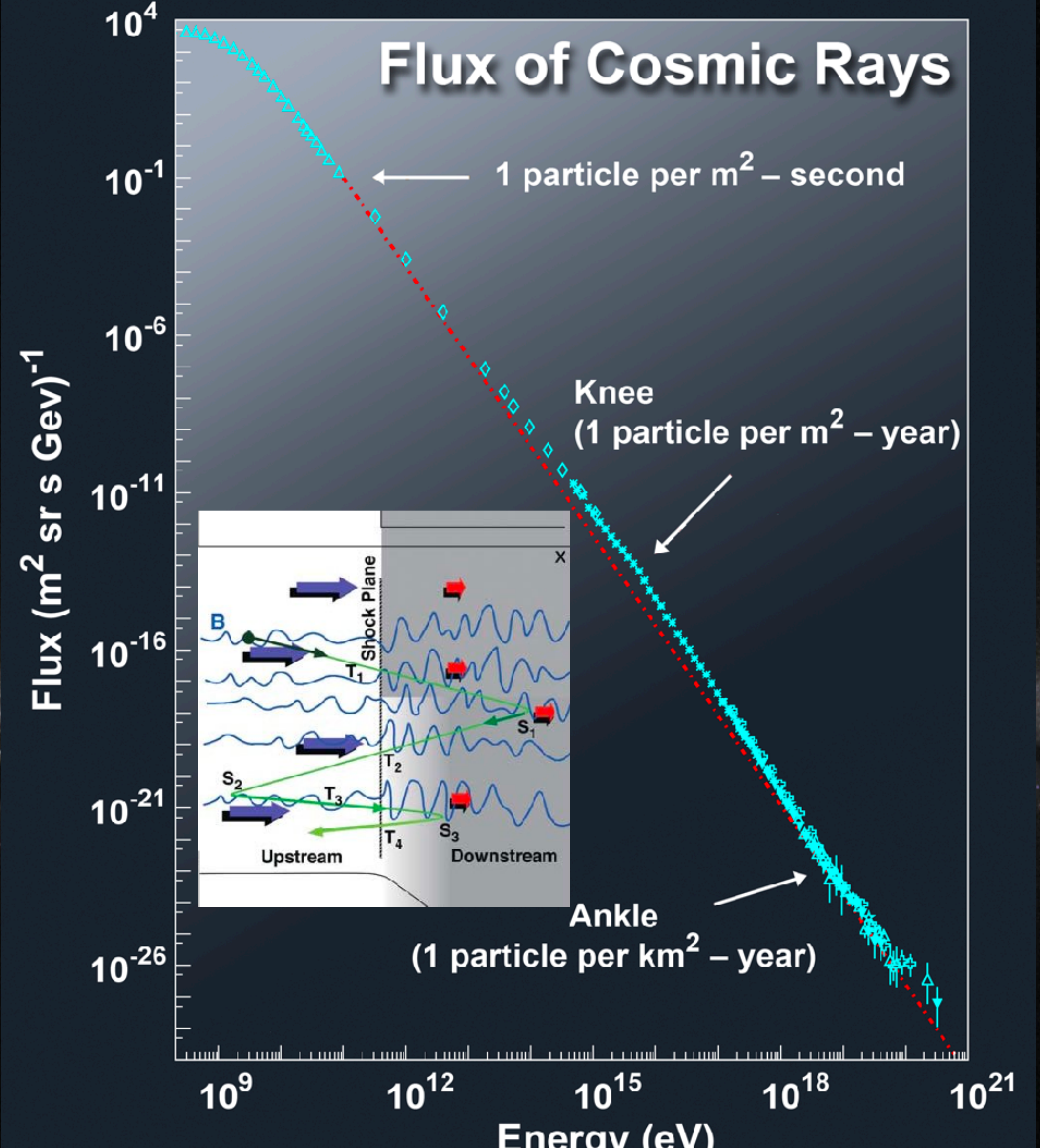
Cosmic-Ray Searches for Dark Matter: Yesterday, Today and Tomorrow

Tim Linden

Stockholm University



(source: Swordy – U.Chicago)

Slide Concept: Ben Buckman

Slide Concept: Ben Buckman


Slide Concept: Ben Buckman
χ
χ
?
b
$\bar{b}$
π^+
π^-
ν
ν
e^+
e^-
$\bar{n}$
$\bar{p}$
$\bar{p}$
$\overline{He}$
Astrophysics
$b\bar{b}$
$\tau^+\tau^-$
$\gamma\gamma$
Energy Flux
Energy (GeV)

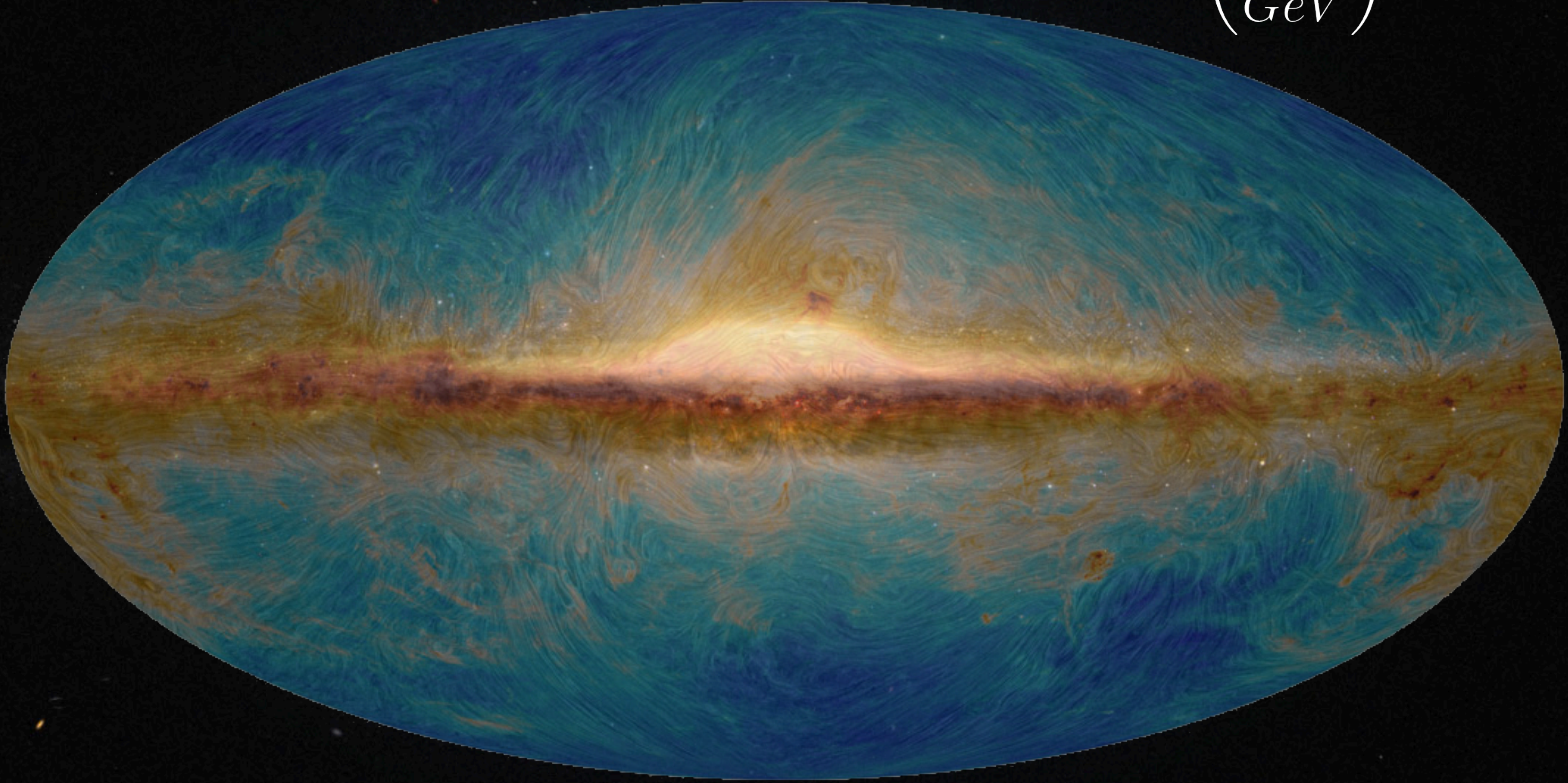
Slide Concept: Ben Buckman

Kuhlen et al. (astro-ph/0611370)

$$B \approx 5\ \mu G$$

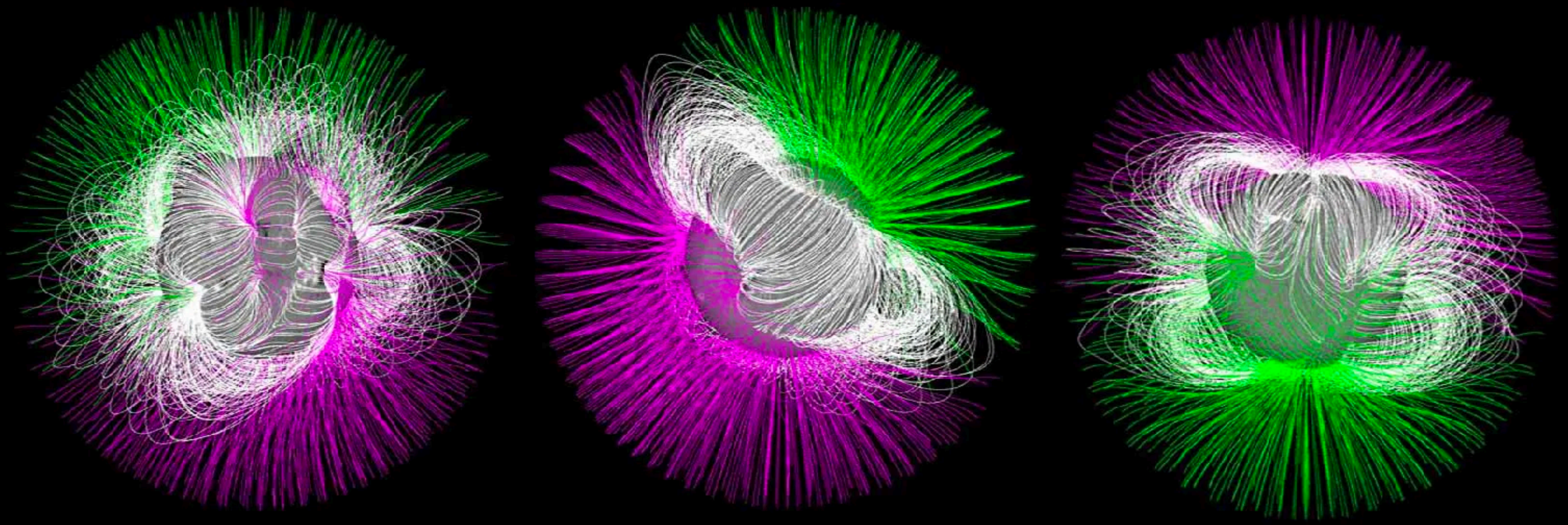
$$D_0 \approx 5 \times 10^{28}\ \mathrm{cm}^2\mathrm{s}^{-1} \left(\frac{E}{GeV}\right)^{0.3}$$

$$l_c \approx 0.1pc \left(\frac{E}{GeV}\right)^{0.3}$$




Termination Shock
Sun
Heliopause
Bow Wave


2013 Jun 2




InterDiurnal Variability Index IDV and Reconstructed Heliospheric Magnetic Field B
nT
IDV
B
HMF
StDev
N
18
16
14
12
10
8
6
4
2
0
90
80
70
60
50
40
30
20
10
0
1840
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010


AMS
AMS


Propagation
Production
Instrumental
Solar Modulation


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


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

Dark Matter and Astrophysical Fluxes

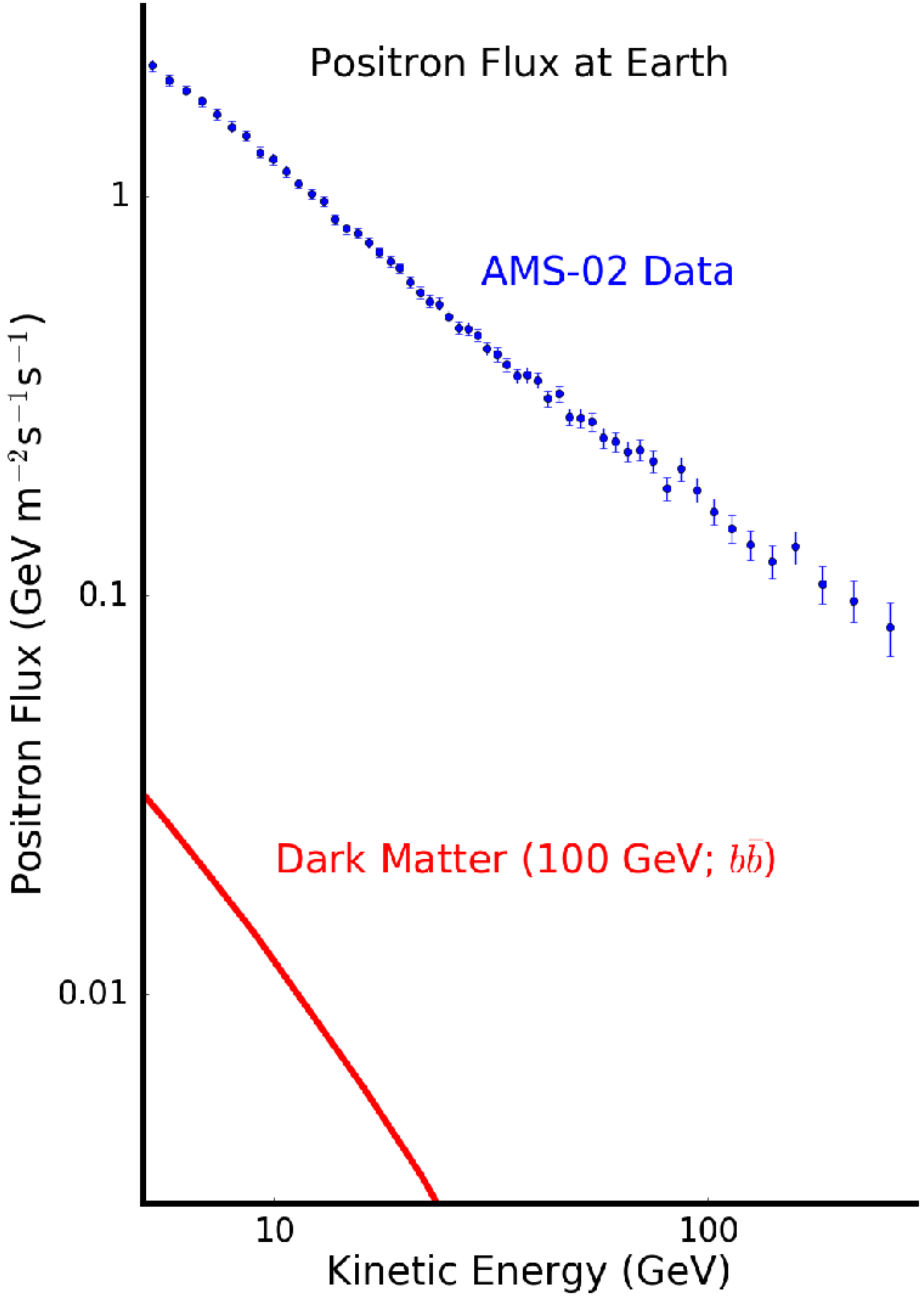
Local Dark Matter Density

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

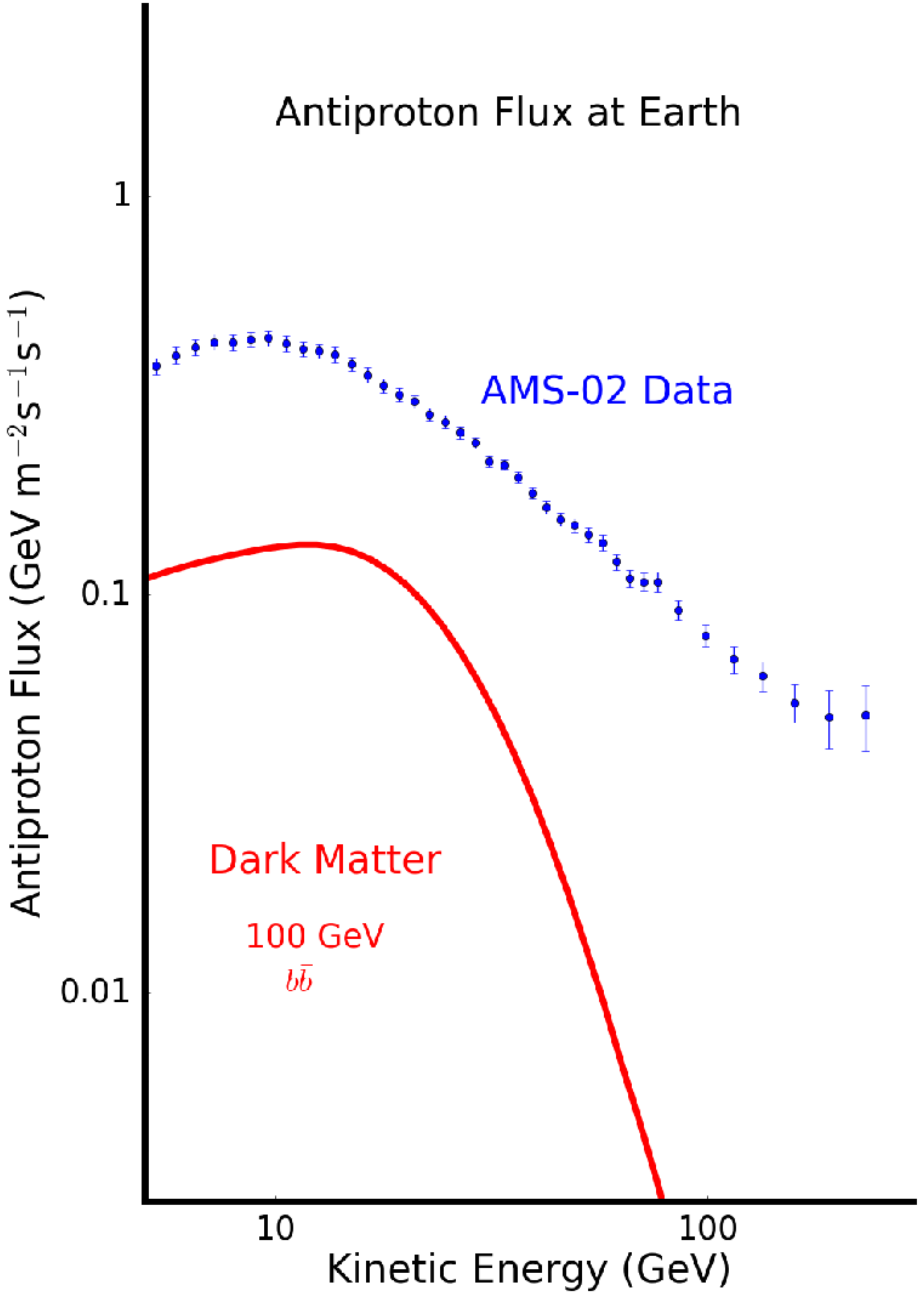
Local Dark Matter Density

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

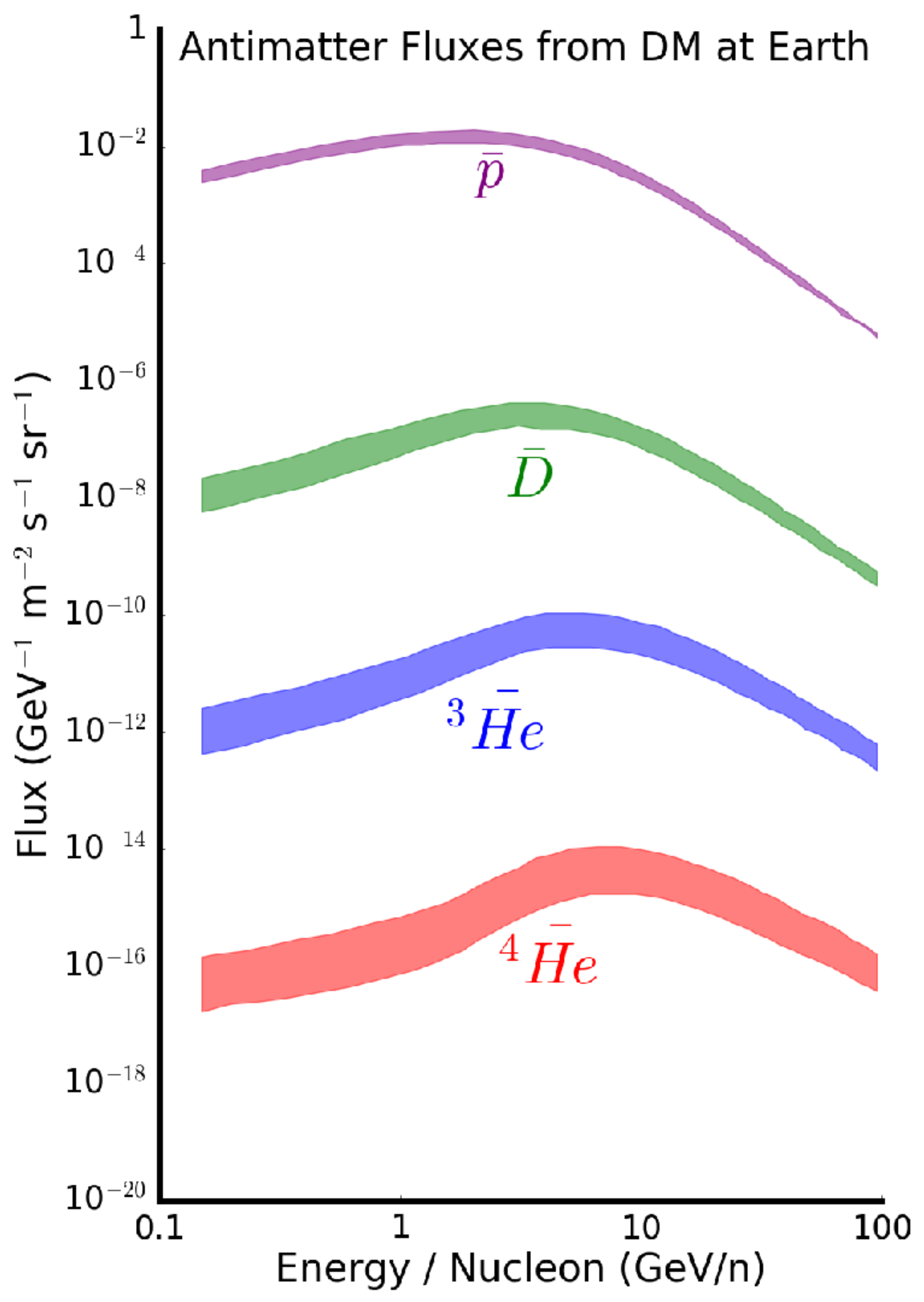
Local Dark Matter Density

Thermal Cross-Section (Early Universe)

Coalescence of baryons into heavier nuclei

Convection of Annihilation Products from GC (Winds?)

Astrophysical Flux - Undetected, likely much lower

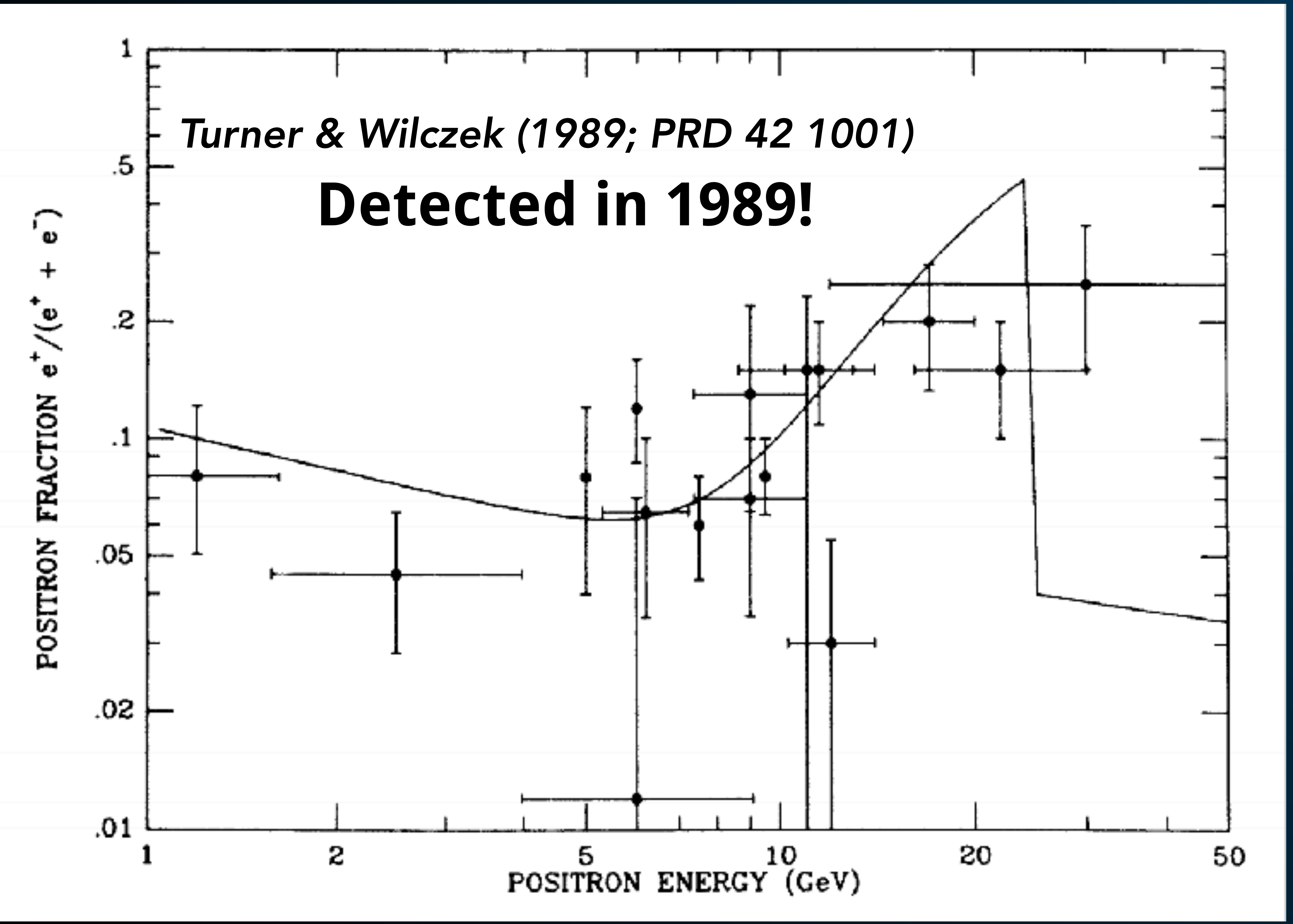


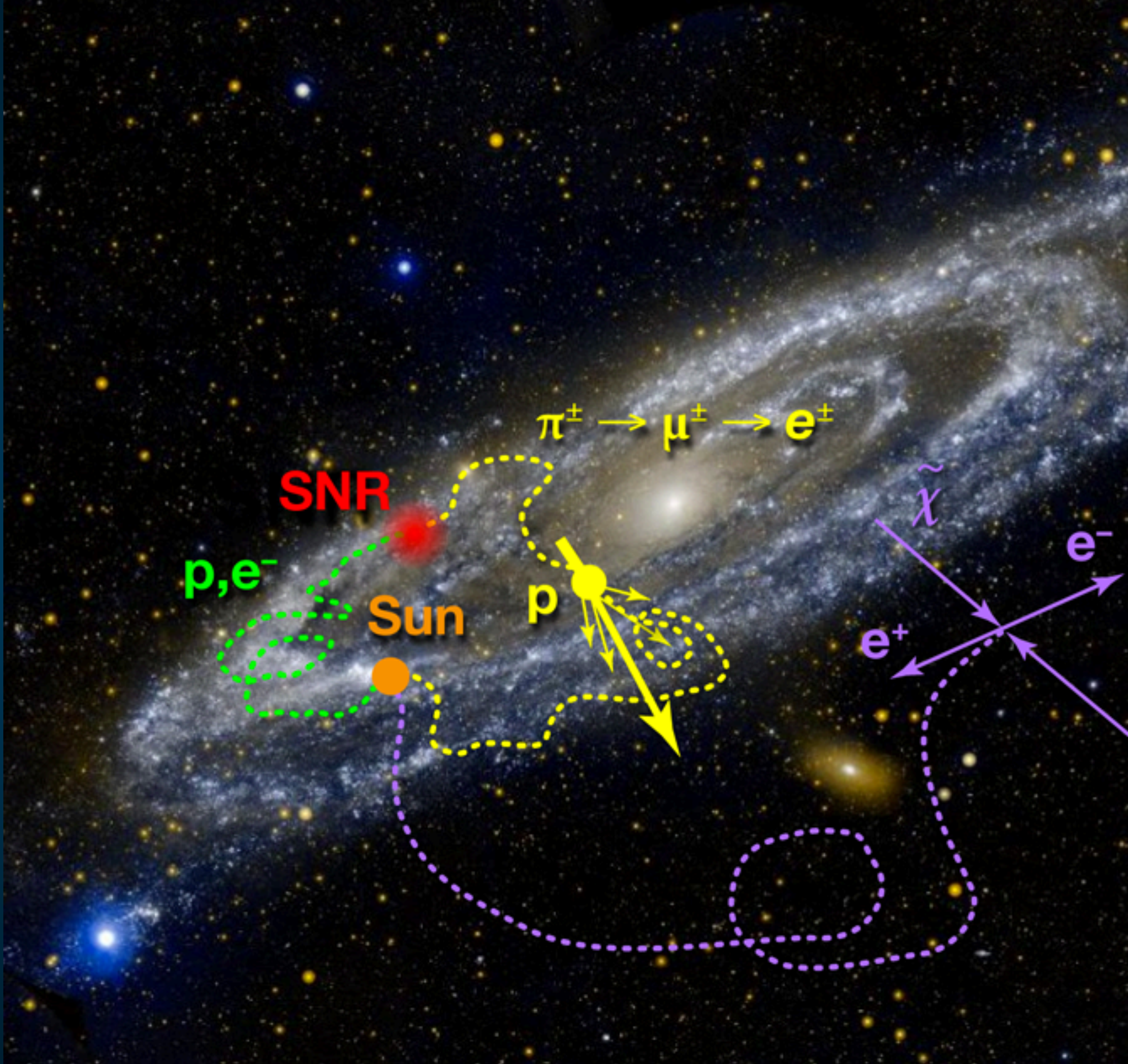
Positron fraction
10^-1
AMS-02
Fit to Data
1
10
10^2
positron, electron energy [GeV]
The Positron Excess

The Positron Excess

Key Idea: Investigate the Positron Fraction!

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

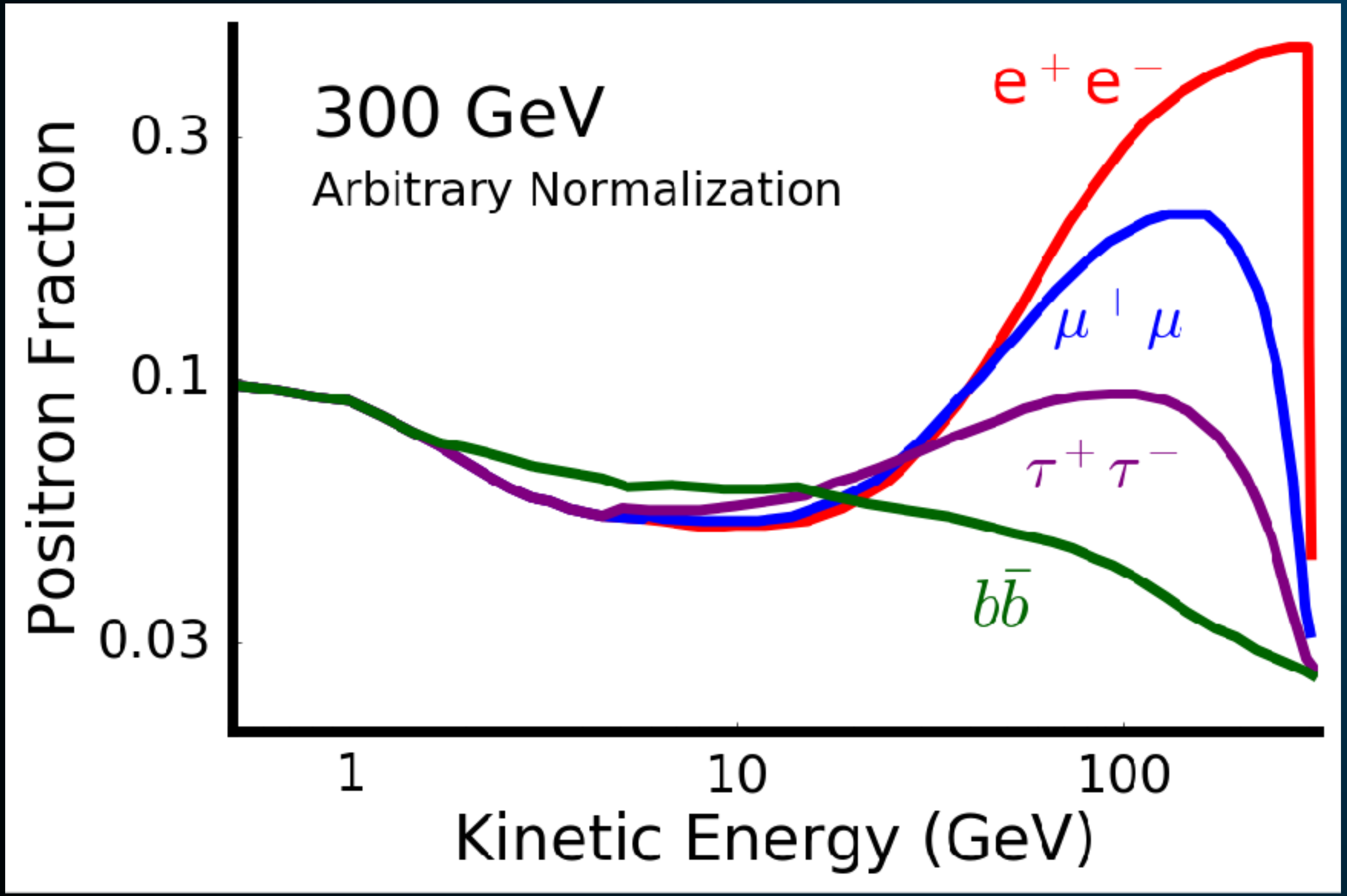


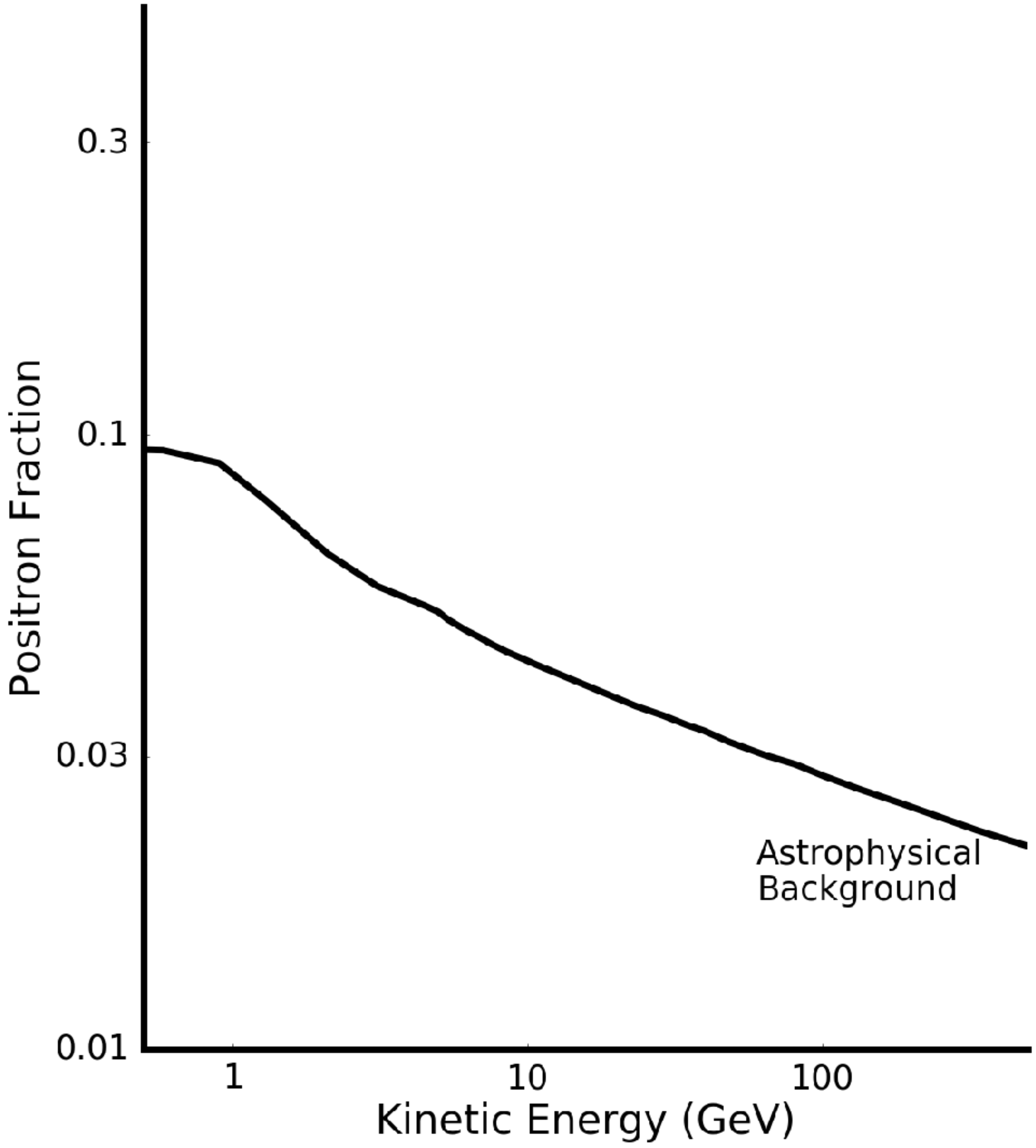


The Positron Excess

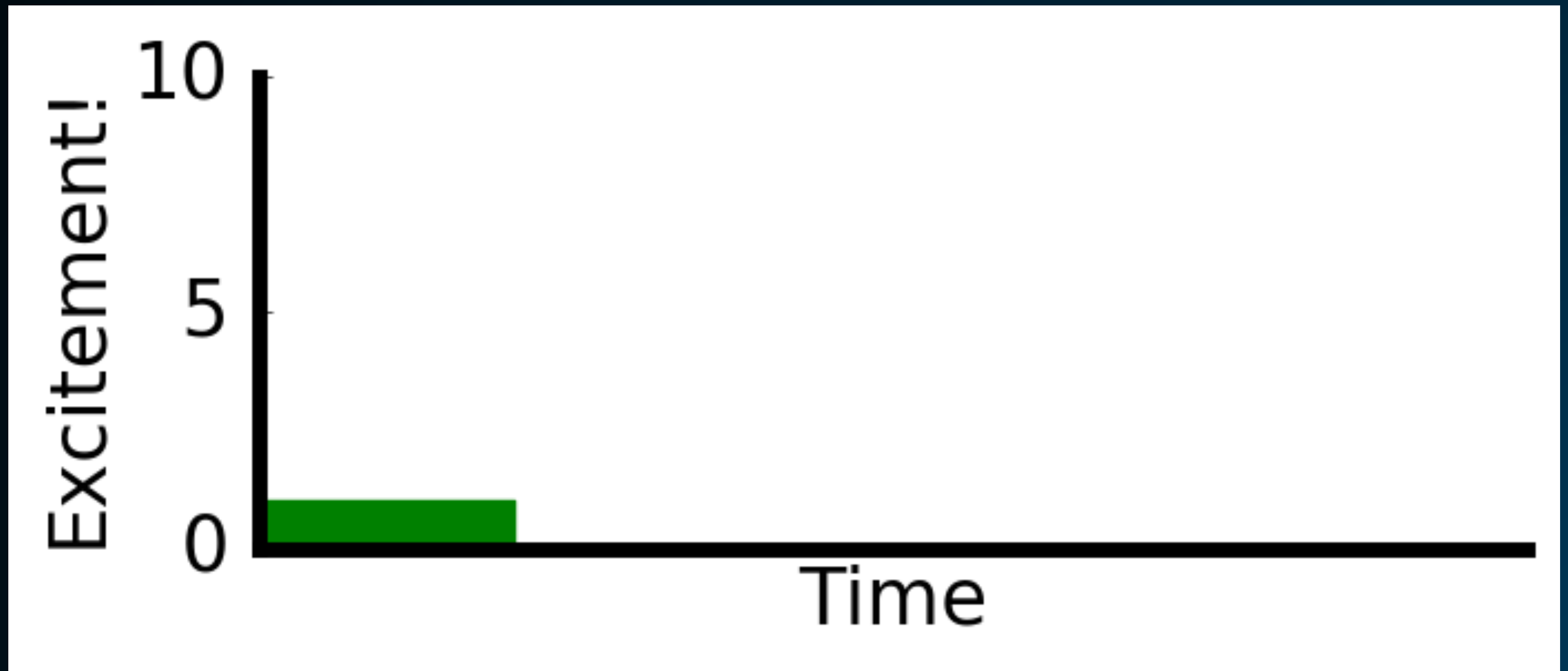
Astrophysics - Slowly Decreasing

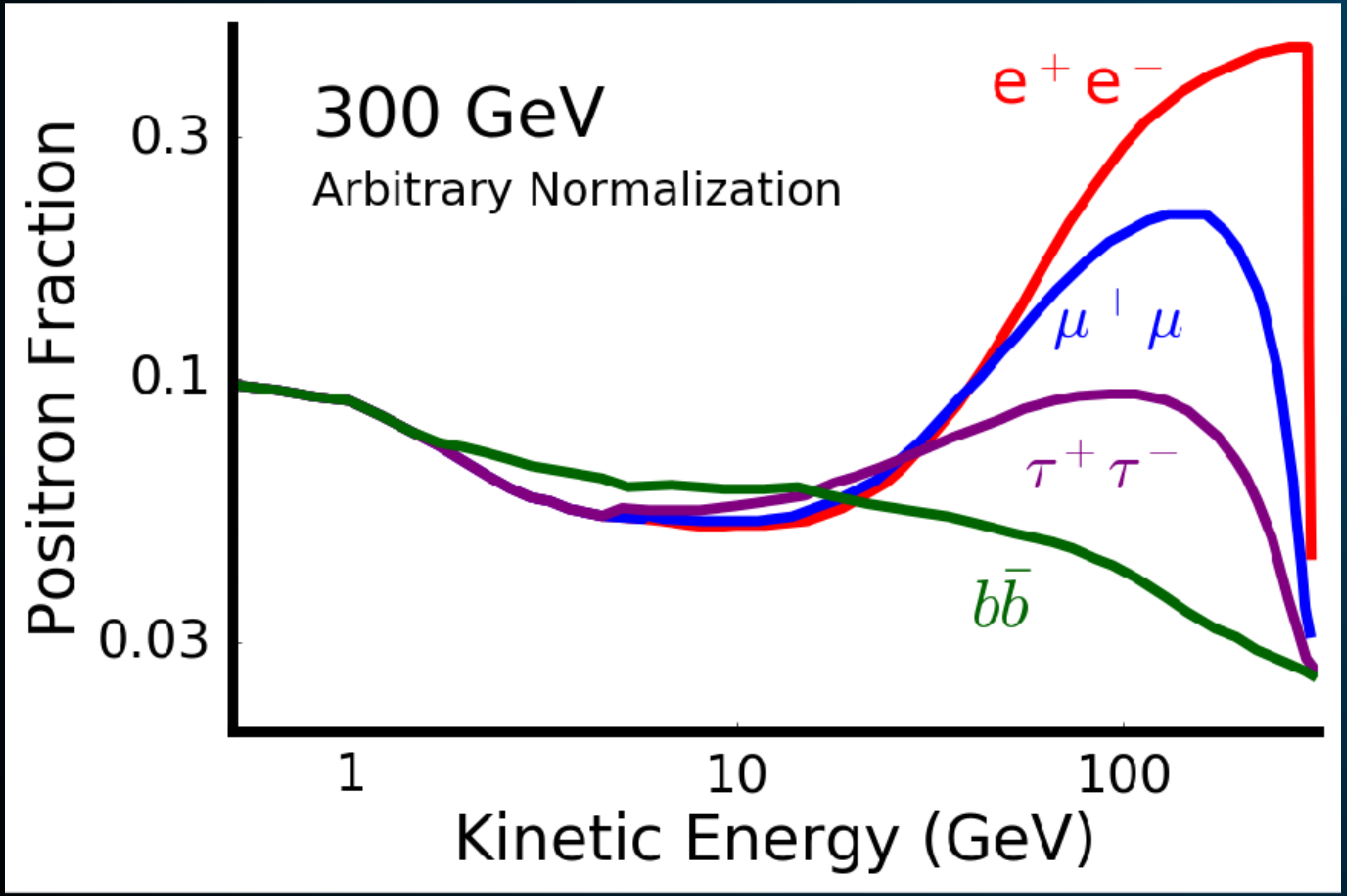
Dark Matter - Sharp Bump!



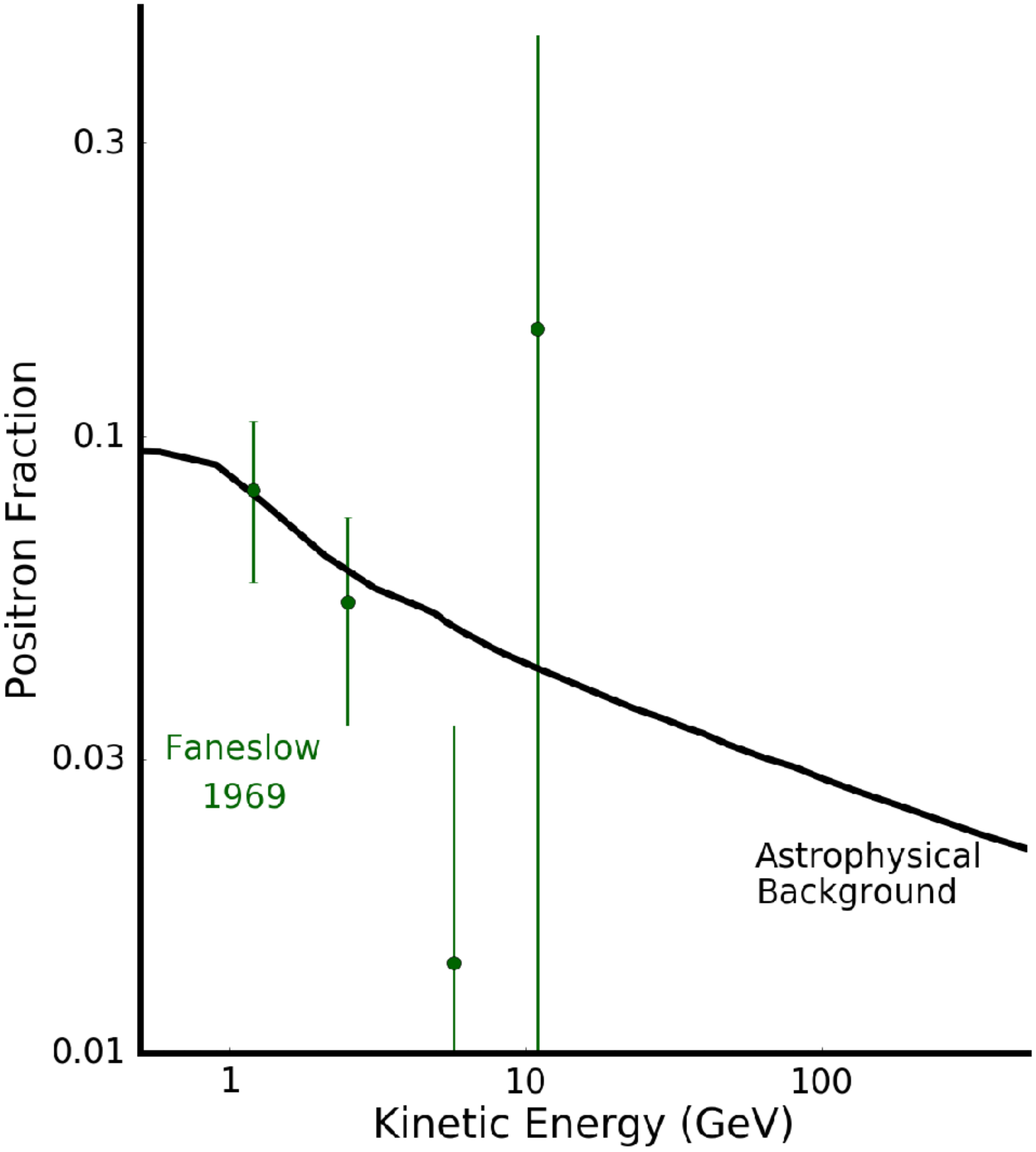


The Positron Excess





(Not an exhaustive list of observations)



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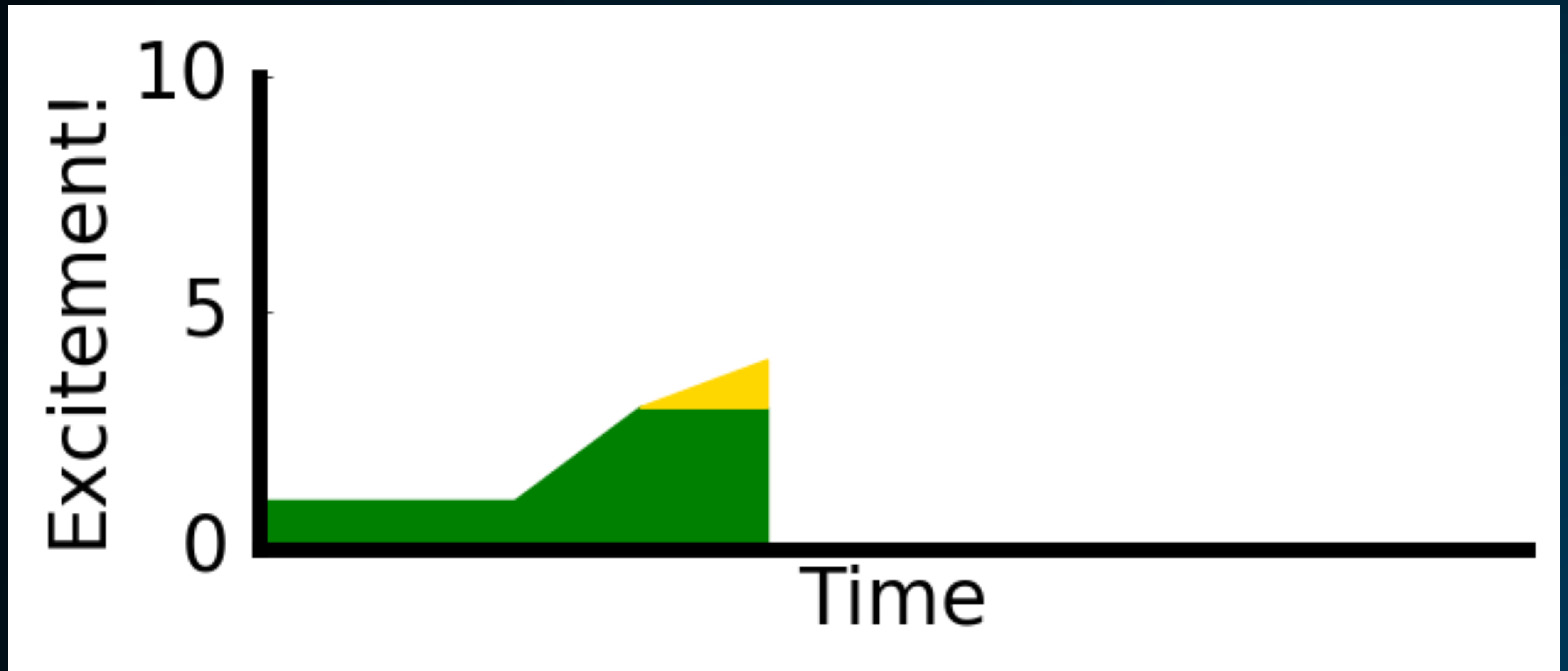

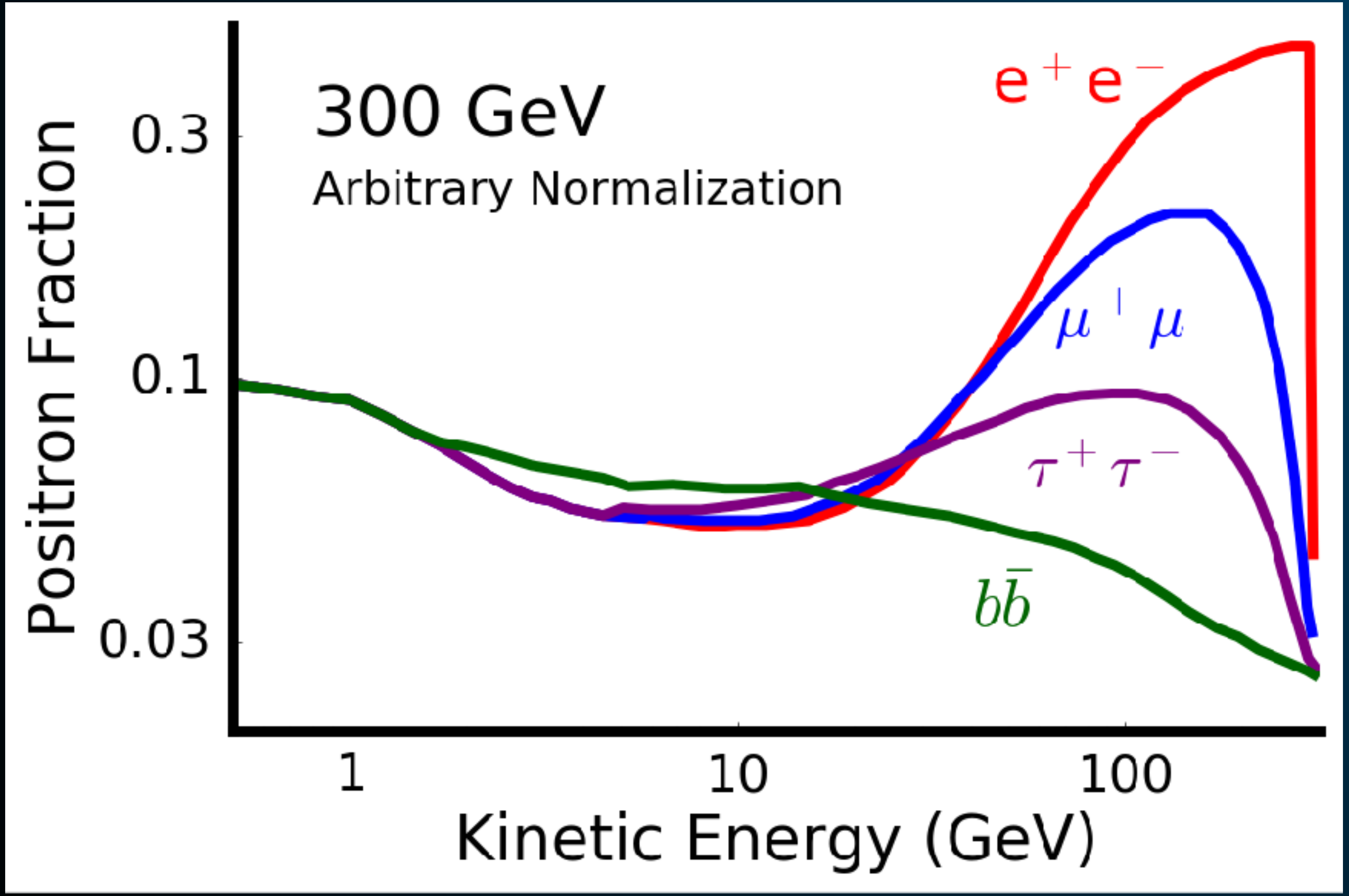

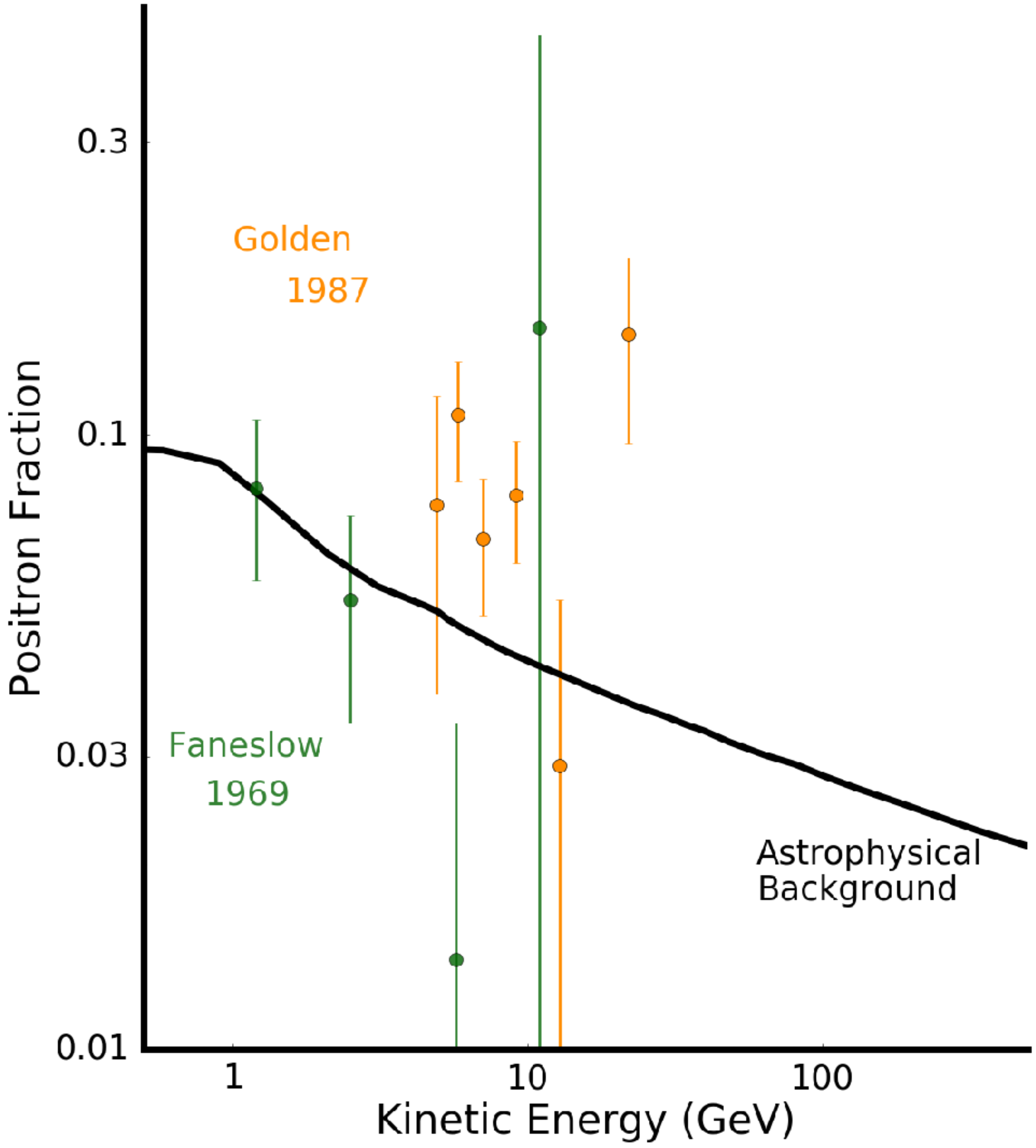

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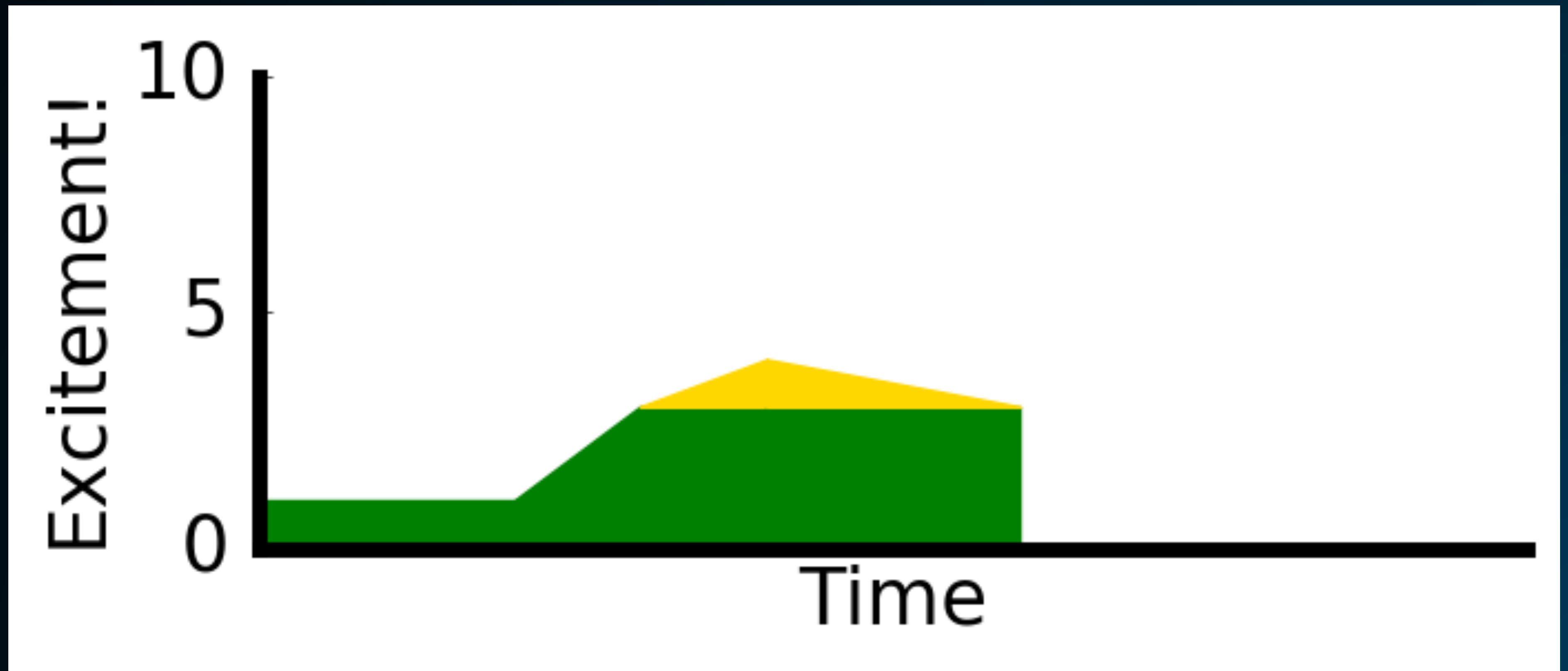
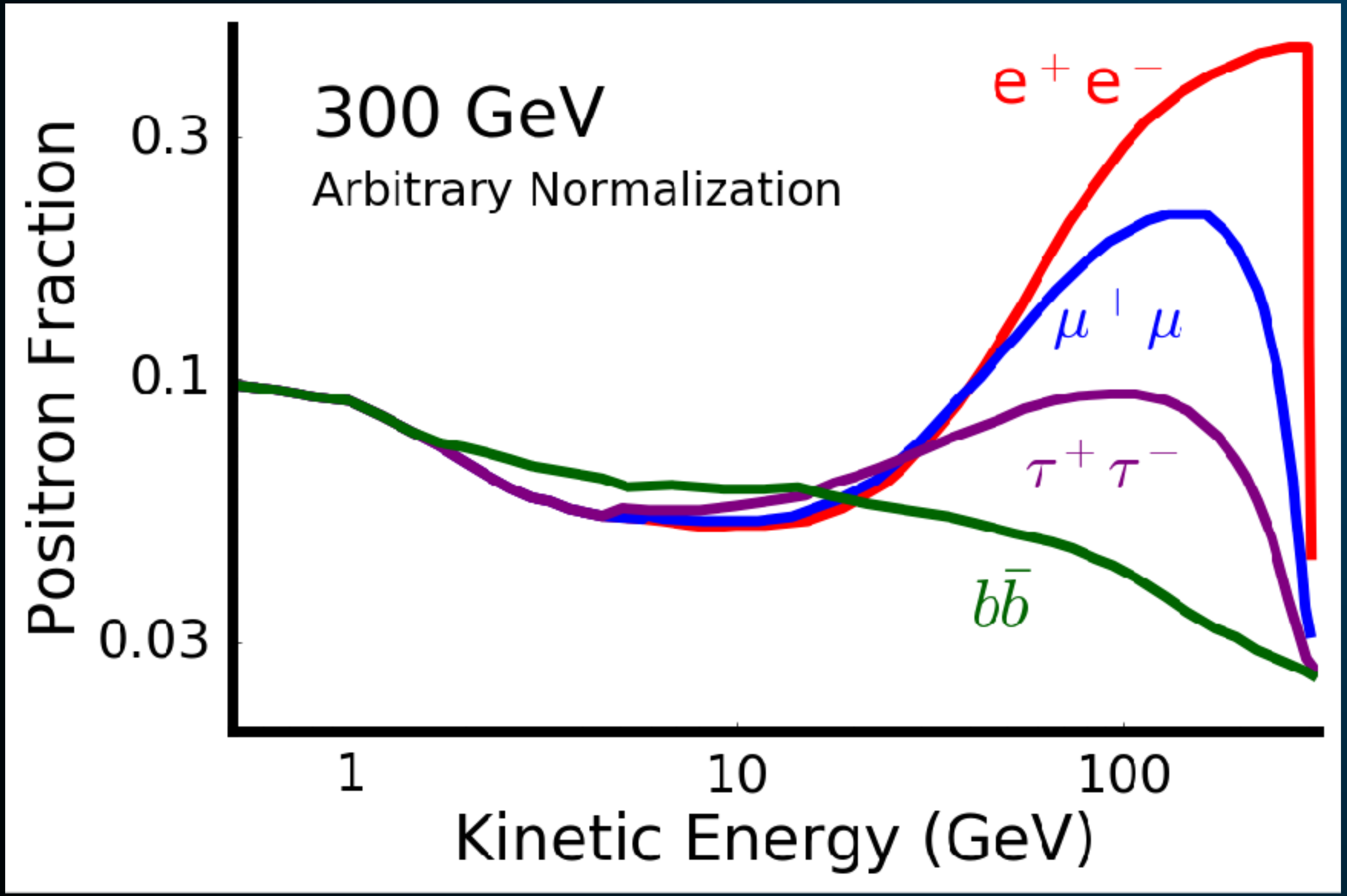
The Positron Excess





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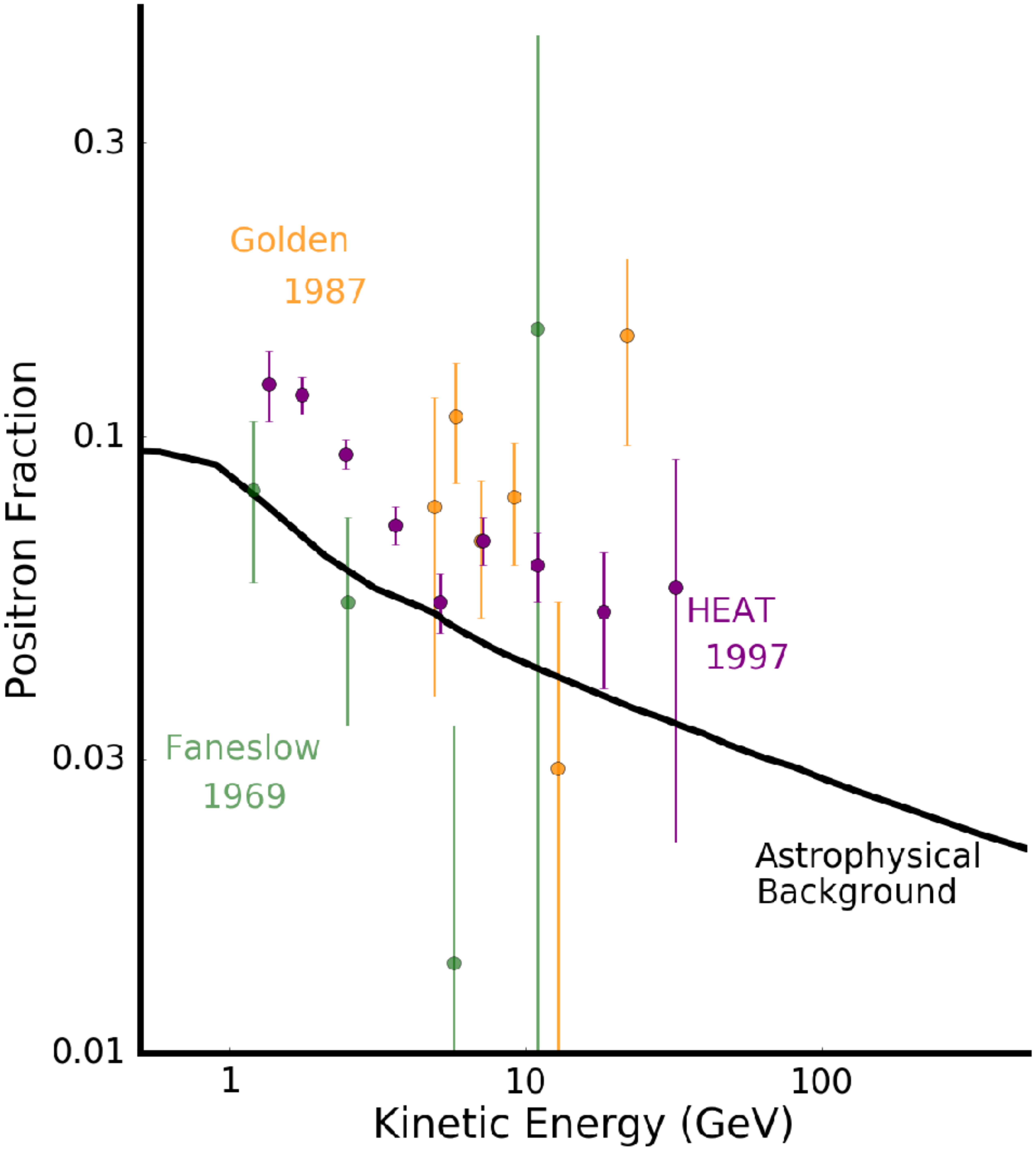

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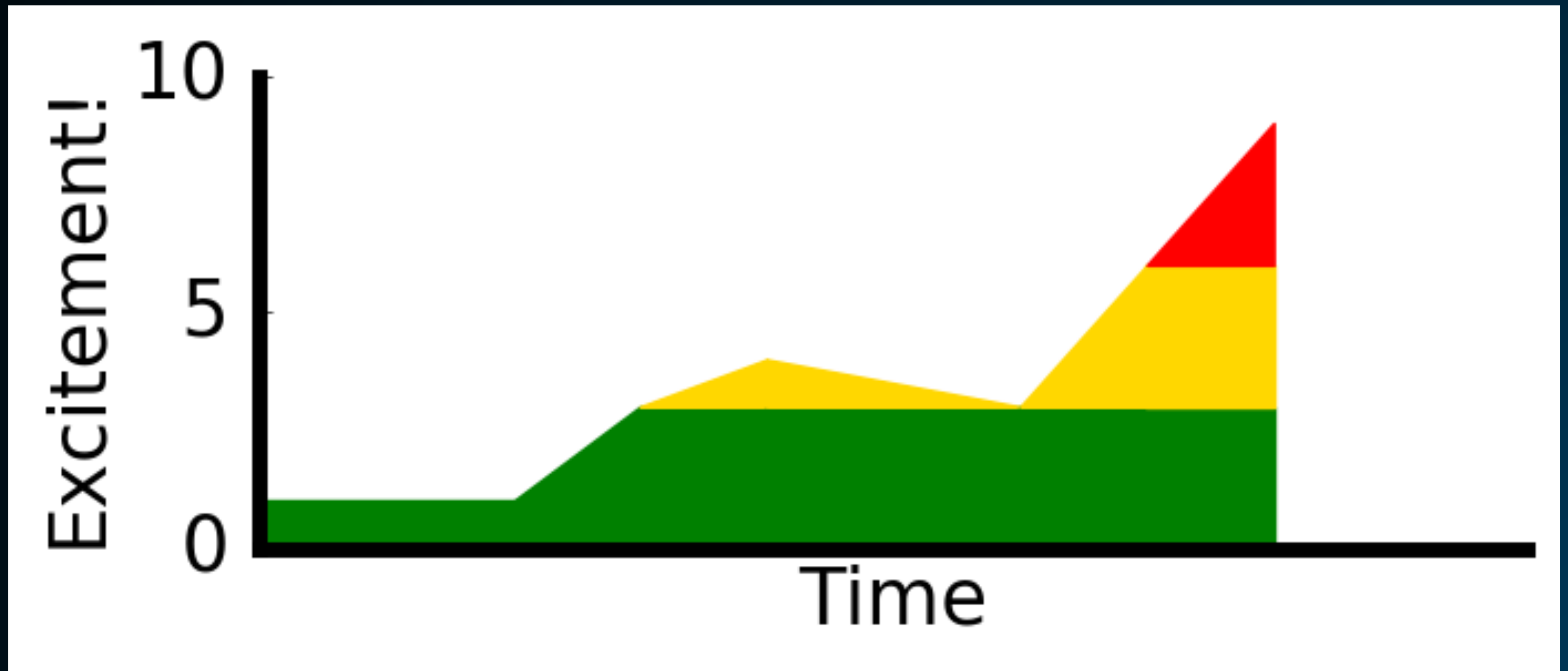

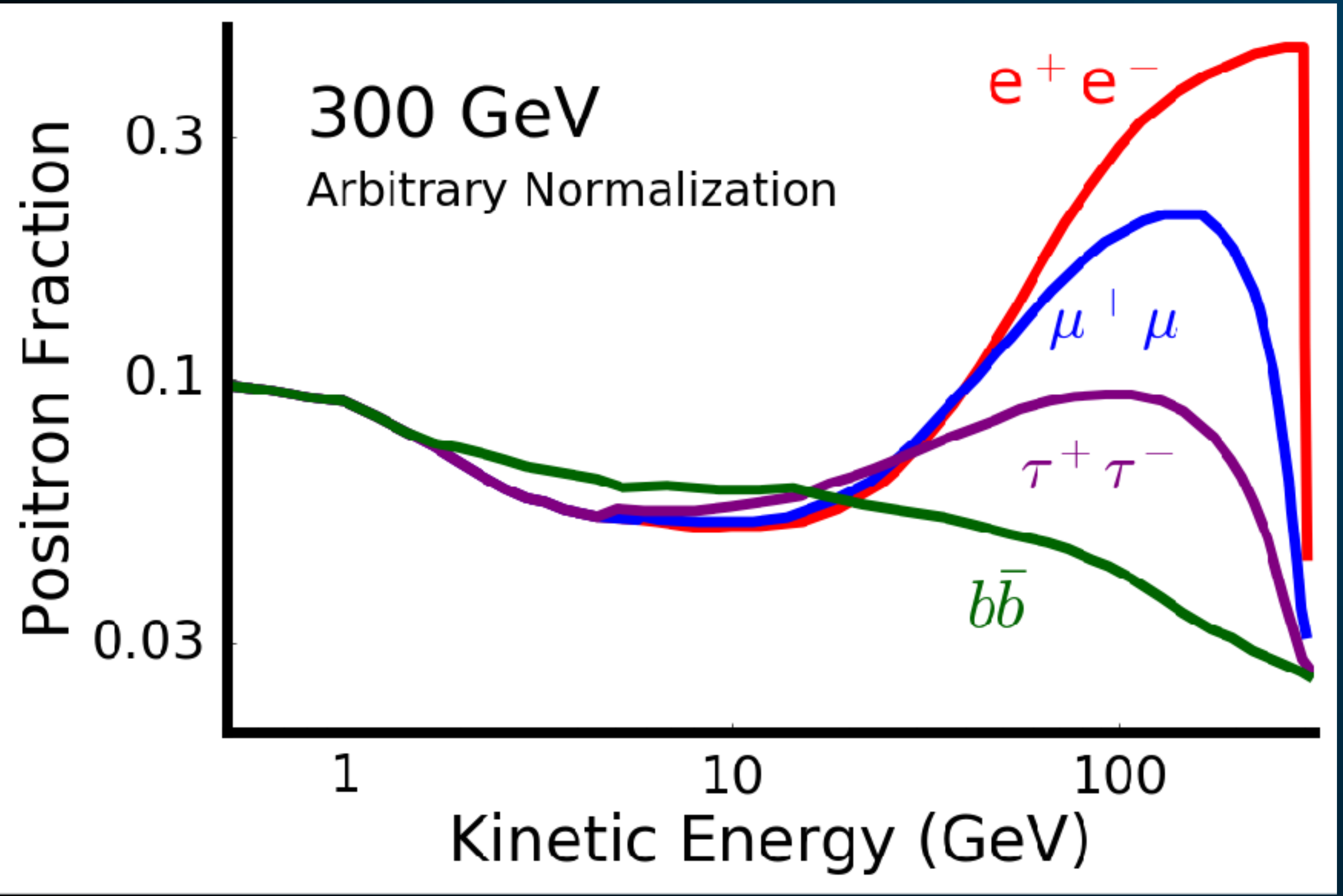

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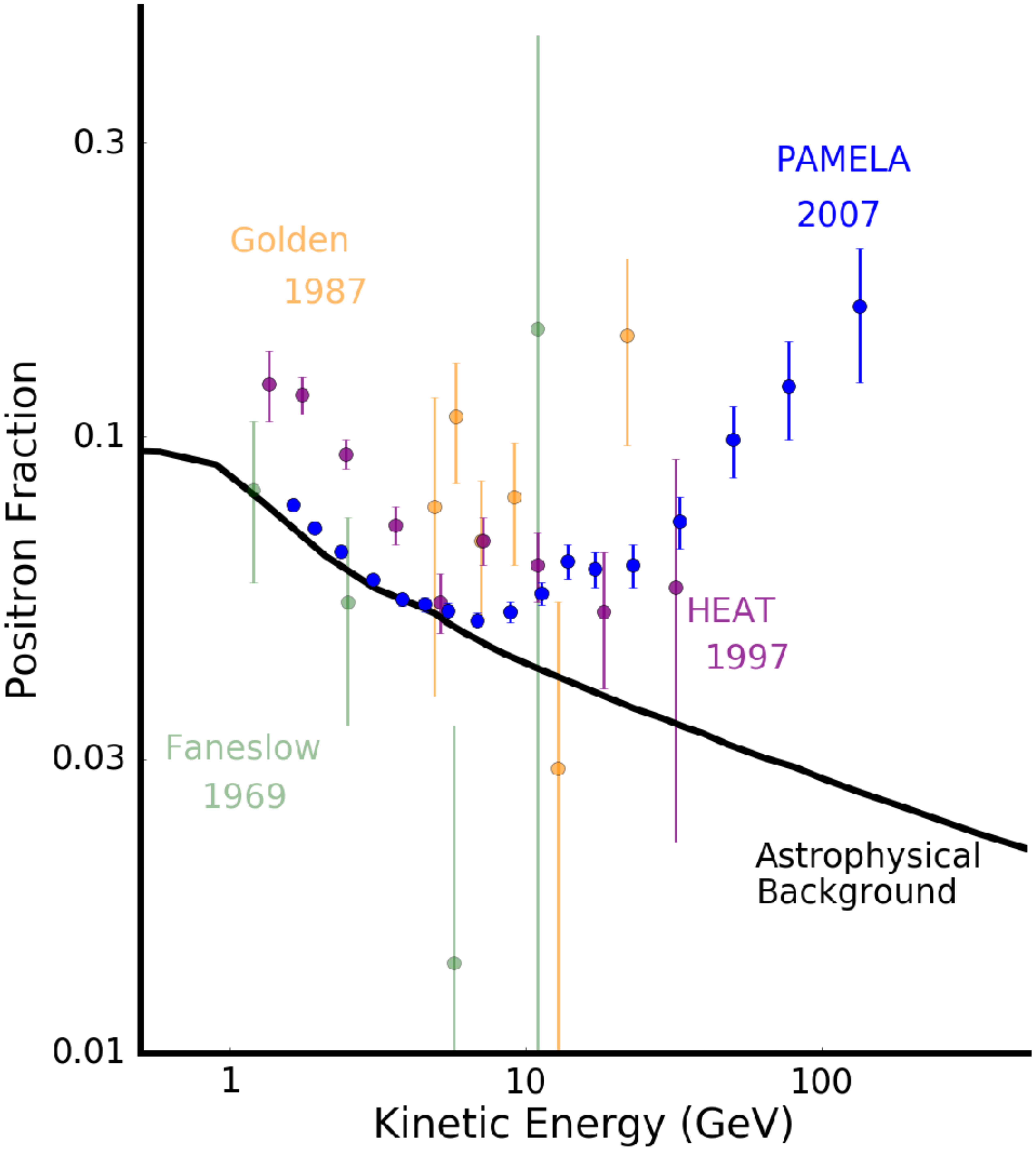

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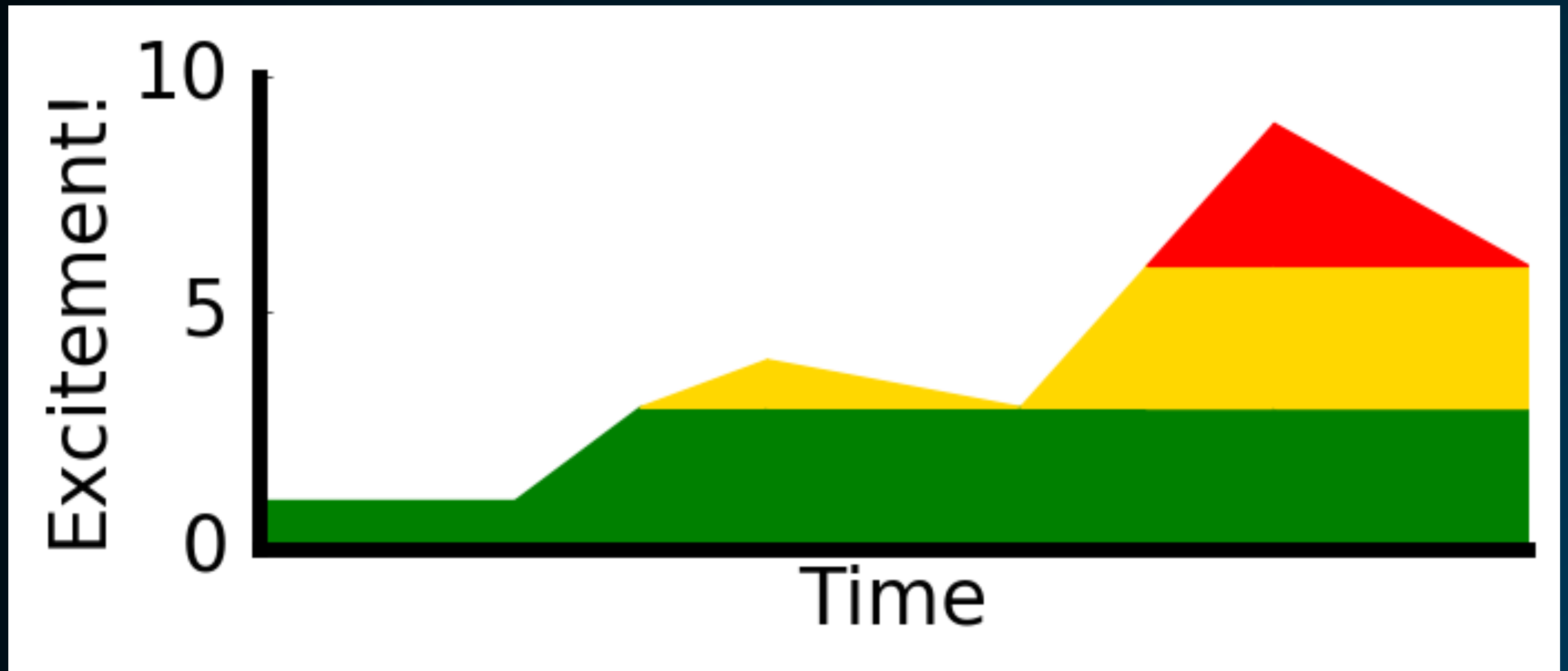

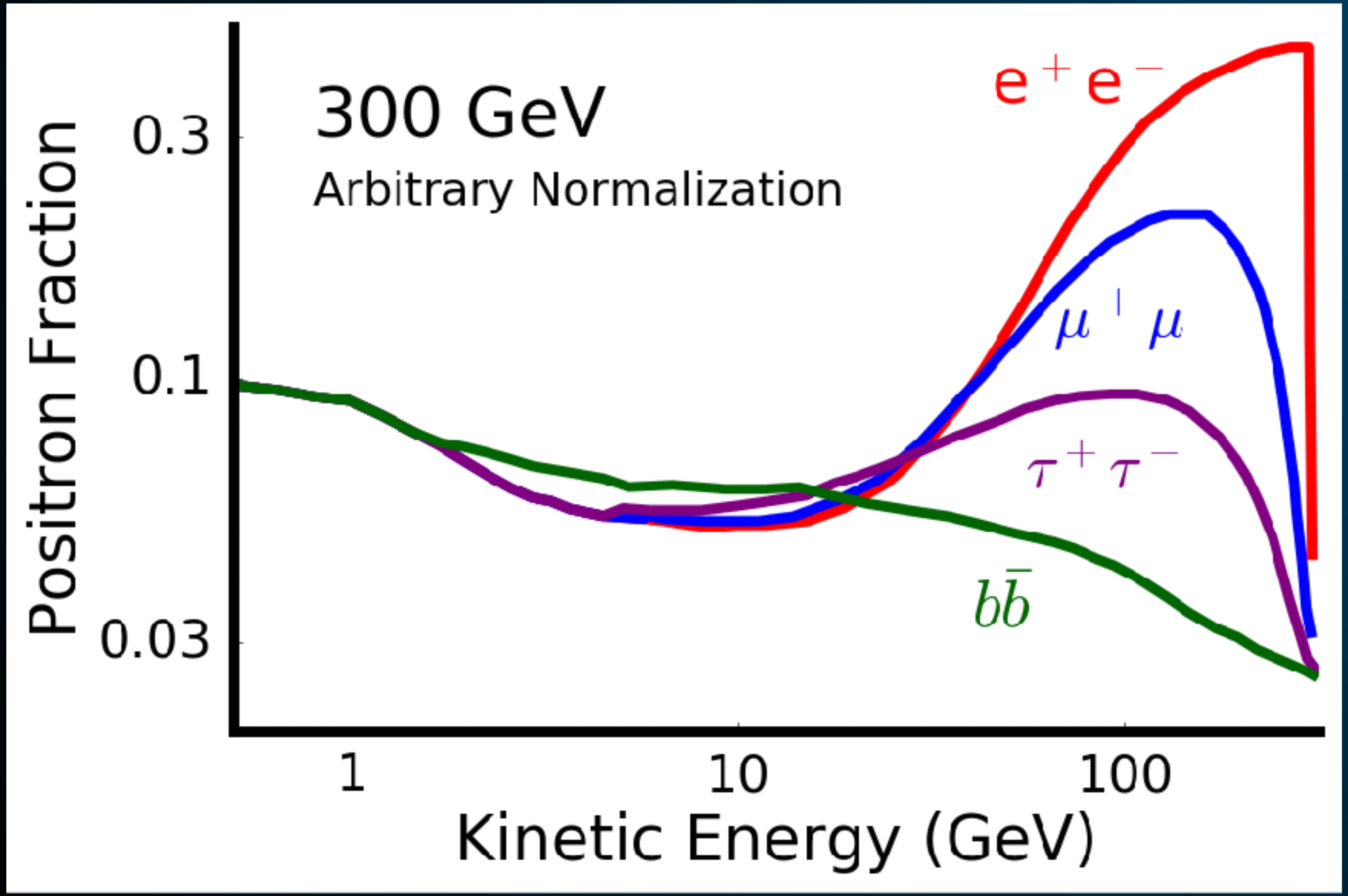

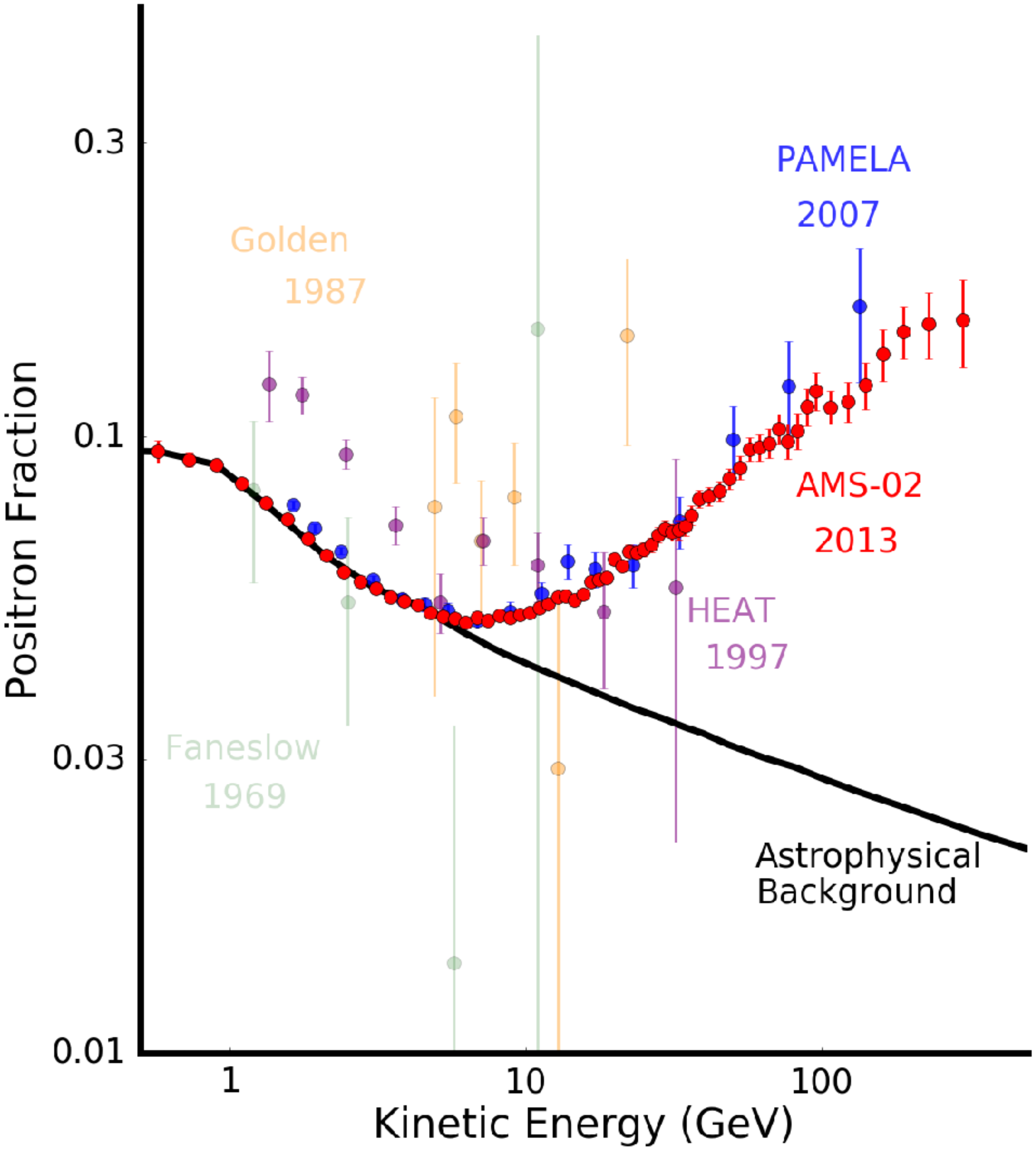

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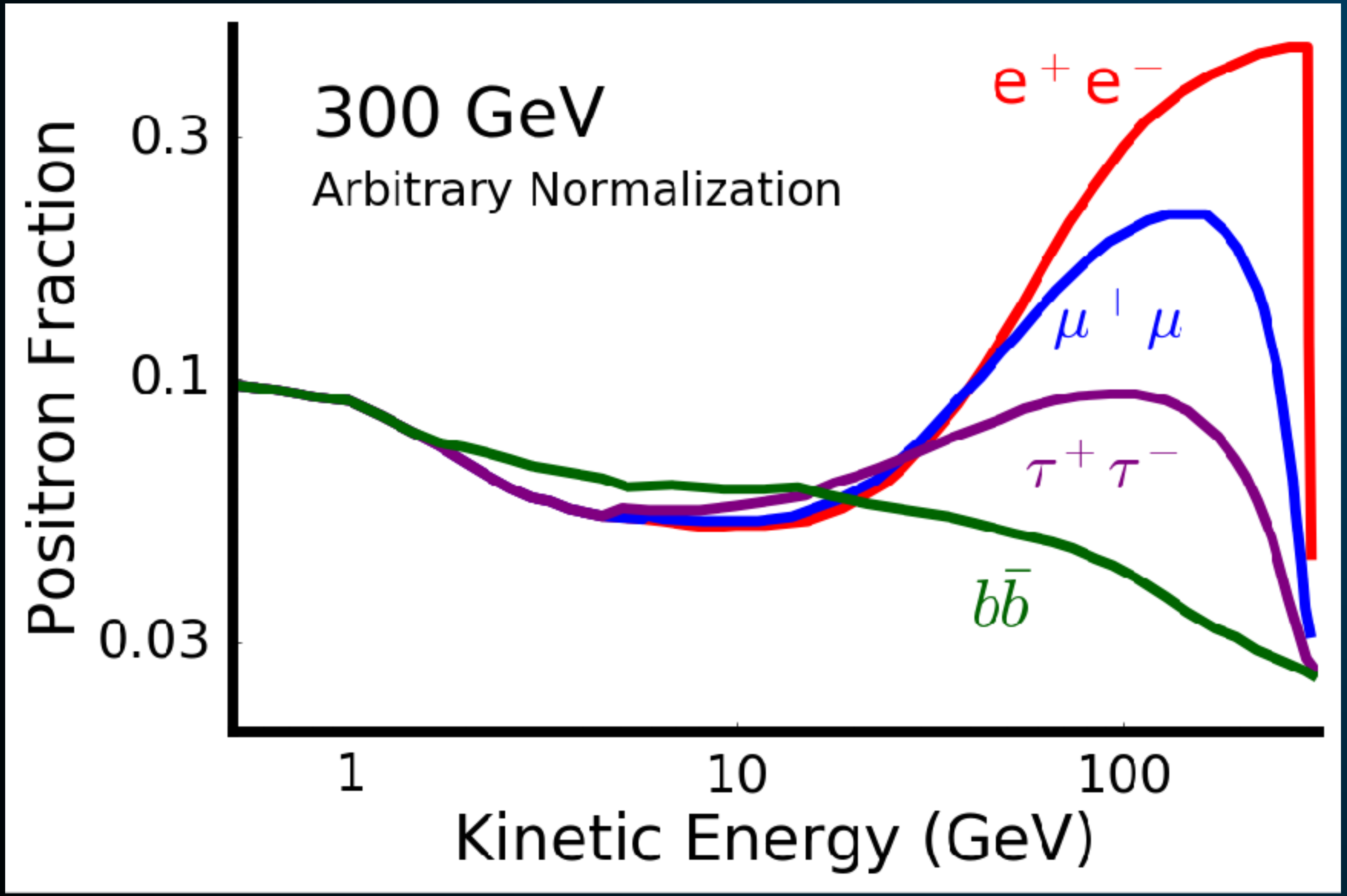
The Positron Excess

Why Less Excitement?

Continues to Higher Mass

Spectrum Relatively Smooth



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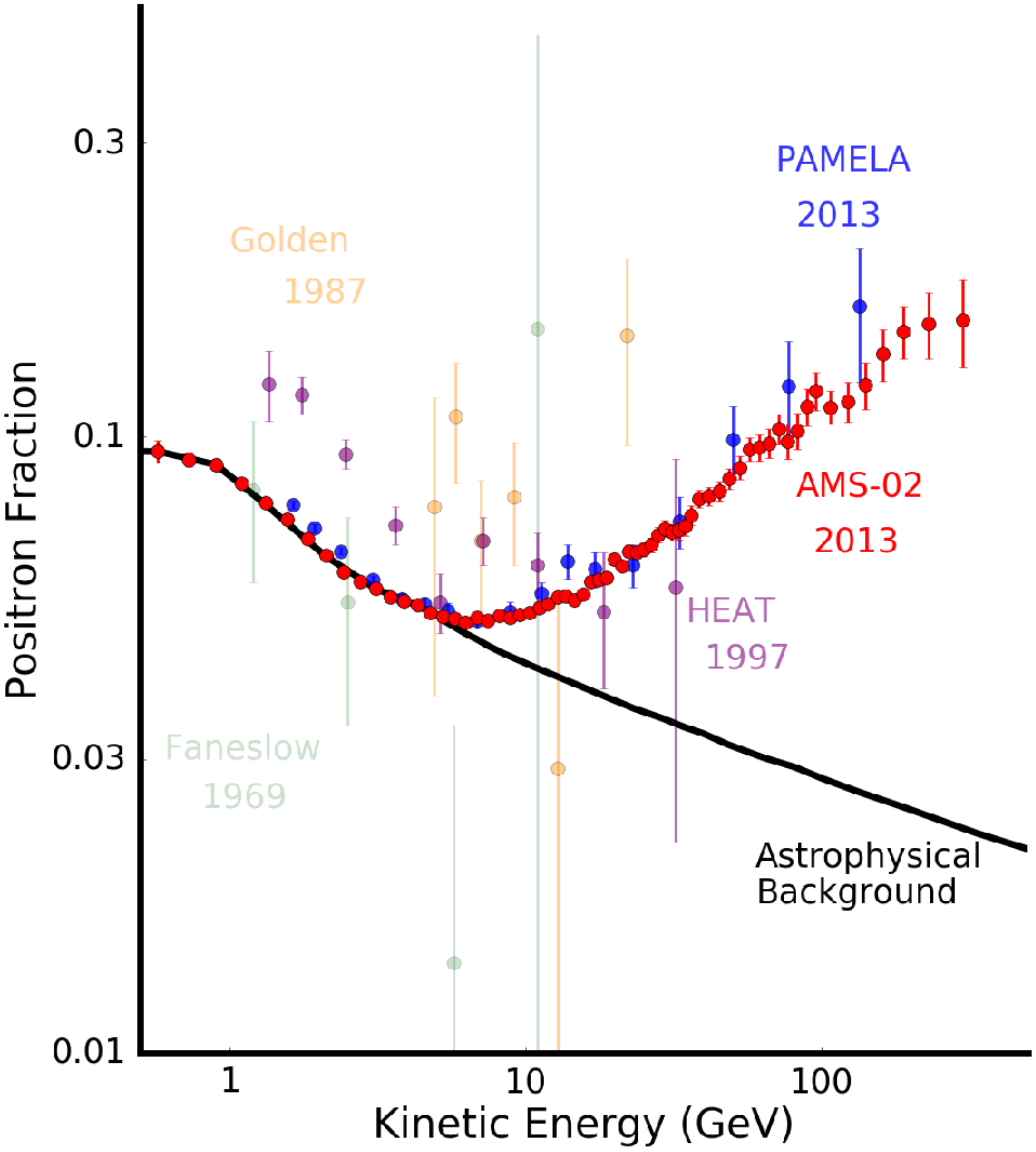

The Positron Excess

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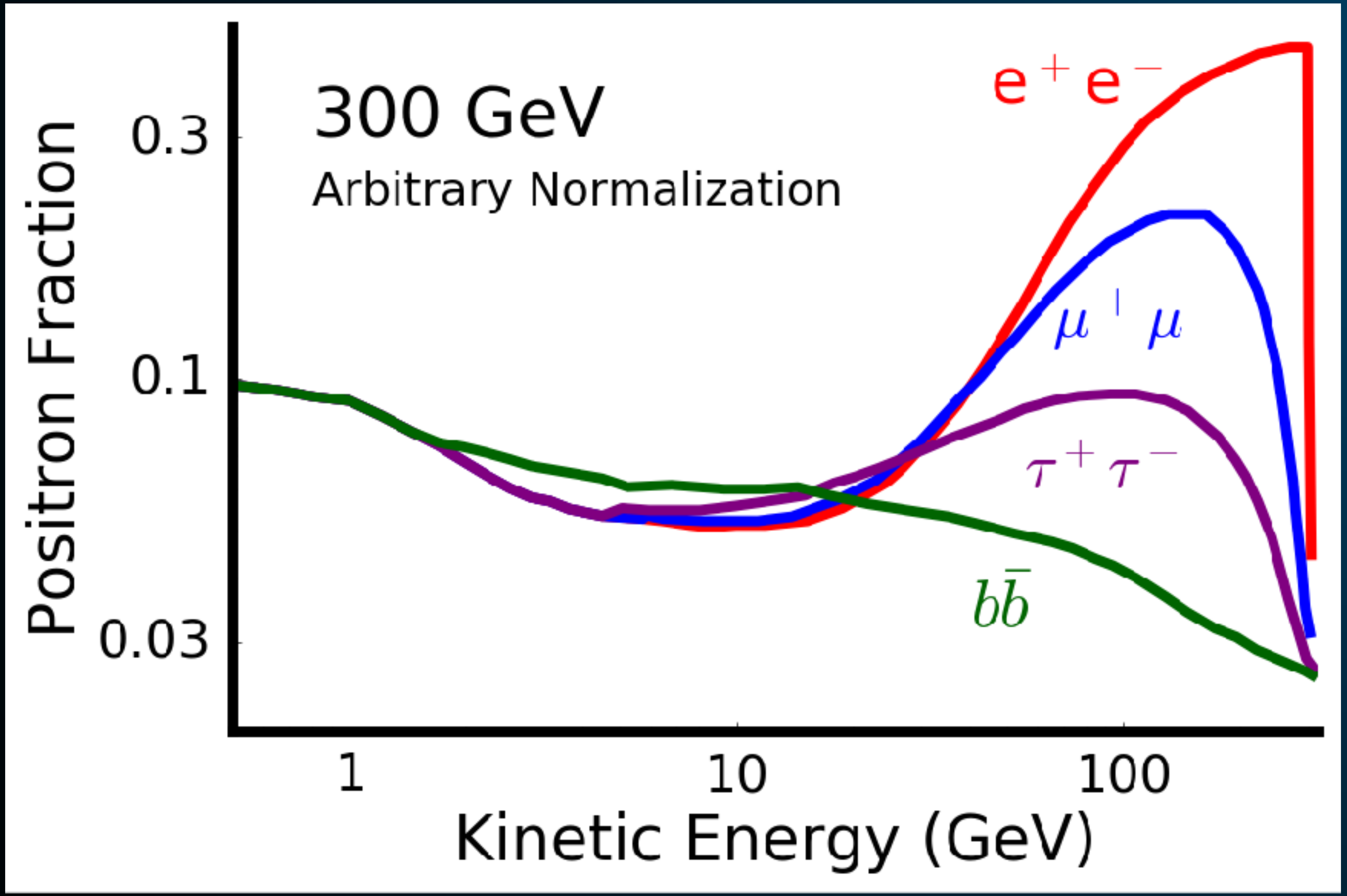
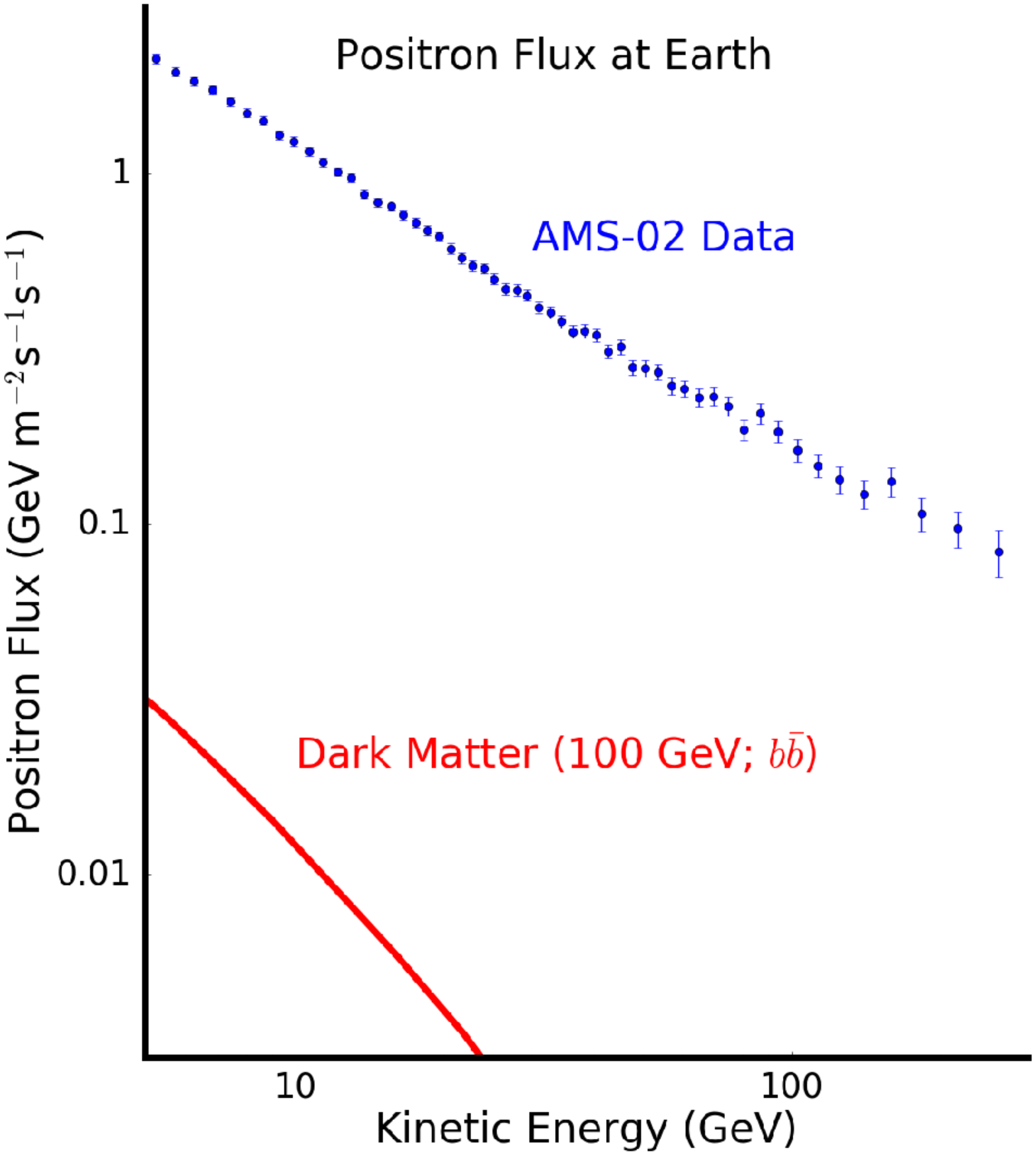




Not a Thermal WIMP!

Not a Thermal WIMP!

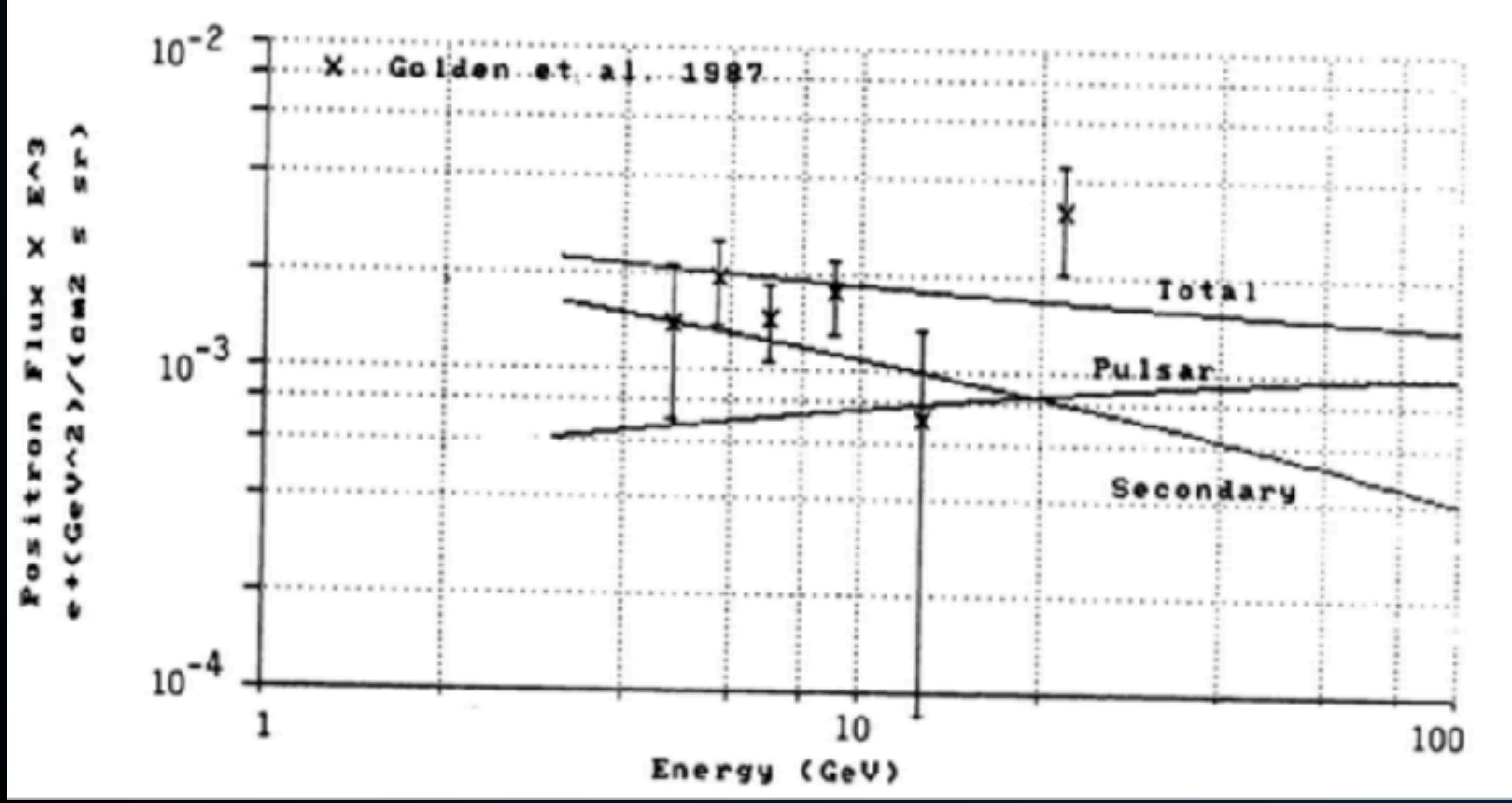
Not a Thermal WIMP!
$b\bar{b}$
e^+e^-
$b\bar{b}$ Limit (Planck)
e^+e^- Limit (Planck)
Thermal Cross-Section
Strong Gamma-Ray Constraints too!
$<\sigma v>$ (cm^3s^{-1})
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
0.1
1
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

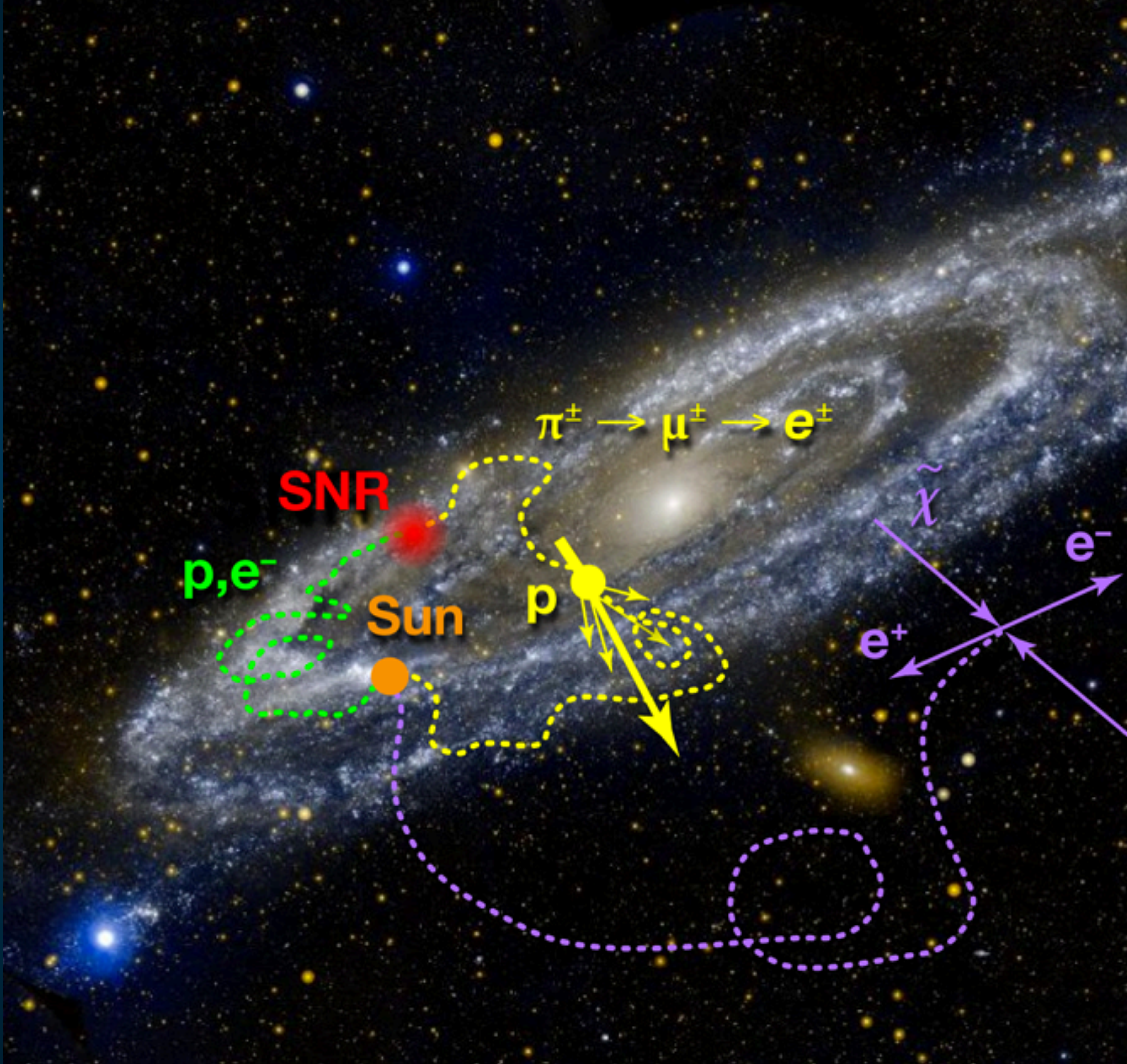
The Positron Excess

Key Idea: Investigate the Positron Fraction!

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

Harding & Ramaty (ICRC! 1987)





Pulsar Fits to the Positron Excess

Philippov et al. (2015; 1412.0673)

Uncertainties in pulsar models:

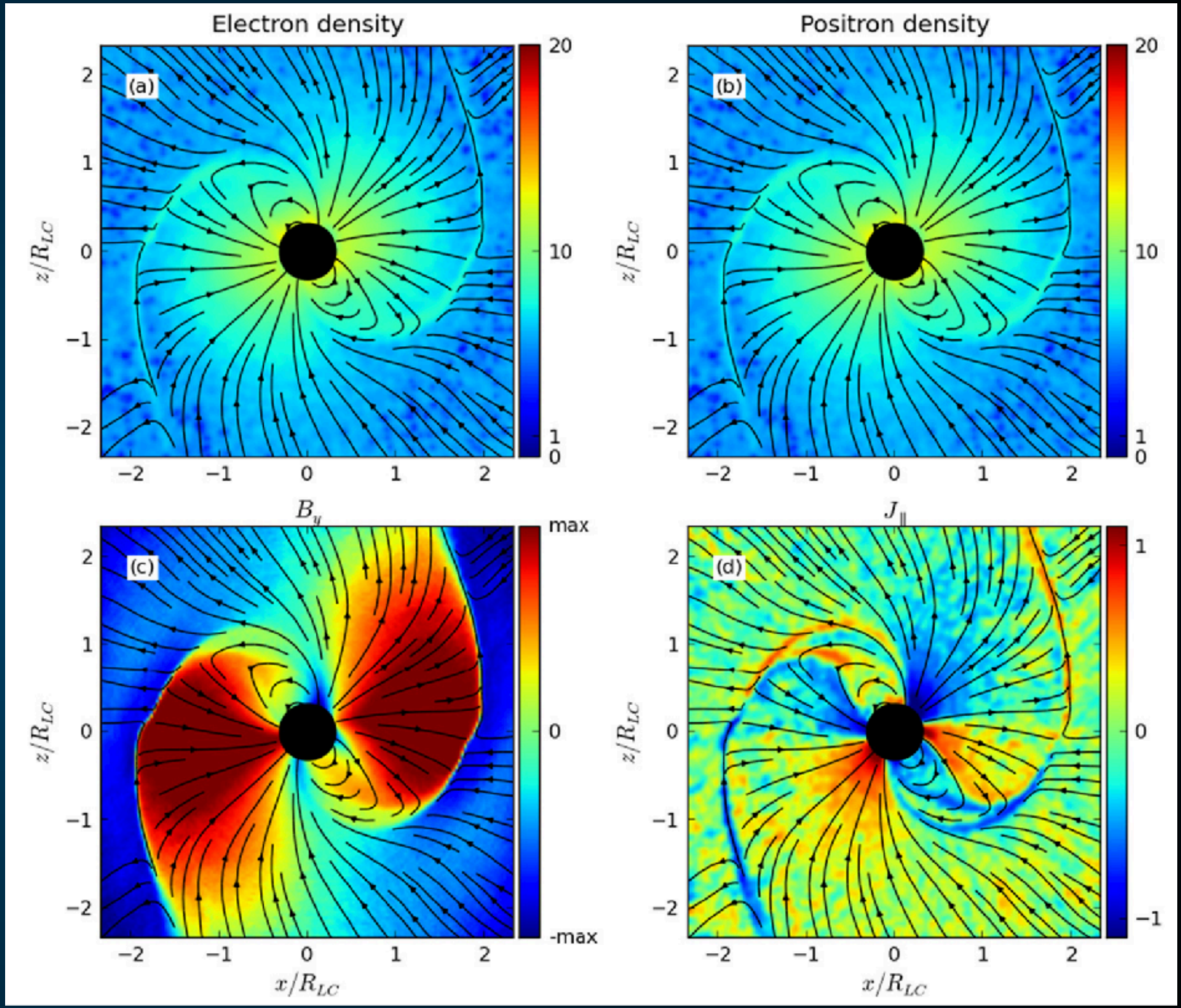
- **I: The e^+e^- production efficiency**

Profumo (0812.4457); Malyshev et al. (0903.1310)

%. A quantitative discussion of plausible values for $f_{e^\pm}$ was recently given in Ref. [38]. We shall not review their discussion here, but Ref. [38] argues (see in particular their very informative App. B and C) that in the context of a standard model for the pulsar wind nebulae, a reasonable range for $f_{e^\pm}$ falls between 1% and 30%.

- **II: The e^+e^- spectrum.**

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



Pulsar Fits to the Positron Excess

Philippov et al. (2015; 1412.0673)

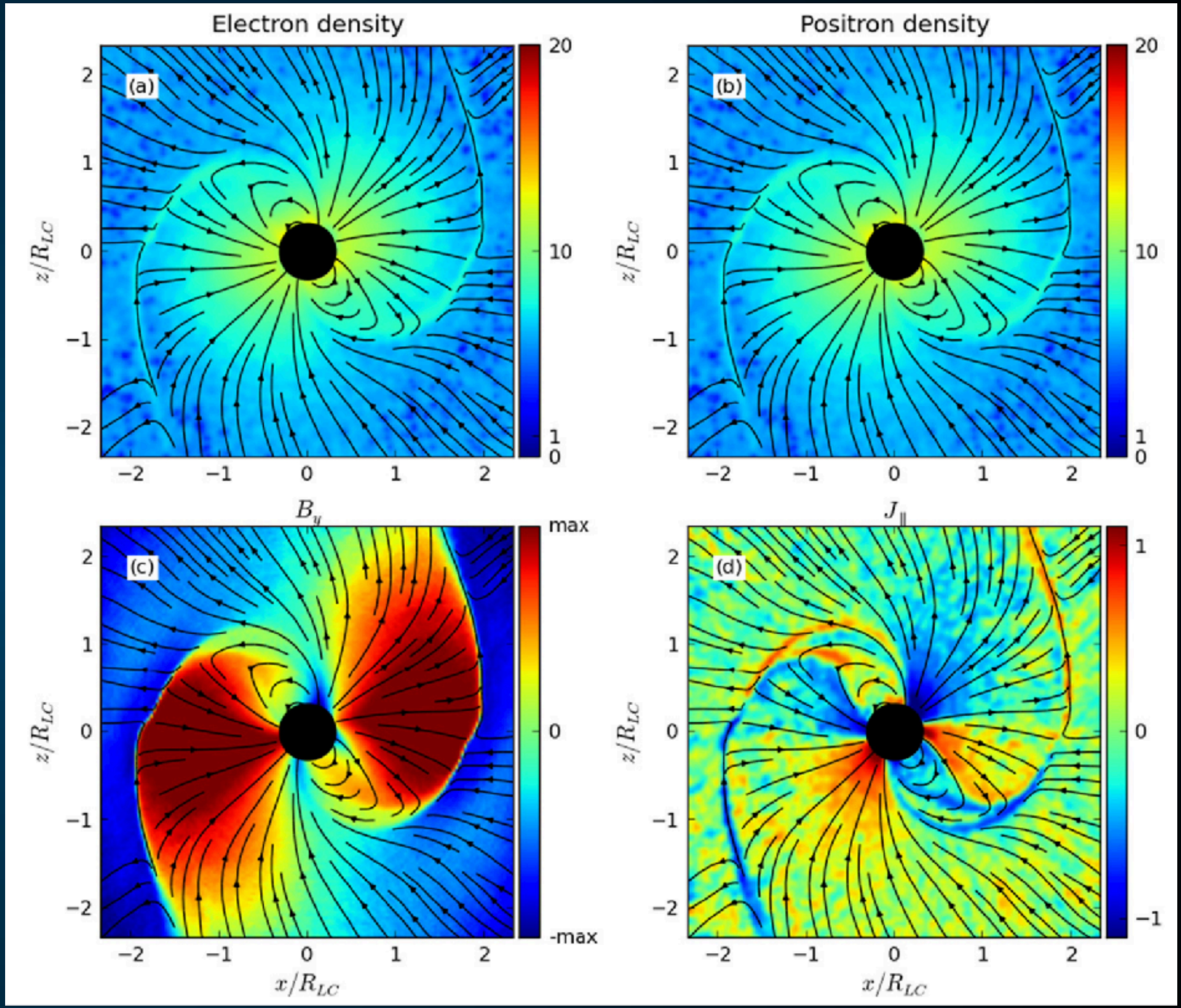
Uncertainties in pulsar models:

- I: The e^+e^- production efficiency
- II: The e^+e^- spectrum.

Hooper et al. (0810.1527)

part of their energy adiabatically because of the expansion of the wind. The energy spectrum injected by a single pulsar depends on the environmental parameters of the pulsar, but some attempts to calculate the average spectrum injected by a population of mature pulsars suggest that the spectrum may be relatively hard, having a slope of ~1.5-1.6 [18]. This spectrum, however, results from a complex interplay of individual pulsar spectra, of the spatial and age distributions of pulsars in the Galaxy, and on the assumption that the chief channel for pulsar spin down is magnetic dipole radiation. Due to the related uncertainties, variations from this injection spectra cannot be ruled out. Typically, one concentrates the attention on pulsars of age $\sim 10^5$ years because younger pulsars are likely to still

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



Pulsar Fits to the Positron Excess

Philippov et al. (2015; 1412.0673)

- **Uncertainties in pulsar models:**
  - **I: The e^+e^- production efficiency**
  - **II: The e^+e^- spectrum.**
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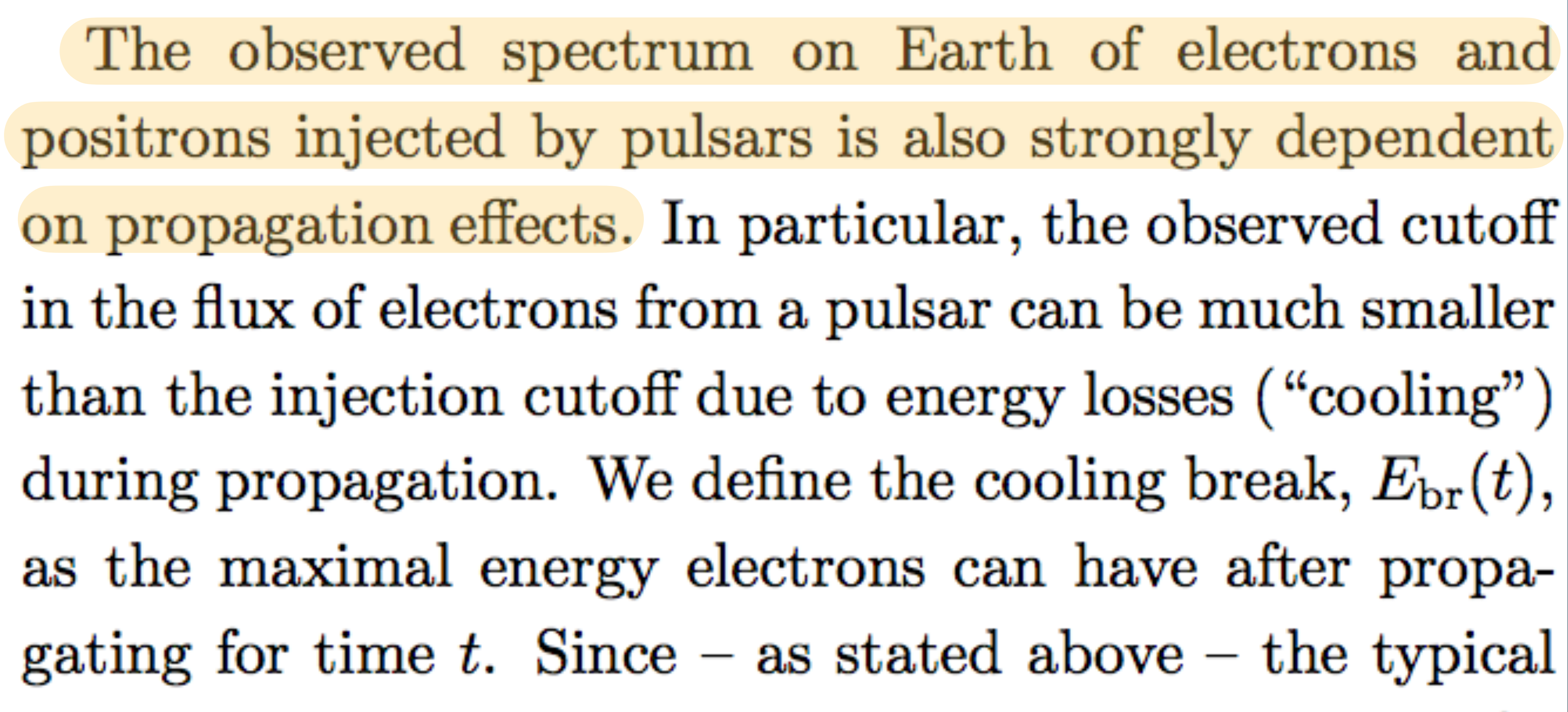
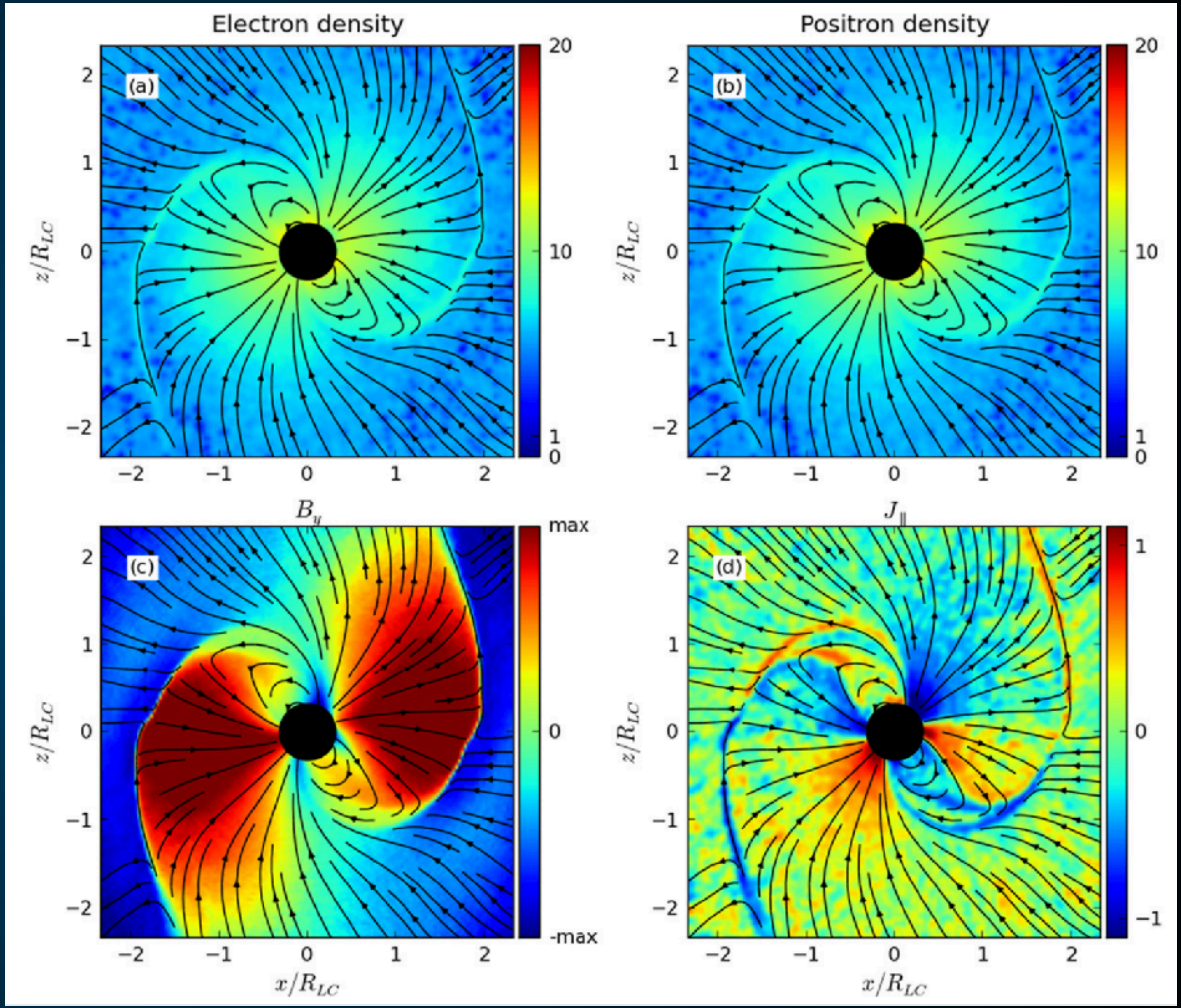
Malyshev et al. (0903.1310)


The observed spectrum on Earth of electrons and positrons injected by pulsars is also strongly dependent on propagation effects. In particular, the observed cutoff in the flux of electrons from a pulsar can be much smaller than the injection cutoff due to energy losses ("cooling") during propagation. We define the cooling break, $E_{\rm br}(t)$, as the maximal energy electrons can have after propagating for time t. Since – as stated above – the typical



HAWC Collaboration (2017; 1711.06223)


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


HAWC Collaboration (2017; 1711.06223)
Moon (To Scale)
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SNR
(hadronic/leptonic)
TeV Halo
(escaped e⁺e⁻)
PWN
(confined e⁺e⁻)
Geminga
α = 1.9
$E_\gamma\, dN_\gamma/dE_\gamma\ (\mathrm{cm^{-2}\,s^{-1}})$
E_γ (GeV)
Hooper, Cholis, TL, Fang (2017;1702.08436)

HAWC Collaboration (2017; 1711.06223)
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Geminga
$\alpha = 1.9$
$E_\gamma\, dN_\gamma/dE_\gamma\ (\mathrm{cm^{-2}\,s^{-1}})$
$E_\gamma\ (\mathrm{GeV})$
10 - 30% Efficiency!
Hooper, Cholis, TL, Fang (2017;1702.08436)


HAWC Collaboration (2017; 1711.06223)
Moon (To Scale)
Geminga
Linden et al. (2017; 1703.09704)
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SNR
(hadronic/leptonic)
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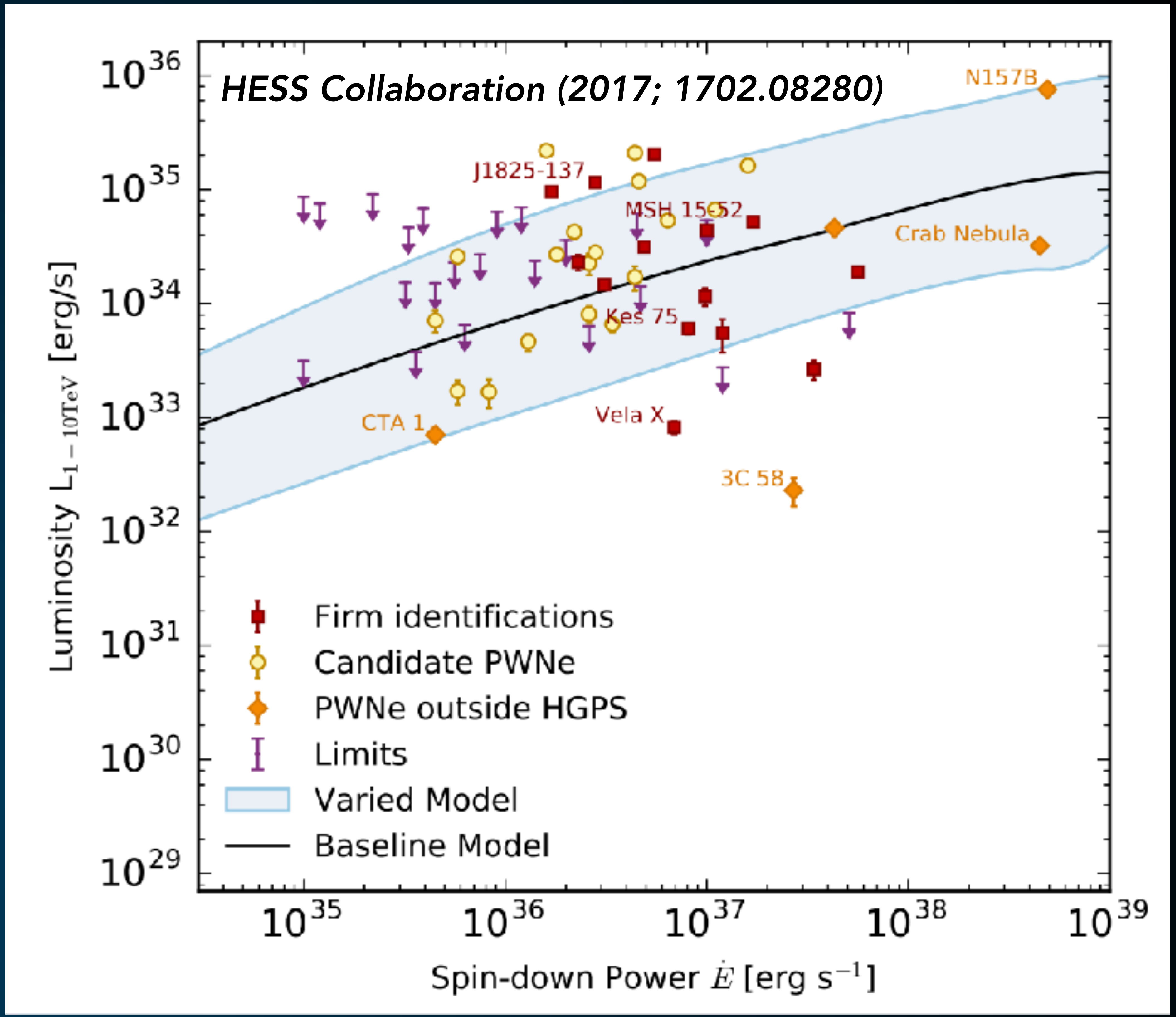
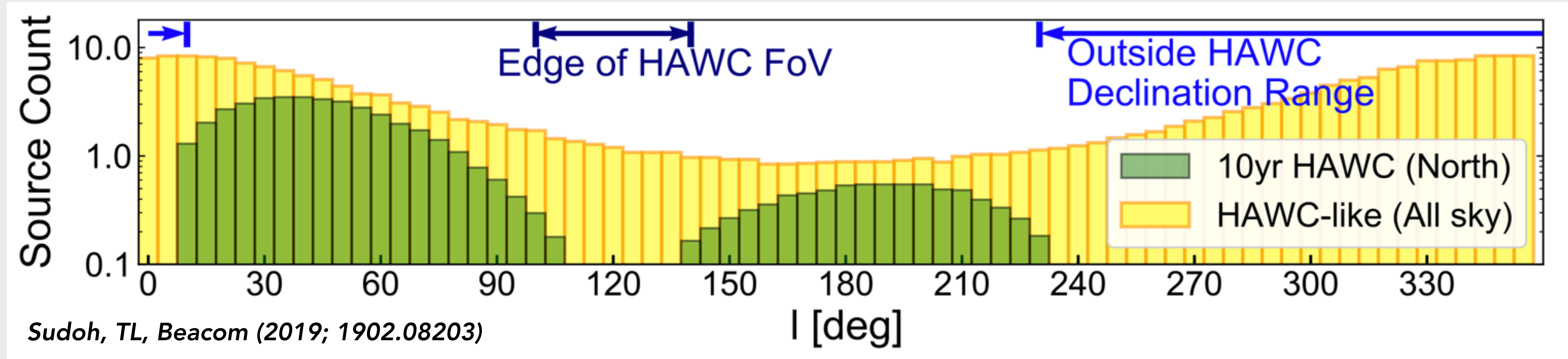
(escaped e+e−)
PWN
(confined e+e−)
Geminga
α = 1.9
α = 1.5 — 1.9
Hooper, Cholis, TL, Fang (2017;1702.08436)
E_γ dN_γ/dE_γ (cm^−2 s^−1)
E_γ (GeV)

The Positron Excess

- **Geminga and Monogem are not unique!**
  - **Nearly every bright pulsar observation is consistent with ~10% e^+e^- efficiency!**
  - **Upcoming observations will detect >100 systems**





Pulsar Fits to the Positron Excess

- **Uncertainties in pulsar models:**
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  - **II: The e^+e^- spectrum.**
  - **III: The propagation of e^+e^- to Earth.**

Malyshev et al. (0903.1310)

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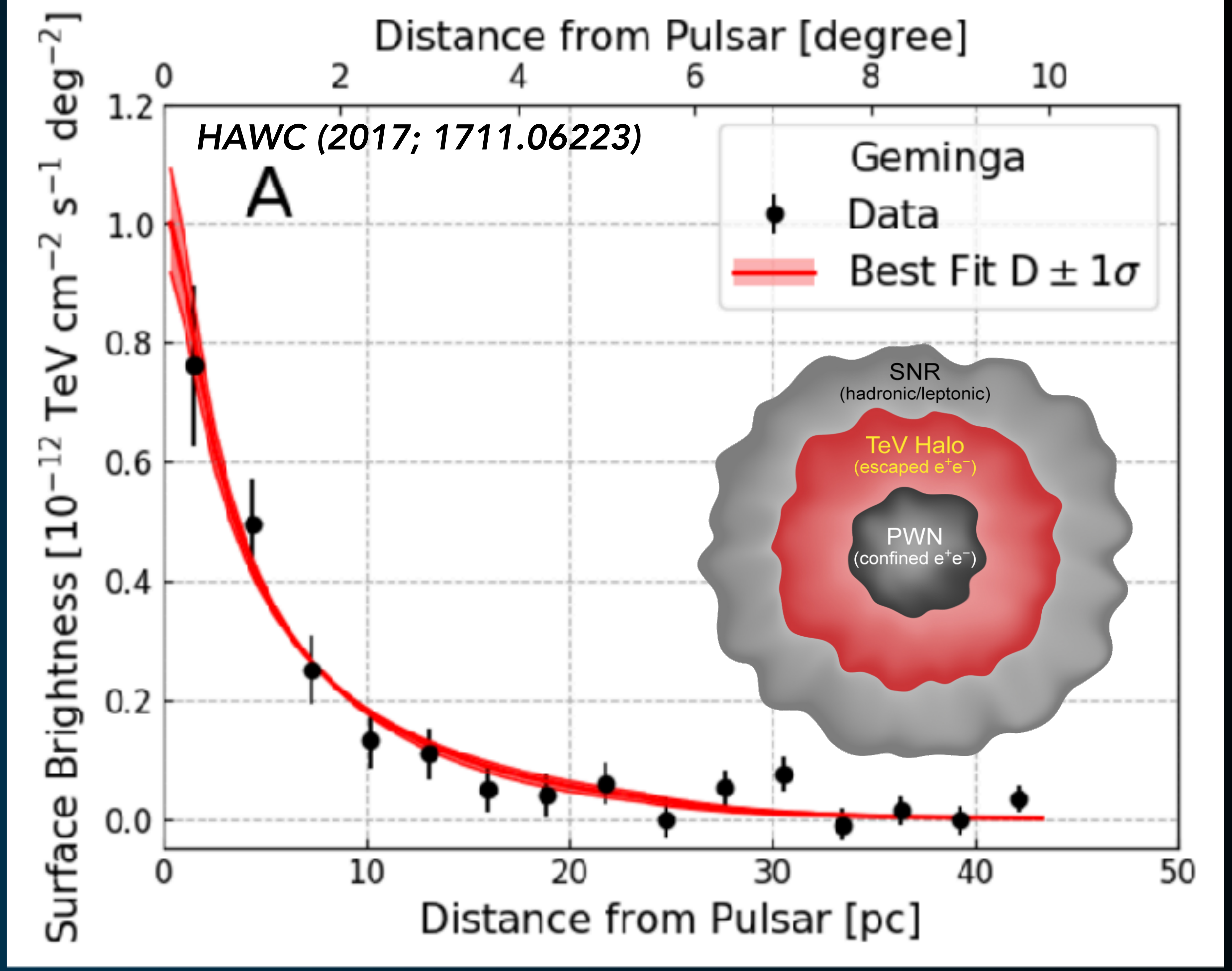
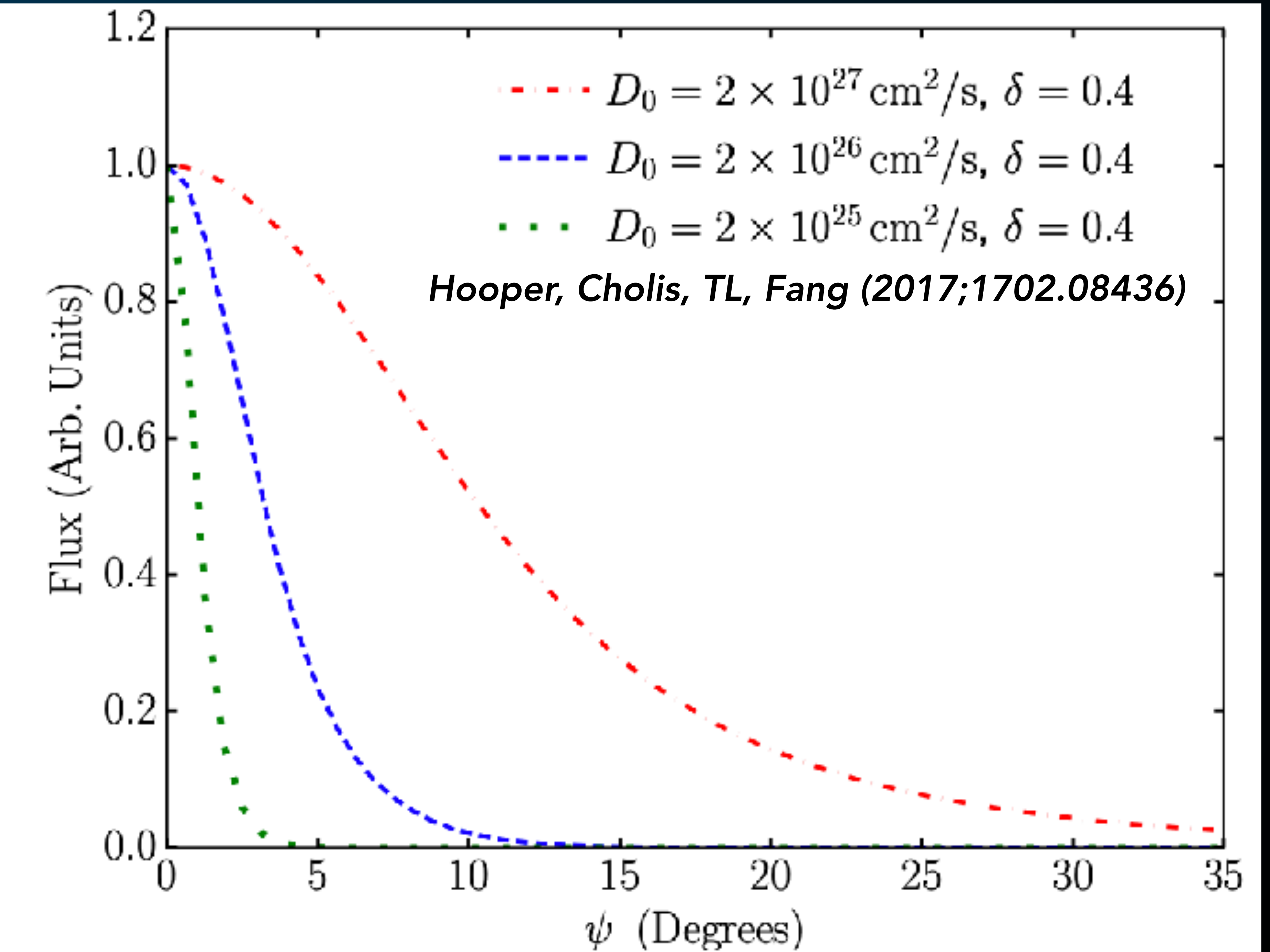
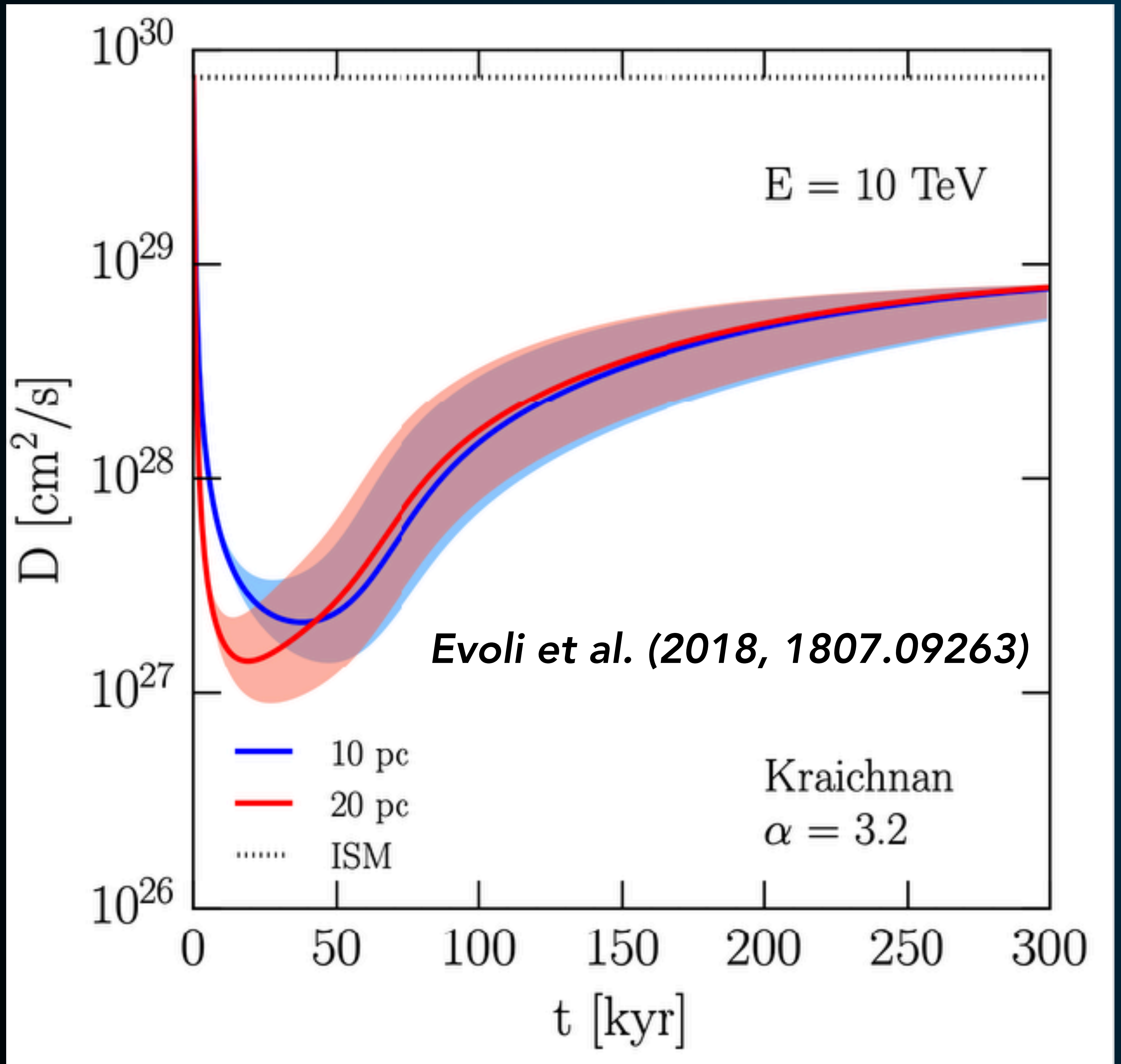


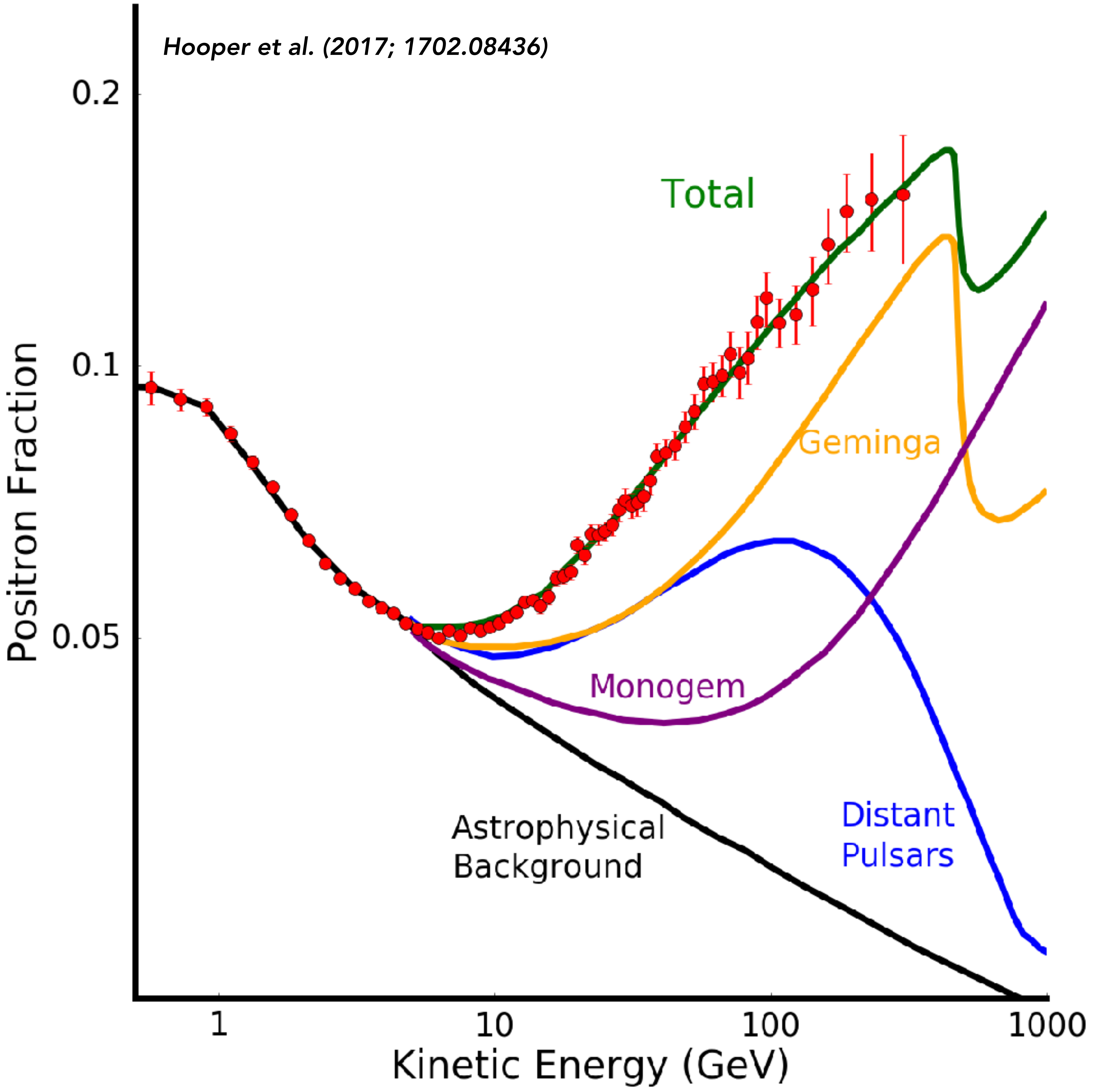


The Positron Excess

This can easily match the positron fraction

Some transport issues are possible - but easy to solve in models with inhomogeneous diffusion.





The Antiproton Excess

The Antiproton Excess

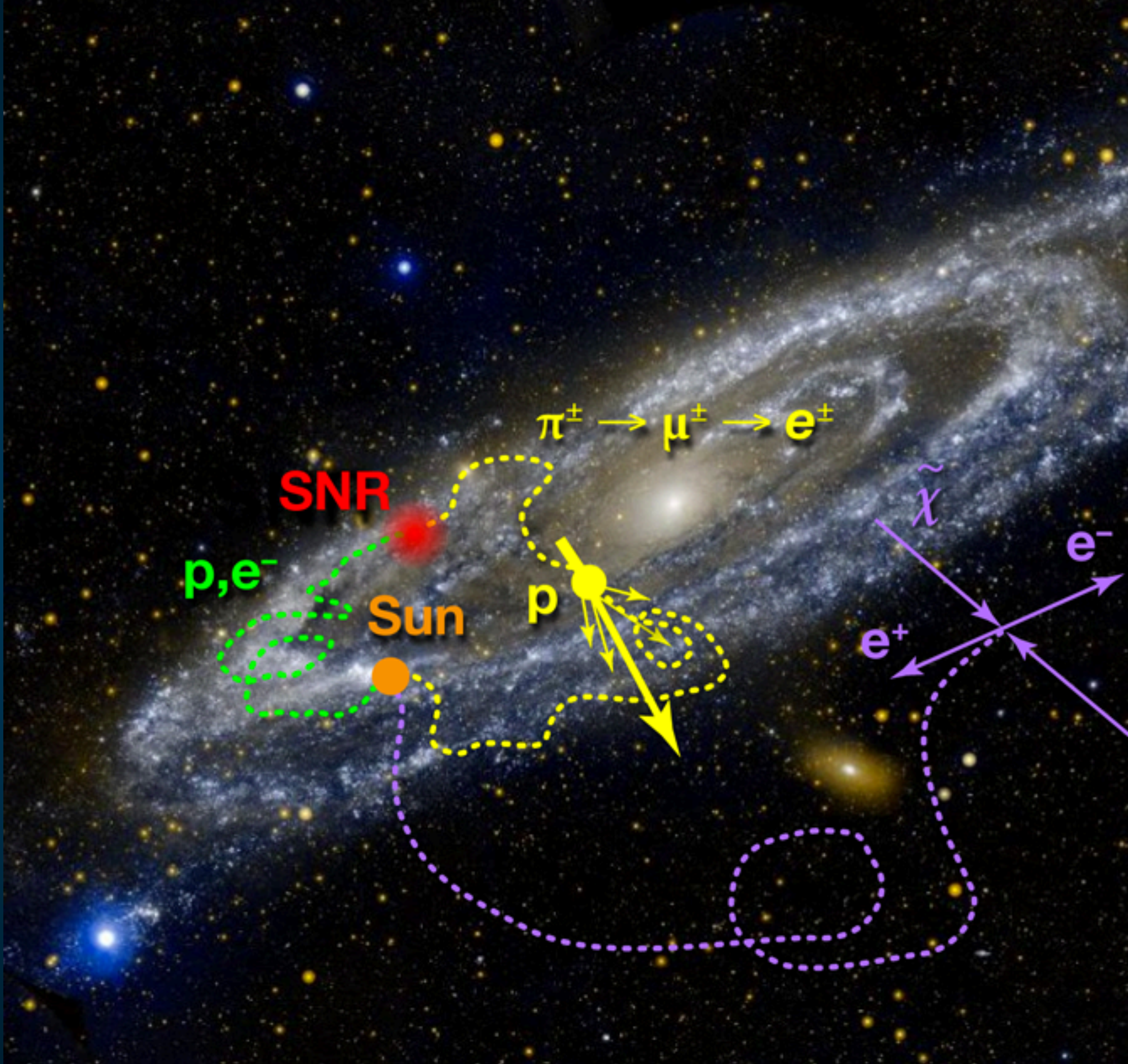
Investigate the Antiproton Fraction!

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

Two Changes:

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

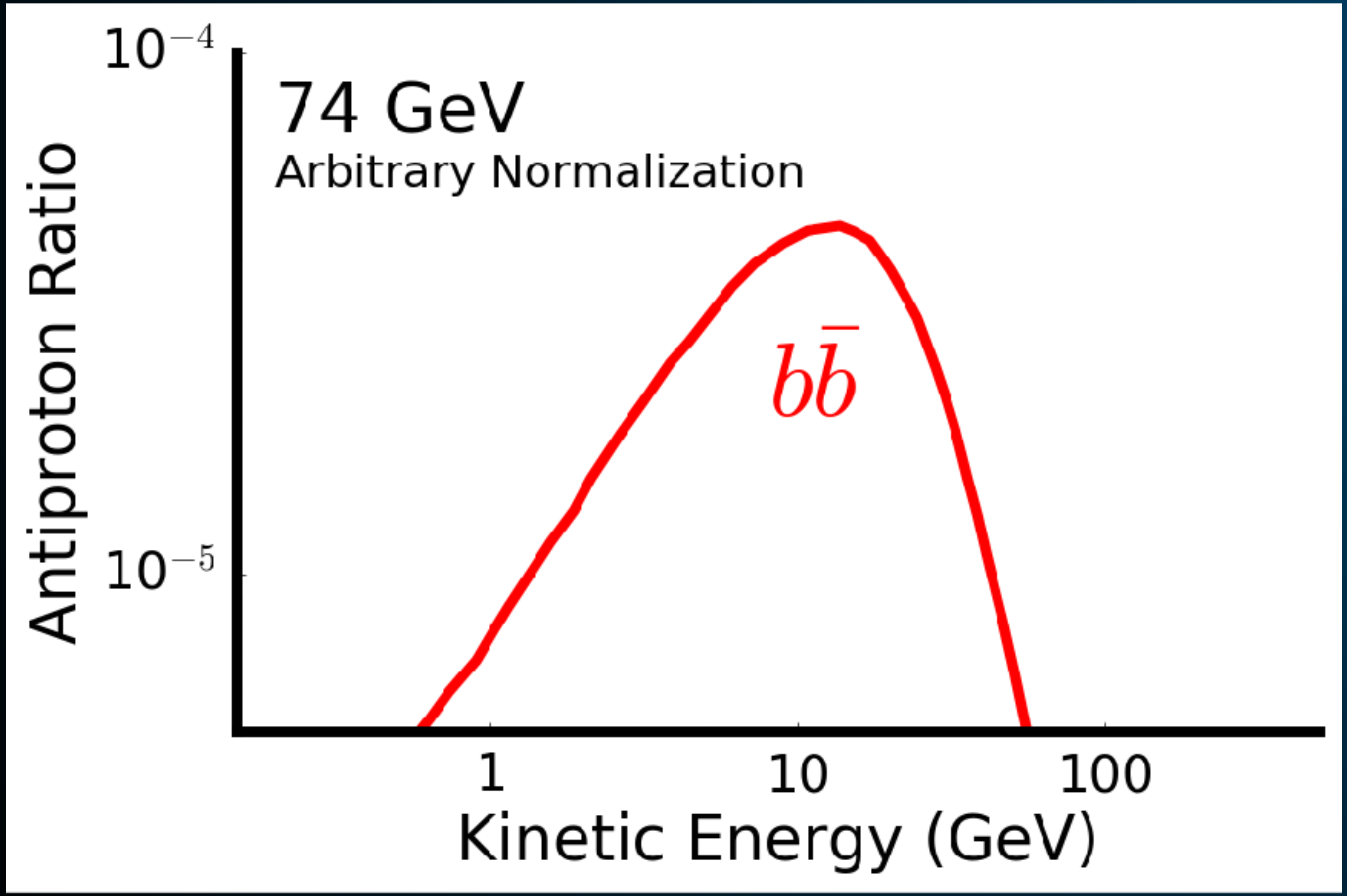
Hadronic Energy losses are slower (sensitive to antiproton production throughout the Galaxy)

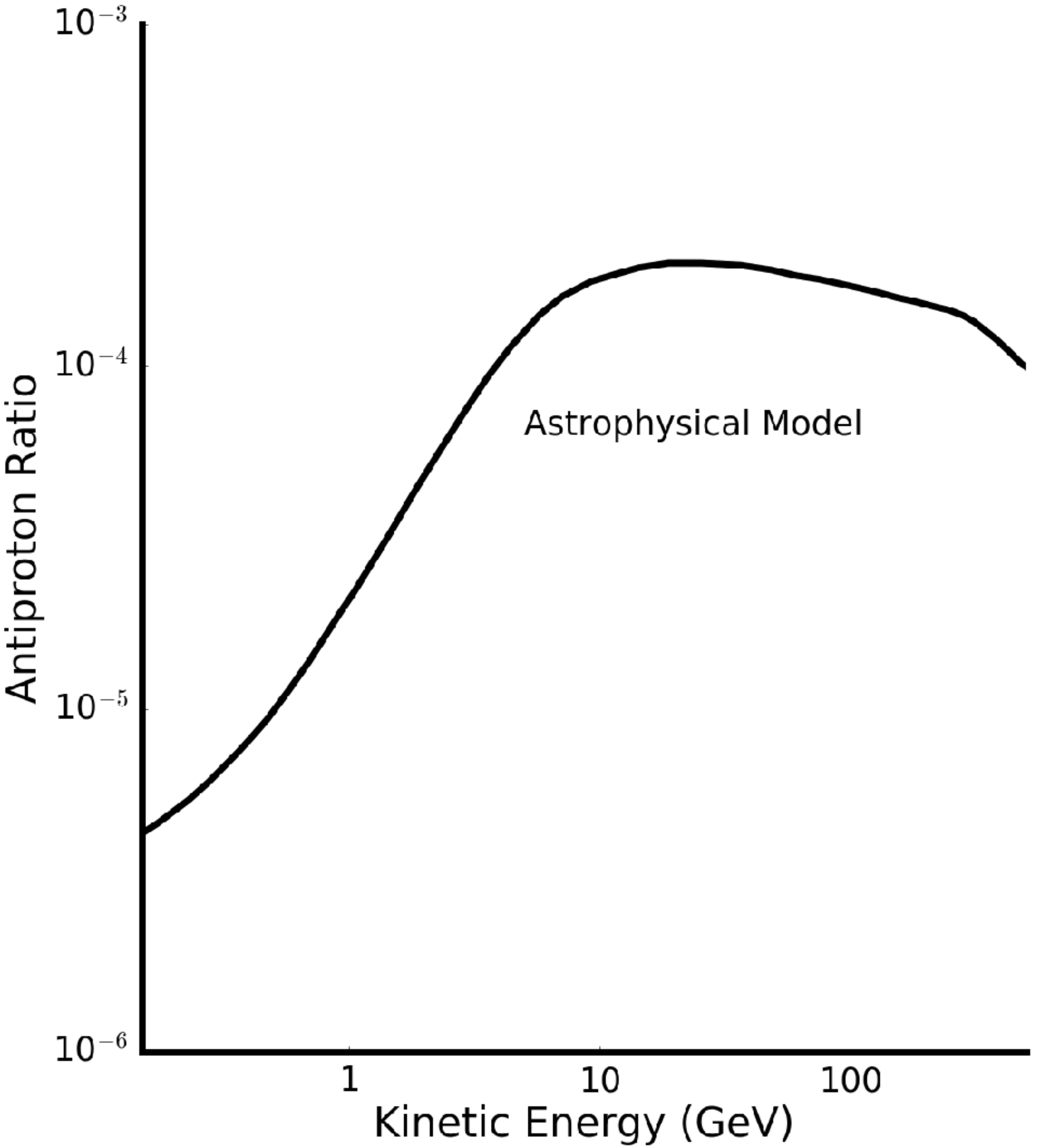


The Antiproton Excess

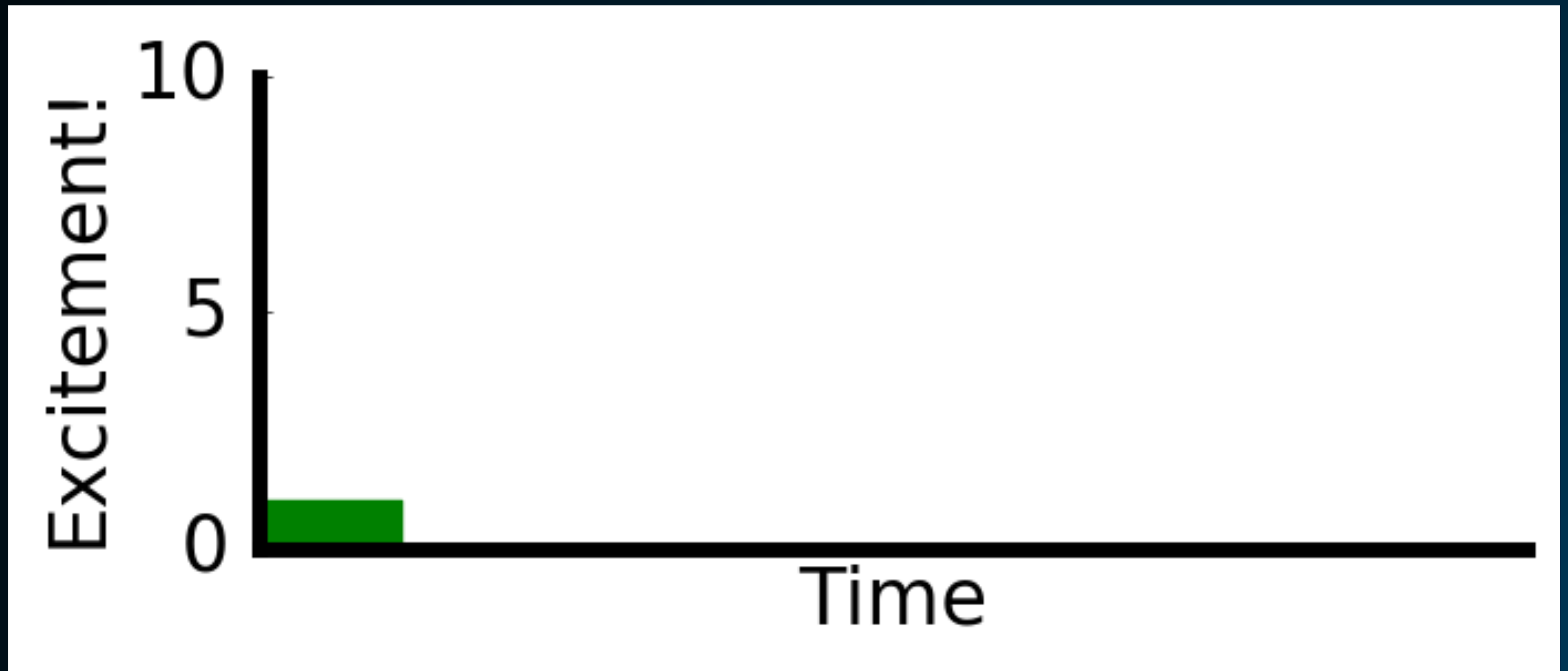
Astrophysics - Smooth Profile

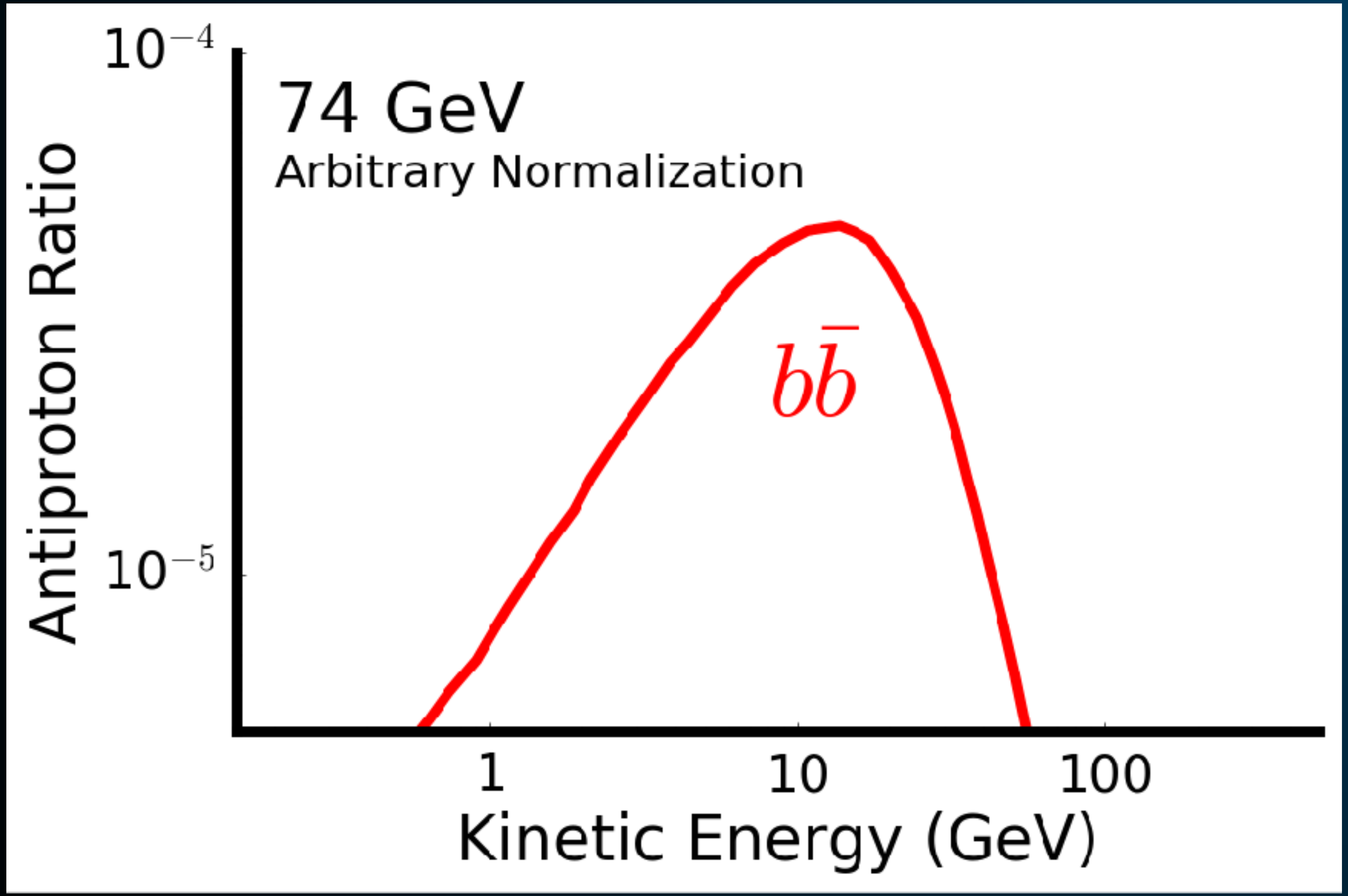
Dark Matter - Sharp Bump!



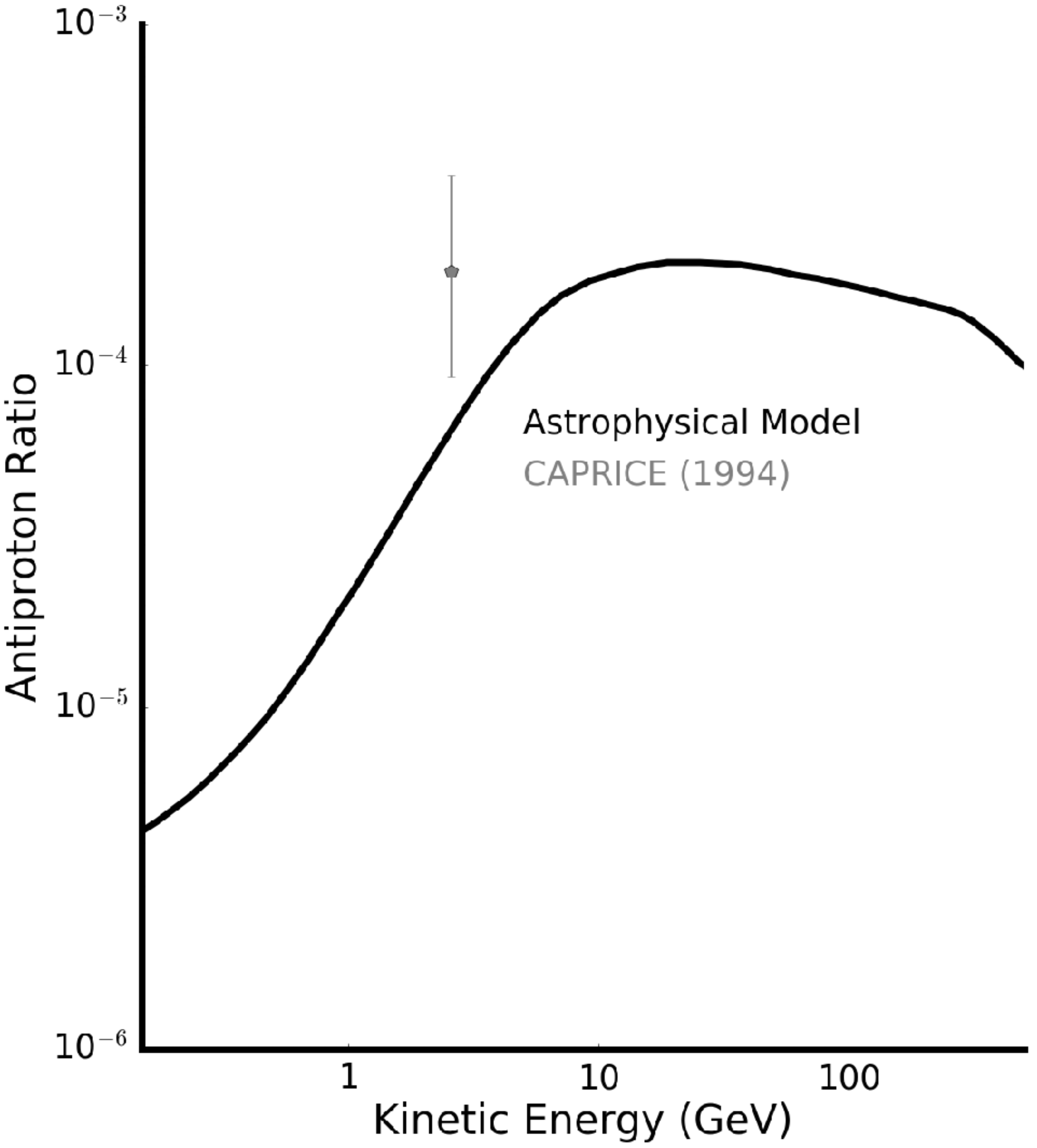


The Antiproton Excess





(Not an exhaustive list of observations)



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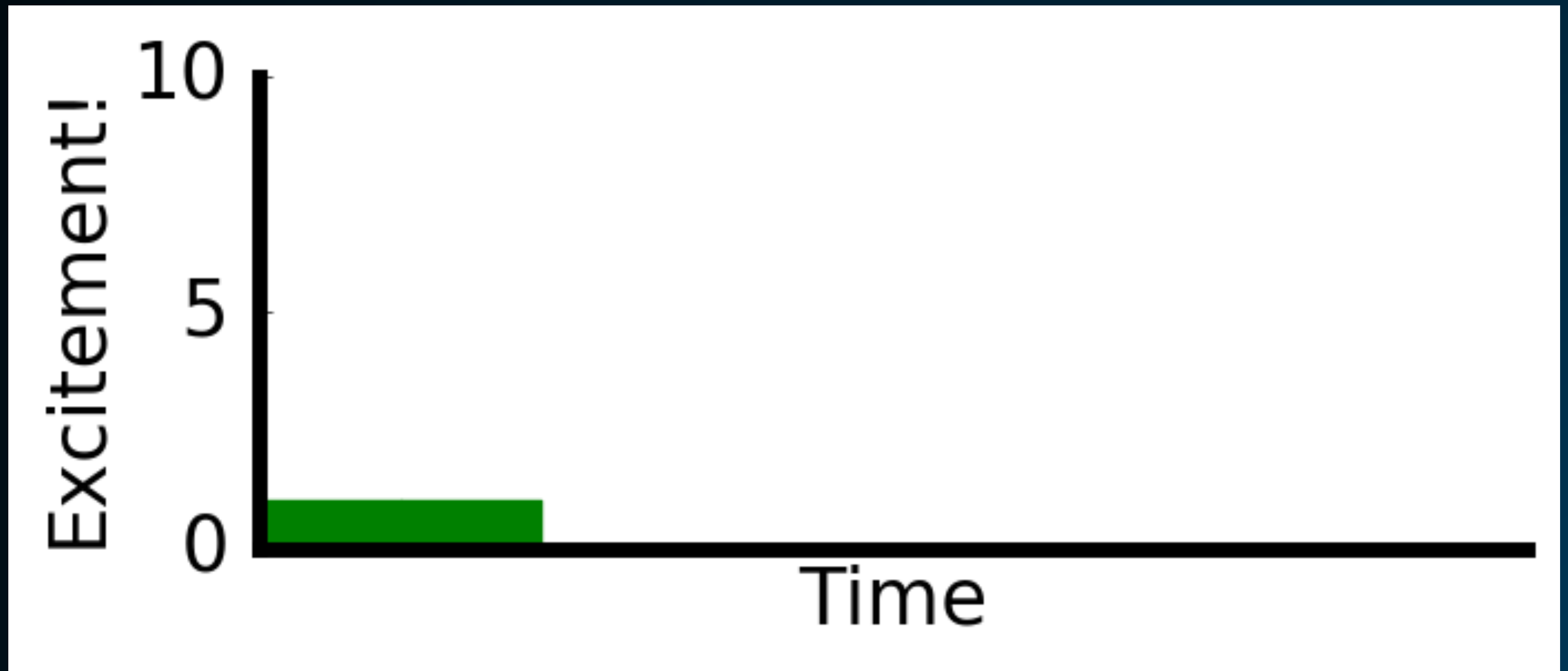
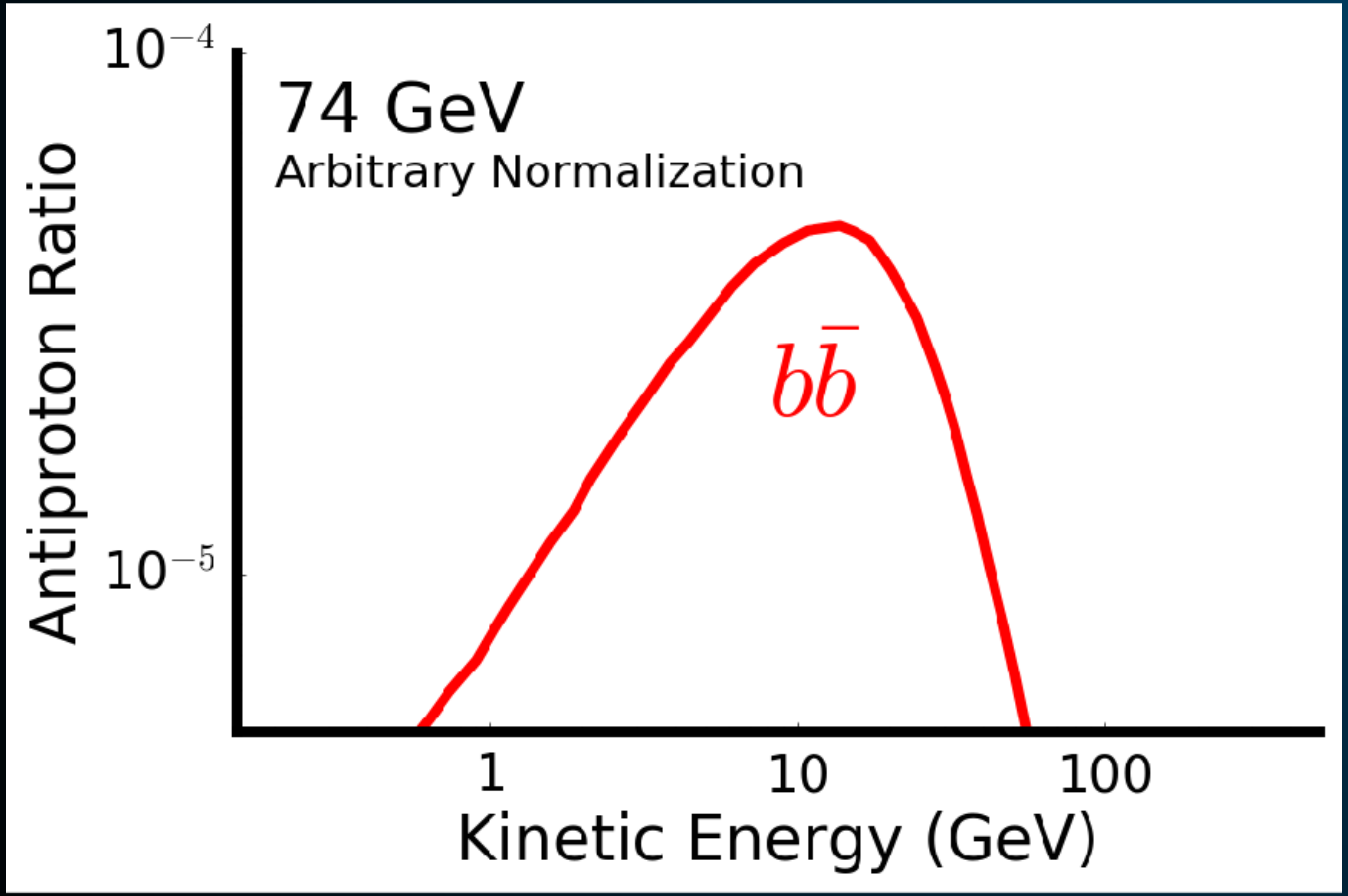
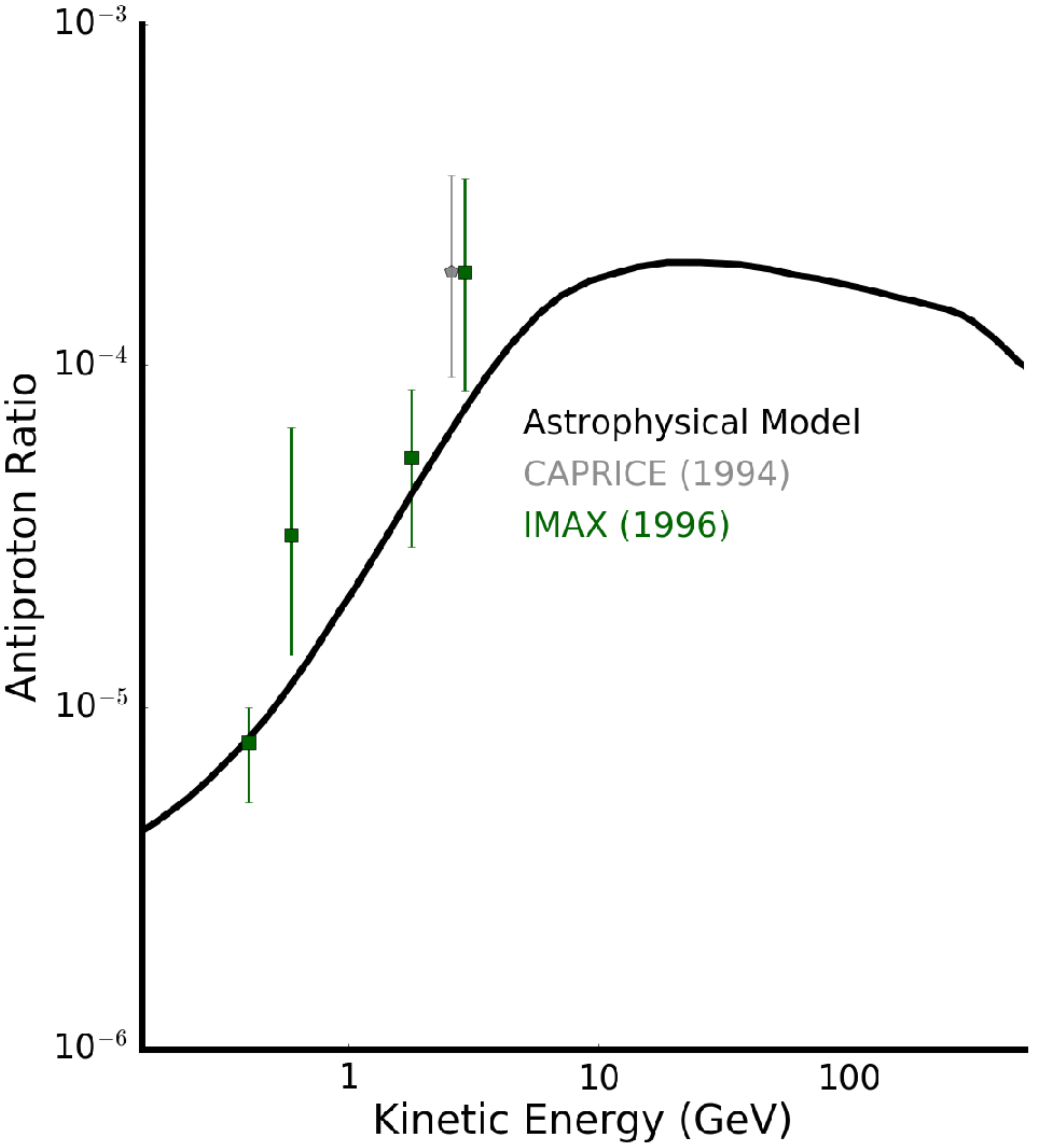
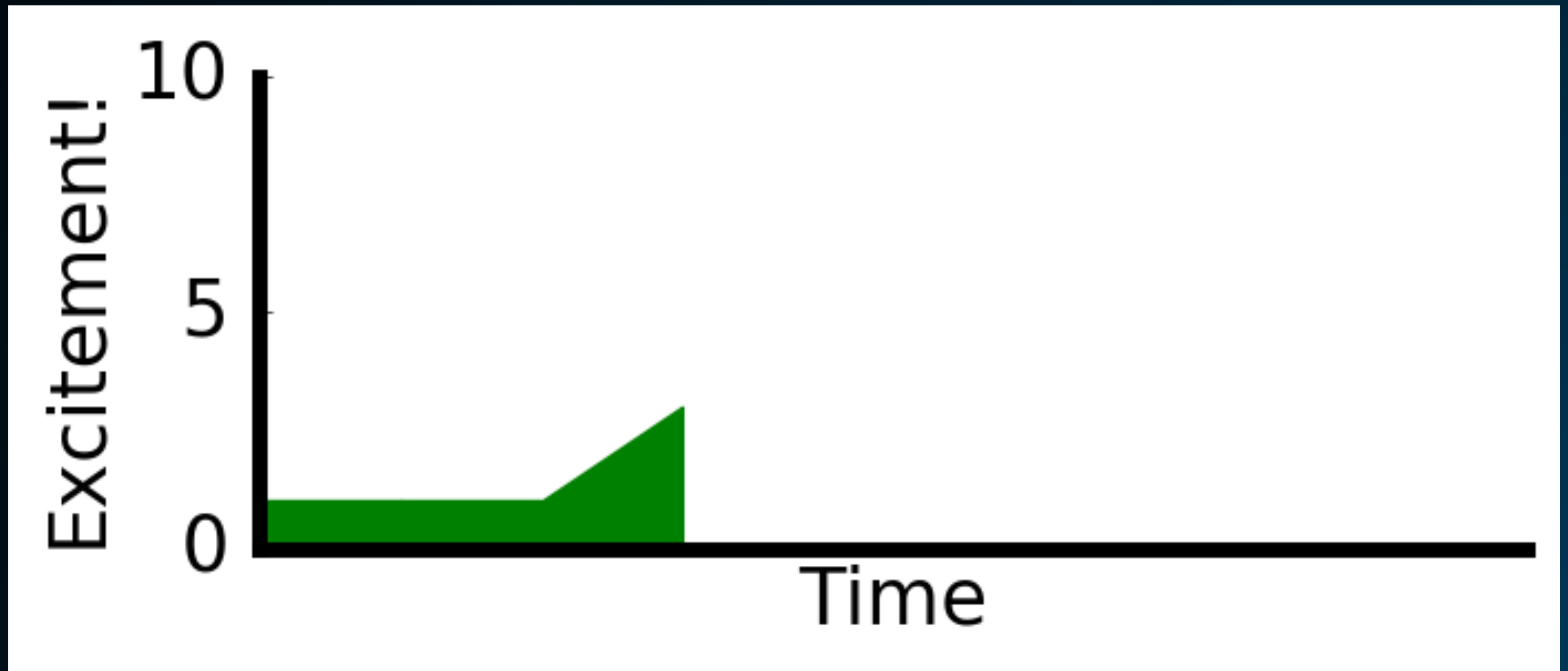


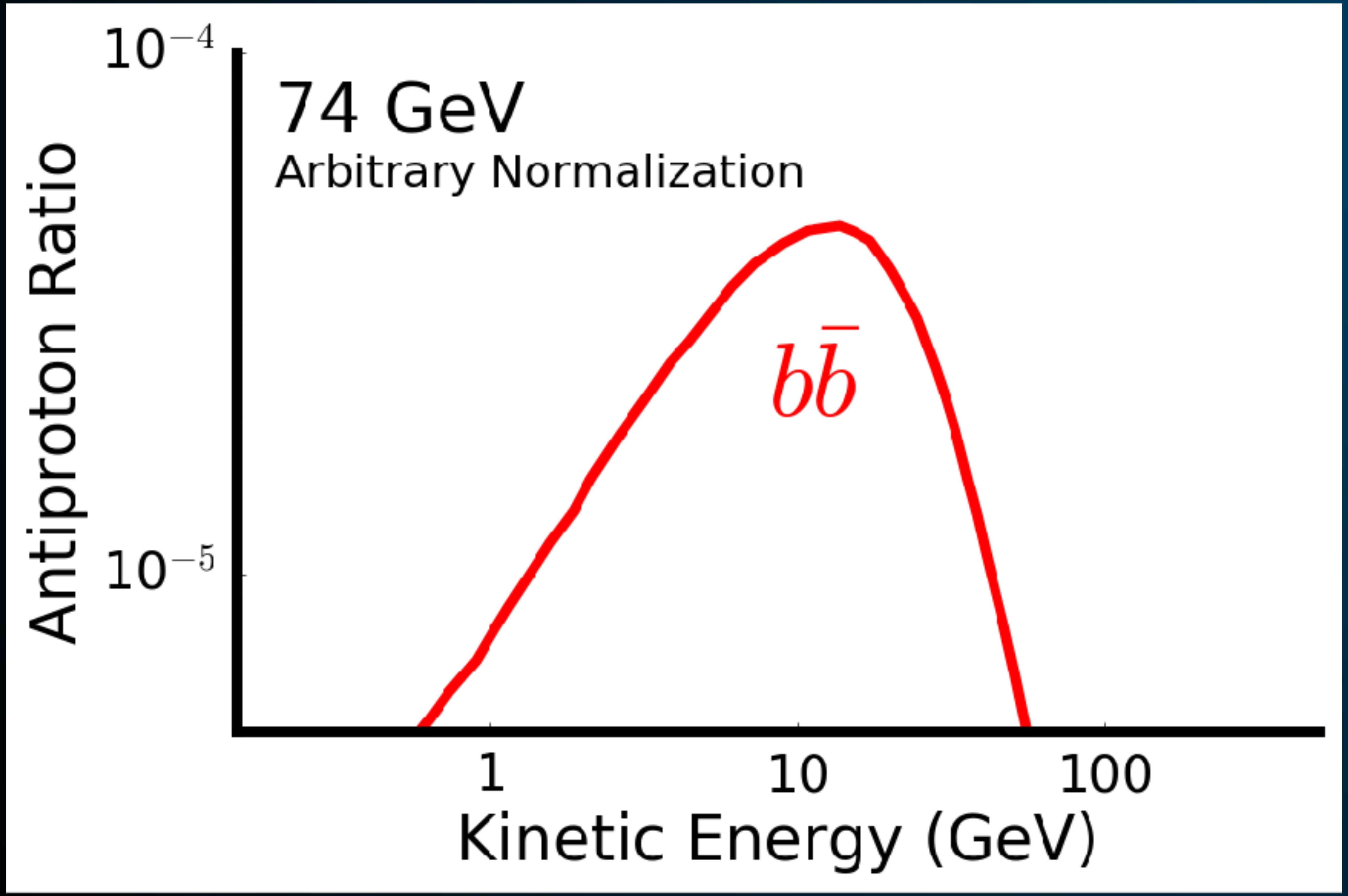


(Not an exhaustive list of observations)

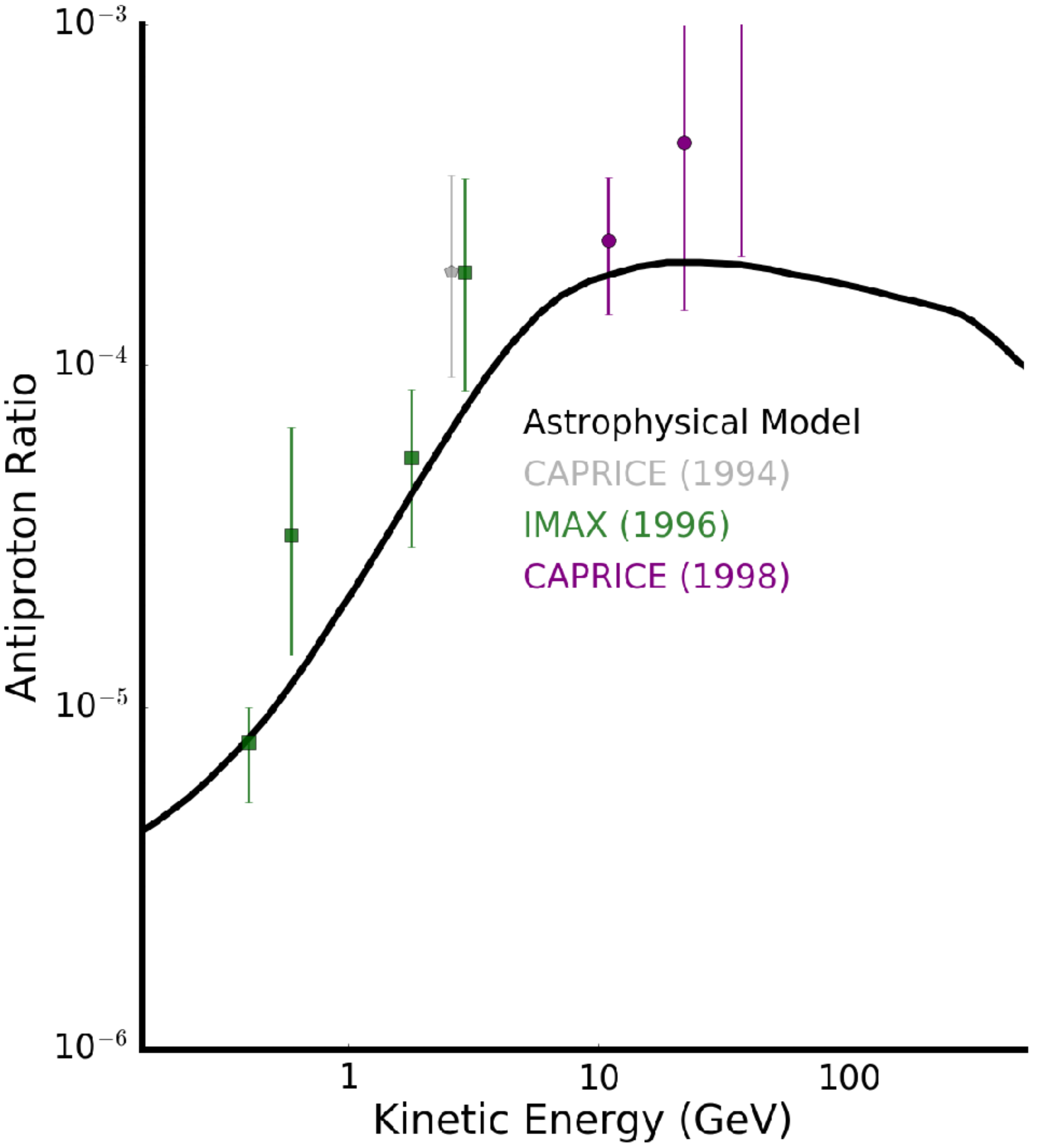


The Antiproton Excess

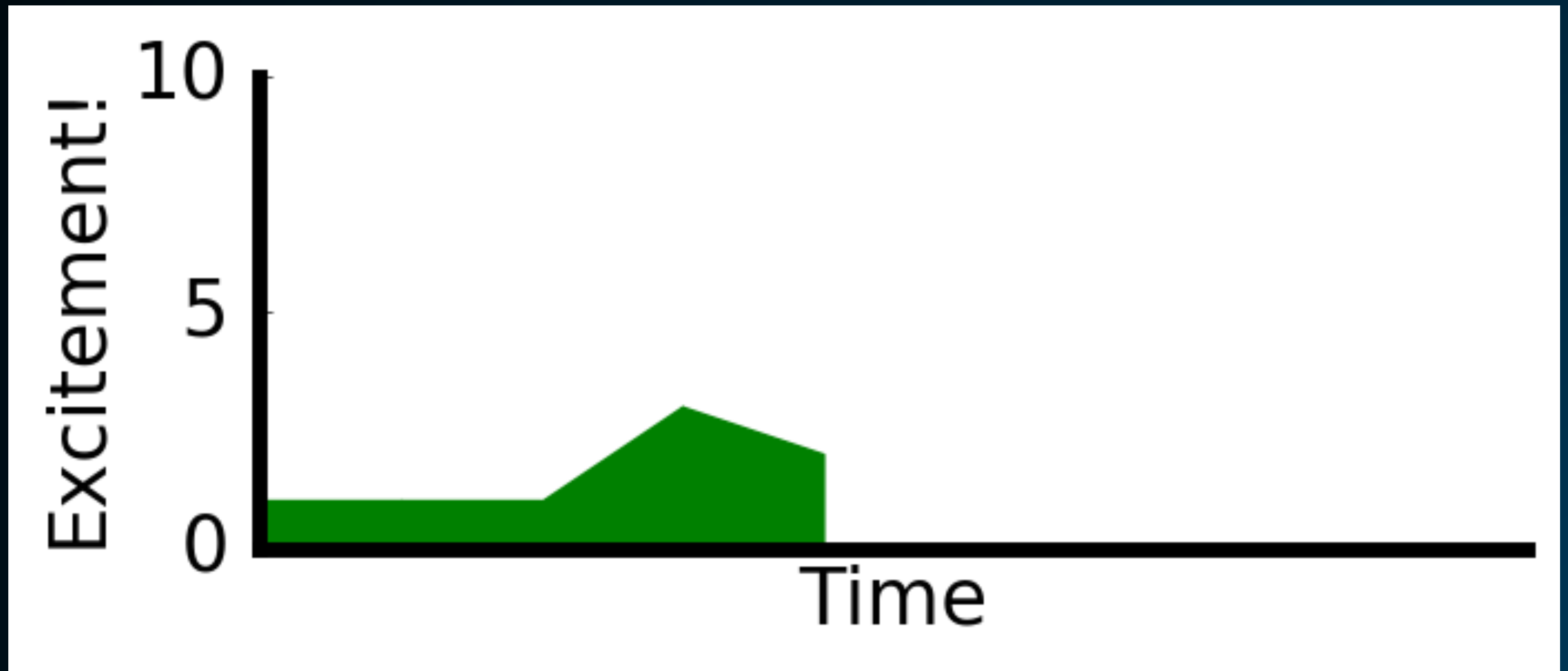


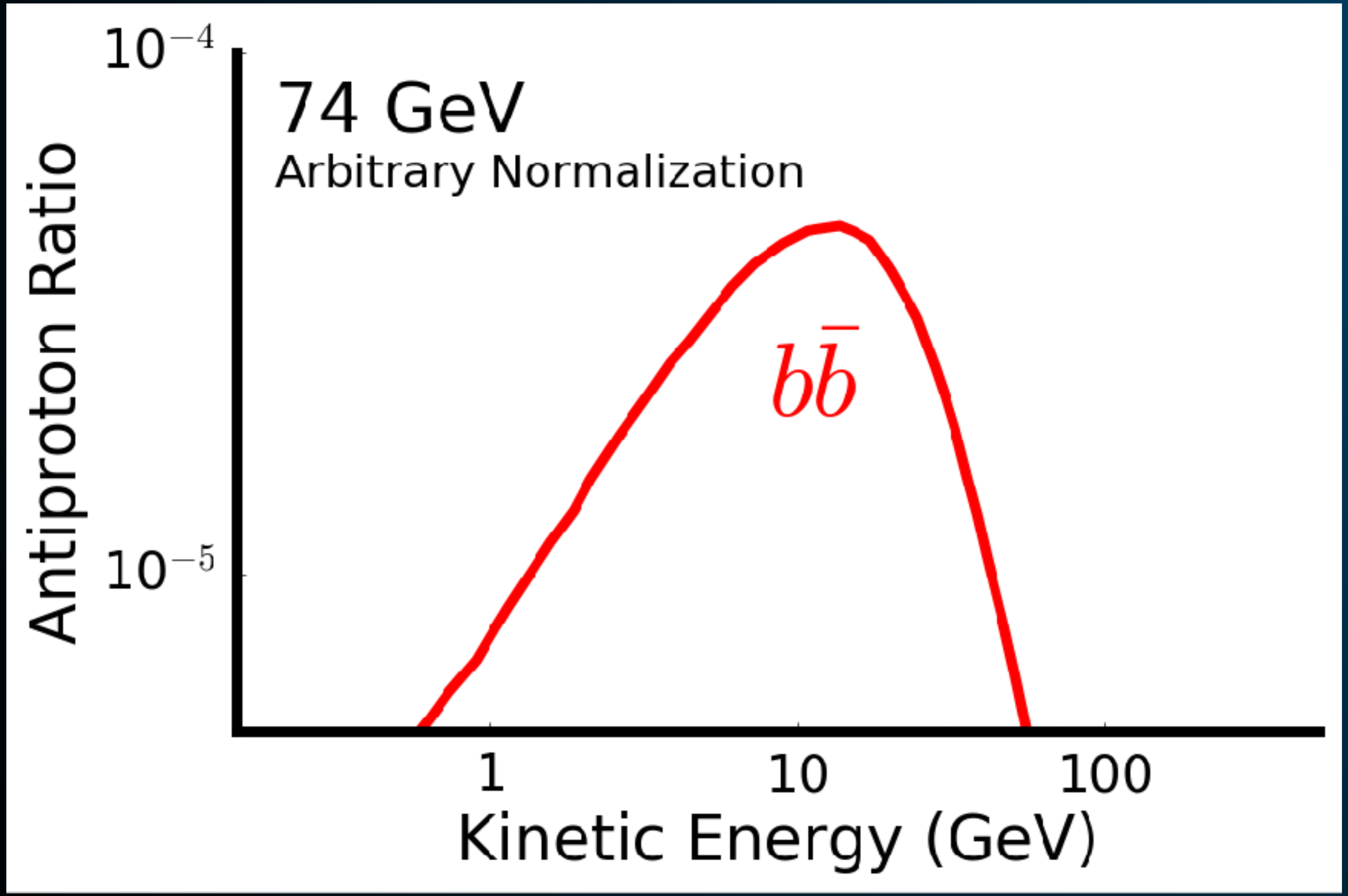


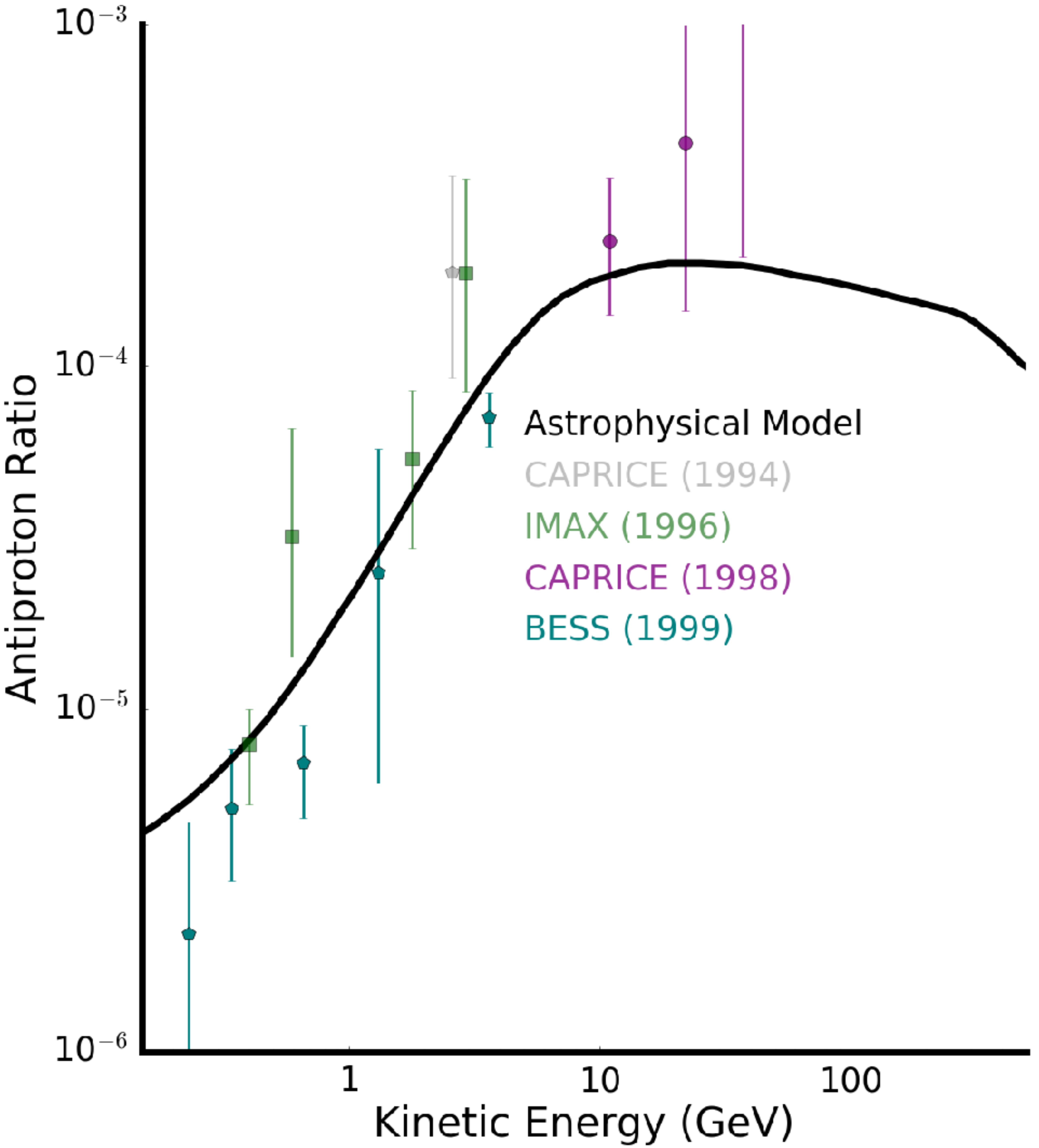
(Not an exhaustive list of observations)



The Antiproton Excess

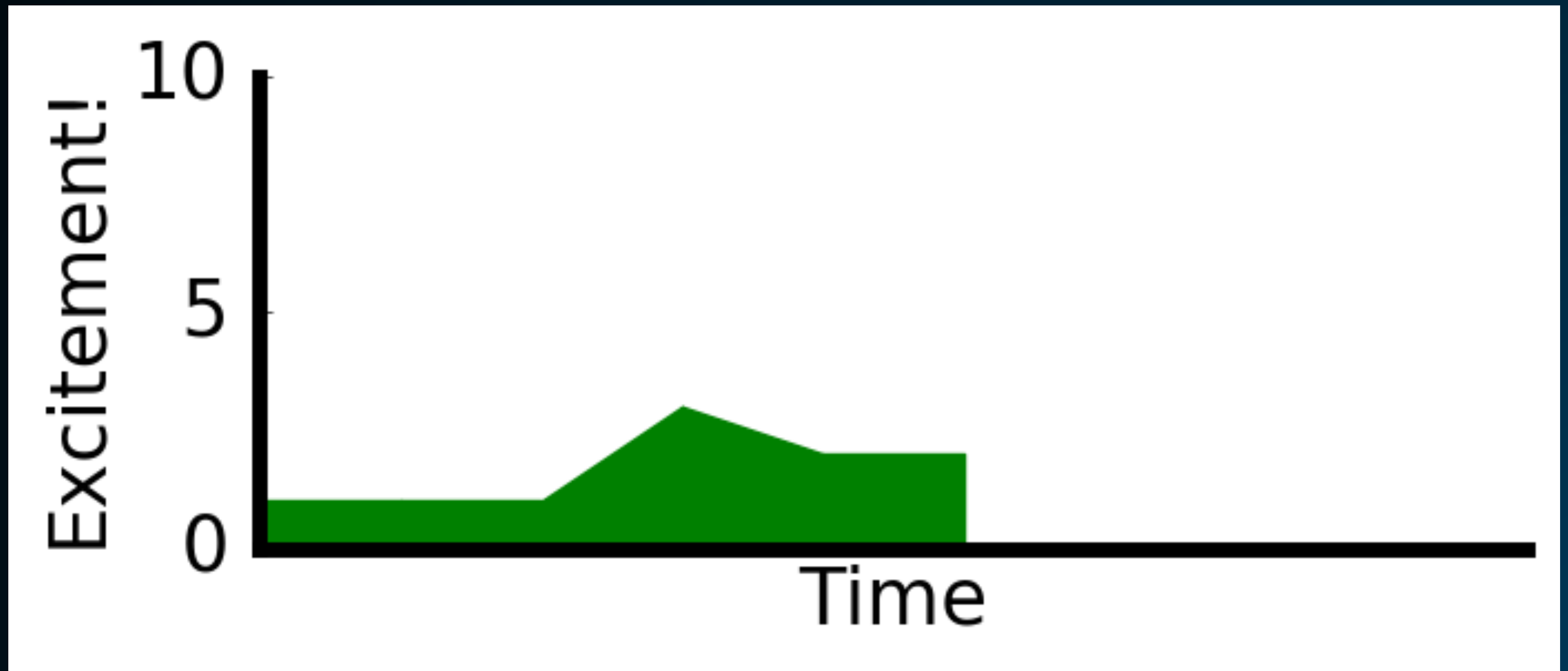


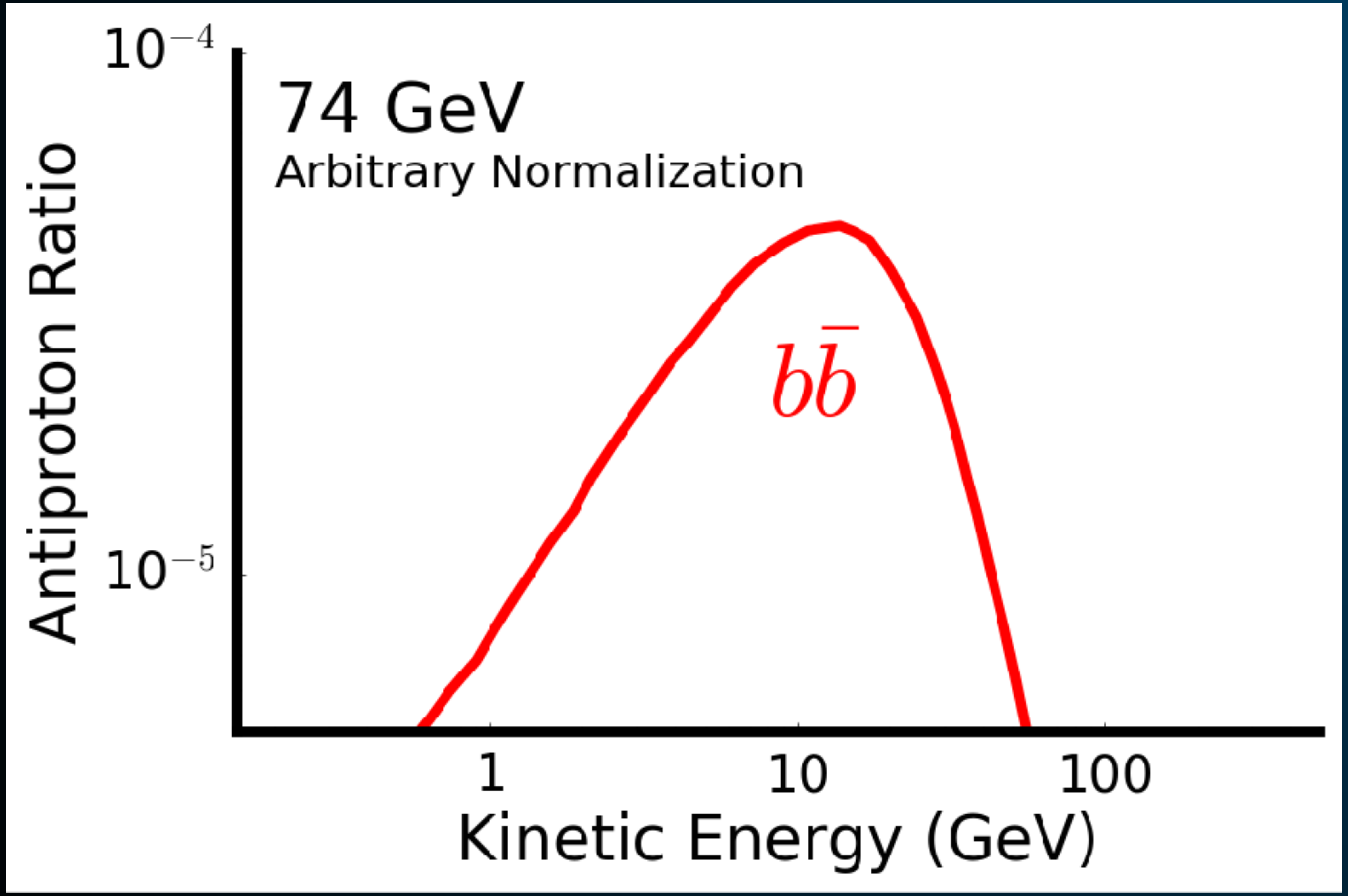




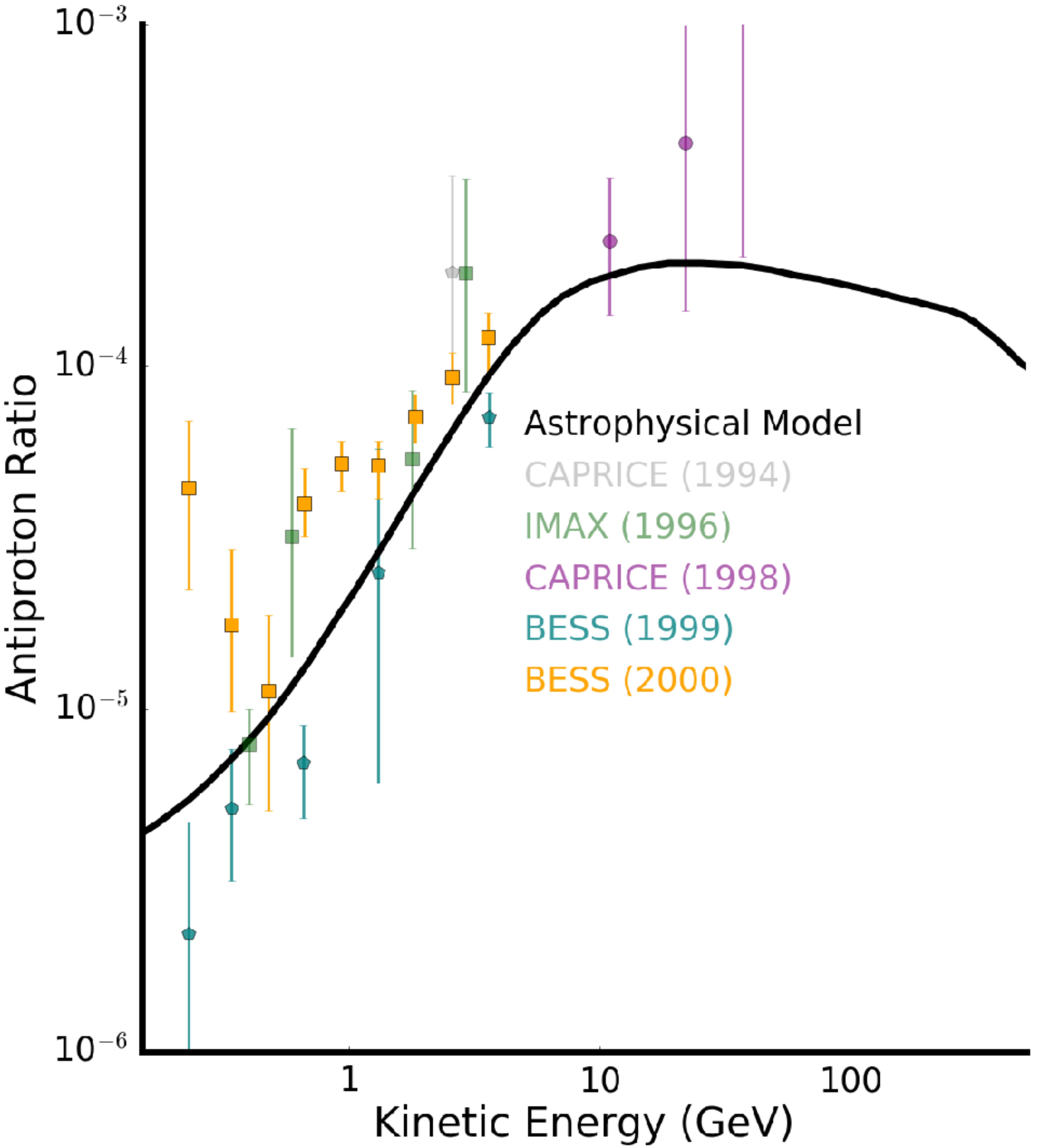
(Not an exhaustive list of observations)

The Antiproton Excess

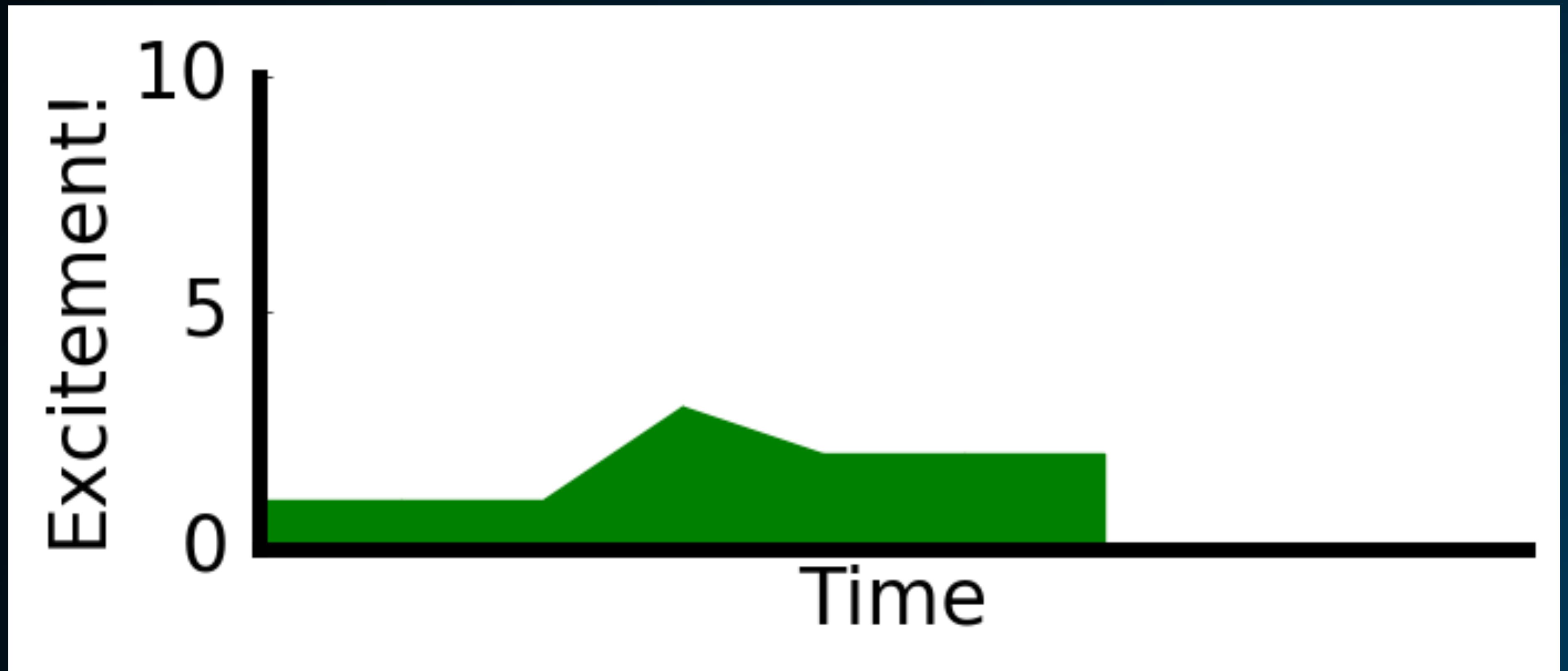


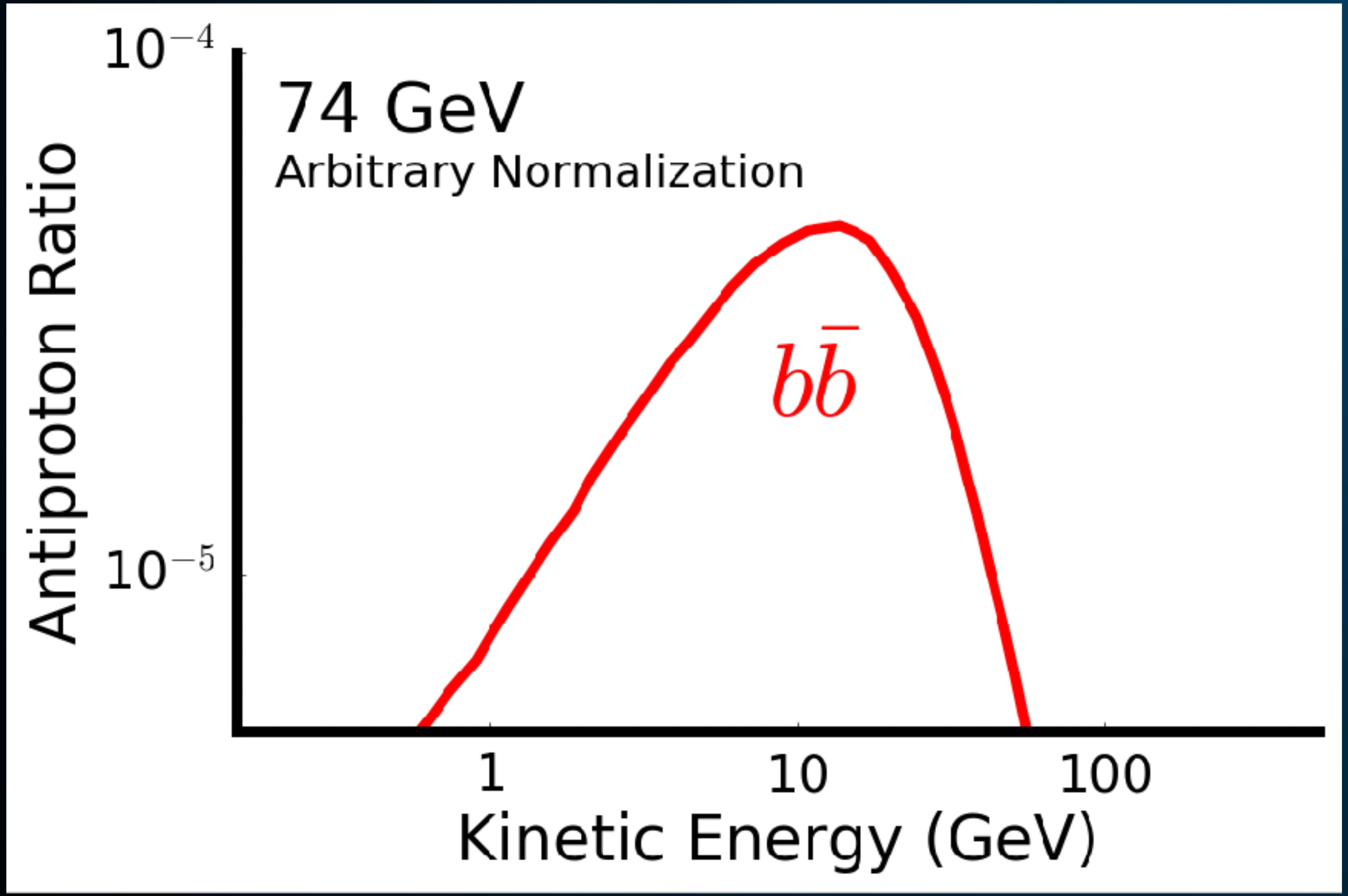


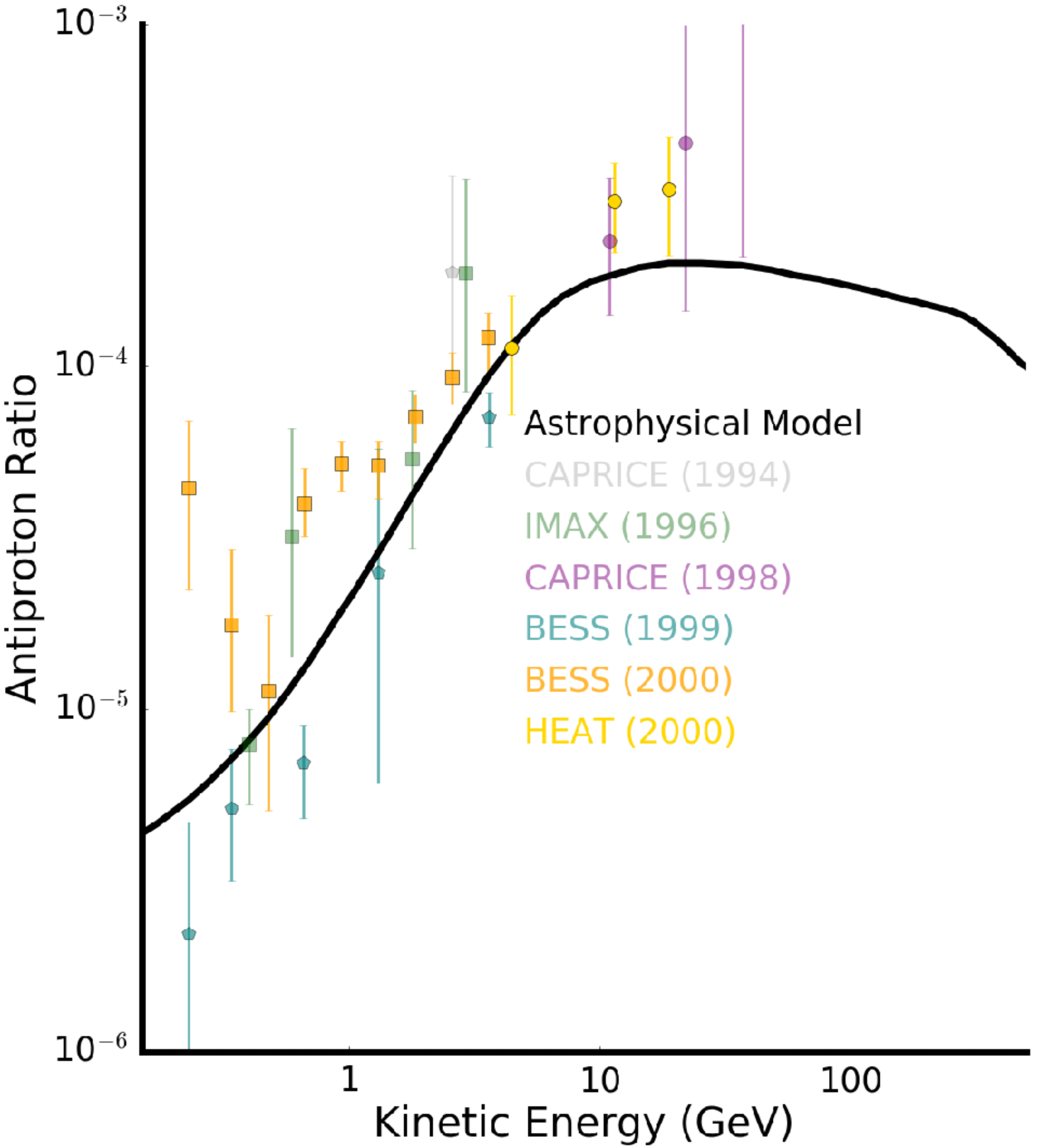
(Not an exhaustive list of observations)



The Antiproton Excess

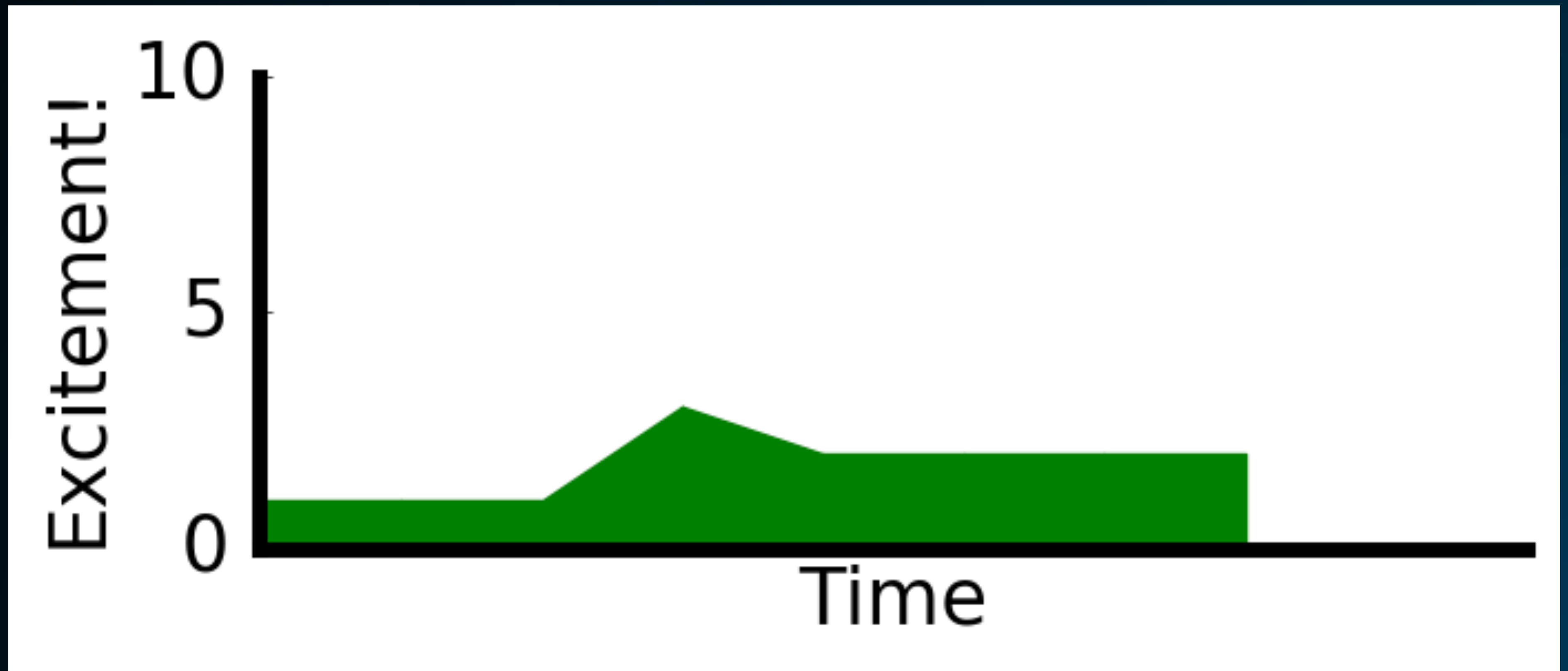


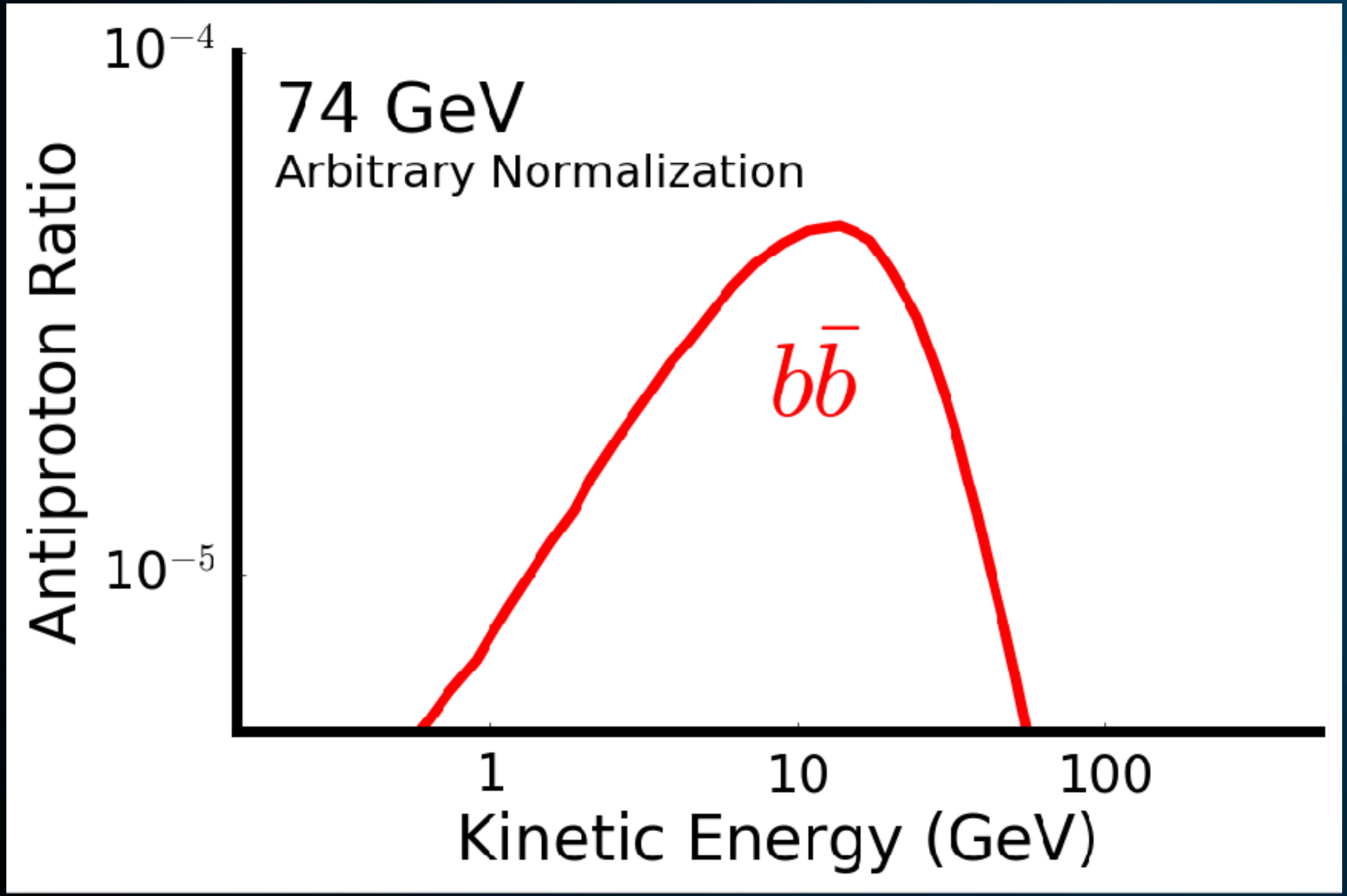




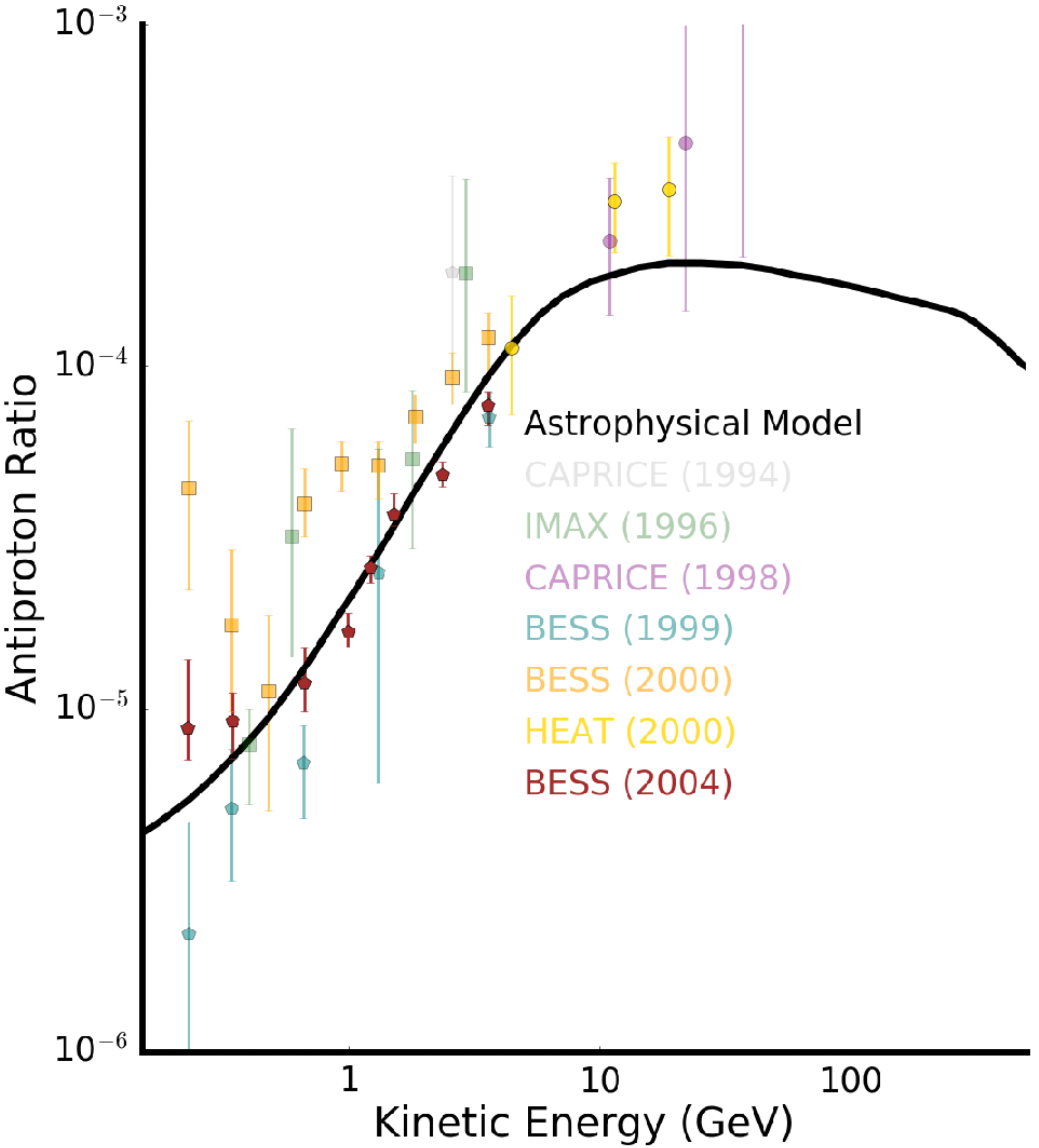
(Not an exhaustive list of observations)

The Antiproton Excess

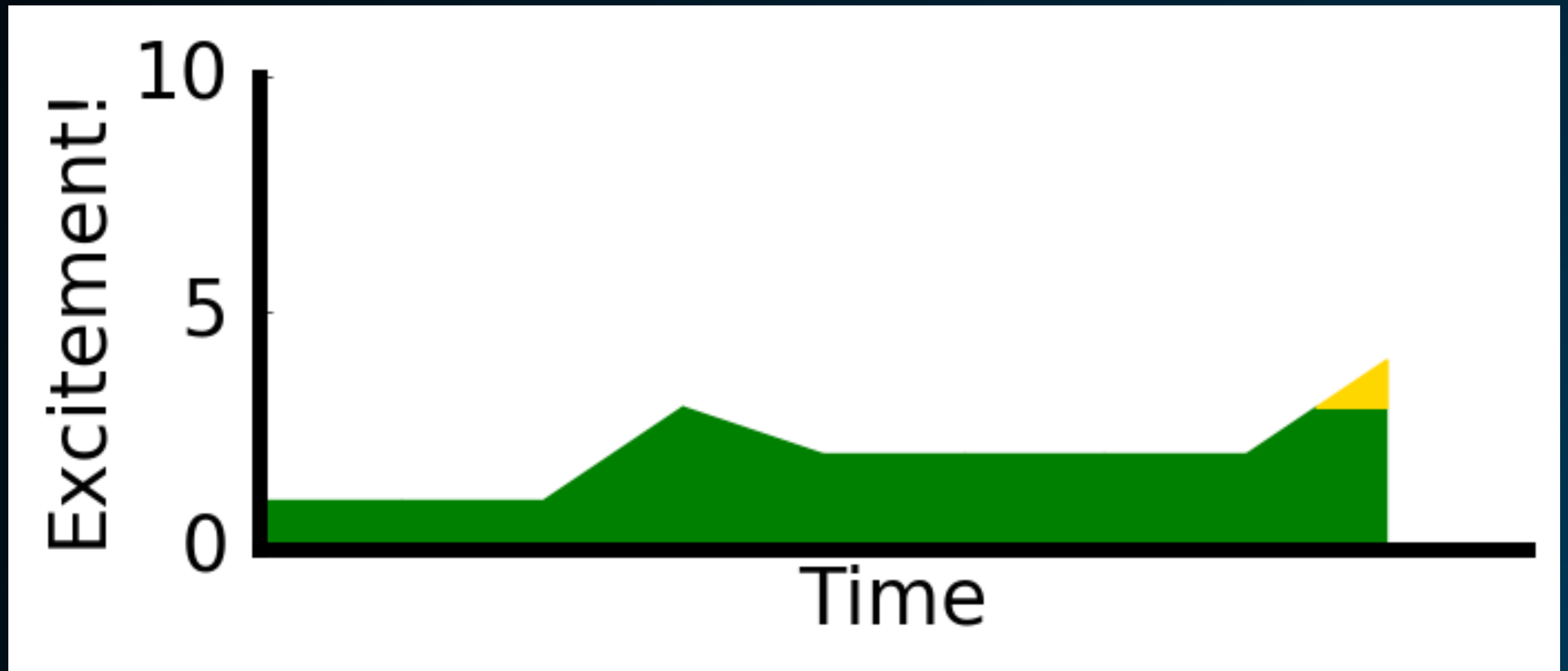


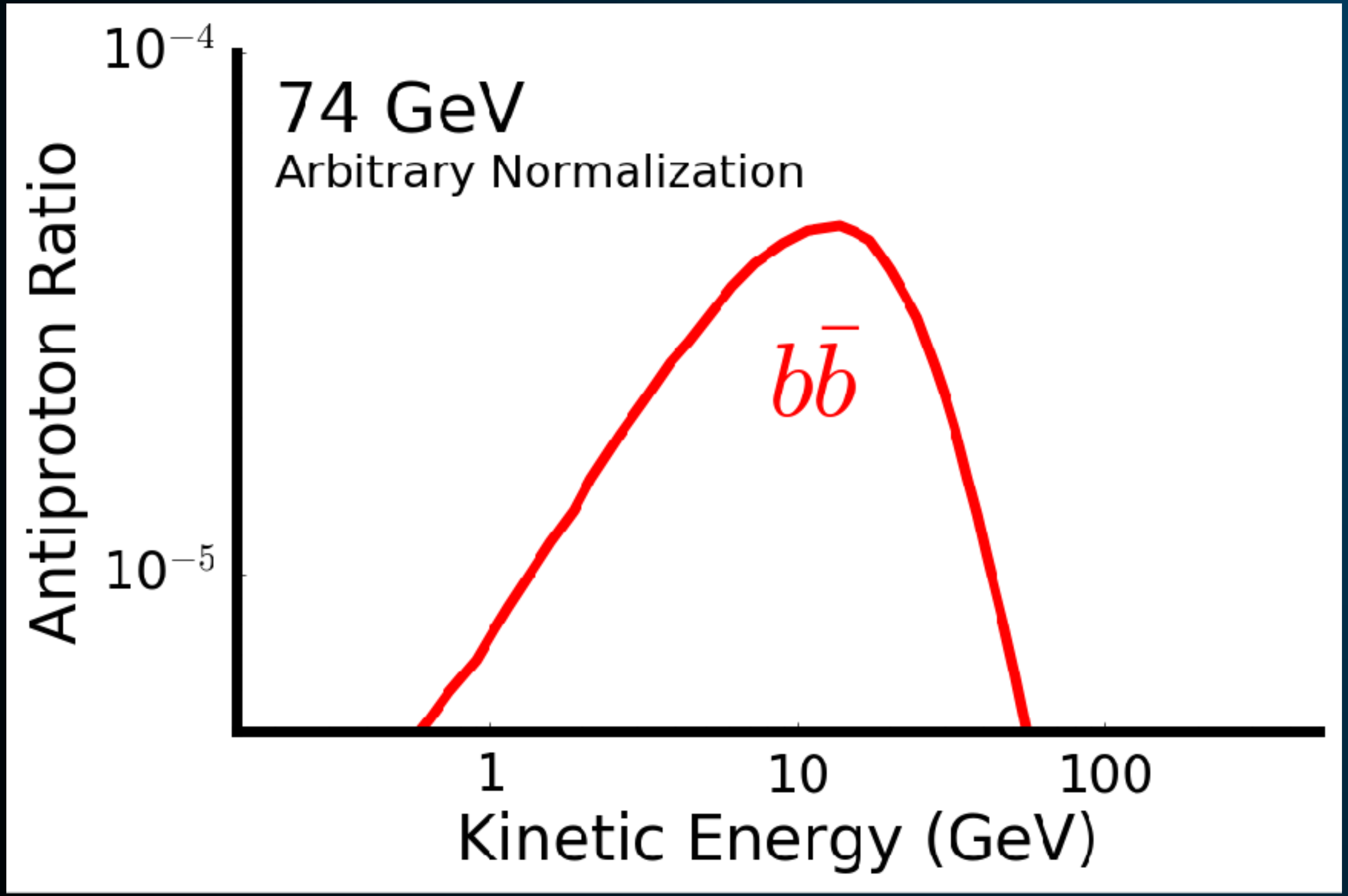


(Not an exhaustive list of observations)

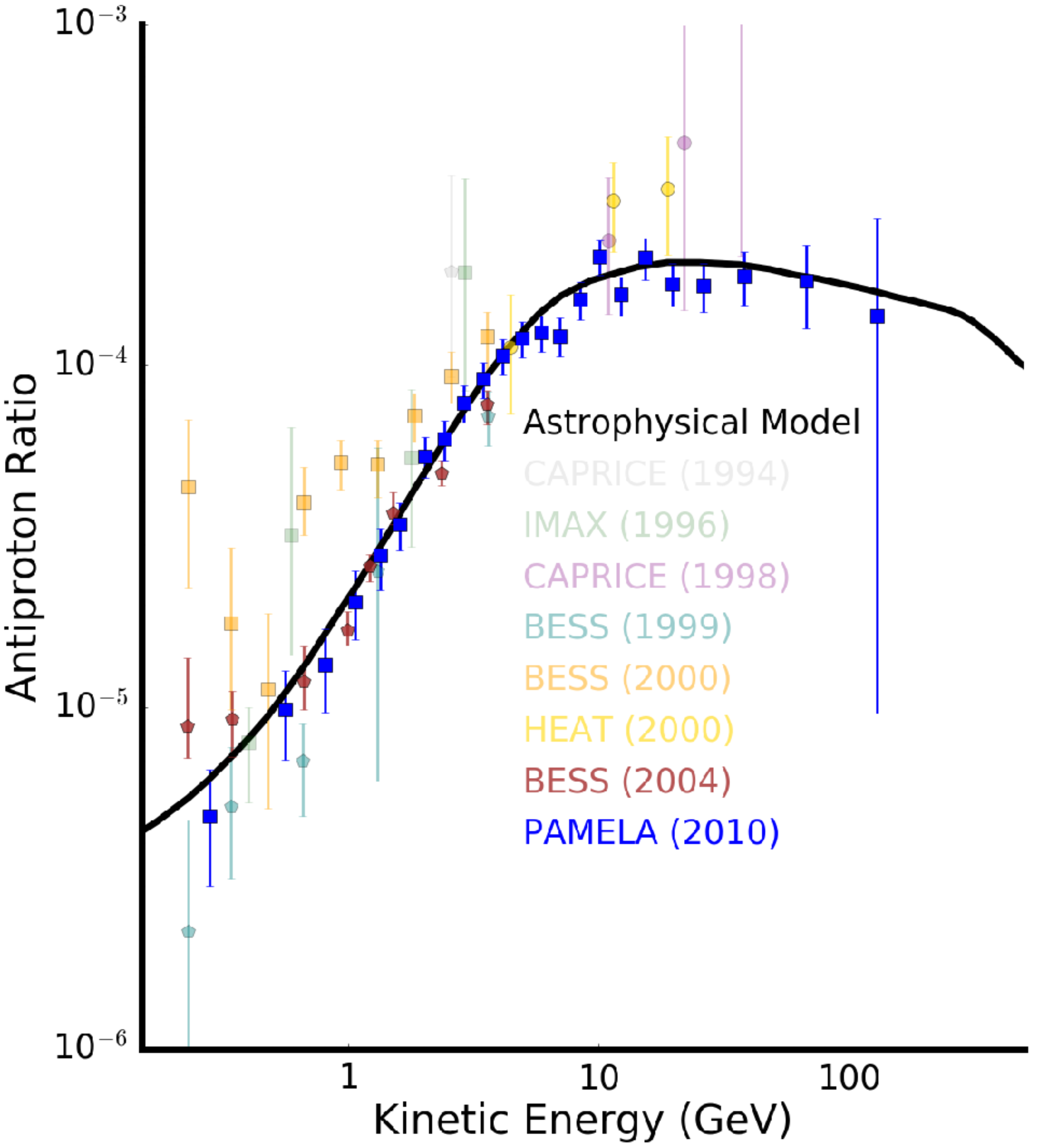


The Antiproton Excess

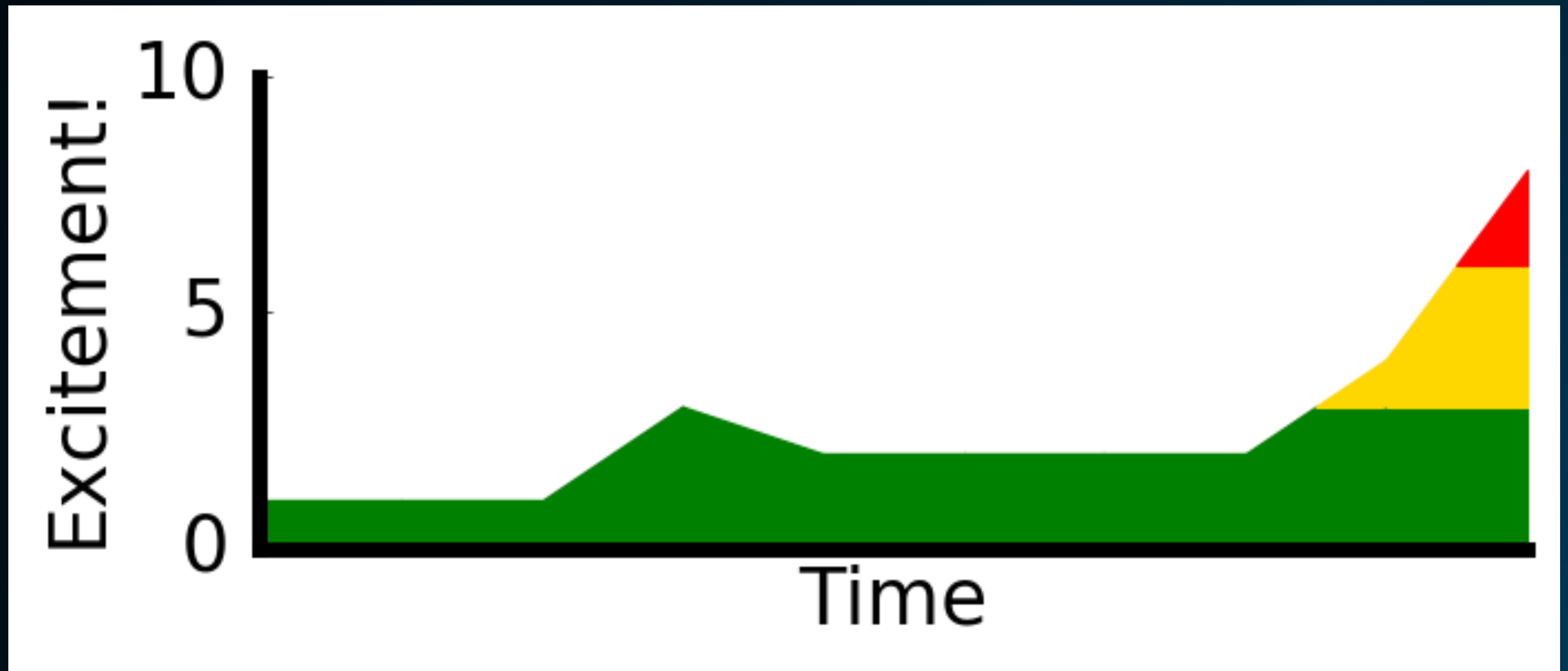


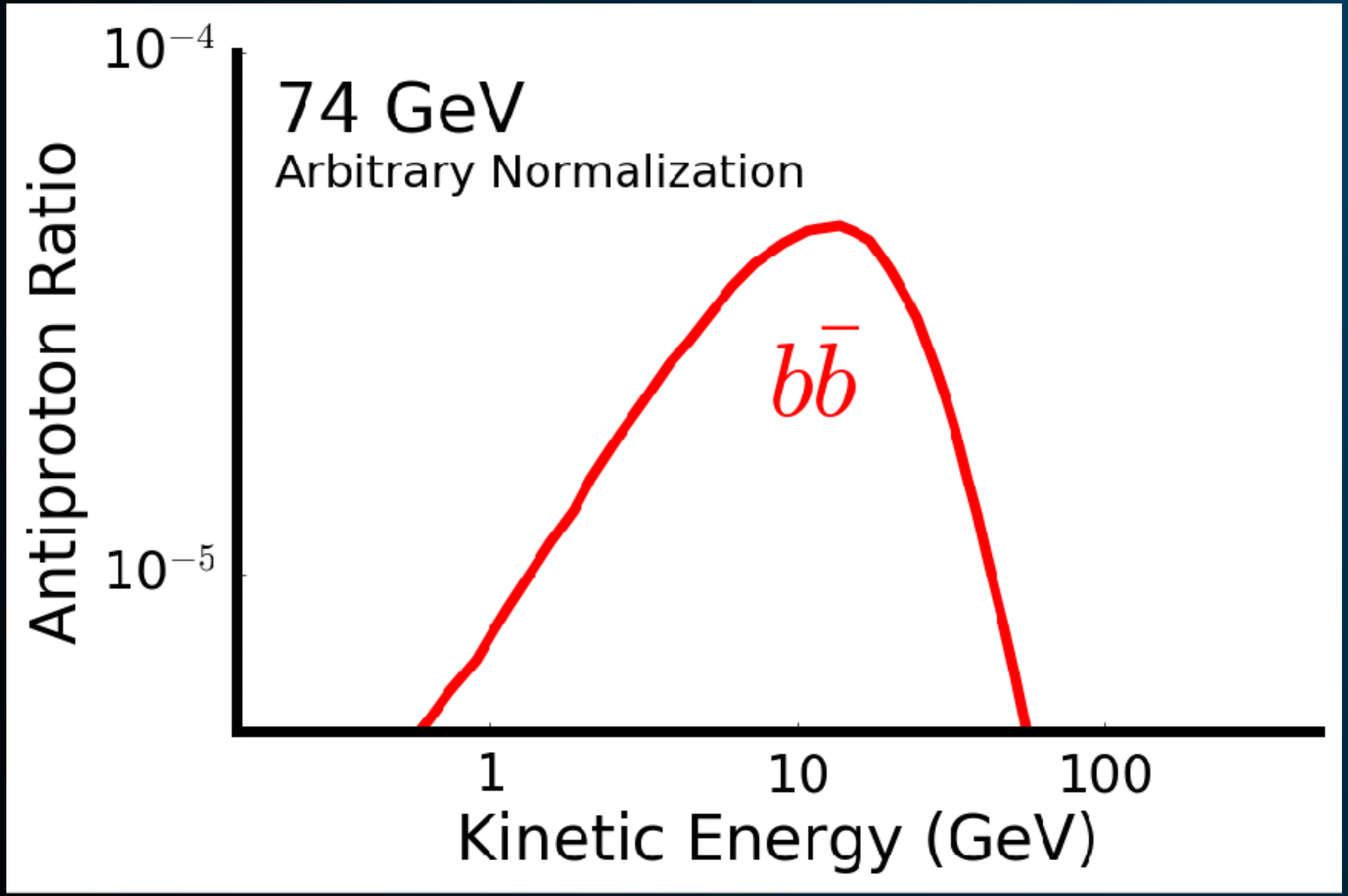


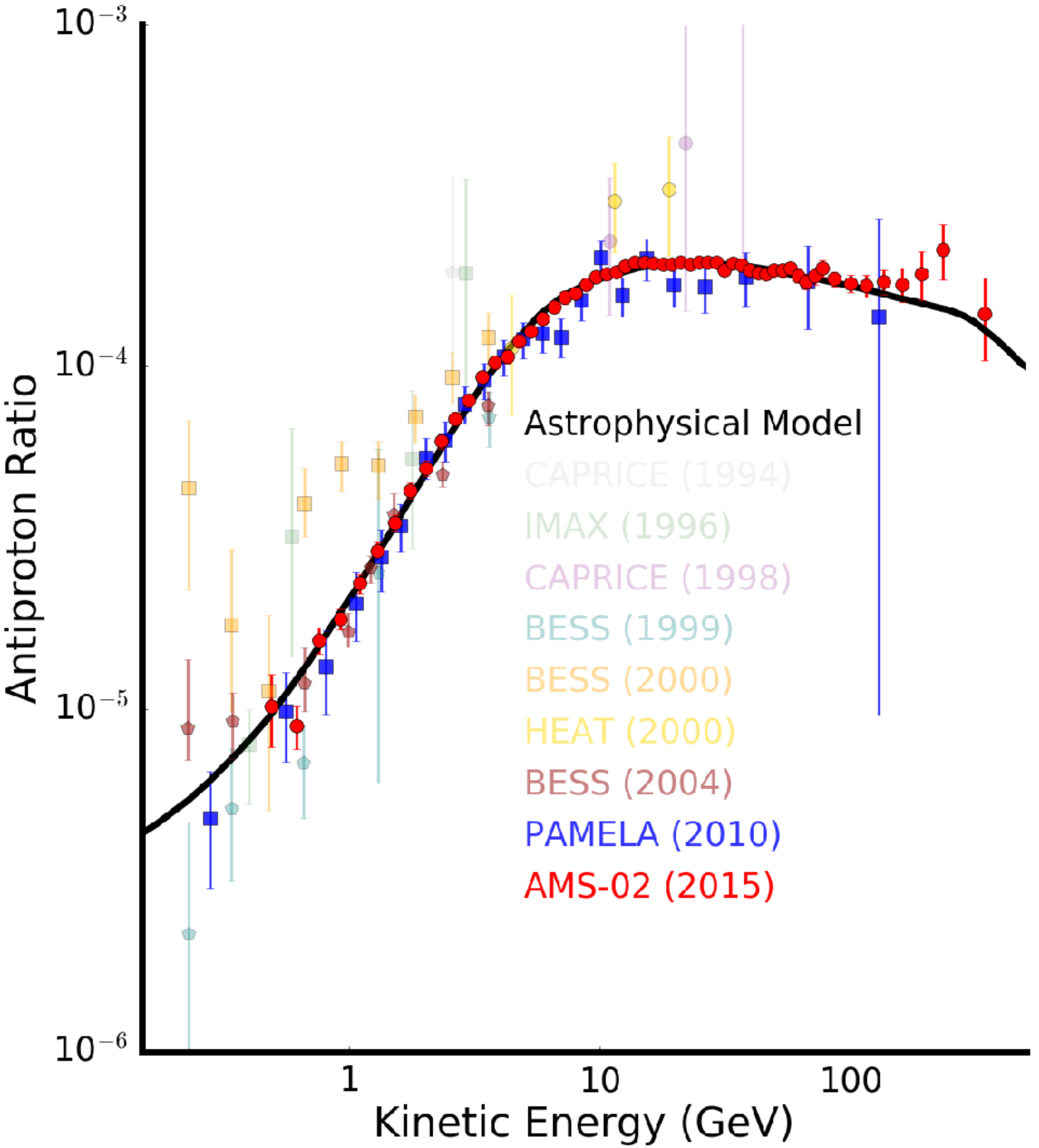
(Not an exhaustive list of observations)



The Antiproton Excess

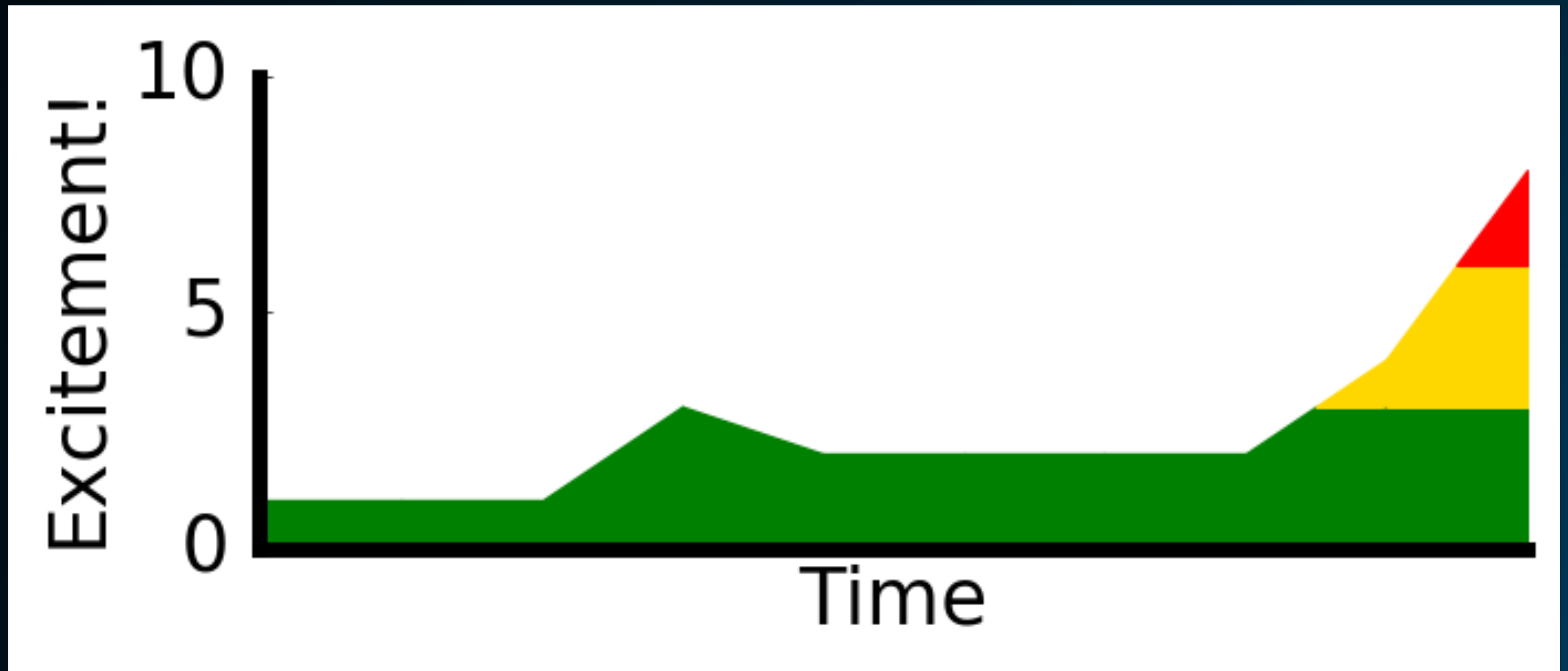


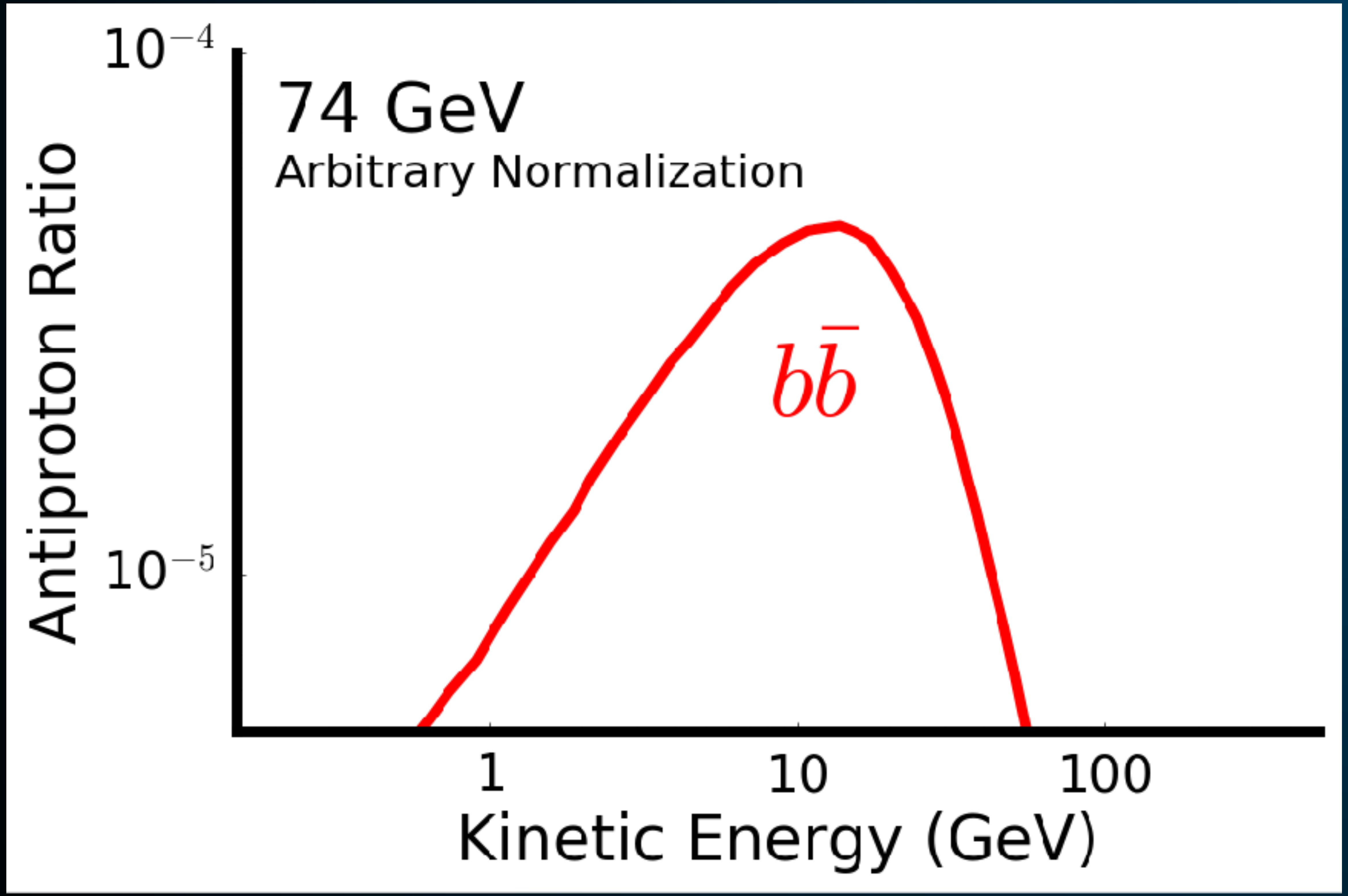


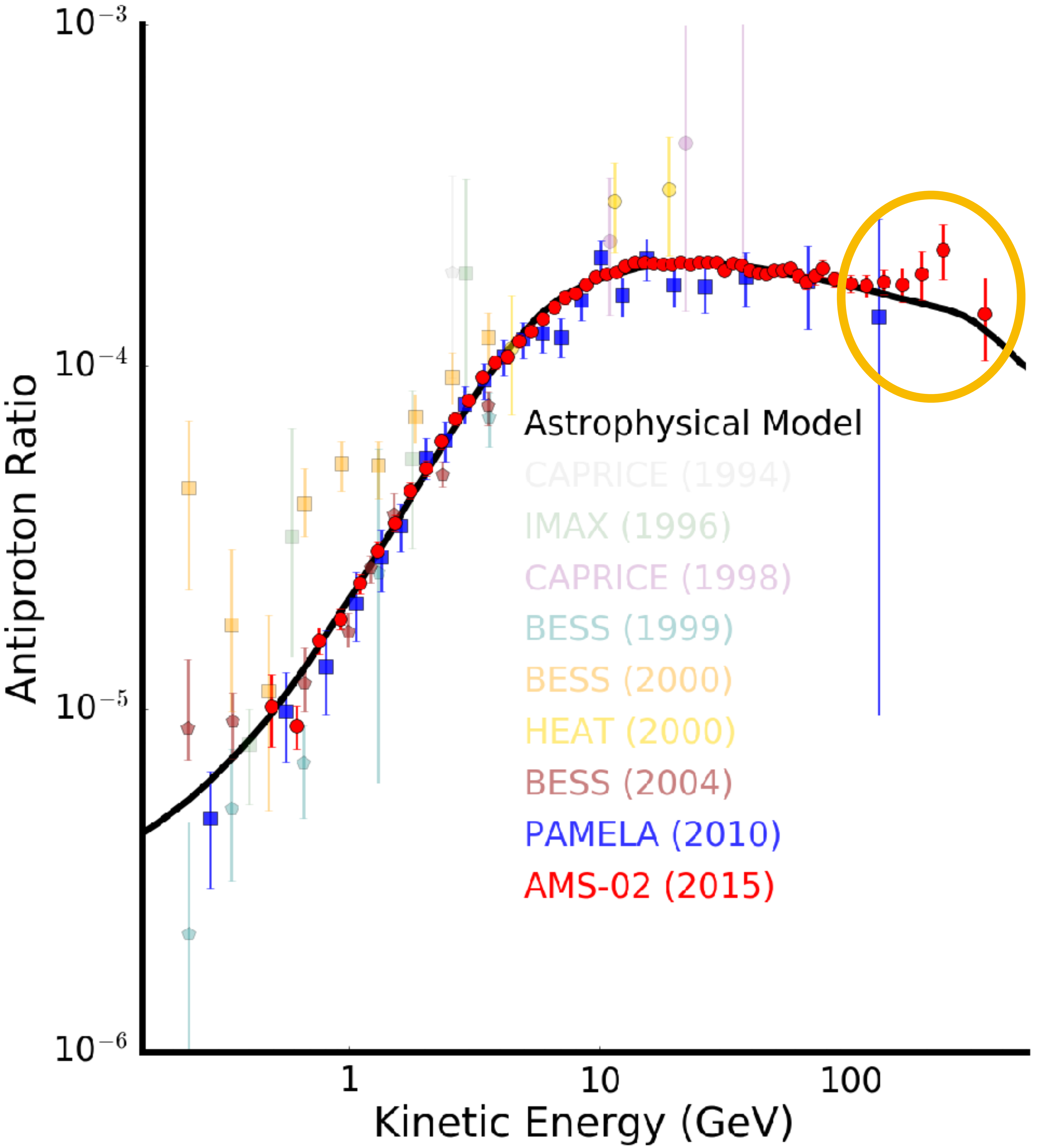


(Not an exhaustive list of observations)

The Antiproton Excess

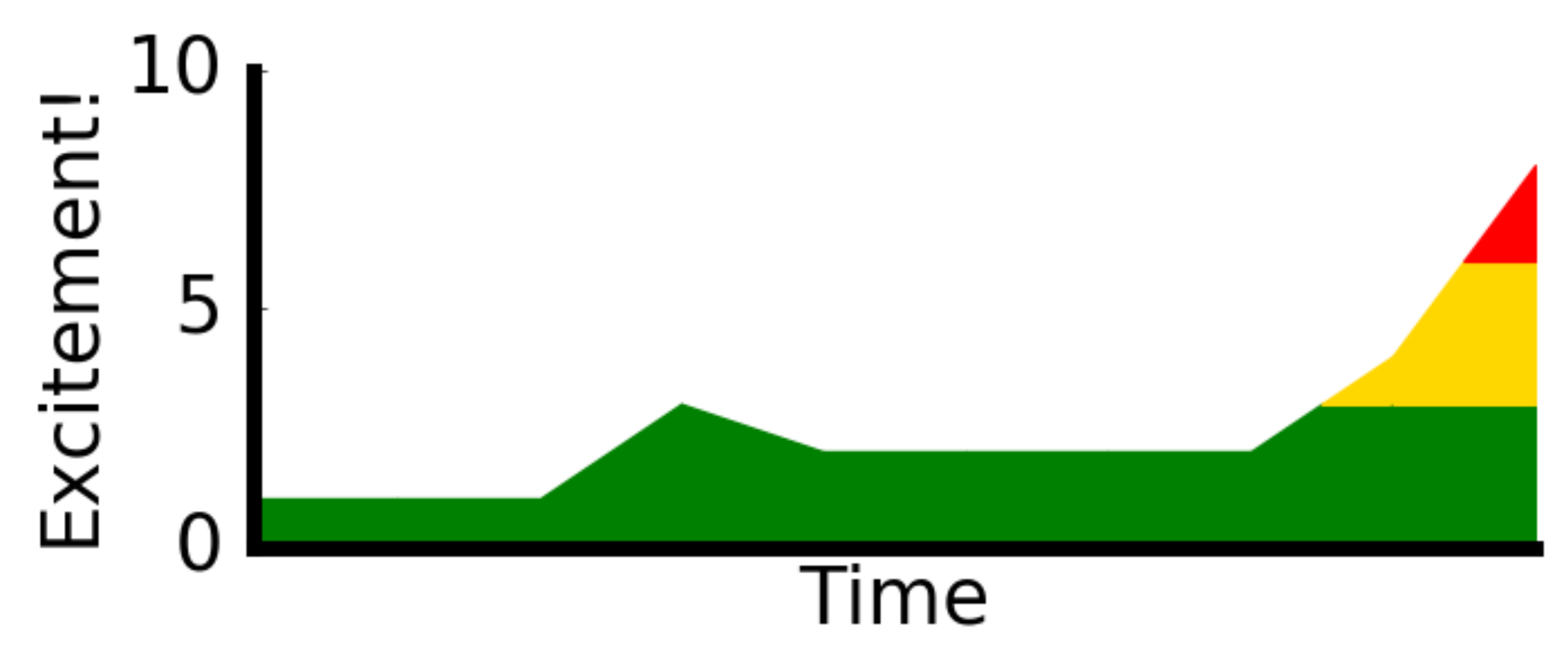


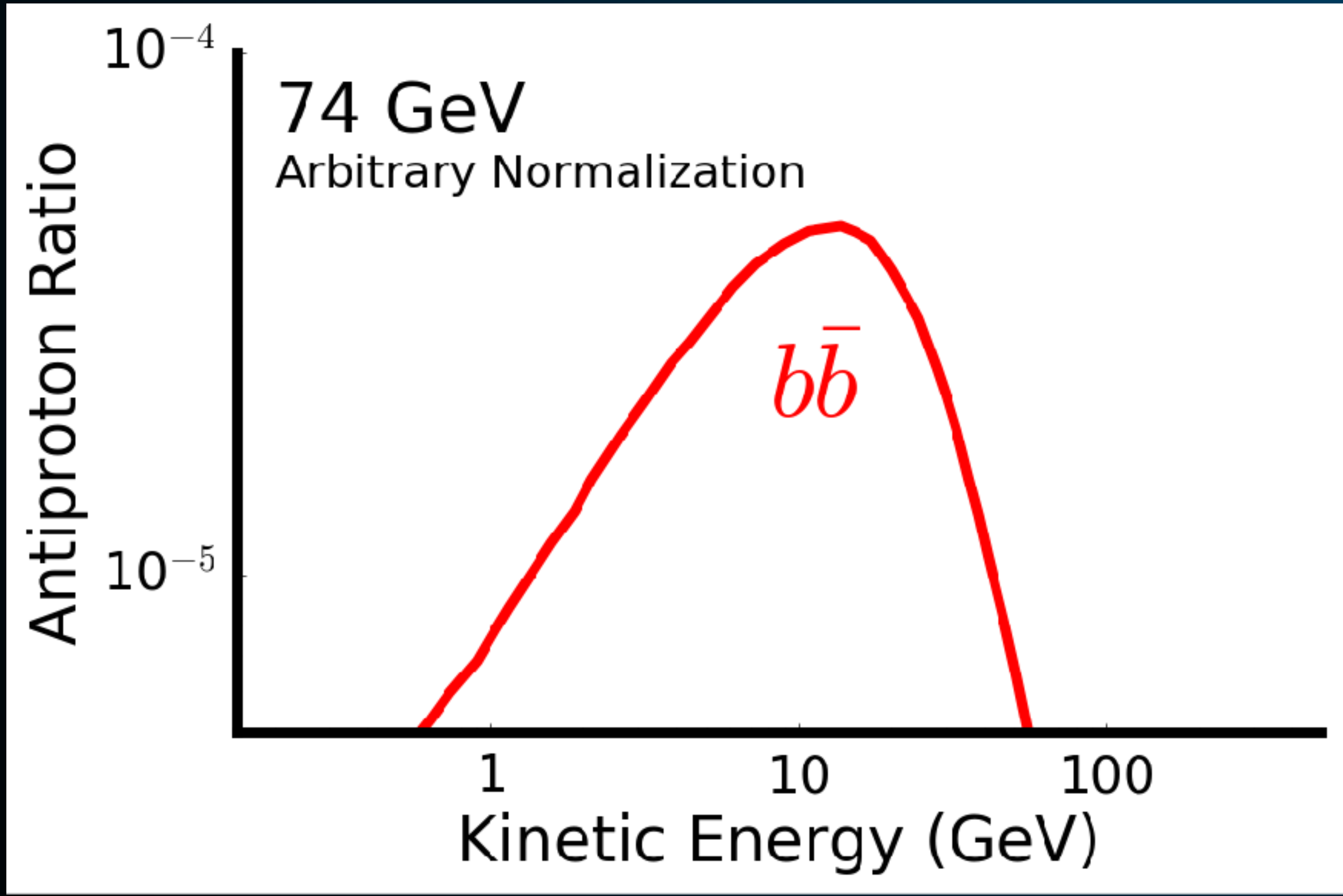


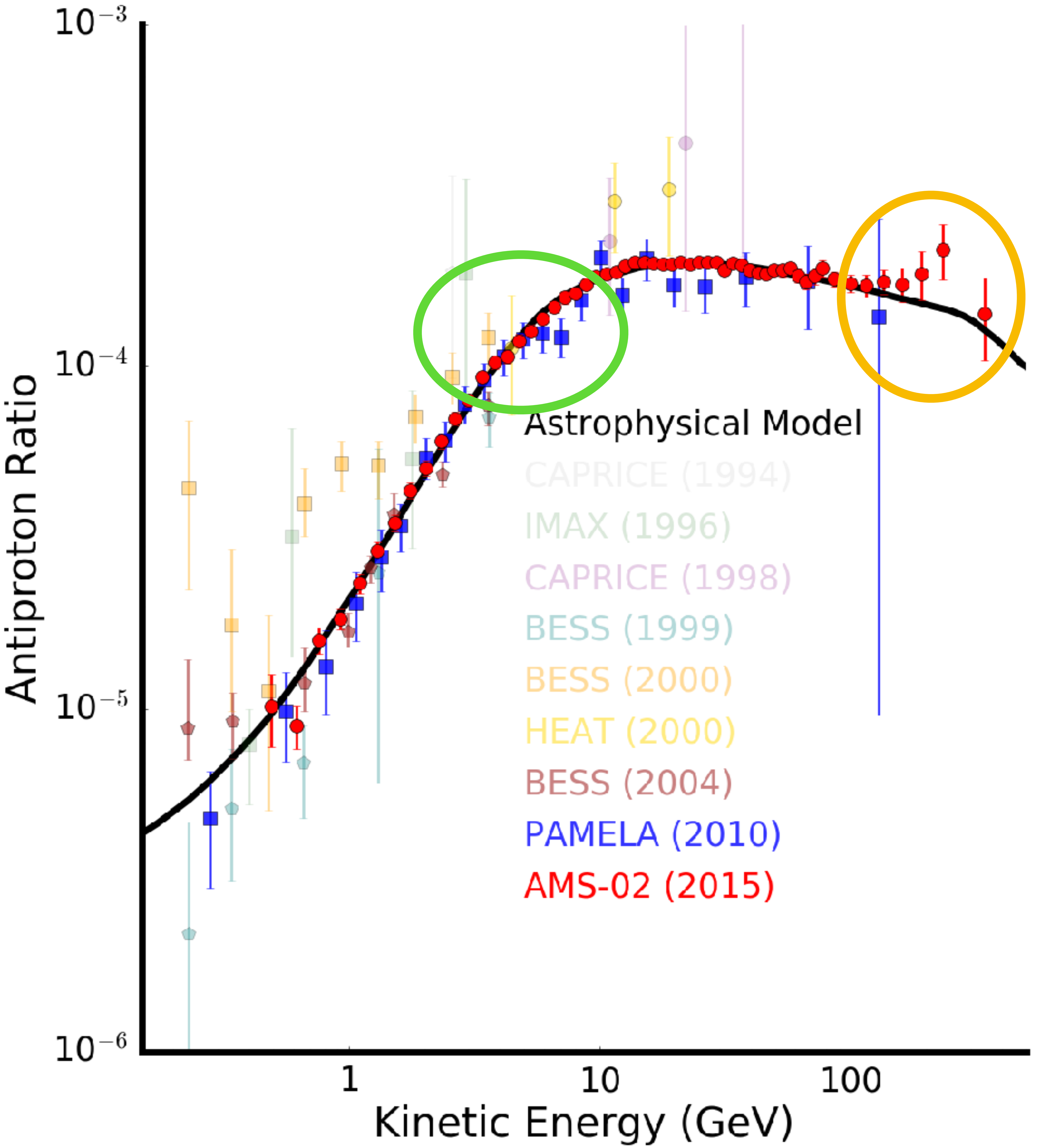


(Not an exhaustive list of observations)

The Antiproton Excess





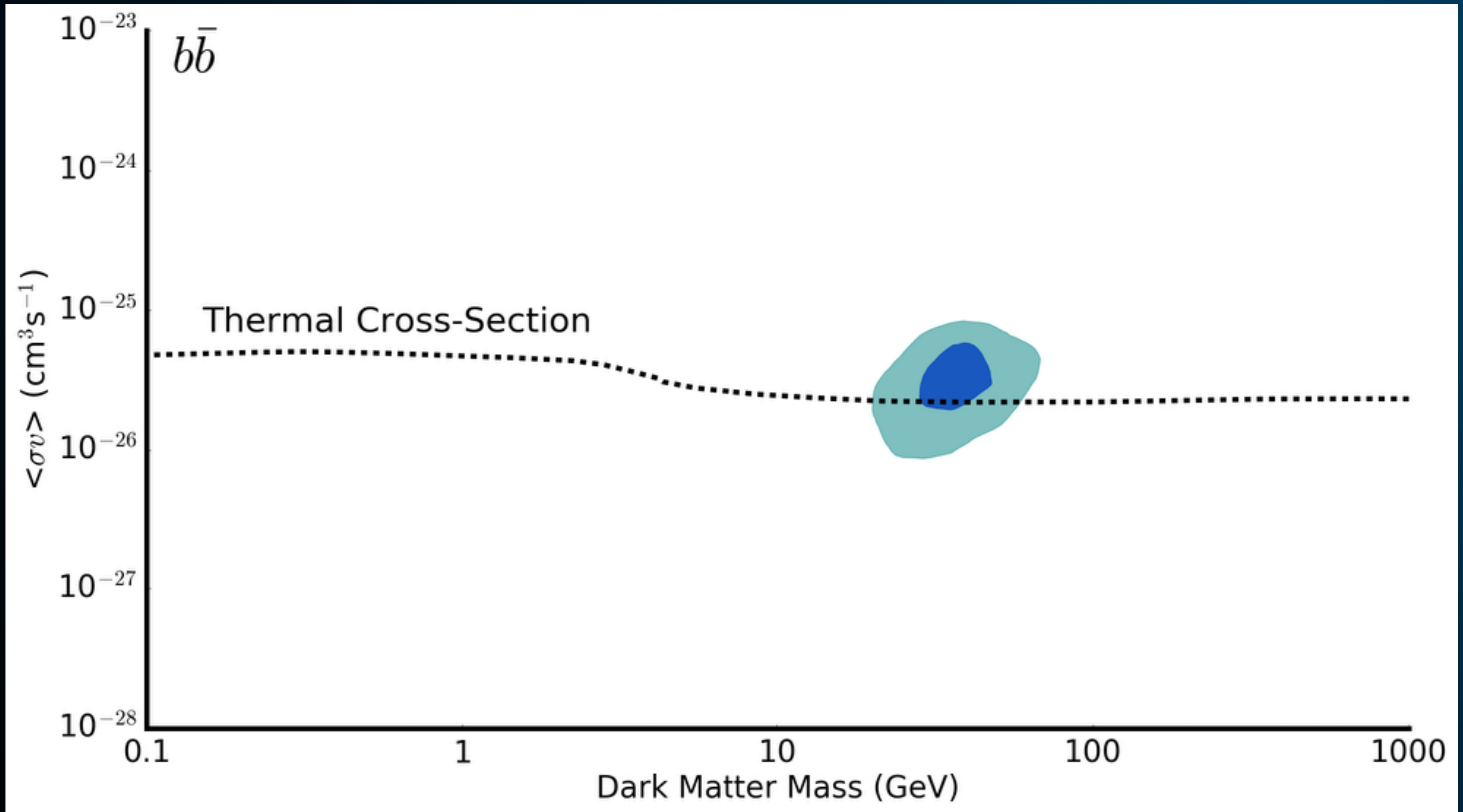


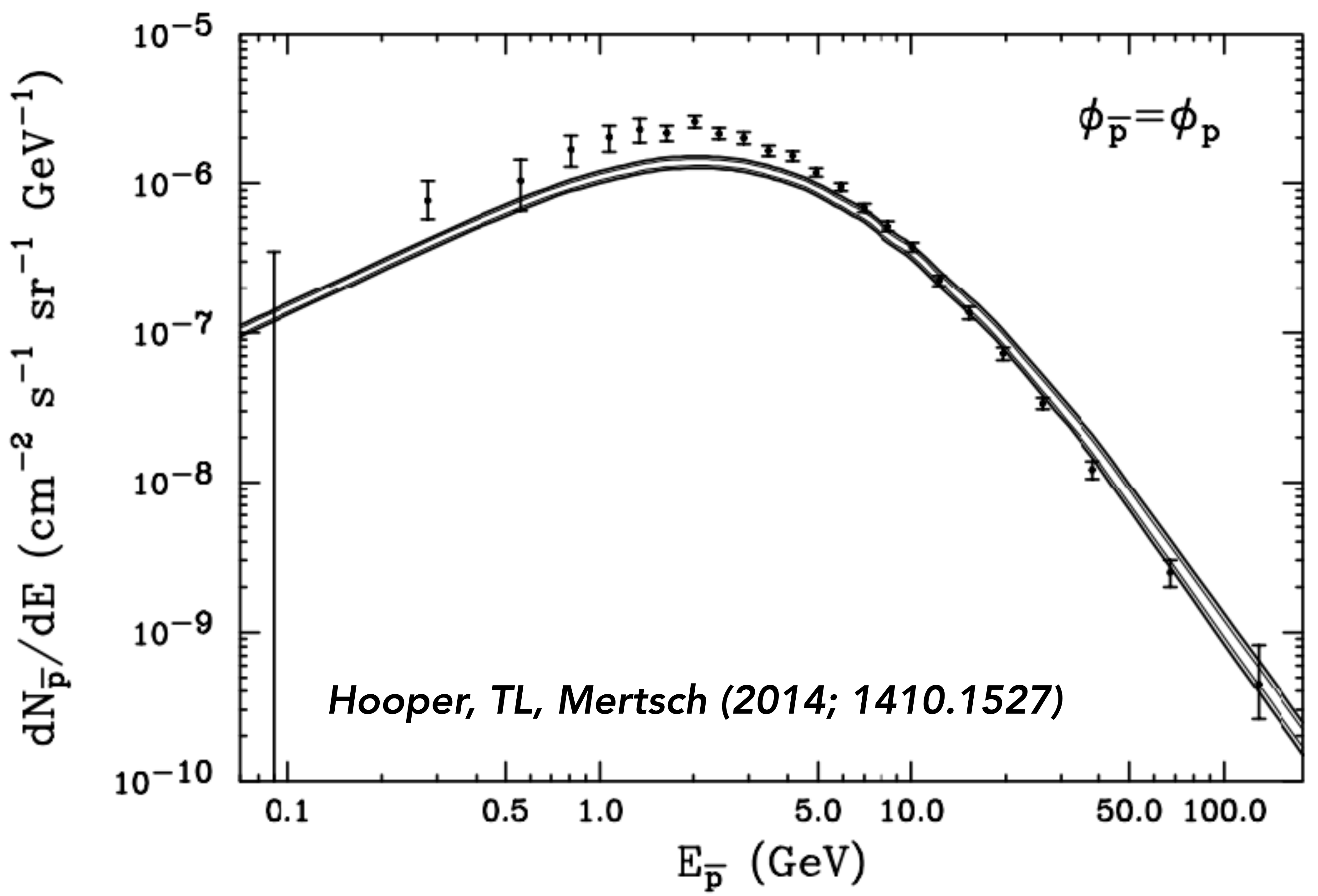
(Not an exhaustive list of observations)

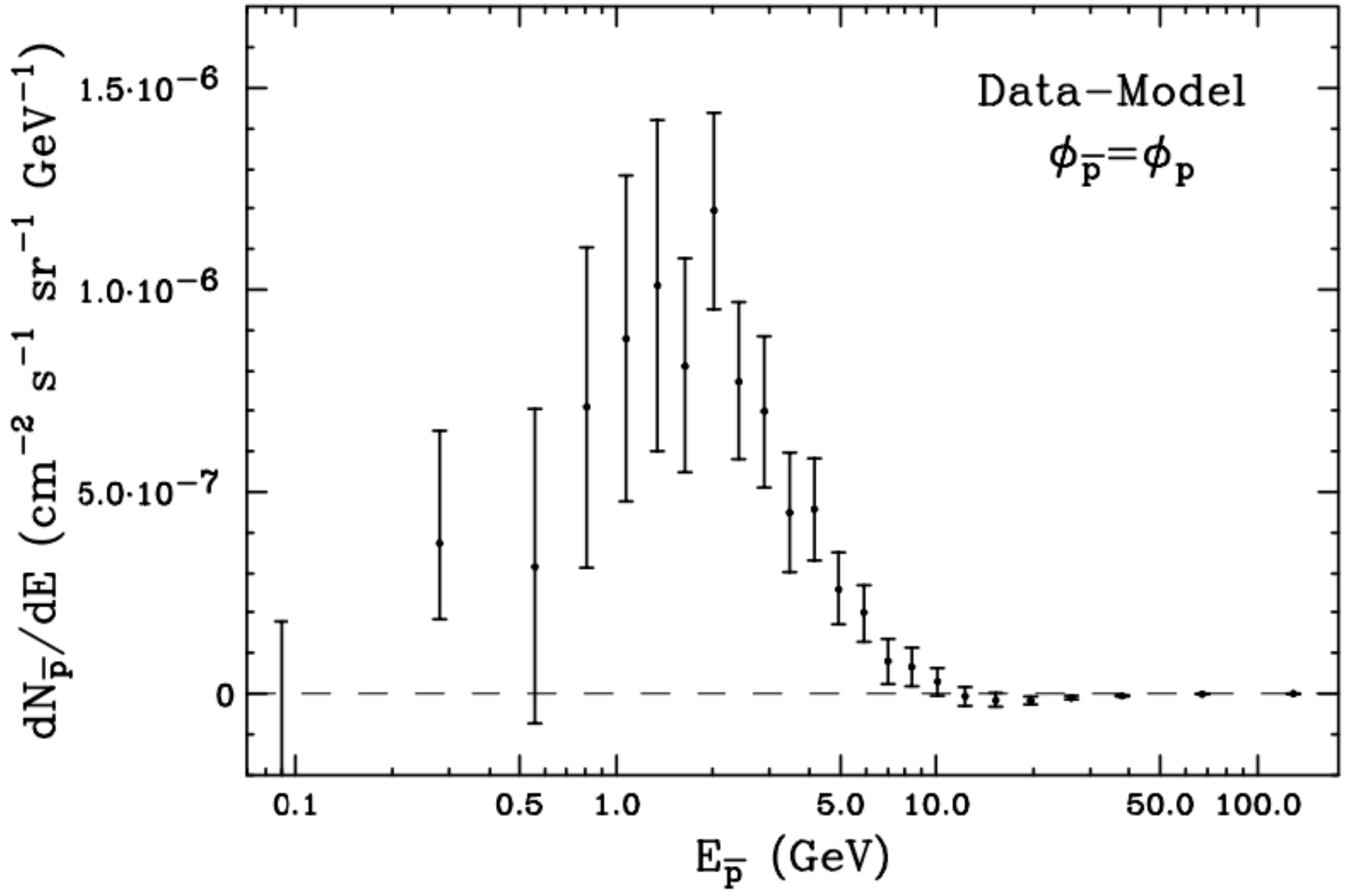
The Antiproton Excess

Hint of Excess in ~5 GeV antiprotons!

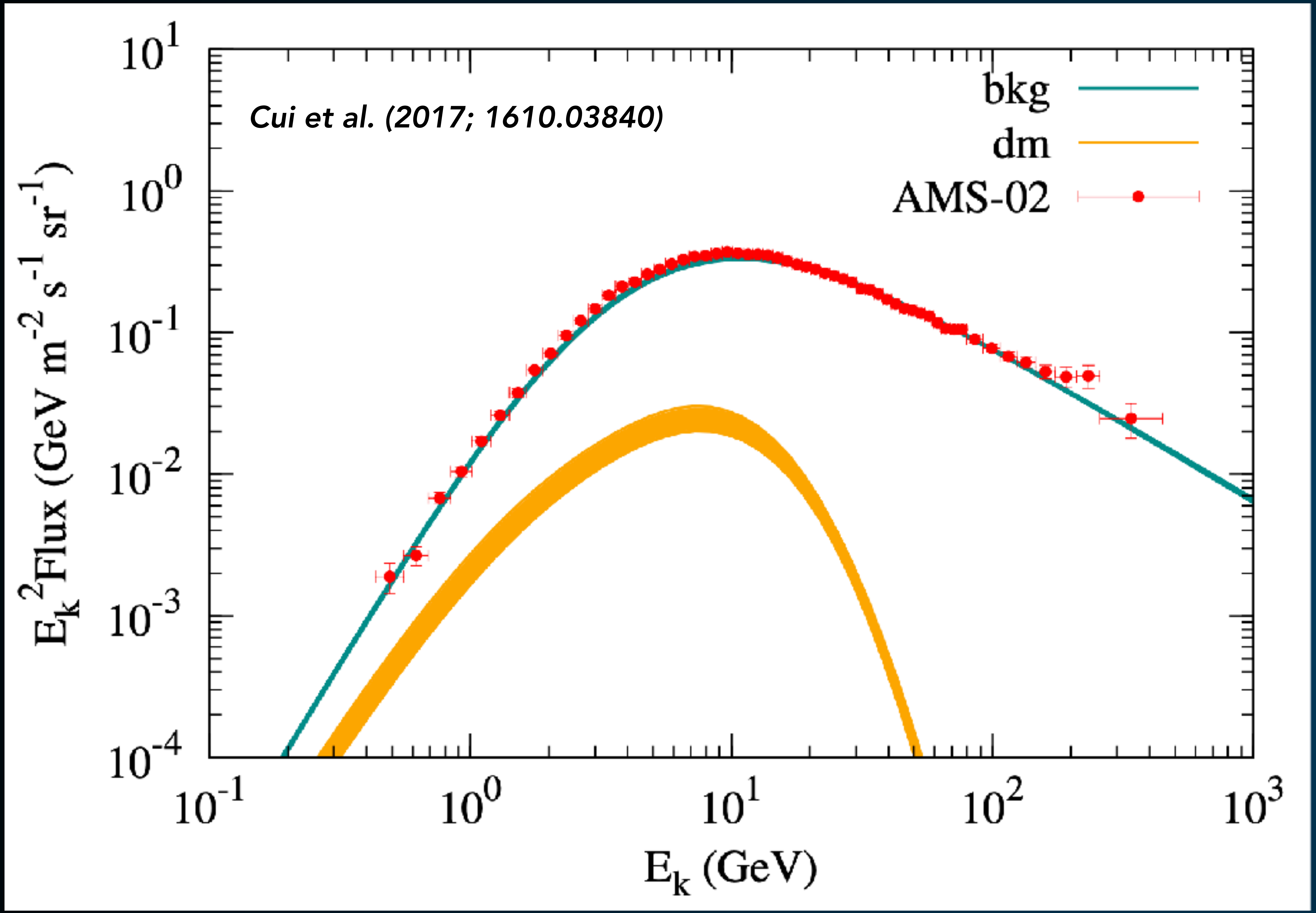
Astrophysical Uncertainties can significantly affect the signal.

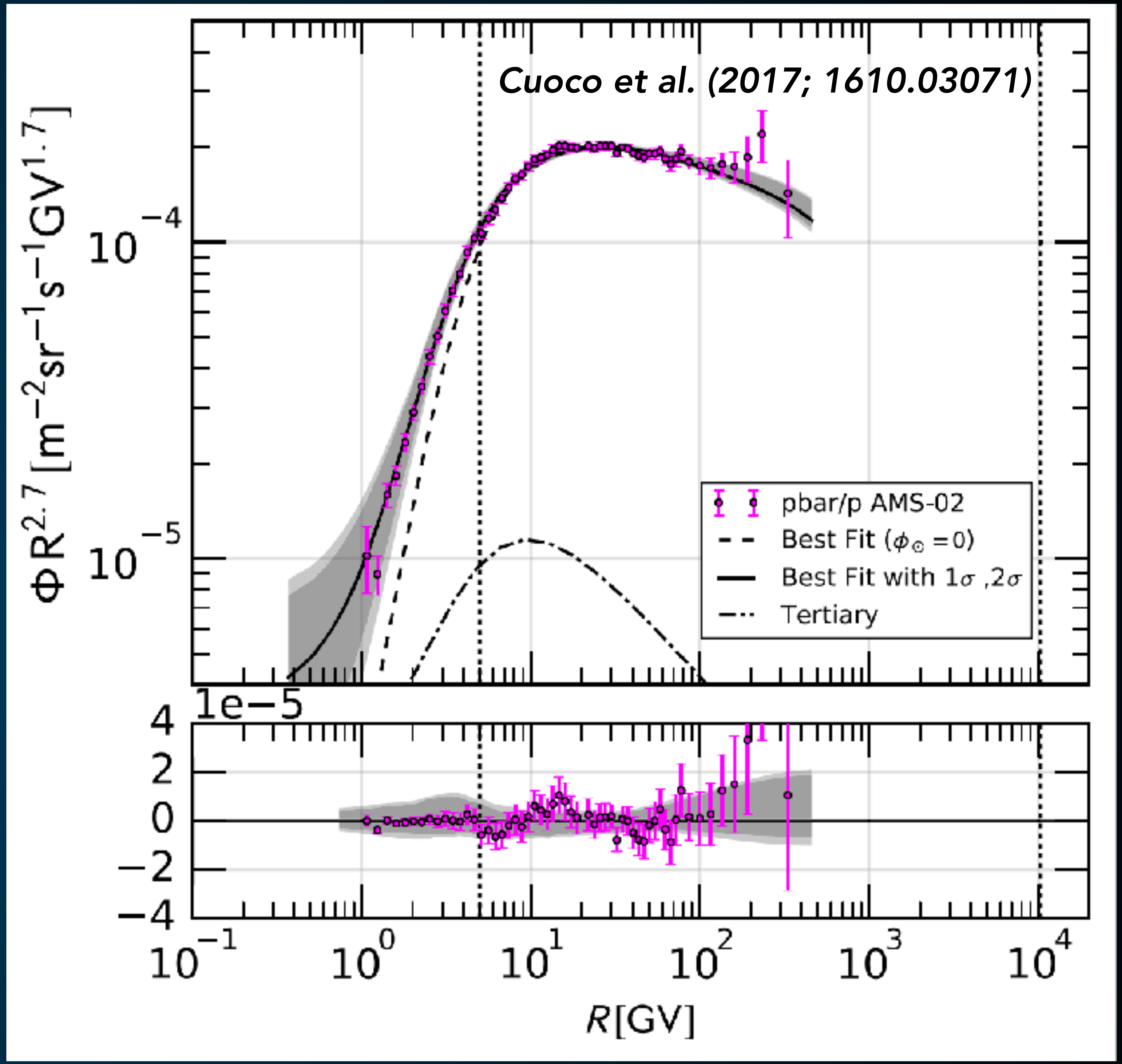






The Antiproton Excess





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

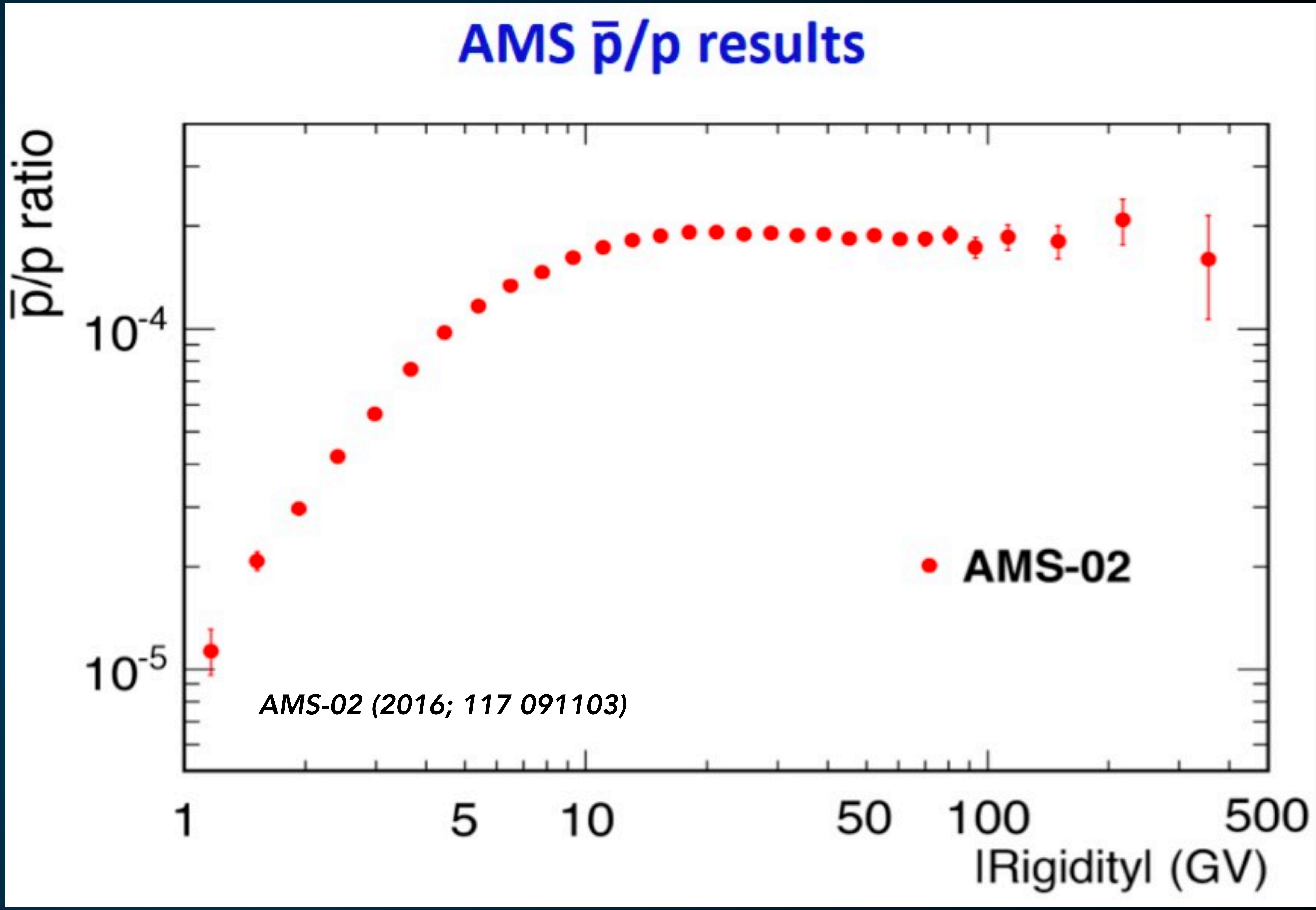
Significance approaching (or past) 5σ !

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

The Antiproton Excess

With great precision comes great responsibility:

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




Propagation
Production
Instrumental
Solar Modulation

The Antiproton Excess

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

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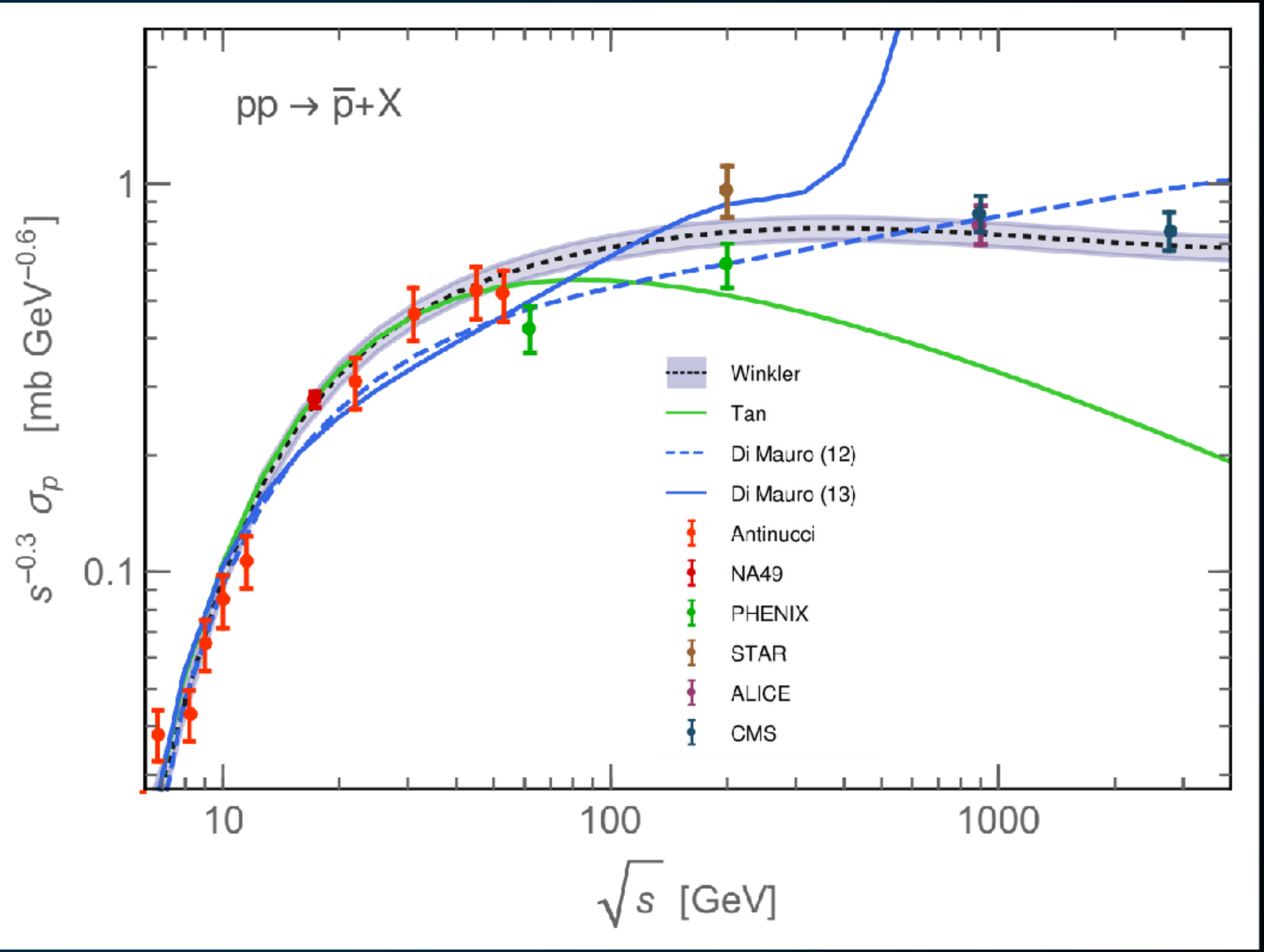
- Instrumental Uncertainties



The Antiproton Excess

With great precision comes great responsibility:

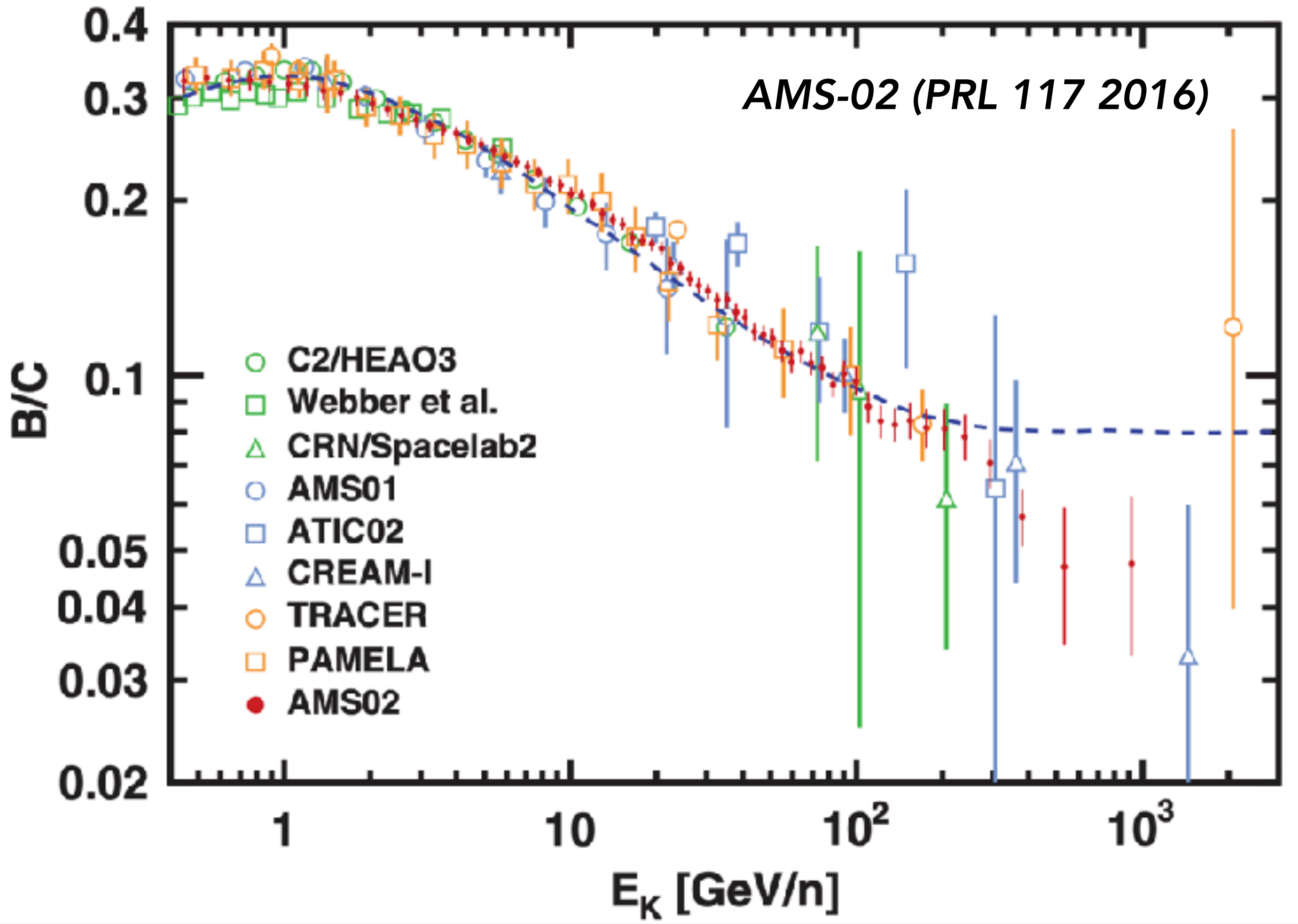
Antiproton Production Cross-Section

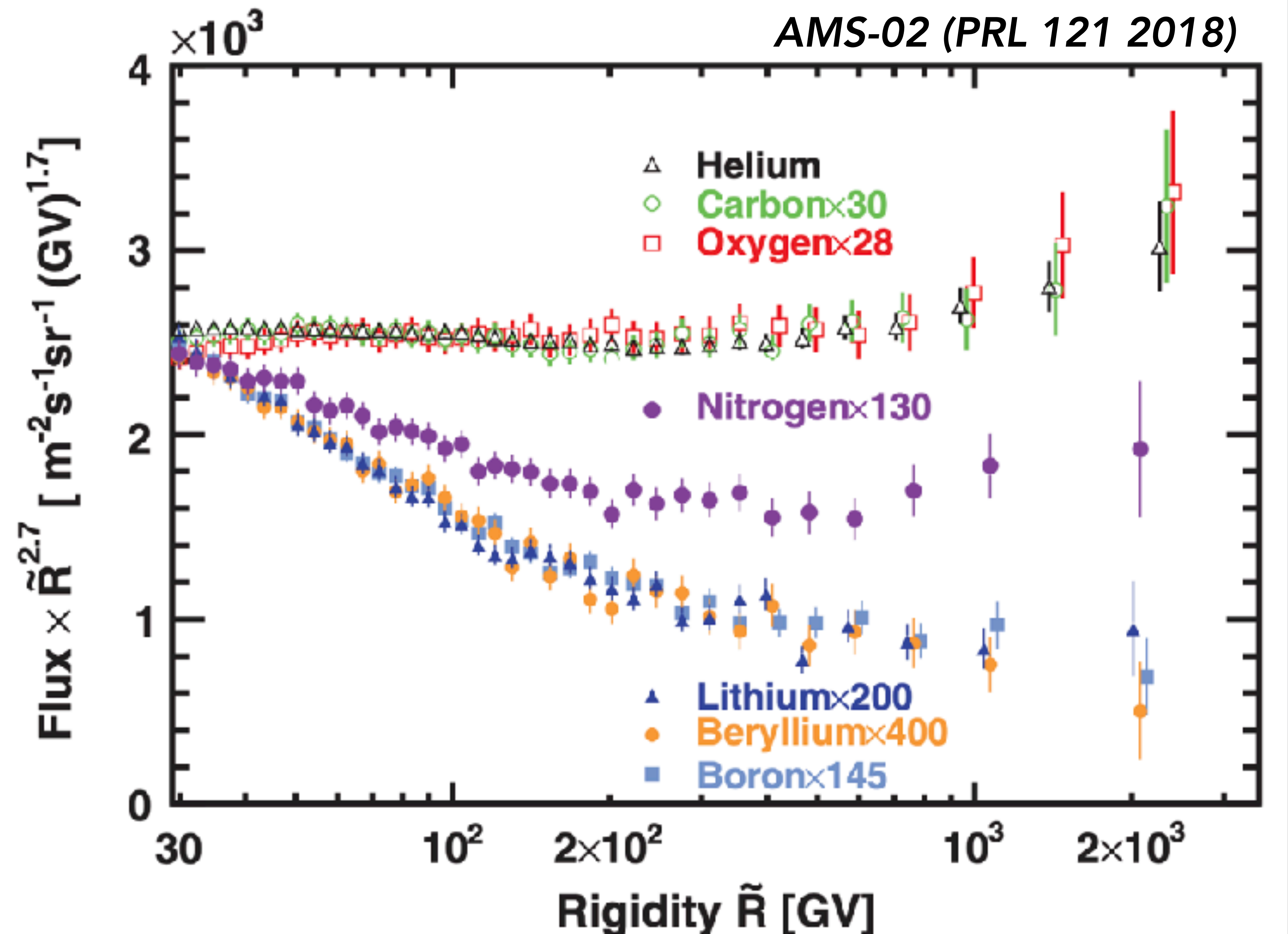
Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

Solar Modulation

Instrumental Uncertainties

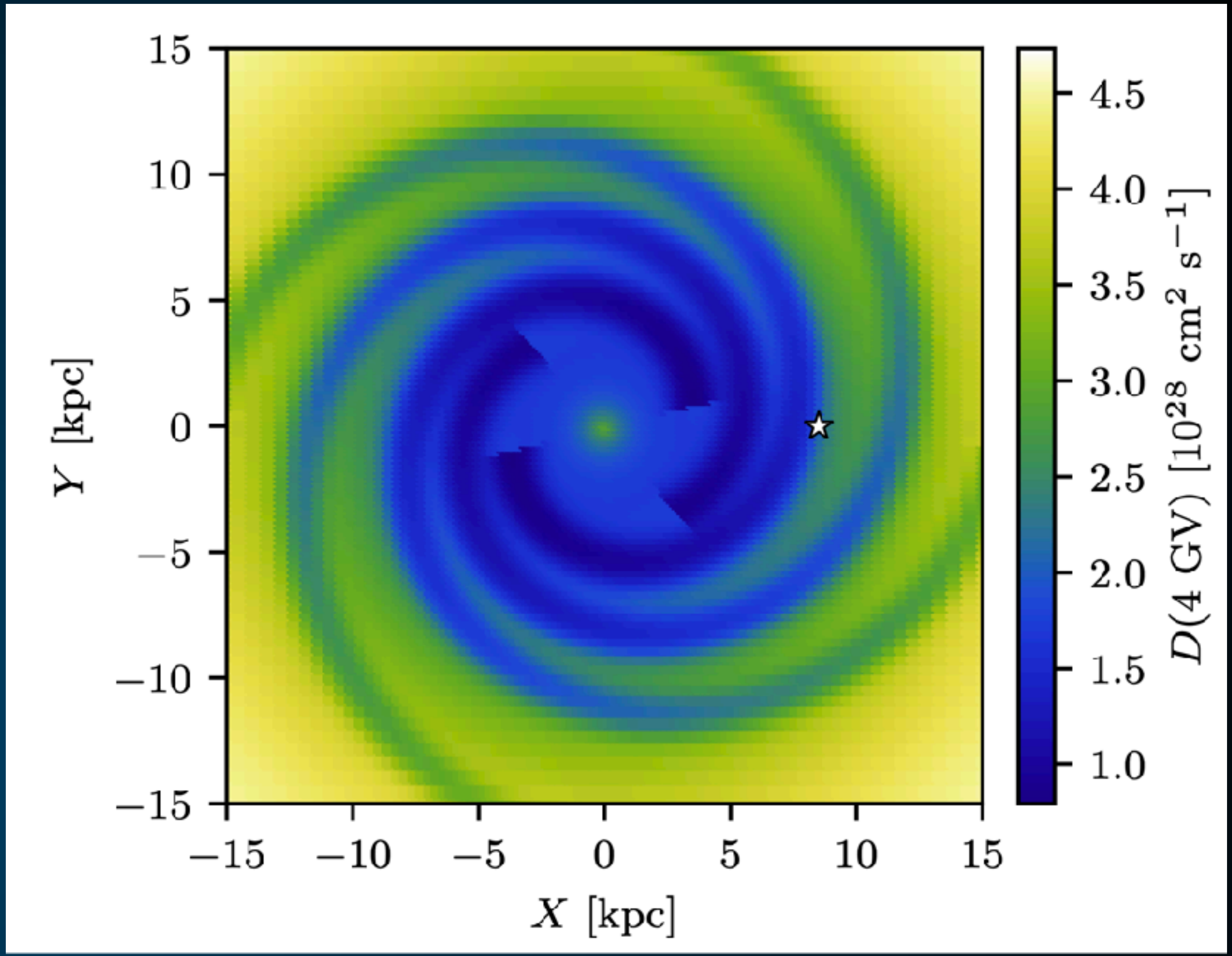




See e.g., Weinrich et al. (2002; 2002.11406)

The Antiproton Excess

Johannesson et al. (1903.05509)

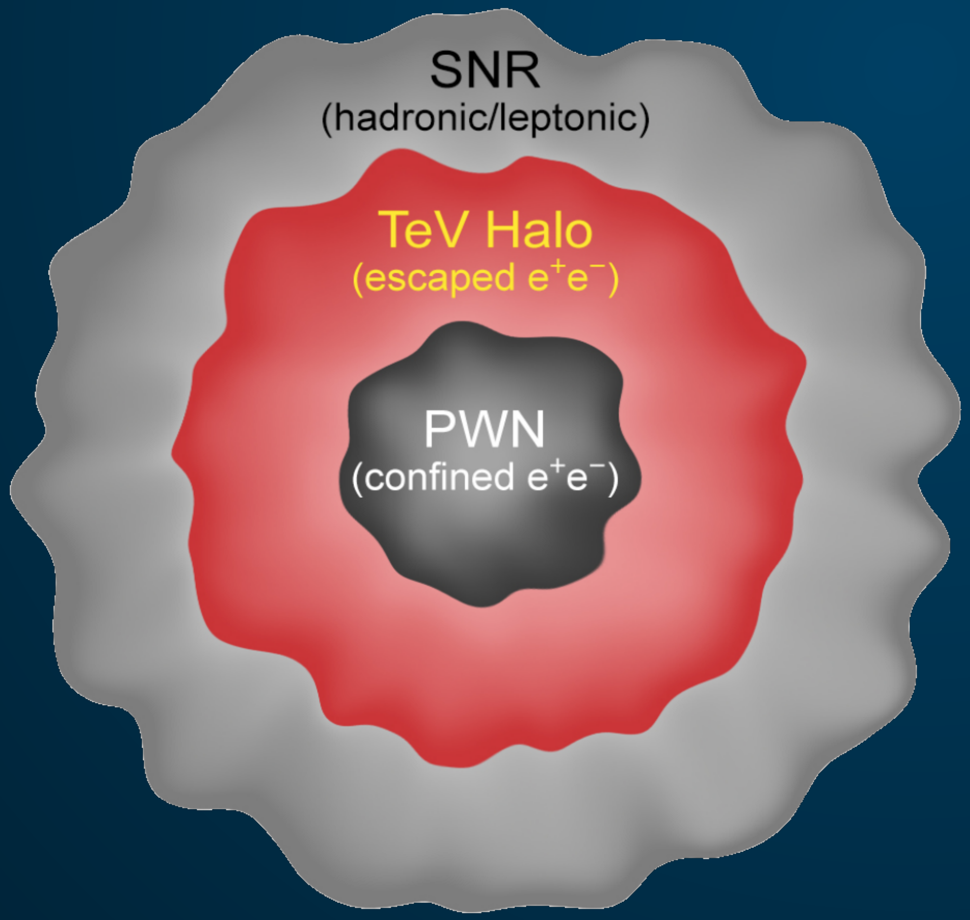


With great precision comes great responsibility:

Antiproton Production Cross-Section

Galactic Primary to Secondary Ratios

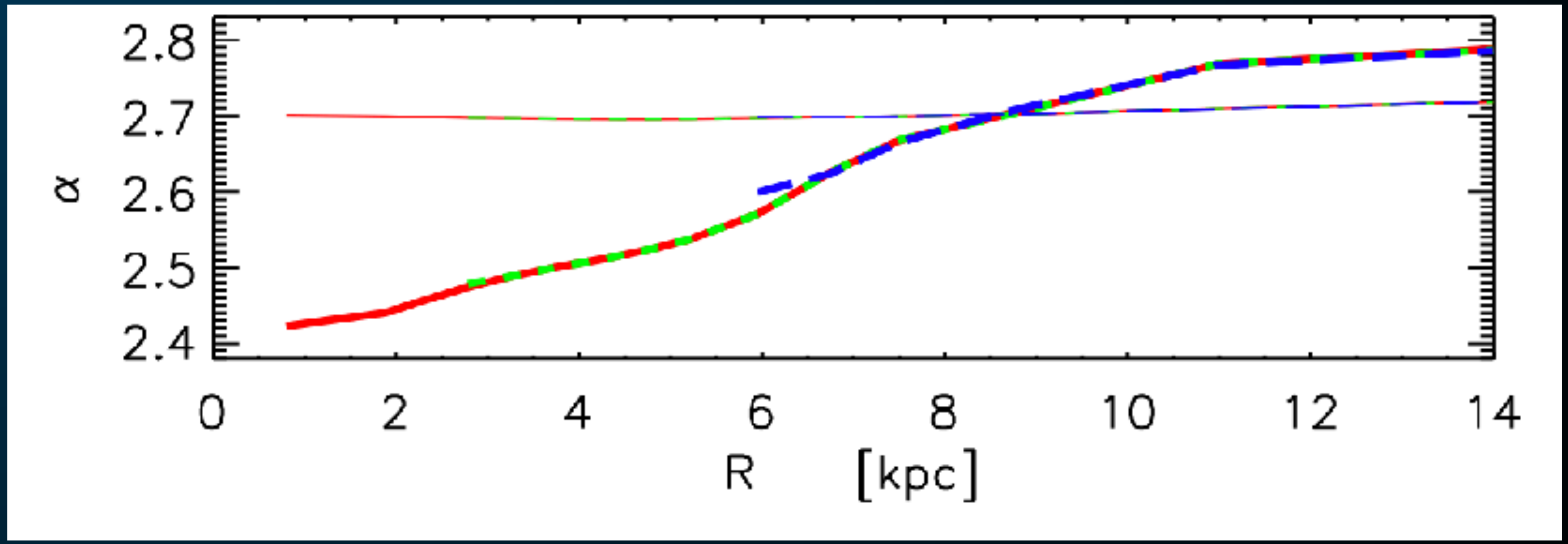
Inhomogeneous Diffusion



Solar Modulation

Instrumental Uncertainties

Evoli et al. (2014; 1411.7623)



The Antiproton Excess

AMS-02 (PRL 121 2018)

With great precision comes great responsibility:

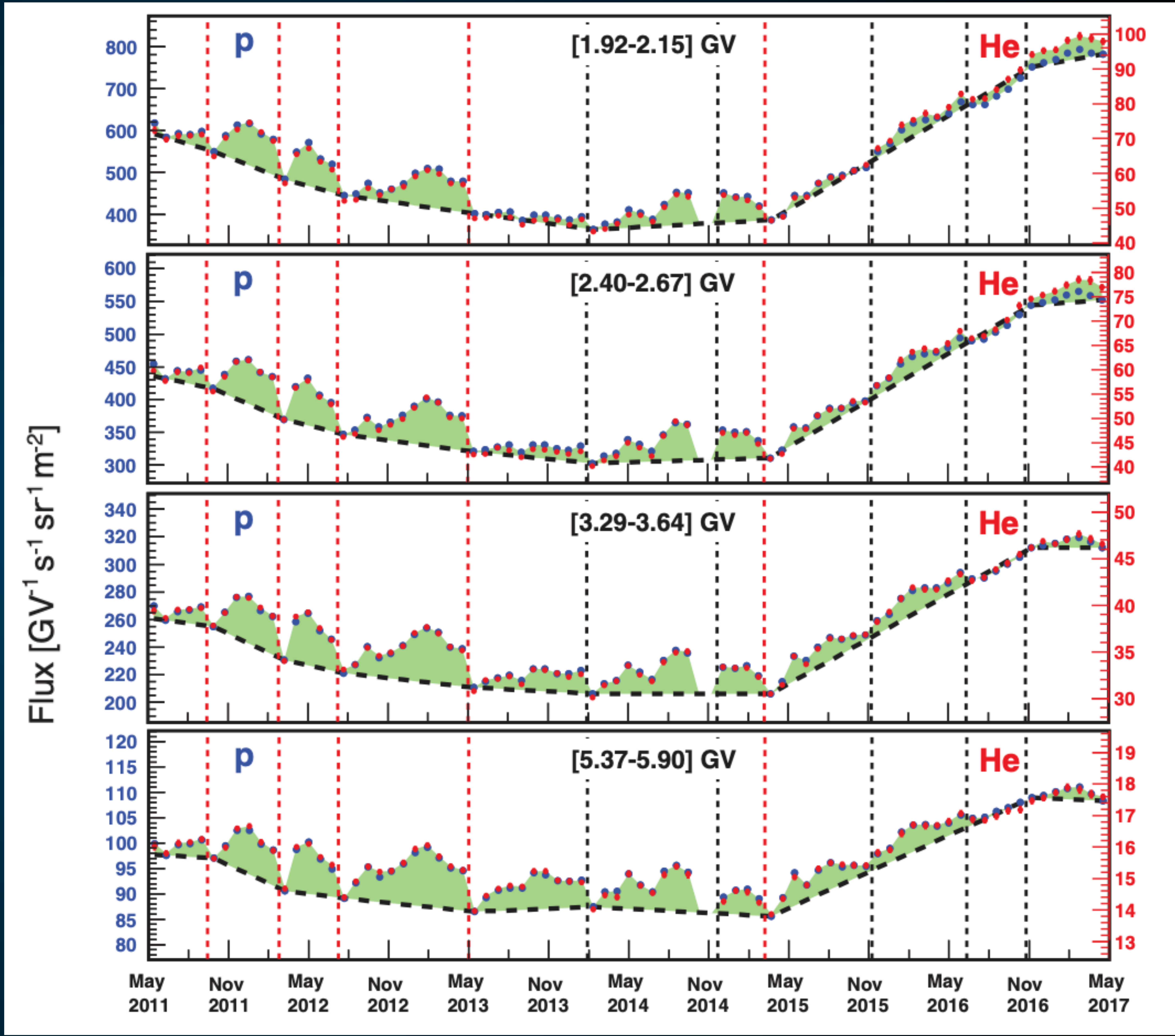
Antiproton Production Cross-Section

Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

Solar Modulation

Instrumental Uncertainties



The Antiproton Excess

With great precision comes great responsibility:

Antiproton Production Cross-Section

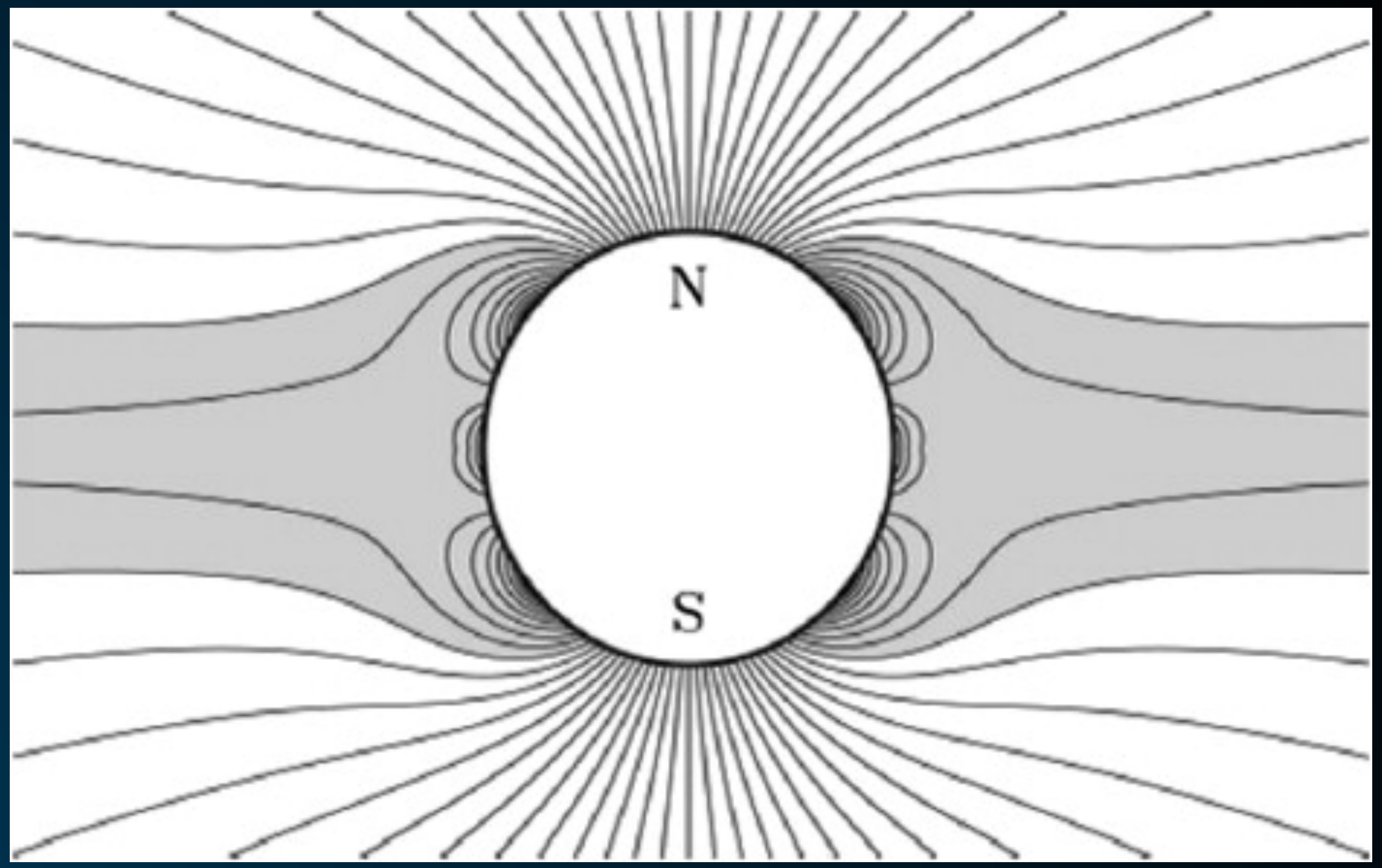
Galactic Primary to Secondary Ratios

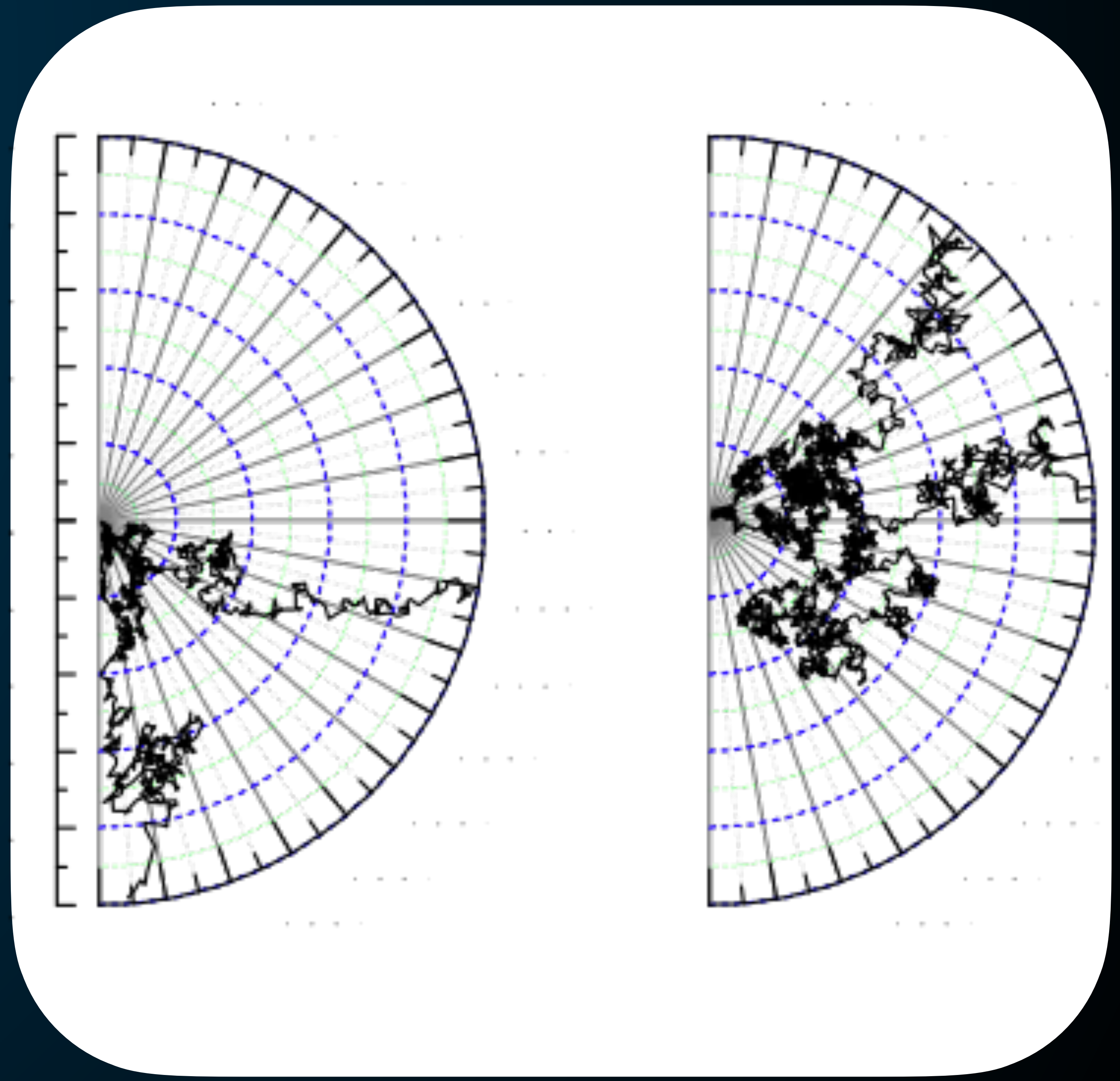
Inhomogeneous Diffusion

Solar Modulation

Instrumental Uncertainties

Fisk Potential





HELMOD Collaboration (2011, 1110.4315)

The Antiproton Excess

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Antiproton Production Cross-Section

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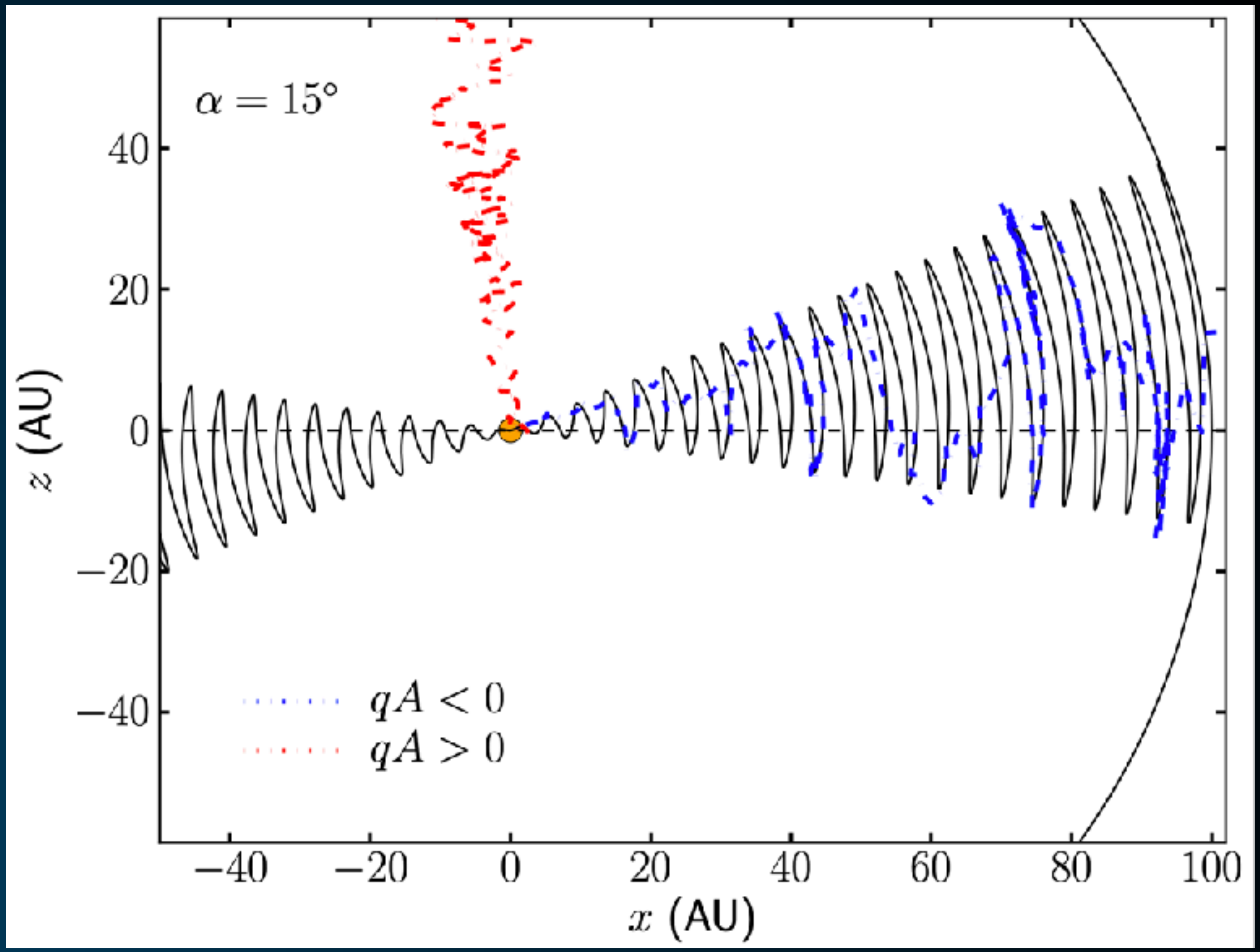
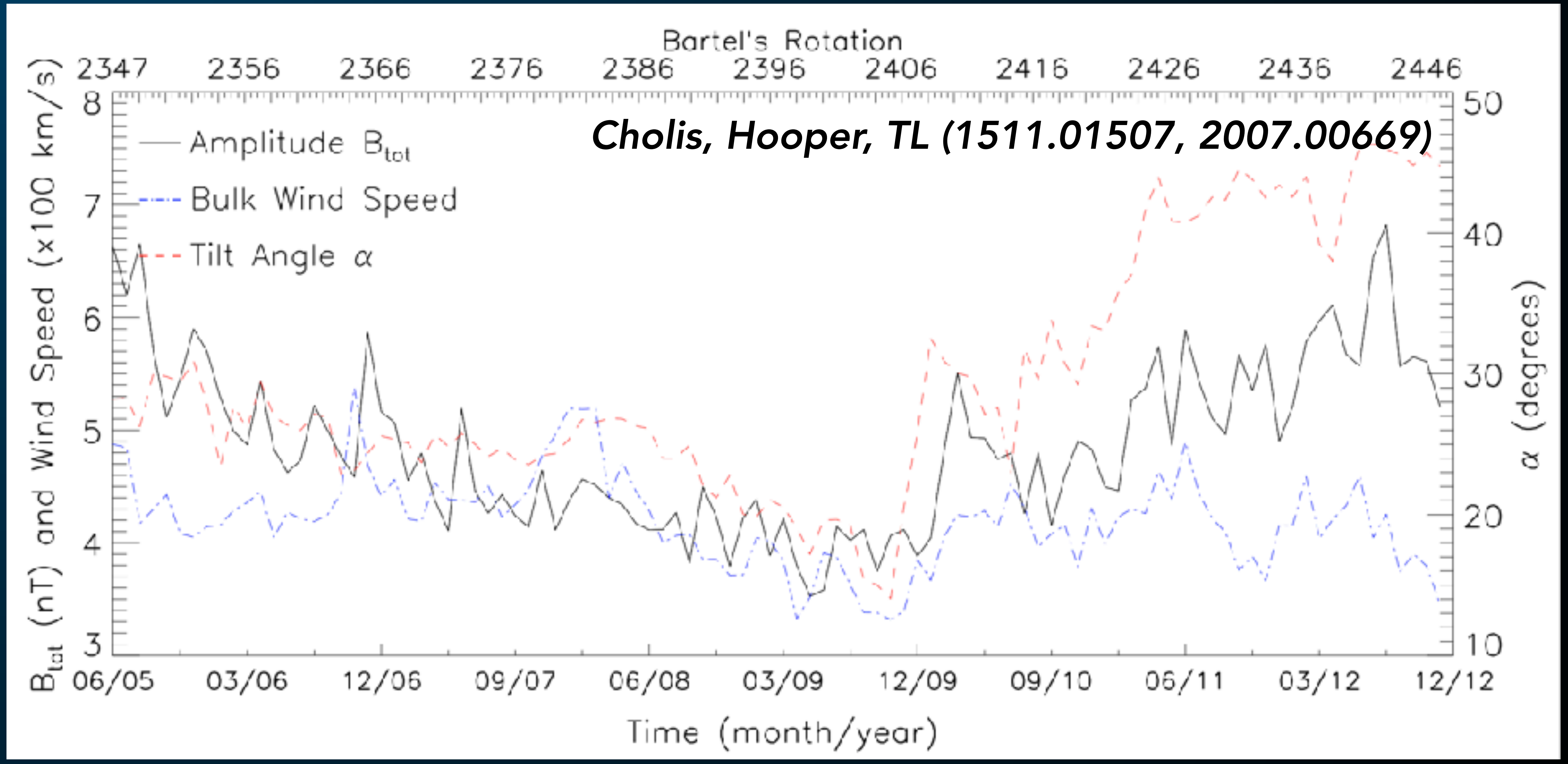
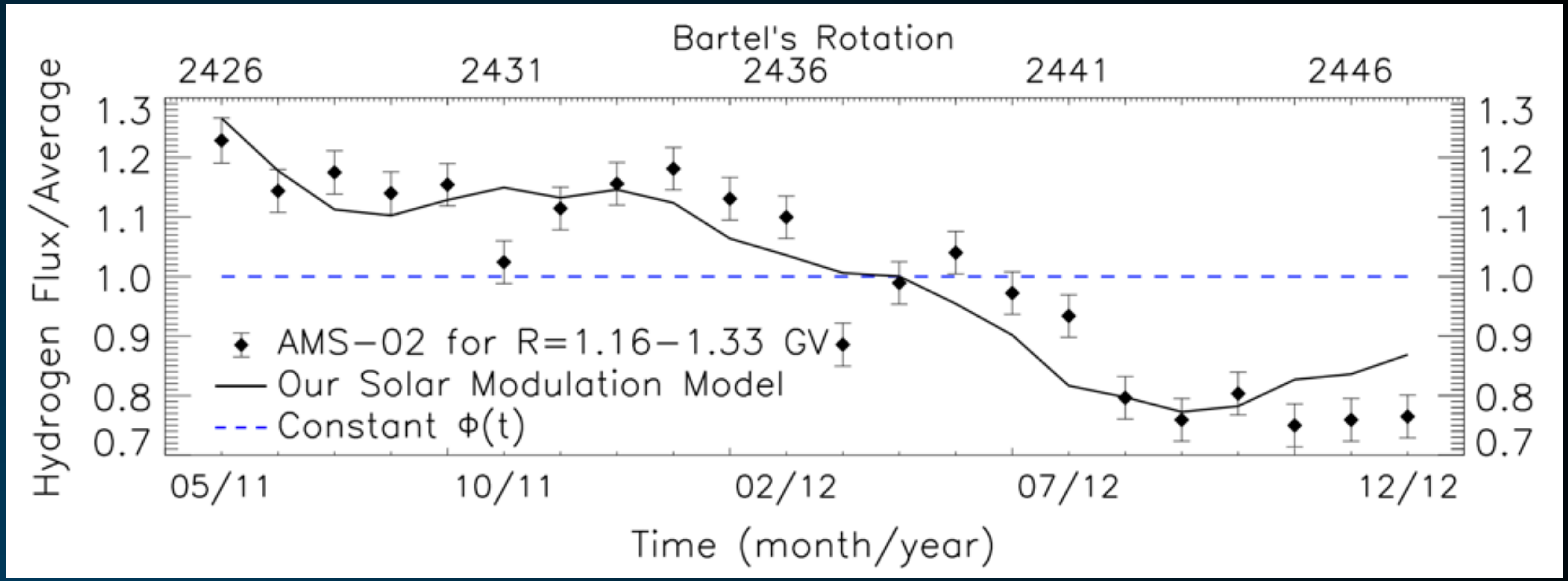




The Antiproton Excess

Cholis, Hooper, TL (2007.00669)



With great precision comes great responsibility:

Antiproton Production Cross-Section

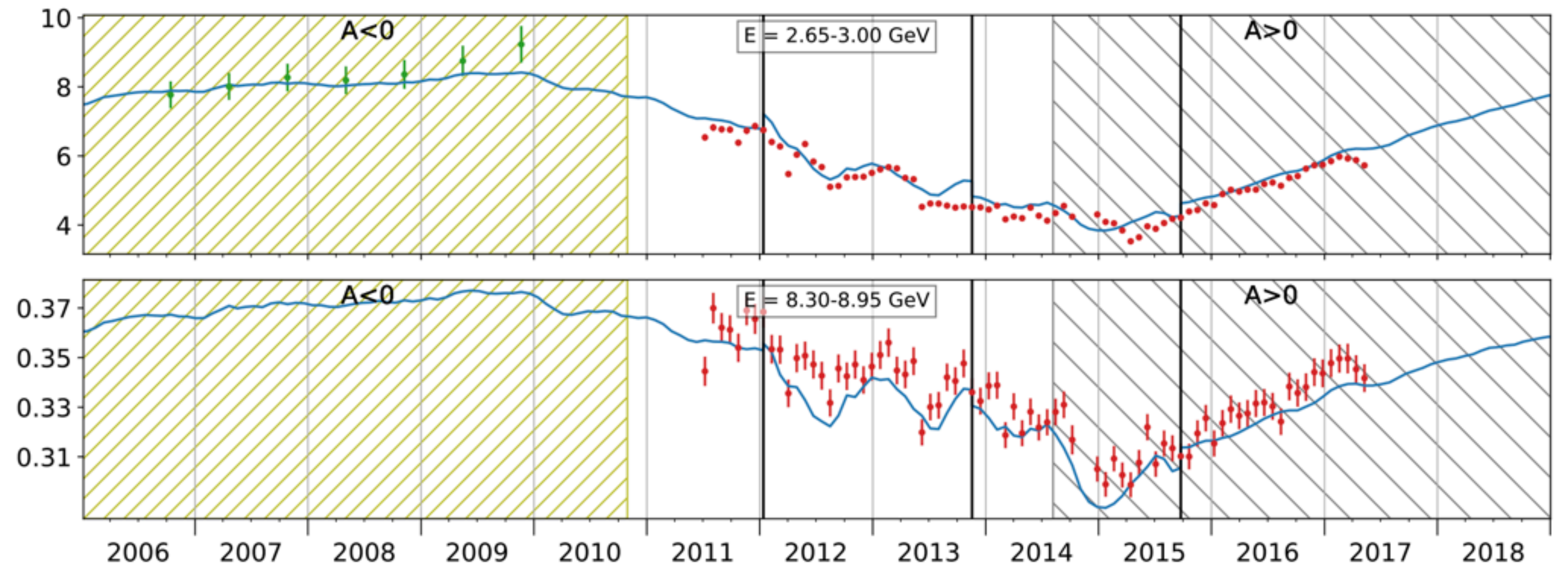
Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

Solar Modulation

Instrumental Uncertainties

Kuhlen, Mertsch (1909.01154)



The Antiproton Excess

With great precision comes great responsibility:

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

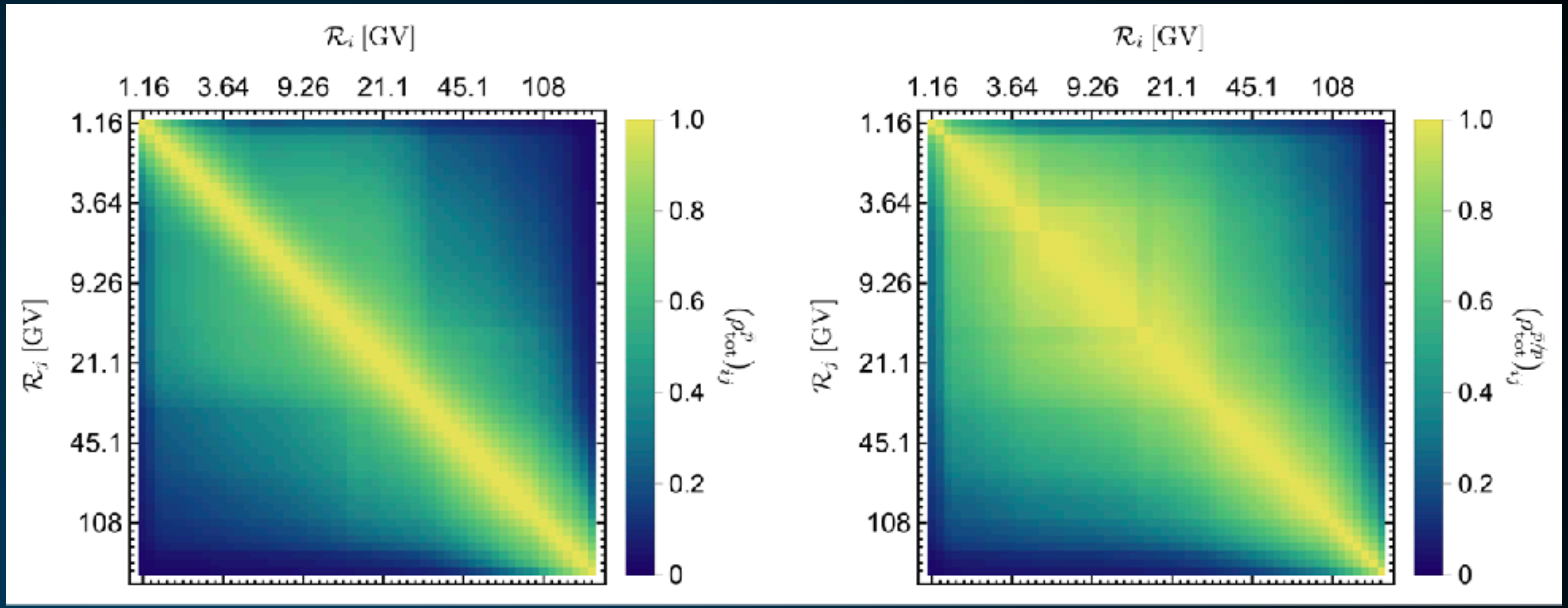
Rigidity [GV]	$\tilde{N}^{\bar{p}}$	$\Phi^{\bar{p}}$ σ_{stat} σ_{syst}	$\Phi^{\bar{p}}/\Phi^{p}$ σ_{stat} σ_{syst}
1.00 – 1.16	21	$(5.94\ 1.31\ 0.58)\times10^{-3}$	$(1.02\ 0.23\ 0.08)\times10^{-5}$
1.16 – 1.33	74	$(5.57\ 0.68\ 0.51)\times10^{-3}$	$(8.93\ 1.09\ 0.66)\times10^{-6}$
1.33 – 1.51	233	$(9.75\ 0.68\ 0.68)\times10^{-3}$	$(1.59\ 0.11\ 0.09)\times10^{-5}$
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)

AMS-02 (PRL 117 2016)

The Antiproton Excess

Heisig et al. (2020; 2005.04237)



With great precision comes great responsibility:

Antiproton Production Cross-Section

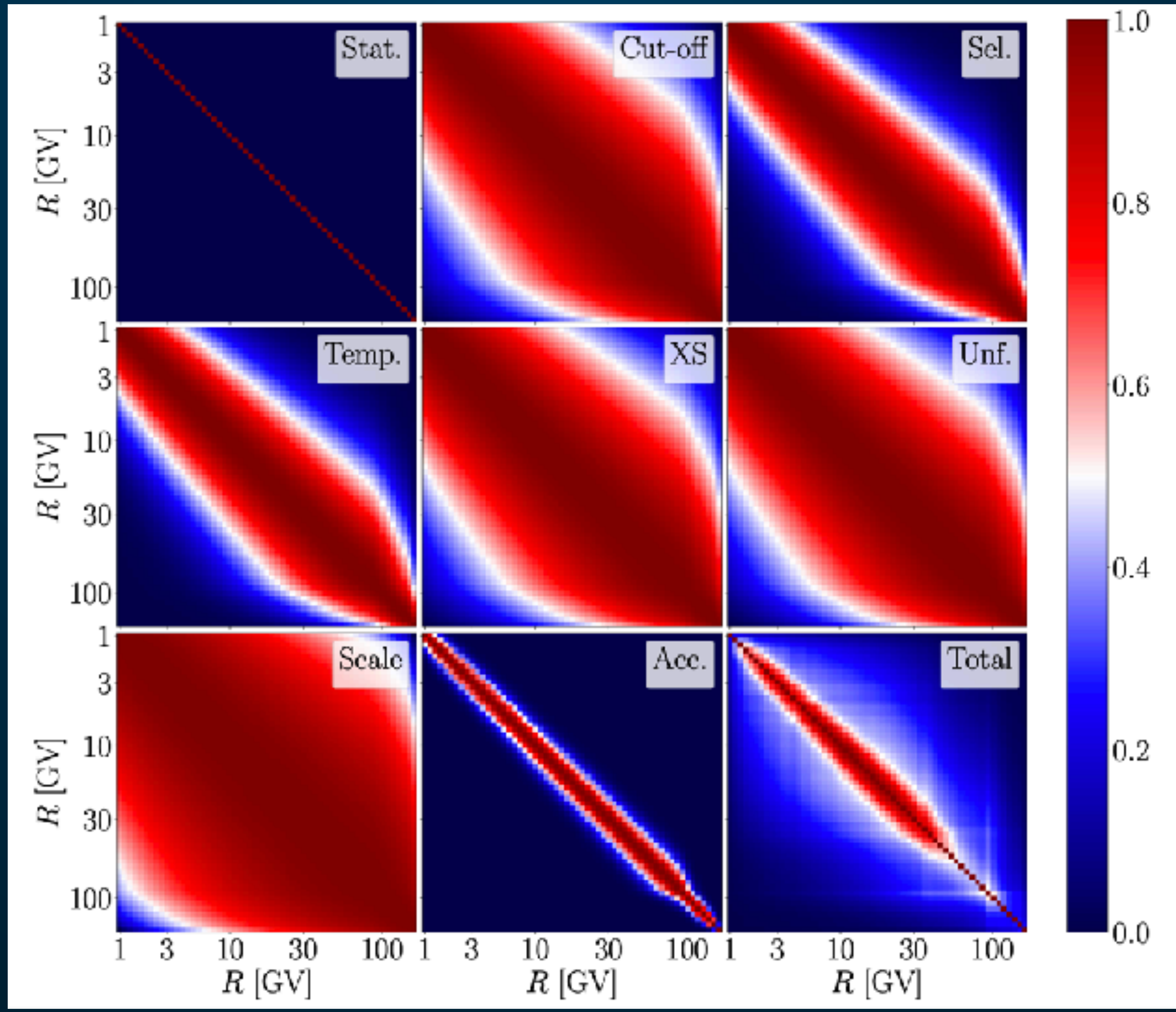
Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

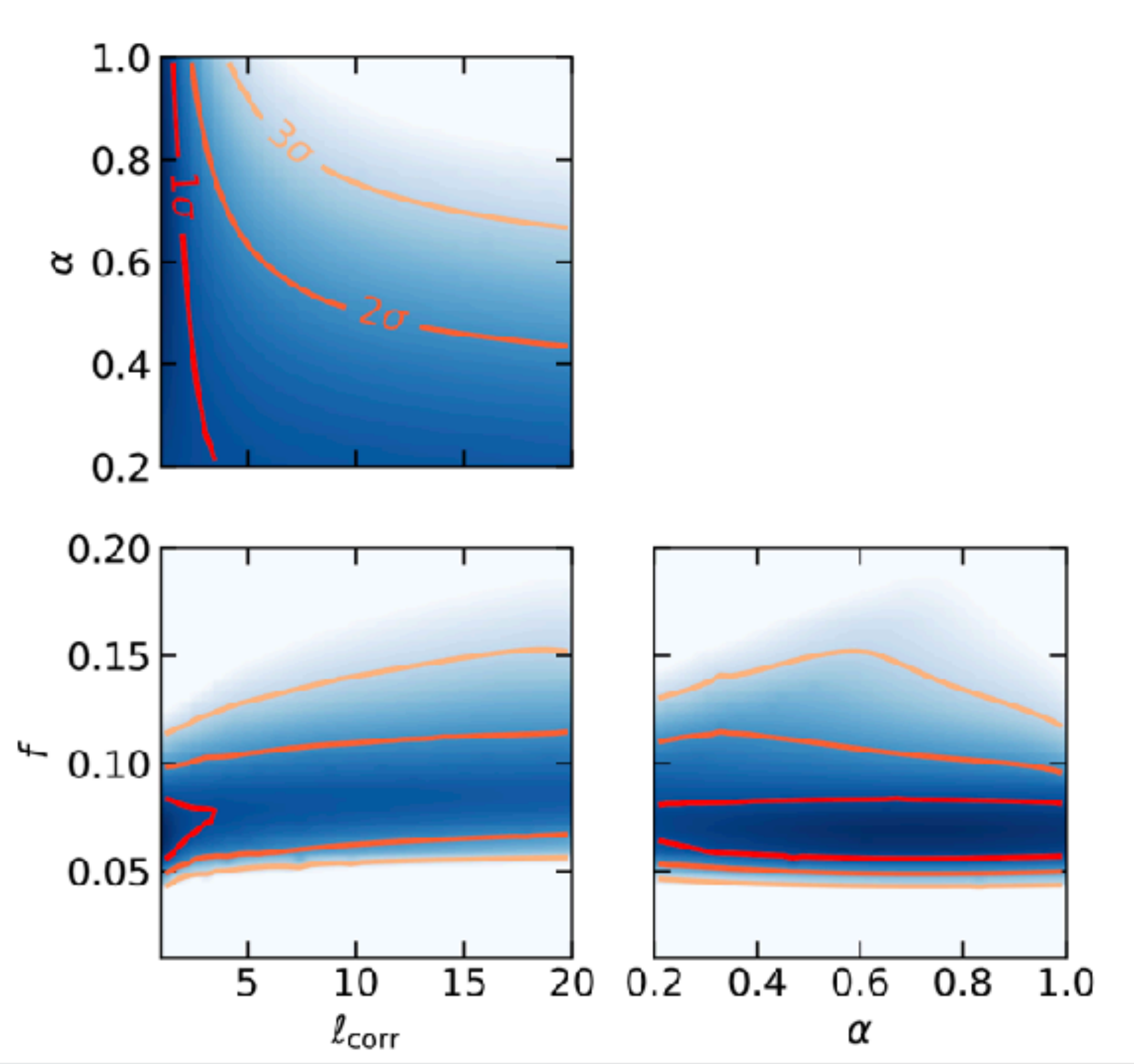
Solar Modulation

Instrumental Uncertainties

Boudaud et al. (2019; 1906.07119)

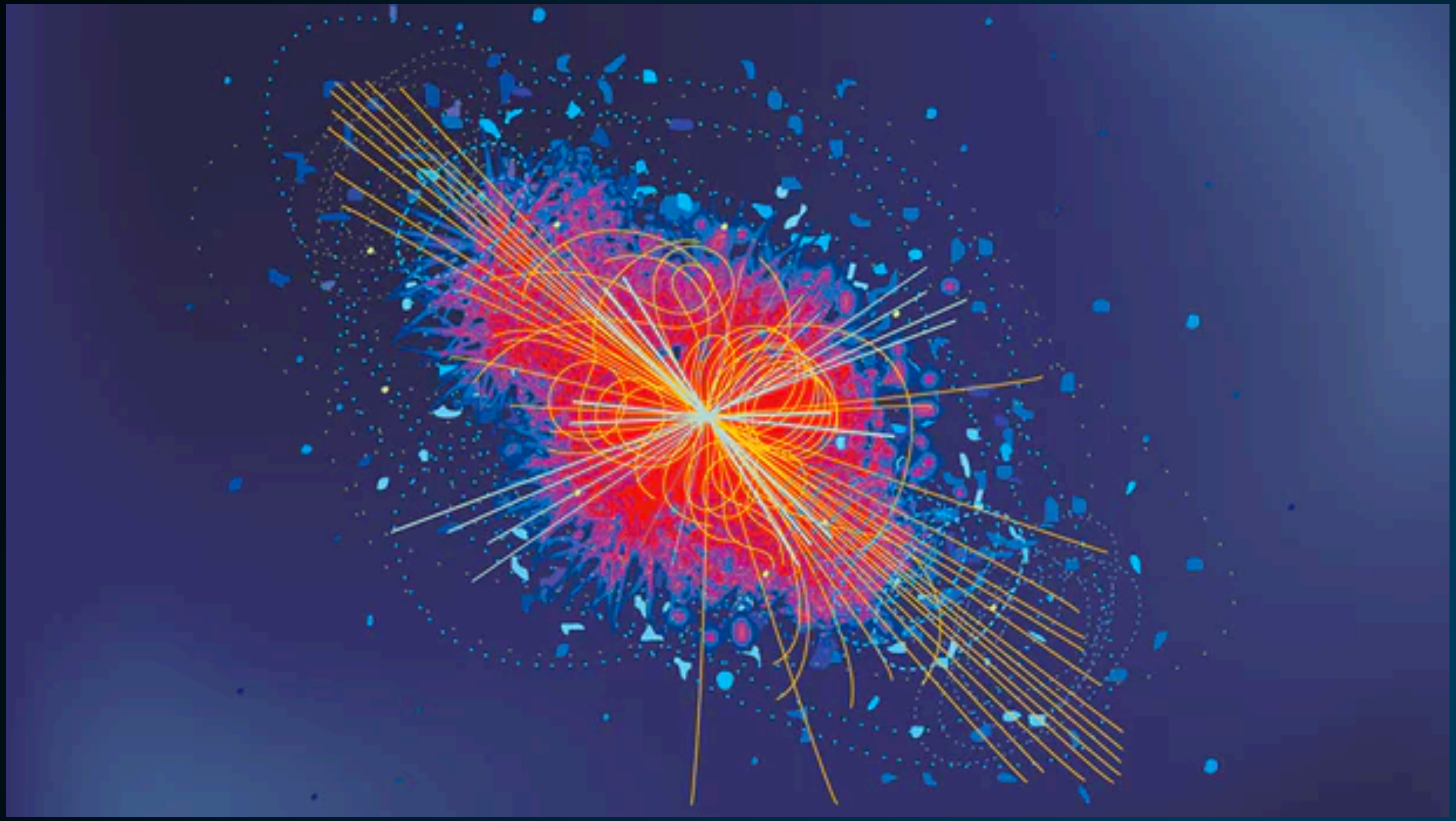


Cuoco et. al. (2019; 1903.01472)



Antinuclei !?

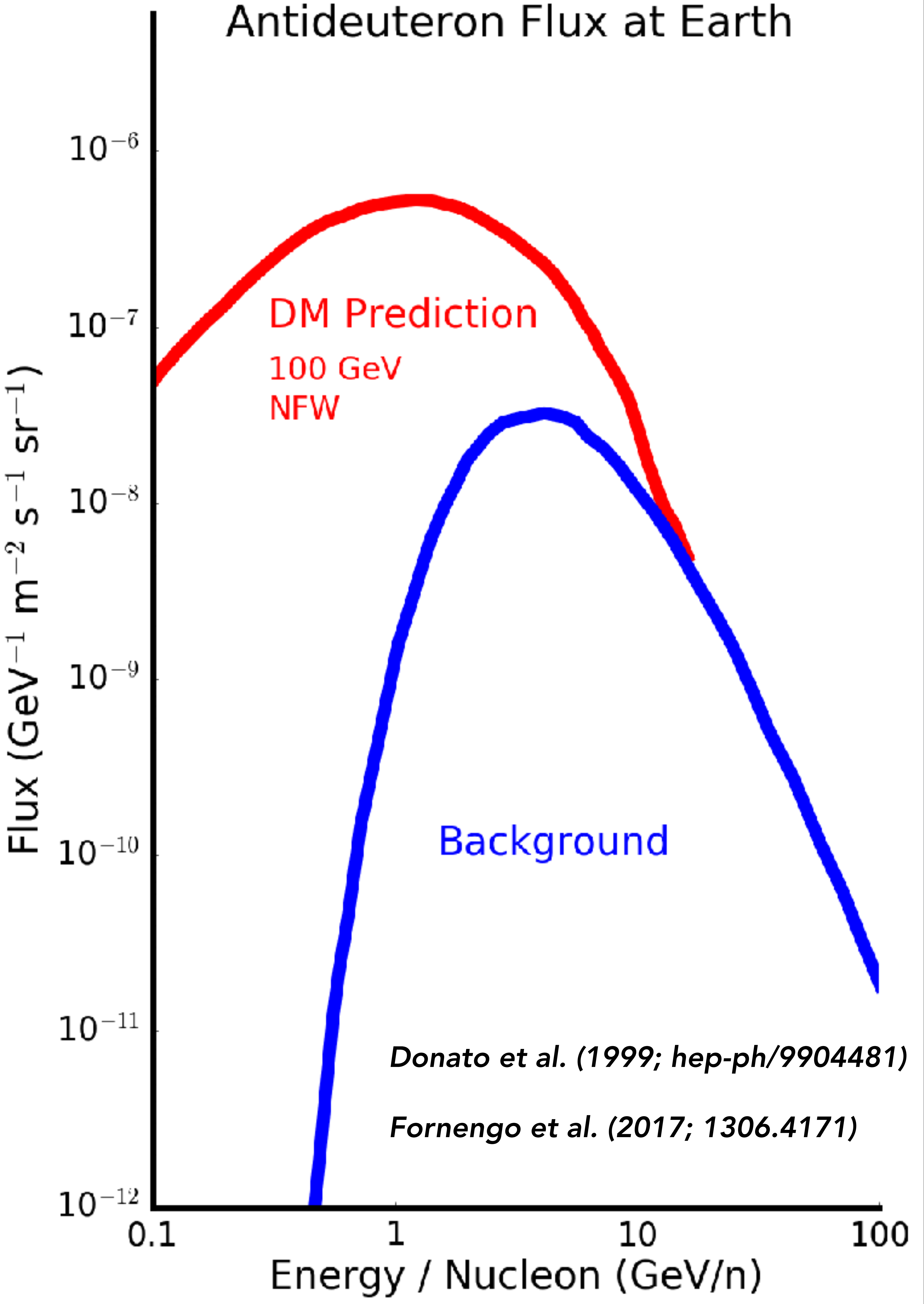
AntiNuclei - A Clean Search Strategy ?



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 $\overline{He}$ events is less than 3×10^{-8}. For the two $^{4}\overline{He}$ 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}.

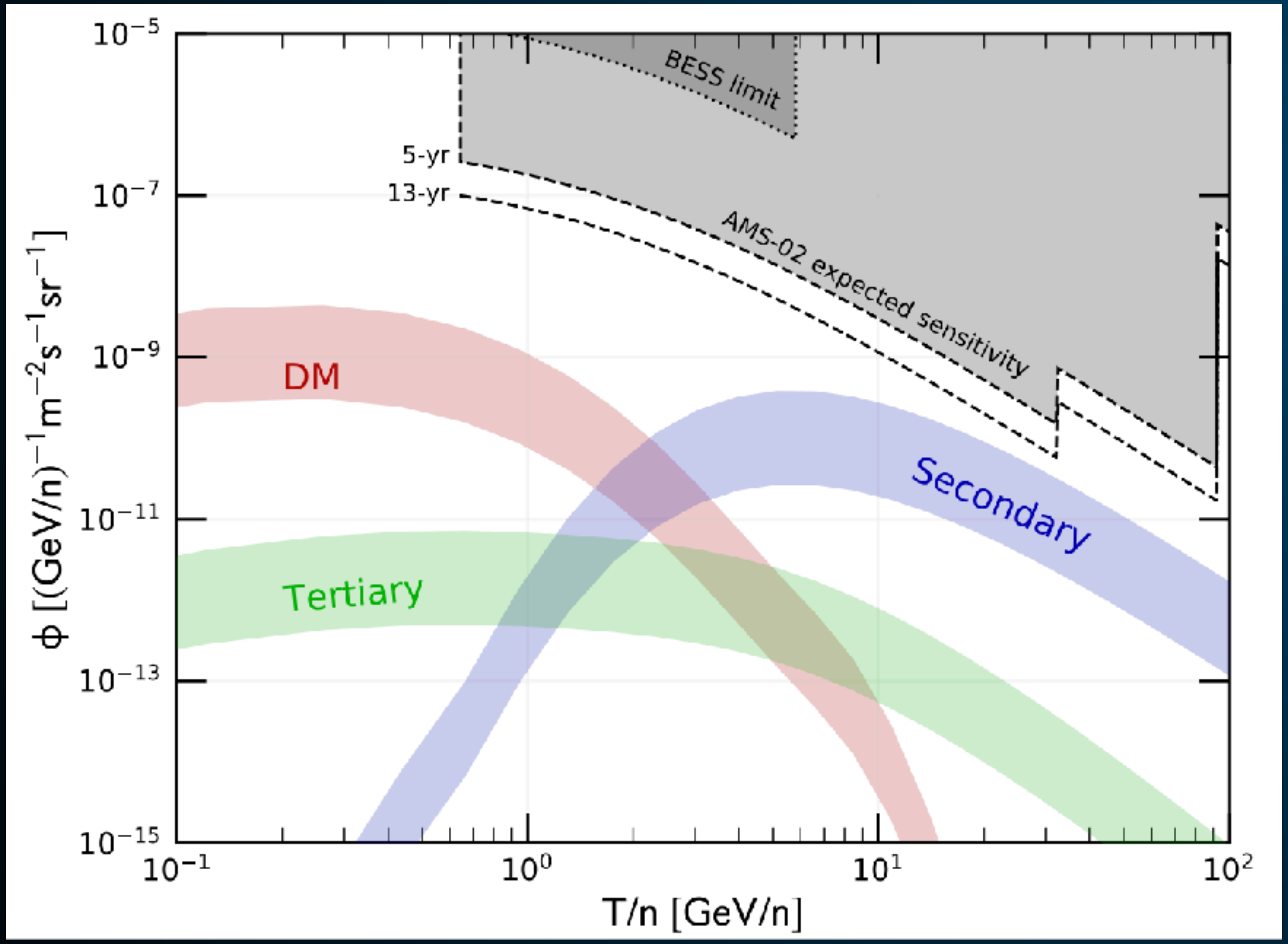
Note that for $^{4}\overline{He}$, projecting based on the statistics we have today, by using an additional 400 million core hours for simulation the background probability would be 10^{-4}. Simultaneously, continuing to run until 2023, which doubles the data sample, the background probability for $^{4}\overline{He}$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

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

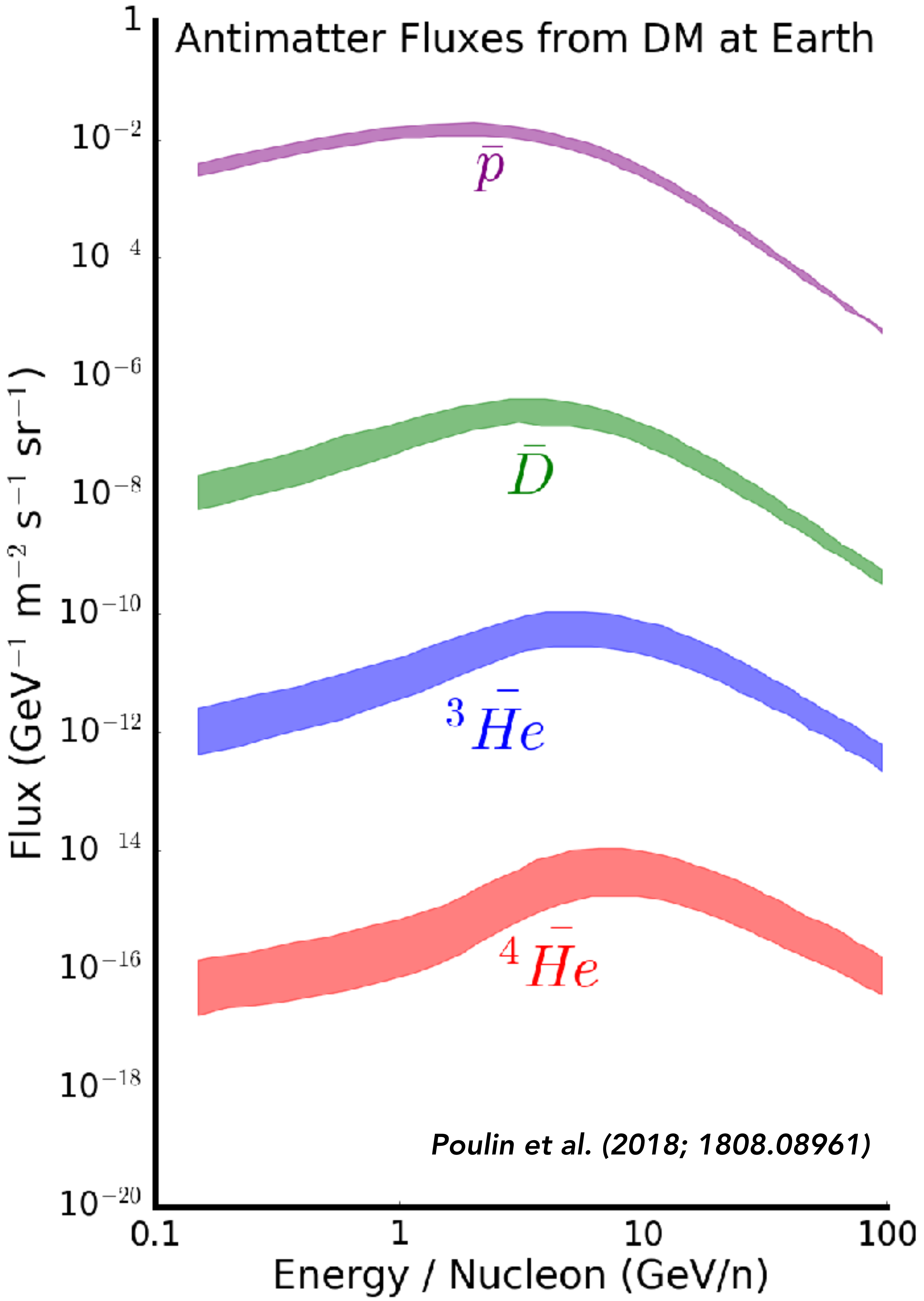
AntiNuclei - A Clean Search Strategy ?

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 ?

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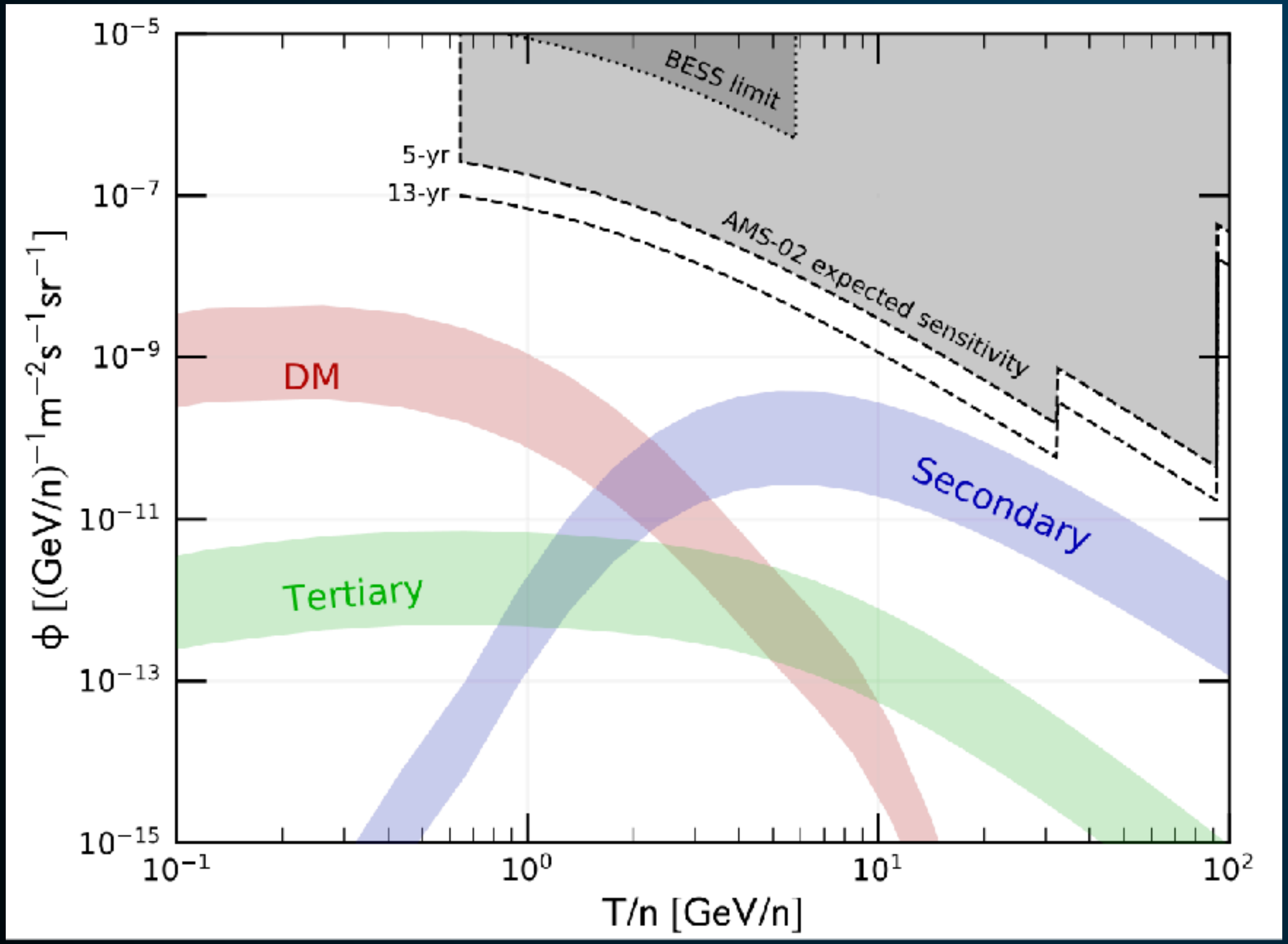

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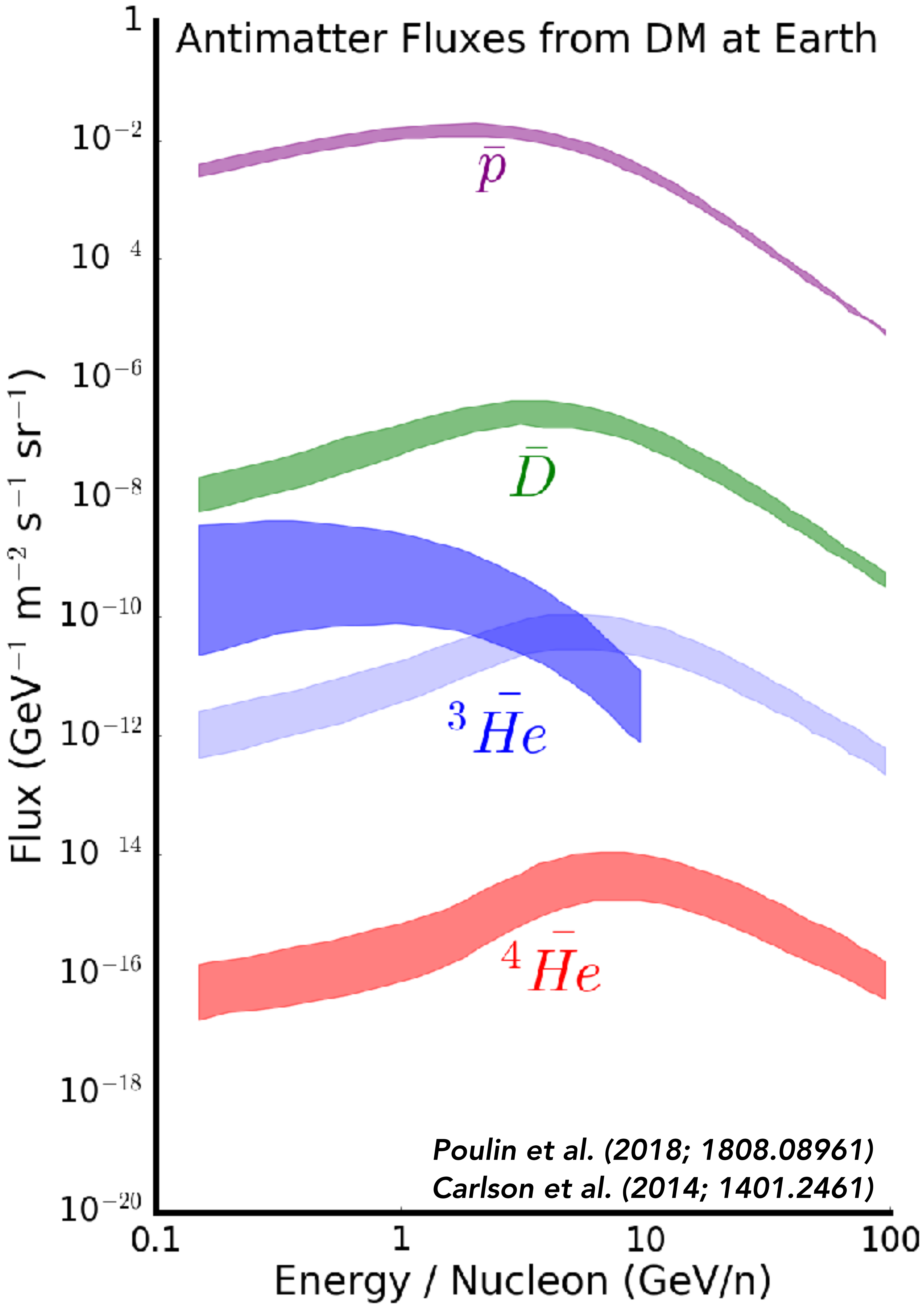
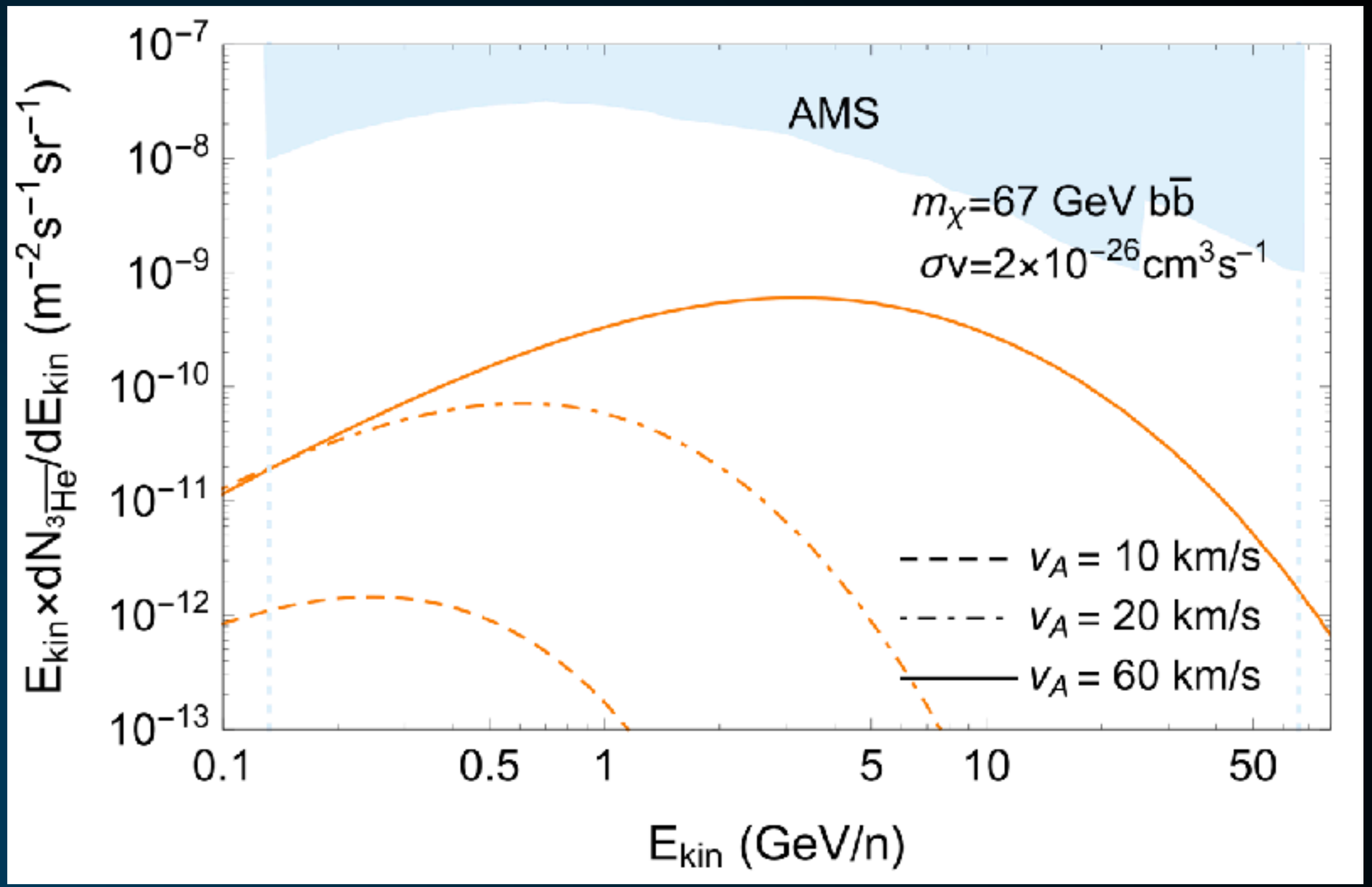


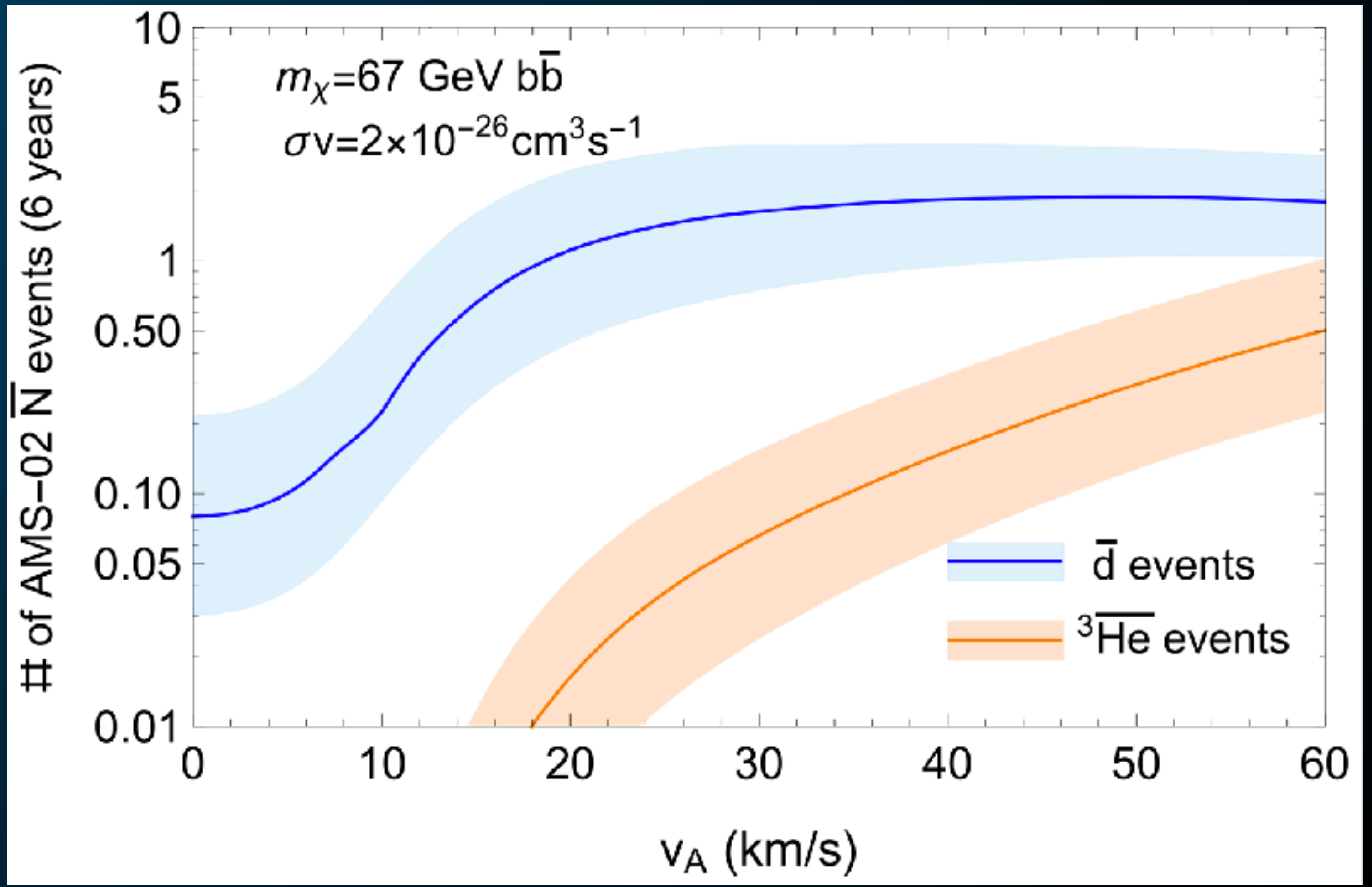
Enhancing the Dark Matter Flux

Method I: Astrophysics

The dark matter induced-antihelium bump is at too low of an energy to be detected.

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





Cholis, Linden, Hooper (2020; 2001.08749)

Enhancing the Dark Matter Flux

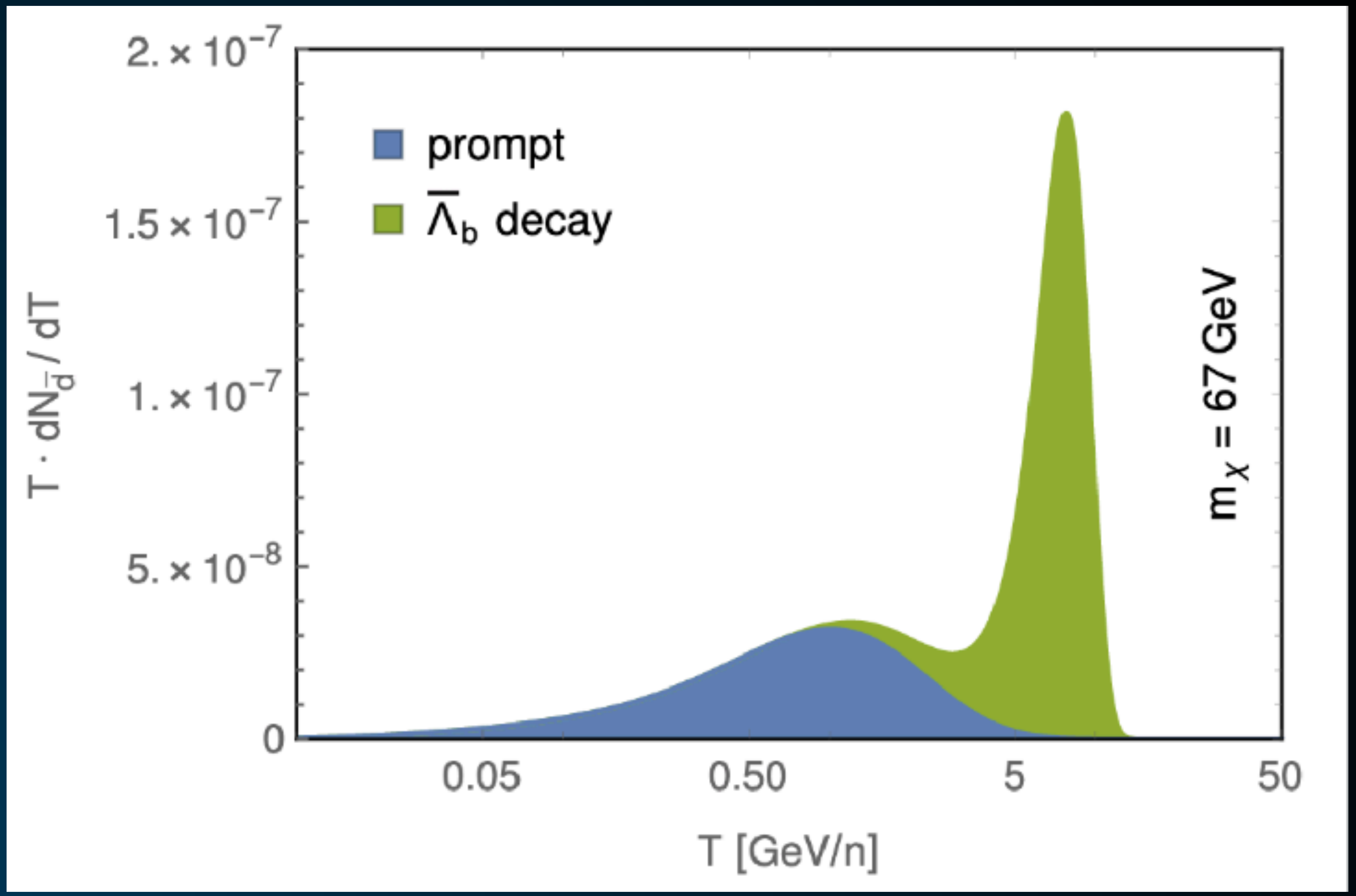
Method II: Particle Physics

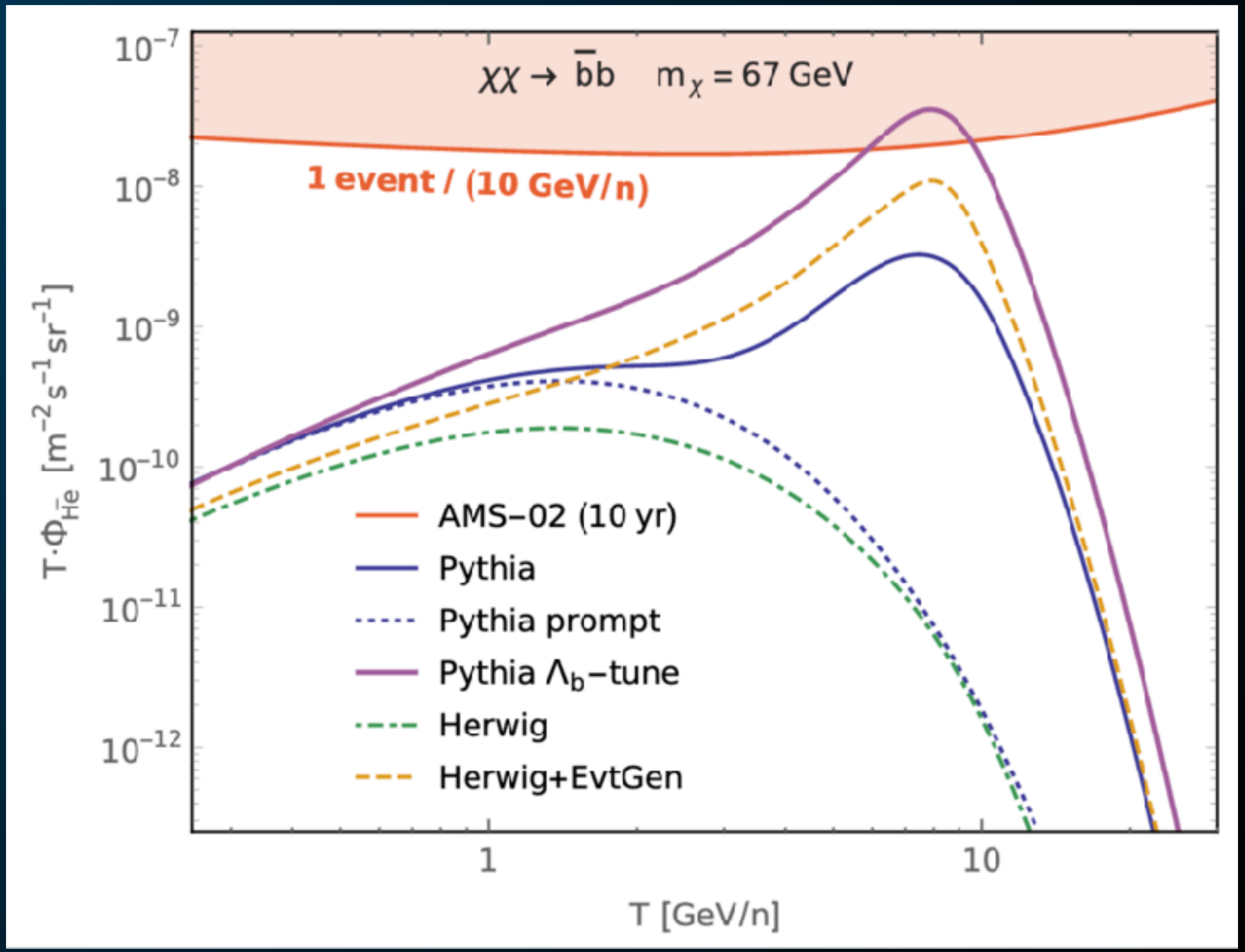
Previous analyses may have missed the dominant antihelium production pathway from dark matter.

Including this term boosts the antihelium production rate by a factor of 100!

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)





Enhancing the Dark Matter Flux

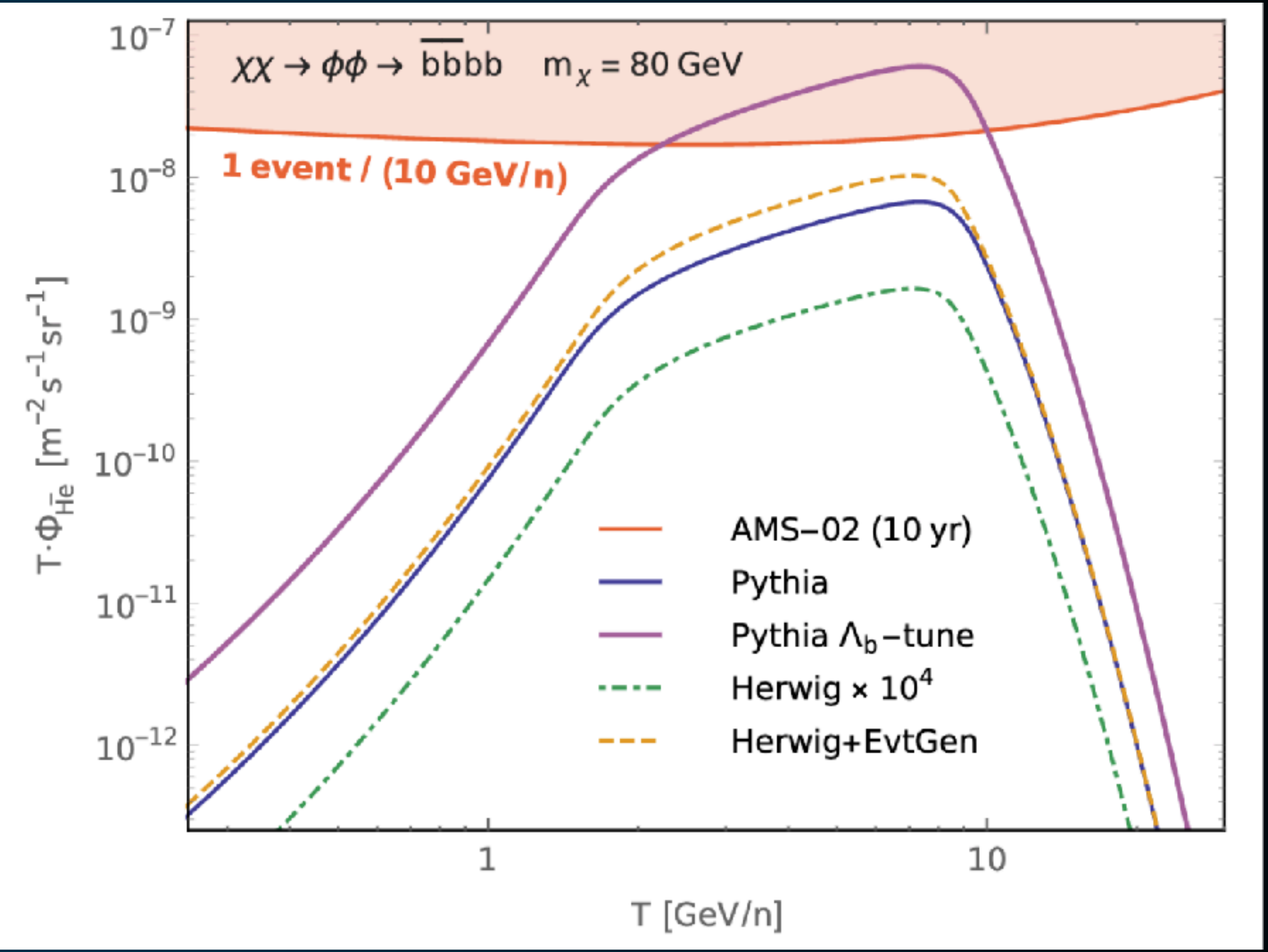
Method III: Tuned Models

Winkler & Linden (2020; 2020.16251)

If the goal is to fit the antihelium data.

Can combine astrophysical and particle physics mechanisms.

Can develop non-standard particle physics models.



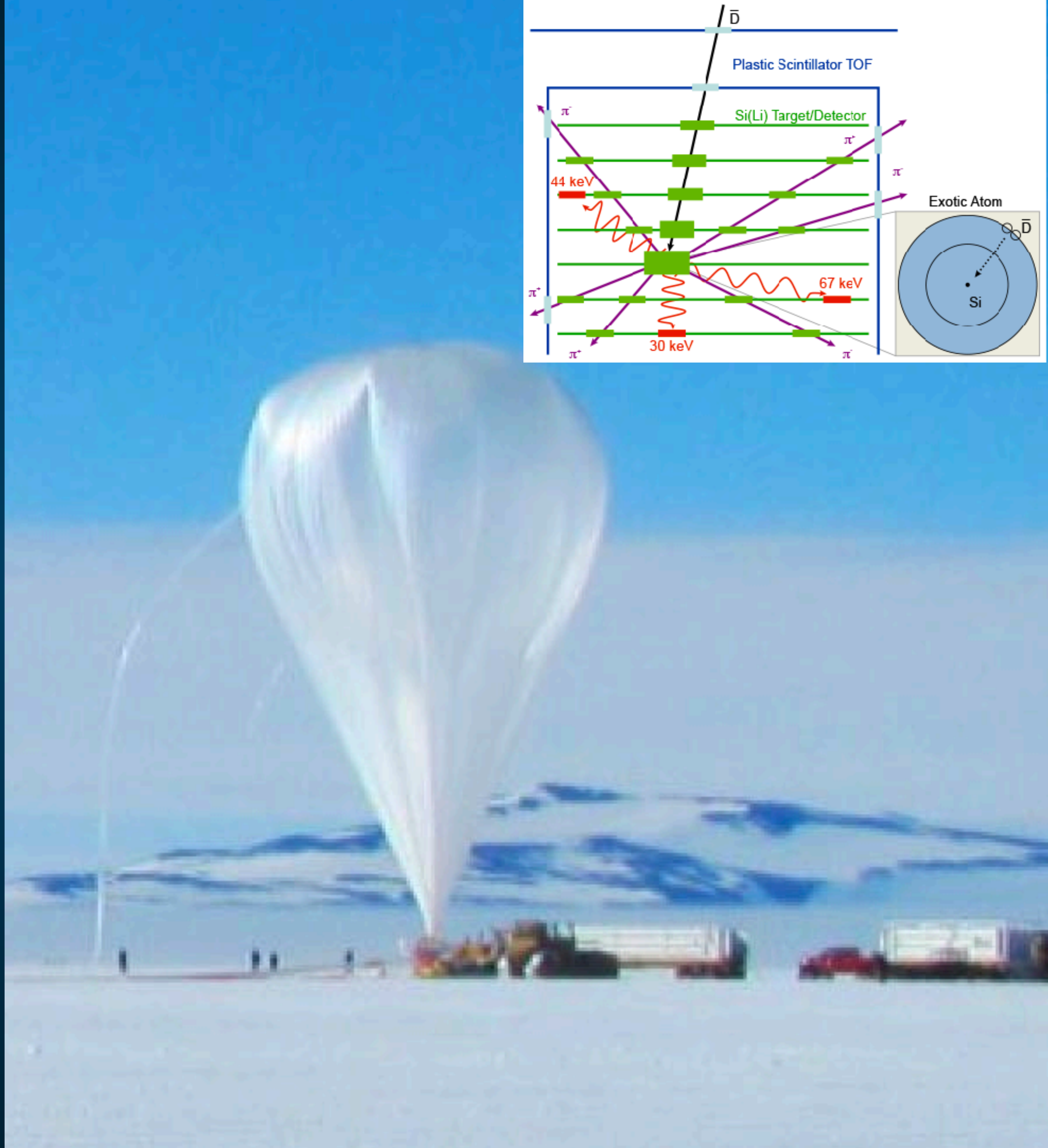
Difficulties

Method III: Tuned Models

Can we verify the observation of antihelium against a much larger background?

Can we produce enough ^3He without violating antideuteron and antiproton constraints?

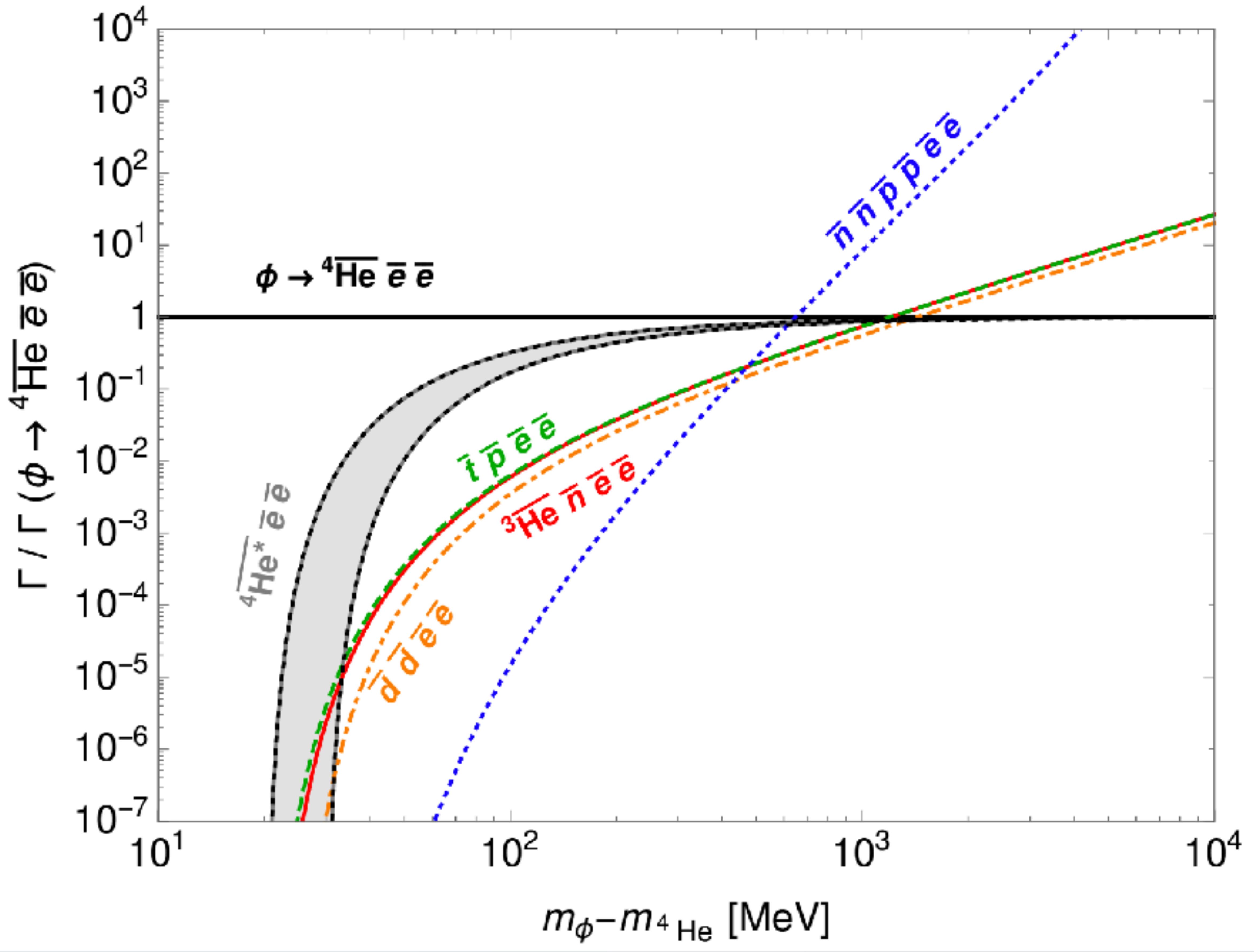
What about ^4He?



Difficulties

Method III: Tuned Models

Heeck & Rajaraman (2019; 1906.01667)



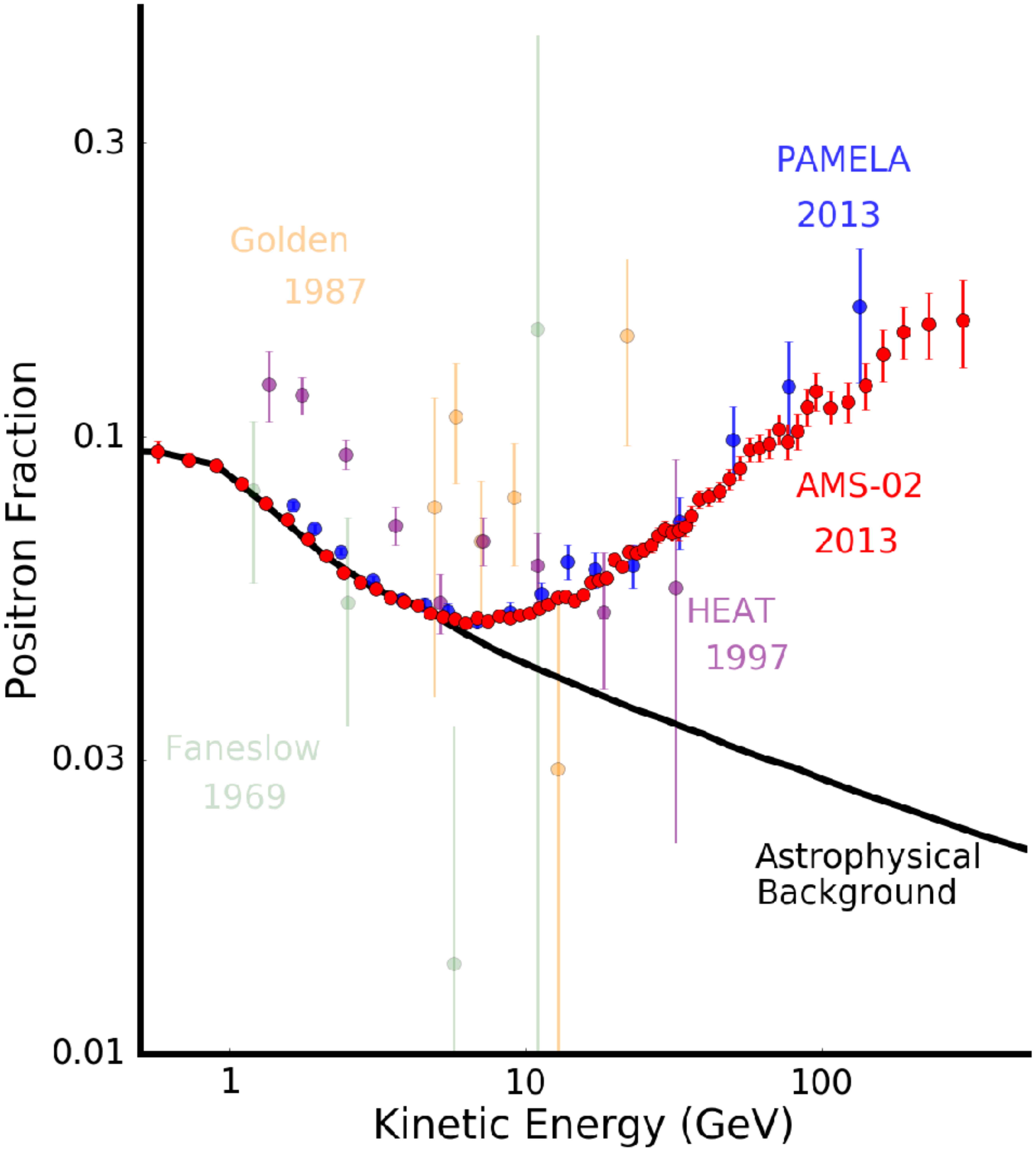
Can we verify the observation of antihelium against a much larger background?

Can we produce enough ^{3}He without violating antideuteron and antiproton constraints?

What about ^{4}He?

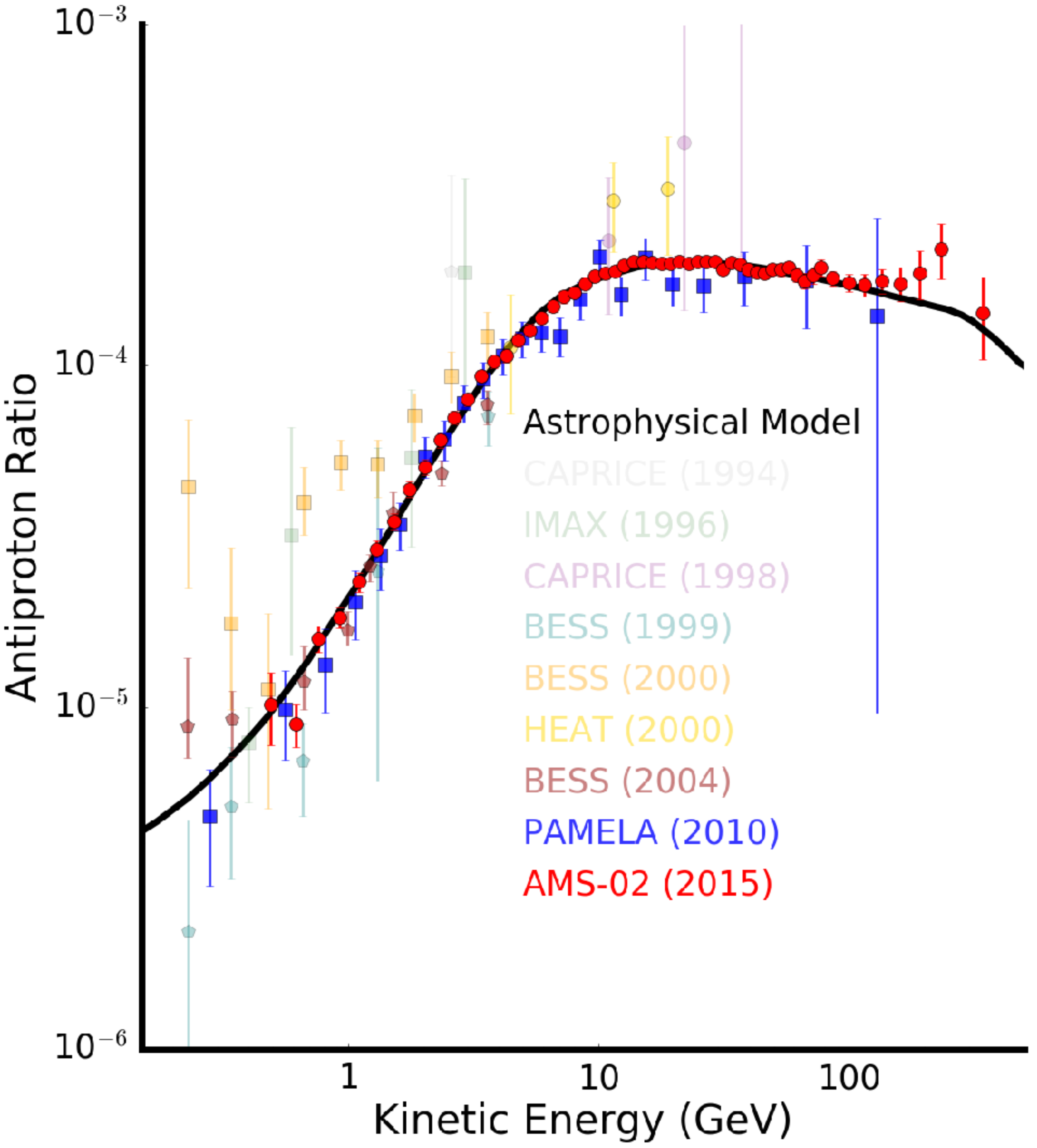
Provocative Questions

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



Provocative Questions

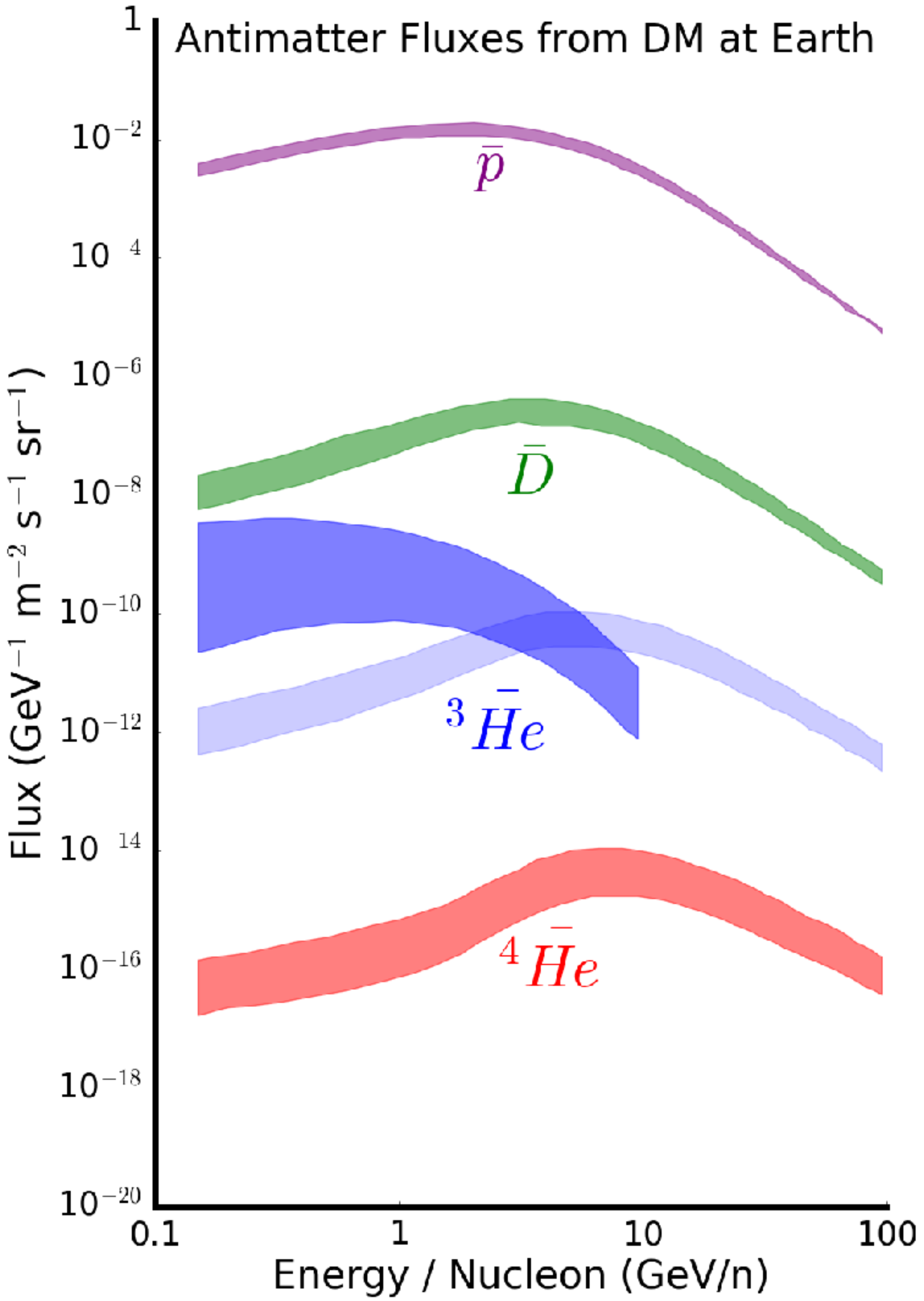
Is it possible to find dark matter as a $\mathcal{O}$(1%) effect?



Provocative Questions

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

^{4}He?



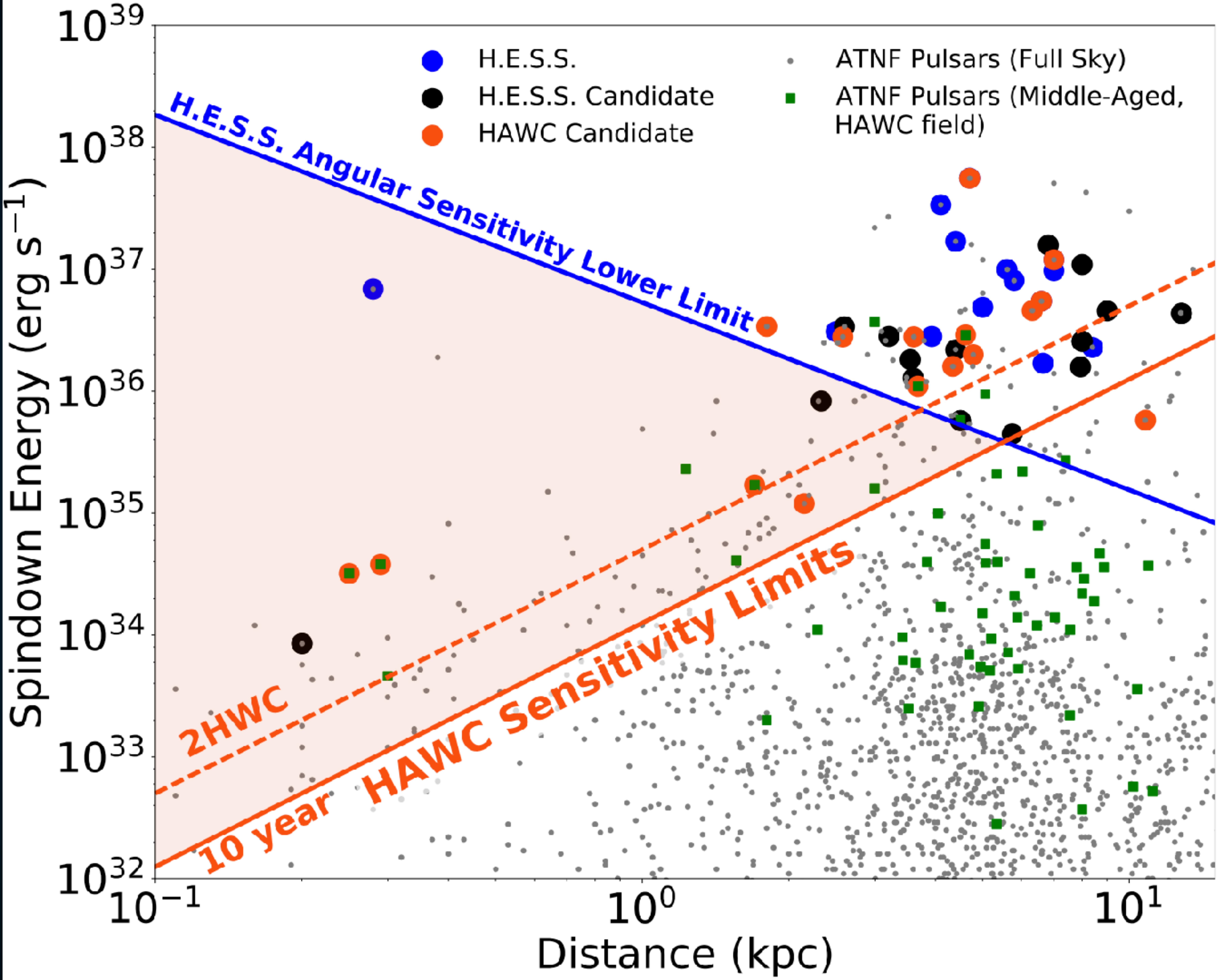
Dark Matter Searches with Cosmic-Rays

Yesterday, Today, and Tomorrow

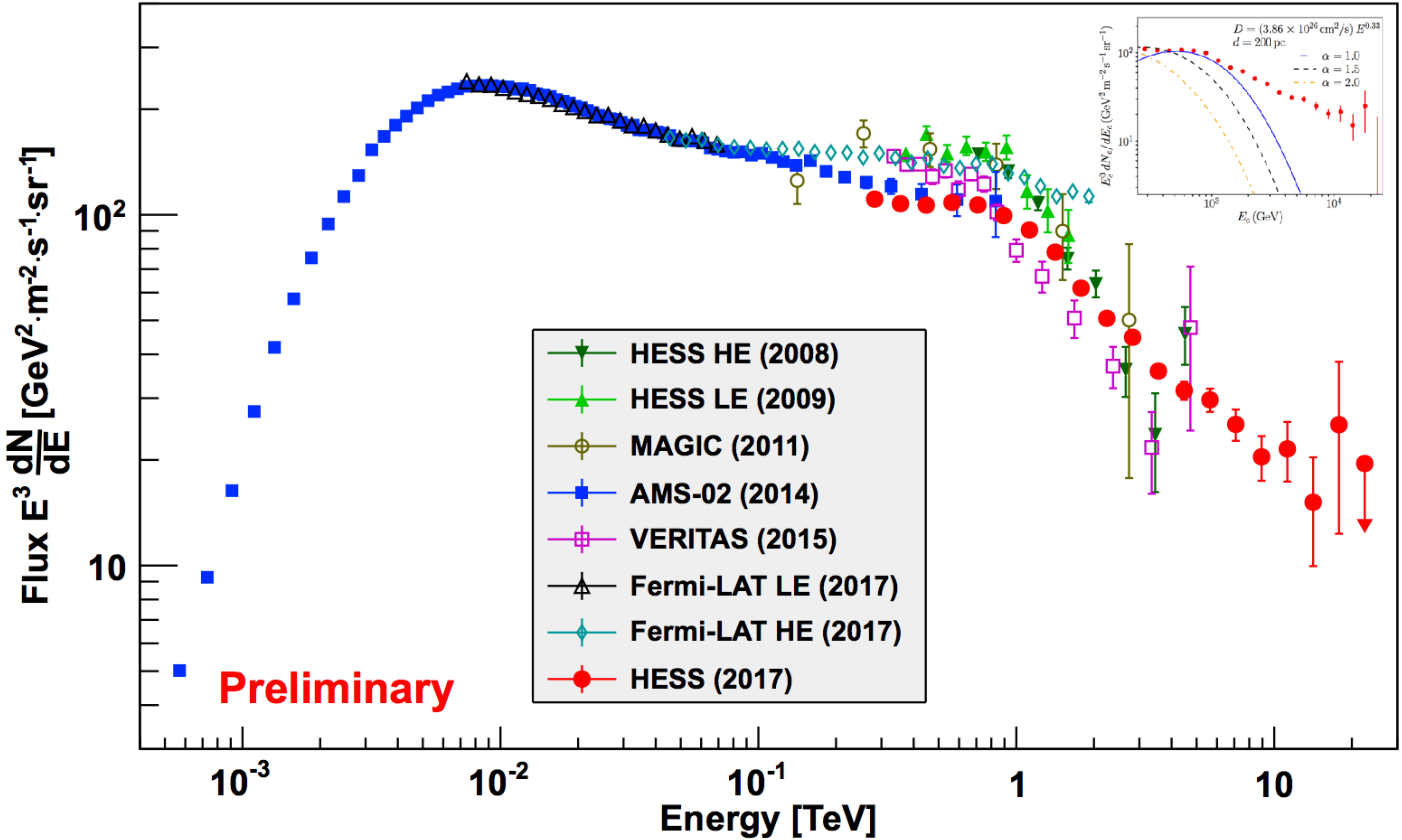
Need to produce a complete model of antiprotons/antideuterons/antihelium from a dark matter annihilation model.

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

More surprises may be in store!



H.E.S.S.
H.E.S.S. Candidate
HAWC Candidate
ATNF Pulsars (Full Sky)
ATNF Pulsars (Middle-Aged, HAWC field)
H.E.S.S. Angular Sensitivity Lower Limit
2HWC
10 year HAWC Sensitivity Limits
Spindown Energy (erg s^{-1})
Distance (kpc)
10^{39}
10^{38}
10^{37}
10^{36}
10^{35}
10^{34}
10^{33}
10^{32}
10^{-1}
10^{0}
10^{1}



Flux $E^3 \frac{dN}{dE}$ [$GeV^2 \cdot m^{-2} \cdot s^{-1} \cdot sr^{-1}$]
Energy [TeV]
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
10
HESS HE (2008)
HESS LE (2009)
MAGIC (2011)
AMS-02 (2014)
VERITAS (2015)
Fermi-LAT LE (2017)
Fermi-LAT HE (2017)
HESS (2017)
Preliminary
$D = (3.86 \times 10^{26}\ cm^2/s)\ E^{0.33}$
$d = 200$ pc
$\alpha = 1.0$
$\alpha = 1.5$
$\alpha = 2.0$
$E_e^3\ dN_e/dE_e$ ($GeV^2\ m^{-2}\ s^{-1}\ sr^{-1}$)
E_e (GeV)

10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
<σv> (cm³s⁻¹)
0.1
1
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)
300 GeV
Arbitrary Normalization
Positron Fraction
0.3
0.1
0.03
1
10
100
Kinetic Energy (GeV)
e^+e^-
$\mu^+\mu^-$
$\tau^+\tau^-$
$b\bar{b}$
$b\bar{b}$
e^+e^-
$b\bar{b}$ Limit (Planck)
e^+e^- Limit (Planck)
Thermal Cross-Section
$\tau^+\tau^-$
e^+e^-
Bergström et al. (2013; 1306.3983)