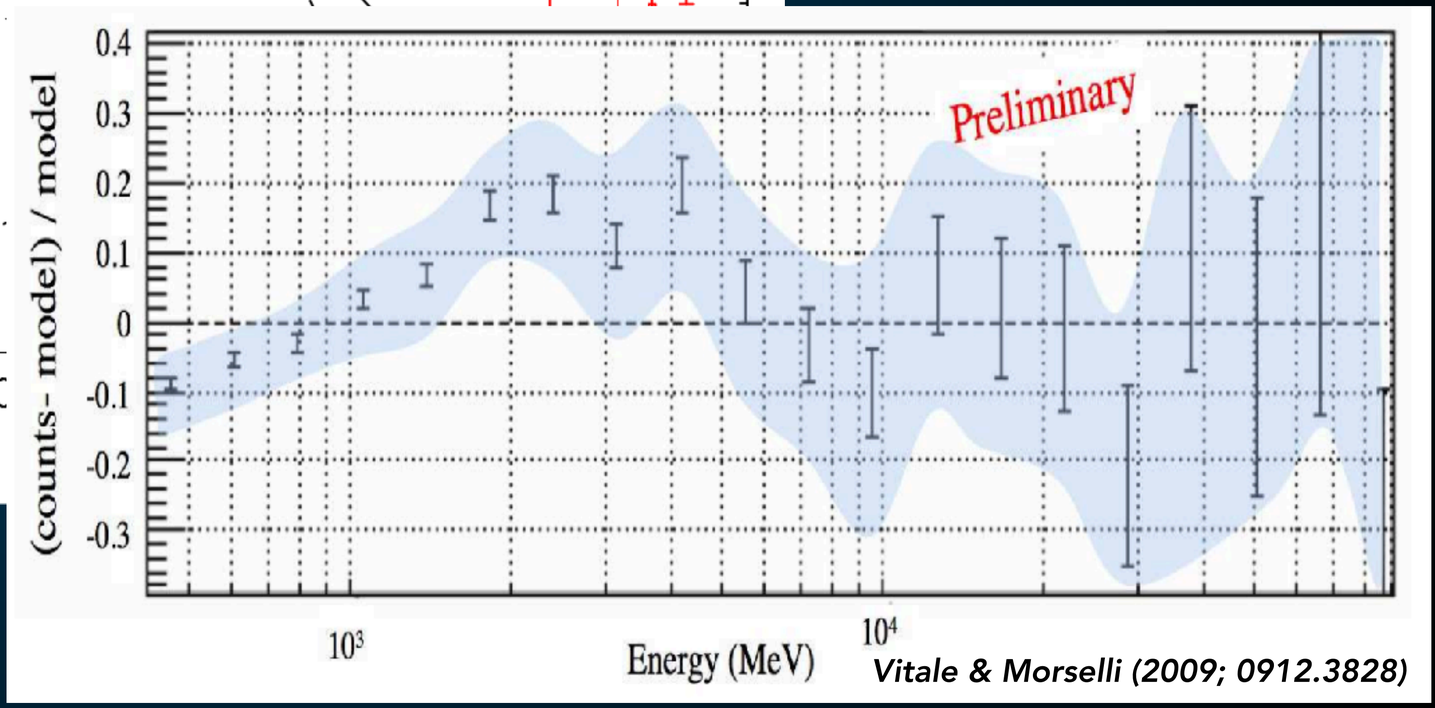


Goodenough & Hooper (2009; 0910.2998)

The Galactic Center: The Easiest Place to Find Dark Matter

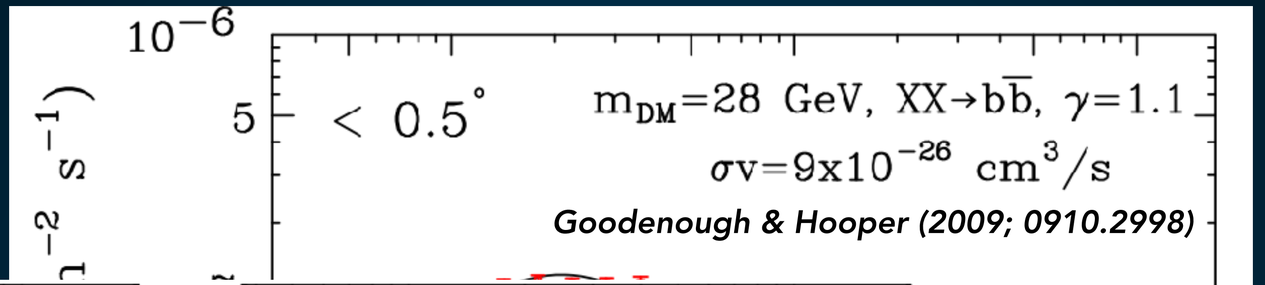


Goodenough & Hooper (2009; 0910.2998)



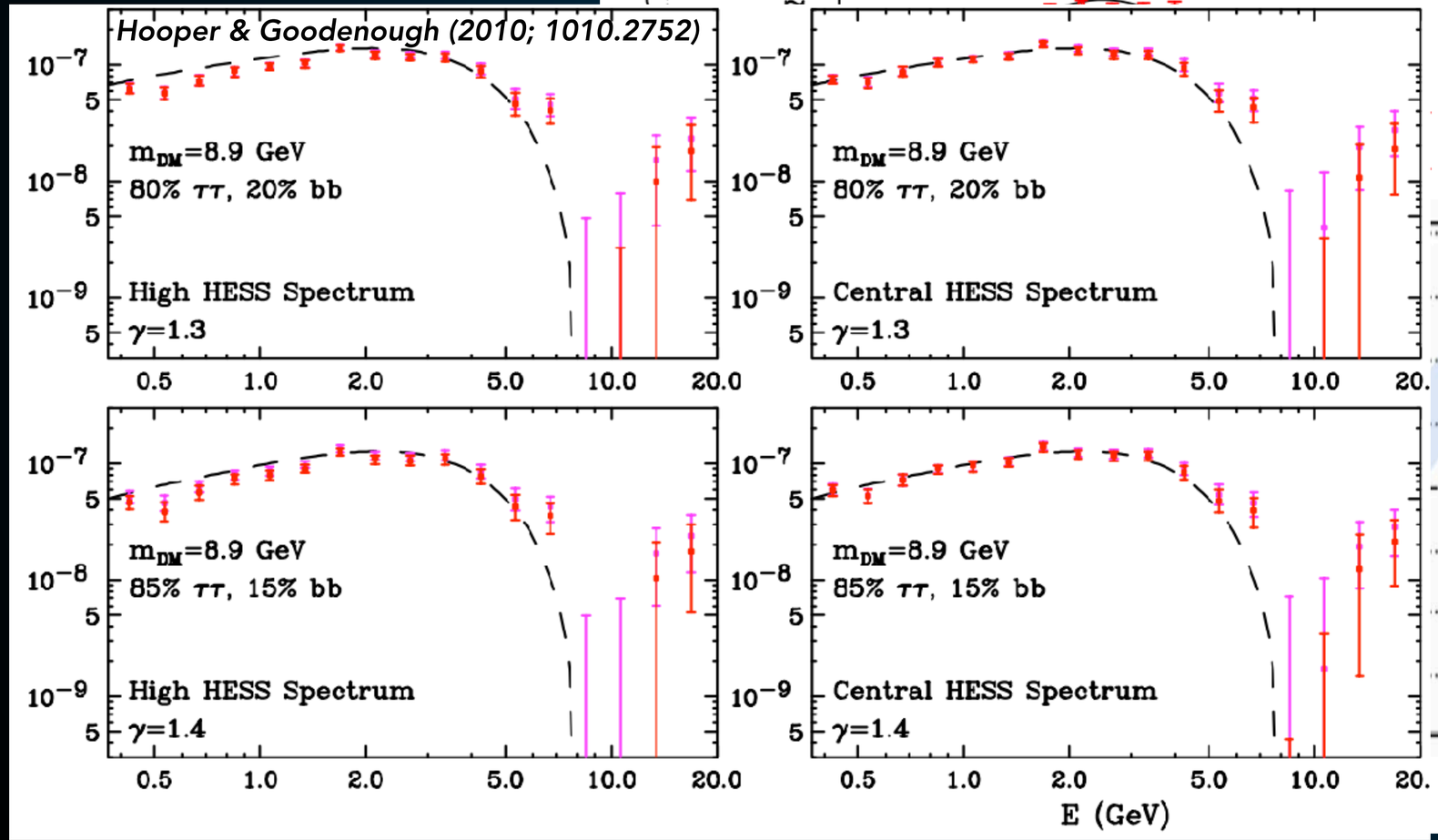
Vitale & Morselli (2009; 0912.3828)

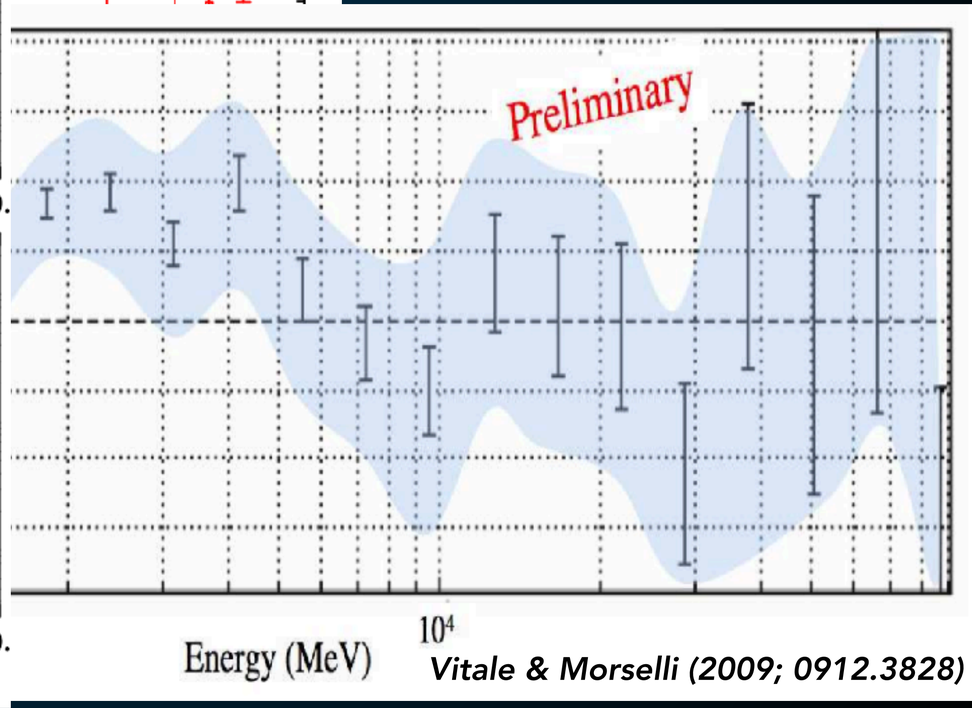
The Galactic Center: The Easiest Place to Find Dark Matter



Goodenough & Hooper (2009; 0910.2998)

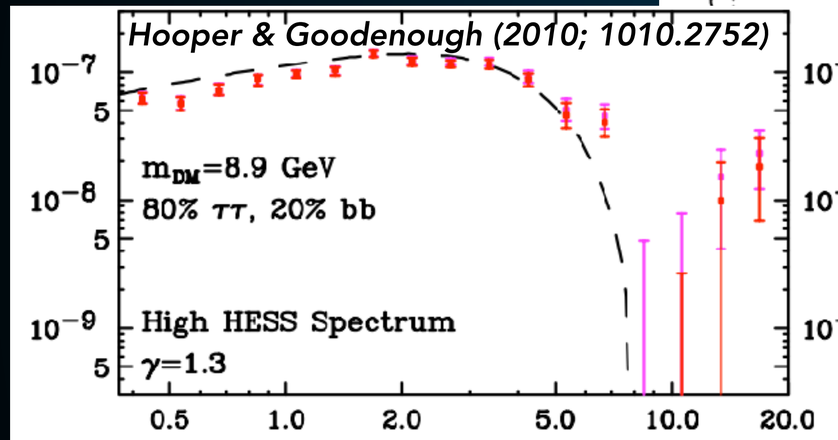
Hooper & Goodenough (2010; 1010.2752)

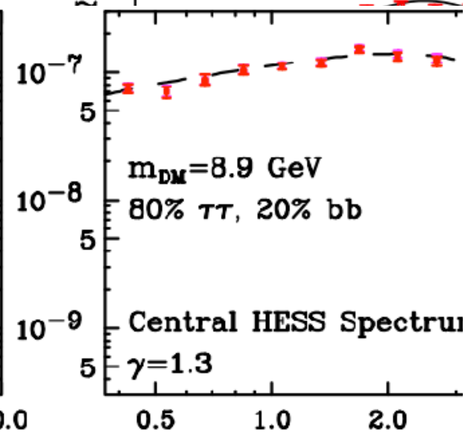


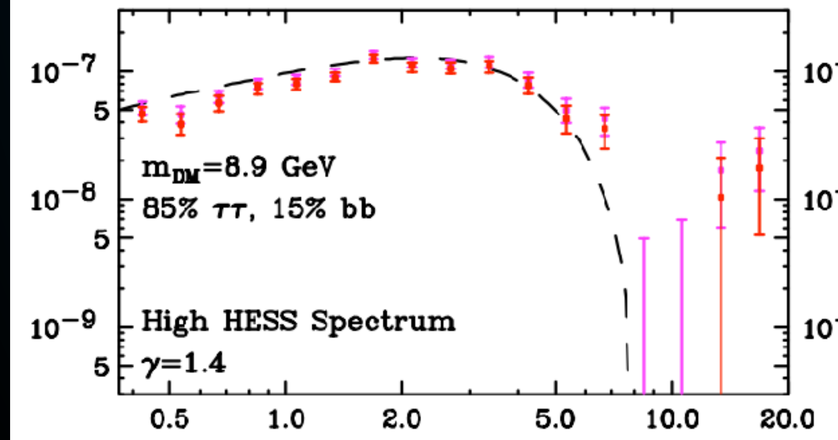


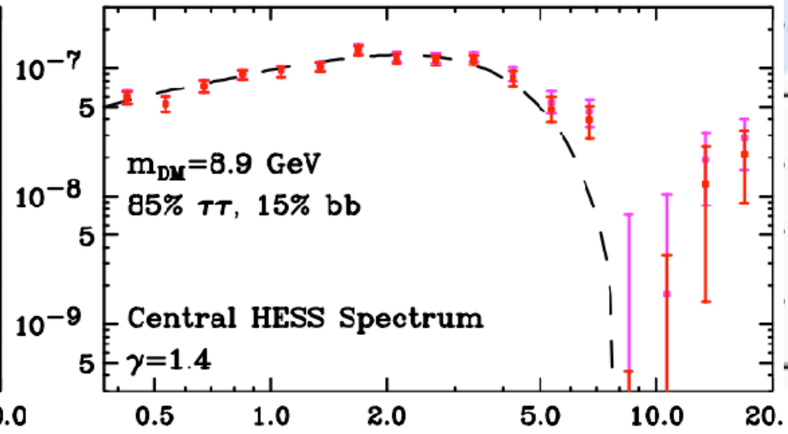
Vitale & Morselli (2009; 0912.3828)

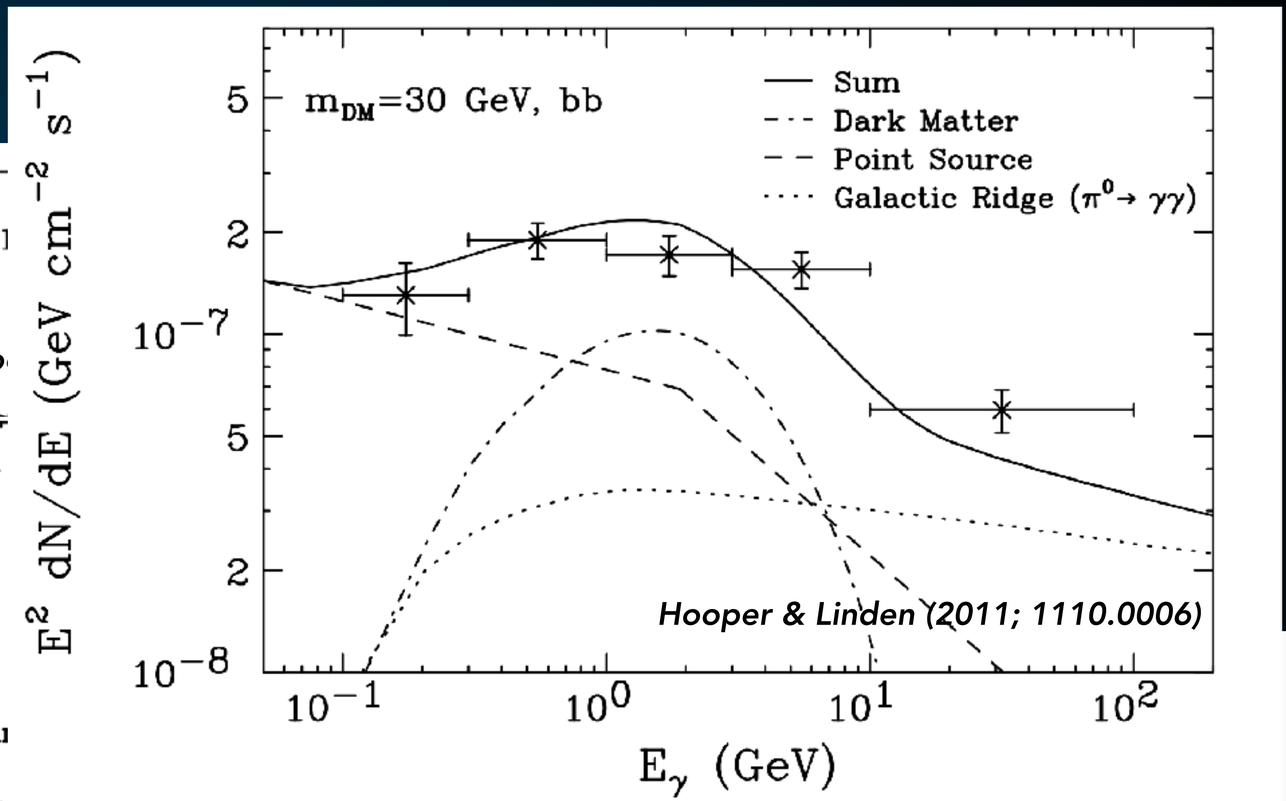
The Galactic Center: The Easiest Place to Find Dark Matter

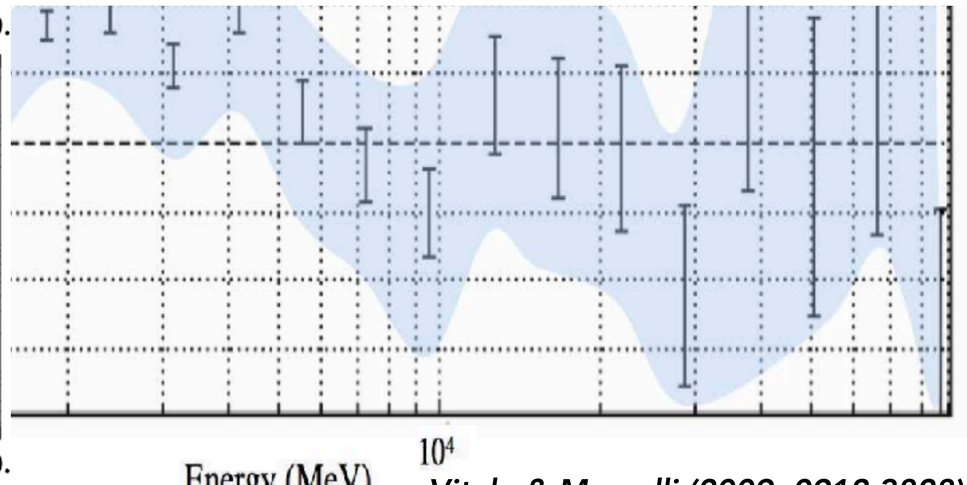




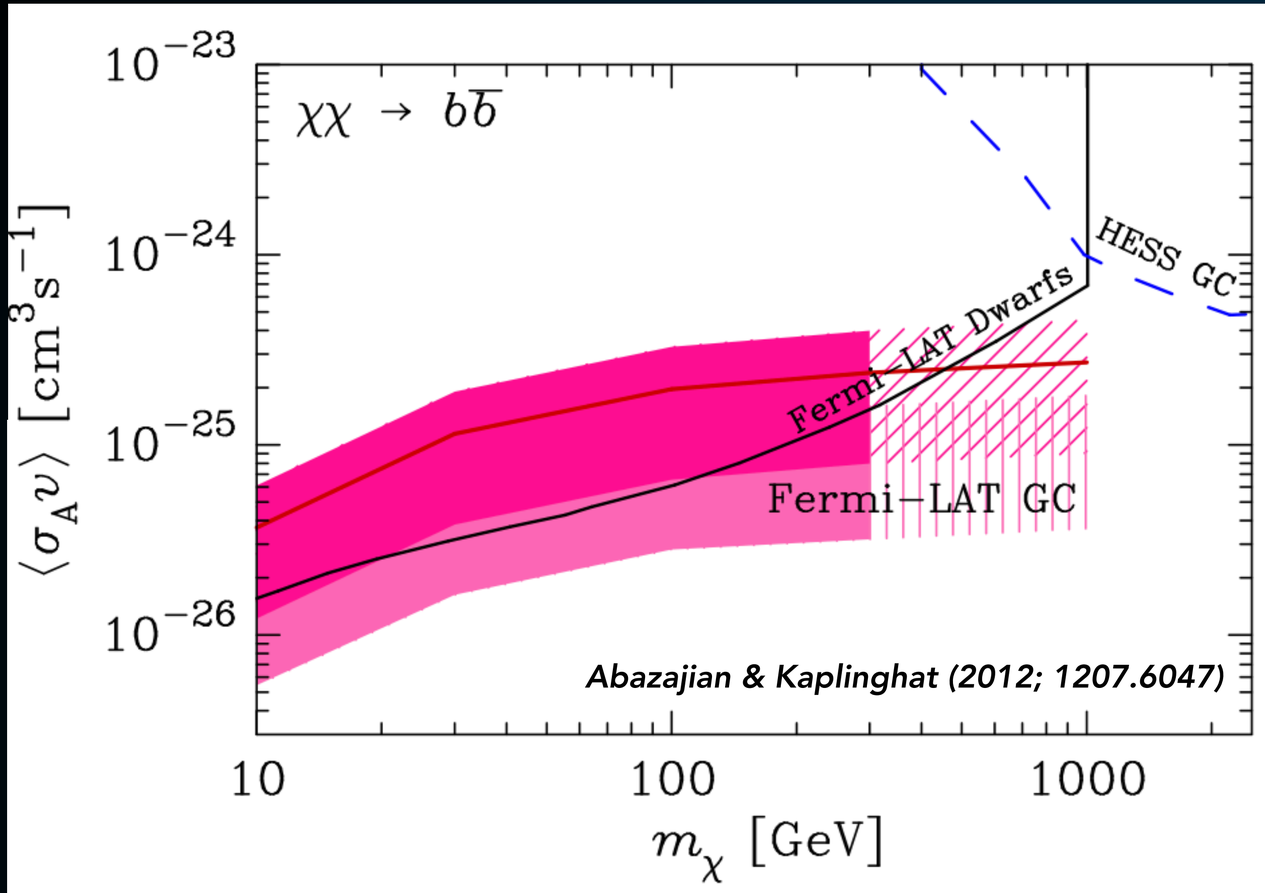




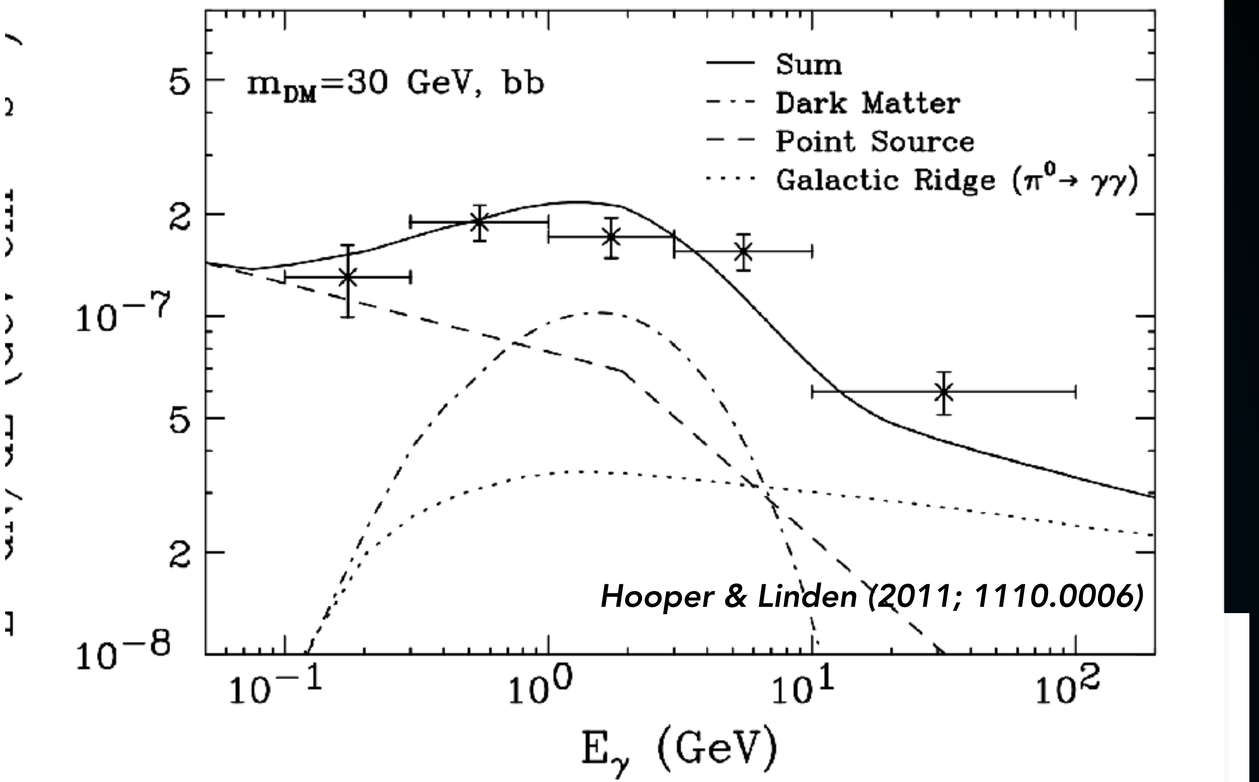




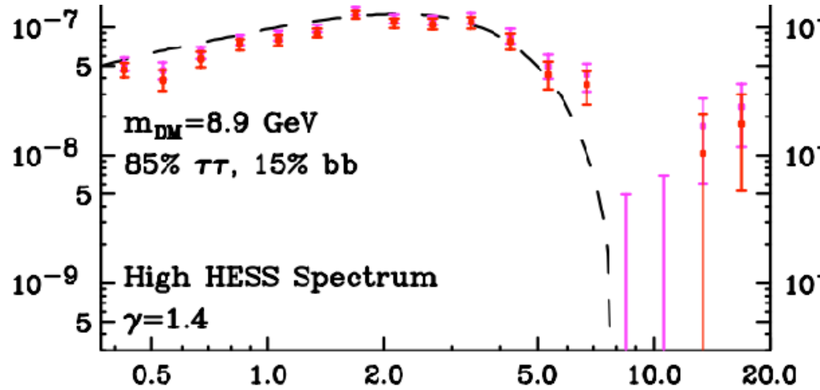
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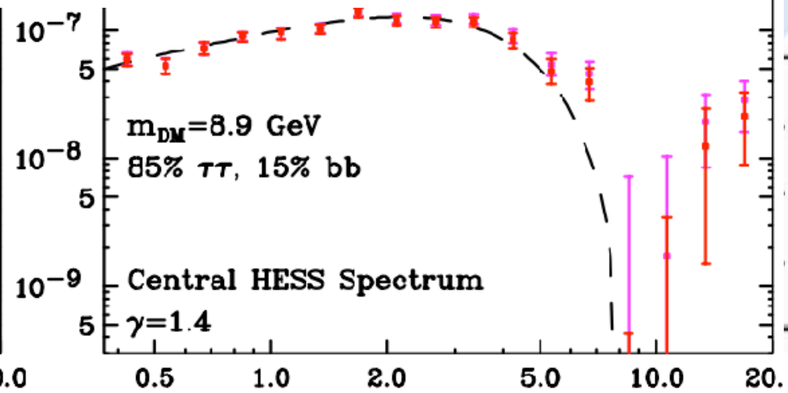


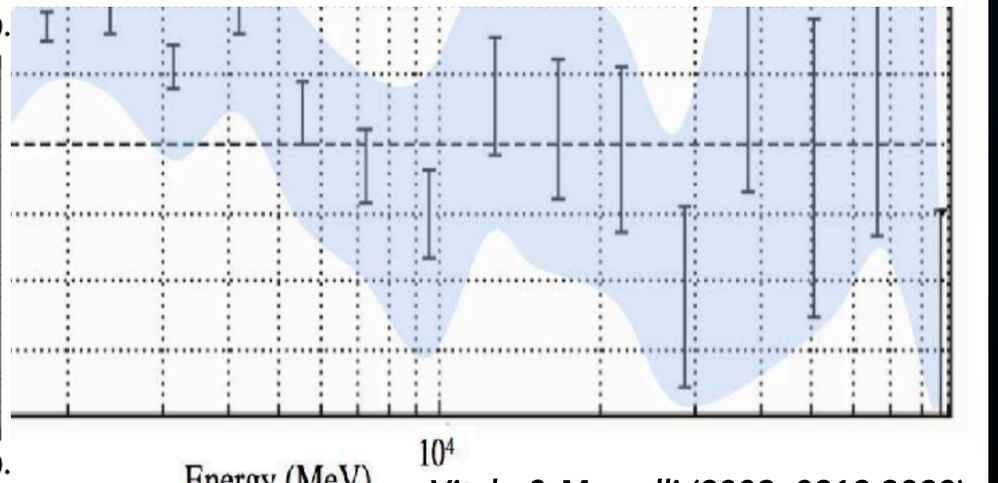
Abazajian & Kaplinghat (2012; 1207.6047)



Hooper & Linden (2011; 1110.0006)

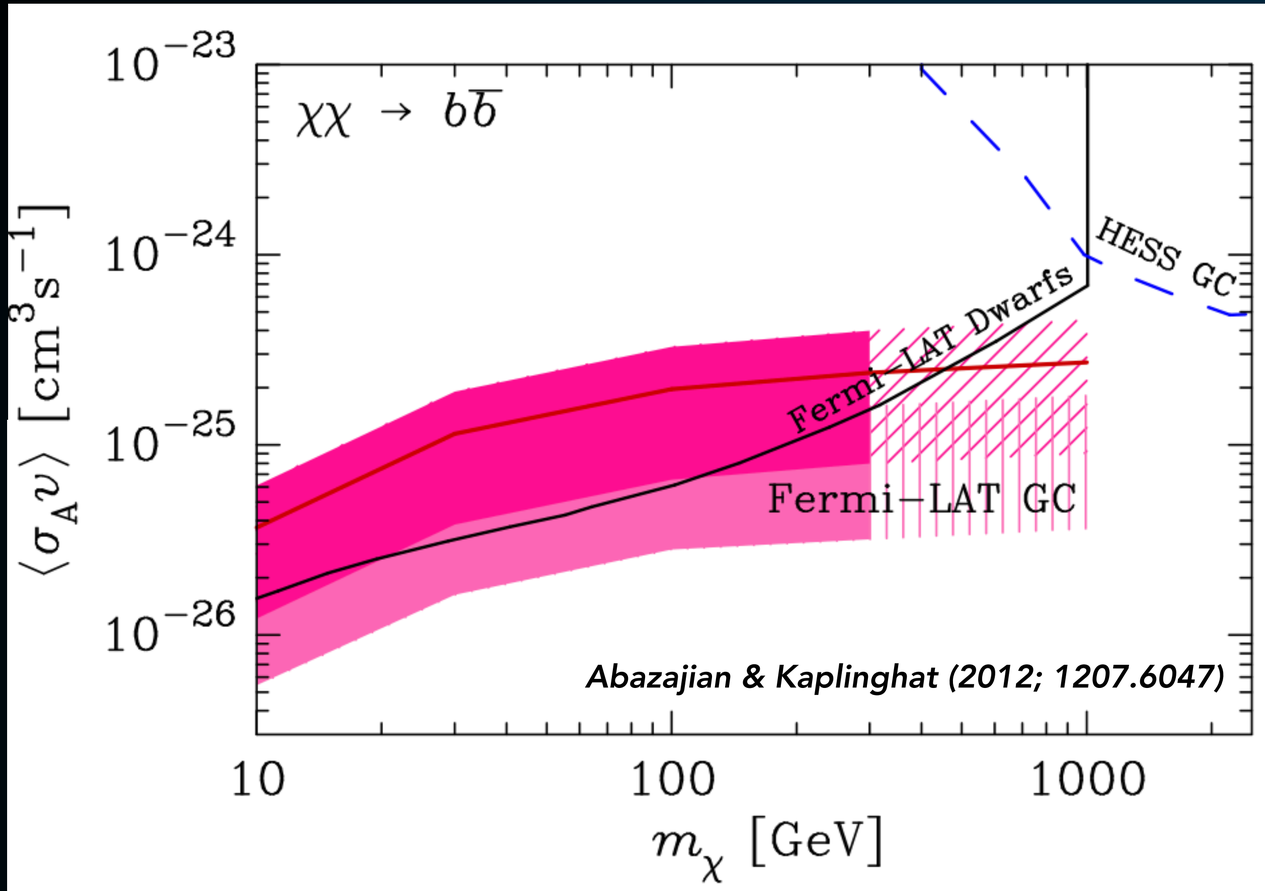


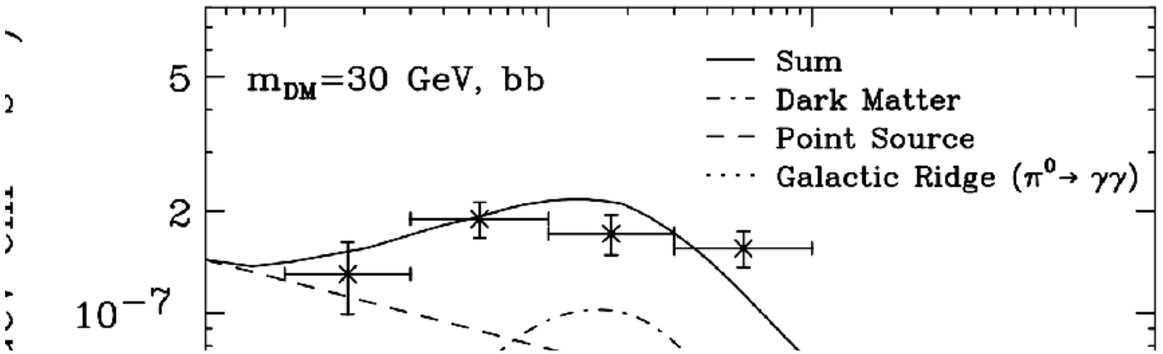


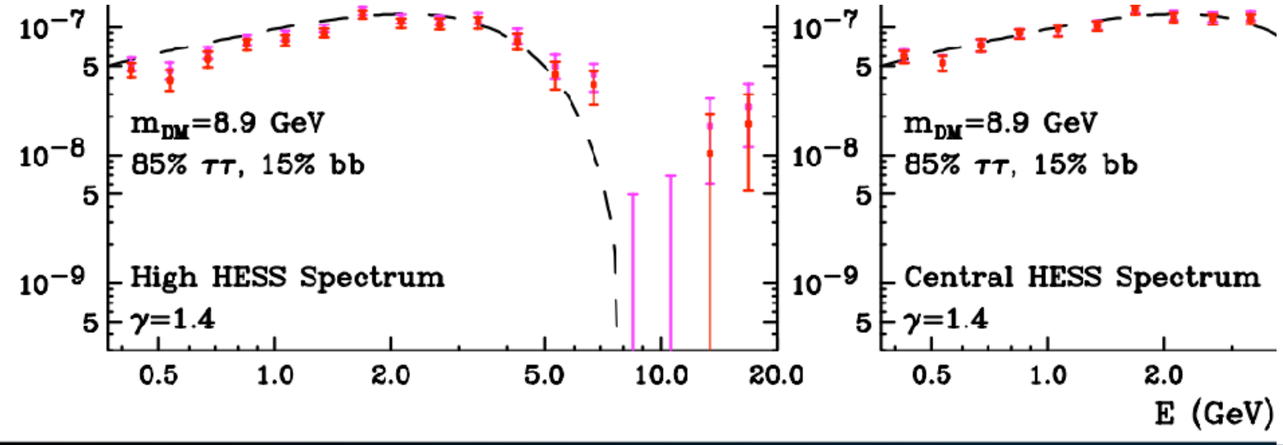


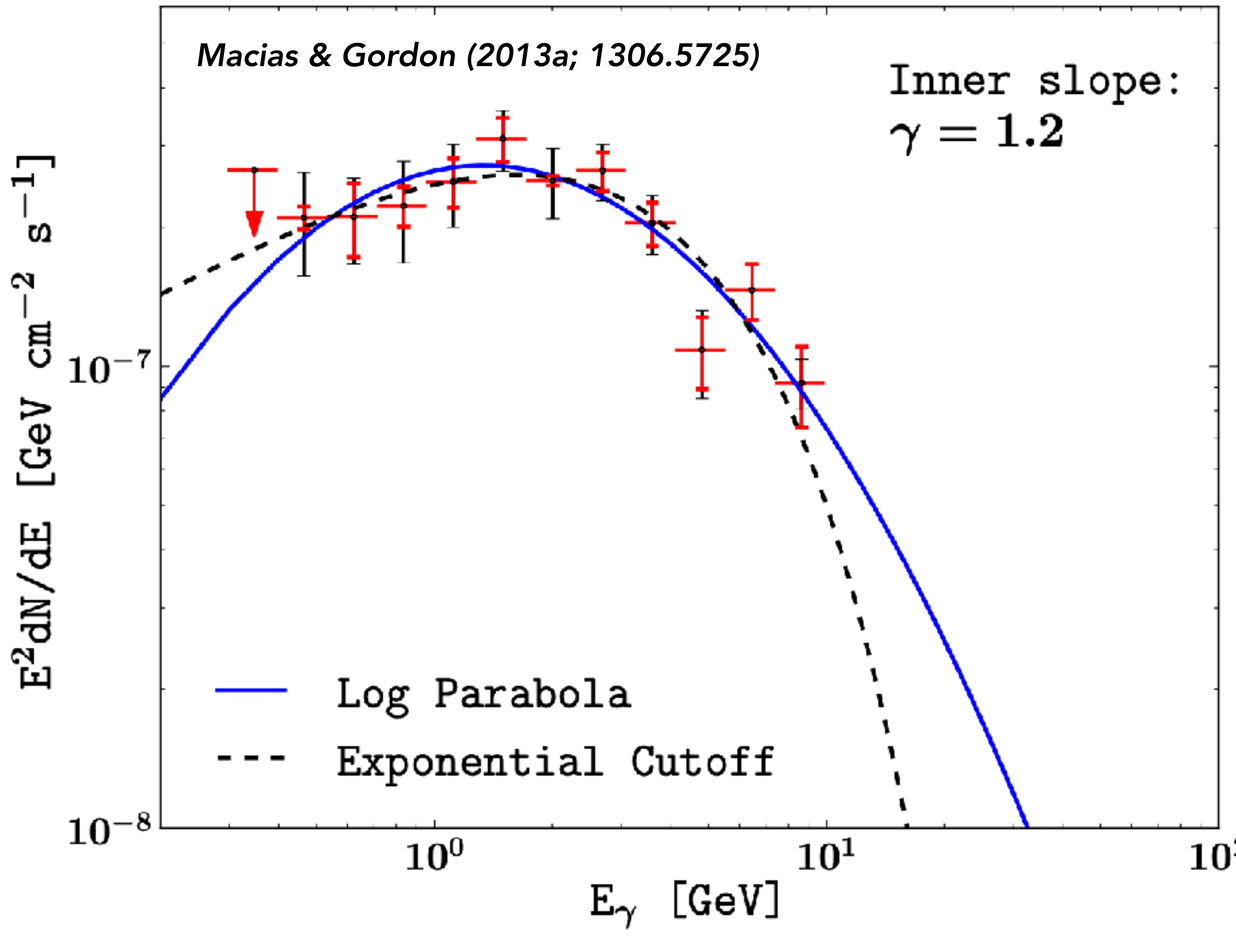
Vitale & Morselli (2009; 0912.3828)

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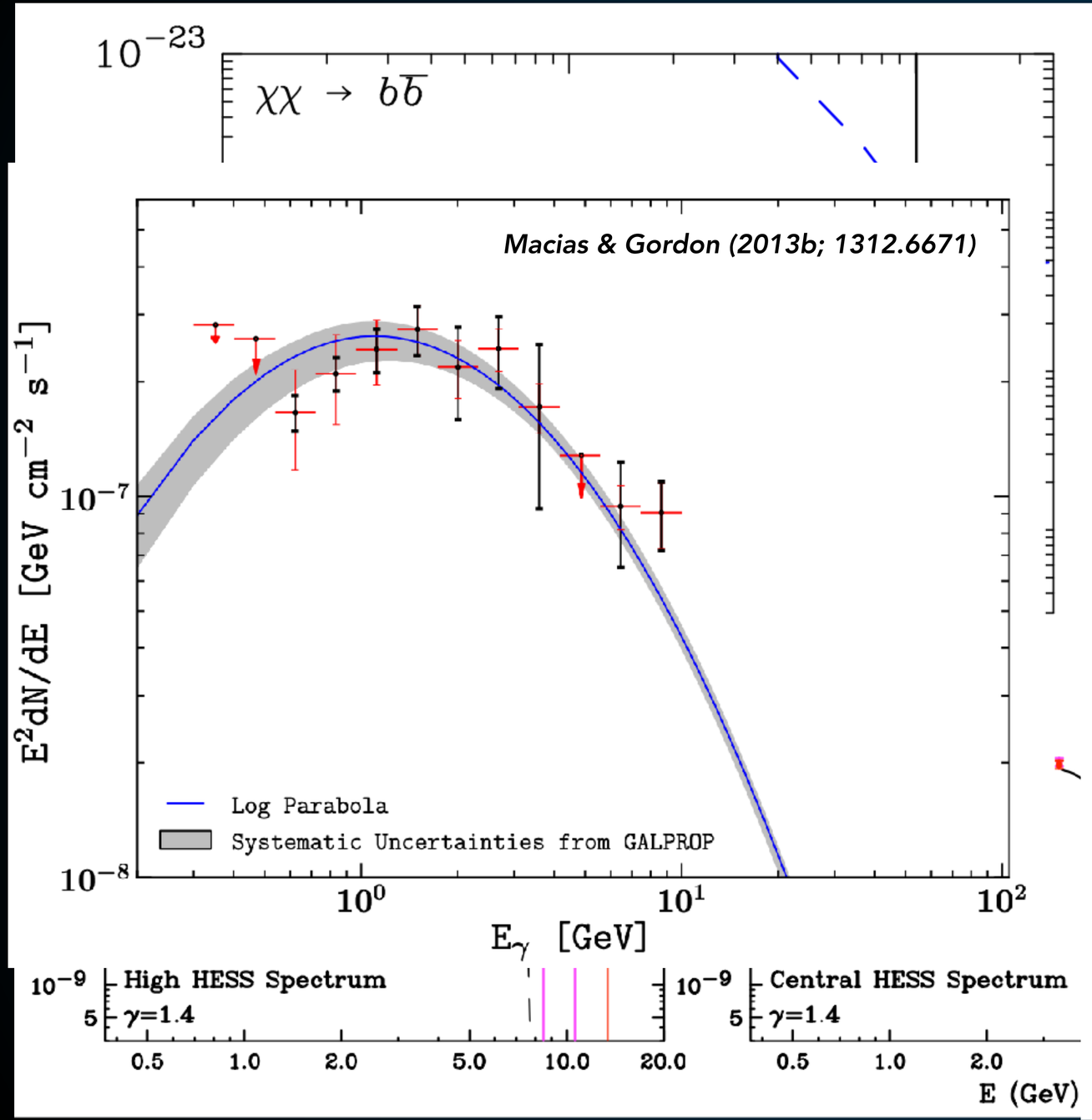


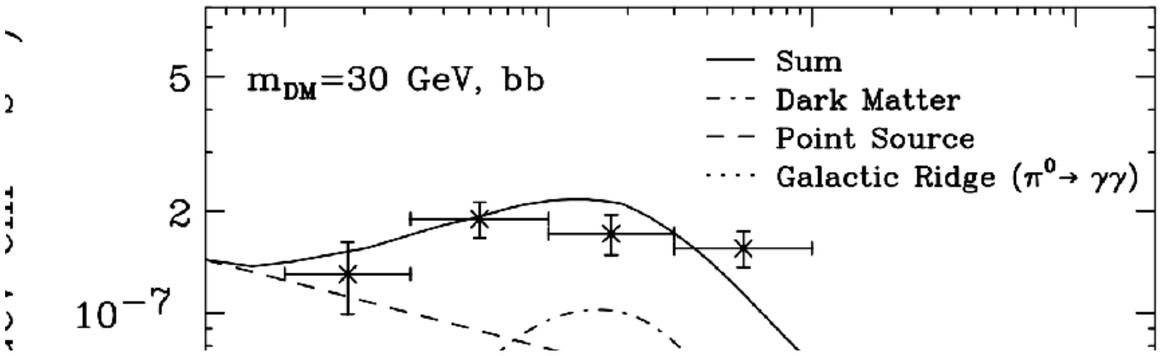


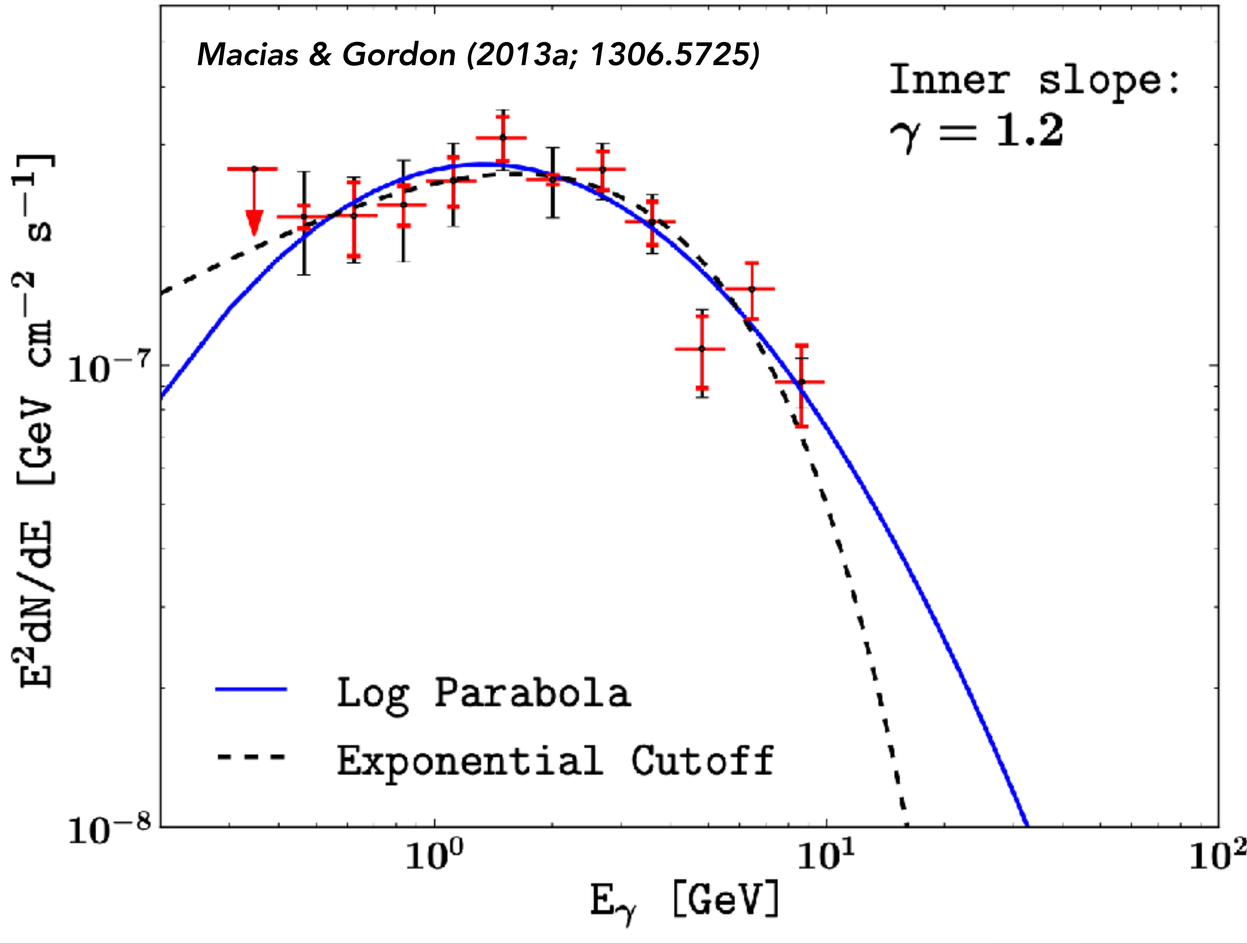




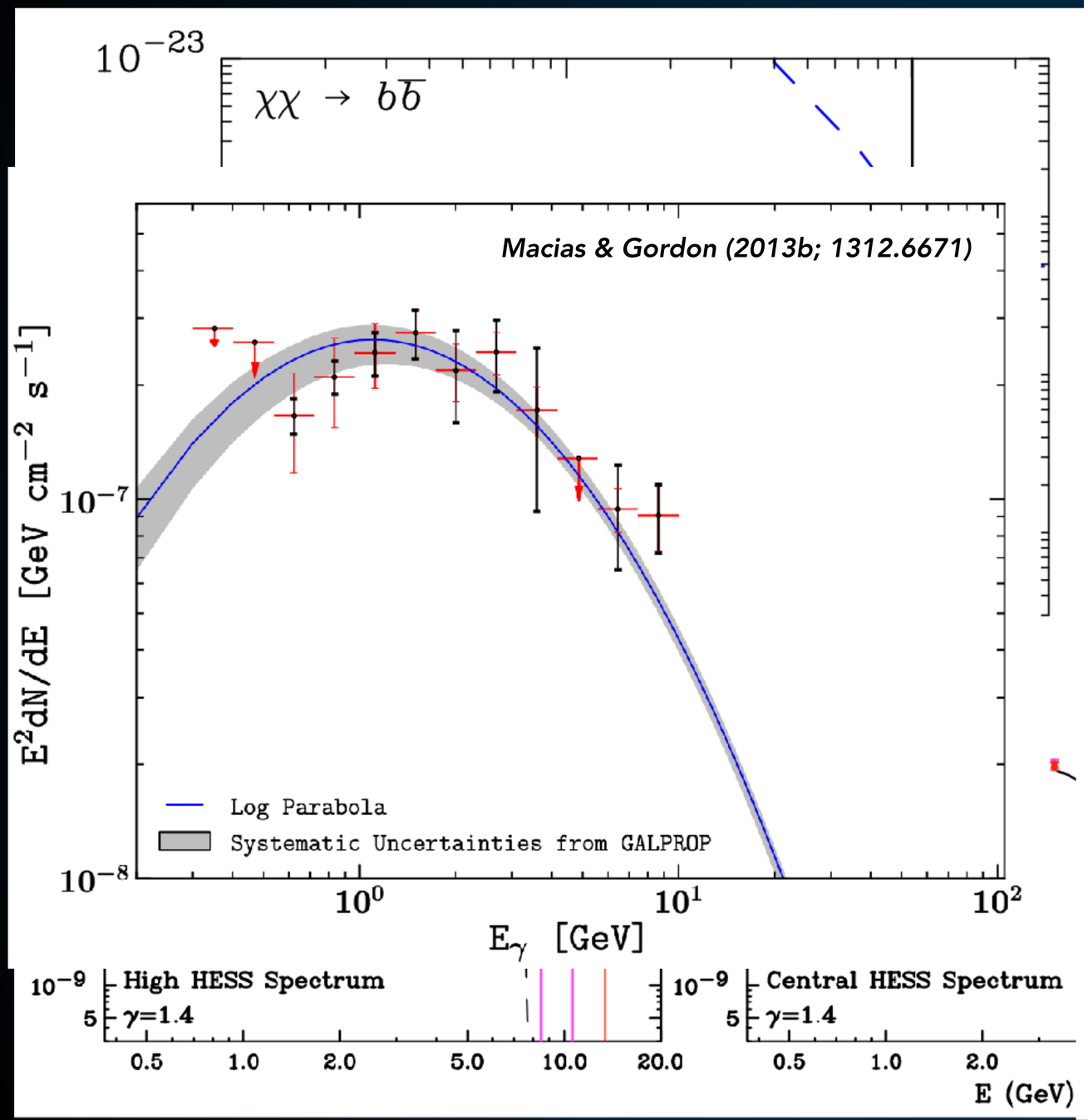
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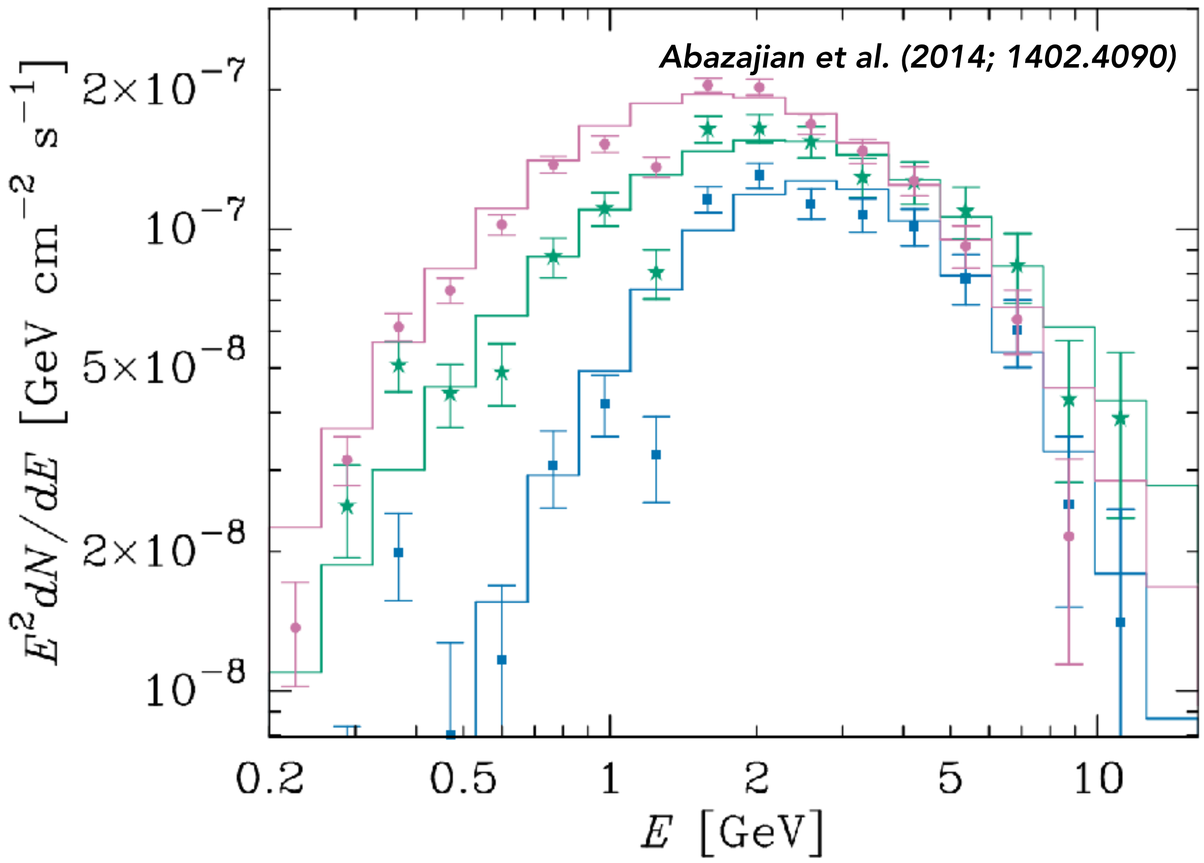


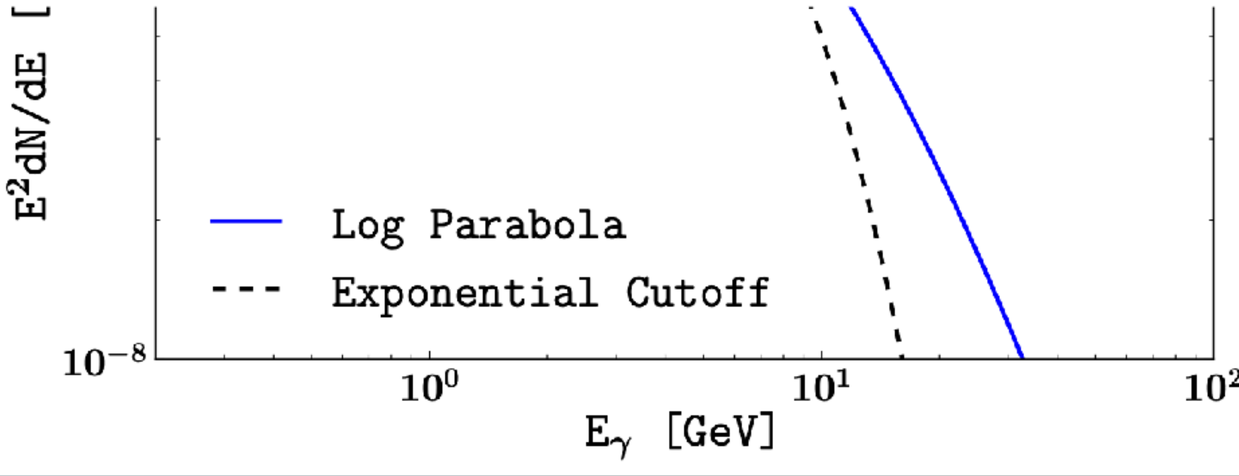




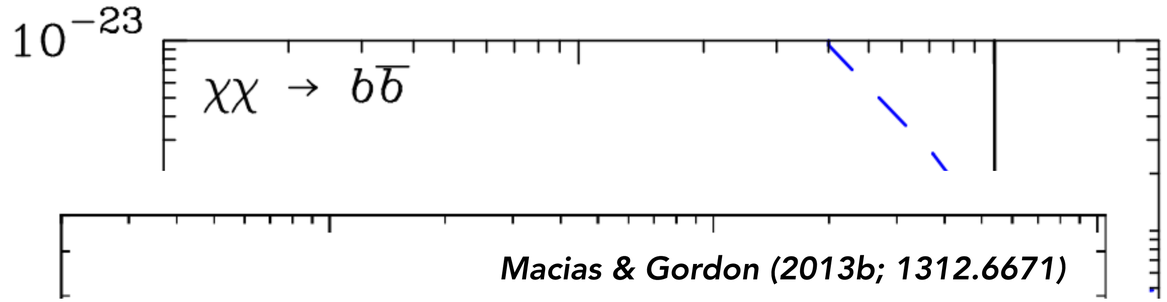
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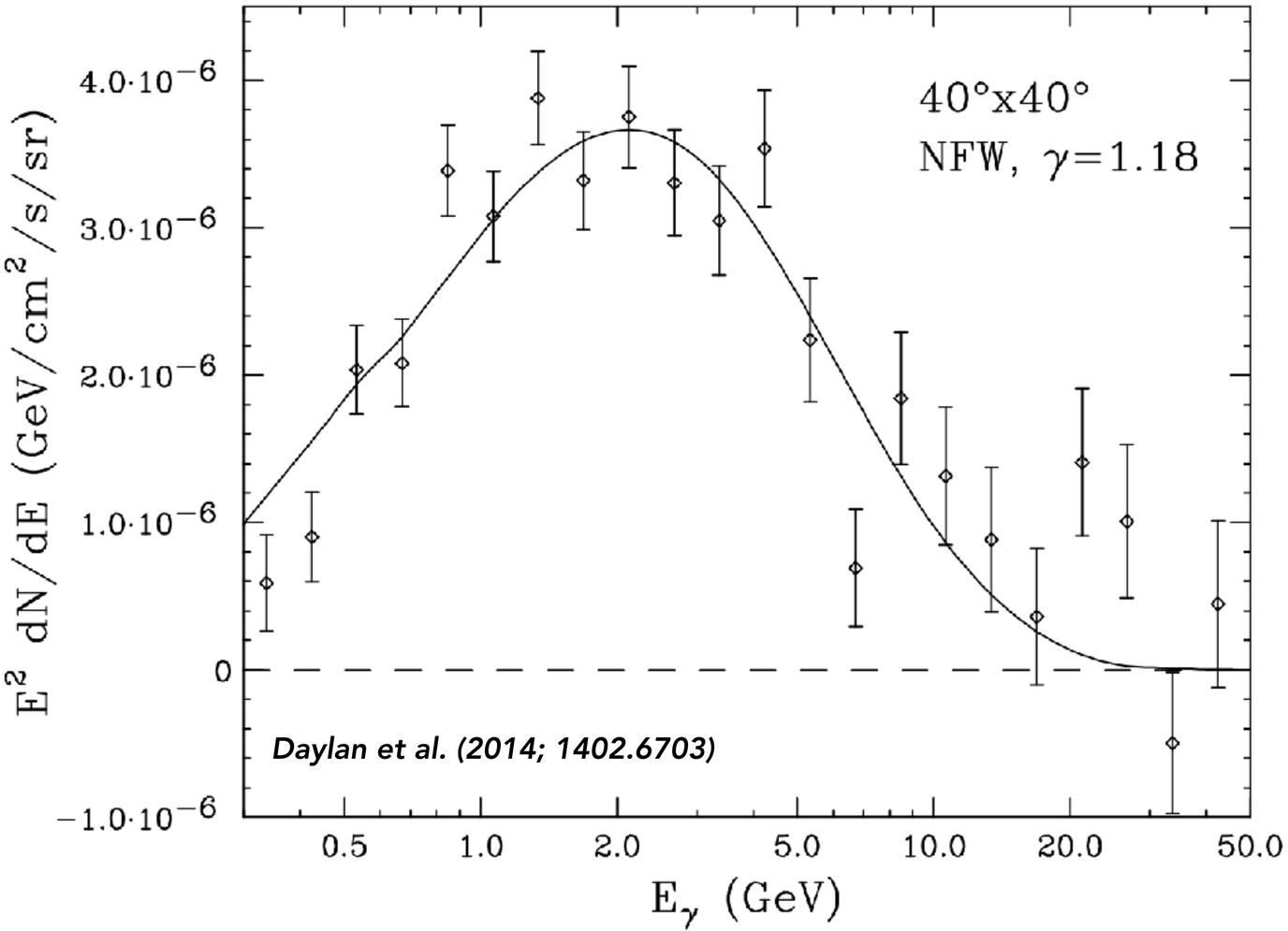




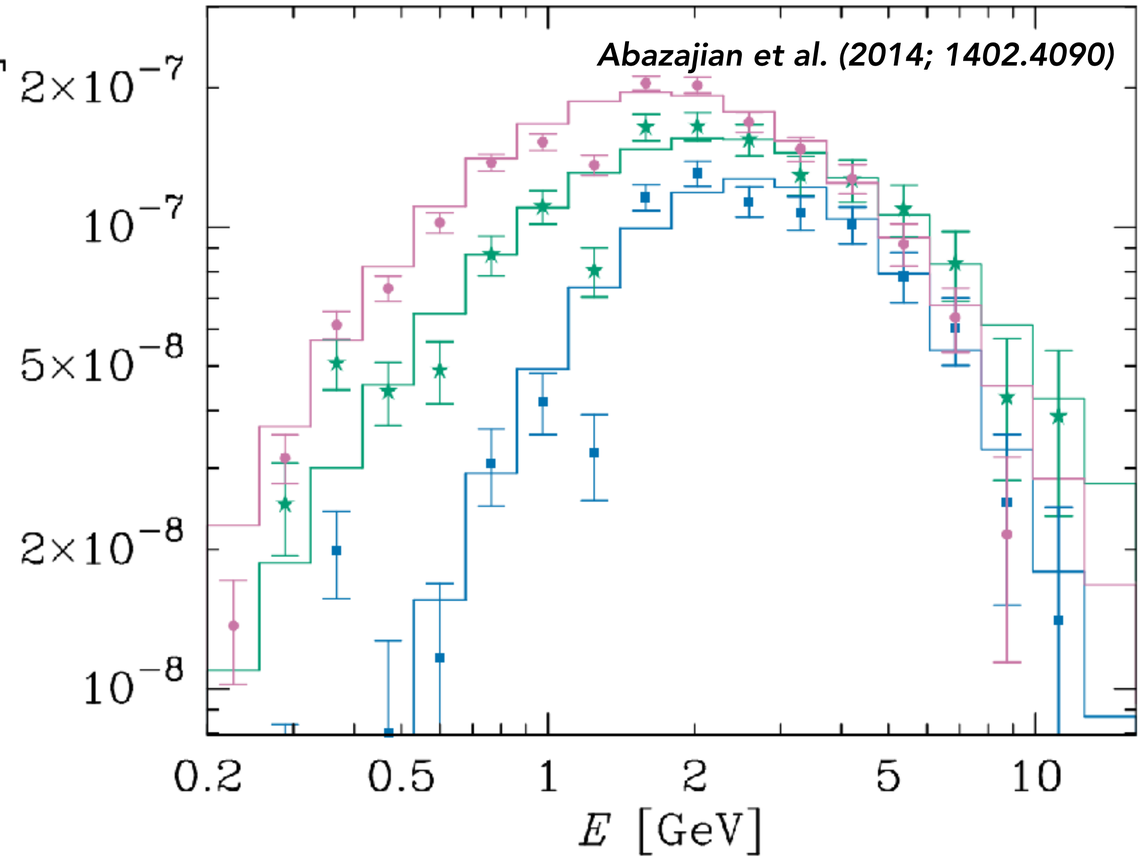
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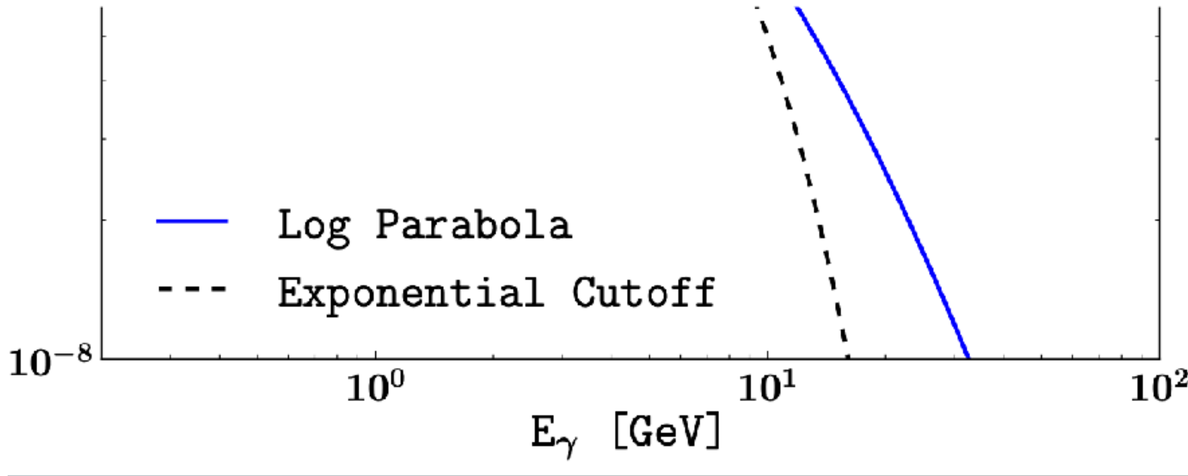


Macias & Gordon (2013b; 1312.6671)

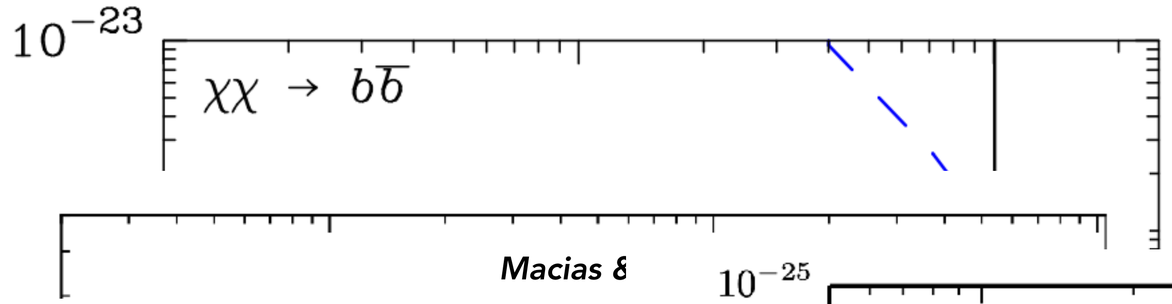


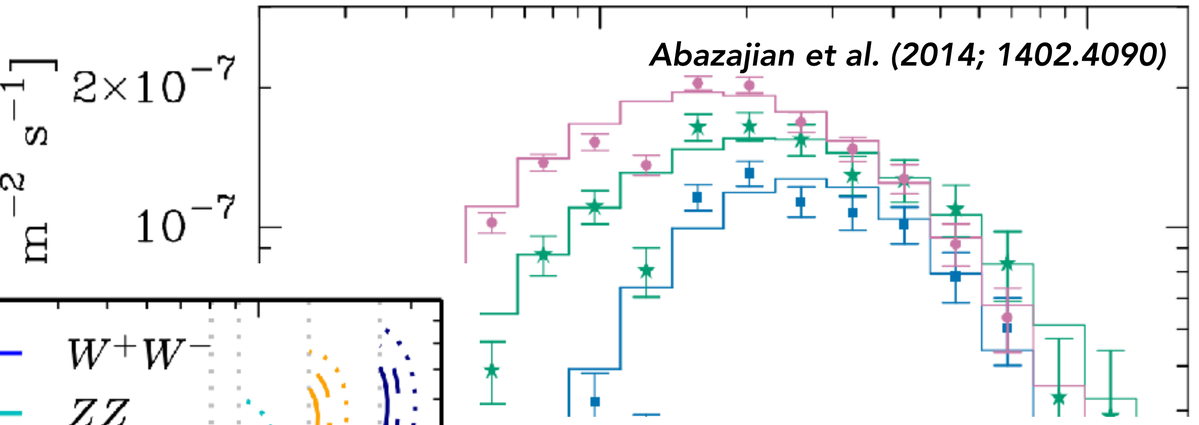
Daylan et al. (2014; 1402.6703)

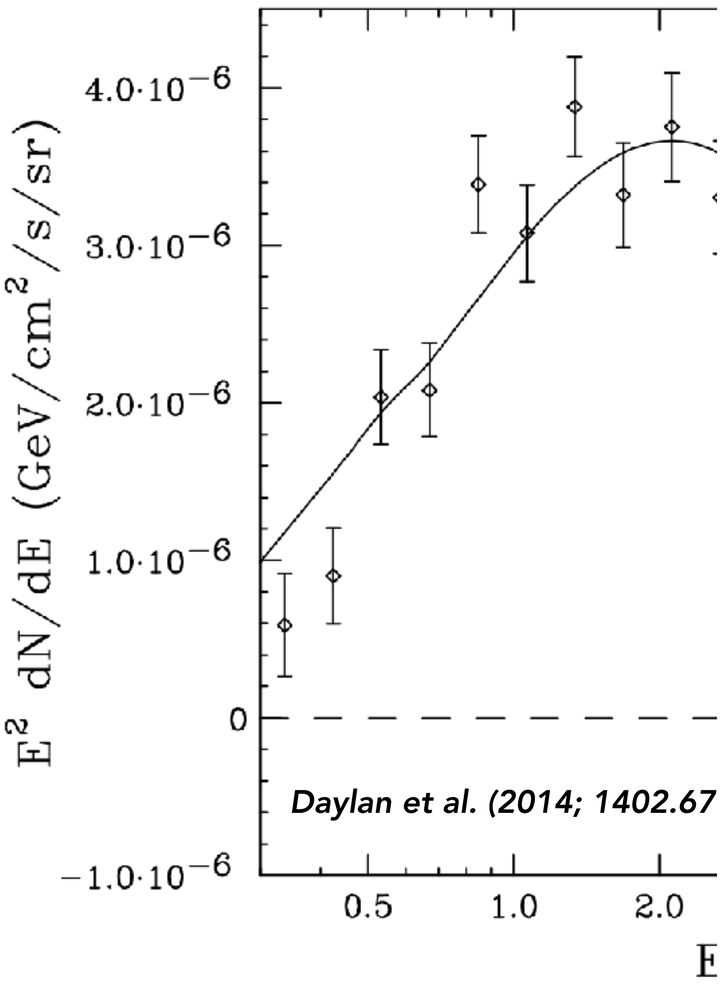


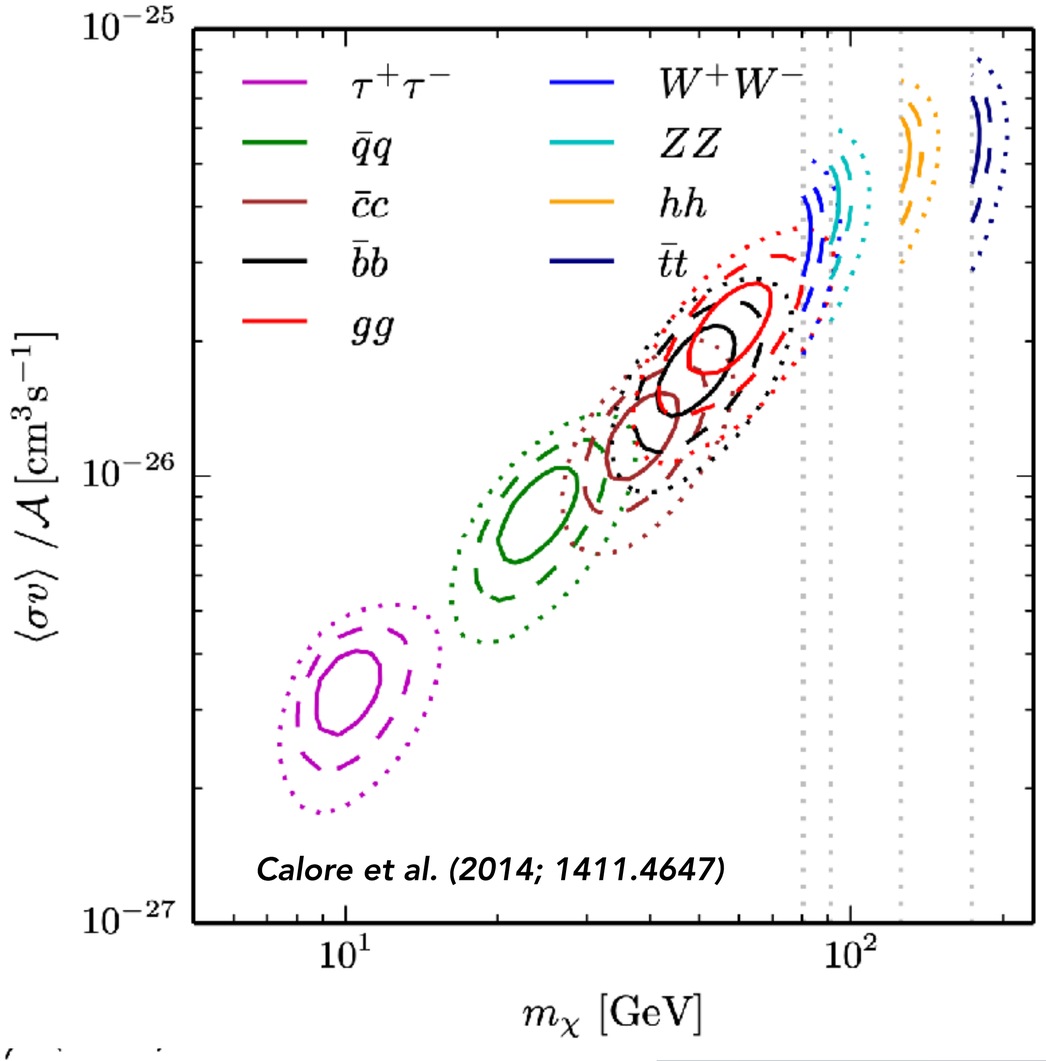


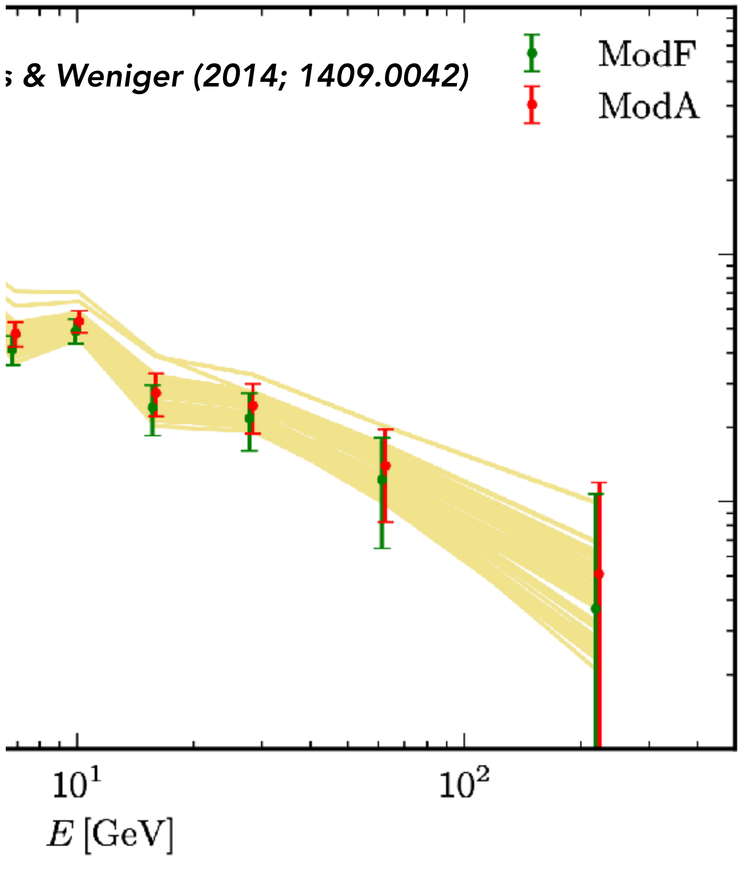
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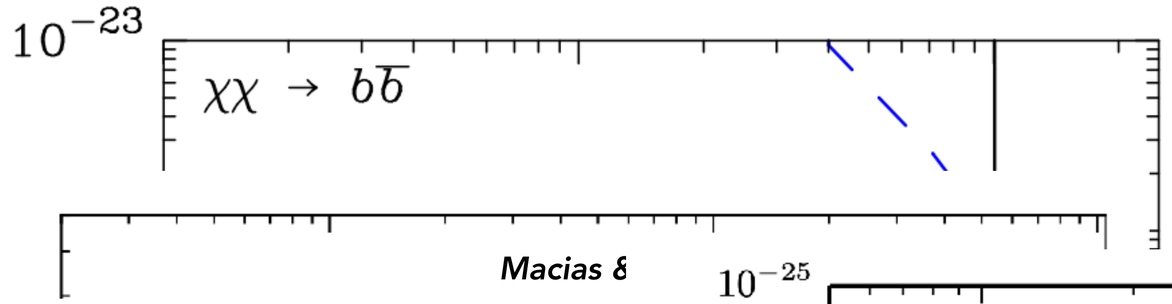


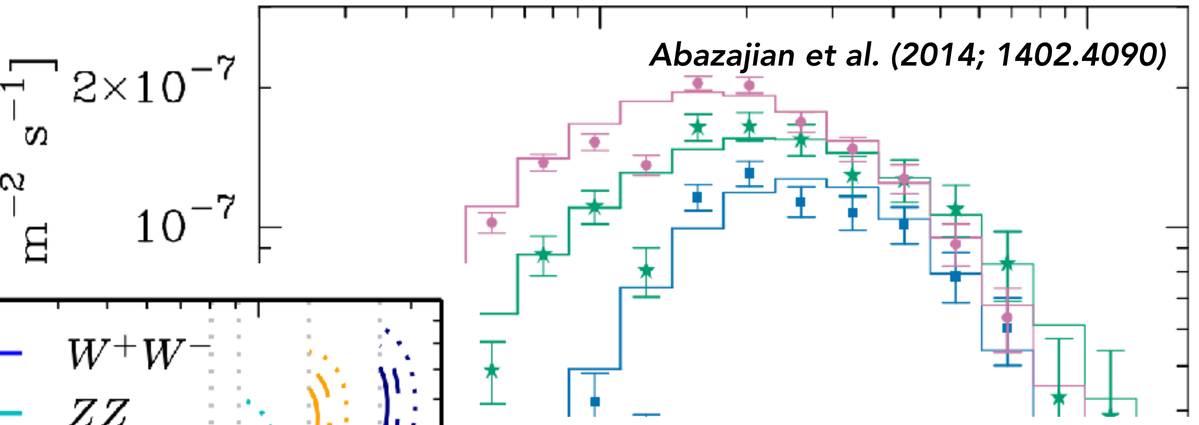


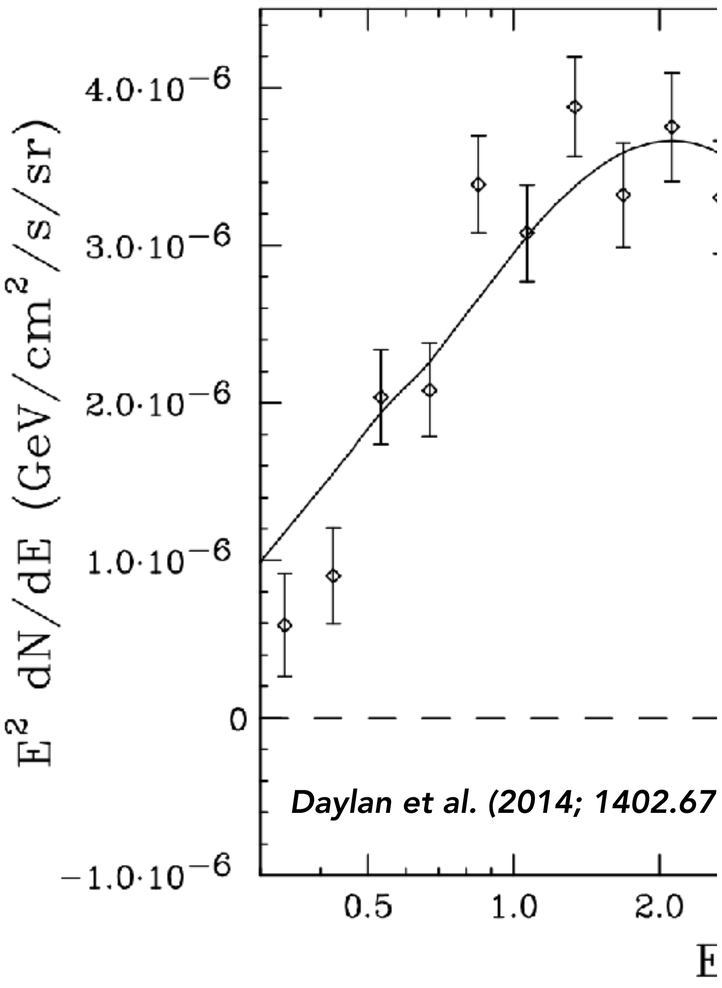


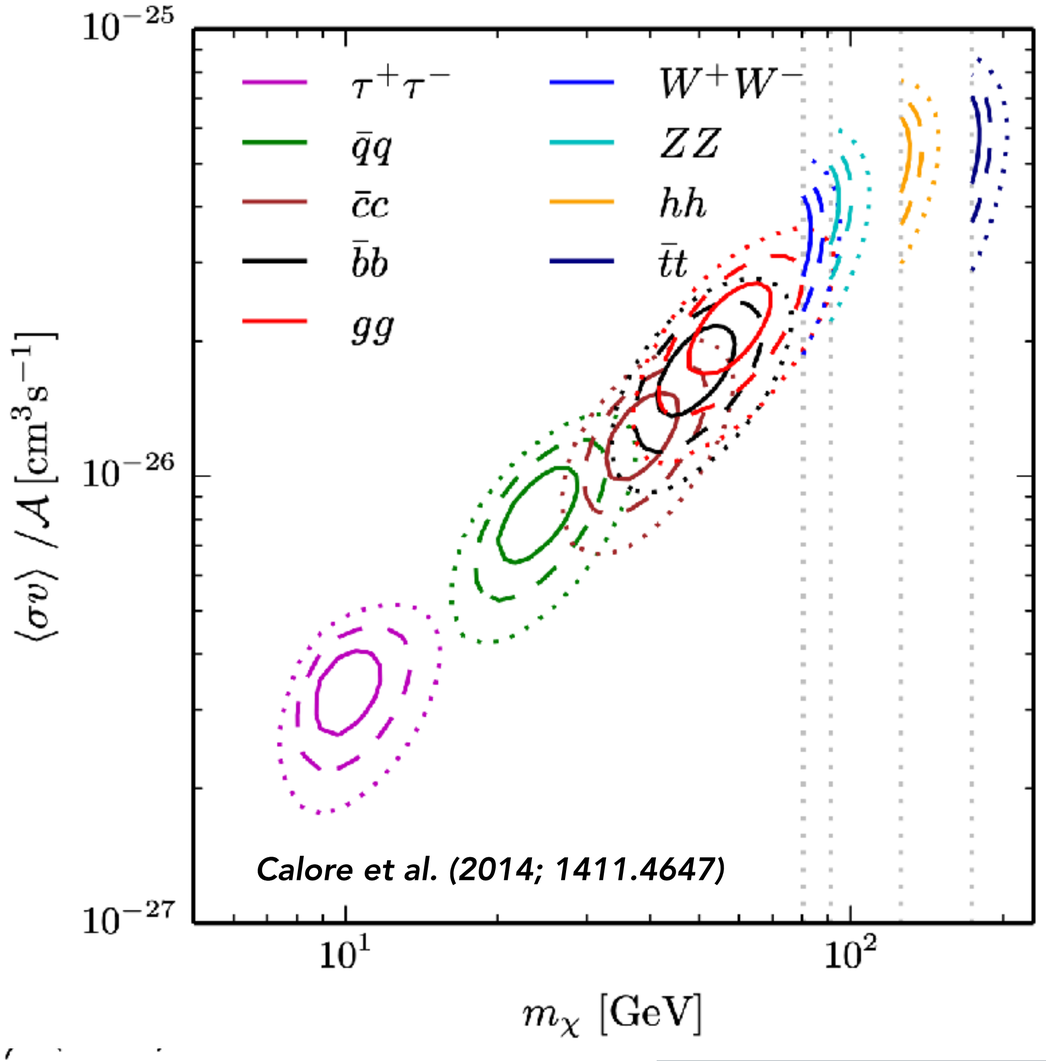


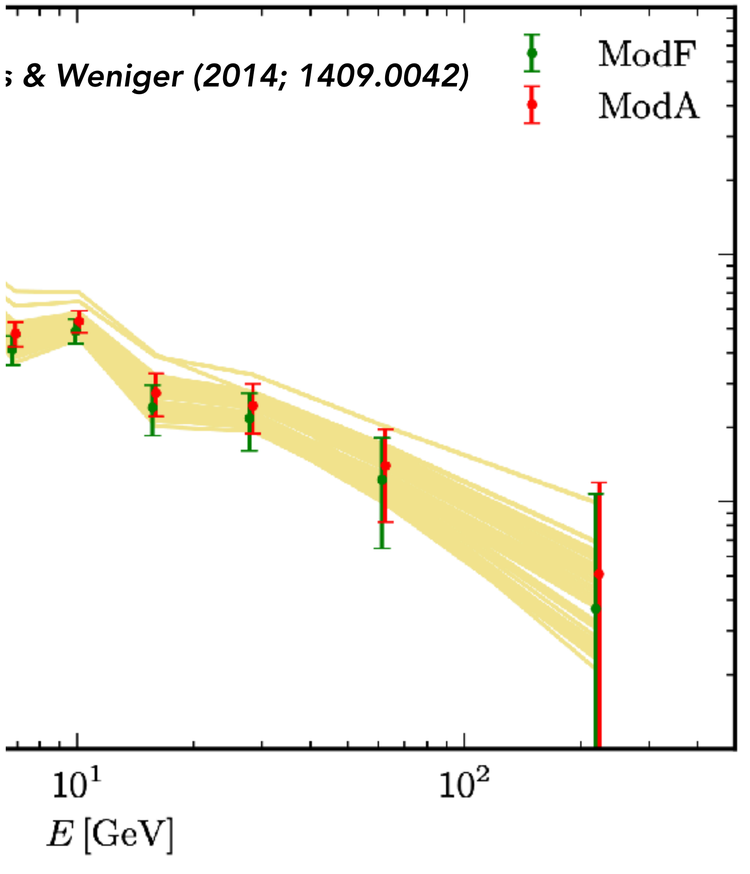
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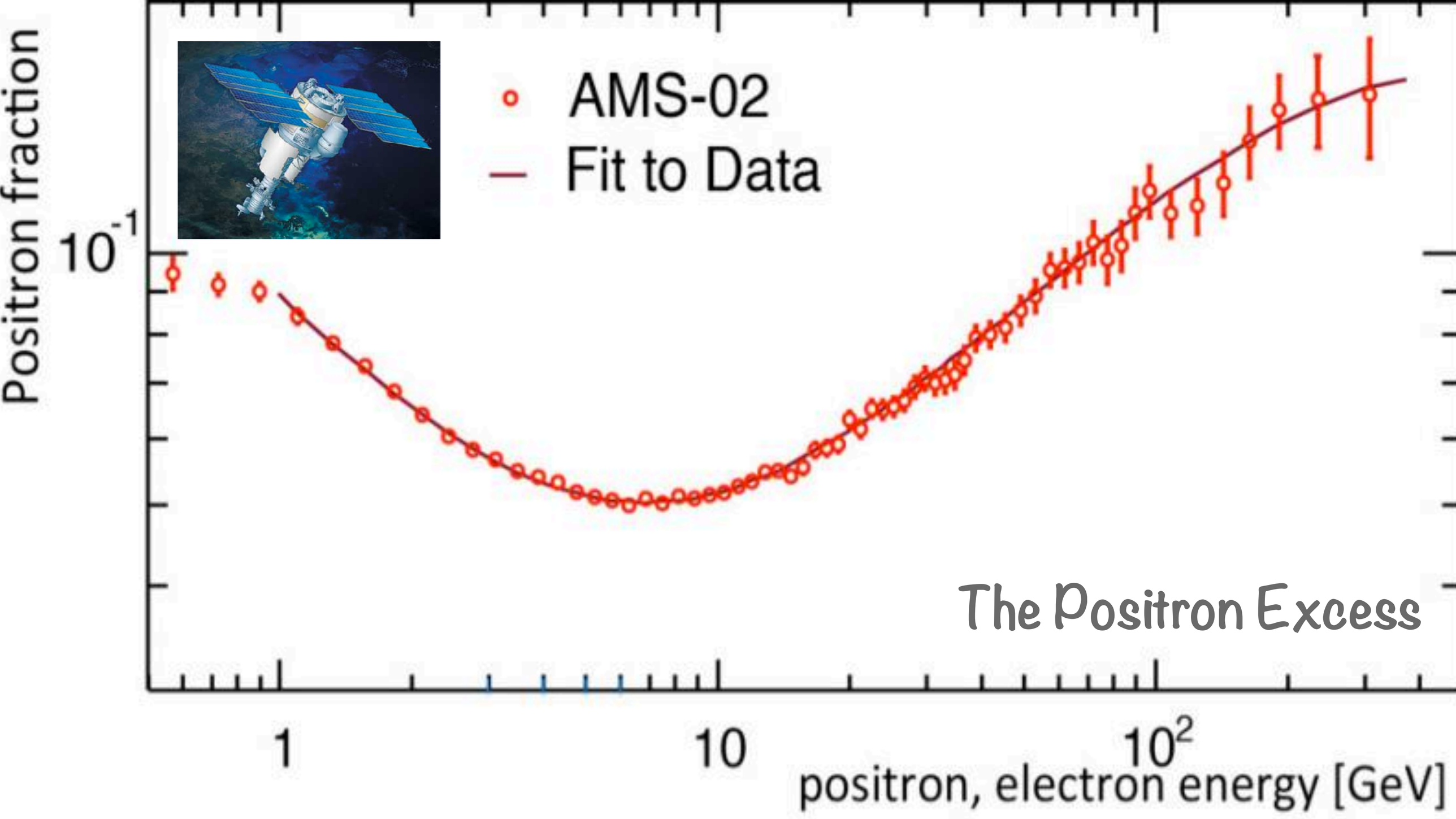








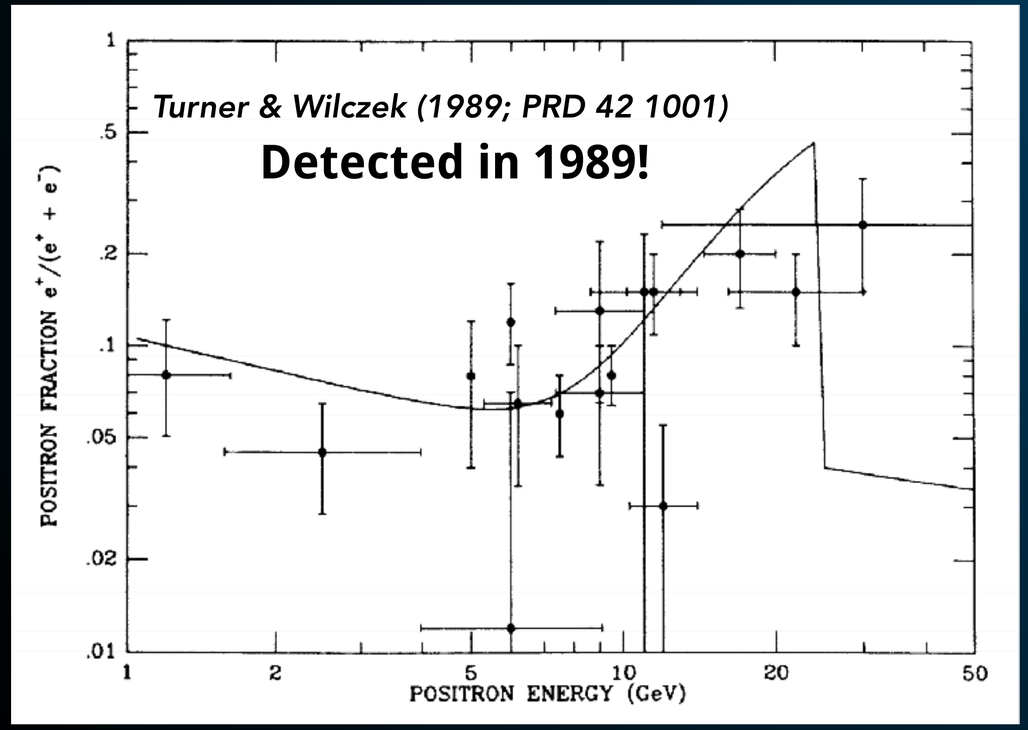


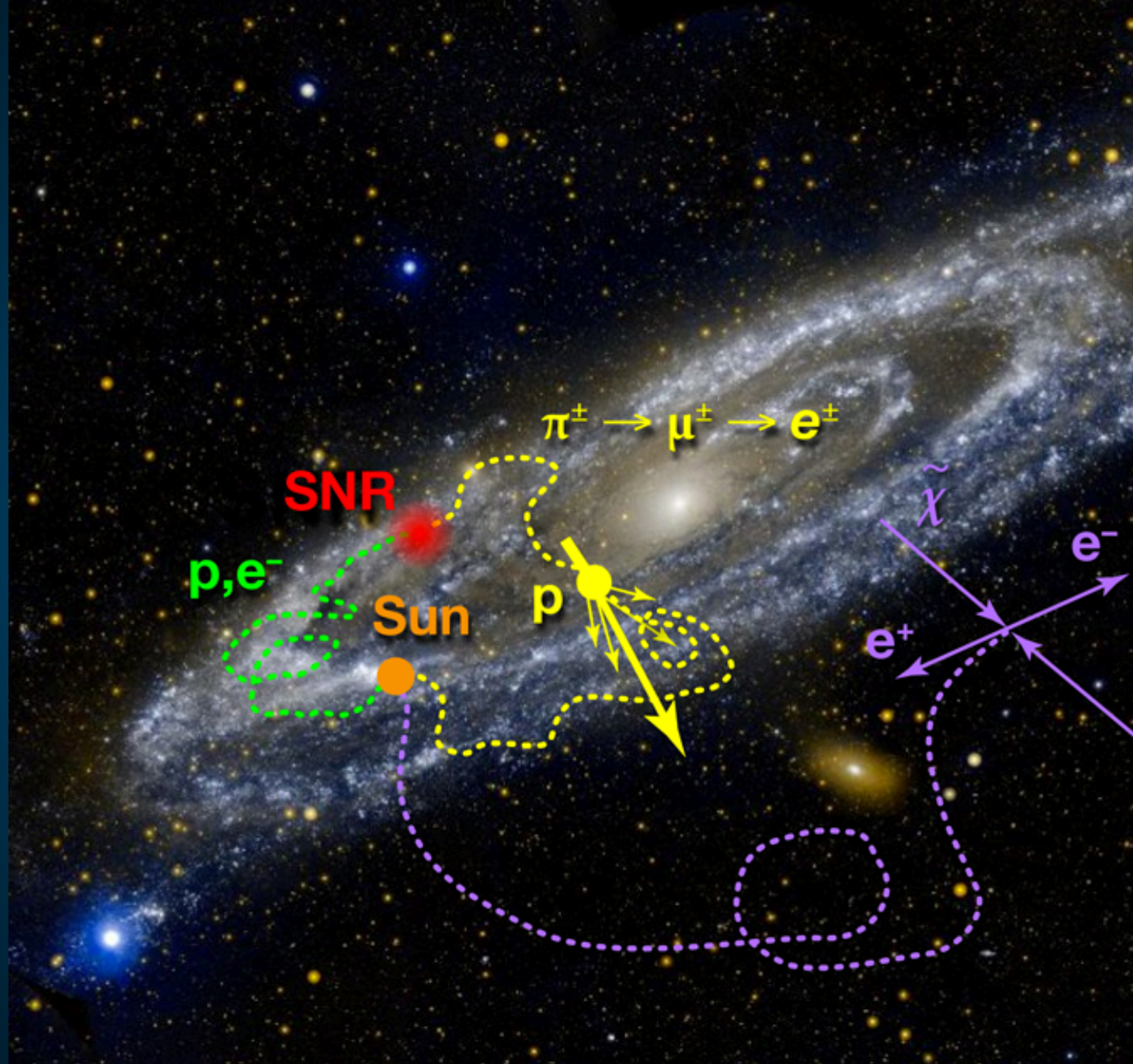

Positron fraction
10^{-1}
AMS-02
Fit to Data
The Positron Excess
1
10
10^2
positron, electron energy [GeV]

The Positron Excess

Key Idea: Investigate the Positron Fraction!

$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$

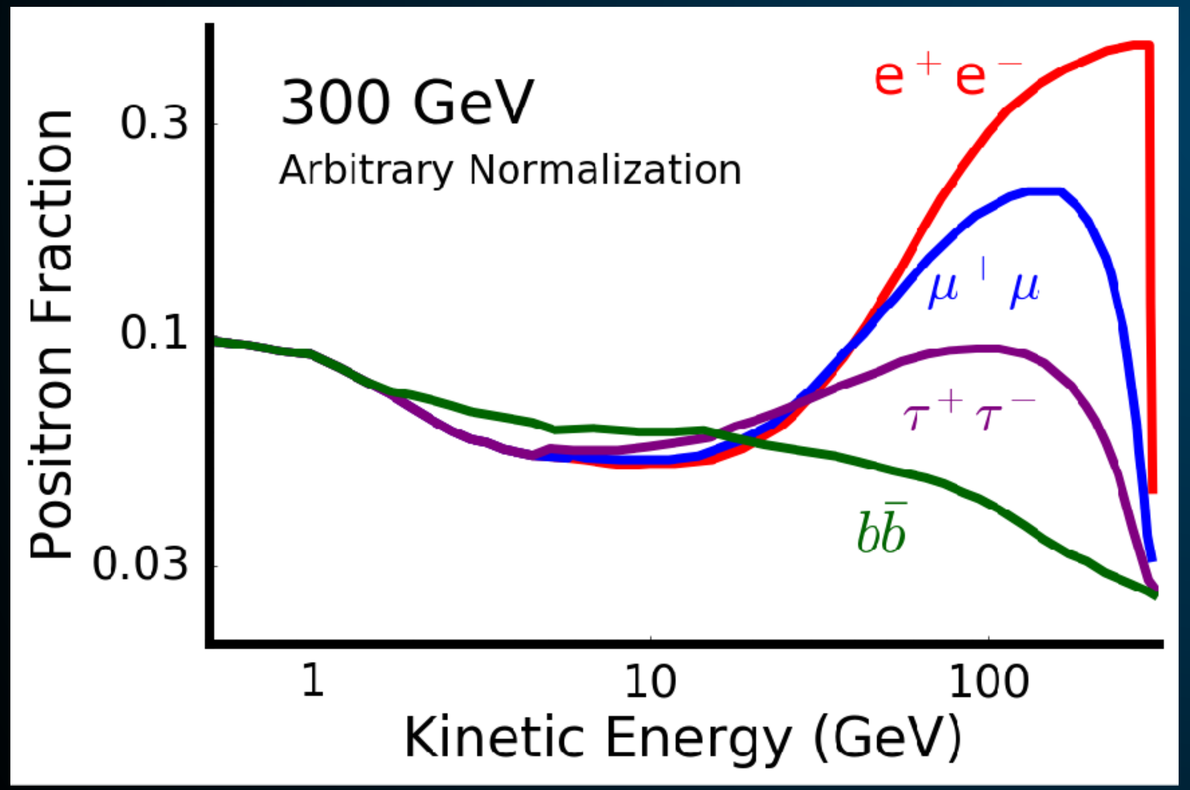


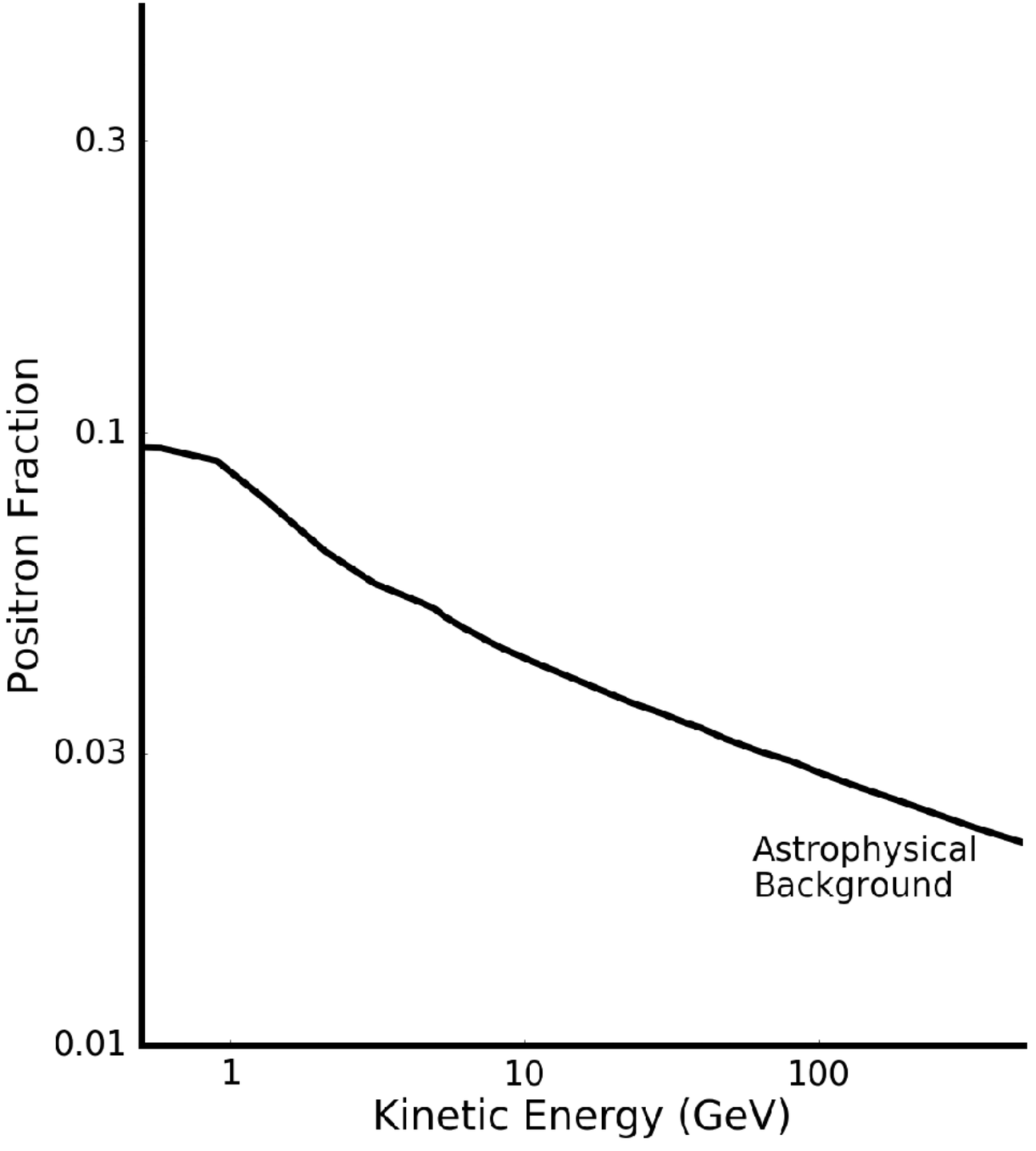


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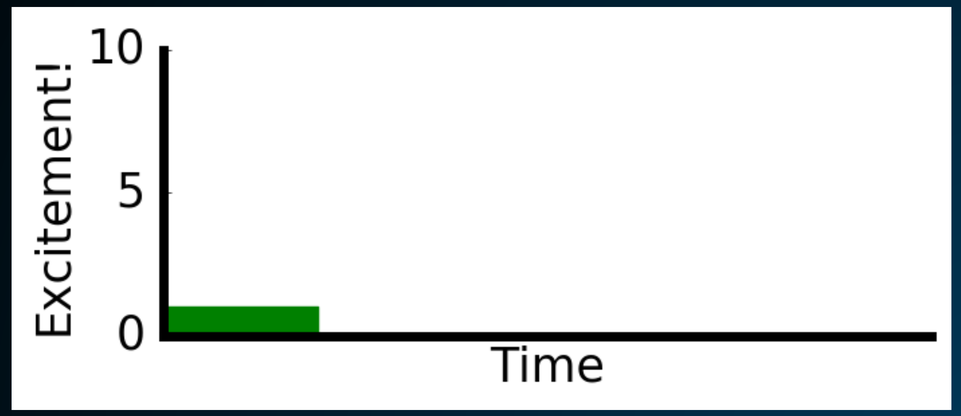
Astrophysics - Slowly Decreasing

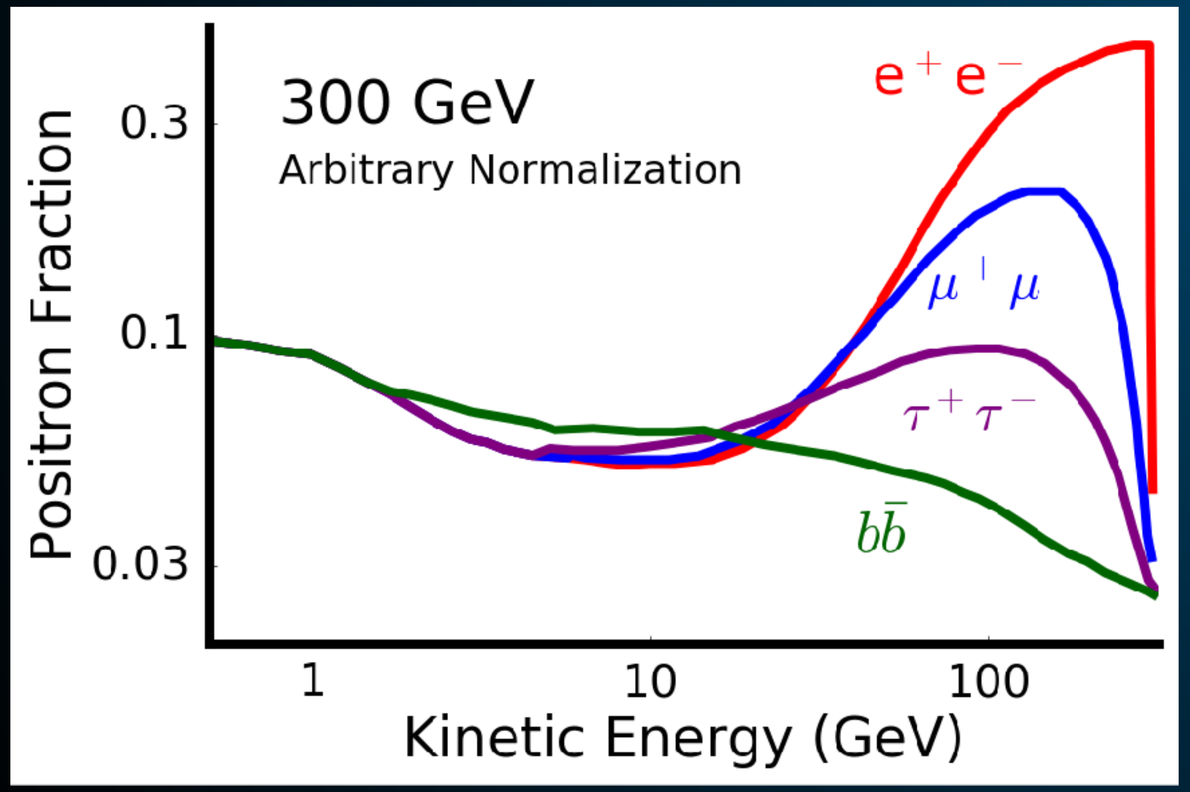
Dark Matter - Sharp Bump!



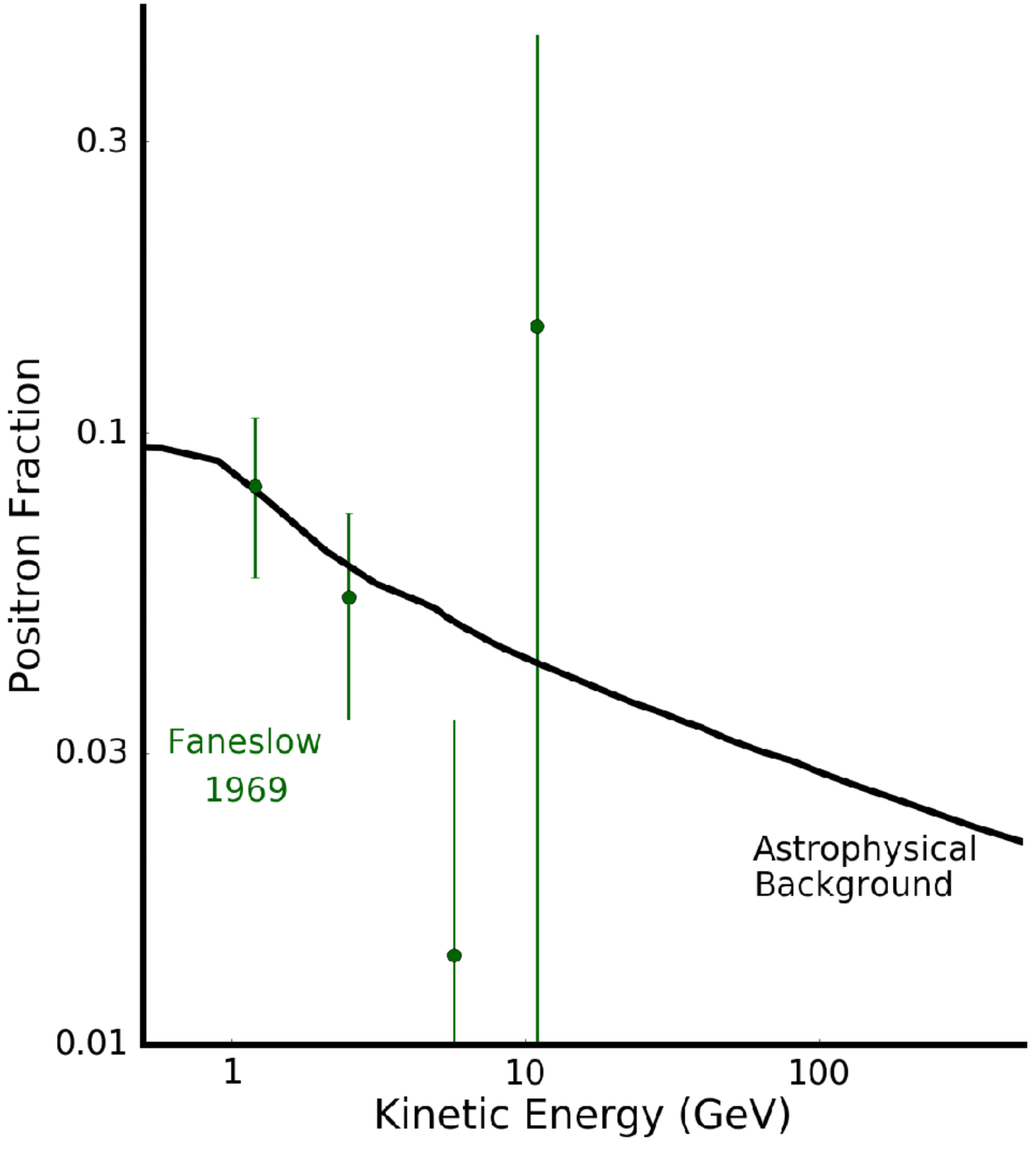


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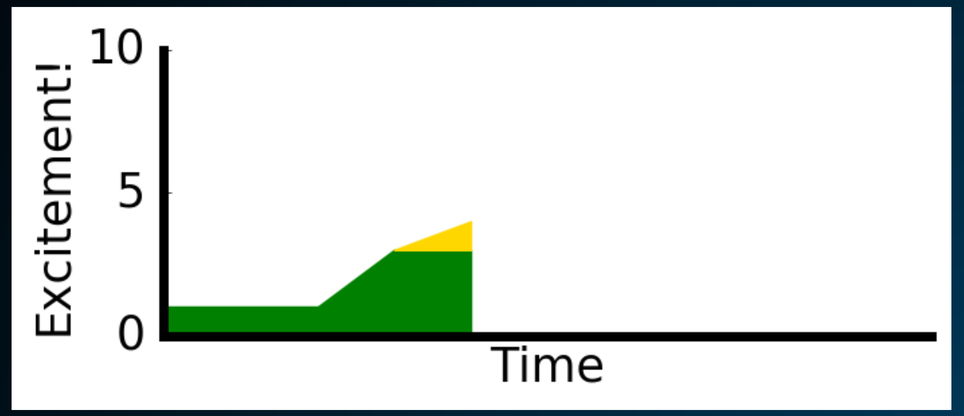


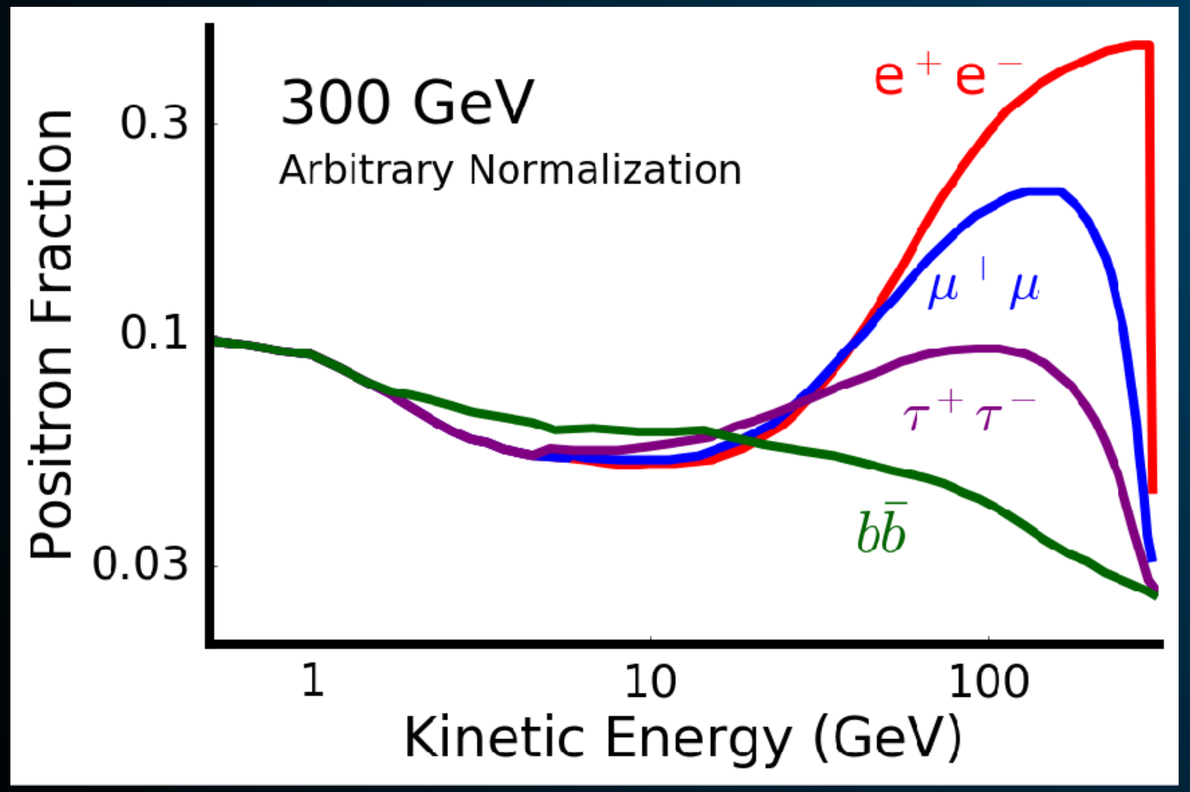


(Not an exhaustive list of observations)

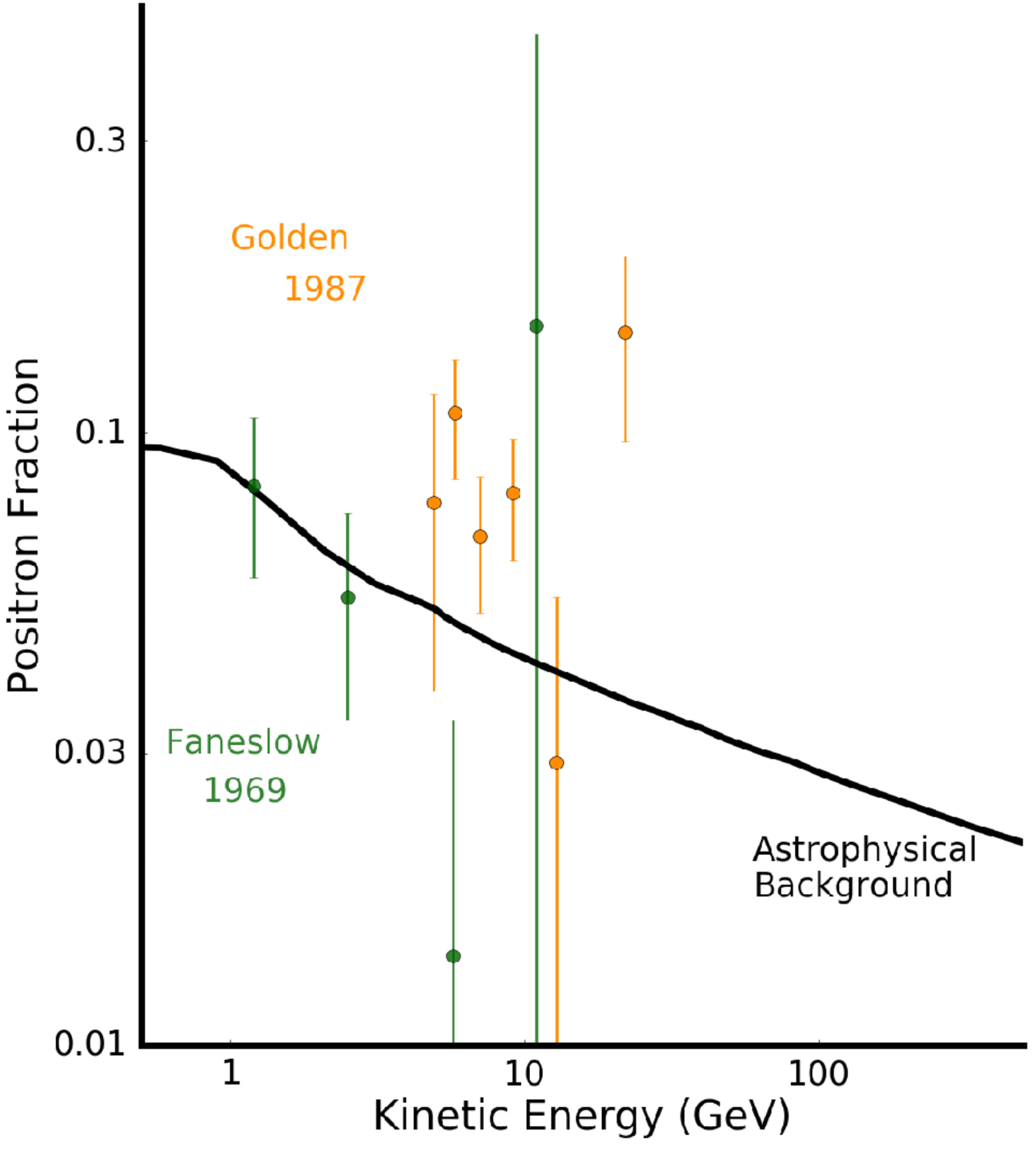


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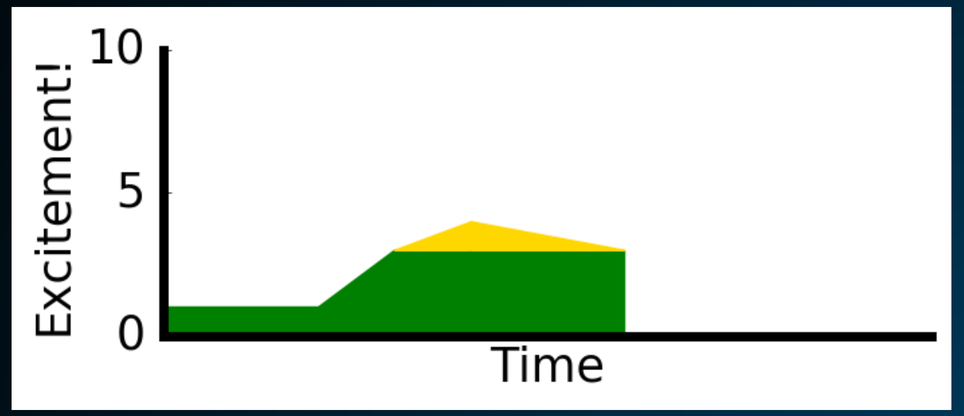


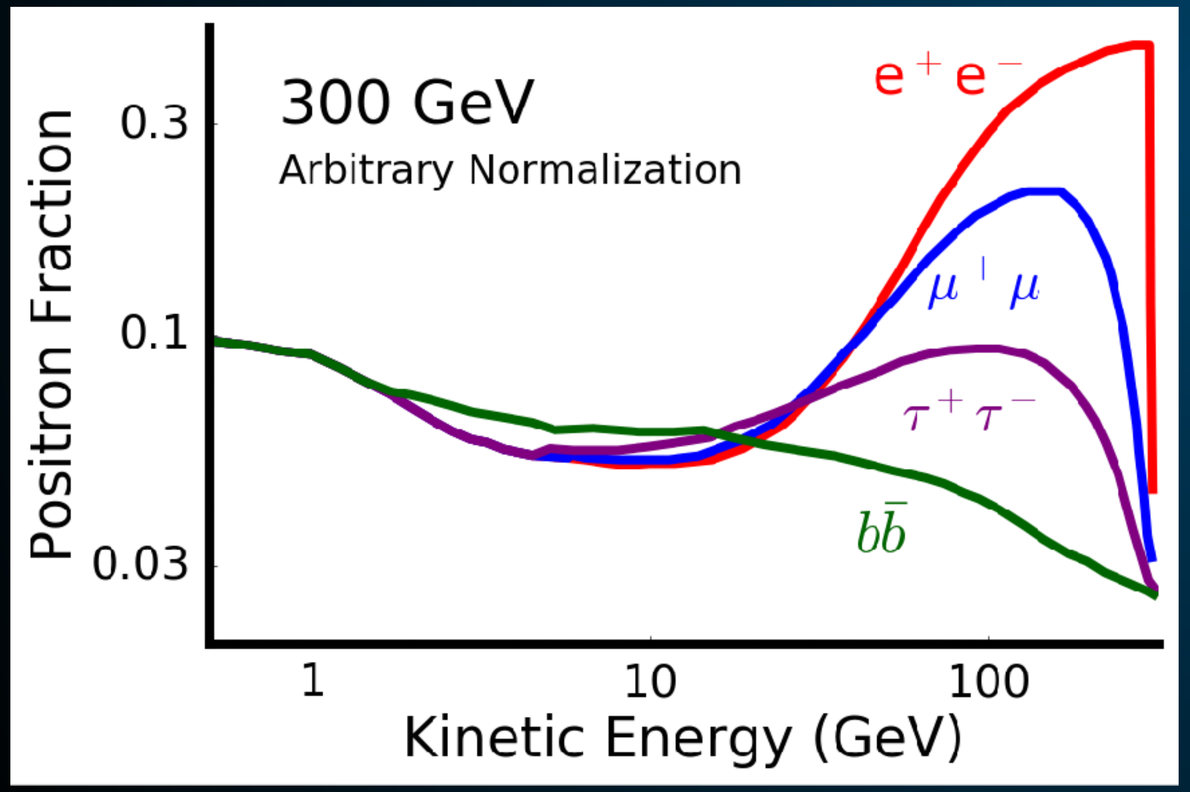


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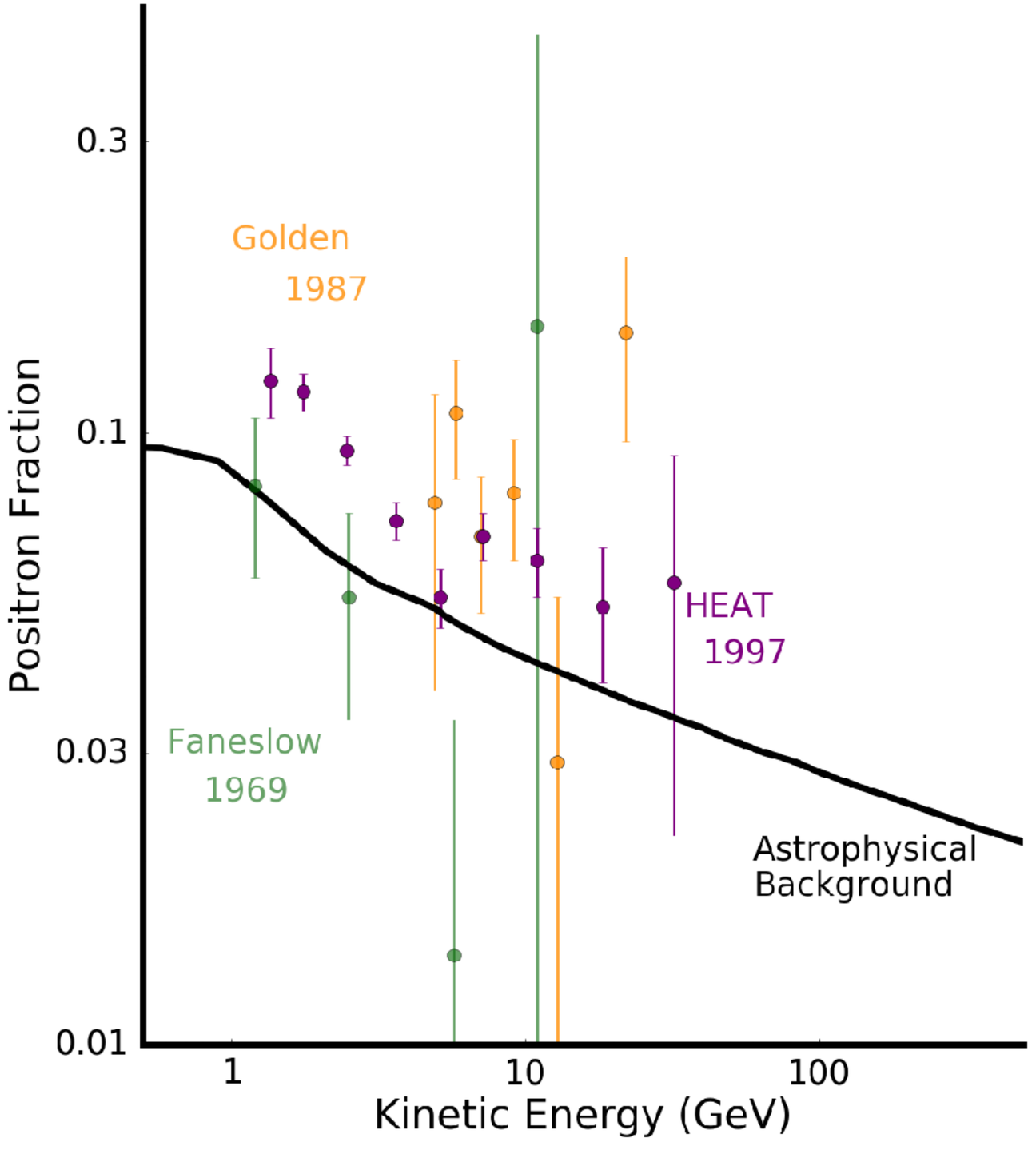


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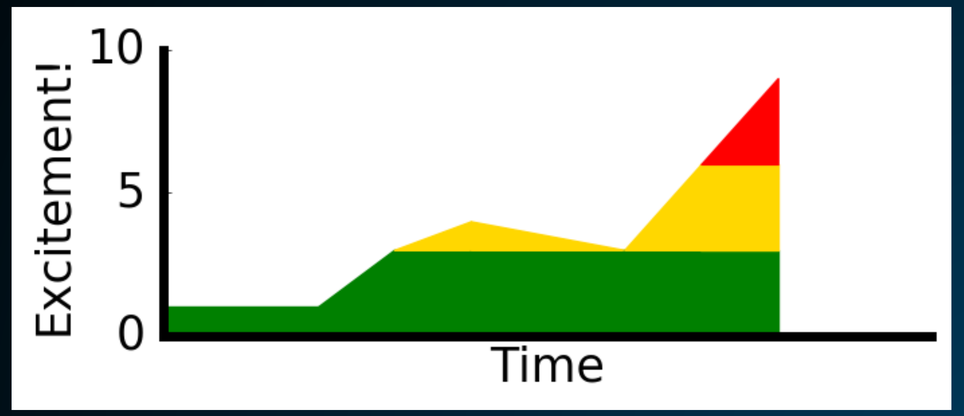


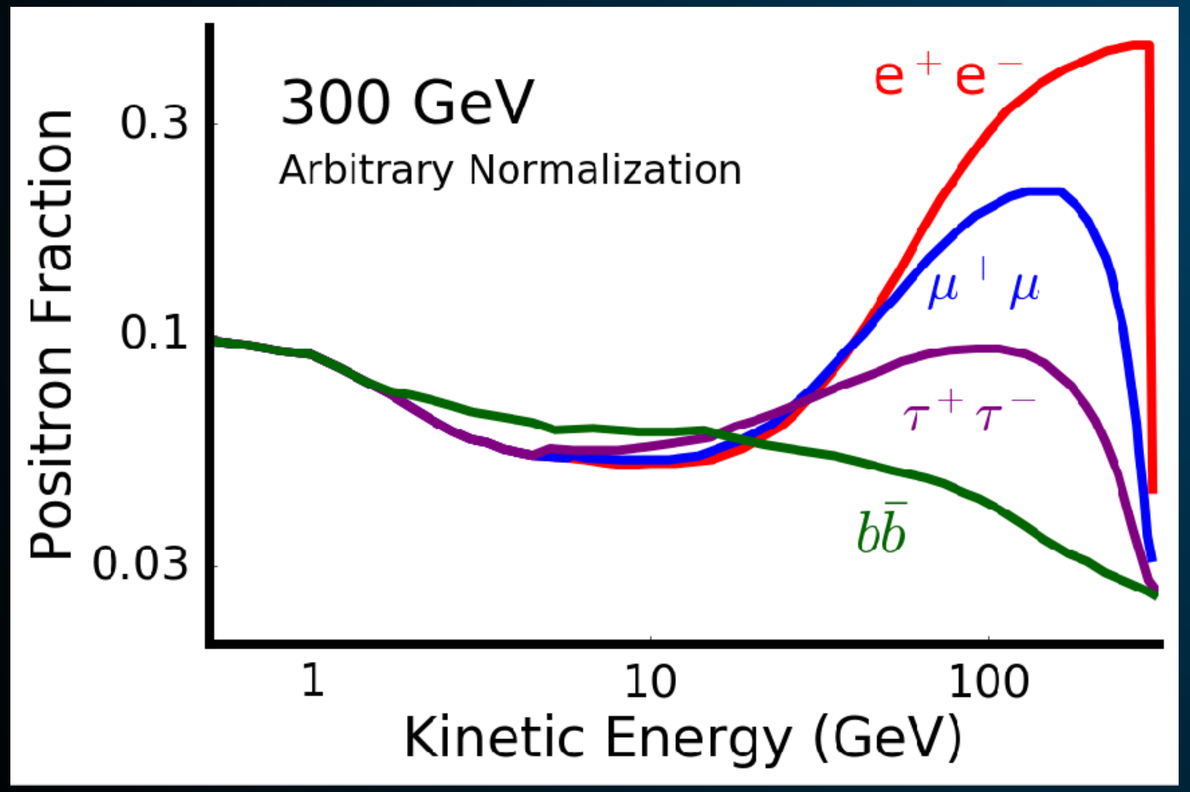


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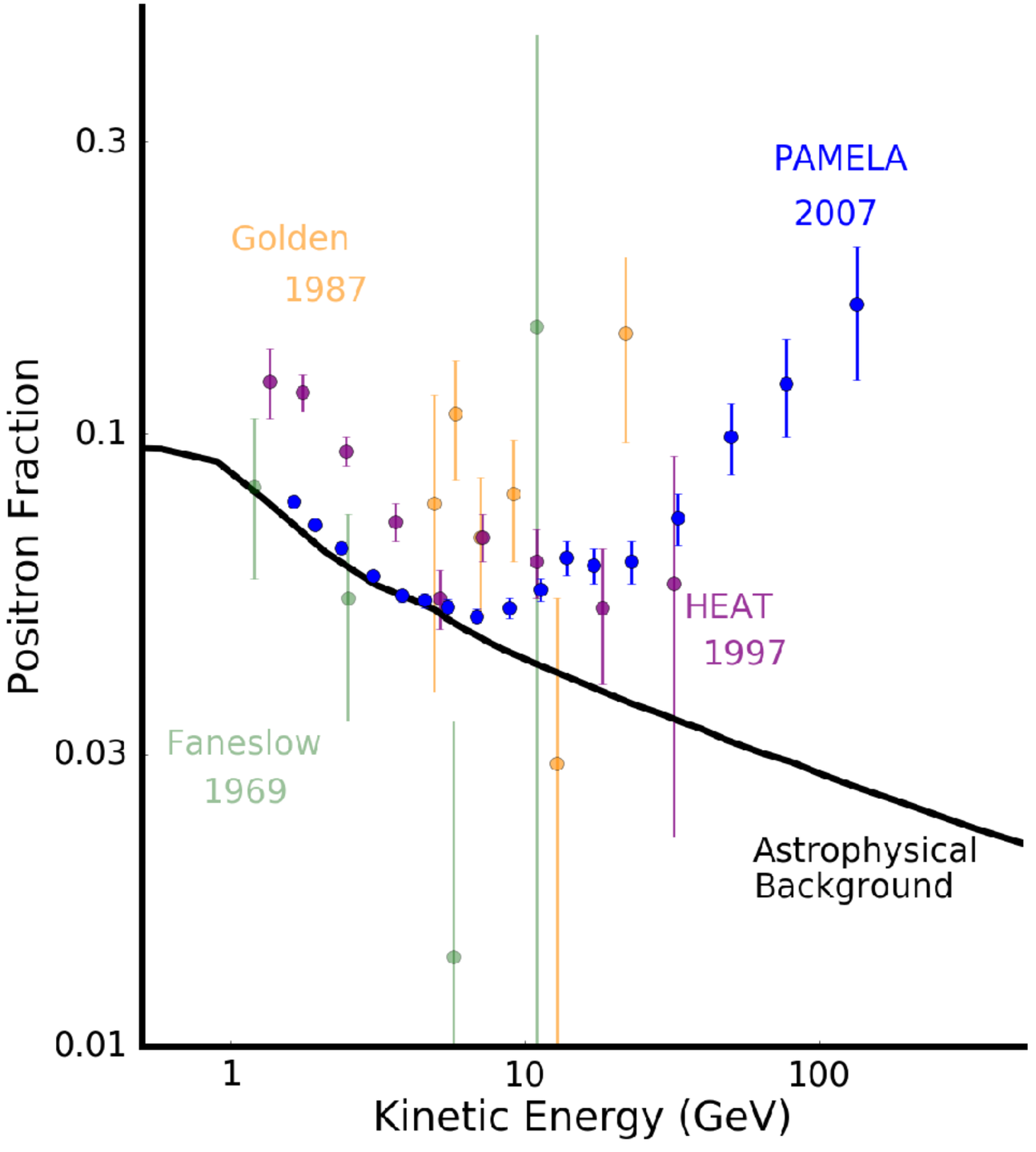


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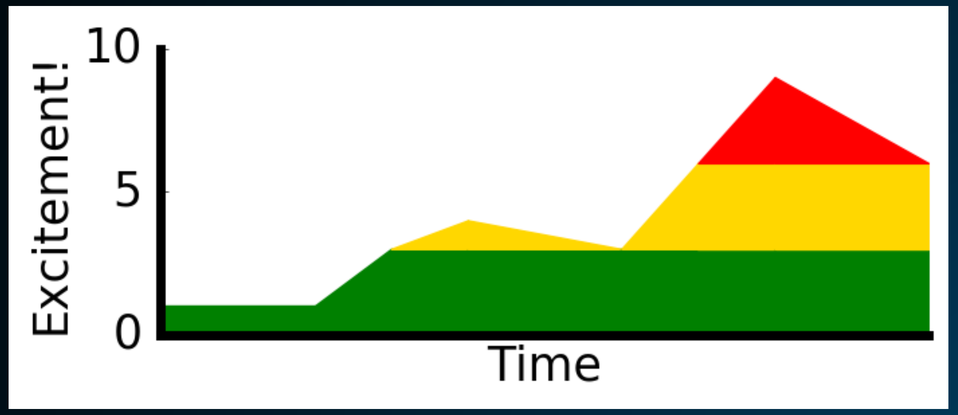


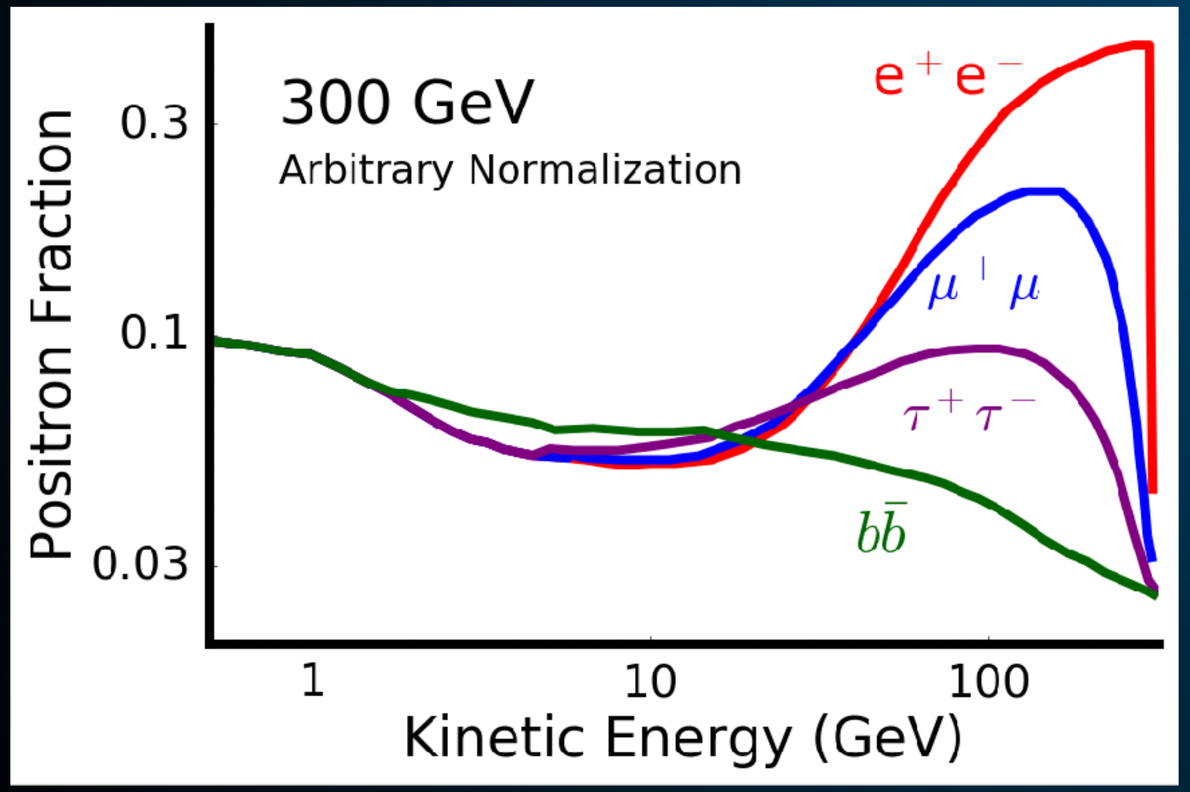


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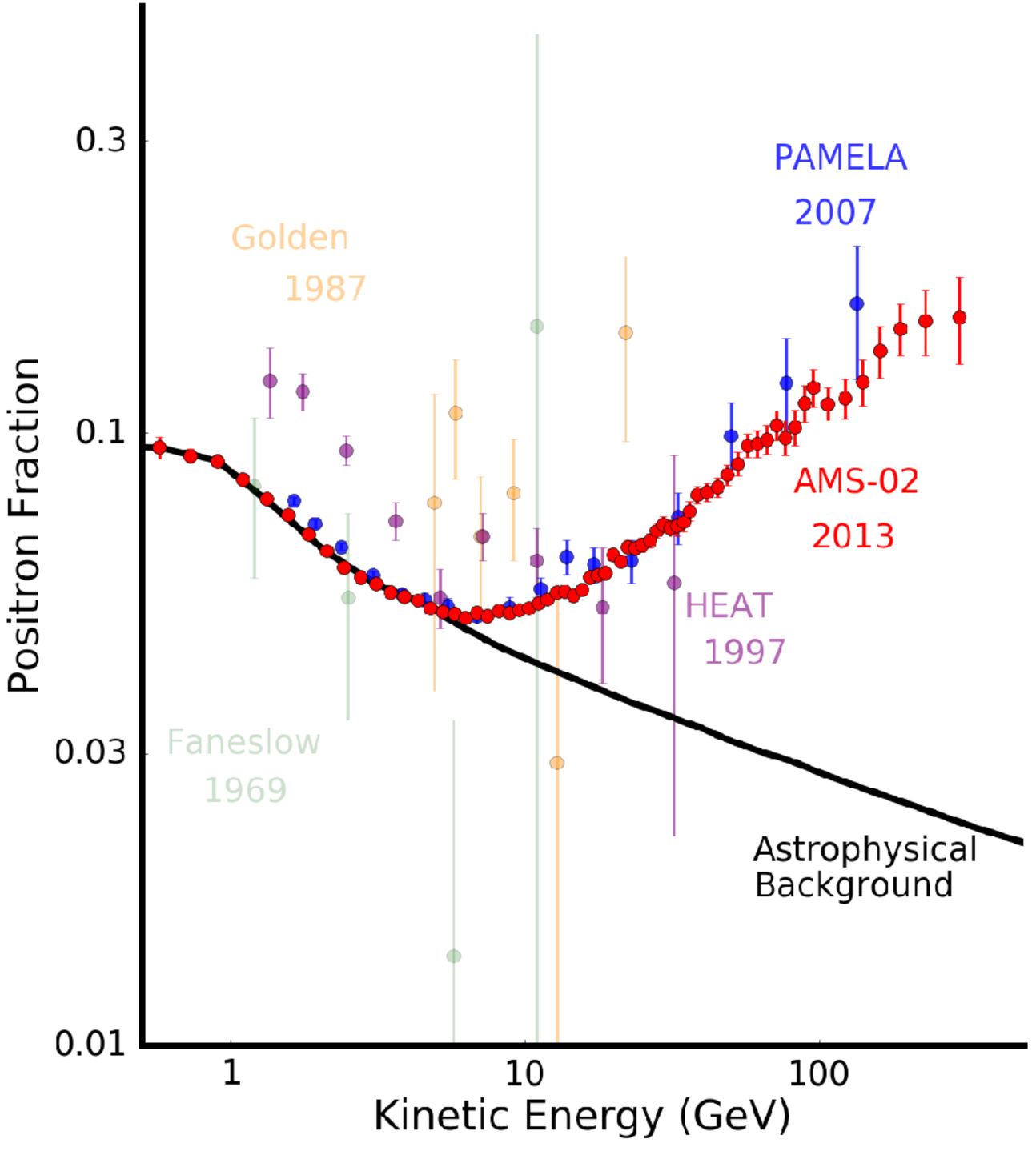


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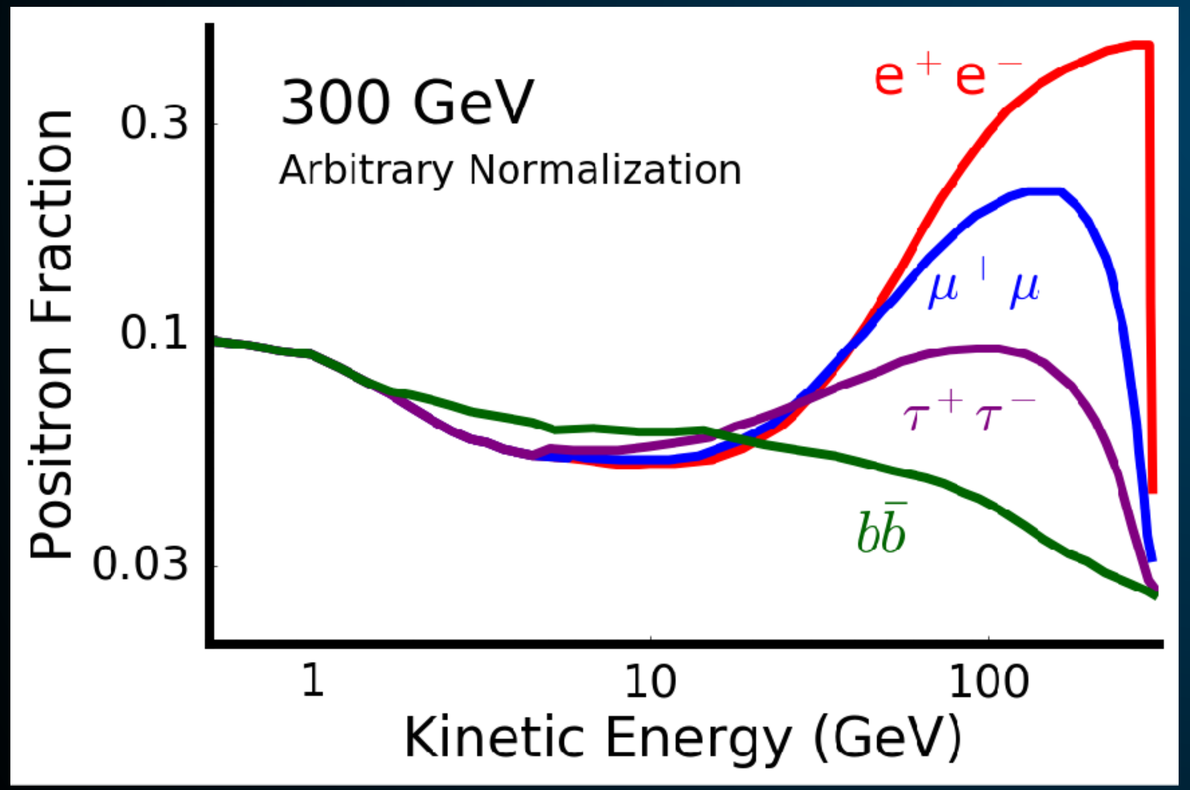


The Positron Excess

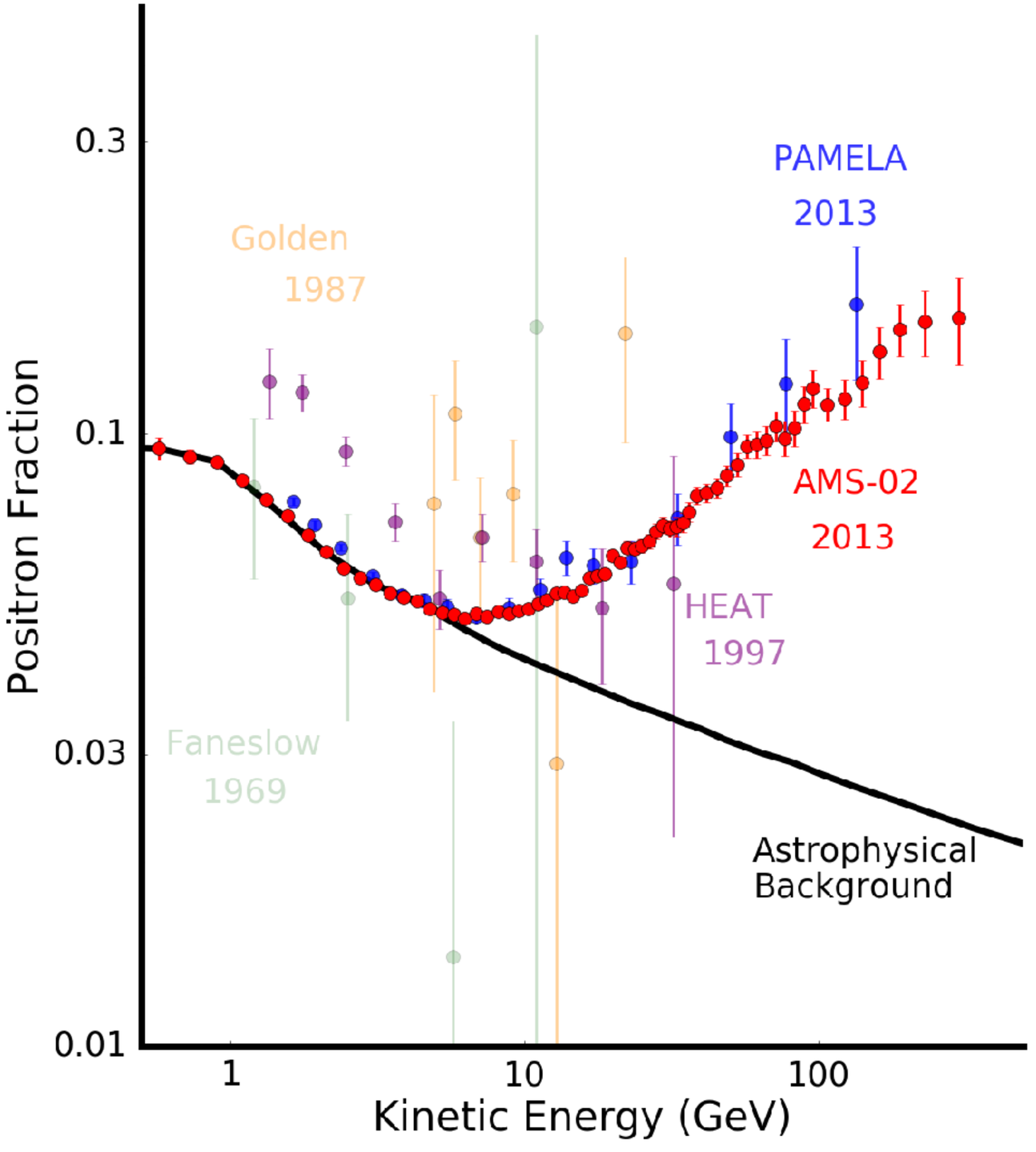
Why Less Excitement?

Continues to Higher Mass

Spectrum Relatively Smooth



(Not an exhaustive list of observations)

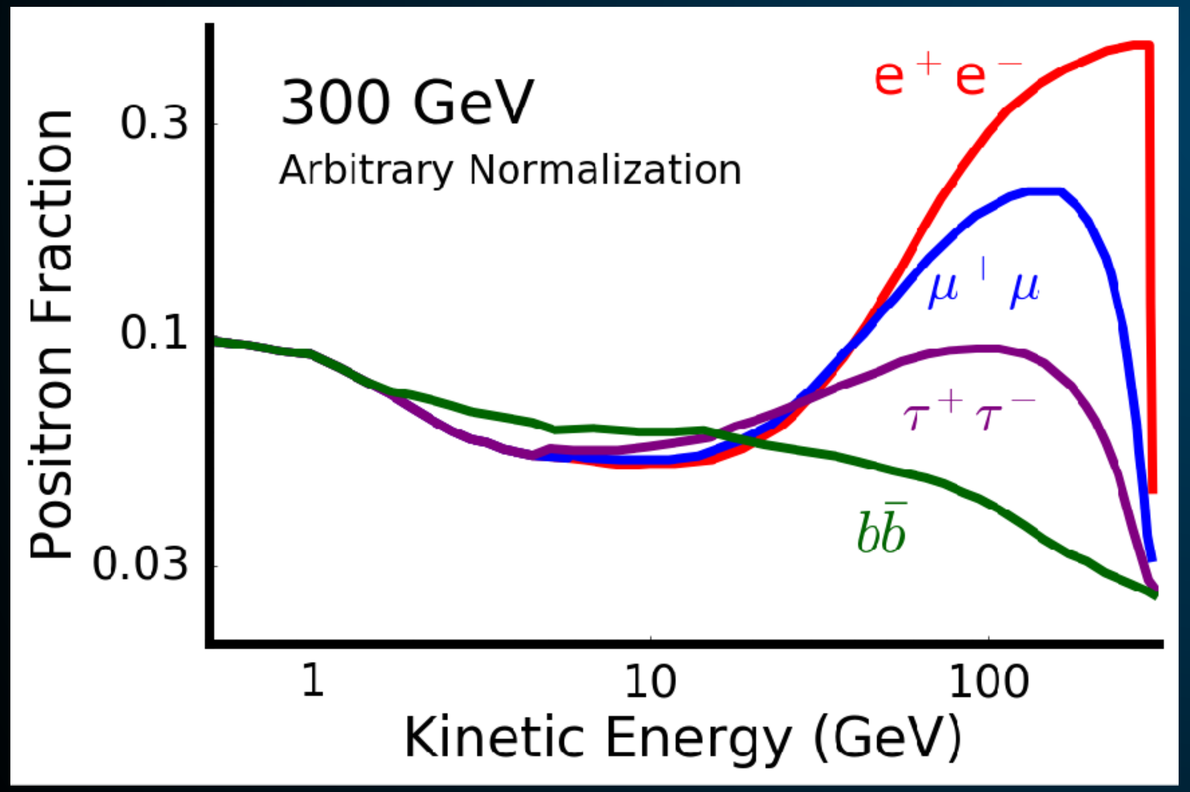


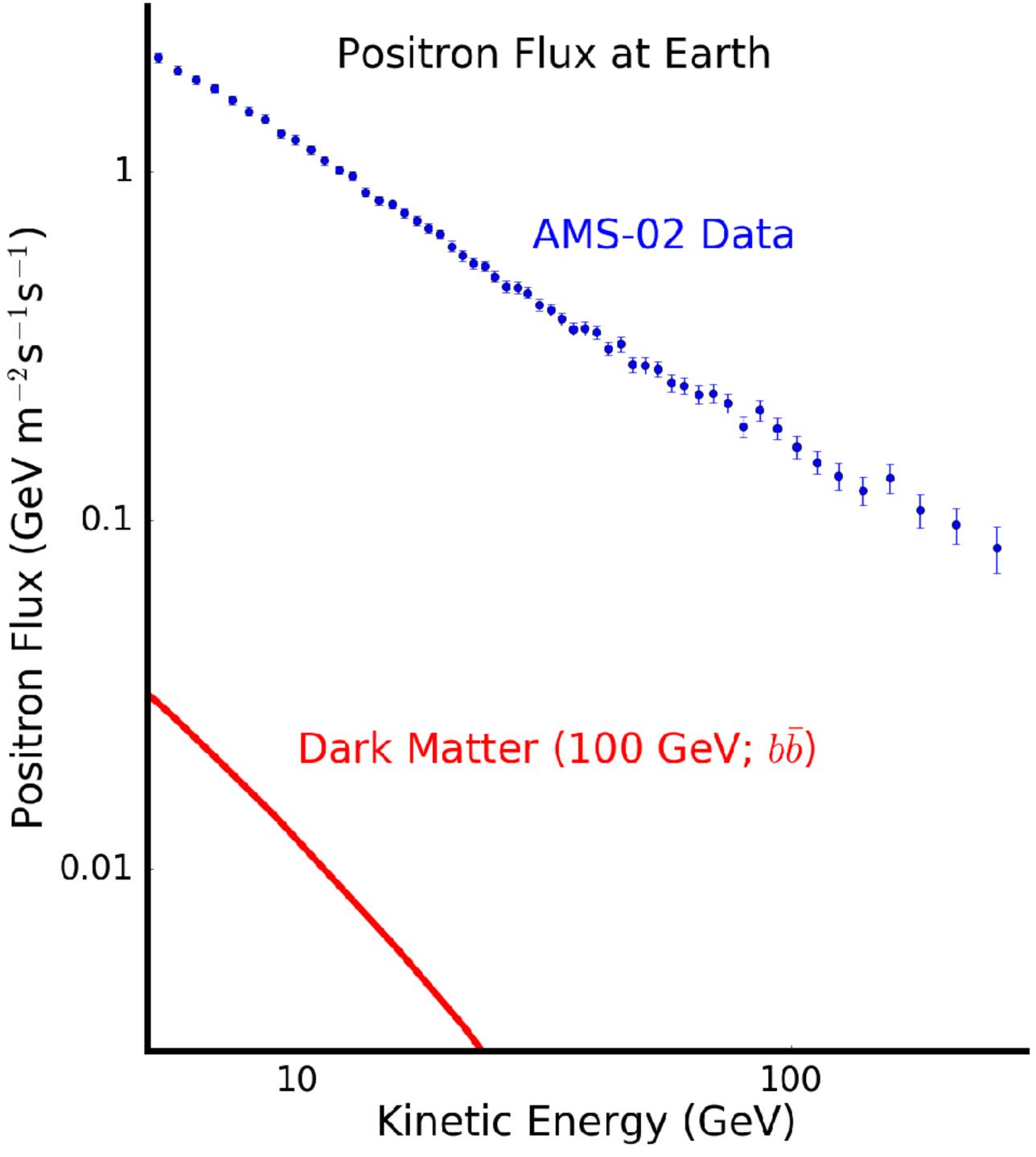
The Positron Excess

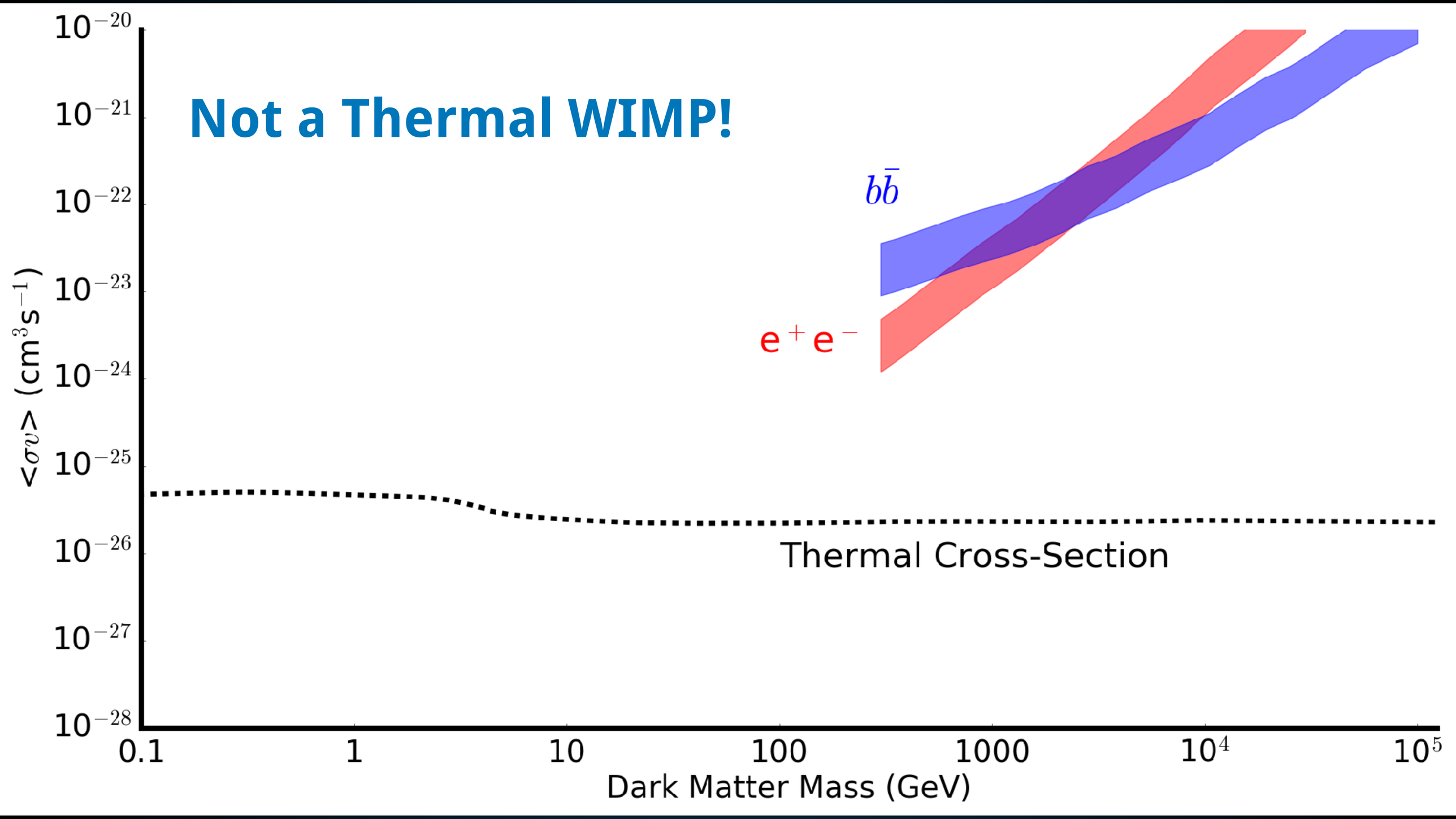
Why Less Excitement?

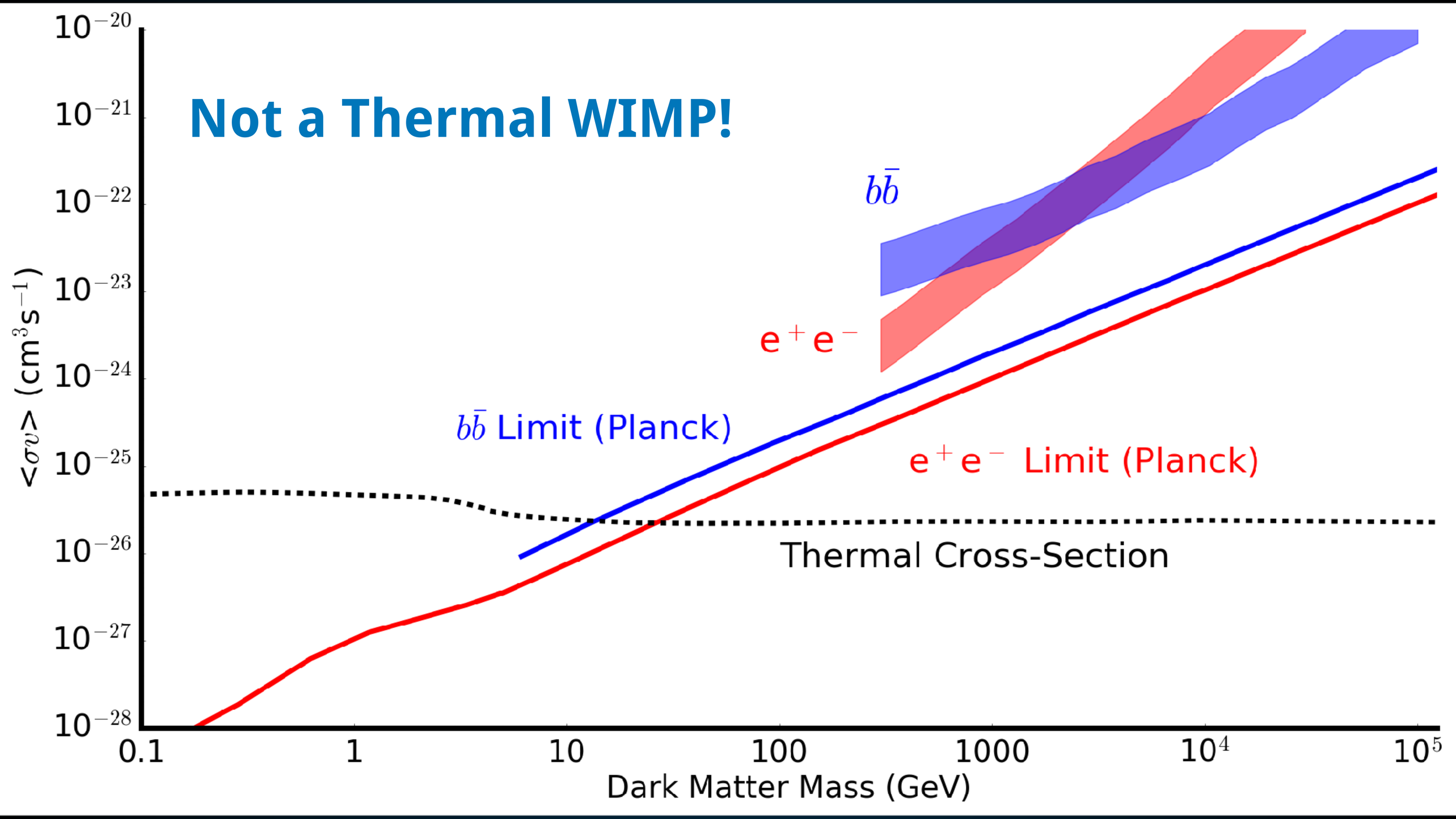
Continues to Higher Mass

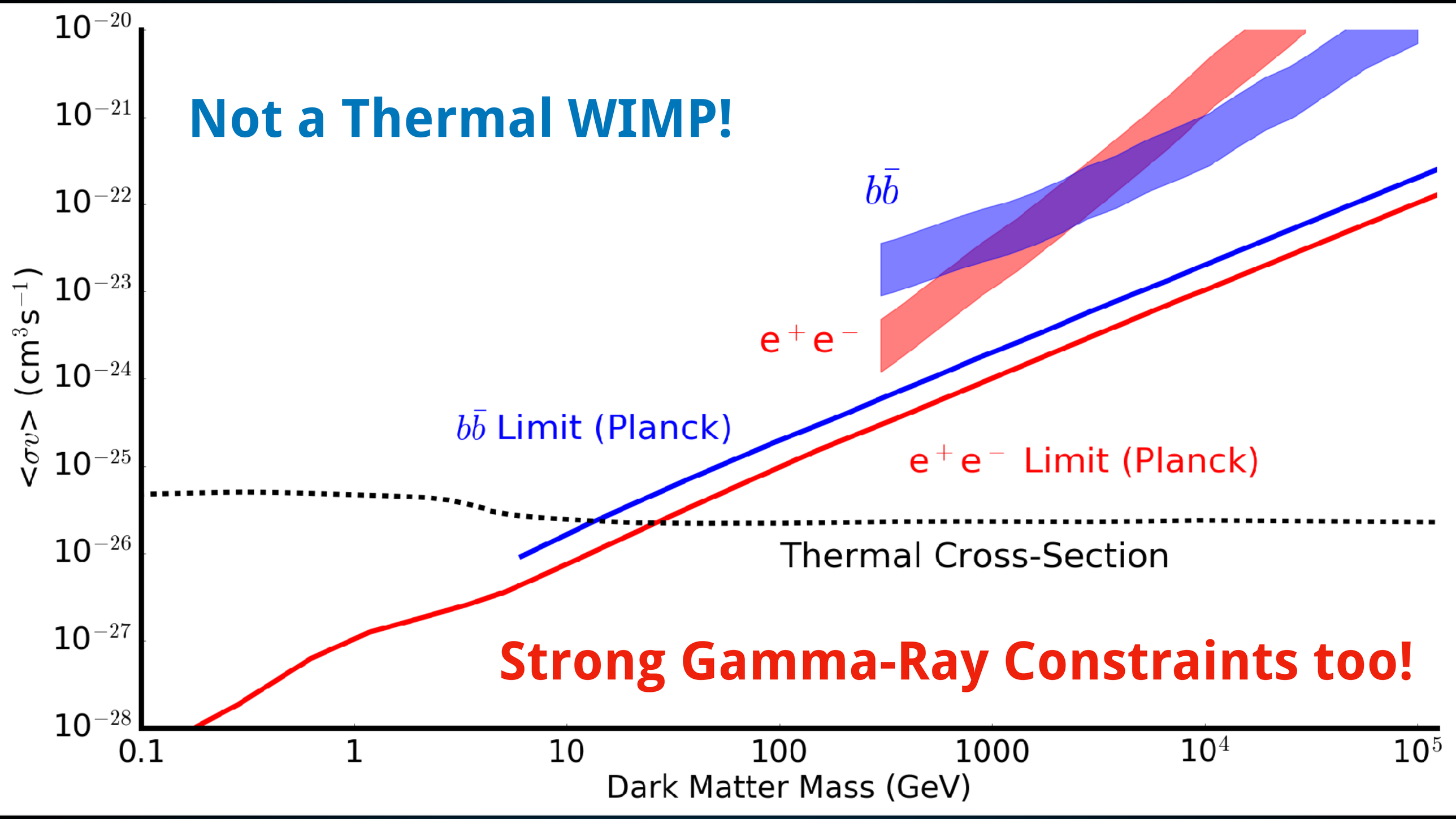
Spectrum Relatively Smooth






Not a Thermal WIMP!
$b\bar{b}$
e^+e^-
Thermal Cross-Section
$<\sigma v>$ (cm^3s^{-1})
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
0.1
1
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)


Not a Thermal WIMP!
$b\bar{b}$
e^+e^-
$b\bar{b}$ Limit (Planck)
e^+e^- Limit (Planck)
Thermal Cross-Section
$<\sigma v>$ (cm^3s^{-1})
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
0.1
1
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

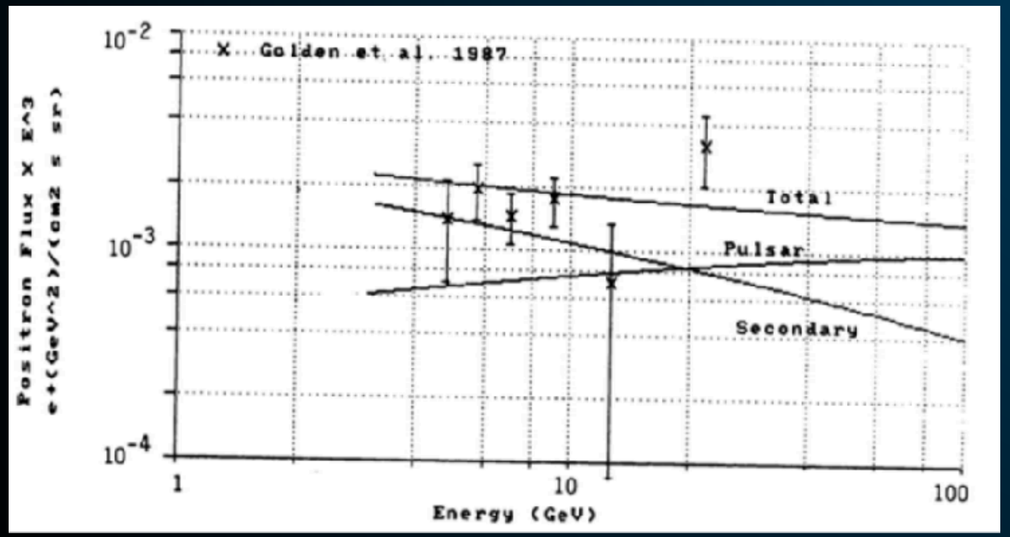

Not a Thermal WIMP!
$b\bar{b}$
e^+e^-
$b\bar{b}$ Limit (Planck)
e^+e^- Limit (Planck)
Thermal Cross-Section
Strong Gamma-Ray Constraints too!
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ ($cm^3 s^{-1}$)
0.1
1
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

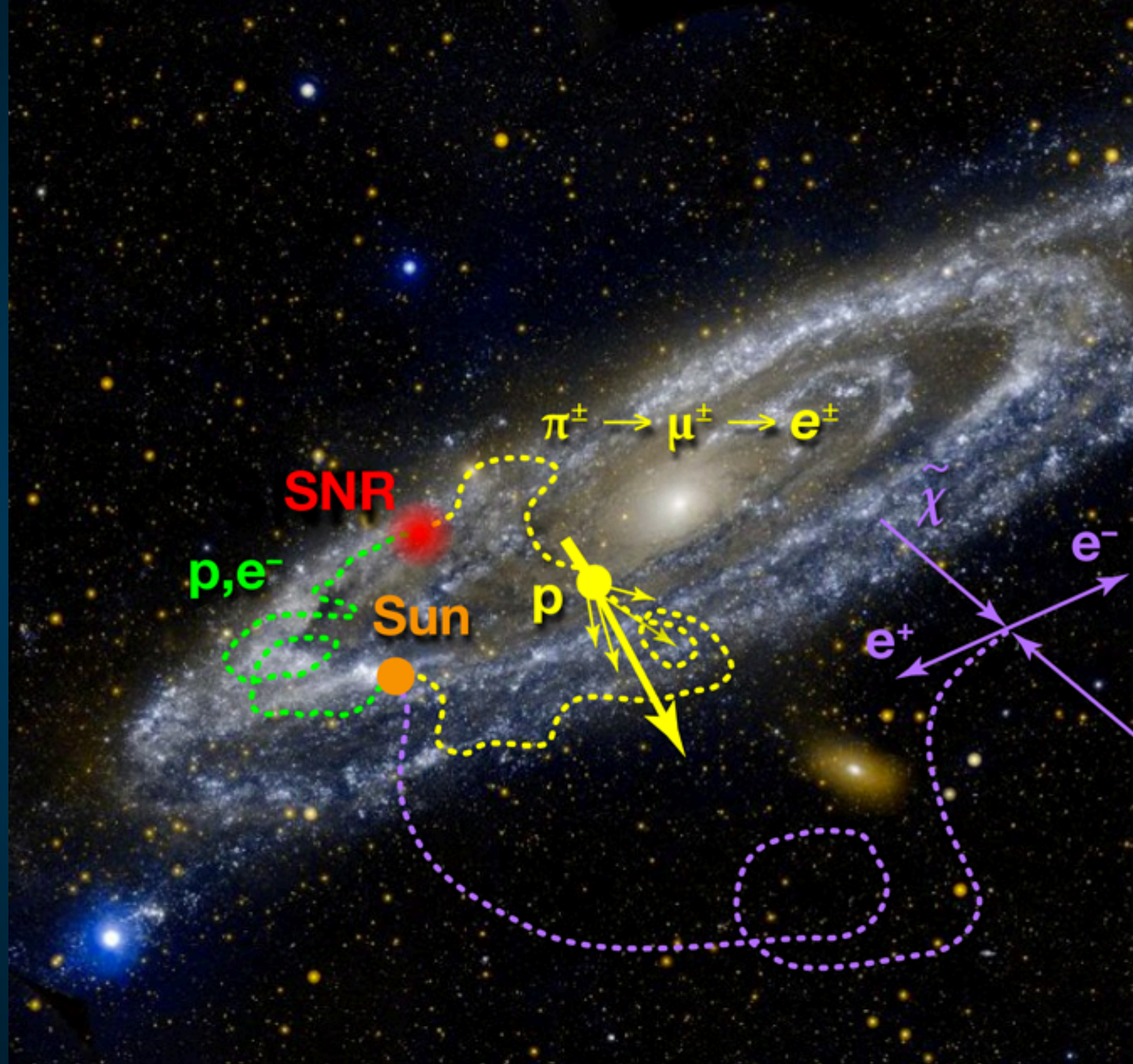
The Positron Excess

Key Idea: Investigate the Positron Fraction!

$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$

Harding & Ramaty (ICRC! 1987)





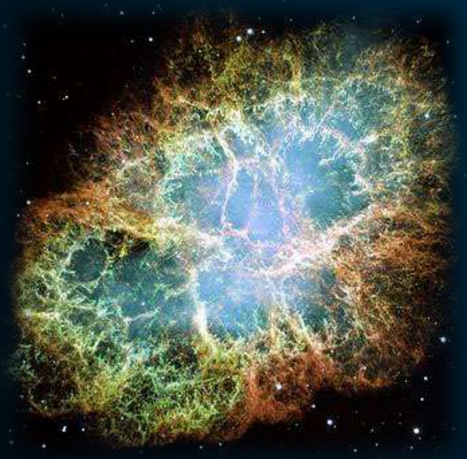
The Positron Excess

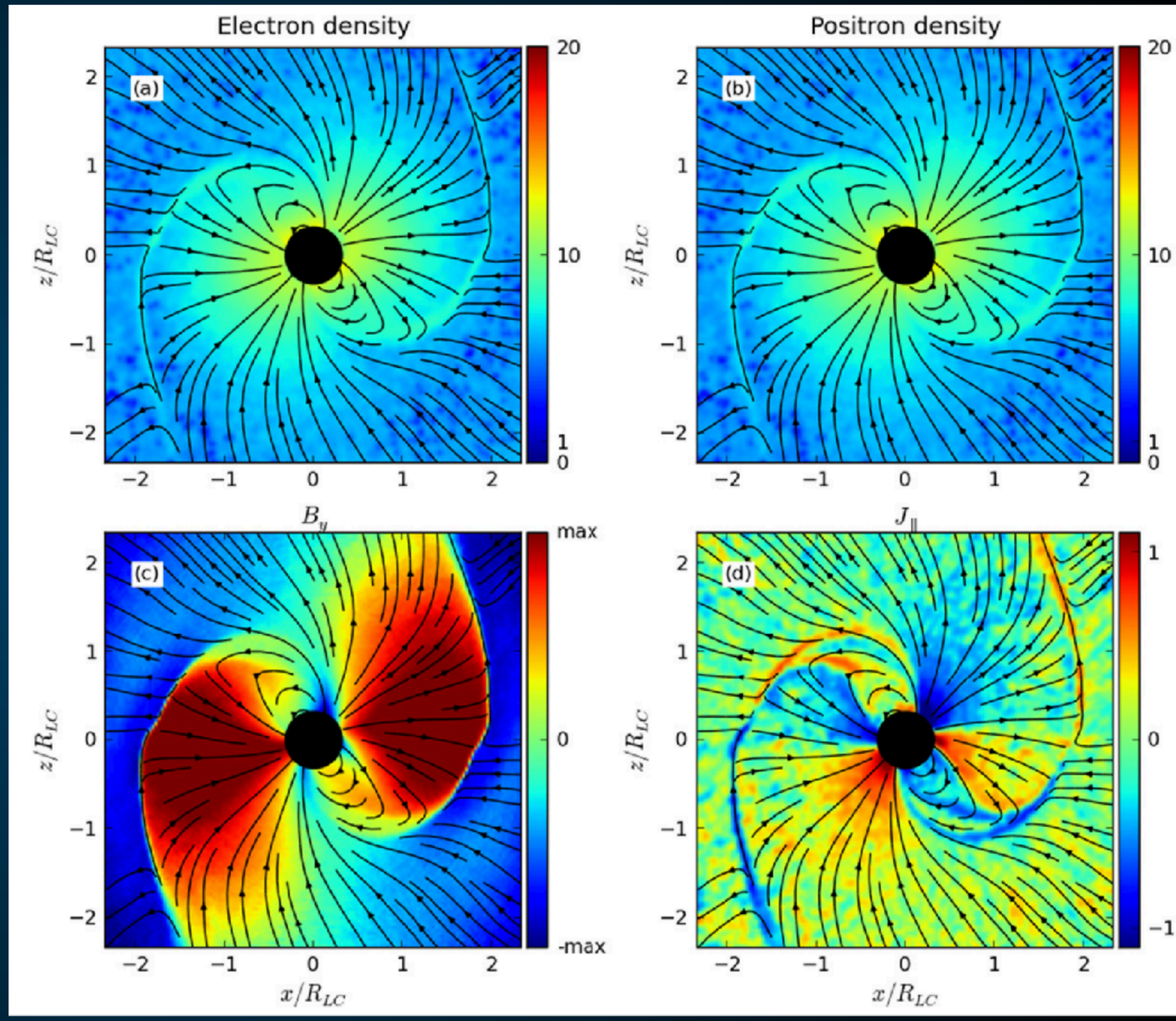
Philippov et al. (2015; 1412.0673)

Simulations indicate that pulsars accelerate a significant e^+e^- population.

But what is the pulsar e^+e^- efficiency?

How many e^+e^- escape the pulsar magnetosphere and pulsar wind nebula?





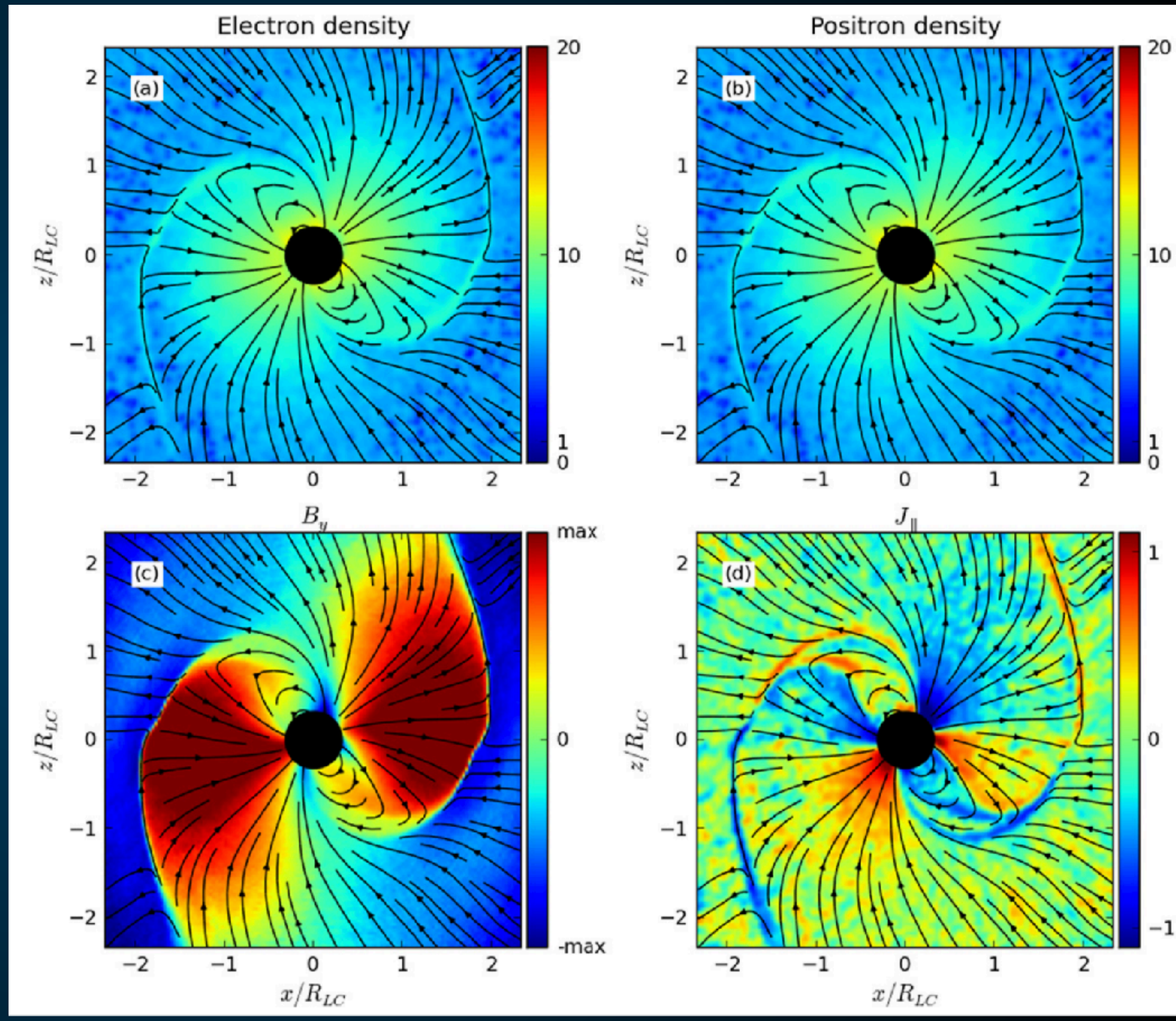
The Positron Excess

Philippov et al. (2015; 1412.0673)

Simulations indicate that pulsars accelerate a significant e^+e^- population.

But what is the pulsar e^+e^- efficiency?

How many e^+e^- escape the pulsar magnetosphere and pulsar wind nebula?



%. 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^+} falls between 1% and 30%.

Profumo (2008, 0812.4457)

Moon (To Scale)

Geminga

PSR B0656+14





Moon (To Scale)

Geminga

SNR
(hadronic/leptonic)

TeV Halo
(escaped e^+e^-)

PWN
(confined e^+e^-)



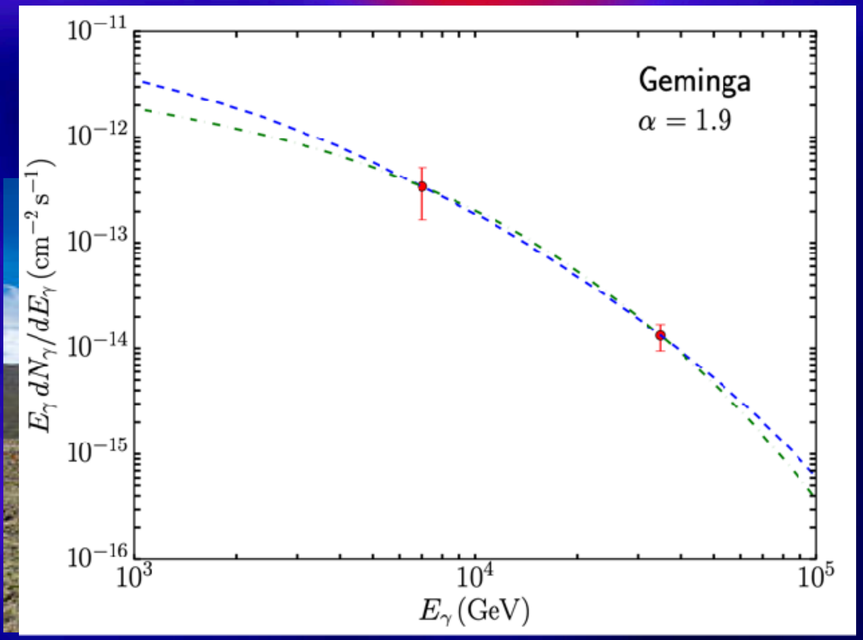
Moon (To Scale)

Geminga

SNR
(hadronic/leptonic)

TeV Halo
(escaped e^+e^-)

PWN
(confined e^+e^-)



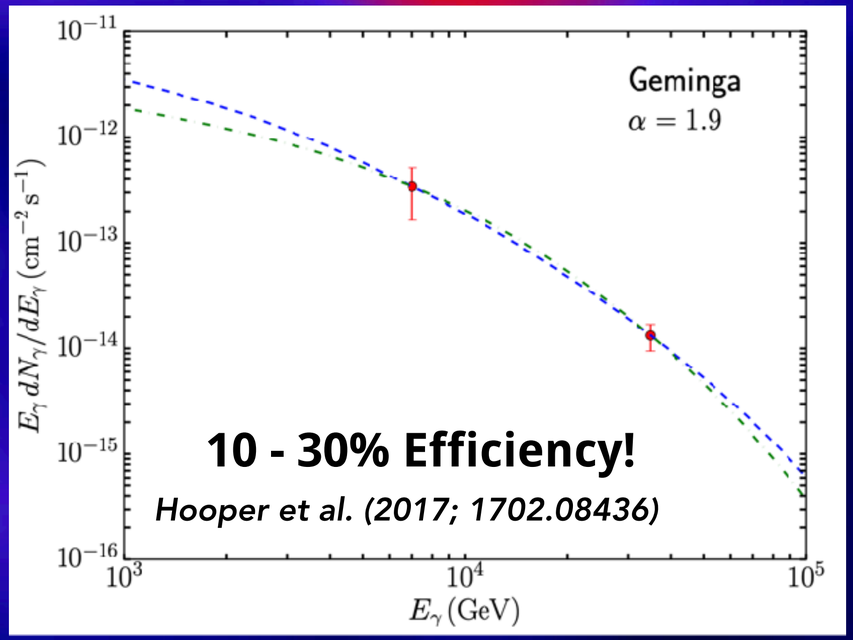
Moon (To Scale)

Geminga

SNR
(hadronic/leptonic)

TeV Halo
(escaped e^+e^-)

PWN
(confined e^+e^-)



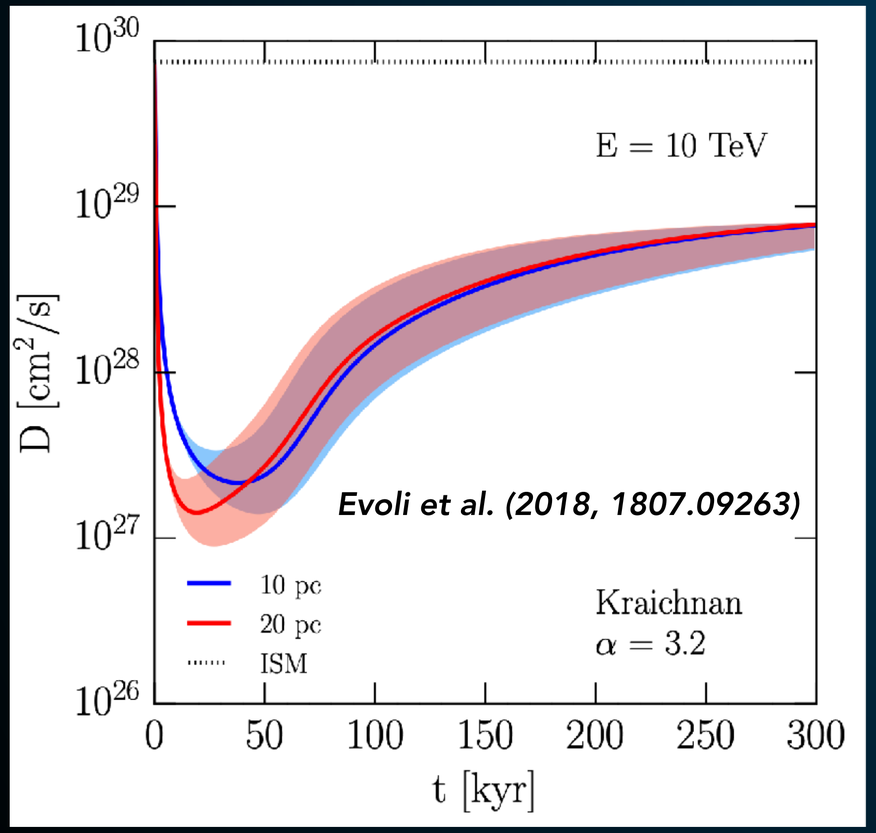
10 - 30% Efficiency!

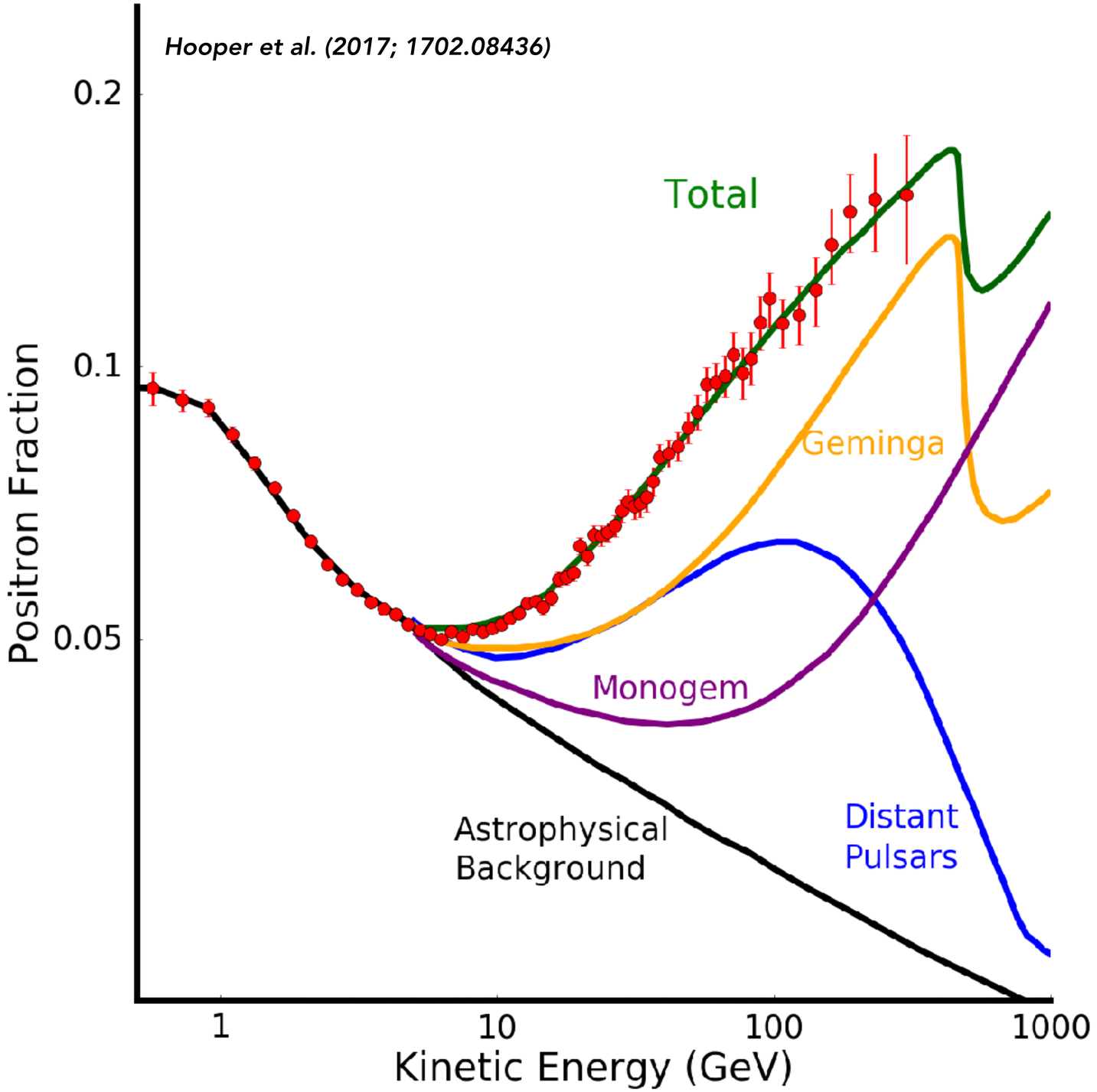
Hooper et al. (2017; 1702.08436)

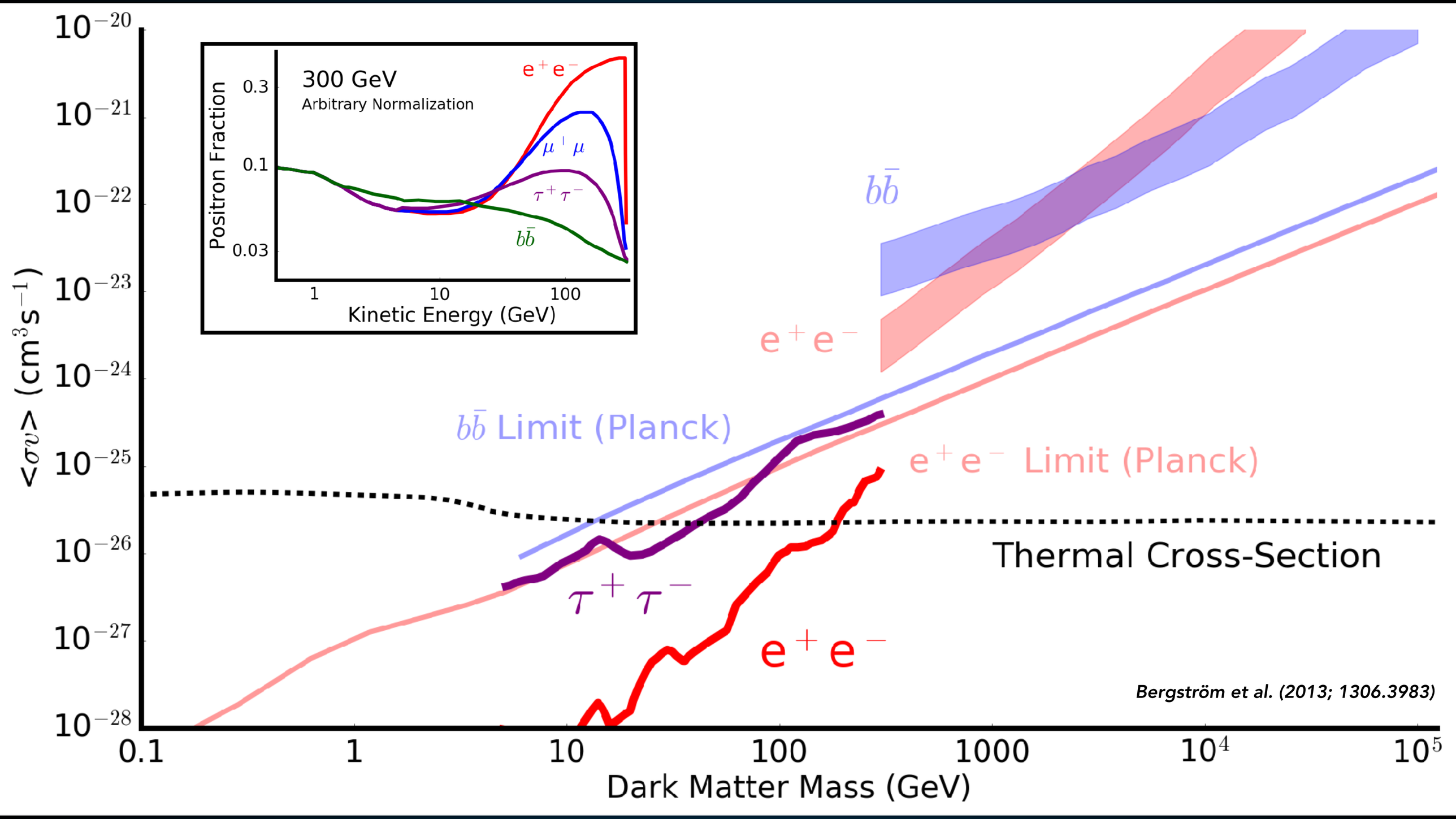
The Positron Excess

This can easily match the positron fraction

Some transport issues are possible - but easy to solve in models with inhomogeneous diffusion.

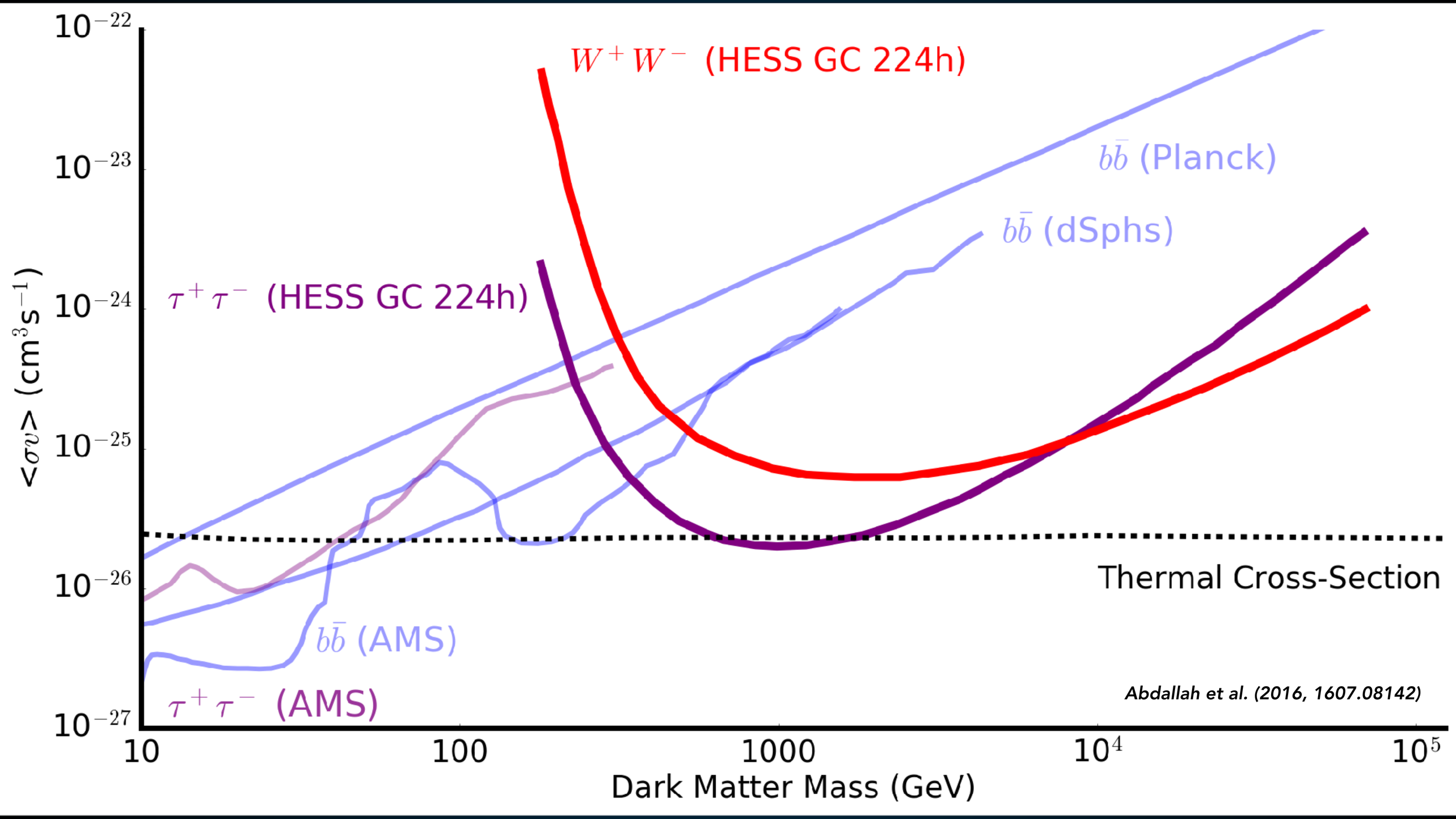


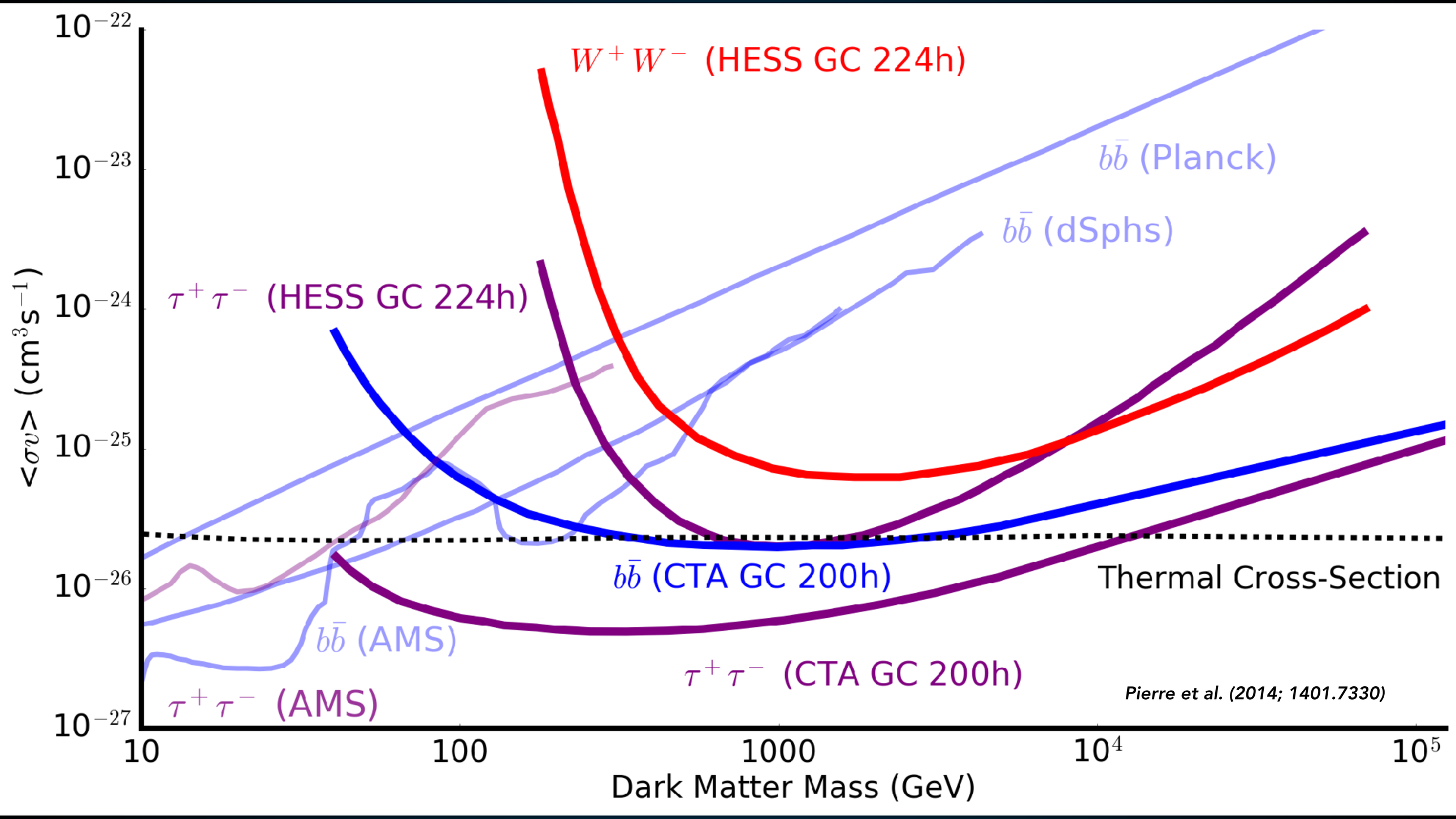


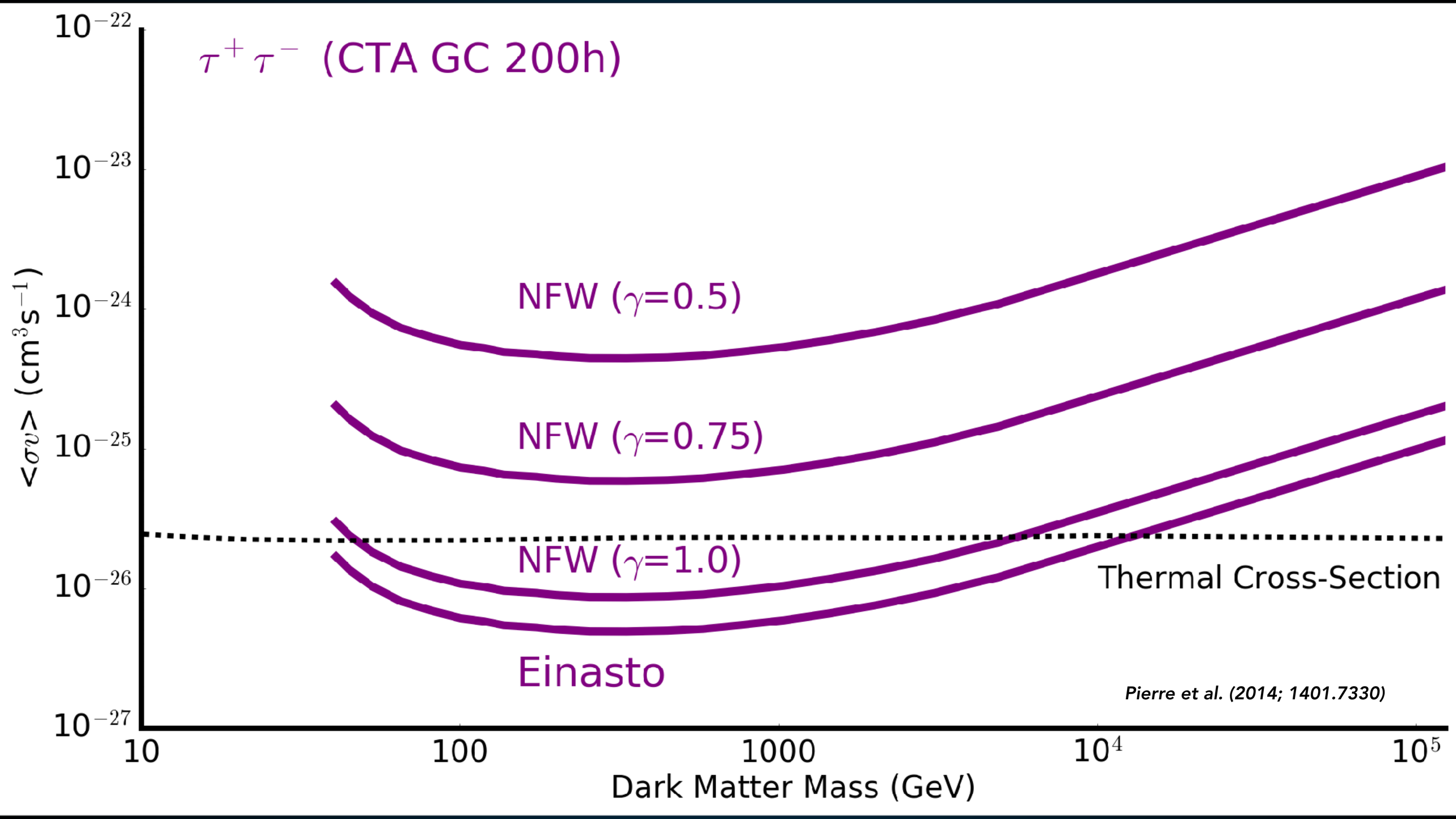

300 GeV
Arbitrary Normalization
Positron Fraction
Kinetic Energy (GeV)
e^+e^-
$\mu^+\mu^-$
$\tau^+\tau^-$
$b\bar{b}$
$b\bar{b}$
e^+e^-
$b\bar{b}$ Limit (Planck)
e^+e^- Limit (Planck)
Thermal Cross-Section
$\tau^+\tau^-$
e^+e^-
$<\sigma v>$ ($cm^3 s^{-1}$)
Dark Matter Mass (GeV)
Bergström et al. (2013; 1306.3983)

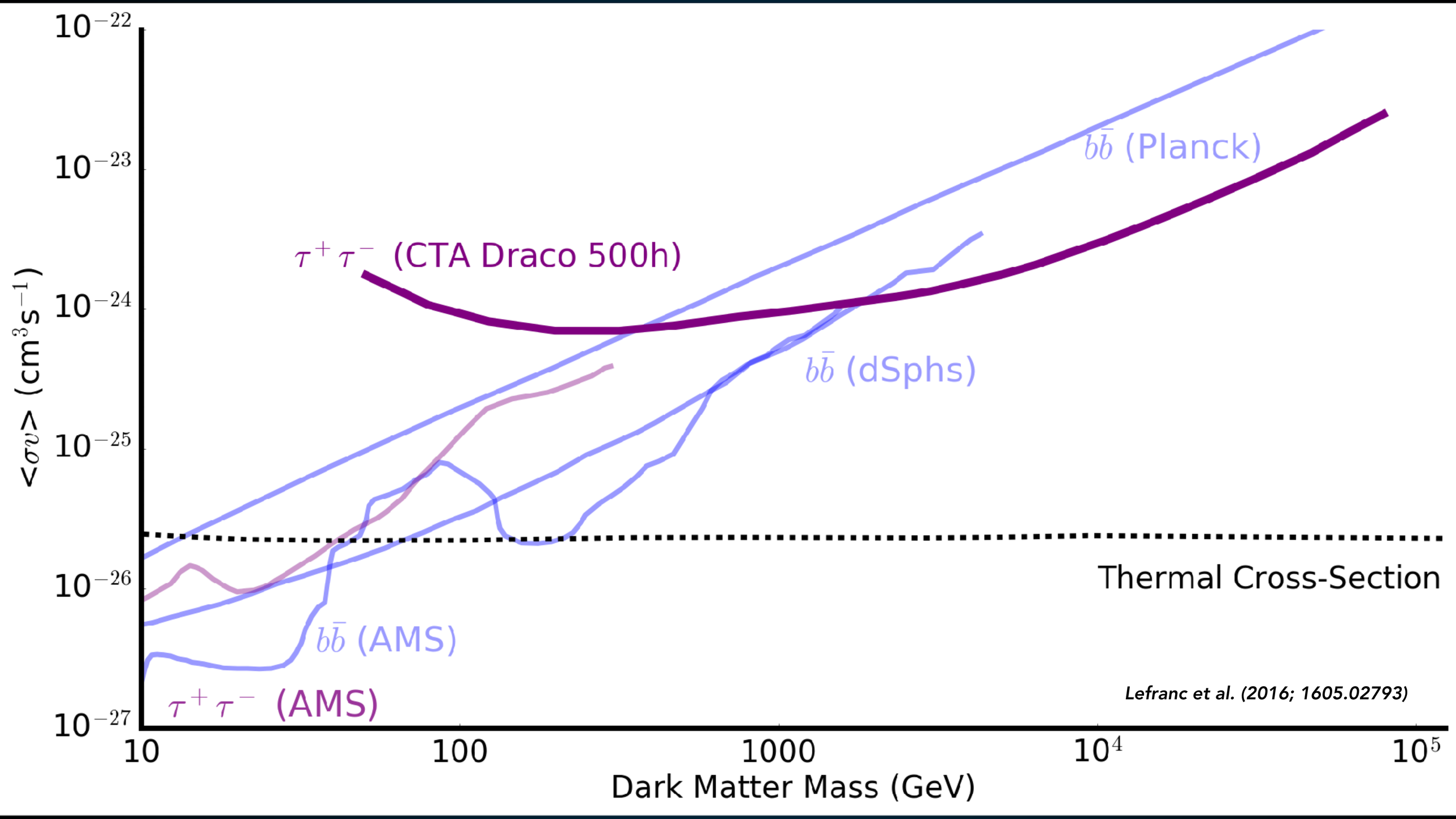


What About TeV WIMPS?


10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
$<\sigma v>$ ($cm^3 s^{-1}$)
W^+W^- (HESS GC 224h)
$b\bar{b}$ (Planck)
$b\bar{b}$ (dSphs)
$\tau^+\tau^-$ (HESS GC 224h)
Thermal Cross-Section
$b\bar{b}$ (AMS)
$\tau^+\tau^-$ (AMS)
Abdallah et al. (2016, 1607.08142)
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

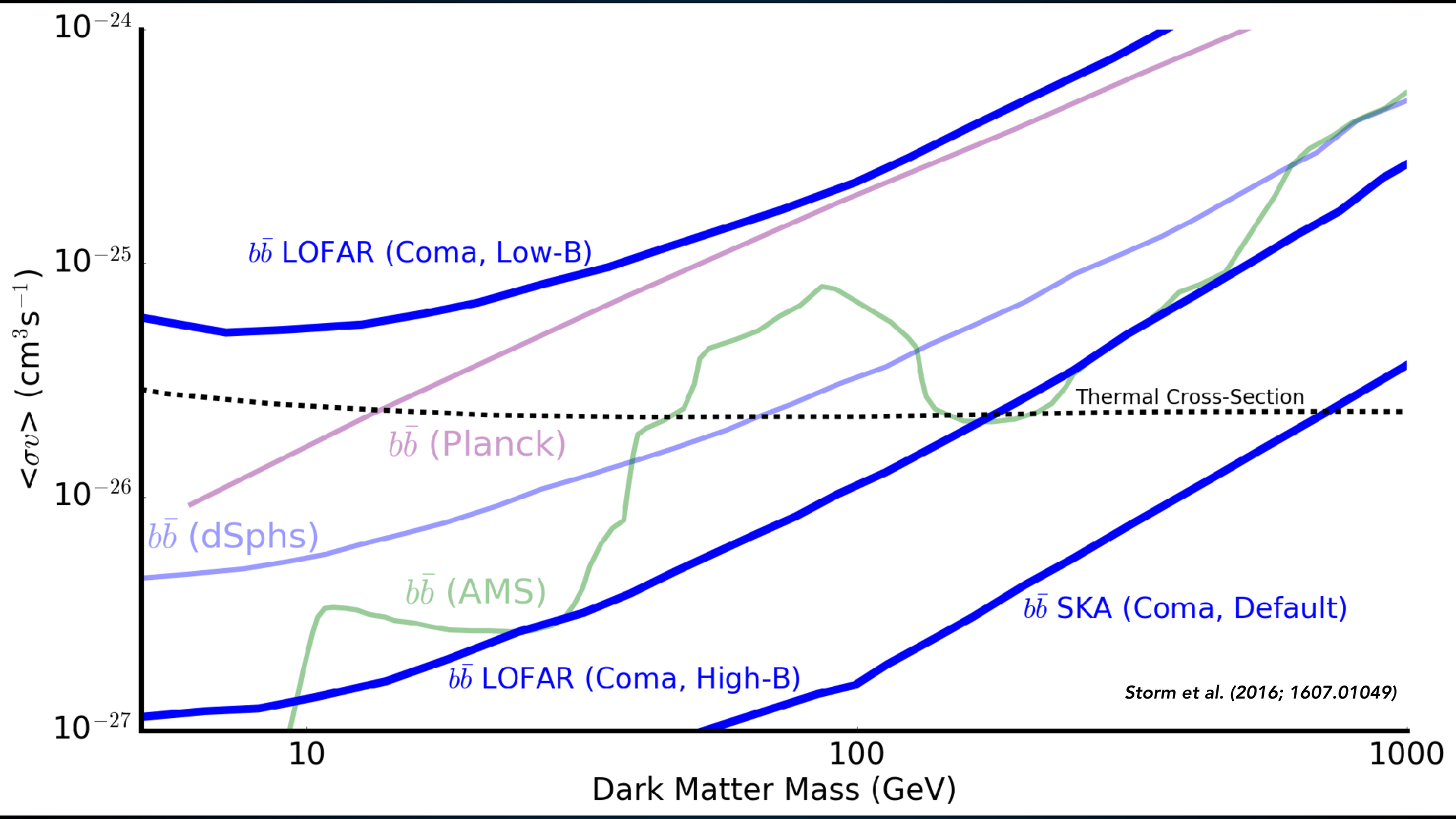

10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
$<\sigma v>$ ($cm^3 s^{-1}$)
W^+W^- (HESS GC 224h)
$b\bar{b}$ (Planck)
$b\bar{b}$ (dSphs)
$\tau^+\tau^-$ (HESS GC 224h)
$b\bar{b}$ (CTA GC 200h)
Thermal Cross-Section
$b\bar{b}$ (AMS)
$\tau^+\tau^-$ (CTA GC 200h)
$\tau^+\tau^-$ (AMS)
Pierre et al. (2014; 1401.7330)
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)


$\tau^+\tau^-$ (CTA GC 200h)
NFW (γ=0.5)
NFW (γ=0.75)
NFW (γ=1.0)
Einasto
Thermal Cross-Section
Pierre et al. (2014; 1401.7330)
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
<σv> (cm^{3}s^{-1})
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

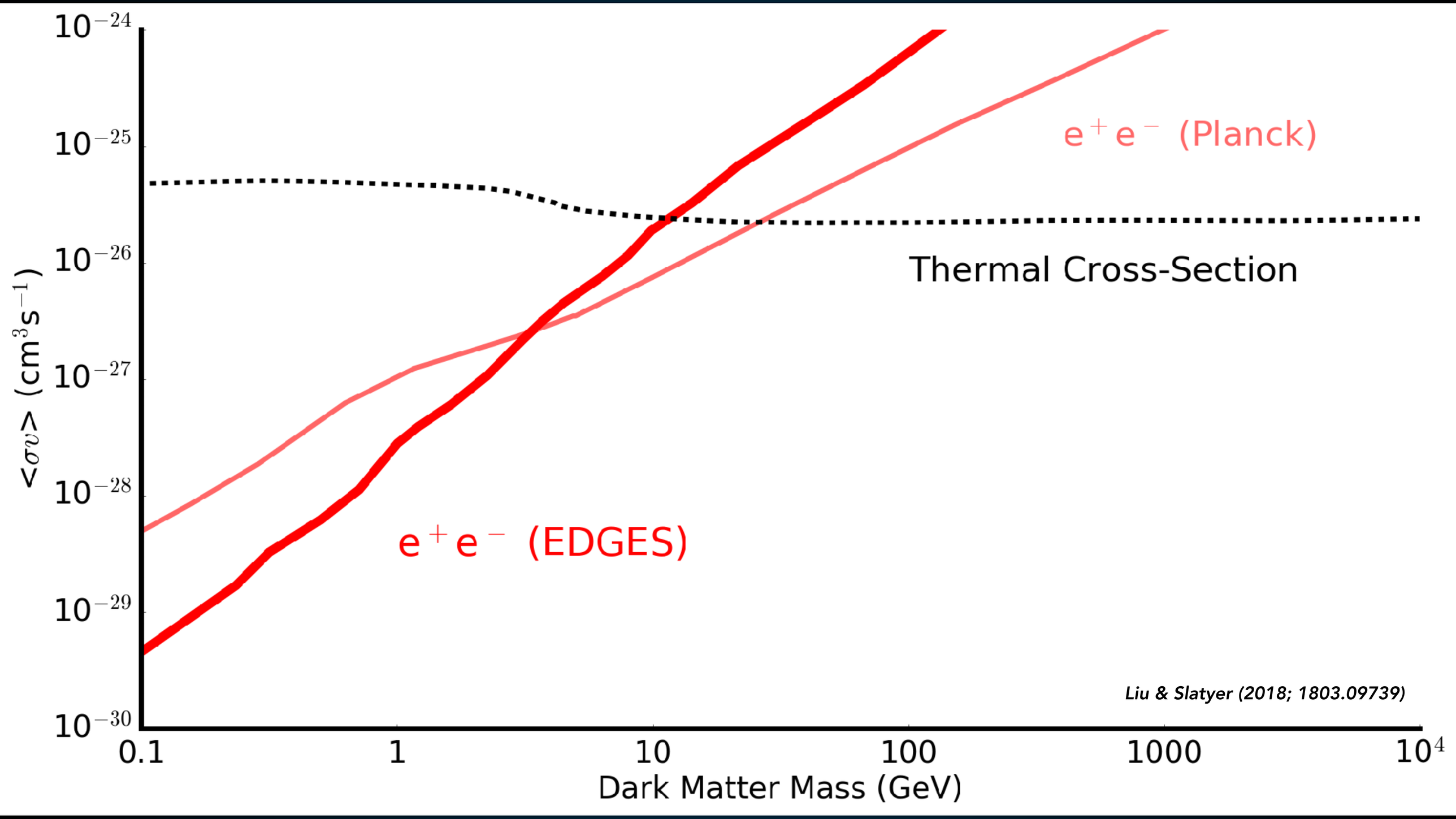

10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
$<\sigma v>$ ($cm^3 s^{-1}$)
$\tau^+\tau^-$ (CTA Draco 500h)
$b\bar{b}$ (Planck)
$b\bar{b}$ (dSphs)
Thermal Cross-Section
$b\bar{b}$ (AMS)
$\tau^+\tau^-$ (AMS)
Lefranc et al. (2016; 1605.02793)
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

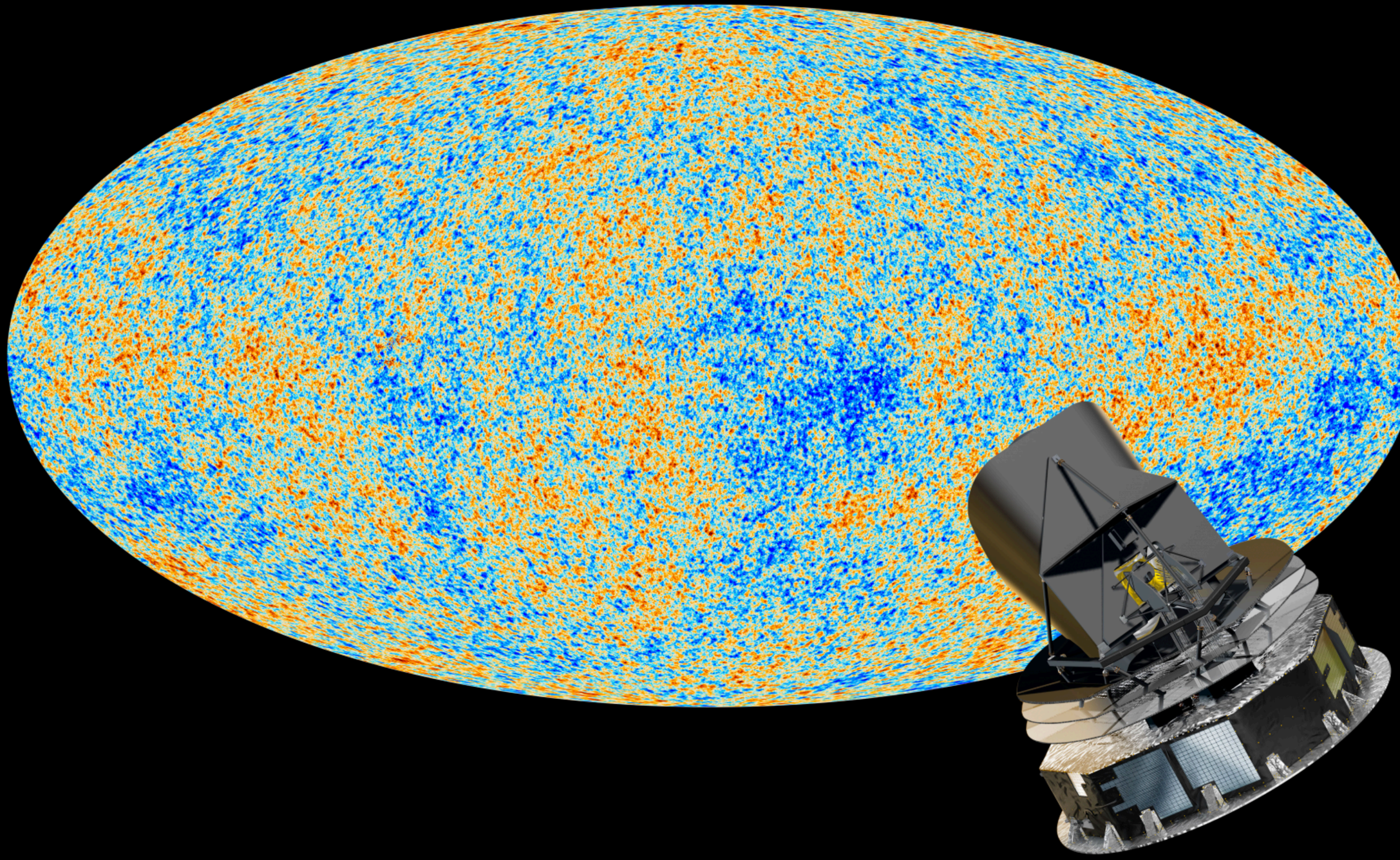
What About Radio Searches?

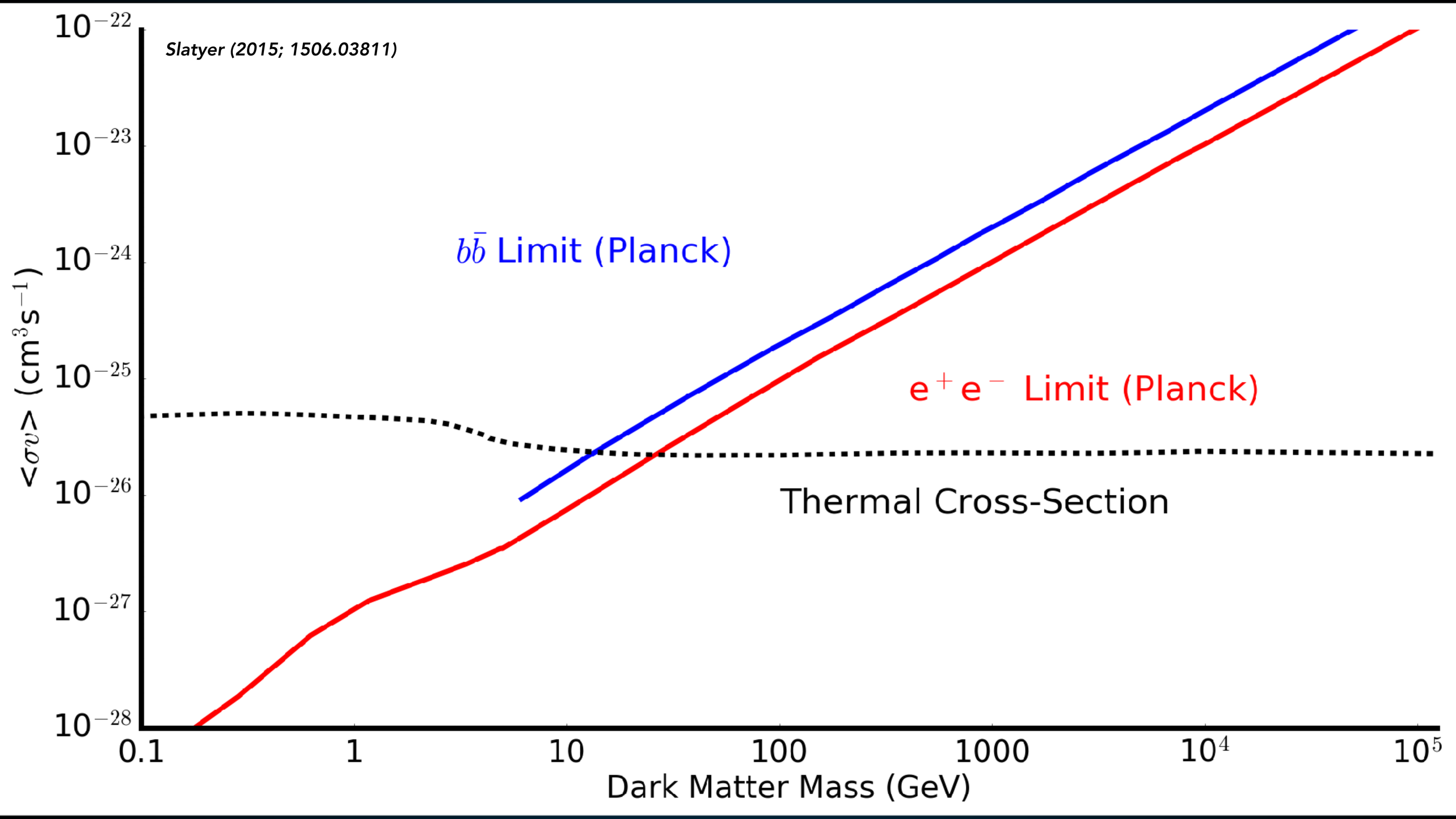


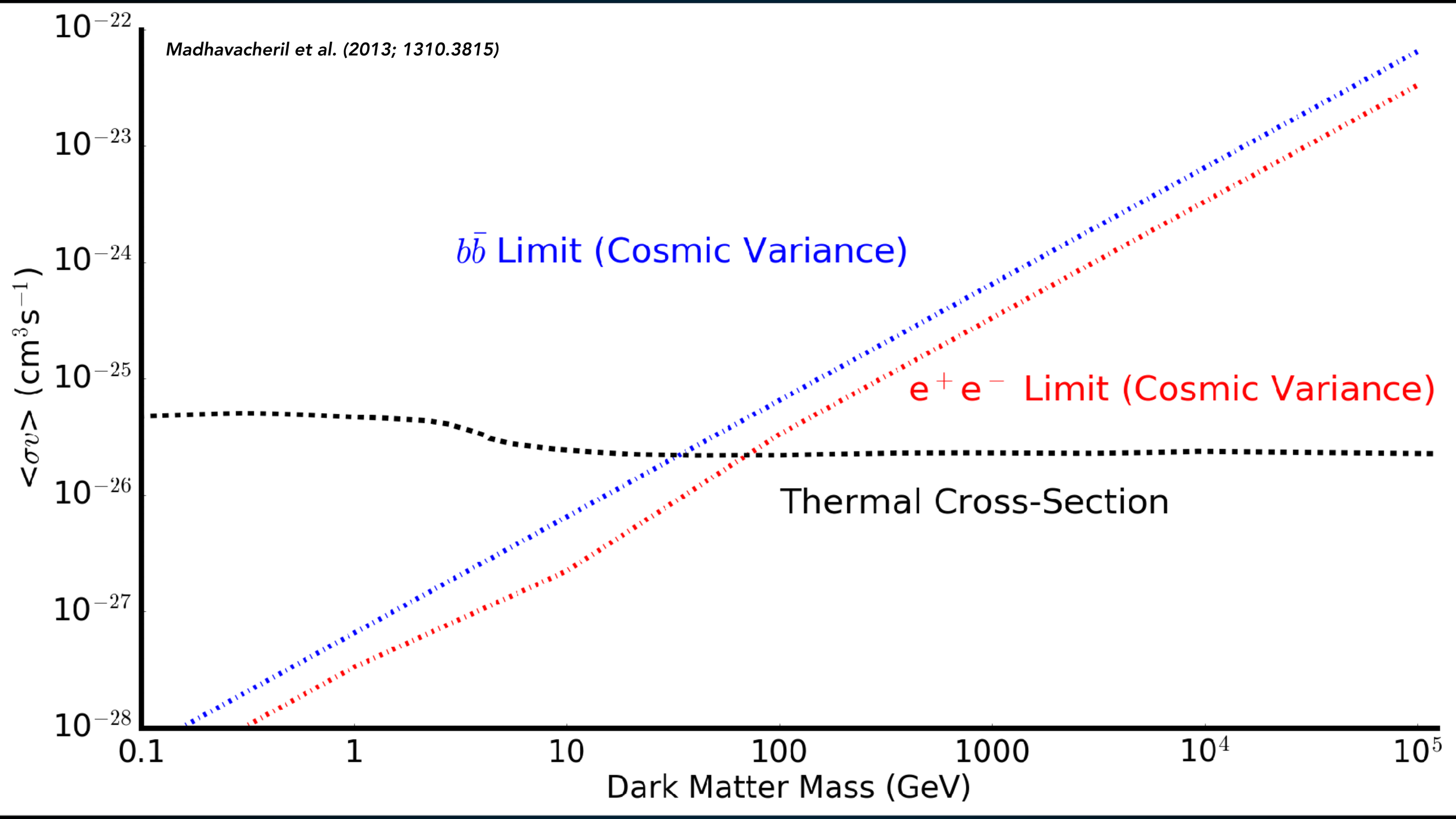

10^{-24}
10^{-25}
10^{-26}
10^{-27}
$<\sigma v>$ ($cm^3 s^{-1}$)
$b\bar{b}$ LOFAR (Coma, Low-B)
Thermal Cross-Section
$b\bar{b}$ (Planck)
$b\bar{b}$ (dSphs)
$b\bar{b}$ (AMS)
$b\bar{b}$ SKA (Coma, Default)
$b\bar{b}$ LOFAR (Coma, High-B)
Storm et al. (2016; 1607.01049)
10
100
1000
Dark Matter Mass (GeV)

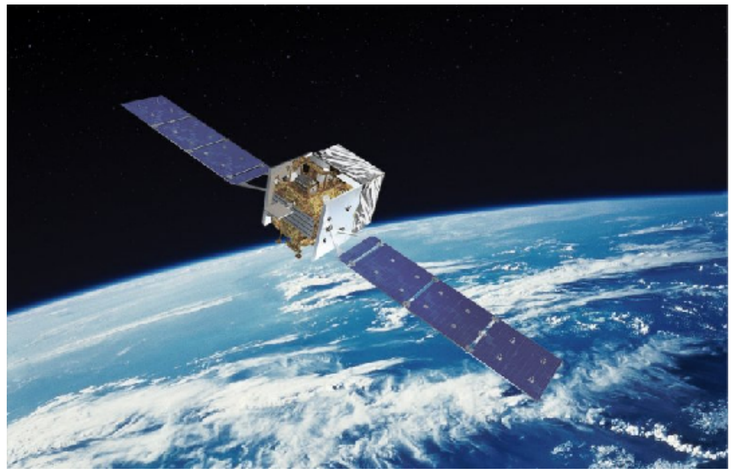

21cm!


10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
$<\sigma v>$ ($cm^3 s^{-1}$)
e^+e^- (Planck)
Thermal Cross-Section
e^+e^- (EDGES)
Liu & Slatyer (2018; 1803.09739)
0.1
1
10
100
1000
10^4
Dark Matter Mass (GeV)




Slatyer (2015; 1506.03811)
$b\bar{b}$ Limit (Planck)
e^+e^- Limit (Planck)
Thermal Cross-Section
$<\sigma v>$ (cm^3s^{-1})
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
0.1
1
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)


Madhavacheril et al. (2013; 1310.3815)
$b\bar{b}$ Limit (Cosmic Variance)
e^+e^- Limit (Cosmic Variance)
Thermal Cross-Section
$<\sigma v>$ (cm^3s^{-1})
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
0.1
1
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)



Thermal Cross-Section

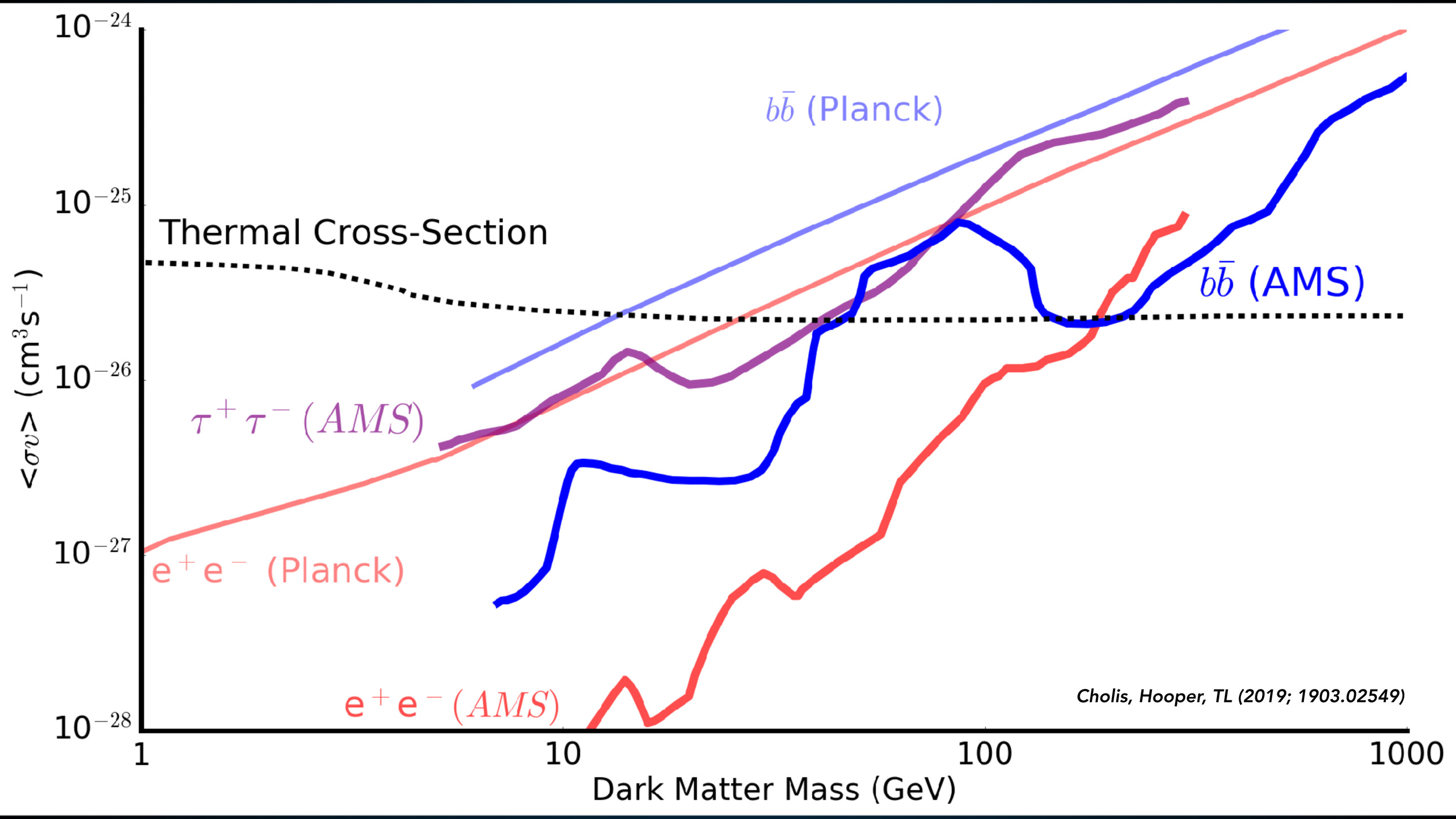
1 Observed Photon Within 10° of Galactic Center

10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}

$<\sigma v>$ ($cm^3 s^{-1}$)

10
100
1000
10^4
10^5

Dark Matter Mass (GeV)


10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ ($cm^3 s^{-1}$)
Thermal Cross-Section
$b\bar{b}$ (Planck)
$b\bar{b}$ (AMS)
$\tau^+\tau^-$ (AMS)
e^+e^- (Planck)
e^+e^- (AMS)
1
10
100
1000
Dark Matter Mass (GeV)
Cholis, Hooper, TL (2019; 1903.02549)

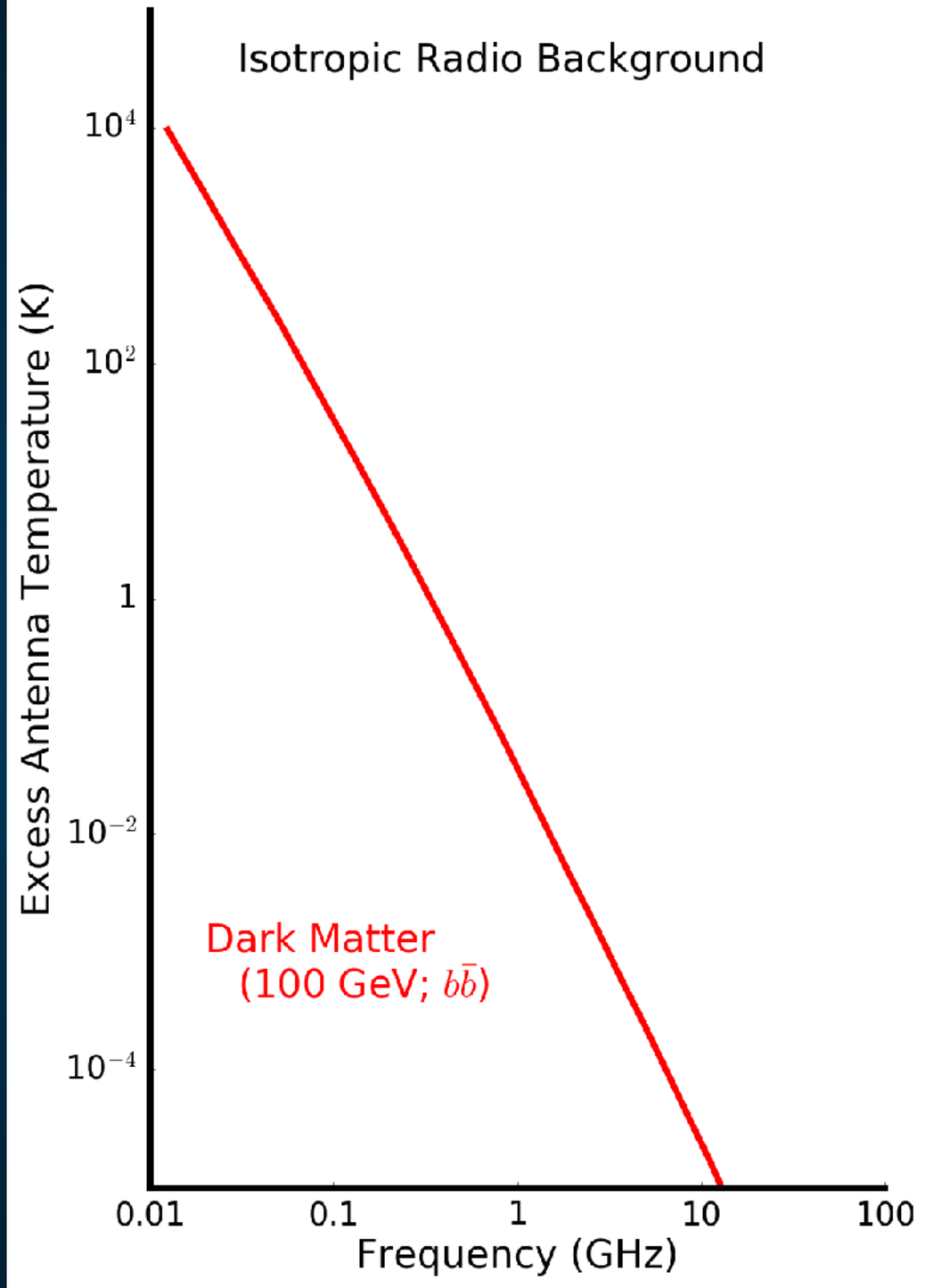
Thermal WIMPs and the Story of Tantalus

Extragalactic Dark Matter Density

Thermal Cross-Section (Early Universe)

e+e- Energy Fraction in Dark Matter Annihilation

Intergalactic Magnetic Fields



Thermal WIMPs and the Story of Tantalus

Extragalactic Dark Matter Density

Thermal Cross-Section (Early Universe)

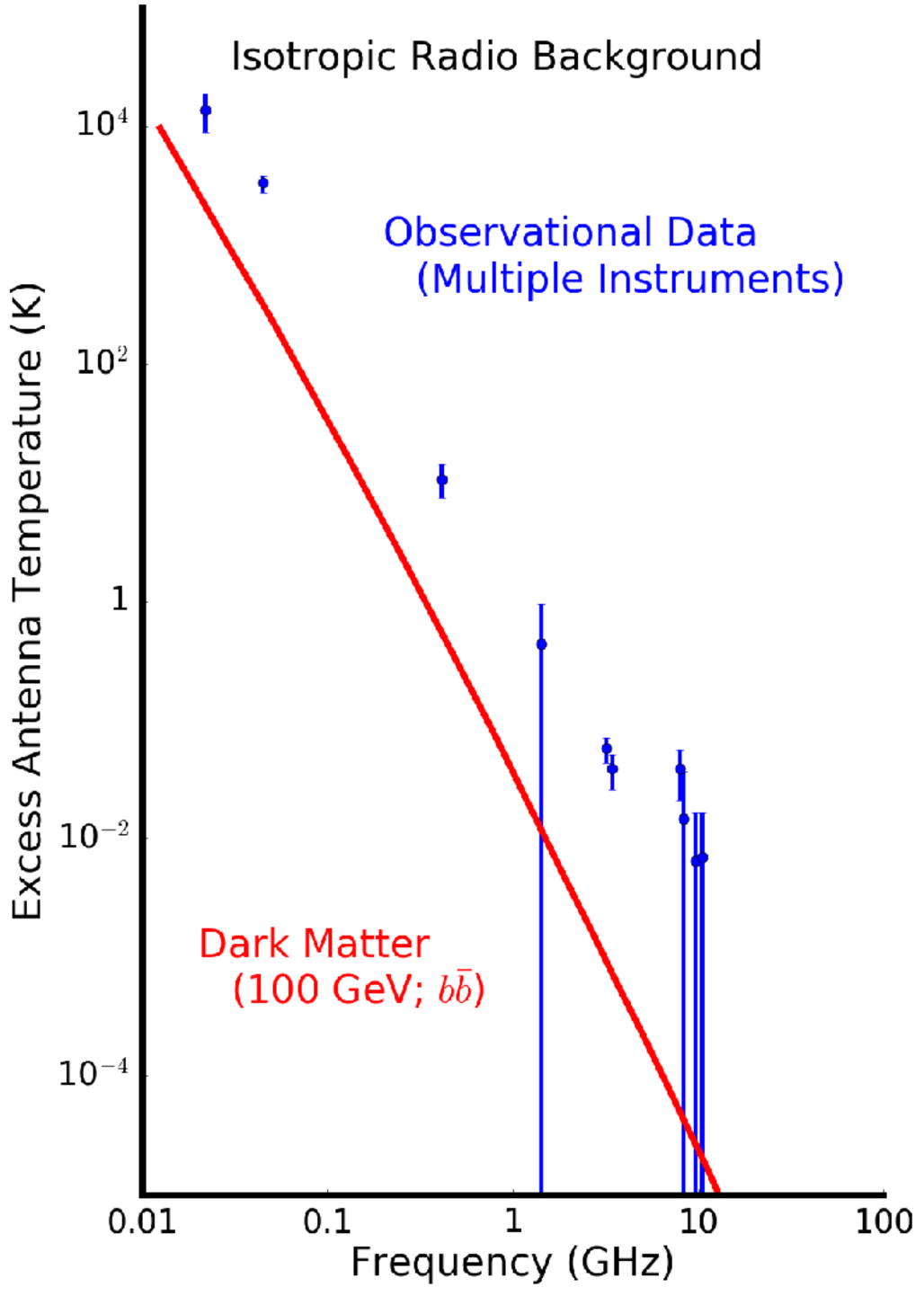
e+e- Energy Fraction in Dark Matter Annihilation

Intergalactic Magnetic Fields

Radio Luminosity in Starbursts and AGN

e+e- Reacceleration in Cluster Mergers

Redshift Dependence of Signal vs. CMB





Galactic Center Excess

