



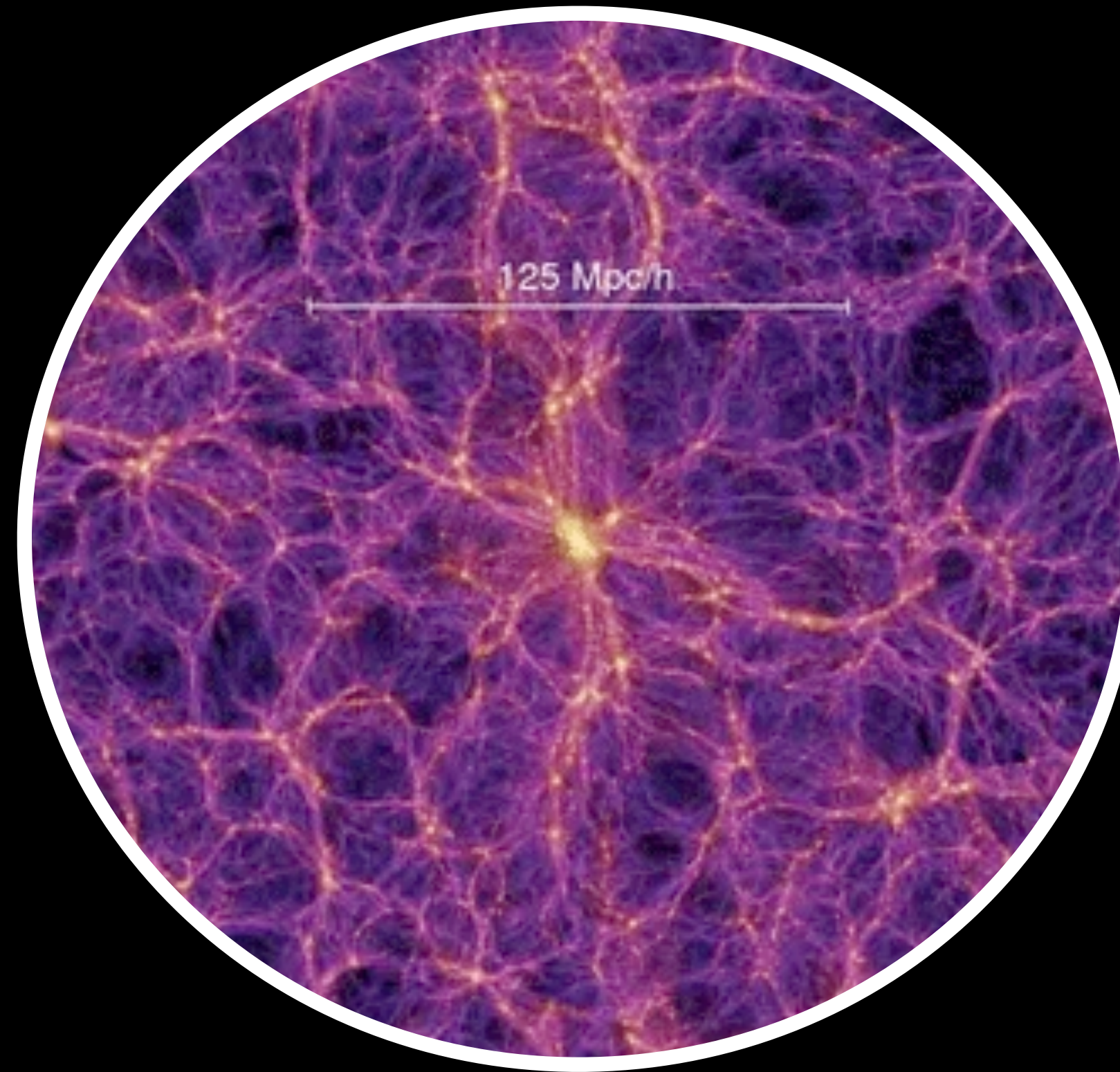
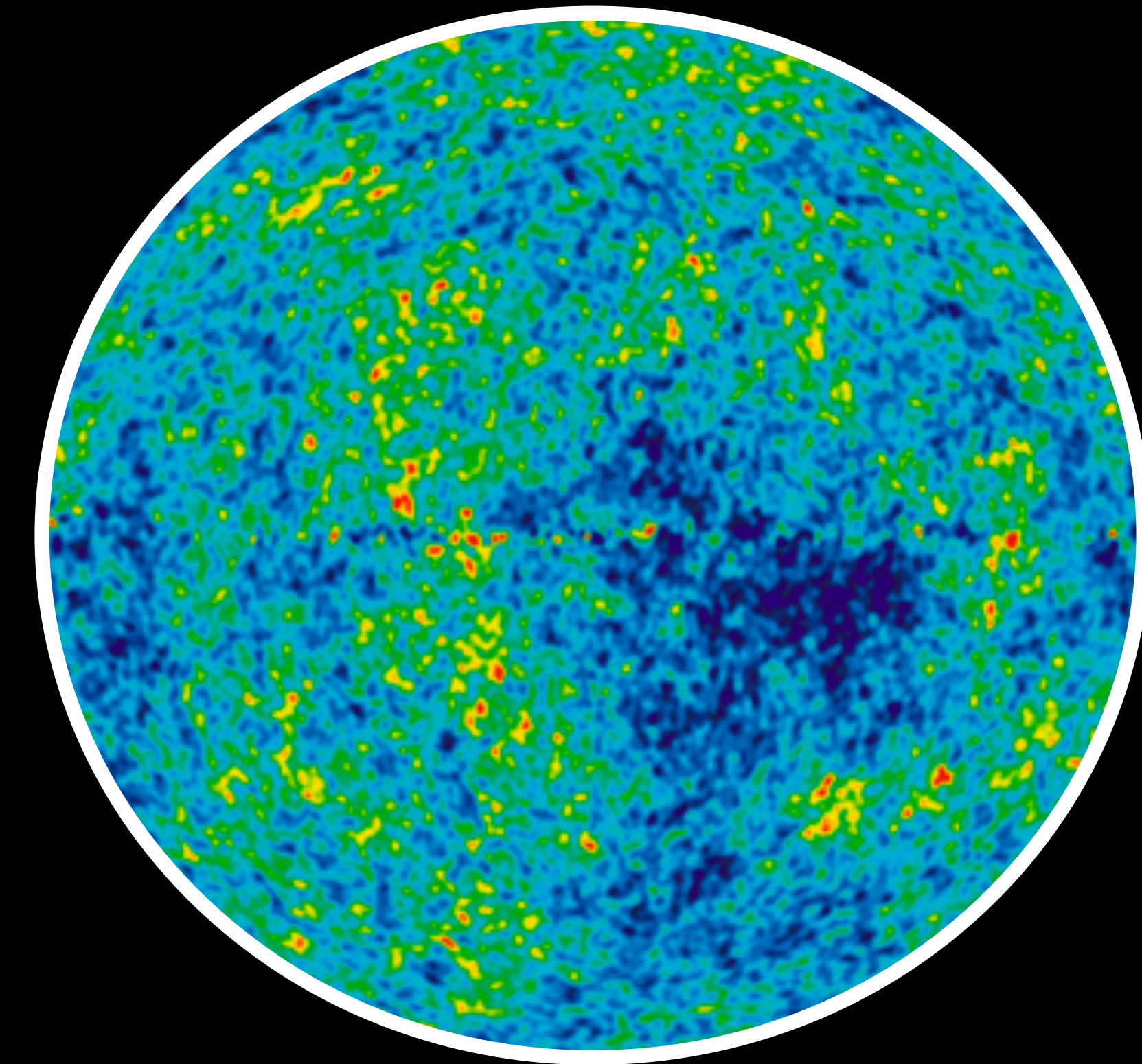
Tim Linden

Thermal WIMP Dark Matter on the Brink

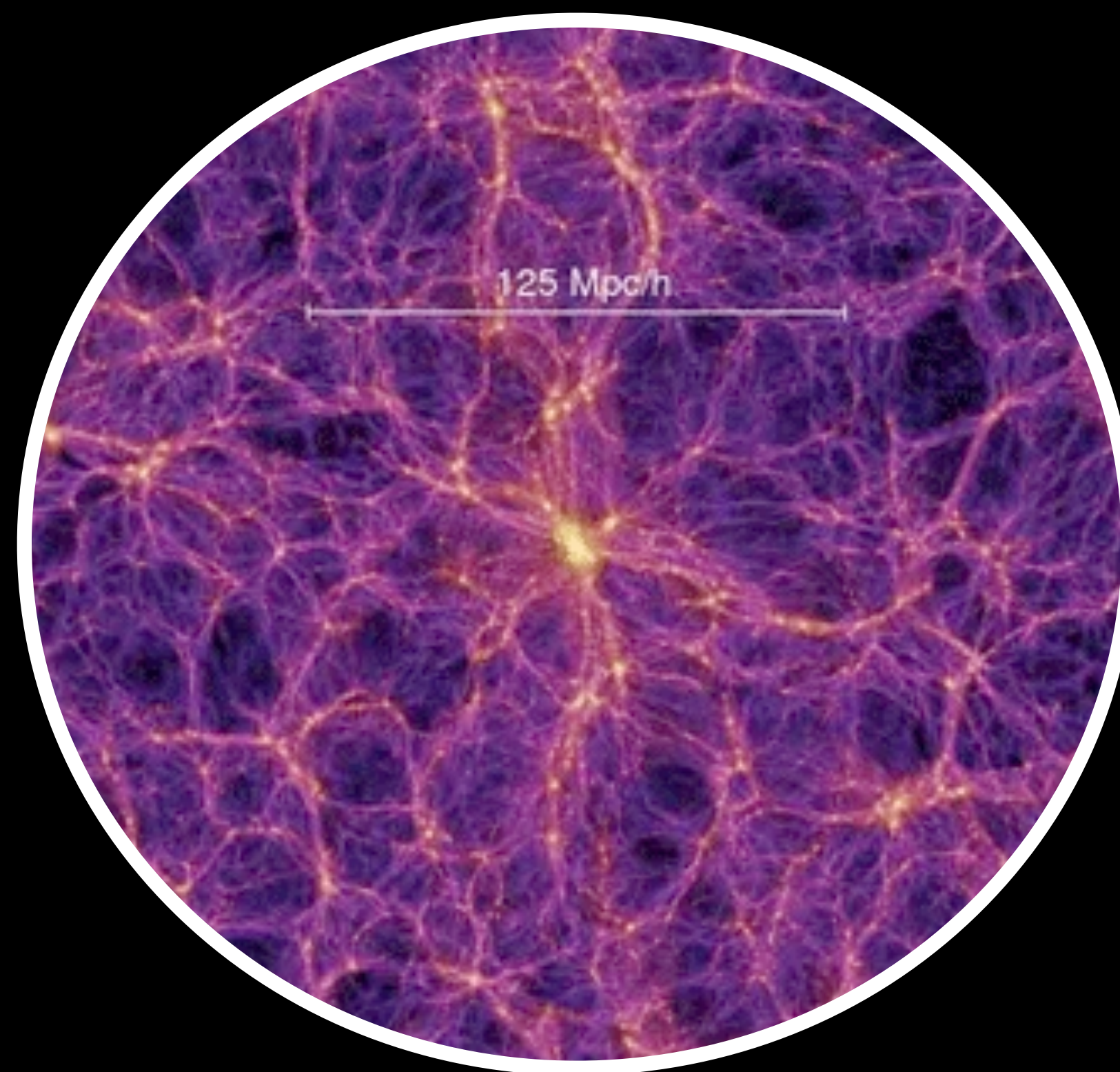
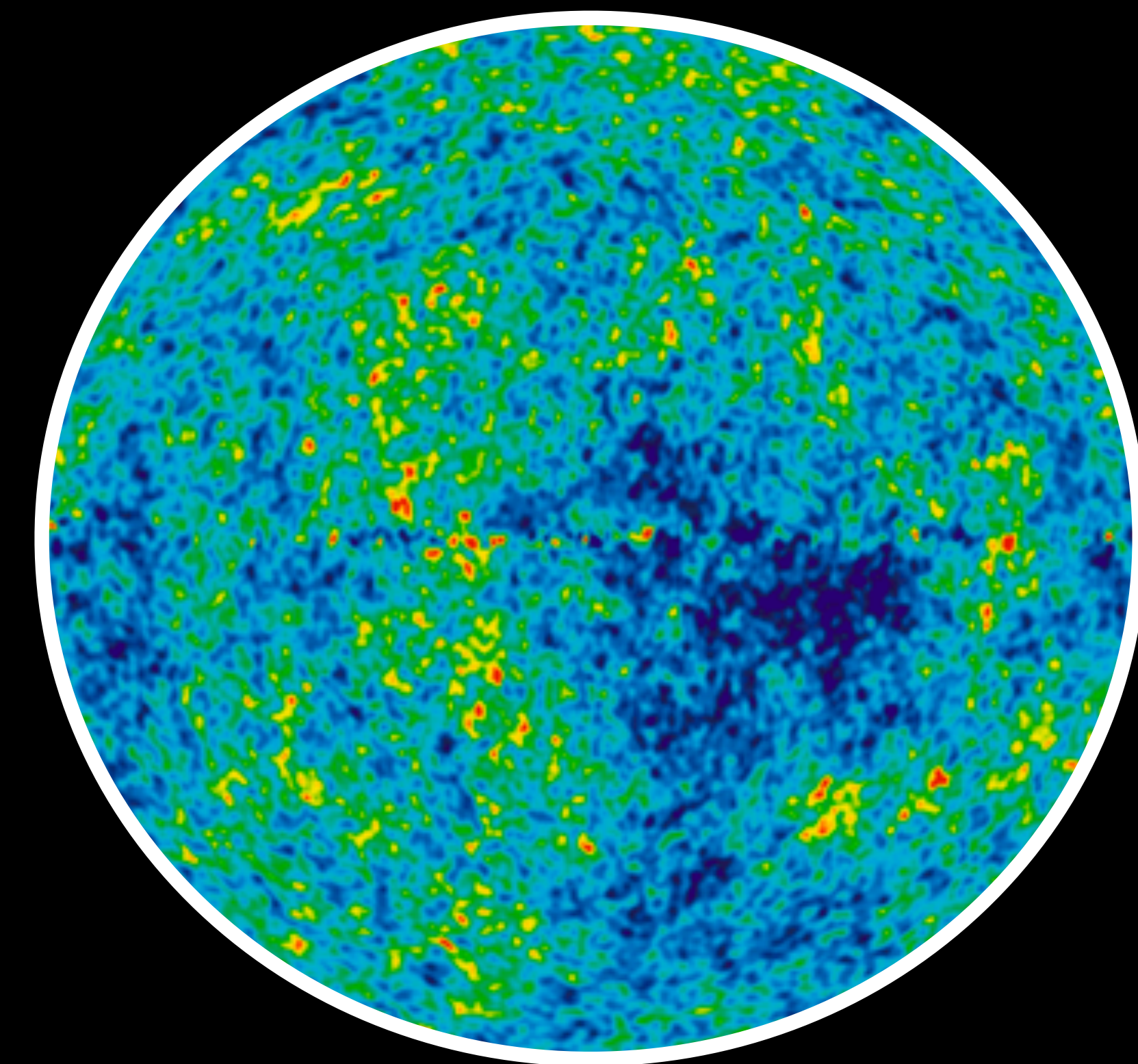


Stockholms
universitet

The Present



The Present

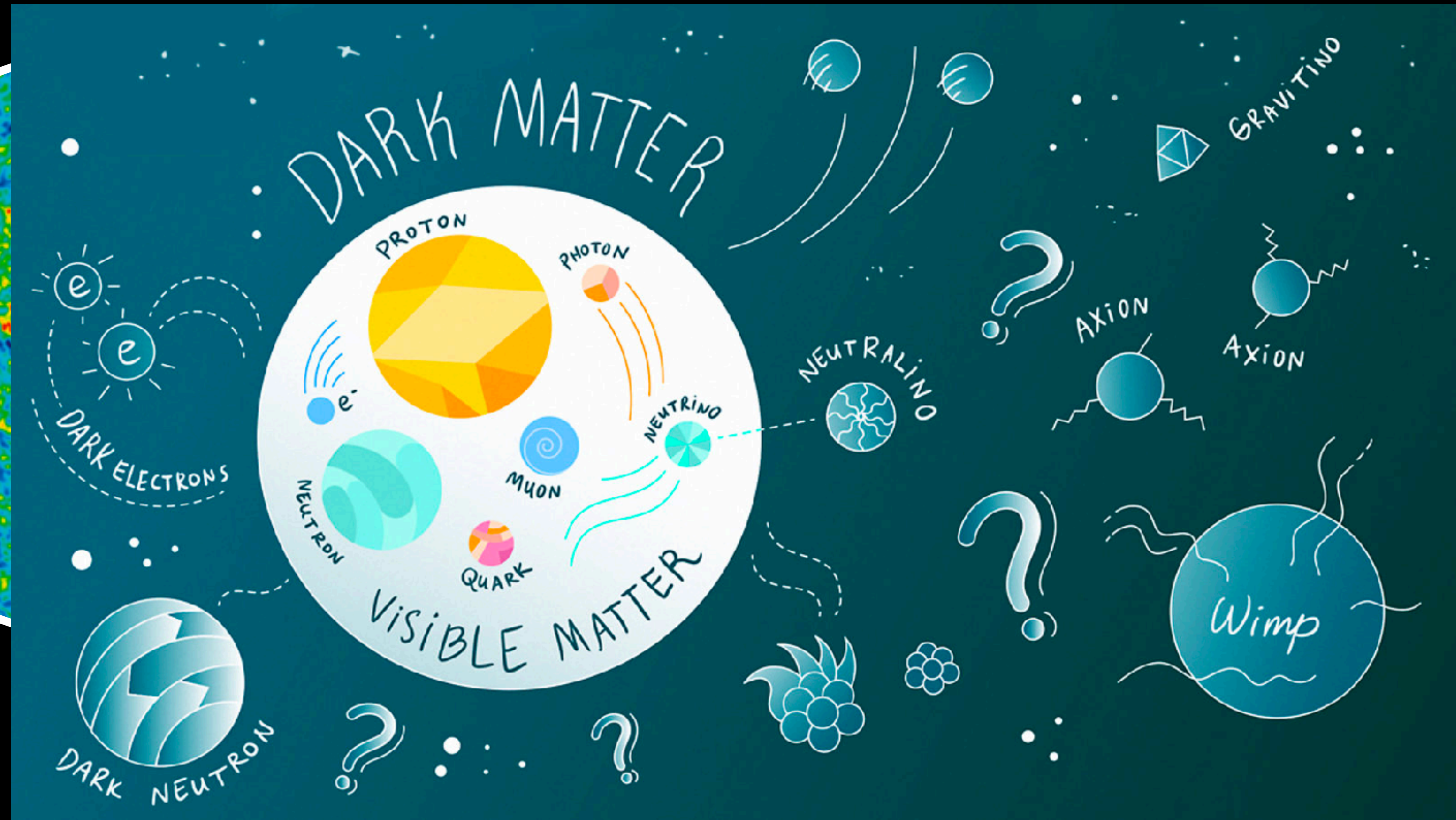


10^{-25} GeV
 $R_{DM} > R_{UFD}$

slide concept courtesy of Asher Berlin

10^{62} GeV
 $M_{DM} > M_{UFD}$

The Present



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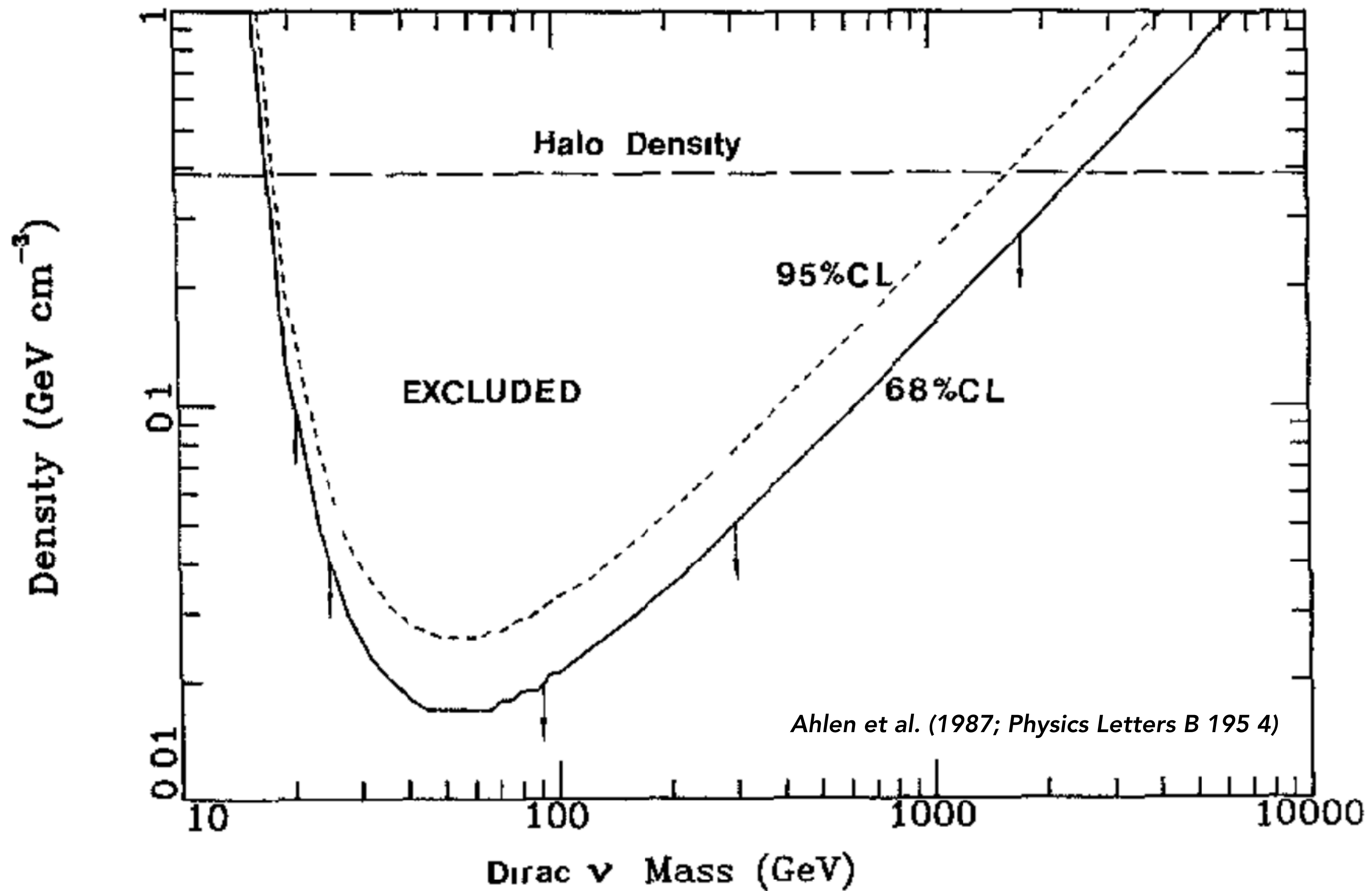
Thermal WIMP Dark Matter on the Brink



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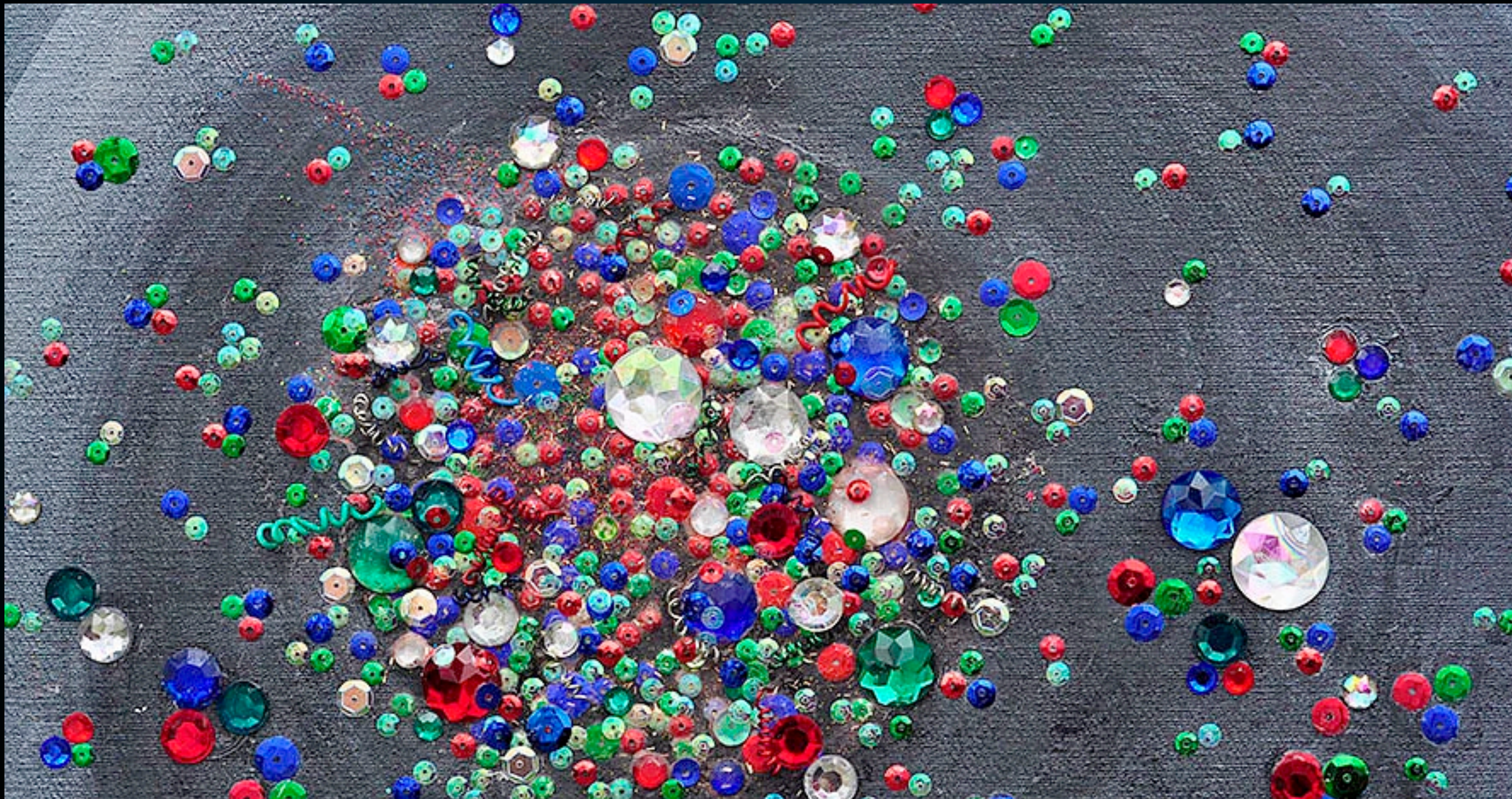
Can We Eliminate Classes of Dark Matter Models?

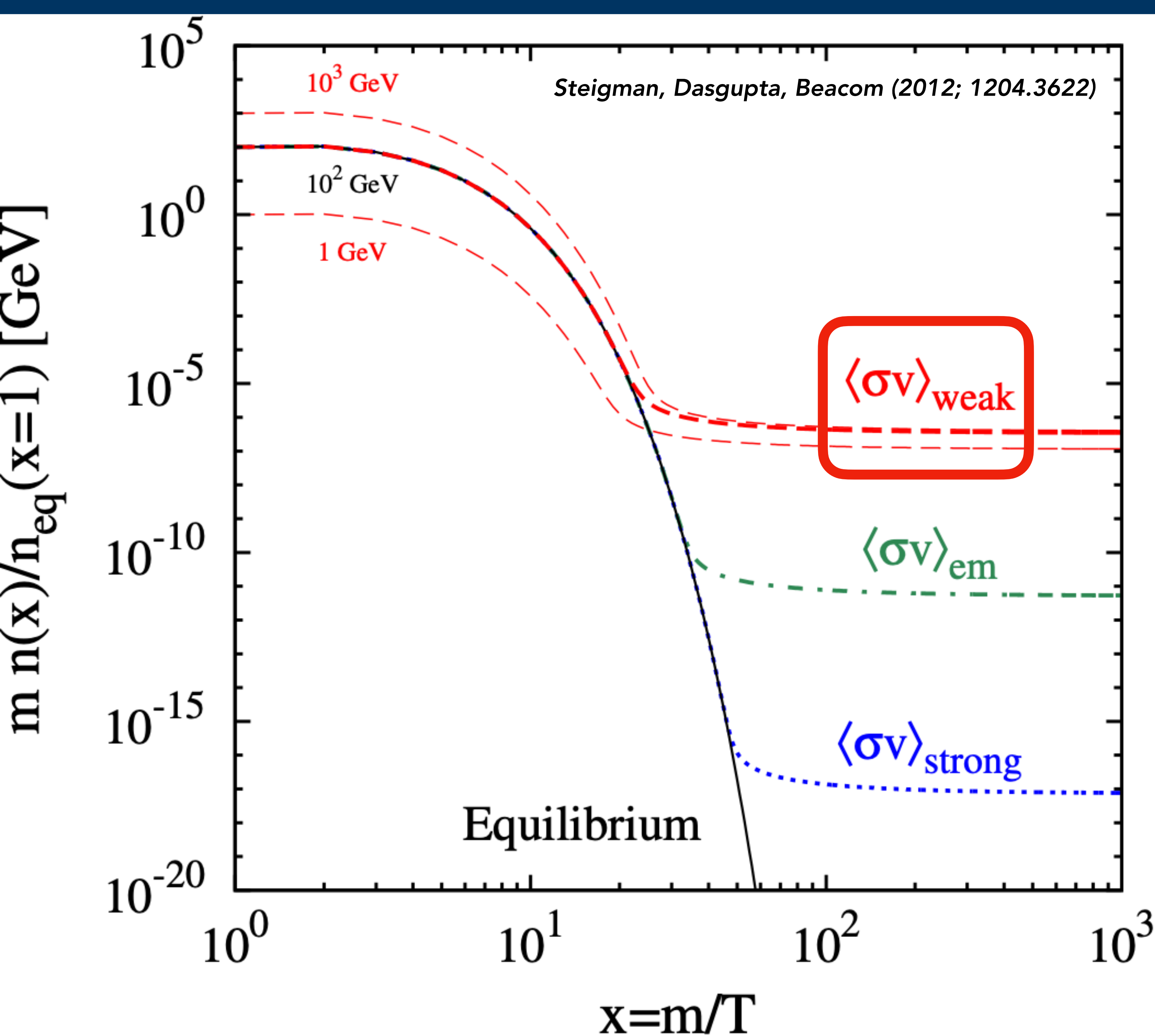
Yes!



Thermal Dark Matter

artist: Sarah Szabo



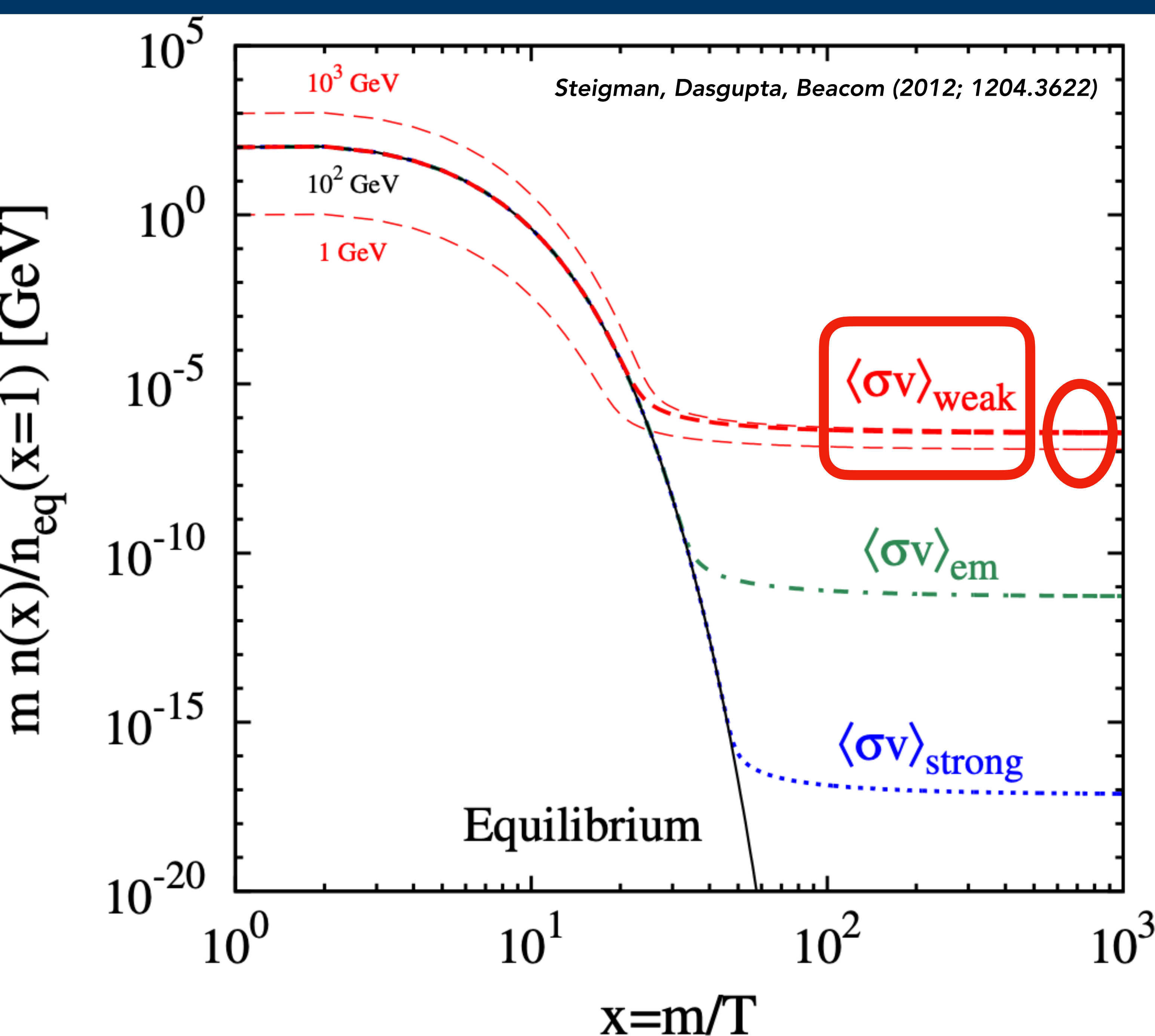


Thermal Dark Matter Density

Present density inversely proportional to the strength of the interaction.

Almost independent of particle mass.

Weak-Interaction Produces the right density!



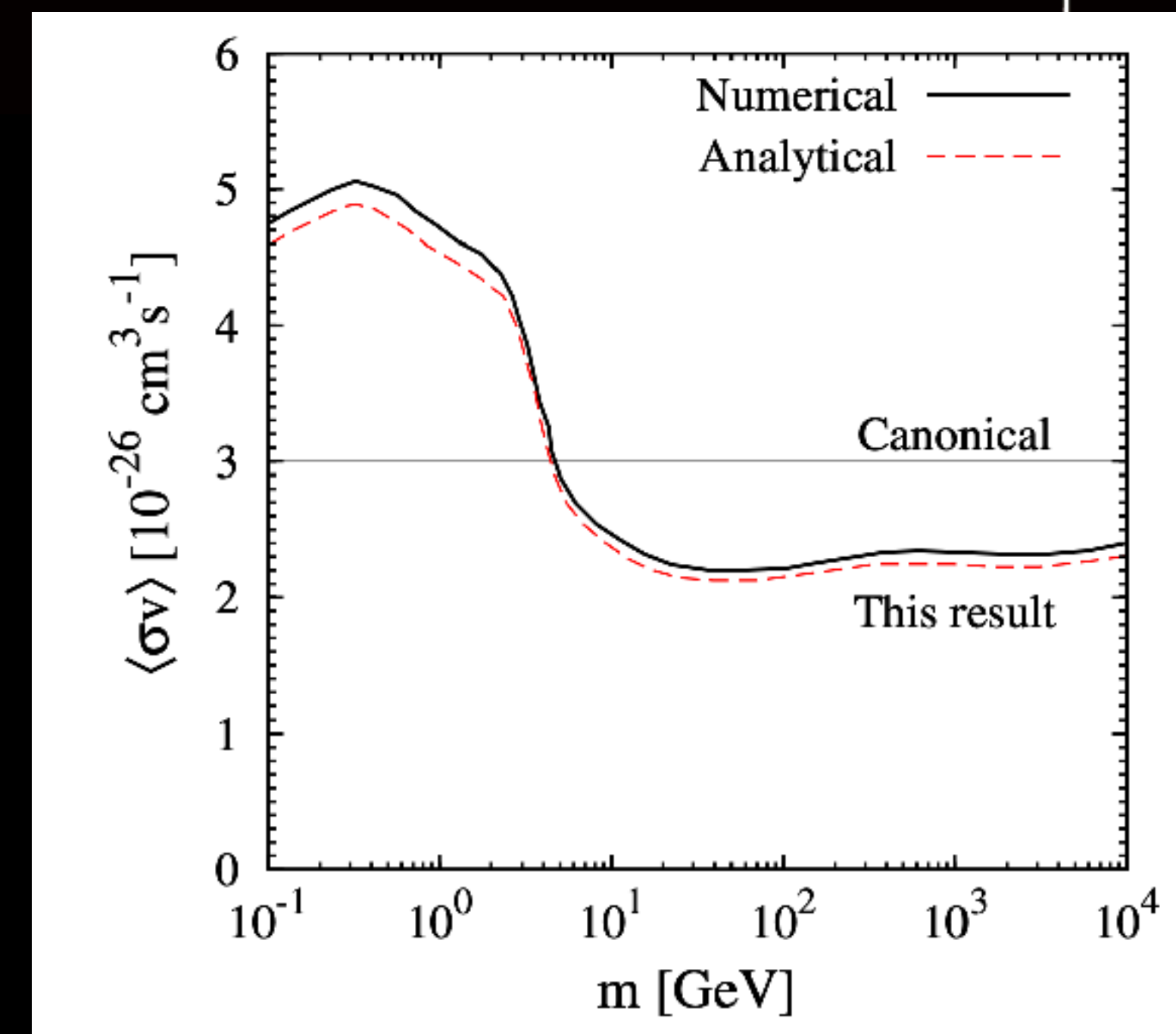
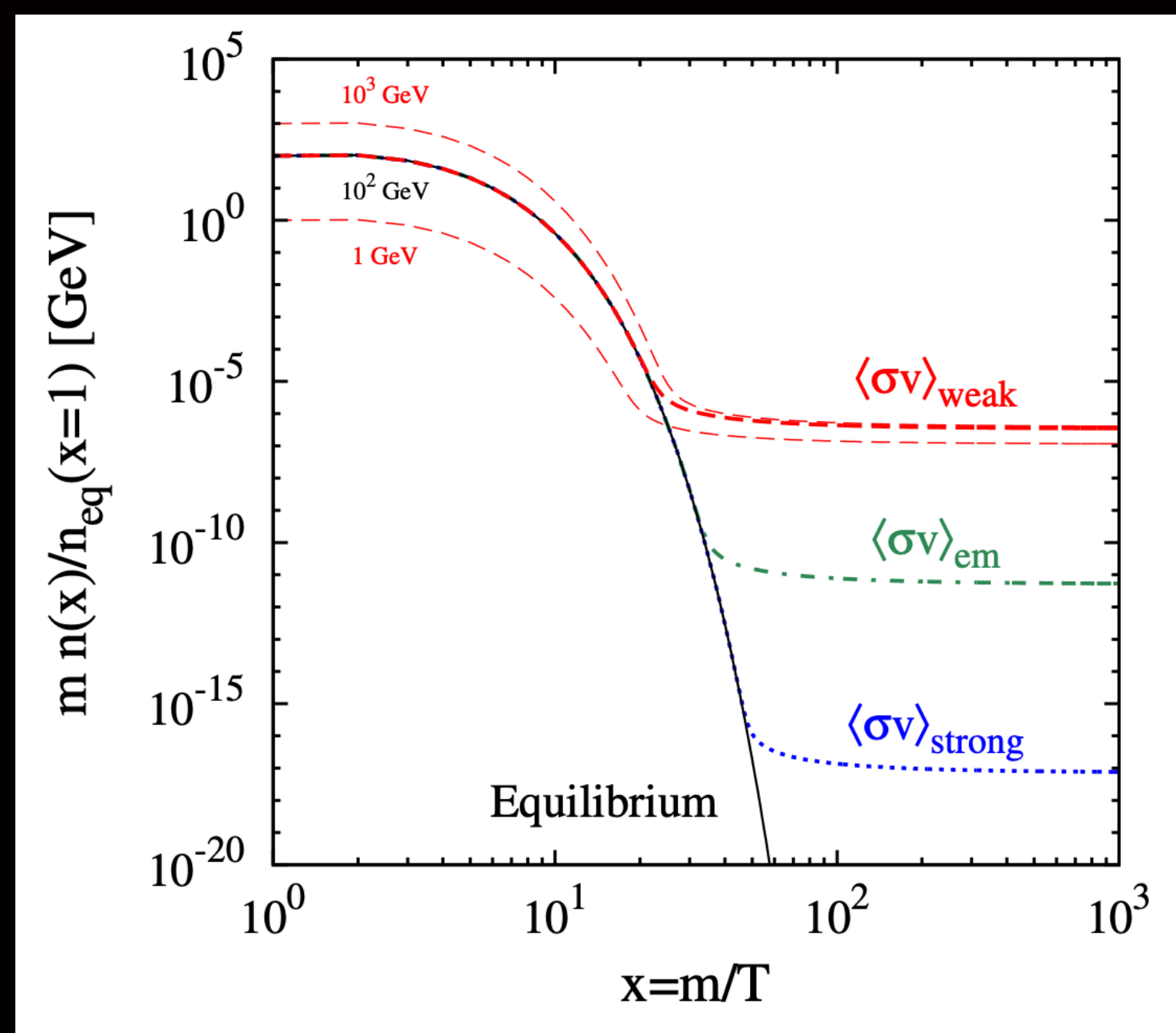
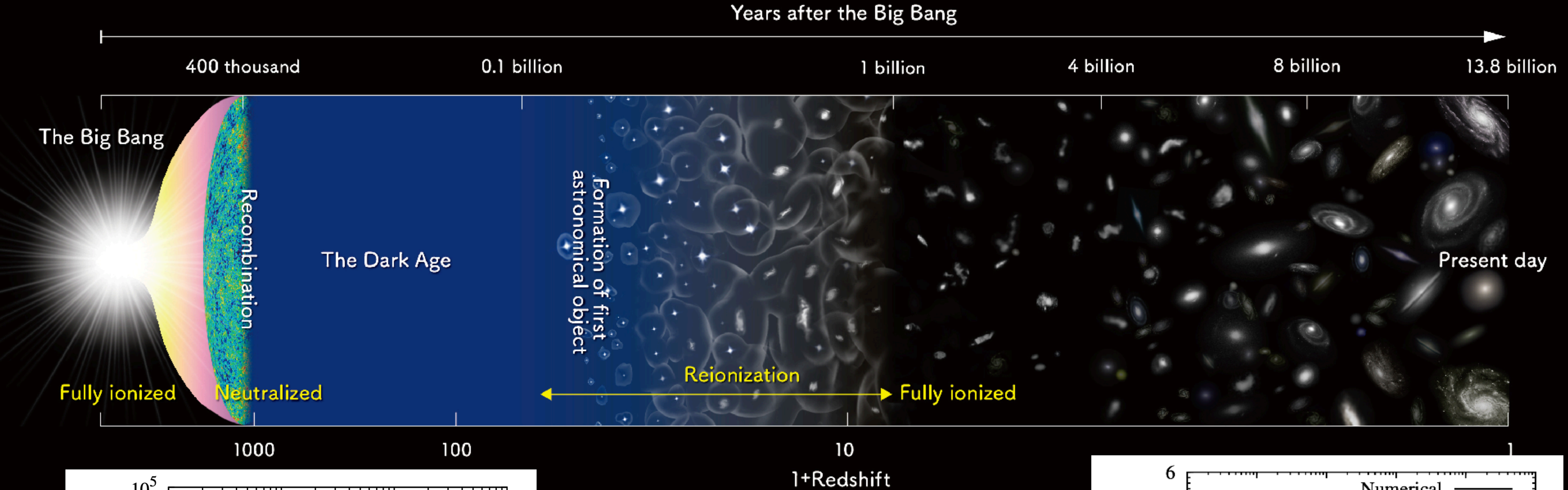
Thermal Dark Matter Density

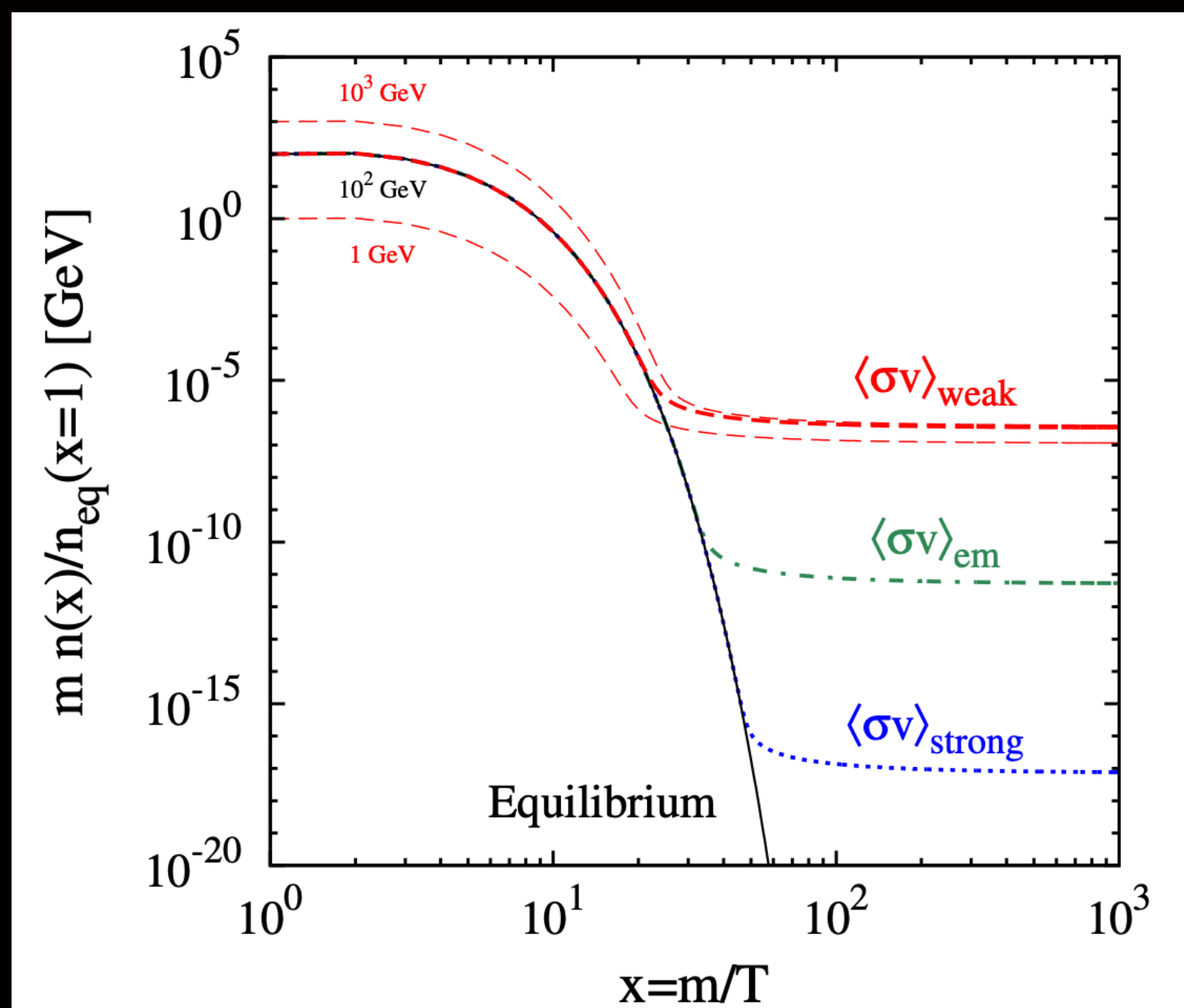
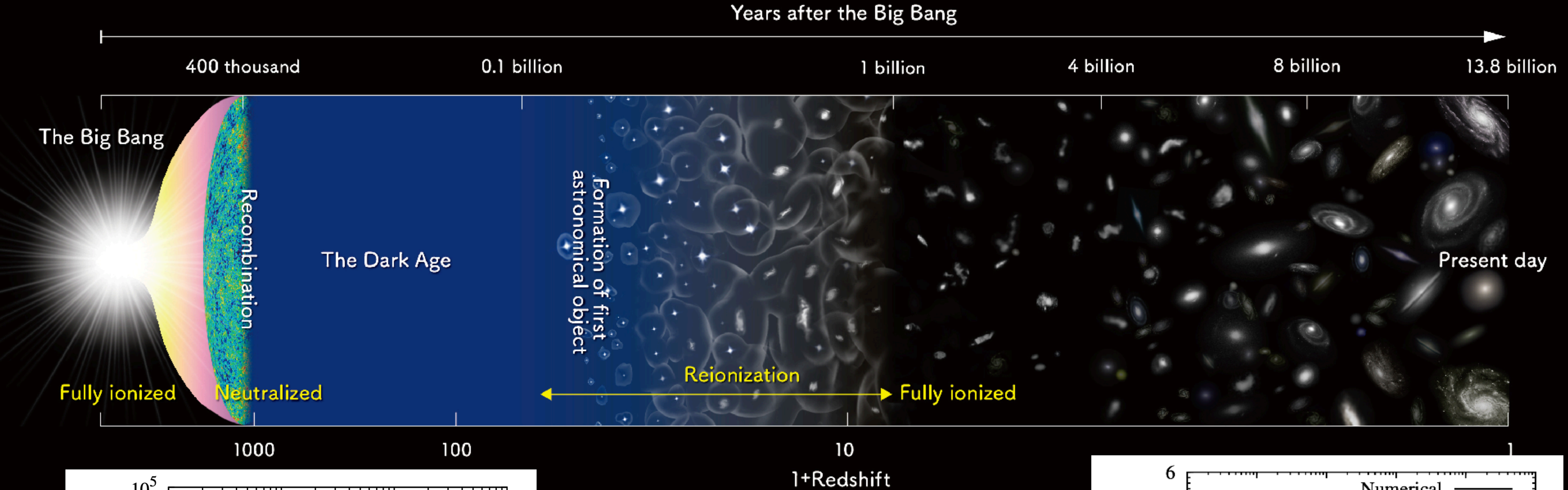
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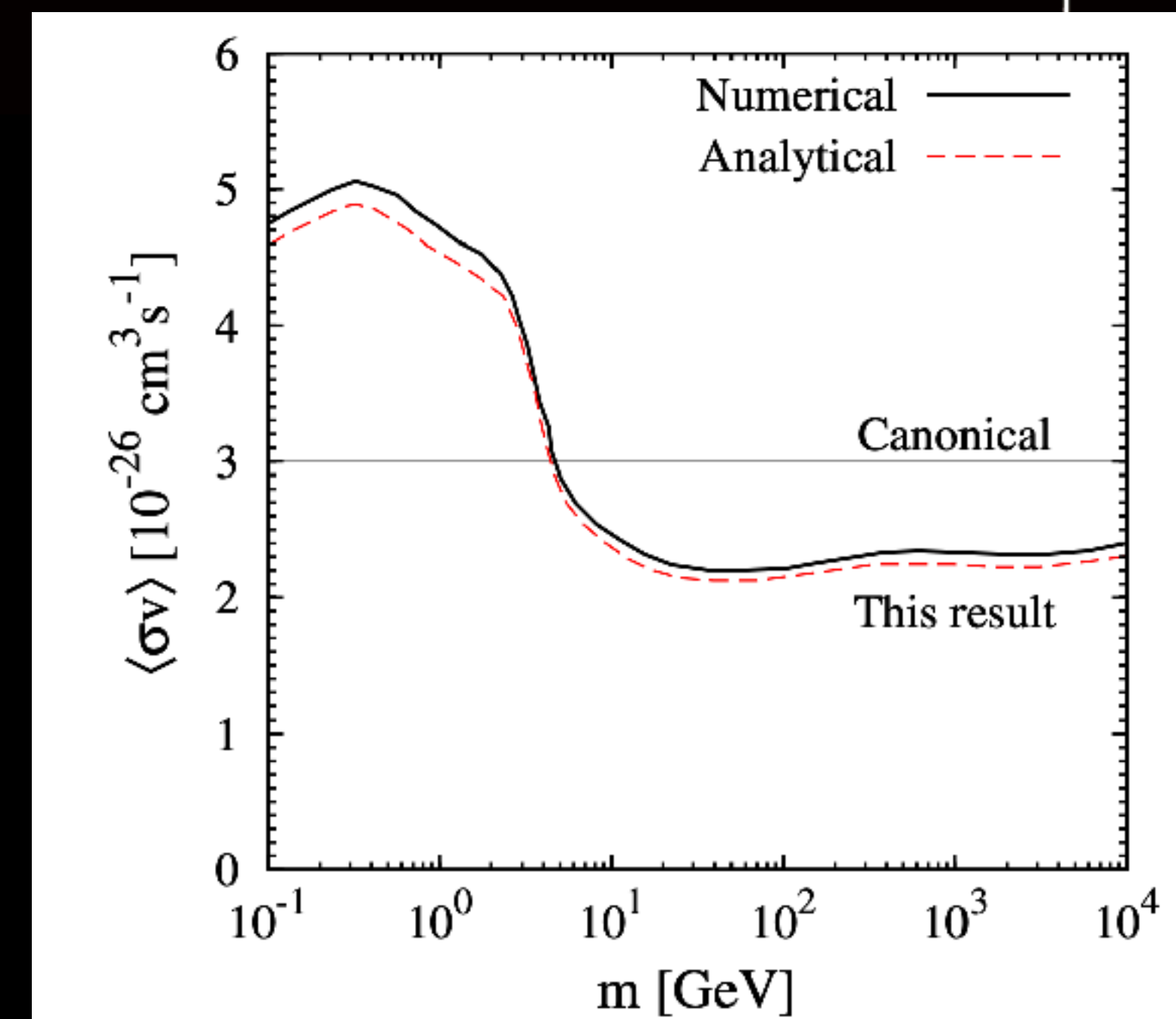
10 MeV - 100 TeV !

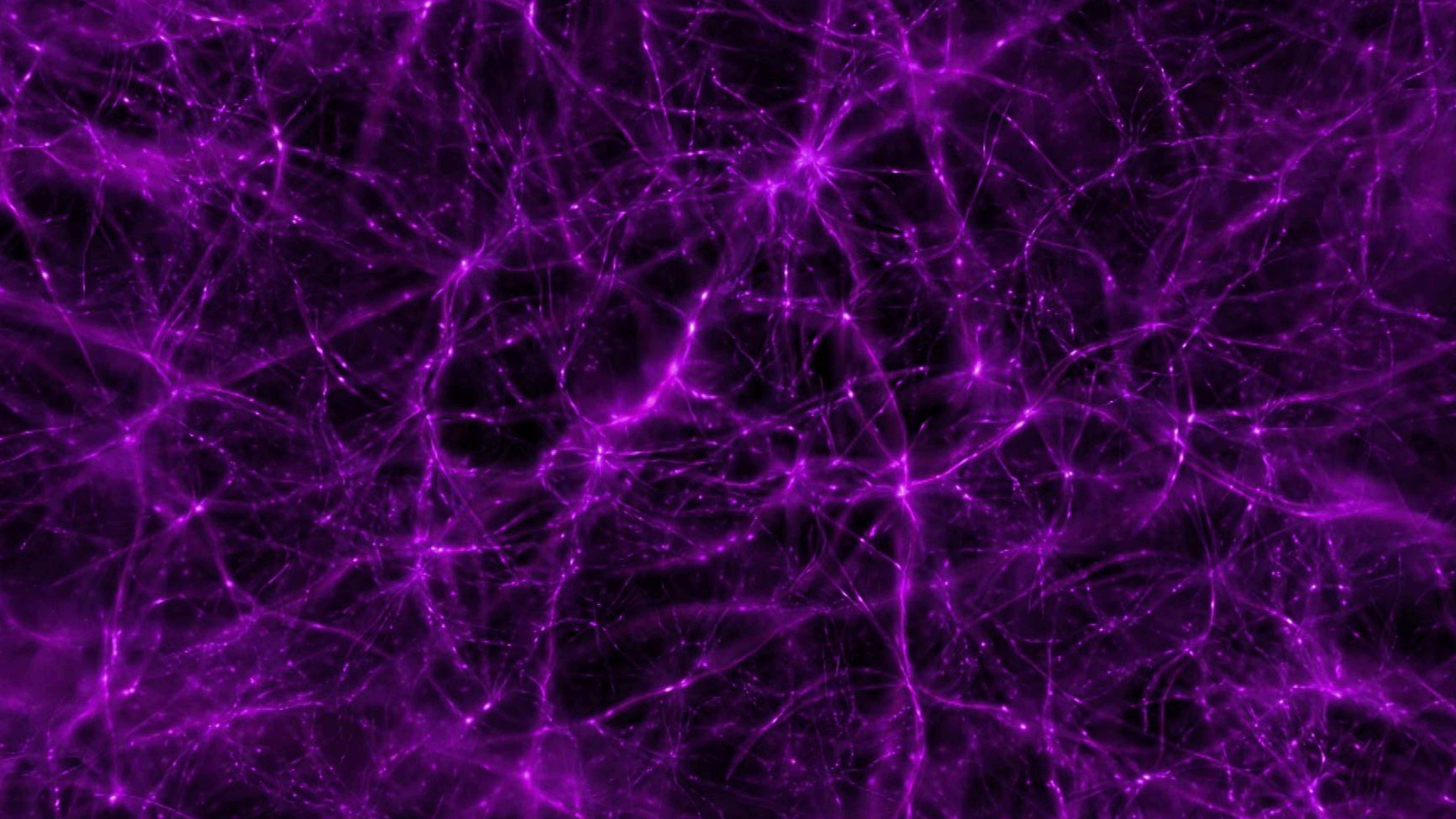


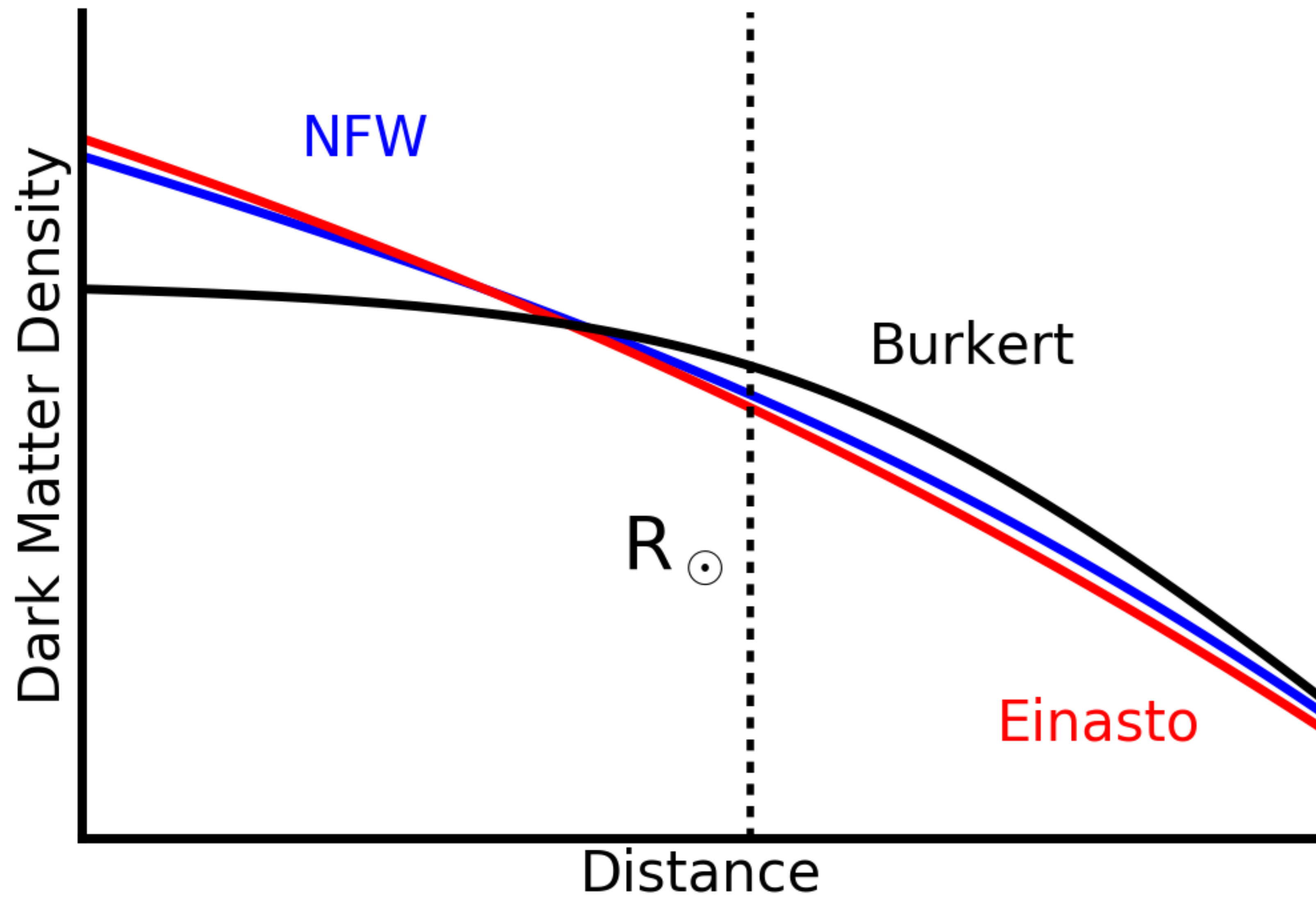


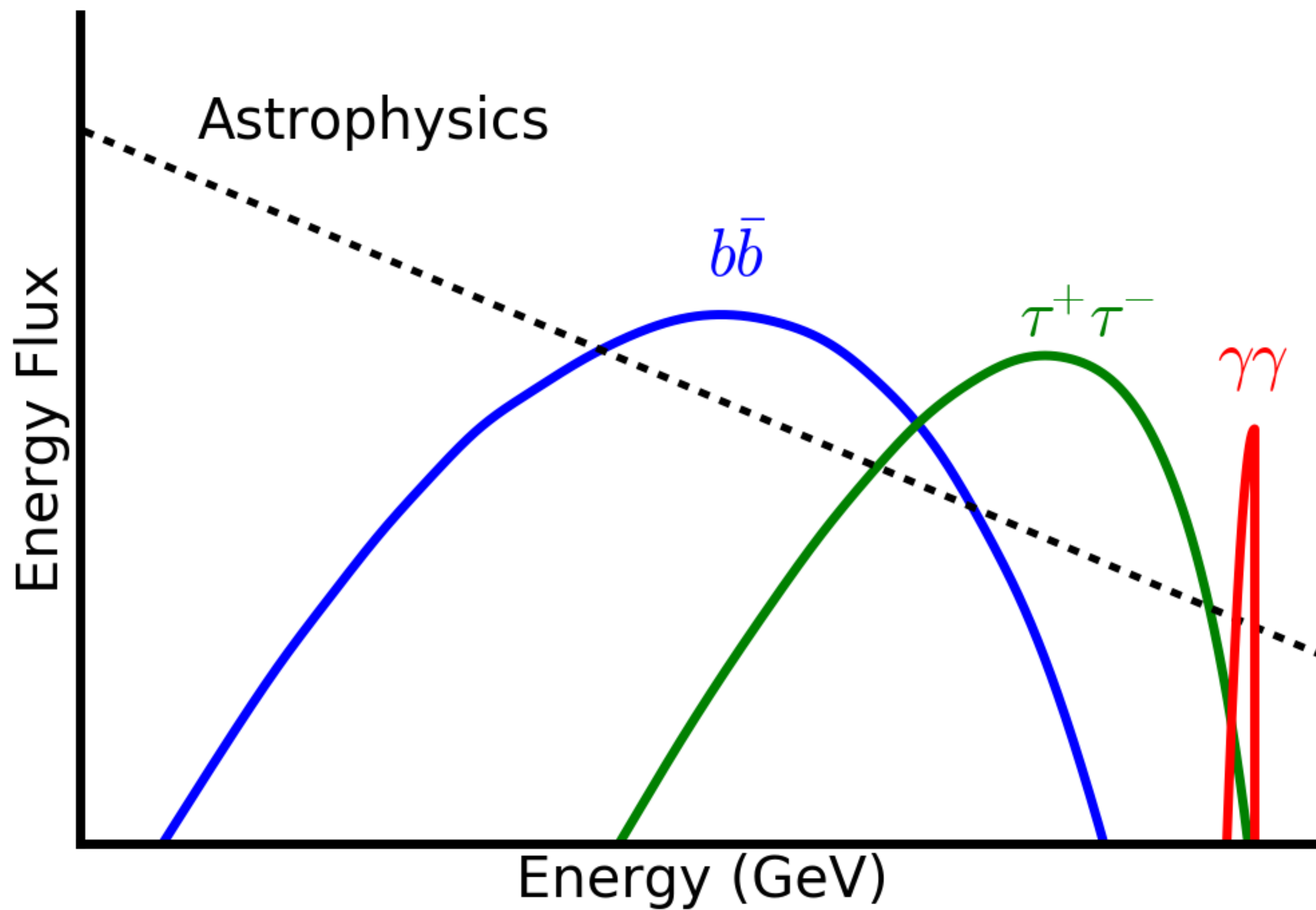
Philosophy:

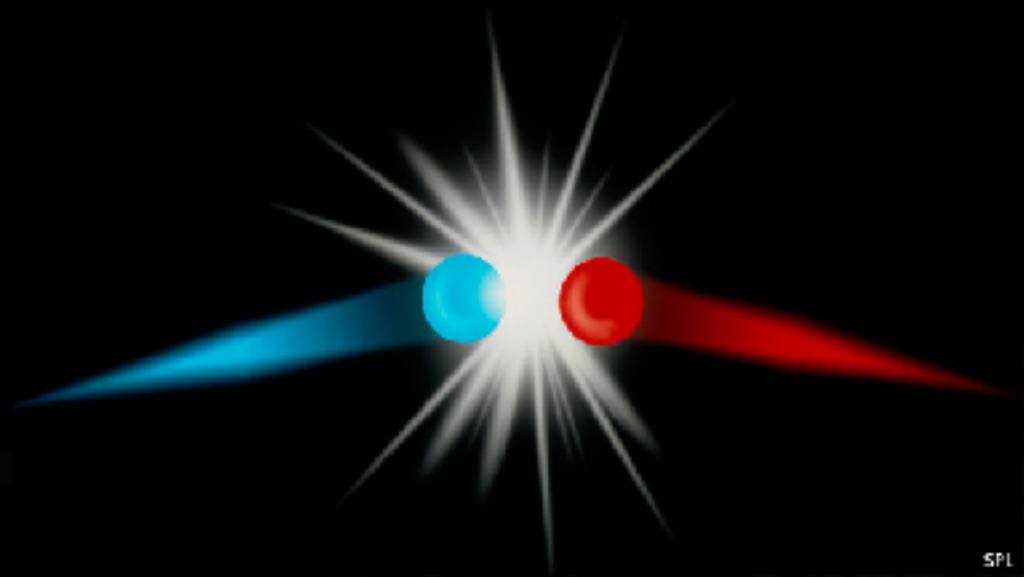
**Constrain the
simplest model first**





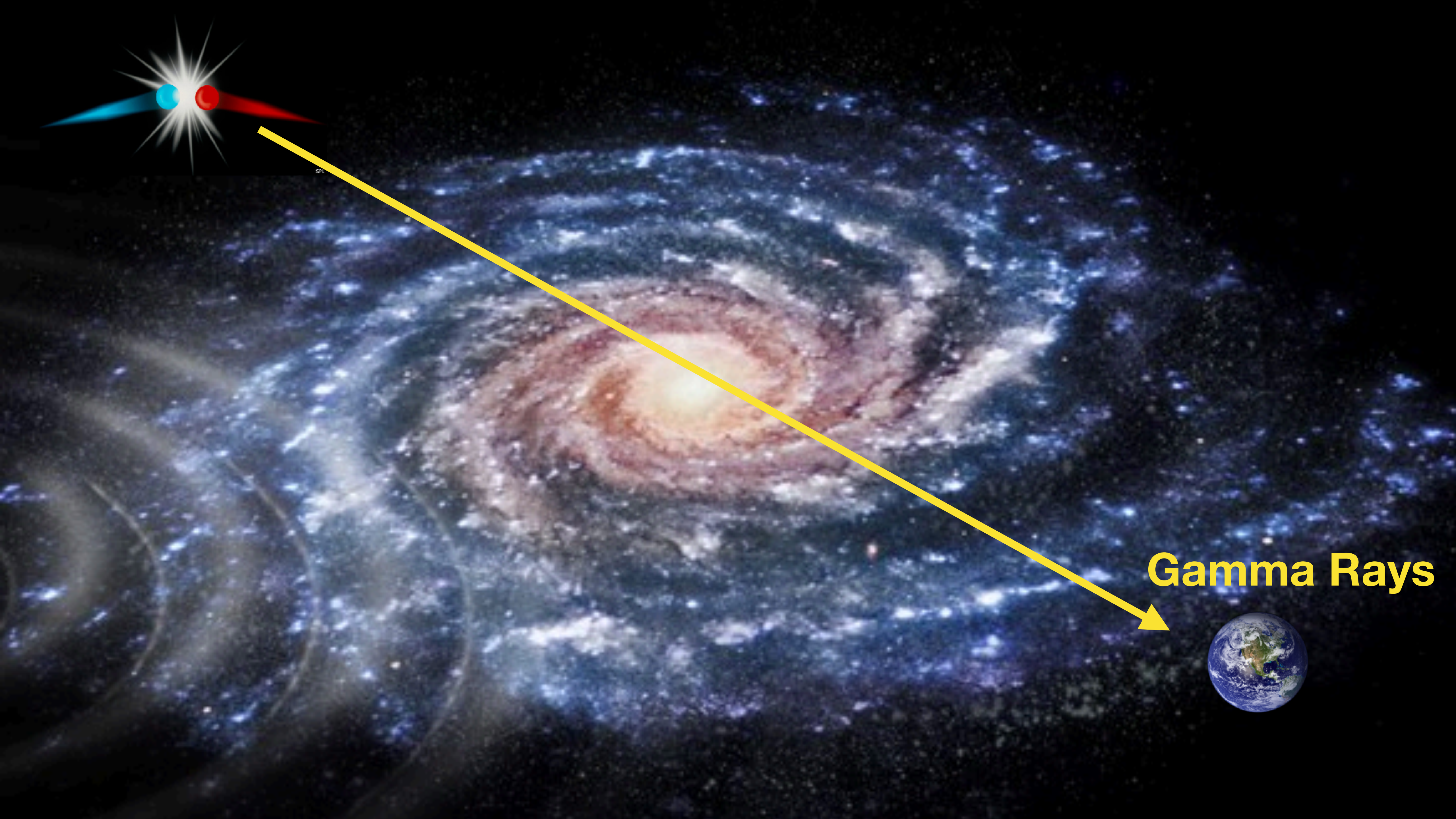






SPI



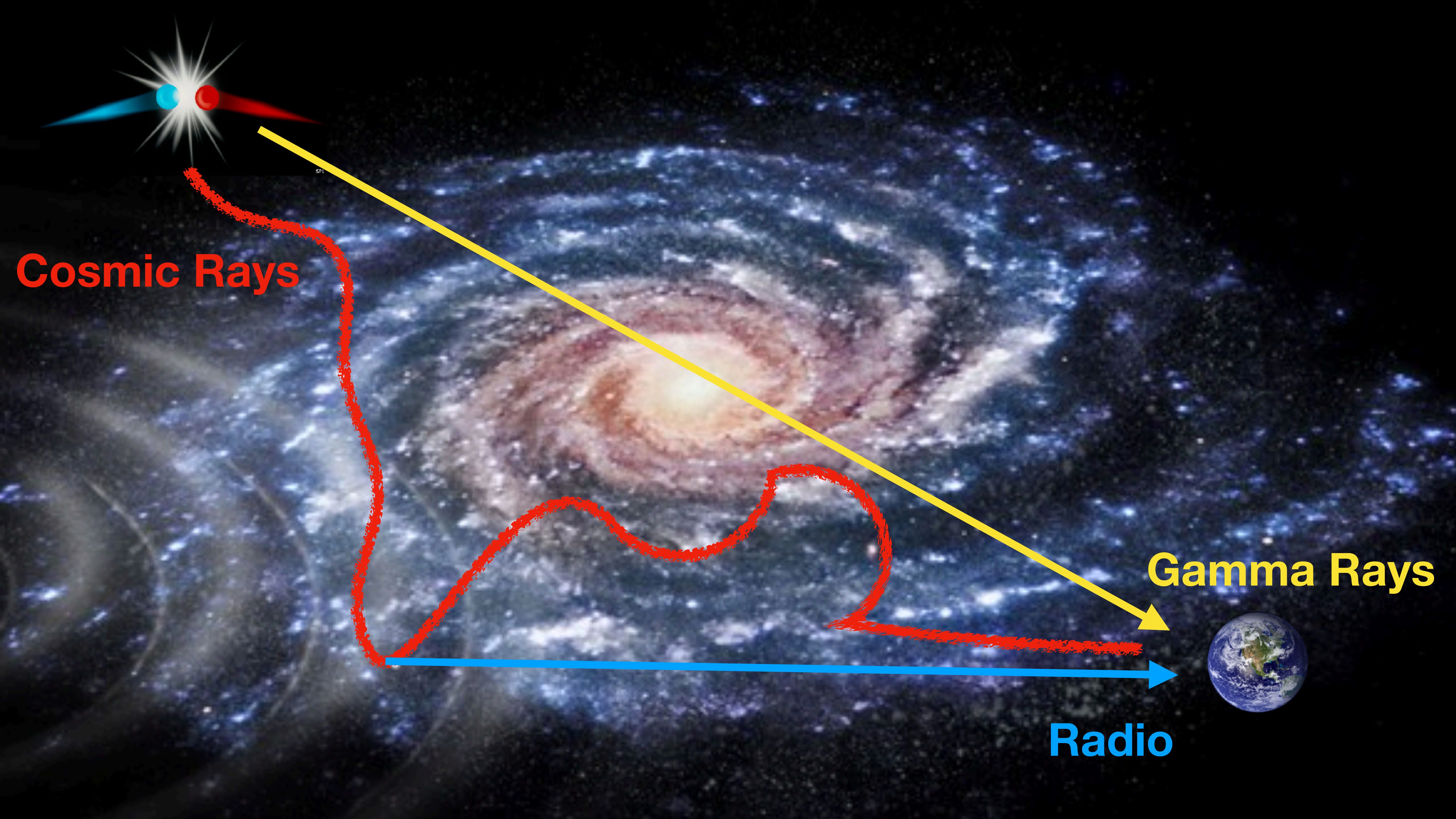


Gamma Rays



Cosmic Rays

Gamma Rays



Cosmic Rays

Gamma Rays

Radio

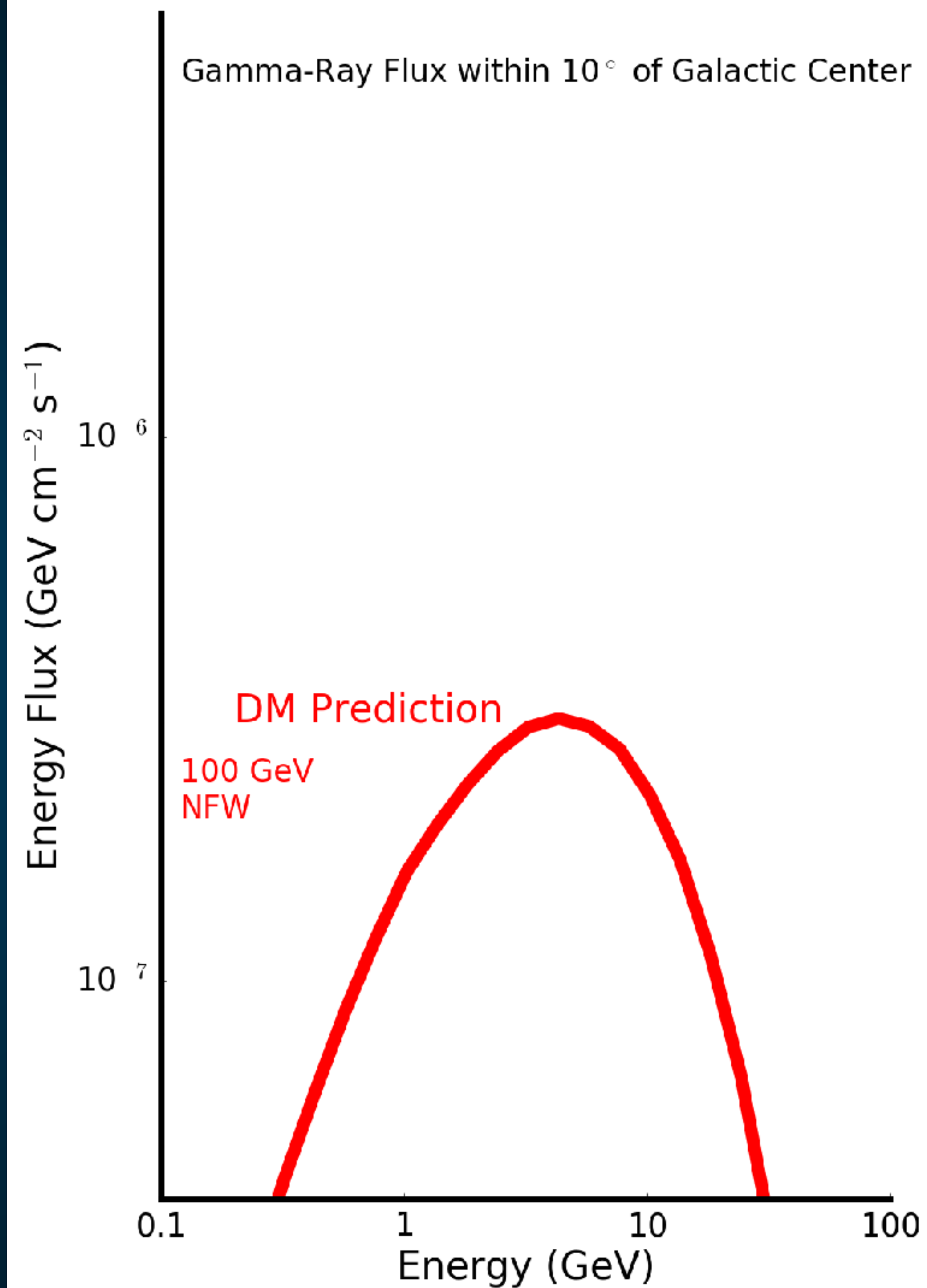
Thermal WIMPs and the Story of Tantalus

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)

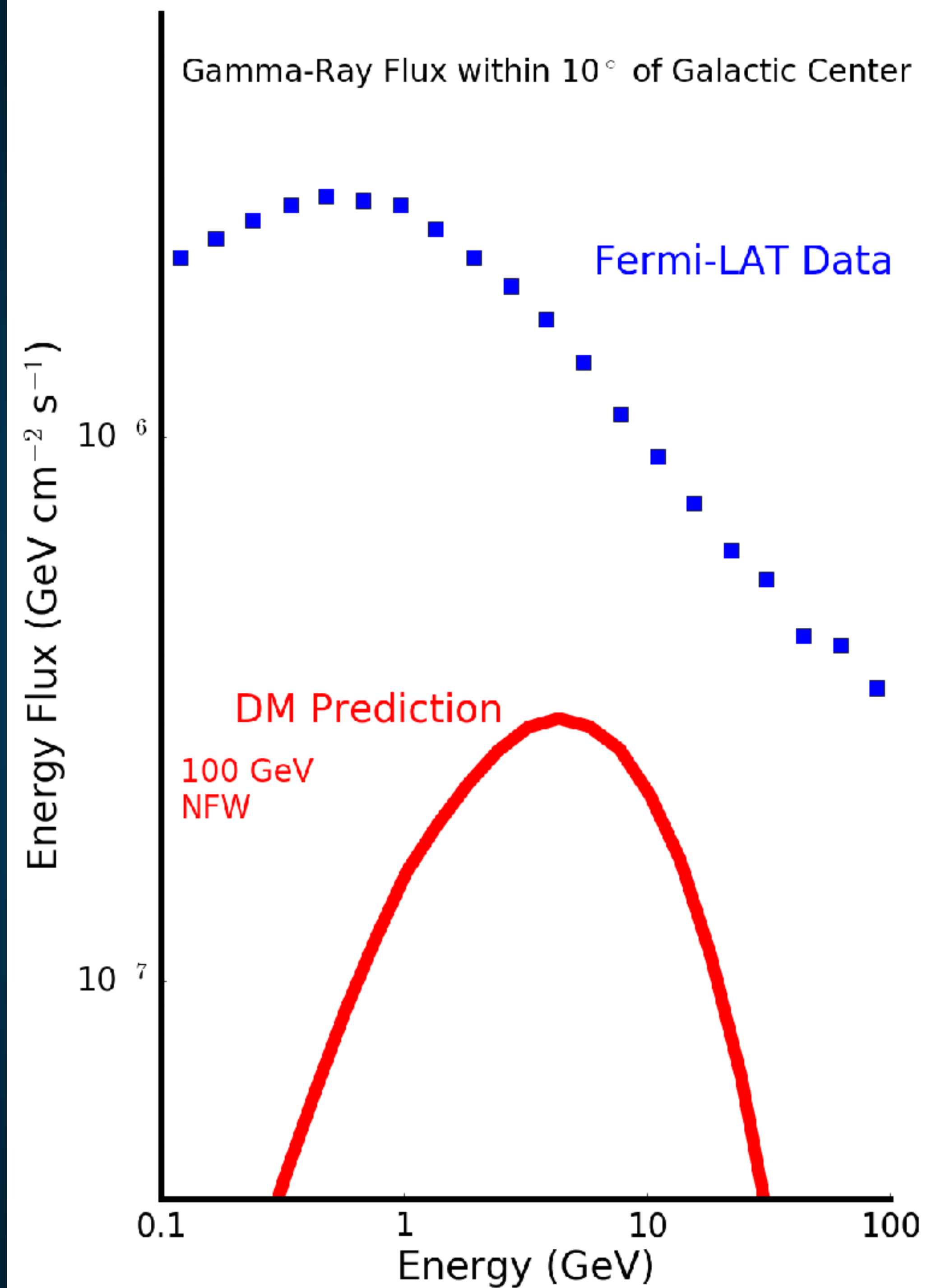
Dark Matter Mass (?)

Annihilation Final State (?)

Milky Way Star-Formation Rate (Galactic Dynamics)

Diffusion Constant in Galactic Center (Hydrodynamics)

Activity of Supermassive Blackhole (?)



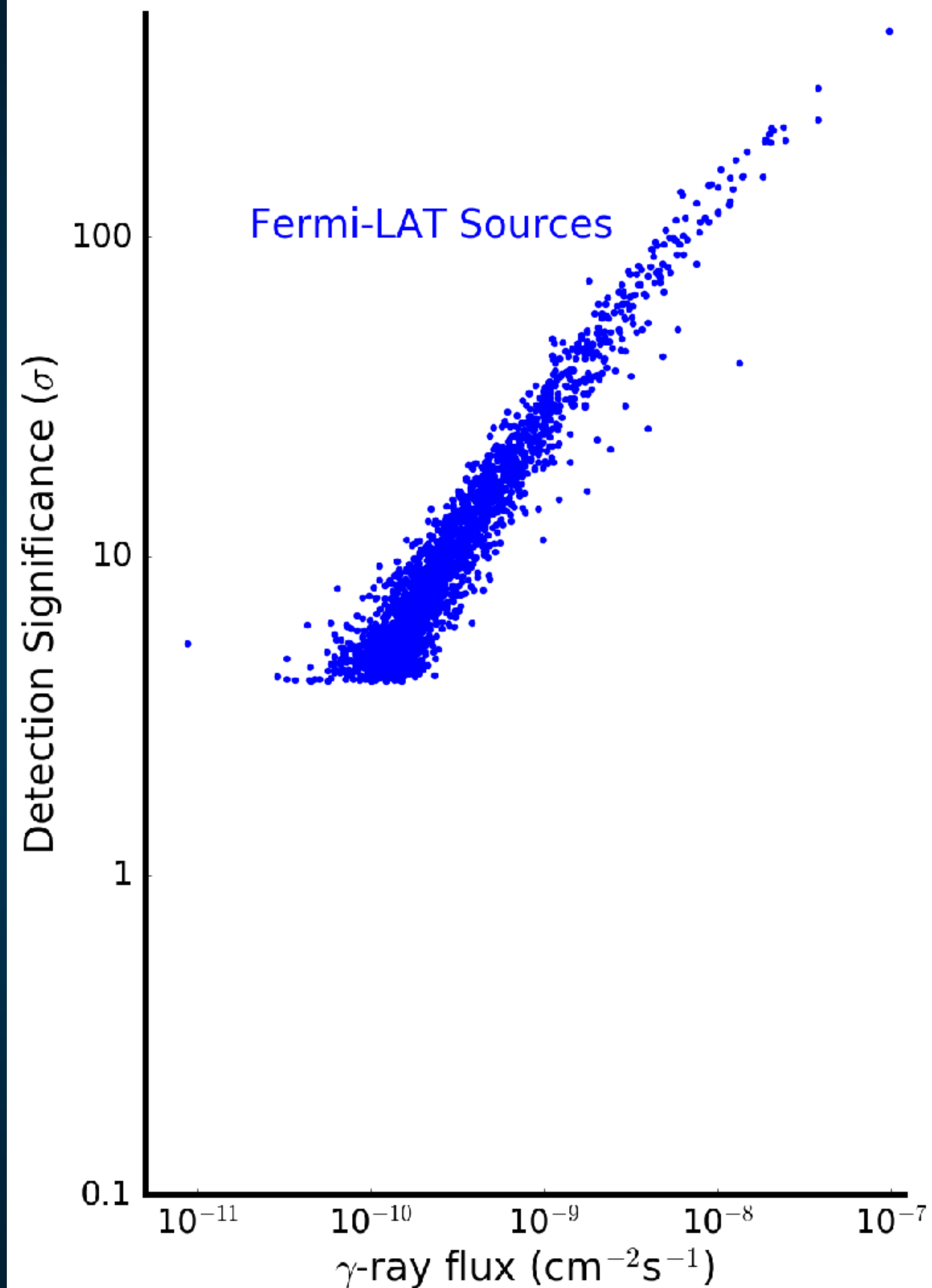
Thermal WIMPs and the Story of Tantalus

SMBH Accretion Efficiency (Magnetohydrodynamics)

Blazar Acceleration Mechanisms (Leptonic? Hadronic?)

Radio Galaxy Emission Models

Star-Formation Rates in Starburst Galaxies



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SMBH Accretion Efficiency (Magnetohydrodynamics)

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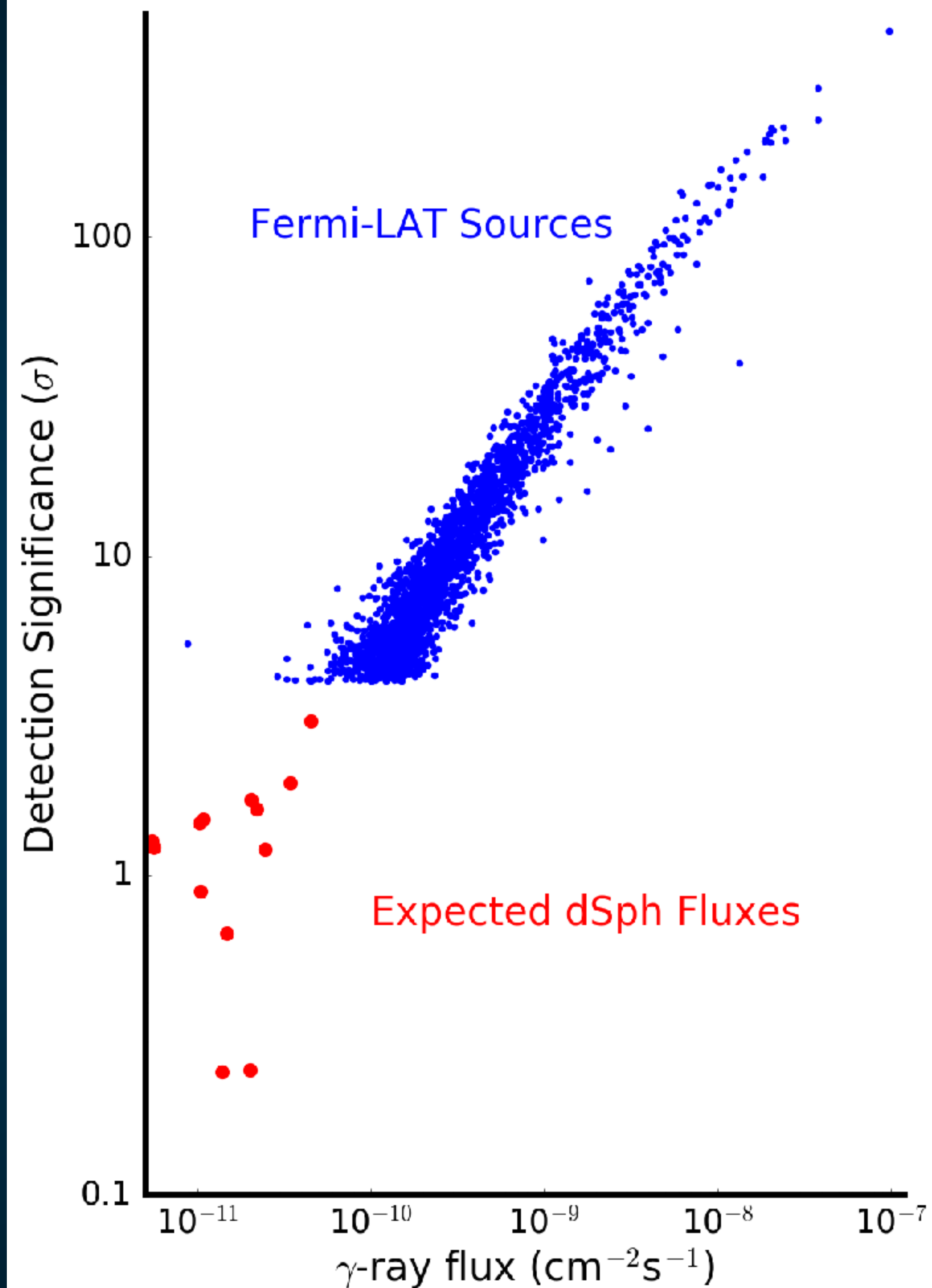
Radio Galaxy Emission Models

Star-Formation Rates in Starburst Galaxies

dSph Proximity

Substructure Models

Milky Way Merger History



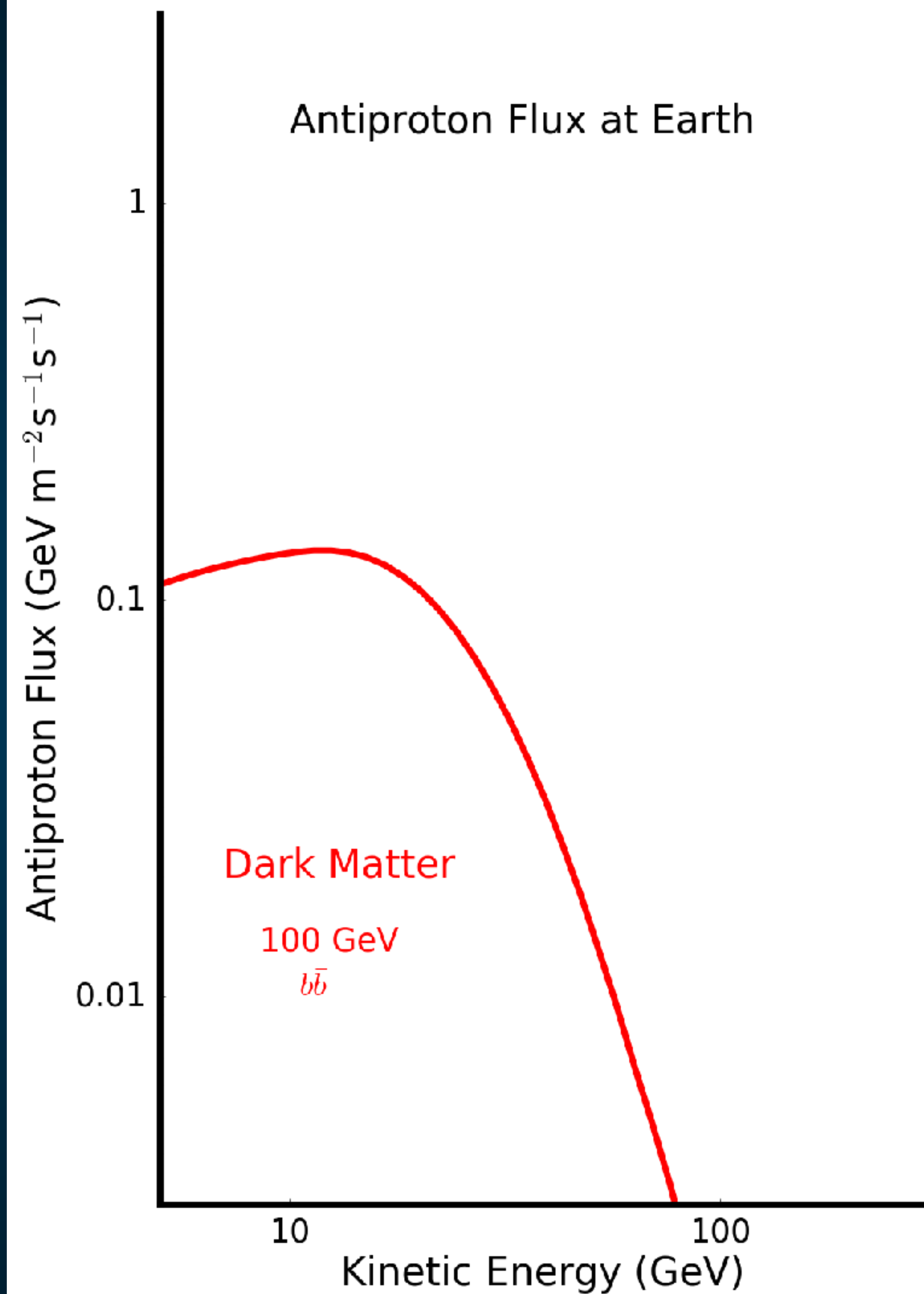
Thermal WIMPs and the Story of Tantalus

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

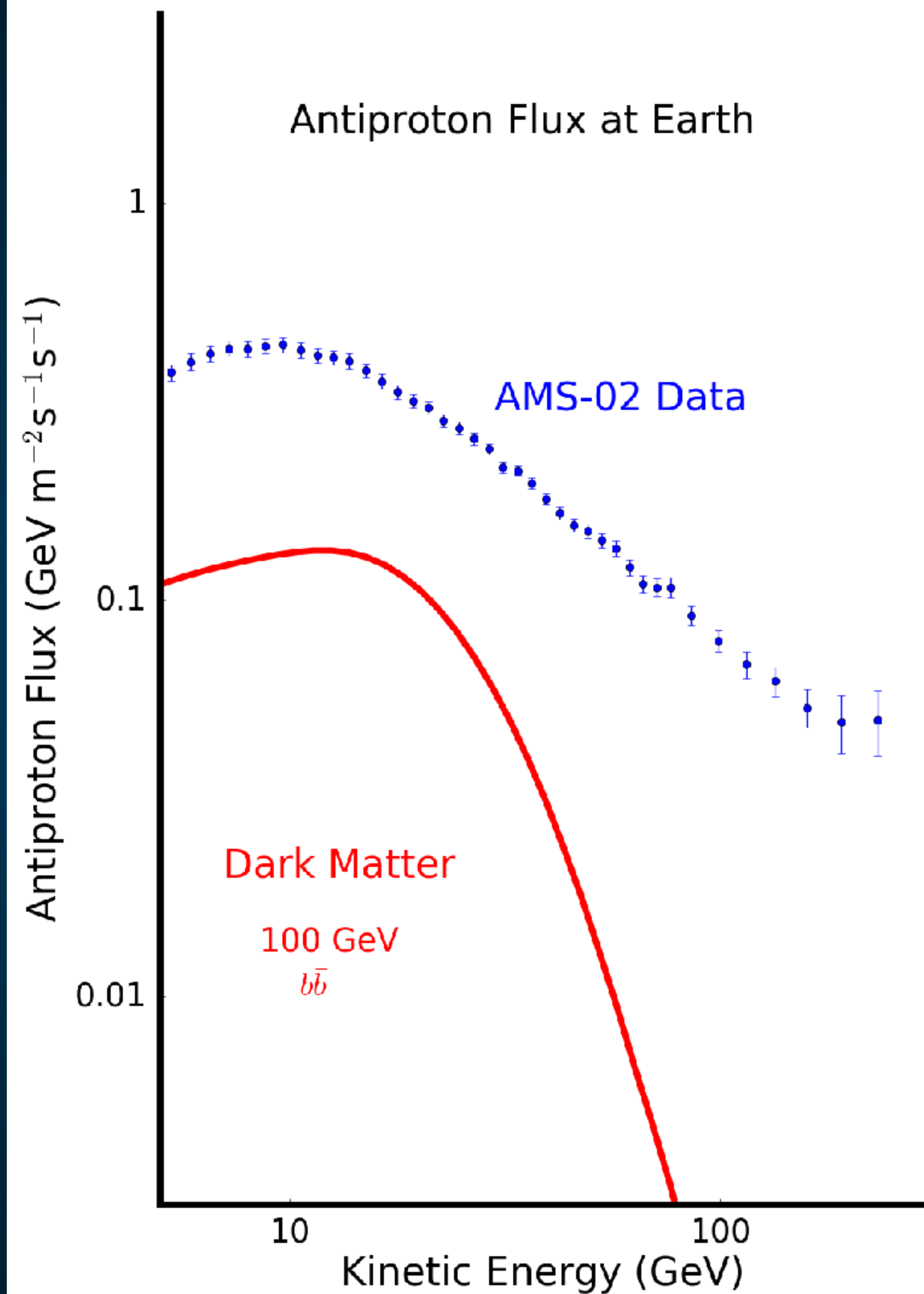
Thermal Cross-Section (Early Universe)

Hadronic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Local Gas Density

Local Supernova Rate



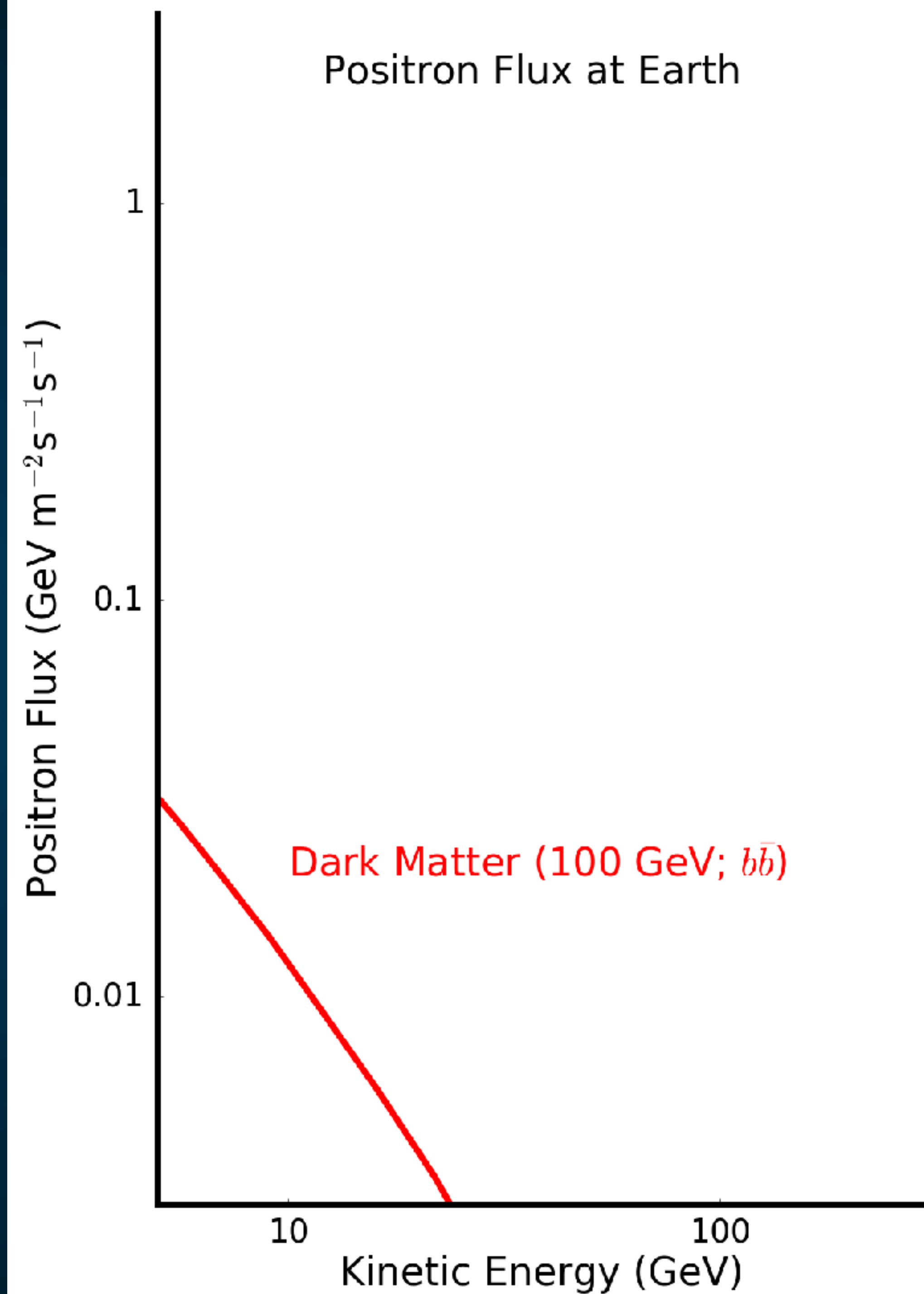
Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

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Local Dark Matter Density

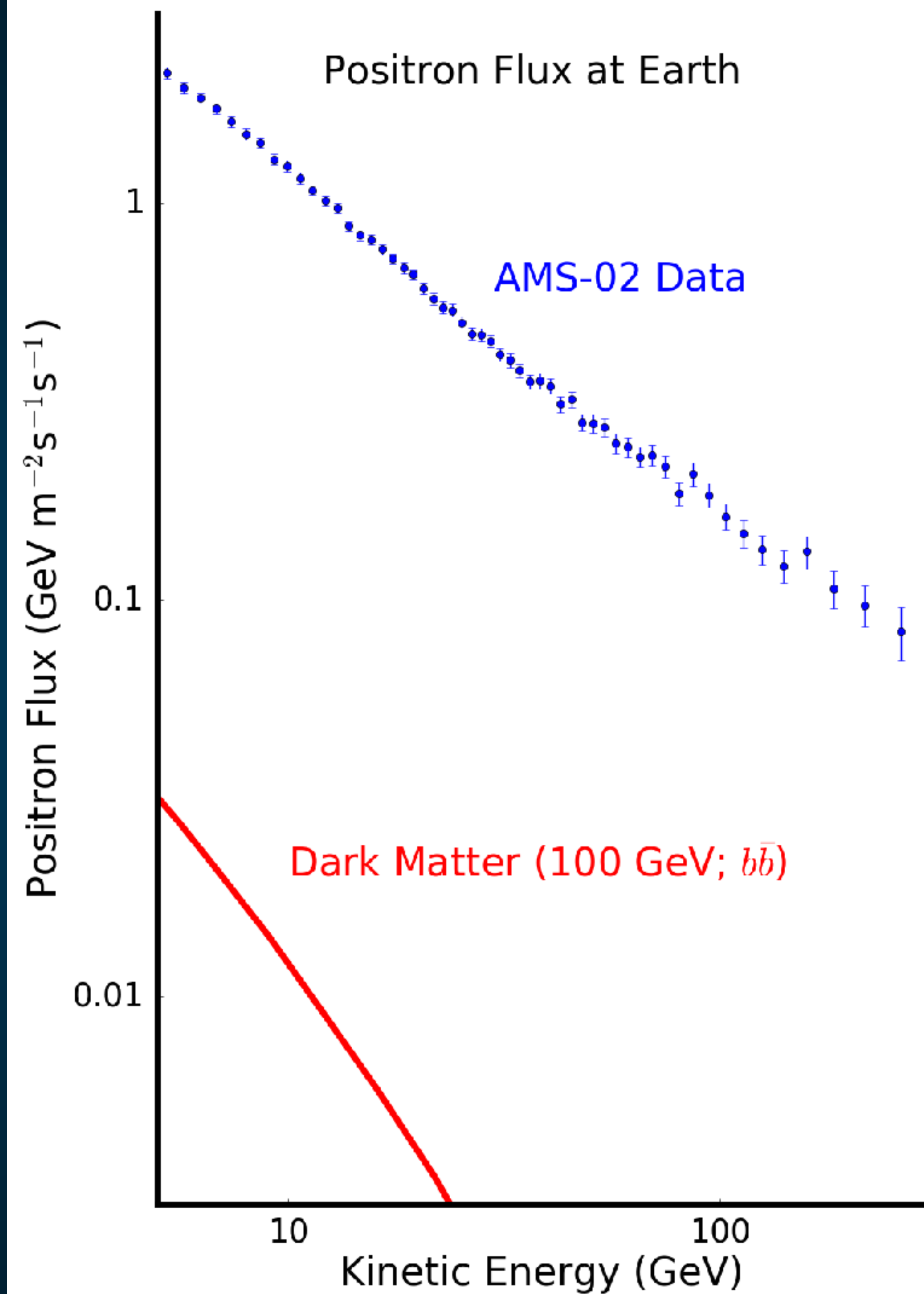
Thermal Cross-Section (Early Universe)

Leptonic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Pulsar Birth Rate

e^+e^- Acceleration Efficiency in Pulsar Magnetospheres





Specificity (DM Flux / Astrophysics Flux)

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

Fraction of Dark Matter Flux

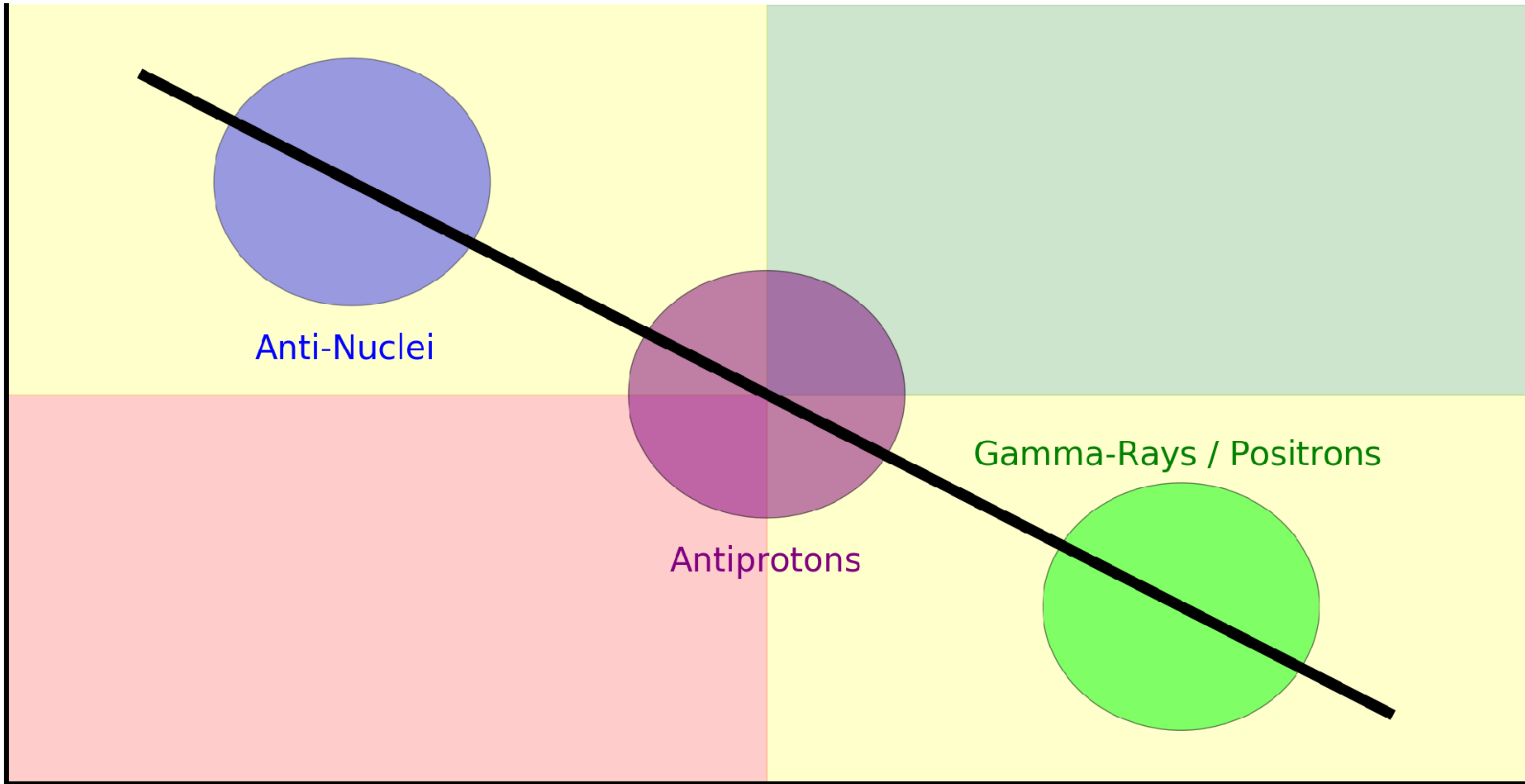
Specificity (DM Flux / Astrophysics Flux)

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

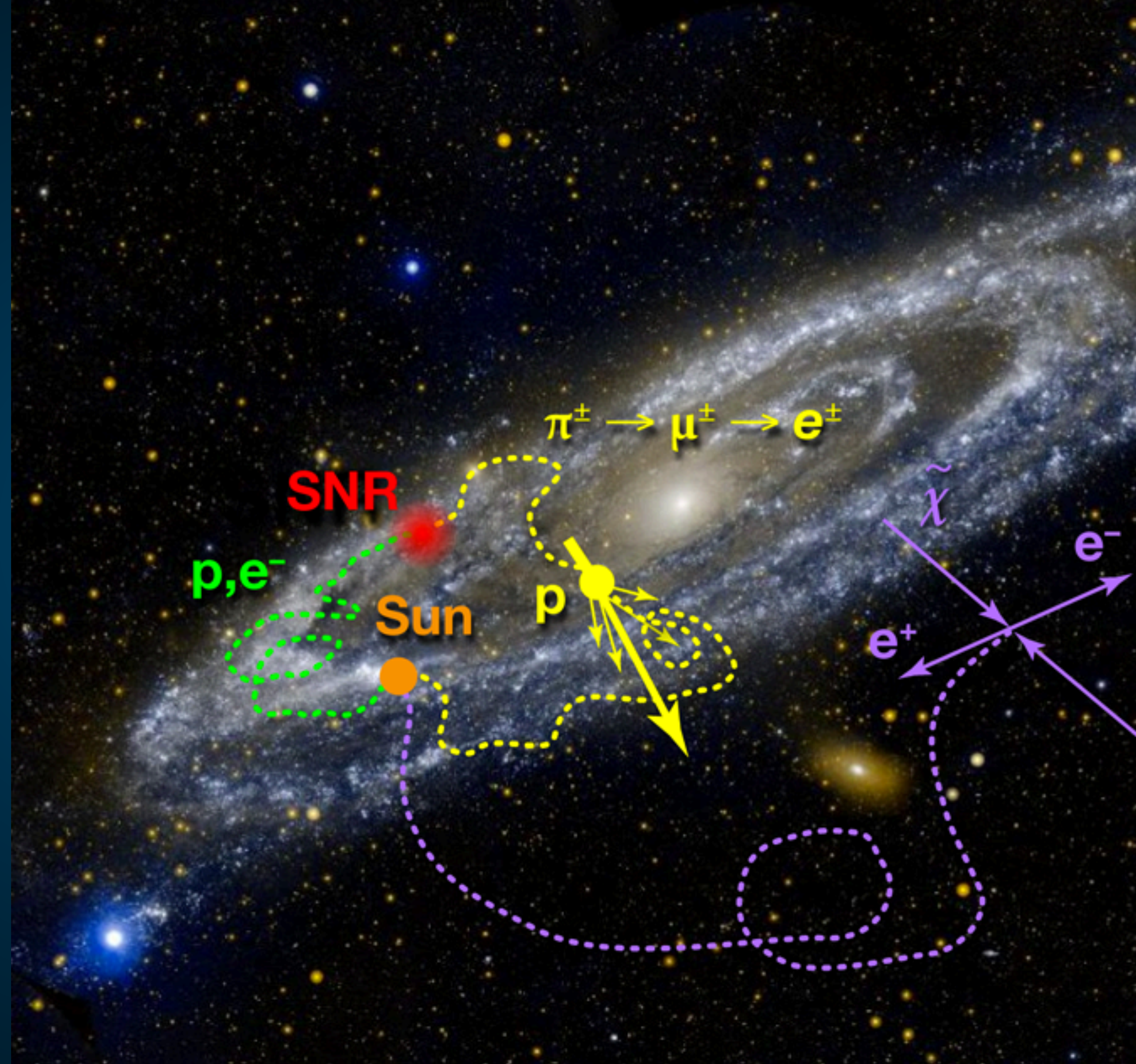
Investigate the Antiproton Fraction!

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

Two Changes:

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

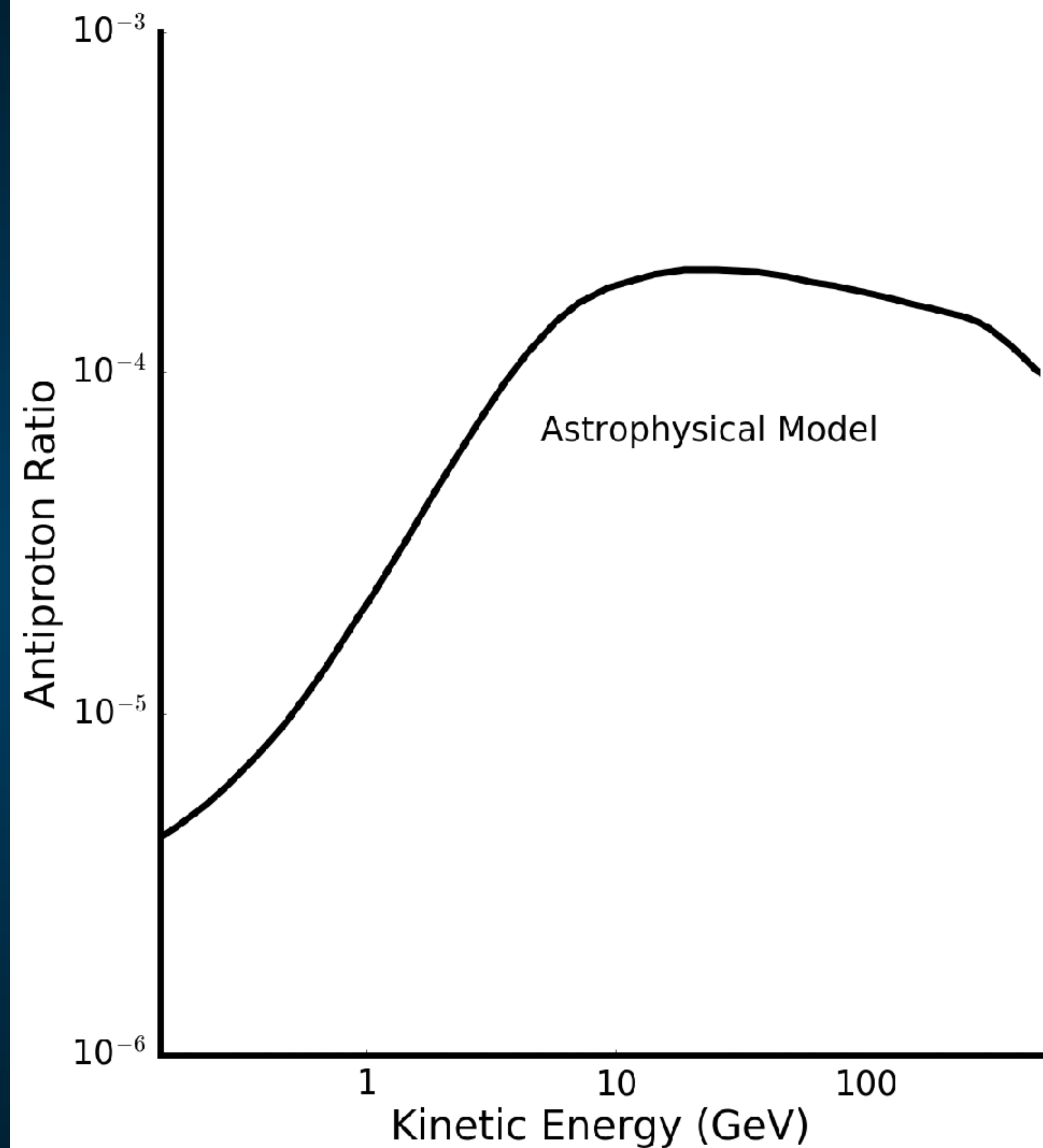
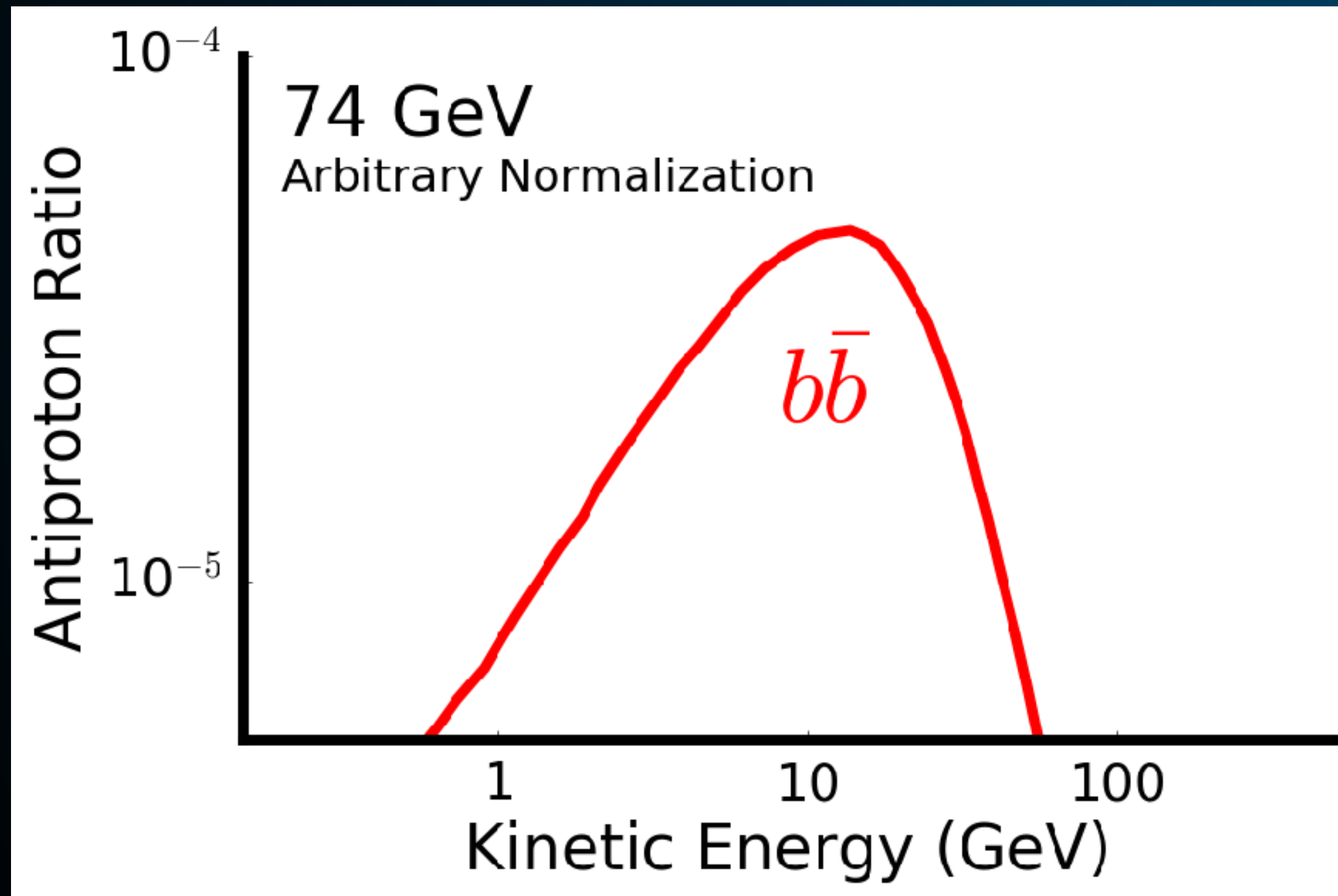
Hadronic Energy losses are slower
(sensitive to antiproton production throughout the Galaxy)



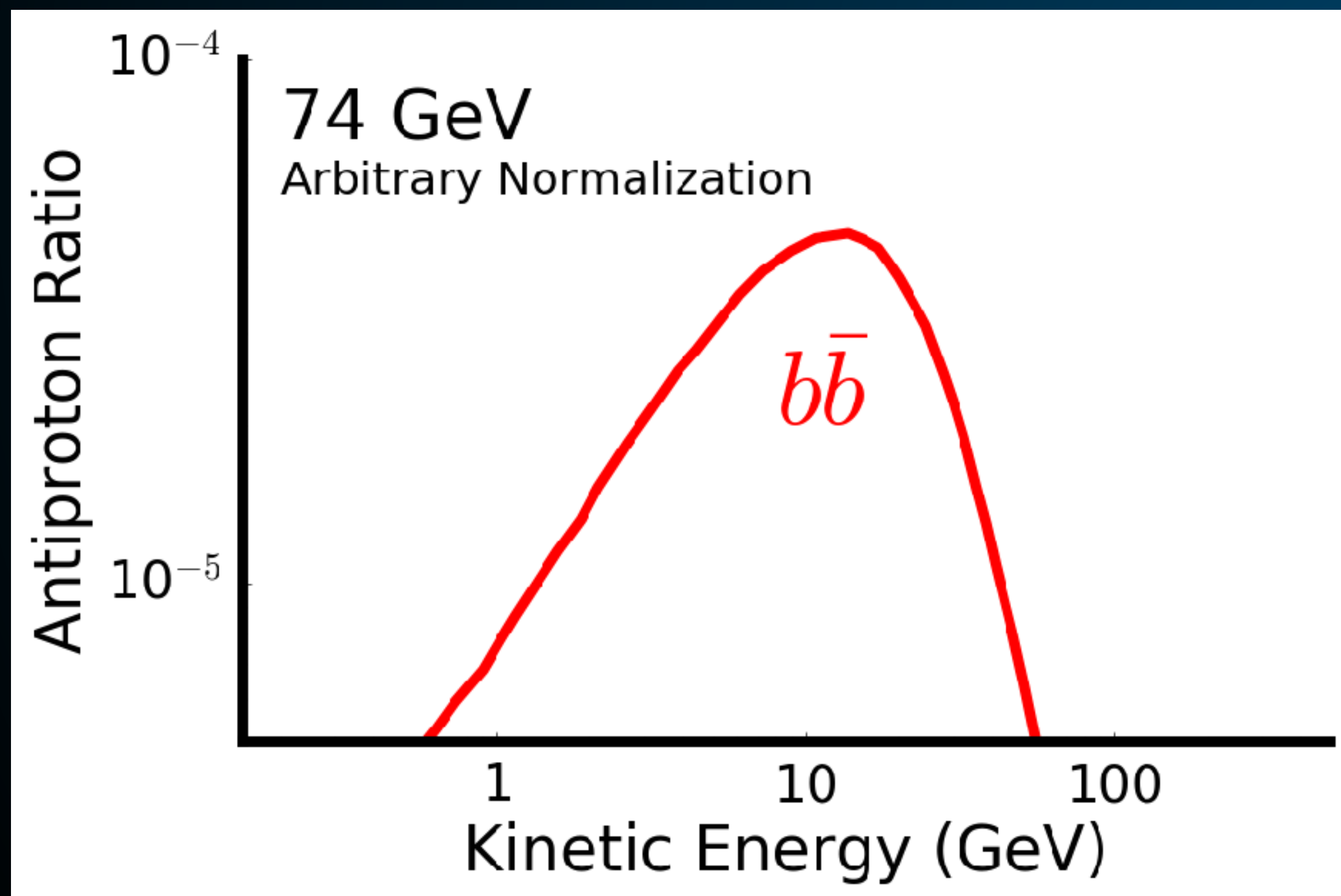
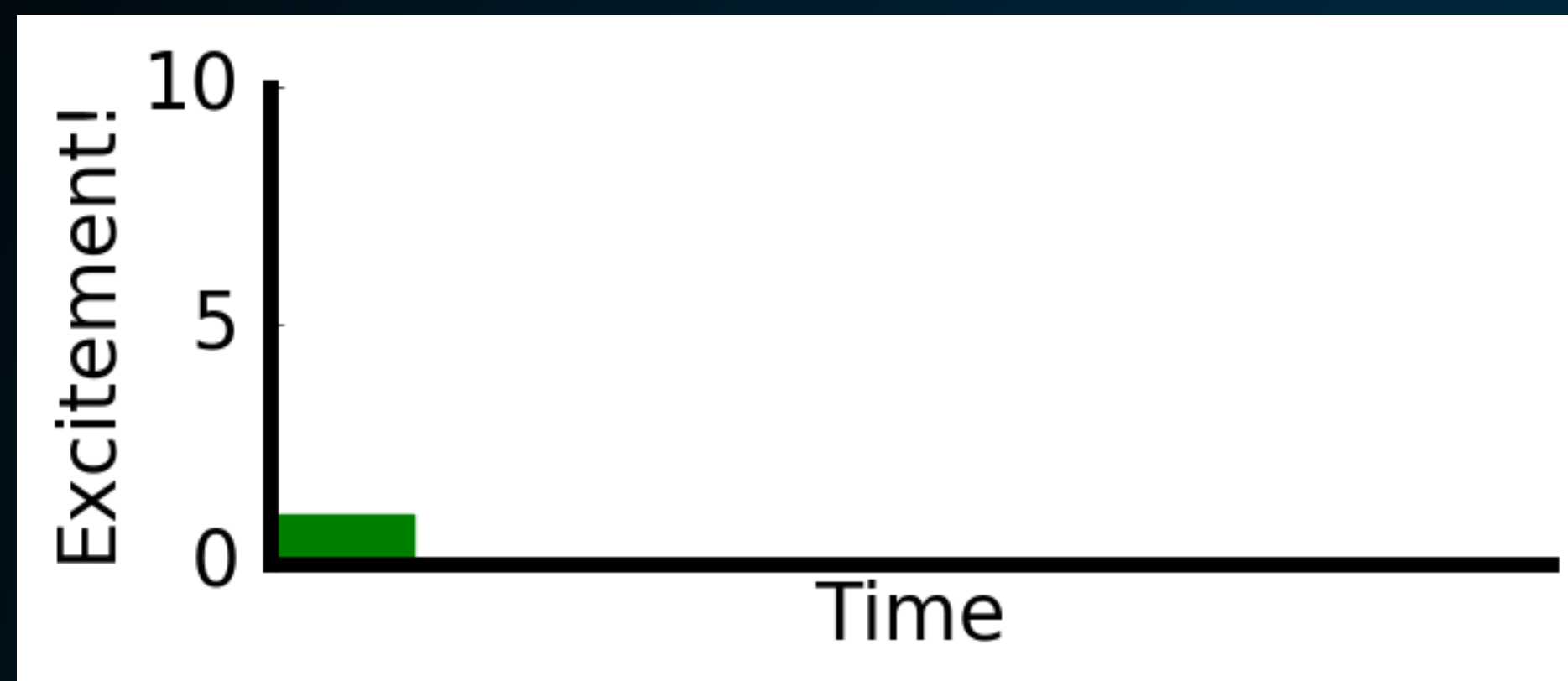
The Antiproton Excess

Astrophysics - Smooth Profile

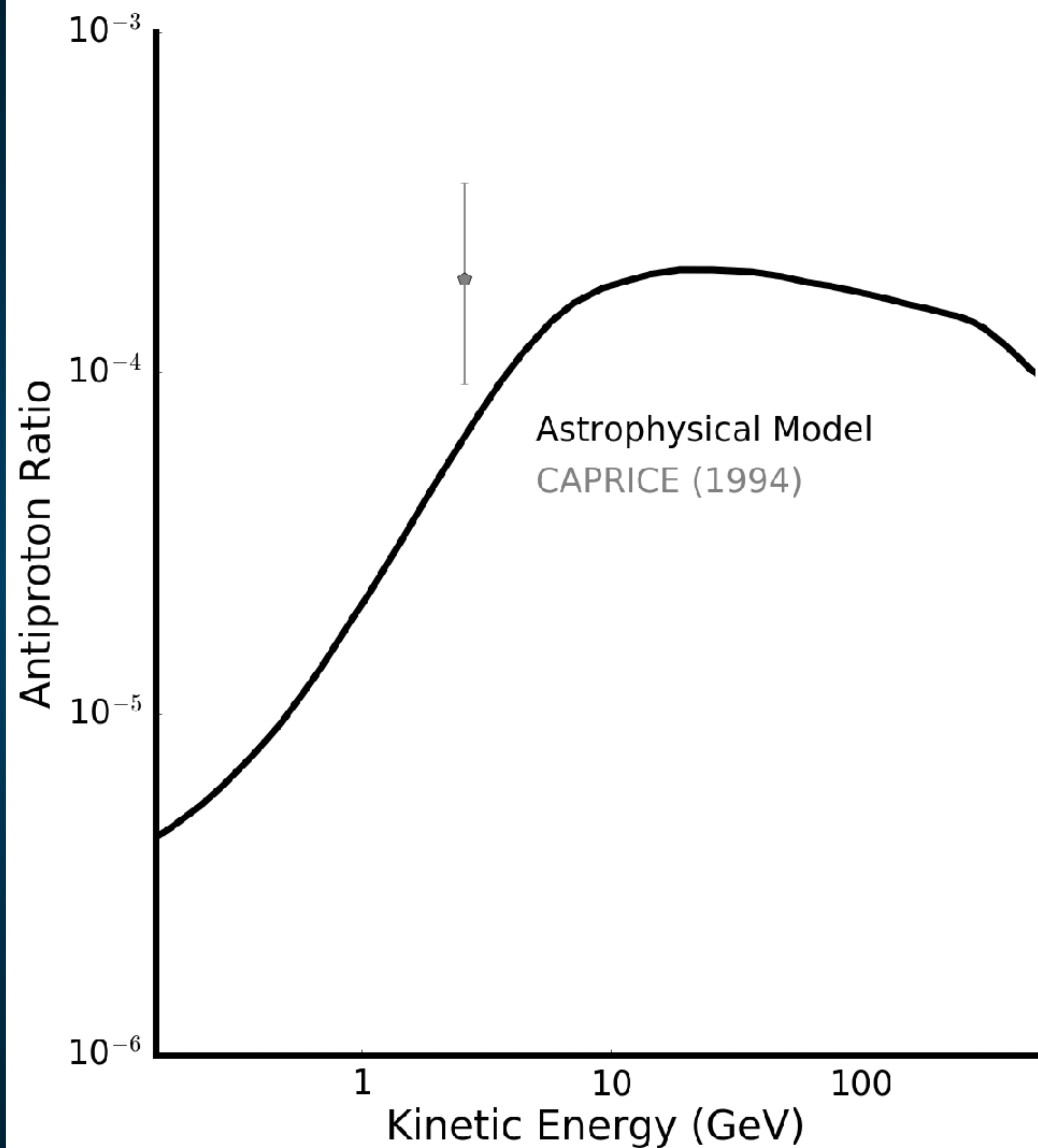
Dark Matter - Sharp Bump!



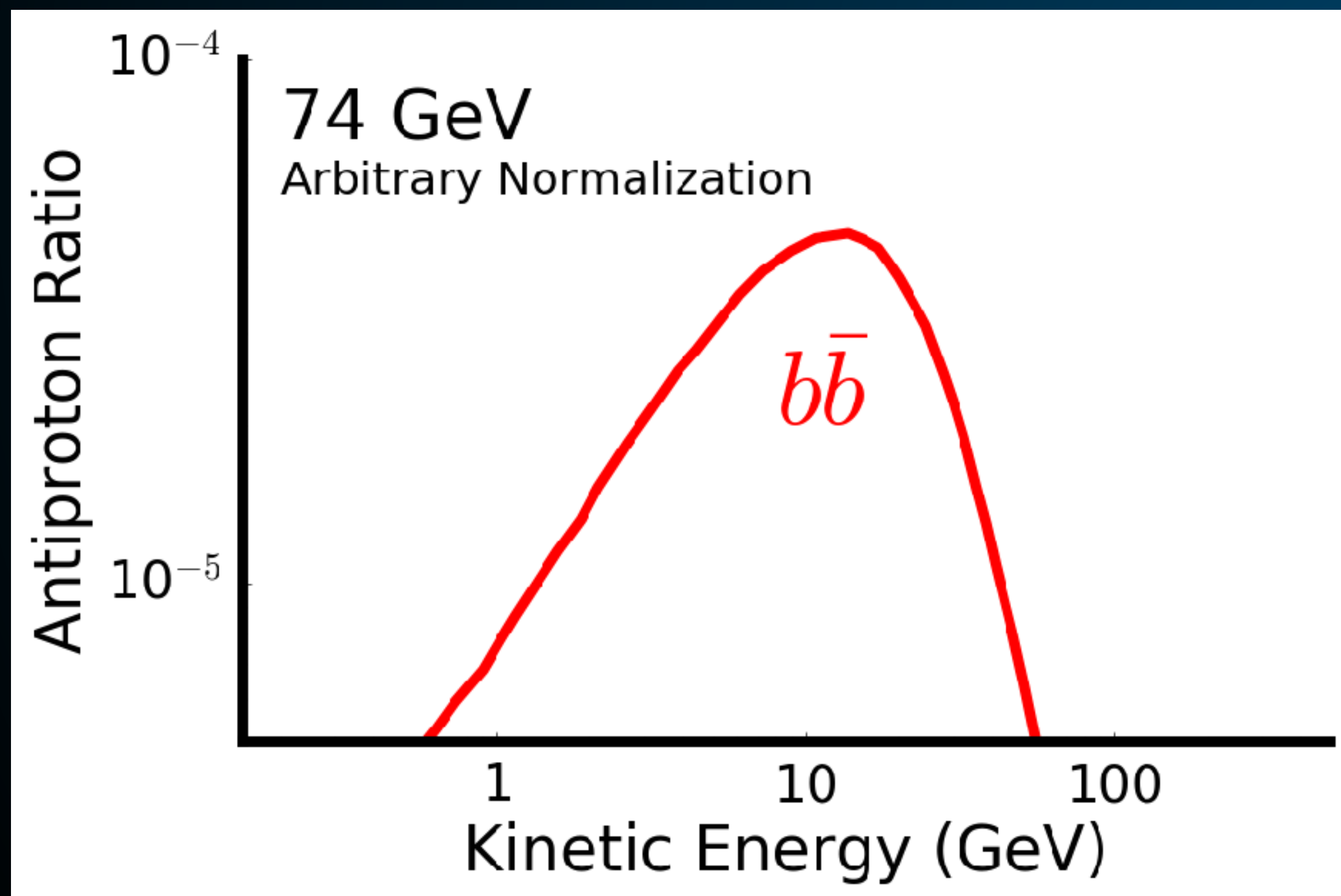
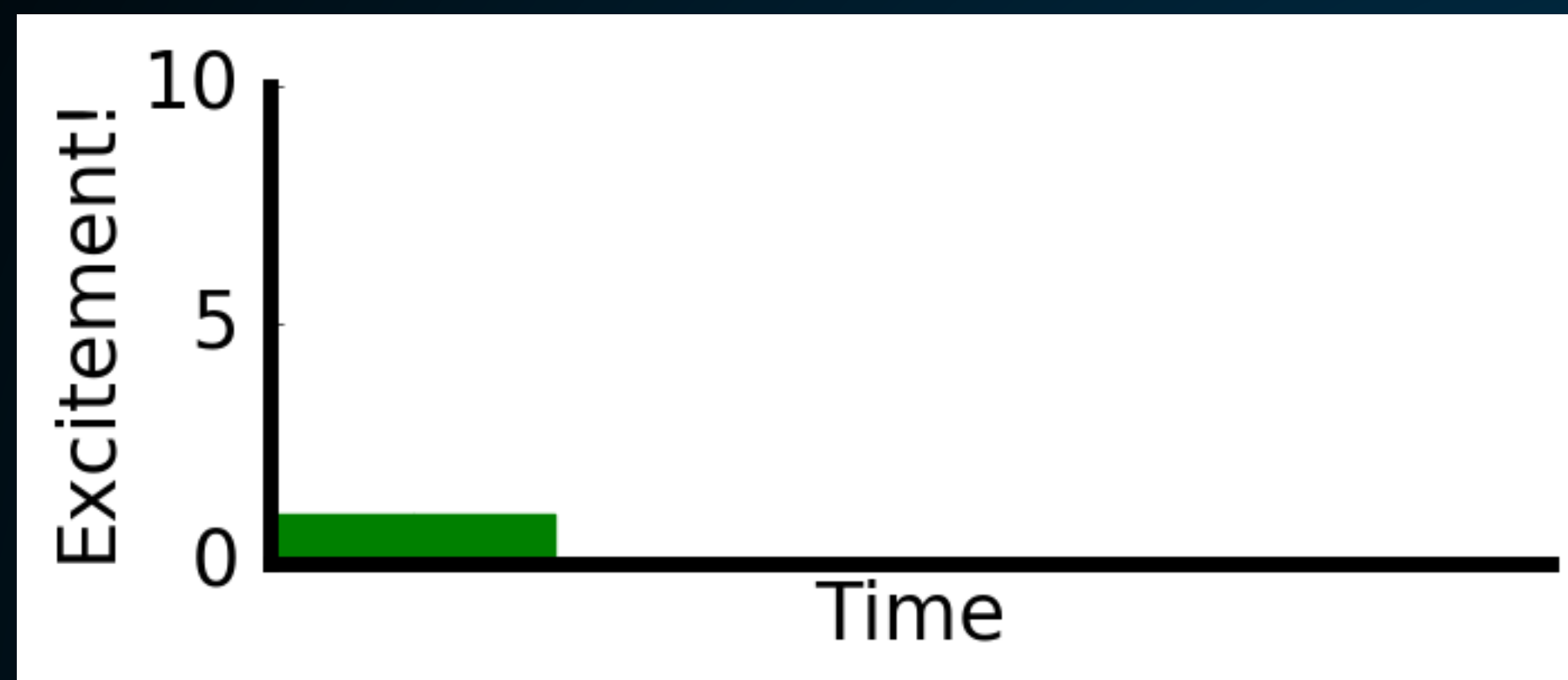
The Antiproton Excess



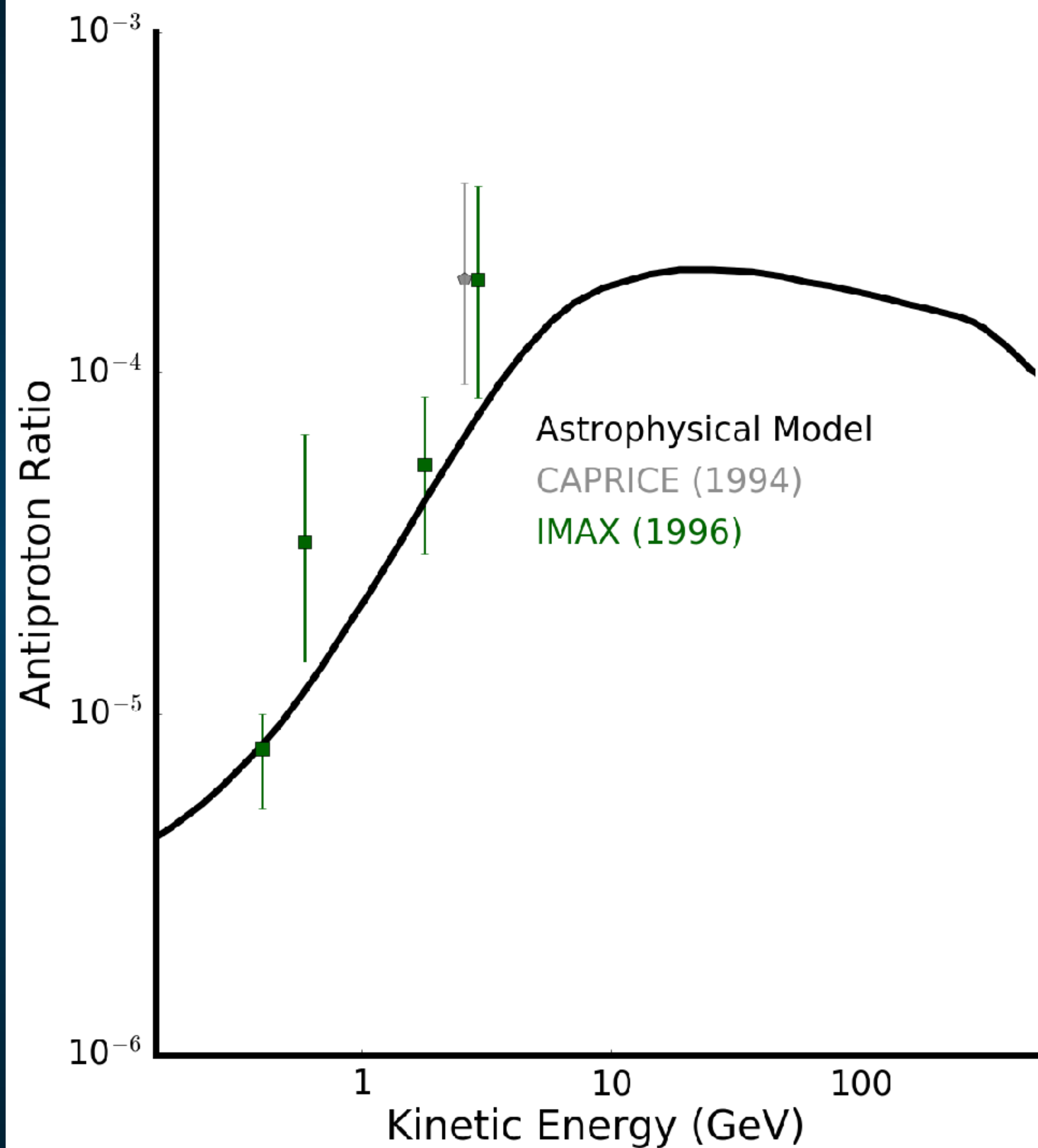
(Not an exhaustive list of observations)



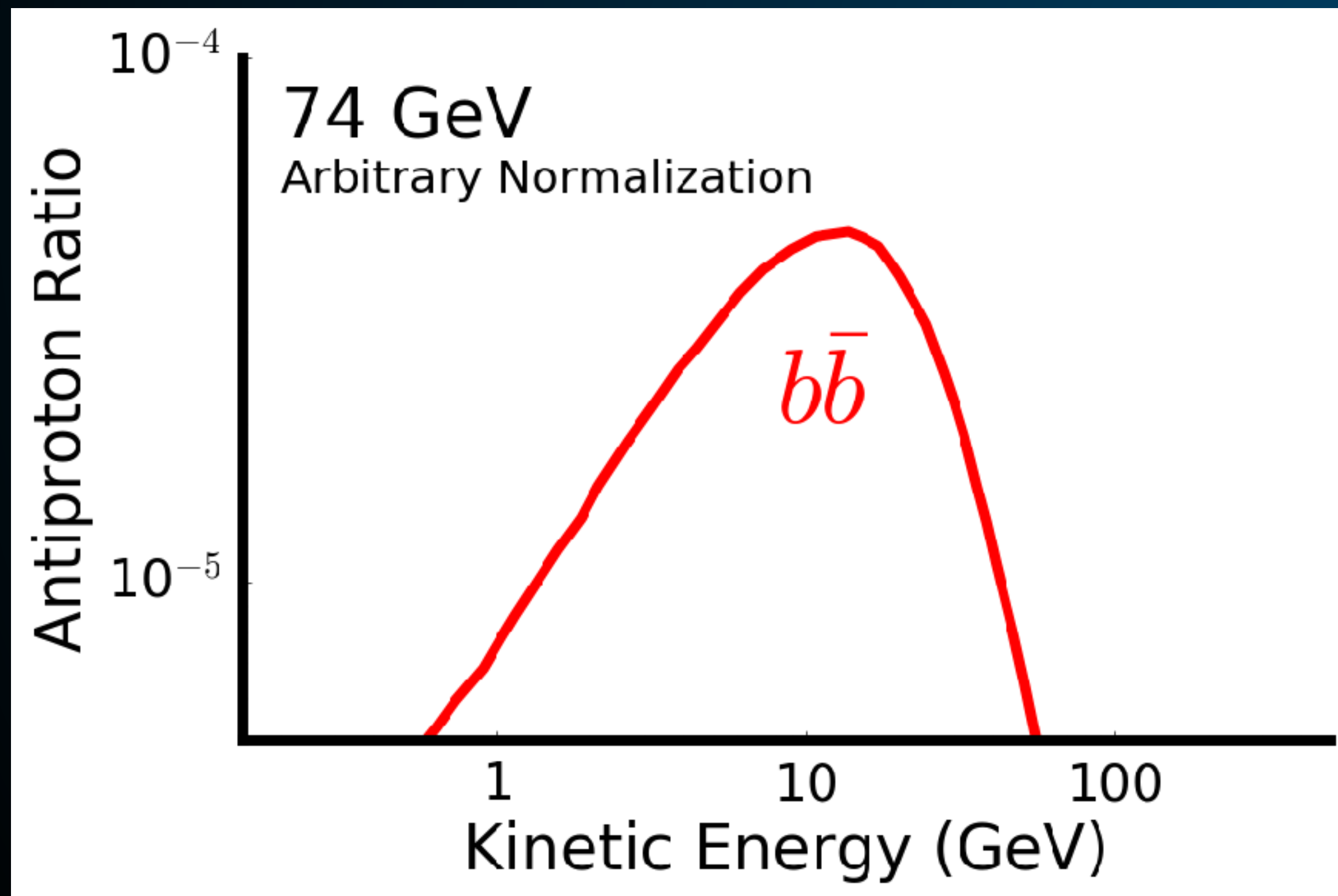
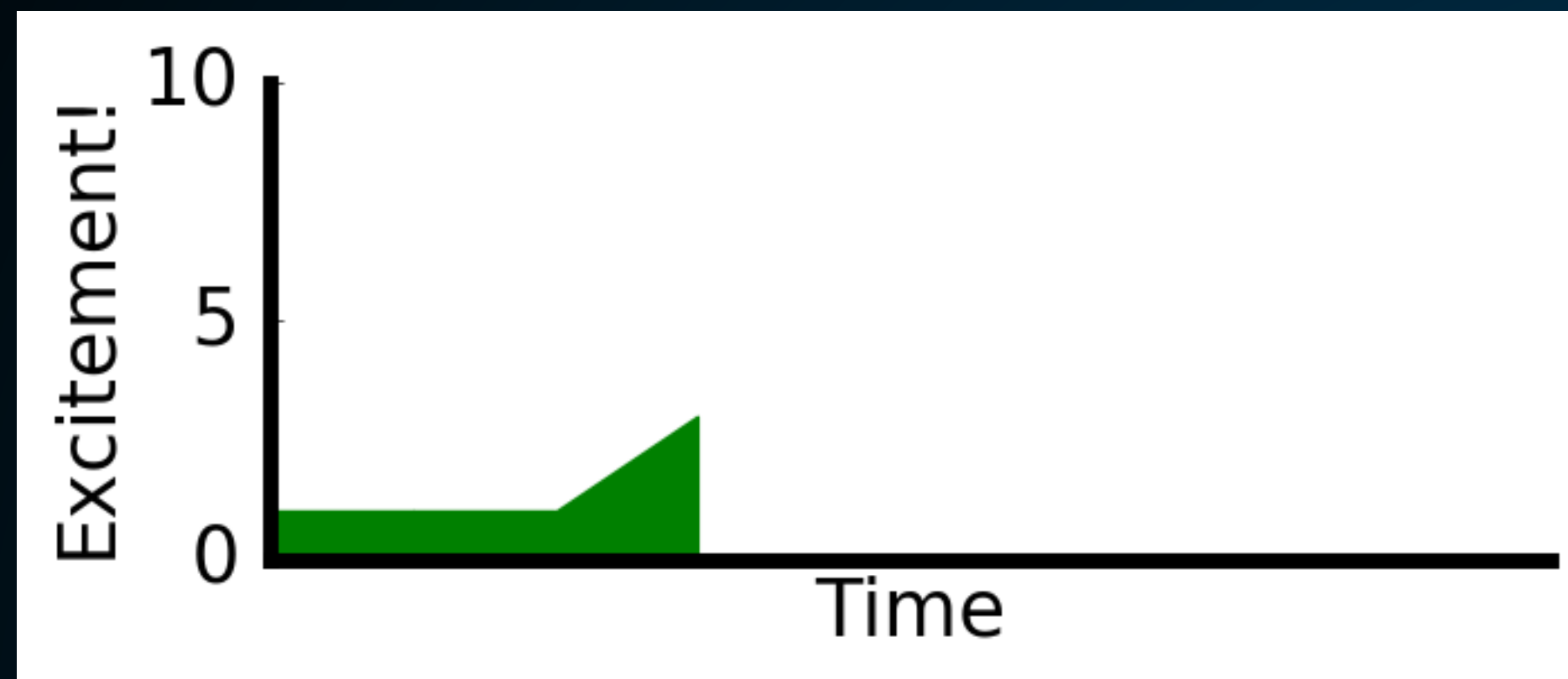
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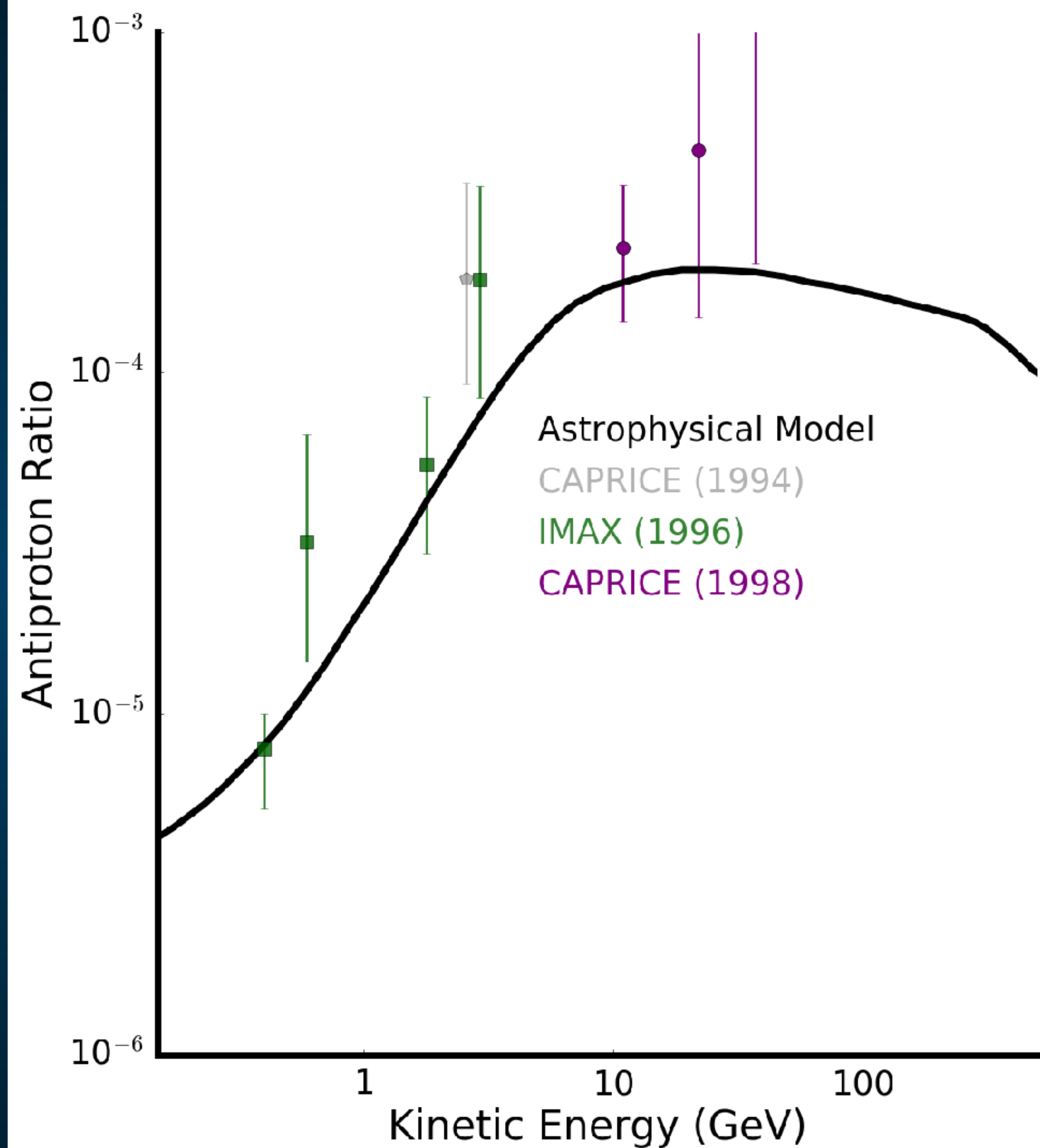
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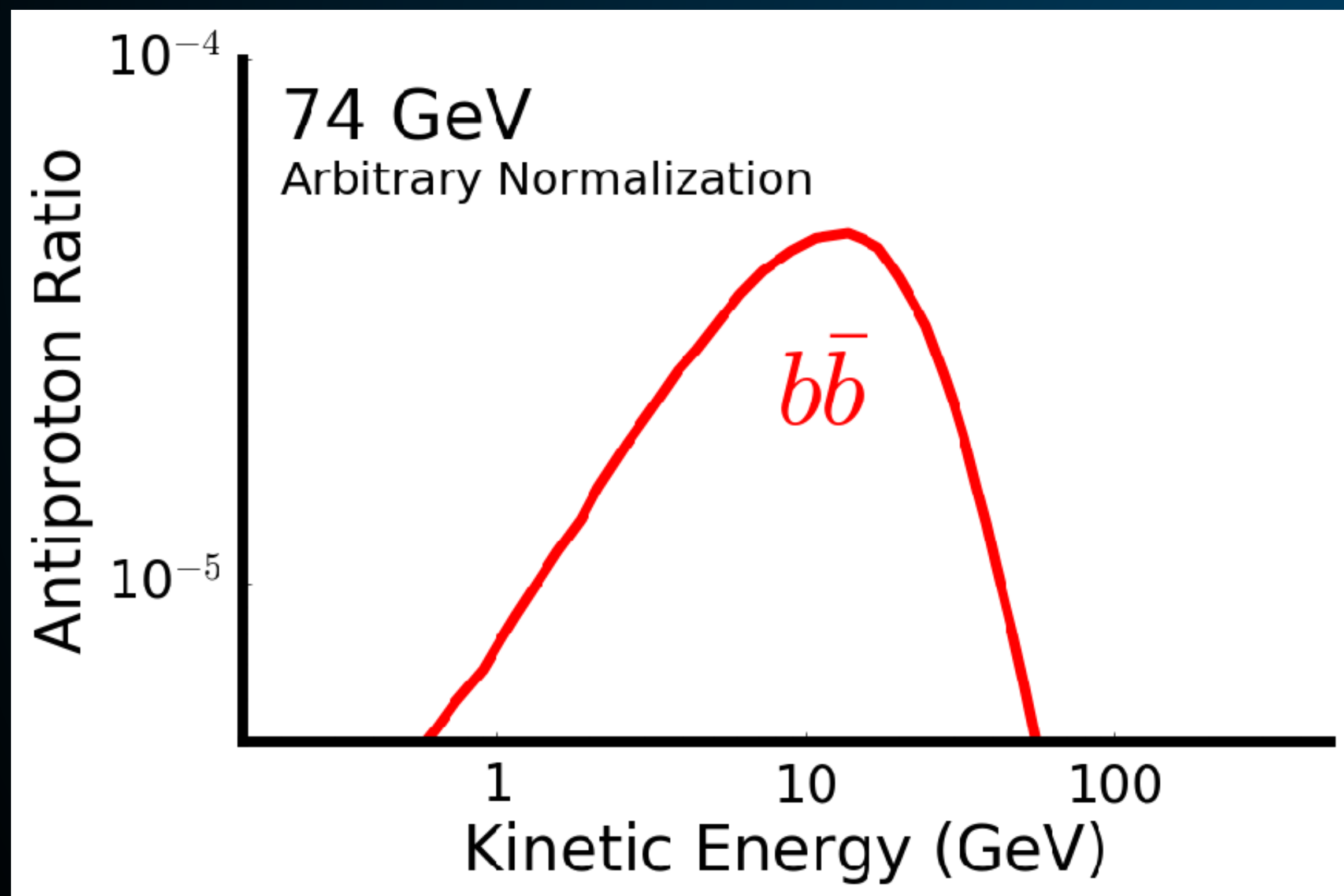
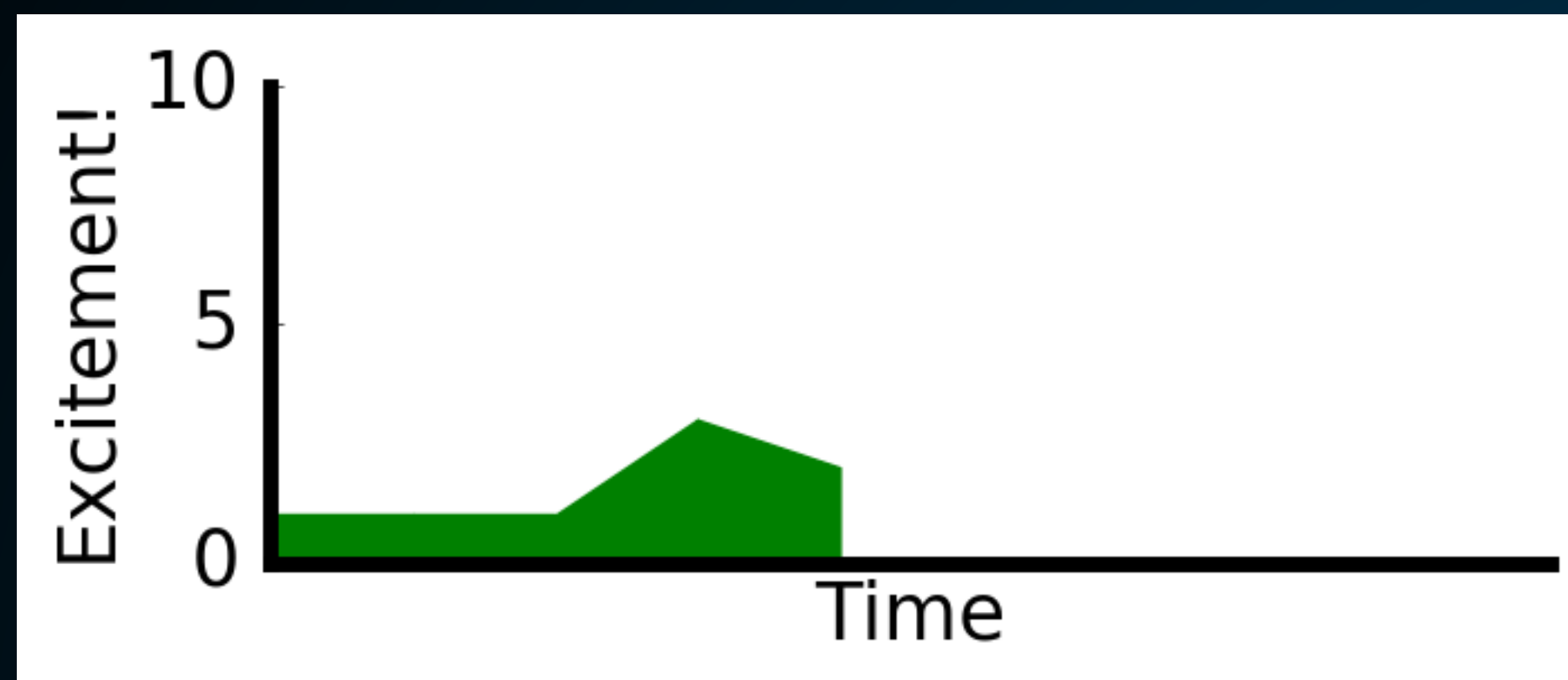
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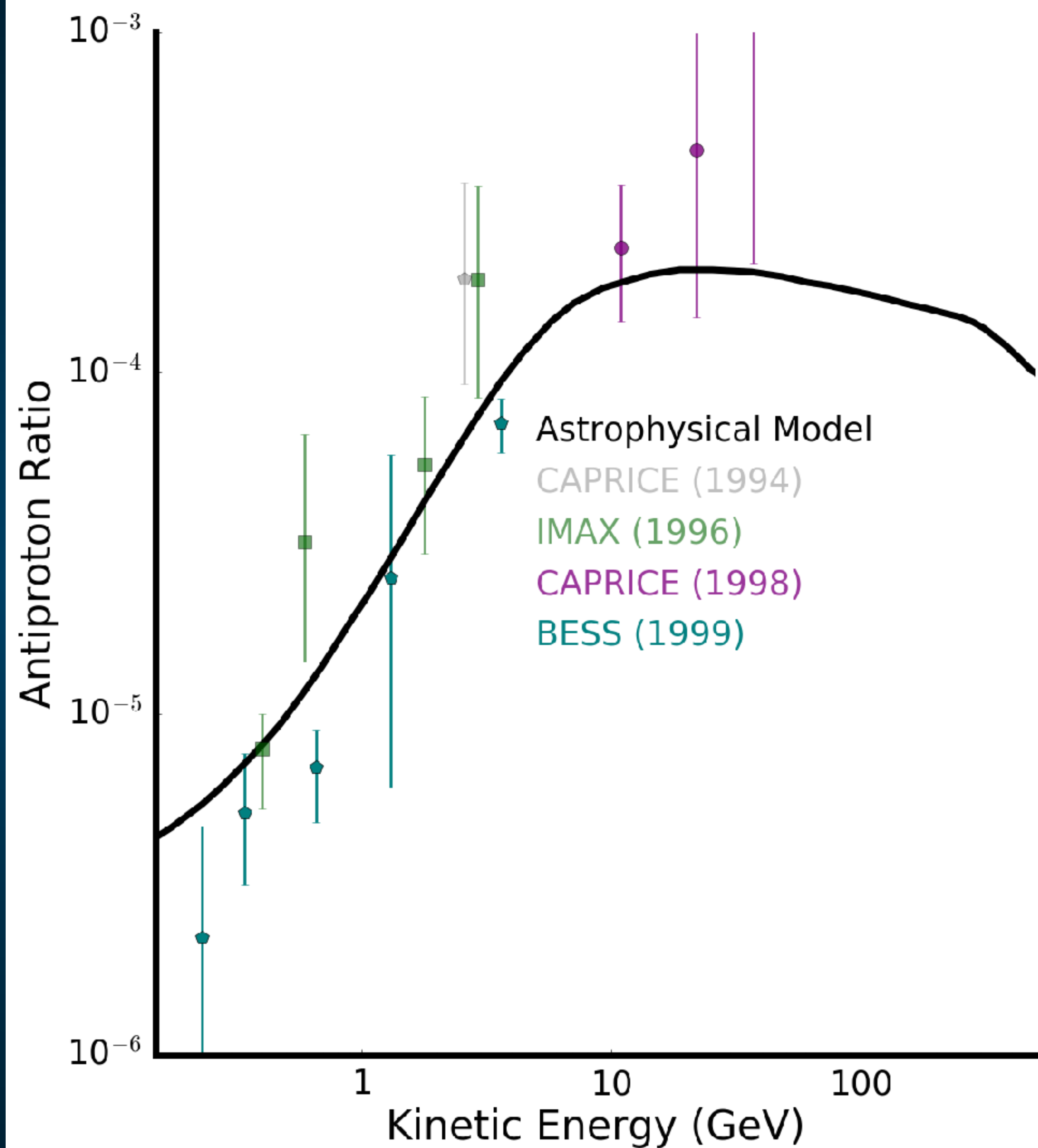
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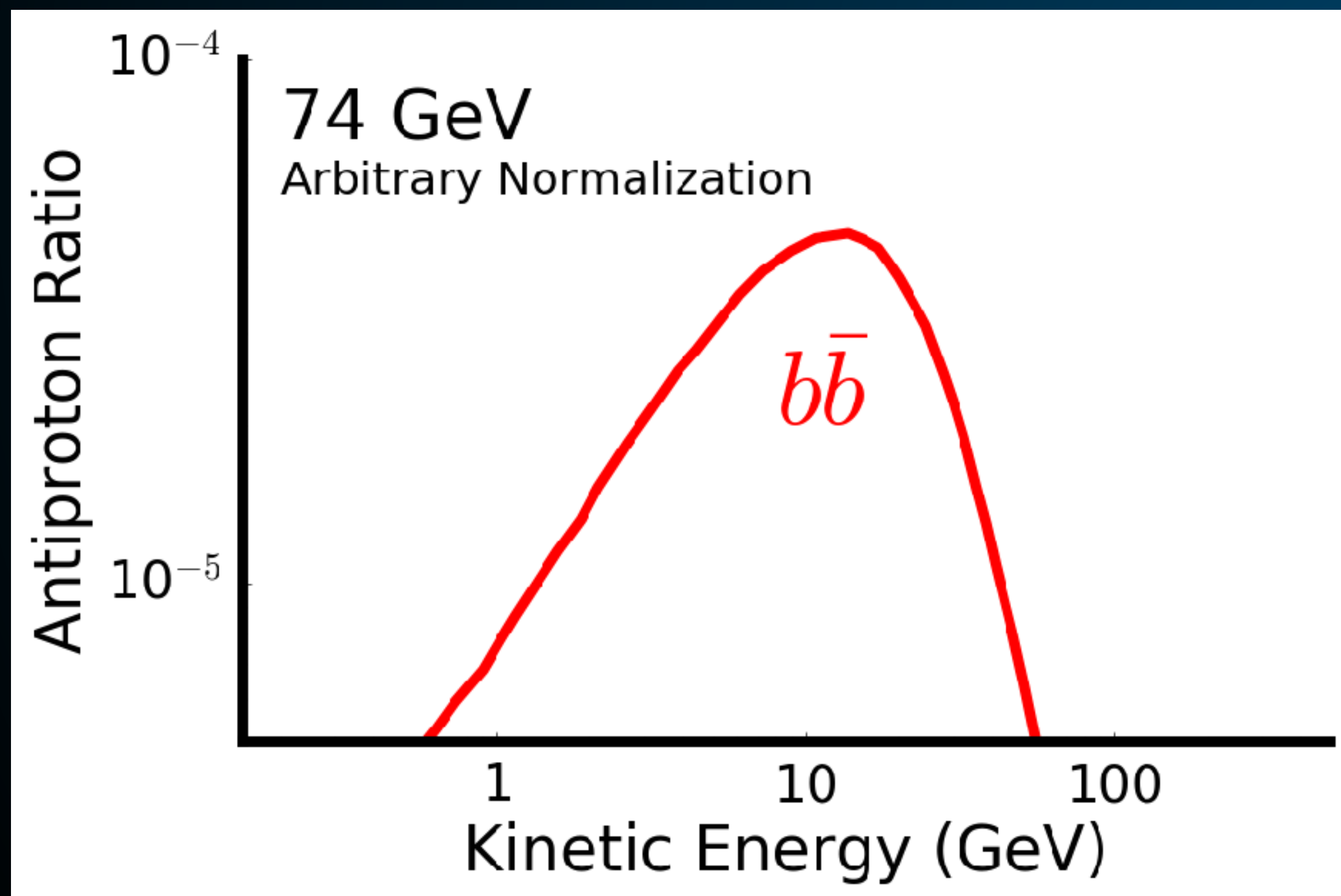
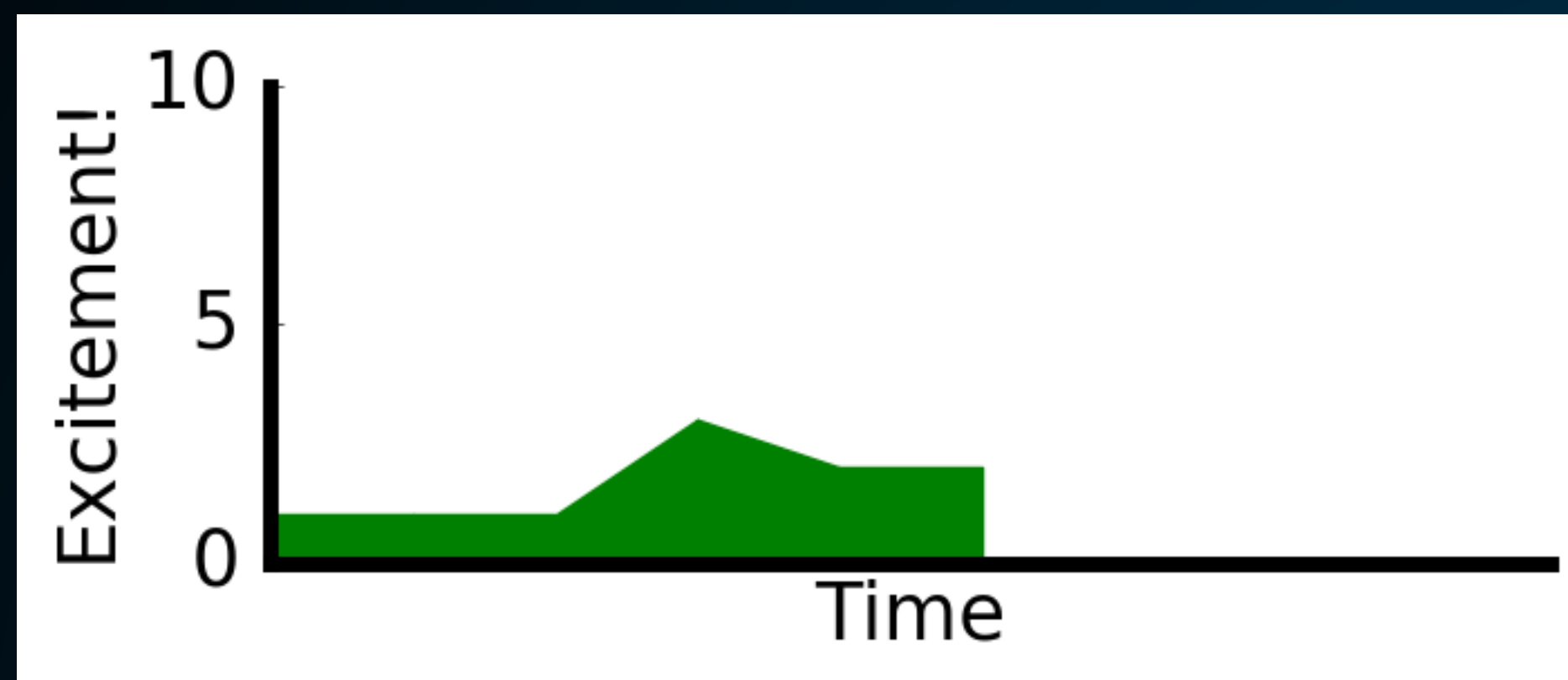
The Antiproton Excess



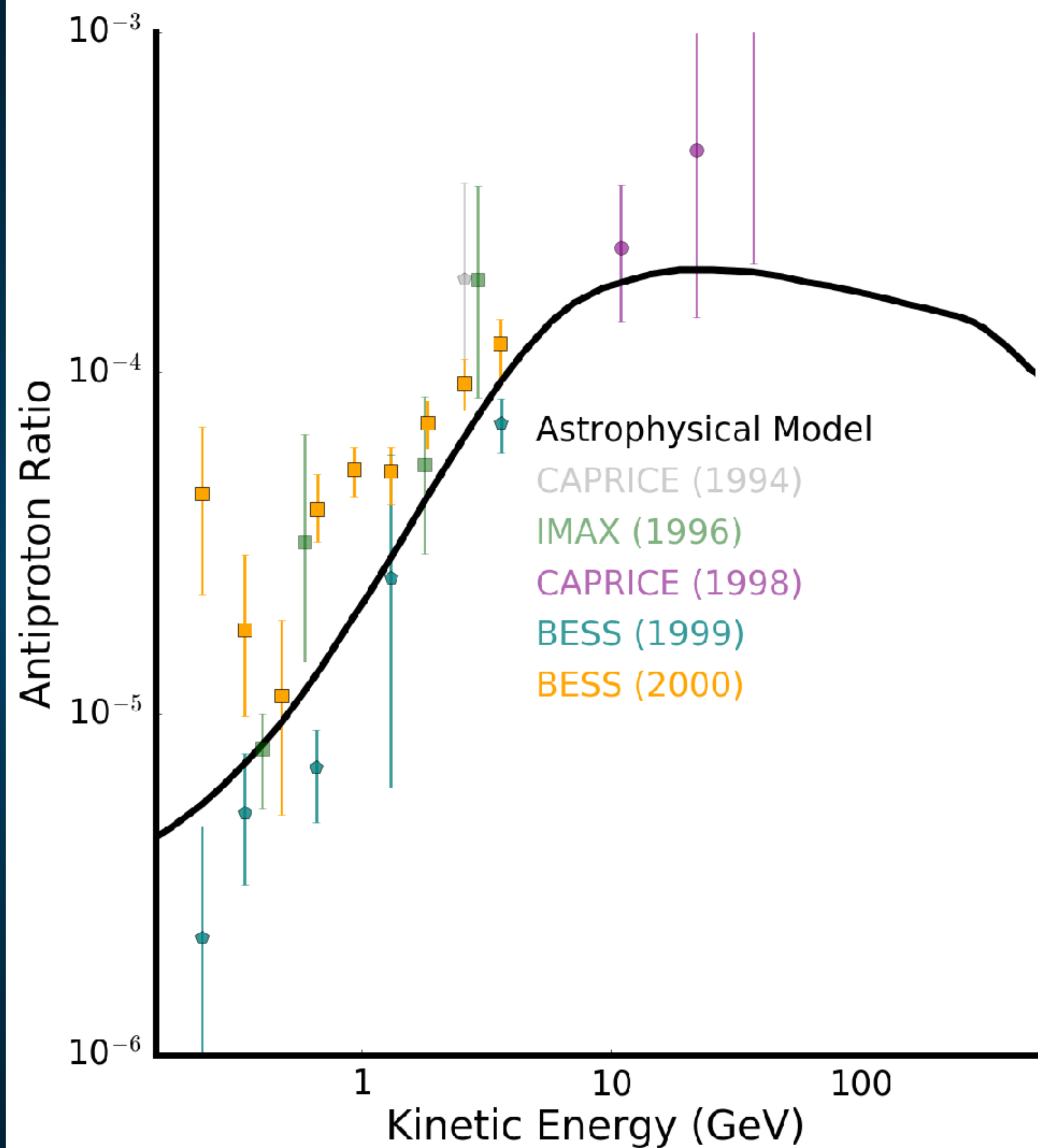
(Not an exhaustive list of observations)



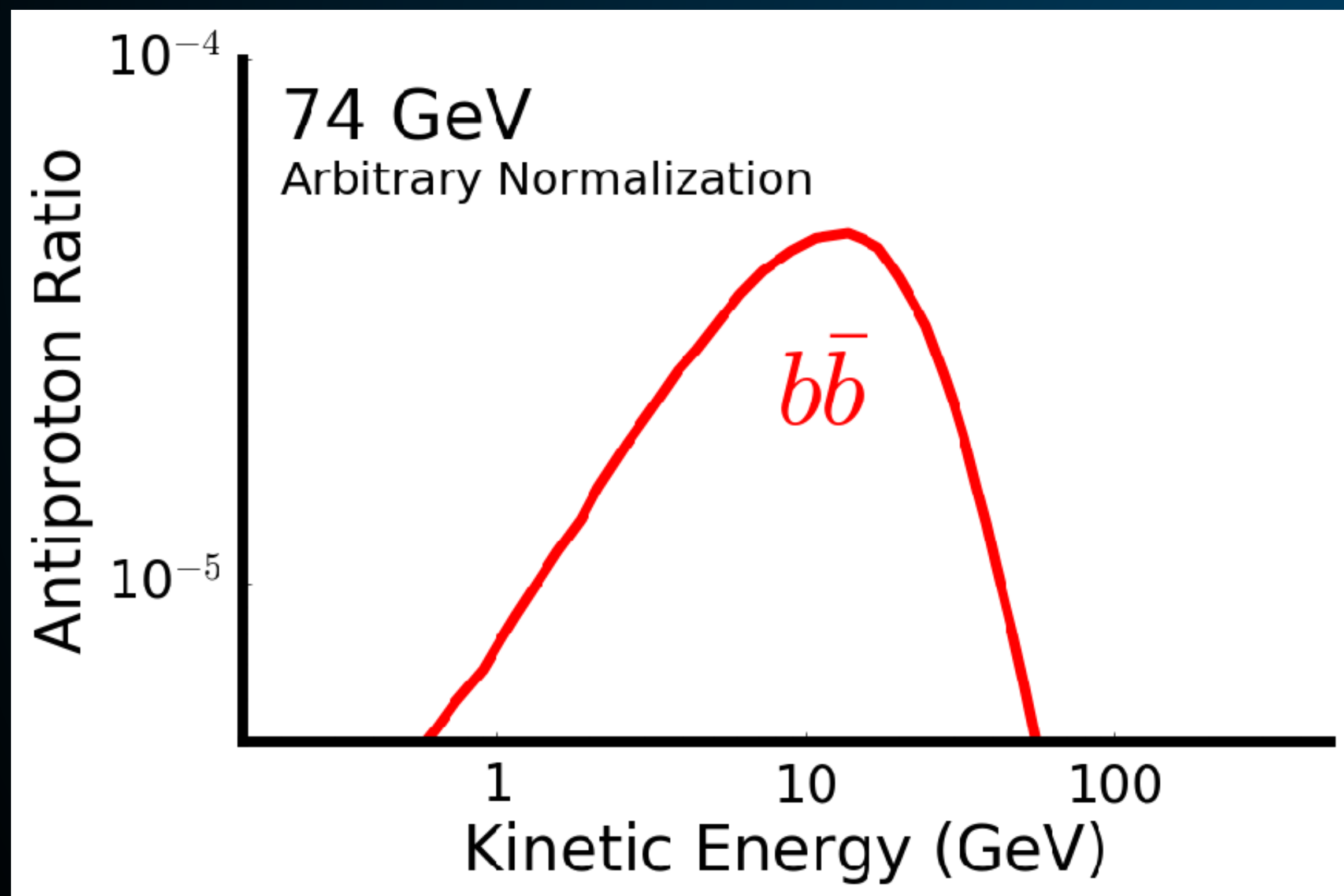
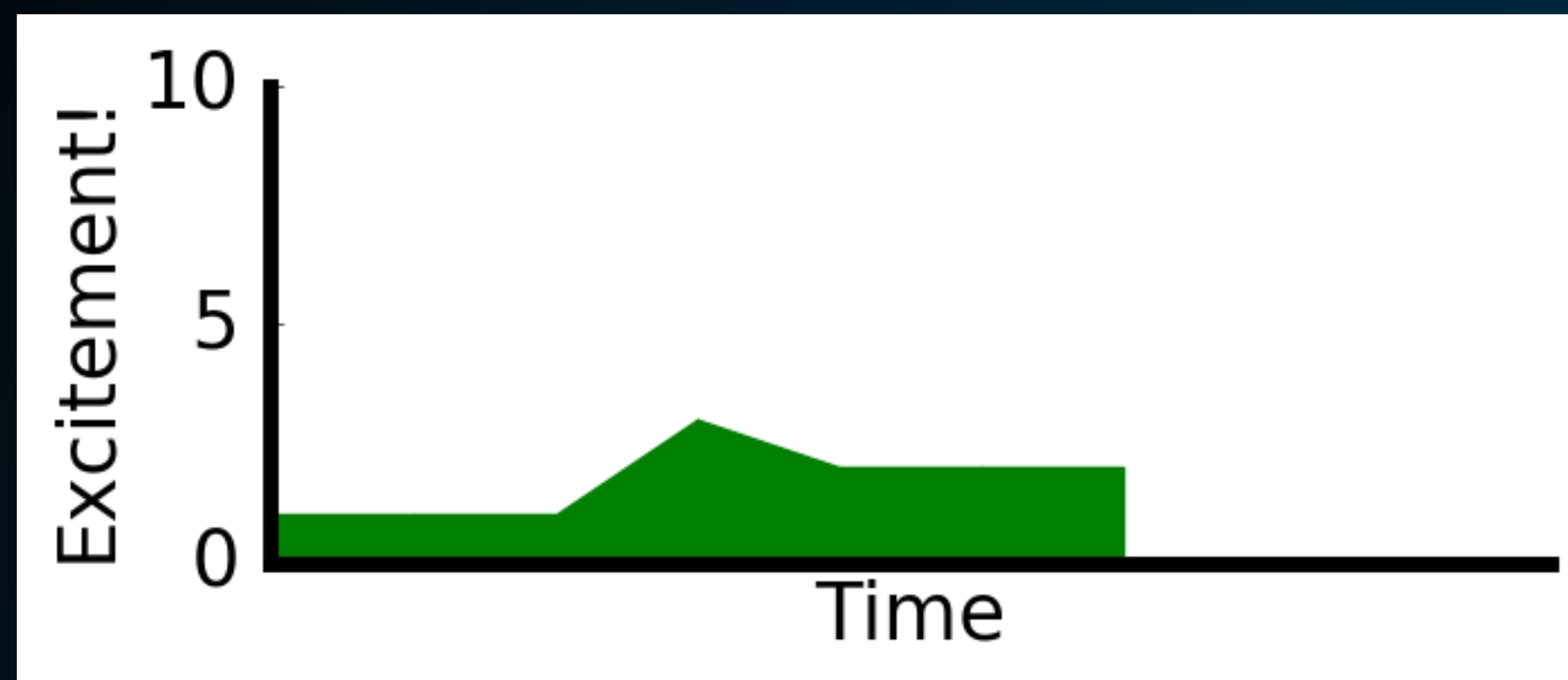
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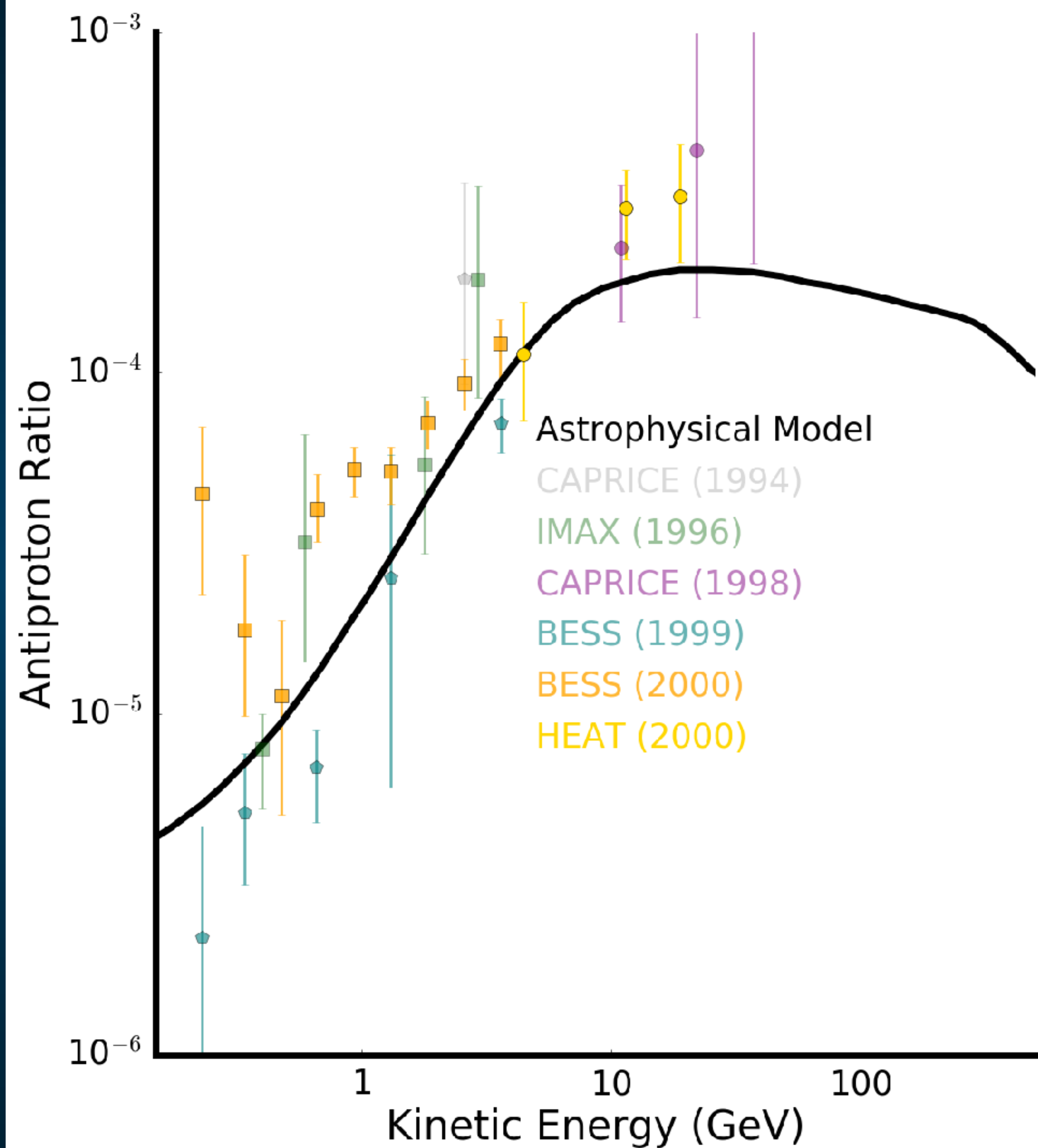
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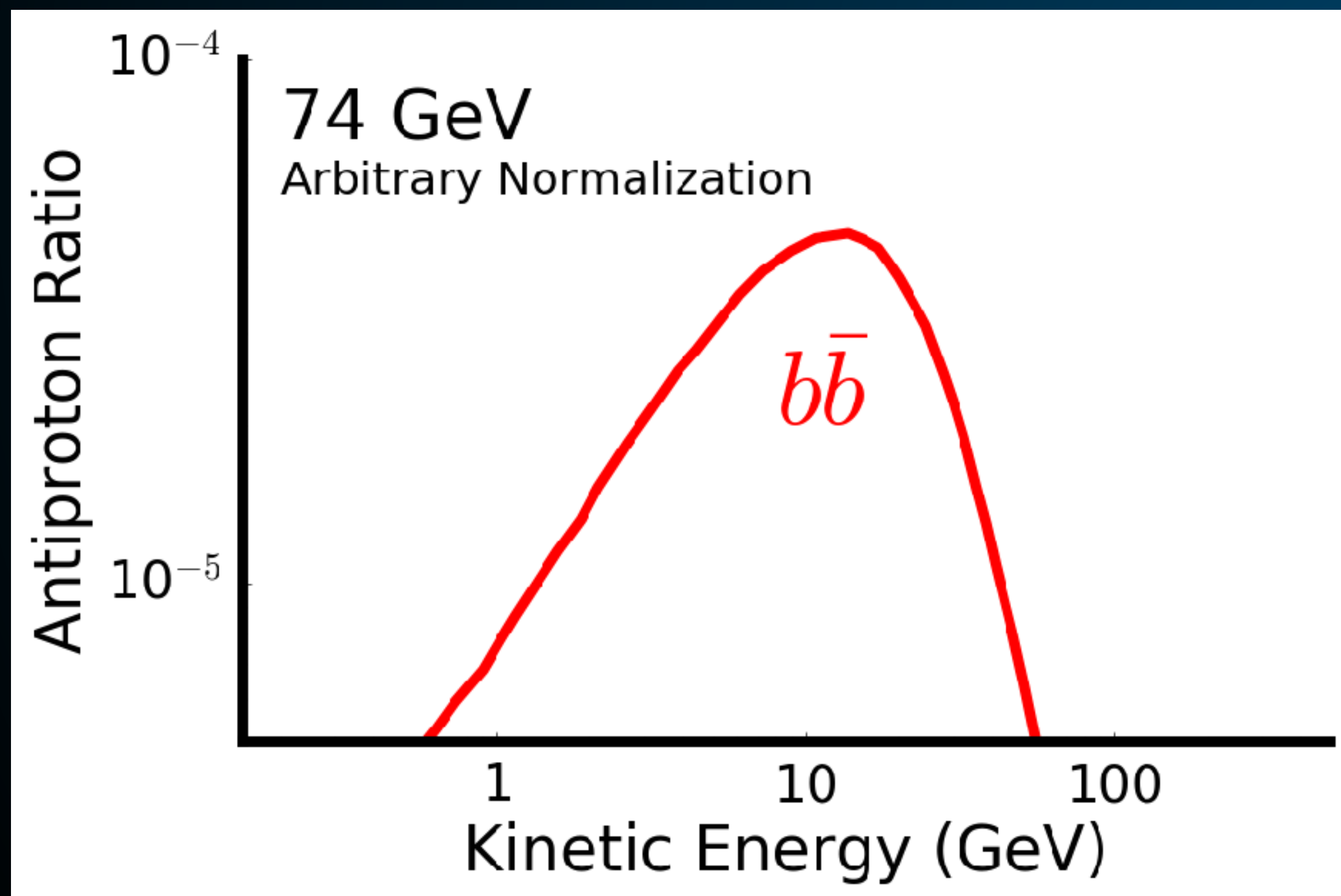
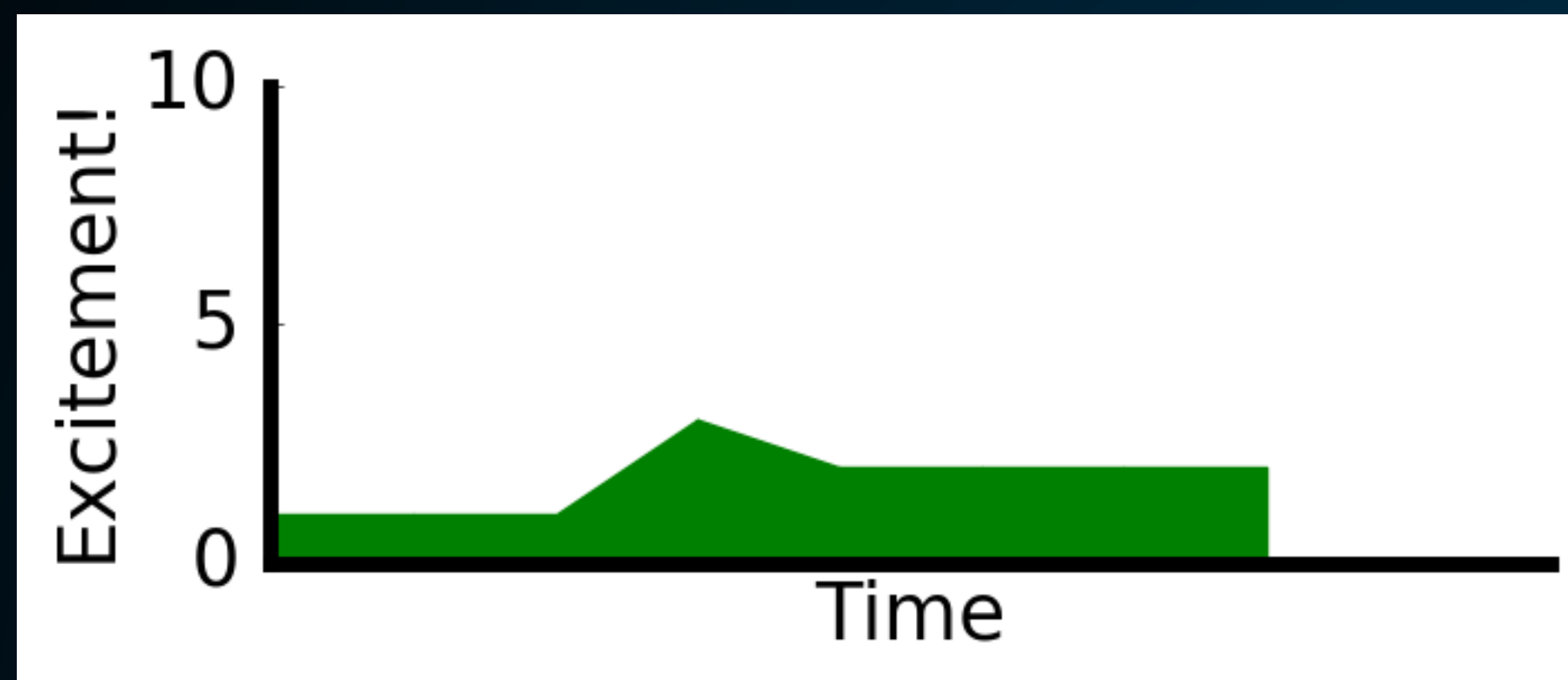
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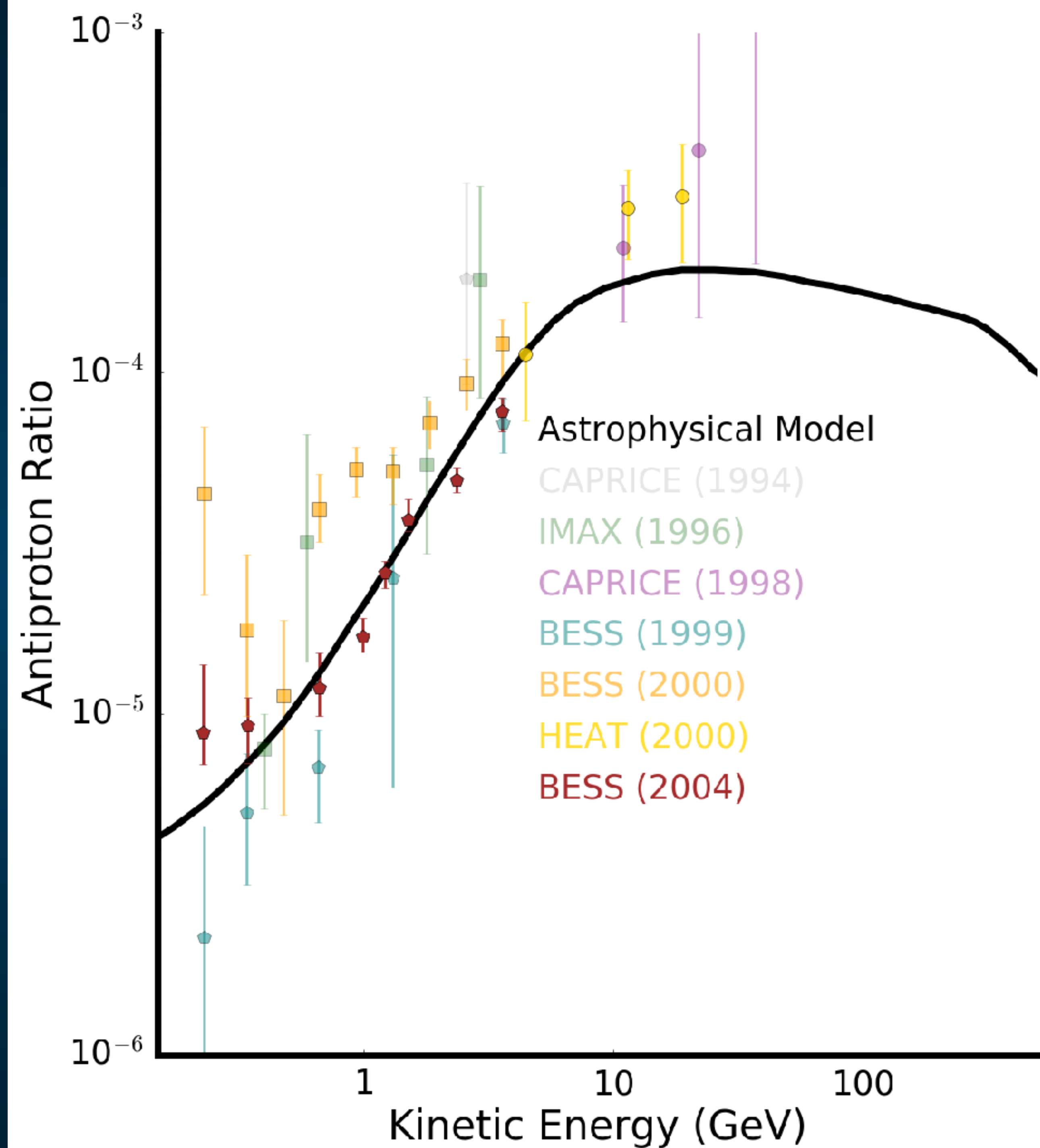
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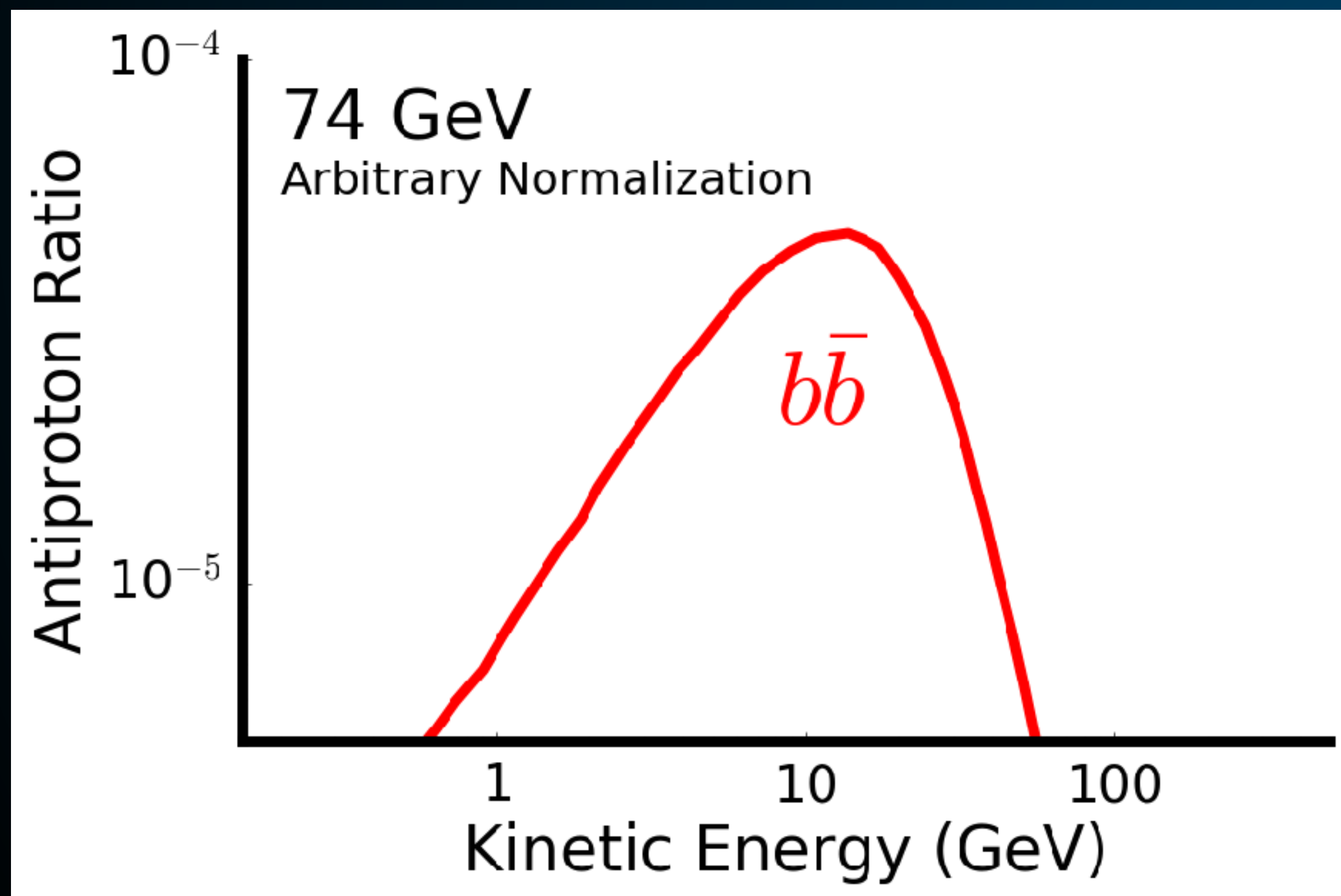
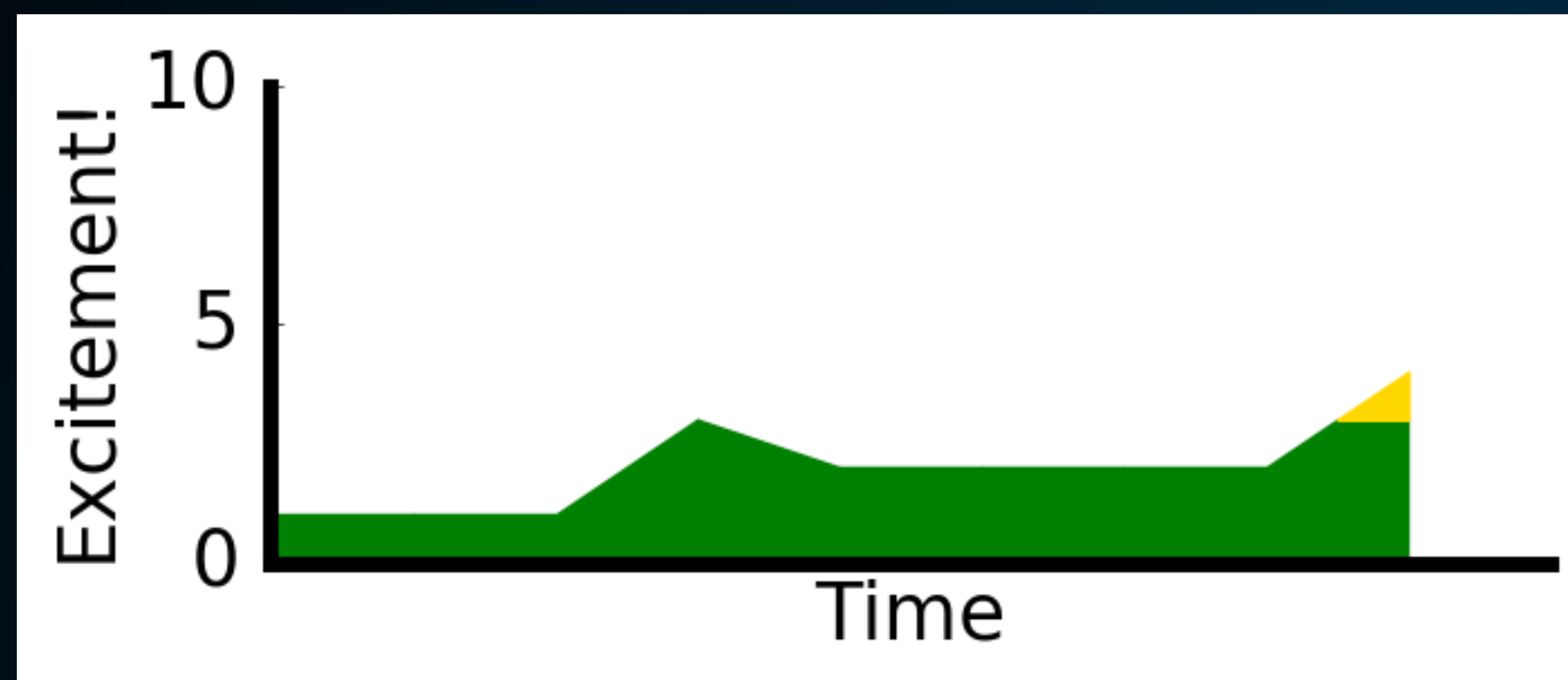
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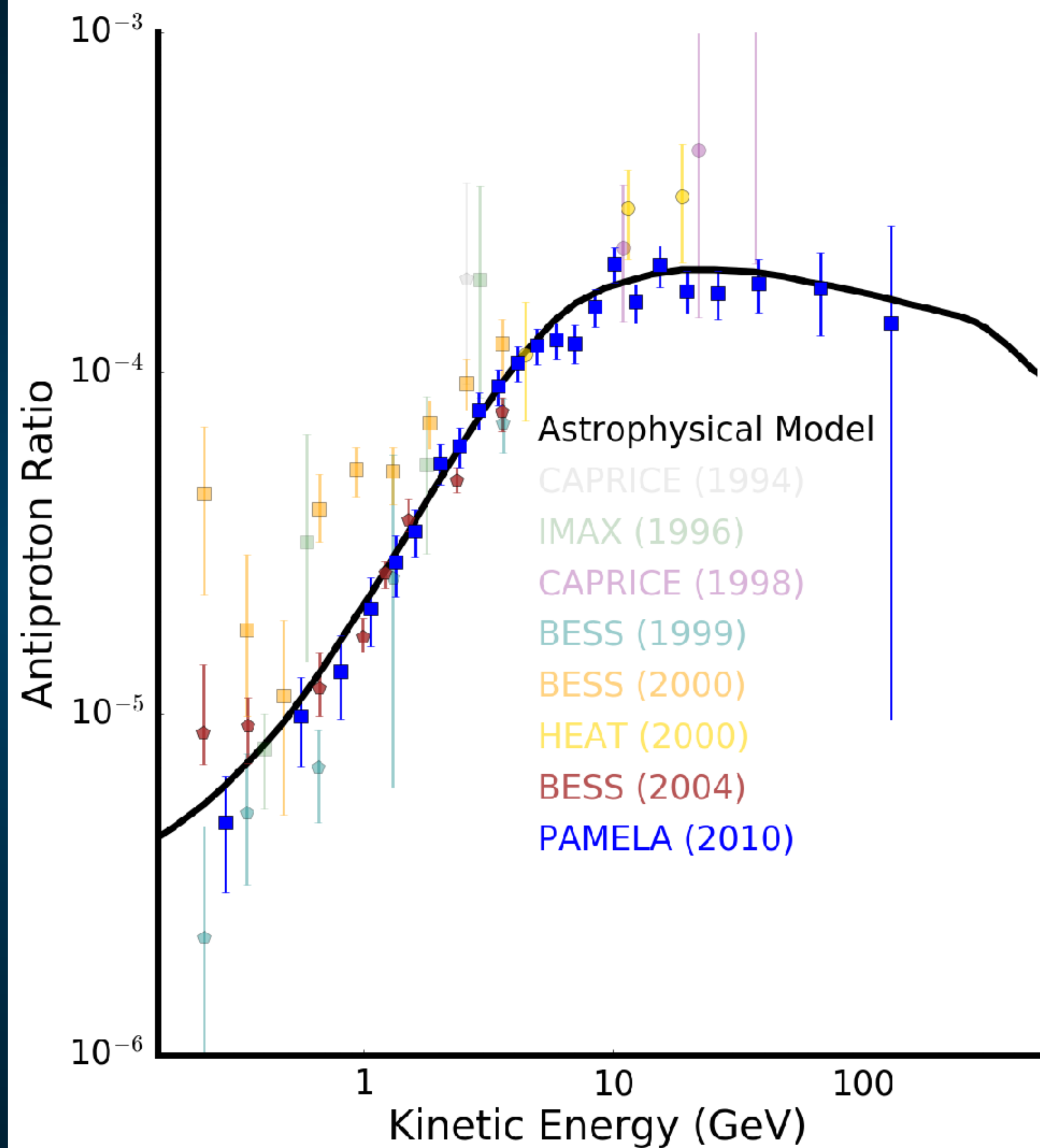
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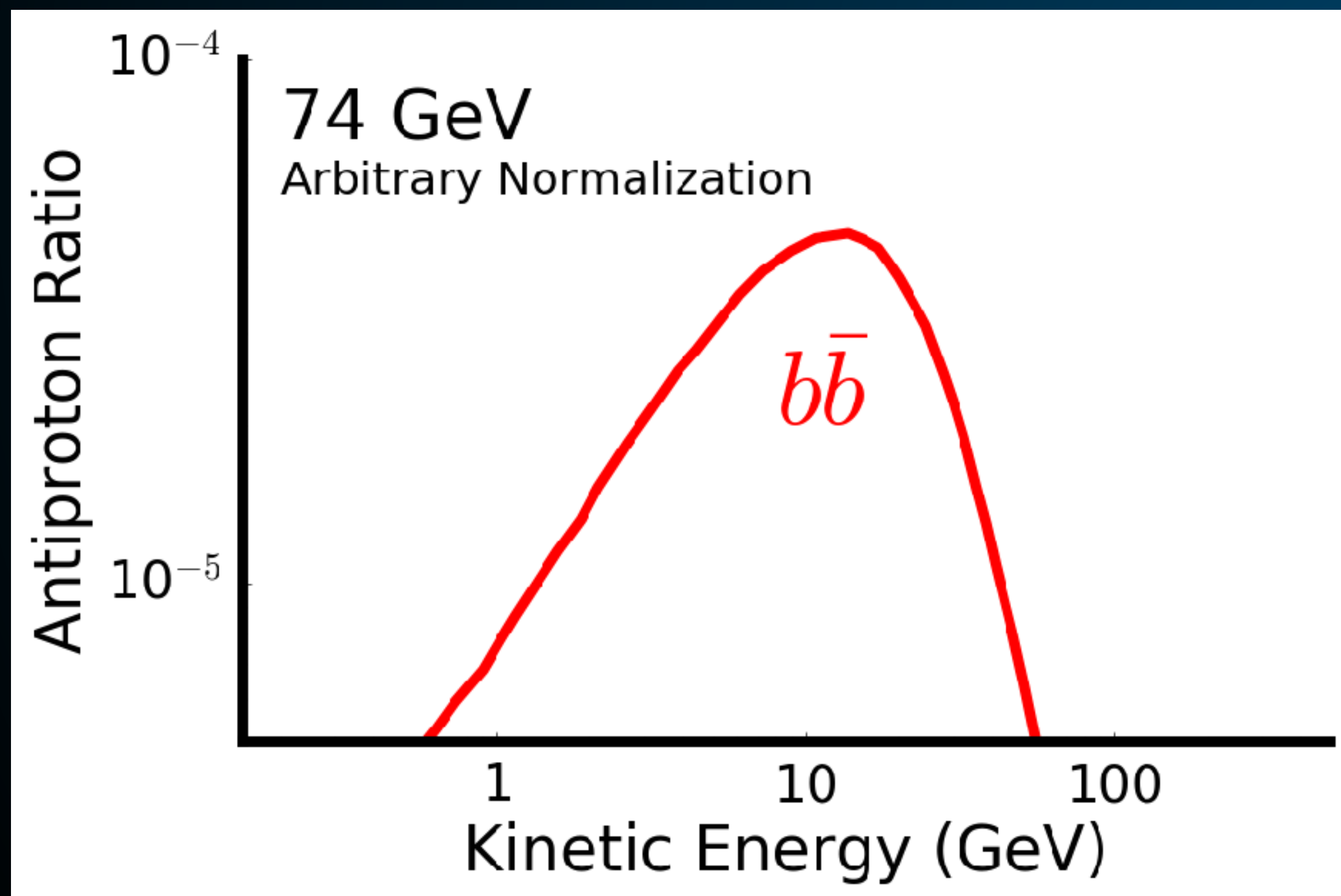
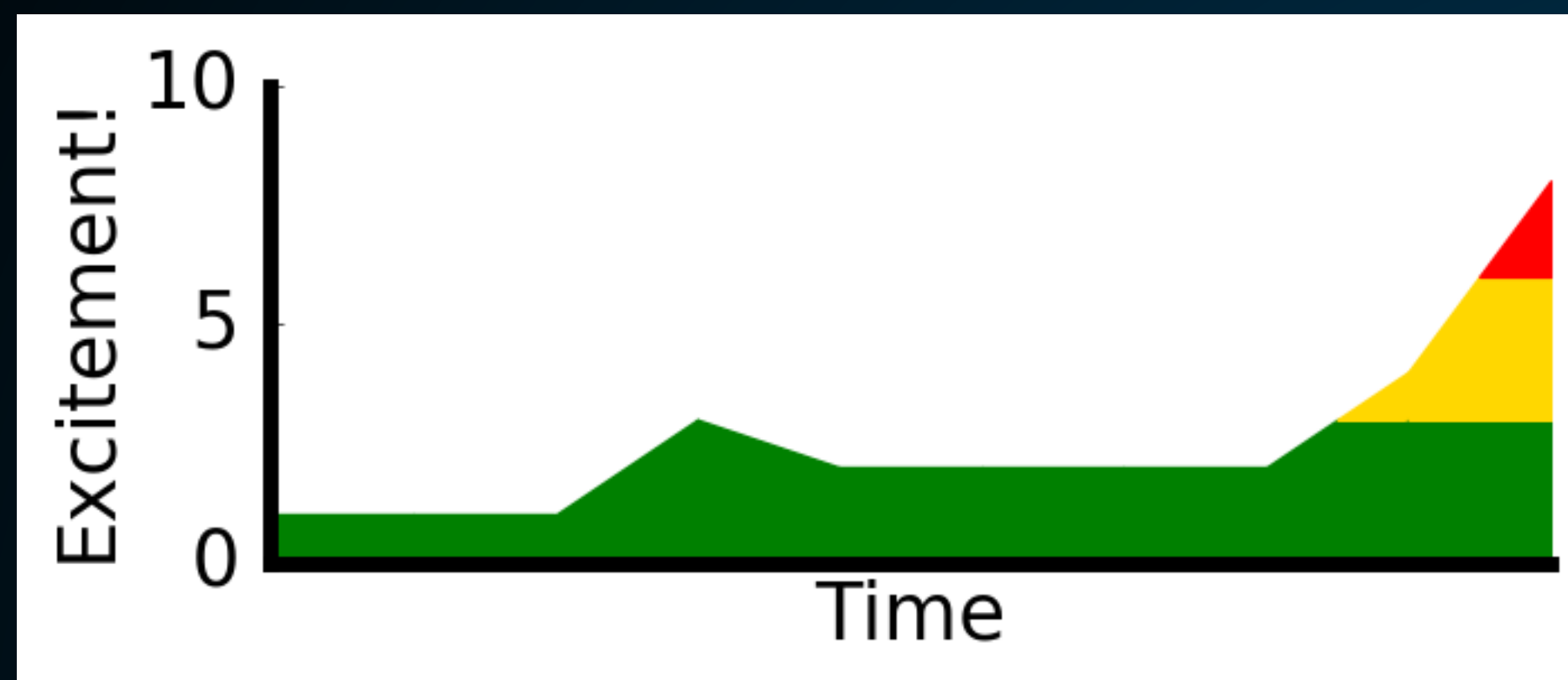
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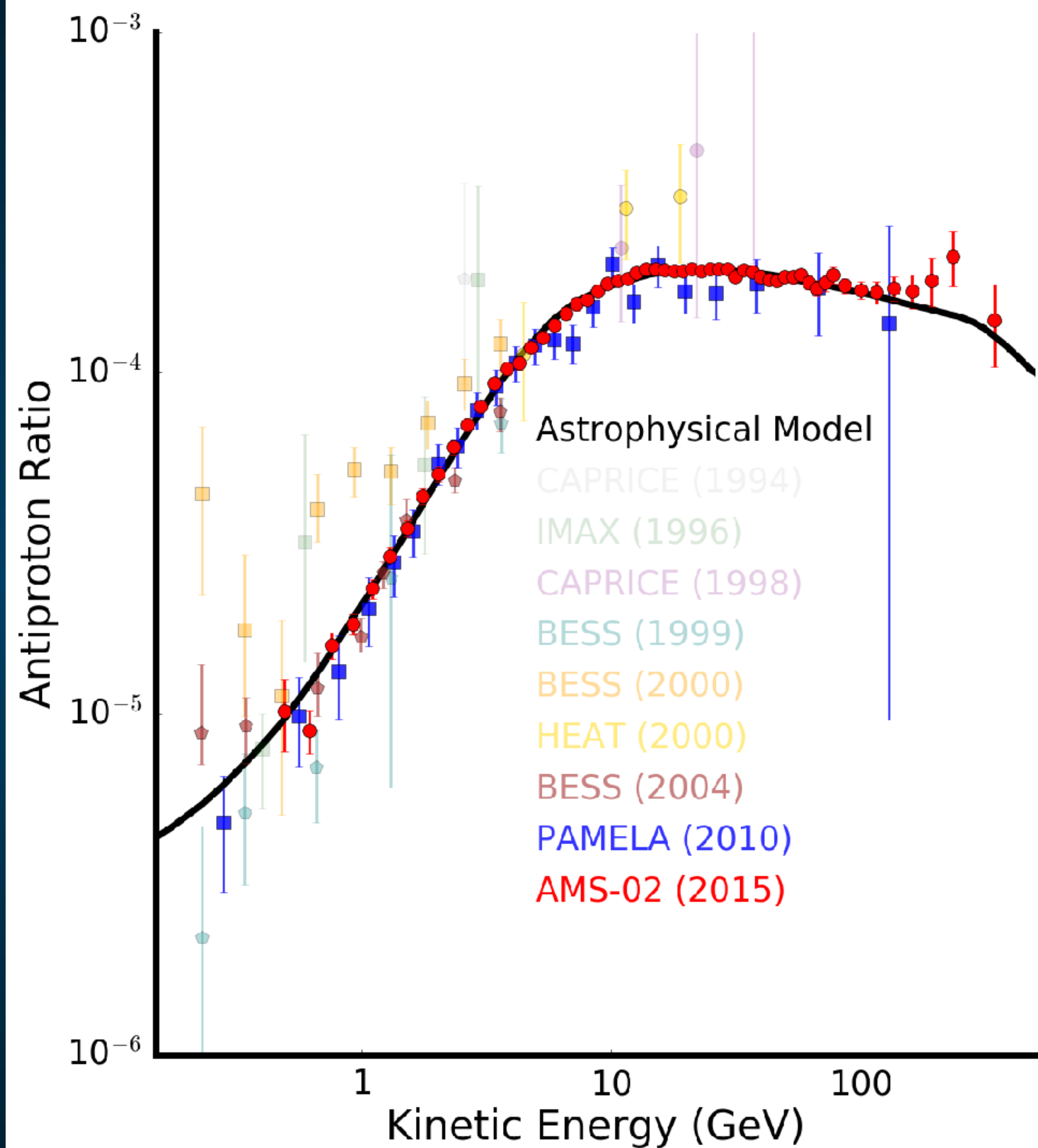
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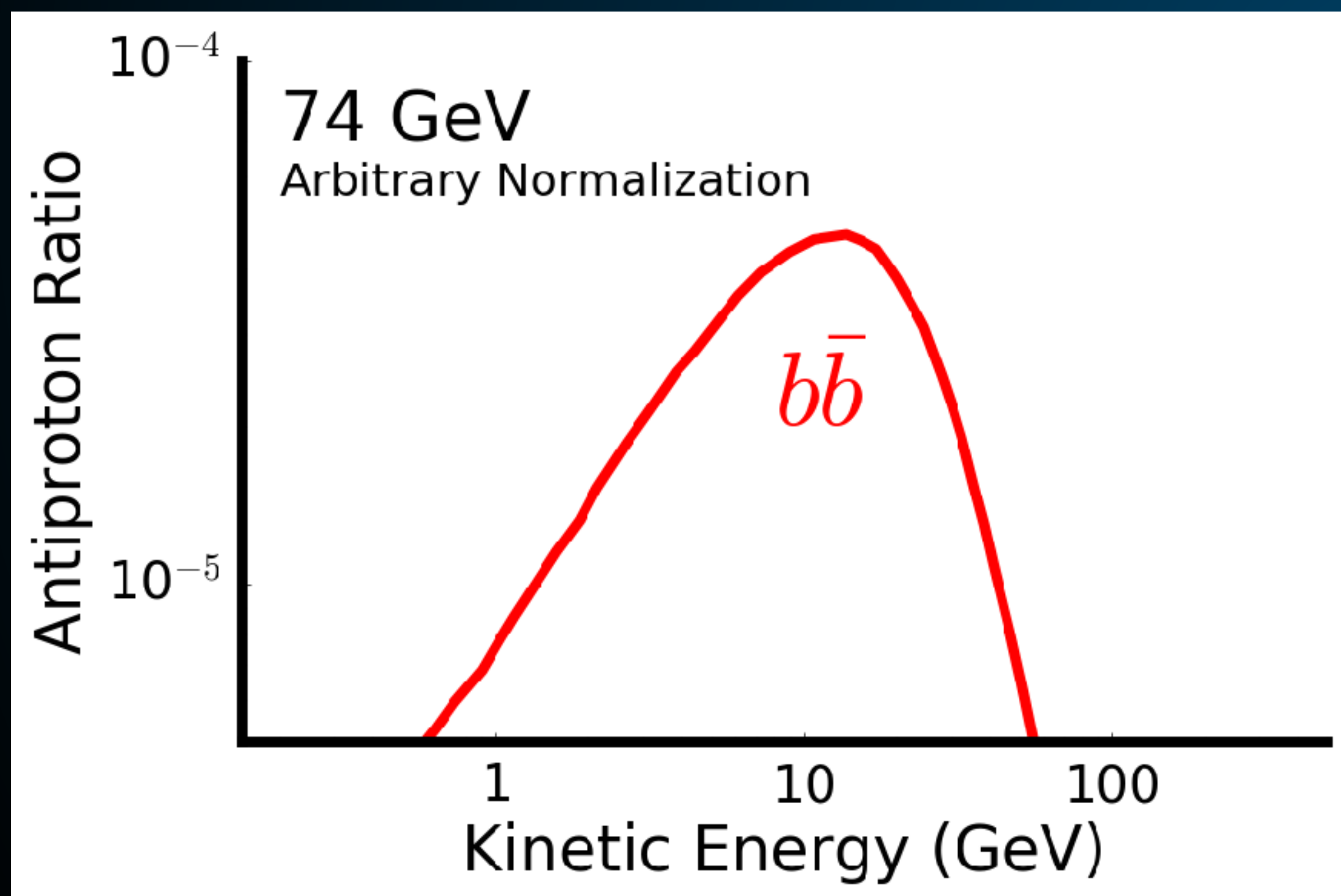
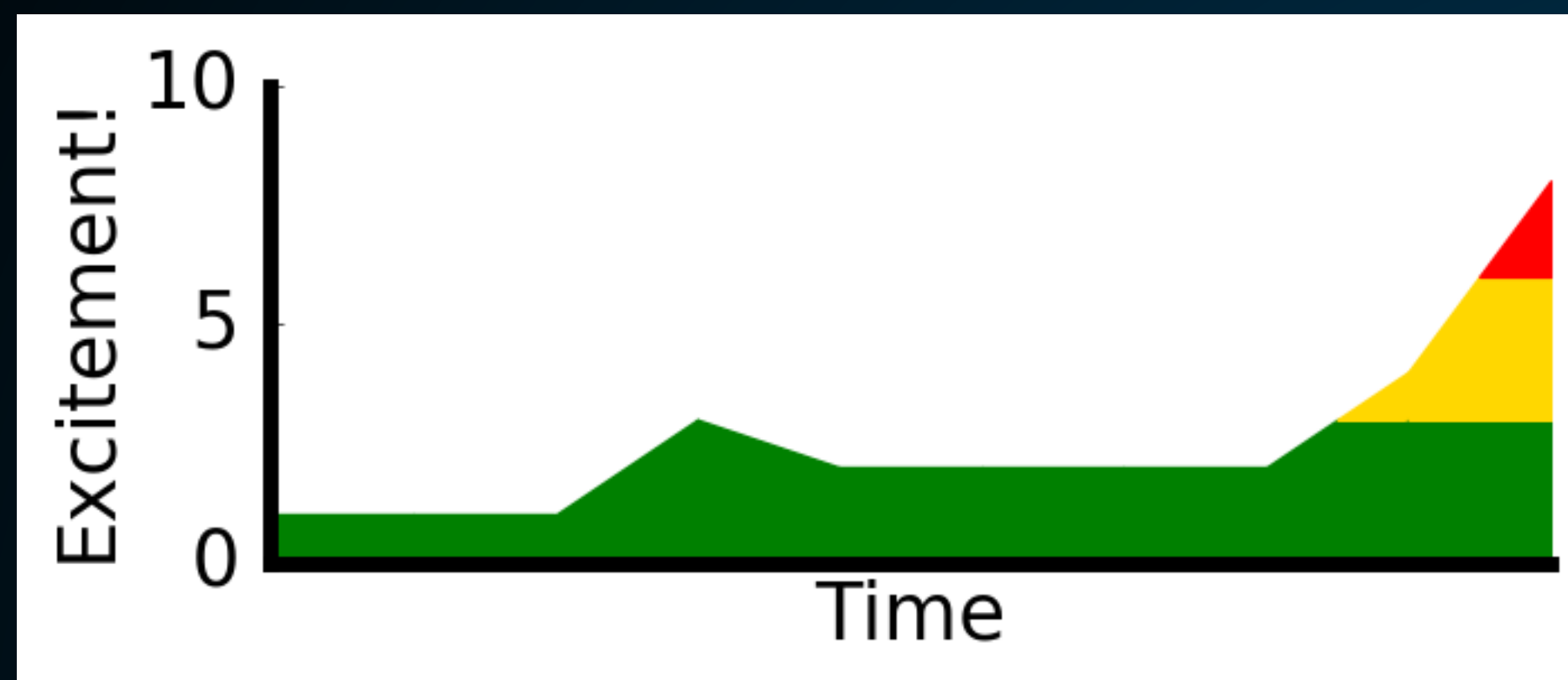
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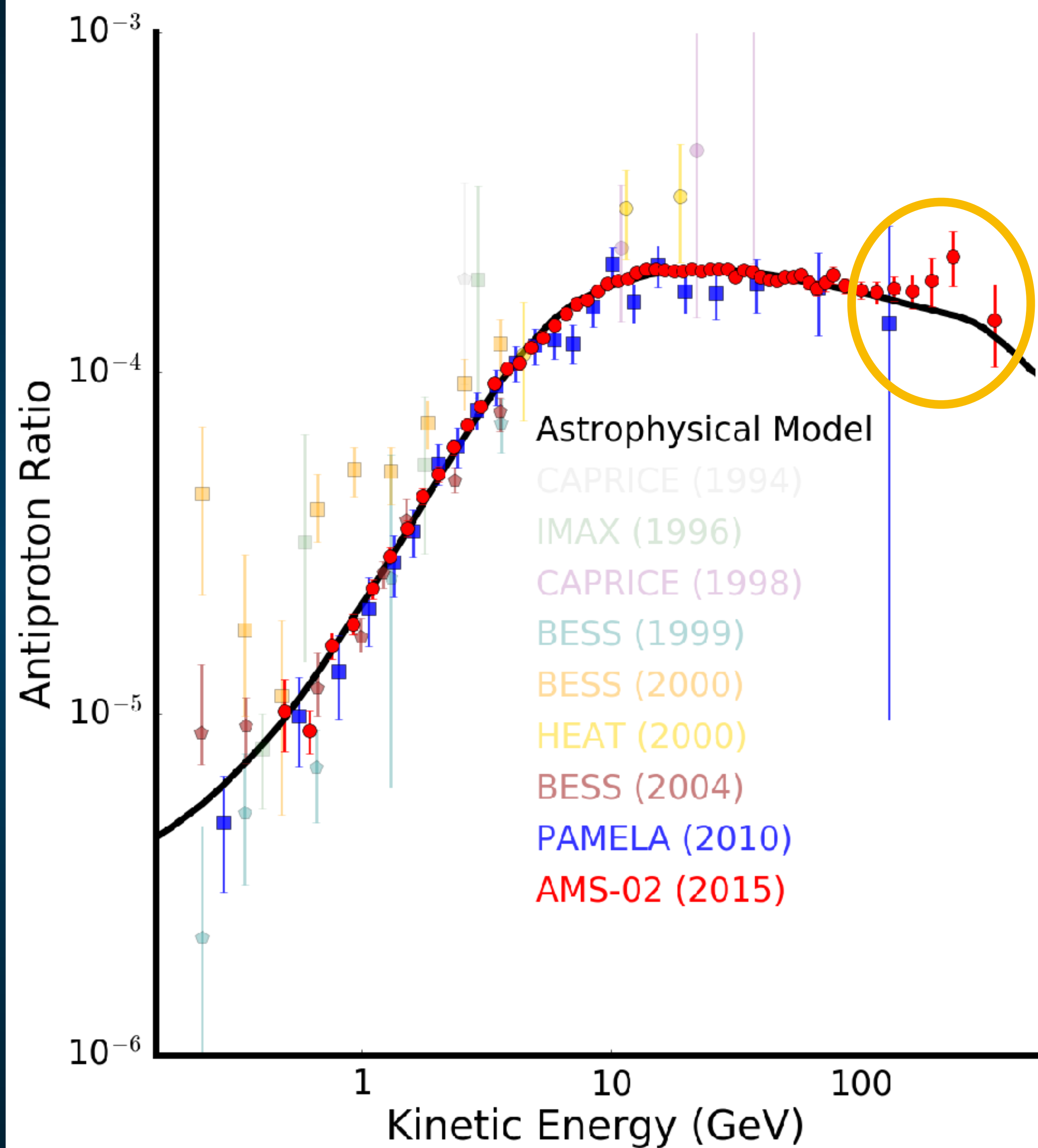
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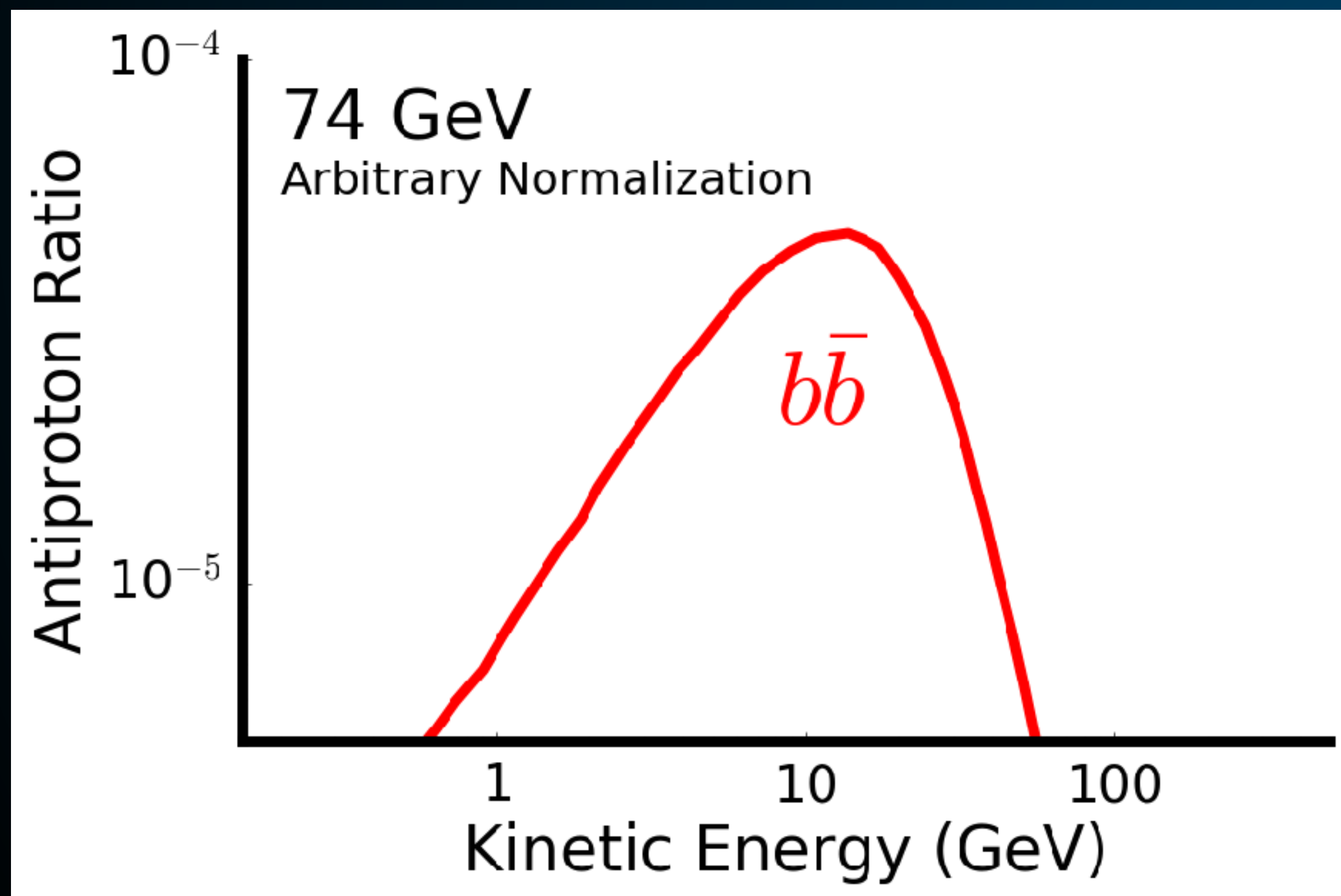
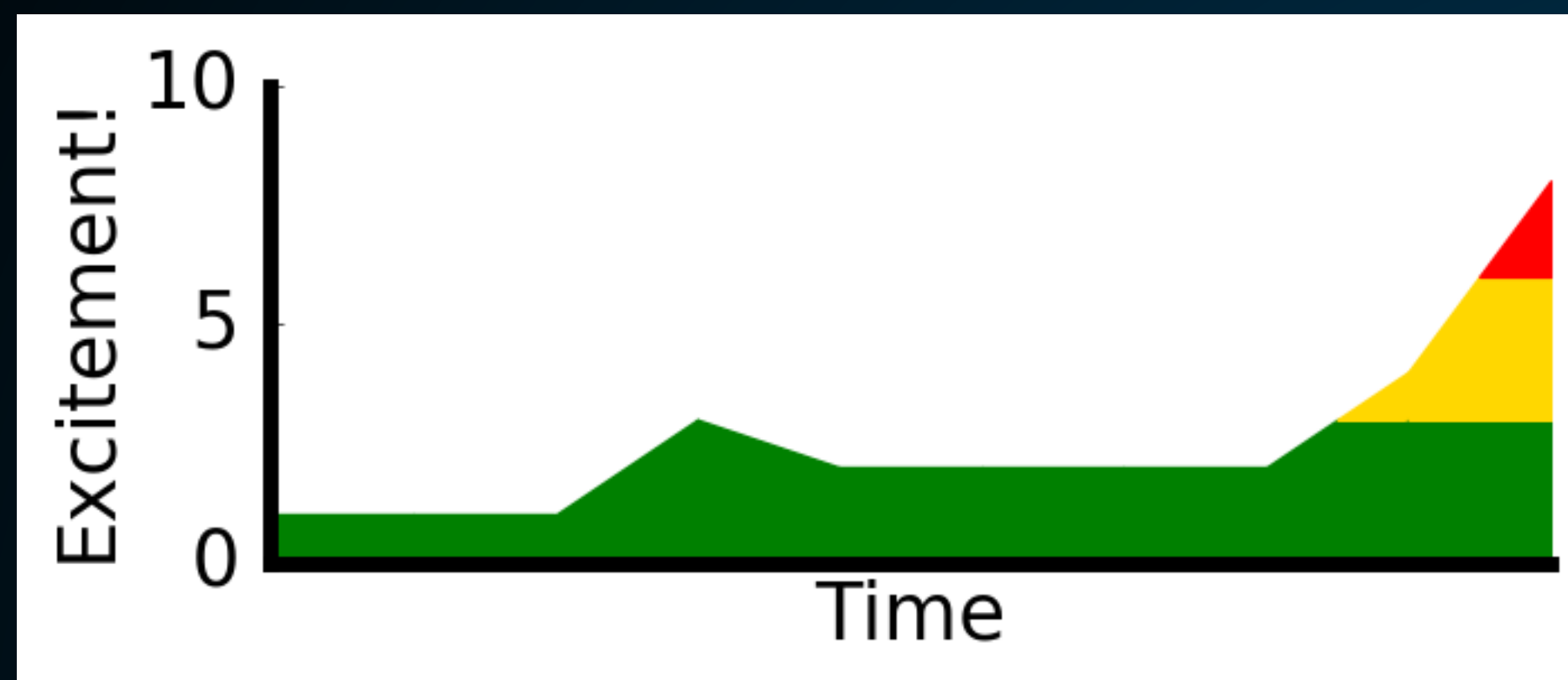
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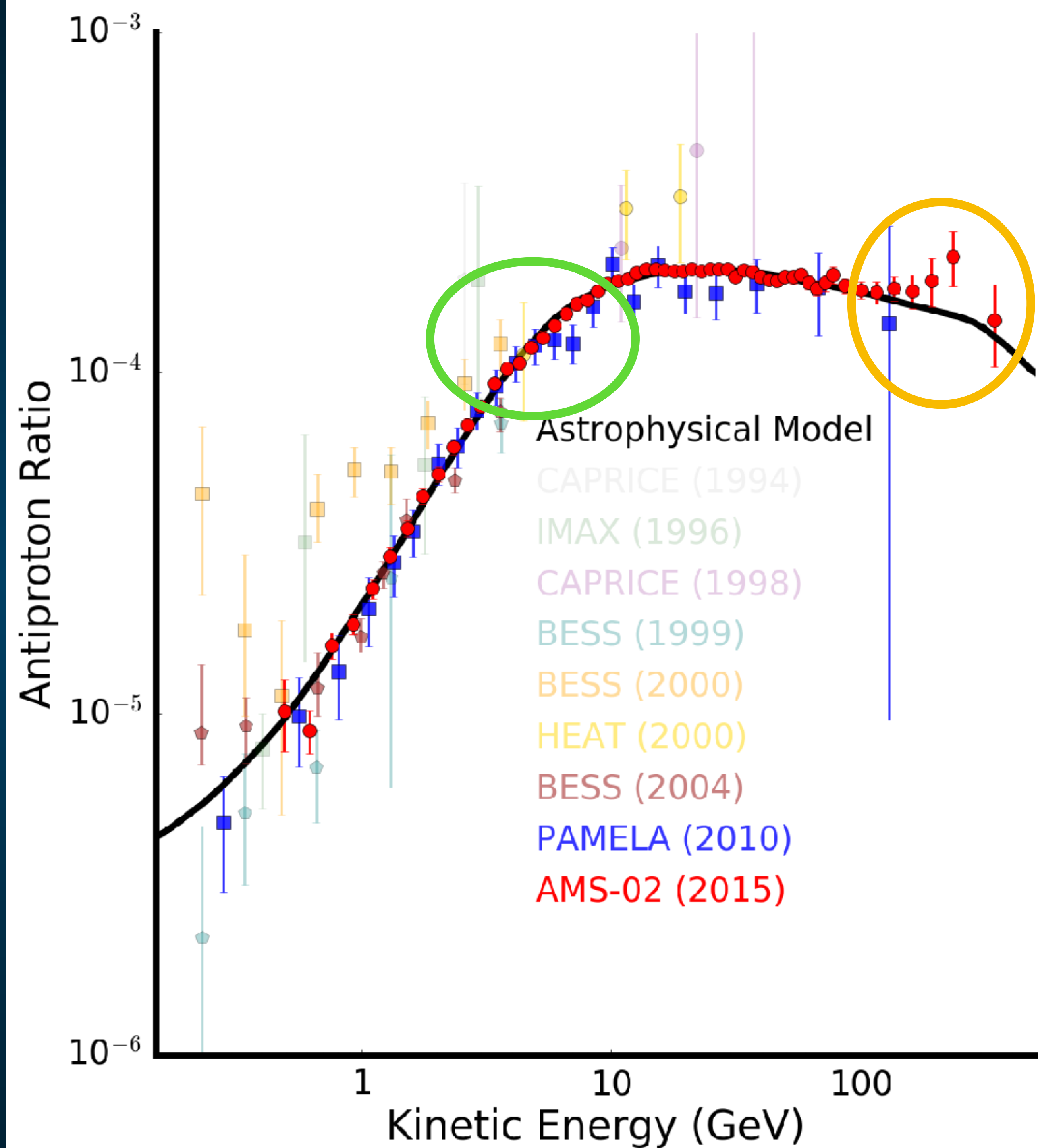
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The Antiproton Excess



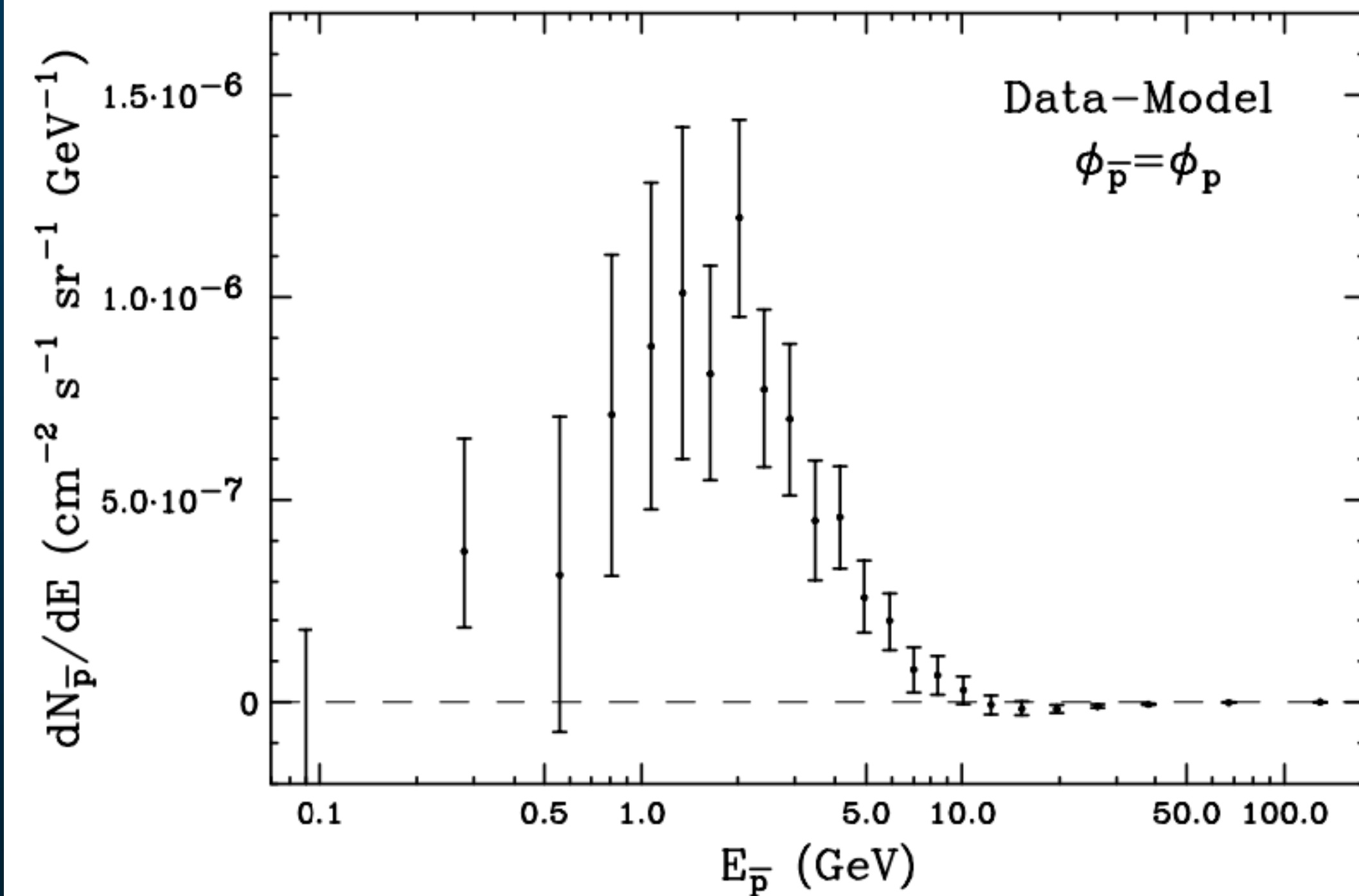
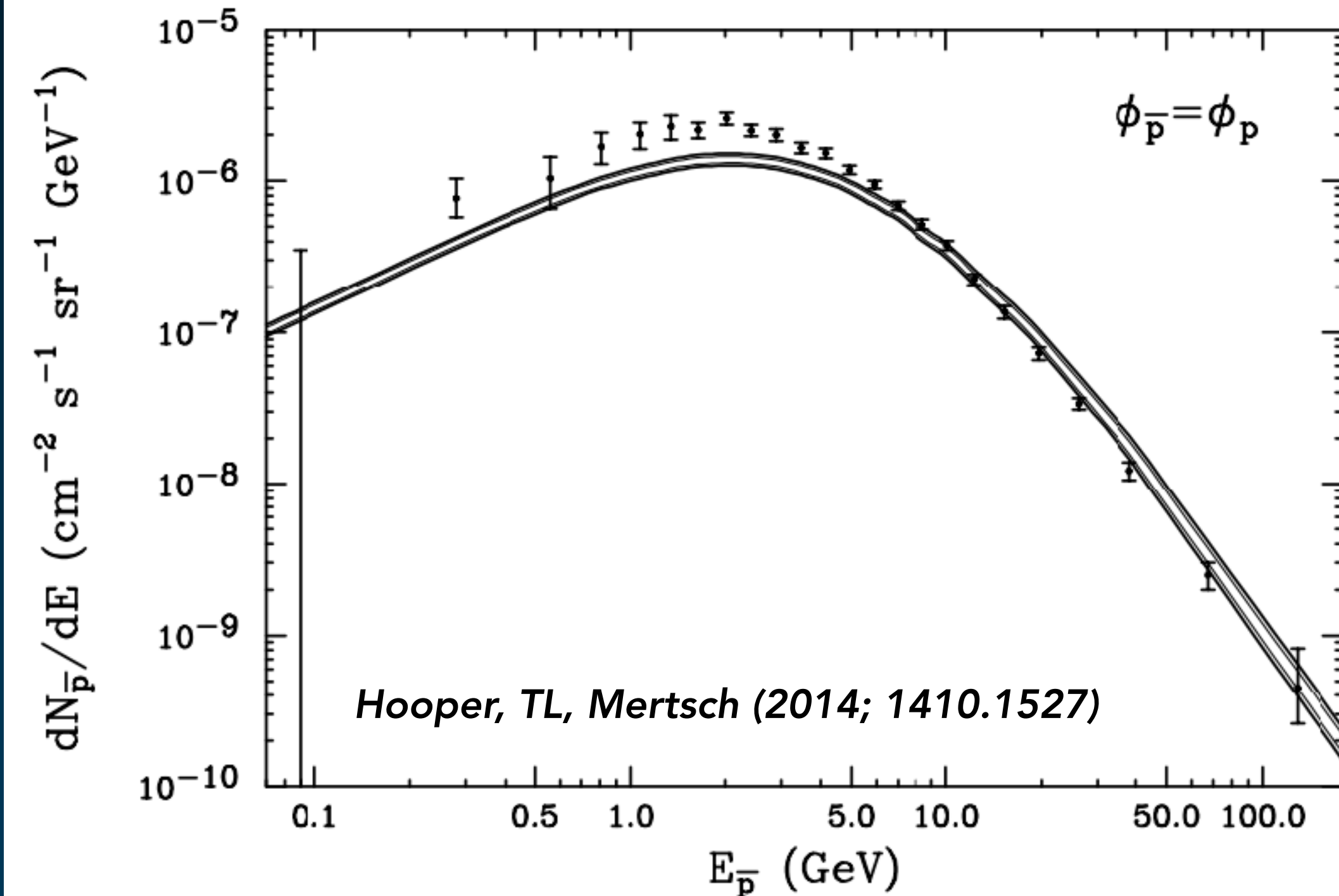
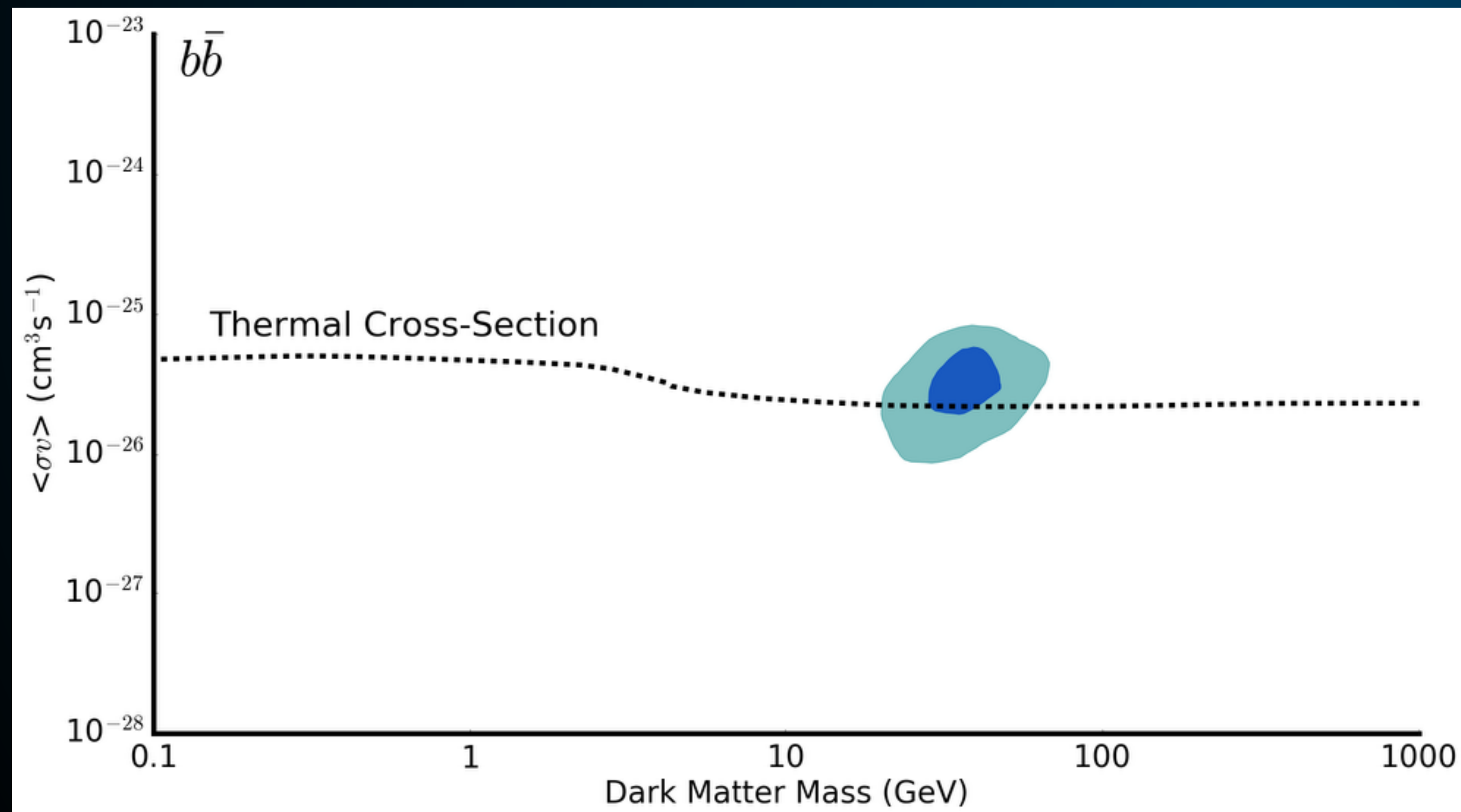
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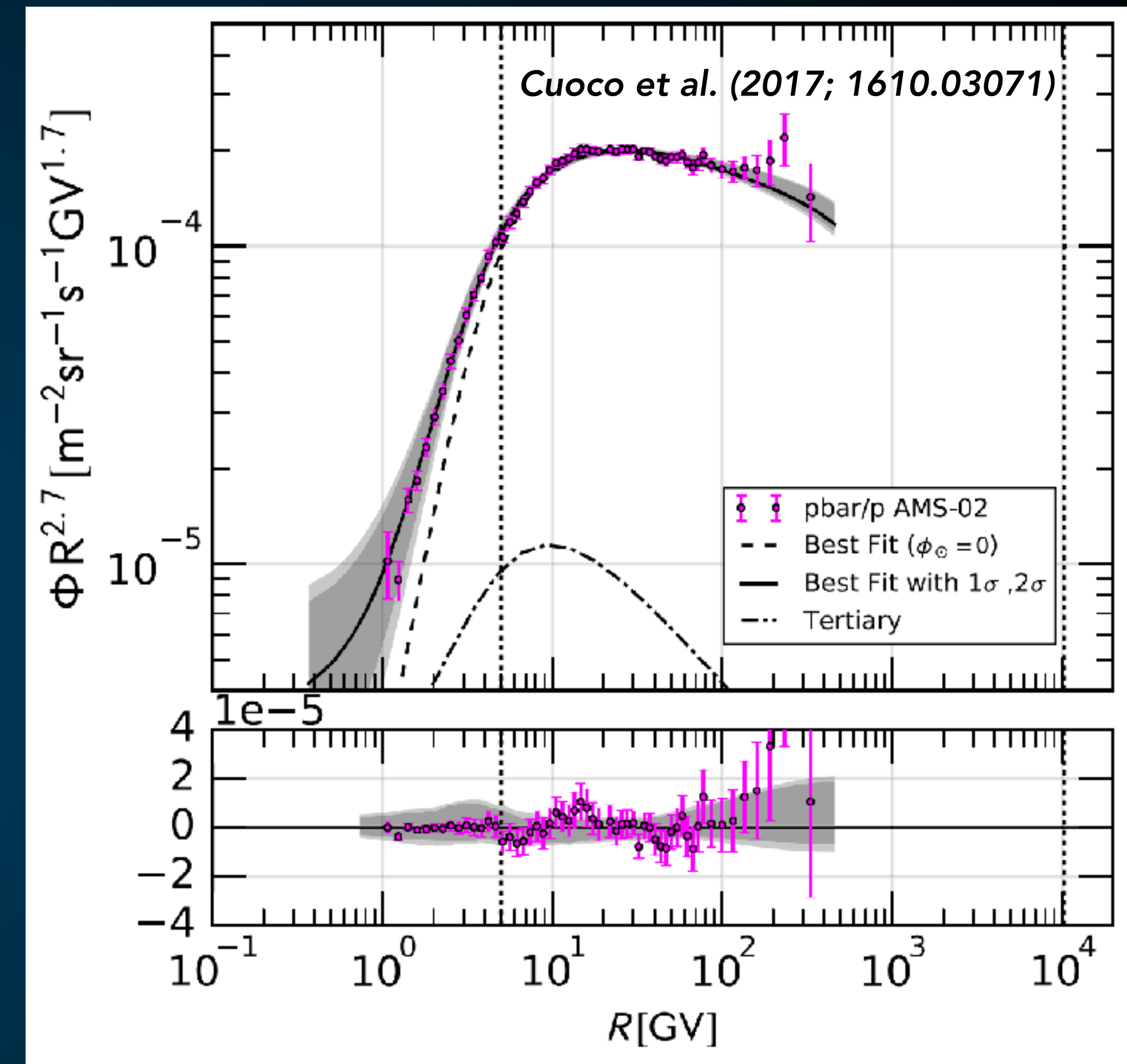
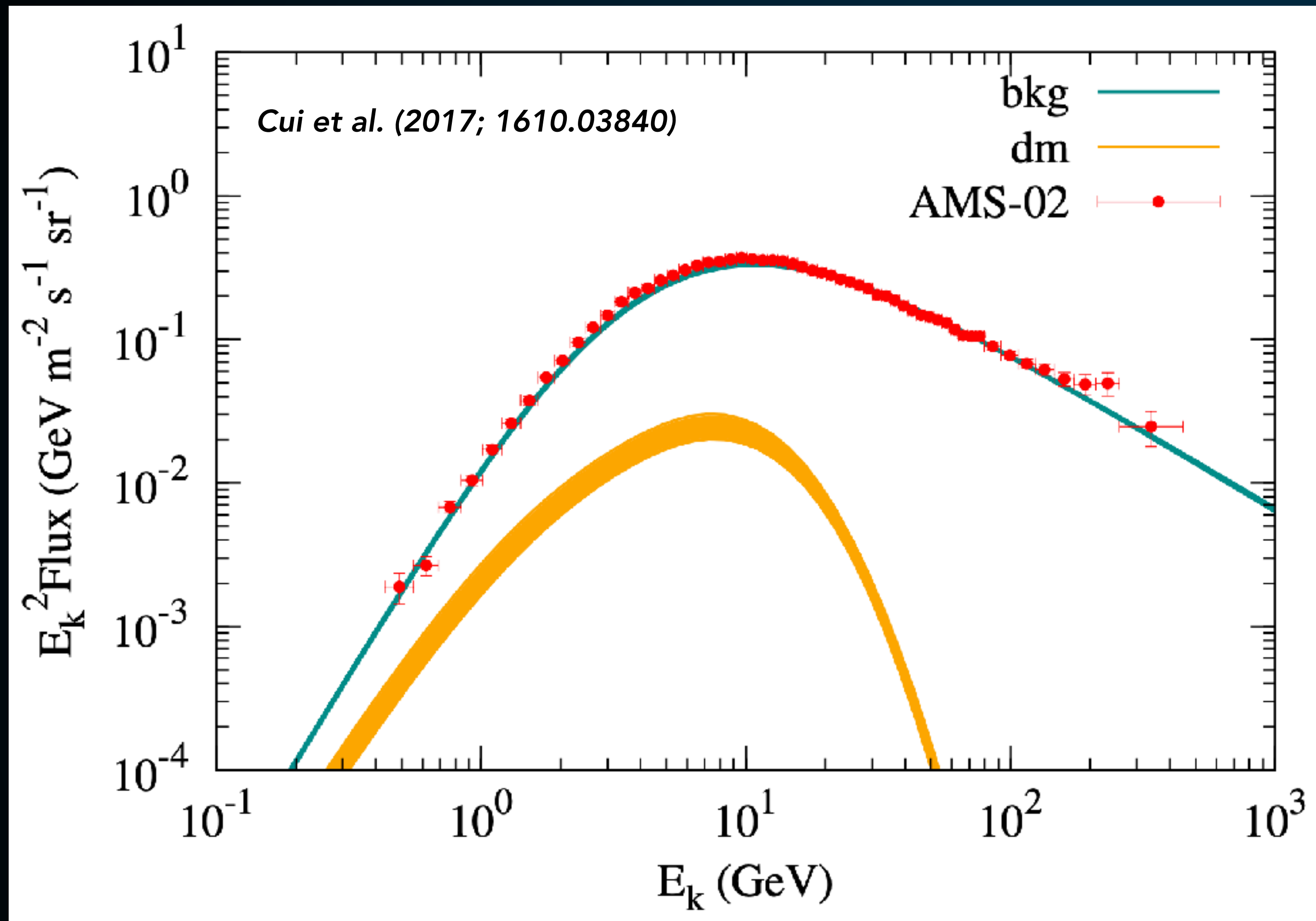
The Antiproton Excess

Hint of Excess in ~5 GeV antiprotons!

Astrophysical Uncertainties can significantly affect the signal.

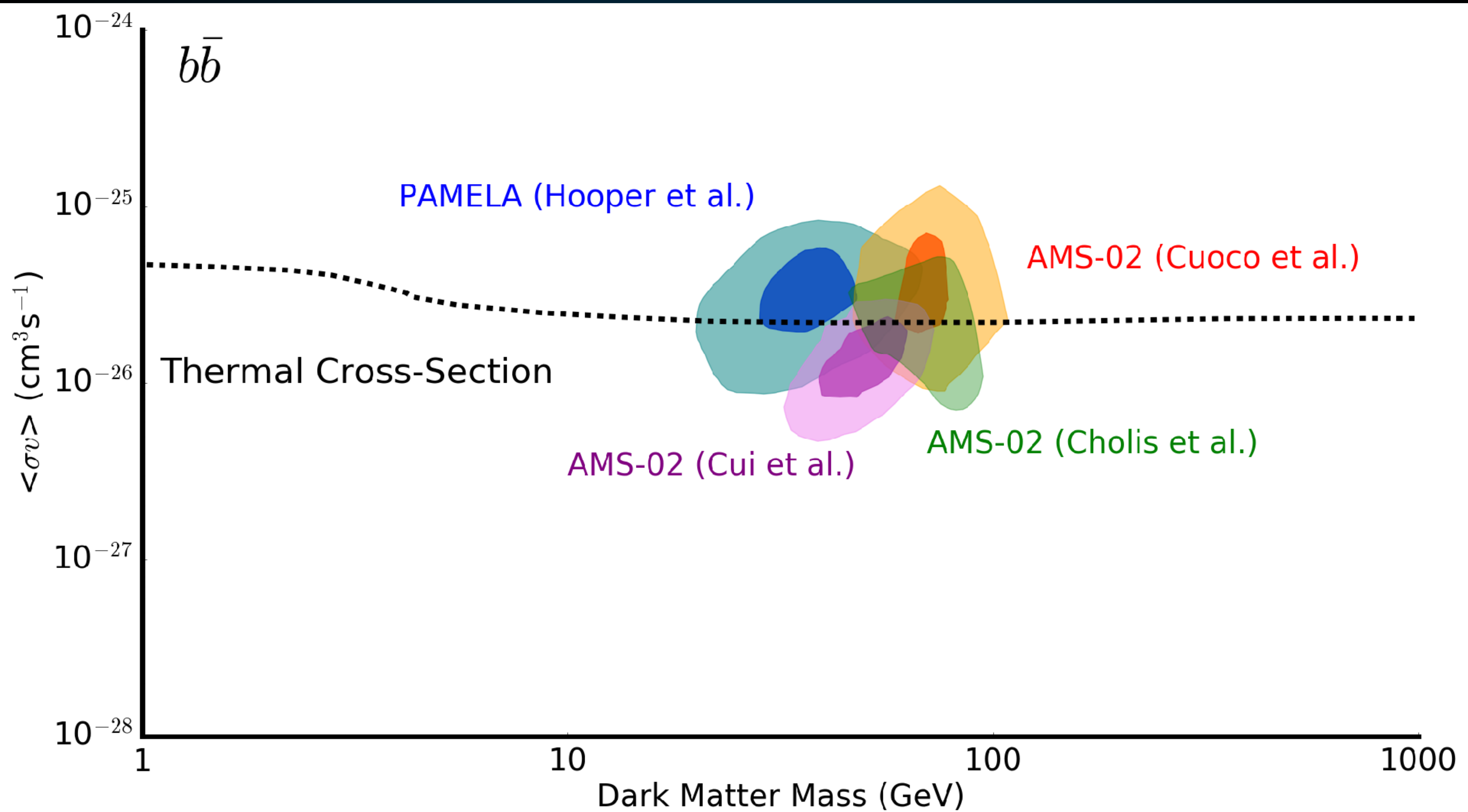


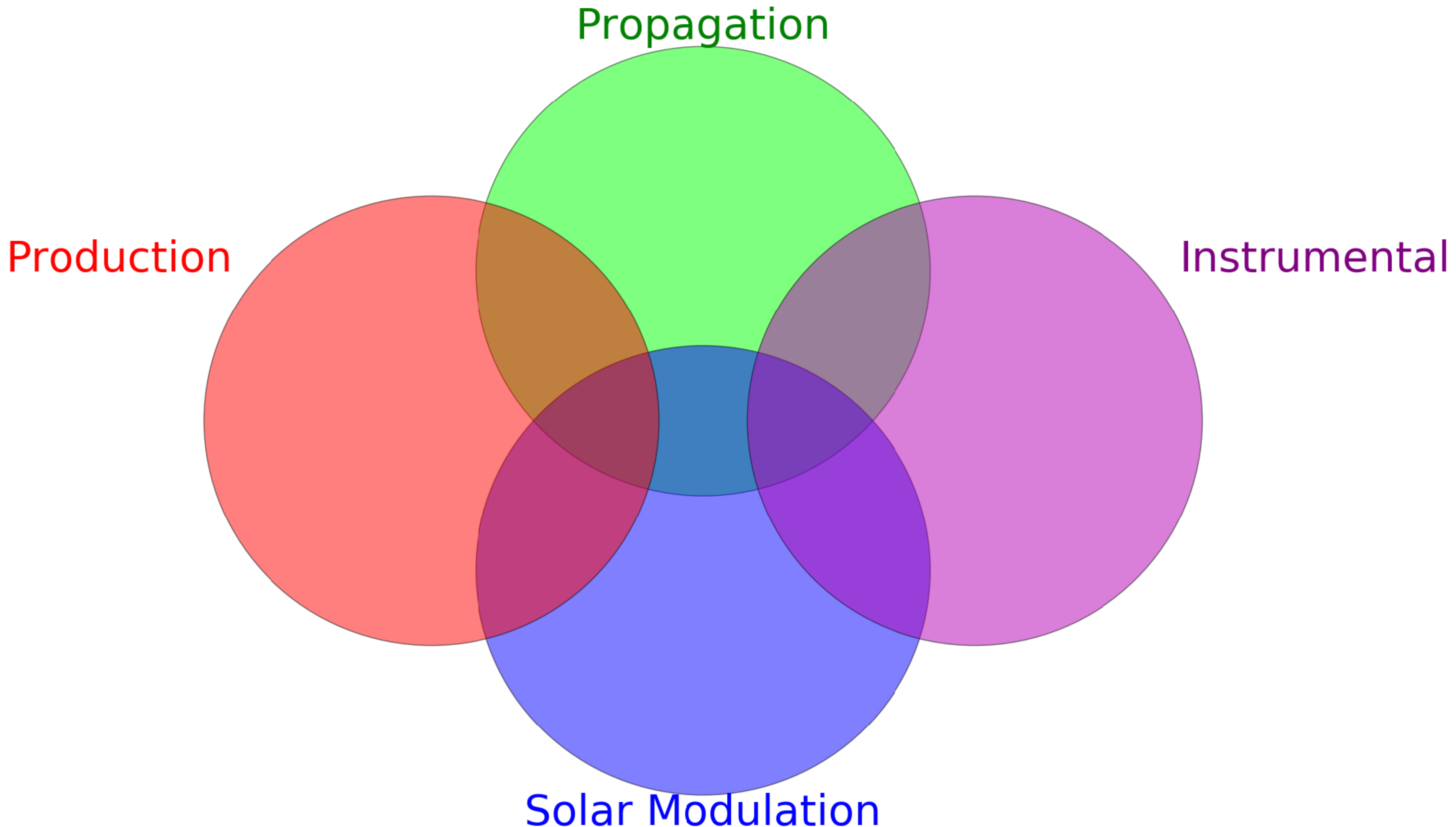
The Antiproton Excess



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

Significance approaching (or past) 5σ !





The Antiproton Excess

With great precision comes great responsibility:

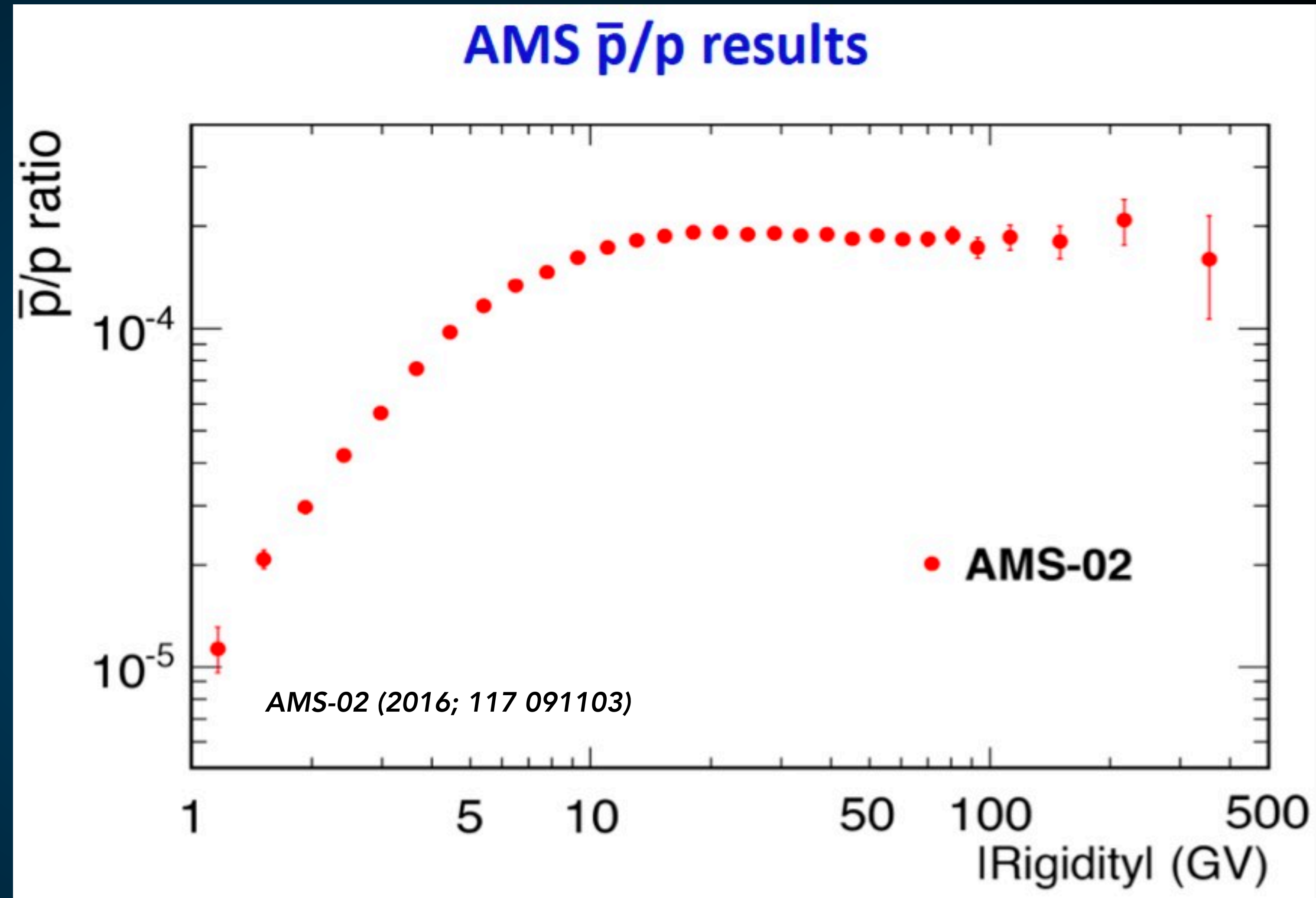
Antiproton Production Cross-Section

Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

Solar Modulation

Instrumental Uncertainties



The Antiproton Excess

Winkler (2017; 1701.04866)

Reinert, Winkler (2018; 1712.00002)

With great precision comes great responsibility:

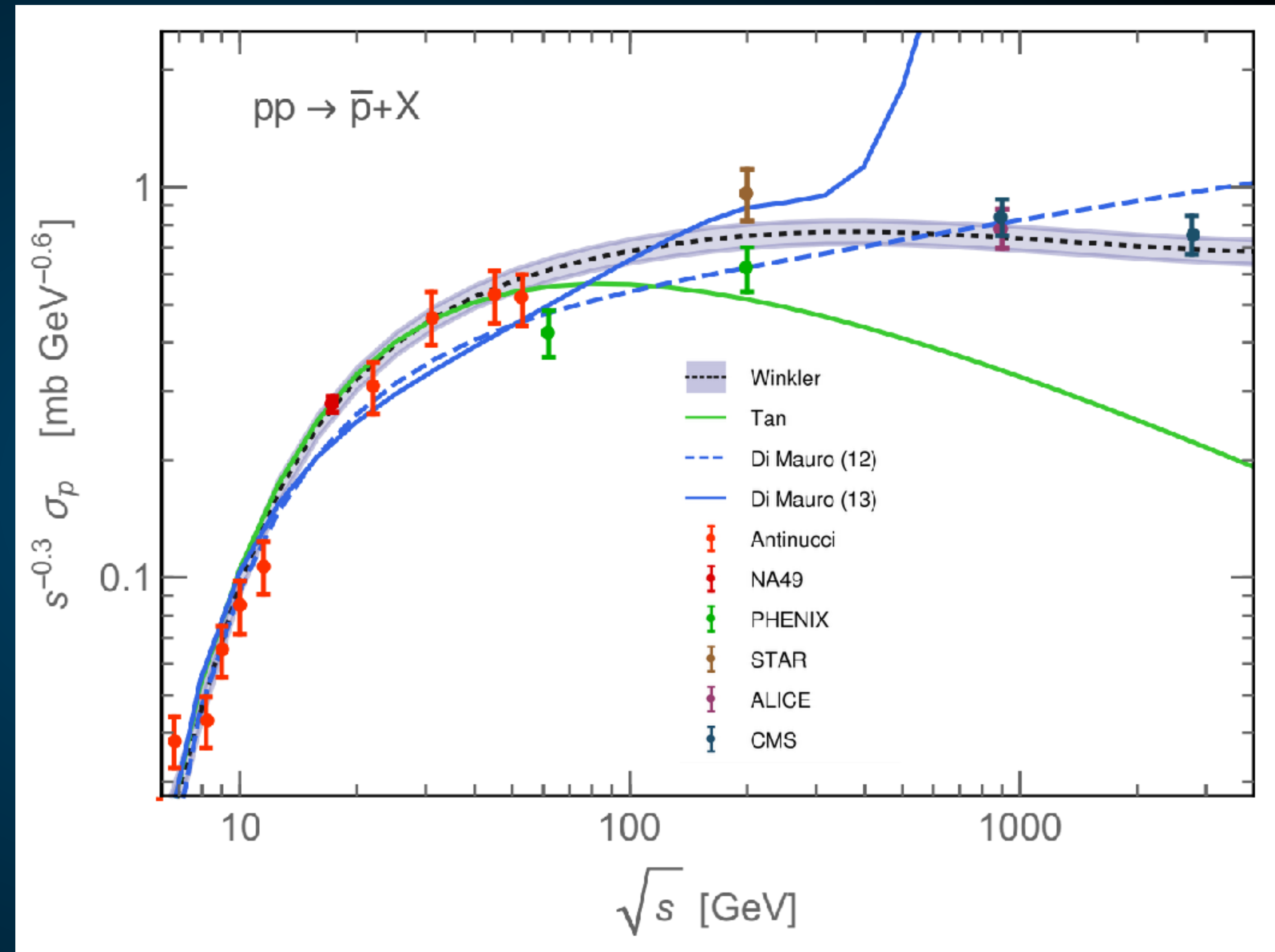
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Antiproton Production Cross-Section

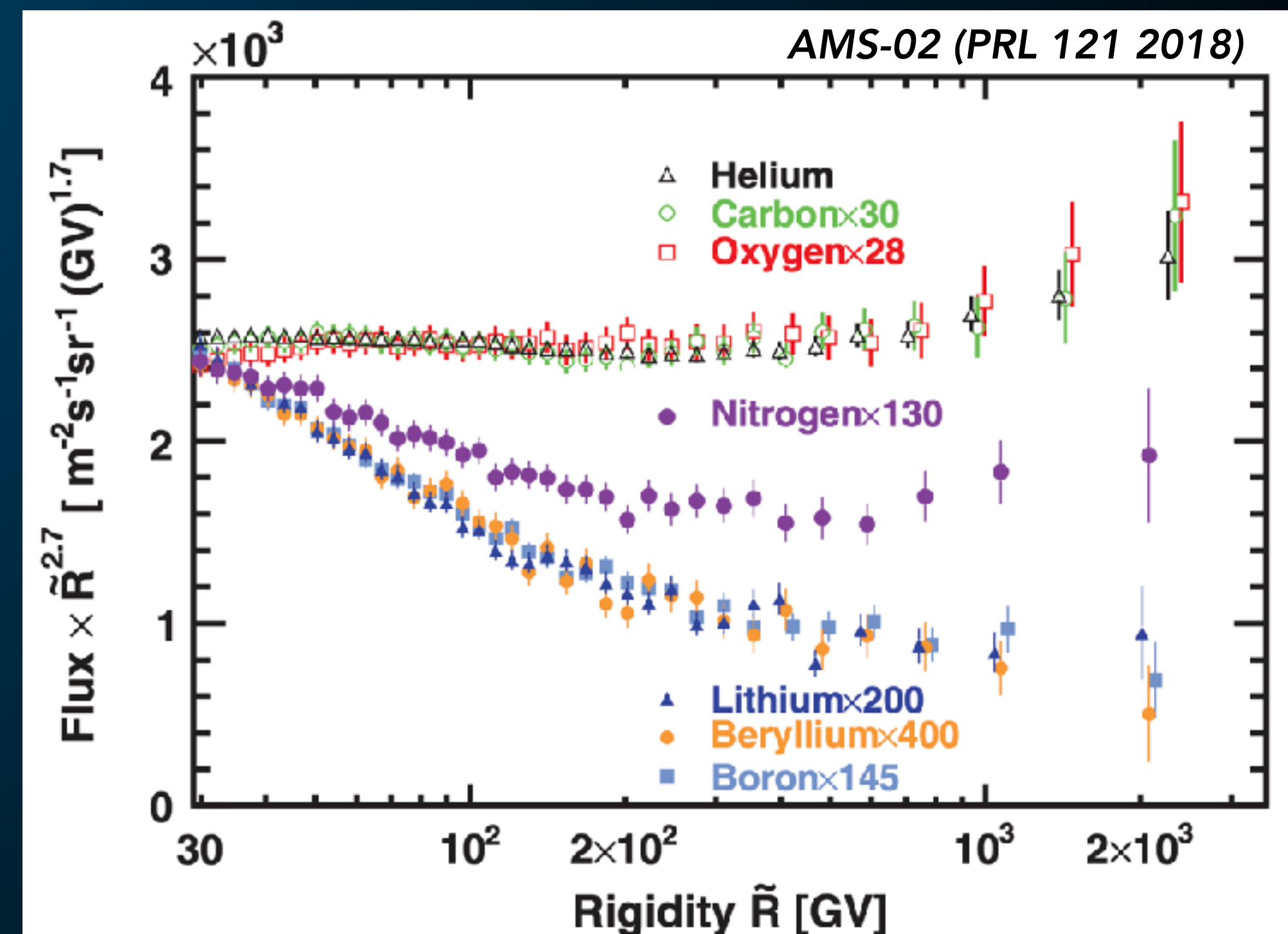
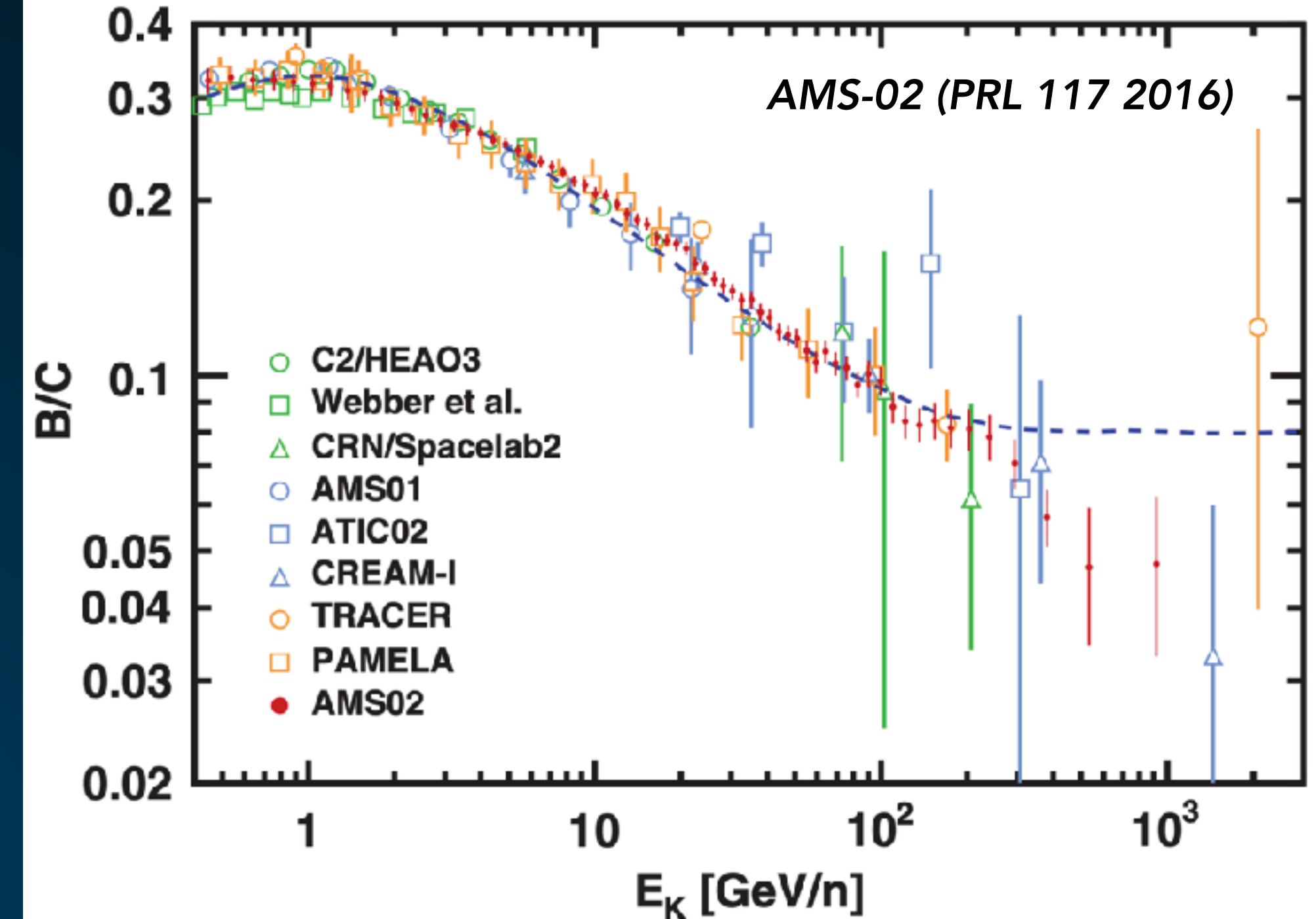
Galactic Primary to Secondary Ratios

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



The Antiproton Excess

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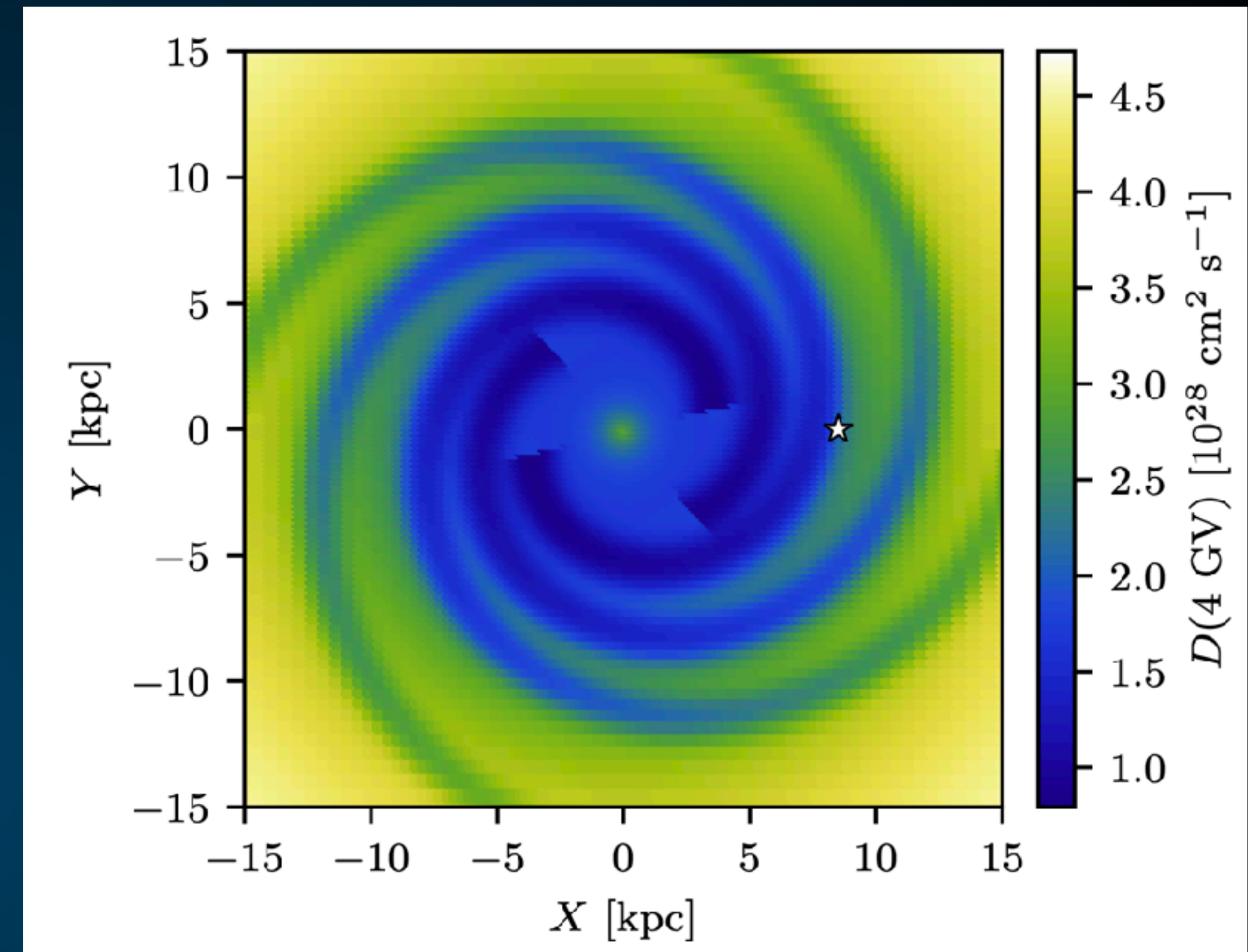
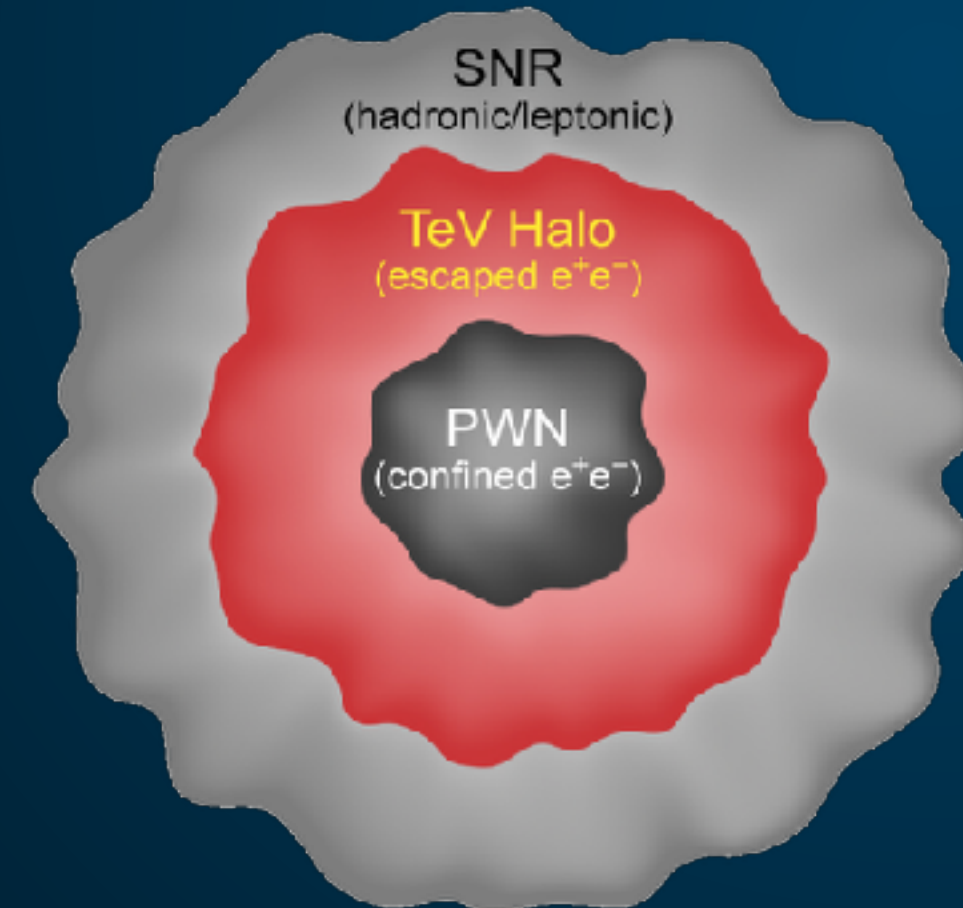
Antiproton Production Cross-Section

Galactic Primary to Secondary Ratios

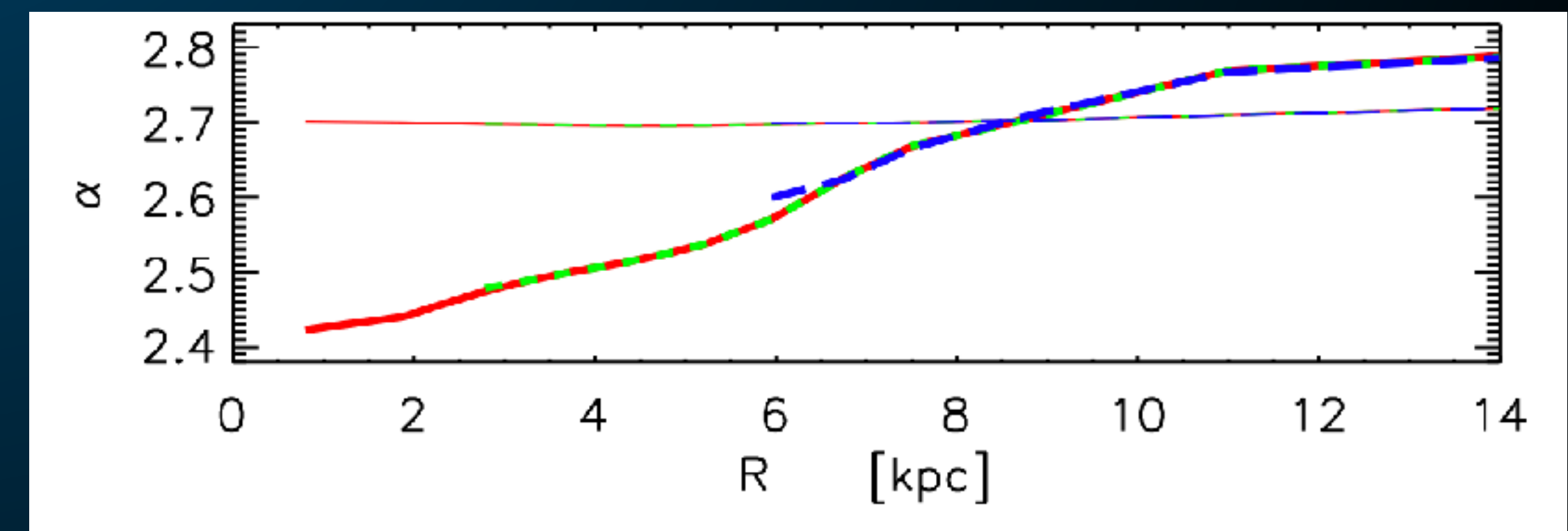
Inhomogeneous Diffusion

Solar Modulation

Instrumental Uncertainties



Evoli et al. (2014; 1411.7623)



The Antiproton Excess

AMS-02 (PRL 121 2018)

With great precision comes great responsibility:

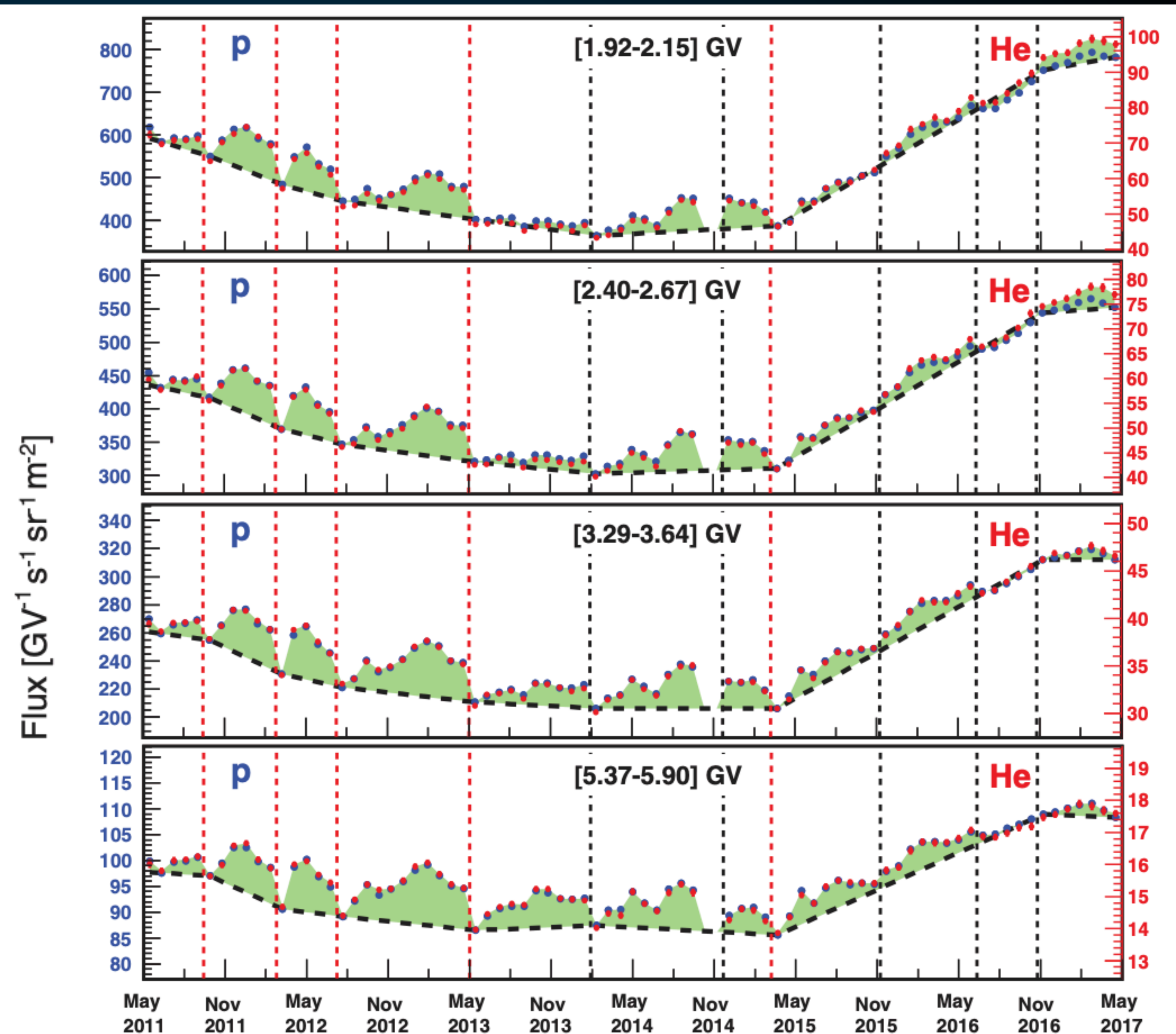
Antiproton Production Cross-Section

Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

Solar Modulation

Instrumental Uncertainties



The Antiproton Excess

With great precision comes great responsibility:

Antiproton Production Cross-Section

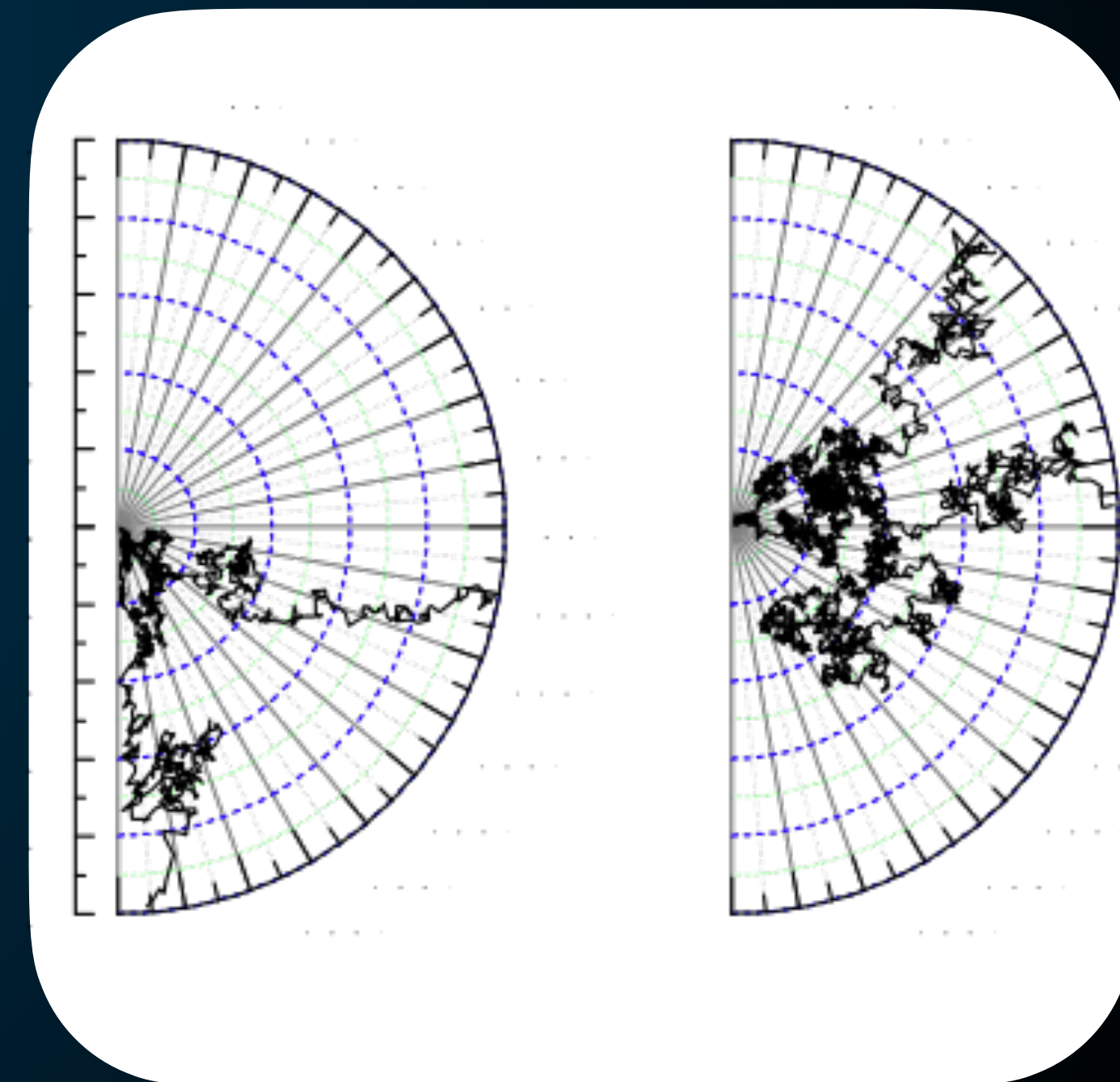
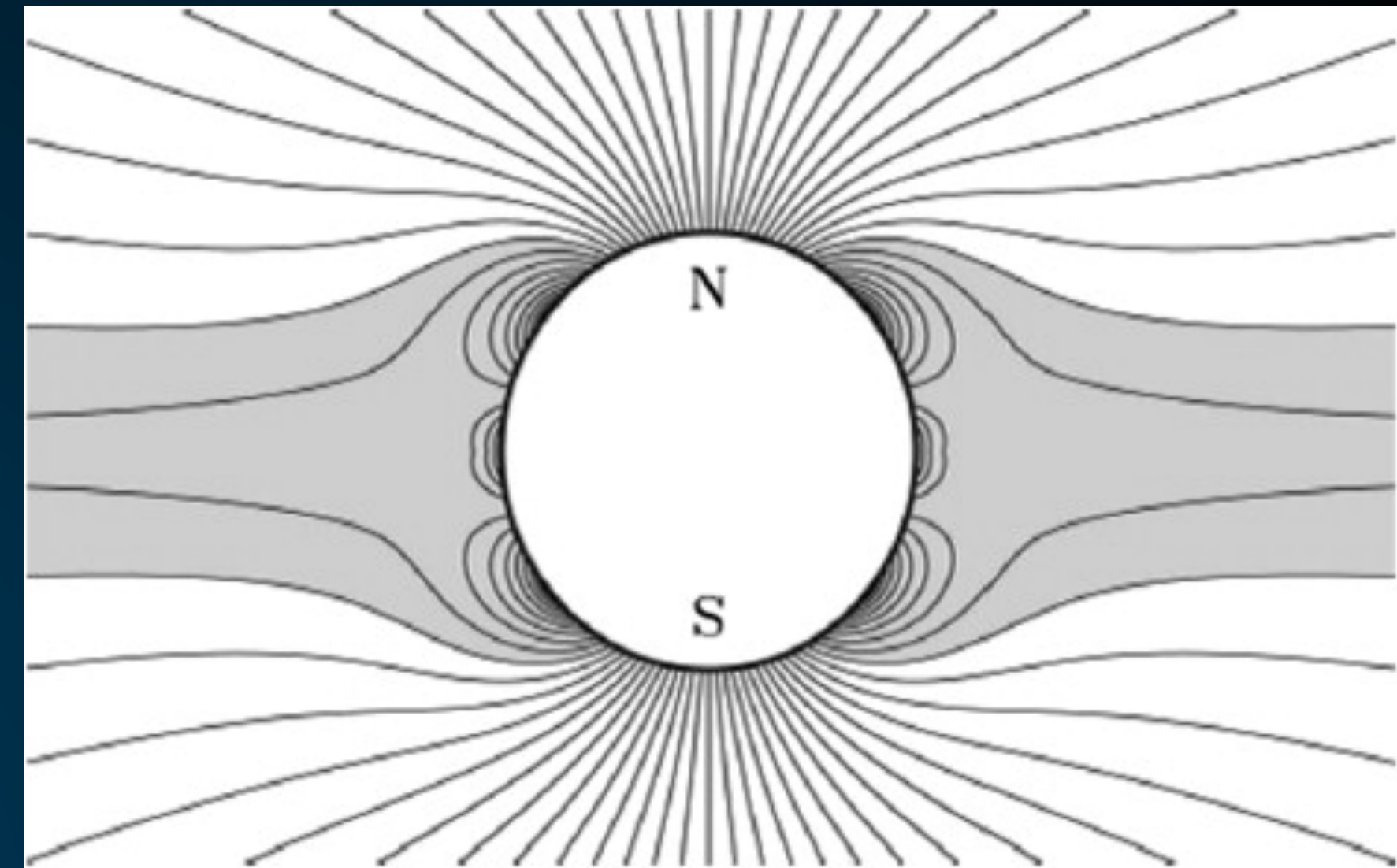
Galactic Primary to Secondary Ratios

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Fisk Potential



HELMOD Collaboration (2011, 1110.4315)

The Antiproton Excess

With great precision comes great responsibility:

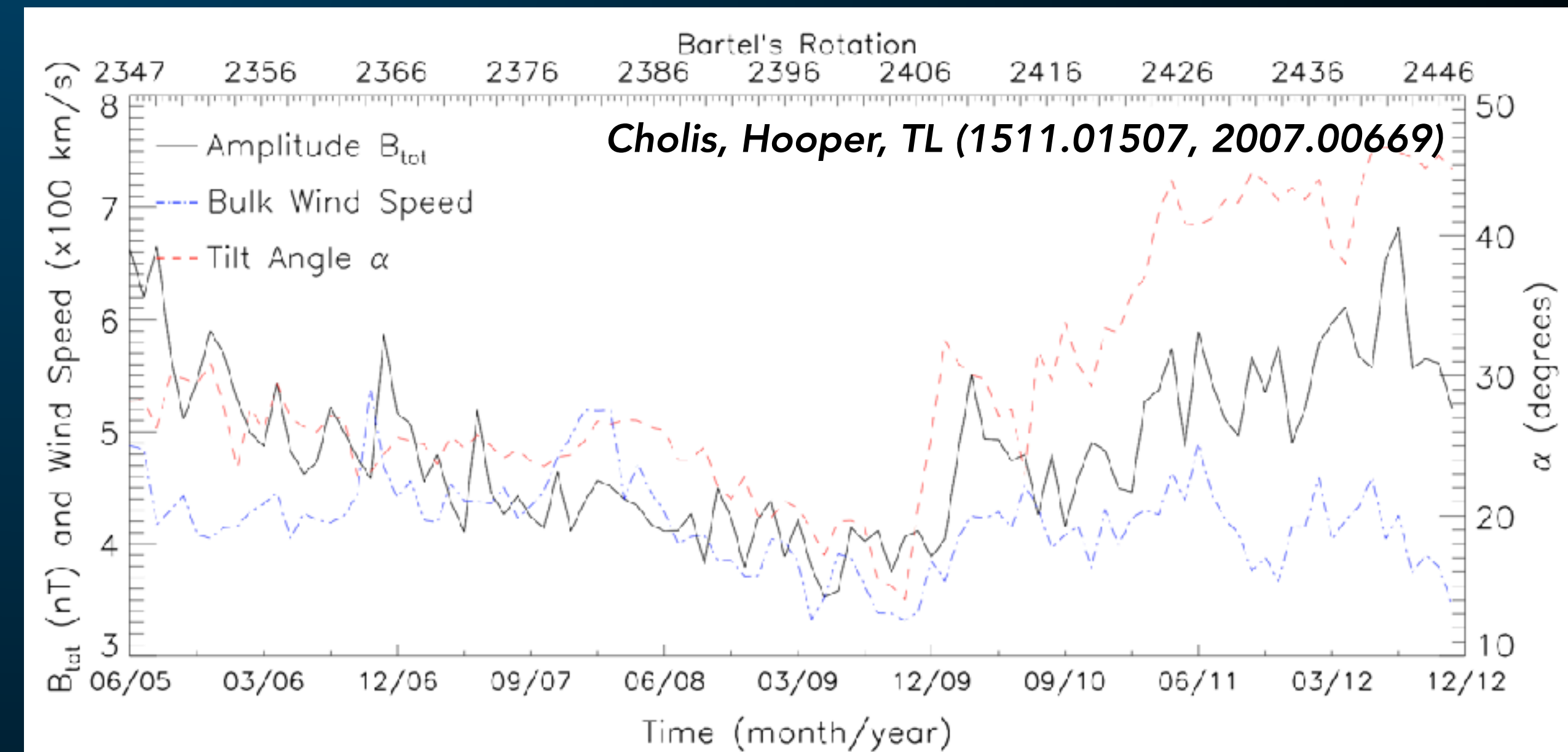
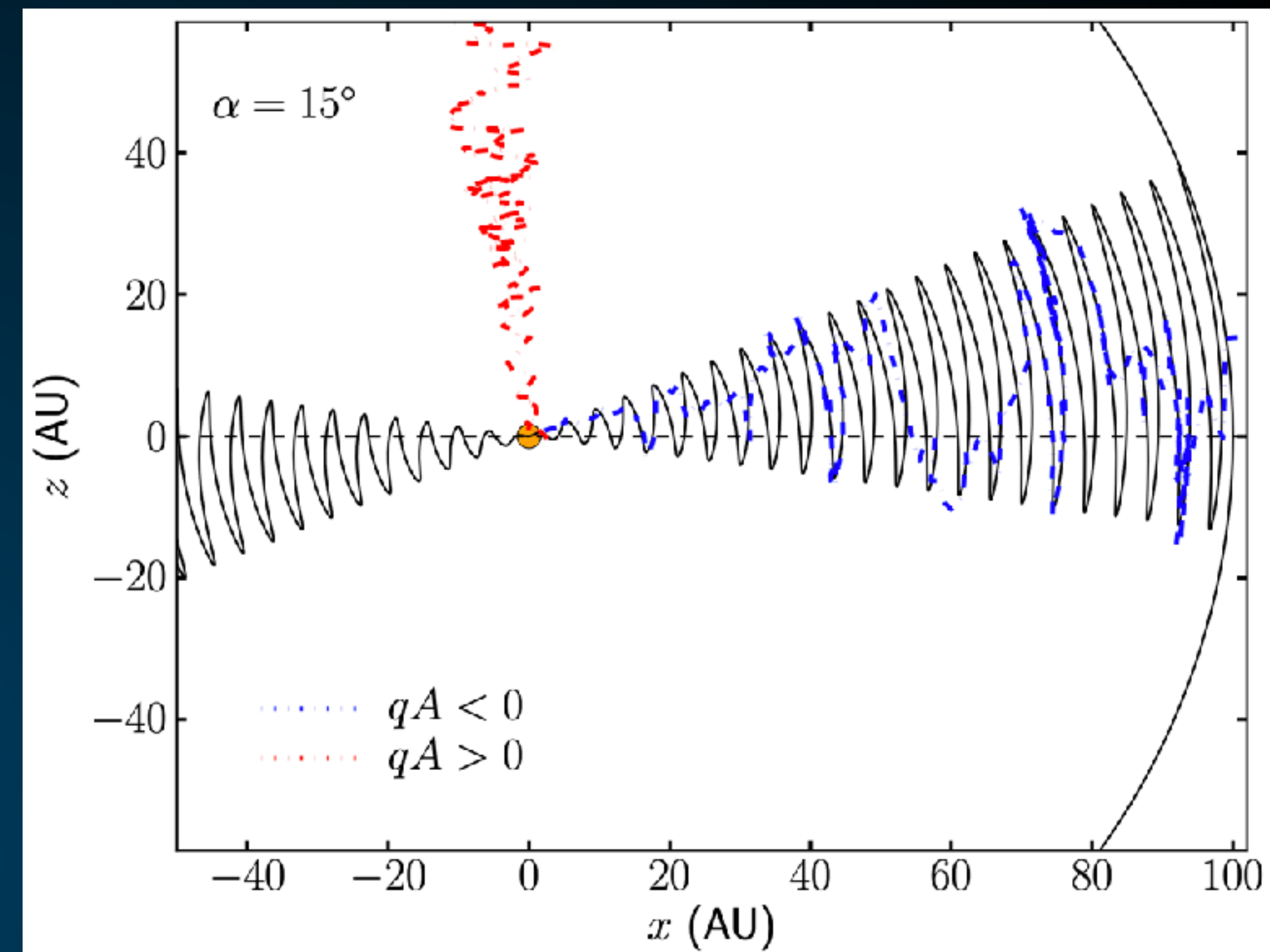
Antiproton Production Cross-Section

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The Antiproton Excess

Cholis, Hooper, TL (2007.00669)

With great precision comes great responsibility:

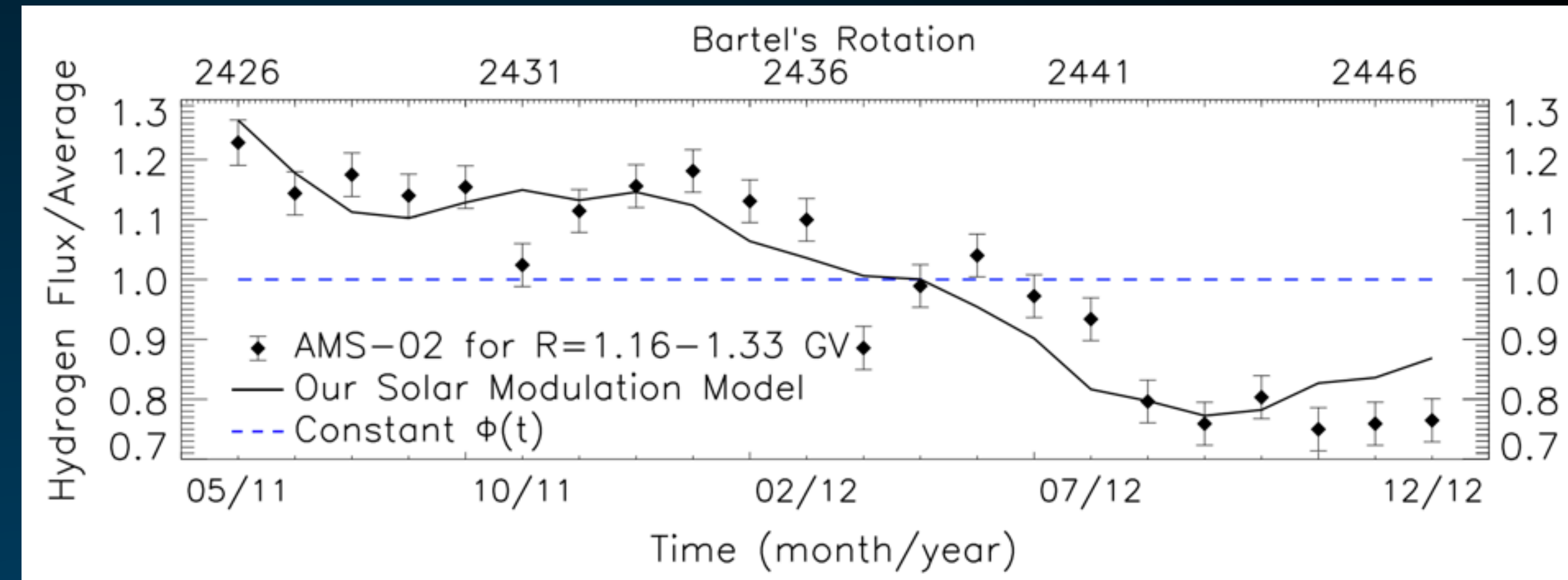
Antiproton Production Cross-Section

Galactic Primary to Secondary Ratios

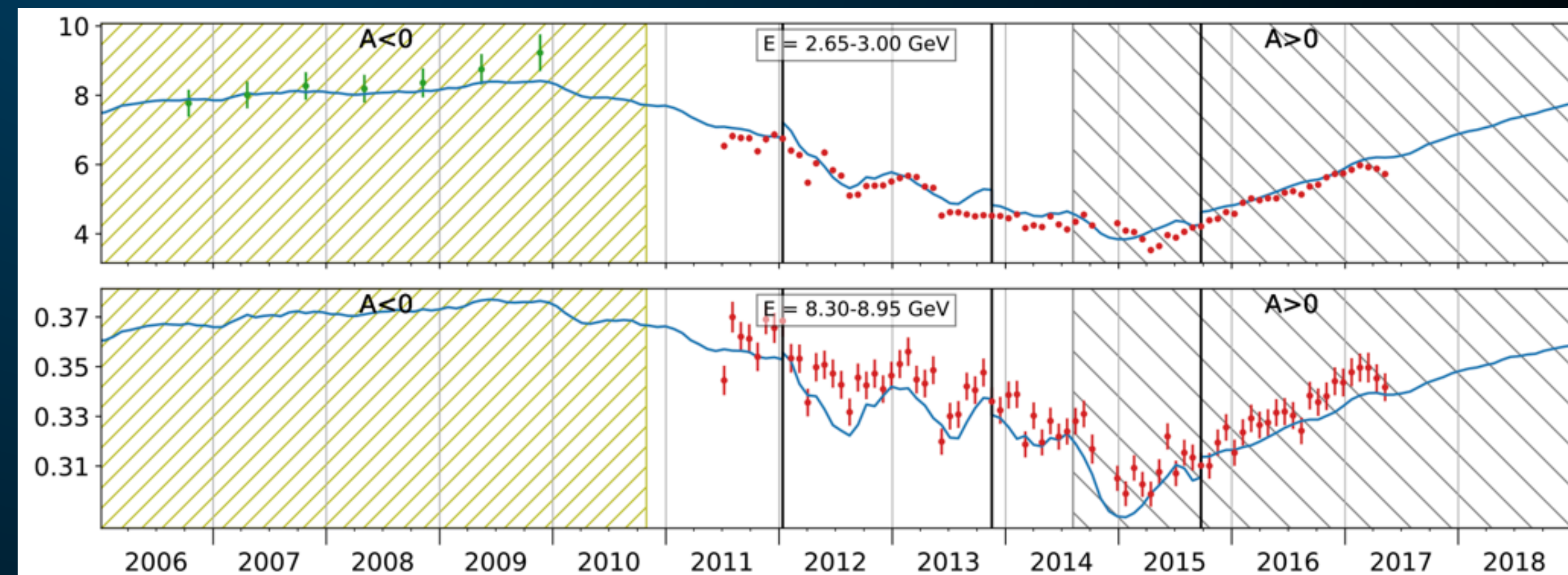
Inhomogeneous Diffusion

Solar Modulation

Instrumental Uncertainties



Kuhlen, Mertsch (1909.01154)



The Antiproton Excess

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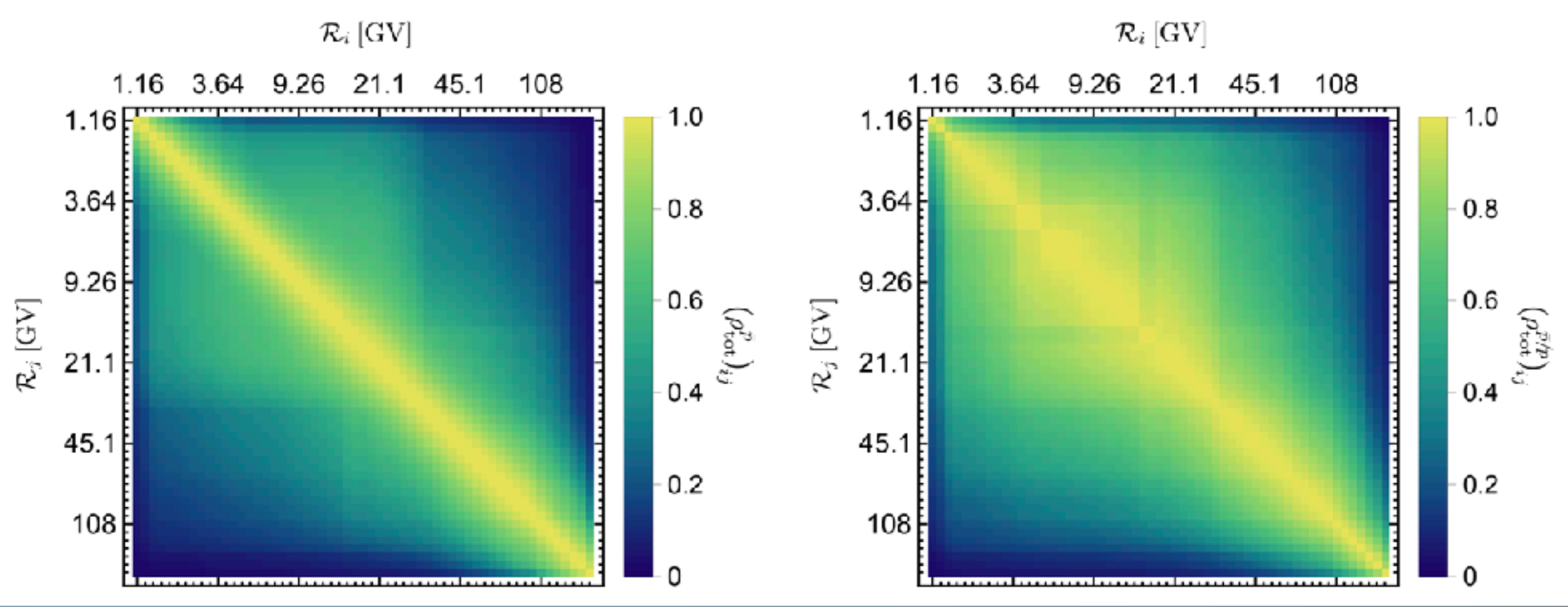
Instrumental Uncertainties

Rigidity [GV]	$\tilde{N}^{\bar{p}}$	$\Phi^{\bar{p}}$	σ_{stat}	σ_{syst}	$\Phi^{\bar{p}}/\Phi^p$	σ_{stat}	σ_{syst}
1.00 – 1.16	21	(5.94 1.31 0.58) × 10 ⁻³	(1.02	0.23	(0.08) × 10 ⁻⁵		
1.16 – 1.33	74	(5.57 0.68 0.51) × 10 ⁻³	(8.93	1.09	(0.66) × 10 ⁻⁶		
1.33 – 1.51	233	(9.75 0.68 0.68) × 10 ⁻³	(1.59	0.11	(0.09) × 10 ⁻⁵		
1.51 – 1.71	502	(1.06 0.05 0.07) × 10 ⁻²	(1.83	0.09	(0.09) × 10 ⁻⁵		
1.71 – 1.92	888	(1.25 0.05 0.08) × 10 ⁻²	(2.33	0.10	(0.12) × 10 ⁻⁵		
1.92 – 2.15	1449	(1.40 0.05 0.08) × 10 ⁻²	(2.90	0.10	(0.14) × 10 ⁻⁵		
2.15 – 2.40	2192	(1.50 0.05 0.09) × 10 ⁻²	(3.50	0.11	(0.17) × 10 ⁻⁵		
2.40 – 2.67	3366	(1.64 0.04 0.09) × 10 ⁻²	(4.36	0.11	(0.20) × 10 ⁻⁵		
2.67 – 2.97	4474	(1.64 0.04 0.09) × 10 ⁻²	(5.05	0.12	(0.23) × 10 ⁻⁵		
2.97 – 3.29	6028	(1.69 0.04 0.09) × 10 ⁻²	(6.07	0.13	(0.27) × 10 ⁻⁵		
3.29 – 3.64	7321	(1.67 0.03 0.09) × 10 ⁻²	(7.05	0.14	(0.30) × 10 ⁻⁵		
3.64 – 4.02	8592	(1.59 0.03 0.08) × 10 ⁻²	(7.96	0.15	(0.32) × 10 ⁻⁵		
4.02 – 4.43	1932	(1.56 0.04 0.08) × 10 ⁻²	(9.31	0.21	(0.37) × 10 ⁻⁵		
4.43 – 4.88	3083	(1.43 0.03 0.07) × 10 ⁻²	(1.03	0.02	(0.04) × 10 ⁻⁴		
4.88 – 5.37	3880	(1.23 0.02 0.06) × 10 ⁻²	(1.07	0.02	(0.04) × 10 ⁻⁴		
5.37 – 5.90	4780	(1.12 0.02 0.05) × 10 ⁻²	(1.19	0.02	(0.05) × 10 ⁻⁴		
5.90 – 6.47	5472	(9.80 0.13 0.45) × 10 ⁻³	(1.27	0.02	(0.05) × 10 ⁻⁴		
6.47 – 7.09	6538	(8.69 0.11 0.39) × 10 ⁻³	(1.38	0.02	(0.05) × 10 ⁻⁴		
7.09 – 7.76	7369	(7.59 0.09 0.34) × 10 ⁻³	(1.49	0.02	(0.05) × 10 ⁻⁴		
7.76 – 8.48	7818	(6.54 0.08 0.29) × 10 ⁻³	(1.59	0.02	(0.06) × 10 ⁻⁴		
8.48 – 9.26	7821	(5.46 0.06 0.24) × 10 ⁻³	(1.64	0.02	(0.06) × 10 ⁻⁴		
9.26 – 10.1	20382	(4.67 0.03 0.20) × 10 ⁻³	(1.74	0.01	(0.06) × 10 ⁻⁴		
10.1 – 11.0	19445	(3.96 0.03 0.17) × 10 ⁻³	(1.83	0.01	(0.07) × 10 ⁻⁴		
11.0 – 12.0	18769	(3.23 0.02 0.14) × 10 ⁻³	(1.86	0.01	(0.07) × 10 ⁻⁴		
12.0 – 13.0	16372	(2.65 0.02 0.11) × 10 ⁻³	(1.89	0.02	(0.07) × 10 ⁻⁴		
13.0 – 14.1	16076	(2.23 0.02 0.09) × 10 ⁻³	(1.96	0.02	(0.07) × 10 ⁻⁴		
14.1 – 15.3	15578	(1.85 0.02 0.08) × 10 ⁻³	(2.02	0.02	(0.07) × 10 ⁻⁴		
15.3 – 16.6	14734	(1.49 0.01 0.06) × 10 ⁻³	(2.02	0.02	(0.07) × 10 ⁻⁴		
16.6 – 18.0	15816	(1.19 0.01 0.05) × 10 ⁻³	(2.00	0.02	(0.07) × 10 ⁻⁴		
18.0 – 19.5	15049	(9.53 0.08 0.37) × 10 ⁻⁴	(1.99	0.02	(0.06) × 10 ⁻⁴		
19.5 – 21.1	14426	(7.72 0.07 0.29) × 10 ⁻⁴	(1.99	0.02	(0.06) × 10 ⁻⁴		
21.1 – 22.8	13511	(6.33 0.06 0.23) × 10 ⁻⁴	(2.02	0.02	(0.06) × 10 ⁻⁴		
22.8 – 24.7	12943	(5.02 0.05 0.18) × 10 ⁻⁴	(1.99	0.02	(0.06) × 10 ⁻⁴		
24.7 – 26.7	11723	(4.11 0.04 0.14) × 10 ⁻⁴	(2.02	0.02	(0.05) × 10 ⁻⁴		
26.7 – 28.8	10411	(3.32 0.04 0.11) × 10 ⁻⁴	(2.02	0.02	(0.05) × 10 ⁻⁴		
28.8 – 31.1	9508	(2.68 0.03 0.08) × 10 ⁻⁴	(2.02	0.02	(0.05) × 10 ⁻⁴		
31.1 – 33.5	7876	(2.07 0.03 0.06) × 10 ⁻⁴	(1.92	0.02	(0.04) × 10 ⁻⁴		
33.5 – 36.1	7212	(1.75 0.02 0.05) × 10 ⁻⁴	(2.00	0.03	(0.05) × 10 ⁻⁴		

The Antiproton Excess

With great precision comes great responsibility:

Antiproton Production Cross-Section



Galactic Primary to Secondary Ratios

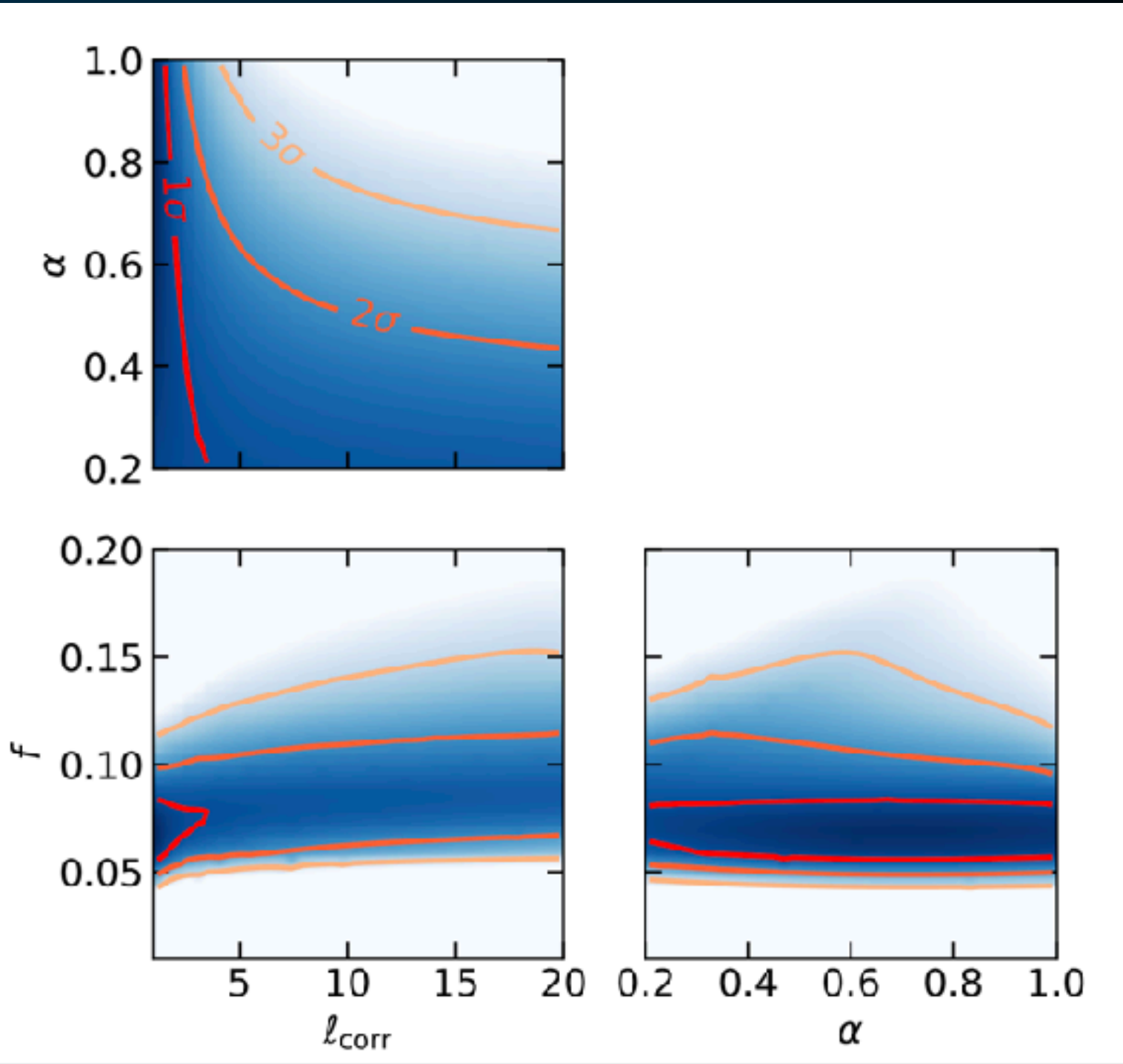
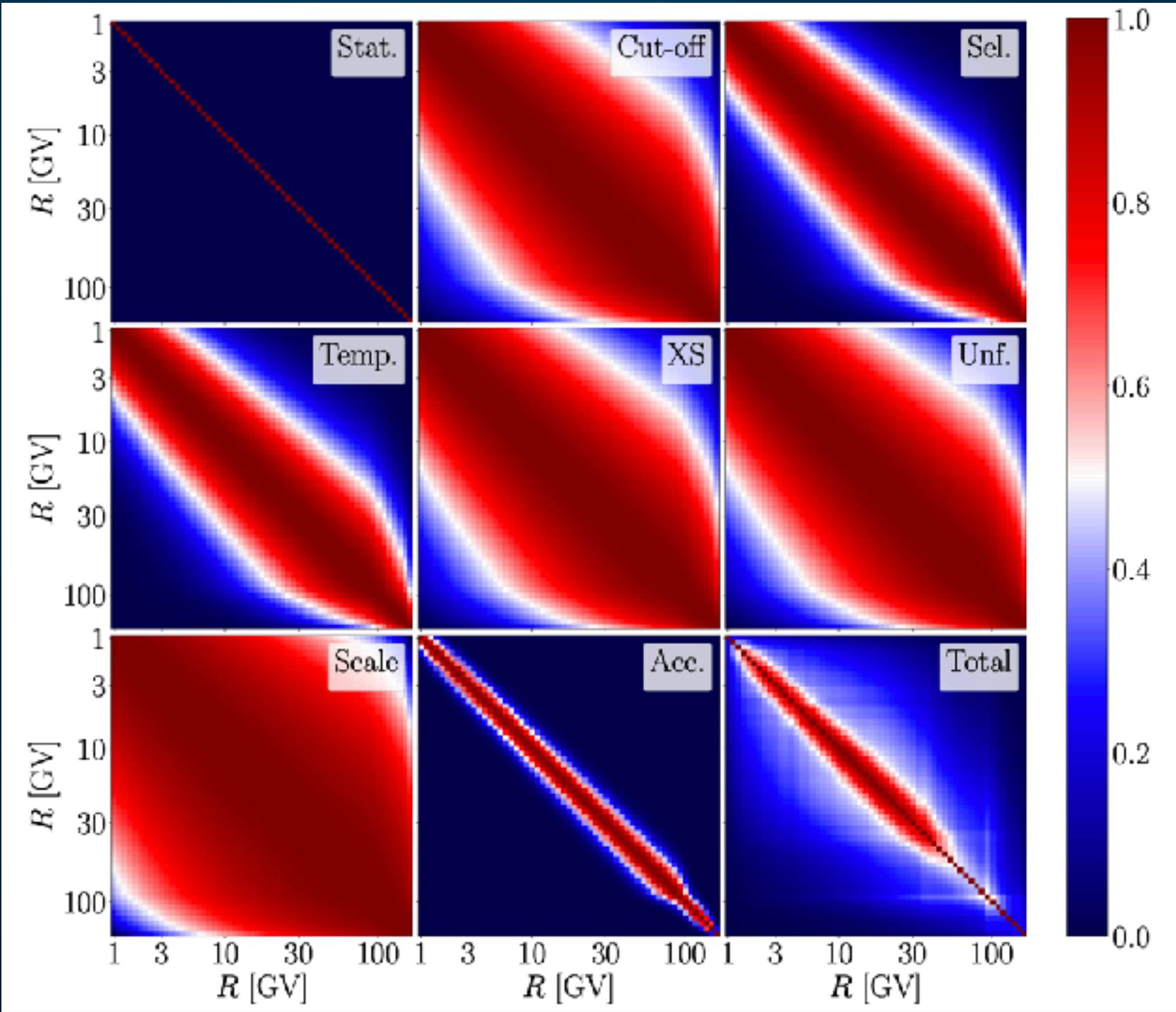
Boudaud et al. (2019; 1906.07119)

Cuoco et. al. (2019; 1903.01472)

Inhomogeneous Diffusion

Solar Modulation

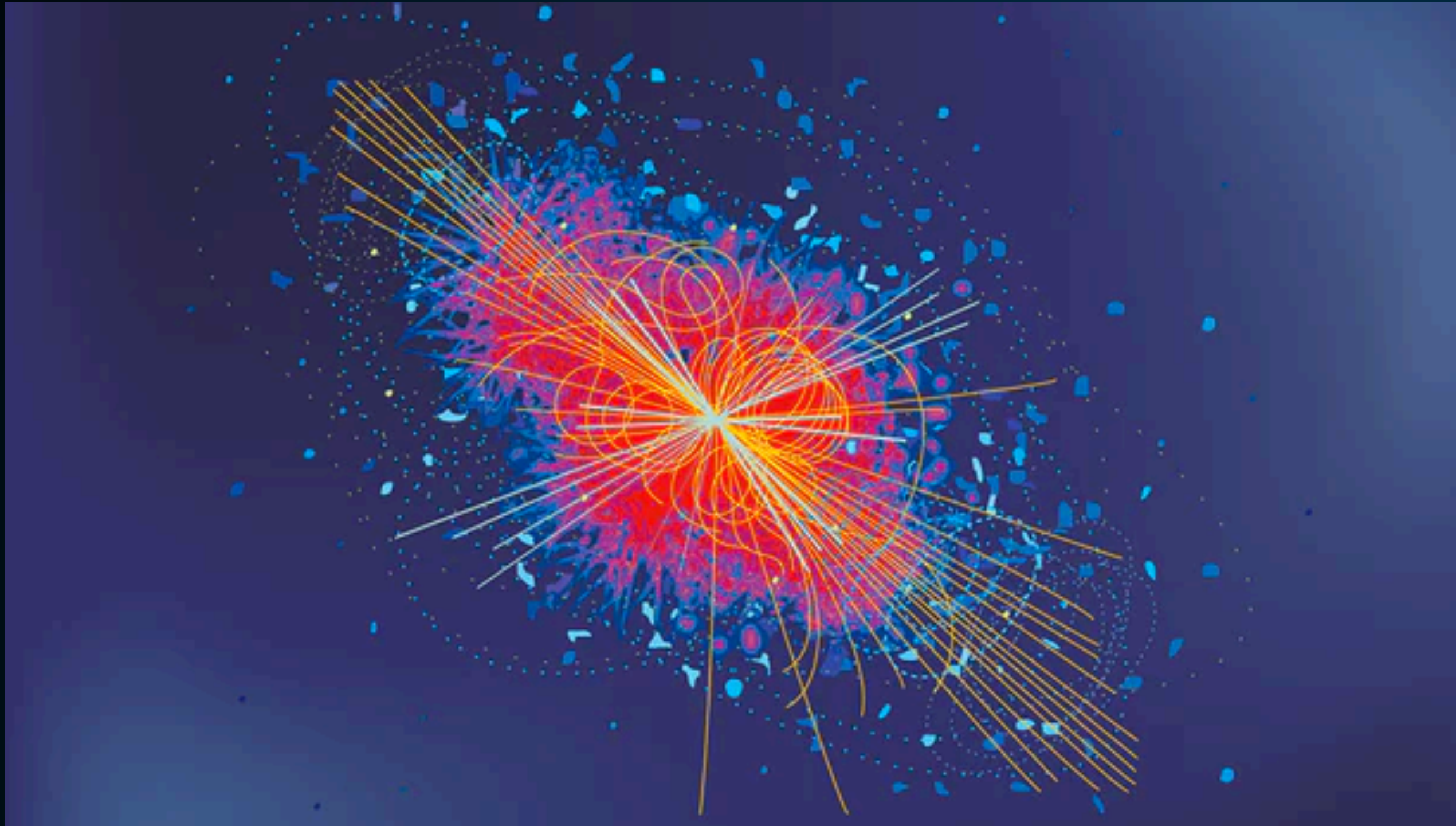
Instrumental Uncertainties





Antinuclei !?

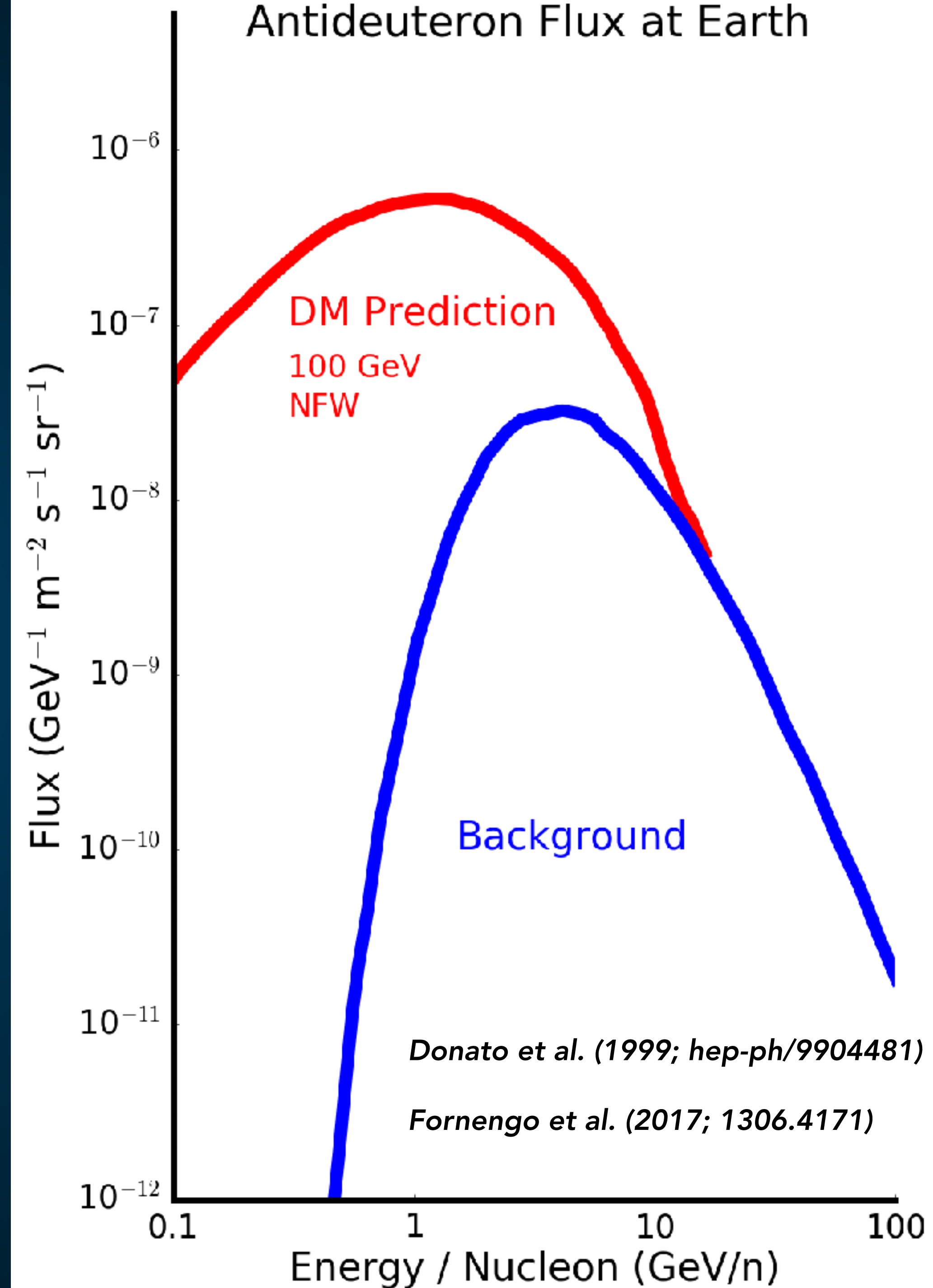
AntiNuclei - A Clean Search Strategy ?



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.

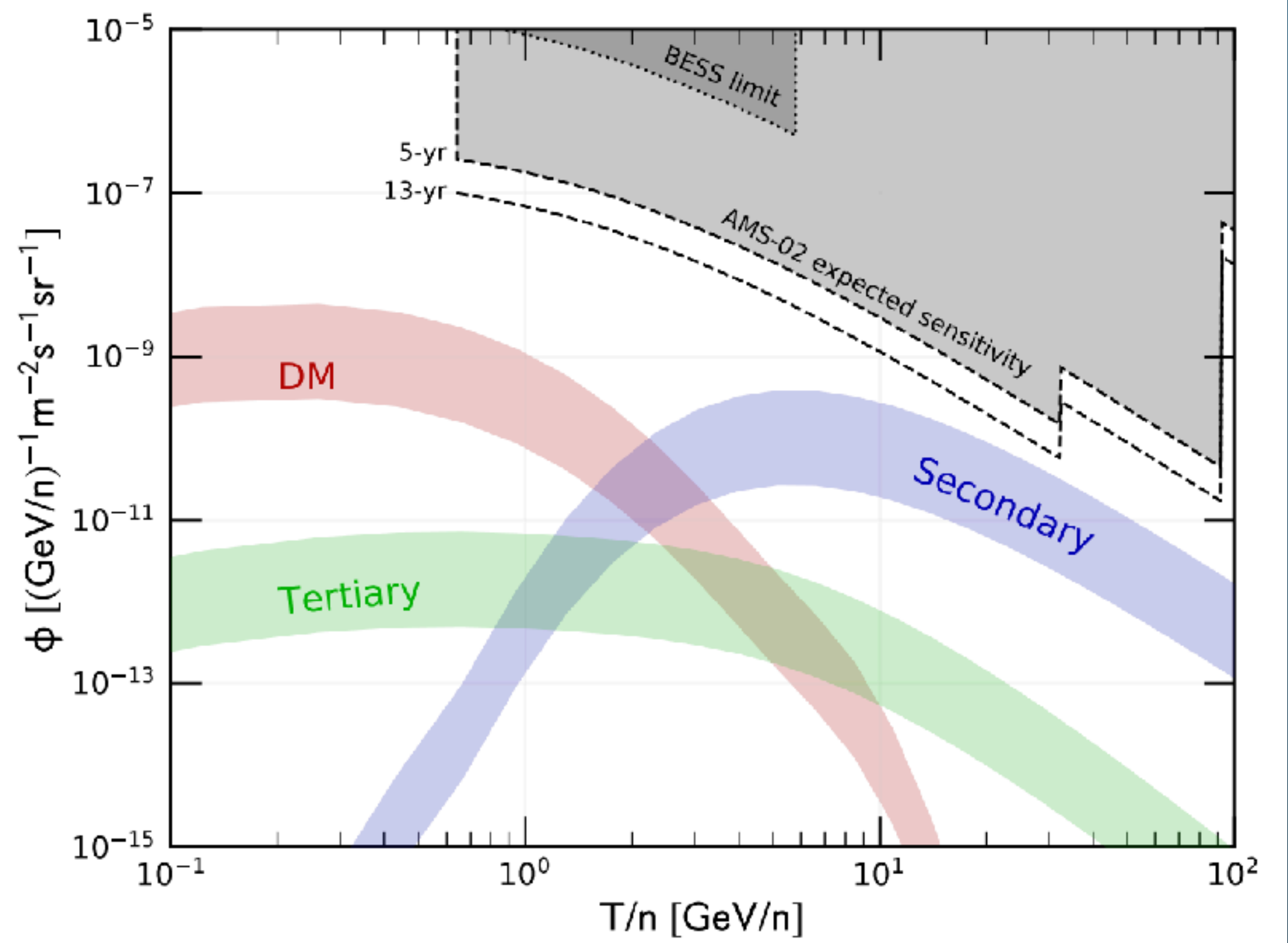
Currently (having used 50 million core hours to generate 7 times more simulated events than measured events and having found no background events from the simulation), our best evaluation of the probability of the background origin for the eight $\bar{\text{He}}$ events is **less than 3×10^{-8}** . For the two ${}^4\bar{\text{He}}$ 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 ${}^4\bar{\text{He}}$, 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 ${}^4\bar{\text{He}}$ would be **2×10^{-7}** , i.e., greater than 5-sigma significance.

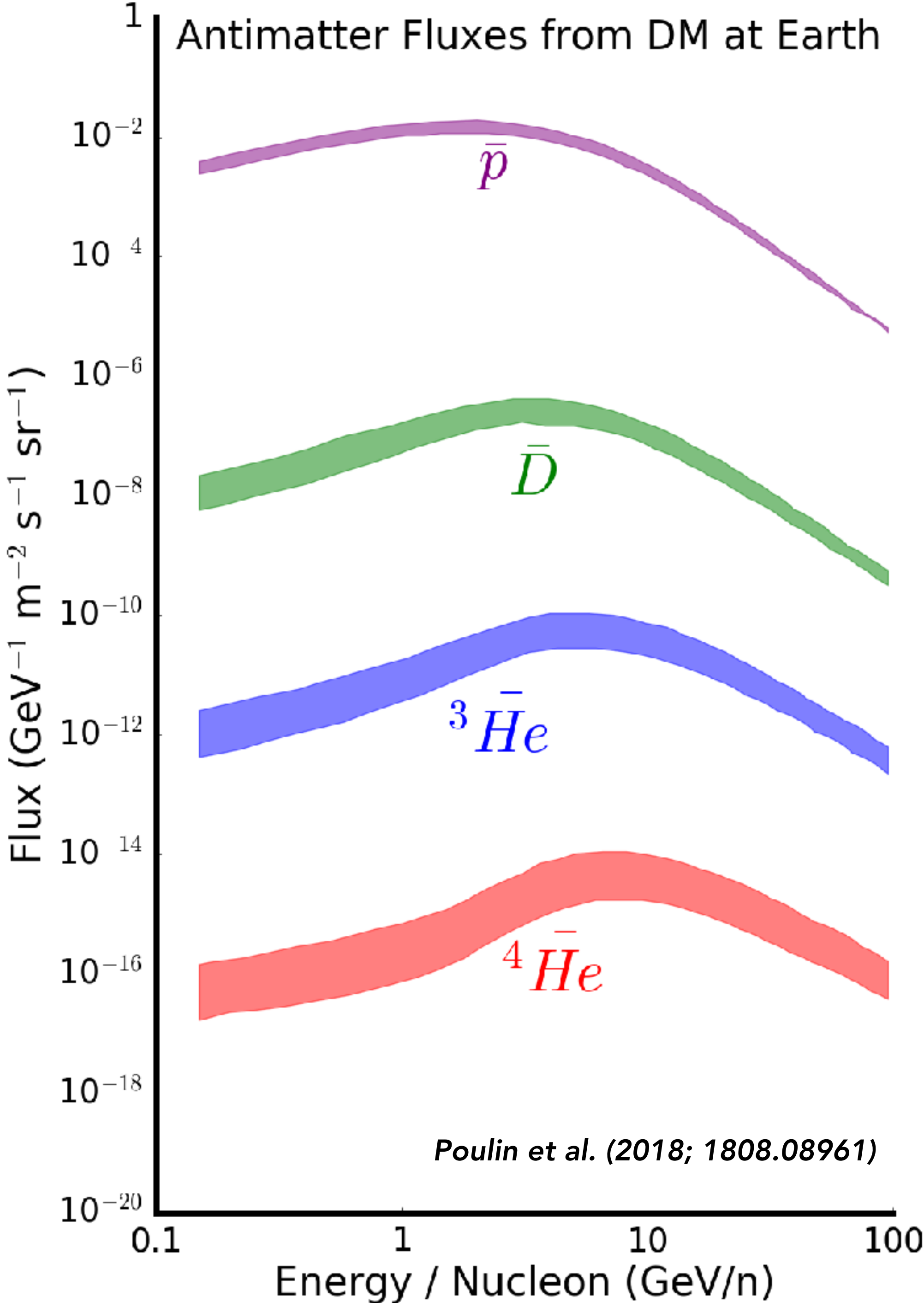
AntiNuclei - A Clean Search Strategy ?

Antihelium background even cleaner than antideuterons

But the flux is supposed to be much smaller.



Korsmeier (2017; 1711.08465)

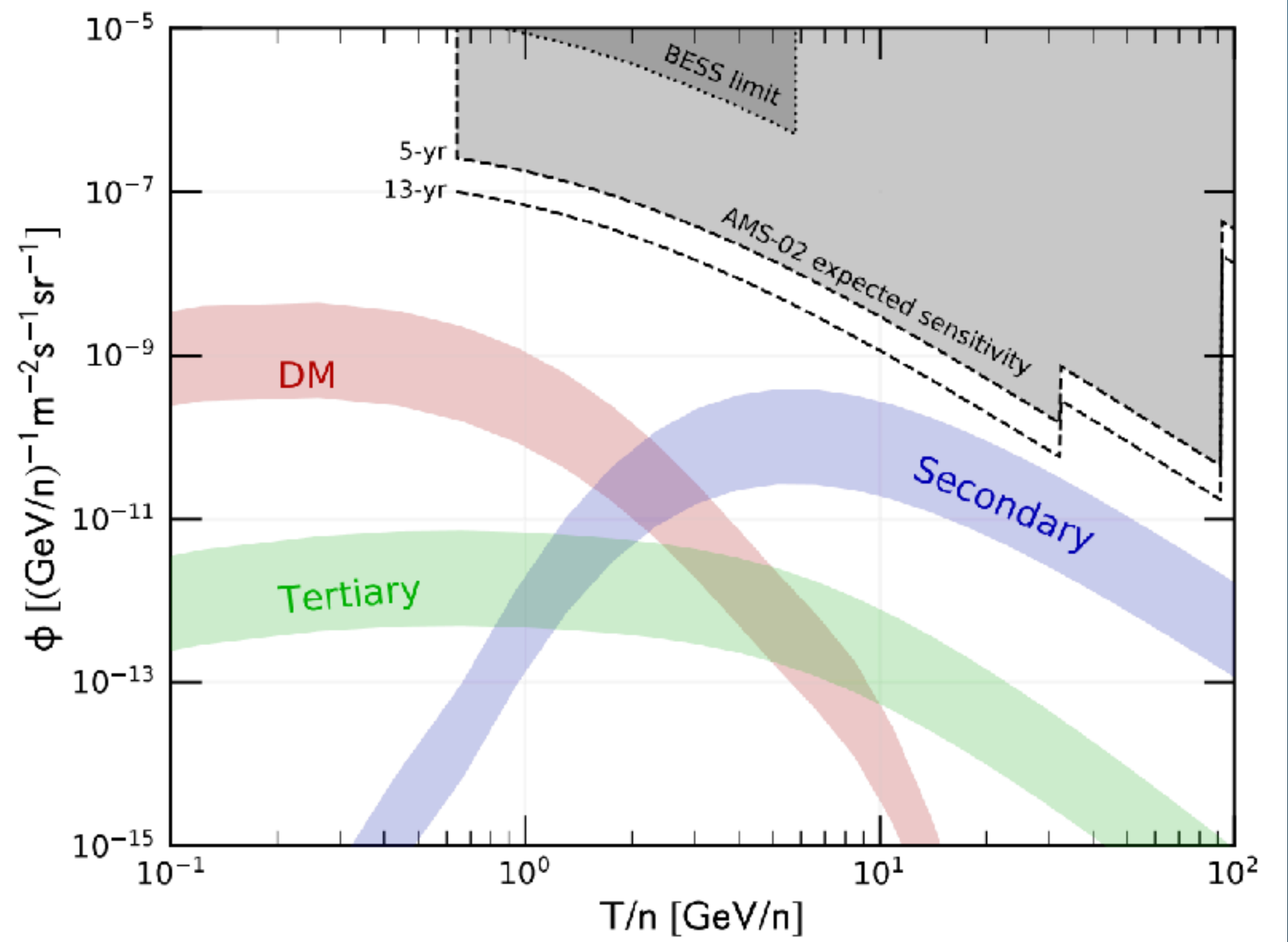


Poulin et al. (2018; 1808.08961)

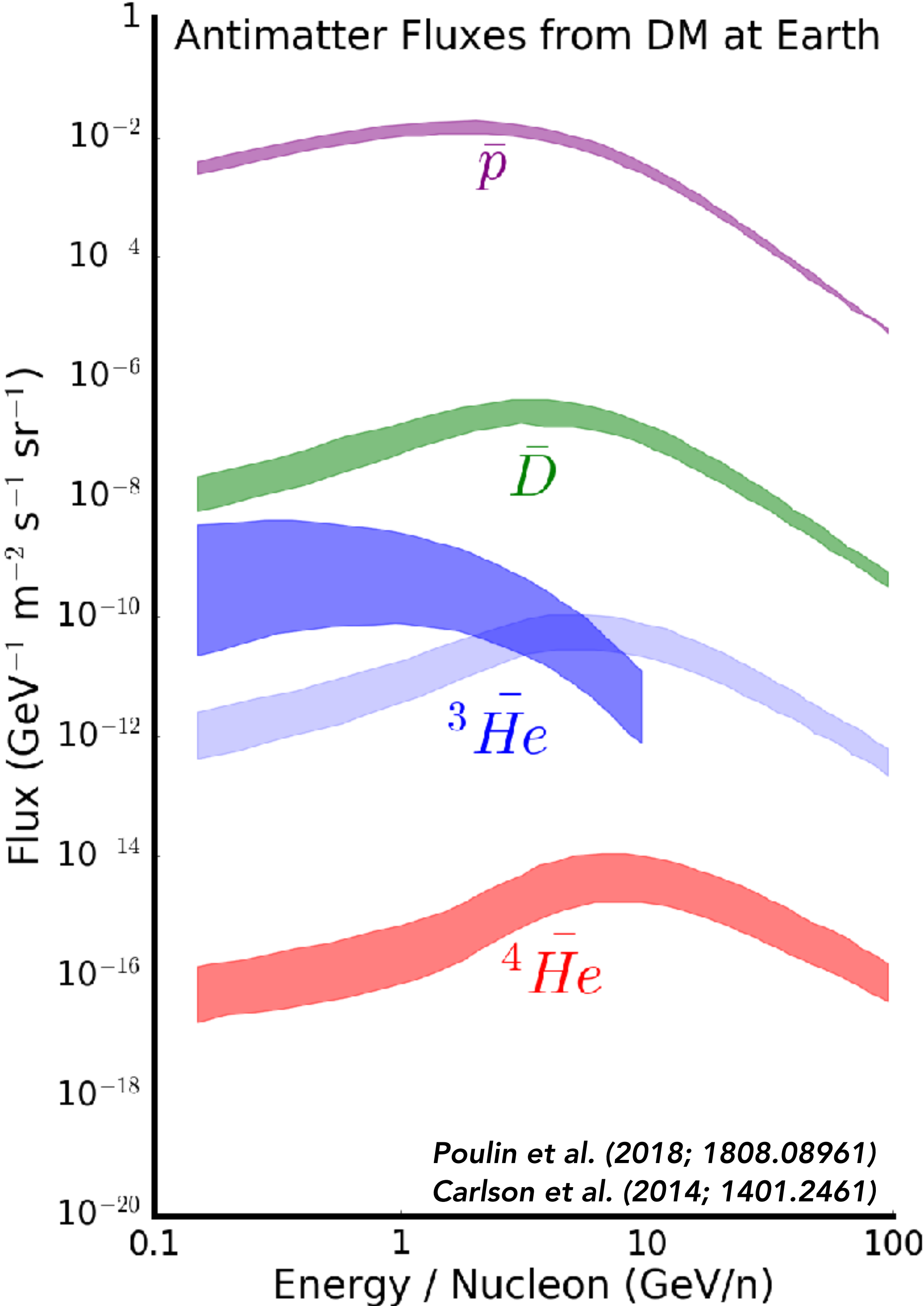
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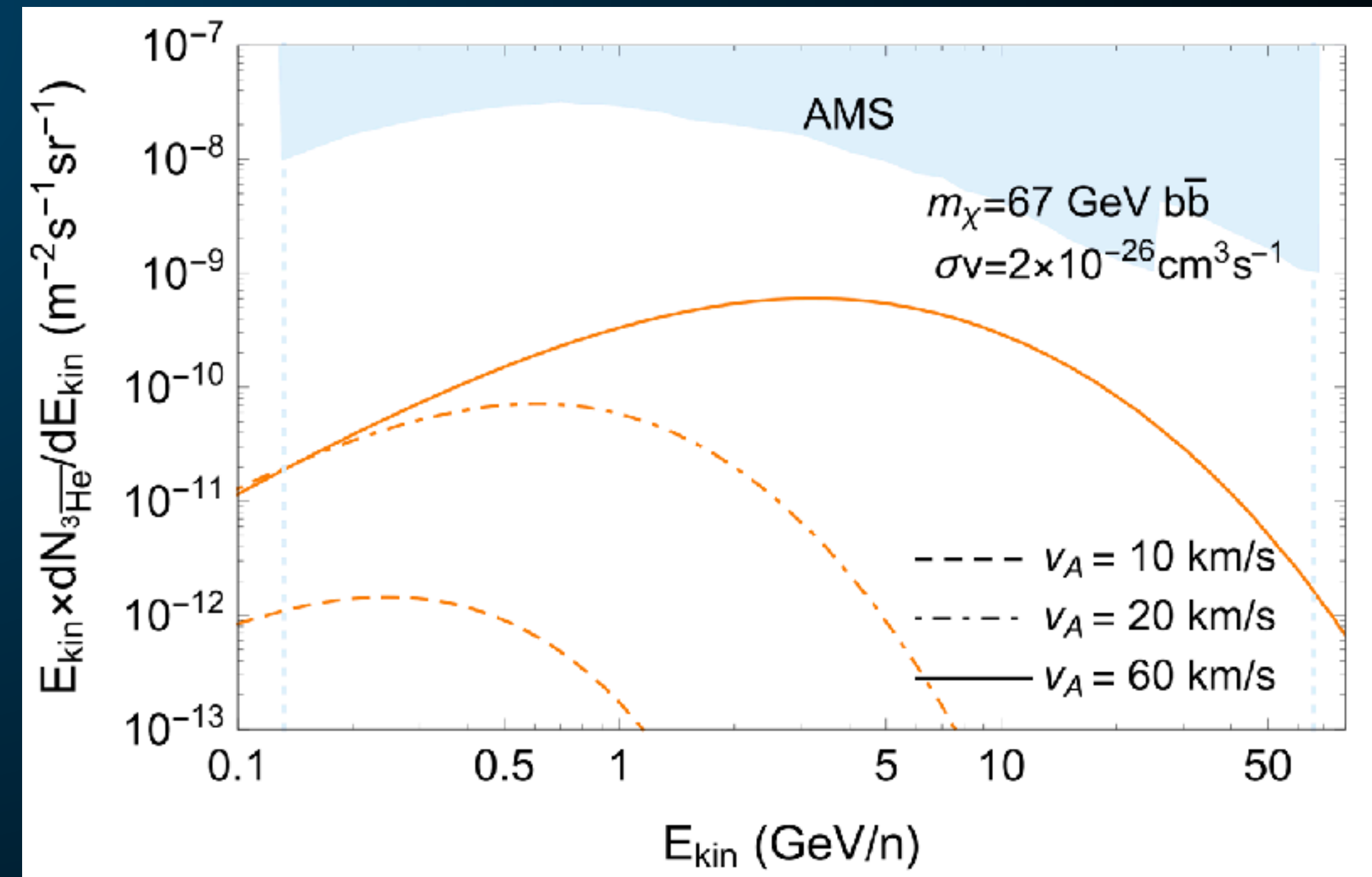
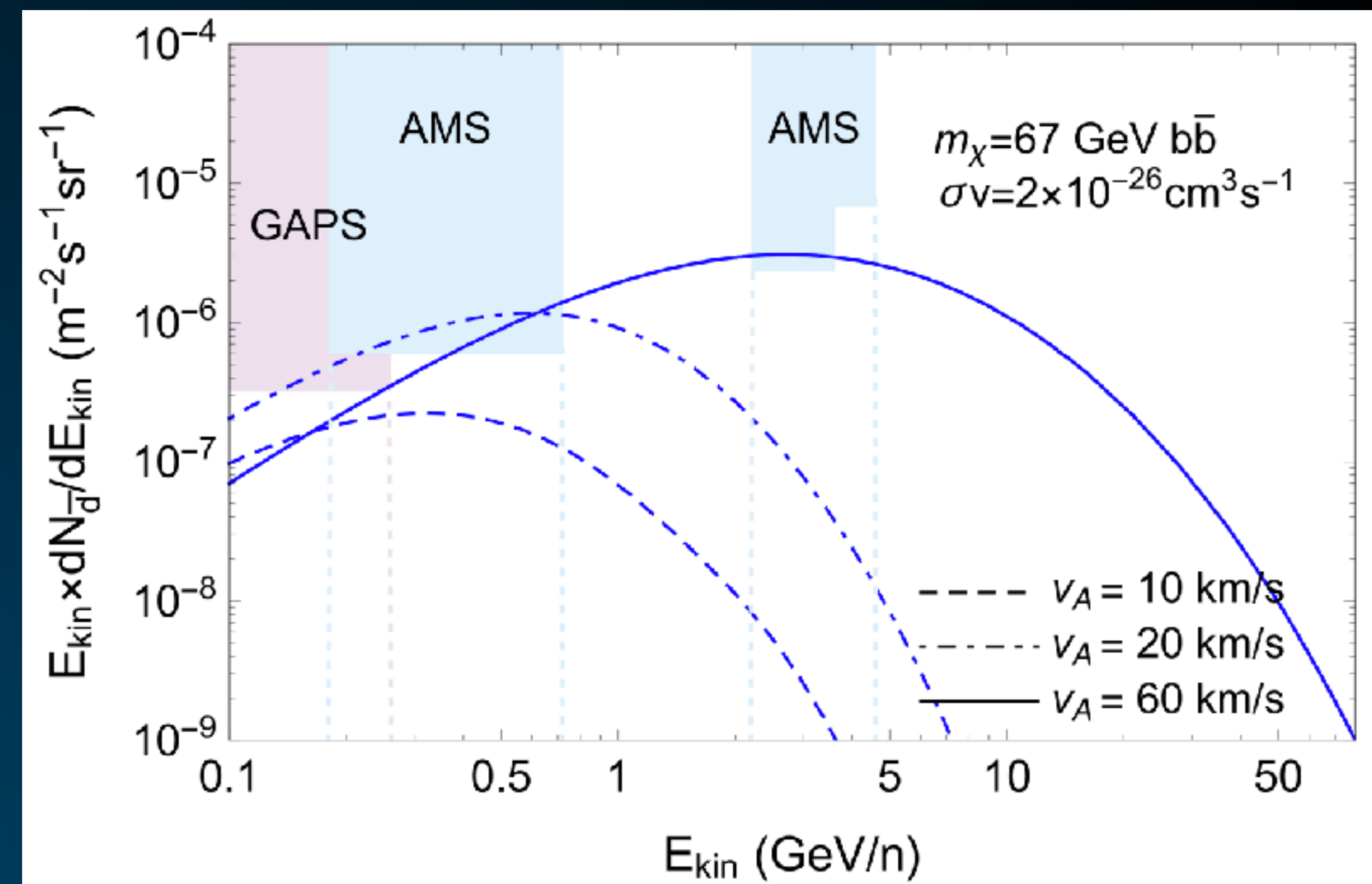
Poulin et al. (2018; 1808.08961)
Carlson et al. (2014; 1401.2461)

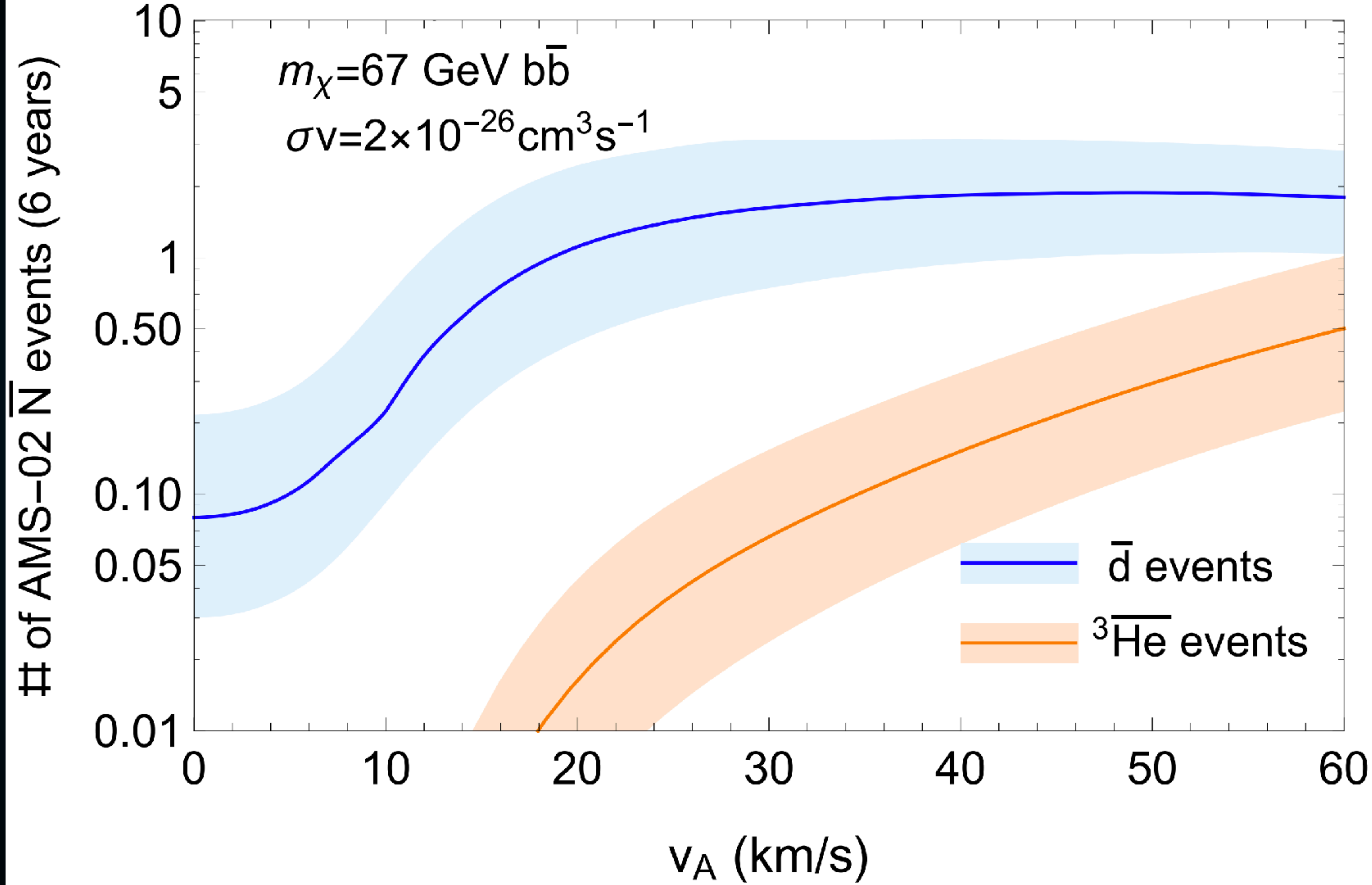
Astrophysical Enhancements!

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!





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.

I. INTRODUCTION

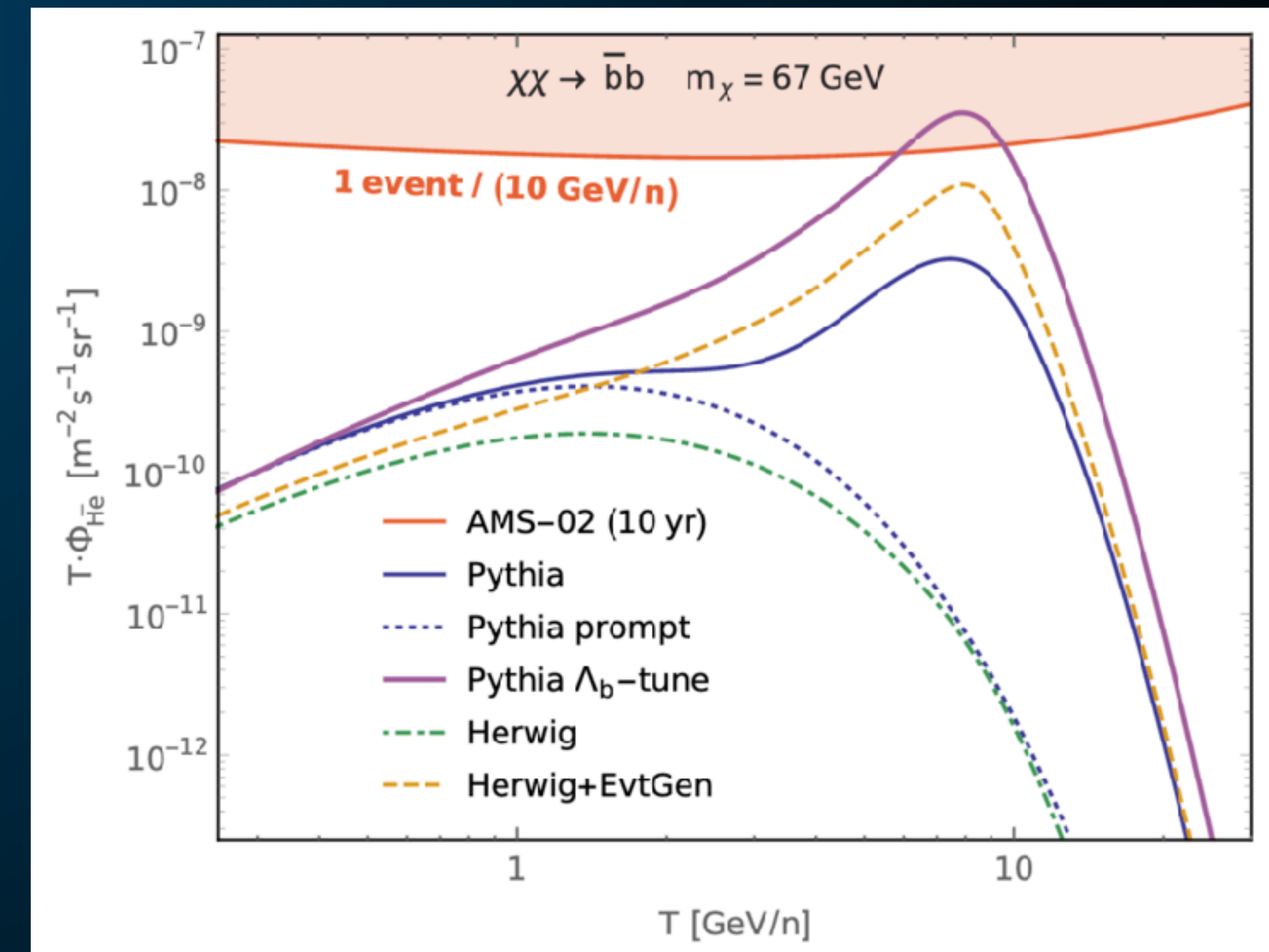
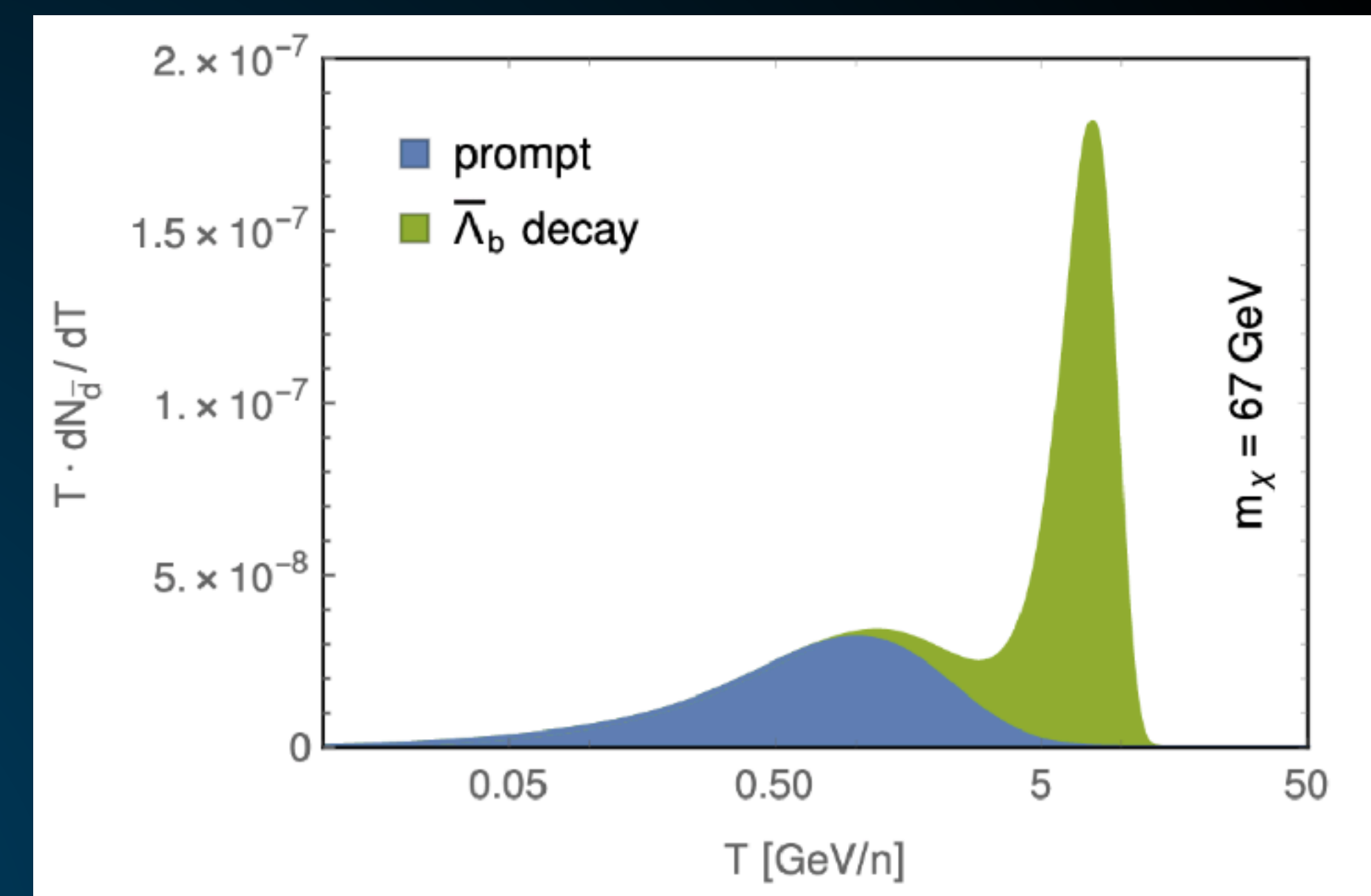
The detection of massive cosmic-ray antinuclei has long been considered a holy grail in searches for WIMP dark matter [1, 2]. Primary cosmic-rays from astrophysical sources are matter-dominated, accelerated by nearby supernova, pulsars, and other extreme objects. The secondary cosmic-rays produced by 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 ${}^3\bar{\text{He}}$ 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].

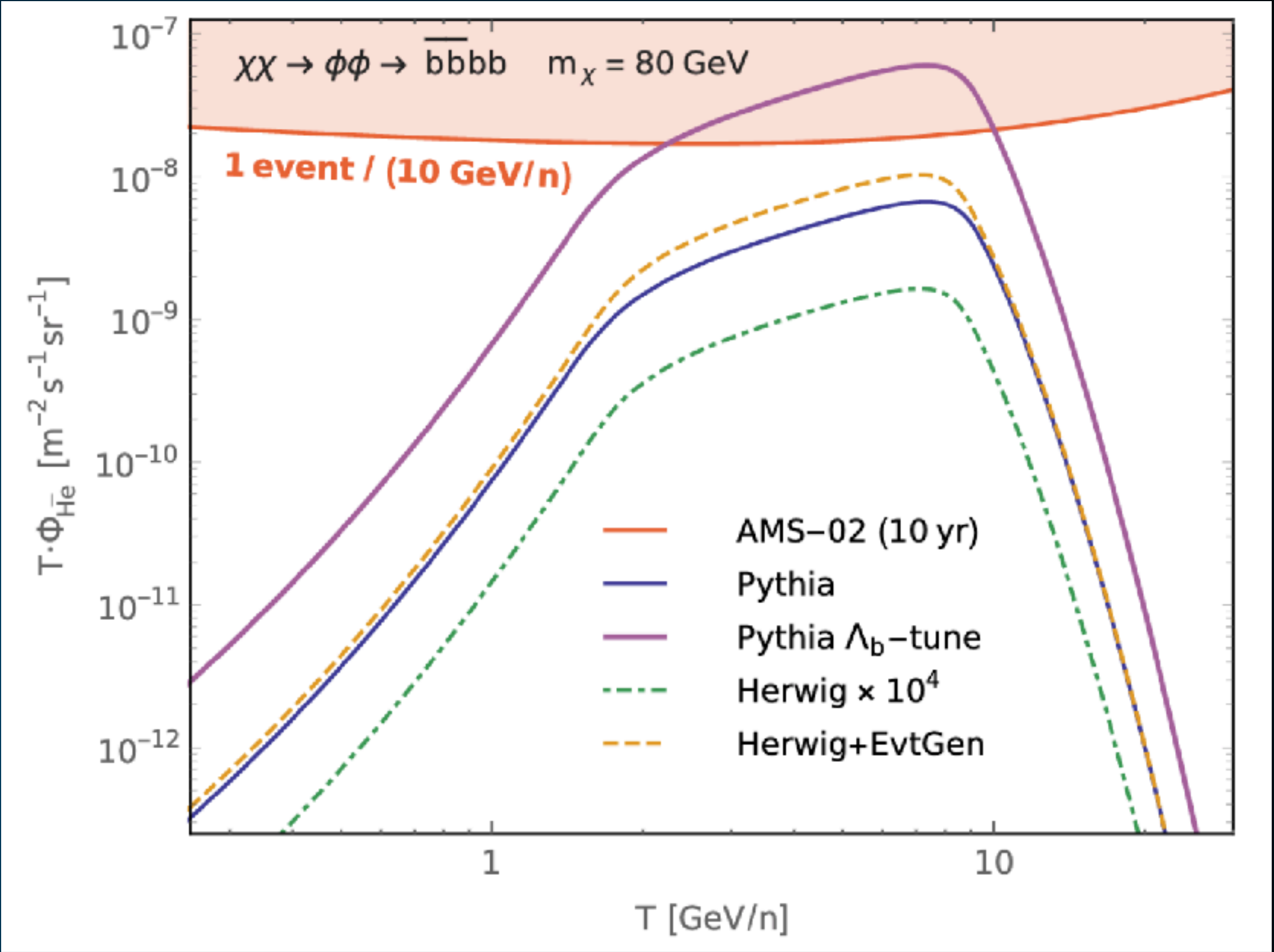
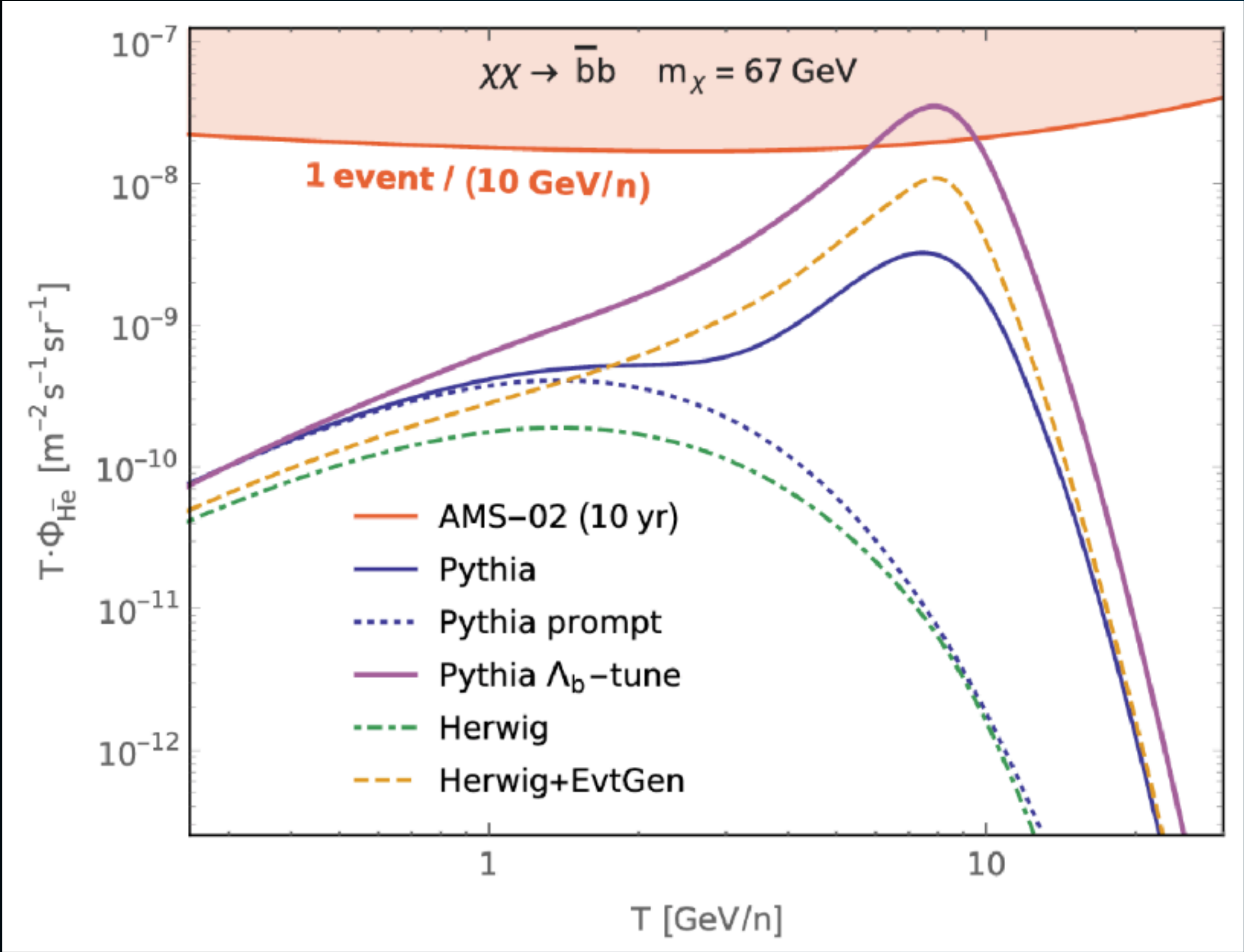
Particle Physics Enhancements!

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

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

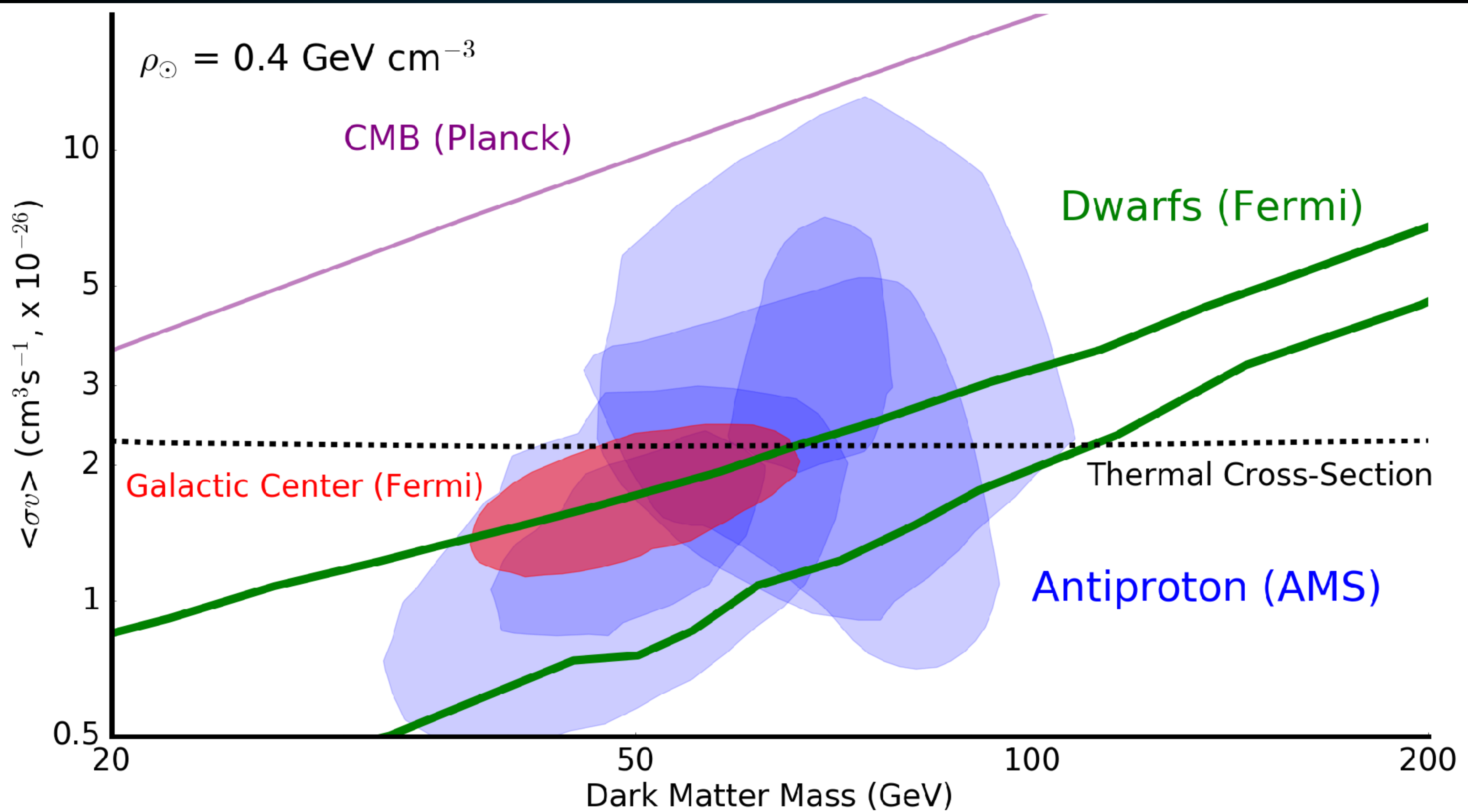


Particle Physics Enhancements!

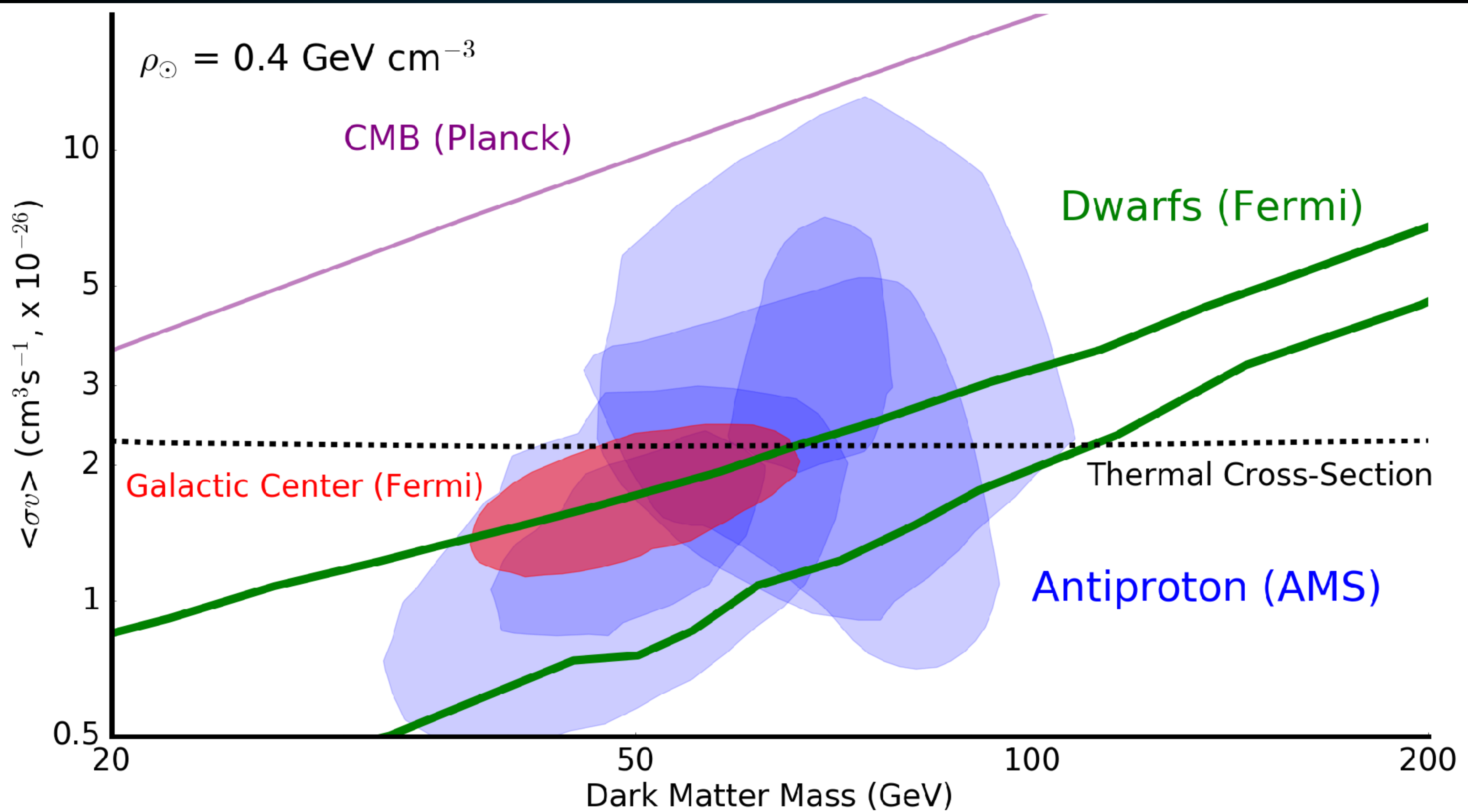


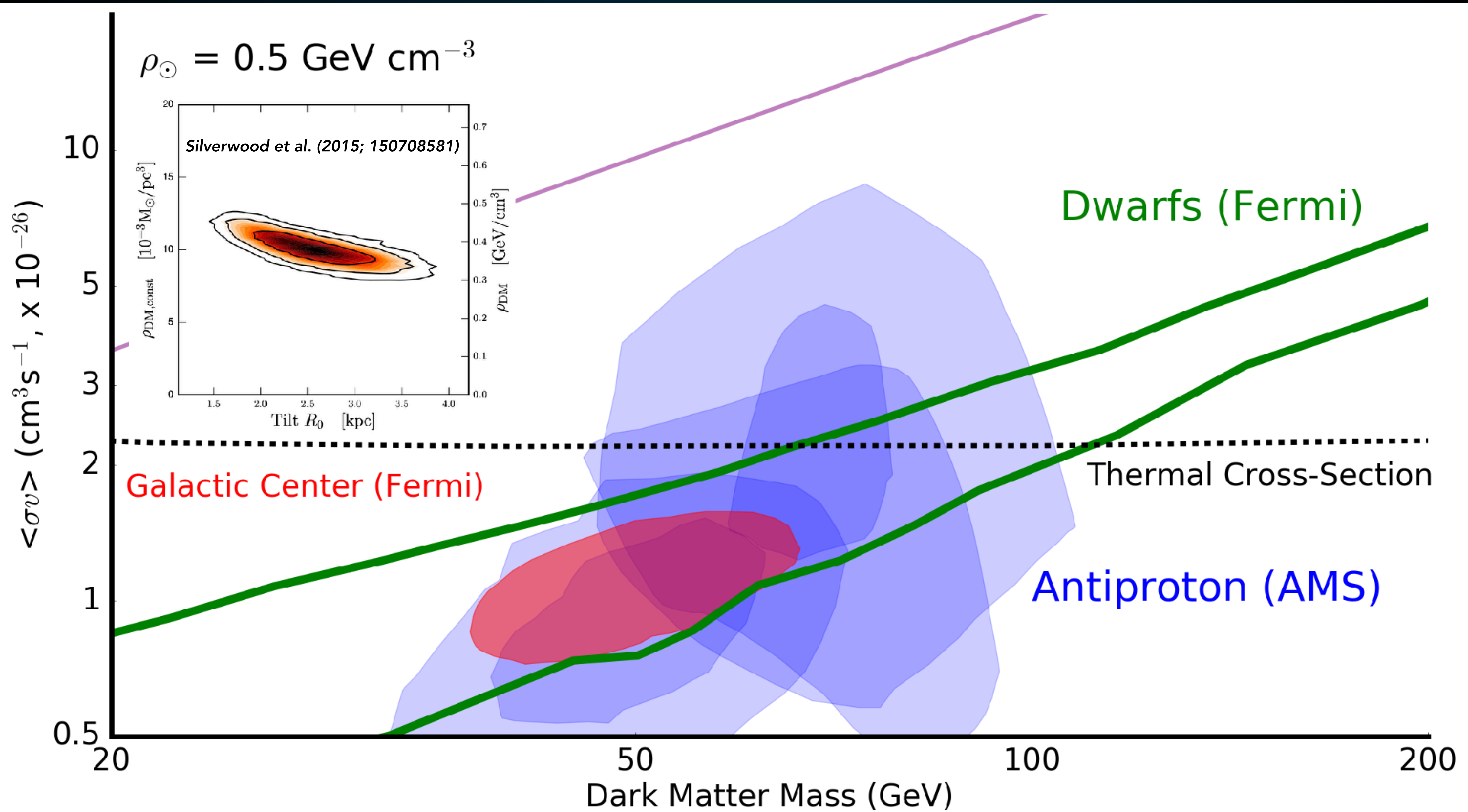
Generator	P	P [Λ_b -tune]	H	H+EvtGen
$^3\bar{\text{He}}$ events	0.1 (0.007)	0.9	0.003	0.3
\bar{d} events	3.7 (3.5)	4.2	1.7	2.1

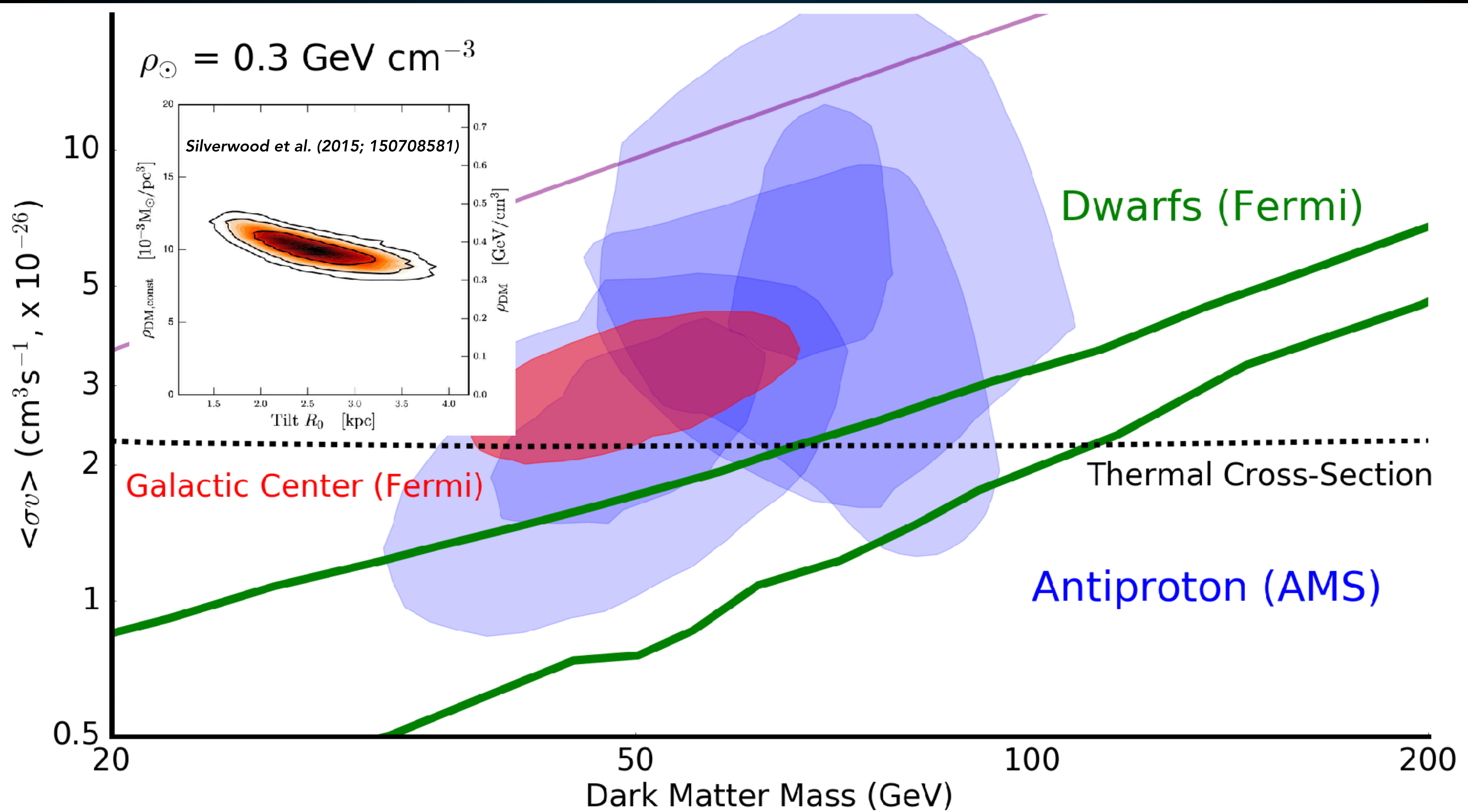
WHERE
ARE
WE NOW?

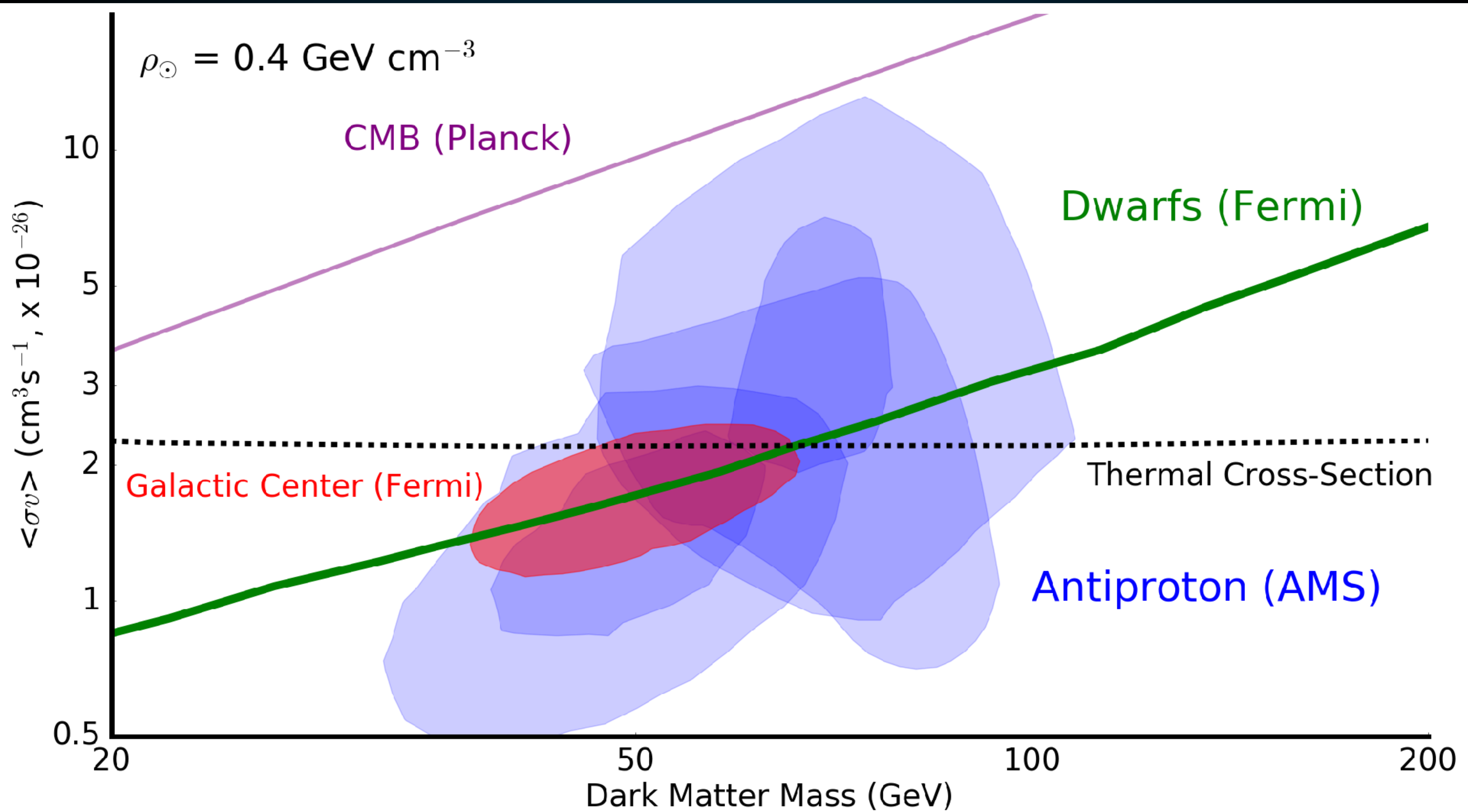


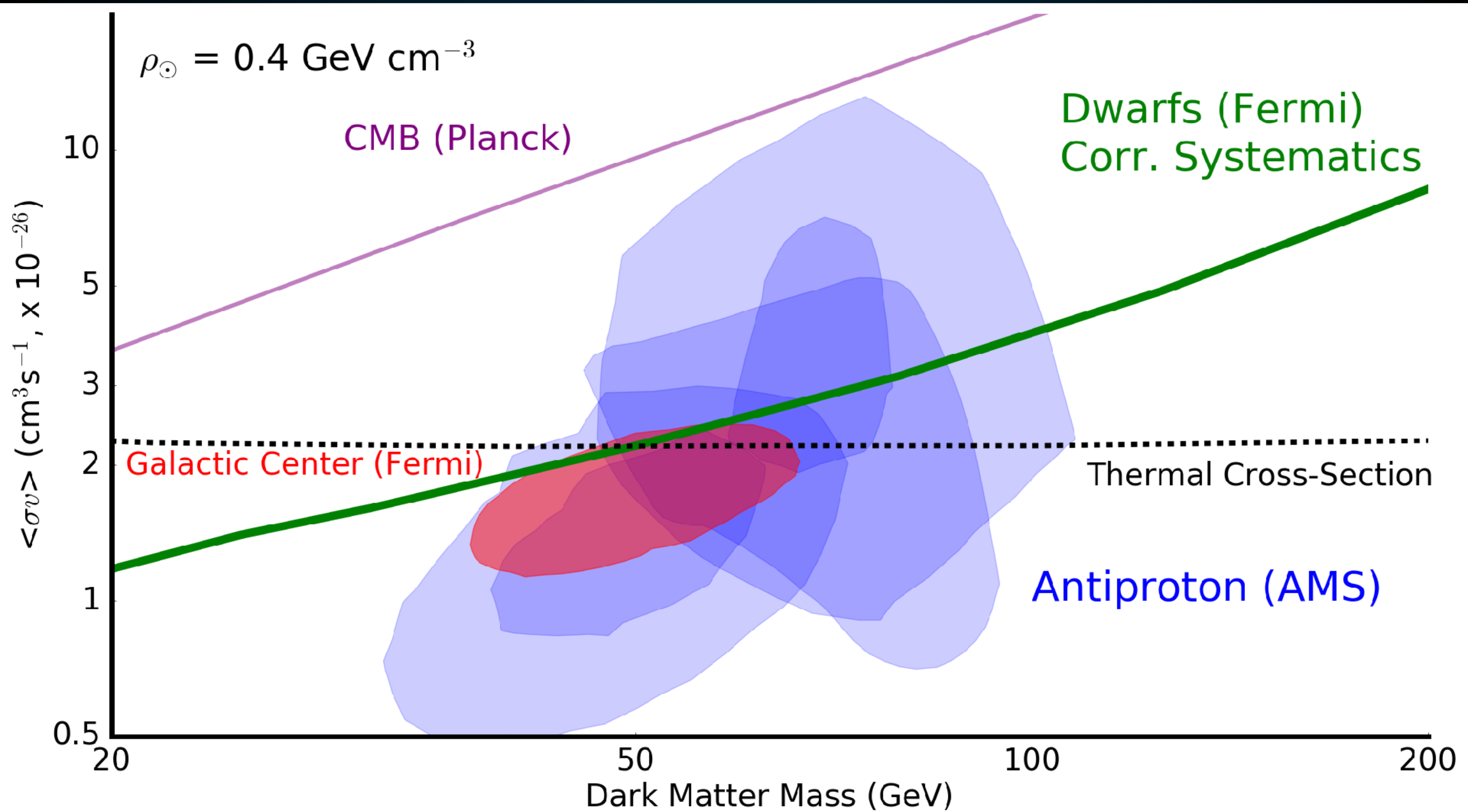










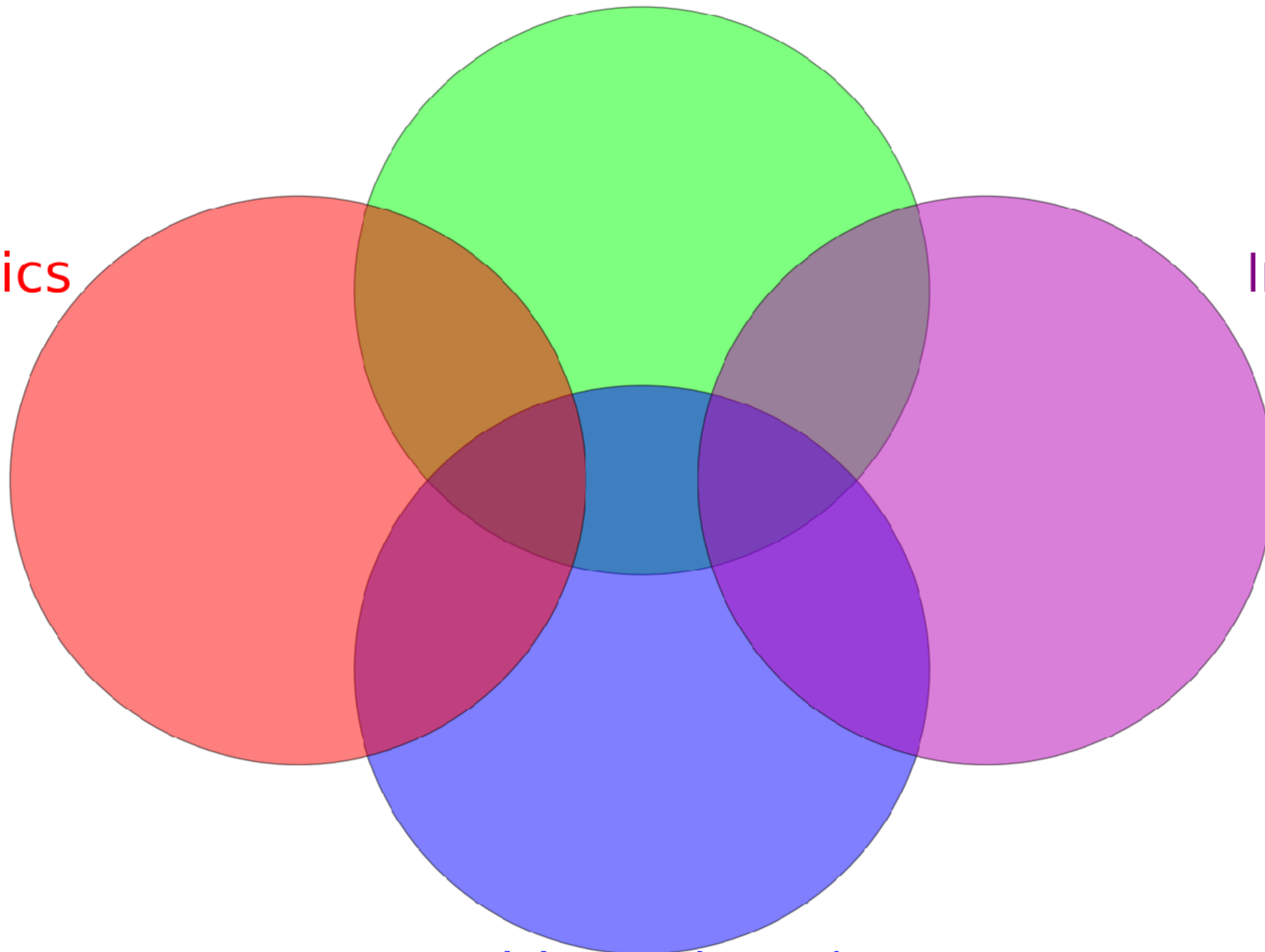


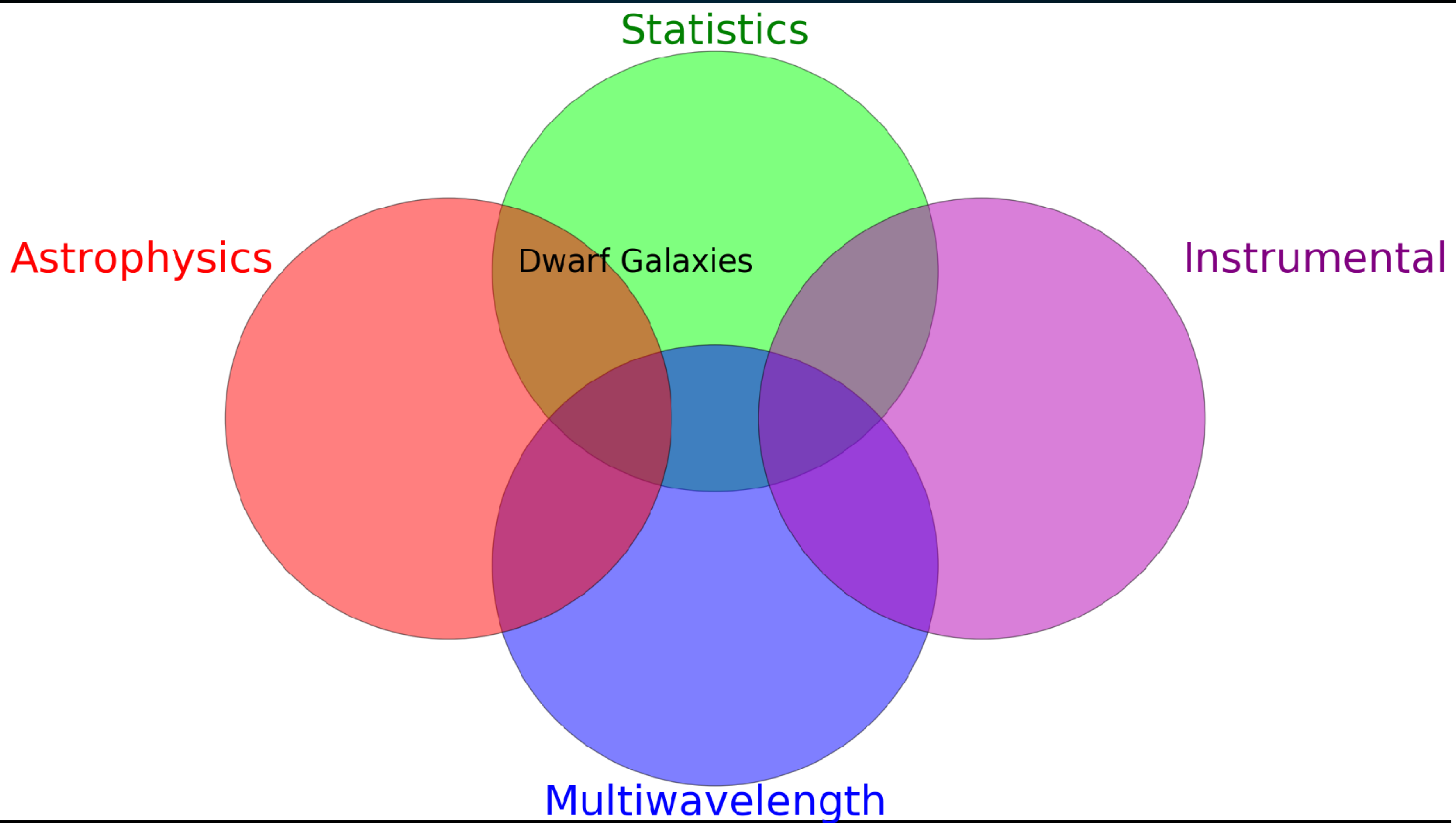
Statistics

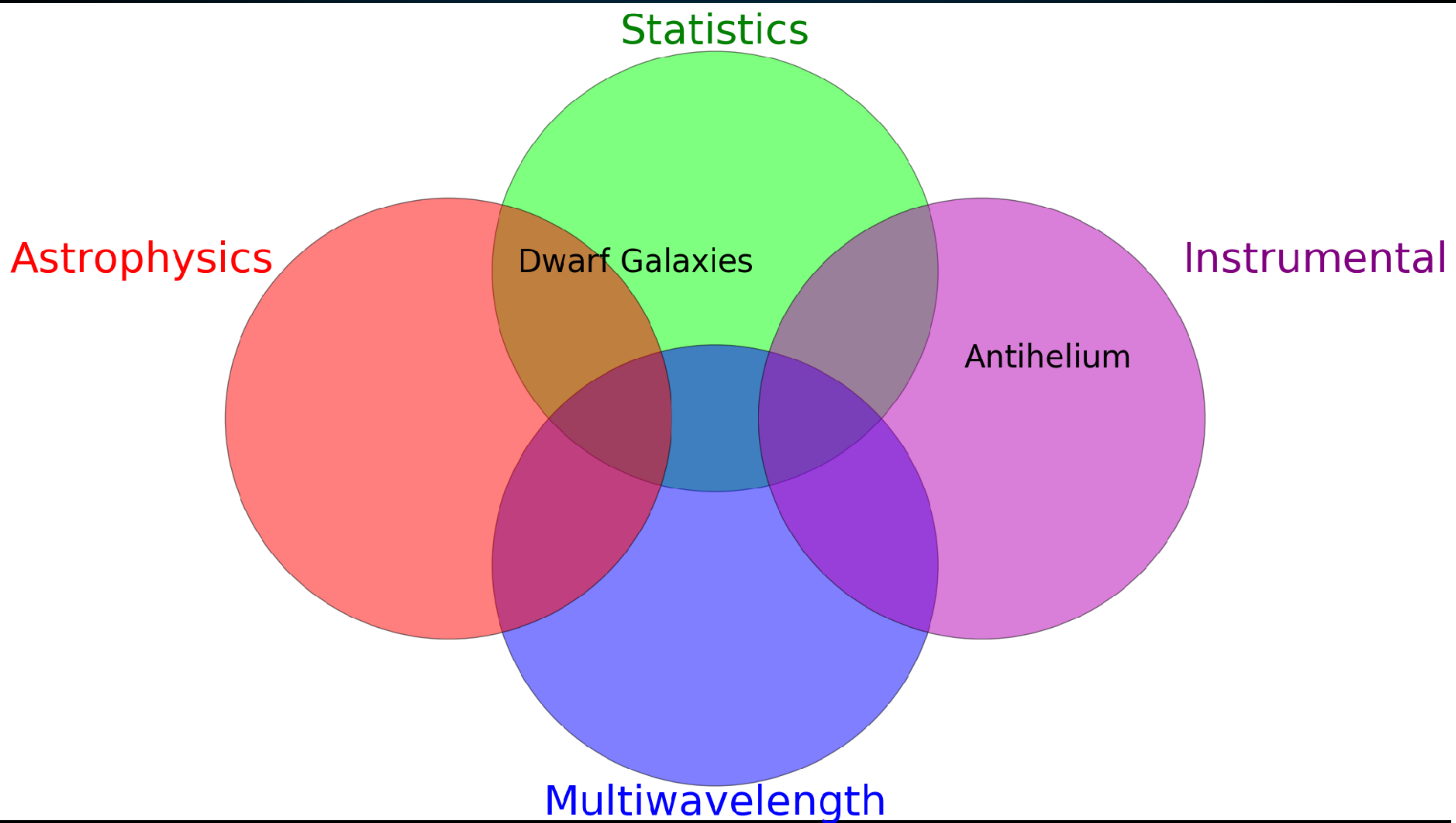
Astrophysics

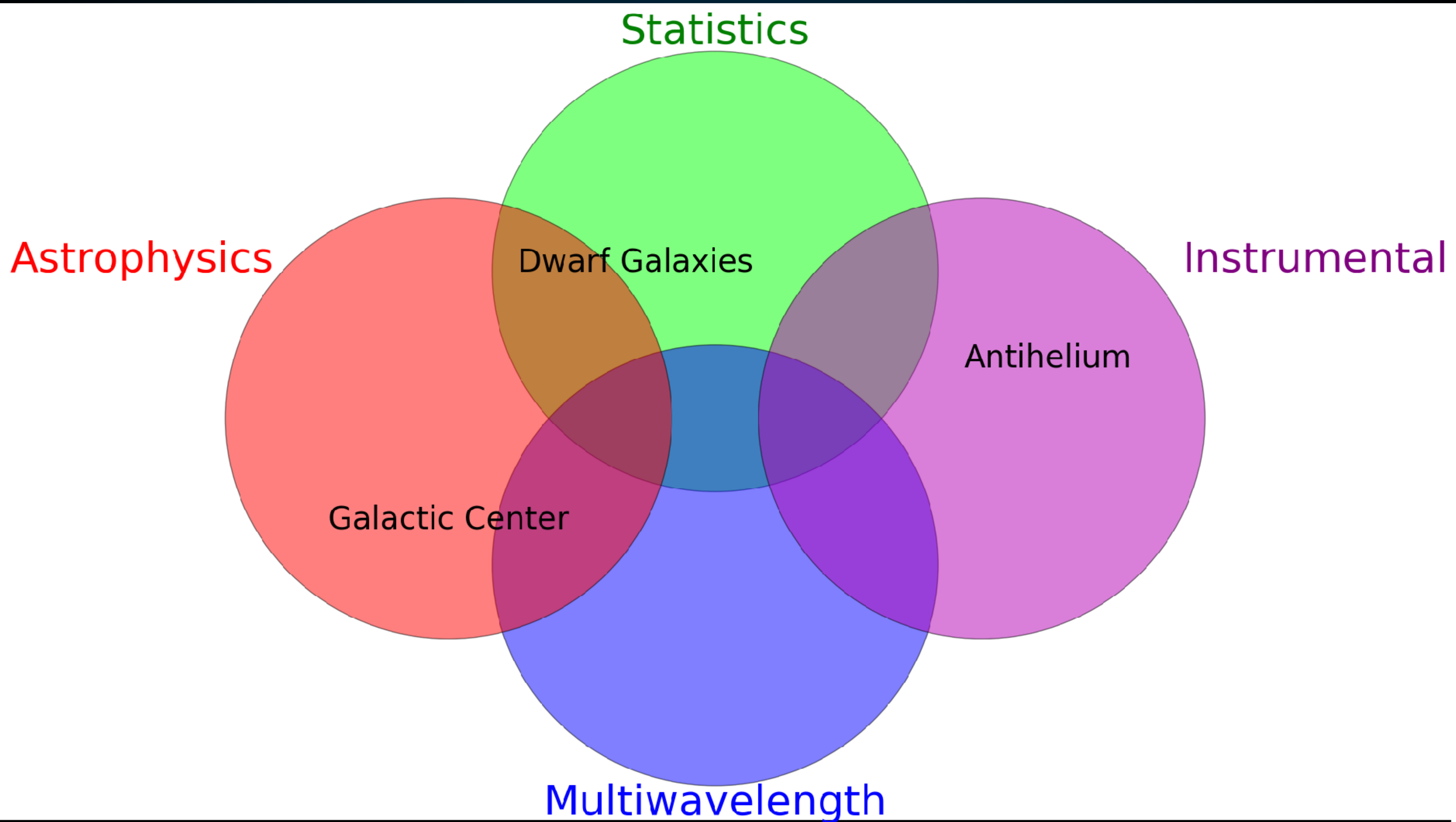
Instrumental

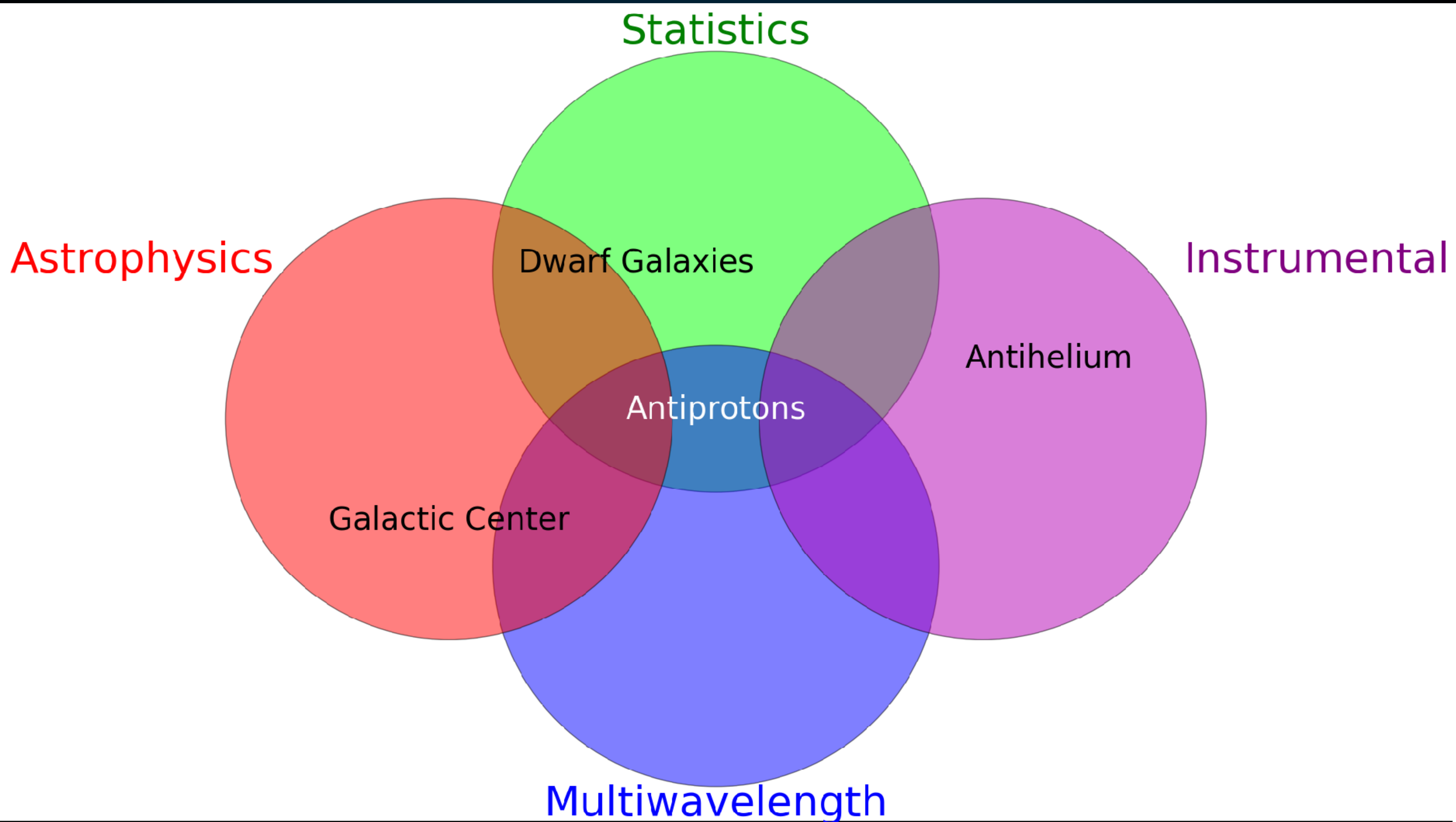
Multiwavelength



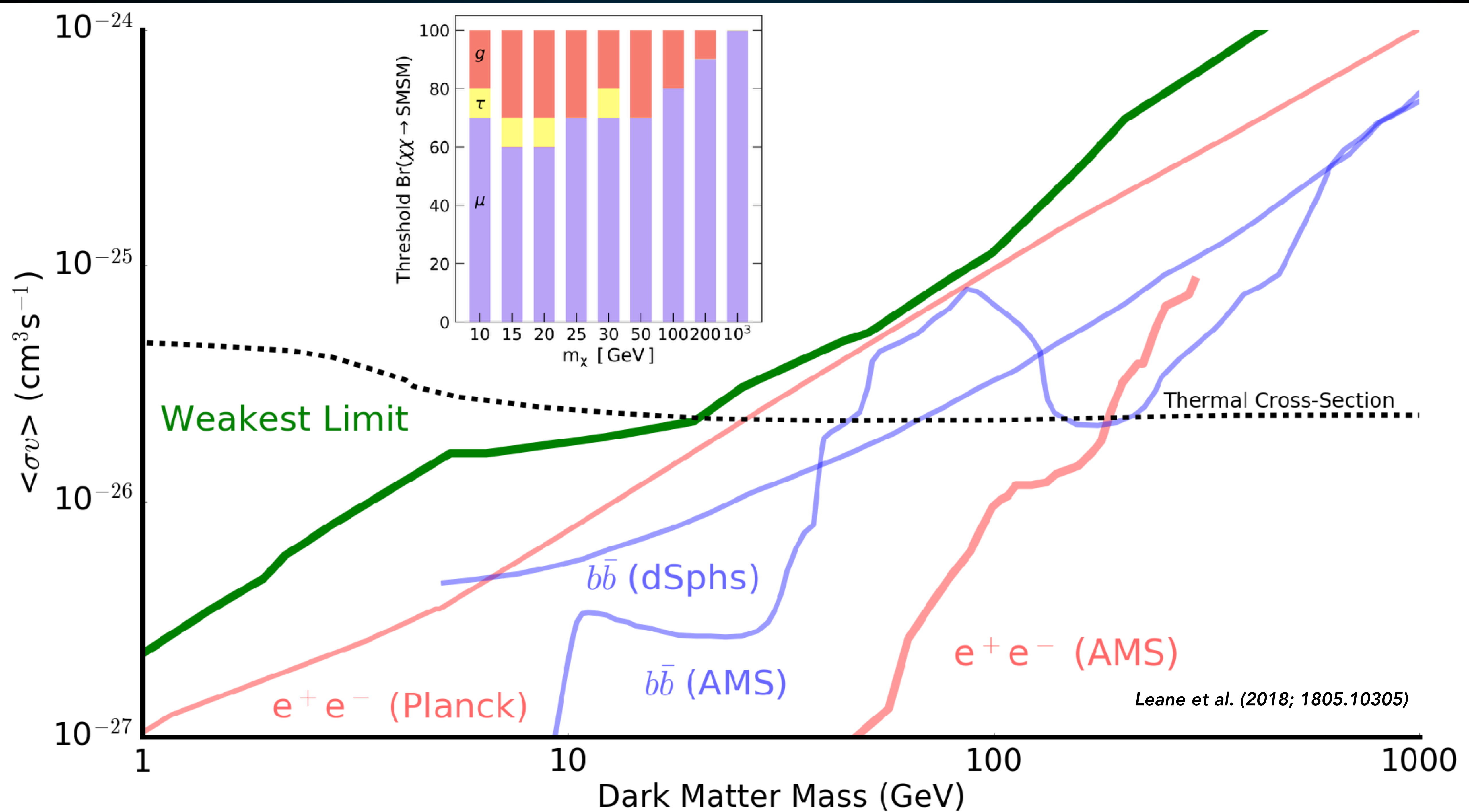


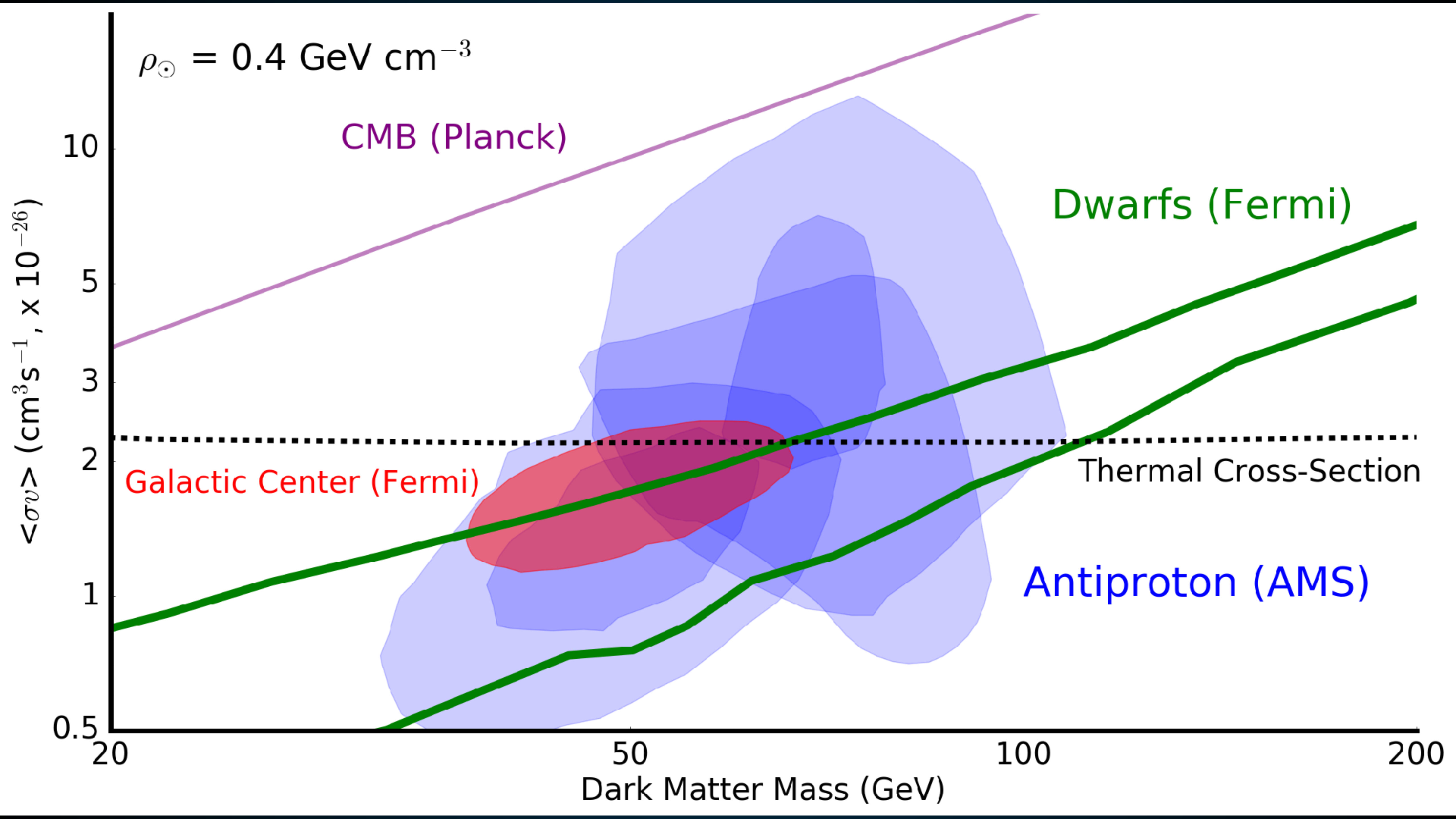


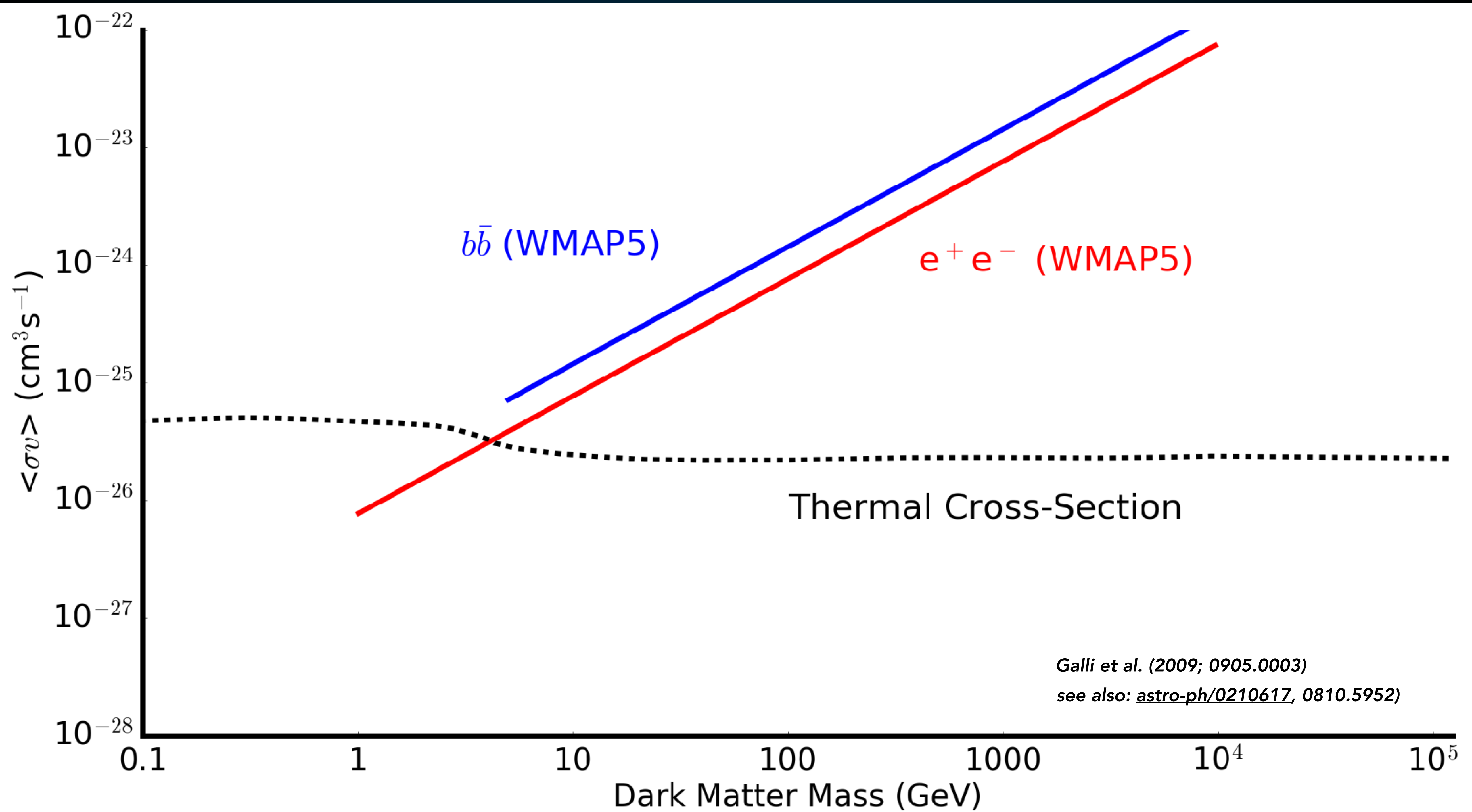


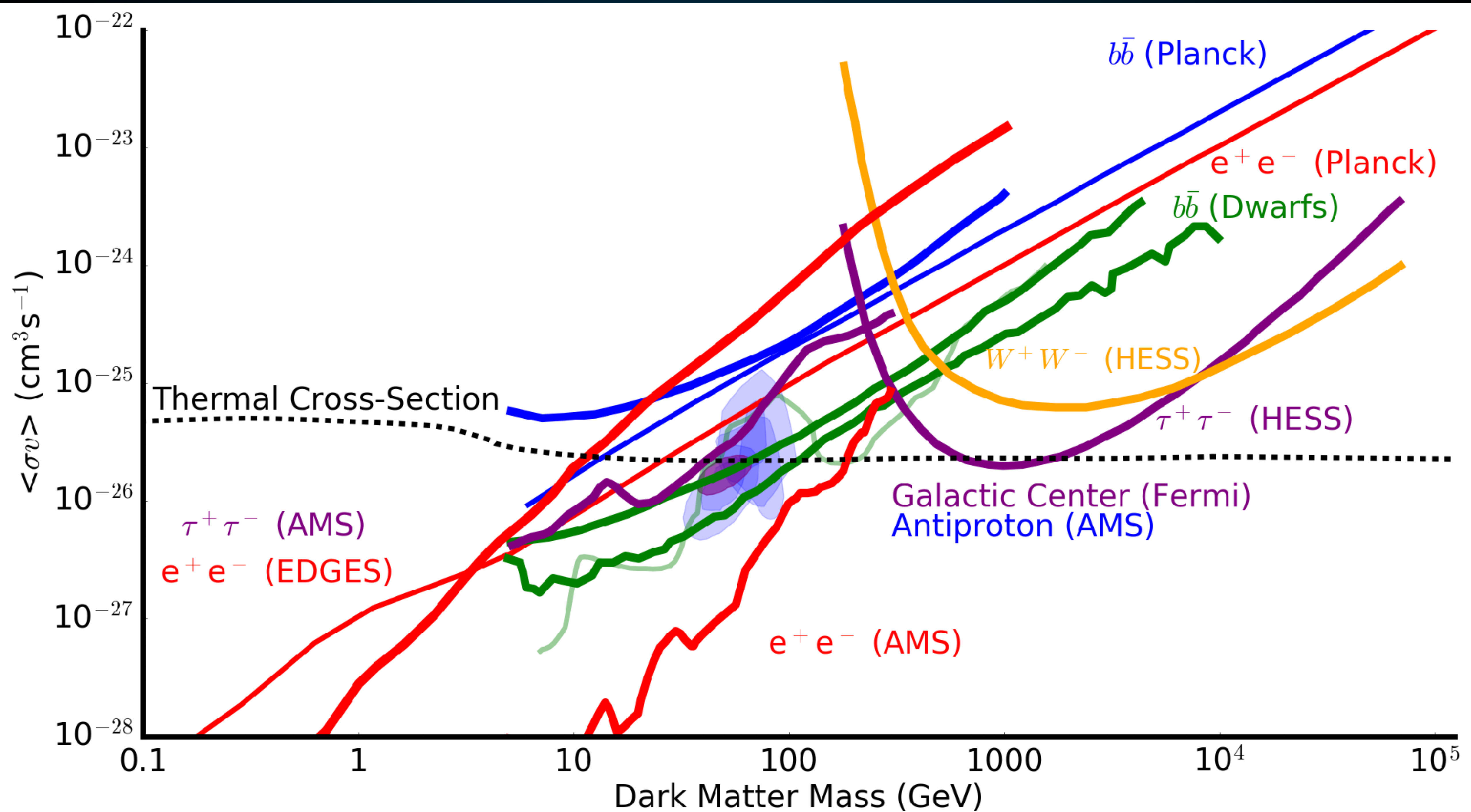


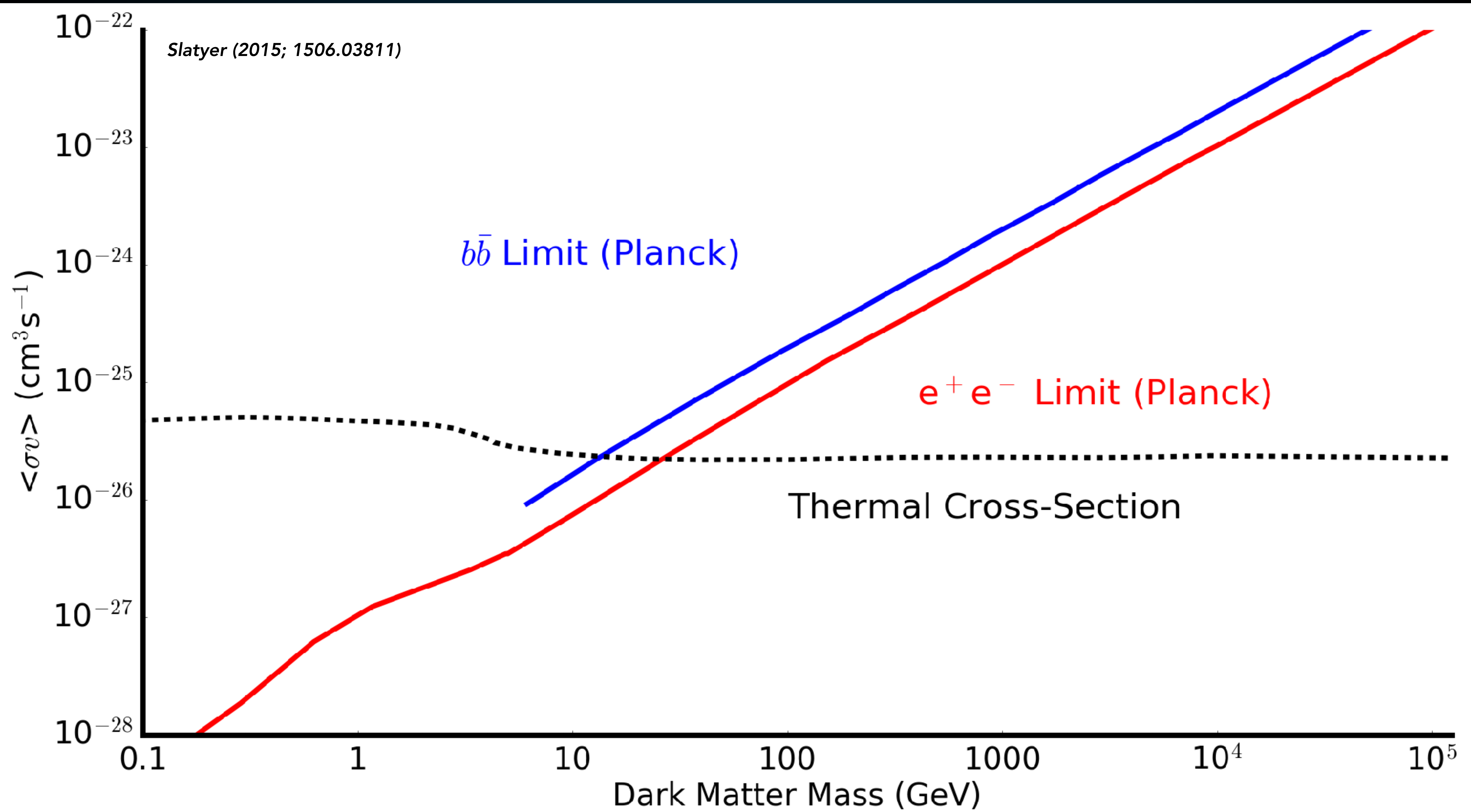




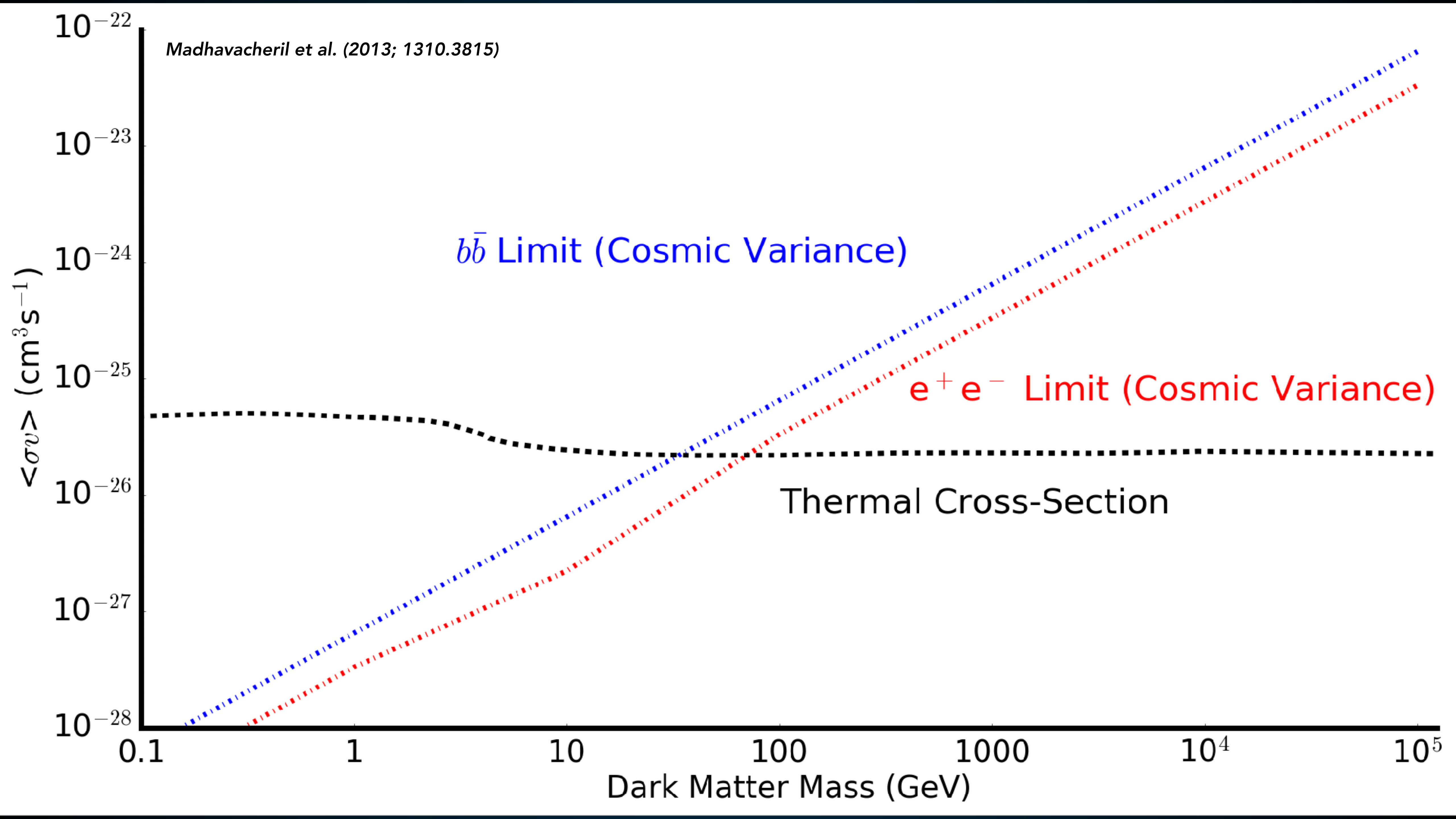


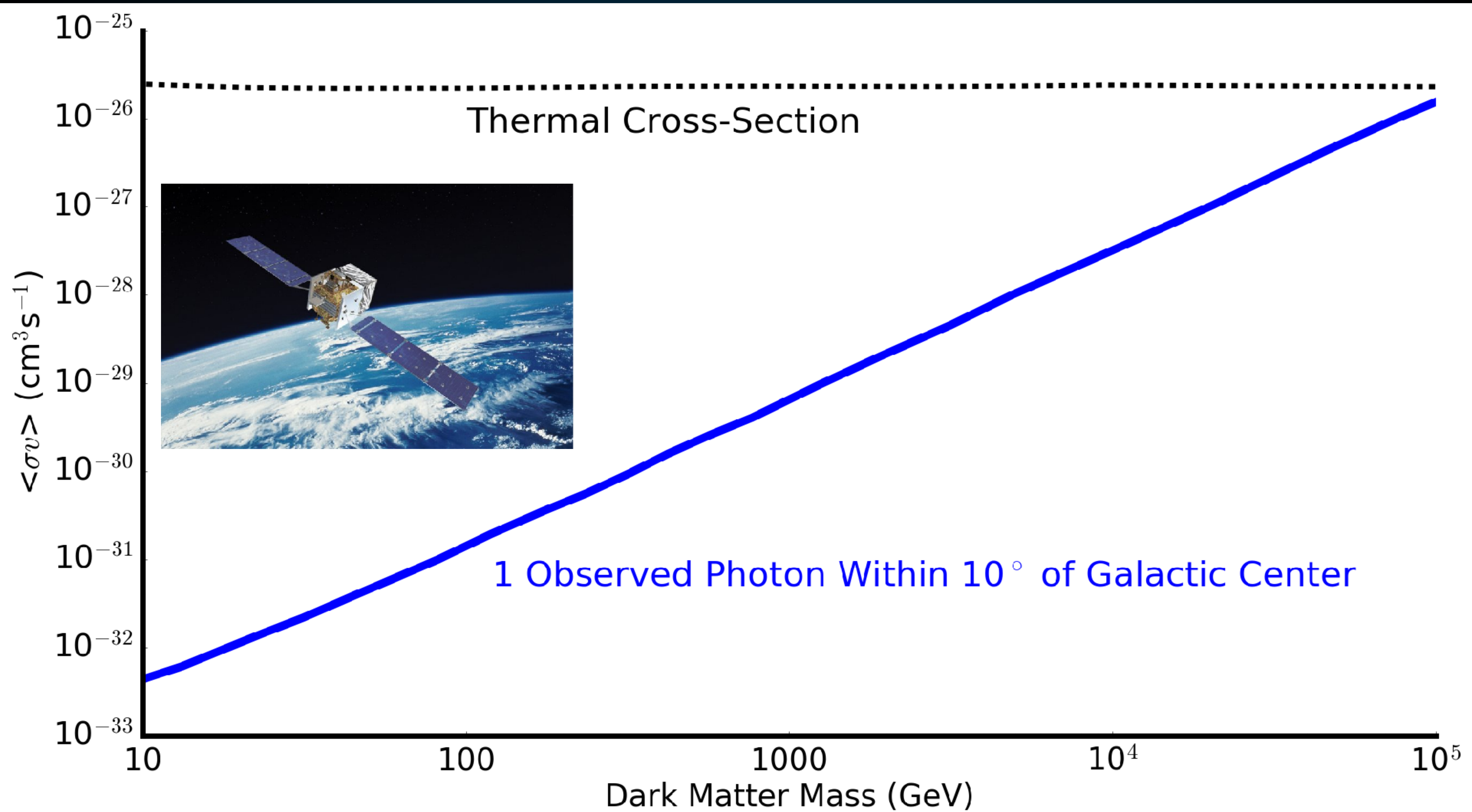


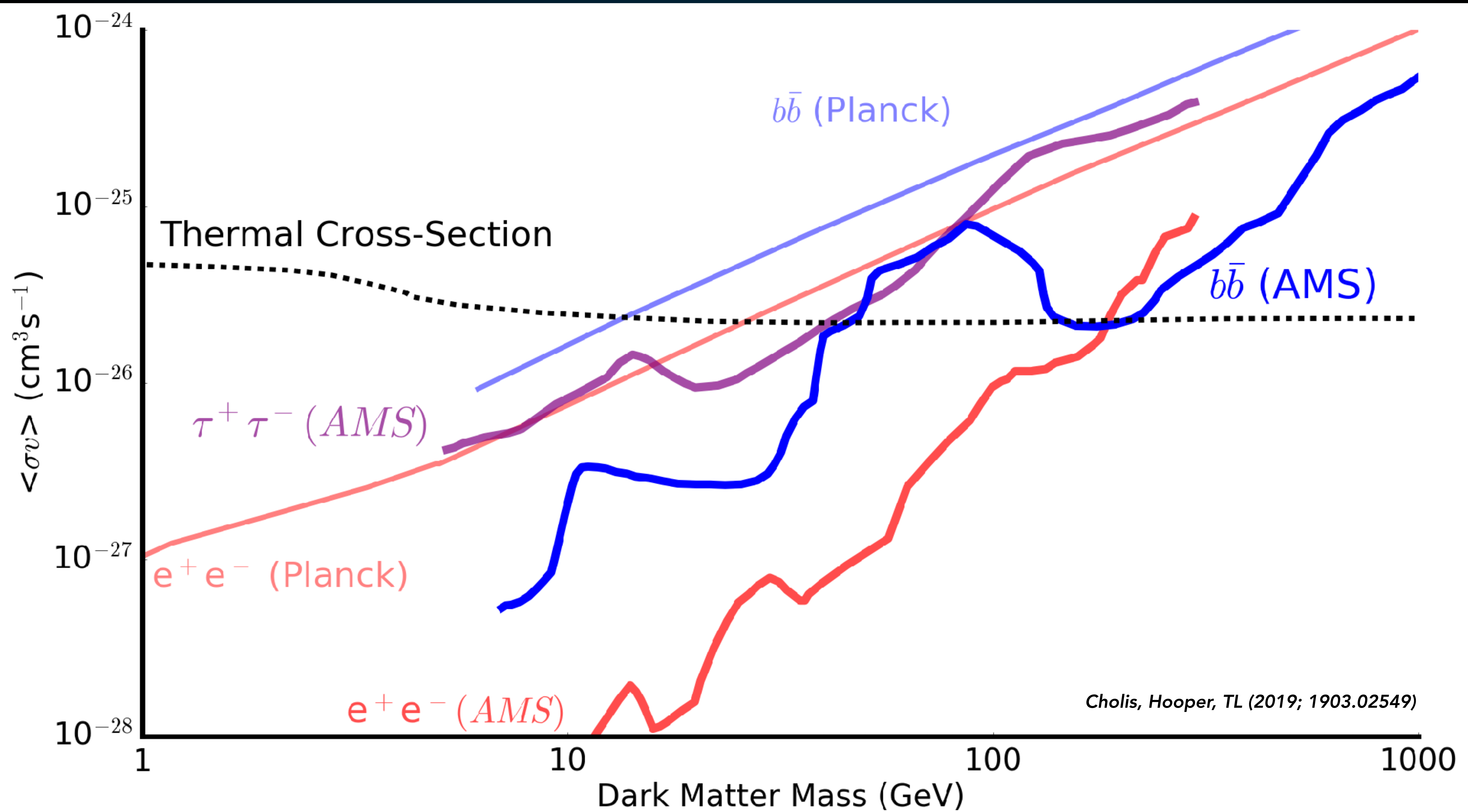




Madhavacheril et al. (2013; 1310.3815)







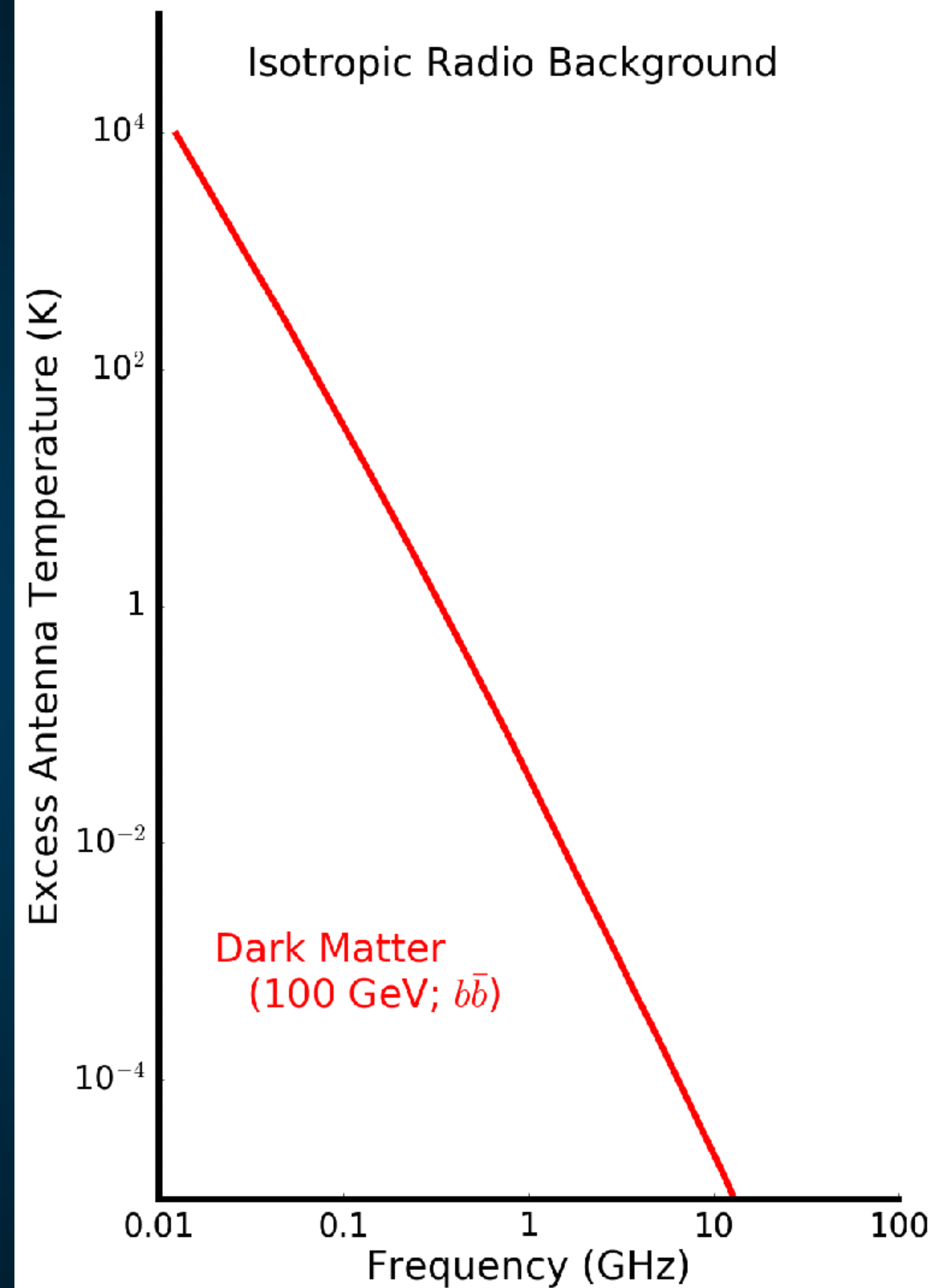
Thermal WIMPs and the Story of Tantalus

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

