Tim Linden

Precision Cosmic-Ray Searches with AMS-02

The Ohio State University
CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

AMS has collected

145,449,075,035

cosmic ray events

Last update: September 21, 2019, 4:07 PM

Welcome

AMS on ISS

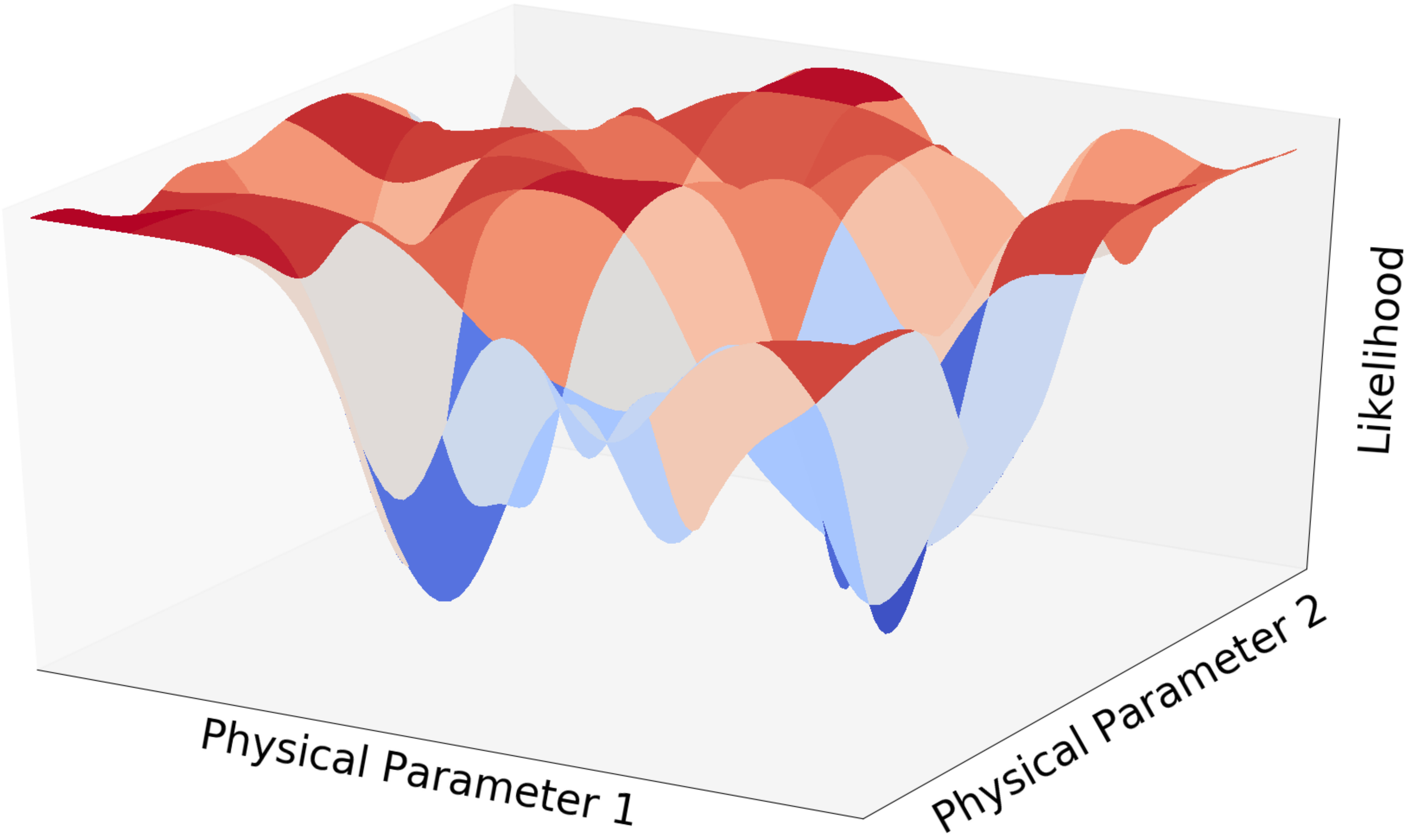
AMS Events

With Great Precision Comes Great Responsibility

Tim Linden

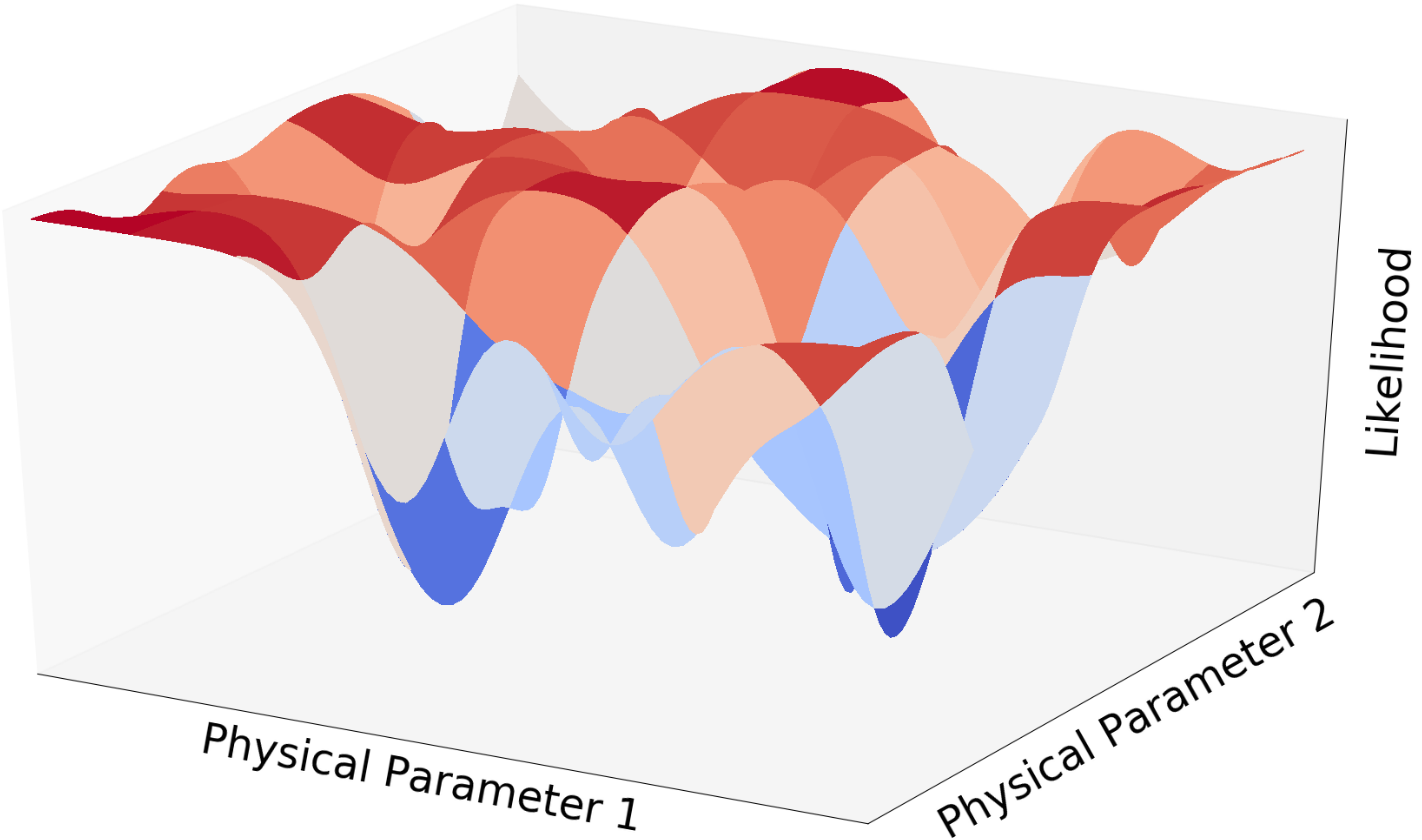
Precision Cosmic-Ray Searches with AMS-02

THE OHIO STATE UNIVERSITY
CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

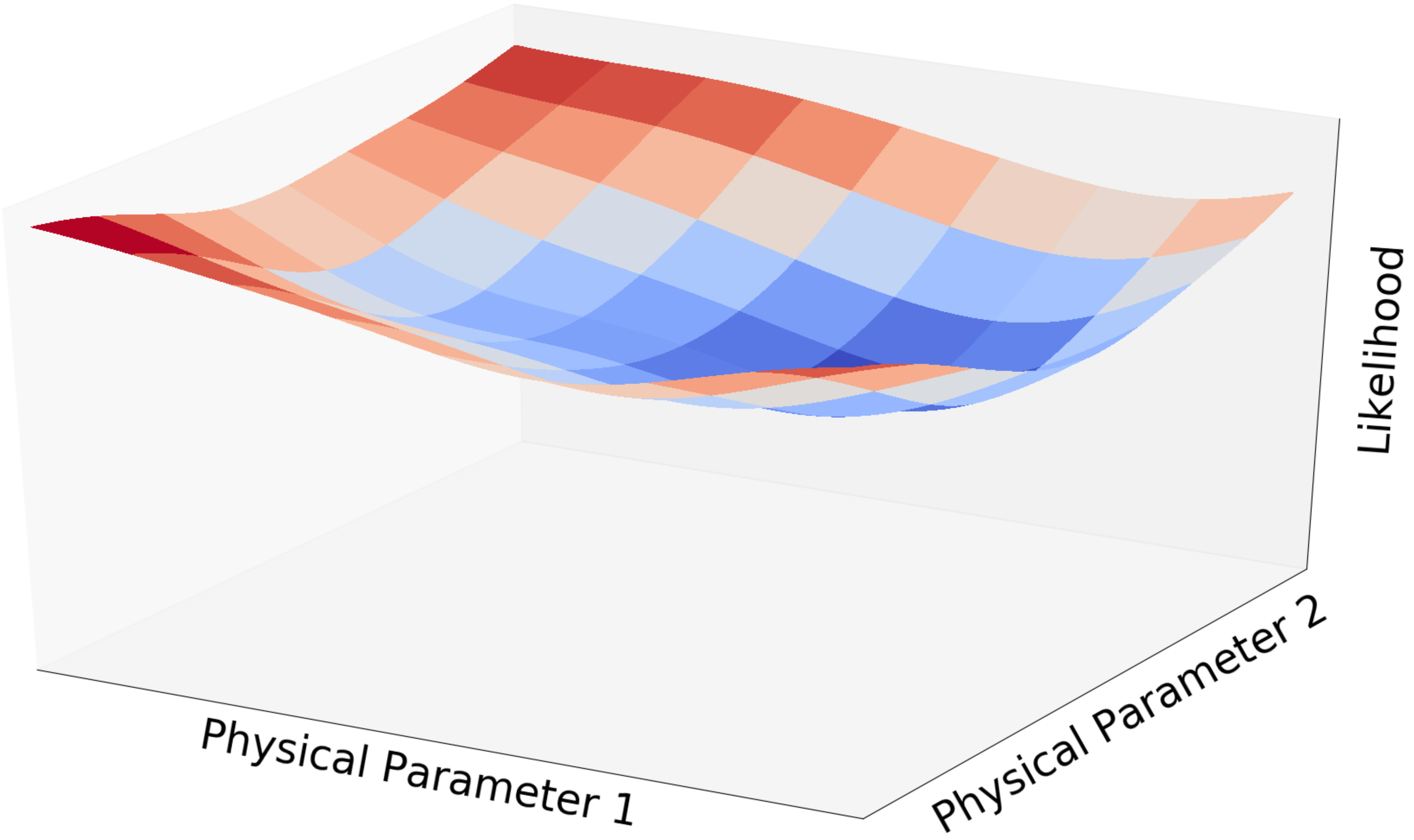

Likelihood
Physical Parameter 1
Physical Parameter 2

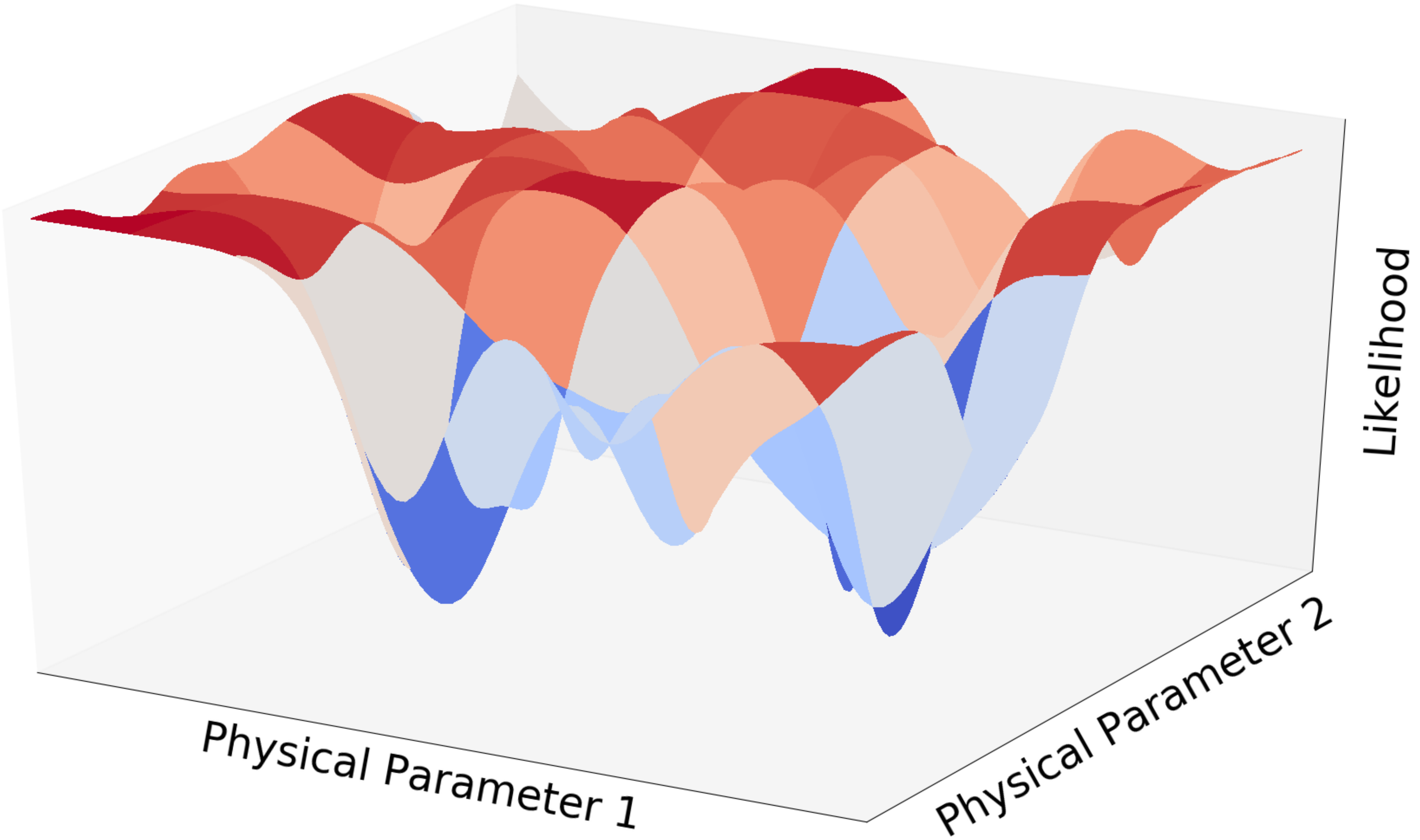
Antiproton Ratio ($\times 10^{-5}$)
30
20
10
5
3
1
10
100
1000
Kinetic Energy (GeV)


Antiproton Ratio ($\times 10^{-5}$)
30
20
10
5
3
1
10
100
1000
Kinetic Energy (GeV)
Proton Anisotropy ($\times 10^{-4}$)
100
30
10
3
1
1
10
100
1000
Kinetic Energy (GeV)


Likelihood
Physical Parameter 1
Physical Parameter 2

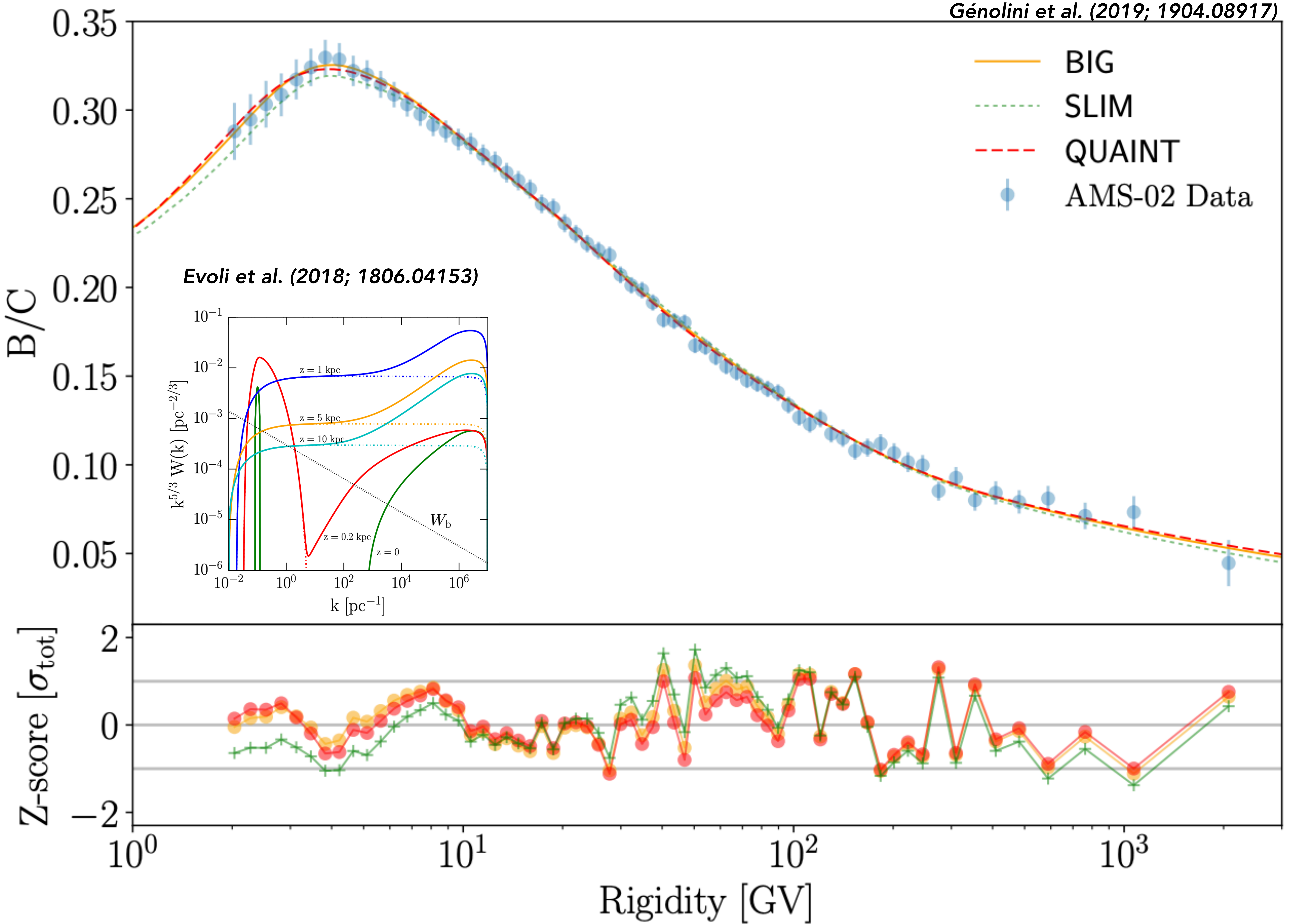
0.3
0.2
0.1
0.05
0.03
B/C
1
10
100
1000
Rigidity (GV)


Likelihood
Physical Parameter 1
Physical Parameter 2

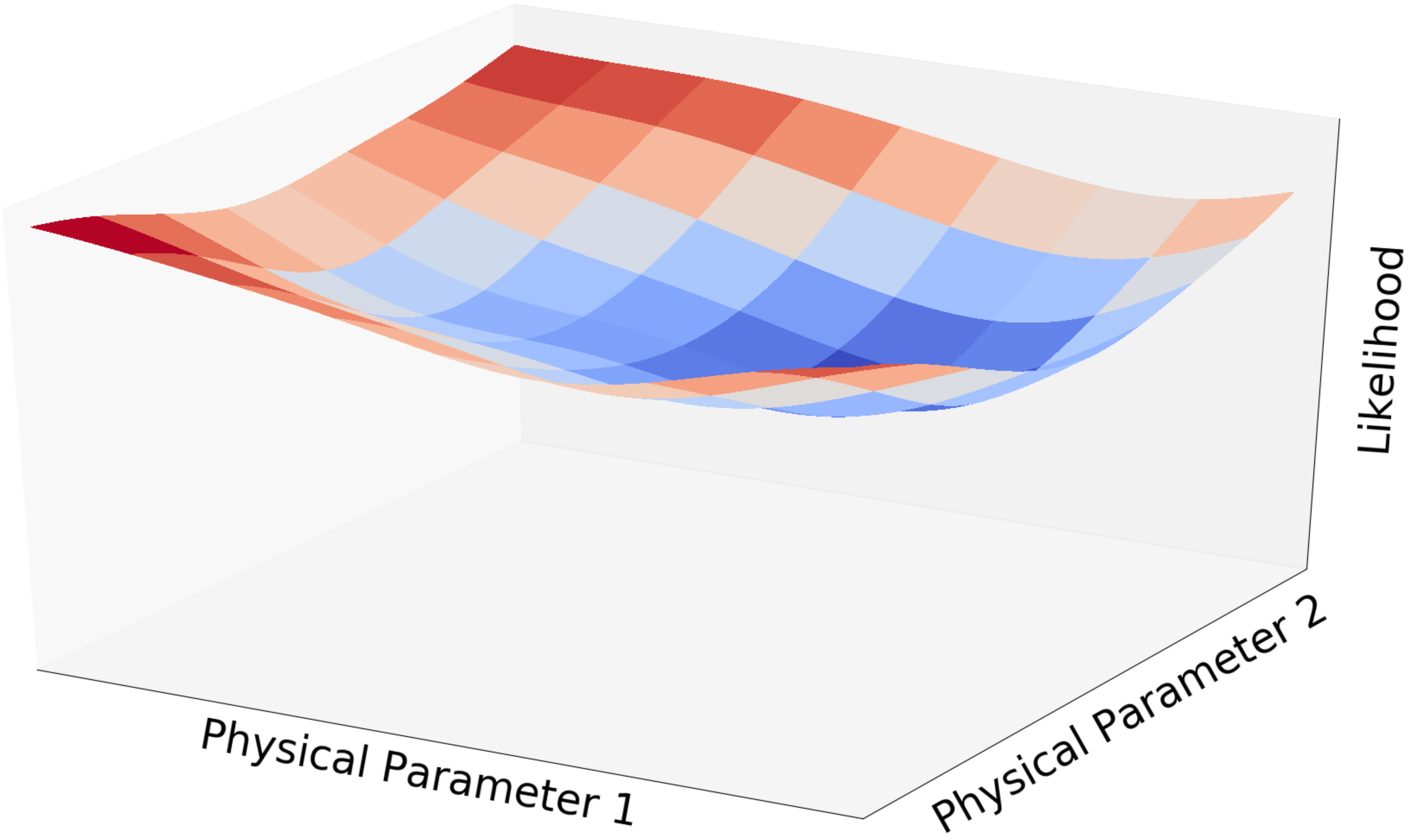

Physical Parameter 1
Physical Parameter 2
Likelihood


PLANCK Collaboration


π± → μ± → e±
SNR
p,e⁻
Sun
p
χ̃
e⁻
e⁺
χ̃



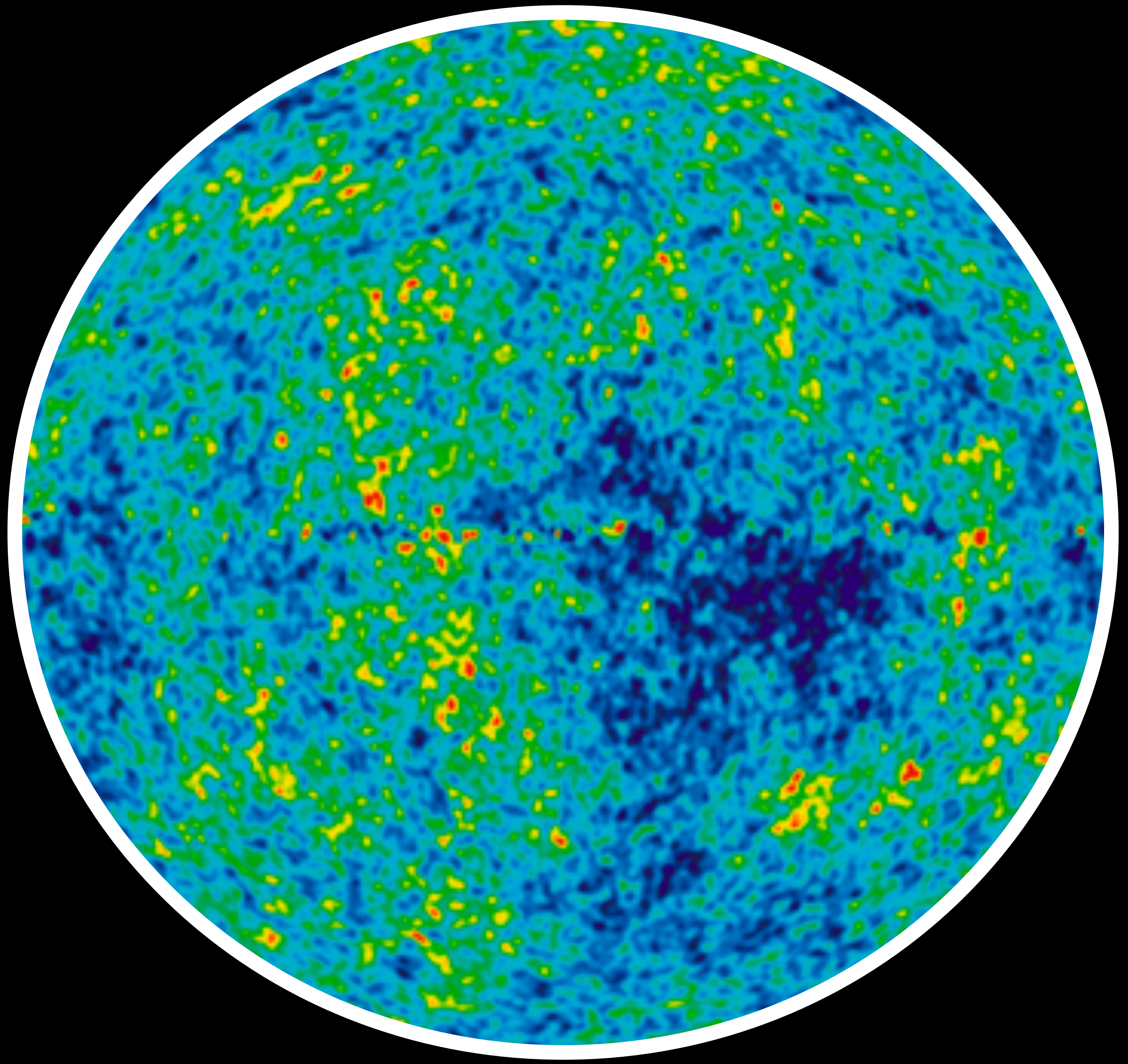
Génolini et al. (2019; 1904.08917)
BIG
SLIM
QUAINT
AMS-02 Data
B/C
Evoli et al. (2018; 1806.04153)
z = 1 kpc
z = 5 kpc
z = 10 kpc
z = 0.2 kpc
z = 0
W_b
$k^{5/3}$ W(k) [$pc^{-2/3}$]
k [pc^{-1}]
Z-score [σ_{tot}]
Rigidity [GV]

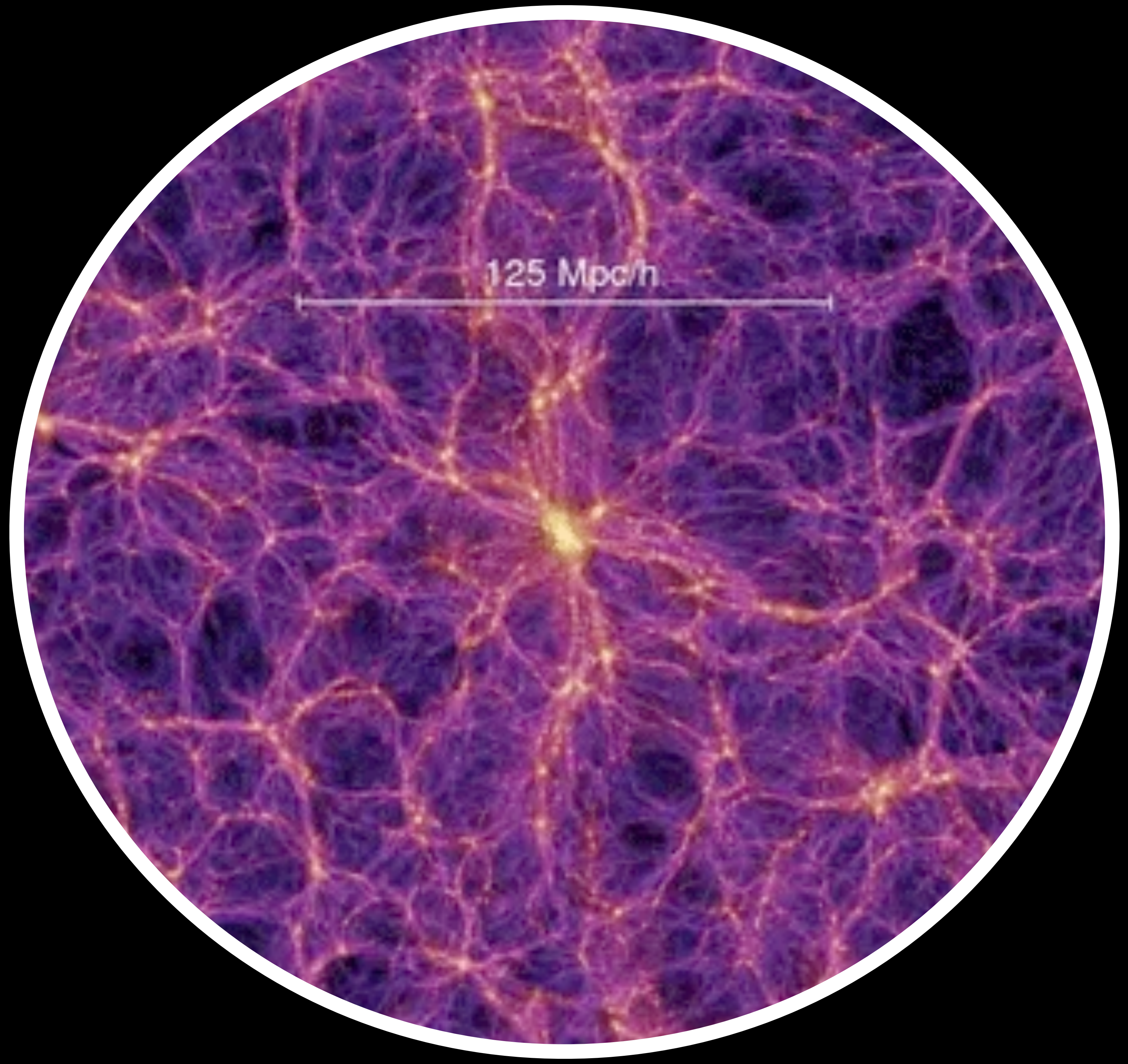

Likelihood
Physical Parameter 1
Physical Parameter 2

Topic 1: Dark Matter

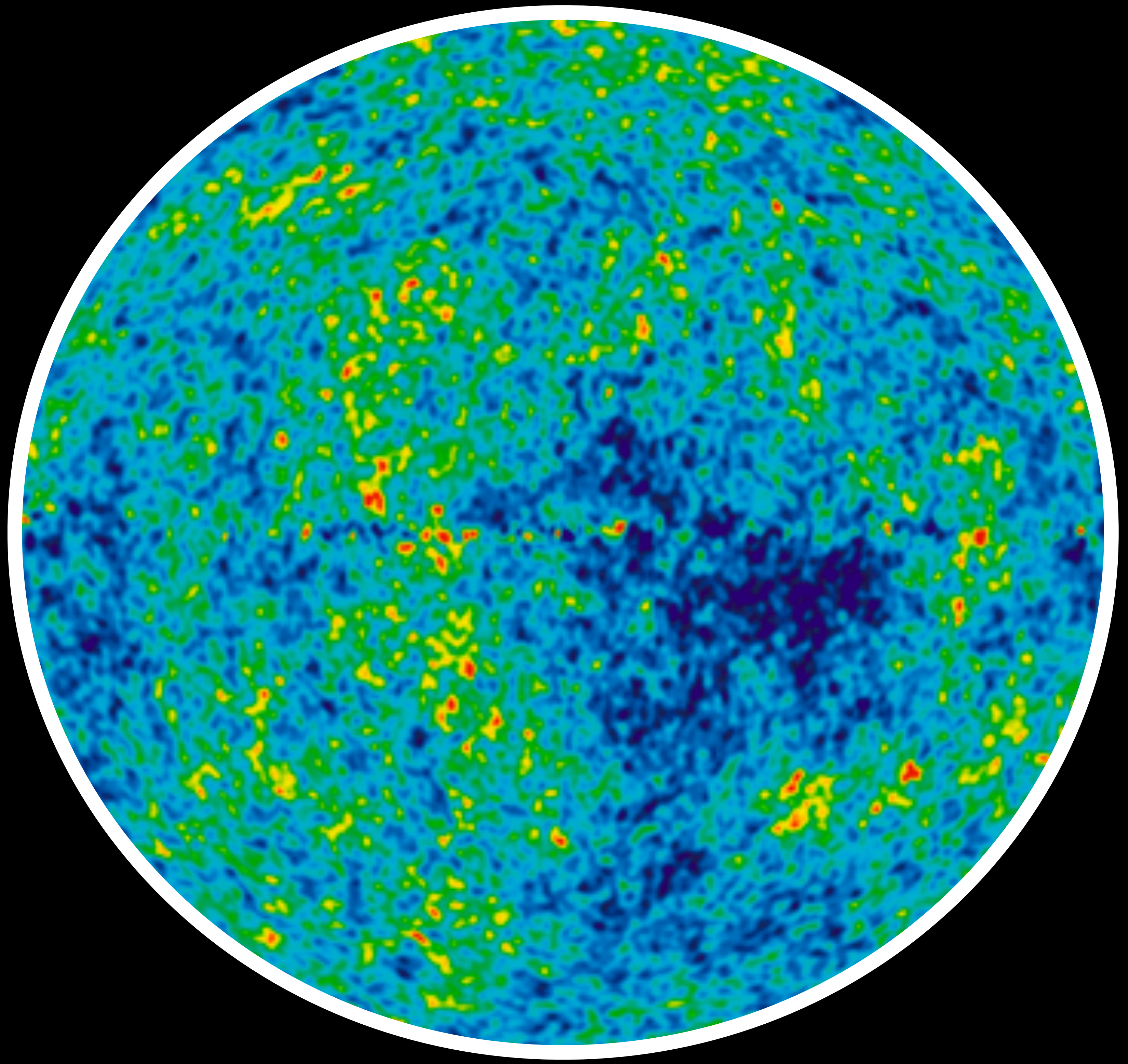
Topic 2: Solar Physics

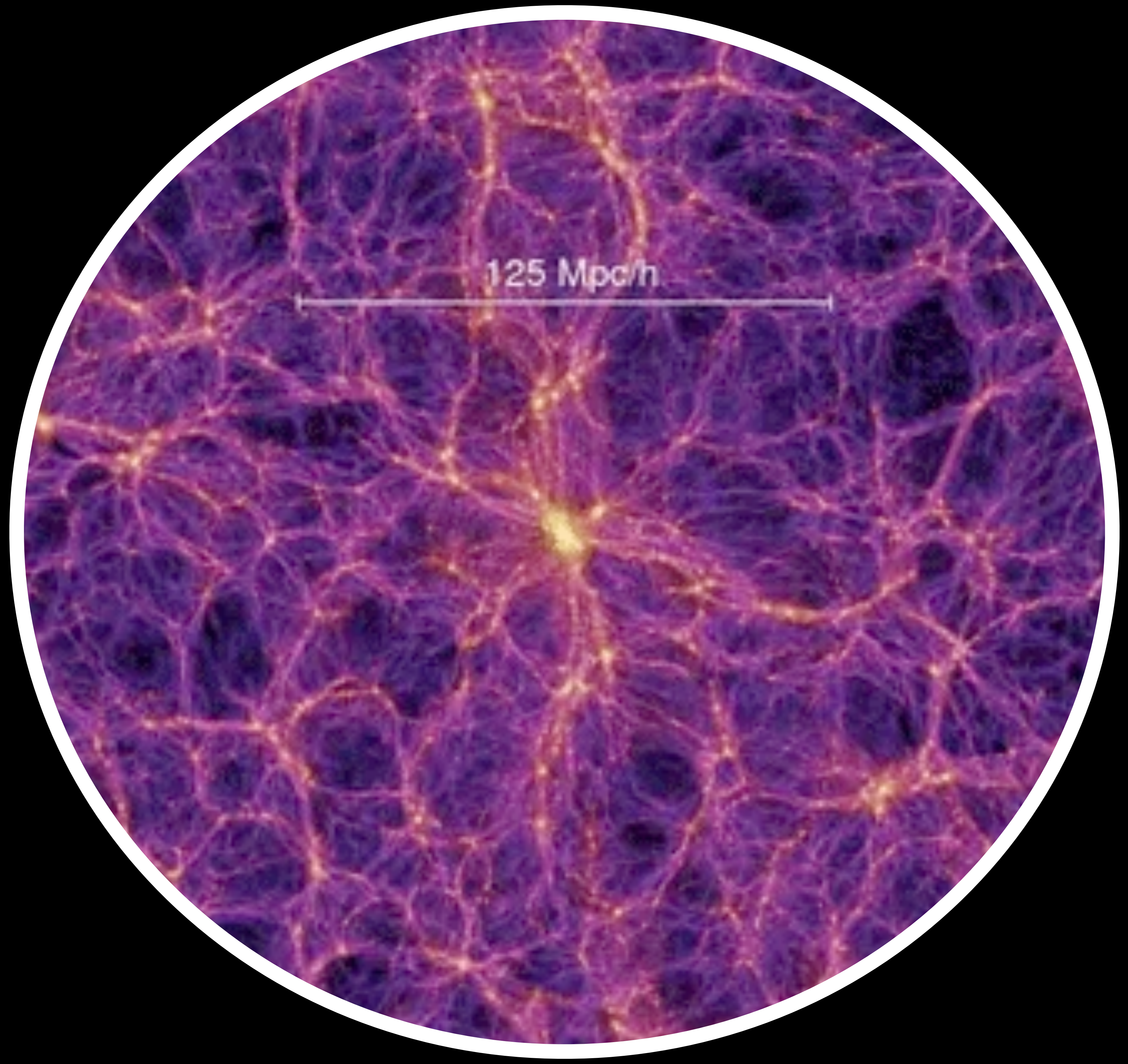
The Present





The Present





10^{-25} GeV

$R_{DM} > R_{UFD}$

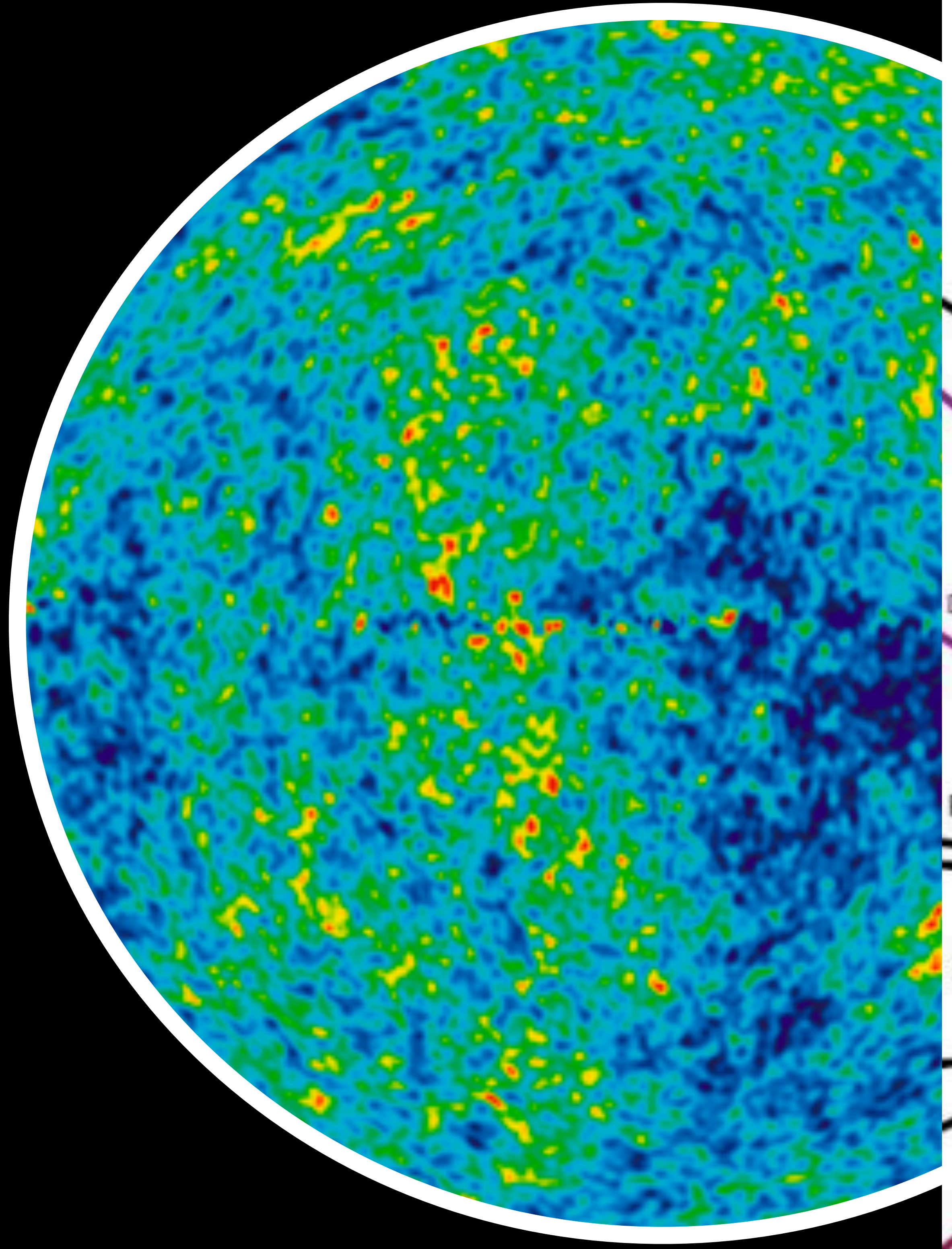
10^{62} GeV

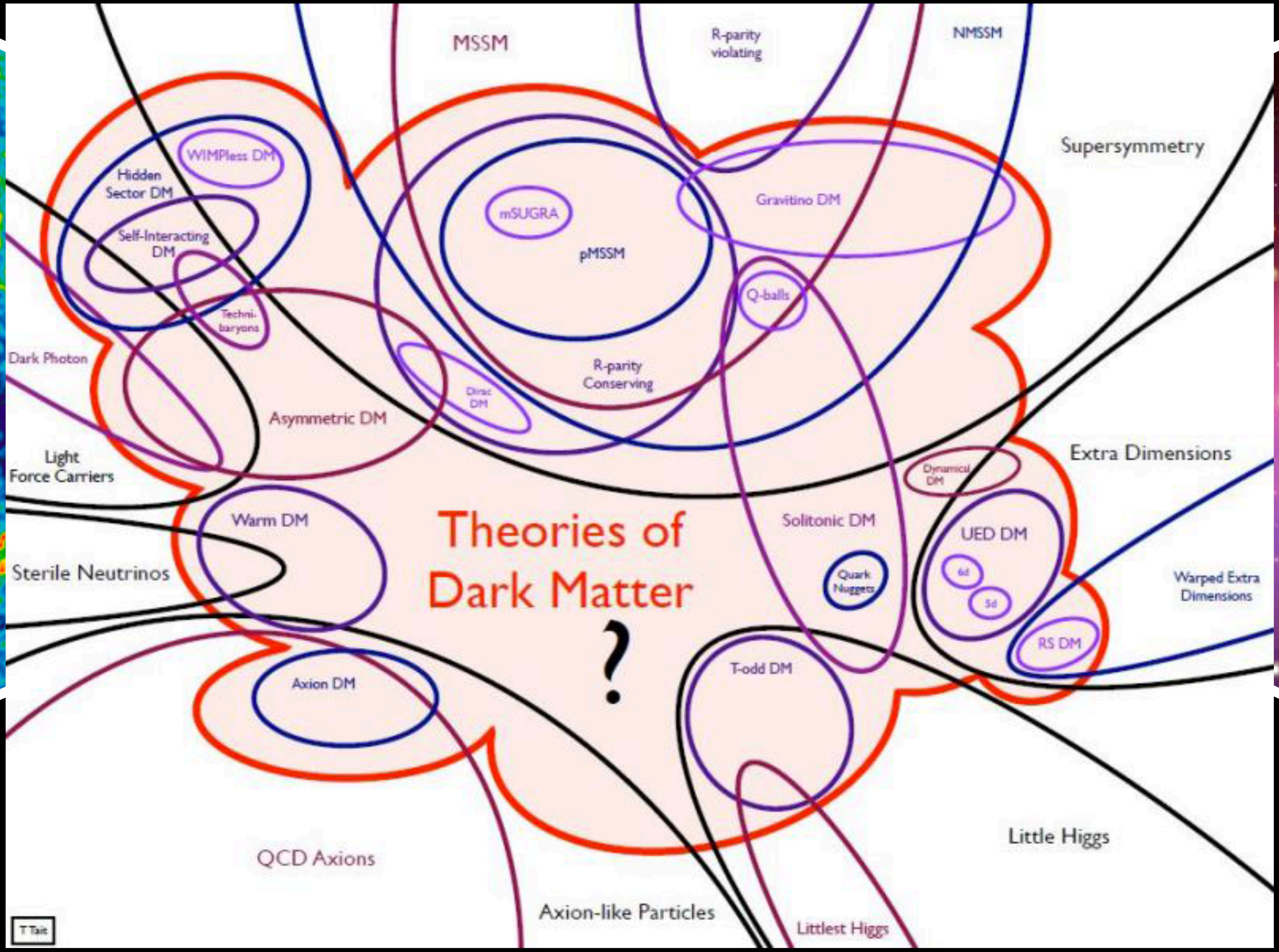
$M_{DM} > M_{UFD}$

slide concept courtesy of Asher Berlin

The Present

courtesy: Tim Tait





10^{-25} GeV

$R_{DM} > R_{UFD}$

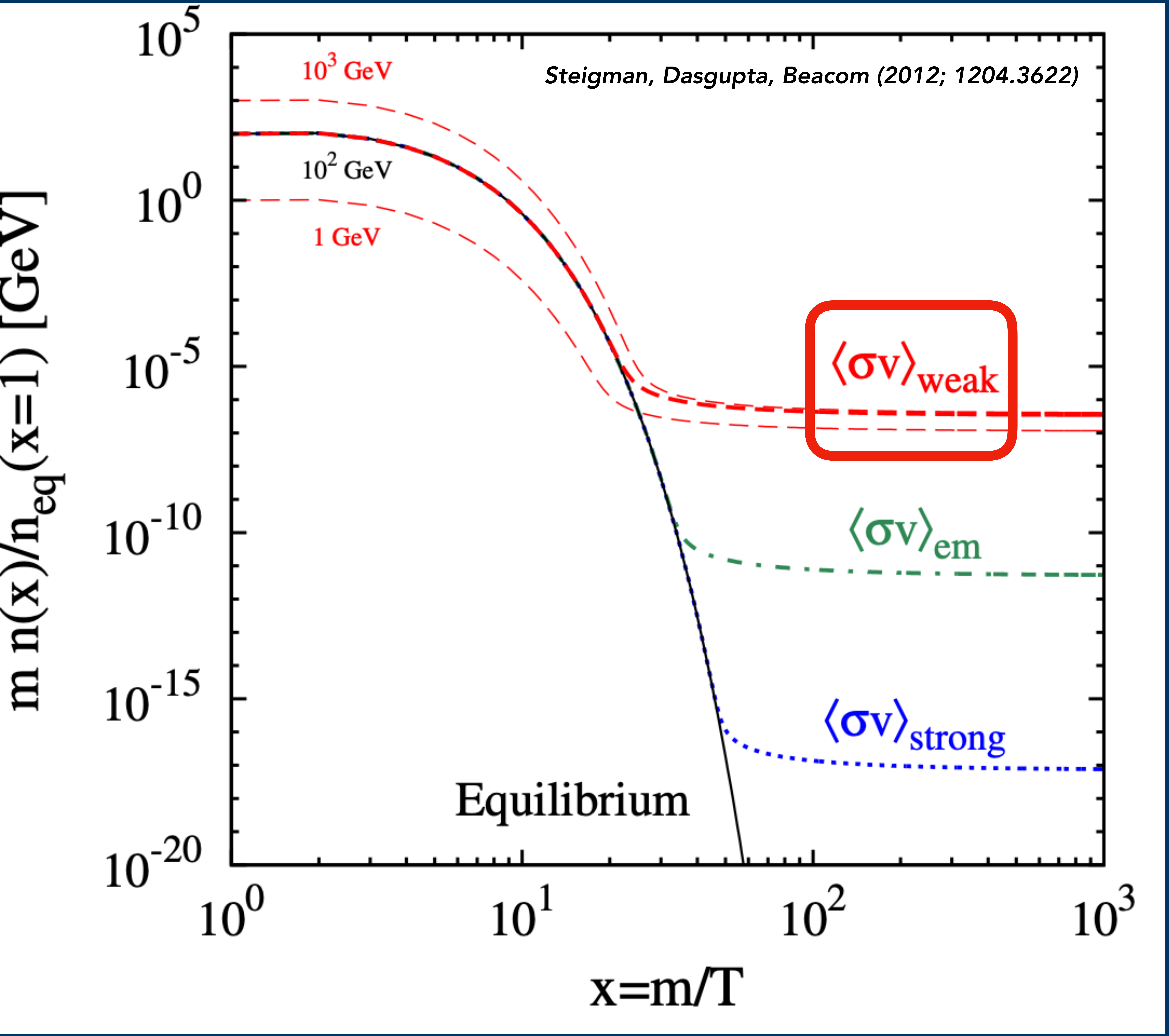
slide concept courtesy of Asher Berlin

10^{62} GeV

$M_{DM} > M_{UFD}$

Thermal Dark Matter

artist: Sarah Szabo

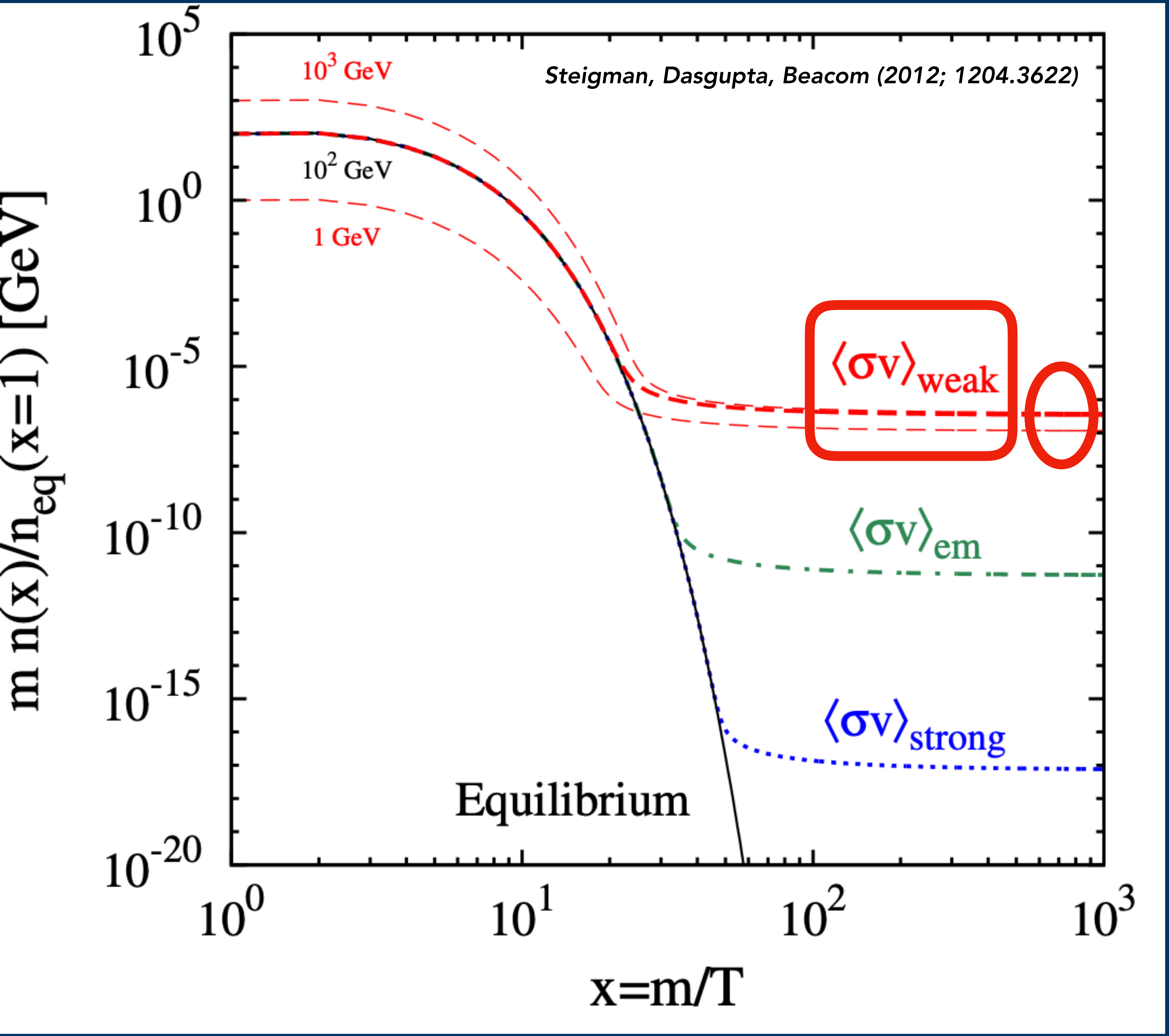


Thermal Dark Matter Density

Present density inversely proportional to the strength of the interaction.

Almost independent of particle mass.

Weak-Interaction Produces the right density!



Thermal Dark Matter Density

Present density inversely proportional to the strength of the interaction.

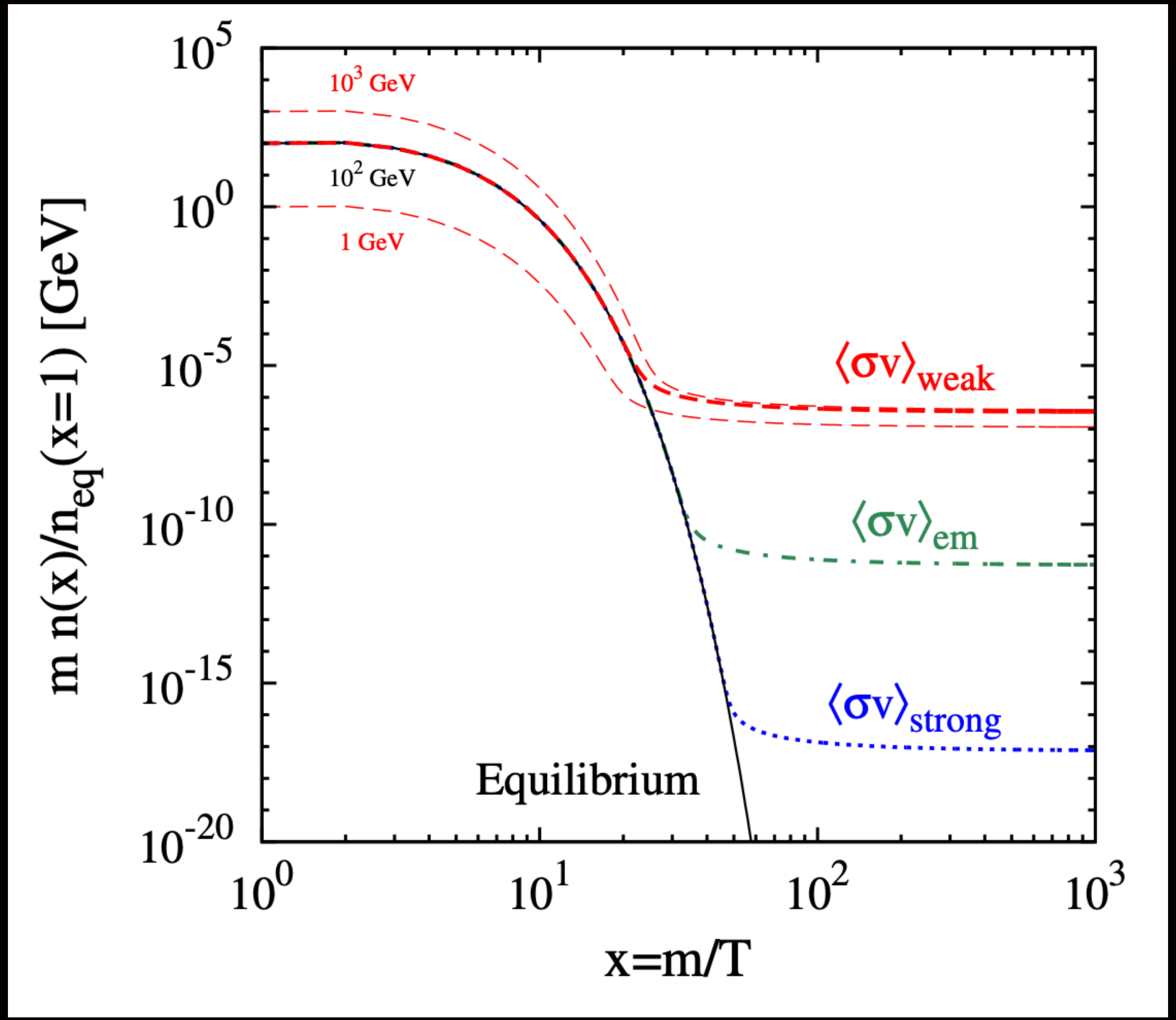
Almost independent of particle mass.

Weak-Interaction Produces the right density!

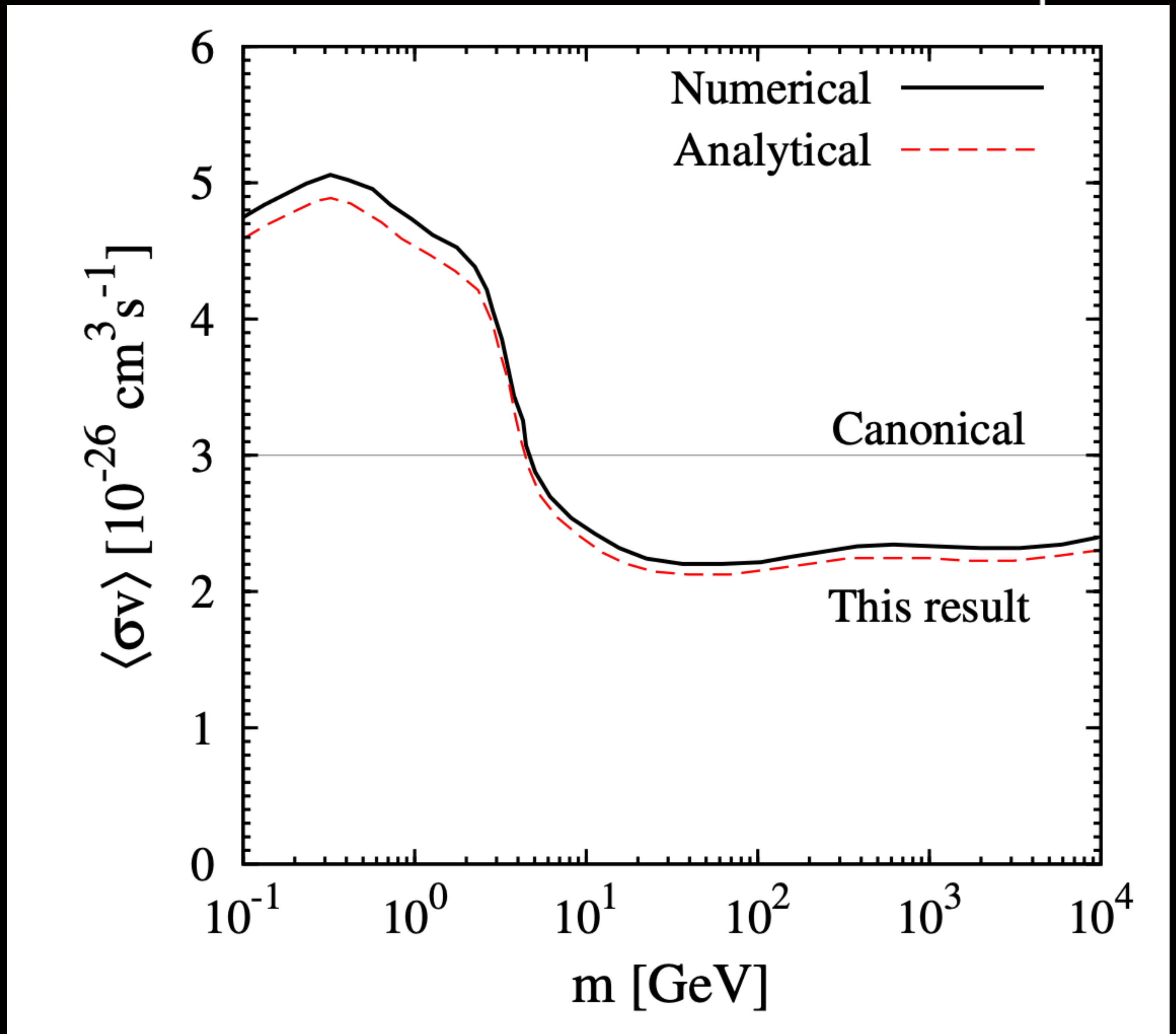
10 MeV - 100 TeV !

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

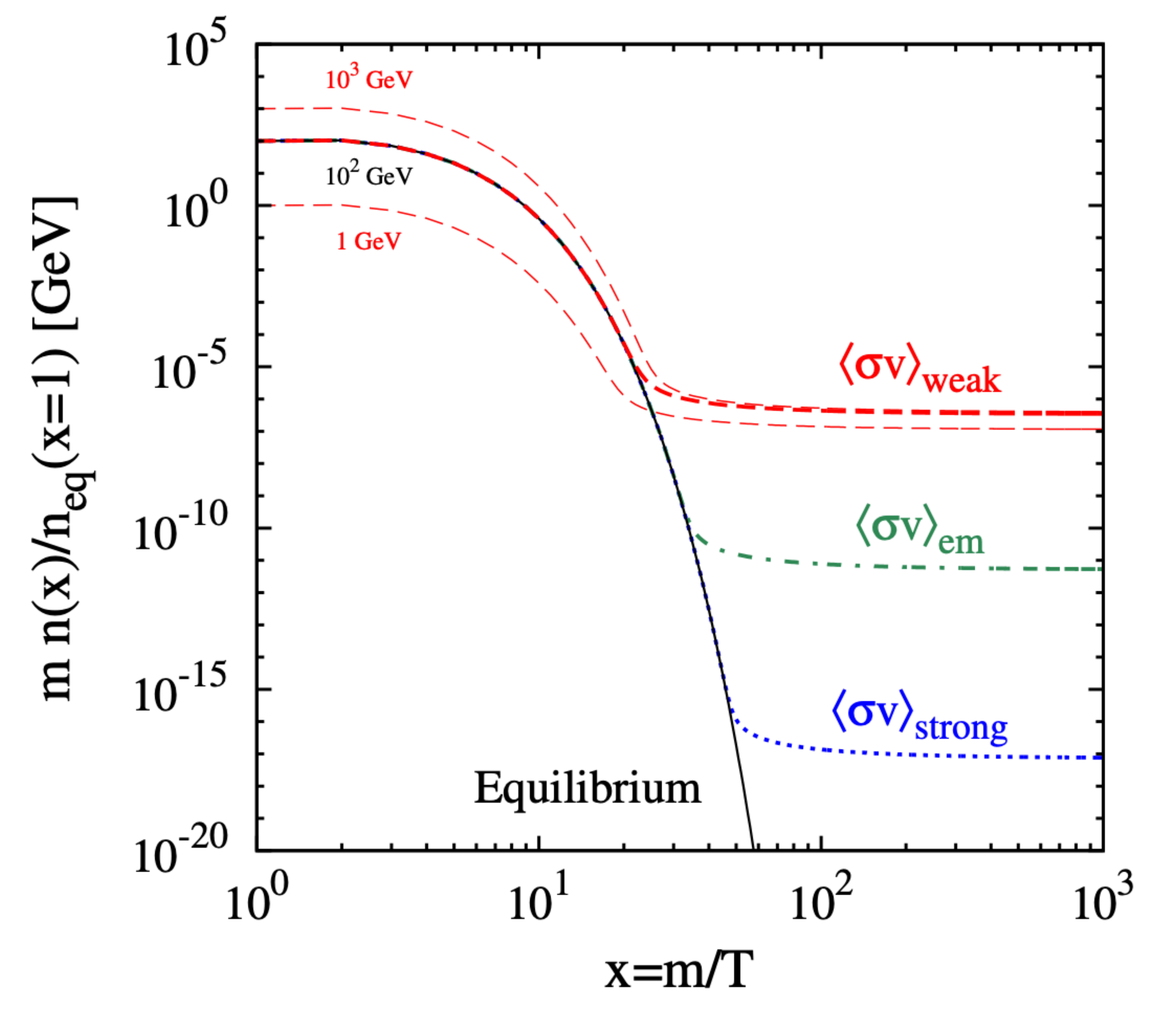
Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Age
Formation of first astronomical object
Present day
Fully ionized
Neutralized
Reionization
Fully ionized
1000
100
10
1
1+Redshift



10^3 GeV
10^2 GeV
1 GeV
$\langle\sigma v\rangle_{weak}$
$\langle\sigma v\rangle_{em}$
$\langle\sigma v\rangle_{strong}$
Equilibrium
m n(x)/n_eq(x=1) [GeV]
x=m/T

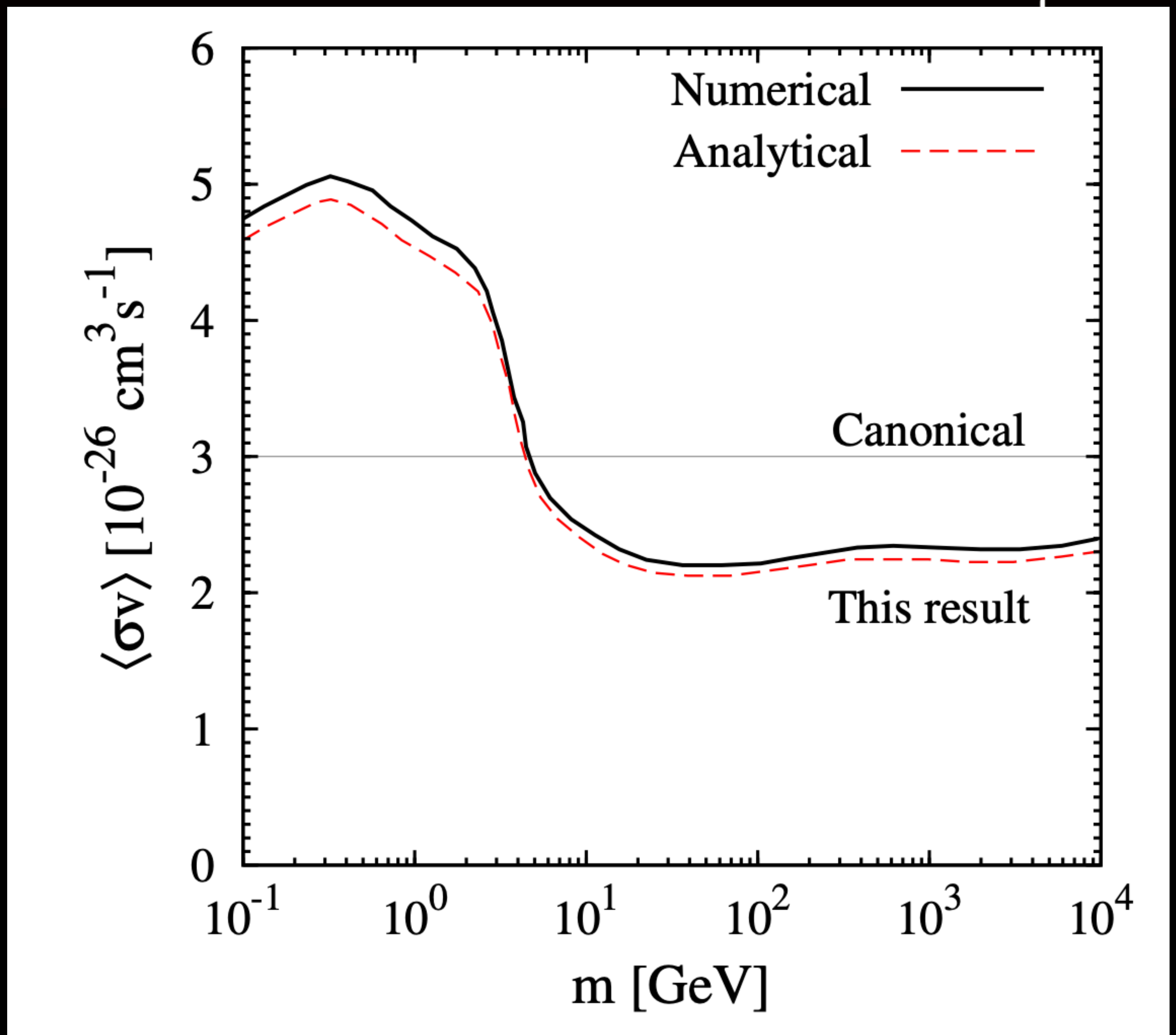


Numerical
Analytical
Canonical
This result
$\langle\sigma v\rangle$ [10^{-26} cm^3 s^{-1}]
m [GeV]



Philosophy:

Constrain the simplest model first



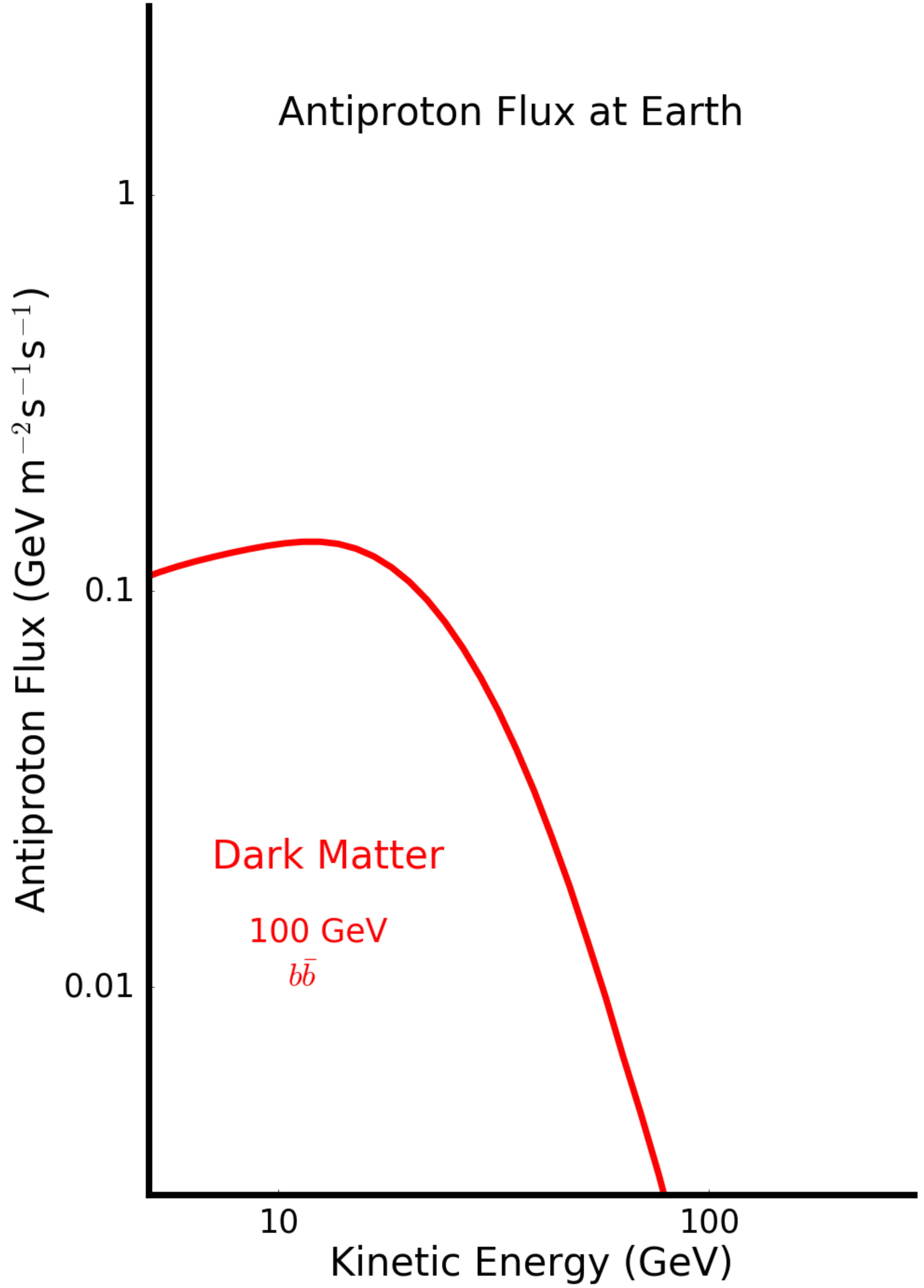
Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

Thermal Cross-Section (Early Universe)

Dark Matter Mass (?)

Convection of Annihilation Products from GC (Winds?)



Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

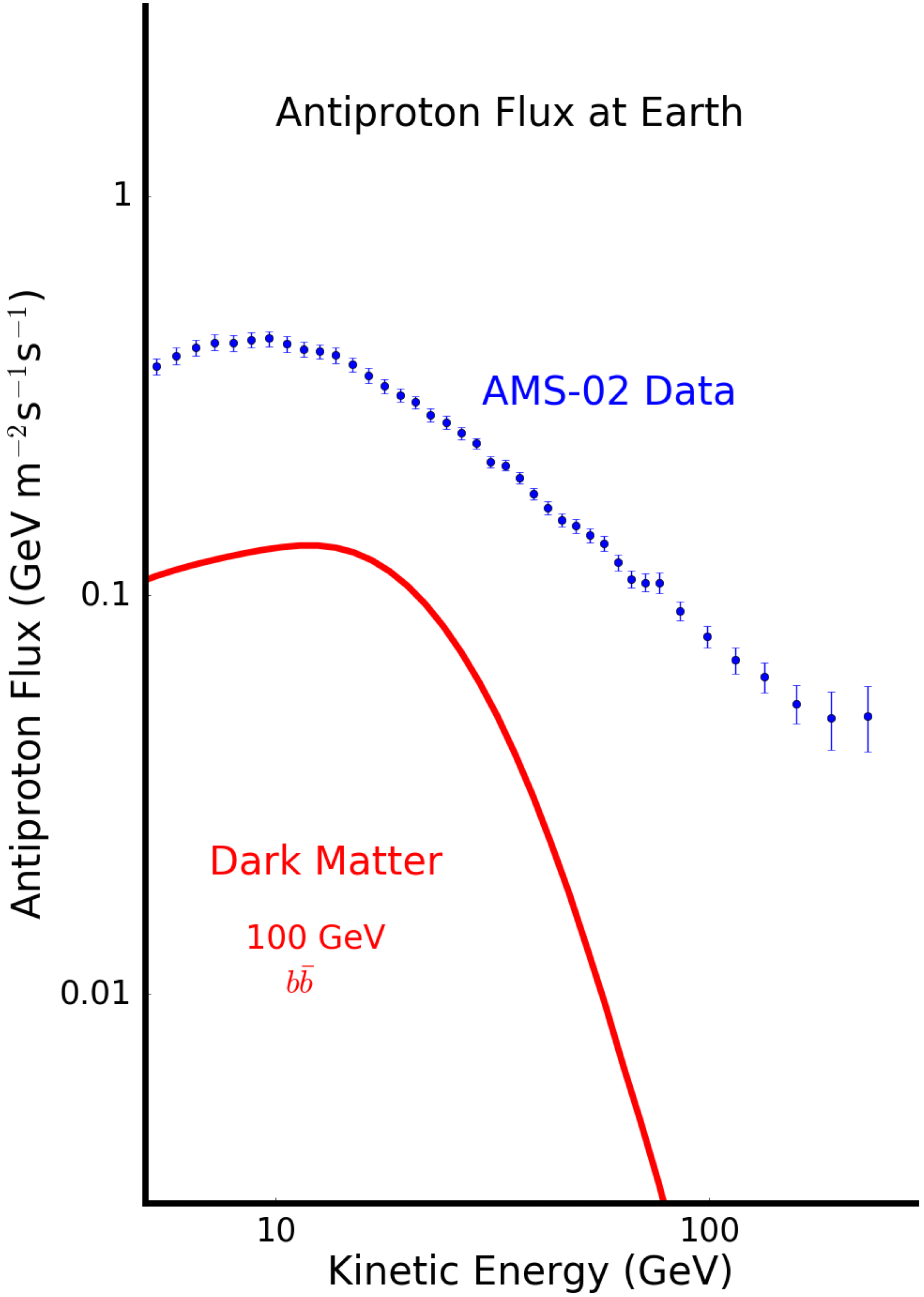
Thermal Cross-Section (Early Universe)

Hadronic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Local Gas Density

Local Supernova Rate



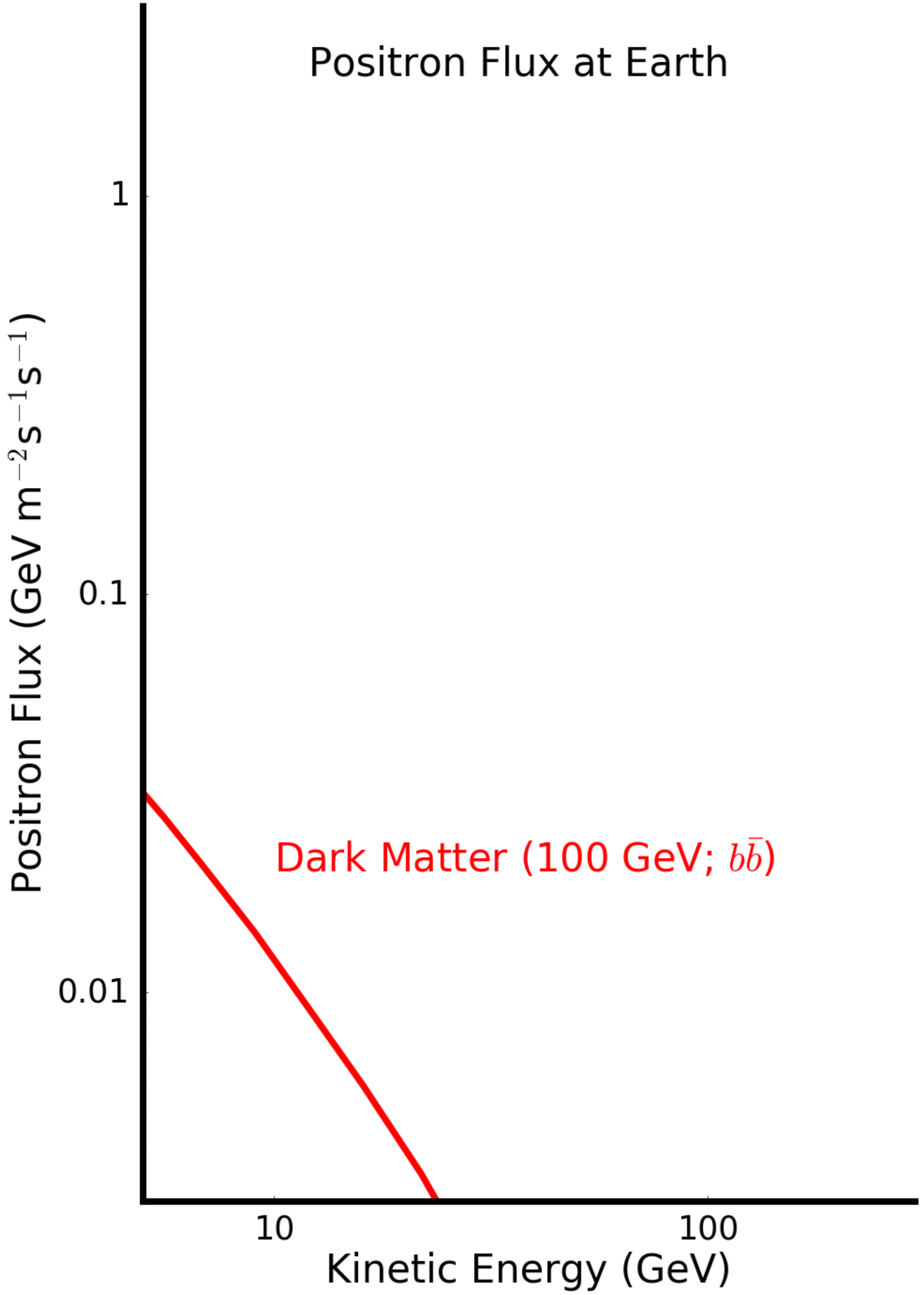
Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

Thermal Cross-Section (Early Universe)

Leptonic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)



Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

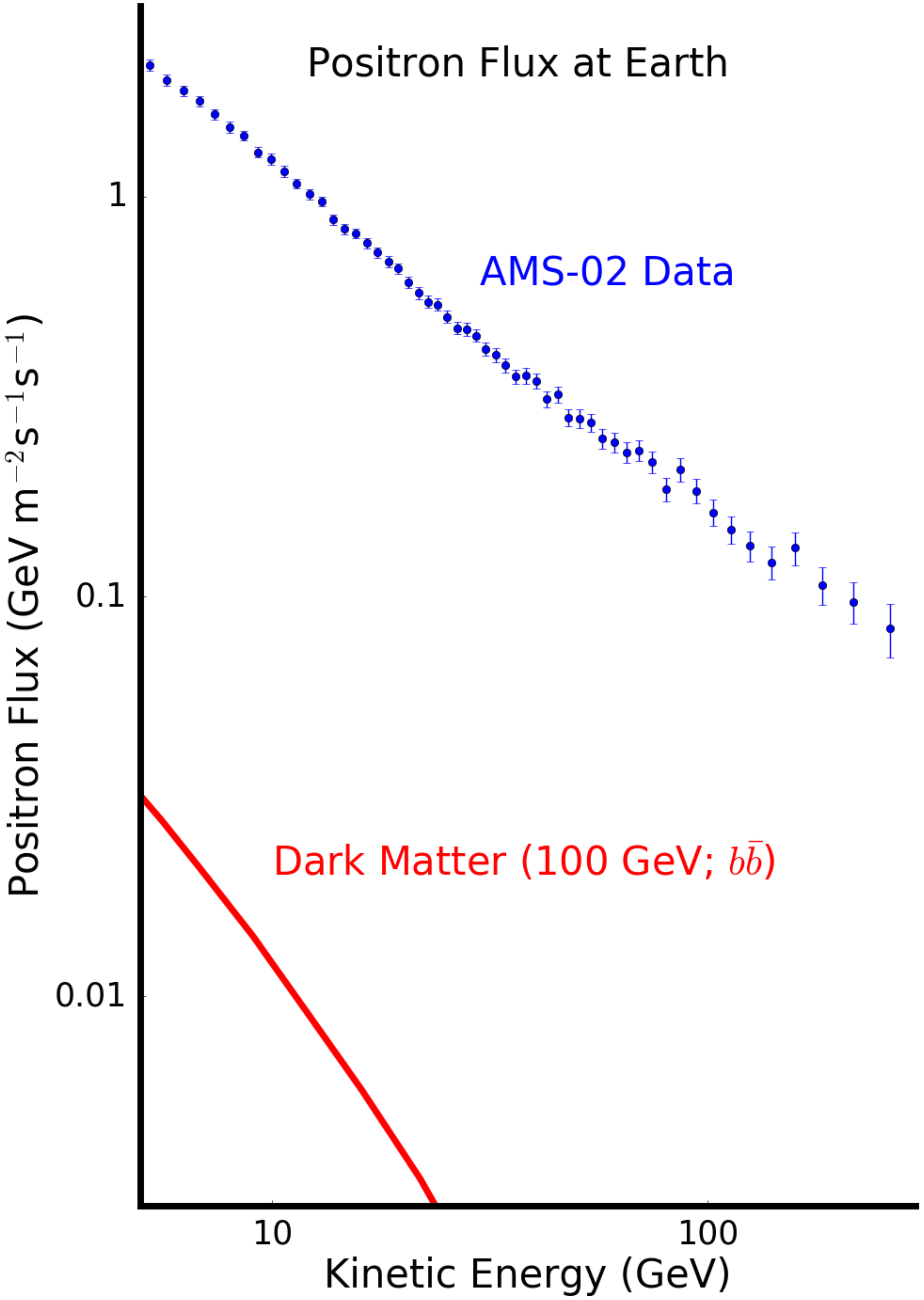
Thermal Cross-Section (Early Universe)

Leptonic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Pulsar Birth Rate

e^+e^- Acceleration Efficiency in Pulsar Magnetospheres



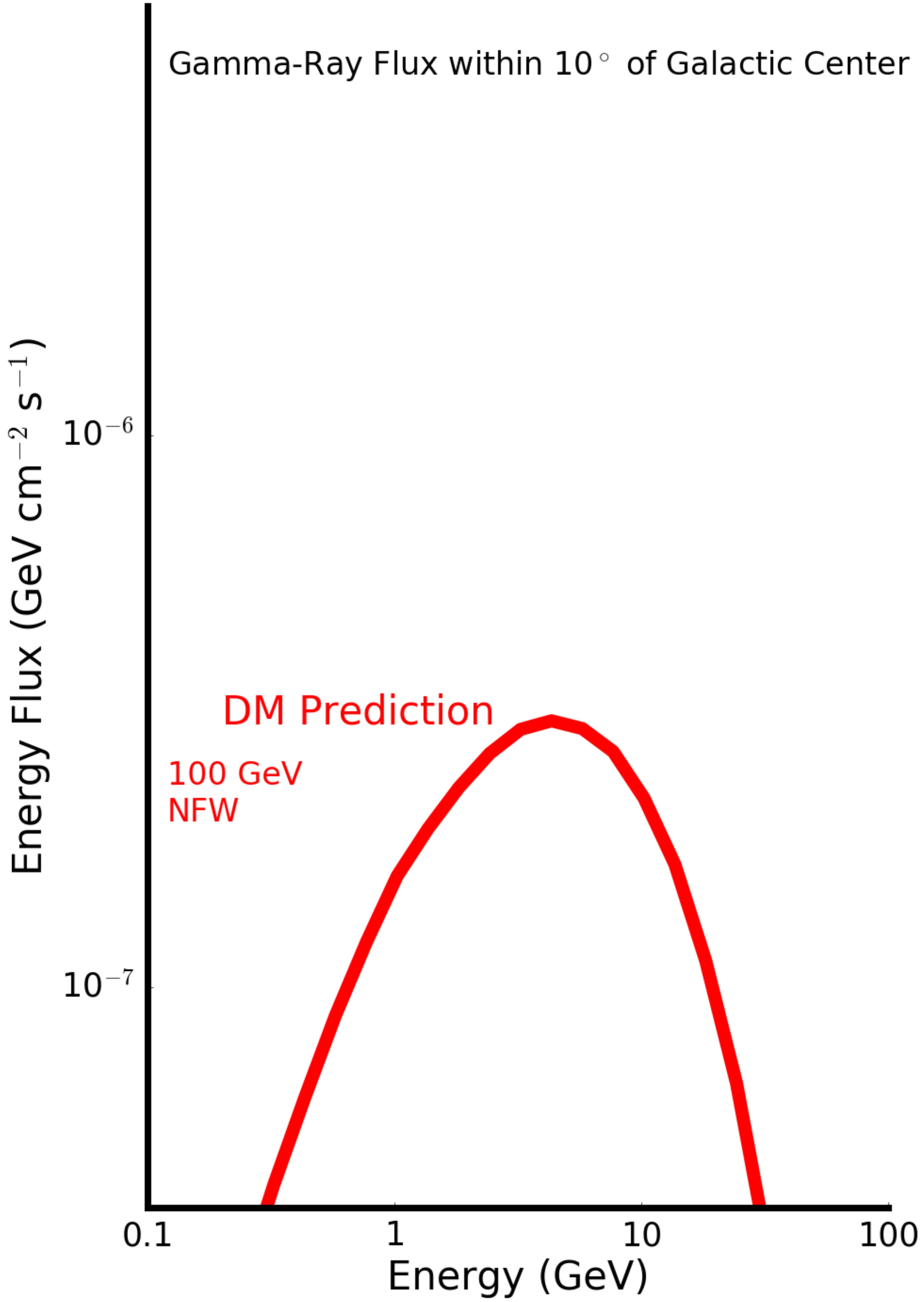
Thermal WIMPs and the Story of Tantalus

NFW Profile (Mass of Milky Way)

Thermal Cross-Section (Early Universe)

Dark Matter Mass (?)

Annihilation Final State (?)



Thermal WIMPs and the Story of Tantalus

NFW Profile (Mass of Milky Way)

Thermal Cross-Section (Early Universe)

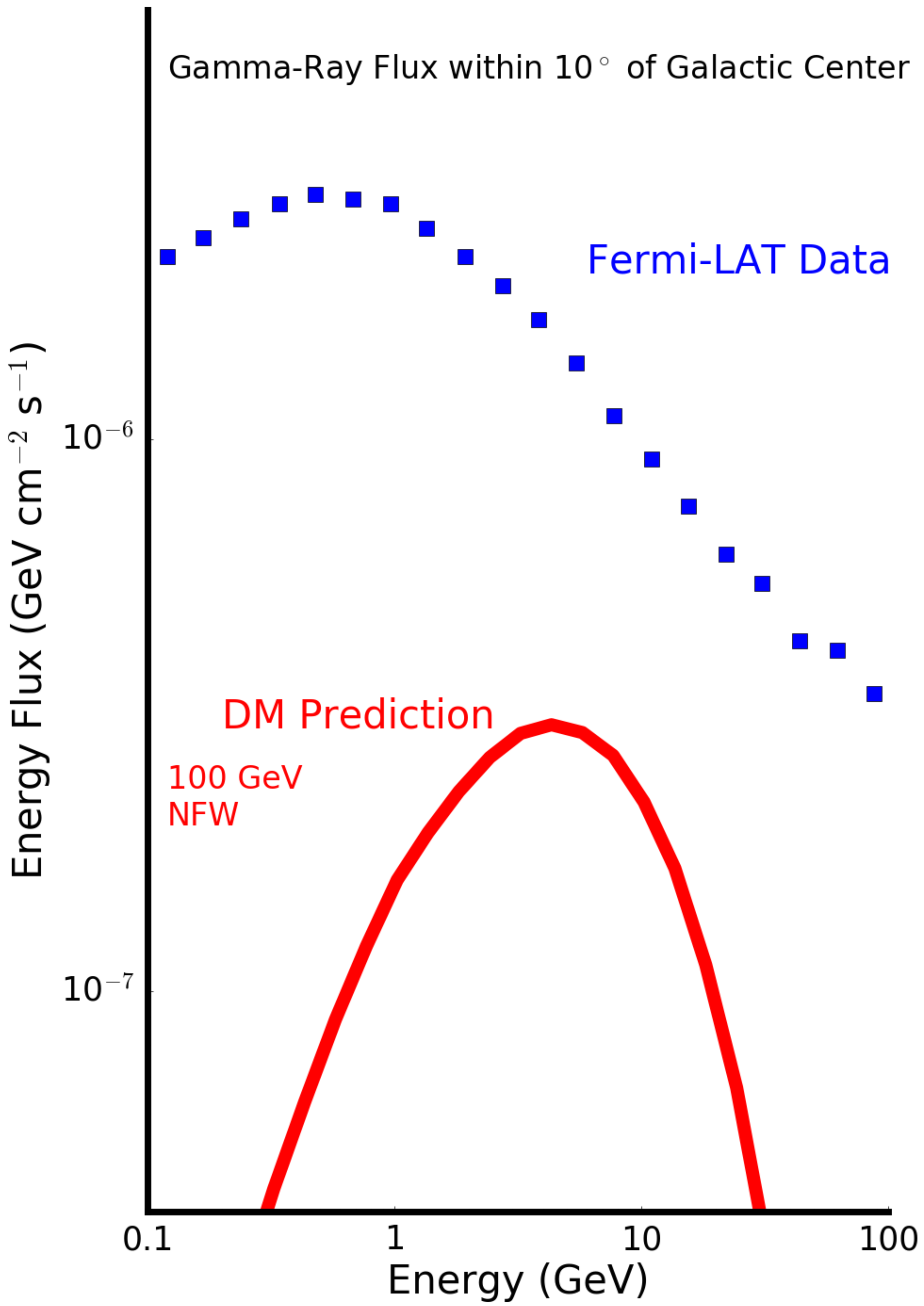
Dark Matter Mass (?)

Annihilation Final State (?)

Milky Way Star-Formation Rate (Galactic Dynamics)

Diffusion Constant in Galactic Center (Hydrodyanmics)

Activity of Supermassive Blackhole (?)



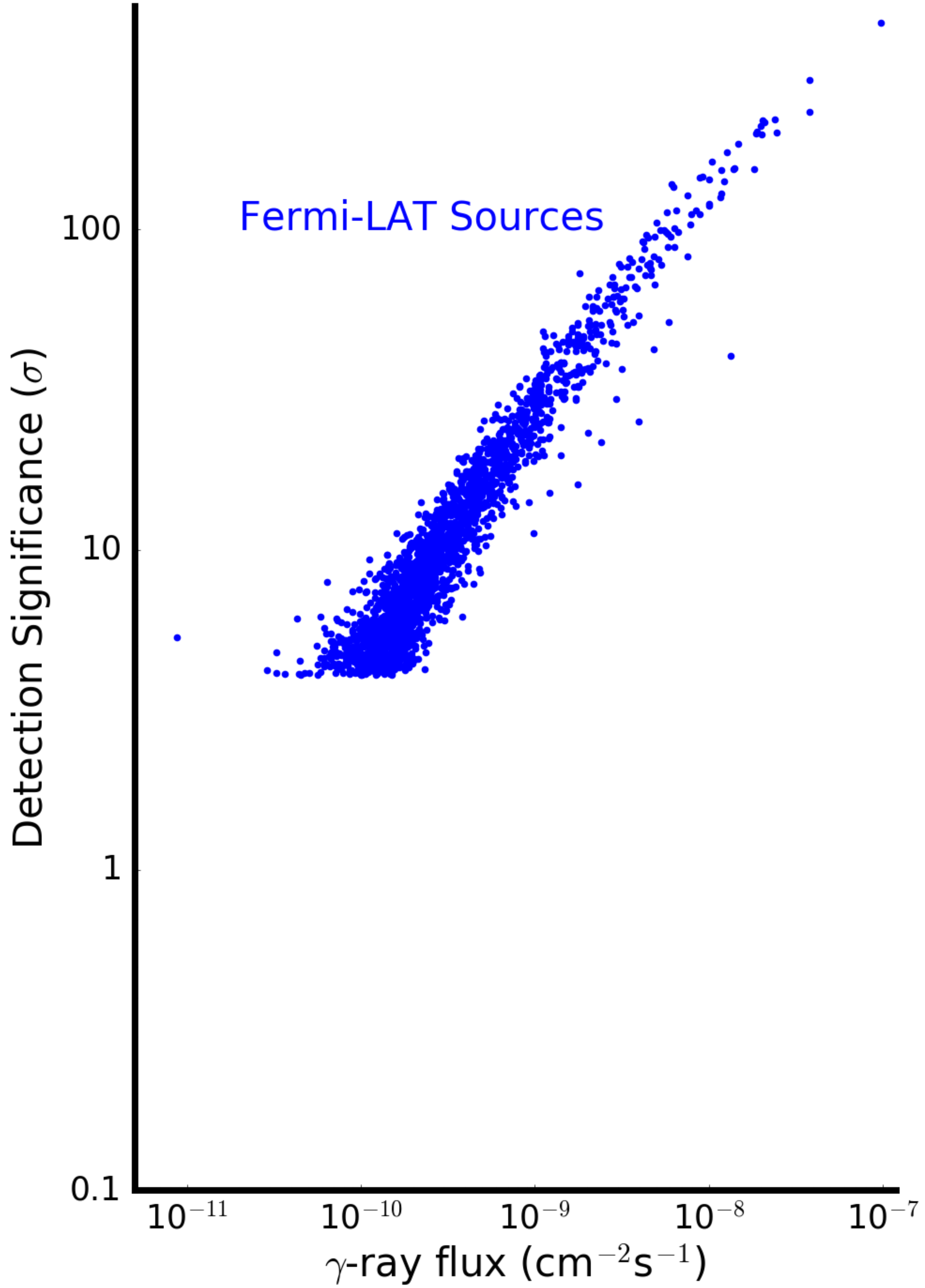
Thermal WIMPs and the Story of Tantalus

SMBH Accretion Efficiency (Magnetohydrodynamics)

Blazar Acceleration Mechanisms (Leptonic? Hadronic?)

Radio Galaxy Emission Models

Star-Formation Rates in Starburst Galaxies



Thermal WIMPs and the Story of Tantalus

SMBH Accretion Efficiency (Magnetohydrodynamics)

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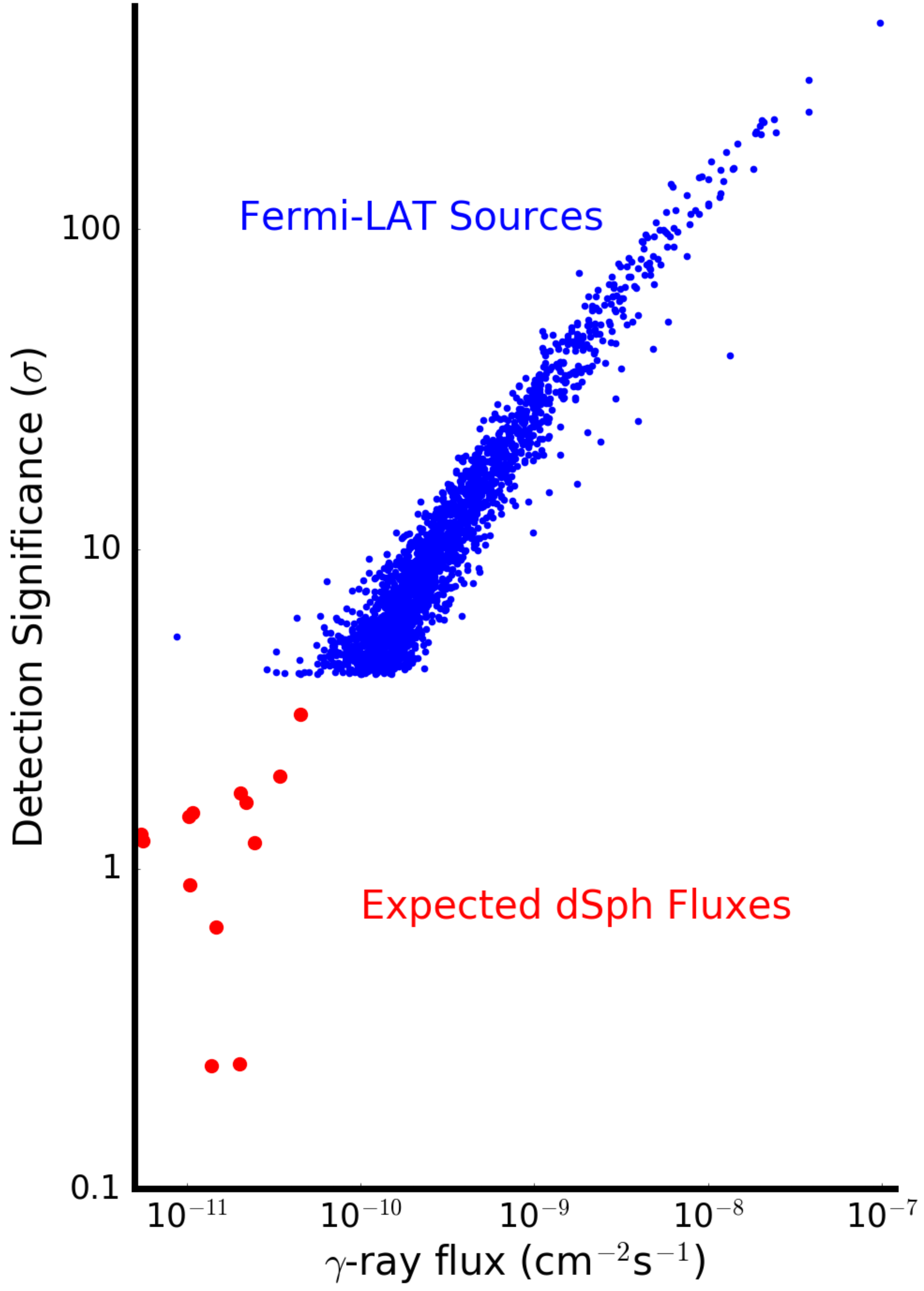
Radio Galaxy Emission Models

Star-Formation Rates in Starburst Galaxies

dSph Proximity

Substructure Models

Milky Way Merger History



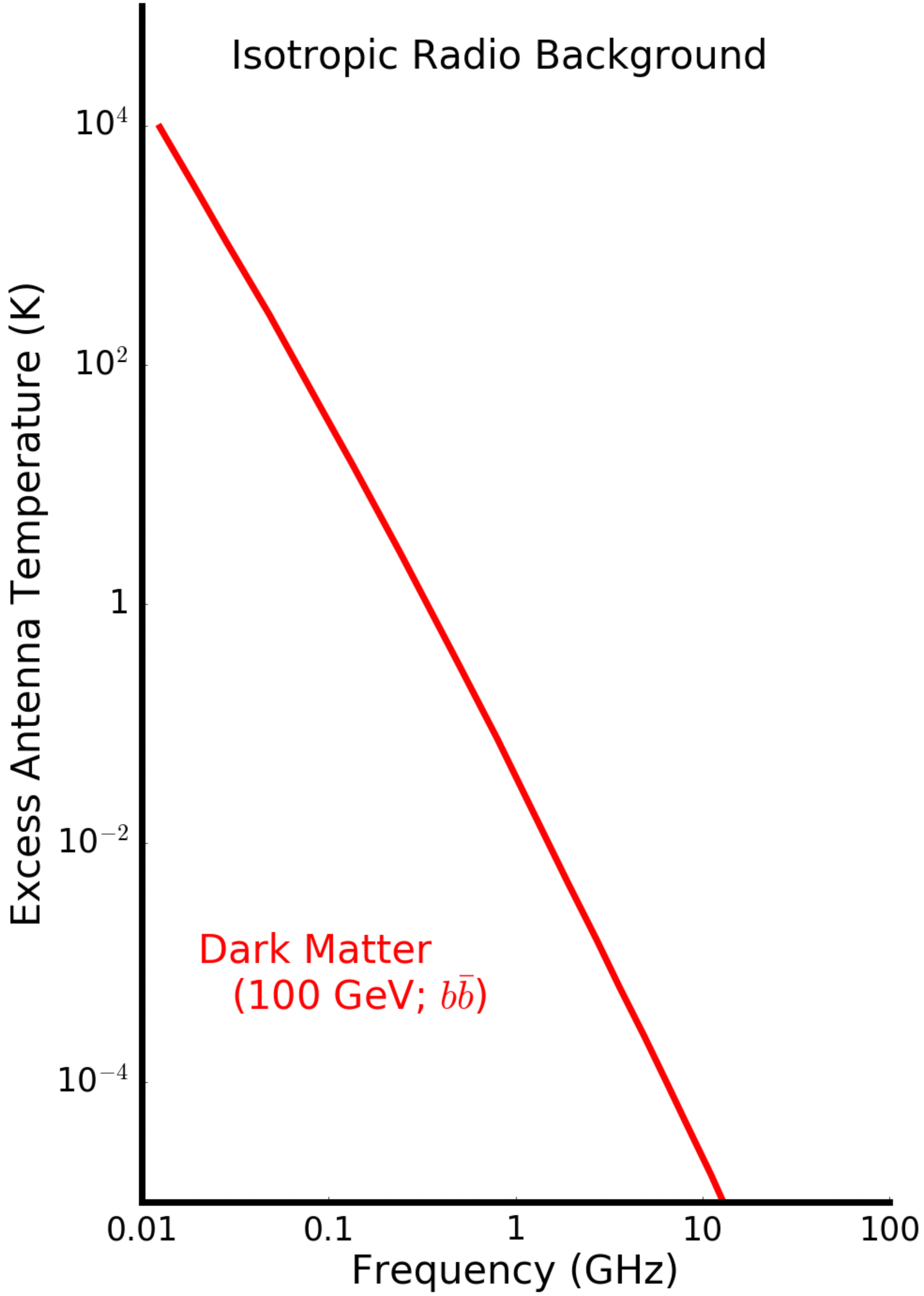
Thermal WIMPs and the Story of Tantalus

Extragalactic Dark Matter Density

Thermal Cross-Section (Early Universe)

e+e- Energy Fraction in Dark Matter Annihilation

Intergalactic Magnetic Fields



Thermal WIMPs and the Story of Tantalus

Extragalactic Dark Matter Density

Thermal Cross-Section (Early Universe)

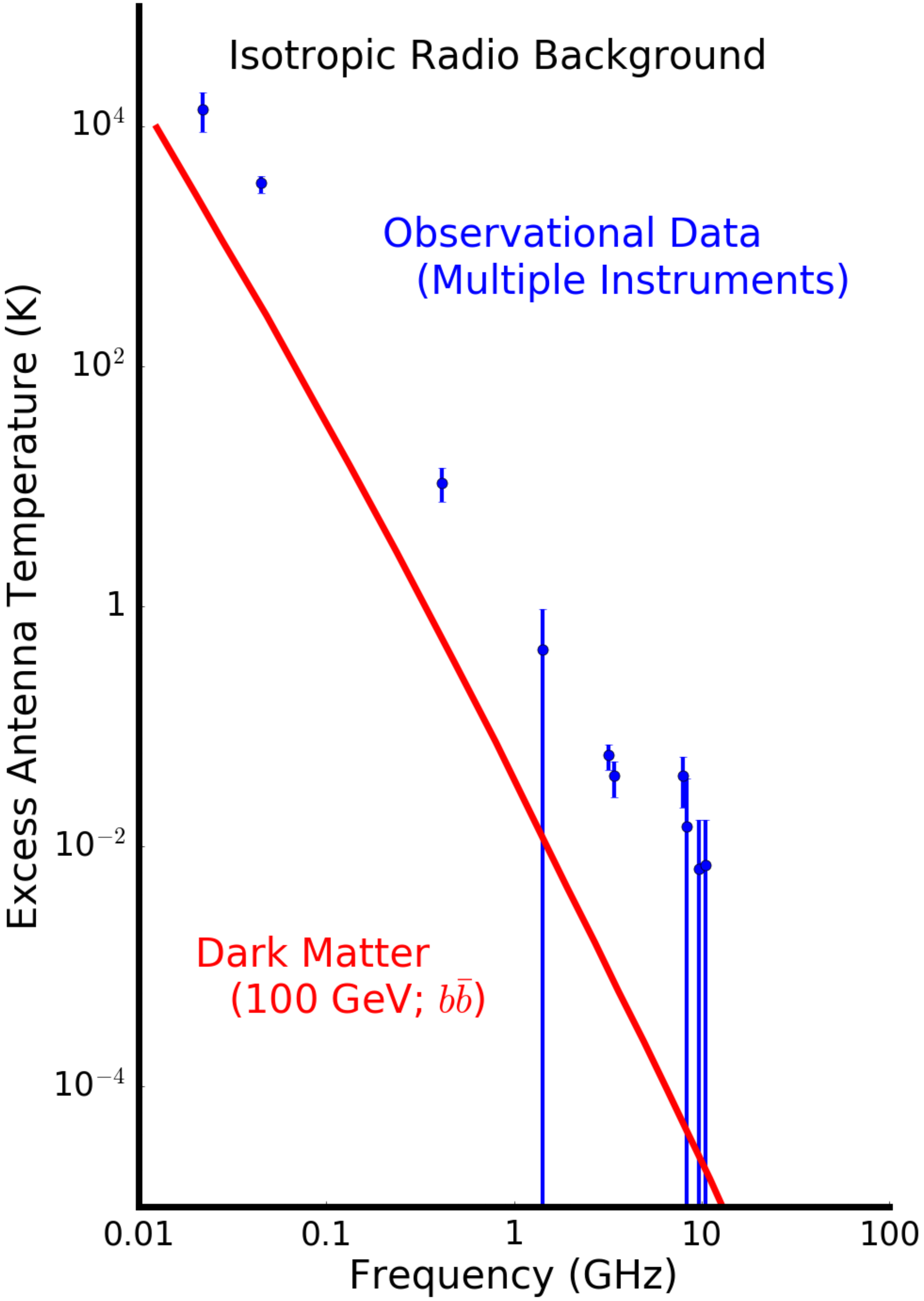
e+e- Energy Fraction in Dark Matter Annihilation

Intergalactic Magnetic Fields

Radio Luminosity in Starbursts and AGN

e+e- Reacceleration in Cluster Mergers

Redshift Dependence of Signal vs. CMB




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
Gamma-Rays / Positrons
Fraction of Dark Matter Flux

Thermal WIMPs and the Story of Tantalus

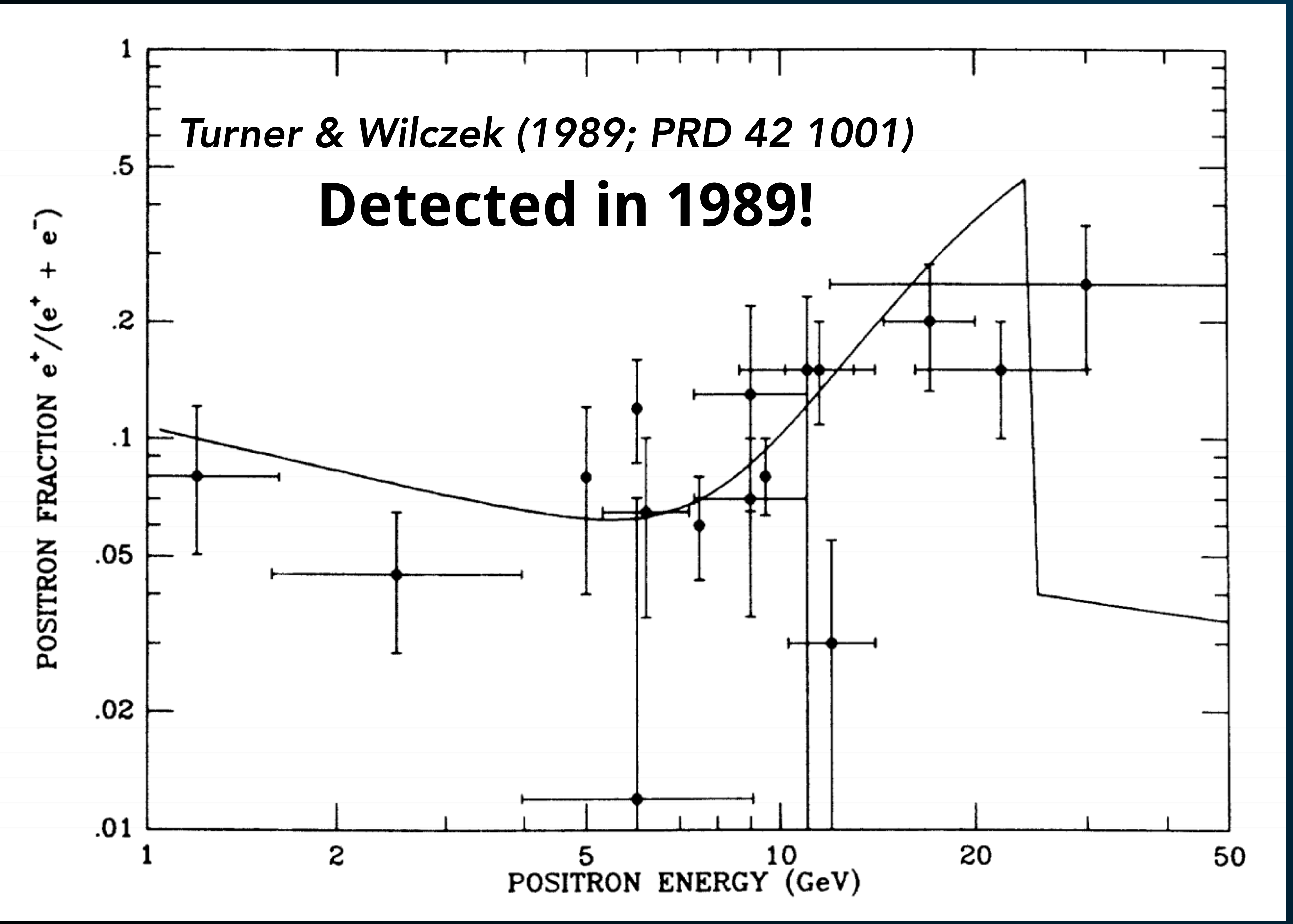
Thermal WIMPs and the Story of Tantalus

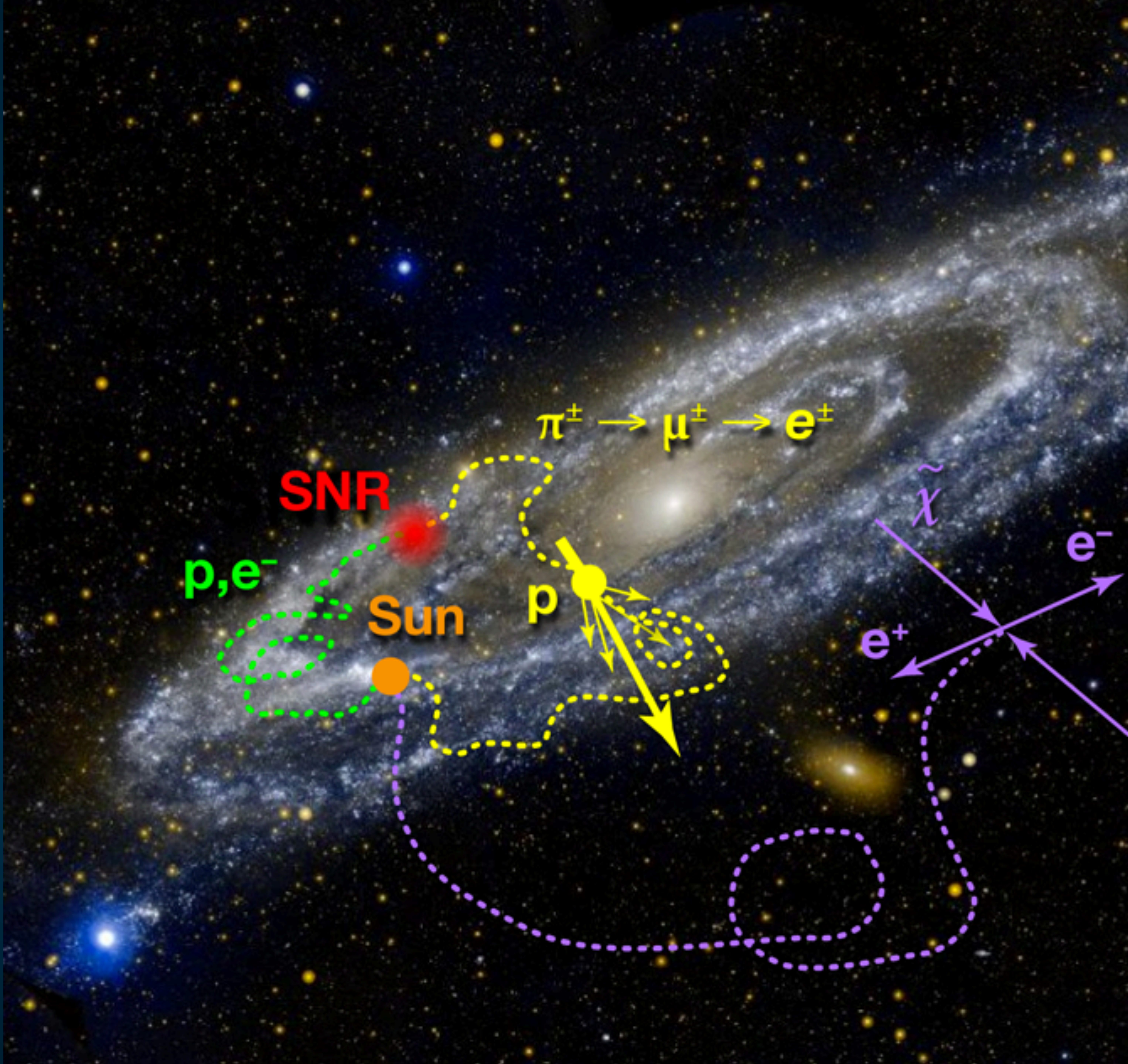

AMS-02
Fit to Data
Positron fraction
10^{-1}
1
10
10^2
positron, electron energy [GeV]
The Positron Excess

The Positron Excess

Key Idea: Investigate the Positron Fraction!

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

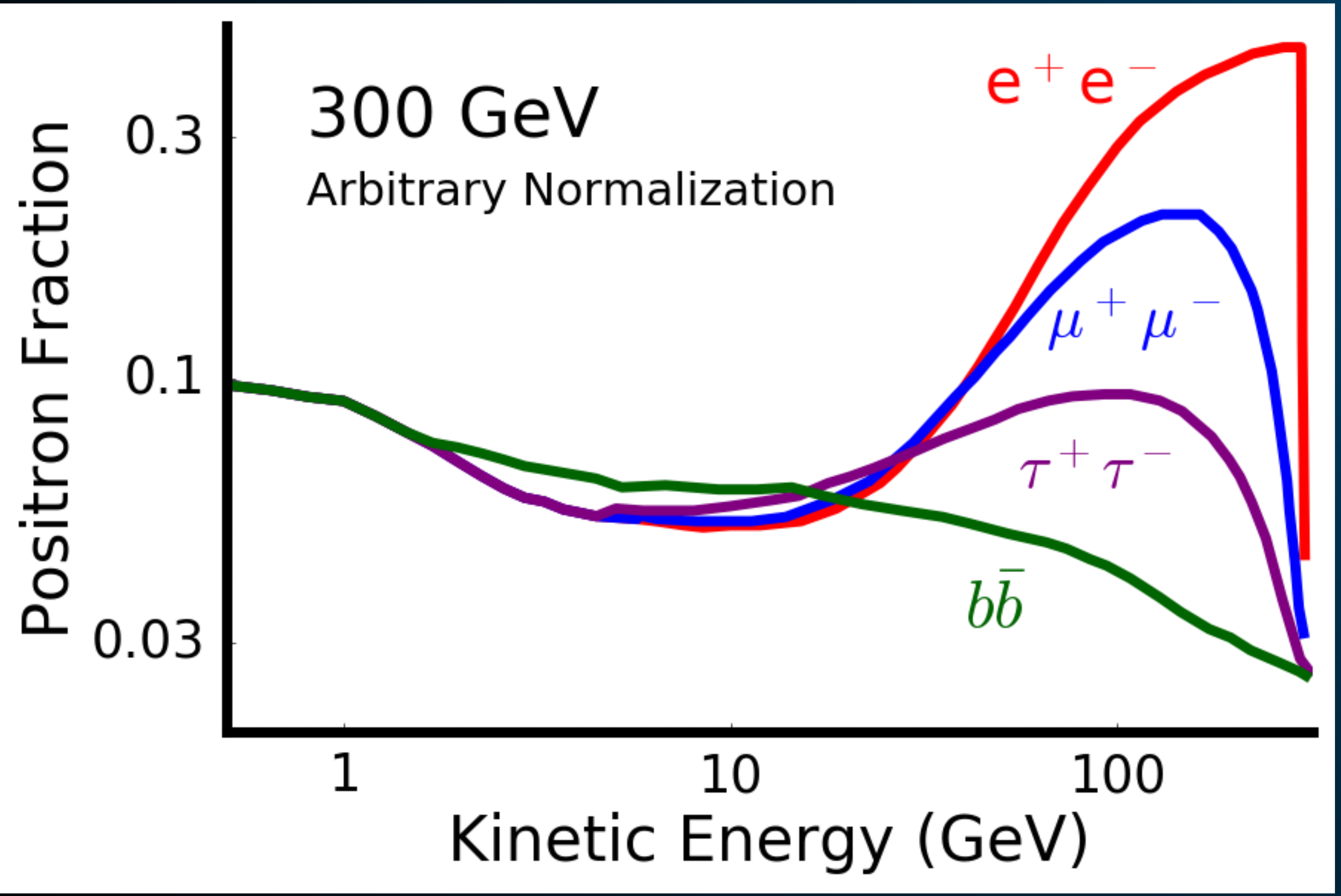


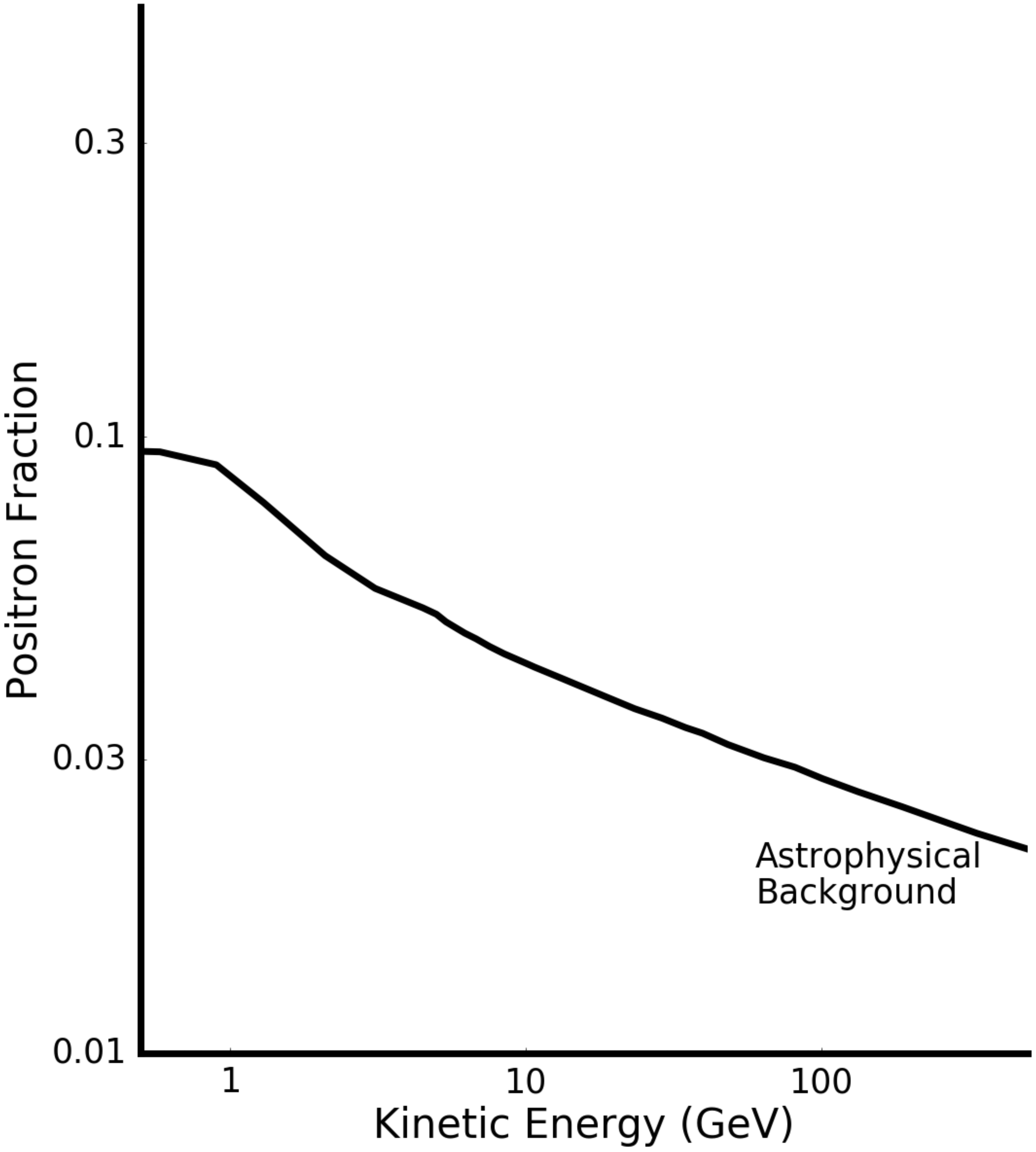


The Positron Excess

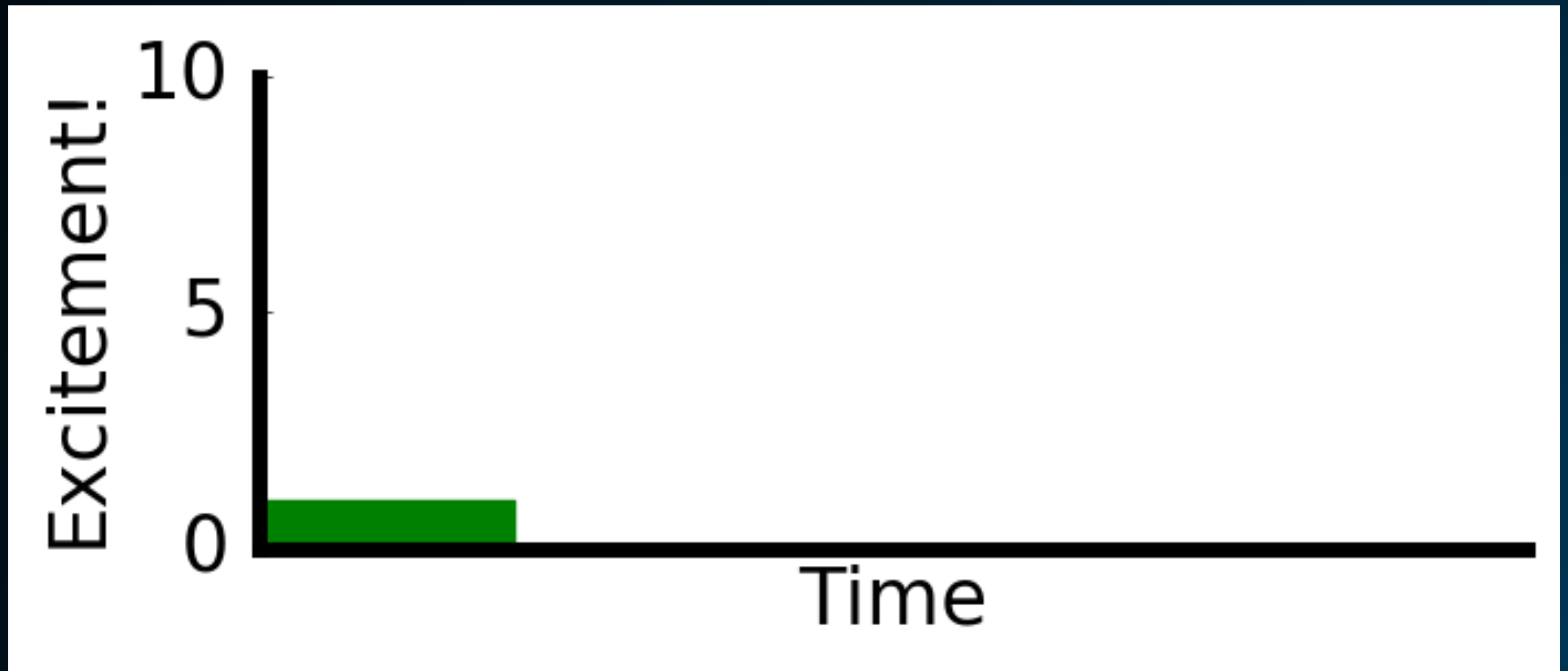
Astrophysics - Slowly Decreasing

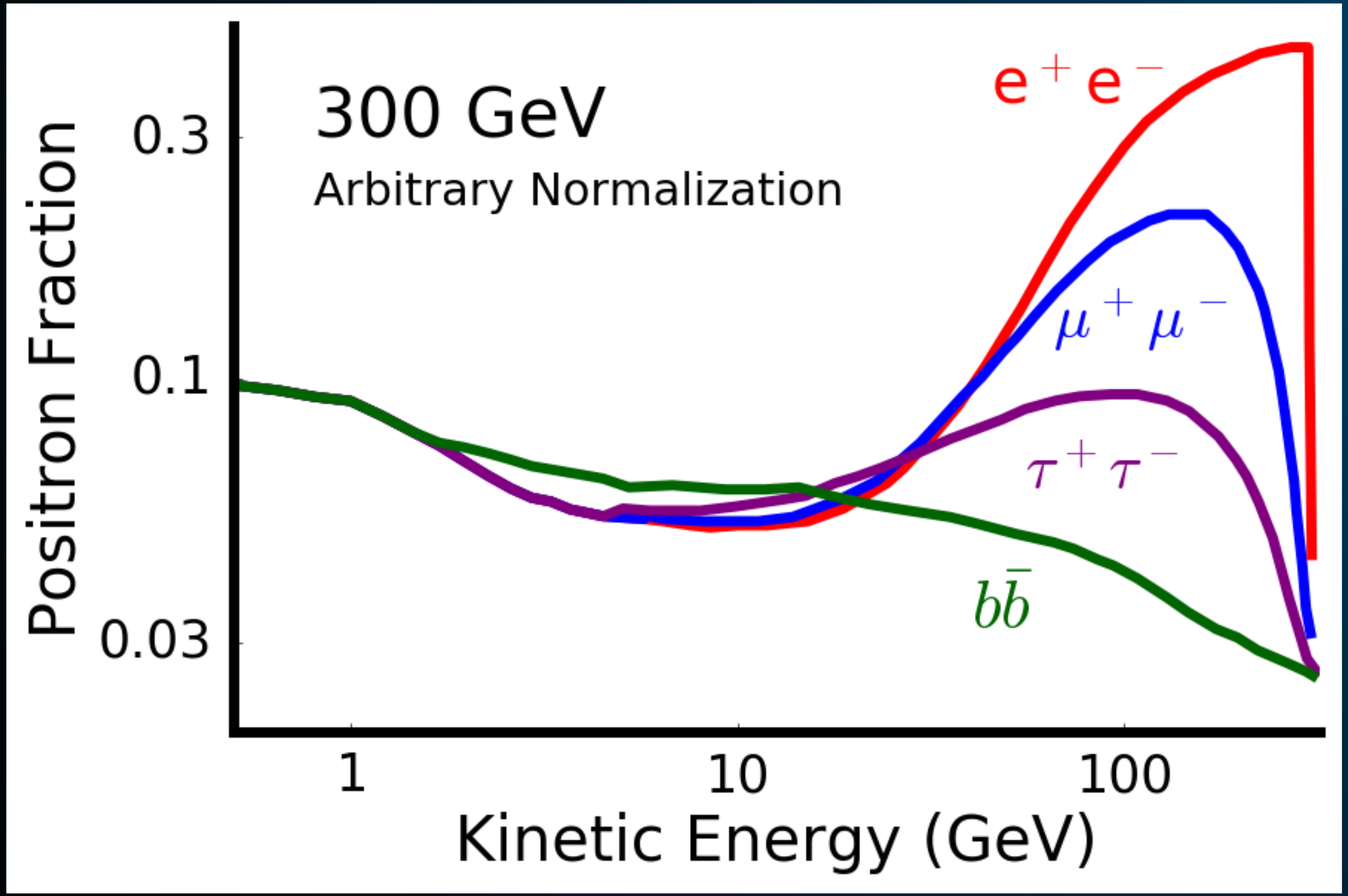
Dark Matter - Sharp Bump!



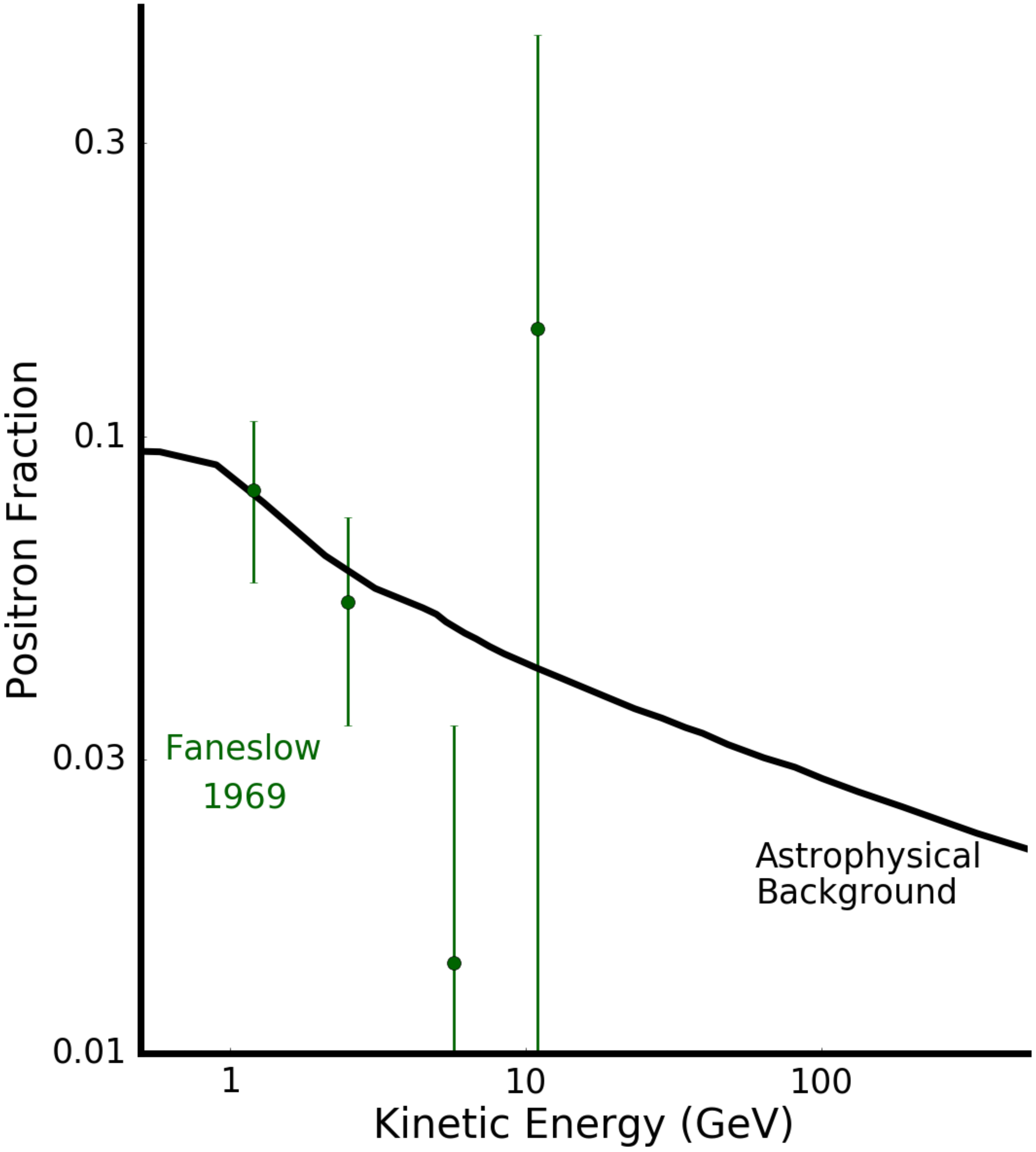


The Positron Excess

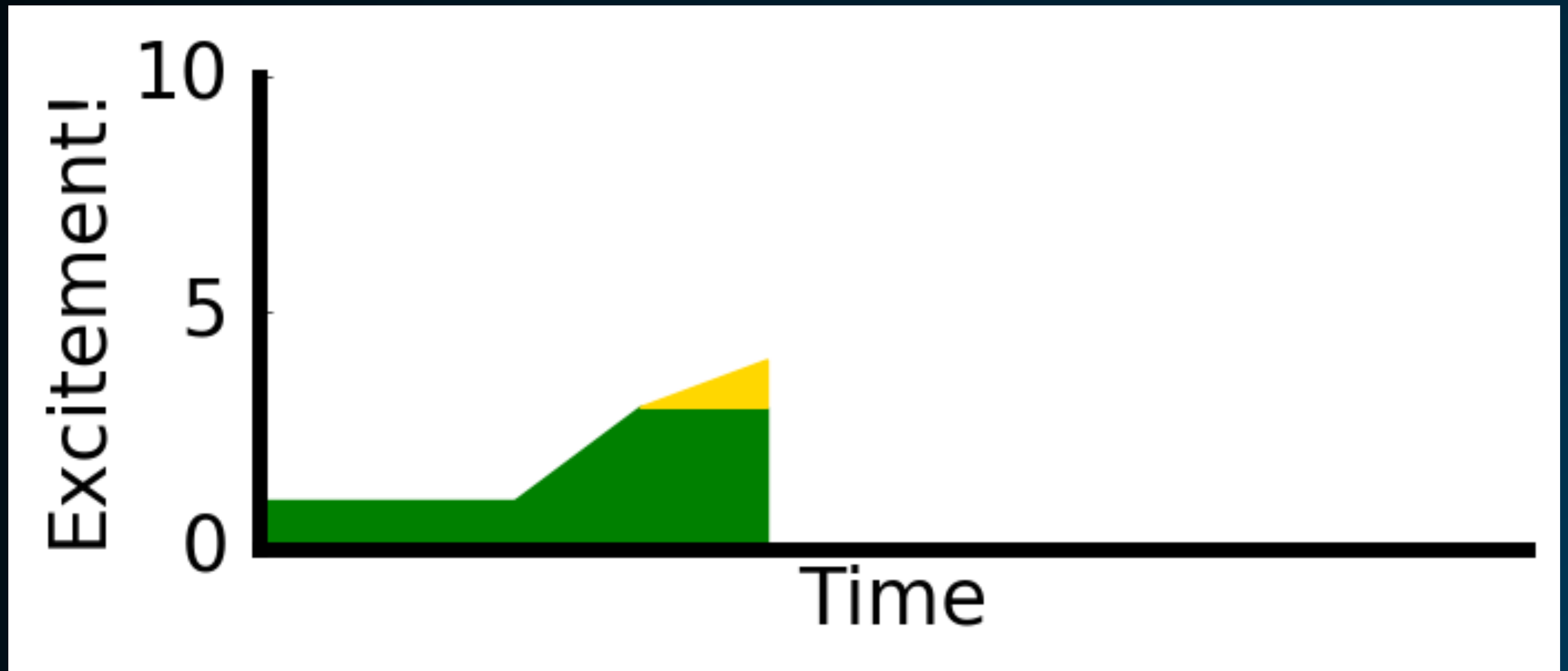


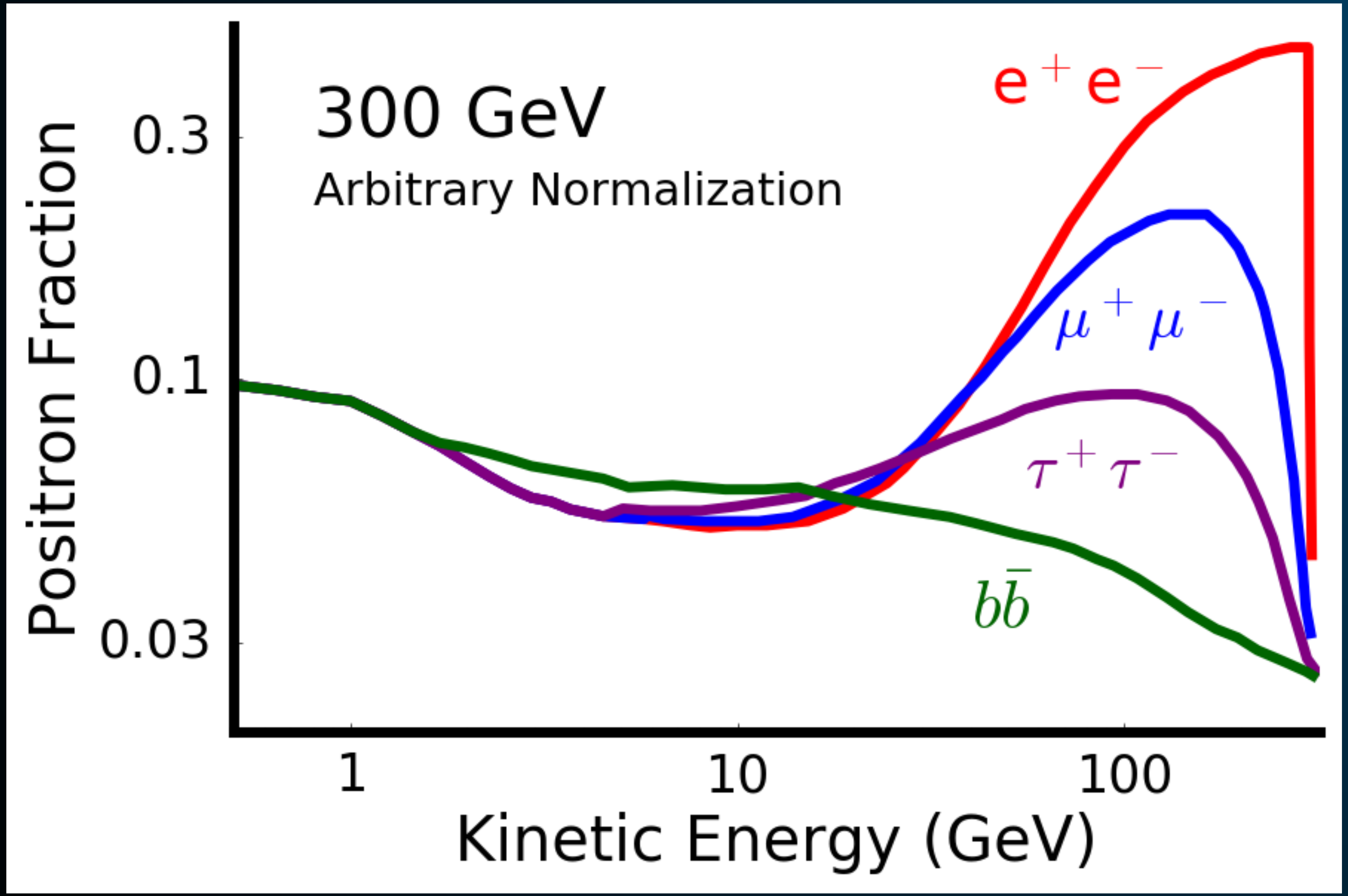


(Not an exhaustive list of observations)



The Positron Excess





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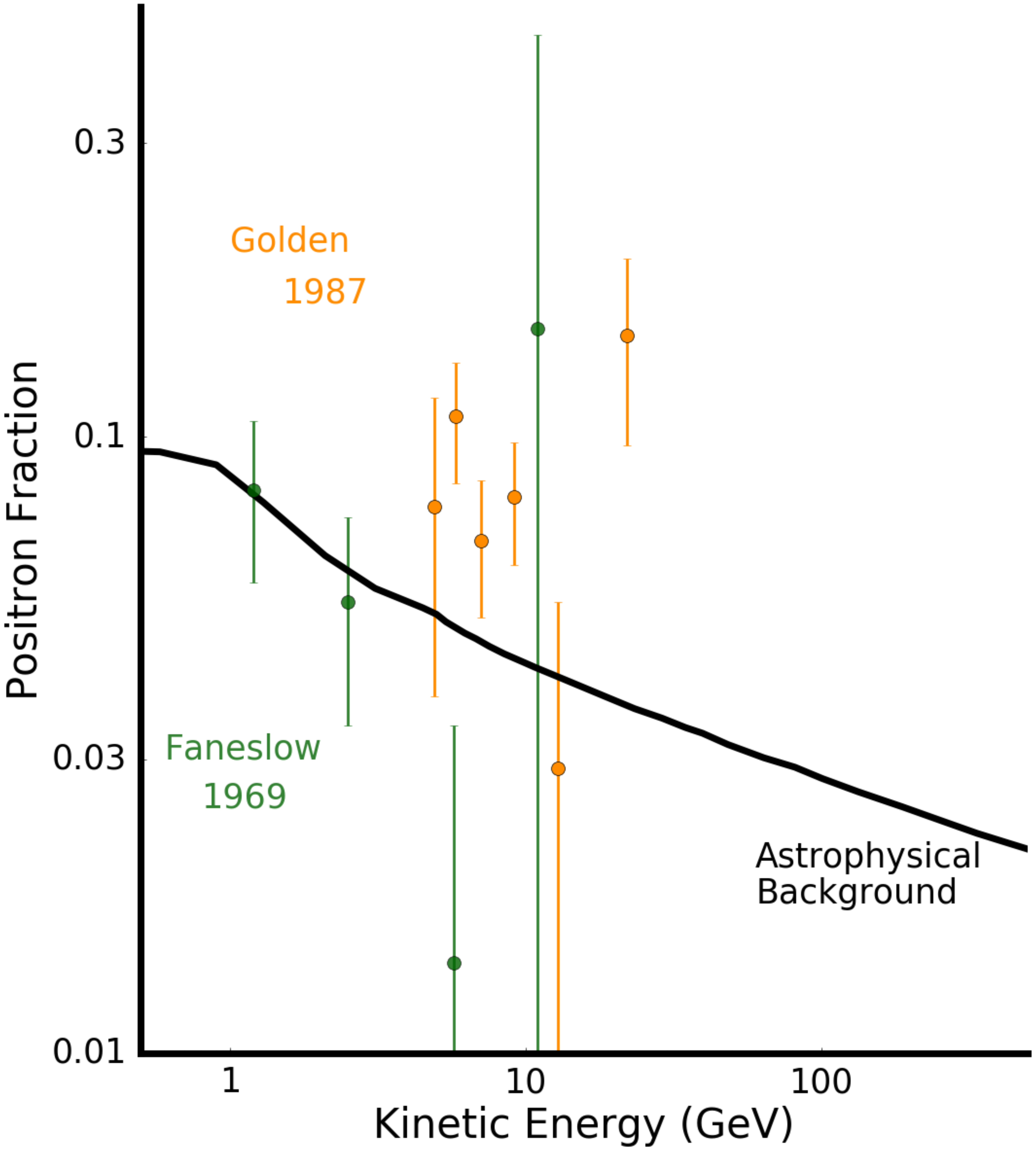
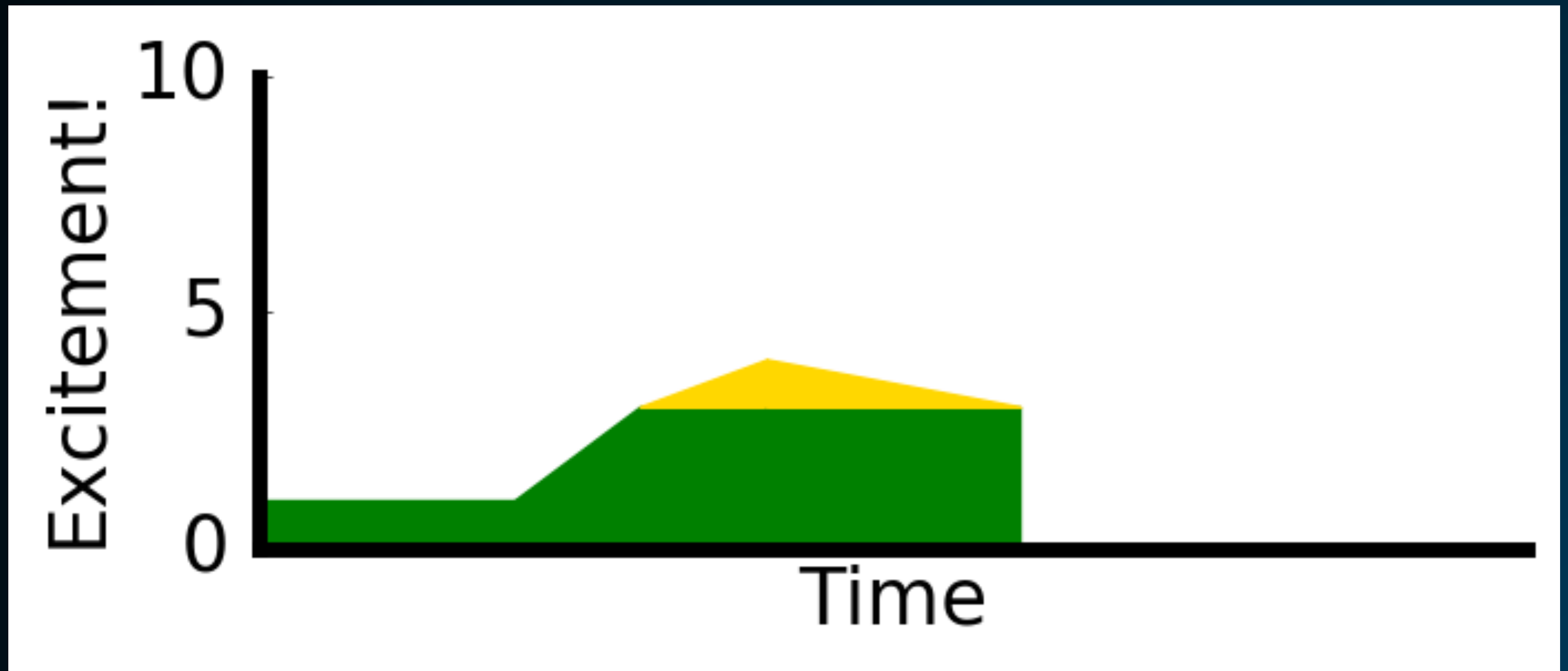
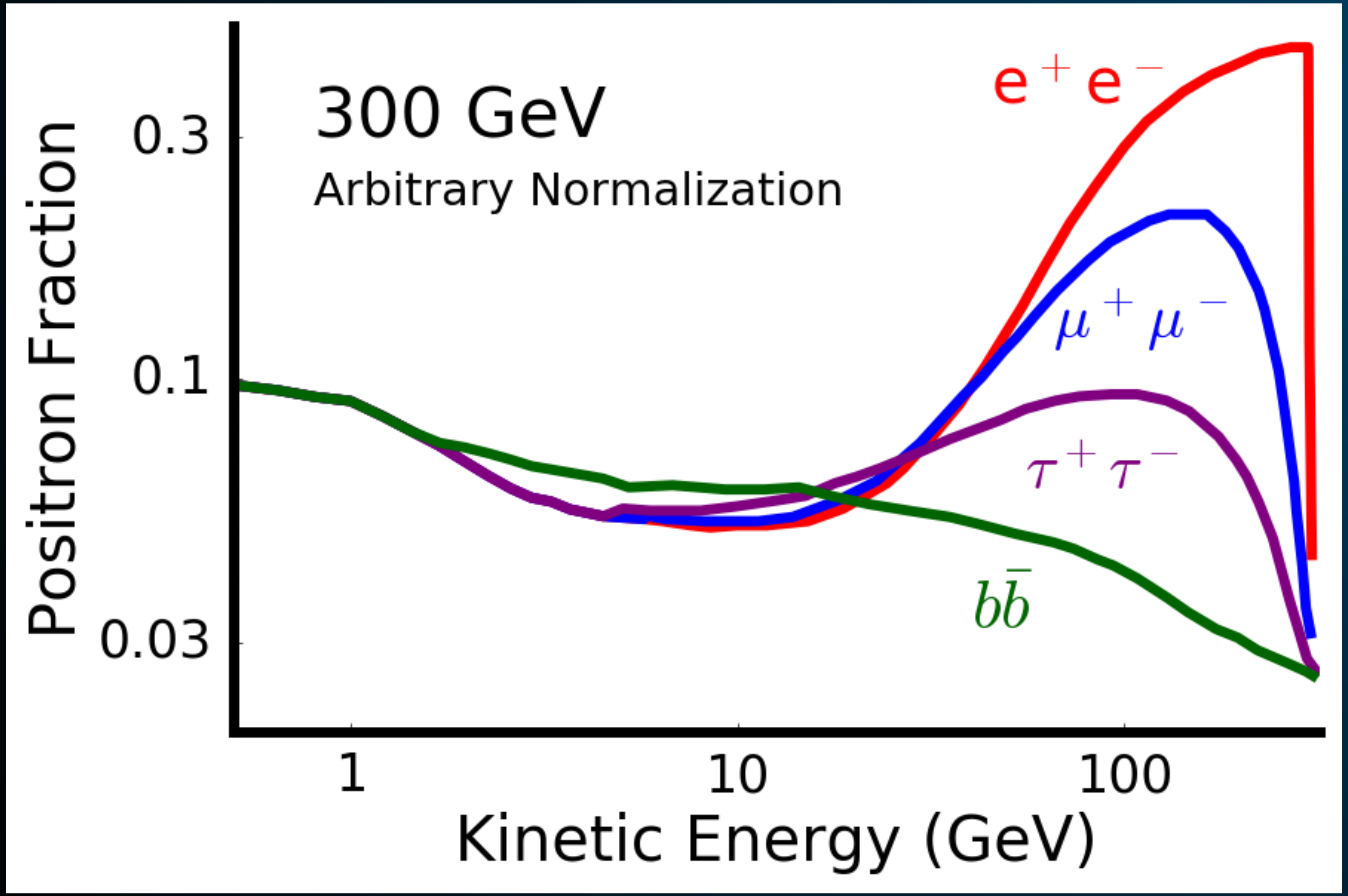


The Positron Excess





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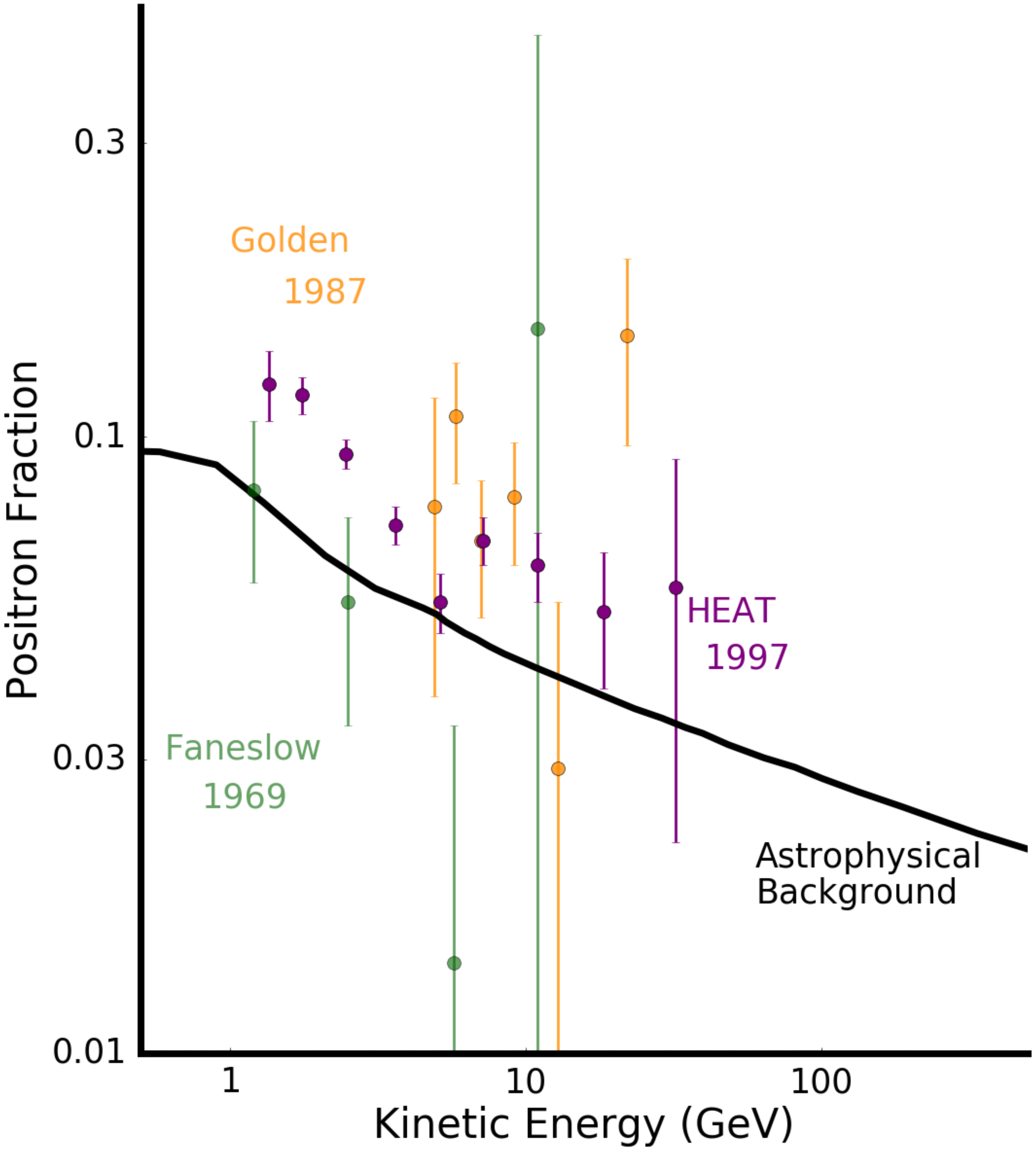
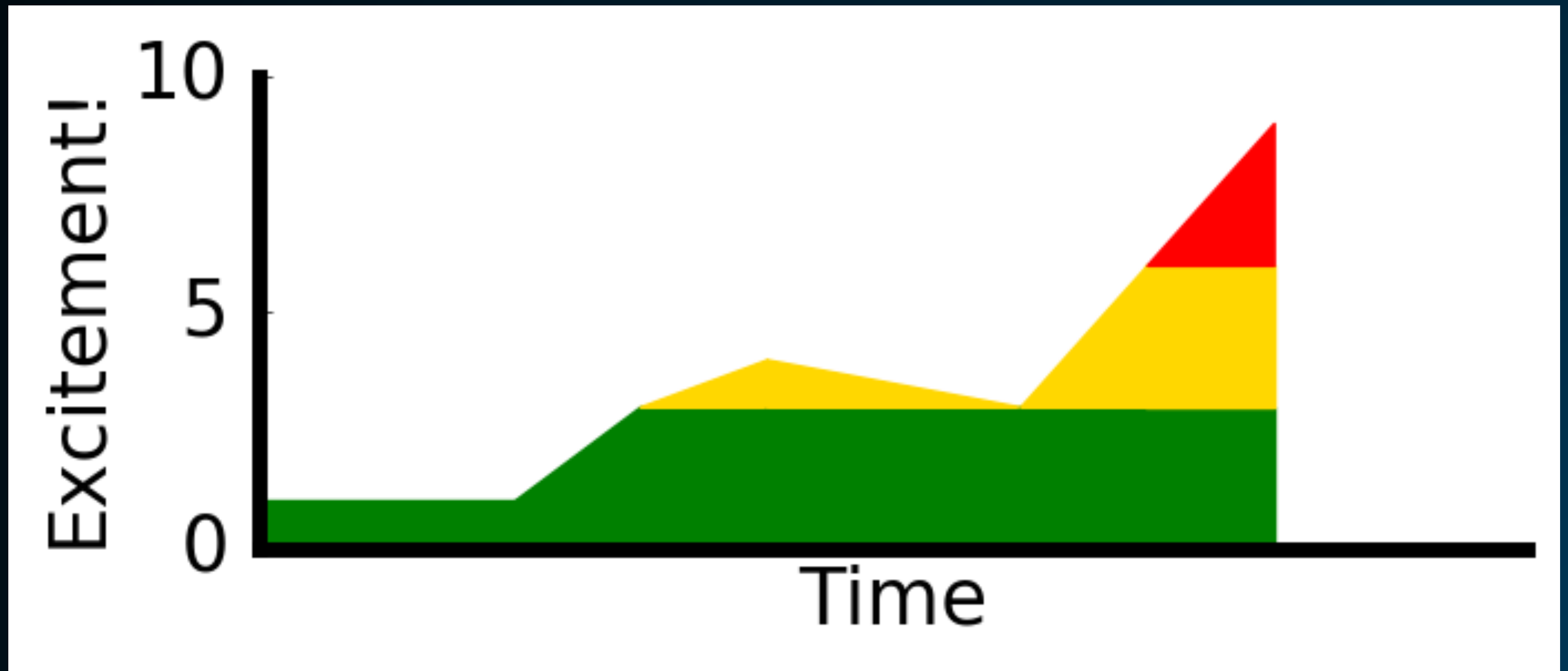
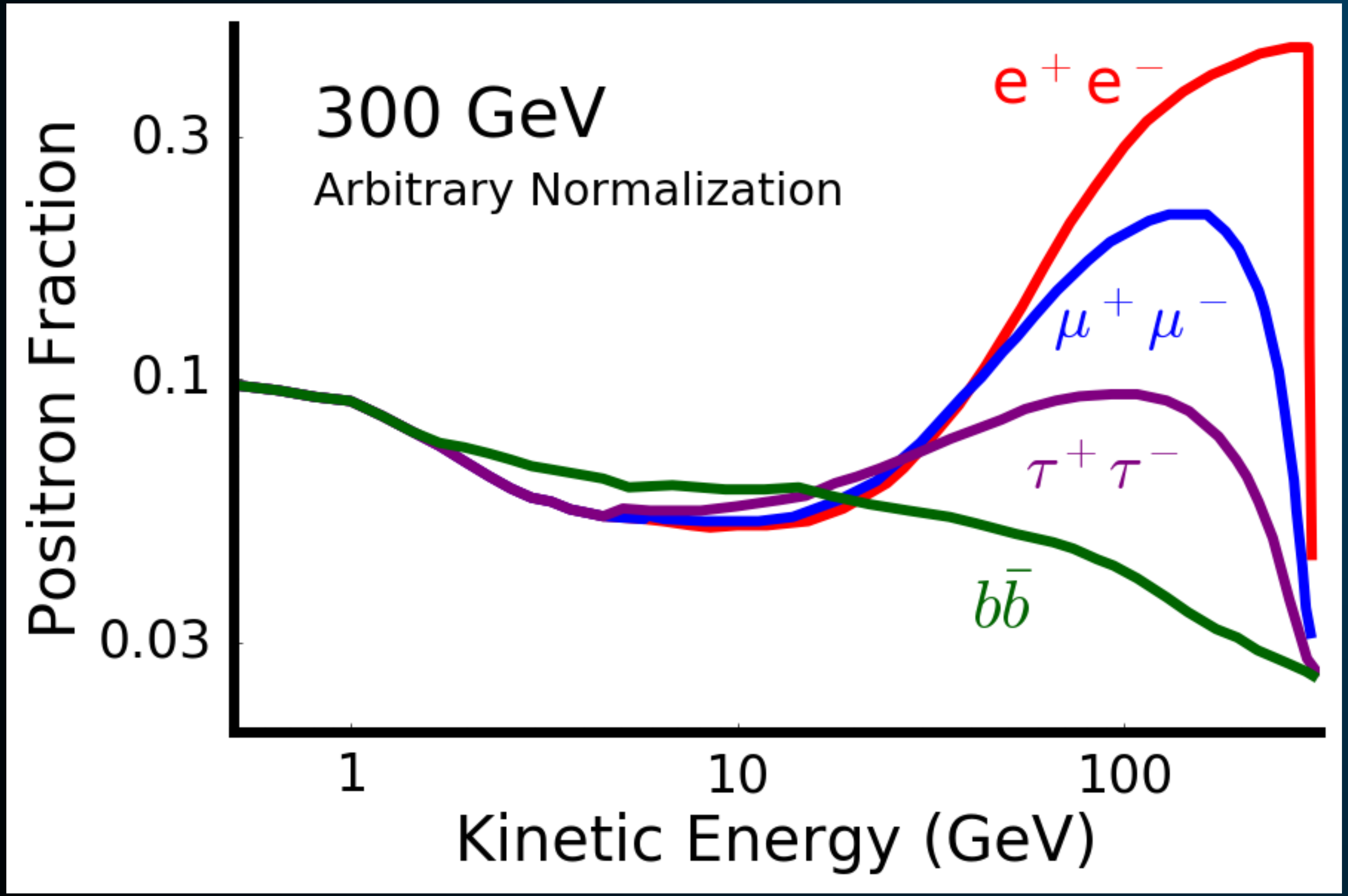


The Positron Excess





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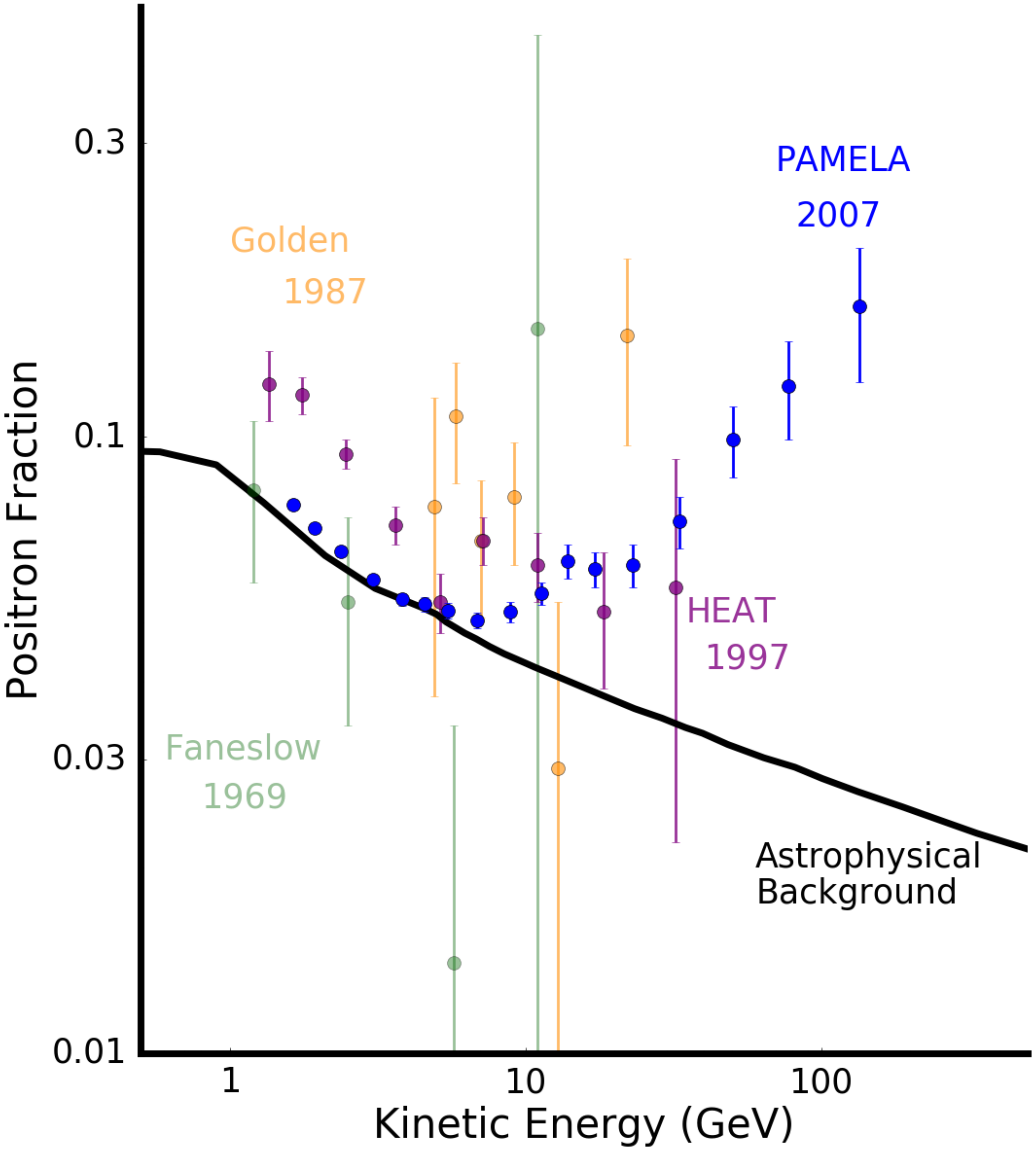
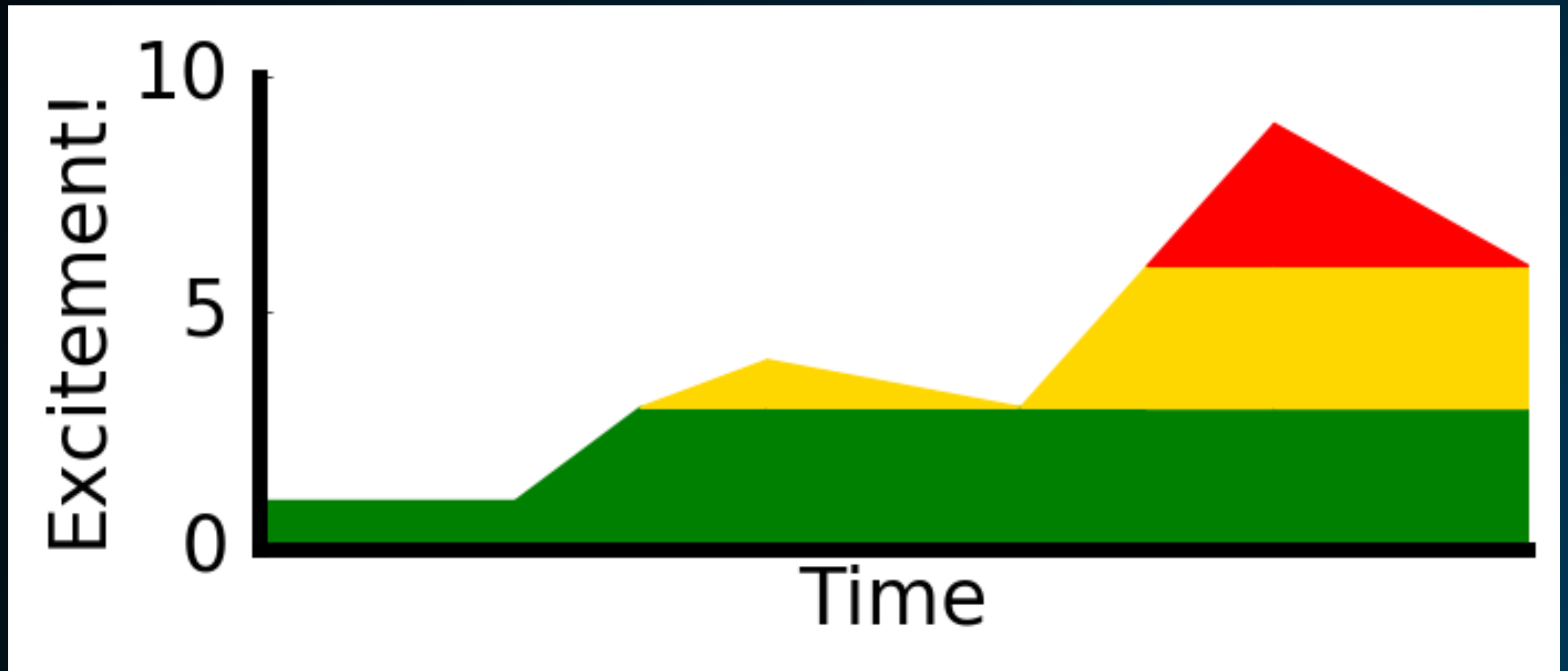
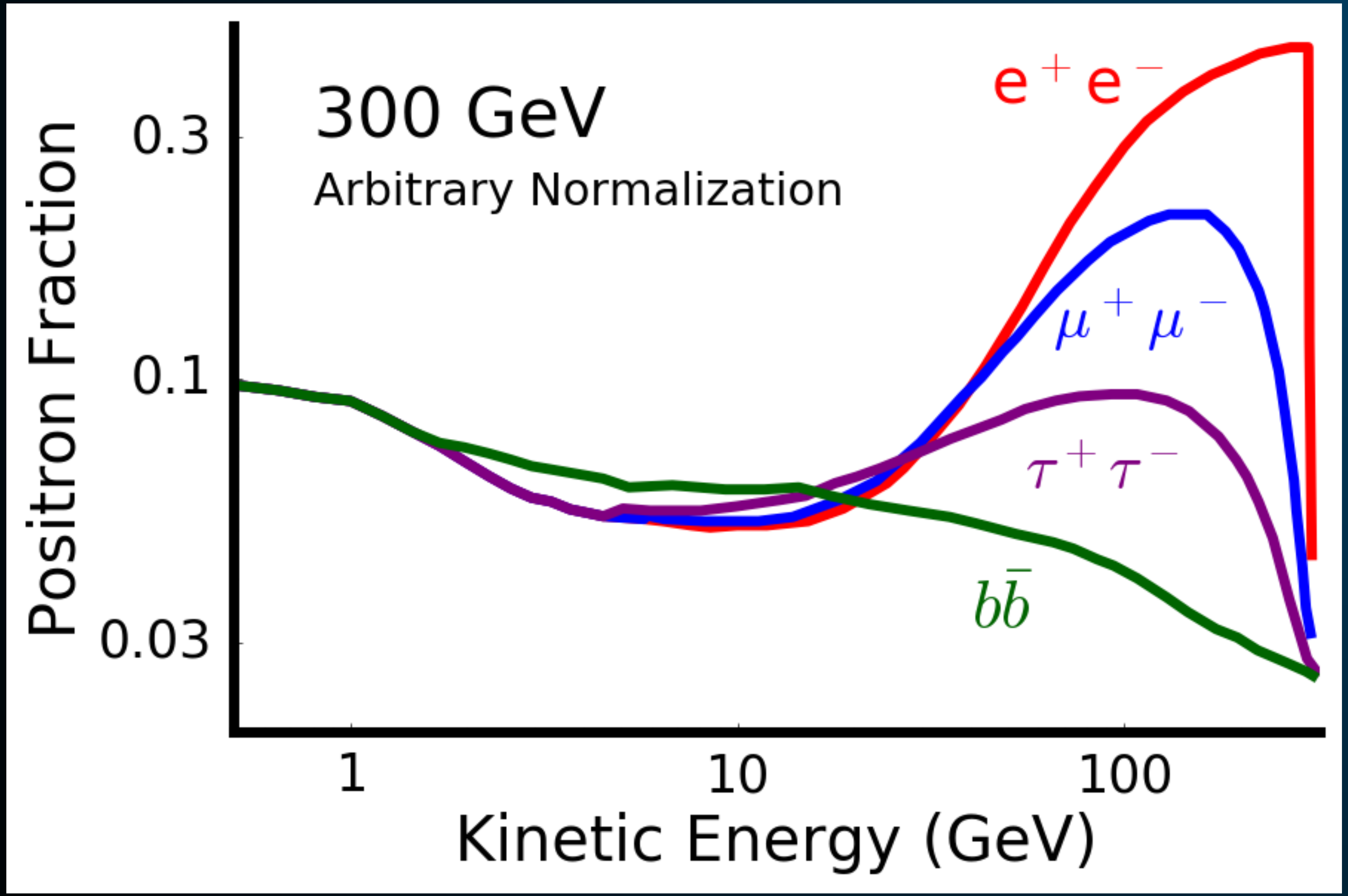
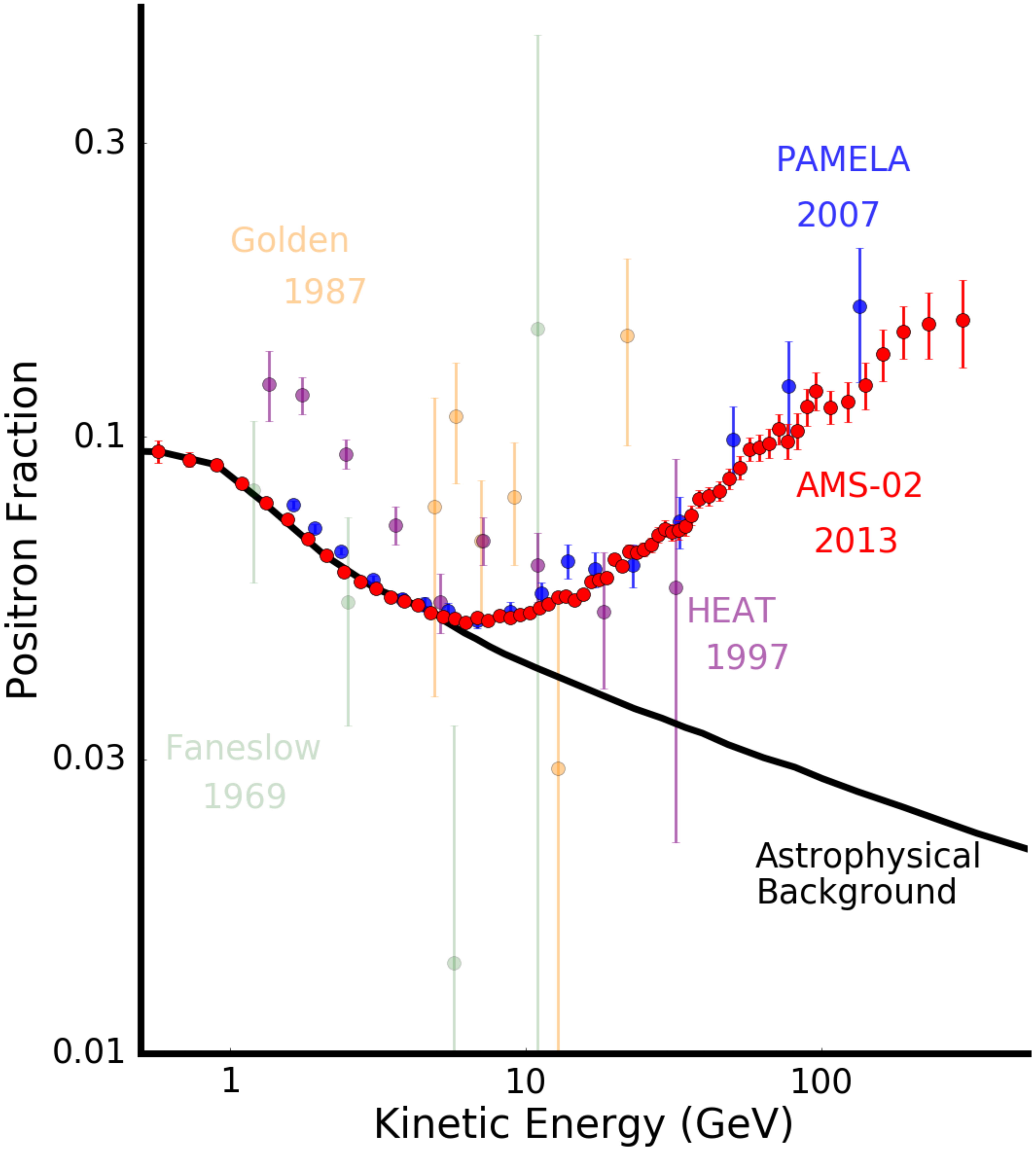


The Positron Excess







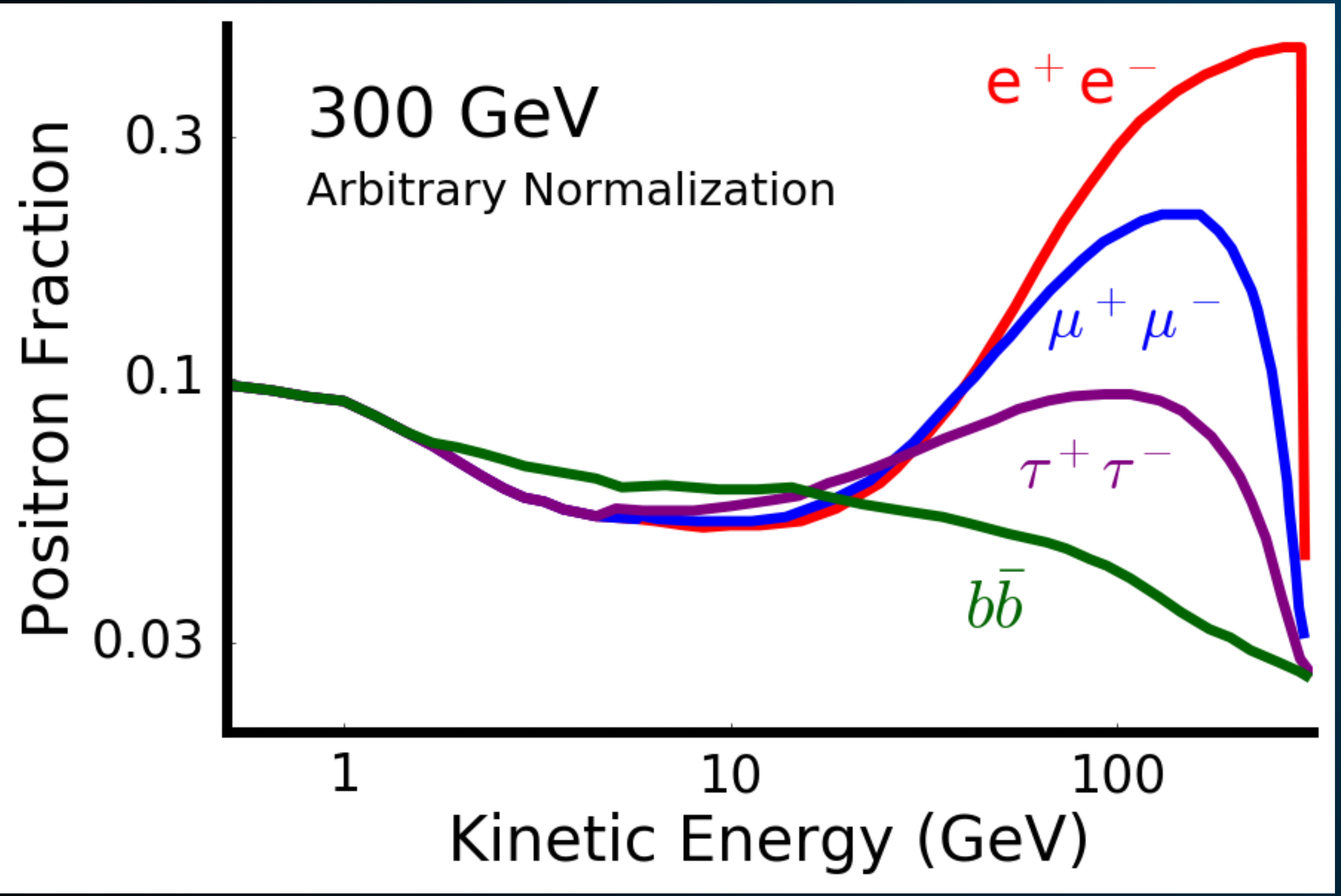
(Not an exhaustive list of observations)

The Positron Excess

Why Less Excitement?

Continues to Higher Mass

Spectrum Relatively Smooth



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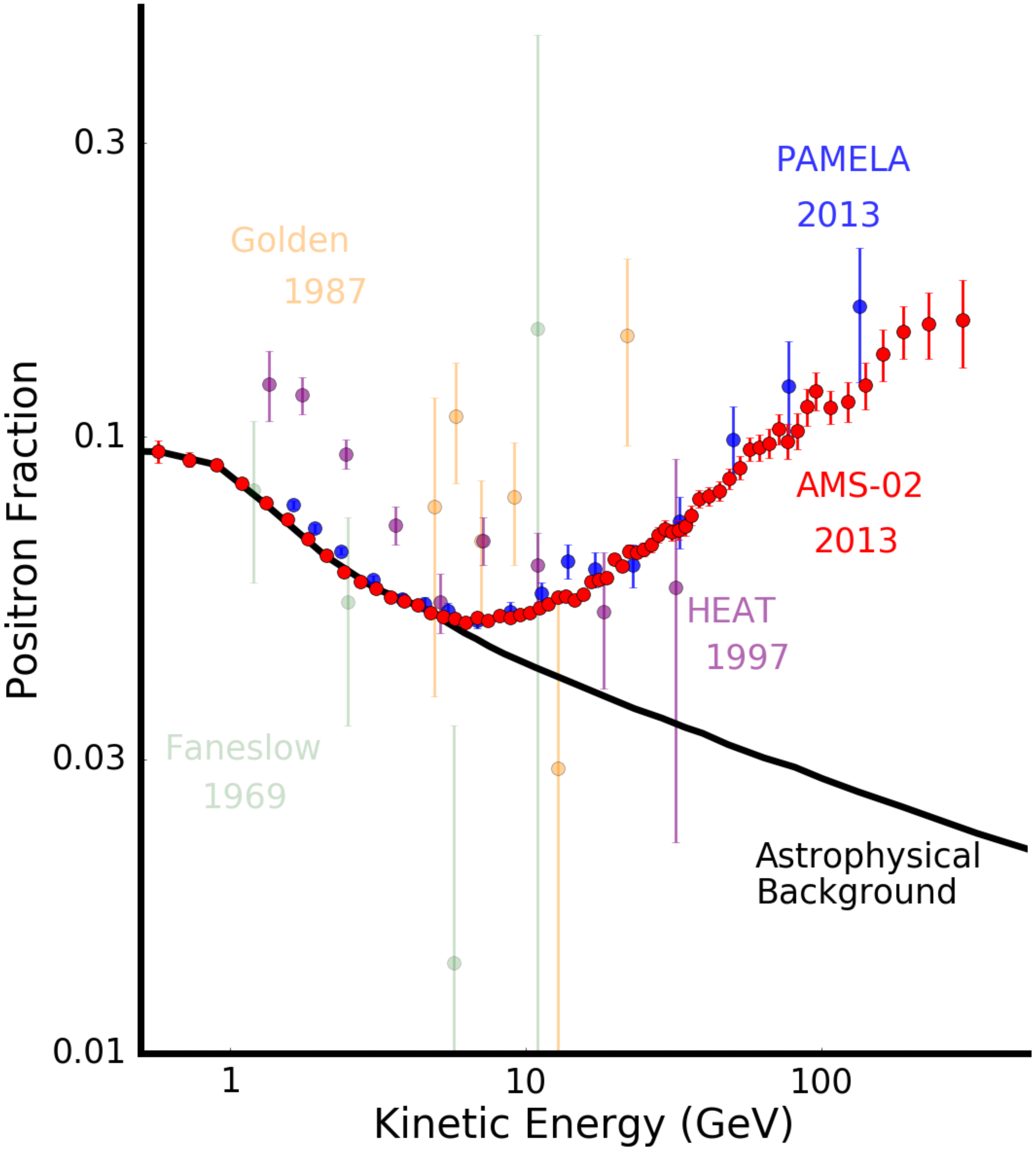
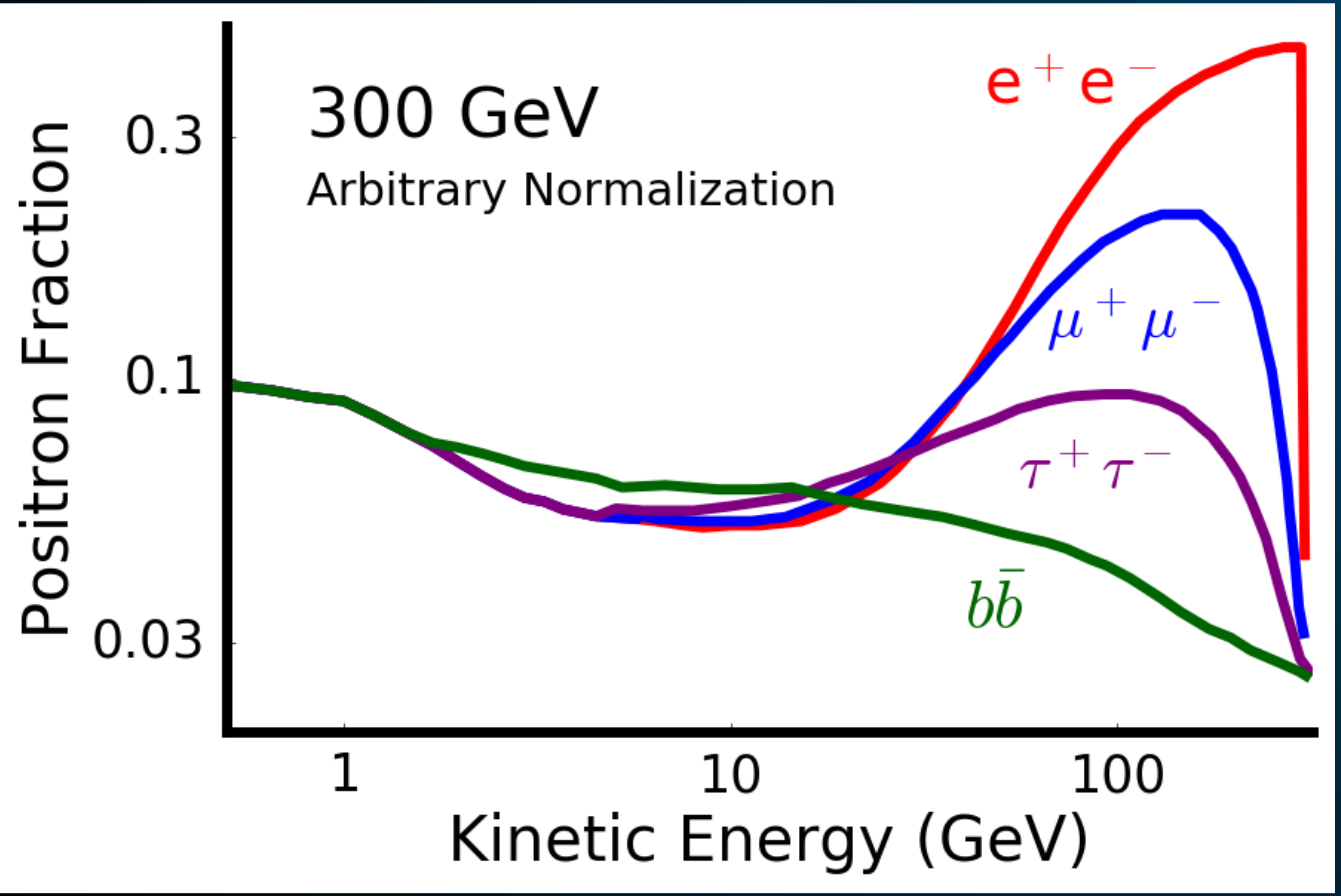


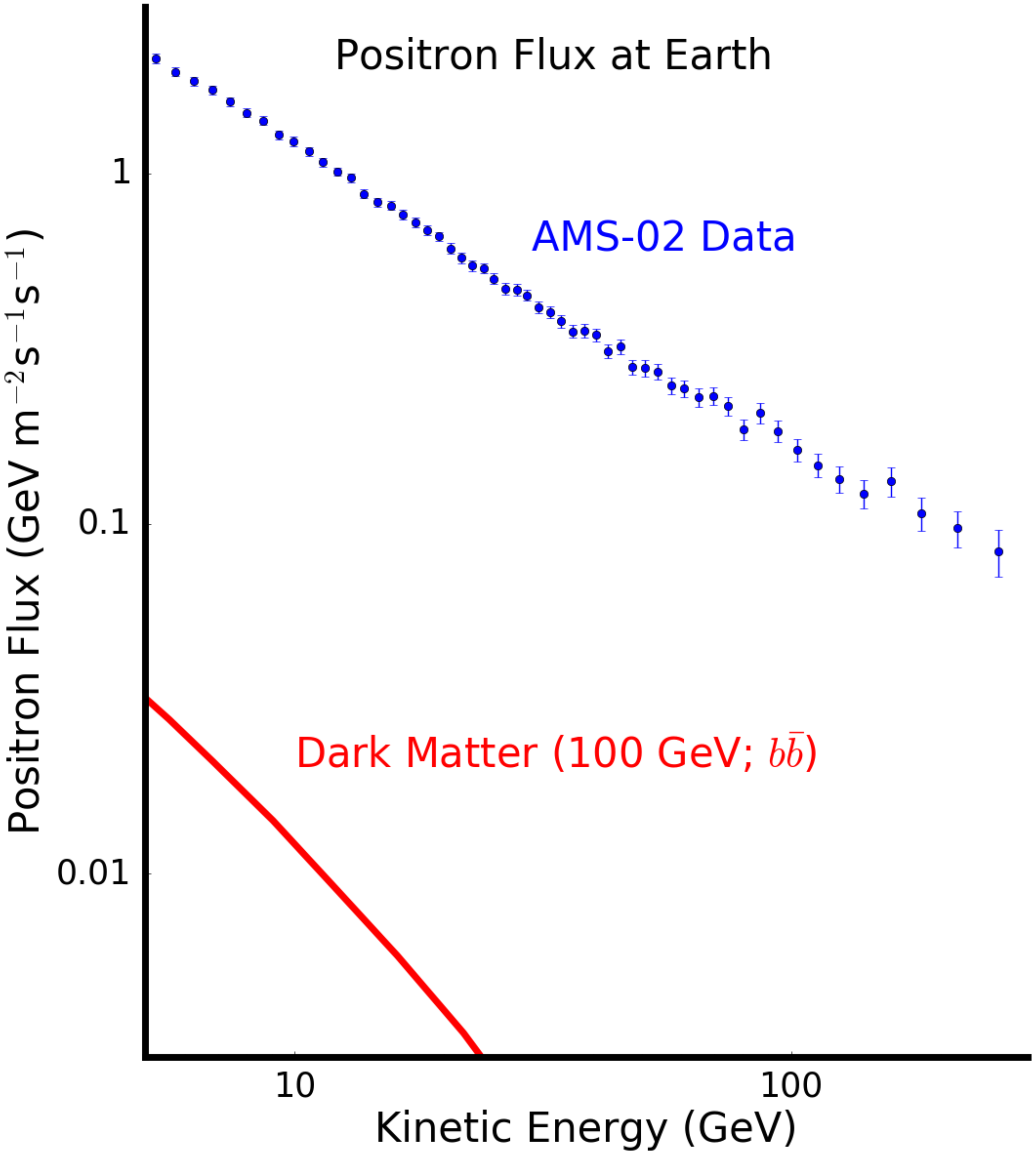
The Positron Excess

Why Less Excitement?

Continues to Higher Mass

Spectrum Relatively Smooth






Not a Thermal WIMP!
$b\bar{b}$
e^+e^-
Thermal Cross-Section
$<\sigma v>$ ($cm^3 s^{-1}$)
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)

Not a Thermal WIMP!

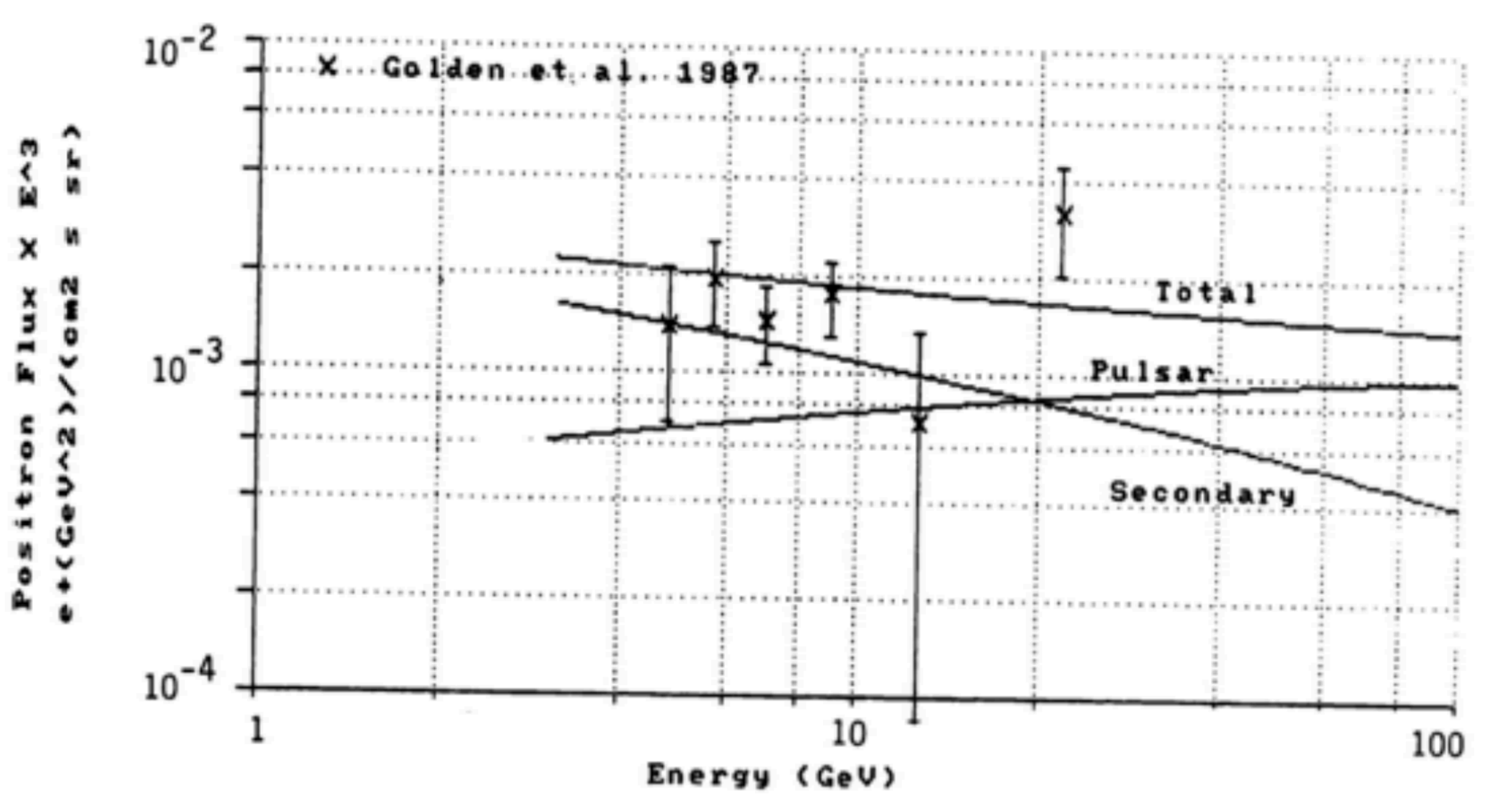
Not a Thermal WIMP!
$b\bar{b}$
e^+e^-
$b\bar{b}$ Limit (Planck)
e^+e^- Limit (Planck)
Thermal Cross-Section
Strong Gamma-Ray Constraints too!
$<\sigma v>$ (cm^3s^{-1})
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
0.1
1
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

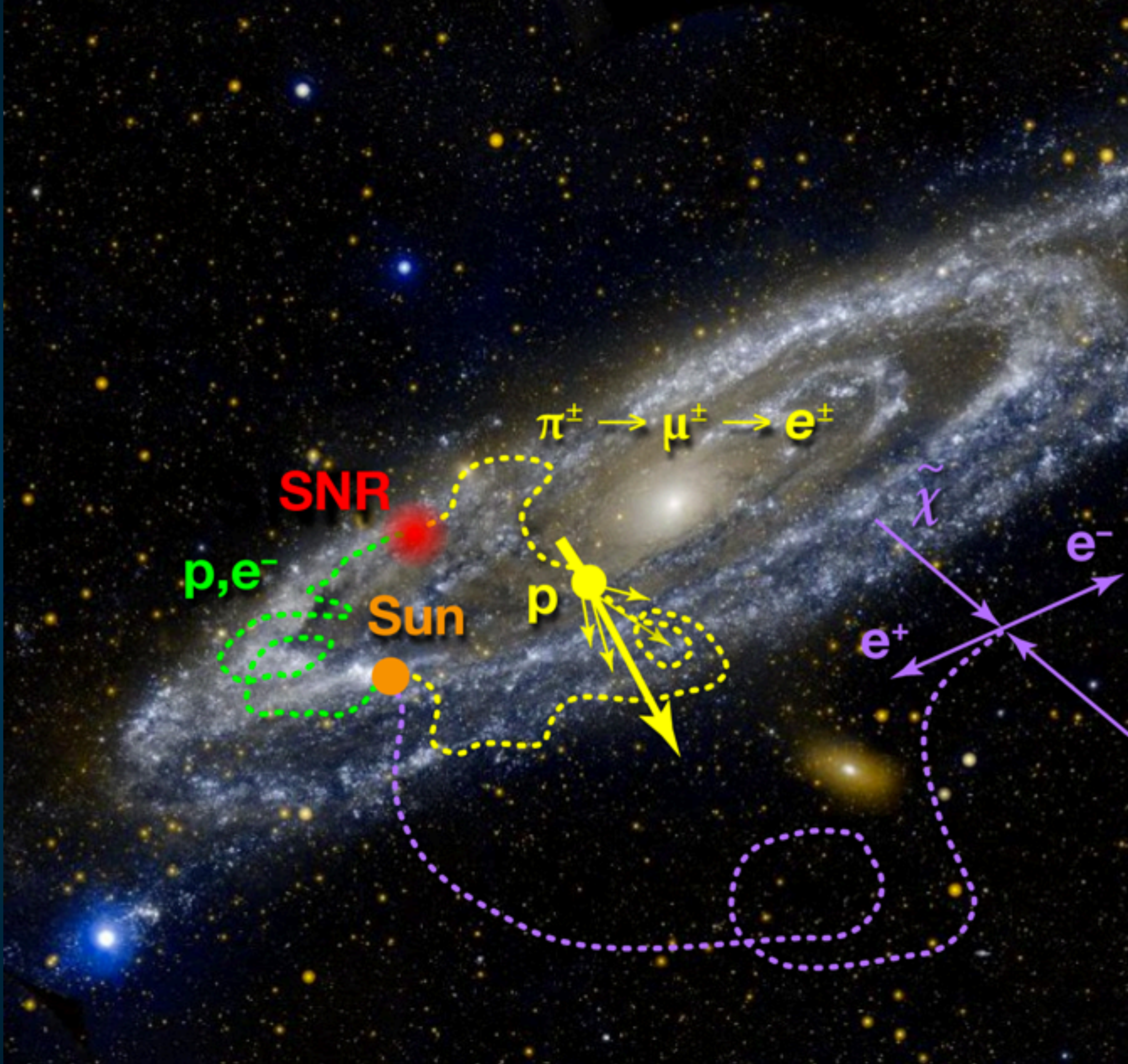
The Positron Excess

Key Idea: Investigate the Positron Fraction!

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

Harding & Ramaty (ICRC! 1987)

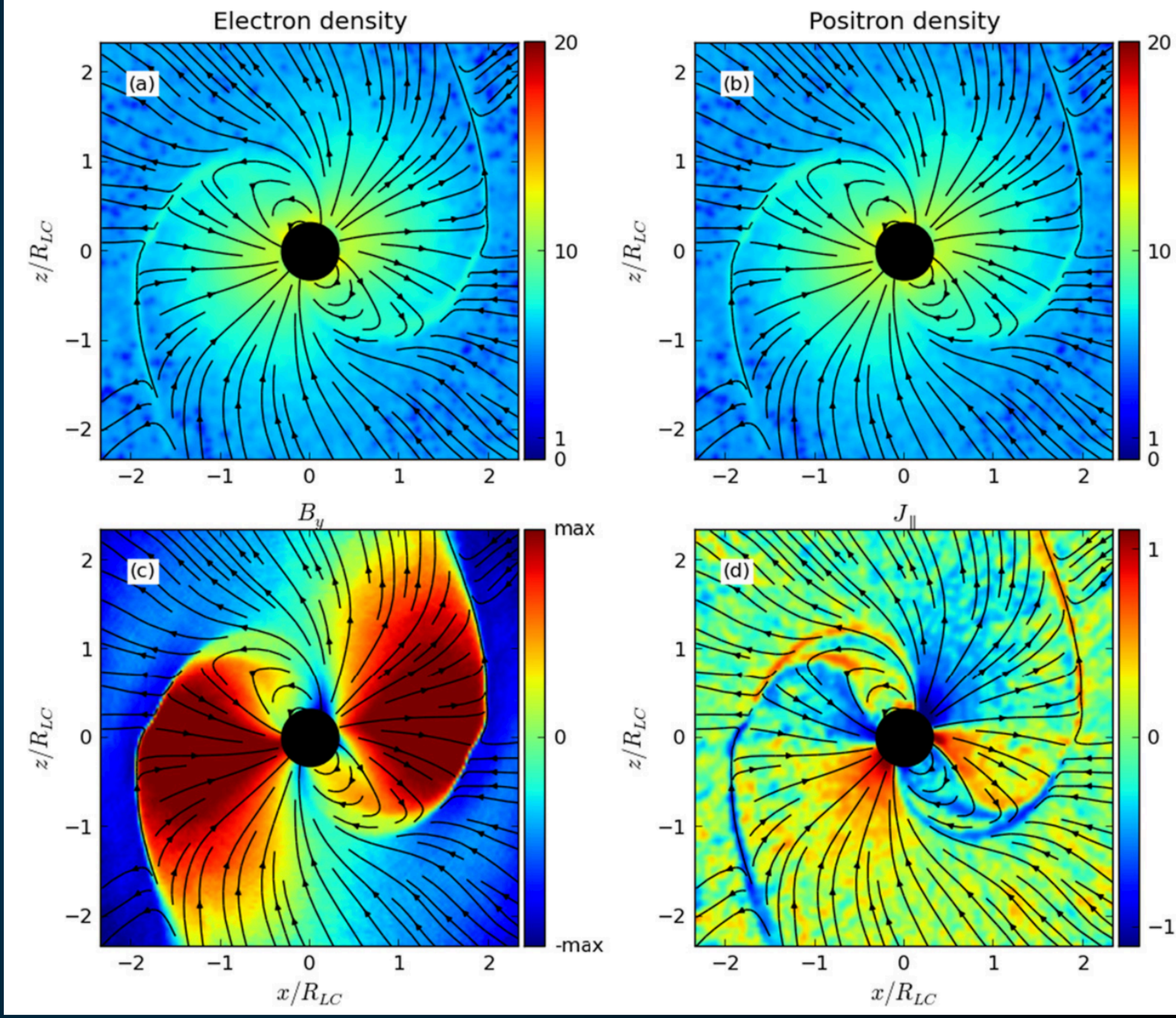




The Positron Excess

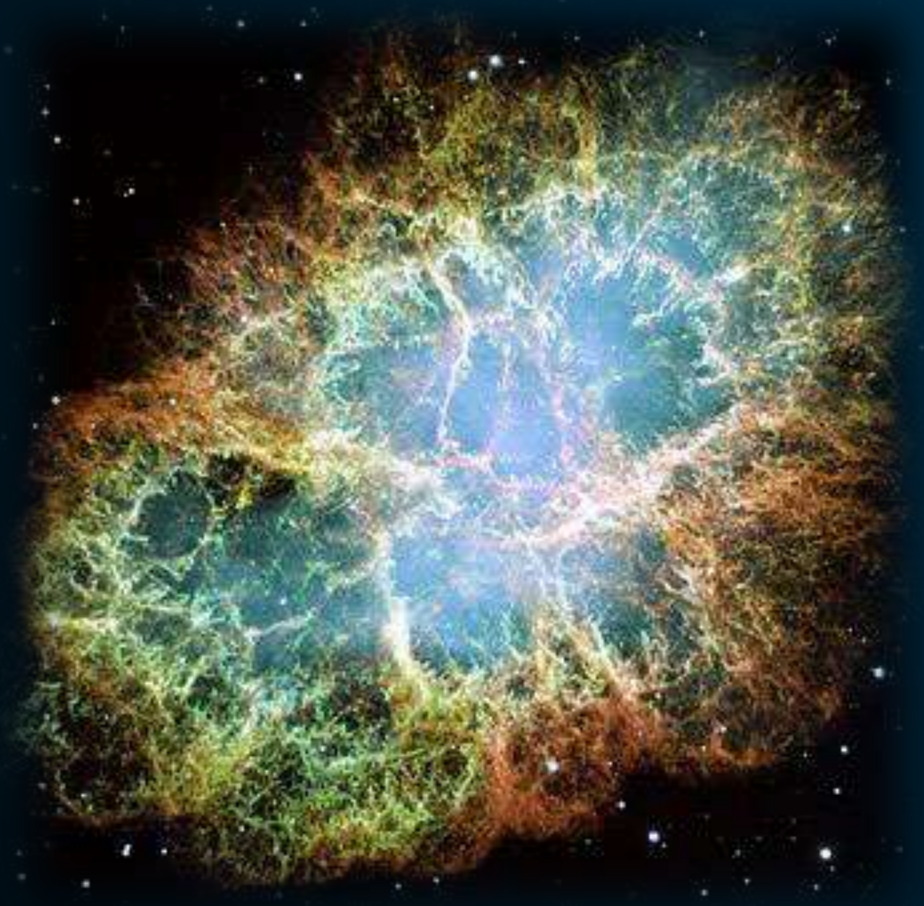
Philippov et al. (2015; 1412.0673)

Simulations indicate that pulsars accelerate a significant e^+e^- population.



But what is the pulsar e^+e^- efficiency?

How many e^+e^- escape the pulsar magnetosphere and pulsar wind nebula?



The Positron Excess

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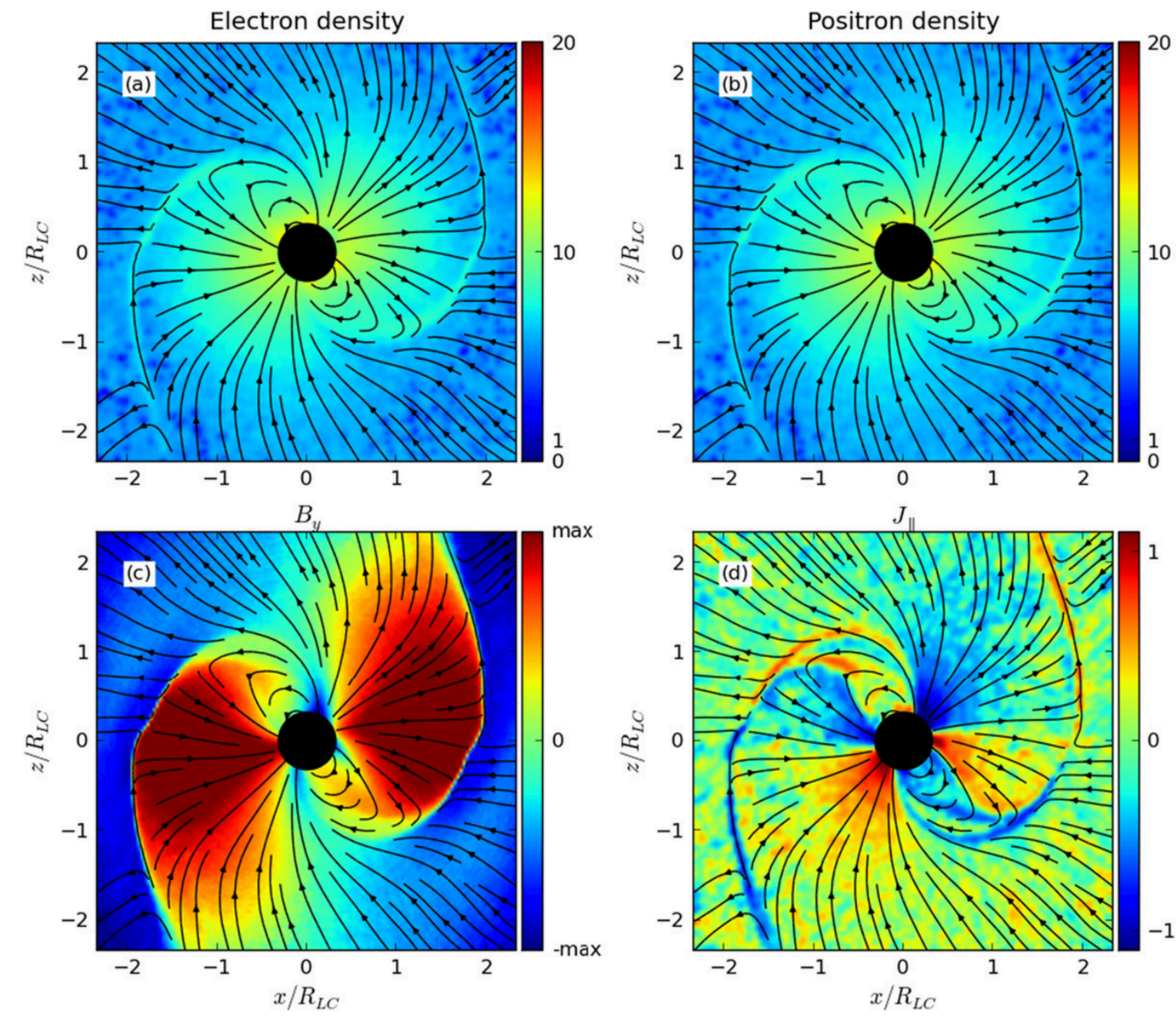


But what is the pulsar e^+e^- efficiency?

How many e^+e^- escape the pulsar magnetosphere and pulsar wind nebula?

%. 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%.

Profumo (2008, 0812.4457)


Moon (To Scale)
Geminga
PSR B0656+14

Moon (To Scale)
Geminga
SNR
(hadronic/leptonic)
TeV Halo
(escaped e+e−)
PWN
(confined e+e−)

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


Moon (To Scale)
Geminga
SNR
(hadronic/leptonic)
TeV Halo
(escaped e+e−)
PWN
(confined e+e−)
Geminga
α = 1.9
10 - 30% Efficiency!
Hooper et al. (2017; 1702.08436)
E_γ dN_γ/dE_γ (cm^−2 s^−1)
E_γ (GeV)

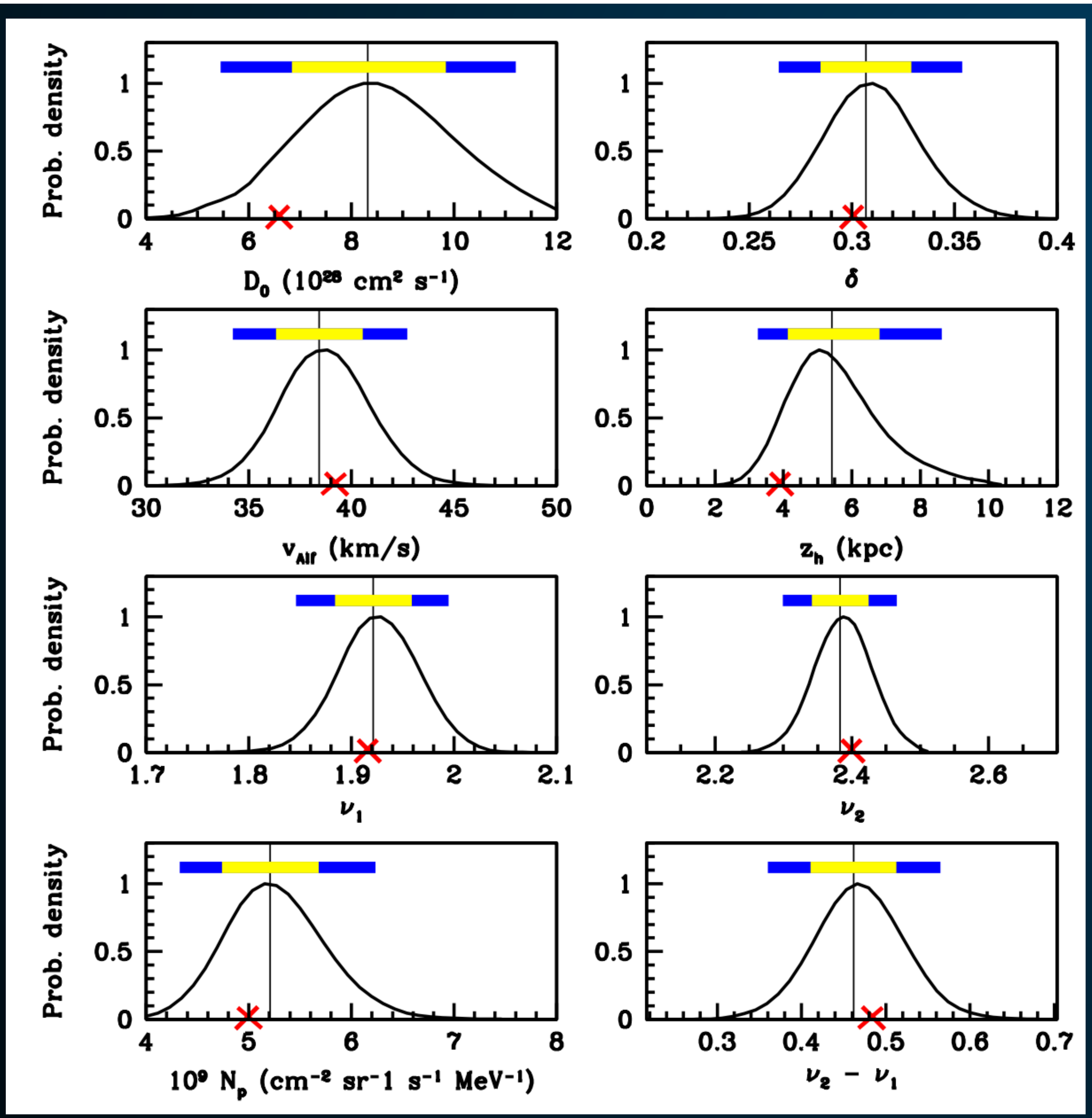
HAWC Collaboration (1711.06223)

D_{100} (Diffusion coefficient of 100TeV electrons from joint fit of two PWNe)	[x10^{27} cm^2/sec]	4.5 ± 1.2	4.5 ± 1.2
D_{100}(Diffusion coefficient of 100TeV electrons from individual fit of PWN)	[x10^{27} cm^2/sec]	$3.2^{+1.4}_{-1.0}$	15^{+49}_{-9}

The Positron Excess

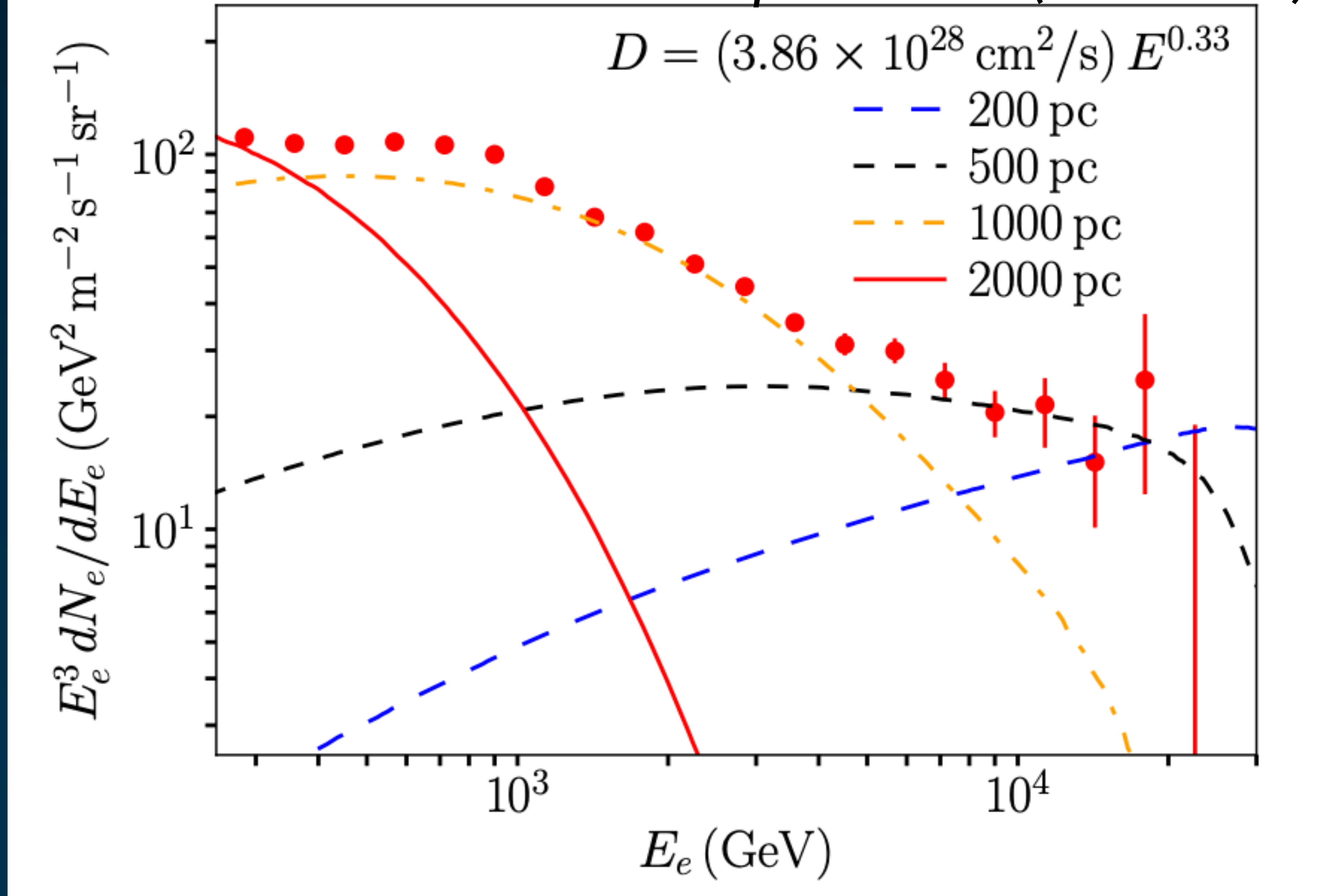
Global Problems

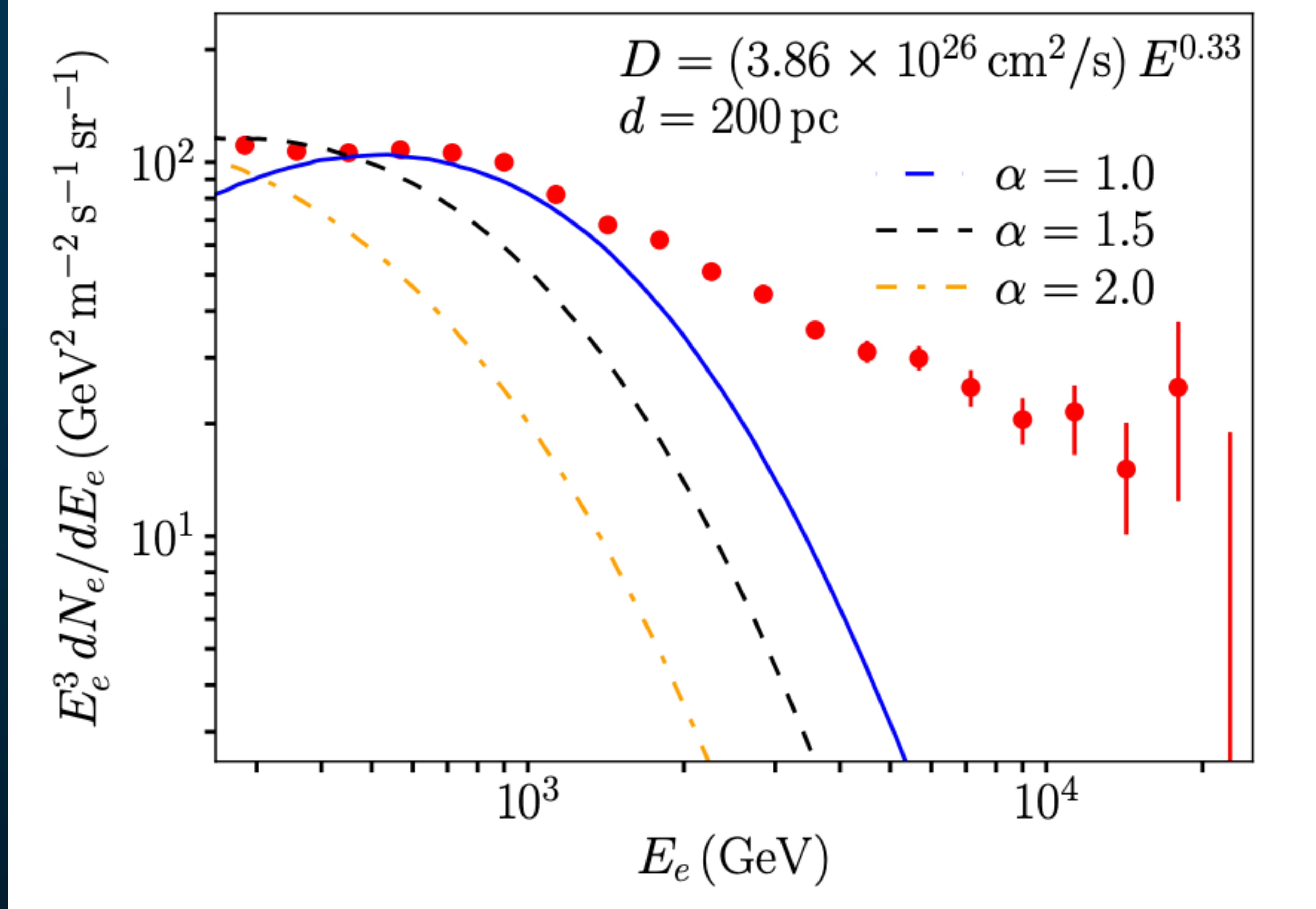
$$f \sim \frac{N_{\rm region} \times \frac{4\pi}{3} r_{\rm region}^3}{\pi R_{\rm MW}^2 \times 2 z_{\rm MW}}$$
$$\sim 0.25 \times \left(\frac{r_{\rm region}}{100\,{\rm pc}}\right)^3 \left(\frac{\dot{N}_{\rm SN}}{0.03\,{\rm yr}^{-1}}\right) \left(\frac{\tau_{\rm region}}{10^6\,{\rm yr}}\right) \left(\frac{20\,{\rm kpc}}{R_{\rm MW}}\right)^2 \left(\frac{200\,{\rm pc}}{z_{\rm MW}}\right),$$



Local Problems

Hooper & Linden (1711.07482)





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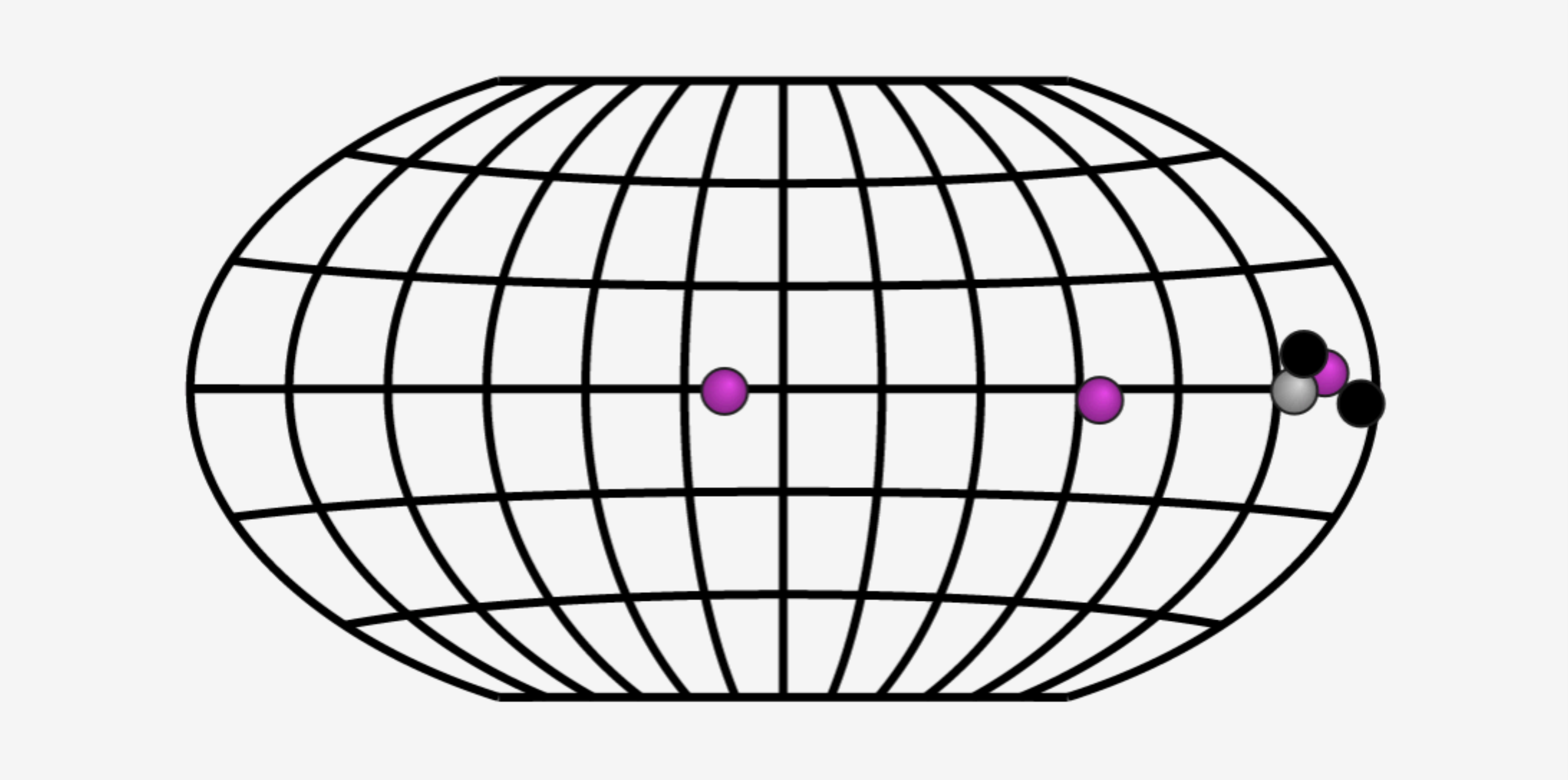


Source Name:	HAWC J0543+233
Source Type:	Gal | TeVHalo
Distance:	z=0.0
GLON:	184.4300
GLAT:	-3.3706

RegExp Search

× TeVHalo | AND

Filter by Observer | AND

Reset | Table Columns | Sync To Map | Filter Selected

Name	RA	Dec	Type Tags	Distance	Catalog
HAWC J0543+233	05 43 07.2	+23 24 00	Gal,TeVHalo	z=0.0	Newly Announced
Geminga	06 32 28	+17 22 00	Gal,SNR,P...	0.25 kpc	Default Catalog
HAWC J0635+070	06 34 50.4	+07 00 00	UNID,TeVH...	z=0.0	Newly Announced
2HWC J0700+143	07 00 28.8	+14 19 12	Gal,TeVHalo	z=0.0	Default Catalog
Vela X	08 35 00	-45 36 00	Gal,SNR,P...	0.29 kpc	Default Catalog
HESS J1825-137	18 25 49	-13 46 35	Gal,SNR,P...	3.9 kpc	Default Catalog

The Positron Excess

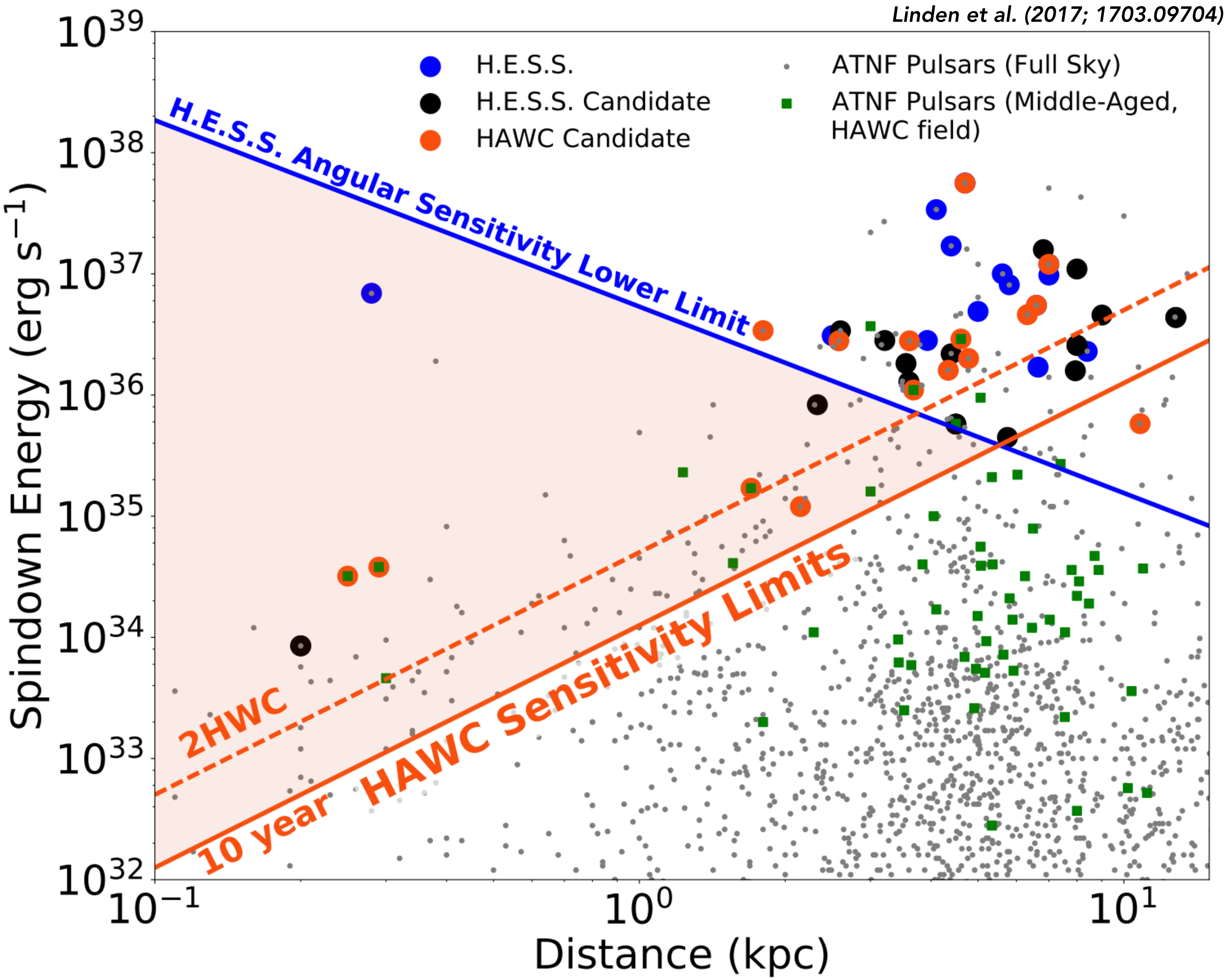
HAWC Collaboration (2019; 1909.08609)

HAWC source	PSR name	$\dot{E}$ (erg/s)	Age ($\frac{P}{2\dot{P}}$) (kyr)	Distance to Earth (kpc)	Distance between HAWC source and PSR [° (pc)]	HAWC source extent (pc)
eHWC J0534+220	J0534+2200	4.5×10^{38}	1.3	2.00	0.03 (1.05)	-
eHWC J1809-193	J1809-1917	1.8×10^{36}	51.3	3.27	0.05 (2.86)	19.4
-	J1811-1925	6.4×10^{36}	23.3	5.00	0.40 (34.9)	29.7
eHWC J1825-134	J1826-1334	2.8×10^{36}	21.4	3.61	0.26 (16.4)	22.1
-	J1826-1256	3.6×10^{36}	14.4	1.55	0.45 (12.2)	9.47
eHWC J1839-057	J1838-0537	6.0×10^{36}	4.89	2.0[a]	0.10 (3.50)	11.9
eHWC J1842-035	J1844-0346	4.2×10^{36}	11.6	2.40[b]	0.49 (20.5)	16.3
eHWC J1850+001	J1849-0001	9.8×10^{36}	42.9	7.00[c]	0.37 (45.2)	45.2
eHWC J1907+063	J1907+0602	2.8×10^{36}	19.5	2.37	0.29 (12.0)	21.5
eHWC J2019+368	J2021+3651	3.4×10^{36}	17.2	1.80	0.27 (8.48)	6.28
eHWC J2030+412	J2032+4127	1.5×10^{35}	201	1.33	0.33 (7.66)	4.18

The highest energy Galactic systems are all coincident with pulsars!

Supernova are also coincident with pulsars — more work remains to be done.

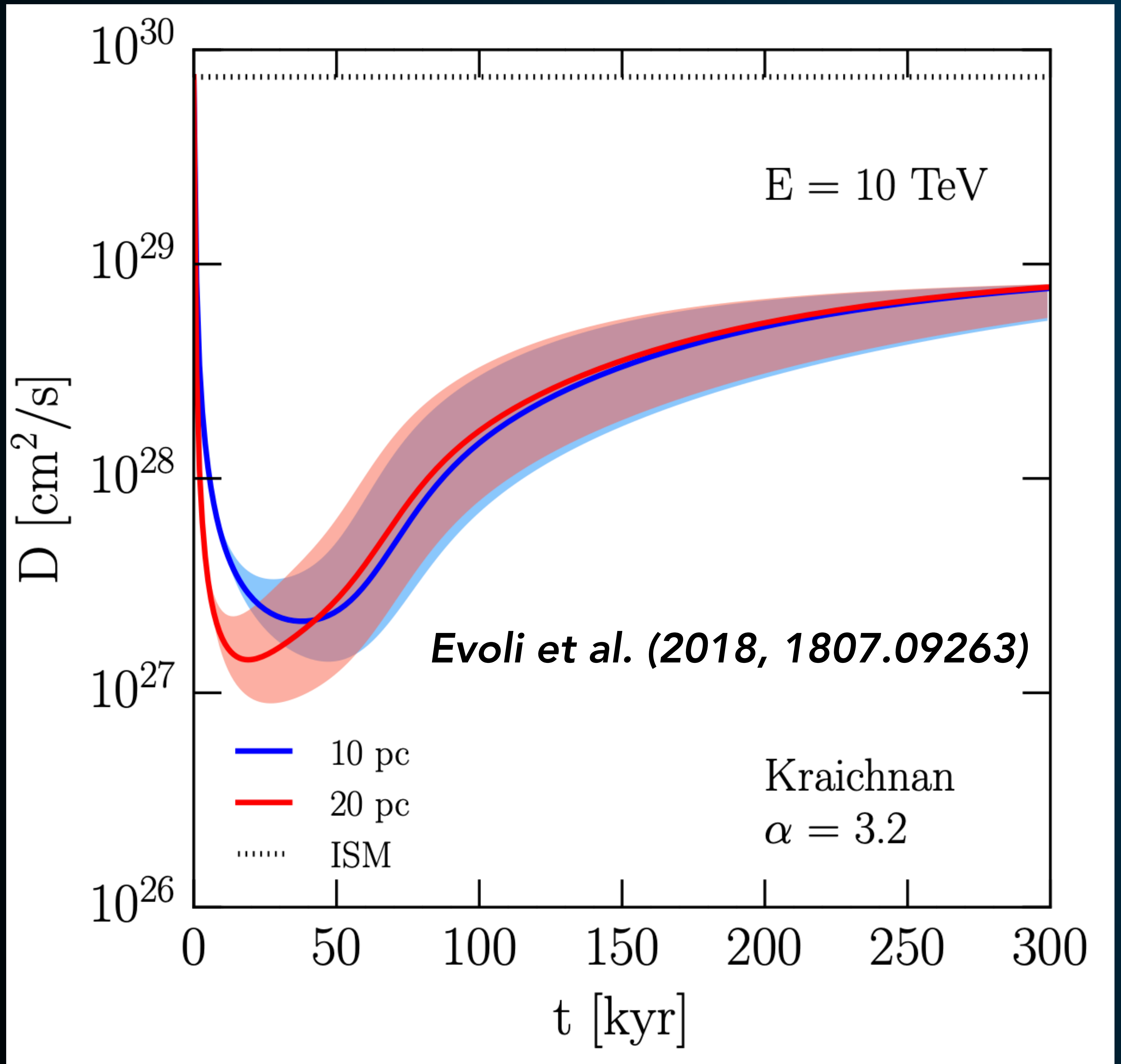
Linden et al. (2017; 1703.09704)

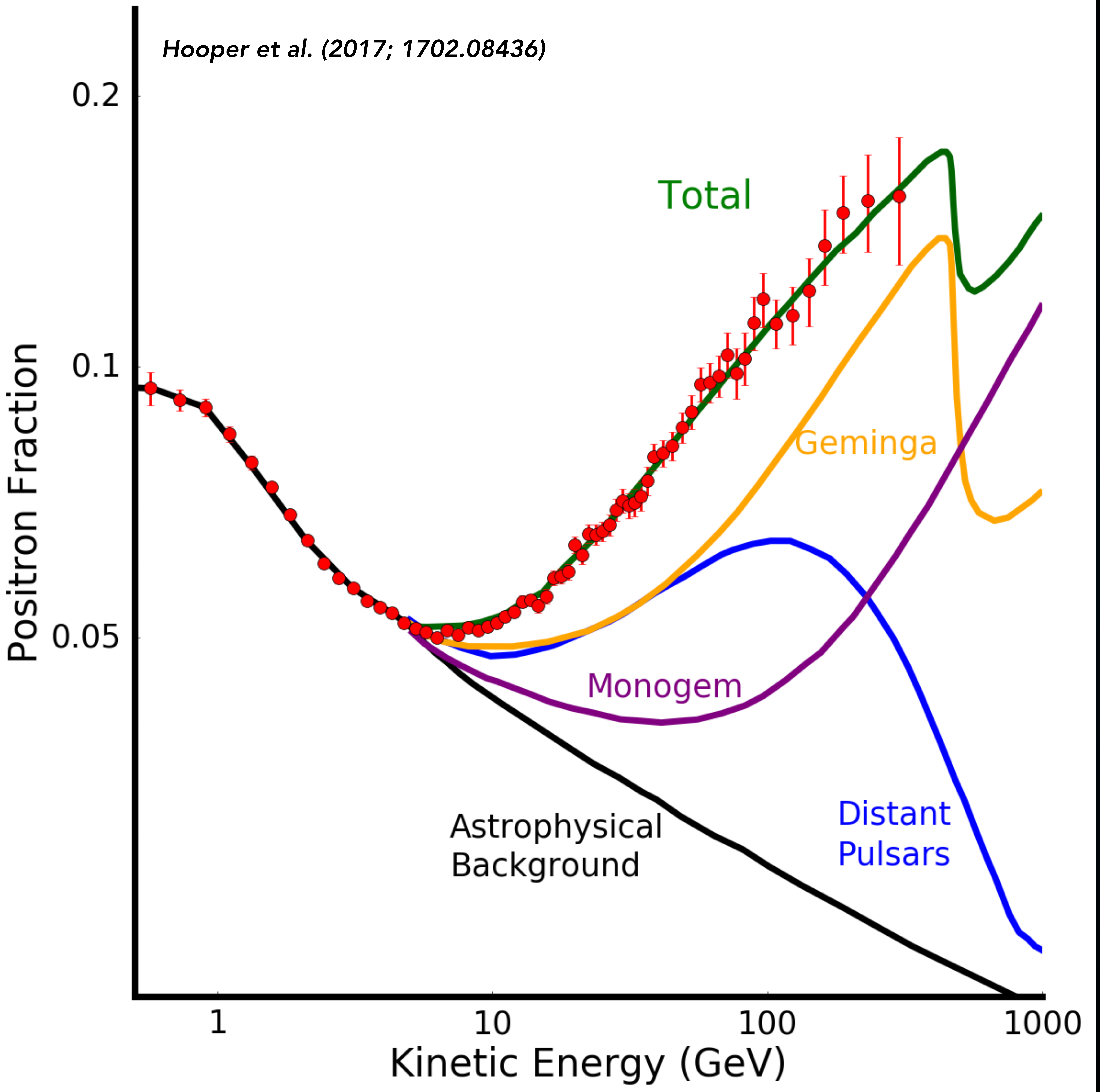


The Positron Excess

This can easily match the positron fraction

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





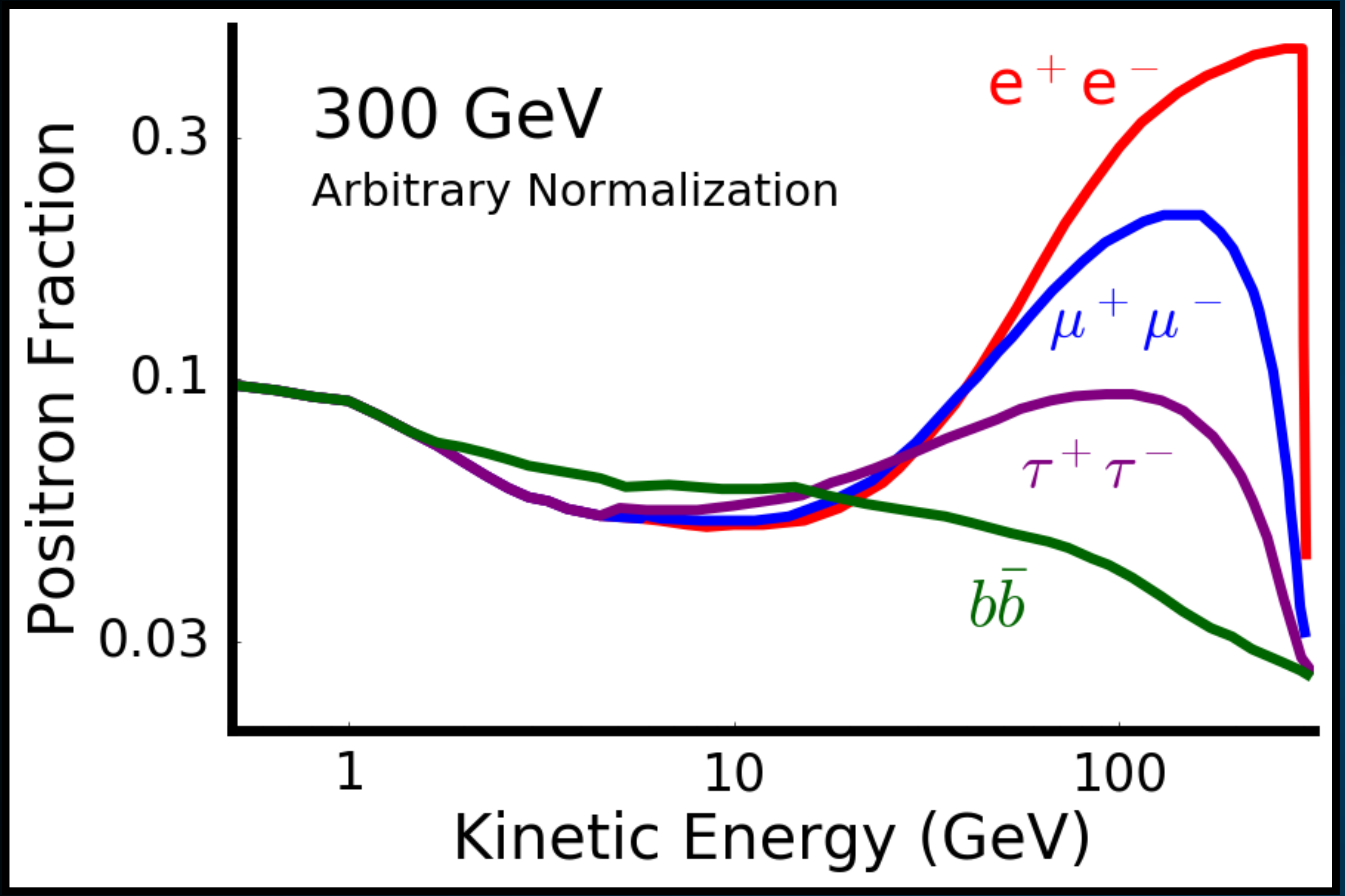
The Positron Excess

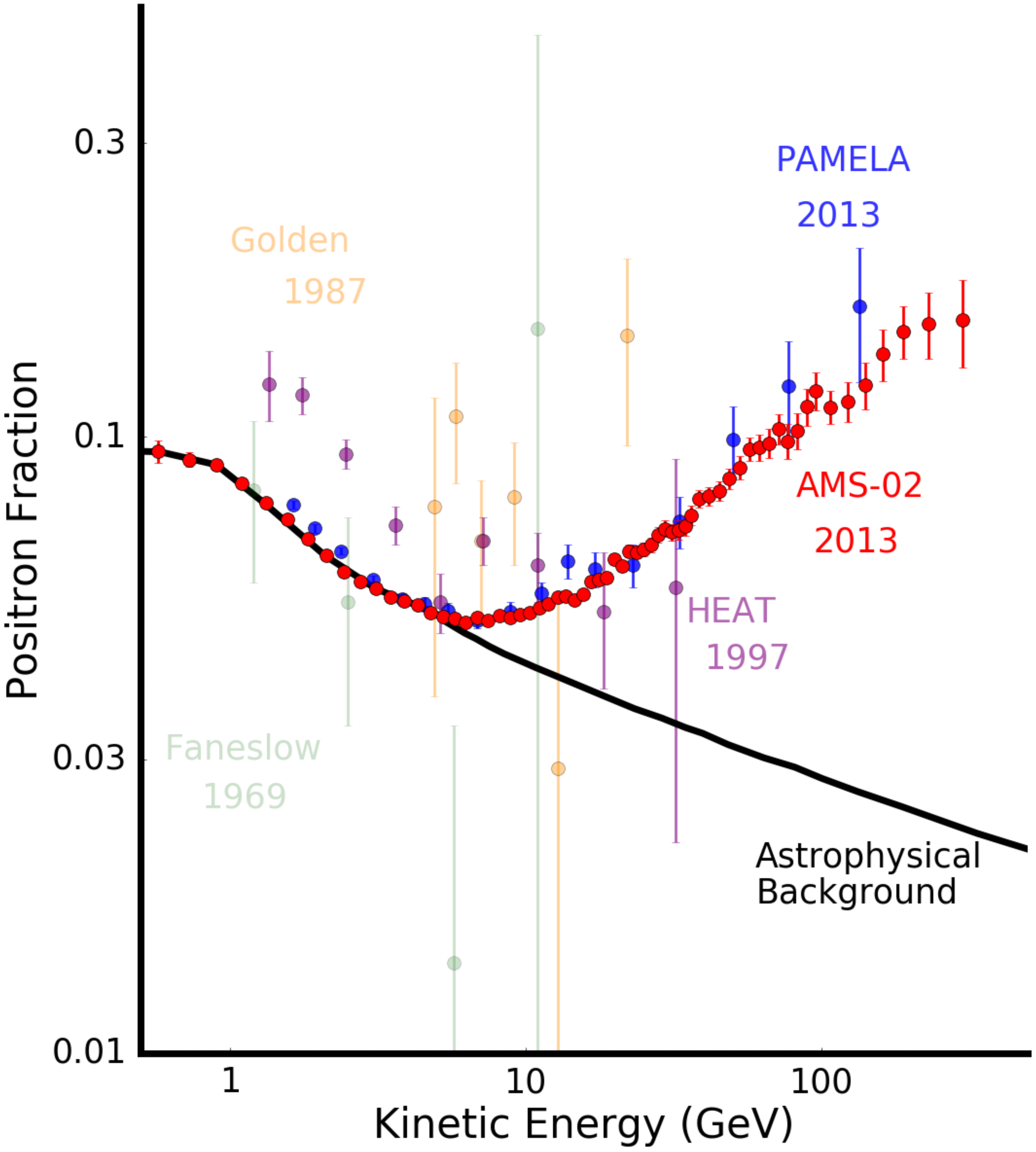
Hooper et al. (2017; 1702.08436)

Jóhannesson (2019; 1903.05509)

Exciting implications for our understanding of Galactic Diffusion!

Constraints on Leptonic Channels






300 GeV
Arbitrary Normalization
Positron Fraction
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^-
$<\sigma v>$ (cm^3s^{-1})
Dark Matter Mass (GeV)
Bergström et al. (2013; 1306.3983)

The Antiproton Excess

The Antiproton Excess

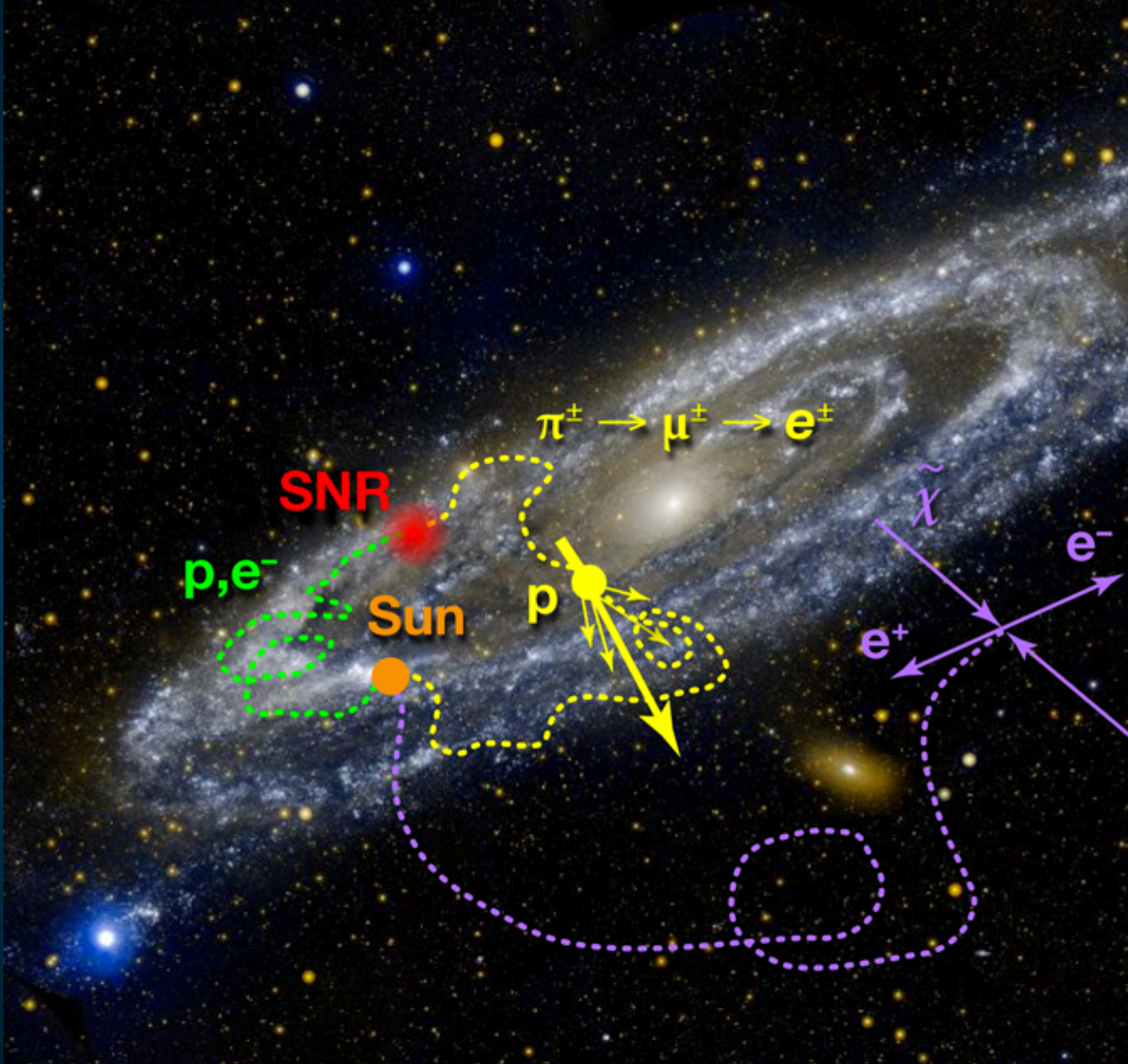
Investigate the Antiproton Fraction!

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

Two Changes:

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

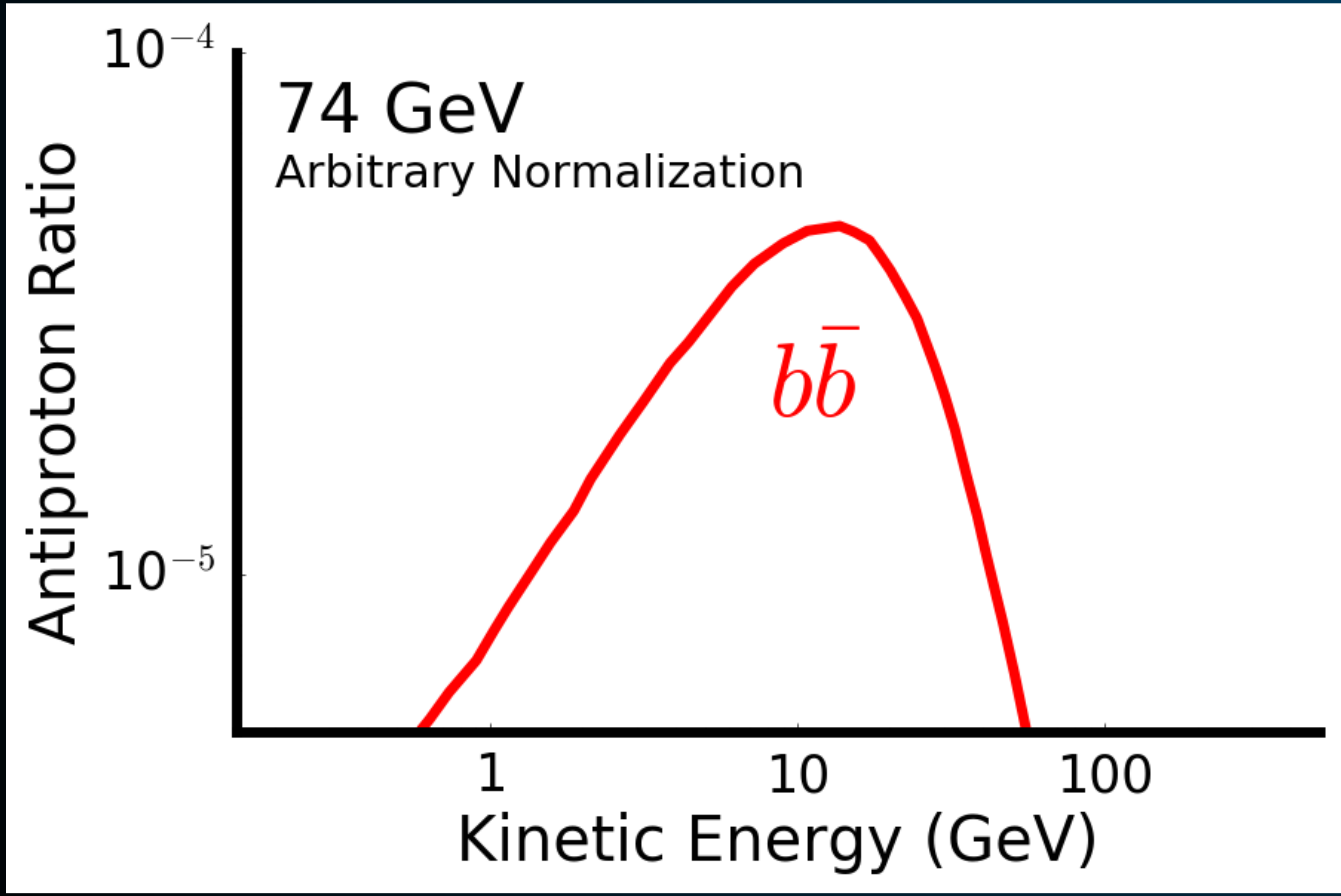
Hadronic Energy losses are slower (sensitive to antiproton production throughout the Galaxy)

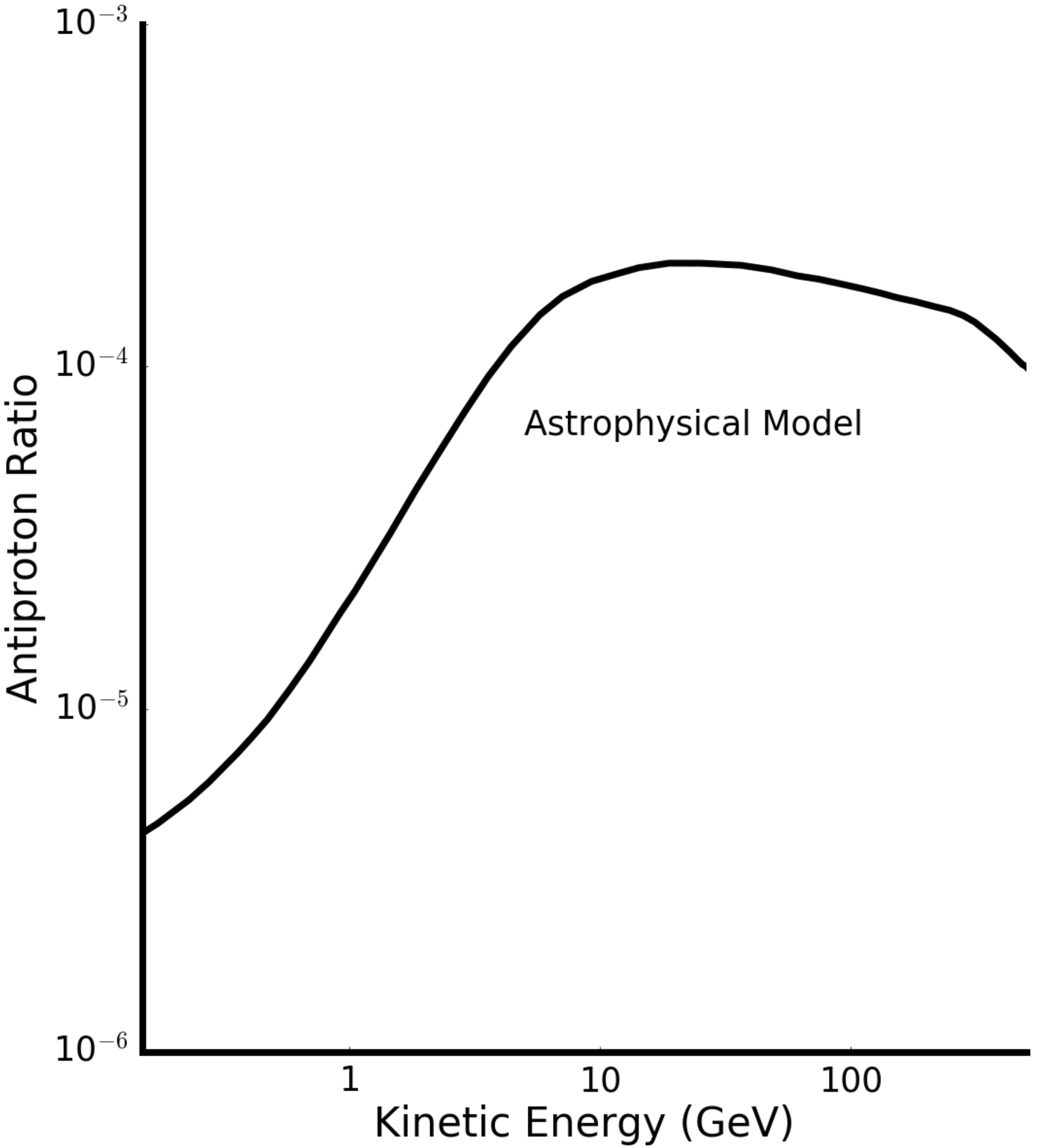


The Antiproton Excess

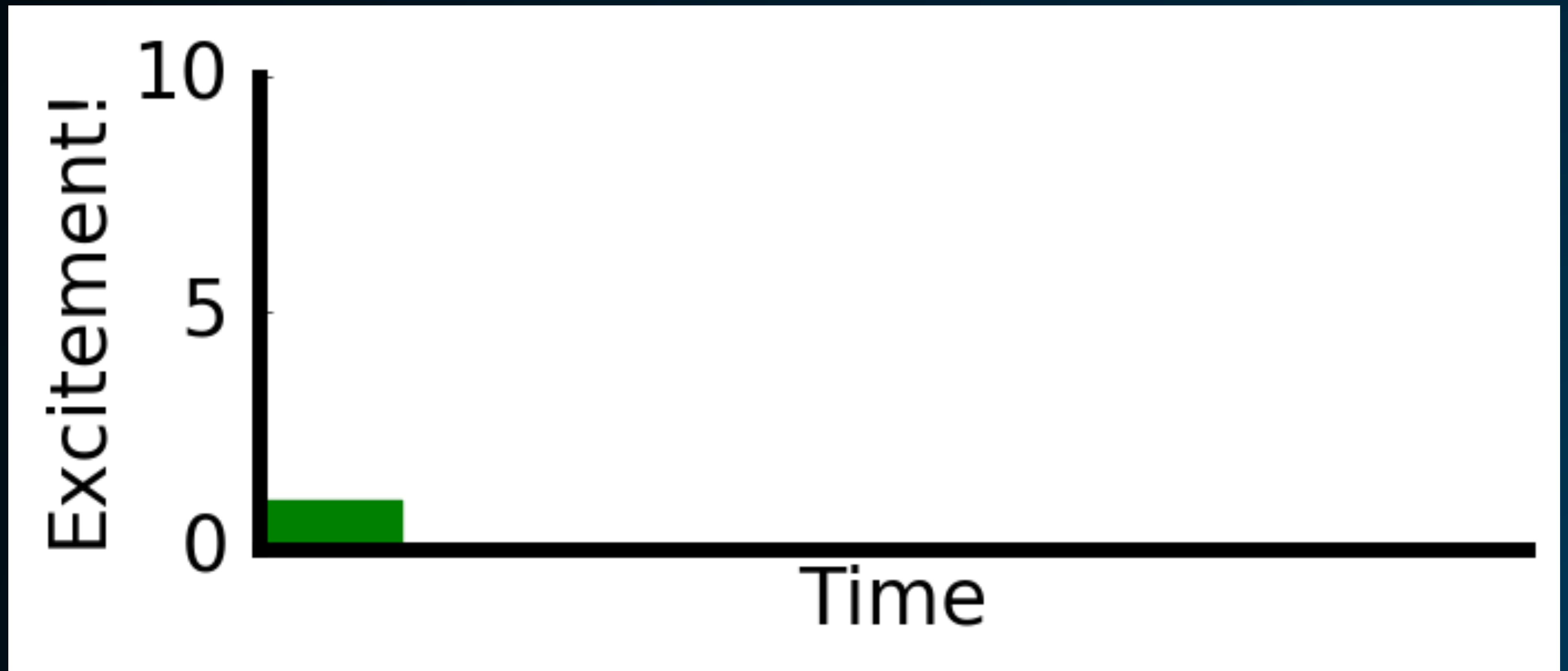
Astrophysics - Smooth Profile

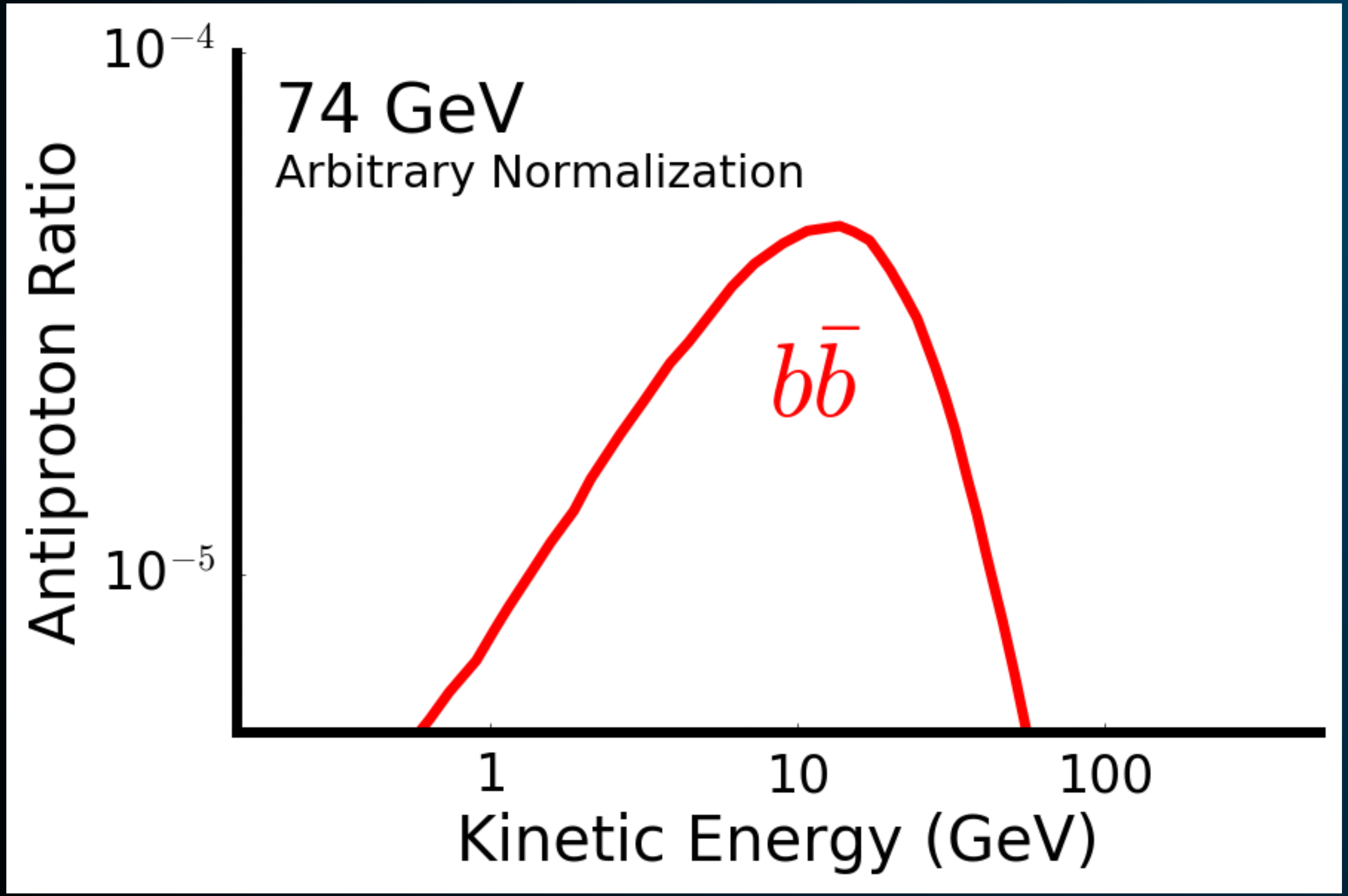
Dark Matter - Sharp Bump!



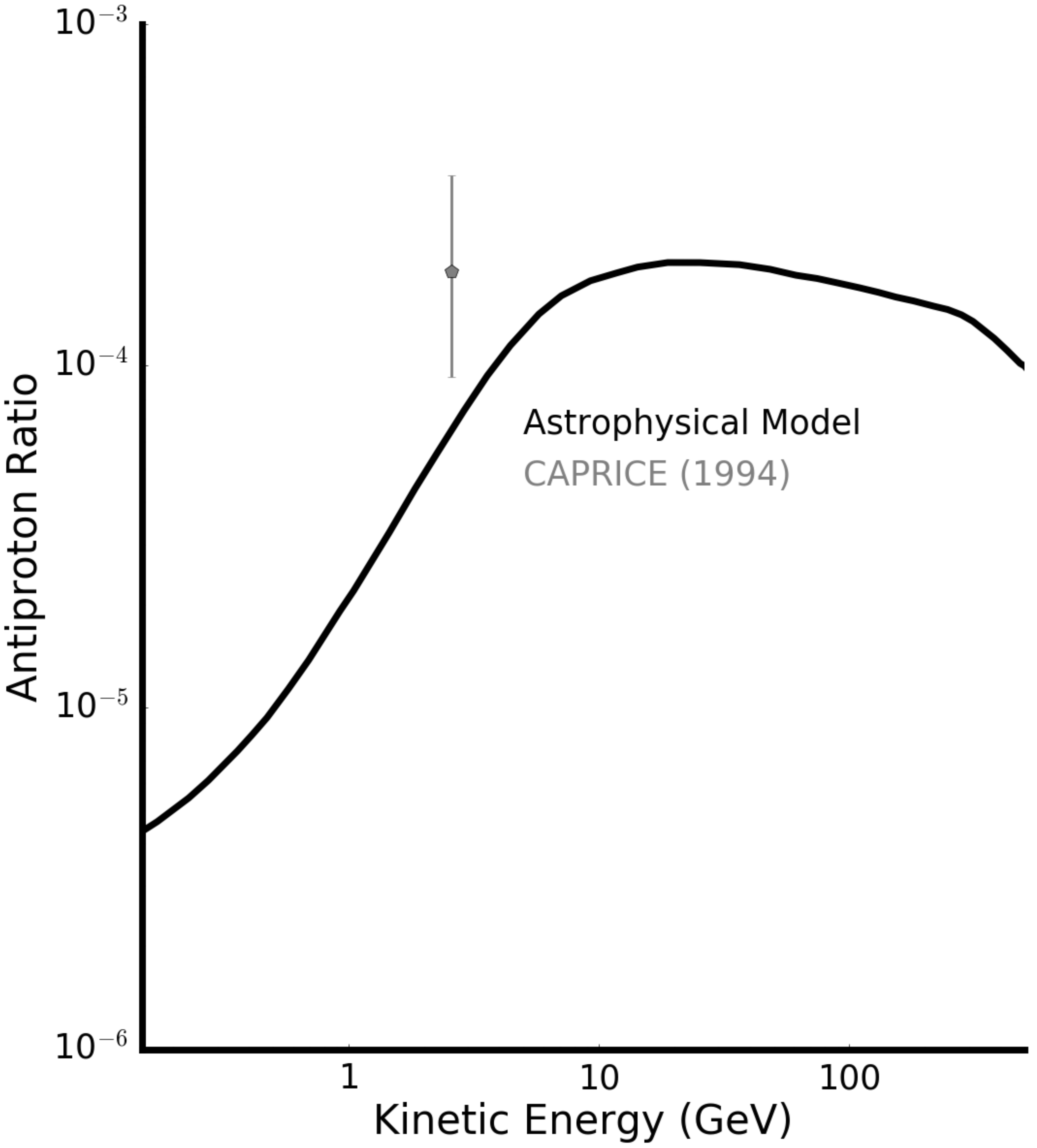


The Antiproton Excess

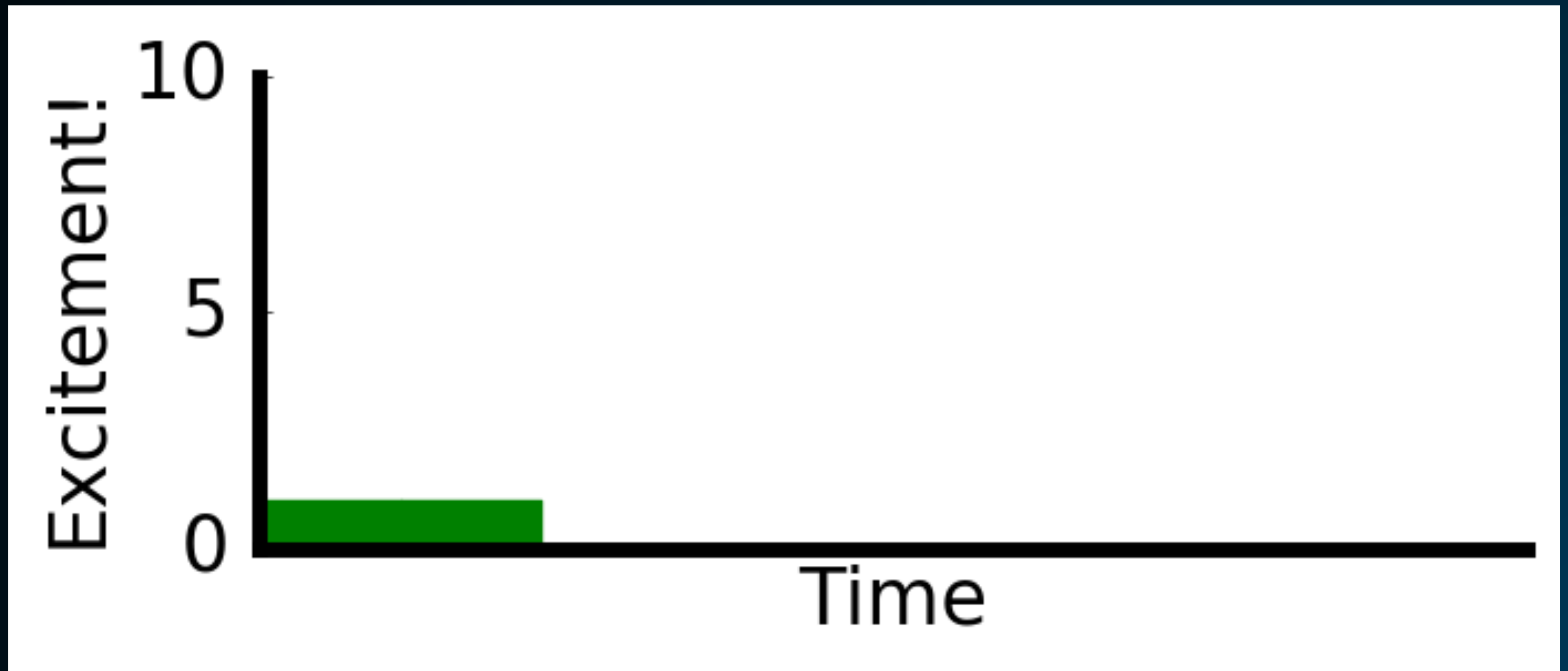


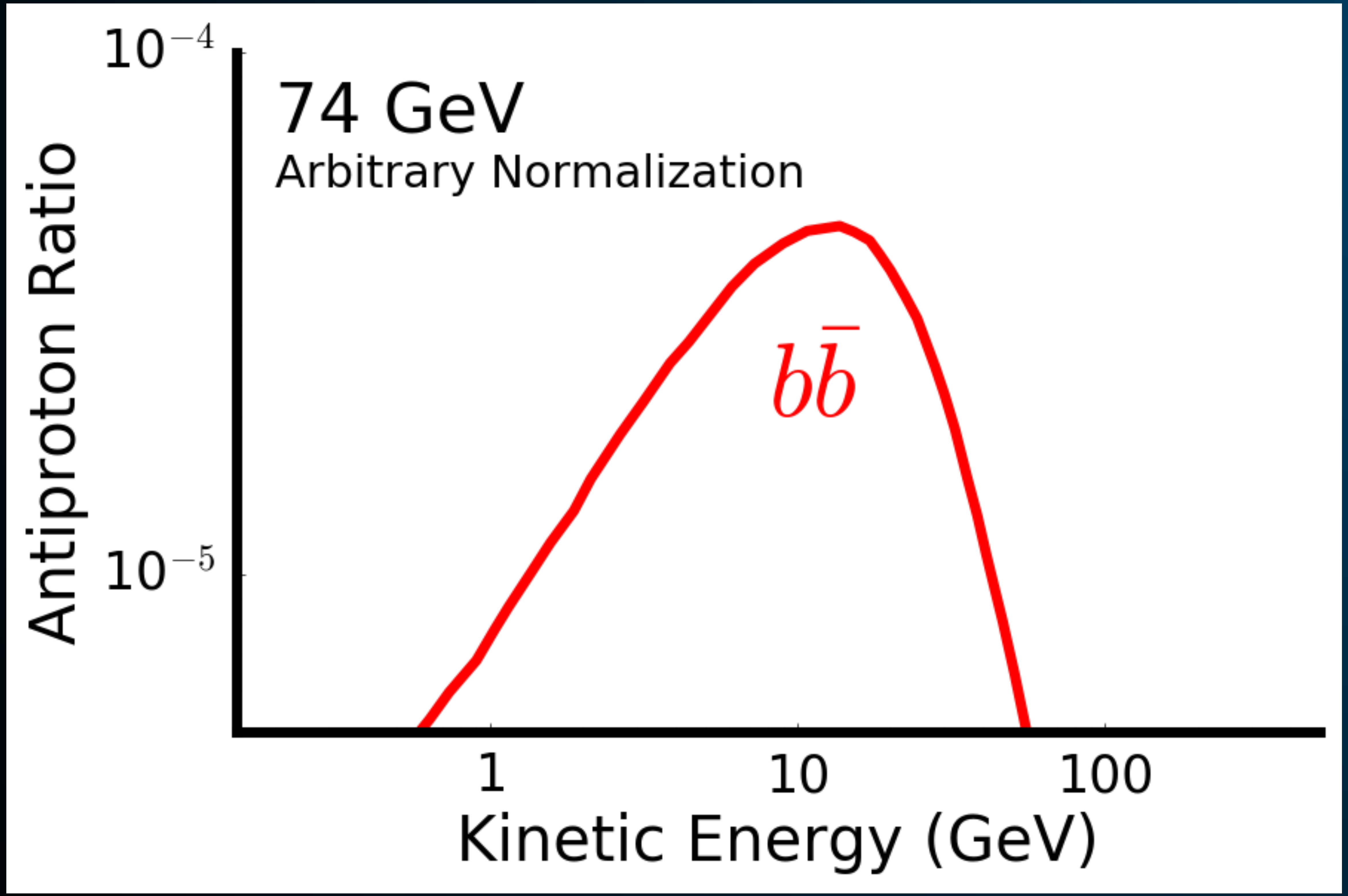


(Not an exhaustive list of observations)



The Antiproton Excess





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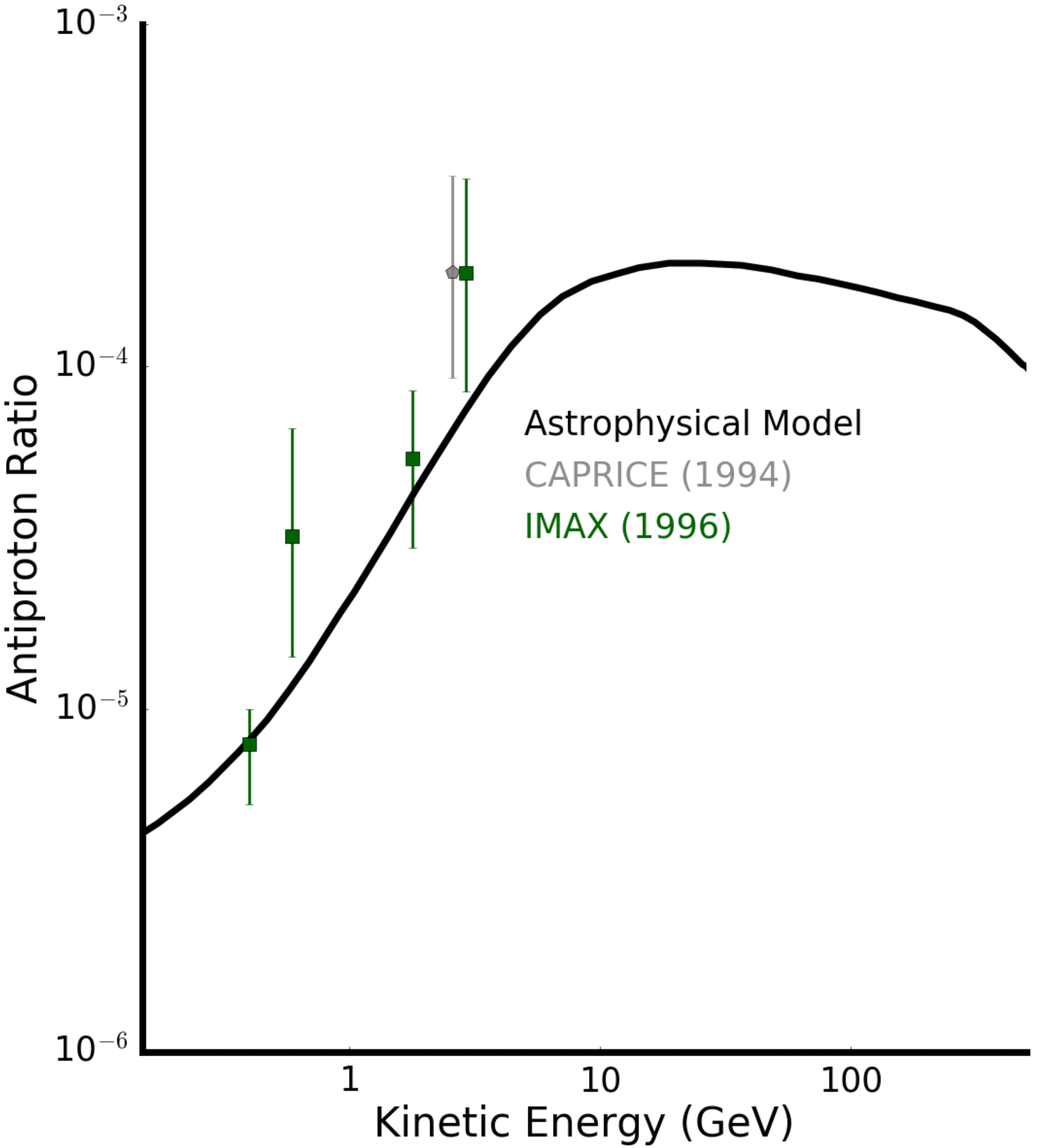

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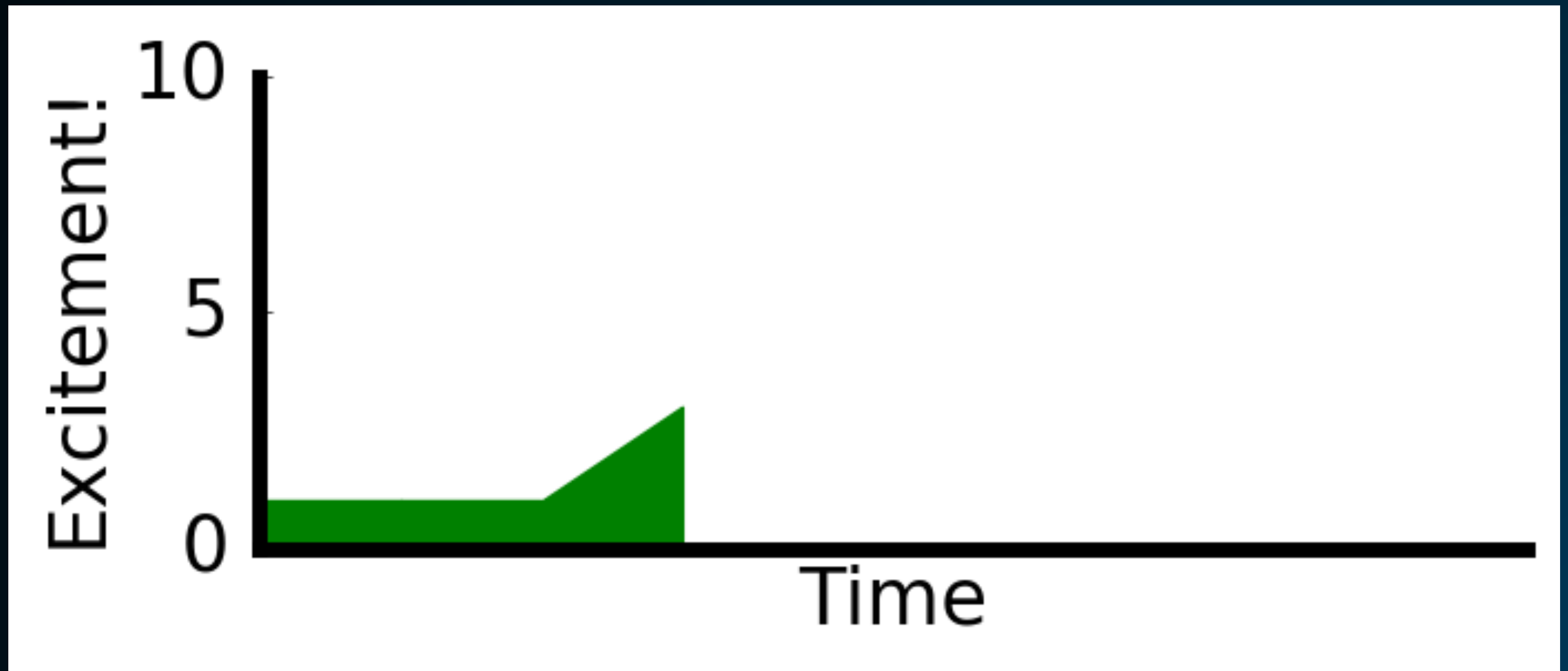

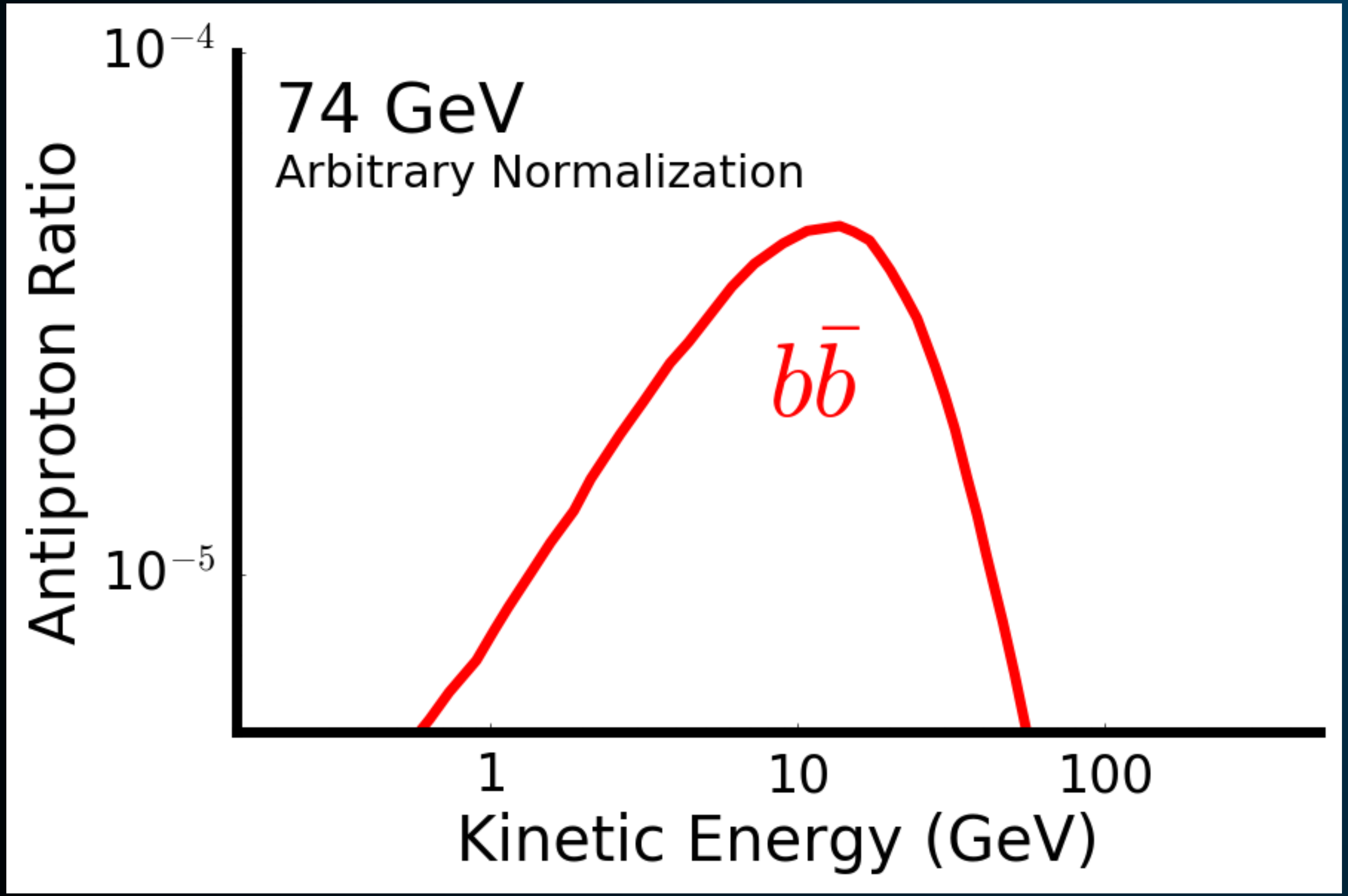

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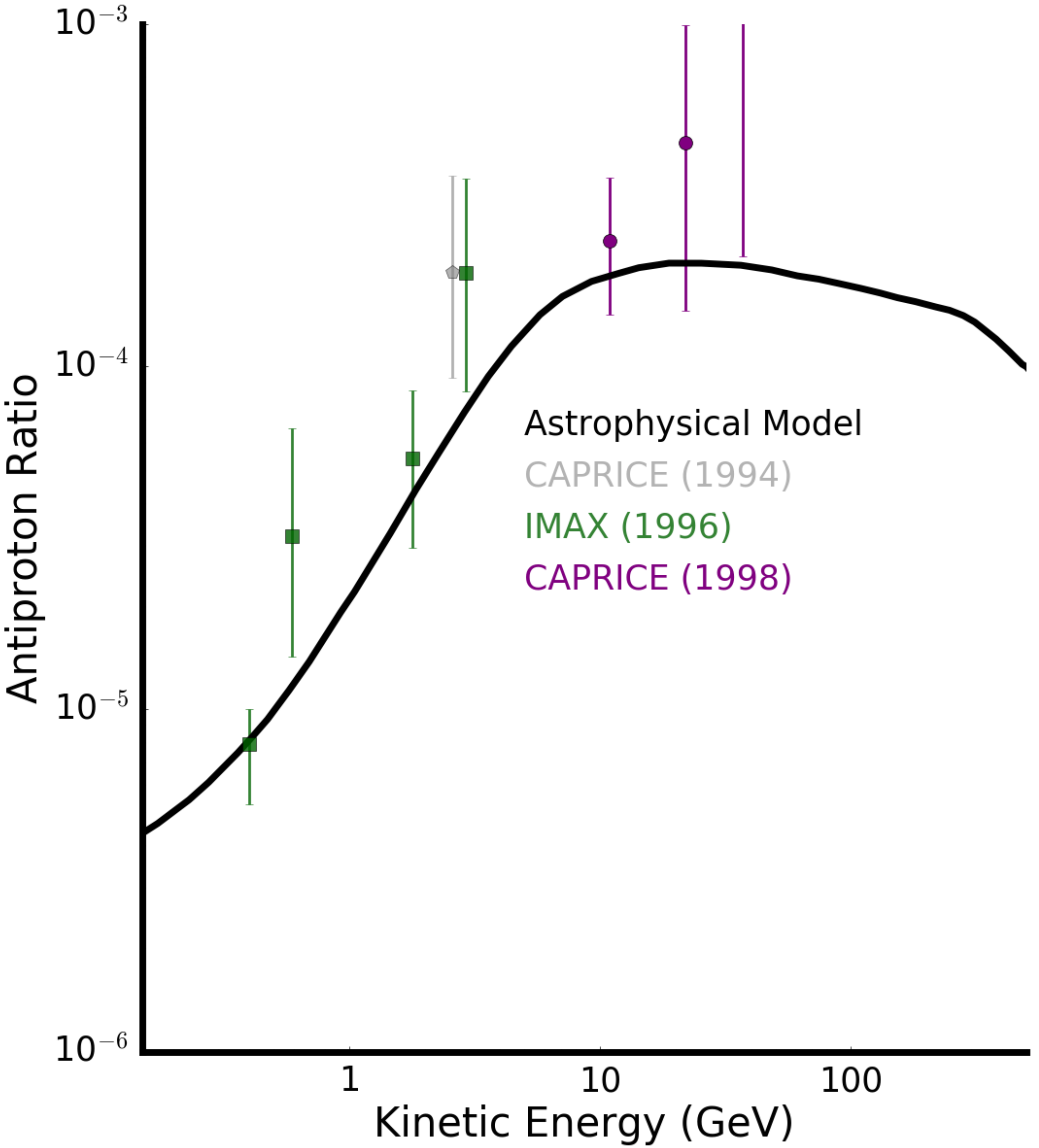
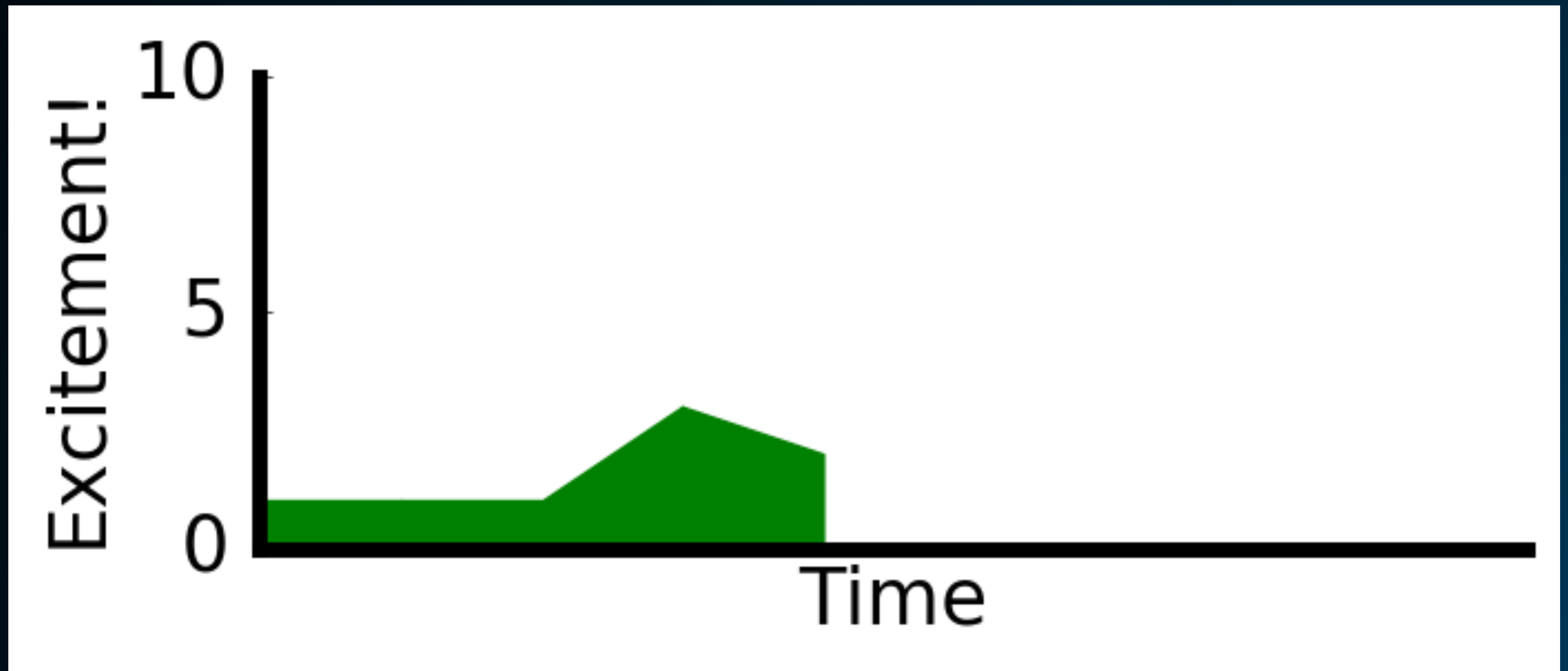
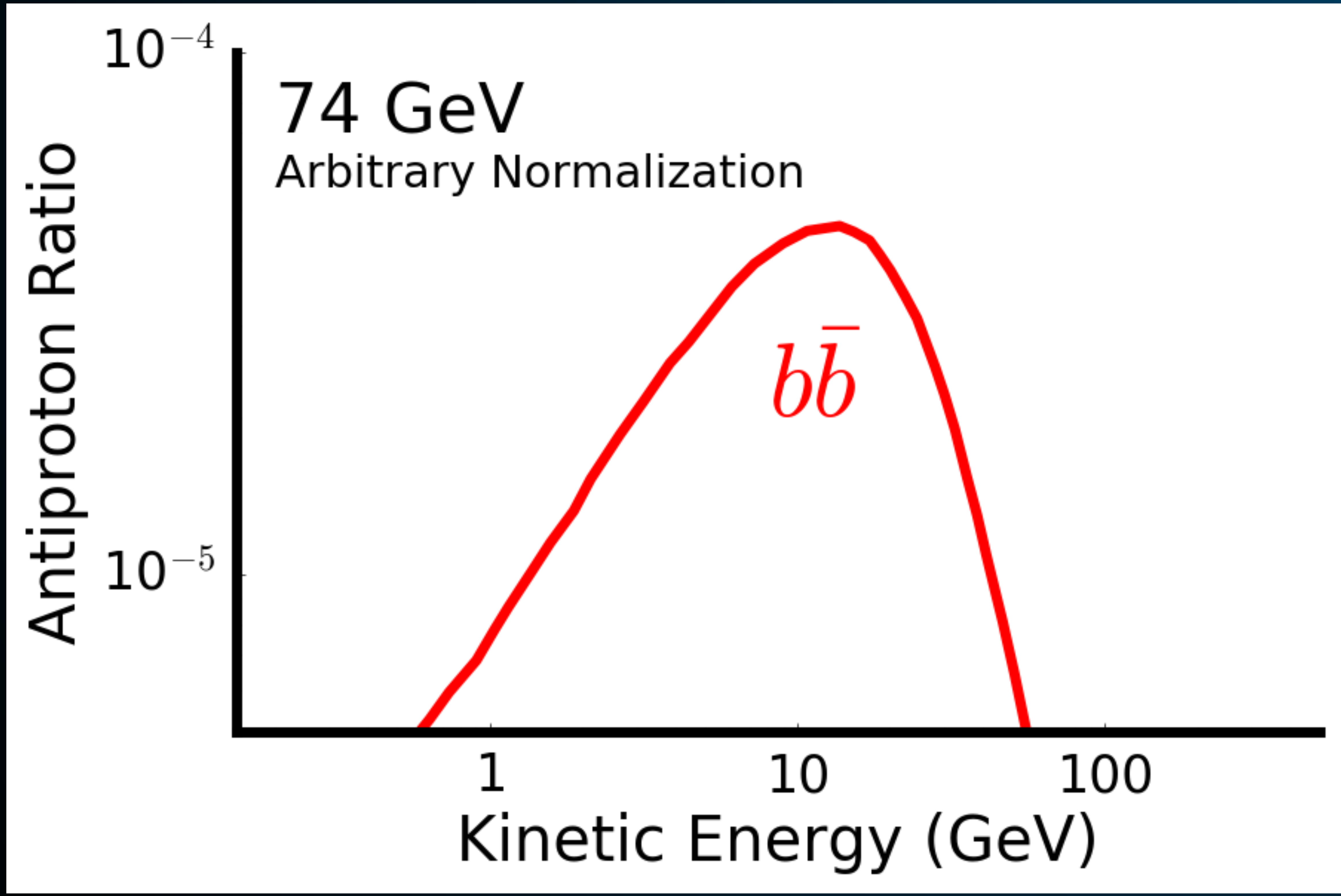
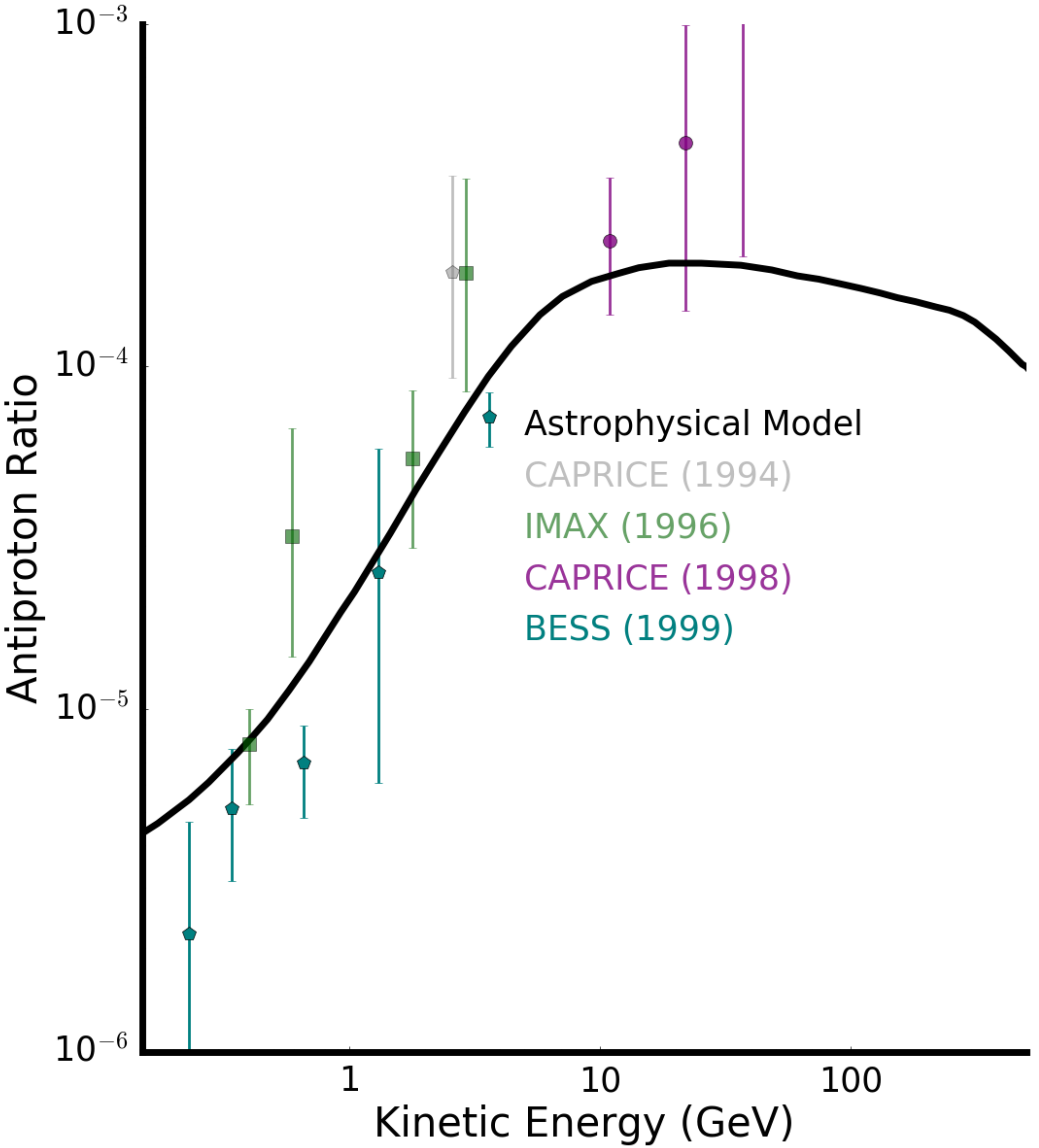


The Antiproton Excess

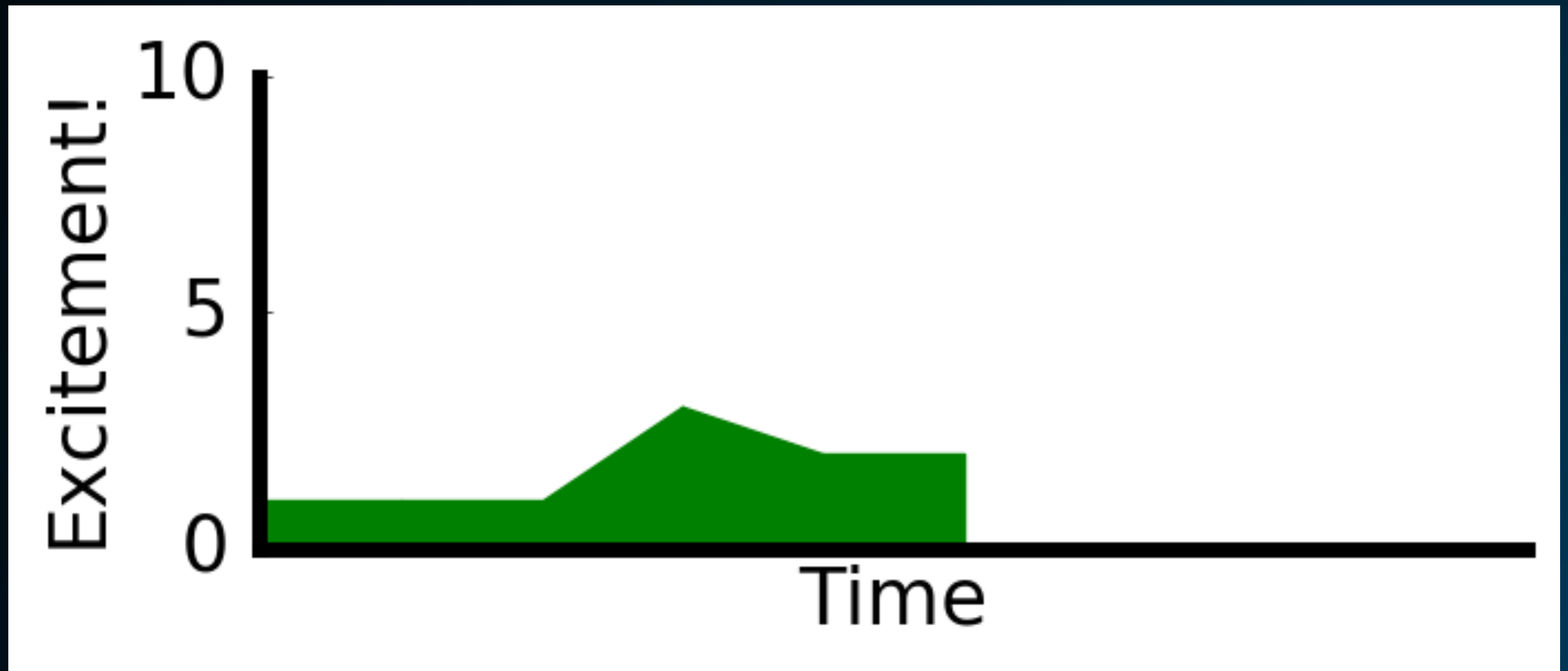


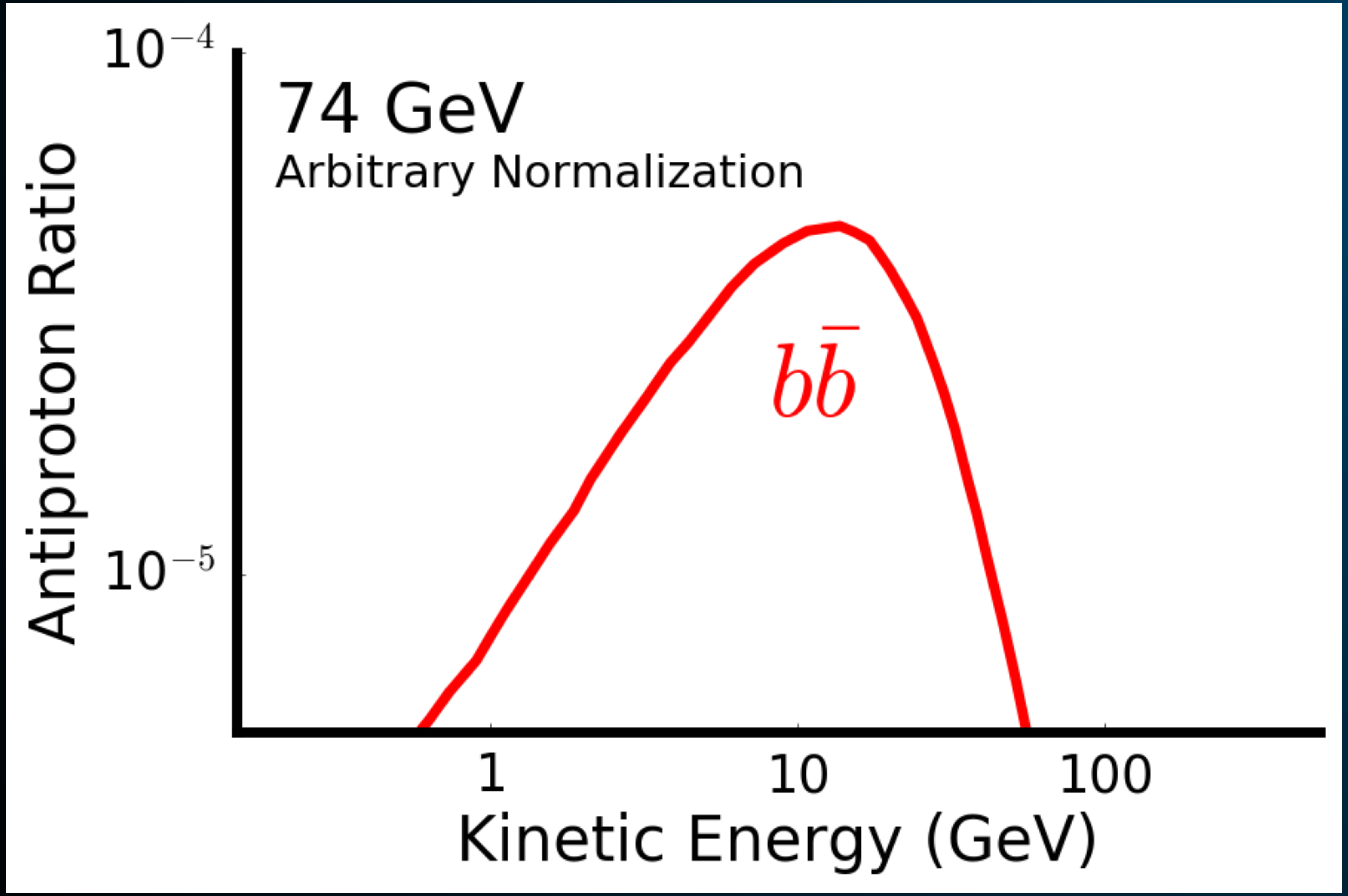




(Not an exhaustive list of observations)

The Antiproton Excess





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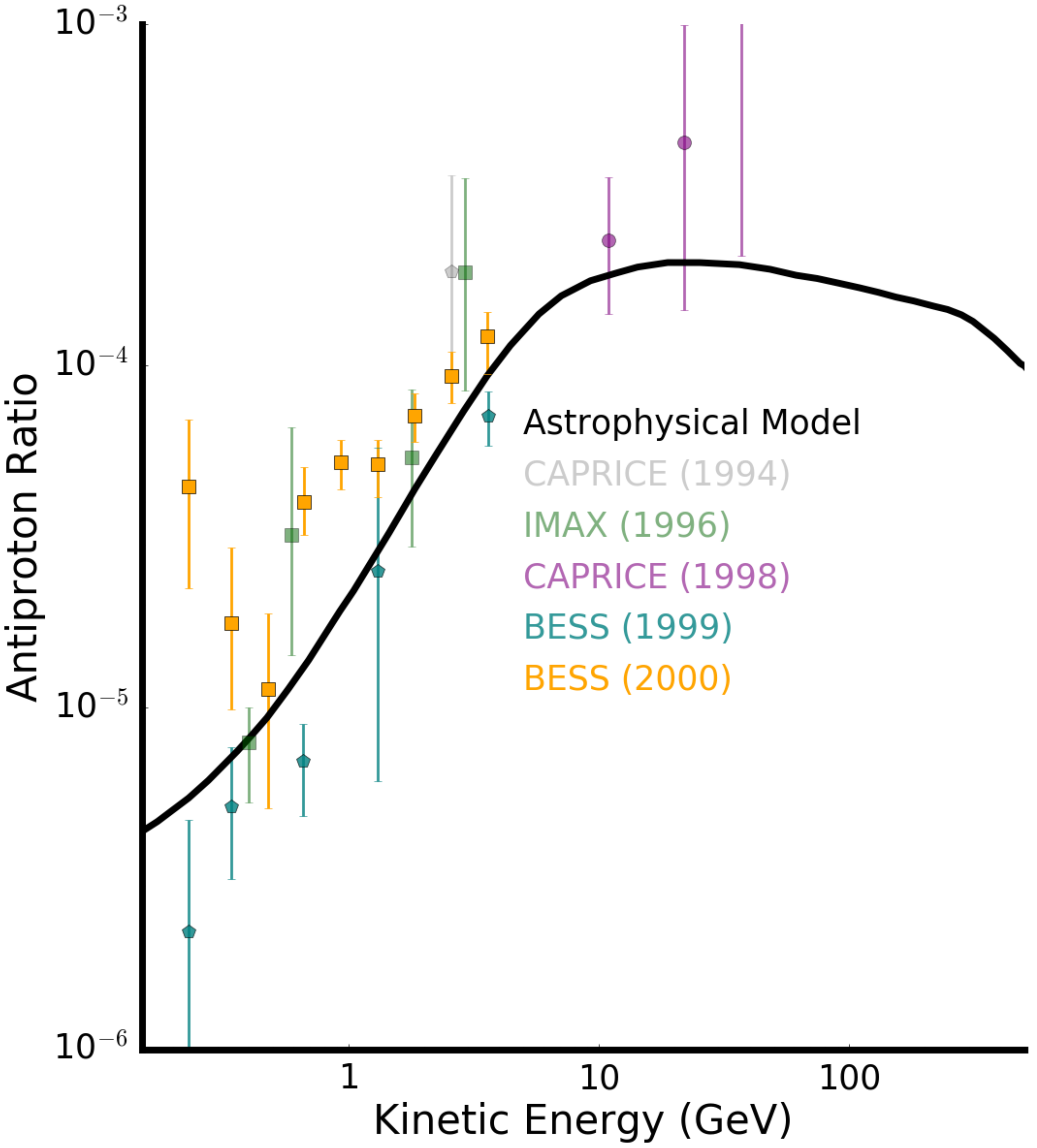

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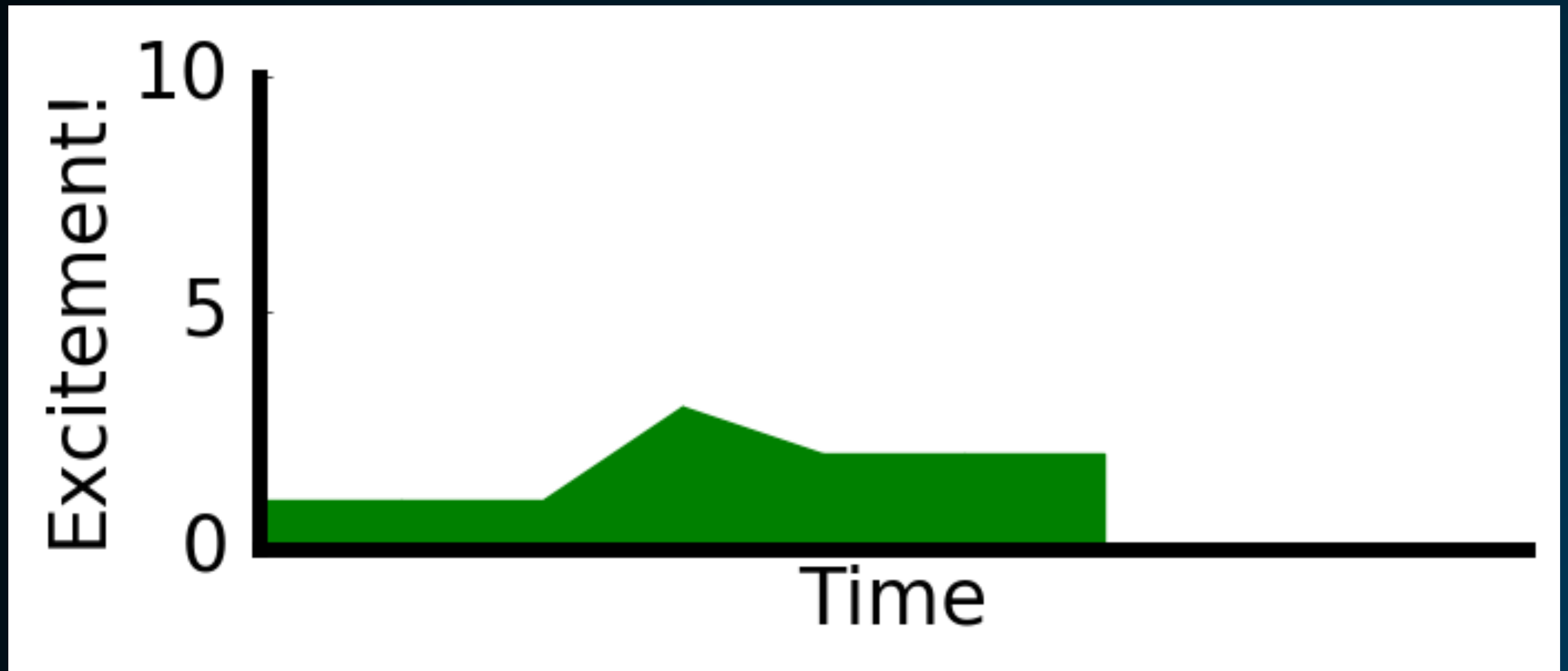

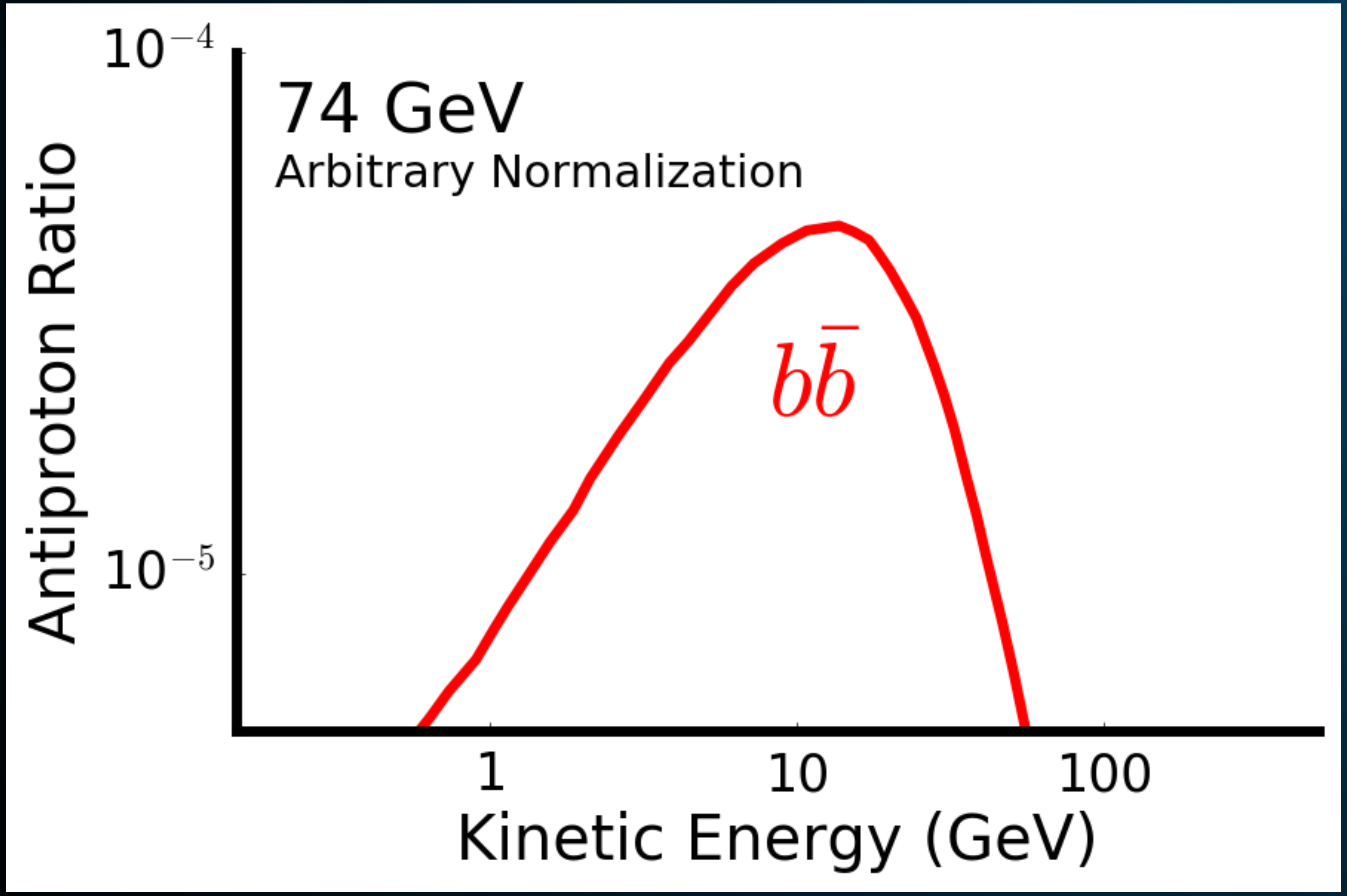

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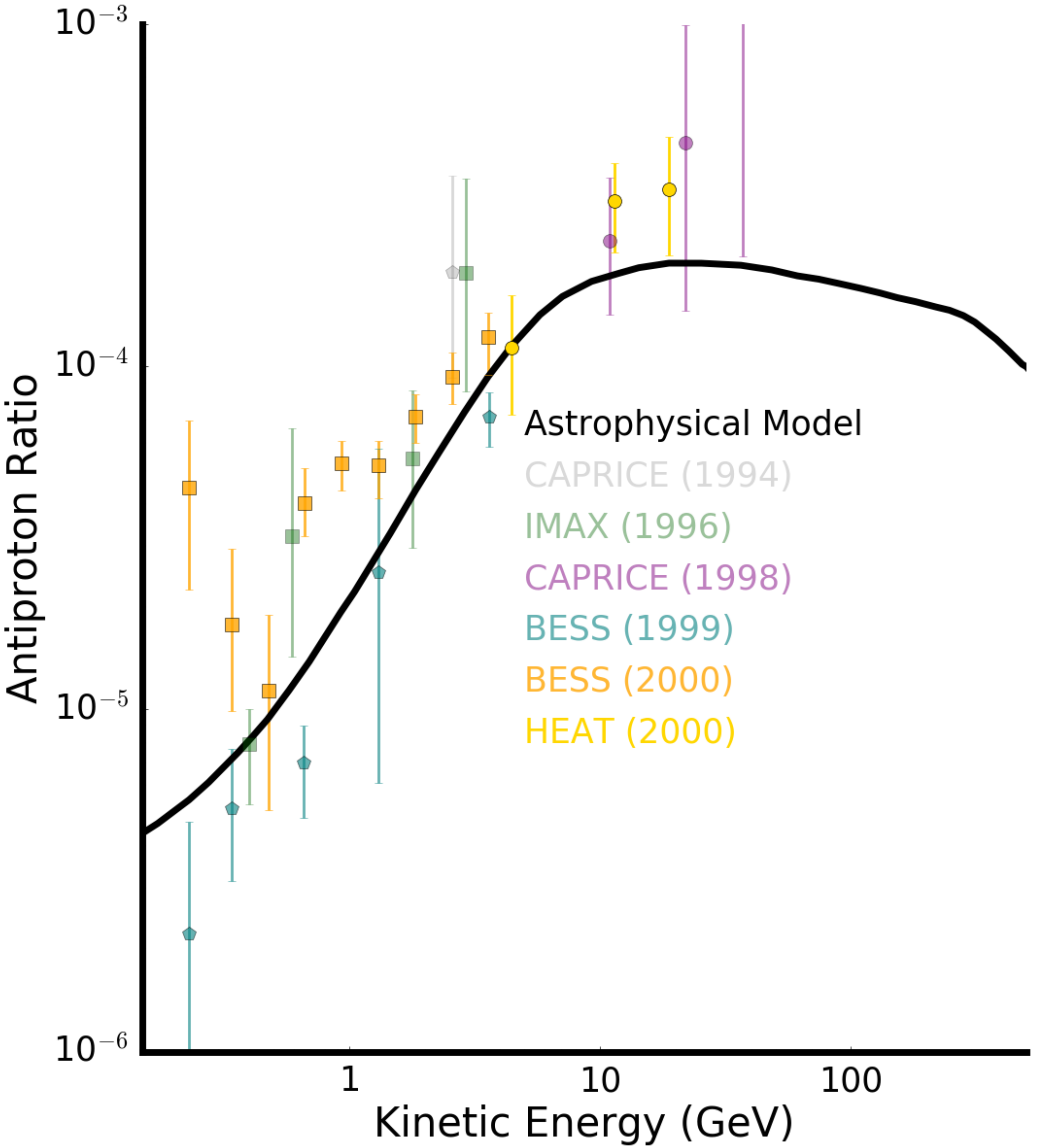
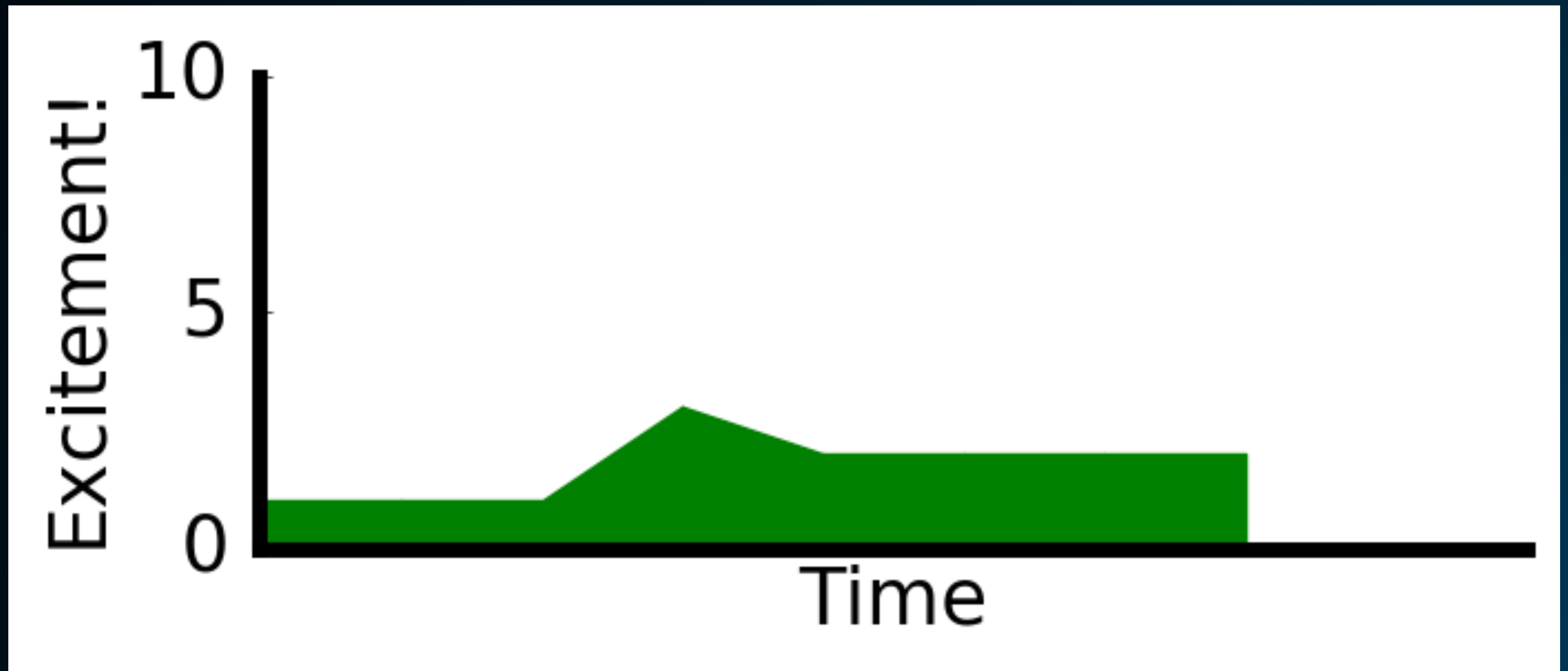
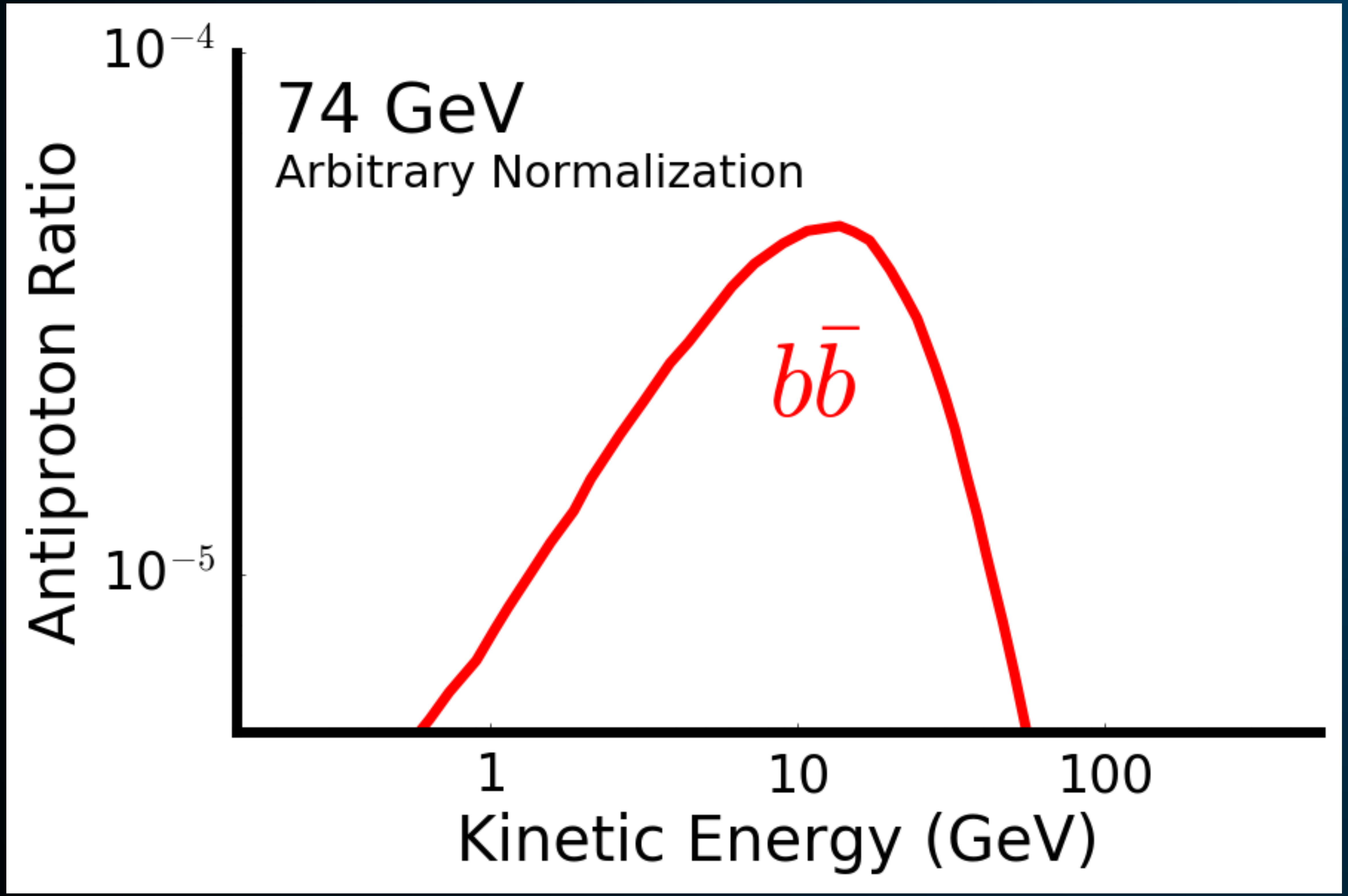


The Antiproton Excess





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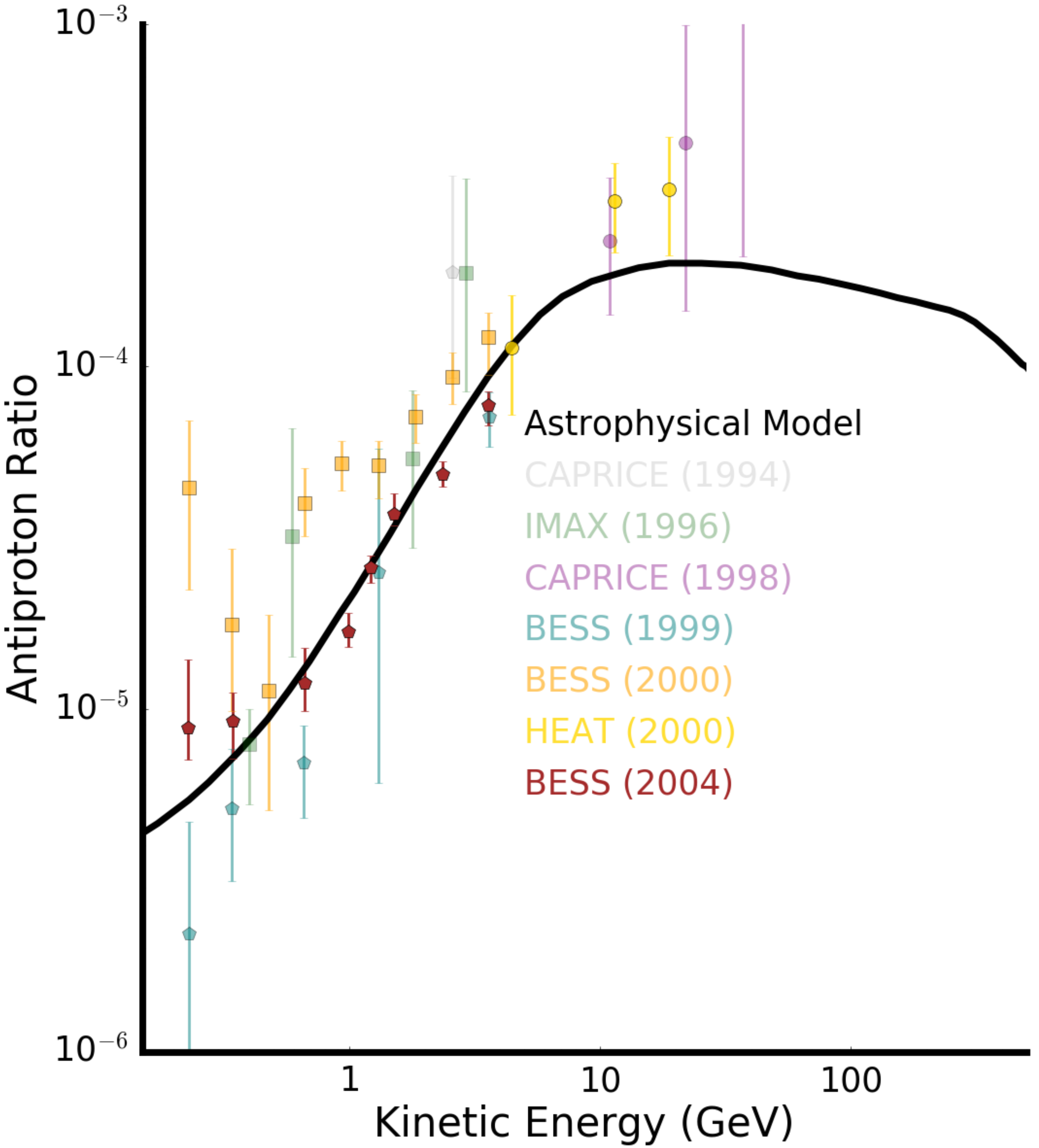
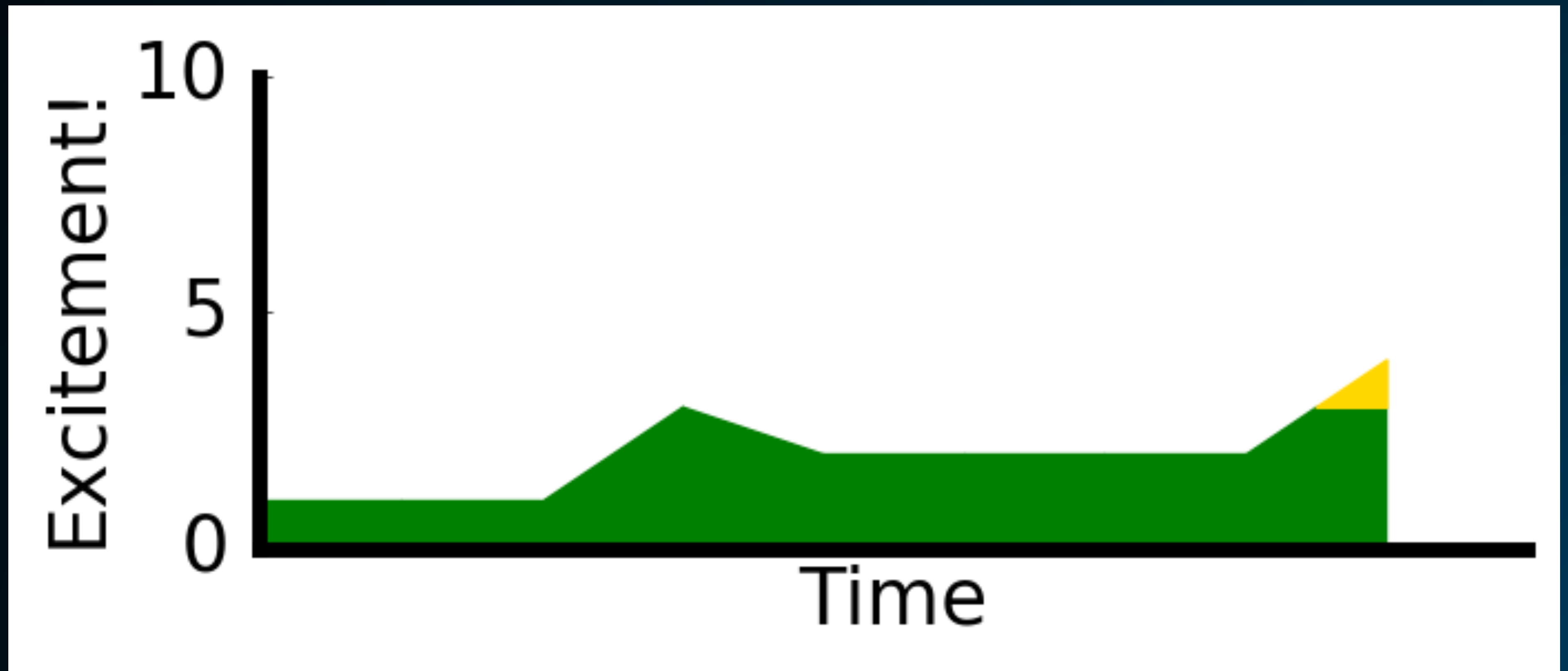
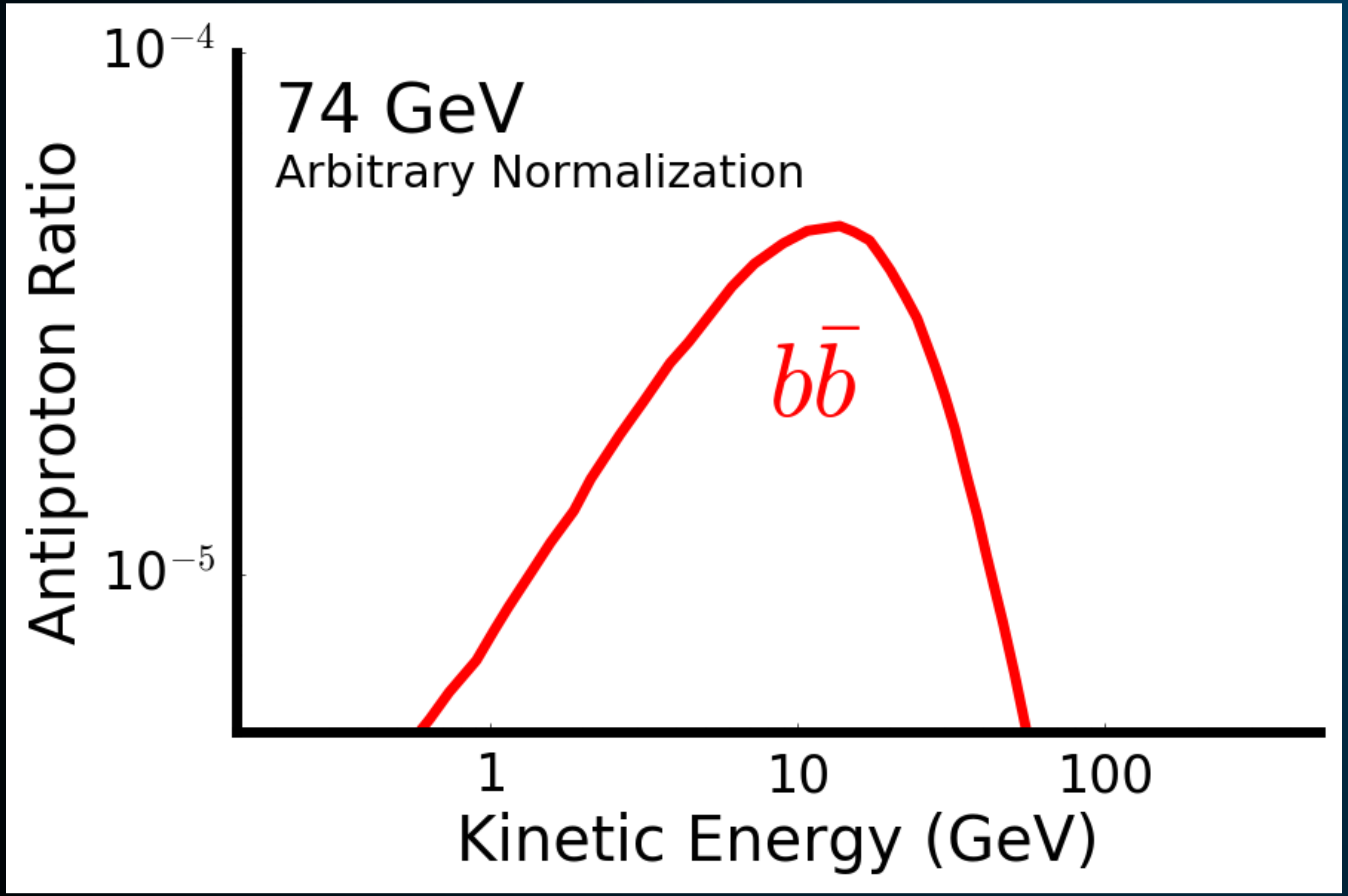


The Antiproton Excess





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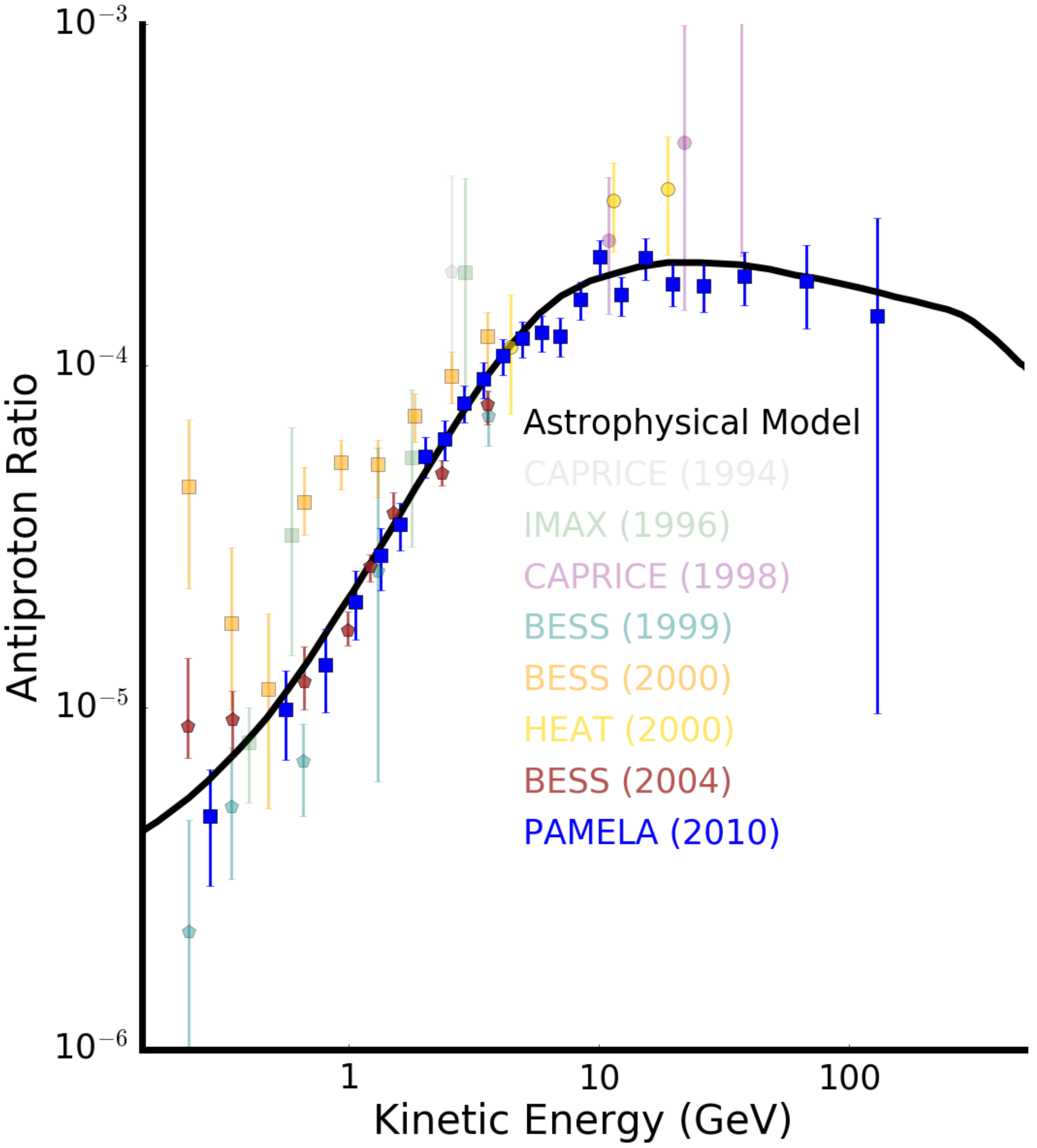
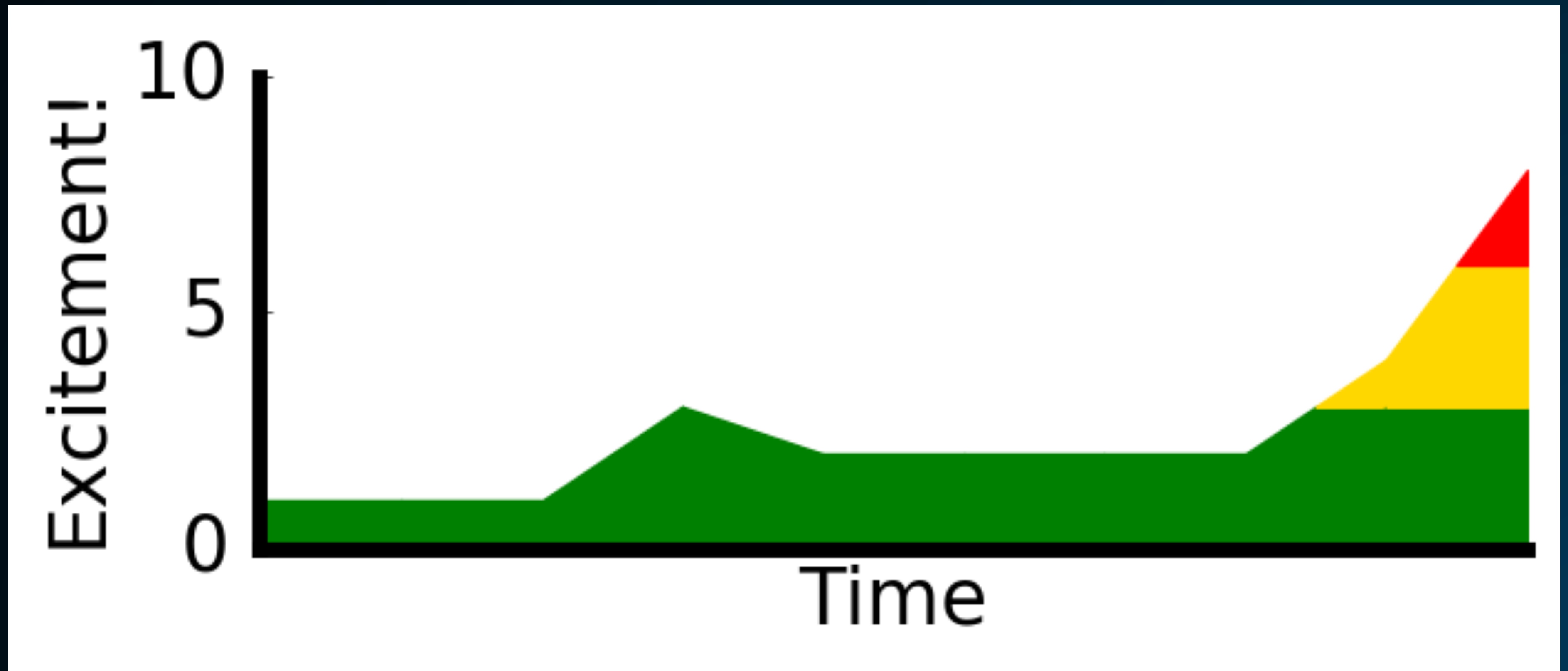
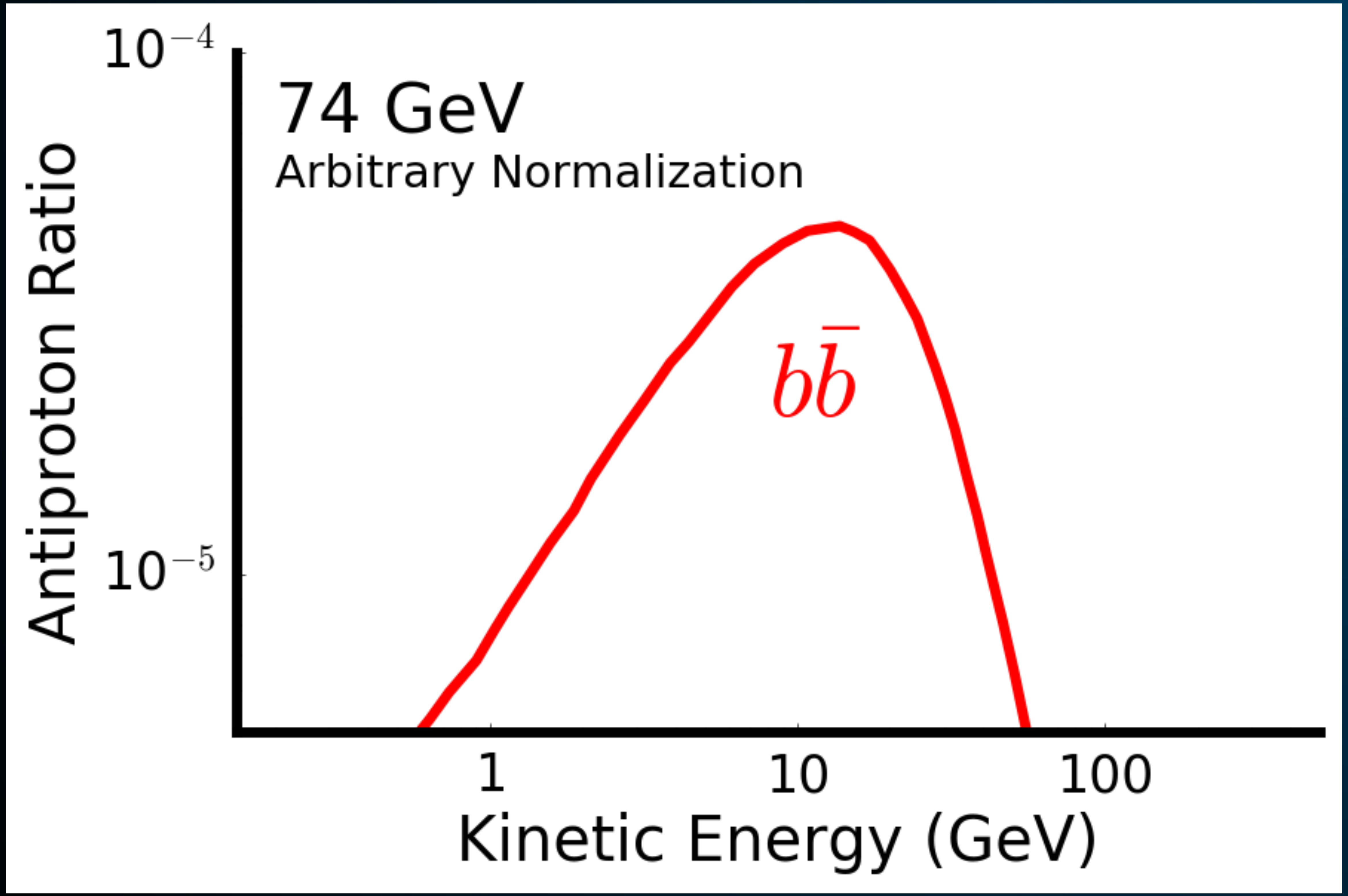
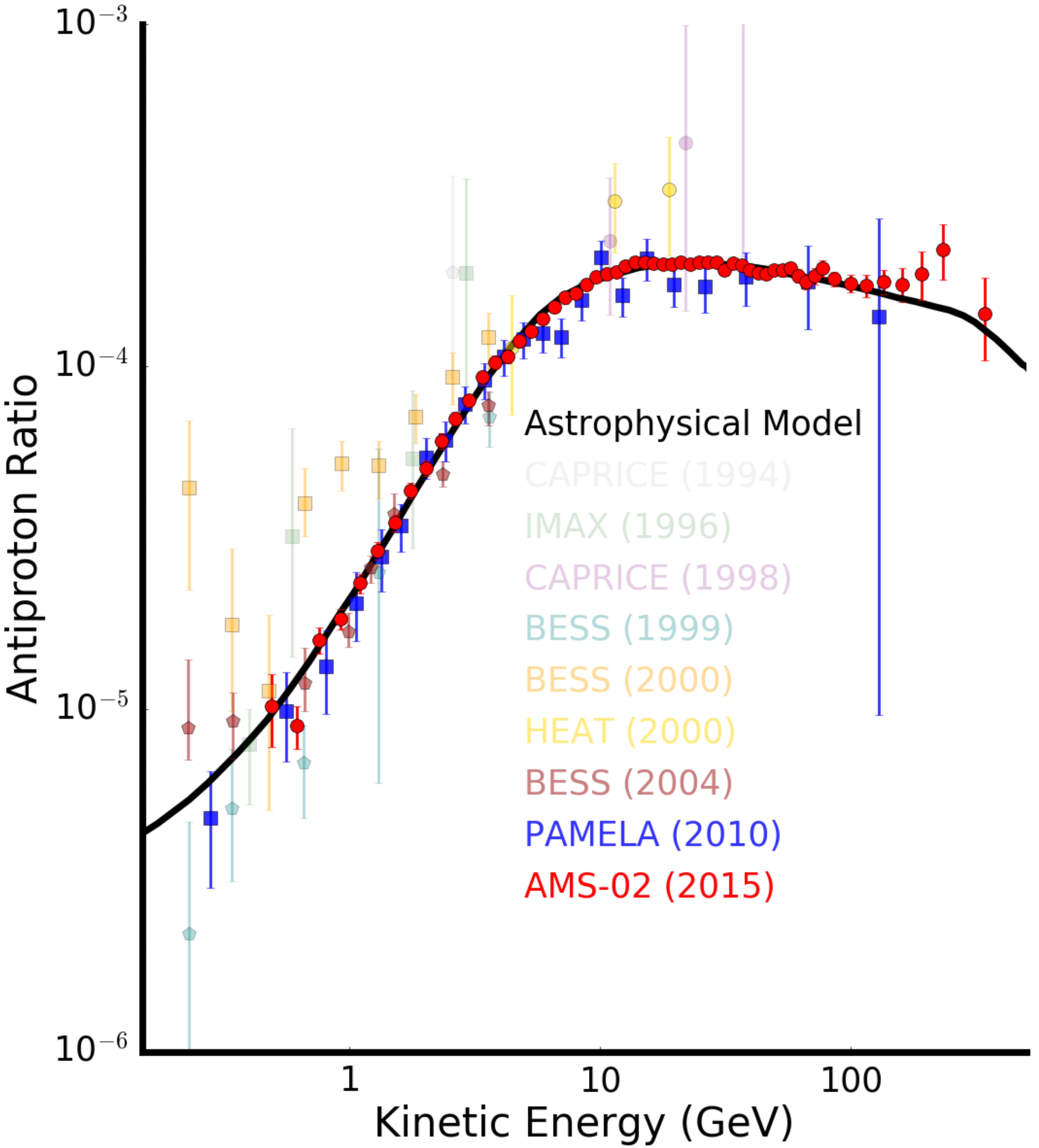


The Antiproton Excess



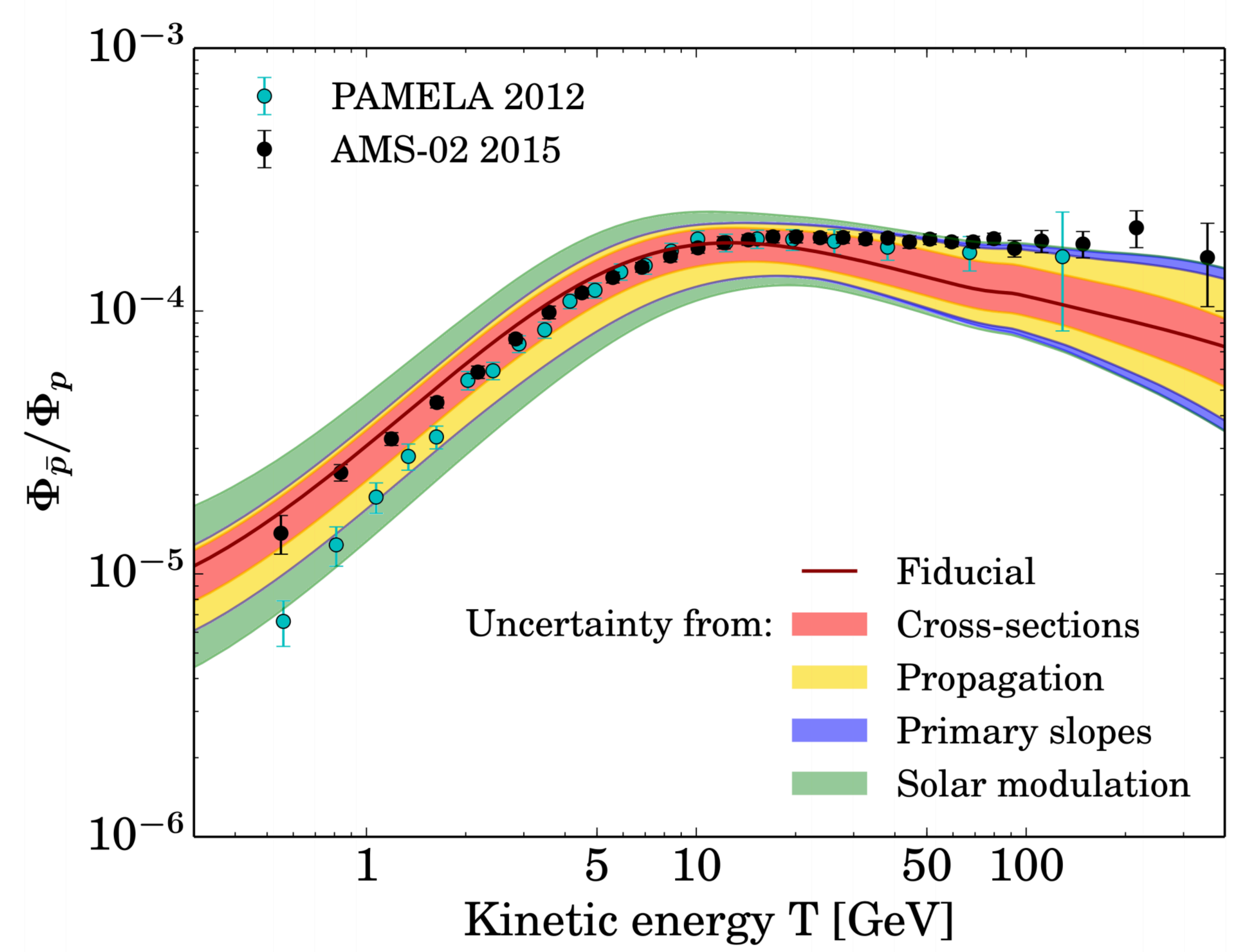




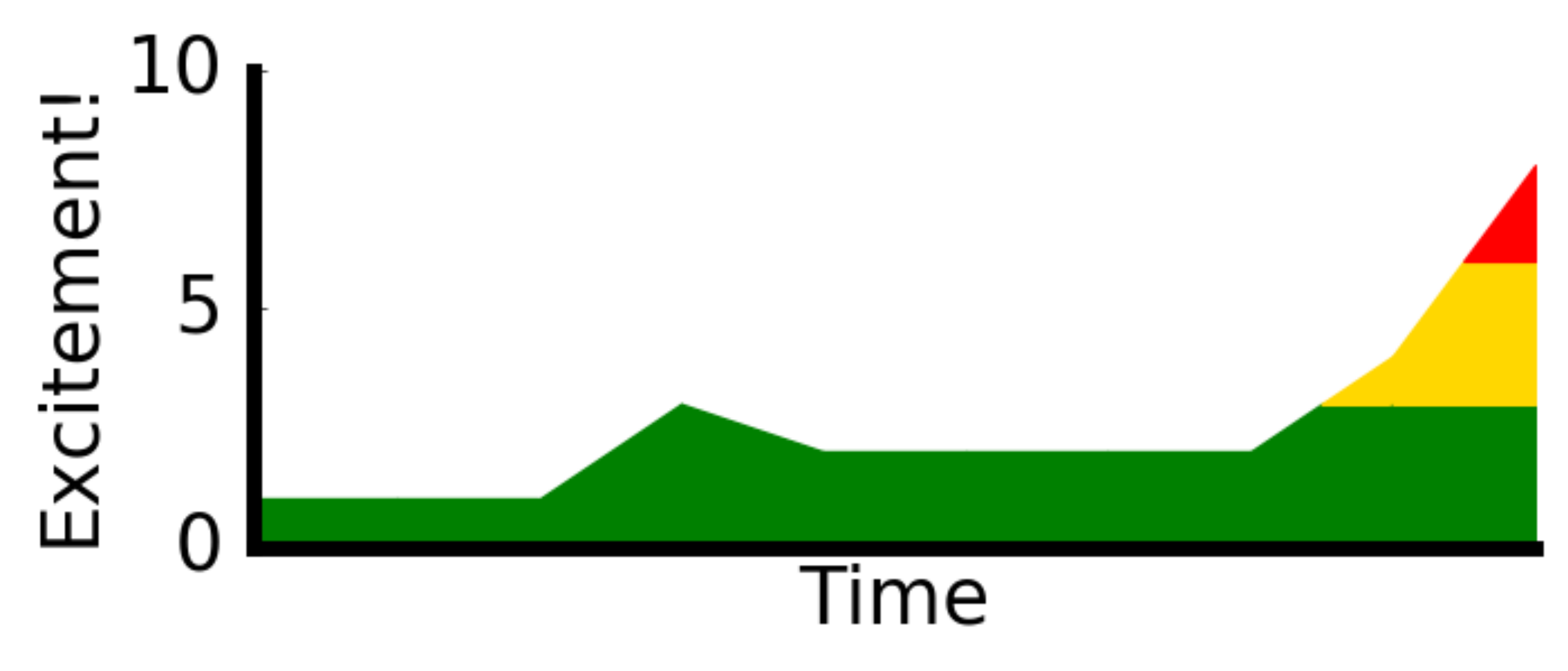
(Not an exhaustive list of observations)

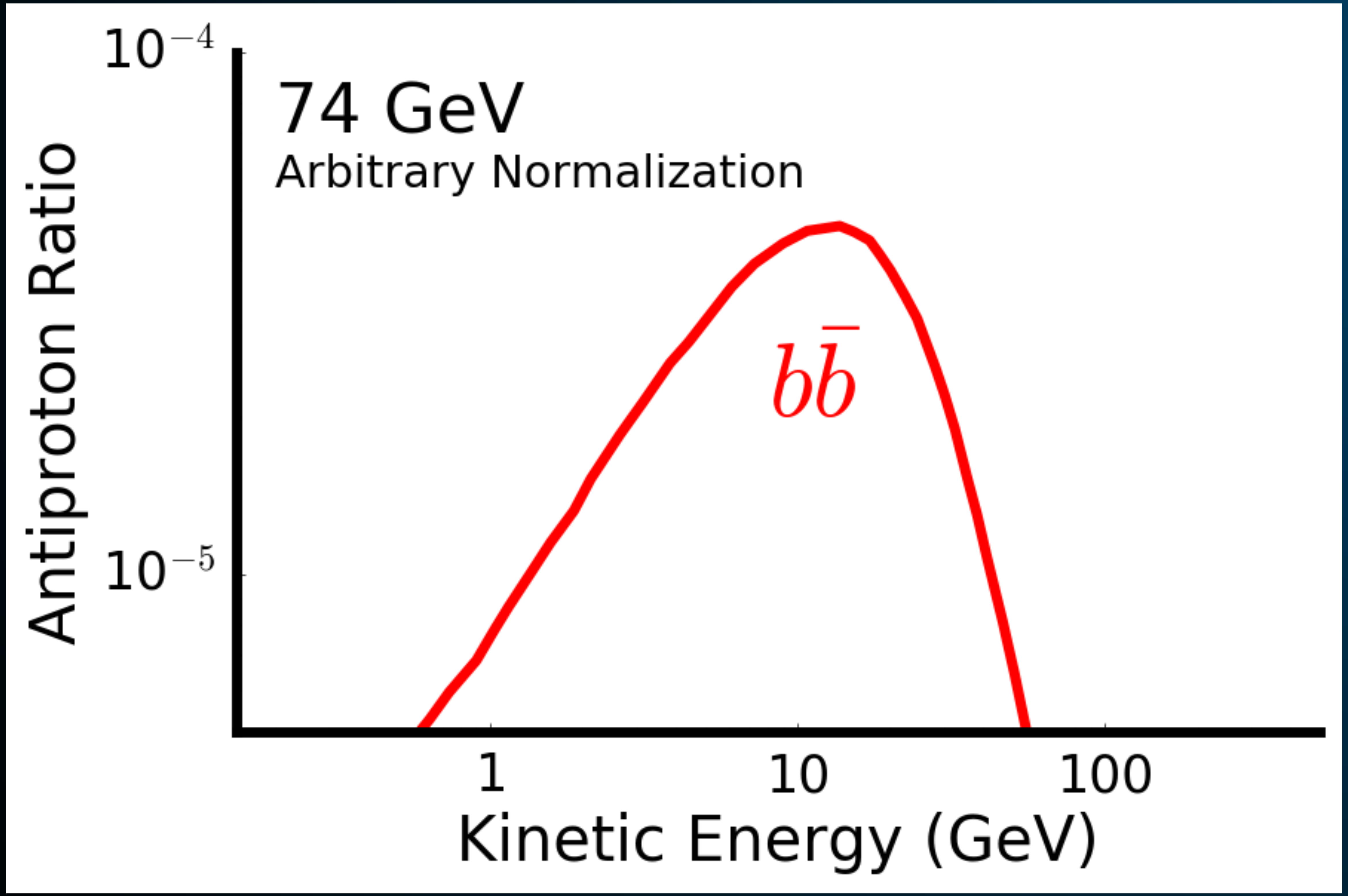
The Antiproton Excess

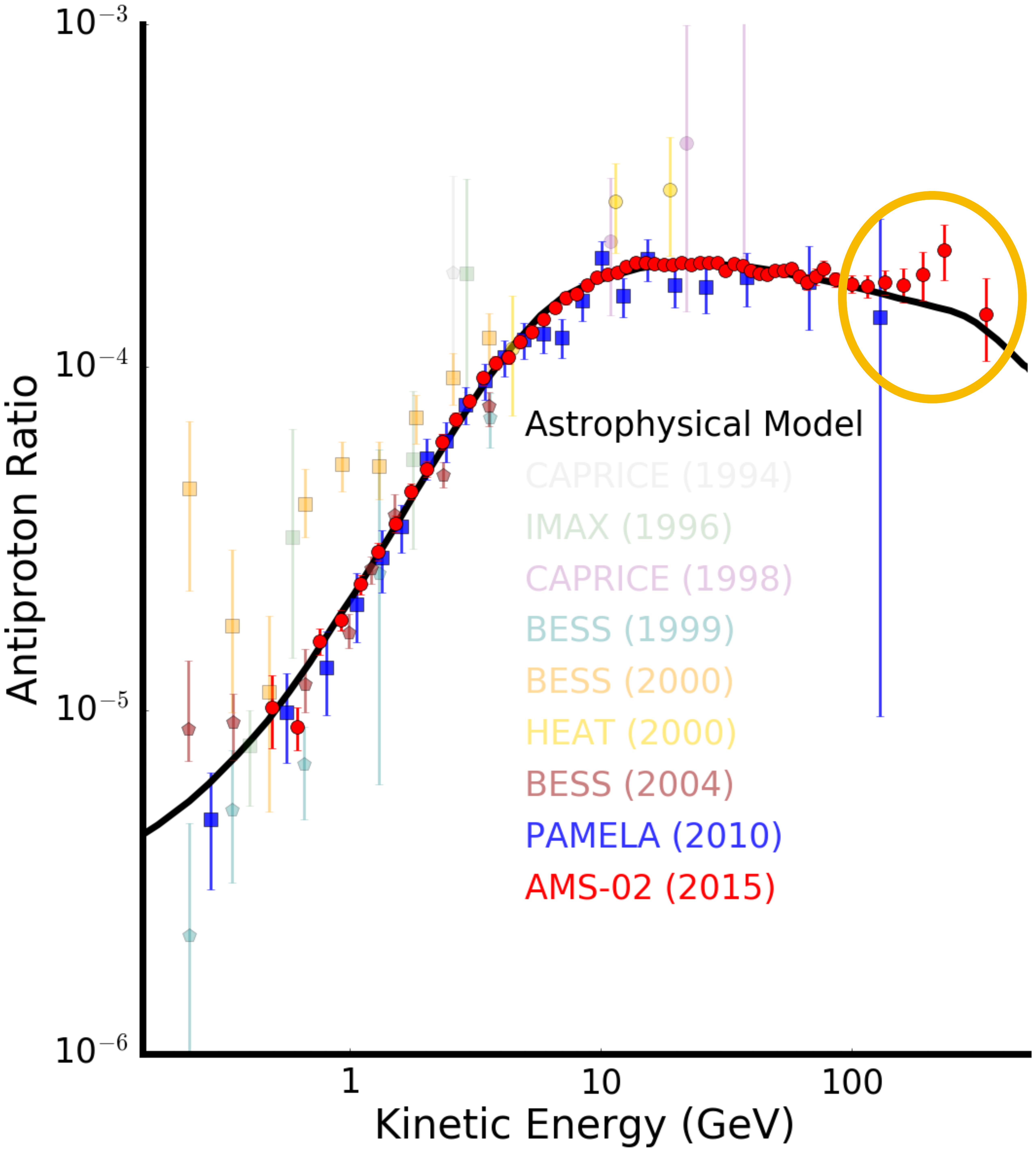
Giesen et al. (2015; 1504.04276)



The Antiproton Excess







(Not an exhaustive list of observations)

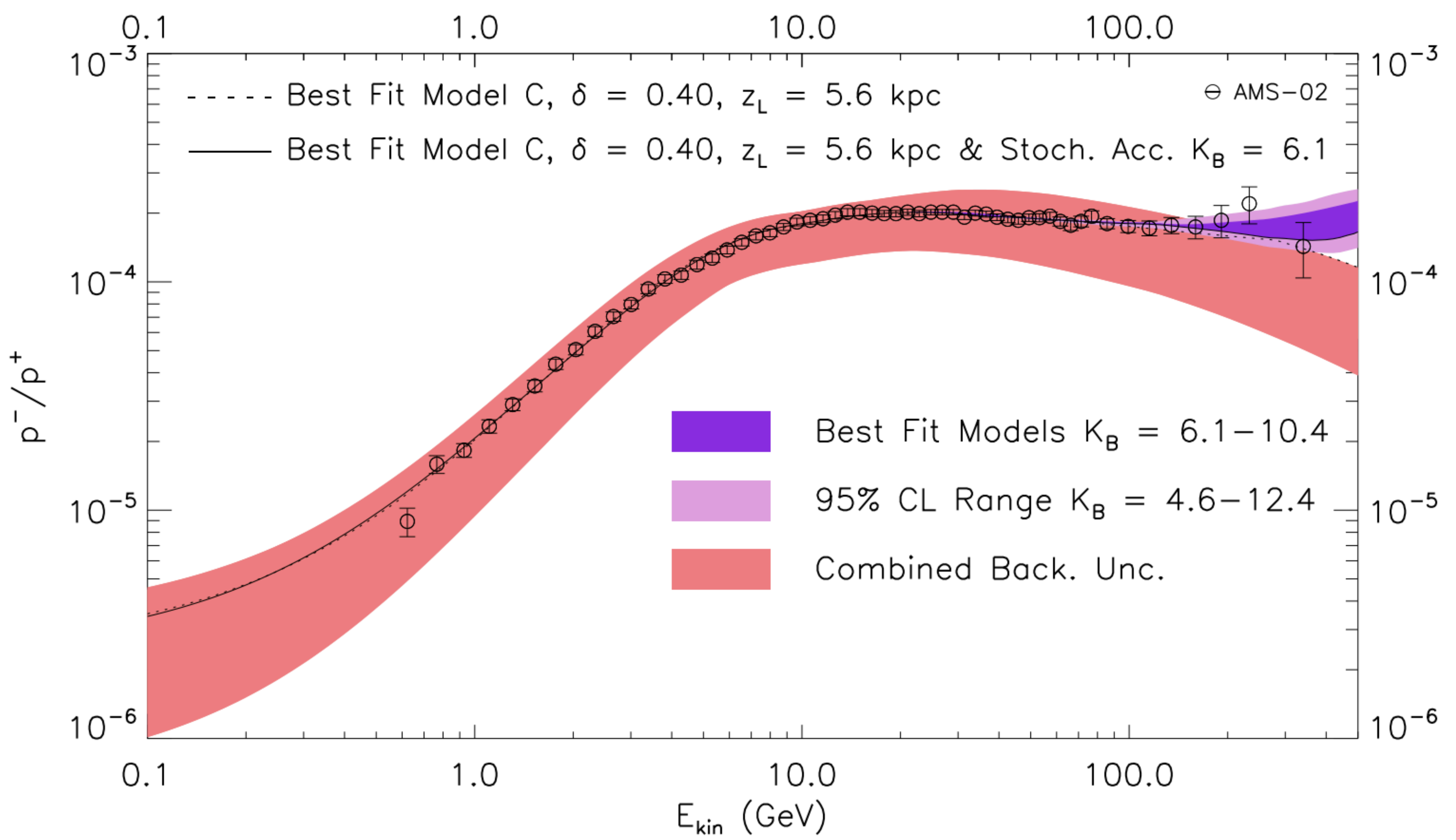
The Antiproton Excess

Secondary Acceleration in SNR

Cosmic-Ray Antiprotons created inside of supernova remnants are reaccelerated by the SNR shock.

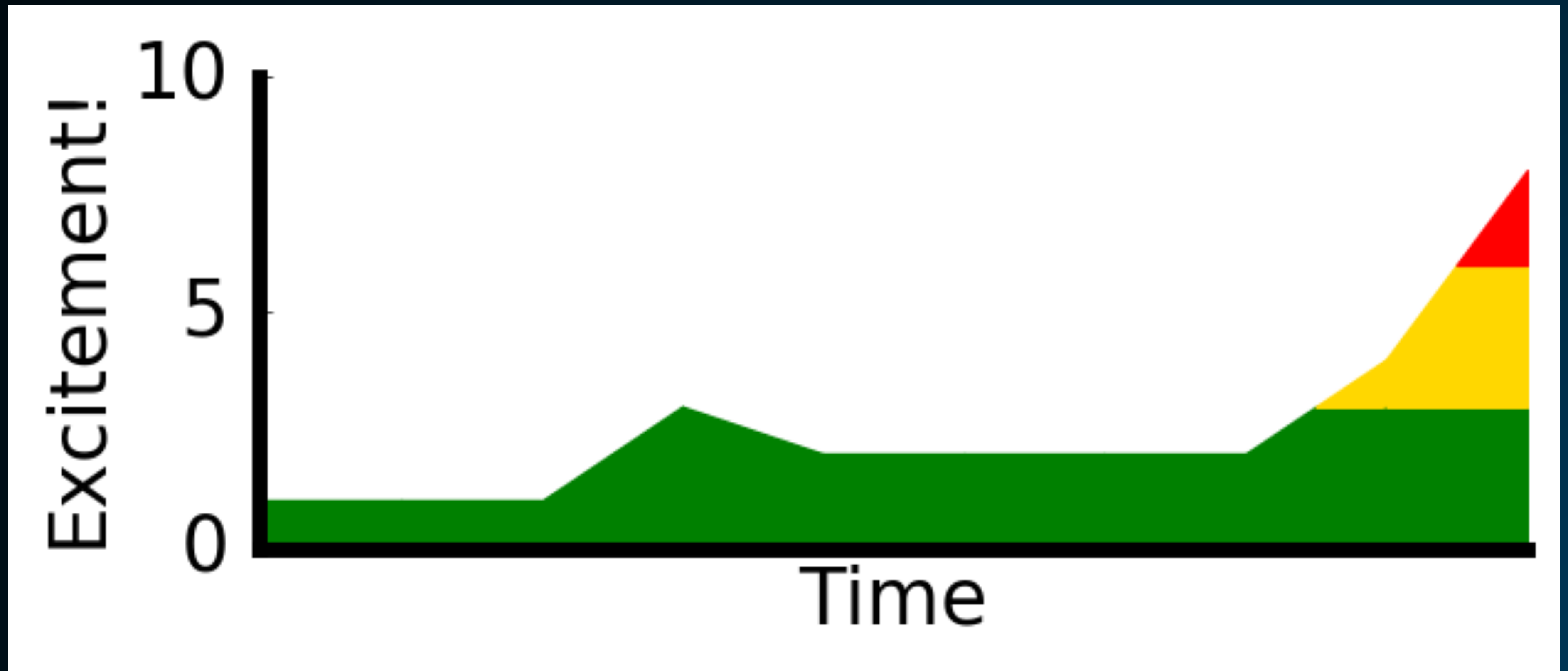
Obtain the same spectrum as the proton spectrum.

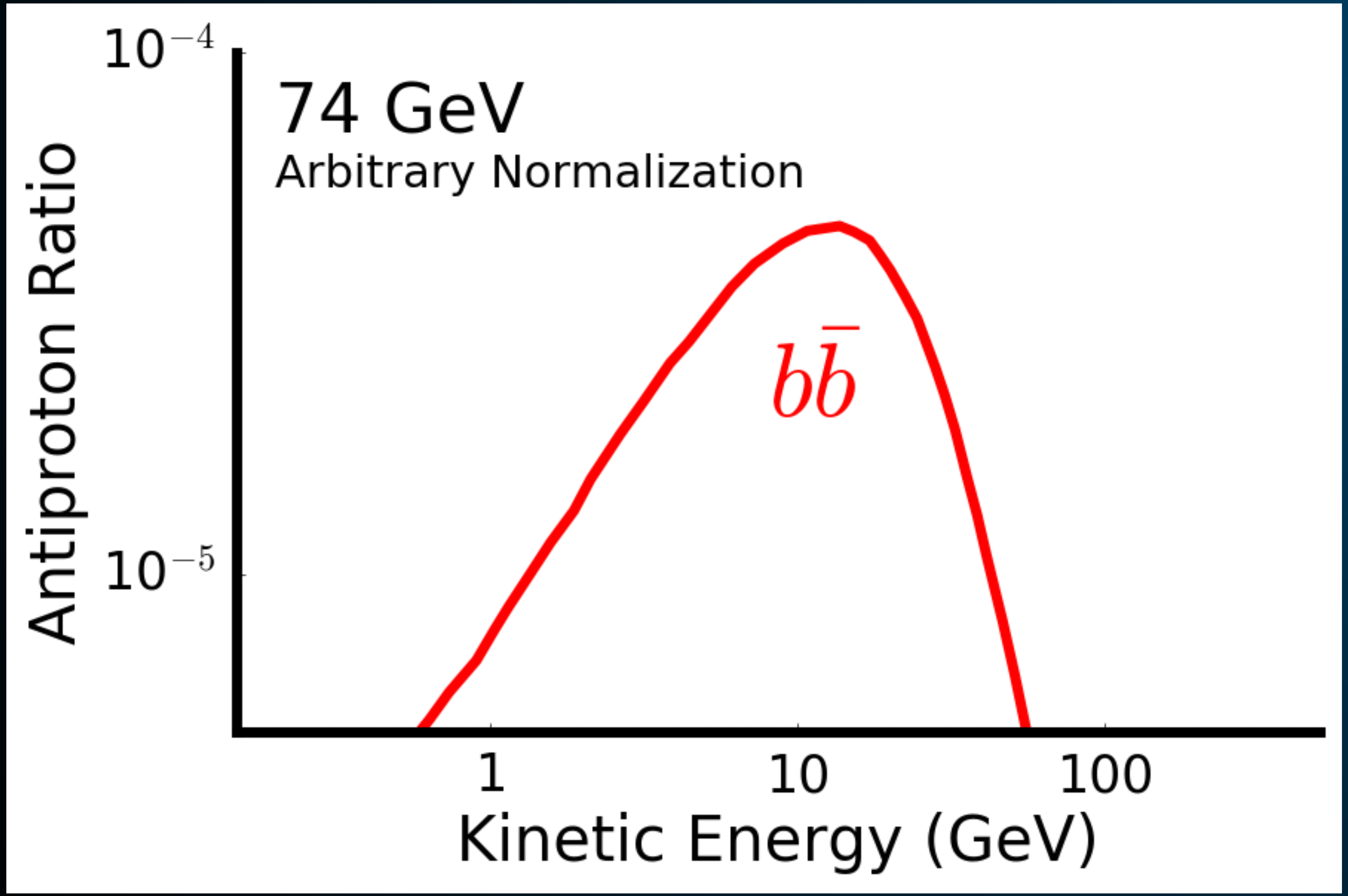
Effect most important at high energies, where the galactic cosmic-ray confinement time is smallest.

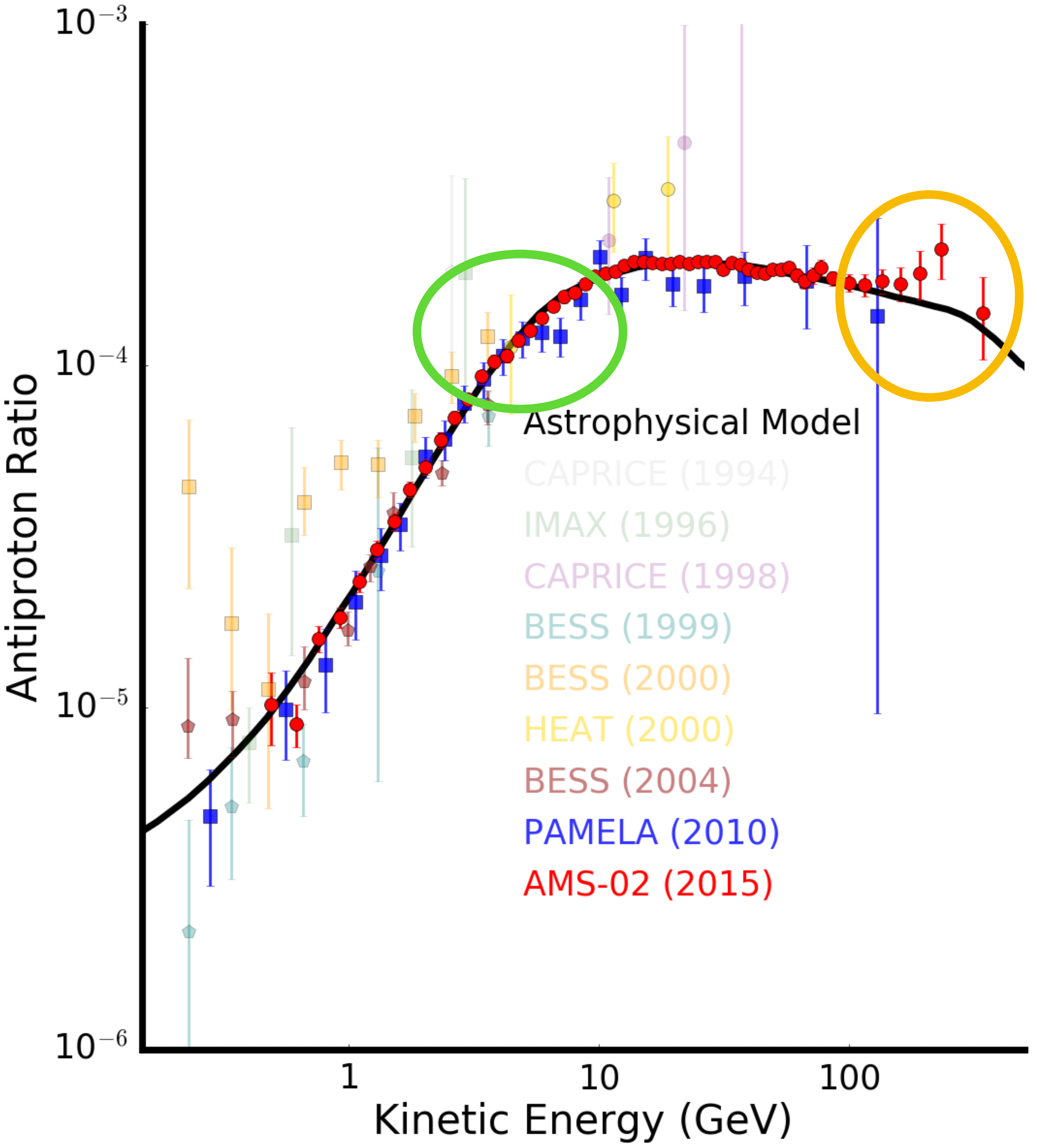


0.1
1.0
10.0
100.0
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Best Fit Model C, δ = 0.40, z_L = 5.6 kpc
Best Fit Model C, δ = 0.40, z_L = 5.6 kpc & Stoch. Acc. K_B = 6.1
AMS-02
Best Fit Models K_B = 6.1–10.4
95% CL Range K_B = 4.6–12.4
Combined Back. Unc.
p^-/p^+
E_{kin} (GeV)

The Antiproton Excess





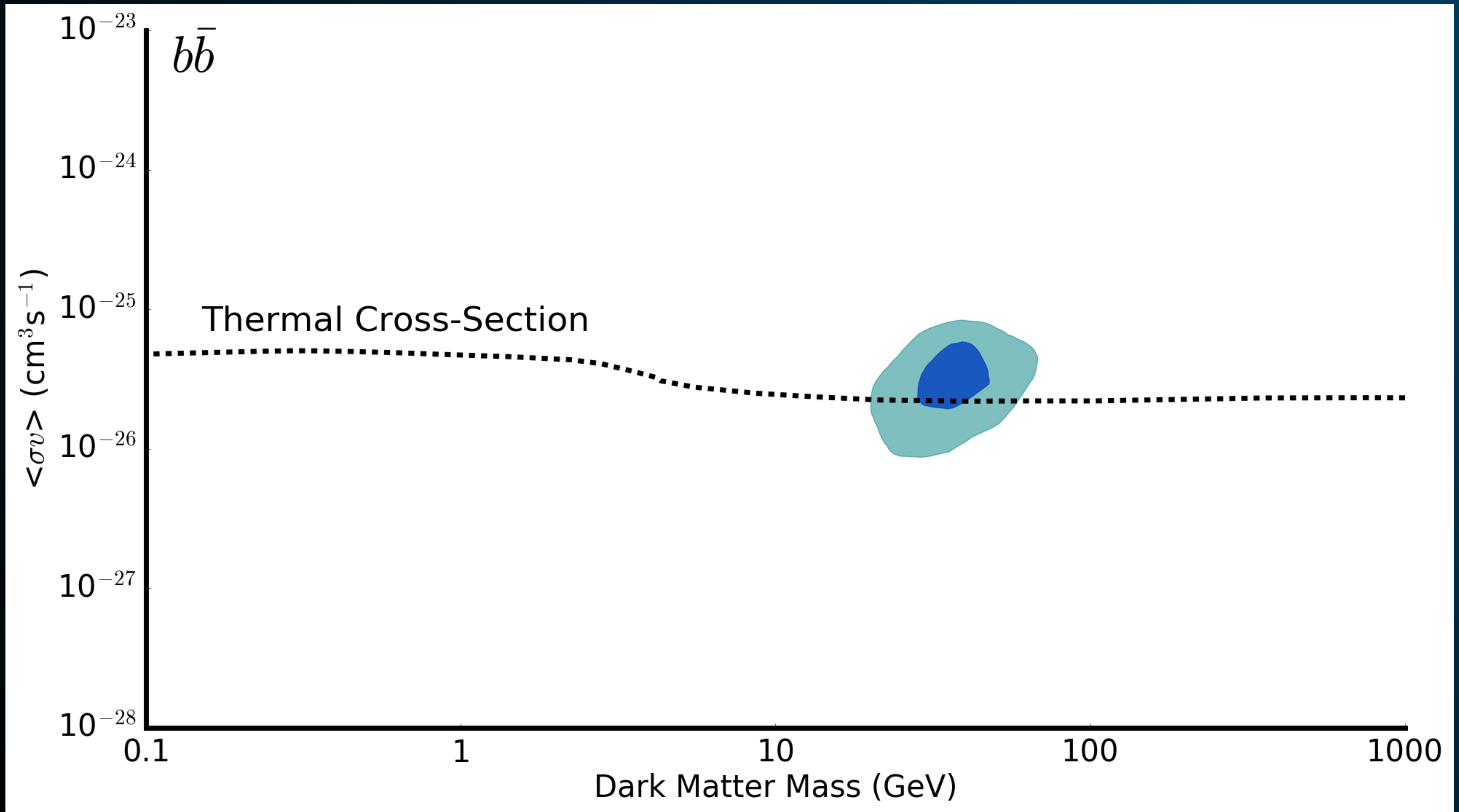


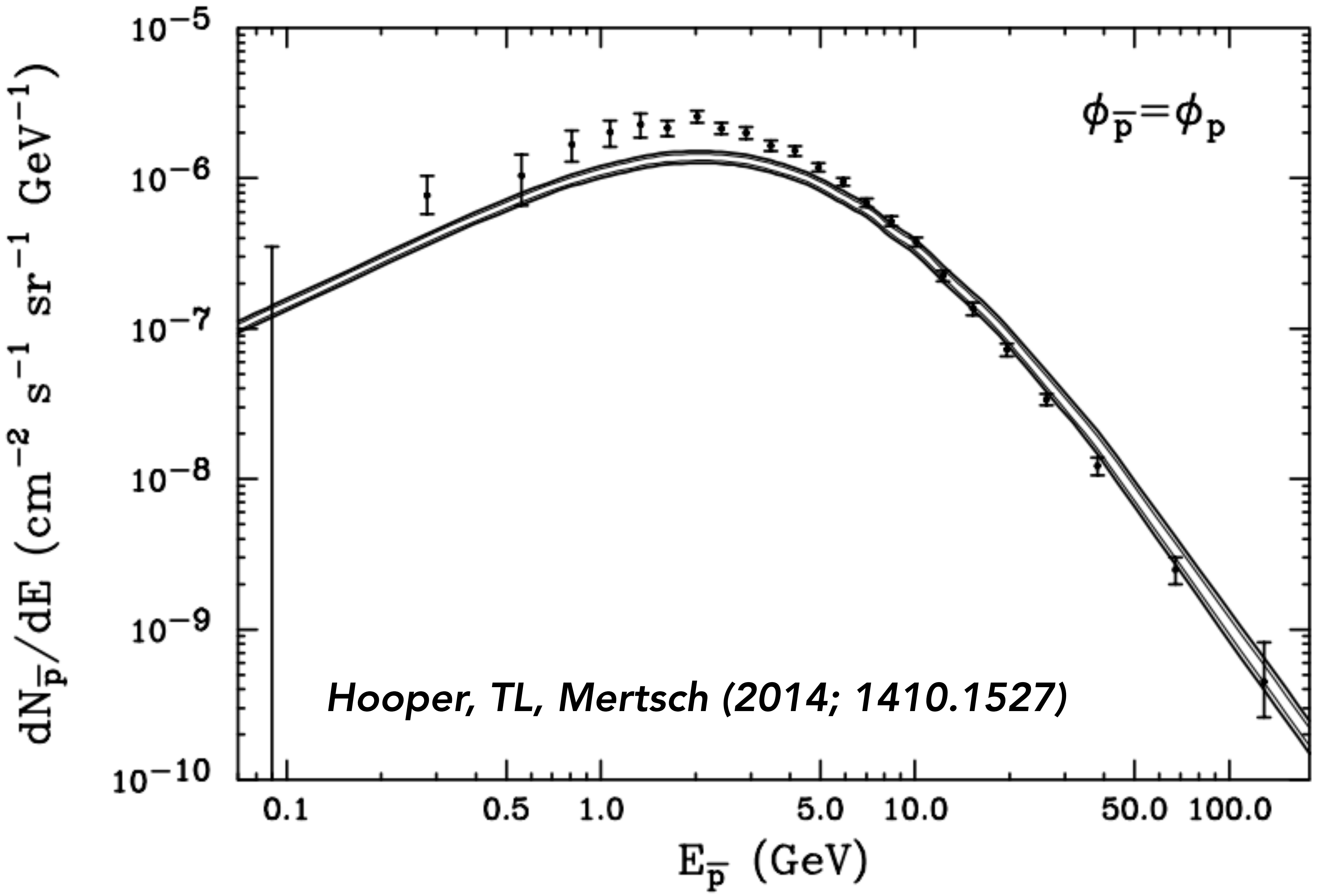
(Not an exhaustive list of observations)

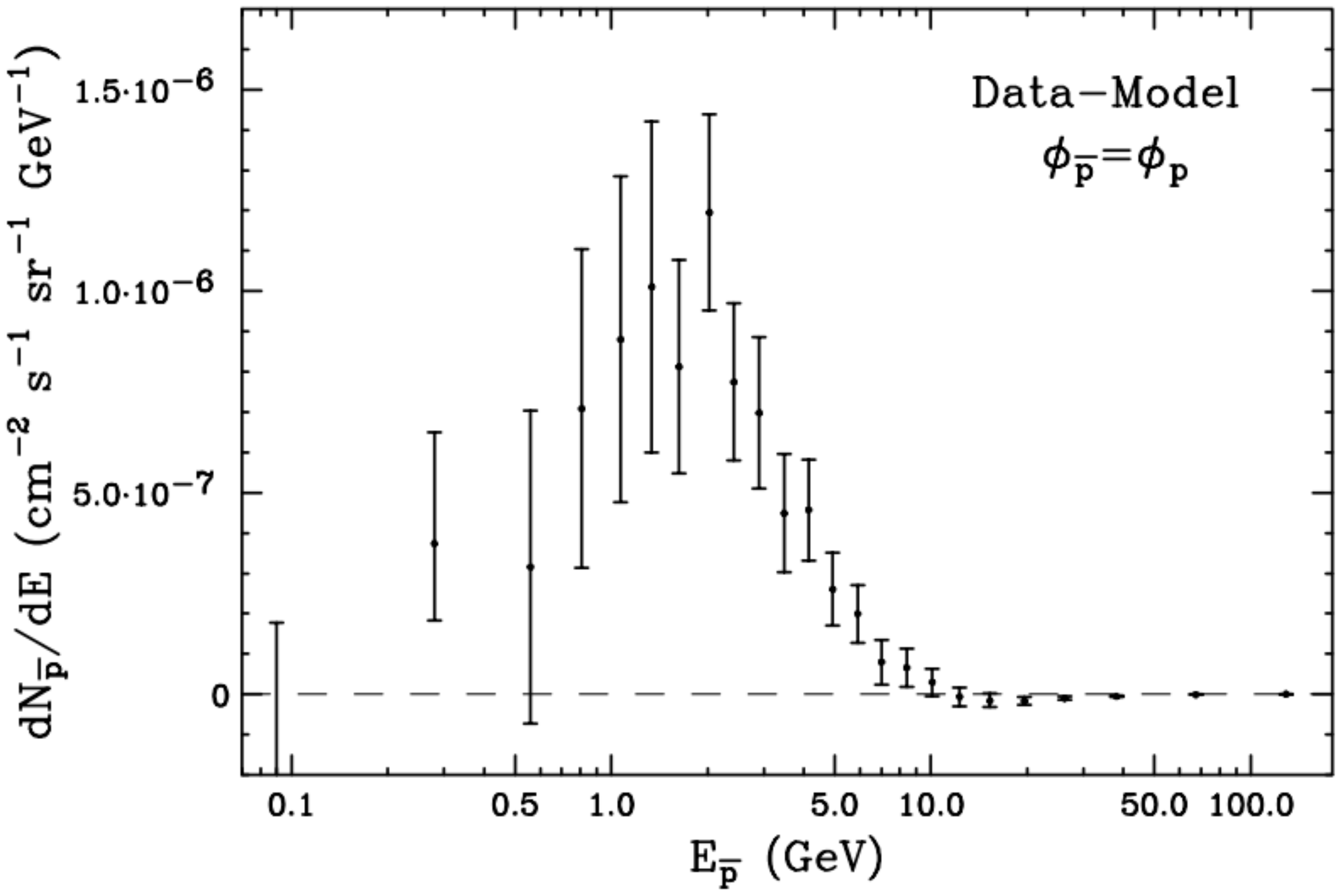
The Antiproton Excess

Hint of Excess in ~5 GeV antiprotons!

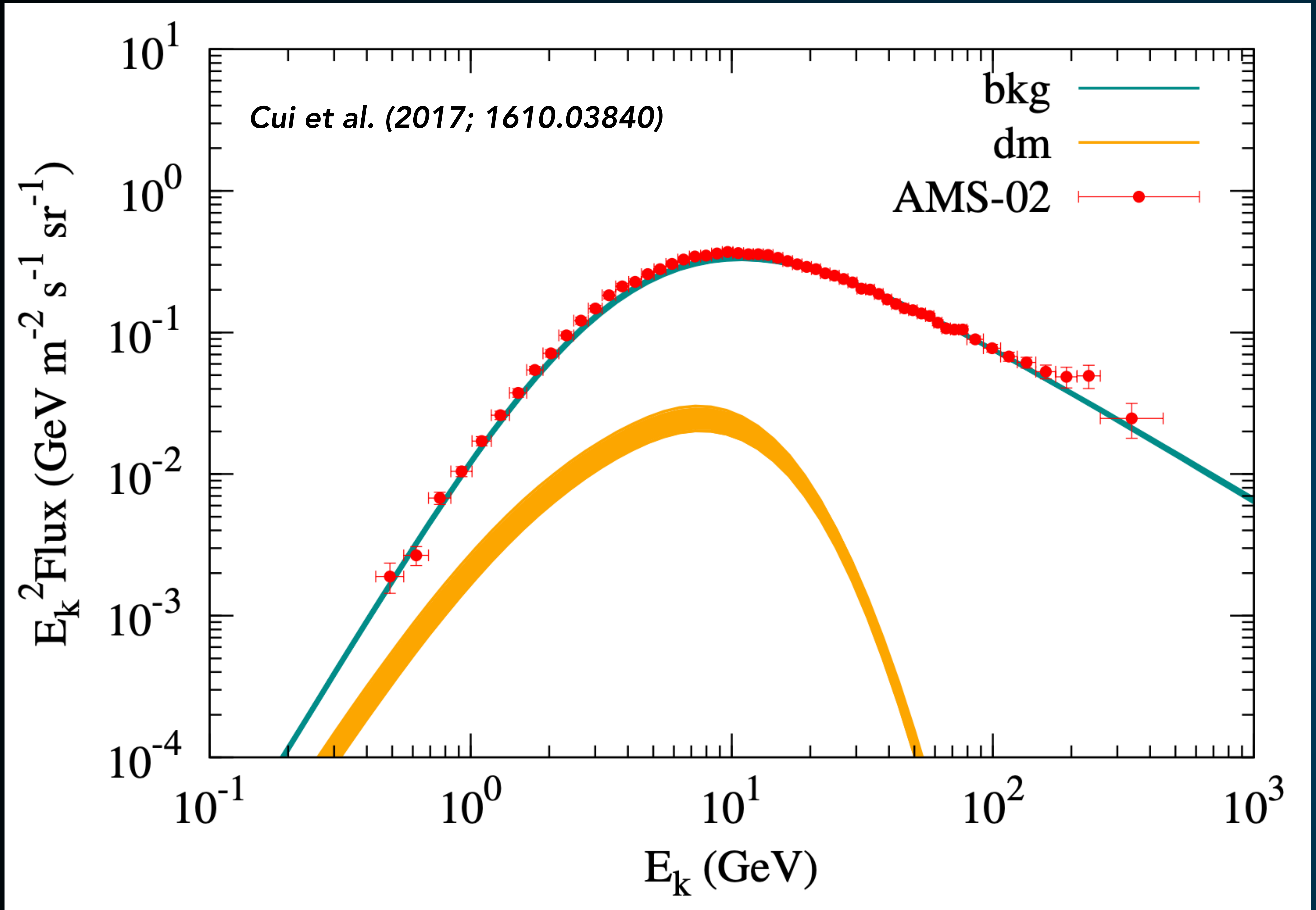
Astrophysical Uncertainties can significantly affect the signal.

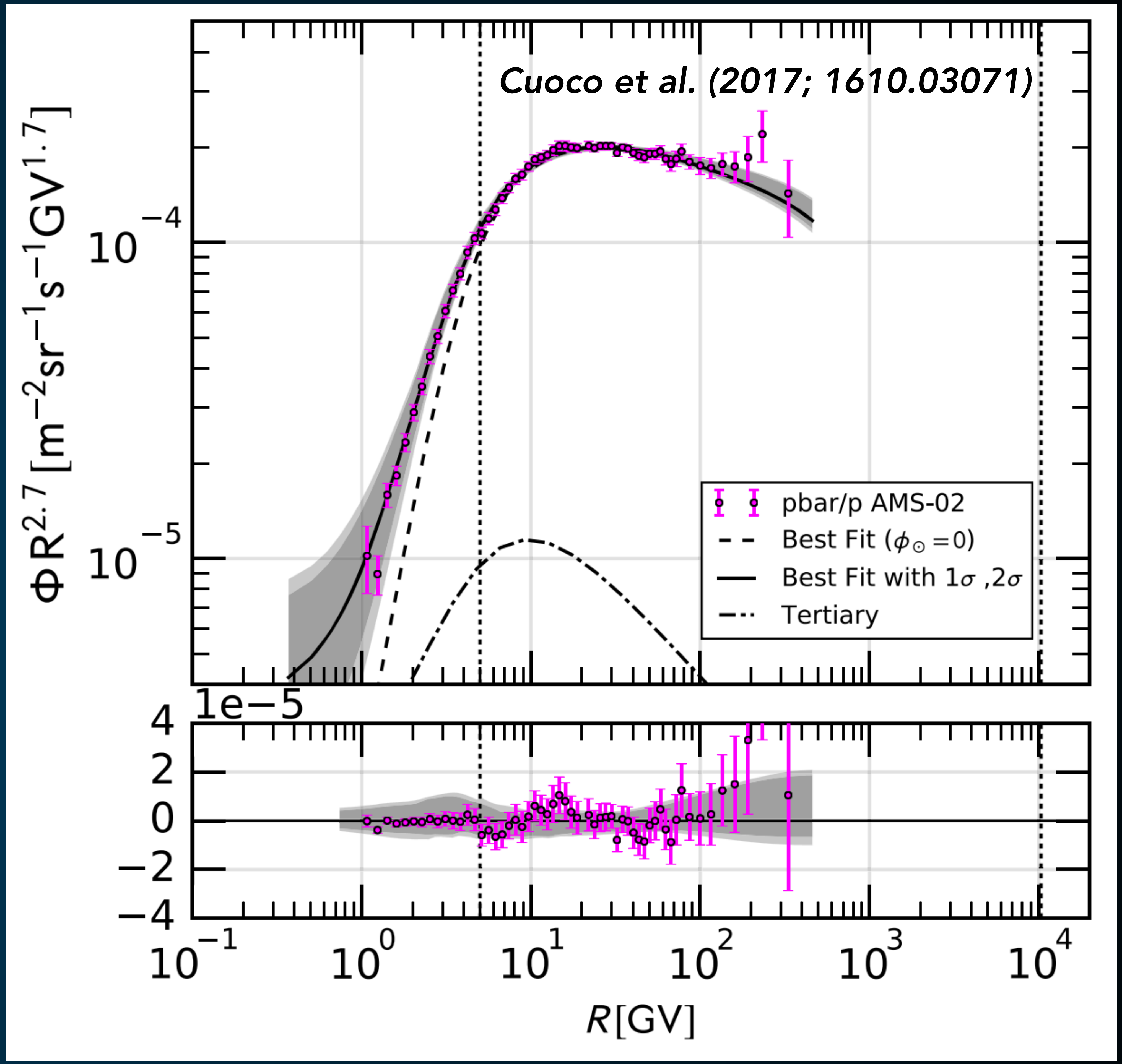






The Antiproton Excess





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

Significance approaching (or past) 5σ !

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

The Antiproton Excess - A Detection?

Cholis, Linden, Hooper (2019; 1903.02549)

With great precision comes great responsibility:

Need to carefully examine the relevant uncertainties.

The Antiproton Excess - A Detection?

Boudaud et al. (2019; 1906.07119)

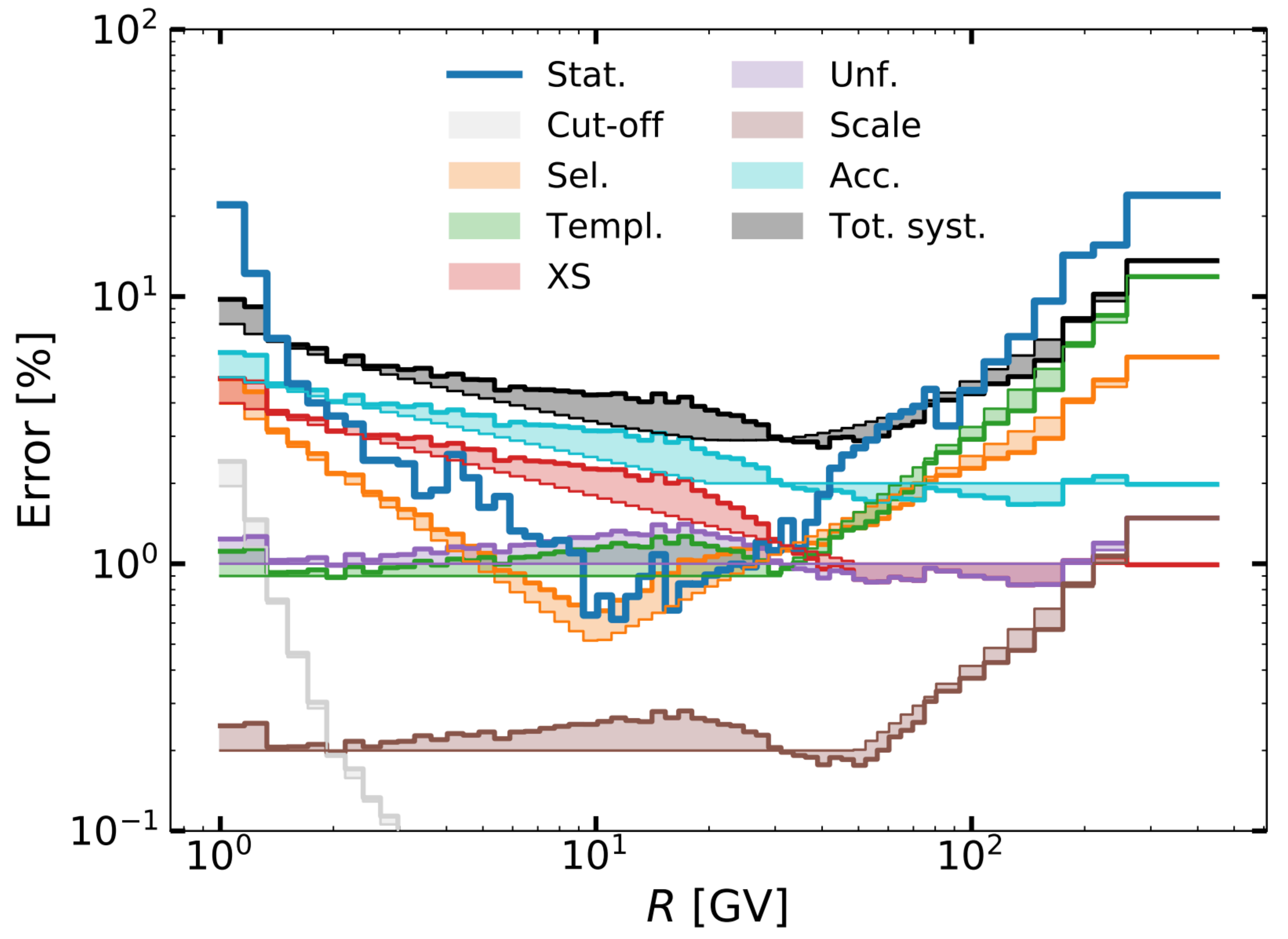
With great precision comes great responsibility:

Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

Solar Modulation

Antiproton Production Cross-Section



Boudaud et al. (2019):

"AMS-02 antiprotons are consistent with a secondary astrophysical origin"

The Antiproton Excess - A Detection?

Cholis, Linden, Hooper (2019; 1903.02549)

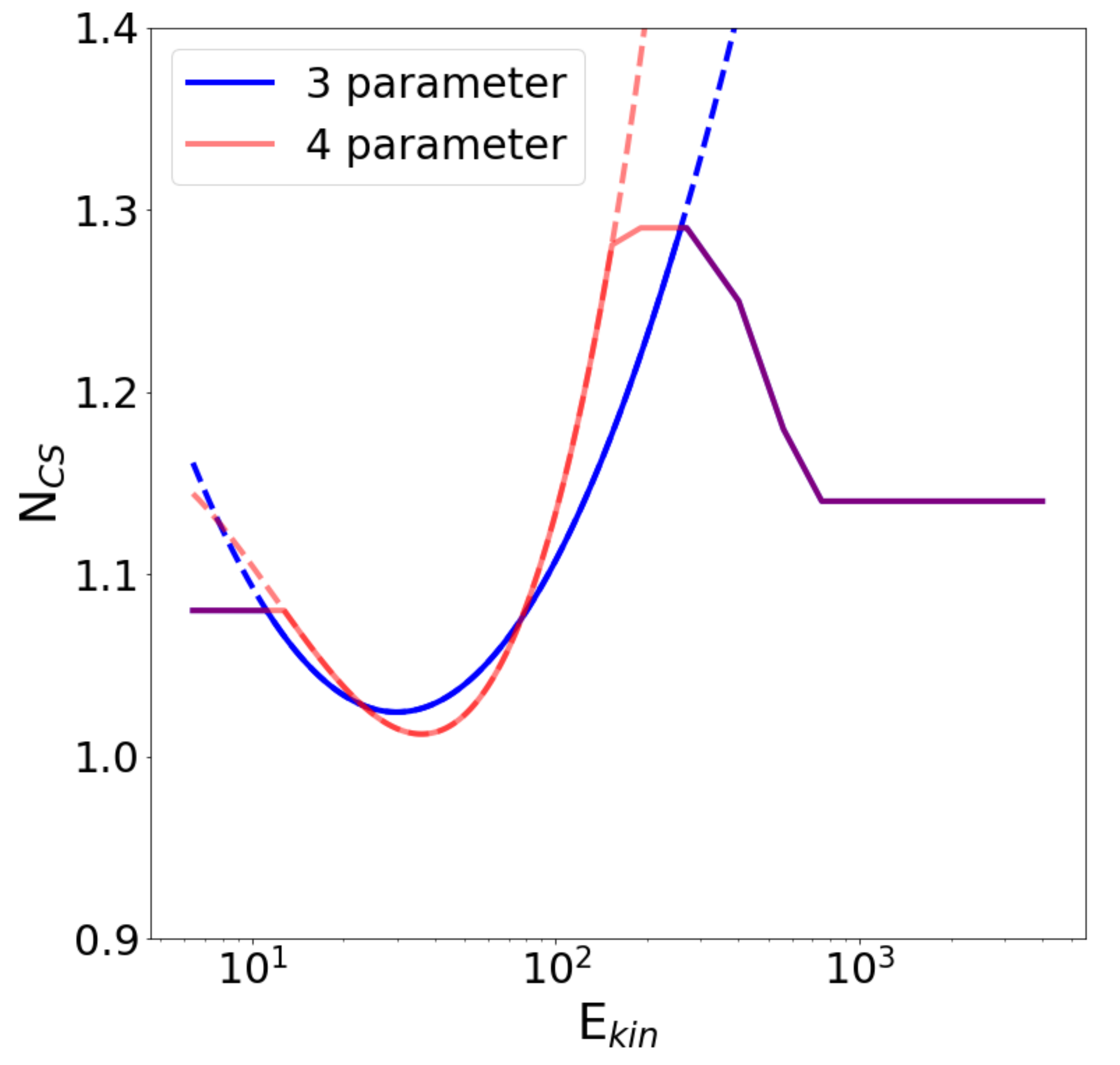
With great precision comes great responsibility:

Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

Solar Modulation

Antiproton Production Cross-Section



$$N_{CS}(E_{\rm kin}) = a + b\,\ln\left(\frac{E_{\rm kin}}{\rm GeV}\right) + c\left[\ln\left(\frac{E_{\rm kin}}{\rm GeV}\right)\right]^2$$

Cholis et al. (2019):

"After accounting for these uncertainties, we confirm the presence of a 4.7σ antiproton excess"

The Antiproton Excess - A Detection?

Cuoco et al. (2019; 1903.01472)

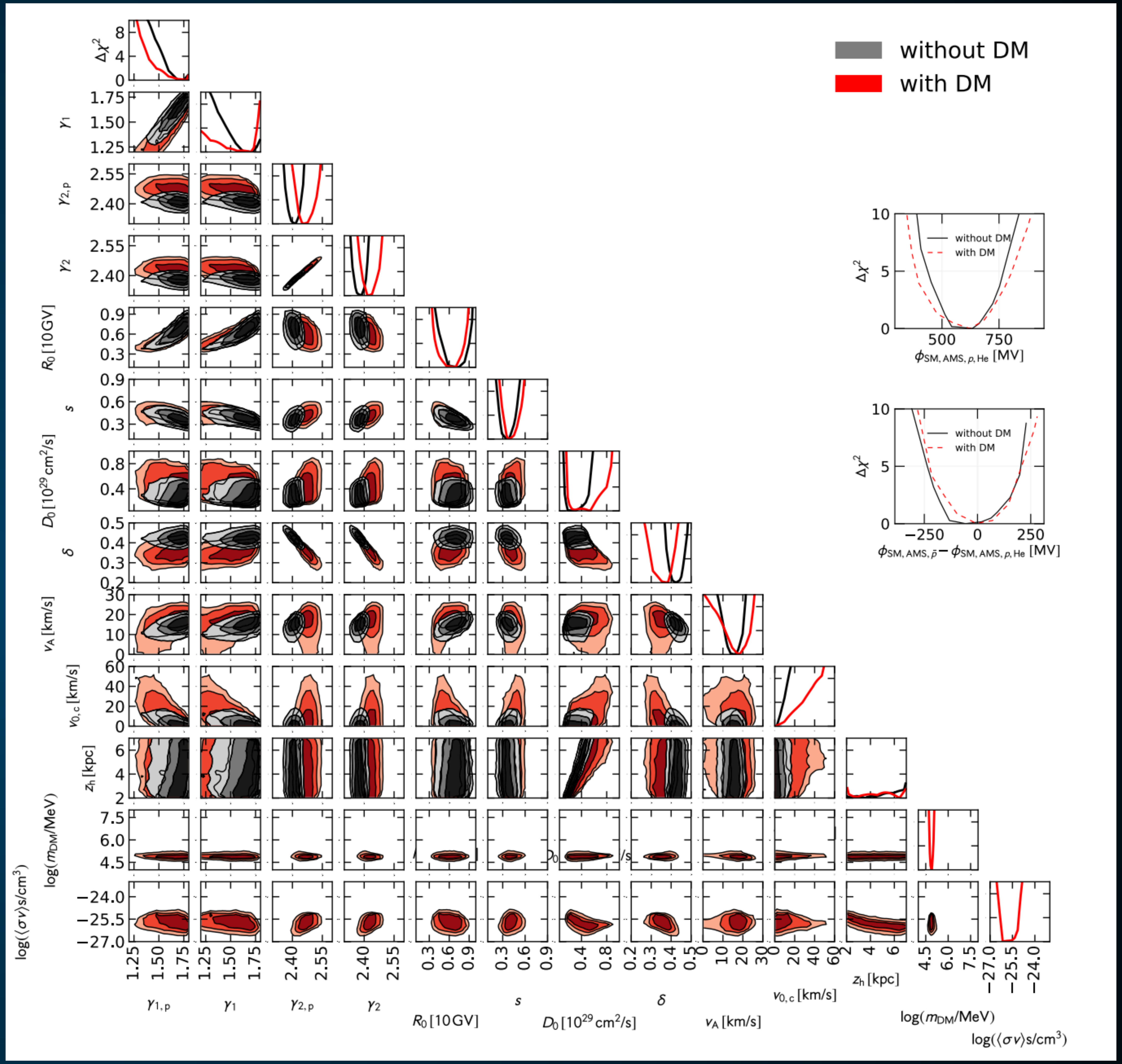
With great precision comes great responsibility:

Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

Solar Modulation

Antiproton Production Cross-Section

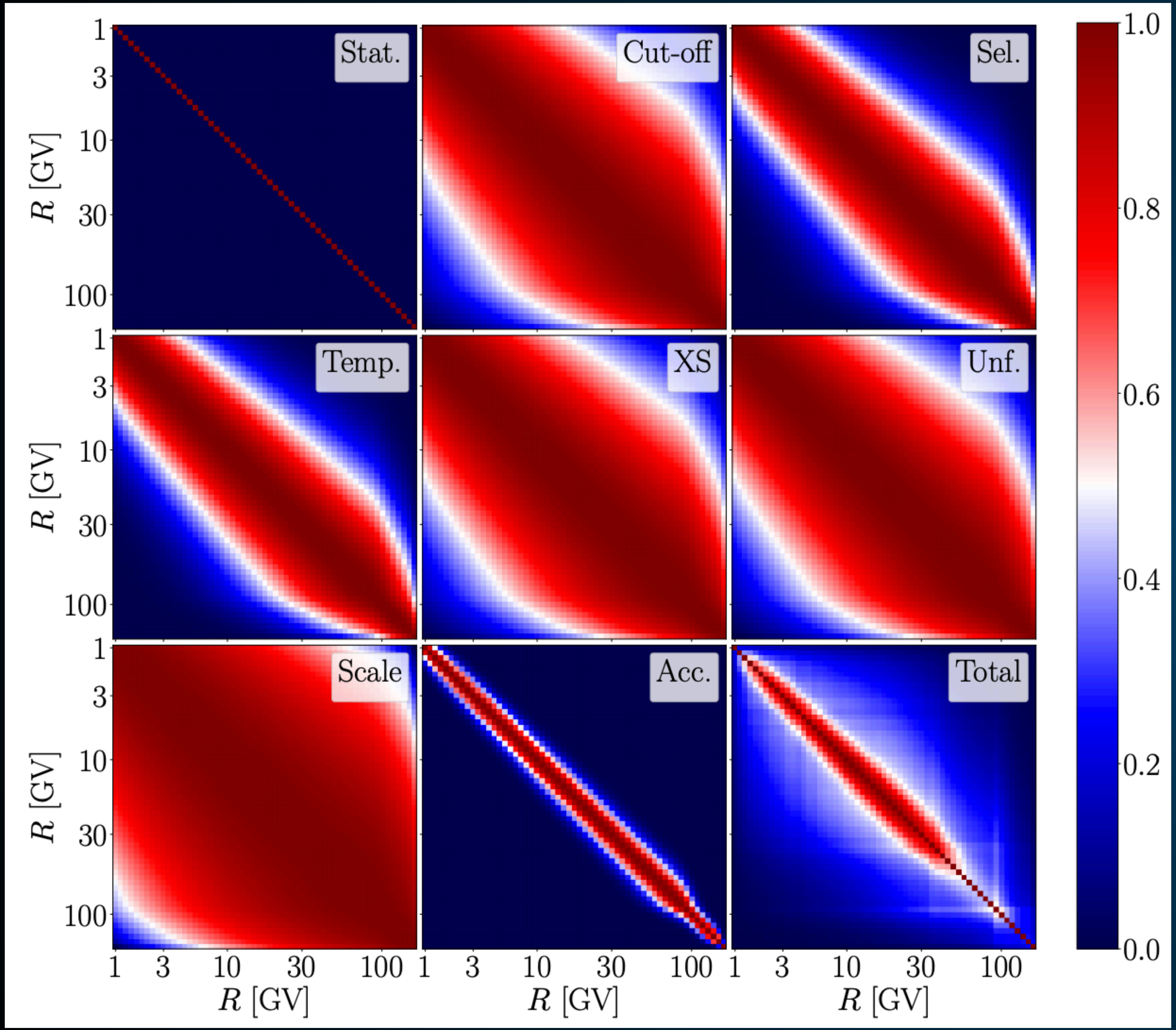


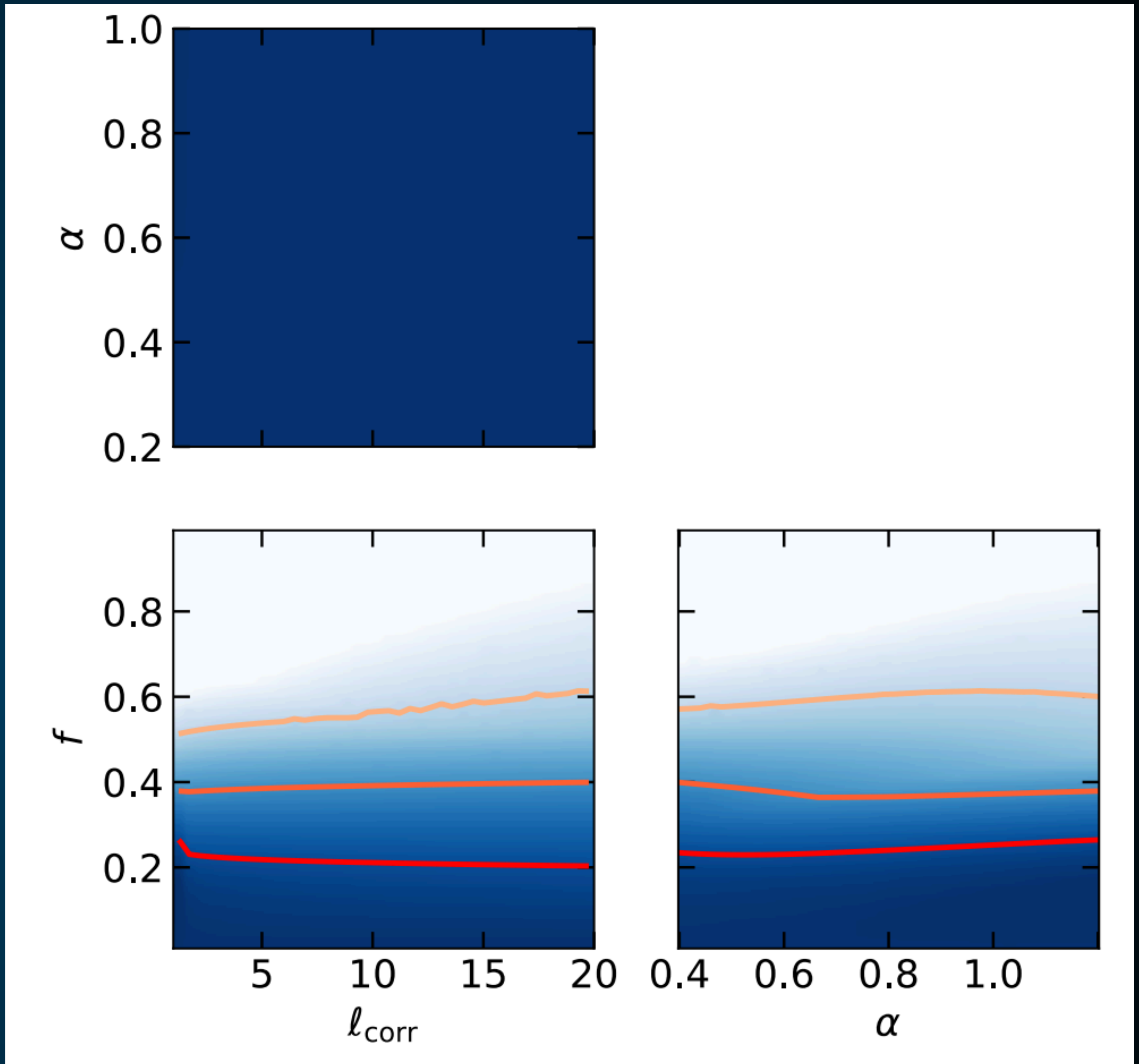
Cuoco et al. (2019):

"The inclusion of correlations strongly improves the constraints on the propagation model and, furthermore, enhances the significance of the DM signal up to above 5σ."

The Antiproton Excess - A Detection?

Cuoco et al. (2019; 1903.01472)





	$\ell_{corr}=0$			$\ell_{corr}=5$			$\ell_{corr}=10$		
dataset	p	He	$\bar{p}/p$	p	He	$\bar{p}/p$	p	He	$\bar{p}/p$
f	0.062	0.080	0.30	0.079	0.103	0.30	0.082	0.101	0.30
α	0.63	0.81	1.00	0.20	0.21	1.00	0.20	0.20	1.00

Boudaud et al. (2019; 1906.07119)

The Antiproton Excess - A Detection?

Boudaud et al. (2019; 1906.07119)

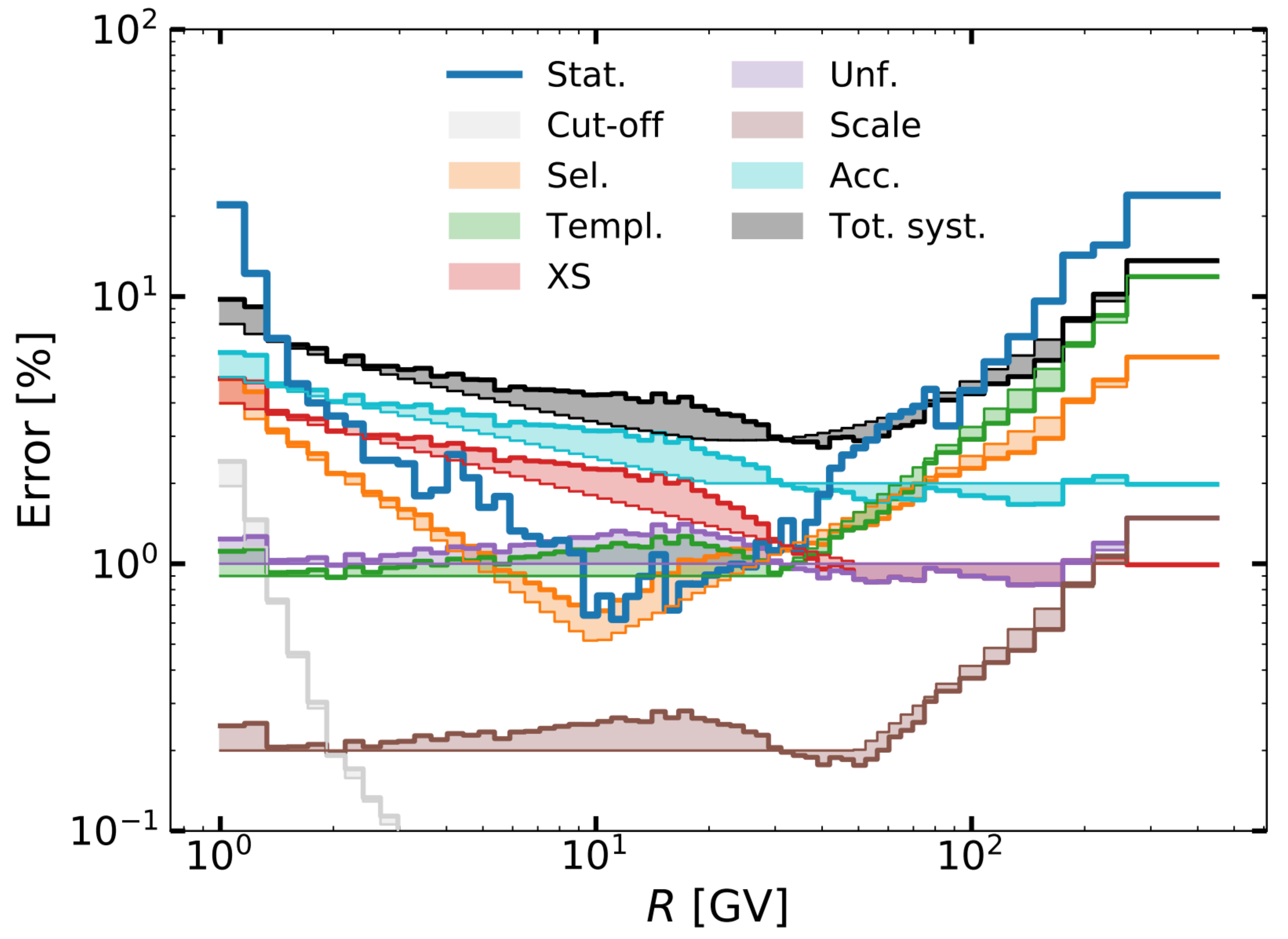
With great precision comes great responsibility:

Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

Solar Modulation

Antiproton Production Cross-Section



Galactic Primary to Secondary Ratios - Future AMS-02 Data!

Inhomogeneous Diffusion - TeV Halos

Solar Modulation - Voyager Data, Time-Dependent AMS-02 Data

Antiproton Production Cross-Section - LHCb / Laboratory Experiments

10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
<σv> (cm^3s^{-1})
$b\bar{b}$ (Planck)
Thermal Cross-Section
$b\bar{b}$ (AMS)
$\tau^+\tau^-$ (AMS)
e^+e^- (Planck)
e^+e^- (AMS)
Cholis, Hooper, TL (2019; 1903.02549)
1
10
100
1000
Dark Matter Mass (GeV)

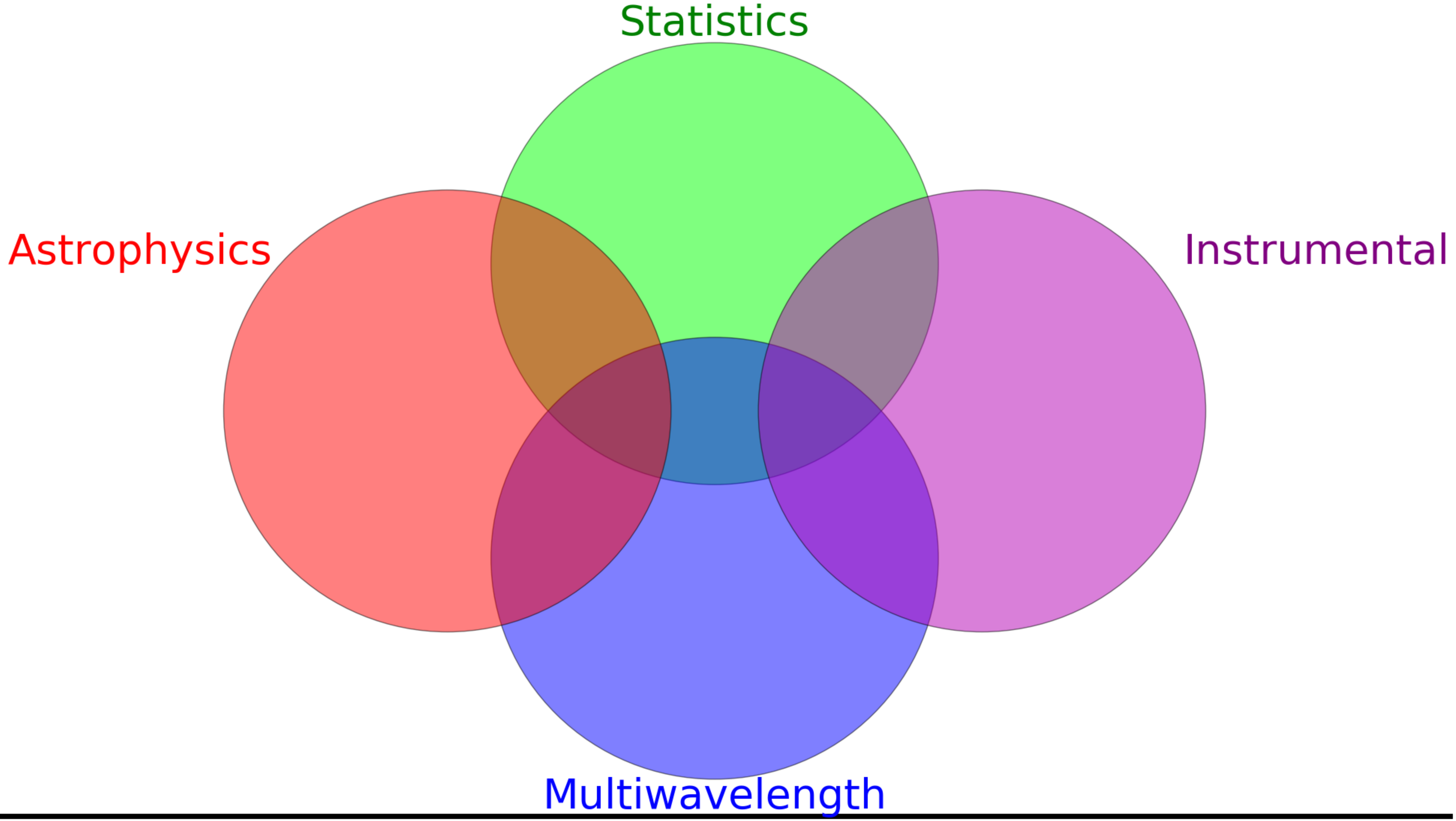
WHERE ARE WE NOW?

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


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

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


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


Statistics
Astrophysics
Instrumental
Multiwavelength


Statistics
Astrophysics
Dwarf Galaxies
Instrumental
Multiwavelength


Statistics
Astrophysics
Dwarf Galaxies
Instrumental
Antihelium
Multiwavelength


Statistics
Astrophysics
Dwarf Galaxies
Instrumental
Antihelium
Galactic Center
Multiwavelength


Statistics
Astrophysics
Dwarf Galaxies
Instrumental
Antihelium
Antiprotons
Galactic Center
Multiwavelength

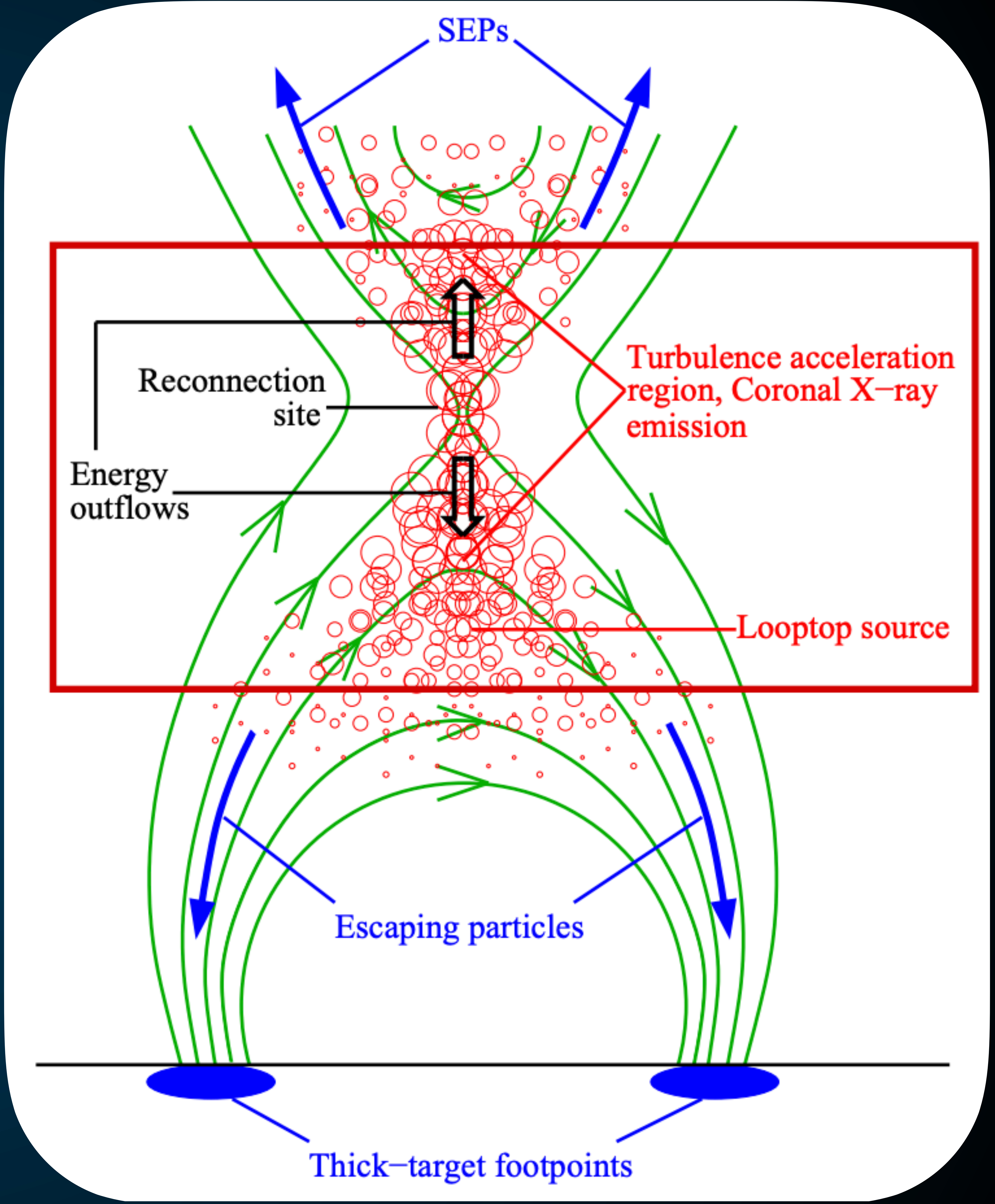
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ (cm^{3}s^{-1})
$b\bar{b}$ (WMAP5)
e^+e^- (WMAP5)
Thermal Cross-Section
Galli et al. (2009; 0905.0003)
see also: astro-ph/0210617, 0810.5952)
0.1
1
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

$b\bar{b}$ (Planck)
e^+e^- (Planck)
$b\bar{b}$ (Dwarfs)
W^+W^- (HESS)
$\tau^+\tau^-$ (HESS)
Thermal Cross-Section
Galactic Center (Fermi)
Antiproton (AMS)
$\tau^+\tau^-$ (AMS)
e^+e^- (EDGES)
e^+e^- (AMS)
$<\sigma v>$ (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

Topic 2: Solar Physics

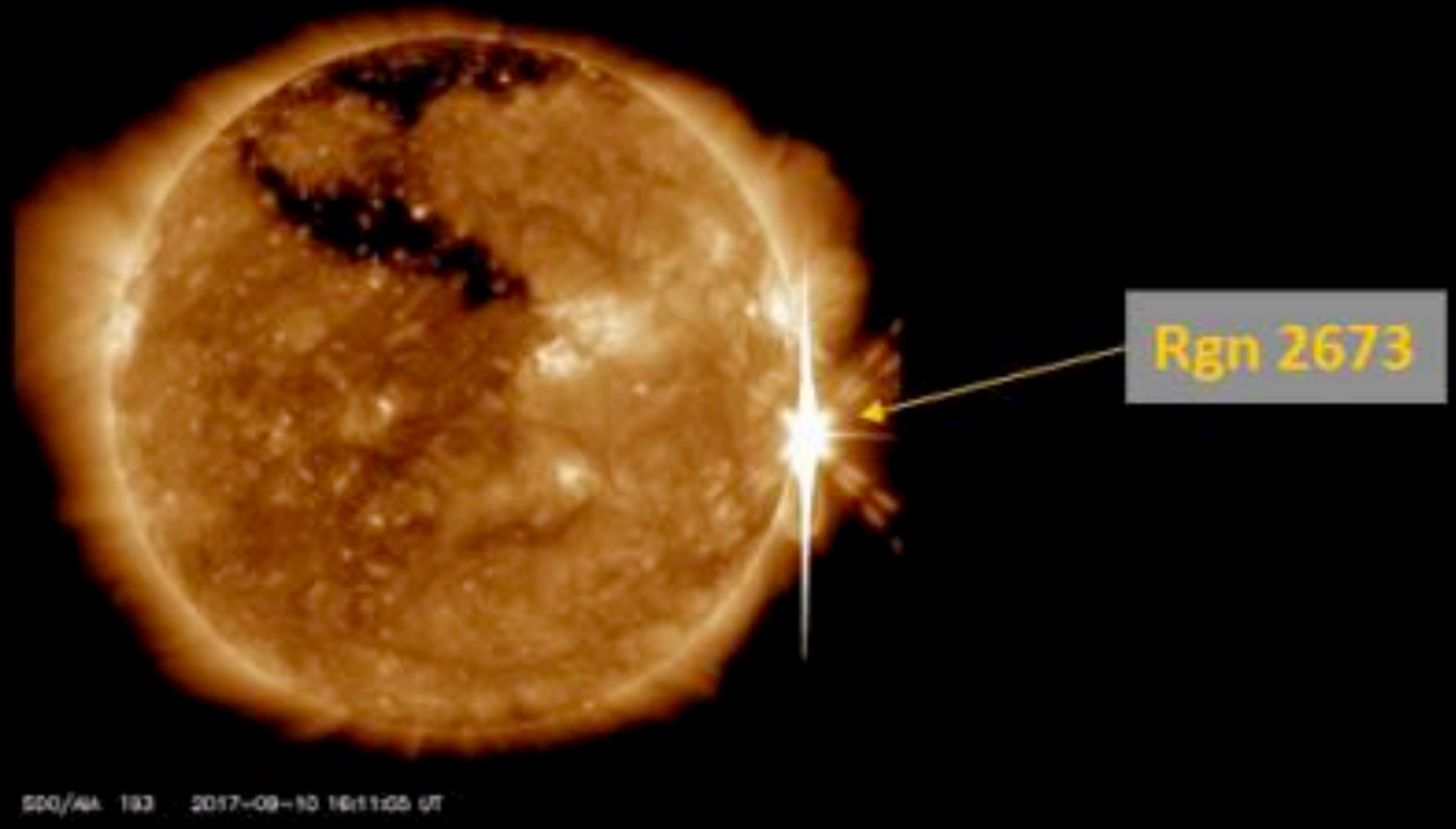
Producing Solar Gamma-Rays

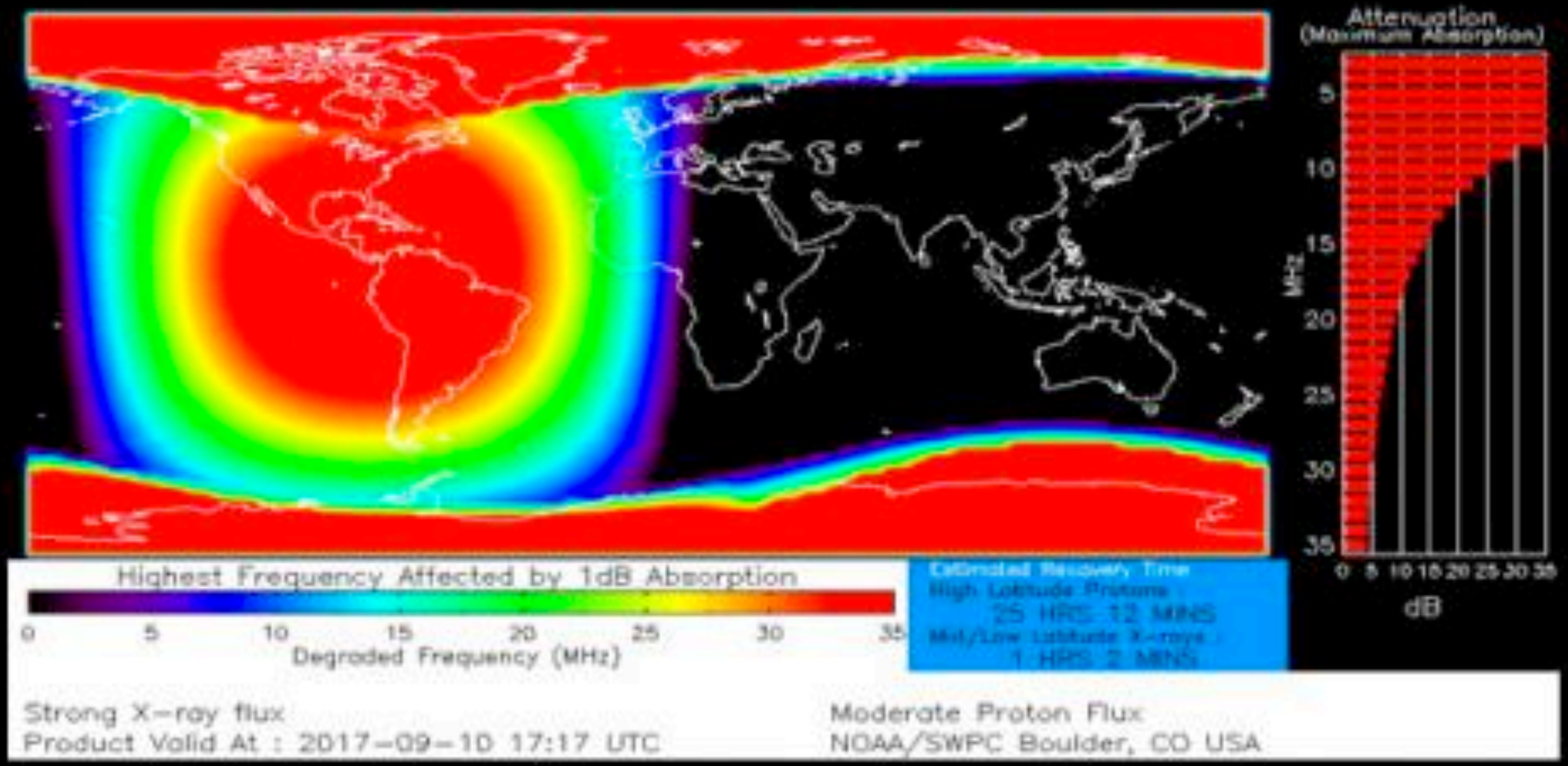
- **Solar Flares and Reconnection events.**



Petrosian (2016; 1605.04022)

Strong Radio Blackout 10 Sep 17 at 1606 UTC





R3

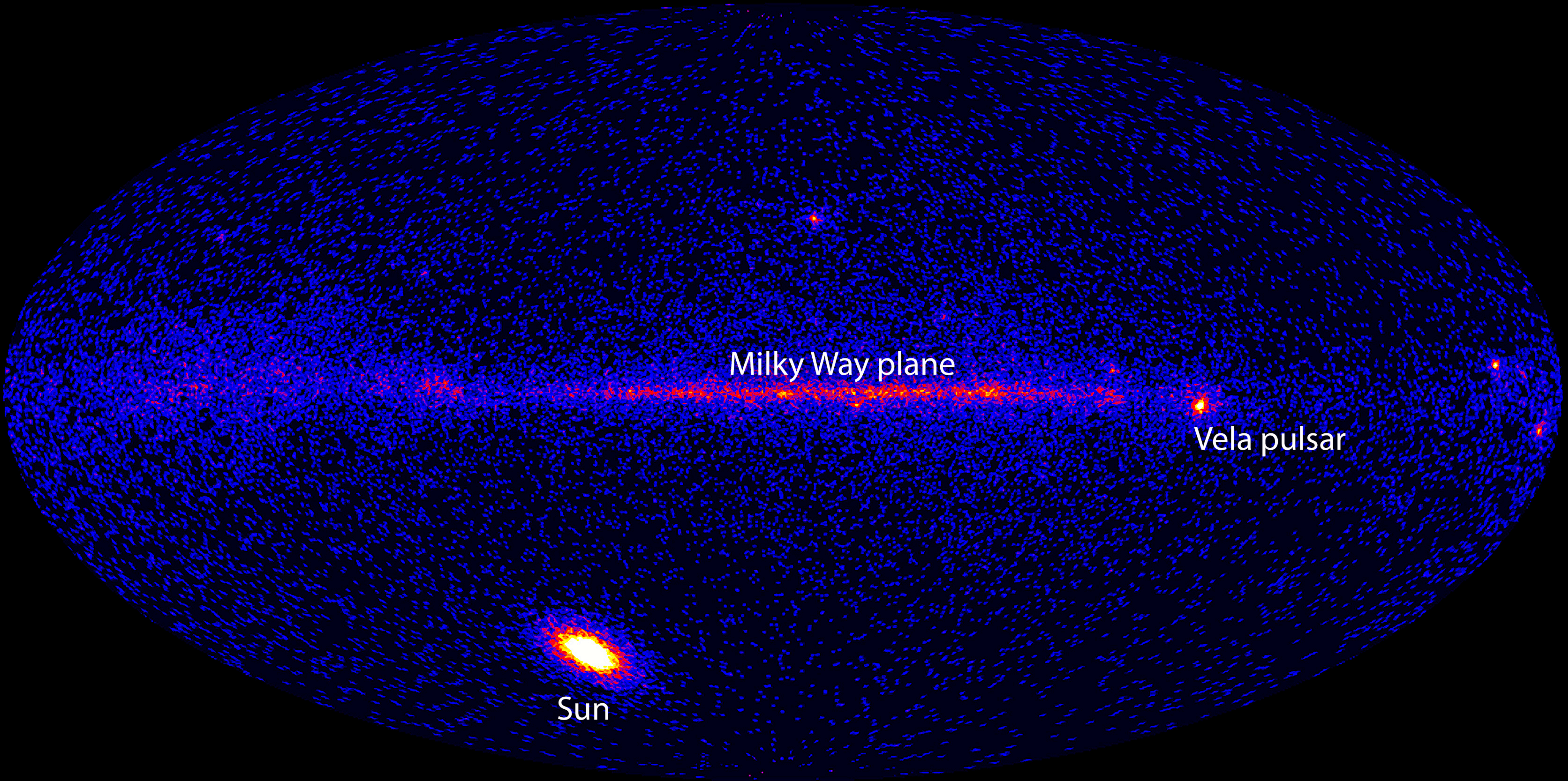
PRIMARY AREA of IMPACTS

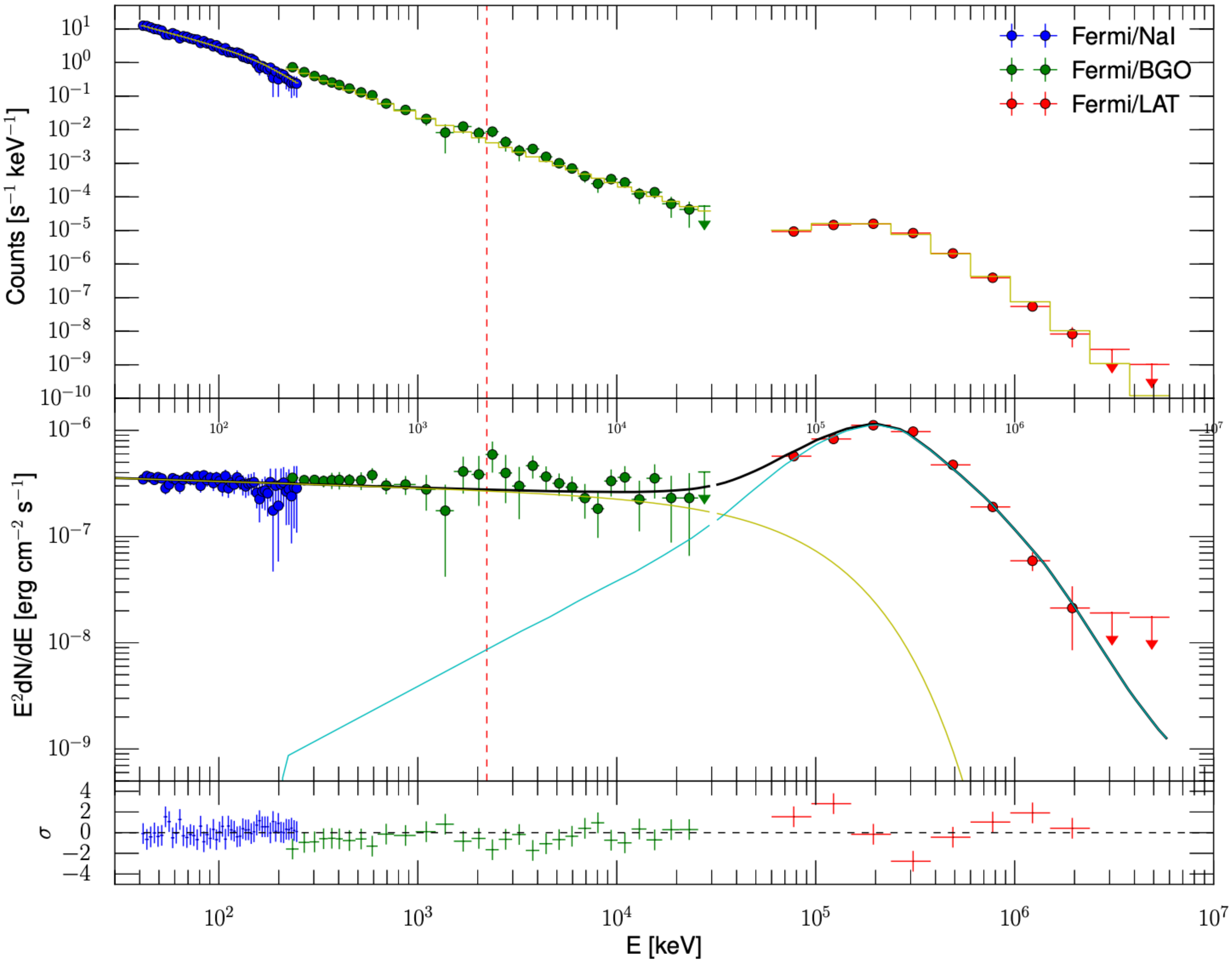
Large portions of sunlit side of Earth

POSSIBLE EFFECTS

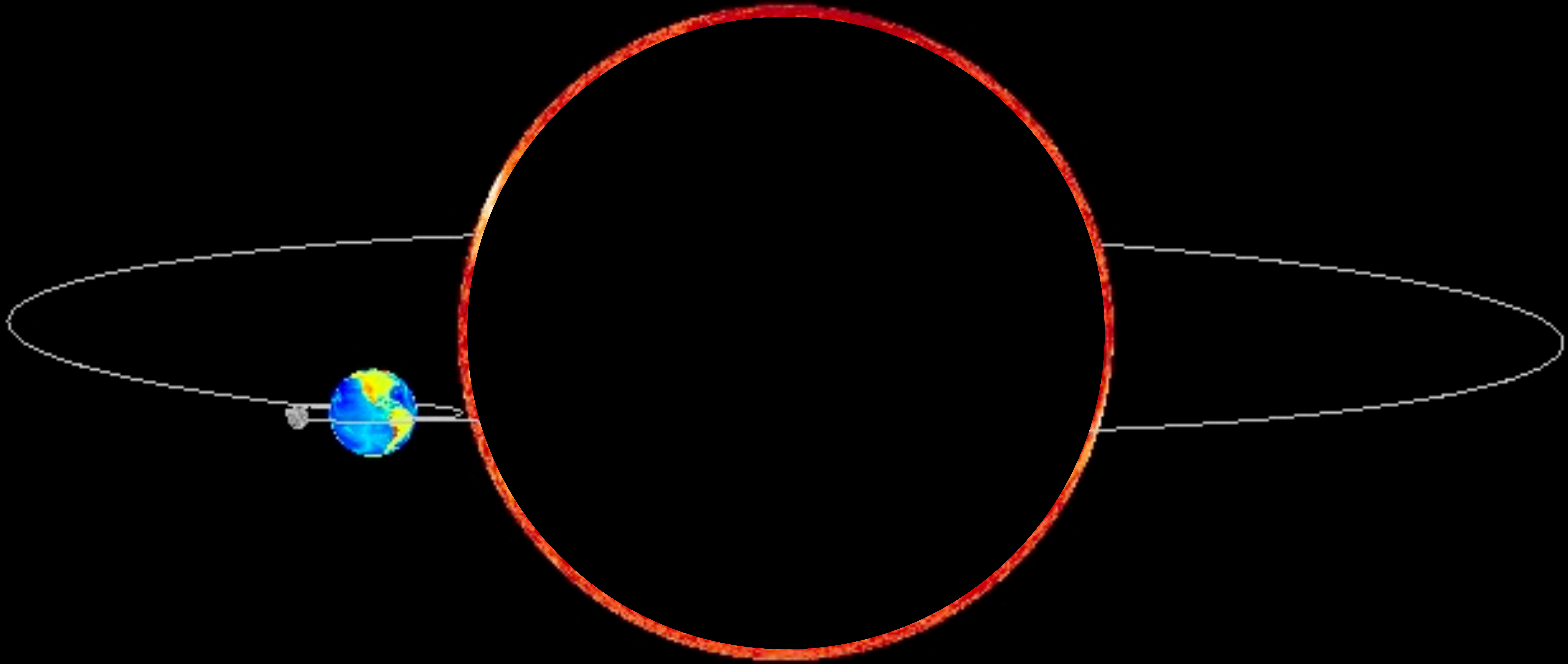
HF Radio: Wide area of blackouts; loss of contact for up to an hour over sunlit side of Earth

Navigation: Low frequency communication degraded for about an hour


Milky Way plane
Vela pulsar
Sun



Fermi/NaI
Fermi/BGO
Fermi/LAT
Counts [s^{-1} keV^{-1}]
E^{2}dN/dE [erg cm^{-2} s^{-1}]
σ
E [keV]



Fermi-LAT Sensitivity Threshold
Limb Emission
$E_\gamma^2 dF/dE_\gamma$ [GeV cm^{-2} s^{-1}]
E_γ [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-1}
10^{0}
10^{1}
10^{2}

THE ASTROPHYSICAL JOURNAL, 382:652–666, 1991 December 1

SIGNATURES OF COSMIC-RAY INTERACTIONS ON THE SOLAR SURFACE

D. SECKEL, TODOR STANEV, AND T. K. GAISSER
Bartol Research Institute, University of Delaware, Newark, DE 19716
Received 1991 March 21; accepted 1991 June 5

ABSTRACT

We estimate the fluxes of neutrinos, gamma rays, antiprotons, neutrons, and antineutrons that result from collisions of high-energy Galactic cosmic rays with the solar atmosphere. The results are sensitive to assumptions about cosmic-ray transport in the magnetic fields of the inner solar system. The high-energy photon flux should be observable by the Gamma Ray Observatory. The neutrino flux should produce less than one event per year in the next generation of neutrino telescopes. The antiproton flux is unobservable against the Galactic background. The neutron and antineutron fluxes are detectable only if neutrons produced in terrestrial cosmic-ray events may be discriminated against.

Subject headings: cosmic rays: general — gamma rays: general — neutrinos — Sun: activity

1. INTRODUCTION

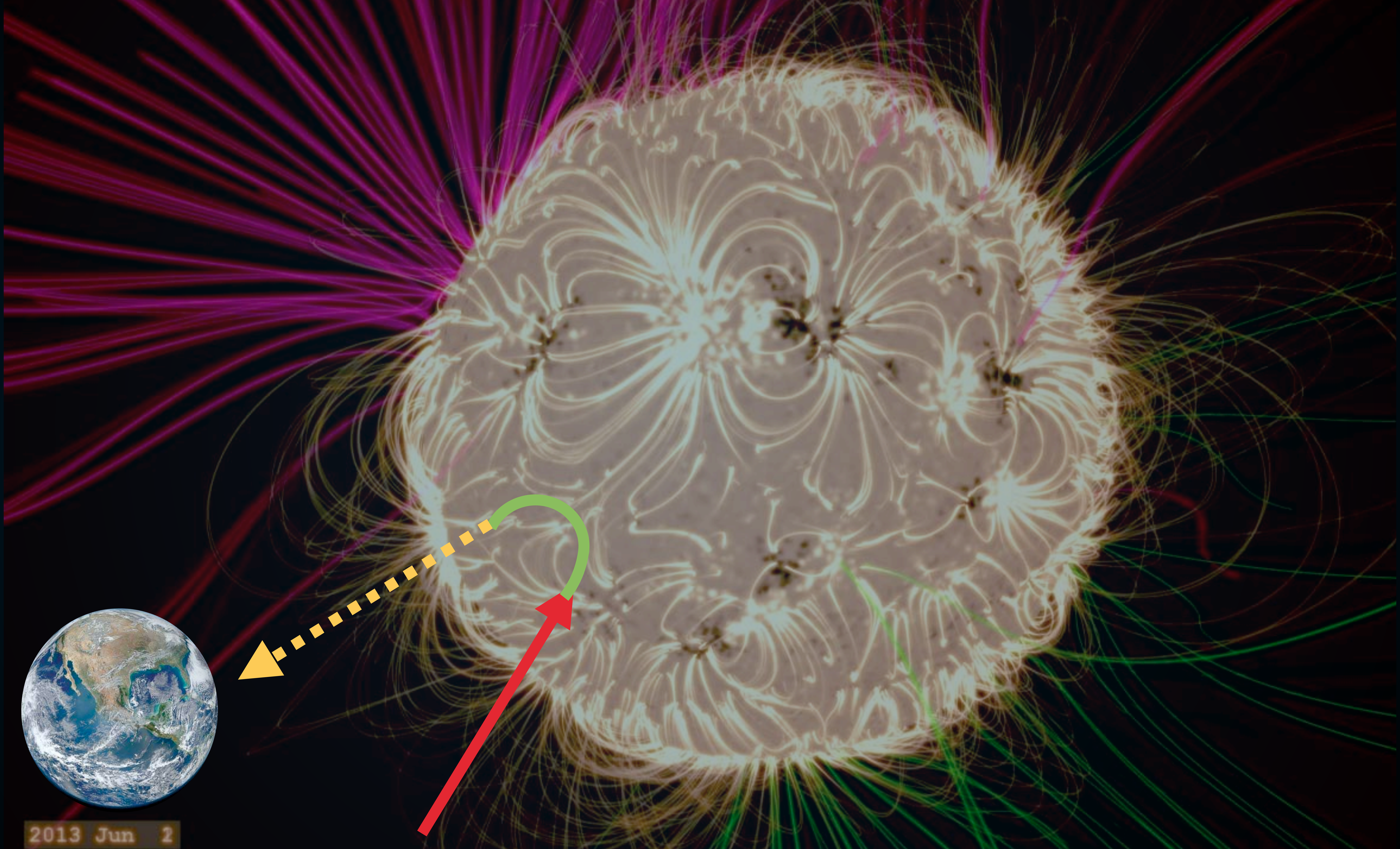
The interactions of high-energy cosmic-ray nuclei with matter have been studied in a variety of settings. In our own atmosphere, these interactions produce cascades which include, or in turn produce, detectable fluxes of electrons, positrons, muons, gamma rays, Čerenkov light, neutrons and other nuclear fragments, and neutrinos. Interactions with interstellar gas are thought to produce the observed Galactic flux of γ-rays (Mayer-Hasselwander et al. 1982; Fichtel & Kniffen 1984; Fichtel et al. 1977) with energies above $\sim$500 MeV, antiprotons (Stephens & Golden 1987), and positrons (Protheroe 1982). In this paper we explore another place where interactions between cosmic-ray nuclei and gas may produce observable signals: the Sun.

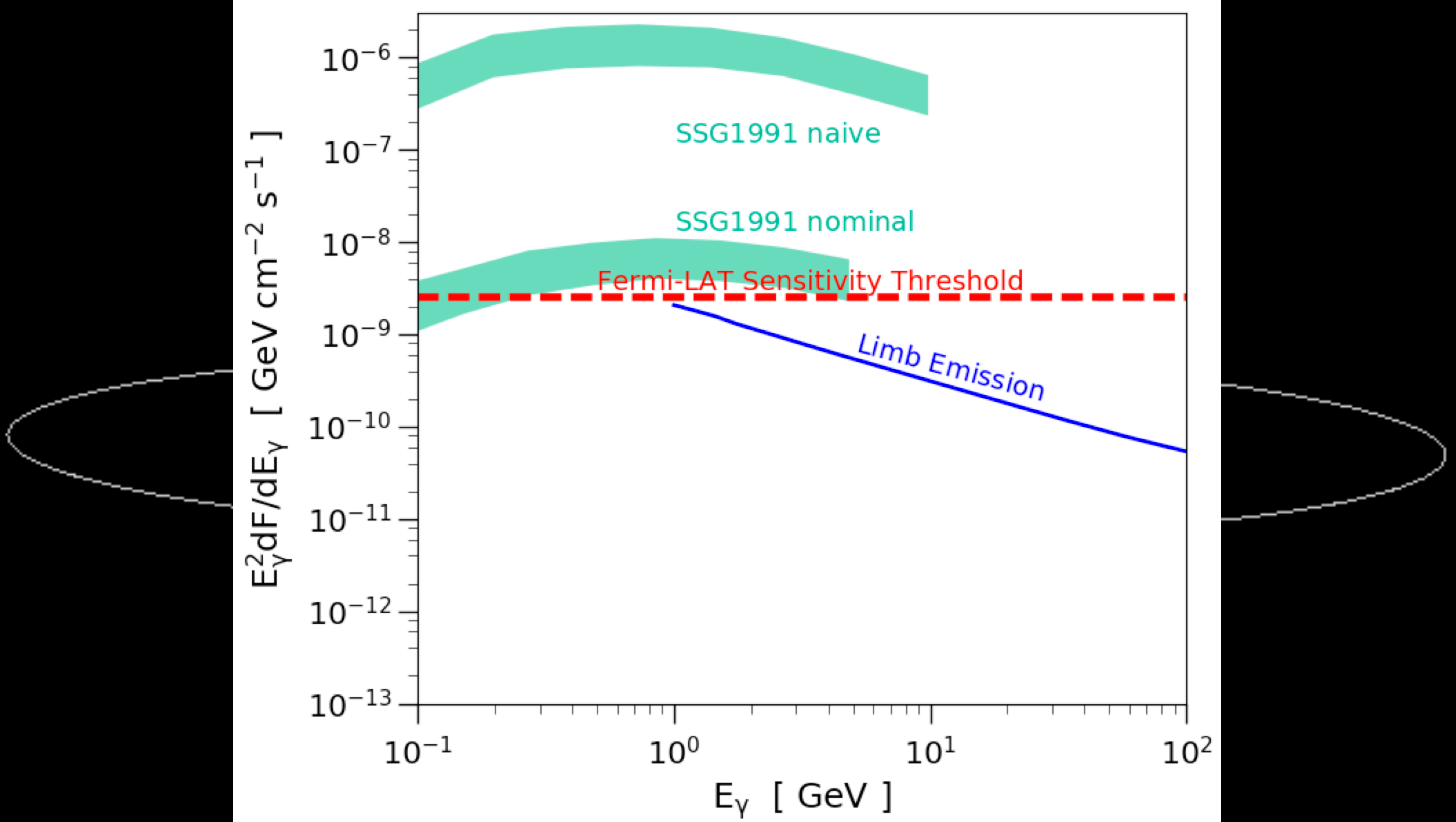
At first, the Sun may seem an inappropriate source. Although nearby, it covers a fairly small fraction of the sky:

appropriate thickness to generate high-energy photons without reabsorbing them. The high-energy cascade products would then be suppressed from the naive value by an amount of order $h_\oplus/R_\oplus \sim 10^{-3}$, where $h_\oplus$ is the scale height of Earth's atmosphere, and $R_\oplus$ is Earth's radius. Although we will argue otherwise, one might worry that a similar suppression occurs for the Sun.

Third, to calculate fluxes from the Sun, one must take into account the details of the solar atmosphere. For example, typical cascades will take place in a less dense environment than for Earth, and that increases the yields of some by-products.

Despite these uncertainties, it is possible to make some quick estimates of the fluxes of by-products. The total cosmic-ray flux of nucleons above 1 GeV is $I_{\rm cr}(E > 1~{\rm GeV}) \simeq 1~{\rm cm^{-2}~s^{-1}~sr^{-1}}$. Absorbing this primary flux on the solar disk and reemit-

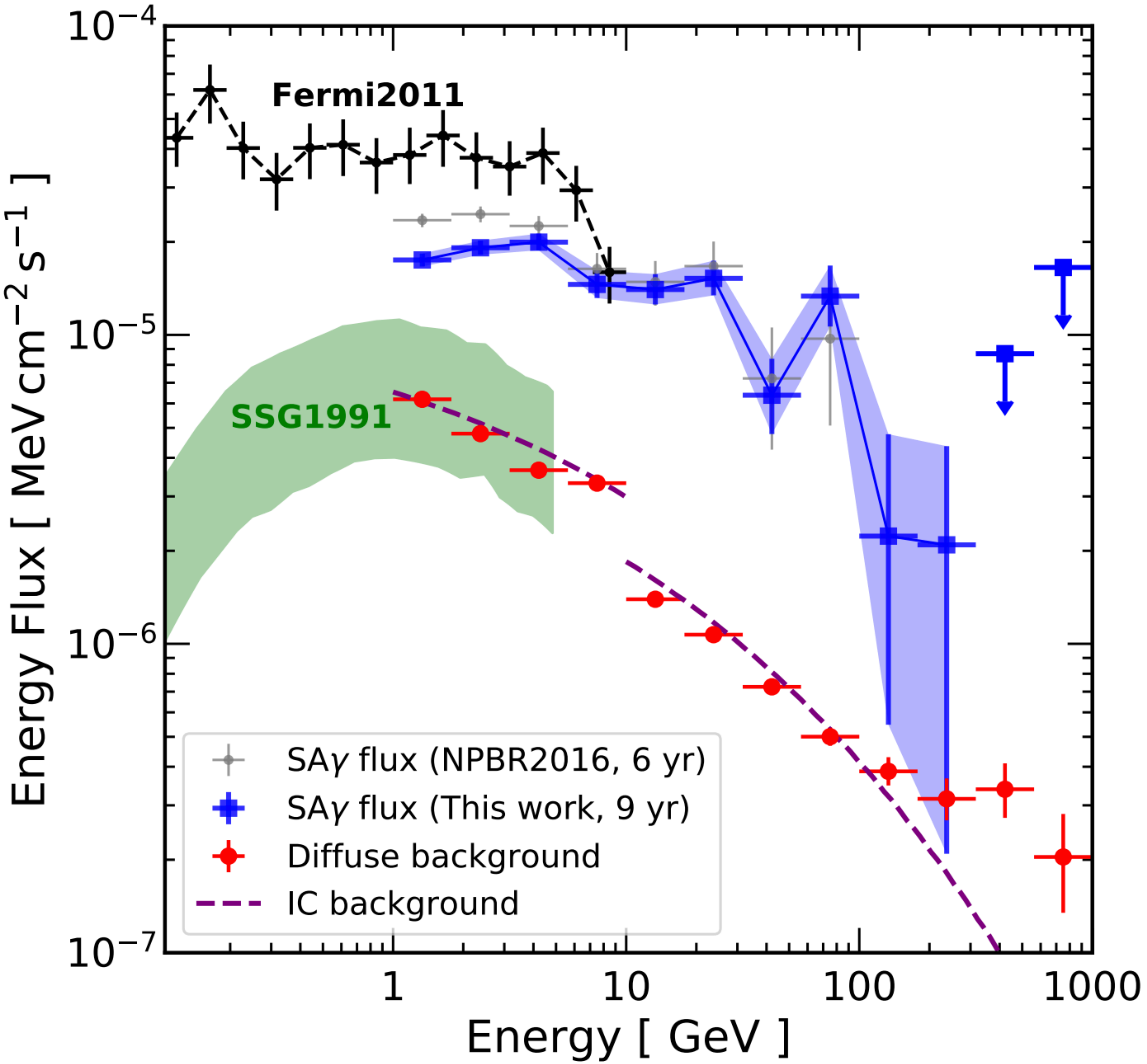

2013 Jun 2


SSG1991 naive
SSG1991 nominal
Fermi-LAT Sensitivity Threshold
Limb Emission
$E_\gamma^2 dF/dE_\gamma$ [GeV cm^{-2} s^{-1}]
E_γ [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-1}
10^{0}
10^{1}
10^{2}

Fermi2011 (1.5 yr)
This work (6 yr)
SSG1991 nominal
Energy Flux [MeV cm^{-2} s^{-1}]
Energy [GeV]
10^{-4}
10^{-5}
10^{-6}
10^{-1}
10^{0}
10^{1}
10^{2}

Intensity

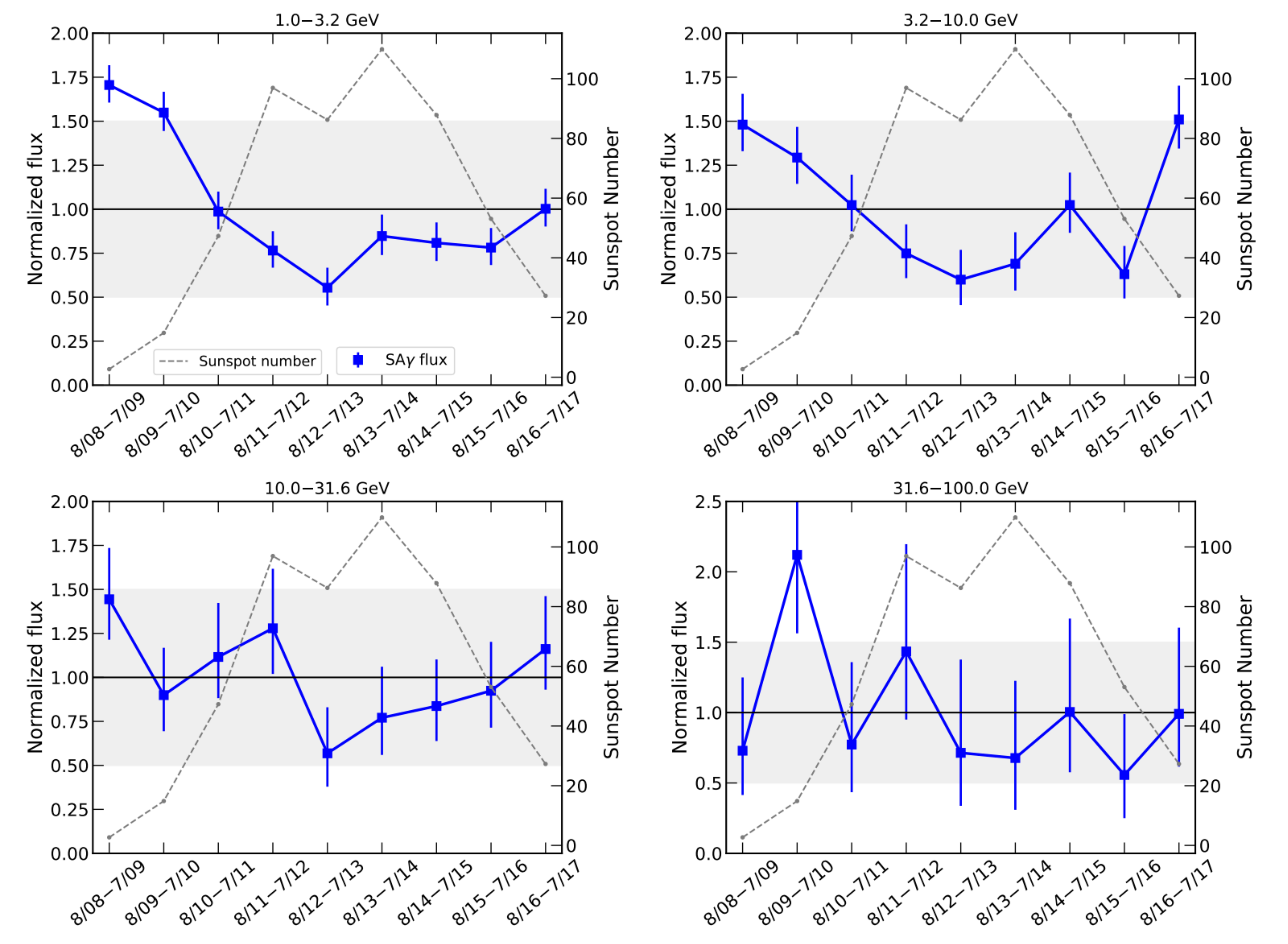
X



Fermi2011
SSG1991
SAγ flux (NPBR2016, 6 yr)
SAγ flux (This work, 9 yr)
Diffuse background
IC background
Energy Flux [MeV cm^{-2} s^{-1}]
Energy [GeV]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
1
10
100
1000

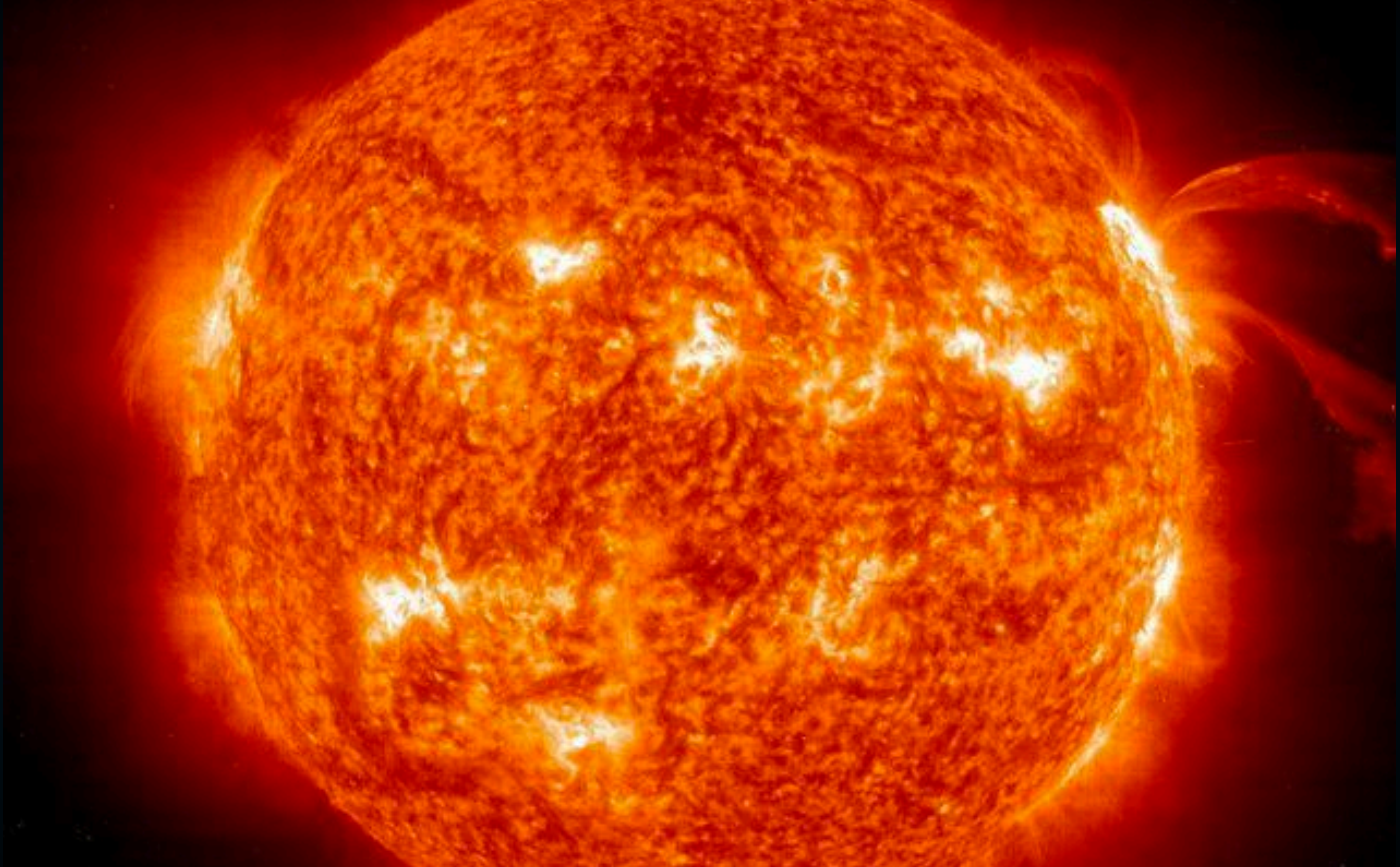
Intensity	**X**
Spectrum	**X**


Yearly Averaged Sunspot Numbers 1610-2010
Sunspot Number
200
150
100
50
0
Maunder
Minimum
1600
1650
1700
1750
1800
1850
1900
1950
2000
2050
DATE



1.0−3.2 GeV
3.2−10.0 GeV
10.0−31.6 GeV
31.6−100.0 GeV
Normalized flux
Sunspot Number
Sunspot number
SAγ flux
8/08−7/09
8/09−7/10
8/10−7/11
8/11−7/12
8/12−7/13
8/13−7/14
8/14−7/15
8/15−7/16
8/16−7/17

Intensity	X
Spectrum	X
Time Variability	X



PSF
10 - 50 GeV
< 2010 (17 months)
0.5
0.25
0
-0.25
-0.5
F_{pol}=13.1±2.5
F_{eq}=12.1±2.5
(x10^{-6} MeV cm^{-2} s^{-1})
-0.5
-0.25
0
0.25
0.5


PSF
10 - 50 GeV
< 2010 (17 months)
PSF
10 - 50 GeV
≥ 2010 (94 months)
F_pol=13.1±2.5
F_eq=12.1±2.5
(x10^-6 MeV cm^-2 s^-1)
F_pol=13.9±0.8
F_eq=4.5±0.8
(x10^-6 MeV cm^-2 s^-1)
PSF
> 50 GeV
< 2010 (17 months)
PSF
> 50 GeV
≥ 2010 (94 months)
F_pol=5.7±4.1
F_eq=20.1±4.1
(x10^-6 MeV cm^-2 s^-1)
F_pol=6.4±0.5
F_eq=0.5±0.5
(x10^-6 MeV cm^-2 s^-1)
Helioprojective Solar Latitude (T_y, degrees)
Helioprojective Solar Longitude (T_x, degrees)
log10(Energy / 1 MeV)
0.5
0.25
0
-0.25
-0.5
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0

Intensity	**X**
Spectrum	**X**
Time Variability	**X**
Morphology	**X**

Solar Minimum
Not Solar Minimum
Data
Polar
Eq.
E^2 dϕ/dE (MeV cm^{-2} s^{-1})
10^{-5}
10^{-6}
10
20
50
100
200
Energy (GeV)

Time (UTC)	Energy	R.A.	Dec	Solar Distance	Event Class	PSF Class	Edisp Class	P6	P7	BG Contribution
2008-11-09 03:47:51	212.8 GeV	224.497	-16.851	0.068°	UltraCleanVeto	PSF0	EDISP3	✓	✓	0.00050
2008-12-13 03:25:55	139.3 GeV	260.707	-23.243	0.126°	UltraCleanVeto	PSF2	EDISP1	X	X	0.00038
2008-12-13 07:04:07	103.3 GeV	260.346	-23.102	0.399°	UltraCleanVeto	PSF0	EDISP2	X	X	0.00052
2009-03-22 08:43:13	117.2 GeV	1.337	0.703	0.255°	UltraCleanVeto	PSF1	EDISP3	✓	✓	0.00027
2009-08-15 01:14:17	138.5 GeV	144.416	14.300	0.261°	UltraCleanVeto	PSF2	EDISP3	✓	✓	0.00021
2009-11-20 07:55:20	112.6 GeV	235.905	-19.473	0.288°	UltraCleanVeto	PSF1	EDISP1	X	X	0.00020
2008-12-24 05:41:53	226.9 GeV	272.899	-23.343	0.069°	UltraClean	PSF1	EDISP3	X	X	0.00128
2009-12-20 08:06:31	467.7 GeV	268.046	-23.177	0.338°	UltraCleanVeto	PSF1	EDISP0	X	X	0.00208

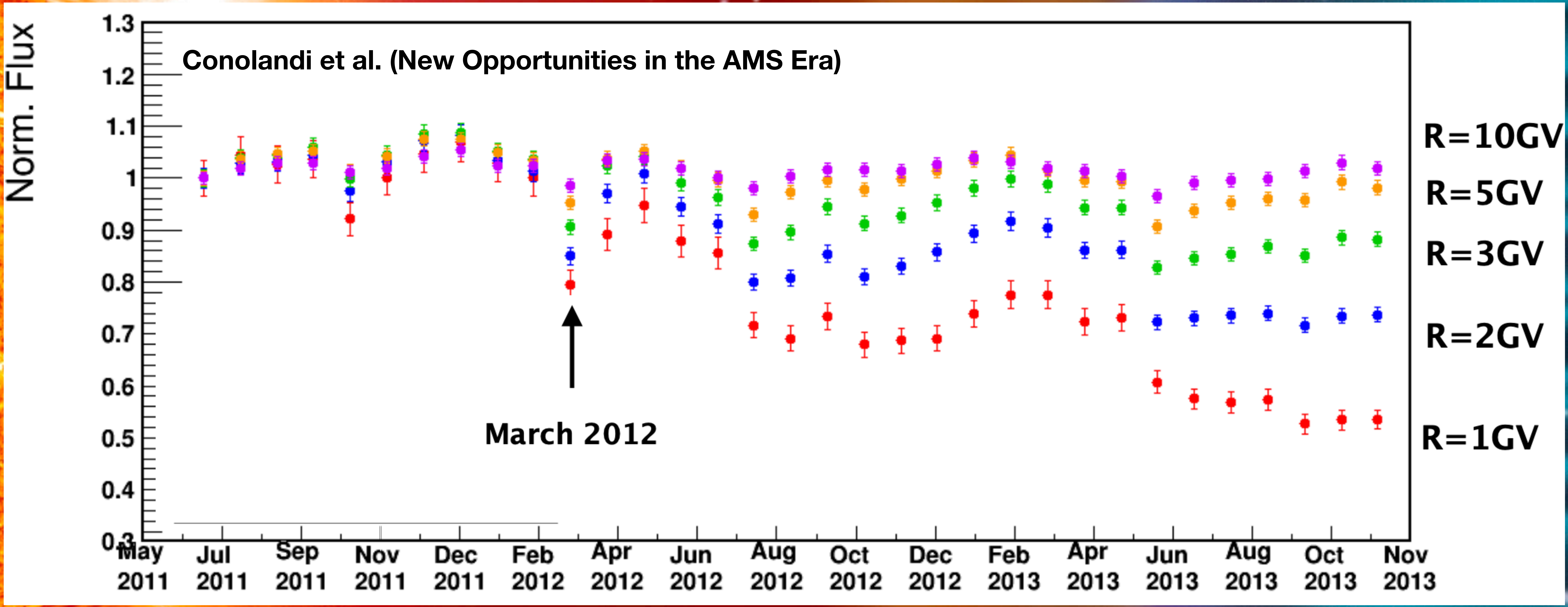
Intensity	X
Spectrum	X
Time Variability	X
Morphology	X
Spectral Variability	X


Fermi2011
SSG1991
Energy Flux [MeV cm⁻² s⁻¹]
Energy [GeV]
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
1
10
100
1000
SAγ flux (NPBR2016, 6 yr)
SAγ flux (This work, 9 yr)
Diffuse background
IC background
(x100)
(x10)
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10
100
SAγ flux
Total flux (|b| > 5°)
Total flux (5° < |b| < 30°)
Total flux (|b| > 30°)
Energy Flux [MeV cm⁻² s⁻¹]
Energy [GeV]

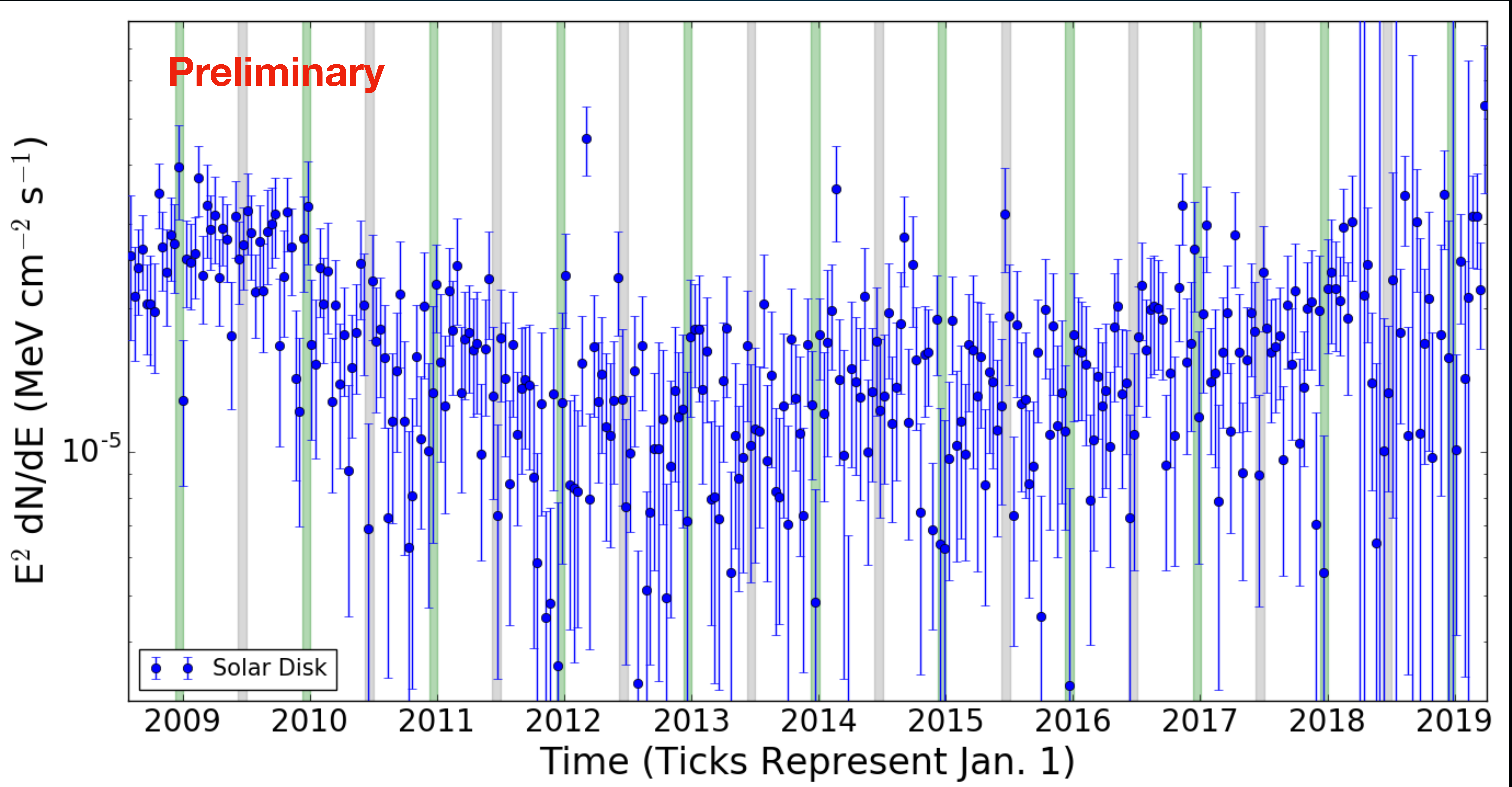
Energy Flux [MeV cm^{-2} s^{-1}]
Energy [GeV]
Fermi2011
SSG1991
HAWC 95% Limits:
(September)
ARGO-YBJ
CR upper bound
HAWC 1 yr
LHAASO 1 yr
SAγ flux (solar min. $|b| > 5°$)
SAγ flux (9 yr $|b| > 30°$)

Intensity	X
Spectrum	X
Time Variability	X
Morphology	X
Spectral Variability	X
Spectral Dip	X

Oh wait… that’s basically everything.


Conolandi et al. (New Opportunities in the AMS Era)
Norm. Flux
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
May 2011
Jul 2011
Sep 2011
Nov 2011
Dec 2011
Feb 2012
Apr 2012
Jun 2012
Aug 2012
Oct 2012
Dec 2012
Feb 2013
Apr 2013
Jun 2013
Aug 2013
Oct 2013
Nov 2013
March 2012
R=10GV
R=5GV
R=3GV
R=2GV
R=1GV

Producing Solar Gamma-Rays



Producing Solar Gamma-Rays

The Antiproton Excess - A Detection?

Reinert, Winkler (2018; 1712.00002)

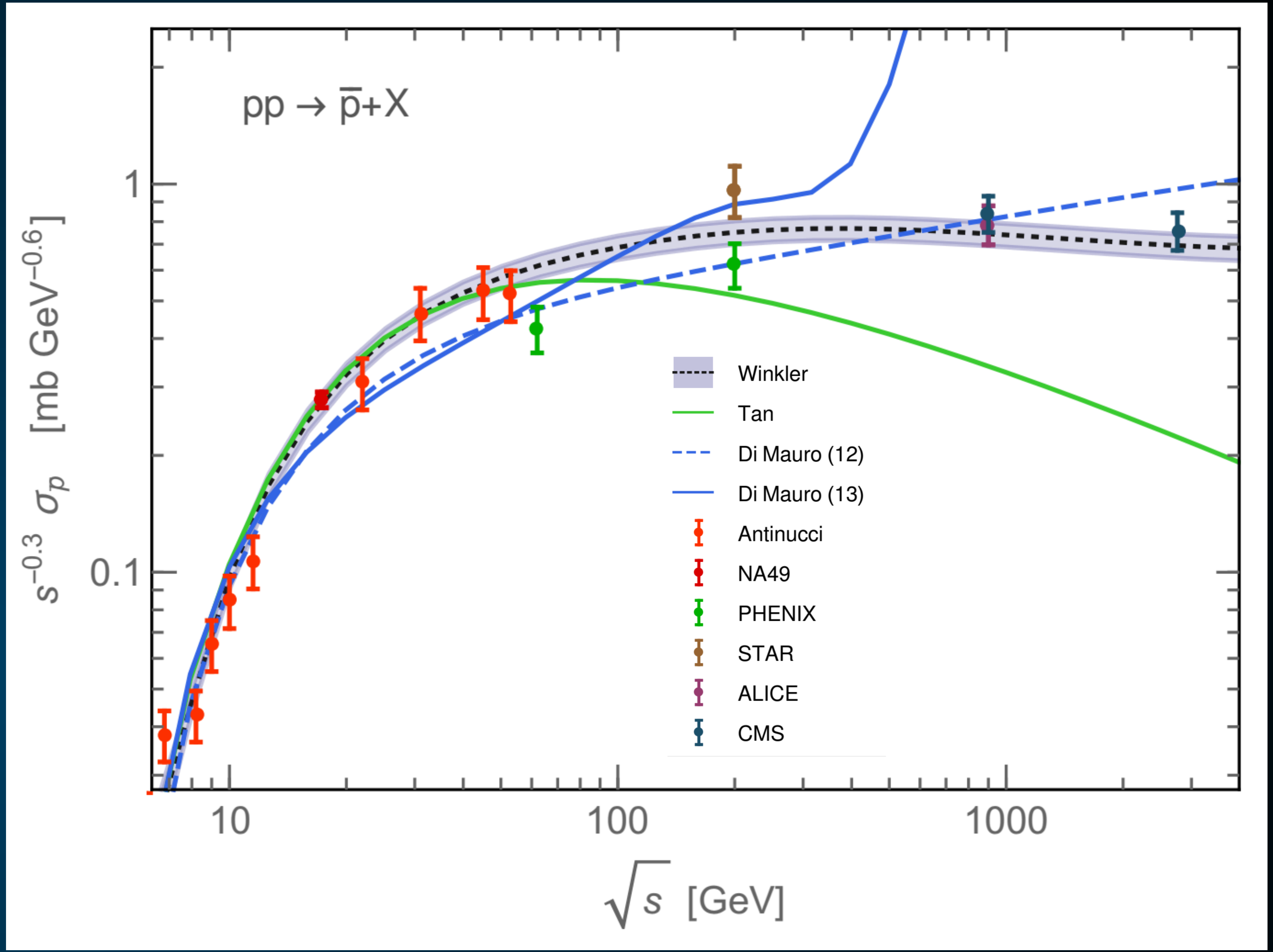
With great precision comes great responsibility:

Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

Solar Modulation

Antiproton Production Cross-Section



Galactic Primary to Secondary Ratios - Future AMS-02 Data!

Inhomogeneous Diffusion - TeV Halos

Solar Modulation - Voyager Data, Time-Dependent AMS-02 Data

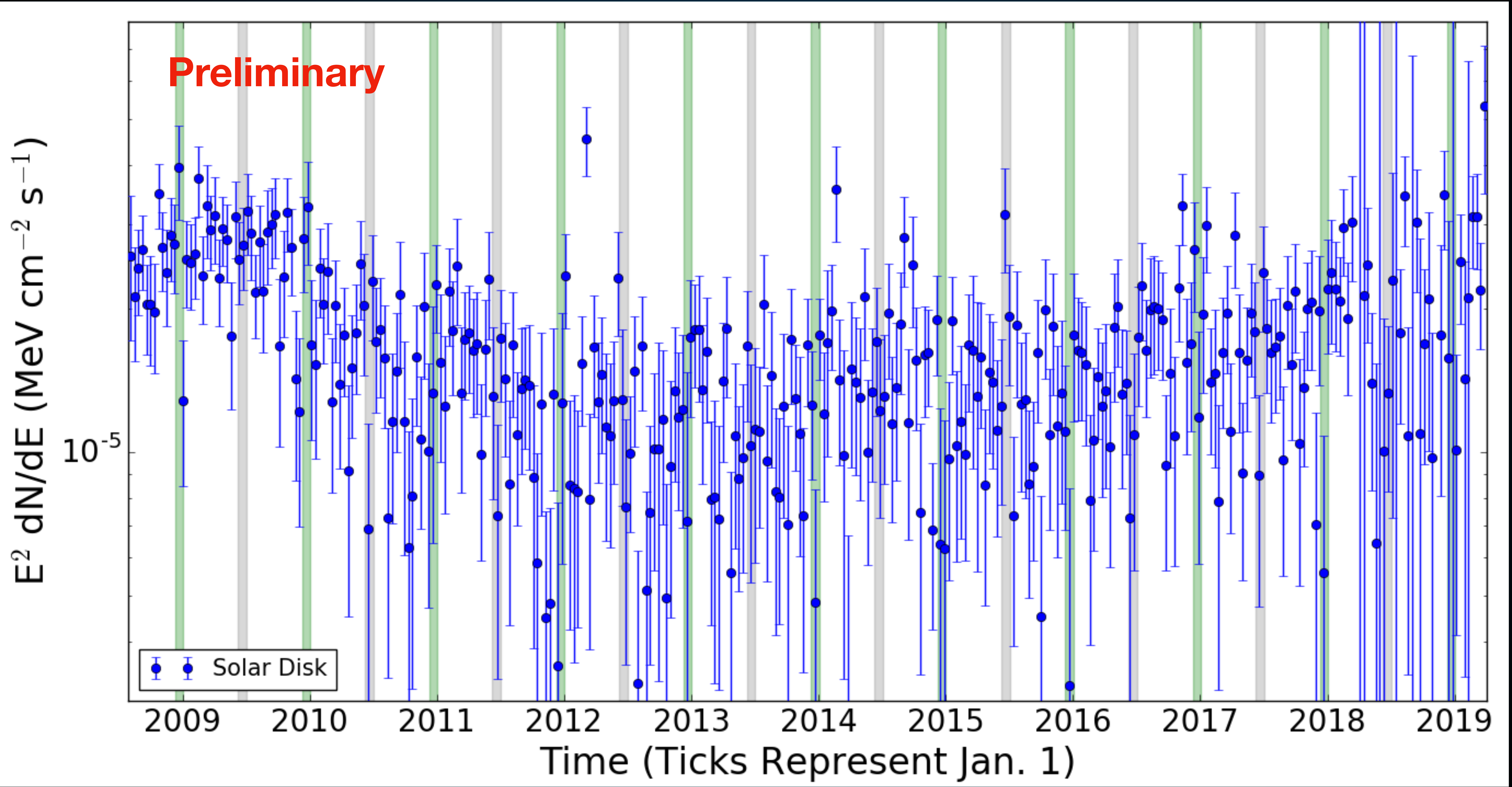
Antiproton Production Cross-Section - LHCb / Laboratory Experiments

$b\bar{b}$ (WMAP5)
e^+e^- (WMAP5)
Thermal Cross-Section
$<\sigma v>$ (cm^3s^{-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
Galli et al. (2009; 0905.0003)
see also: astro-ph/0210617, 0810.5952)

$b\bar{b}$ (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^3s^{-1})
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)


Norm. Flux
Conolandi et al. (New Opportunities in the AMS Era)
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
March 2012
May 2011
Jul 2011
Sep 2011
Nov 2011
Dec 2011
Feb 2012
Apr 2012
Jun 2012
Aug 2012
Oct 2012
Dec 2012
Feb 2013
Apr 2013
Jun 2013
Aug 2013
Oct 2013
Nov 2013
R=10GV
R=5GV
R=3GV
R=2GV
R=1GV

Producing Solar Gamma-Rays



The Antiproton Excess - A Detection?

Boudaud et al. (2019; 1906.07119)

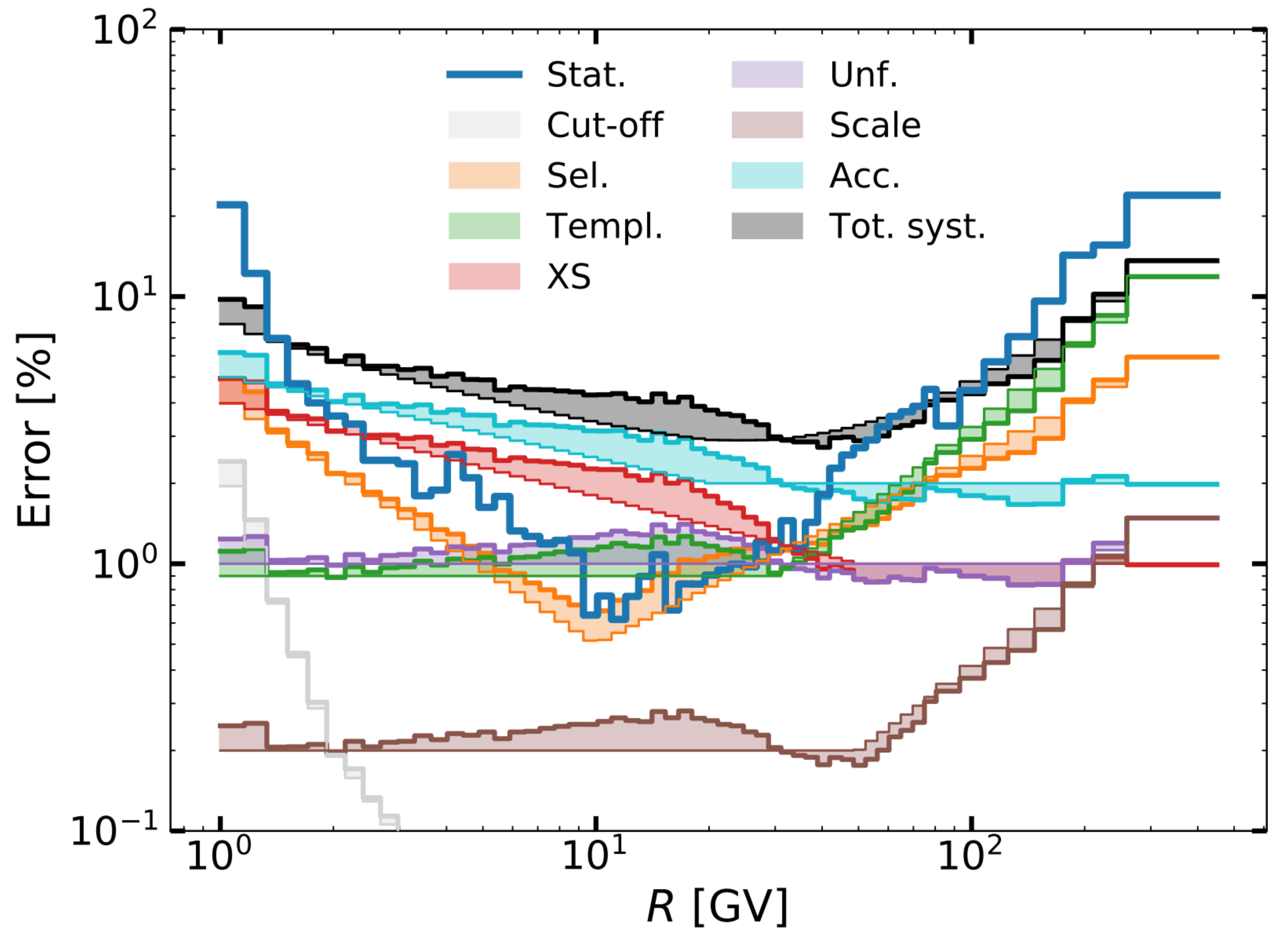
With great precision comes great responsibility:

Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

Solar Modulation

Antiproton Production Cross-Section



Galactic Primary to Secondary Ratios - Future AMS-02 Data!

Inhomogeneous Diffusion - TeV Halos

Solar Modulation - Voyager Data, Time-Dependent AMS-02 Data

Antiproton Production Cross-Section - LHCb / Laboratory Experiments

Extra Slides