

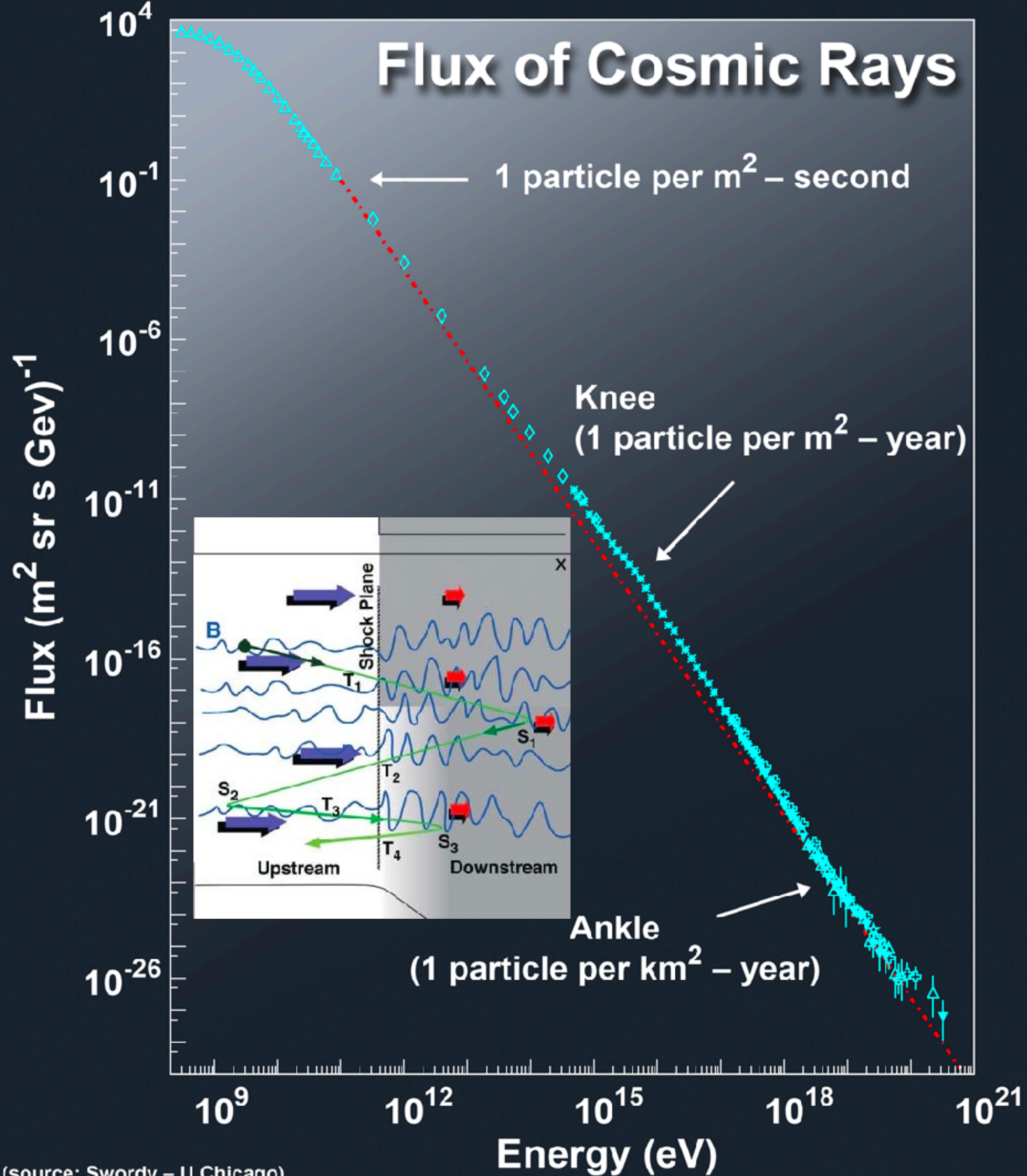


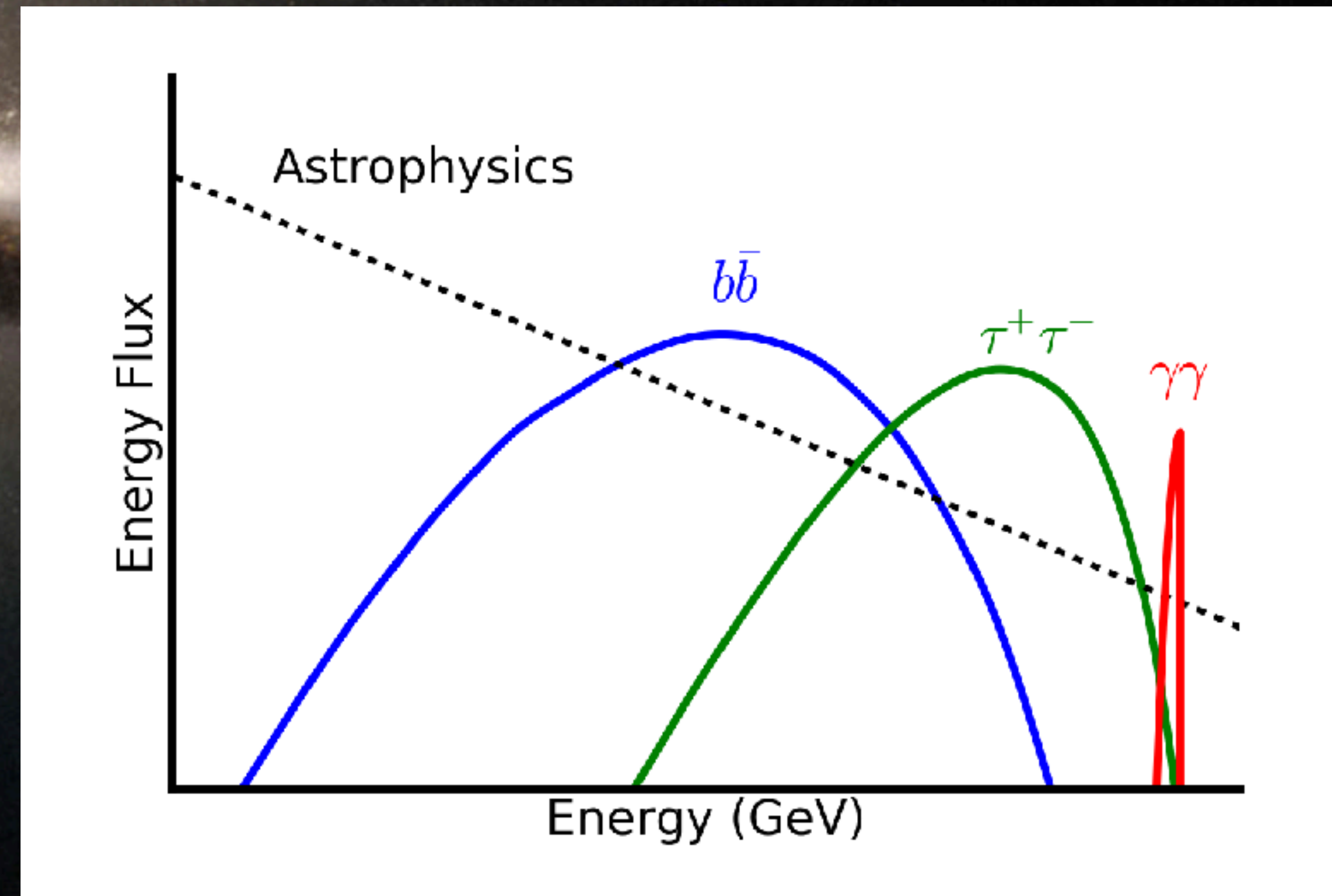
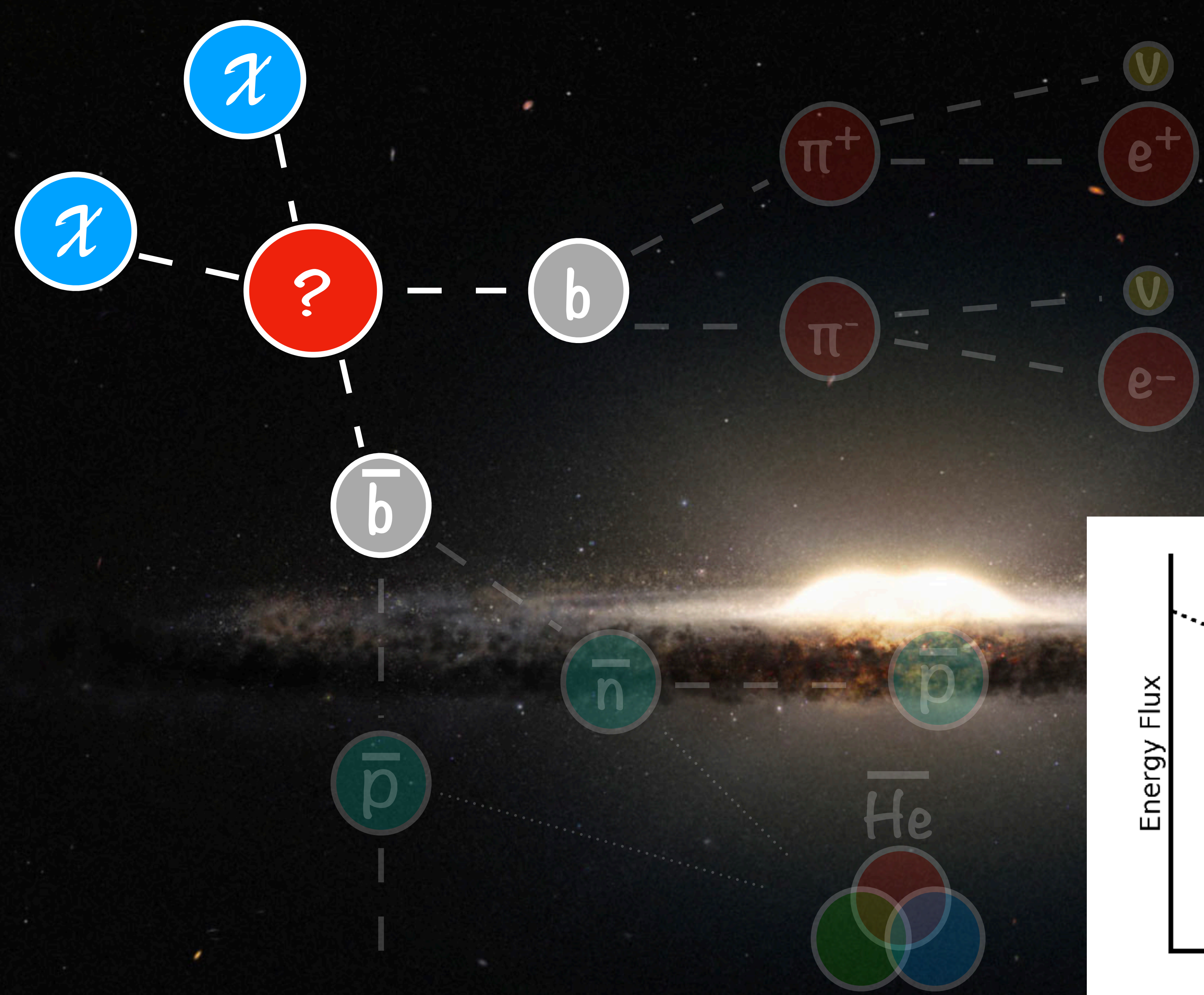
Tim Linden

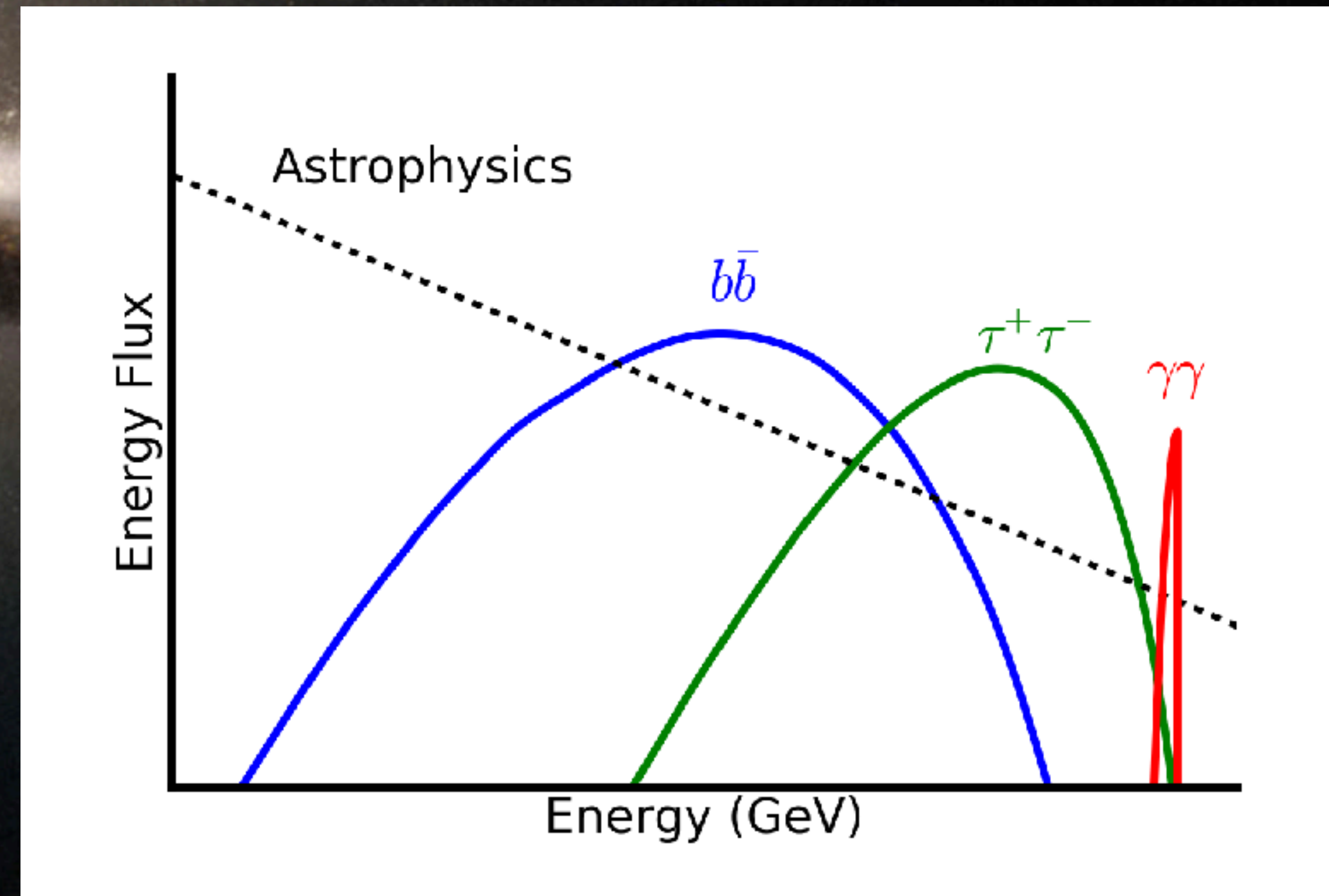
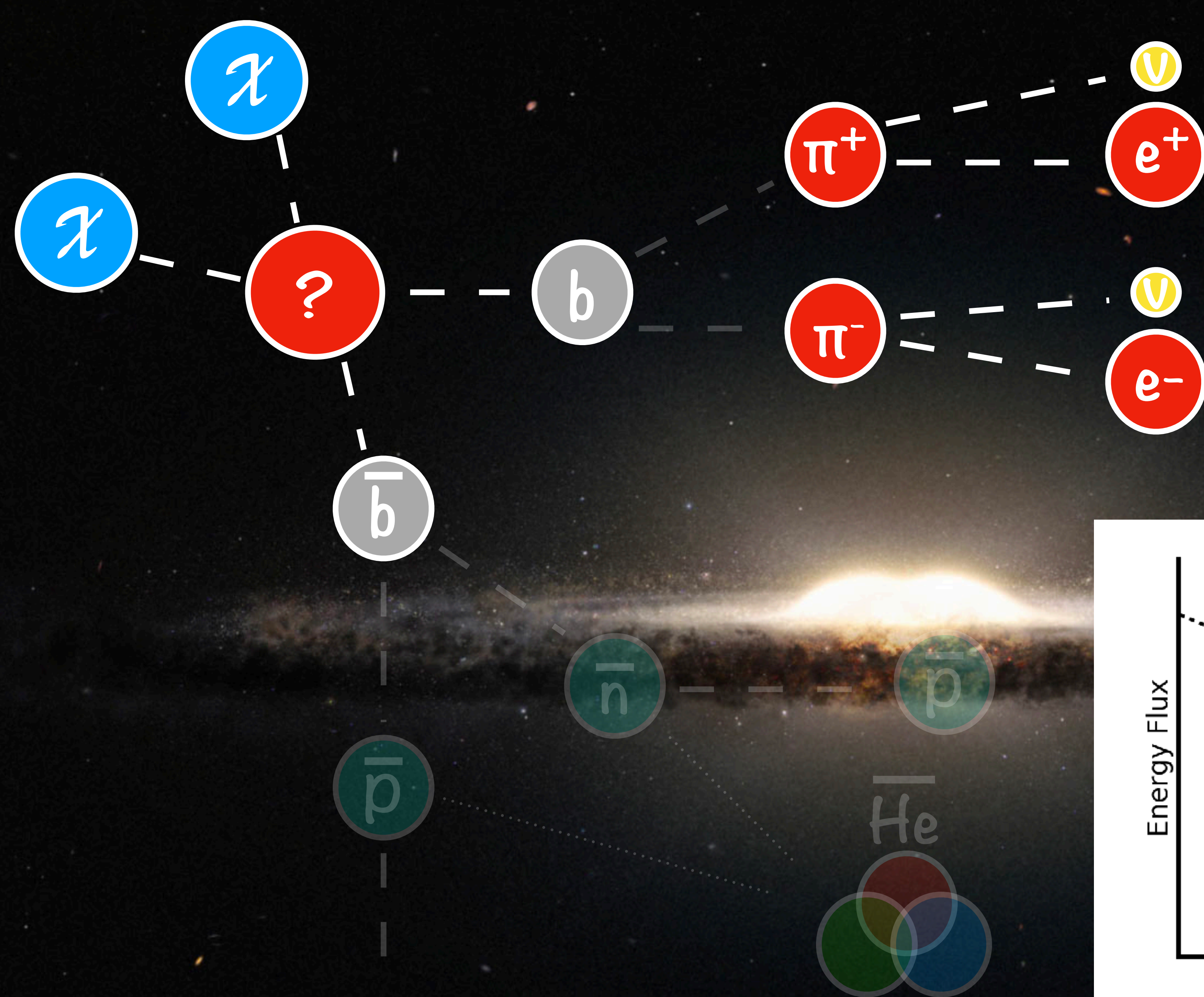


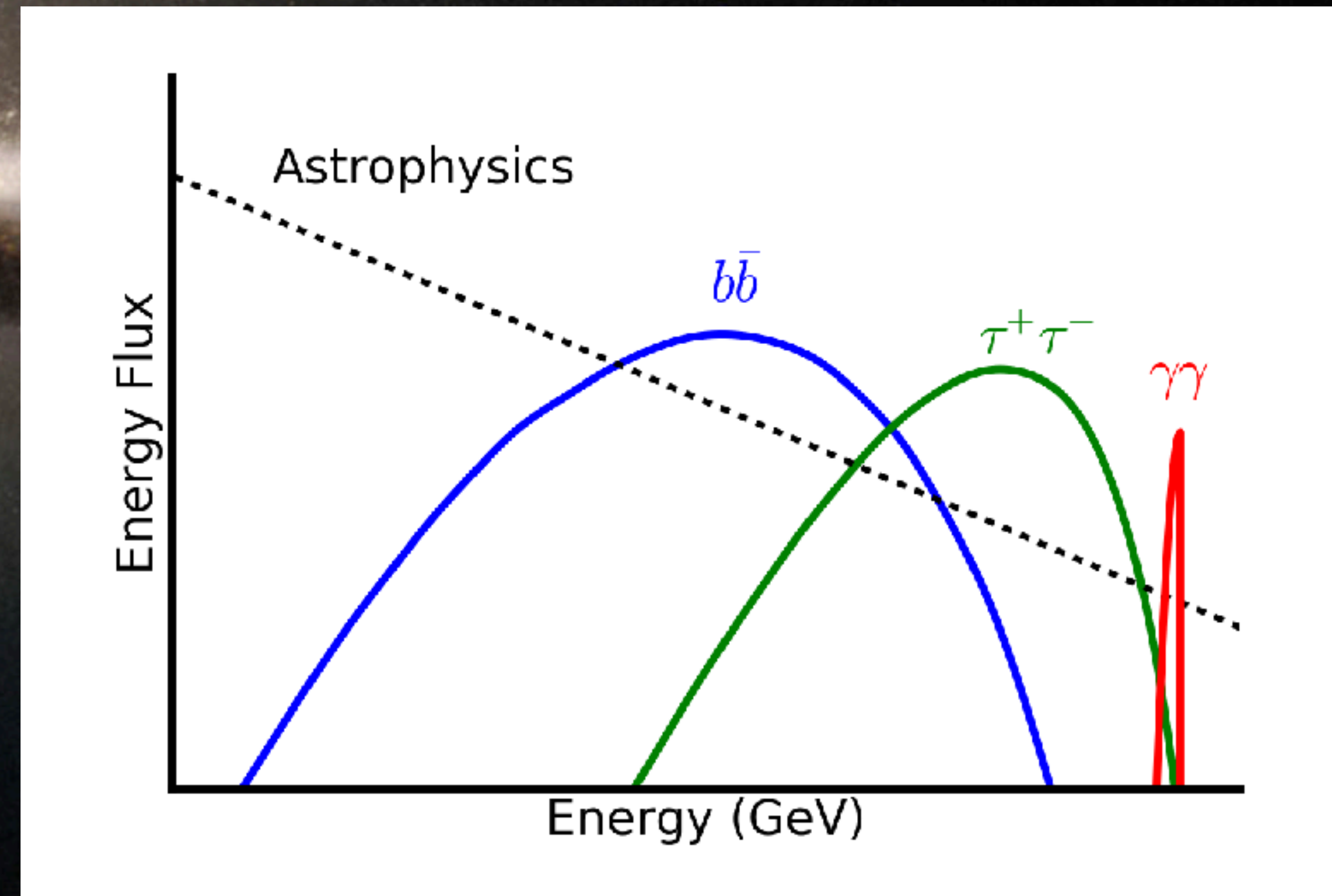
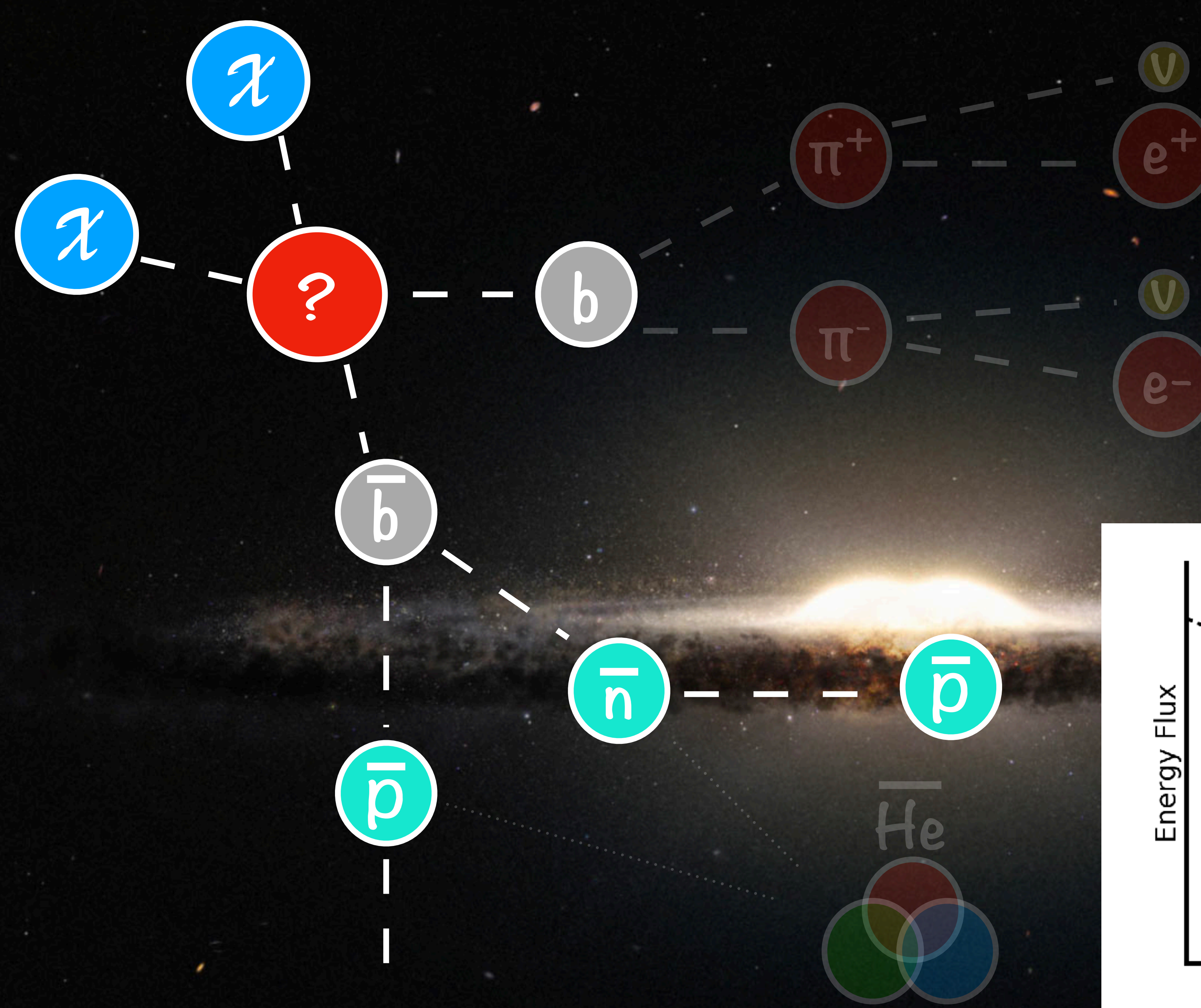
Cosmic-Ray Searches for Dark Matter: Yesterday, Today and Tomorrow

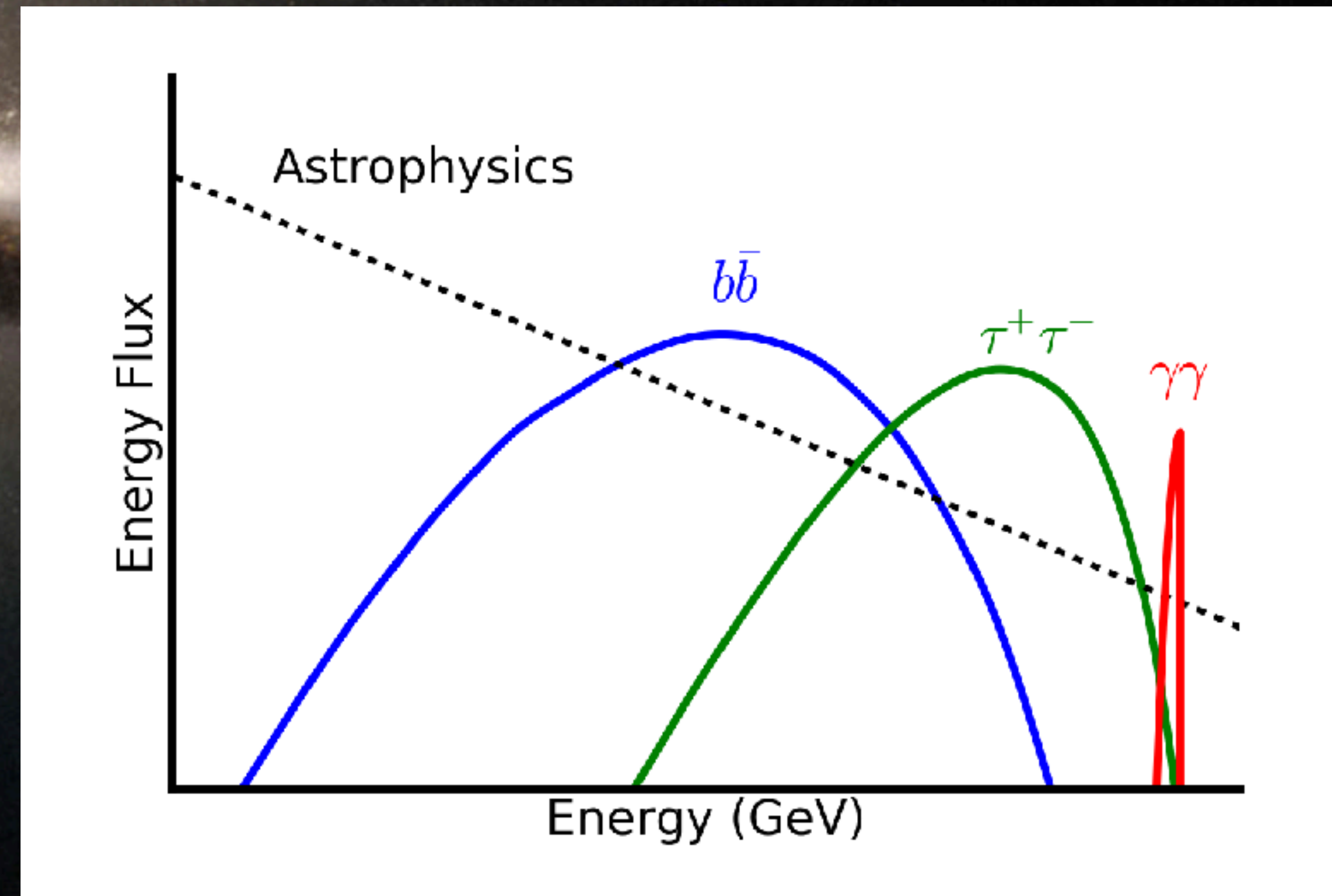
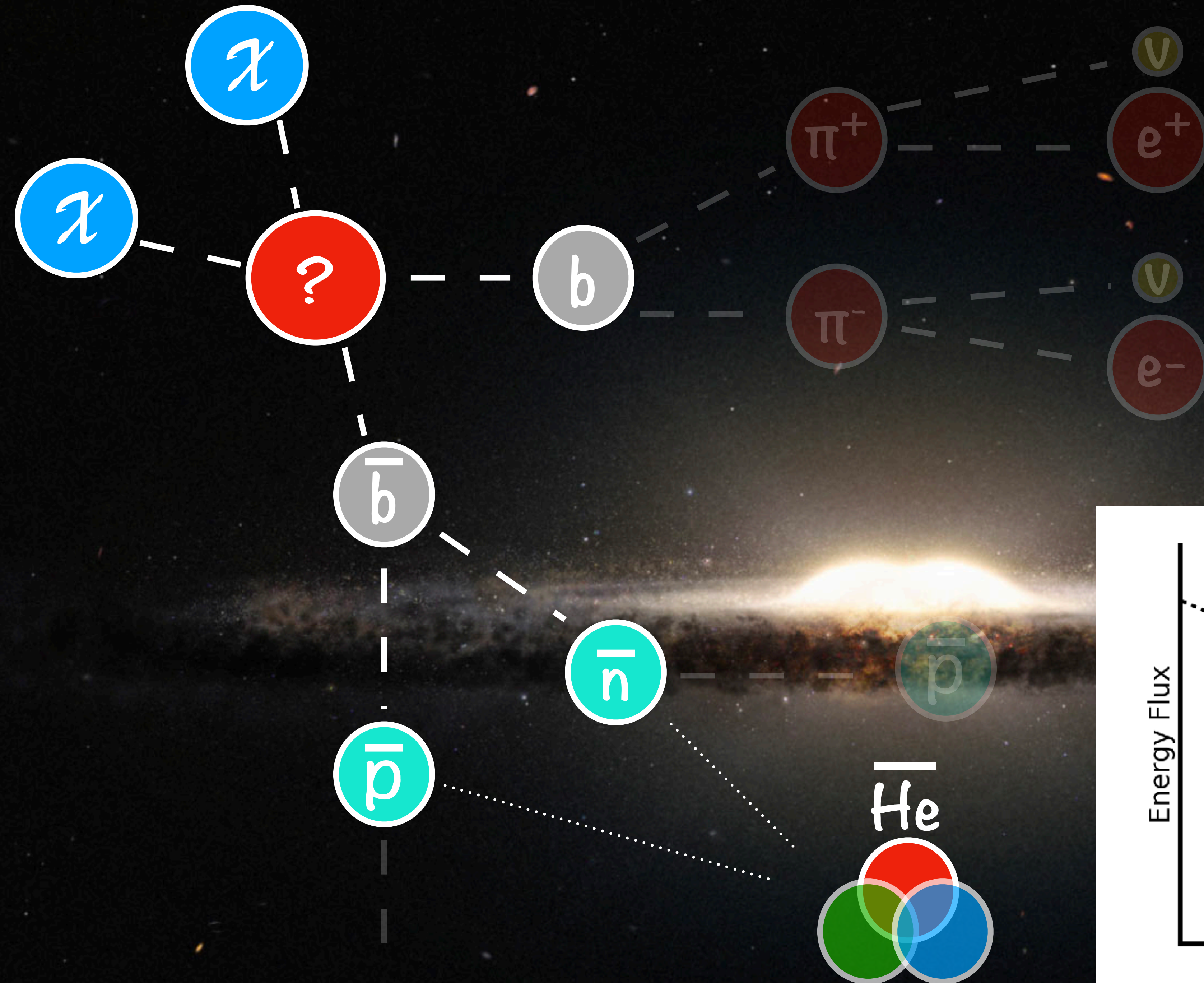
Flux of Cosmic Rays











Specificity (DM Flux / Astrophysics Flux)

Small Dark Matter Signal
Small Astrophysical Background

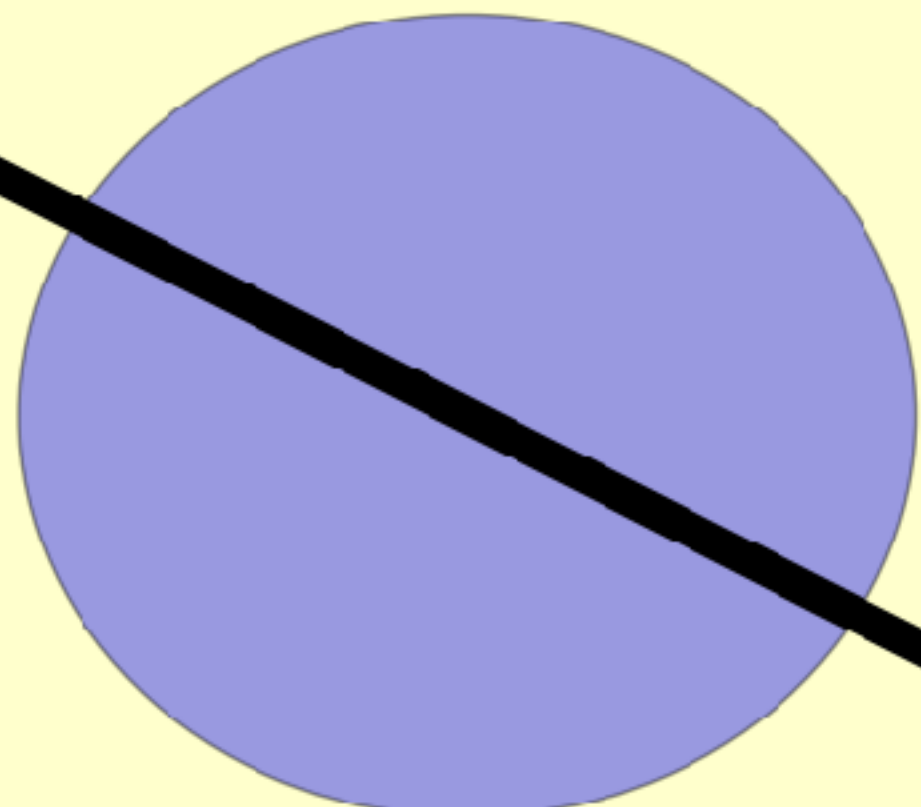
Large Dark Matter Signal
Small Astrophysical Background

Small Dark Matter Signal
Large Astrophysical Background

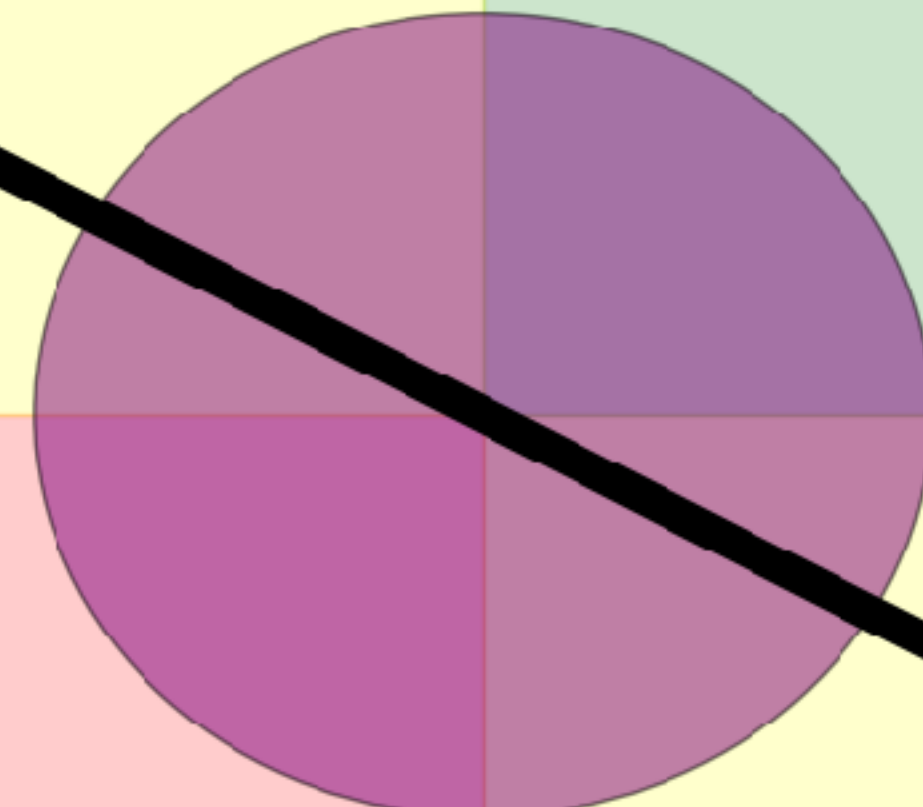
Large Dark Matter Signal
Large Astrophysical Background

Fraction of Dark Matter Flux

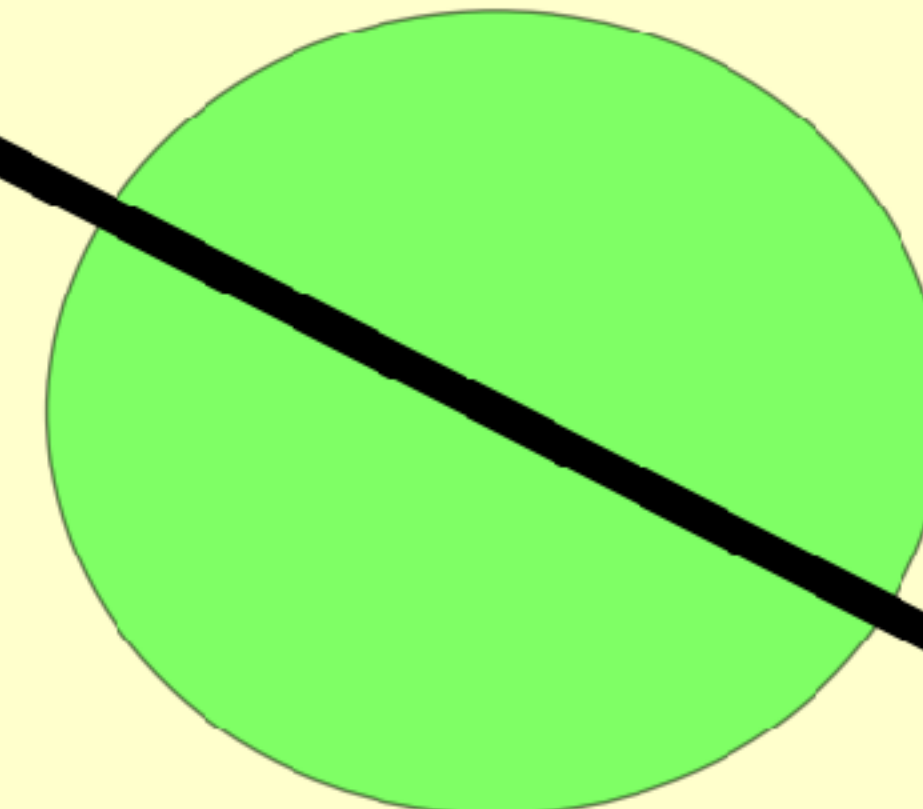
Specificity (DM Flux / Astrophysics Flux)



Anti-Nuclei

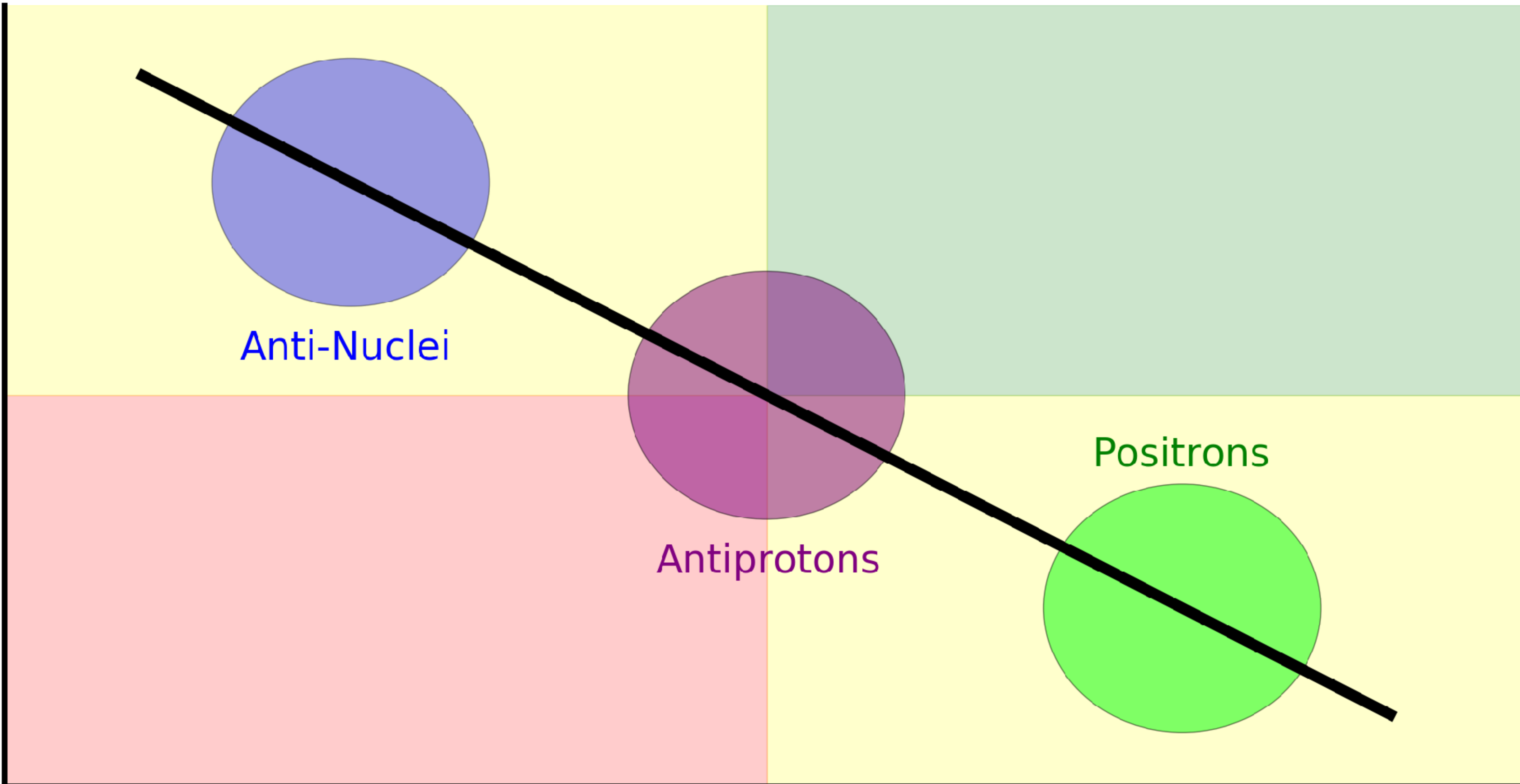
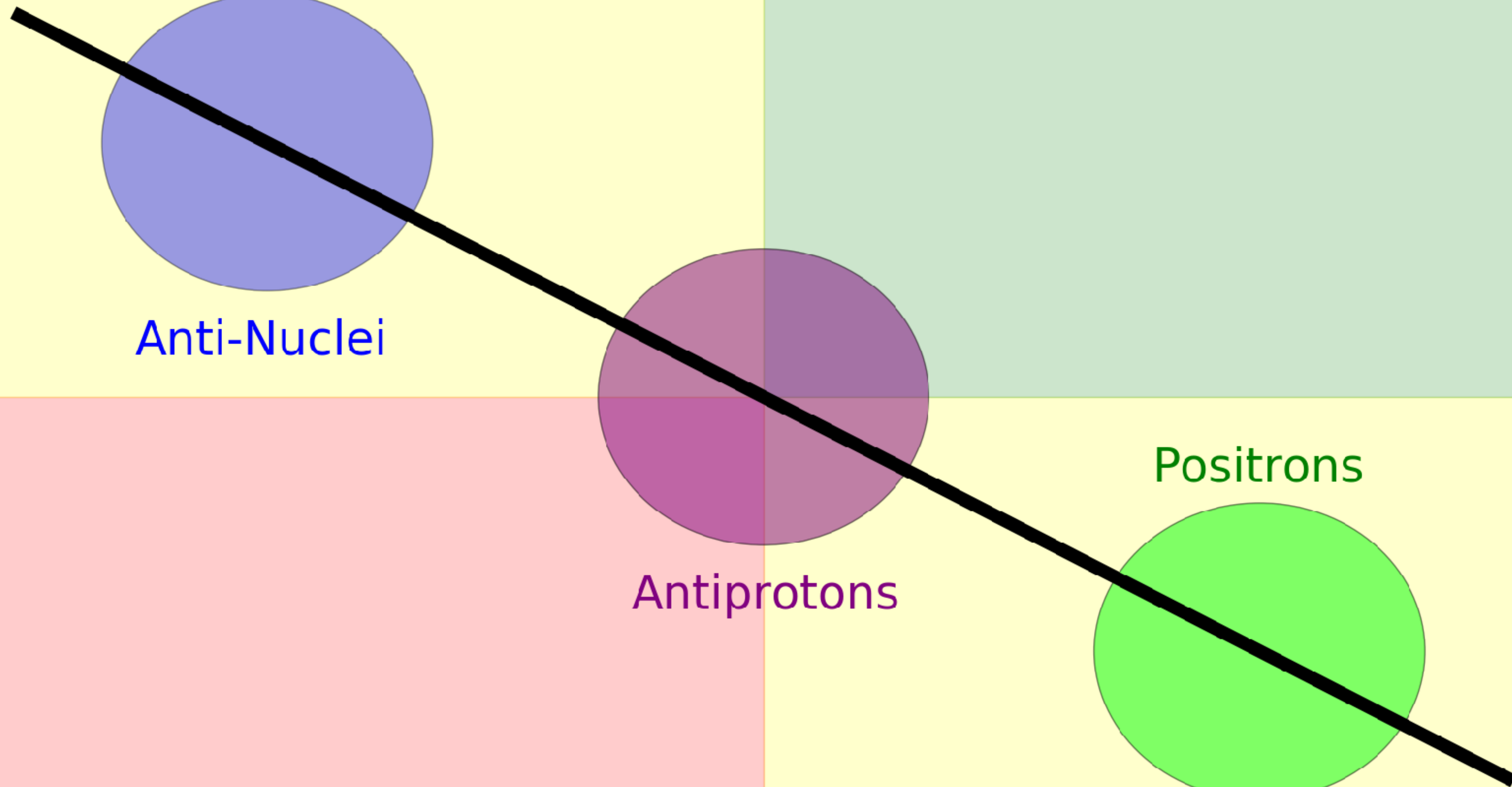


Antiprotons



Positrons

Fraction of Dark Matter Flux



Dark Matter and Astrophysical Fluxes

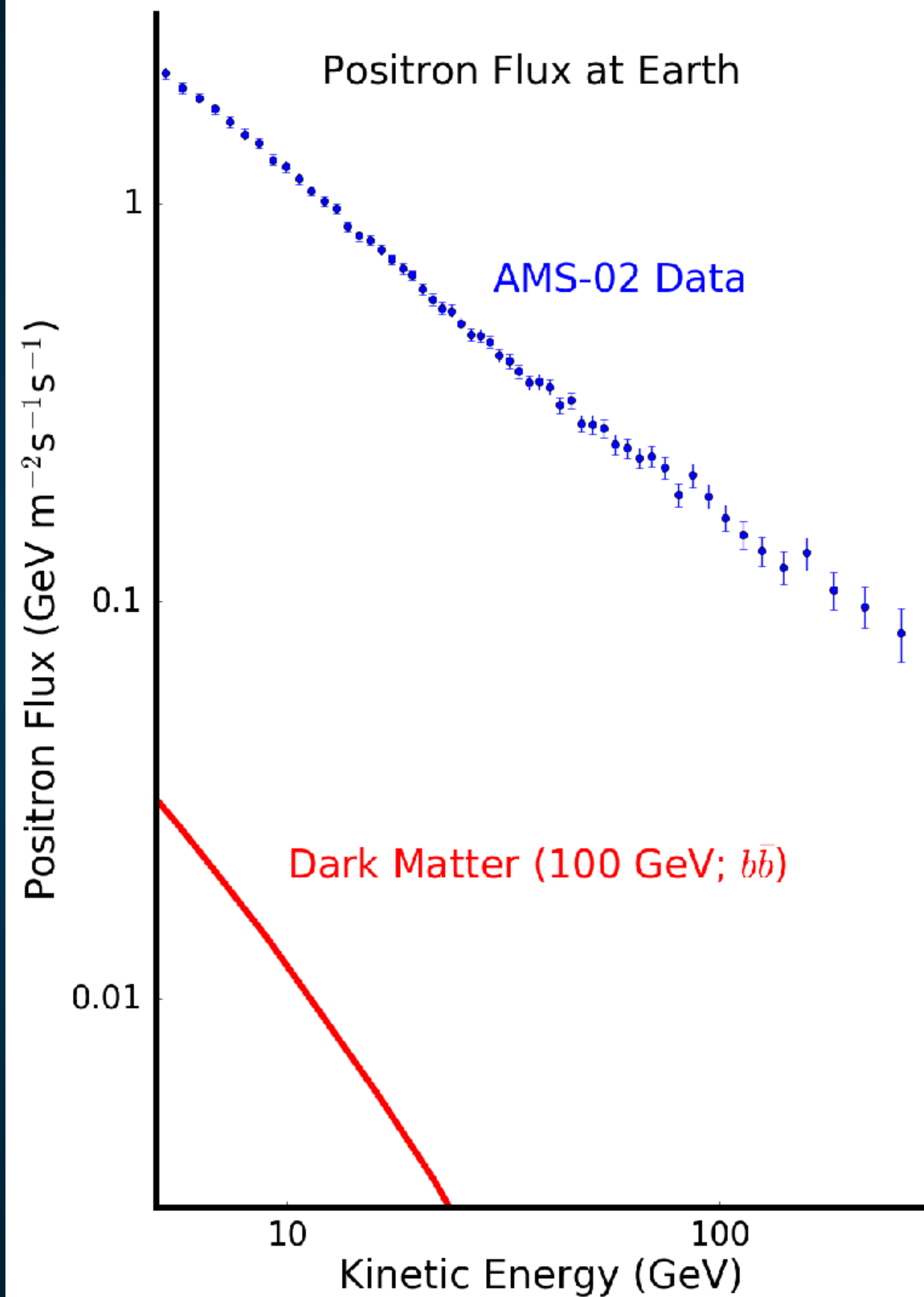
Local Dark Matter Density

Thermal Cross-Section (Early Universe)

Leptonic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

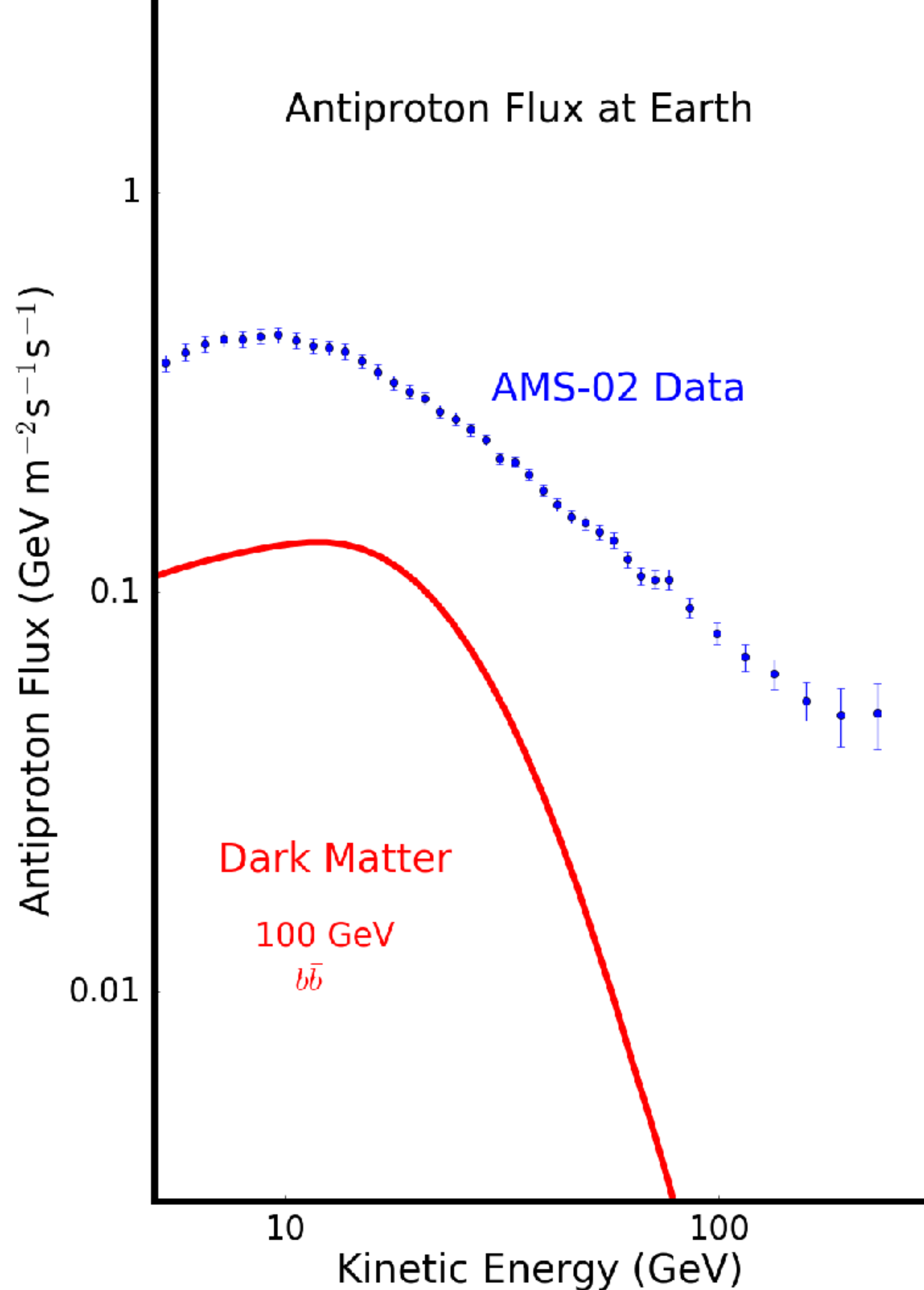
Astrophysical Flux ~ **100x larger**



Dark Matter and Astrophysical Fluxes

- Local Dark Matter Density
- Thermal Cross-Section (Early Universe)
- Hadronic Component of Dark Matter Final State
- Convection of Annihilation Products from GC (Winds?)

Astrophysical Flux ~ **10x larger**



Dark Matter and Astrophysical Fluxes

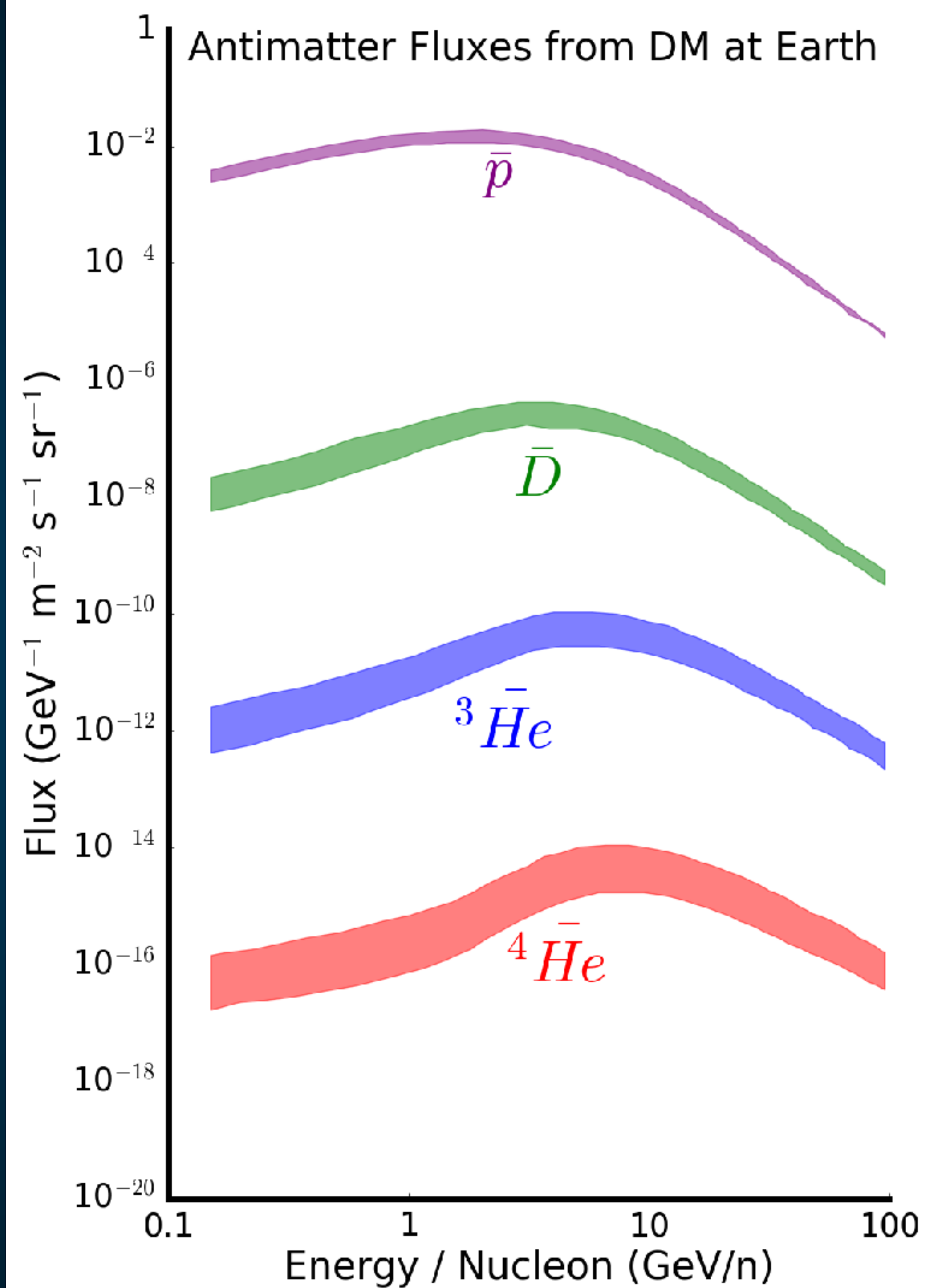
Local Dark Matter Density

Thermal Cross-Section (Early Universe)

Coalescence of baryons into heavier nuclei

Convection of Annihilation Products from GC (Winds?)

Astrophysical Flux - **Undetected, likely much lower**



Specificity (DM Flux / Astrophysics Flux)

Small Dark Matter Signal
Small Astrophysical Background

Instrumentation is Hard

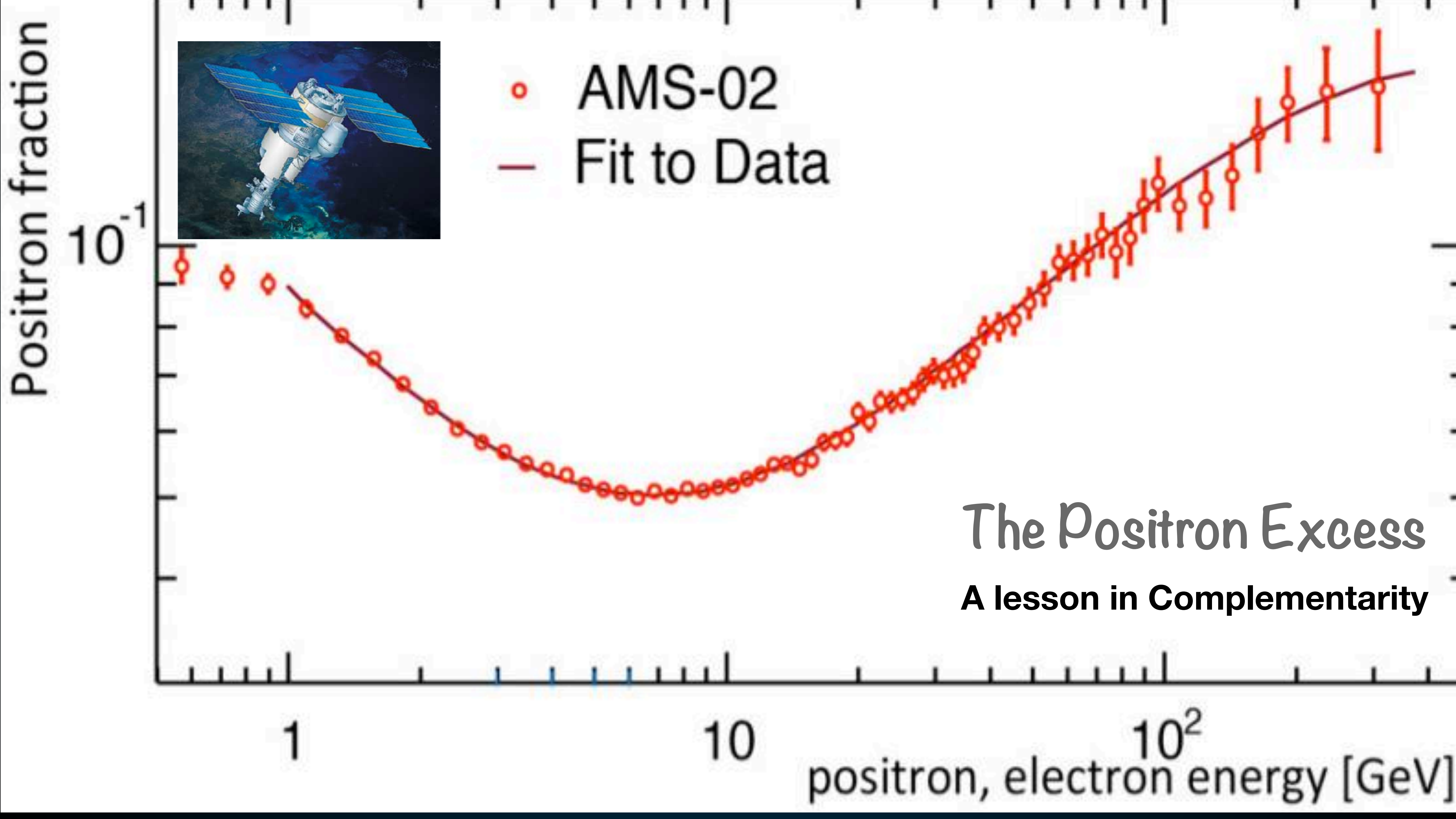
Large Dark Matter Signal
Small Astrophysical Background

Small Dark Matter Signal
Large Astrophysical Background

Modeling is Hard

Large Dark Matter Signal
Large Astrophysical Background

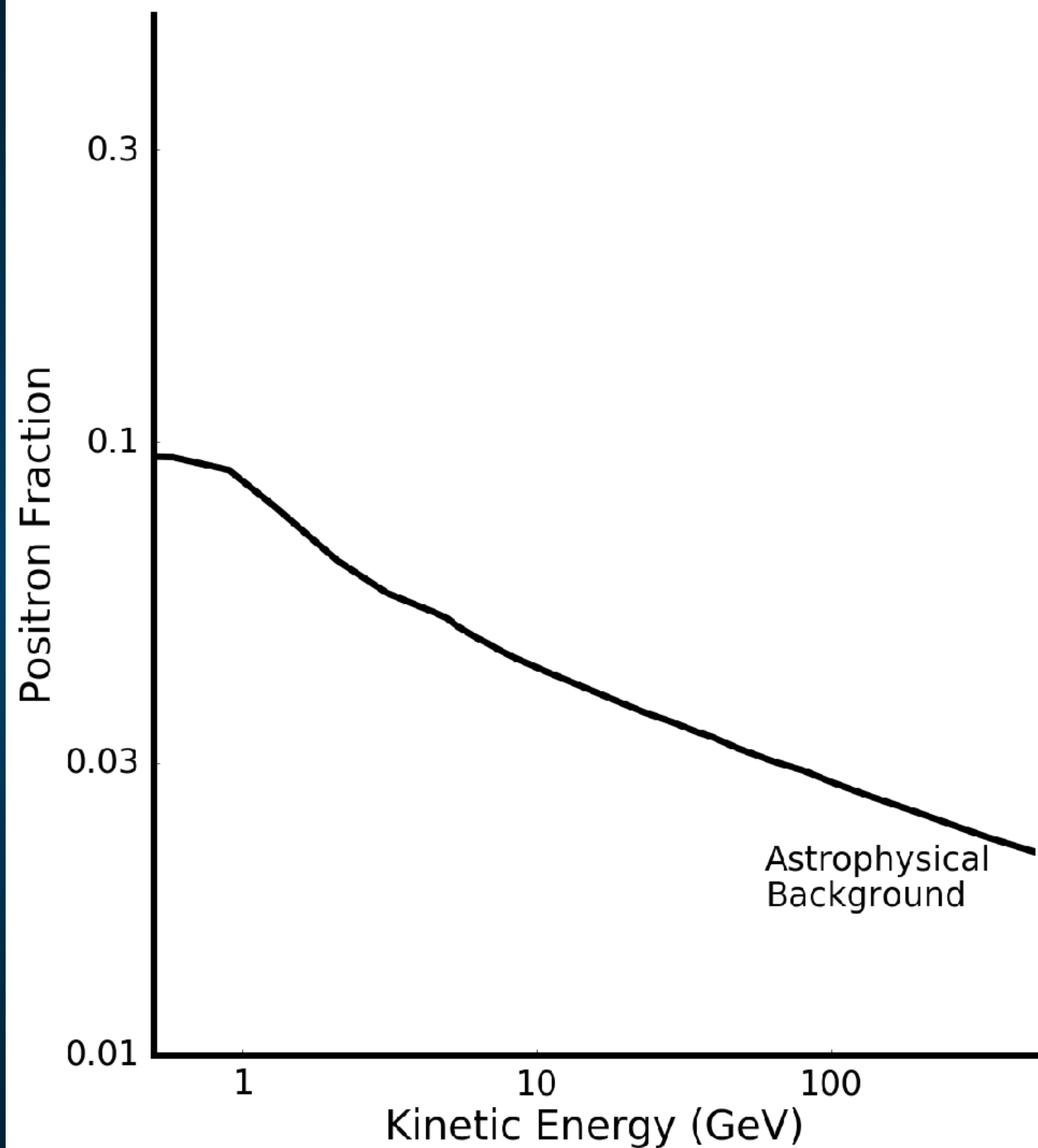
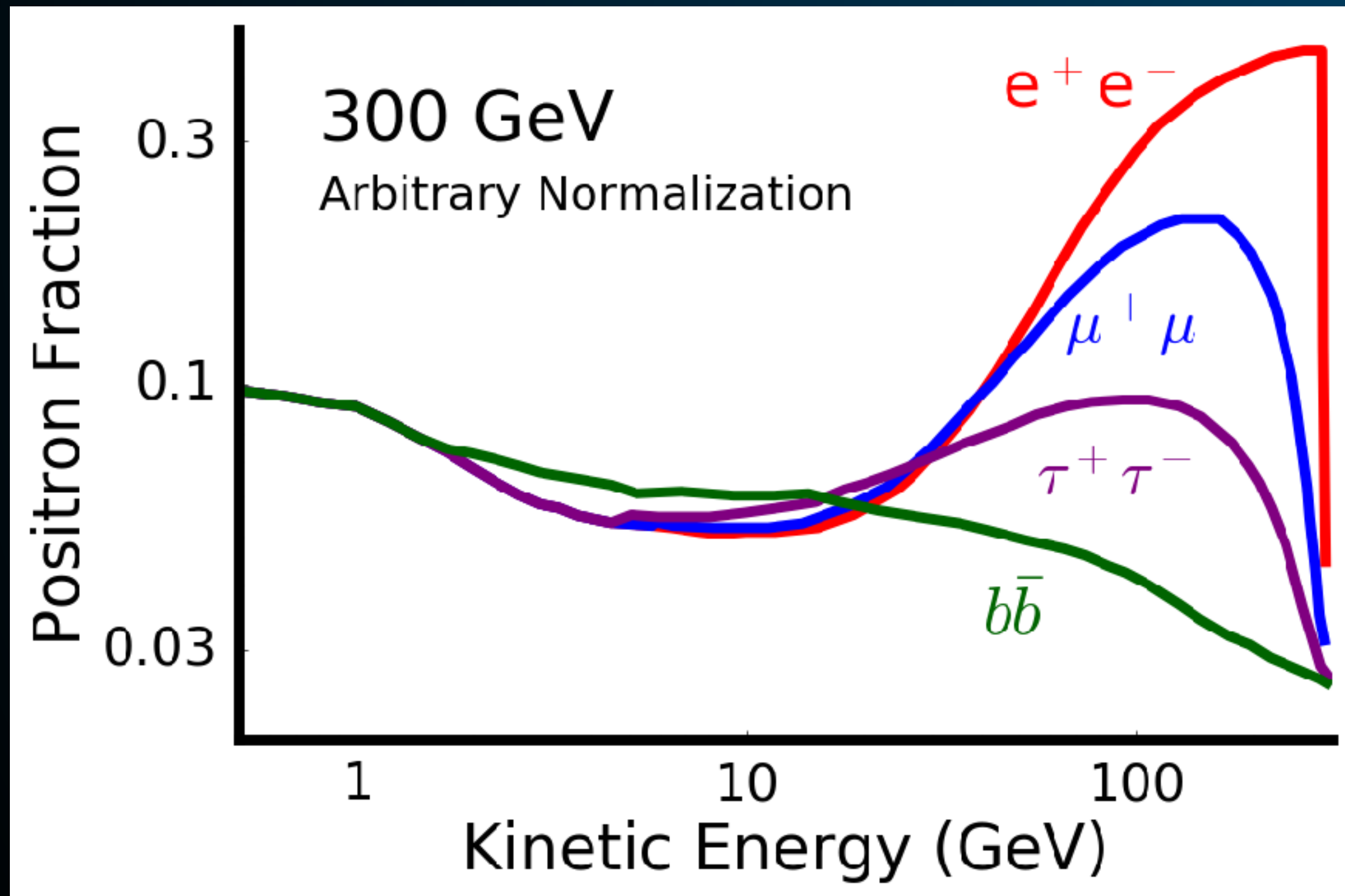
Fraction of Dark Matter Flux



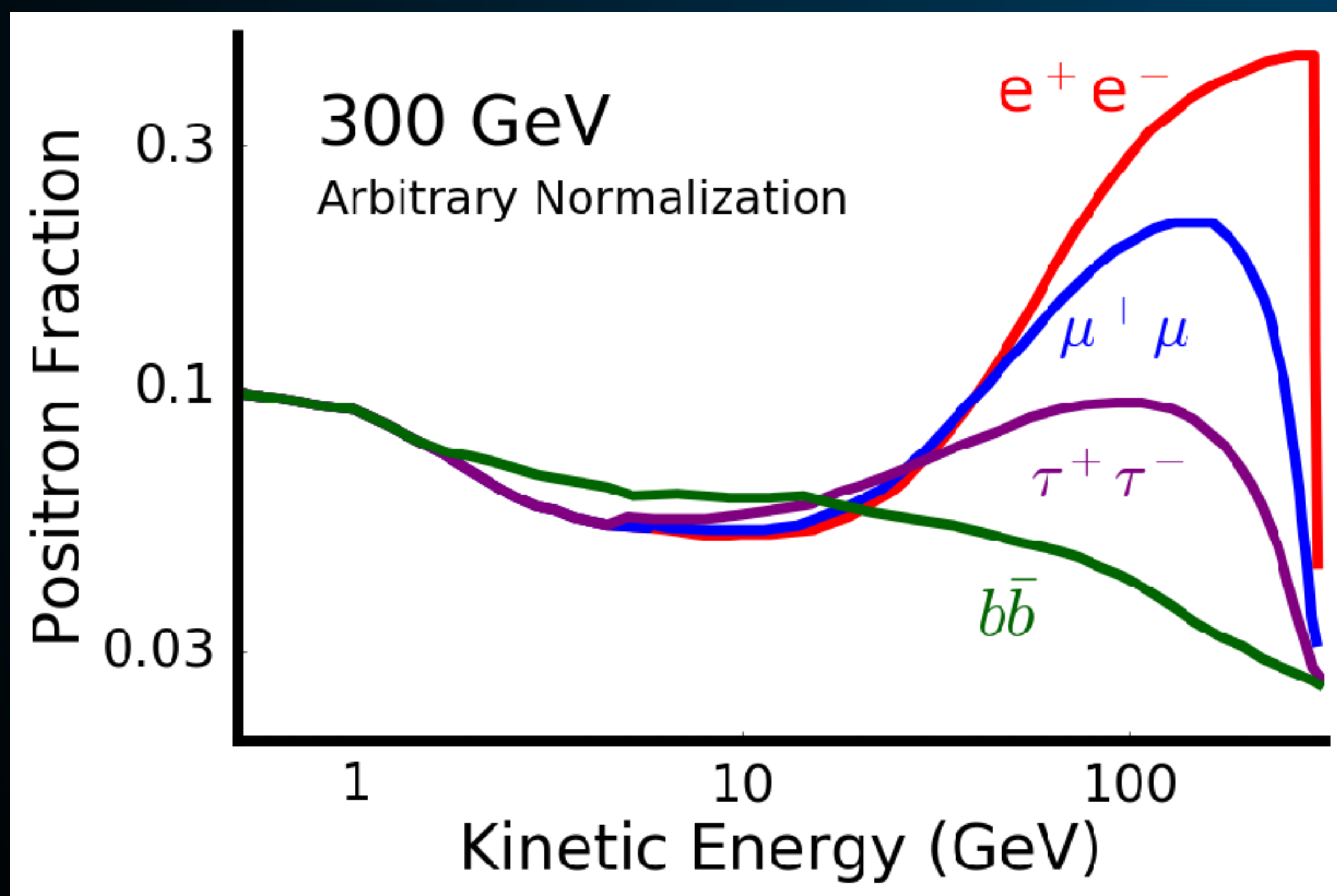
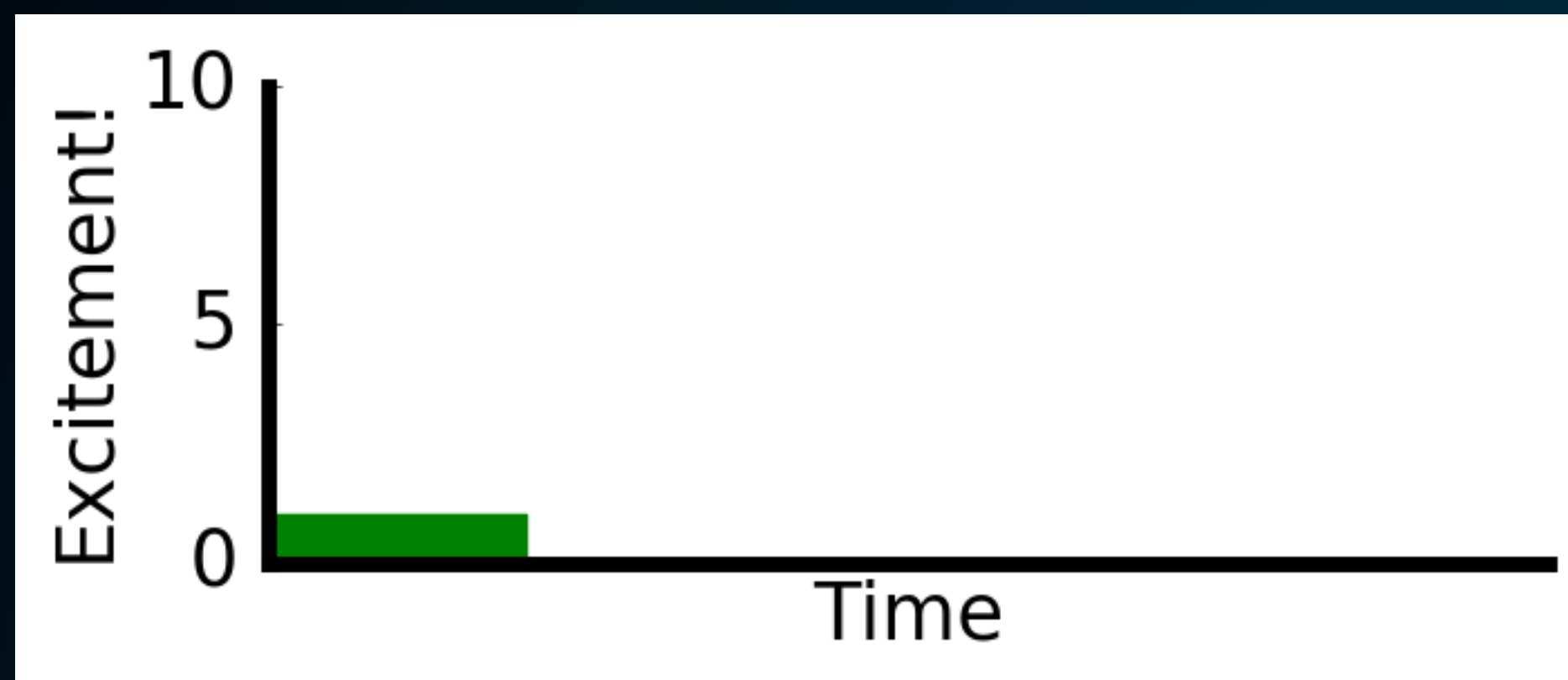
The Positron Excess

Astrophysics - Slowly Decreasing

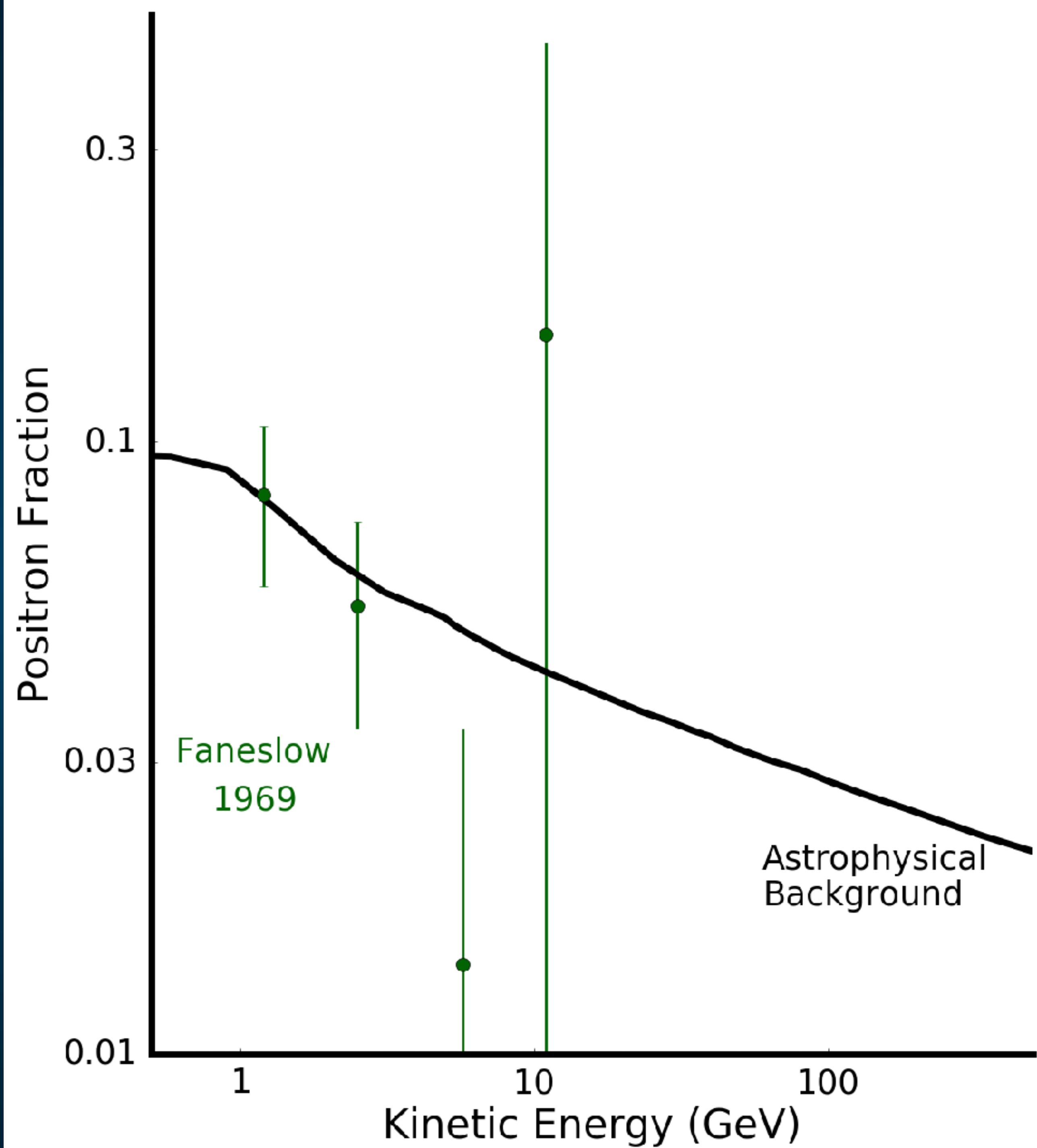
Dark Matter - Sharp Bump!



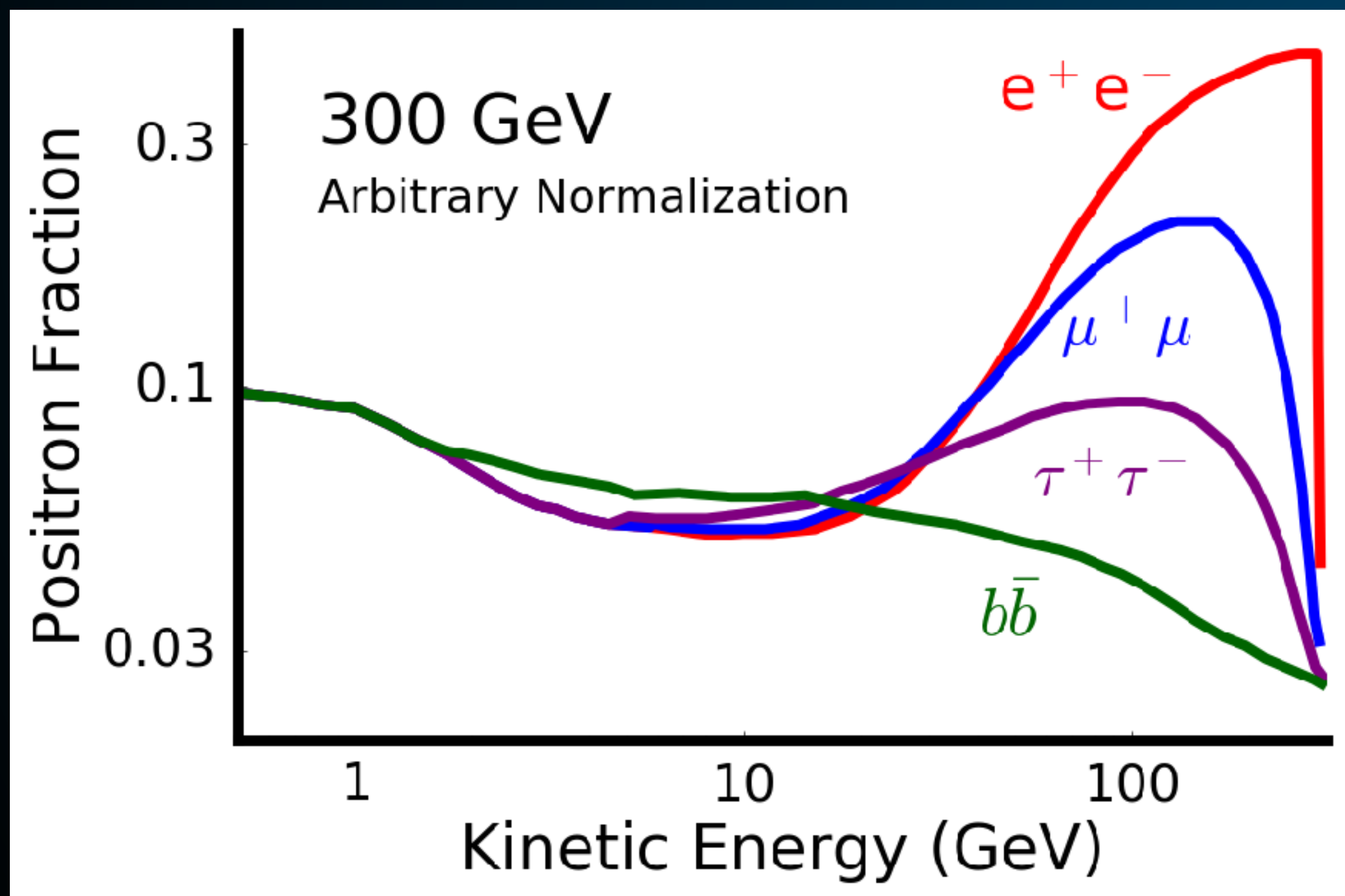
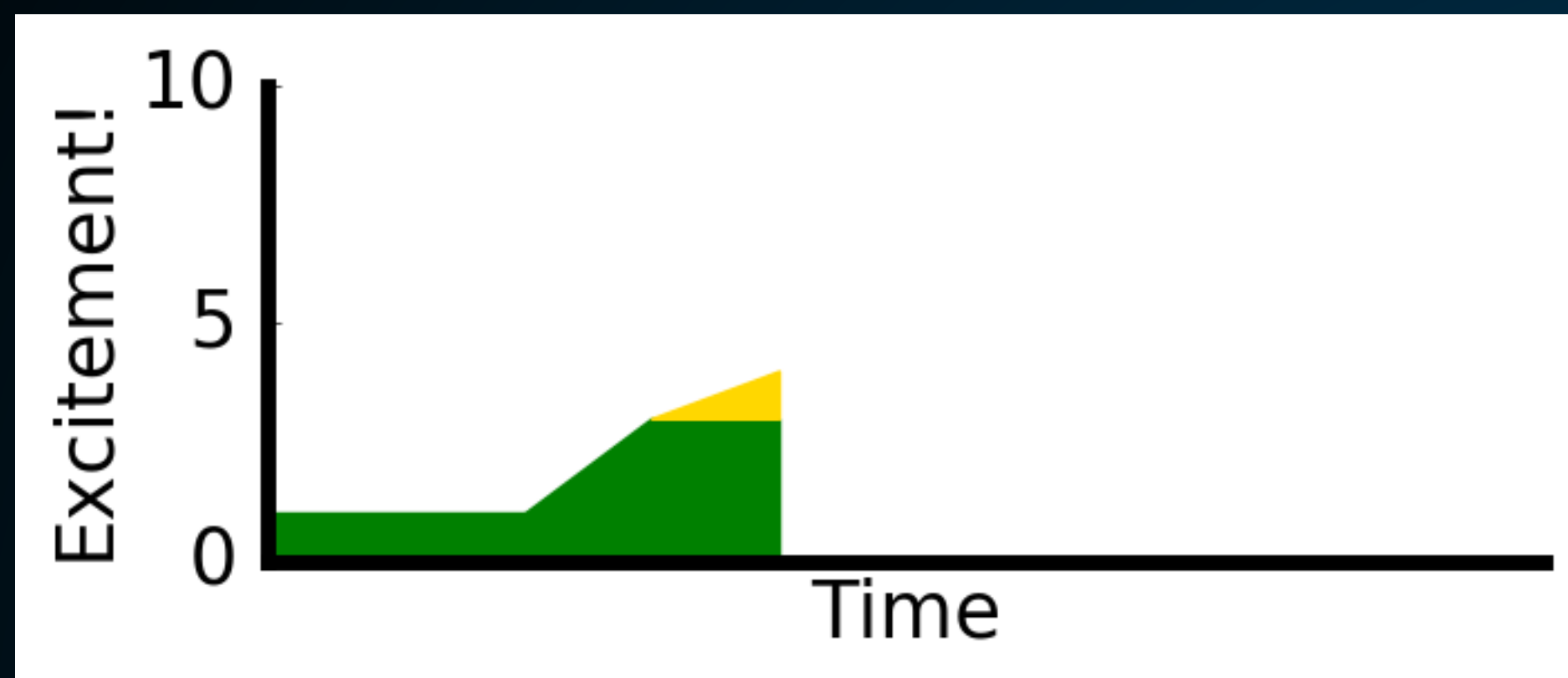
The Positron Excess



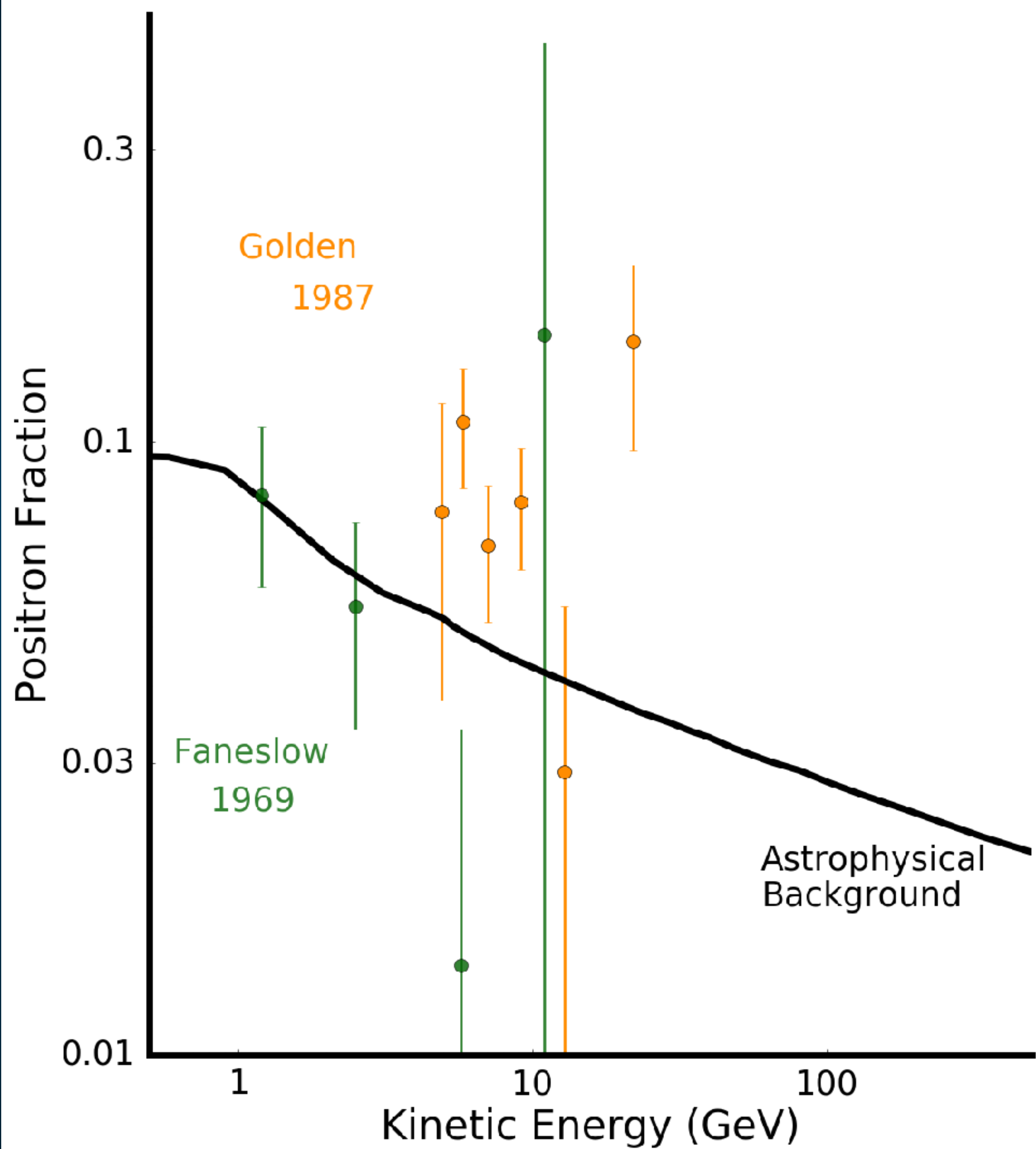
(Not an exhaustive list of observations)



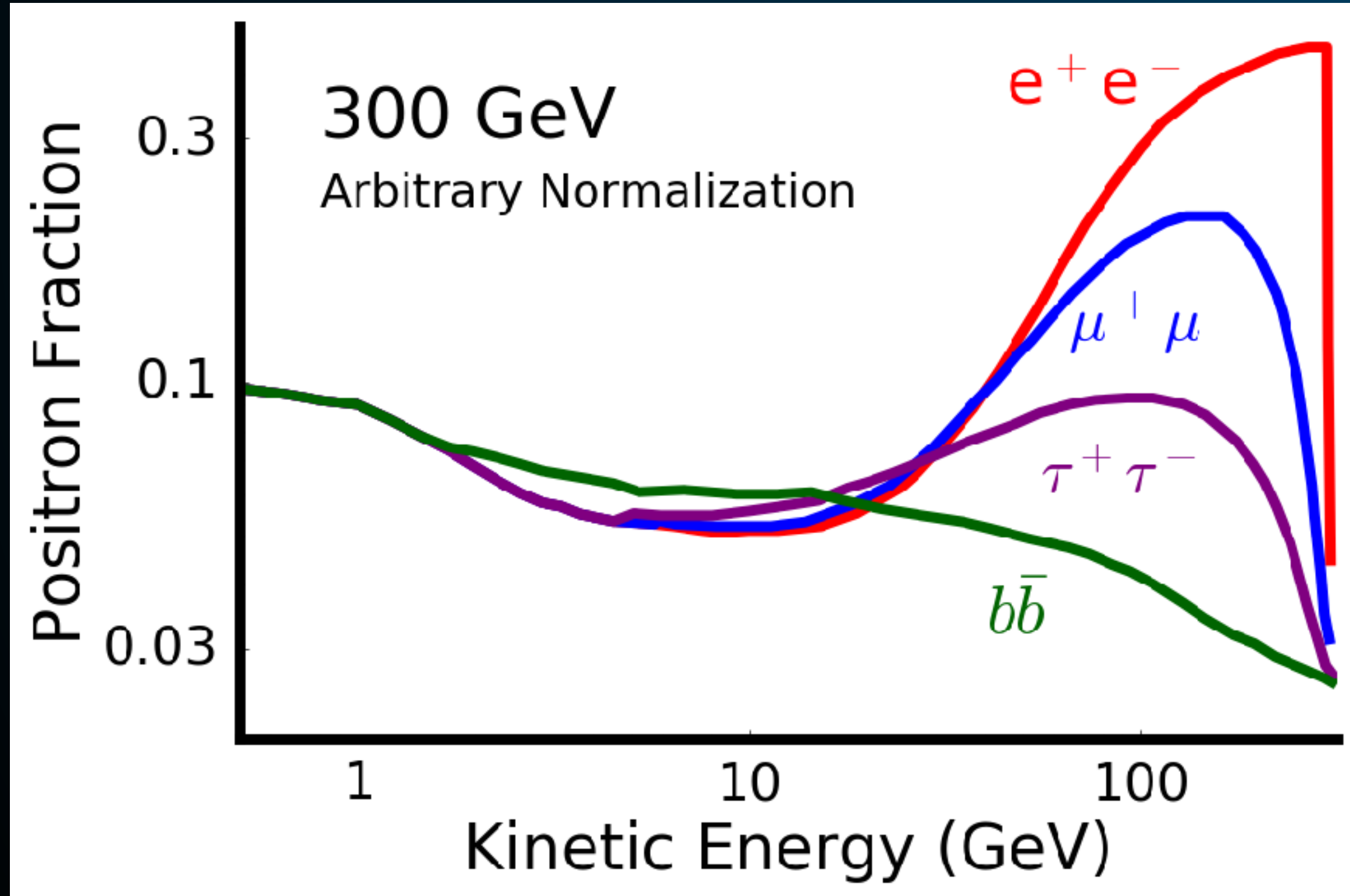
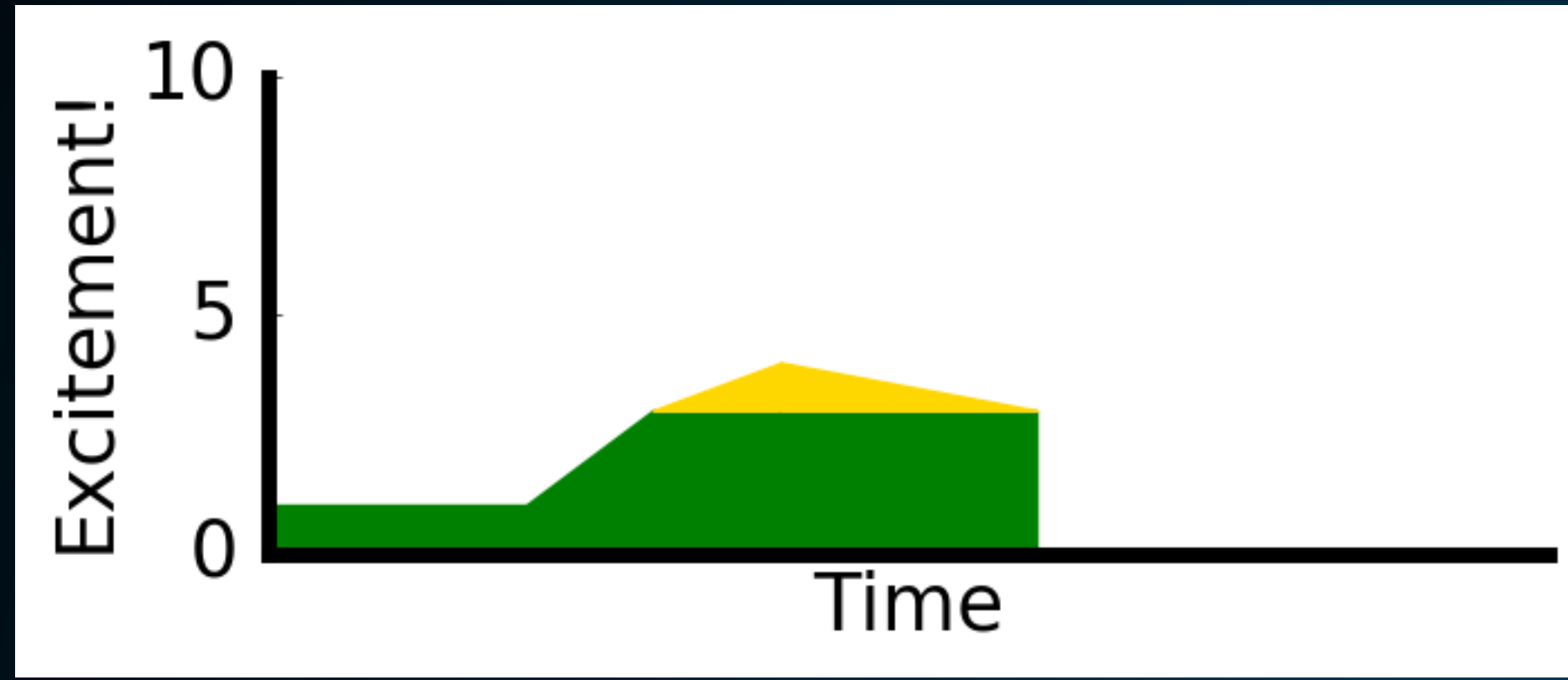
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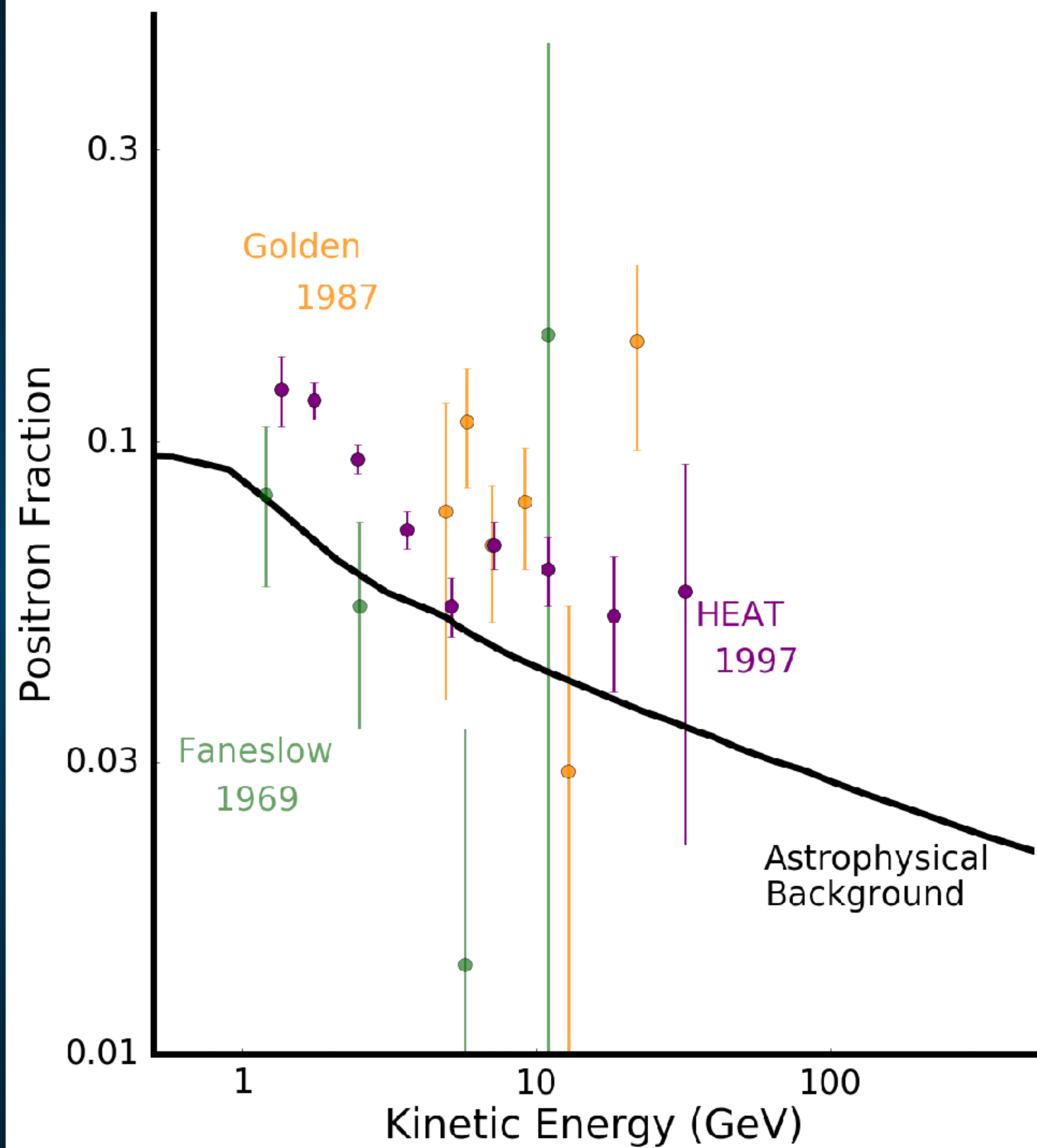
(Not an exhaustive list of observations)



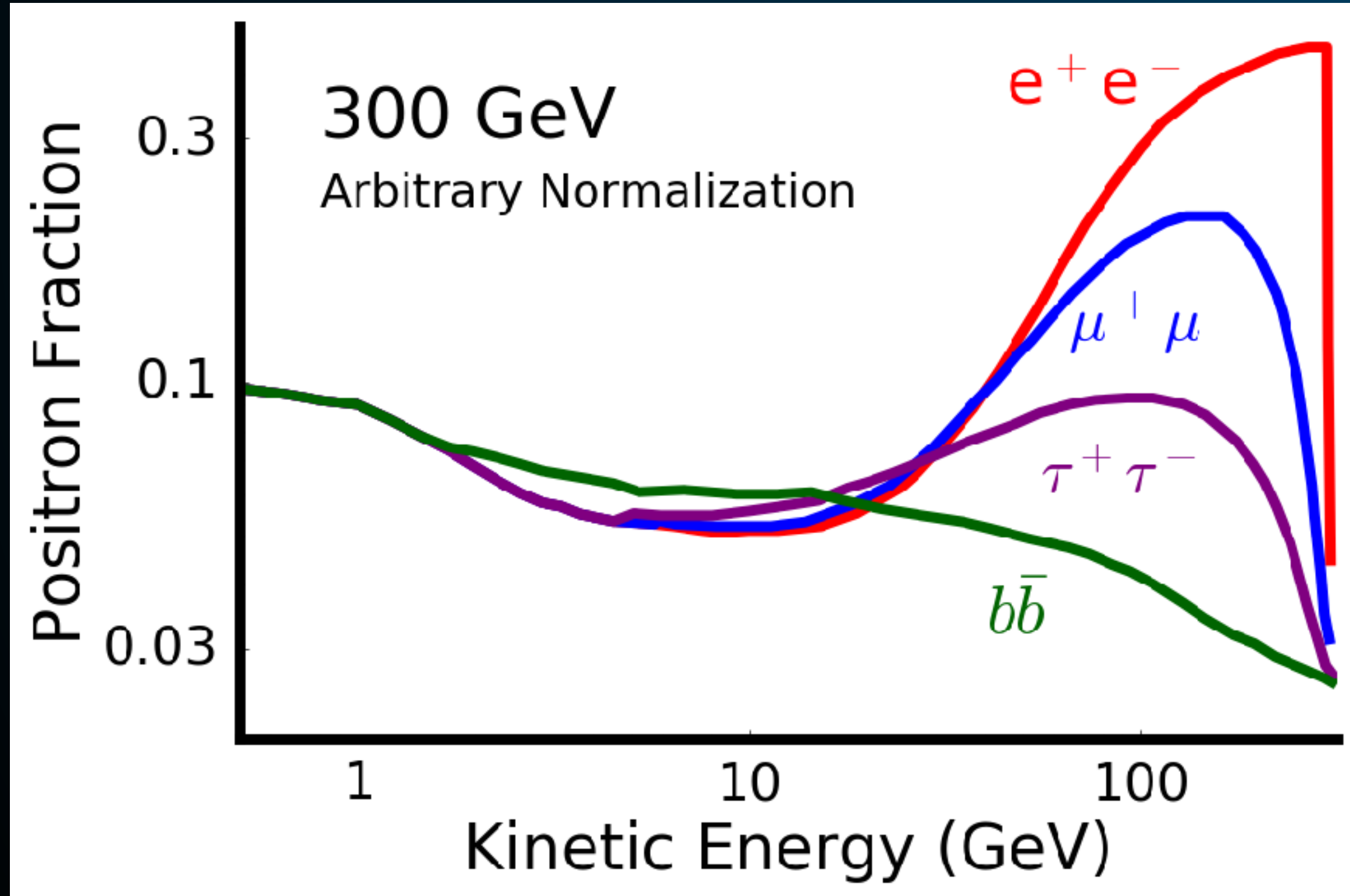
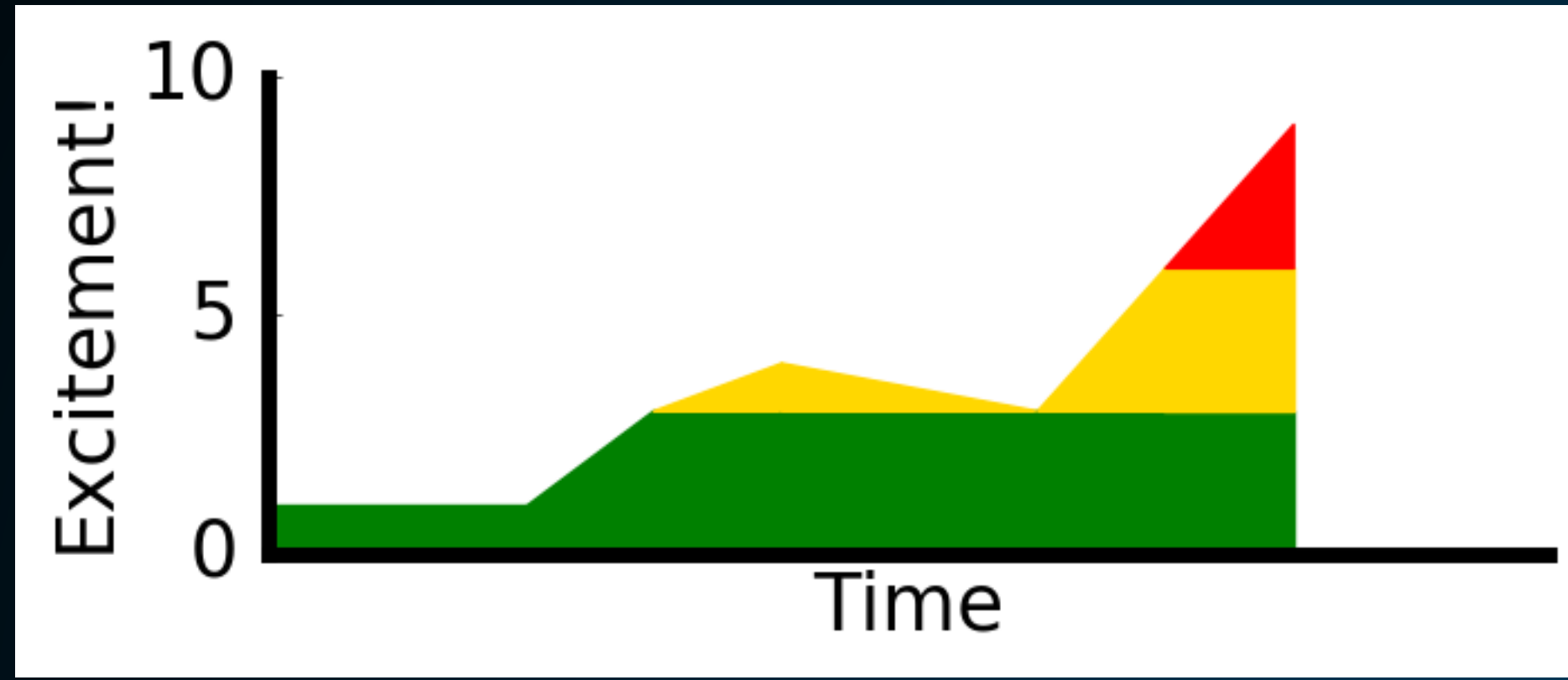
The Positron Excess



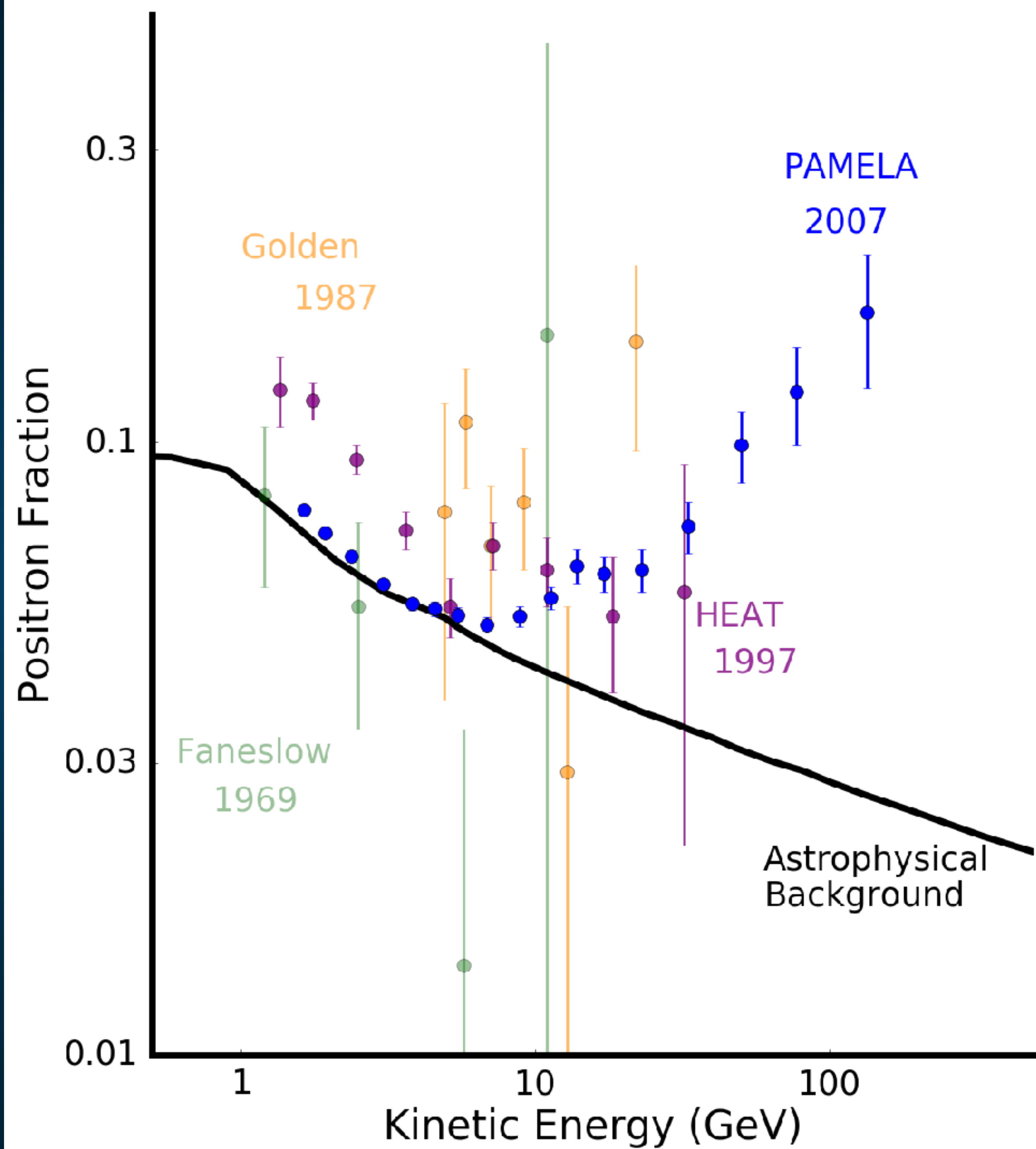
(Not an exhaustive list of observations)



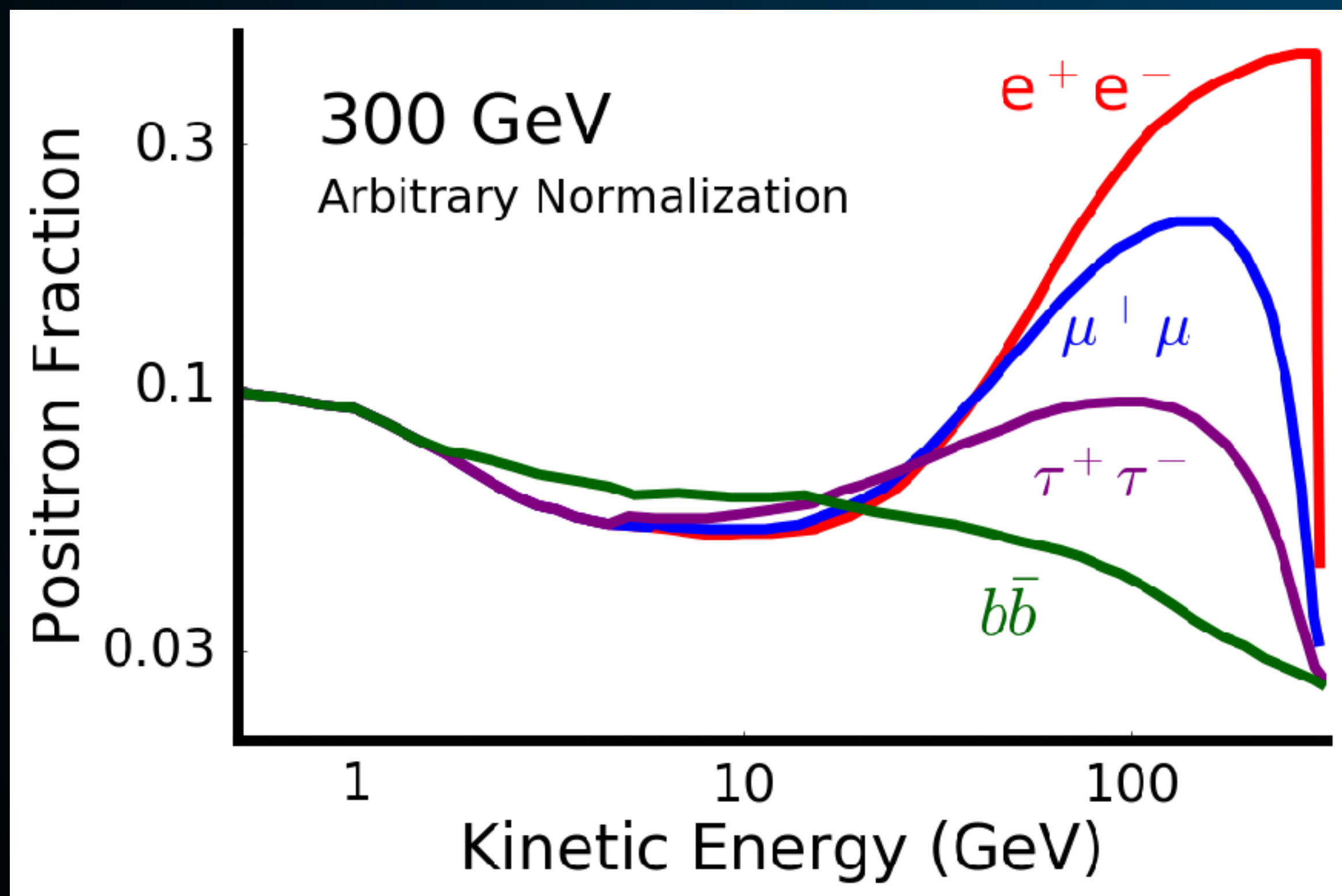
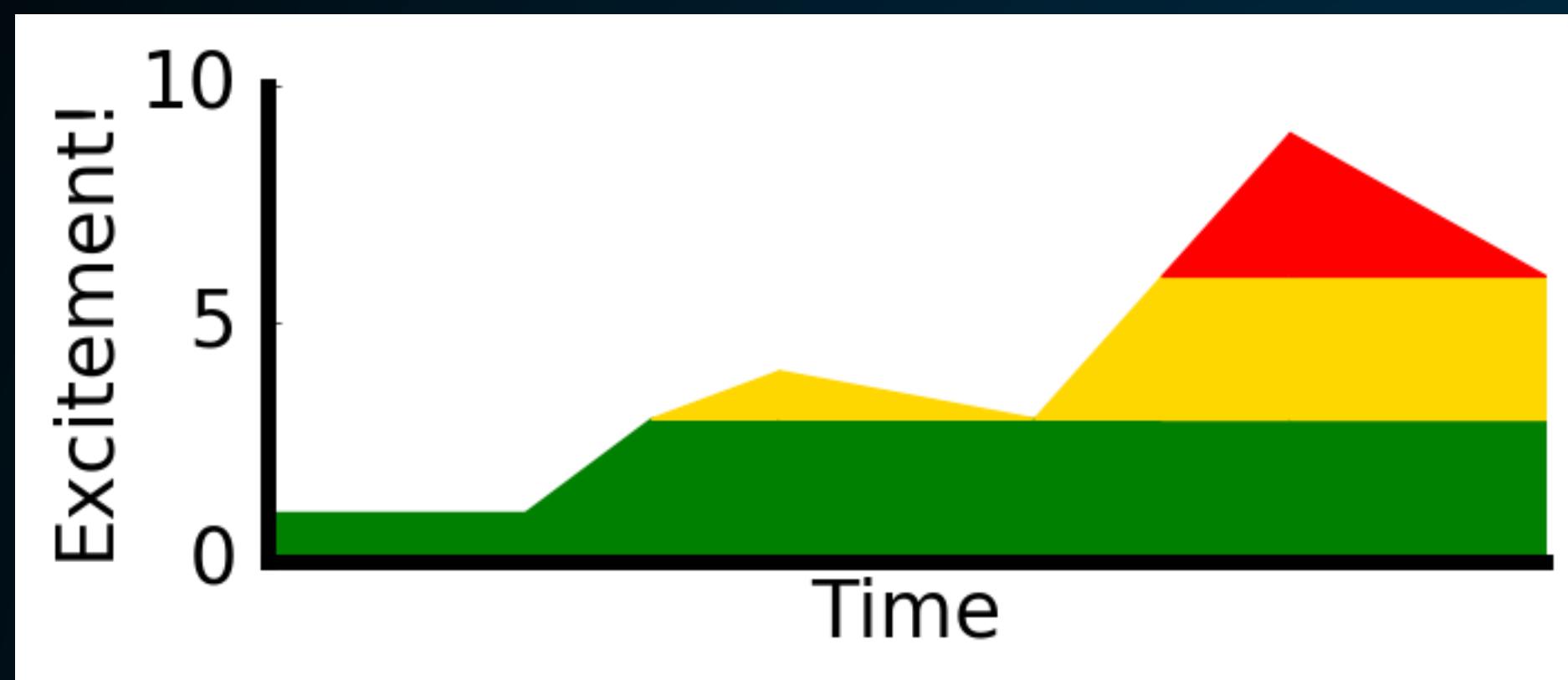
The Positron Excess



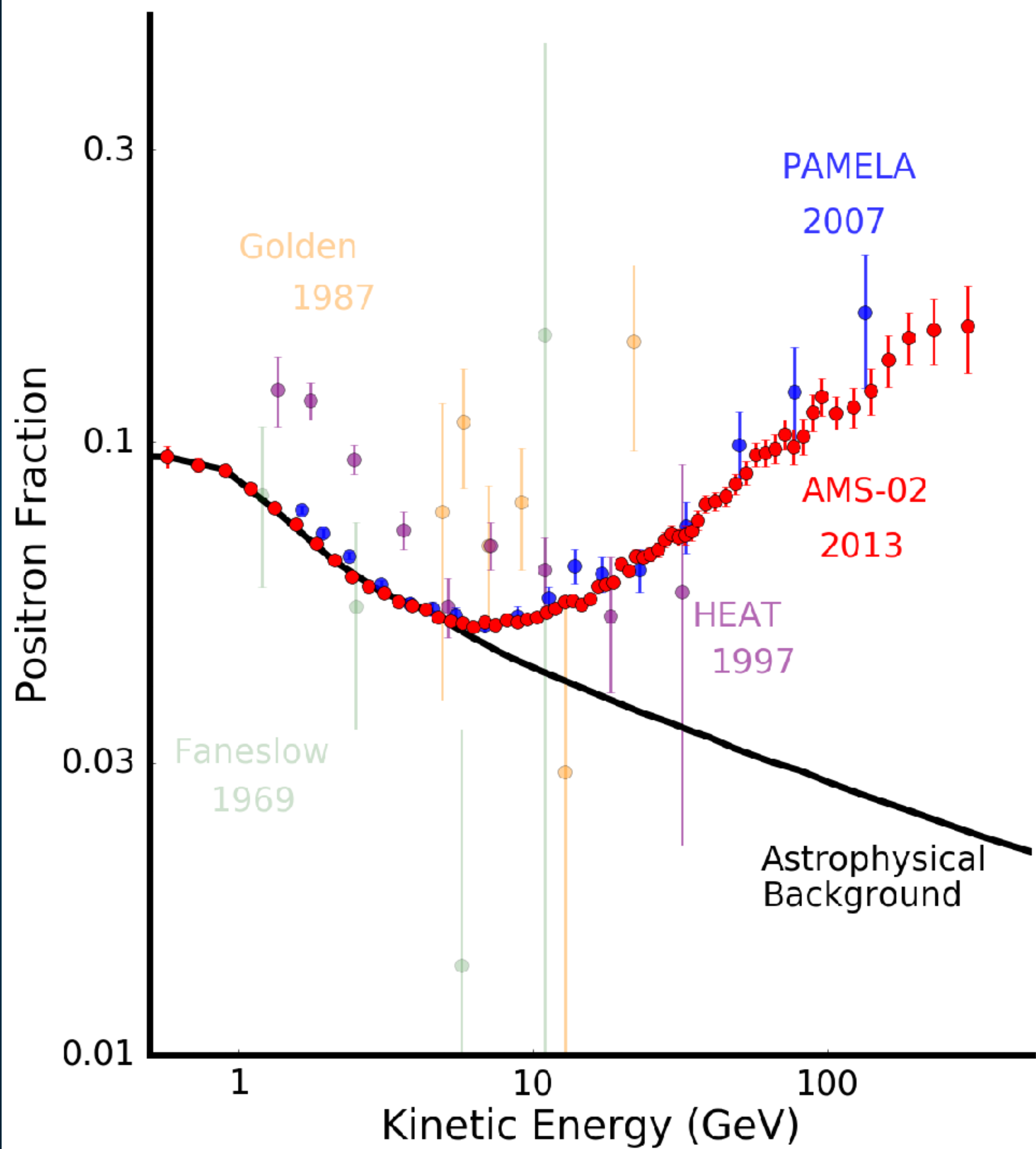
(Not an exhaustive list of observations)



The Positron Excess



(Not an exhaustive list of observations)

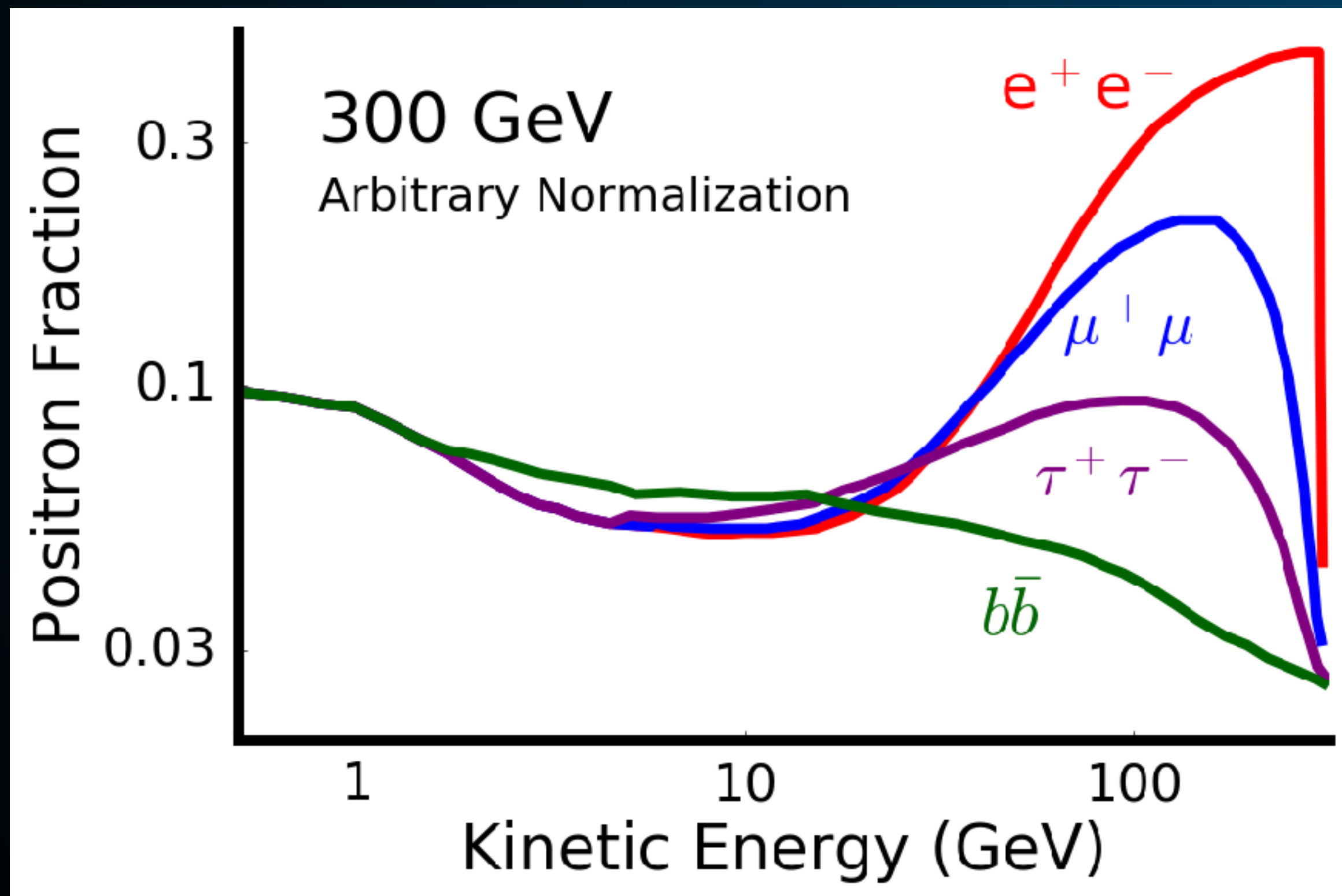


The Positron Excess

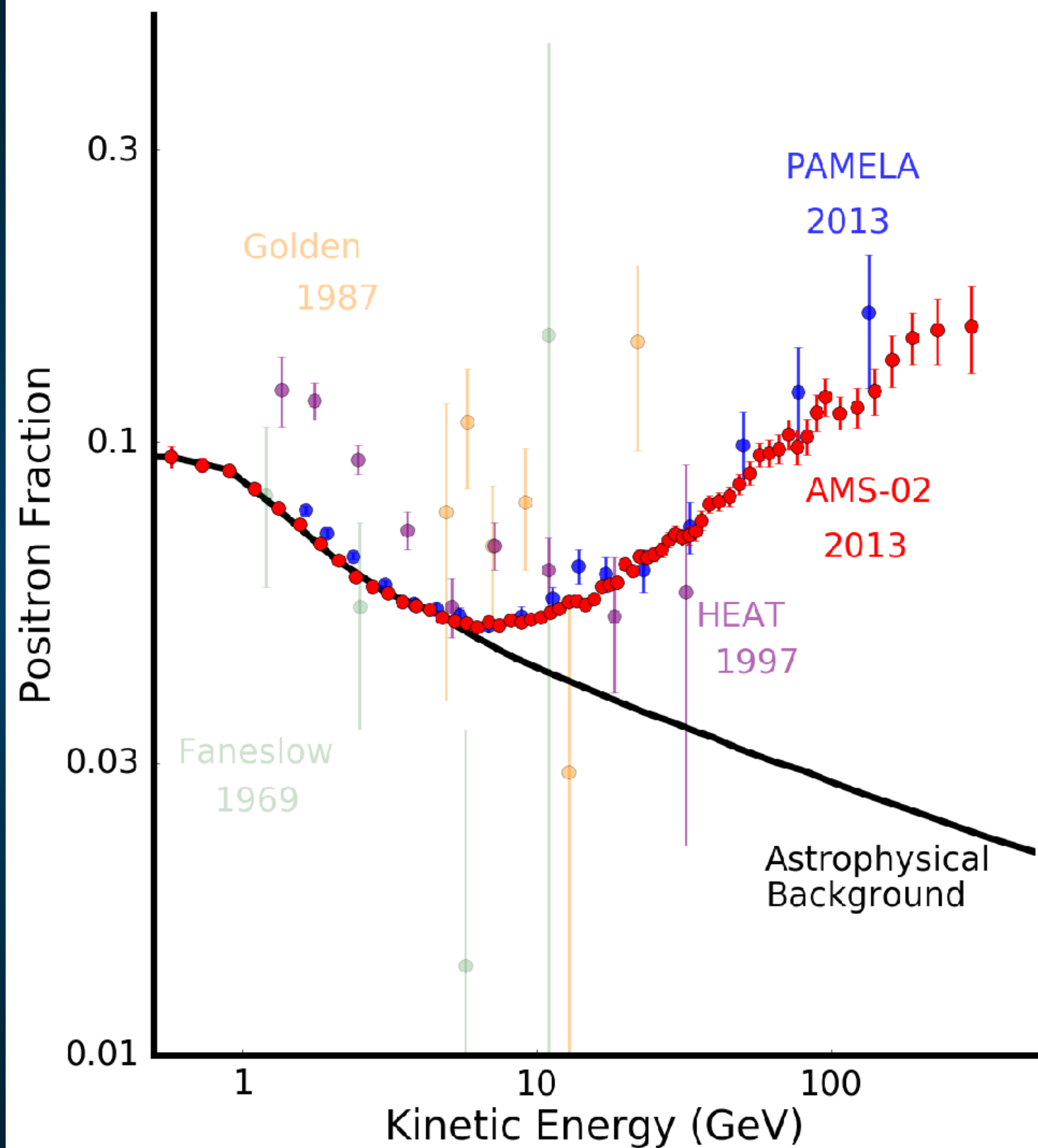
Why Less Excitement?

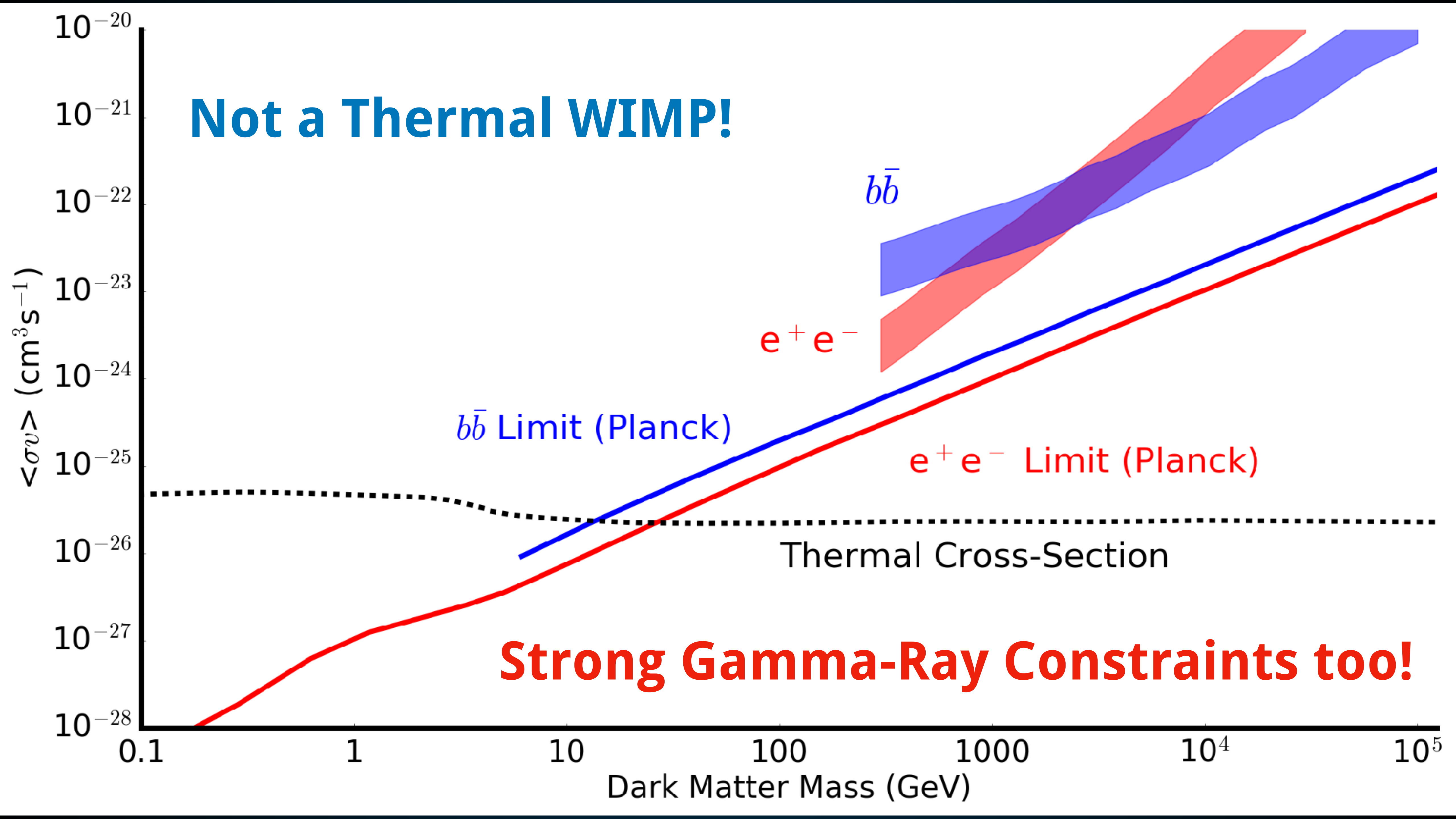
Continues to Higher Mass

Spectrum Relatively Smooth



(Not an exhaustive list of observations)



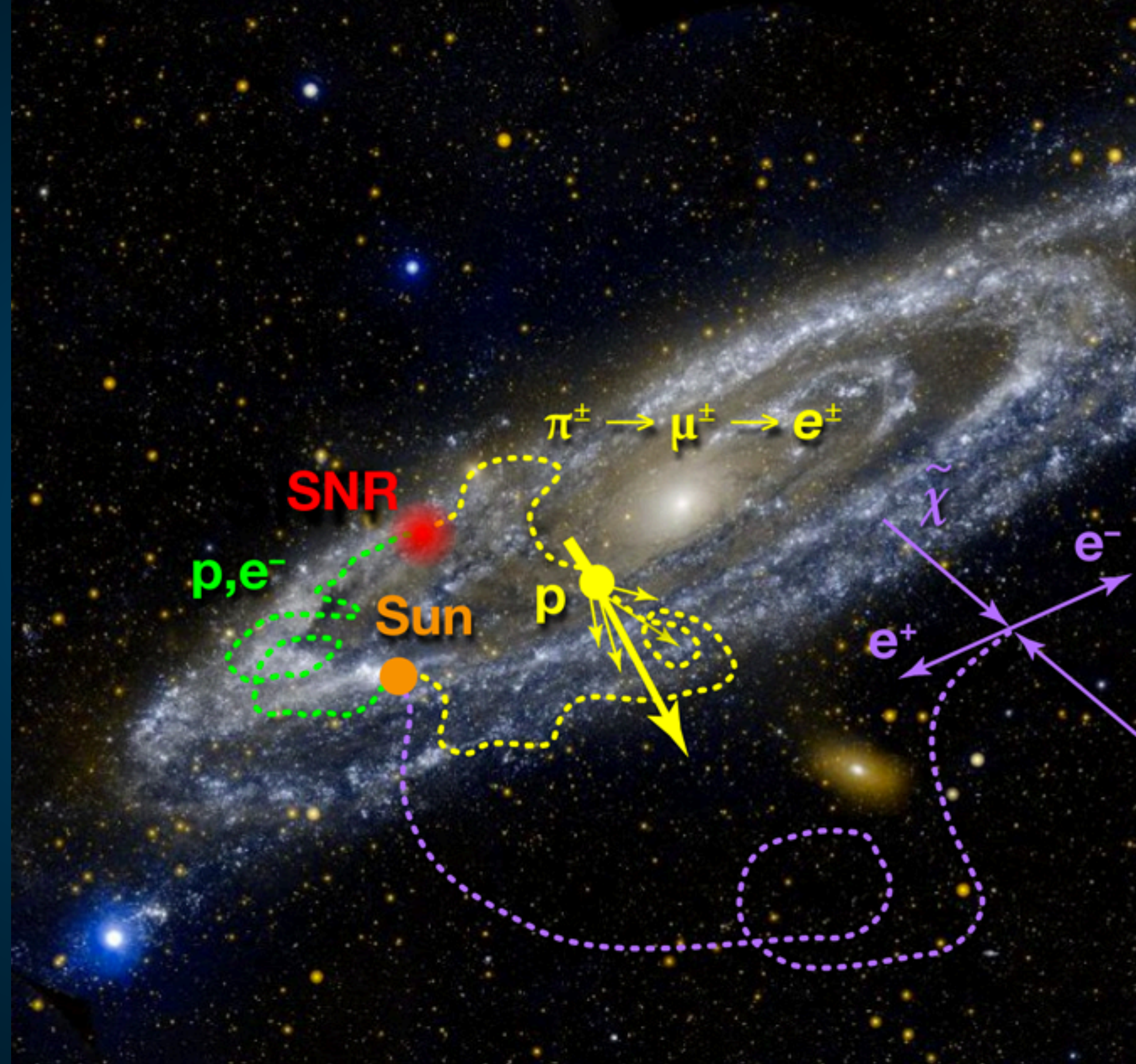
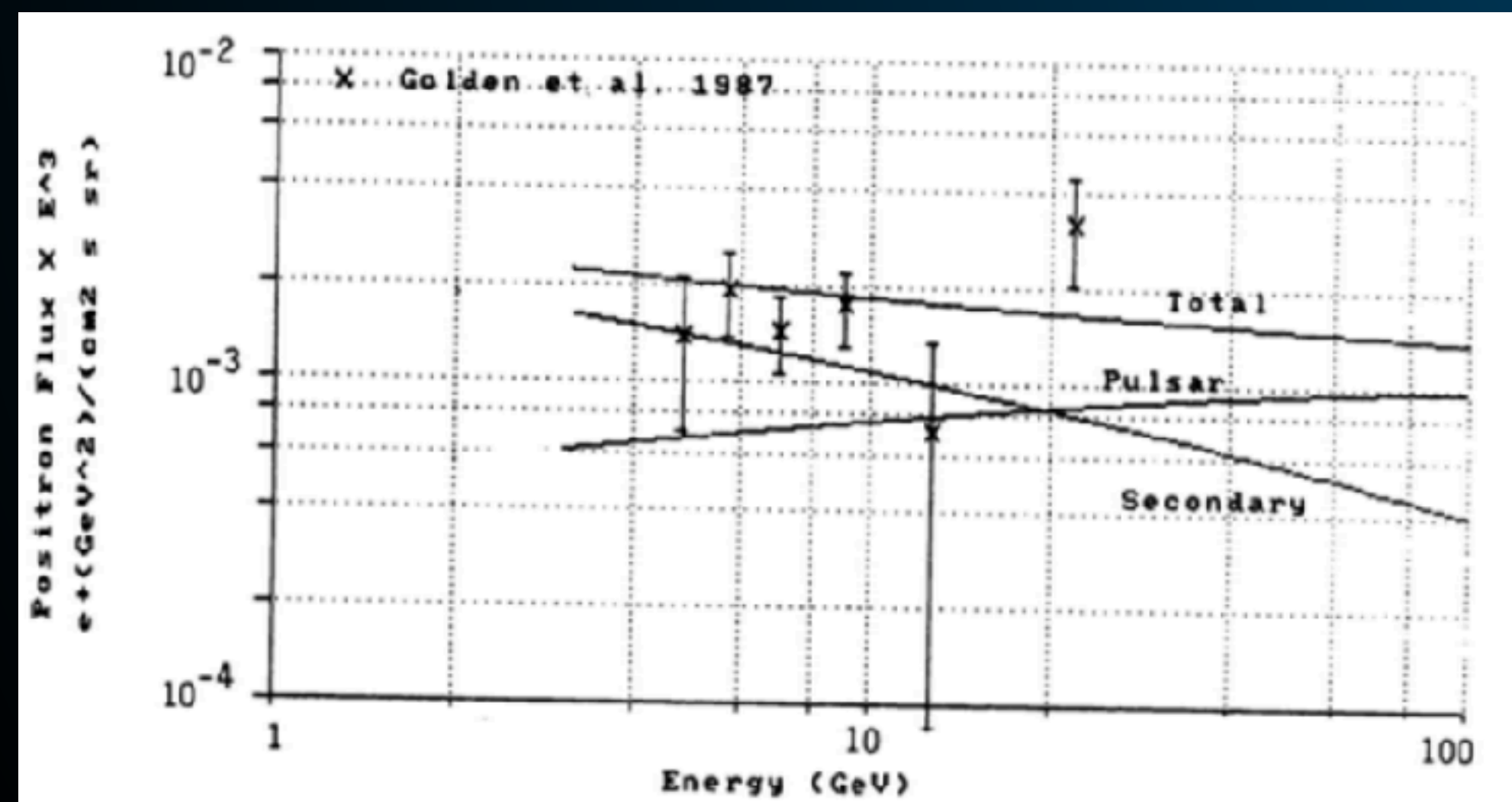


The Positron Excess

Key Idea: Investigate the Positron Fraction!

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

Harding & Ramaty (ICRC! 1987)

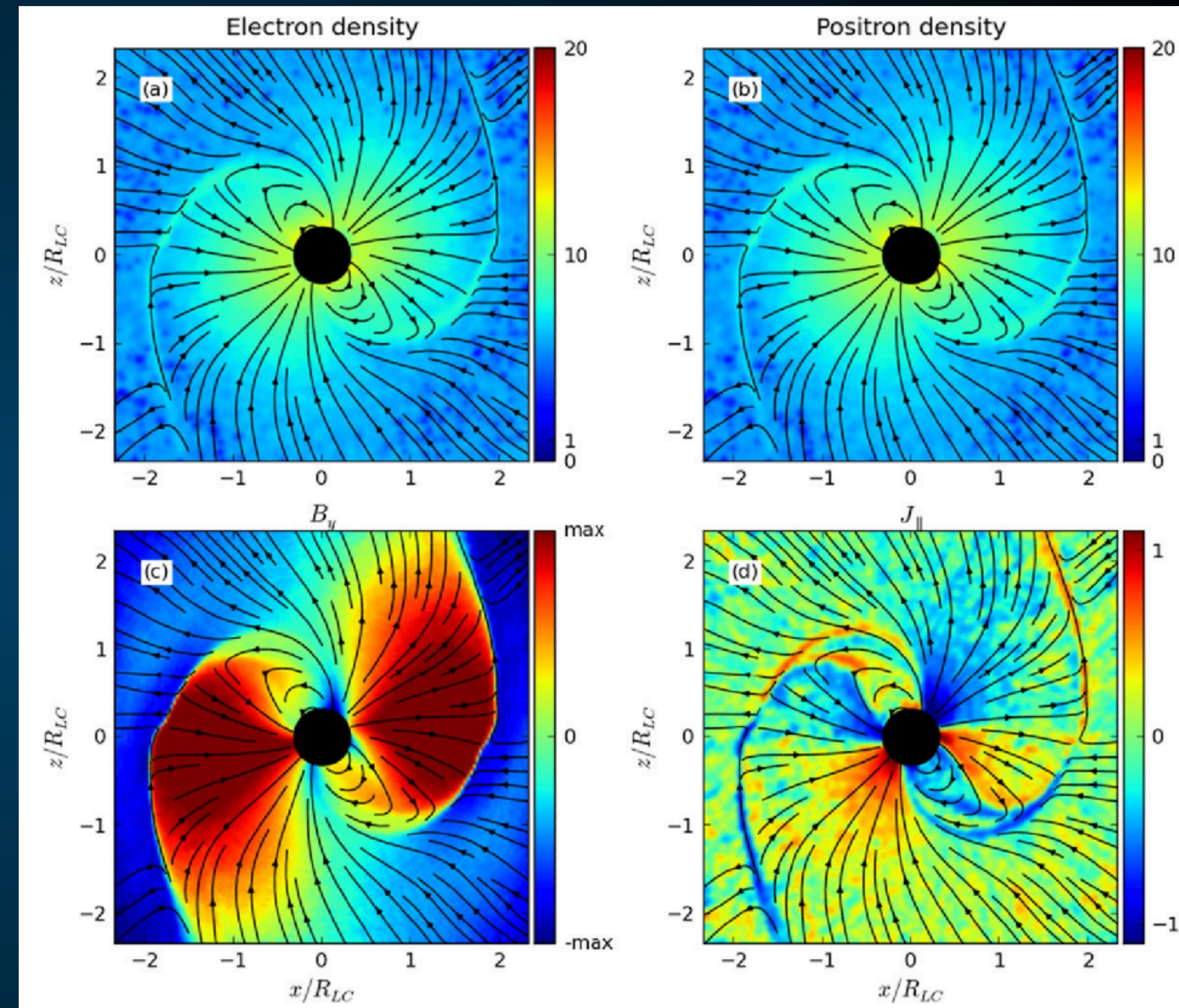


► Uncertainties in pulsar models:

► I: The e^+e^- production efficiency

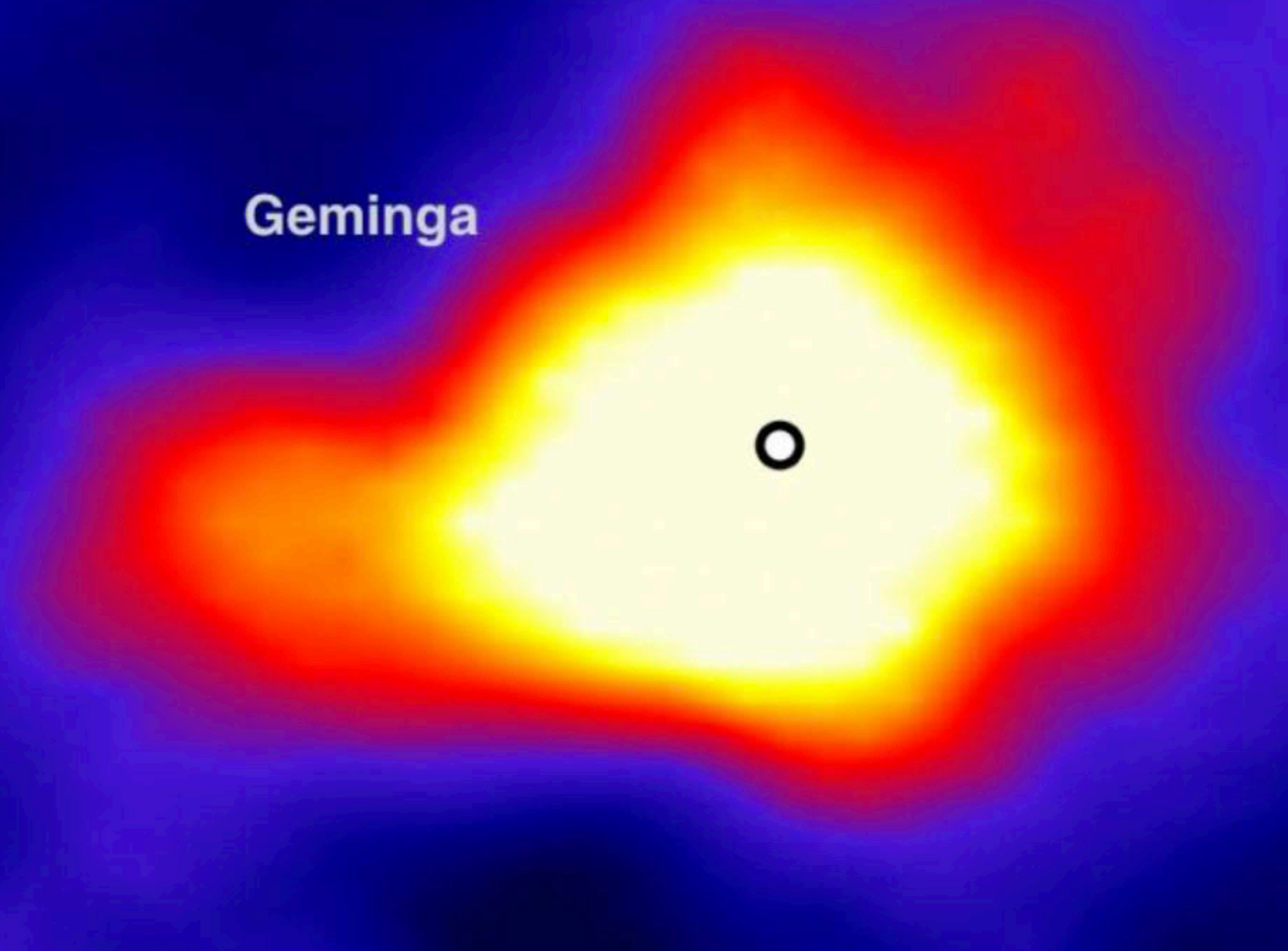
► II: The e^+e^- spectrum.

► III: The propagation of e^+e^- to Earth.

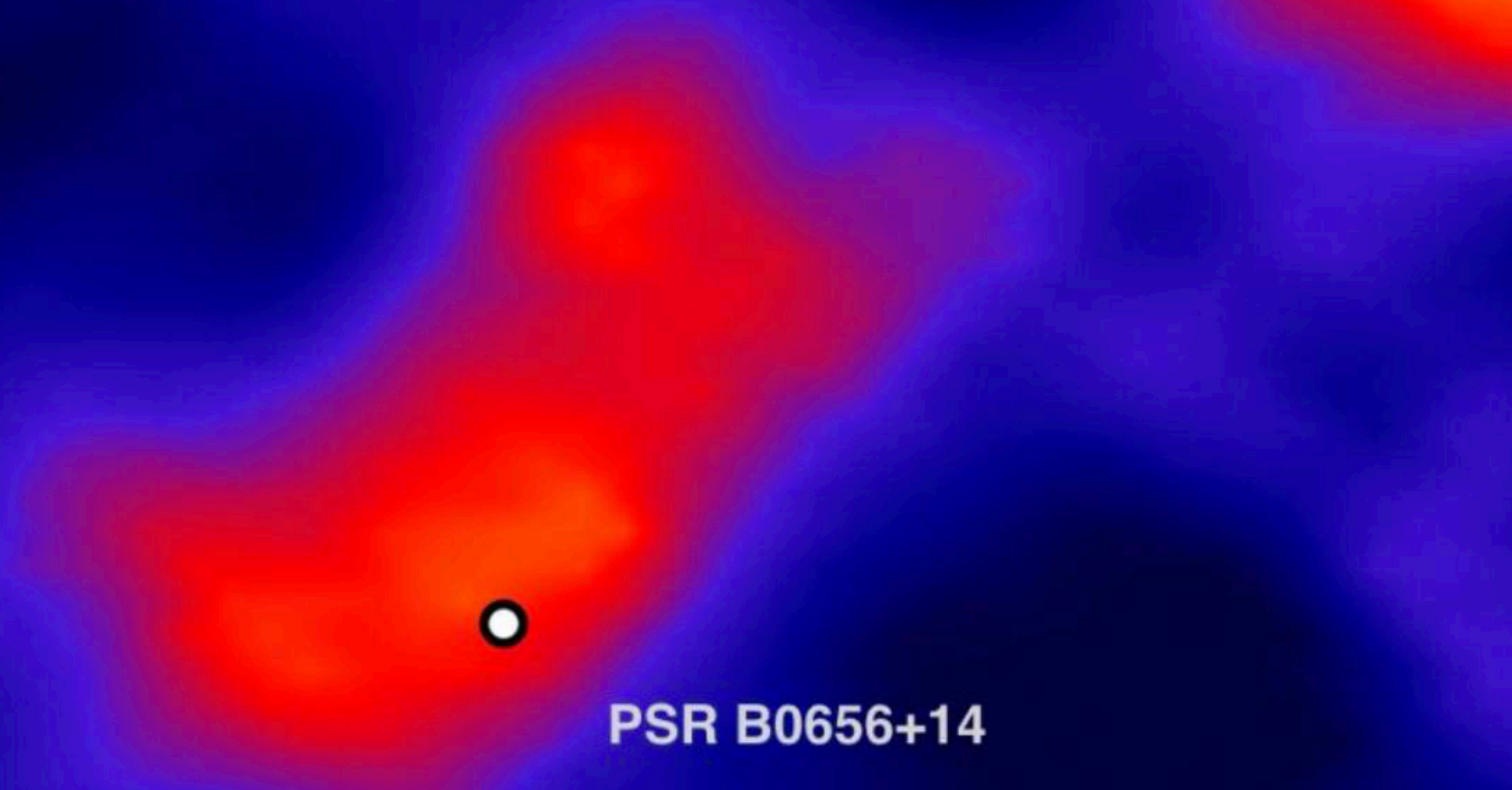




Geminga



PSR B0656+14

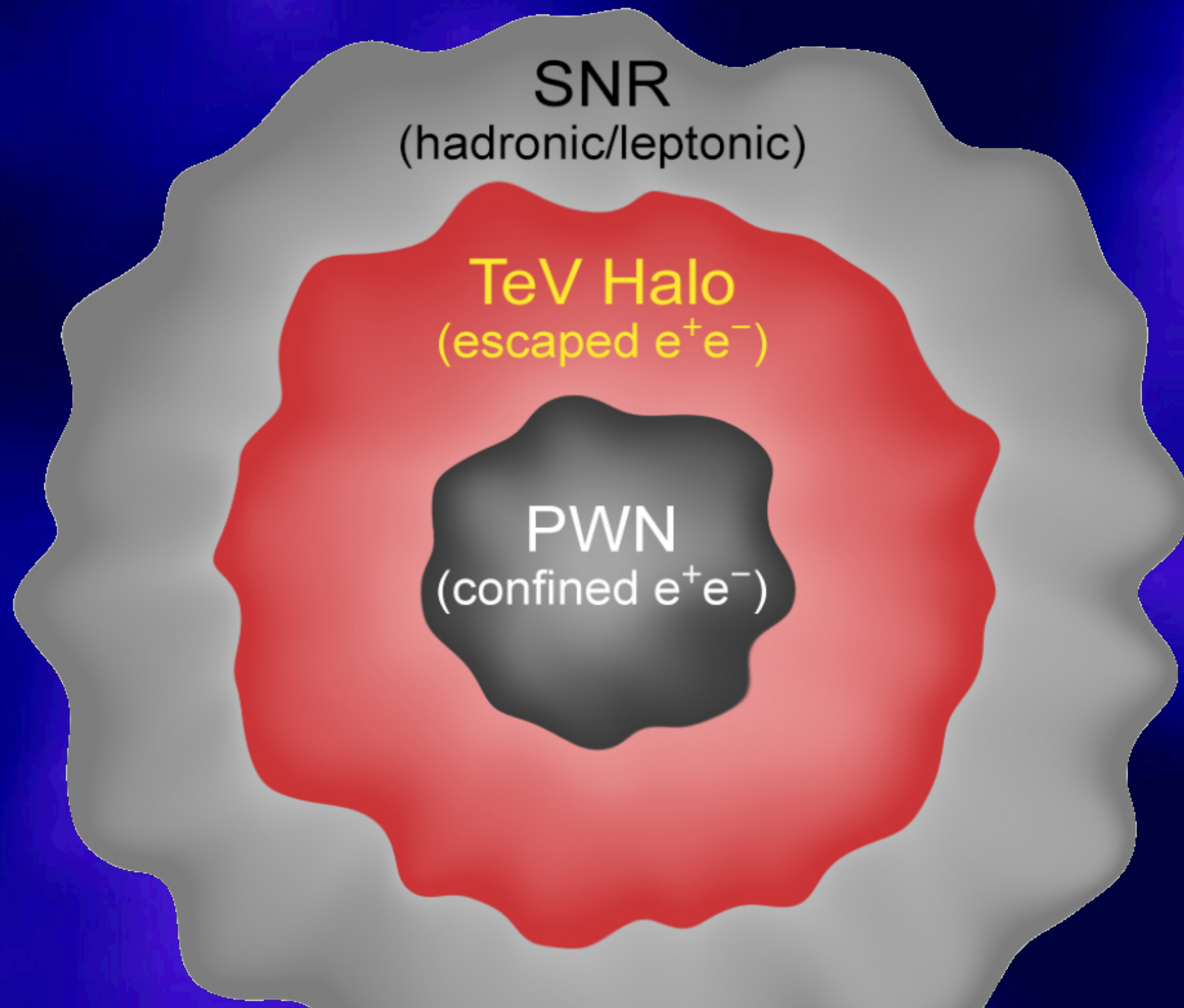




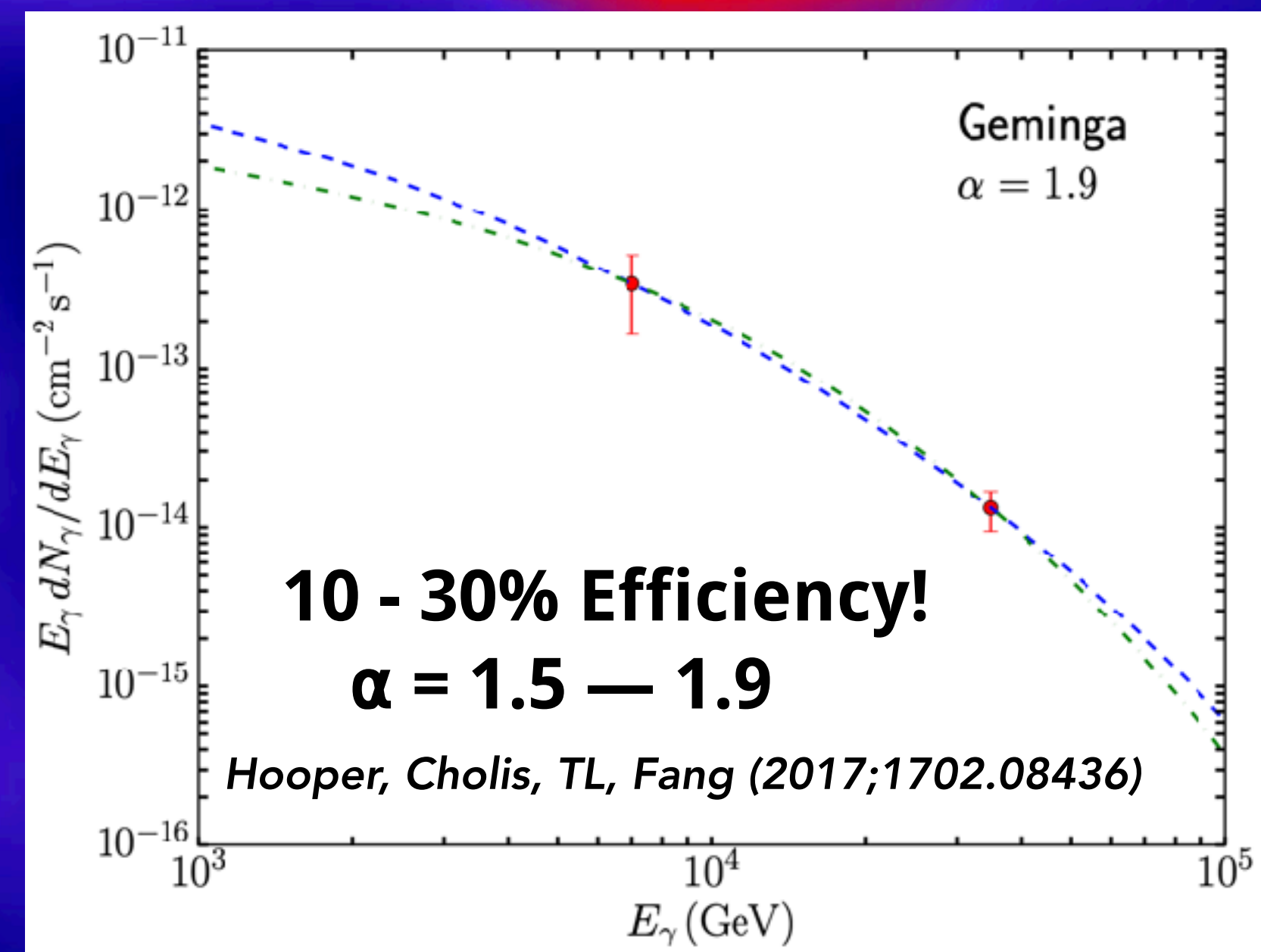
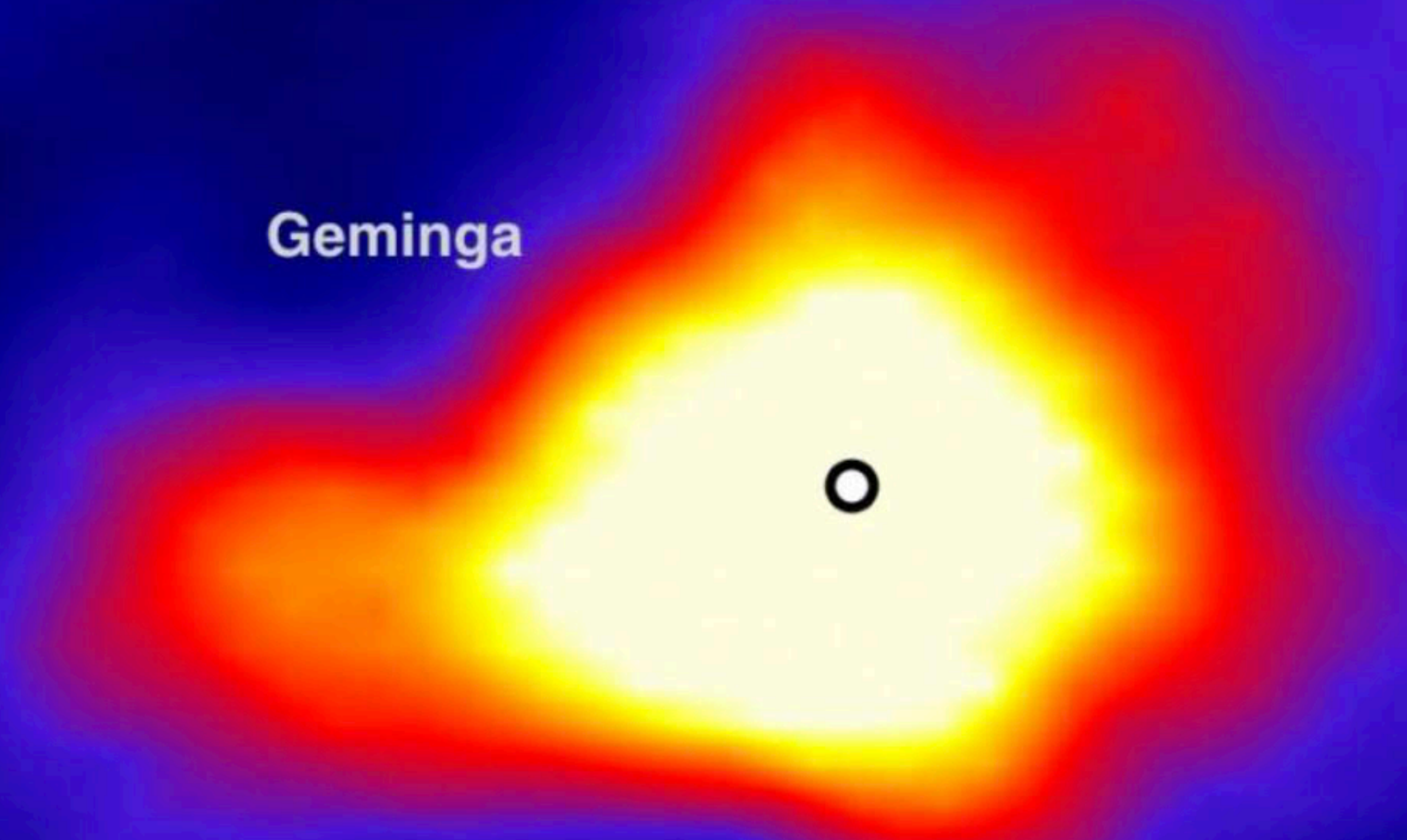
Moon (To Scale)

Linden et al. (2017; 1703.09704)

Sudoh, TL, Beacom (2019; 1902.08203)

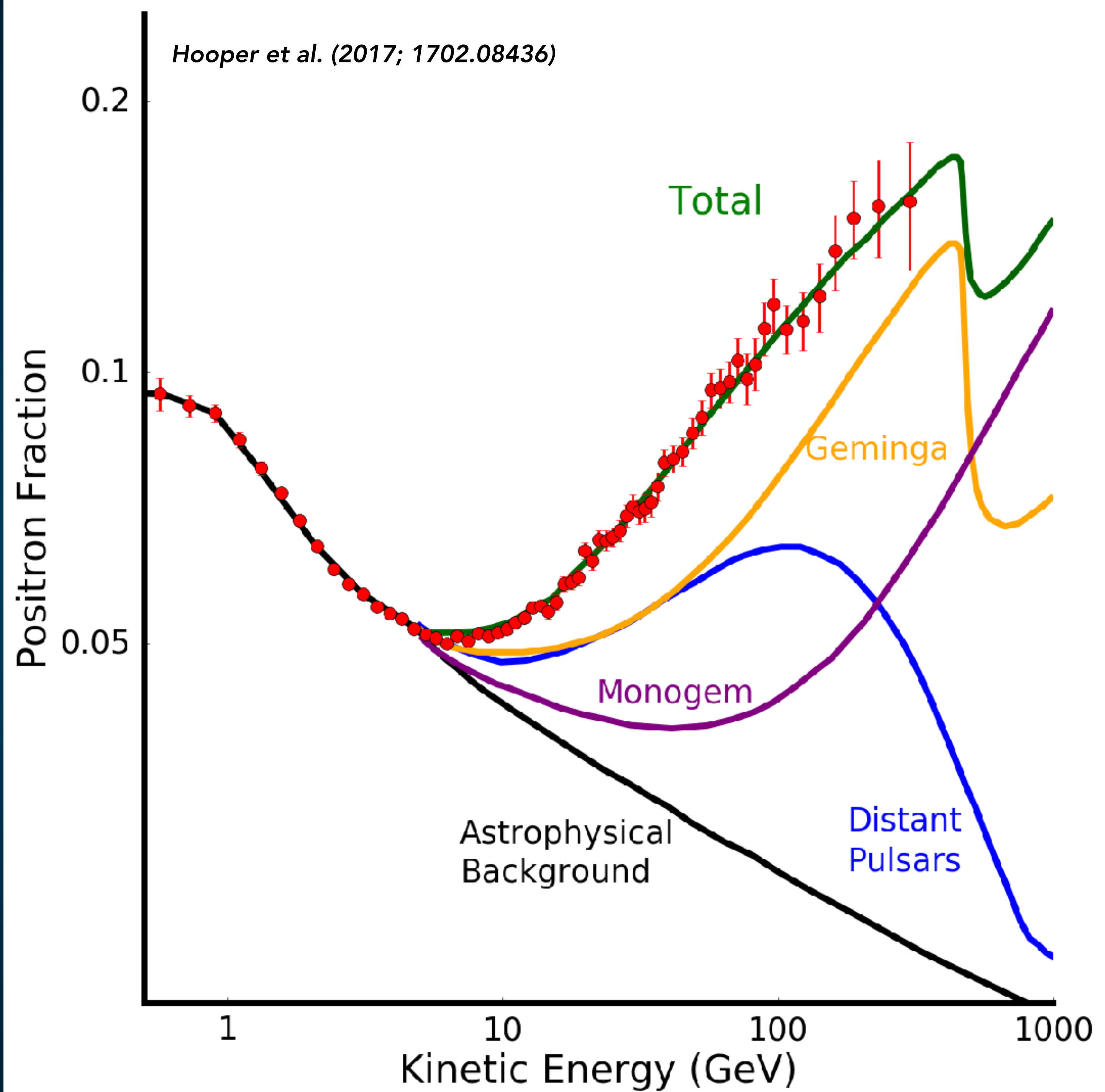
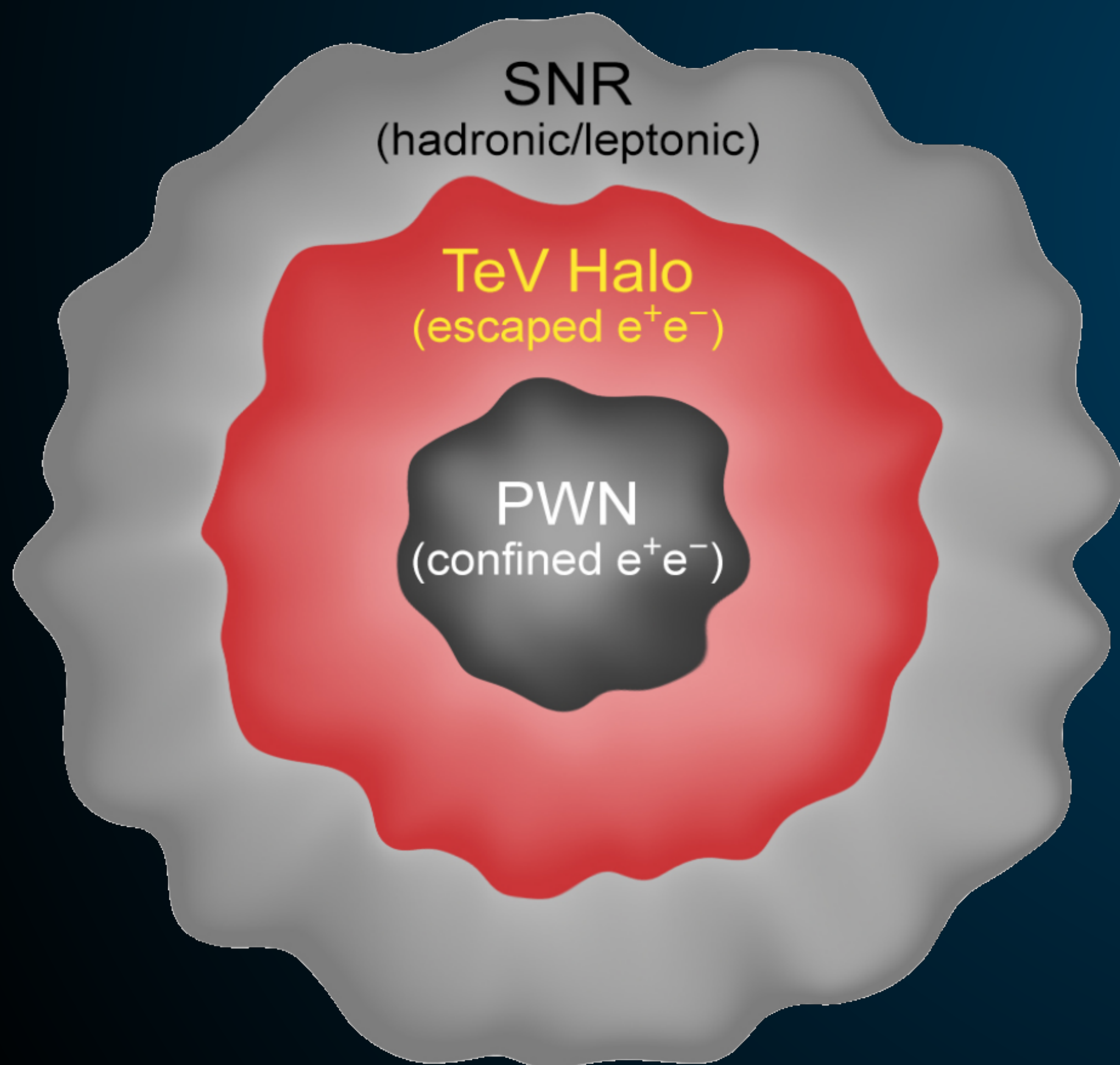


Geminga

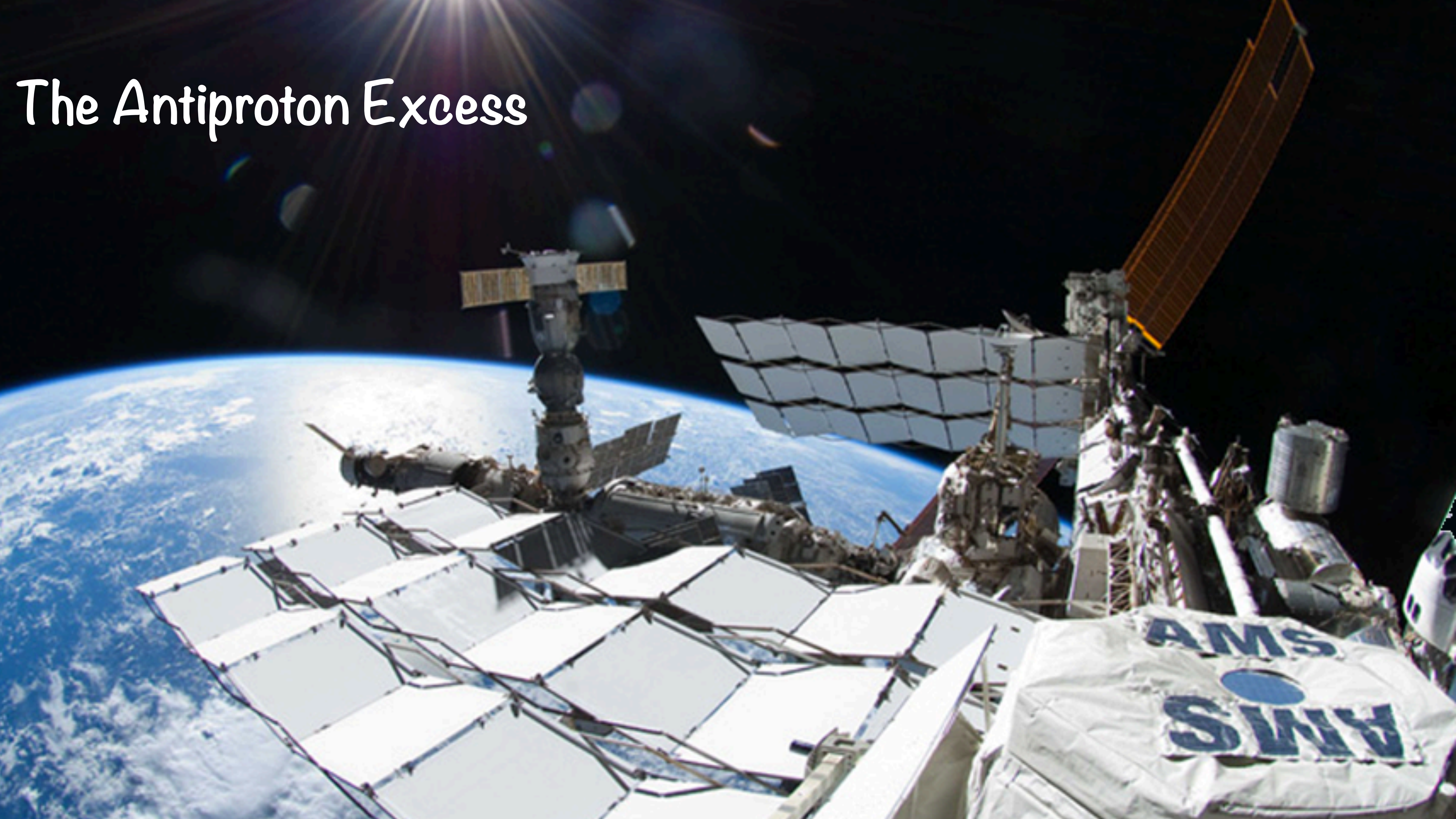


The Positron Excess

This can easily match the positron fraction



The Antiproton Excess



The Antiproton Excess

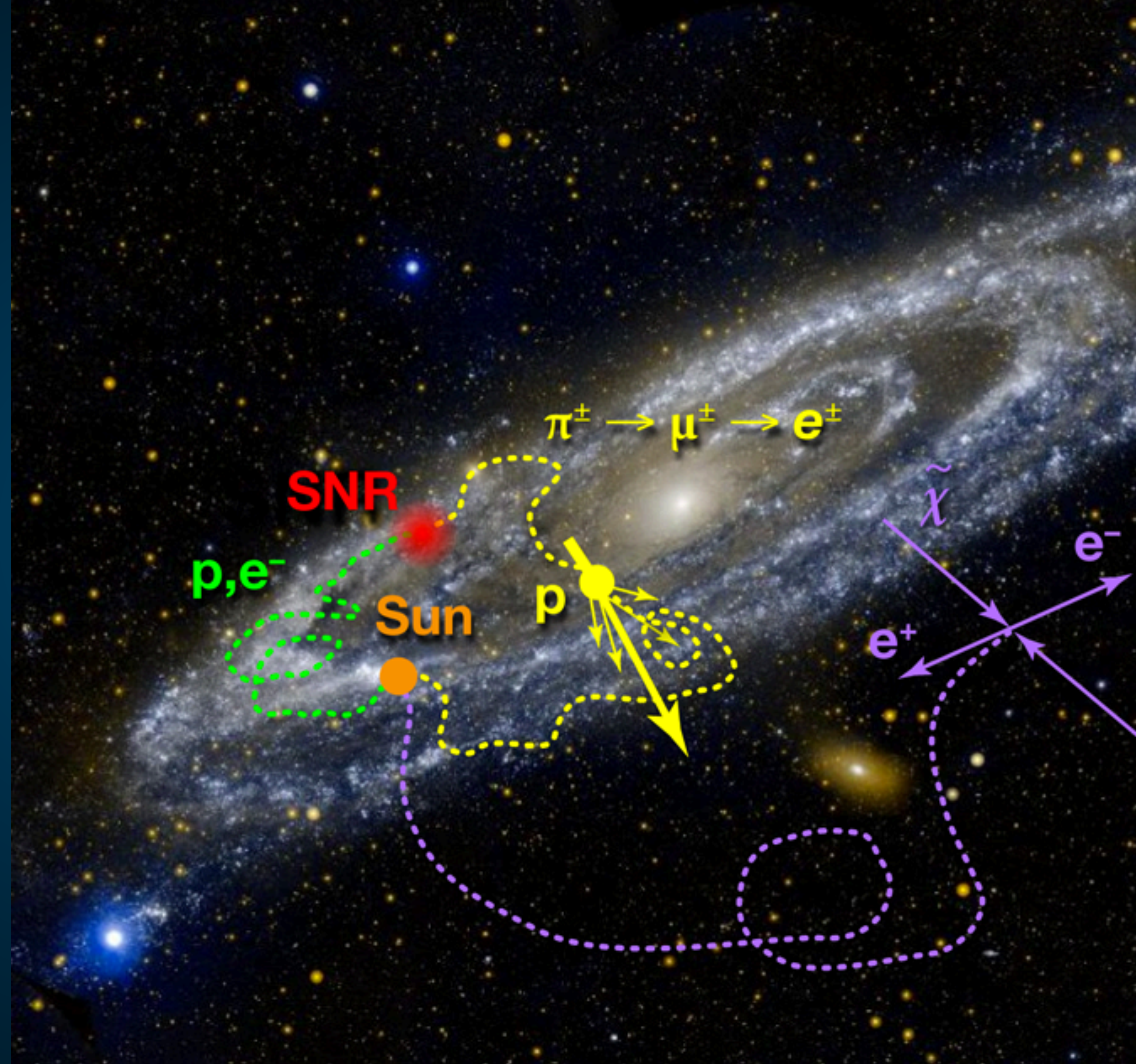
Investigate the Antiproton Fraction!

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

Two Changes:

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

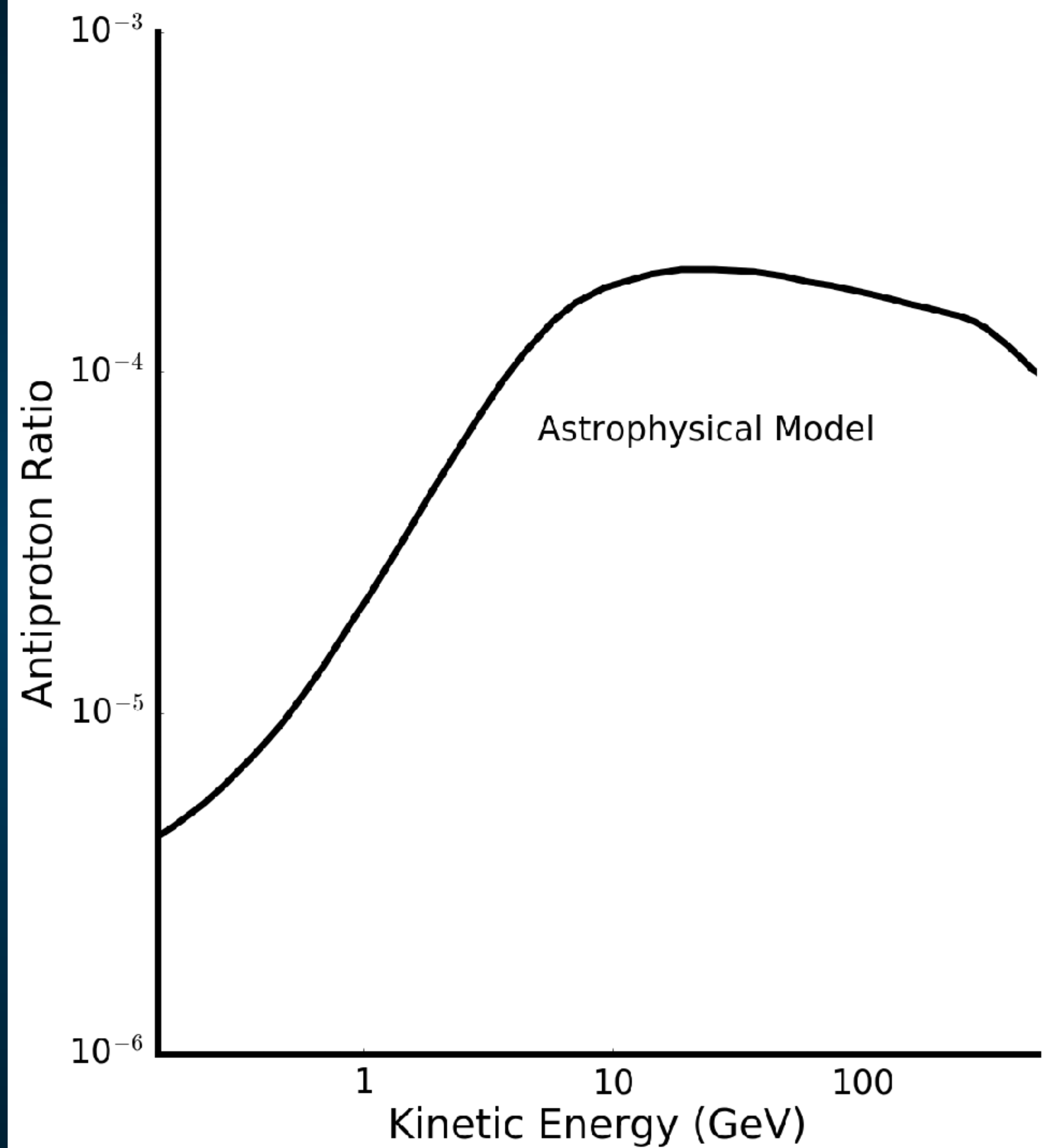
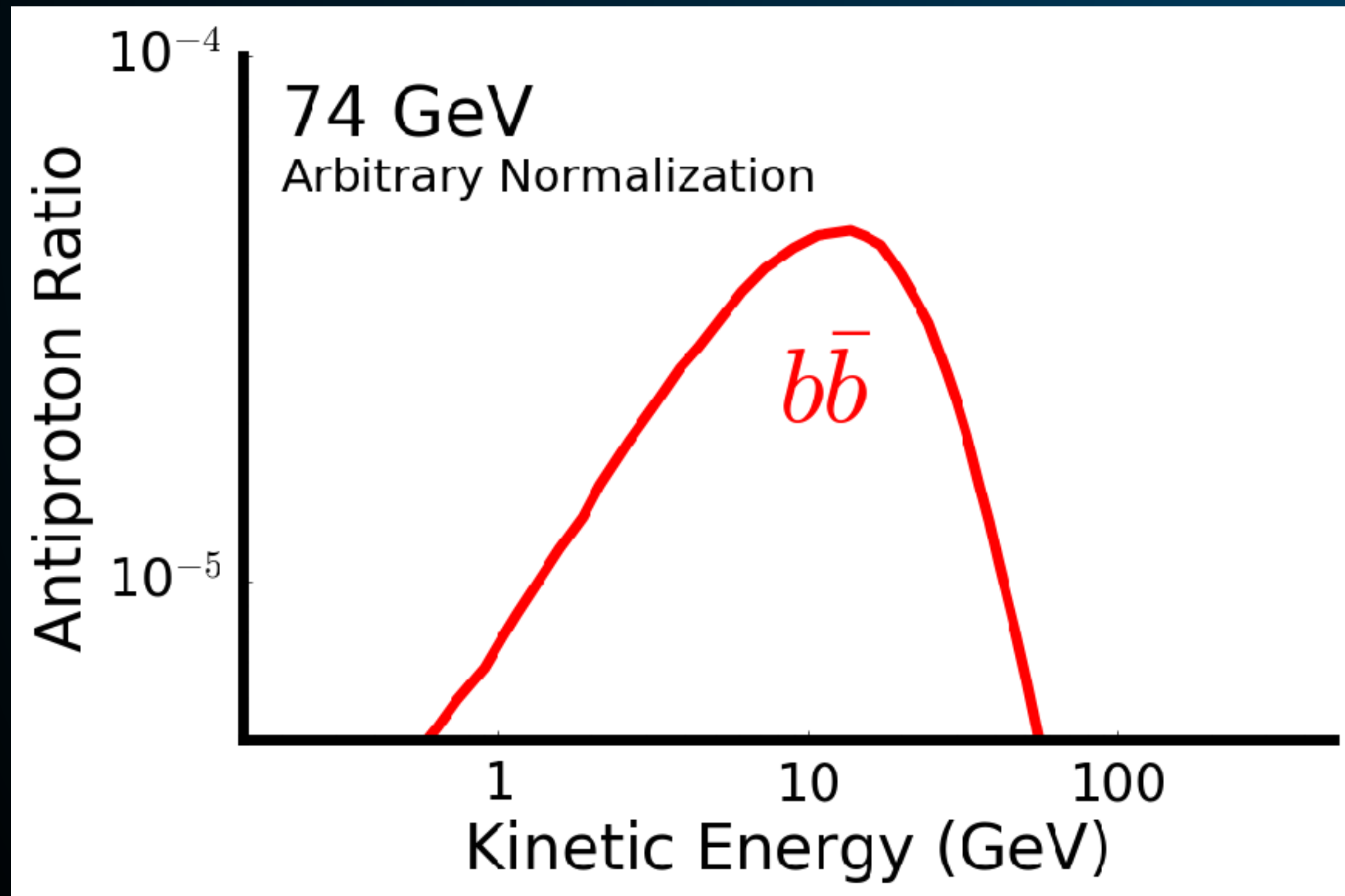
Hadronic Energy losses are slower (sensitive to antiproton production throughout the Galaxy)



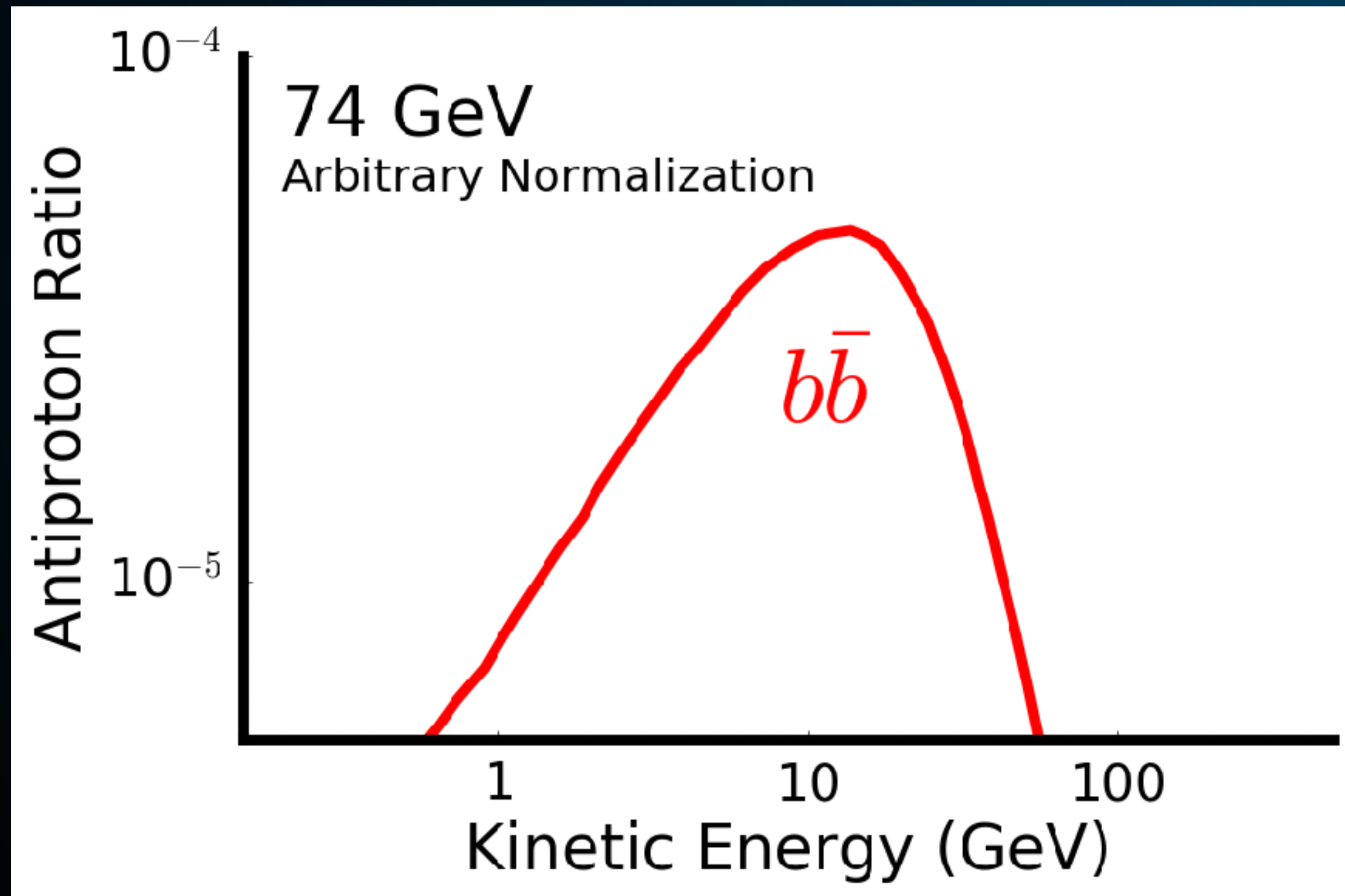
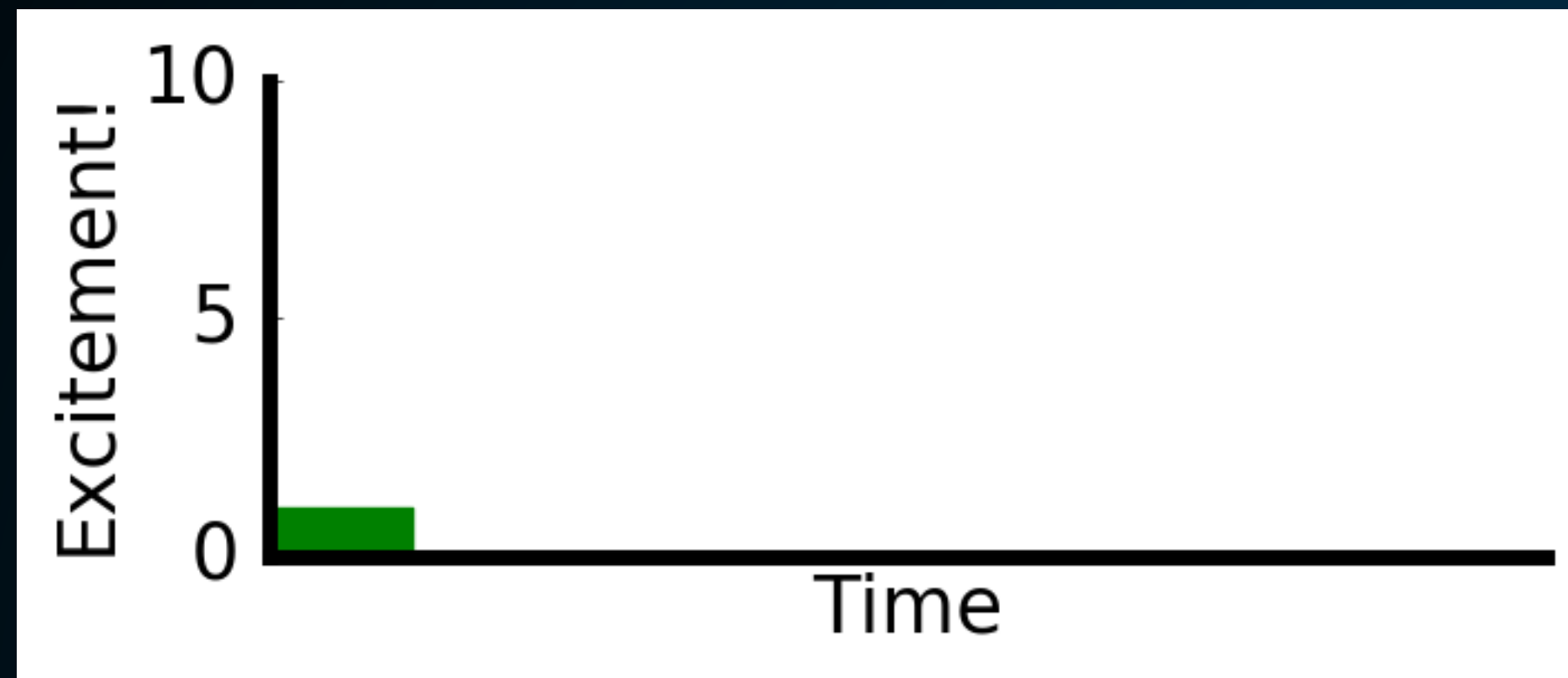
The Antiproton Excess

Astrophysics - Smooth Profile

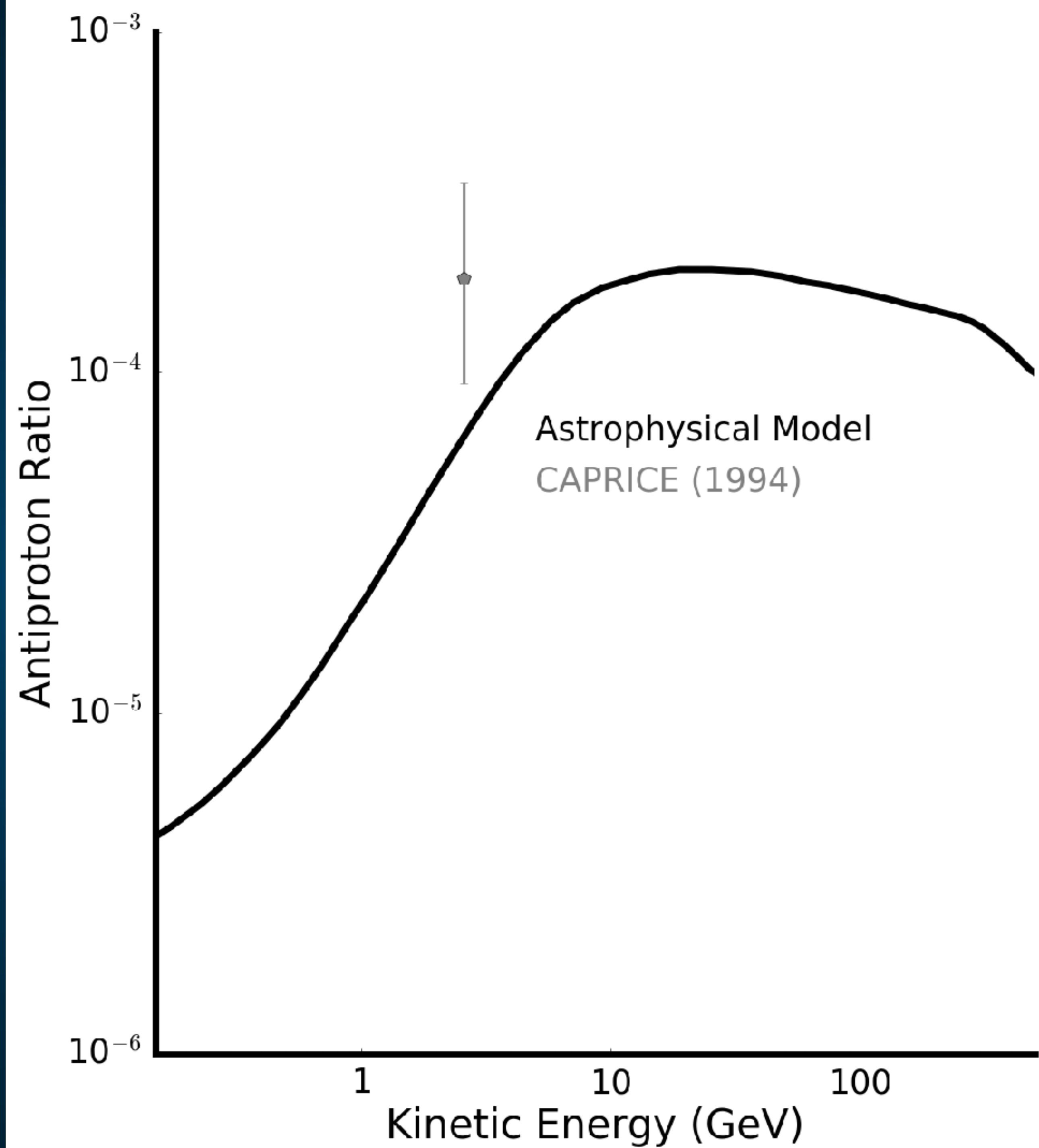
Dark Matter - Sharp Bump!



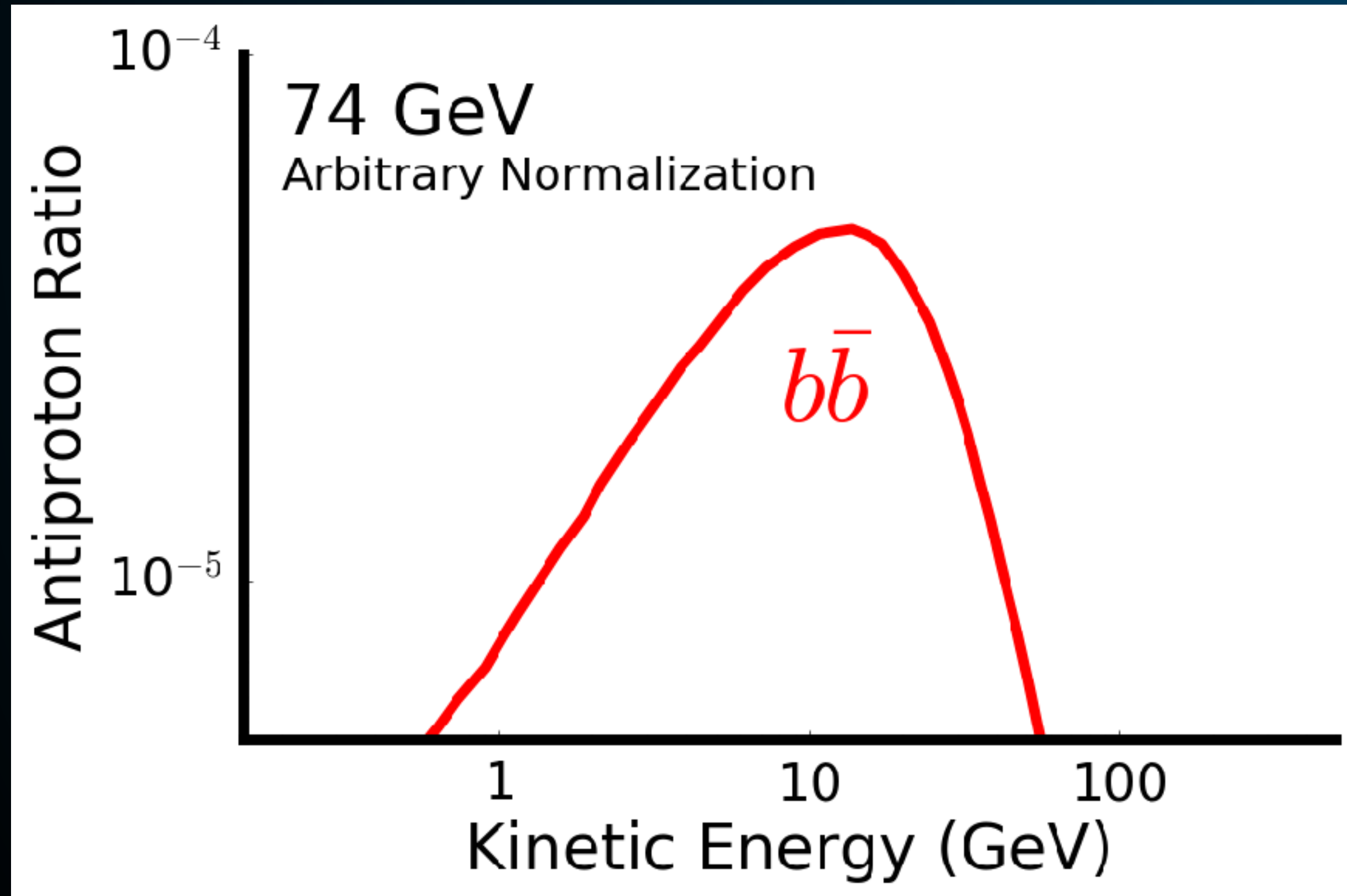
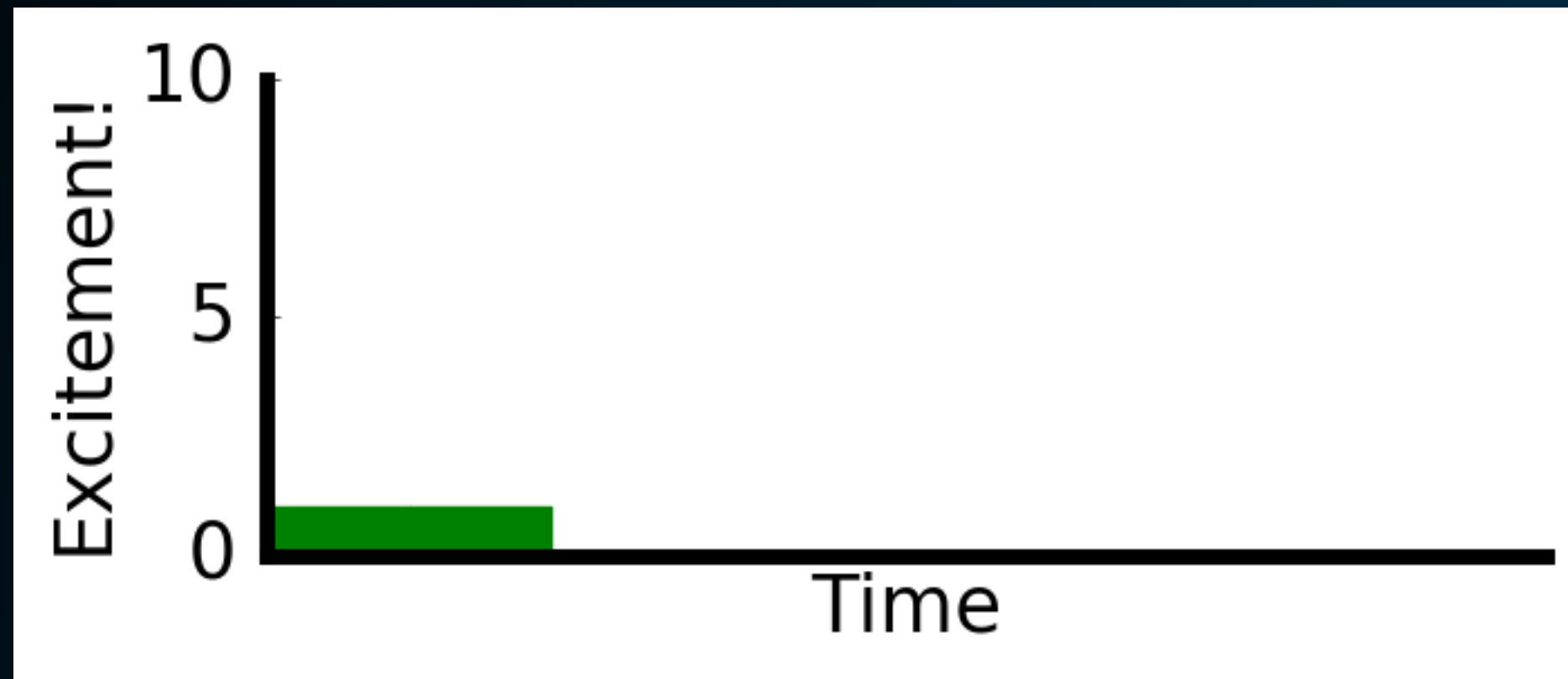
The Antiproton Excess



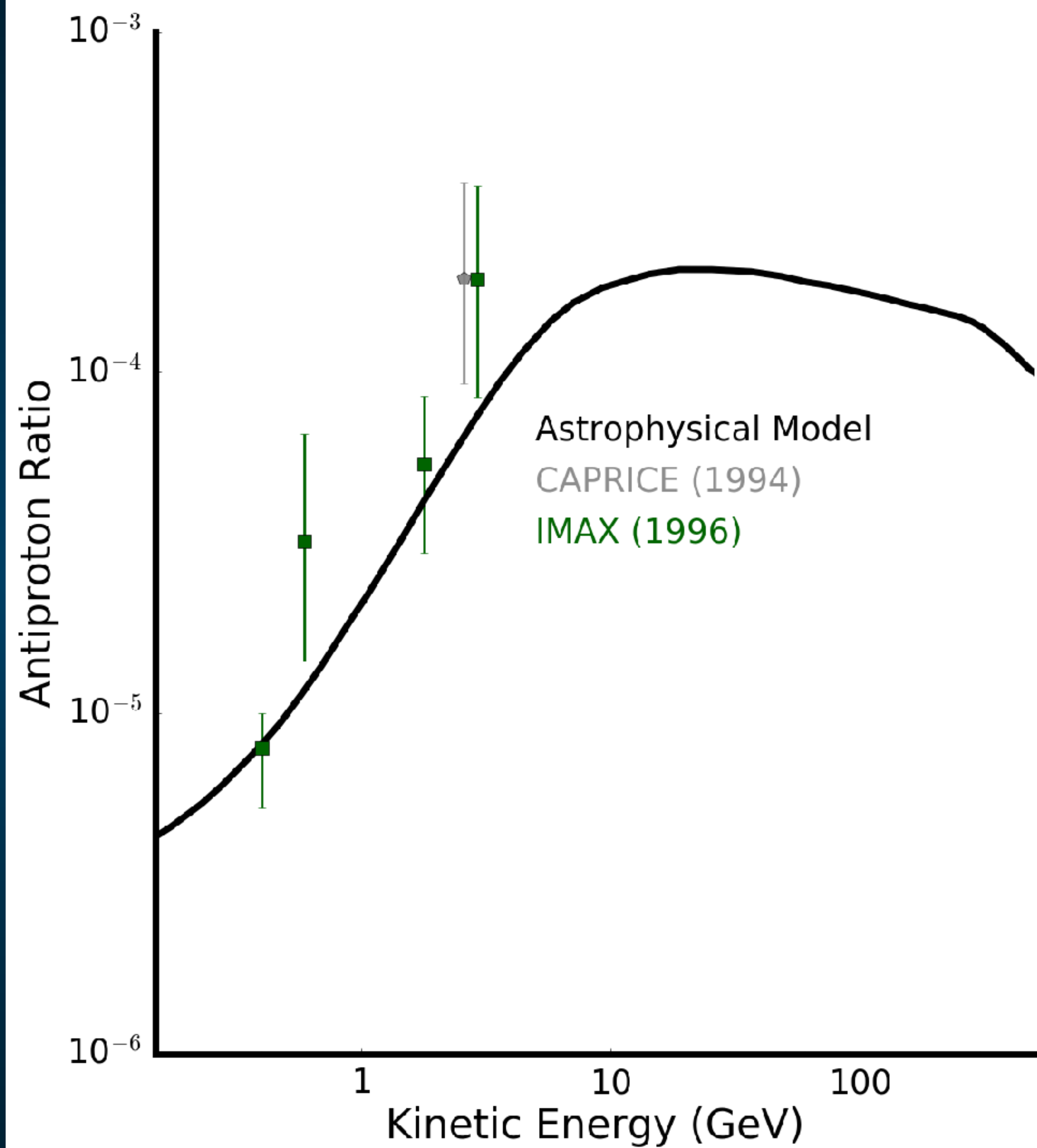
(Not an exhaustive list of observations)



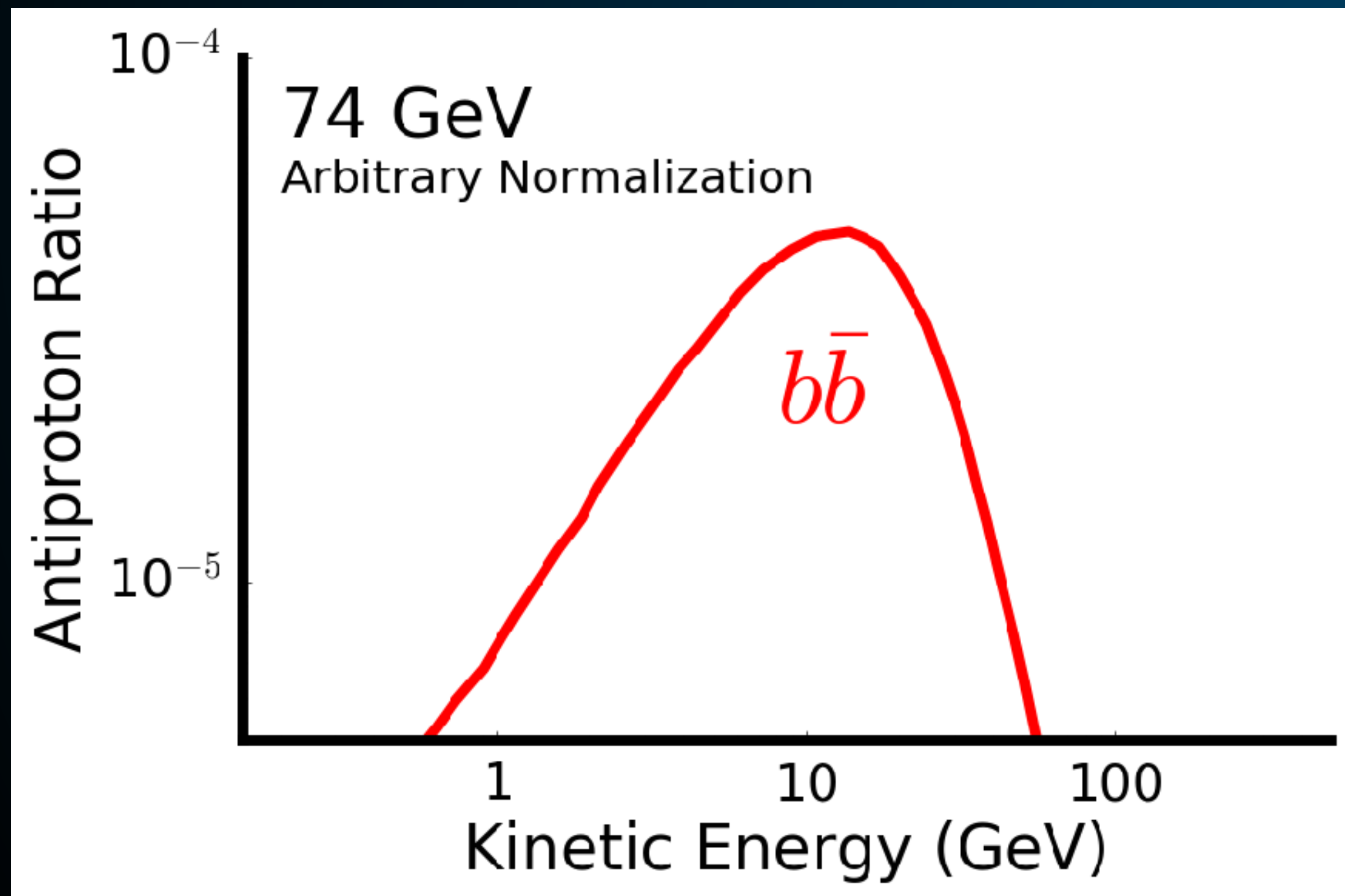
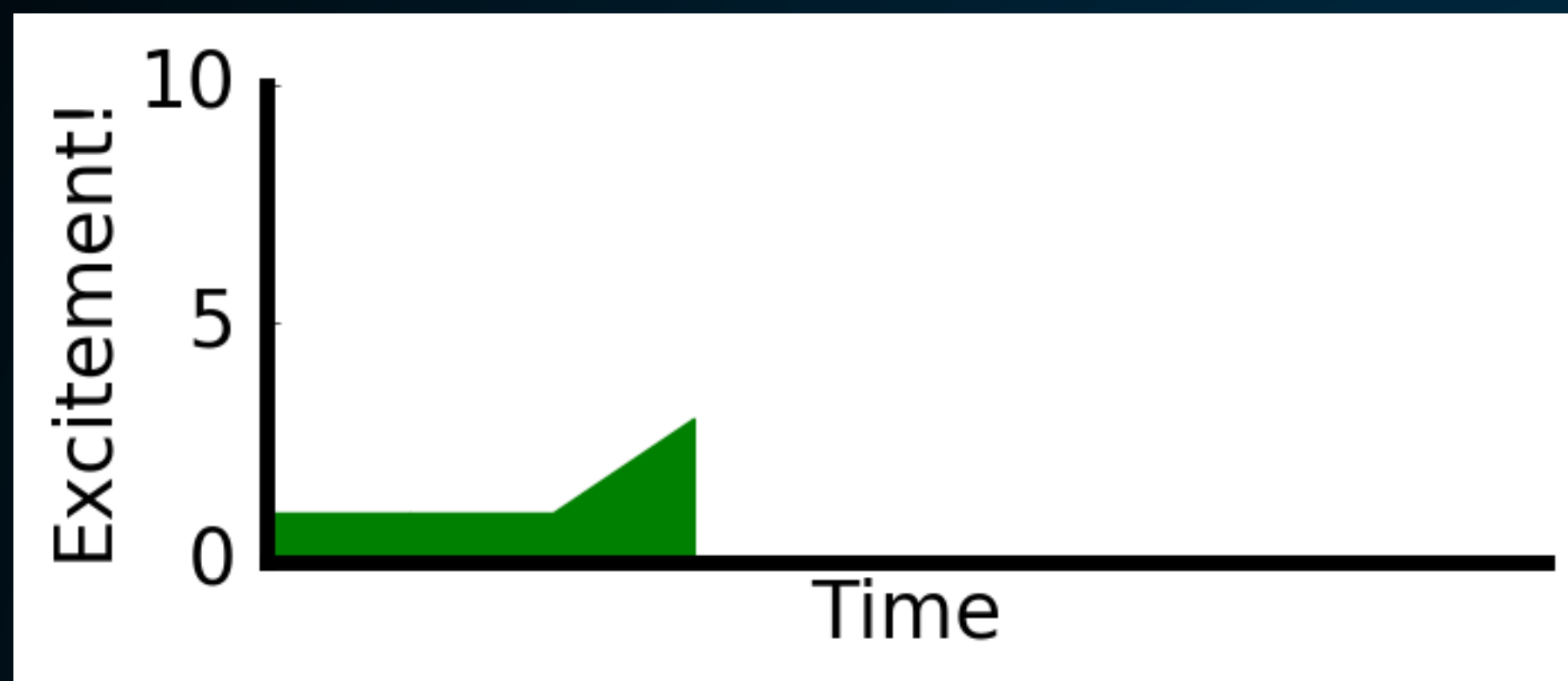
The Antiproton Excess



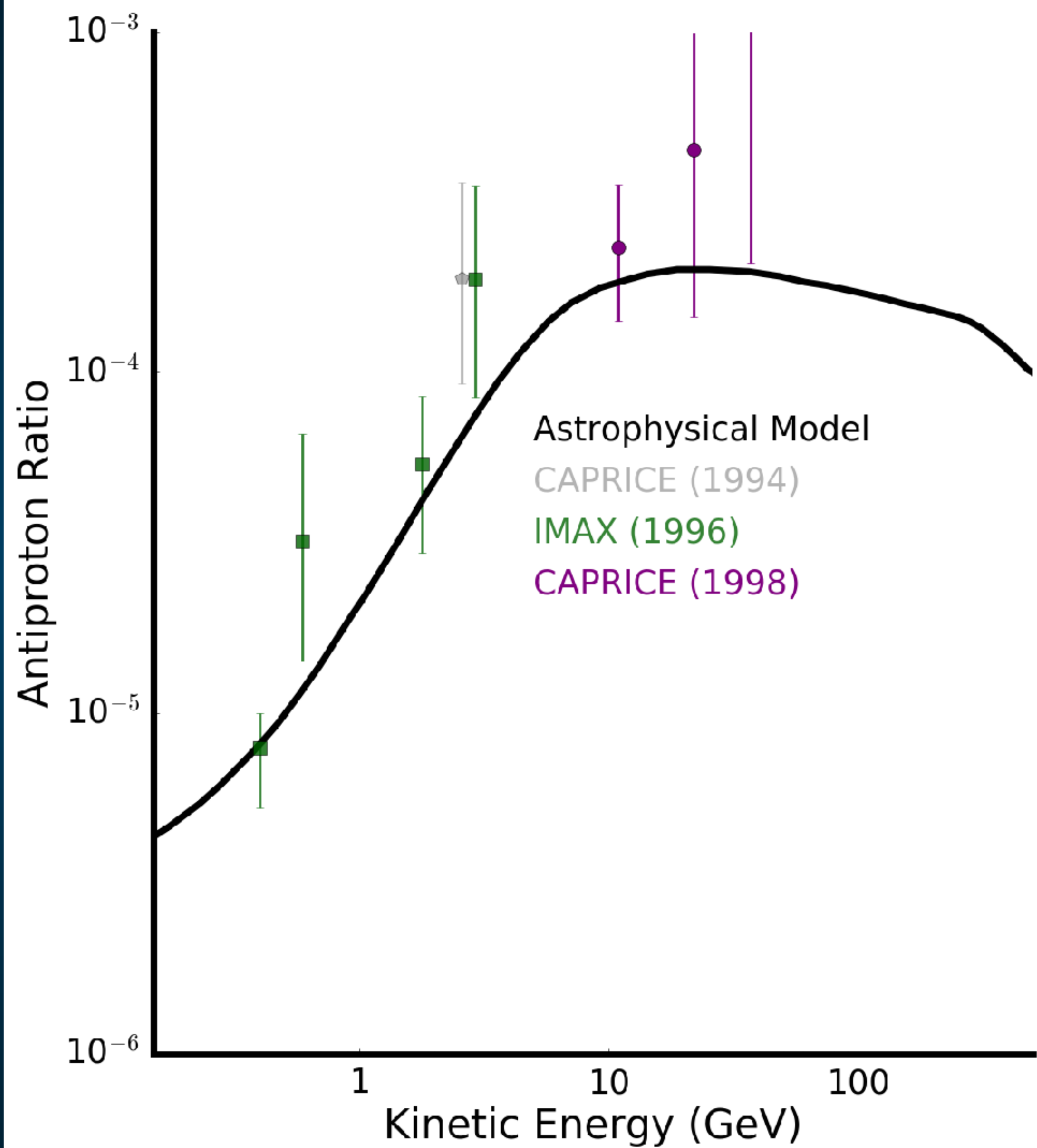
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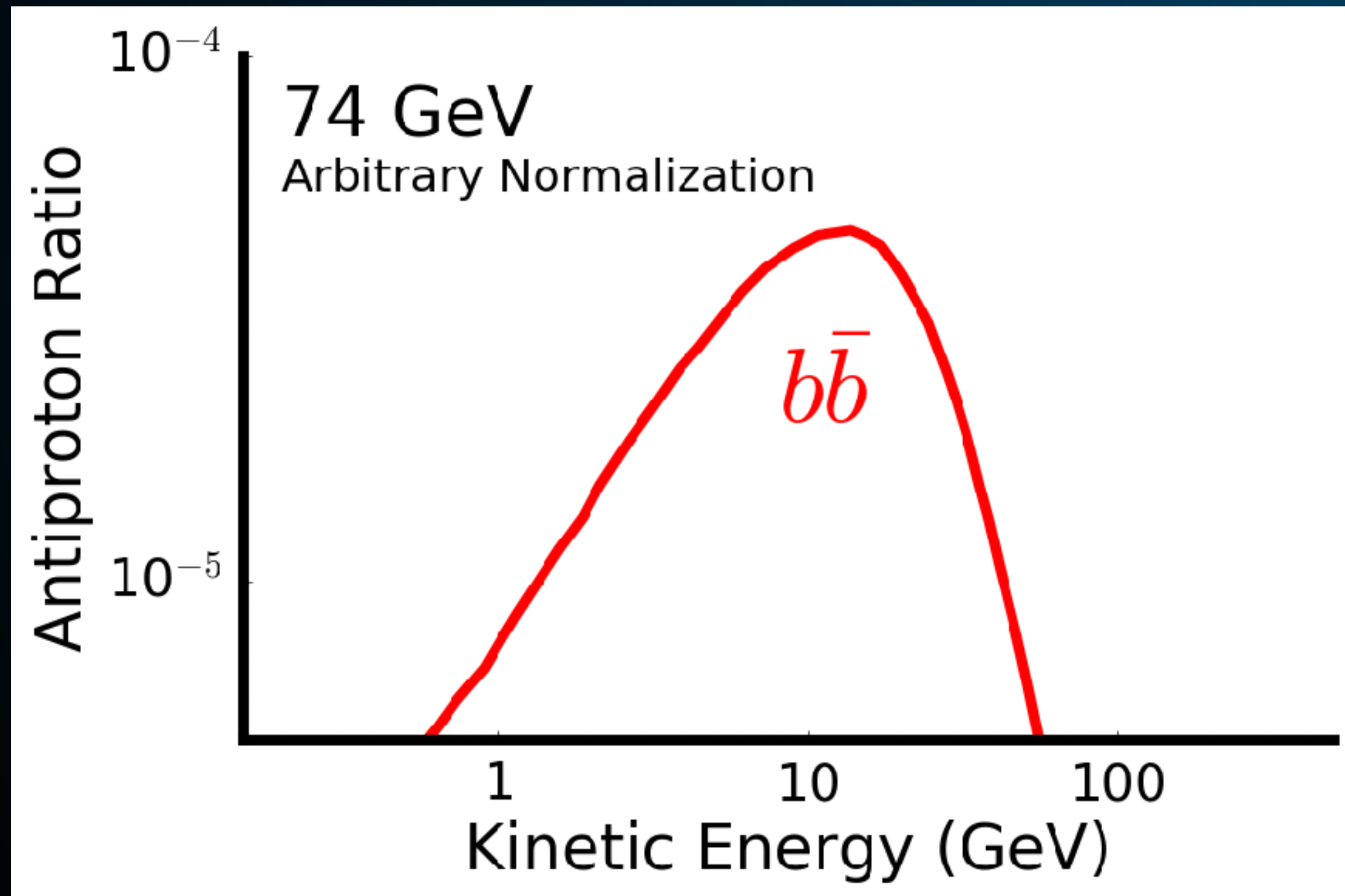
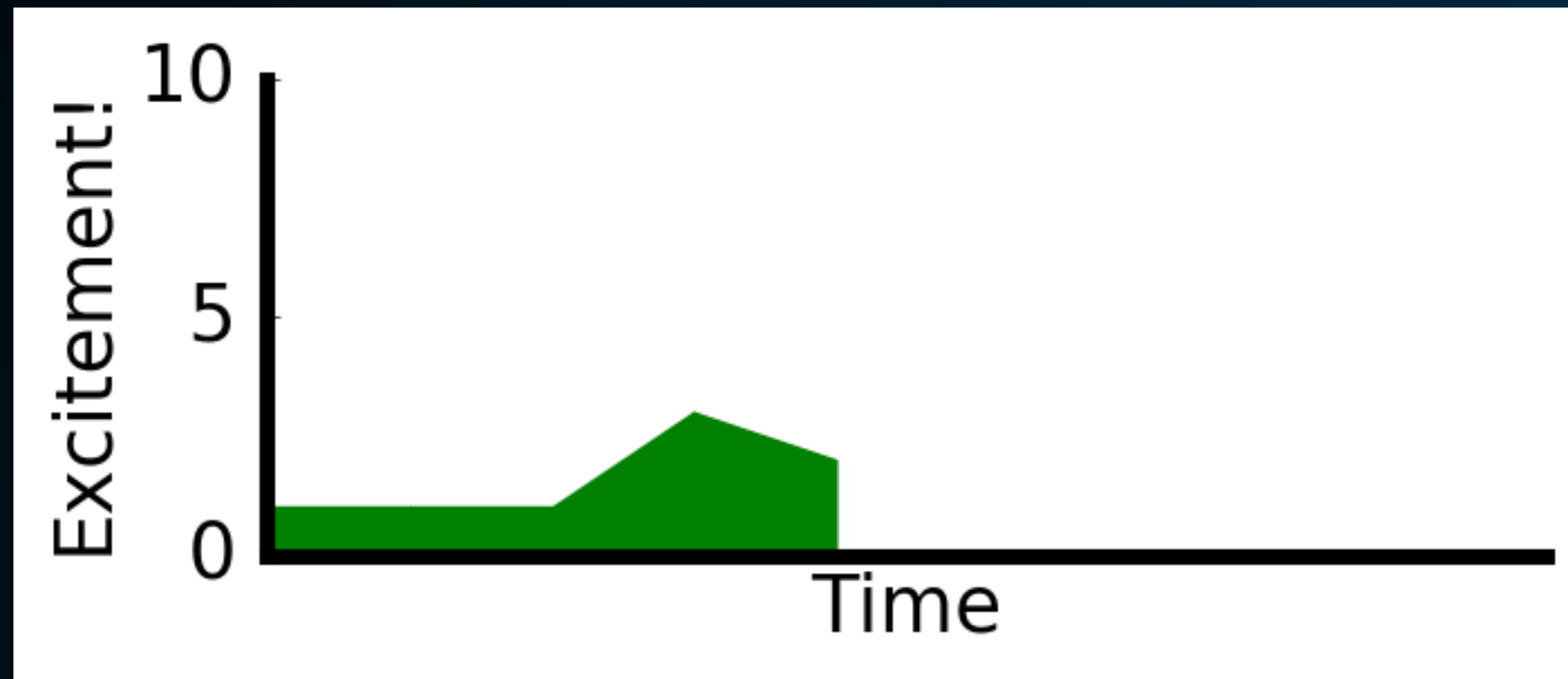
The Antiproton Excess



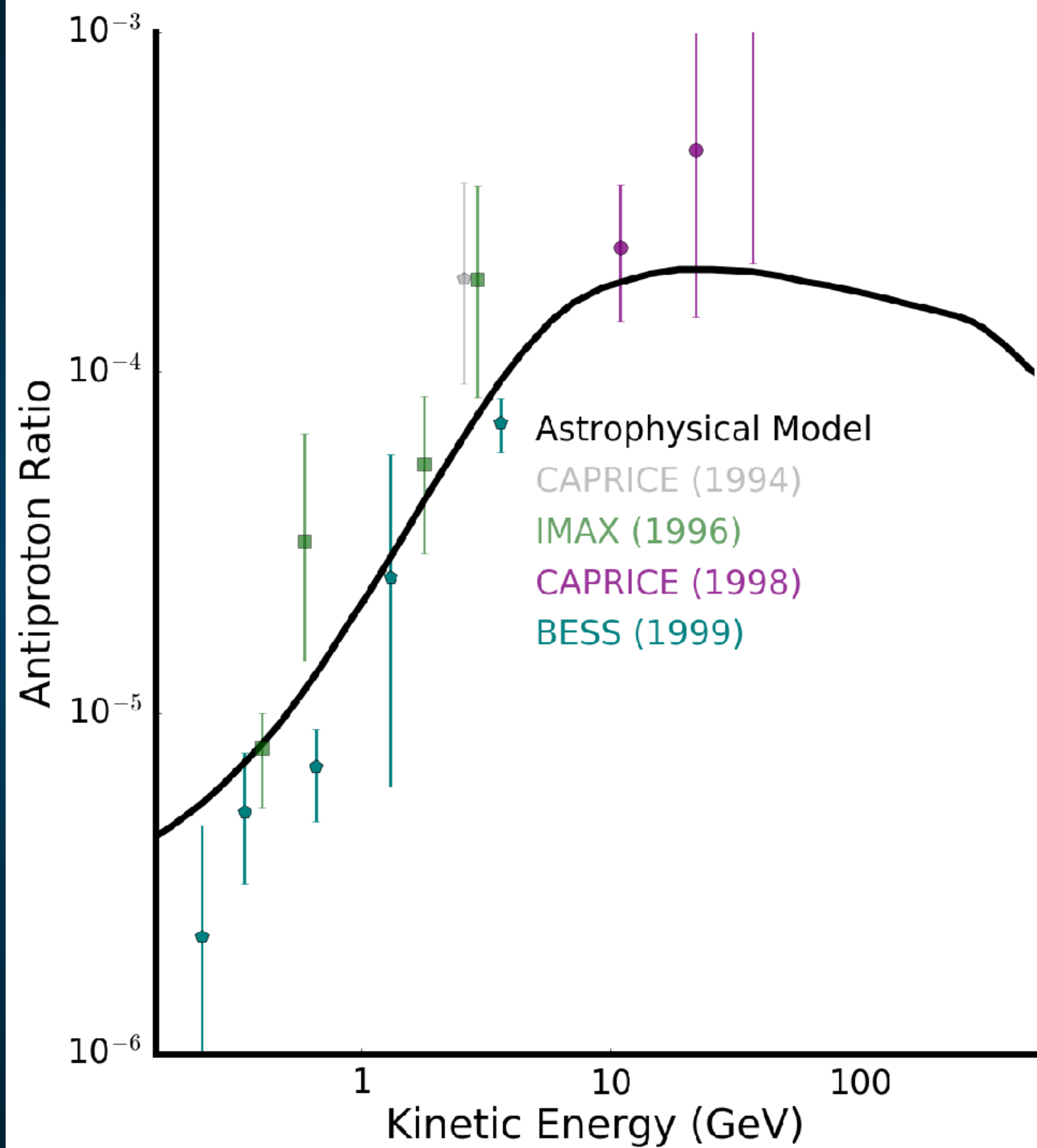
(Not an exhaustive list of observations)



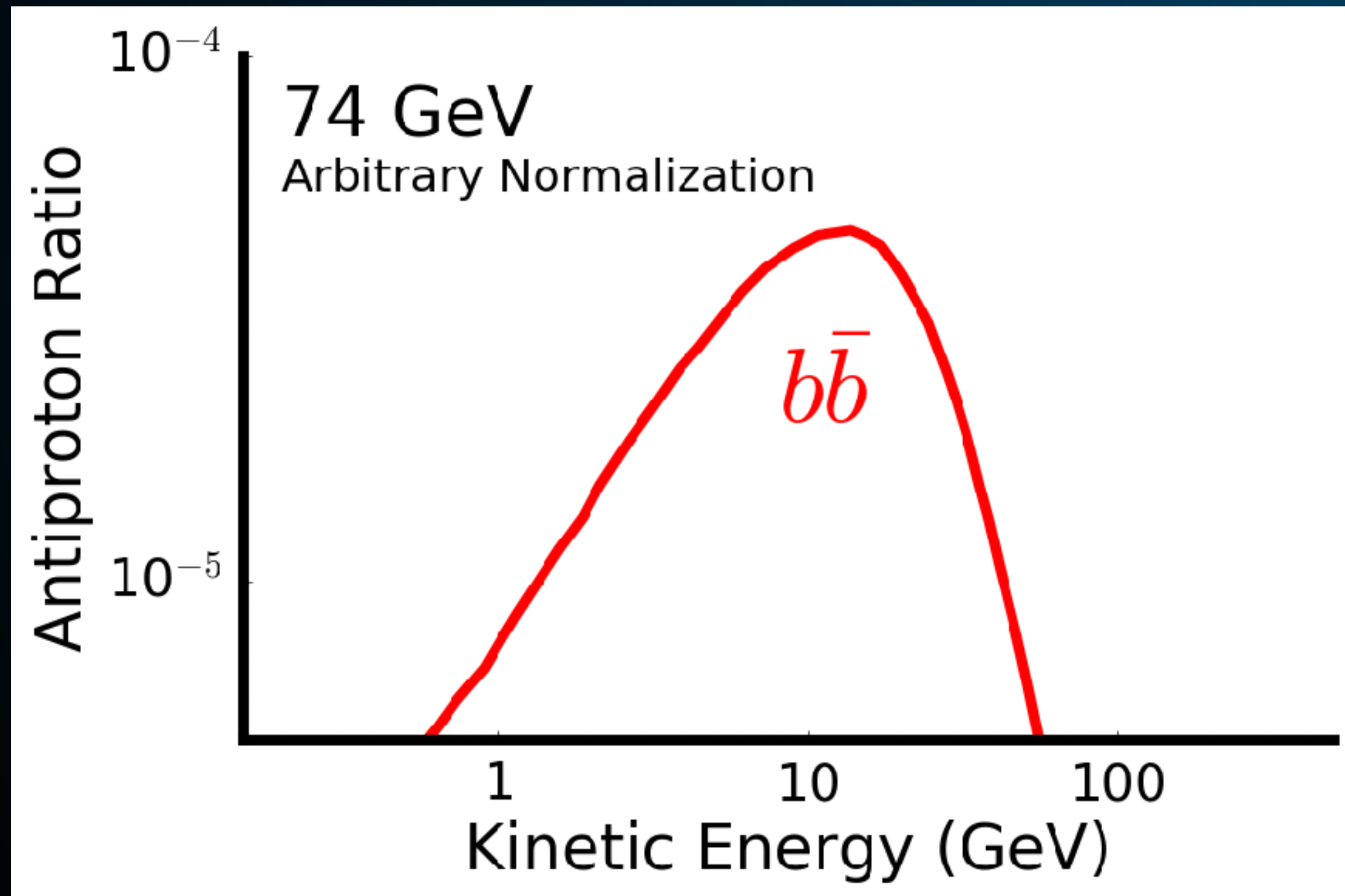
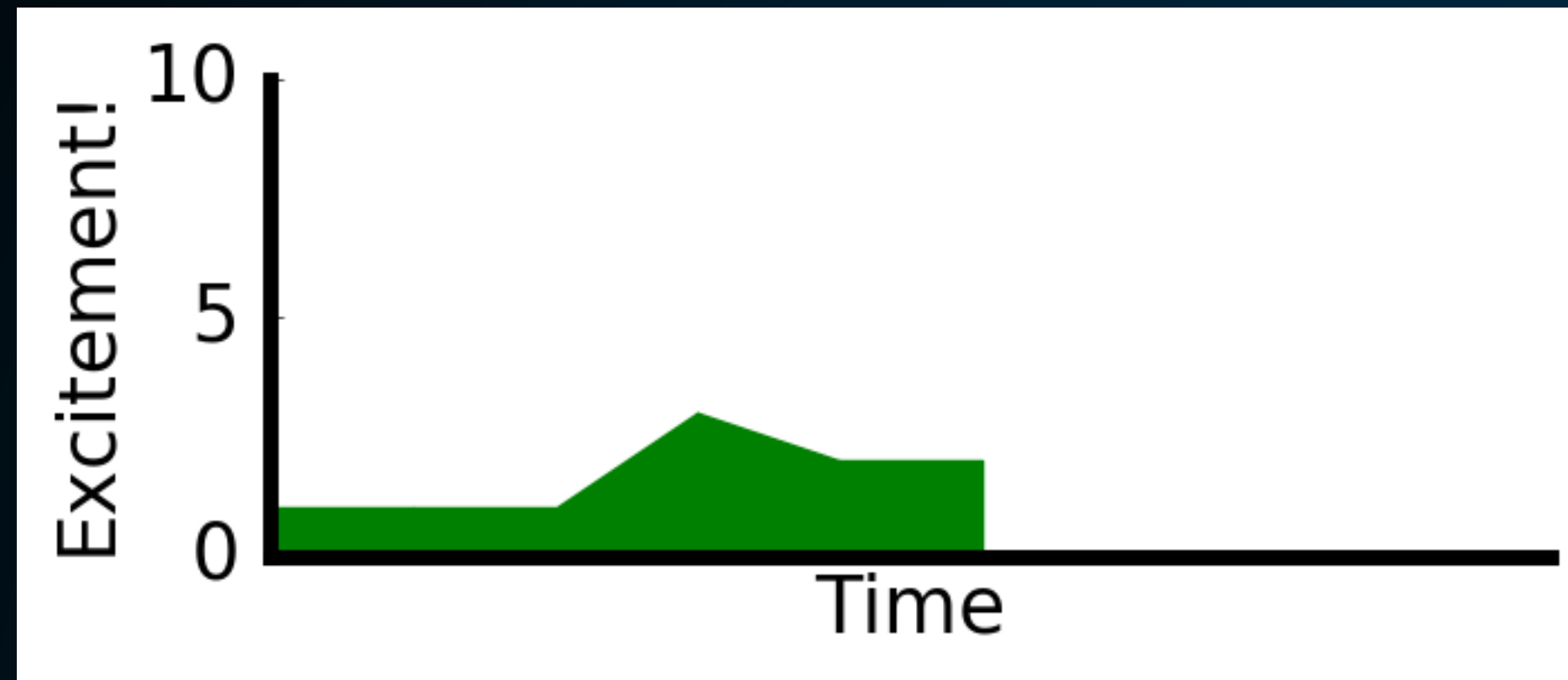
The Antiproton Excess



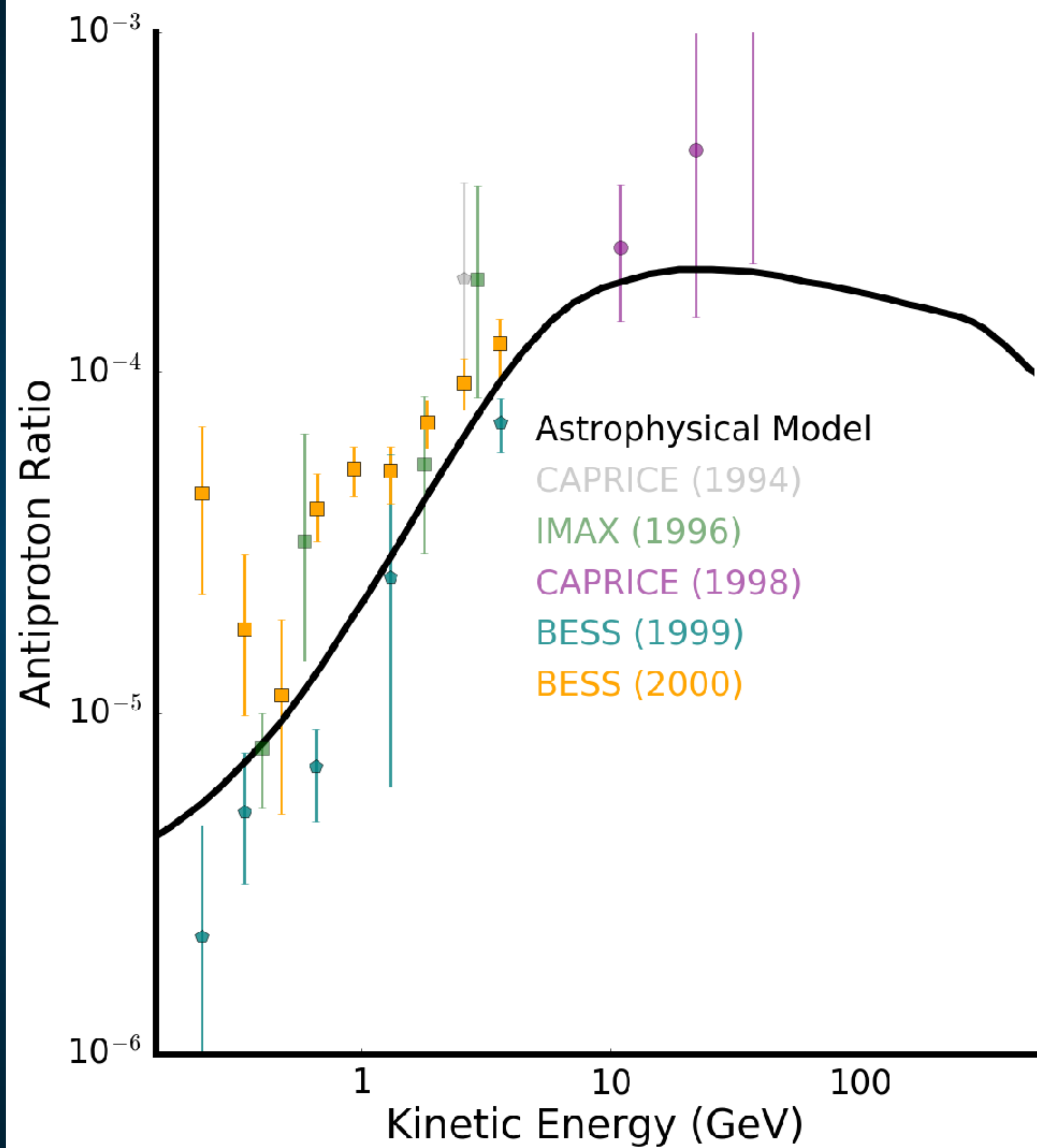
(Not an exhaustive list of observations)



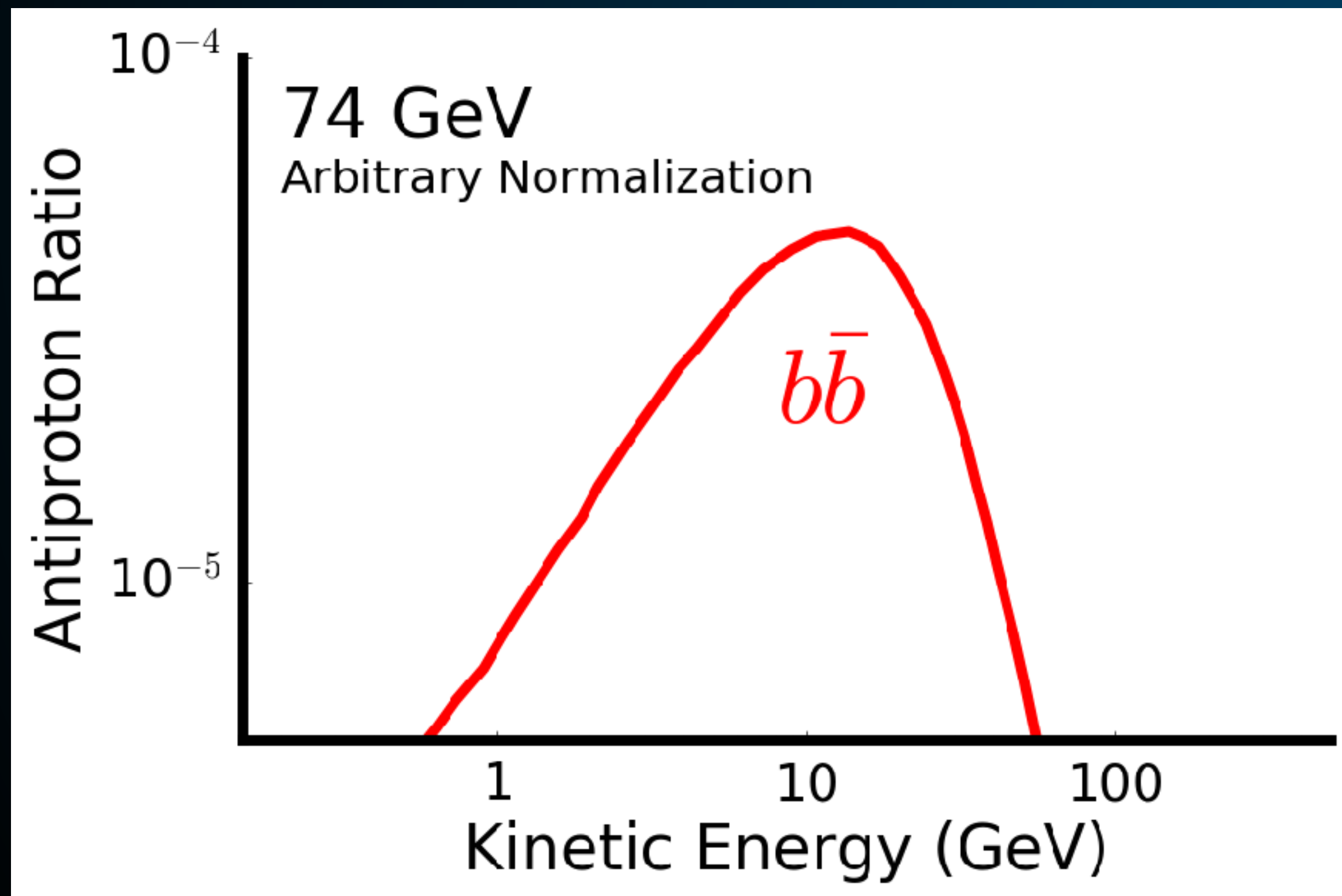
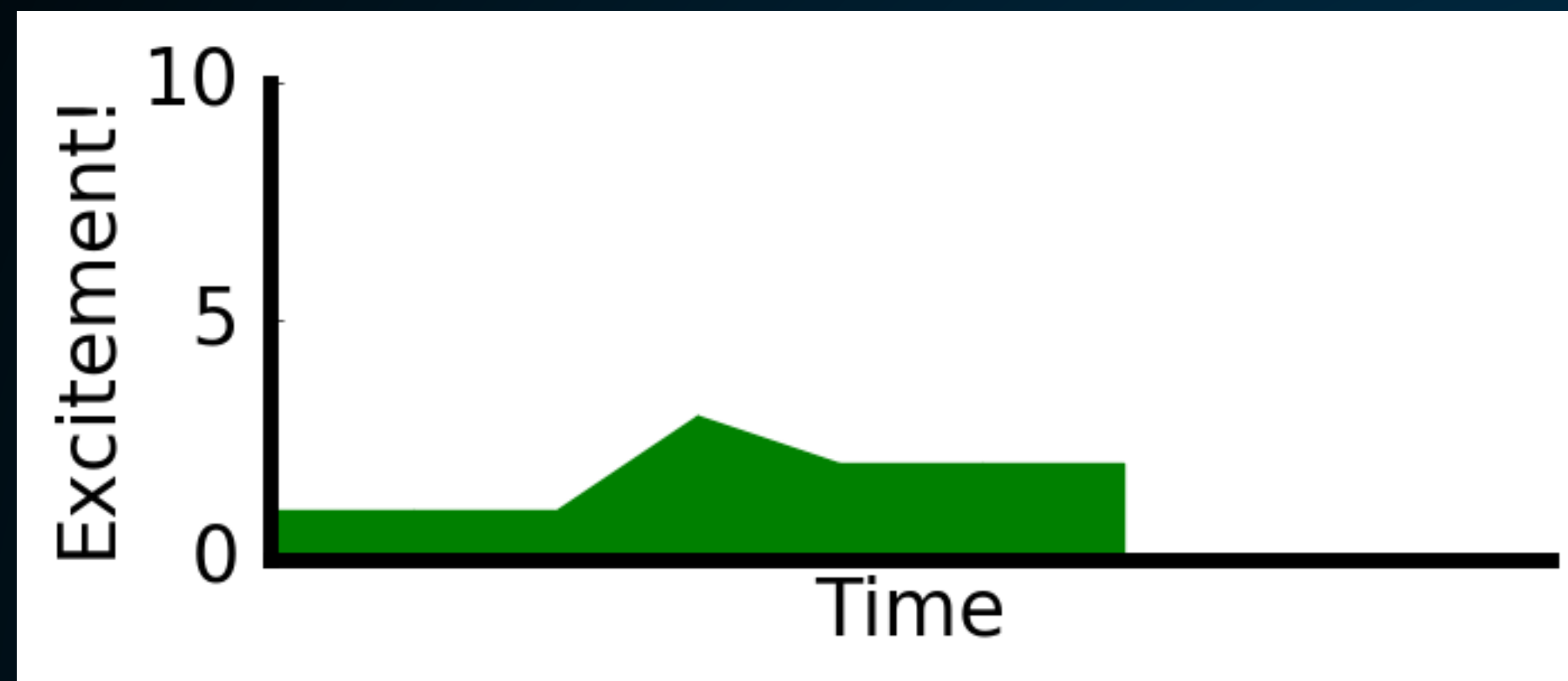
The Antiproton Excess



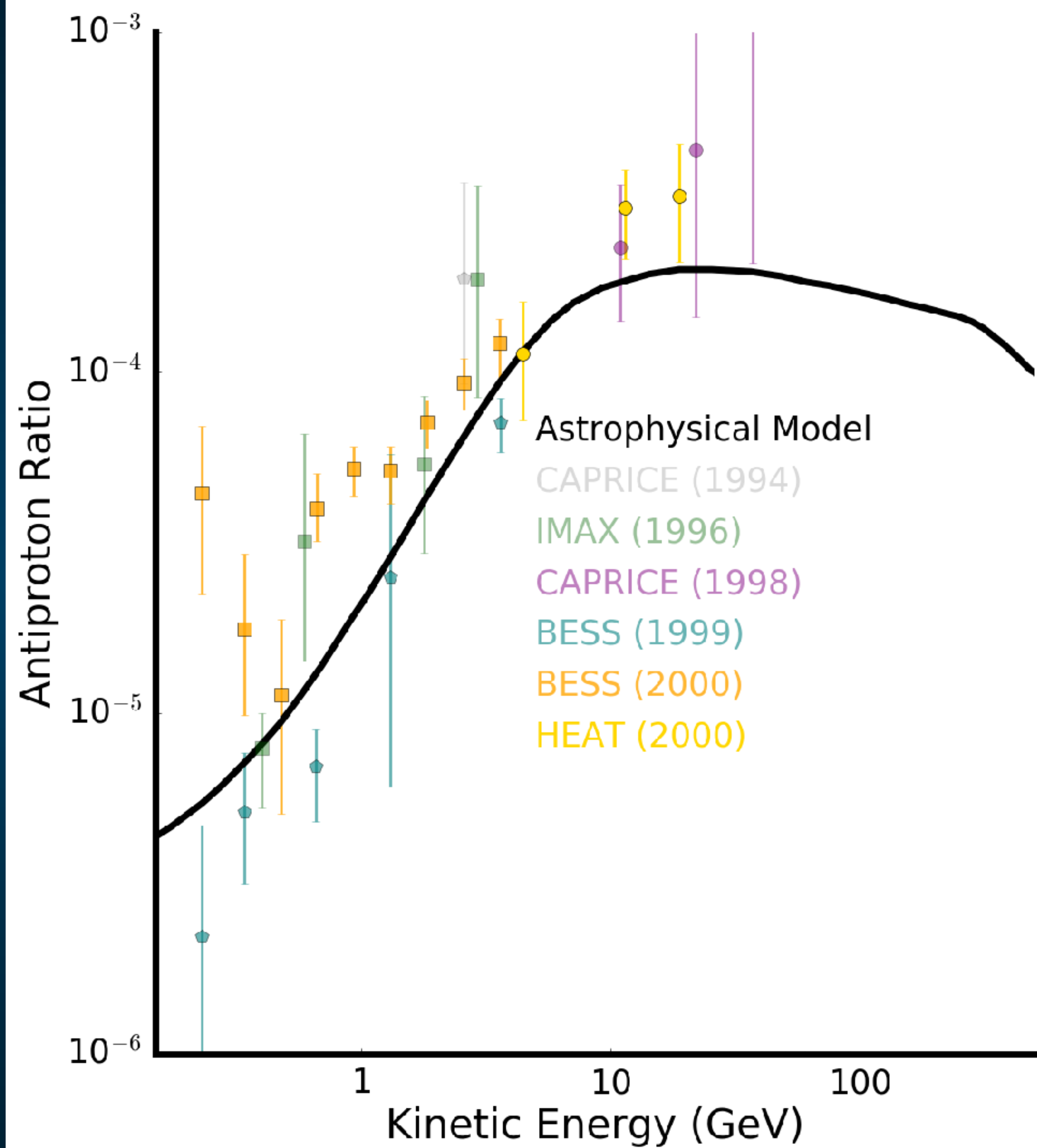
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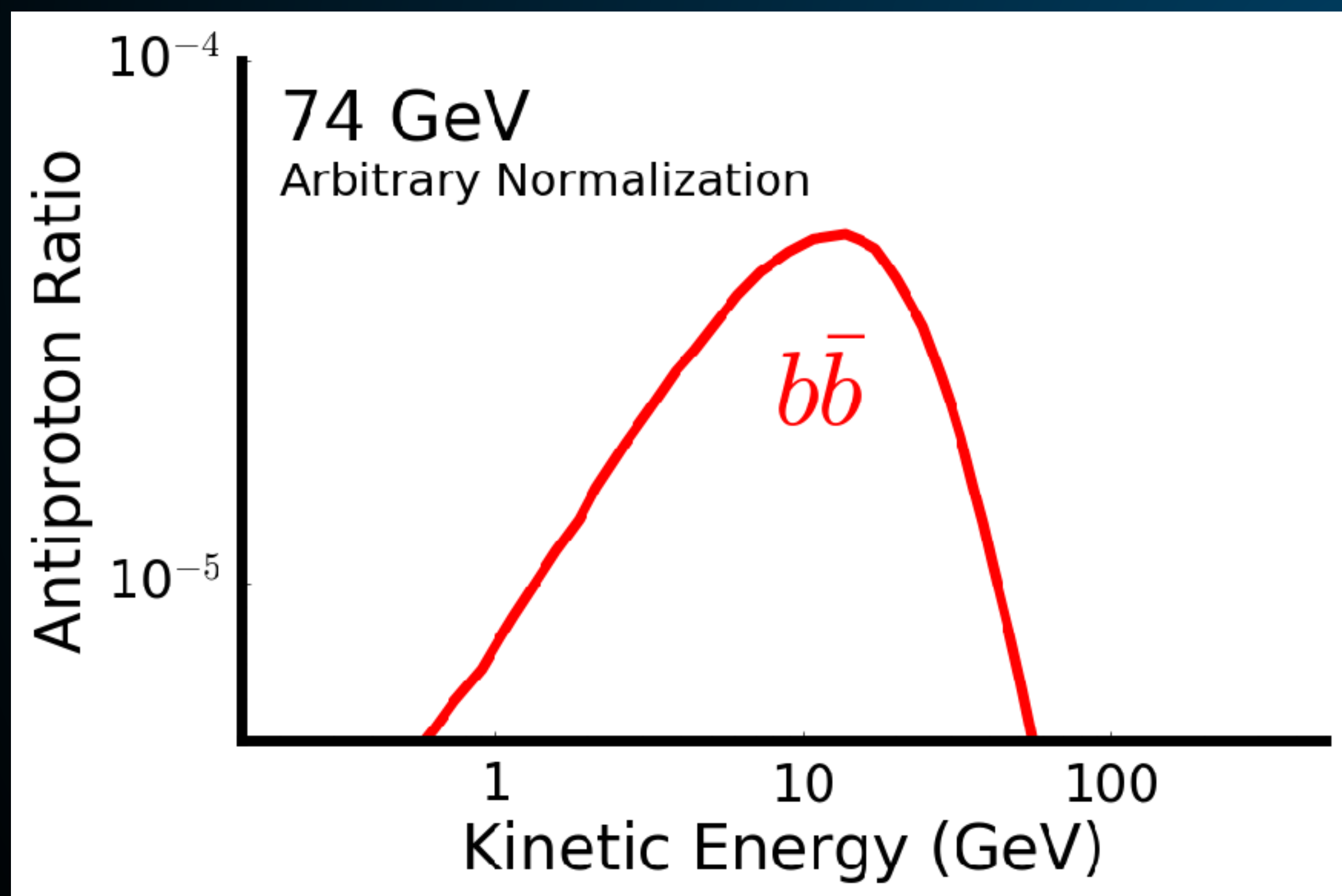
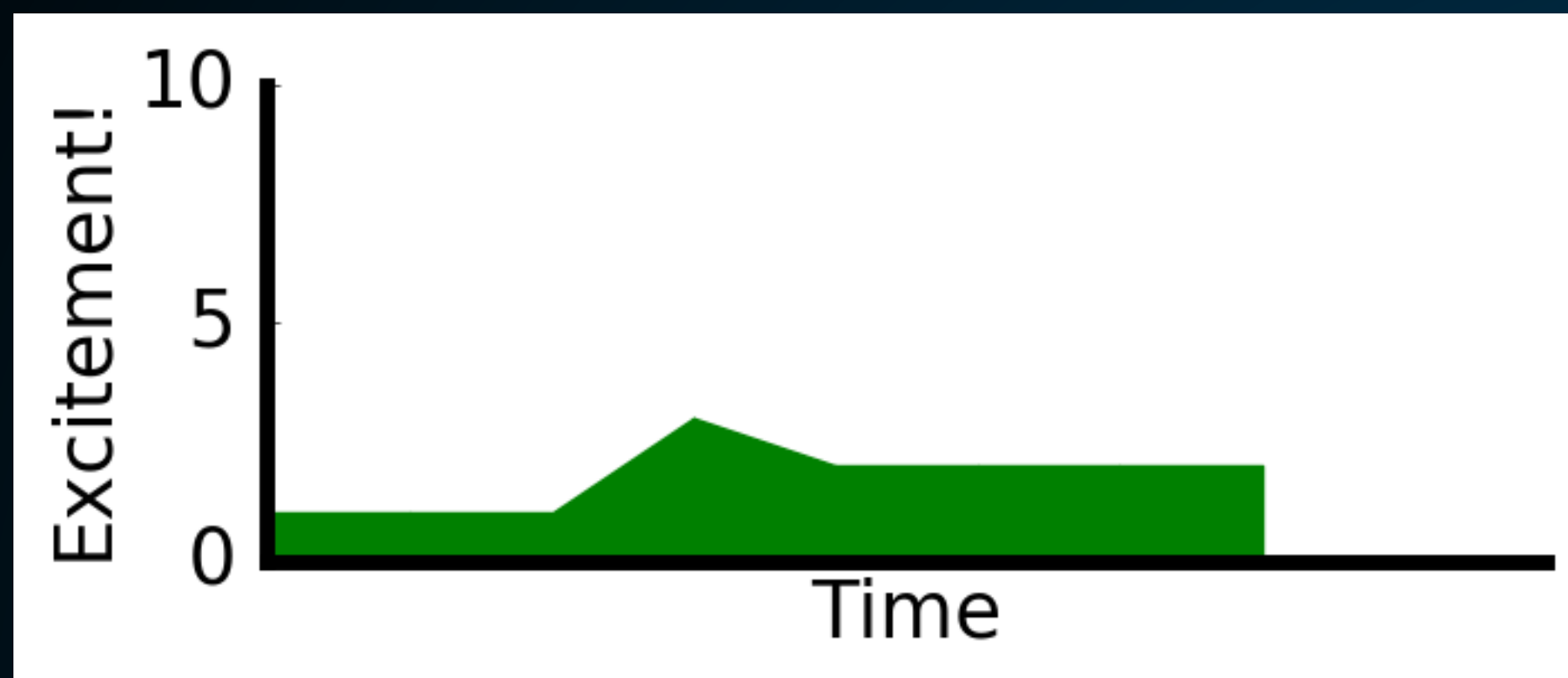
The Antiproton Excess



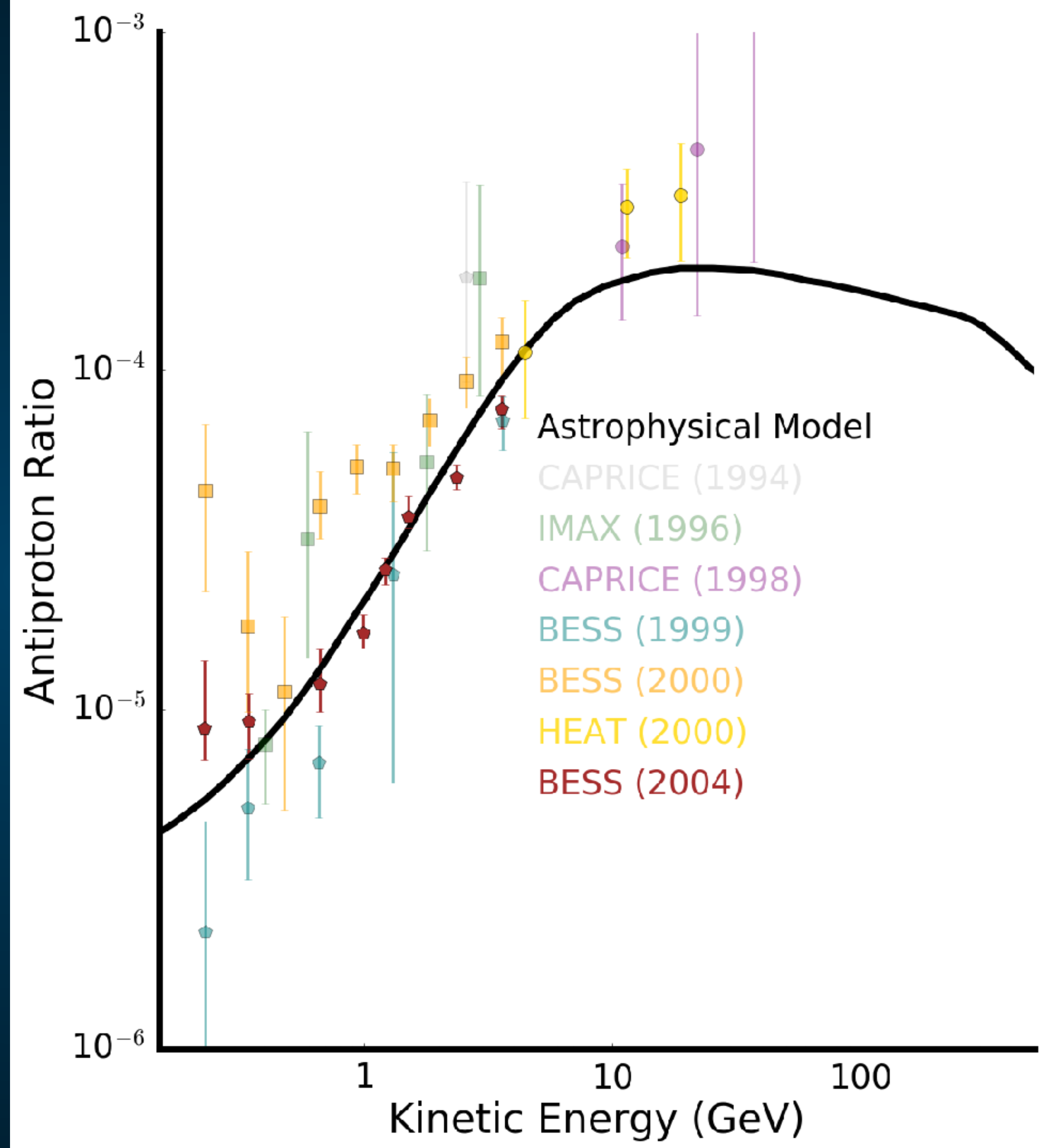
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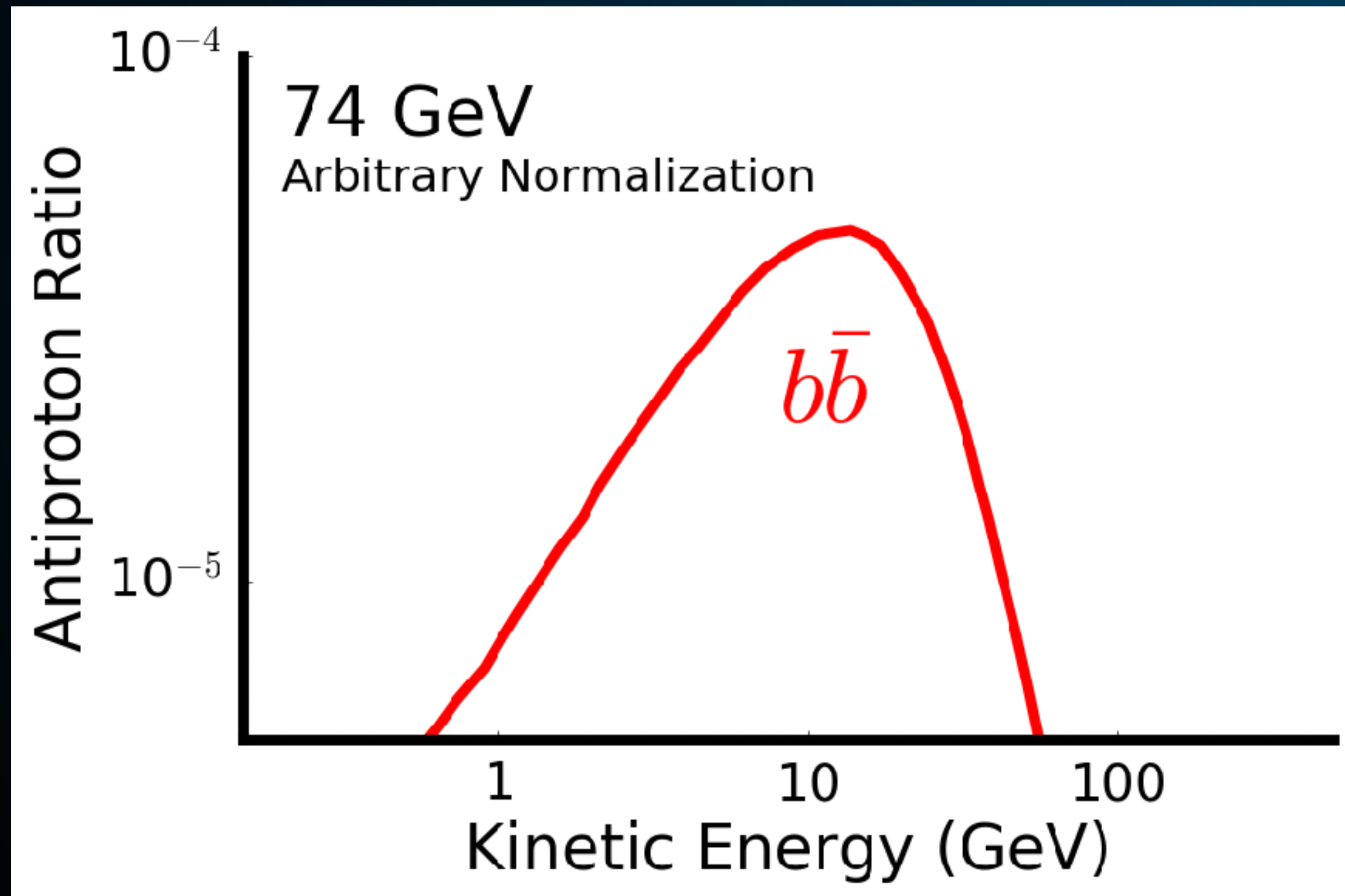
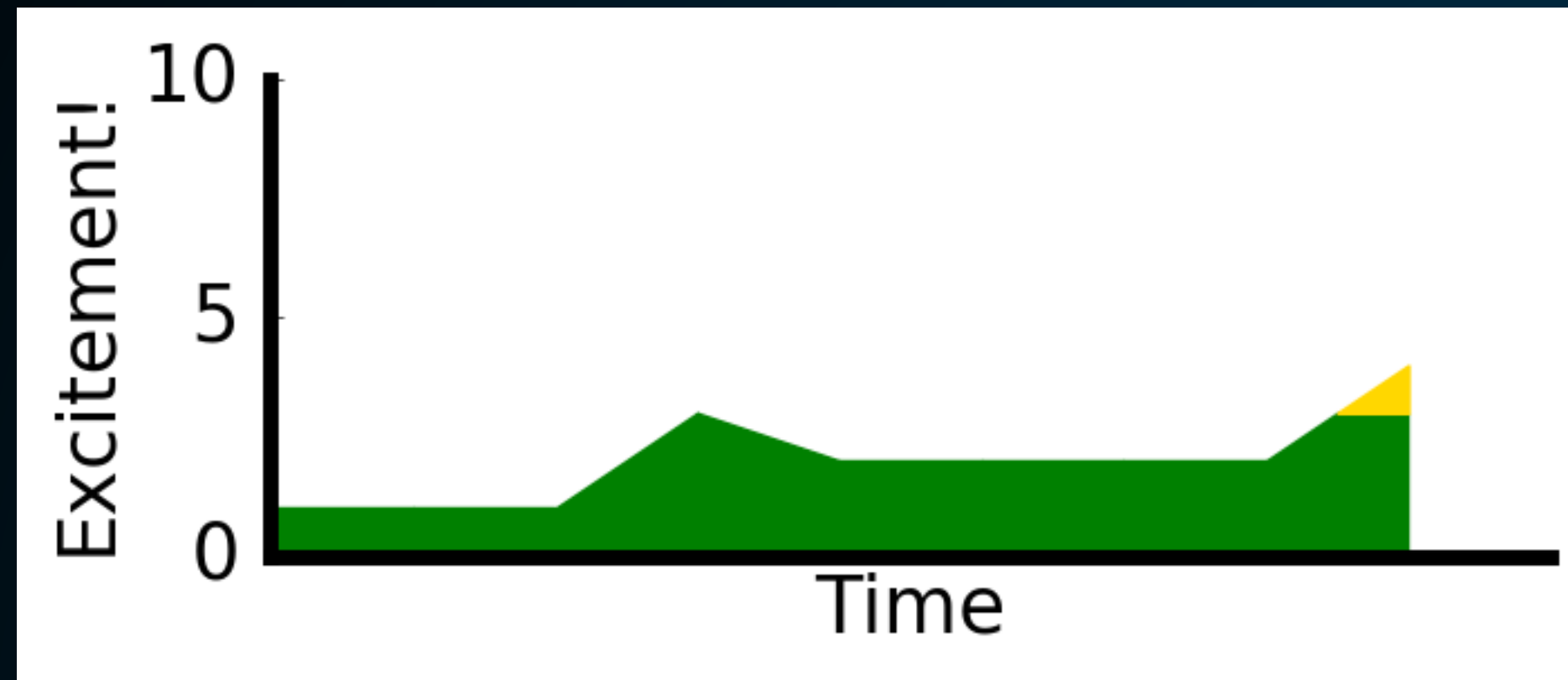
The Antiproton Excess



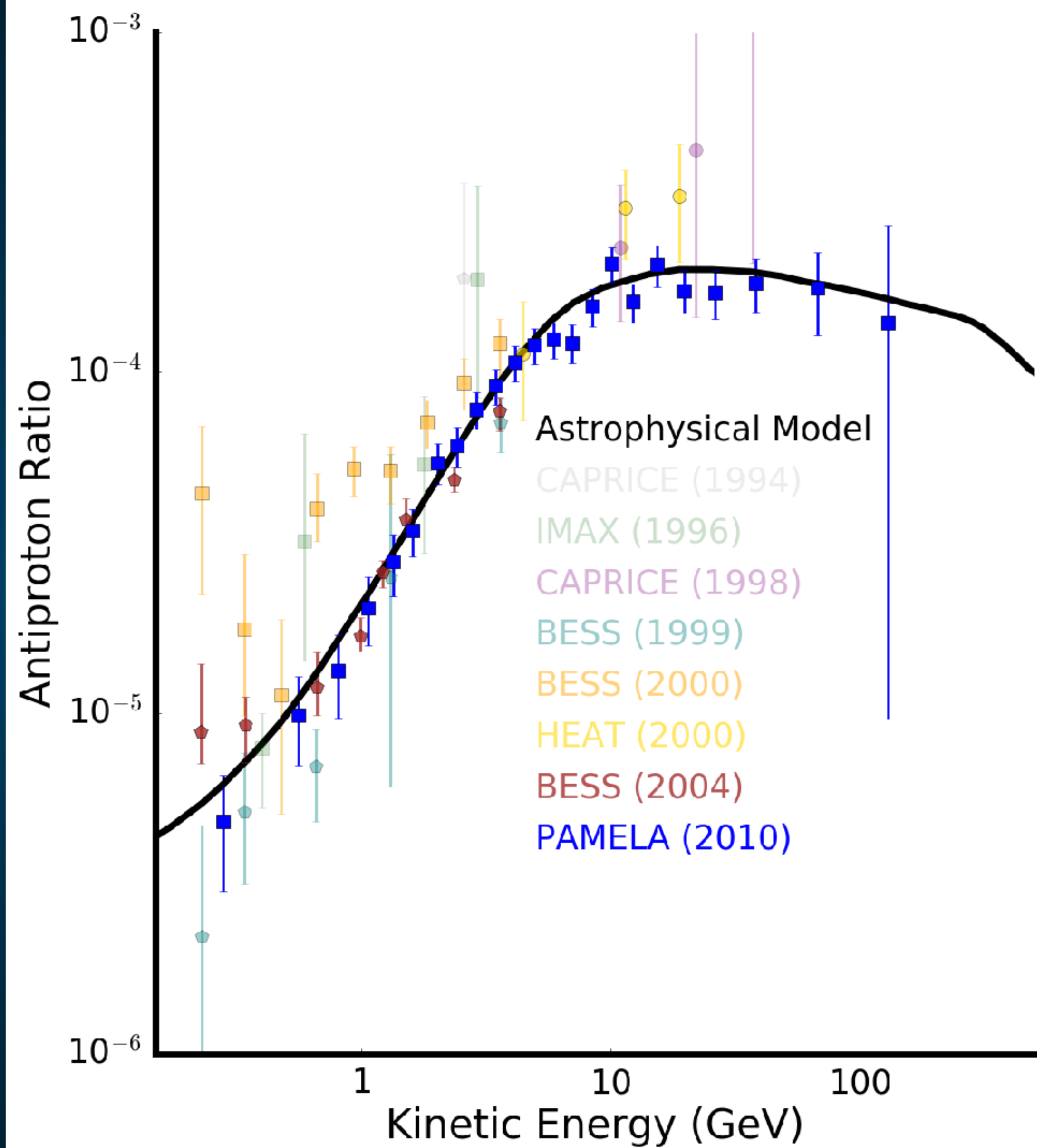
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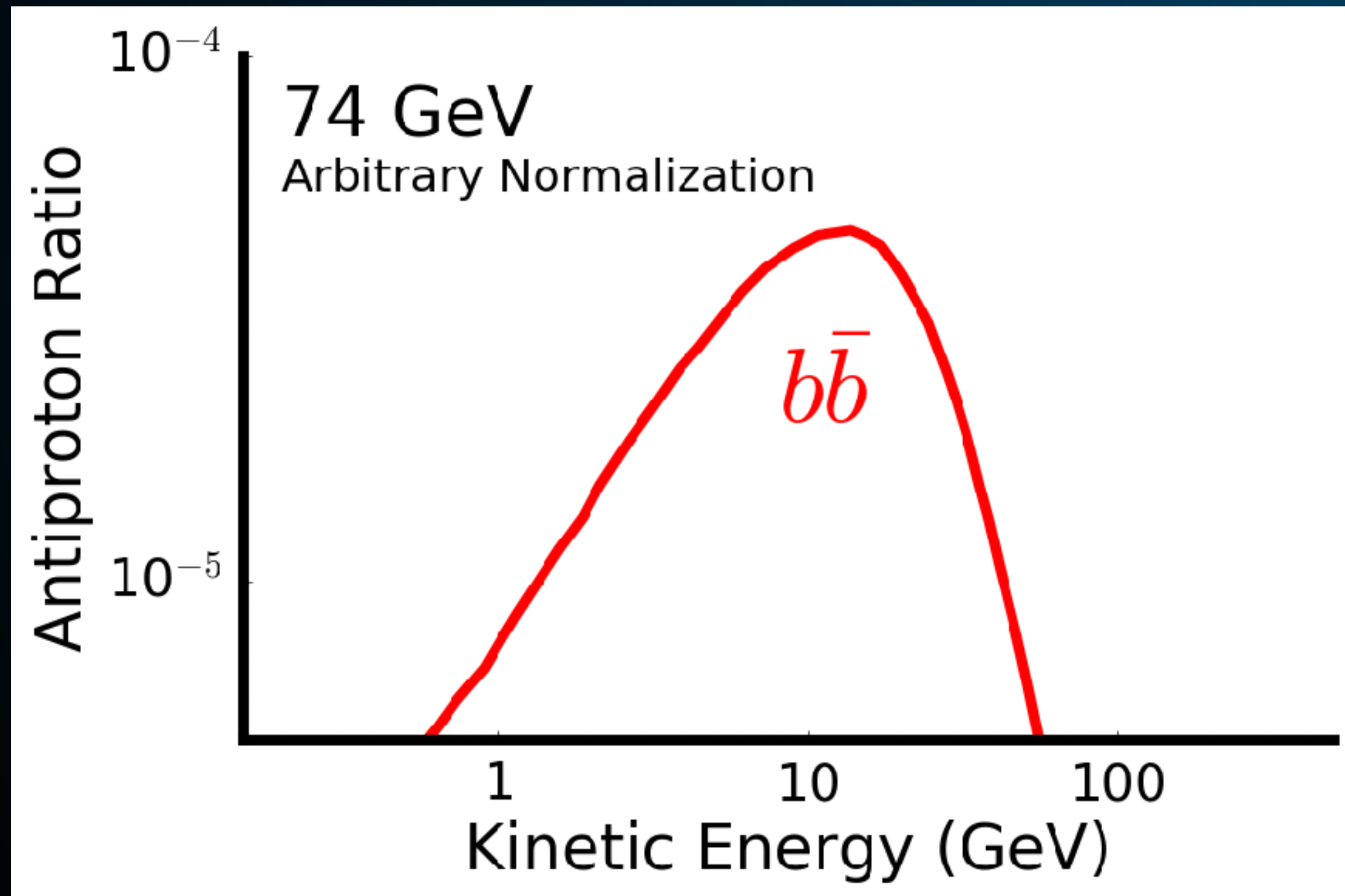
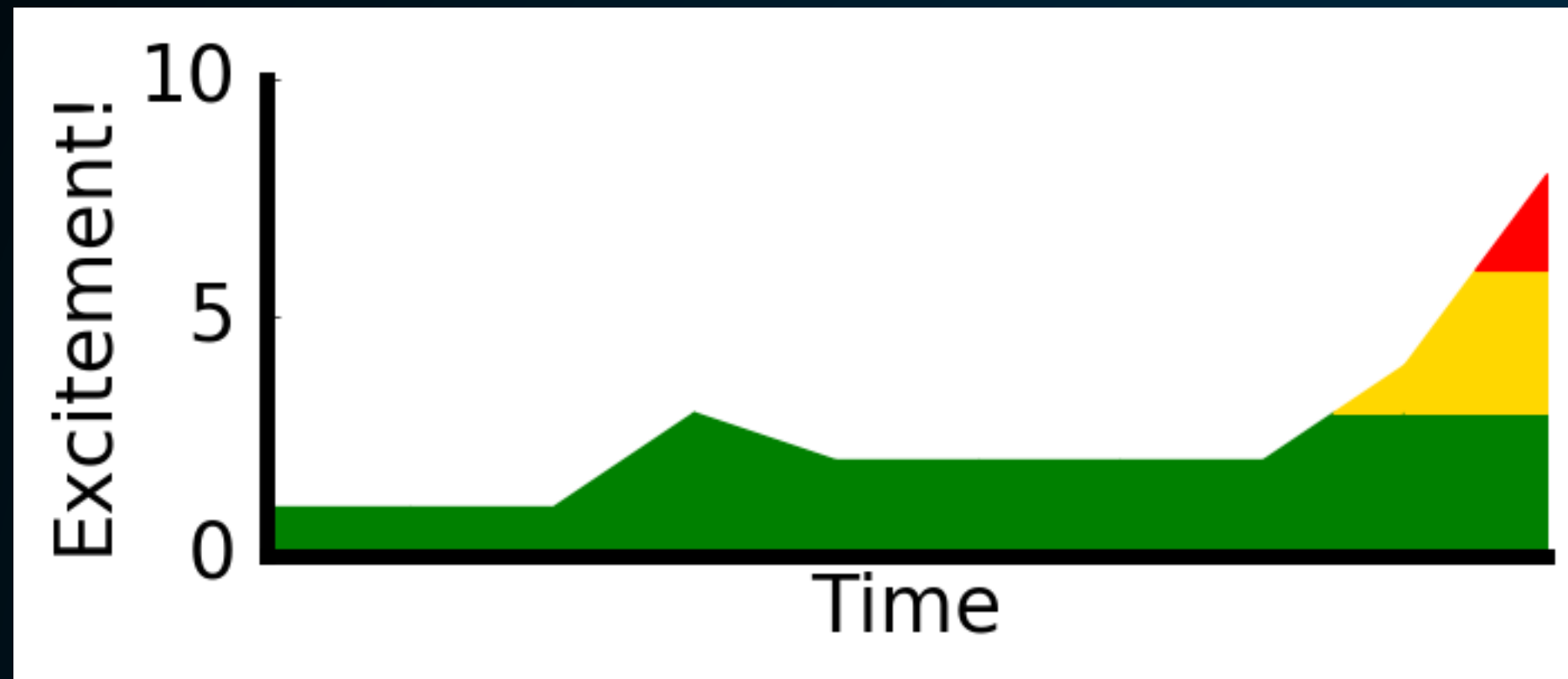
The Antiproton Excess



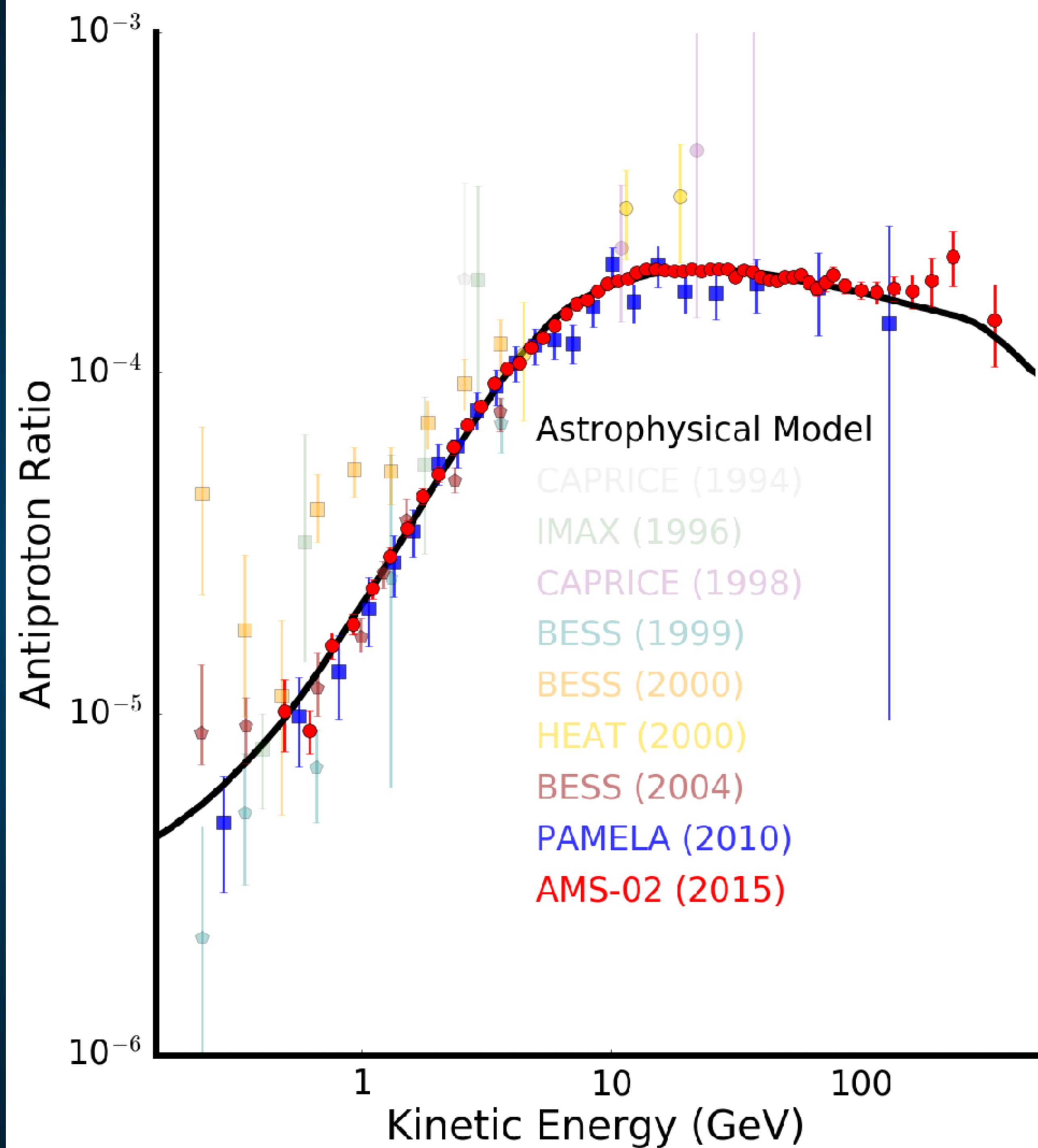
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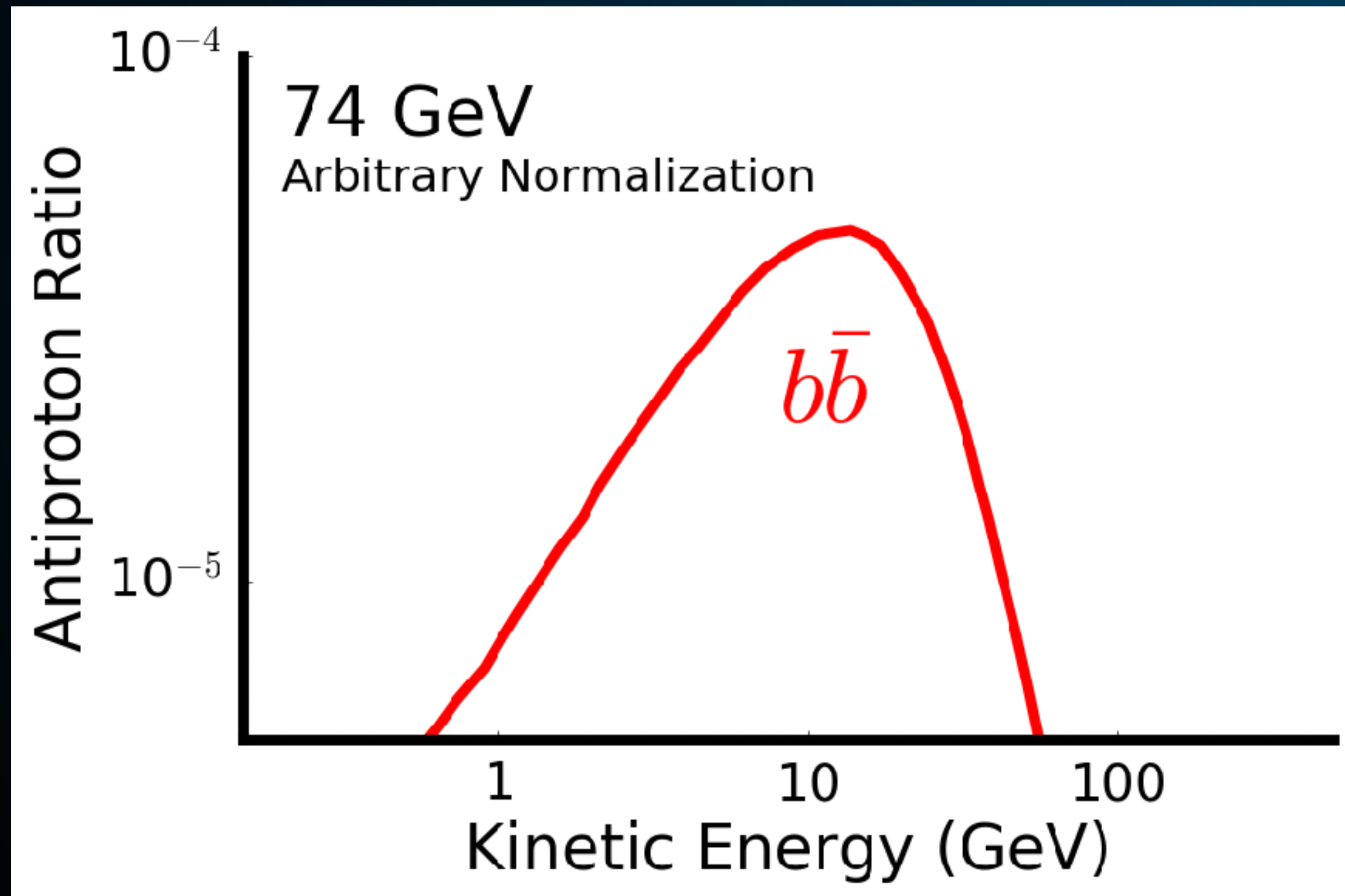
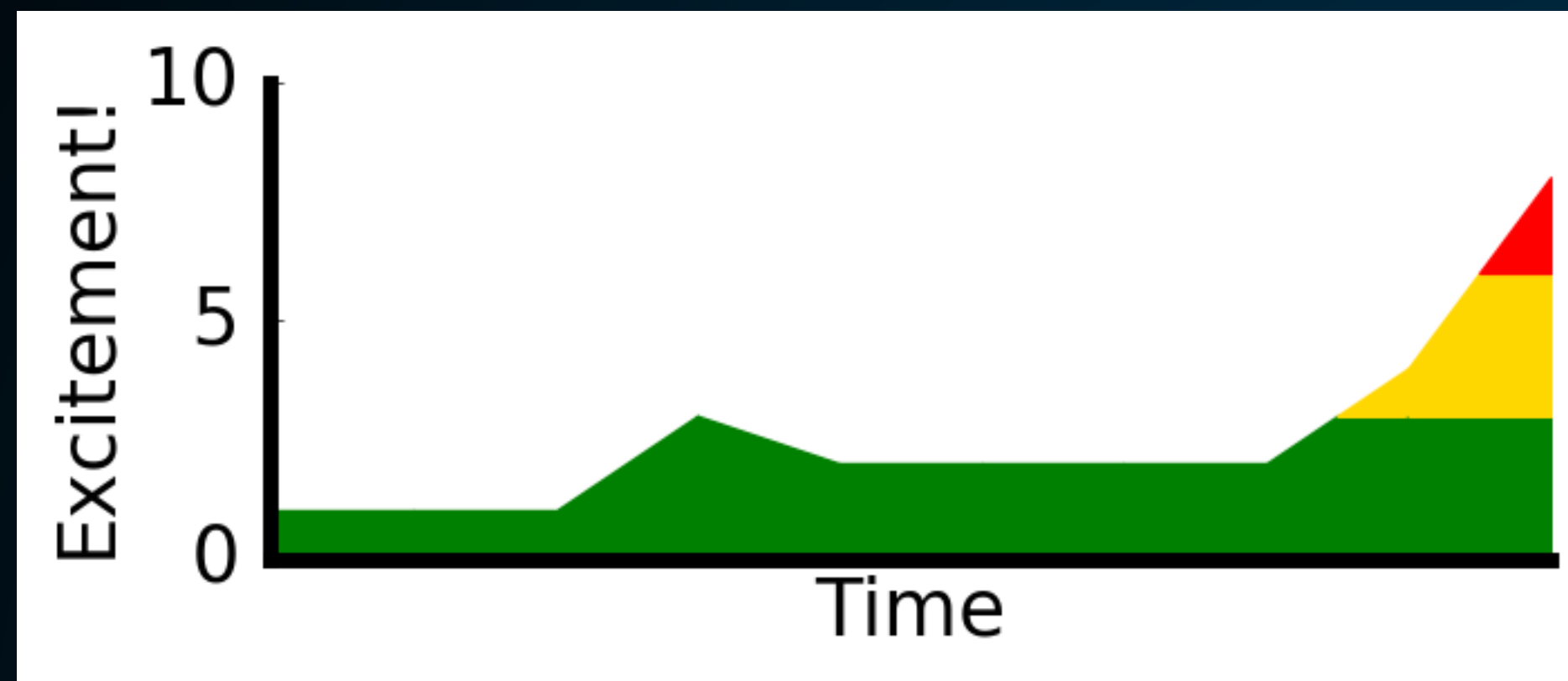
The Antiproton Excess



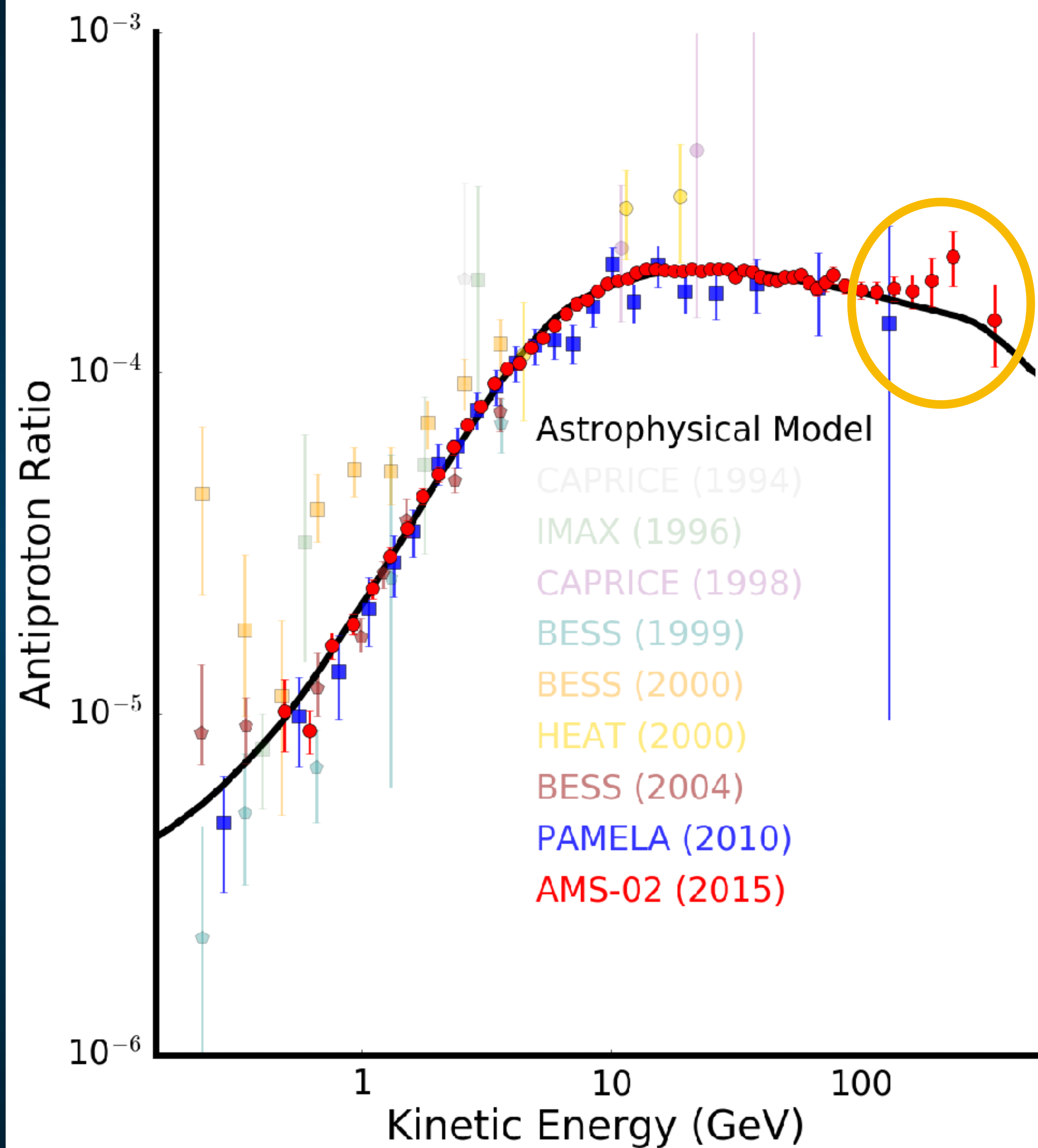
(Not an exhaustive list of observations)



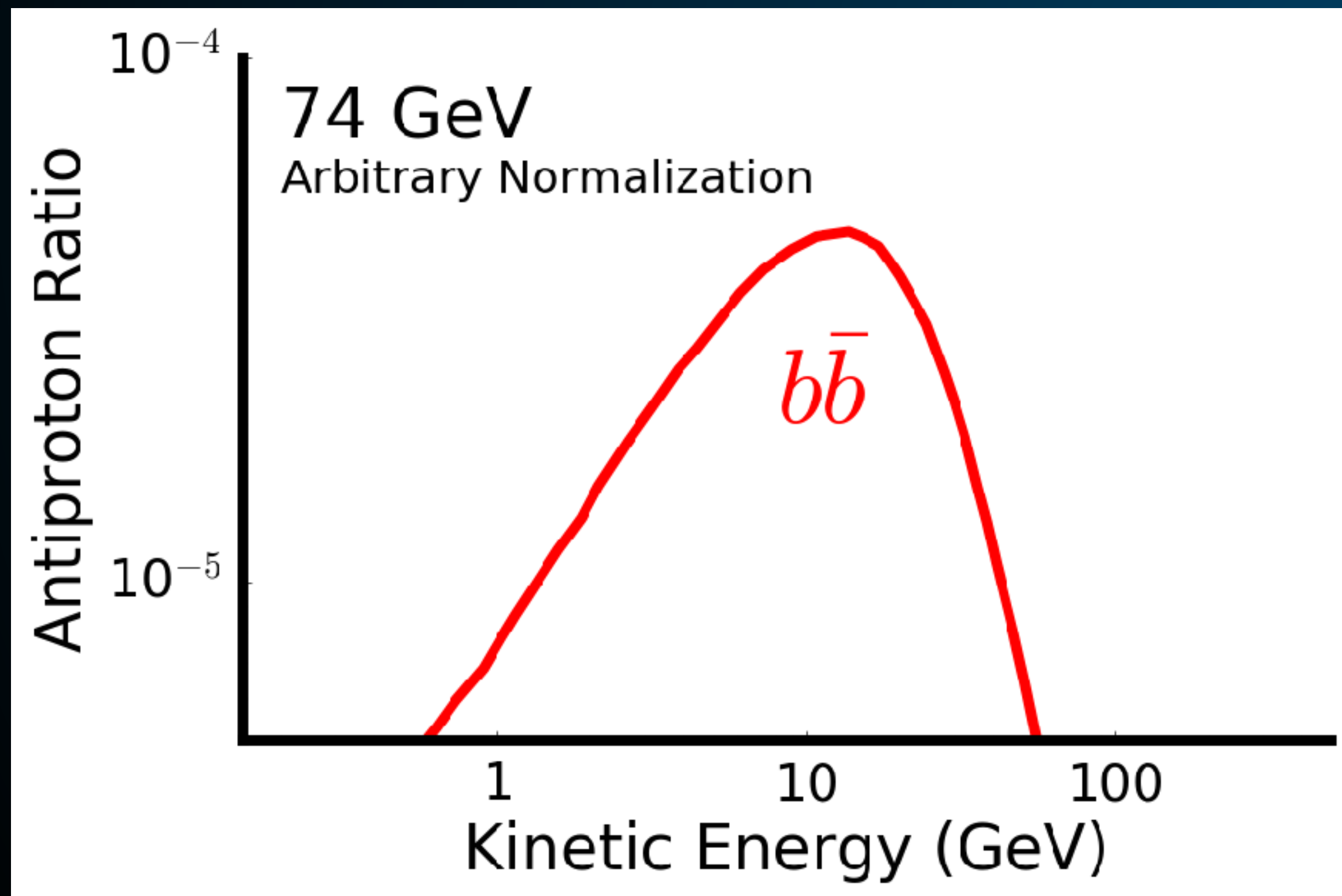
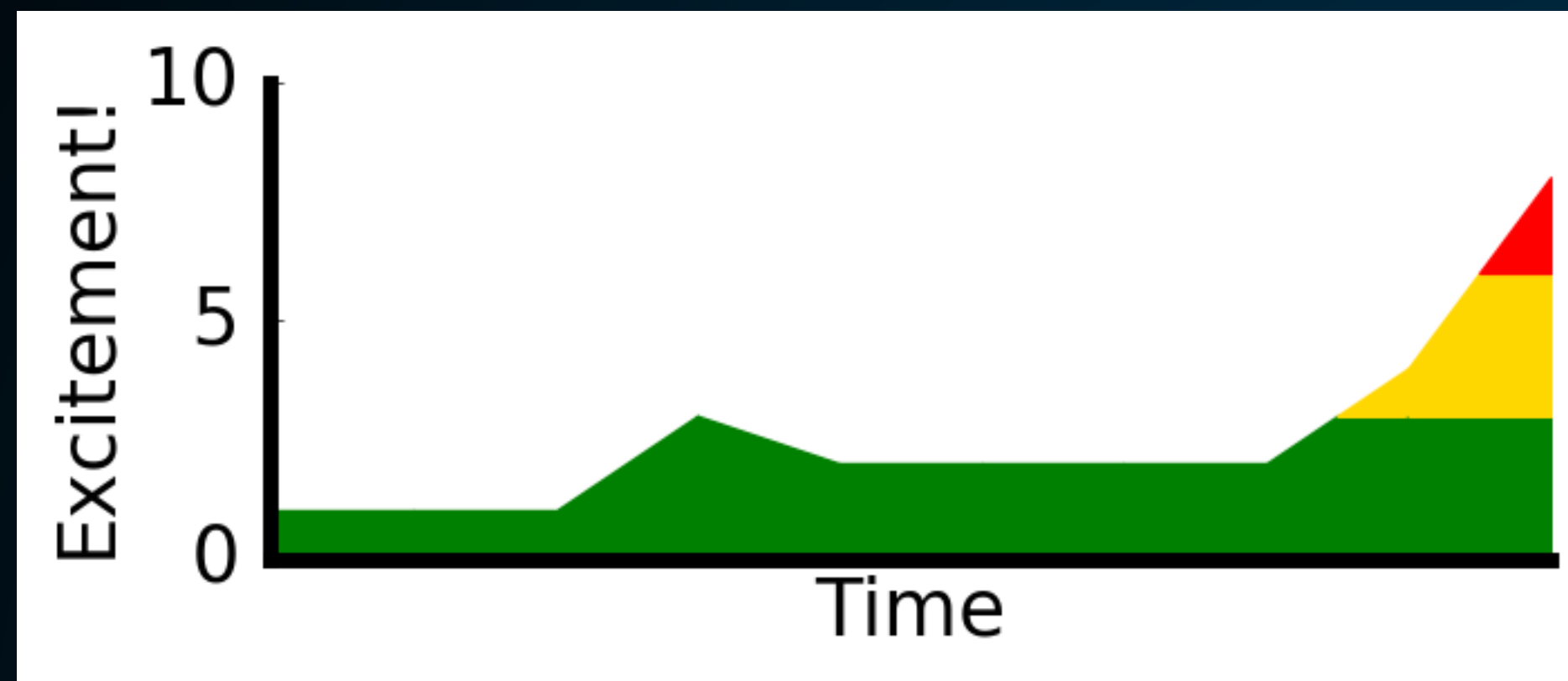
The Antiproton Excess



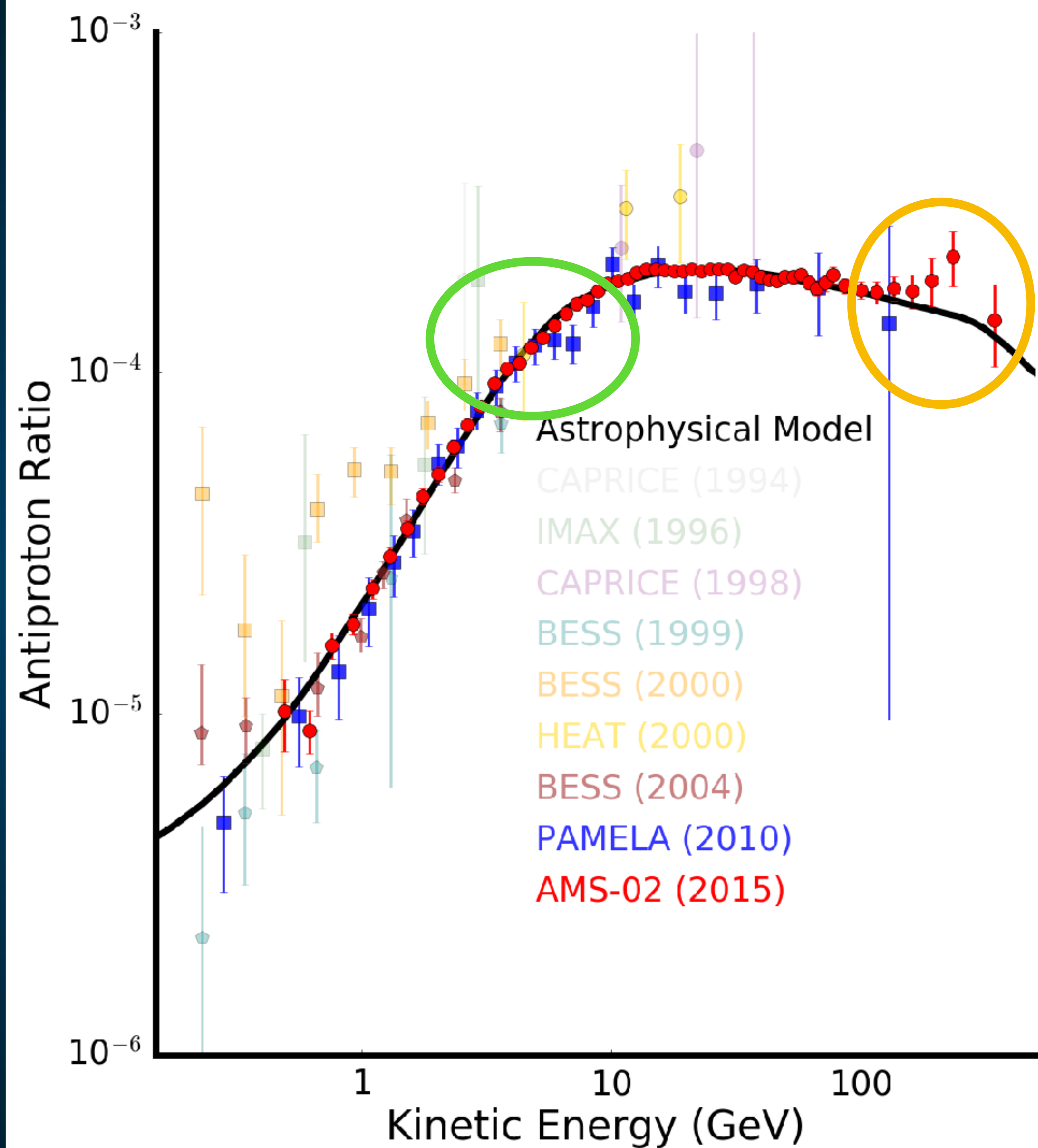
(Not an exhaustive list of observations)



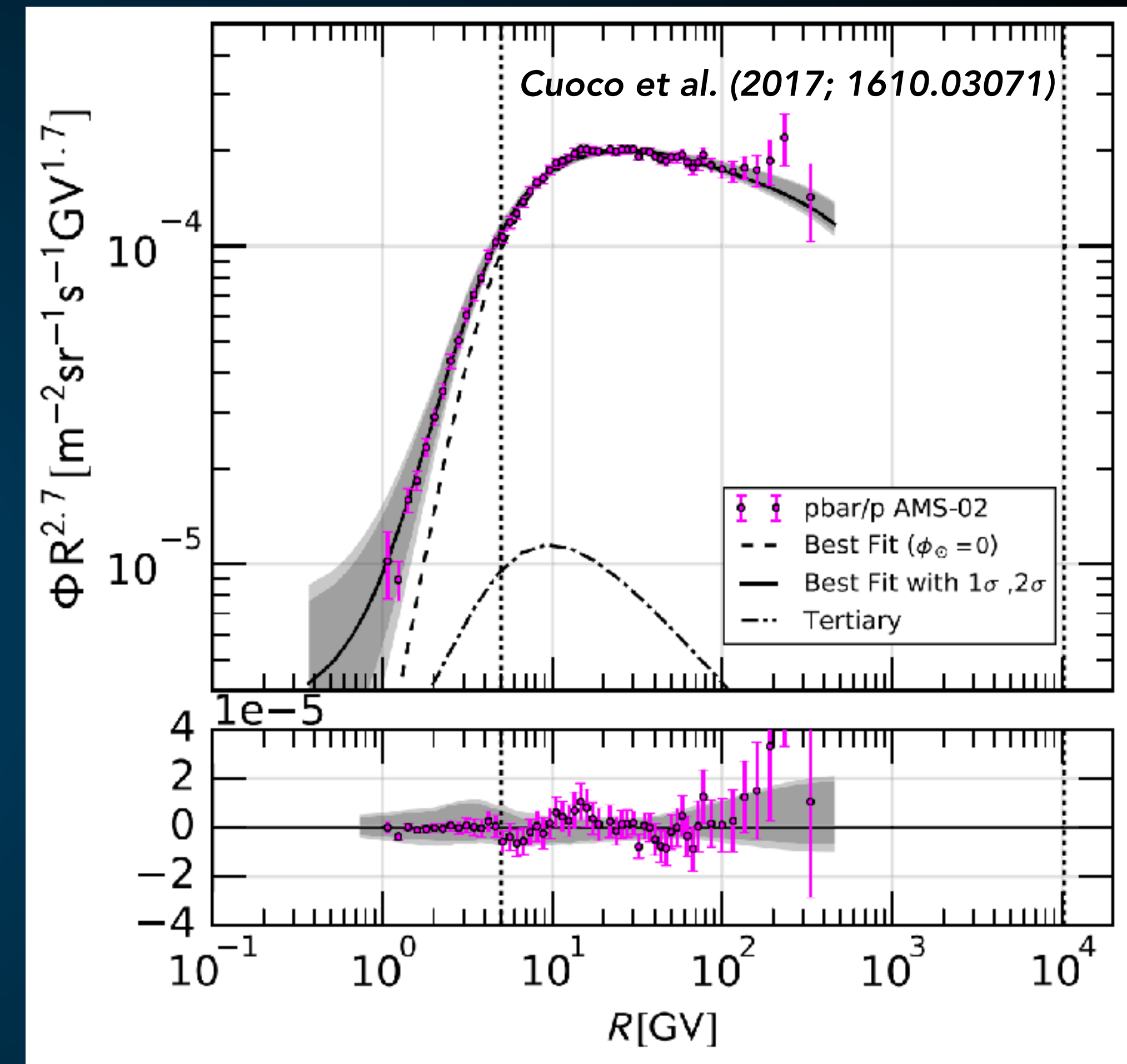
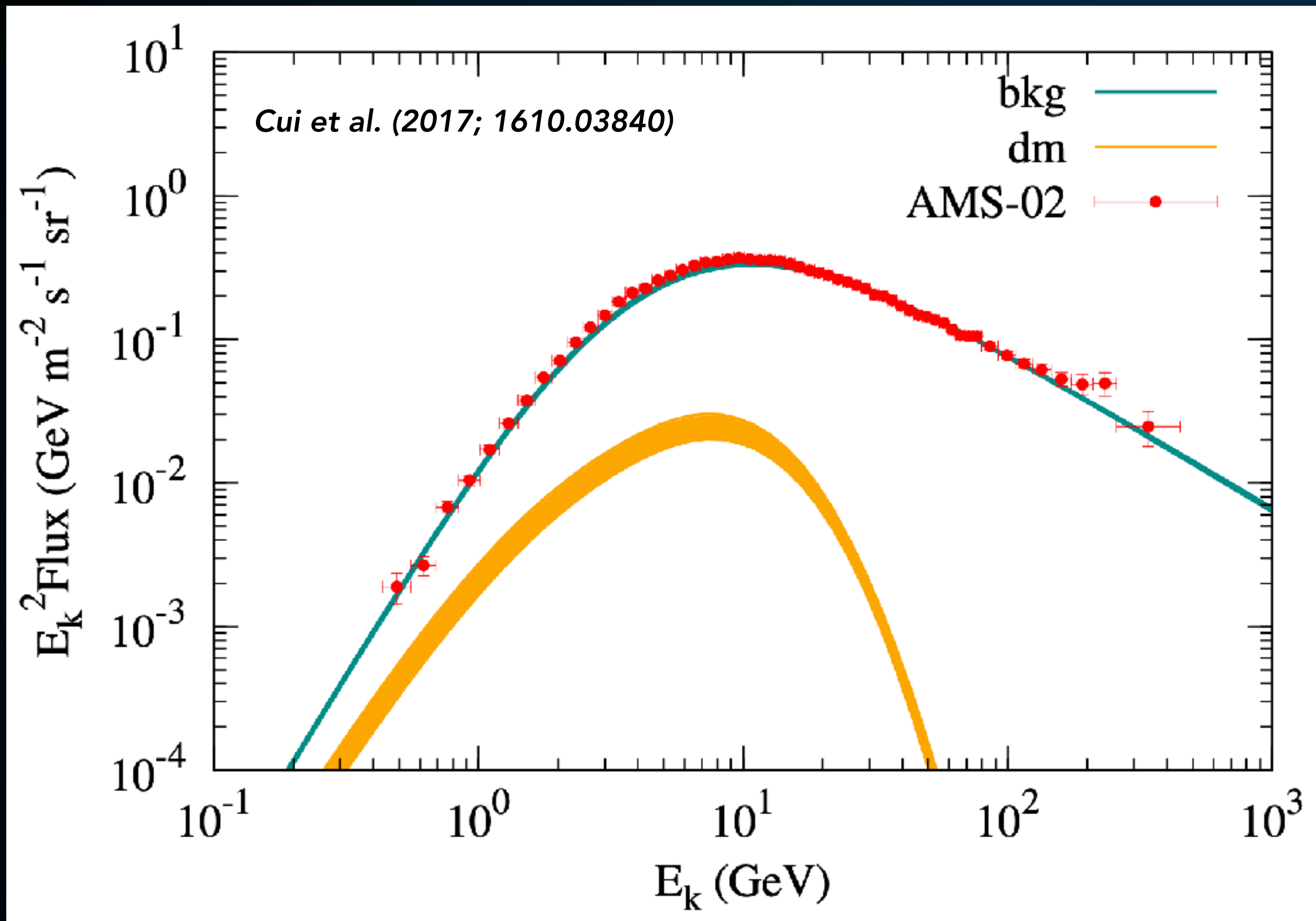
The Antiproton Excess



(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 !

The Antiproton Excess

With great precision comes great responsibility:

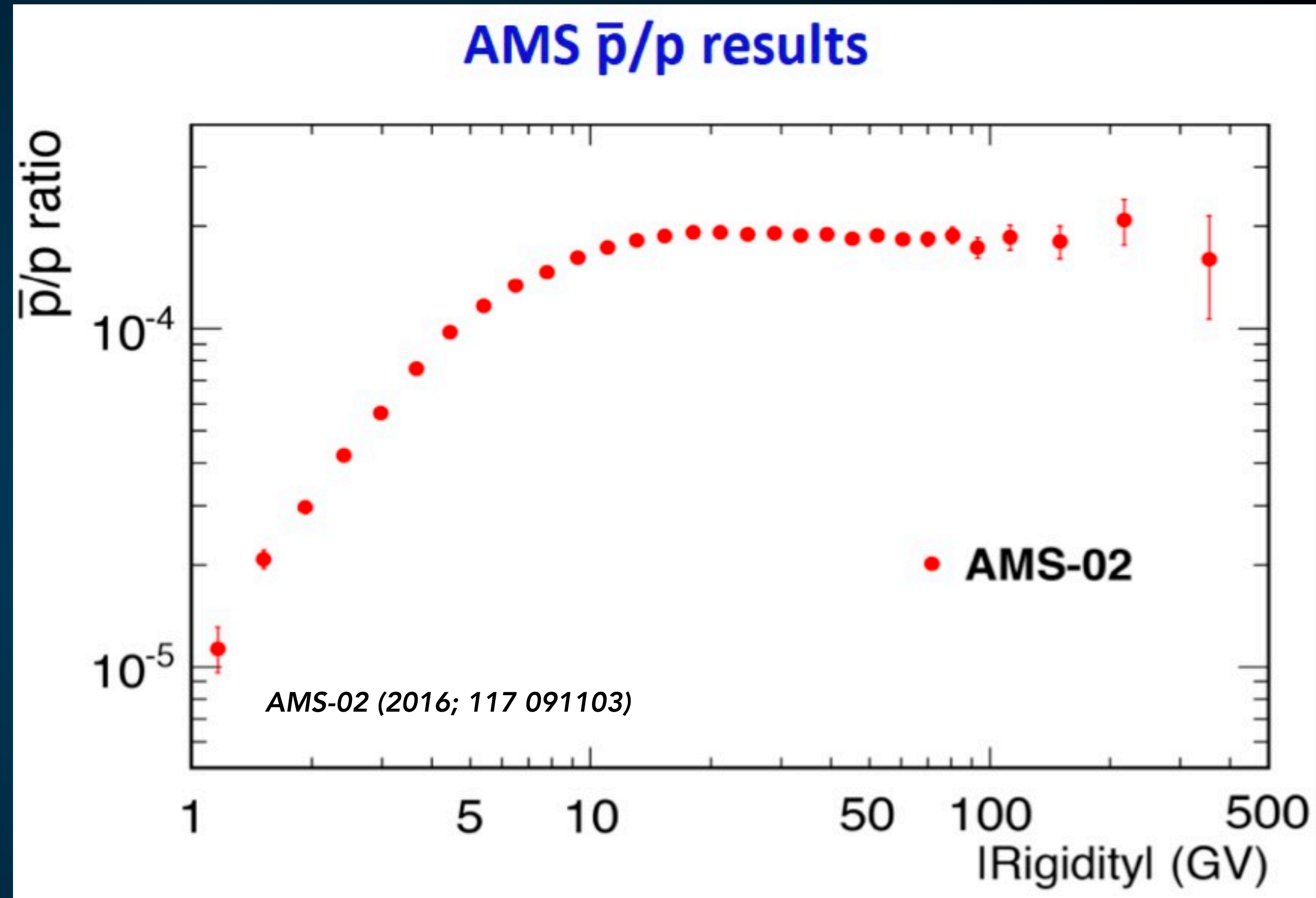
Antiproton Production Cross-Section

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:

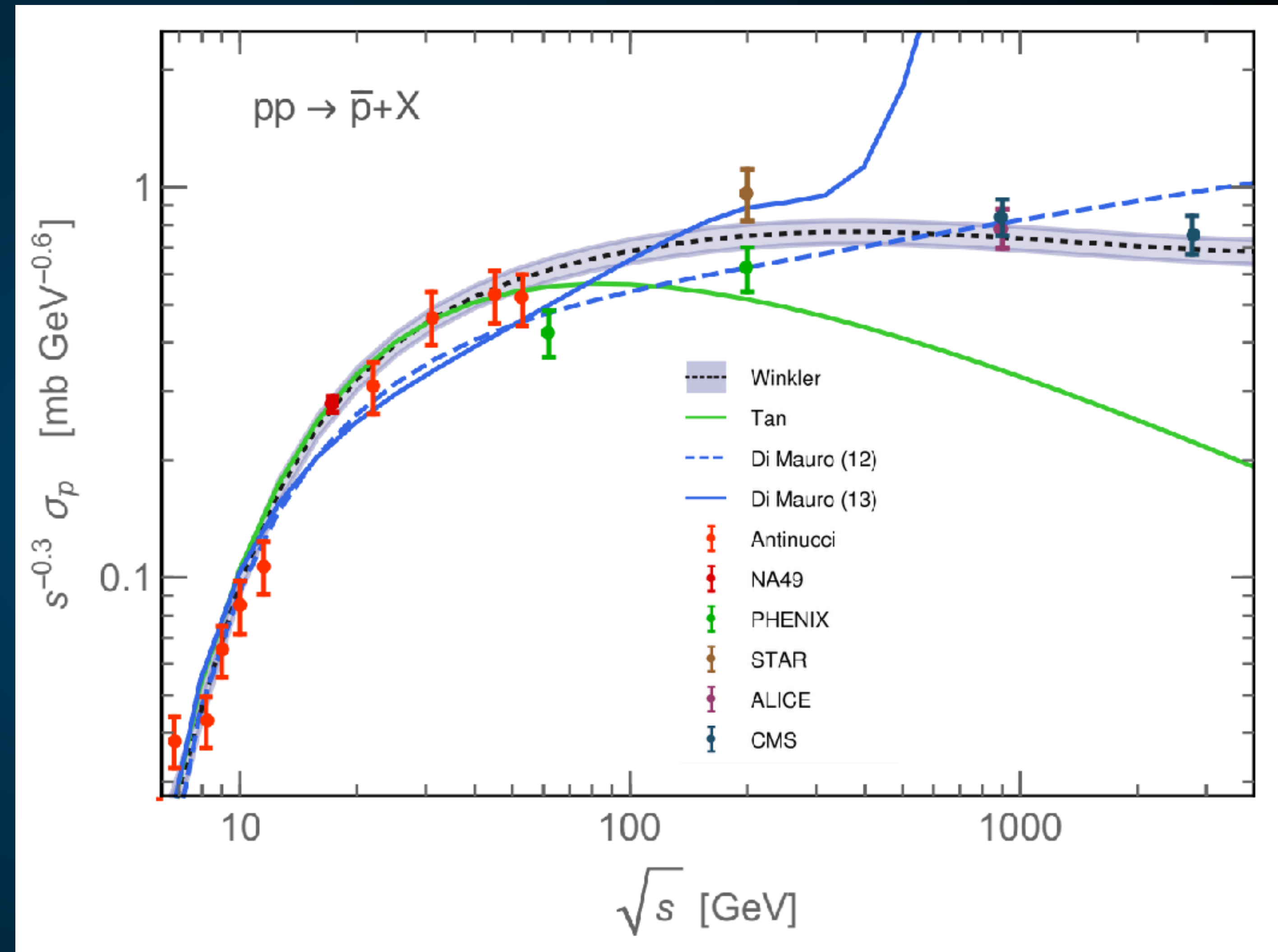
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With great precision comes great responsibility:

Antiproton Production Cross-Section

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

(Table continued)

The Antiproton Excess

With great precision comes great responsibility:

Antiproton Production Cross-Section

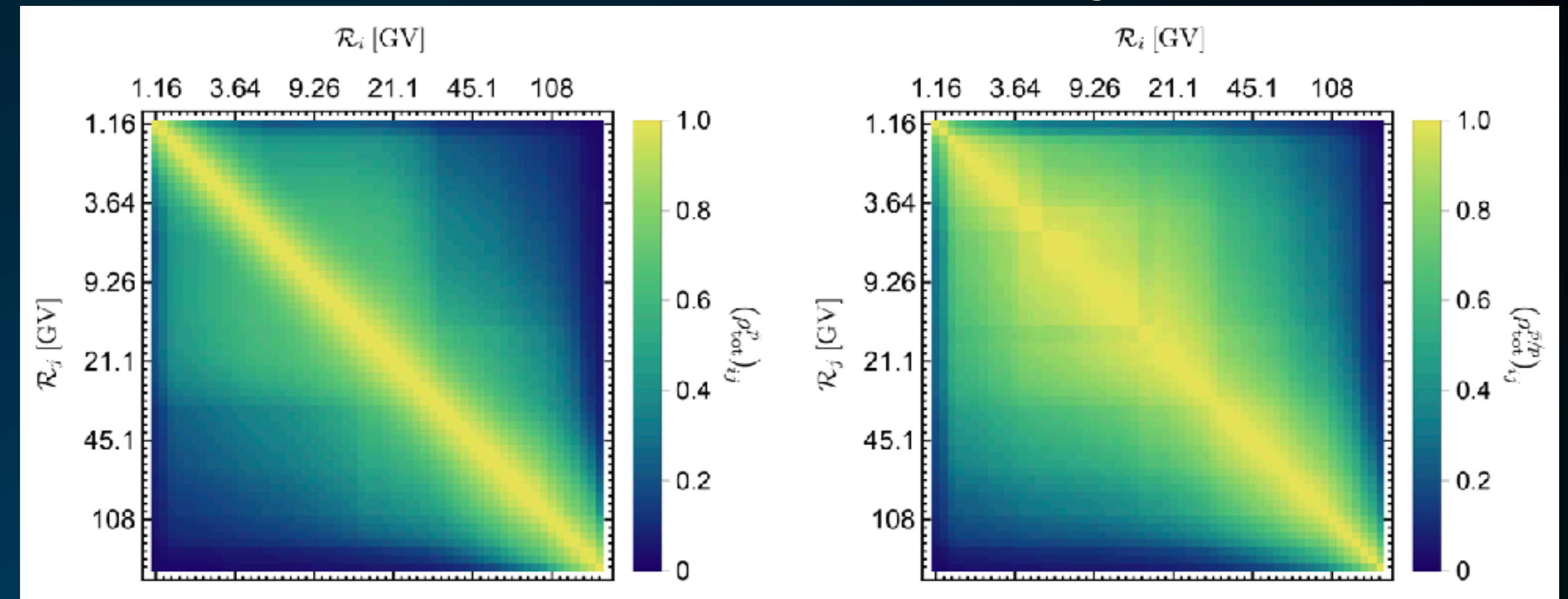
Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

Solar Modulation

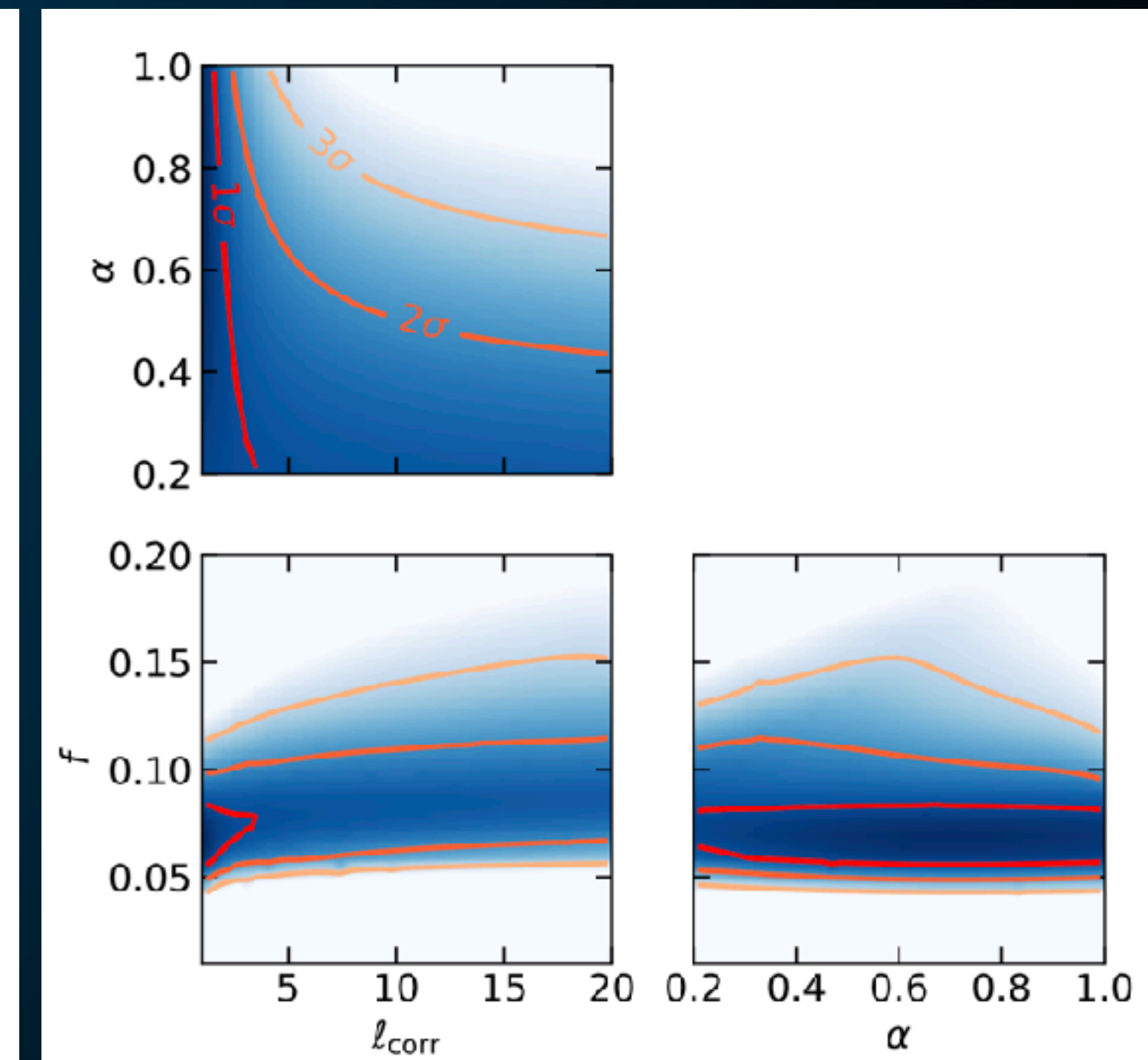
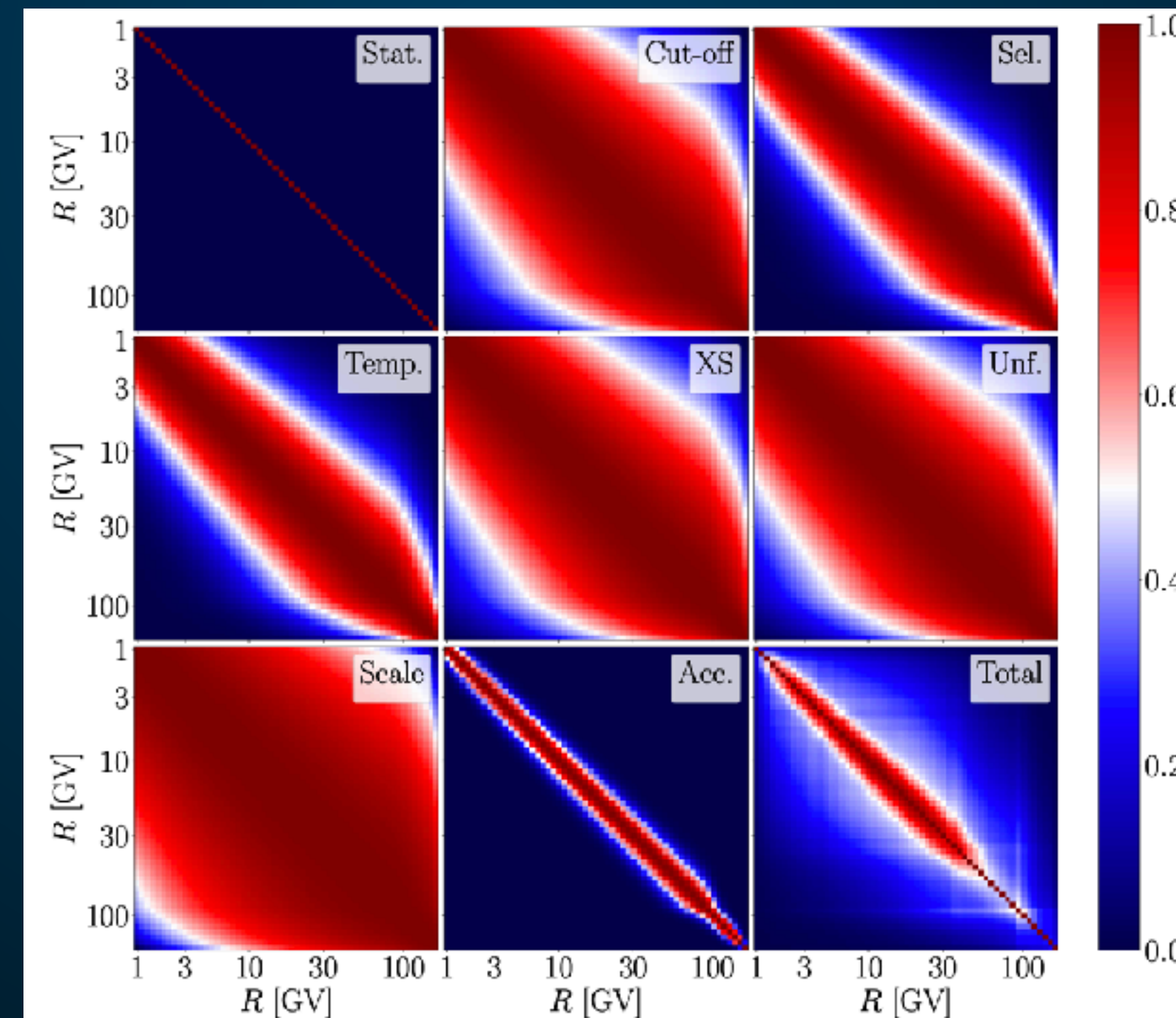
Instrumental Uncertainties

Heisig et al. (2020; 2005.04237)



Boudaud et al. (2019; 1906.07119)

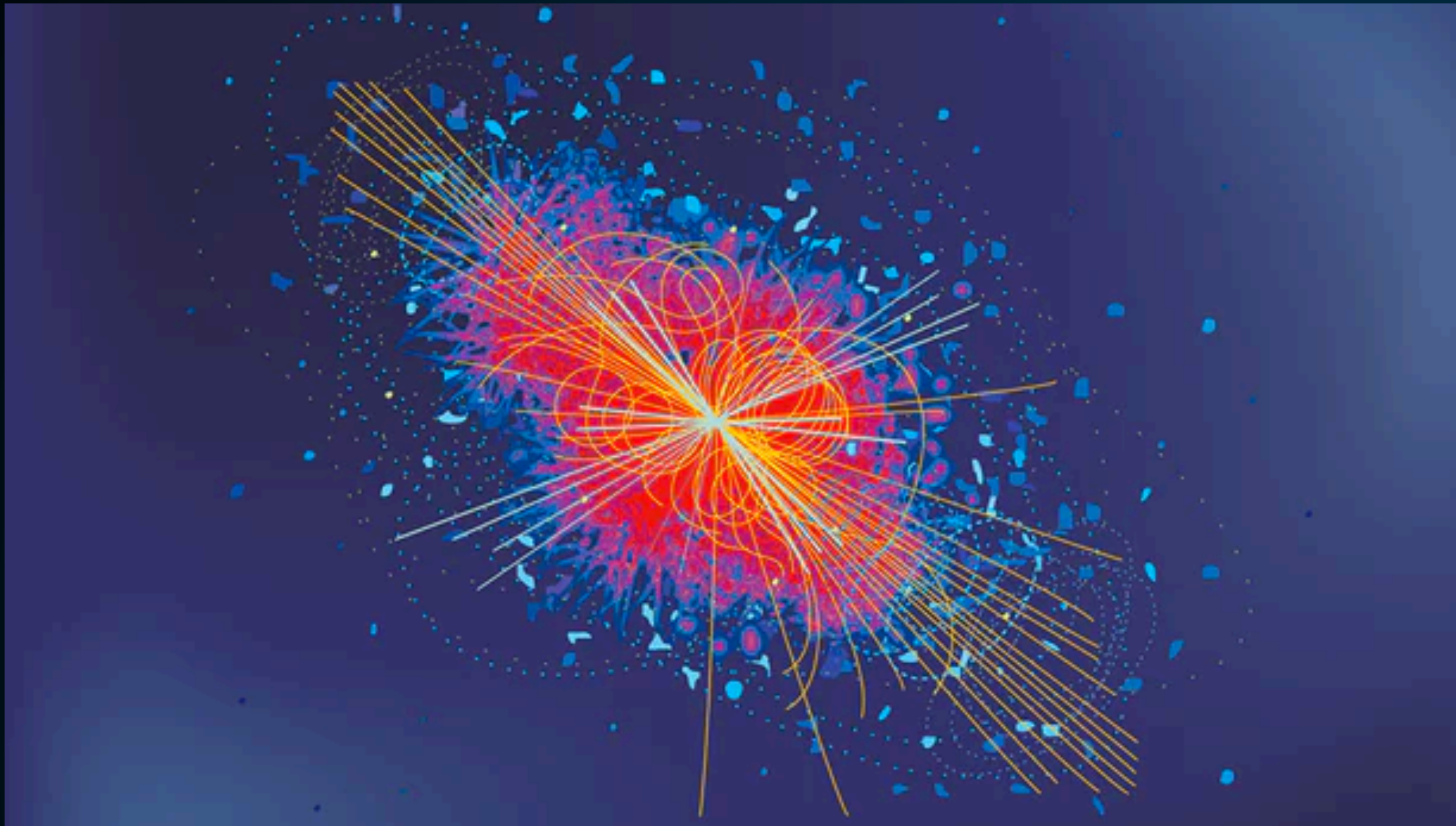
Cuoco et al. (2019; 1903.01472)



Antinuclei!?



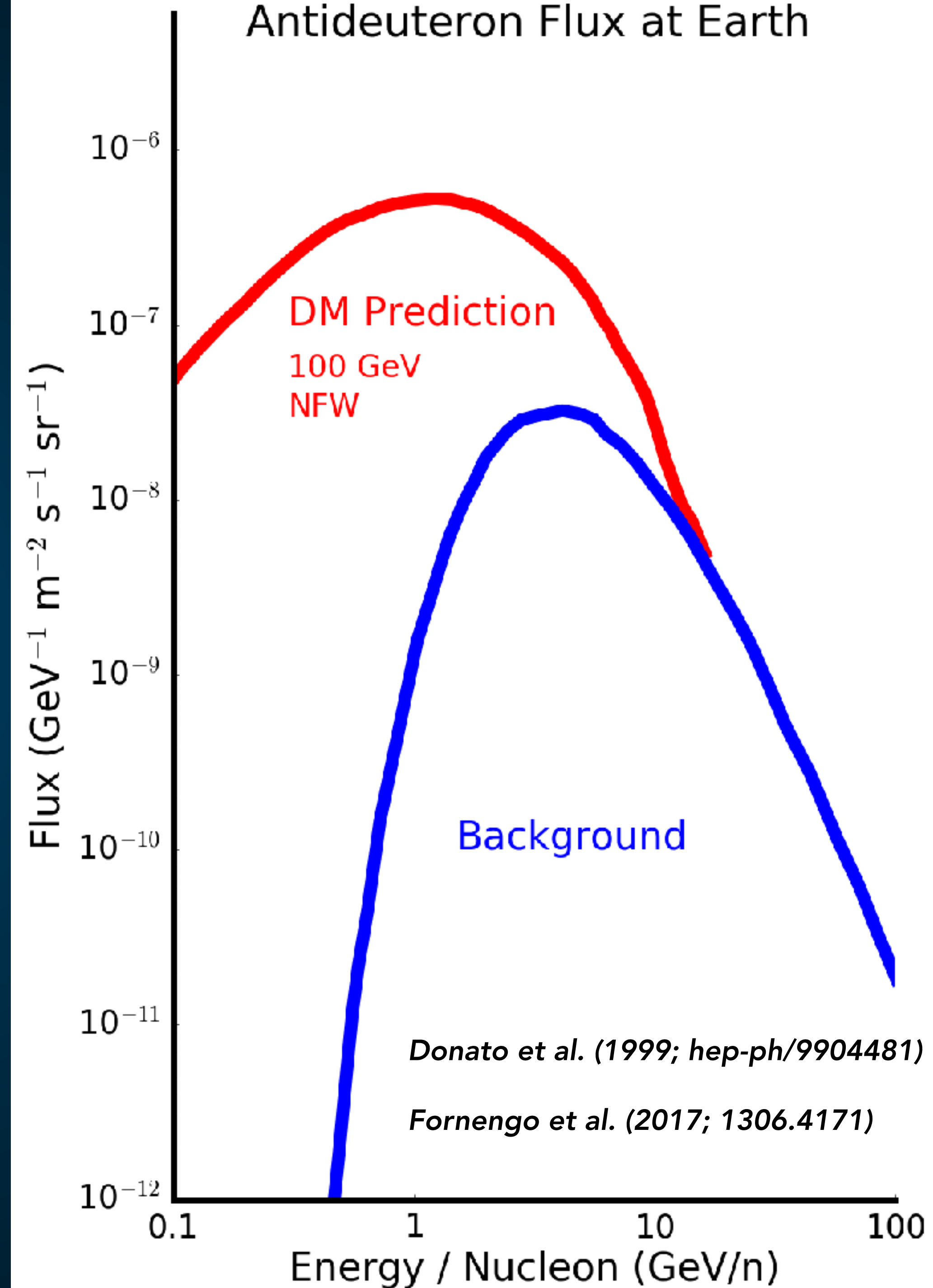
AntiNuclei - A Clean Search Strategy ?



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.

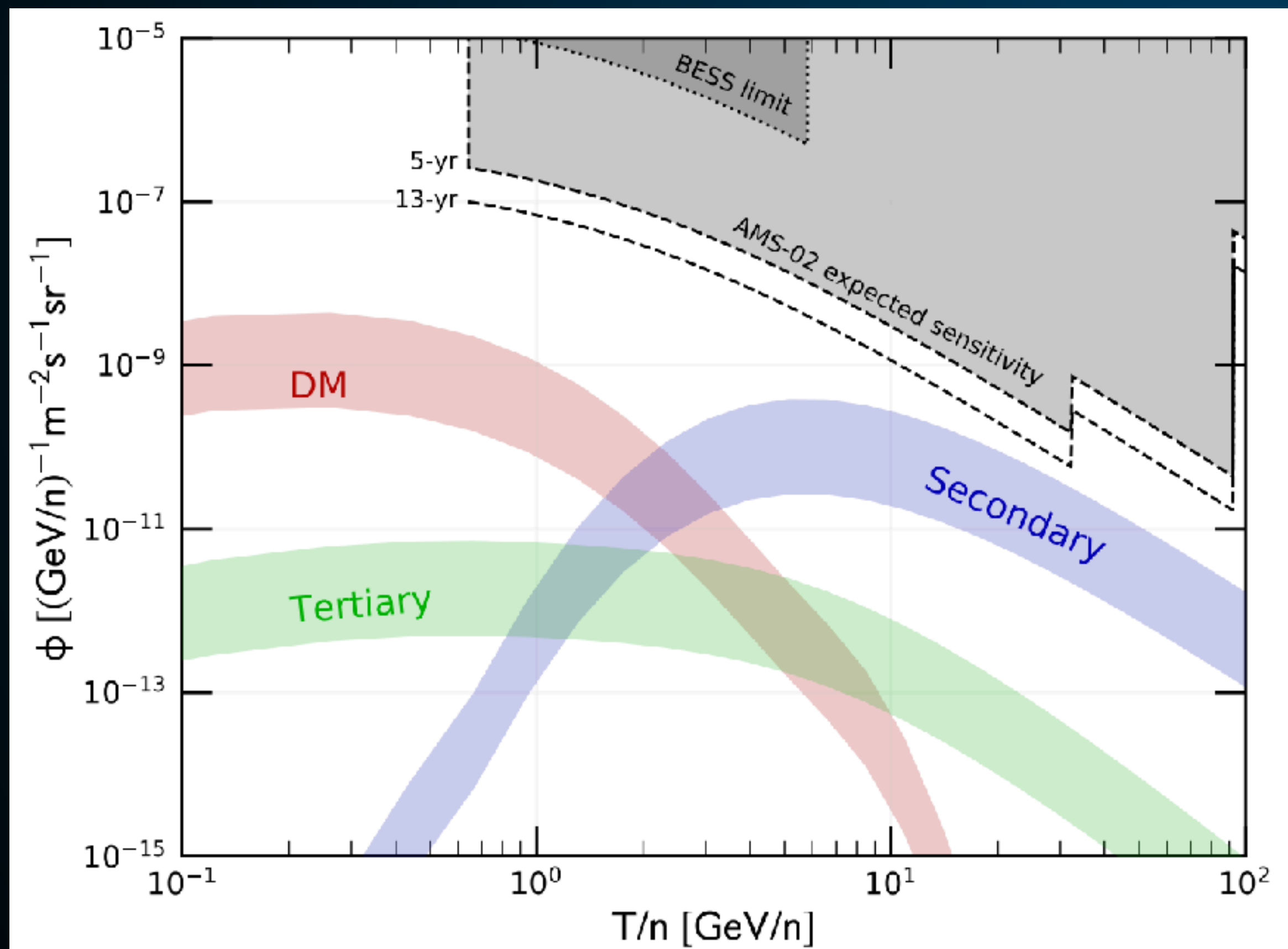
Currently (having used 50 million core hours to generate 7 times more simulated events than measured events and having found no background events from the simulation), our best evaluation of the probability of the background origin for the eight $\bar{\text{He}}$ events is **less than 3×10^{-8}** . For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

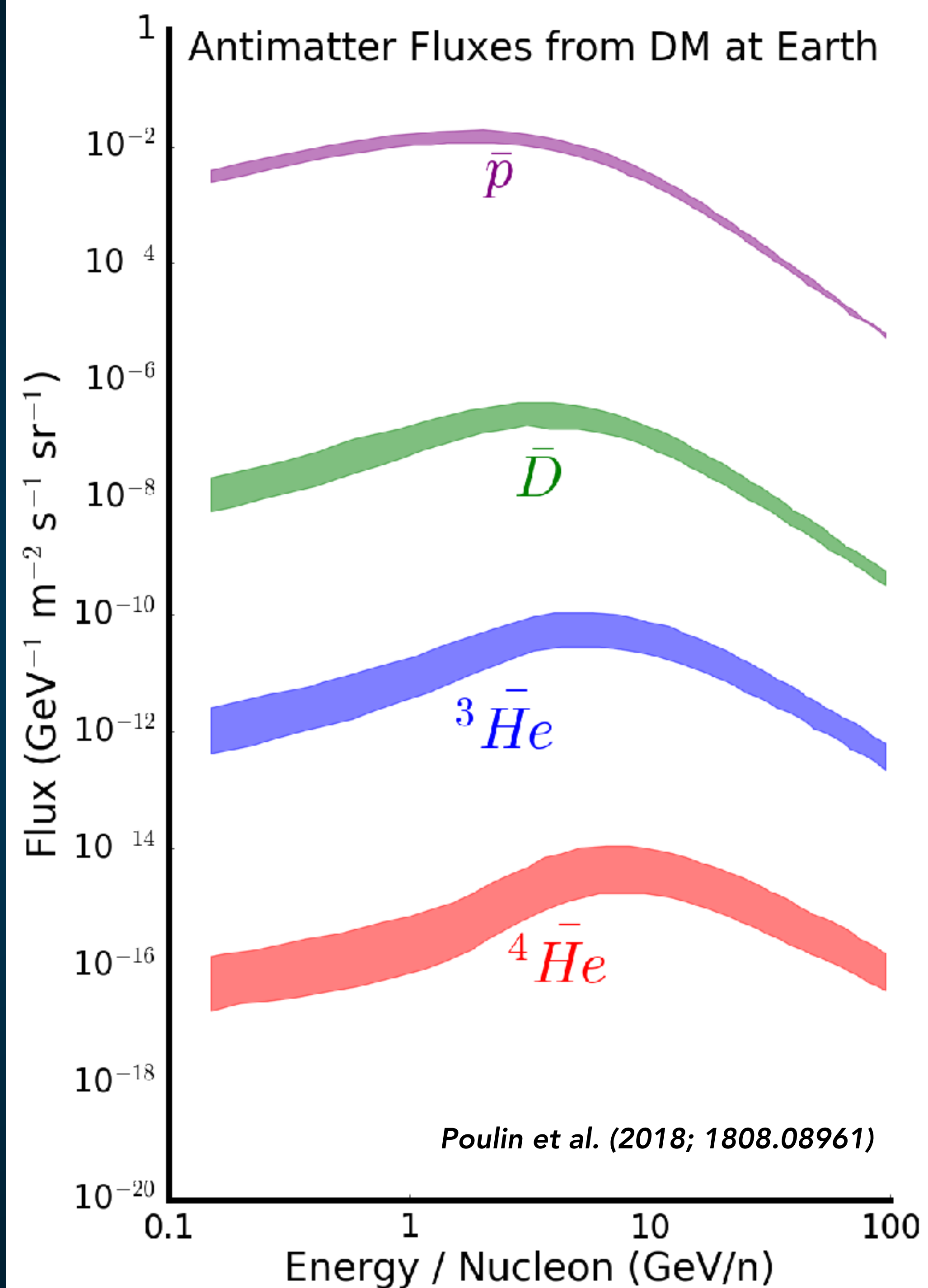
AntiNuclei - A Clean Search Strategy ?

Antihelium background even cleaner than antideuterons

But the flux is supposed to be much smaller.



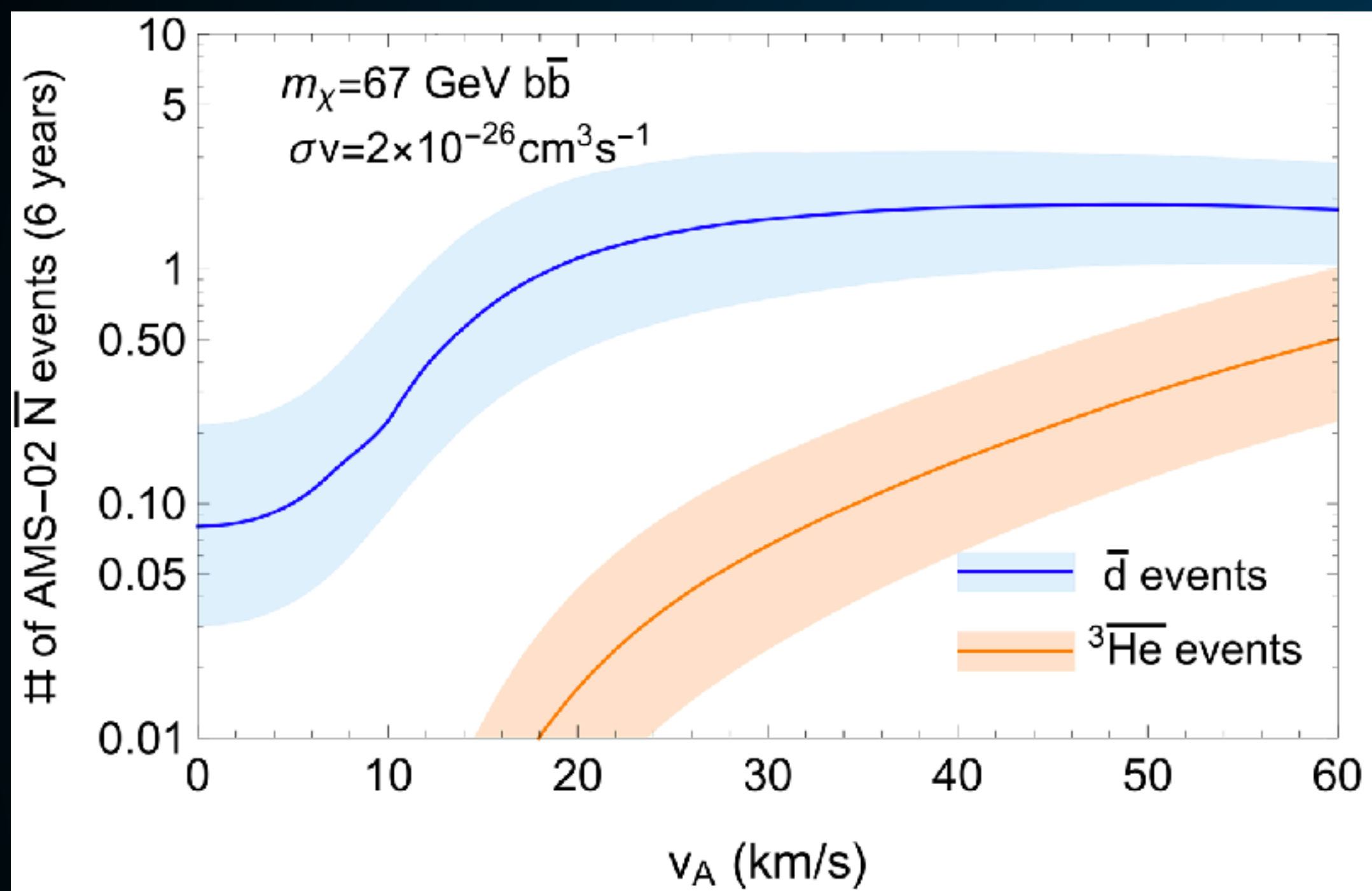
Korsmeier (2017; 1711.08465)



Poulin et al. (2018; 1808.08961)

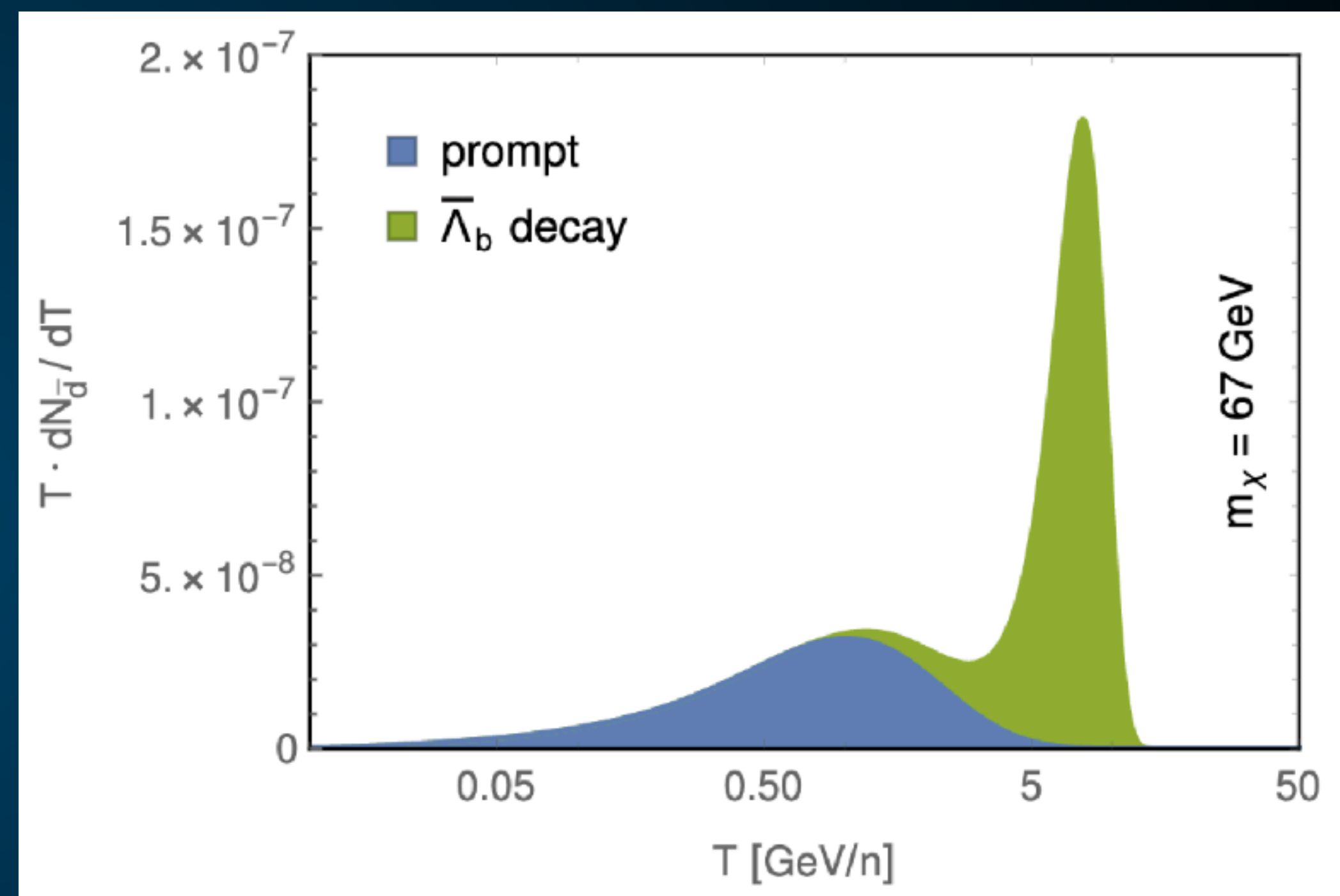
Enhancing the Dark Matter Flux

Method I: Astrophysics



Use reaccelerating to boost the antihelium events into a detectable range.

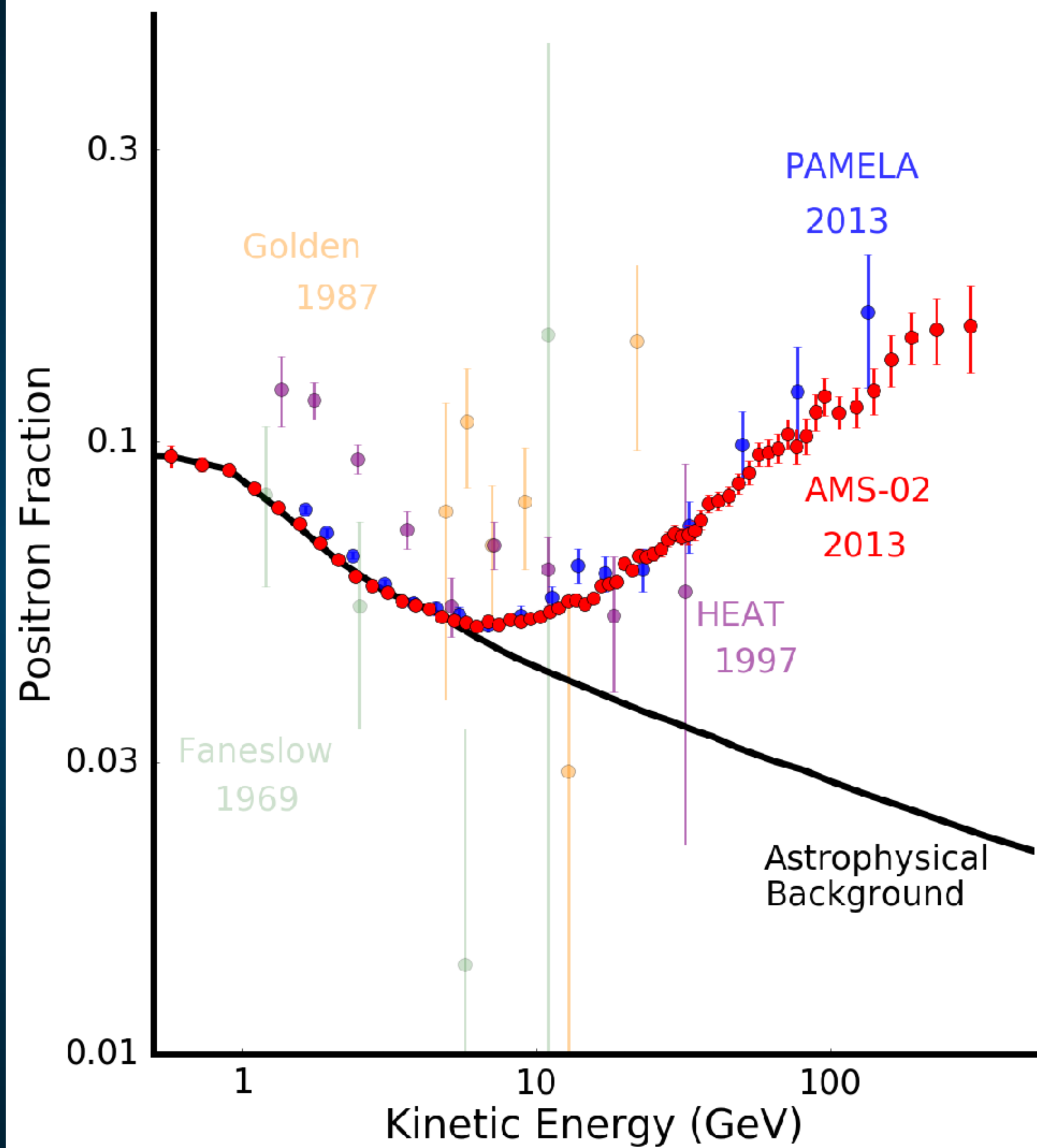
Method II: Particle Physics



Previous analyses may have missed the dominant antihelium production pathway from dark matter.

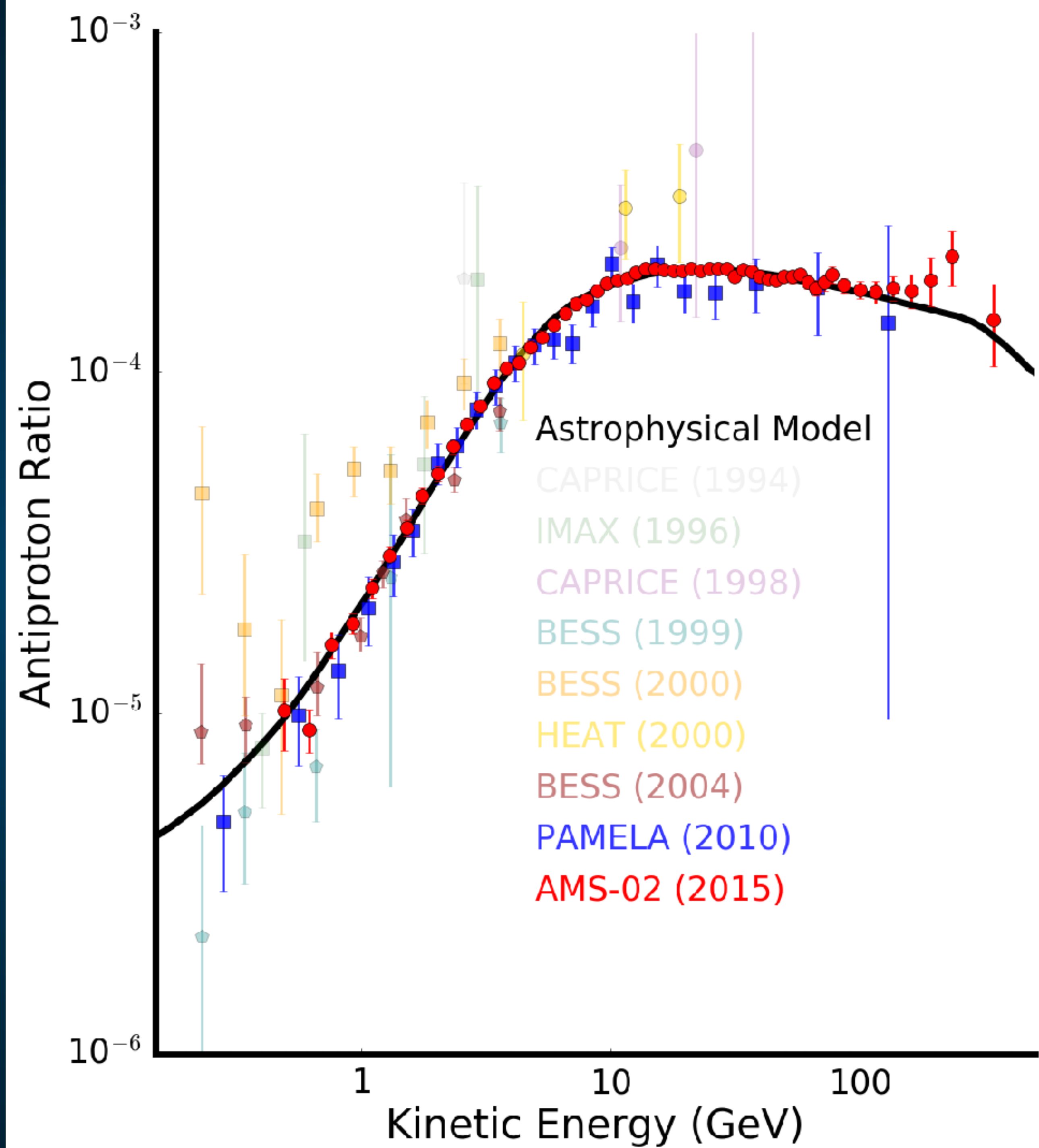
Provocative Questions

Can we produce a robust calculation of e^+e^- from pulsars that allows us to search for dark matter?



Provocative Questions

Is it possible to find dark matter as a $O(1\%)$ effect?

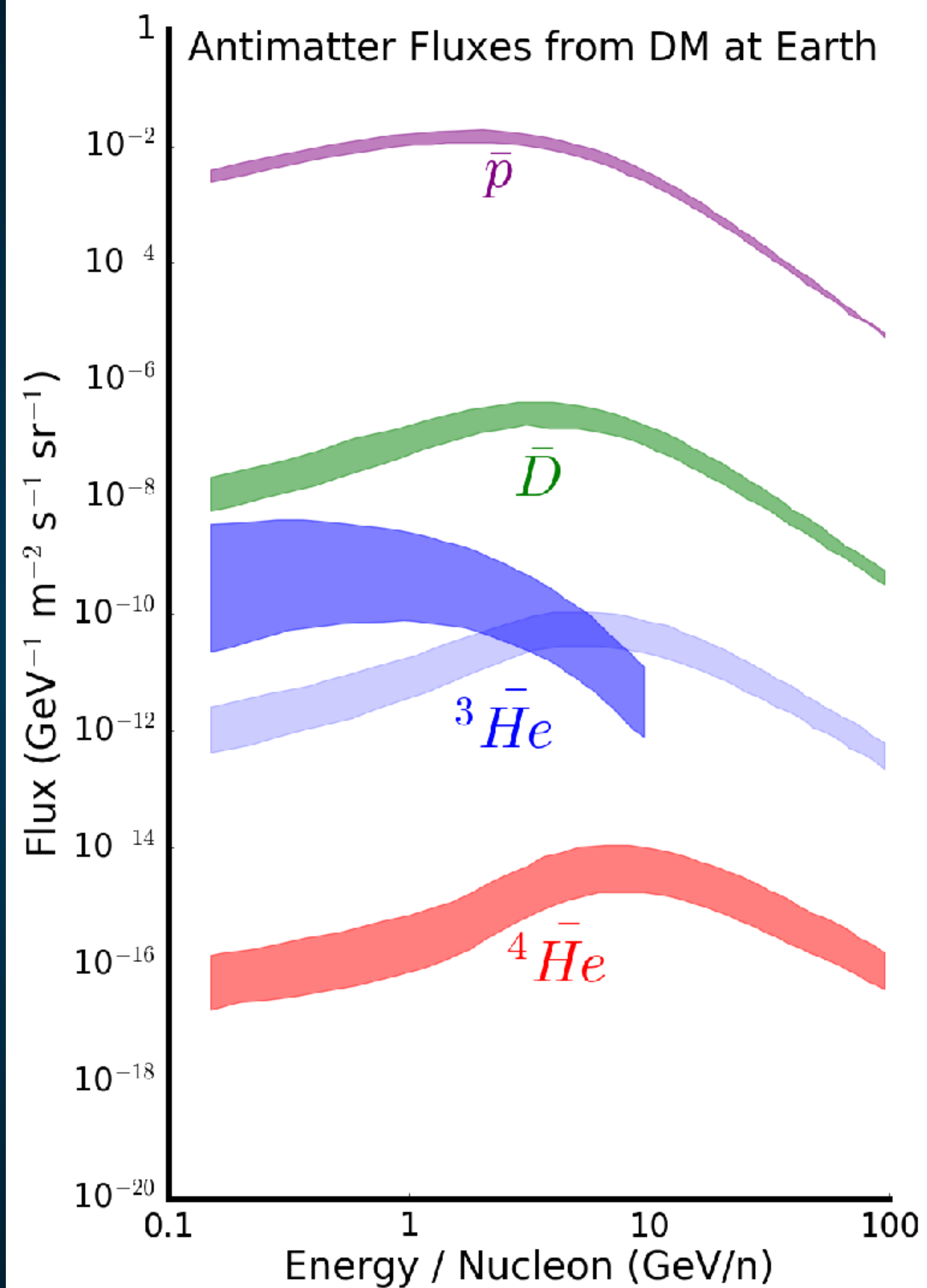


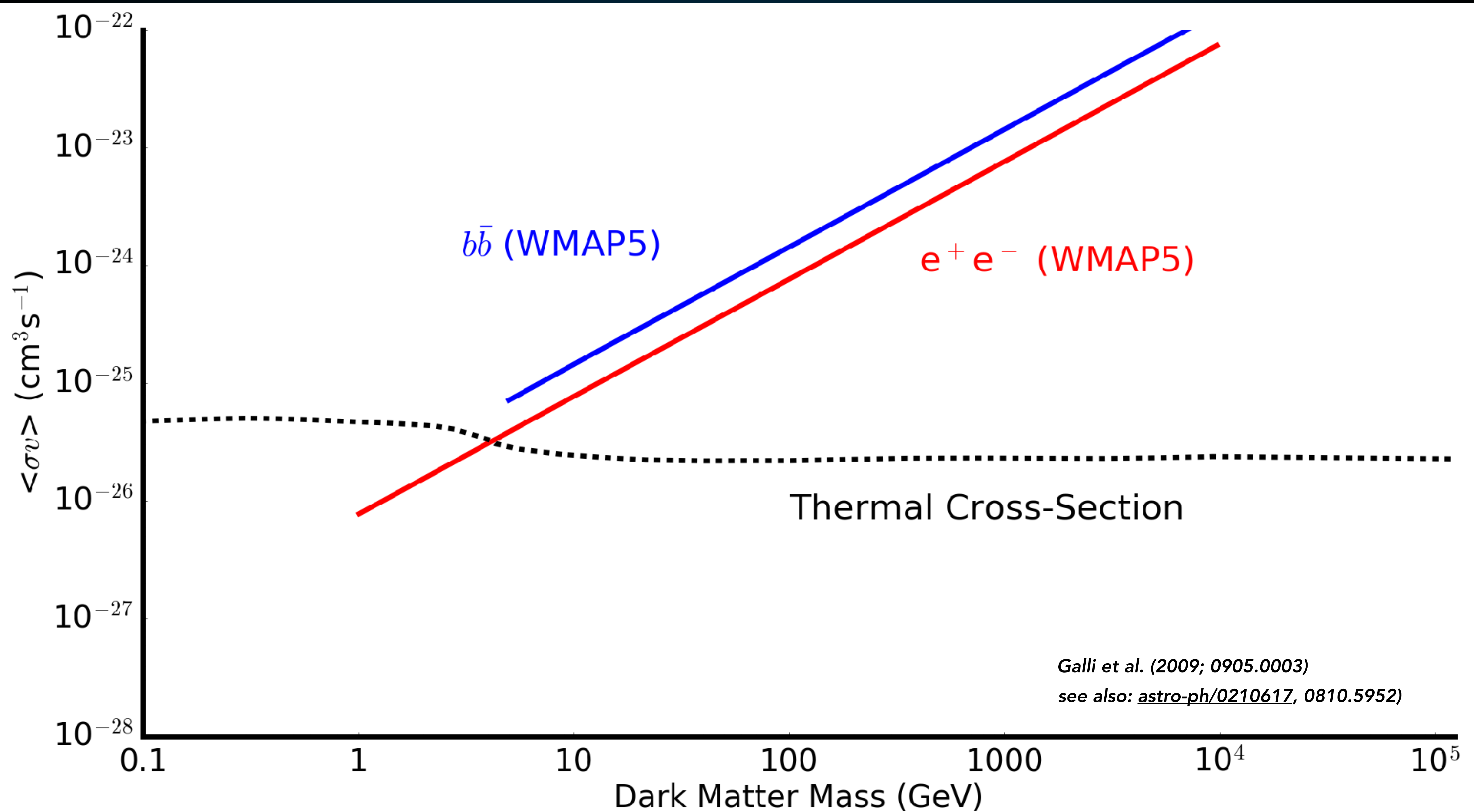
Provocative Questions

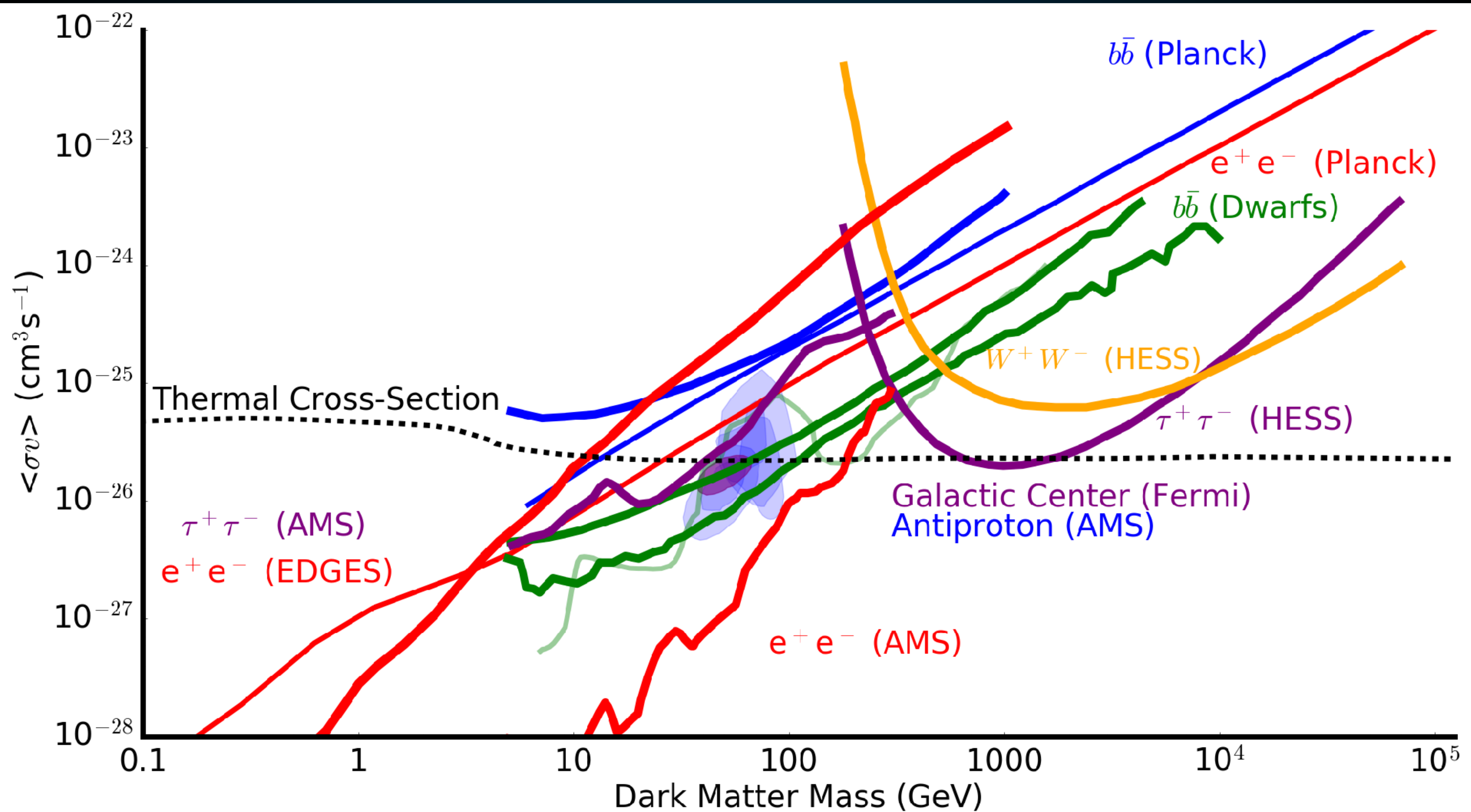
Can we build a machine capable of detecting multiple ${}^3\text{He}$ or ${}^2\text{D}$ particles, while rejecting backgrounds at the necessary level?

Can we understand nucleon coalescence sufficiently to predict the dark matter induced flux?

${}^4\text{He}$?







Dark Matter Searches with Cosmic-Rays

Yesterday, Today, and Tomorrow

Need to produce a complete model of antiprotons/antideuterons/antihelium from a dark matter annihilation model.

Need to constrain systematic uncertainties: instrumental, astrophysical, solar modulation.

Need to consider technologies with larger sensitivities, especially for ${}^3\text{He}$.

