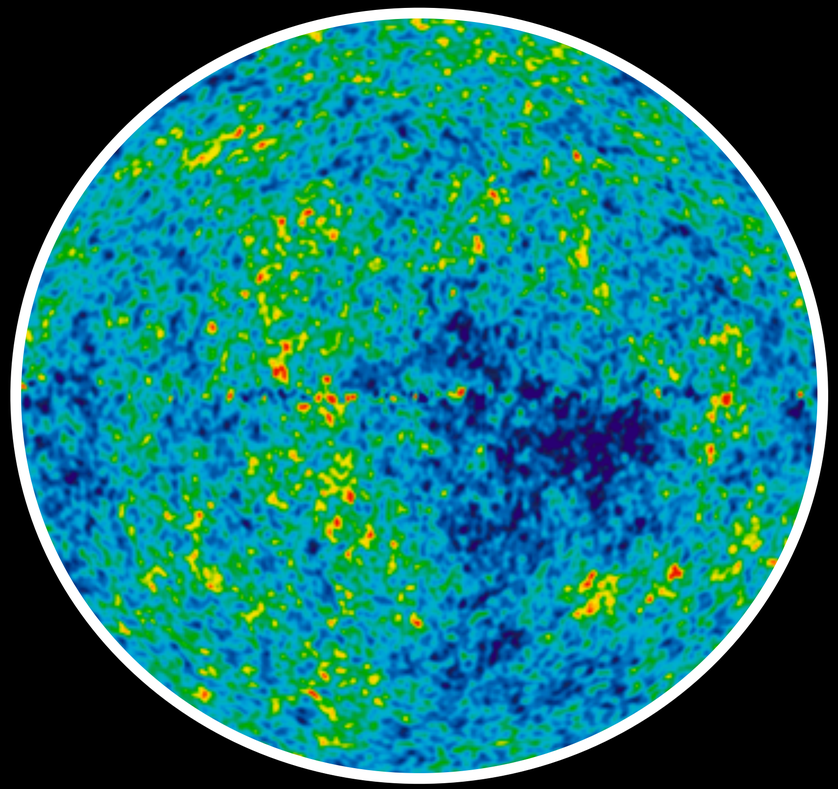
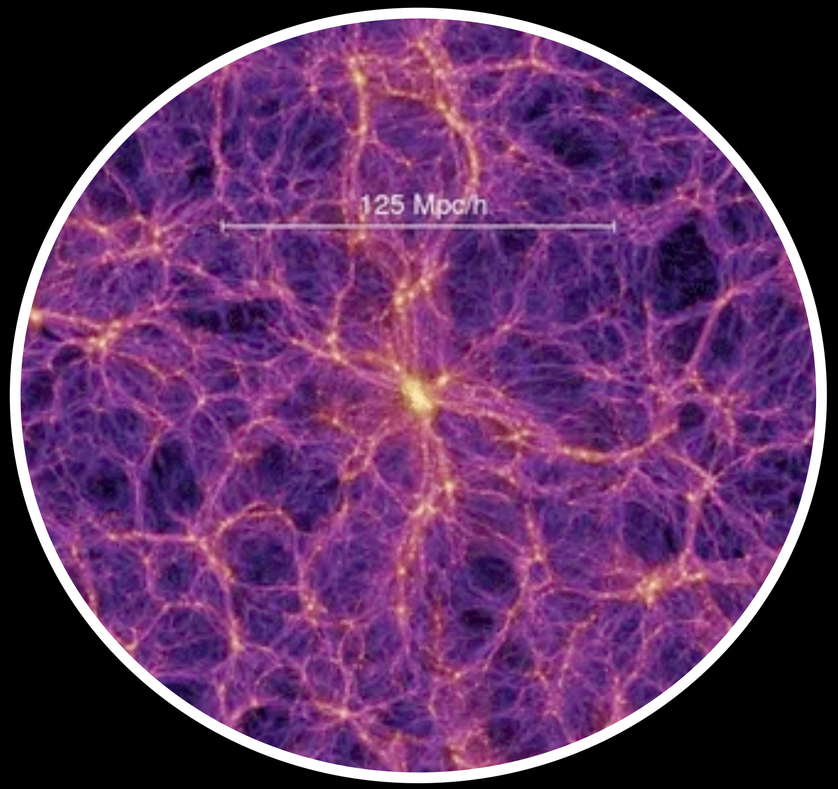
Tim Linden

Thermal WIMP Dark Matter on the Brink

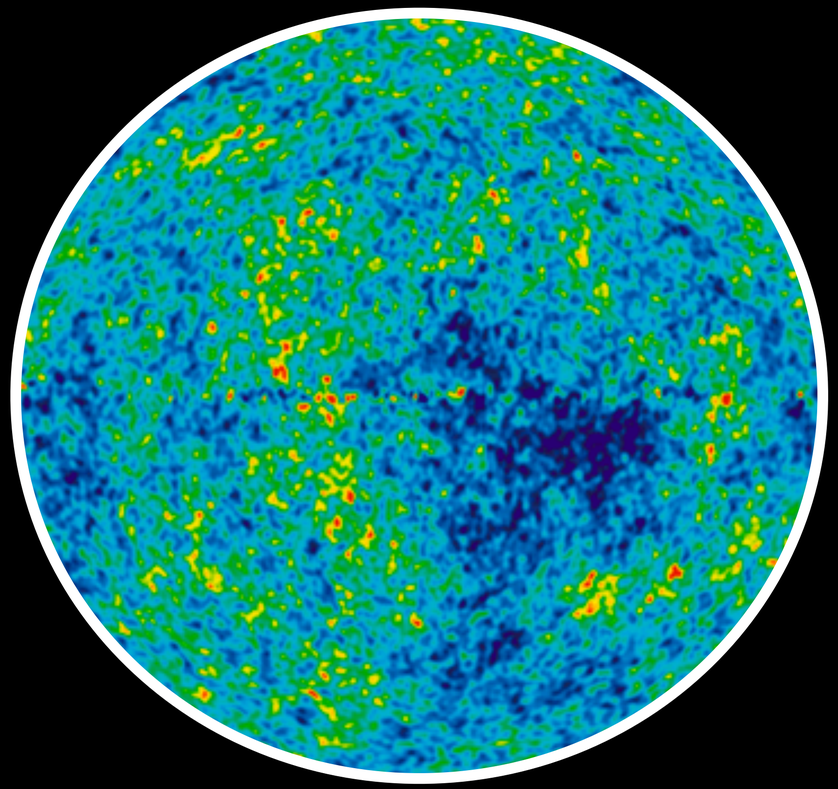
Stockholms universitet

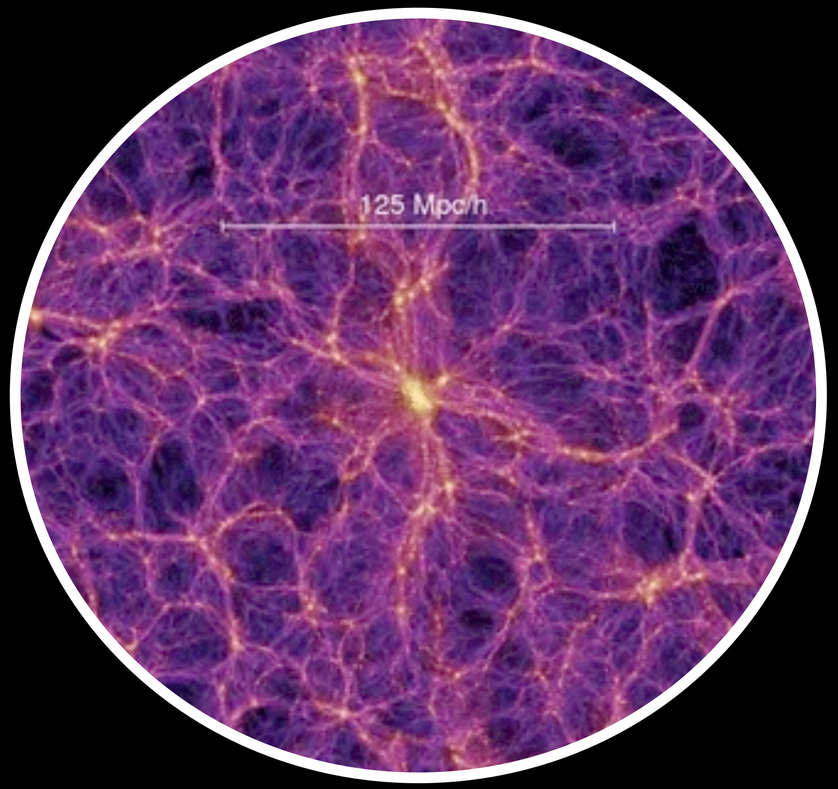
The Present





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

$M_{DM} > M_{UFD}$

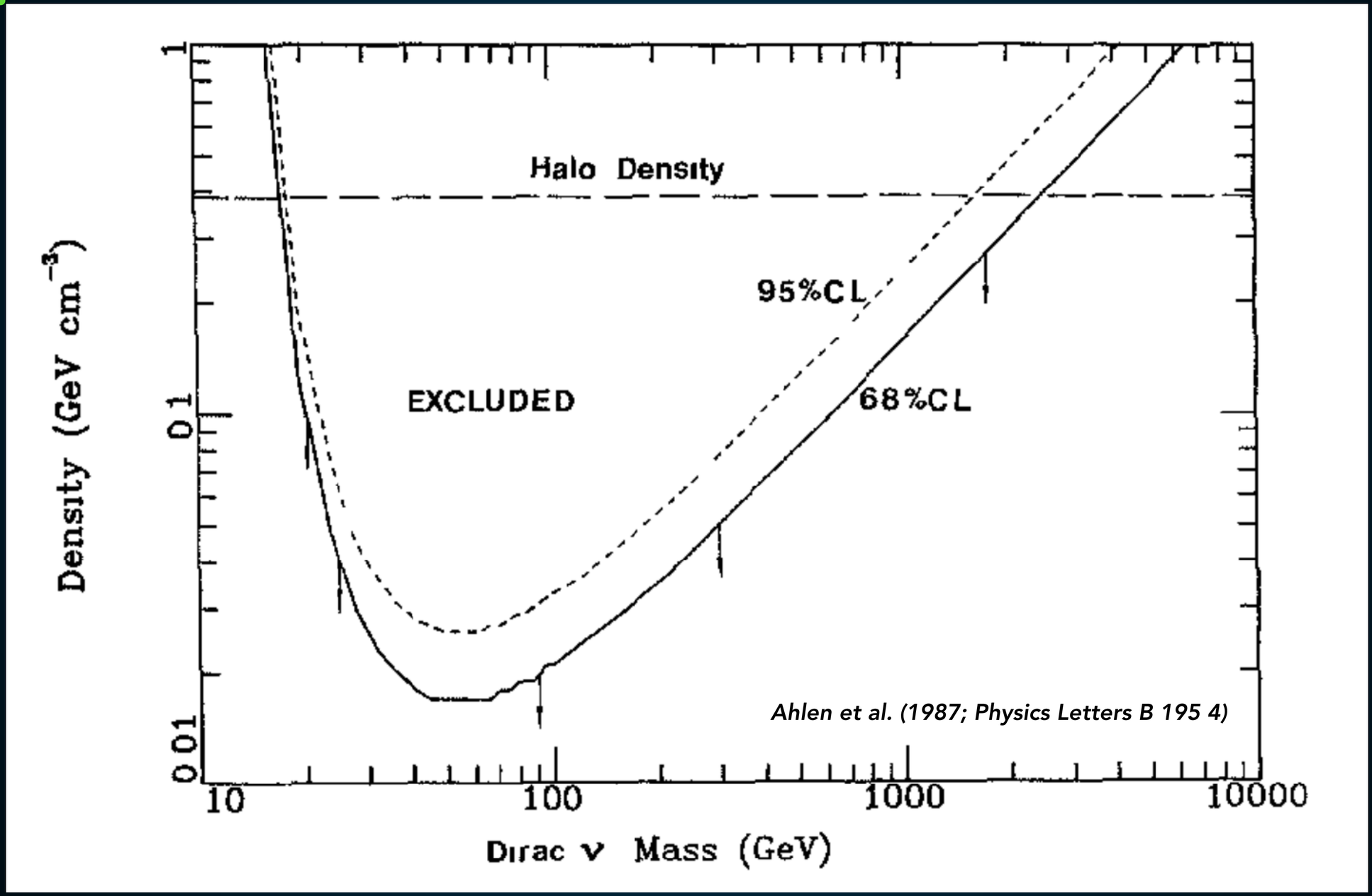
Tim Linden

Thermal WIMP Dark Matter on the Brink

Stockholms universitet

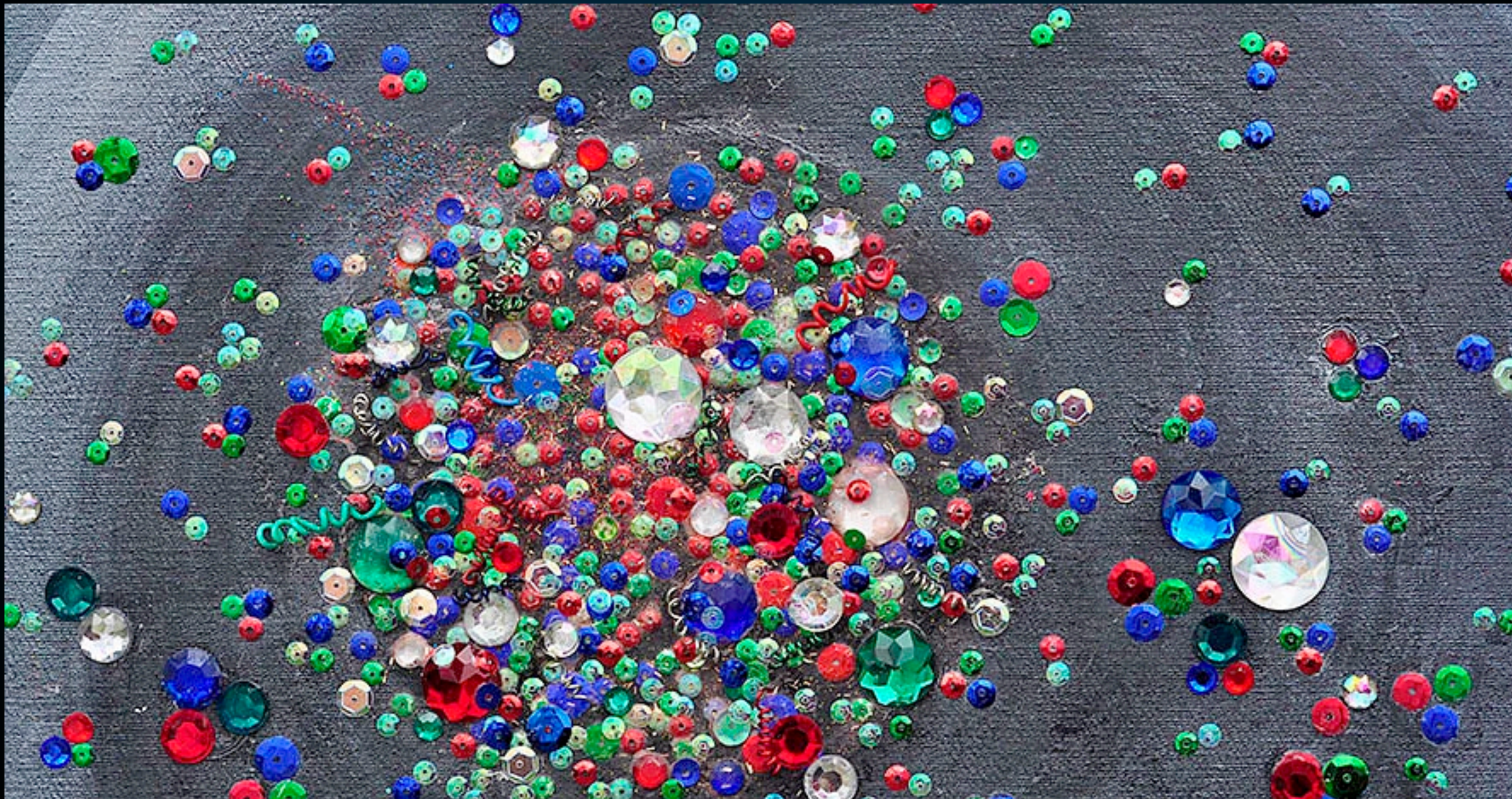
Can We Eliminate Classes of Dark Matter Models?

Yes!

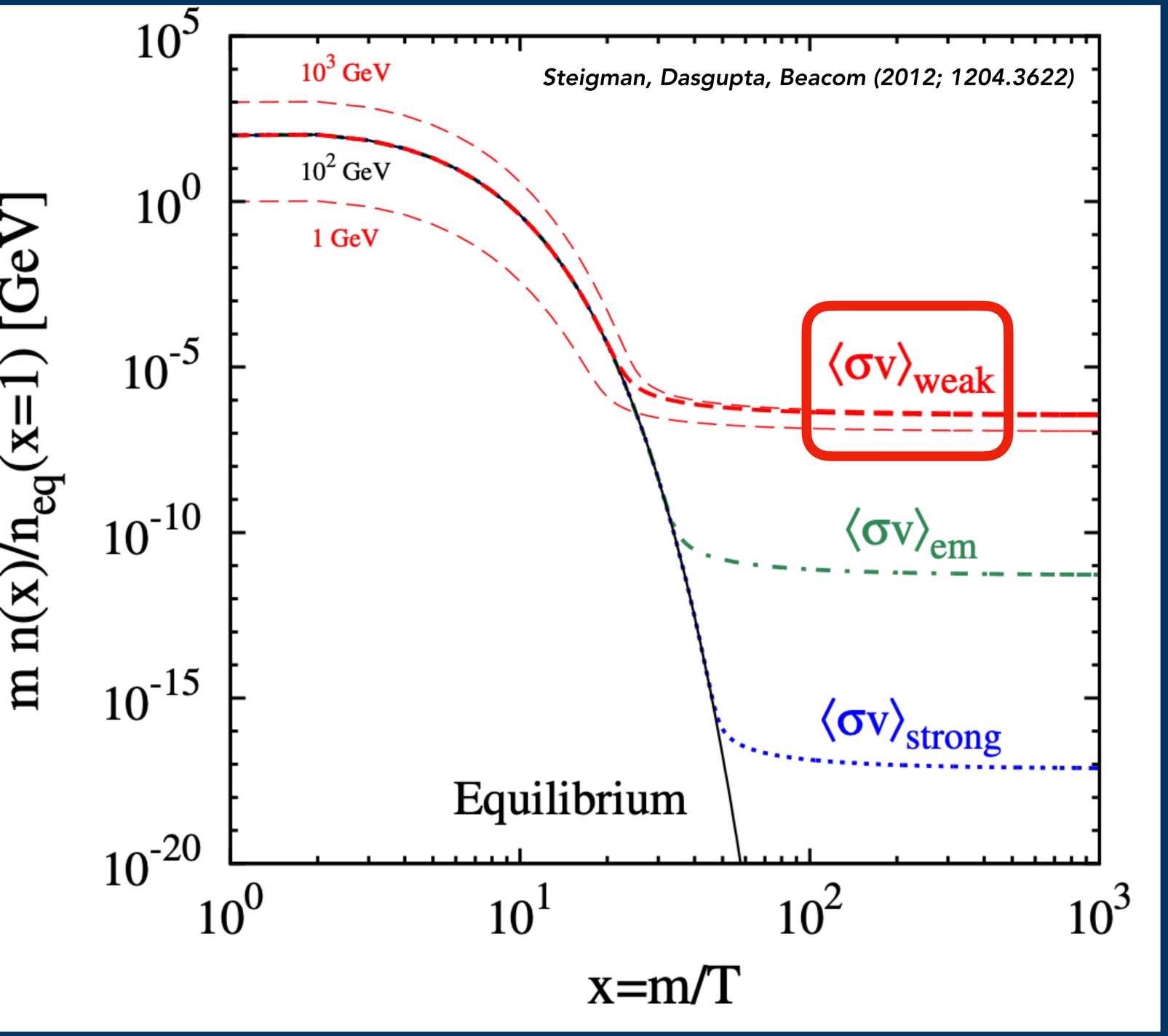


Thermal Dark Matter

artist: Sarah Szabo



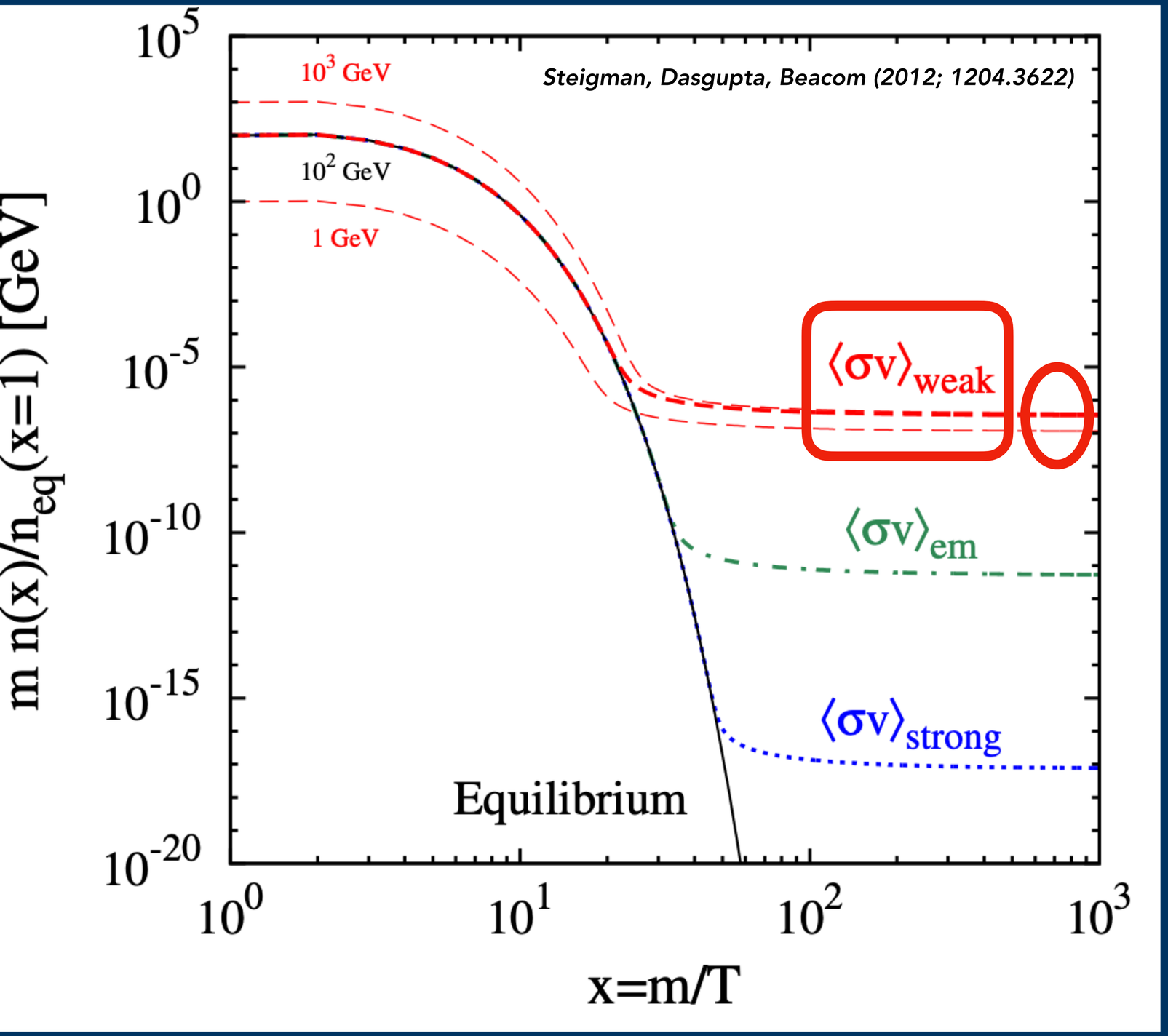
Thermal Dark Matter Density



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

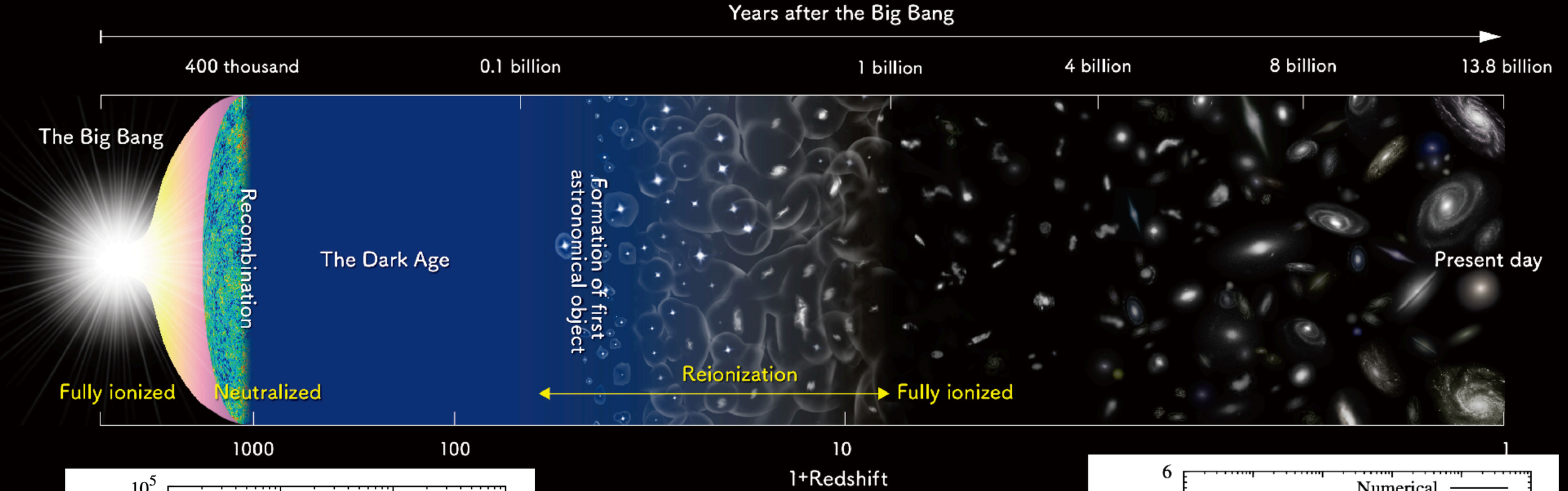
Present density inversely proportional to the strength of the interaction.

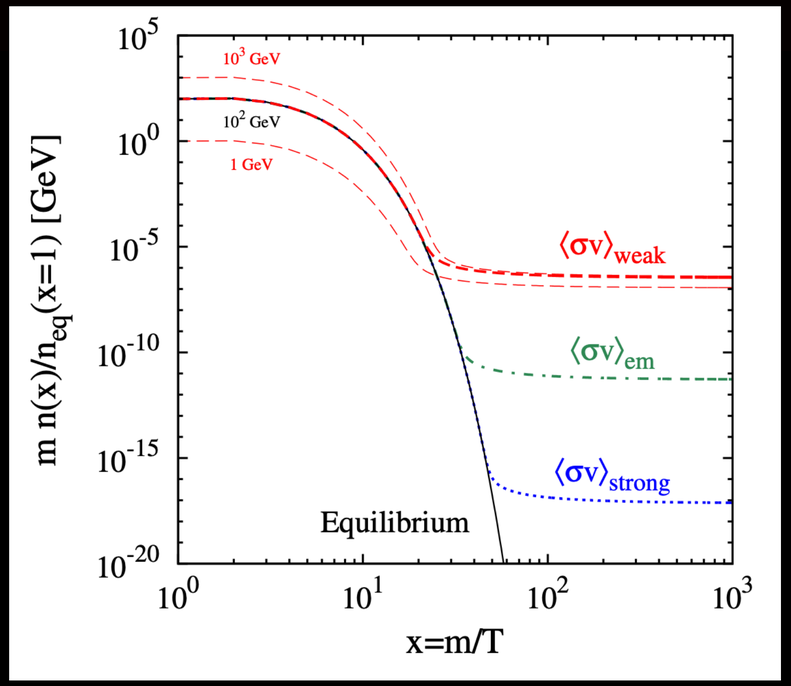
Almost independent of particle mass.

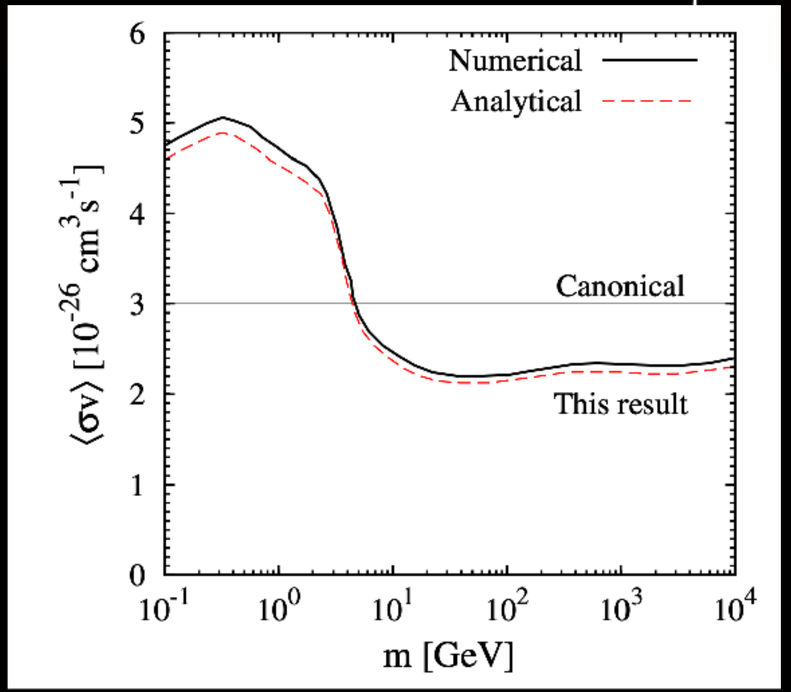
Weak-Interaction Produces the right density!

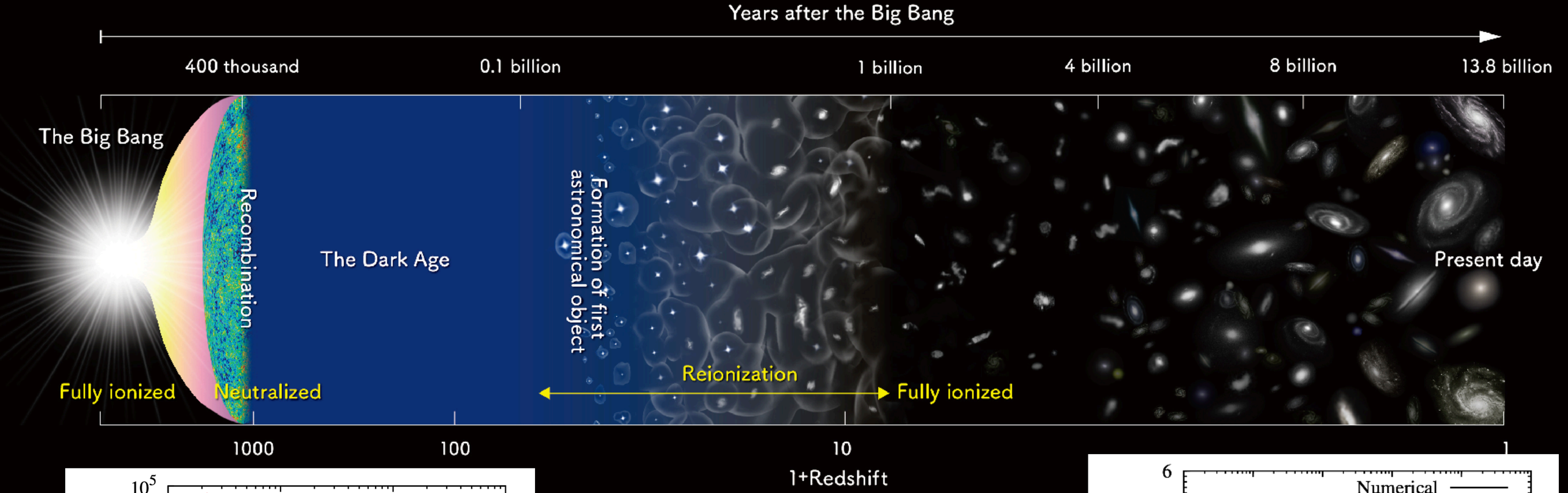
10 MeV - 100 TeV !

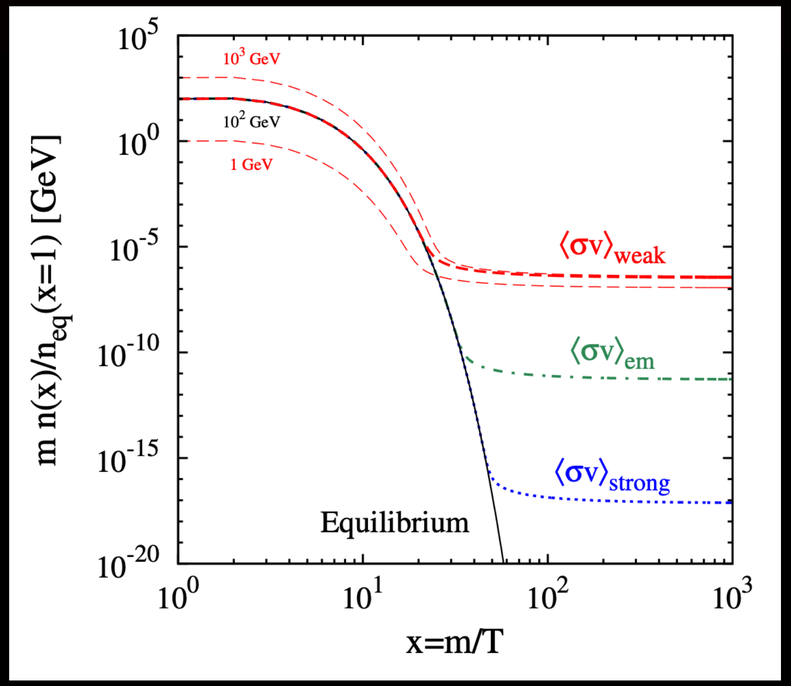
Lee, Weinberg (1977; PRL 39 4)
Ho, Scherrer (2012; 1208.4347)


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

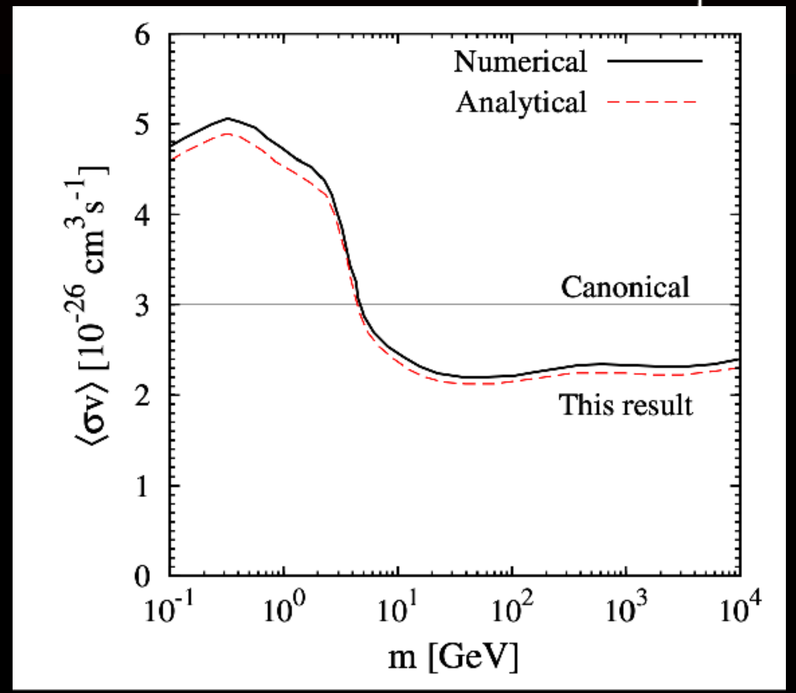

Numerical
Analytical
Canonical
This result
$\langle\sigma v\rangle$ [10^{-26} cm^3 s^{-1}]
0
1
2
3
4
5
6
10^{-1}
10^0
10^1
10^2
10^3
10^4
m [GeV]

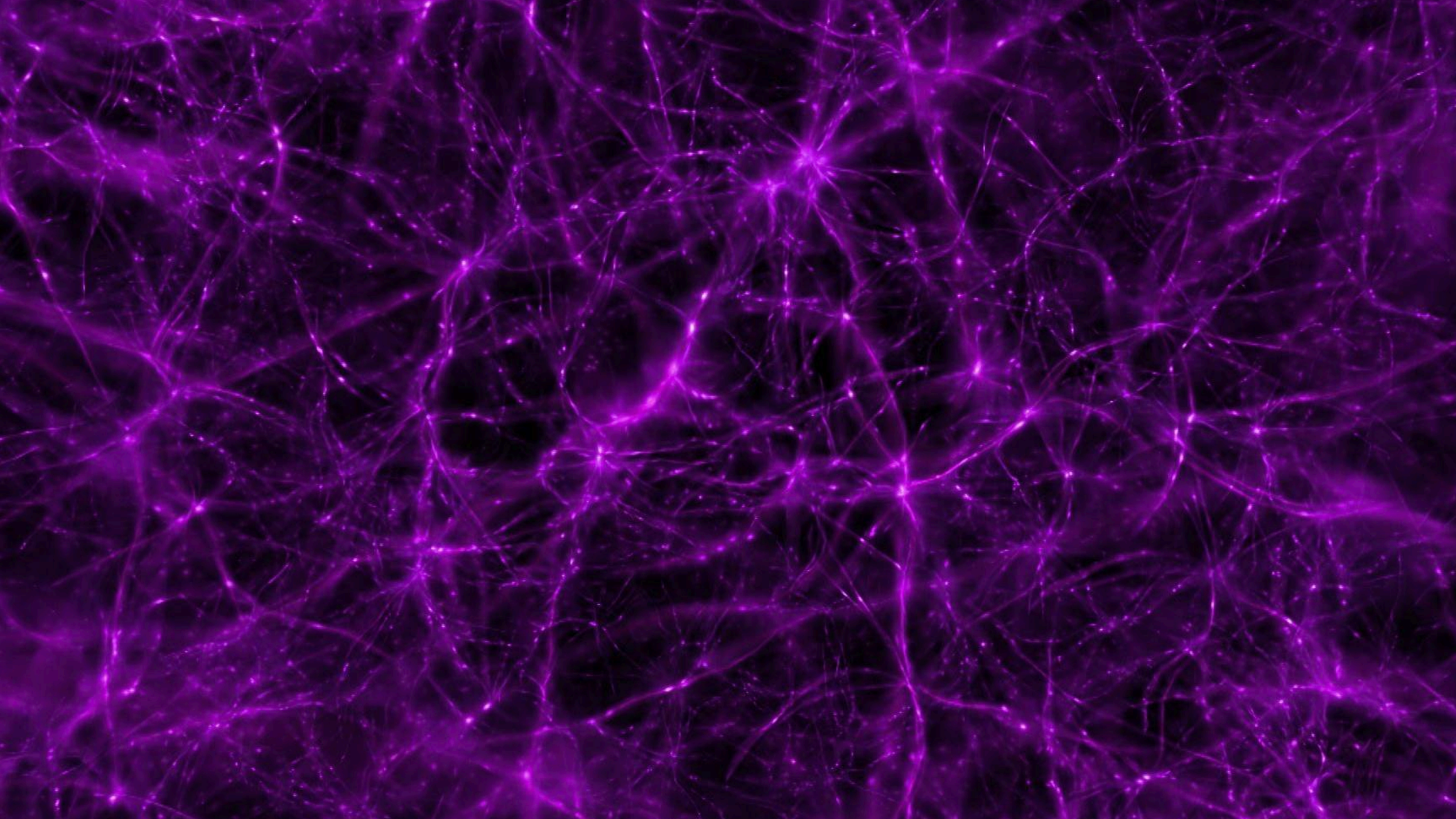


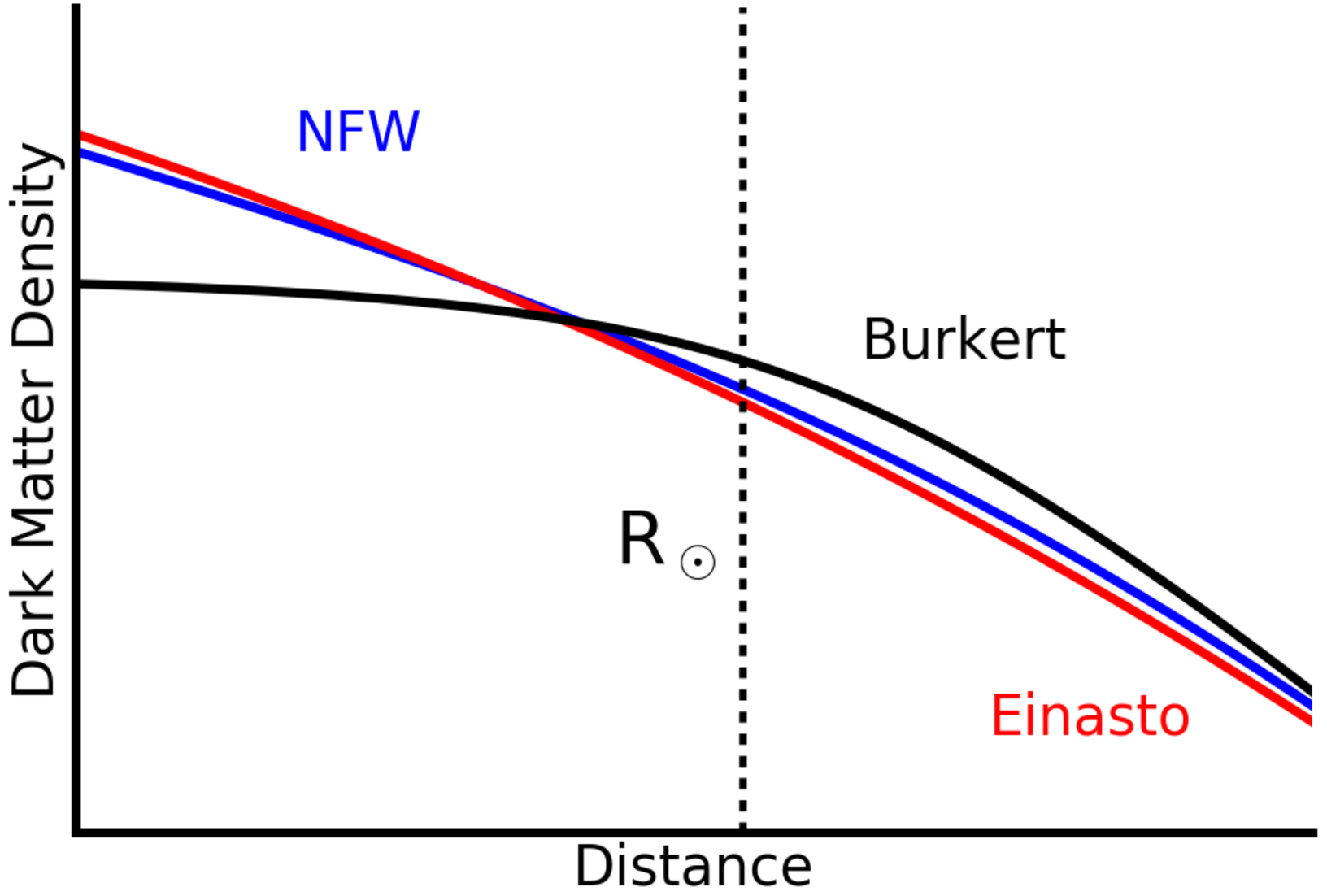


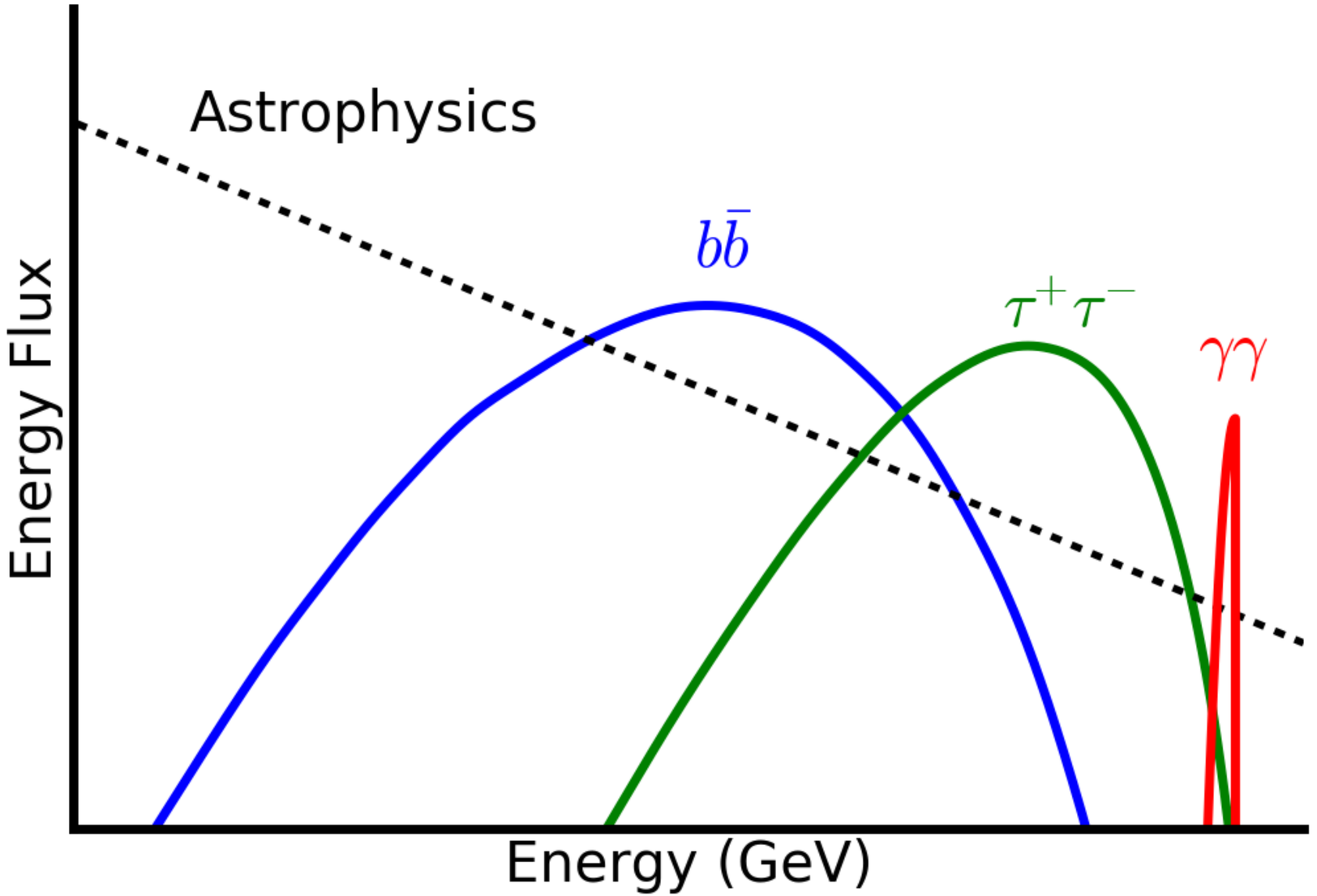
Philosophy:

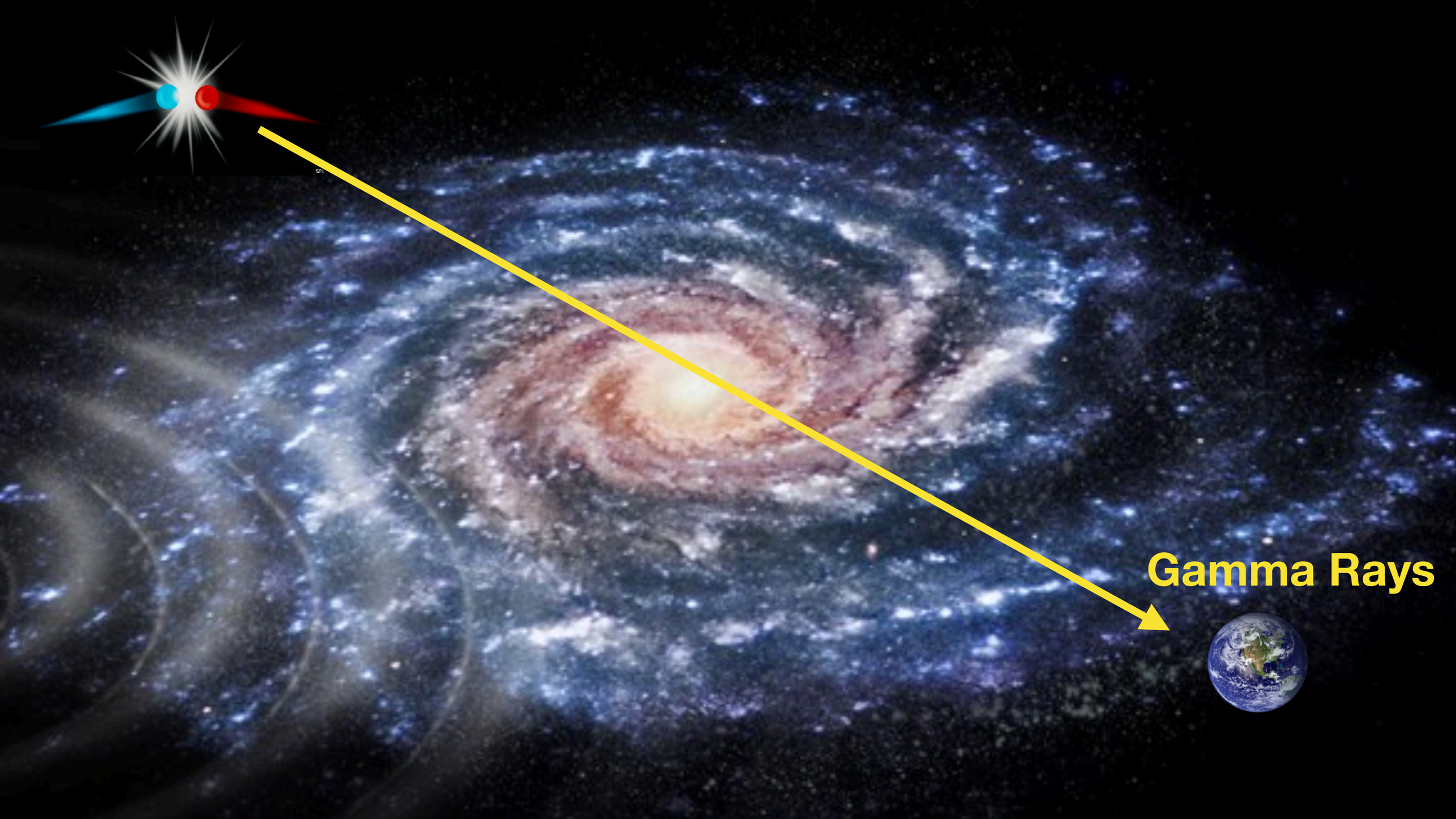
Constrain the simplest model first



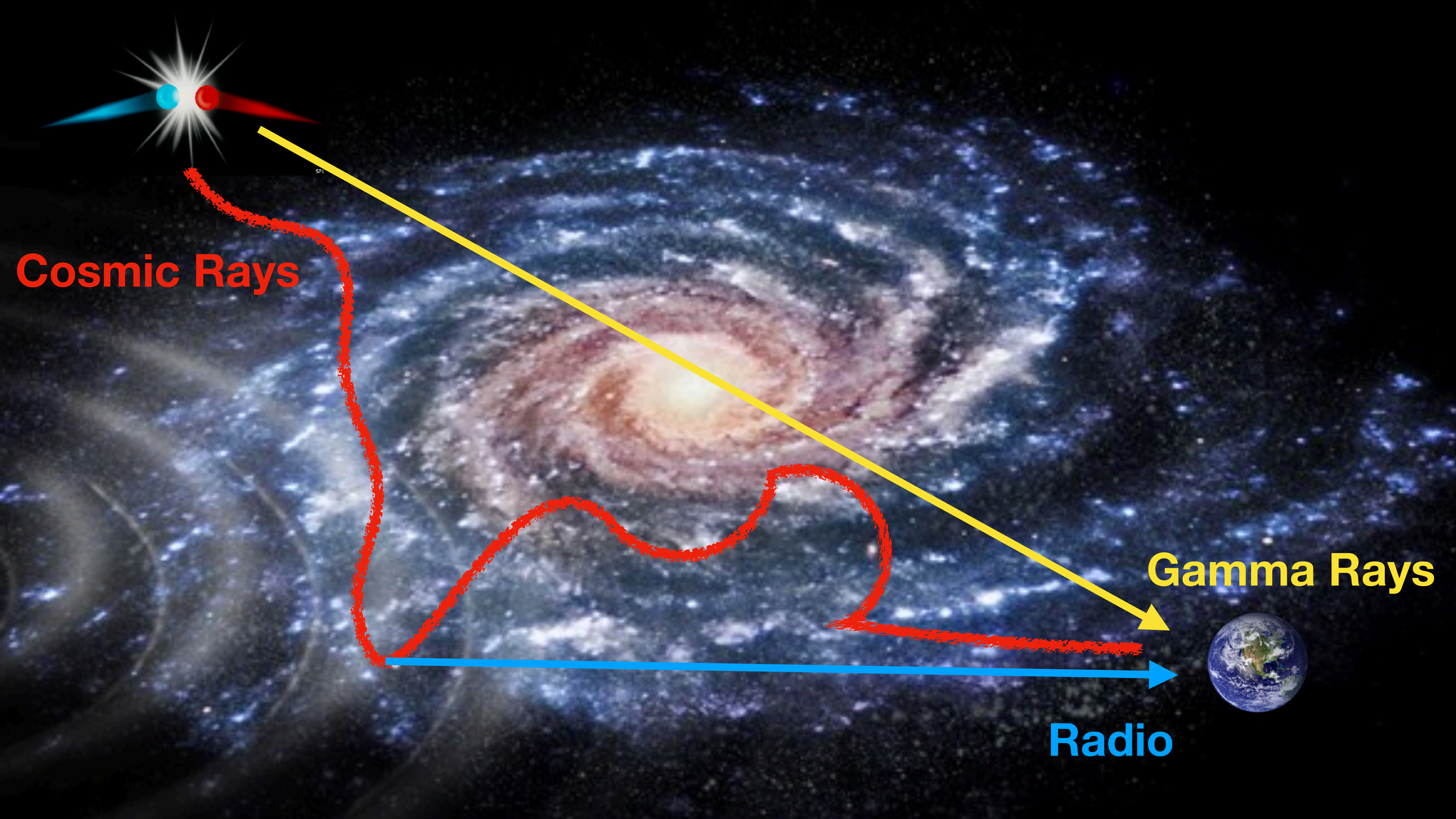



NFW
Burkert
Einasto
R⊙
Dark Matter Density
Distance


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


Gamma Rays

Cosmic Rays
Gamma Rays


Cosmic Rays
Gamma Rays
Radio

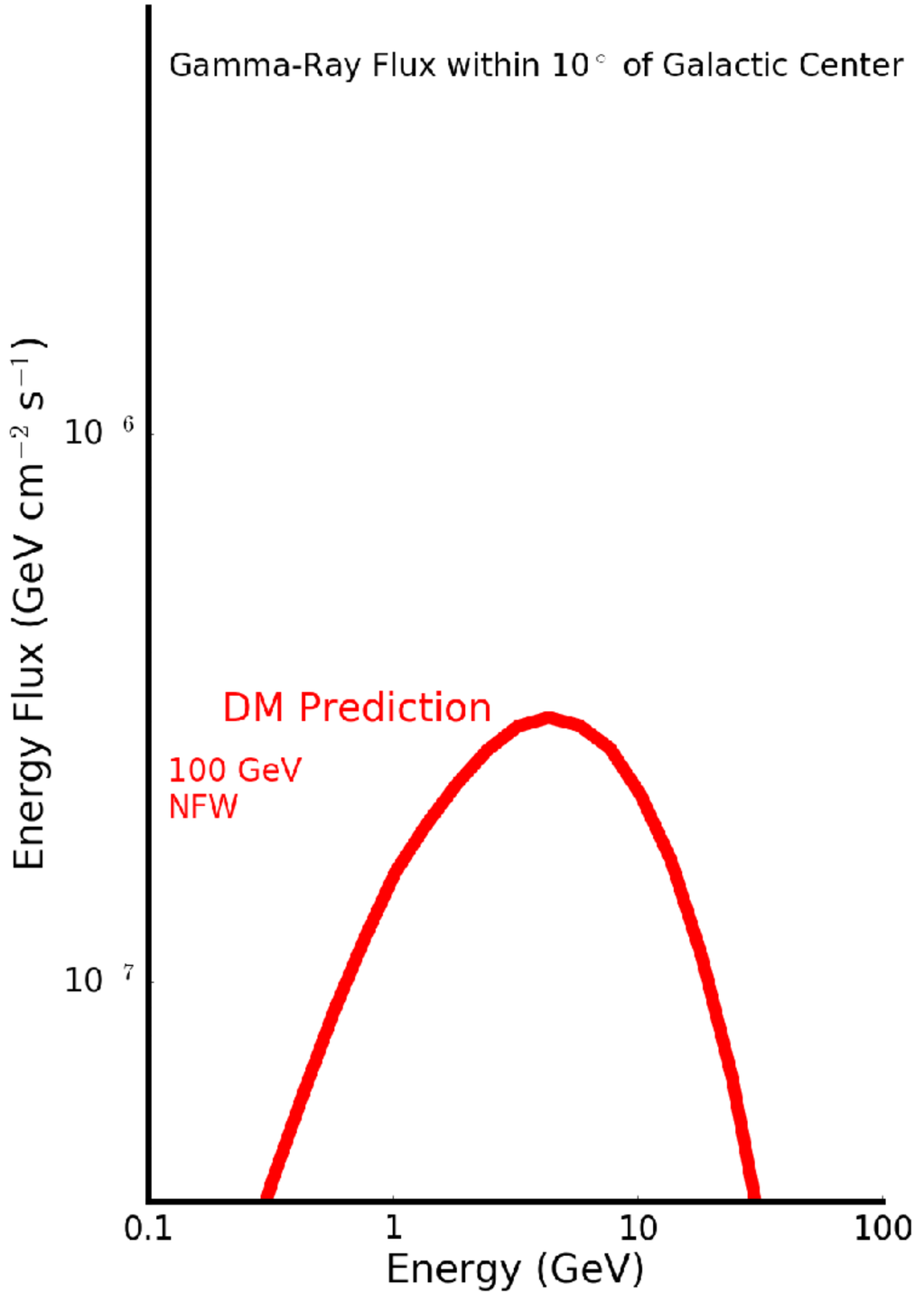
Thermal WIMPs and the Story of Tantalus

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)

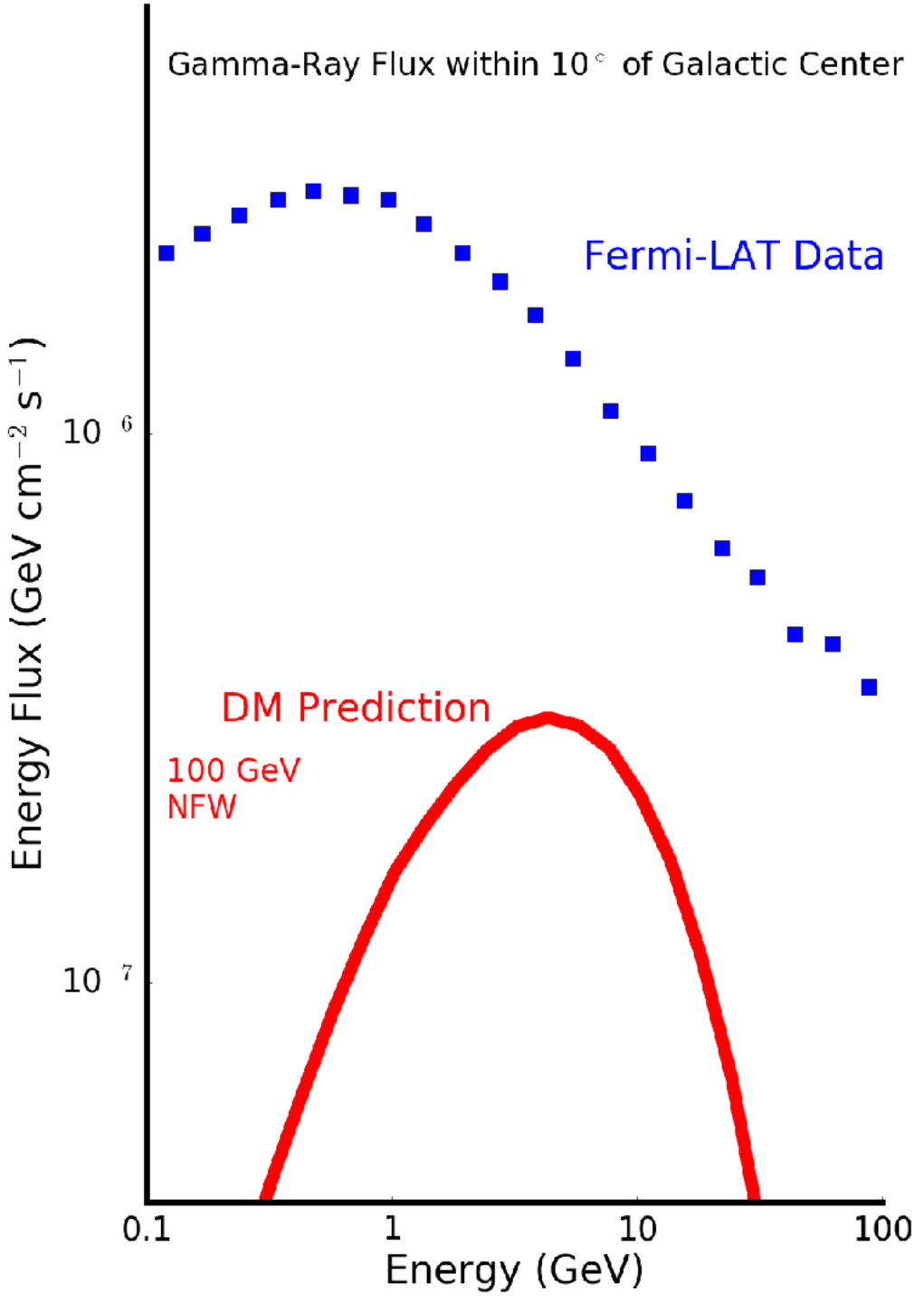
Dark Matter Mass (?)

Annihilation Final State (?)

Milky Way Star-Formation Rate (Galactic Dynamics)

Diffusion Constant in Galactic Center (Hydrodyanmics)

Activity of Supermassive Blackhole (?)



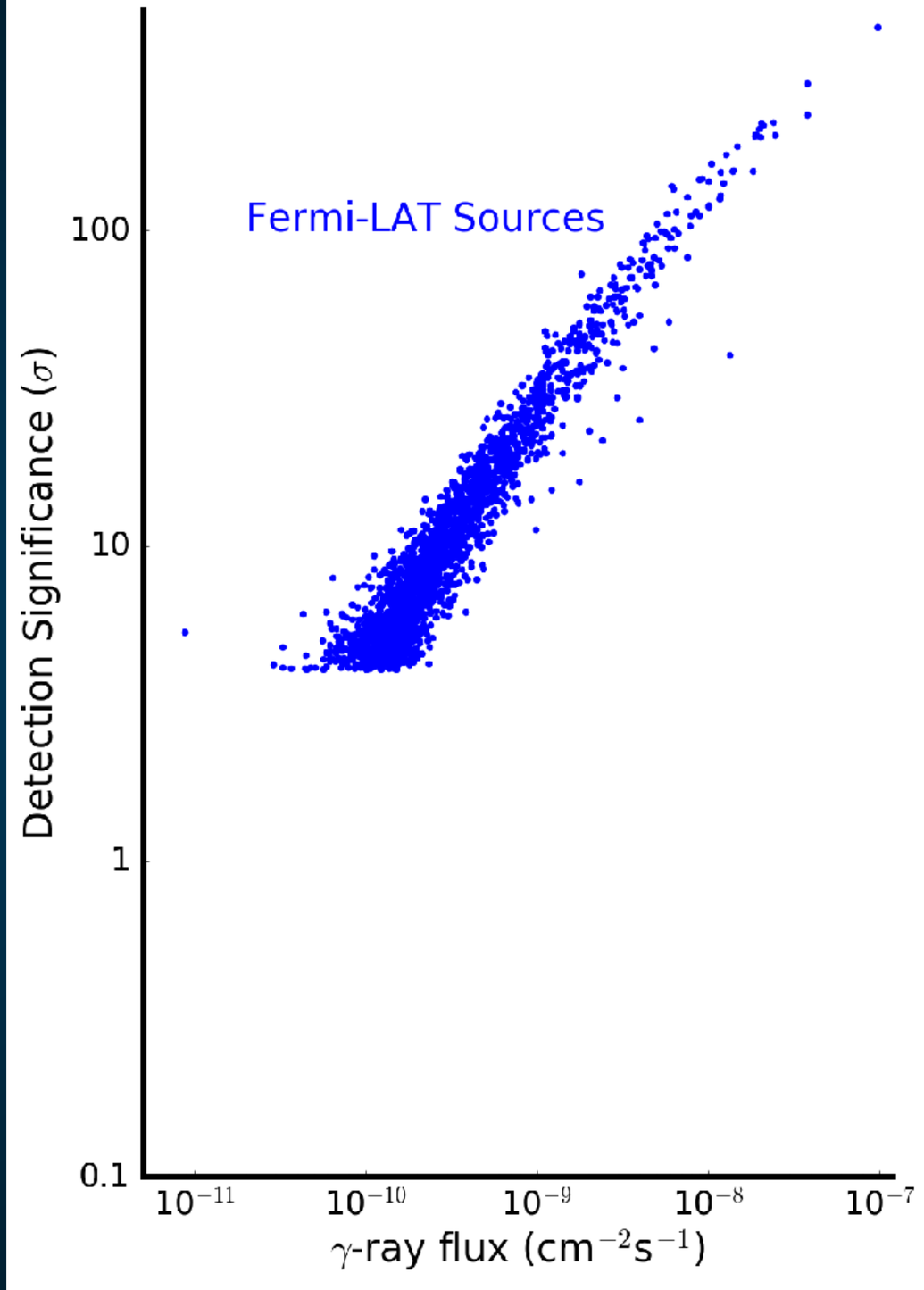
Thermal WIMPs and the Story of Tantalus

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?)

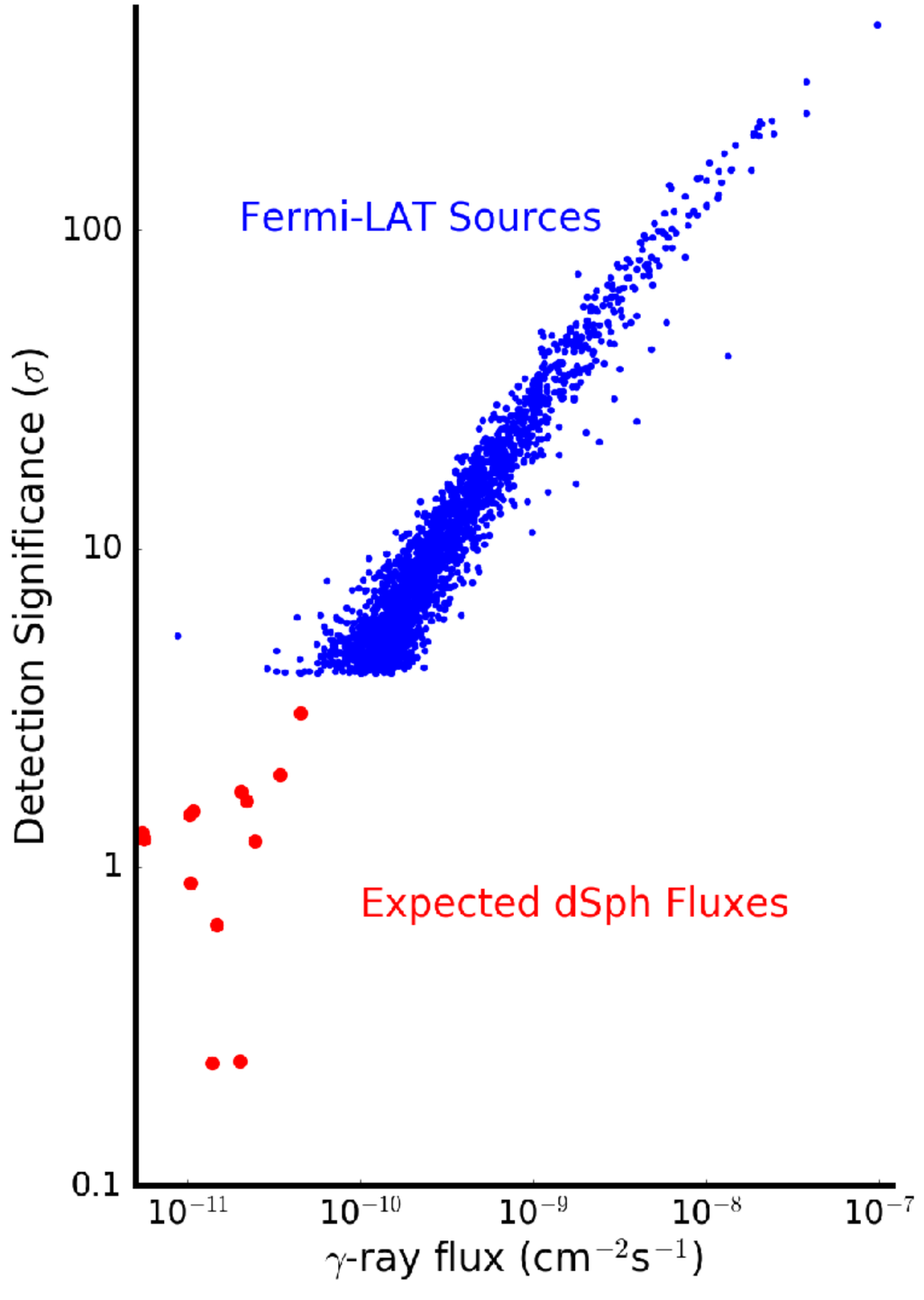
Radio Galaxy Emission Models

Star-Formation Rates in Starburst Galaxies

dSph Proximity

Substructure Models

Milky Way Merger History



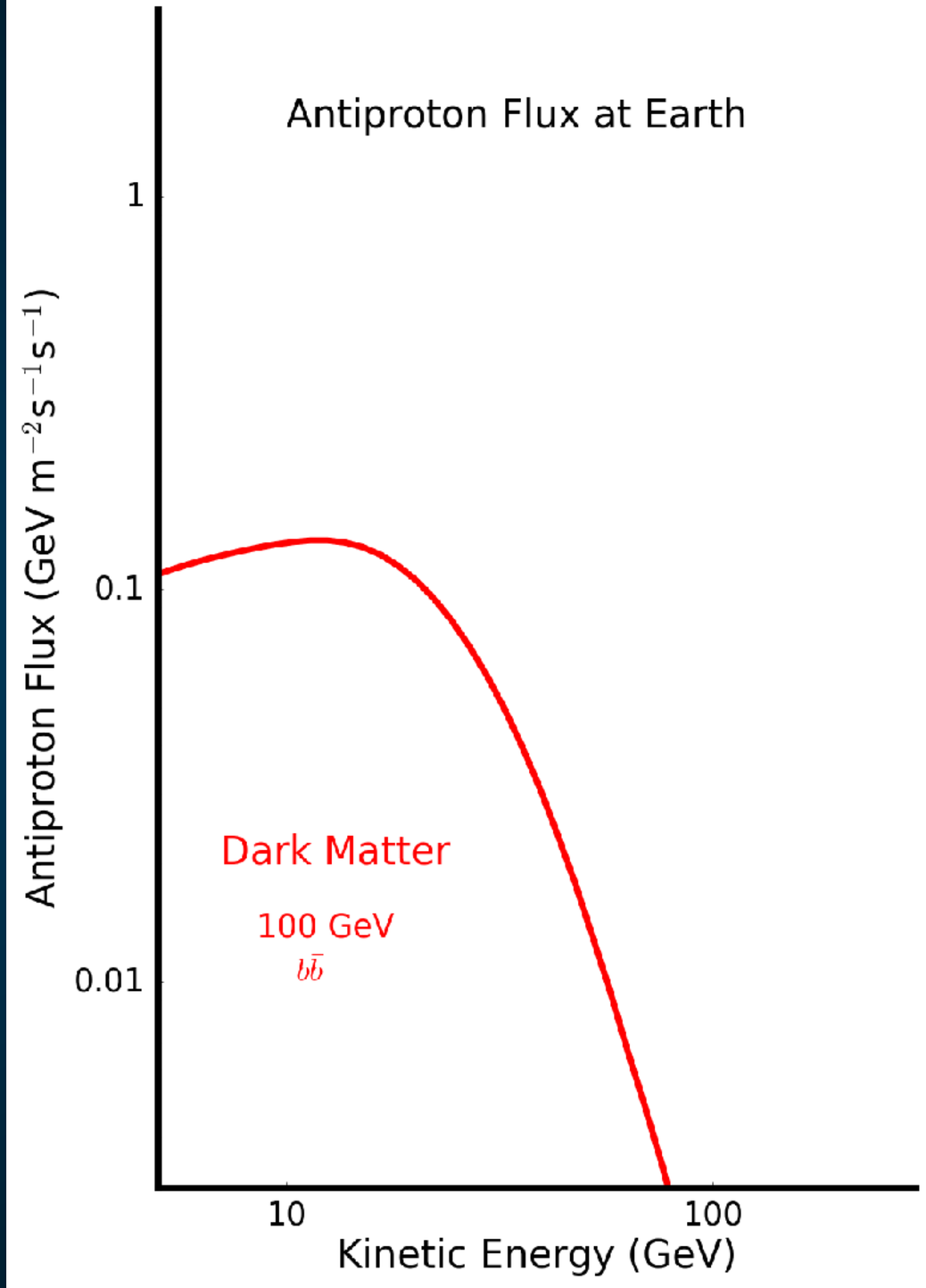
Thermal WIMPs and the Story of Tantalus

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

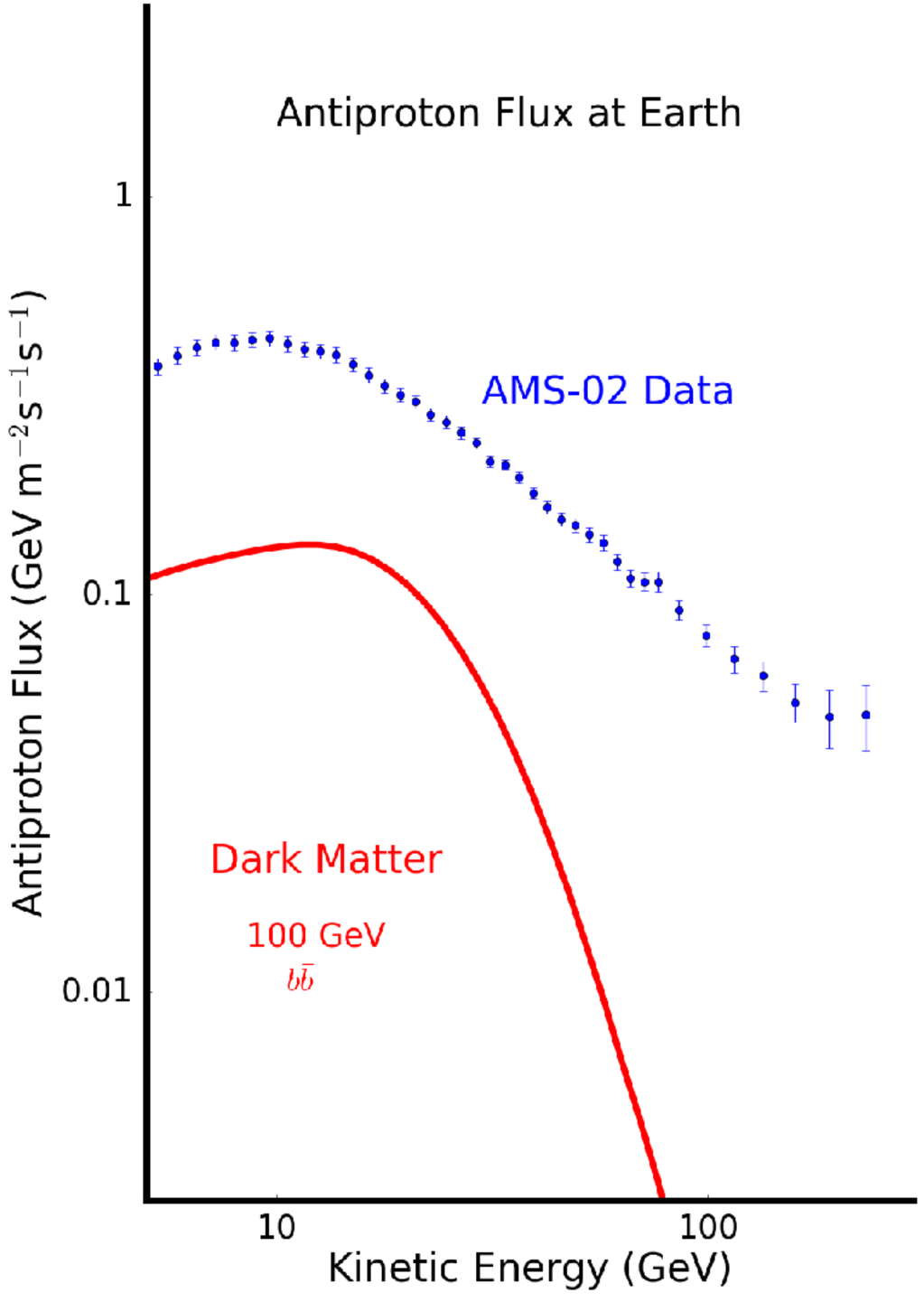
Thermal Cross-Section (Early Universe)

Hadronic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Local Gas Density

Local Supernova Rate



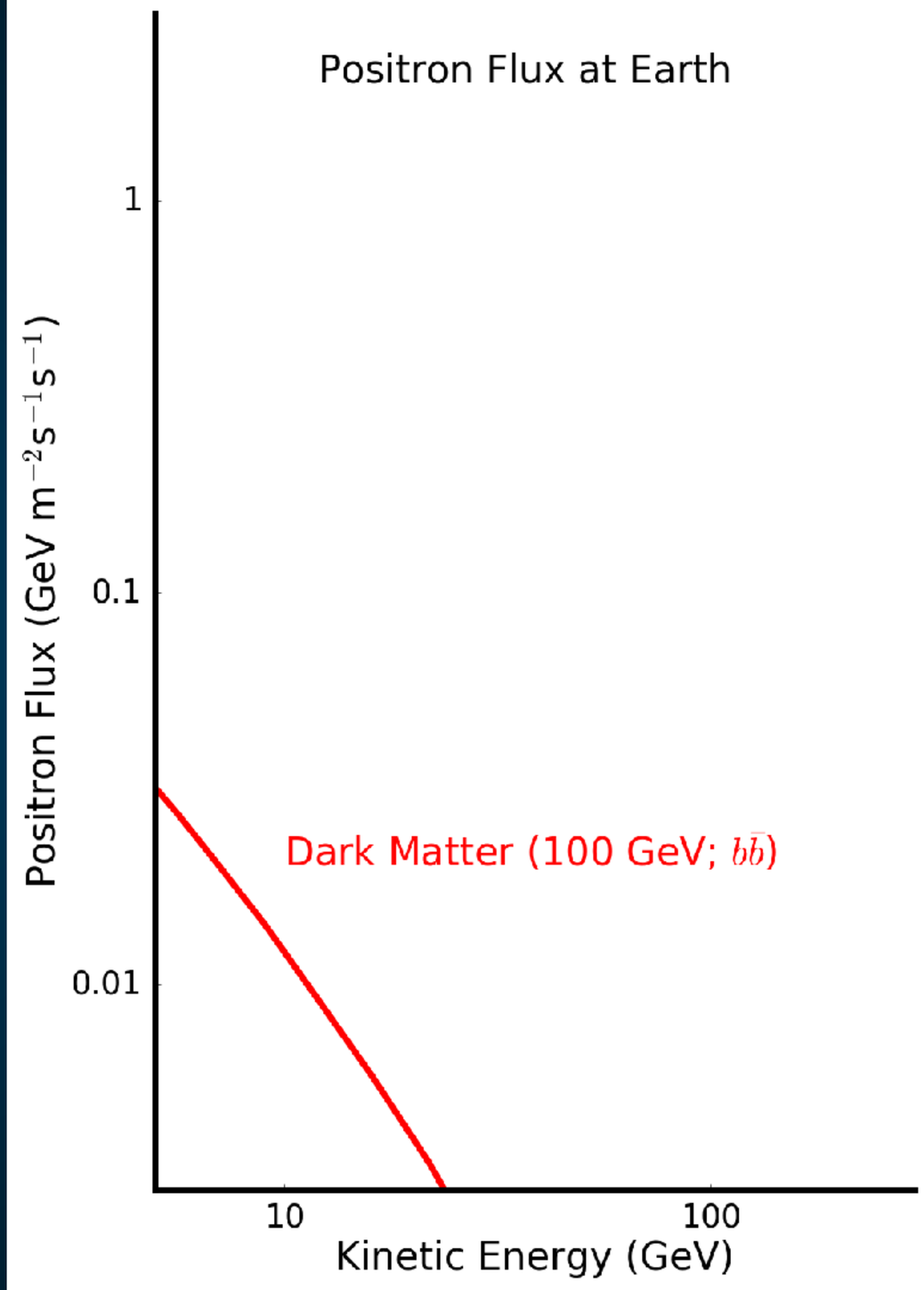
Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

Thermal Cross-Section (Early Universe)

Leptonic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)



Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

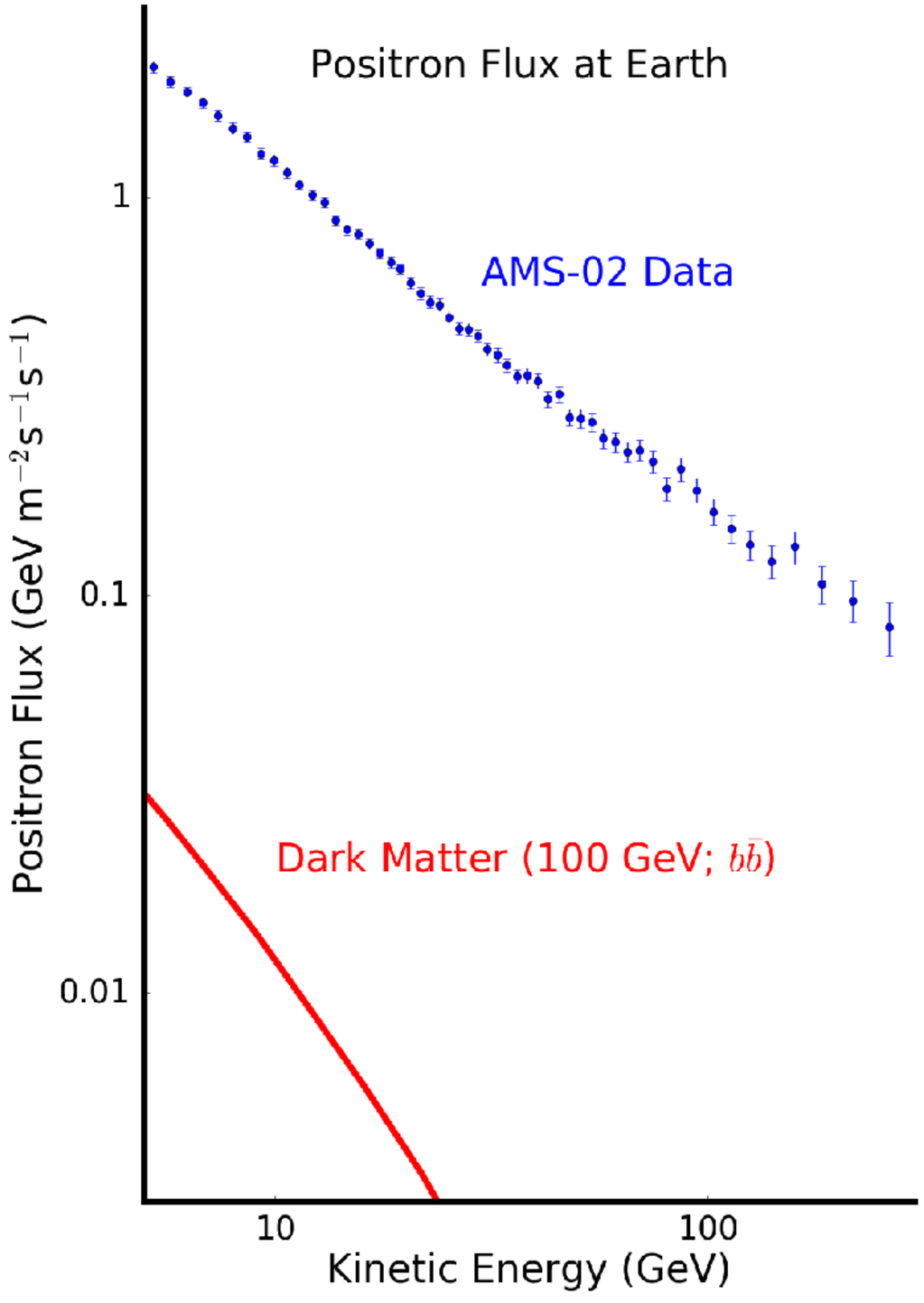
Thermal Cross-Section (Early Universe)

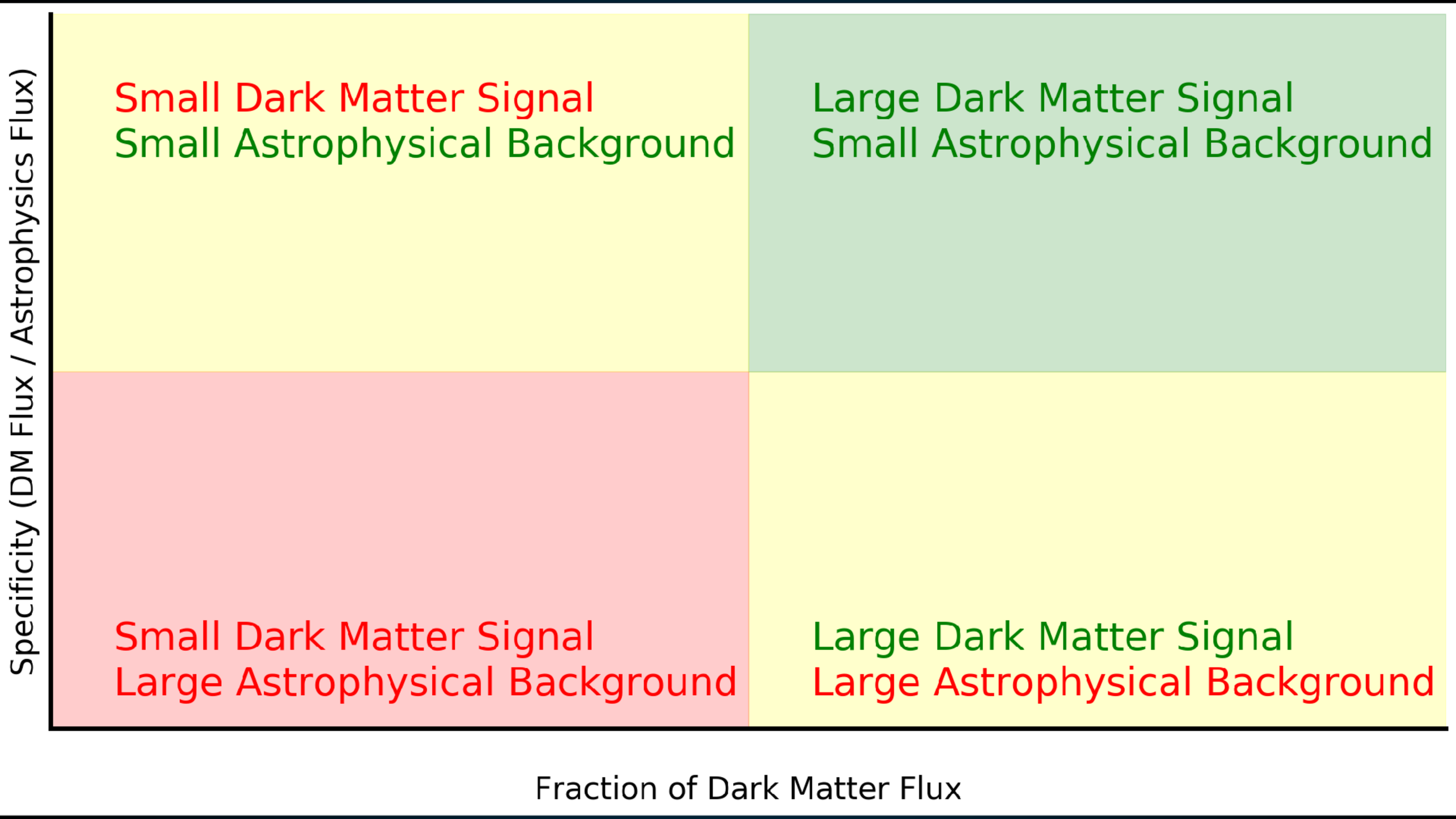
Leptonic Component of Dark Matter Final State

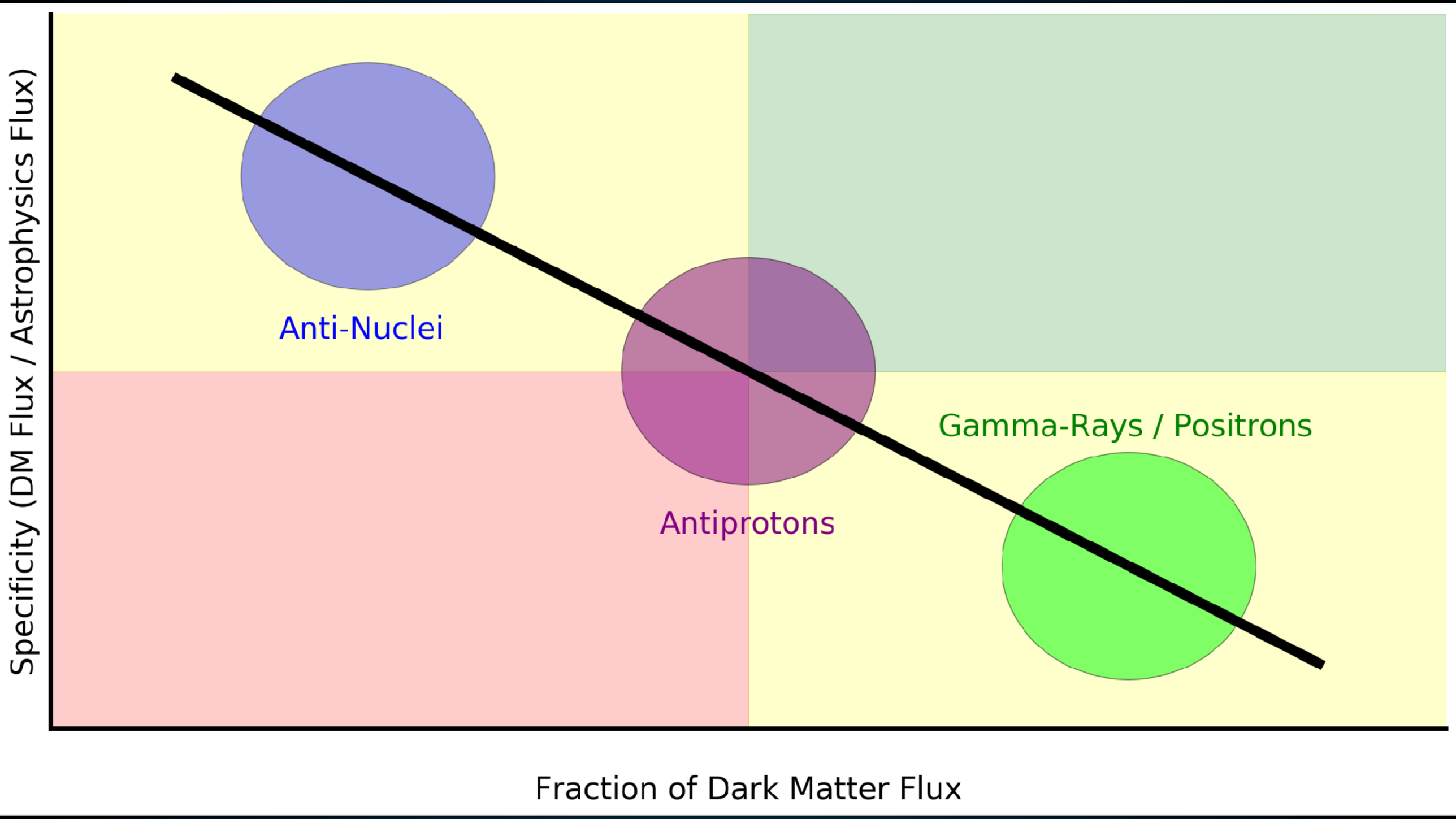
Convection of Annihilation Products from GC (Winds?)

Pulsar Birth Rate

e^+e^- Acceleration Efficiency in Pulsar Magnetospheres



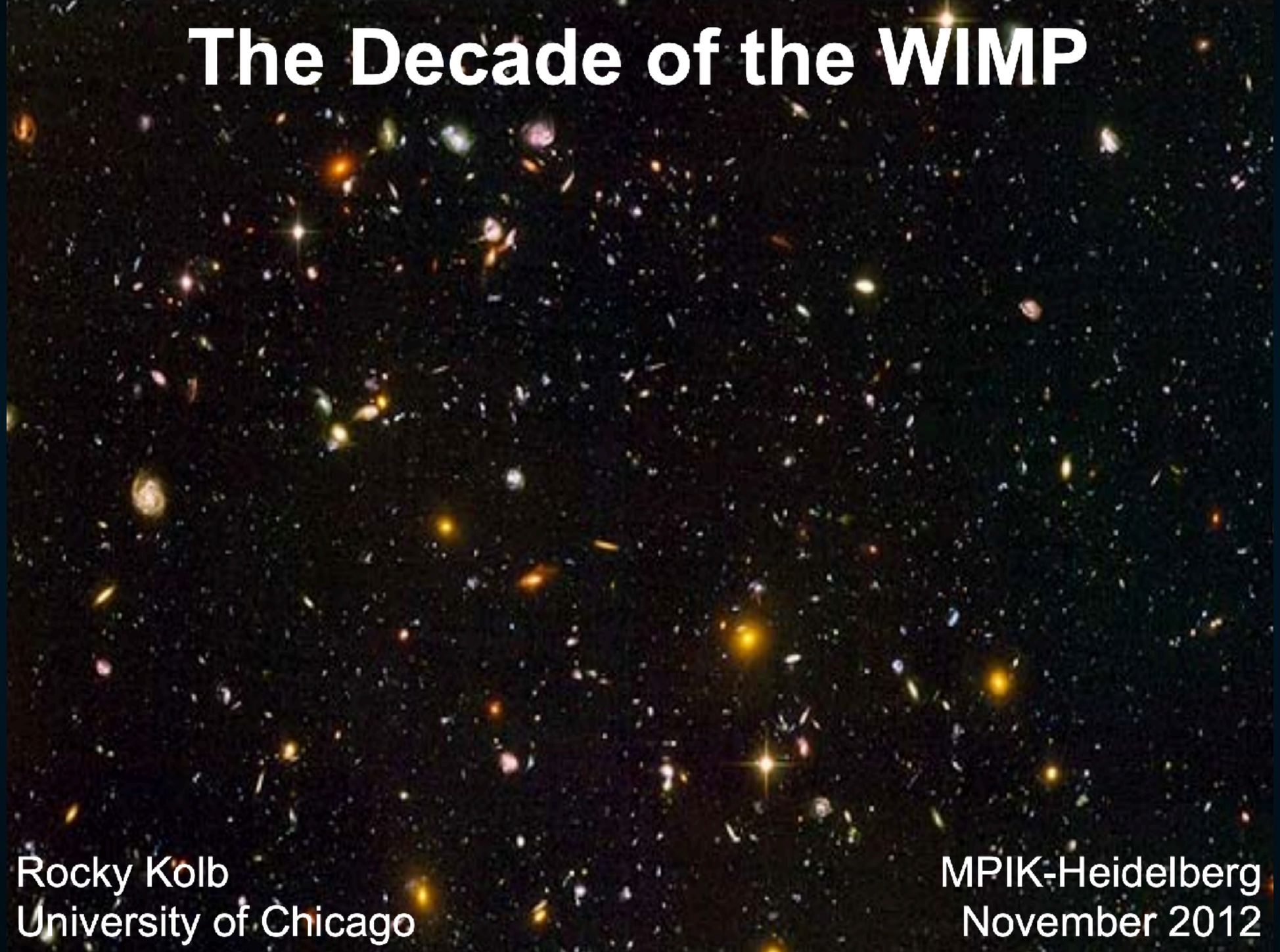

Small Dark Matter Signal
Small Astrophysical Background
Large Dark Matter Signal
Small Astrophysical Background
Small Dark Matter Signal
Large Astrophysical Background
Large Dark Matter Signal
Large Astrophysical Background
Specificity (DM Flux / Astrophysics Flux)
Fraction of Dark Matter Flux


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

Thermal WIMPs and the Story of Tantalus

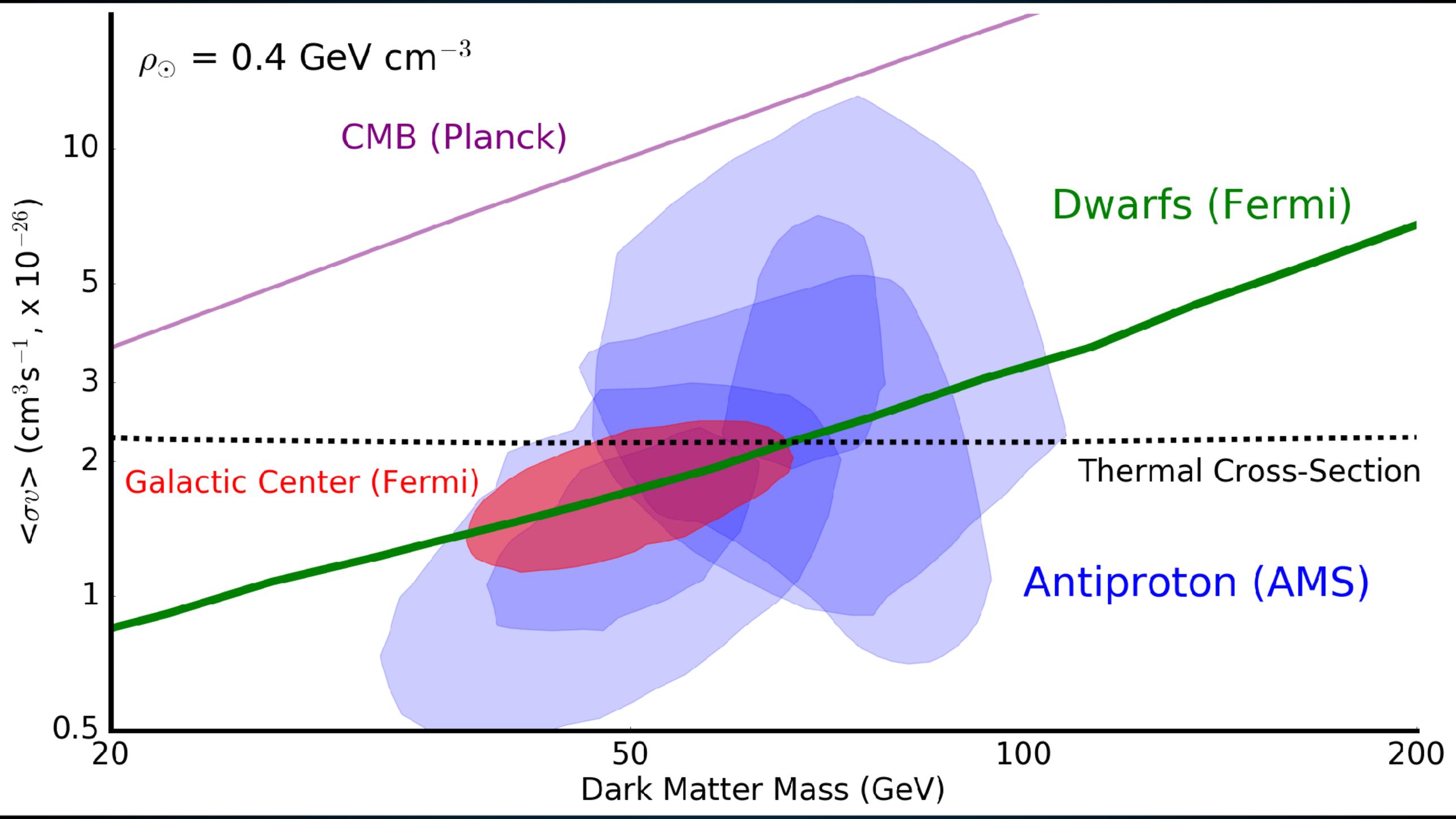
Thermal WIMPs and the Story of Tantalus

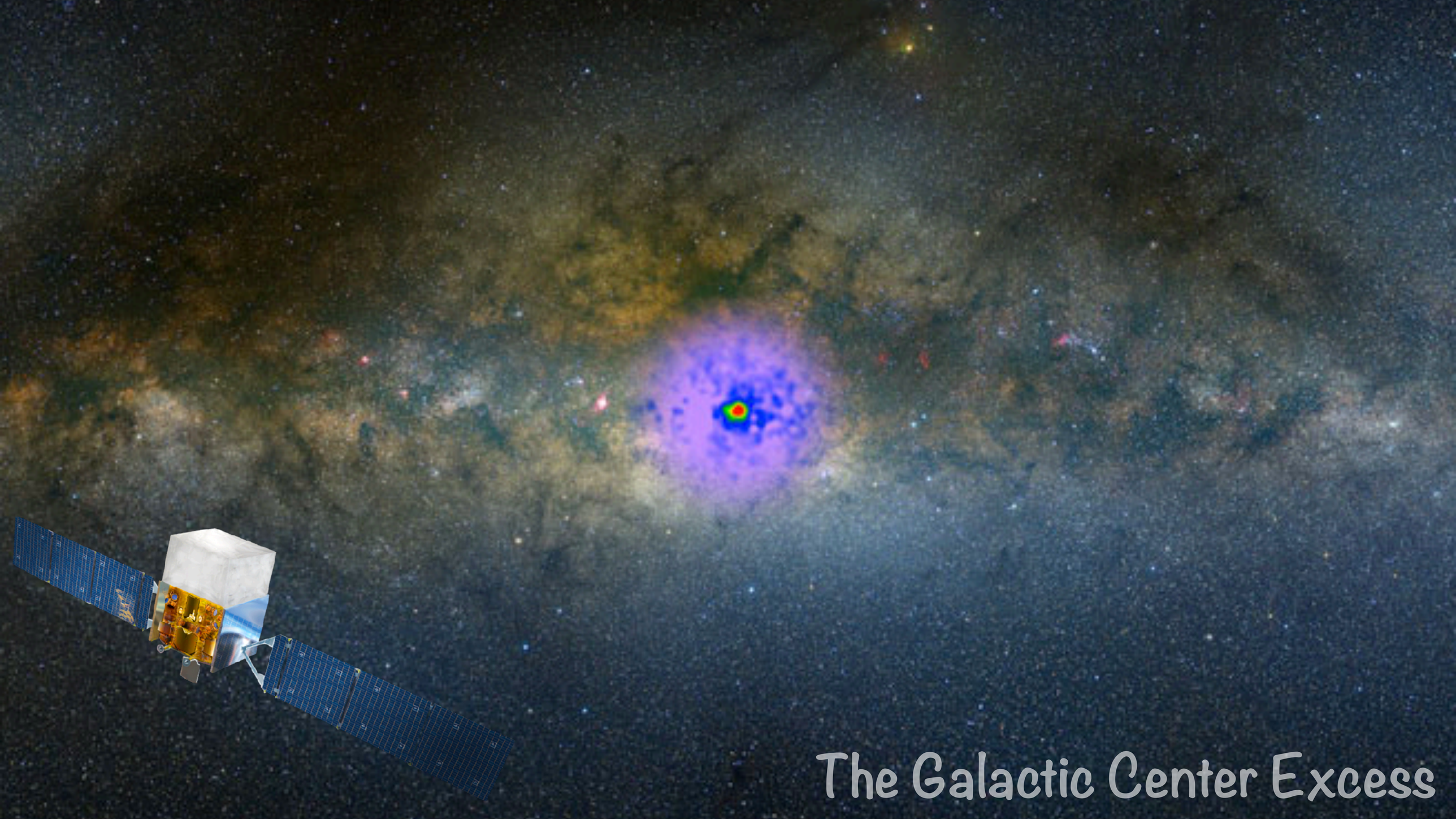
The Decade of the WIMP

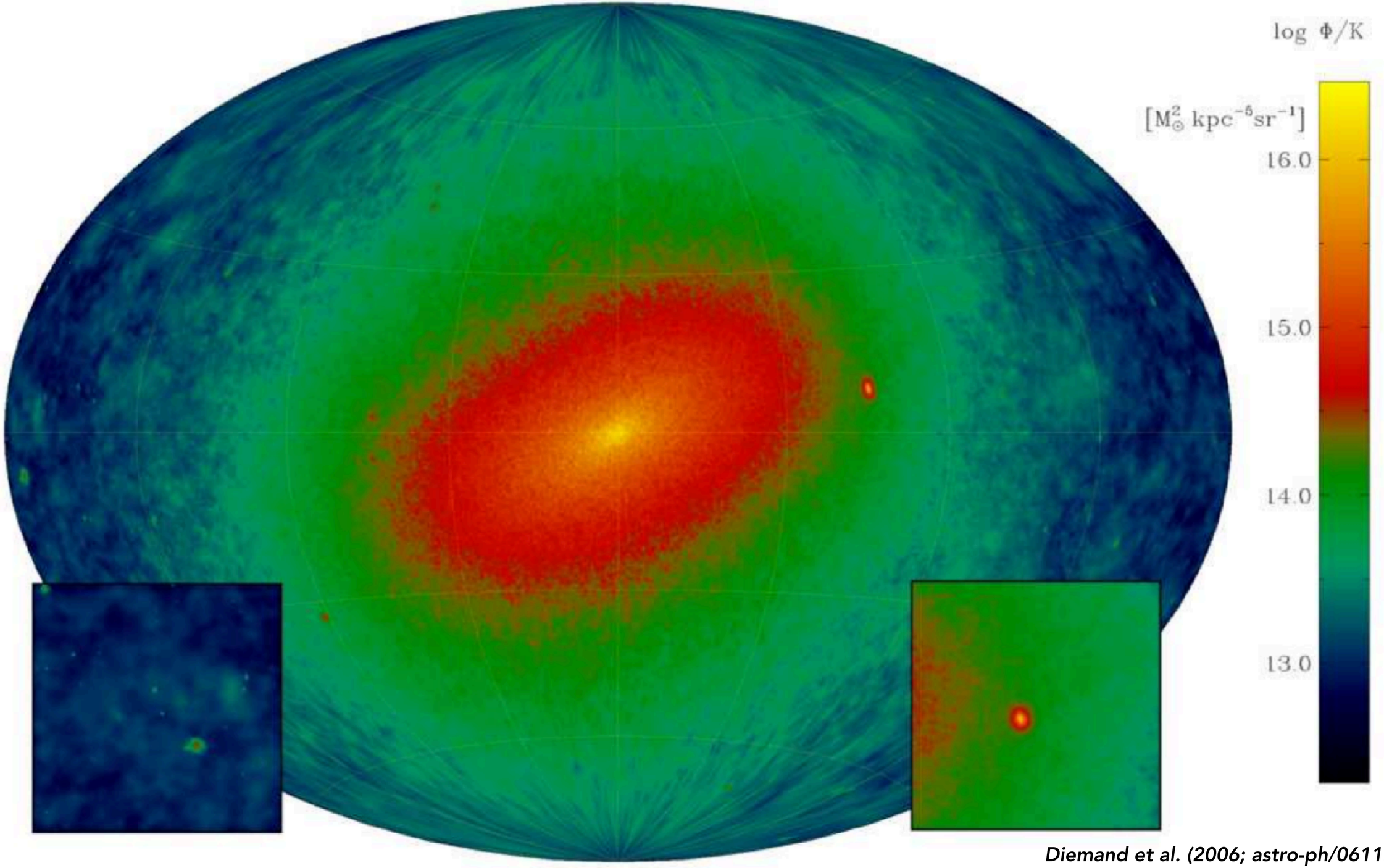


Rocky Kolb
University of Chicago

MPIK-Heidelberg
November 2012

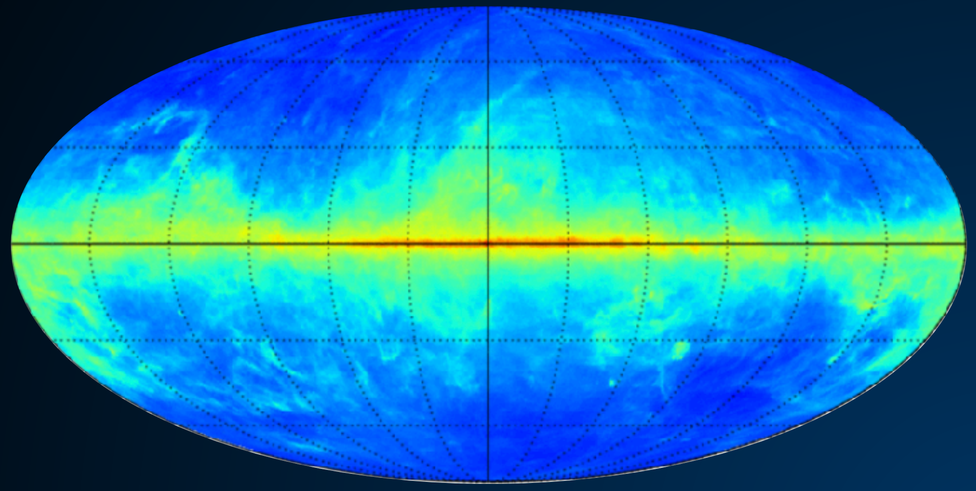

$\rho_\odot$ = 0.4 GeV cm^{-3}
CMB (Planck)
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
10
5
3
2
1
0.5
20
50
100
200
Dark Matter Mass (GeV)


The Galactic Center Excess

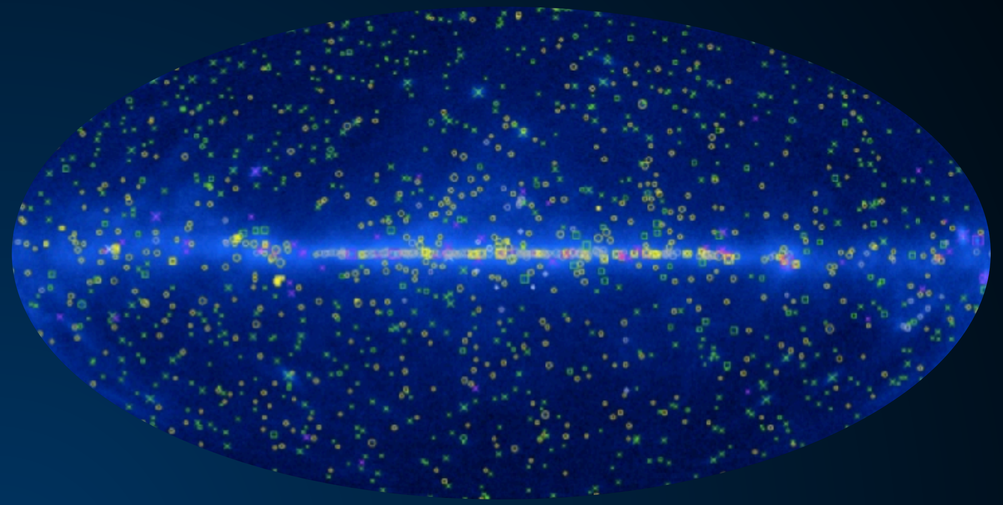


Diemand et al. (2006; astro-ph/0611370)

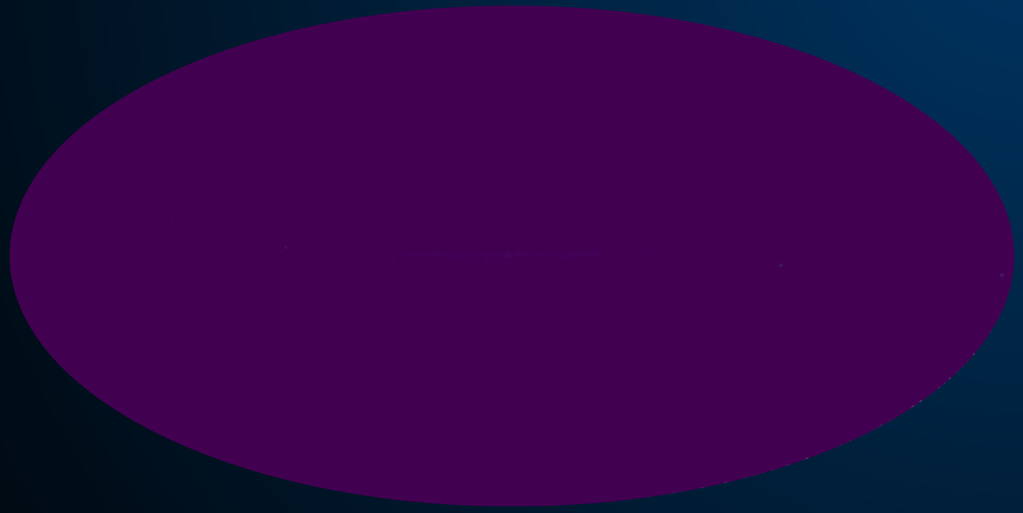
The Galactic Center - Techniques



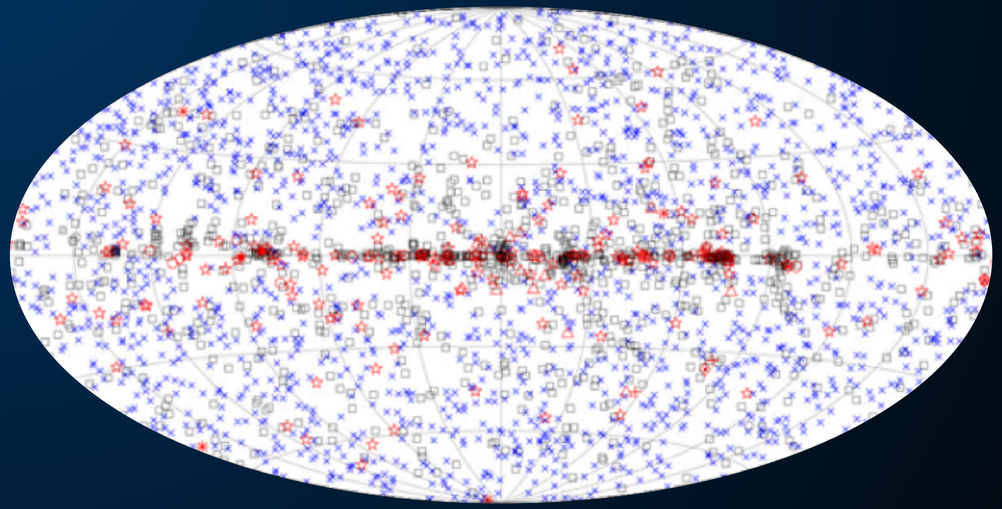
Galactic Diffuse



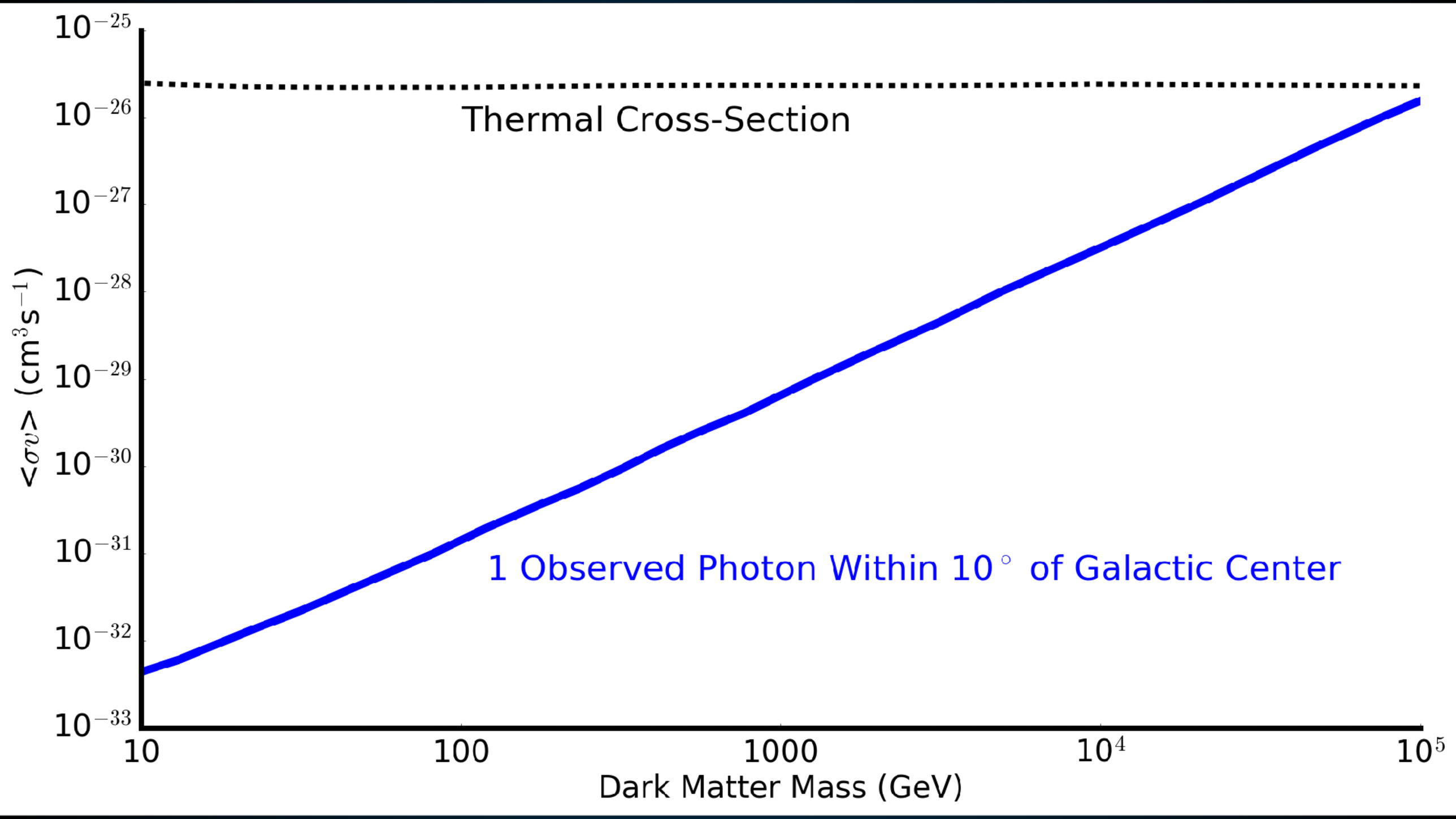
Point Sources



Isotropic Emission

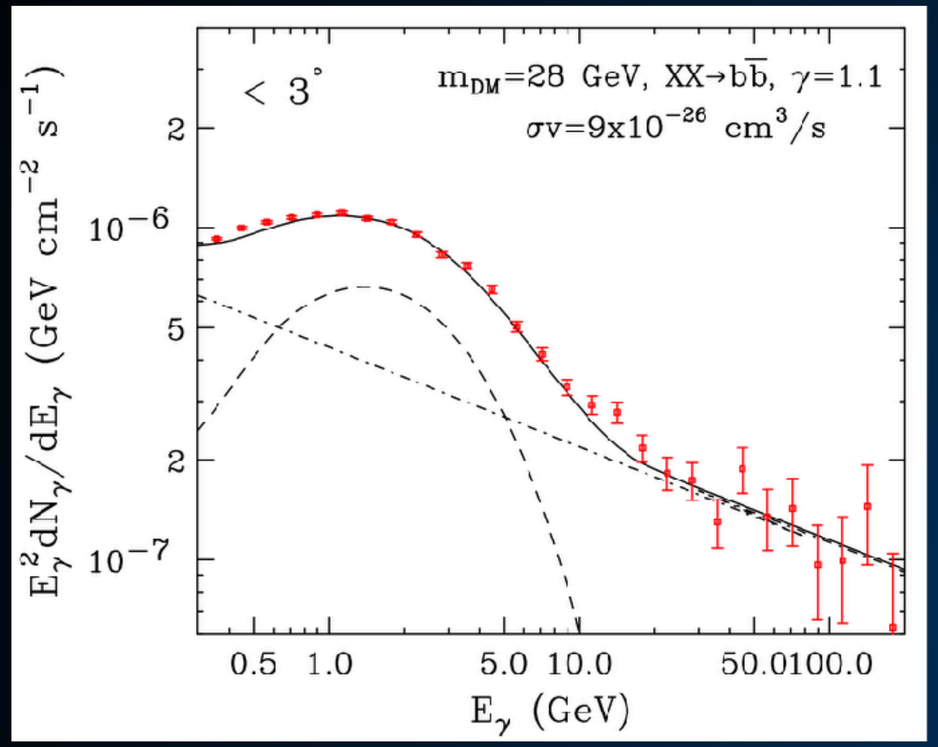


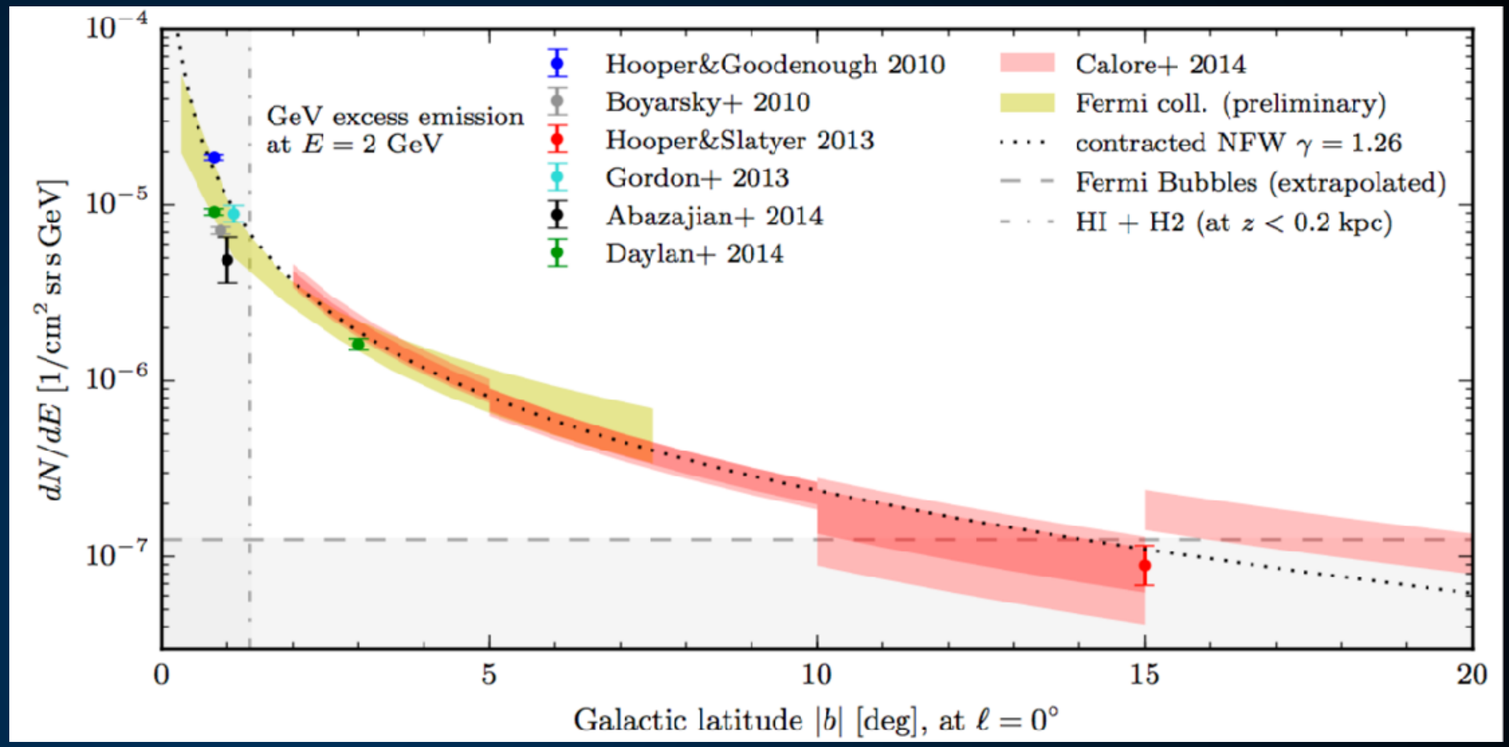
Sub-Threshold Sources


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)



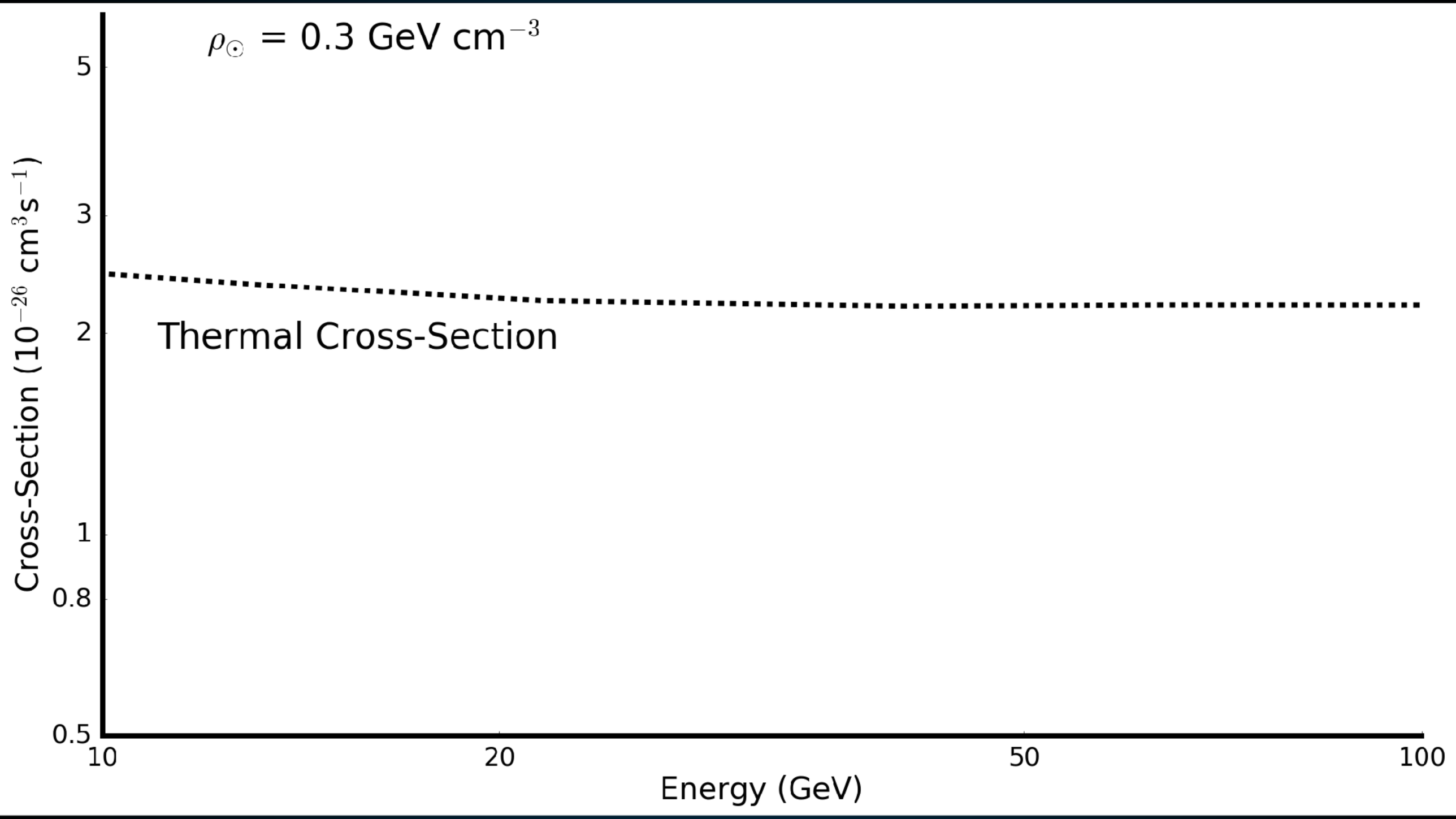


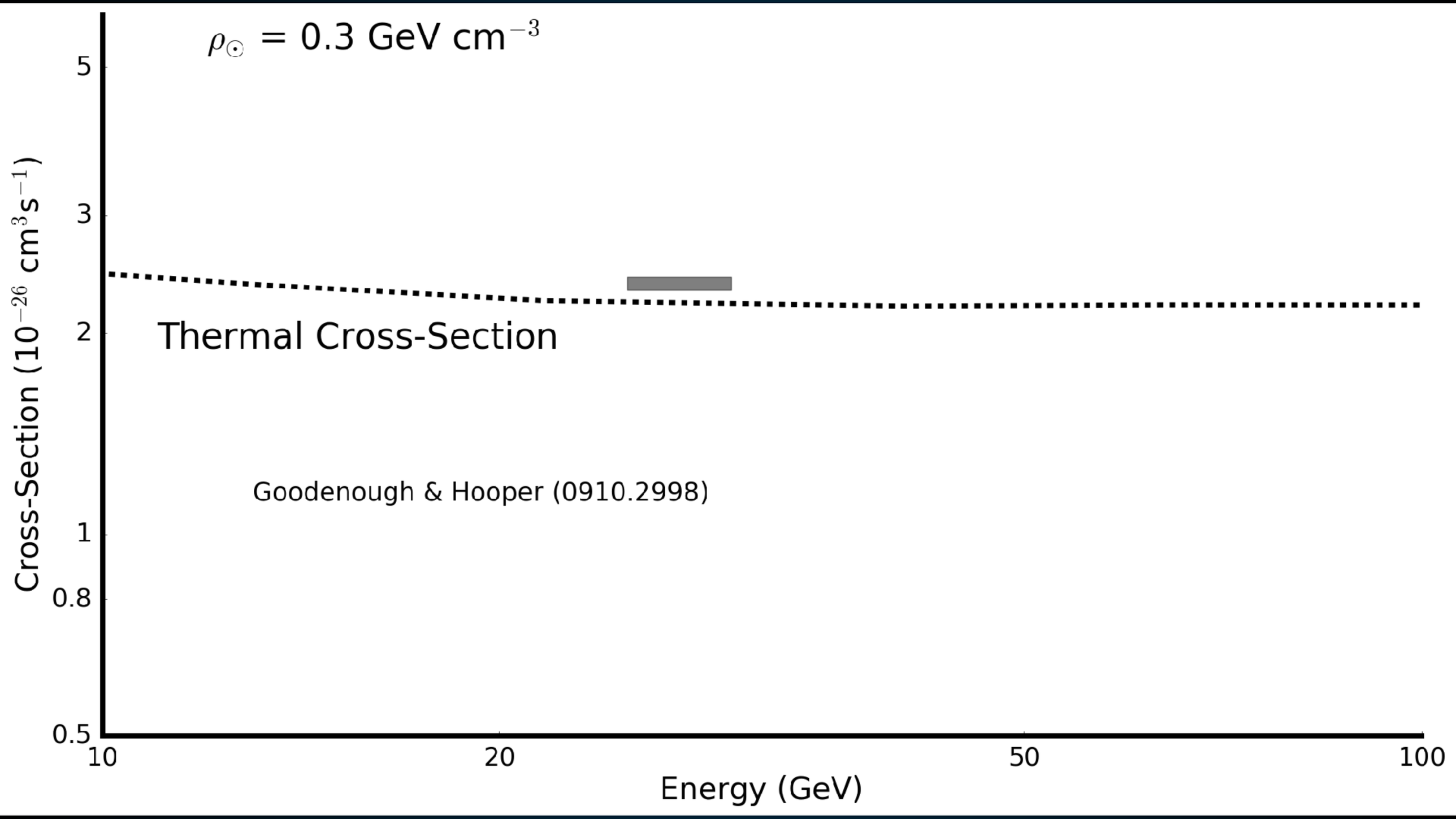
Bright *Detected at >50σ*

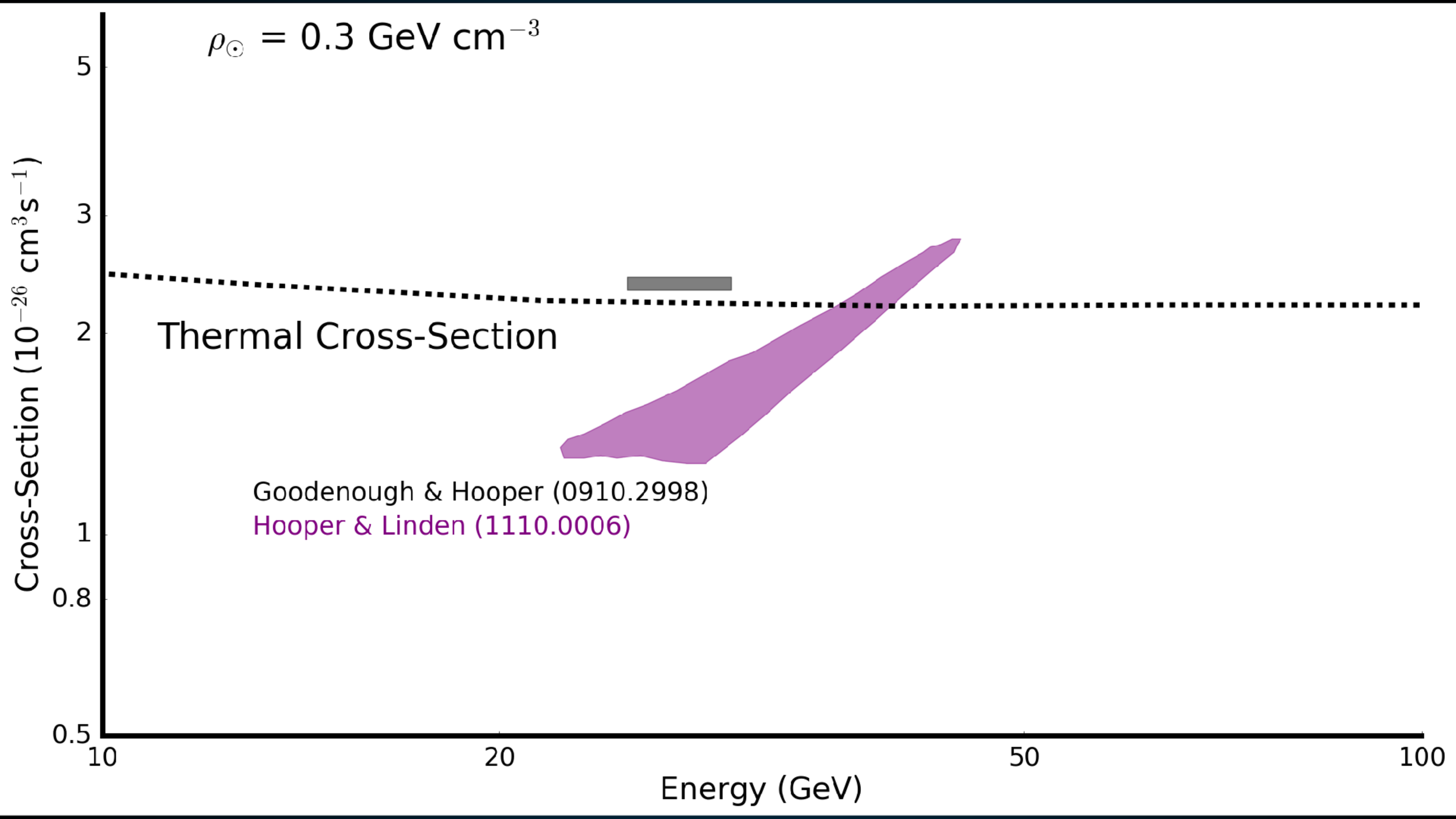
Hard-Spectrum *Incompatible with standard backgrounds*

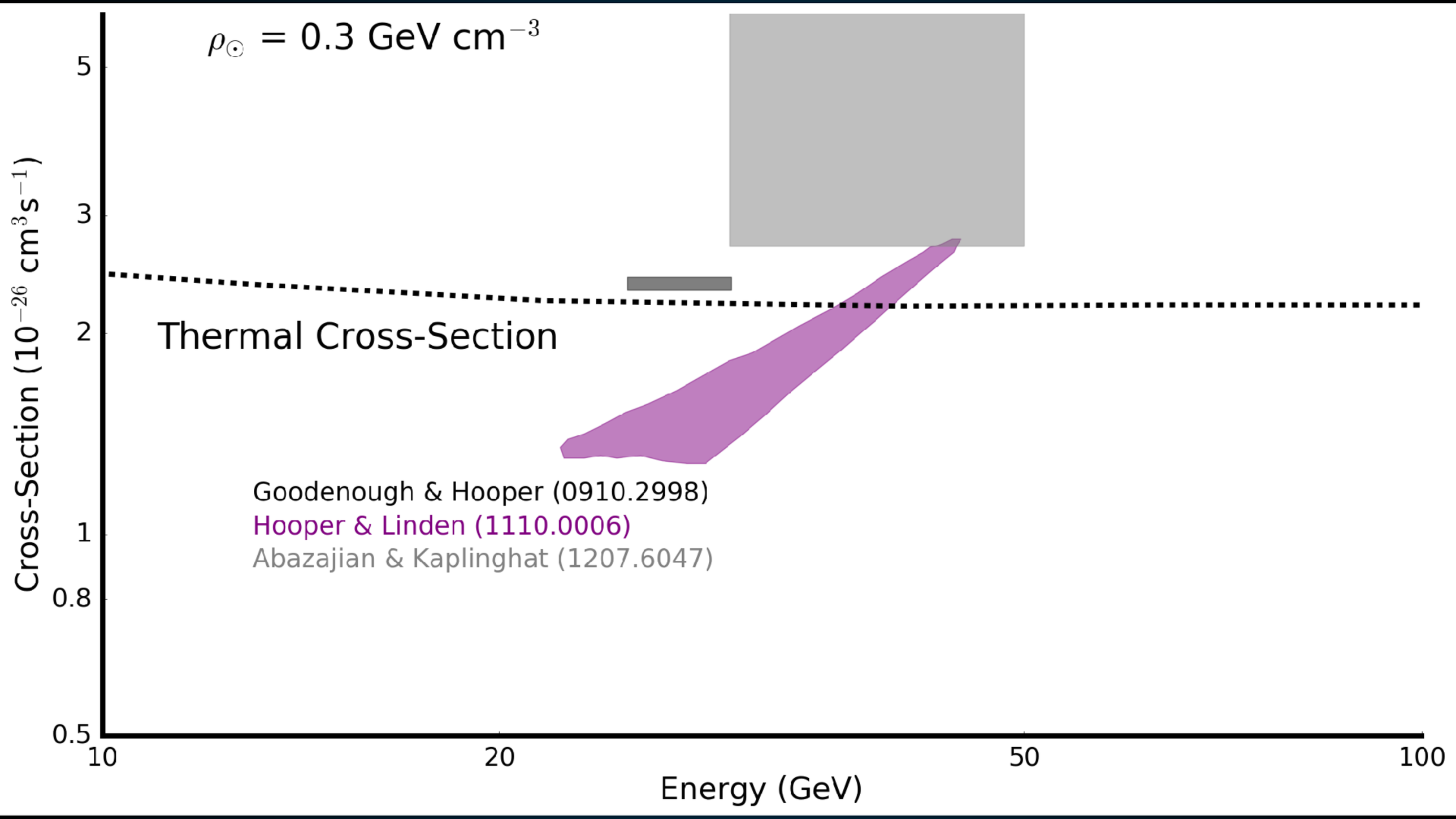
Spherically Symmetric *Expected from Dark Matter*

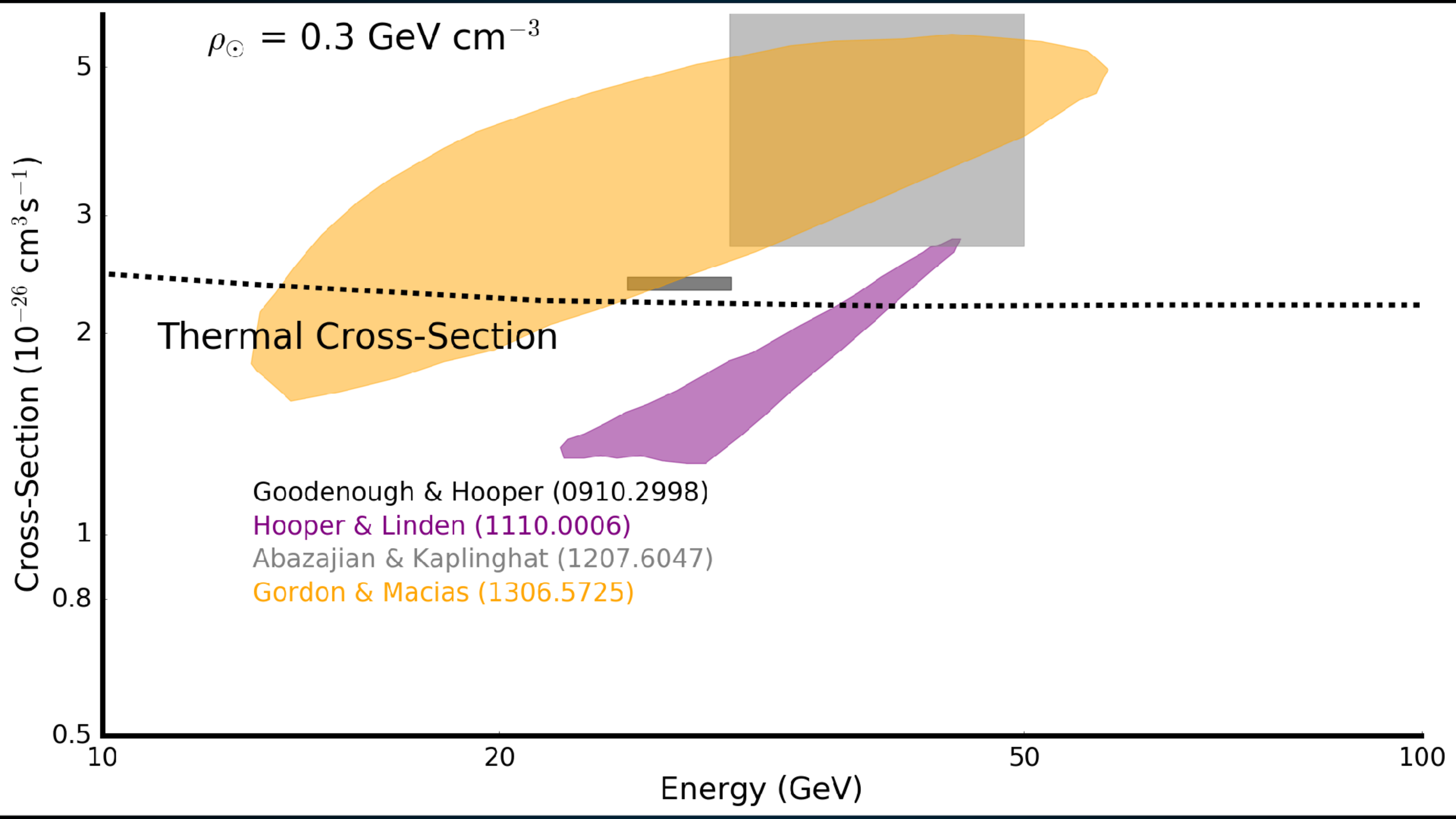
Spatially Extended *to nearly 15 degrees from Galactic center.*

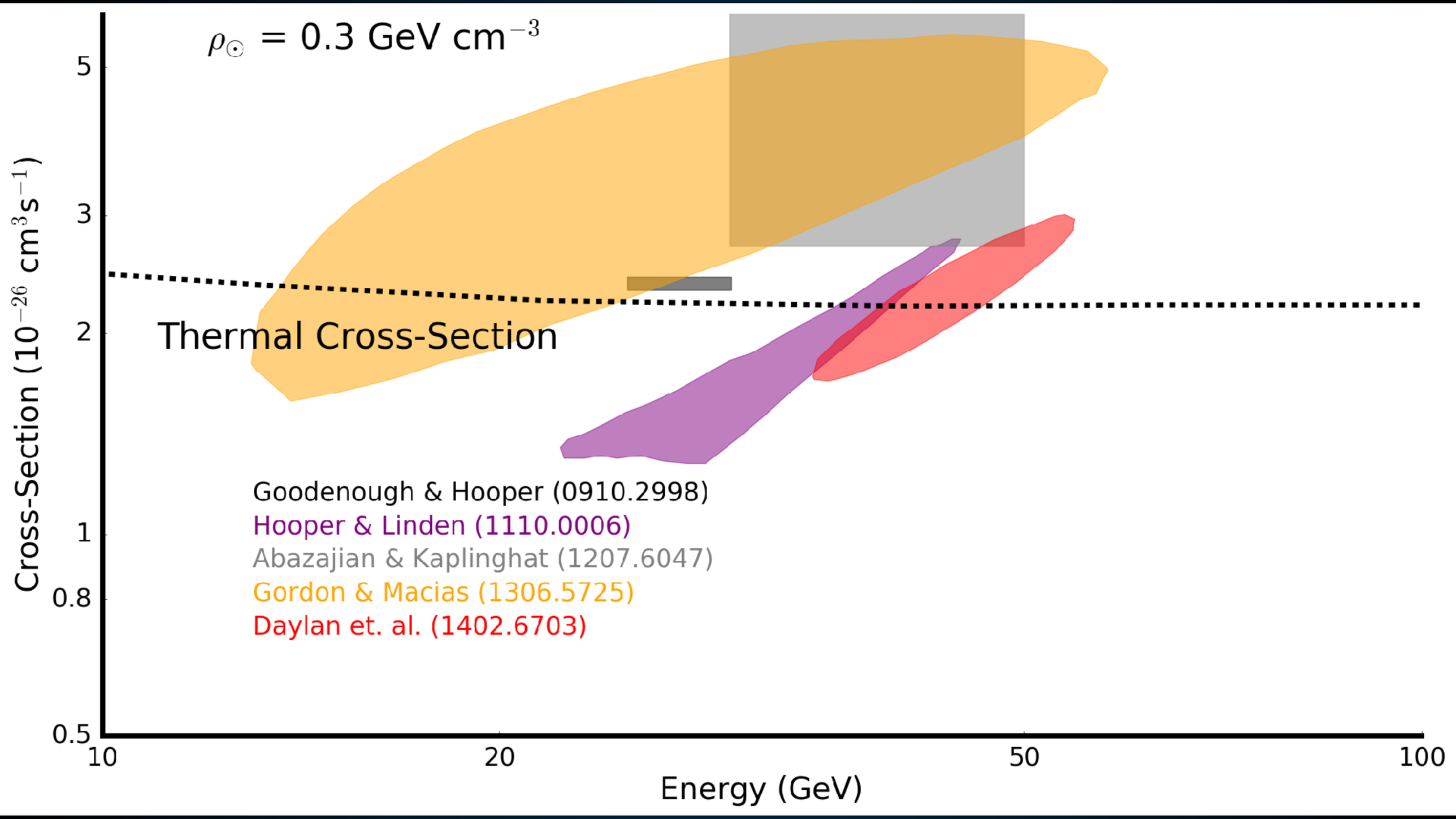

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Cross-Section (10^{-26} cm^{3}s^{-1})
5
3
2
1
0.8
0.5
10
20
50
100
Energy (GeV)

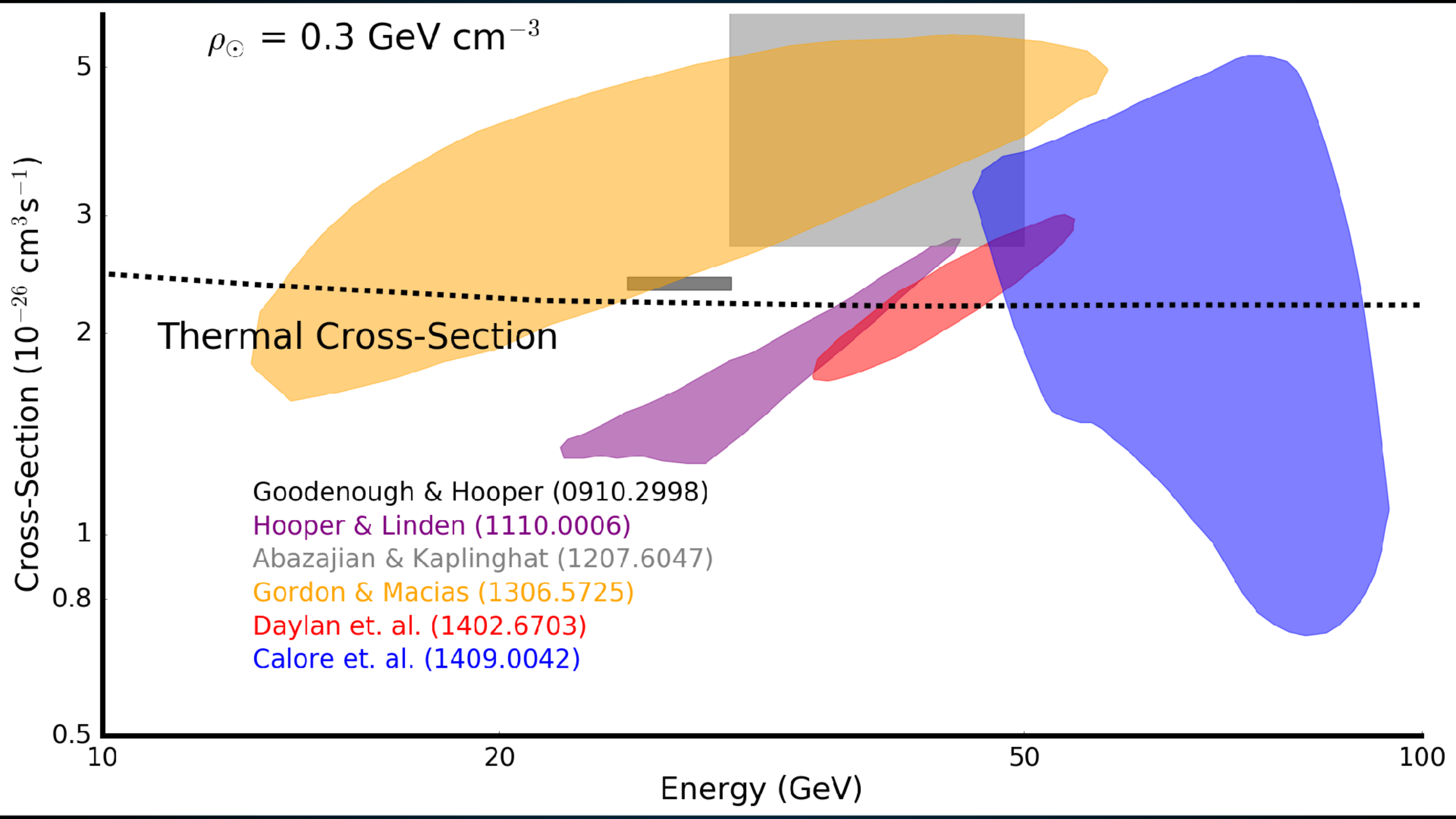

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Cross-Section (10^{-26} cm^{3}s^{-1})
Energy (GeV)
5
3
2
1
0.8
0.5
10
20
50
100

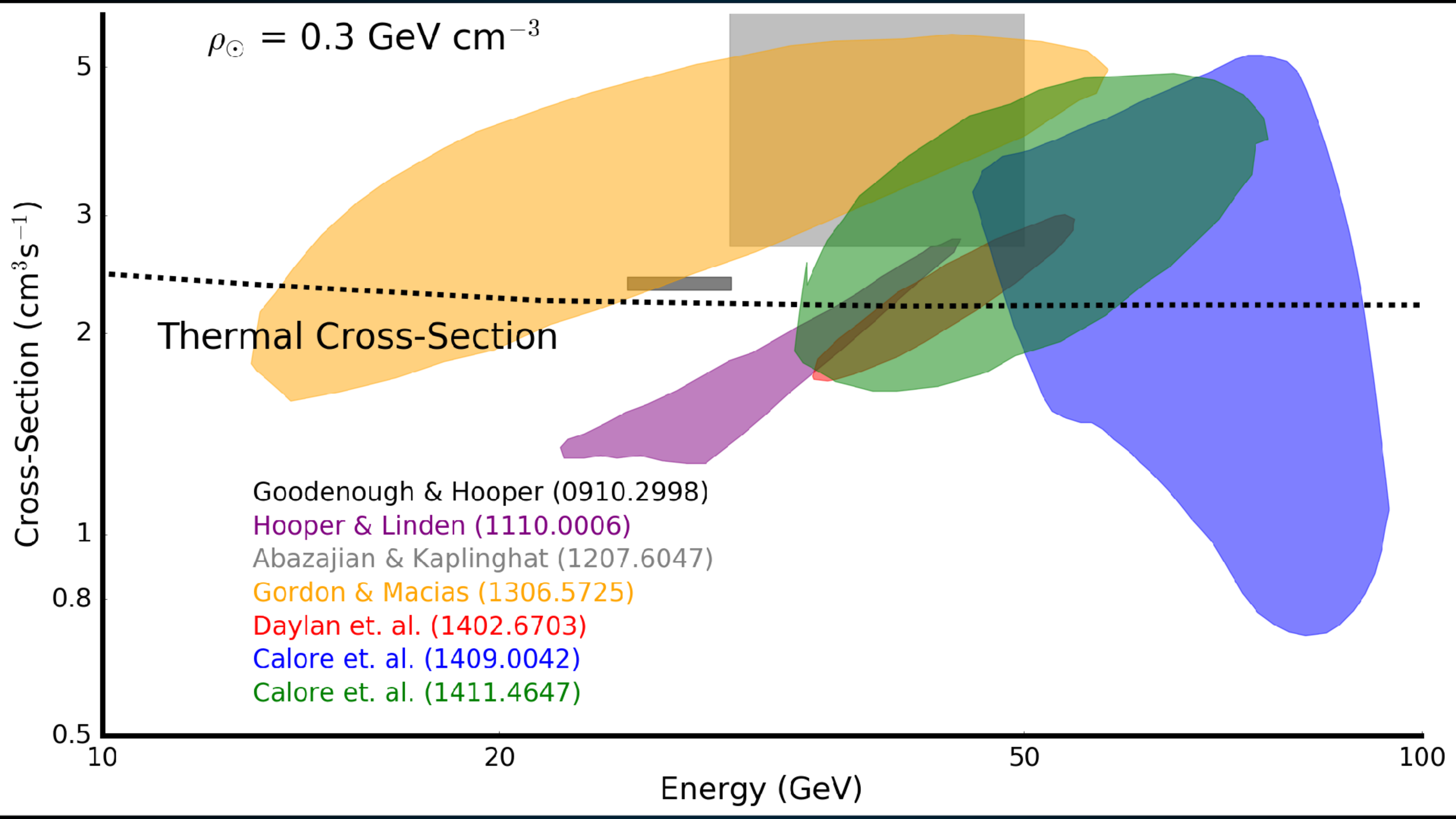

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Cross-Section (10^{-26} cm^{3}s^{-1})
Energy (GeV)
5
3
2
1
0.8
0.5
10
20
50
100

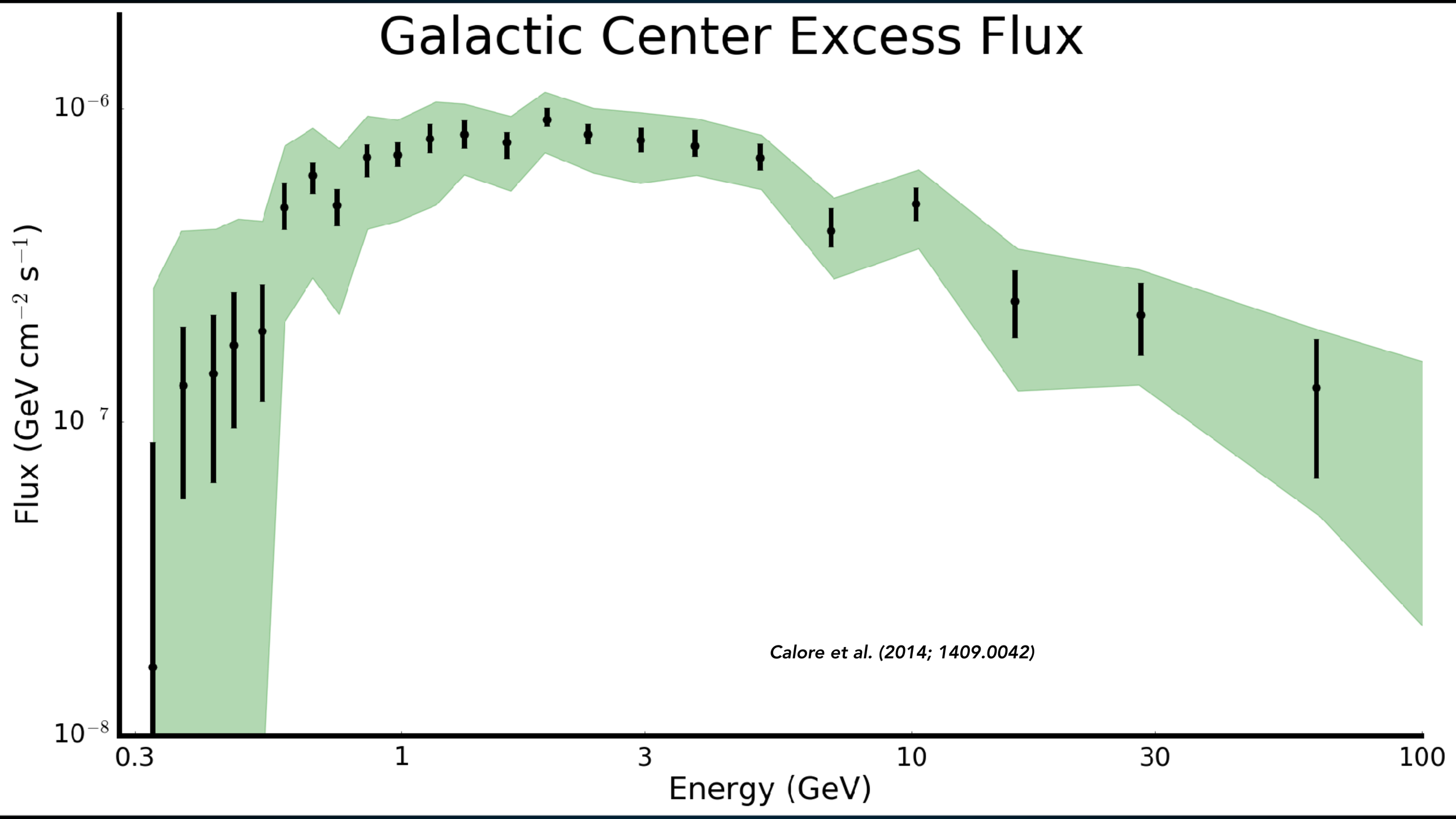

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Abazajian & Kaplinghat (1207.6047)
Cross-Section (10^{-26} cm^{3}s^{-1})
Energy (GeV)
5
3
2
1
0.8
0.5
10
20
50
100

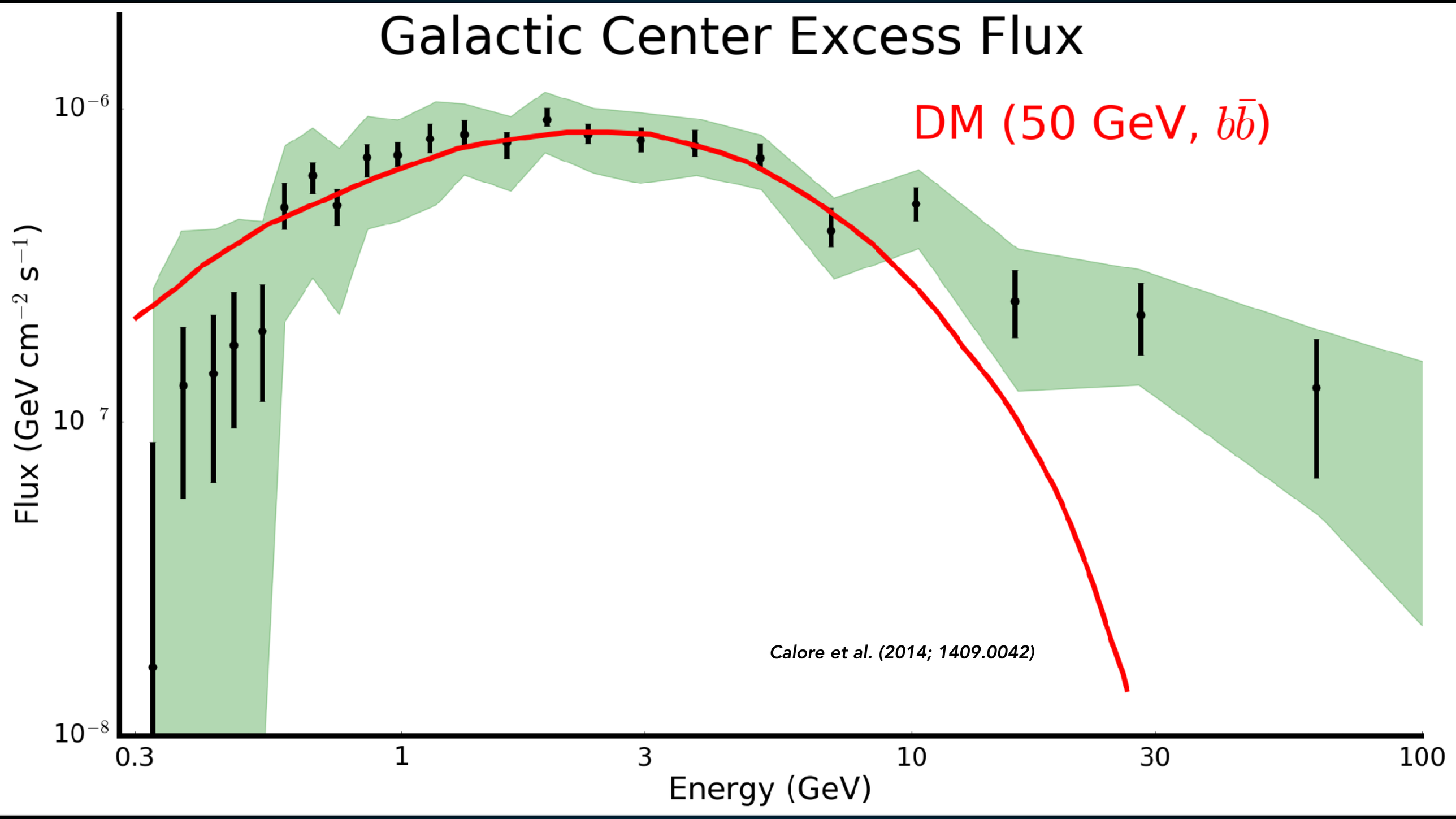

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Abazajian & Kaplinghat (1207.6047)
Gordon & Macias (1306.5725)
Cross-Section (10^{-26} cm^{3}s^{-1})
Energy (GeV)
5
3
2
1
0.8
0.5
10
20
50
100

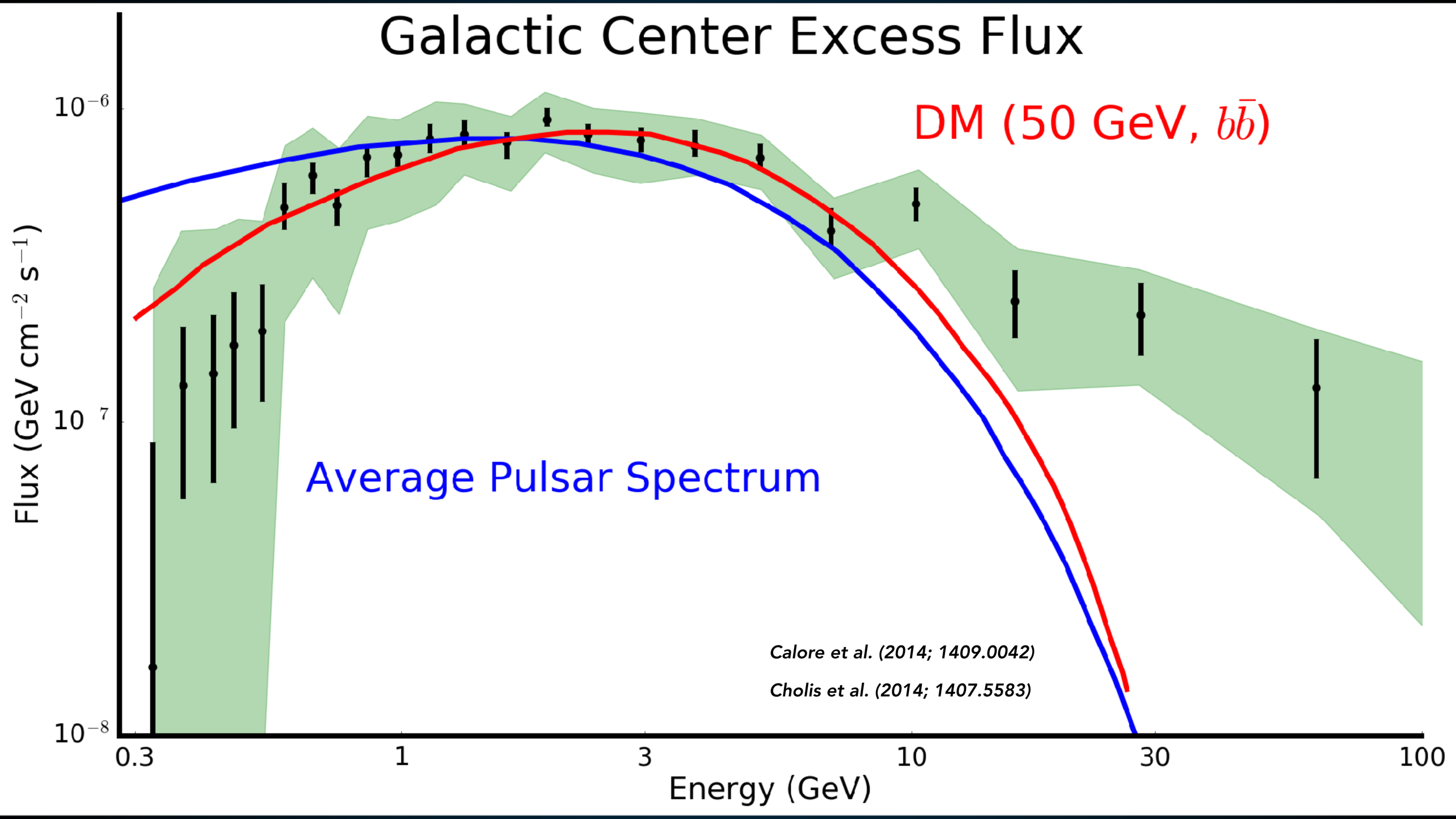

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Abazajian & Kaplinghat (1207.6047)
Gordon & Macias (1306.5725)
Daylan et. al. (1402.6703)
Cross-Section (10^{-26} cm^{3}s^{-1})
5
3
2
1
0.8
0.5
10
20
50
100
Energy (GeV)

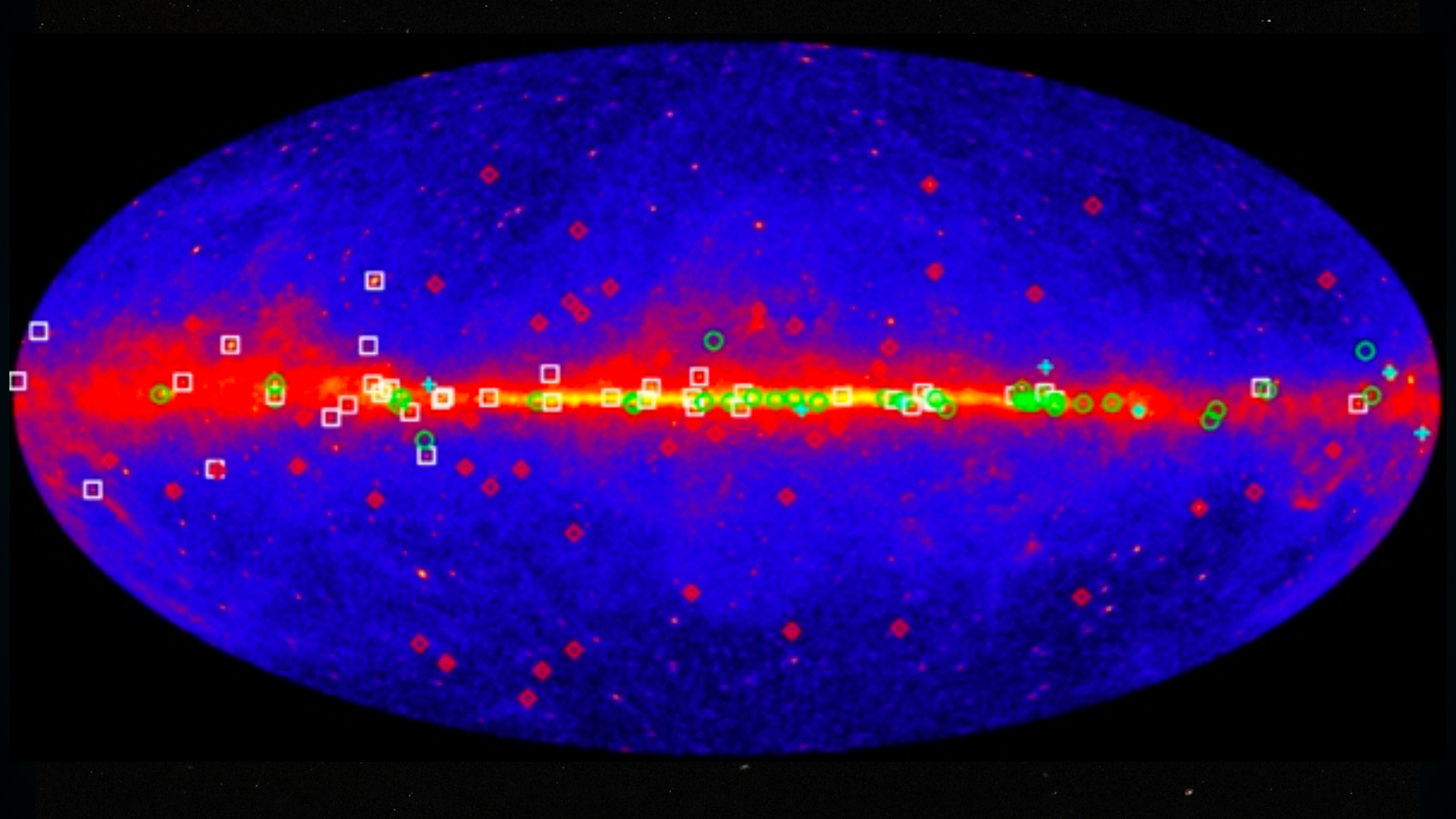

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Abazajian & Kaplinghat (1207.6047)
Gordon & Macias (1306.5725)
Daylan et. al. (1402.6703)
Calore et. al. (1409.0042)
Cross-Section (10^{-26} cm^{3}s^{-1})
5
3
2
1
0.8
0.5
10
20
50
100
Energy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

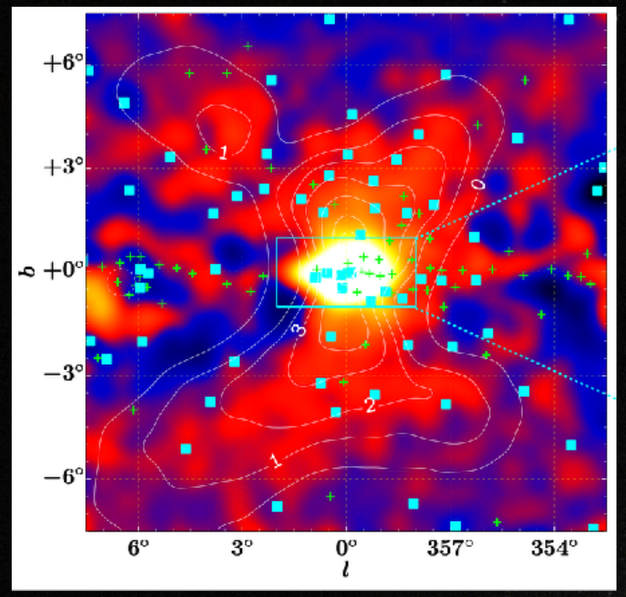

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Abazajian & Kaplinghat (1207.6047)
Gordon & Macias (1306.5725)
Daylan et. al. (1402.6703)
Calore et. al. (1409.0042)
Calore et. al. (1411.4647)
Cross-Section (cm^{3}s^{-1})
Energy (GeV)
5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


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)

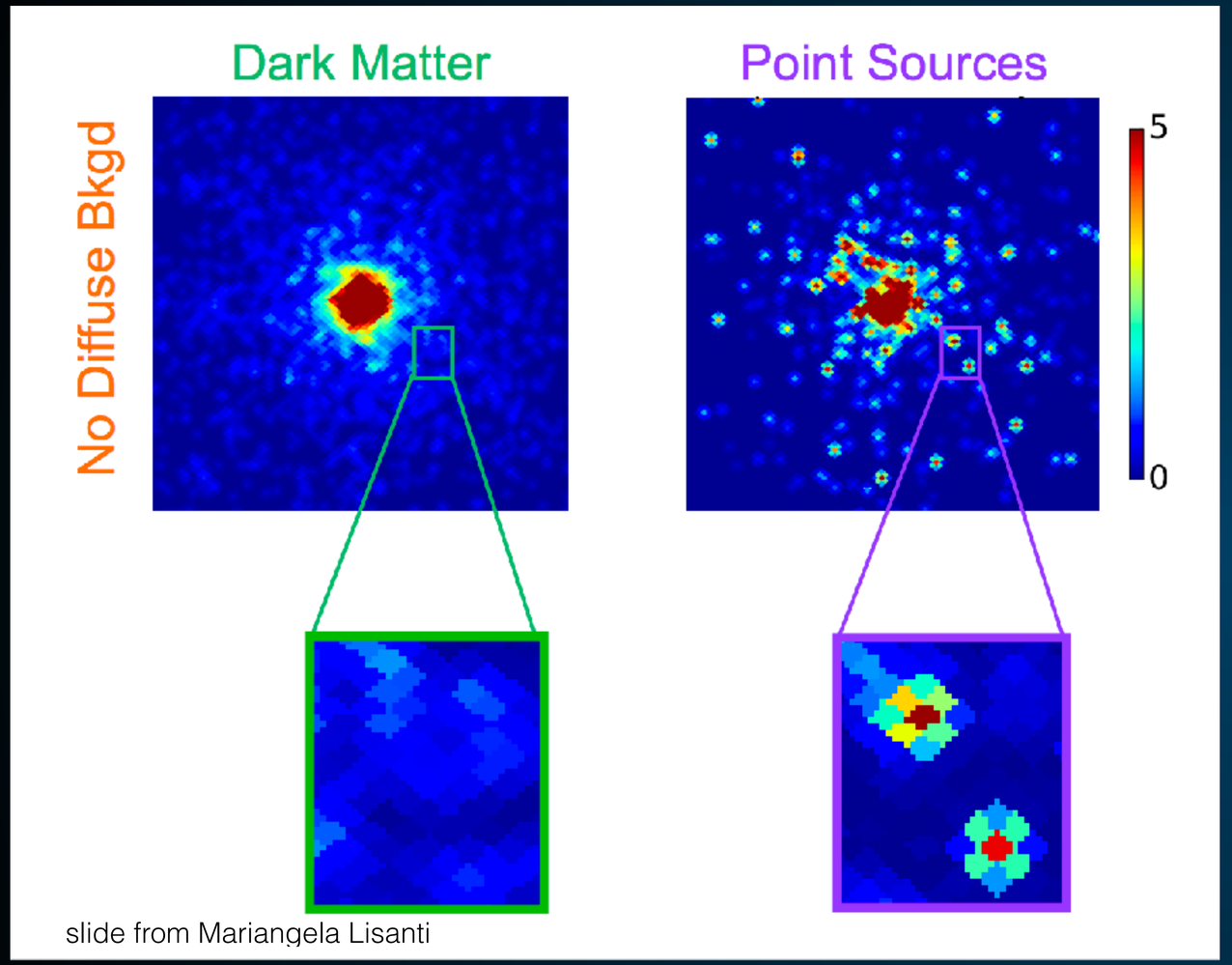
Bartels et al. (2018; 1803.04370)

Macias et al. (2019; 1901.03822)

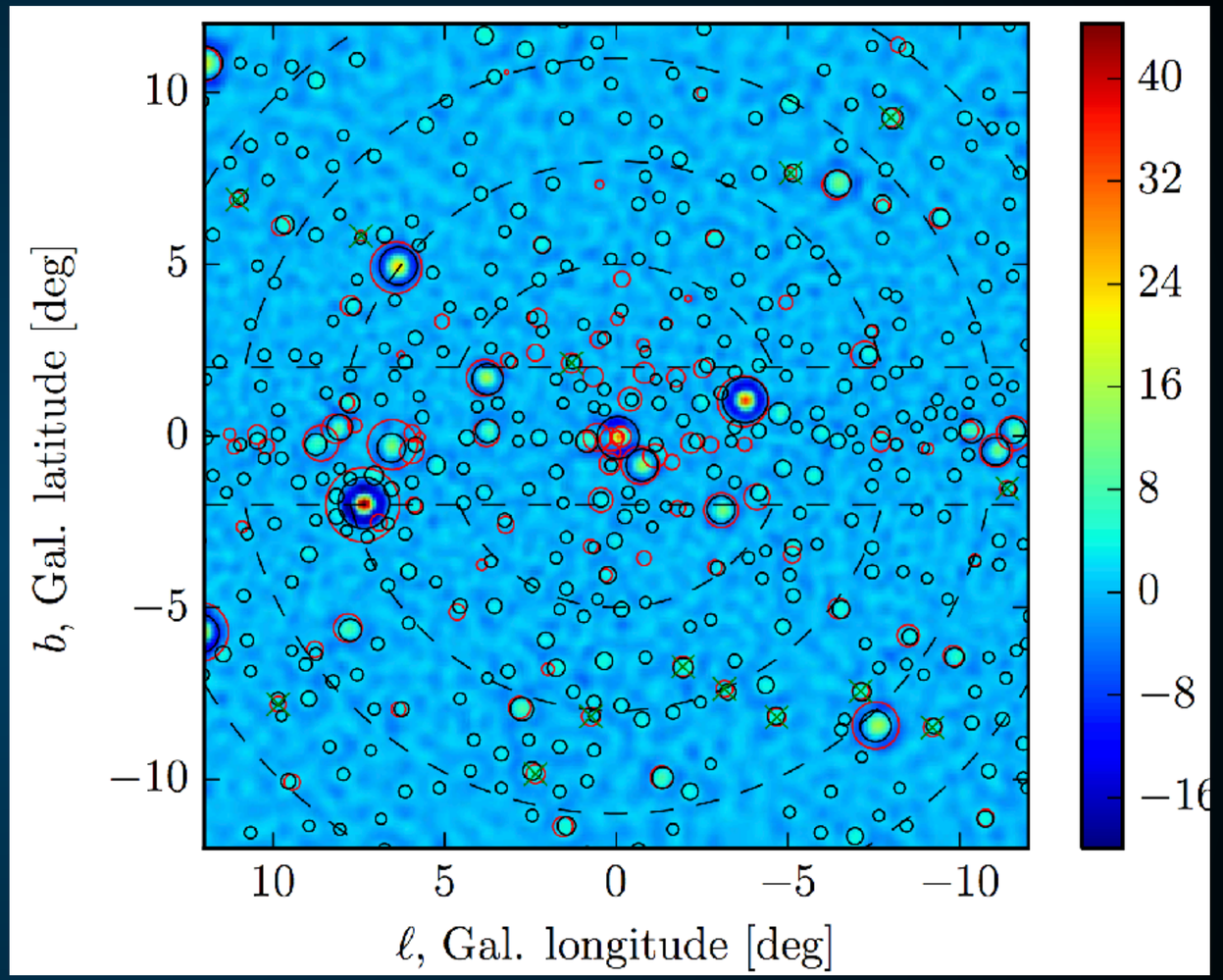
The Galactic Center Excess

Bartels et al. (2015; 1506.05104)

Lee et al. (2015; 1506.05124)



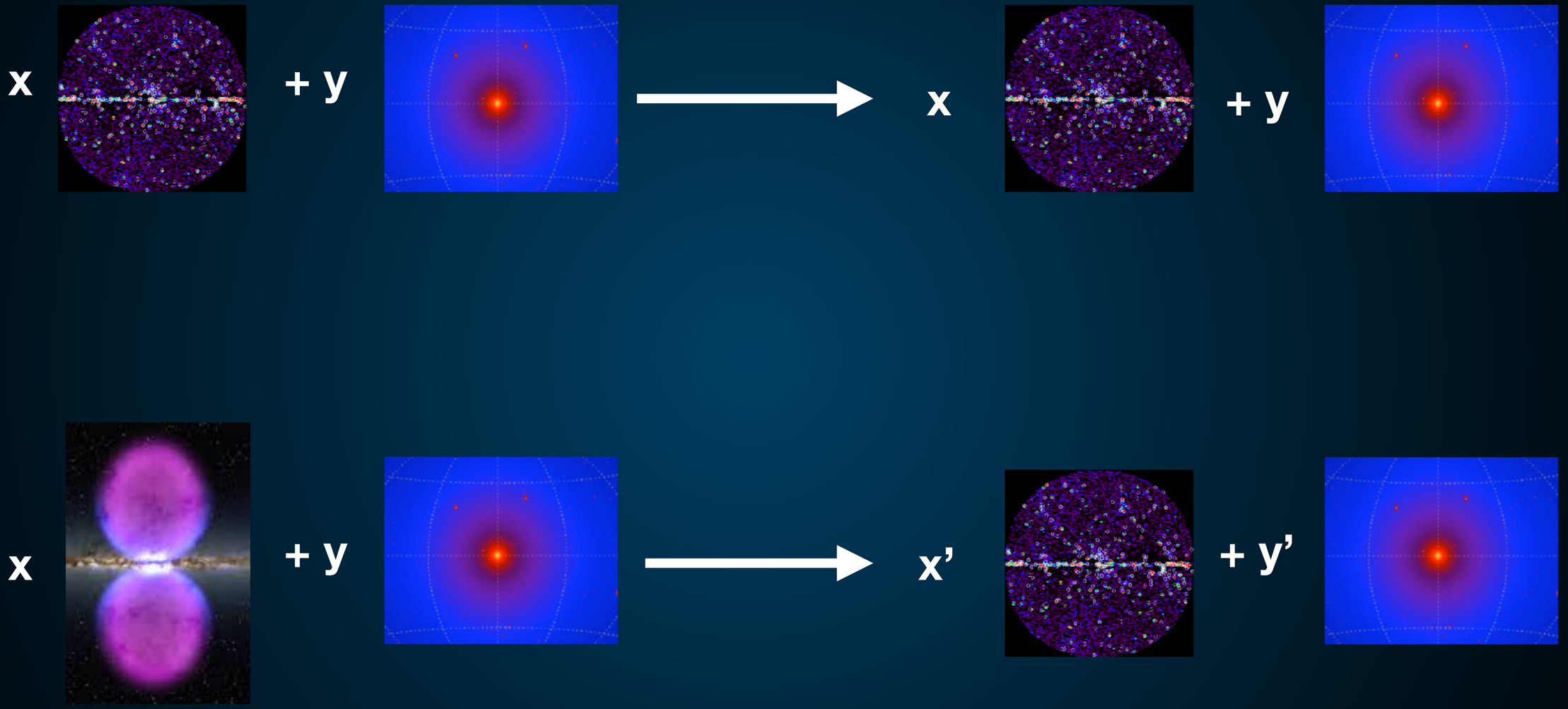
slide from Mariangela Lisanti



Bulletproof evidence for pulsars?

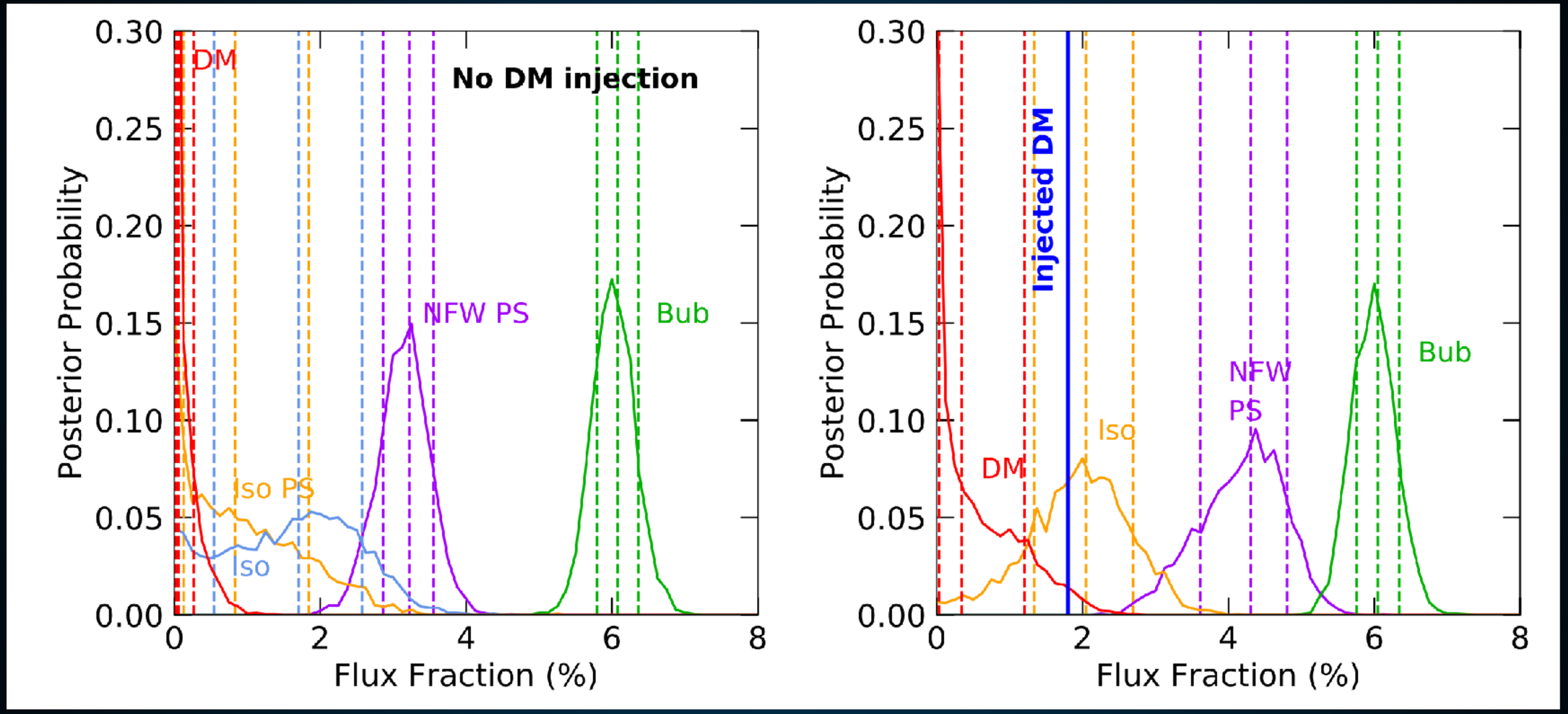
The Galactic Center Excess

Leane & Slatyer (2019; 1904.08430)



The Galactic Center Excess

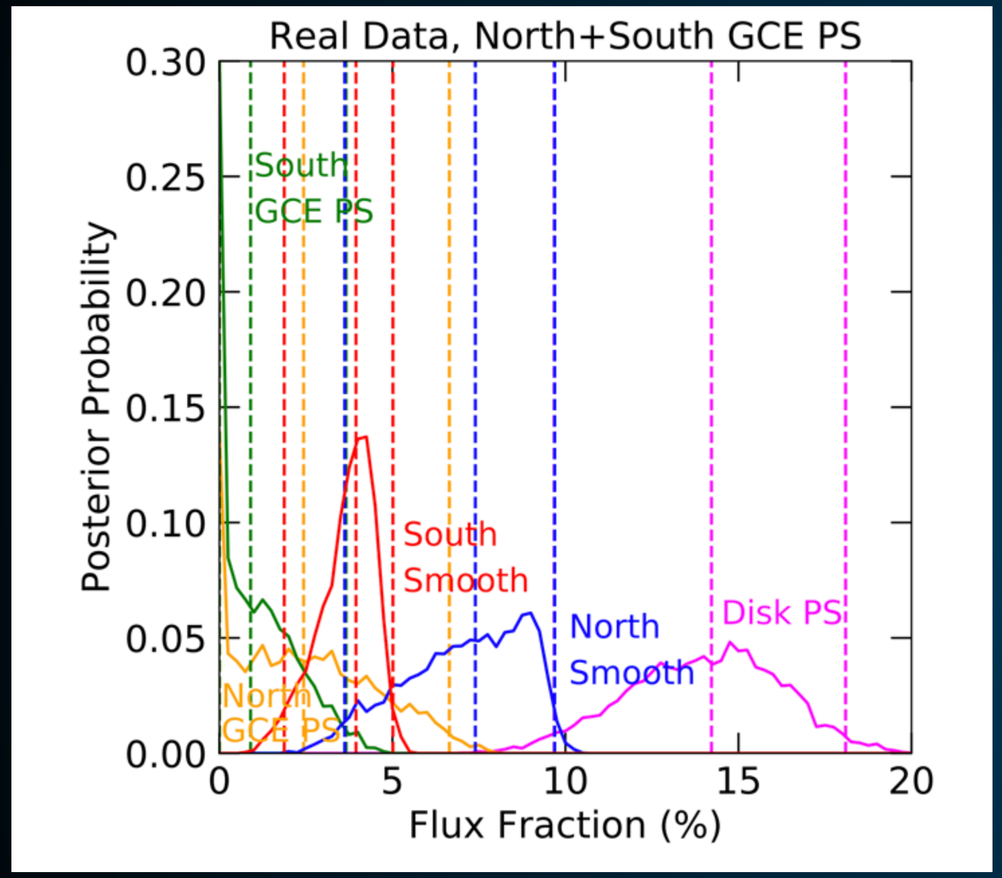
Leane & Slatyer (2019; 1904.08430)



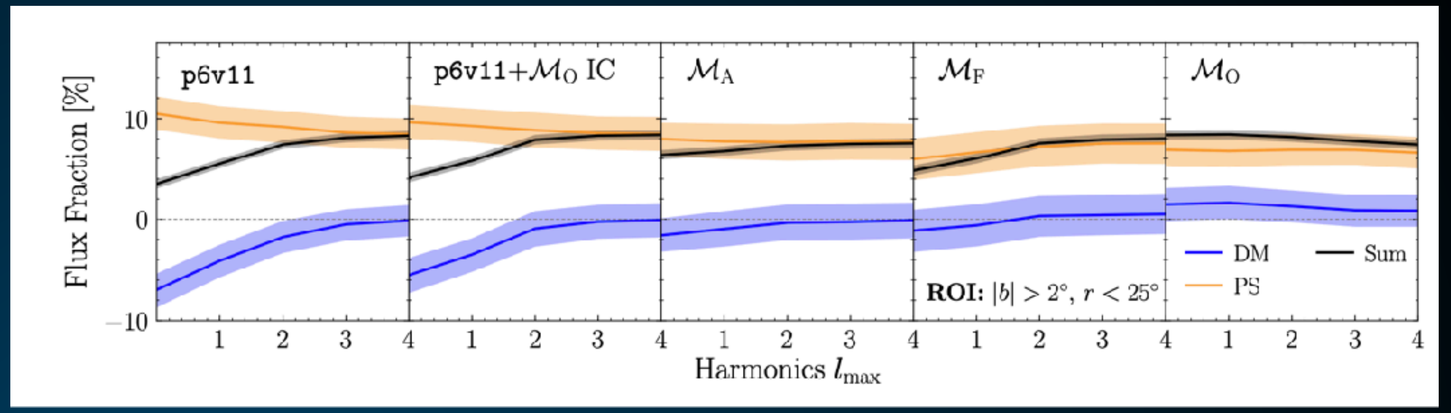
Dark Matter Strikes Back at the Galactic Center

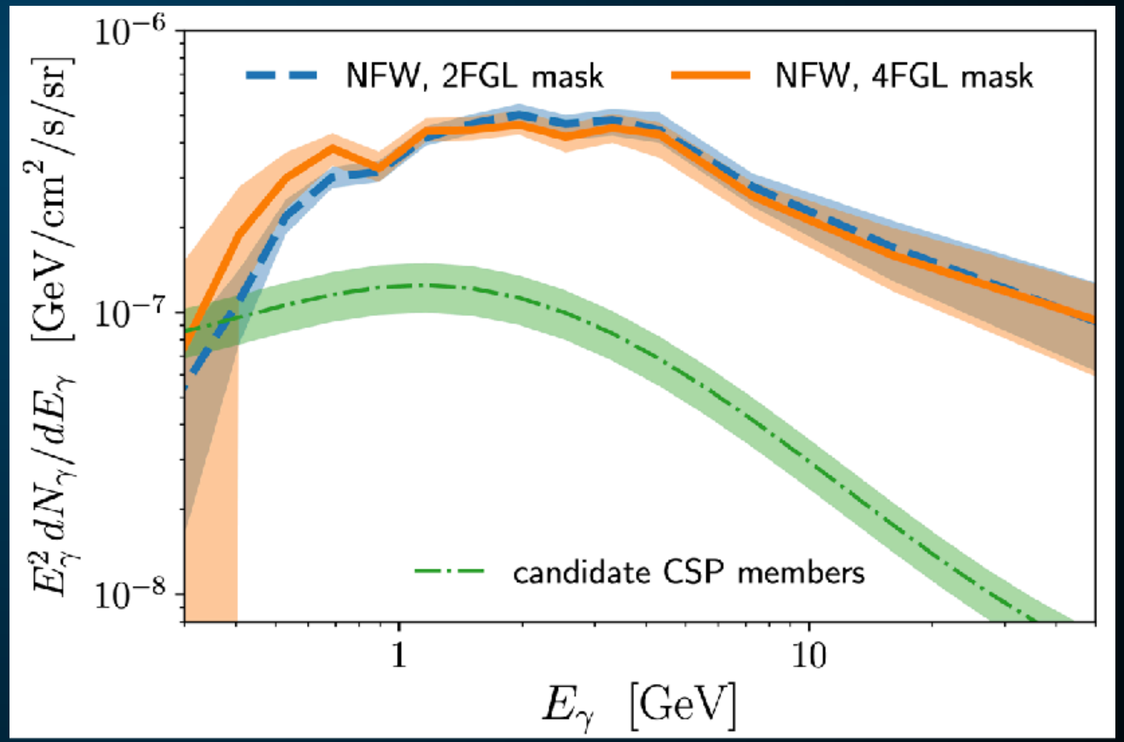
The Galactic Center Excess

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

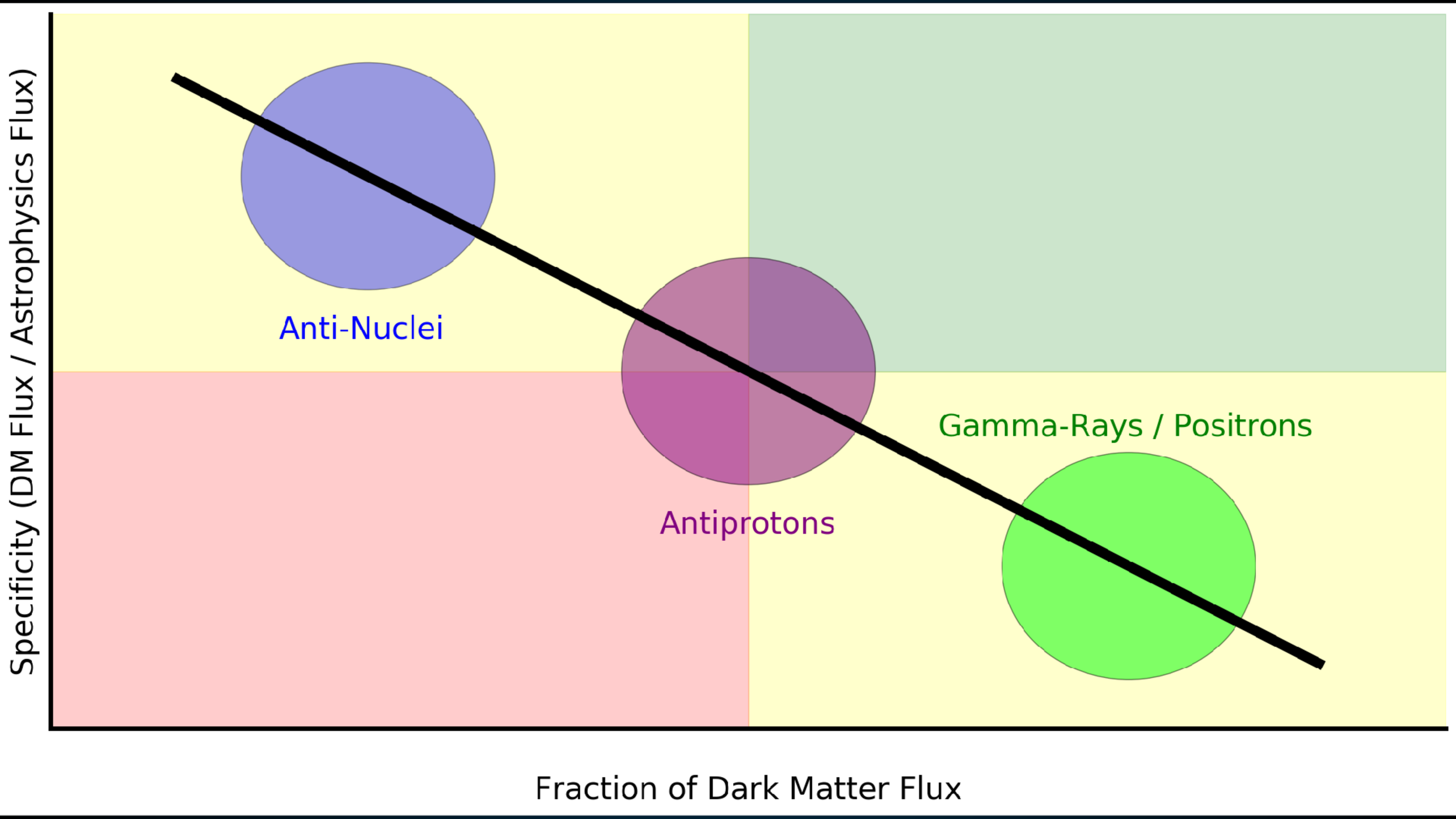


Chang et al. (2019, 1908.10874)
Buschmann et al. (2020, 2002.12373)

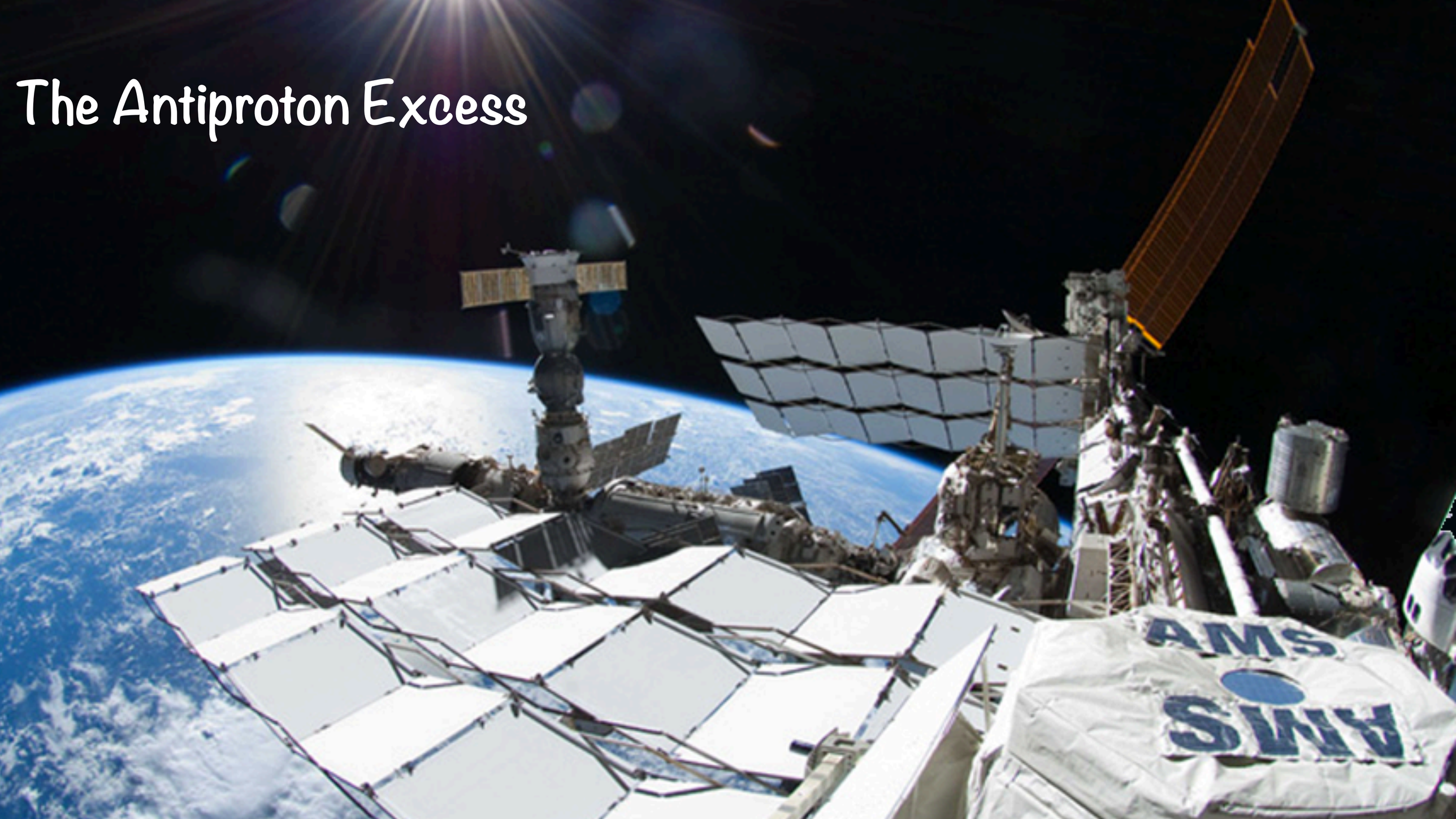




Zhong et al. (2019; 1911.12369)


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

The Antiproton Excess



The Antiproton Excess

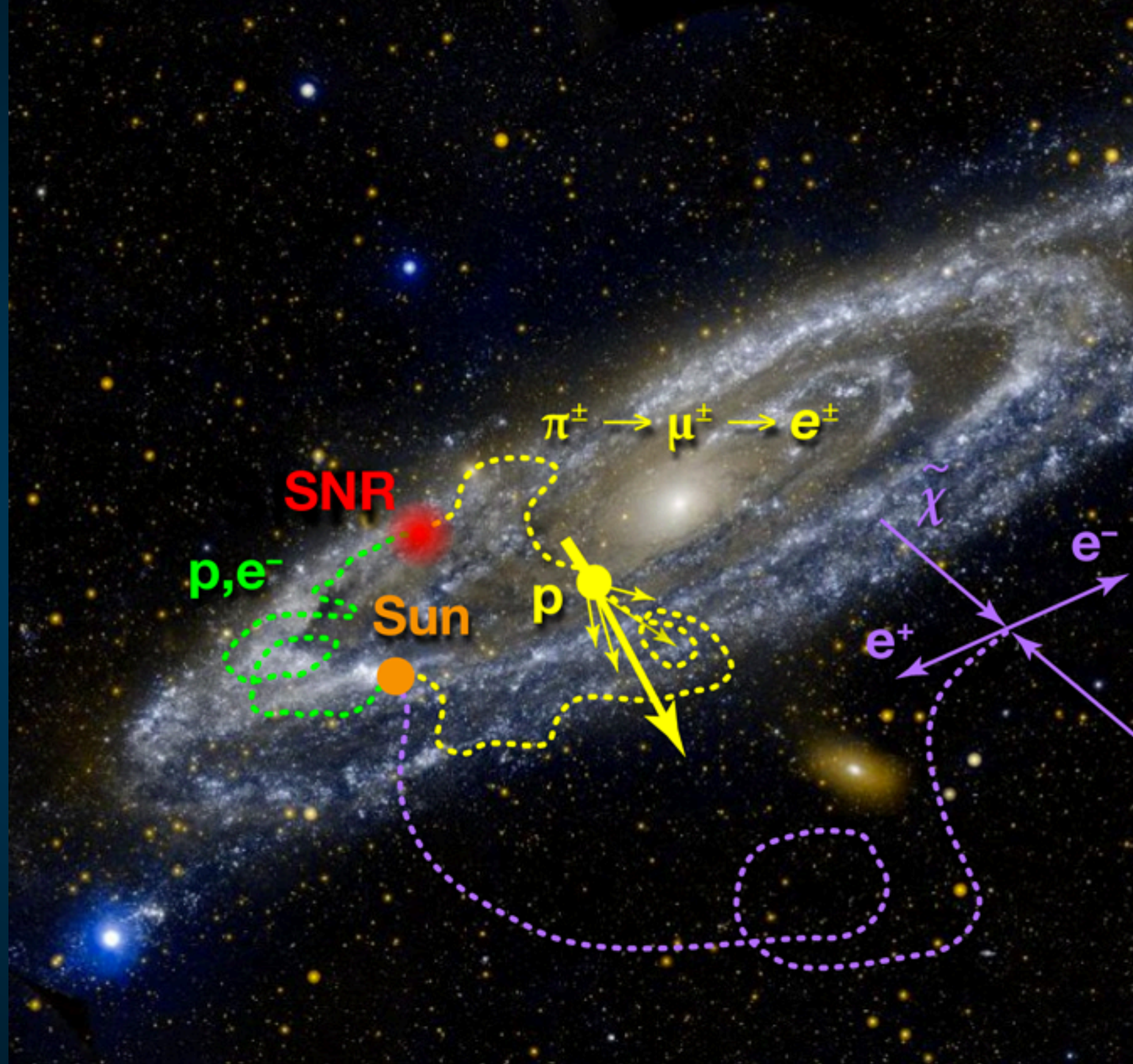
Investigate the Antiproton Fraction!

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

Two Changes:

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

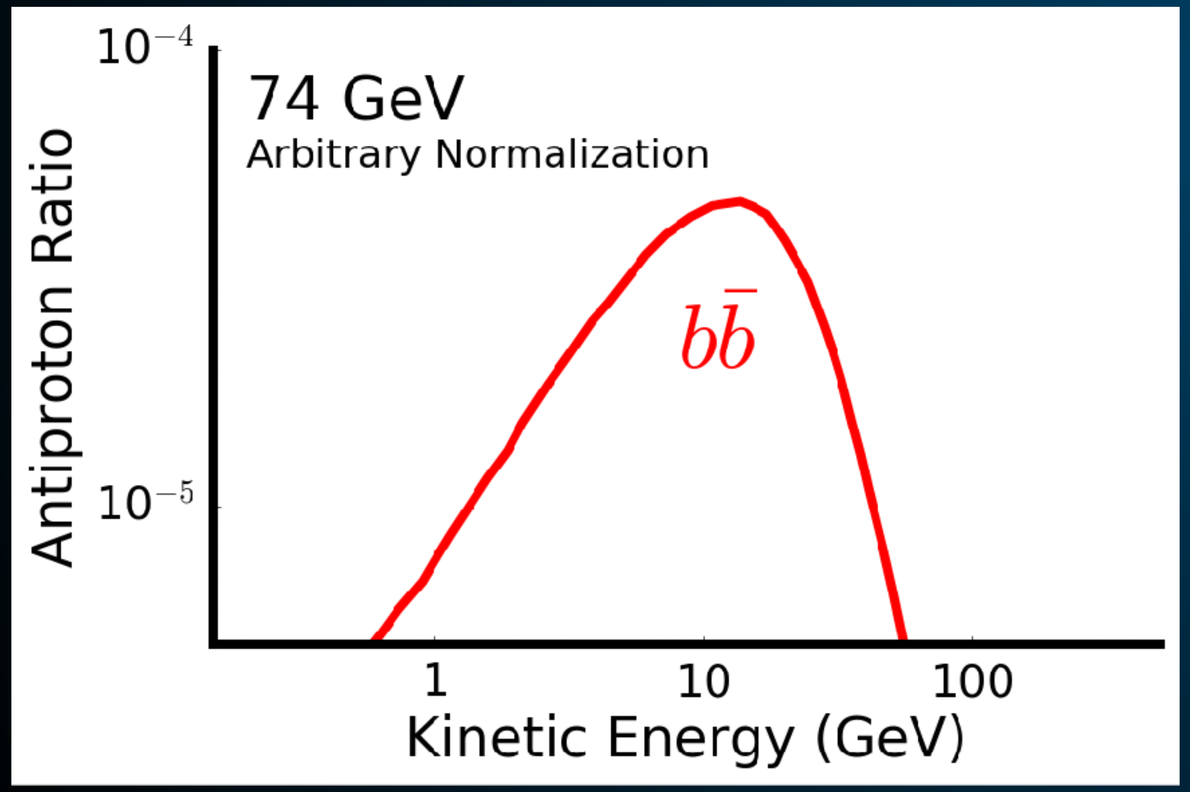
Hadronic Energy losses are slower (sensitive to antiproton production throughout the Galaxy)

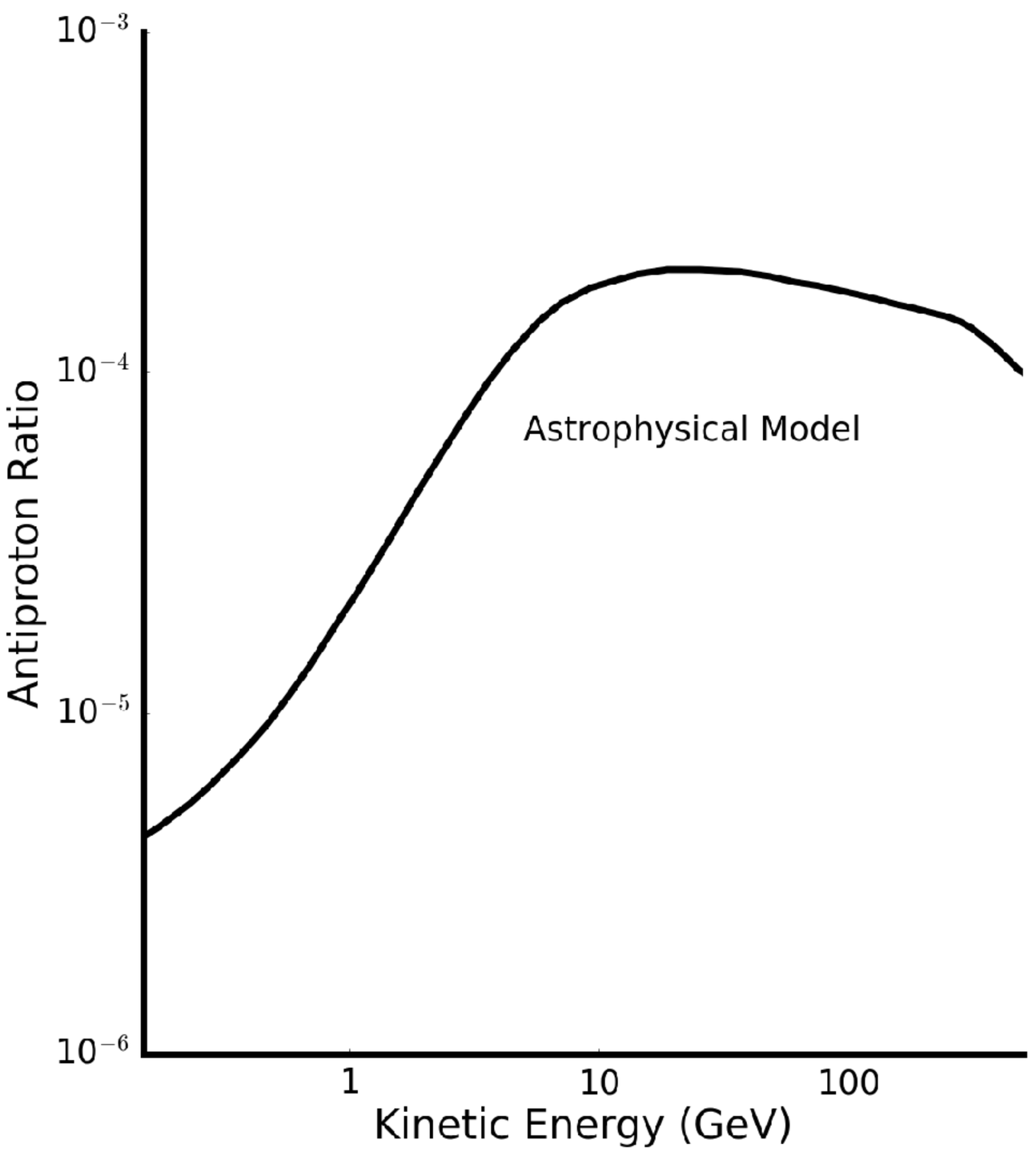


The Antiproton Excess

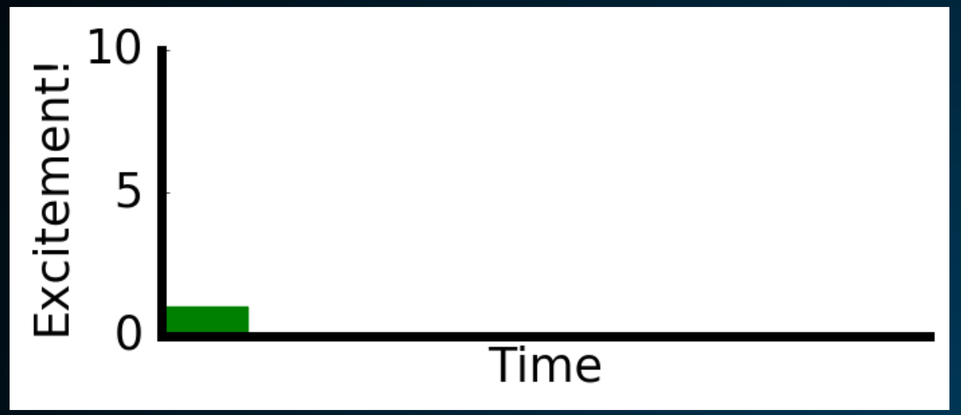
Astrophysics - Smooth Profile

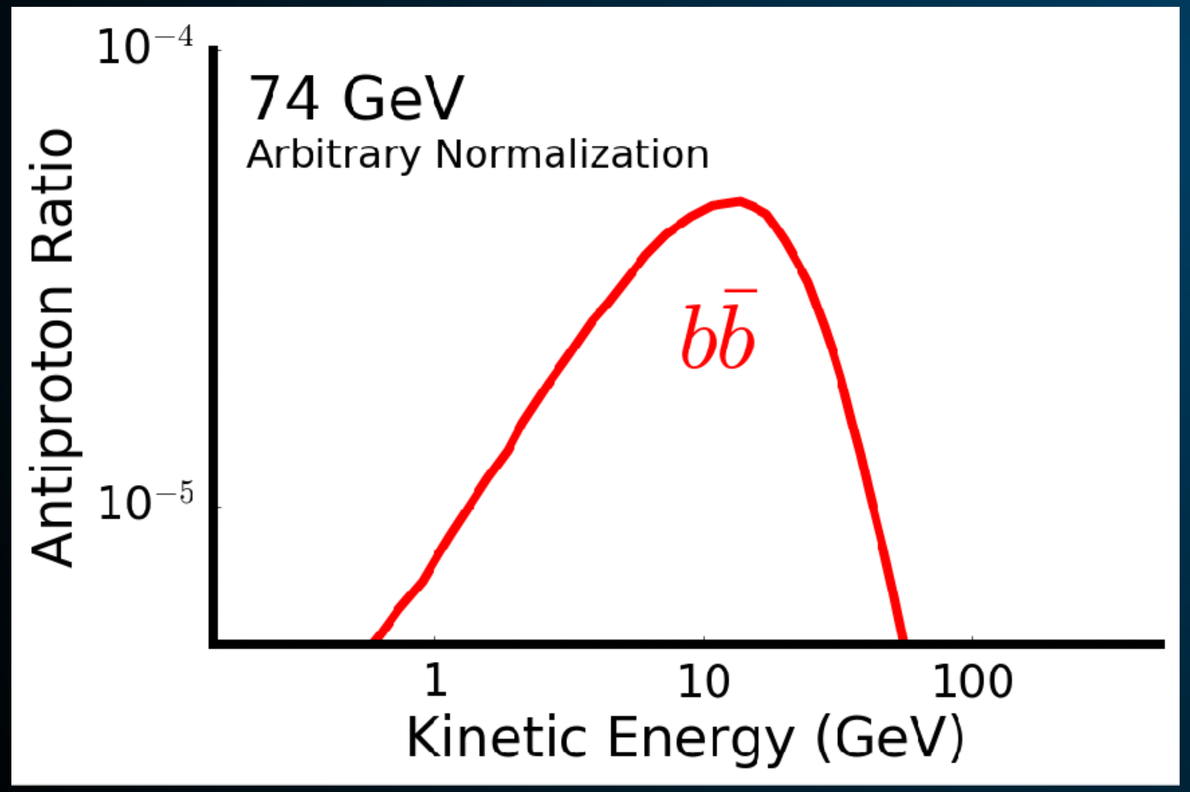
Dark Matter - Sharp Bump!



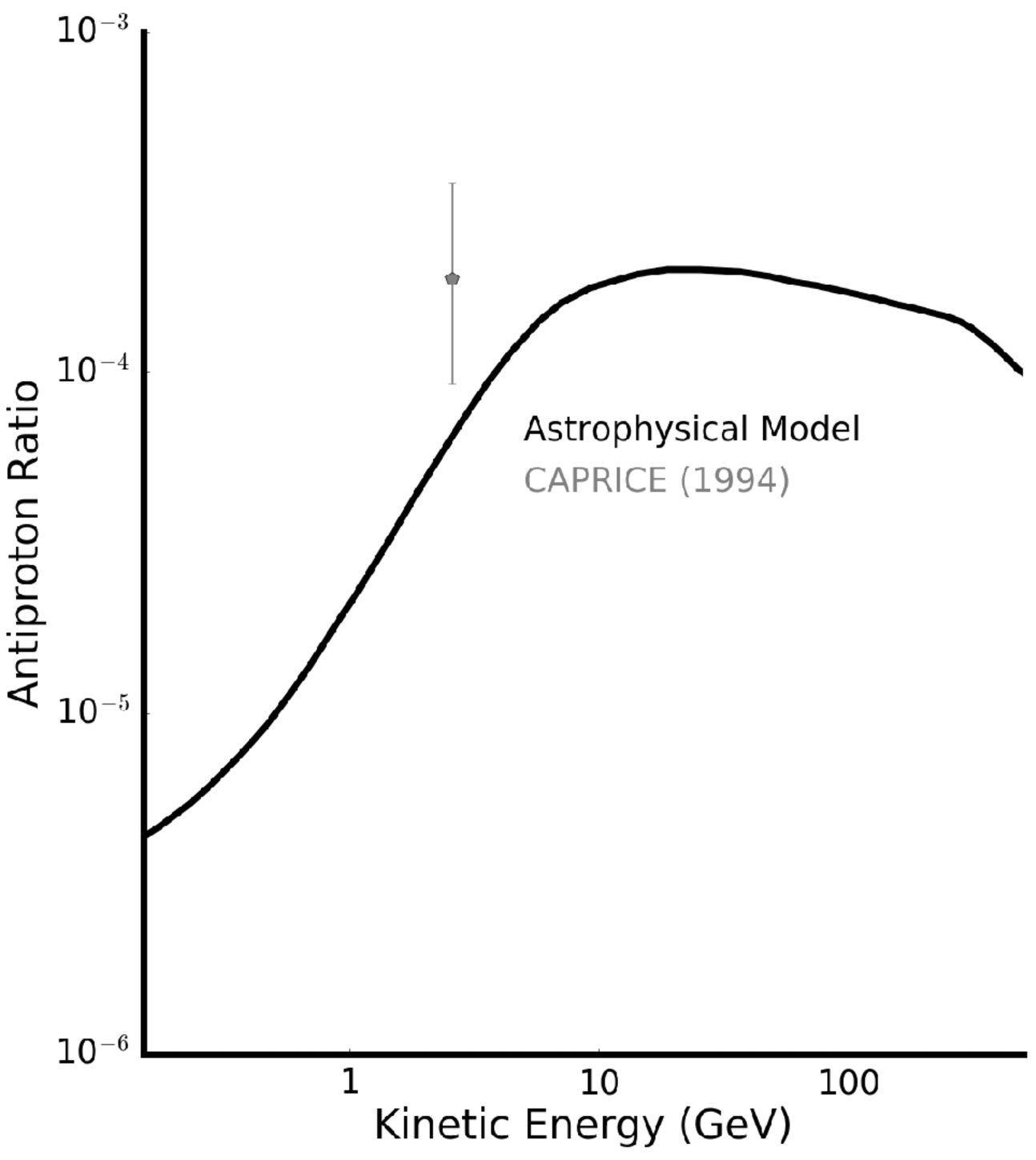


The Antiproton Excess

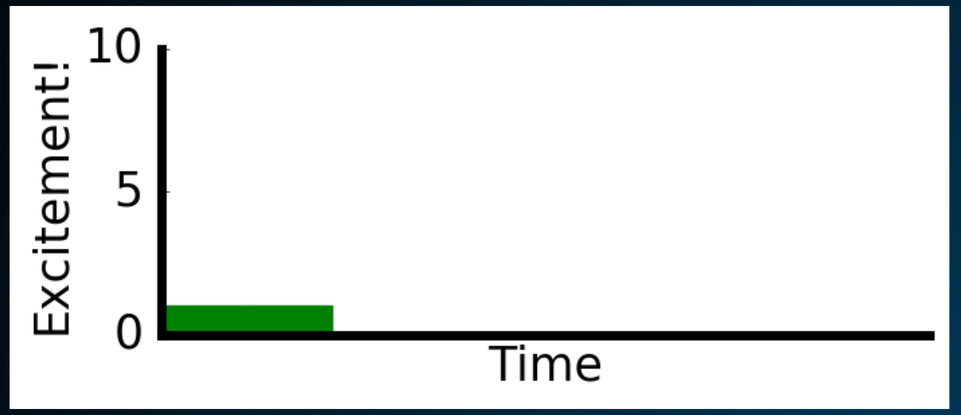


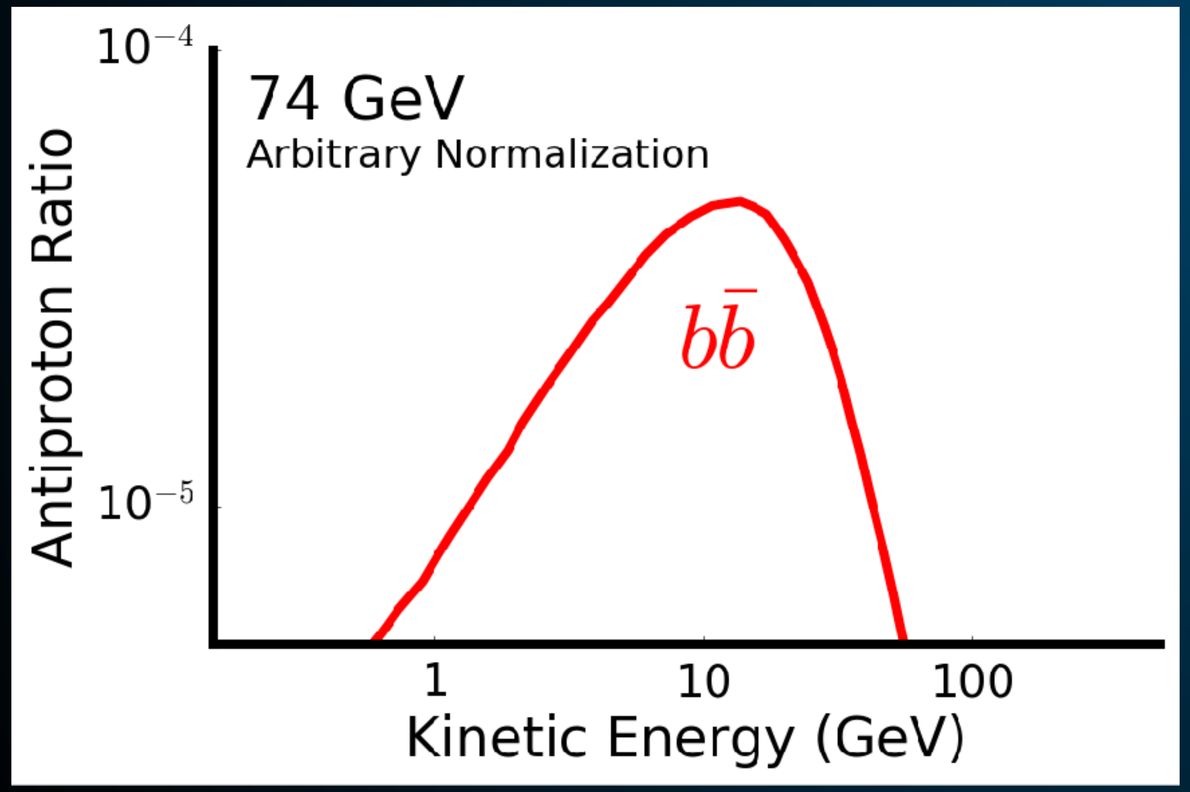


(Not an exhaustive list of observations)



The Antiproton Excess





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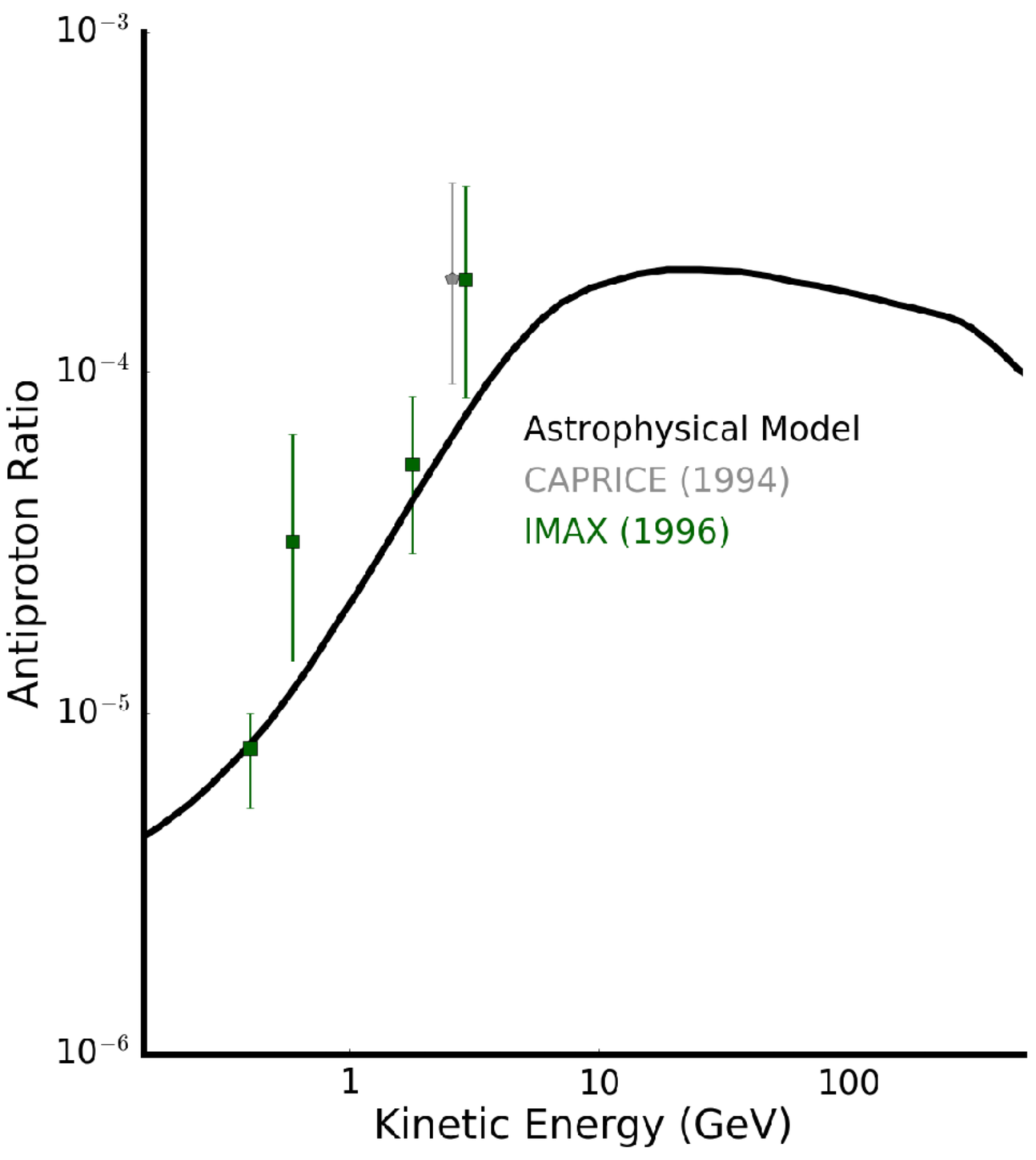
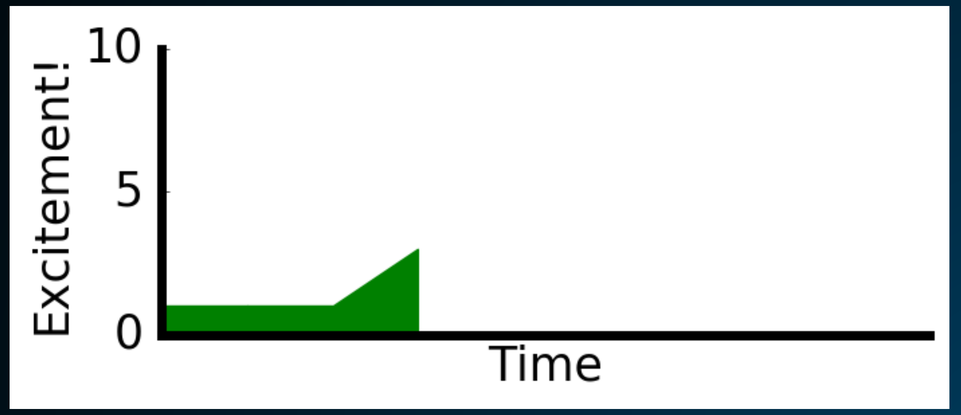
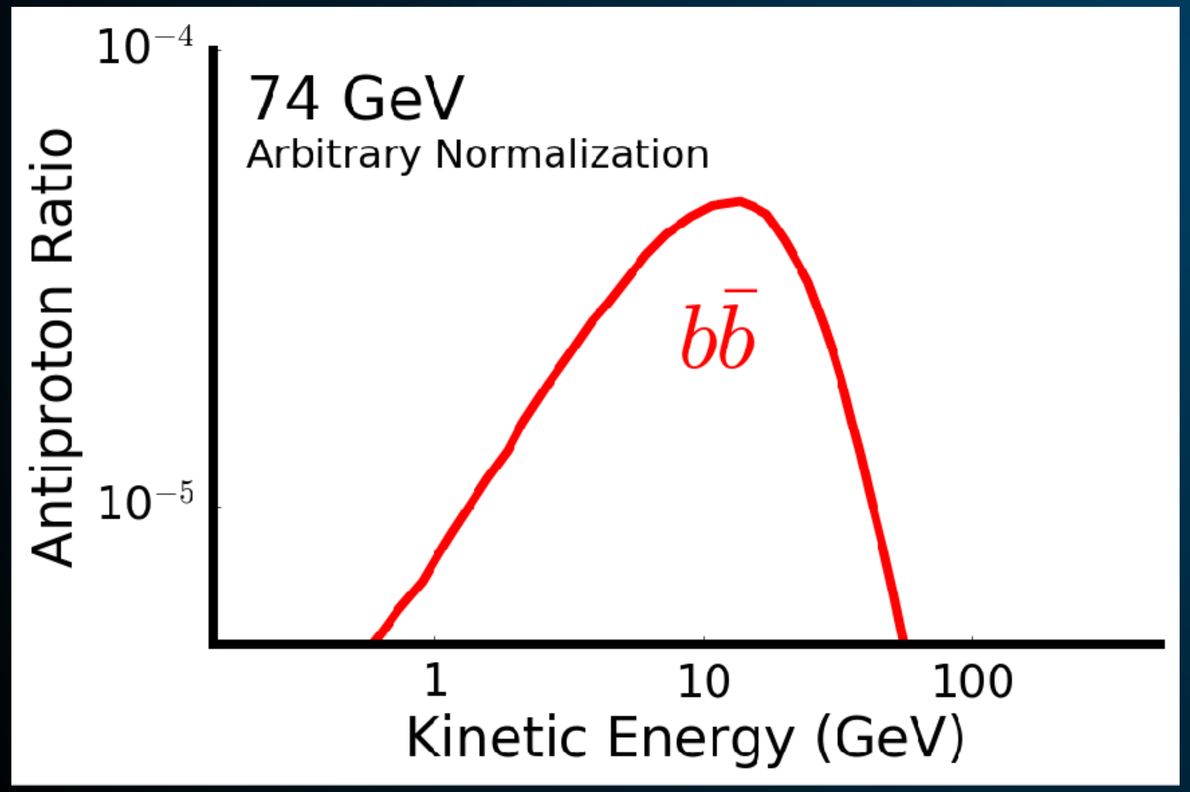
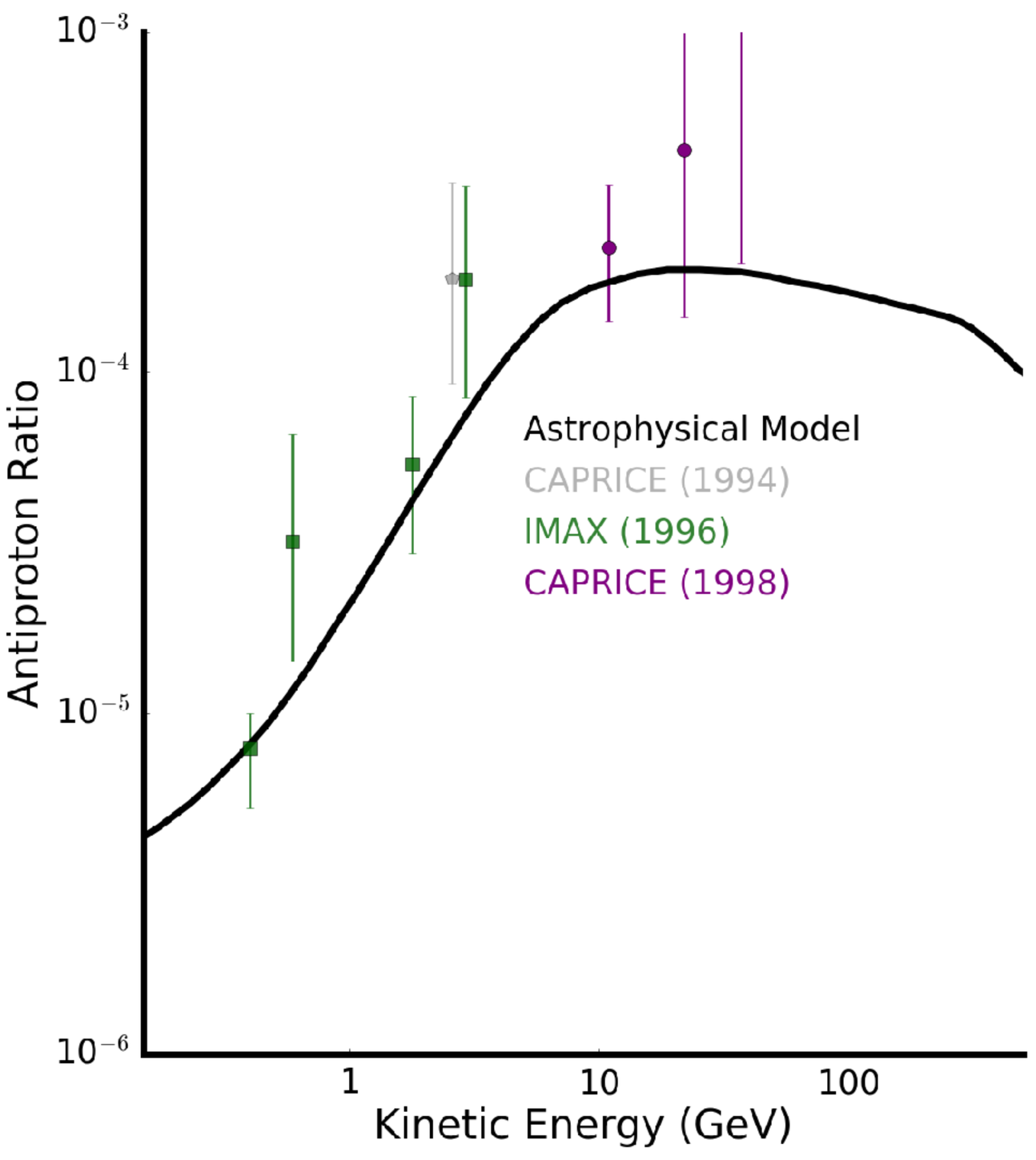


The Antiproton Excess

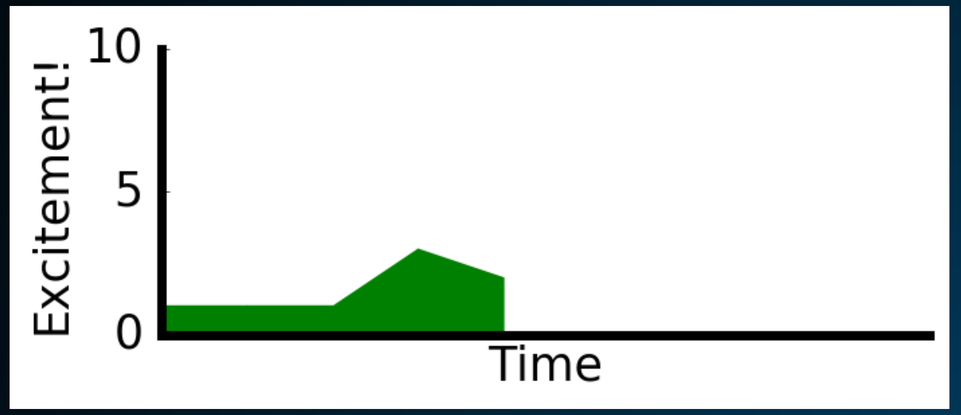


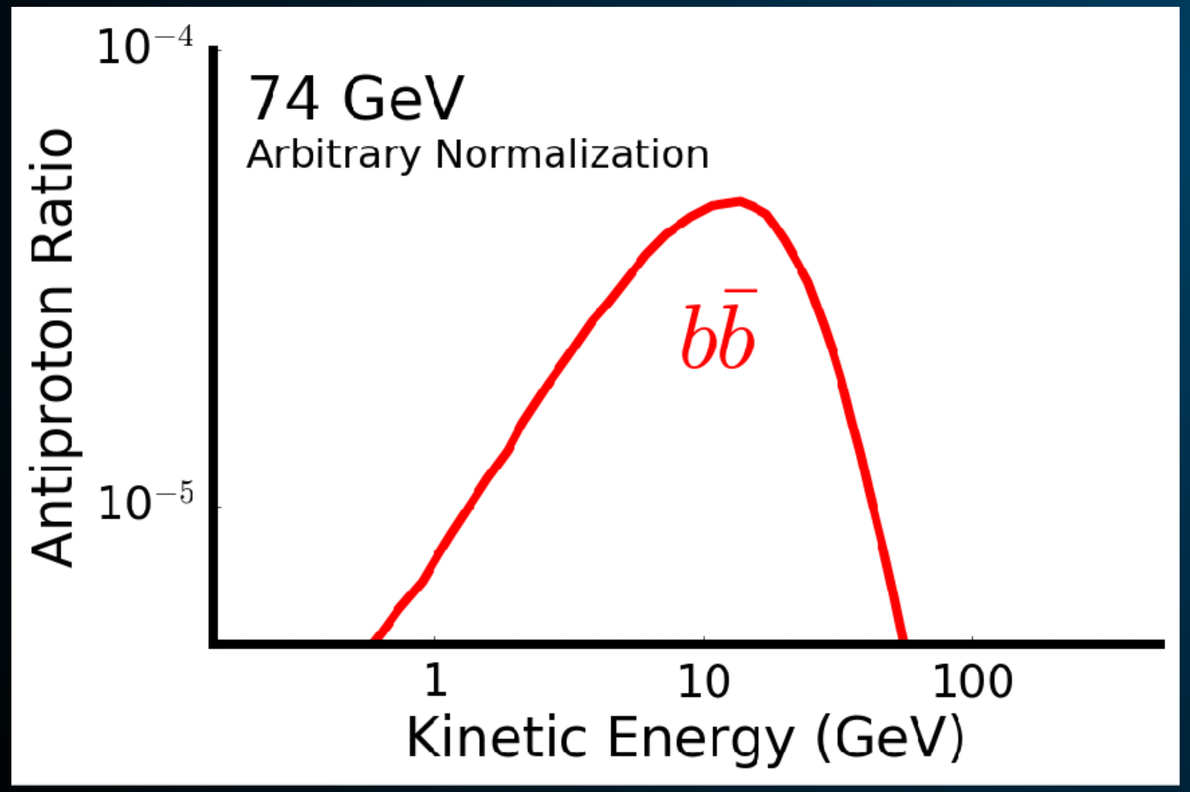


(Not an exhaustive list of observations)

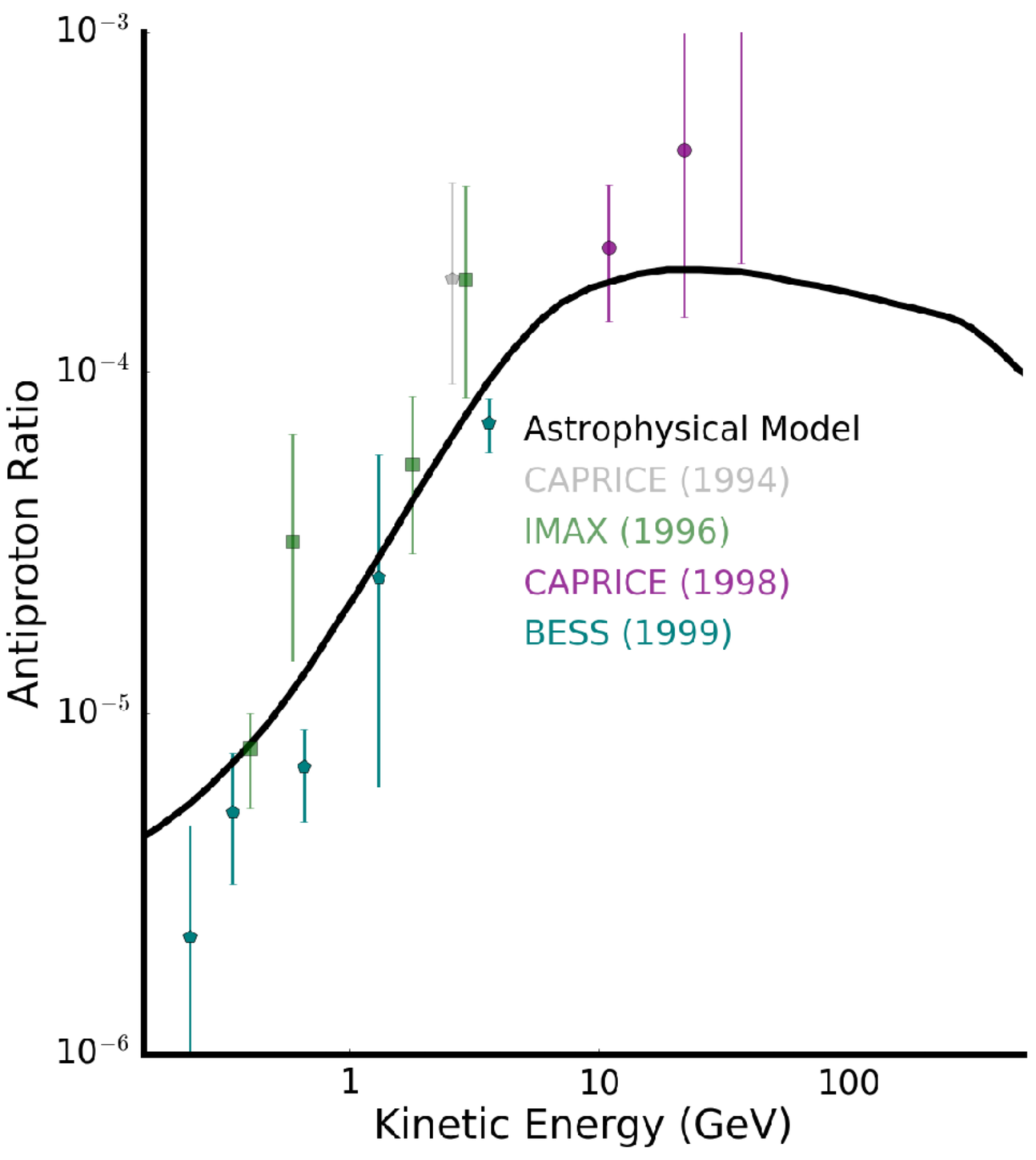


The Antiproton Excess

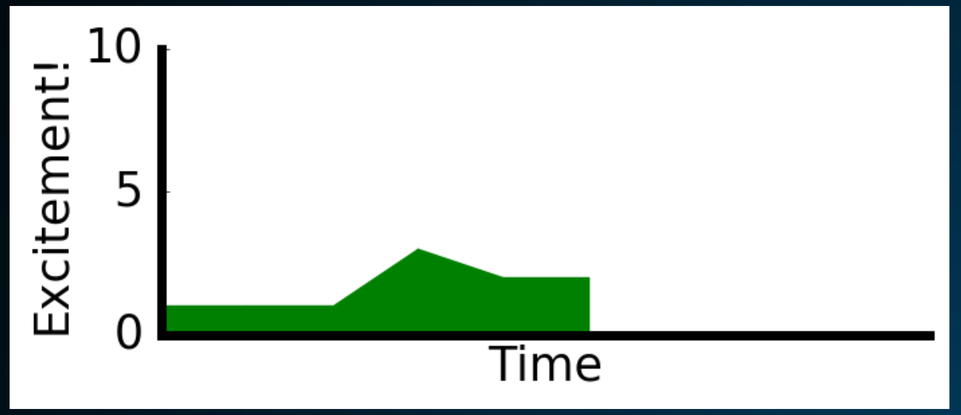


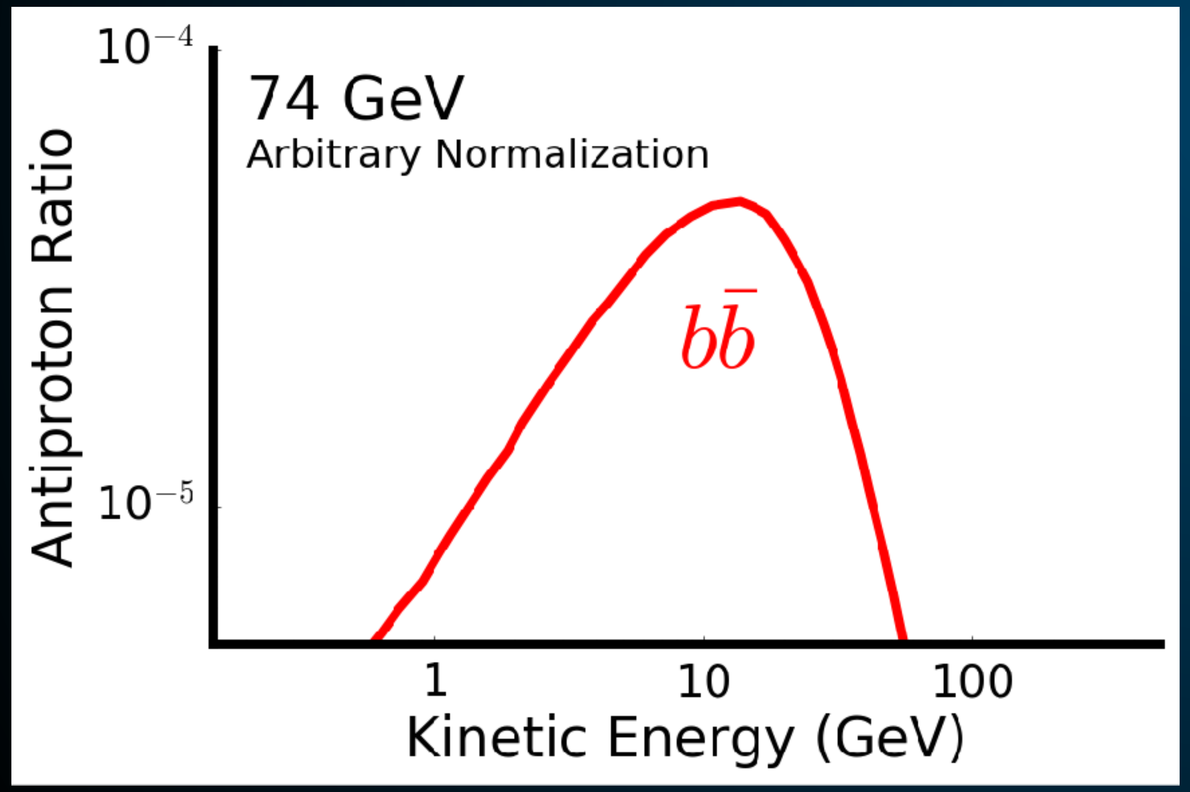


(Not an exhaustive list of observations)

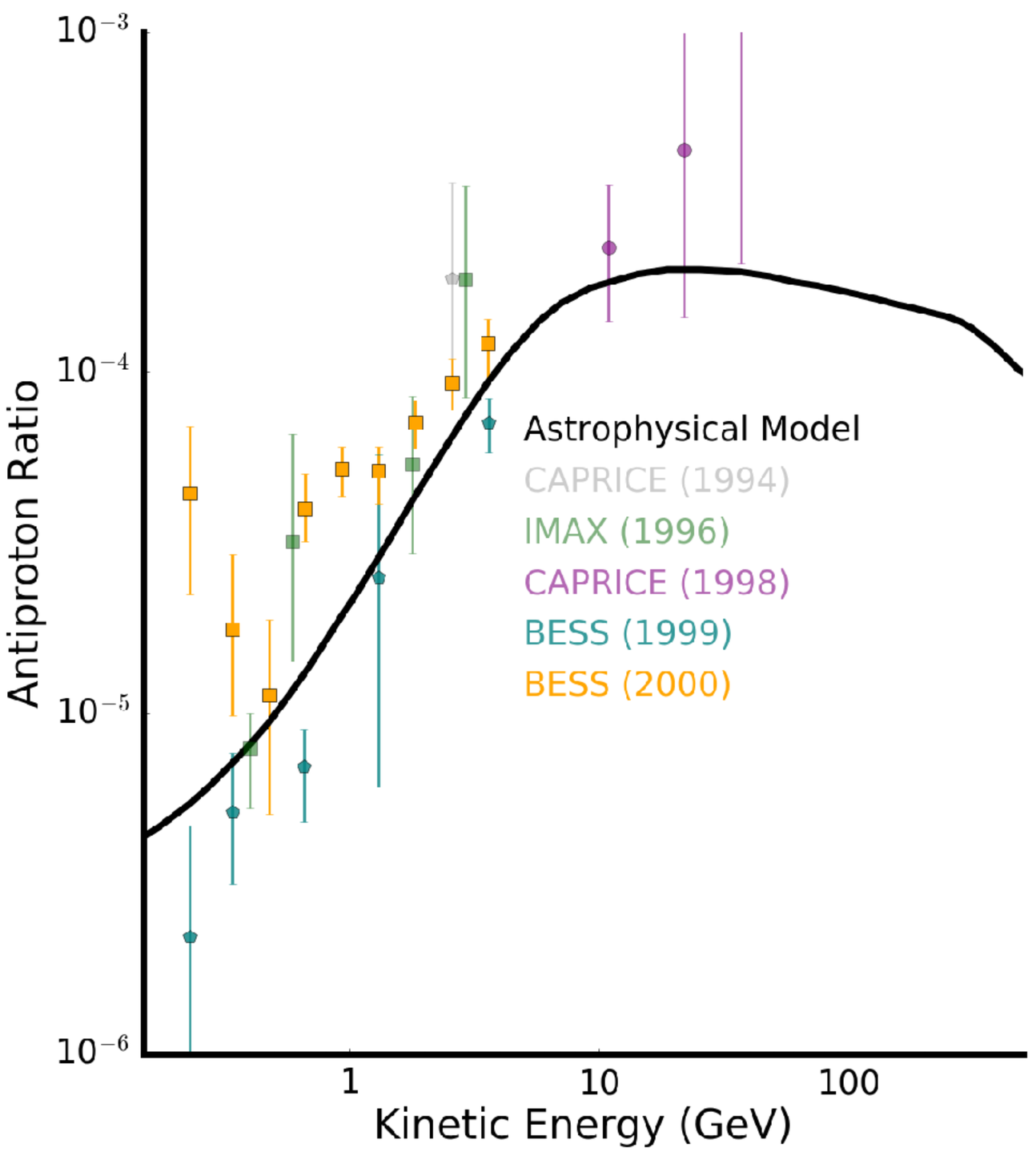


The Antiproton Excess

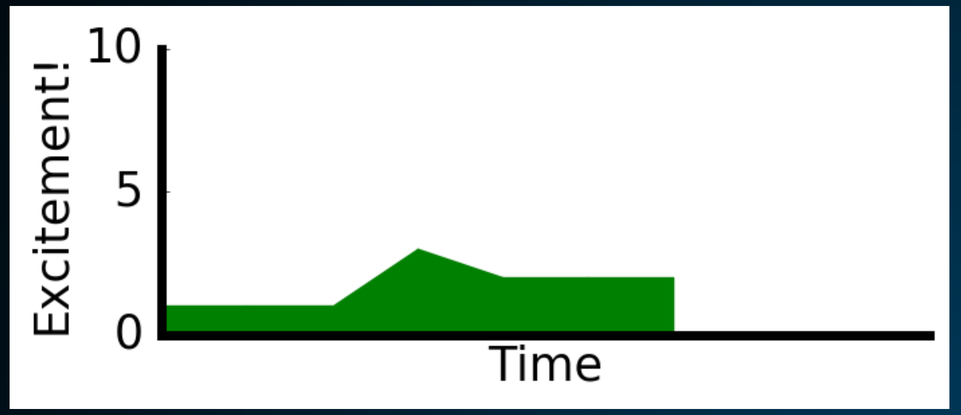


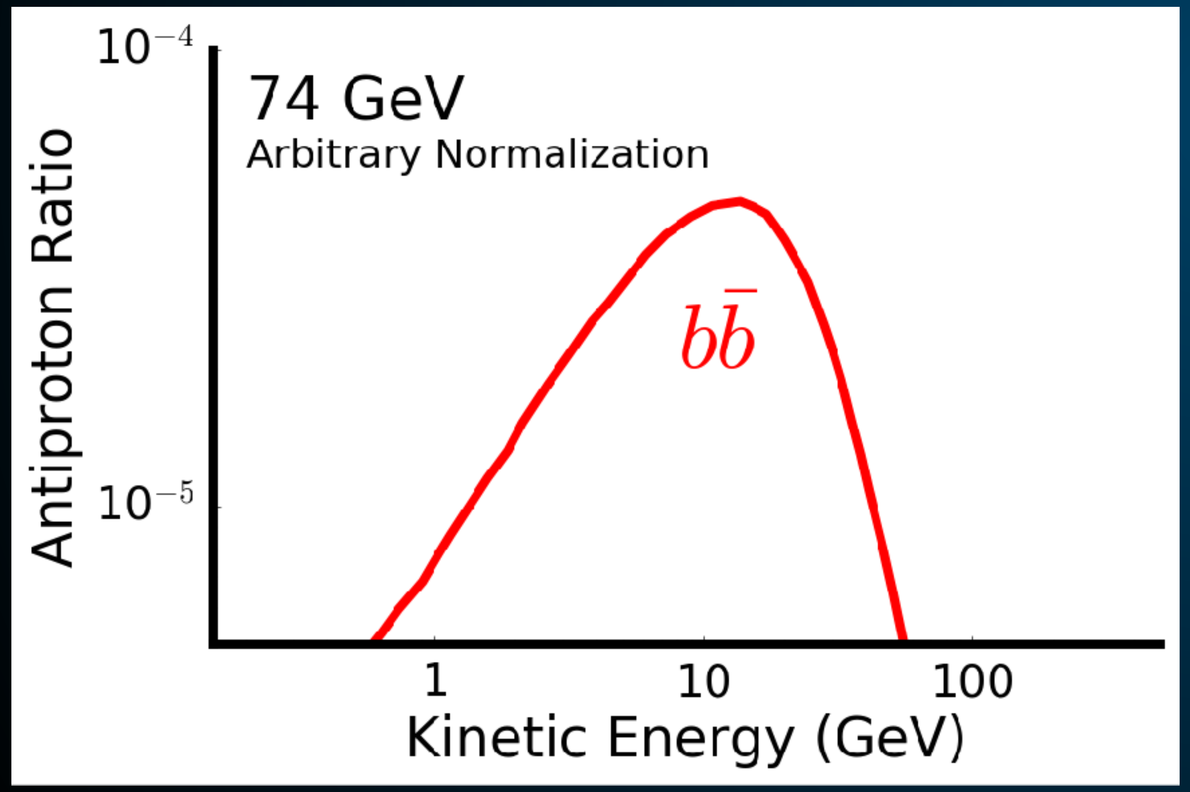


(Not an exhaustive list of observations)



The Antiproton Excess





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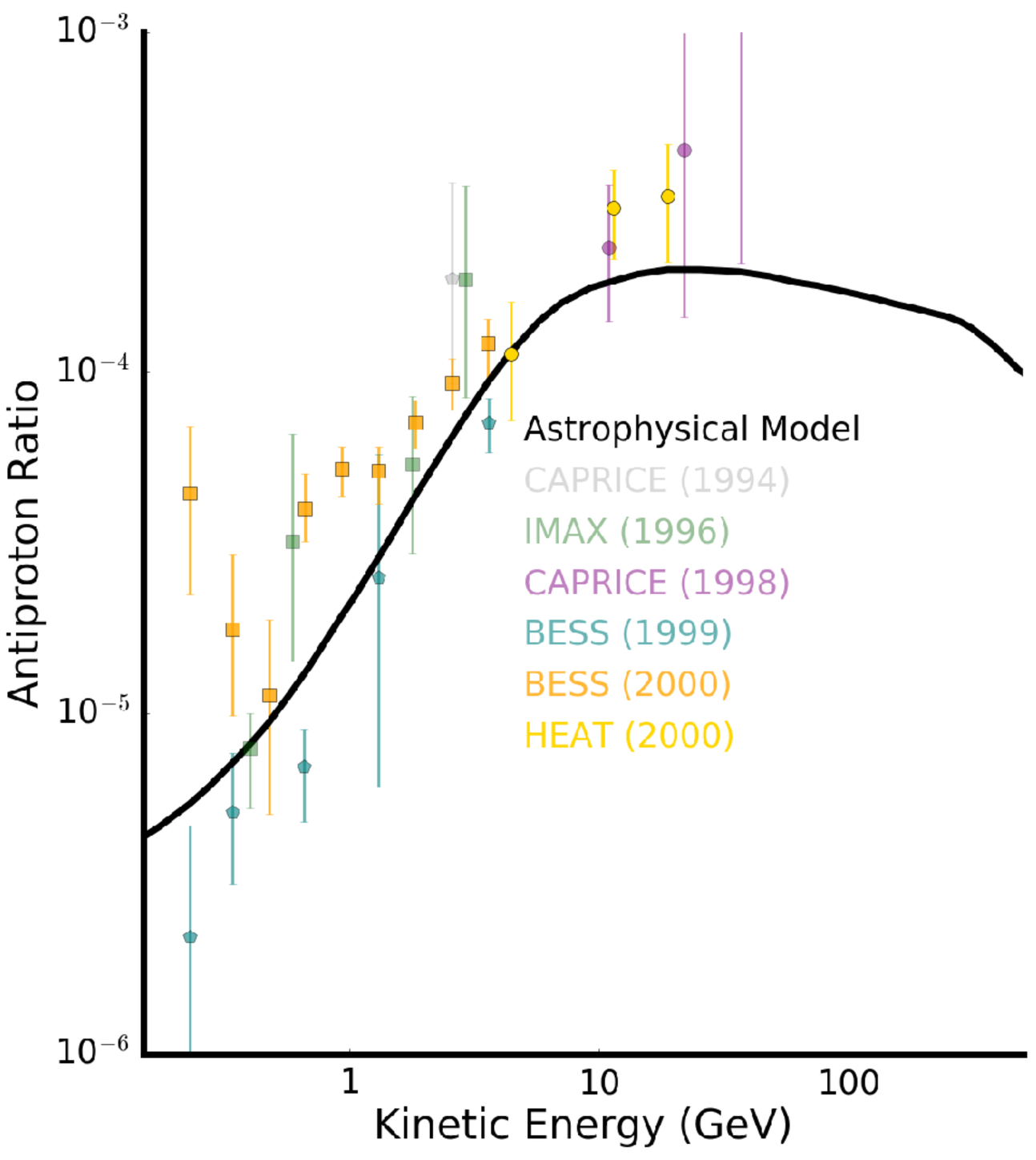
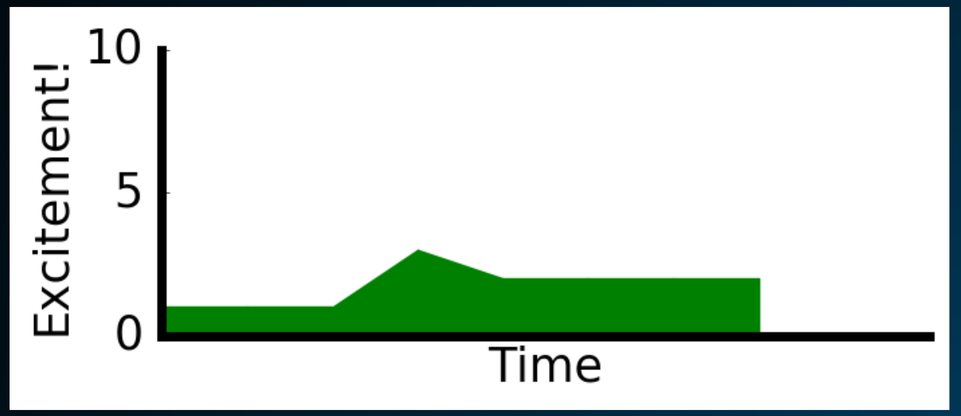
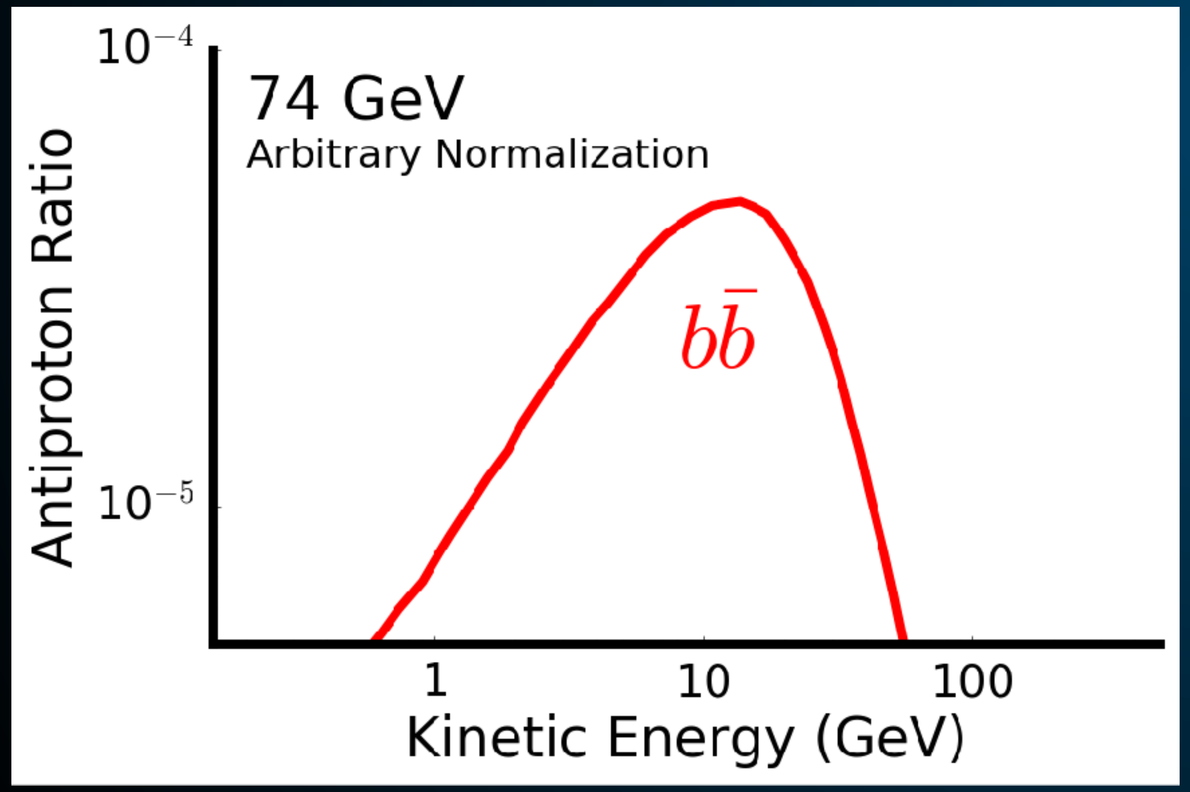


The Antiproton Excess





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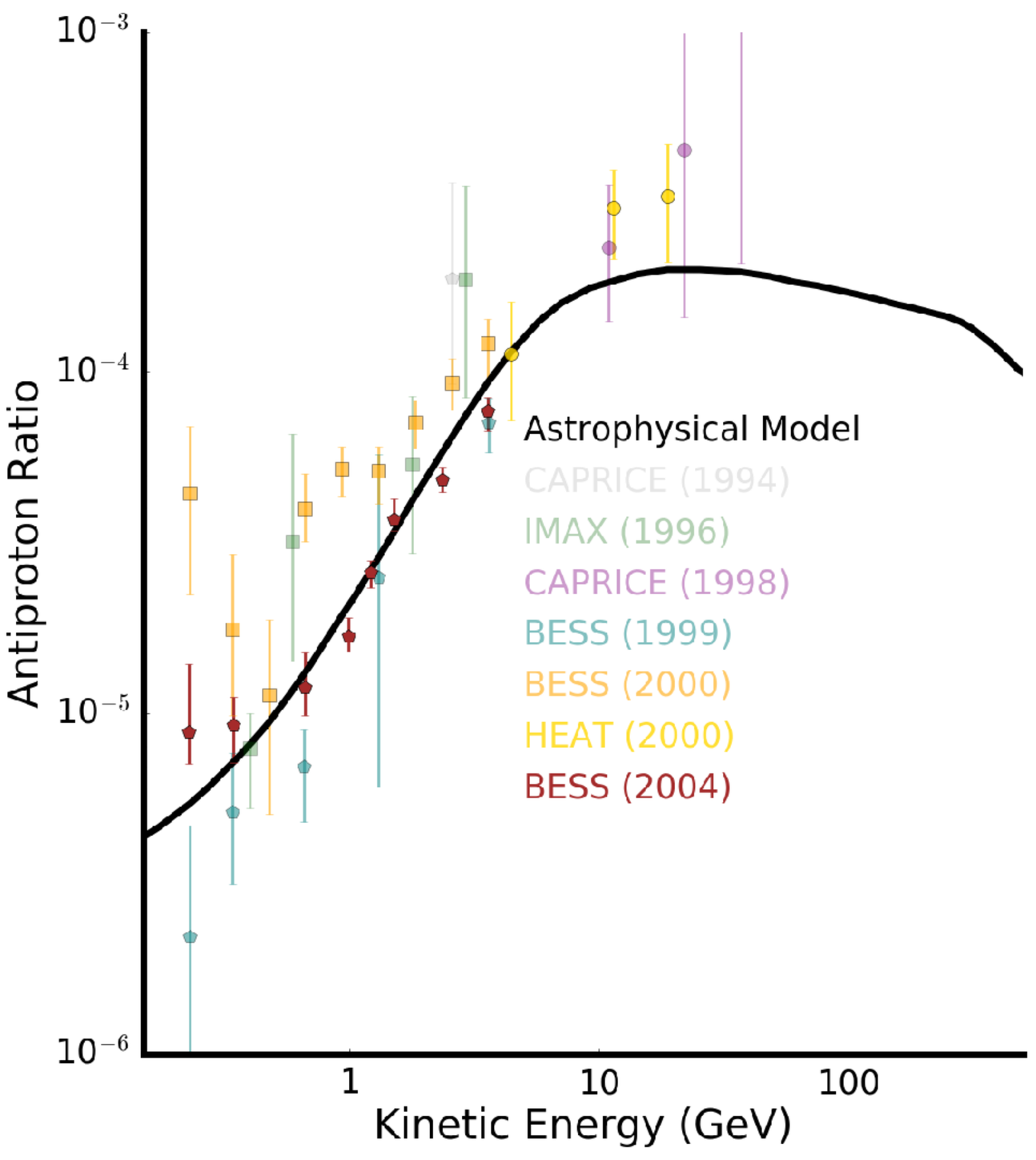
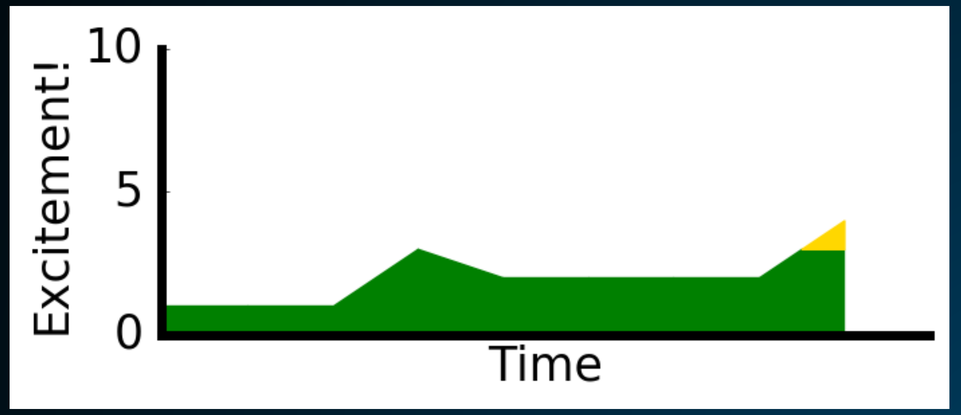
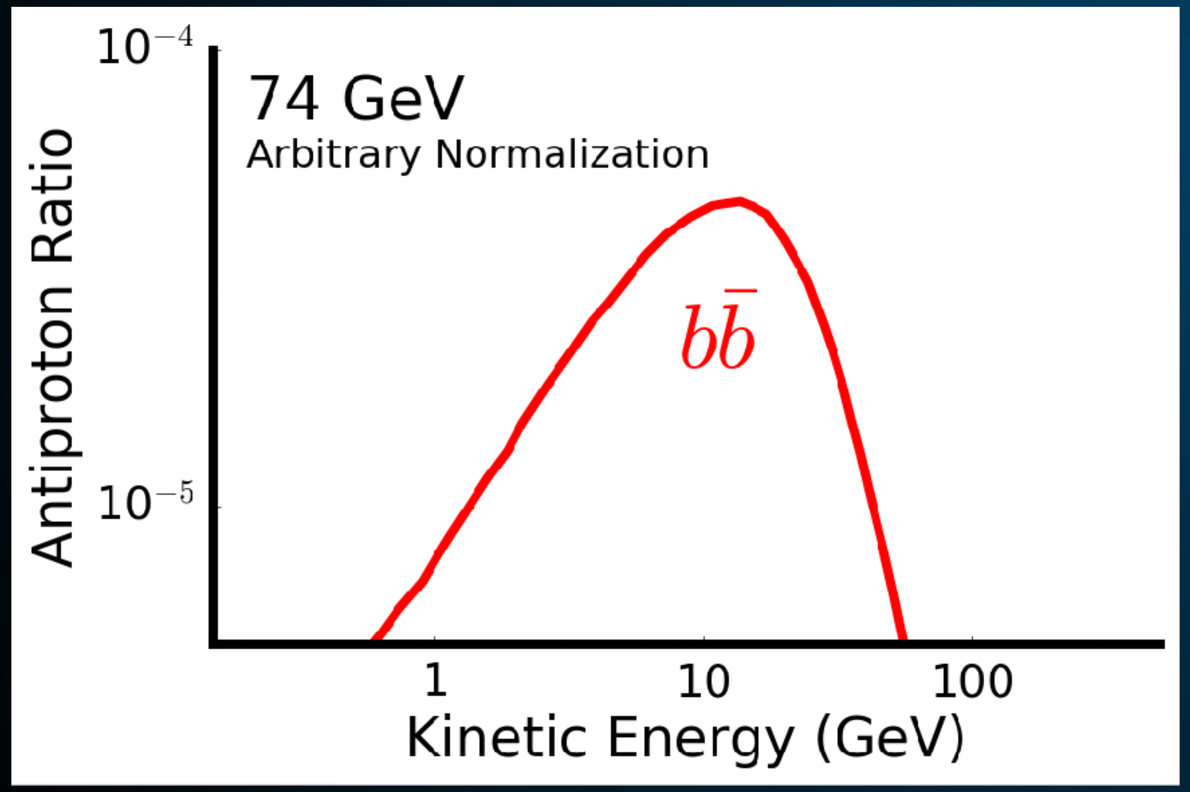


The Antiproton Excess





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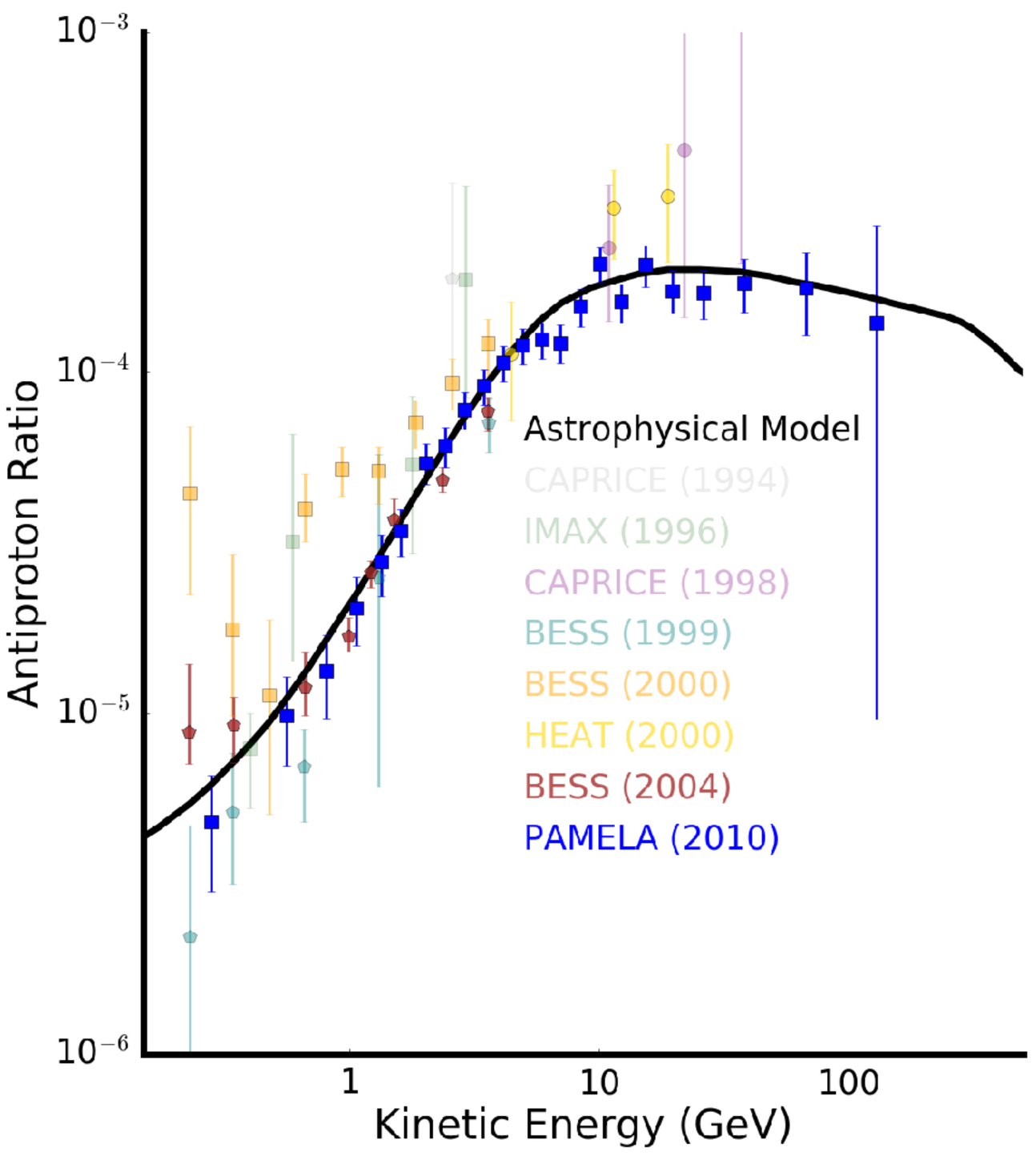
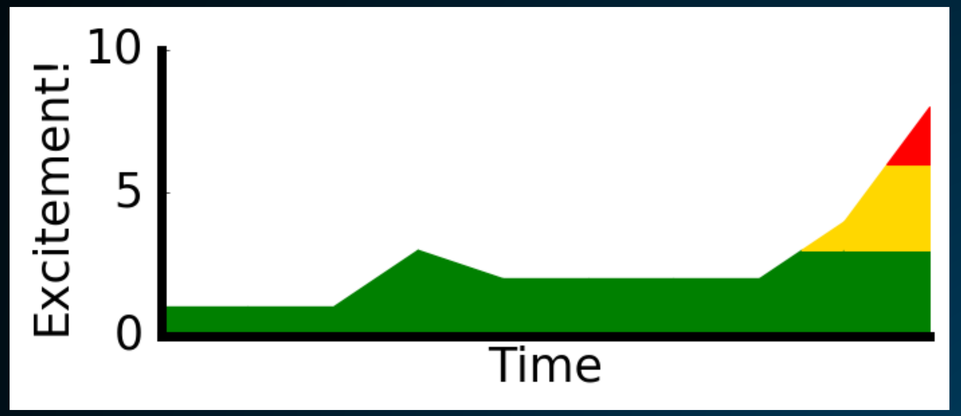
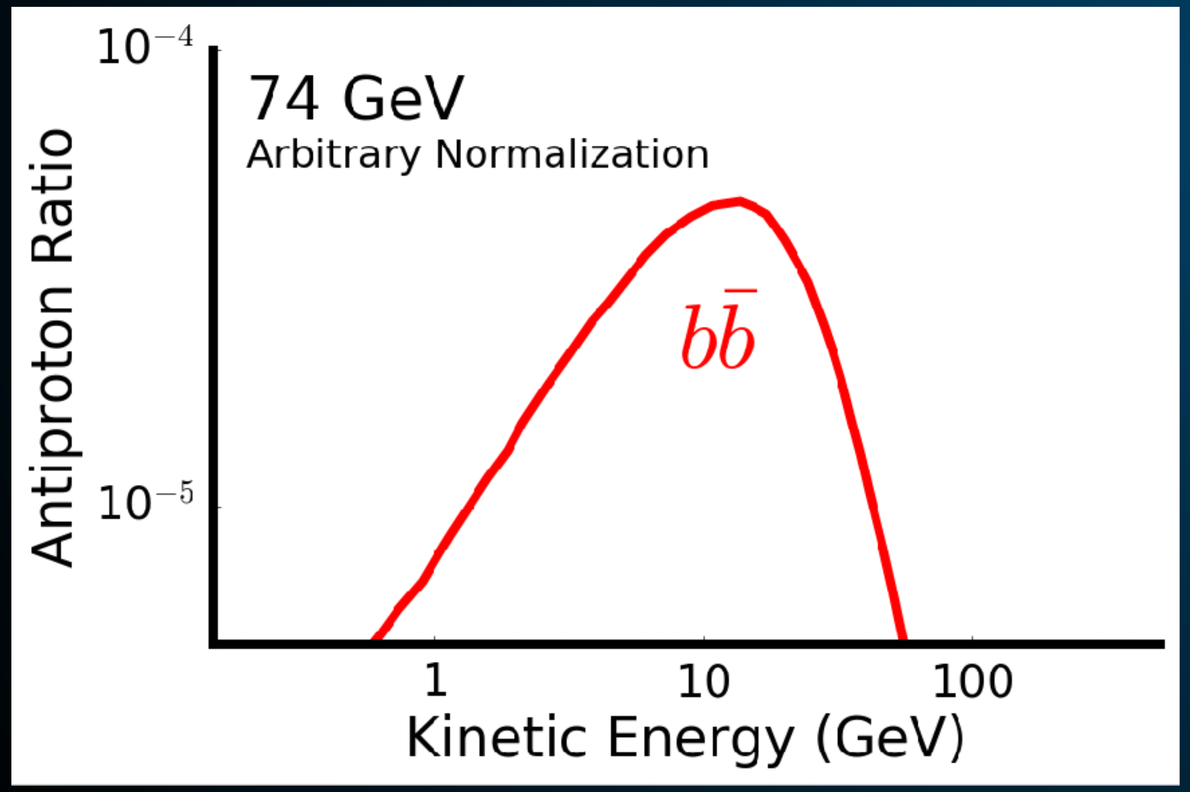
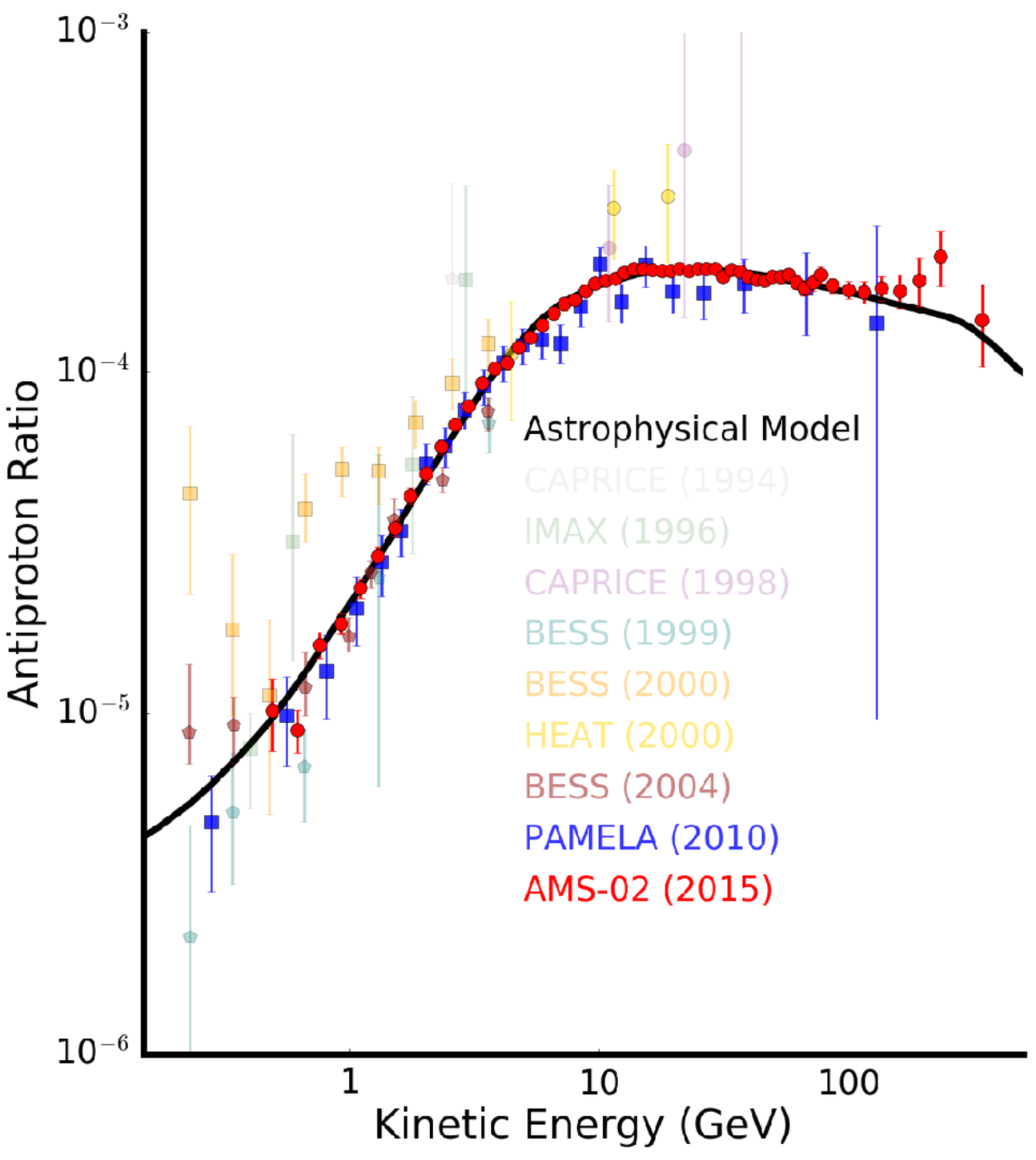


The Antiproton Excess

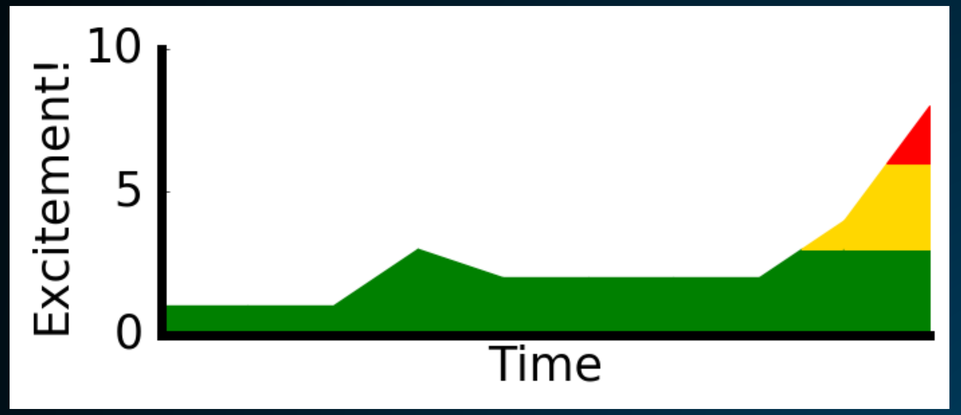


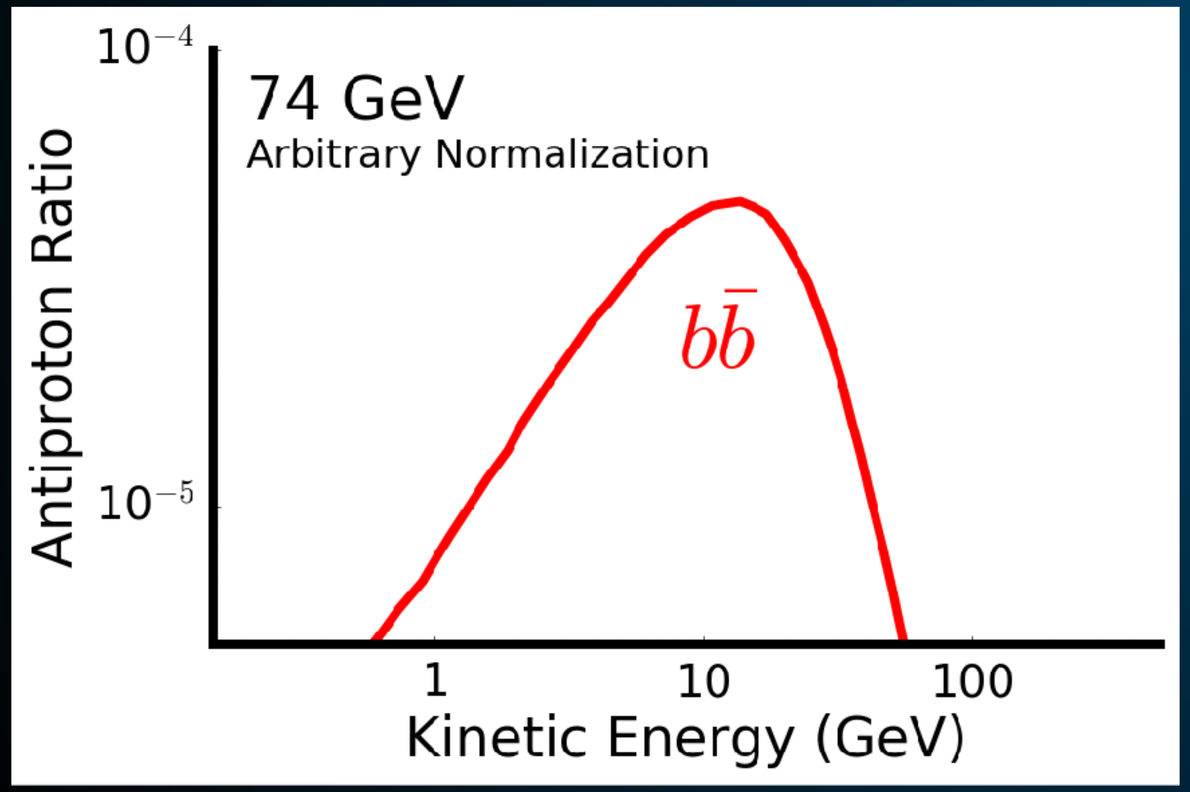


(Not an exhaustive list of observations)

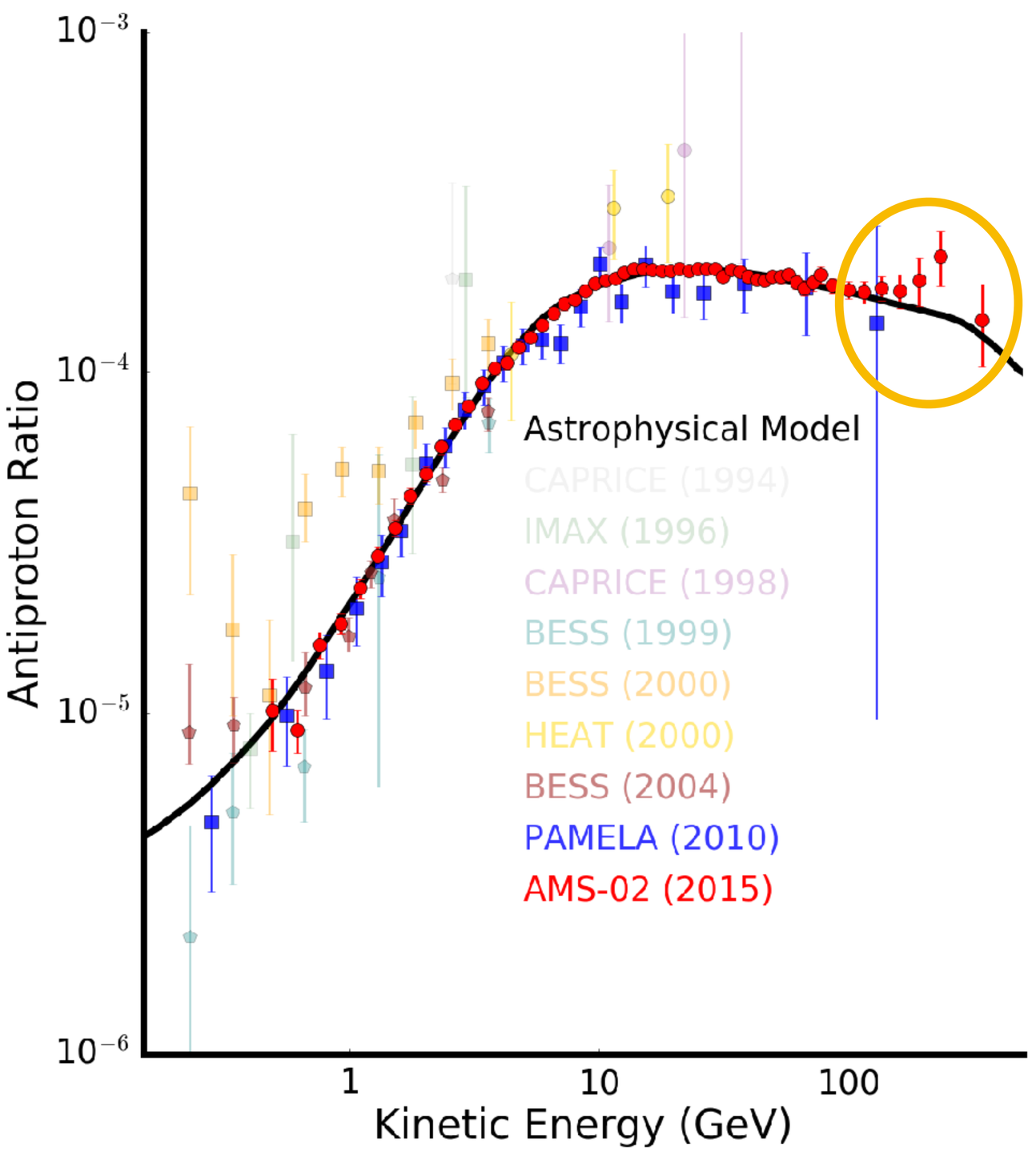


The Antiproton Excess

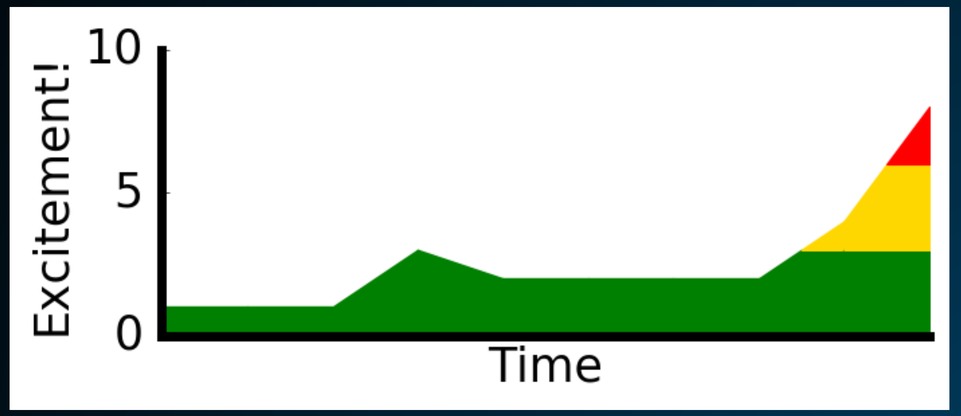


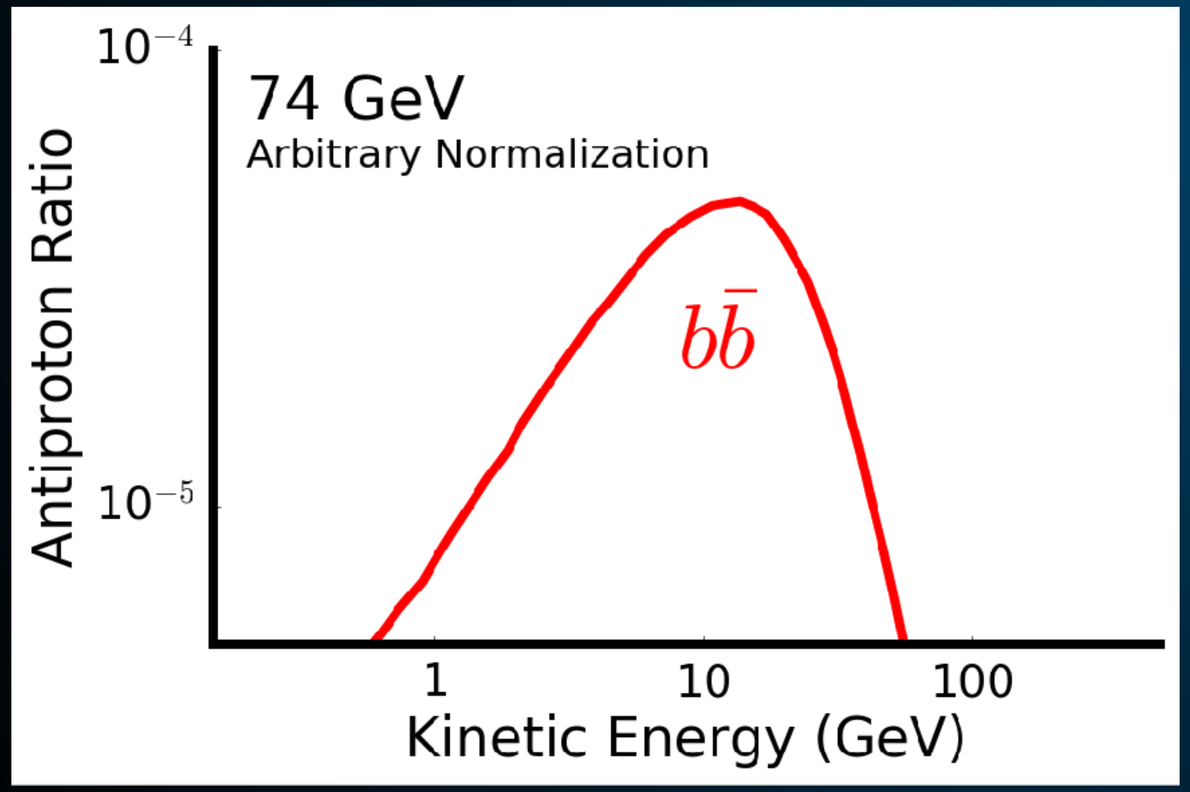


(Not an exhaustive list of observations)



The Antiproton Excess





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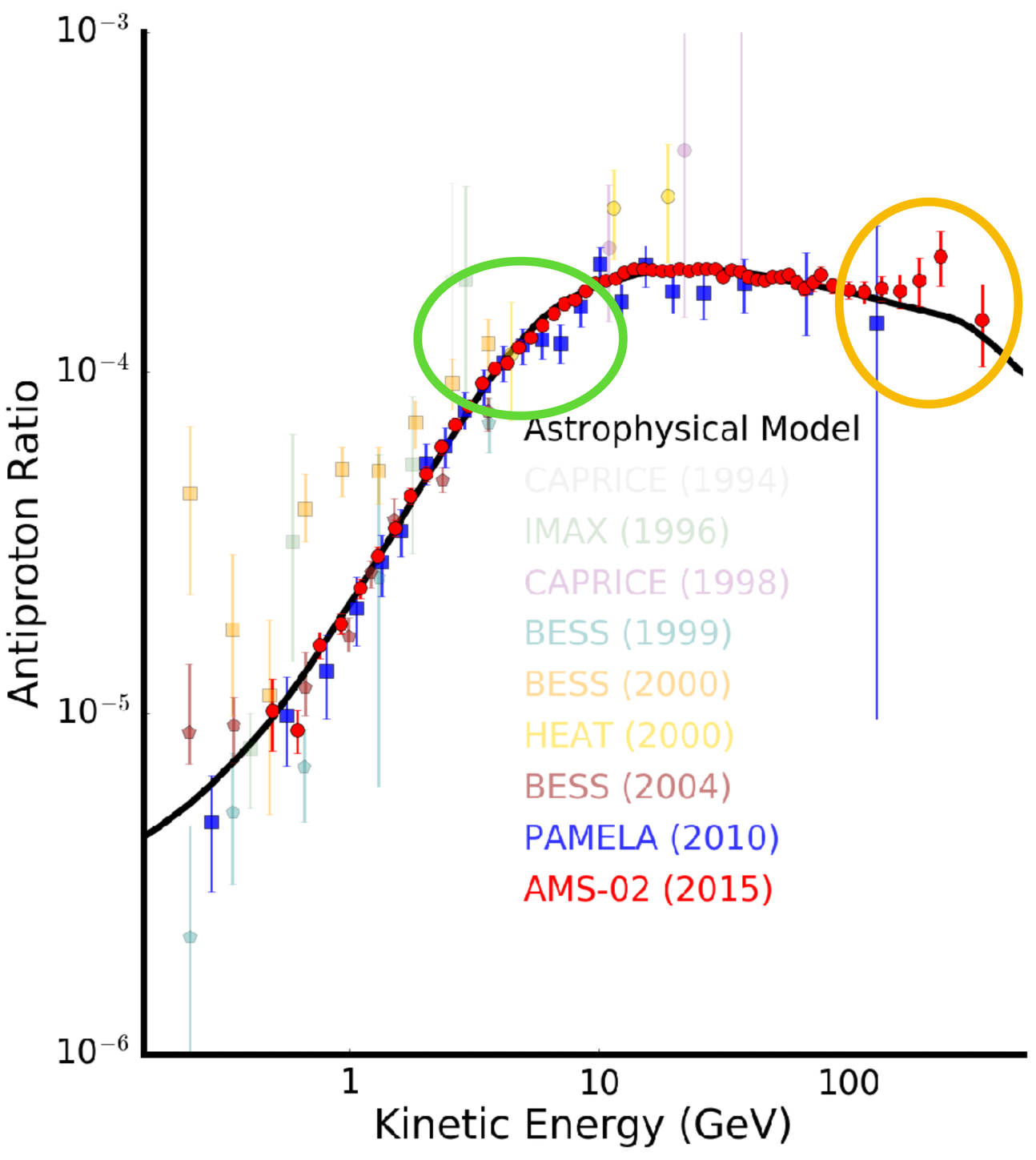
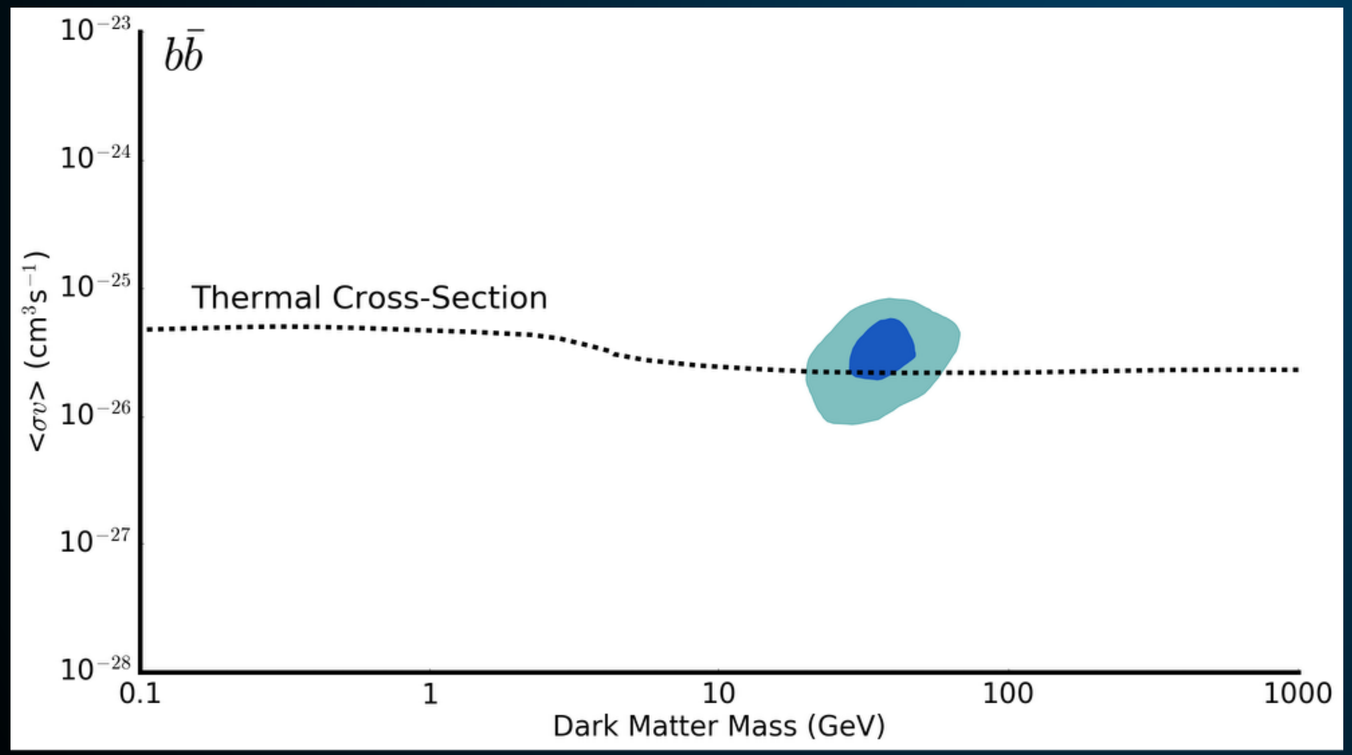
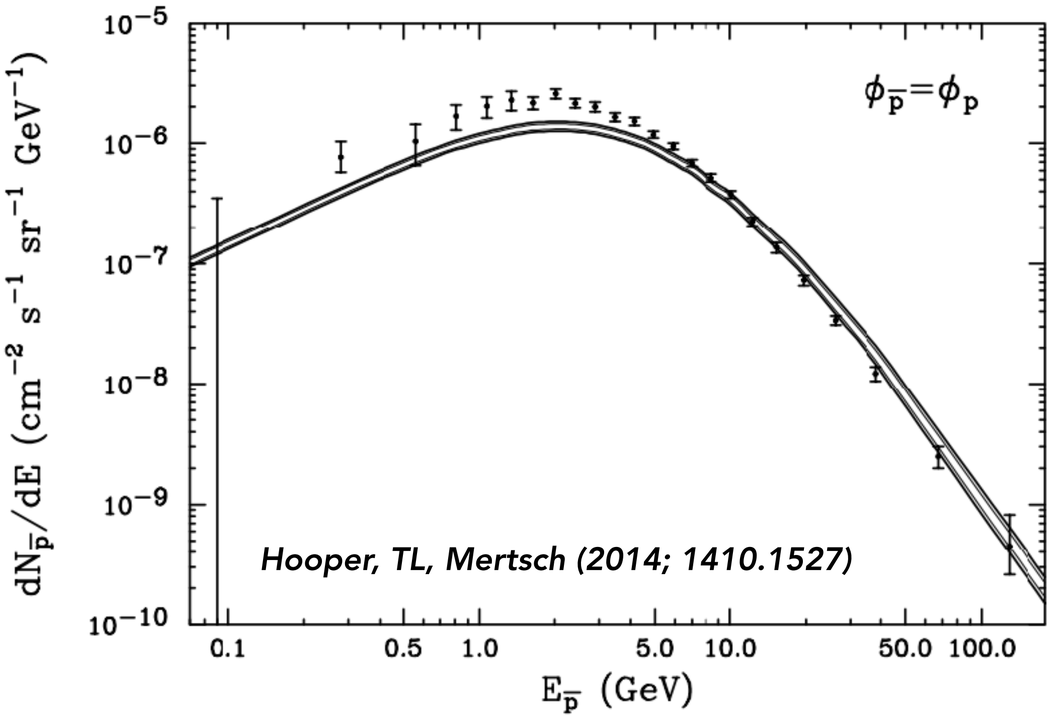


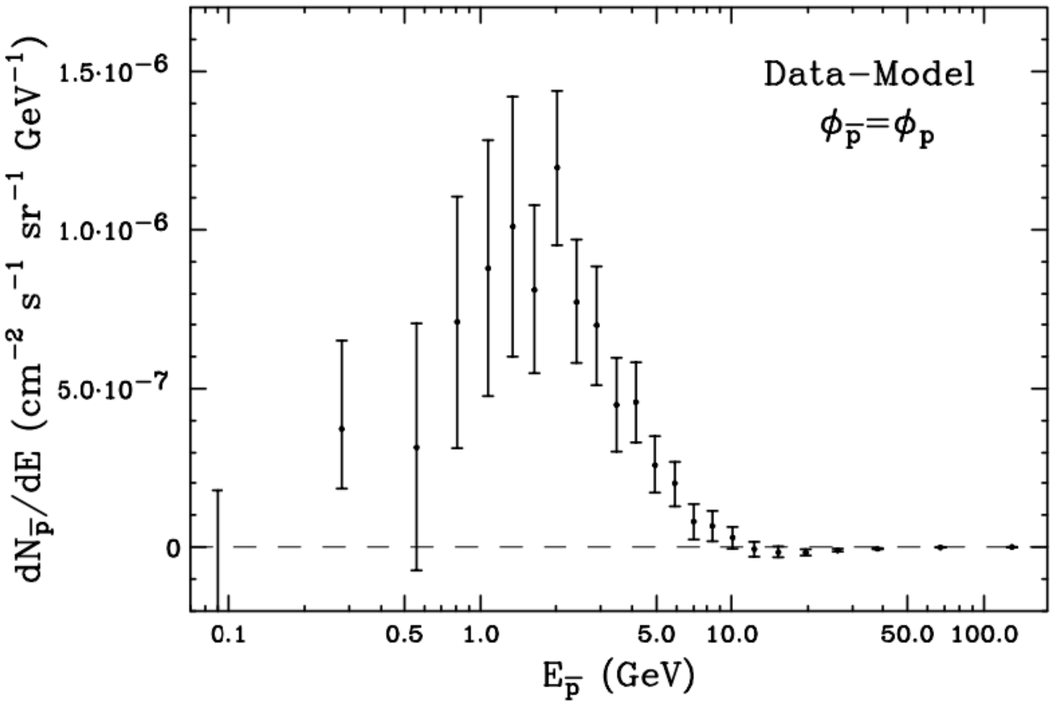
The Antiproton Excess

Hint of Excess in ~5 GeV antiprotons!

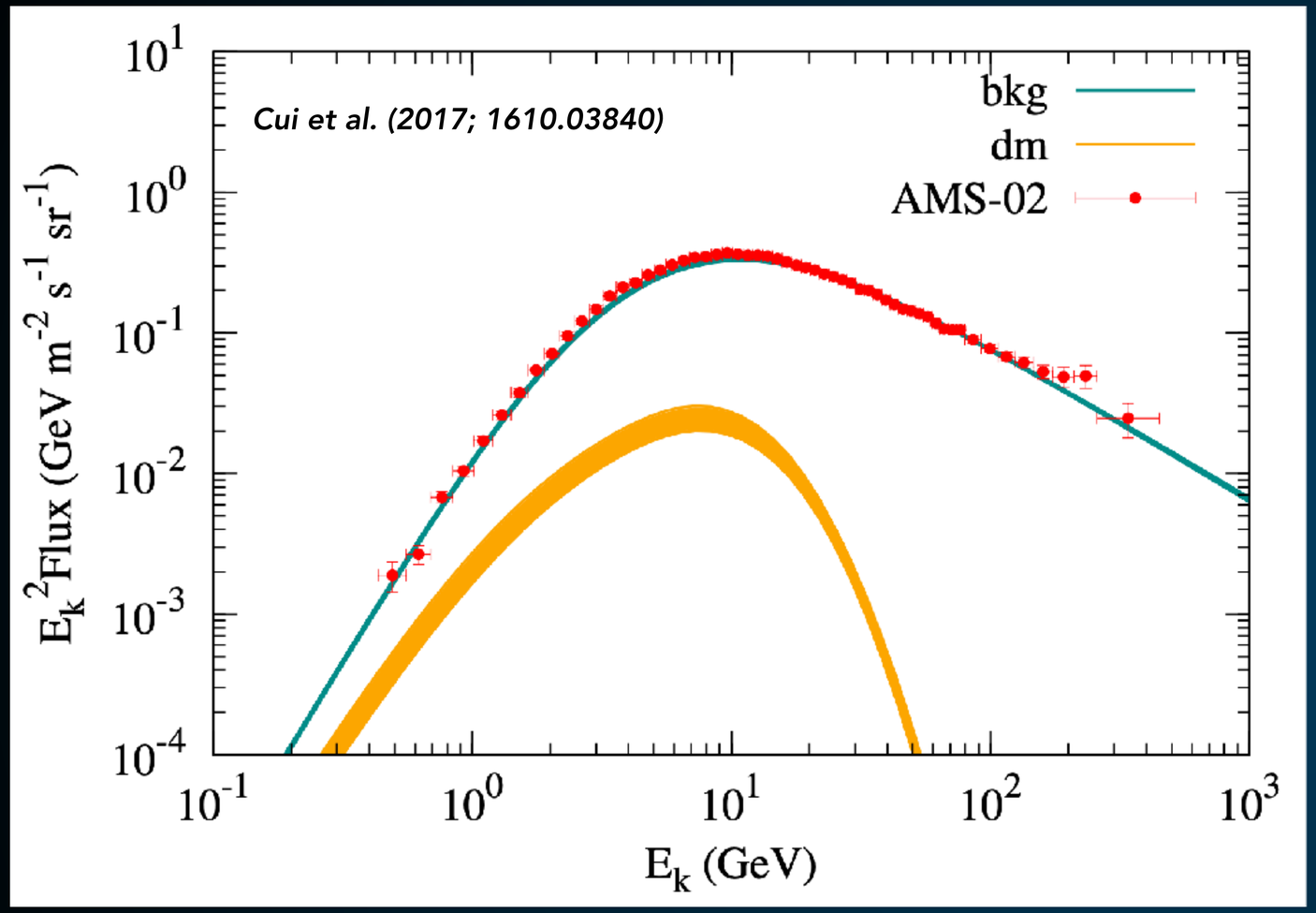
Astrophysical Uncertainties can significantly affect the signal.

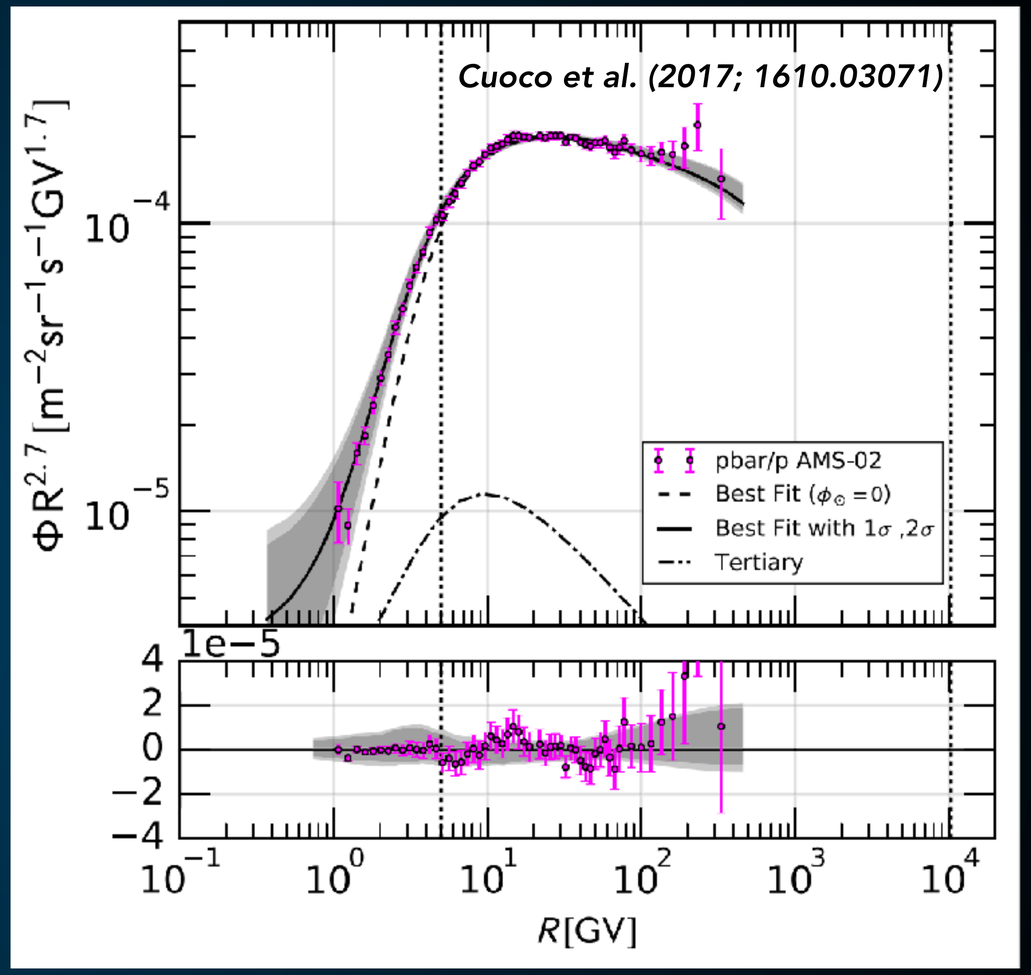






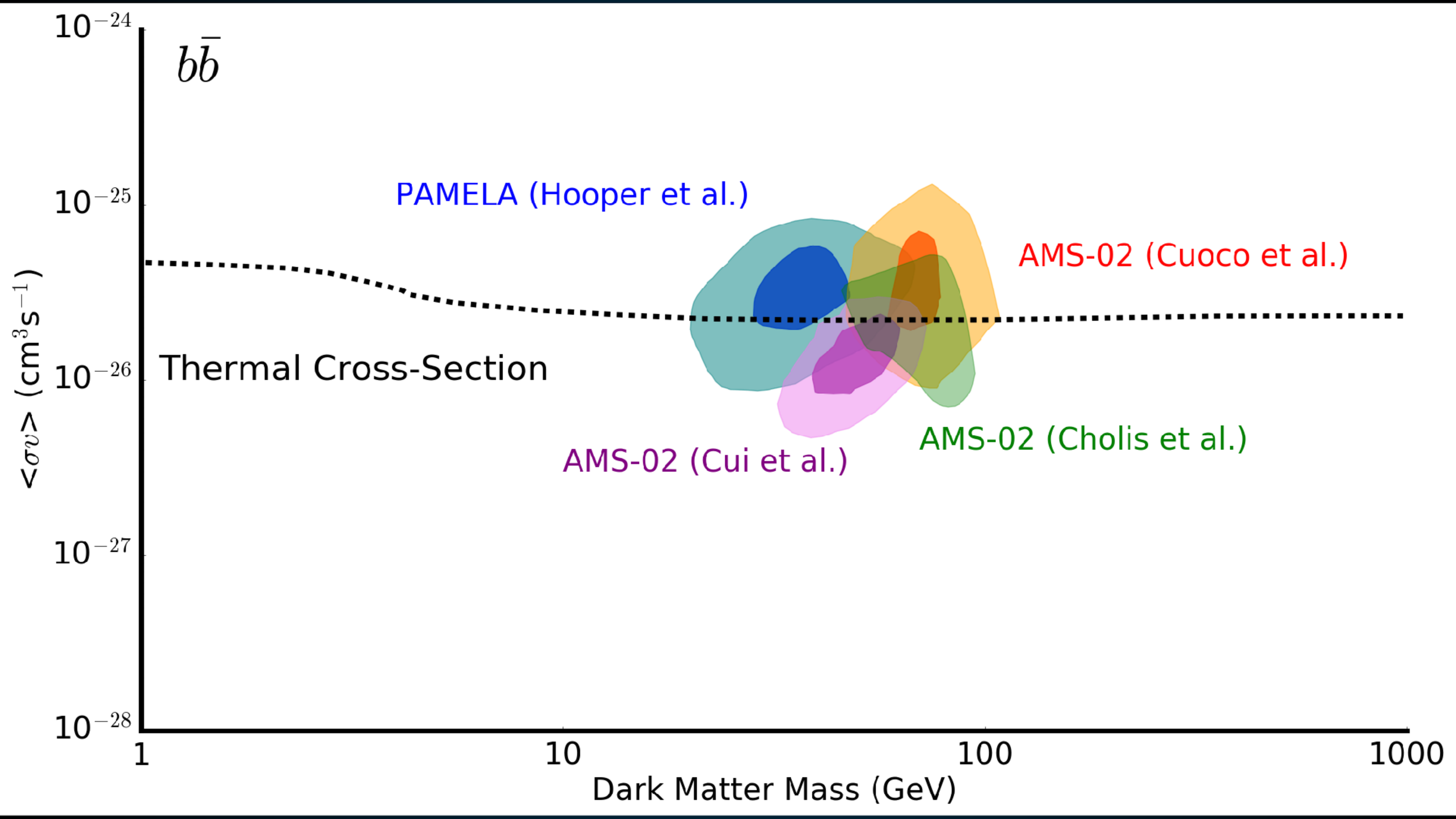
The Antiproton Excess





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

Significance approaching (or past) 5σ !

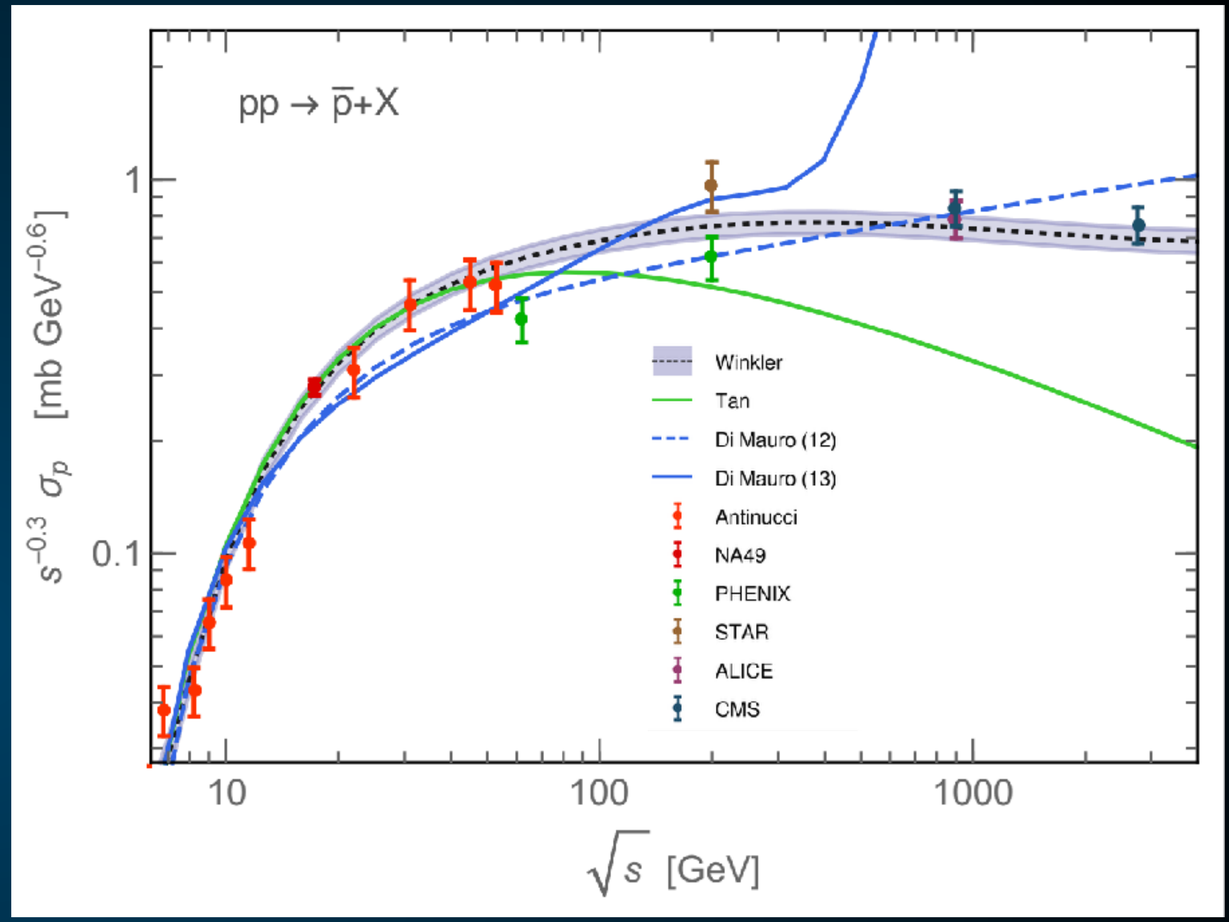

$b\bar{b}$
PAMELA (Hooper et al.)
AMS-02 (Cuoco et al.)
AMS-02 (Cholis et al.)
AMS-02 (Cui et al.)
Thermal Cross-Section
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ ($cm^3 s^{-1}$)
1
10
100
1000
Dark Matter Mass (GeV)

The Antiproton Excess - A Detection?

Reinert, Winkler (2018; 1712.00002)

With great precision comes great responsibility:

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



The Antiproton Excess - A Detection?

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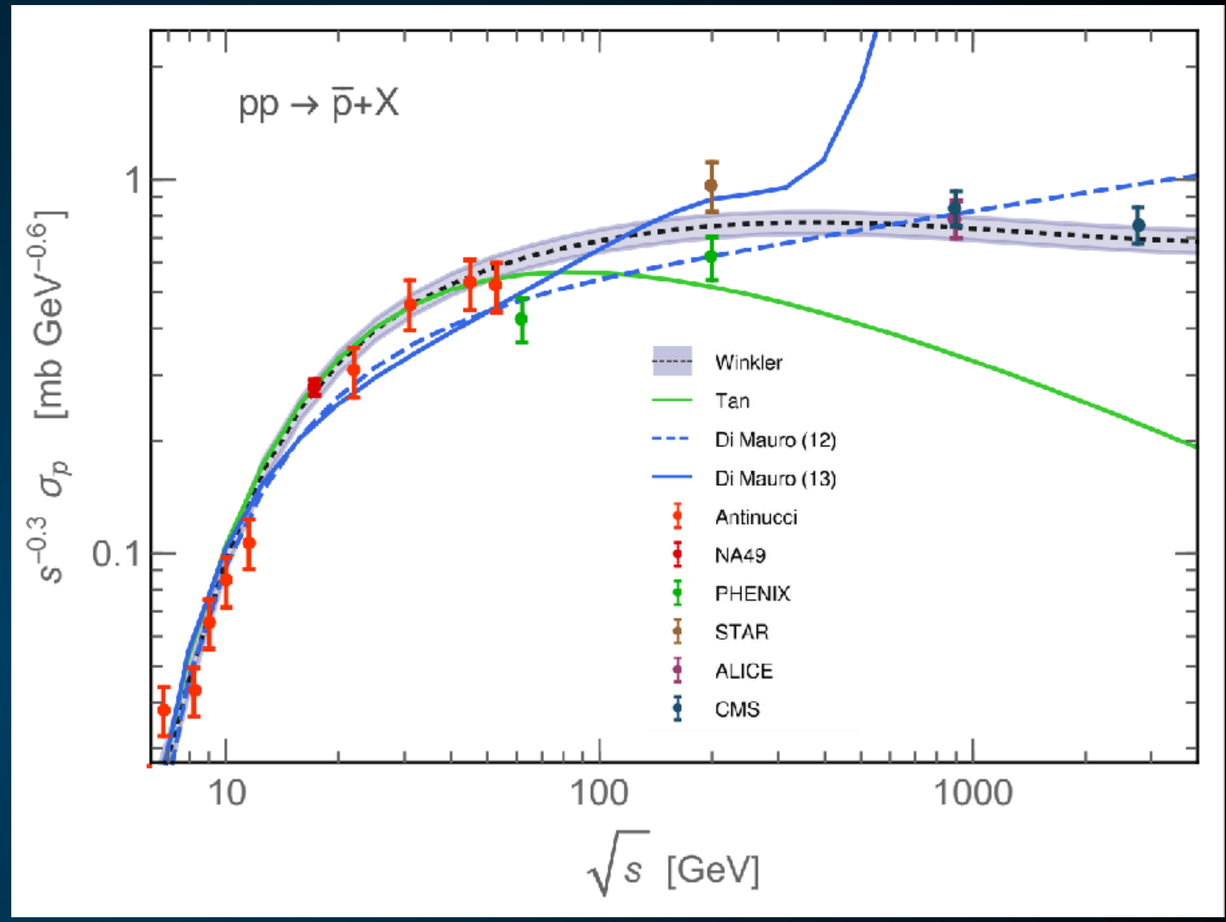
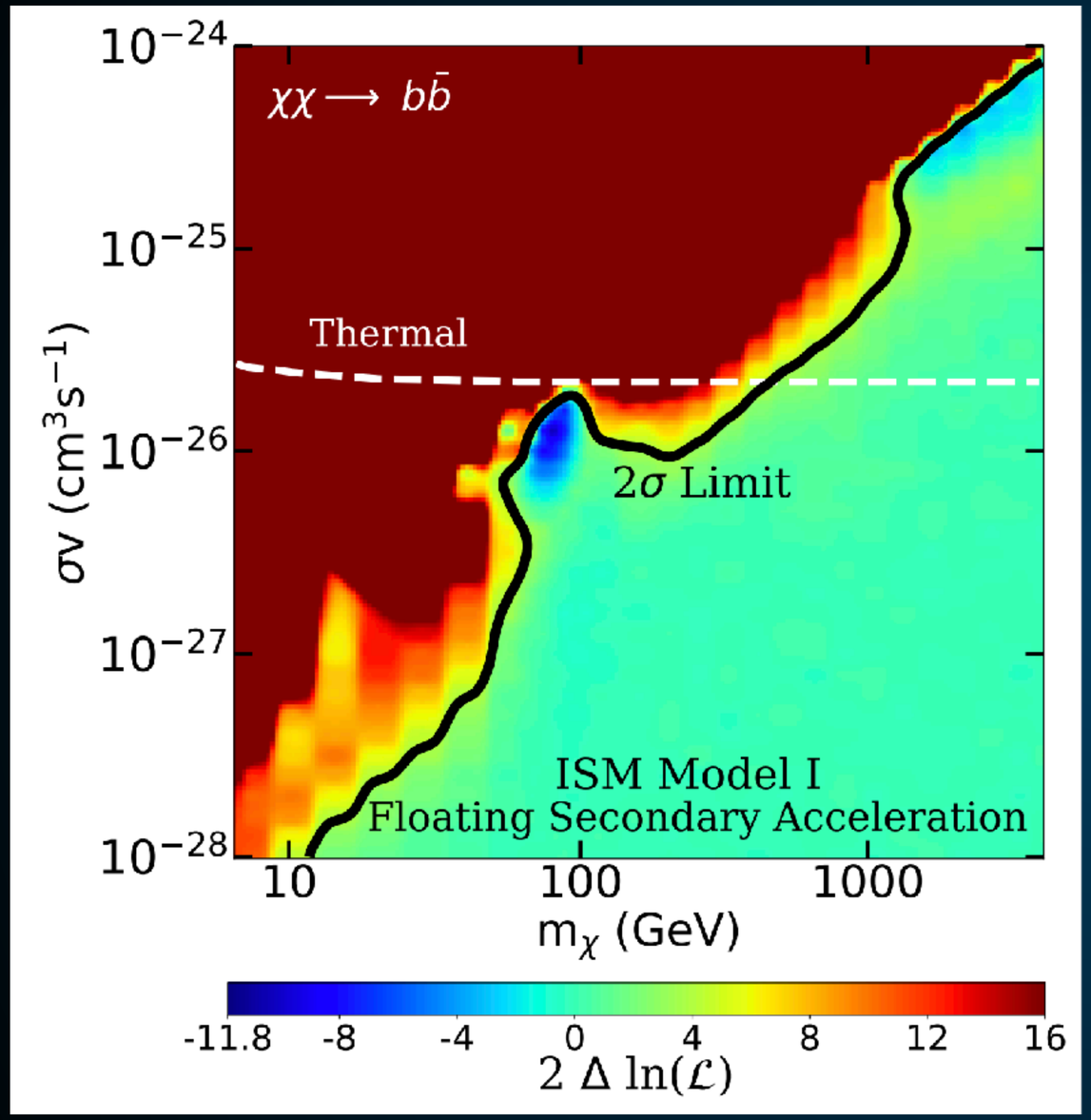
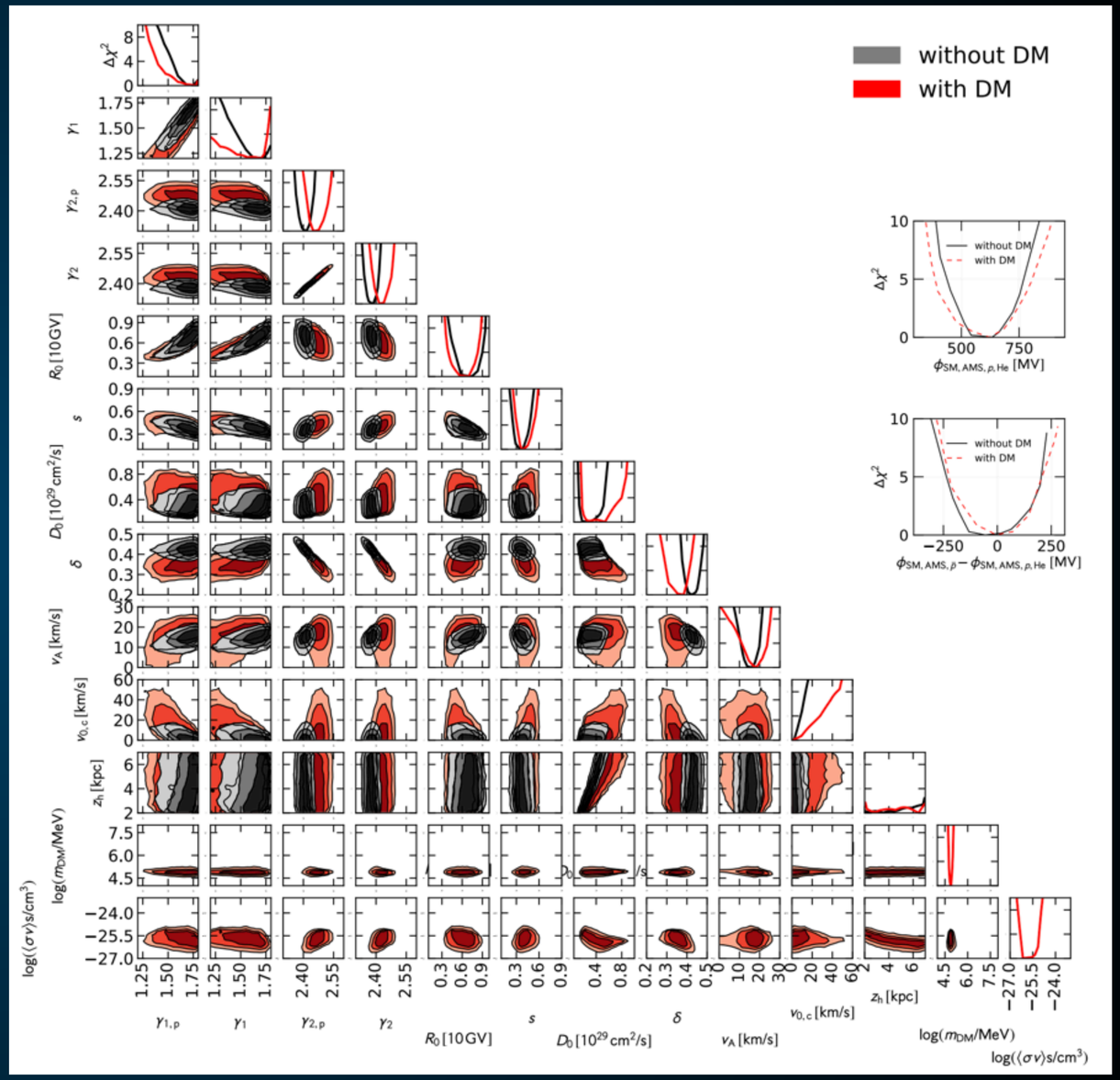


Galactic Primary to Secondary Ratios - Future AMS-02 Data!
Inhomogeneous Diffusion - TeV Halos
Solar Modulation - Voyager Data, Time-Dependent AMS-02 Data
Antiproton Production Cross-Section - LHCb / Laboratory Experiments

The Antiproton Excess — Robust Analyses

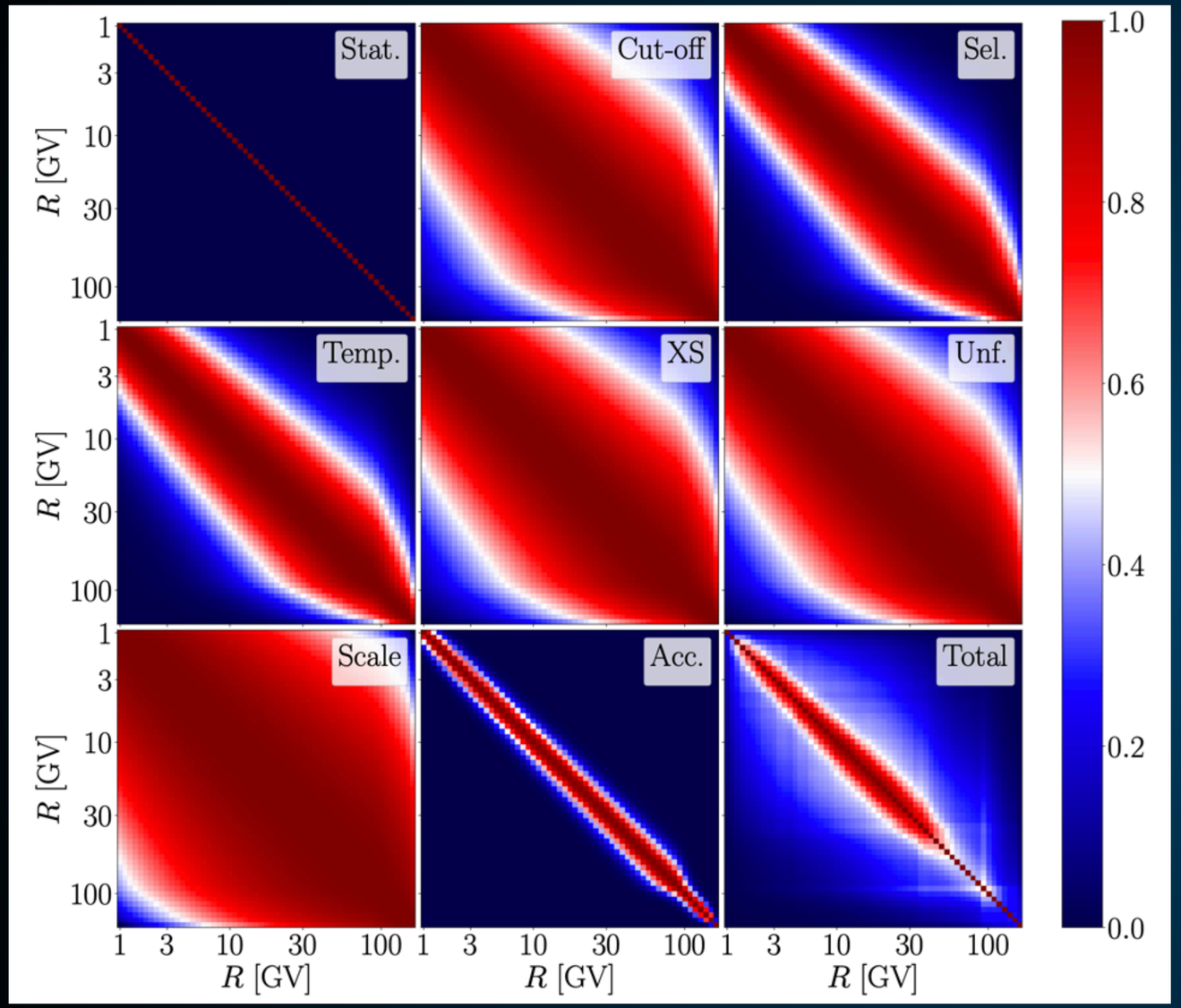


Cholis, Linden, Hooper (2019; 1903.02549)

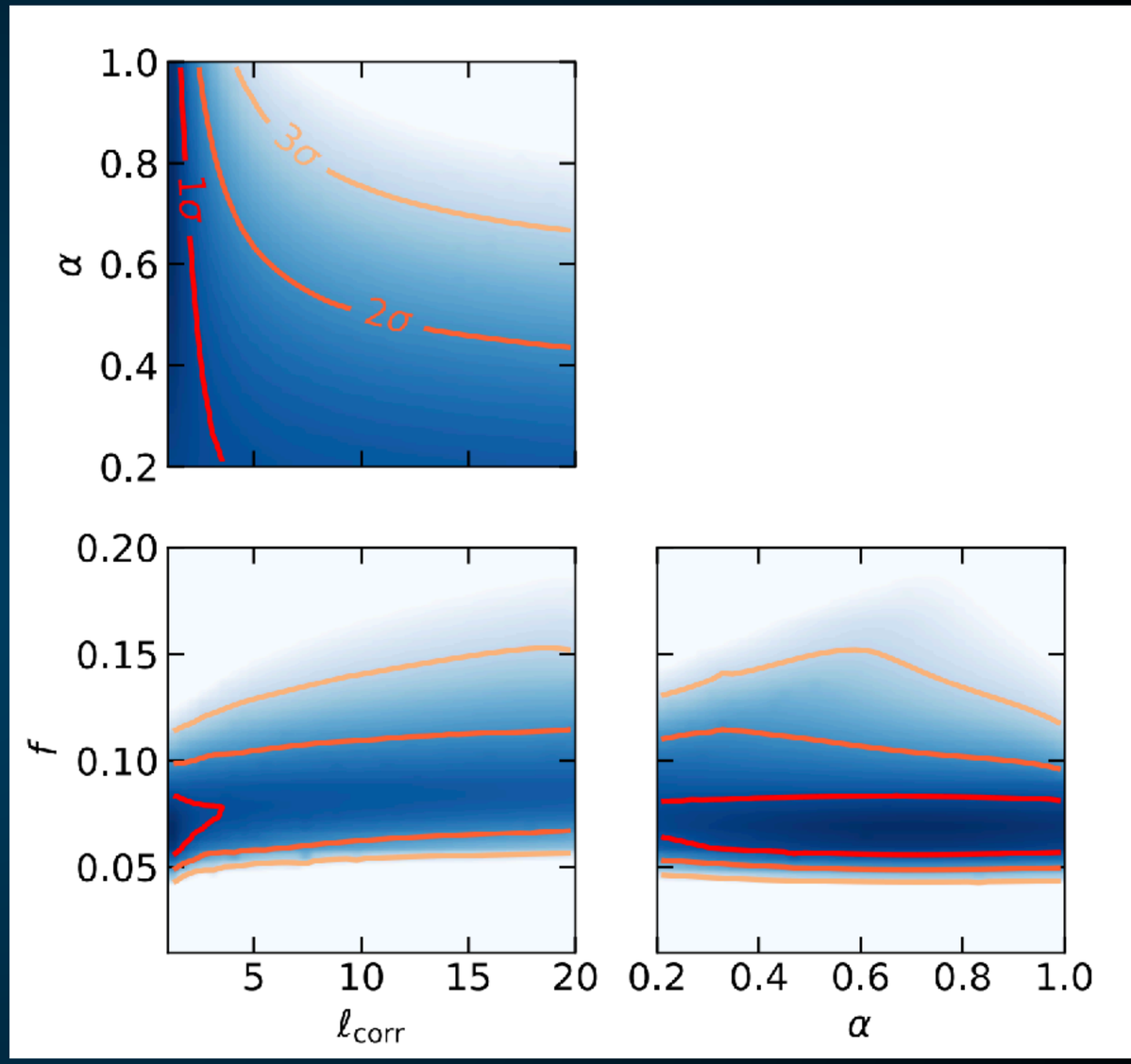


Cuoco et. al. (2019; 1903.01472)

The Antiproton Excess — Correlation Matrices



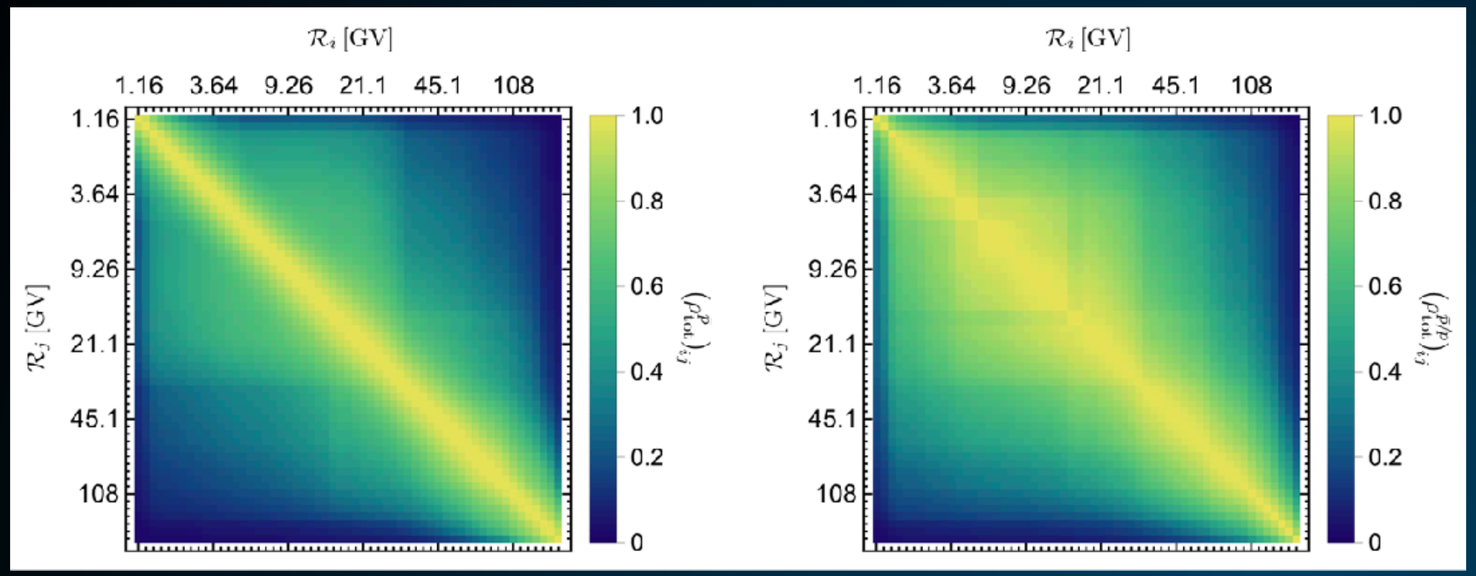
Boudaud et al. (2019; 1906.07119)

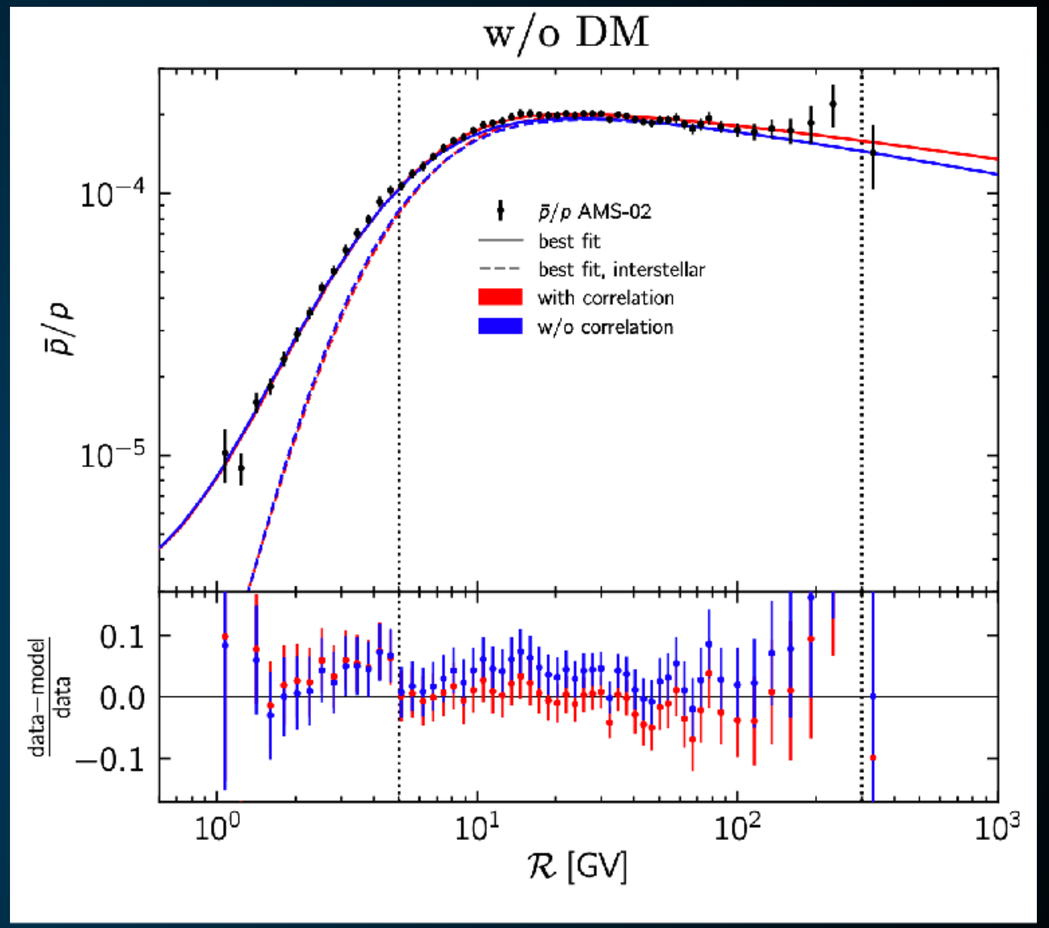


Cuoco et. al. (2019; 1903.01472)

The Antiproton Excess — Correlation Matrices

Heisig et al. (2005.04273)

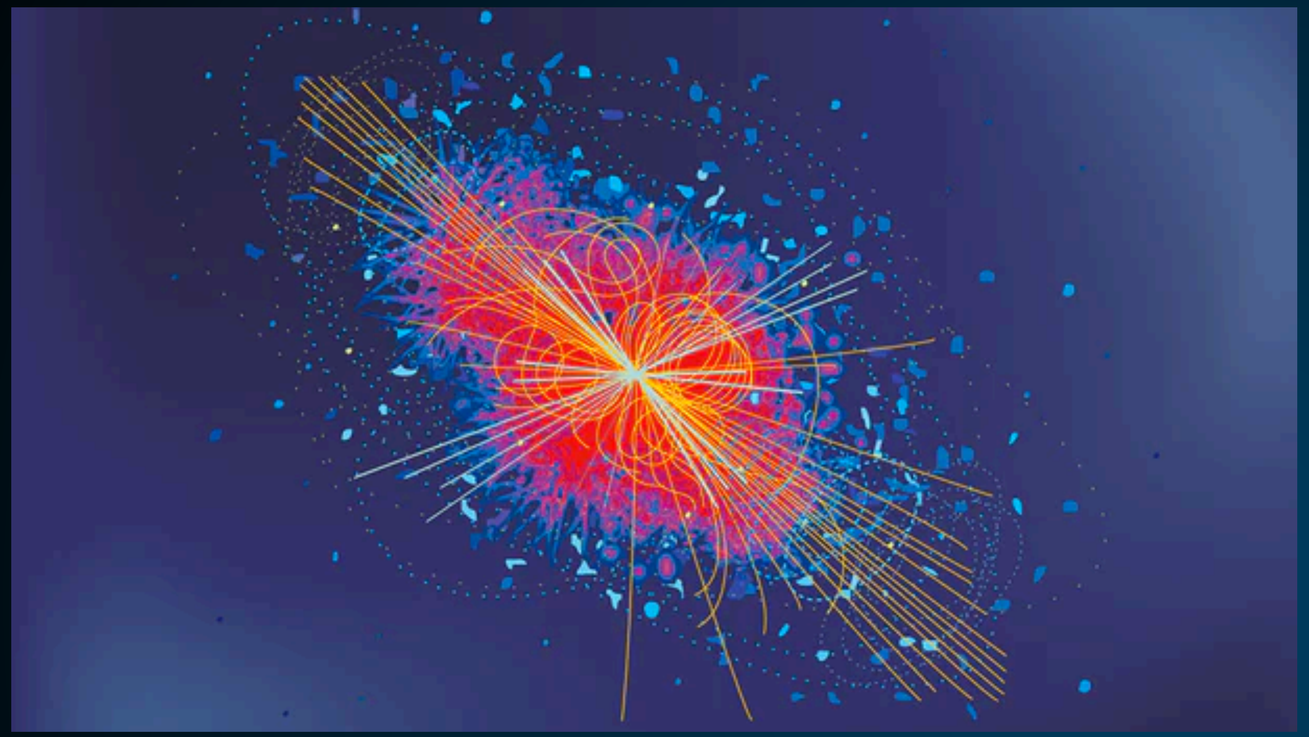




Correlated Systematic Uncertainties?

Antinuclei !?

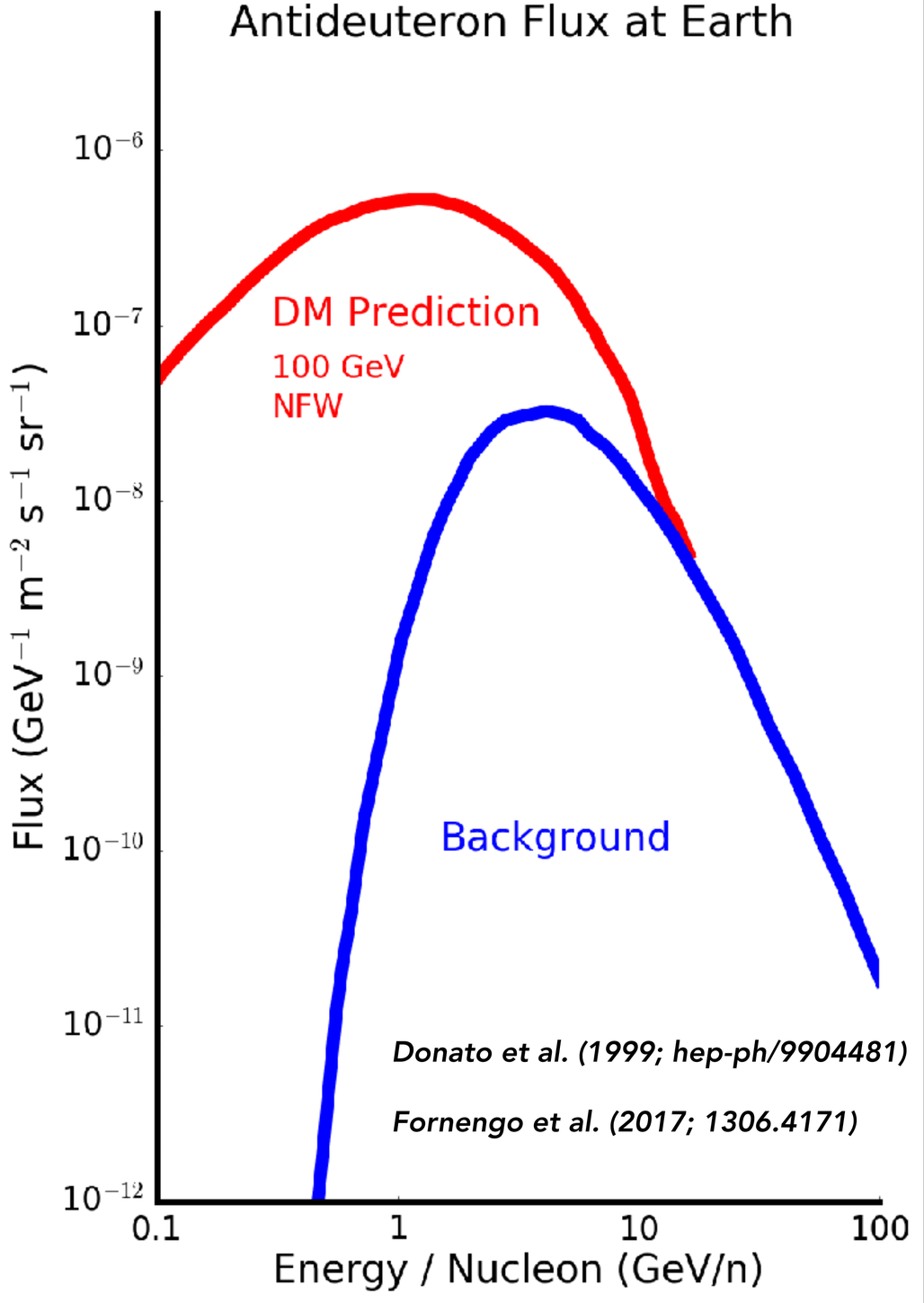
AntiNuclei - A Clean Search Strategy ?



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}.

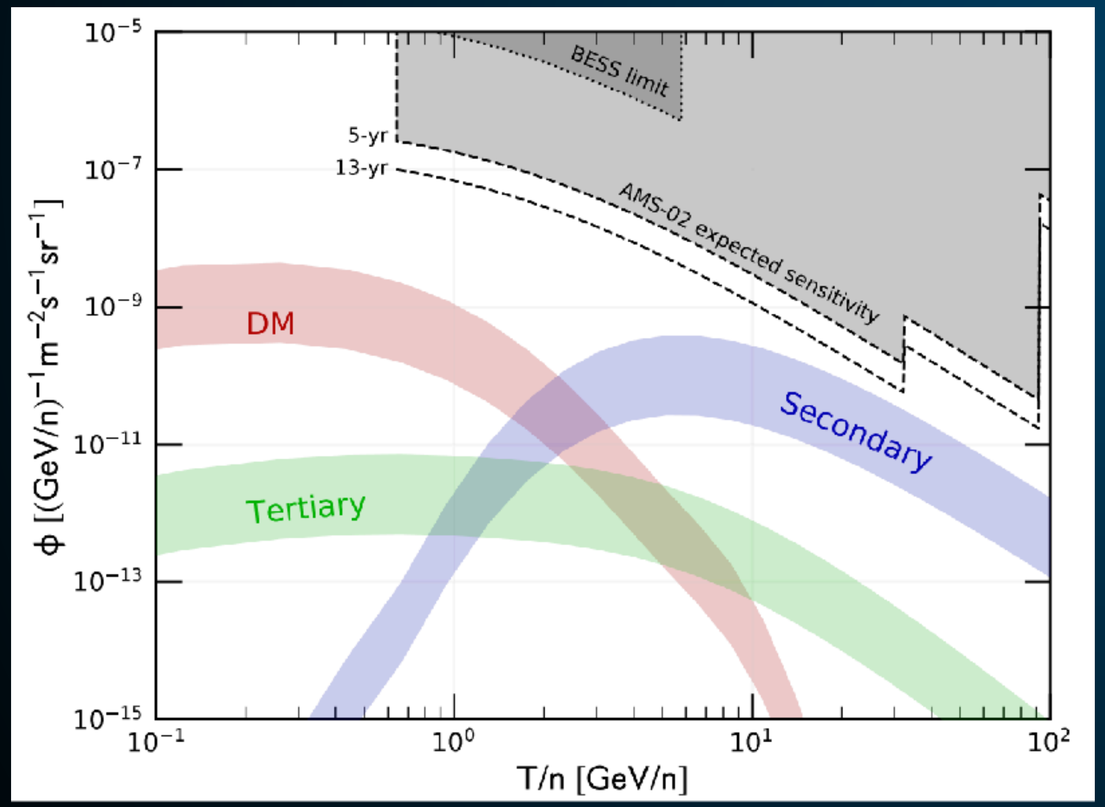
Note that for $^4\bar{He}$, projecting based on the statistics we have today, by using an additional 400 million core hours for simulation the background probability would be 10^{-4}. Simultaneously, continuing to run until 2023, which doubles the data sample, the background probability for $^4\bar{He}$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

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

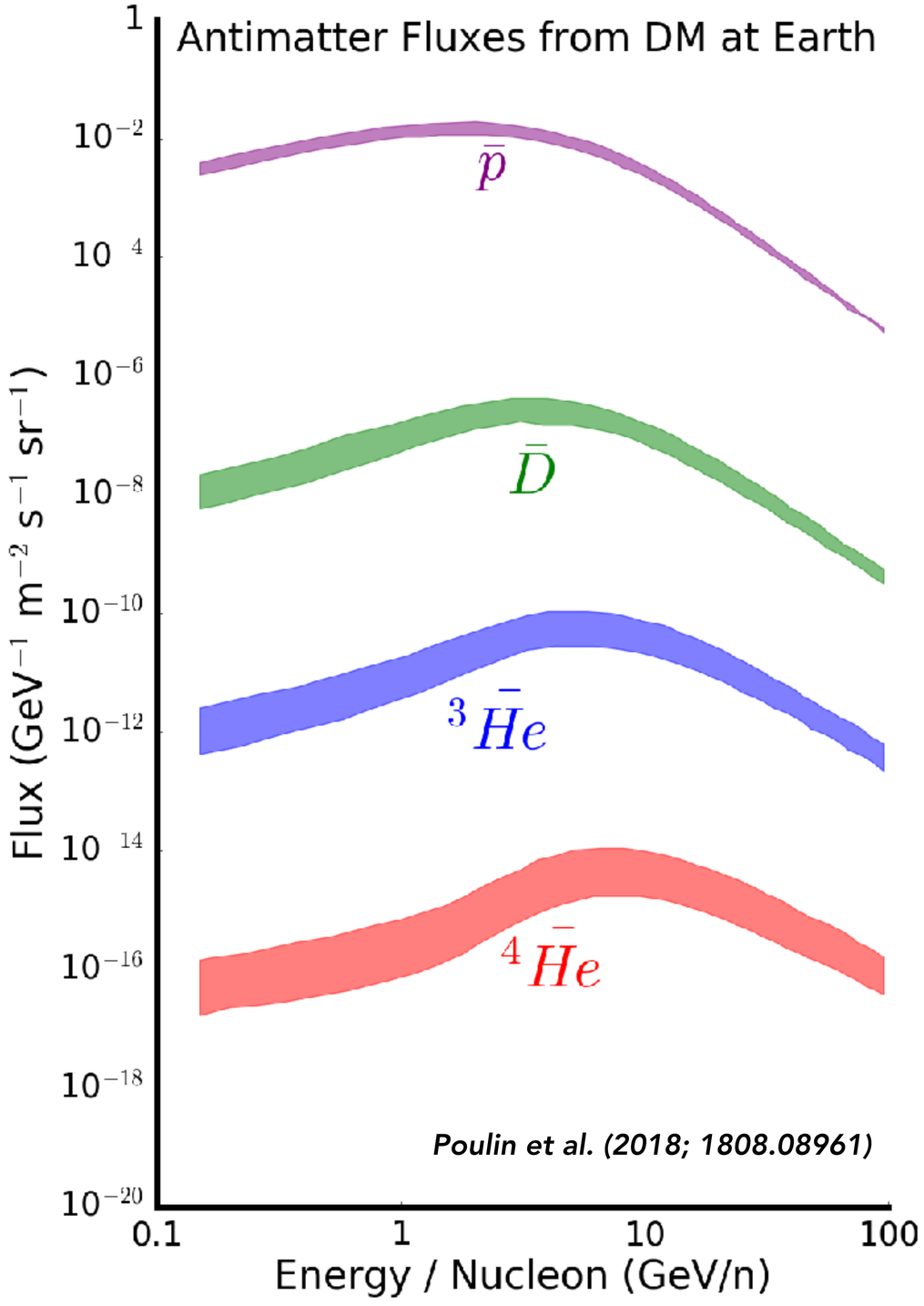
AntiNuclei - A Clean Search Strategy ?

Antihelium background even cleaner than antideuterons

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



Korsmeier (2017; 1711.08465)



Poulin et al. (2018; 1808.08961)

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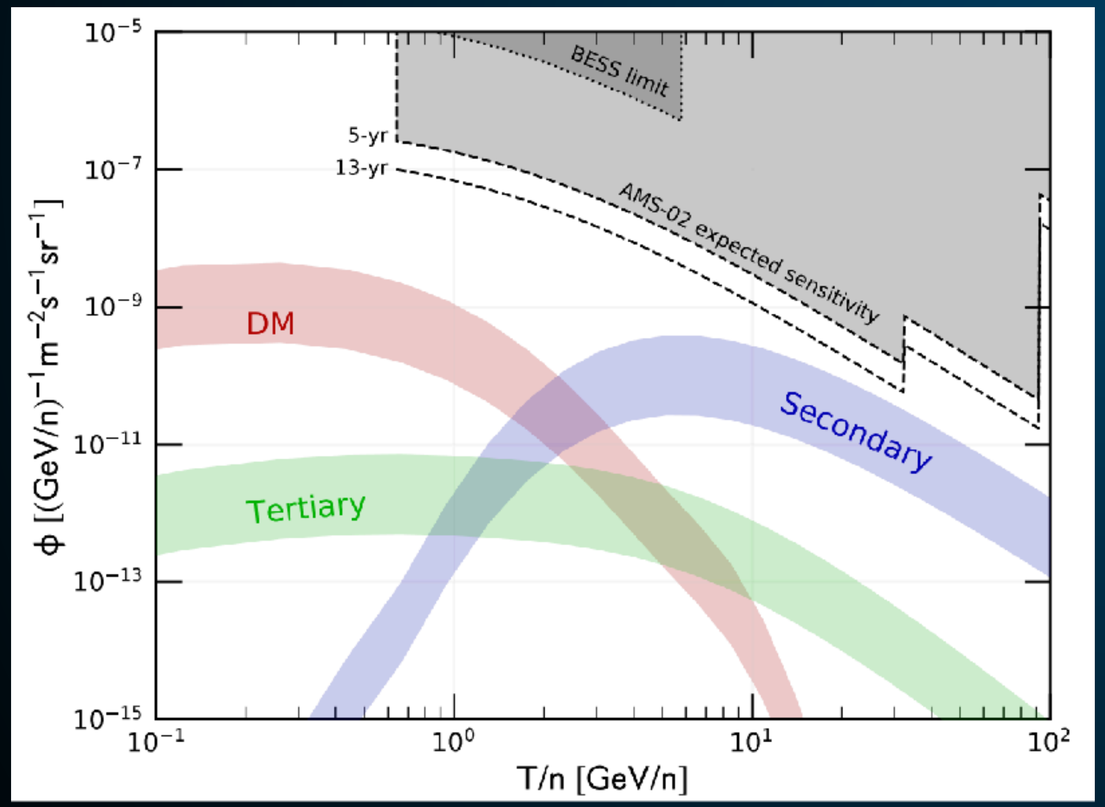

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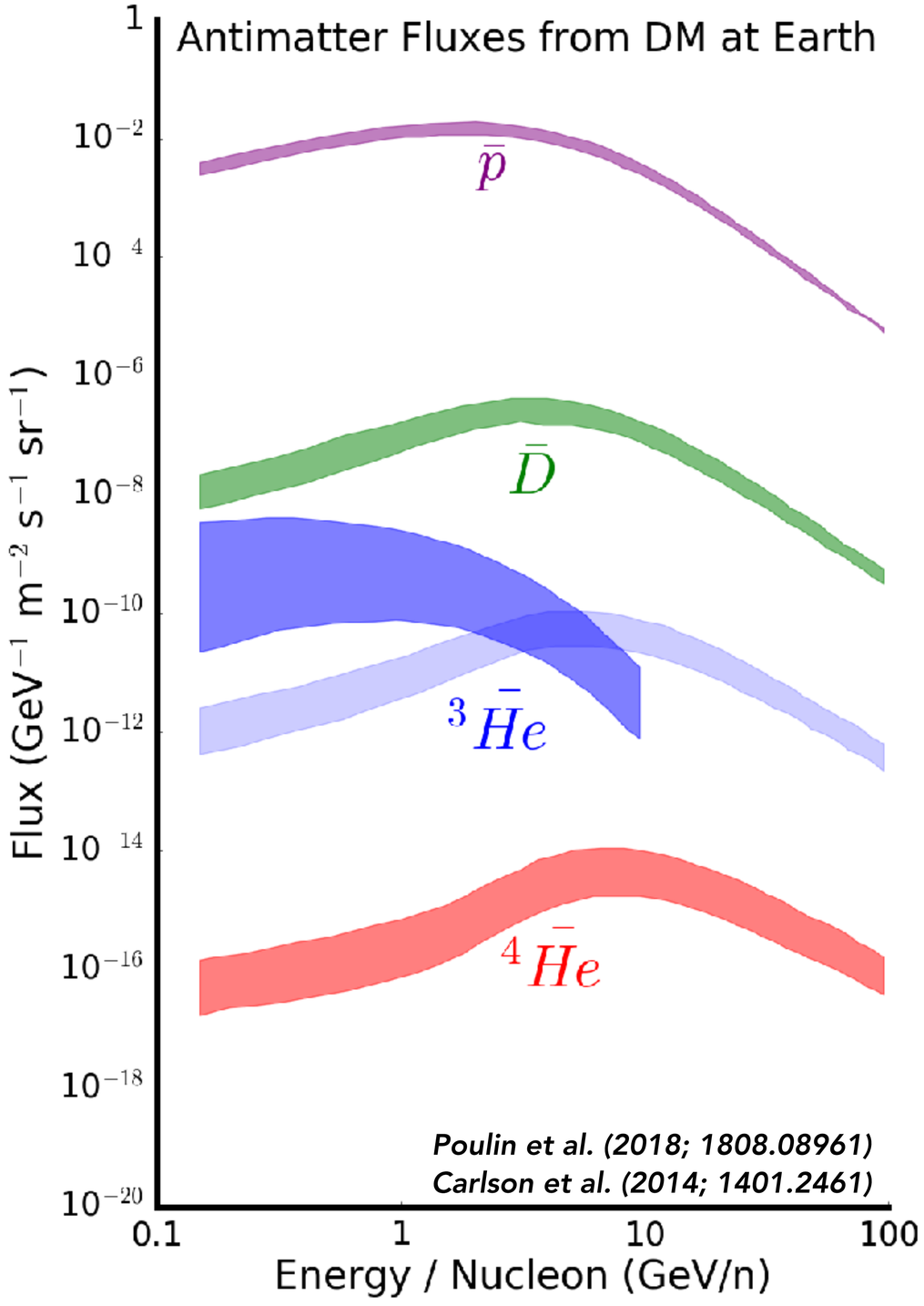
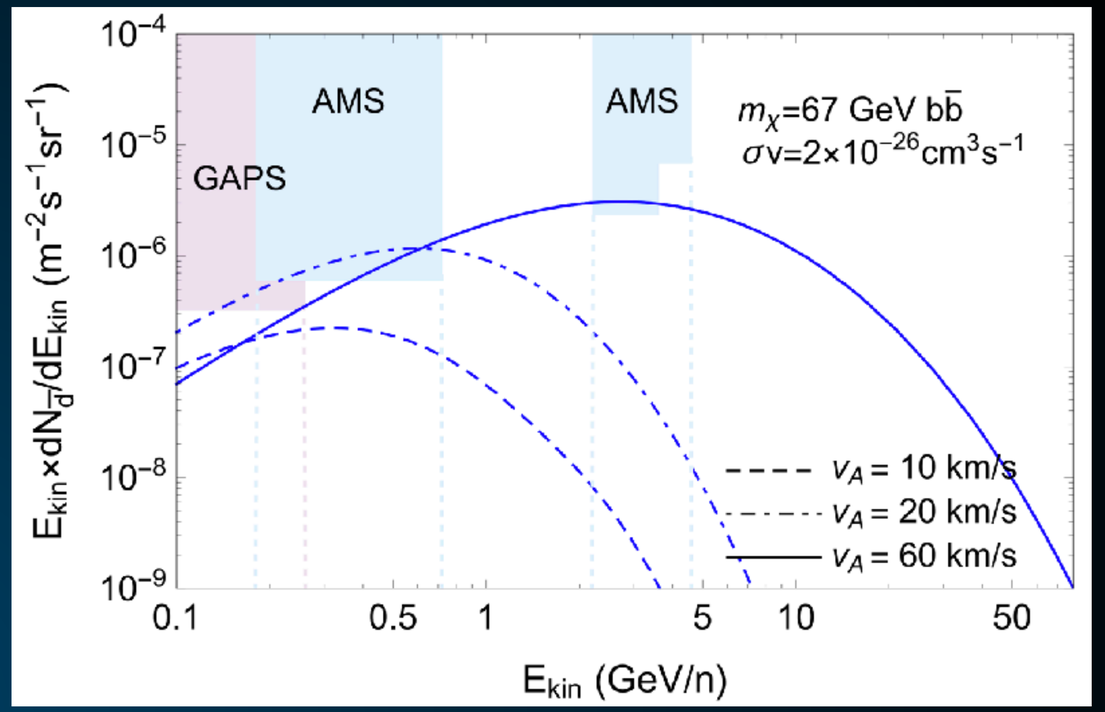


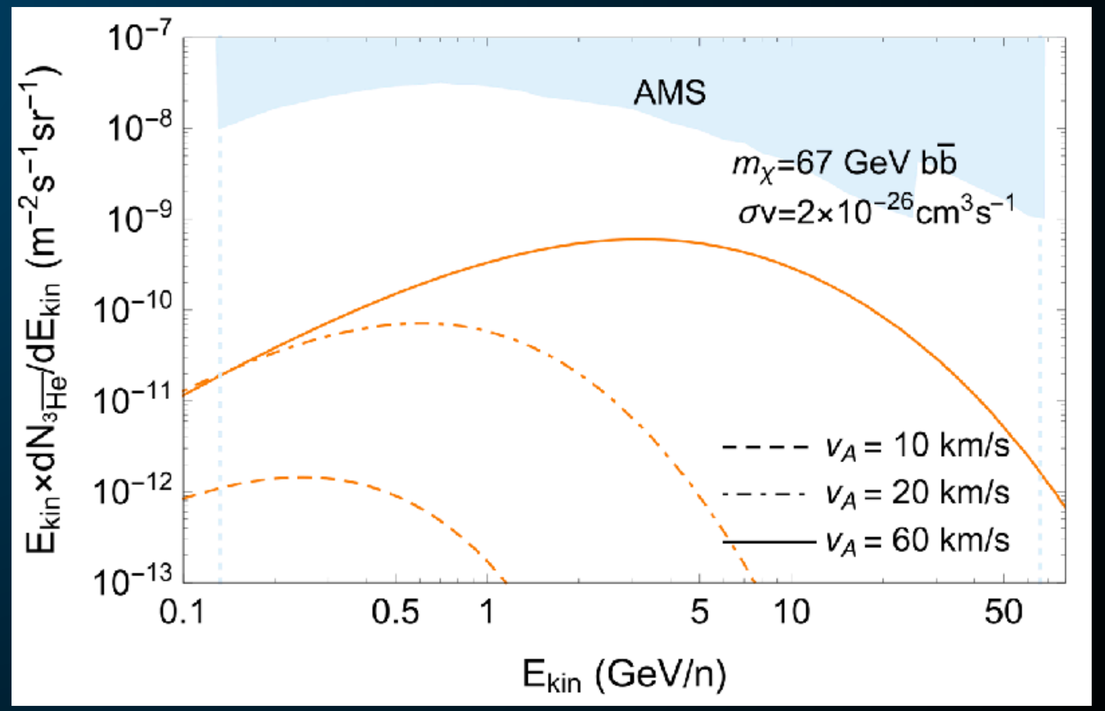
Astrophysical Enhancements!

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

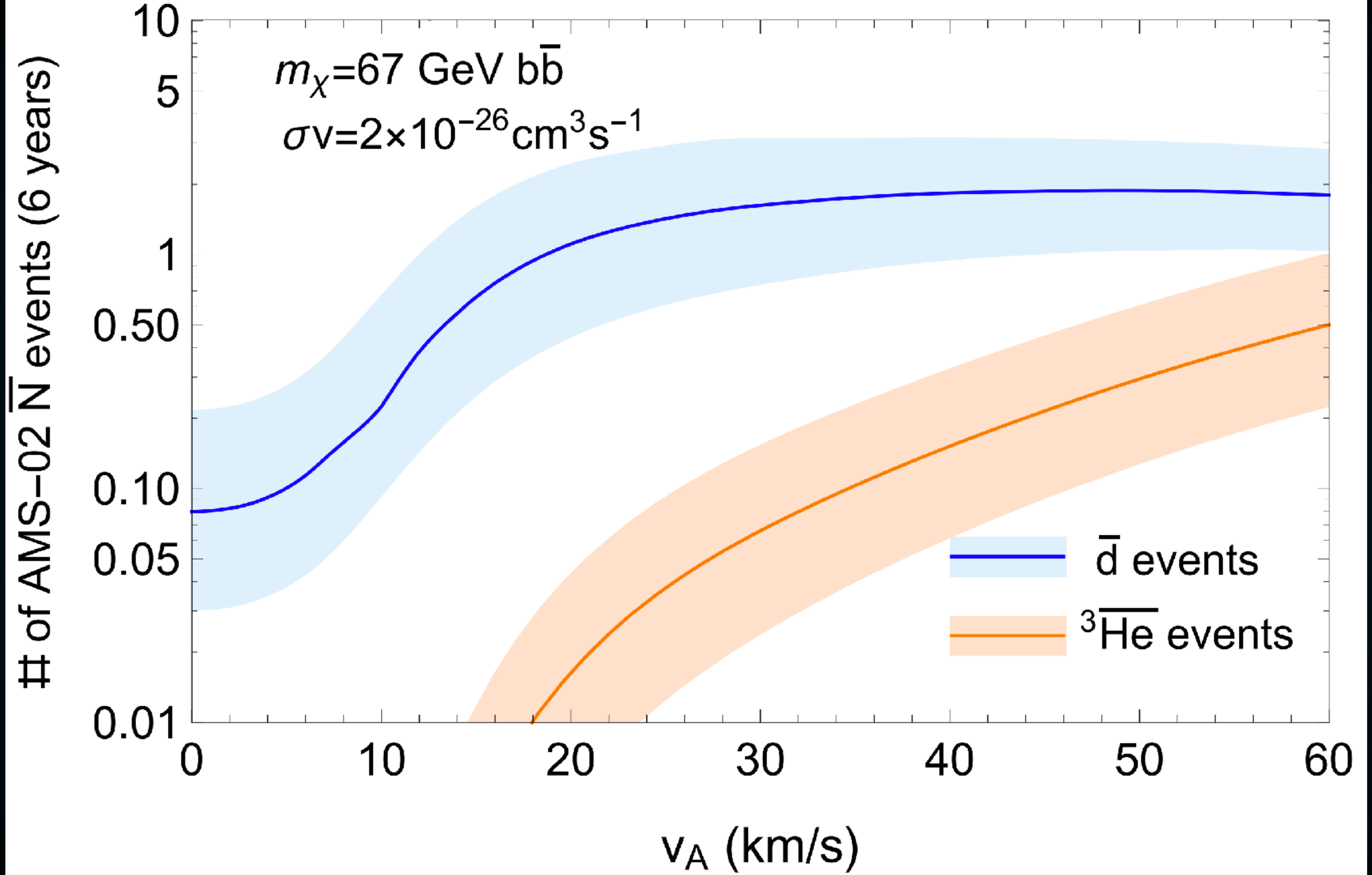
We lose many events because most anti-He are produced at energies that are too small to be detected.

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

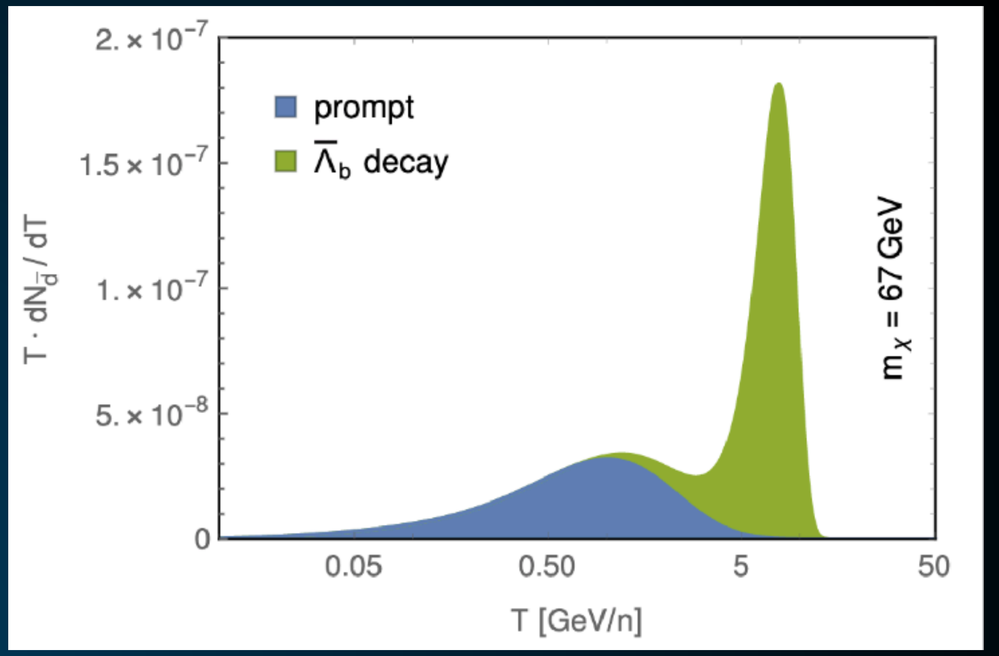
The detection of massive cosmic-ray antinuclei has long been considered a holy grail in searches for WIMP dark matter [1, 2]. Primary cosmic-rays from astrophysical sources are matter-dominated, accelerated by nearby supernova, pulsars, and other extreme objects. The secondary cosmic-rays produced by 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]

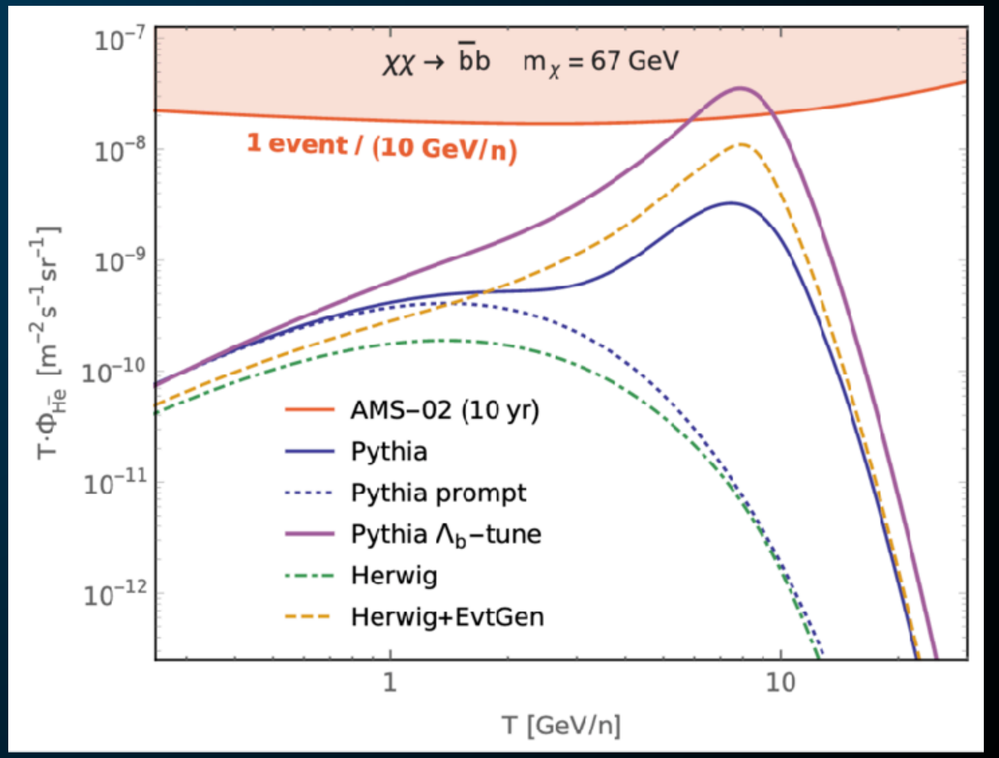
In this *letter*, we challenge the current understanding that standard dark matter annihilation models cannot produce a measurable antihelium flux. Our analysis examines a known, and potentially dominant, antinuclei production mode which has been neglected by previous literature – the production of antihelium 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.

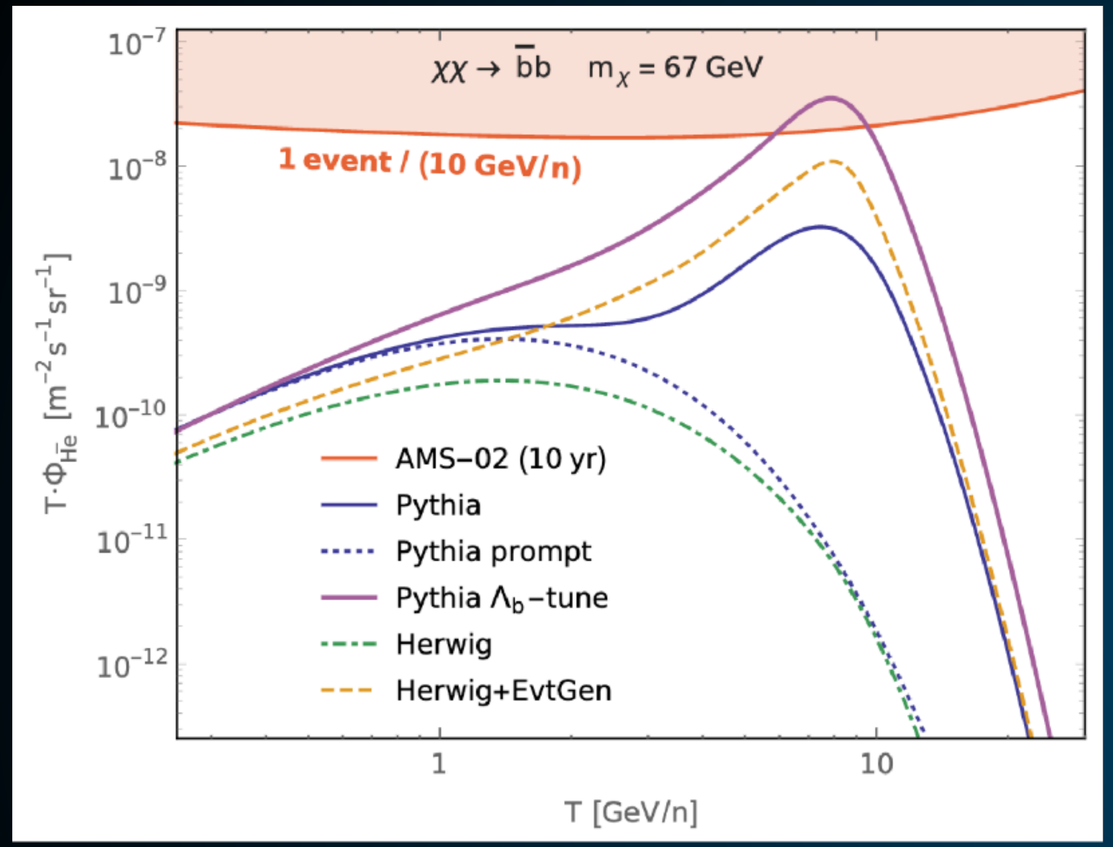
The displaced-vertex decays of Lambda_b baryons potentially boosts the detectable AMS-02 signal by orders of magnitude!

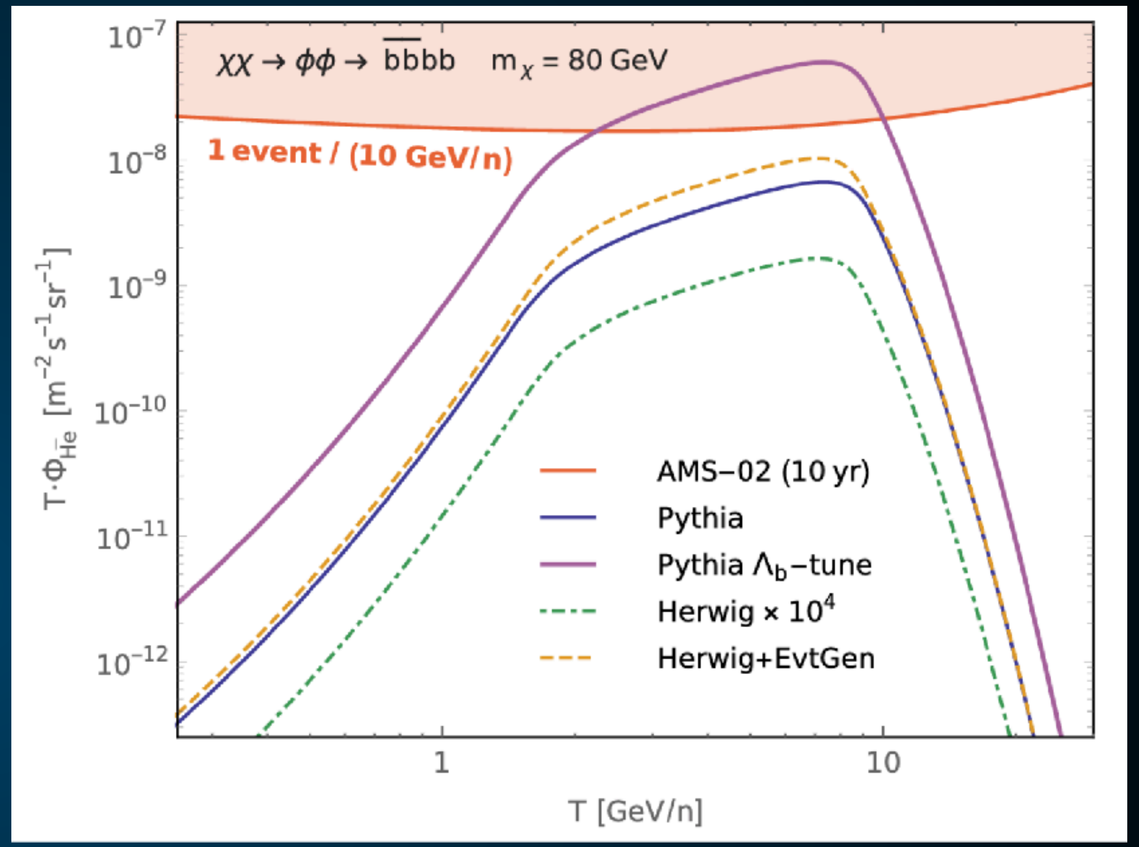




Winkler & Linden (2020; 2020.16251)

Particle Physics Enhancements!



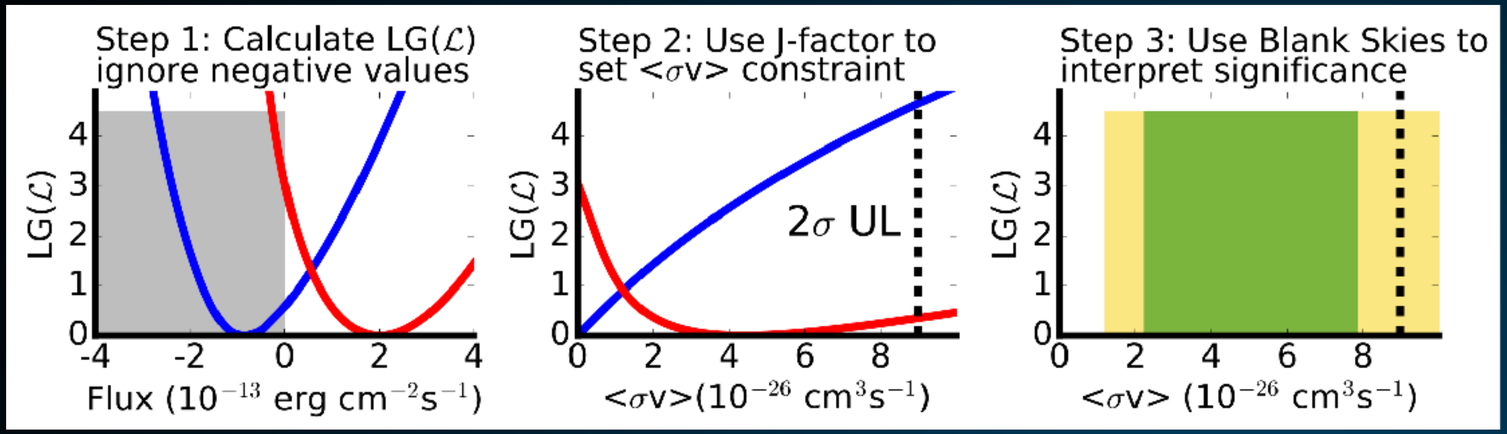


Generator	P	P [Λ_b-tune]	H	H+EvtGen
$^3\overline{\text{He}}$ events	0.1 (0.007)	0.9	0.003	0.3
$\bar{d}$ events	3.7 (3.5)	4.2	1.7	2.1

Winkler & Linden (2020; 2020.16251)

Dwarf Spheroidal Galaxies

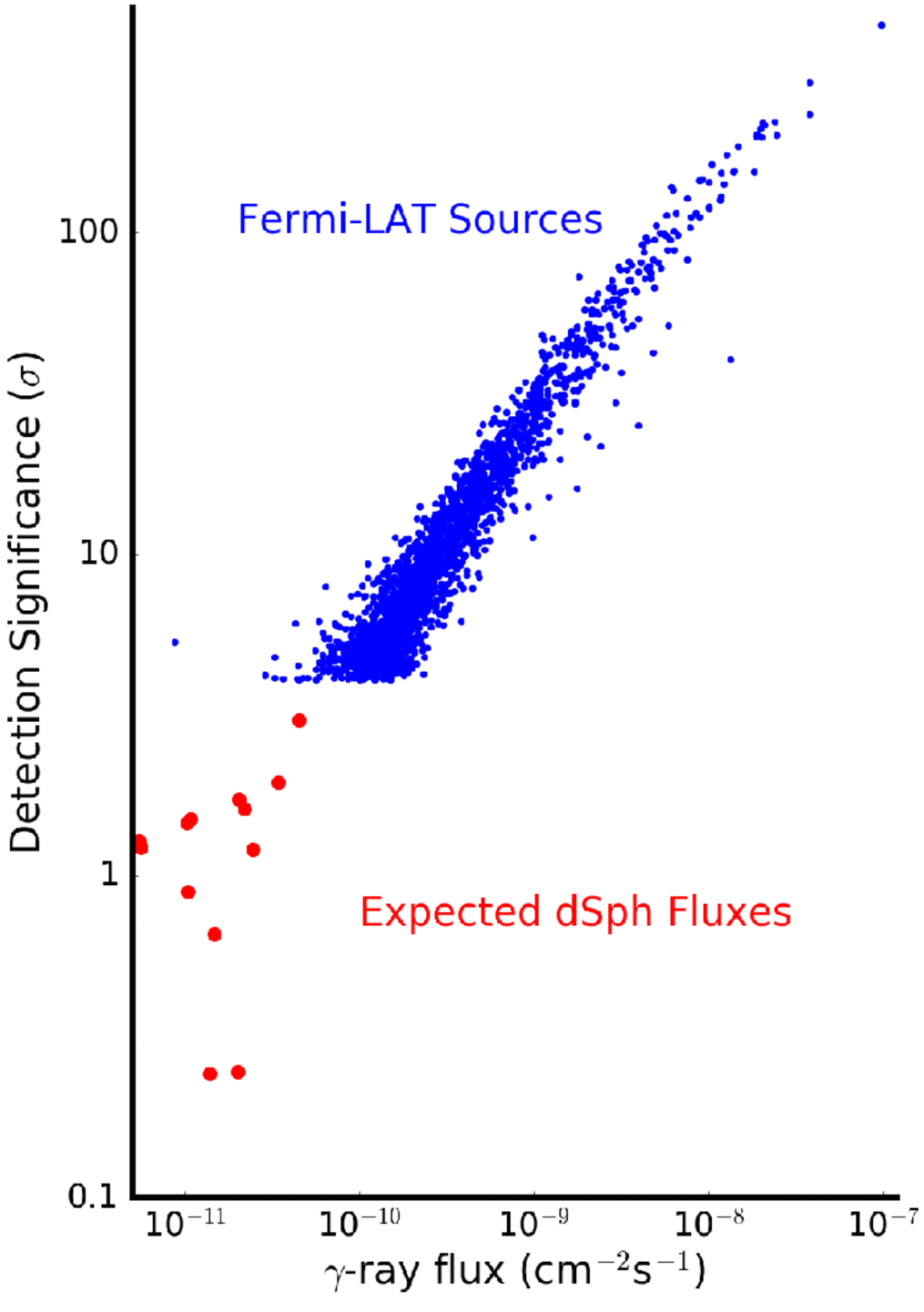
Dwarf Spheroidal Galaxies

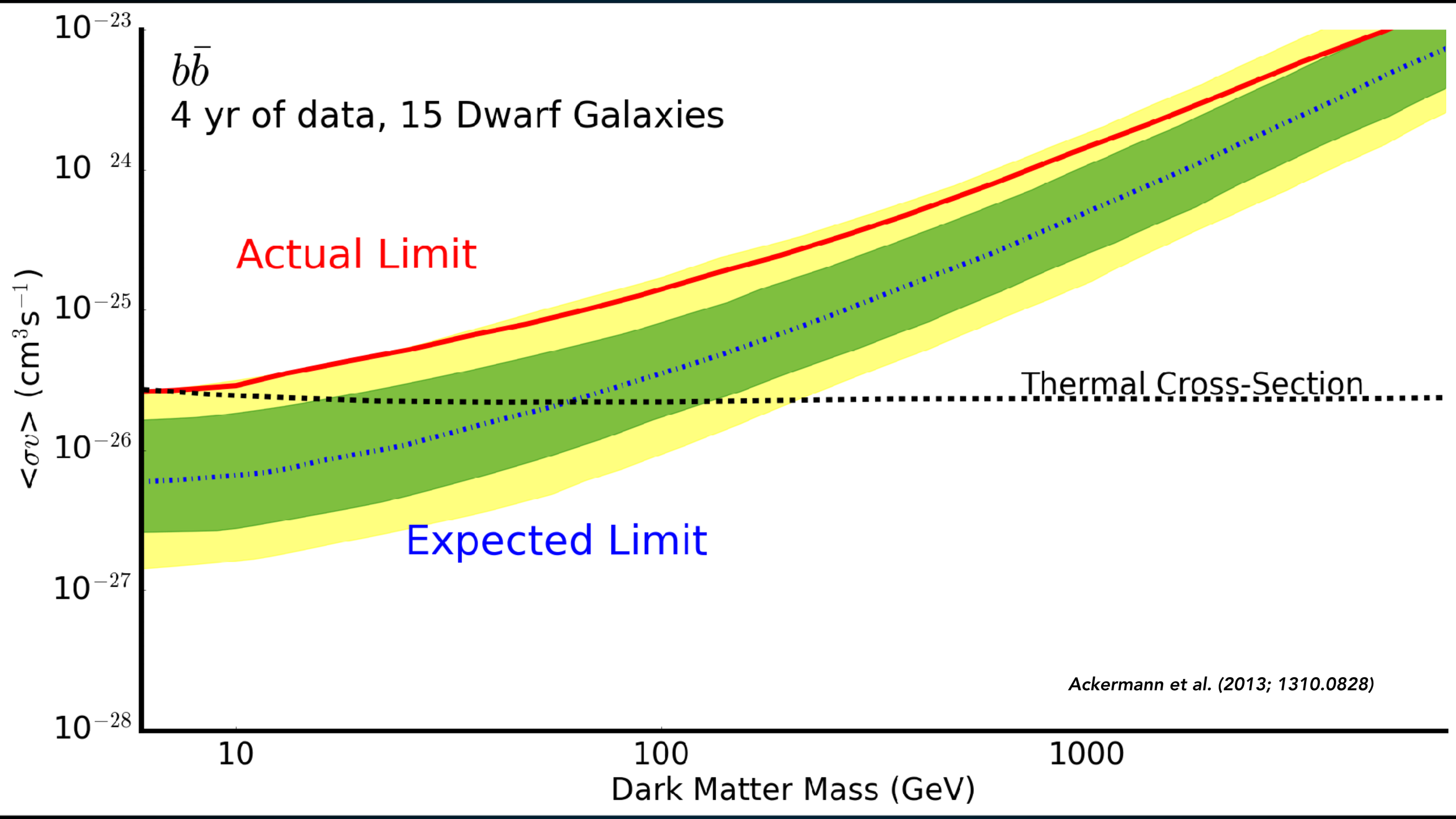


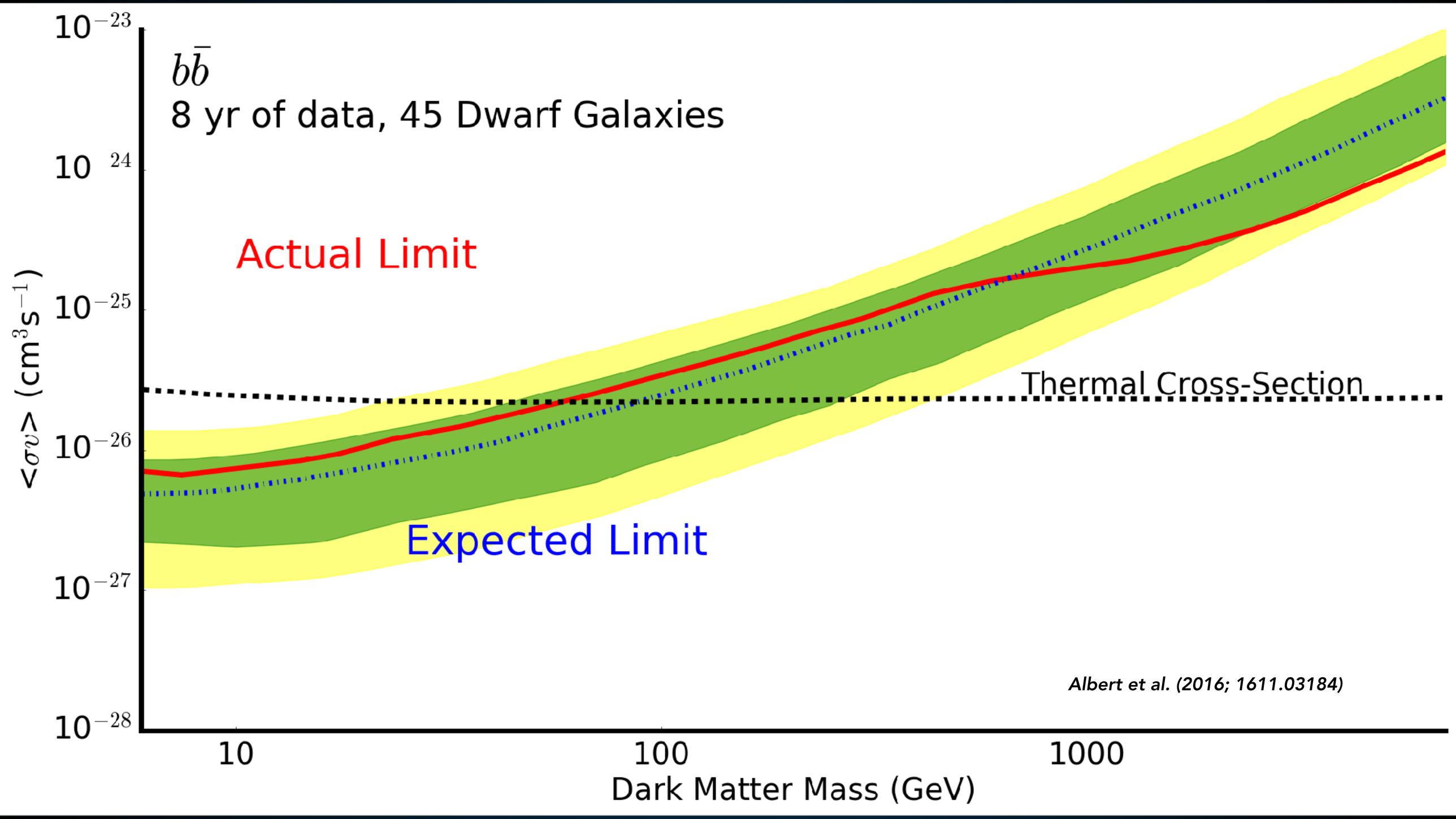
No Astrophysical Background from Dwarfs!

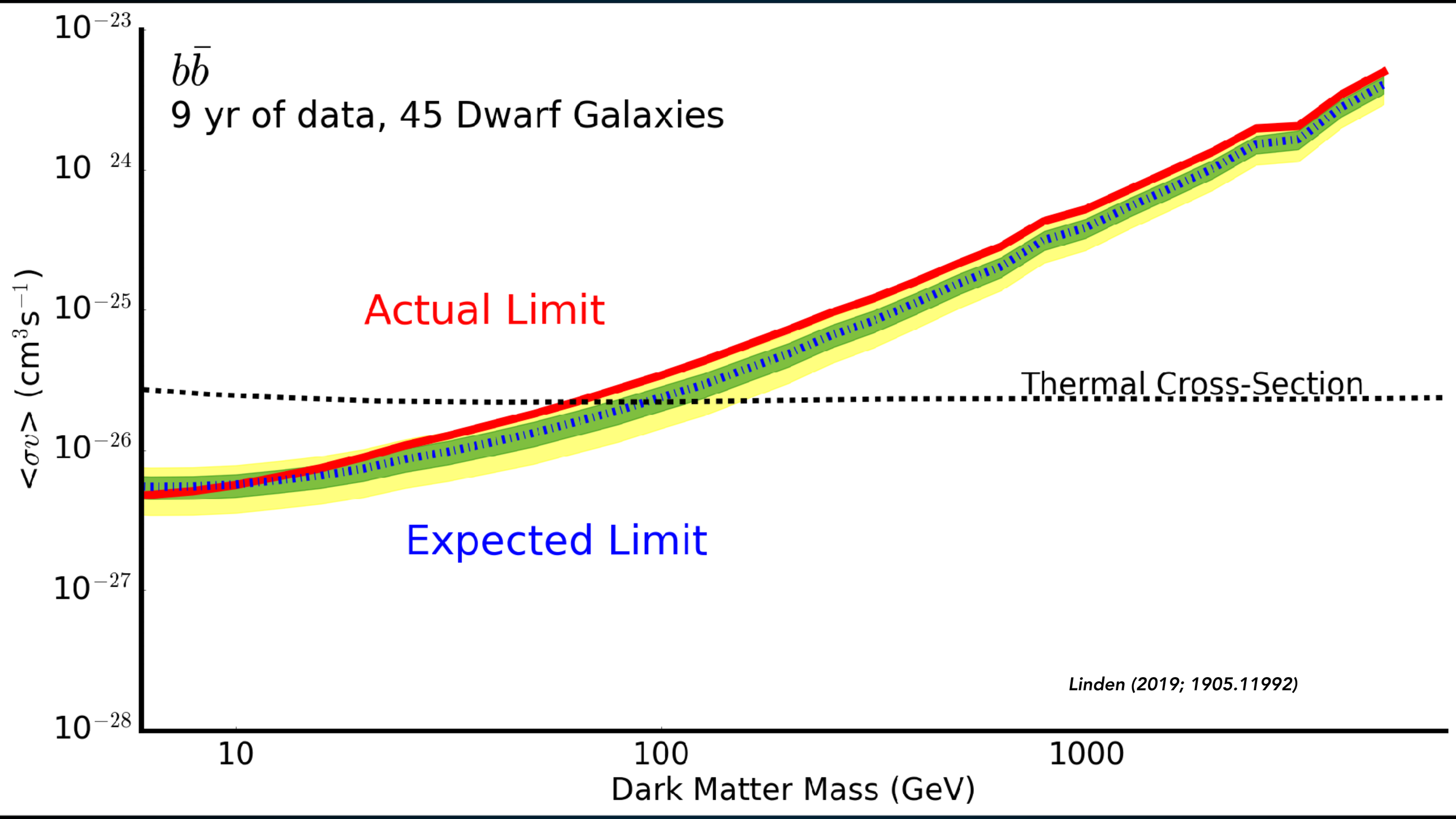
Individual dwarfs are dim

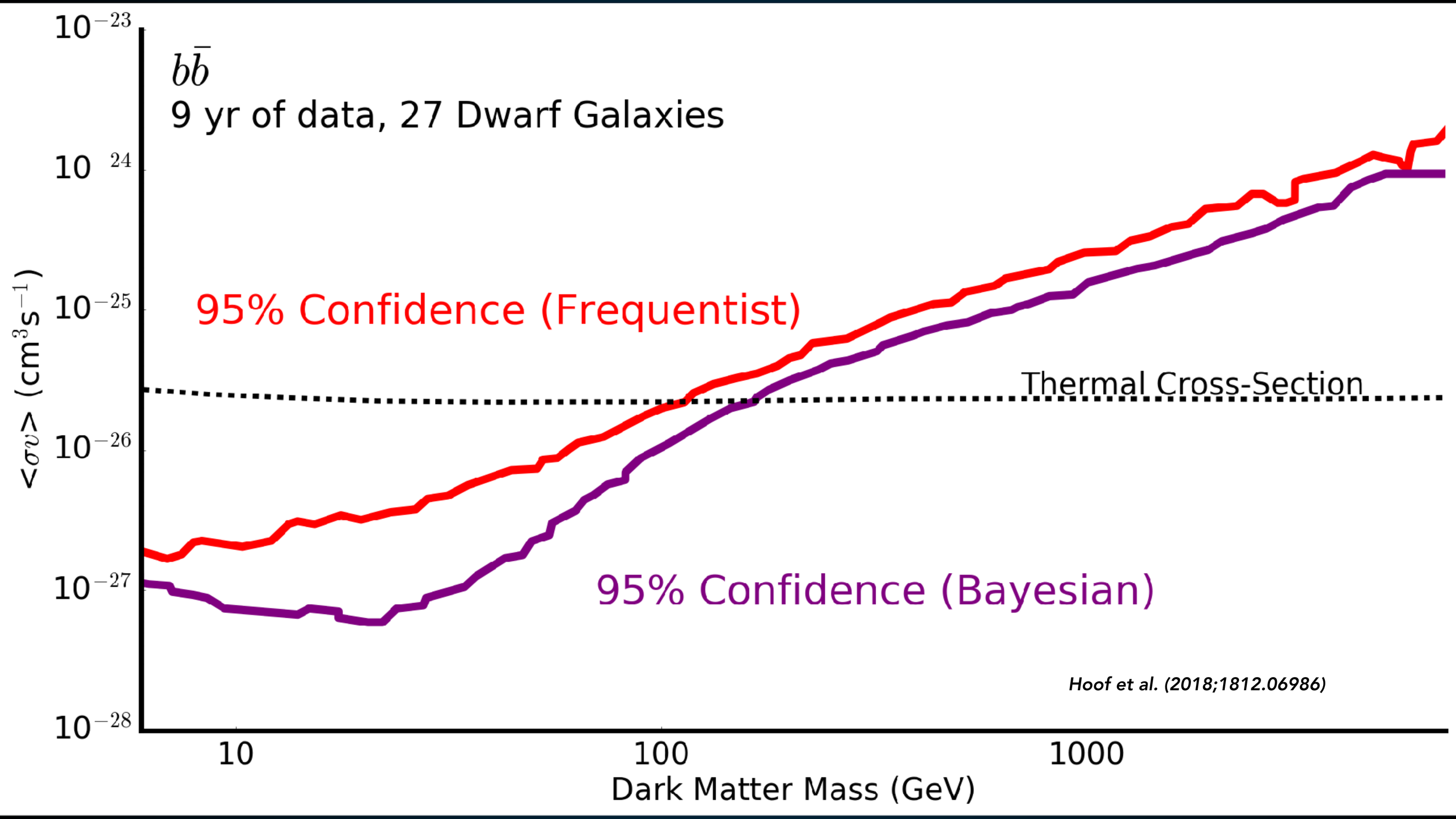
Need to combine observations of multiple dwarfs to constrain thermal cross-section



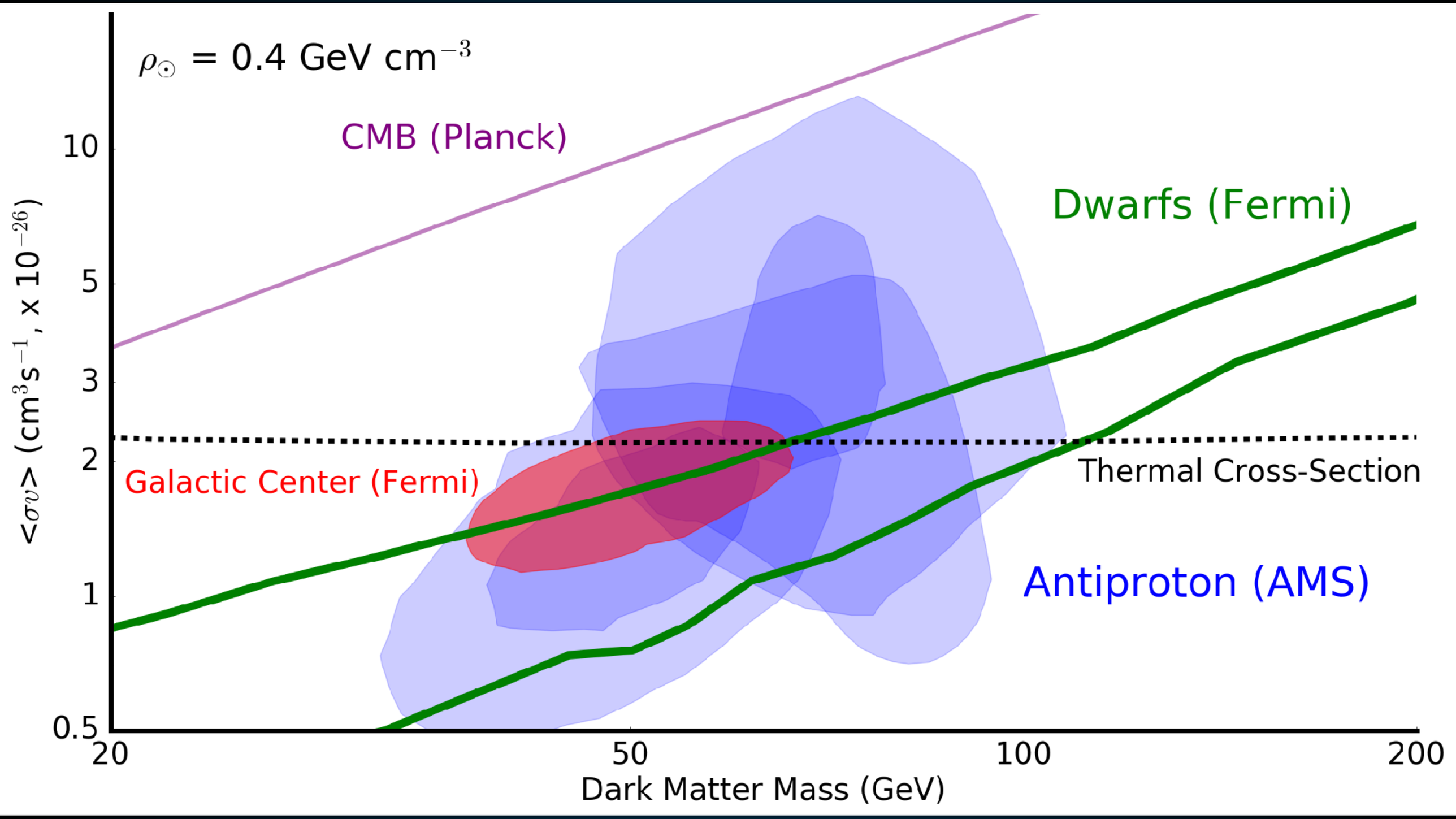

$b\bar{b}$
4 yr of data, 15 Dwarf Galaxies
Actual Limit
Expected Limit
Thermal Cross-Section
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$\langle\sigma v\rangle$ (cm^{3}s^{-1})
10
100
1000
Dark Matter Mass (GeV)
Ackermann et al. (2013; 1310.0828)

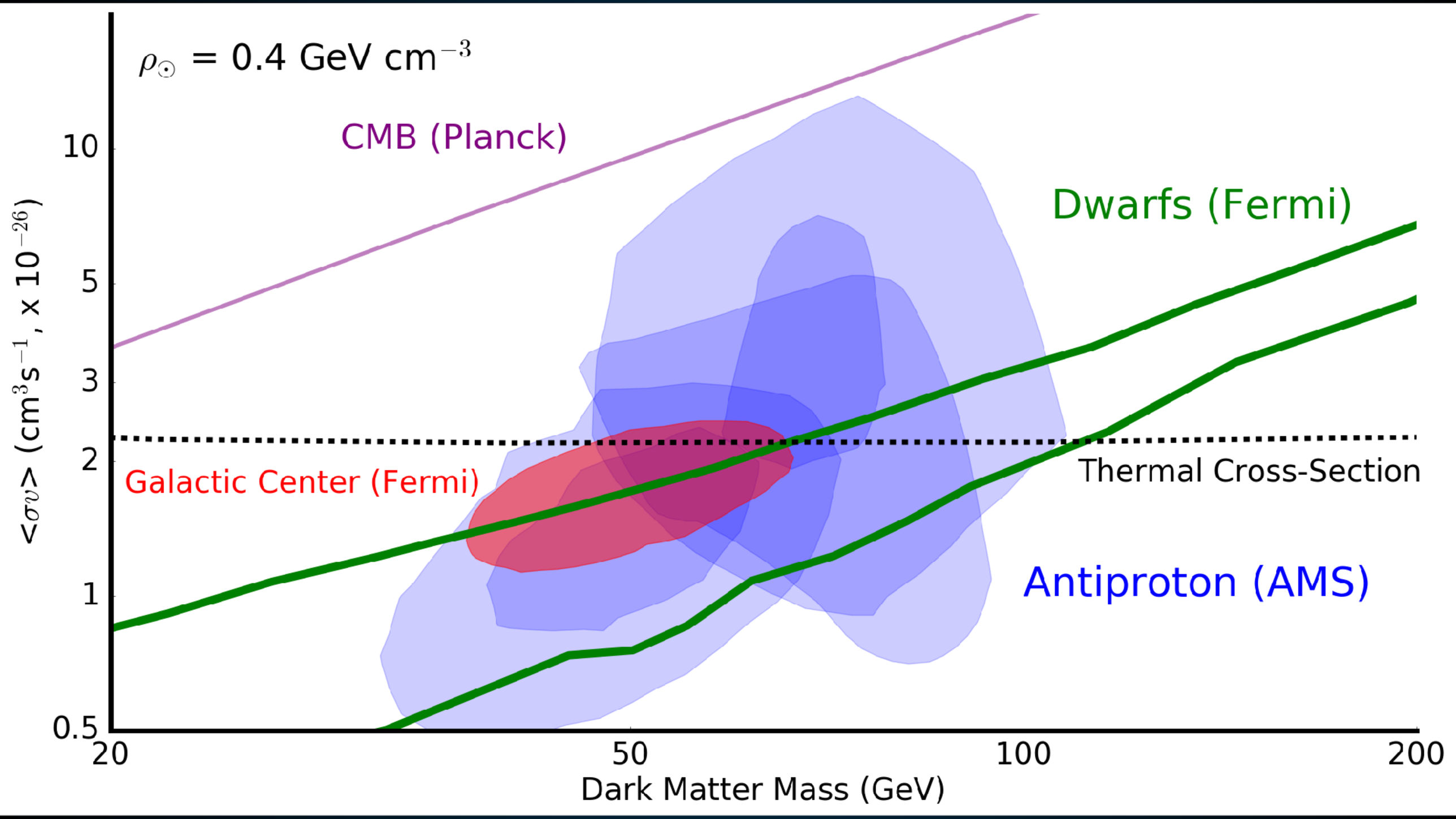

$b\bar{b}$
8 yr of data, 45 Dwarf Galaxies
Actual Limit
Expected Limit
Thermal Cross-Section
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ ($cm^3 s^{-1}$)
10
100
1000
Dark Matter Mass (GeV)
Albert et al. (2016; 1611.03184)

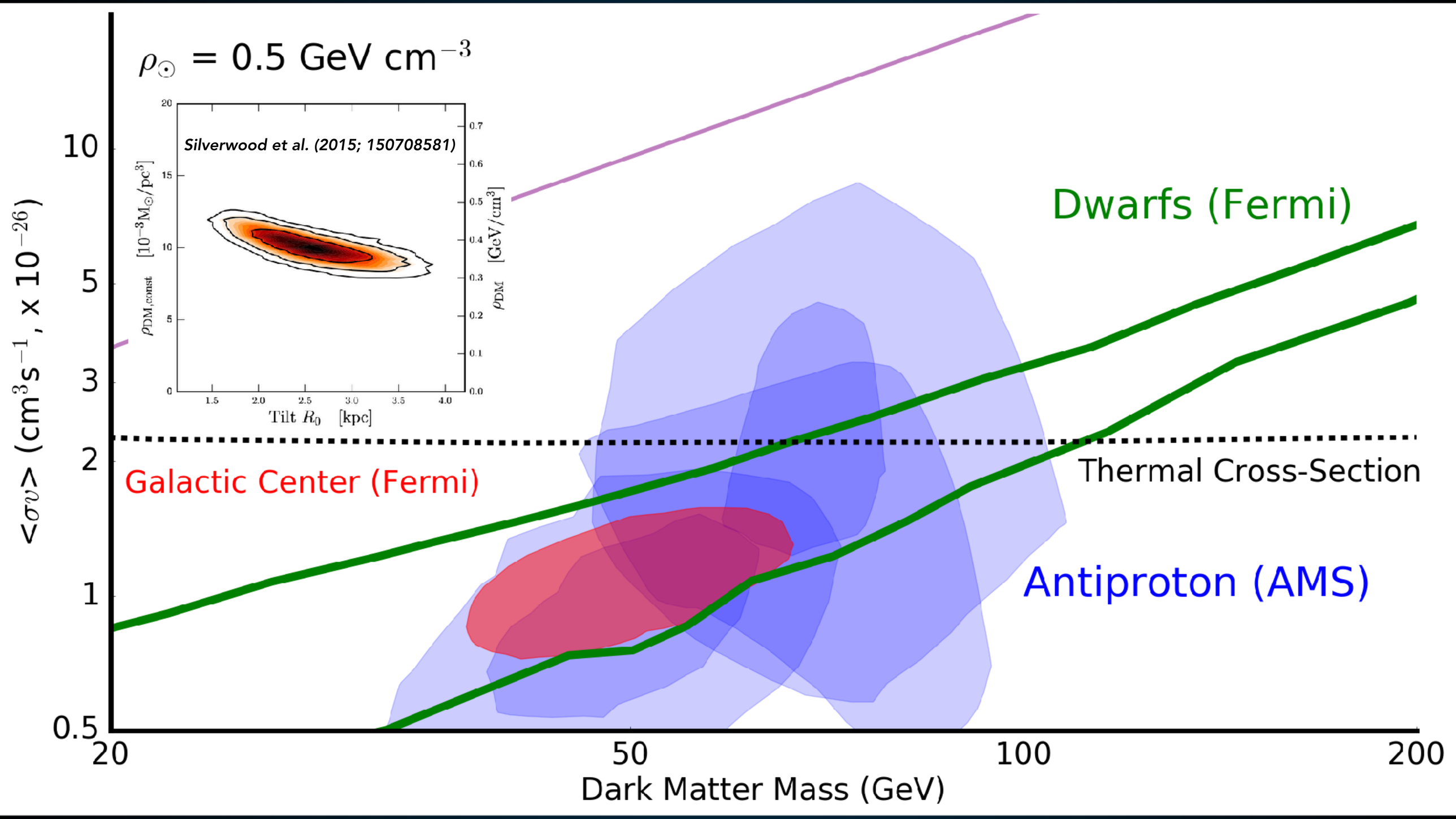

$b\bar{b}$
9 yr of data, 45 Dwarf Galaxies
Actual Limit
Thermal Cross-Section
Expected Limit
Linden (2019; 1905.11992)
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ ($cm^3 s^{-1}$)
10
100
1000
Dark Matter Mass (GeV)

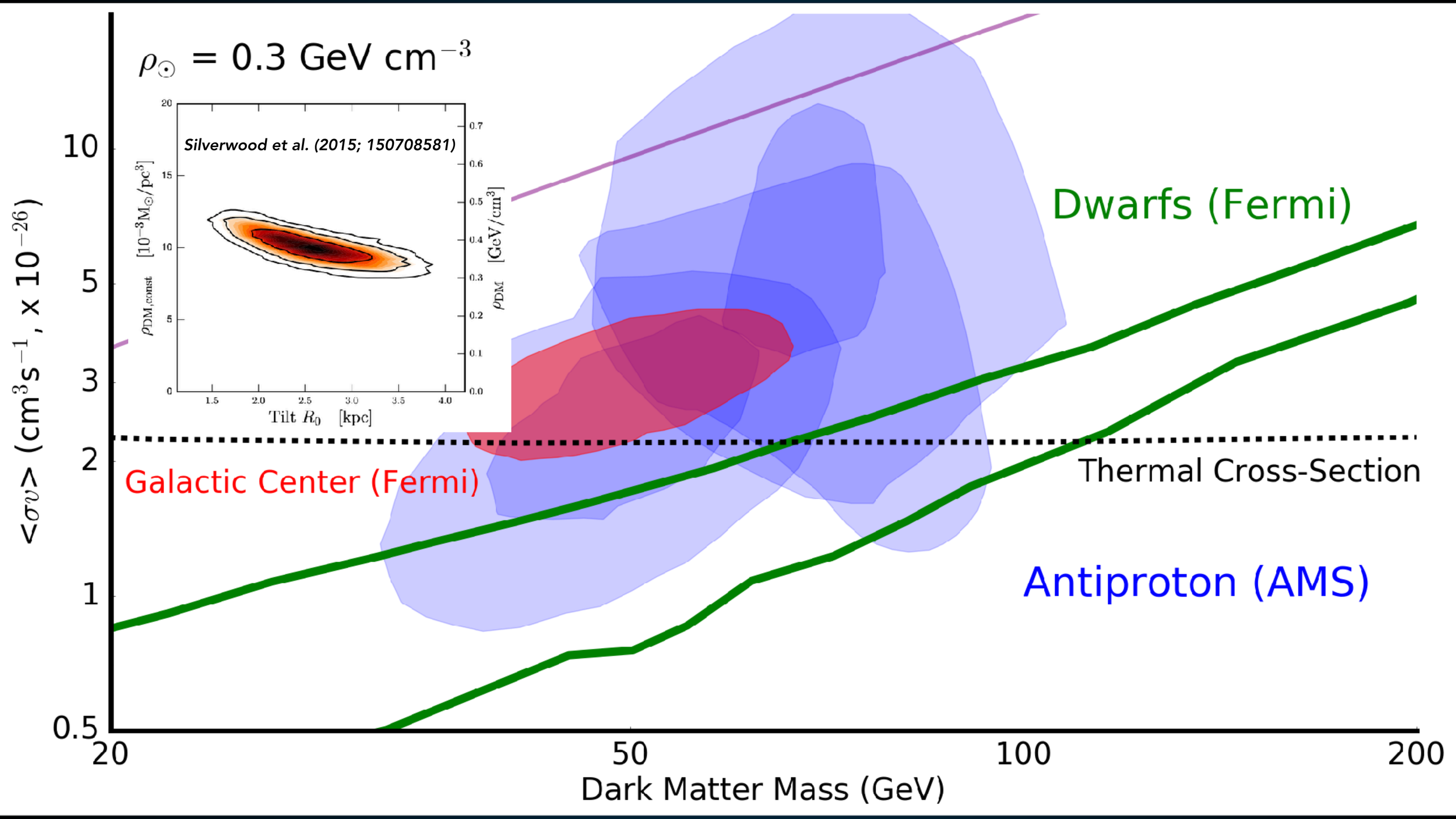

$b\bar{b}$
9 yr of data, 27 Dwarf Galaxies
95% Confidence (Frequentist)
Thermal Cross-Section
95% Confidence (Bayesian)
Hoof et al. (2018;1812.06986)
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$\langle\sigma v\rangle$ (cm^{3}s^{-1})
10
100
1000
Dark Matter Mass (GeV)

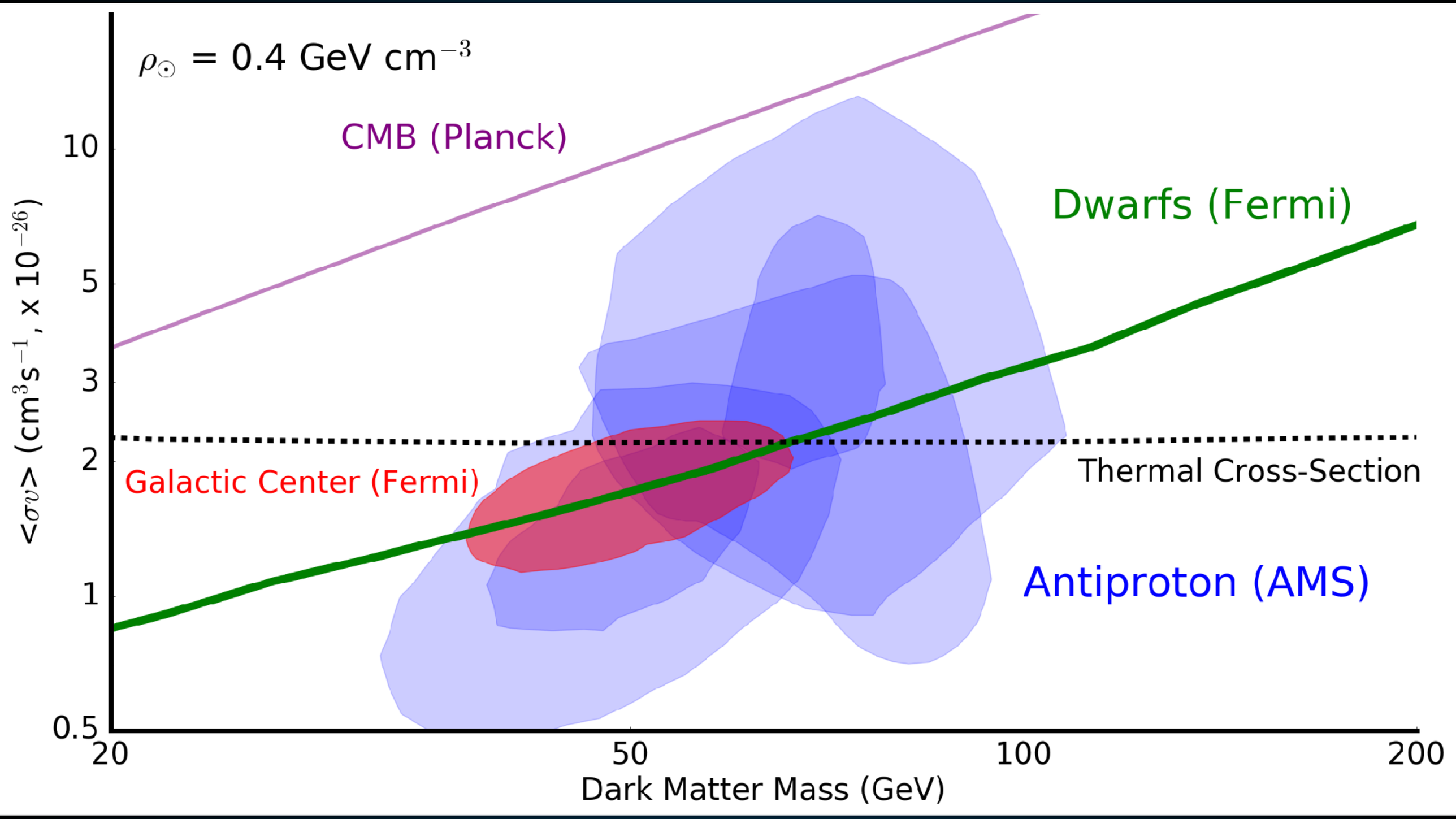
WHERE
ARE
WE NOW?

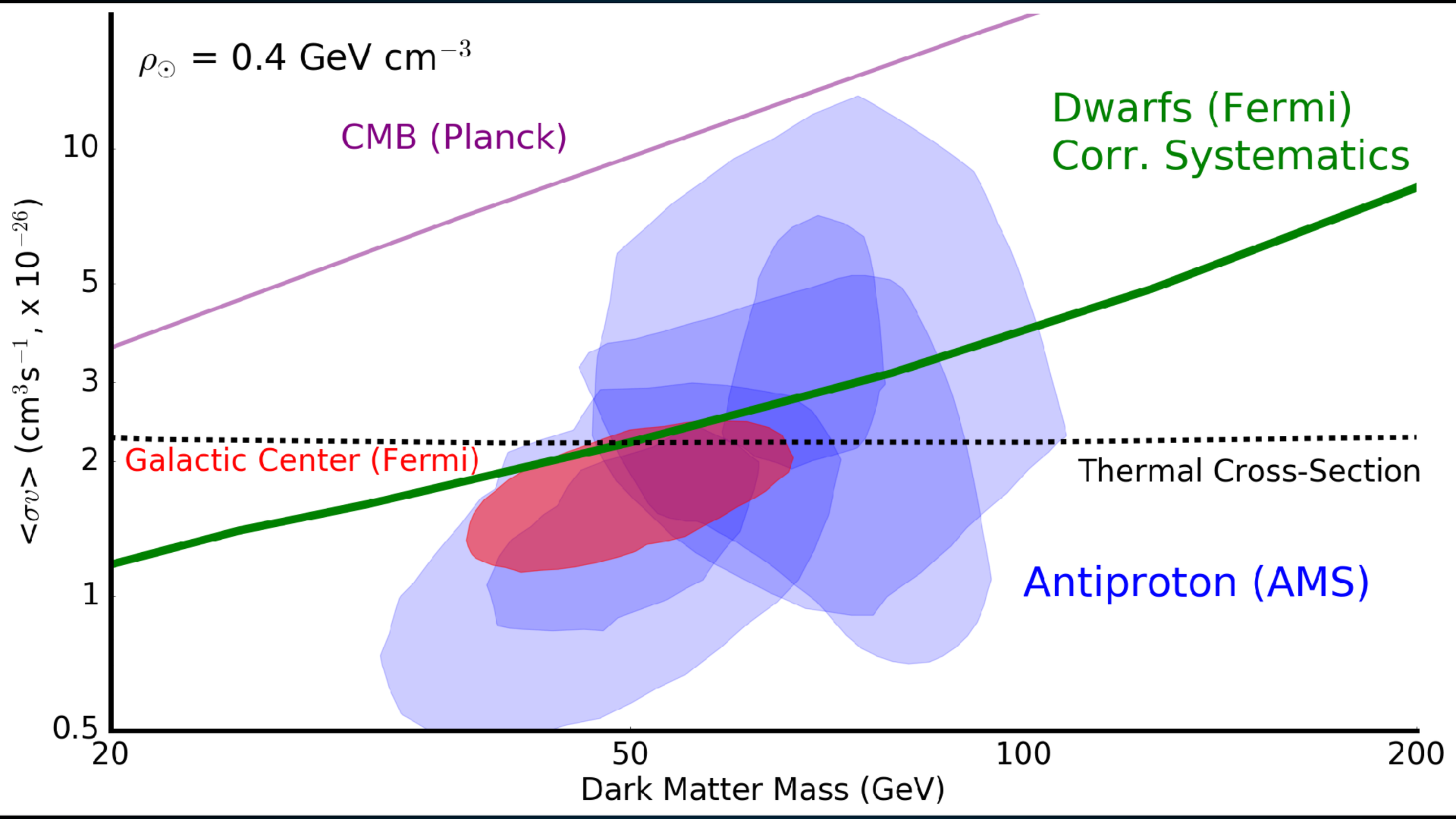

$\rho_\odot$ = 0.4 GeV cm^{-3}
CMB (Planck)
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
10
5
3
2
1
0.5
20
50
100
200
Dark Matter Mass (GeV)

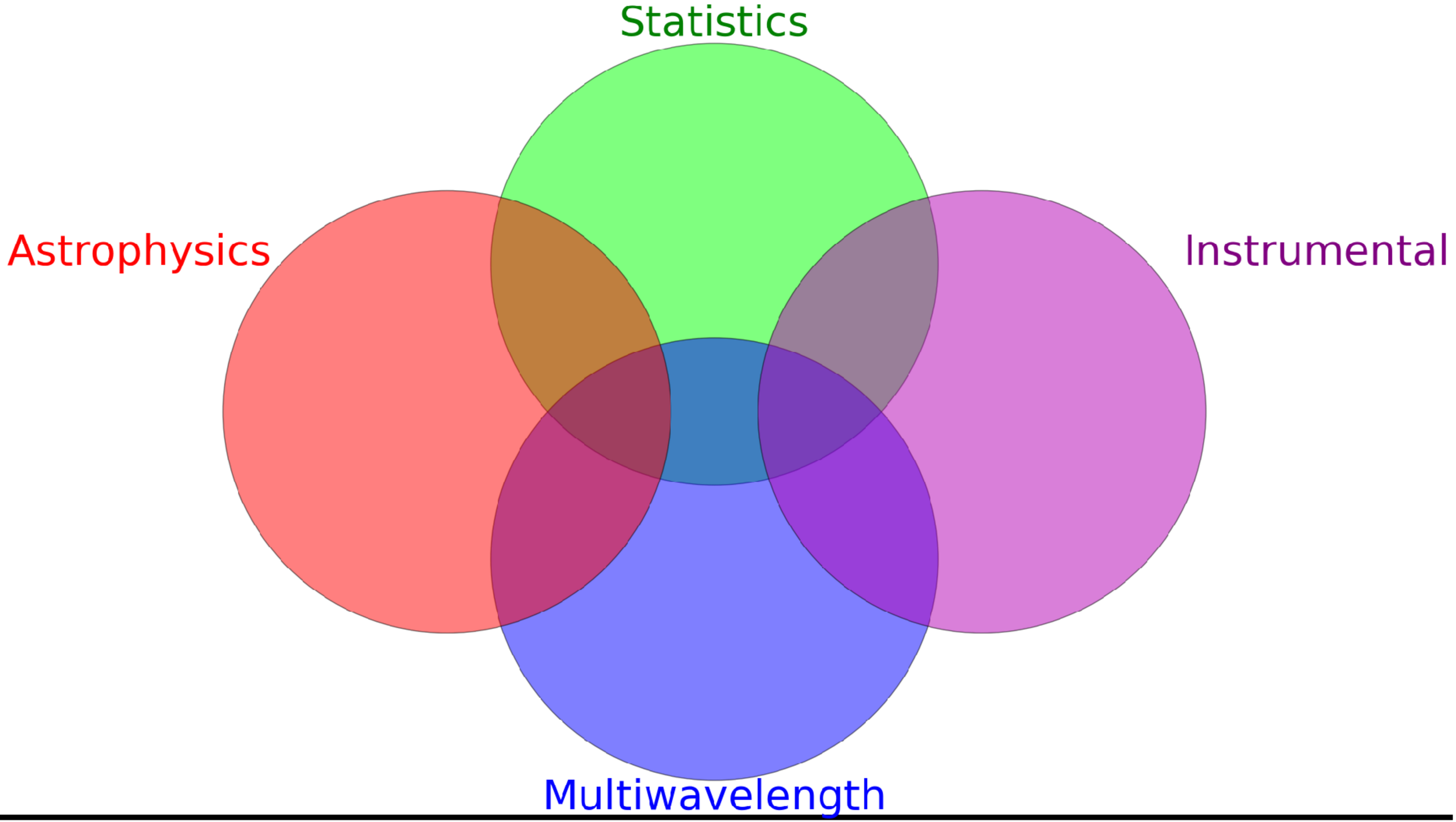

$\rho_\odot$ = 0.4 GeV cm^{-3}
CMB (Planck)
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
10
5
3
2
1
0.5
20
50
100
200
Dark Matter Mass (GeV)

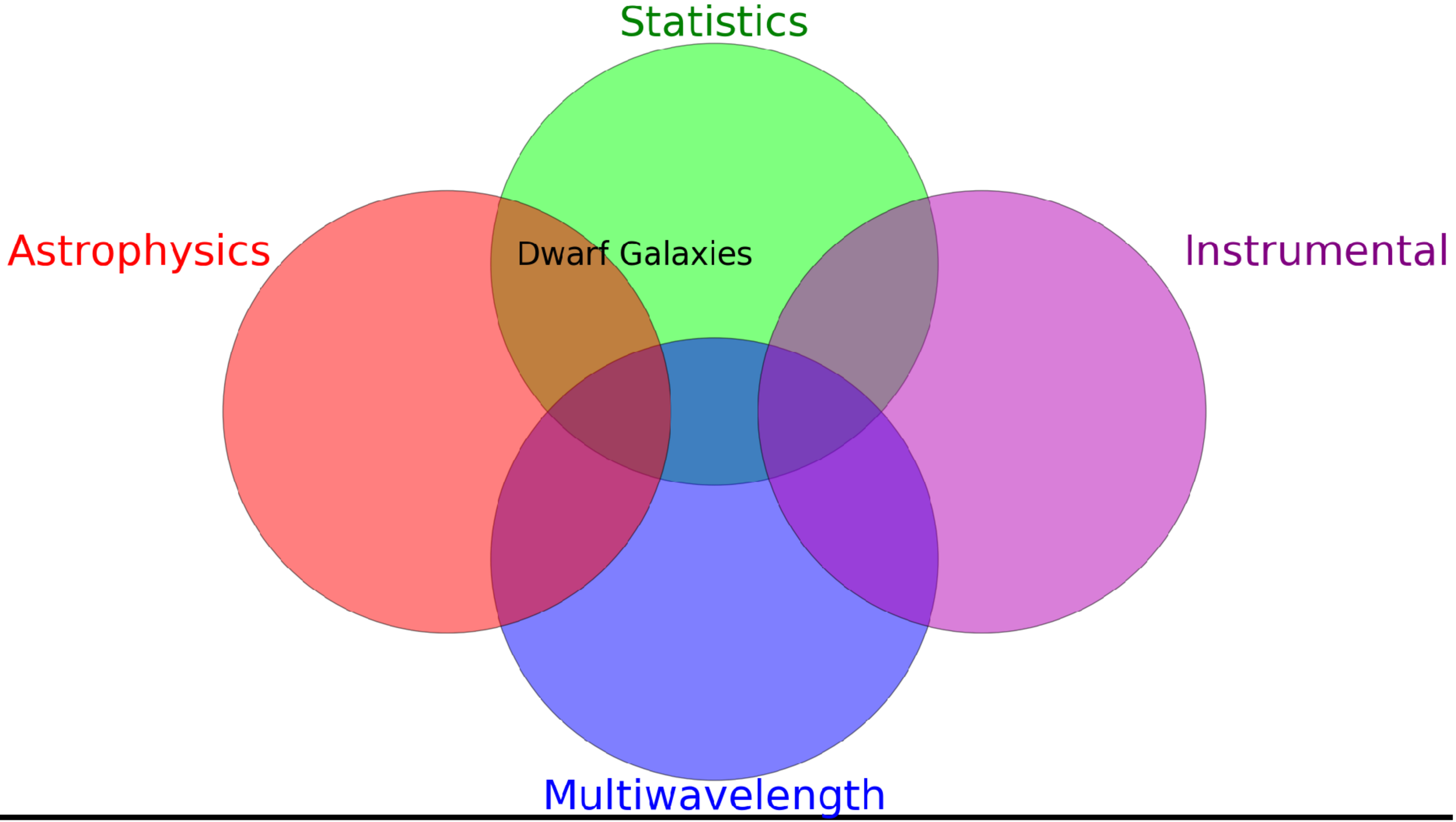

$\rho_\odot$ = 0.5 GeV cm^{-3}
Silverwood et al. (2015; 150708581)
$\rho_{\rm DM,const}$ [10^{-3}M$_\odot$/pc^3]
$\rho_{\rm DM}$ [GeV/cm^3]
Tilt R_0 [kpc]
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
Dark Matter Mass (GeV)
0.5
1
2
3
5
10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

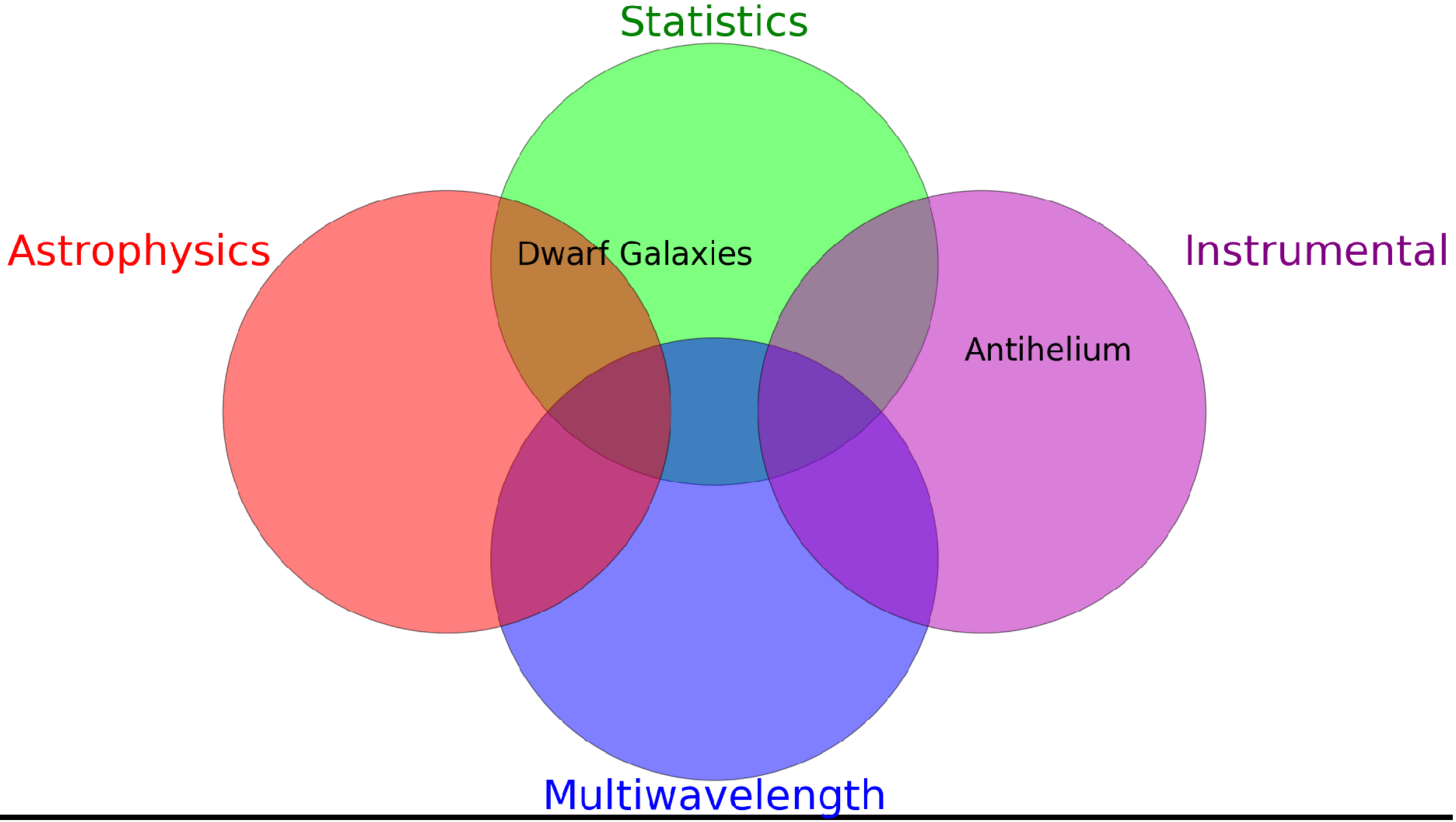

$\rho_\odot$ = 0.3 GeV cm^{-3}
Silverwood et al. (2015; 150708581)
$\rho_{\rm DM,const}$ [10^{-3}M$_\odot$/pc^3]
$\rho_{\rm DM}$ [GeV/cm^3]
Tilt R_0 [kpc]
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
Dark Matter Mass (GeV)

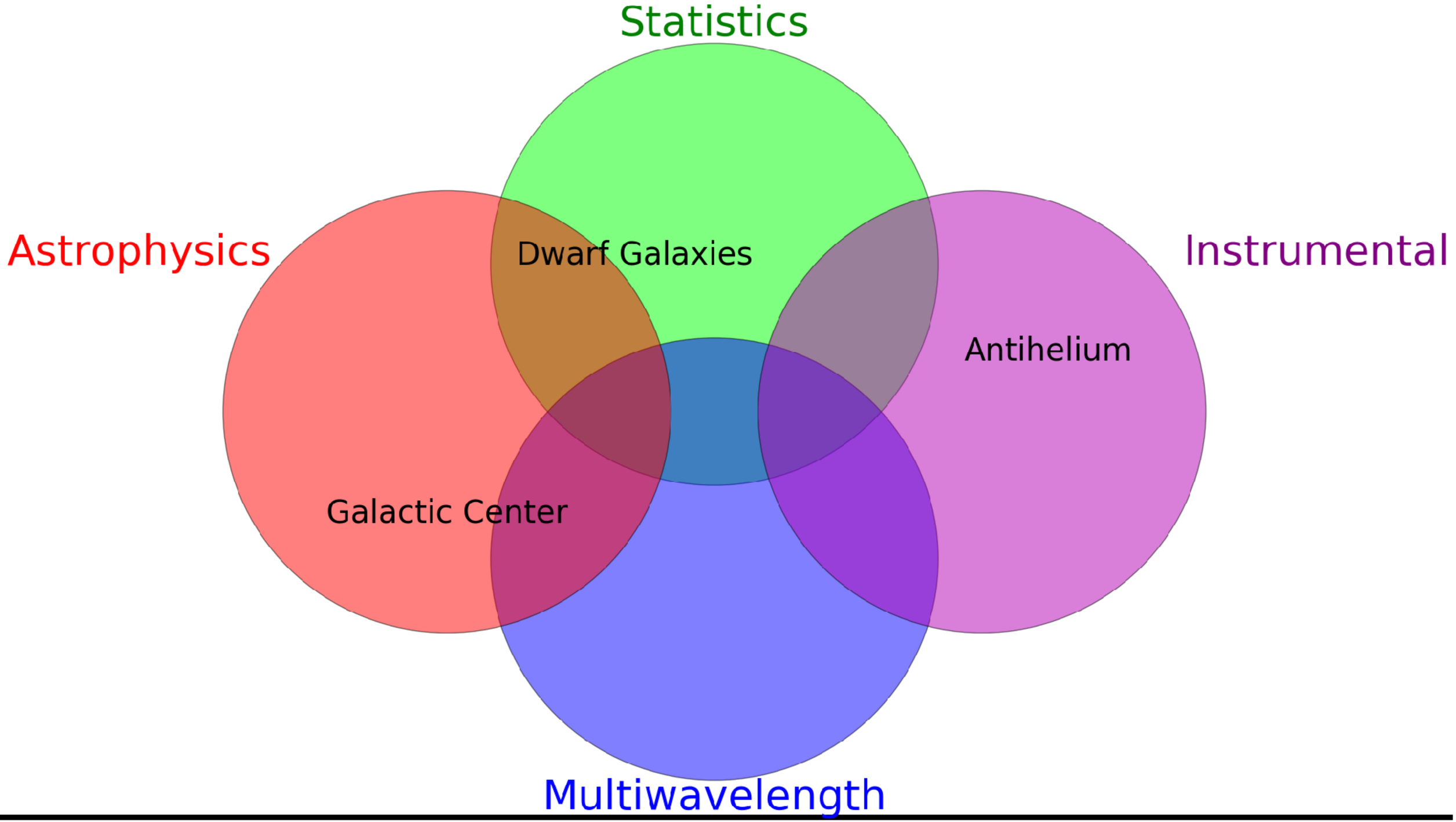

$\rho_\odot$ = 0.4 GeV cm^{-3}
CMB (Planck)
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
10
5
3
2
1
0.5
20
50
100
200
Dark Matter Mass (GeV)

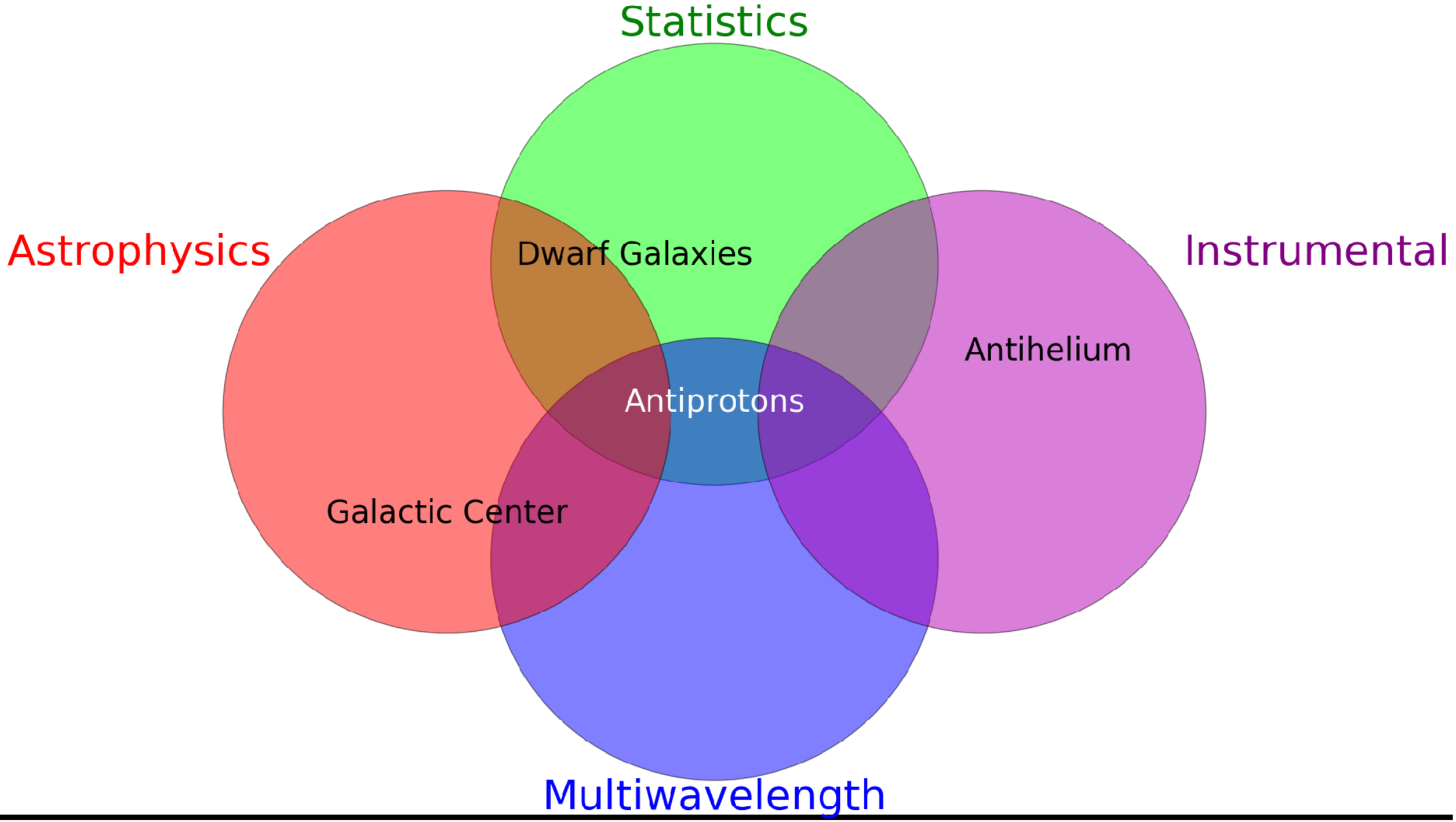

$\rho_\odot$ = 0.4 GeV cm^{-3}
CMB (Planck)
Dwarfs (Fermi)
Corr. Systematics
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
10
5
3
2
1
0.5
20
50
100
200
Dark Matter Mass (GeV)

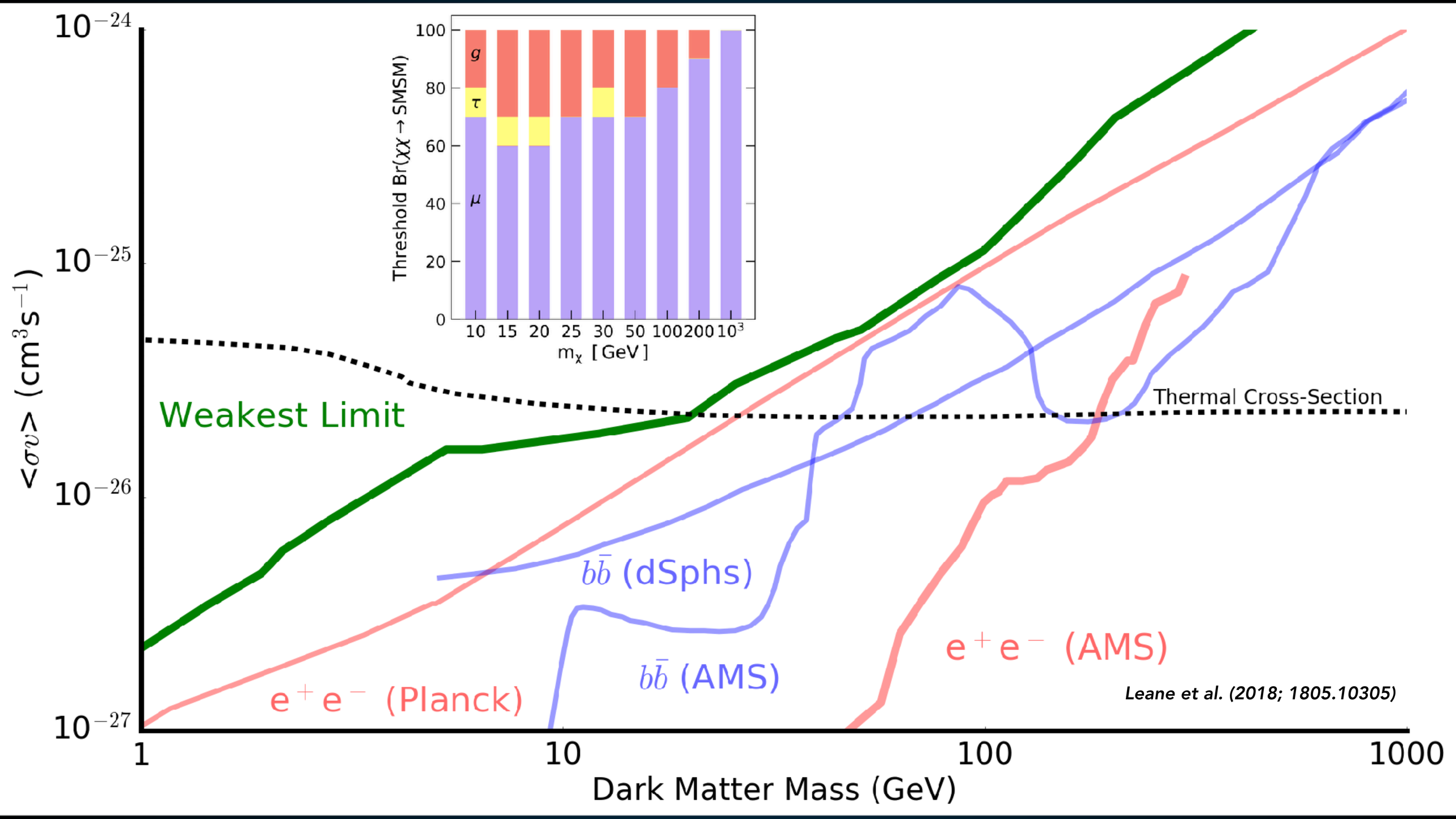

Statistics
Astrophysics
Instrumental
Multiwavelength

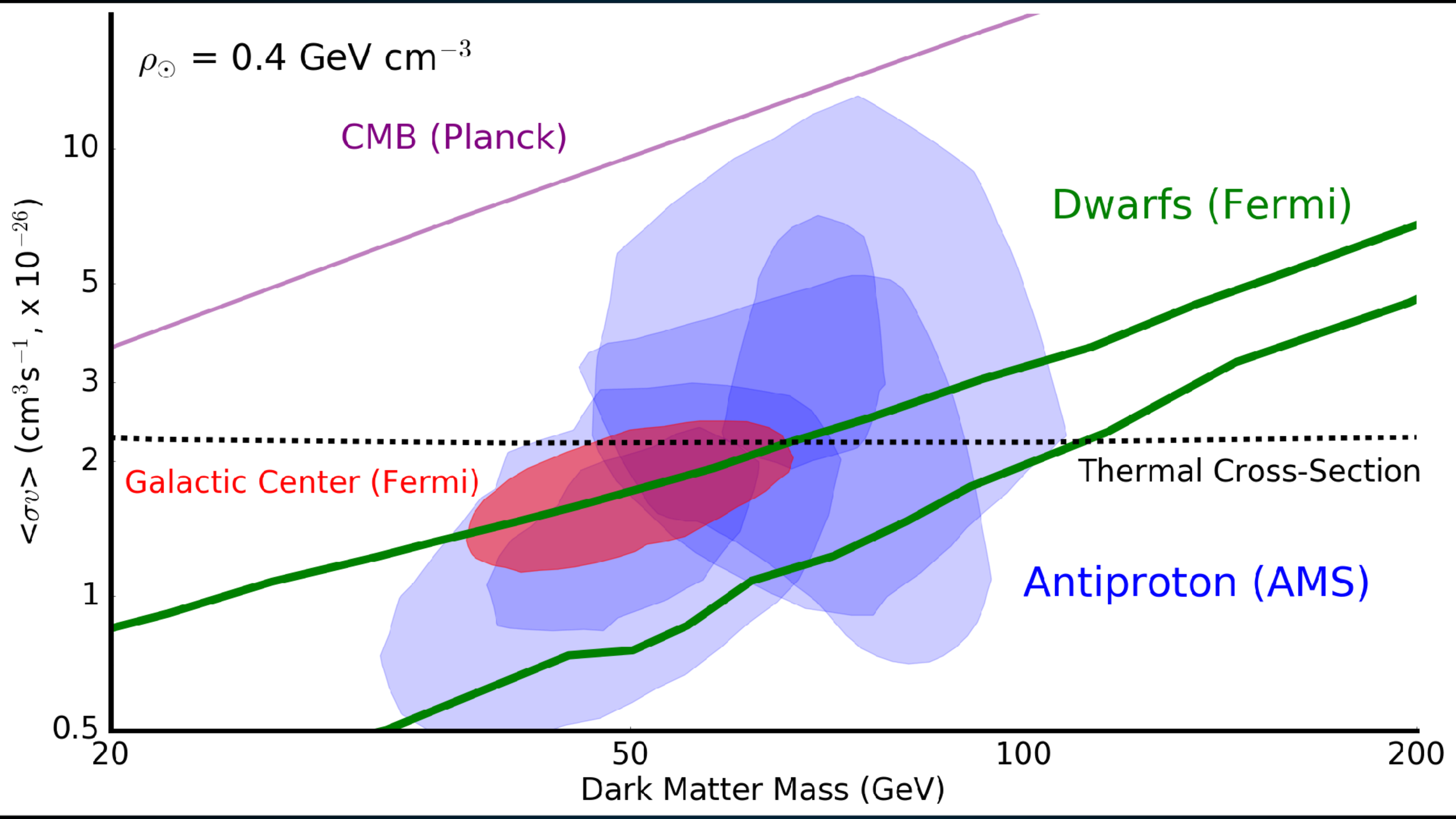

Statistics
Astrophysics
Dwarf Galaxies
Instrumental
Multiwavelength

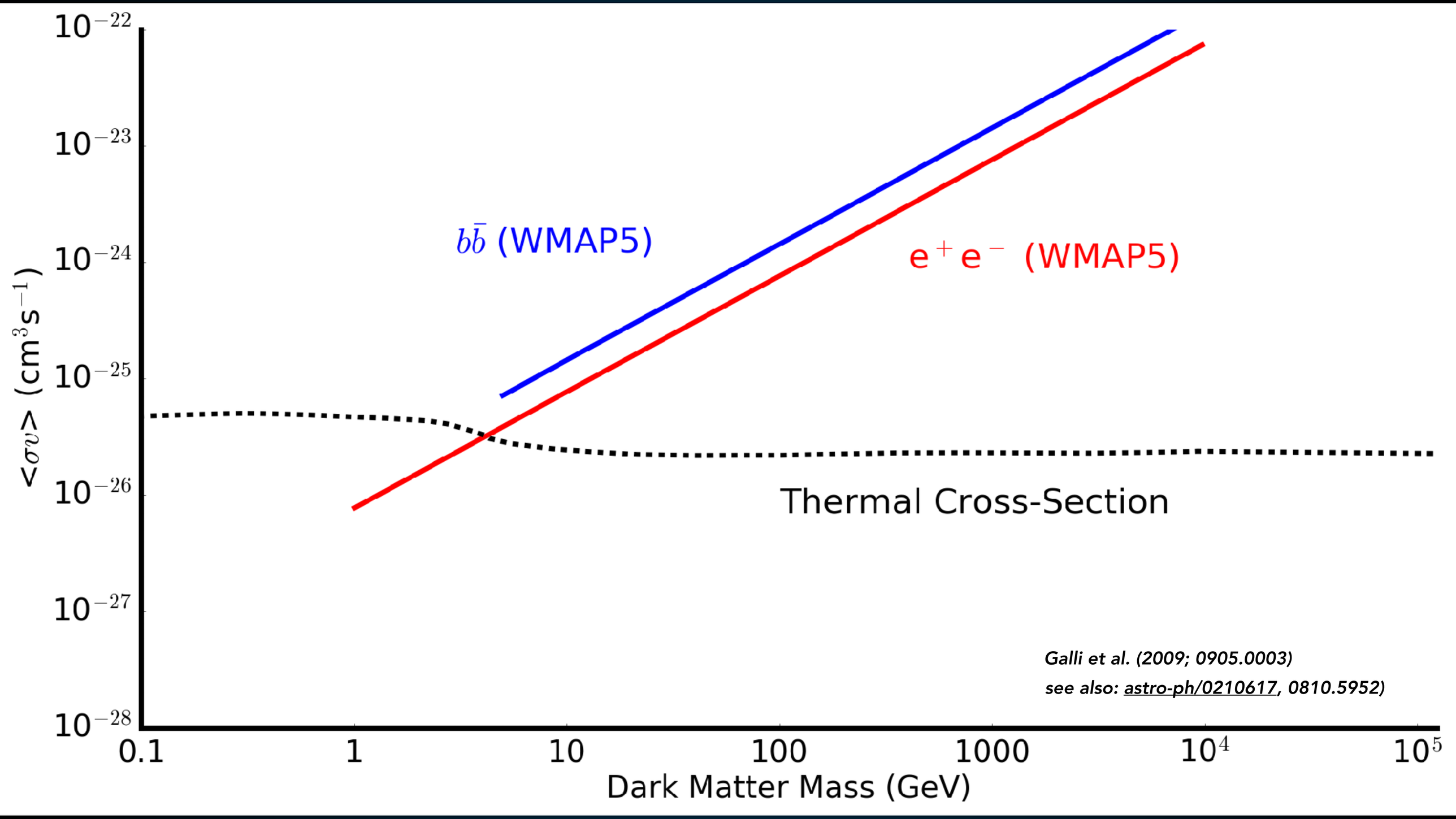

Statistics
Astrophysics
Dwarf Galaxies
Instrumental
Antihelium
Multiwavelength


Statistics
Astrophysics
Instrumental
Multiwavelength
Dwarf Galaxies
Antihelium
Galactic Center


Statistics
Astrophysics
Instrumental
Multiwavelength
Dwarf Galaxies
Antihelium
Antiprotons
Galactic Center

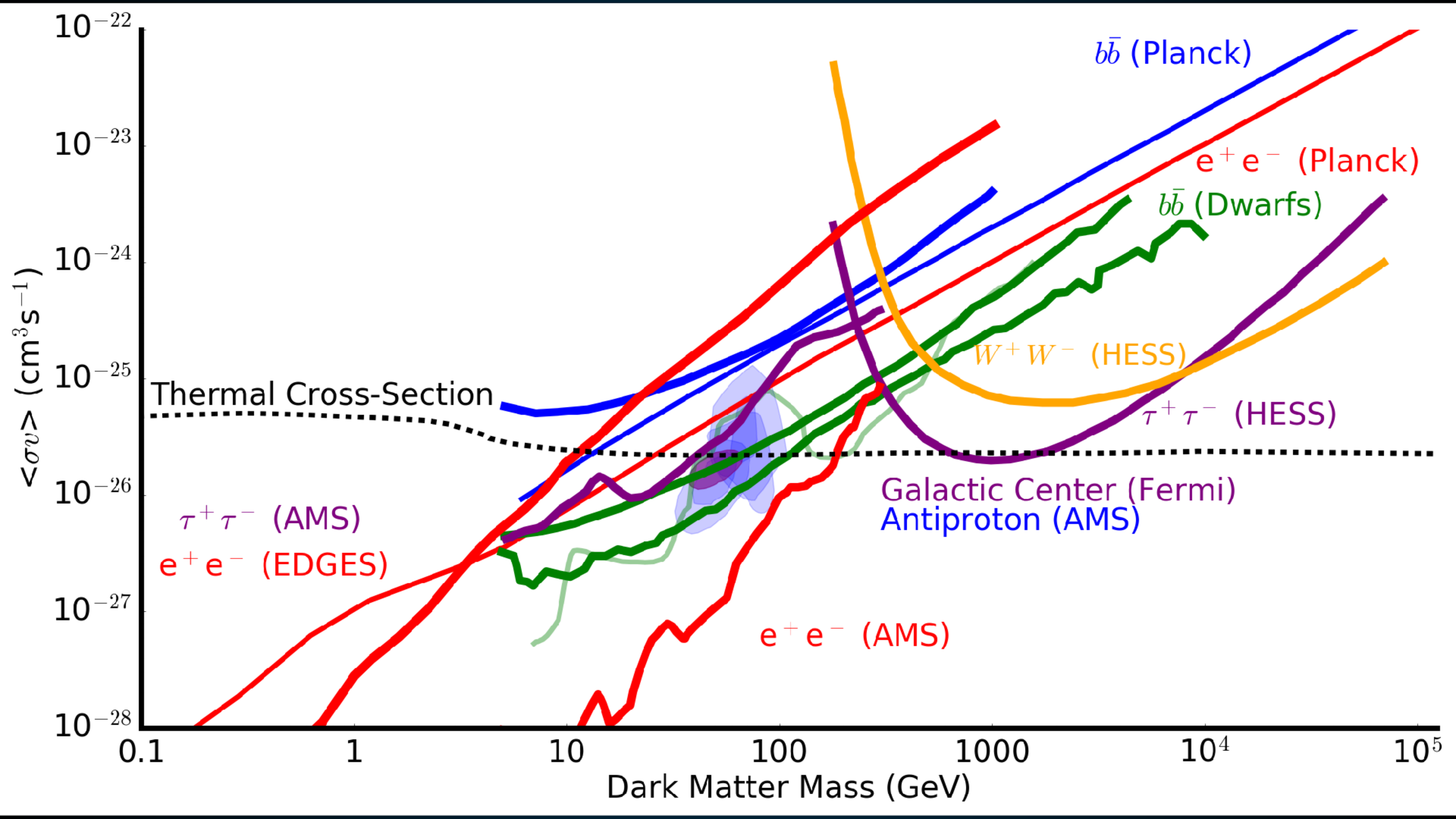

10^{-24}
10^{-25}
10^{-26}
10^{-27}
$\langle\sigma v\rangle$ (cm^{3}s^{-1})
Weakest Limit
Thermal Cross-Section
$b\bar{b}$ (dSphs)
$b\bar{b}$ (AMS)
e$^+$e$^-$ (Planck)
e$^+$e$^-$ (AMS)
Leane et al. (2018; 1805.10305)
1
10
100
1000
Dark Matter Mass (GeV)
Threshold Br($\chi\chi \to$ SMSM)
100
80
60
40
20
0
g
τ
μ
10 15 20 25 30 50 100 200 10^3
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)



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