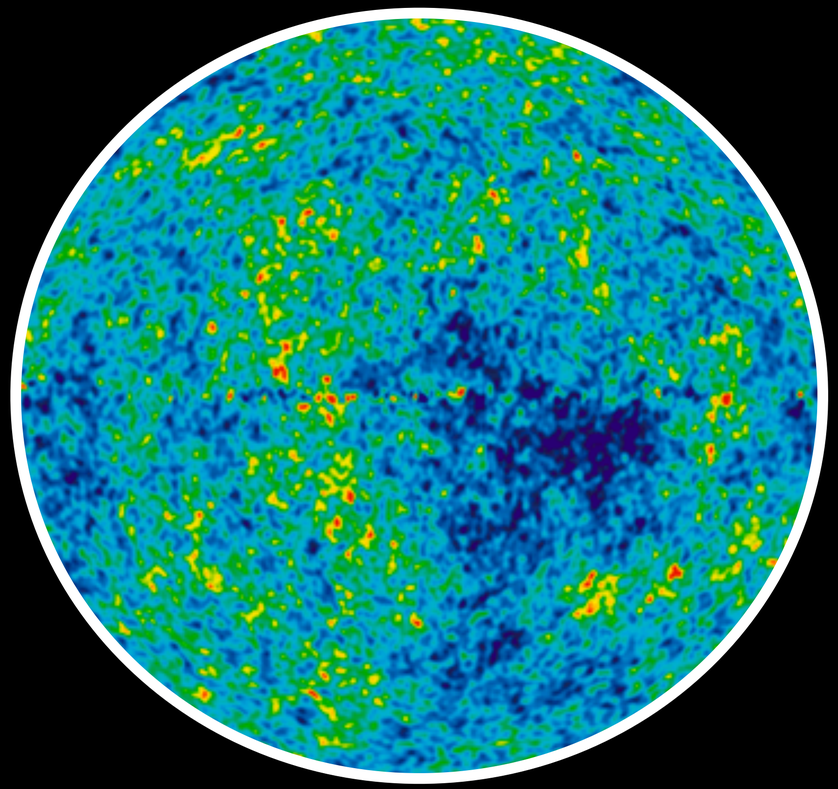
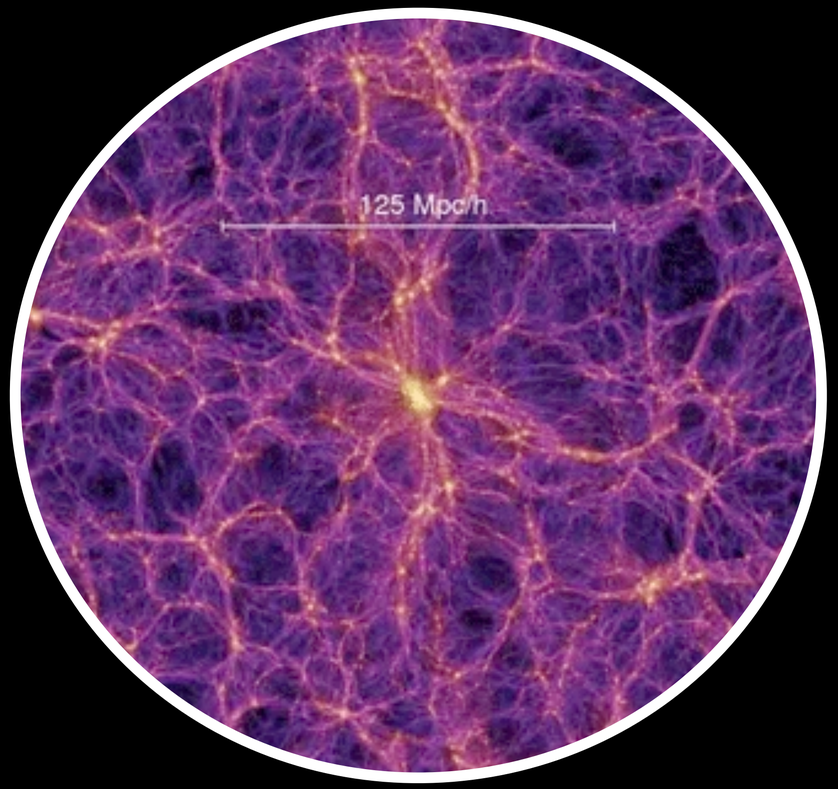
Tim Linden

Testing the Thermal WIMP Paradigm - Status and Prospects

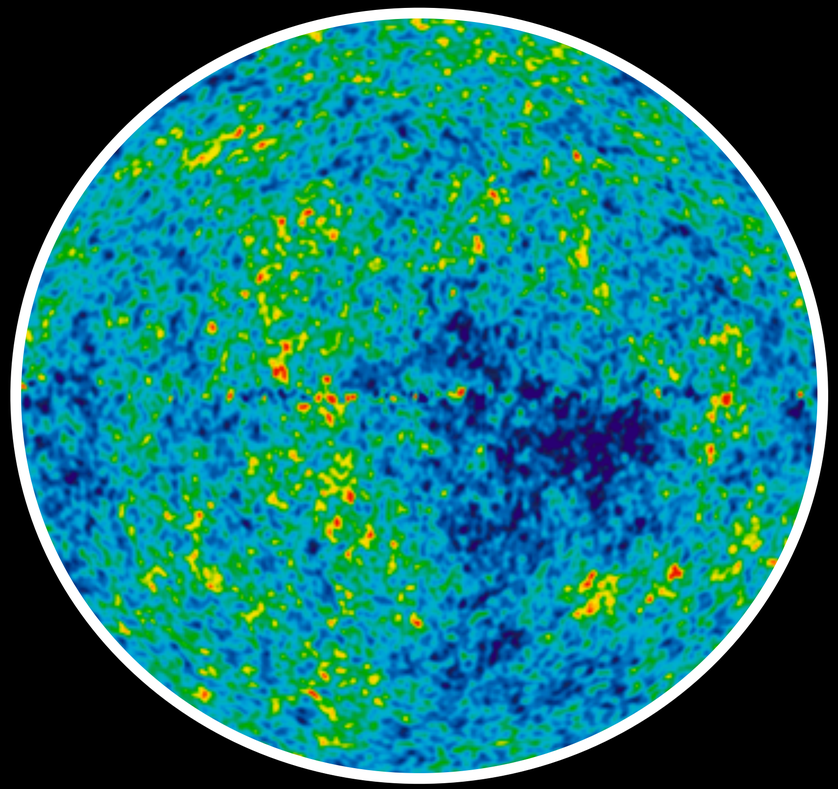
Stockholms universitet

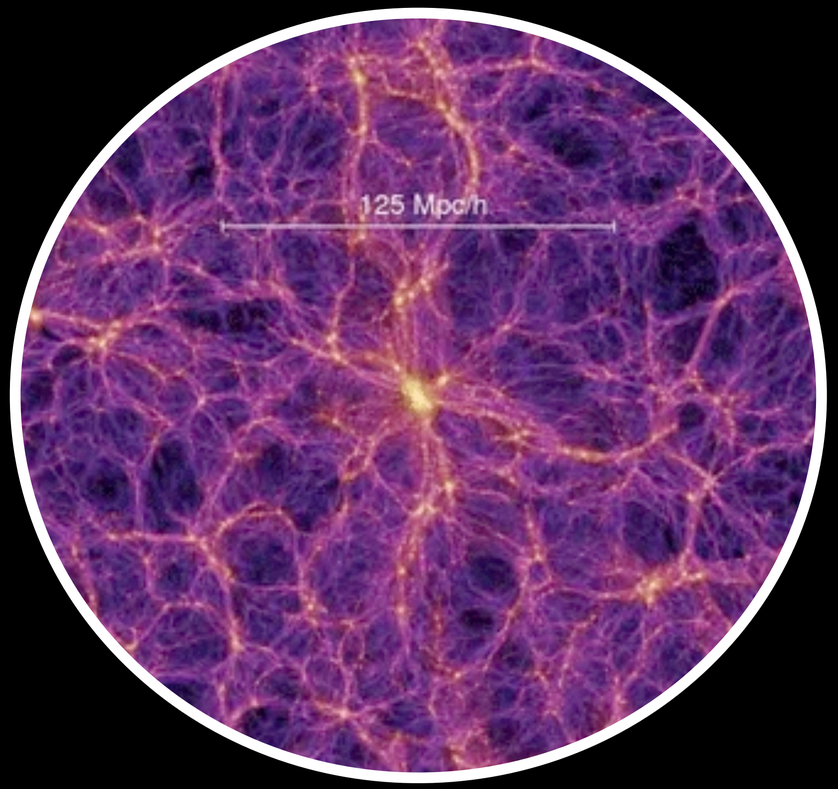
The Present





The Present





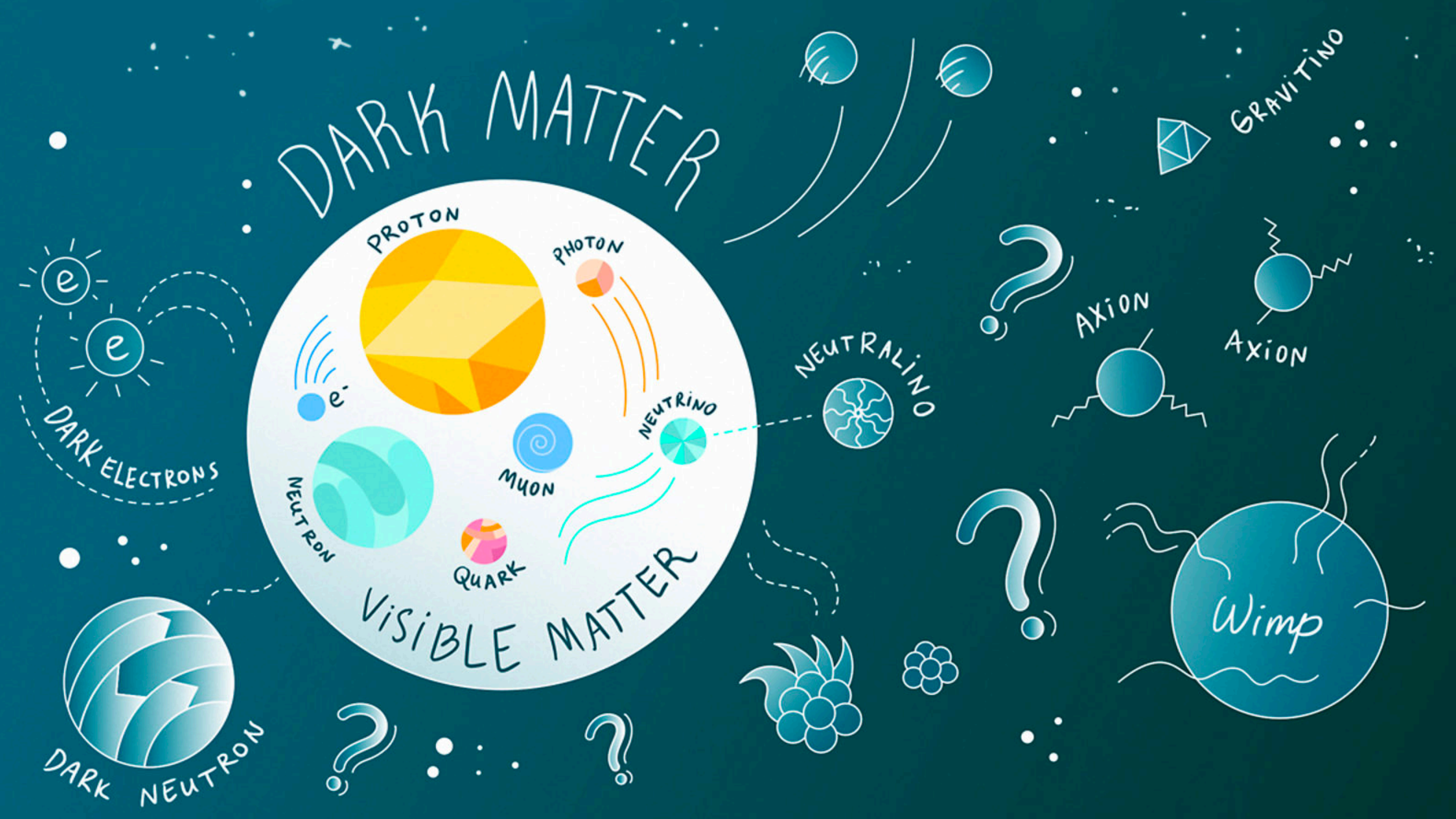
10^{-25} GeV

$R_{DM} > R_{UFD}$

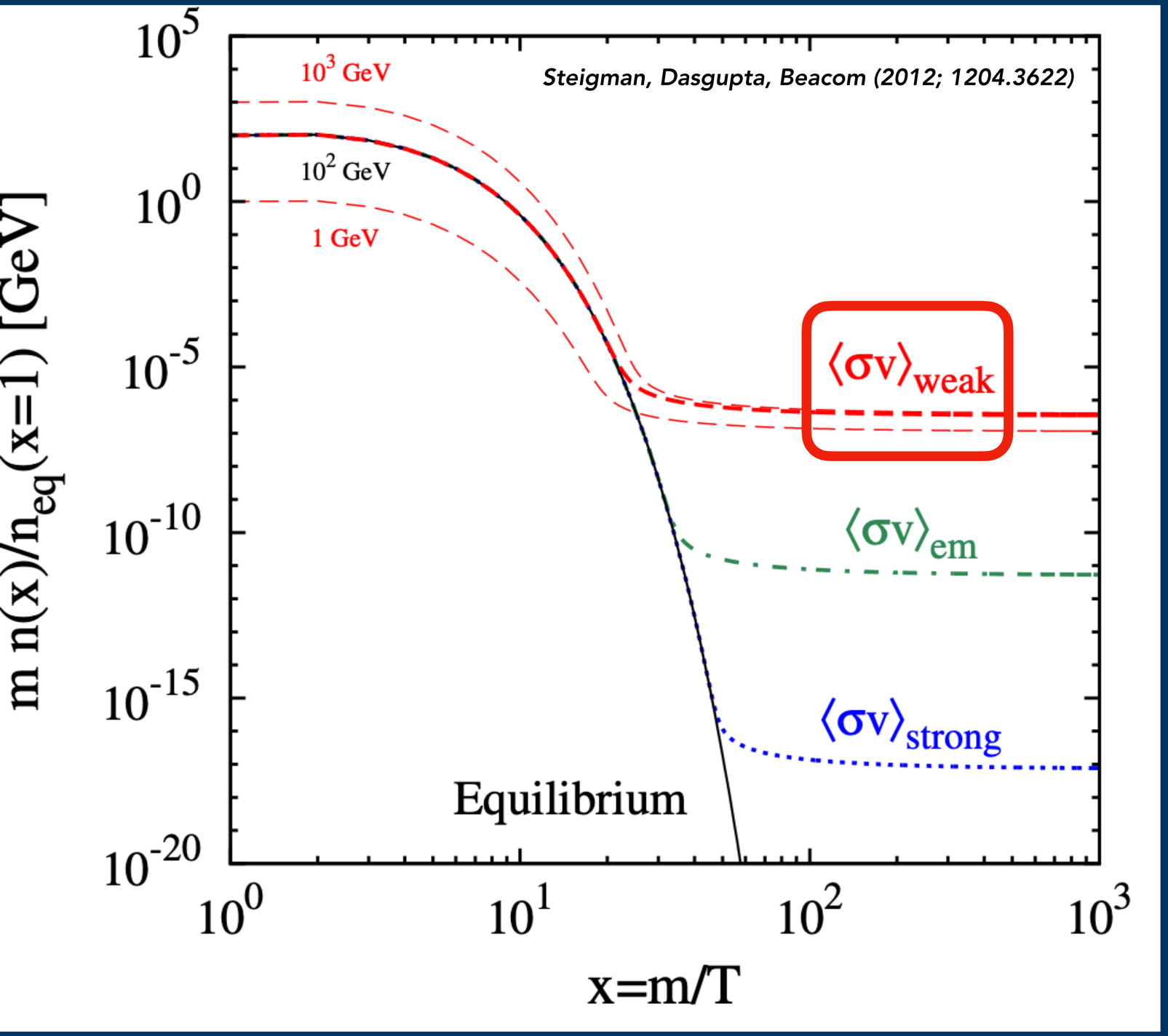
slide concept courtesy of Asher Berlin

10^{62} GeV

$M_{DM} > M_{UFD}$


DARK MATTER
PROTON
PHOTON
e⁻
NEUTRINO
MUON
NEUTRON
QUARK
VISIBLE MATTER
e
e
DARK ELECTRONS
DARK NEUTRON
NEUTRALINO
GRAVITINO
AXION
AXION
Wimp

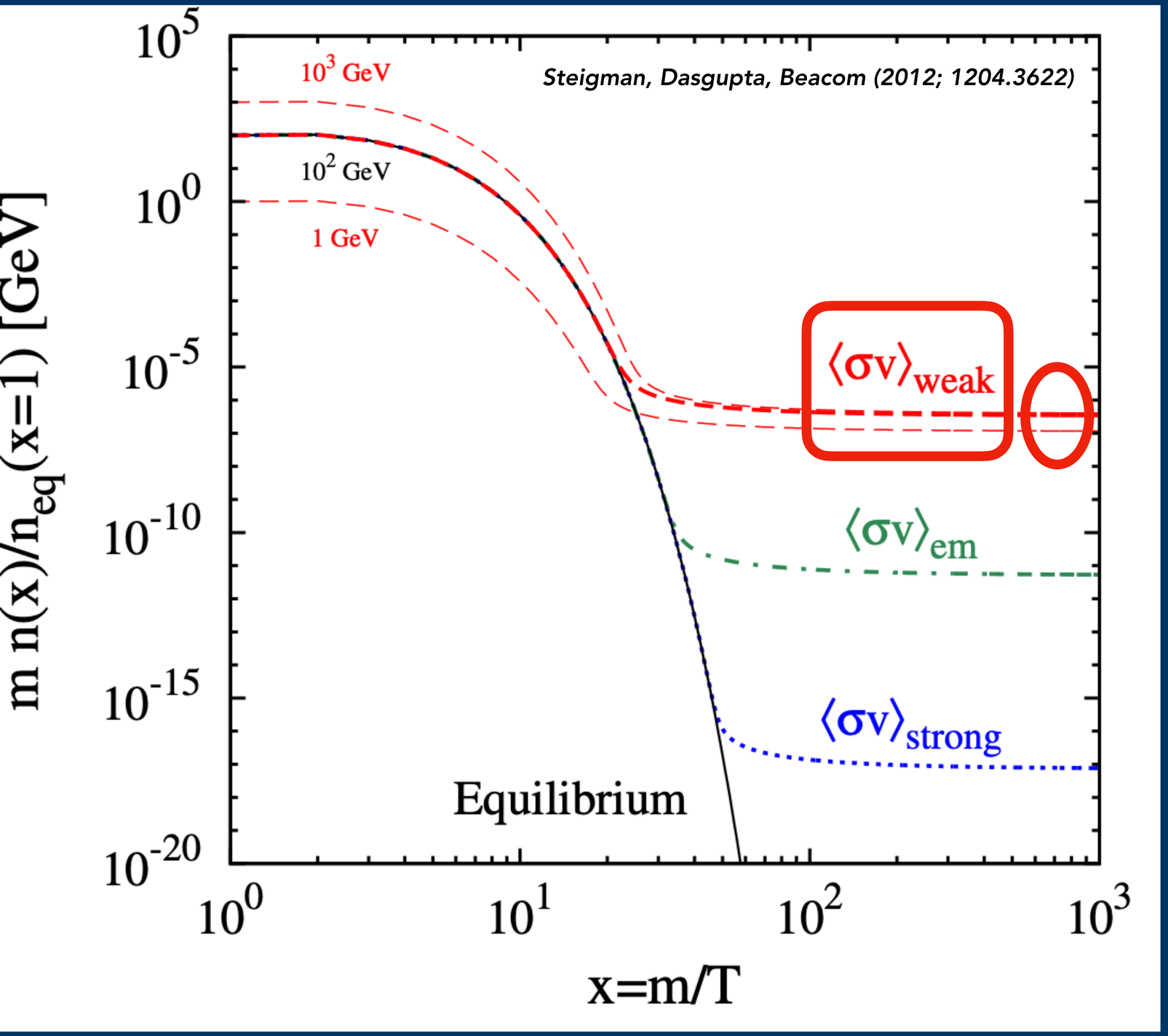
Thermal Dark Matter Density



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

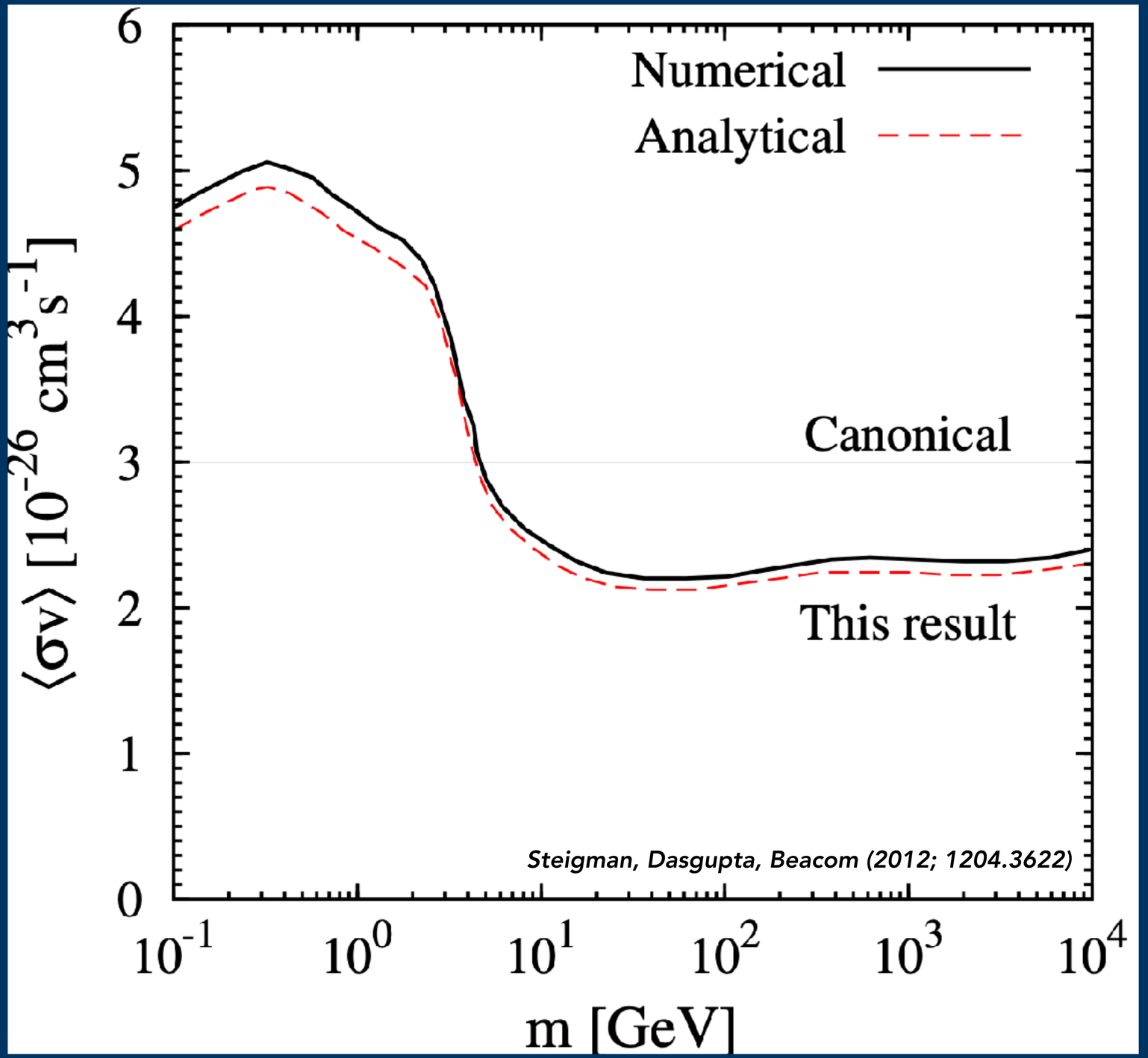
Present density inversely proportional to the strength of the interaction.

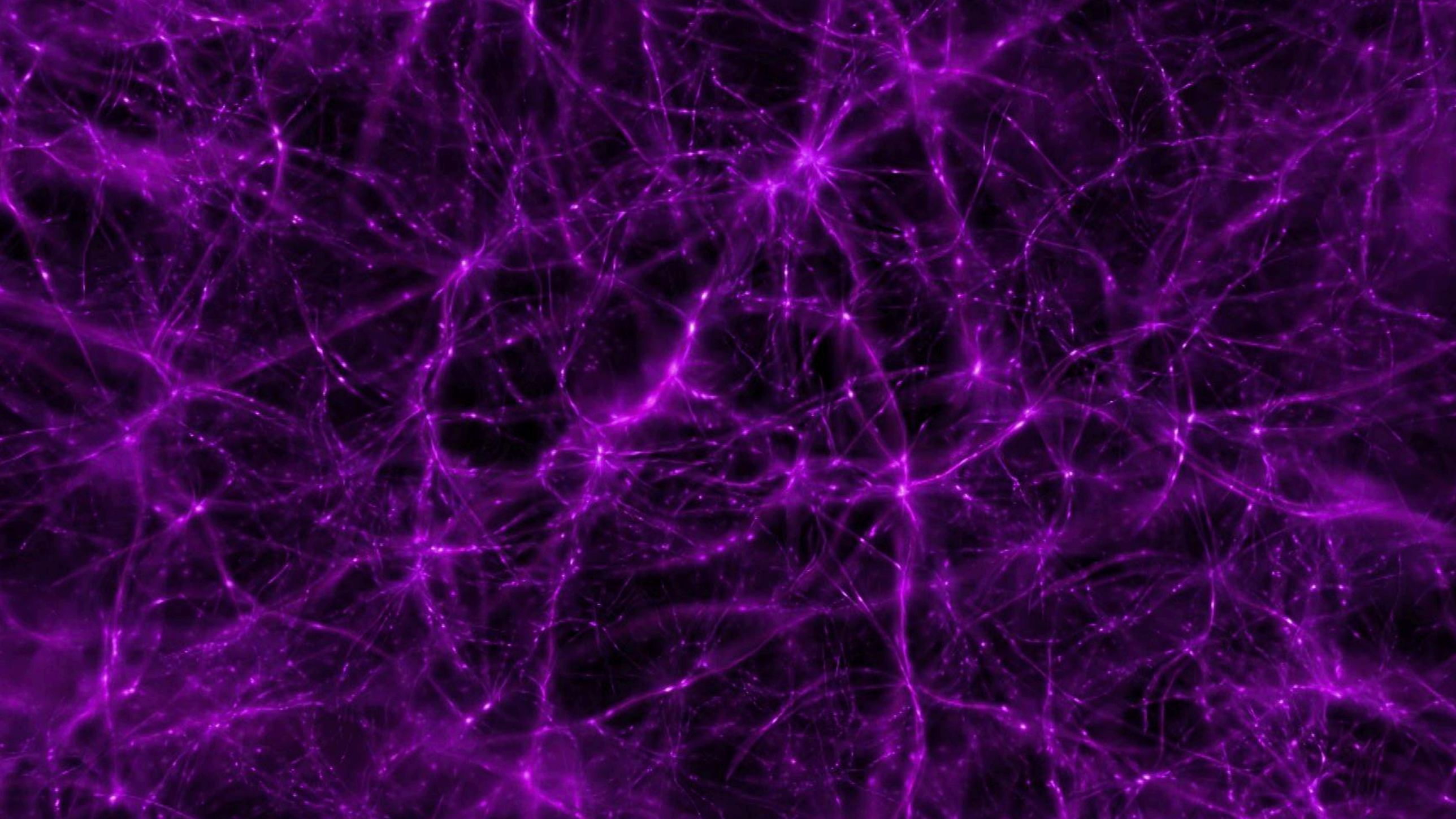
Almost independent of particle mass.

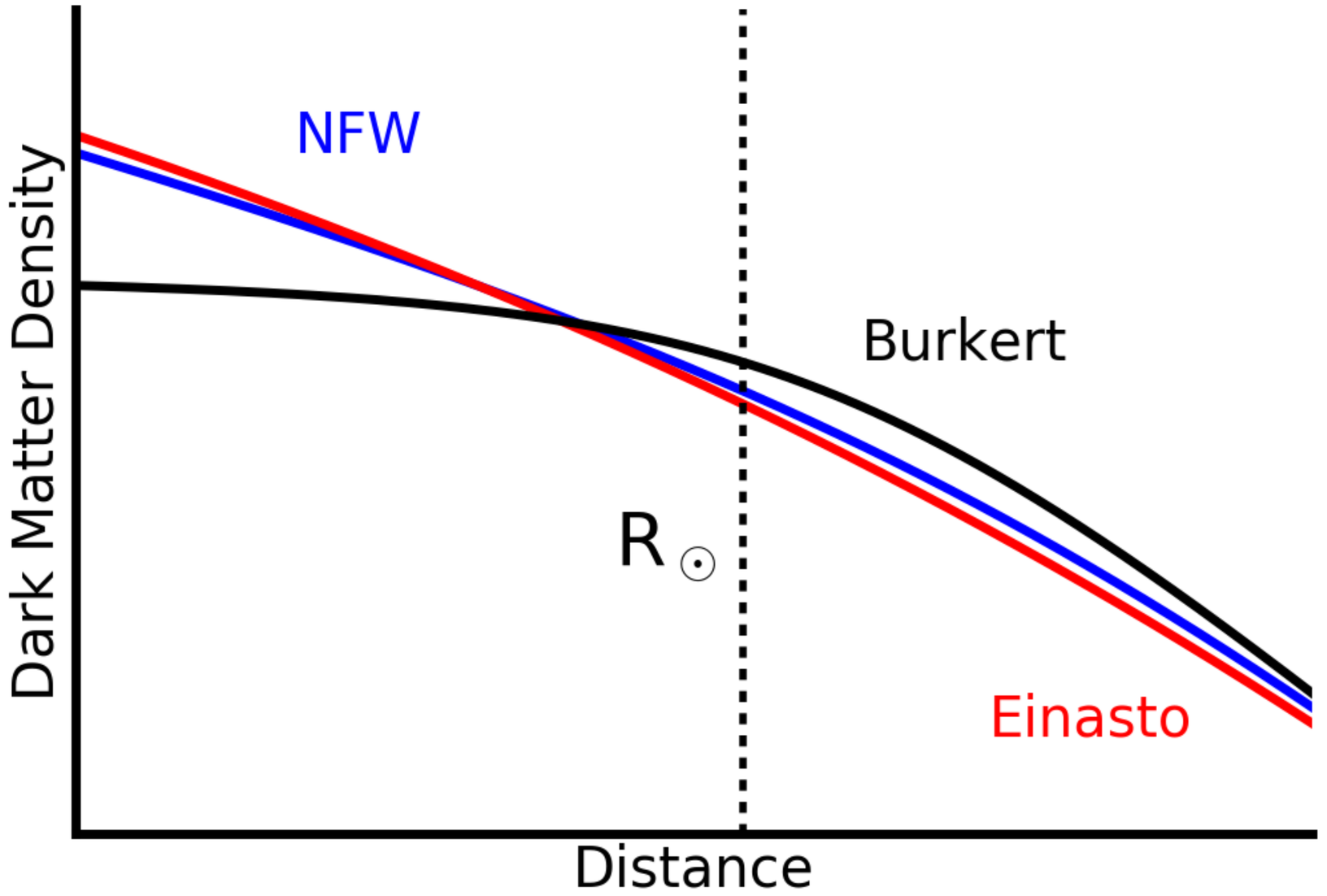
Weak-Interaction Produces the right density!

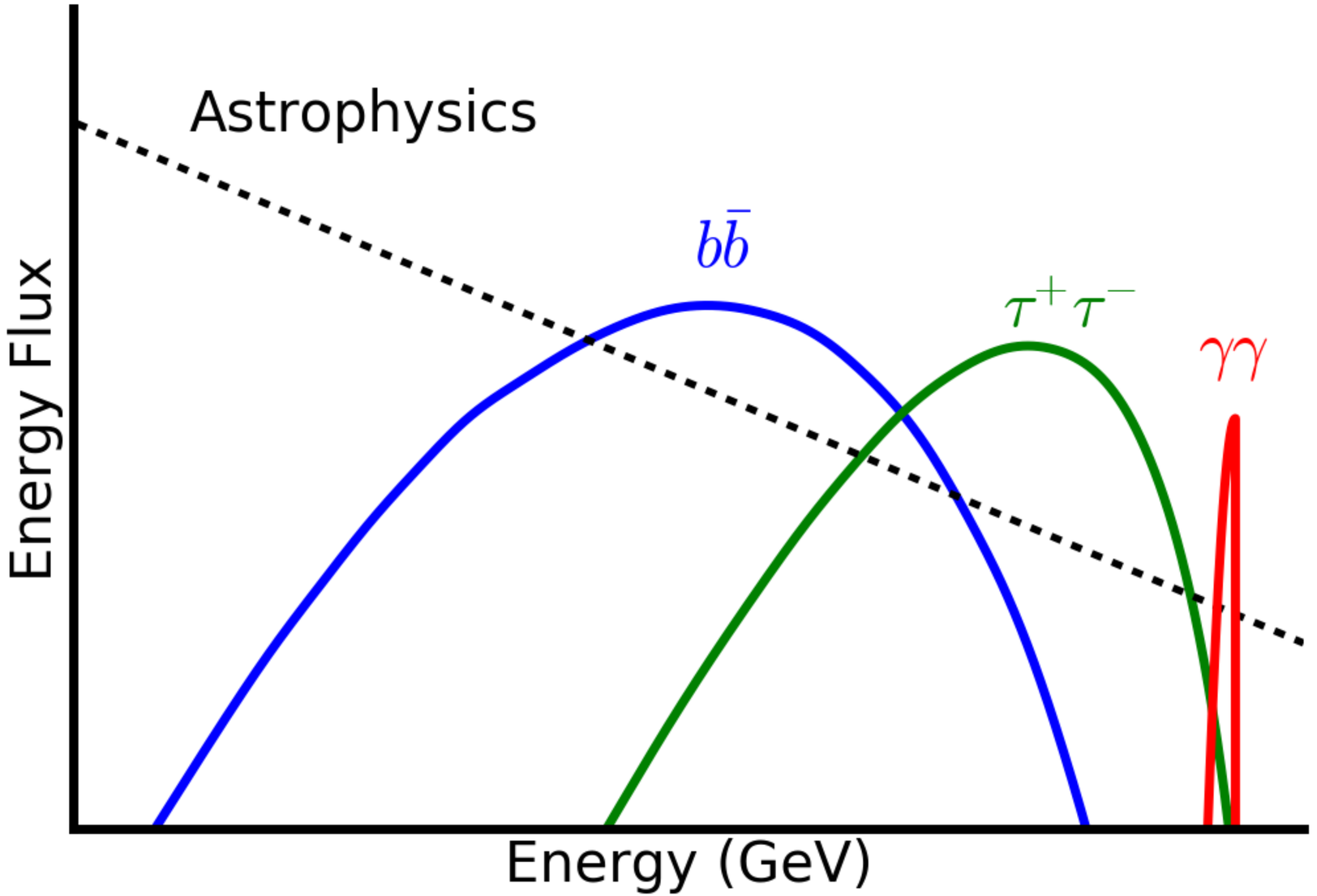
10 MeV - 100 TeV !

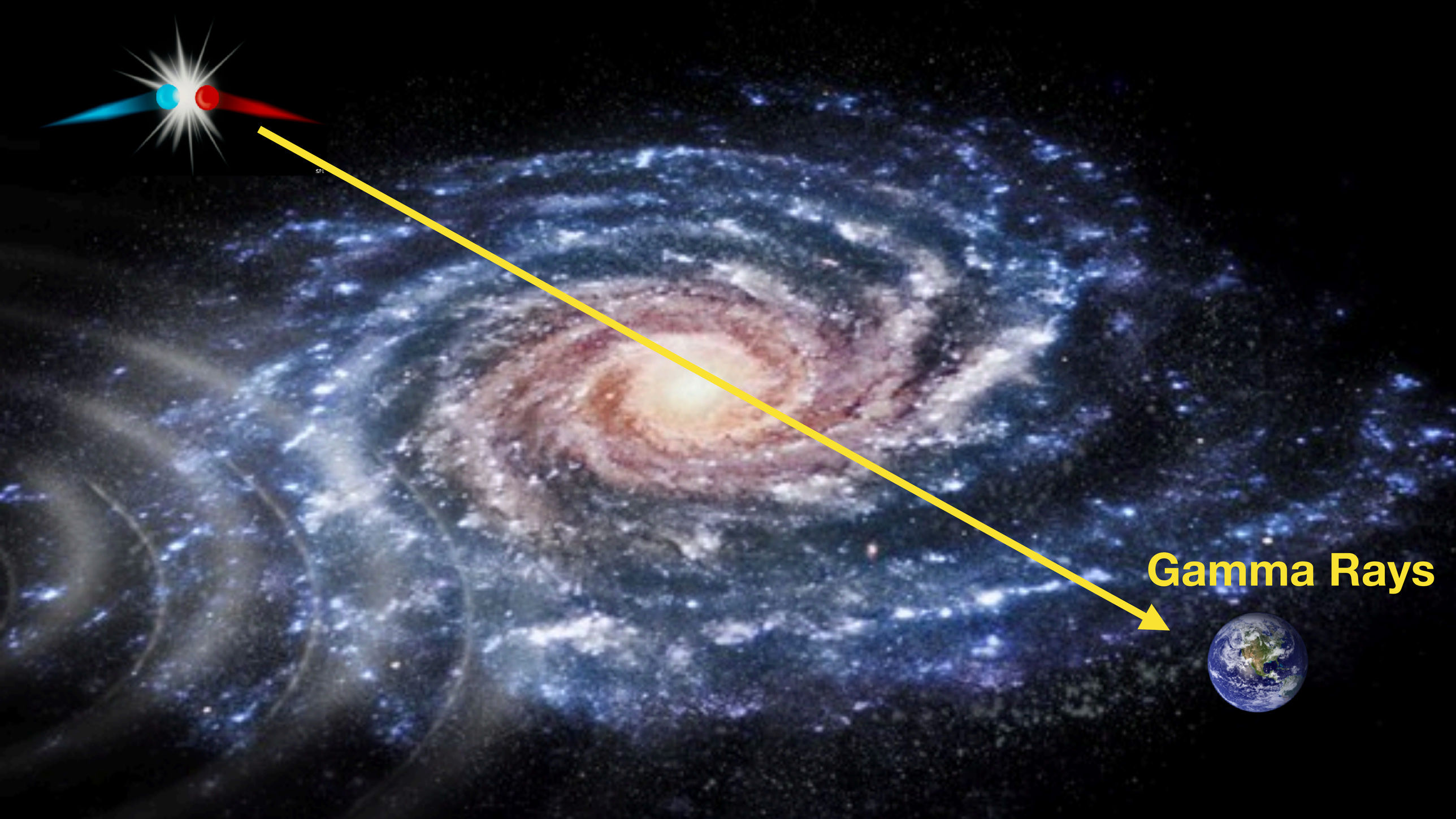
Lee, Weinberg (1977; PRL 39 4)
Ho, Scherrer (2012; 1208.4347)


Numerical
Analytical
Canonical
This result
Steigman, Dasgupta, Beacom (2012; 1204.3622)
⟨σv⟩ [10^-26 cm^3 s^-1]
m [GeV]
0
1
2
3
4
5
6
10^-1
10^0
10^1
10^2
10^3
10^4




NFW
Burkert
Einasto
R⊙
Dark Matter Density
Distance


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

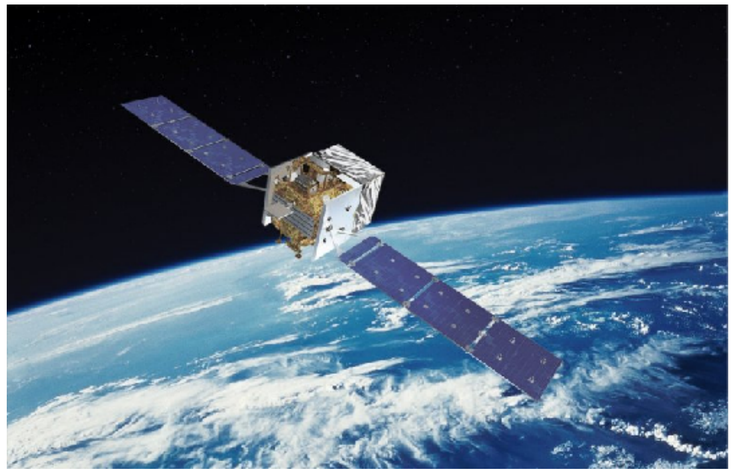

Gamma Rays


Cosmic Rays
Gamma Rays

Most Important Takeaway #1

Most Important Takeaway #1

We might already be seeing these events.



Thermal Cross-Section

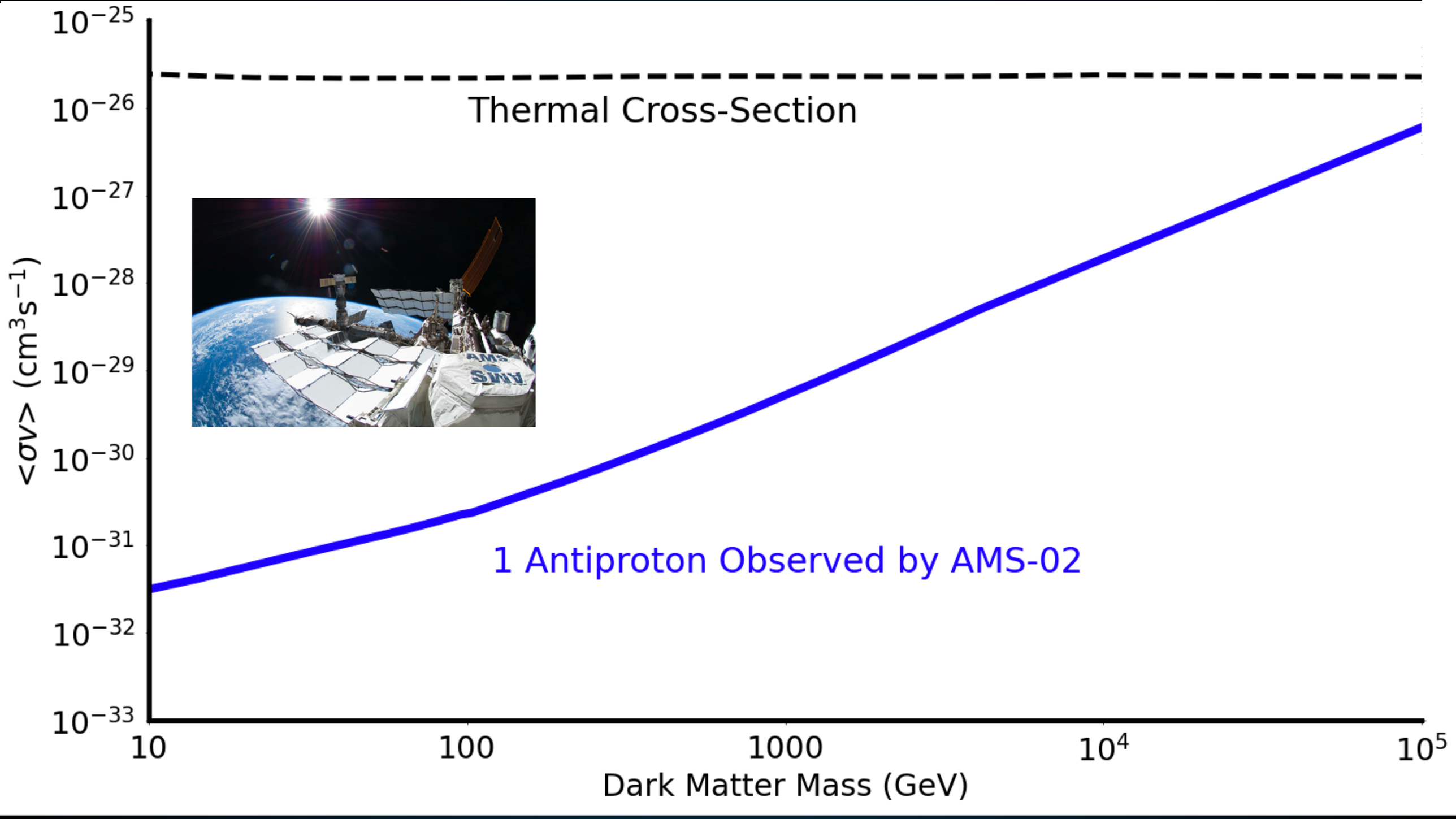
1 Observed Photon Within 10° of Galactic Center

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

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

10
100
1000
10^4
10^5

Dark Matter Mass (GeV)


Thermal Cross-Section
1 Antiproton Observed by AMS-02
AMS
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
$<\sigma v>$ ($cm^3 s^{-1}$)
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

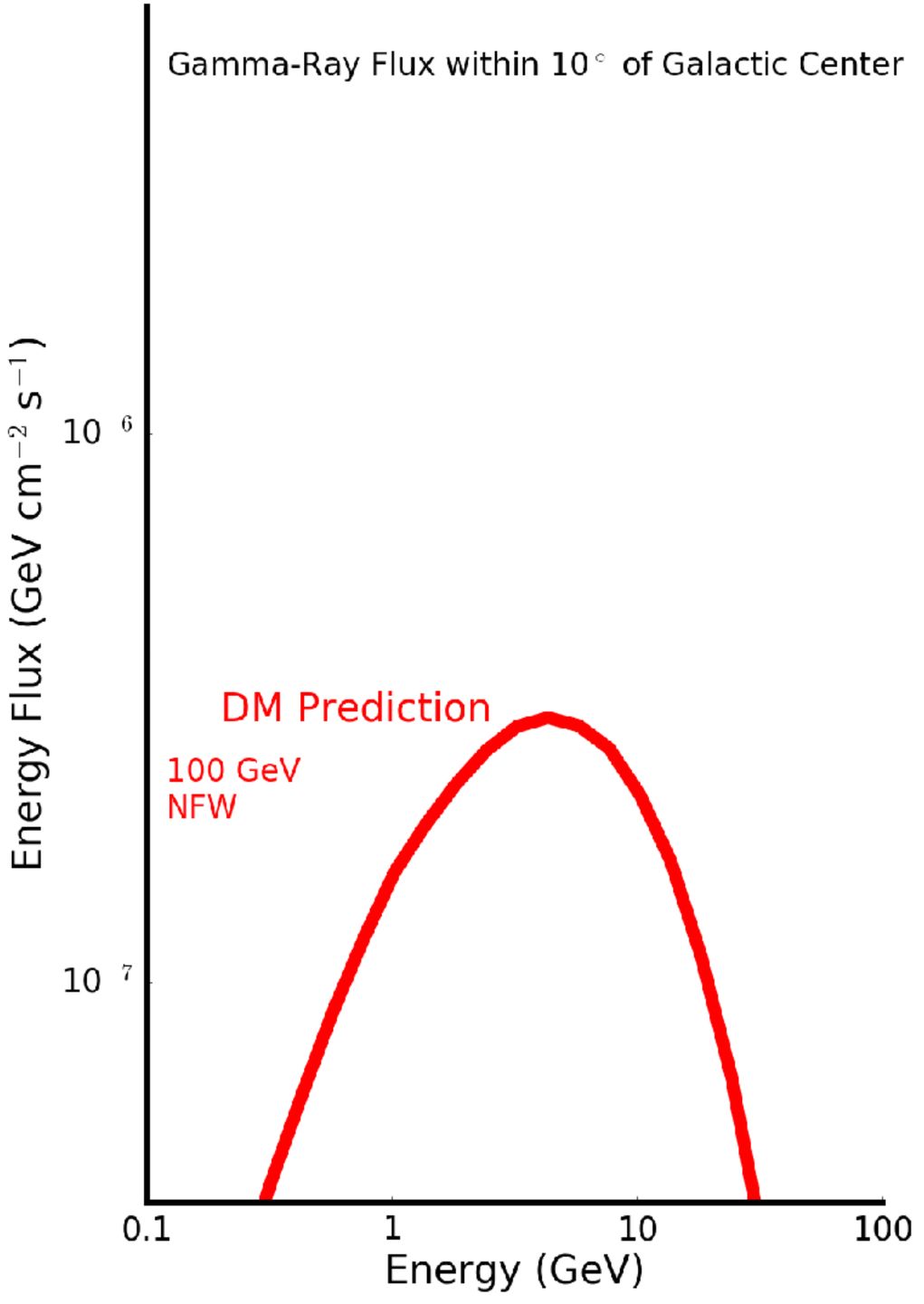
Thermal WIMPs and the Story of Tantalus

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)

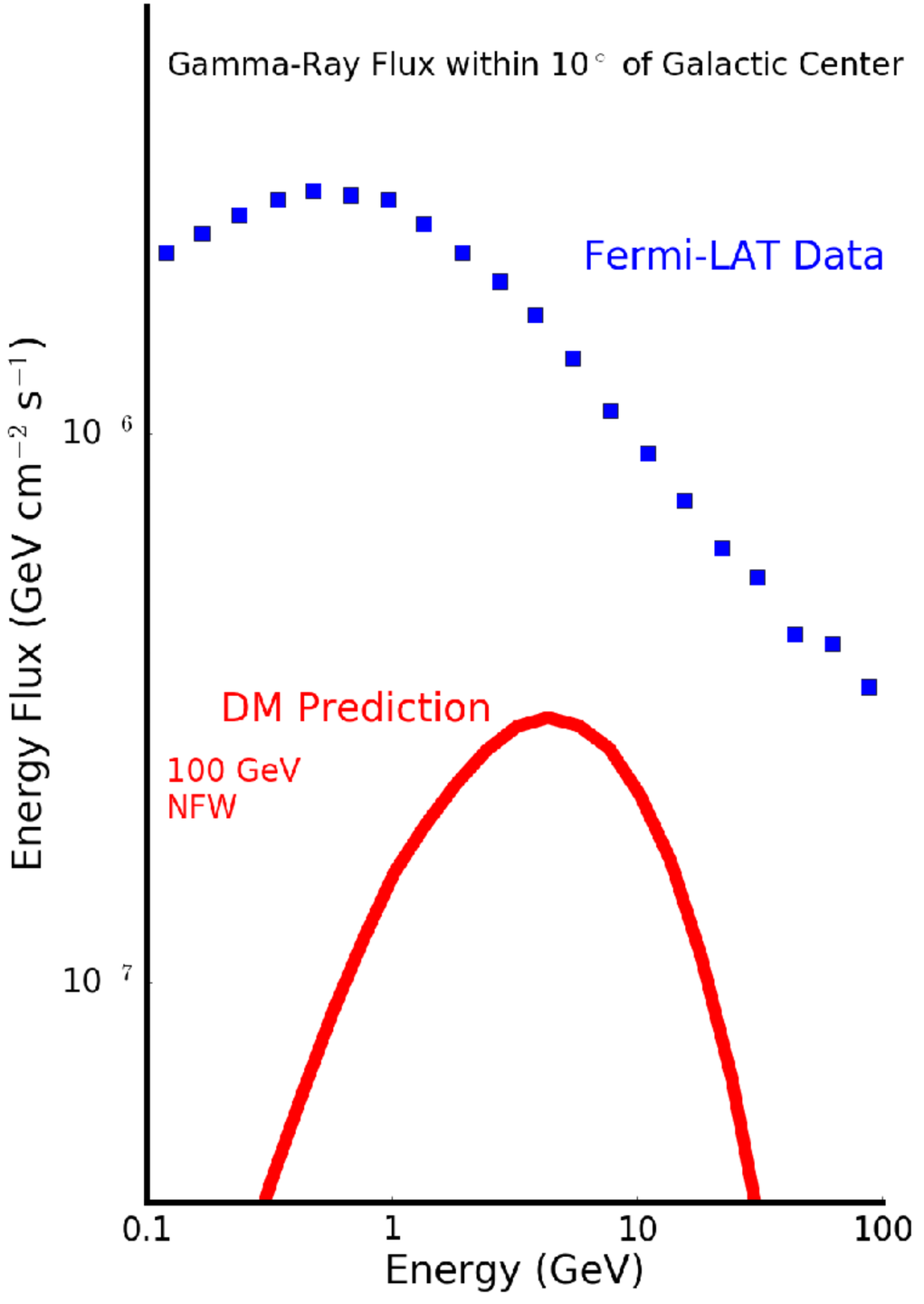
Dark Matter Mass (?)

Annihilation Final State (?)

Milky Way Star-Formation Rate (Galactic Dynamics)

Diffusion Constant in Galactic Center (Hydrodyanmics)

Activity of Supermassive Blackhole (?)



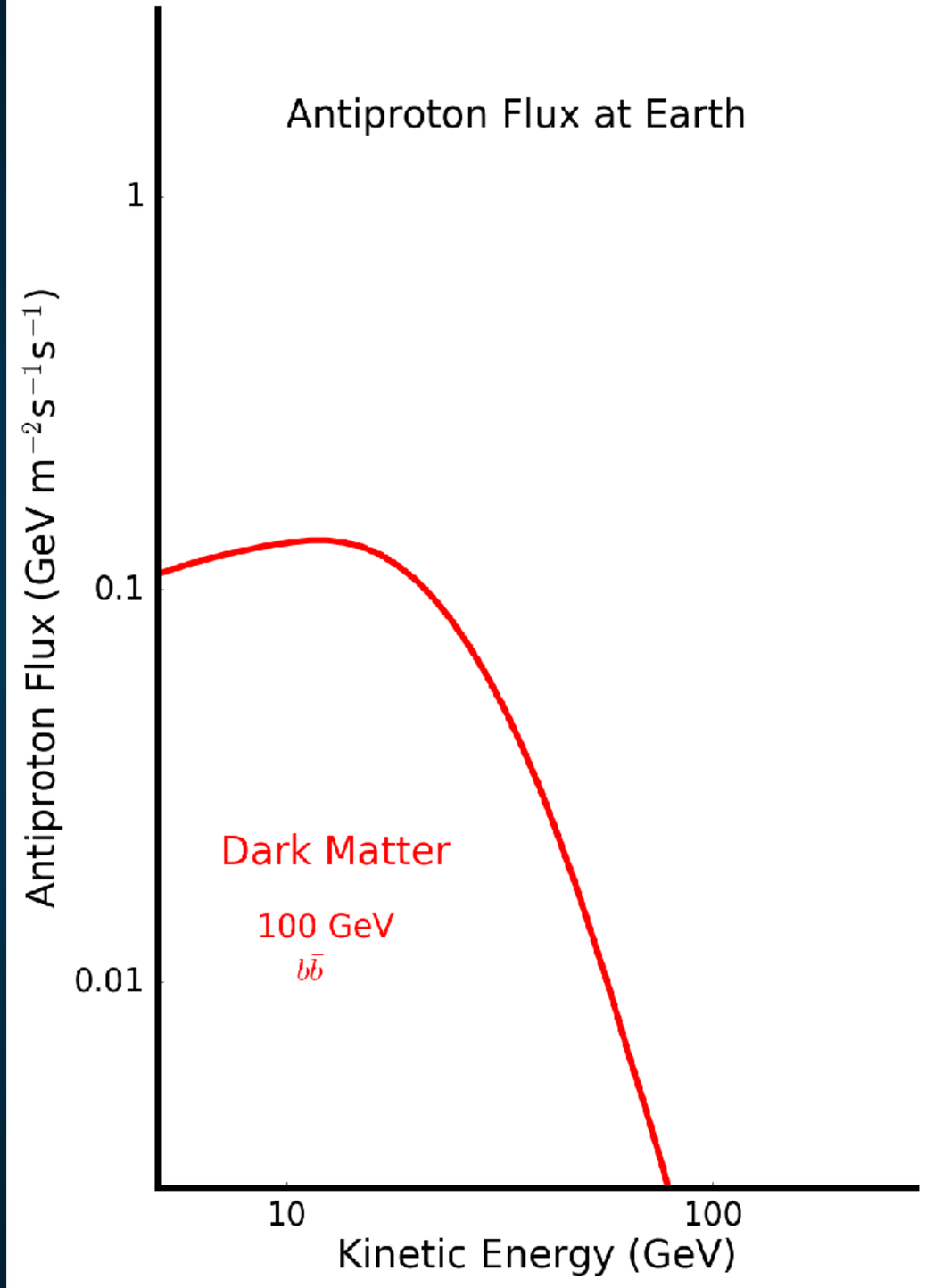
Thermal WIMPs and the Story of Tantalus

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

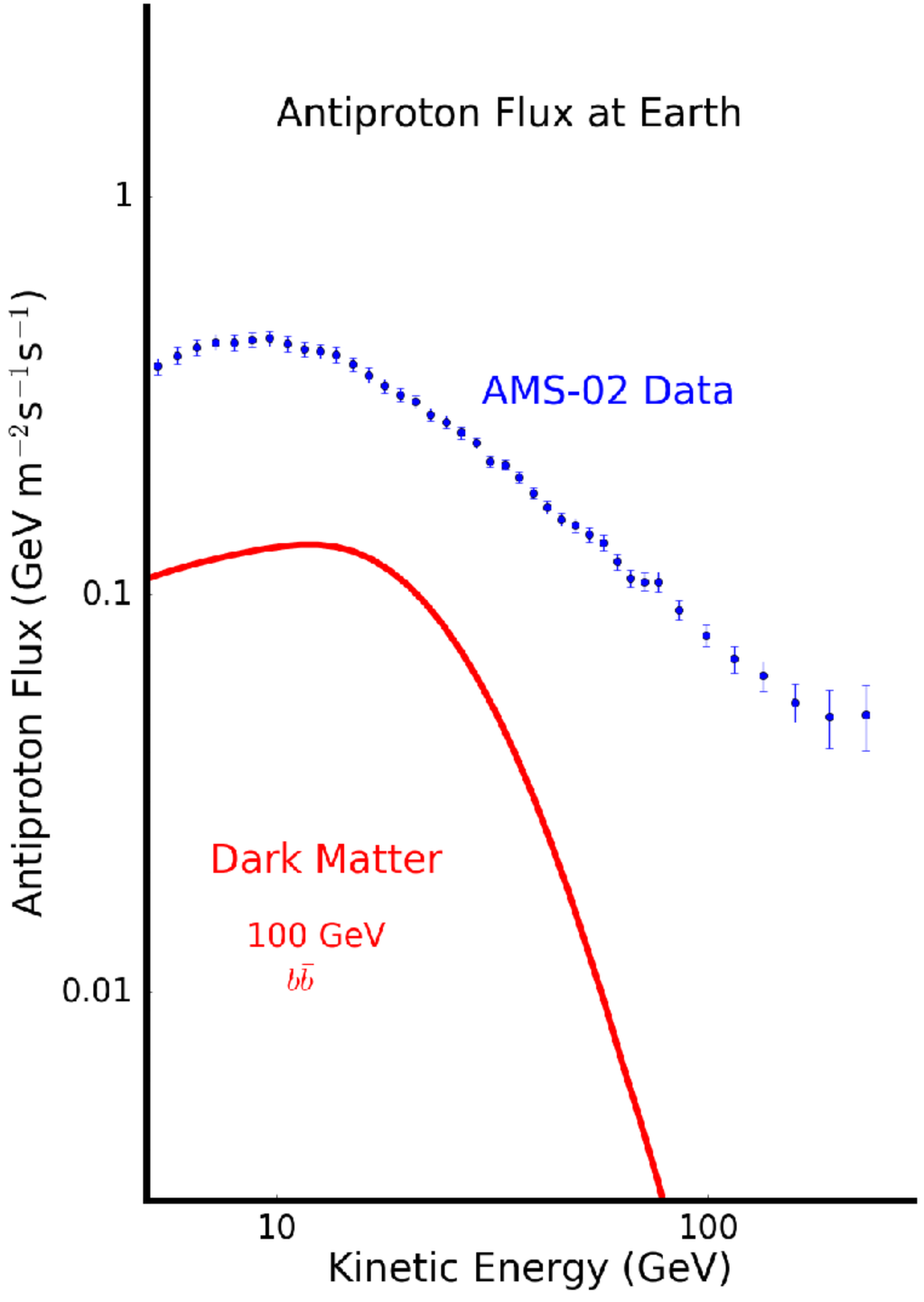
Thermal Cross-Section (Early Universe)

Hadronic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

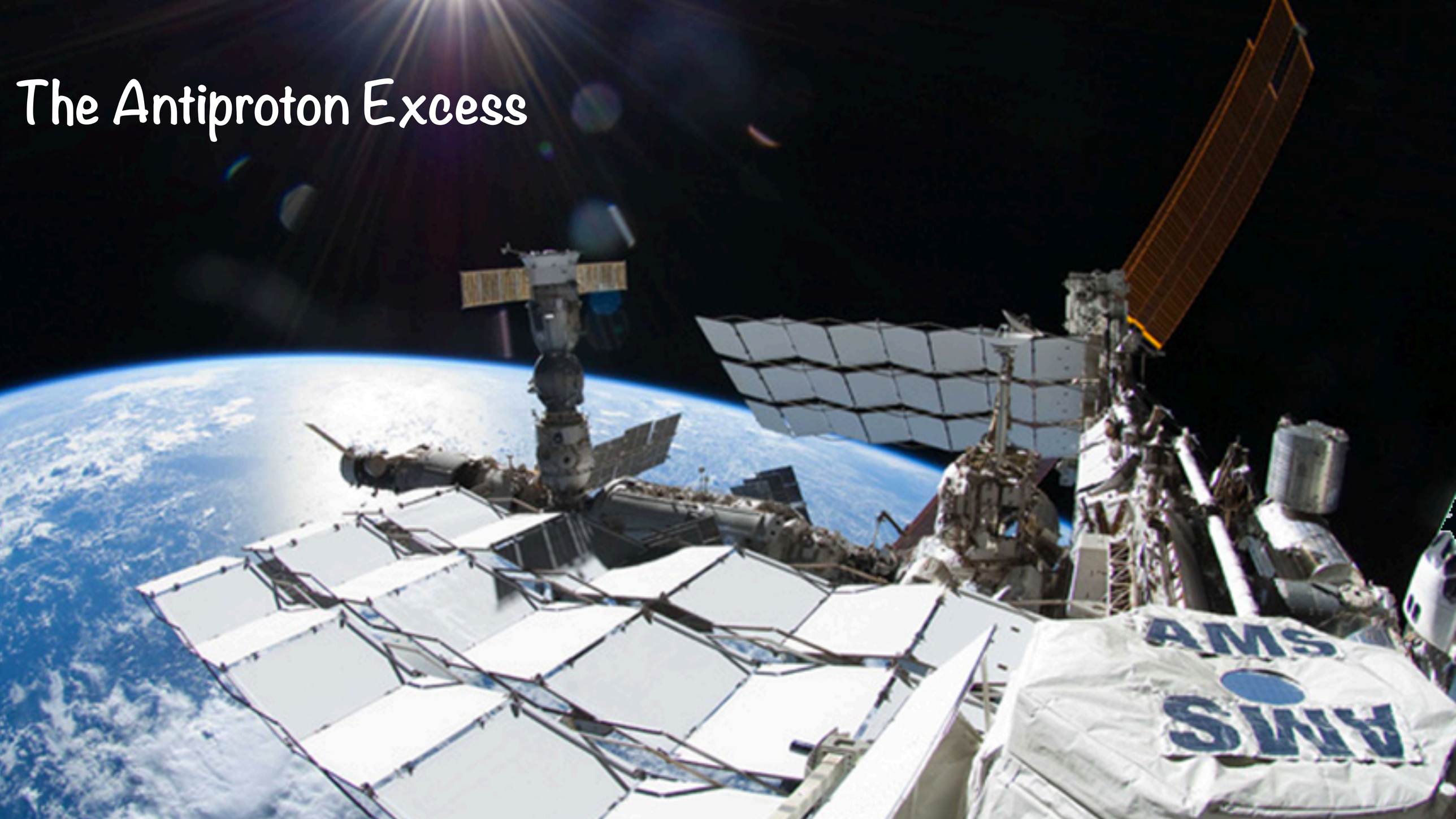
Local Gas Density

Local Supernova Rate



Thermal WIMPs and the Story of Tantalus

The Antiproton Excess



The Antiproton Excess

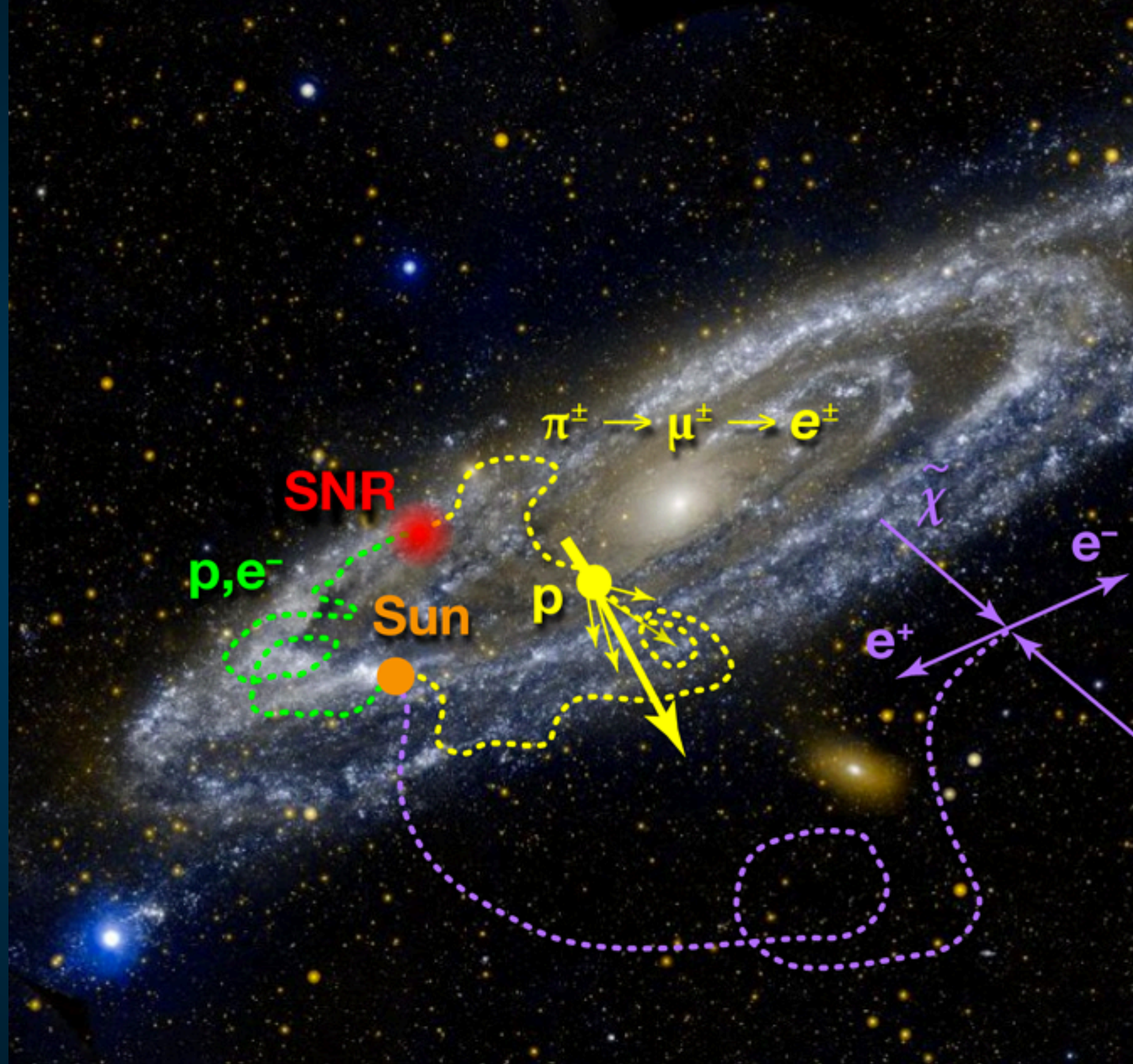
Investigate the Antiproton Fraction!

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

Two Changes:

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

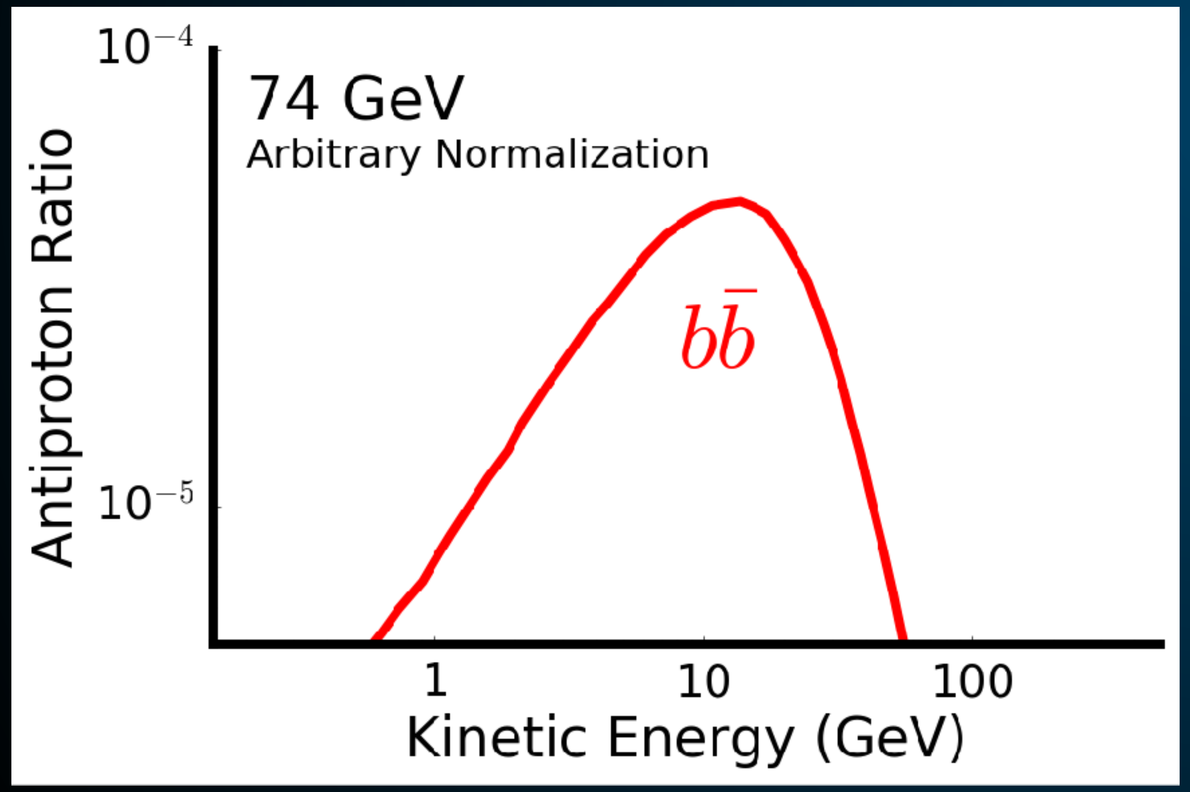
Hadronic Energy losses are slower (sensitive to antiproton production throughout the Galaxy)

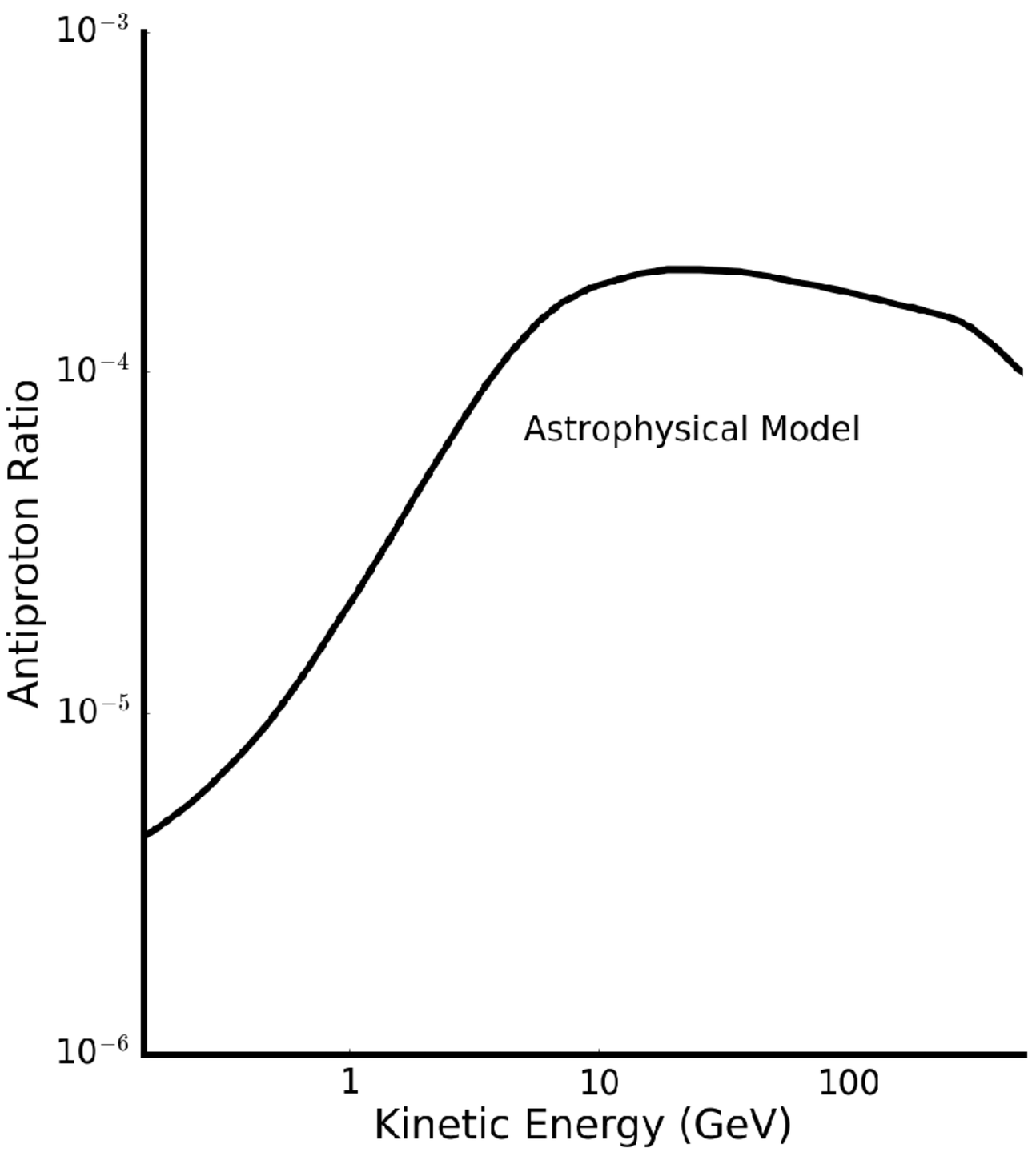


The Antiproton Excess

Astrophysics - Smooth Profile

Dark Matter - Sharp Bump!





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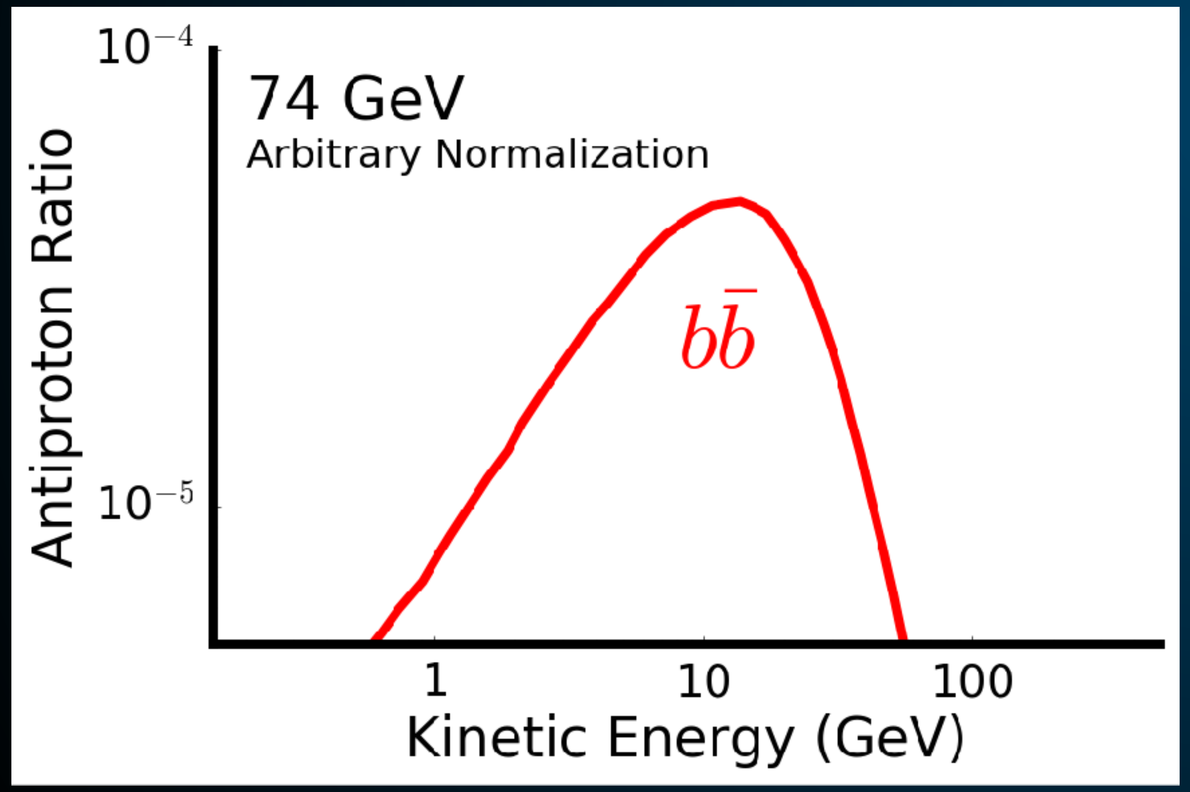
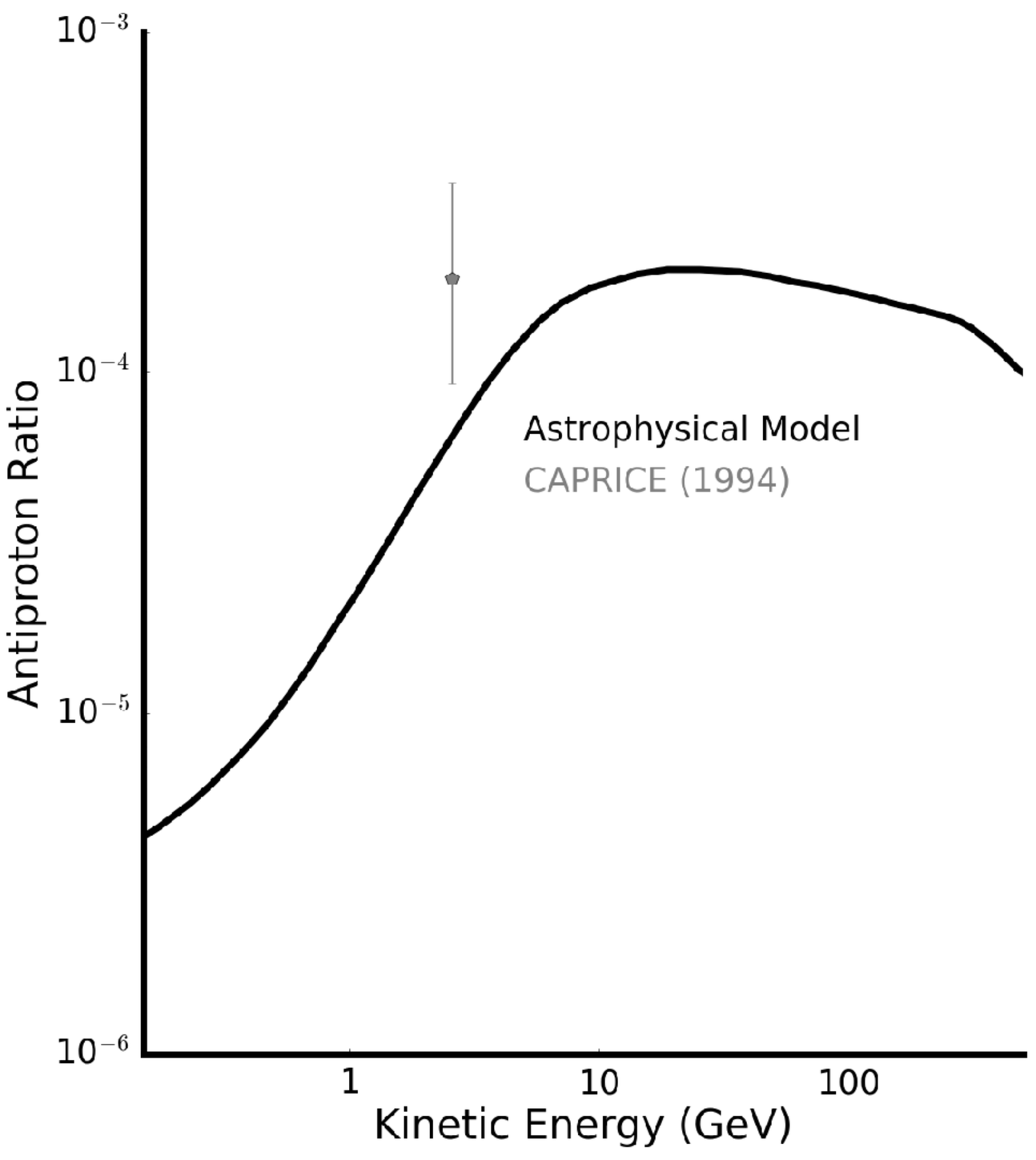


(Not an exhaustive list of observations)



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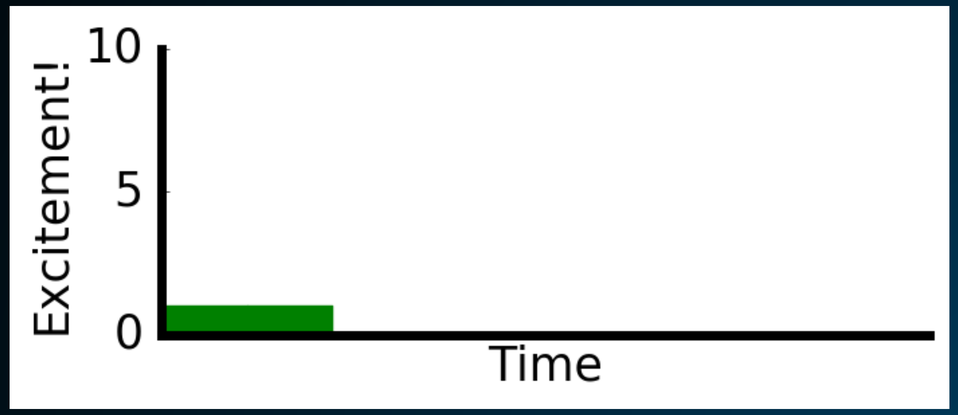

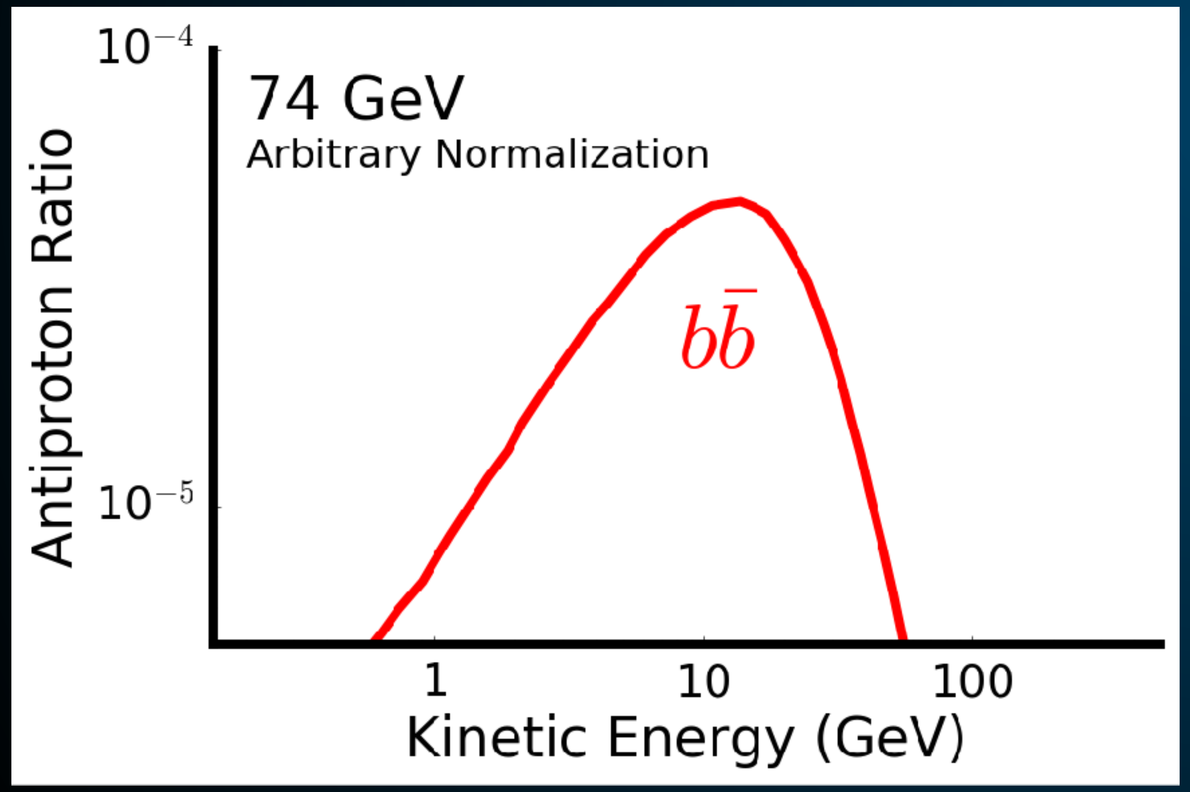

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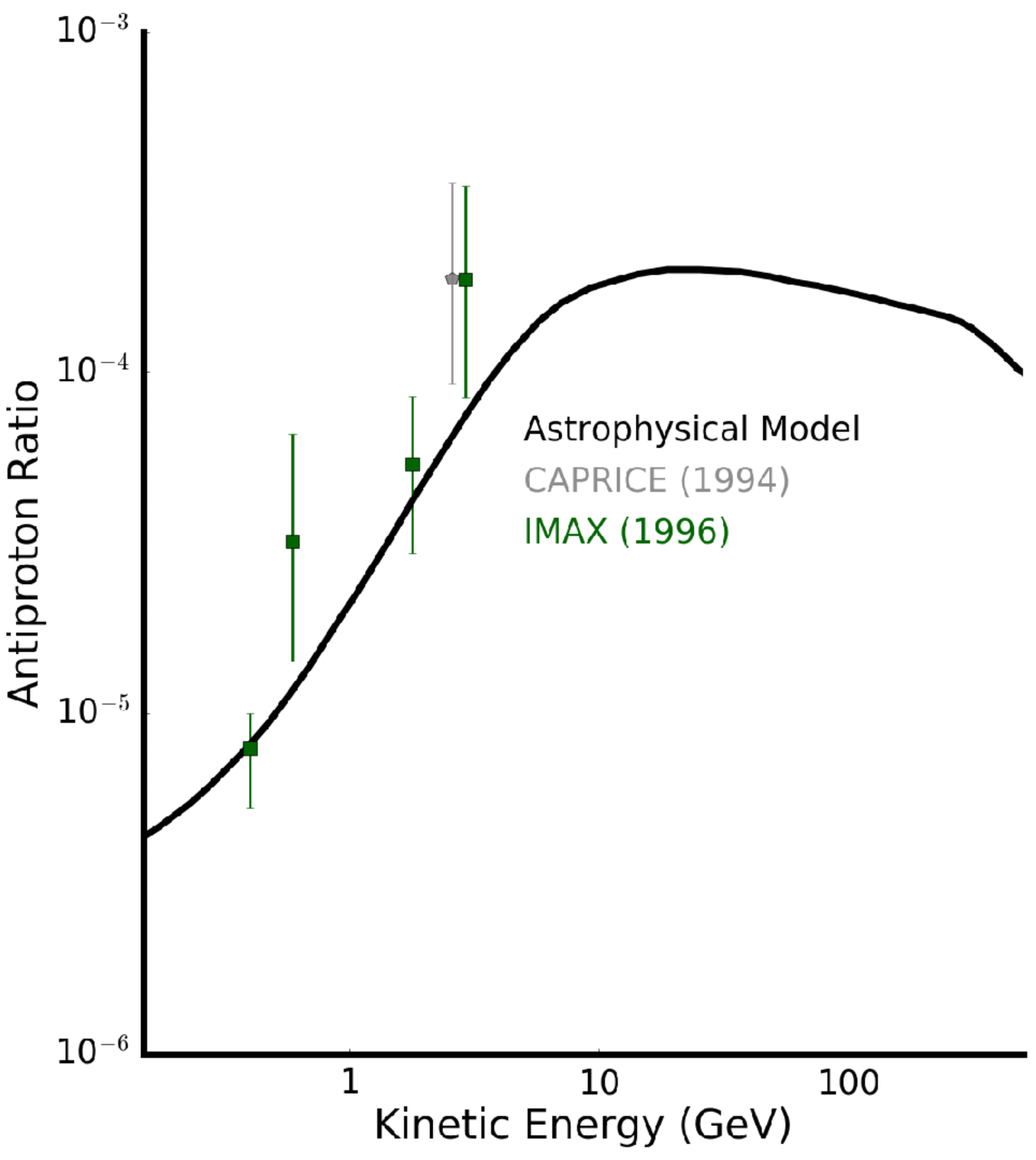

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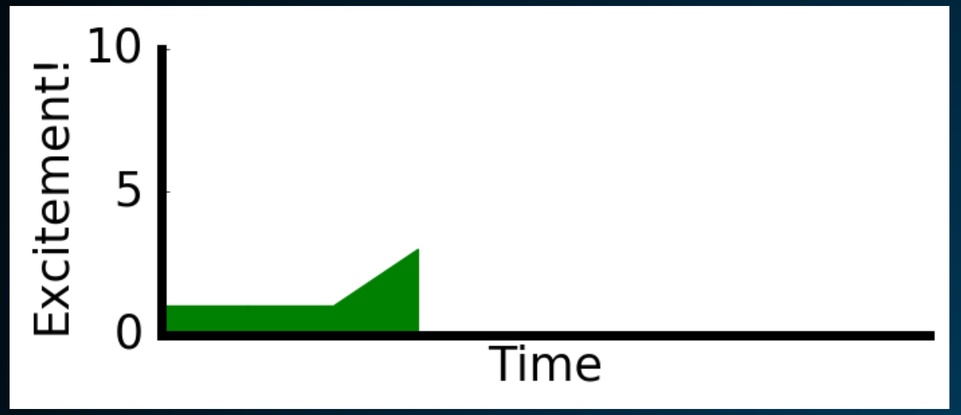

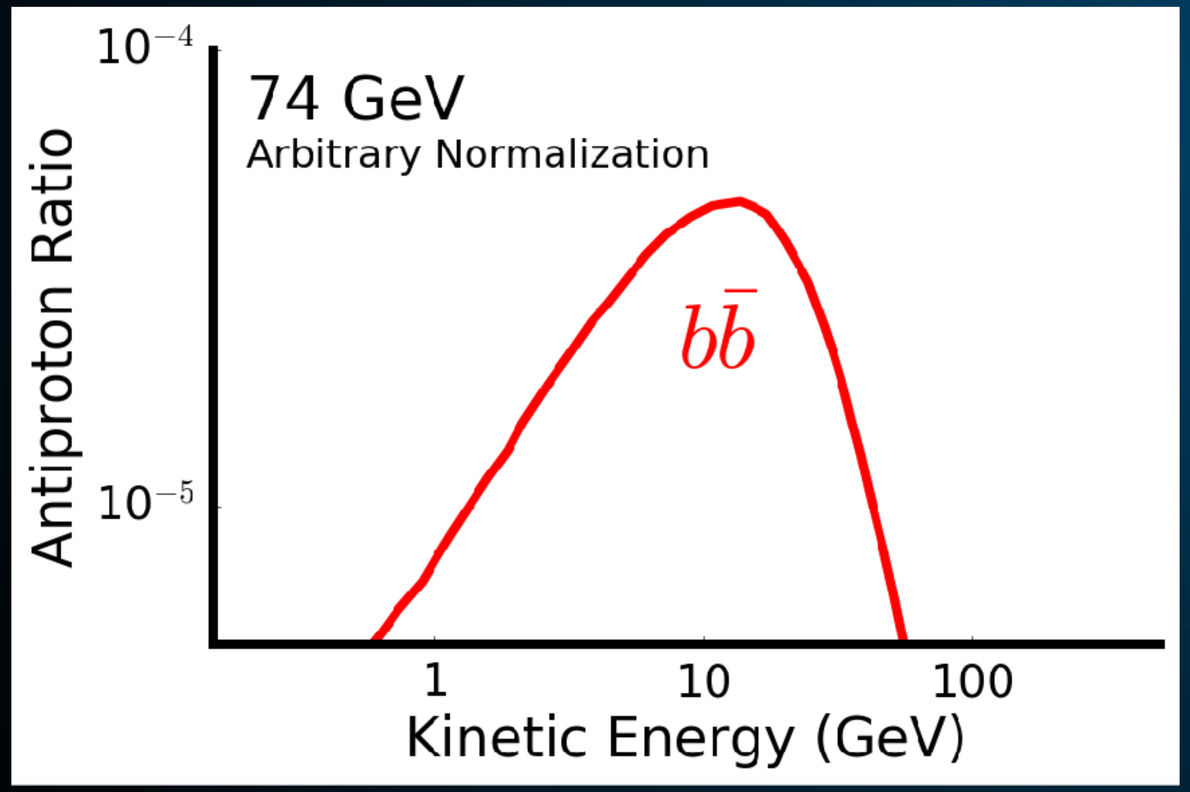

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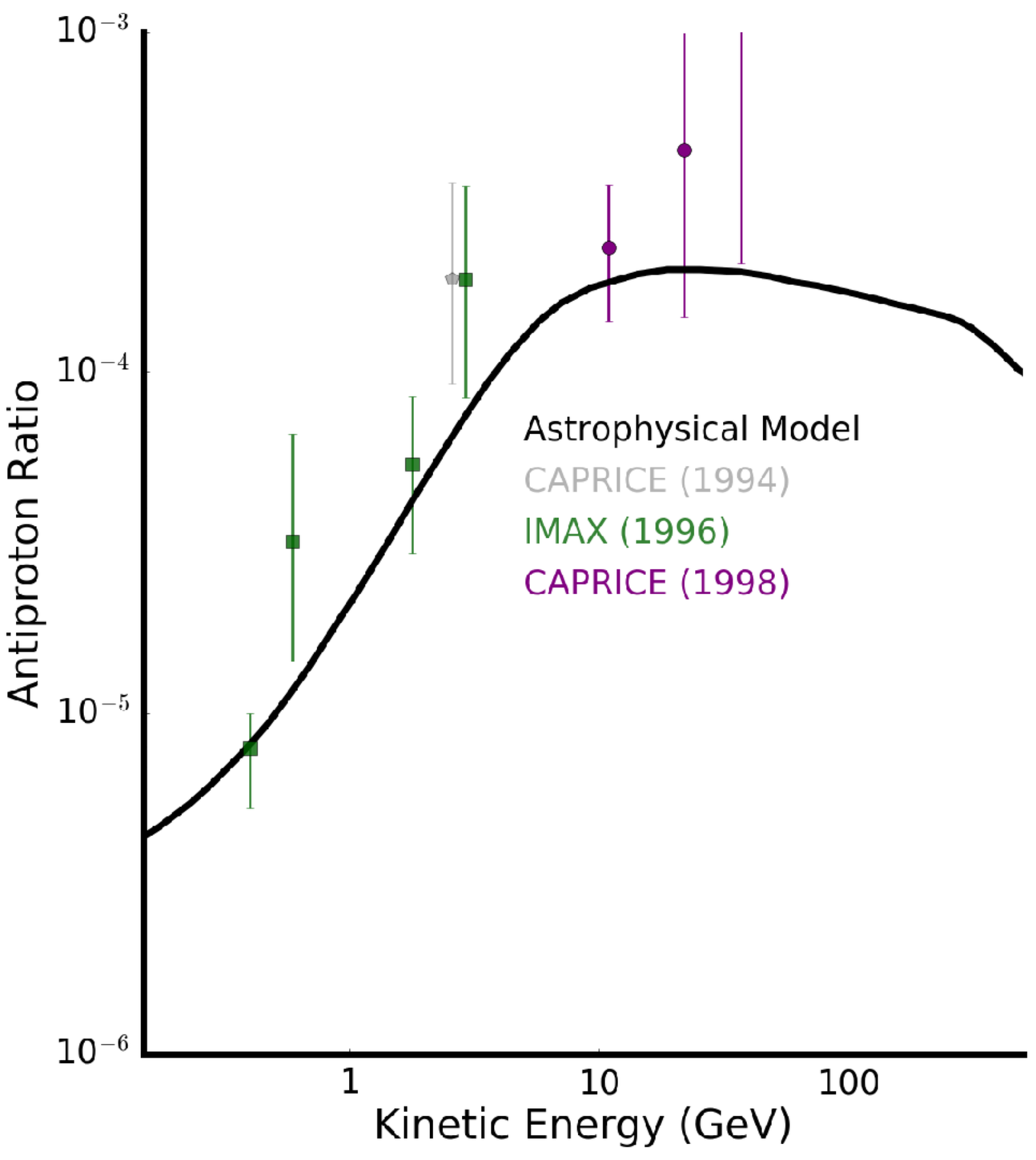

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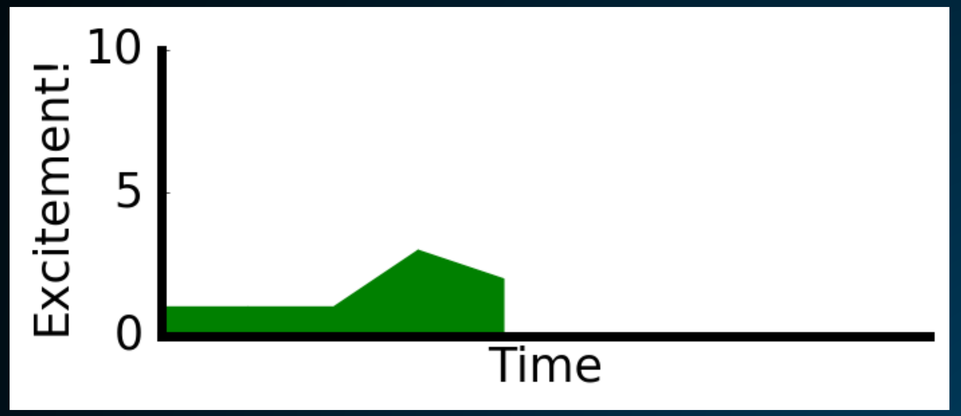

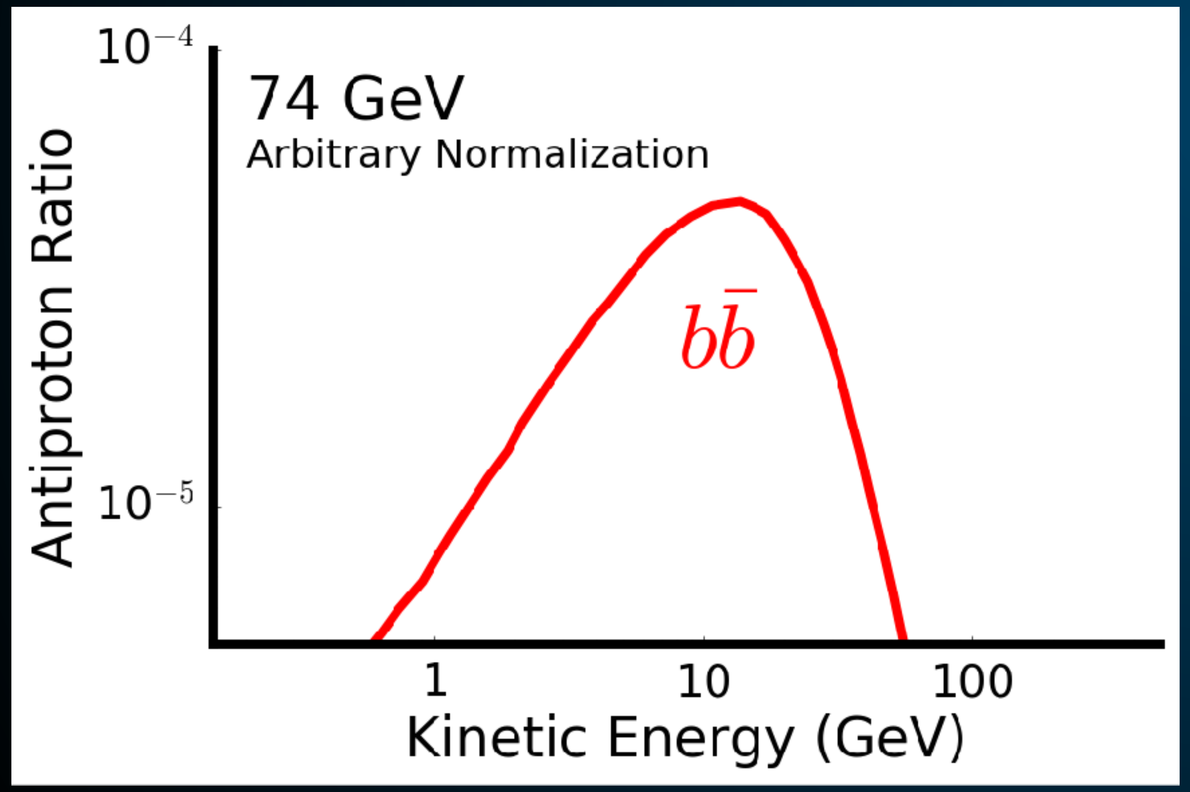

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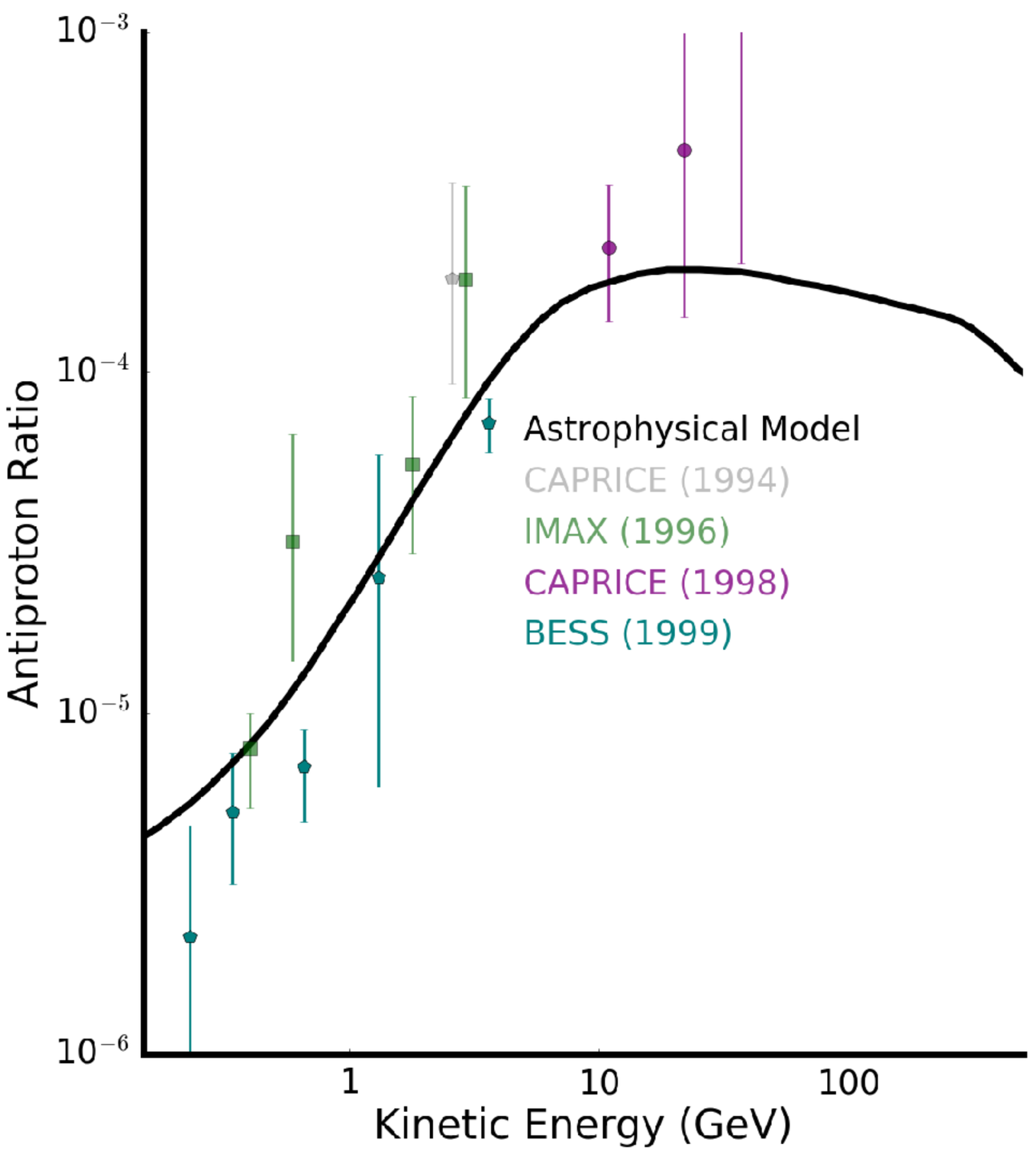

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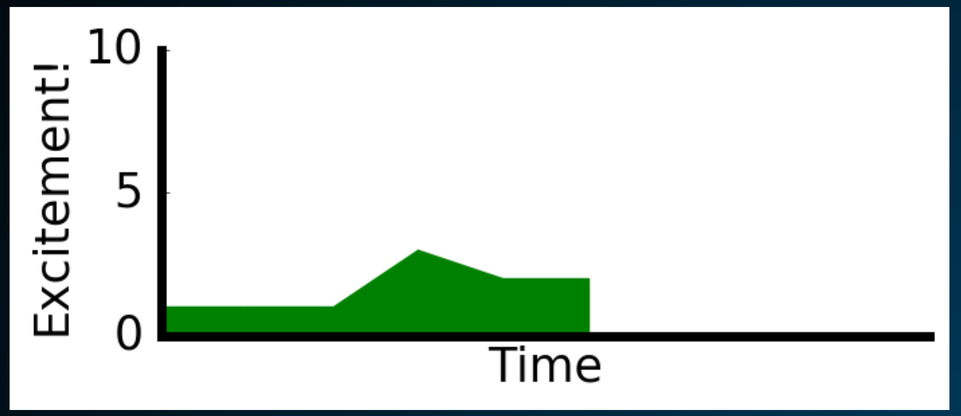

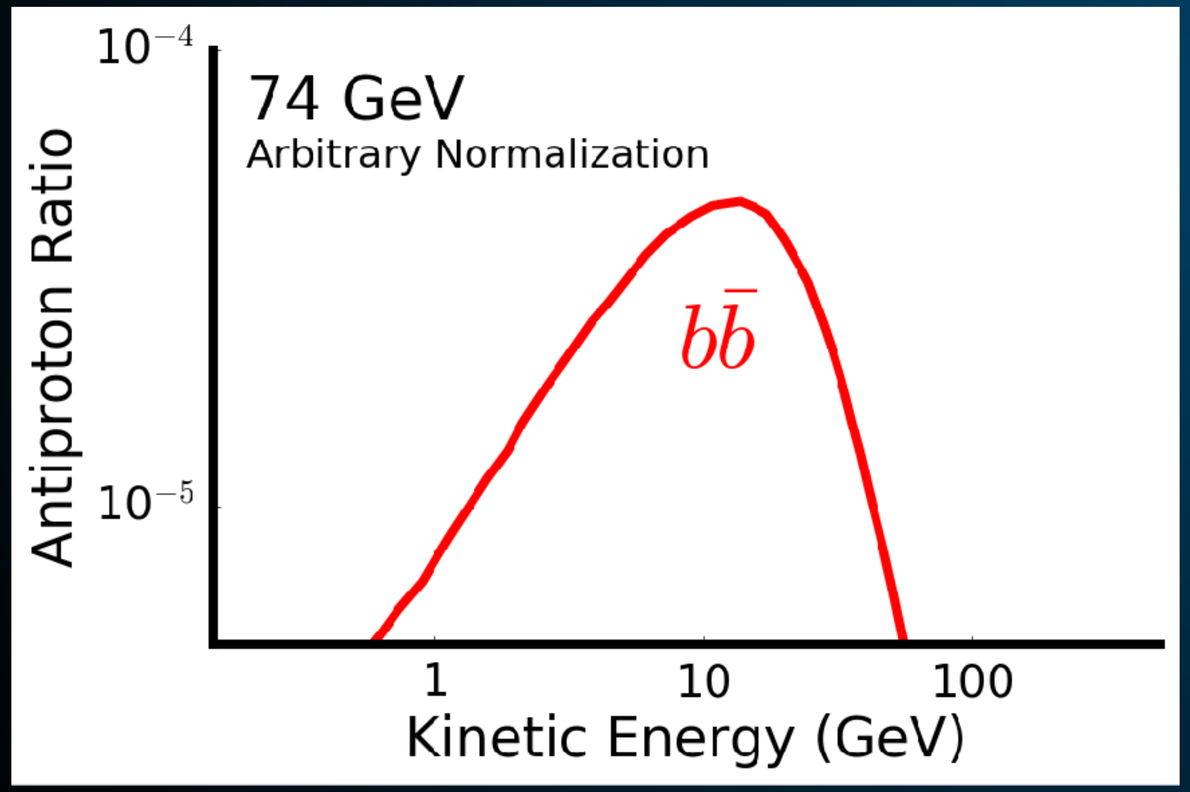

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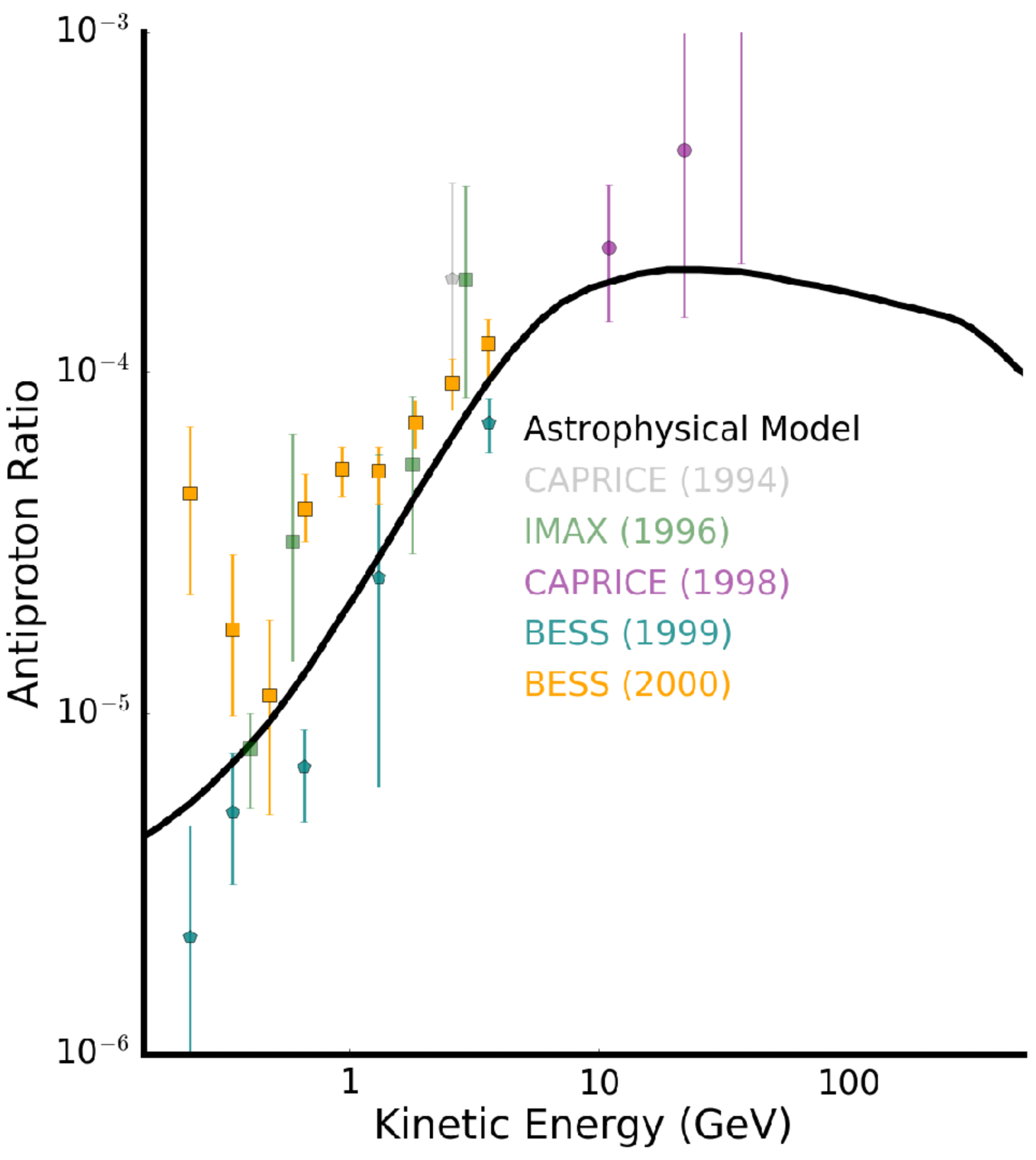

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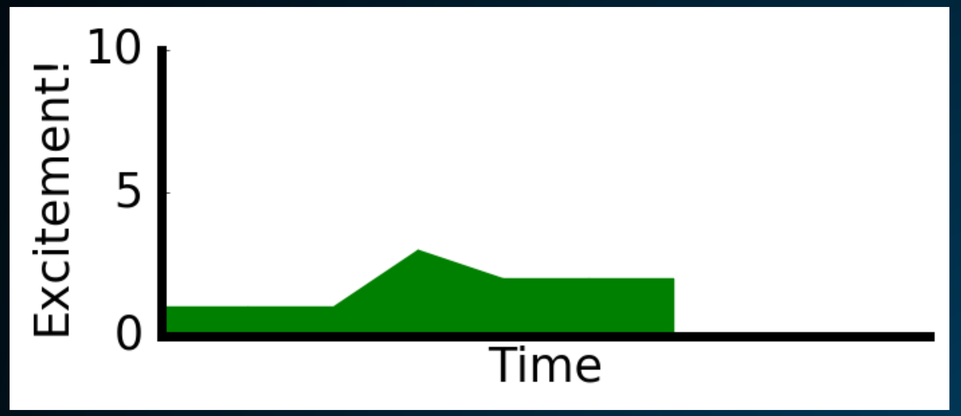

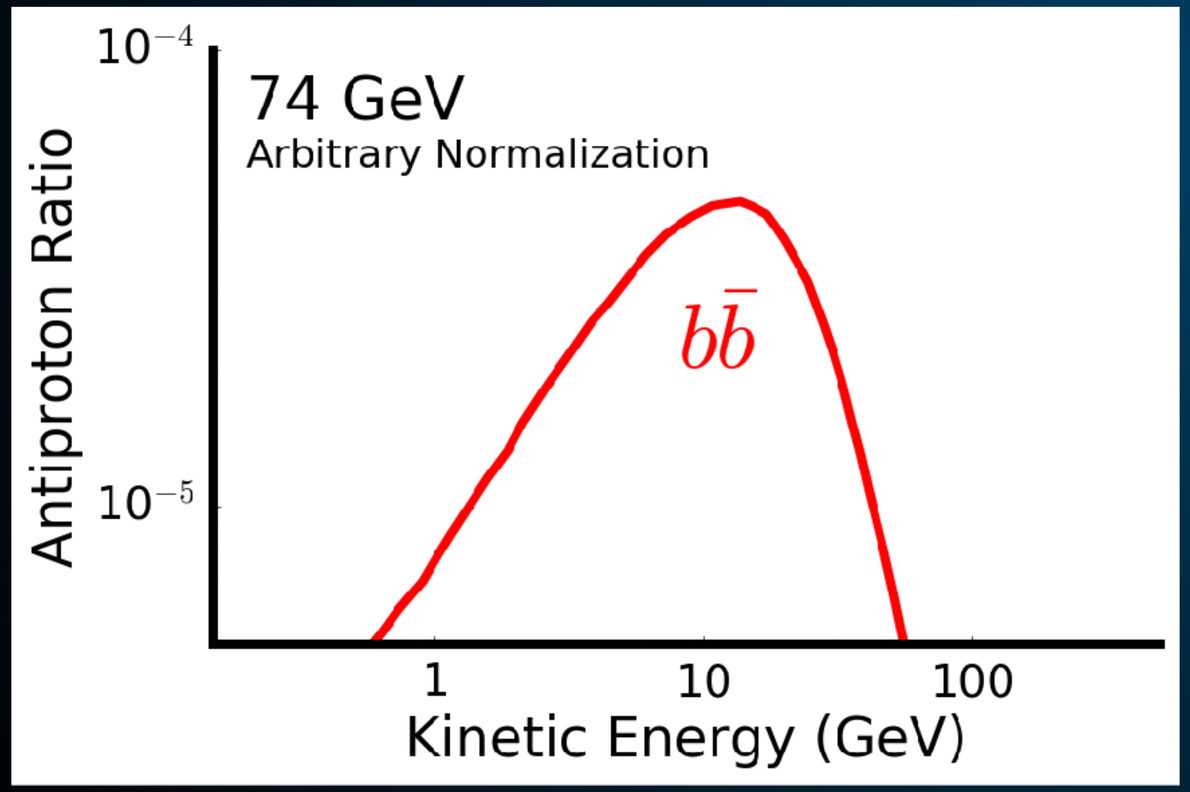

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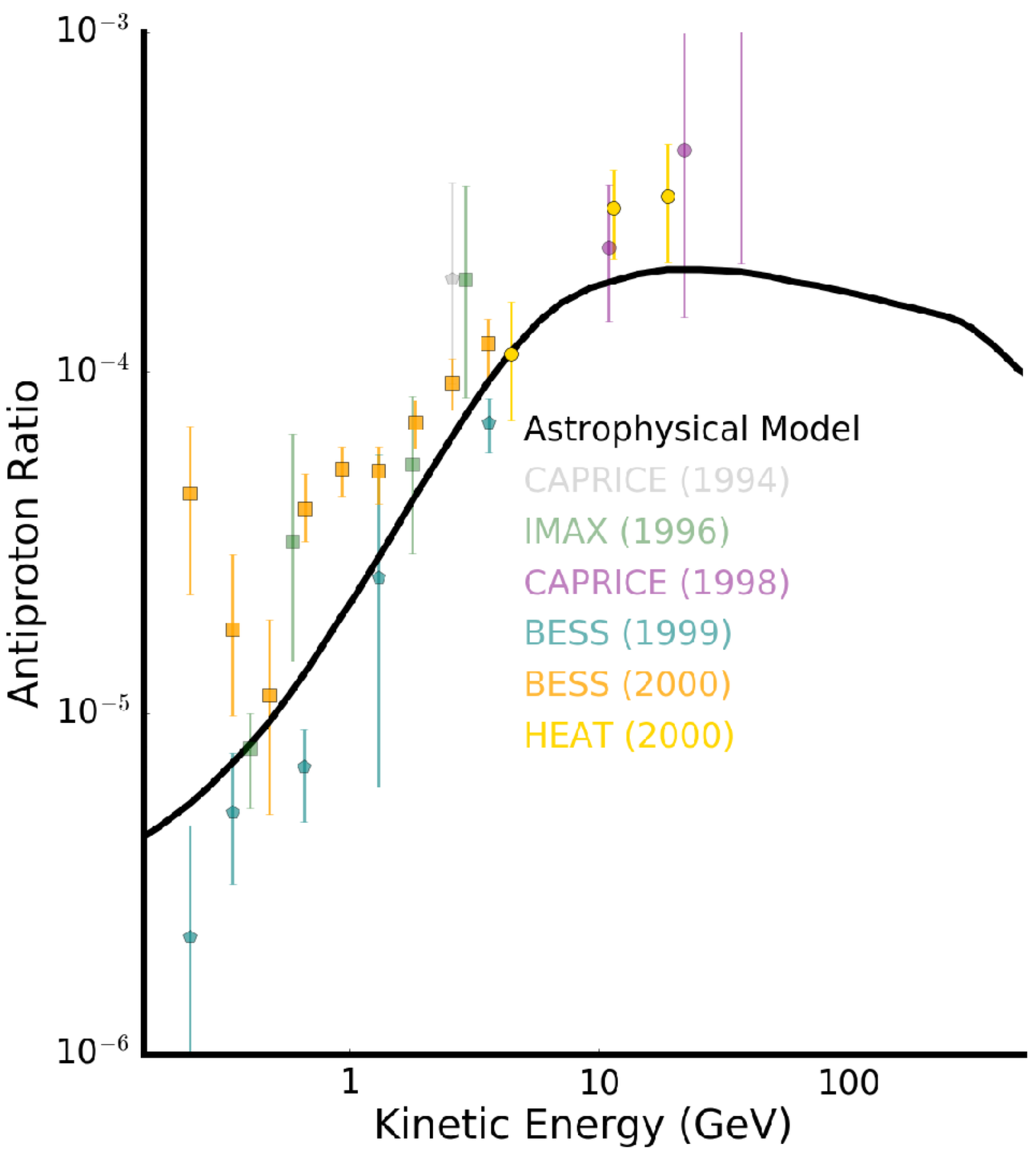

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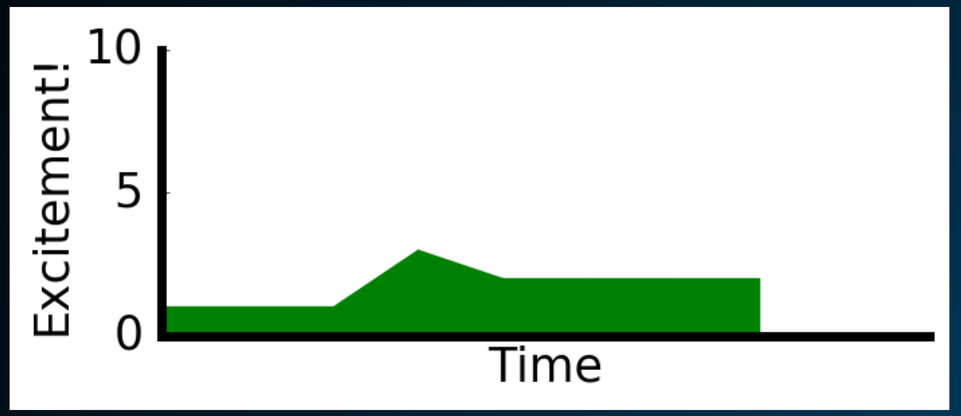

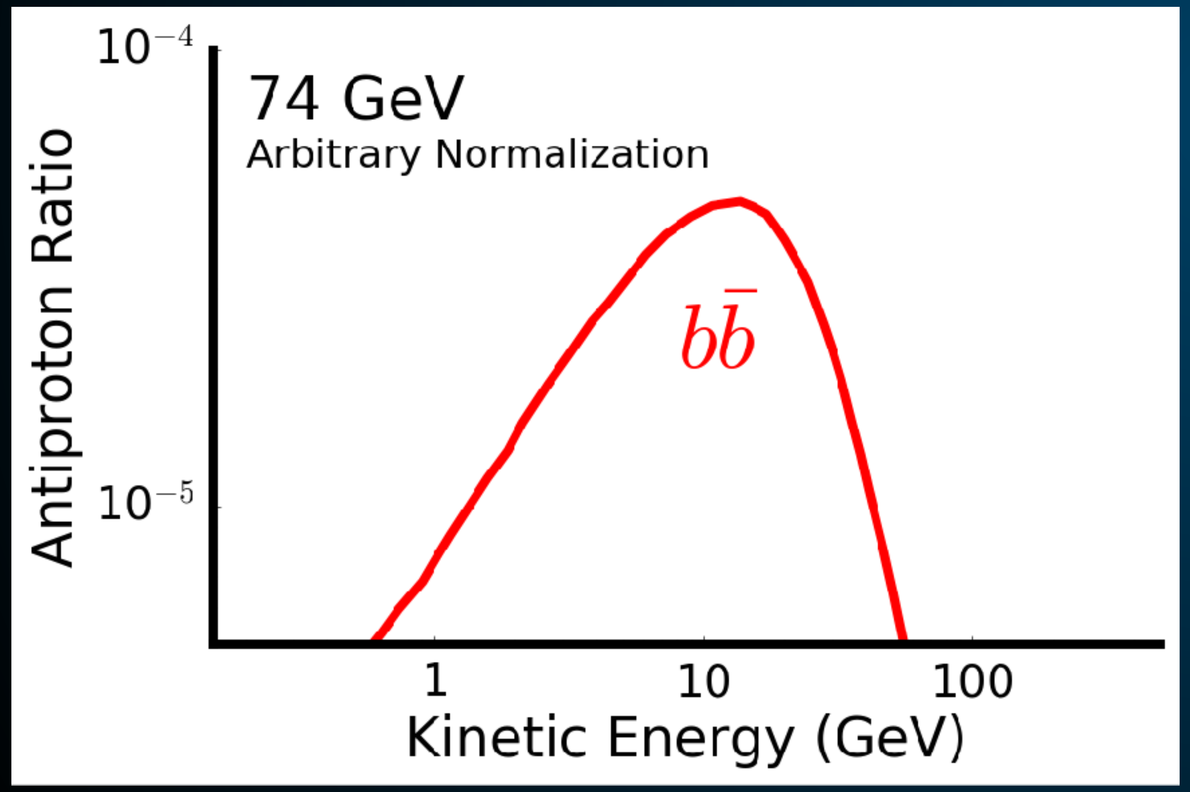

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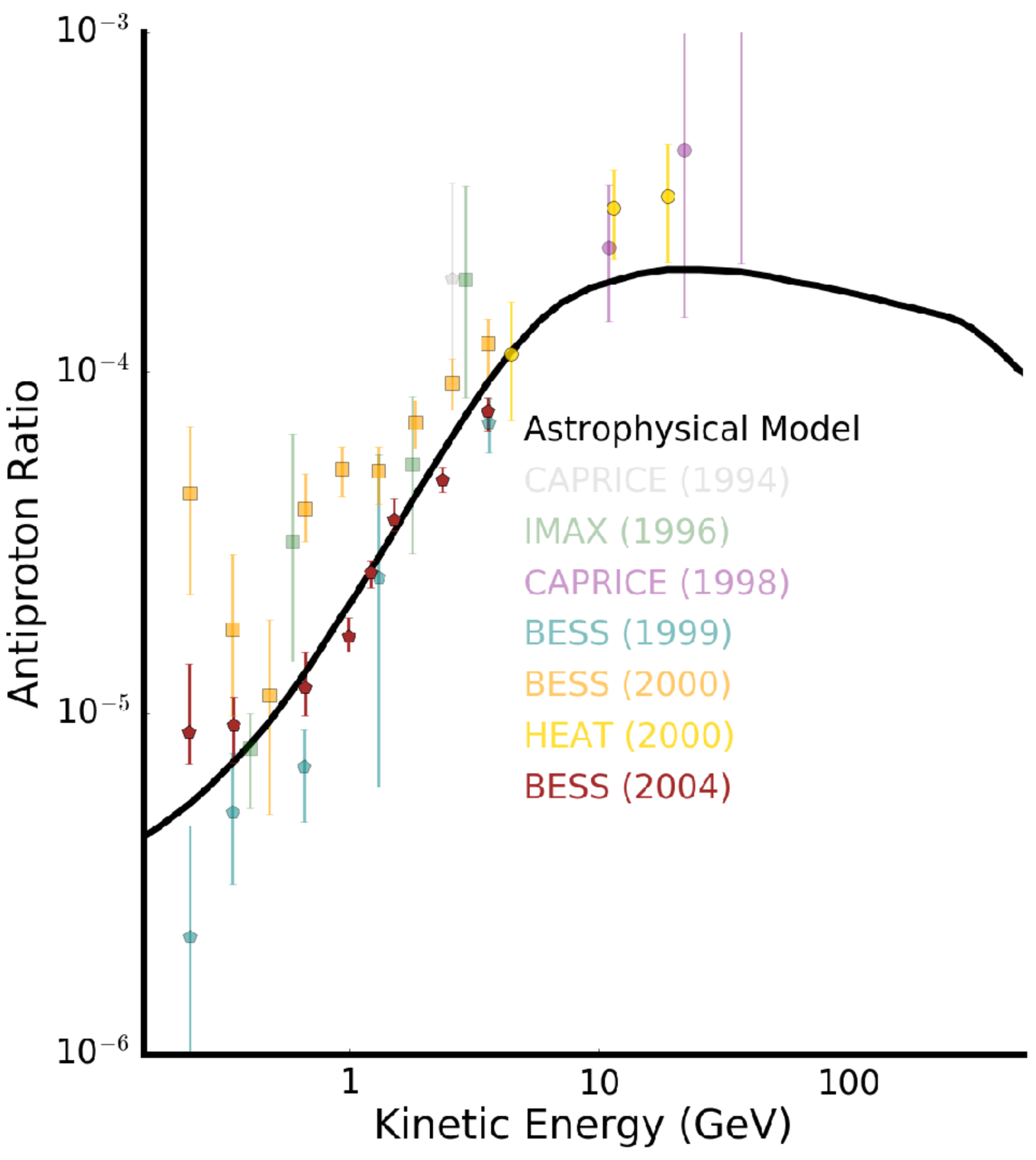

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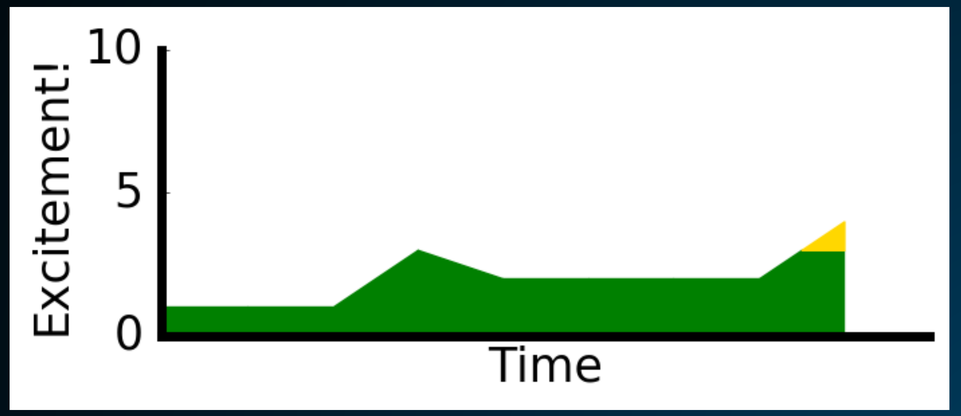

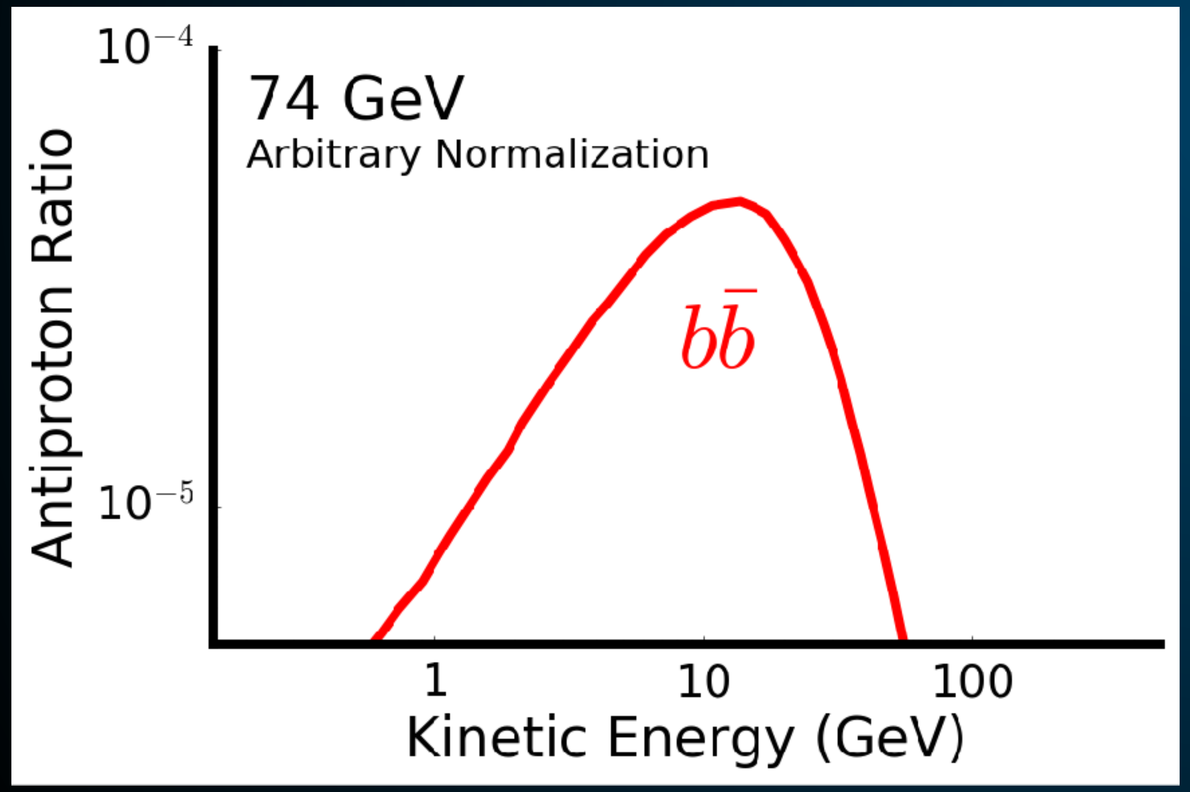

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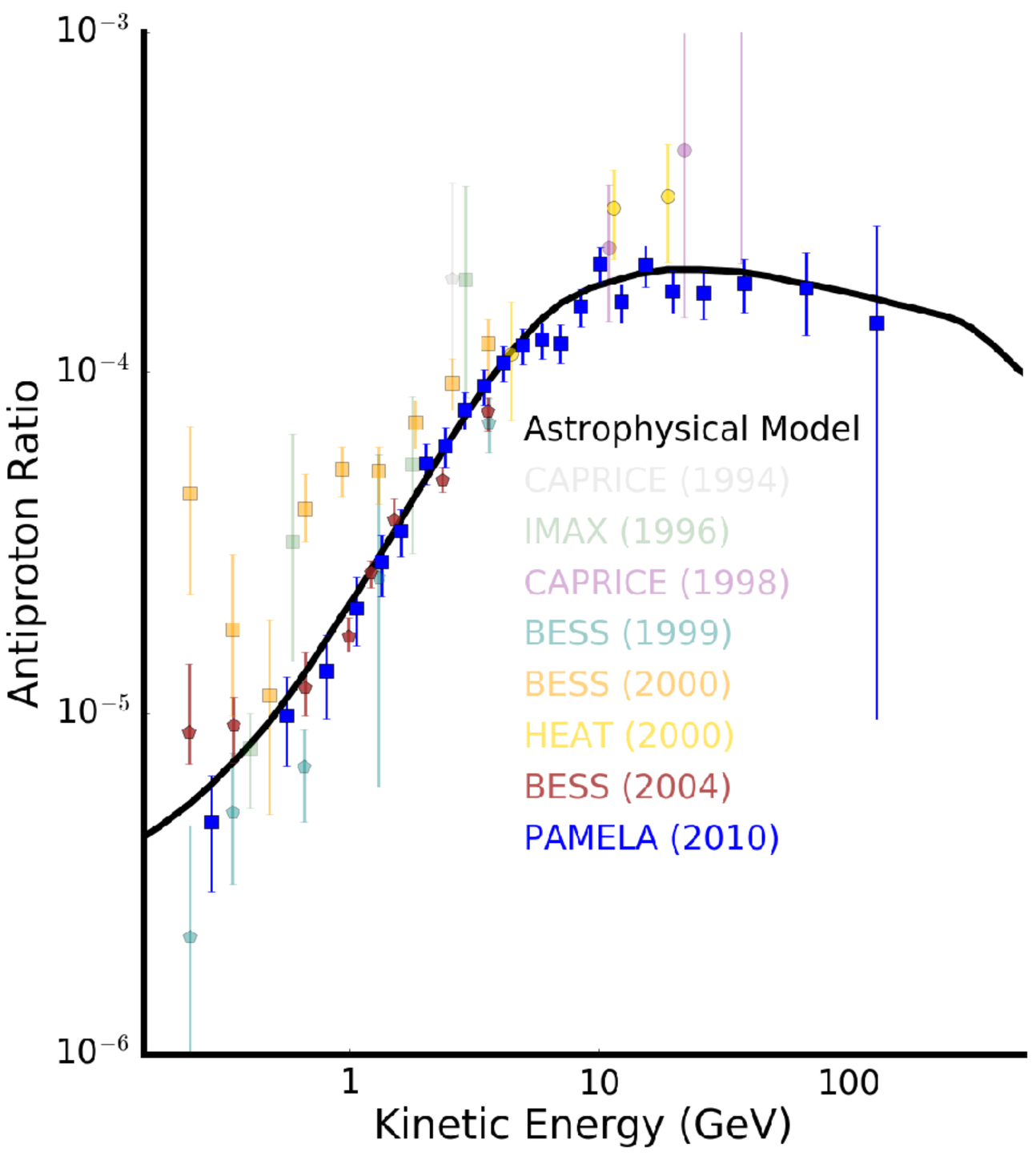

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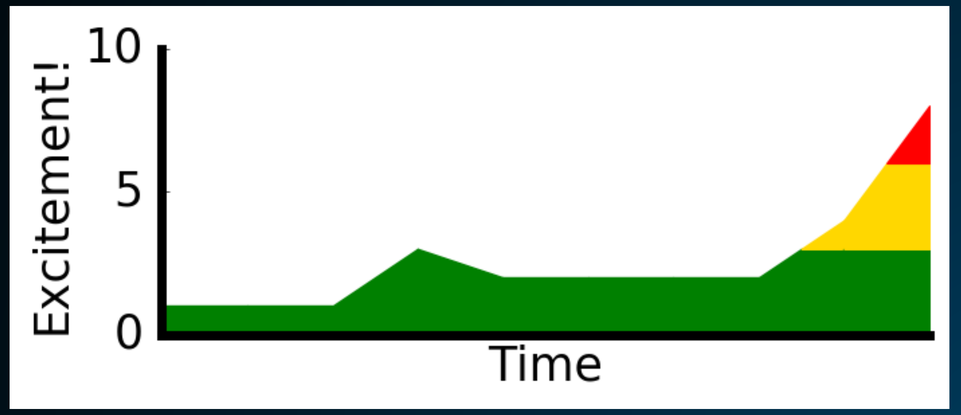

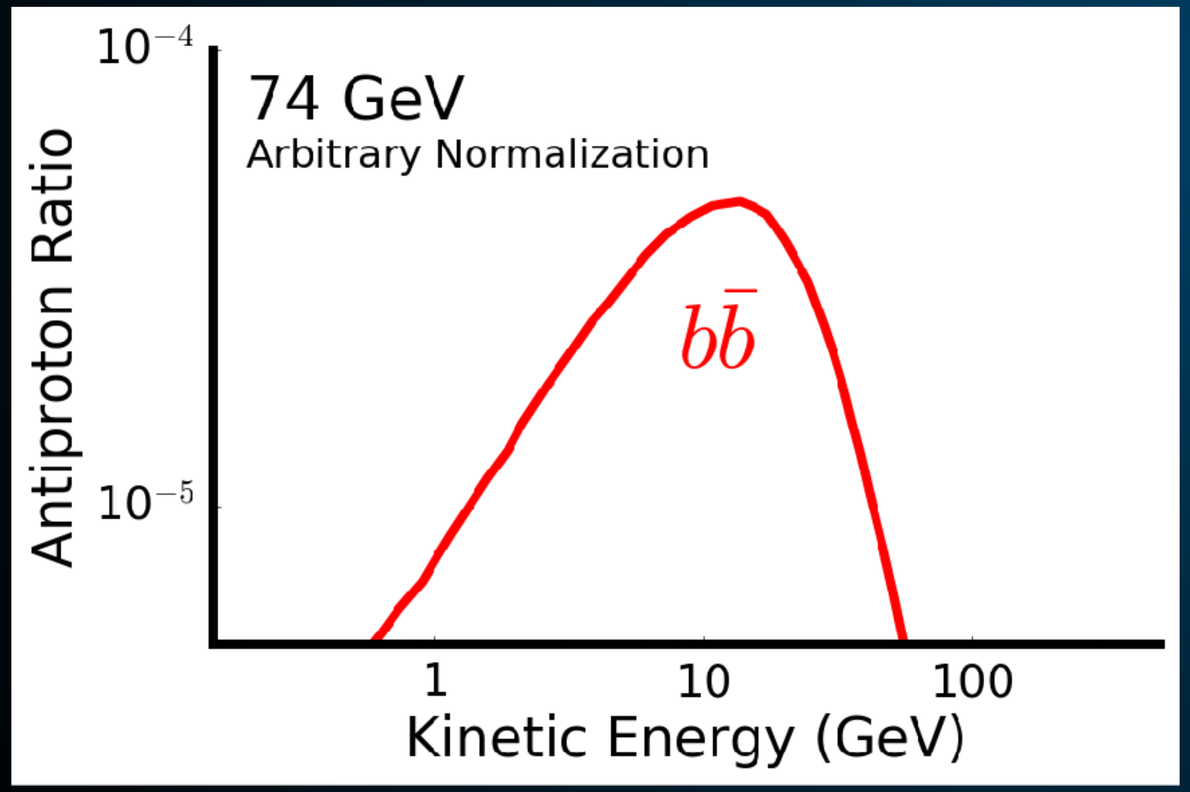

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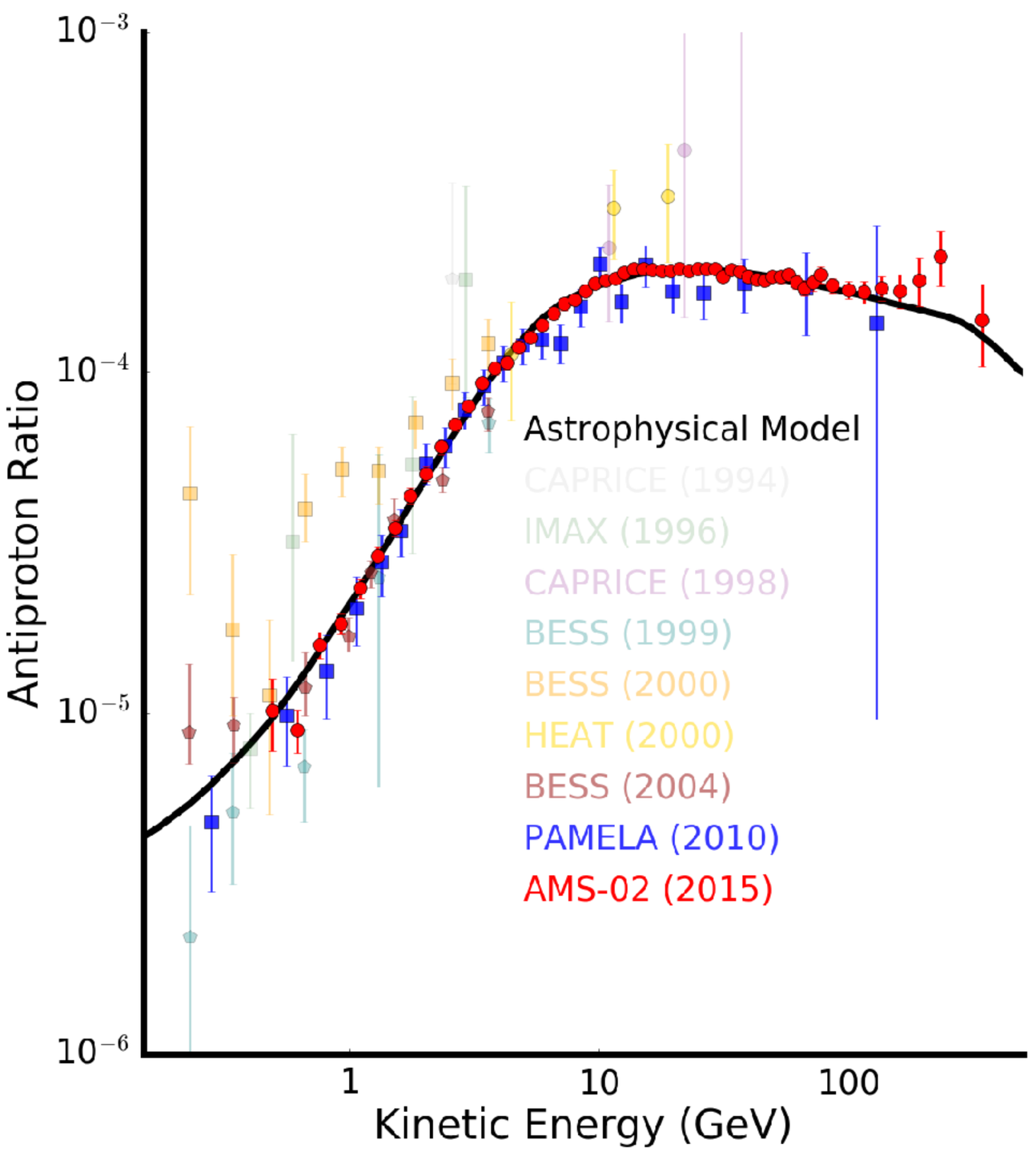

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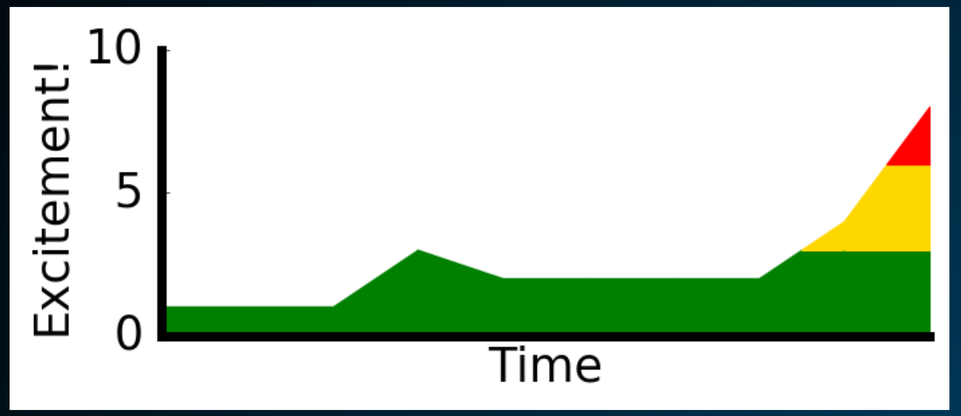

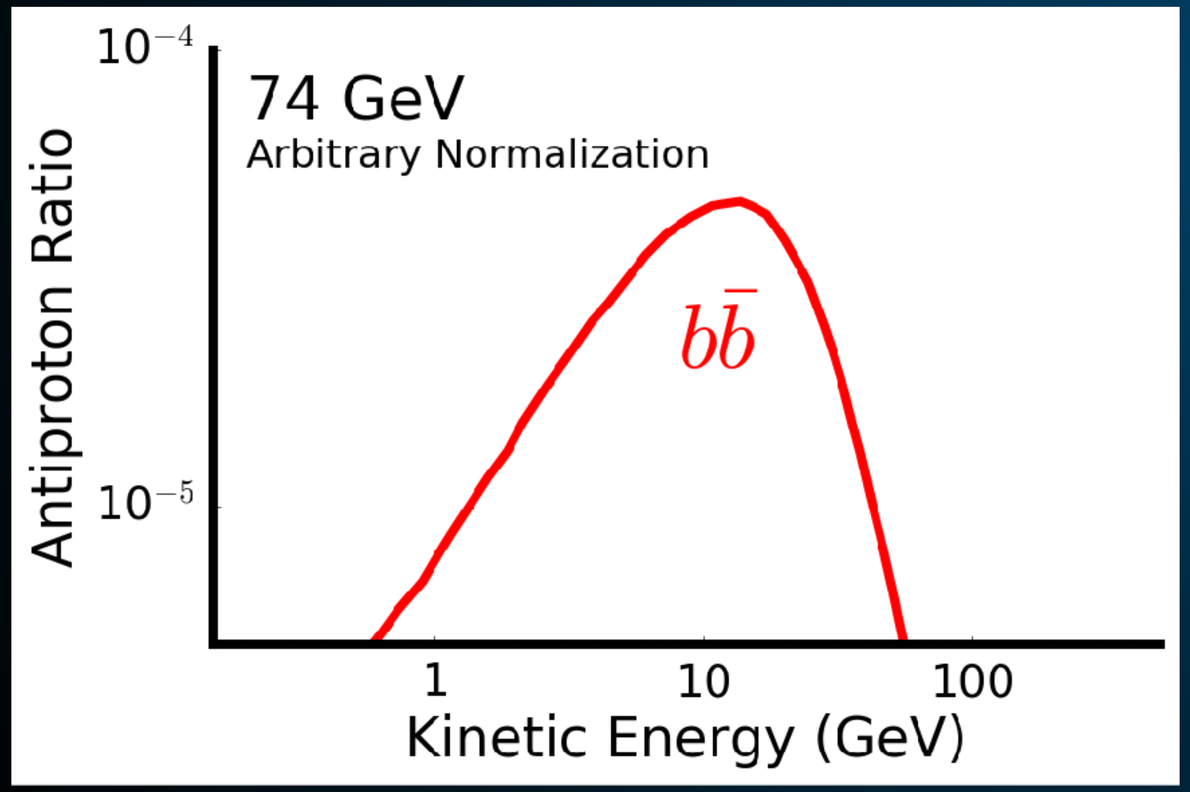

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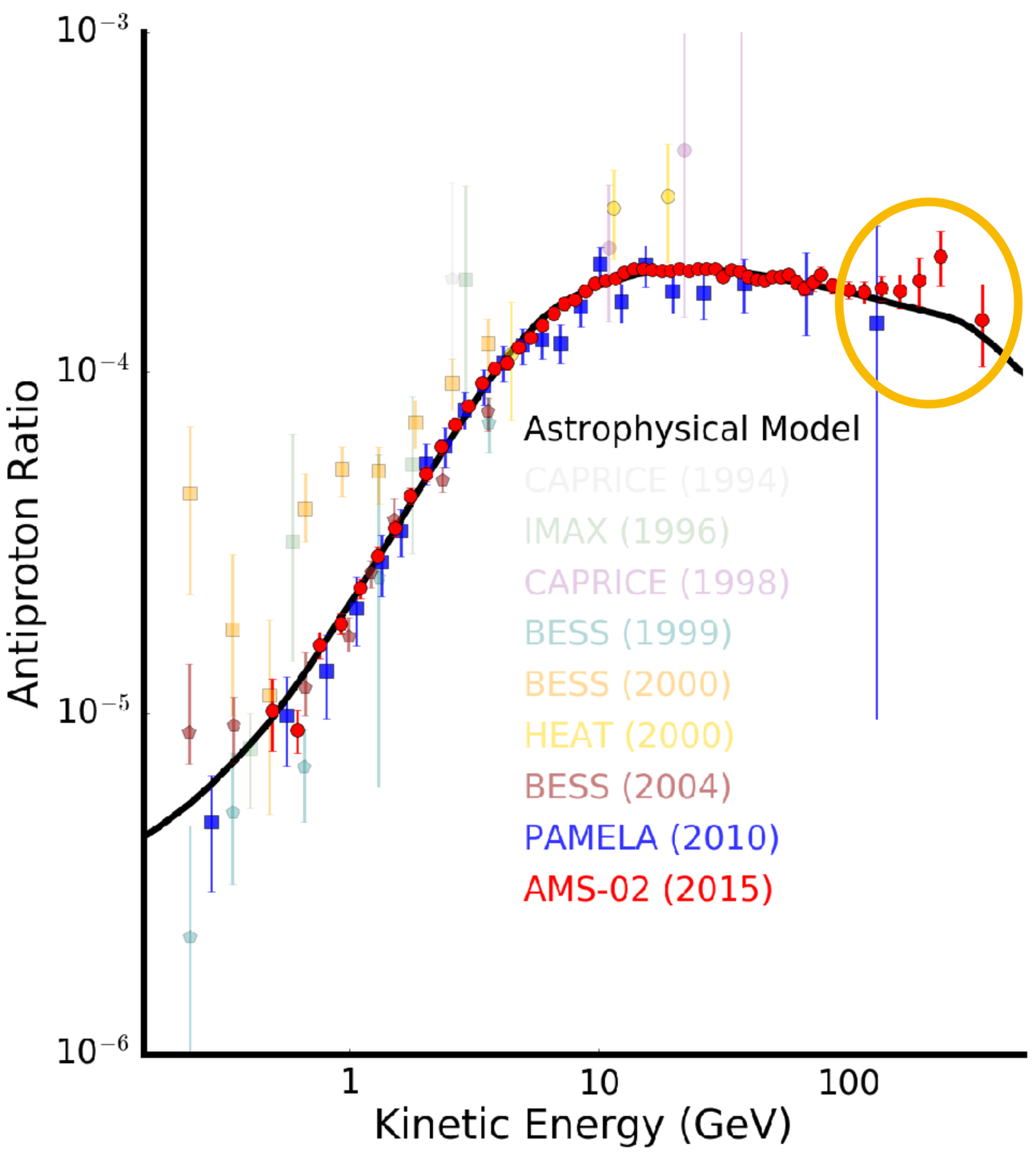

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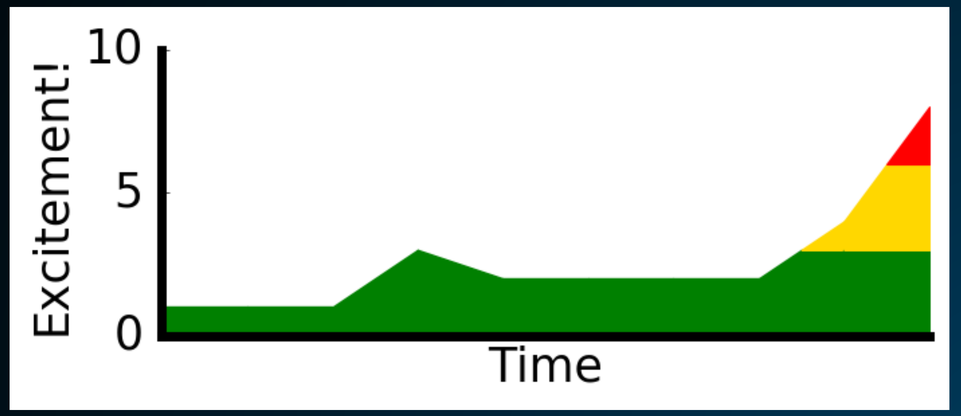
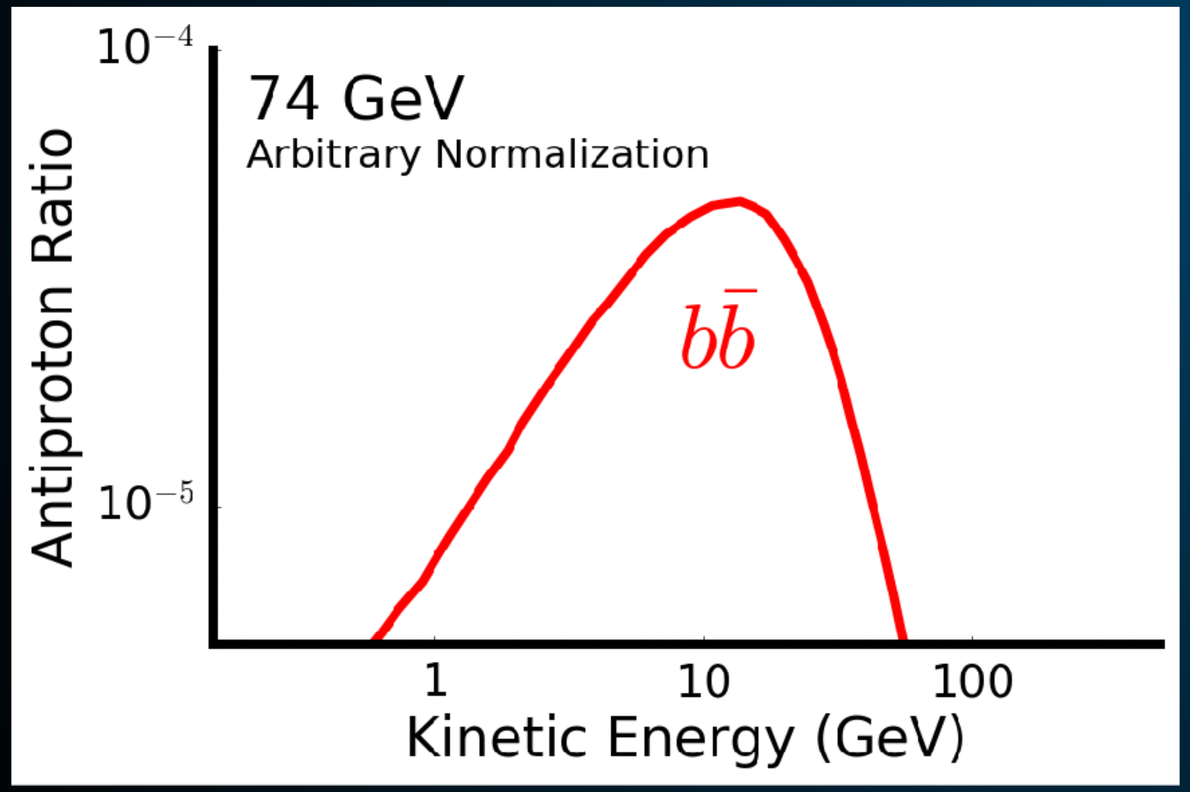
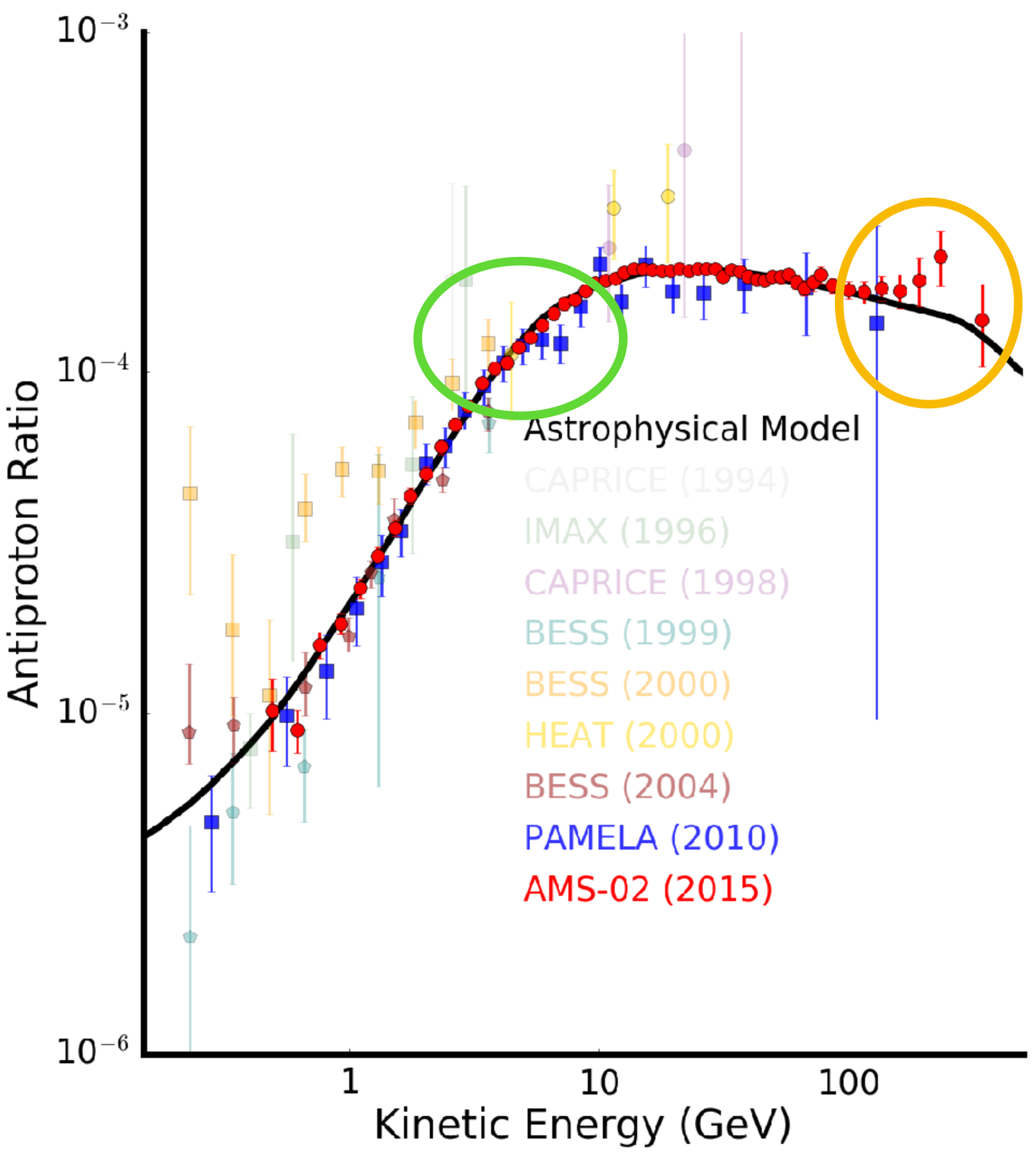
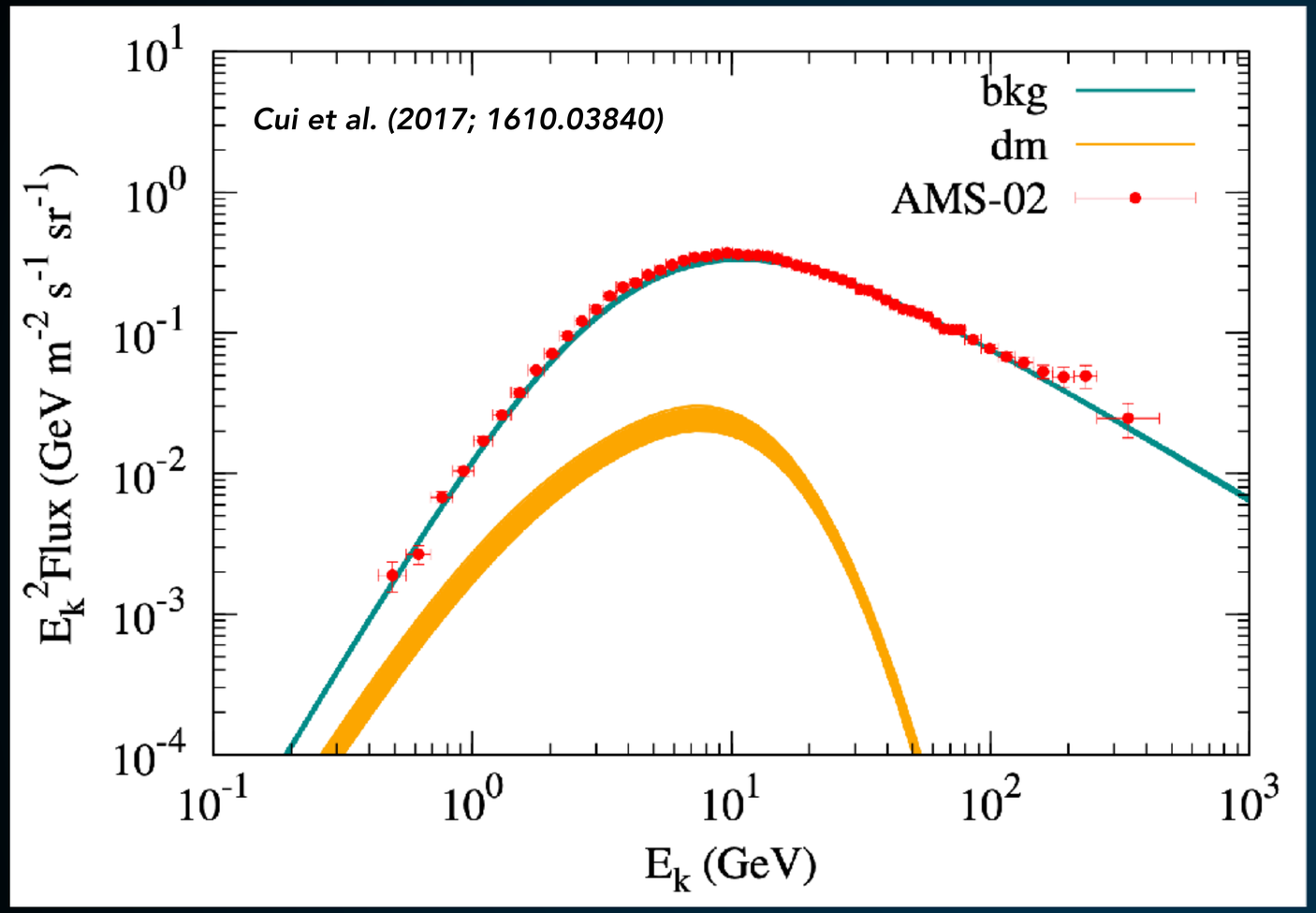


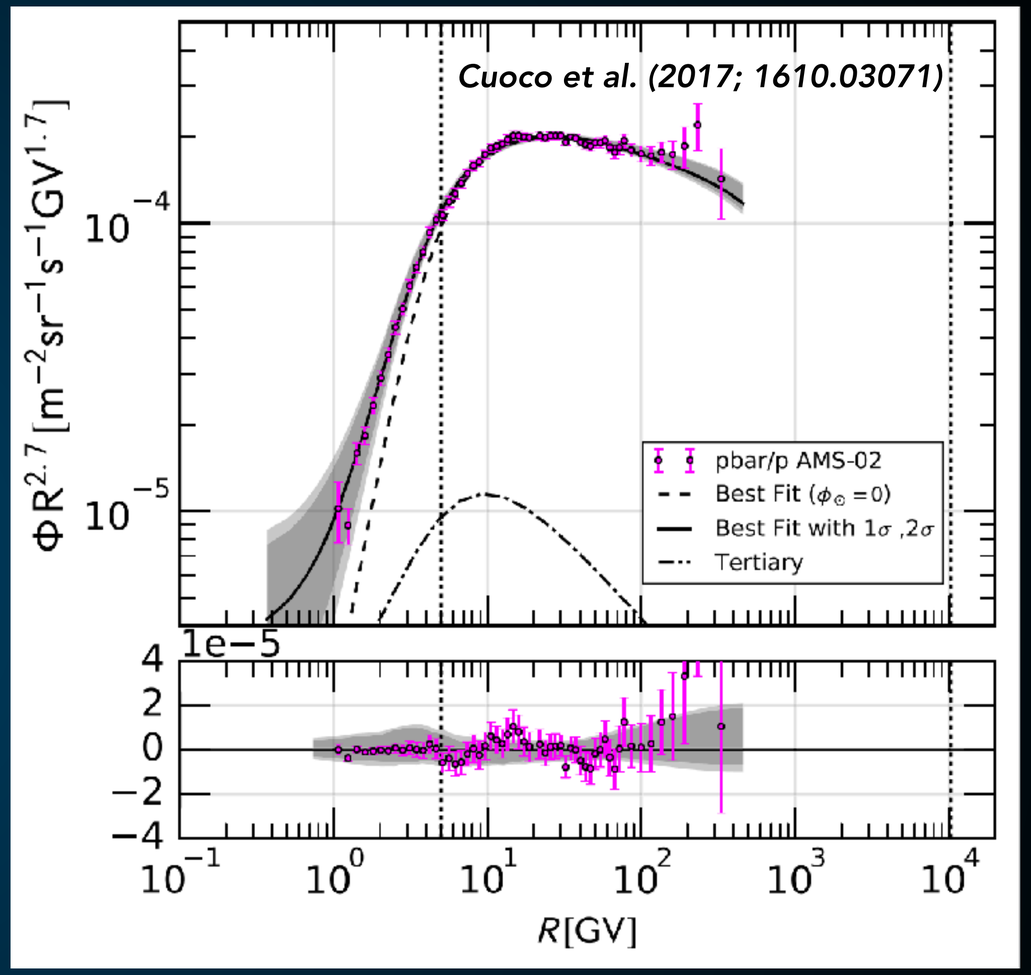


(Not an exhaustive list of observations)



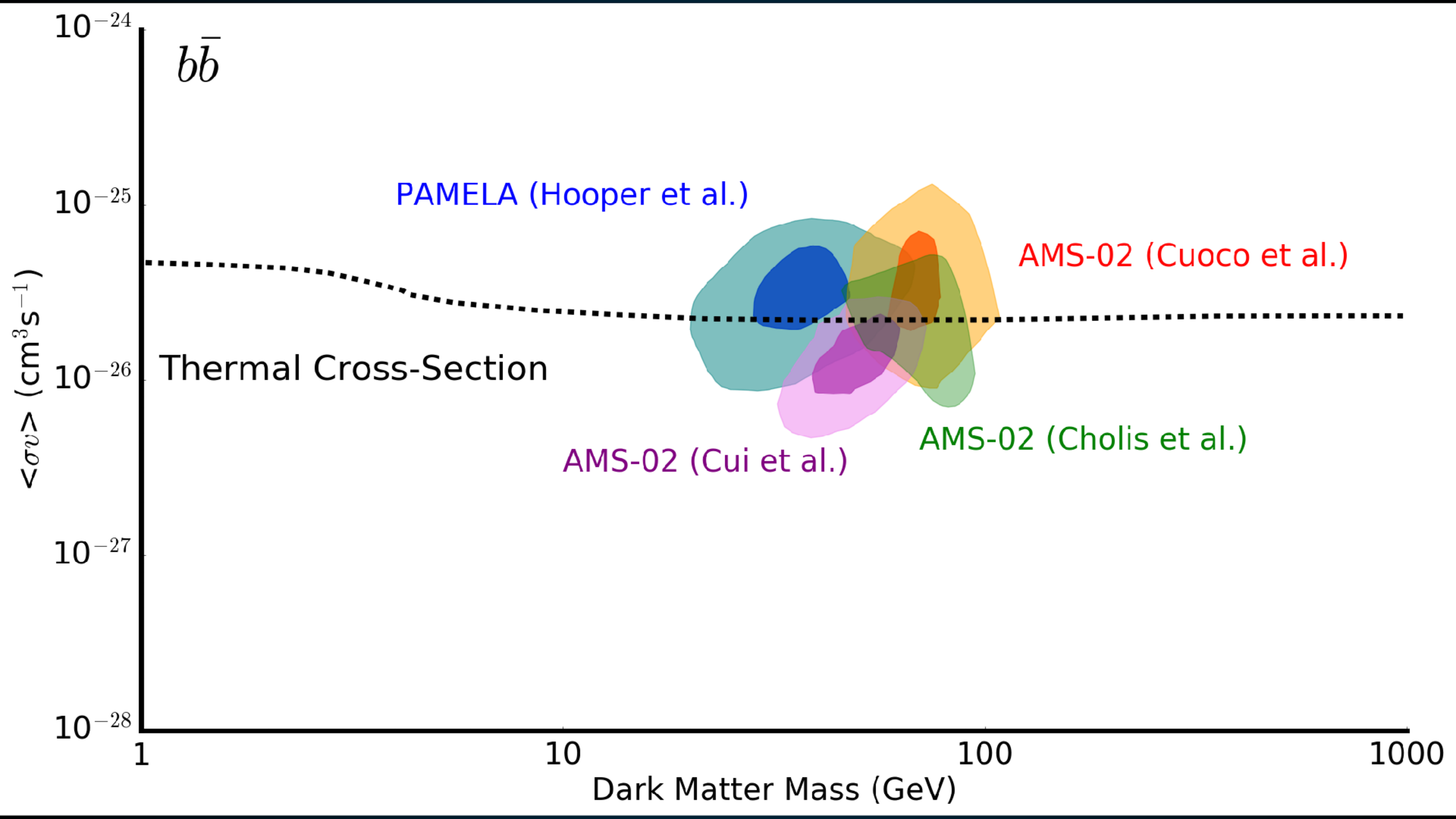
The Antiproton Excess

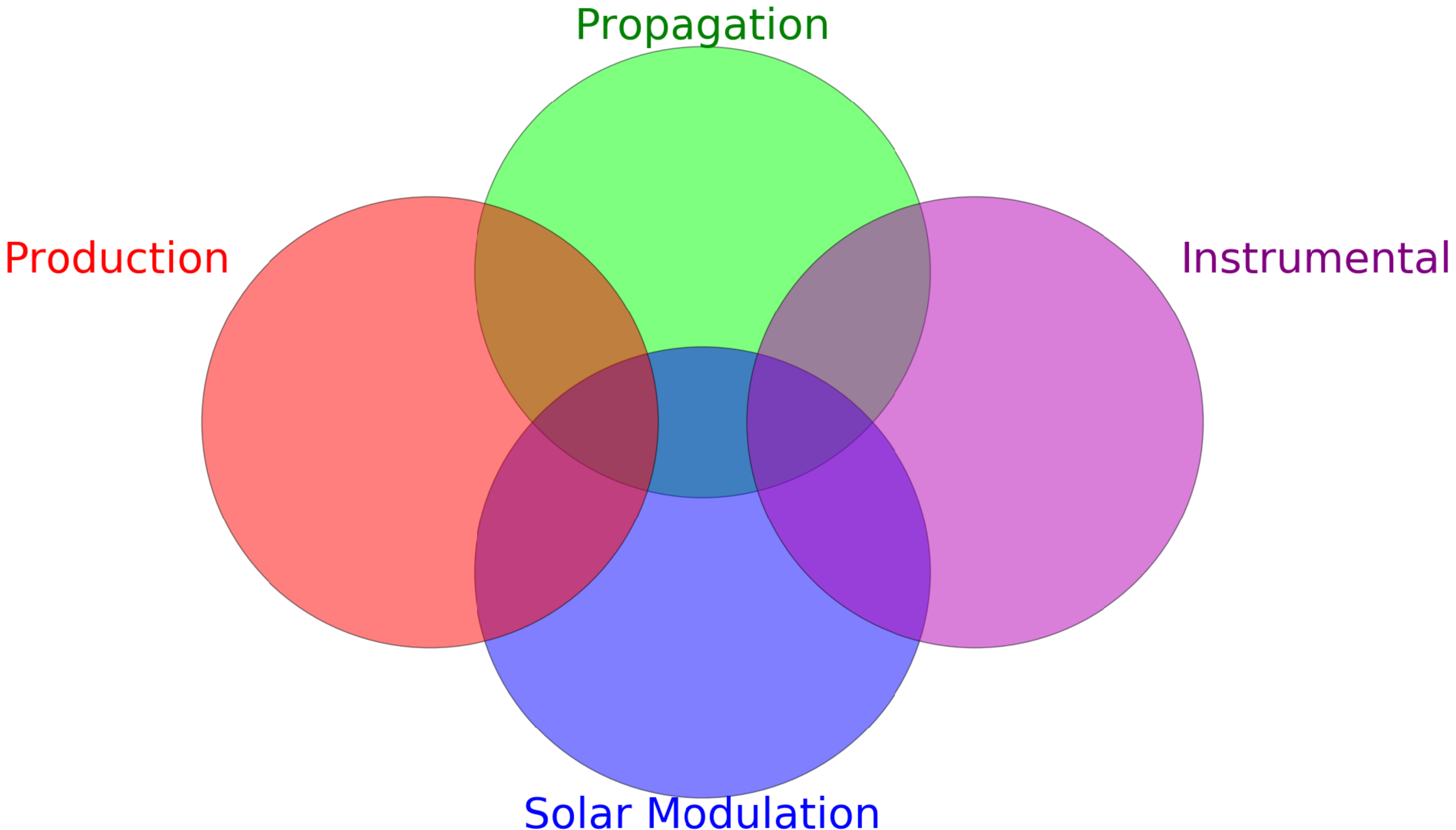




Two papers simultaneously find an excess in the AMS-02 Antiproton Data!

Significance approaching (or past) 5σ !

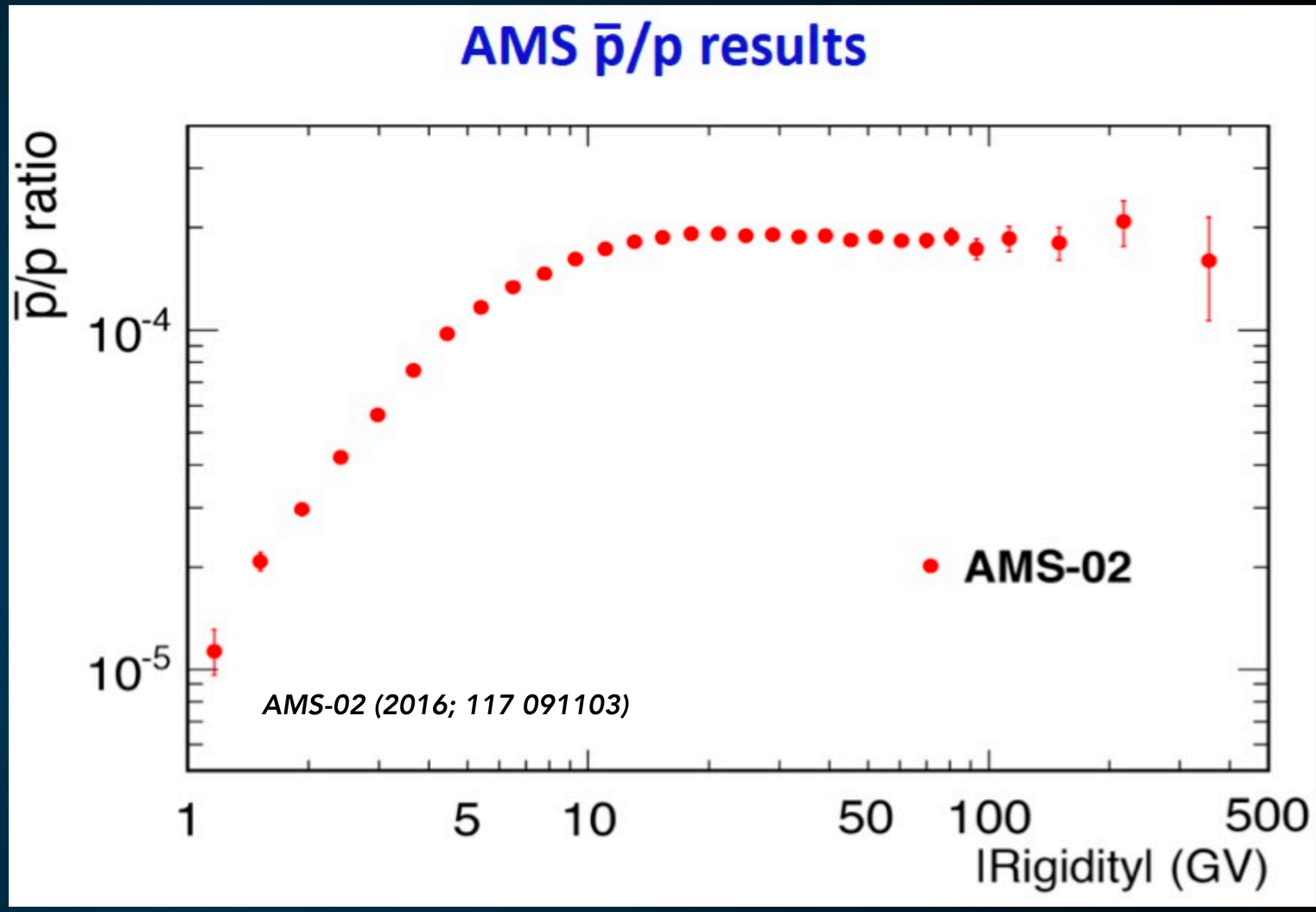

$b\bar{b}$
PAMELA (Hooper et al.)
AMS-02 (Cuoco et al.)
AMS-02 (Cholis et al.)
AMS-02 (Cui et al.)
Thermal Cross-Section
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ ($cm^3 s^{-1}$)
1
10
100
1000
Dark Matter Mass (GeV)


Propagation
Production
Instrumental
Solar Modulation

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)

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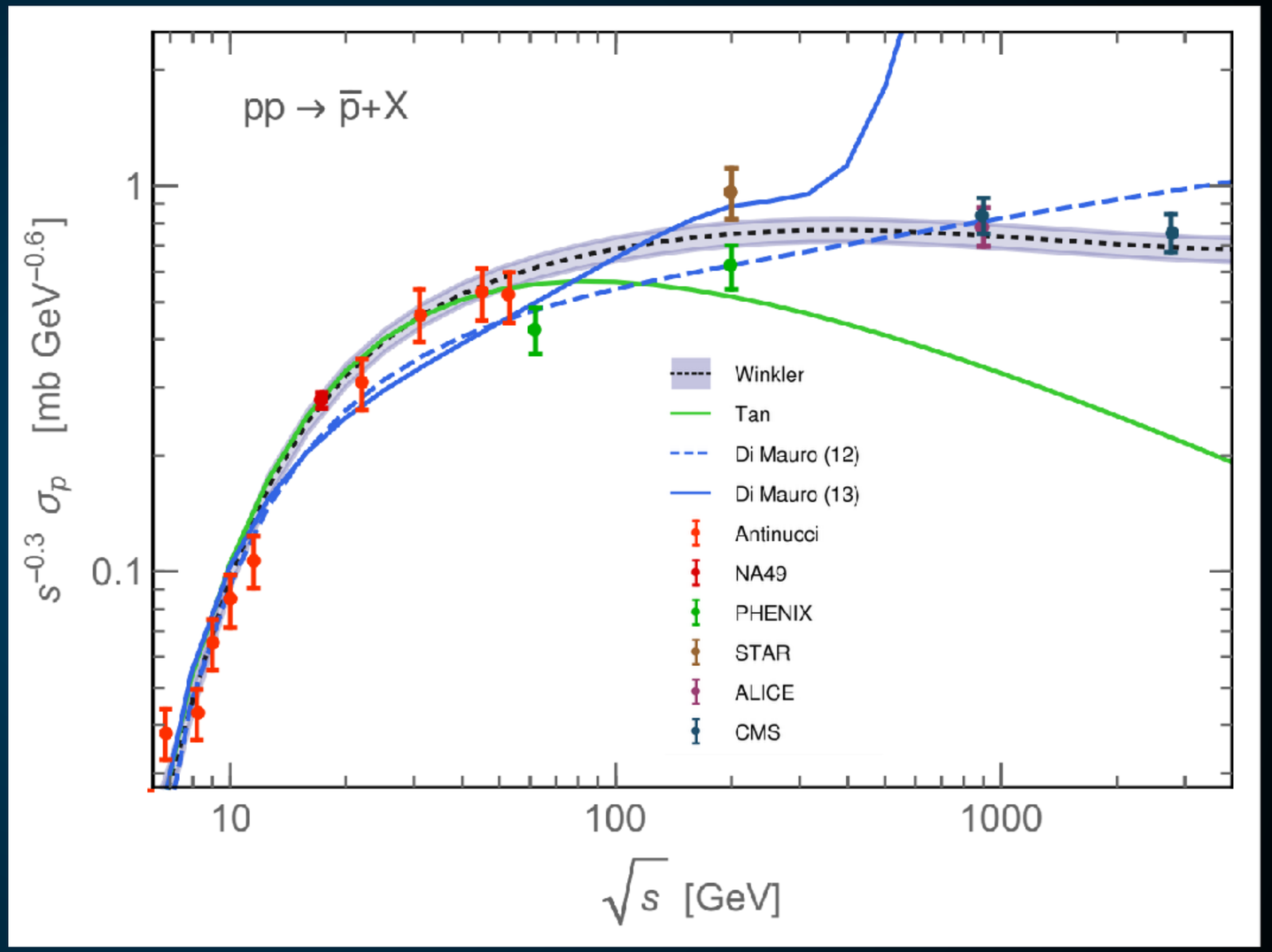

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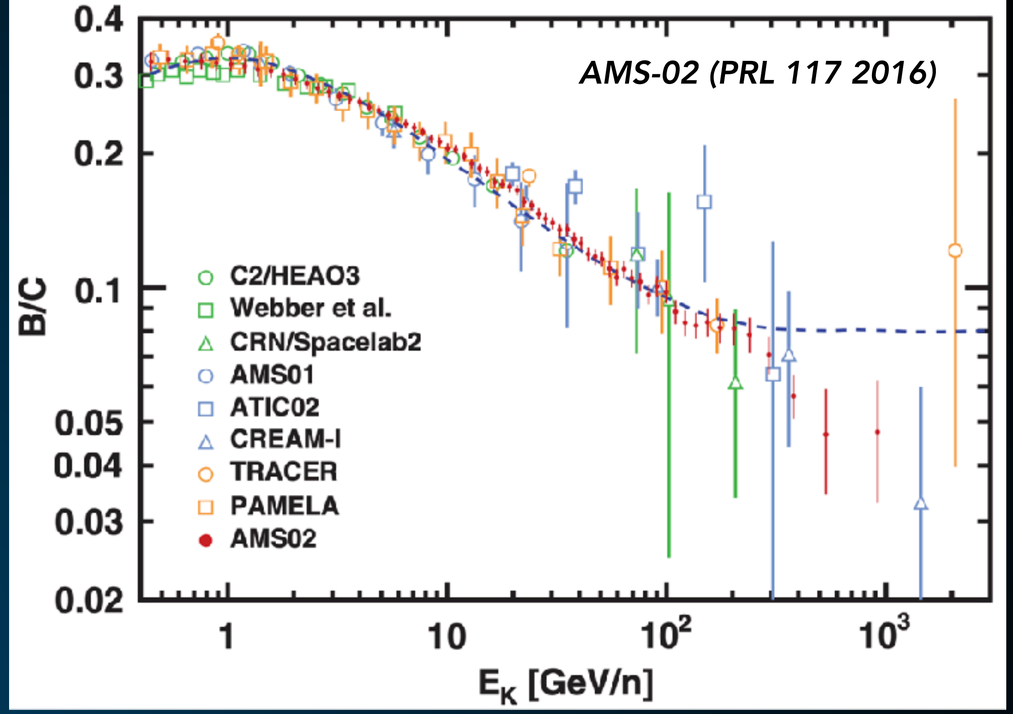

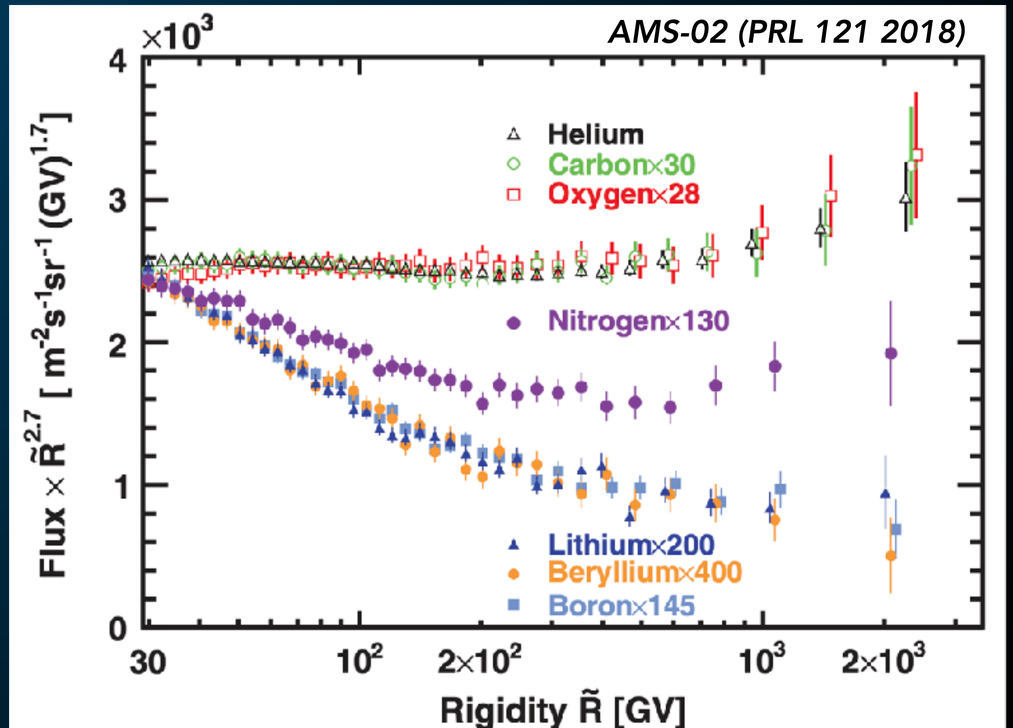

See e.g., Weinrich et al. (2002; 2002.11406)

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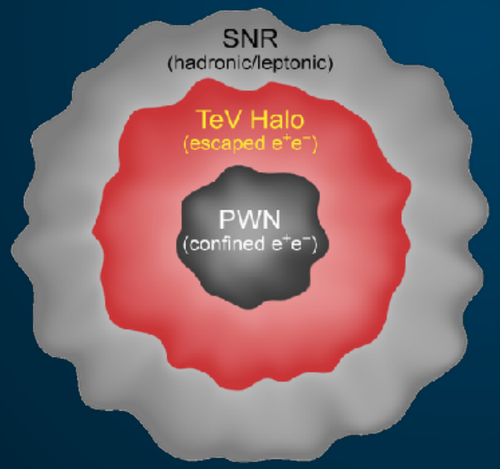
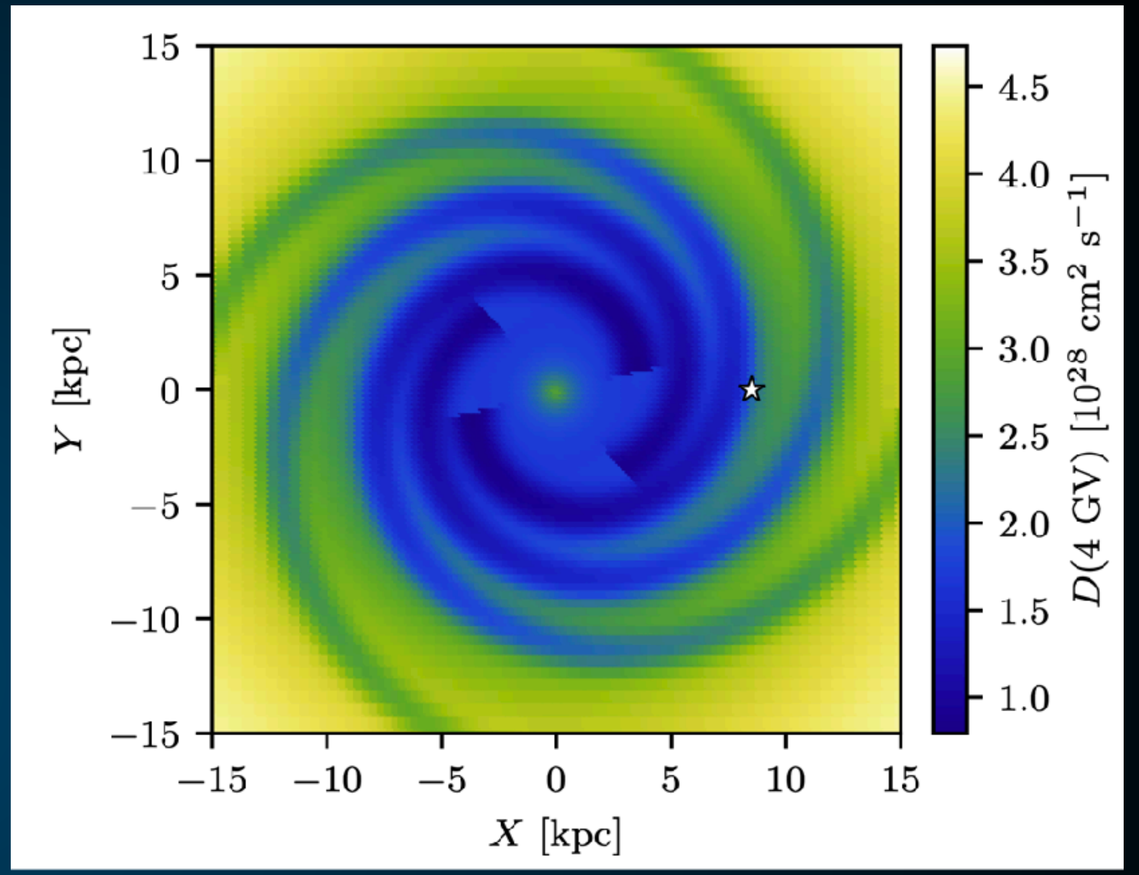
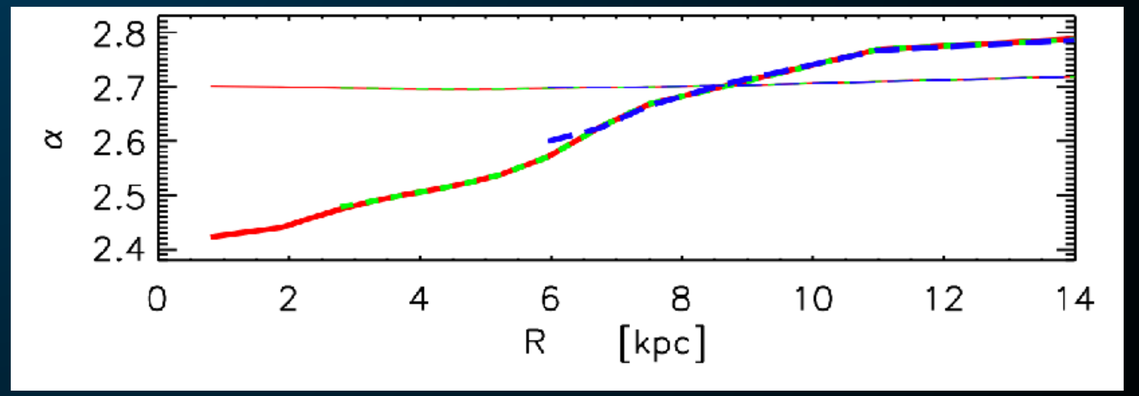


Johannesson et al. (1903.05509)



Evoli et al. (2014; 1411.7623)



The Antiproton Excess

AMS-02 (PRL 121 2018)

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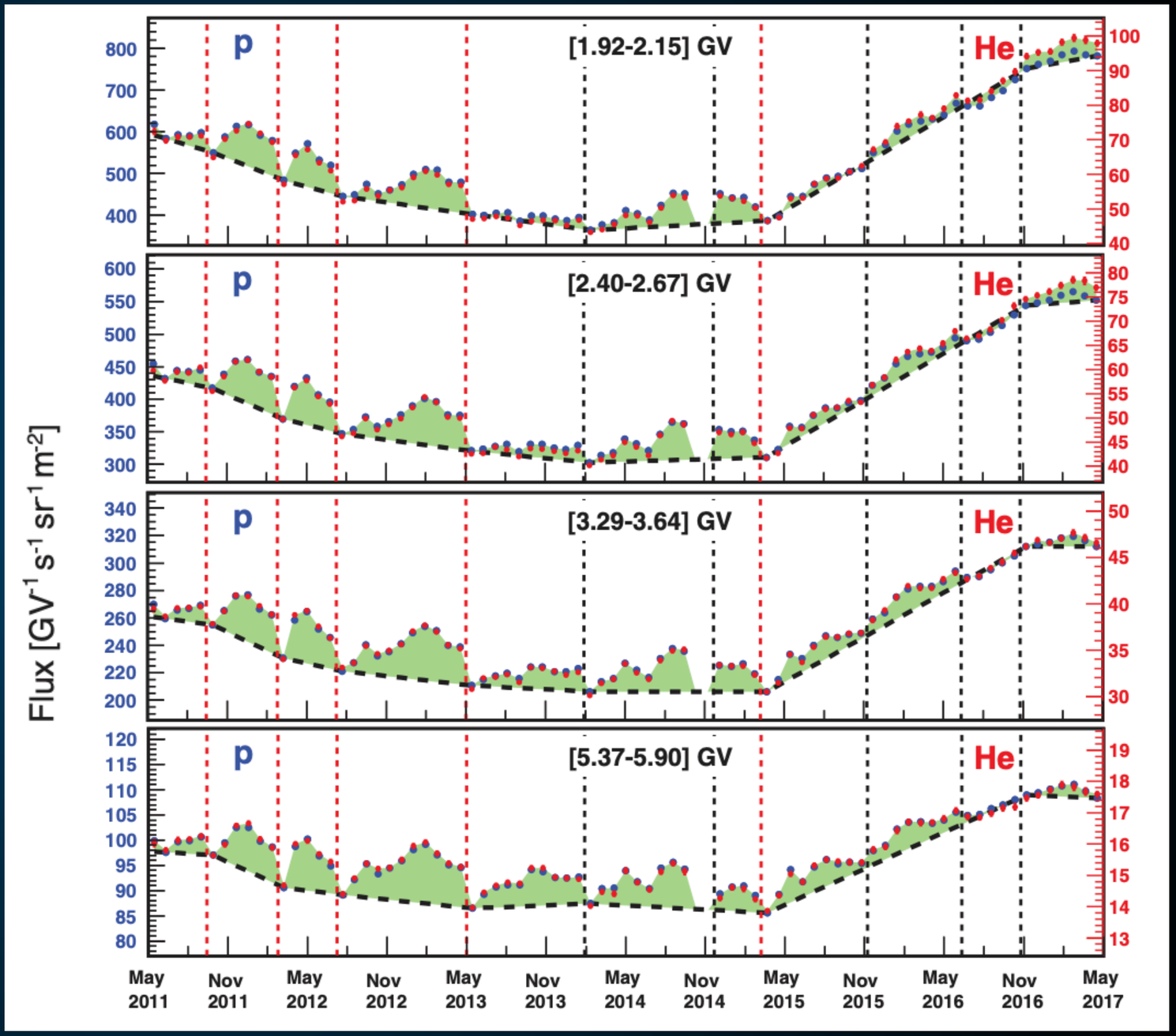


The Antiproton Excess

With great precision comes great responsibility:

Antiproton Production Cross-Section

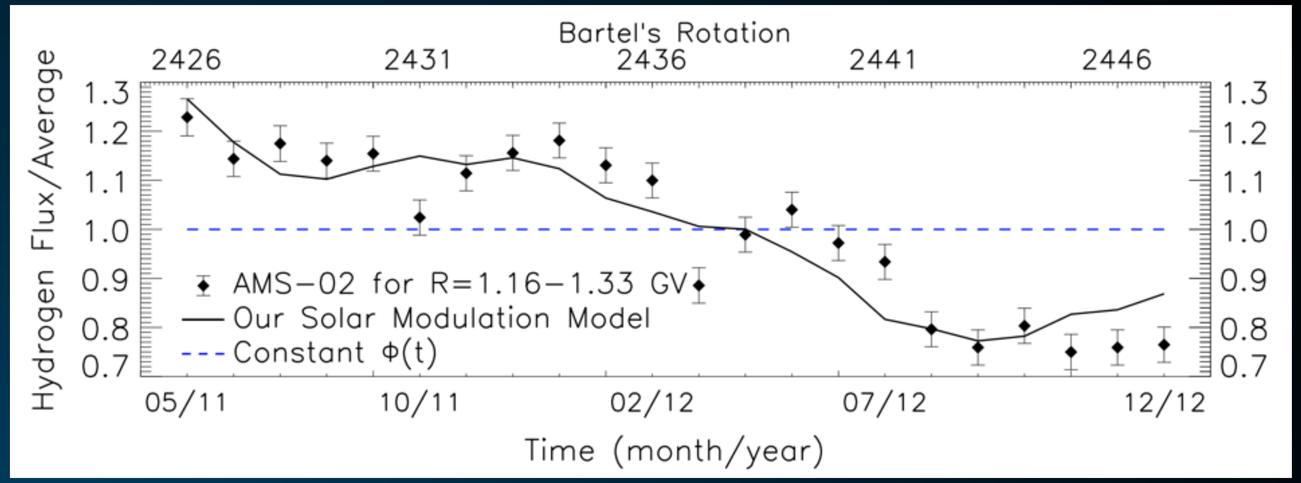
Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

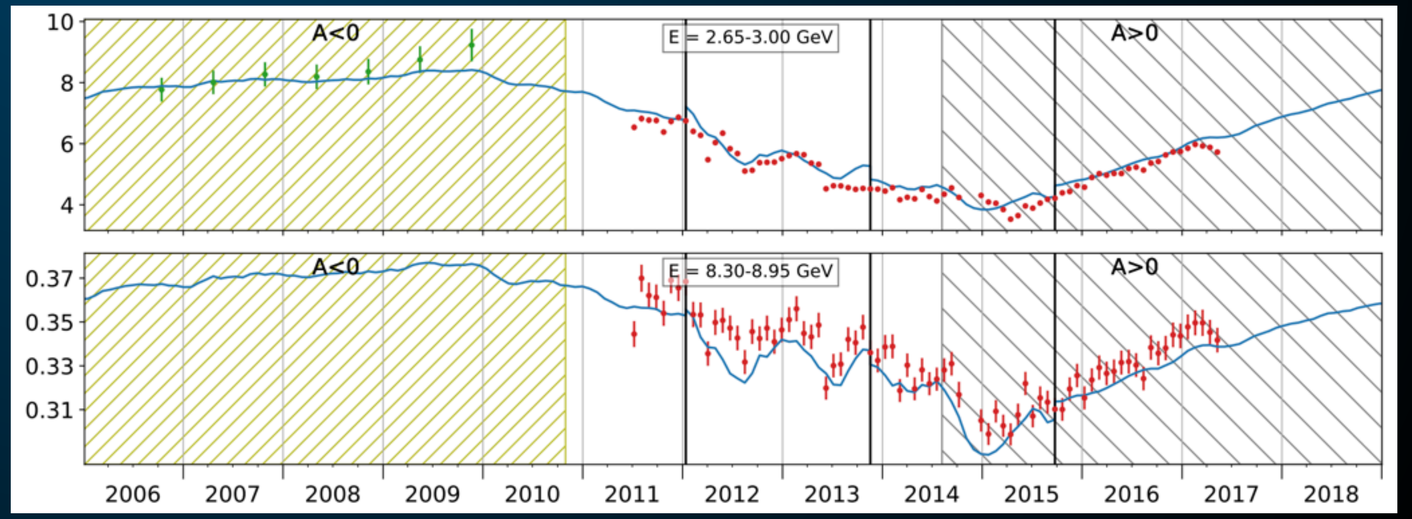
Solar Modulation

Instrumental Uncertainties

Cholis, Hooper, TL (2007.00669)



Kuhlen, Mertsch (1909.01154)



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AMS-02 (PRL 117 2016)

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

(Table continued)

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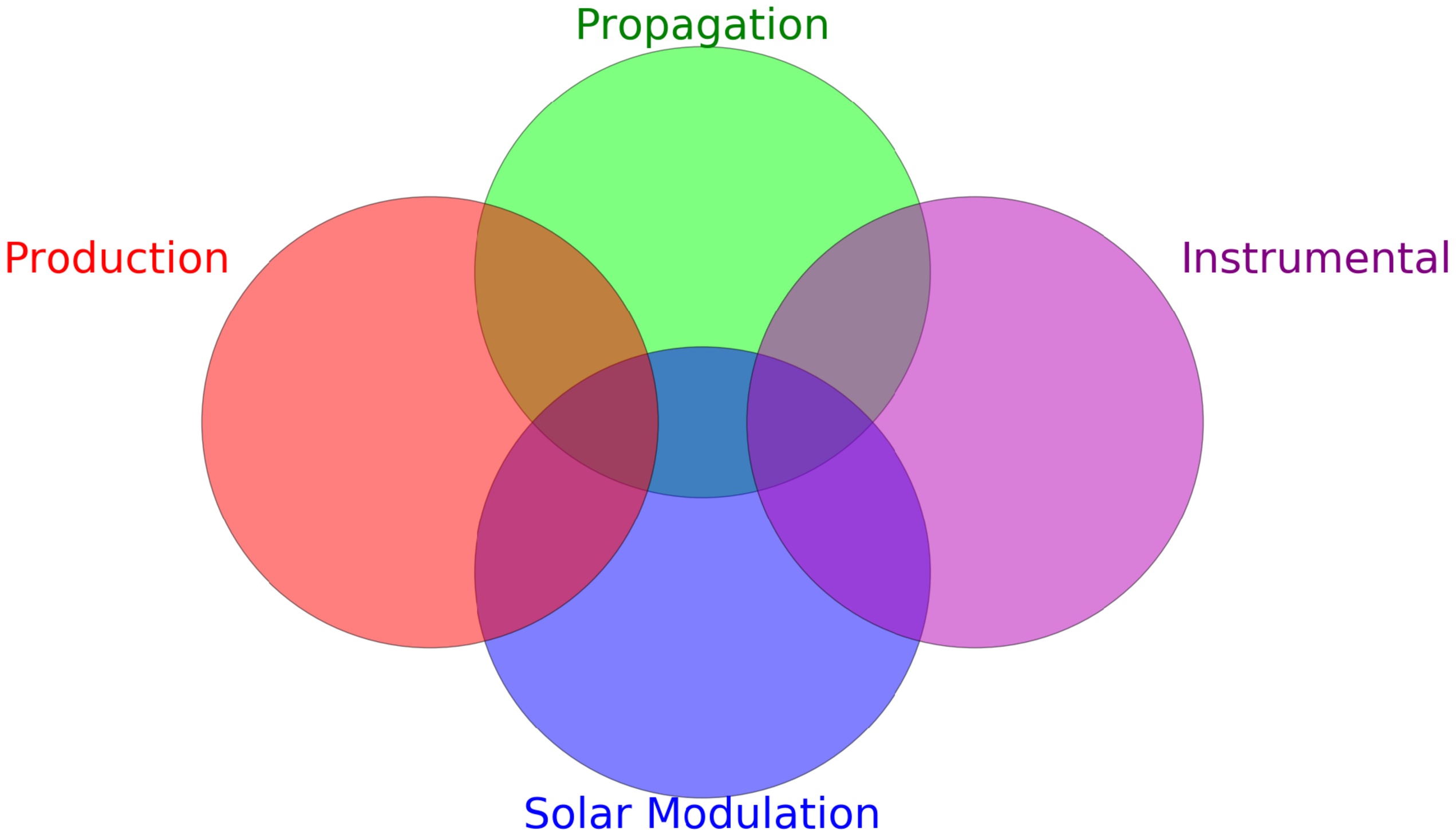
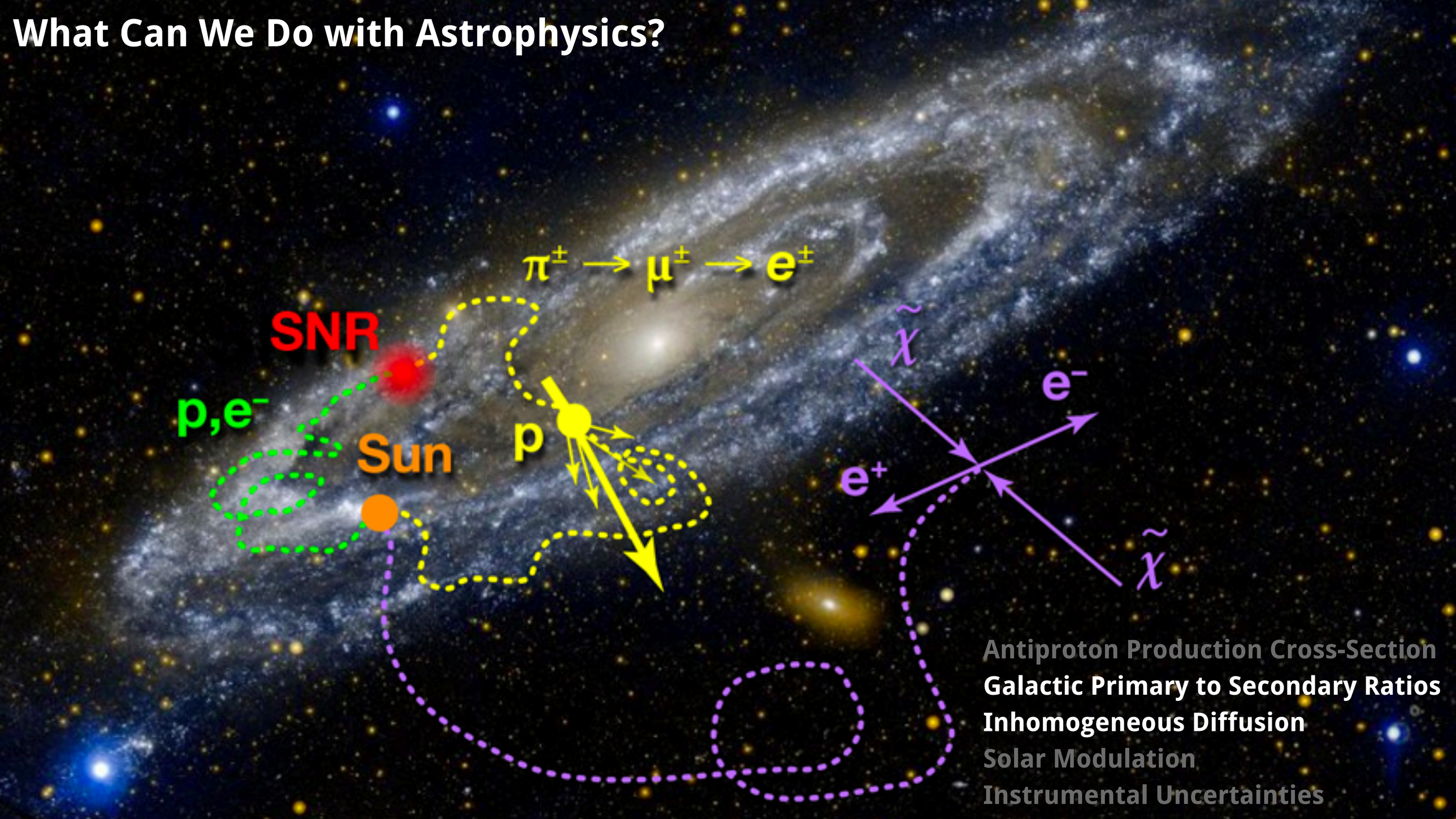

Propagation
Production
Instrumental
Solar Modulation

What Can We Do with Astrophysics?



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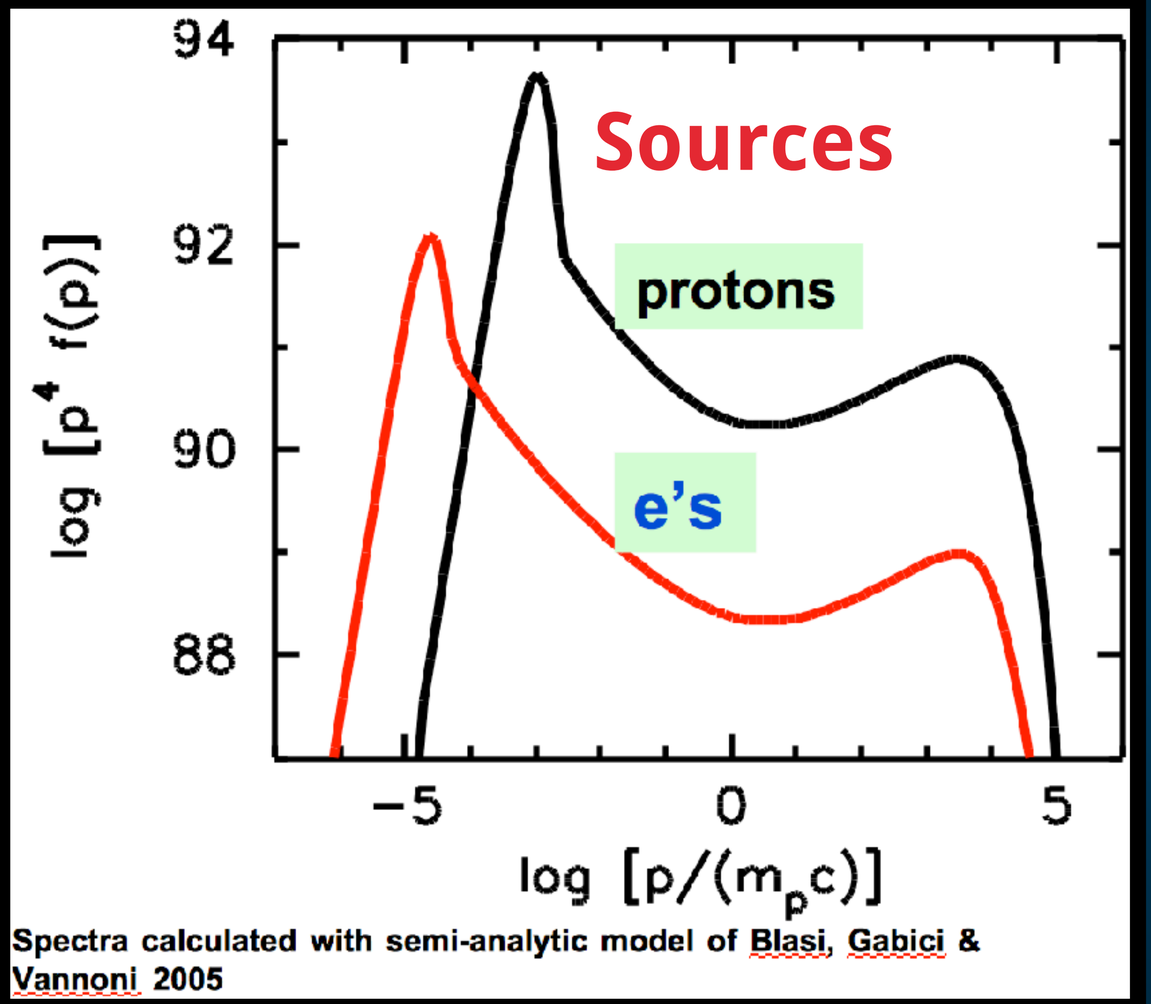
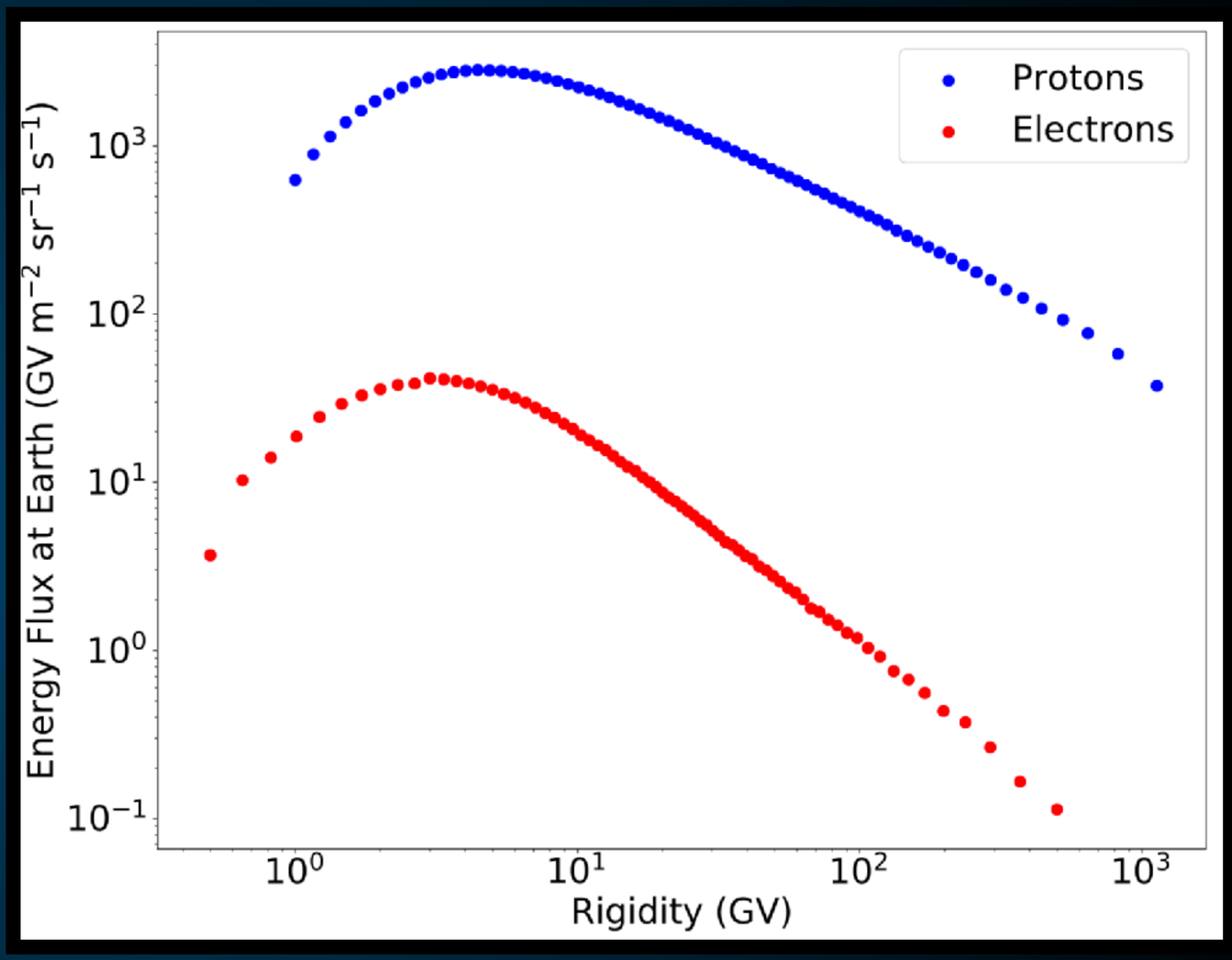
Instrumental Uncertainties

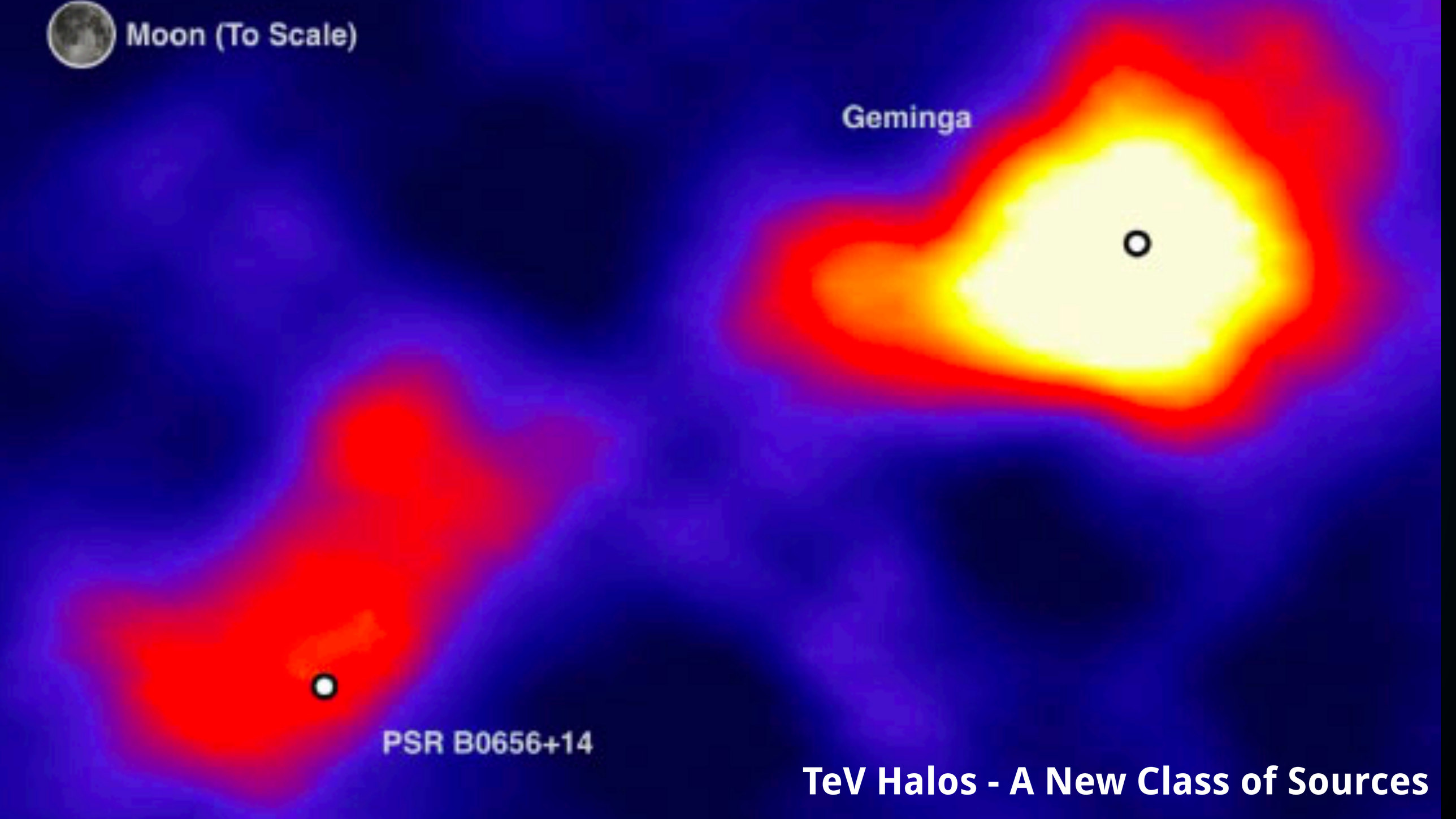
Revolutions in our Understanding of Hadronic and Leptonic Emission



Spectra calculated with semi-analytic model of Blasi, Gabici & Vannoni 2005



+ Evidence both near sources and in the solar neighborhood indicate that protons are the dominant cosmic-ray species.



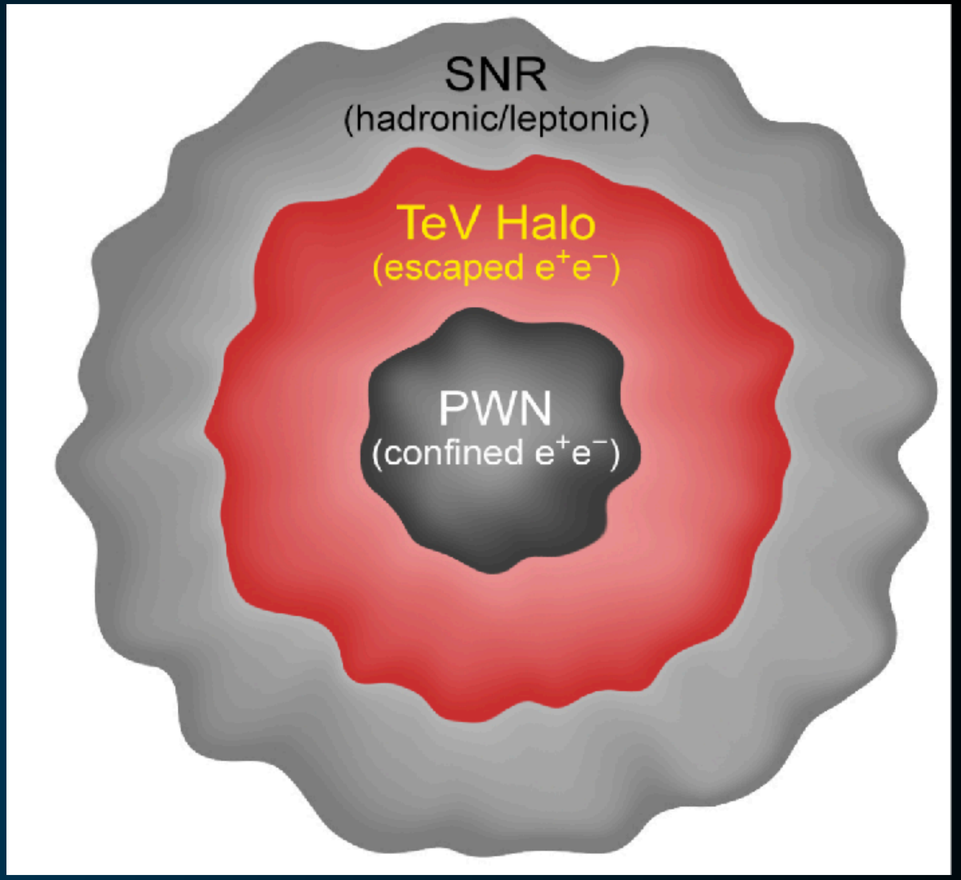
TeV Halos - A New Class of Sources

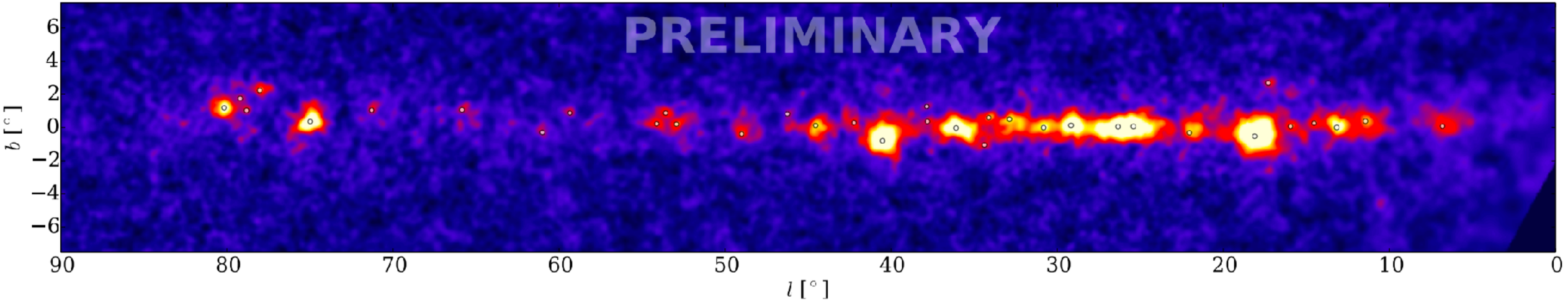
TeV Halos - A New Class of Sources

Two Fundamental Features of Electrons

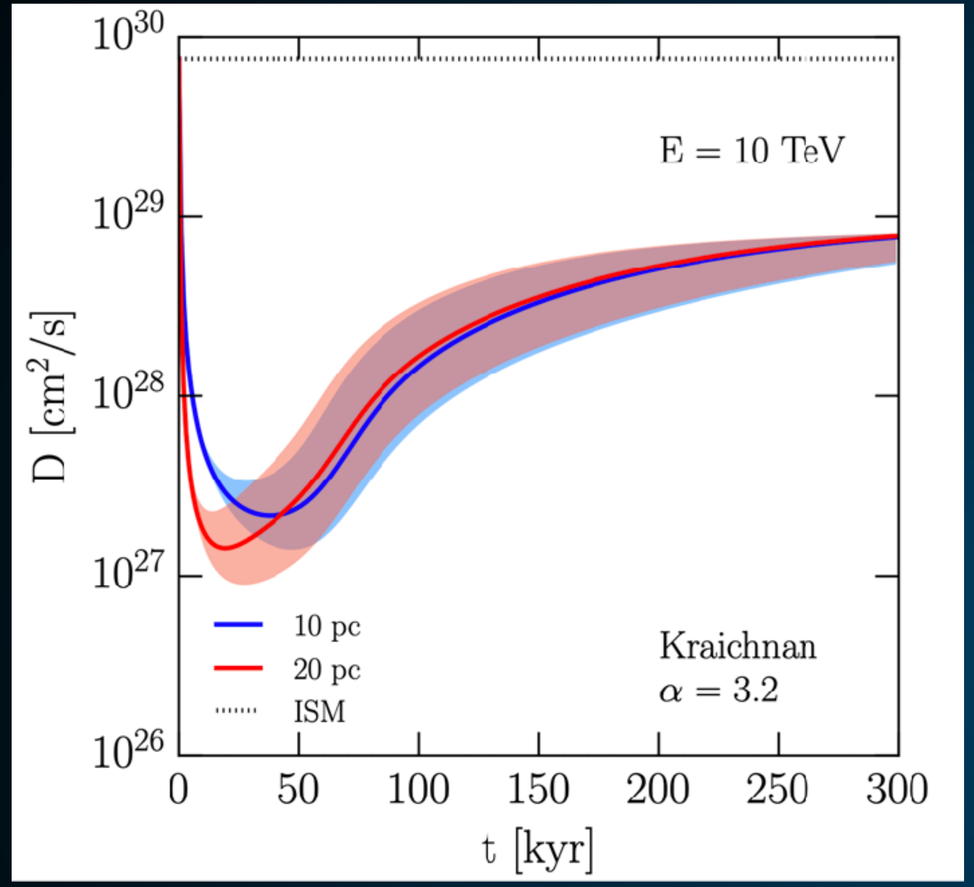
+ Electrons cool quickly, losing most of their energy to radiation (<u>well known</u>).

+ Electrons produce significant cosmic-ray gradients that can influence cosmic-ray diffusion (<u>not known</u>)

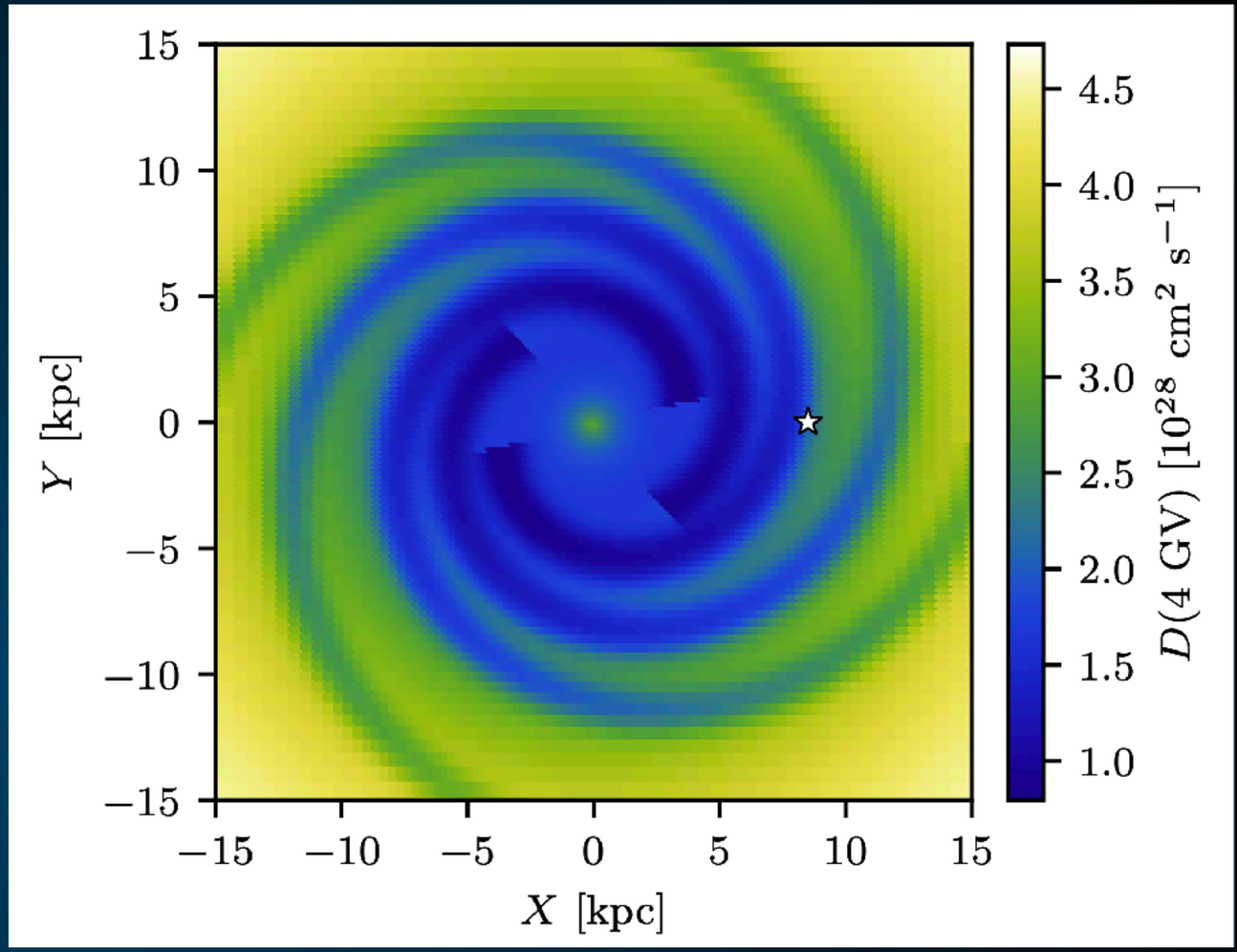




Implications for Cosmic-Ray Diffusion



Evoli et al. (1807.09263)



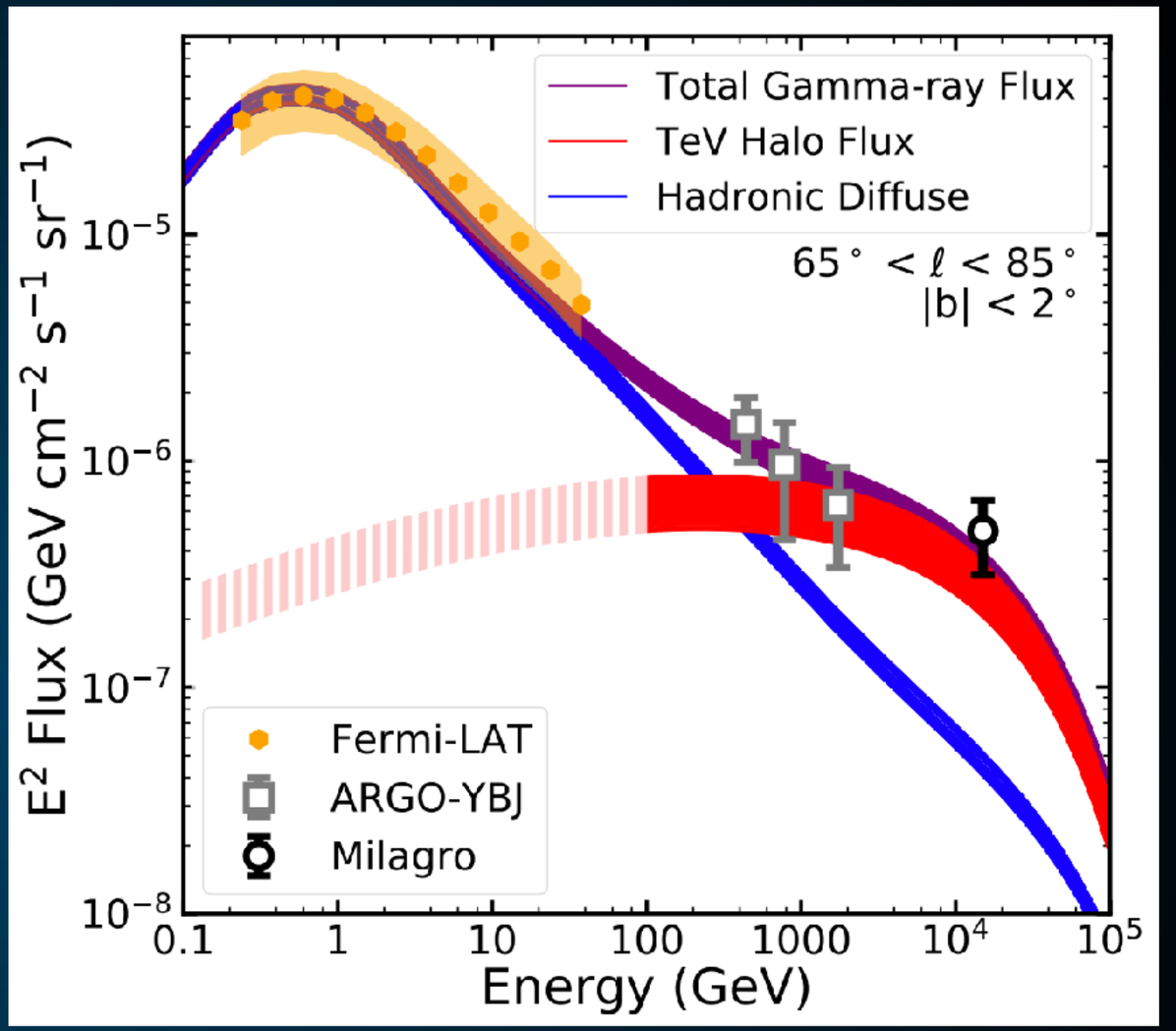
Jóhannesson et al. (1903.05509)

Cosmic-Ray Self-Confinement:

Traced by the rapid loss of electron energy at distances away from sources
Could be powered by either the pulsar itself, or by the associated SNR.

So Is It Really the Rise of the Leptons?

The Sum of these emission sources indicates that leptons could dominate the total gamma-ray emission from the Milky Way above 1 TeV.



W±IV 2021

Implications for the Highest Energy Sources

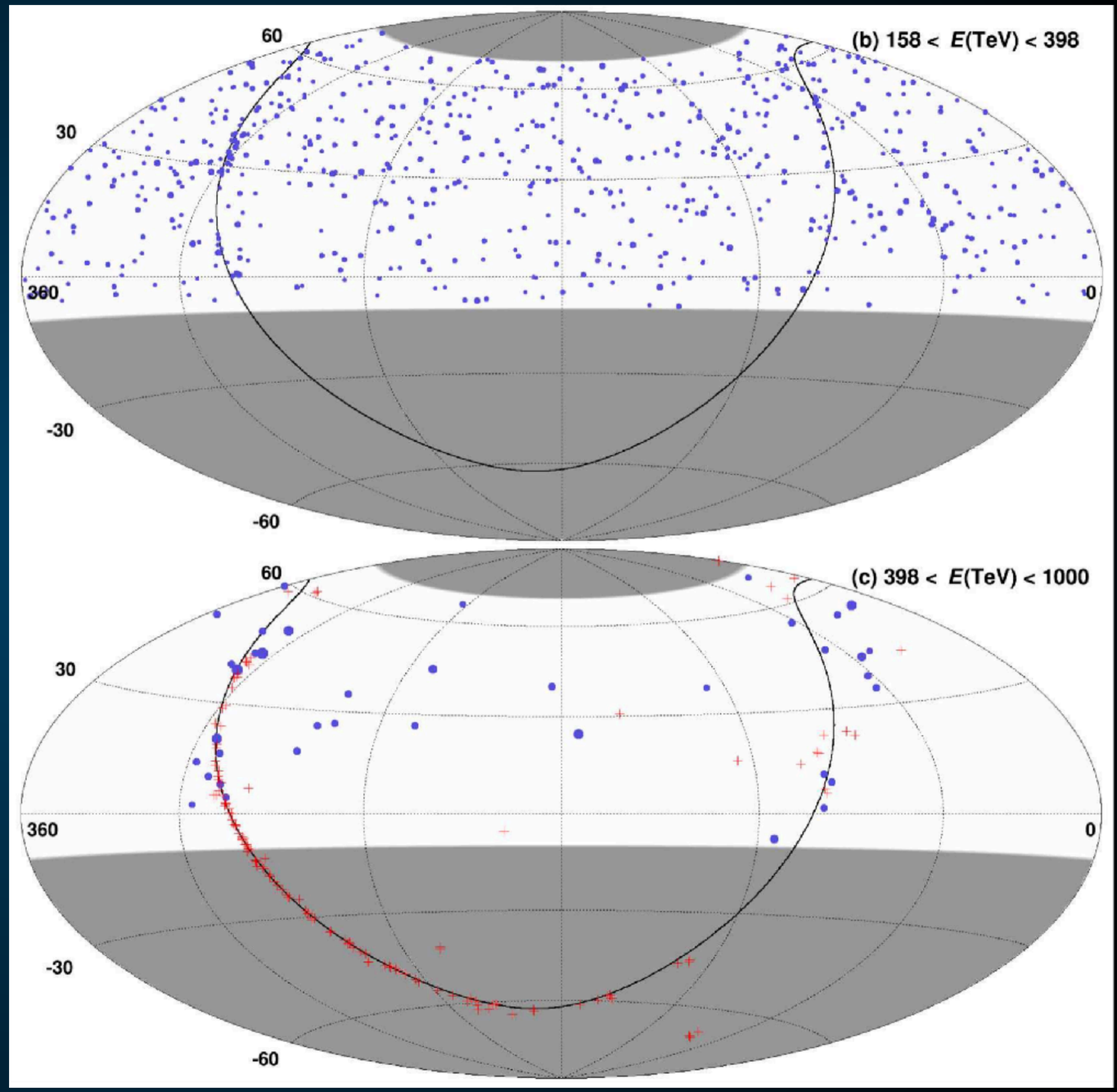
Tibet ASγ Collaboration (2104.05181)

New Observations by Tibet ASγ!

Diffuse Gamma-Ray Emission exceeding 400 TeV!

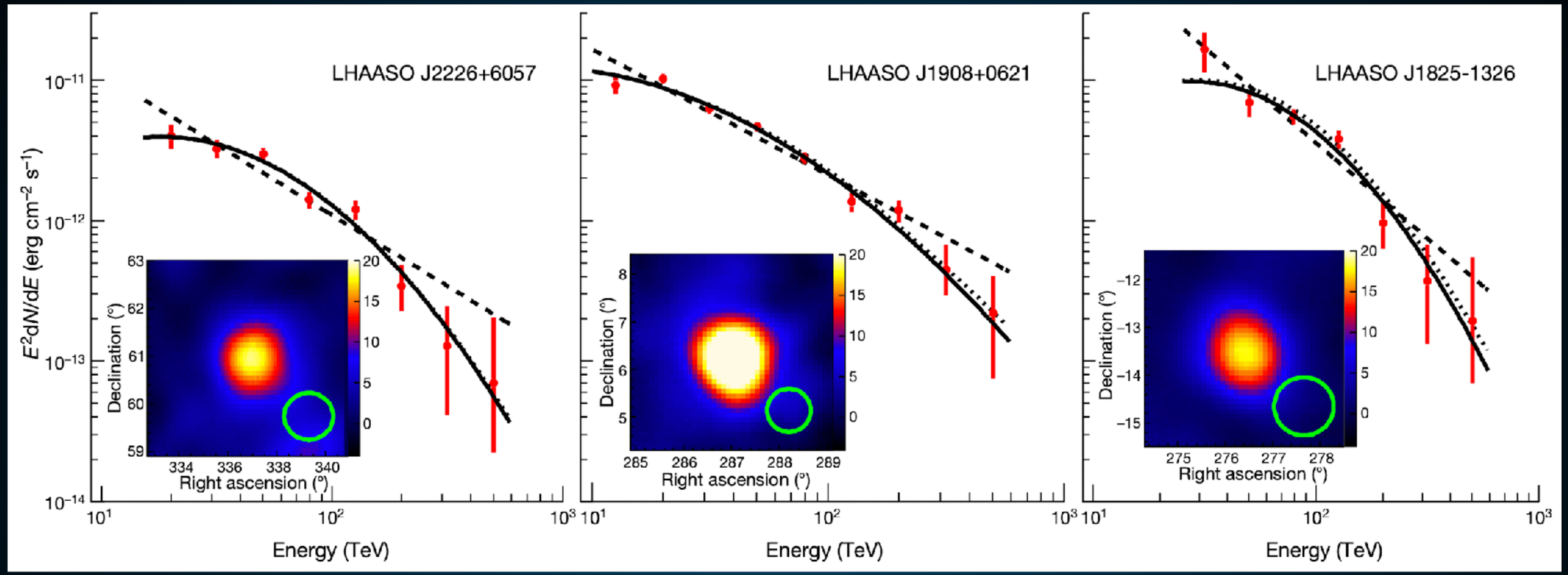
Emission is relatively far from sources and the Galactic plane?

Where do these cosmic-rays come from and why do they interact here?



Implications for the Highest Energy Sources

LHASSO Collaboration (2021)



New Observations by LHASSO!

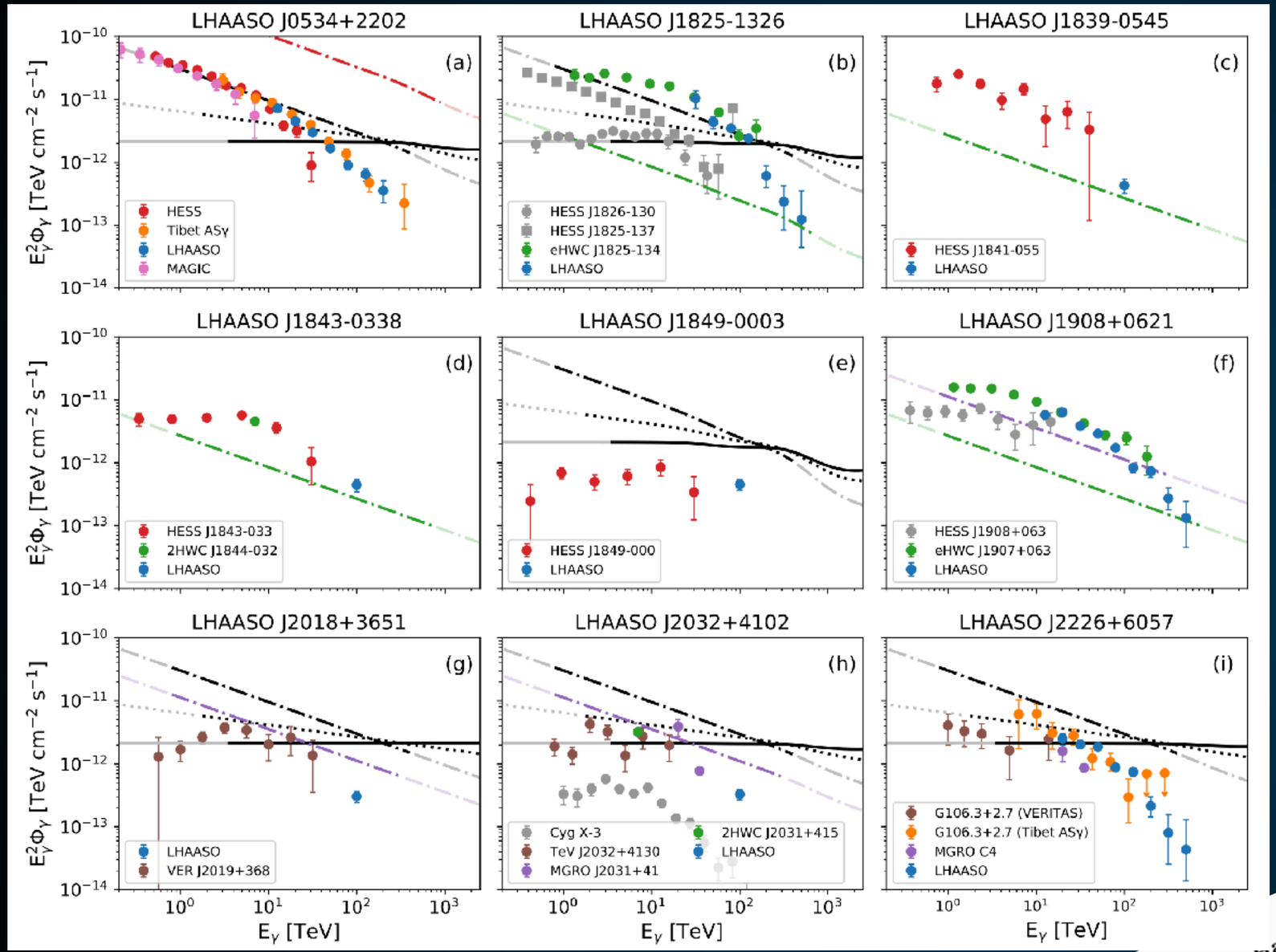
Spectrum of at least 12 Galactic sources extends to nearly 1 PeV!

If Hadronic — Evidence of multi-PeV proton acceleration in Galactic sources

If Leptonic — Evidence of hard spectrum emission capable of overcoming KN Suppression

KN Cutoff for CMB is ~300 TeV, but is not a wall.

Neutrinos as a Powerful Discriminant



Neutrino Observations can definitively discriminate these scenarios.

Several sources have upper limits on hadronic fractions at ~60%!

Several others highly compatible with hadronic origin.

Constraints on Hadronic Contribution to LHAASO Sources with Neutrino Observations

TIAN-QI HUANG [1] AND ZHUO LI [1,2]

[1] *Department of Astronomy, School of Physics, Peking University, Beijing 100871, China*
[2] *Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China*

ABSTRACT

-ray sources above 100 TeV which are the possible origins of Galacti
ino measurements by IceCube and ANTARES in the vicinity
ion of hadronic gamma-rays in these sources. We find t
ic gamma-rays contribute no more than ~60
o LHAASO sources, LHAASO J1825
nponents up to ~200 TeV, un
100 TeV gamma-ray
ergies.

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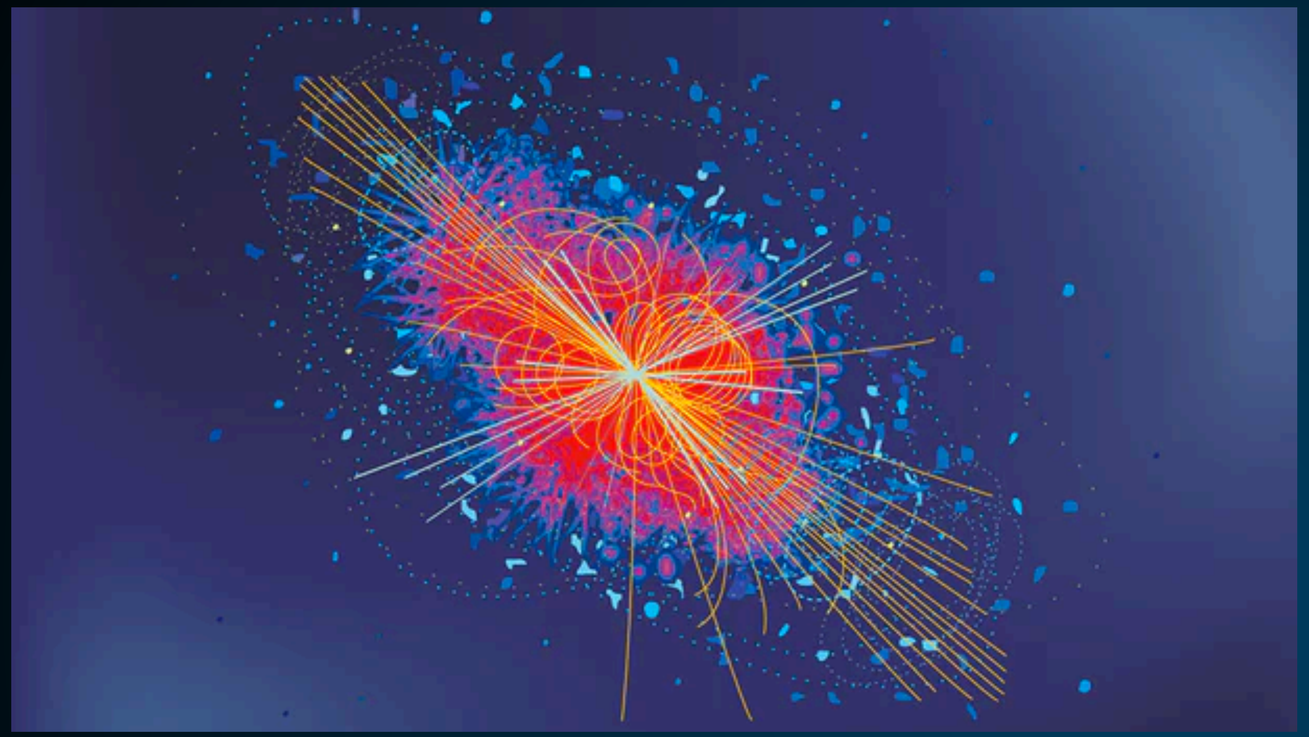
Antinuclei !? - Hope for Dark Matter in a Background Free Environment?

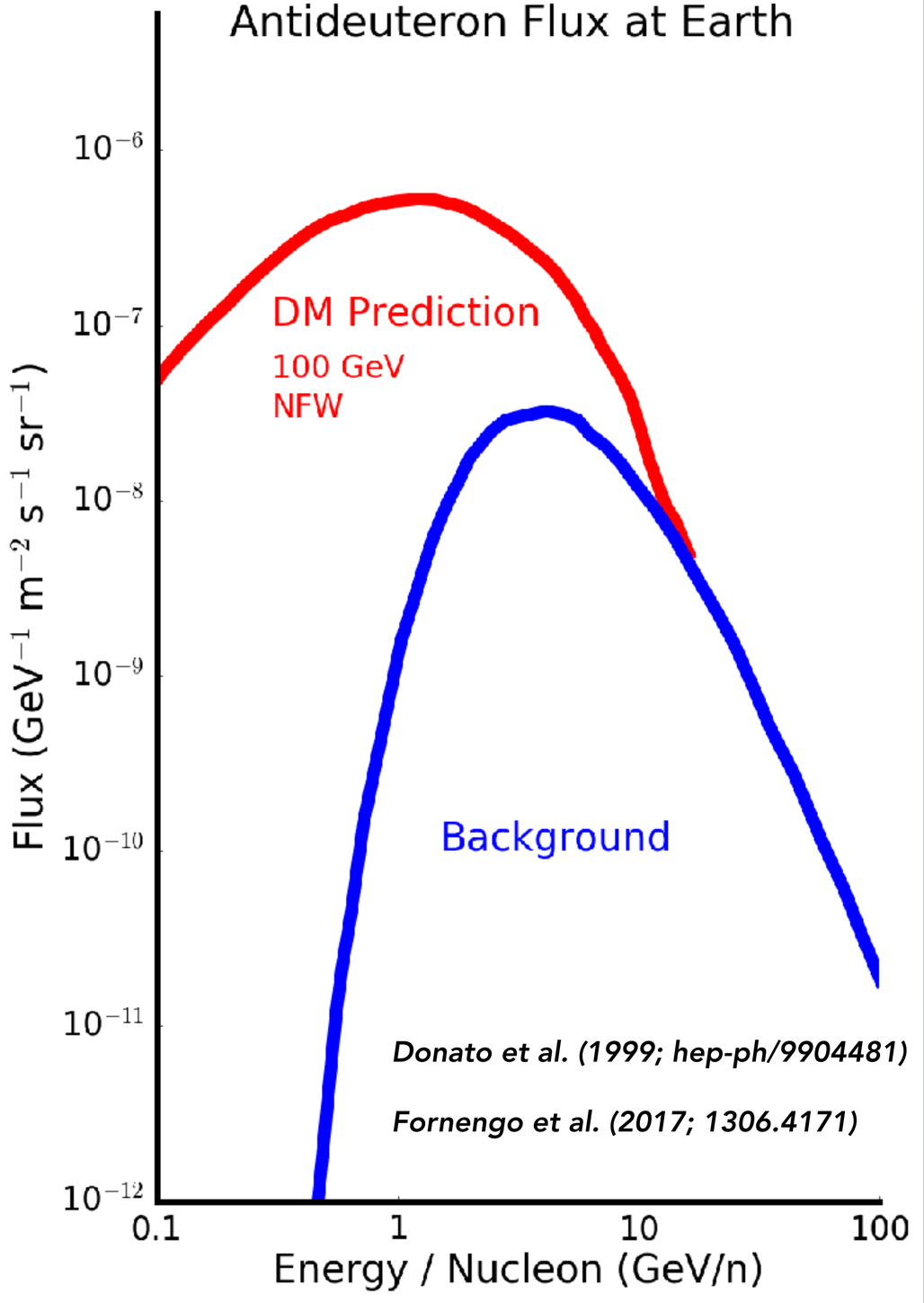
AntiNuclei - A Clean Search Strategy ?



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}.

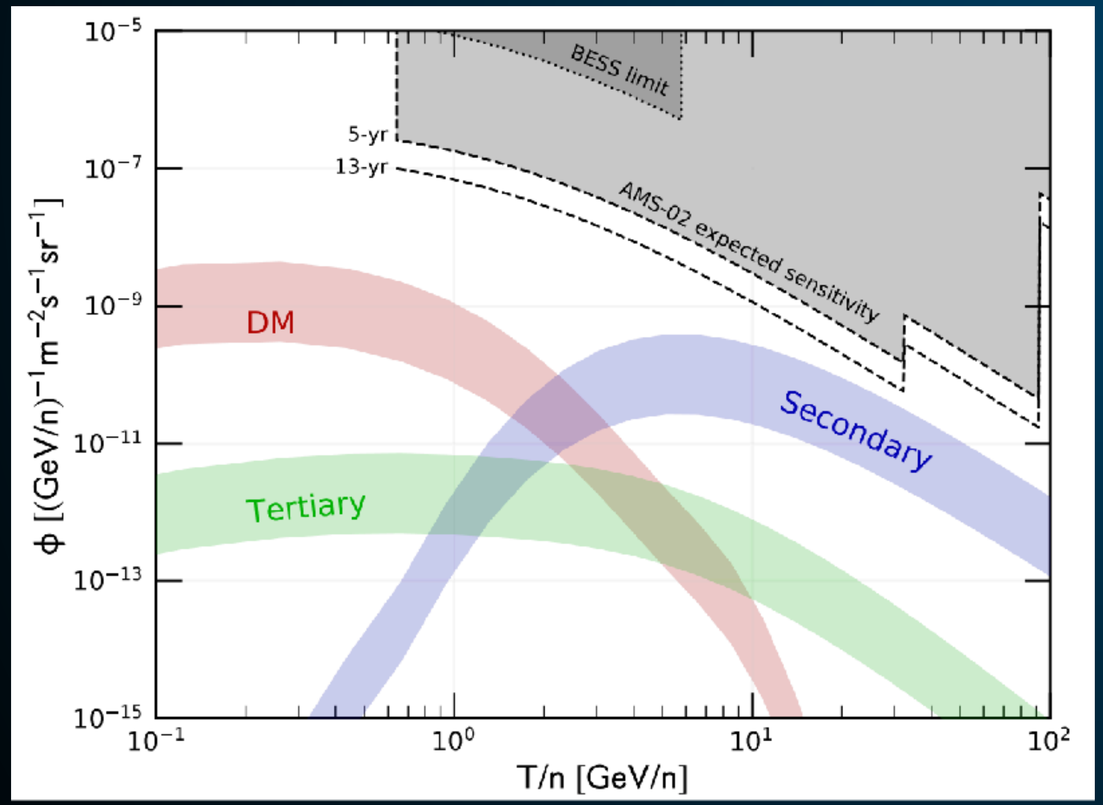
Note that for $^4\bar{He}$, projecting based on the statistics we have today, by using an additional 400 million core hours for simulation the background probability would be 10^{-4}. Simultaneously, continuing to run until 2023, which doubles the data sample, the background probability for $^4\bar{He}$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

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

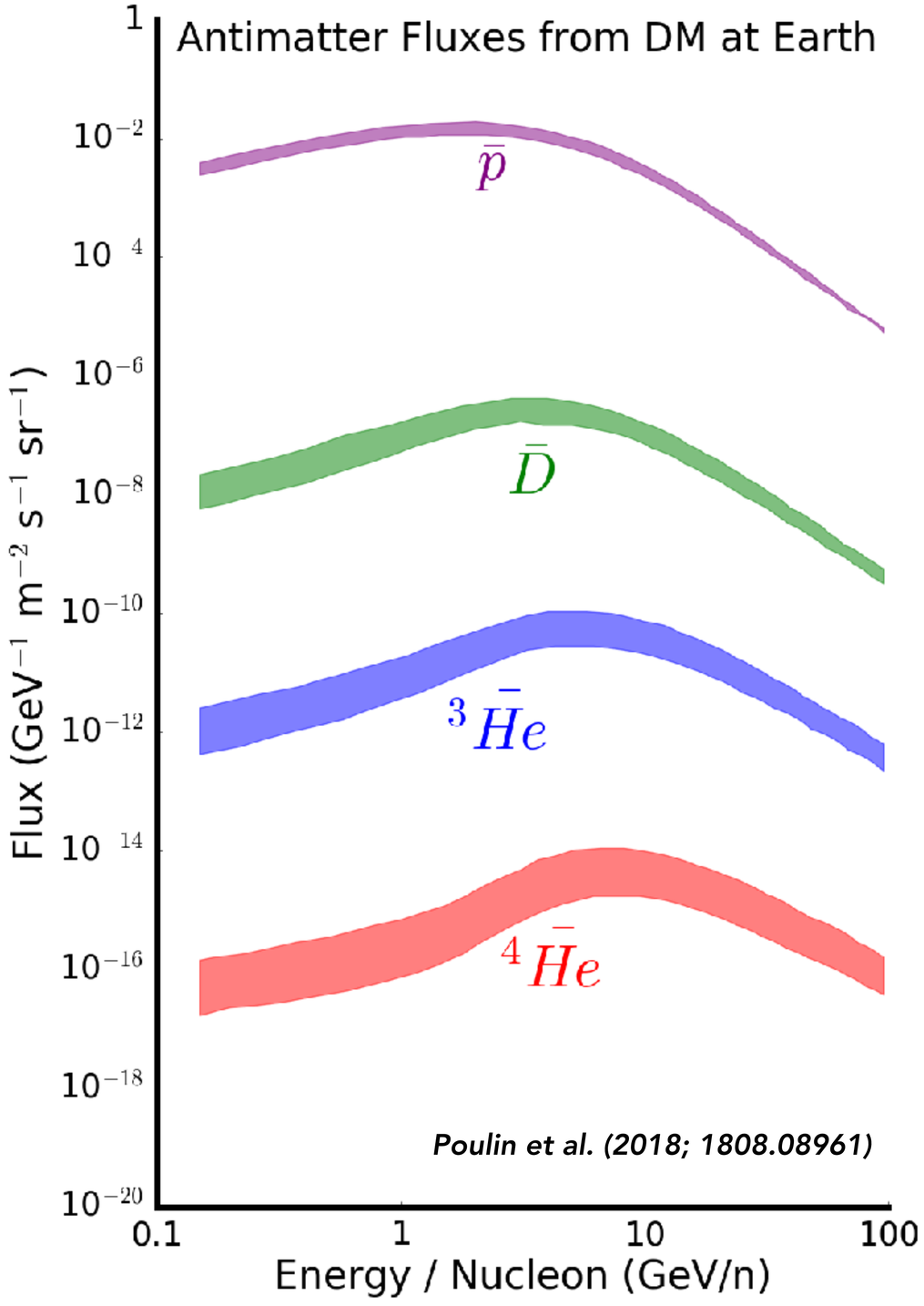
AntiNuclei - A Clean Search Strategy ?

Antihelium background even cleaner than antideuterons

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



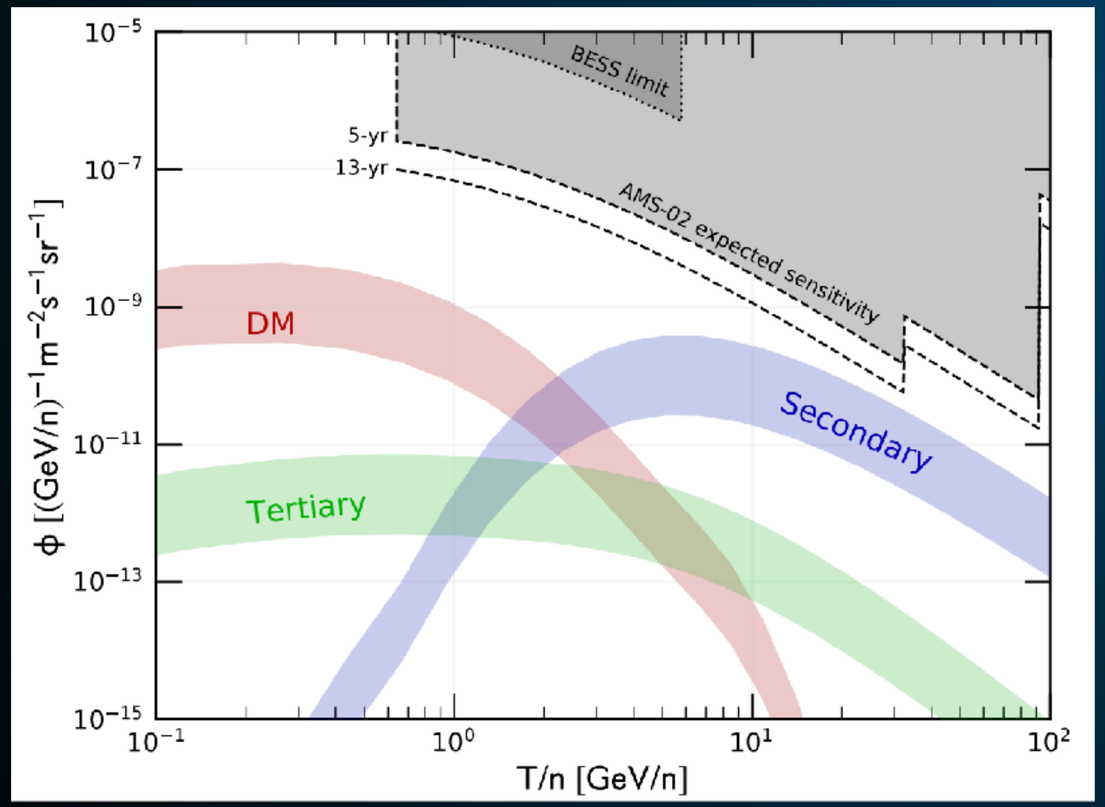
Korsmeier (2017; 1711.08465)



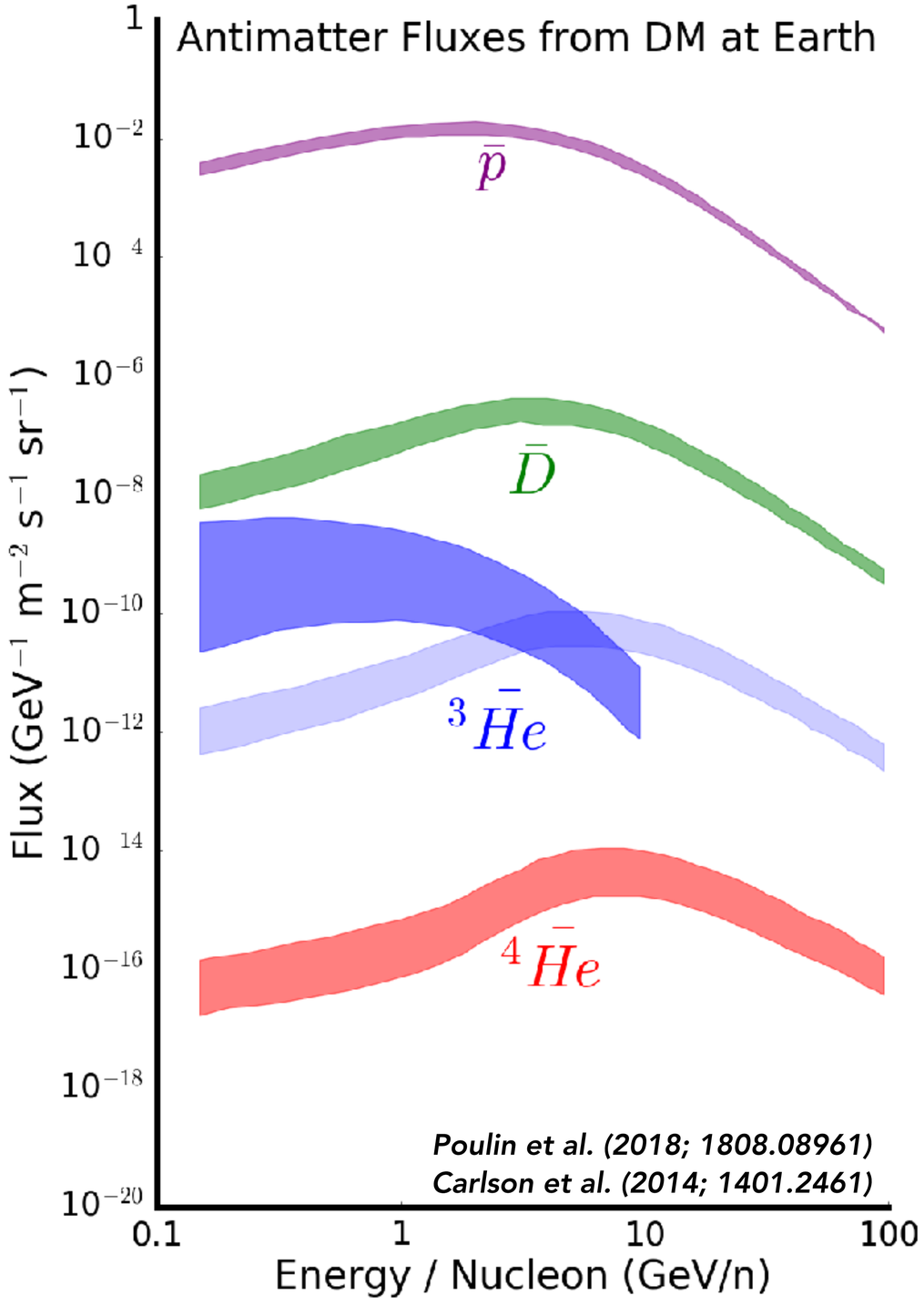
AntiNuclei - A Clean Search Strategy ?

Antihelium background even cleaner than antideuterons

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



Korsmeier (2017; 1711.08465)



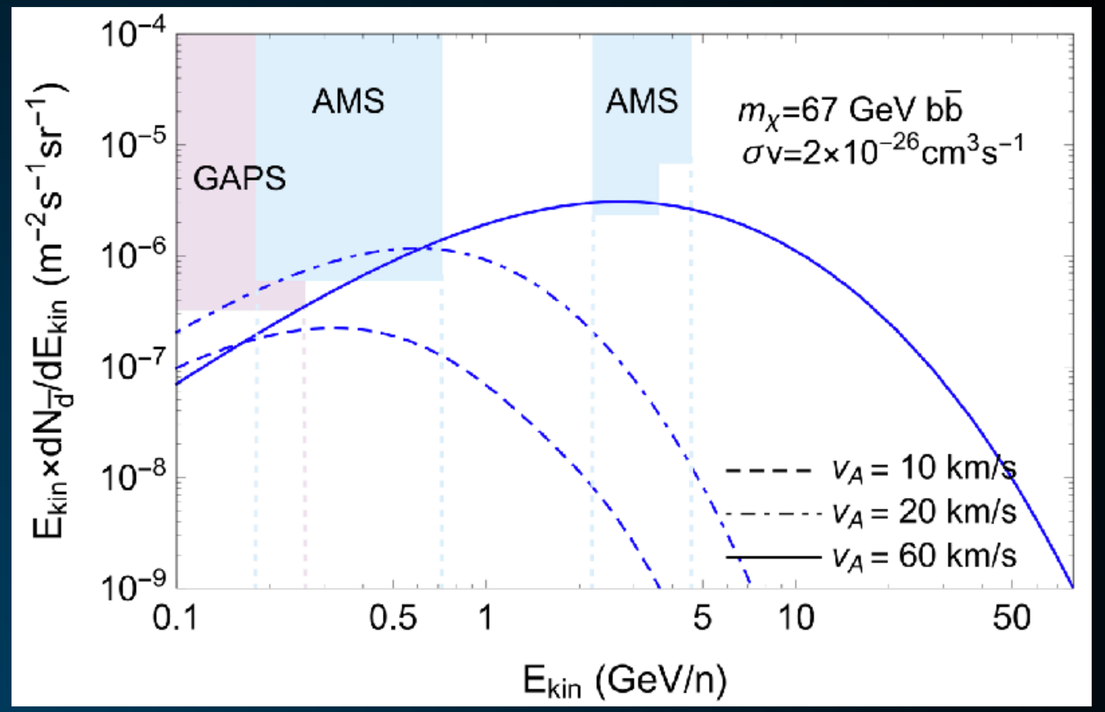
Poulin et al. (2018; 1808.08961)
Carlson et al. (2014; 1401.2461)

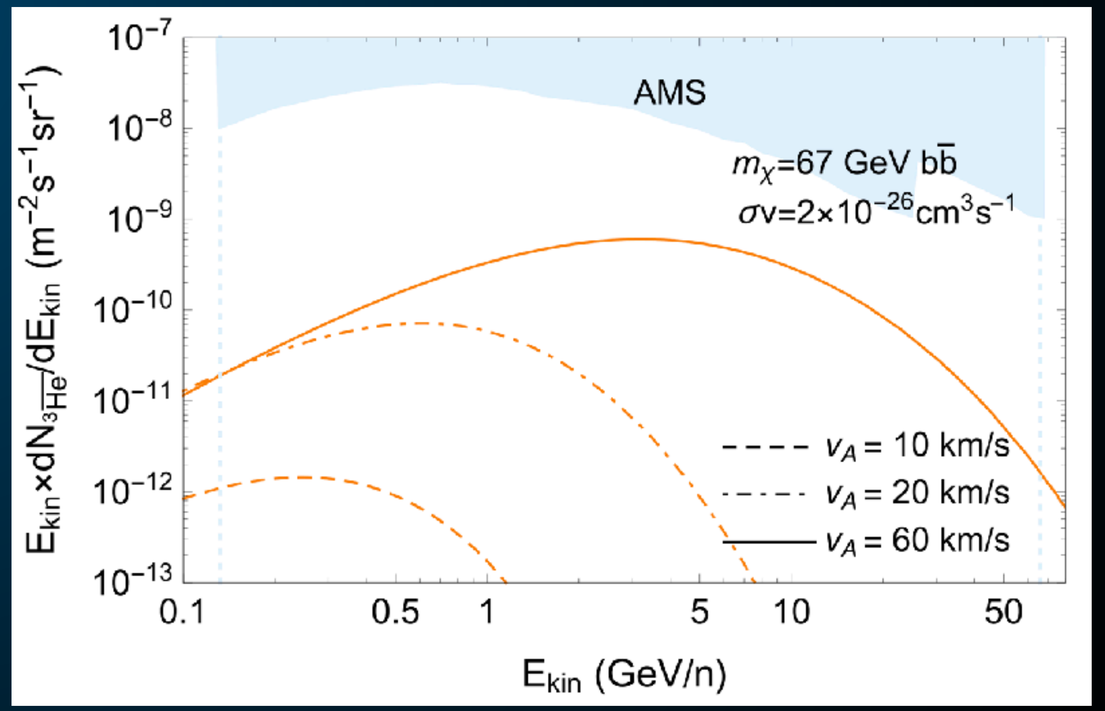
Astrophysical Enhancements!

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

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

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





Cholis, Linden, Hooper (2020; 2001.08749)

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.

I. INTRODUCTION

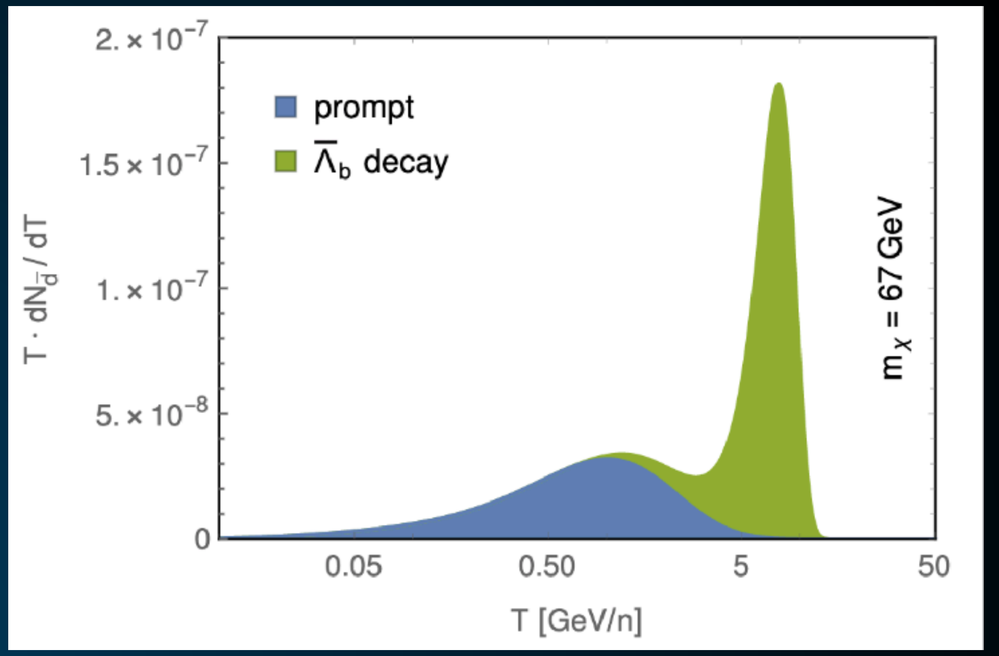
The detection of massive cosmic-ray antinuclei has long been considered a holy grail in searches for WIMP dark matter [1, 2]. Primary cosmic-rays from astrophysical sources are matter-dominated, accelerated by nearby supernova, pulsars, and other extreme objects. The secondary cosmic-rays produced by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

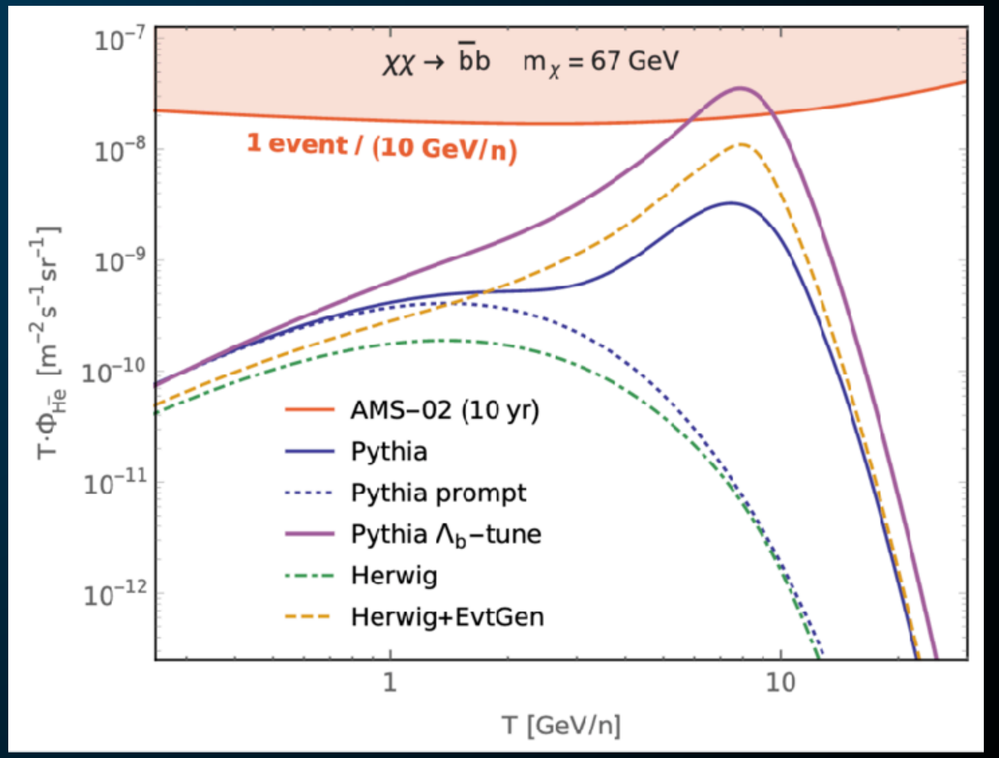
In this *letter*, we challenge the current understanding that standard dark matter annihilation models cannot produce a measurable antihelium flux. Our analysis examines a known, and potentially dominant, antinuclei production mode which has been neglected by previous literature – the production of antihelium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

Particle Physics Enhancements!

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

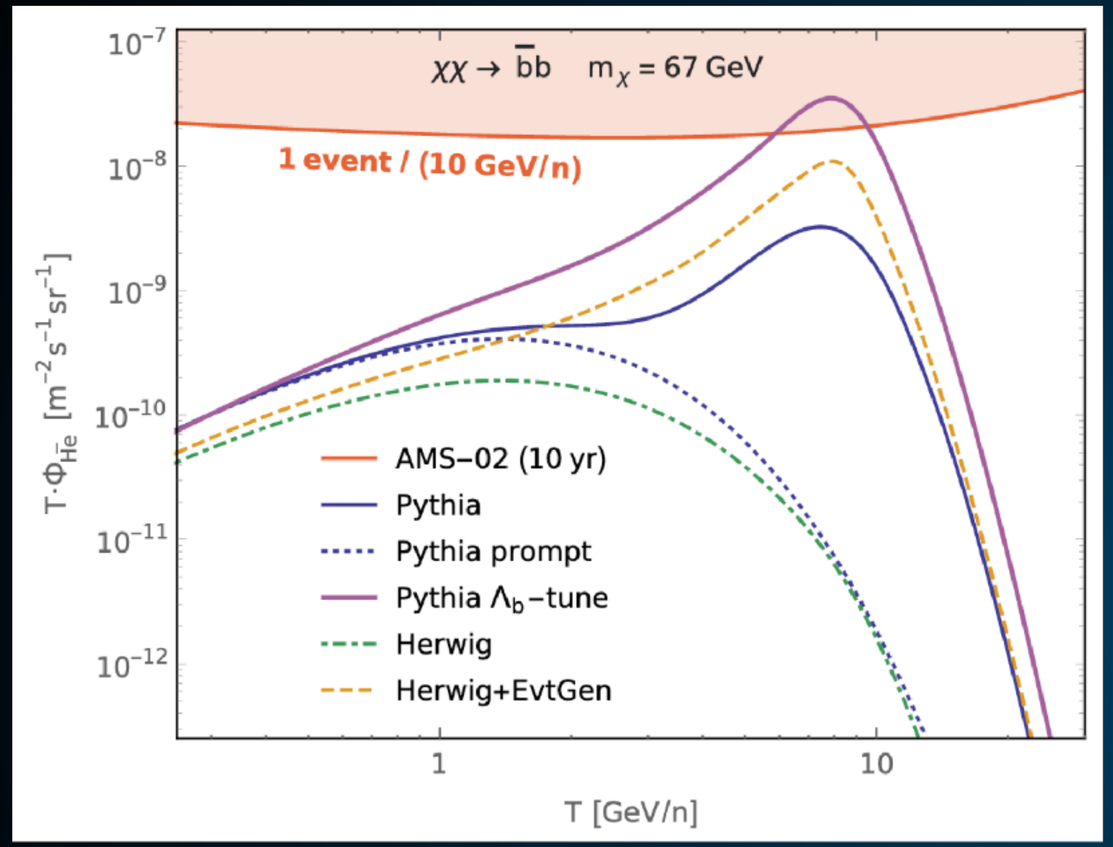
The displaced-vertex decays of Lambda_b baryons potentially boosts the detectable AMS-02 signal by orders of magnitude!

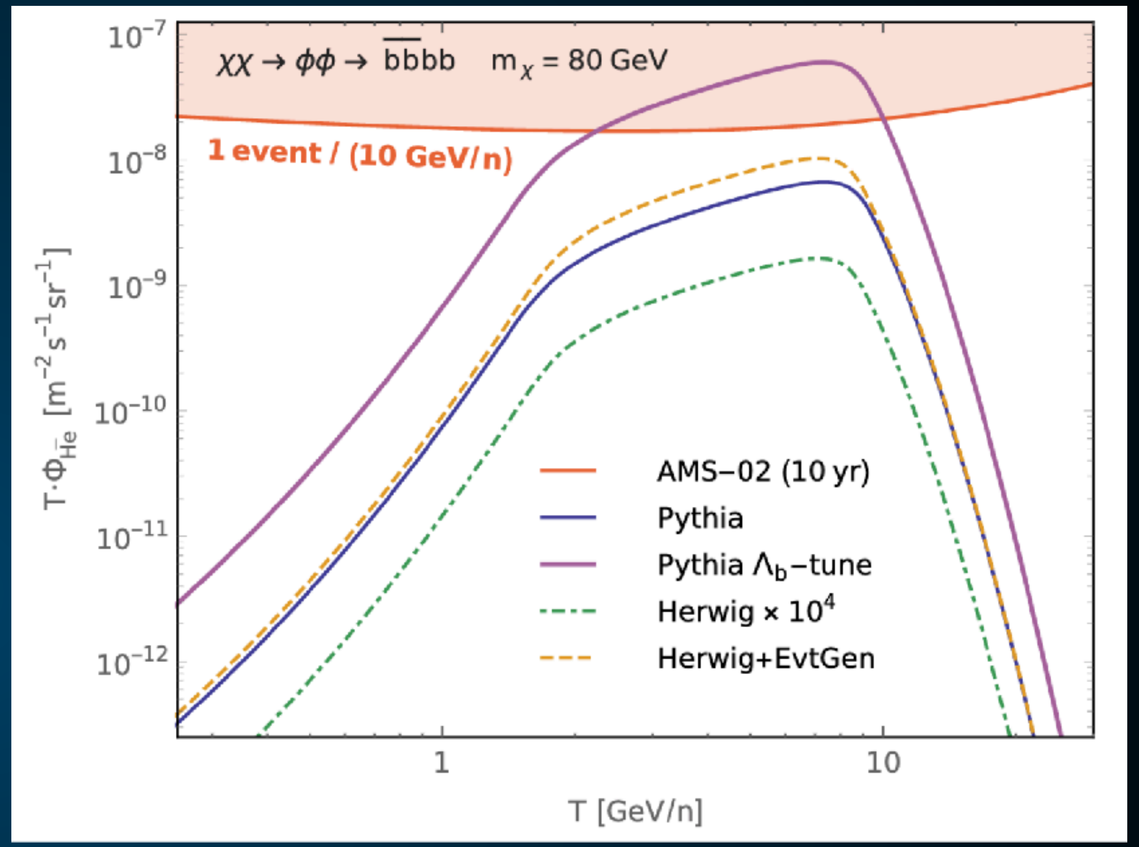




Winkler & Linden (2020; 2020.16251)

Particle Physics Enhancements!

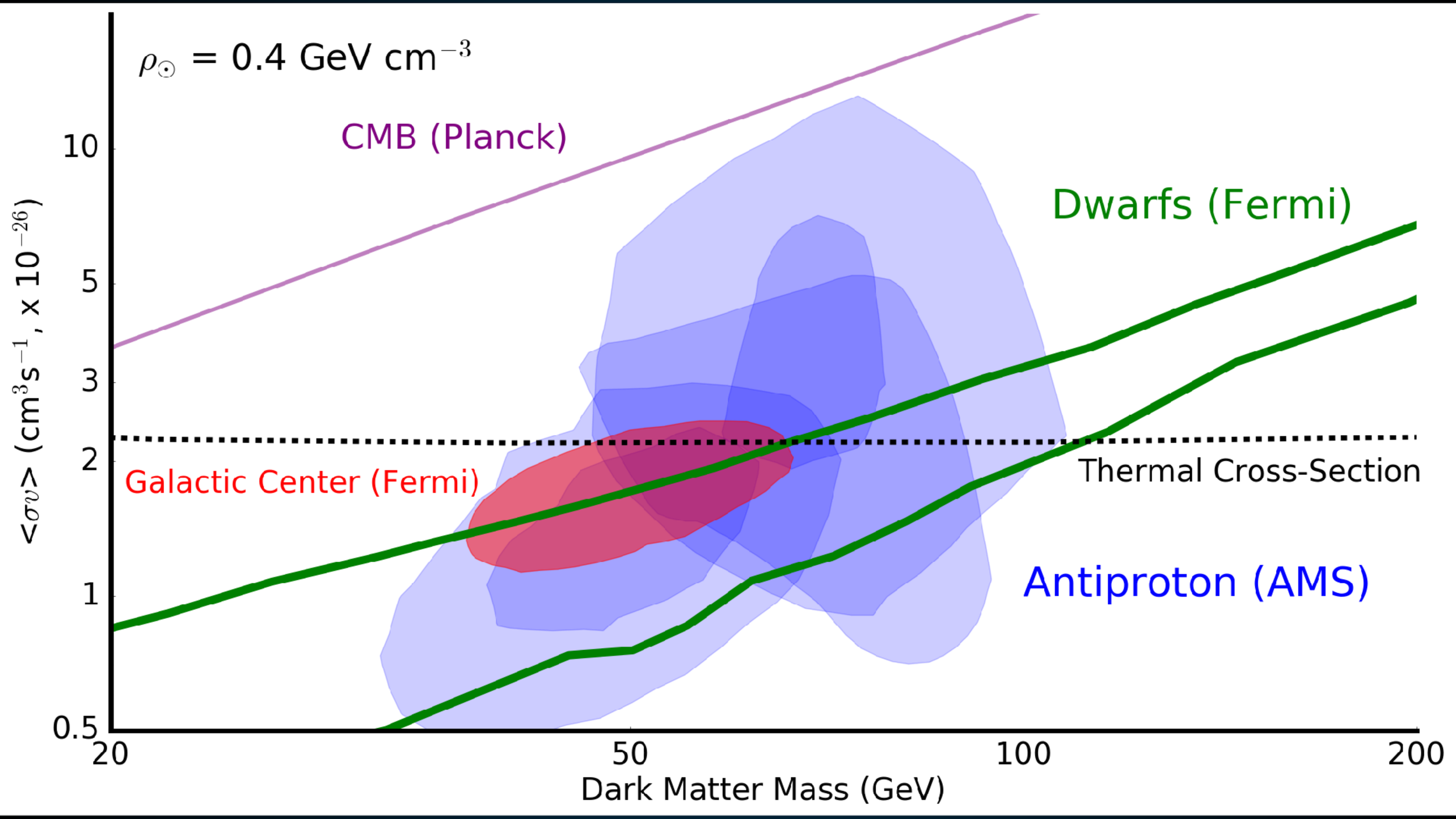


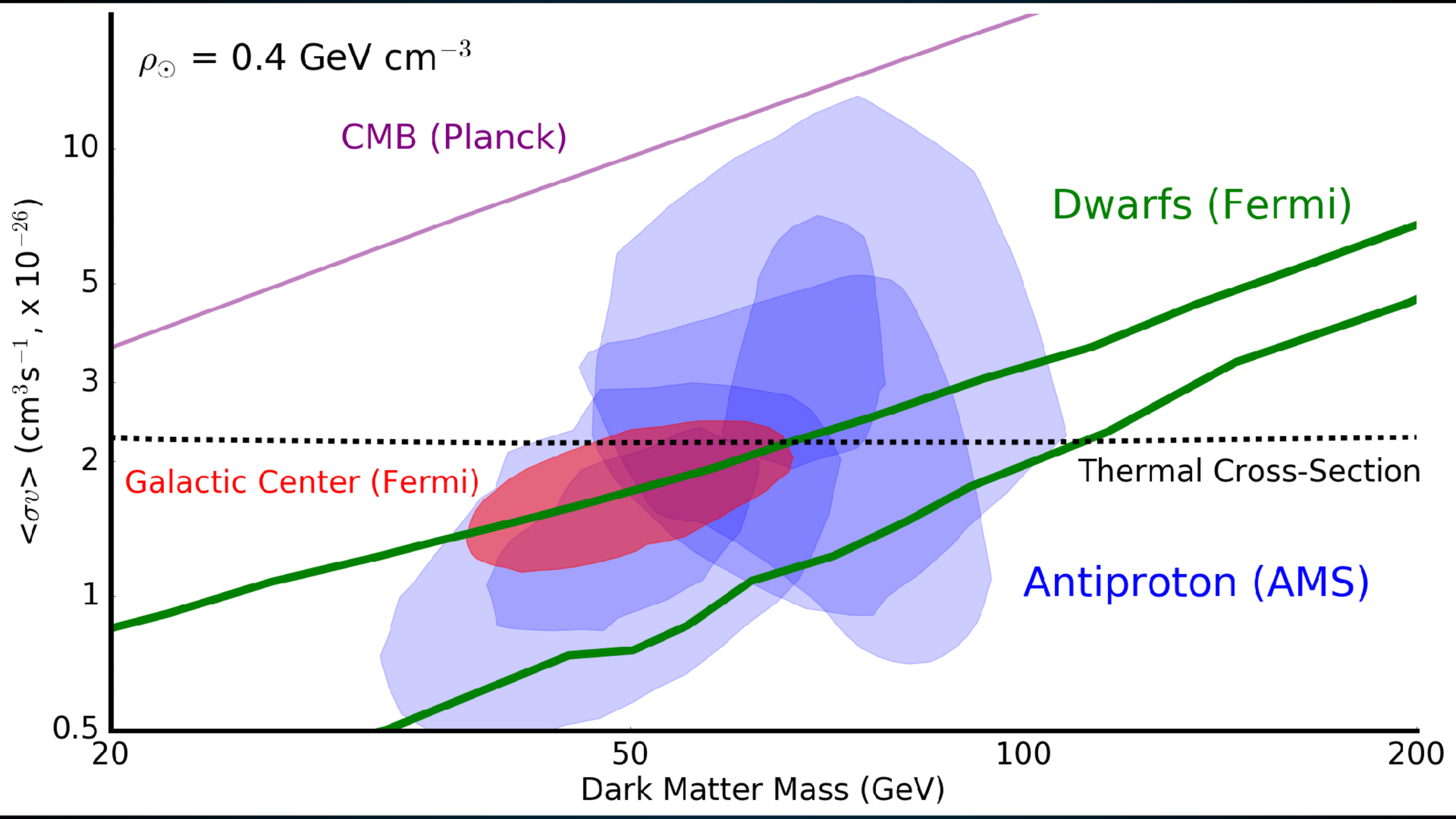


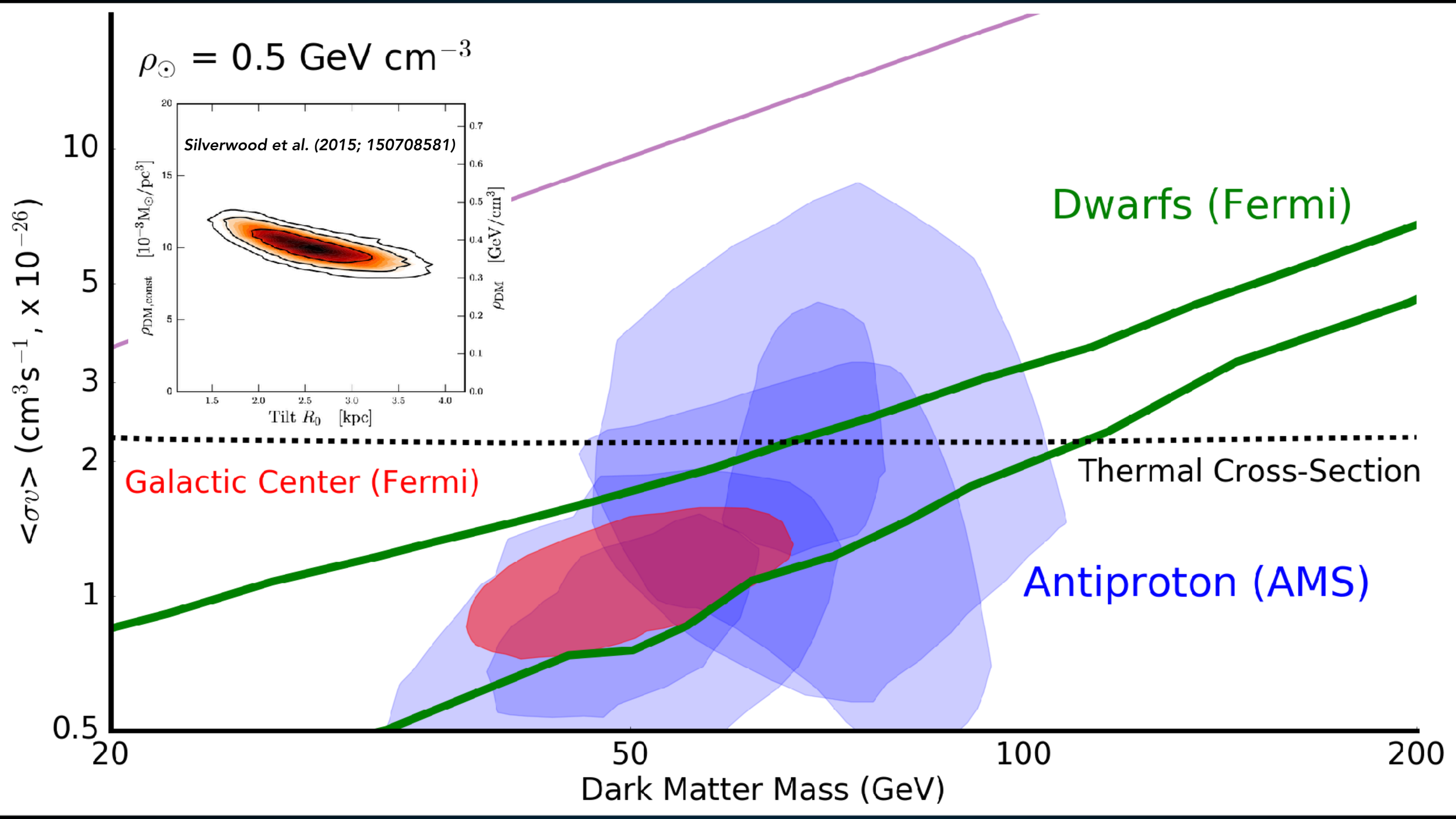
Generator	P	P [Λ_b-tune]	H	H+EvtGen
$^3\overline{\text{He}}$ events	0.1 (0.007)	0.9	0.003	0.3
$\bar{d}$ events	3.7 (3.5)	4.2	1.7	2.1

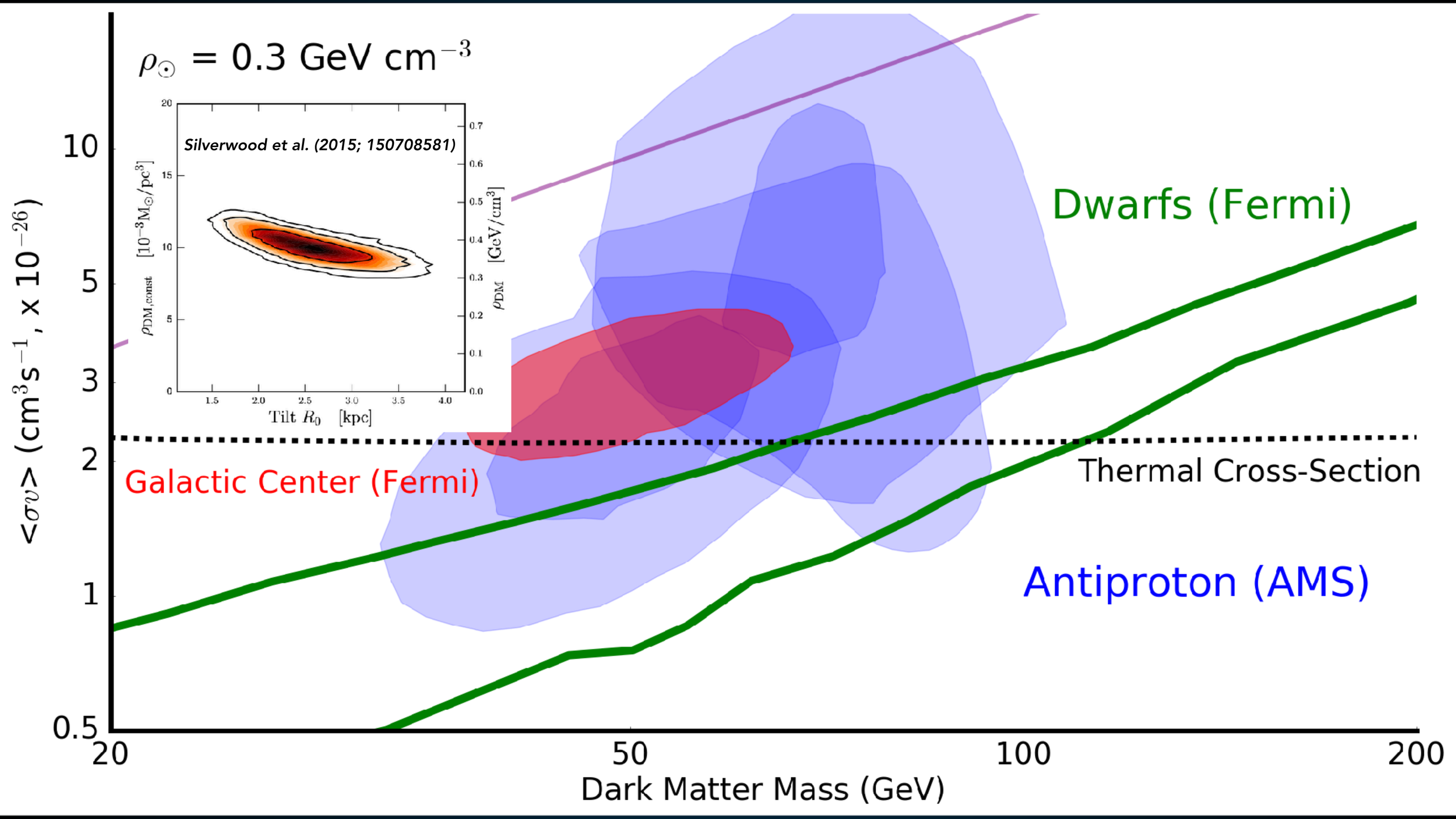
Winkler & Linden (2020; 2020.16251)

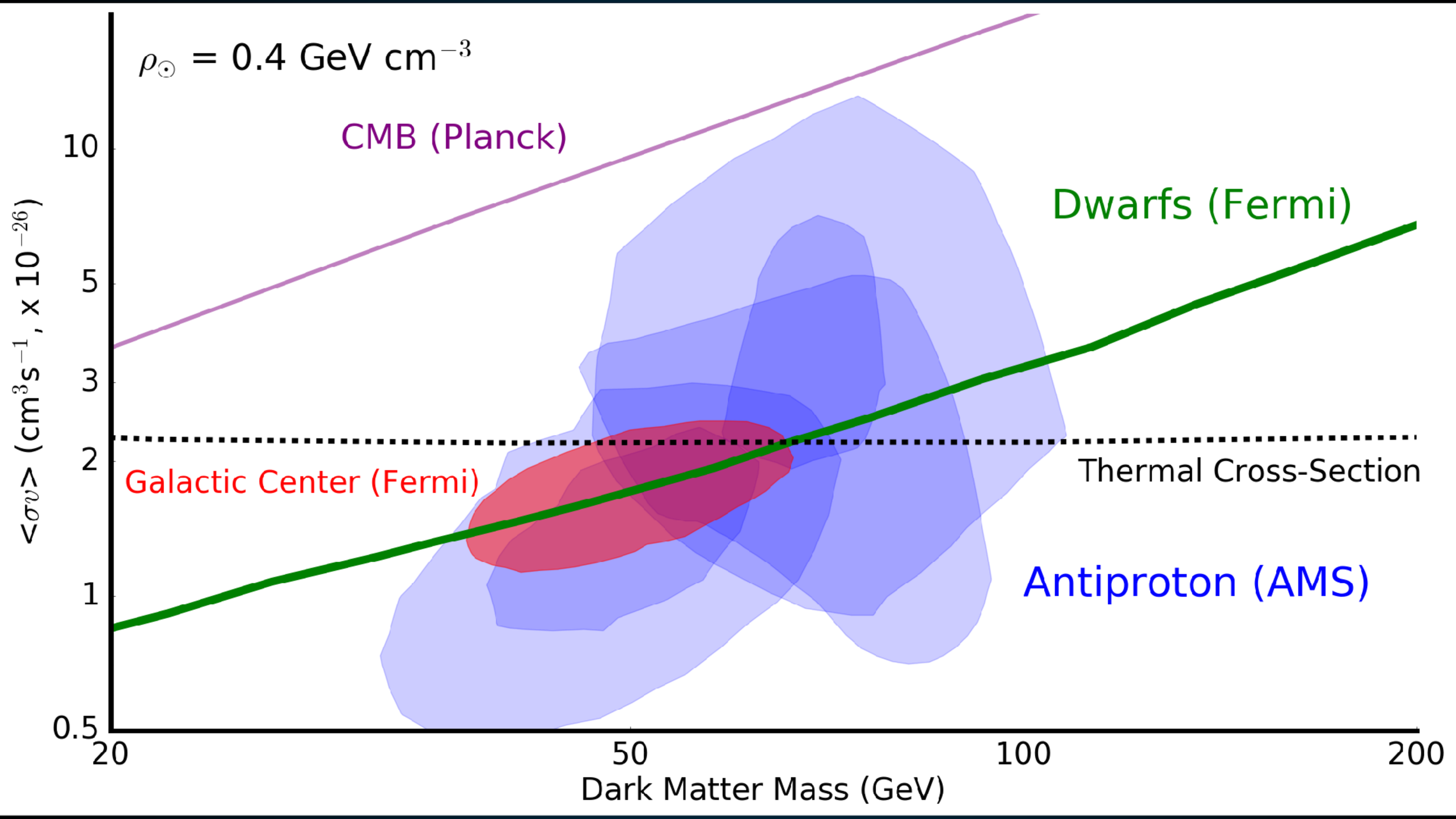

WHERE
ARE
WE NOW?

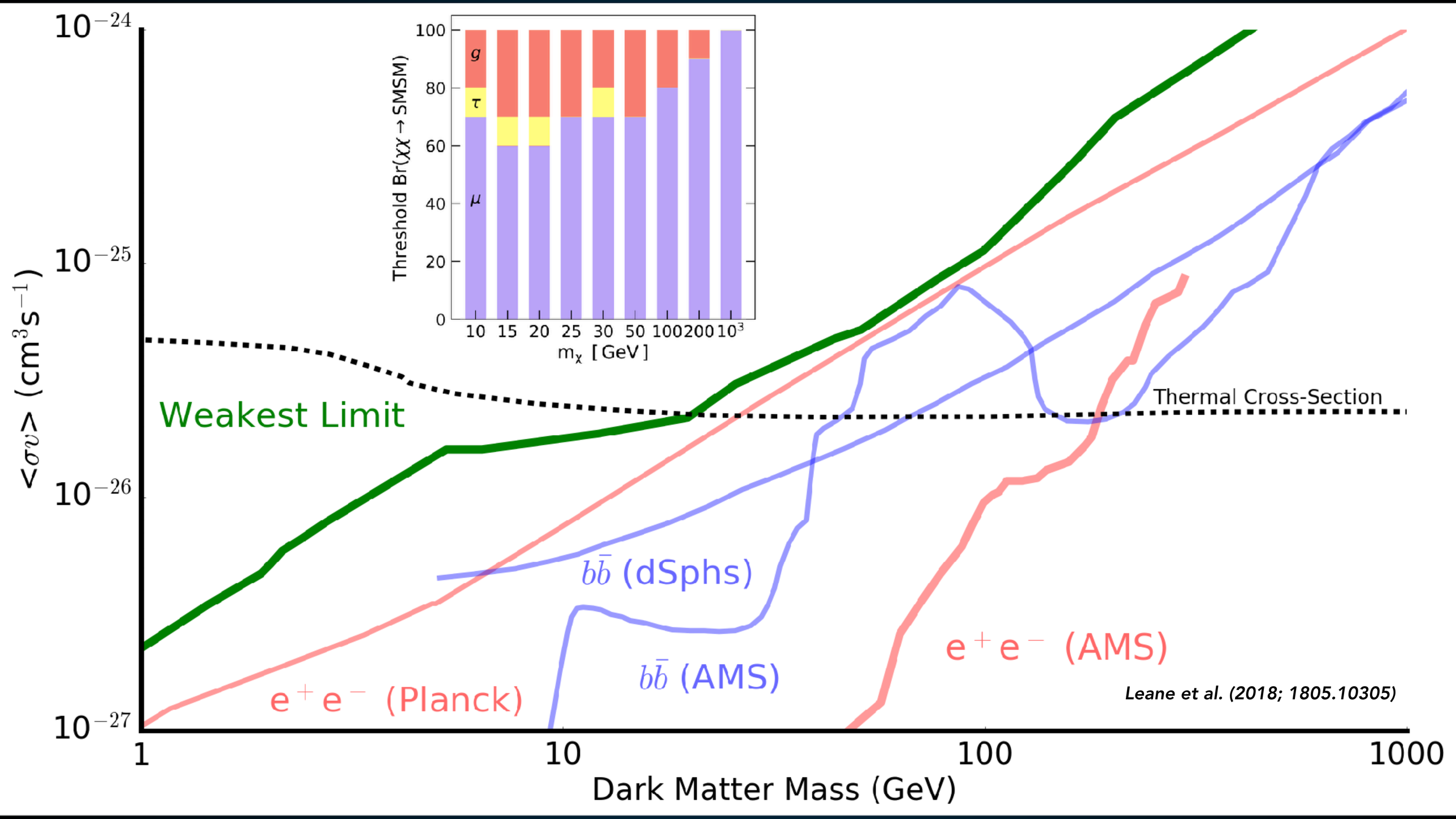

$\rho_\odot$ = 0.4 GeV cm^{-3}
CMB (Planck)
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
10
5
3
2
1
0.5
20
50
100
200
Dark Matter Mass (GeV)

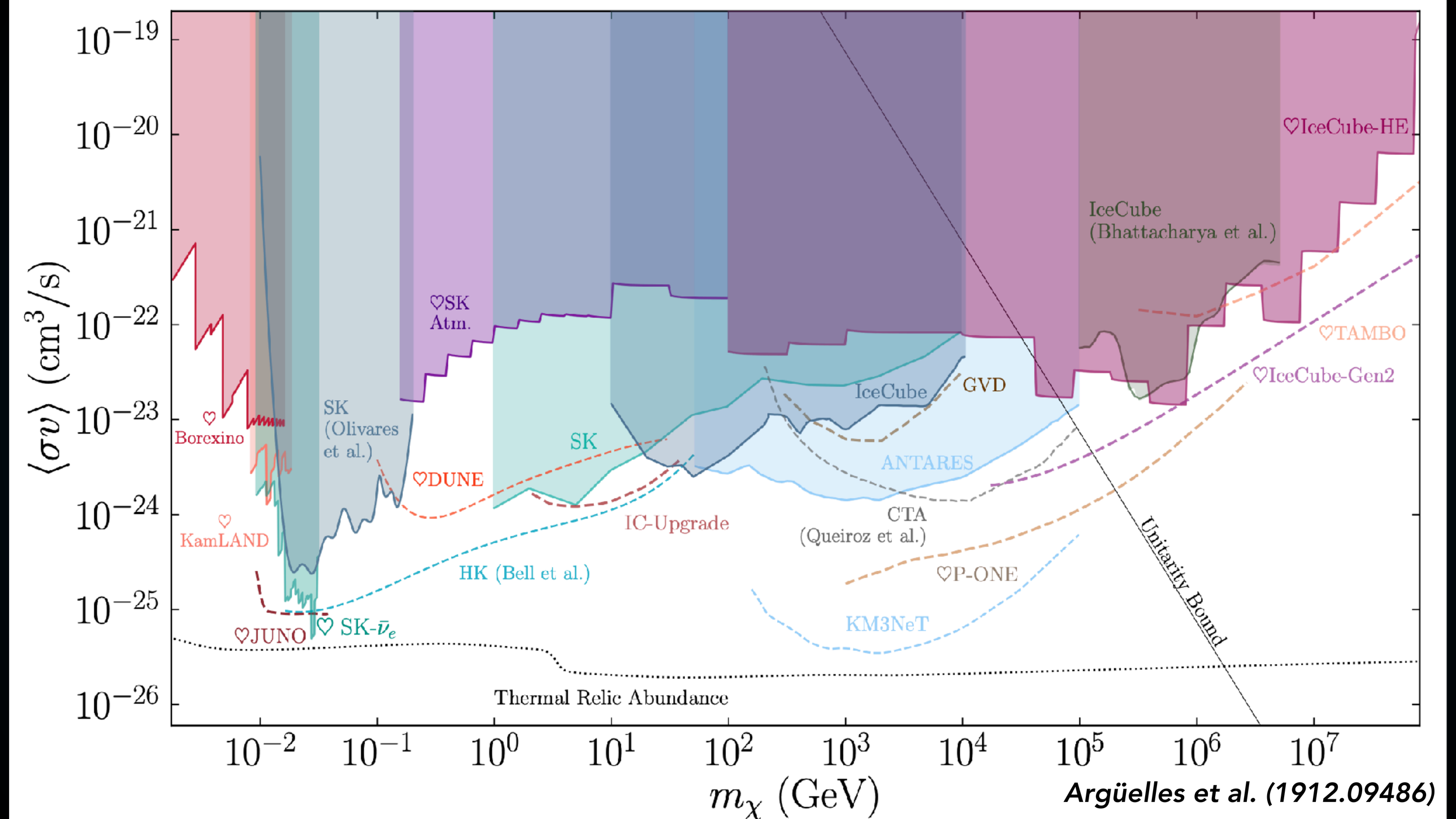

$\rho_\odot$ = 0.4 GeV cm^{-3}
CMB (Planck)
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
10
5
3
2
1
0.5
20
50
100
200
Dark Matter Mass (GeV)


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

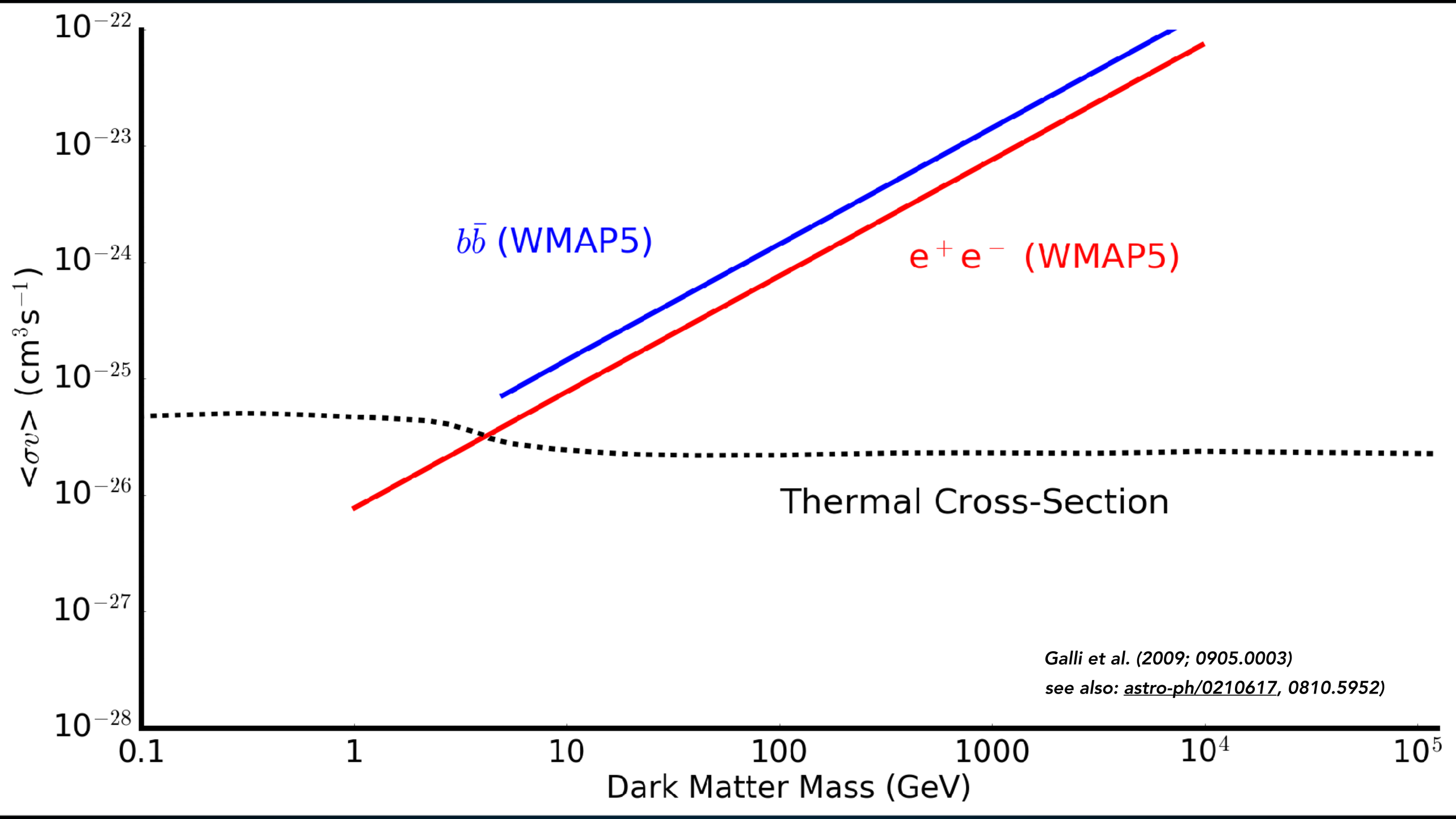

$\rho_\odot$ = 0.3 GeV cm^{-3}
Silverwood et al. (2015; 150708581)
$\rho_{\rm DM,const}$ [10^{-3}M$_\odot$/pc^3]
$\rho_{\rm DM}$ [GeV/cm^3]
Tilt R_0 [kpc]
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
Dark Matter Mass (GeV)


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


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

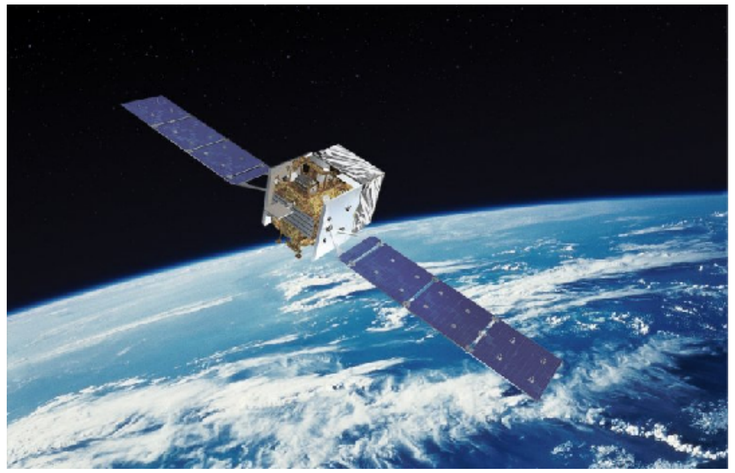


Argüelles et al. (1912.09486)



Galli et al. (2009; 0905.0003)

see also: astro-ph/0210617, 0810.5952)



Thermal Cross-Section

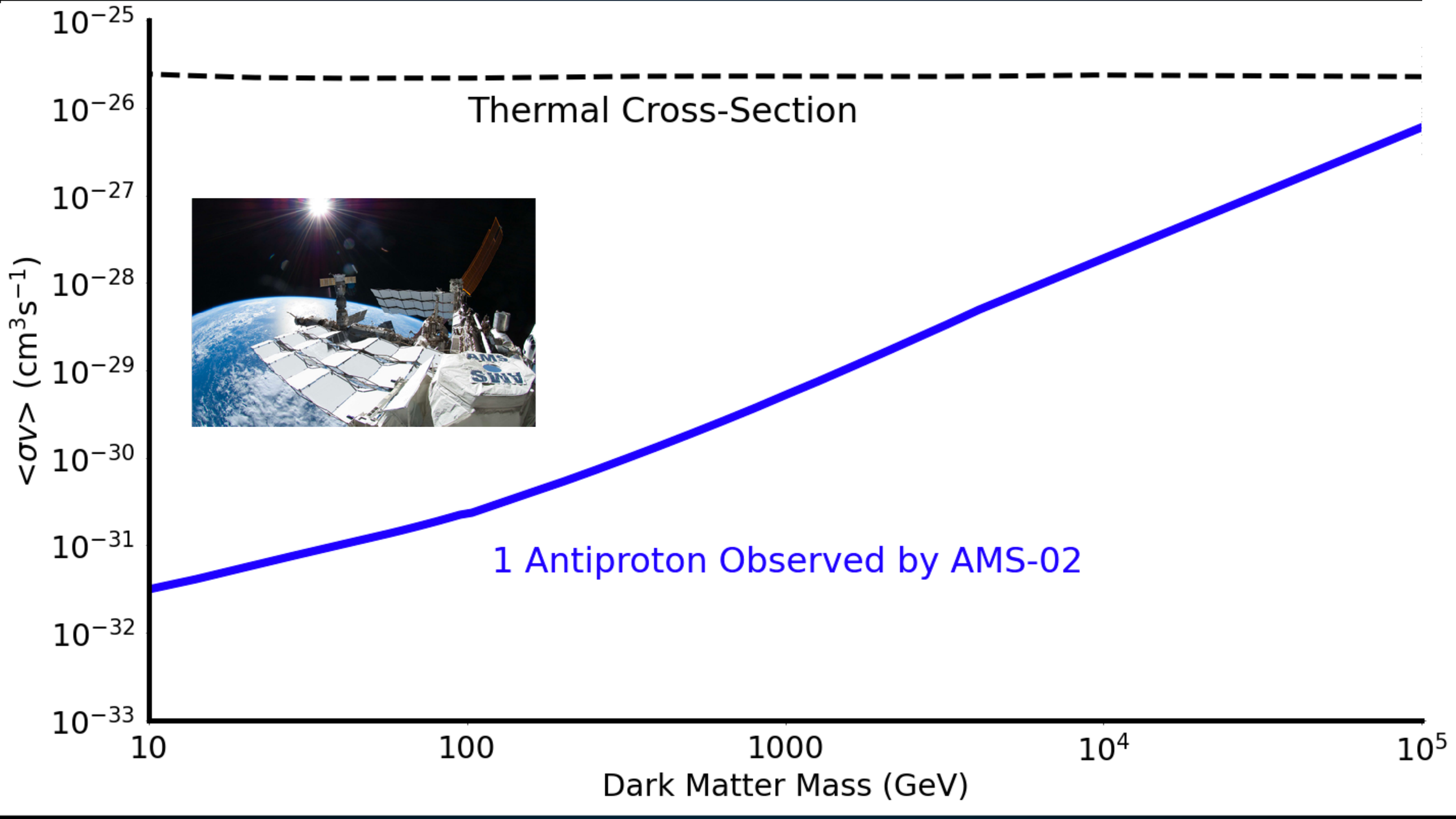
1 Observed Photon Within 10° of Galactic Center

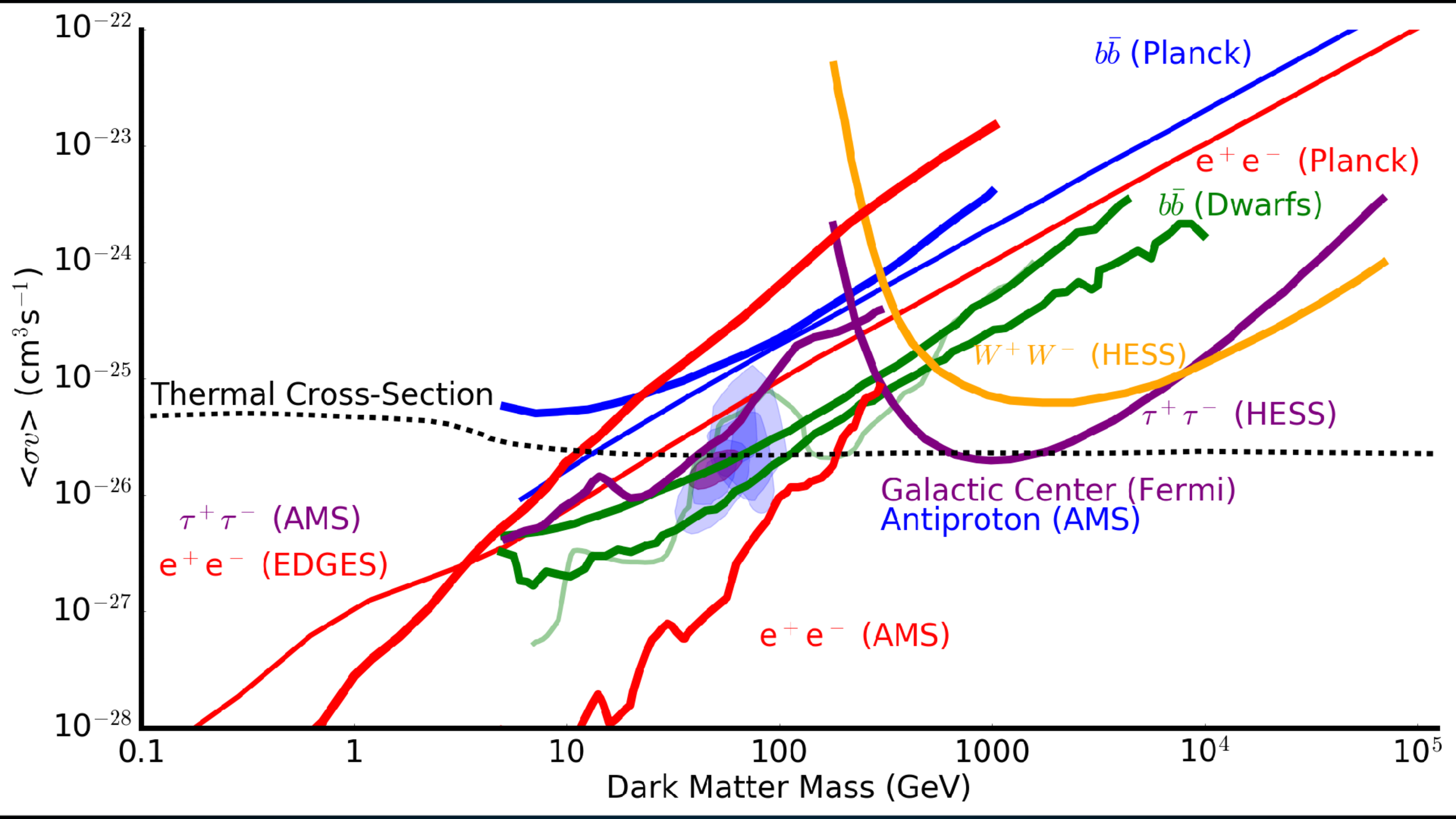
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}

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

10
100
1000
10^4
10^5

Dark Matter Mass (GeV)


Thermal Cross-Section
1 Antiproton Observed by AMS-02
AMS
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
$<\sigma v>$ ($cm^3 s^{-1}$)
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)


10^{-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)