Tim Linden

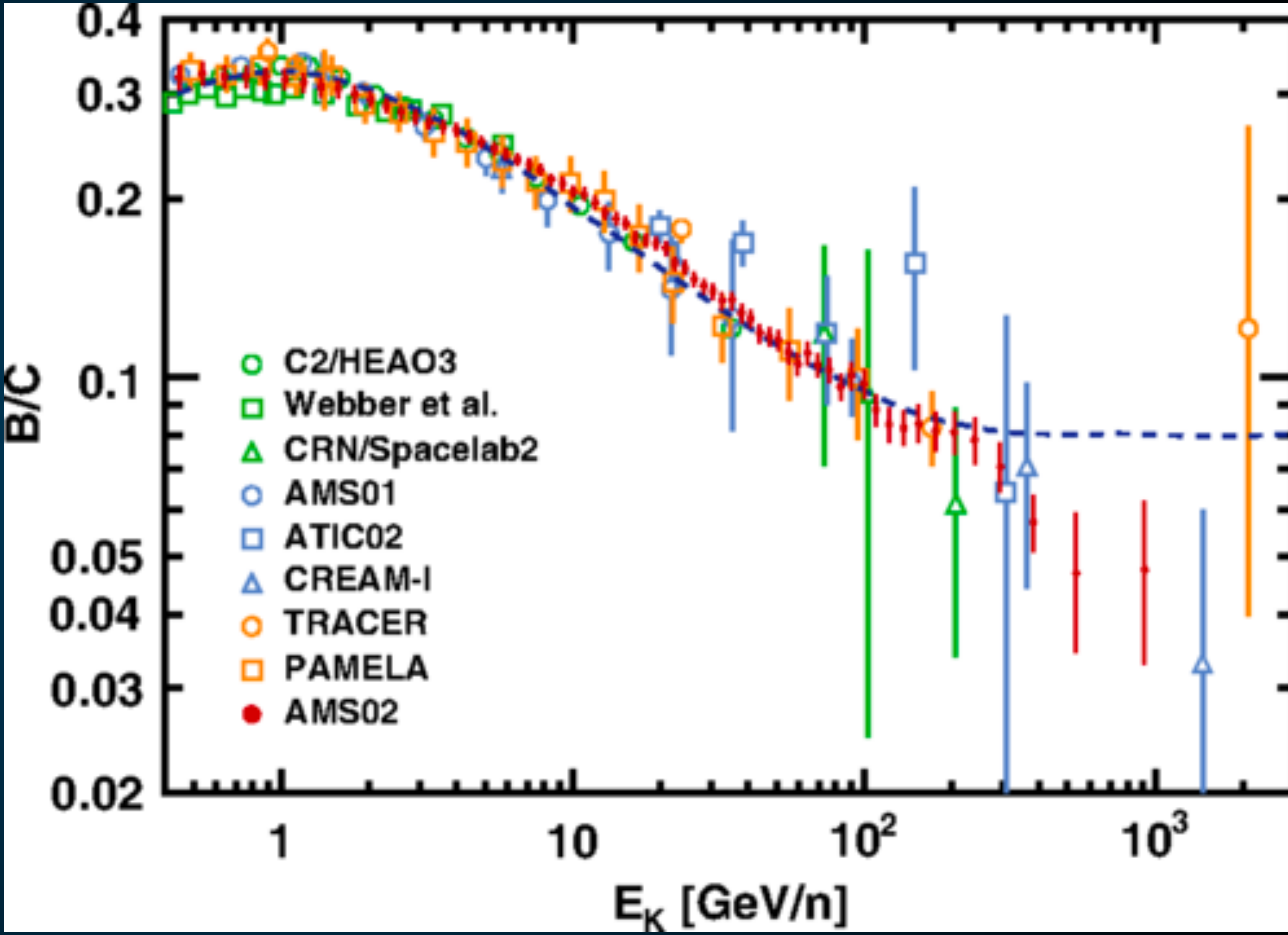
Enhancing Antiheliums with Astrophysics

Stockholms universitet

Precision Cosmic Ray Measurements

Observations of primary to secondary ratios such as the B/C, 10Be/9Be, as well as individual cosmic-ray spectra are becoming increasingly precise.

Can significantly constrain fundamental parameters of cosmic-ray diffusion.



How do we use this precision
to unlock dark matter searches?

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

The Antiproton Excess

The Antiproton Excess

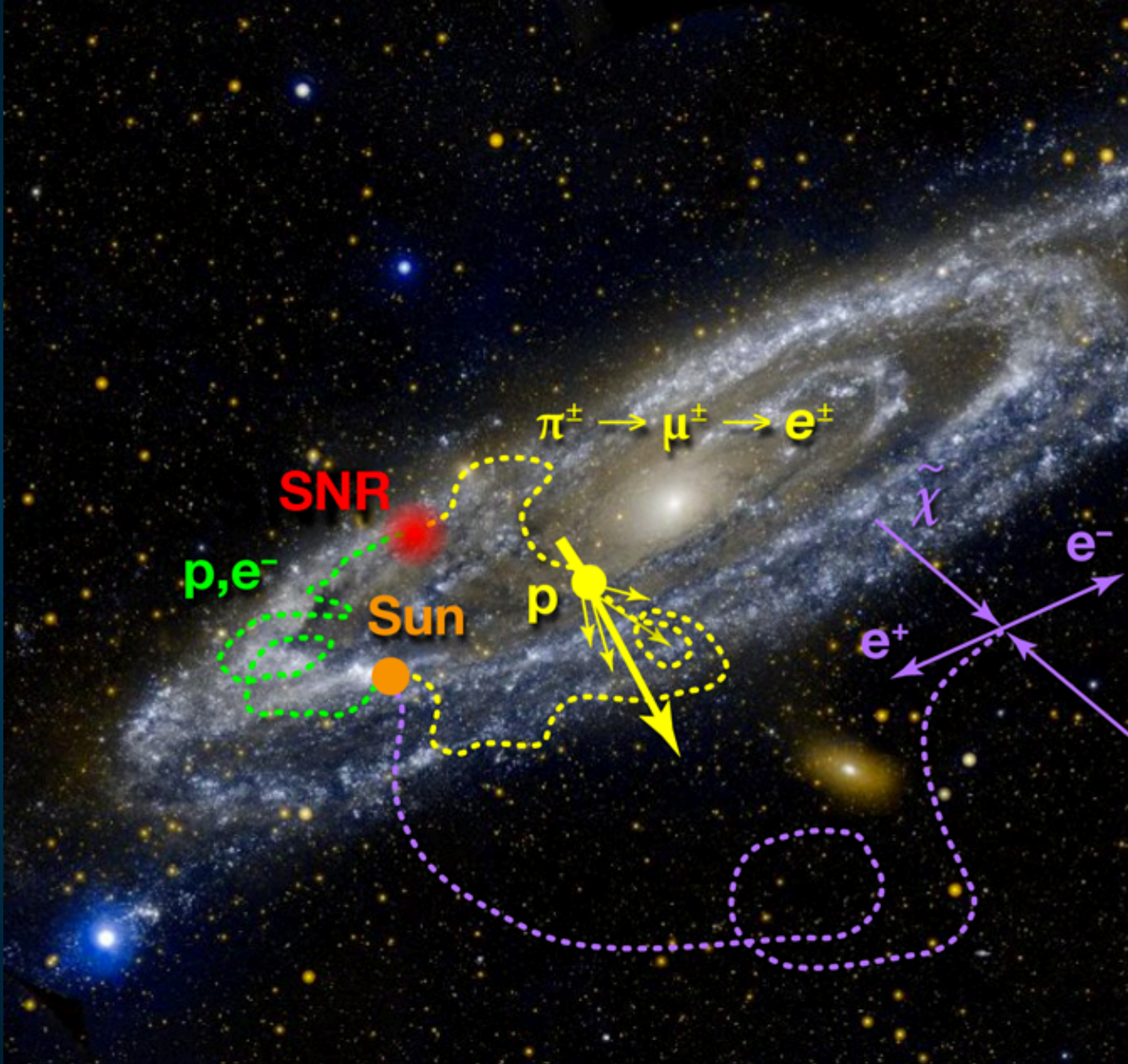
Investigate the Antiproton Fraction!

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

Two Changes:

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

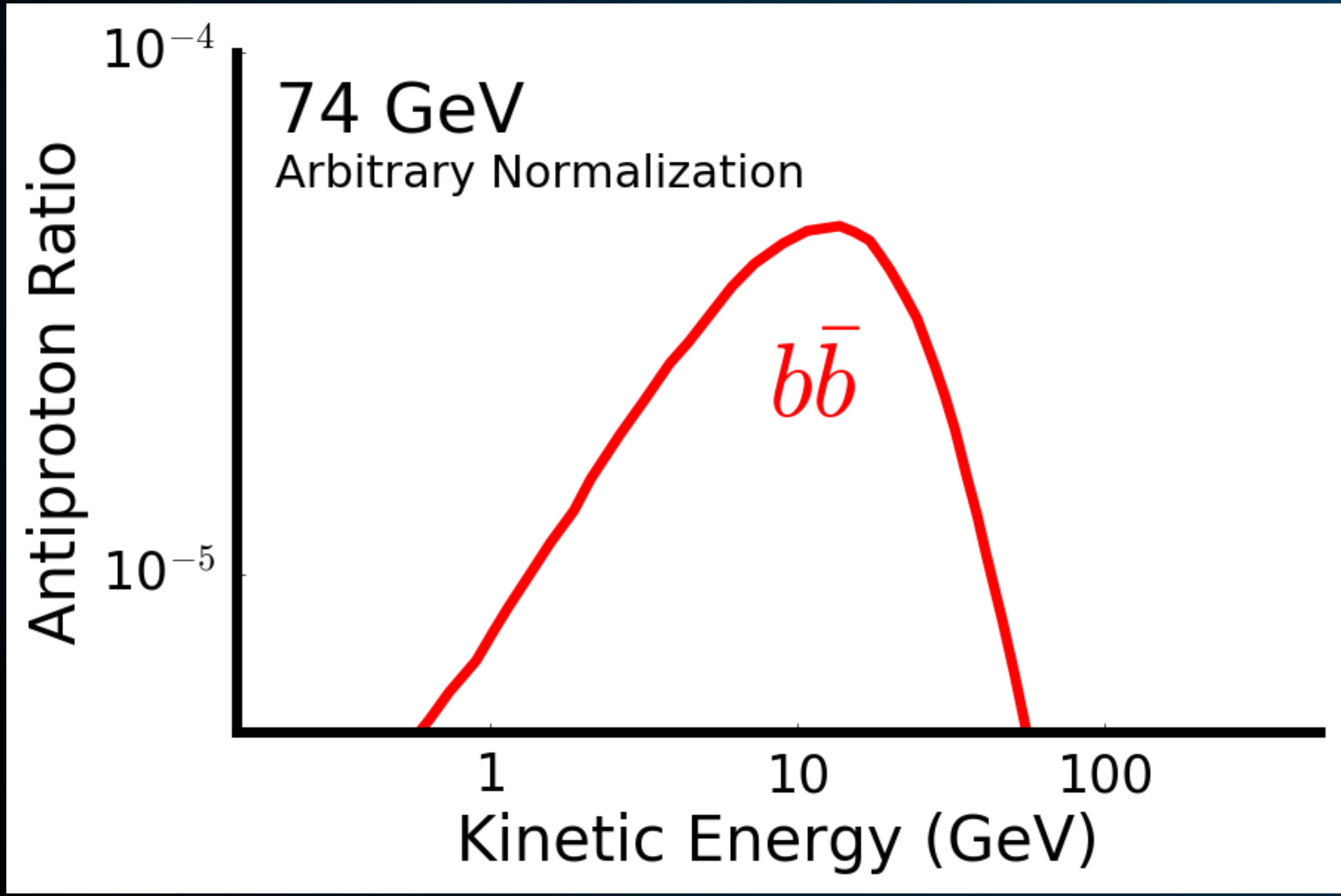
Hadronic Energy losses are slower (sensitive to antiproton production throughout the Galaxy)

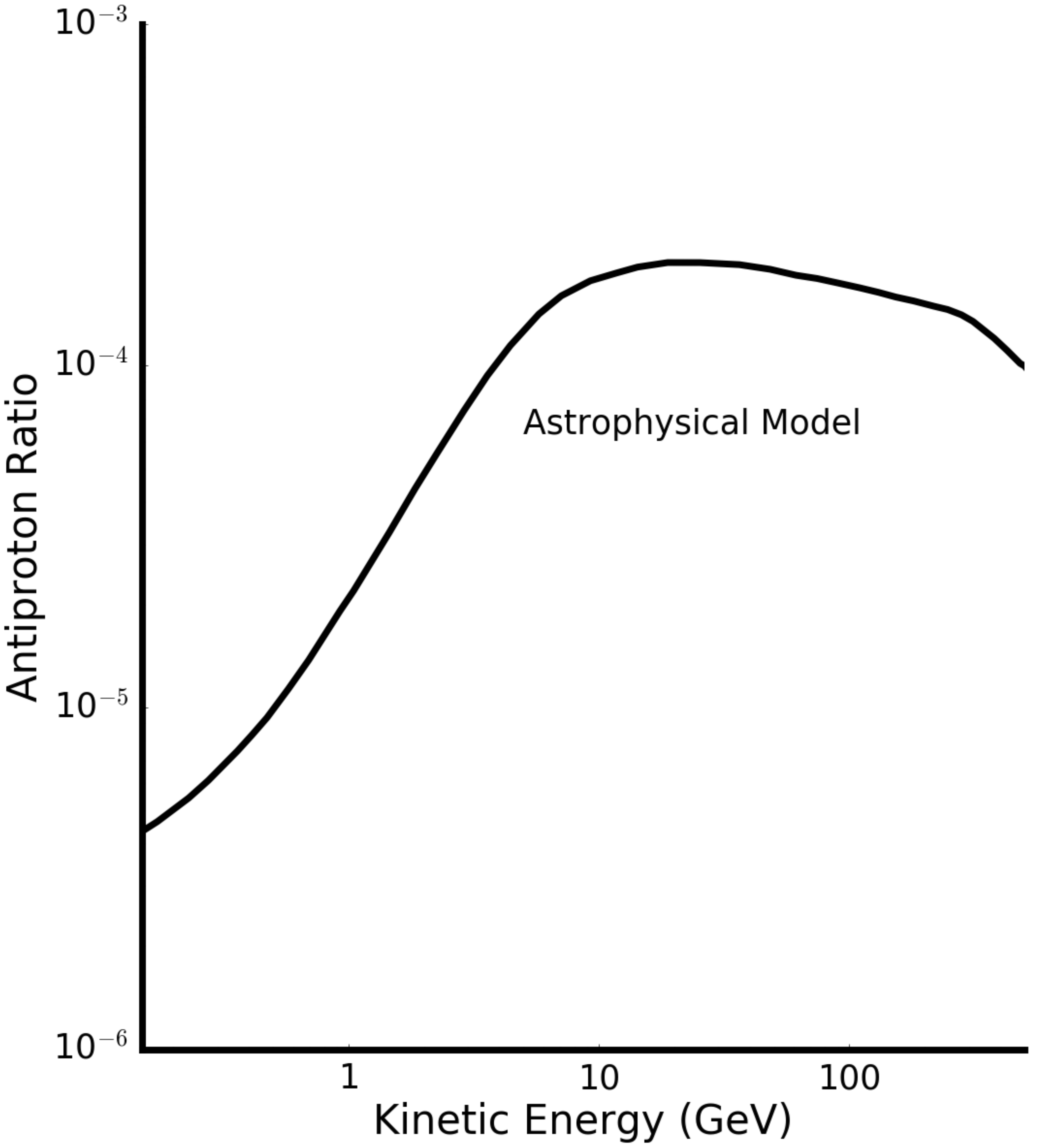


The Antiproton Excess

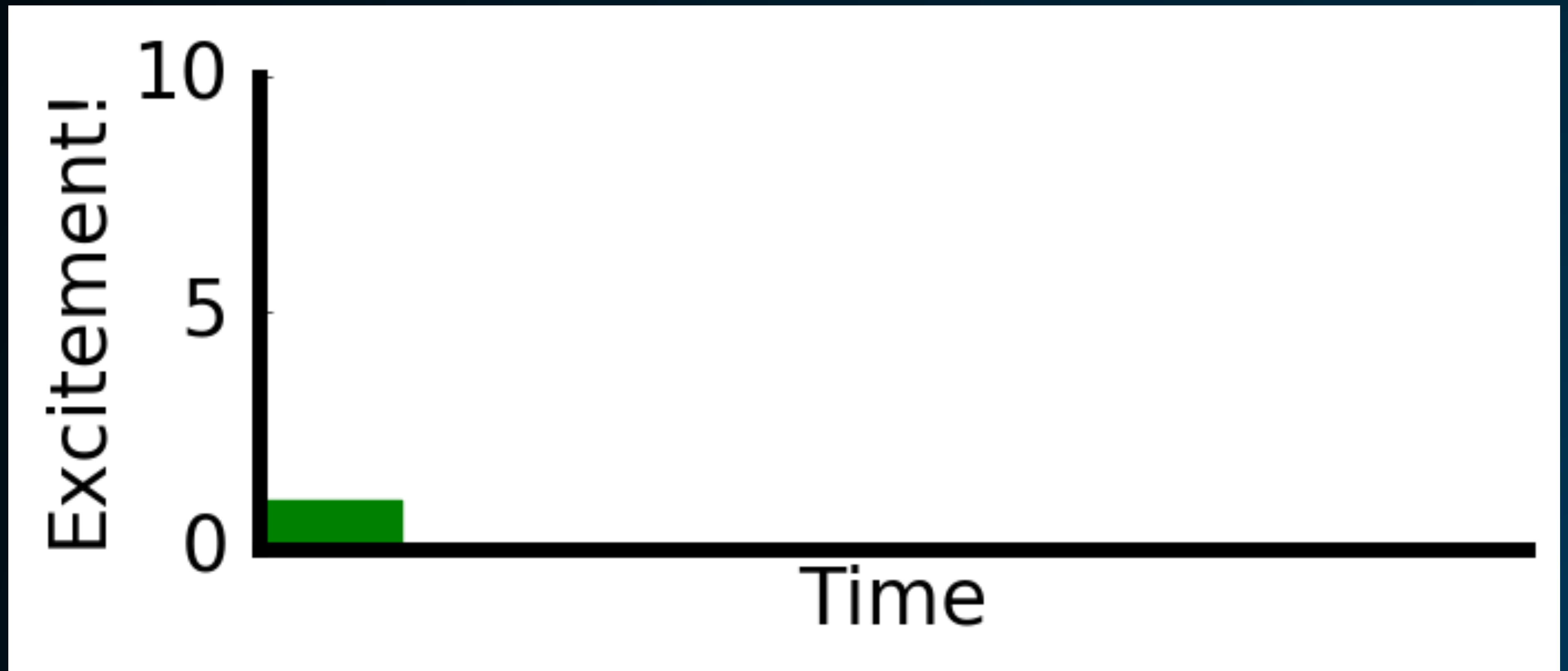
Astrophysics - Smooth Profile

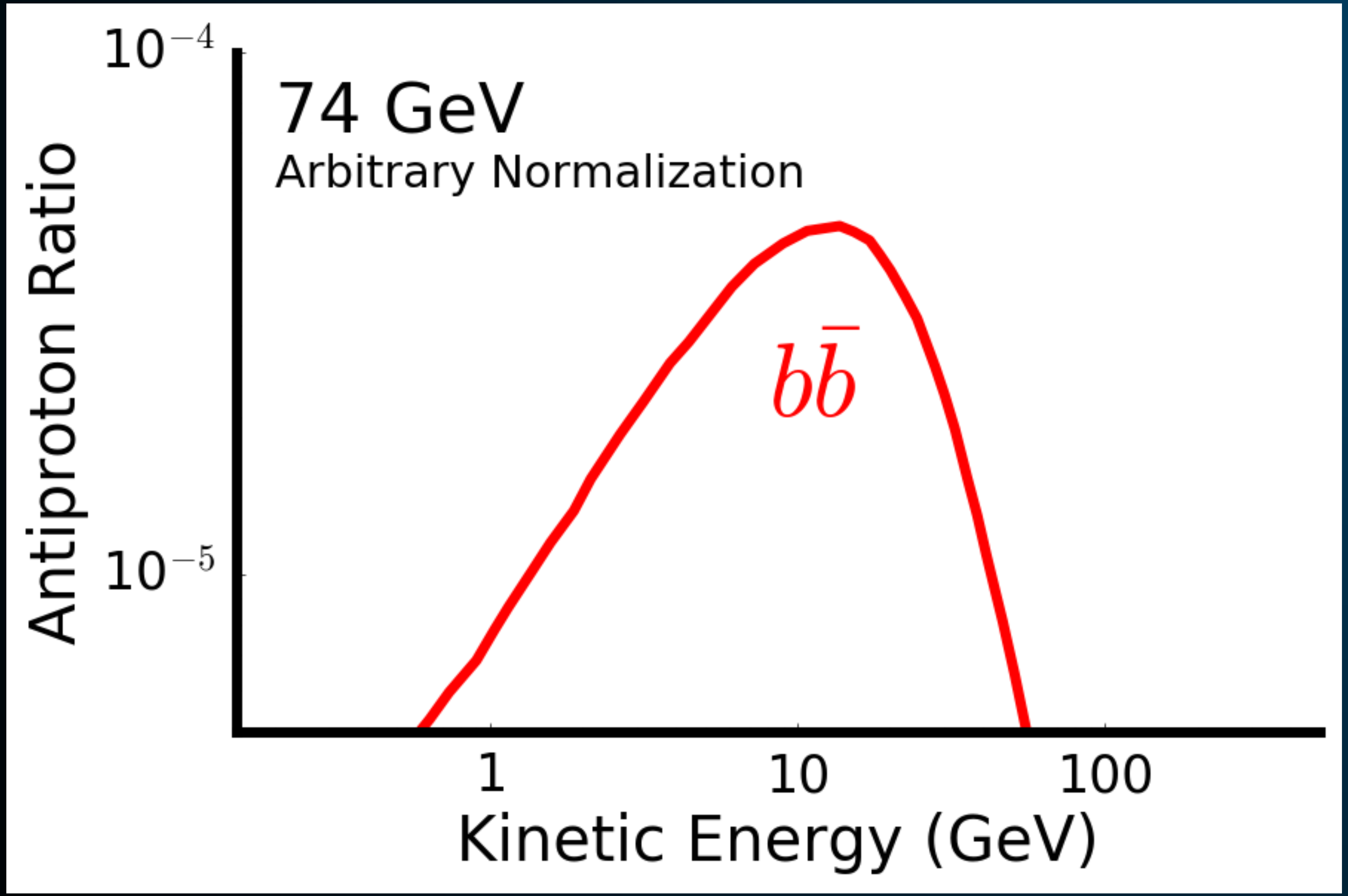
Dark Matter - Sharp Bump!



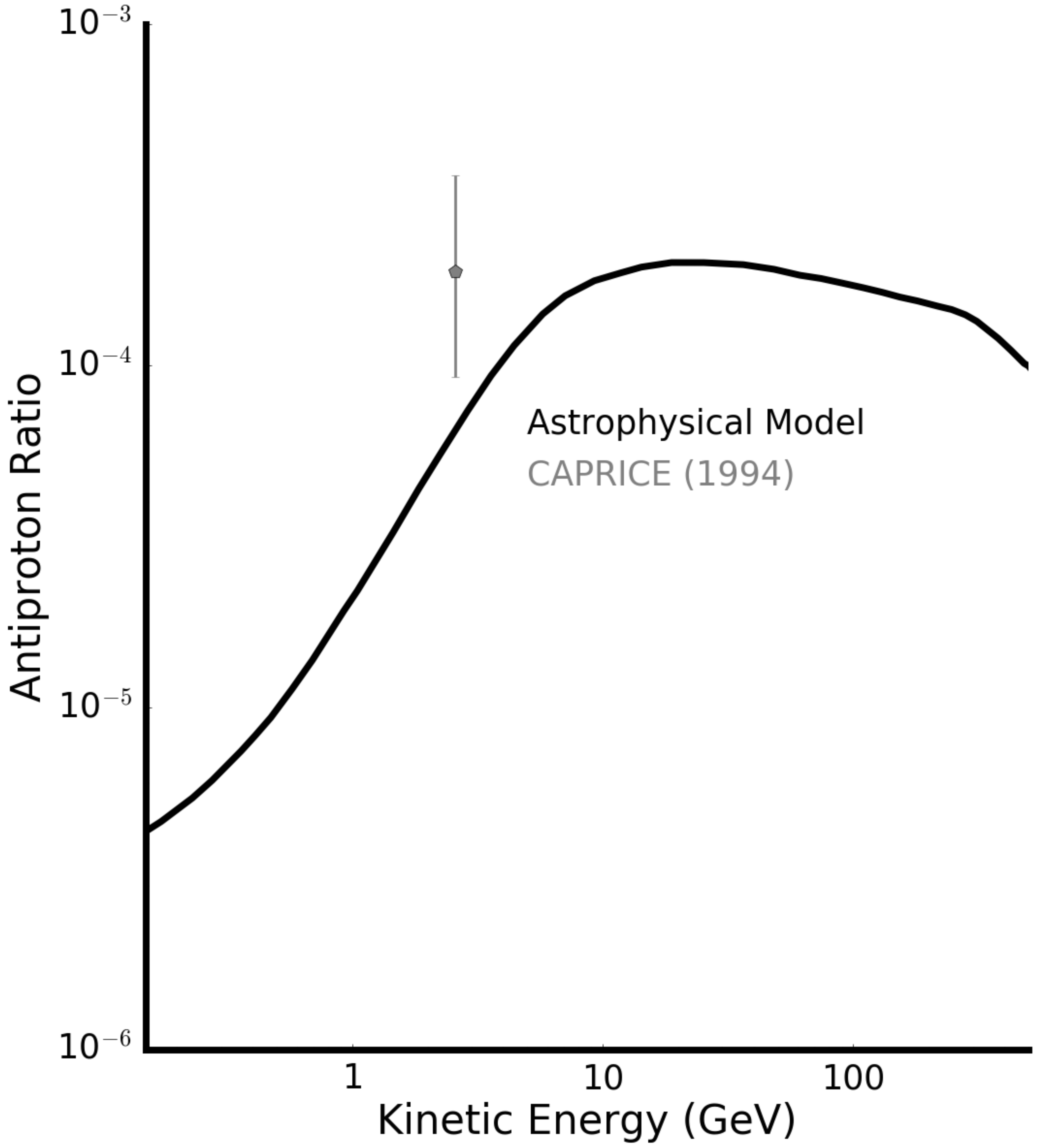


The Antiproton Excess





(Not an exhaustive list of observations)



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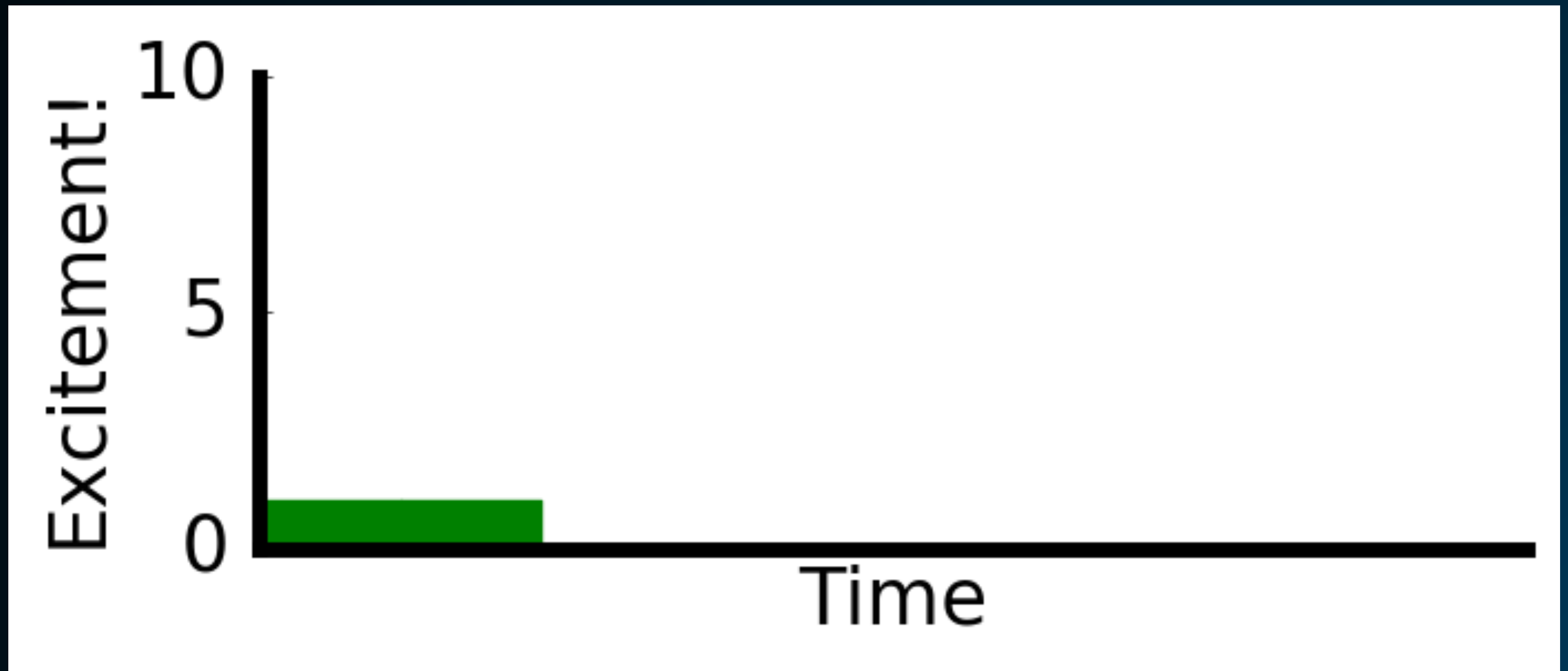

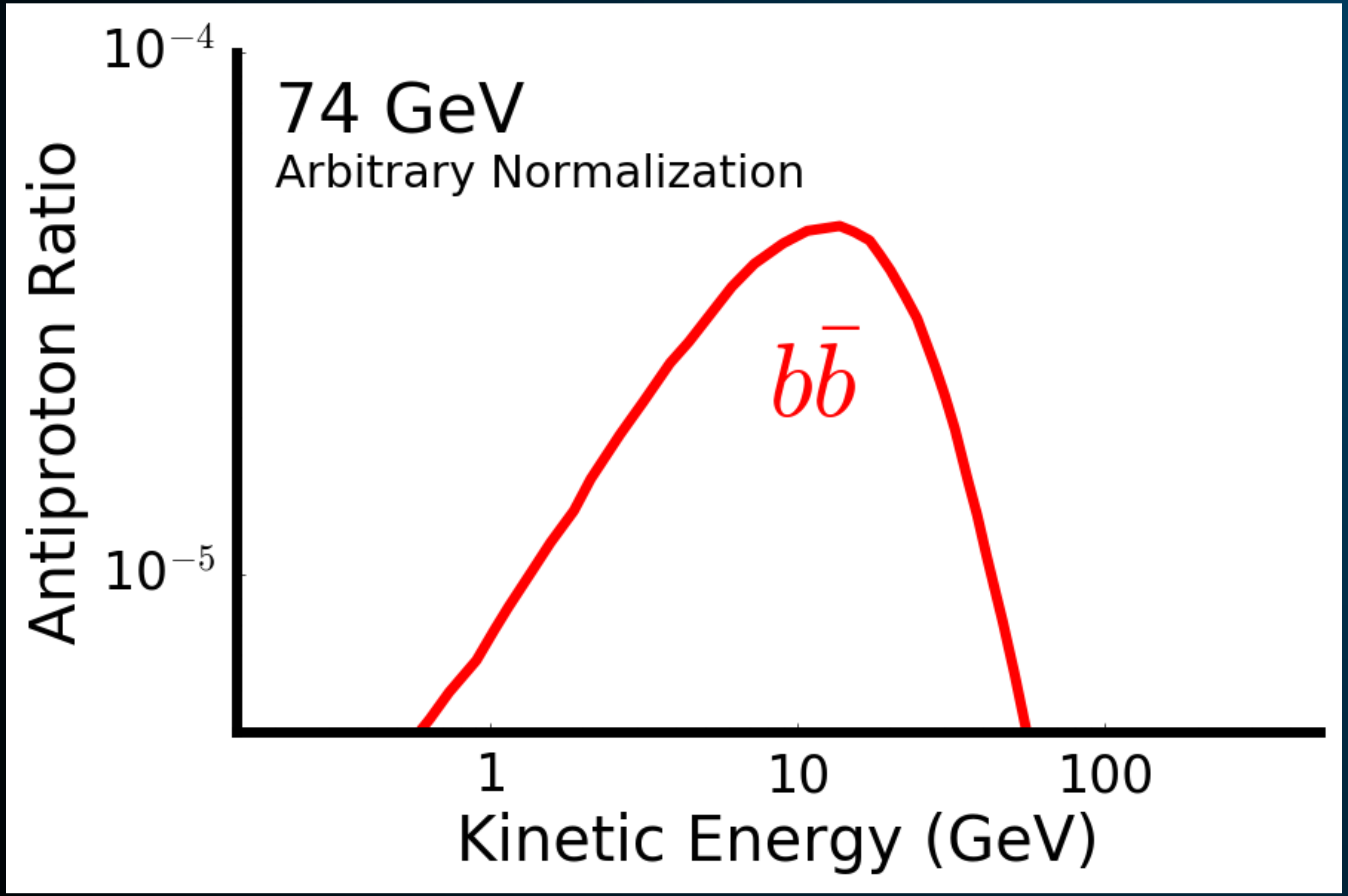

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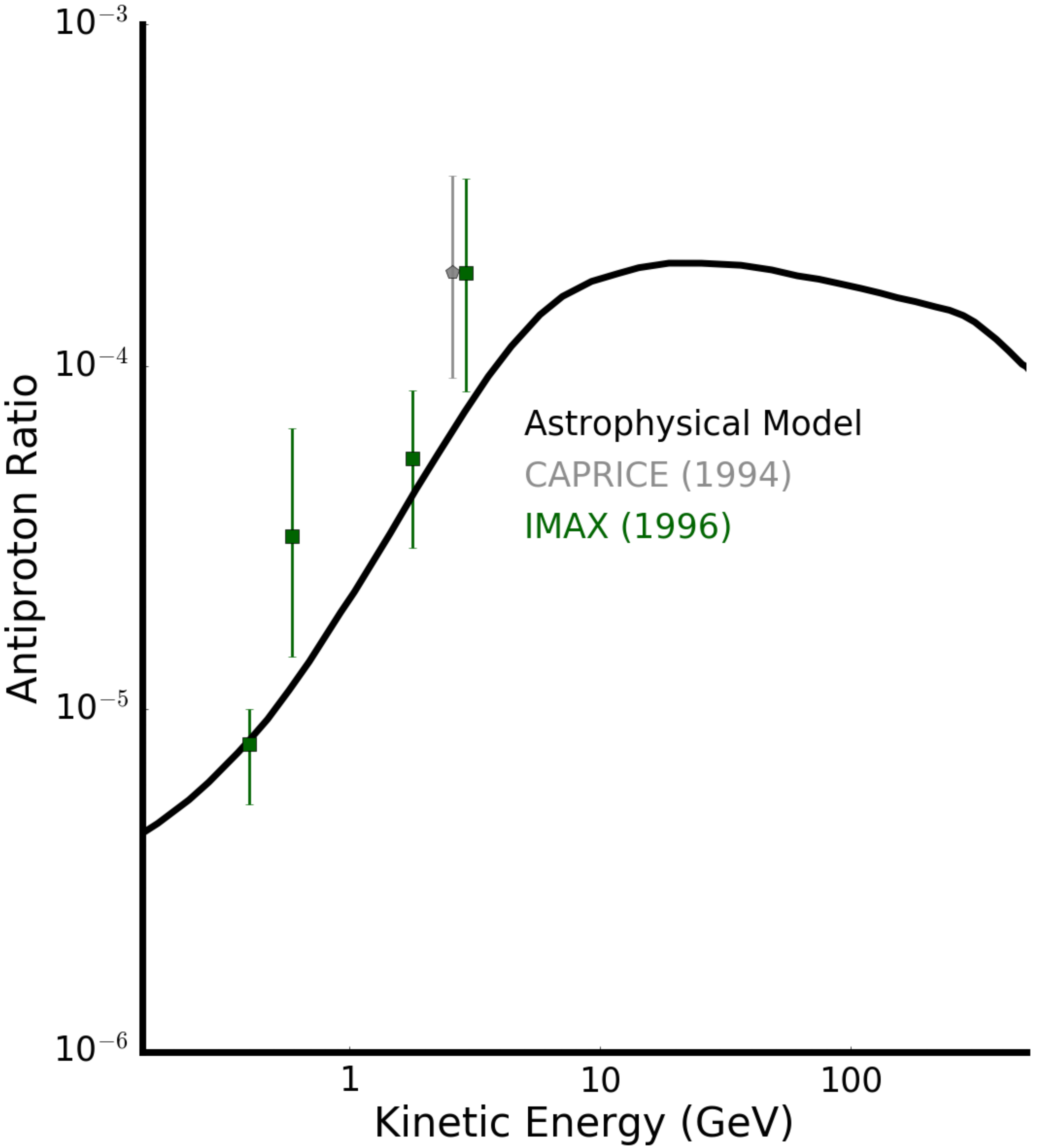

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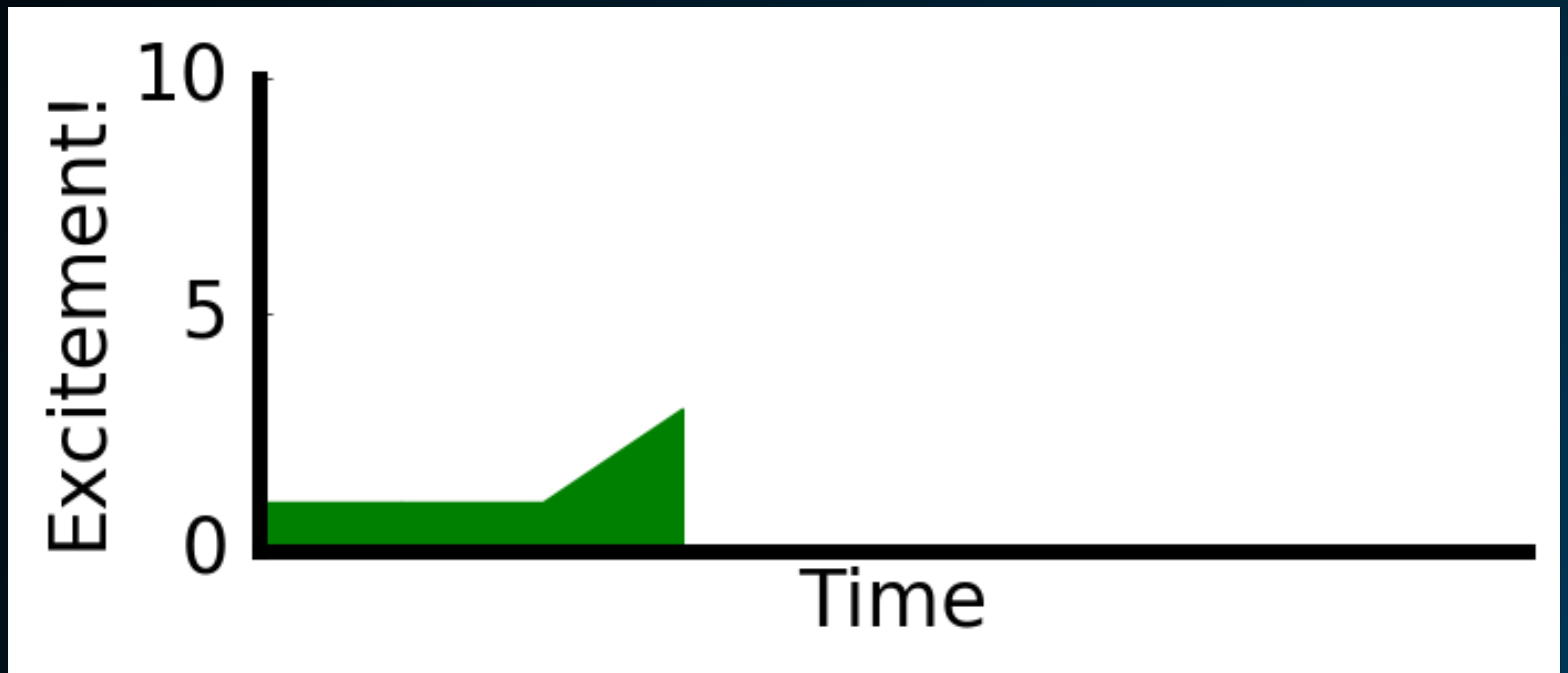

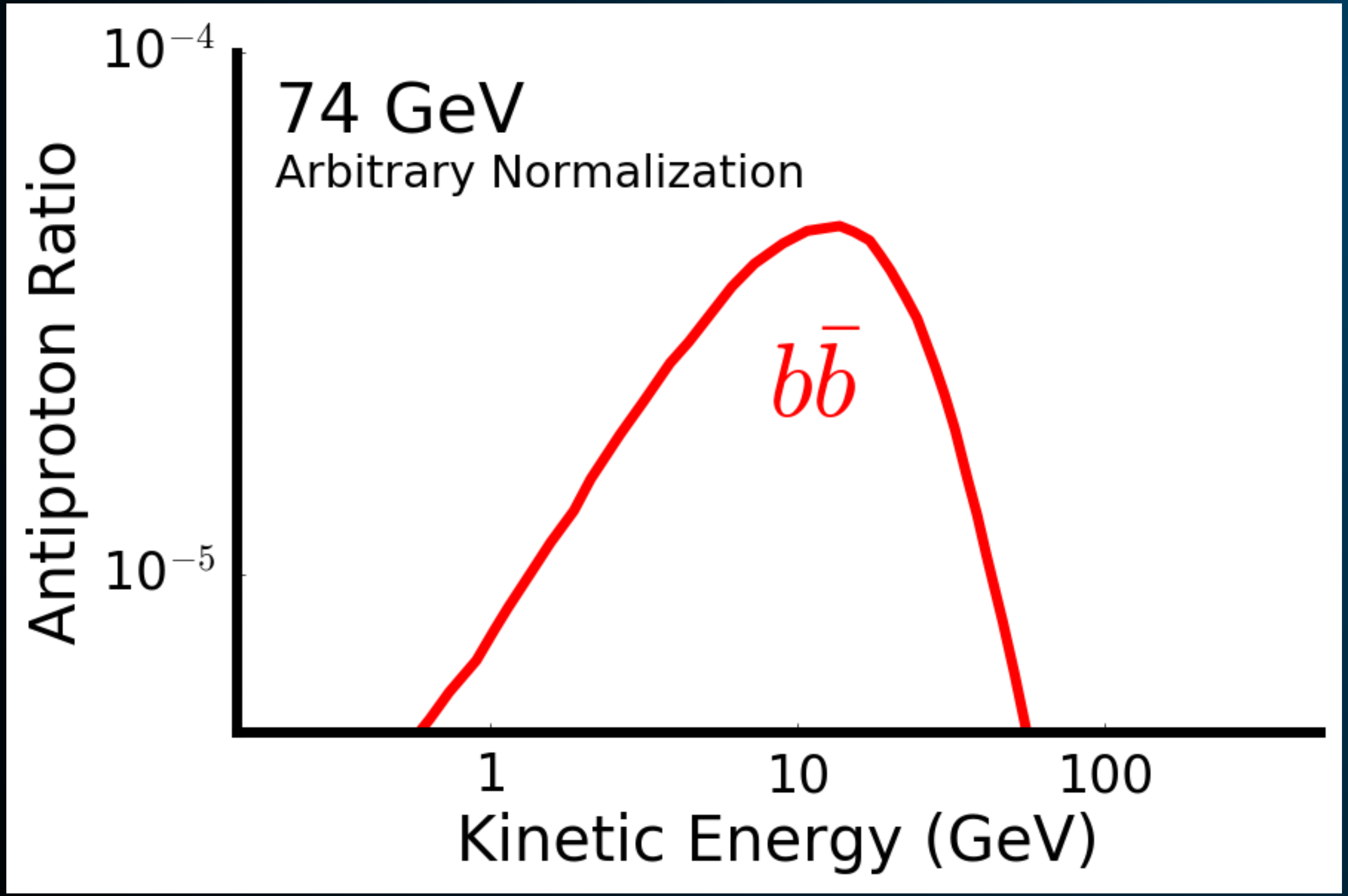

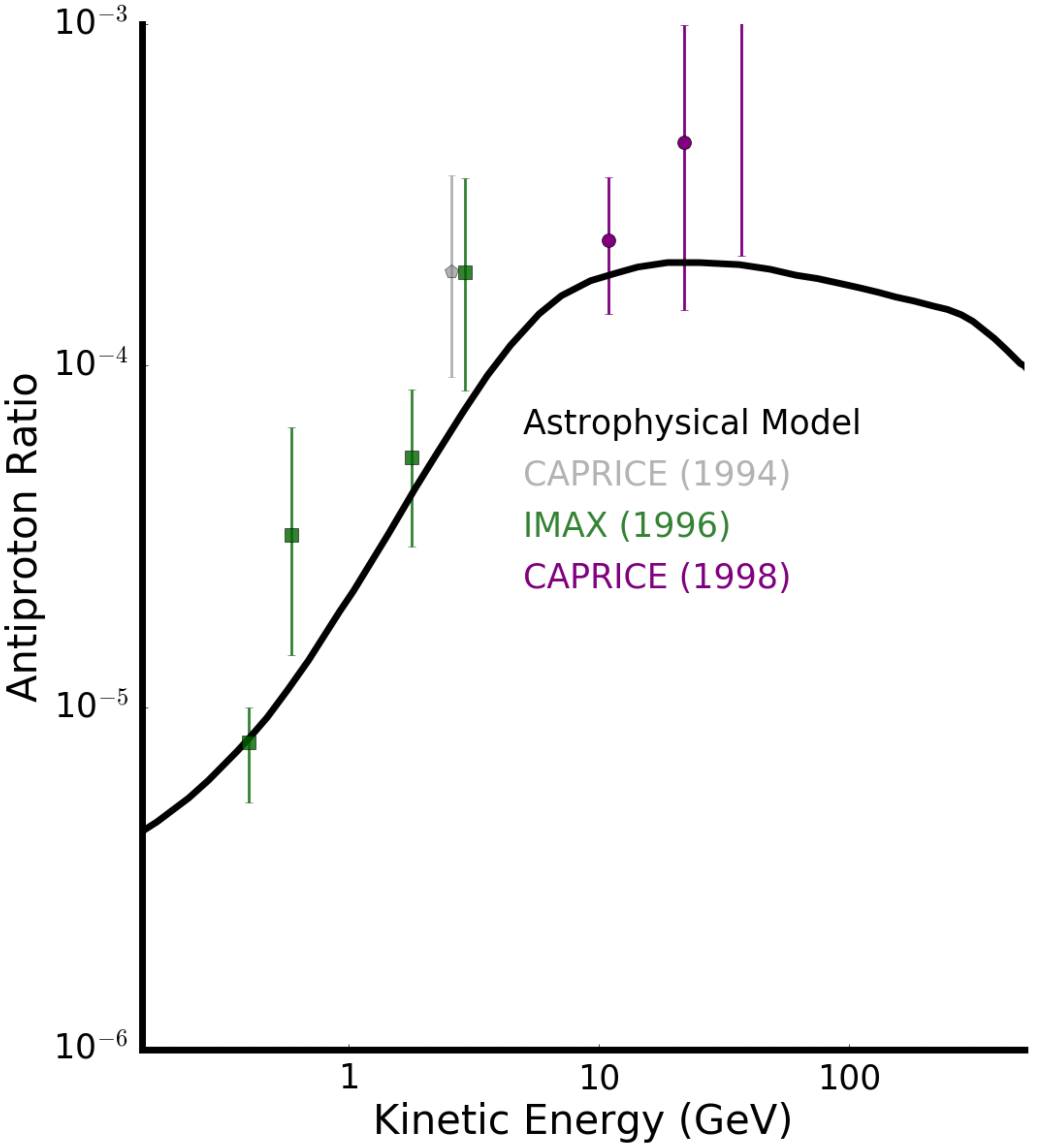

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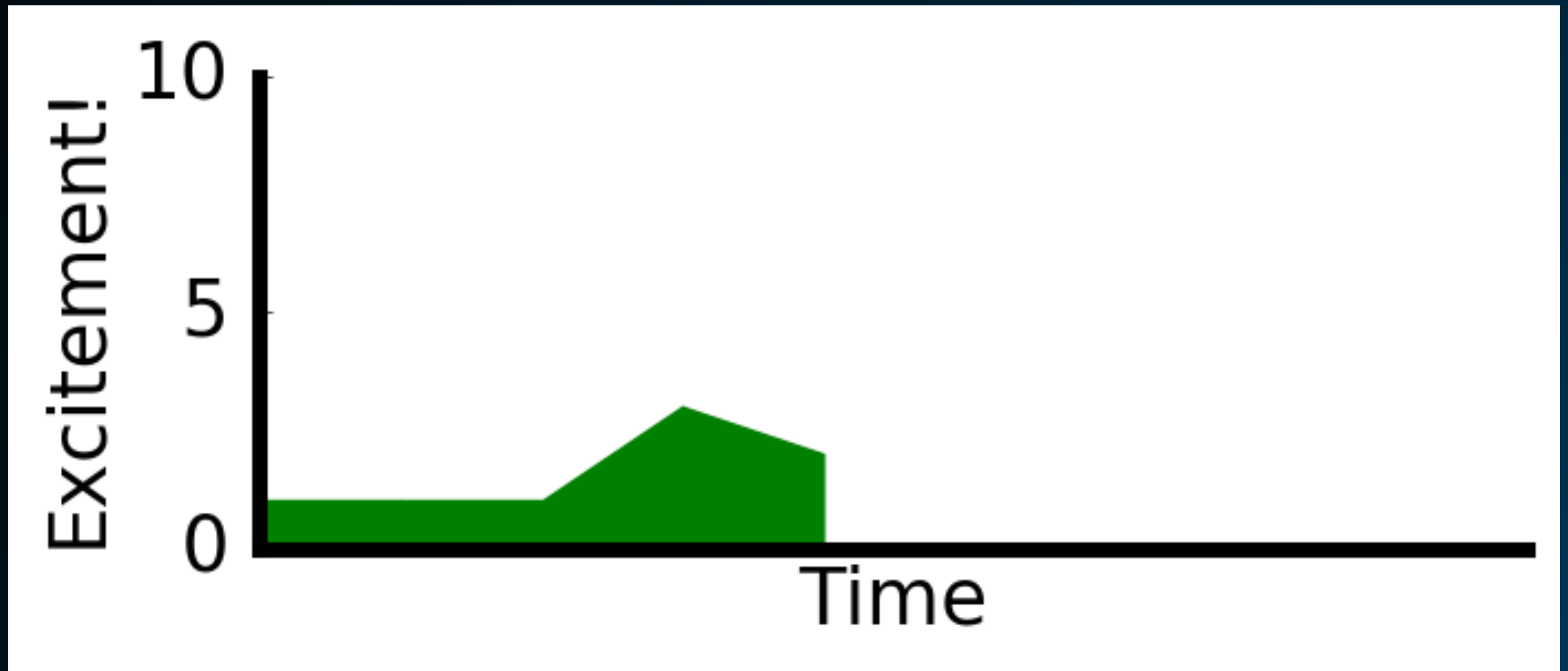

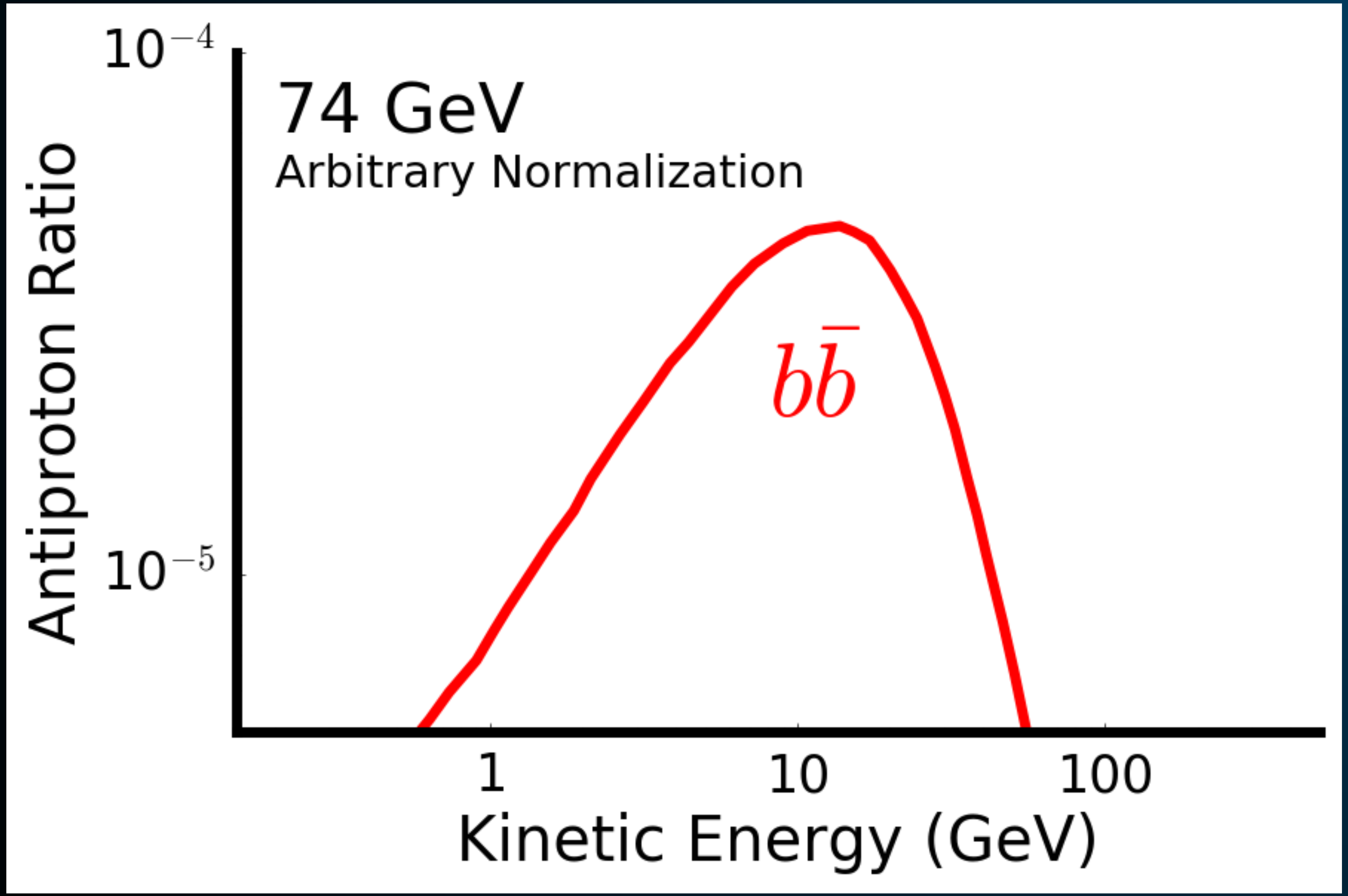

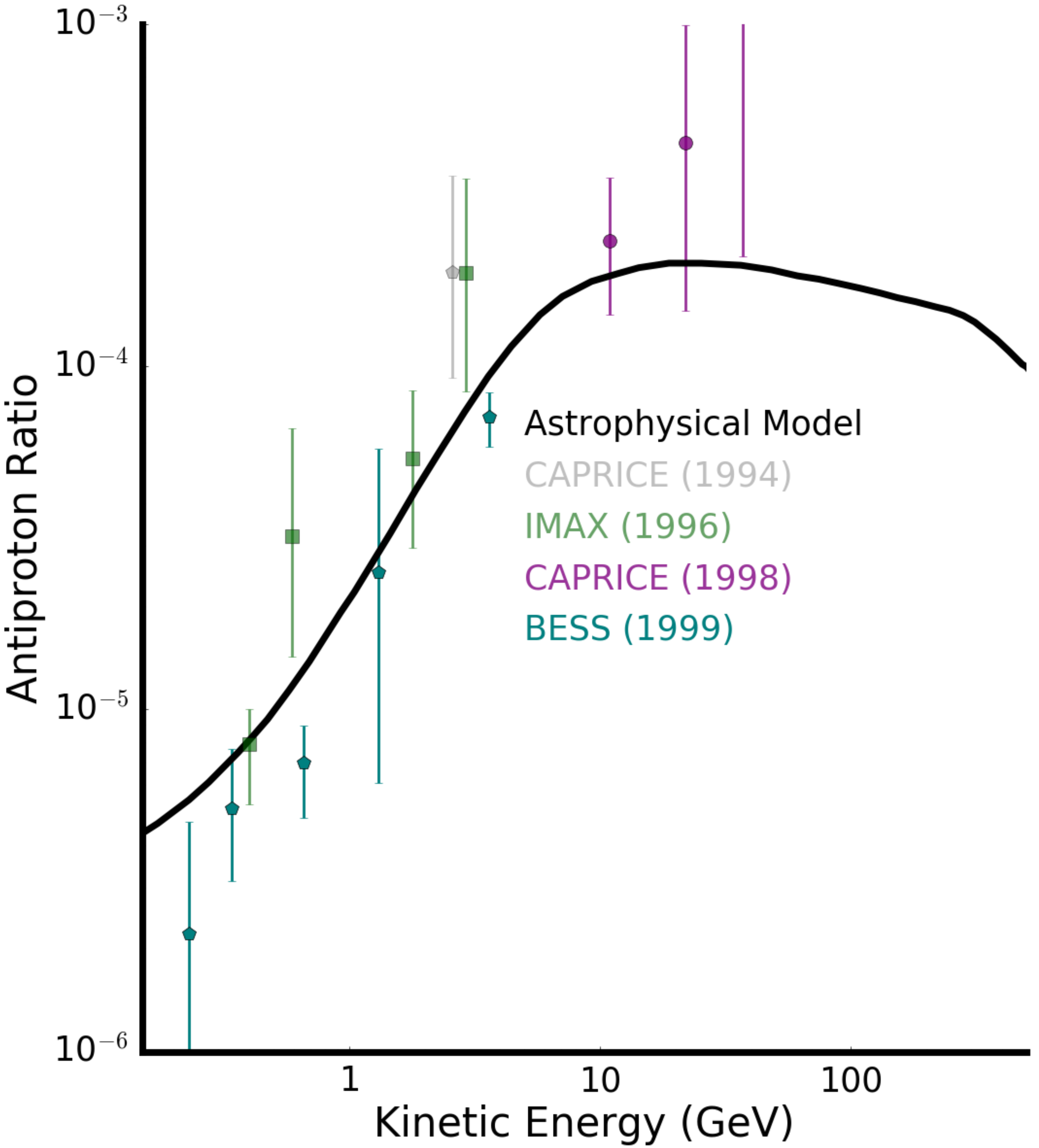

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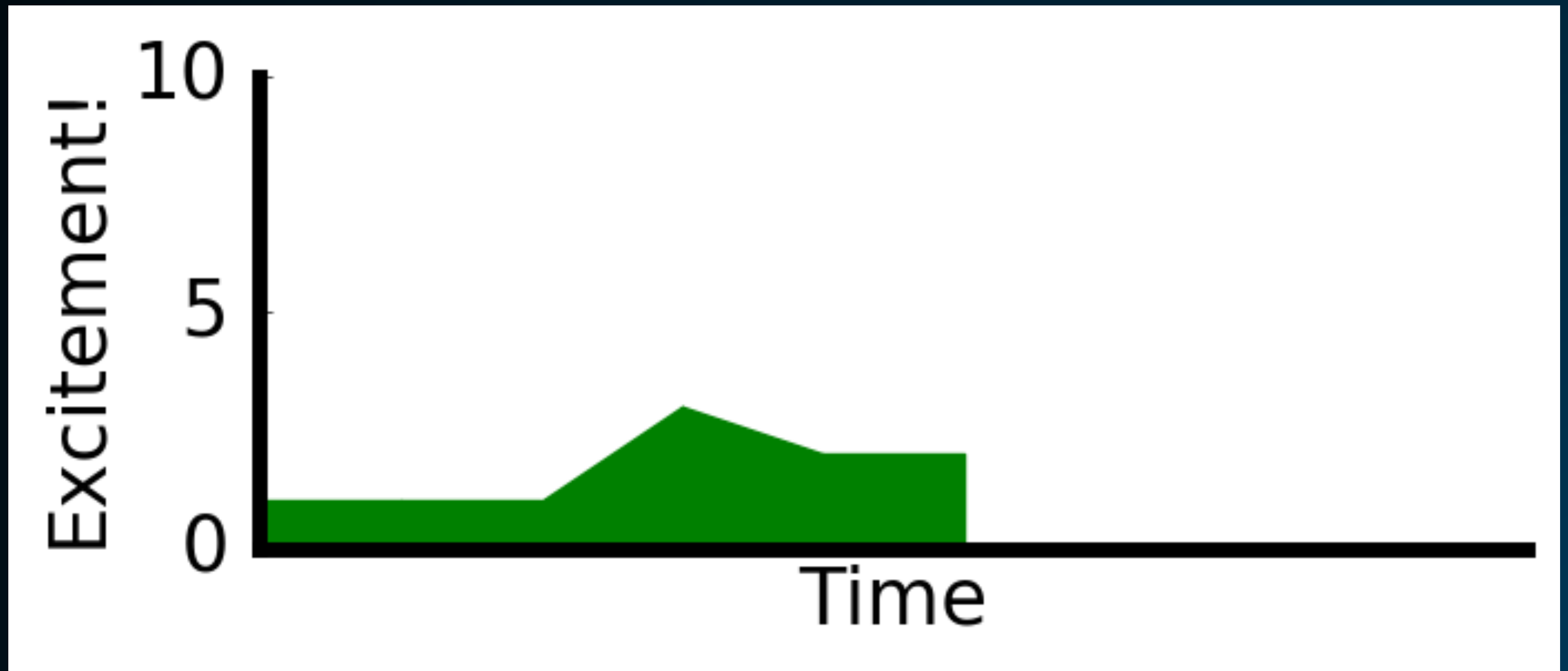

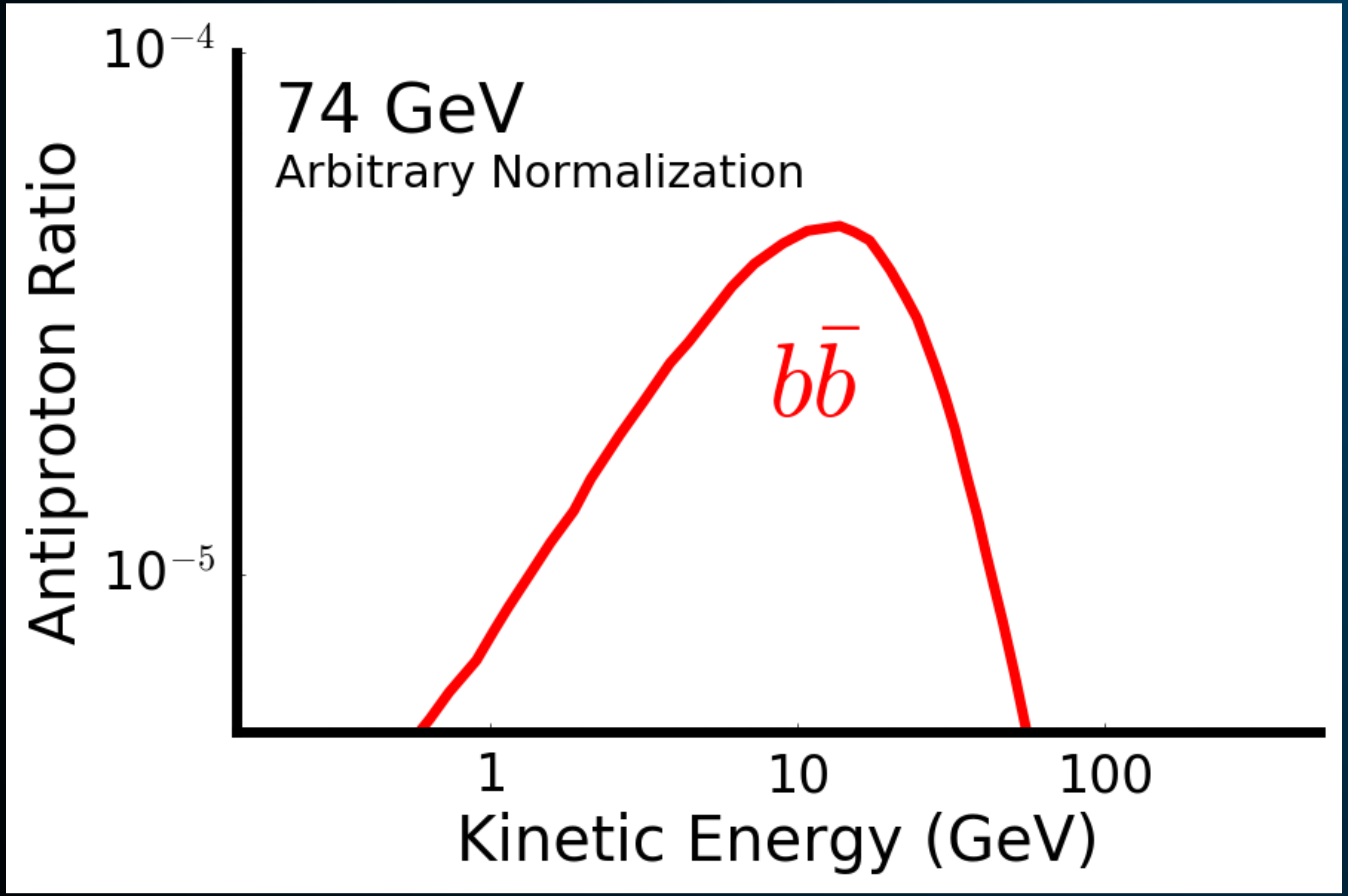

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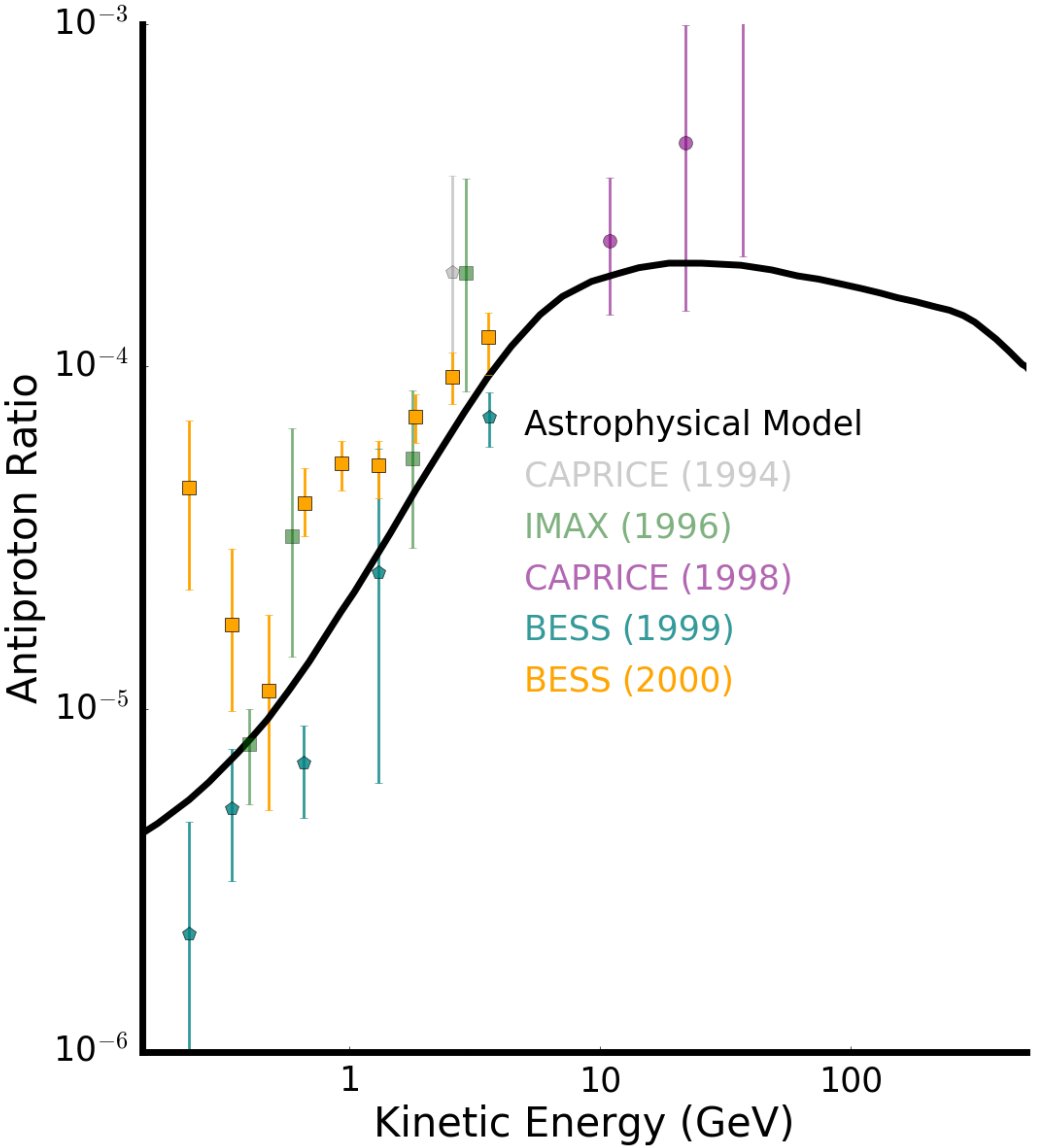

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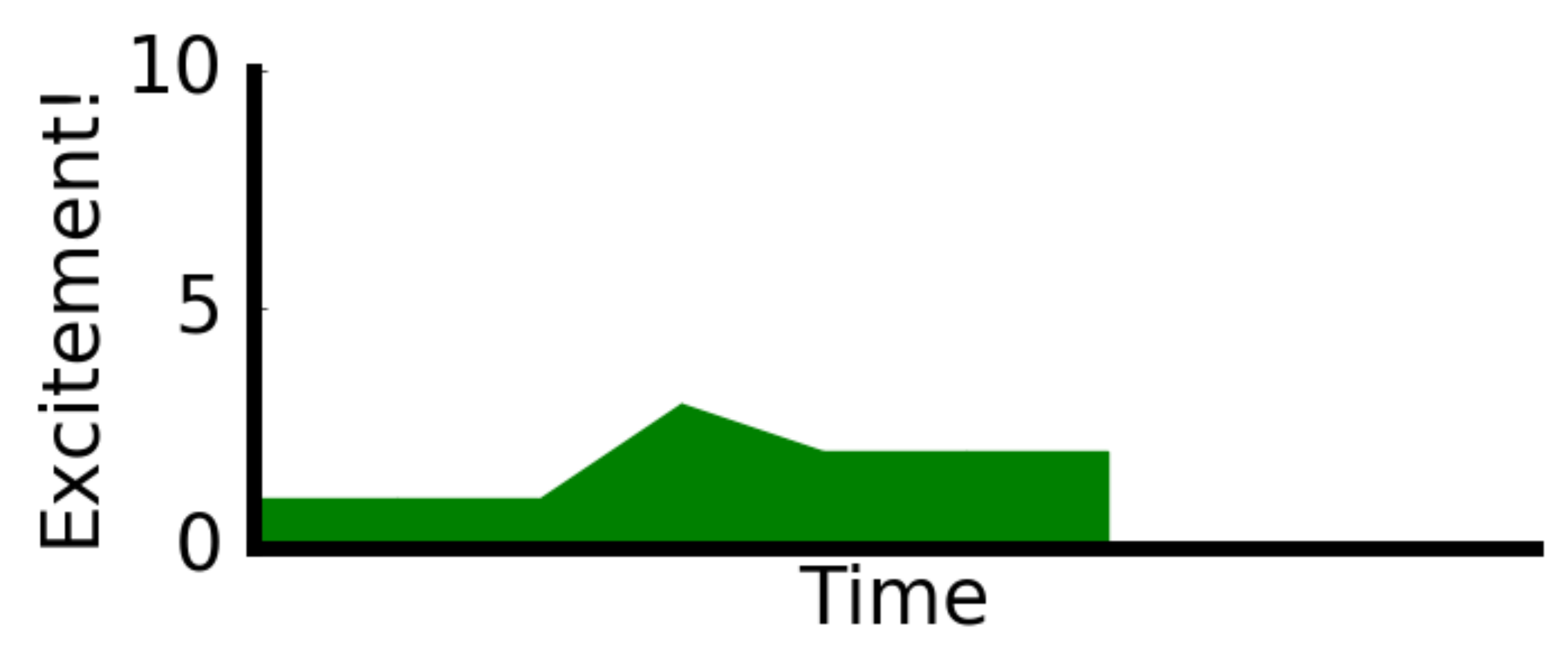

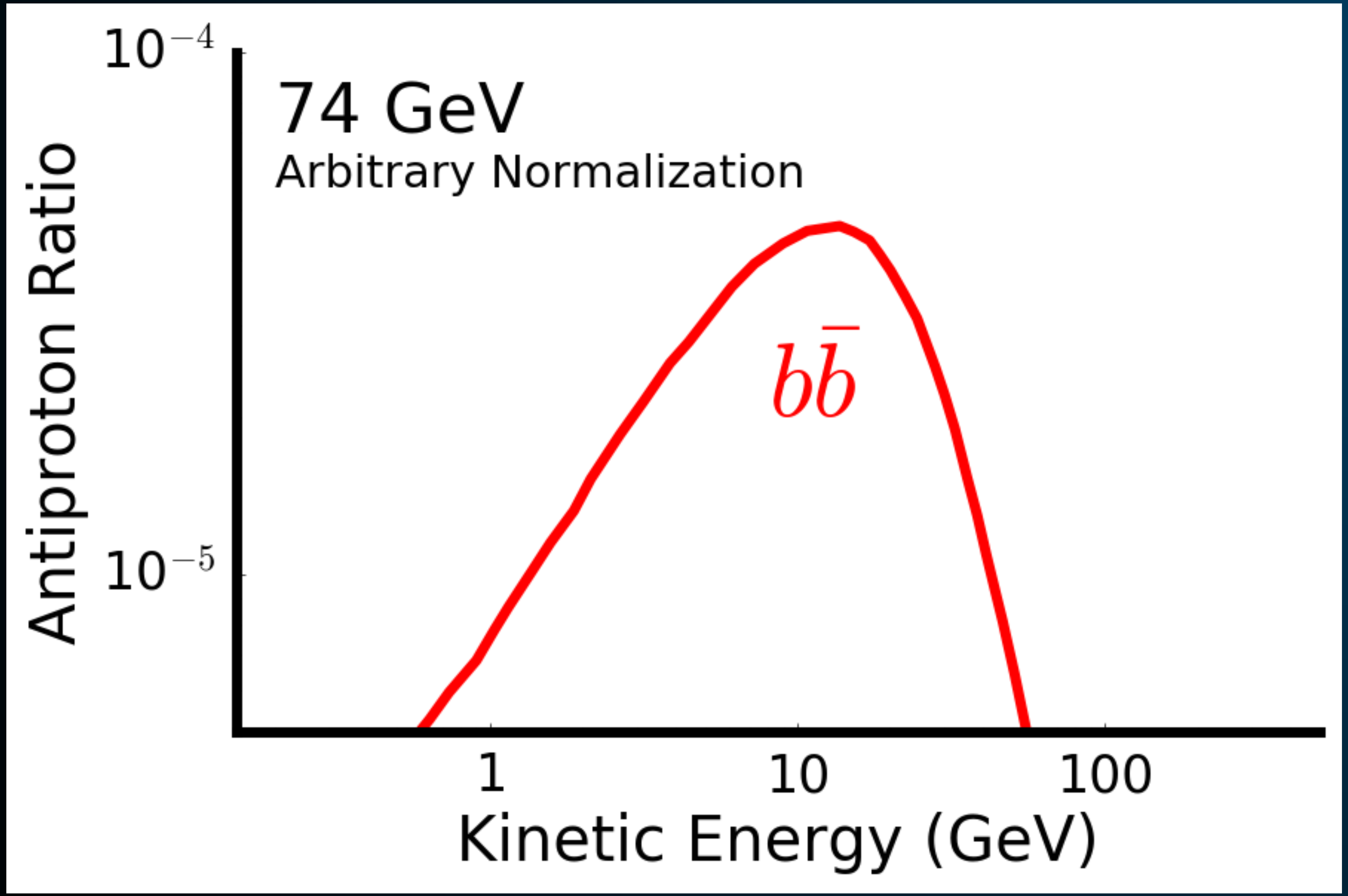

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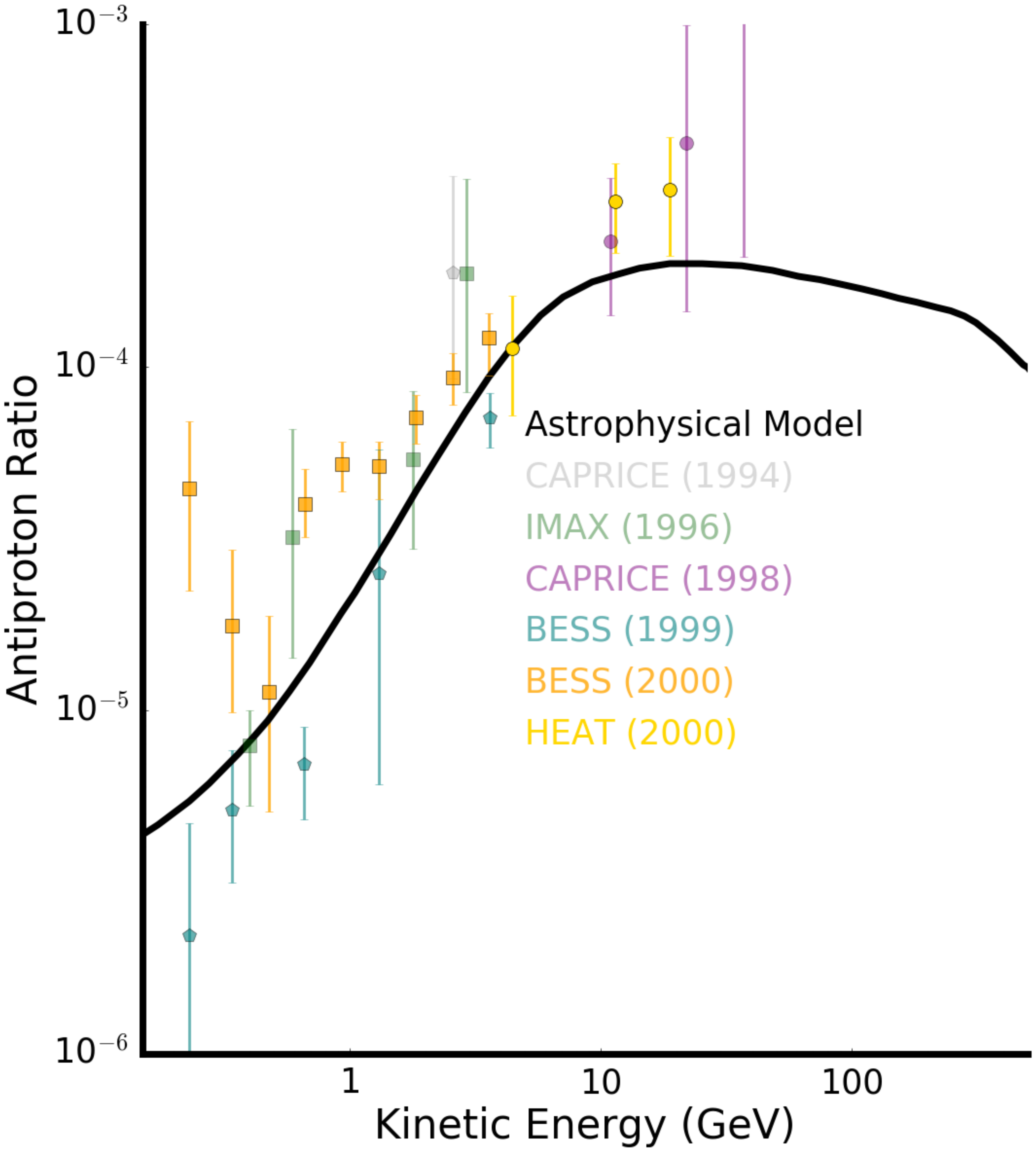

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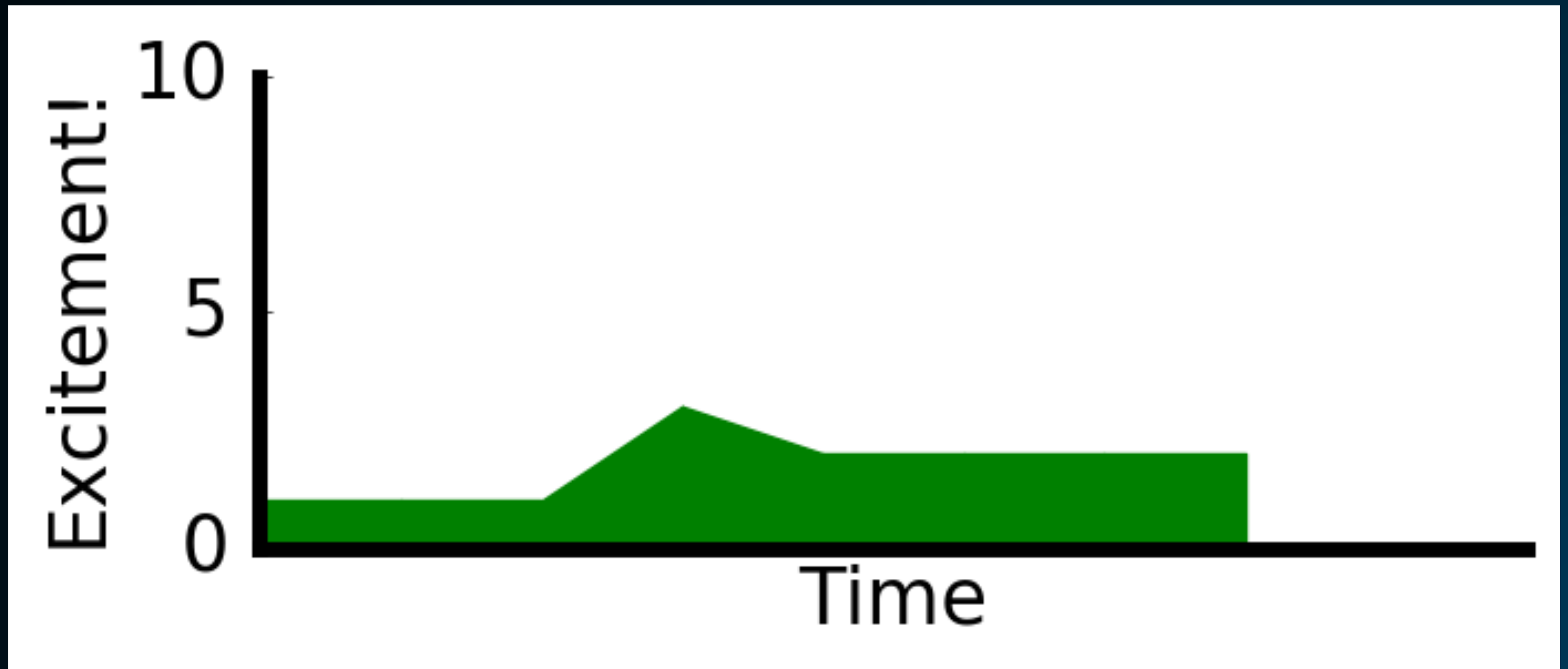

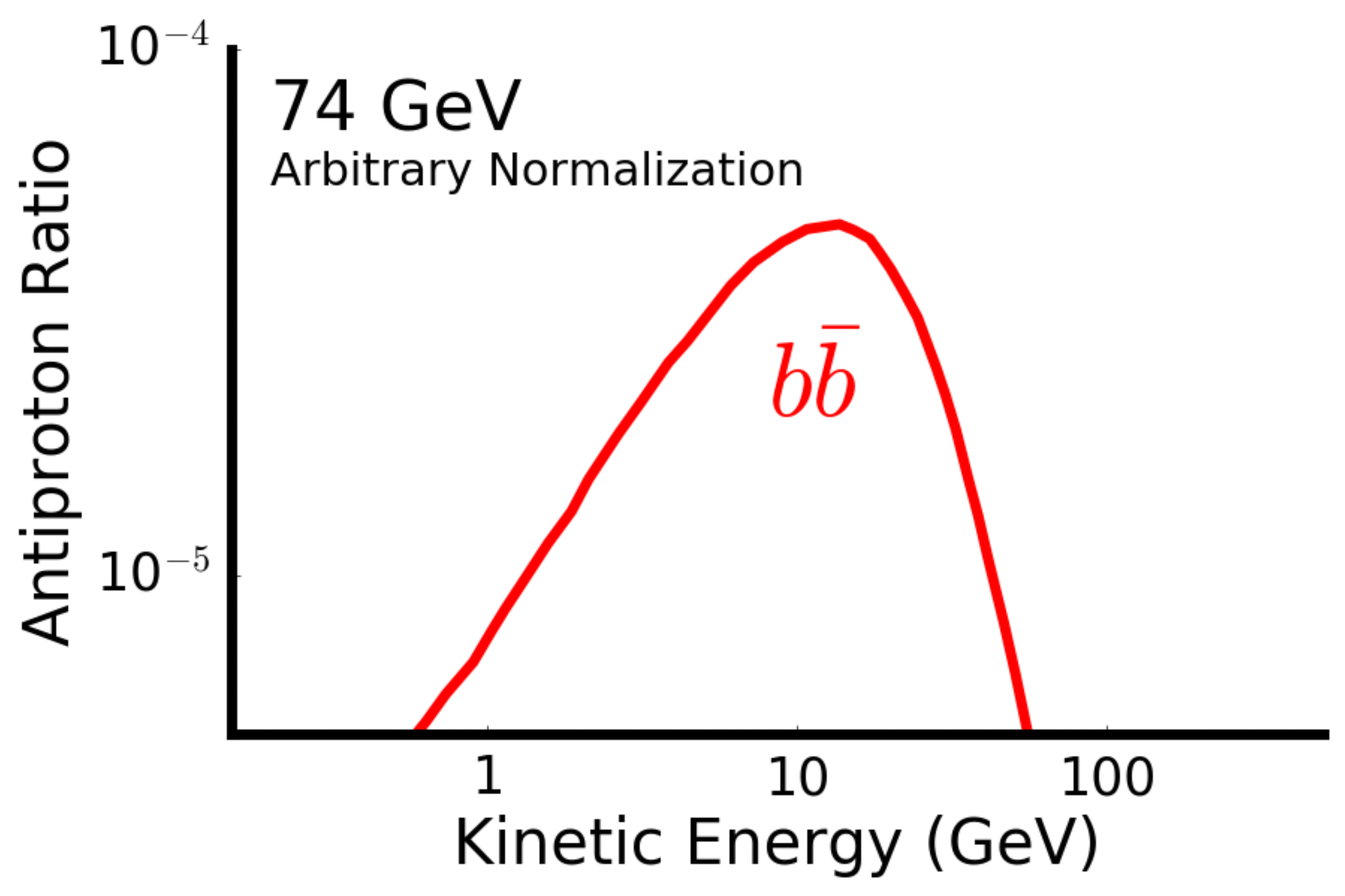

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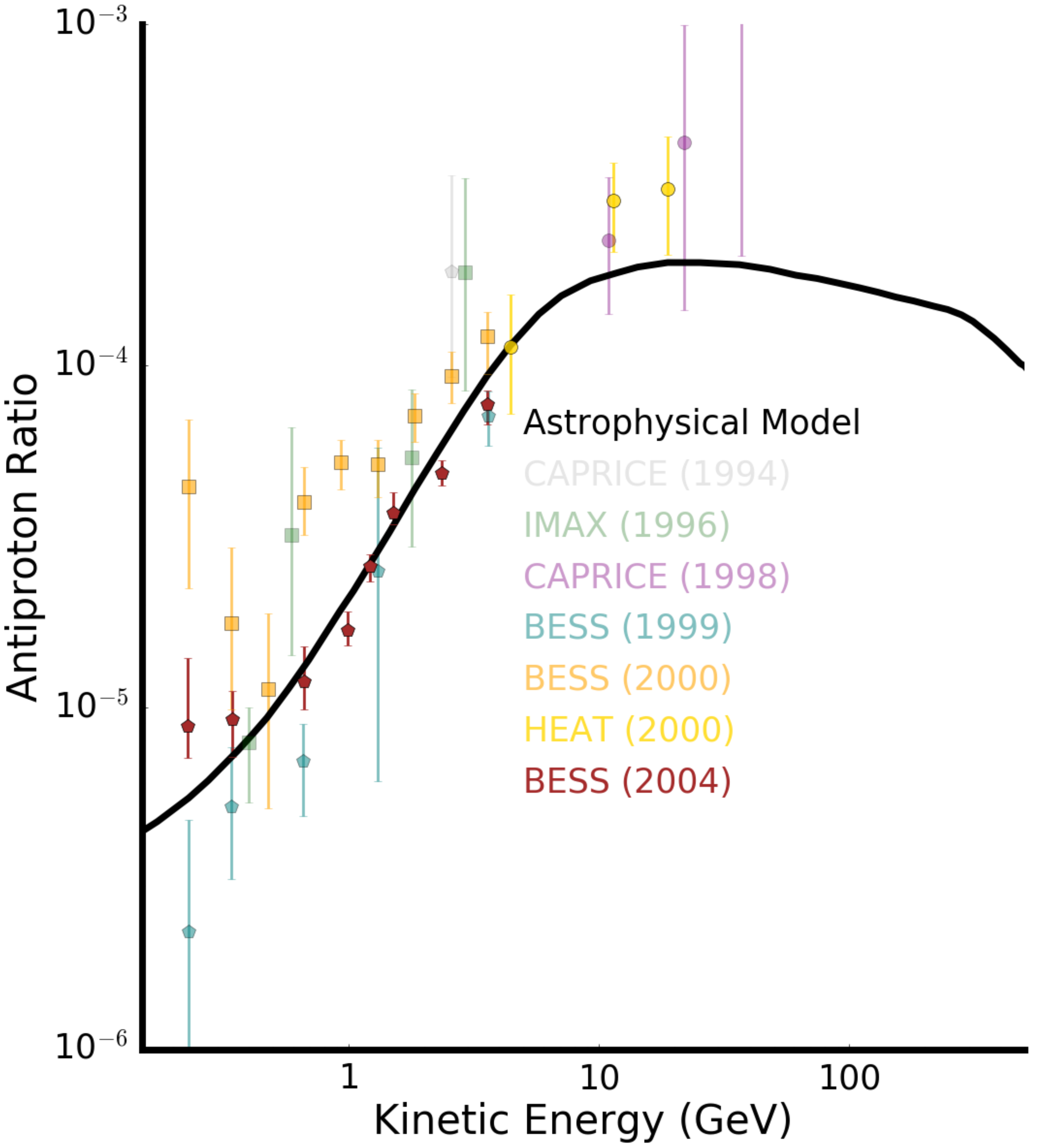

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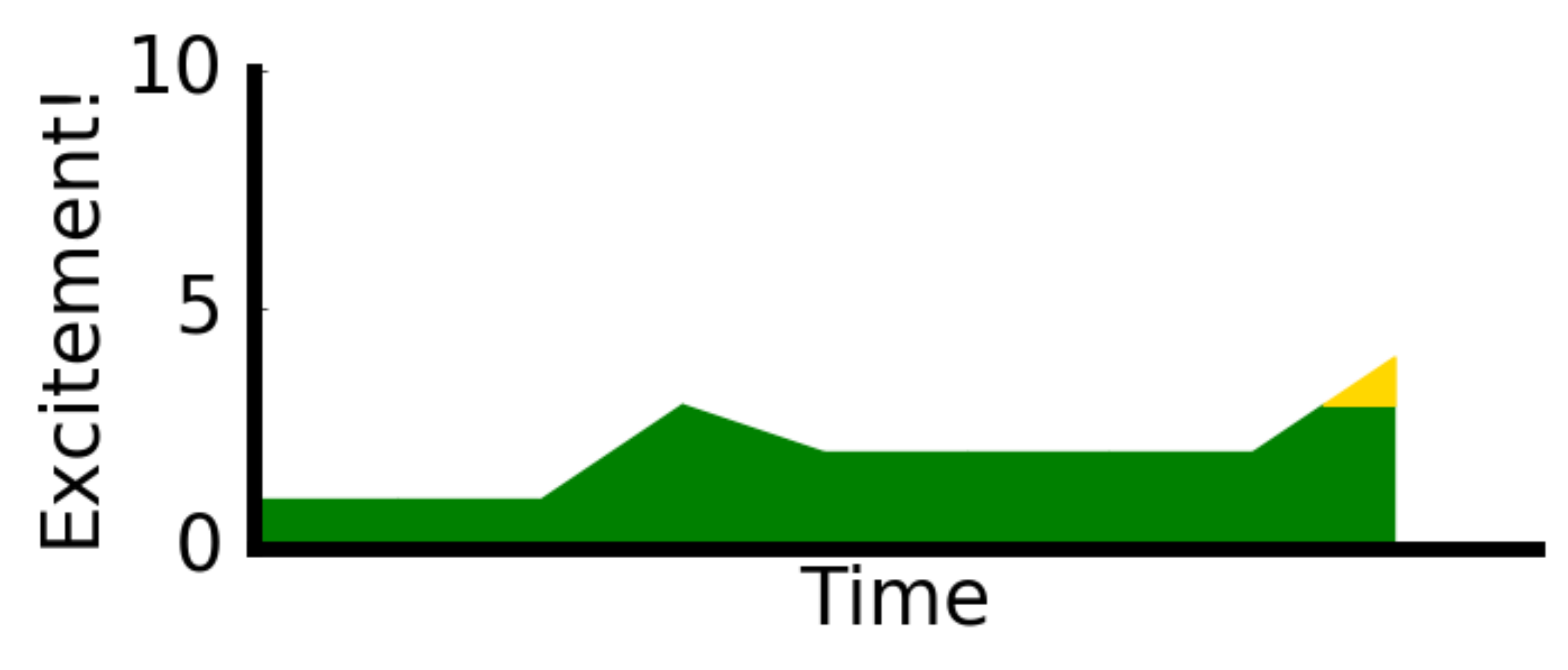

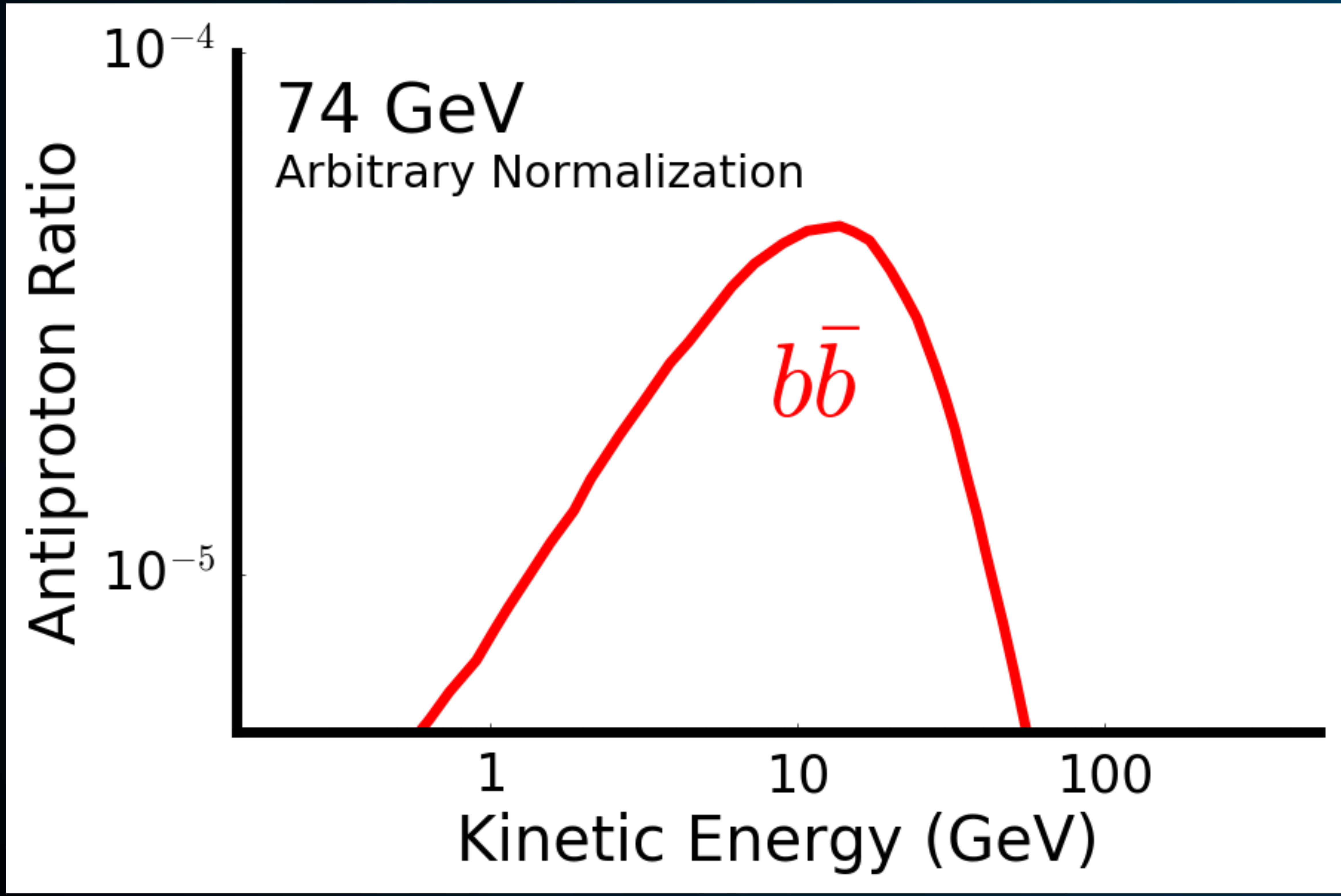

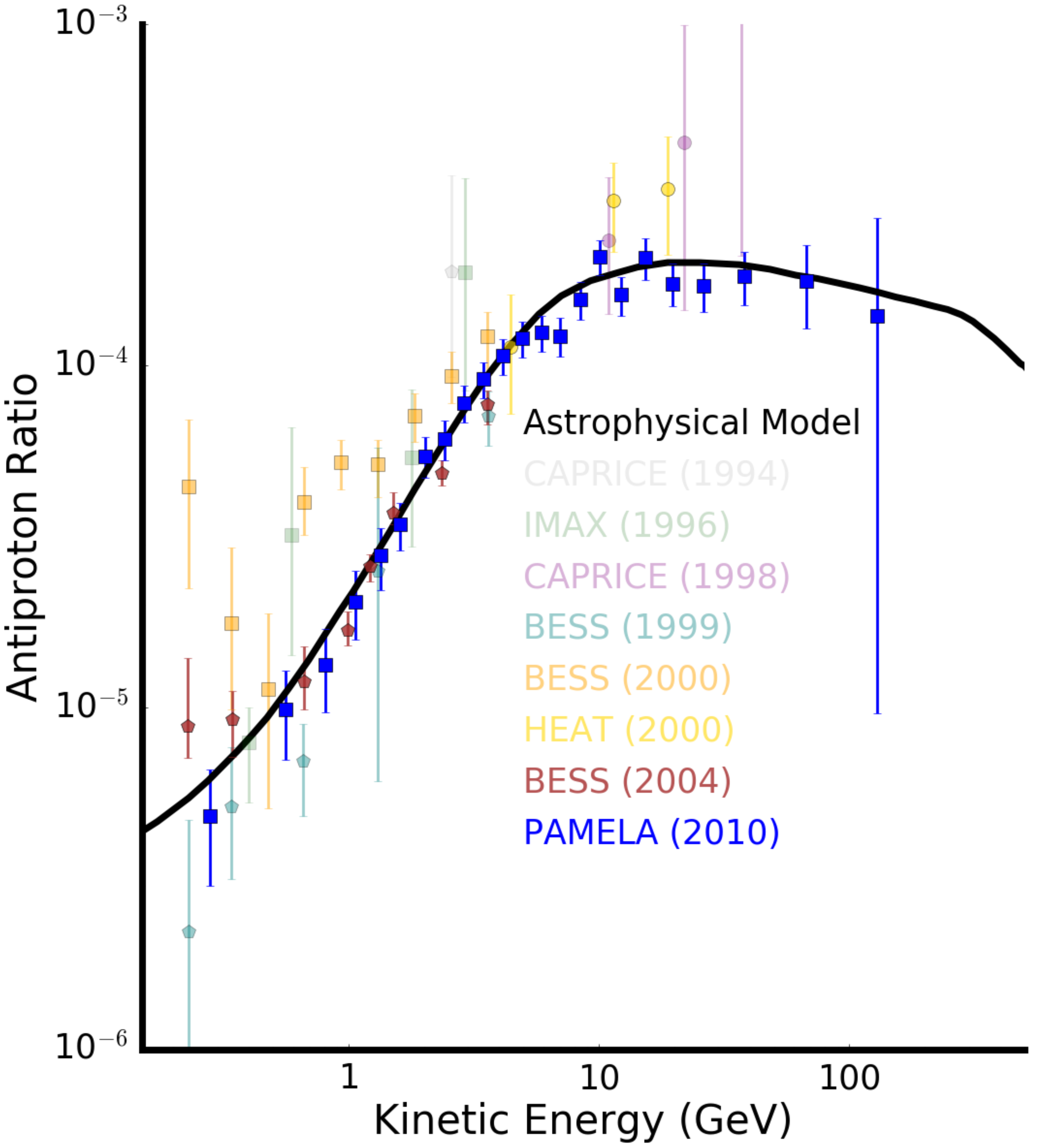

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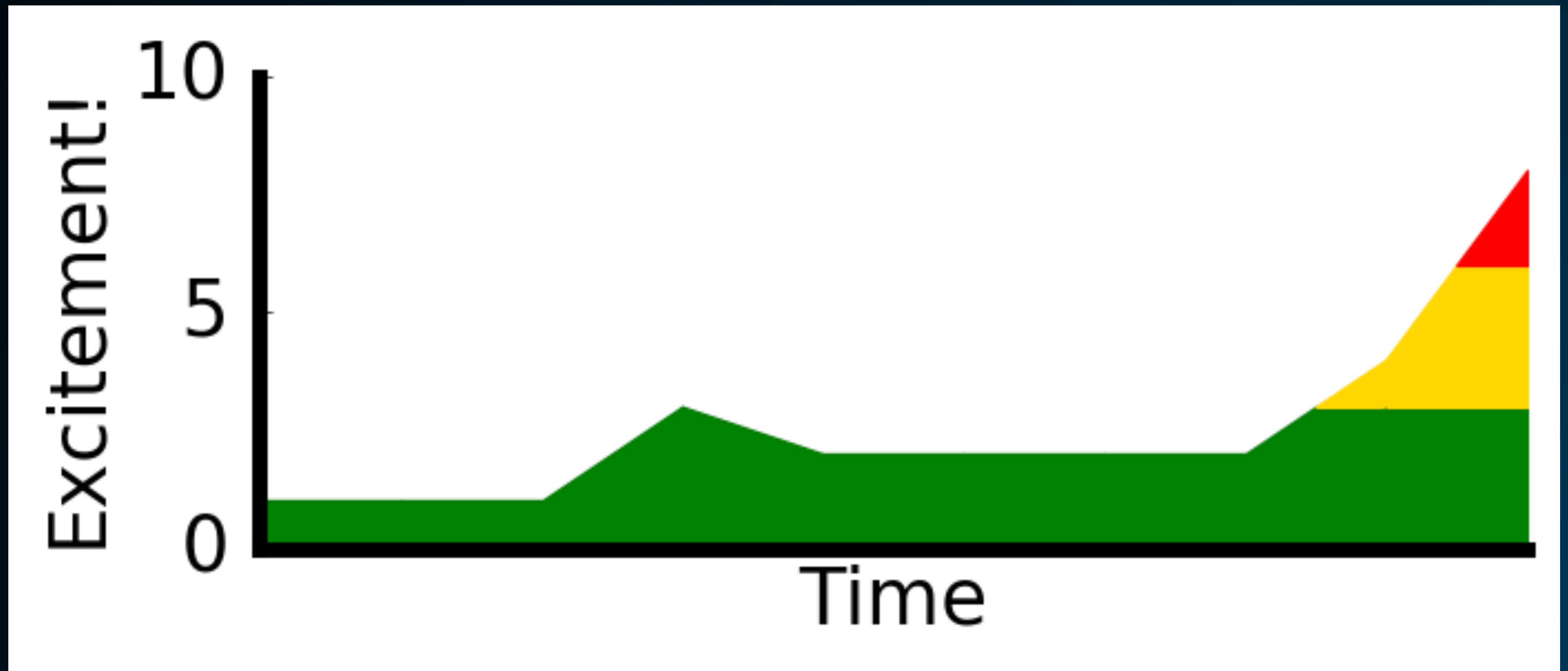

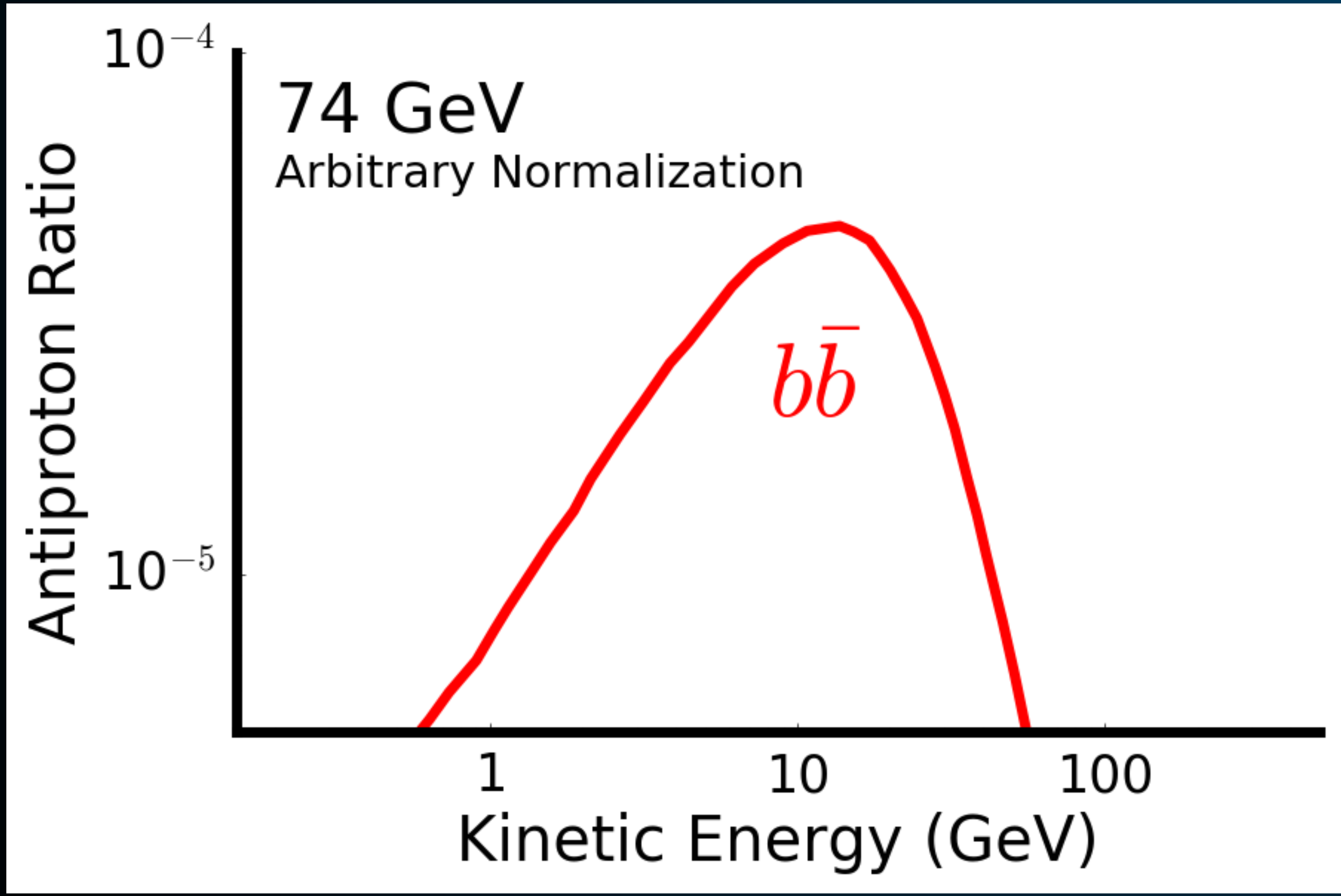

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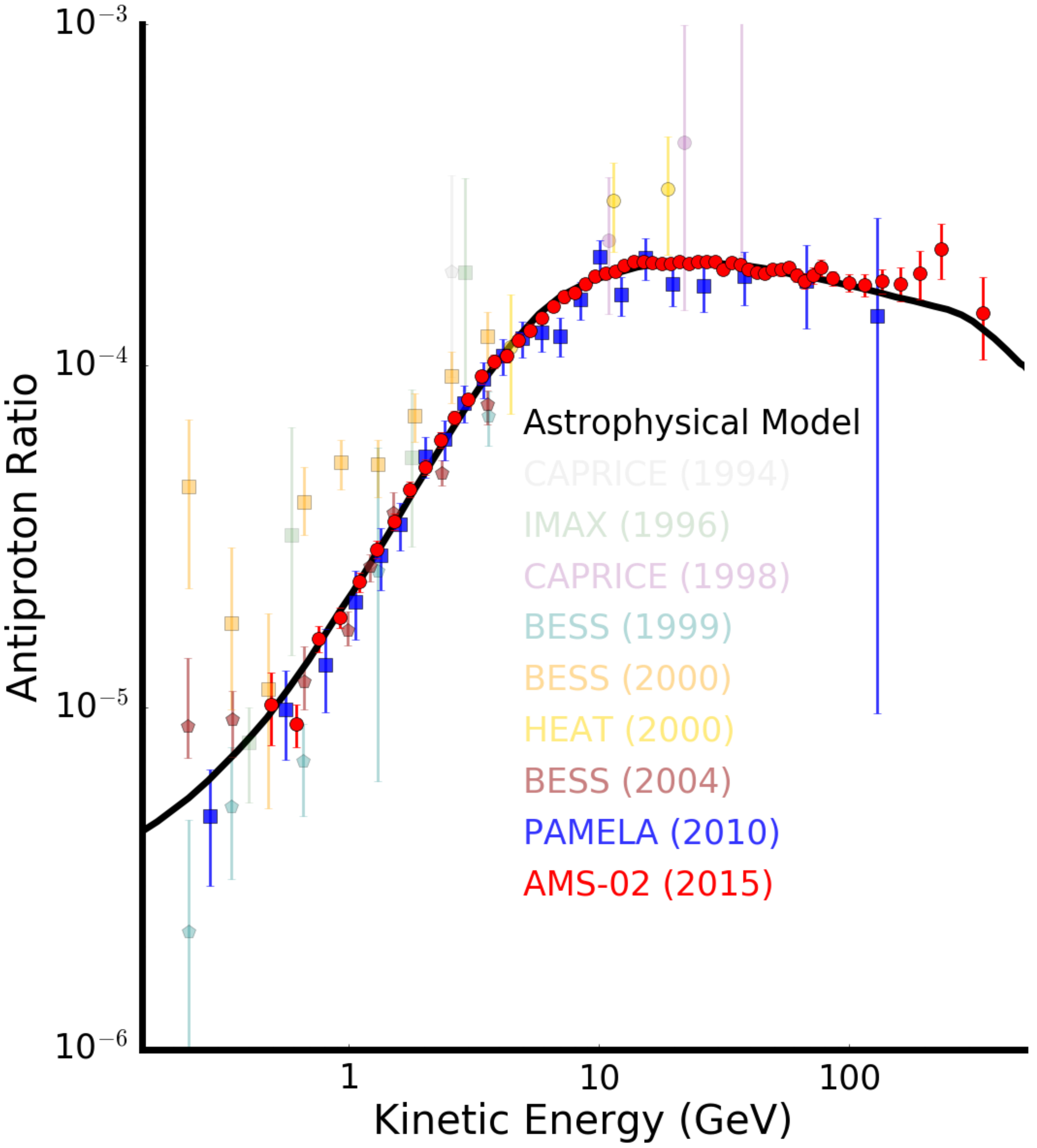

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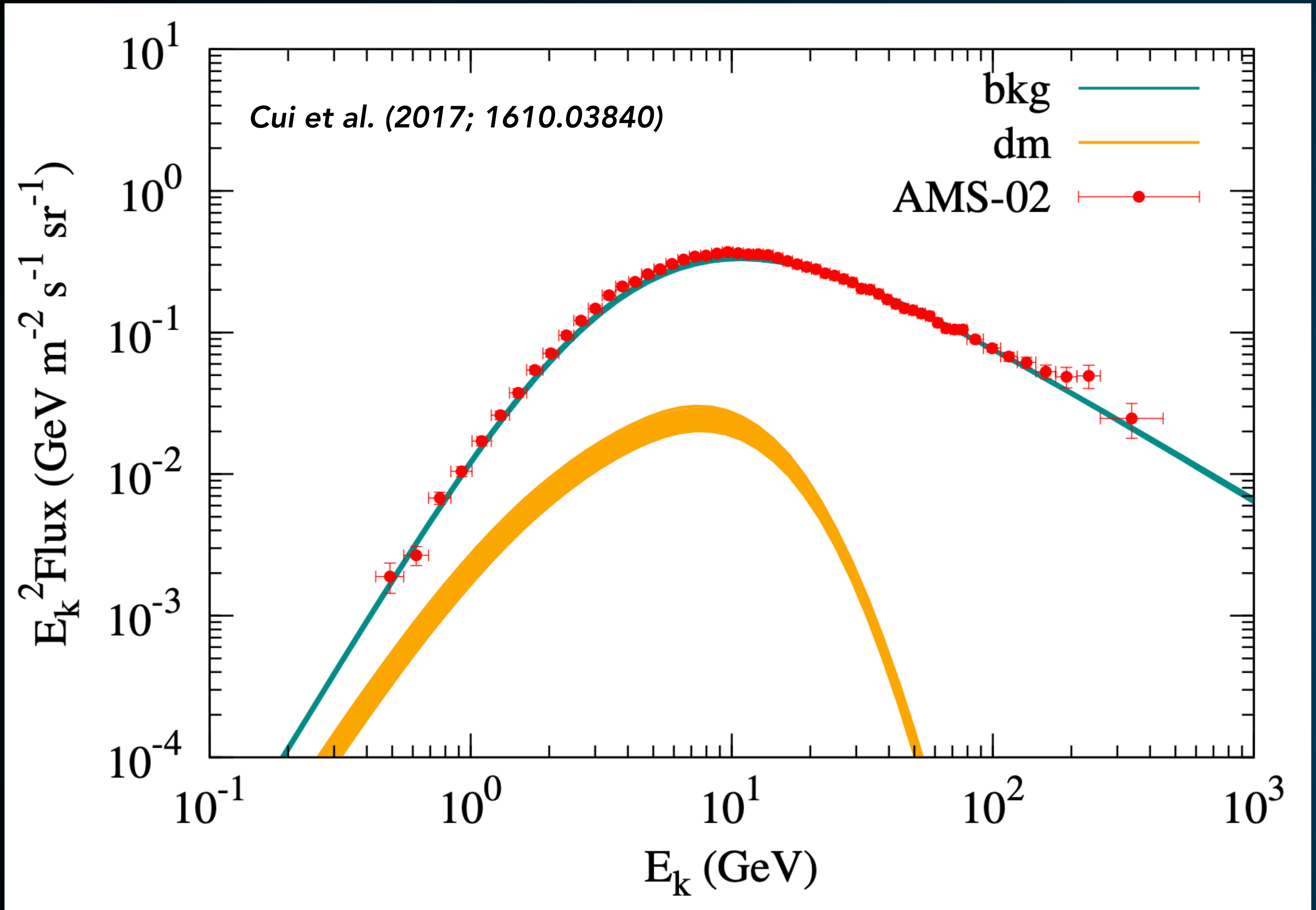
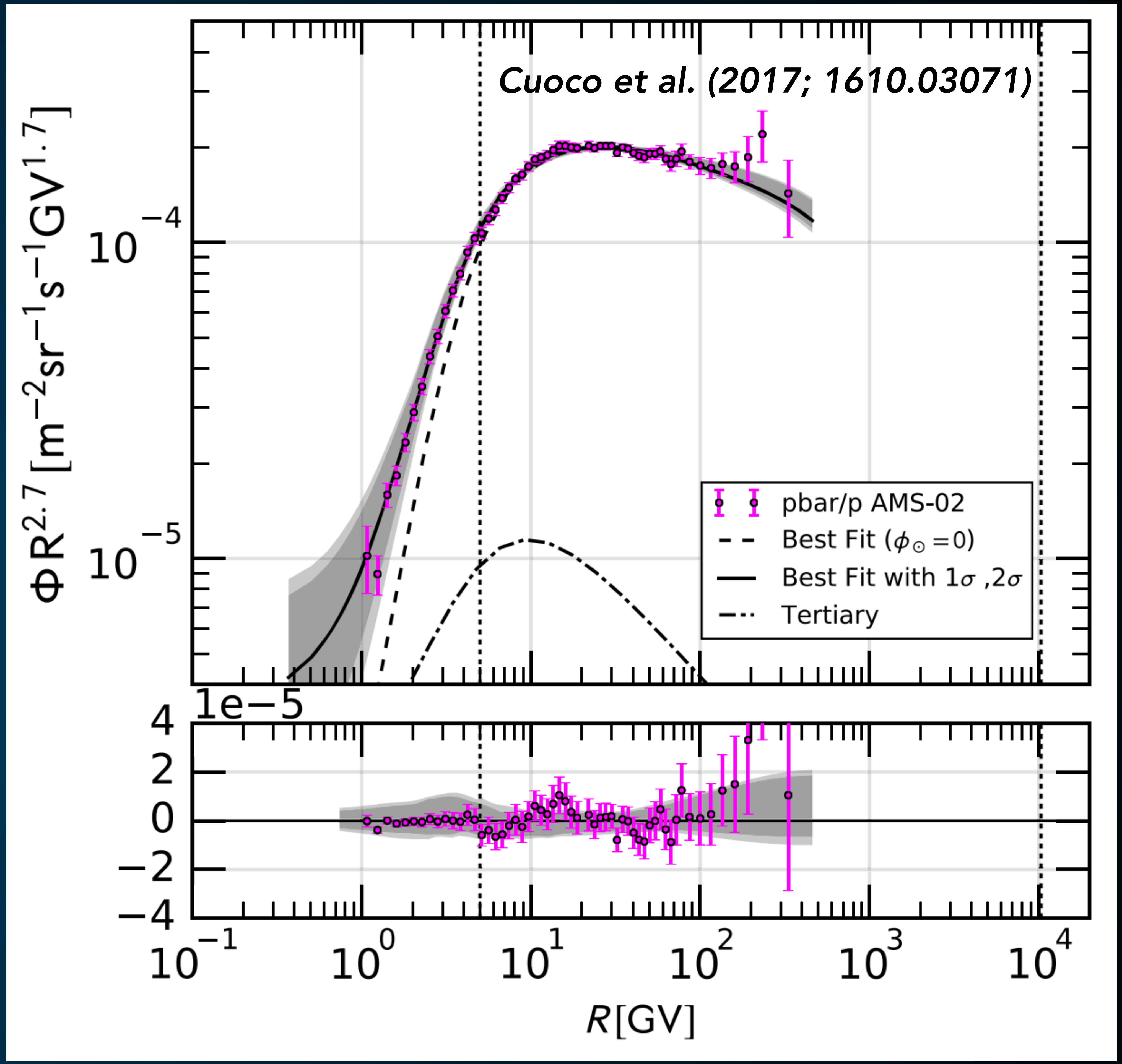




Two papers simultaneously find an excess in the AMS-02 Antiproton Data!

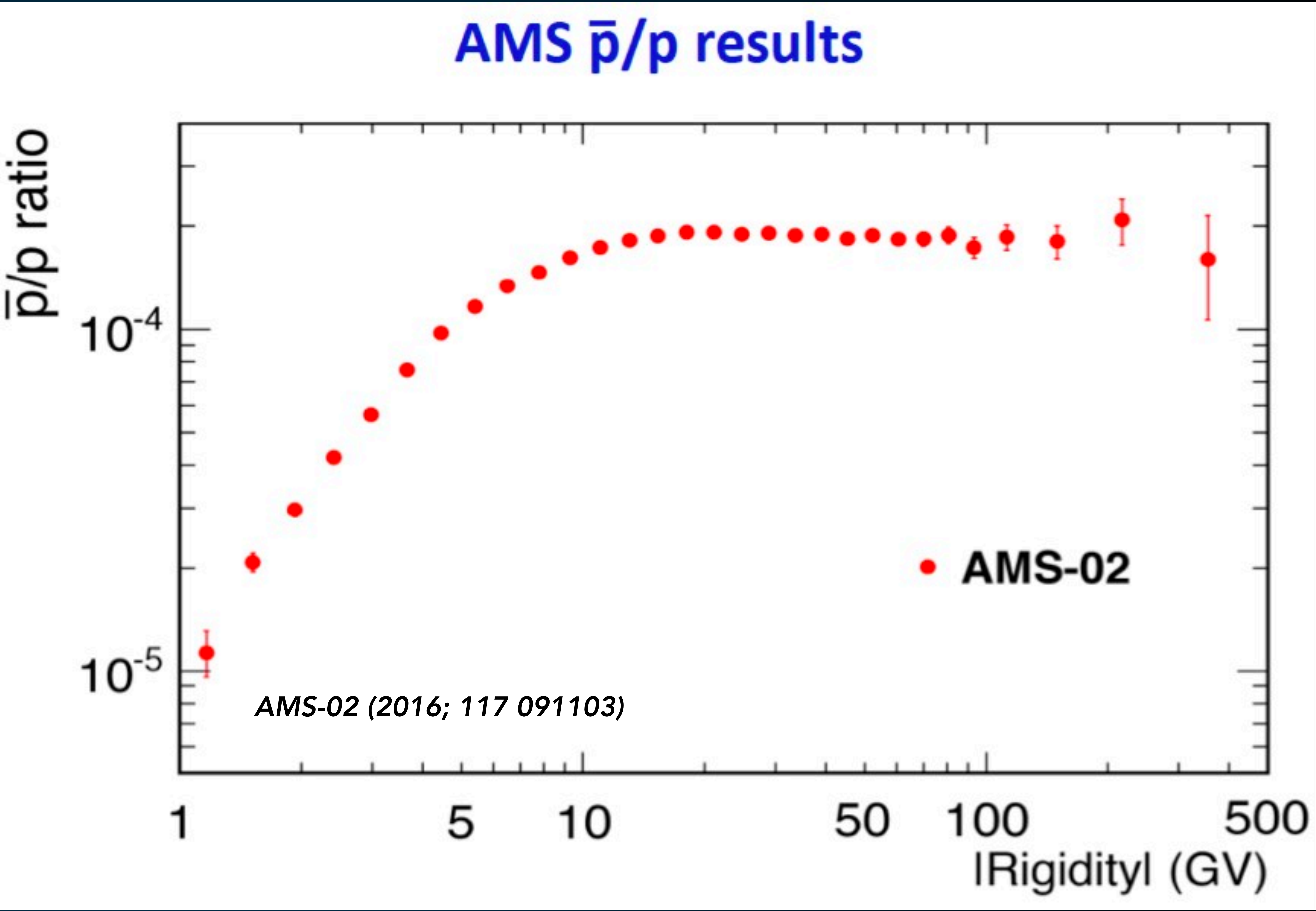
Significance approaching (or past) 5σ !

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

The Antiproton Excess

With great precision comes great responsibility:

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



AMS-02 (2016; 117 091103)

The Antiproton Excess

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

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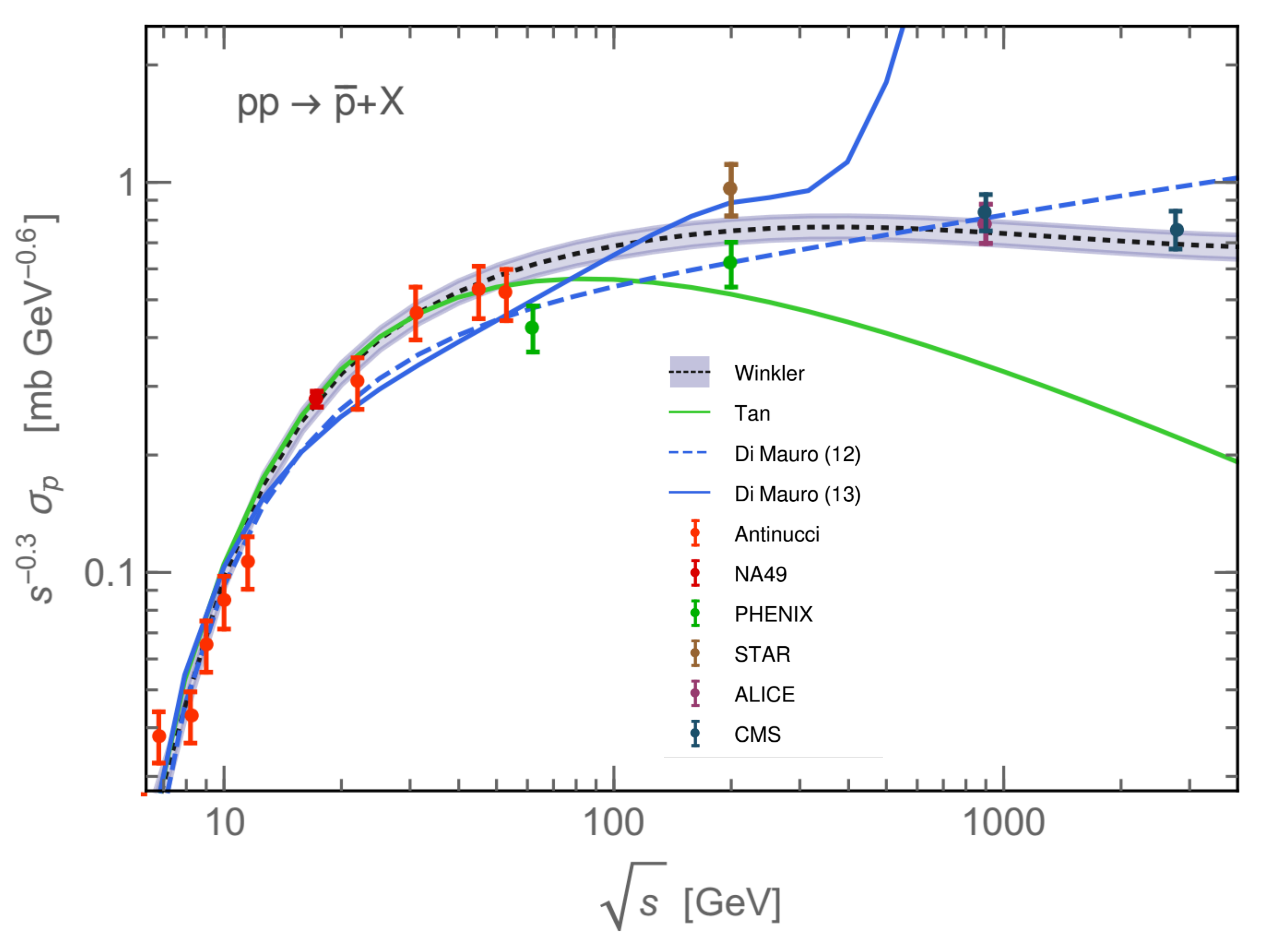

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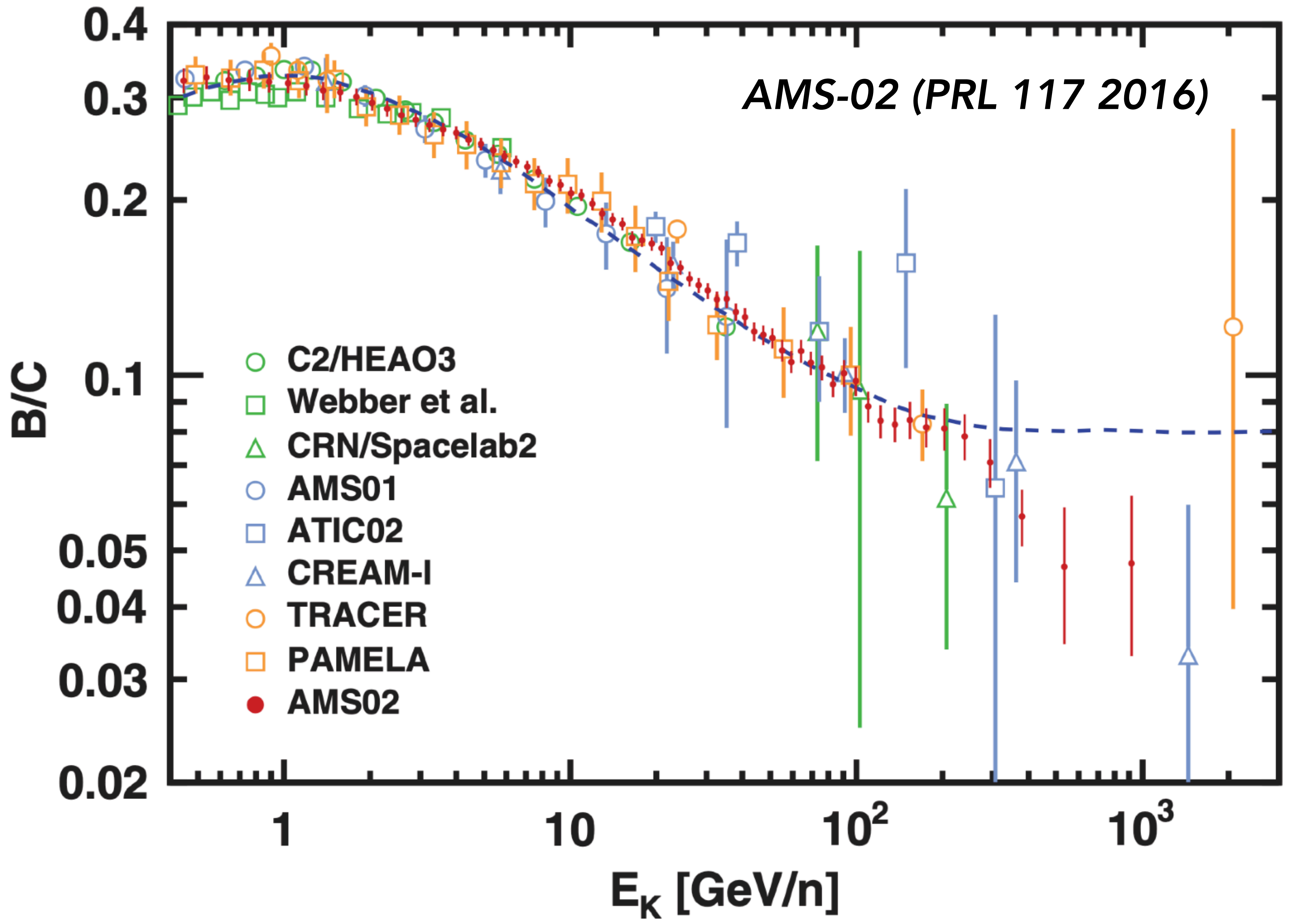

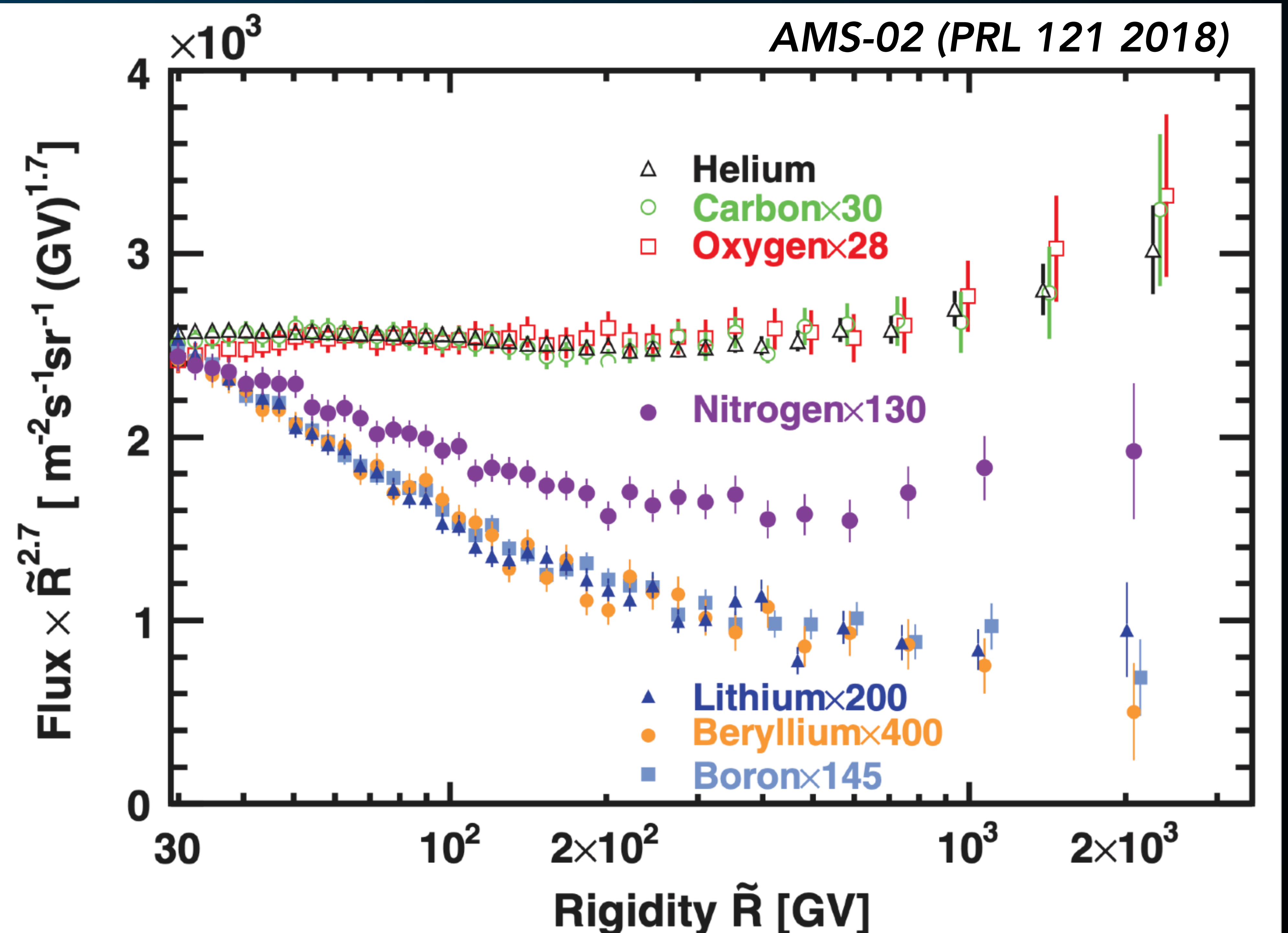

See e.g., Weinrich et al. (2002; 2002.11406)

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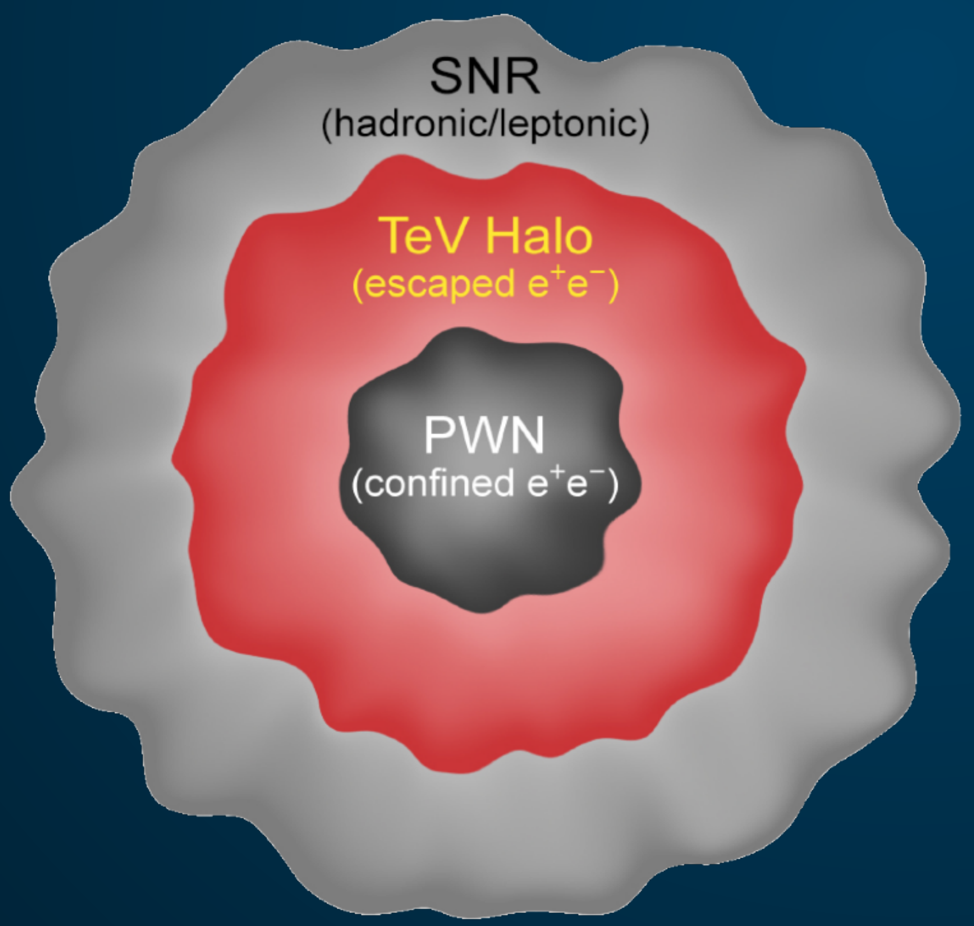
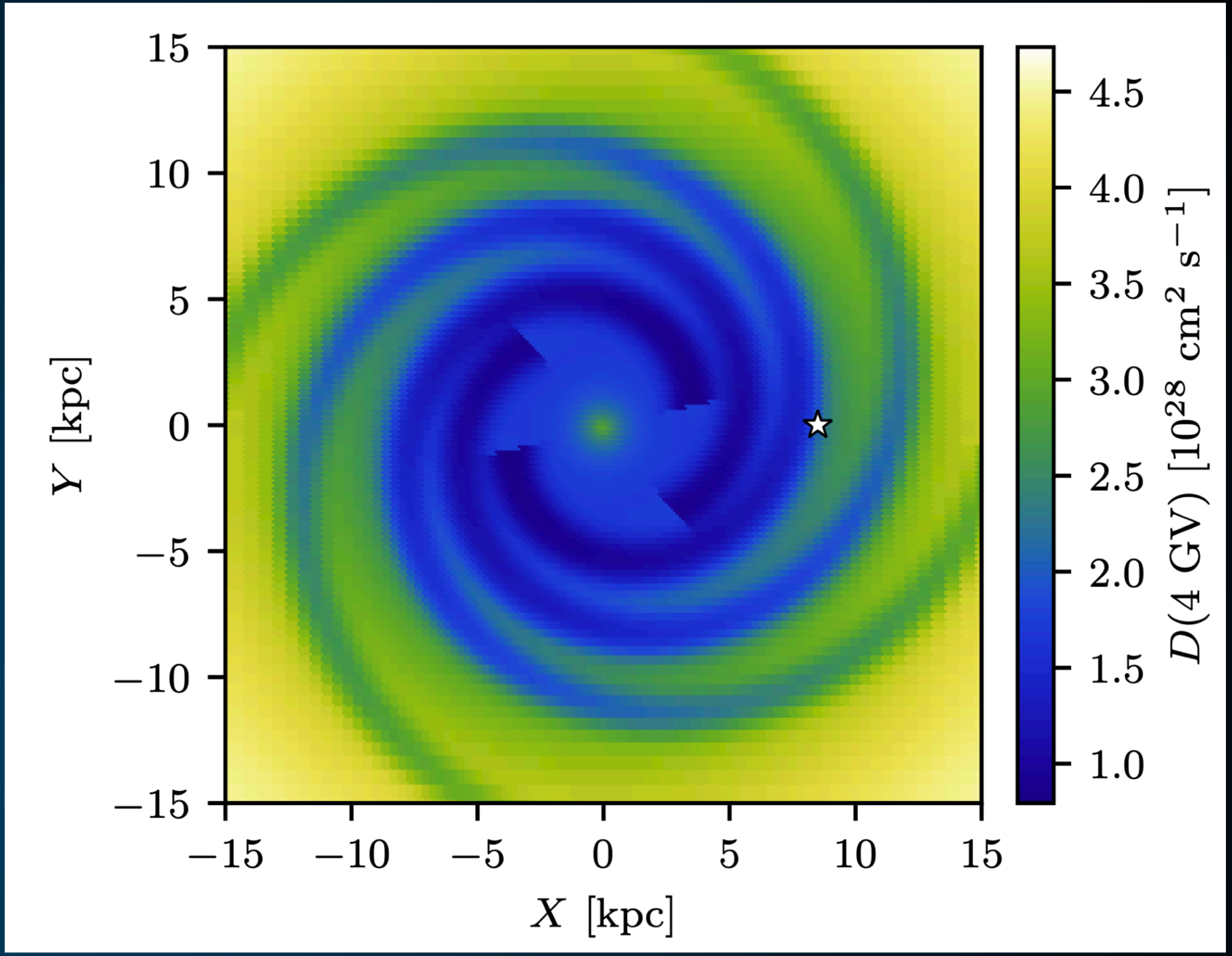
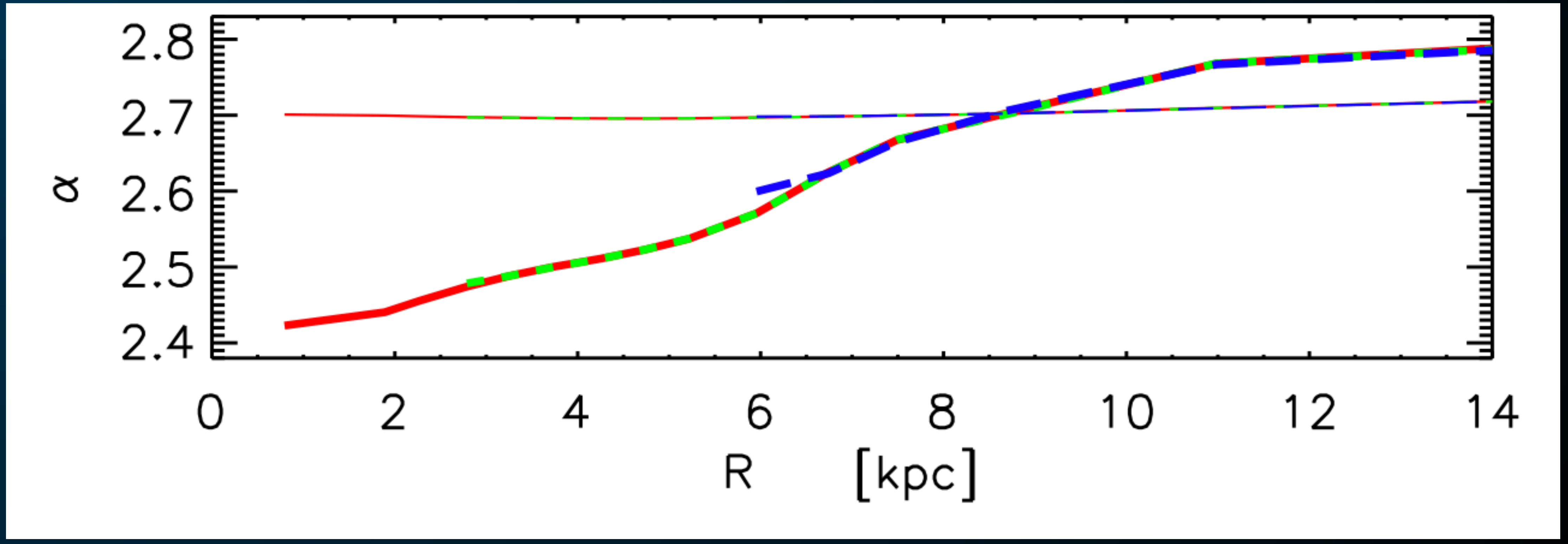


Johannesson et al. (1903.05509)



Evoli et al. (2014; 1411.7623)



The Antiproton Excess

AMS-02 (PRL 121 2018)

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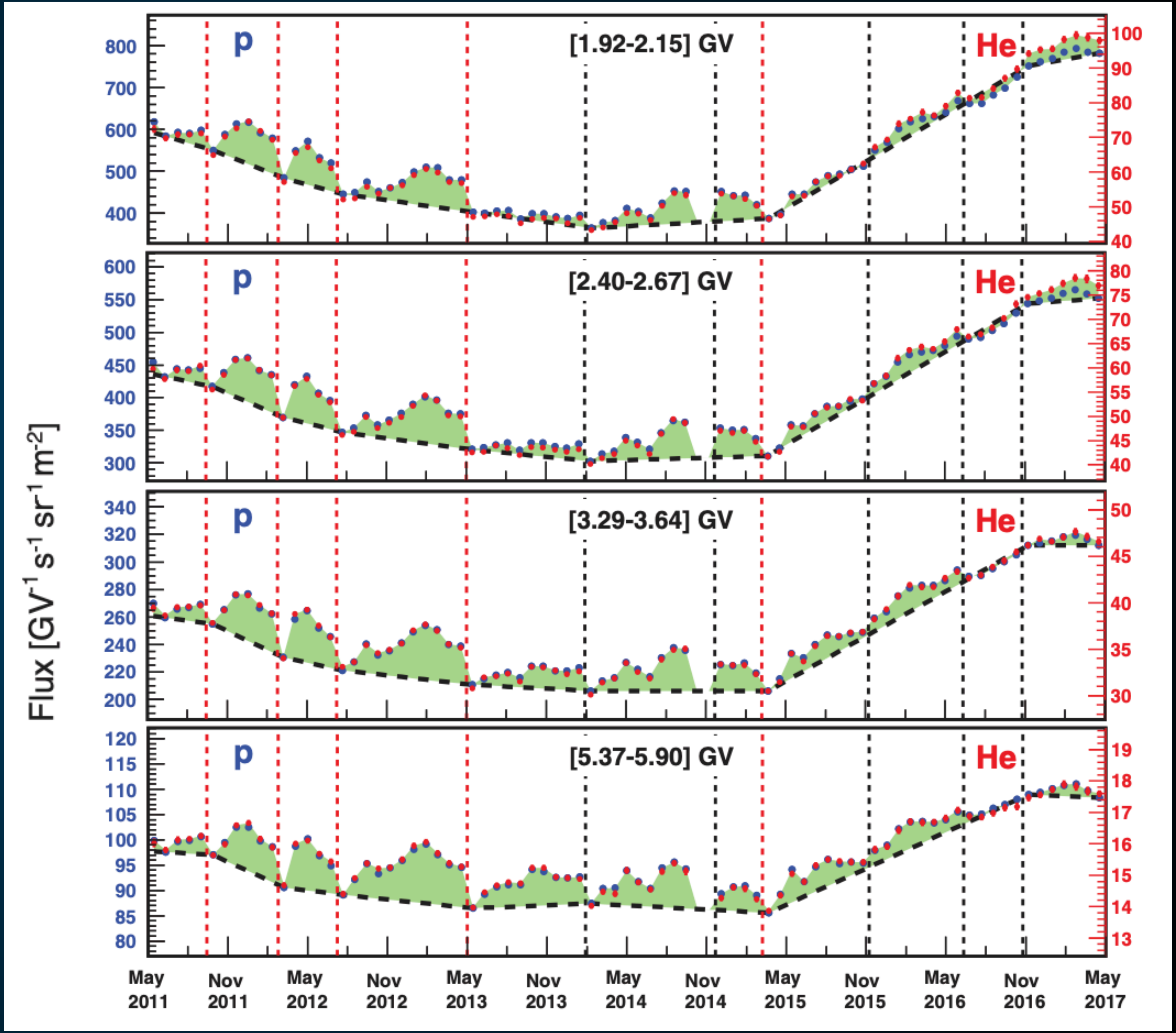
Antiproton Production Cross-Section

Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

Solar Modulation

Instrumental Uncertainties



The Antiproton Excess

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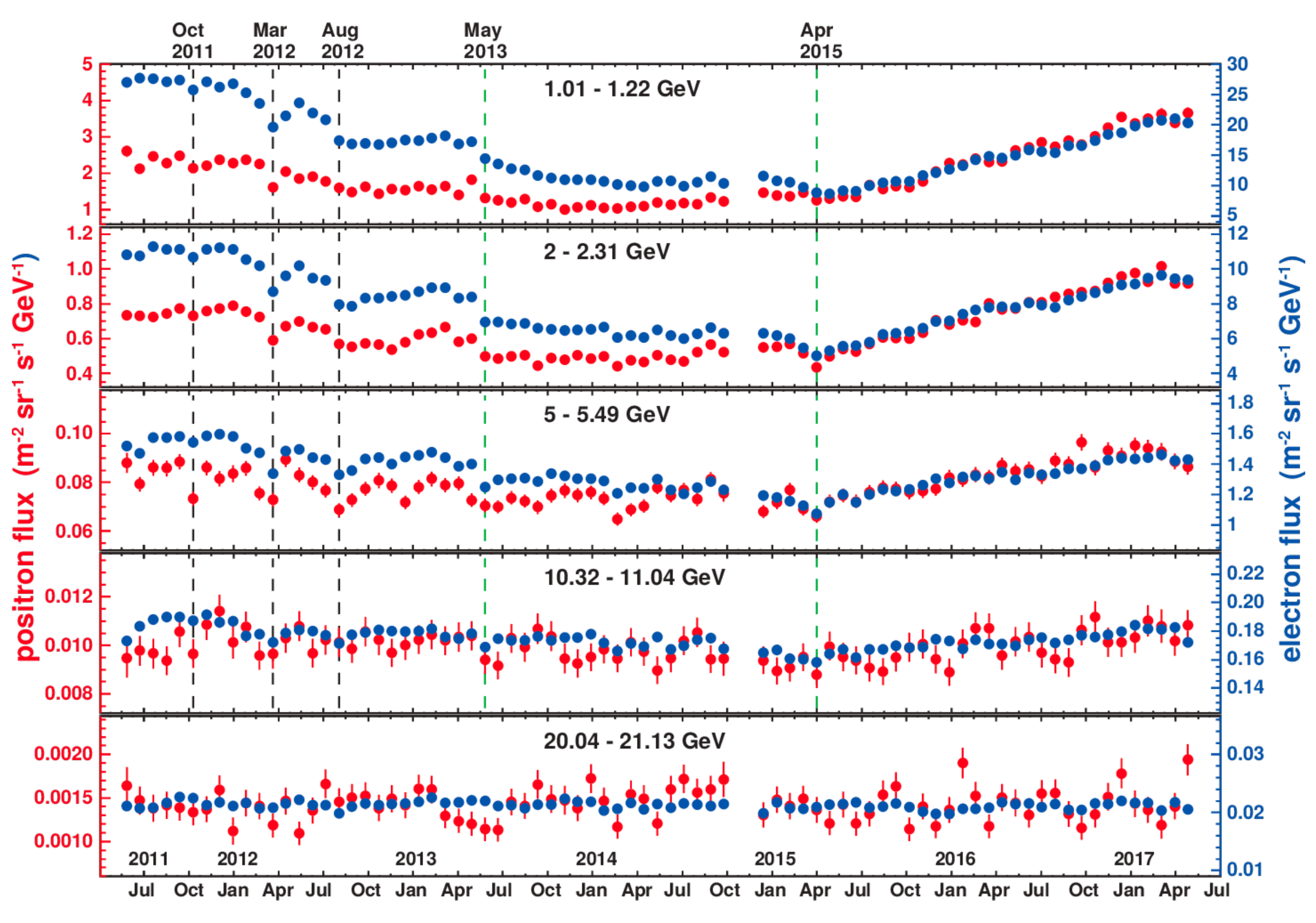
- **Solar Modulation**
- Instrumental Uncertainties



The Antiproton Excess

With great precision comes great responsibility:

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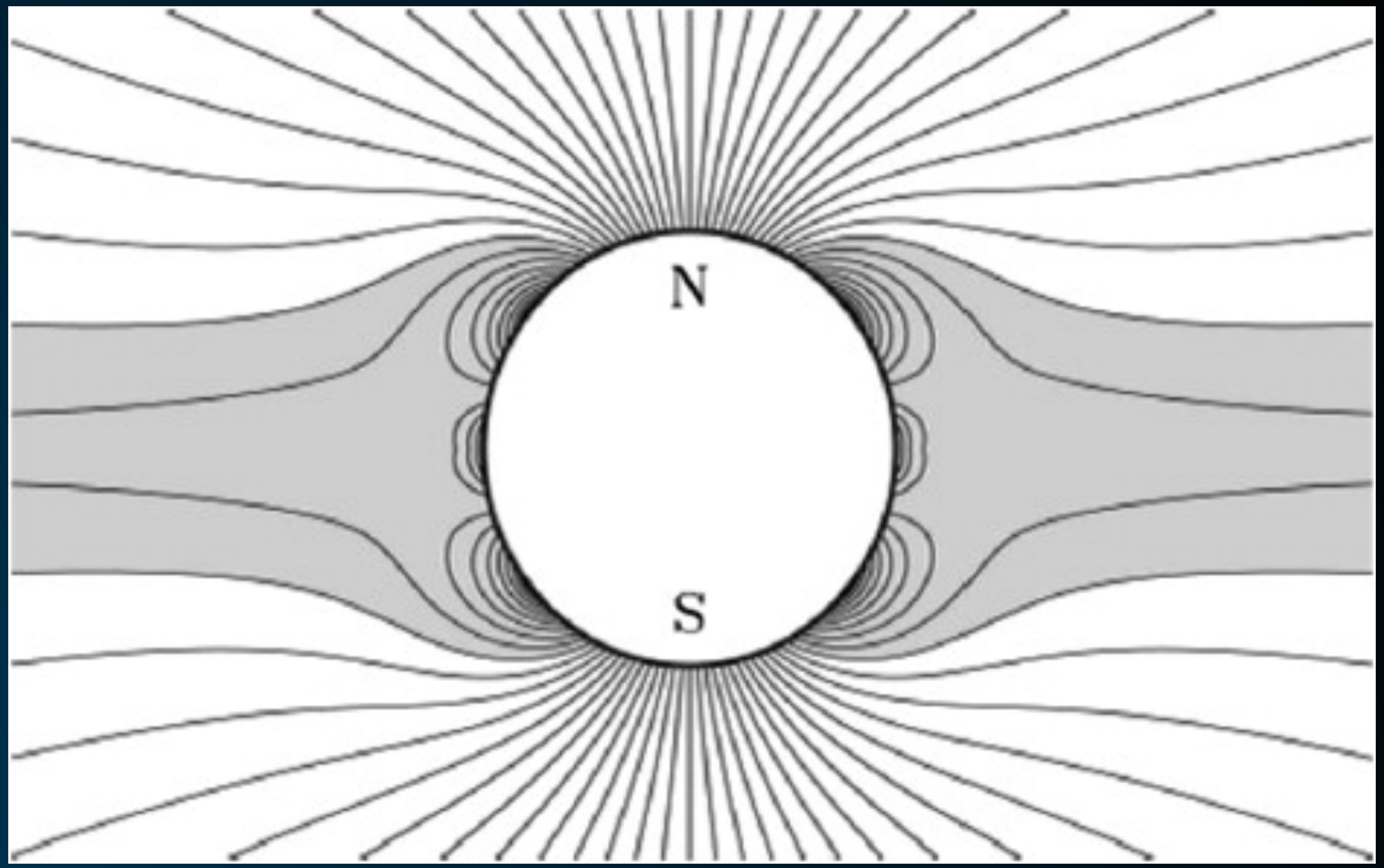
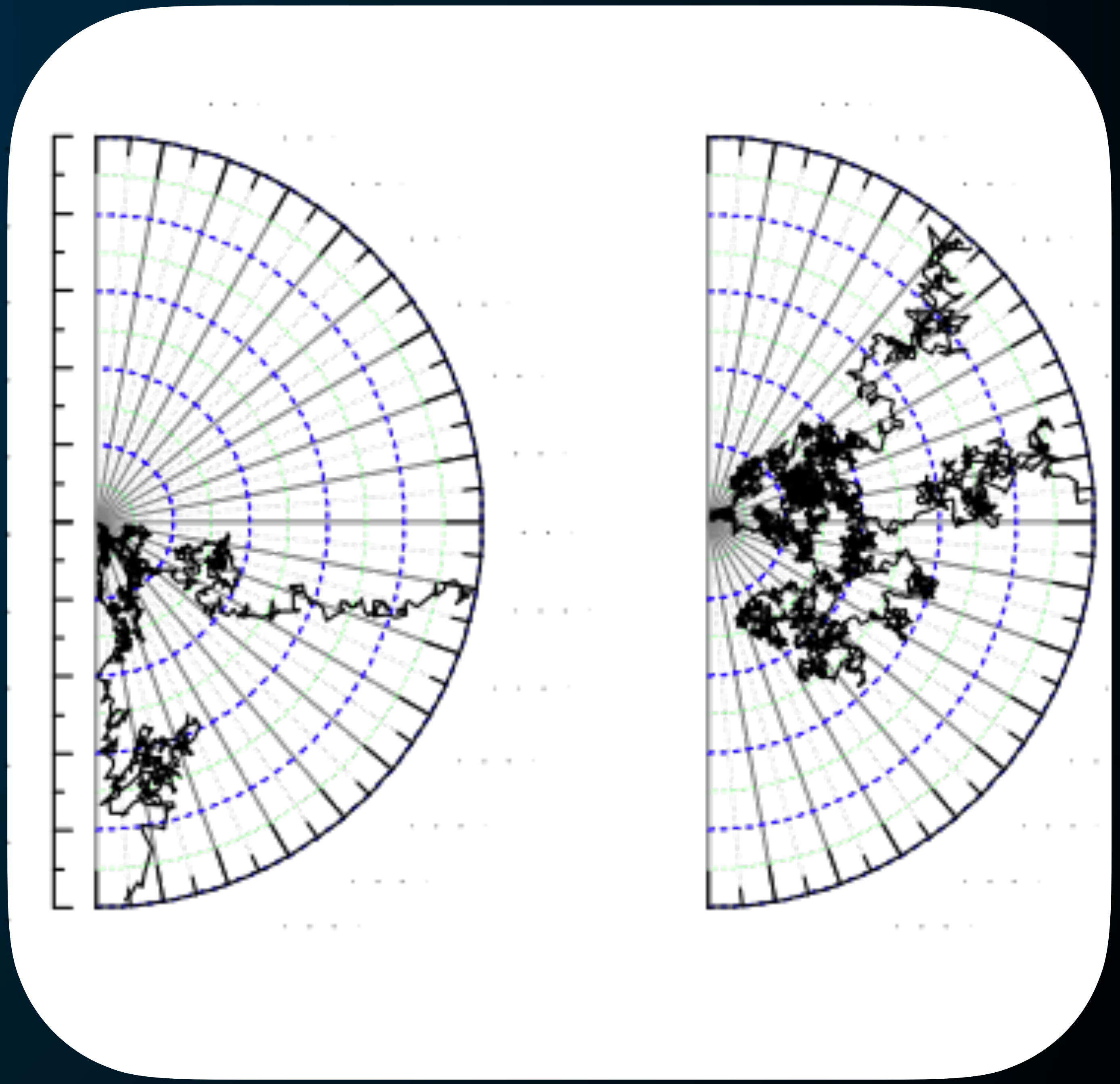
Fisk Potential





HELMOD Collaboration (2011, 1110.4315)

The Antiproton Excess

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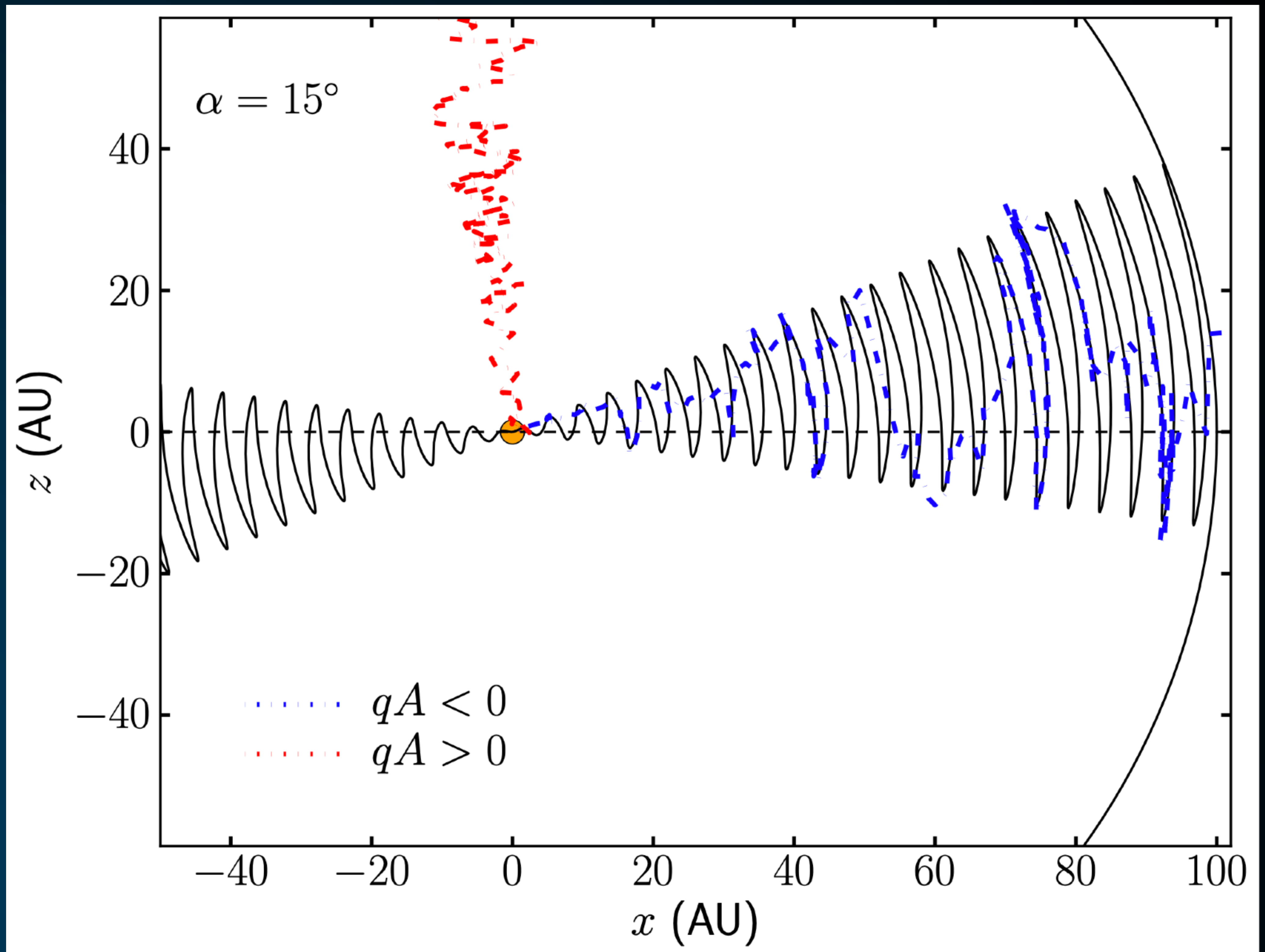
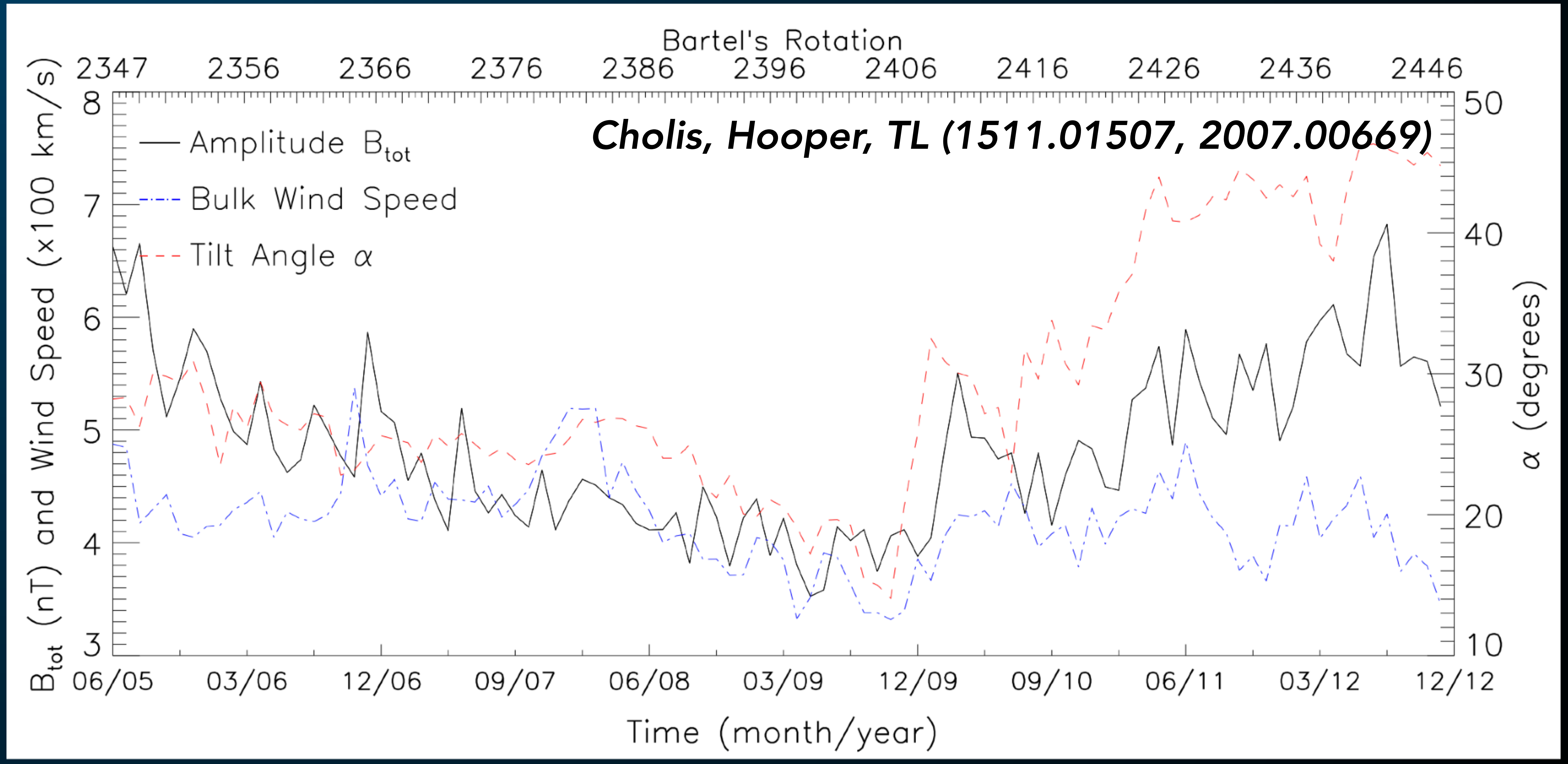
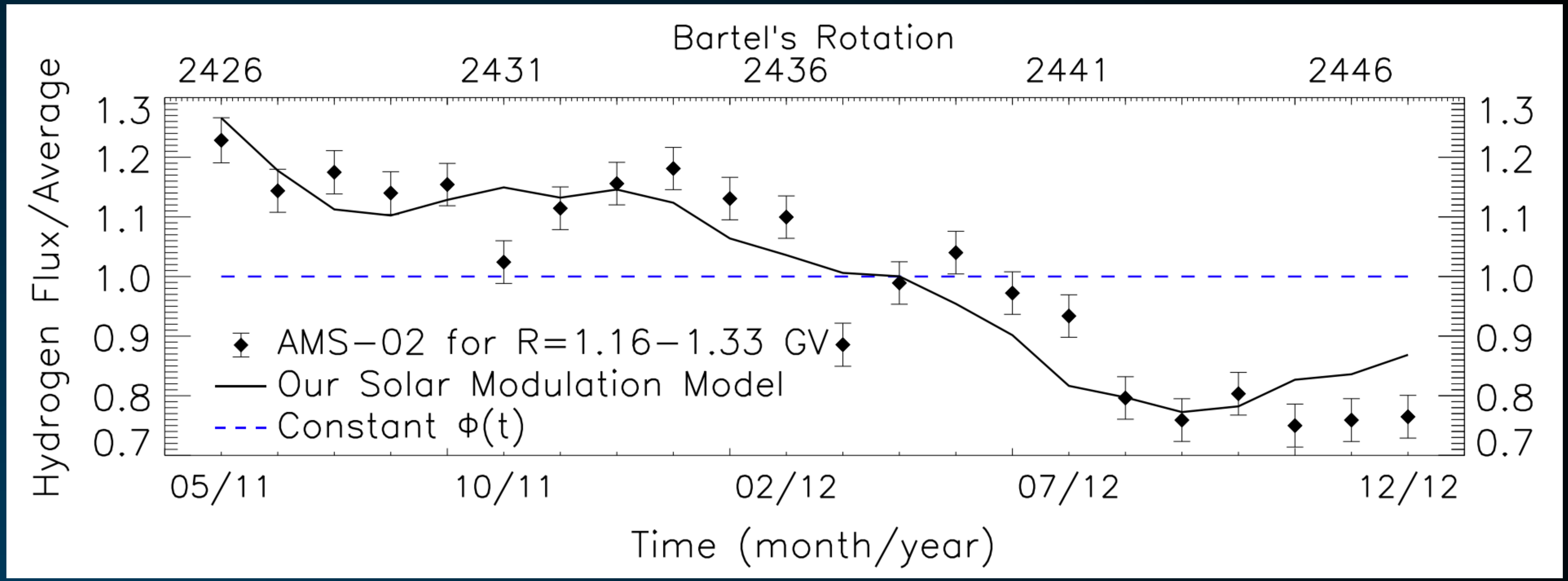




The Antiproton Excess

Cholis, Hooper, TL (2007.00669)



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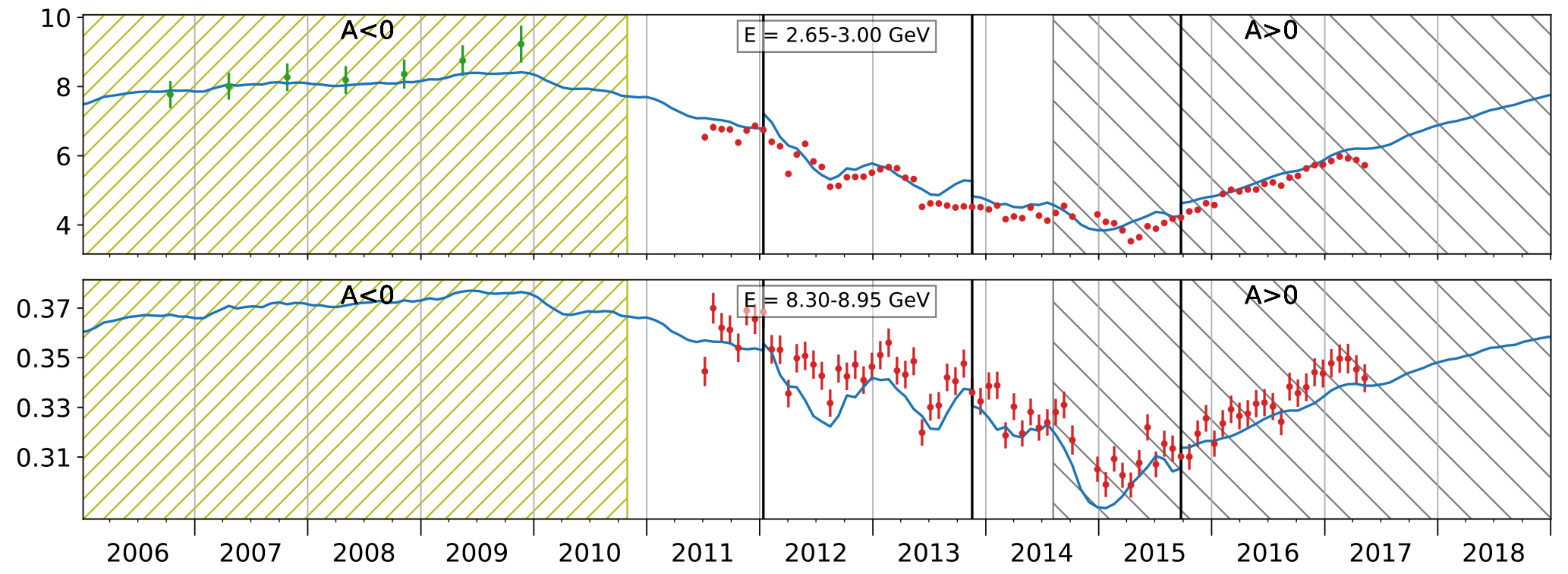
Kuhlen, Mertsch (1909.01154)



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AMS-02 (PRL 117 2016)

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

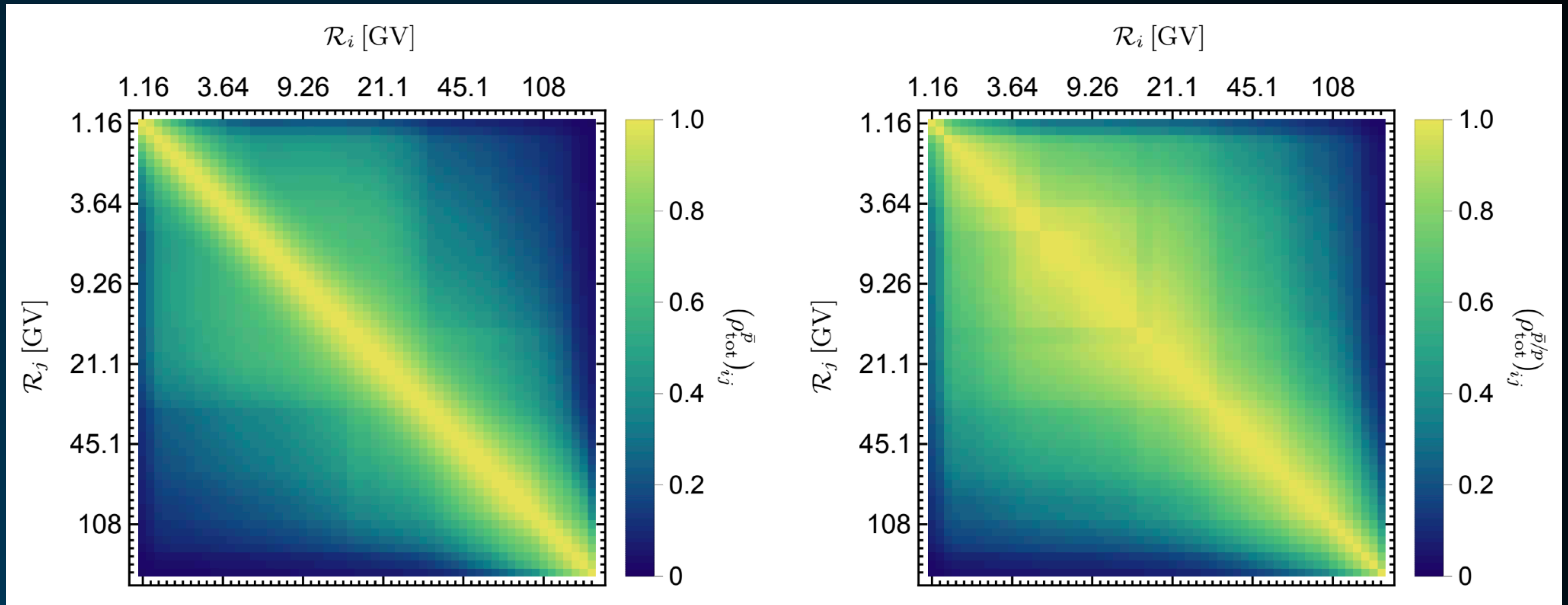
(Table continued)

The Antiproton Excess

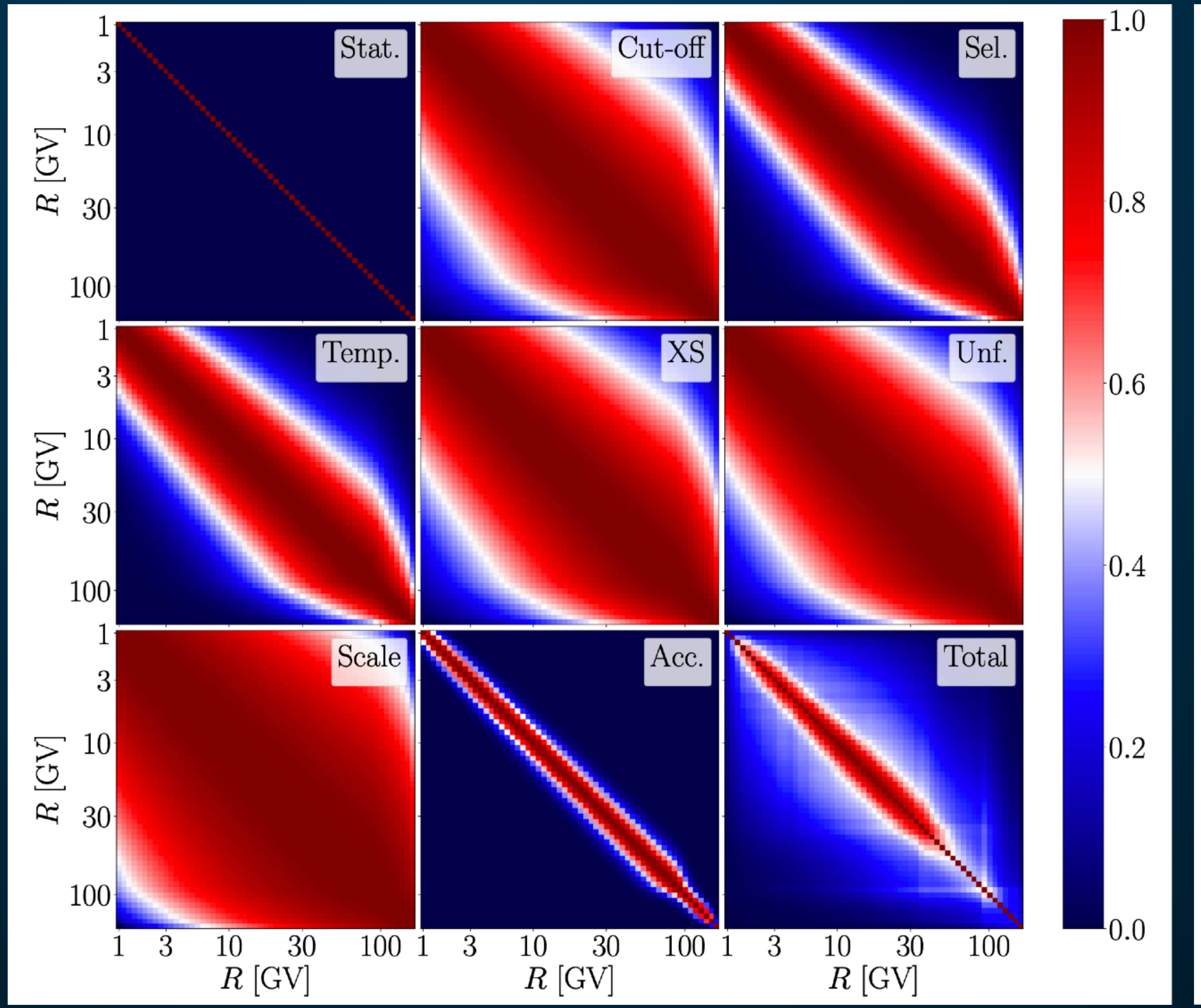
With great precision comes great responsibility:

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

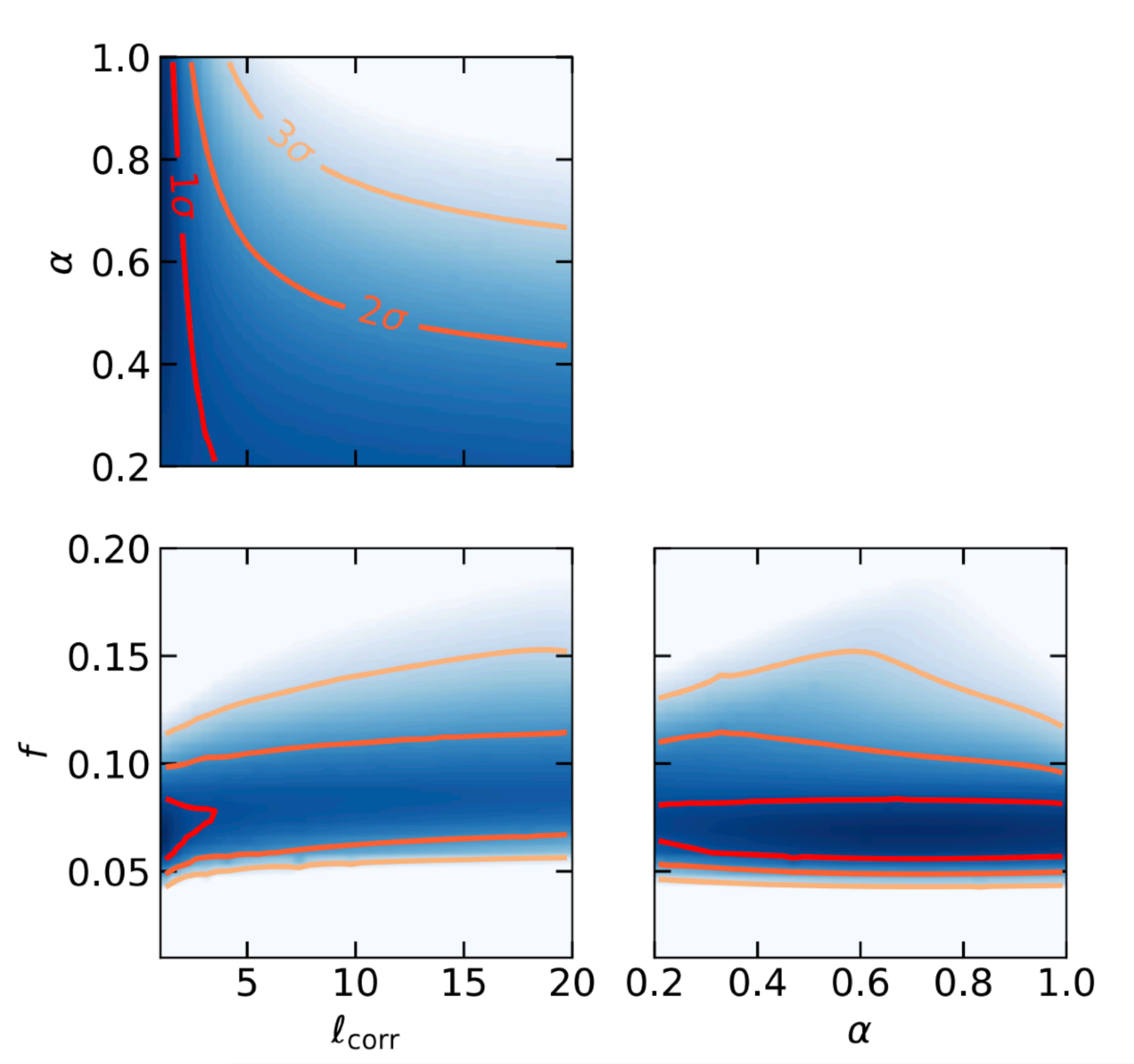
Heisig et al. (2020; 2005.04237)



Boudaud et al. (2019; 1906.07119)



Cuoco et. al. (2019; 1903.01472)



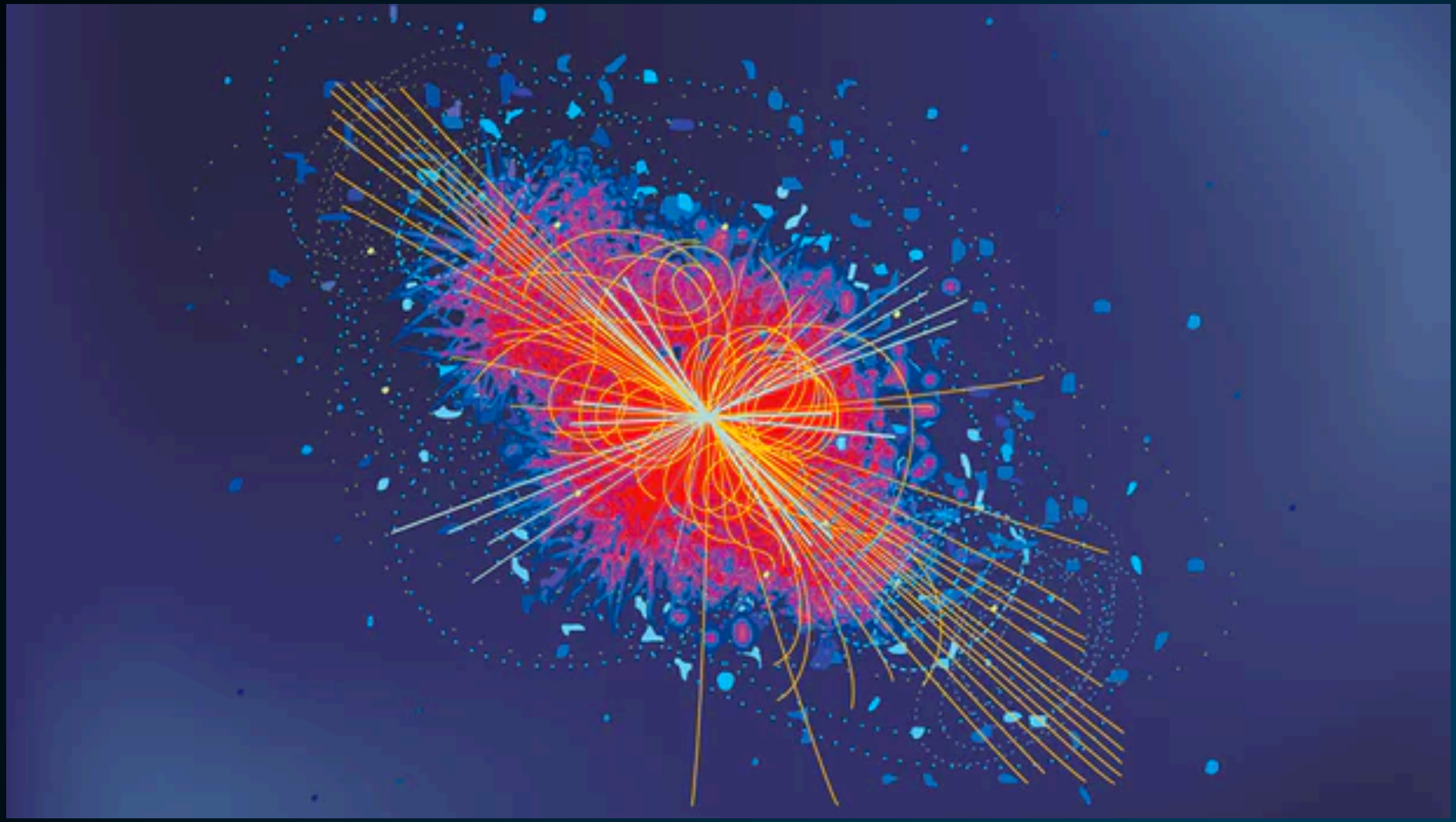
Antinuclei !?

Reflections on Antiproton Excesses

Can we realistically claim a detection of dark matter when signal to noise is small? (Antiprotons, GC Excess, DAMA, etc.)


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

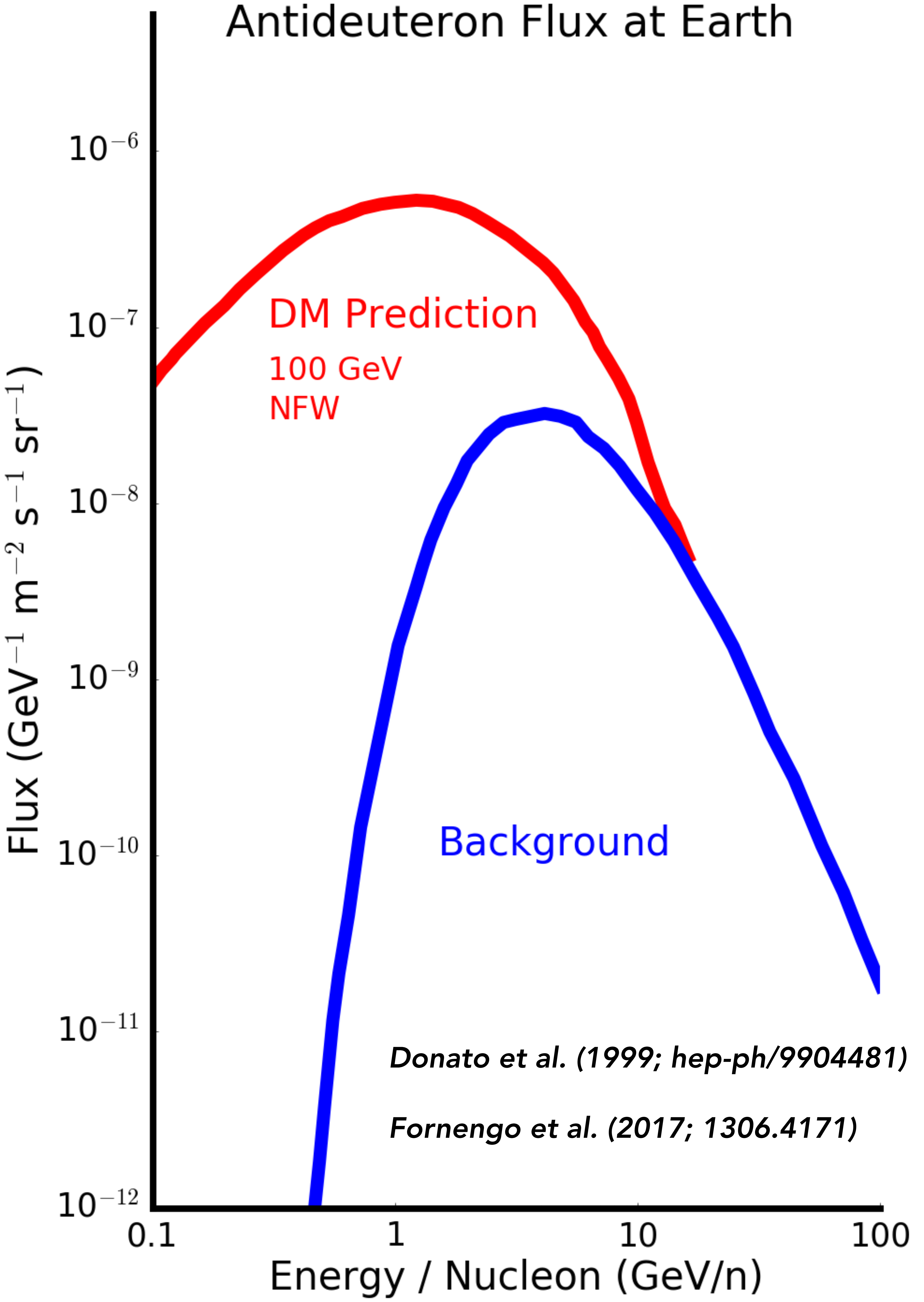
AntiNuclei - A Clean Search Strategy ?



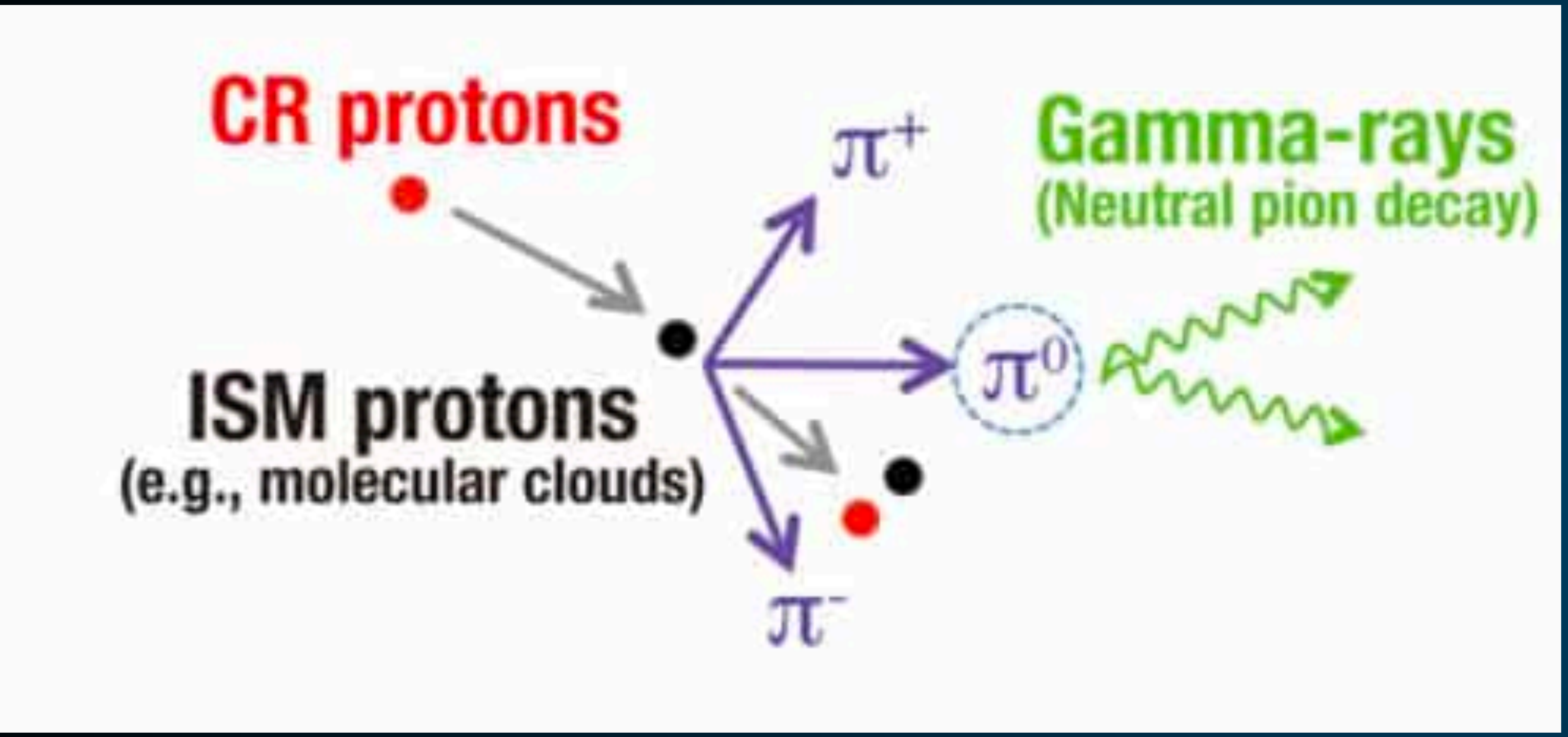
Antinuclei carry away a significant fraction of the total momentum in a particle collision.

Astrophysical Antinuclei - Most be moving relativistically!

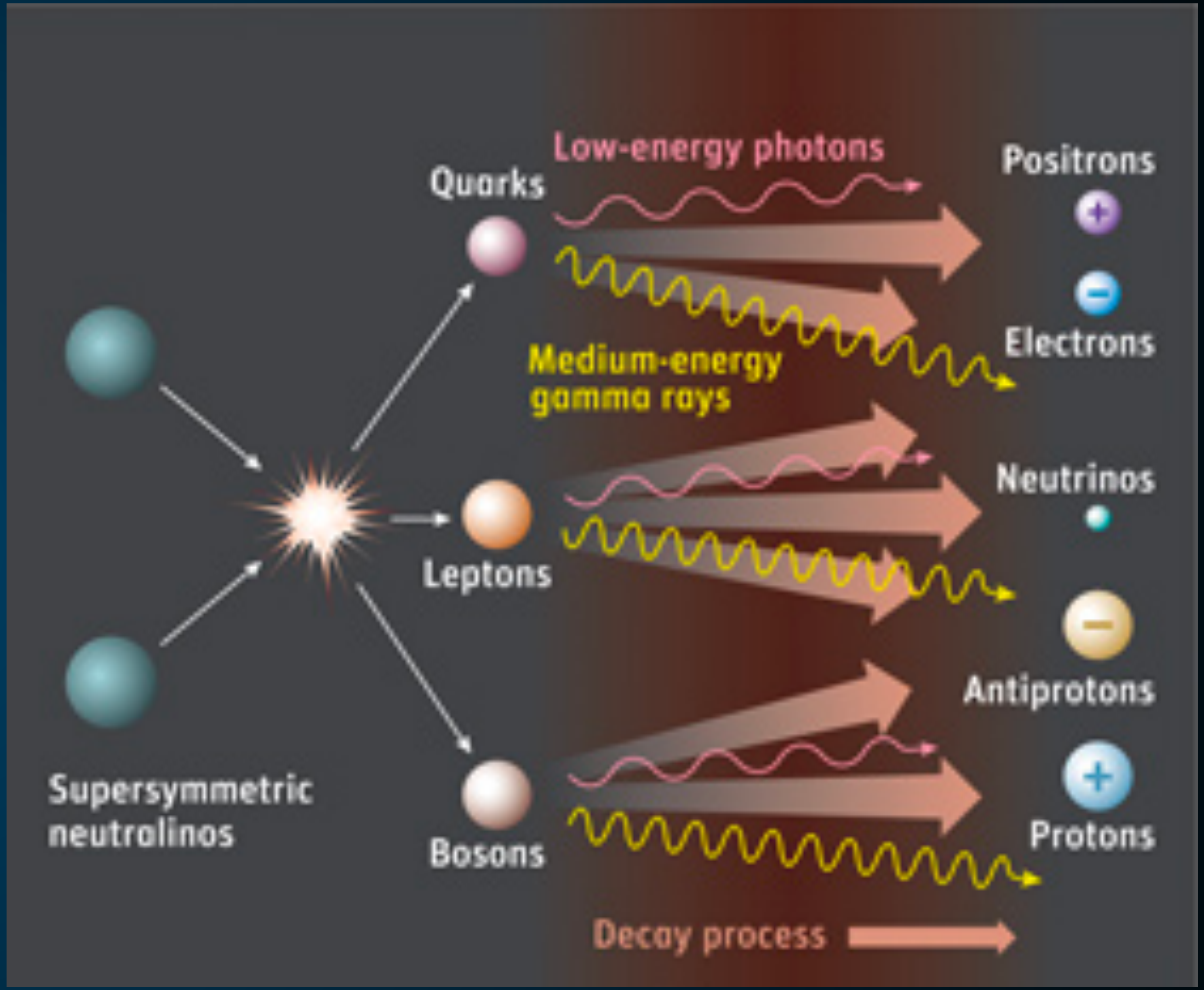
Dark Matter Antinuclei - Can be slow!



AntiNuclei - A Clean Search Strategy ?



Cosmic-Ray Interactions are highly boosted

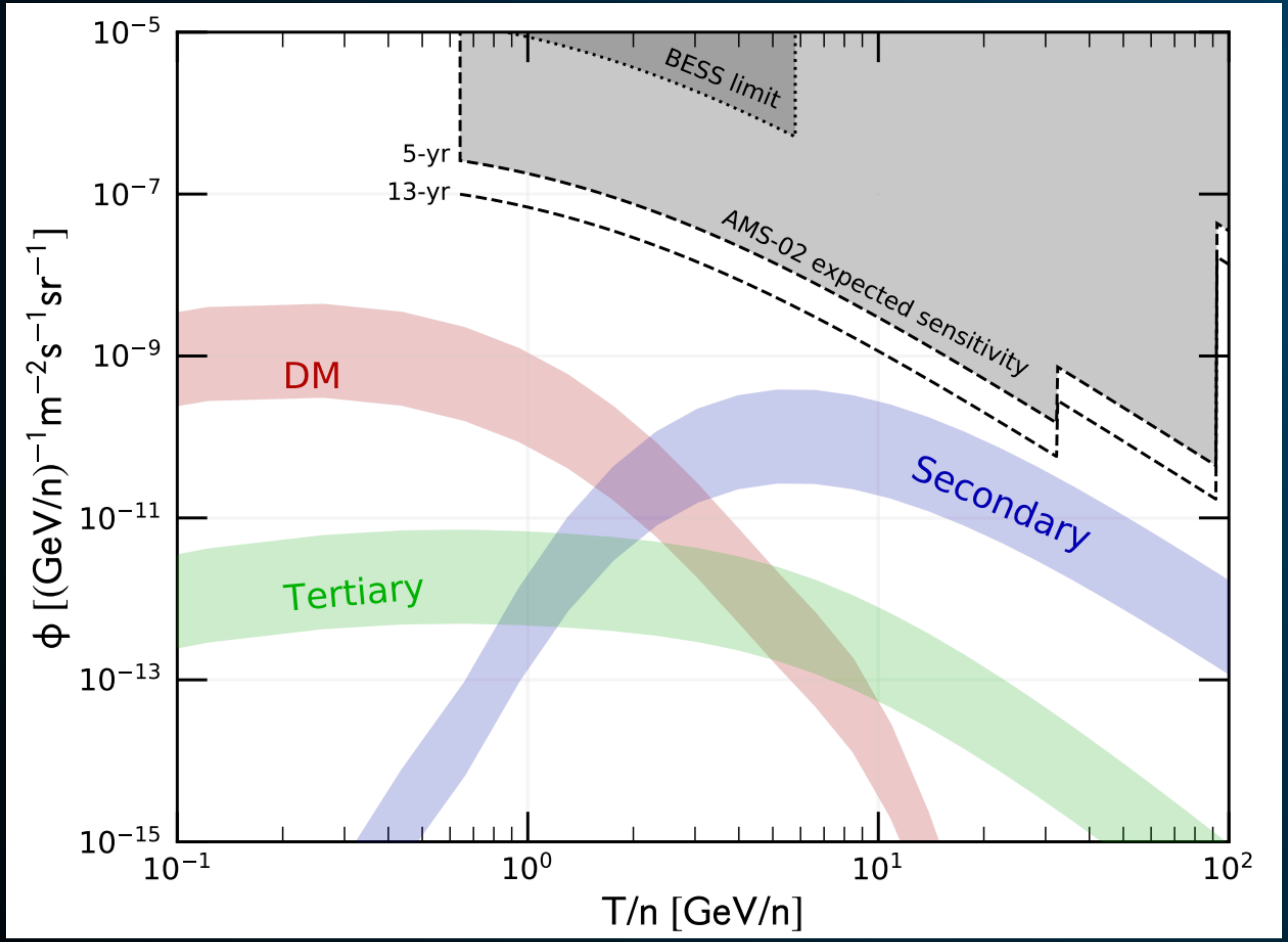


Dark Matter Annihilations Occur in the Galactic Rest Frame

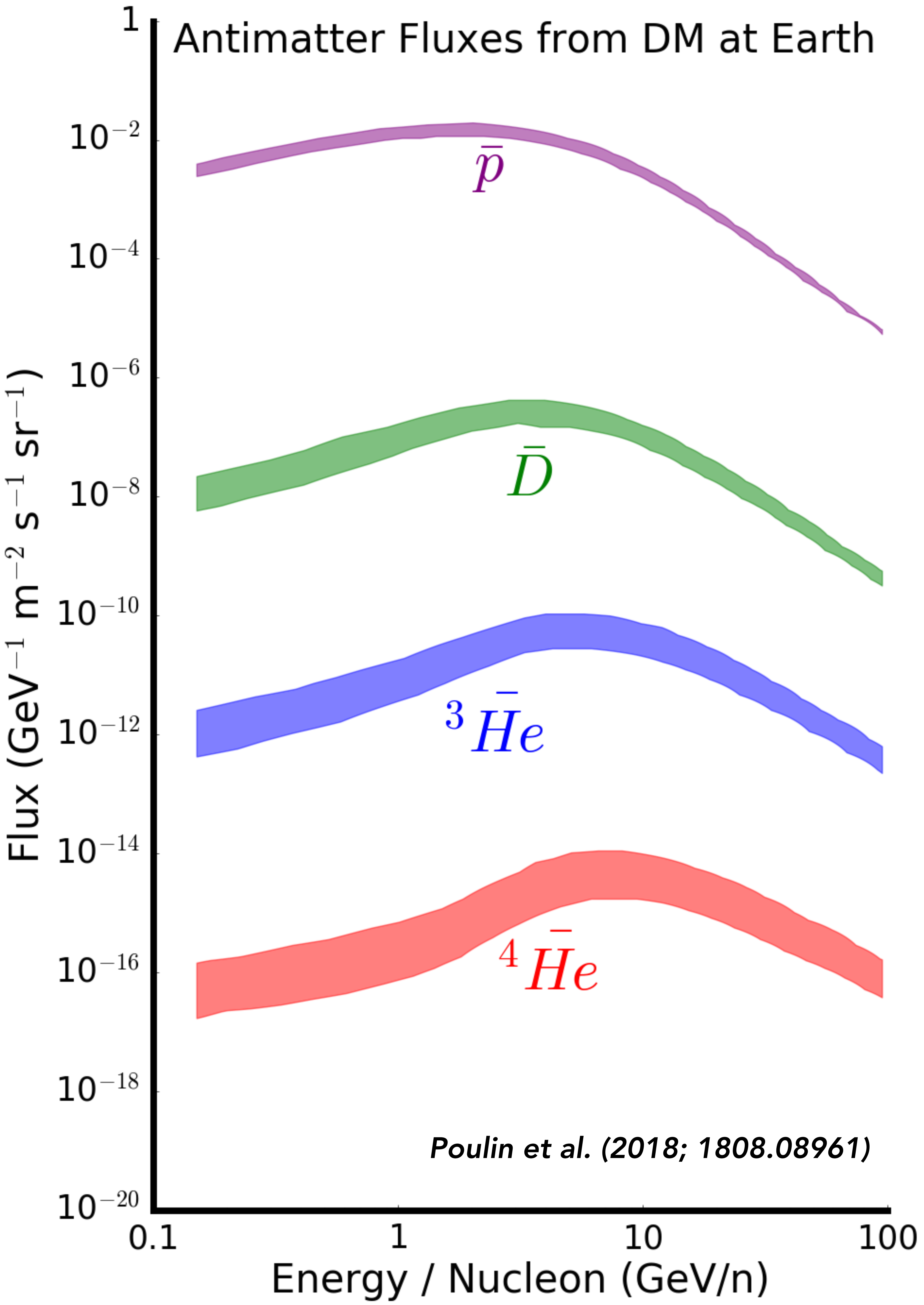
AntiNuclei - A Clean Search Strategy ?

Antihelium background even cleaner than antideuterons

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



Korsmeier (2017; 1711.08465)



To date, we have observed eight events in the mass region from 0 to 10 GeV with Z= –2. All eight events are in the helium mass region.

Currently (having used 50 million core hours to generate 7 times more simulated events than measured events and having found no background events from the simulation), our best evaluation of the probability of the background origin for the eight $\overline{\mathrm{He}}$ events is less than 3×10^{-8}. For the two $^{4}\overline{\mathrm{He}}$ events our best evaluation of the probability (upon completion of the current 100 million core hours of simulation) will be less than 3×10^{-3}.

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

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

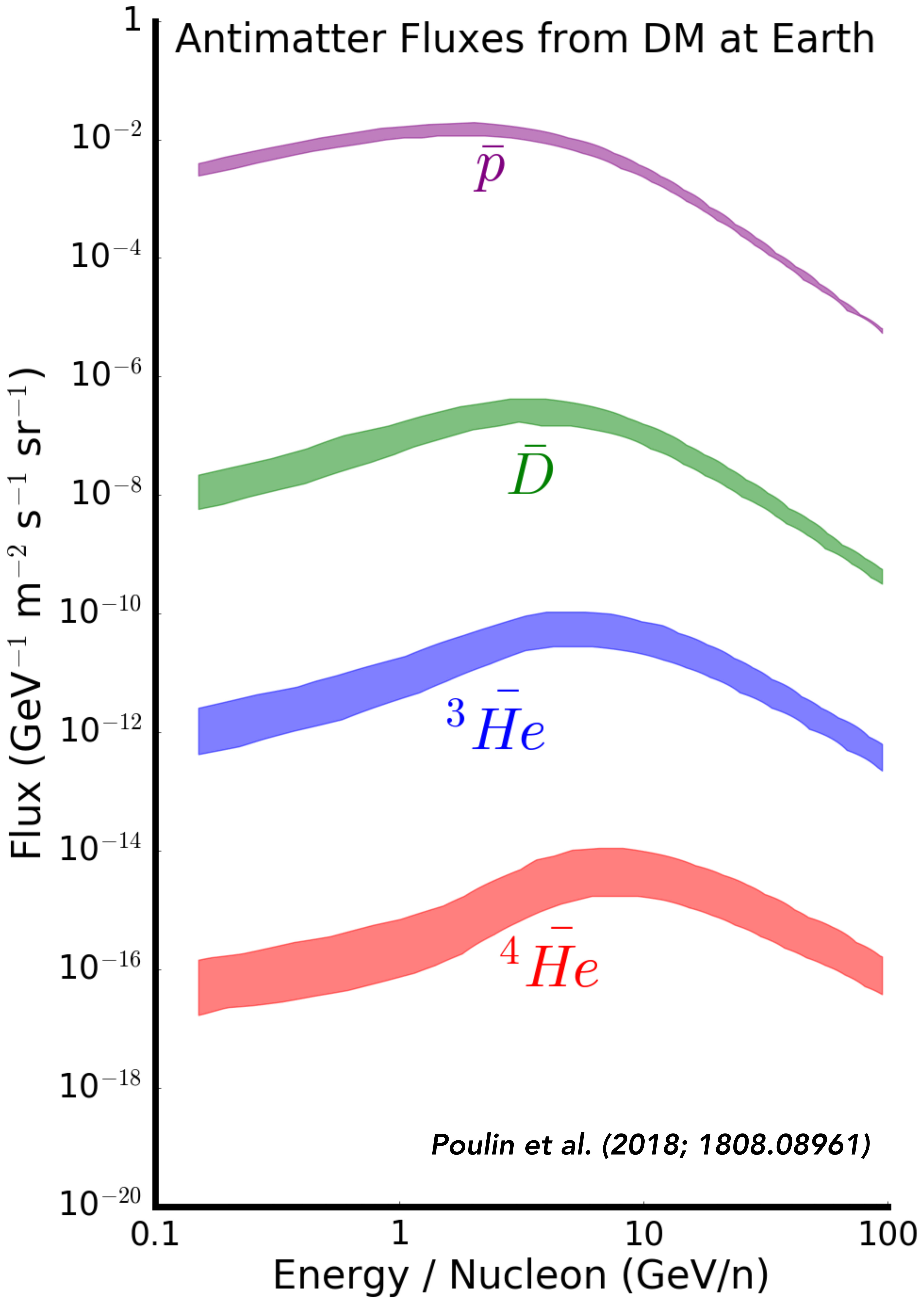
Boosting this Signal to Meet the Challenge?

1.) Hadronic Interaction Rates (should affect Antiprotons)

2.) Coalescence Rates (here)

3.) Astrophysical Acceleration (here)

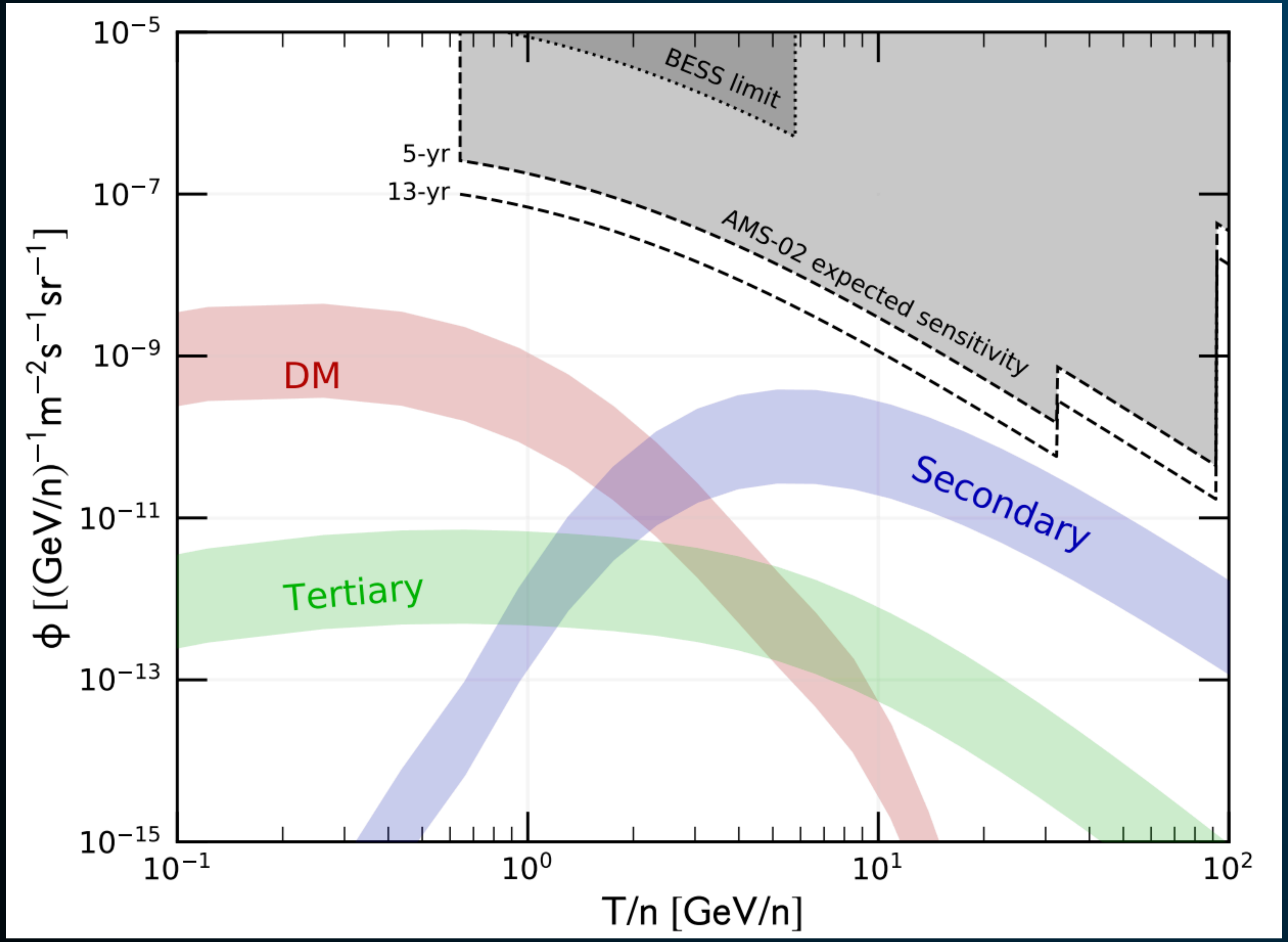
4.) New Channels (Martin Winkler)



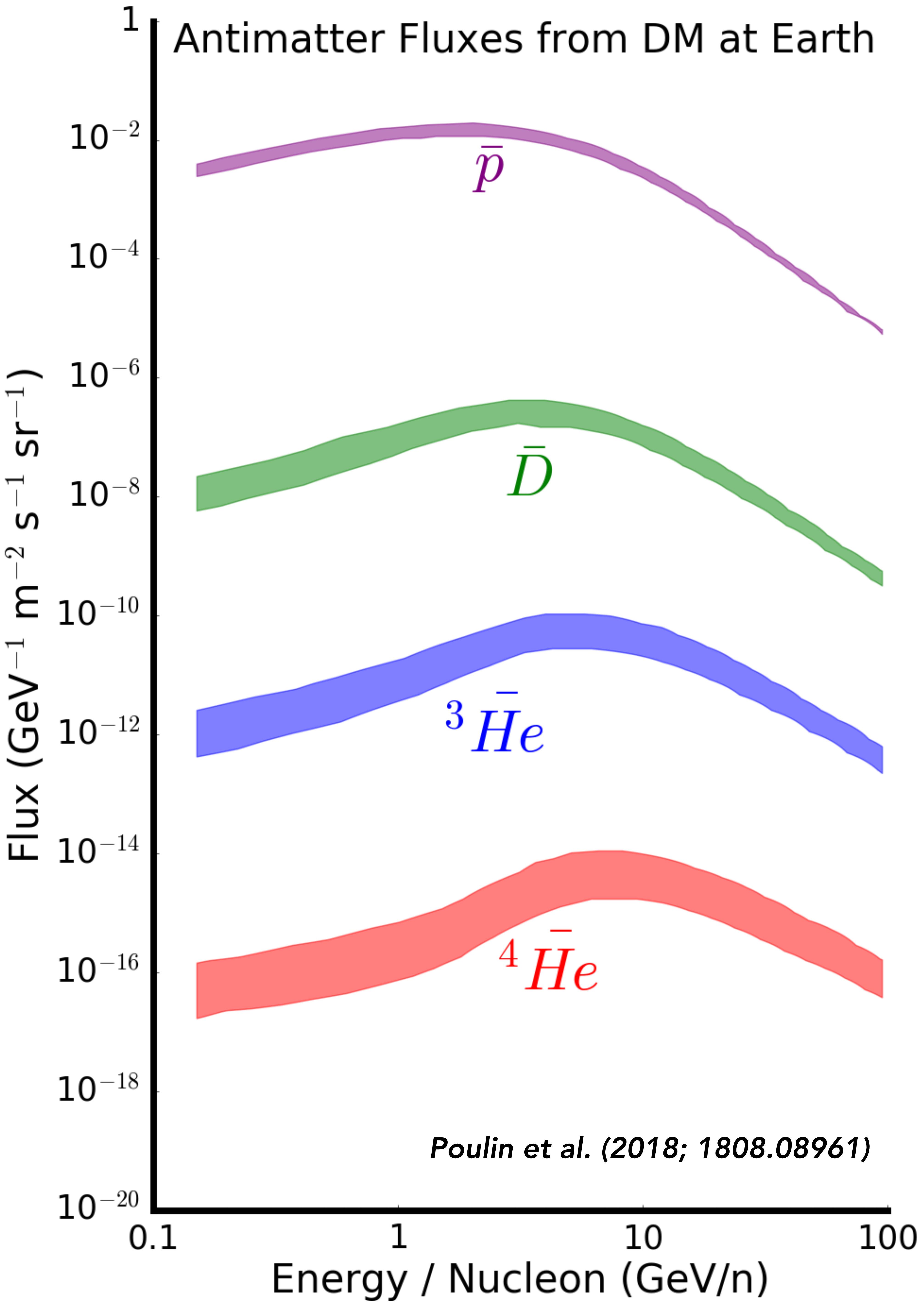
Coalescence Models - Expected Helium Flux

All models of antineutron and anti helium formation will have some assumed coalescence momenta.

Under generic assumptions the anti helium flux is much smaller than that of antineutrons



Korsmeier (2017; 1711.08465)



$$R \propto p_0^{3(A-1)}$$

Antihelium from Dark Matter

Eric Carlson,[1,2] Adam Coogan,[1,2,*] Tim Linden,[1,2,3,4,†] Stefano Profumo,[1,2,‡] Alejandro Ibarra,[5,§] and Sebastian Wild[5,¶]

[1] *Department of Physics, University of California, 1156 High St., Santa Cruz, CA 95064, USA*
[2] *Santa Cruz Institute for Particle Physics, Santa Cruz, CA 95064, USA***
[3] *Department of Physics, University of Chicago, Chicago, IL 60637*
[4] *Kavli Institute for Cosmological Physics, Chicago, IL 60637*
[5] *Physik-Department T30d, Technische Universität München, James-Franck-Straße, 85748 Garching, Germany*

(Dated: March 20, 2014)

Cosmic-ray anti-nuclei provide a promising discovery channel for the indirect detection of particle dark matter. Hadron showers produced by the pair-annihilation or decay of Galactic dark matter generate anti-nucleons which can in turn form light anti-nuclei. Previous studies have only focused on the spectrum and flux of low energy antideuterons which, although very rarely, are occasionally also produced by cosmic-ray spallation. Heavier elements ($A \geq 3$) have instead entirely negligible astrophysical background and a primary yield from dark matter which could be detectable by future experiments. Using a Monte Carlo event generator and an event-by-event phase space analysis, we compute, for the first time, the production spectrum of $^3\overline{\mathrm{He}}$ and $^3\overline{\mathrm{H}}$ for dark matter annihilating or decaying to $b\bar{b}$ and W^+W^- final states. We then employ a semi-analytic model of interstellar and heliospheric propagation to calculate the $^3\overline{\mathrm{He}}$ flux as well as to provide tools to relate the anti-helium spectrum corresponding to an arbitrary antideuteron spectrum. Finally, we discuss prospects for current and future experiments, including GAPS and AMS-02.

I. INTRODUCTION

Within the paradigm of Weakly Interacting Massive Particle (WIMP) dark matter, the pair-annihilation or decay of dark matter particles generically yields high-energy matter and antimatter cosmic rays. While the former are usually buried under large fluxes of cosmic rays of more ordinary astrophysical origin, antimatter is rare enough that a signal from dark matter might be distinguishable and detectable with the current generation of experiments. While astrophysical accelerators of high-energy positrons such as pulsars' magnetospheres are well-known, observations of cosmic anti-nuclei might

cal backgrounds often prohibit the clean disentanglement of exotic sources, a recent analysis projects that the 1-year AMS-02 data will produce robust constraints on WIMP annihilation to heavy quarks below the thermal-relic cross-section for dark matter masses $30 \leq m_\chi \leq 200$ GeV [10].

In addition to antiprotons, Ref. [13] proposed new physics searches using heavier anti-nuclei such as antideuteron ($\overline{\mathrm{D}}$), antihelium-3 ($^3\overline{\mathrm{He}}$), or antitritium ($^3\overline{\mathrm{H}}$) forming from hadronic neutralino annihilation products. Although such production is of course highly correlated with the antiproton spectrum, the secondary astrophysical background decreases much more rapidly than the

Key Insight - Coalescence Momentum for Antihelium Should Be Larger

While particle coalescence is hard to measure, the inverse process (fragmentation) is easier to measure. Helium's binding energy significantly exceeds deuteriums

$$p_0^{A=3} = \sqrt{B_{^3\overline{He}}/B_{\bar{D}}}\; p_0^{A=2} = 0.357 \pm 0.059 \text{ GeV/c}.$$

Can also use Heavy ion results (Berkeley Collider), which provide a lower-measurement of the coalescence momentum at a specific particle energy:

$$p_0^{A=3} = 1.28\; p_0^{A=2} = 0.246 \pm 0.038 \text{ GeV/c}.$$

Key Insight - Coalescence Momentum for Antihelium Should Be Larger

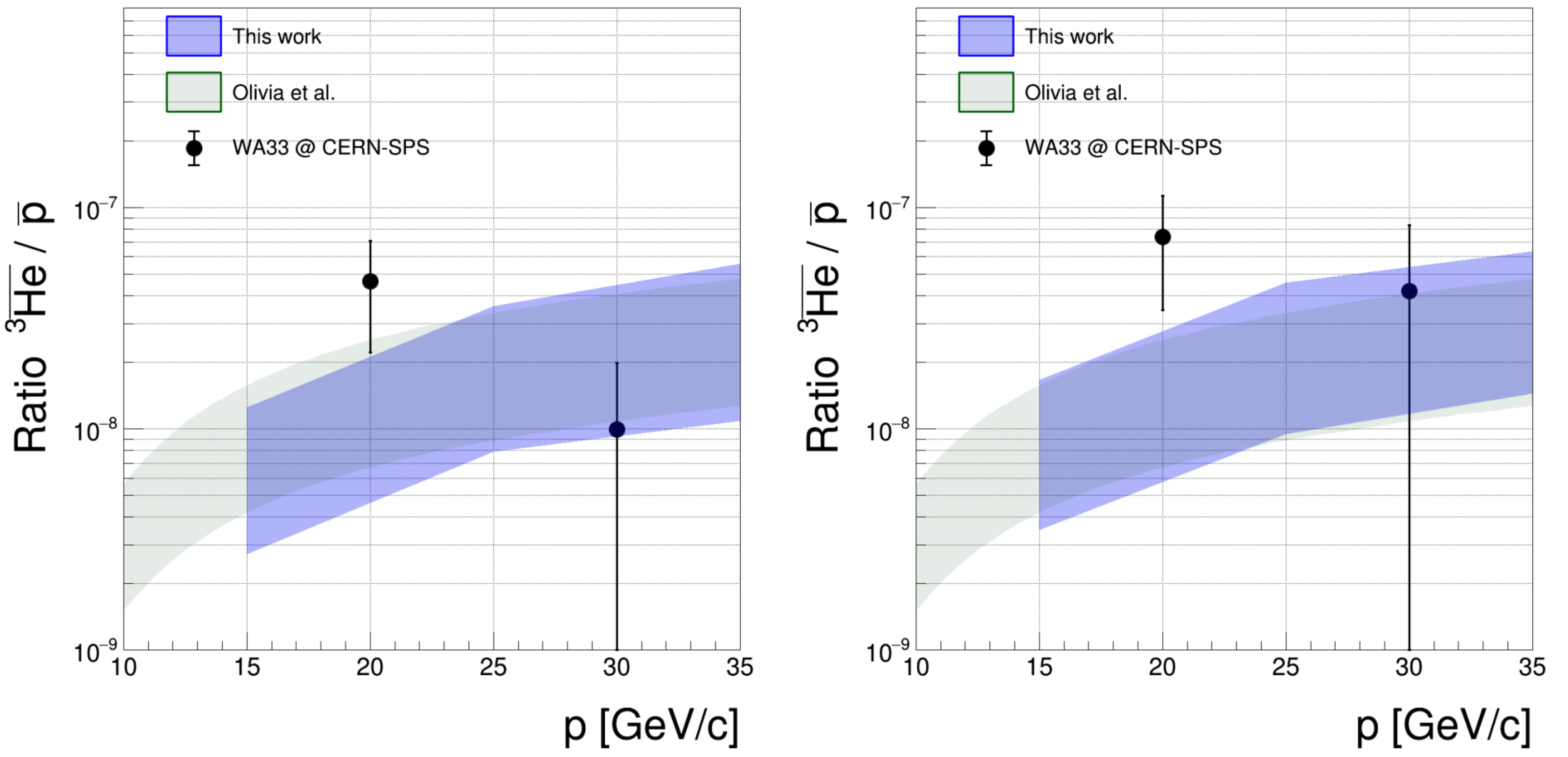
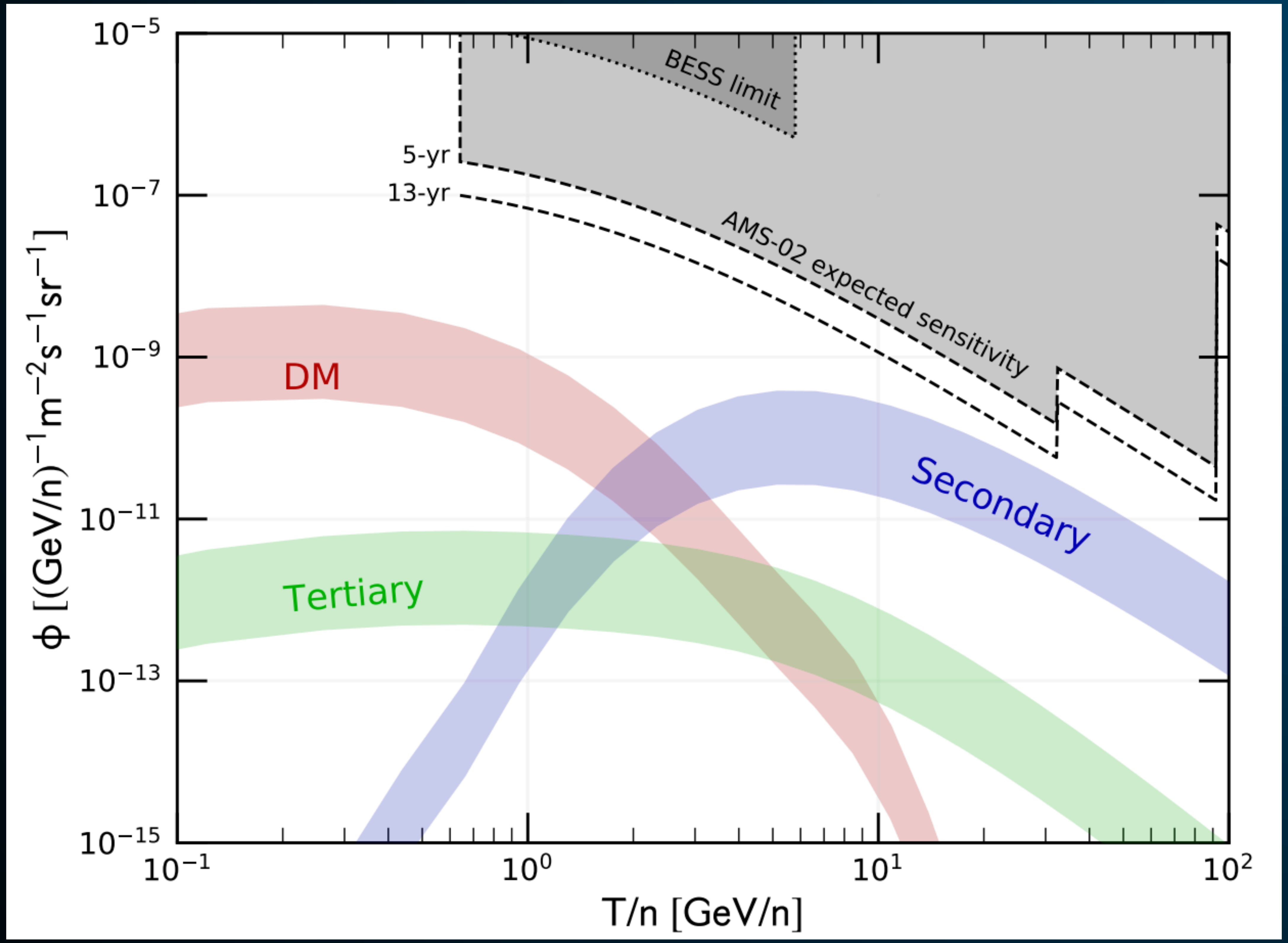


FIG. 4. The invariant production cross section ratio $^3\overline{\mathrm{He}}/\overline{p}$ as function of momentum p [GeV/c] in the laboratory frame for (left) p-Be at $p_{\mathrm{lab}} = 200\,\mathrm{GeV}/c$ and (right) p–Al at $p_{\mathrm{lab}} = 200\,\mathrm{GeV}/c$. The uncertainty bands for this work were estimated by varying the coalescence parameter from $p_{0,G}$ ($59\,\mathrm{MeV}/c$) to 130% of $p_{0,G}$ ($77\,\mathrm{MeV}/c$).

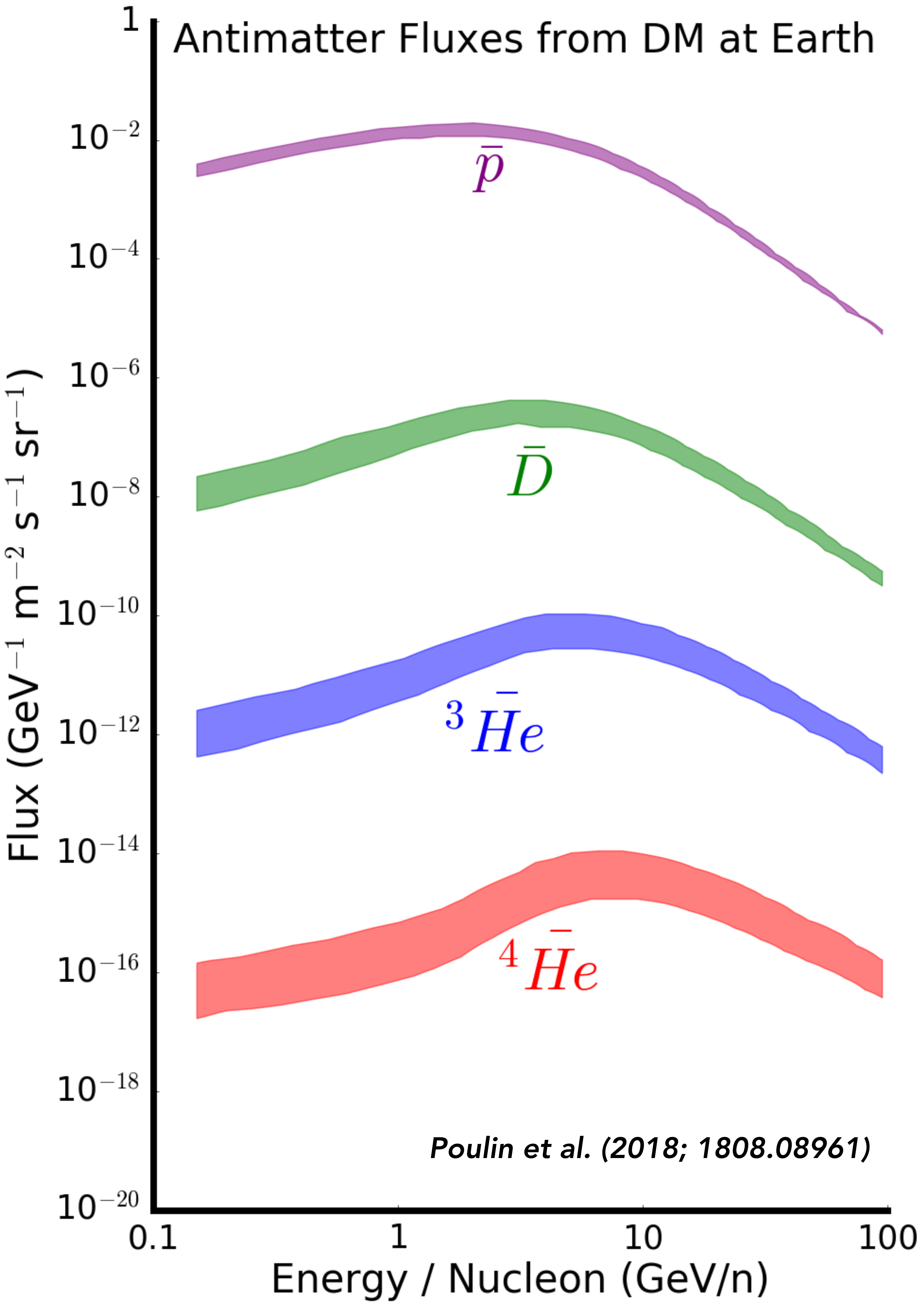
Shukla et al. (2006.12707)

Coalescence Models - Expected Helium Flux

Using more realistic estimates for the anti helium coalescence momentum produces a boosted anti helium flux, especially at low energies.



Korsmeier (2017; 1711.08465)



Coalescence Models - Expected Helium Flux

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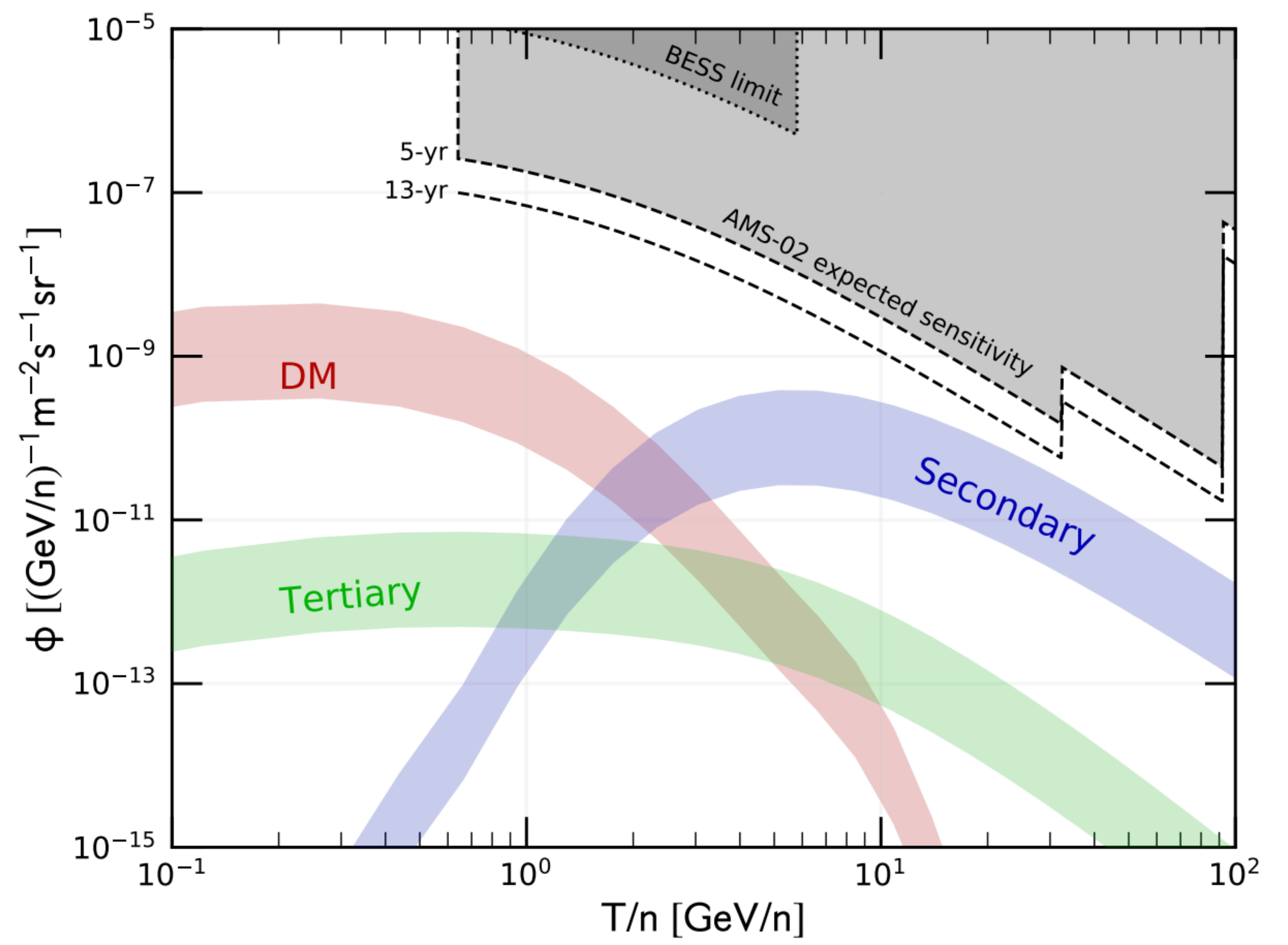
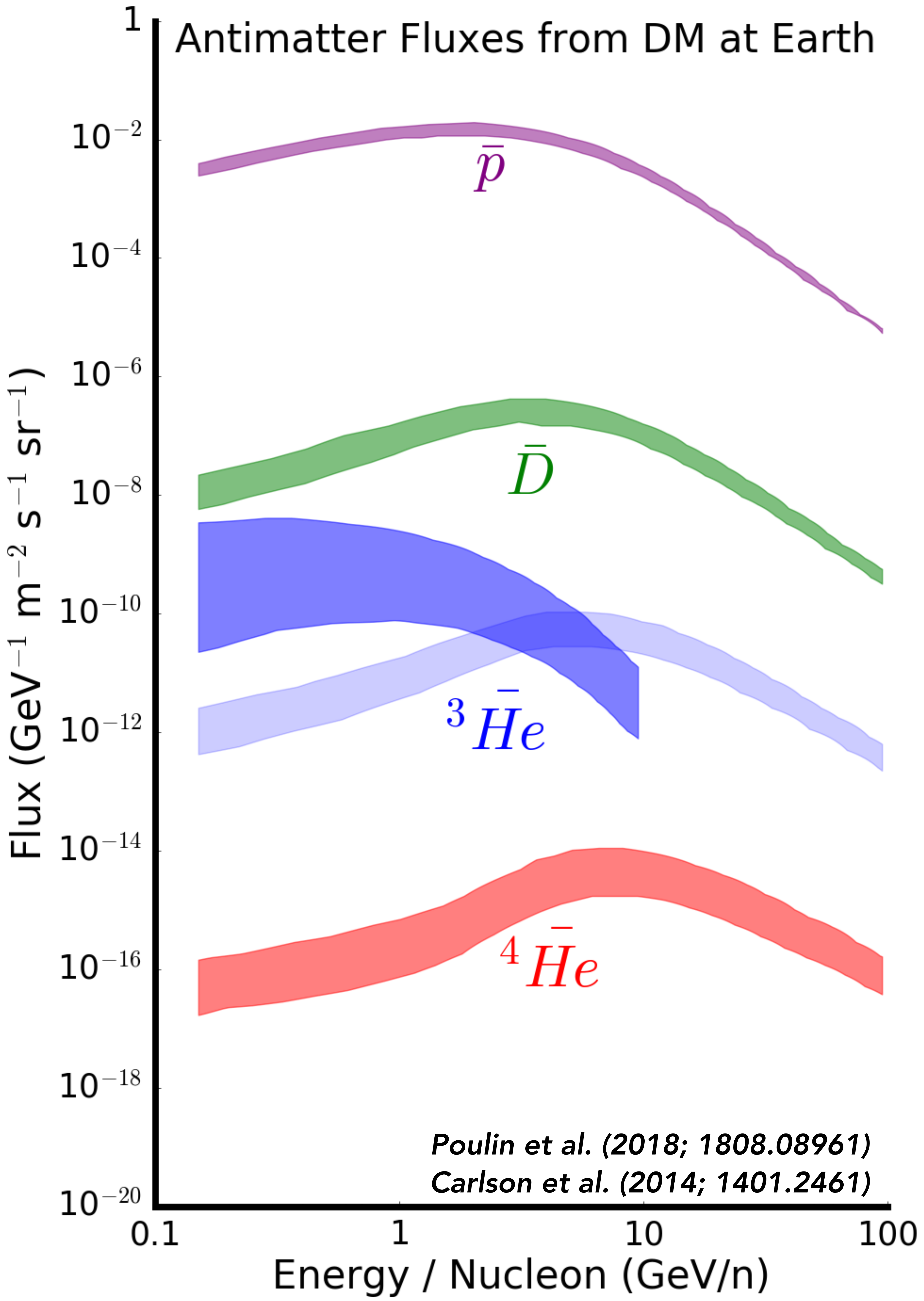
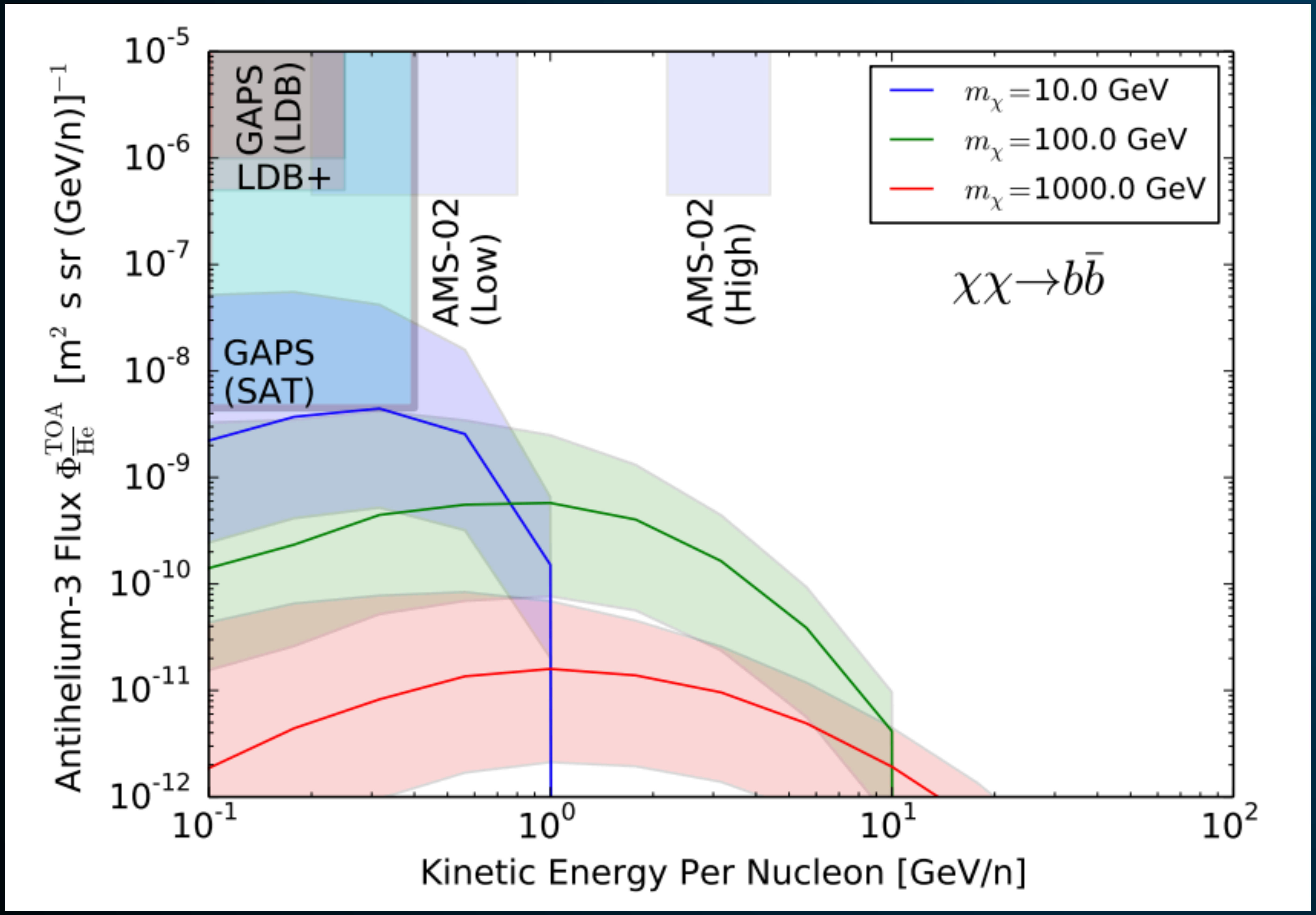


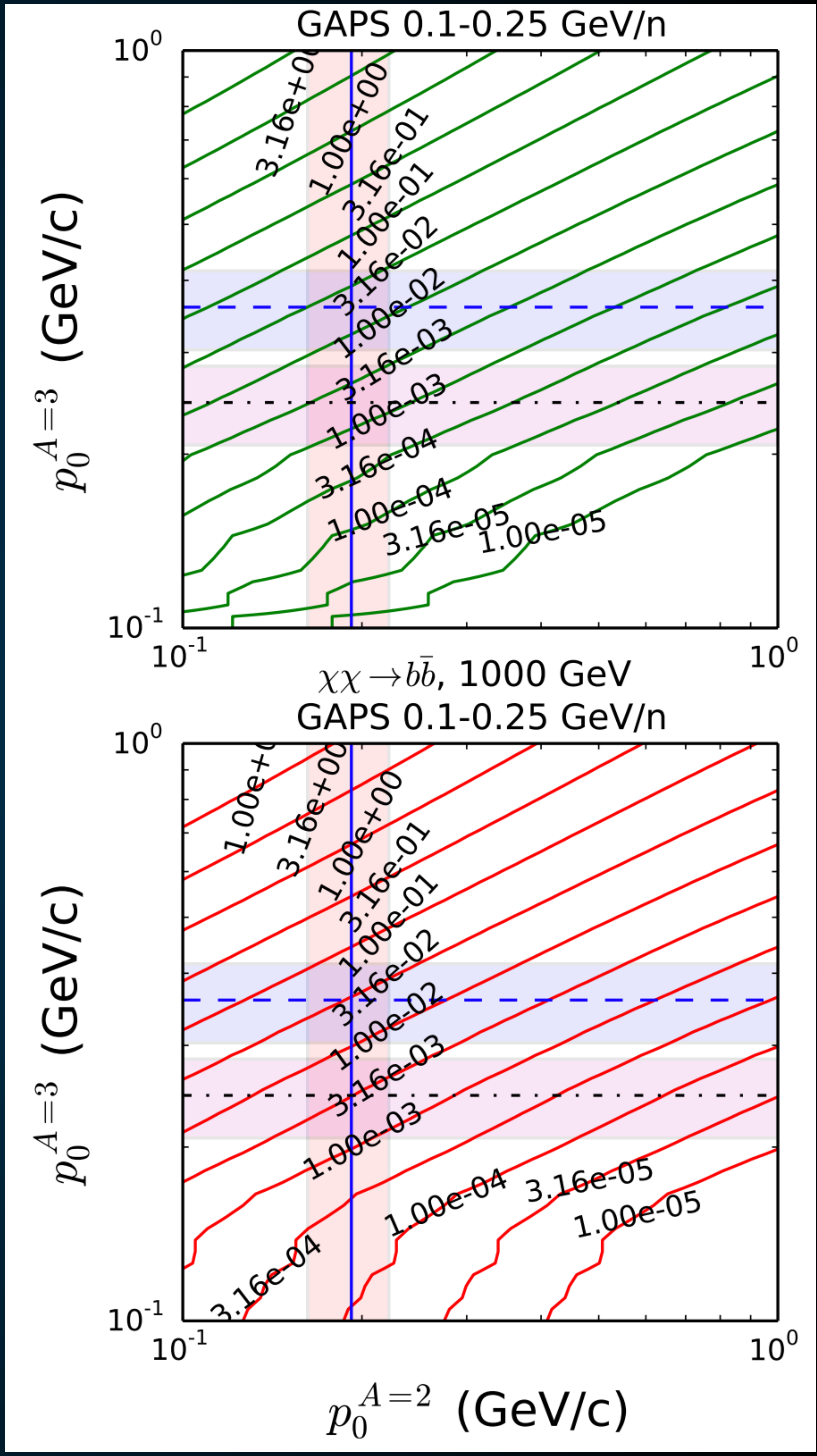
Korsmeier (2017; 1711.08465)



Coalescence Models - Expected Helium Flux

Increasing the coalescence momentum can greatly enhance the





Carlson et al. (2014; 1401.2461)

Coalescence Models - Expected Helium Flux

Anti-helium from Dark Matter annihilations

Marco Cirelli [a], **Nicolao Fornengo** [b,c],
Marco Taoso [a], **Andrea Vittino** [a,b,c]

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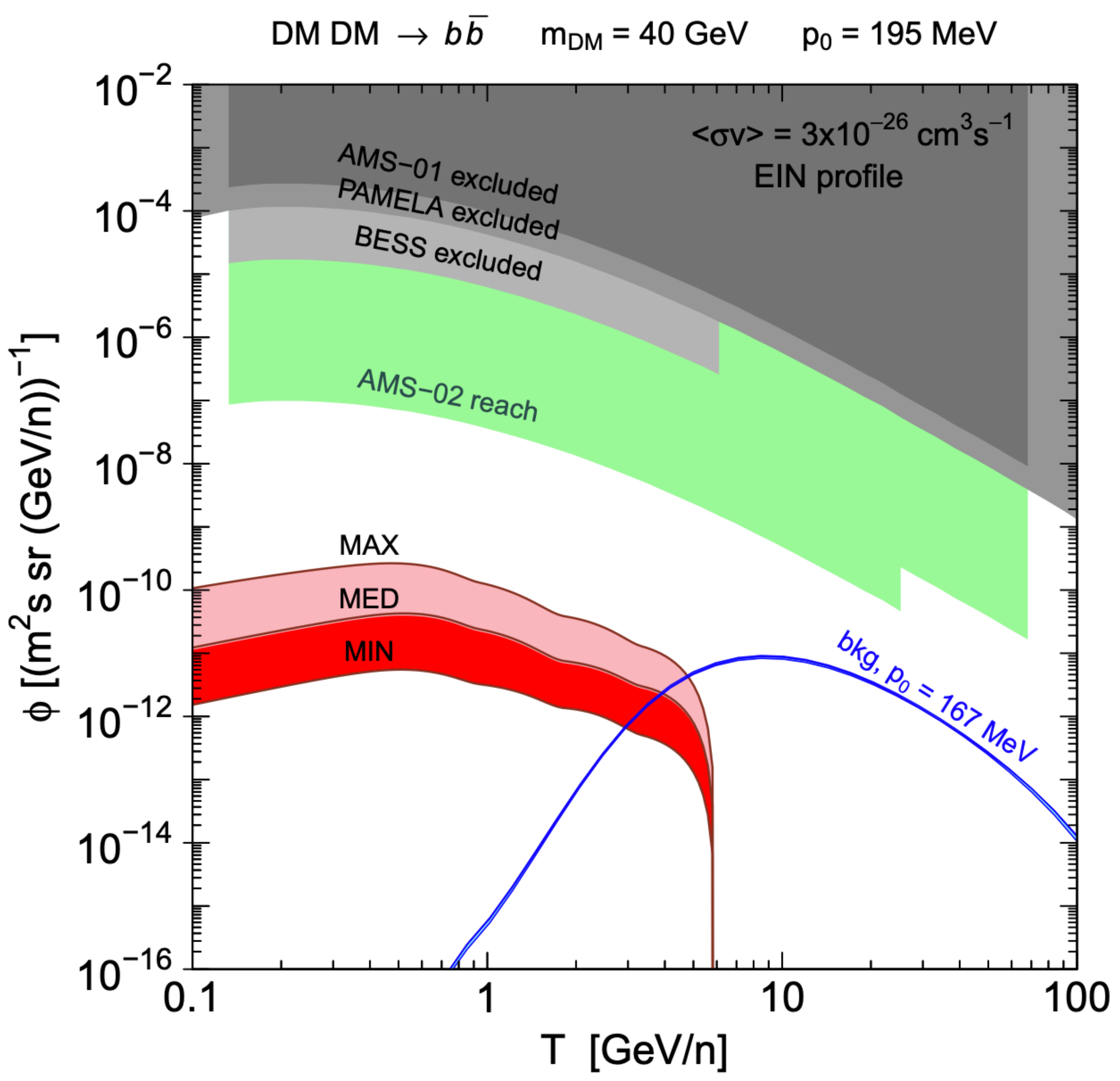
[b] *Department of Physics, University of Torino, via P. Giuria 1, I-10125 Torino, Italy*

[c] *INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Torino, via P. Giuria 1, I-10125 Torino, Italy*

arXiv:1401.4017v3 [hep-ph] 24 Aug 2016

Abstract

Galactic Dark Matter (DM) annihilations can produce cosmic-ray anti-nuclei via the nuclear coalescence of the anti-protons and anti-neutrons originated directly from the annihilation process. Since anti-deuterons have been shown to offer a distinctive DM signal, with potentially good prospects for detection in large portions of the DM-particle parameter space, we explore here the production of heavier anti-nuclei, specifically anti-helium. Even more than for anti-deuterons, the DM-produced anti-He flux can be mostly prominent over the astrophysical anti-He background at low kinetic energies, typically below 3-5 GeV/n. However, the larger number of anti-nucleons involved in the formation process makes the anti-He flux extremely small. We therefore explore, for a few DM benchmark cases, whether the yield is sufficient to allow for anti-He detection in current-generation experiments, such as AMS-02. We account for the uncertainties due to the propagation in the Galaxy and to the uncertain details of the coalescence process, and we consider the constraints already imposed by anti-proton searches. We find that only for very optimistic configurations might it be possible to achieve detection with current generation detectors. We estimate that, in more realistic configurations, an increase in experimental sensitivity at low kinetic energies of about a factor of 500-1000 would allow to start probing DM through the rare cosmic anti-He production.



Problem 2: The AMS-02 Antihelium Excess is not at low energies

1.) Changing the coalescence model primarily affects the Helium yield when the total center of mass energy is small.

2.) Very good for predicted rates with GAPS, or low-energy AMS-02 observations.

3.) But AMS-02 antihelium are (generally reported) at energies of ~10 GeV/n.

Astrophysical Enhancements!

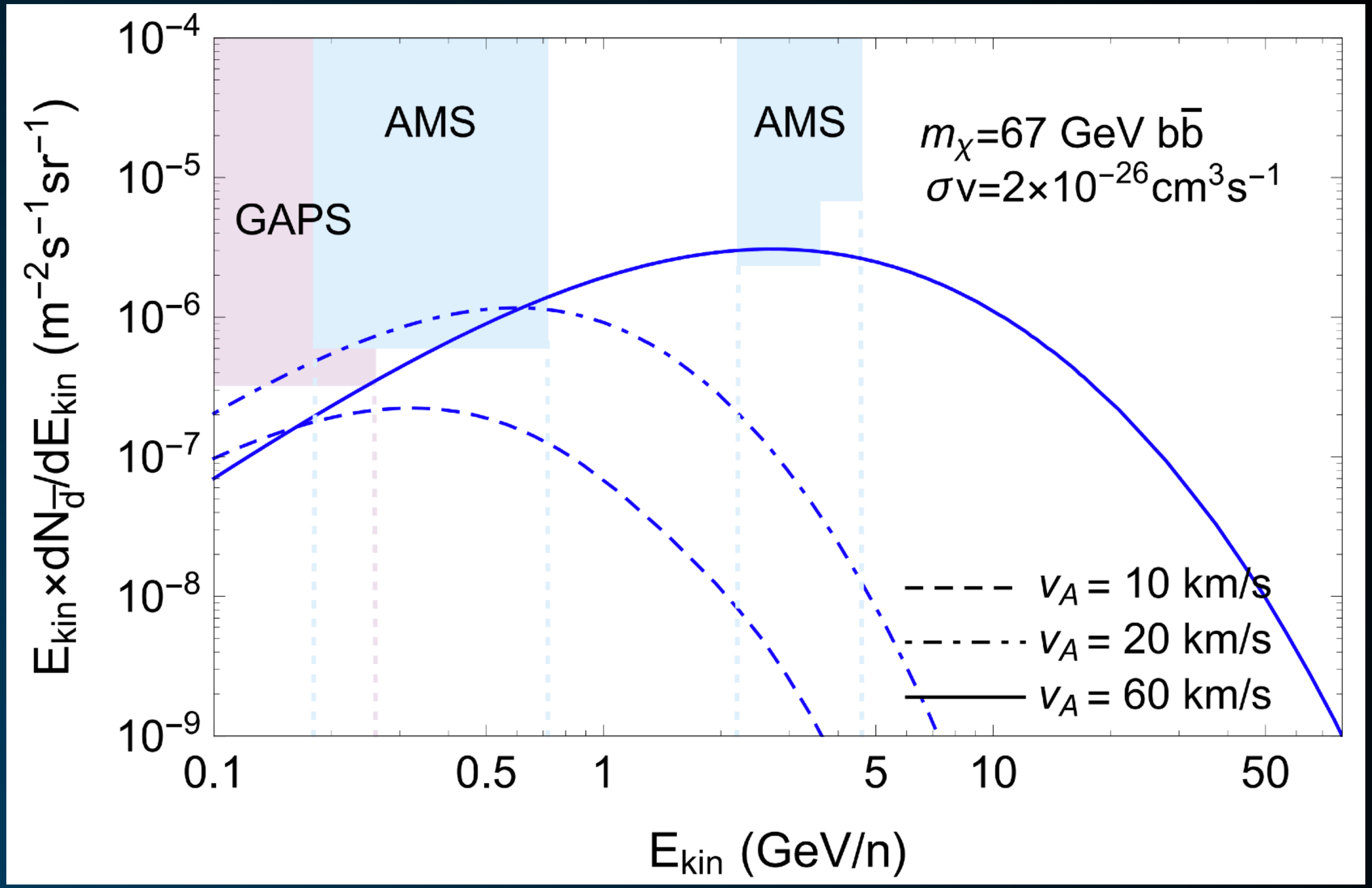
The current event rates depend on the detector sensitivity to anti-Helium.

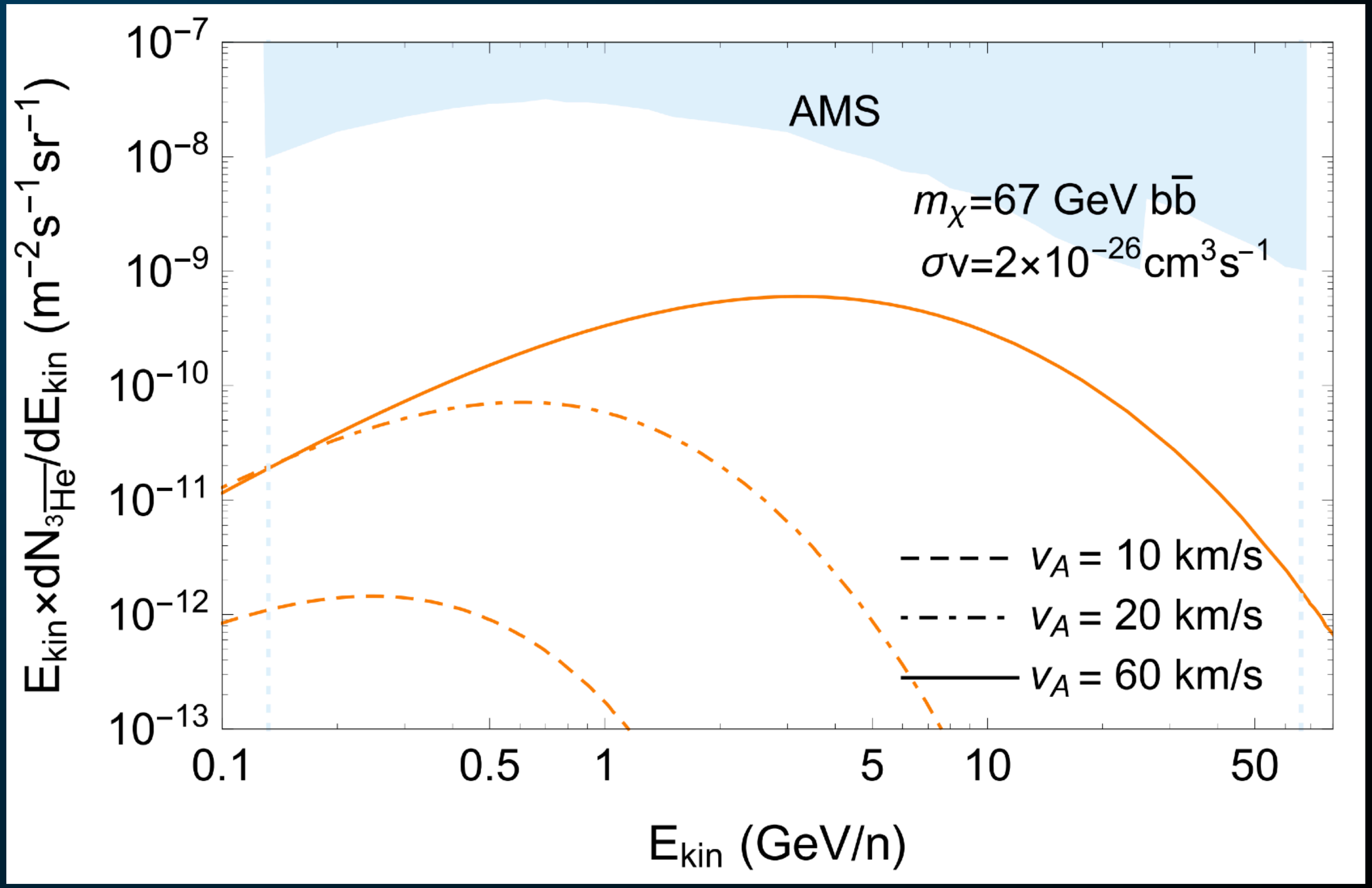
We lose many events because most anti-He are produced at energies that are too small to be detected.

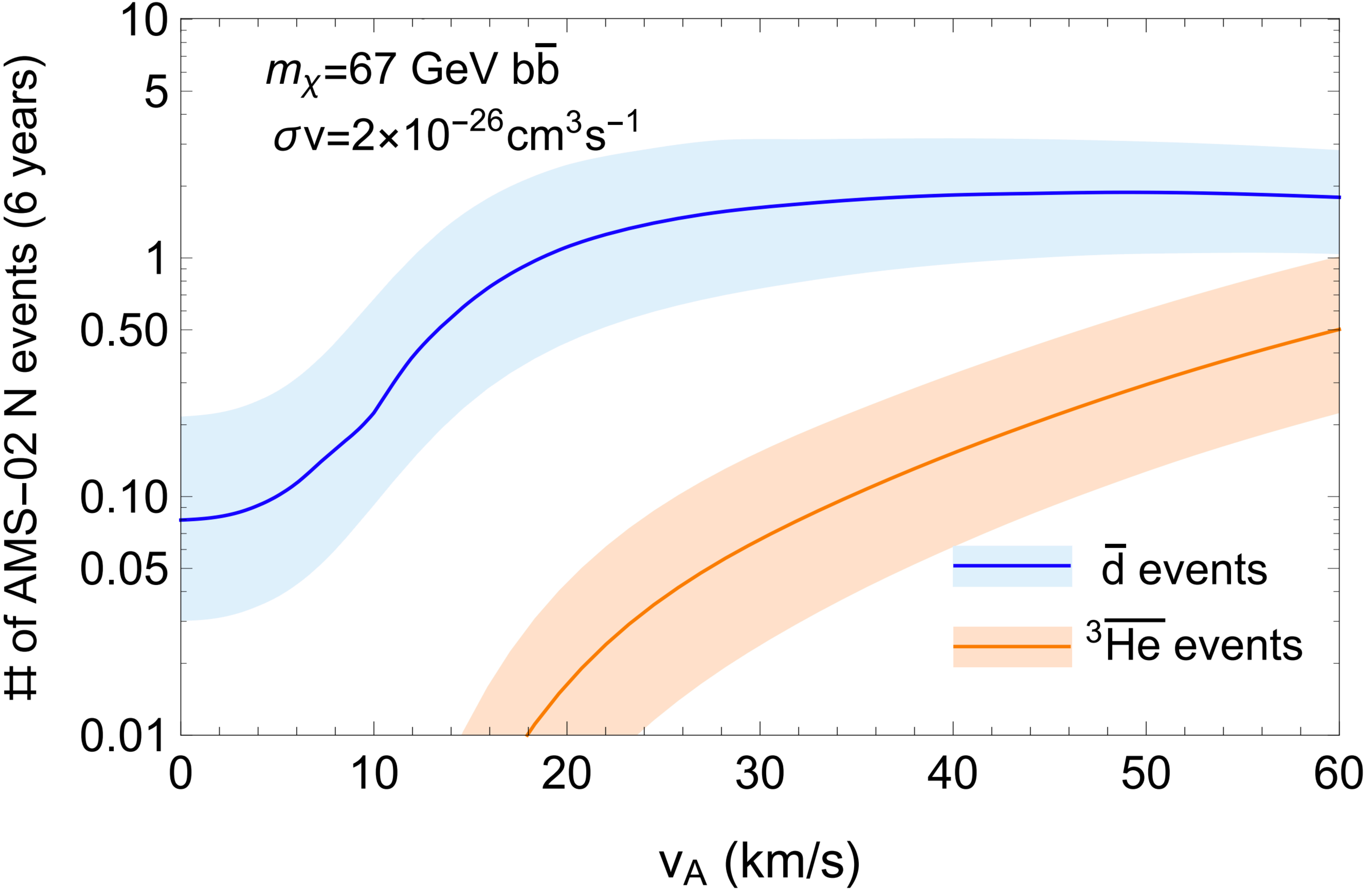
Use re-acceleration to boost the anti-He energies into the detectable range!

$$D_{pp}(R) = \frac{4}{3\delta(2-\delta)(4-\delta)(2+\delta)} \frac{R^2 v_A^2}{D_{xx}(R)}$$

Cholis, Linden, Hooper (2020; 2001.08749)





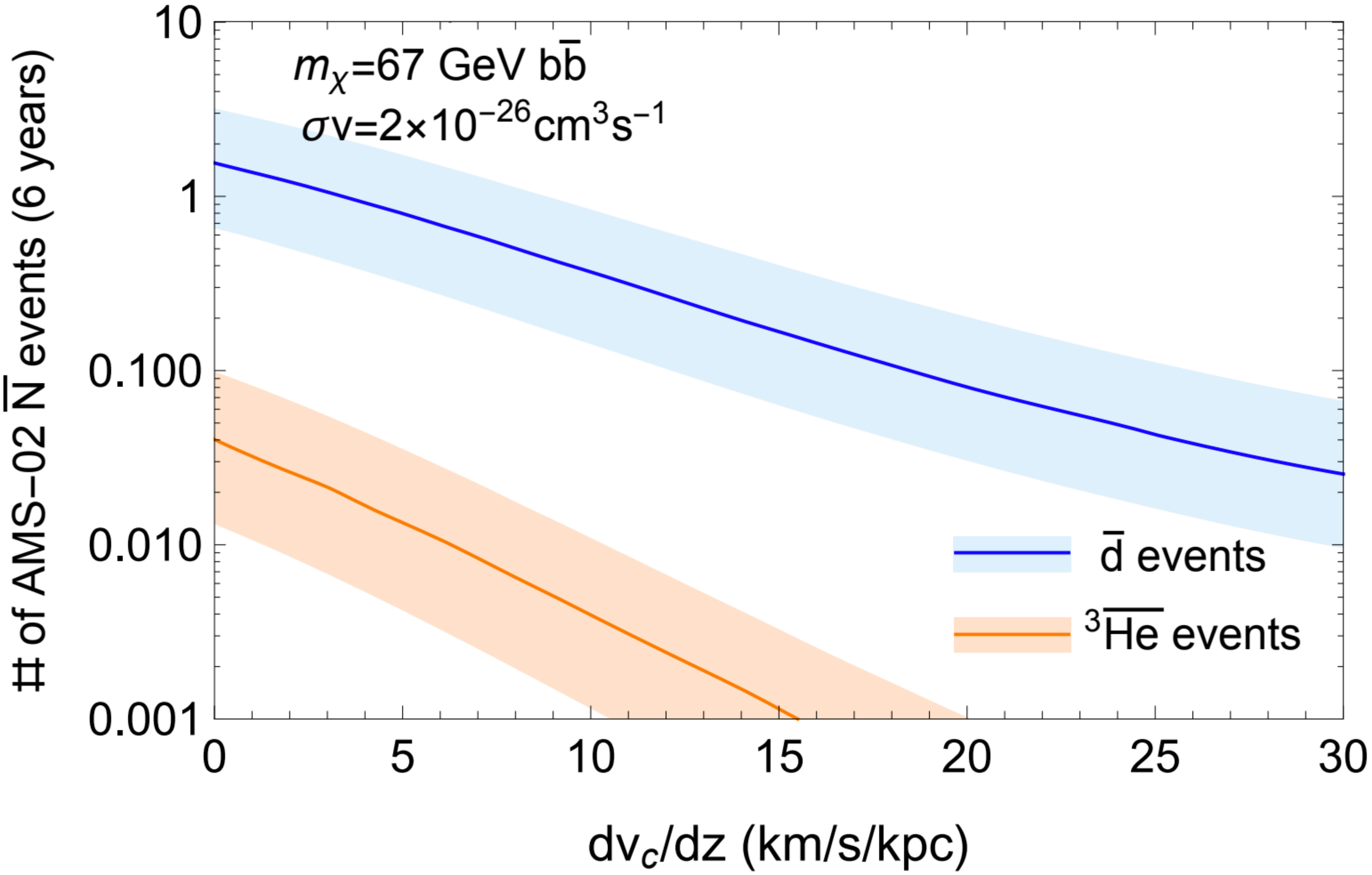


m_χ=67 GeV $b\bar{b}$
$\sigma v = 2\times10^{-26}\,\mathrm{cm^3 s^{-1}}$
$\bar{d}$ events
$^3\overline{He}$ events
# of AMS−02 $\overline{N}$ events (6 years)
v_A (km/s)
10
5
1
0.50
0.10
0.05
0.01
0
10
20
30
40
50
60

Why is this so Powerful for Anti-Helium?

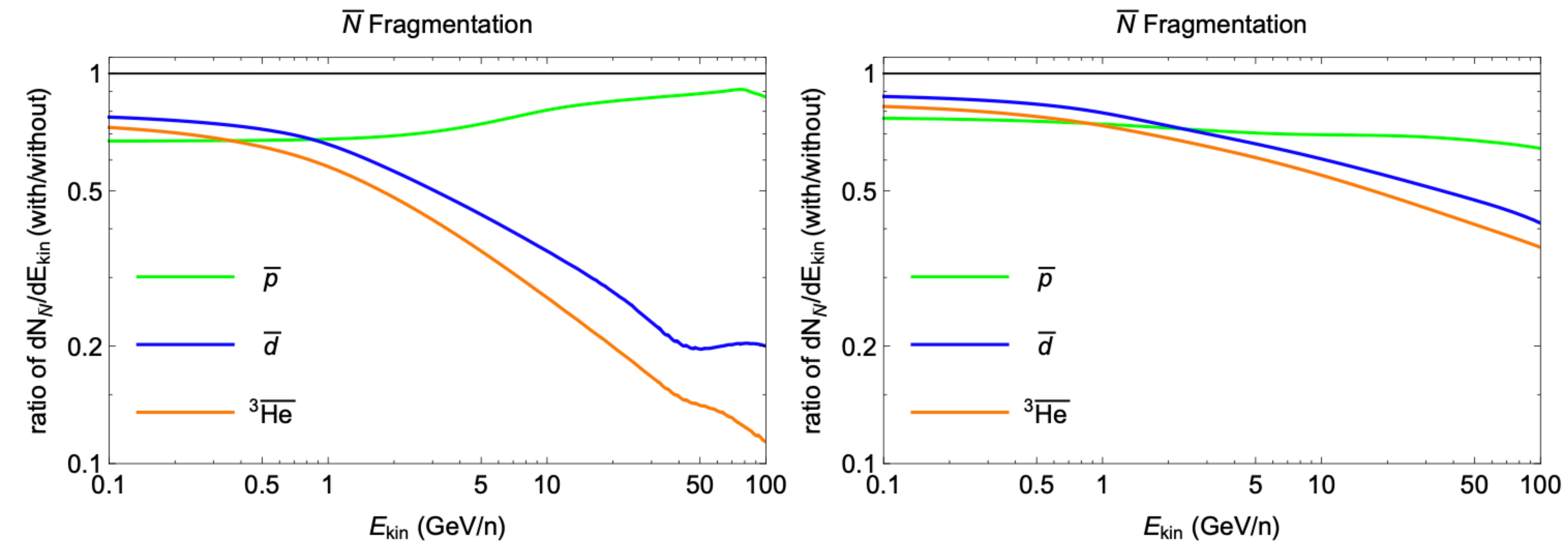
- <u>Compared to Antiprotons</u> - Antihelium spectrum is strongly peaked at low-energies. Momentum diffusion primarily pushes anti helium to higher energies. Antiprotons have a power-law spectrum and momentum is distributed in both directions.

- <u>Compared to Anti-deuterons</u> - Charge/Mass ratio is higher for 3He, leads to more significant diffusion in momentum space.

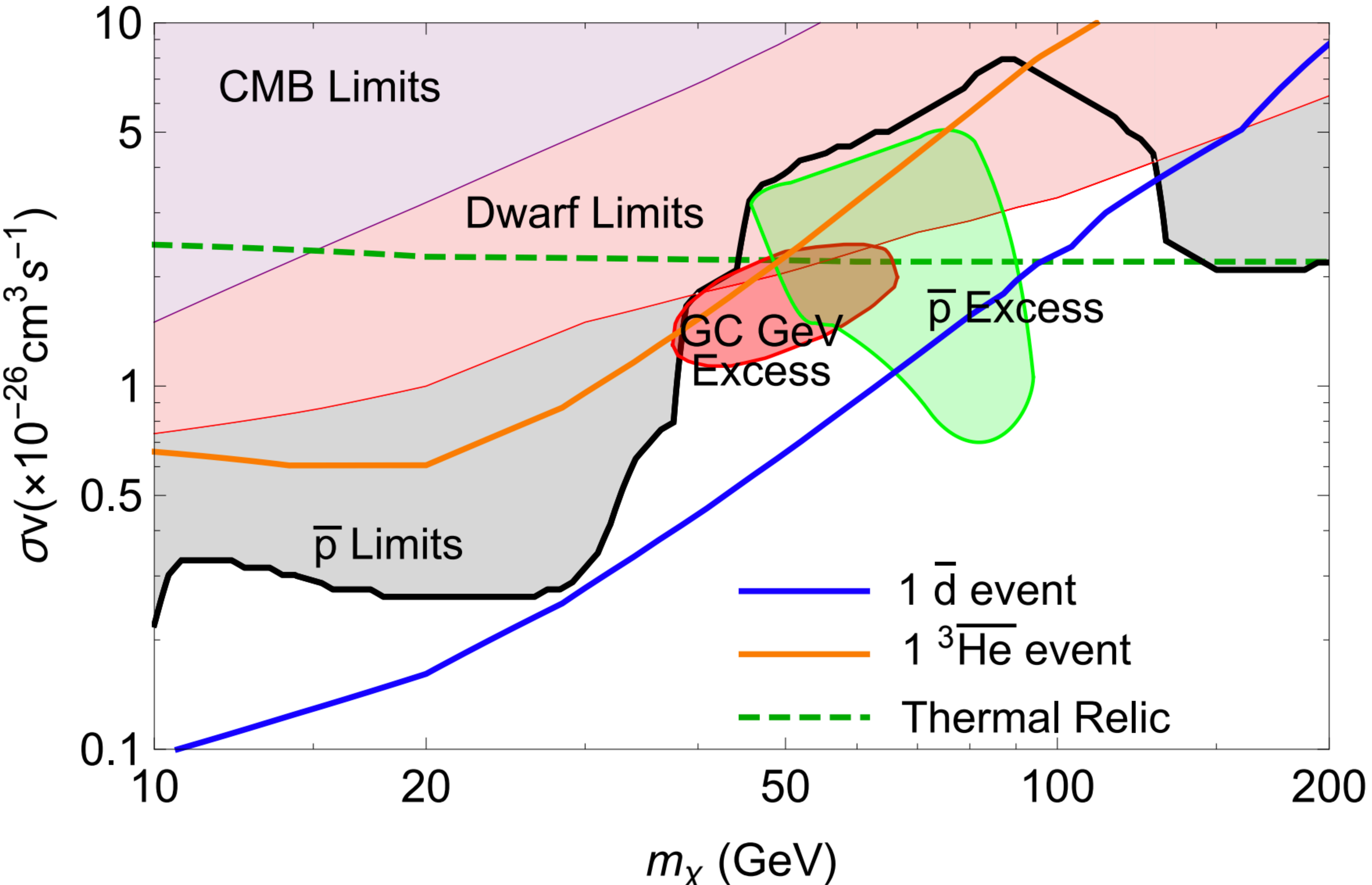


m_χ=67 GeV $b\bar{b}$
$\sigma v=2\times10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$
# of AMS−02 $\overline{N}$ events (6 years)
10
1
0.100
0.010
0.001
0
5
10
15
20
25
30
$\bar{d}$ events
$^3\overline{He}$ events
dv_c/dz (km/s/kpc)

Fragmentation is a Second Competing Effect



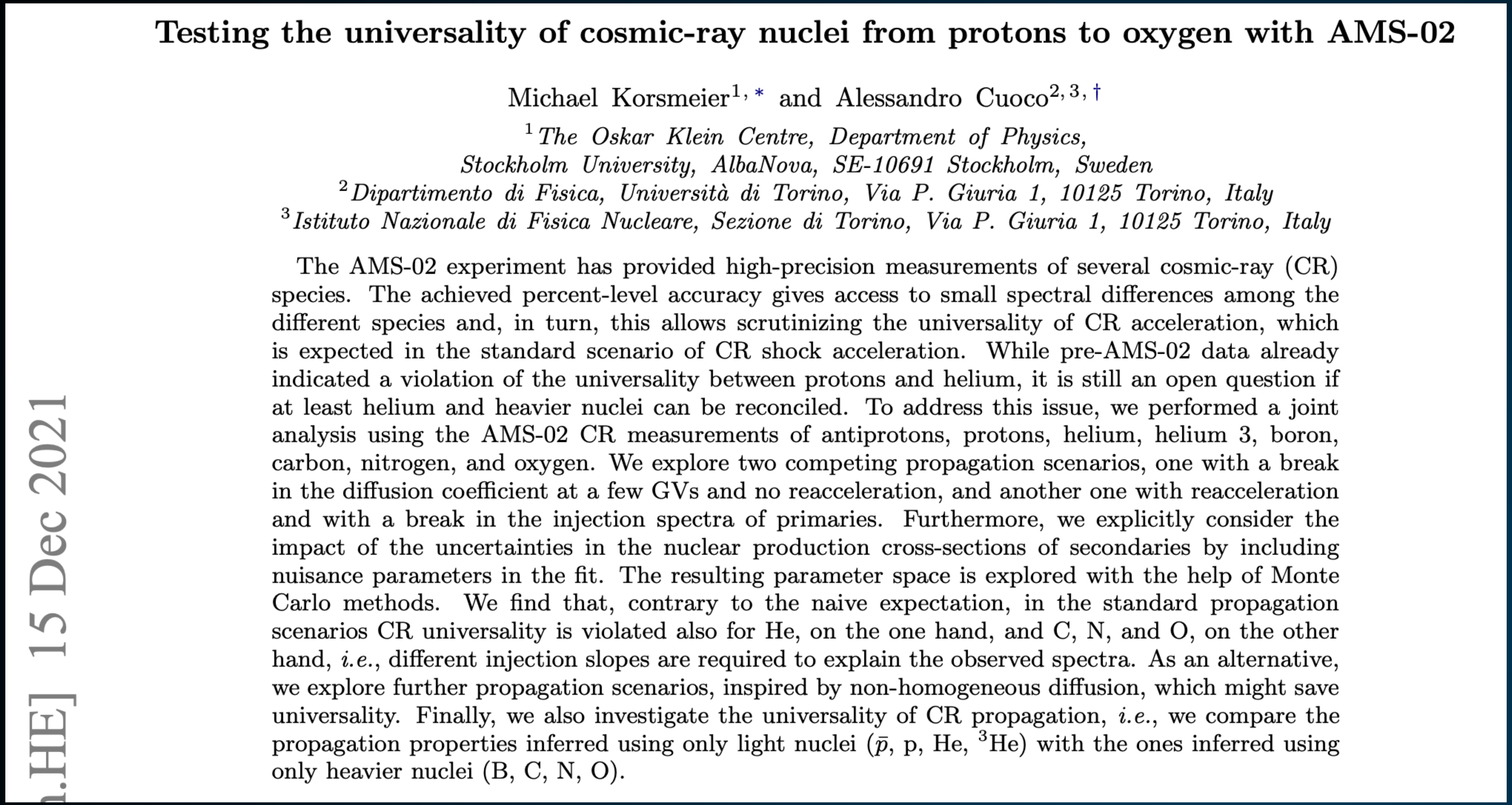
- Fragmentation also significantly decreases the anti helium and antideuteron fluxes.
- This is already correctly implemented in our Galprop modeling - otherwise, the anti helium flux would be much larger.



CMB Limits
Dwarf Limits
GC GeV Excess
p̄ Excess
p̄ Limits
1 d̄ event
1 ³He̅ event
Thermal Relic
$\sigma v(\times 10^{-26}\mathrm{cm}^3 s^{-1})$
m_χ (GeV)
10
5
1
0.5
0.1
10
20
50
100
200

Constraints from Primary-Secondary Ratios

2112.08381

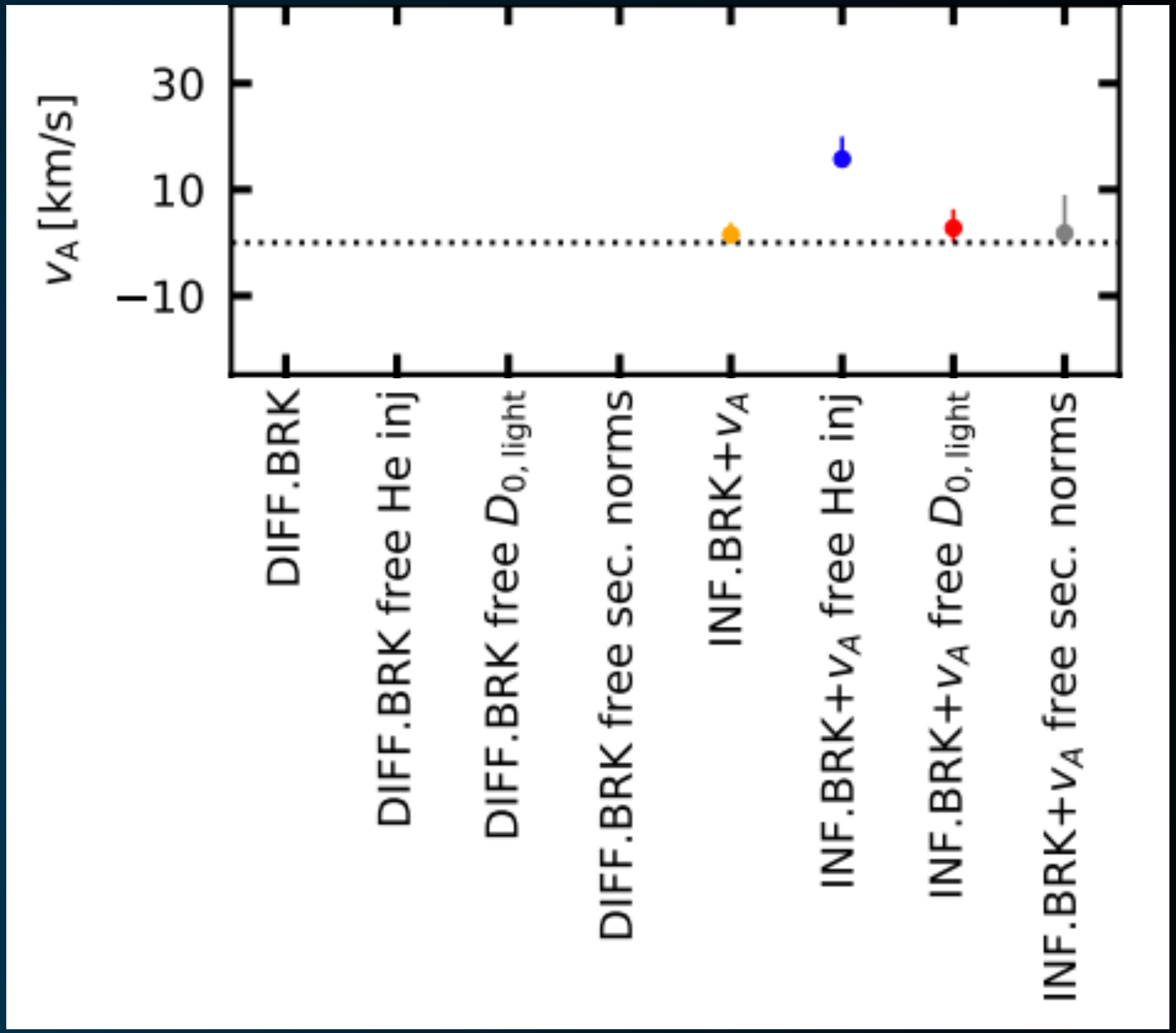


Testing the universality of cosmic-ray nuclei from protons to oxygen with AMS-02

Michael Korsmeier[1,*] and Alessandro Cuoco[2,3,†]

[1] *The Oskar Klein Centre, Department of Physics, Stockholm University, AlbaNova, SE-10691 Stockholm, Sweden*
[2] *Dipartimento di Fisica, Università di Torino, Via P. Giuria 1, 10125 Torino, Italy*
[3] *Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy*

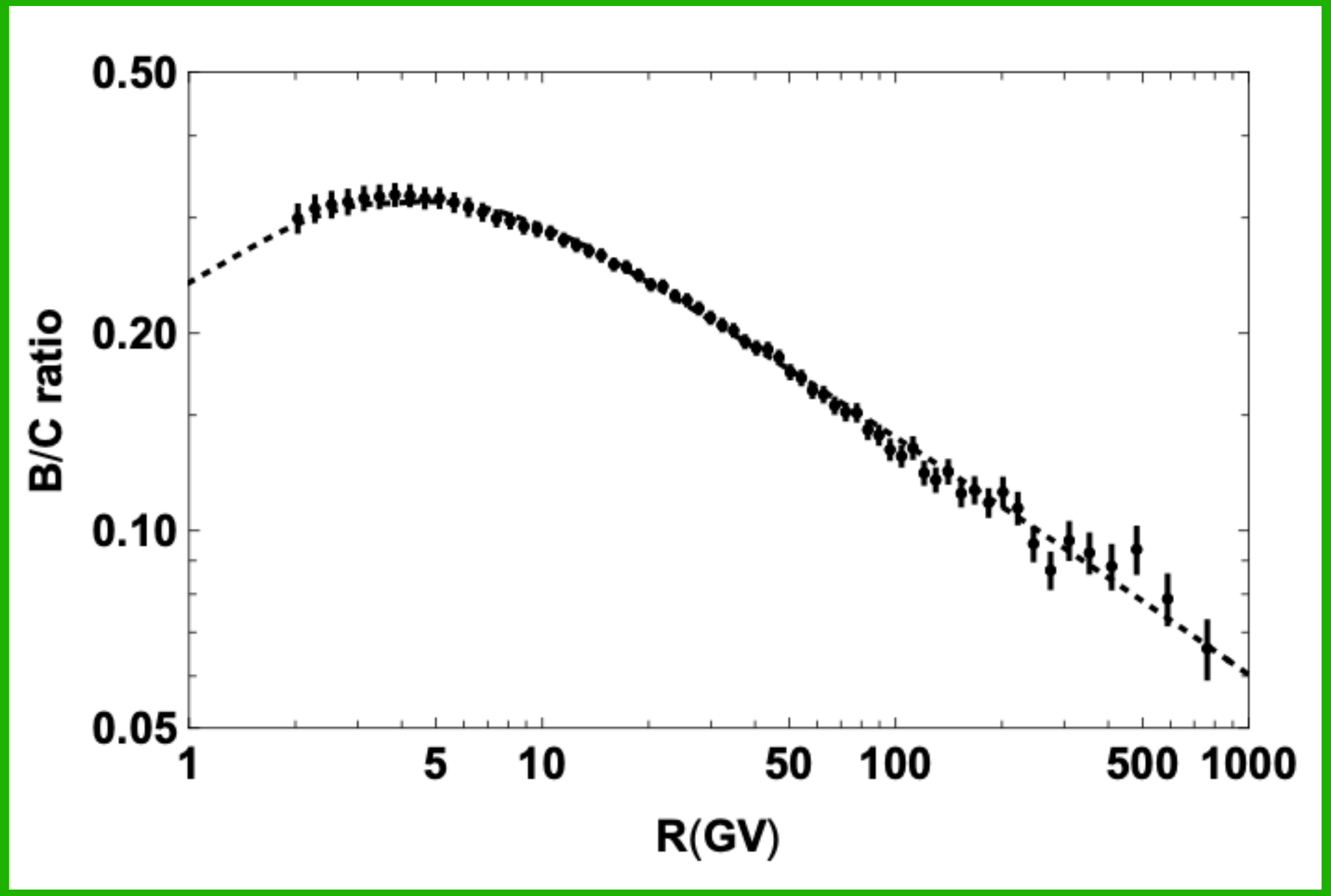
The AMS-02 experiment has provided high-precision measurements of several cosmic-ray (CR) species. The achieved percent-level accuracy gives access to small spectral differences among the different species and, in turn, this allows scrutinizing the universality of CR acceleration, which is expected in the standard scenario of CR shock acceleration. While pre-AMS-02 data already indicated a violation of the universality between protons and helium, it is still an open question if at least helium and heavier nuclei can be reconciled. To address this issue, we performed a joint analysis using the AMS-02 CR measurements of antiprotons, protons, helium, helium 3, boron, carbon, nitrogen, and oxygen. We explore two competing propagation scenarios, one with a break in the diffusion coefficient at a few GVs and no reacceleration, and another one with reacceleration and with a break in the injection spectra of primaries. Furthermore, we explicitly consider the impact of the uncertainties in the nuclear production cross-sections of secondaries by including nuisance parameters in the fit. The resulting parameter space is explored with the help of Monte Carlo methods. We find that, contrary to the naive expectation, in the standard propagation scenarios CR universality is violated also for He, on the one hand, and C, N, and O, on the other hand, *i.e.*, different injection slopes are required to explain the observed spectra. As an alternative, we explore further propagation scenarios, inspired by non-homogeneous diffusion, which might save universality. Finally, we also investigate the universality of CR propagation, *i.e.*, we compare the propagation properties inferred using only light nuclei ($\bar{p}$, p, He, ^{3}He) with the ones inferred using only heavier nuclei (B, C, N, O).

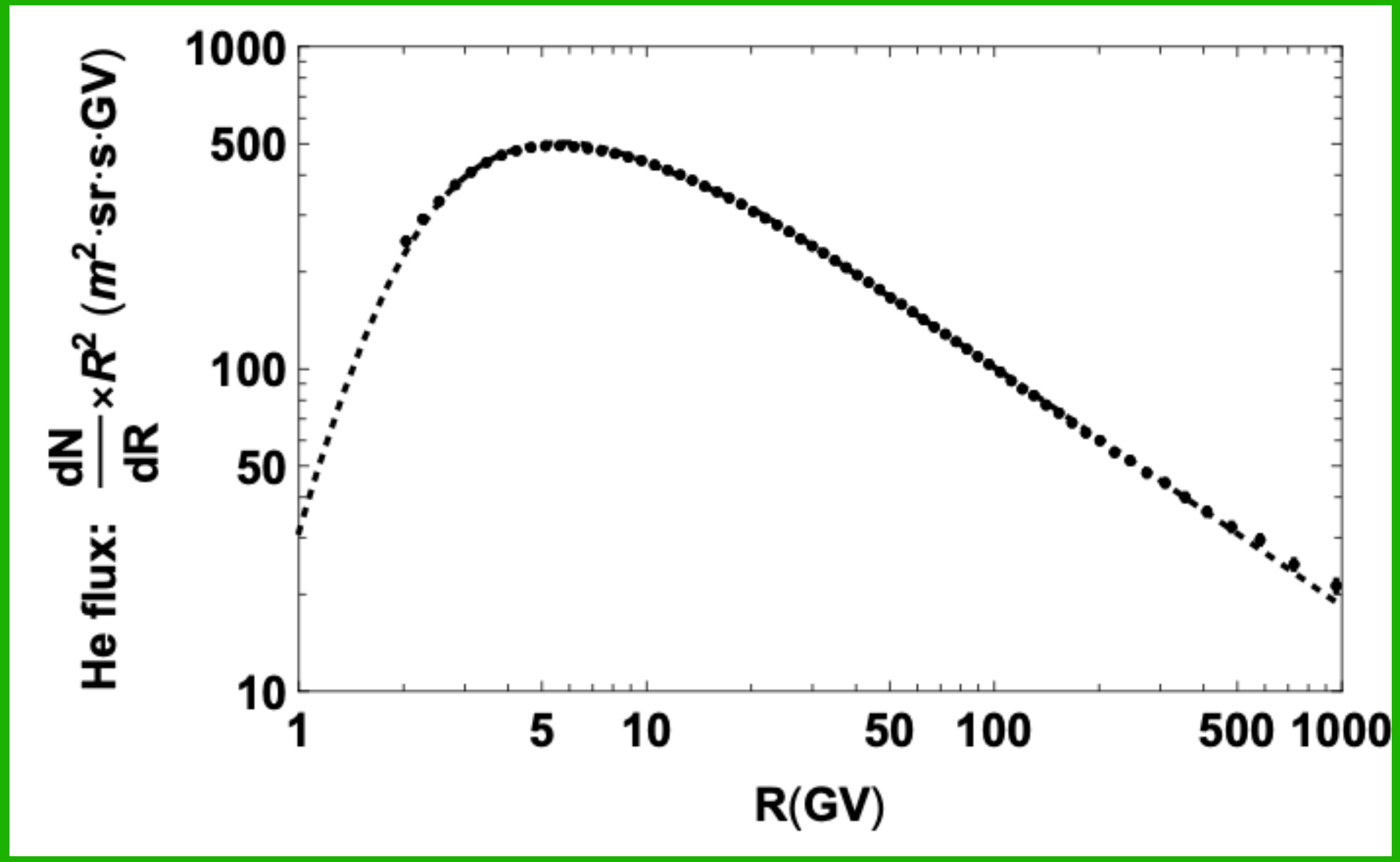


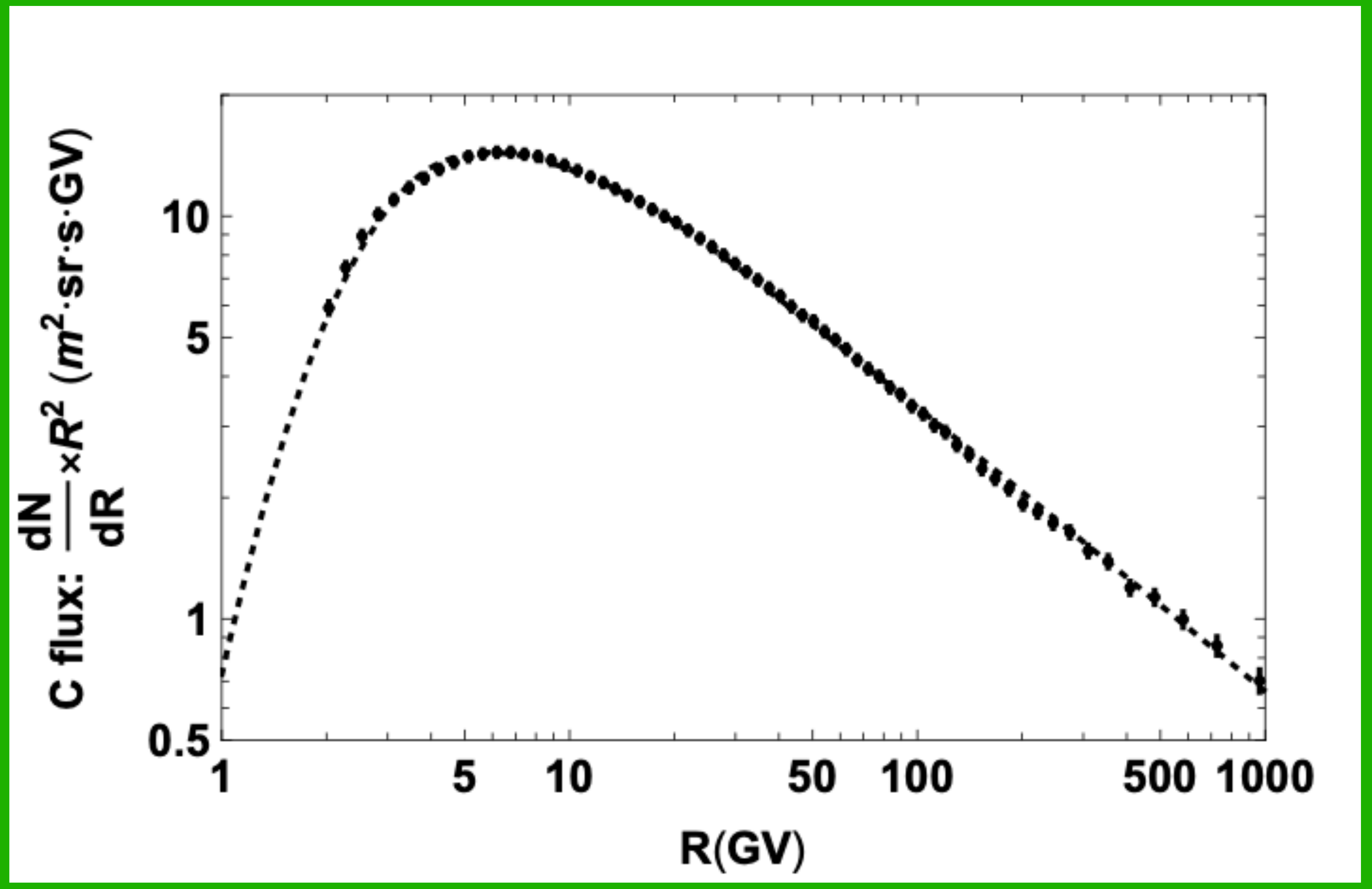
1.) However, the Alfvén velocity can not simply be increased without repercussions. Measurements of cosmic-ray acceleration and propagation indicate small Alfvén velocities: <~ 20 km/s for all models

Constraints from Primary-Secondary Ratios

Ilias Cholis



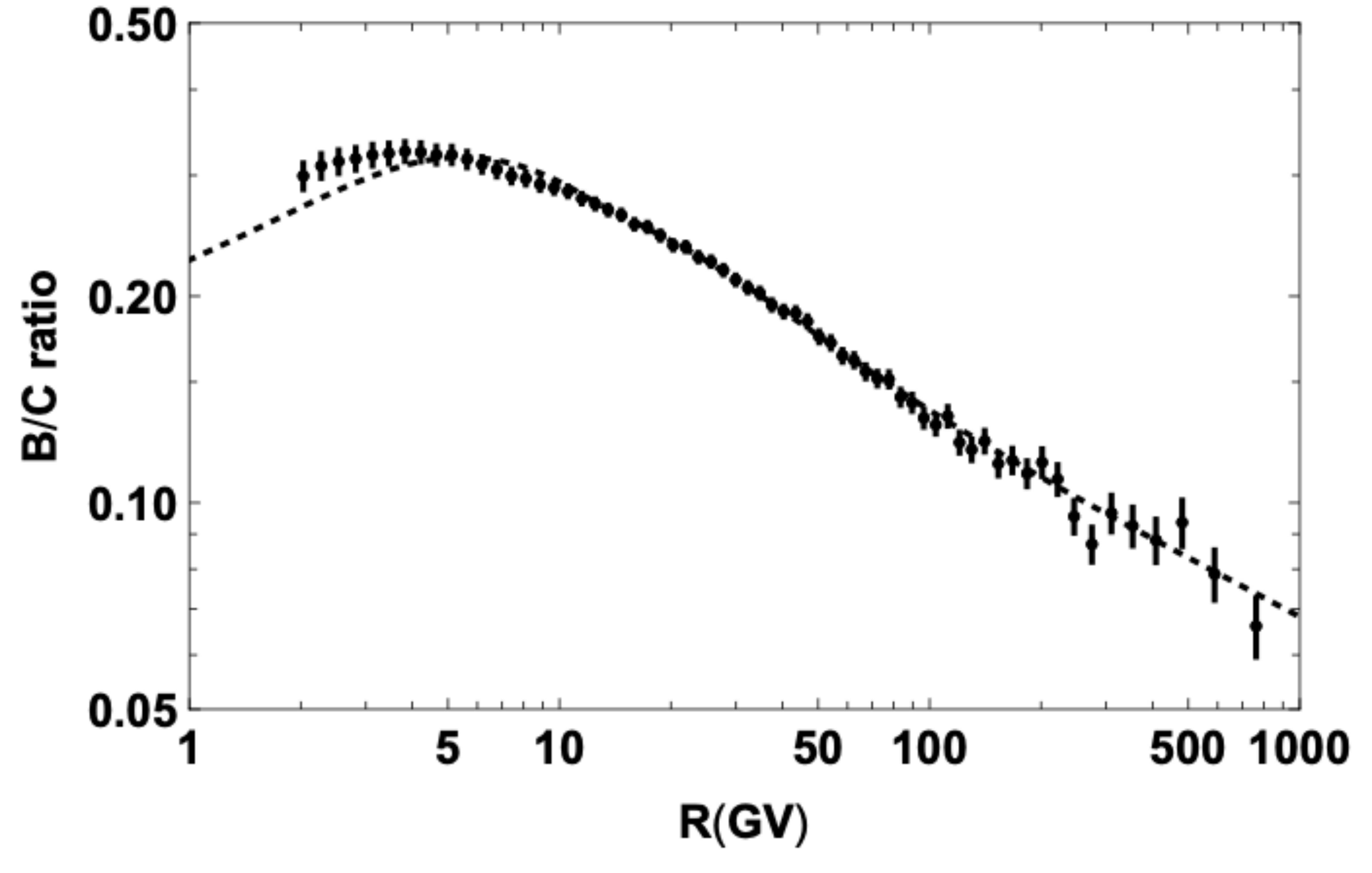




Reasonable fits can still be found for key ratios (B/C, He Flux, Carbon Flux) at 23 km/s.

Constraints from Primary-Secondary Ratios

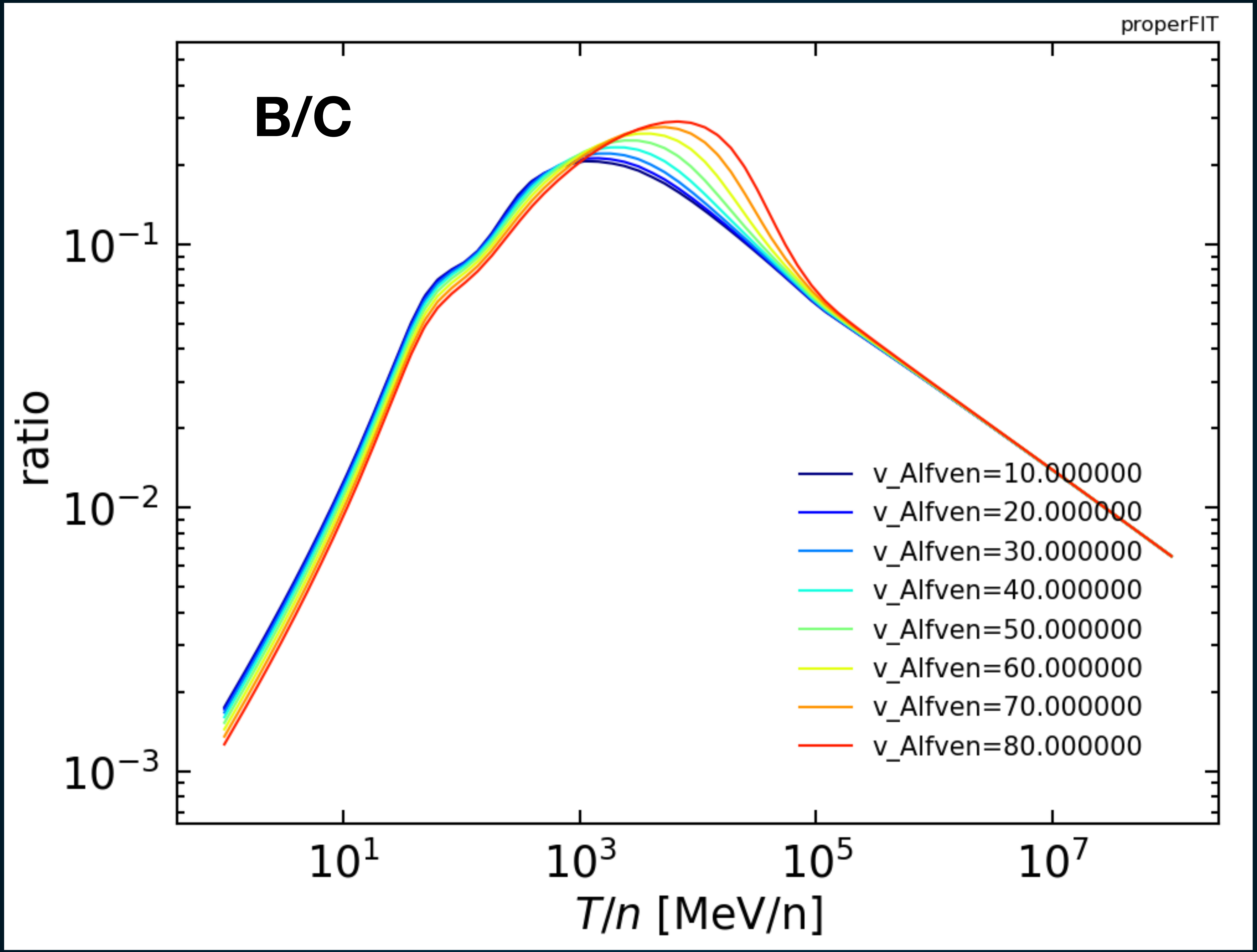
Ilias Cholis



Models at 50 km/s tend to break the B/C ratio.

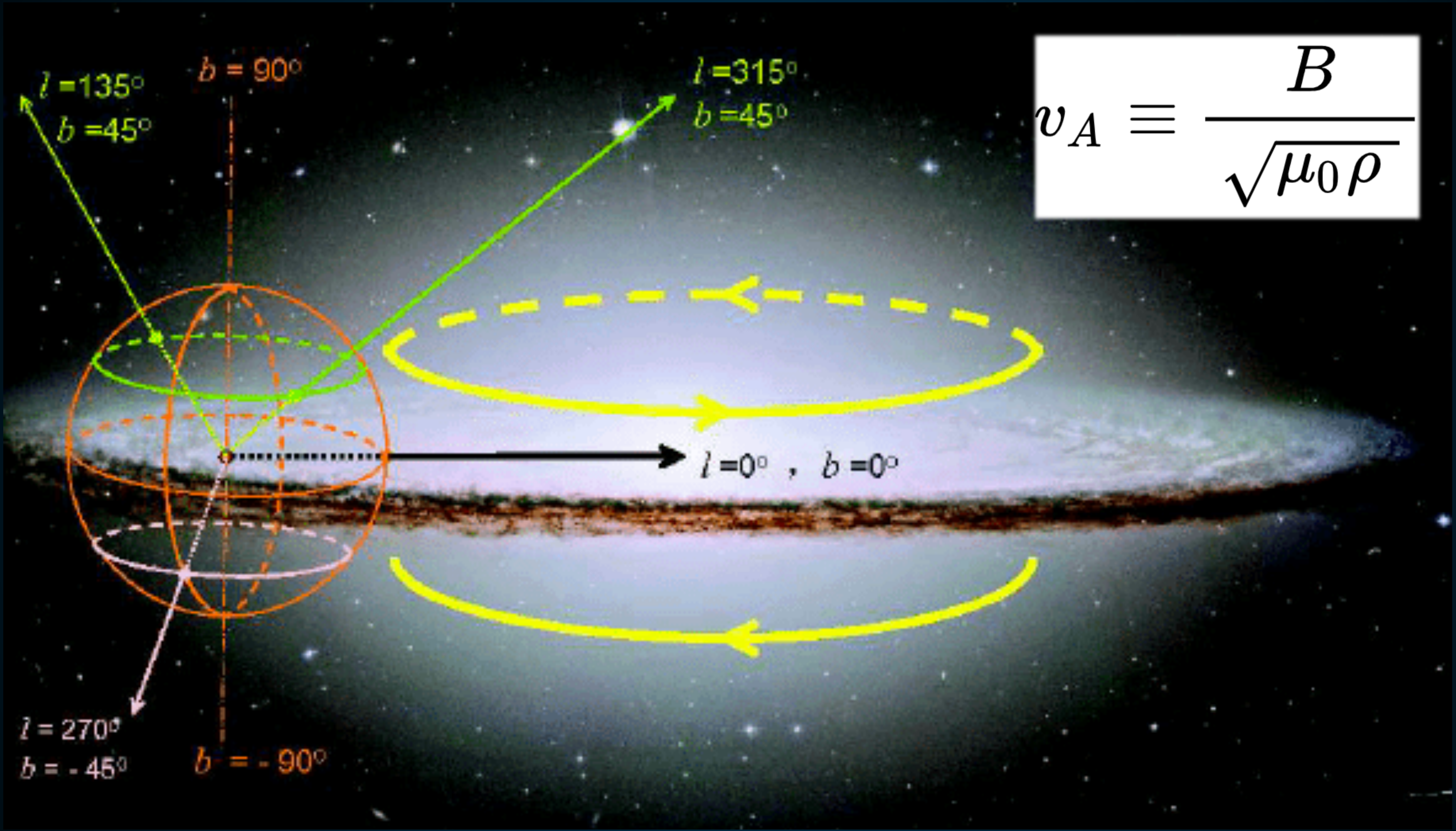
Constraints from Primary-Secondary Ratios

Korsmeier (Preliminary)



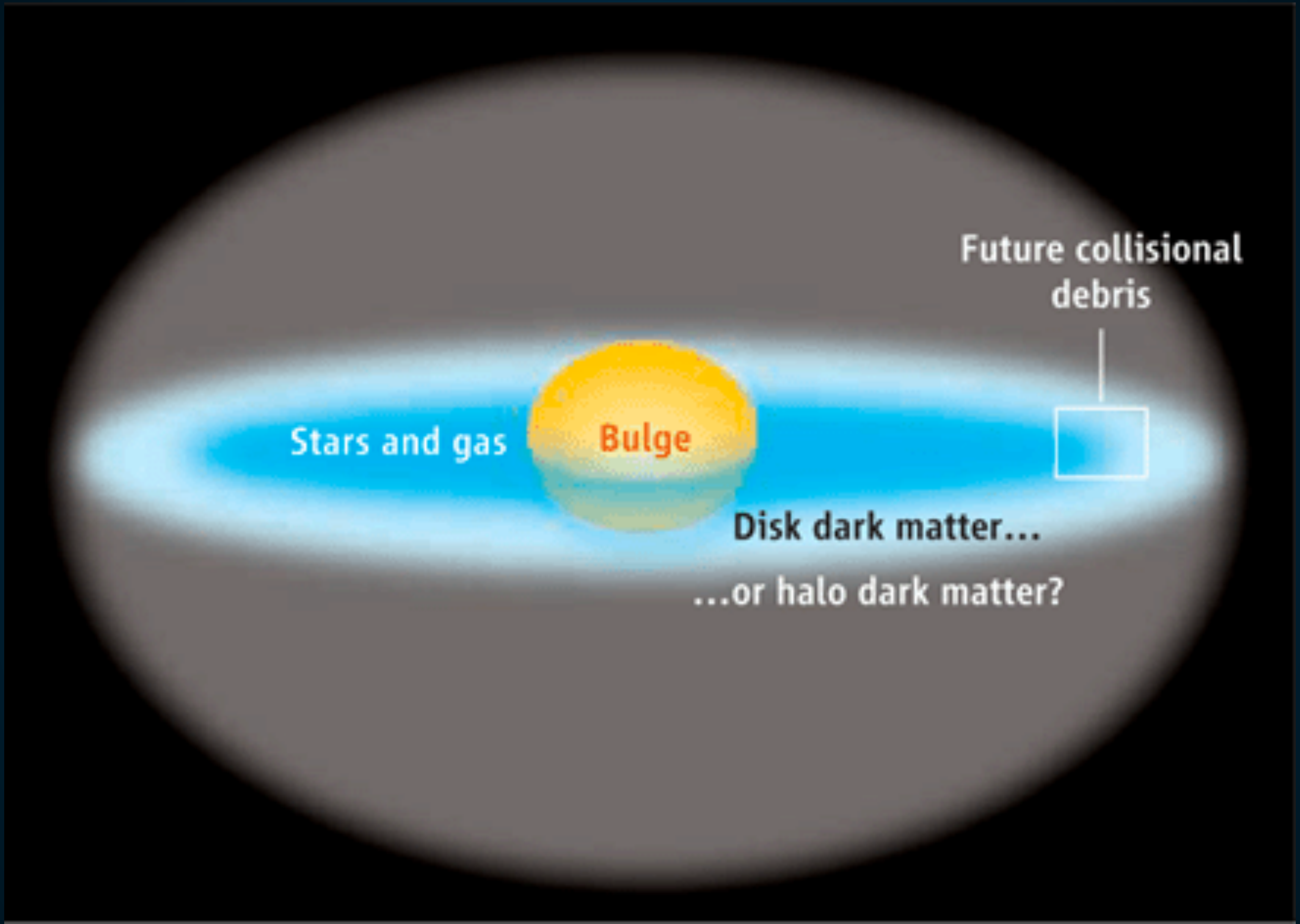
Increases in the Alfvén velocity produce a feature in the B/C — which is not observed.
Maximum reasonable Alfvén velocity is ~30 km/s.

Constraints from Primary-Secondary Ratios



However, the Alfvén velocity does not need to be constant throughout the Galaxy.

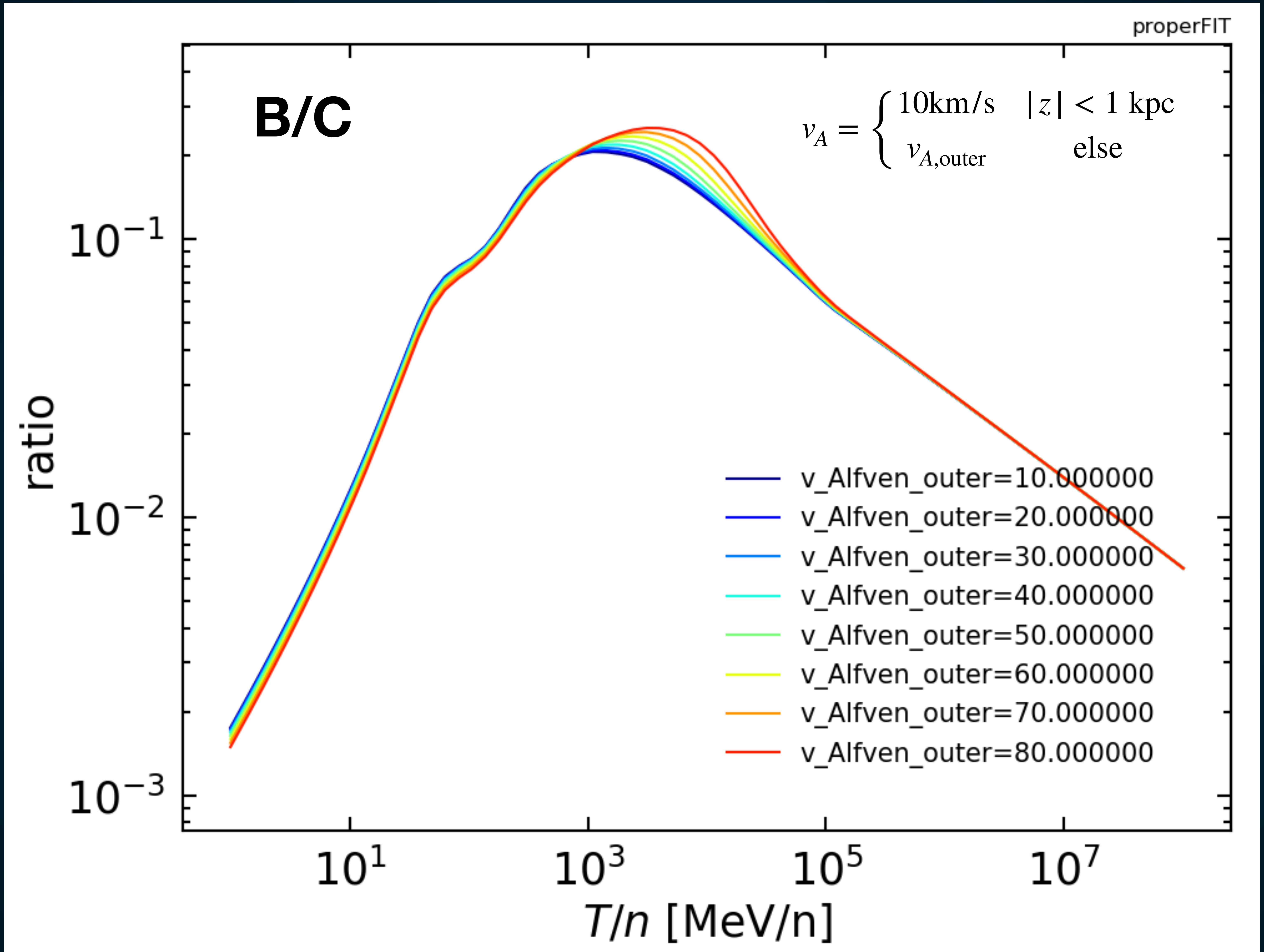
Constraints from Primary-Secondary Ratios



In fact - this is correlated with where dark matter and astrophysical secondaries are expected to be created.

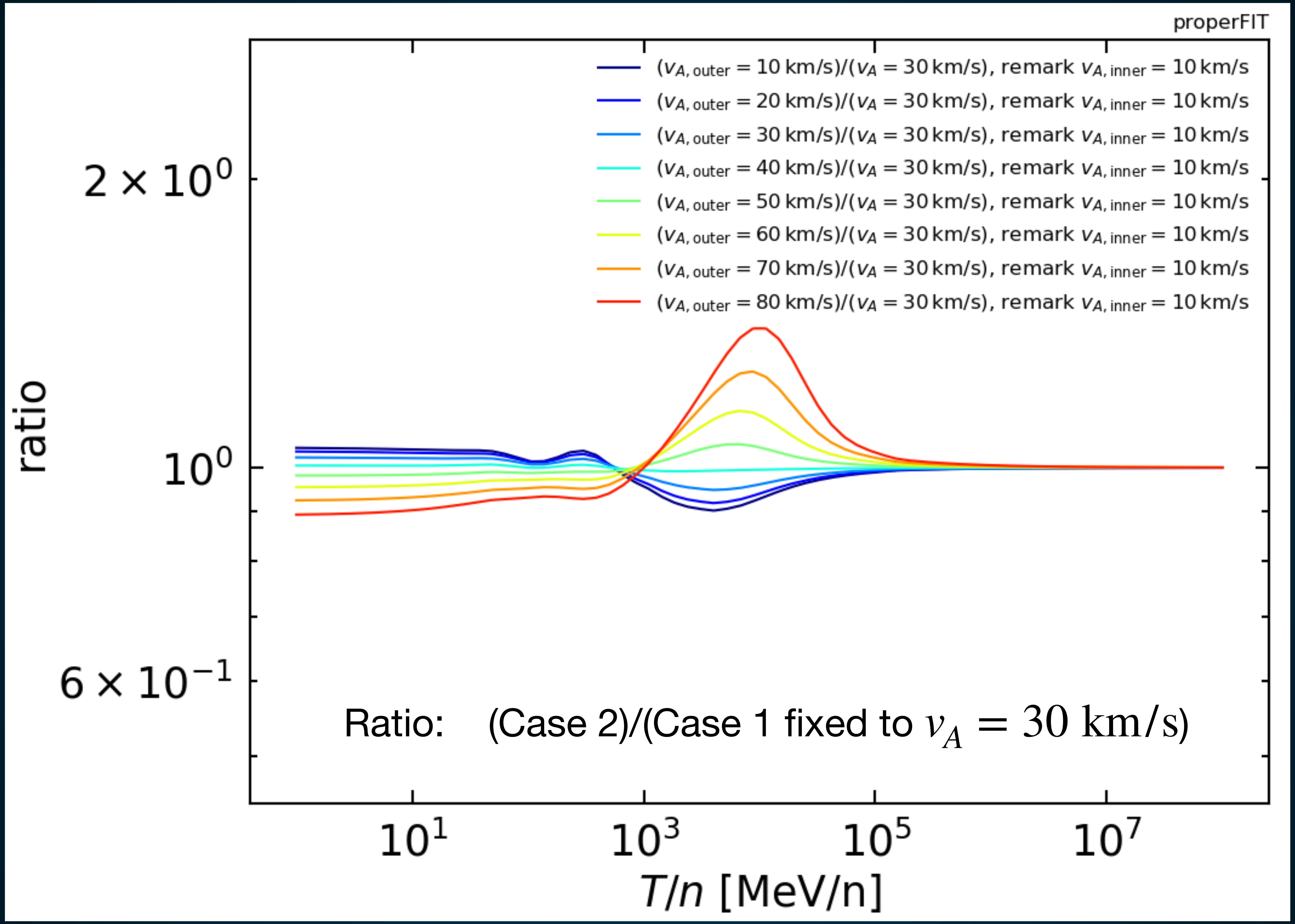
Constraints from Primary-Secondary Ratios

Korsmeier (Preliminary)



Constraints from Primary-Secondary Ratios

Korsmeier (Preliminary)

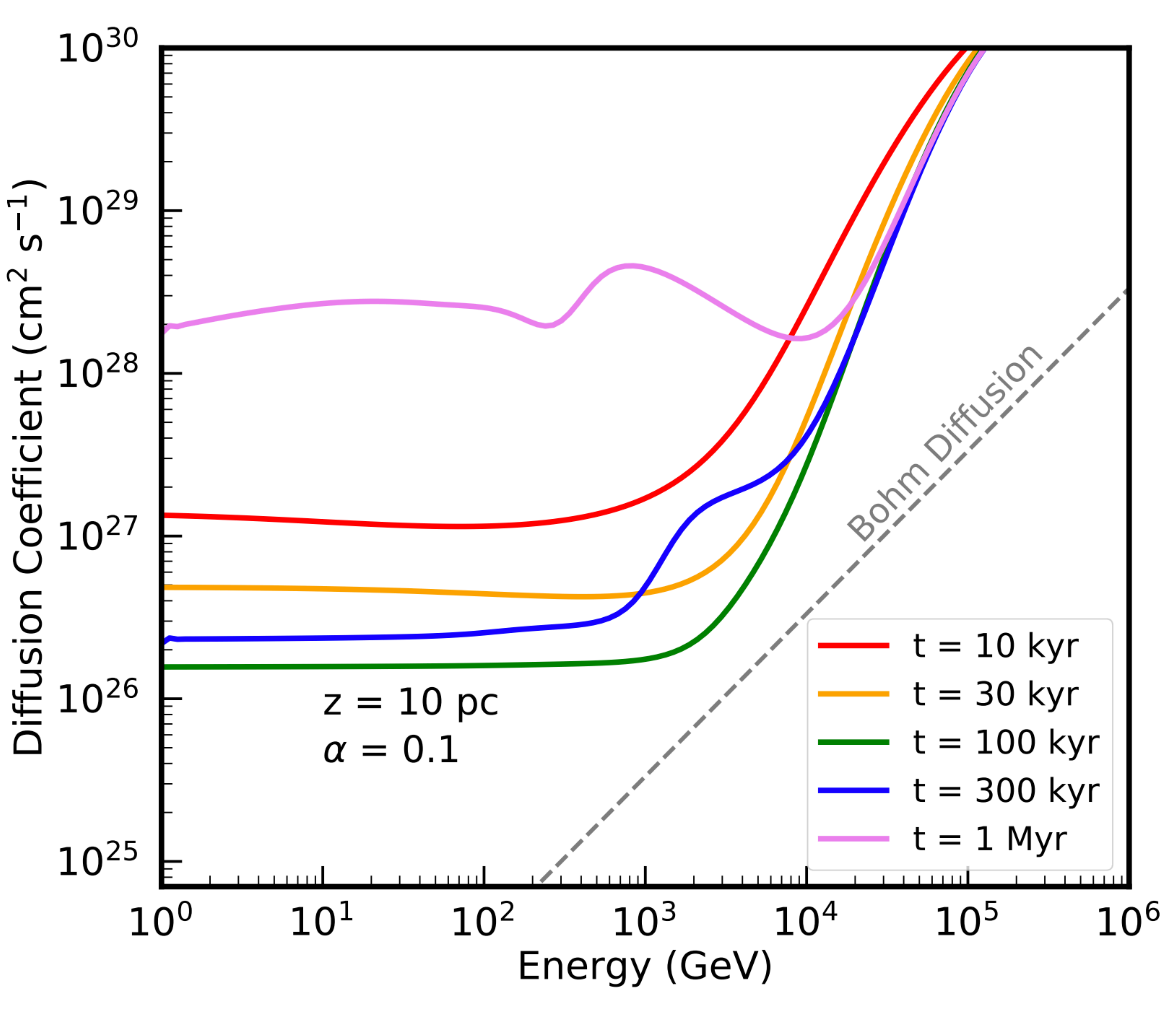


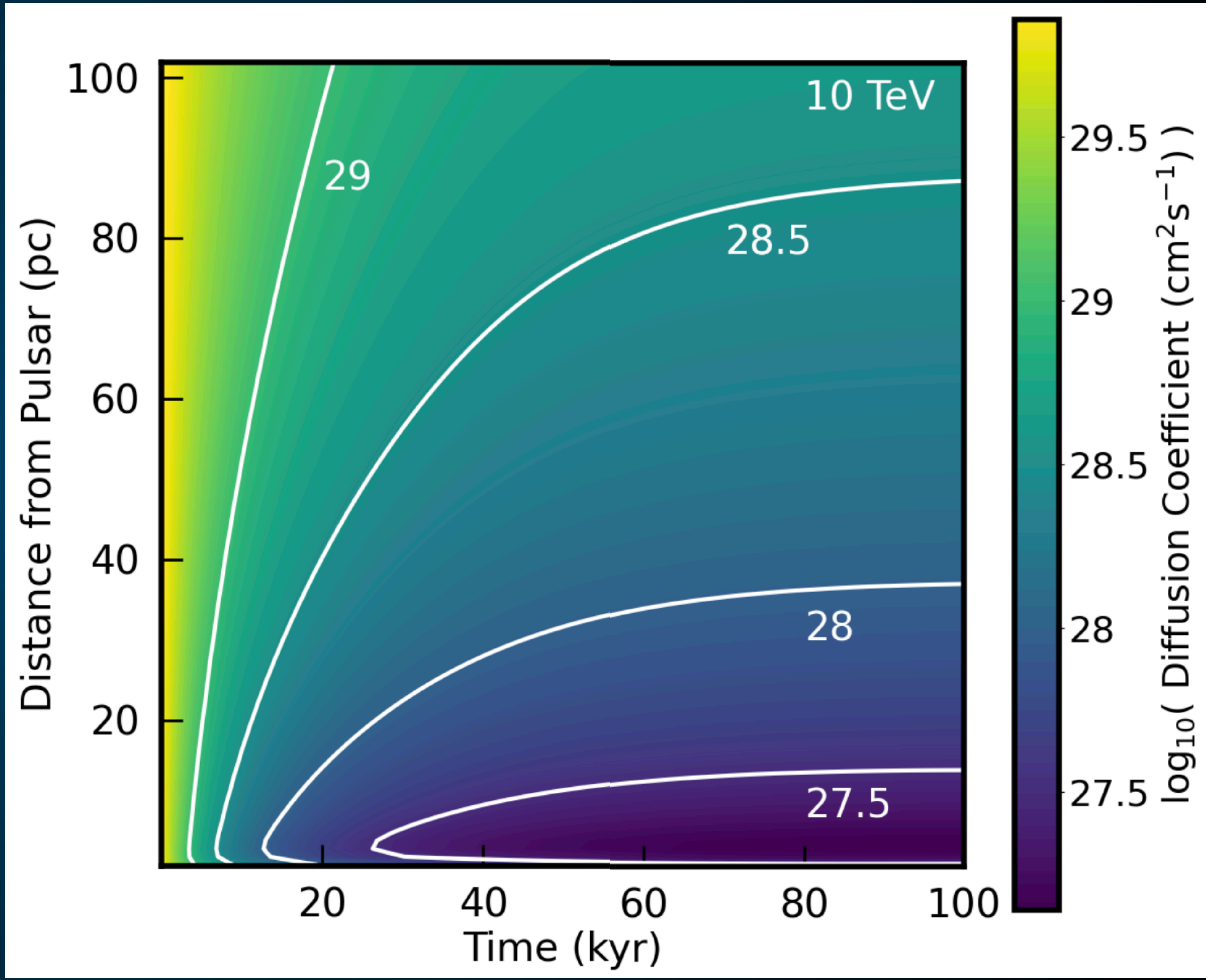
1.) In particular, increases in the Alfvén velocity produce a feature in the B/C


Abeysekhara et al. (2017; 1711.06223)
Moon (To Scale)
Geminga
Linden et al. (2017; 1703.09704)
Sudoh et al. (2019; 1902.08203)
SNR
(hadronic/leptonic)
TeV Halo
(escaped e⁺e⁻)
PWN
(confined e⁺e⁻)

Is There Another Path Forward?

The Diffusion Characteristics of the Galaxy Are More Complicated!

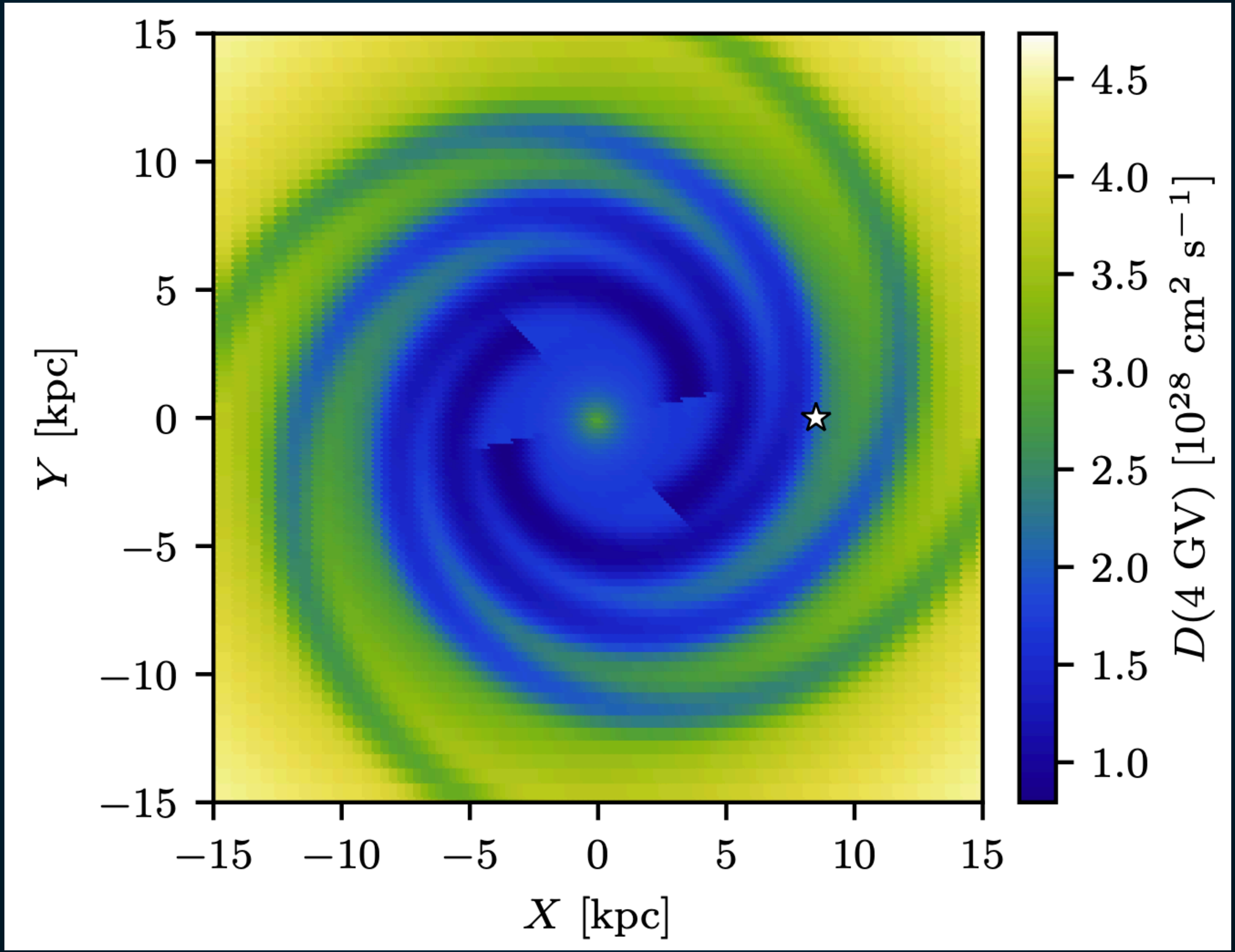




Mukhopadhyay & Linden (2021; 2111.01143)

Is There Another Path Forward?

The Diffusion Characteristics of the Galaxy Are More Complicated!



Johannesson et al. (2019; 1903.05509)

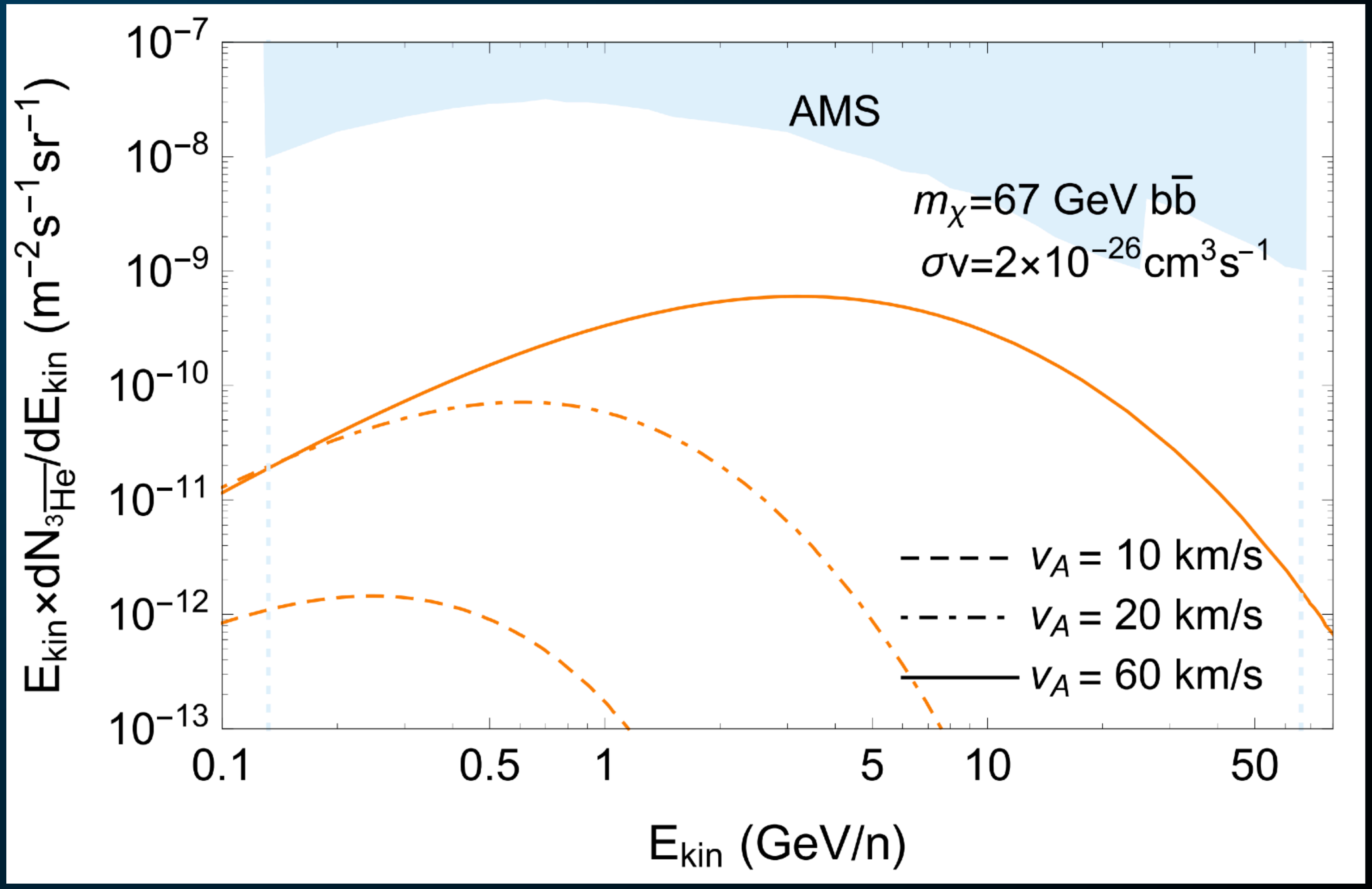
Conclusions

- **Antideuterons and Antihelium provide a dark matter signature where S/N >> 1.**

- **Tentative evidence for O(10) antihelium events in AMS-02 (!?)**

- **Difficult to explain given constraints from antiprotons, dSphs**

- **Need to include some enhancement factor to explain antihelium flux**
  - **Coalescence can be important, but energy is too low**
  - **Astrophysical Reacceleration**

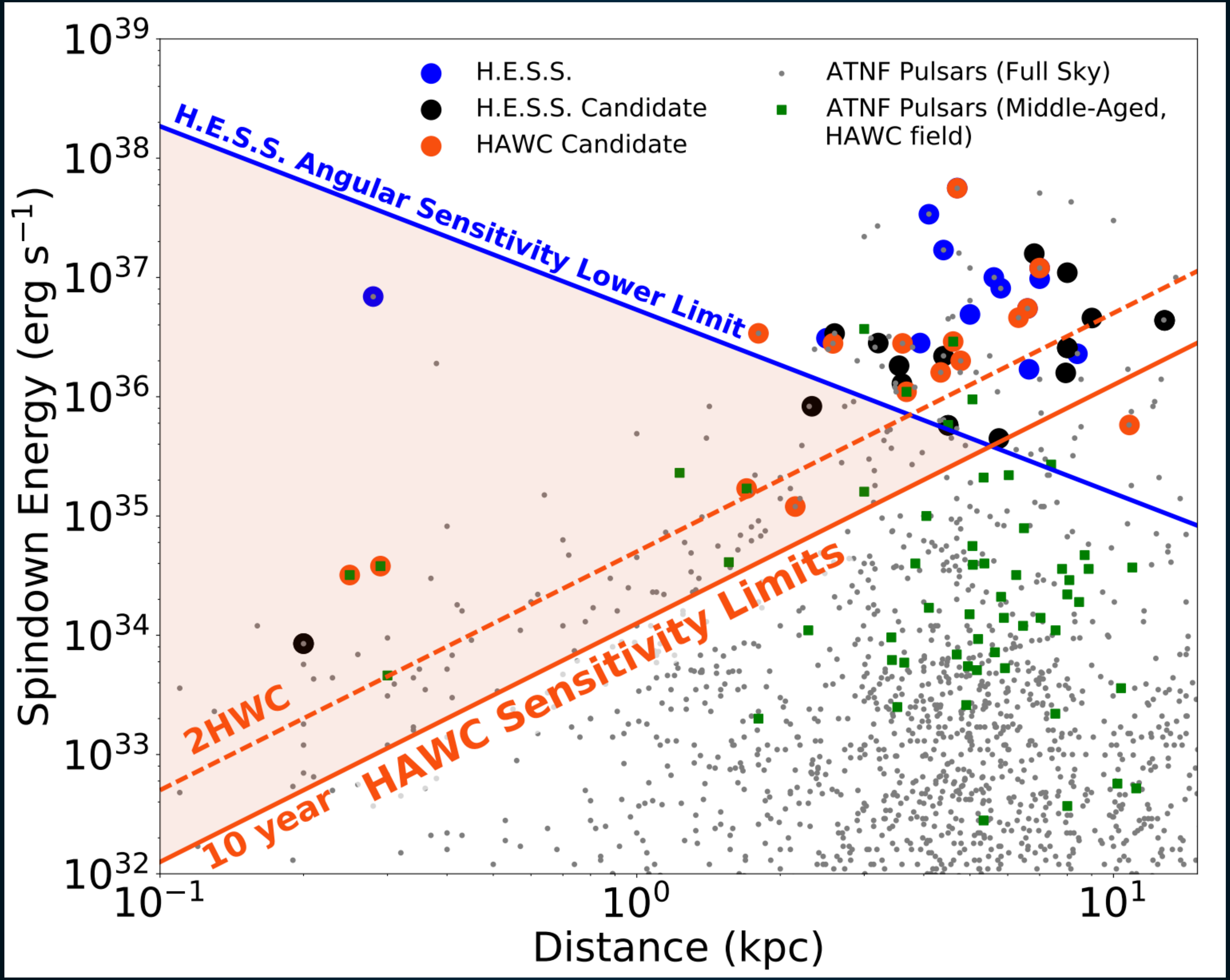


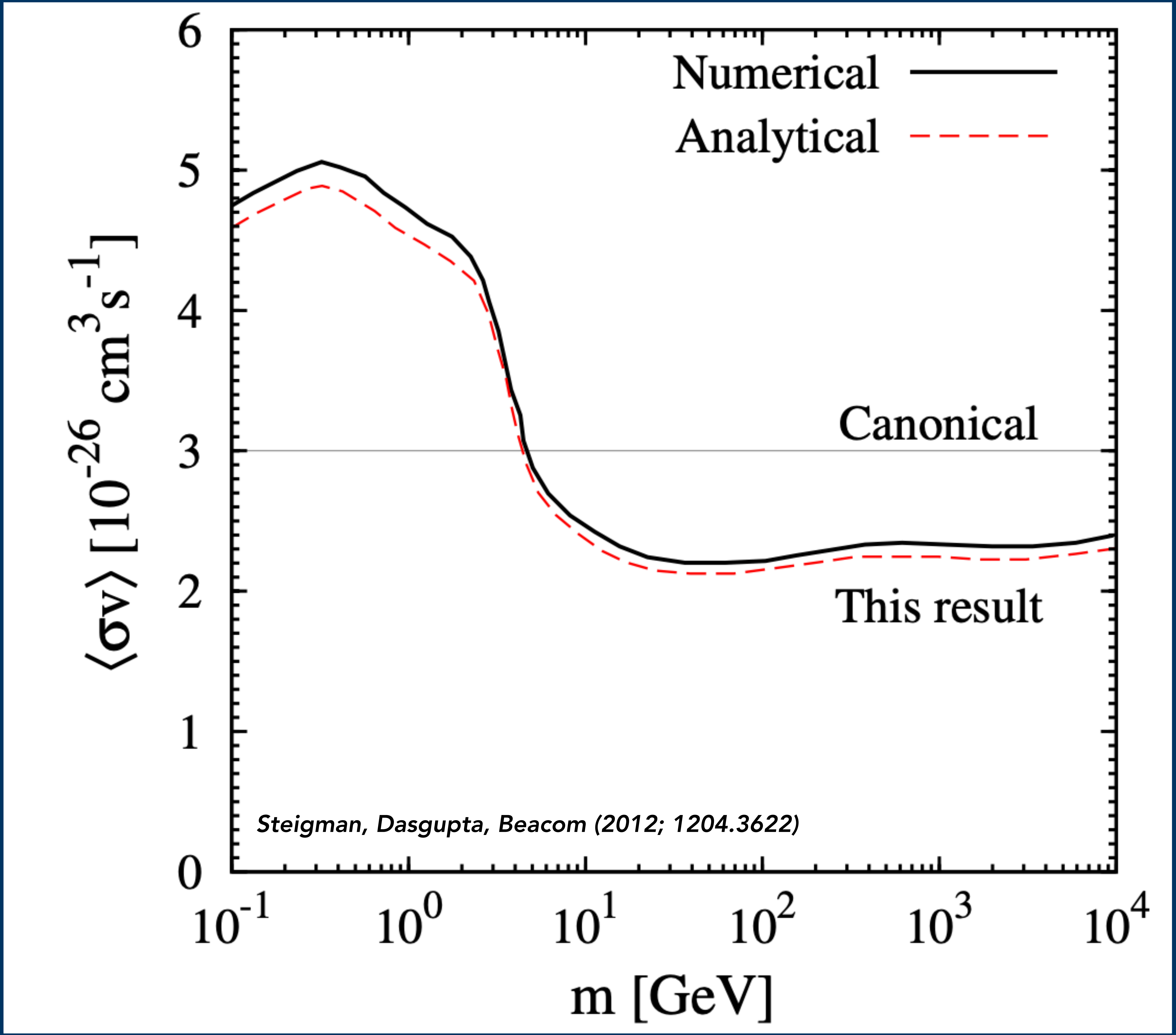
  - **Lambda-Baryons (Stay Tuned!)**

Extra Slides

$b\bar{b}$ (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)
$<\sigma v>$ ($cm^3 s^{-1}$)
Dark Matter Mass (GeV)
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
0.1
1
10
100
1000
10^4
10^5

New Discoveries!



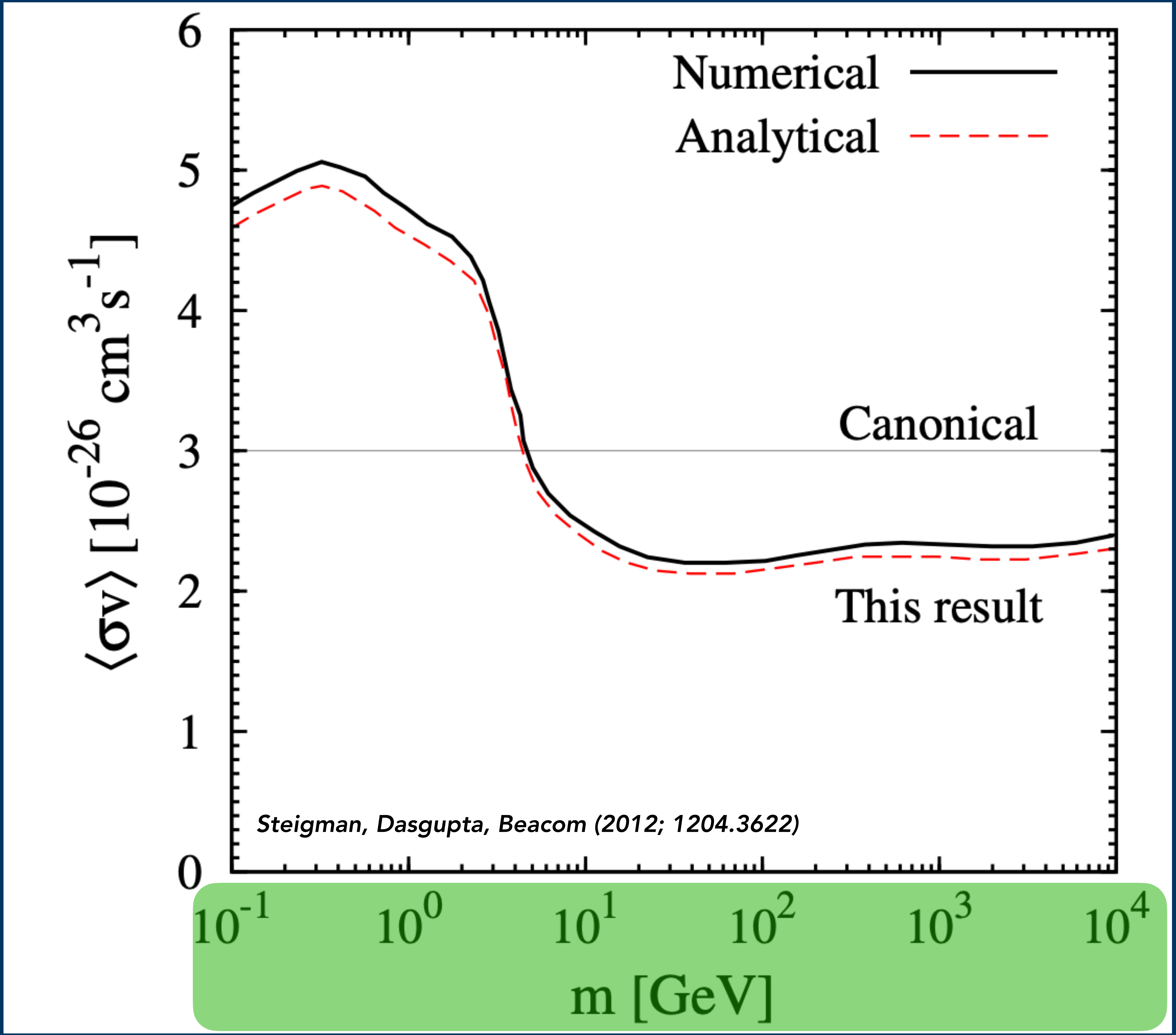


Thermal Dark Matter Density

Simplest model has a known cross-section!

Deviations from this cross-section include complicating effects.

Thermal Dark Matter Density



Simplest model has a known cross-section!

Deviations from this cross-section include complicating effects.

A Mass Scale!

Moon (To Scale)
Geminga
SNR
(hadronic/leptonic)
TeV Halo
(escaped e⁺e⁻)
PWN
(confined e⁺e⁻)
Geminga
$\alpha = 1.9$
$E_\gamma \, dN_\gamma/dE_\gamma \, (\mathrm{cm^{-2}\,s^{-1}})$
E_γ (GeV)