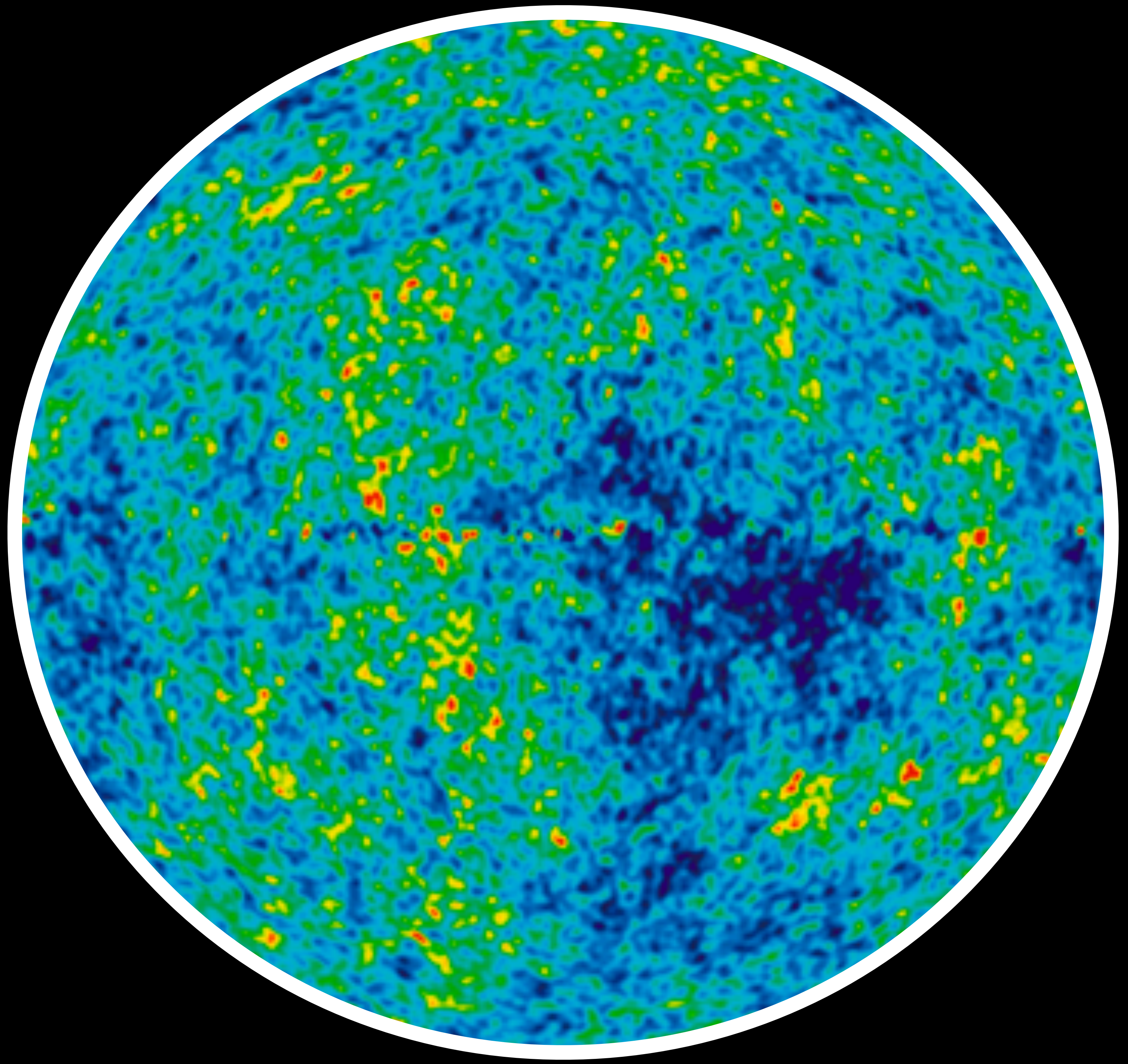
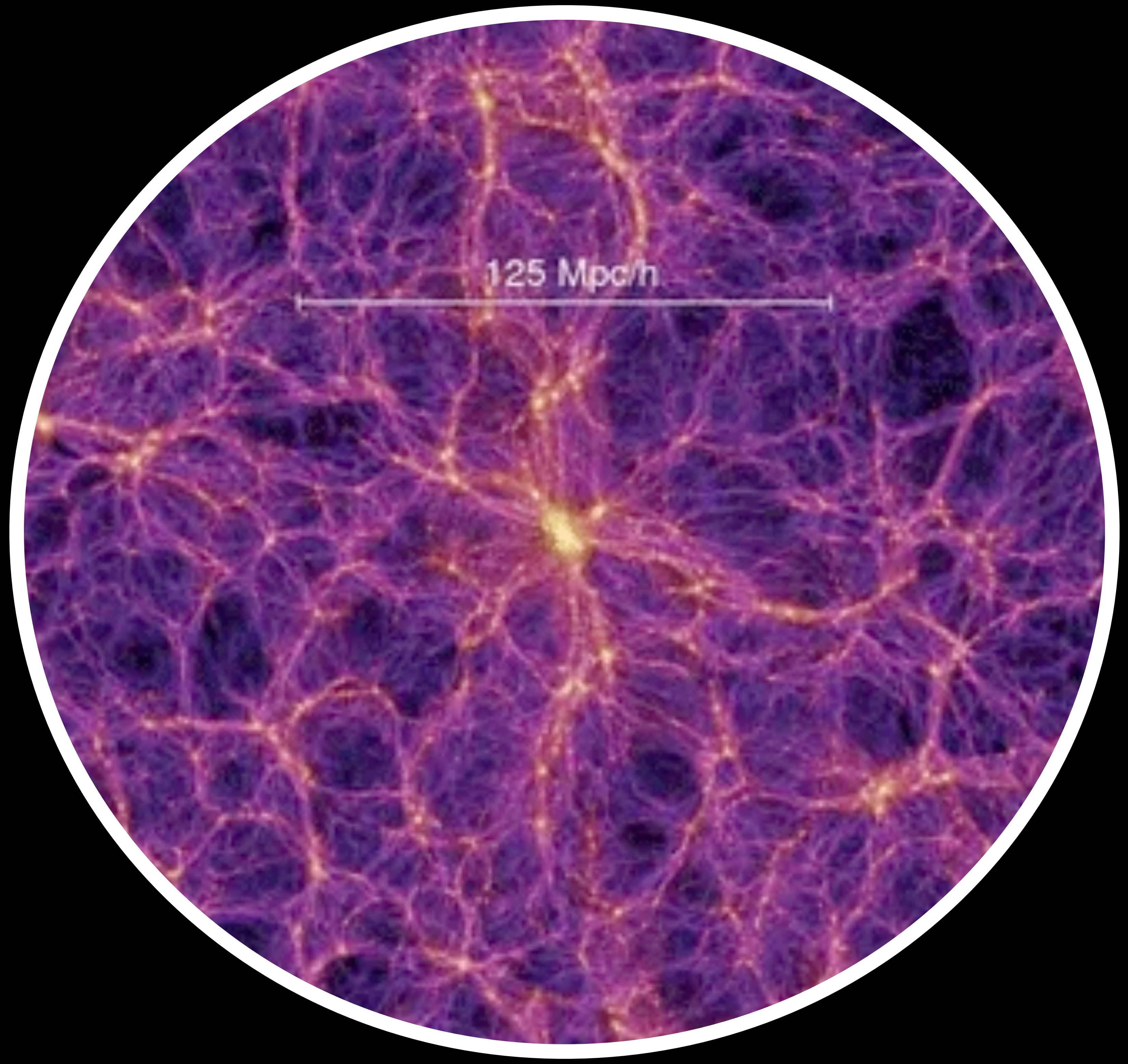
Tim Linden

Thermal WIMP Dark Matter on the Brink

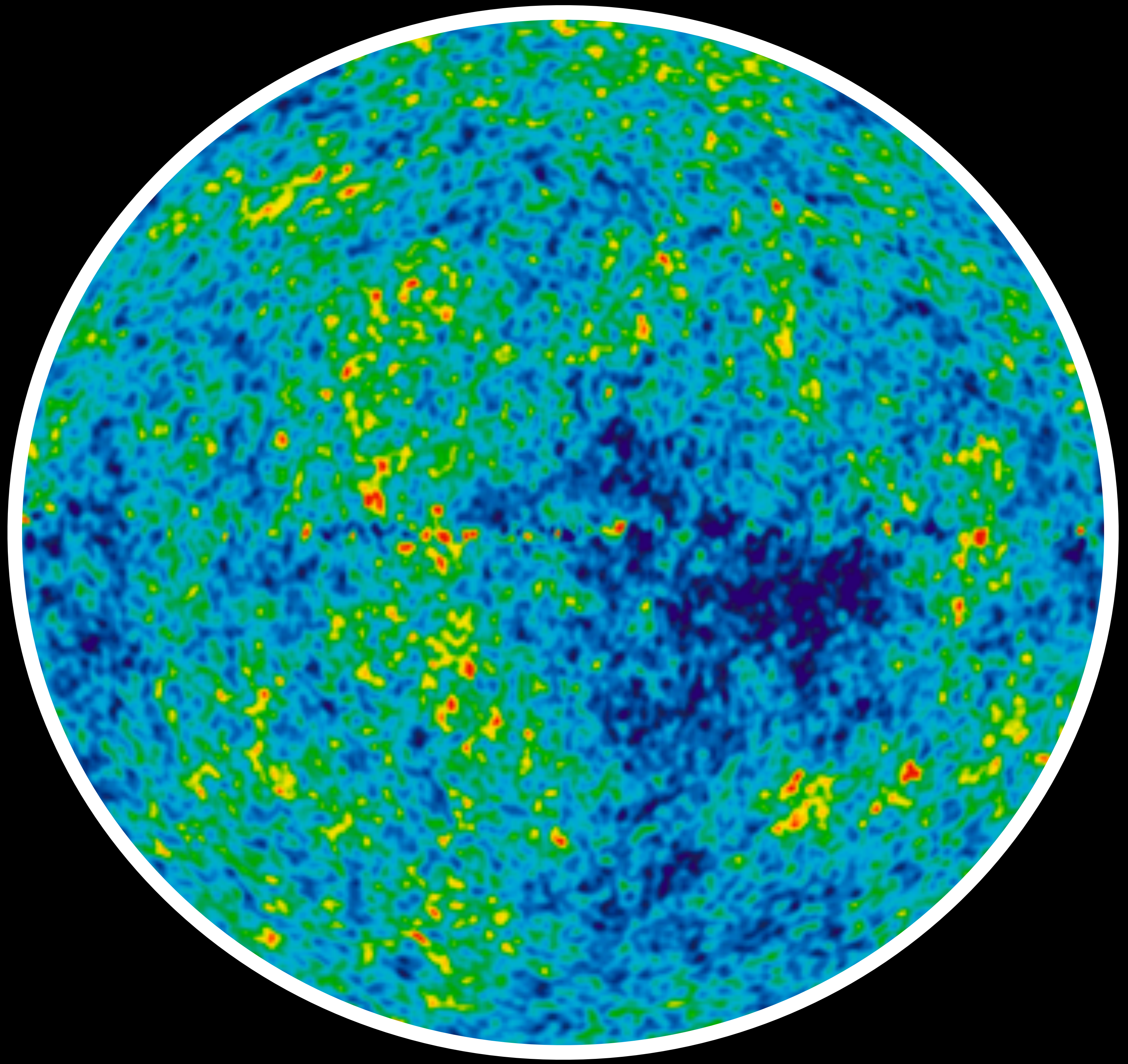
Stockholms universitet

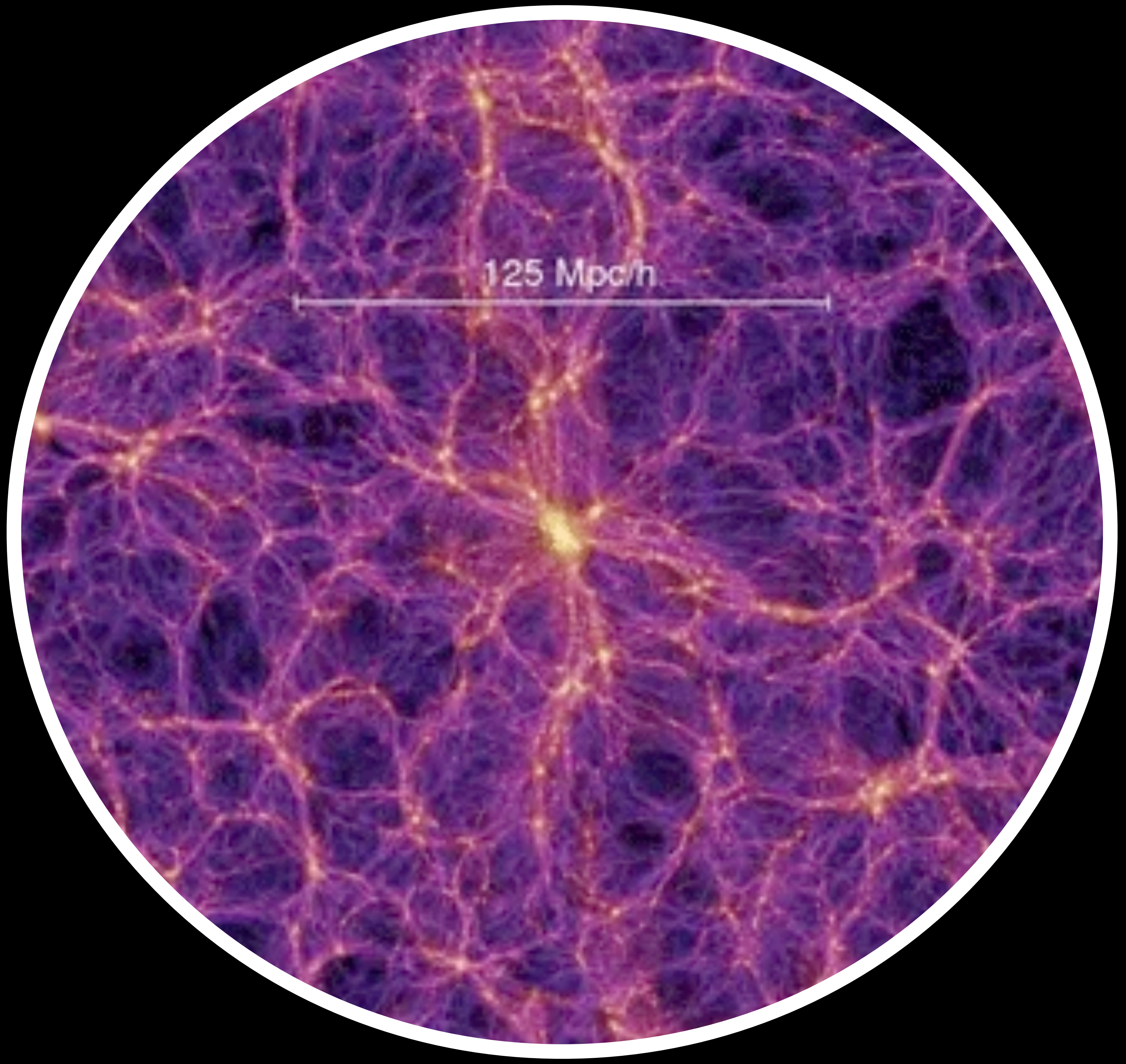
The Present





The Present





10^{-25} GeV

$R_{DM} > R_{UFD}$

10^{62} GeV

$M_{DM} > M_{UFD}$

slide concept courtesy of Asher Berlin

The Present

10^{-25} GeV

$R_{DM} > R_{UFD}$

slide concept courtesy of Asher Berlin

10^{62} GeV

$M_{DM} > M_{UFD}$

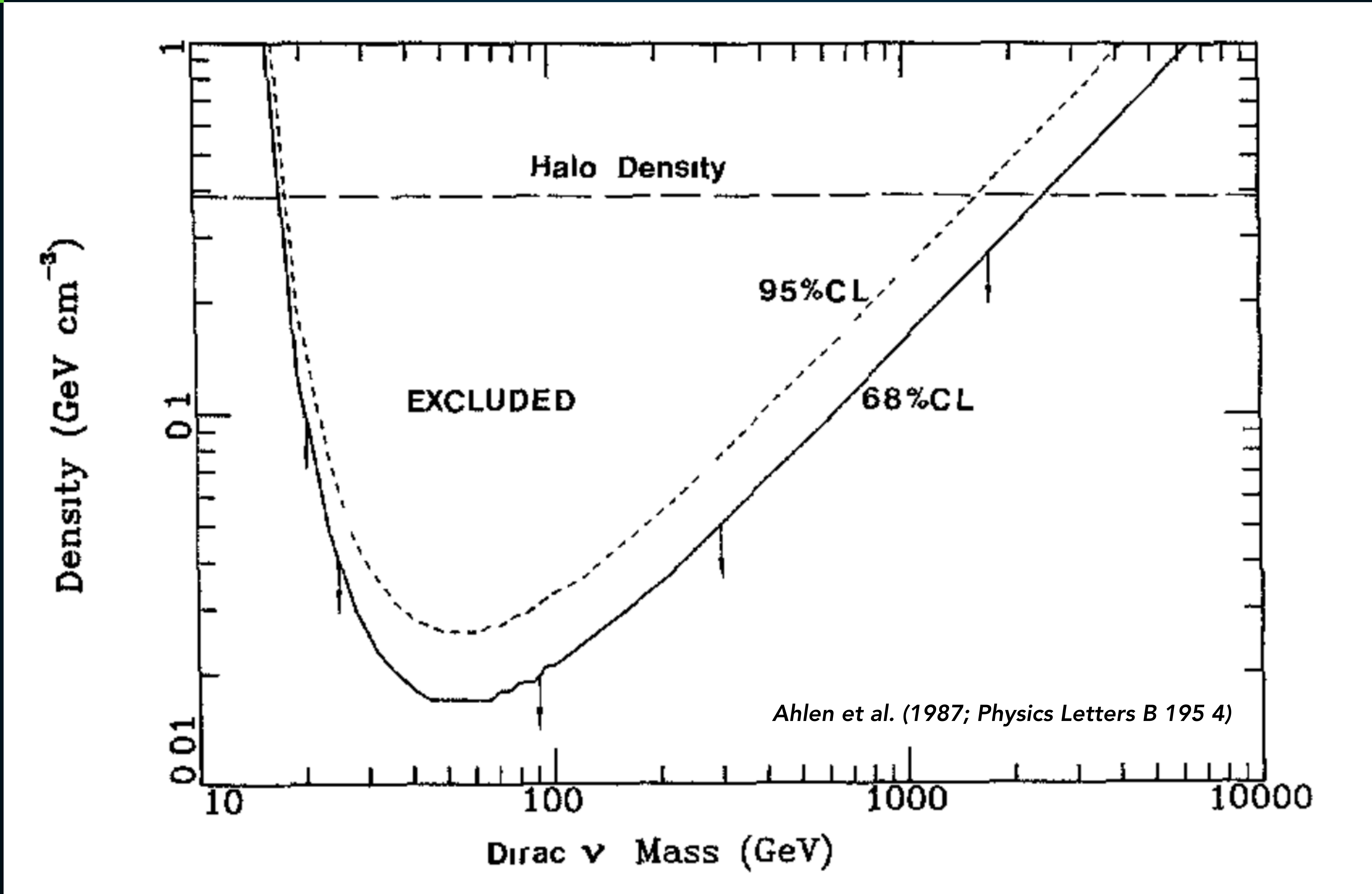
Tim Linden

Thermal WIMP Dark Matter on the Brink

The Ohio State University
Center for Cosmology and Astroparticle Physics

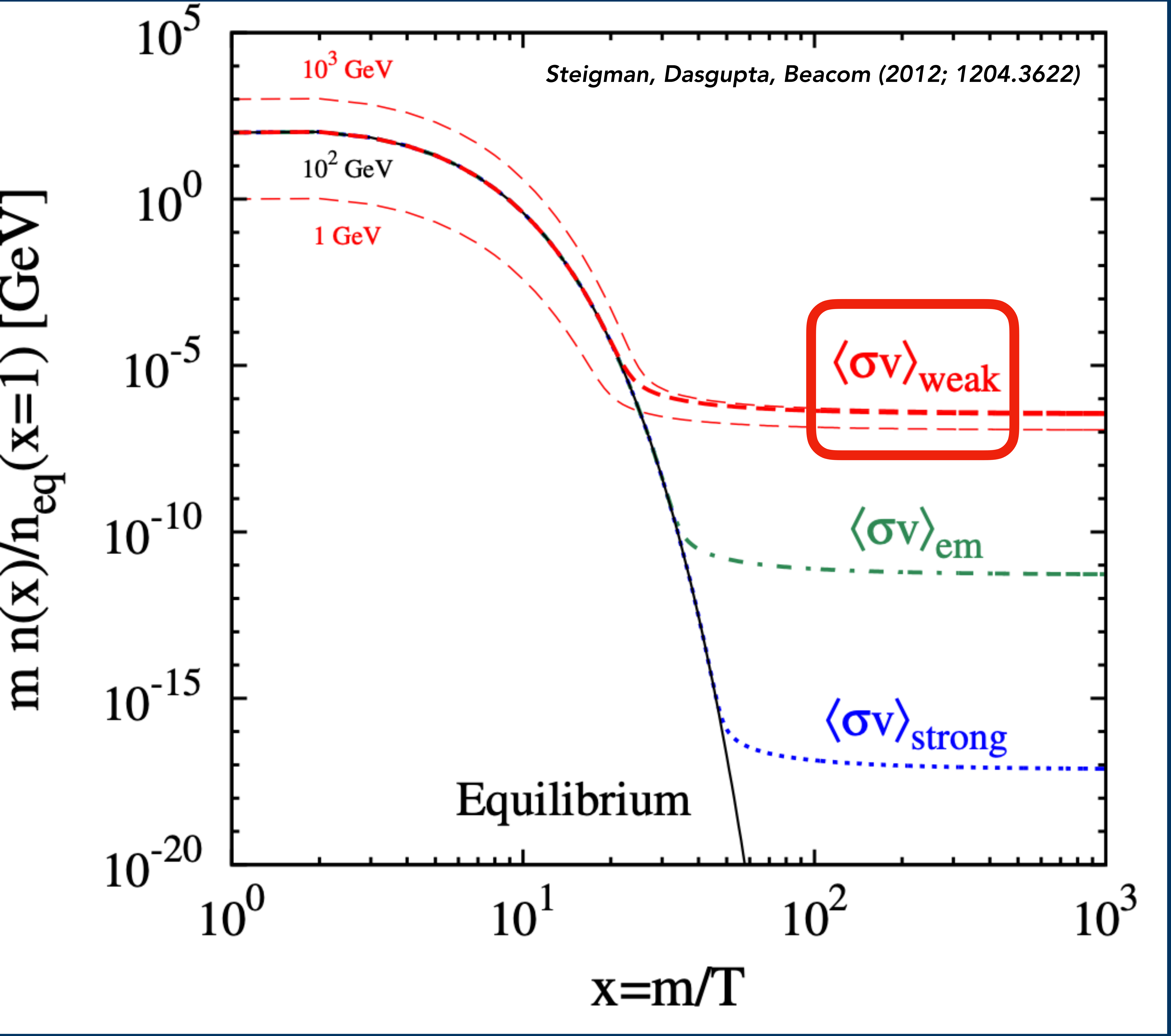
Can We Eliminate Classes of Dark Matter Models?

Yes!



Thermal Dark Matter

artist: Sarah Szabo

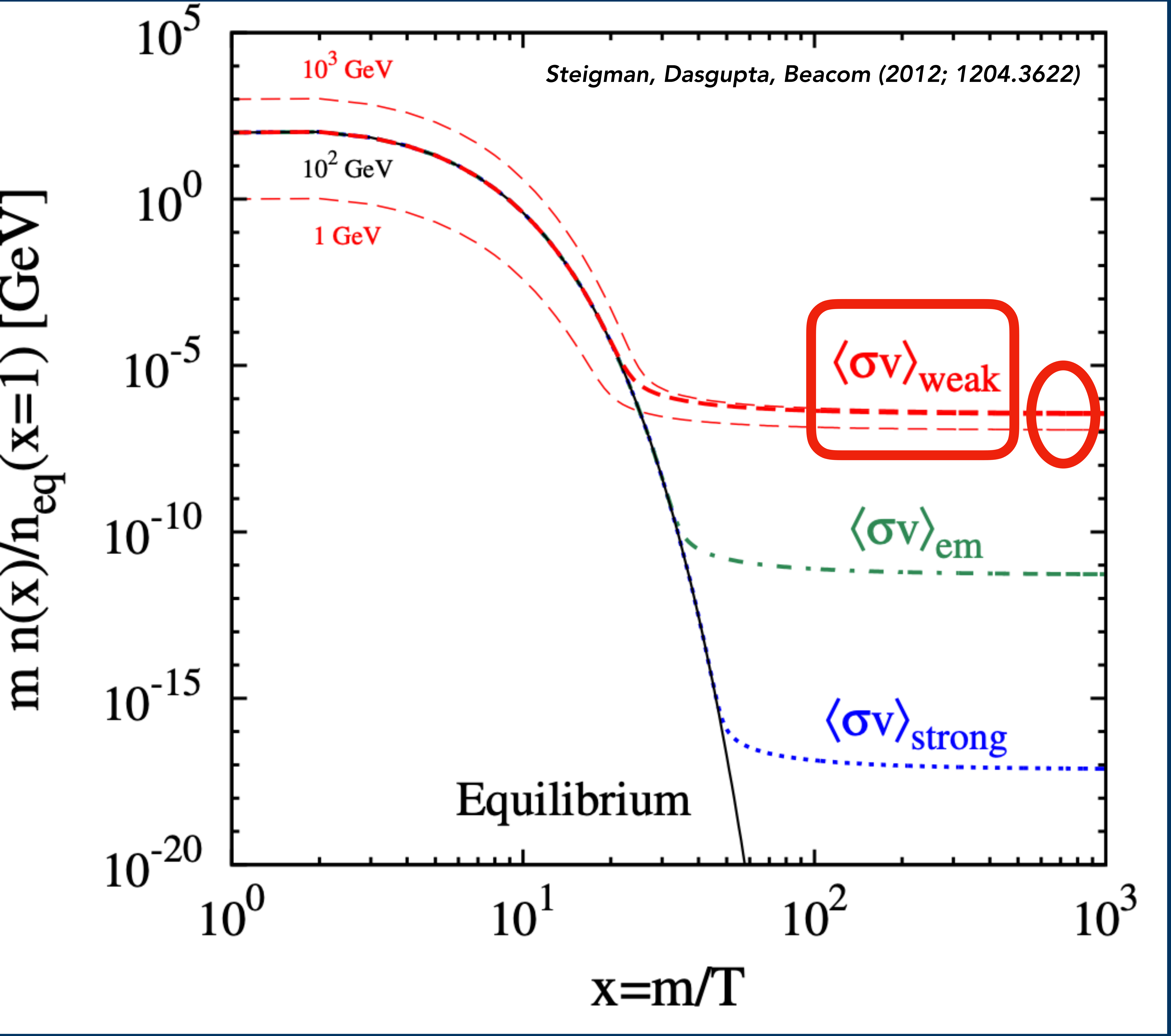


Thermal Dark Matter Density

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.

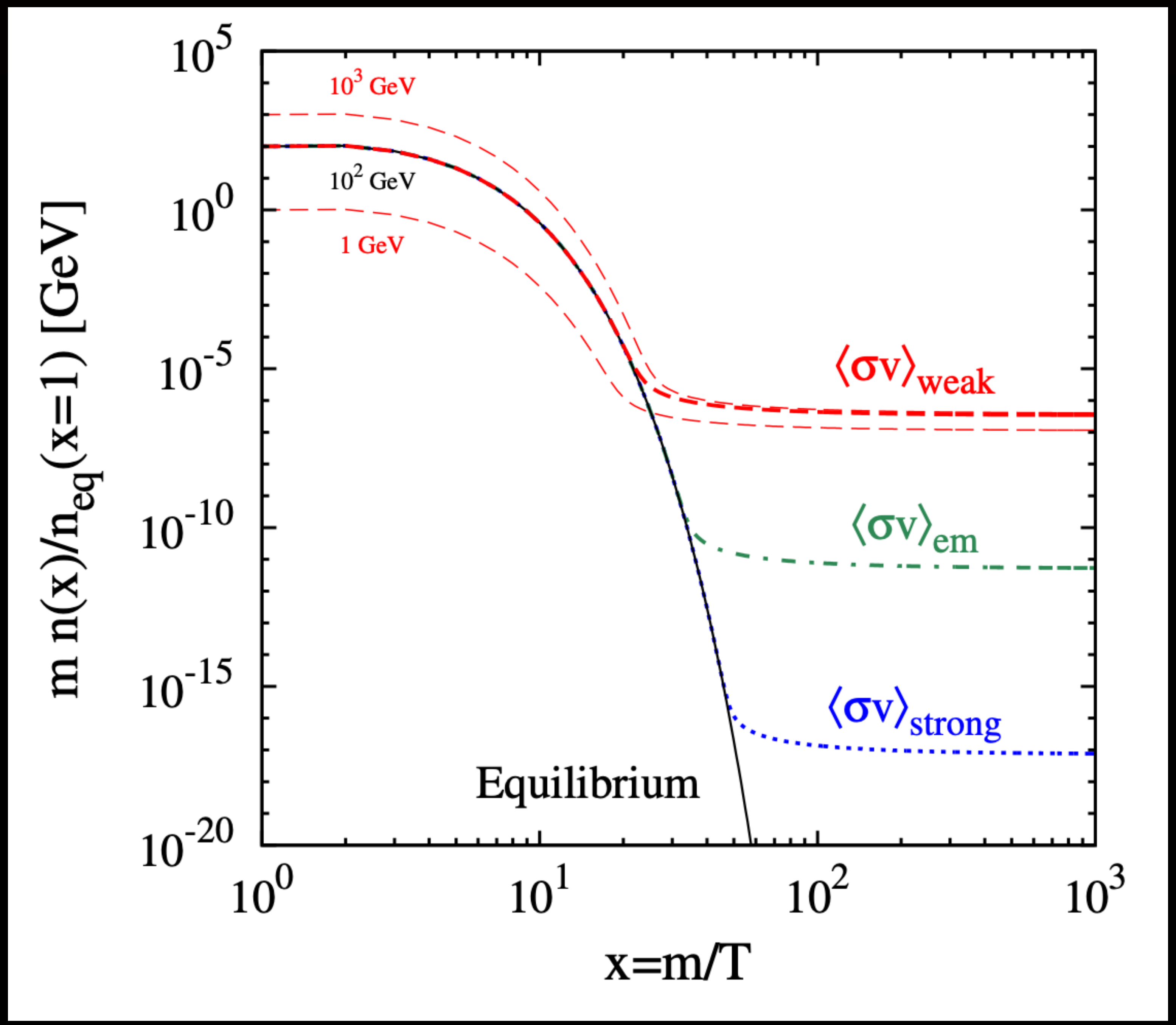
Almost independent of particle mass.

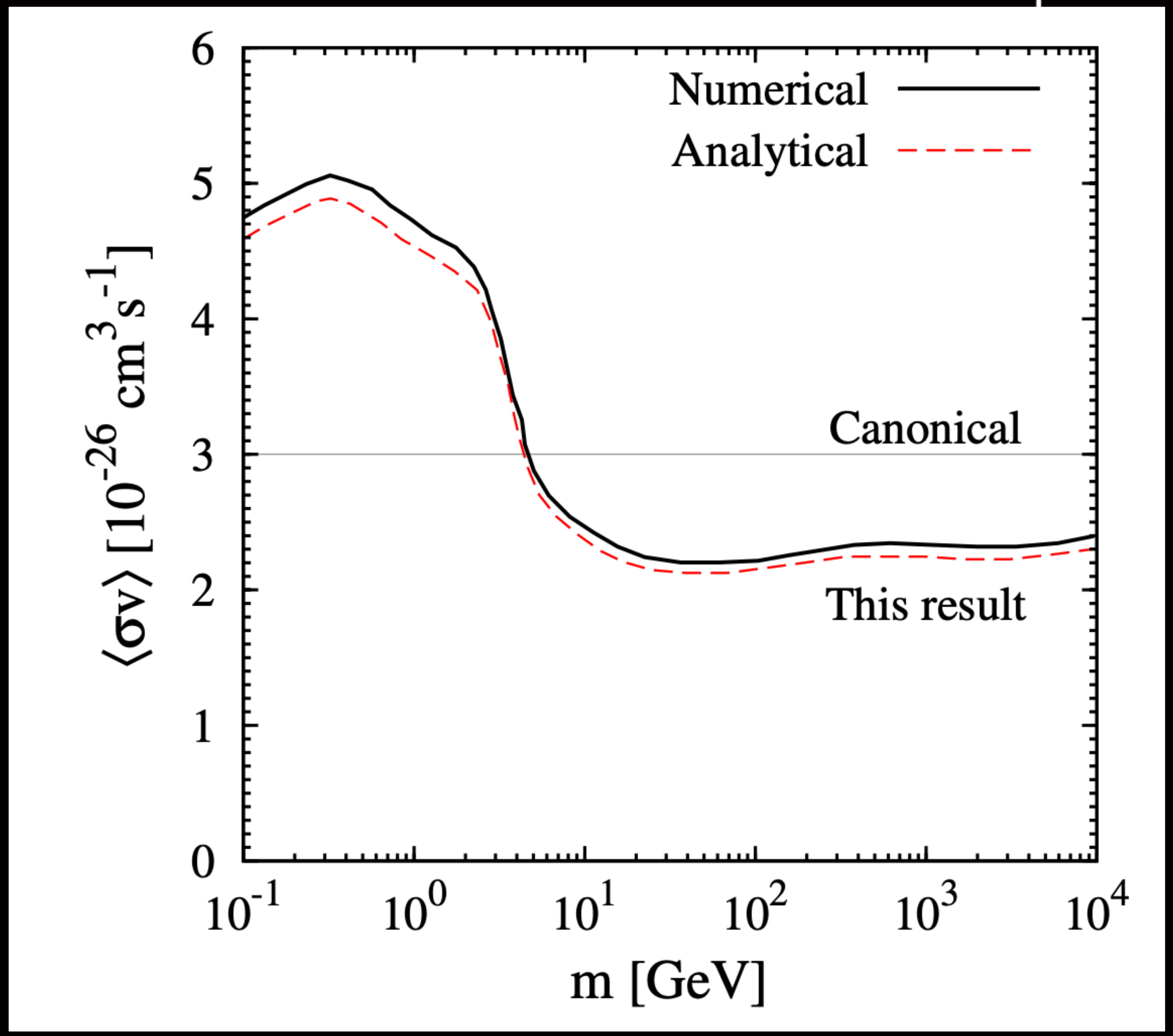
Weak-Interaction Produces the right density!

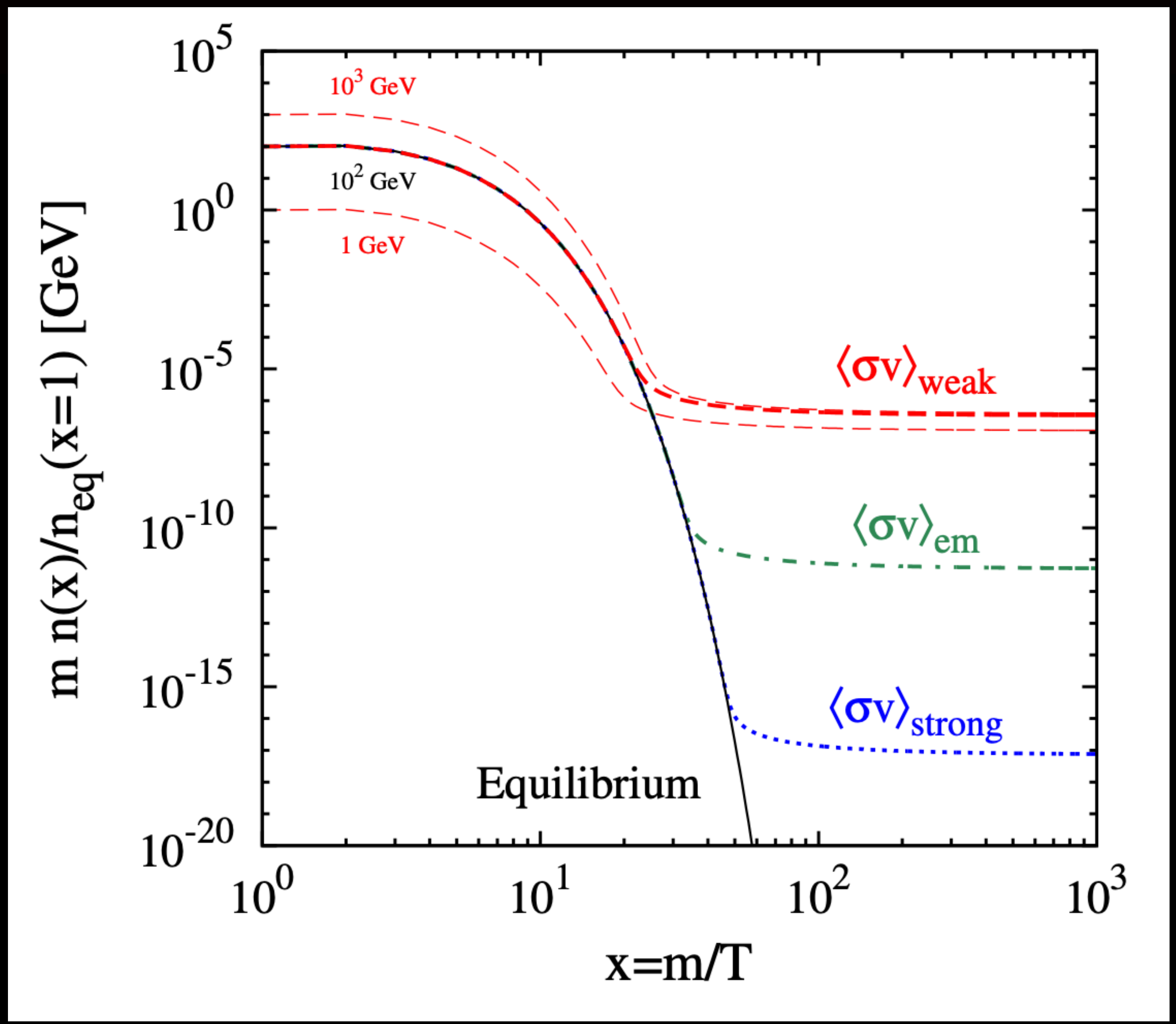
10 MeV - 100 TeV !

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
Reionization
Fully ionized
Neutralized
Fully ionized
1000
100
10
1
1+Redshift

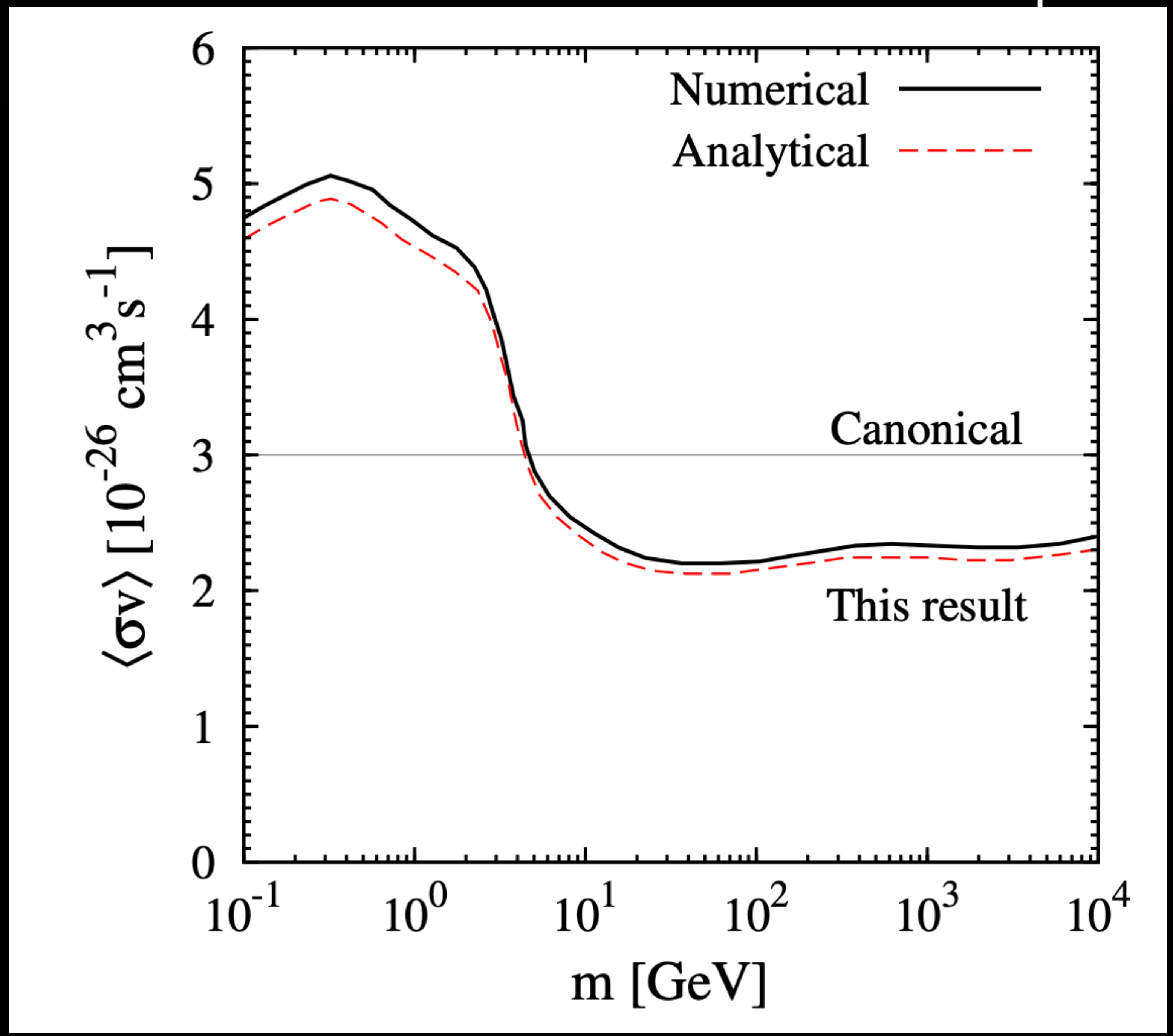

10^3 GeV
10^2 GeV
1 GeV
⟨σv⟩weak
⟨σv⟩em
⟨σv⟩strong
Equilibrium
m n(x)/neq(x=1) [GeV]
x=m/T

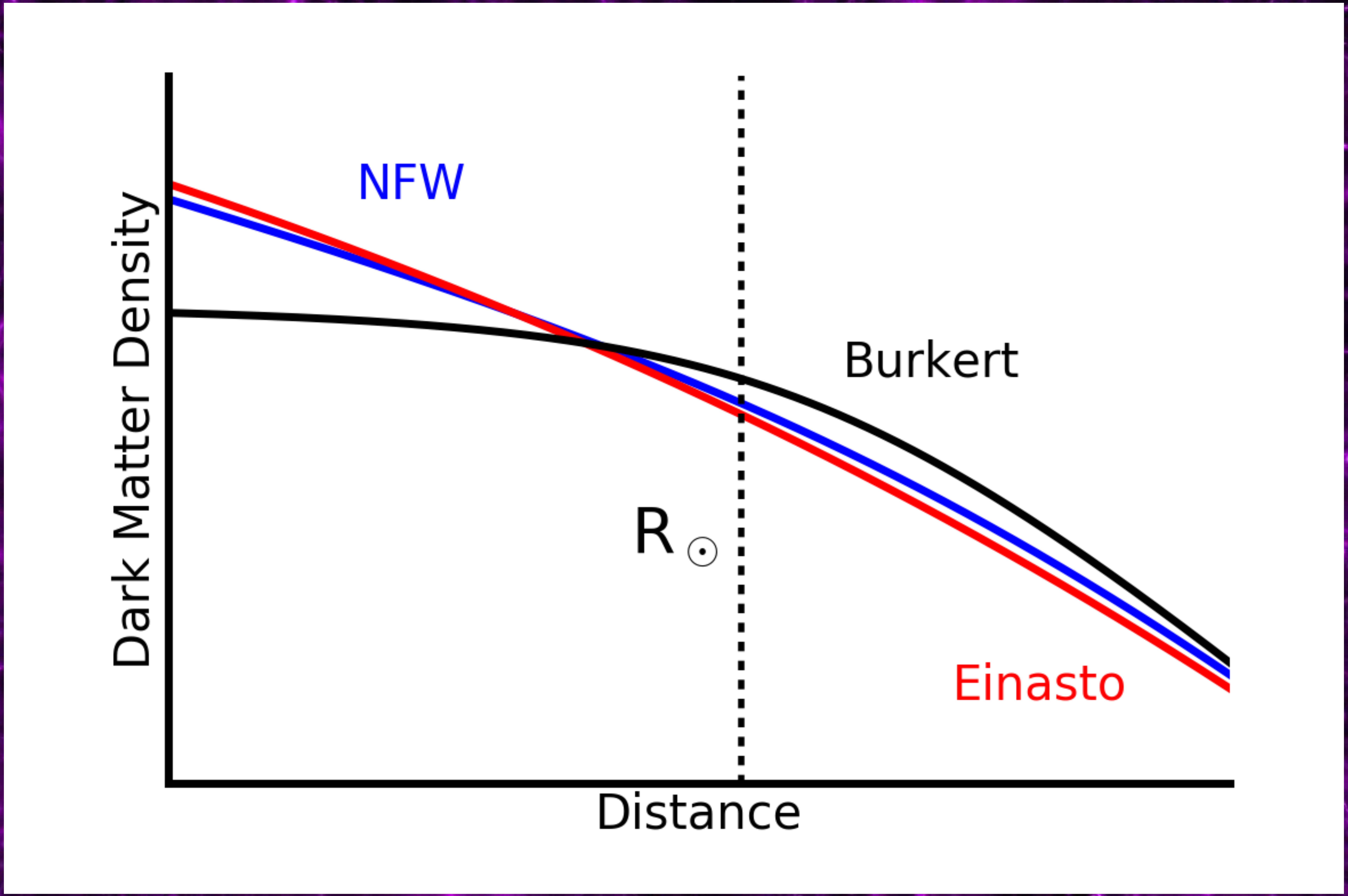

Numerical
Analytical
Canonical
This result
⟨σv⟩ [10^-26 cm^3 s^-1]
m [GeV]

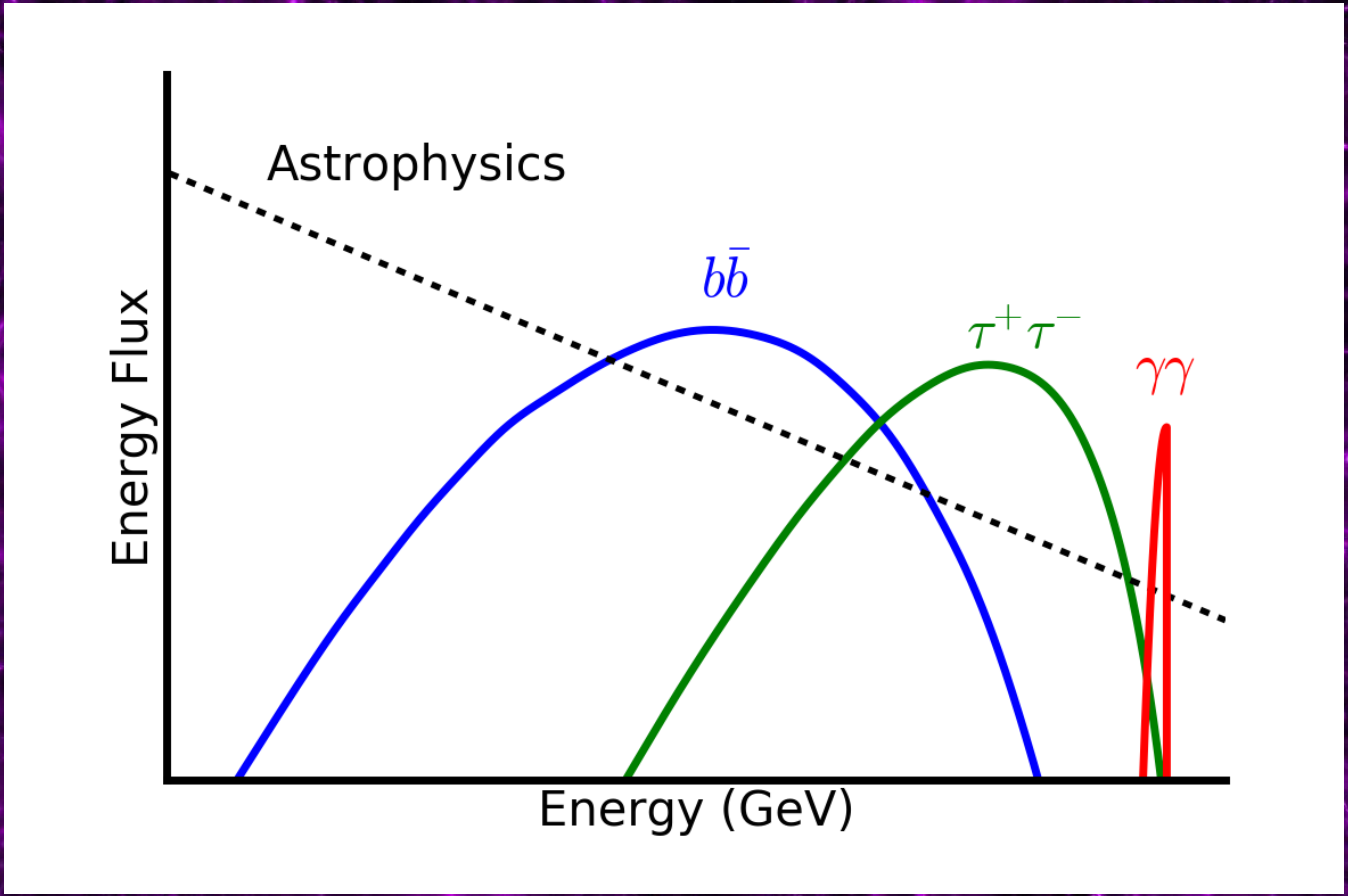


Philosophy:

Constrain the simplest model first




NFW
Burkert
Einasto
$R_\odot$
Dark Matter Density
Distance


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

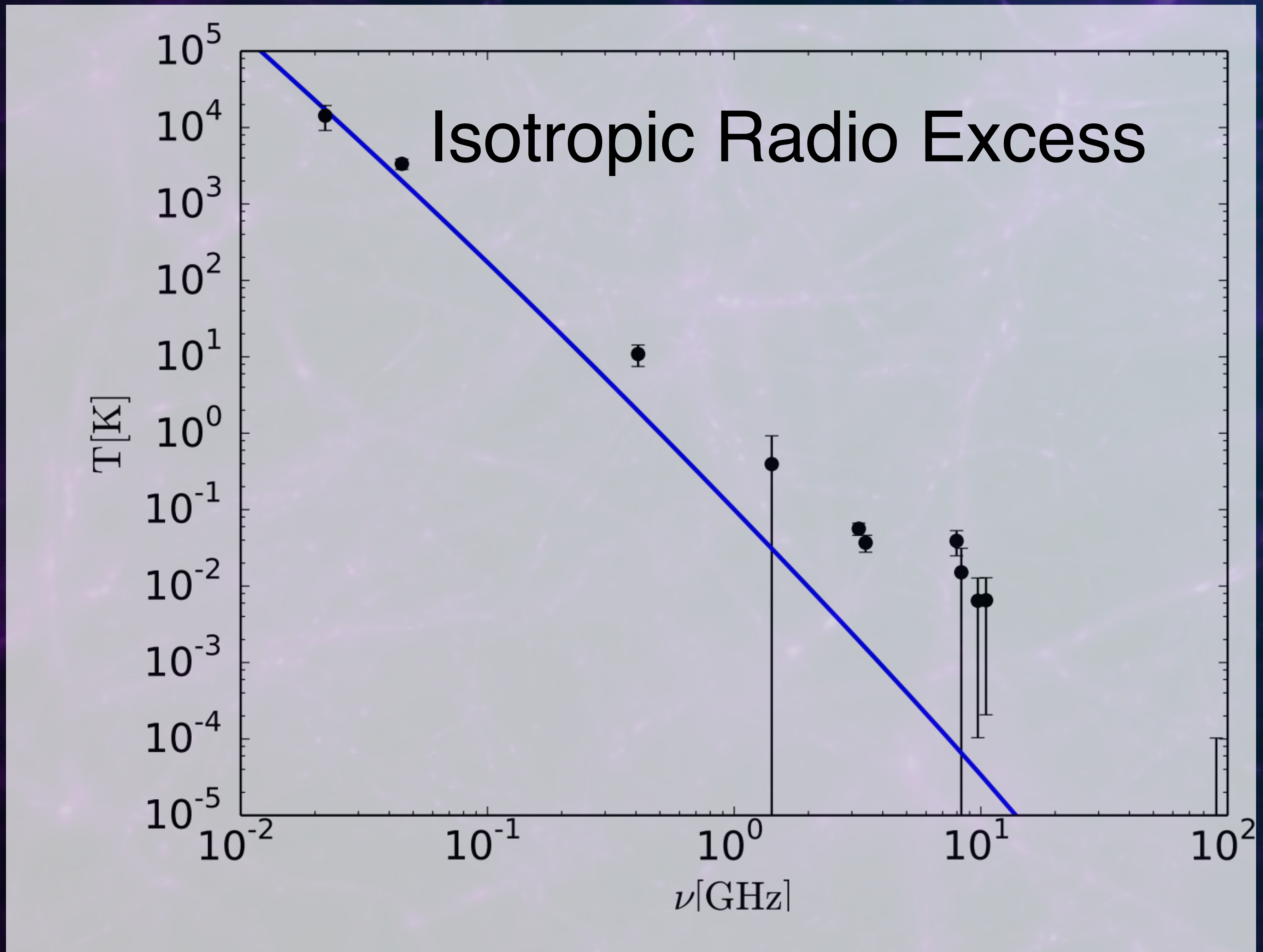

SPL

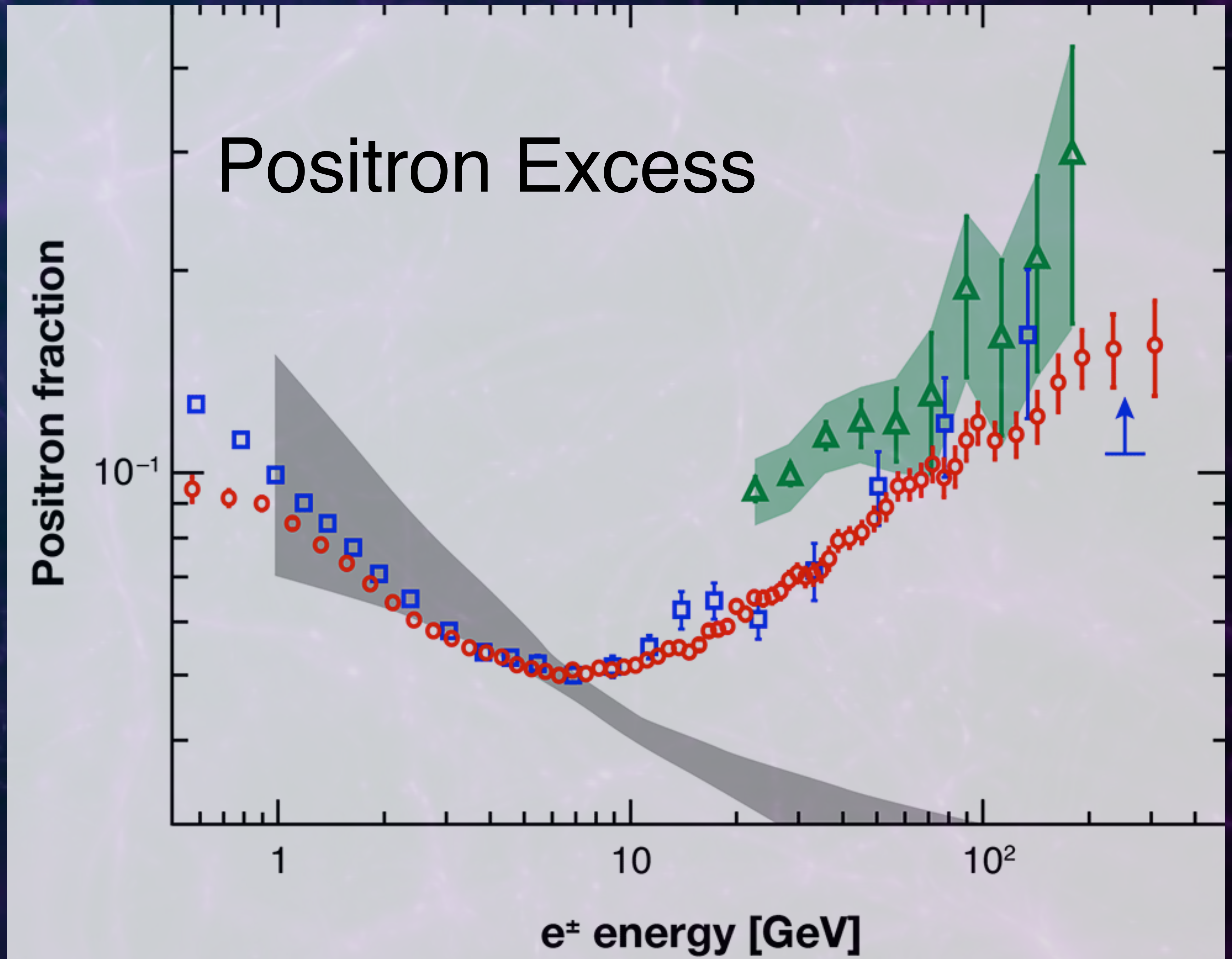

SPL
Gamma Rays


Cosmic Rays
Gamma Rays

Cosmic Rays
Gamma Rays
Radio


Galactic Center Excess


Isotropic Radio Excess
T[K]
ν[GHz]
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-2}
10^{-1}
10^0
10^1
10^2


Positron Excess
Positron fraction
10^{-1}
1
10
10^2
e± energy [GeV]

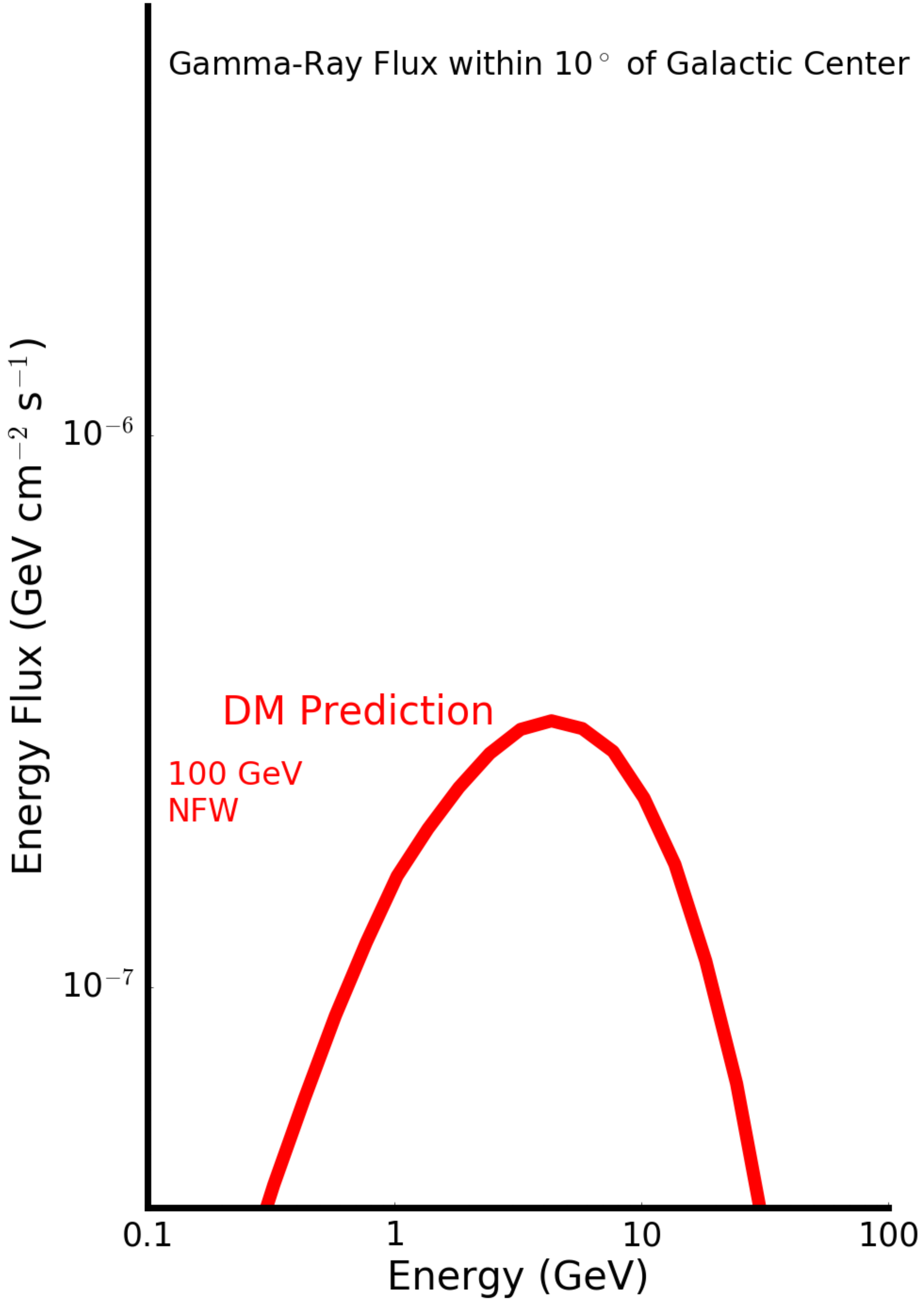
Thermal WIMPs and the Story of Tantalus

NFW Profile (Mass of Milky Way)

Thermal Cross-Section (Early Universe)

Dark Matter Mass (?)

Annihilation Final State (?)



Thermal WIMPs and the Story of Tantalus

NFW Profile (Mass of Milky Way)

Thermal Cross-Section (Early Universe)

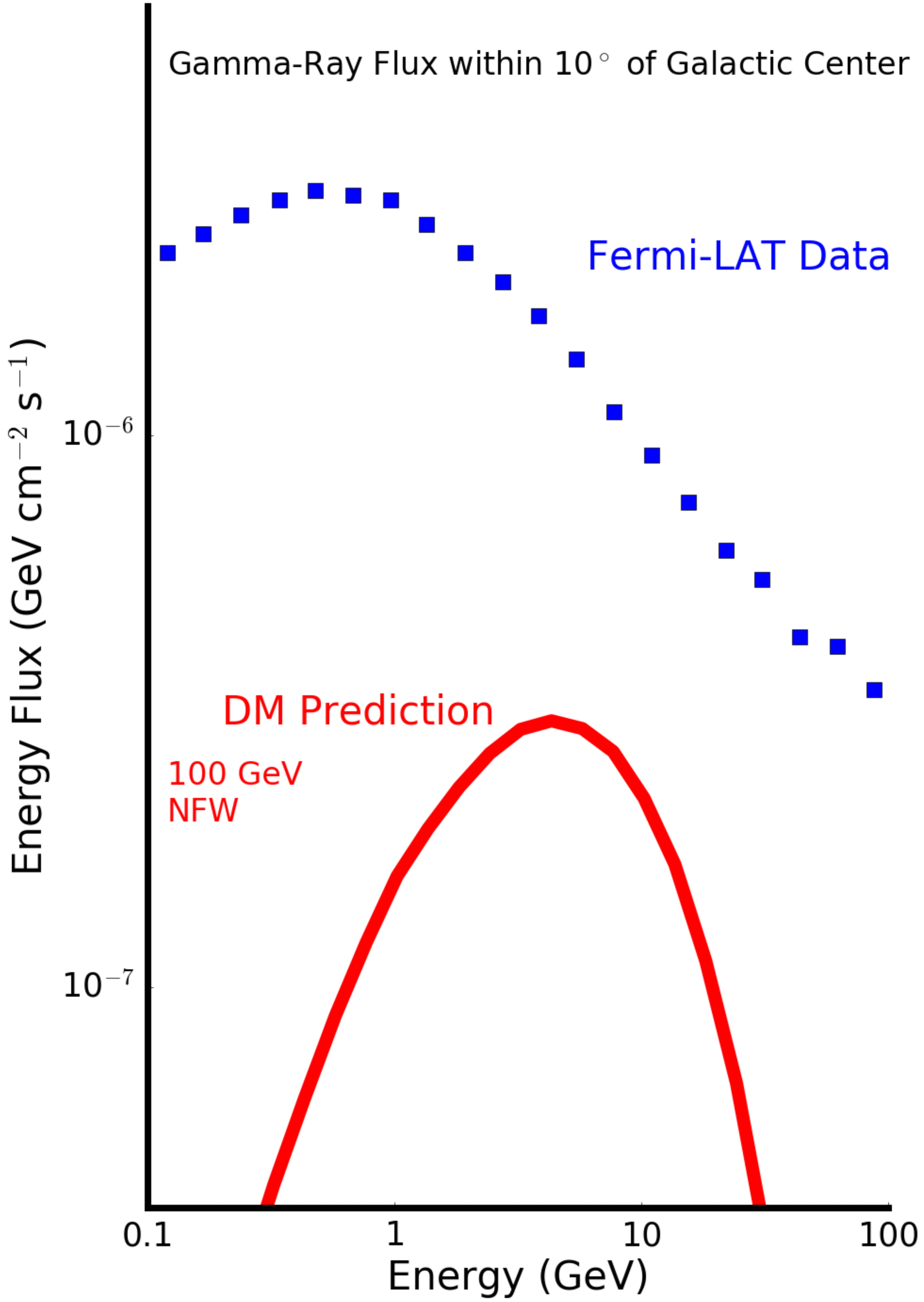
Dark Matter Mass (?)

Annihilation Final State (?)

Milky Way Star-Formation Rate (Galactic Dynamics)

Diffusion Constant in Galactic Center (Hydrodyanmics)

Activity of Supermassive Blackhole (?)



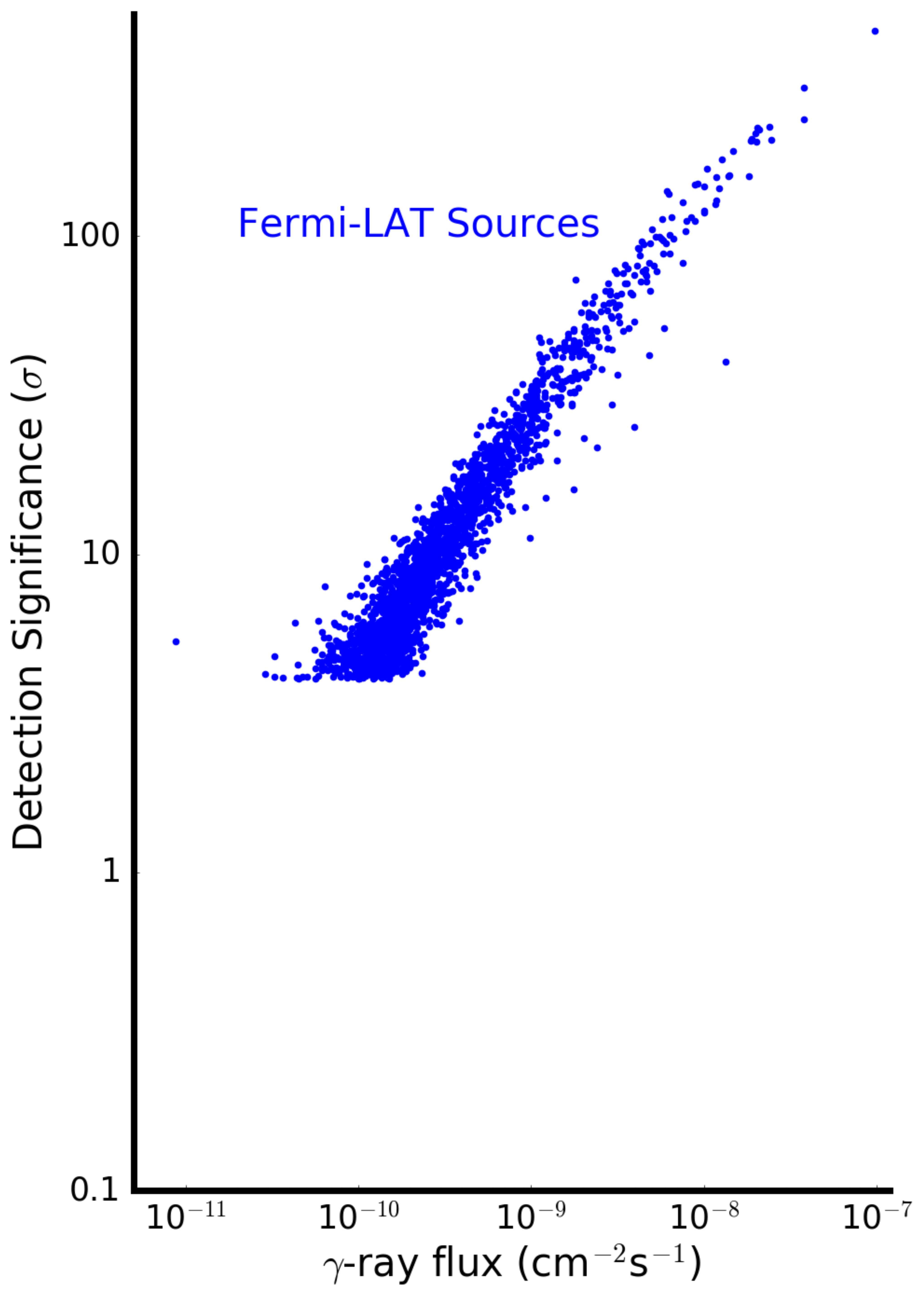
Thermal WIMPs and the Story of Tantalus

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)

Blazar Acceleration Mechanisms (Leptonic? Hadronic?)

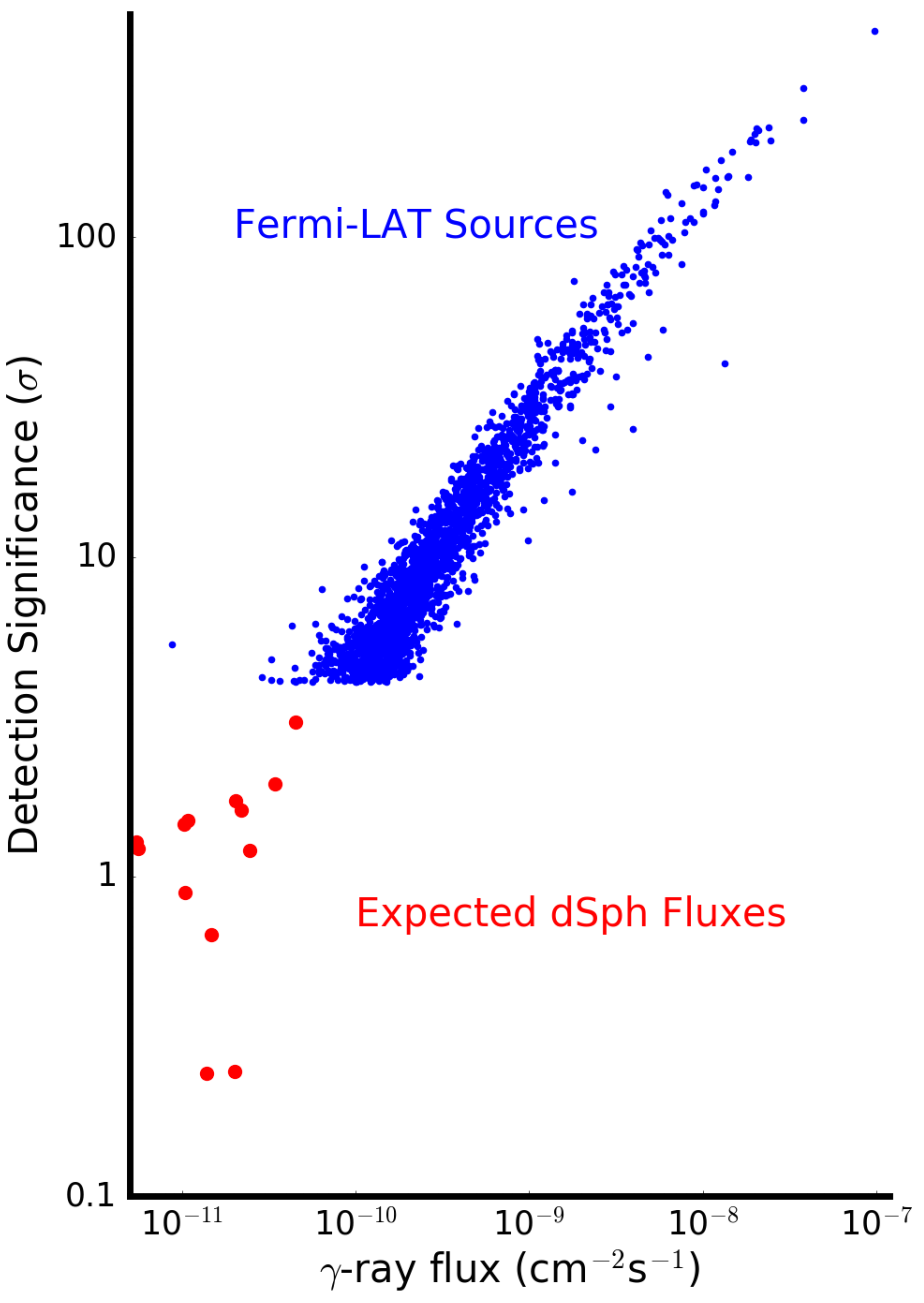
Radio Galaxy Emission Models

Star-Formation Rates in Starburst Galaxies

dSph Proximity

Substructure Models

Milky Way Merger History



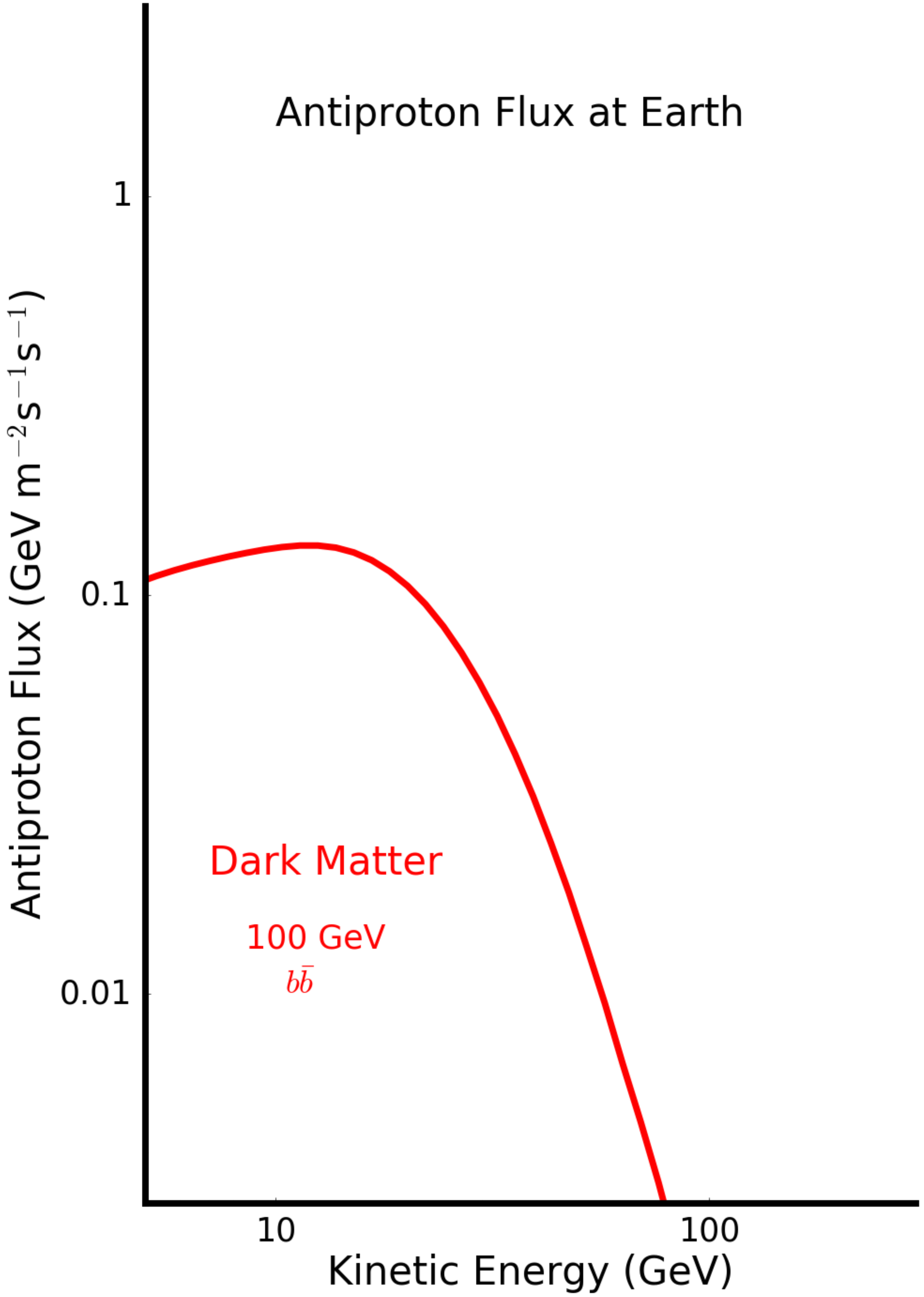
Thermal WIMPs and the Story of Tantalus

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

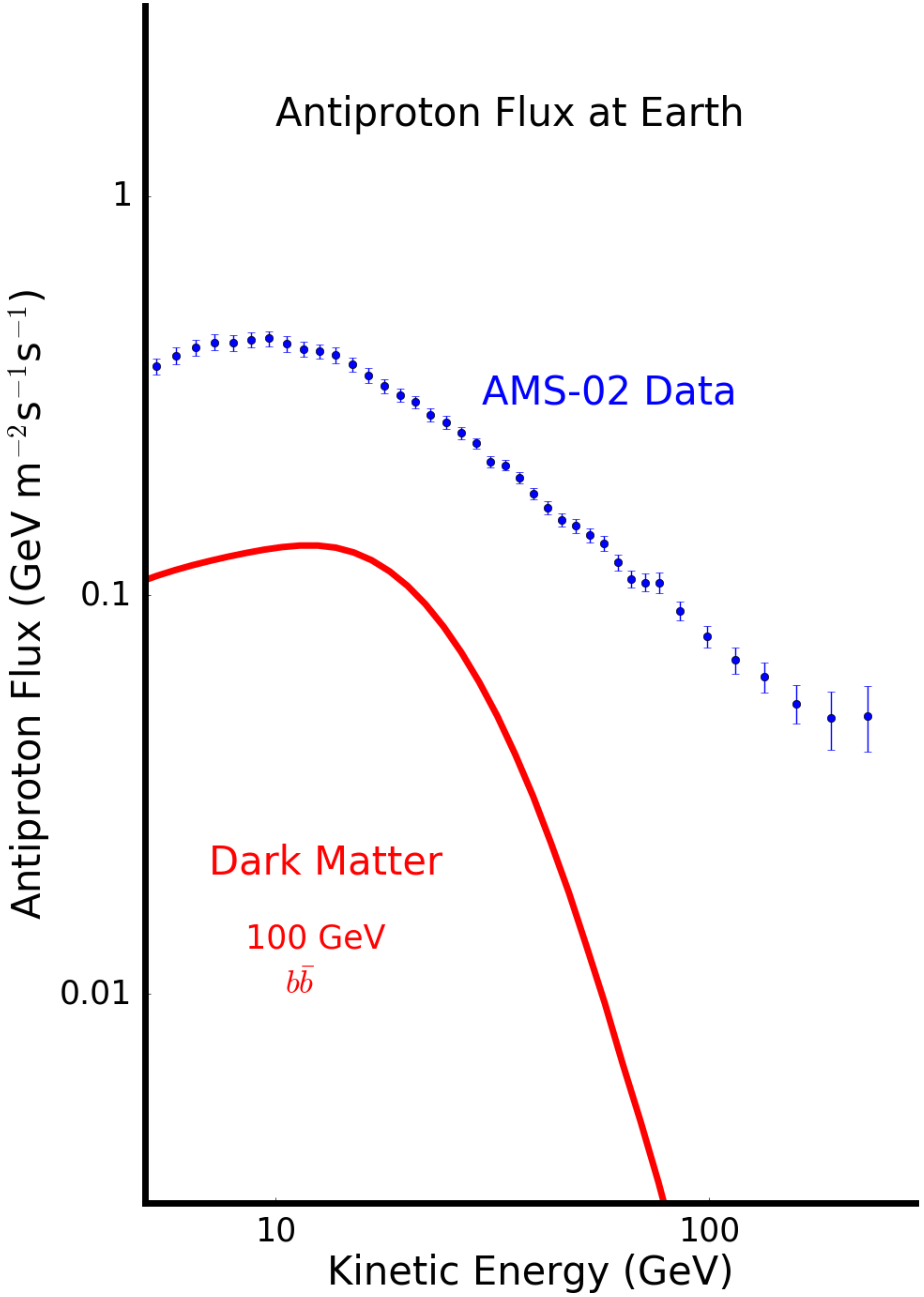
Thermal Cross-Section (Early Universe)

Hadronic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Local Gas Density

Local Supernova Rate



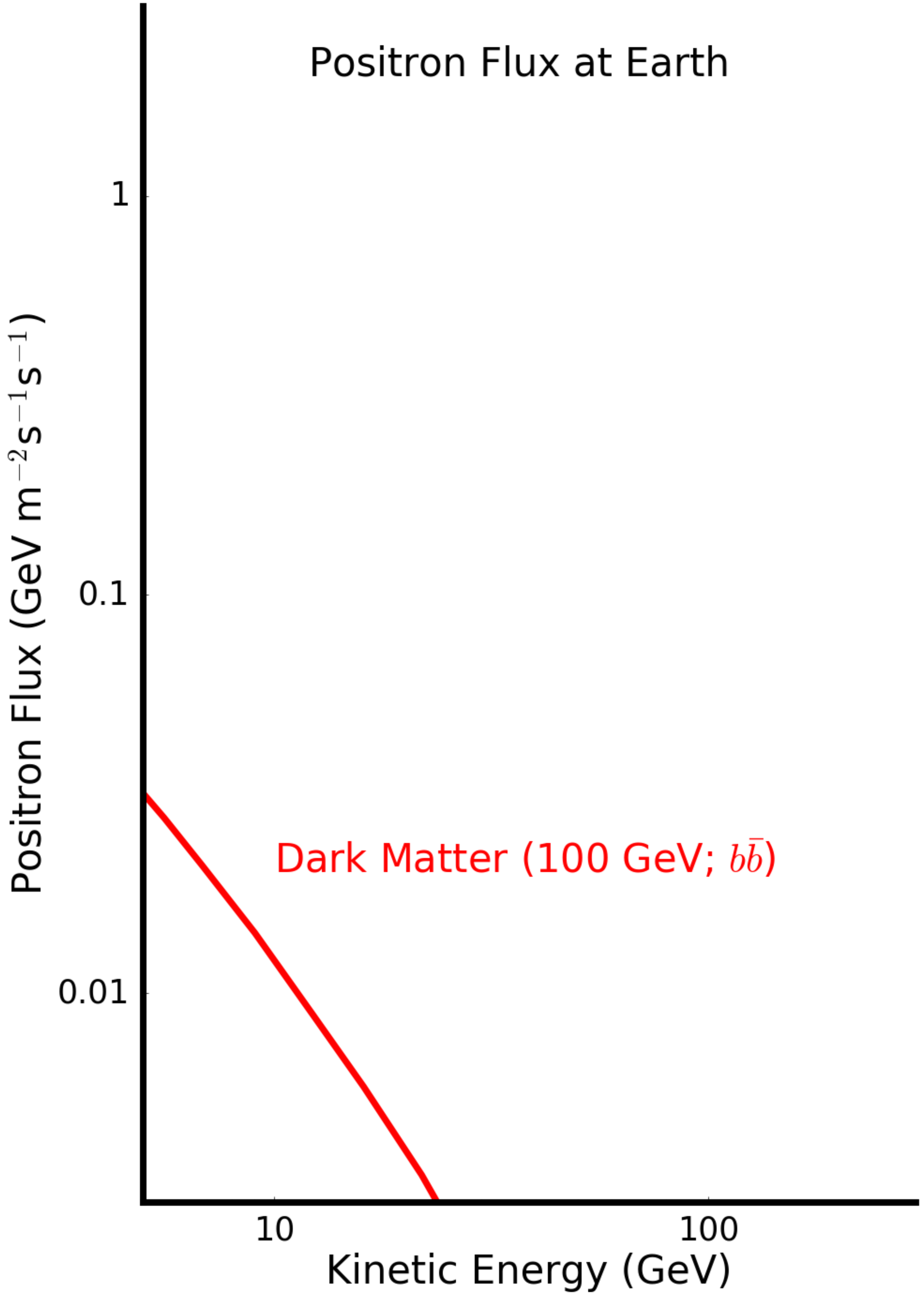
Thermal WIMPs and the Story of Tantalus

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

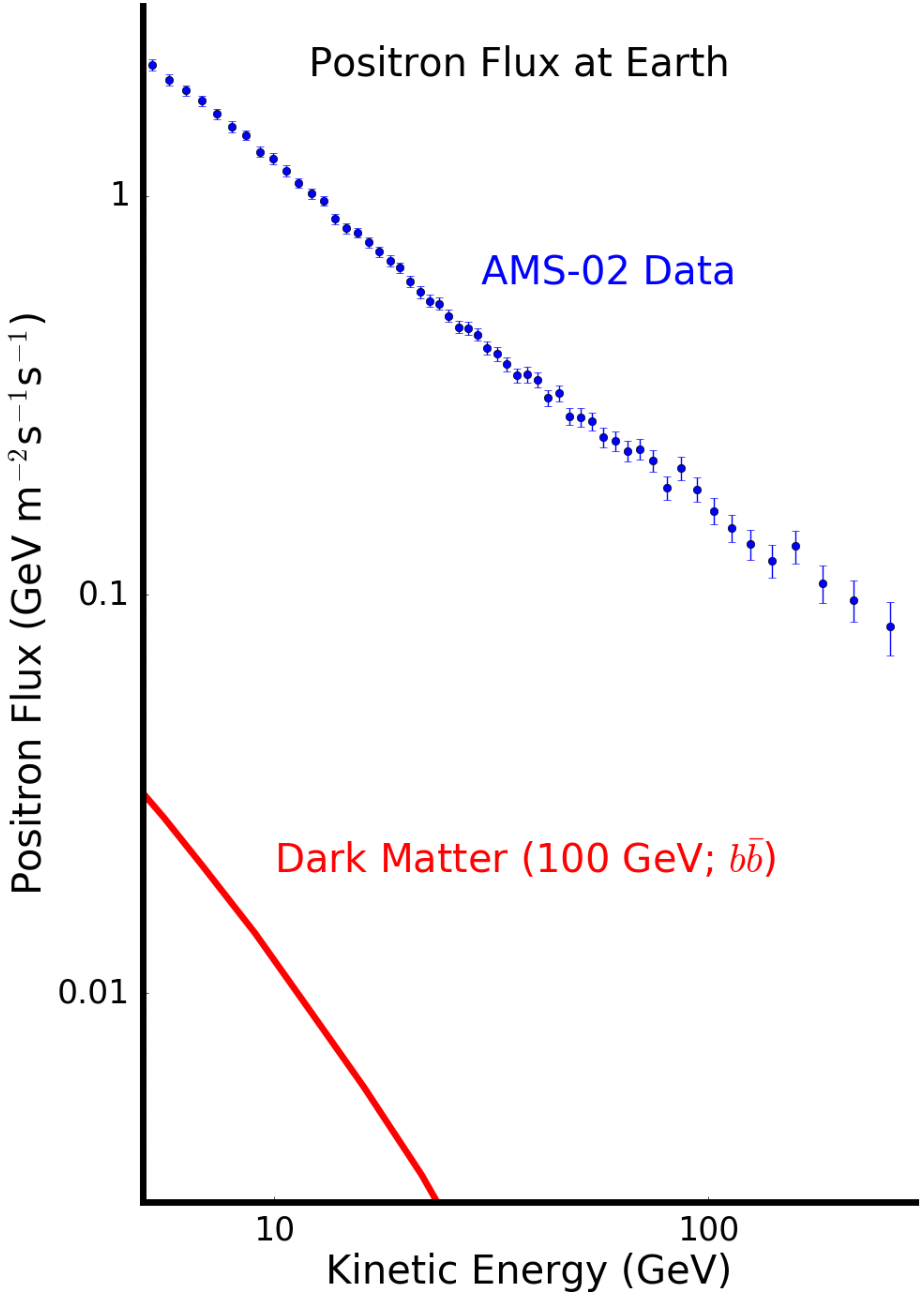
Thermal Cross-Section (Early Universe)

Leptonic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Pulsar Birth Rate

e^+e^- Acceleration Efficiency in Pulsar Magnetospheres



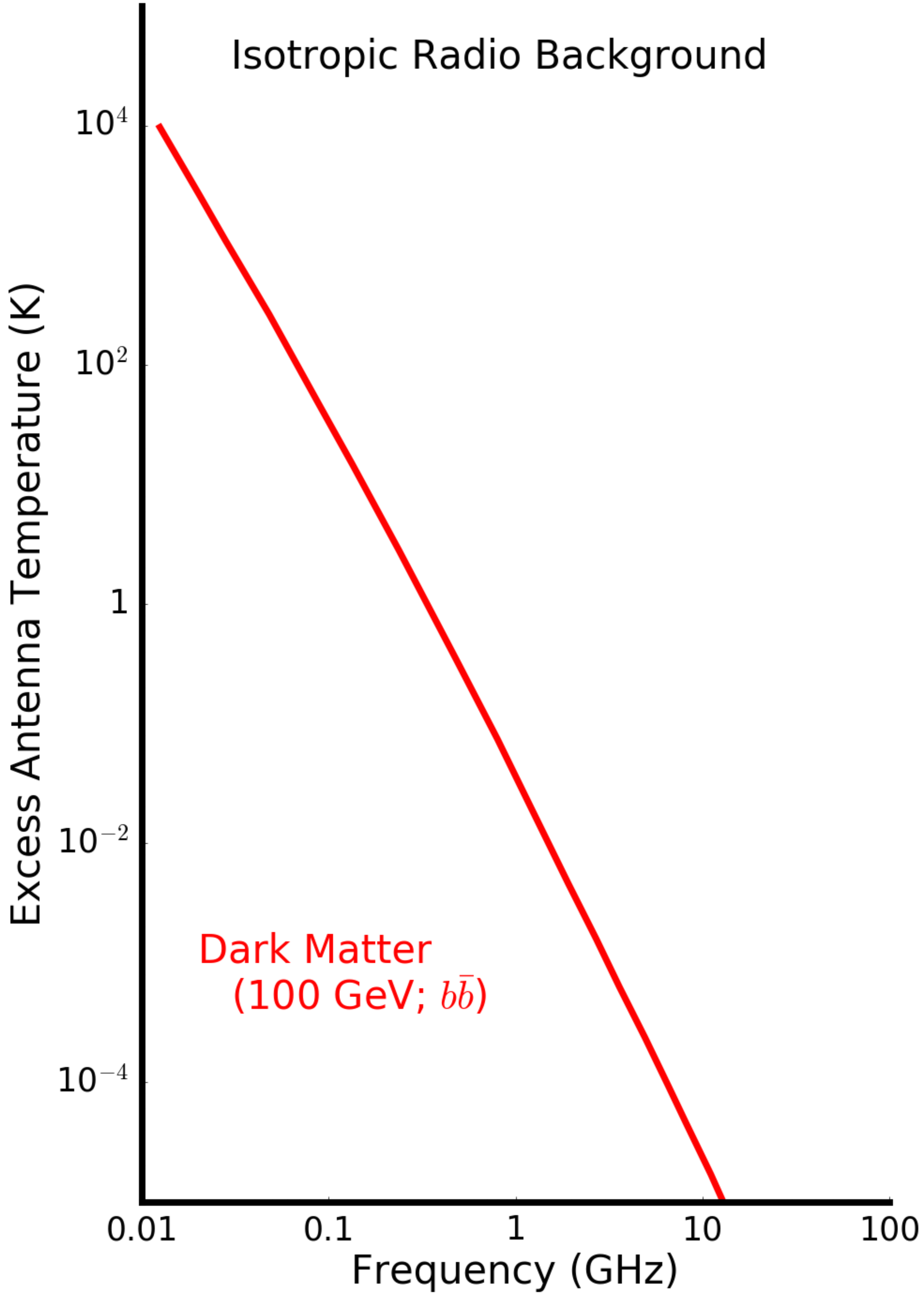
Thermal WIMPs and the Story of Tantalus

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)

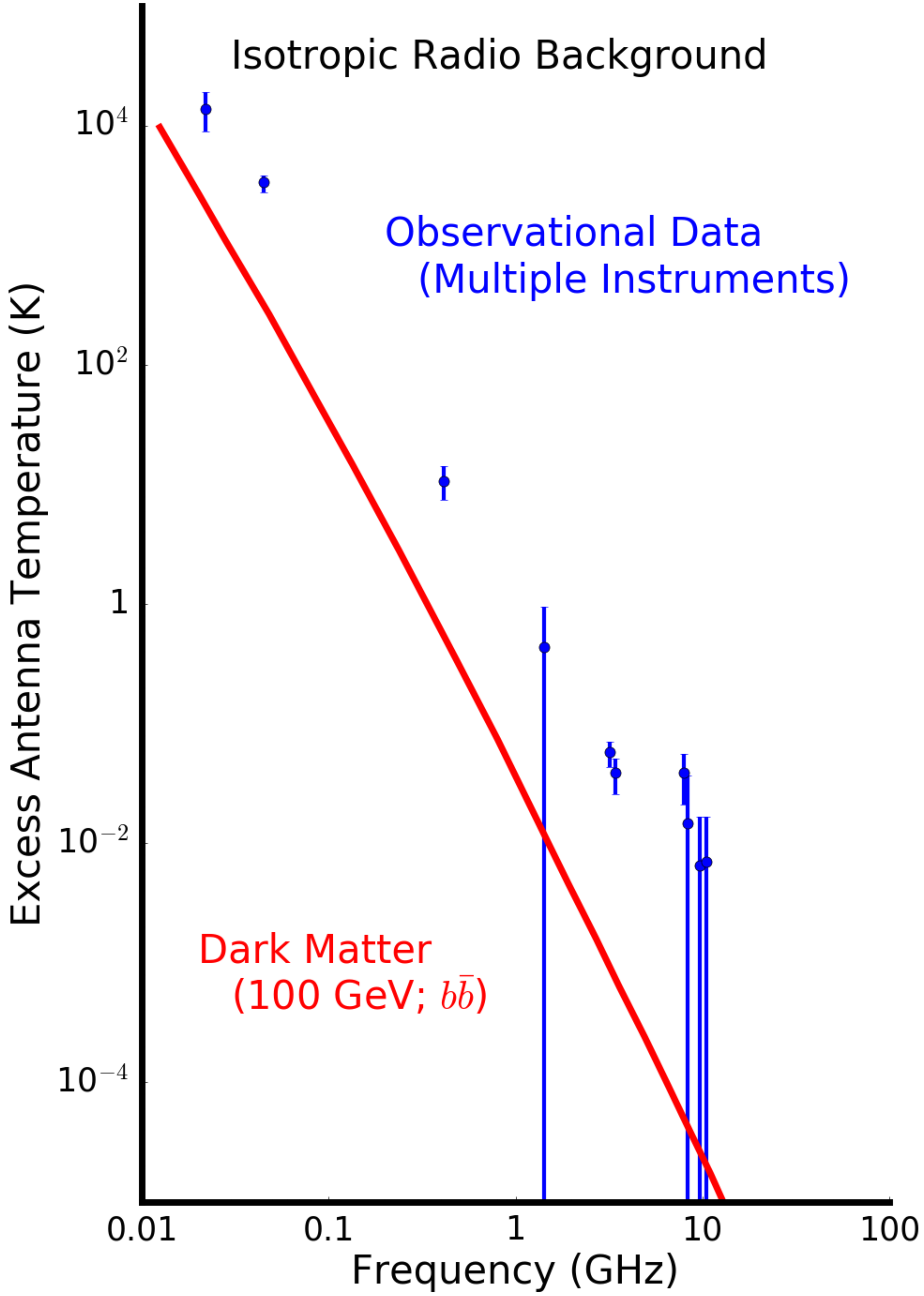
e+e- Energy Fraction in Dark Matter Annihilation

Intergalactic Magnetic Fields

Radio Luminosity in Starbursts and AGN

e+e- Reacceleration in Cluster Mergers

Redshift Dependence of Signal vs. CMB



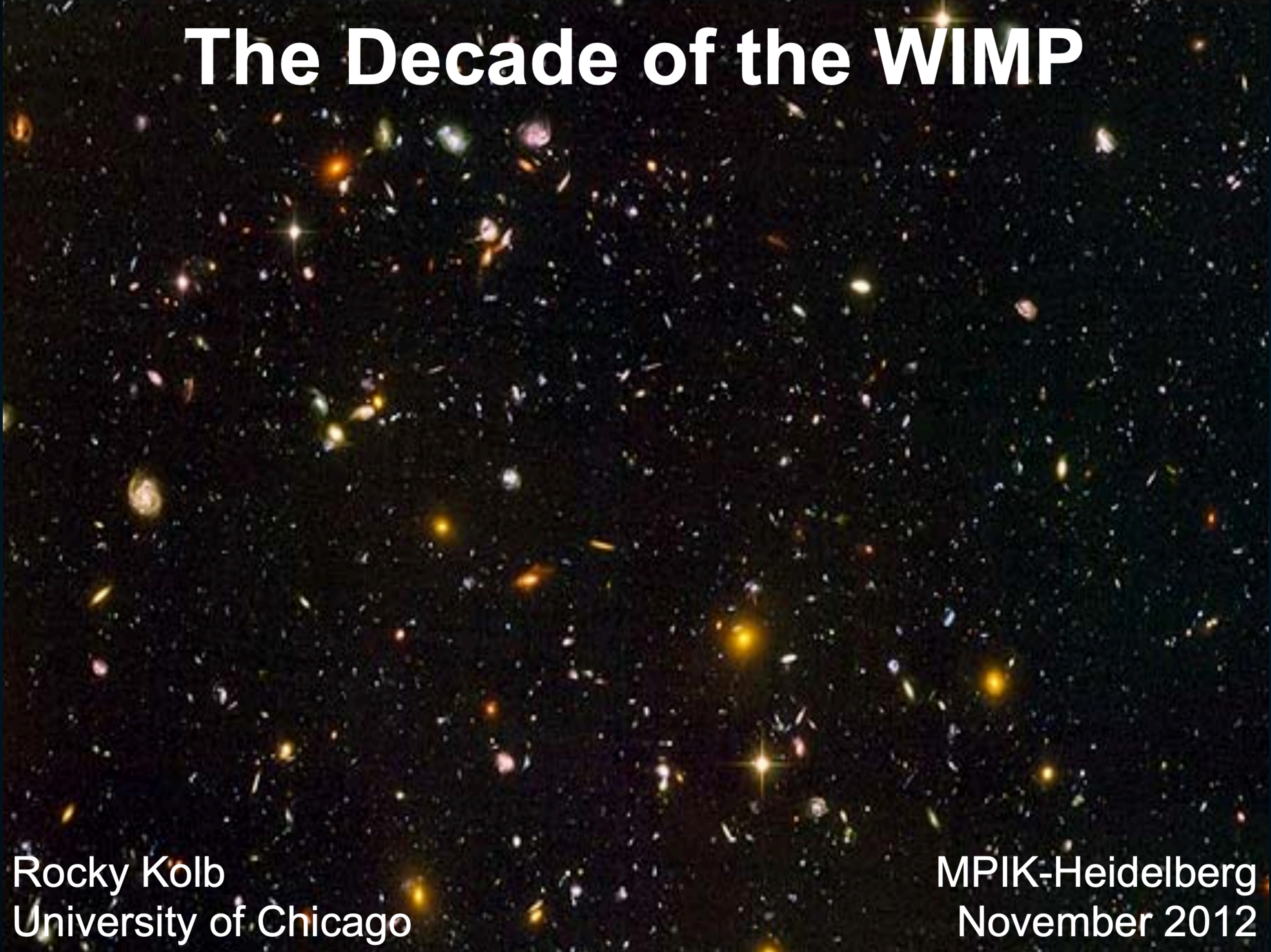

Small Dark Matter Signal
Small Astrophysical Background
Large Dark Matter Signal
Small Astrophysical Background
Small Dark Matter Signal
Large Astrophysical Background
Large Dark Matter Signal
Large Astrophysical Background
Specificity (DM Flux / Astrophysics Flux)
Fraction of Dark Matter Flux

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

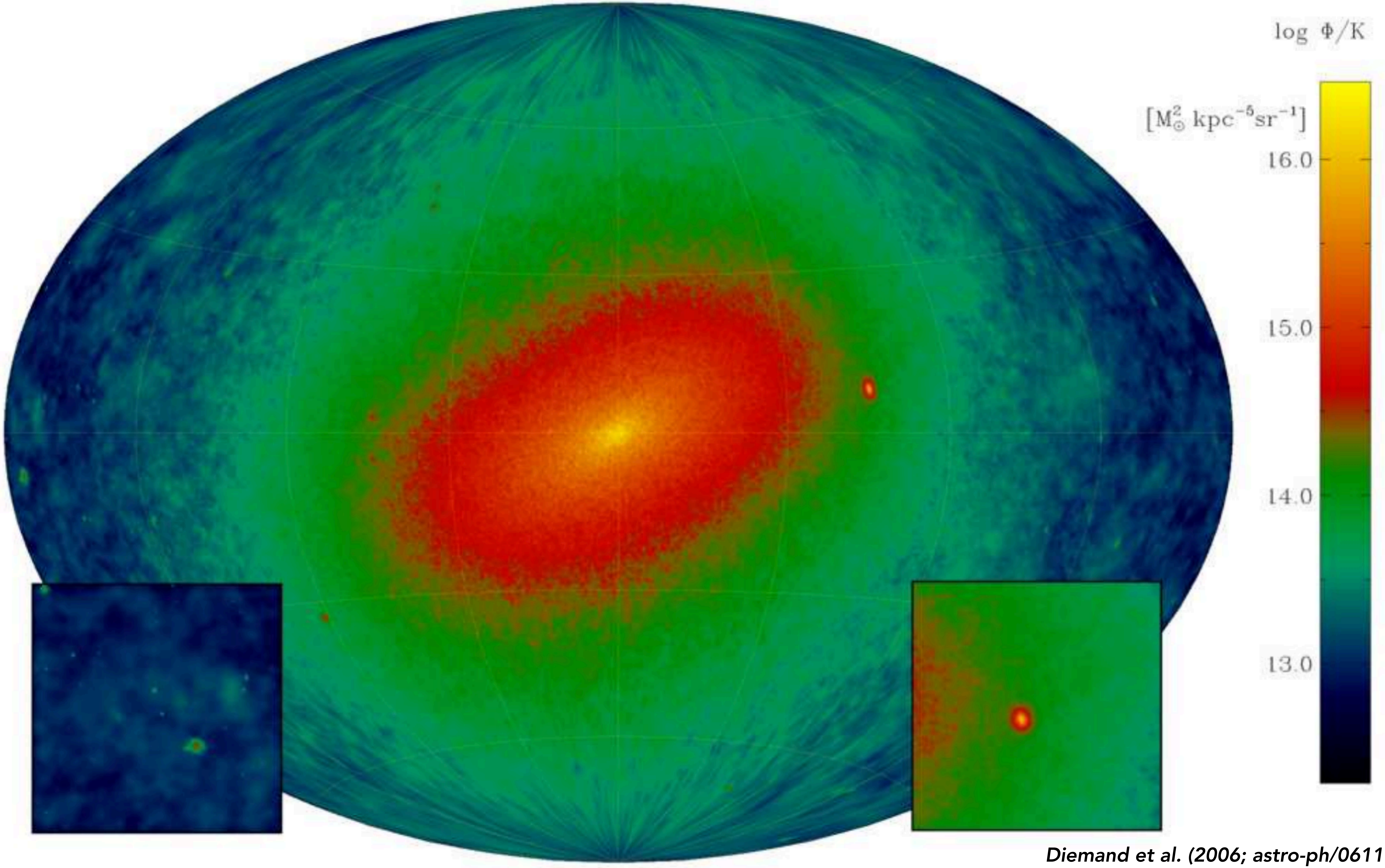
The Decade of the WIMP



Rocky Kolb
University of Chicago

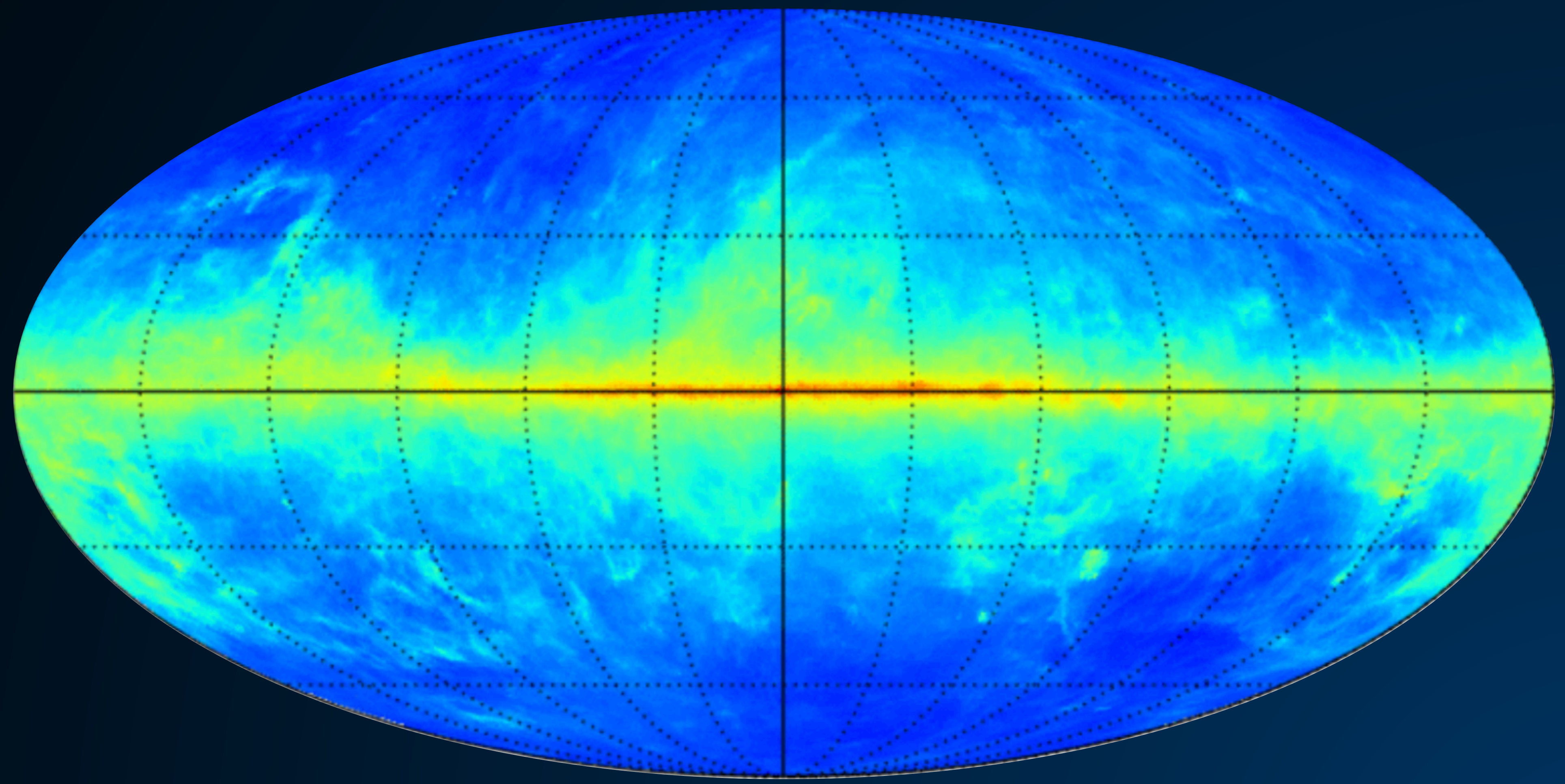
MPIK-Heidelberg
November 2012

The Galactic Center Excess

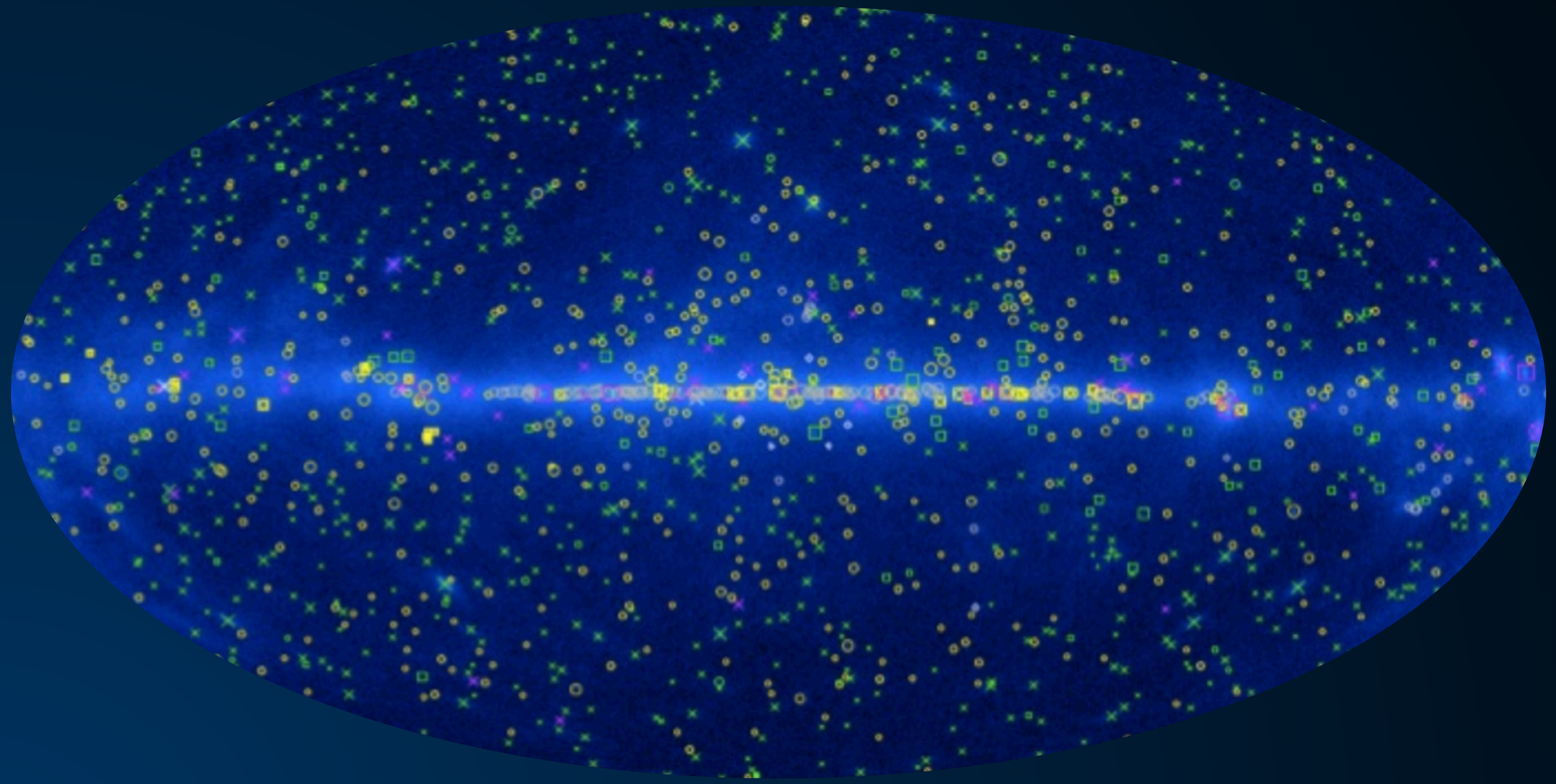


Diemand et al. (2006; astro-ph/0611370)

The Galactic Center - Techniques

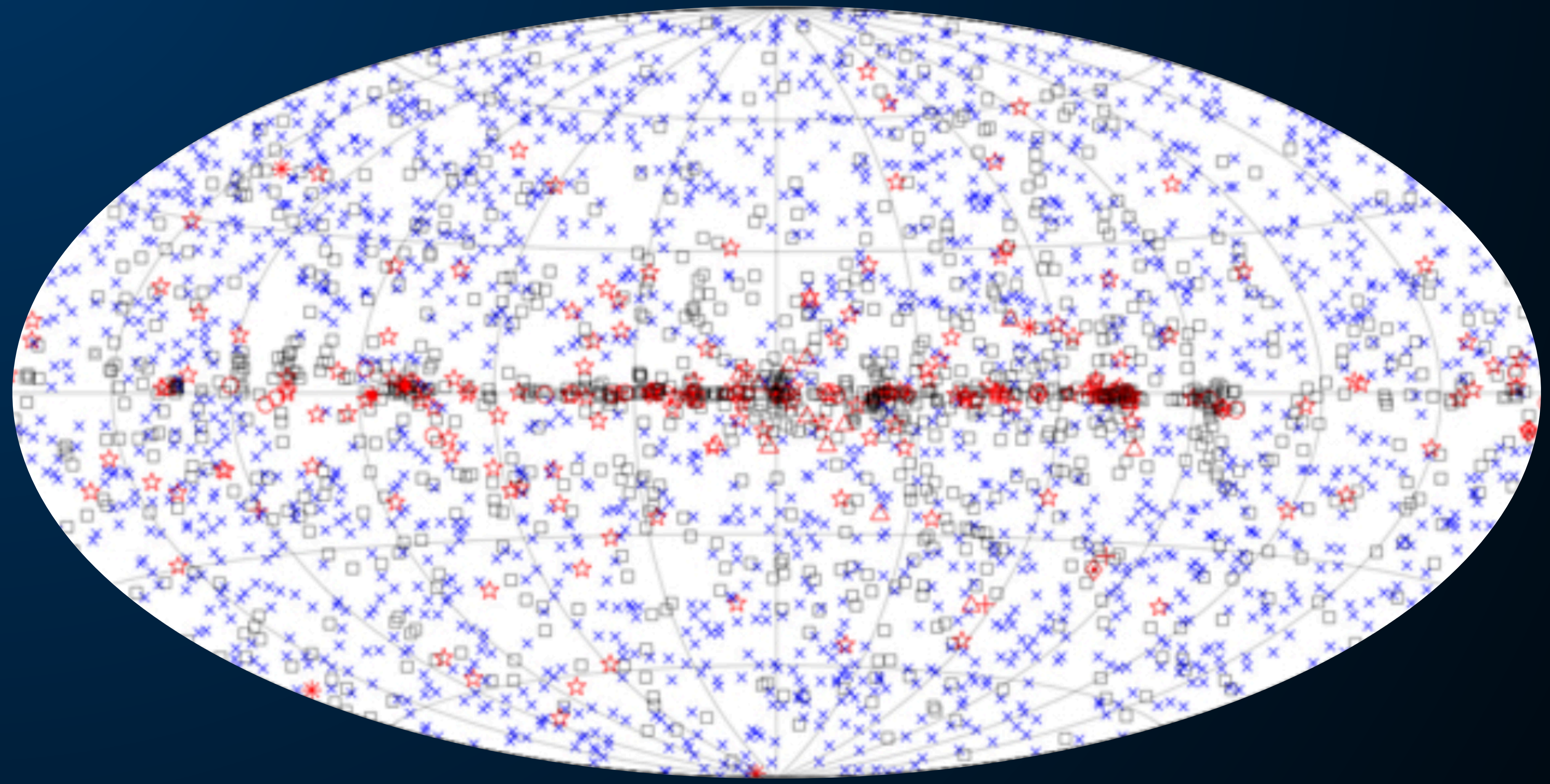


Galactic Diffuse



Point Sources

Isotropic Emission

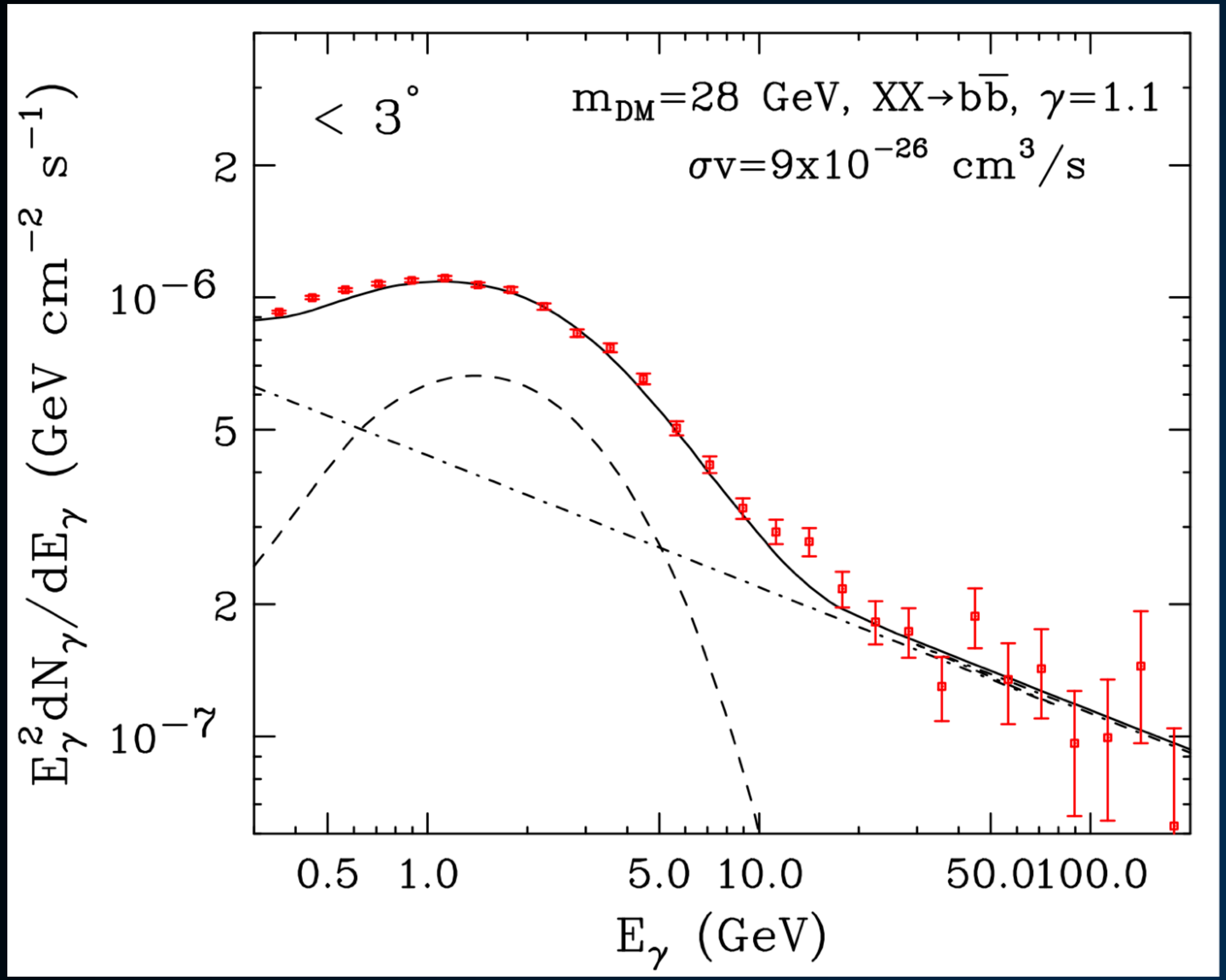


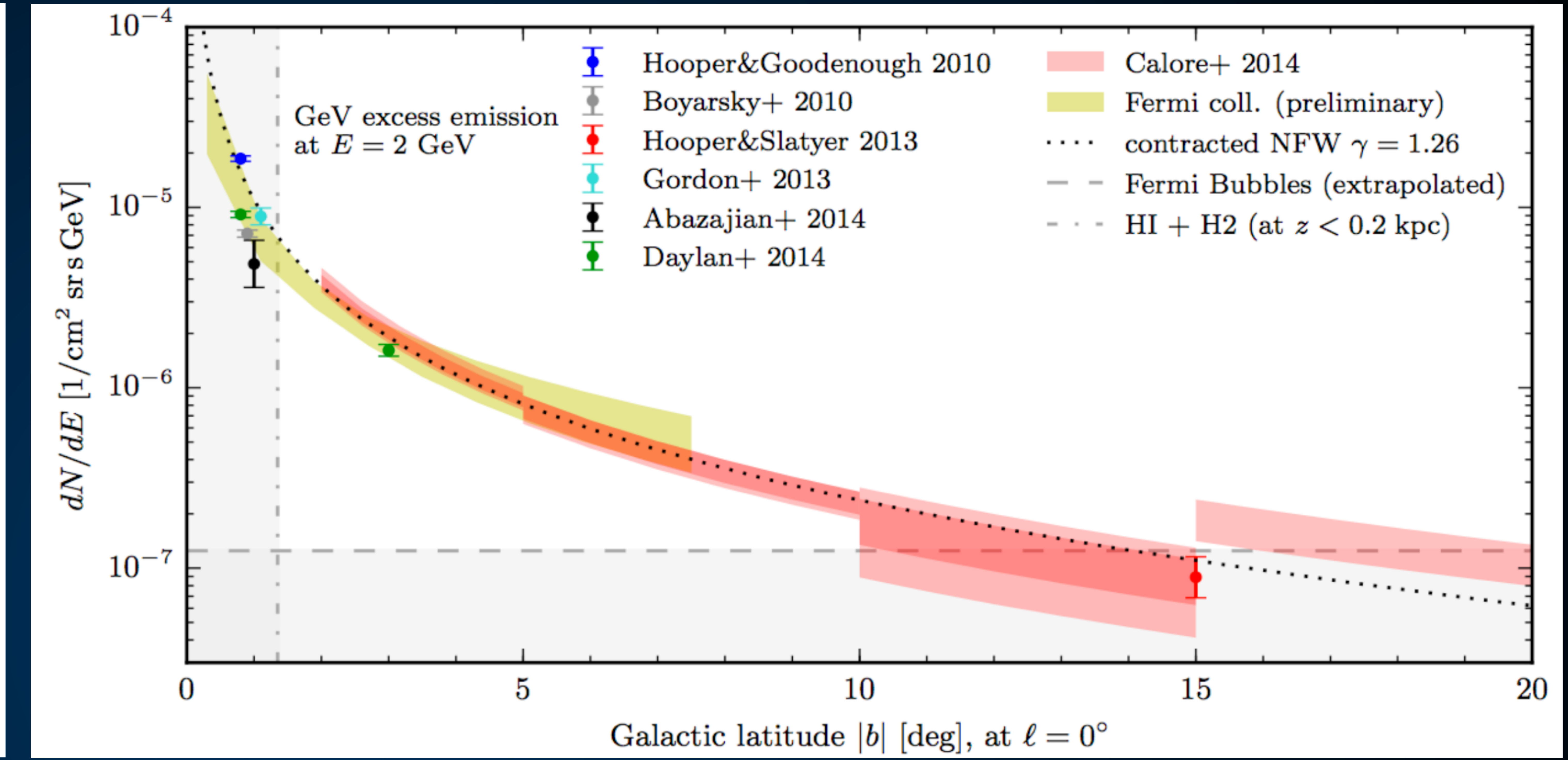
Sub-Threshold Sources

10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
$<\sigma v>$ ($\mathrm{cm}^3\mathrm{s}^{-1}$)
Thermal Cross-Section
1 Observed Photon Within 10° of Galactic Center
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

The Galactic Center Excess

Goodenough & Hooper (2009; 0910.2998)





Bright *Detected at >50σ*

Hard-Spectrum *Incompatible with standard backgrounds*

Spherically Symmetric *Expected from Dark Matter*

Spatially Extended *to nearly 15 degrees from Galactic center.*

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Cross-Section (10^{-26} cm^{3}s^{-1})
5
3
2
1
0.8
0.5
10
20
50
100
Energy (GeV)


$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Cross-Section (10^{-26} cm^{3}s^{-1})
Energy (GeV)
5
3
2
1
0.8
0.5
10
20
50
100

$\rho_\odot$ = 0.3 GeV cm^{-3}
Cross-Section (10^{-26} cm^{3}s^{-1})
5
3
2
1
0.8
0.5
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
10
20
50
100
Energy (GeV)

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Abazajian & Kaplinghat (1207.6047)
Cross-Section (10^{-26} cm^{3}s^{-1})
Energy (GeV)
5
3
2
1
0.8
0.5
10
20
50
100

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Abazajian & Kaplinghat (1207.6047)
Gordon & Macias (1306.5725)
Cross-Section (10^{-26} cm^{3}s^{-1})
Energy (GeV)
5
3
2
1
0.8
0.5
10
20
50
100

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Abazajian & Kaplinghat (1207.6047)
Gordon & Macias (1306.5725)
Daylan et. al. (1402.6703)
Cross-Section (10^{-26} cm^{3}s^{-1})
Energy (GeV)
0.5
0.8
1
2
3
5
10
20
50
100

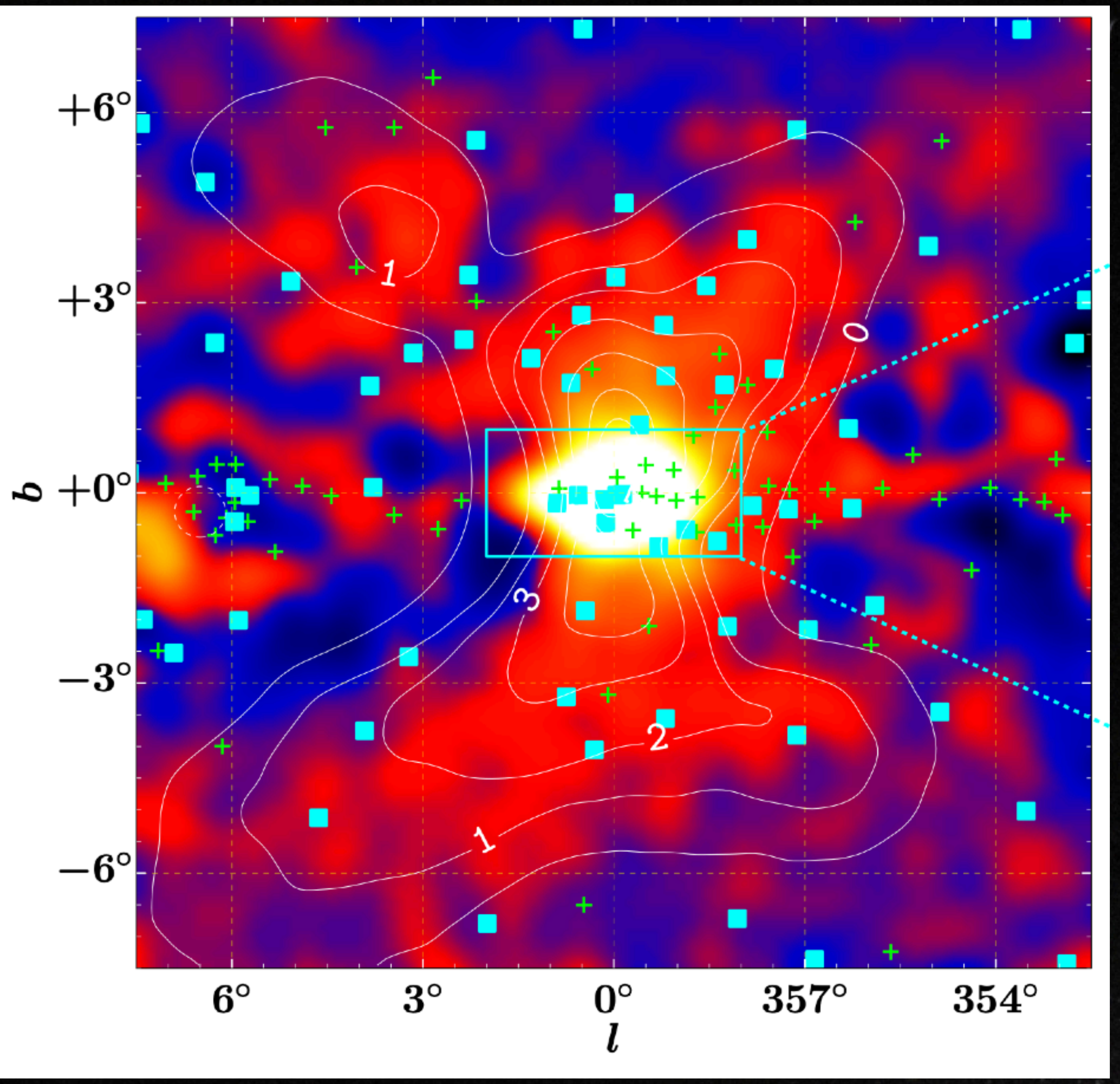
$\rho_{\odot}$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Abazajian & Kaplinghat (1207.6047)
Gordon & Macias (1306.5725)
Daylan et. al. (1402.6703)
Calore et. al. (1409.0042)
Cross-Section (10^{-26} cm^{3}s^{-1})
5
3
2
1
0.8
0.5
10
20
50
100
Energy (GeV)

$\rho_\odot$ = 0.3 GeV cm^{-3}
Thermal Cross-Section
Goodenough & Hooper (0910.2998)
Hooper & Linden (1110.0006)
Abazajian & Kaplinghat (1207.6047)
Gordon & Macias (1306.5725)
Daylan et. al. (1402.6703)
Calore et. al. (1409.0042)
Calore et. al. (1411.4647)
Cross-Section (cm^{3}s^{-1})
Energy (GeV)
0.5
0.8
1
2
3
5
10
20
50
100

Galactic Center Excess Flux
10^{-6}
10^{-7}
10^{-8}
Flux (GeV cm^{-2} s^{-1})
0.3
1
3
10
30
100
Energy (GeV)
Calore et al. (2014; 1409.0042)


Galactic Center Excess Flux
DM (50 GeV, $b\bar{b}$)
Flux (GeV cm^{-2} s^{-1})
10^{-6}
10^{-7}
10^{-8}
0.3
1
3
10
30
100
Energy (GeV)
Calore et al. (2014; 1409.0042)

Galactic Center Excess Flux
DM (50 GeV, $b\bar{b}$)
Average Pulsar Spectrum
Calore et al. (2014; 1409.0042)
Cholis et al. (2014; 1407.5583)
Flux (GeV cm^{-2} s^{-1})
10^{-6}
10^{-7}
10^{-8}
0.3
1
3
10
30
100
Energy (GeV)



Macias et al. (2016; 1611.06644)

Bartels et al. (2017; 1711.04778)

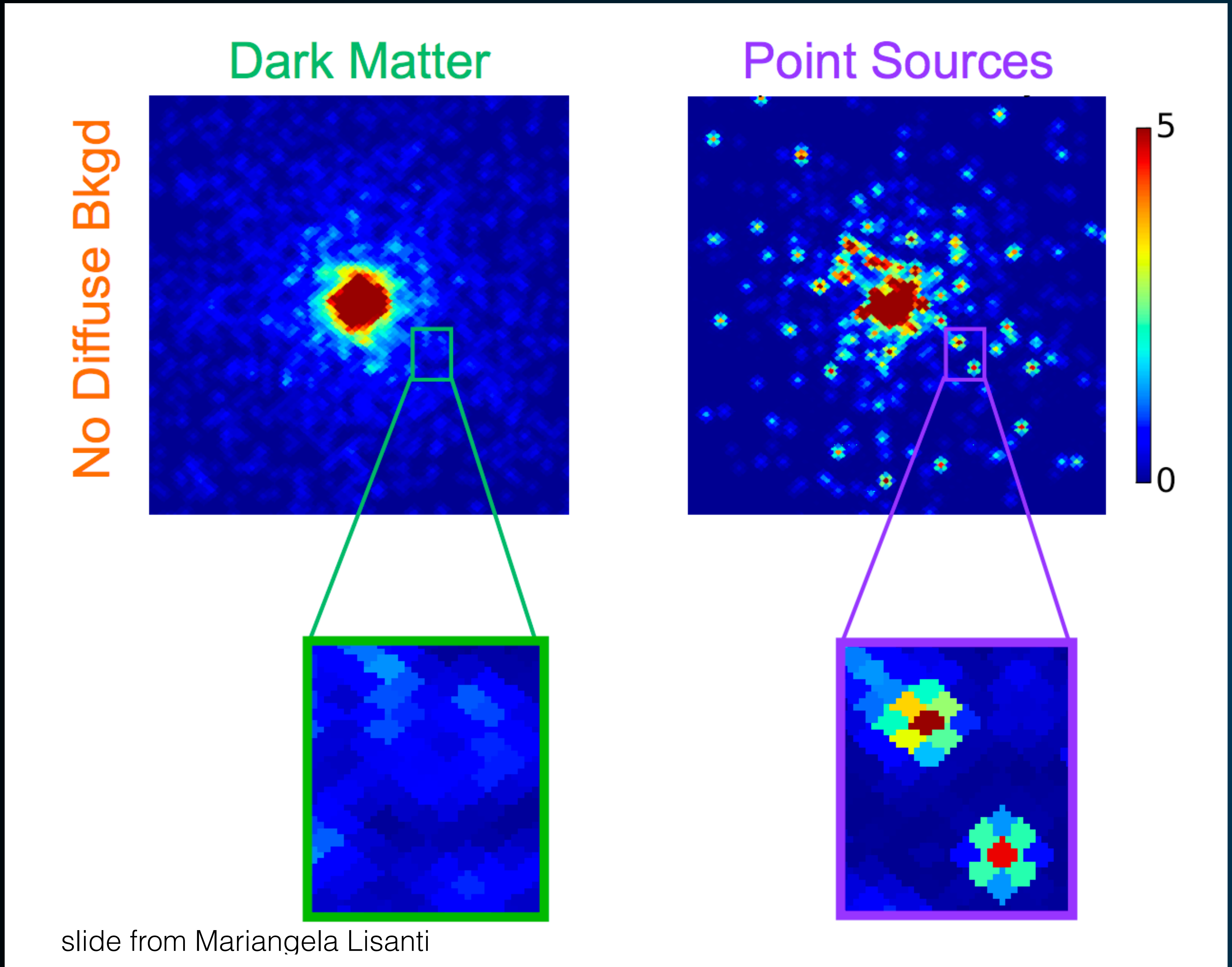
Bartels et al. (2018; 1803.04370)

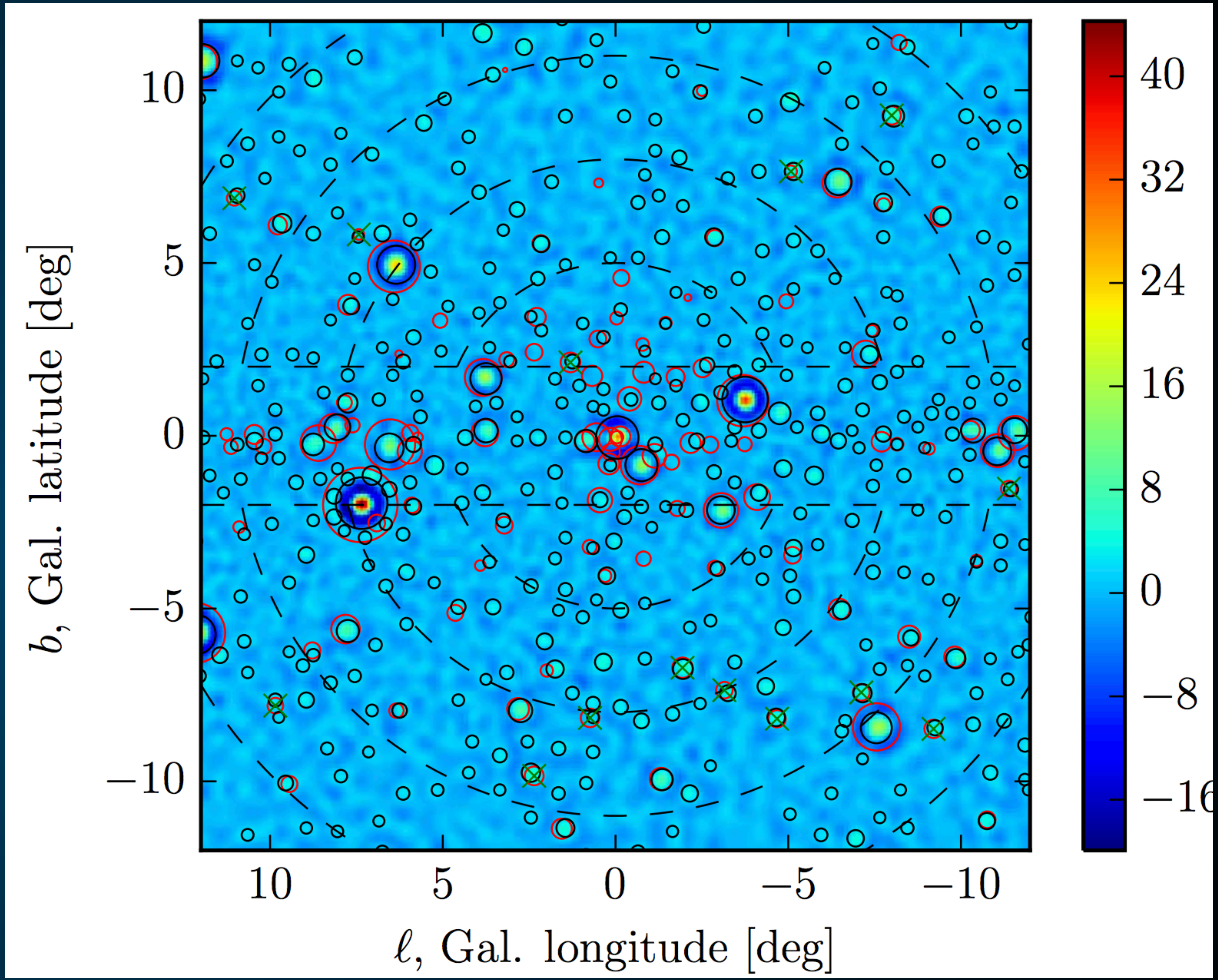
Macias et al. (2019; 1901.03822)

The Galactic Center Excess

Bartels et al. (2015; 1506.05104)

Lee et al. (2015; 1506.05124)

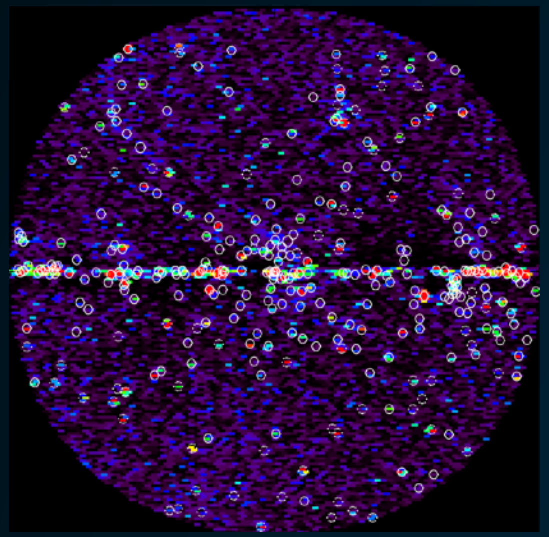
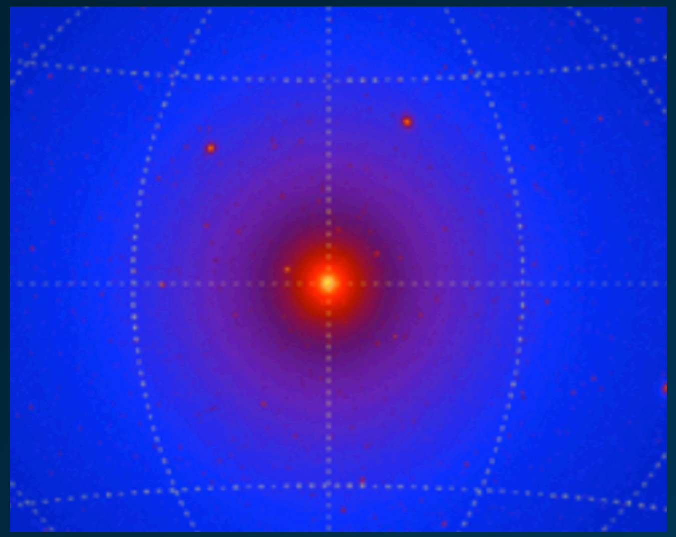
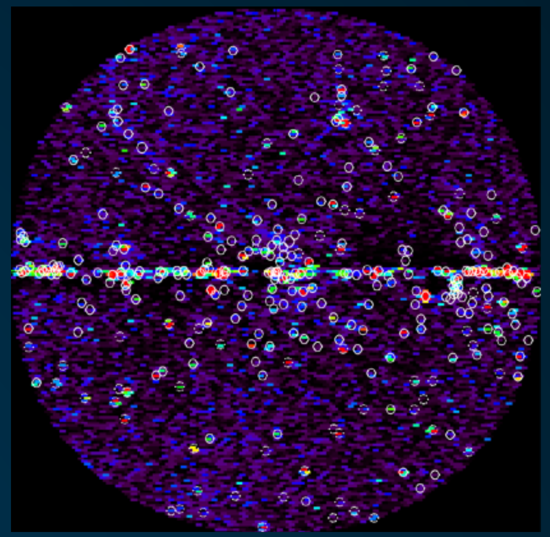
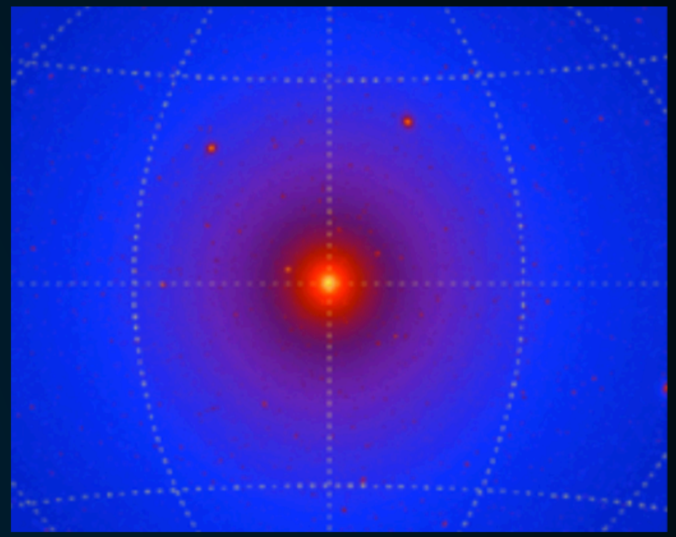


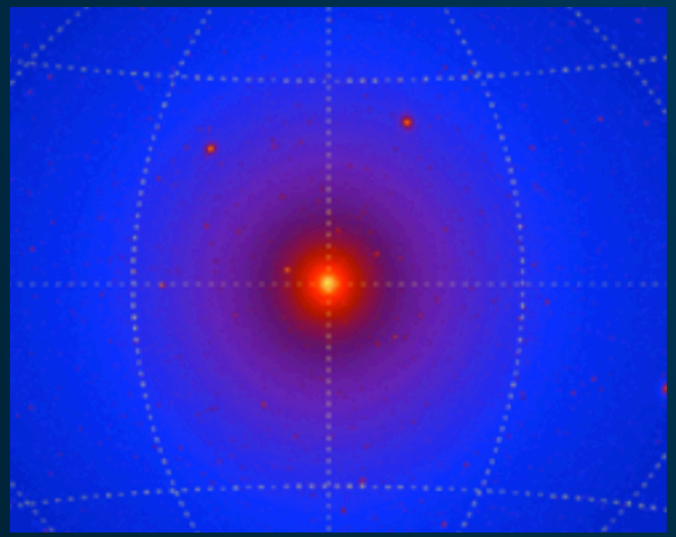
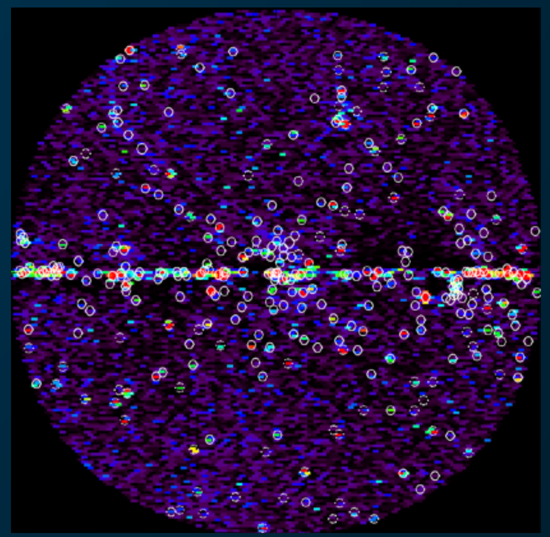
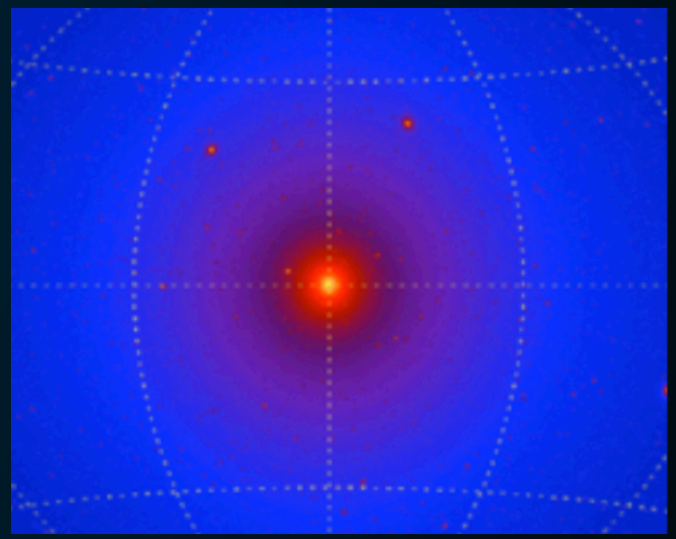


Bulletproof evidence for pulsars?

The Galactic Center Excess

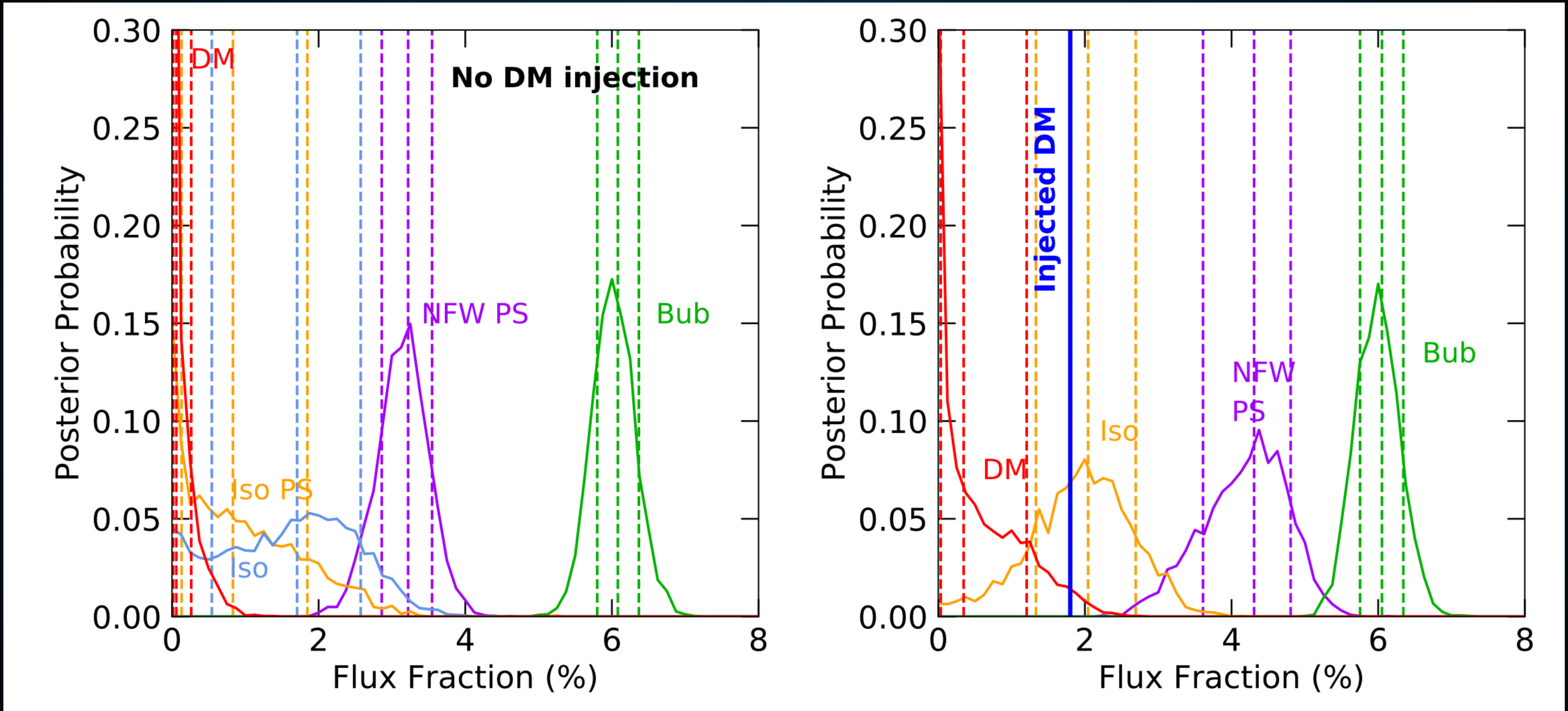
Leane & Slatyer (2019; 1904.08430)

x  + y  → x  + y 

x  + y  → x’  + y’ 

The Galactic Center Excess

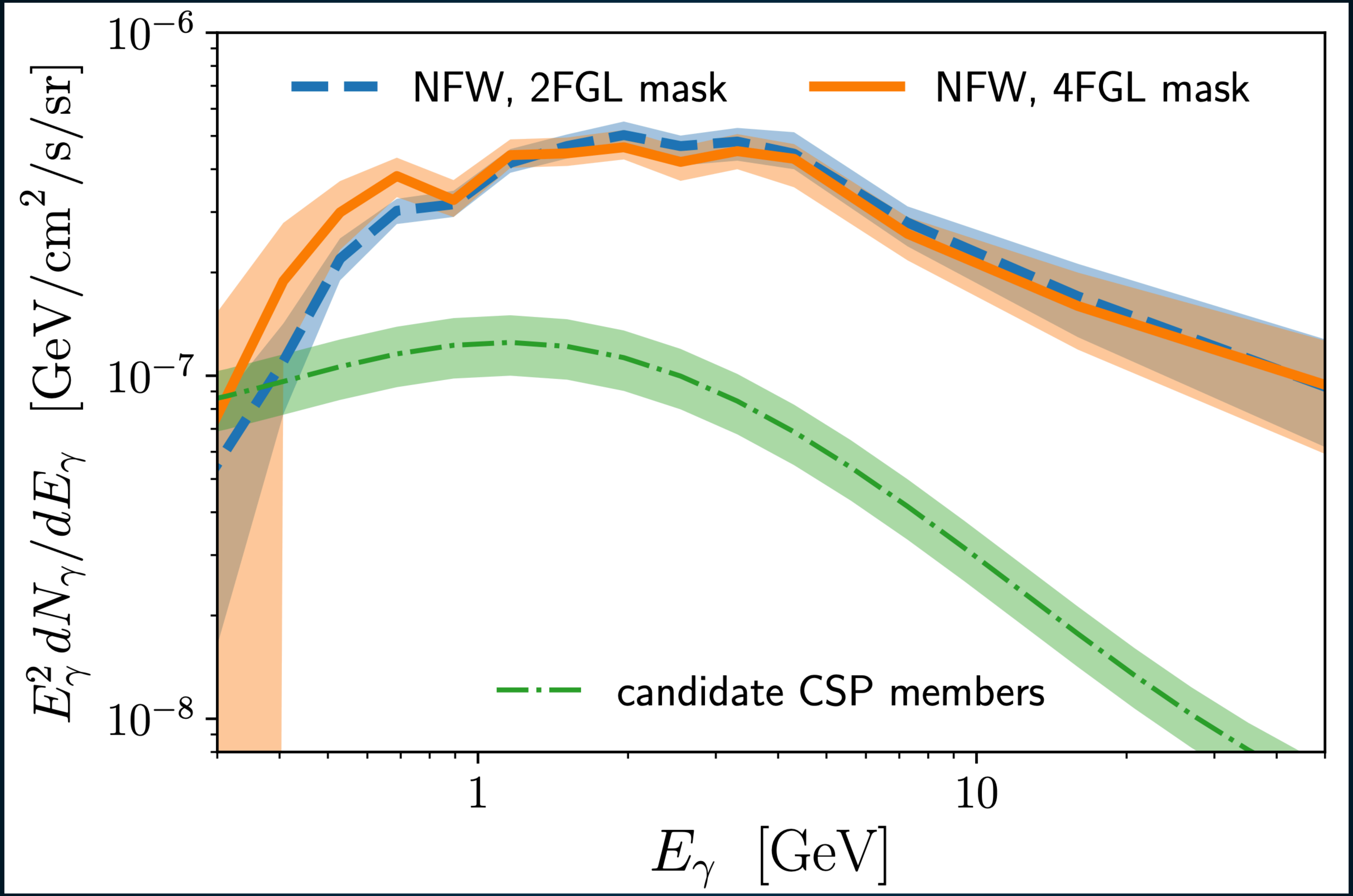
Leane & Slatyer (2019; 1904.08430)



Dark Matter Strikes Back at the Galactic Center

The Galactic Center Excess

Zhong et al. (2019; 1911.12369)



New Catalogs also change the interpretation of the wavelet analysis!


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

The Antiproton Excess

The Antiproton Excess

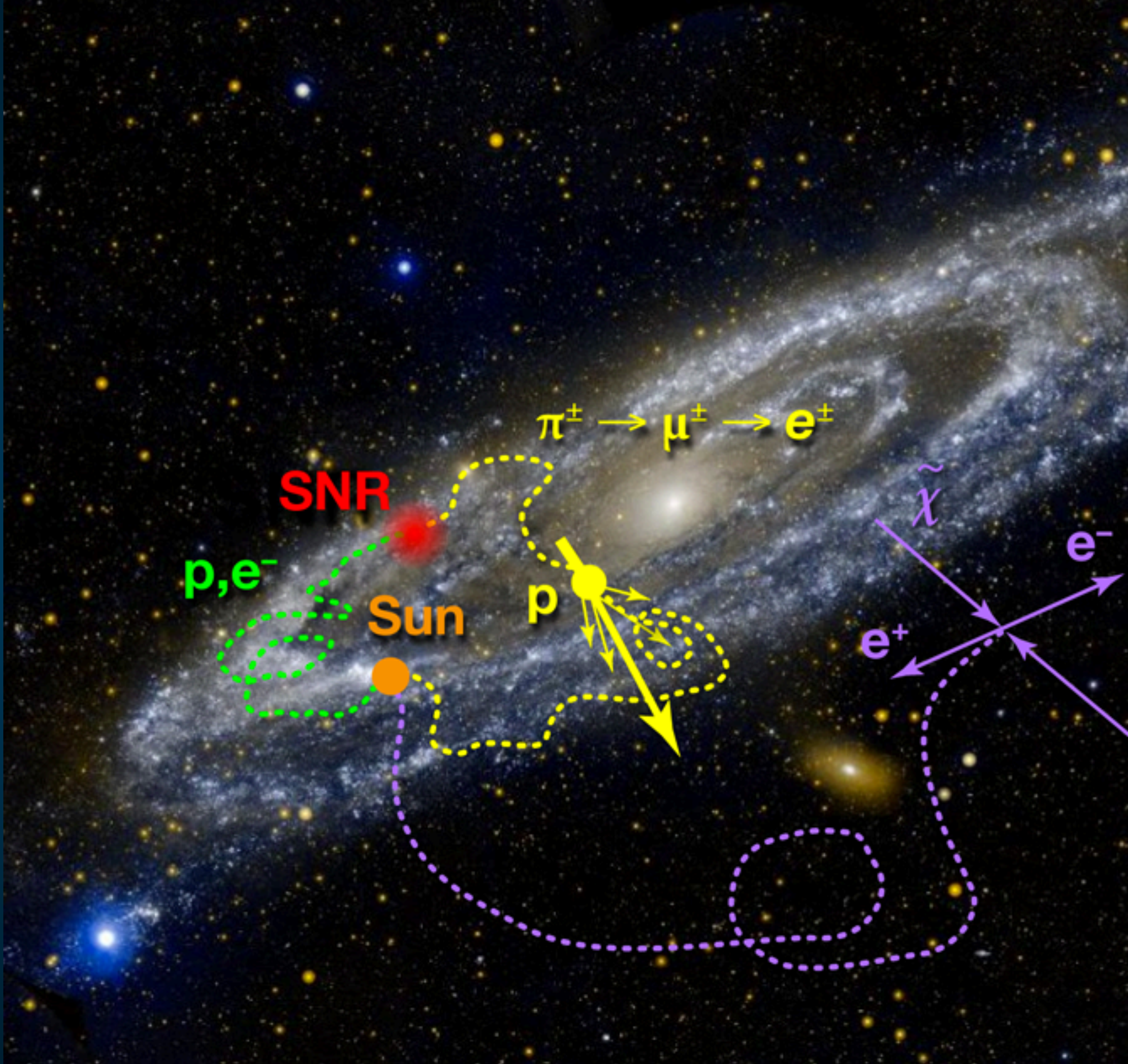
Investigate the Antiproton Fraction!

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

Two Changes:

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

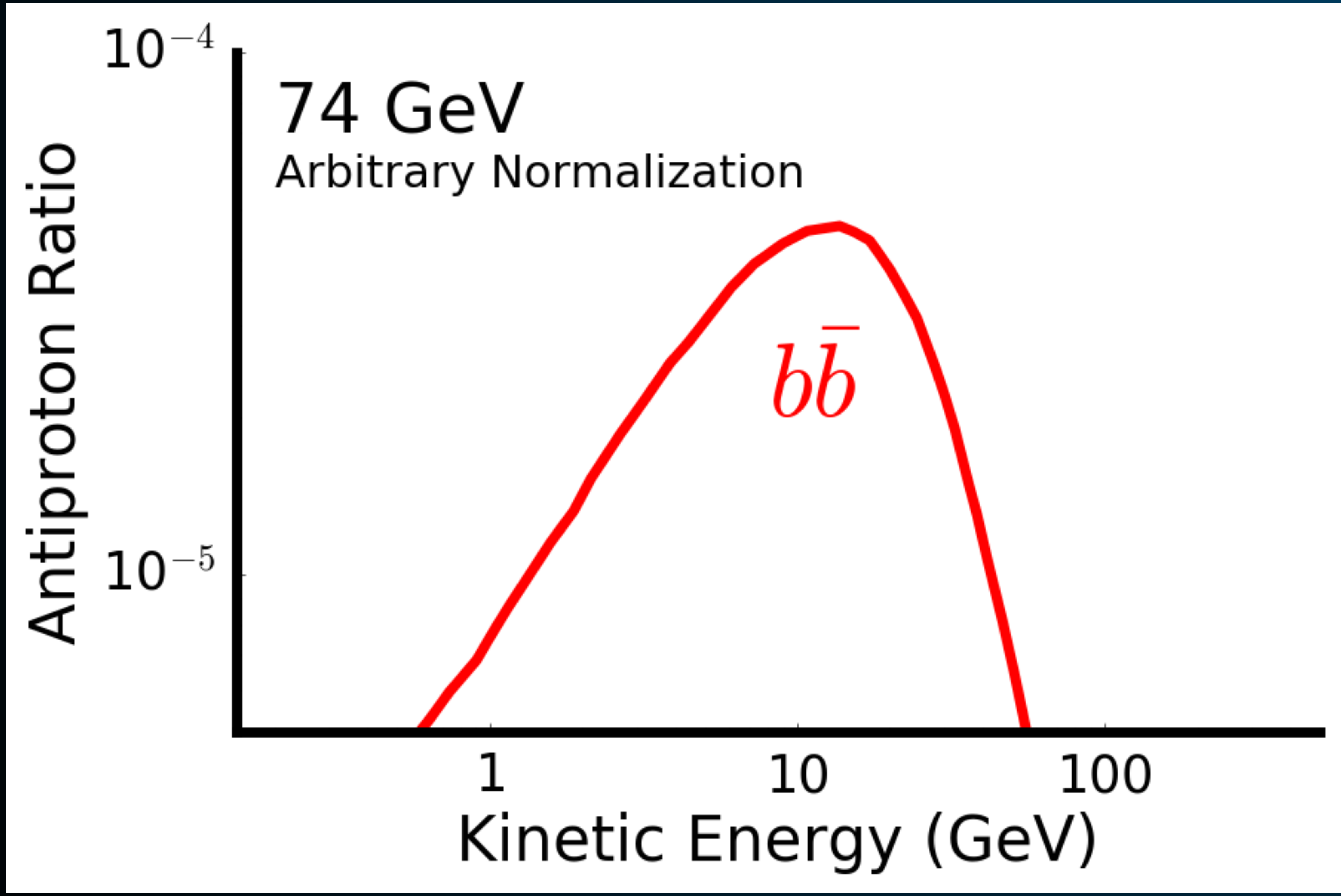
Hadronic Energy losses are slower (sensitive to antiproton production throughout the Galaxy)

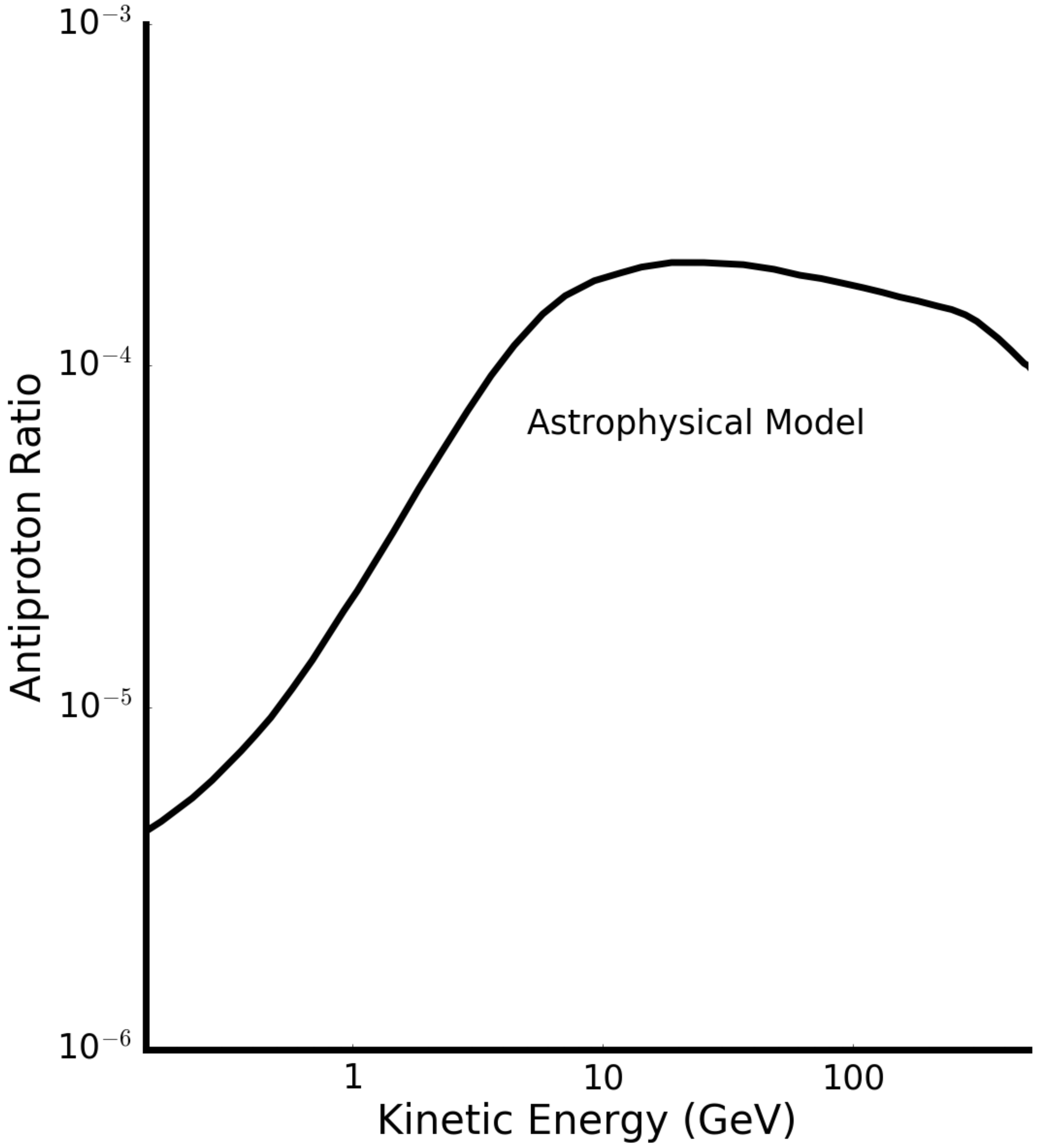


The Antiproton Excess

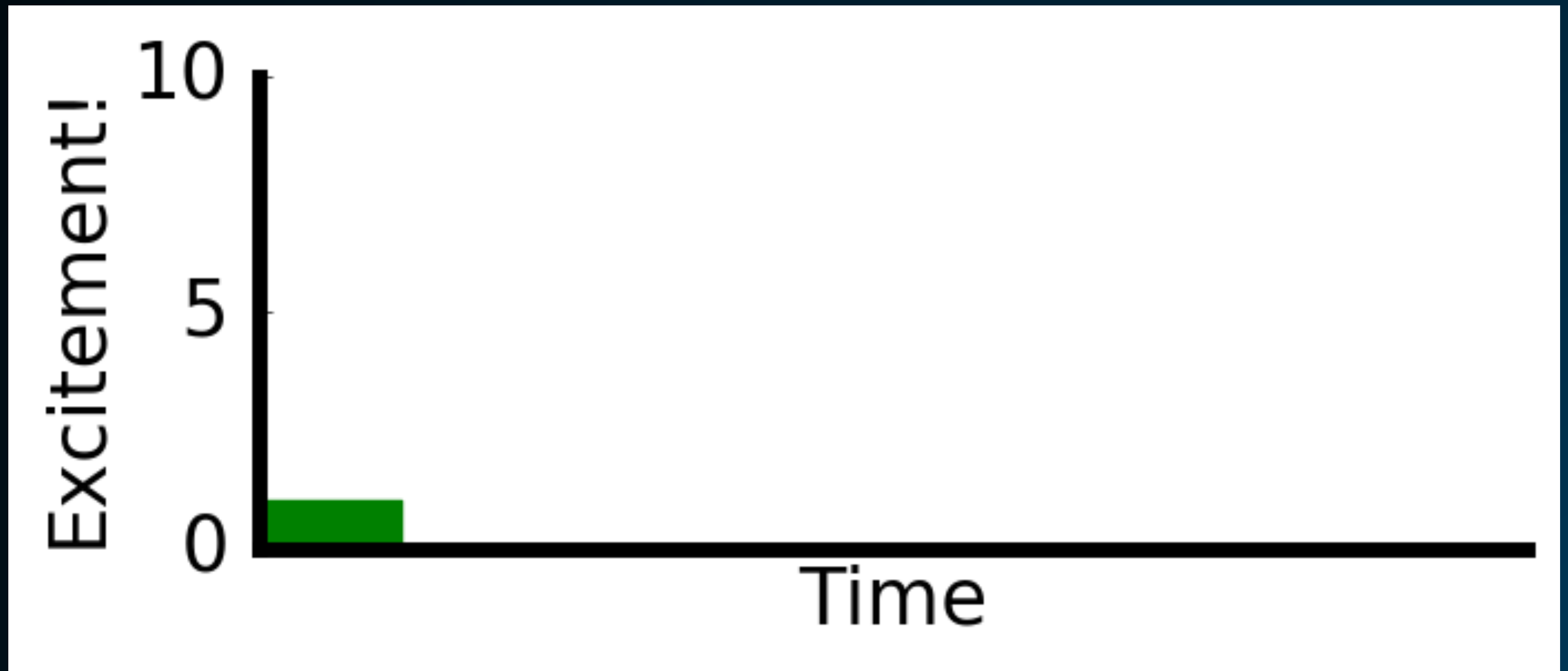
Astrophysics - Smooth Profile

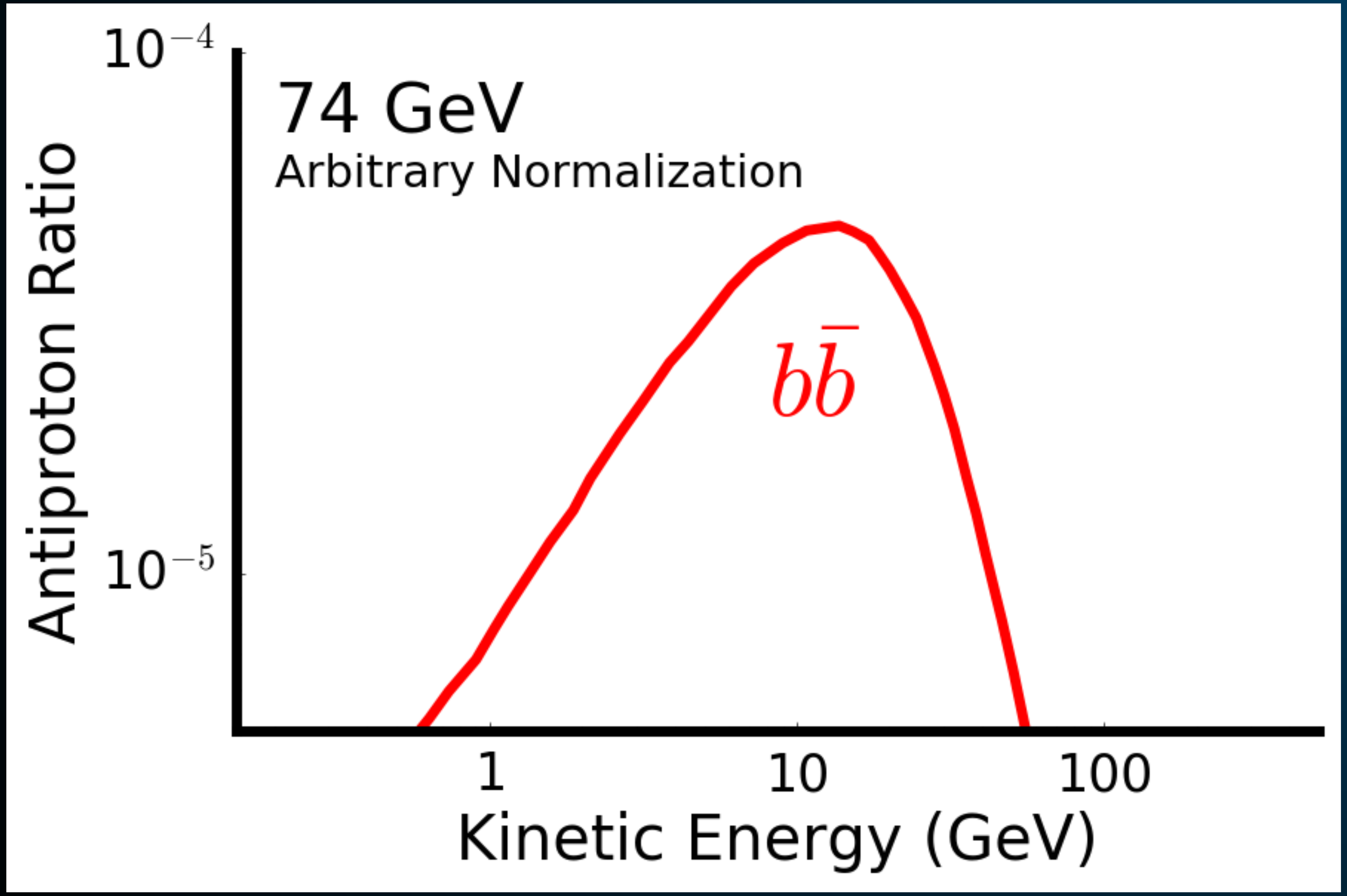
Dark Matter - Sharp Bump!



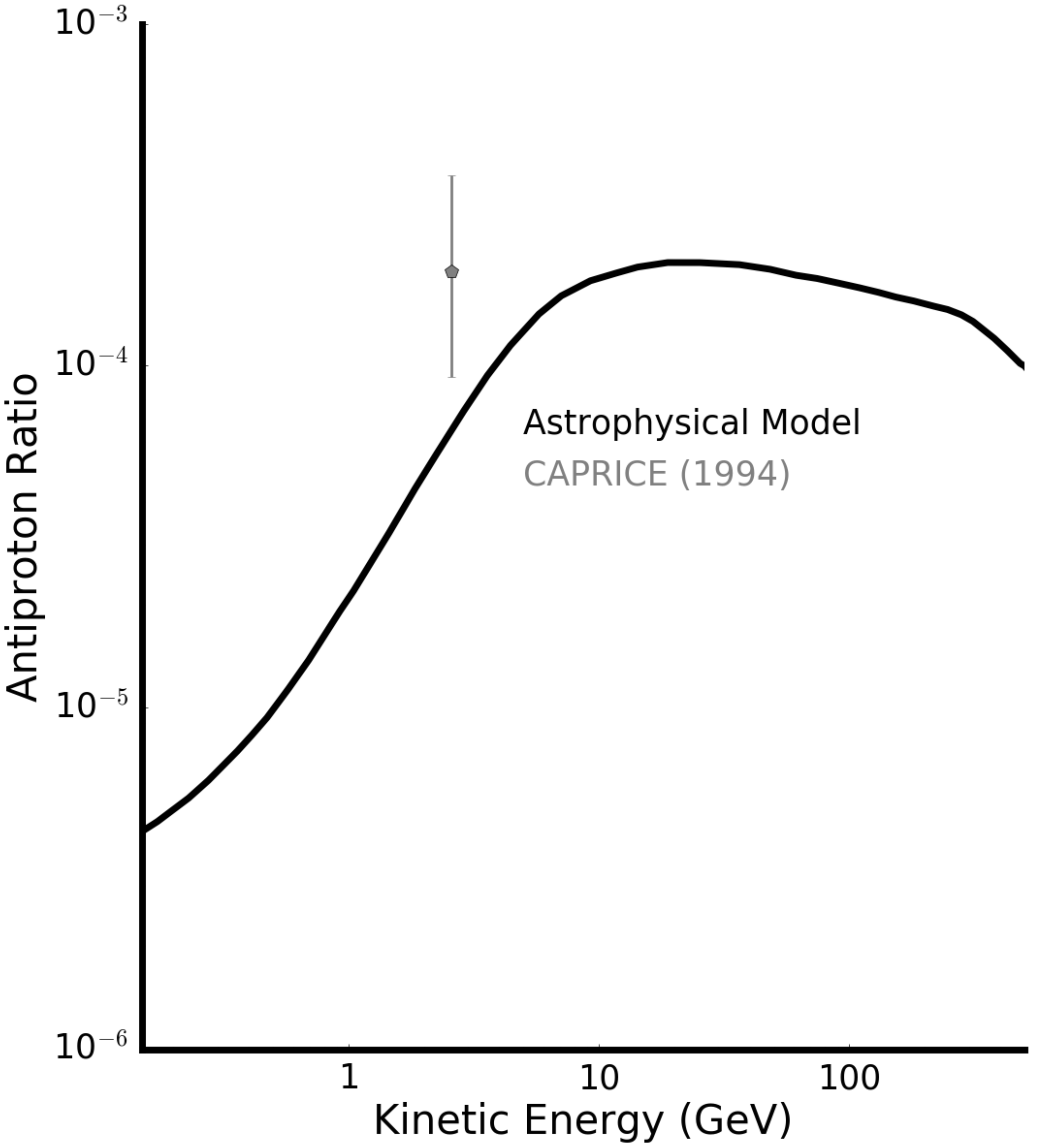


The Antiproton Excess

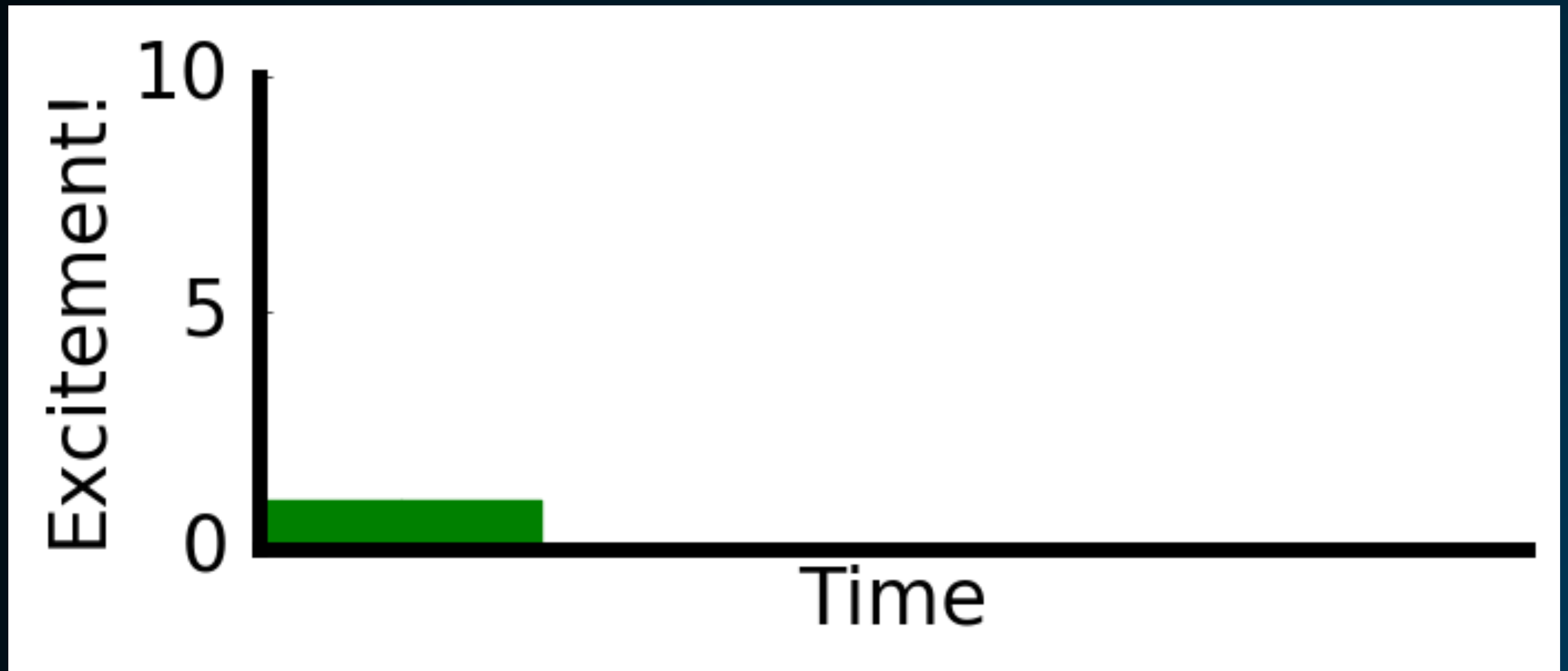


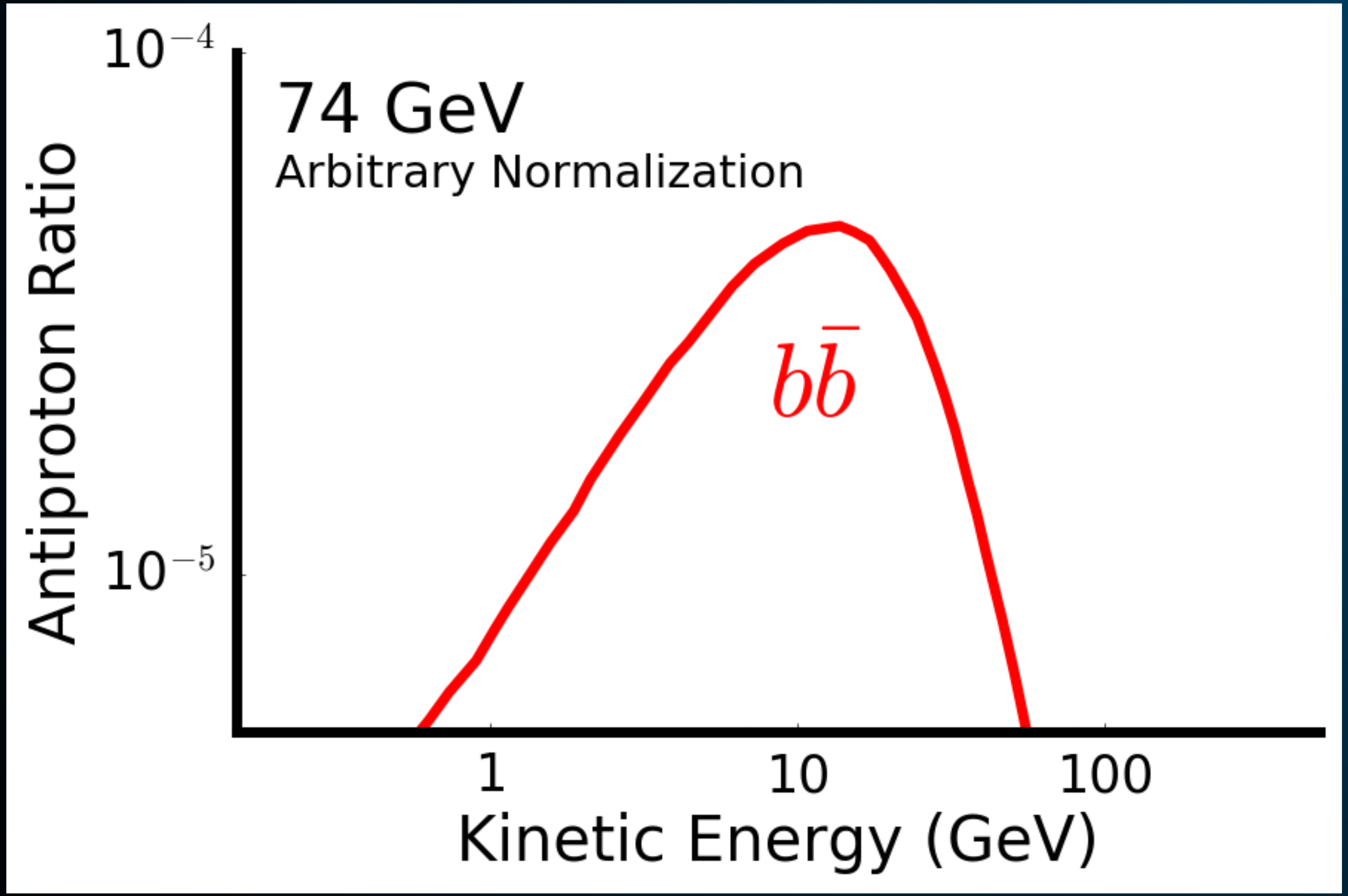


(Not an exhaustive list of observations)

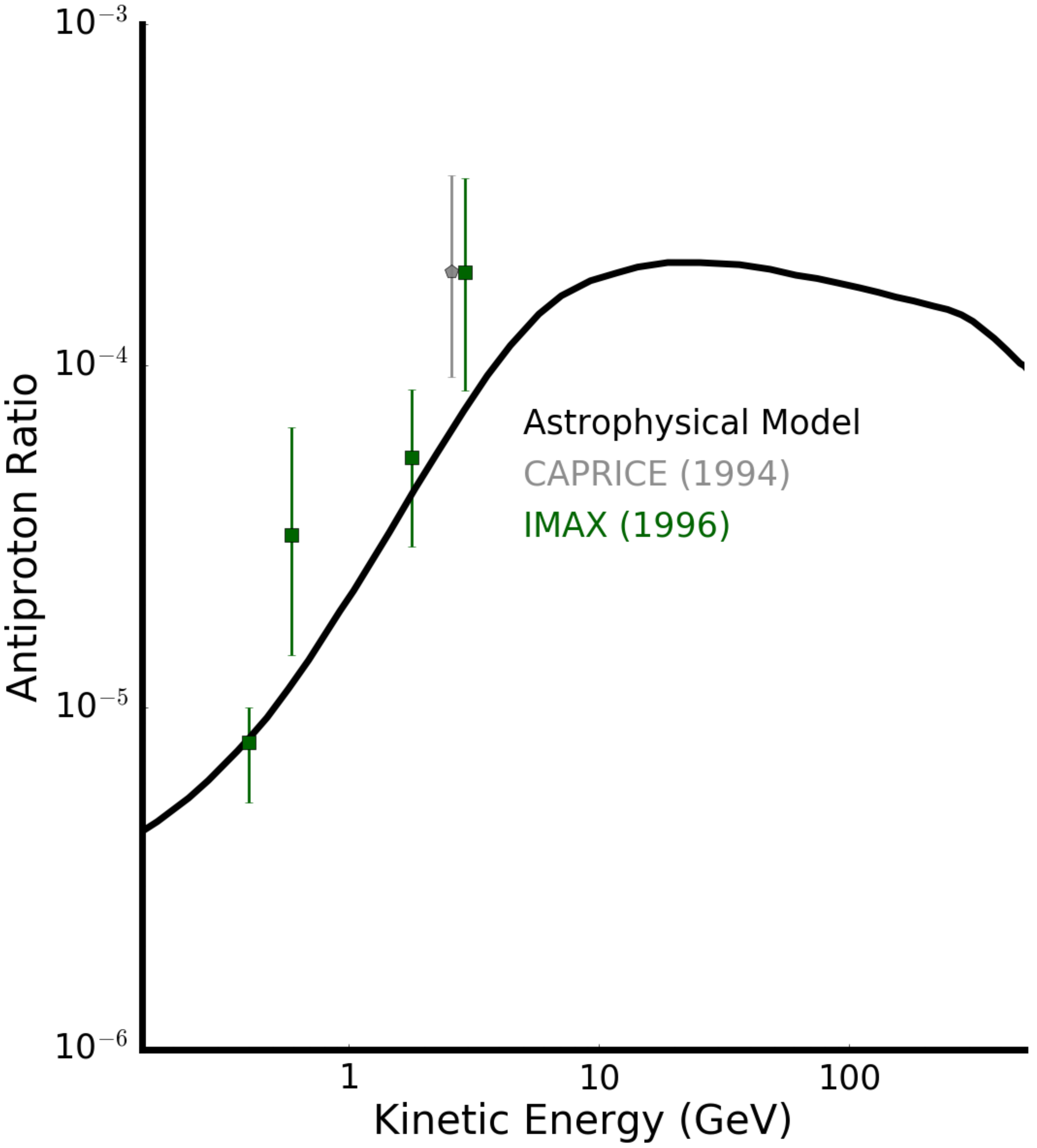


The Antiproton Excess

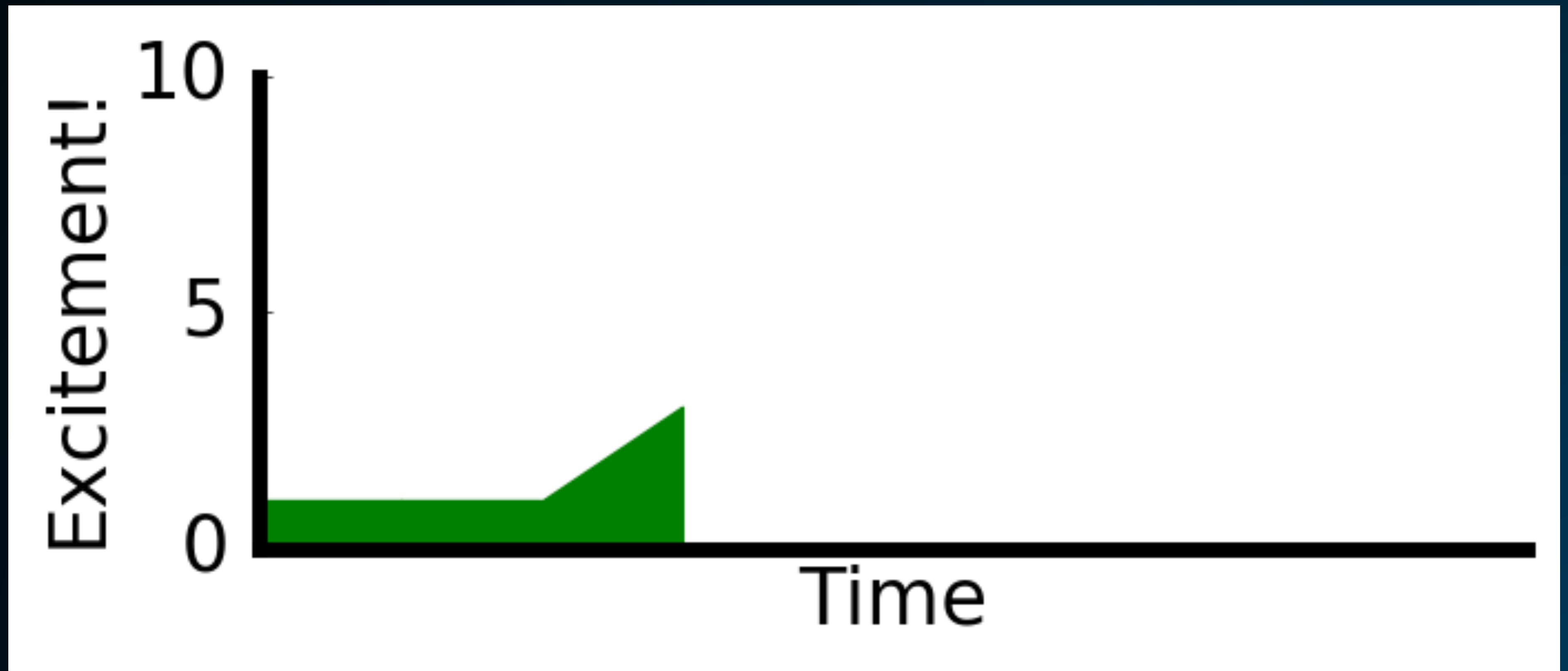


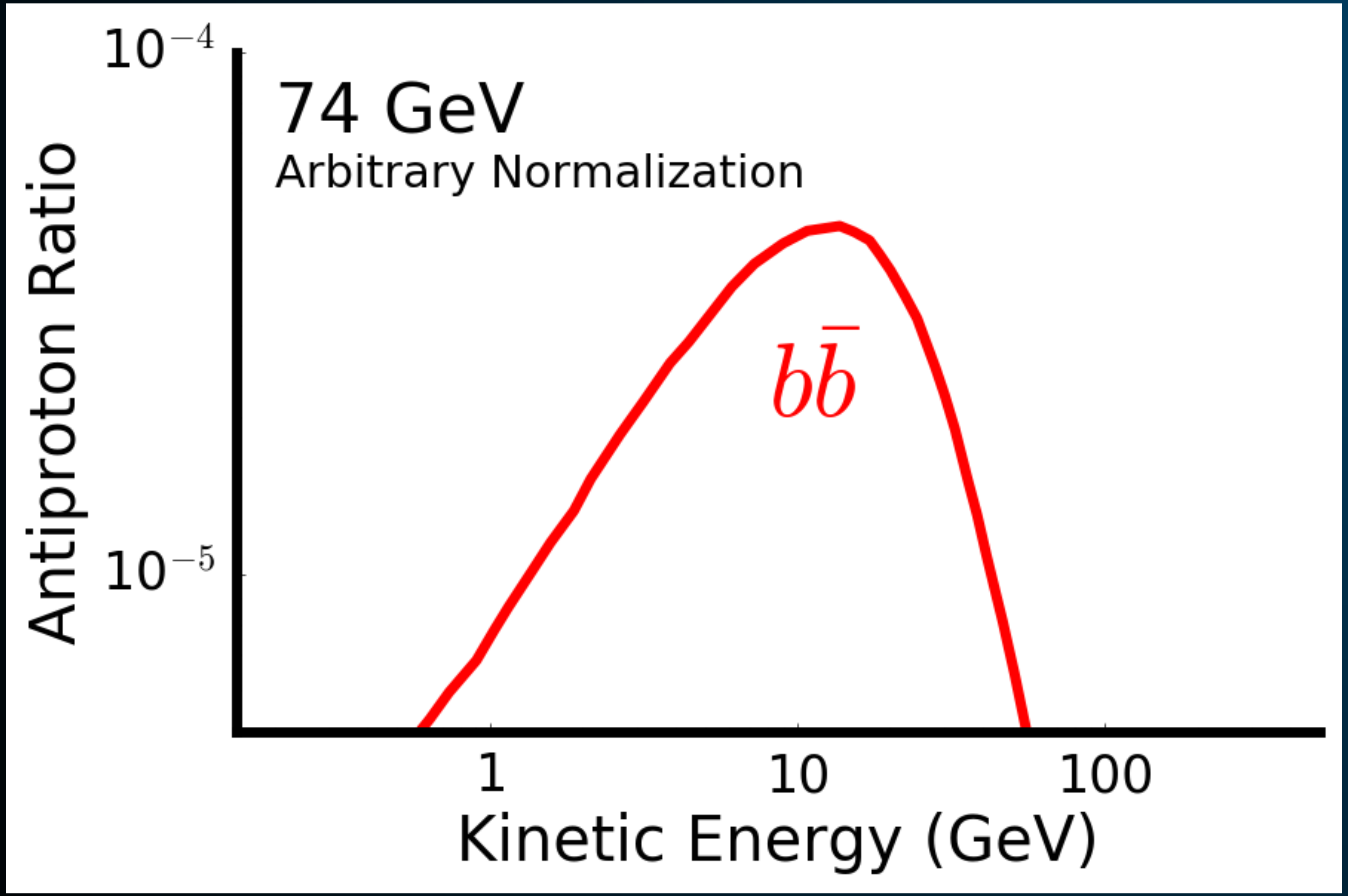


(Not an exhaustive list of observations)

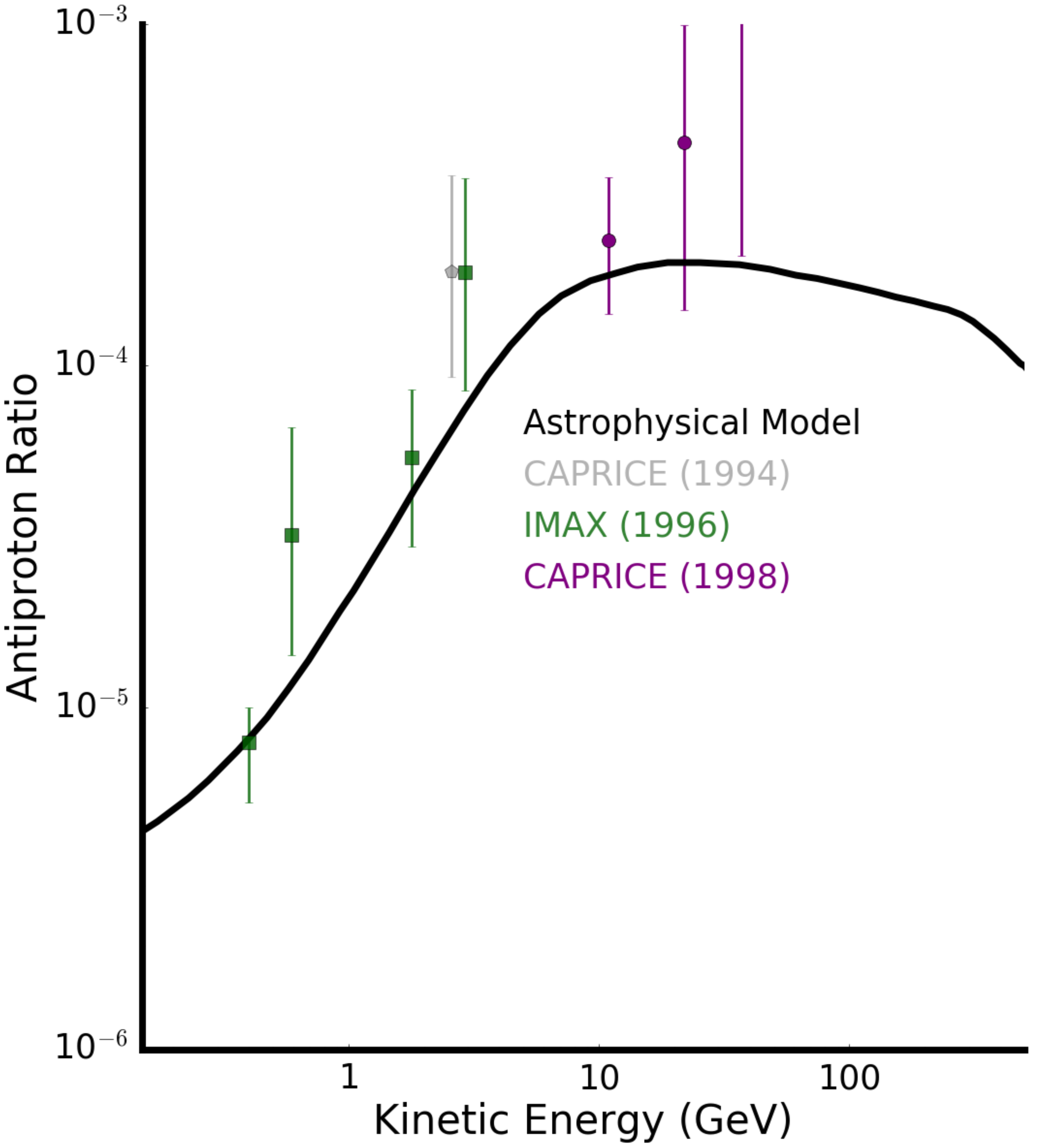


The Antiproton Excess





(Not an exhaustive list of observations)



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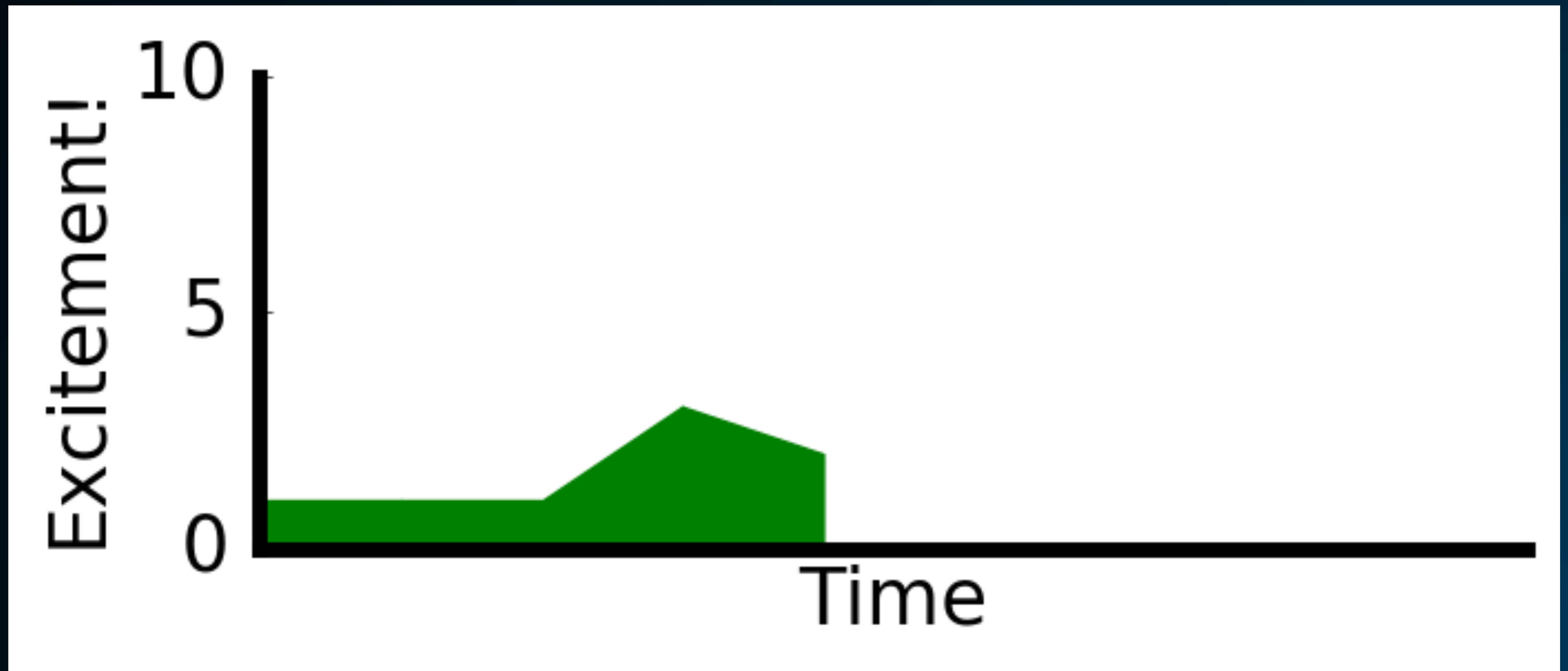

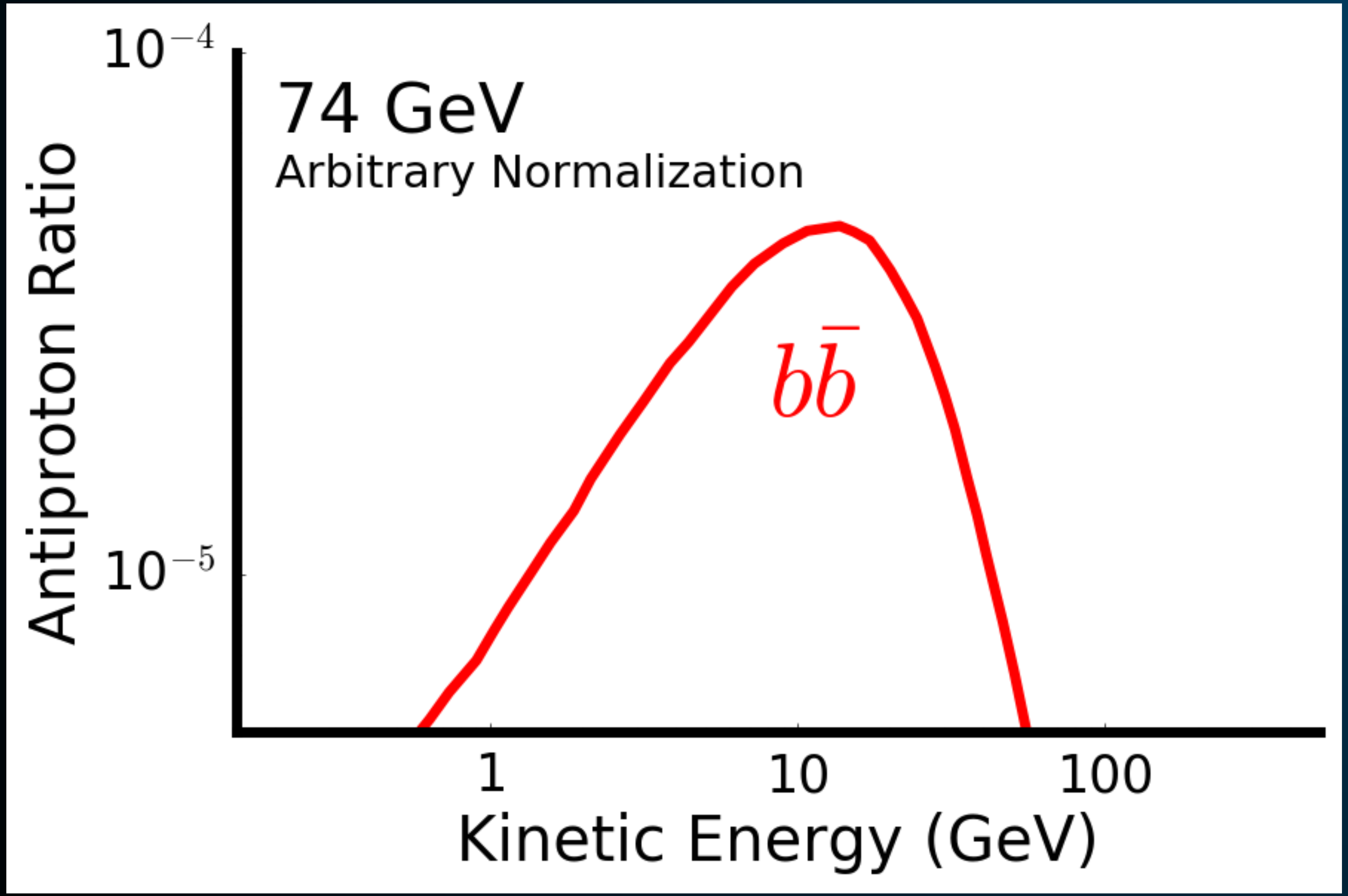

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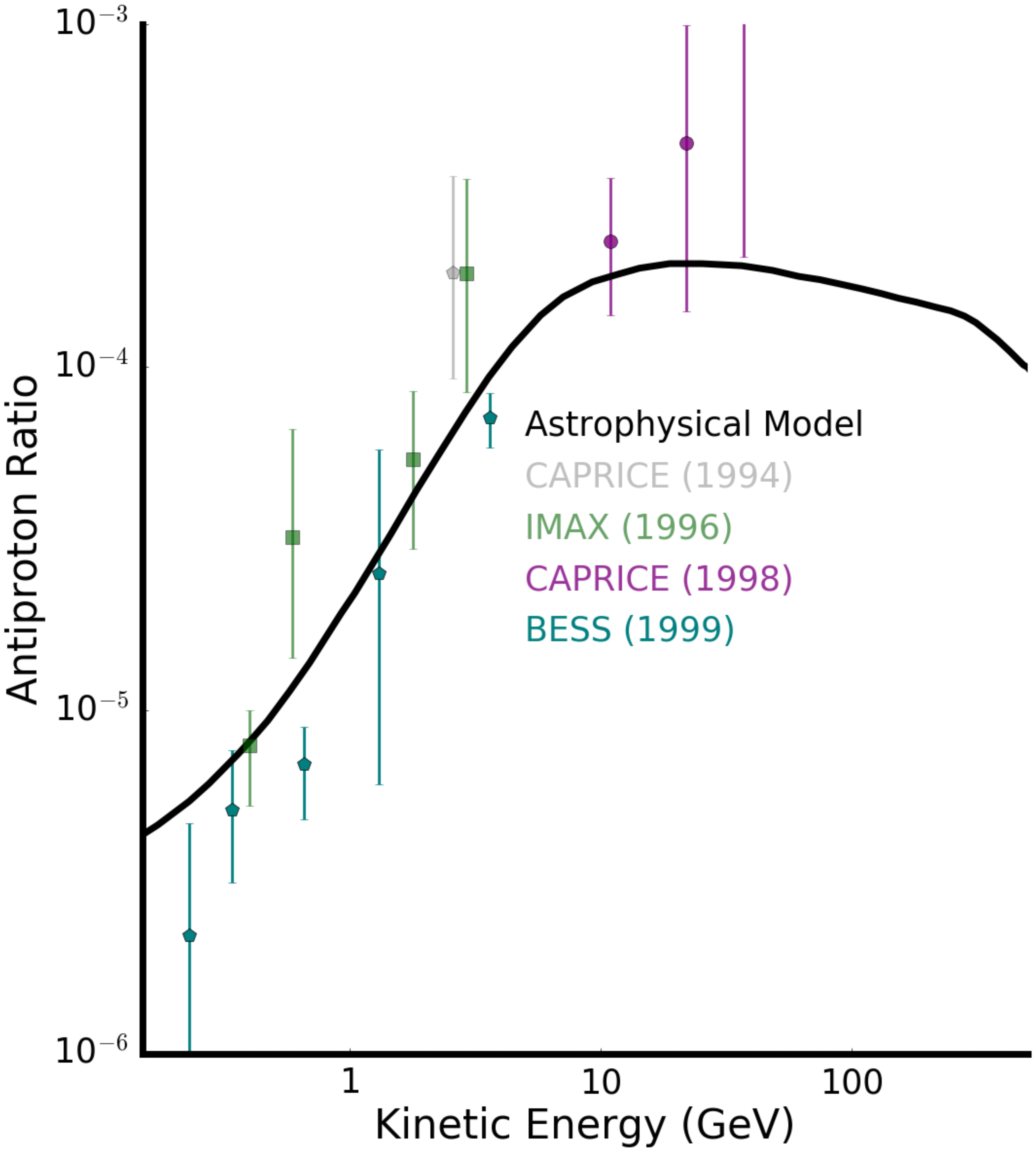
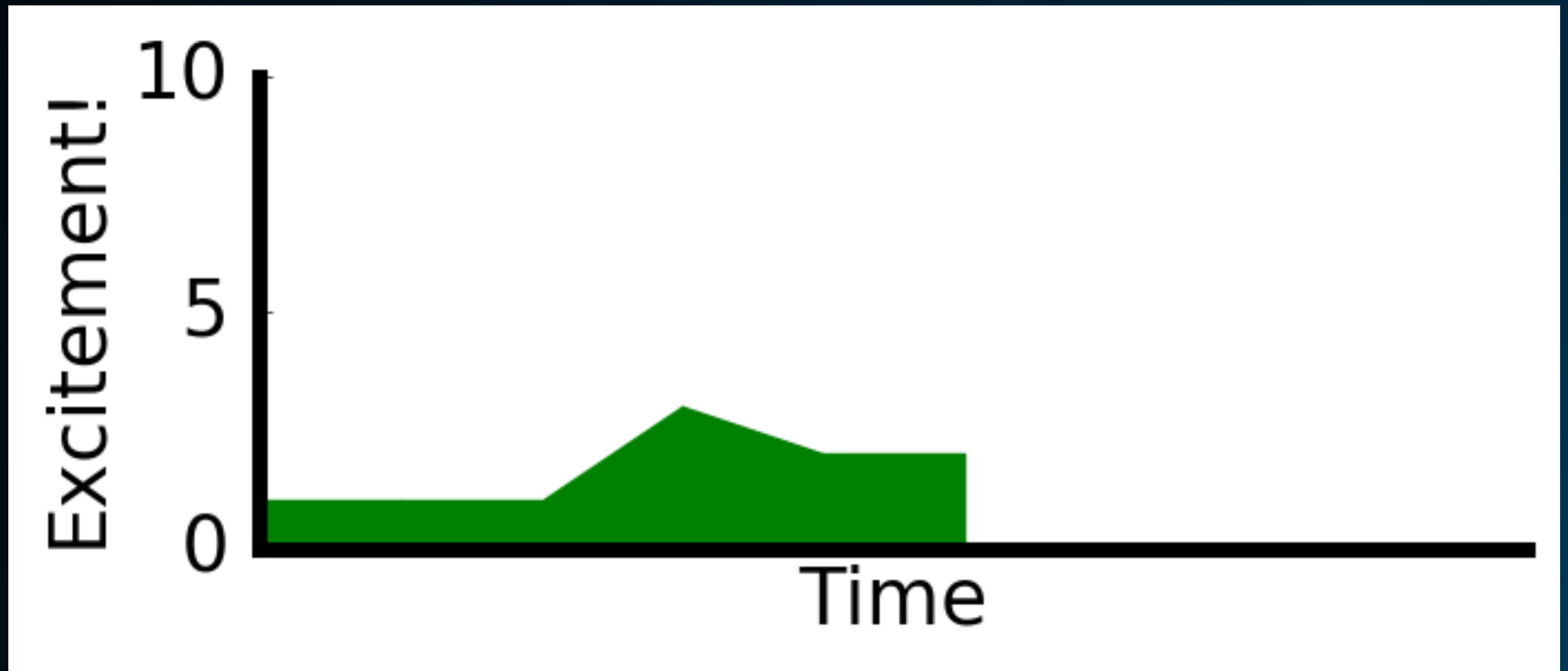
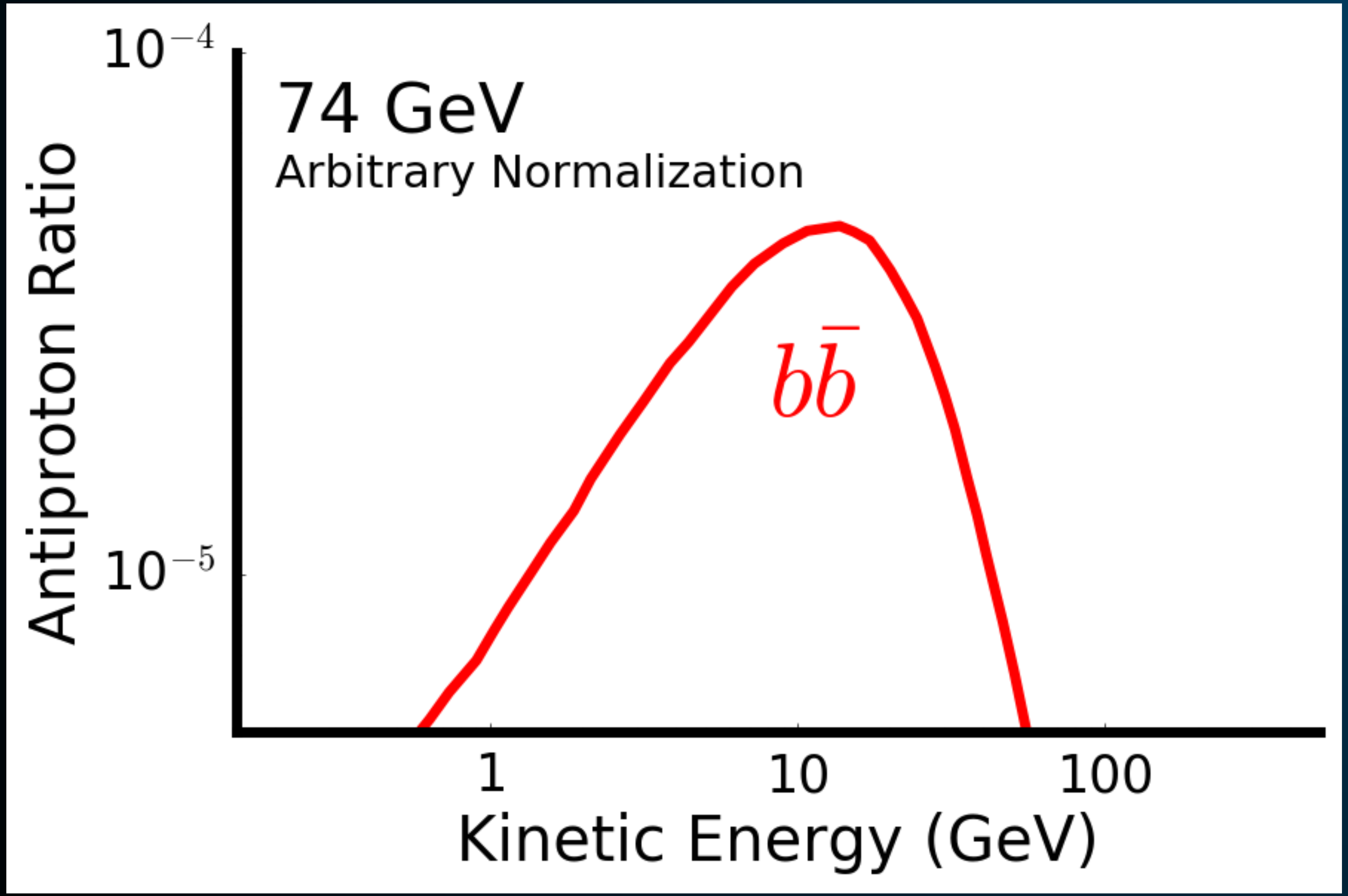
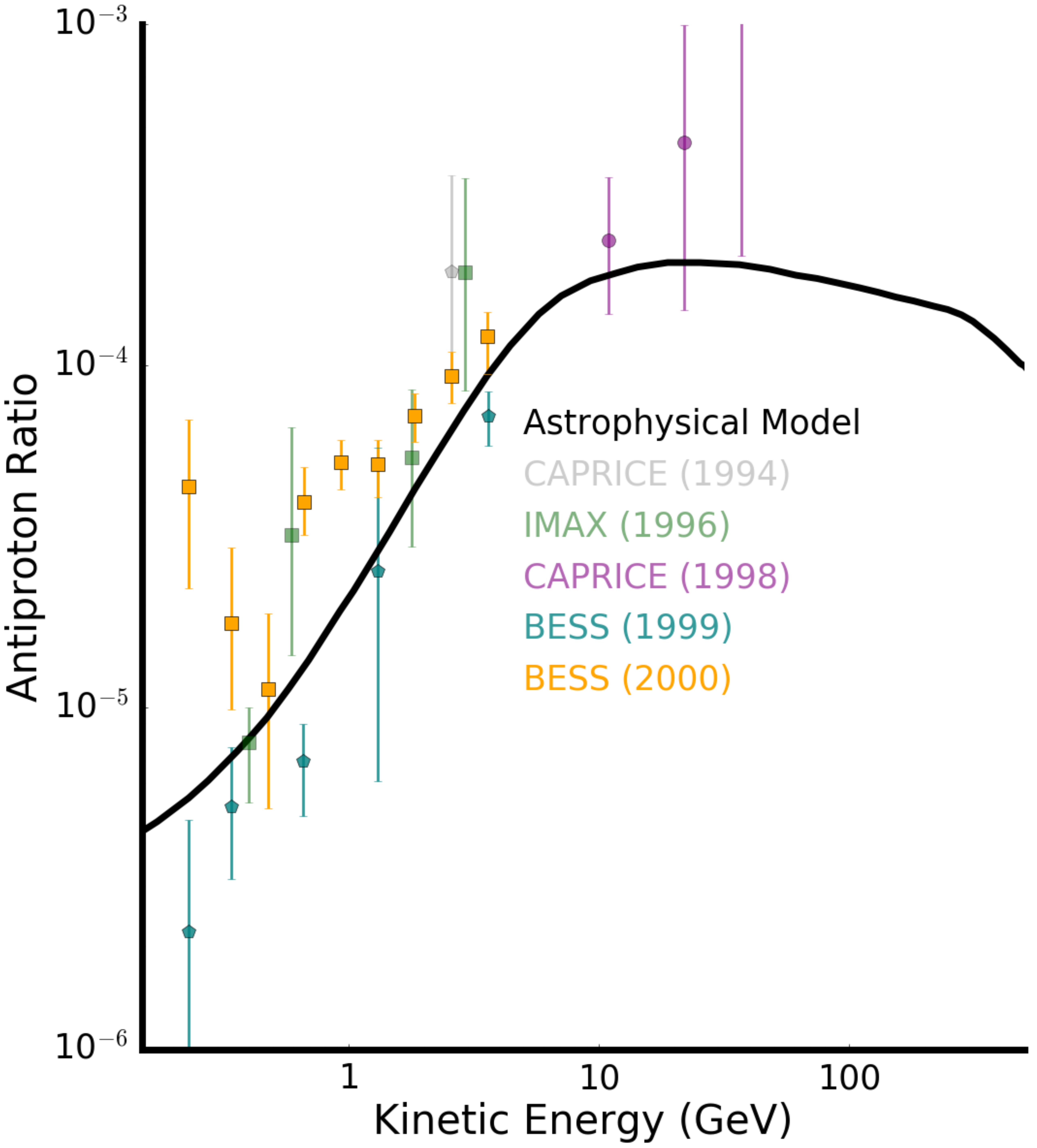


The Antiproton Excess

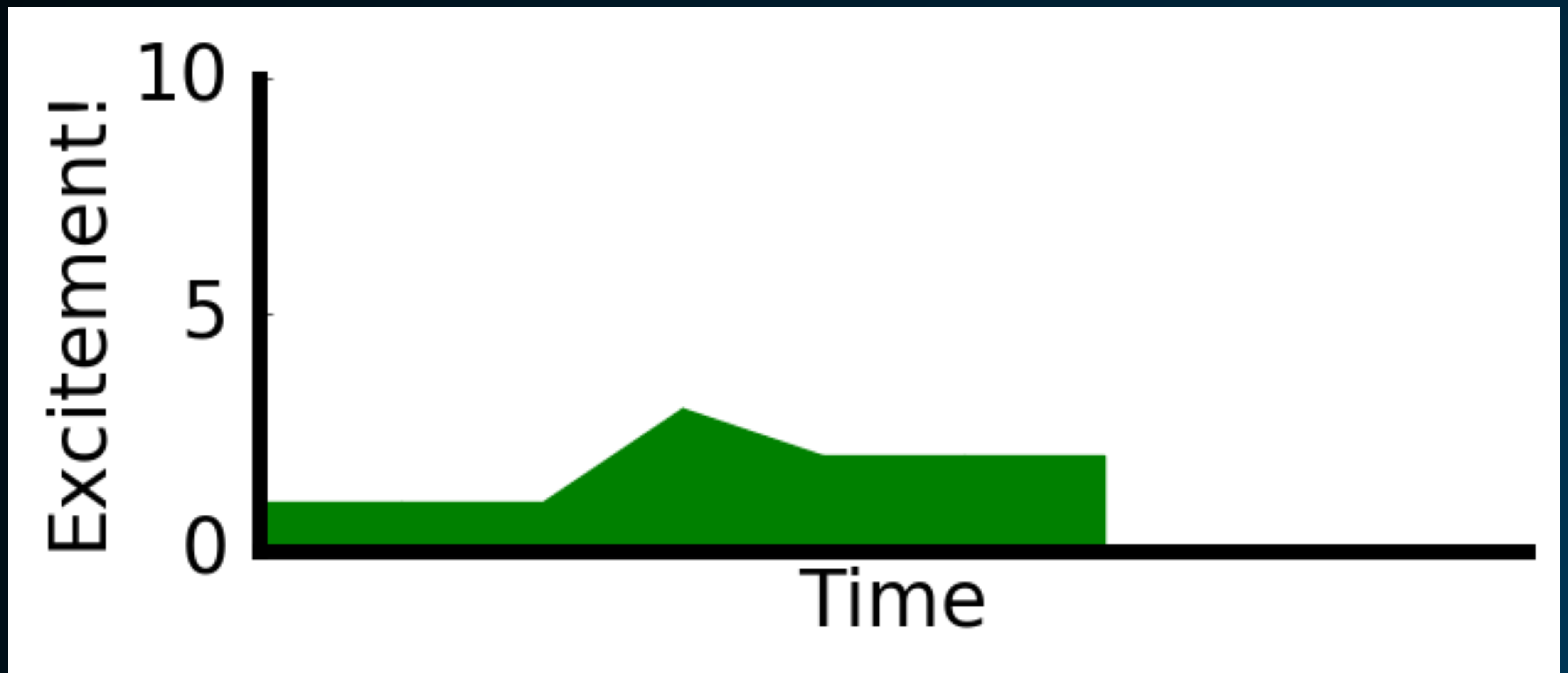


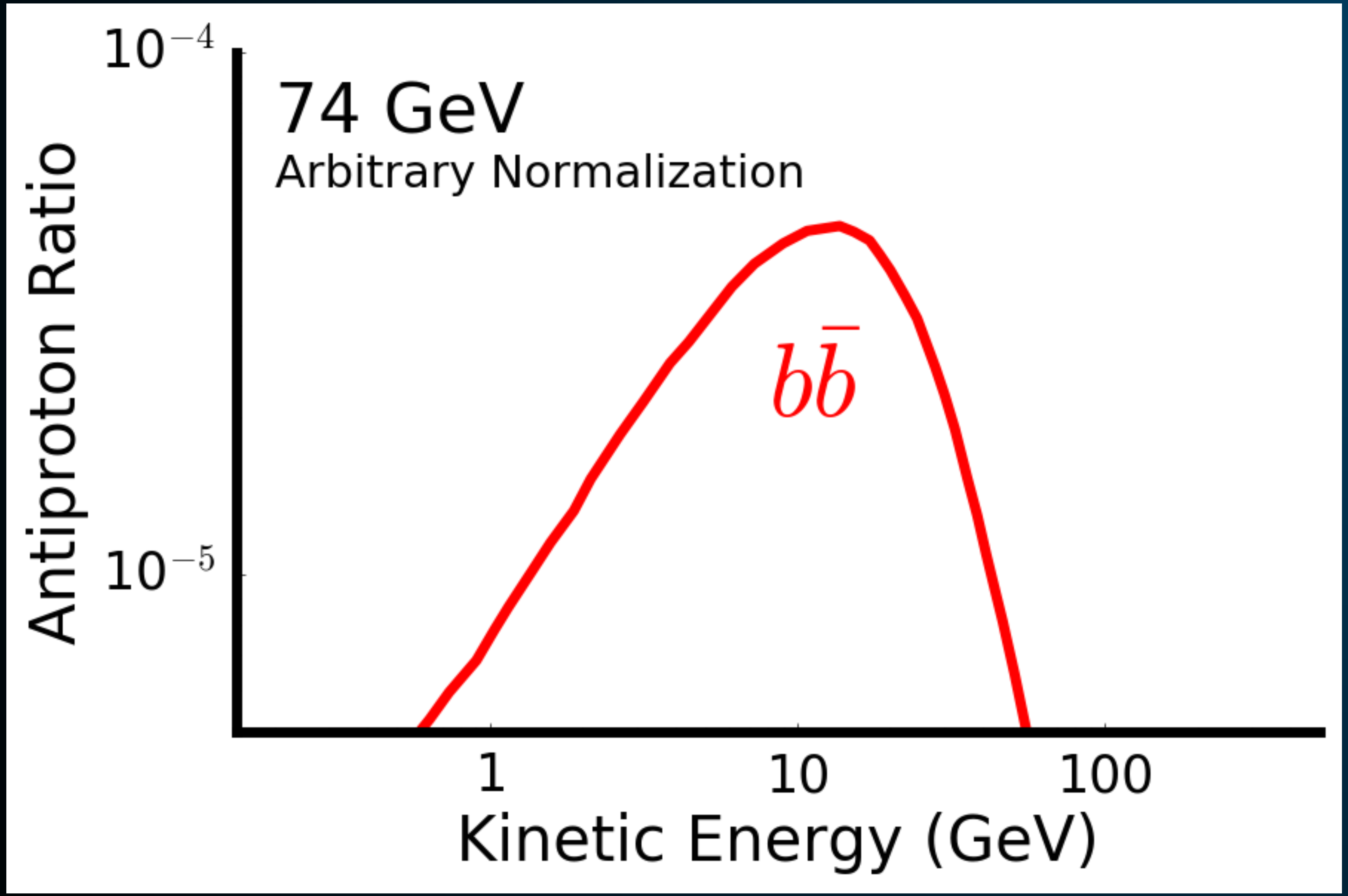


(Not an exhaustive list of observations)

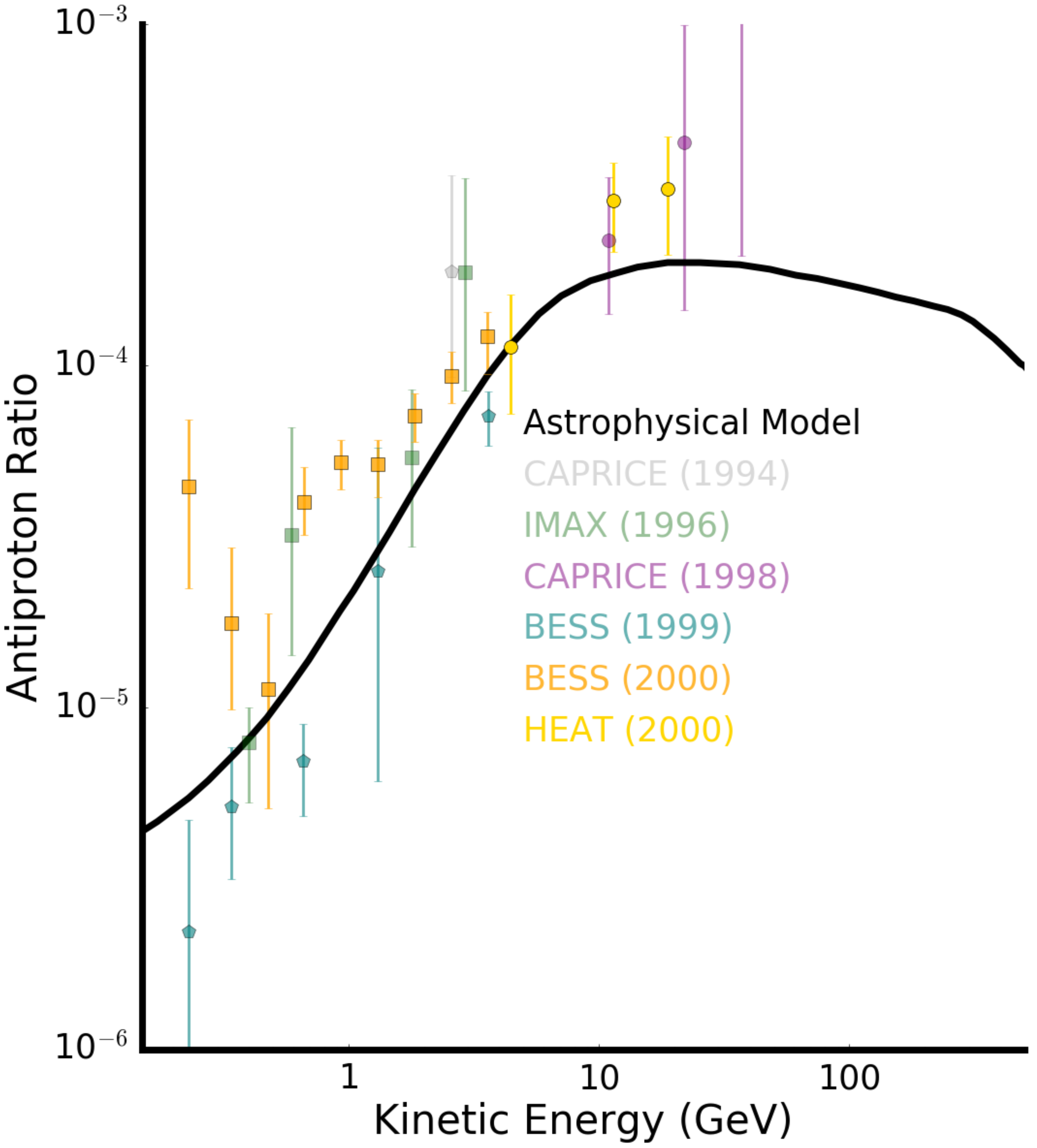


The Antiproton Excess





(Not an exhaustive list of observations)



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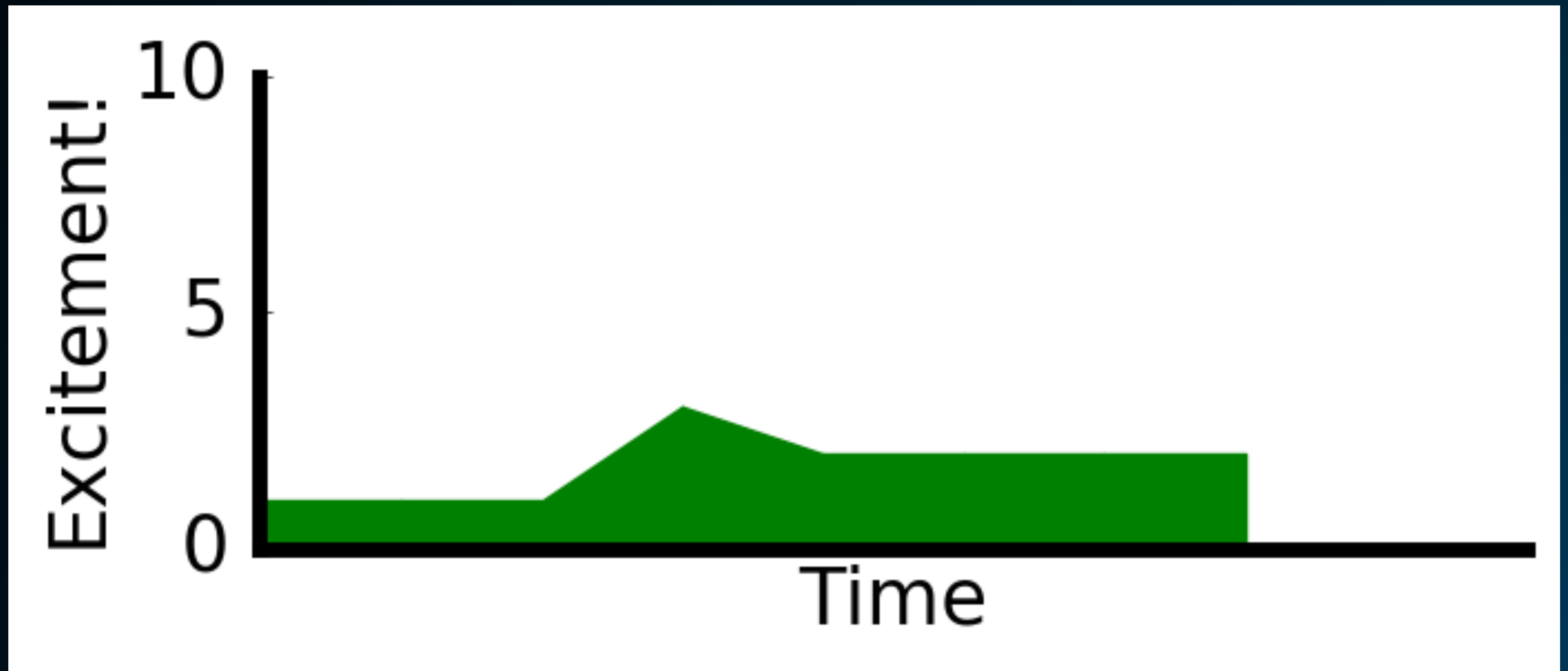
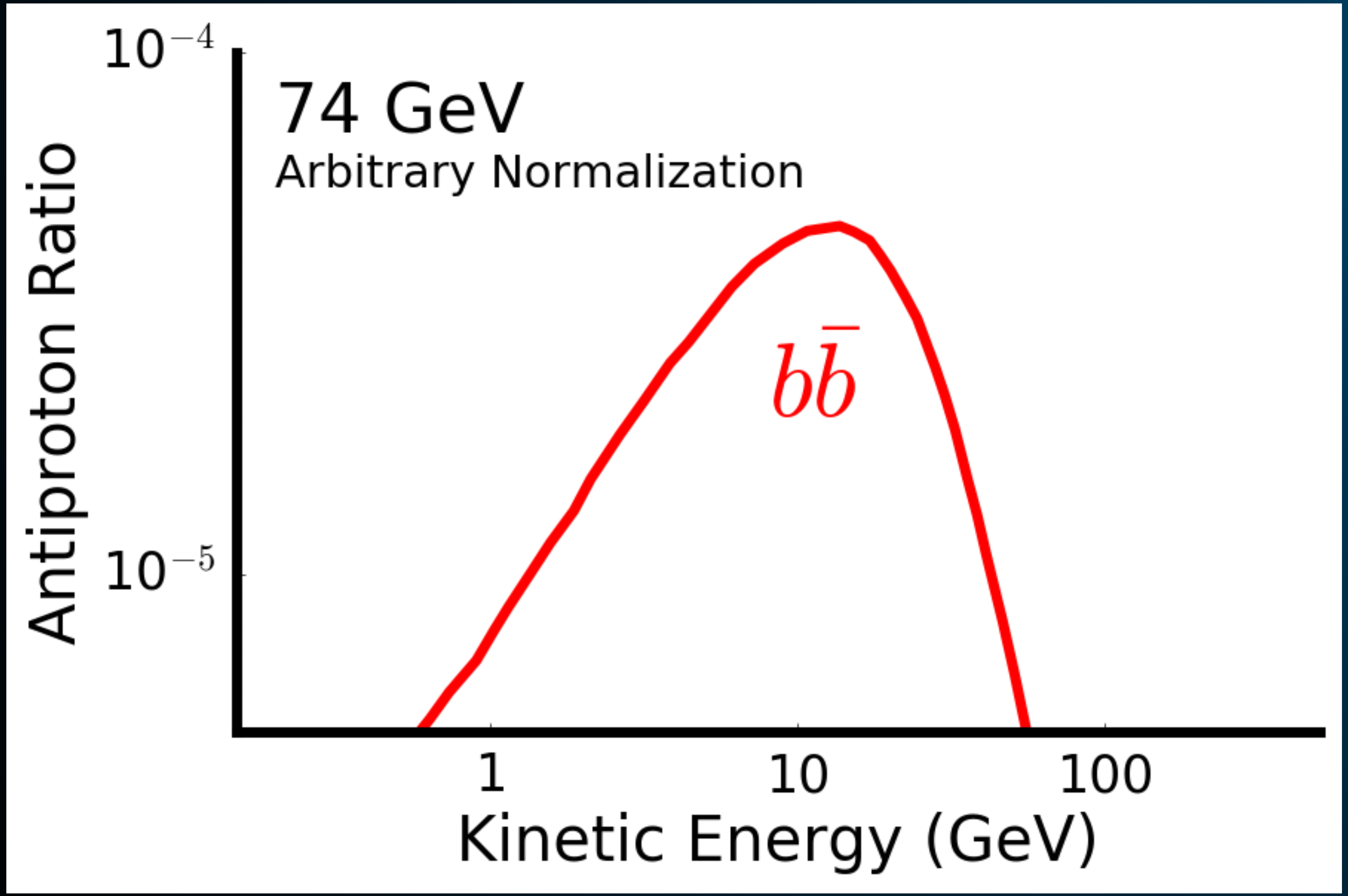
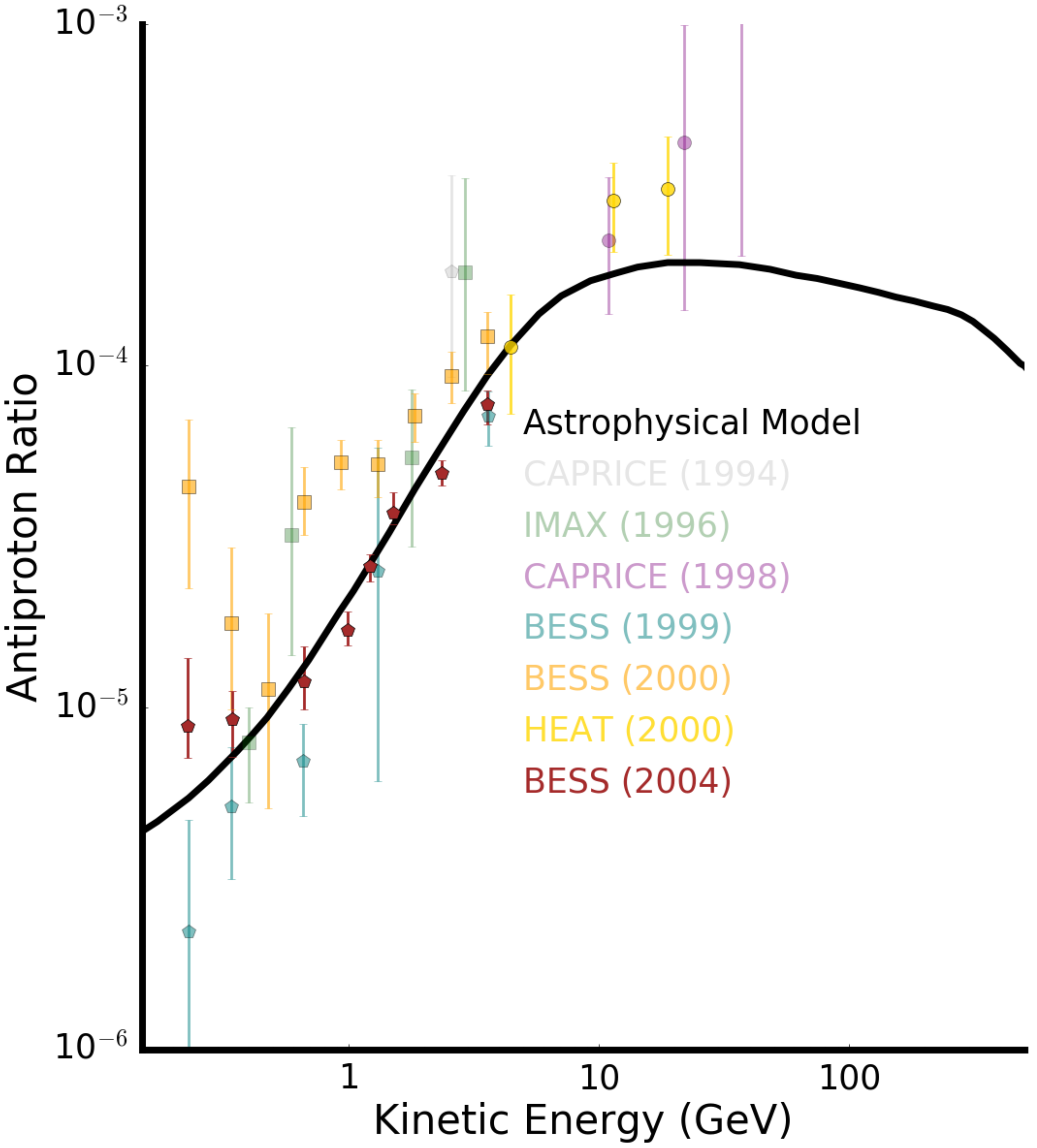
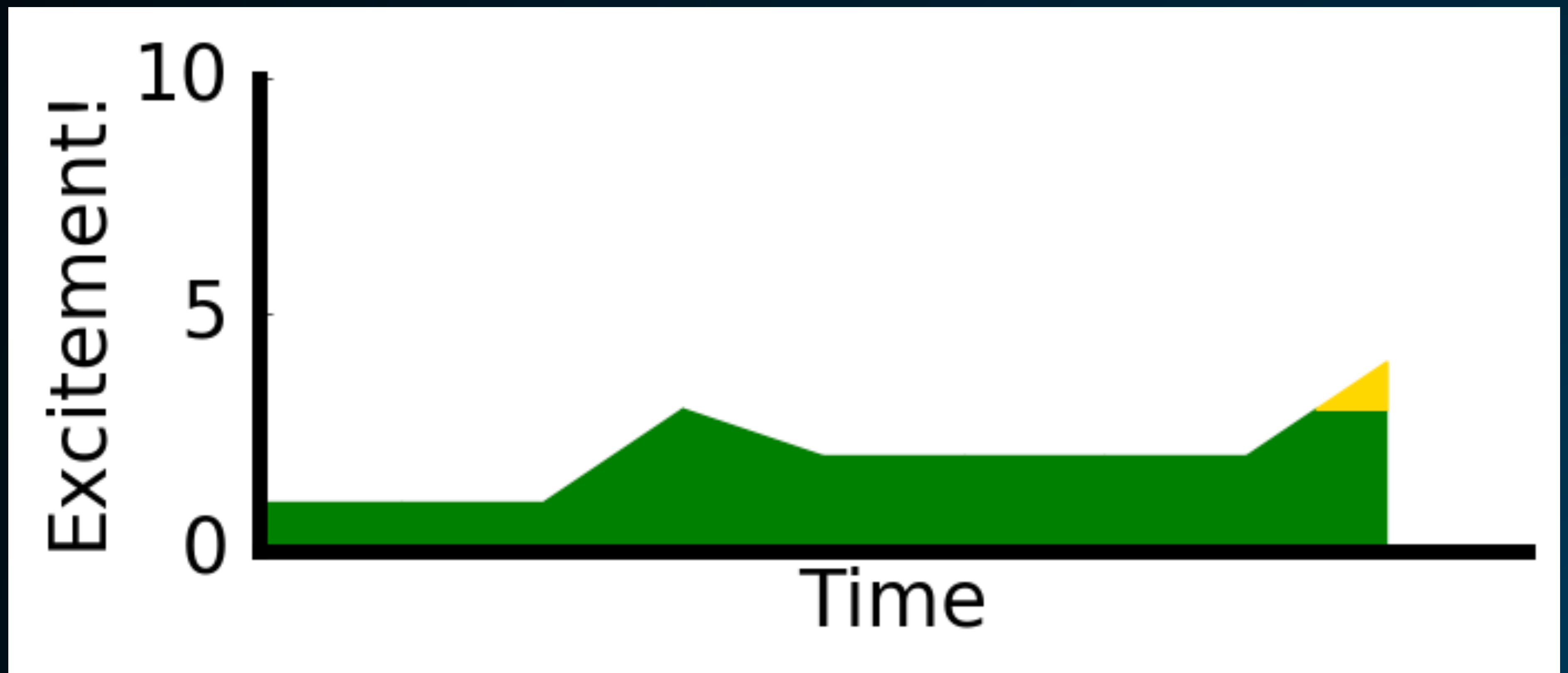


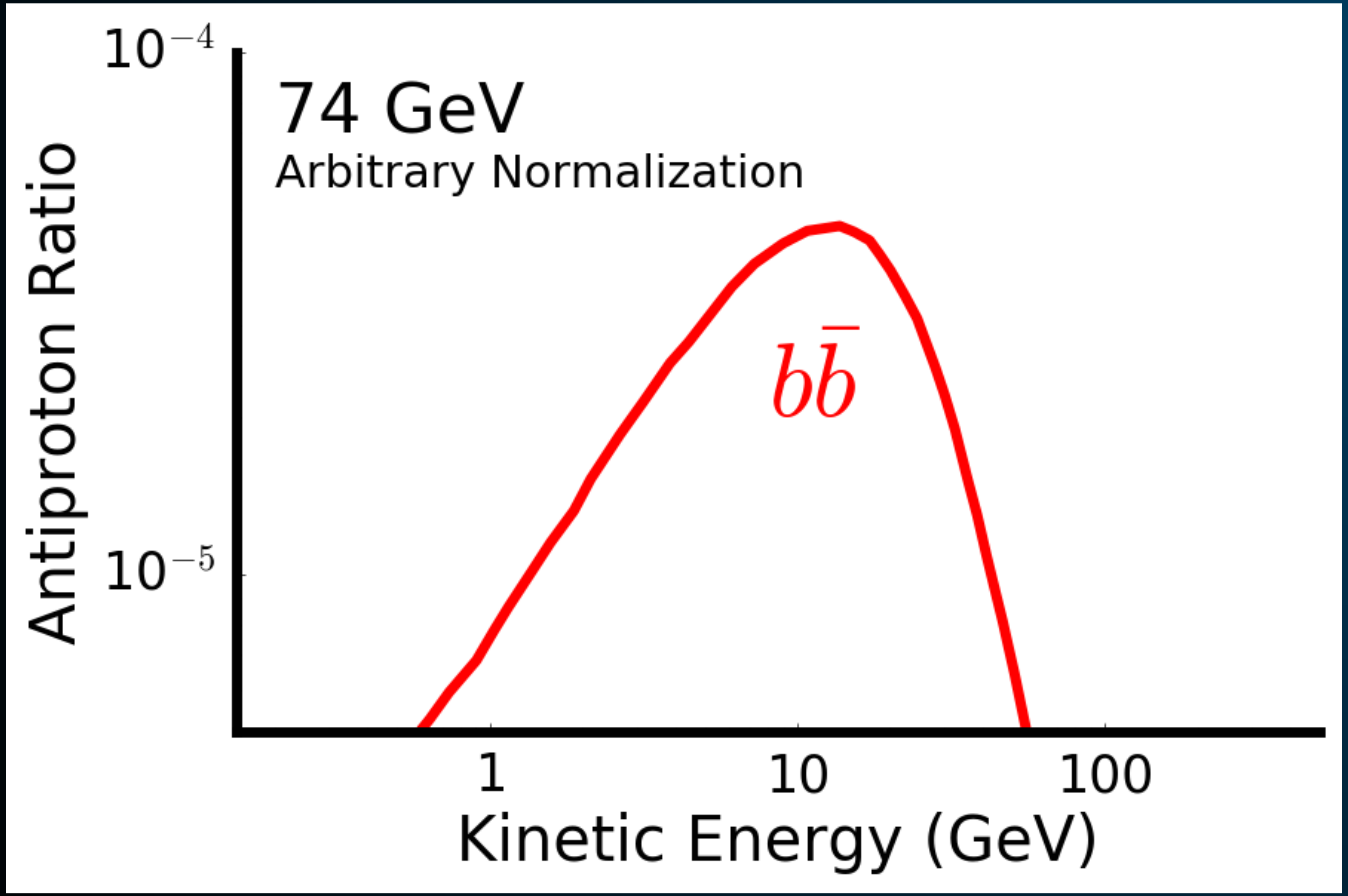


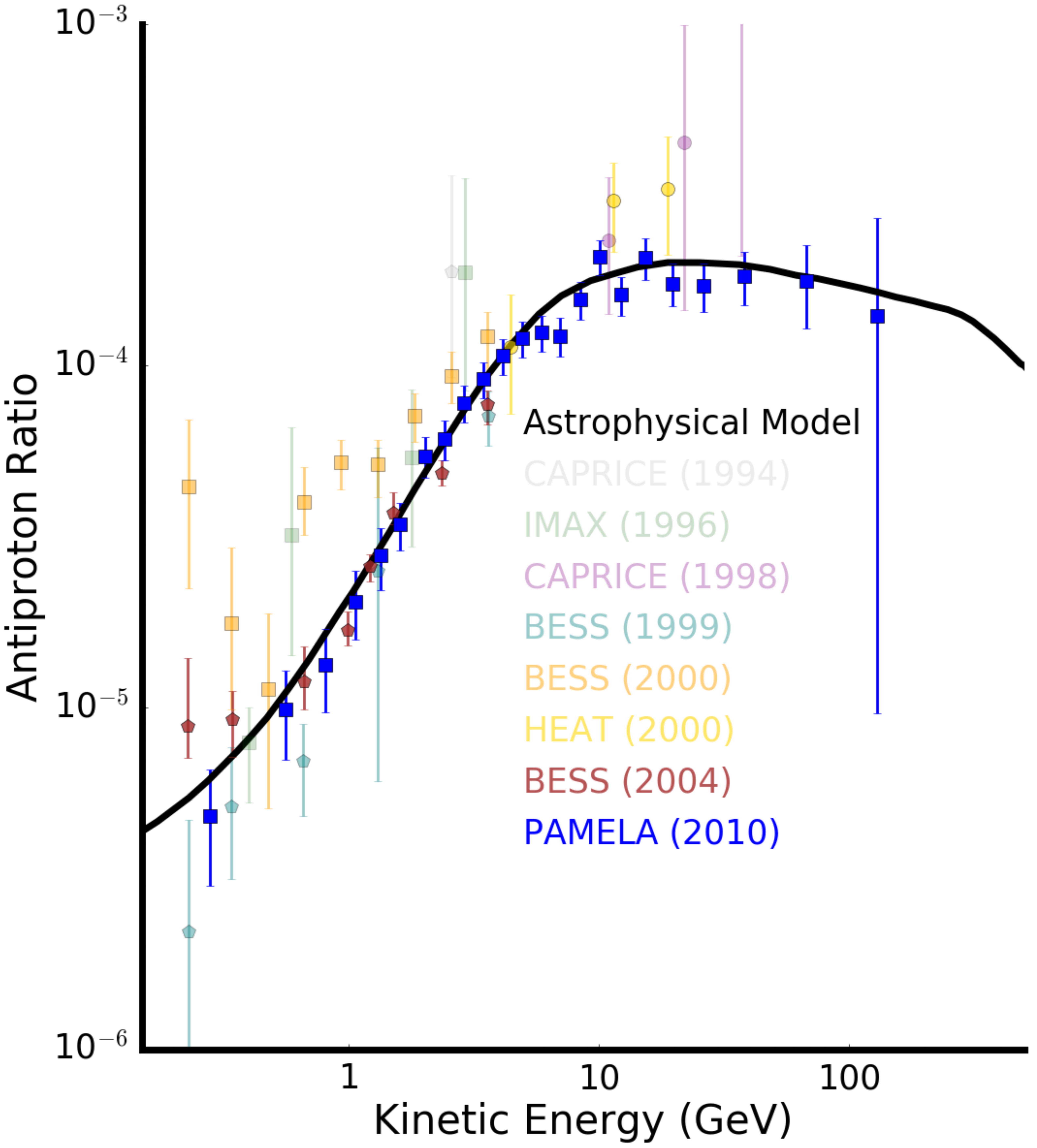
(Not an exhaustive list of observations)



The Antiproton Excess

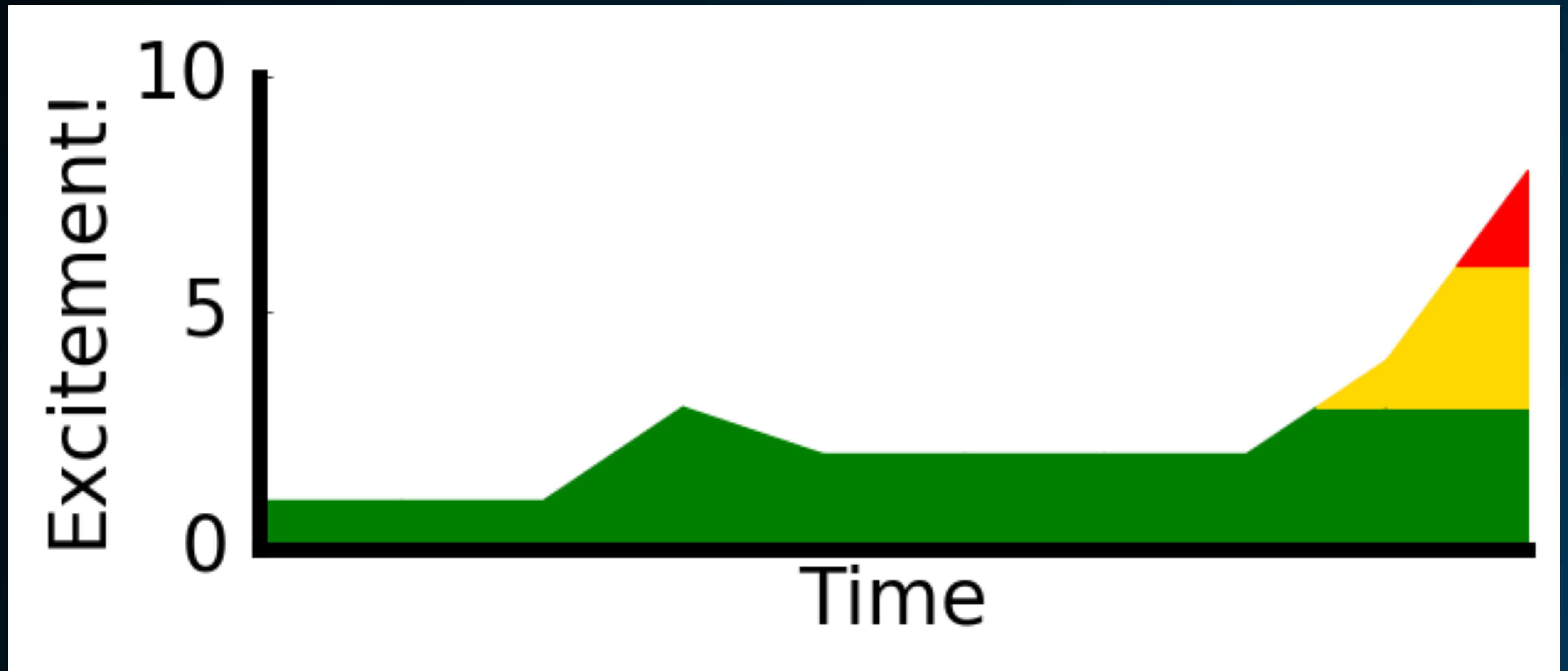


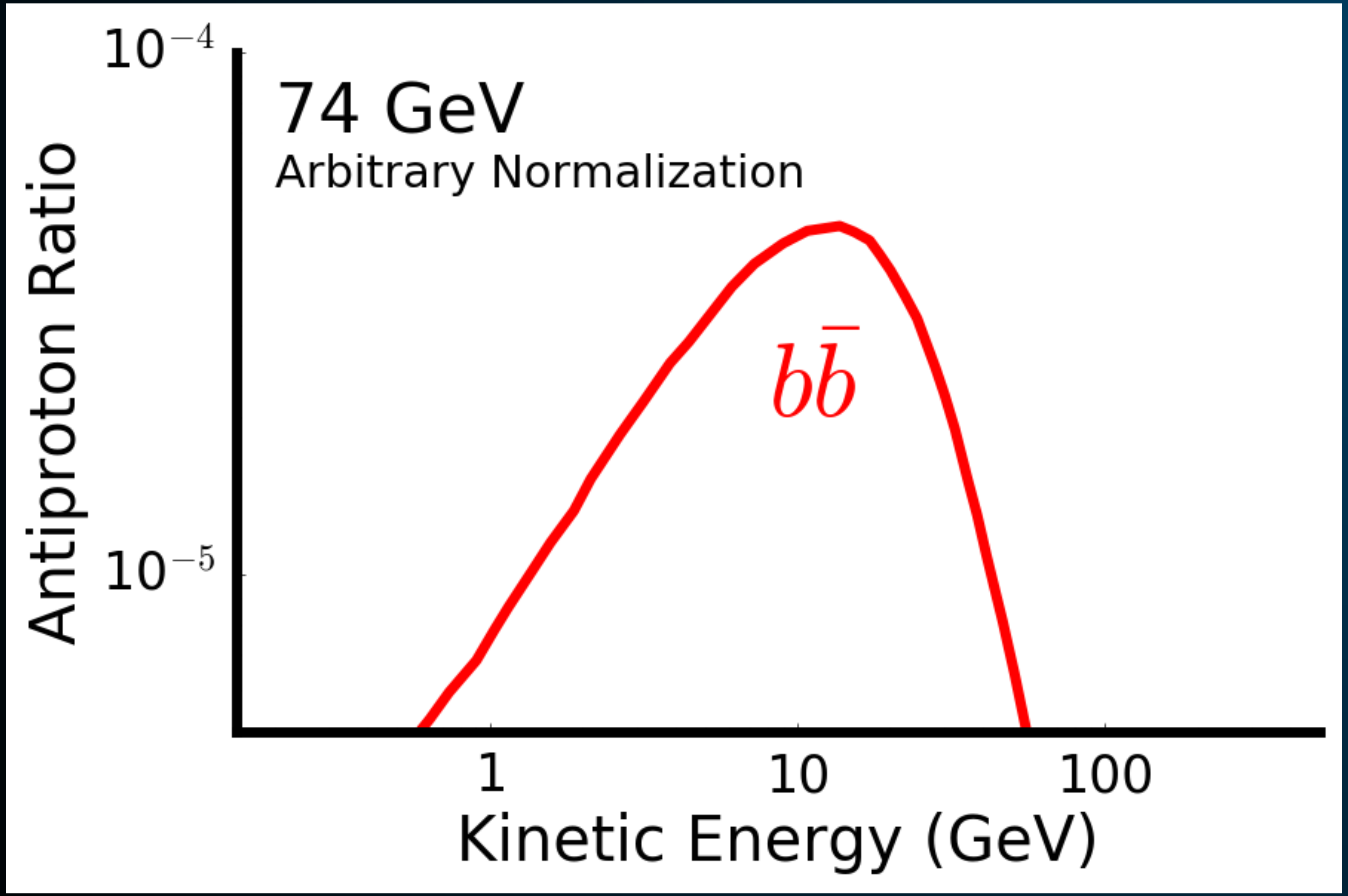




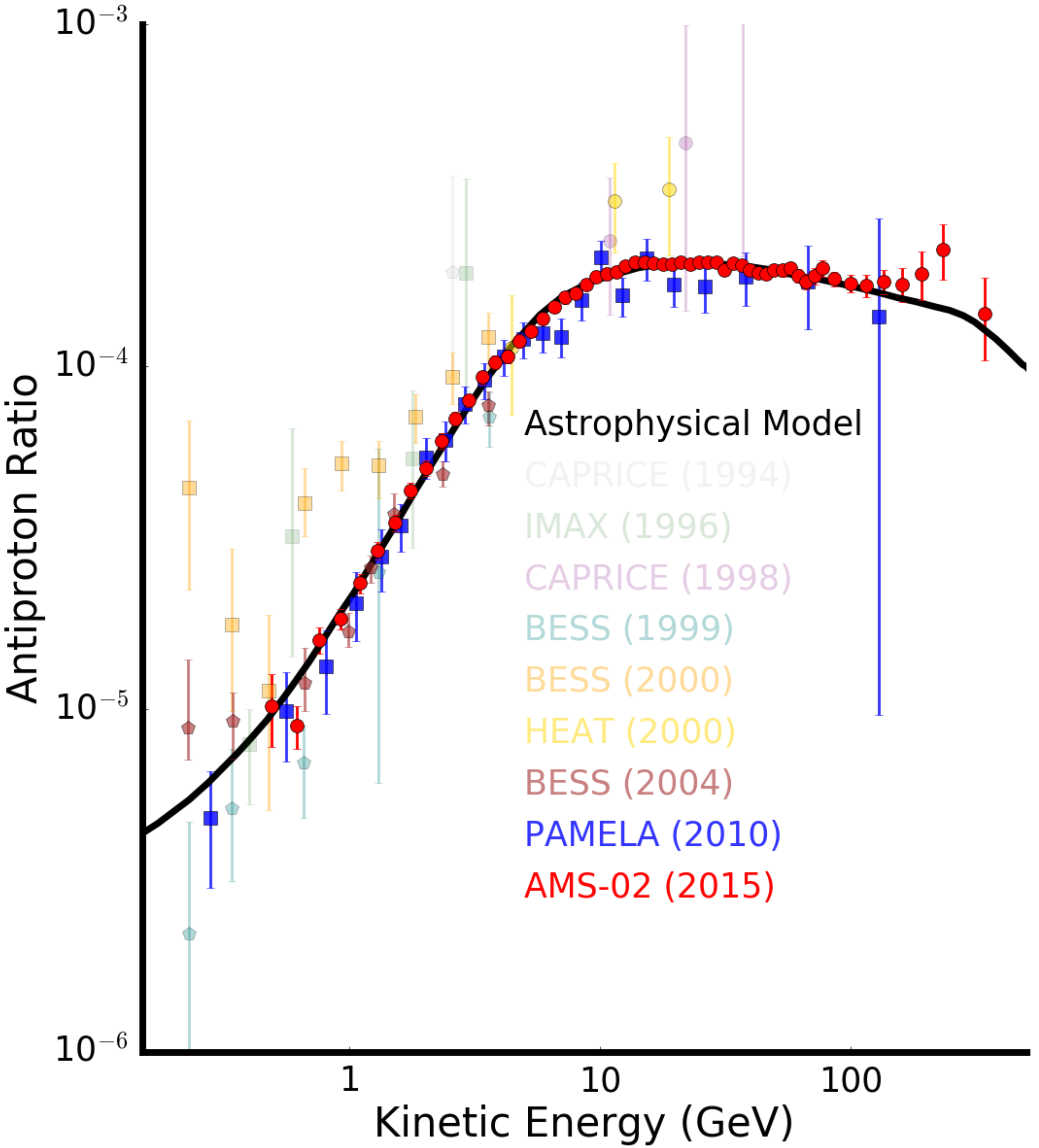
(Not an exhaustive list of observations)

The Antiproton Excess

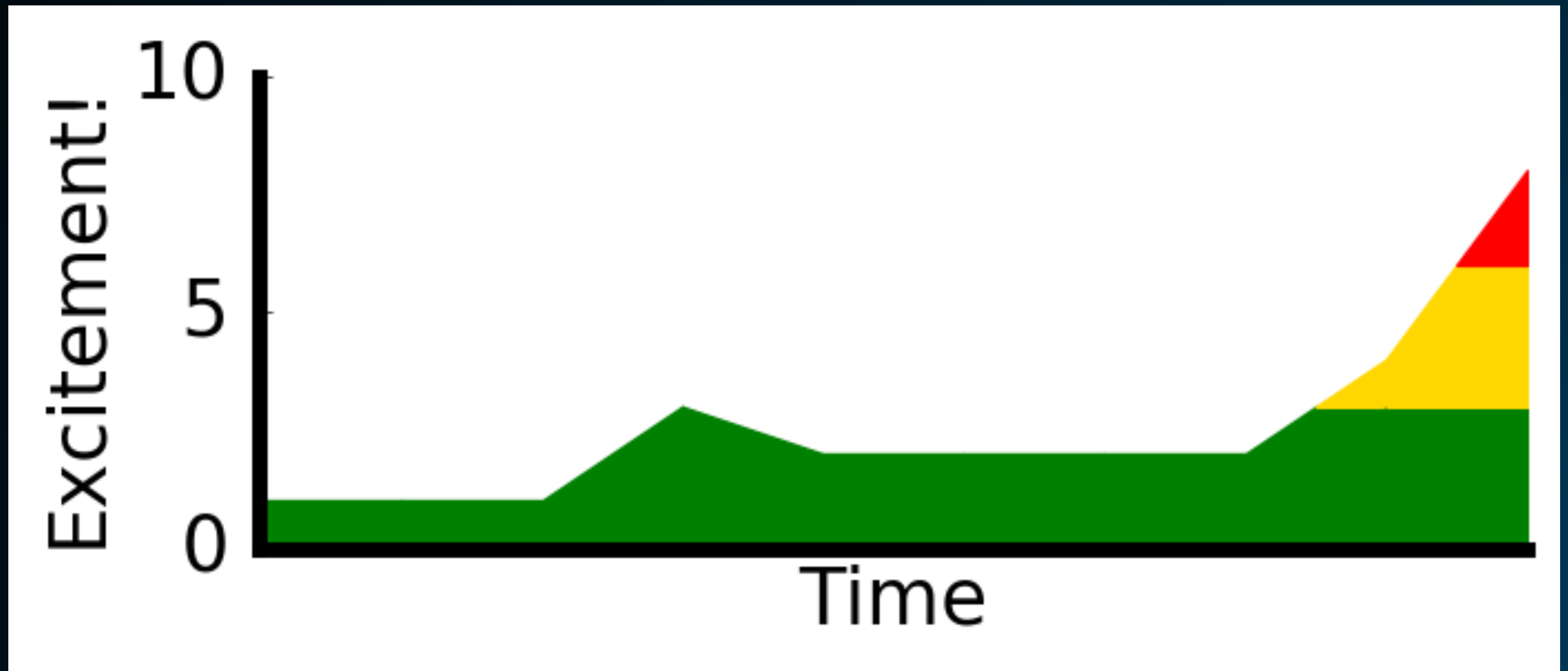


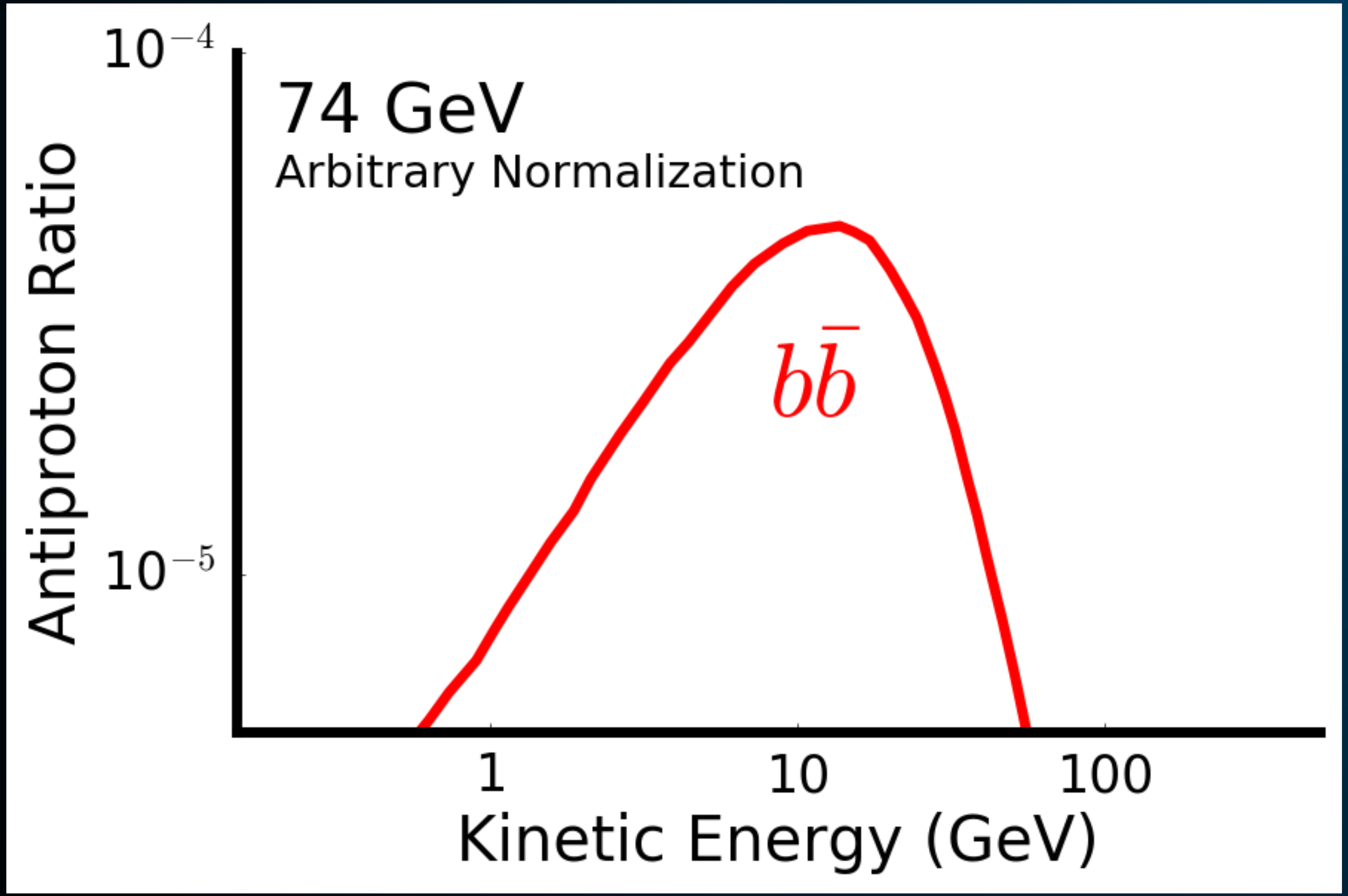


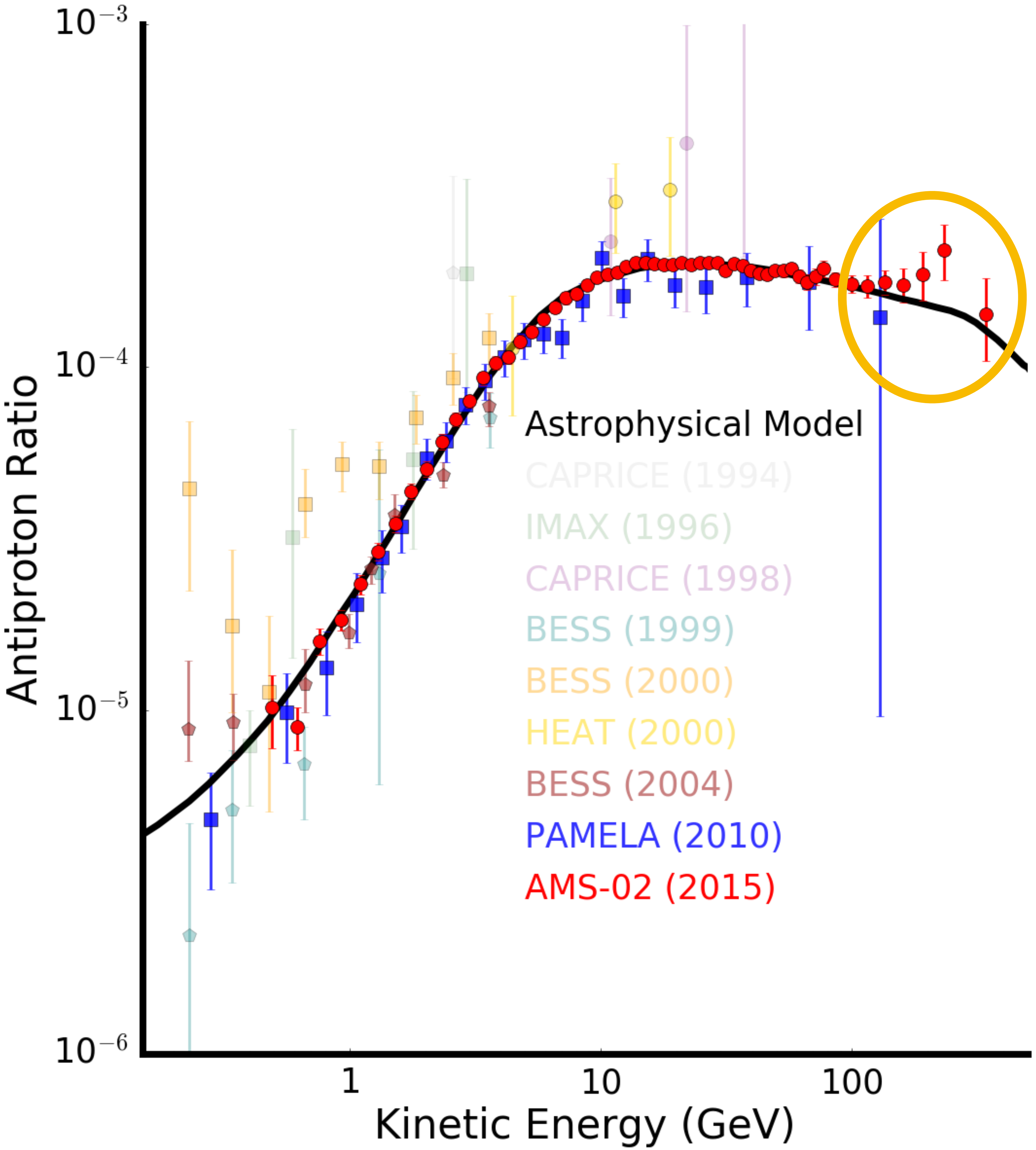
(Not an exhaustive list of observations)



The Antiproton Excess

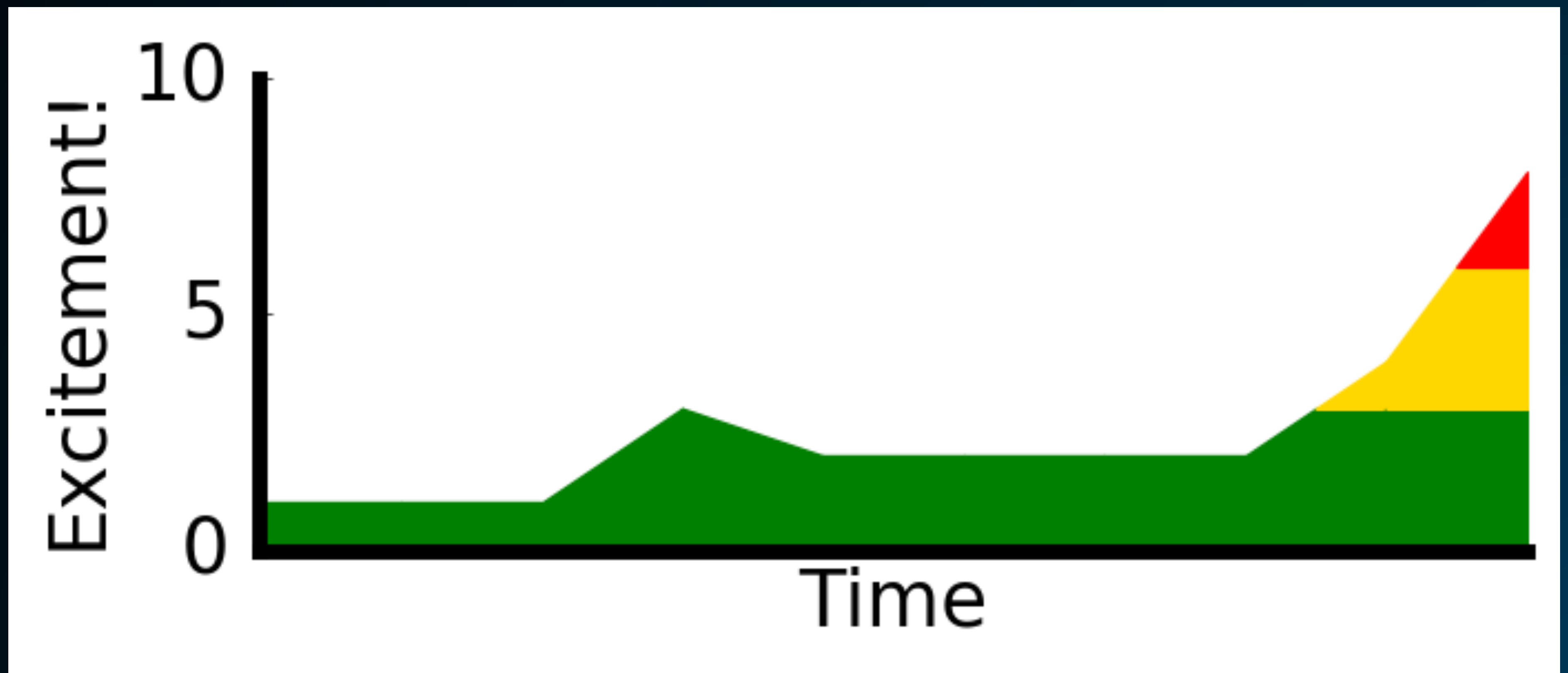


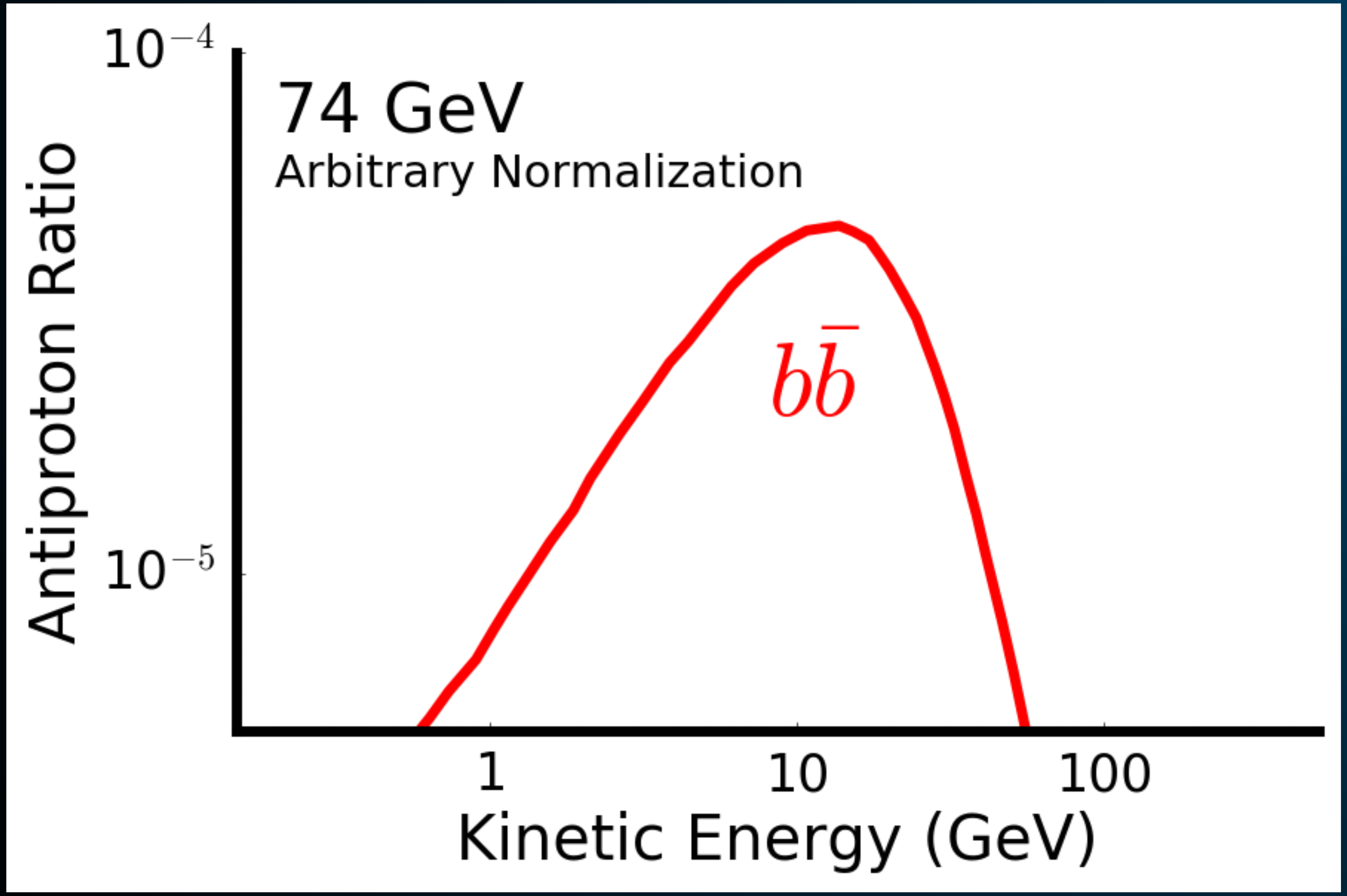


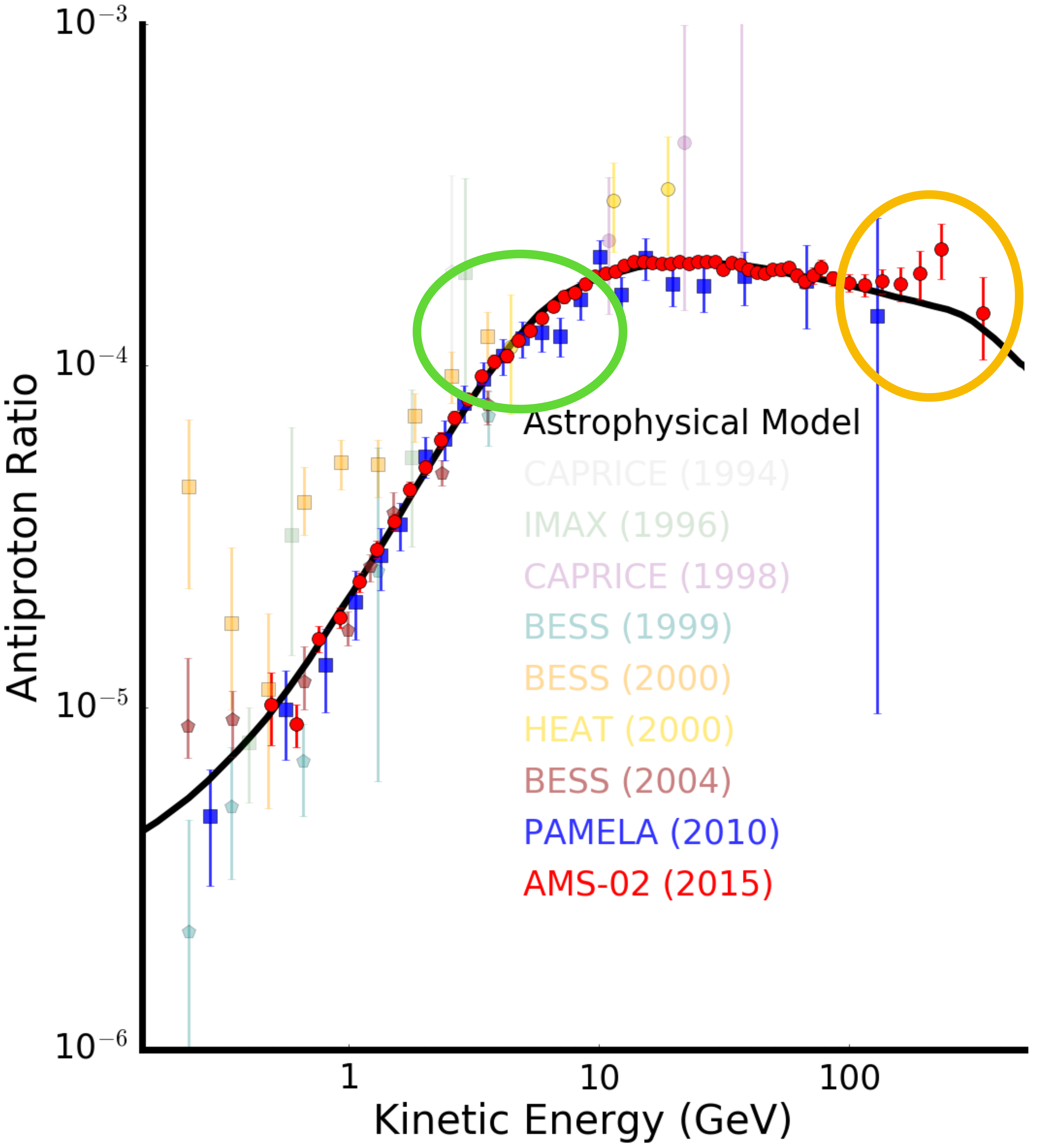


(Not an exhaustive list of observations)

The Antiproton Excess





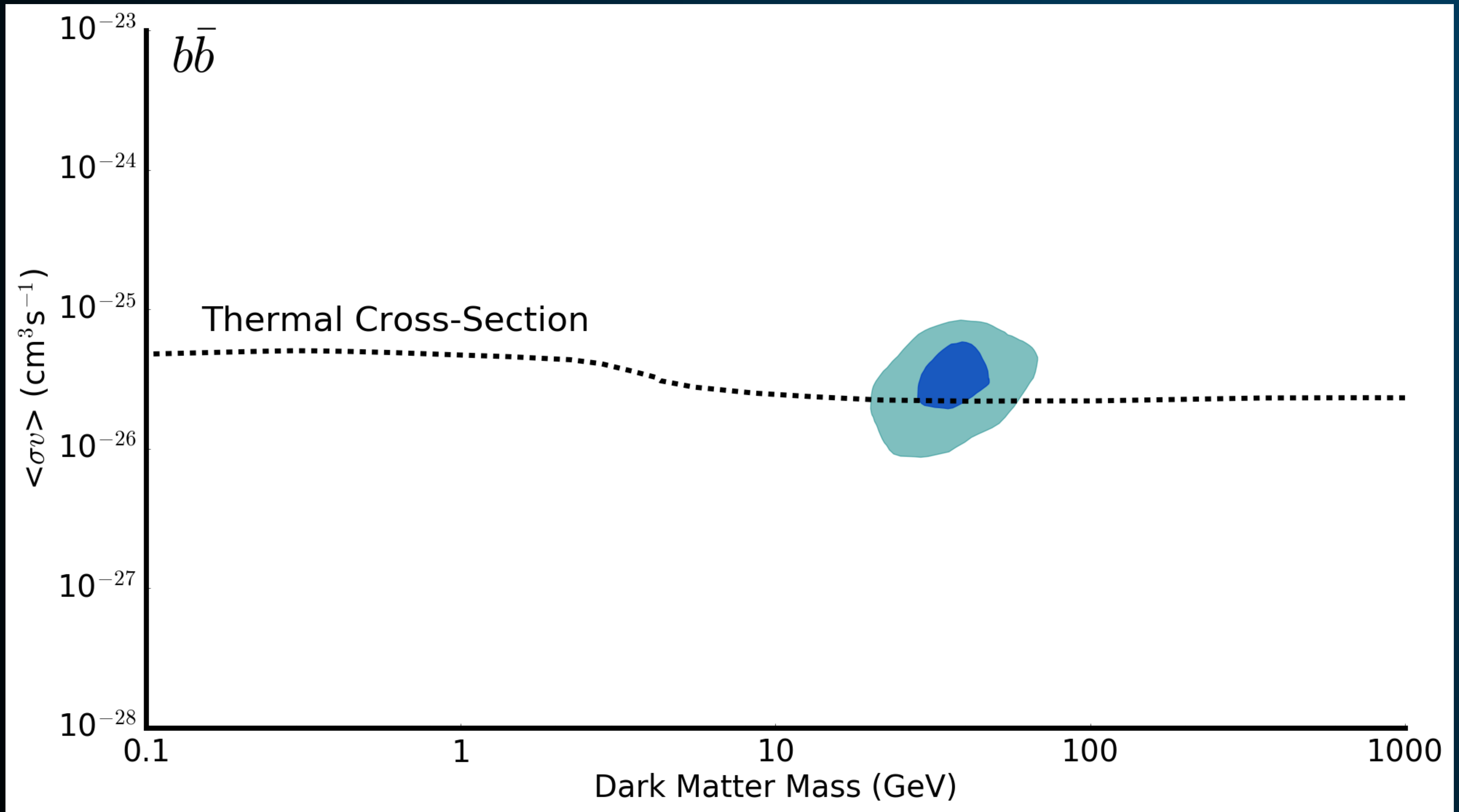


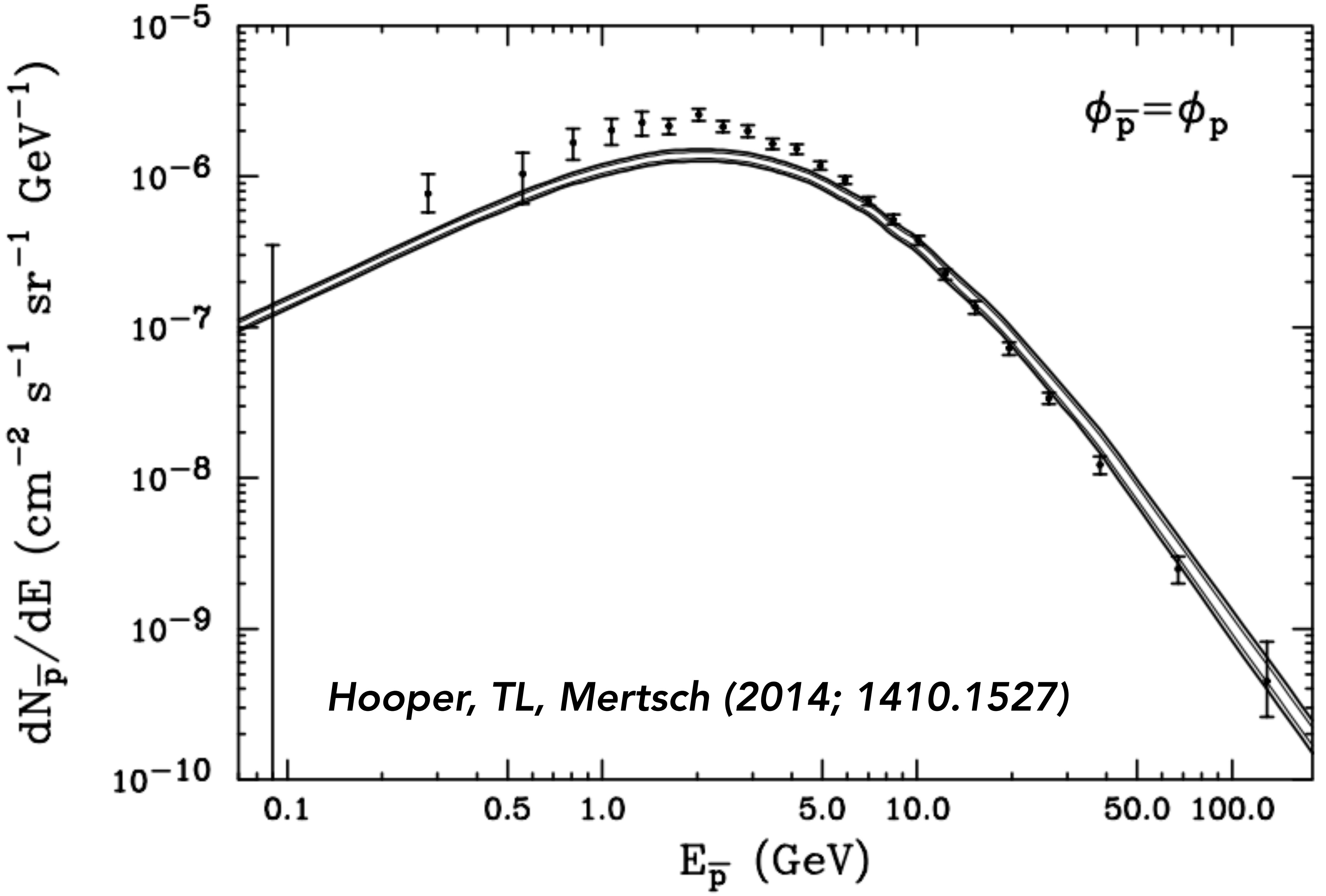
(Not an exhaustive list of observations)

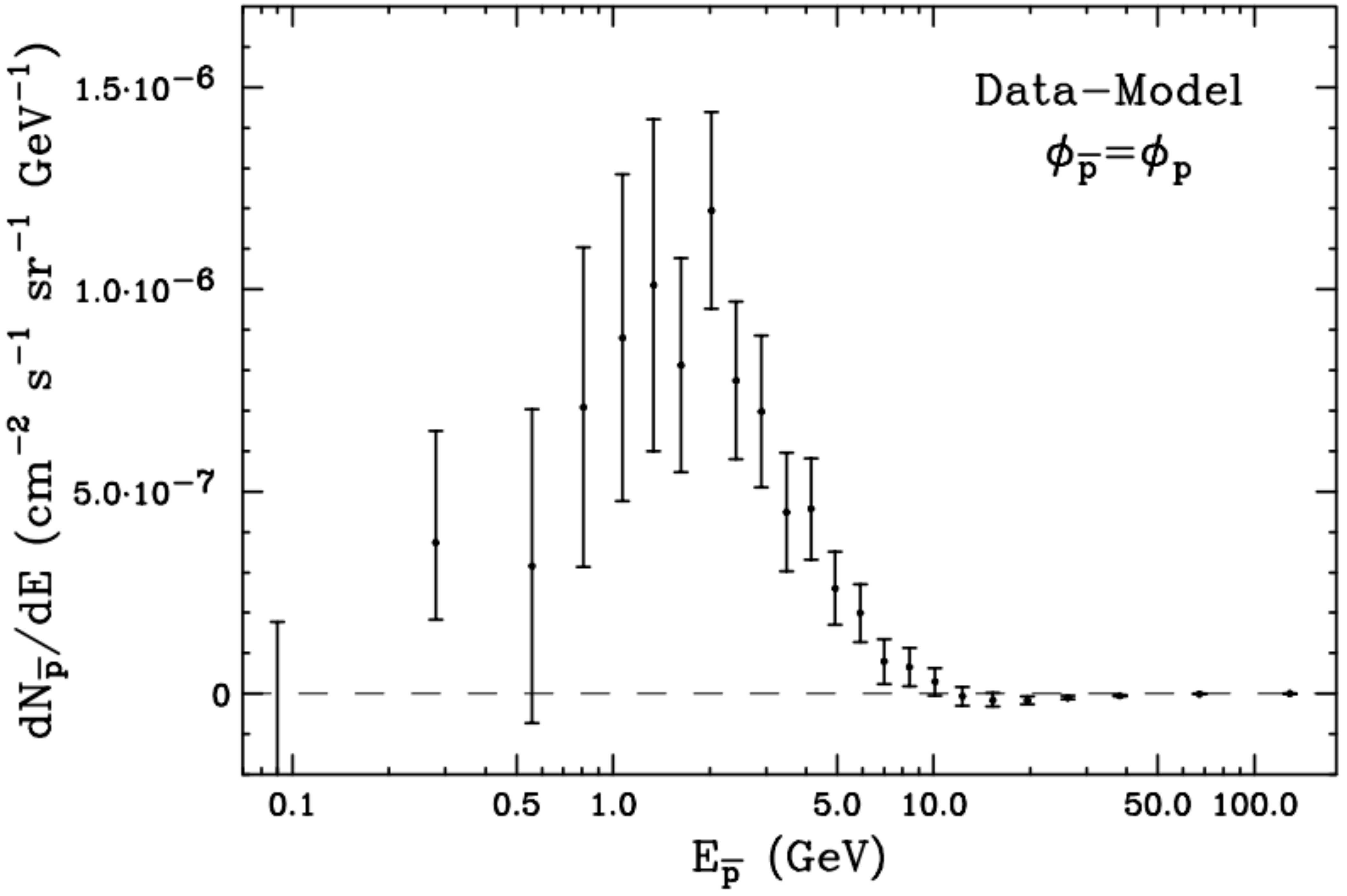
The Antiproton Excess

Hint of Excess in ~5 GeV antiprotons!

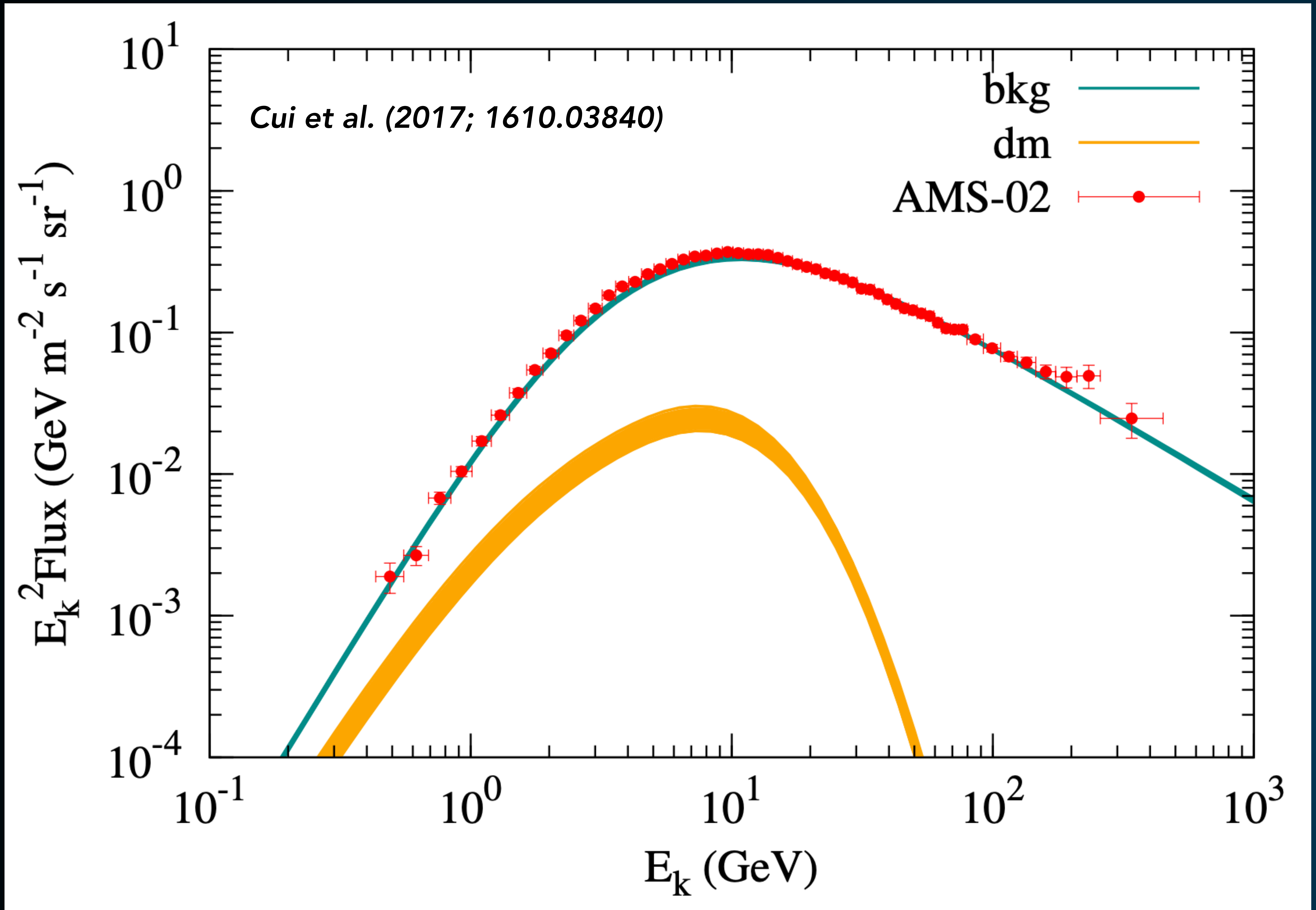
Astrophysical Uncertainties can significantly affect the signal.

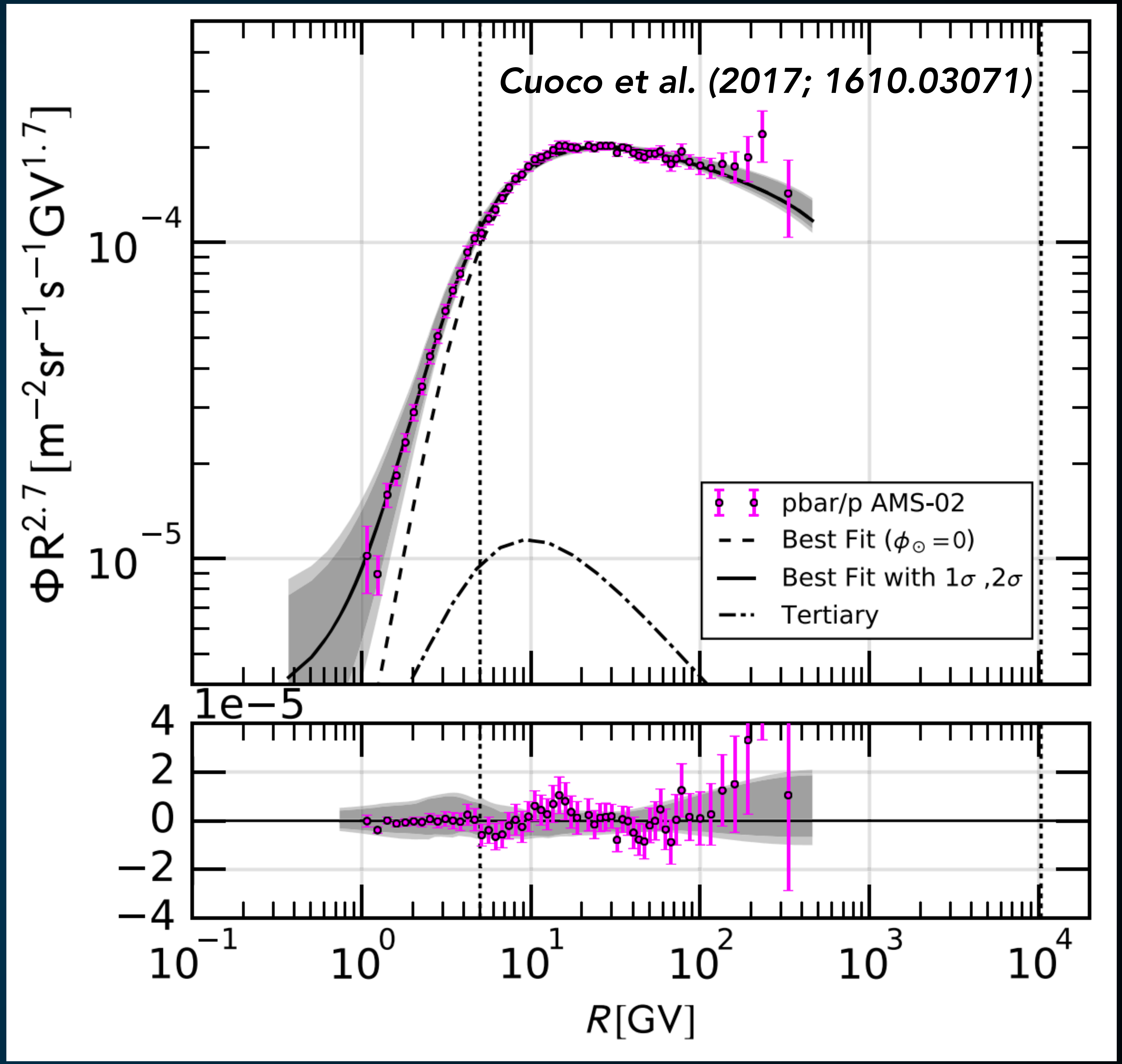






The Antiproton Excess





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

Significance approaching (or past) 5σ !

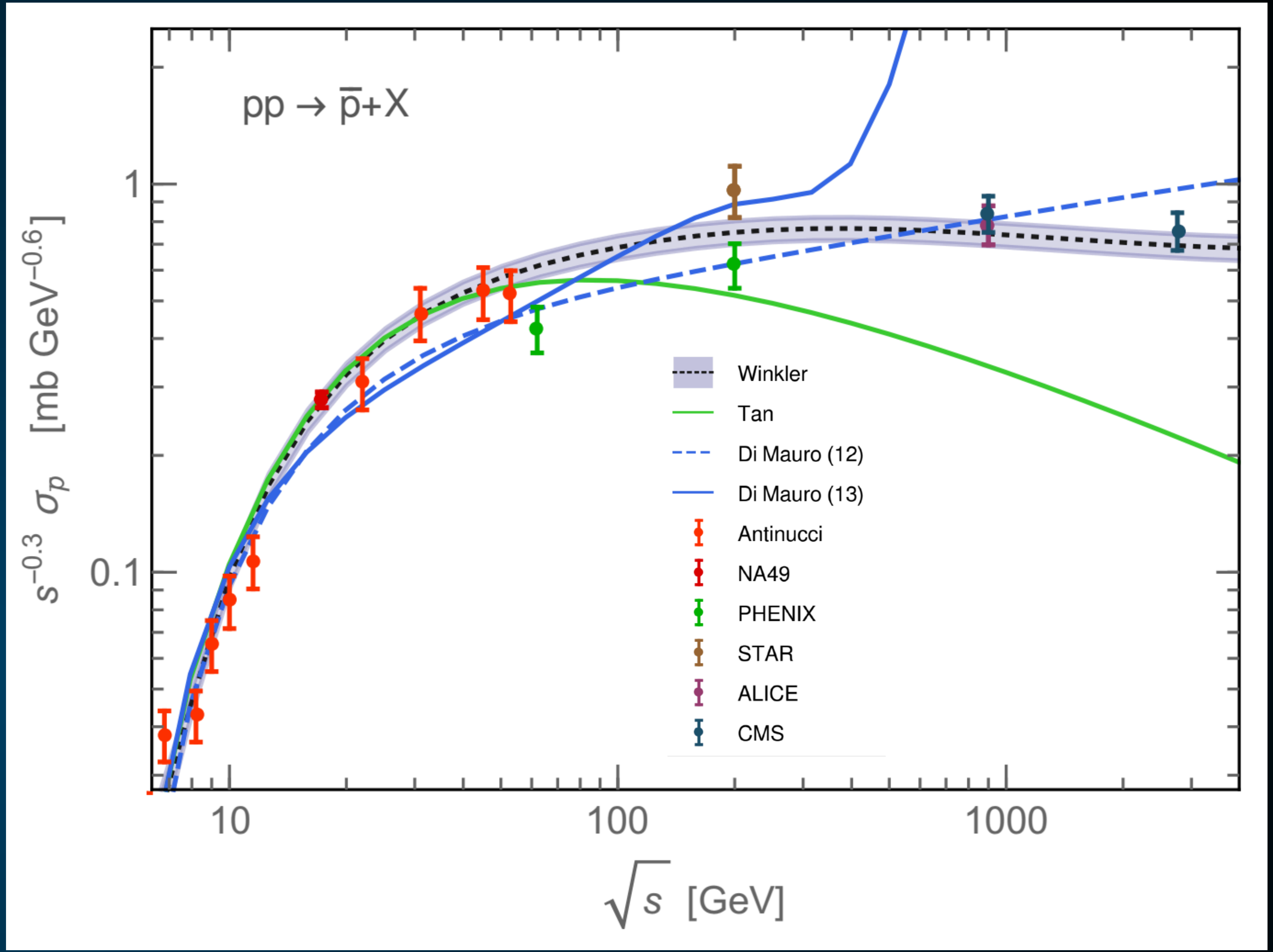

$b\bar{b}$
PAMELA (Hooper et al.)
AMS-02 (Cuoco et al.)
Thermal Cross-Section
AMS-02 (Cholis et al.)
AMS-02 (Cui et al.)
$<\sigma v>$ (cm^{3}s^{-1})
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
1
10
100
1000
Dark Matter Mass (GeV)

The Antiproton Excess - 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



The Antiproton Excess - A Detection?

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Solar Modulation

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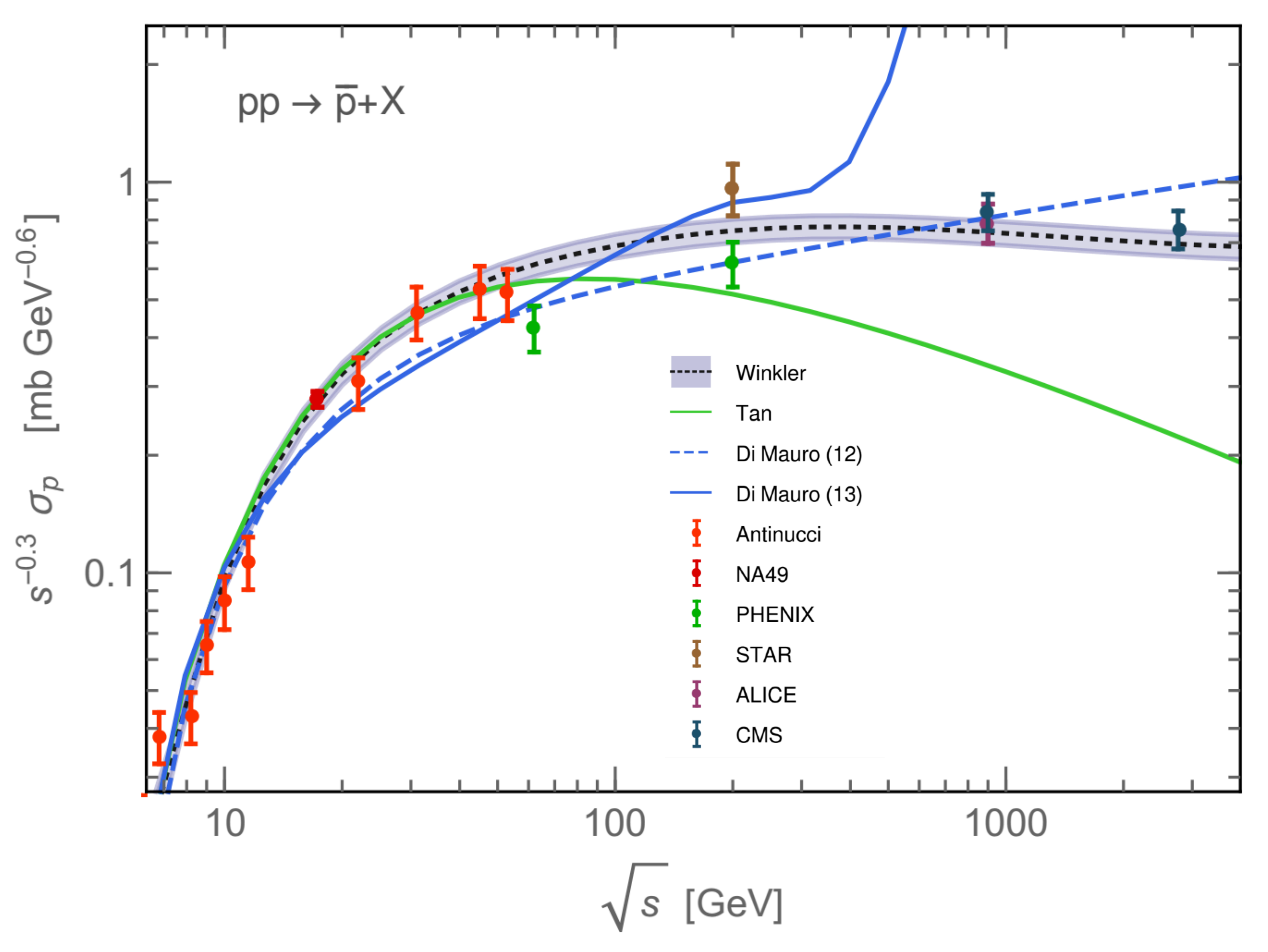


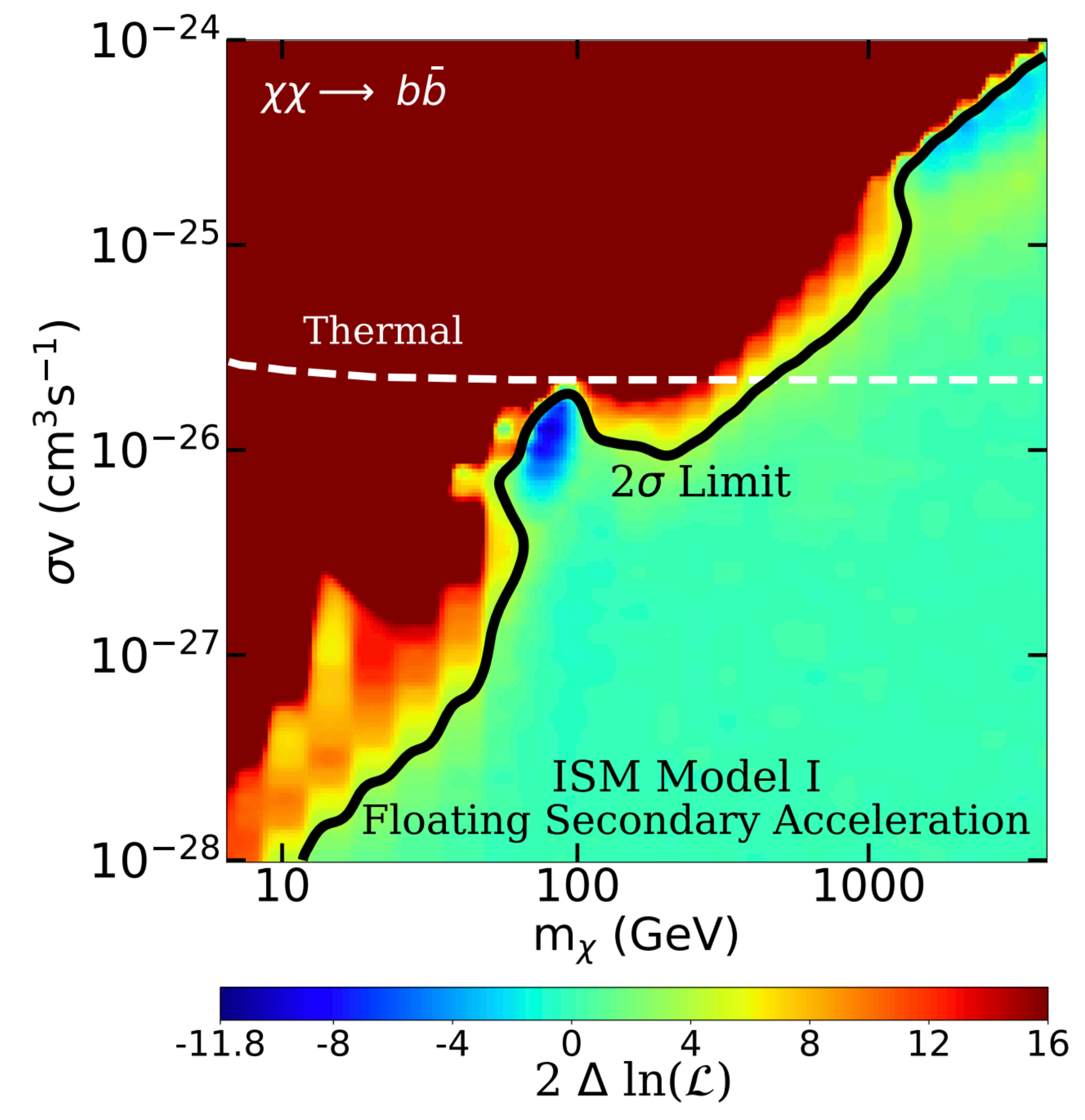
Galactic Primary to Secondary Ratios - Future AMS-02 Data!

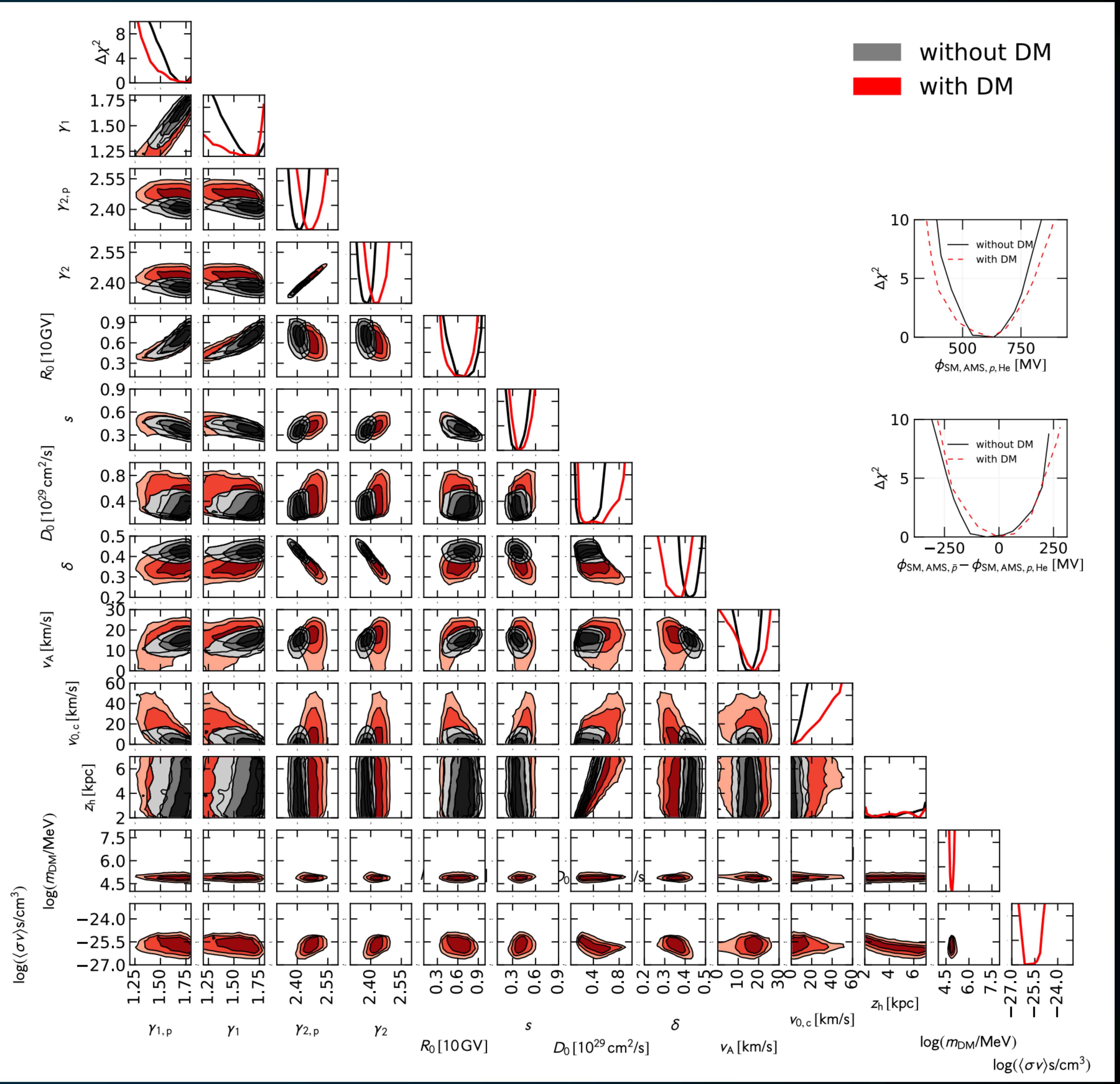
Inhomogeneous Diffusion - TeV Halos

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

Antiproton Production Cross-Section - LHCb / Laboratory Experiments

The Antiproton Excess — Robust Analyses

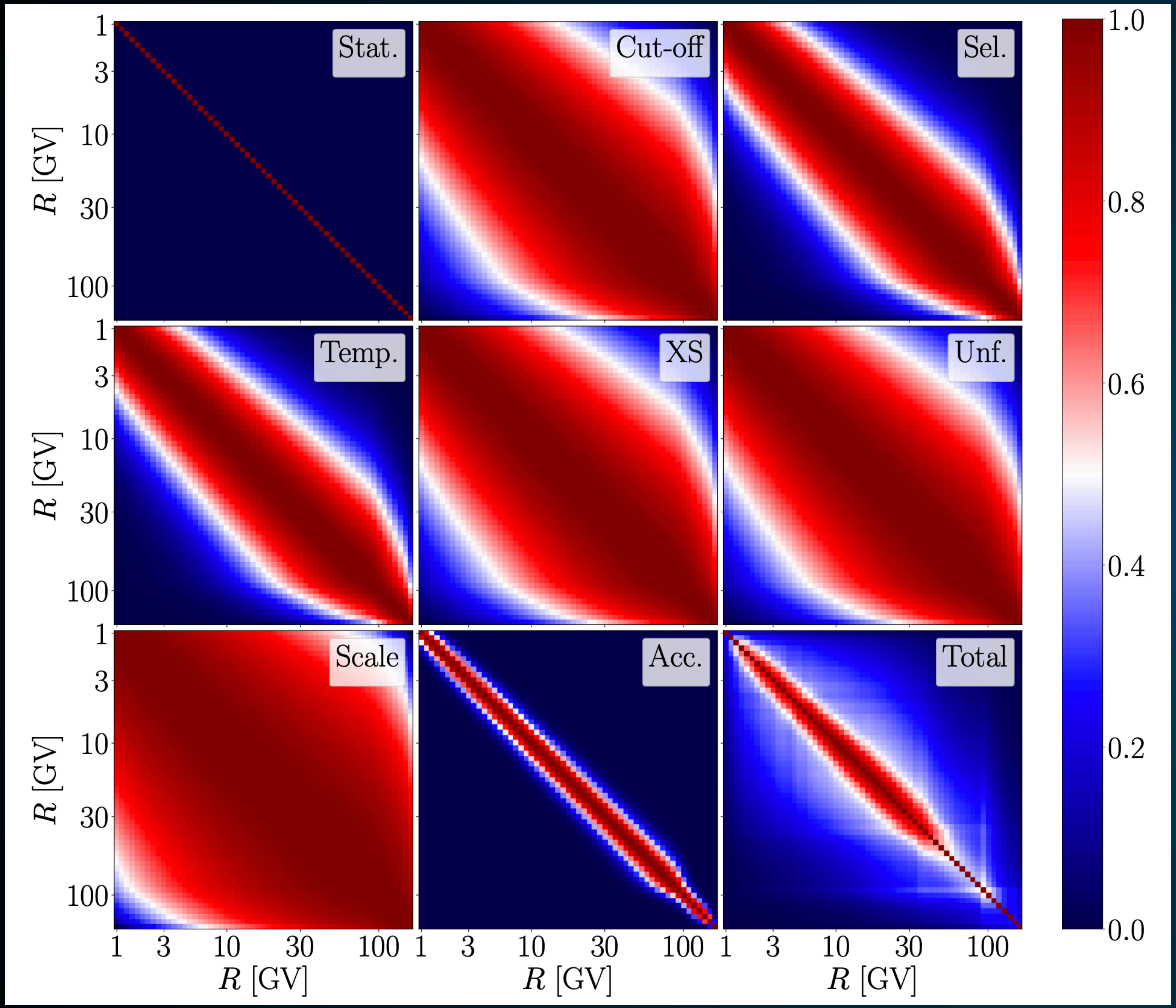


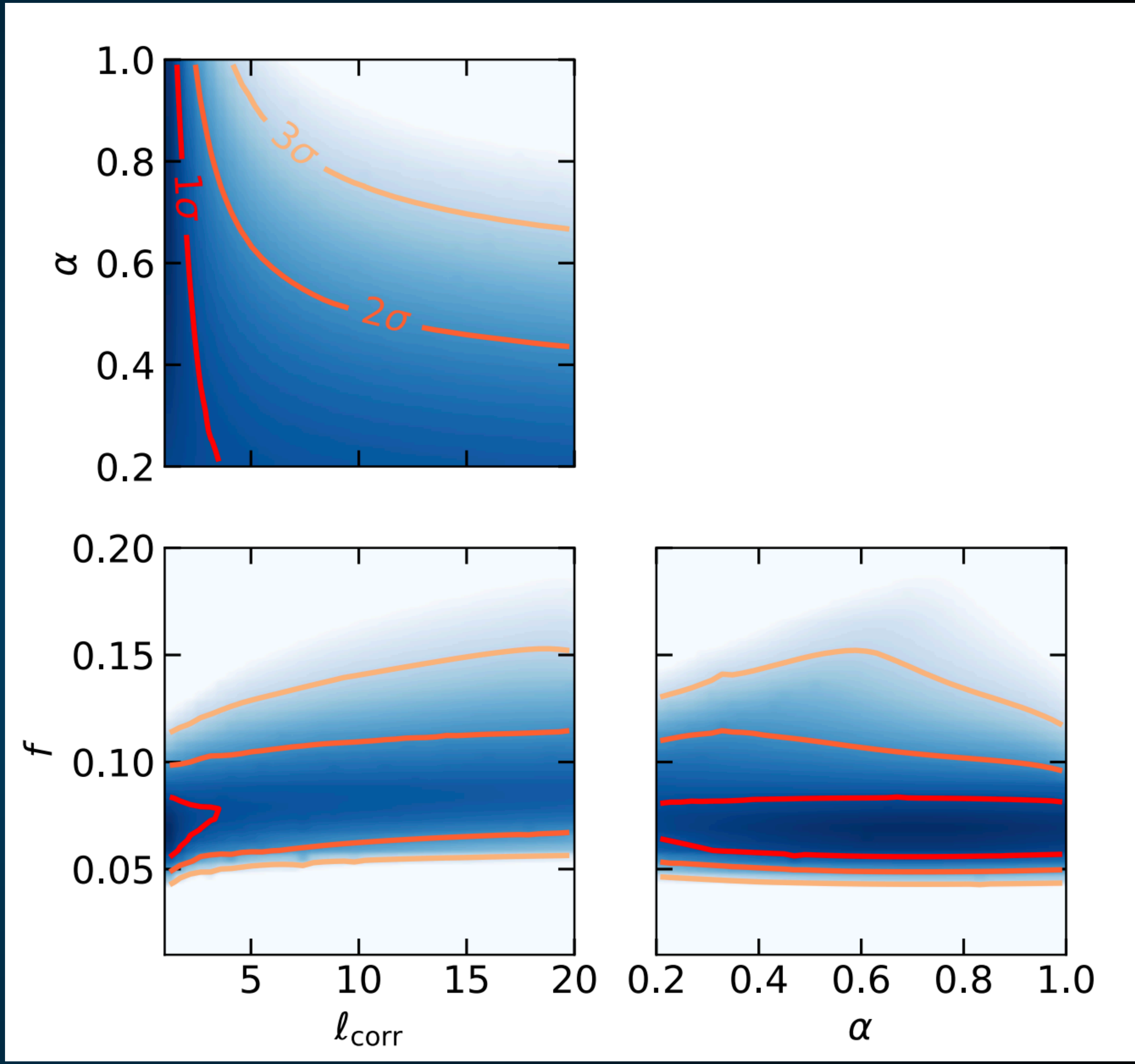


Cholis, Linden, Hooper (2019; 1903.02549)

Cuoco et. al. (2019; 1903.01472)

The Antiproton Excess — Correlation Matrices



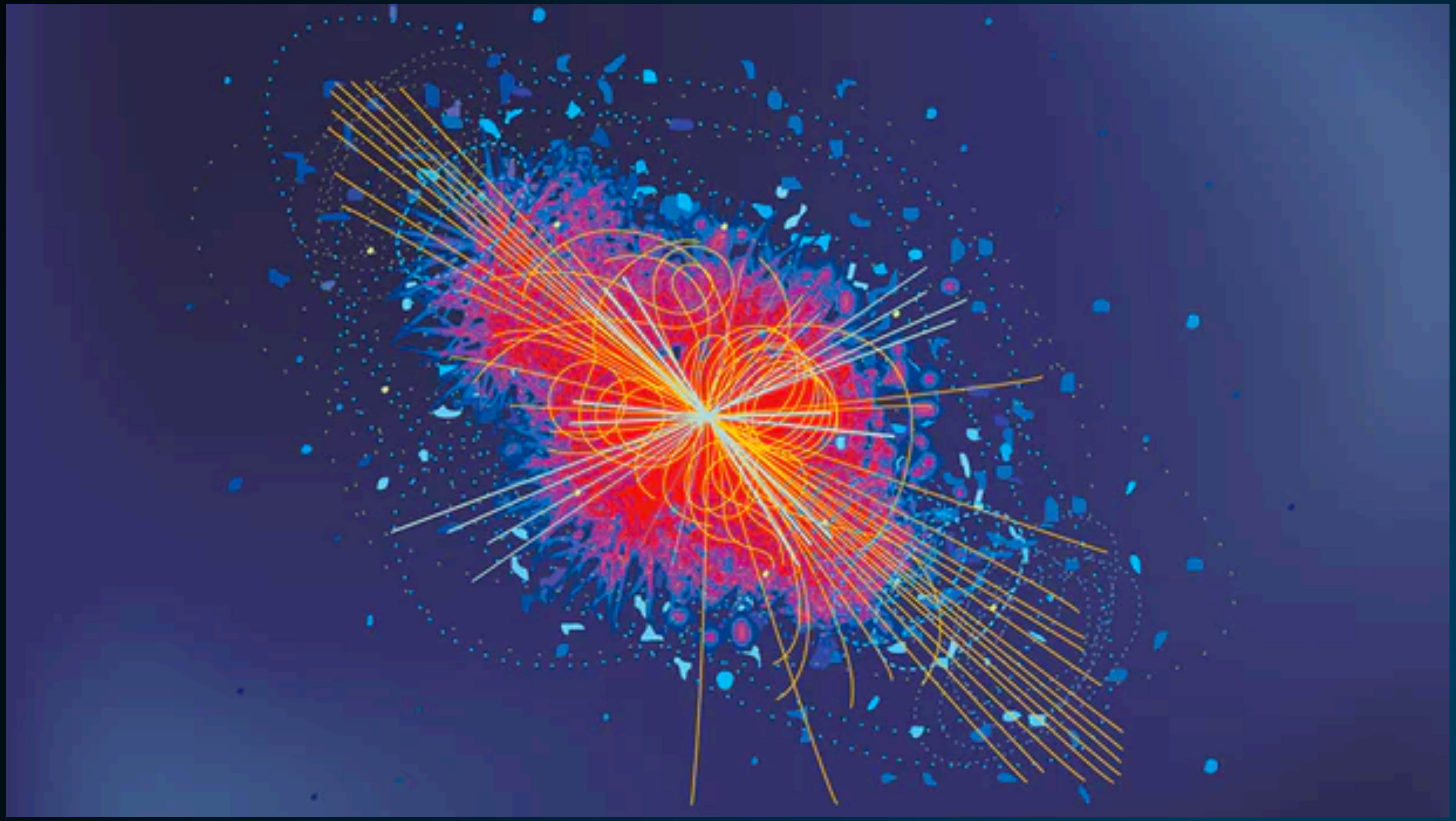


Boudaud et al. (2019; 1906.07119)

Cuoco et. al. (2019; 1903.01472)

Antinuclei !?

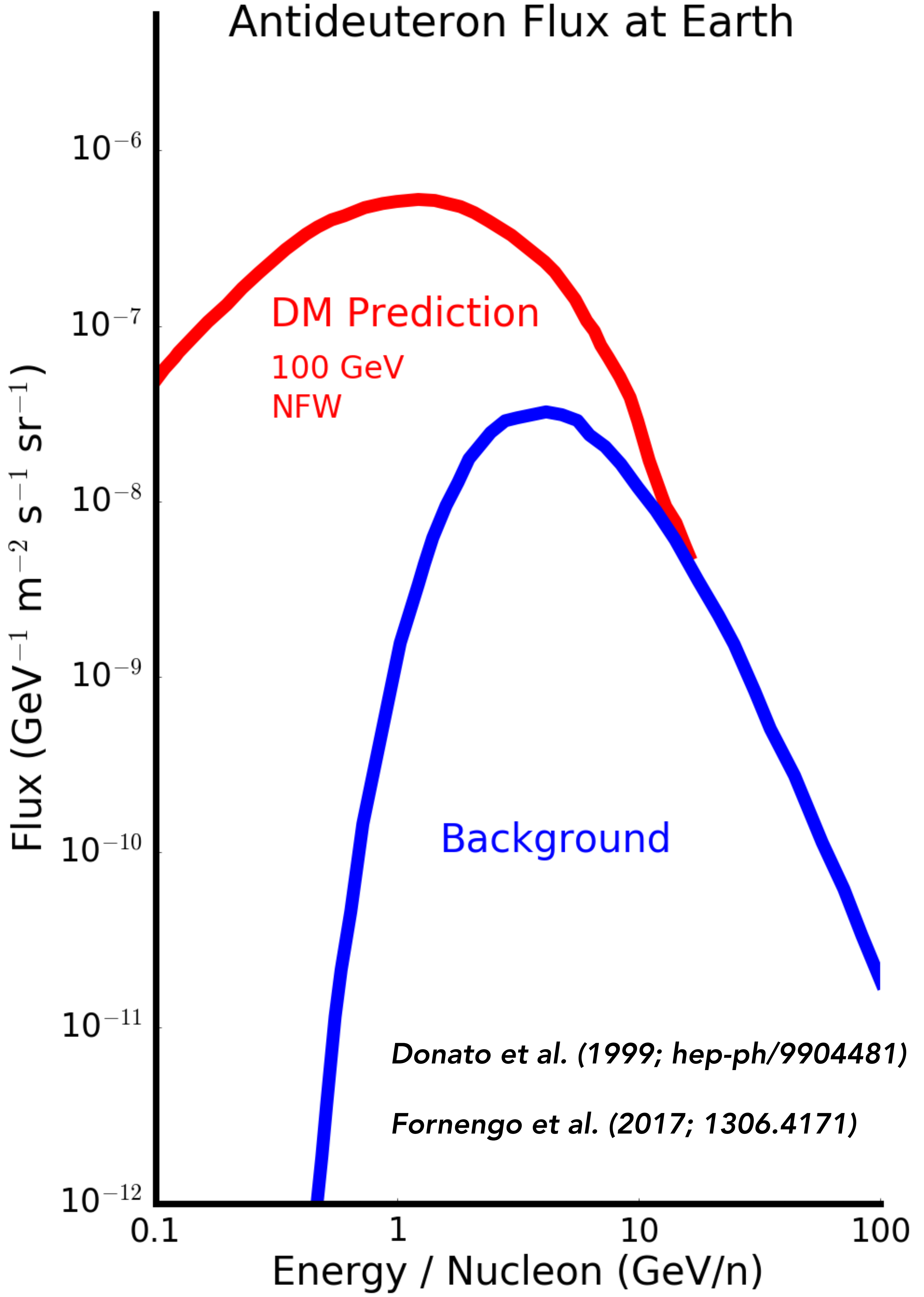
AntiNuclei - A Clean Search Strategy ?



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}.

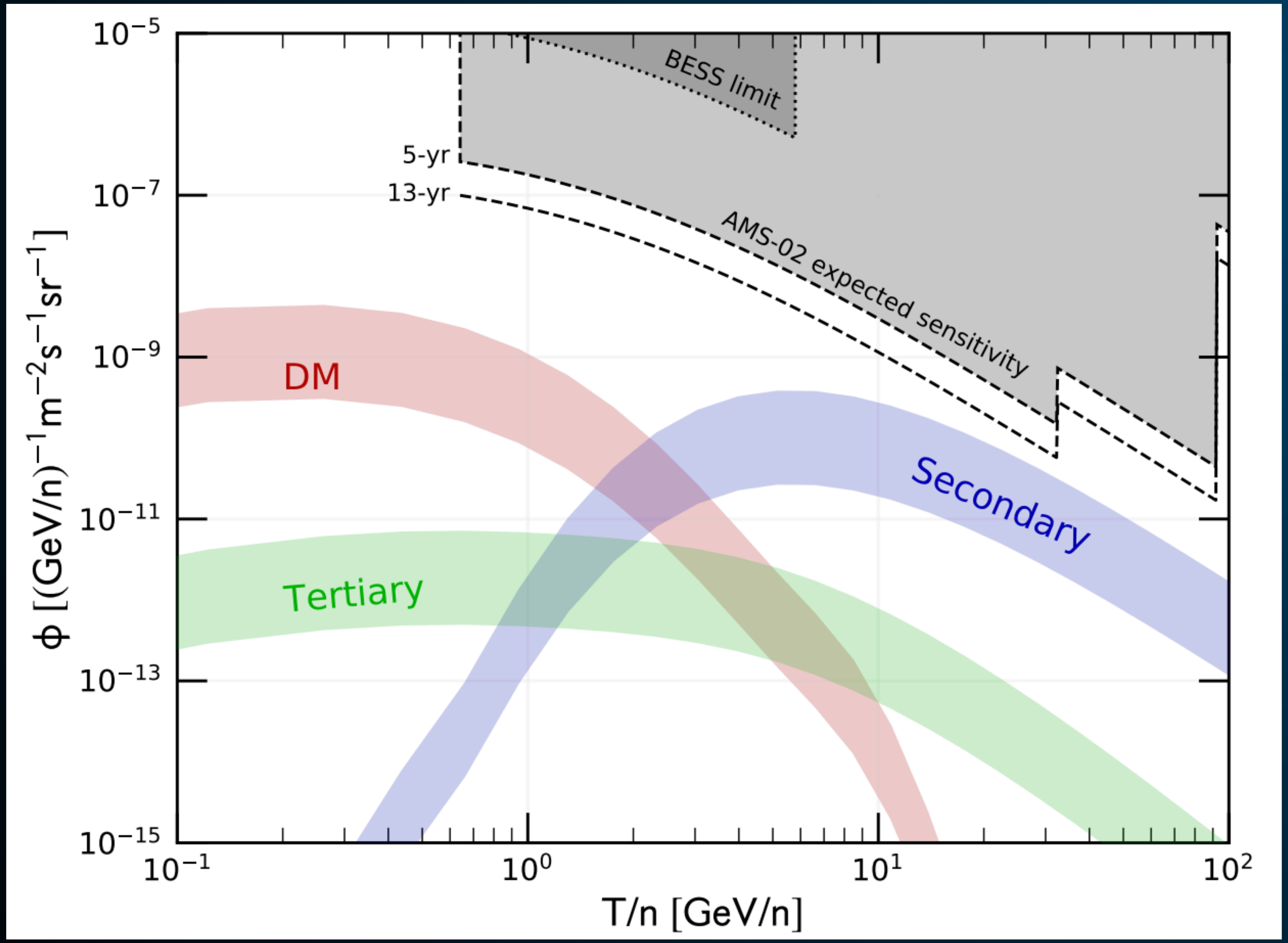
Note that for $^{4}\overline{He}$, projecting based on the statistics we have today, by using an additional 400 million core hours for simulation the background probability would be 10^{-4}. Simultaneously, continuing to run until 2023, which doubles the data sample, the background probability for $^{4}\overline{He}$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

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

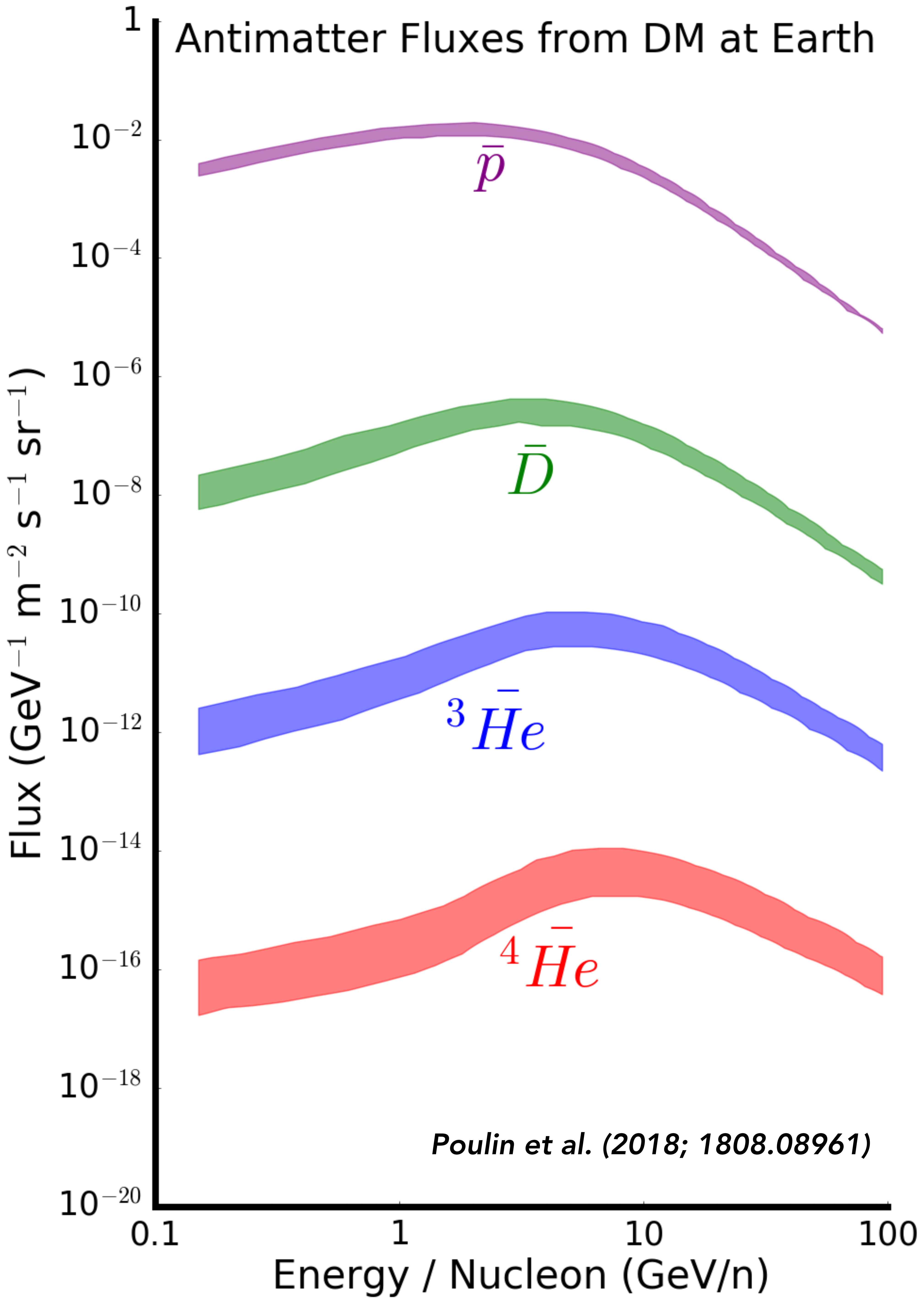
AntiNuclei - A Clean Search Strategy ?

Antihelium background even cleaner than antideuterons

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



Korsmeier (2017; 1711.08465)



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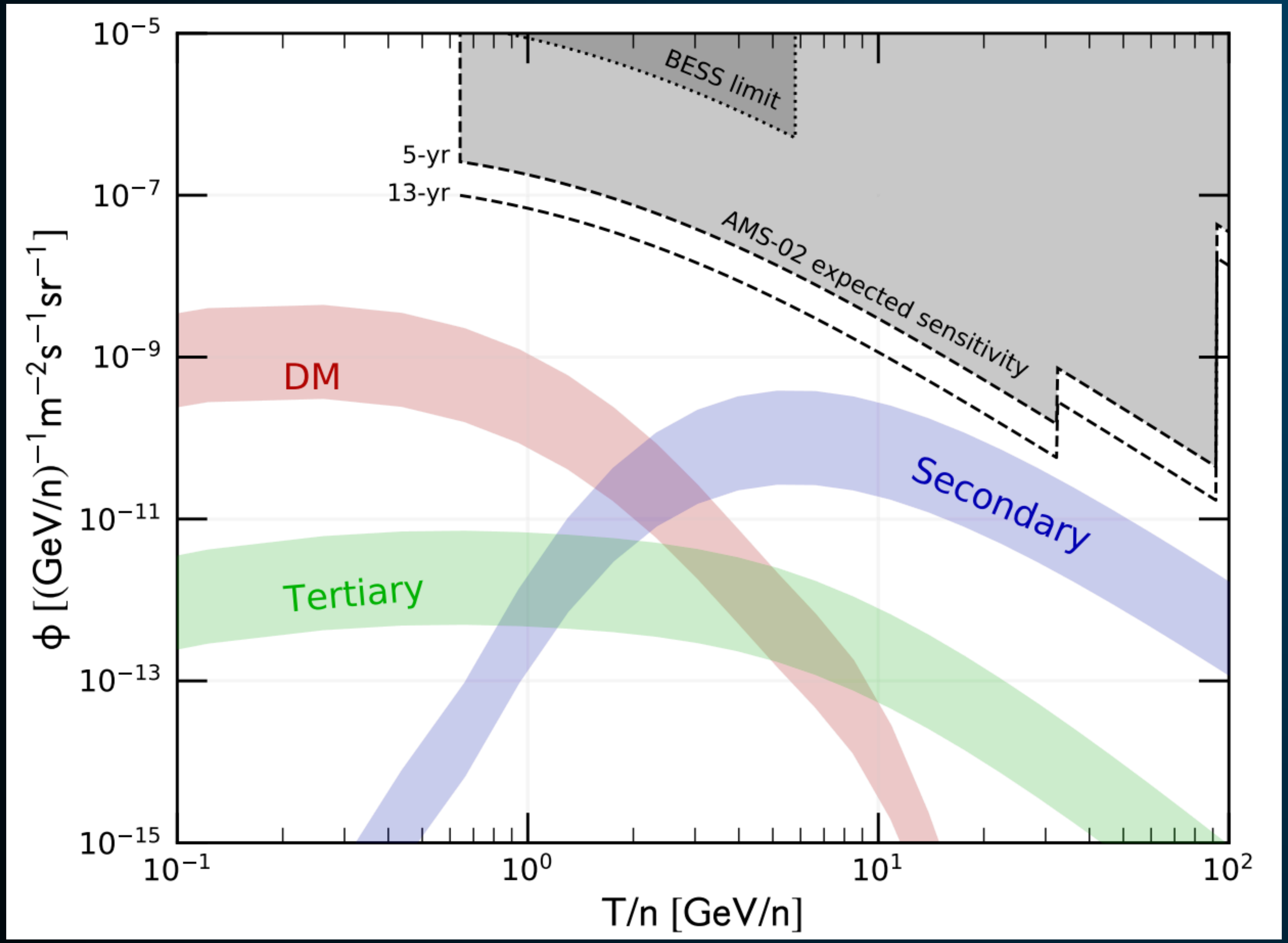

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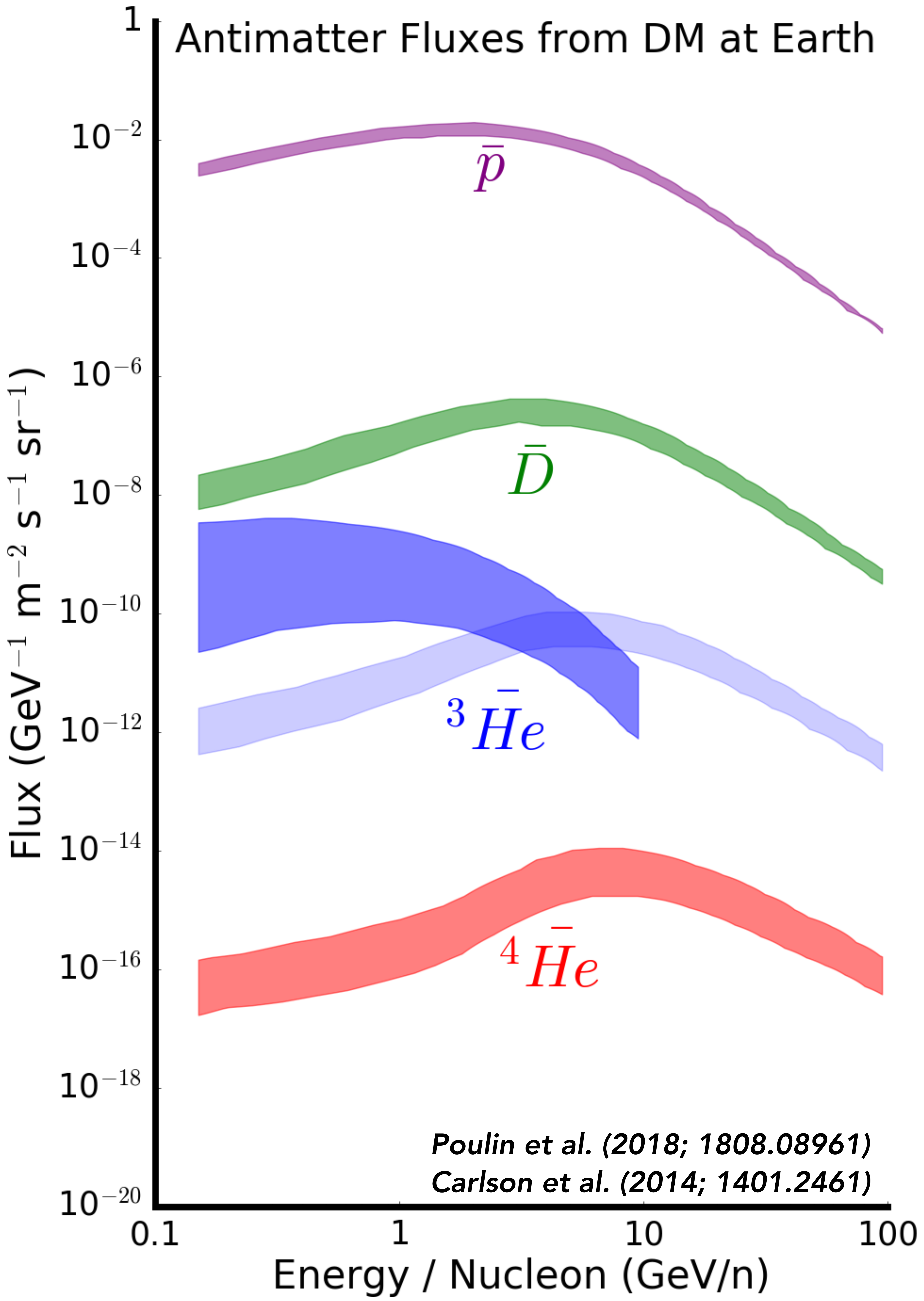
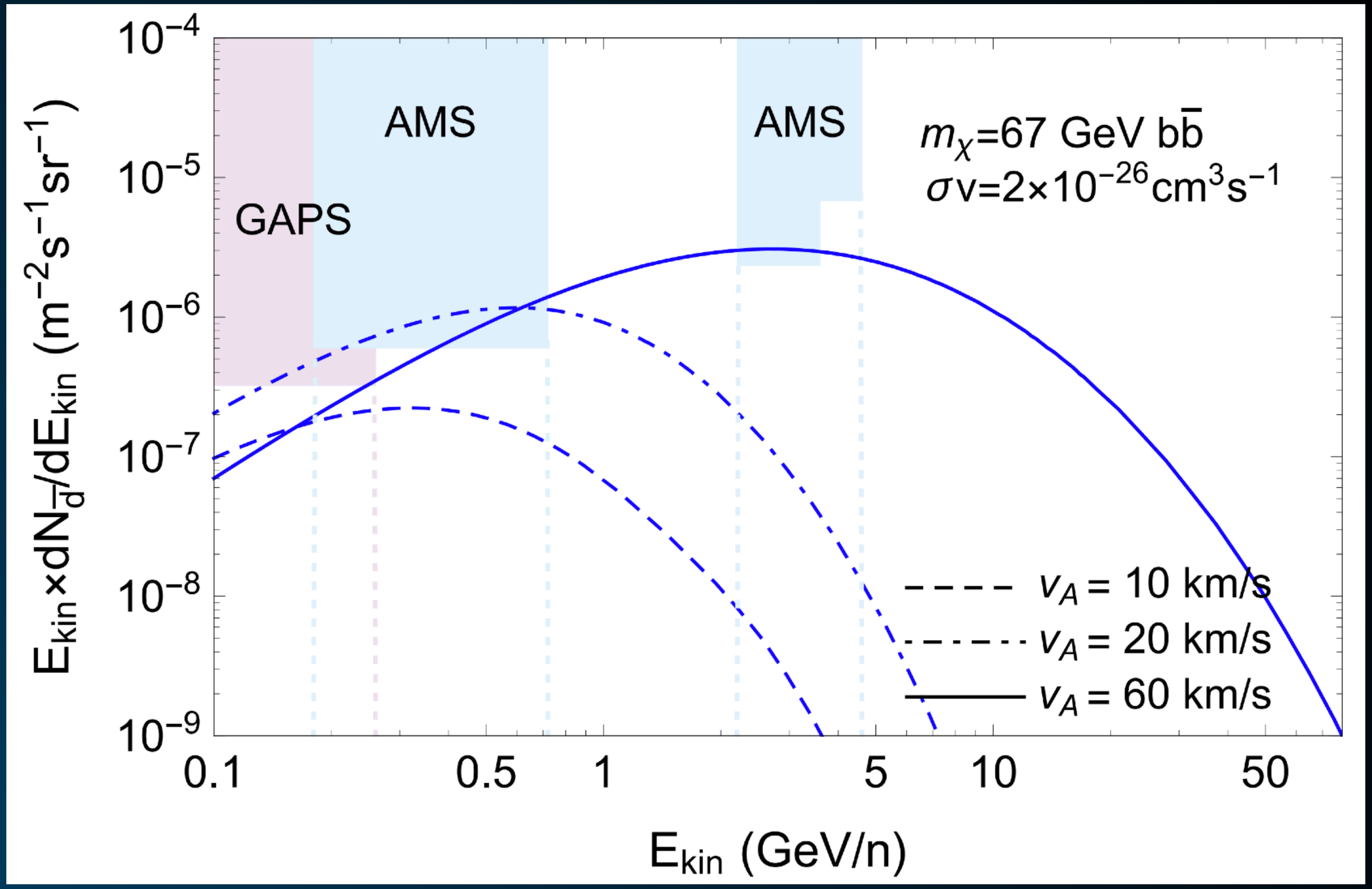


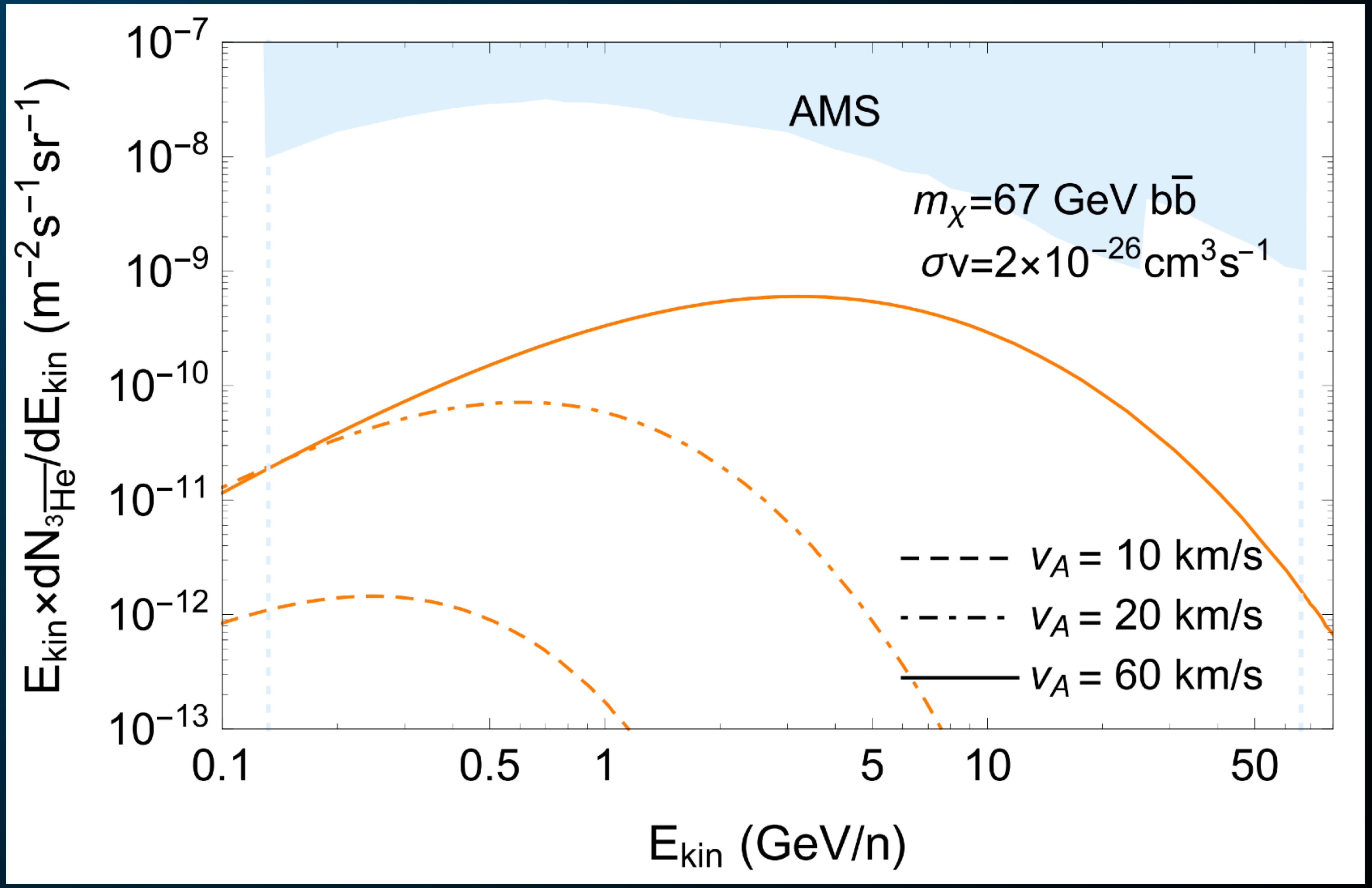
Astrophysical Enhancements!

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

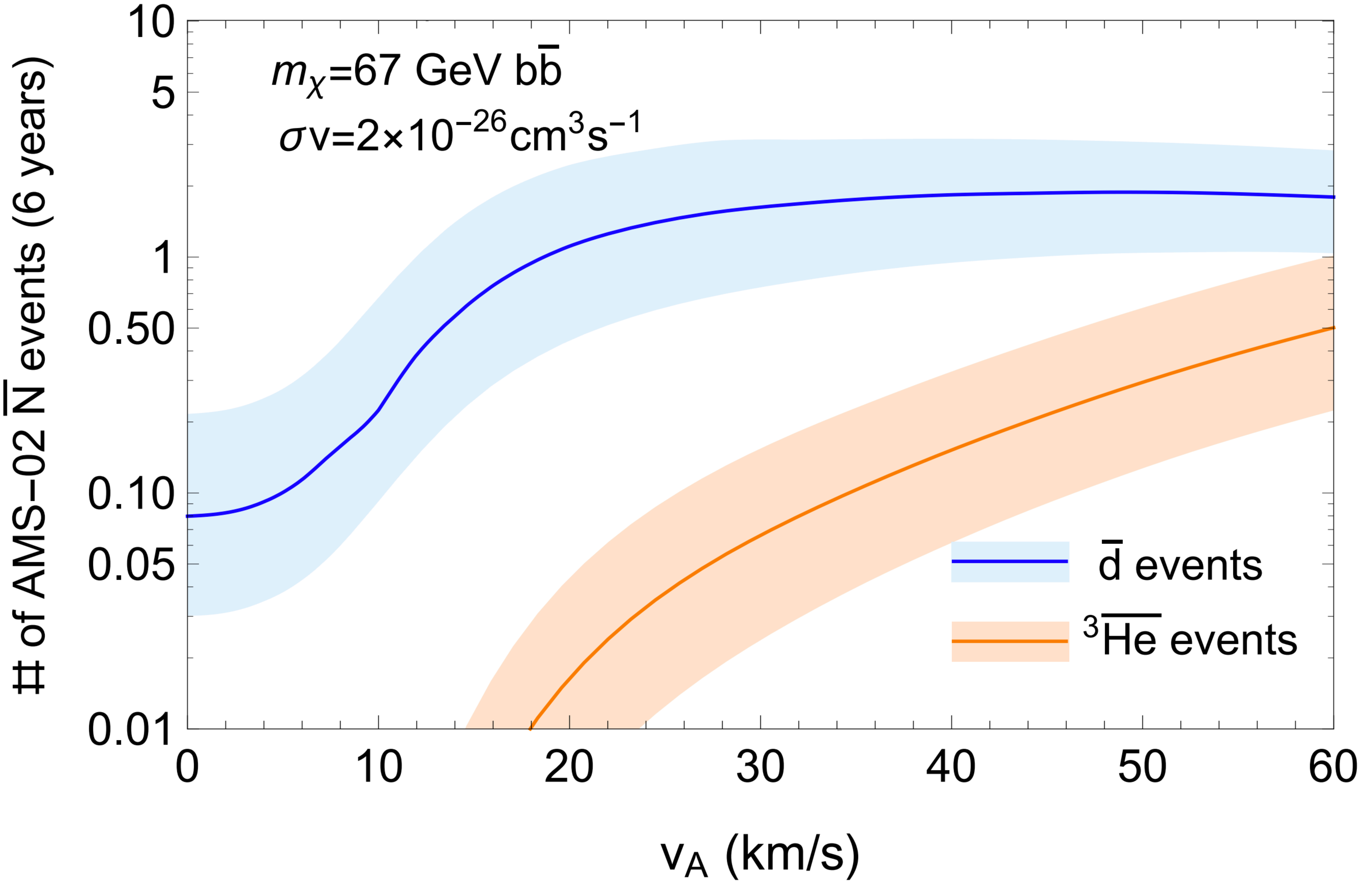
We lose many events because most anti-He are produced at energies that are too small to be detected.

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

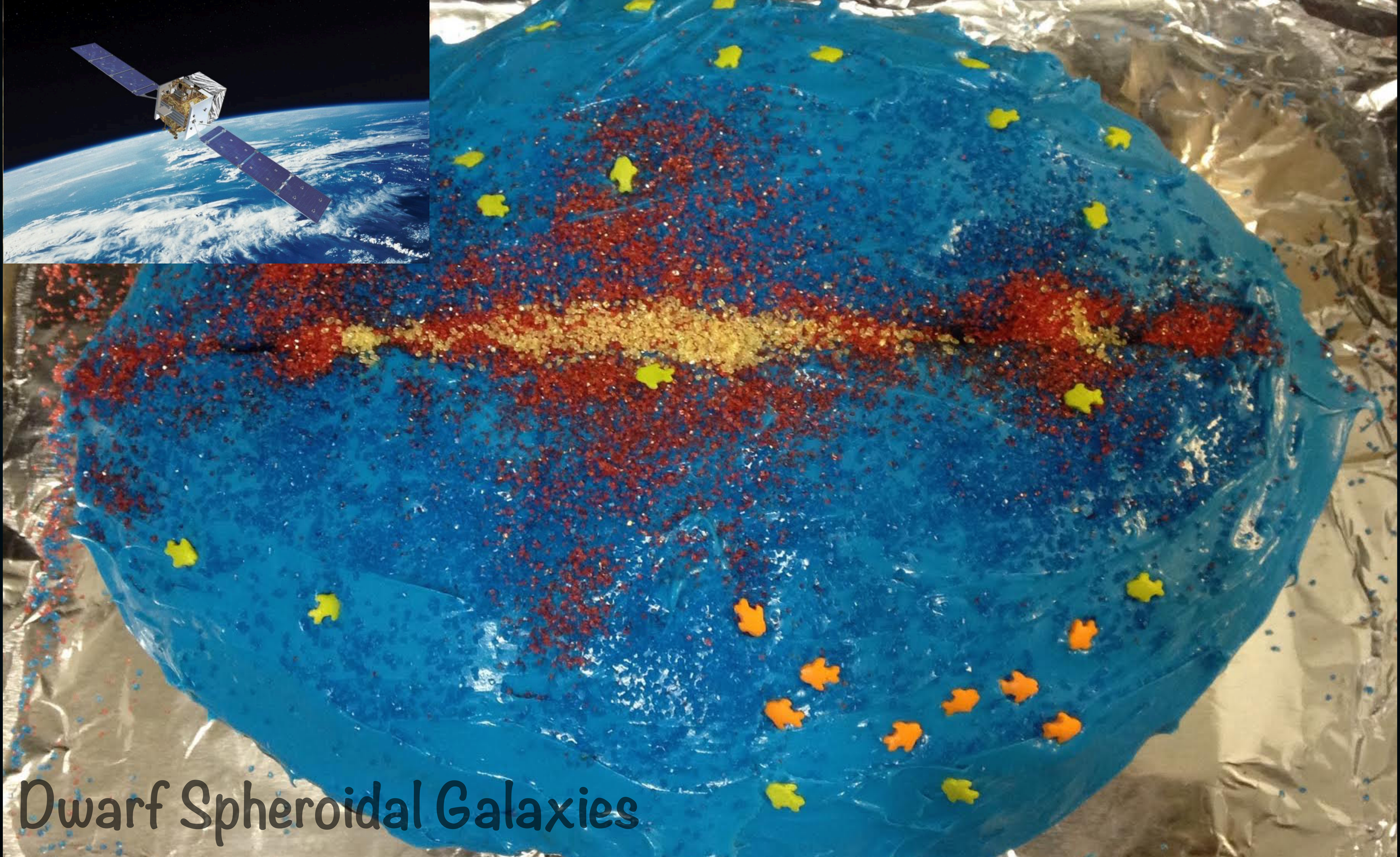




Cholis, Linden, Hooper (2020; 2001.08749)

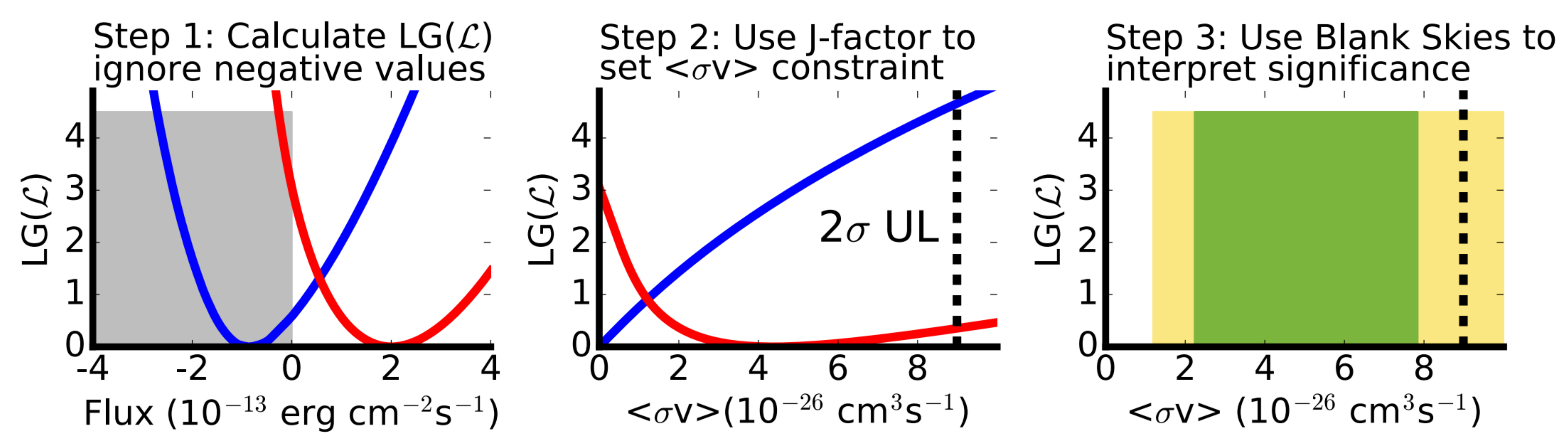


m_χ=67 GeV $b\bar{b}$
$\sigma v=2\times10^{-26}\mathrm{cm^3s^{-1}}$
$\bar{d}$ events
$^3\overline{He}$ events
# of AMS−02 $\overline{N}$ events (6 years)
v_A (km/s)
10
5
1
0.50
0.10
0.05
0.01
0
10
20
30
40
50
60



Dwarf Spheroidal Galaxies

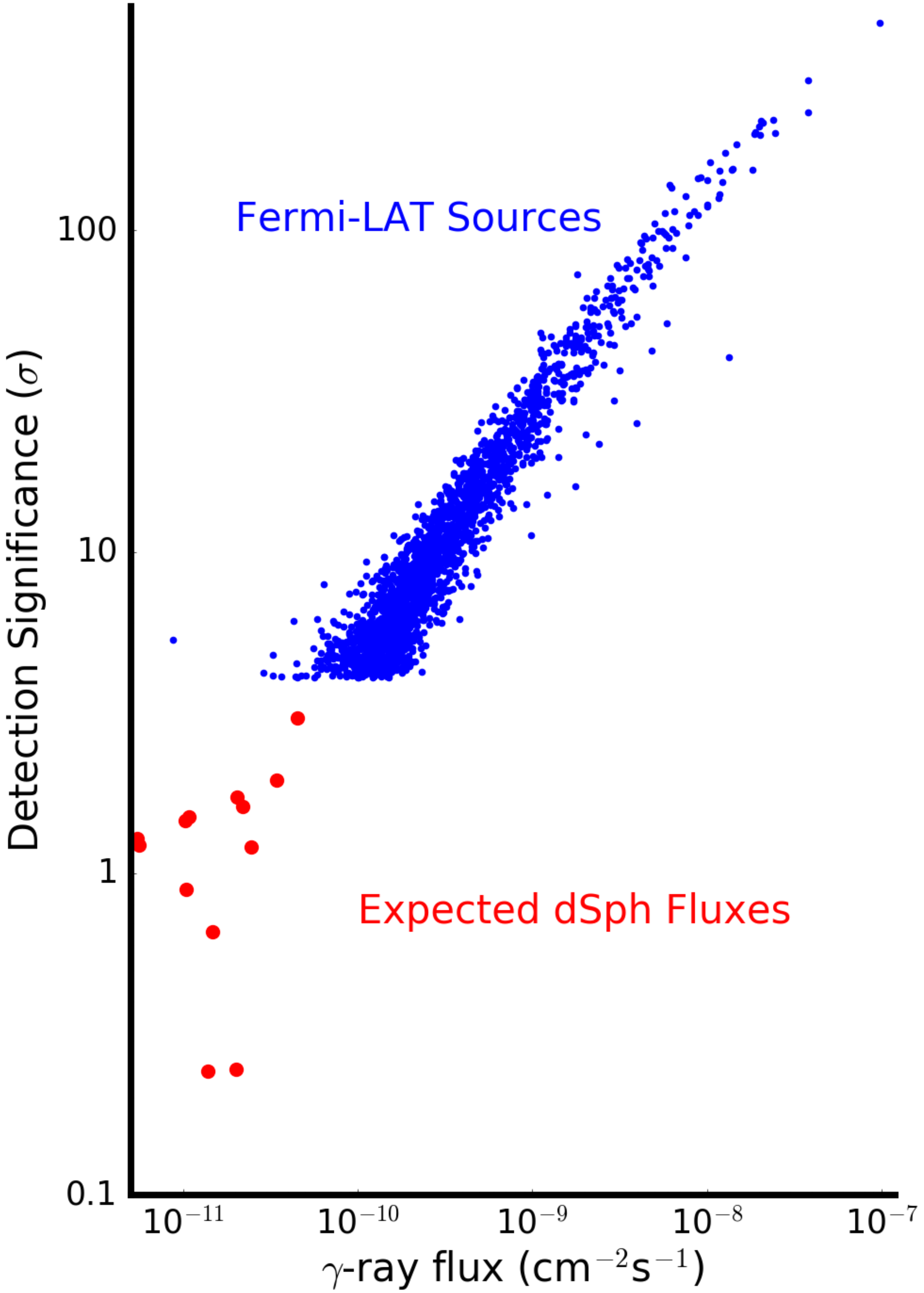
Dwarf Spheroidal Galaxies



No Astrophysical Background from Dwarfs!

Individual dwarfs are dim

Need to combine observations of multiple dwarfs to constrain thermal cross-section



$b\bar{b}$
4 yr of data, 15 Dwarf Galaxies
Actual Limit
Expected Limit
Thermal Cross-Section
Ackermann et al. (2013; 1310.0828)
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ (cm^{3}s^{-1})
10
100
1000
Dark Matter Mass (GeV)

$b\bar{b}$
8 yr of data, 45 Dwarf Galaxies
Actual Limit
Expected Limit
Thermal Cross-Section
Albert et al. (2016; 1611.03184)
$<\sigma v>$ ($\mathrm{cm^3 s^{-1}}$)
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10
100
1000
Dark Matter Mass (GeV)


$b\bar{b}$
9 yr of data, 45 Dwarf Galaxies
Actual Limit
Expected Limit
Thermal Cross-Section
Linden (2019; 1905.11992)
$<\sigma v>$ (cm^{3}s^{-1})
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10
100
1000
Dark Matter Mass (GeV)


$b\bar{b}$
9 yr of data, 27 Dwarf Galaxies
95% Confidence (Frequentist)
Thermal Cross-Section
95% Confidence (Bayesian)
Hoof et al. (2018;1812.06986)
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ (cm^{3}s^{-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})
Dark Matter Mass (GeV)
10
5
3
2
1
0.5
20
50
100
200

$\rho_\odot$ = 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})
Dark Matter Mass (GeV)
10
5
3
2
1
0.5
20
50
100
200

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

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


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
Instrumental
Dwarf Galaxies
Antihelium
Antiprotons
Galactic Center
Multiwavelength

10^{-24}
10^{-25}
10^{-26}
10^{-27}
$<\sigma v>$ (cm^{3}s^{-1})
1
10
100
1000
Dark Matter Mass (GeV)
Weakest Limit
Thermal Cross-Section
$b\bar{b}$ (dSphs)
$b\bar{b}$ (AMS)
e$^+$e$^-$ (AMS)
e$^+$e$^-$ (Planck)
Leane et al. (2018; 1805.10305)
Threshold Br($\chi\chi \to$ SMSM)
0
20
40
60
80
100
g
τ
μ
10
15
20
25
30
50
100
200
10^3
m$_\chi$ [GeV]

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


$b\bar{b}$ (WMAP5)
e^+e^- (WMAP5)
Thermal Cross-Section
Galli et al. (2009; 0905.0003)
see also: astro-ph/0210617, 0810.5952)
$<\sigma v>$ ($cm^3 s^{-1}$)
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

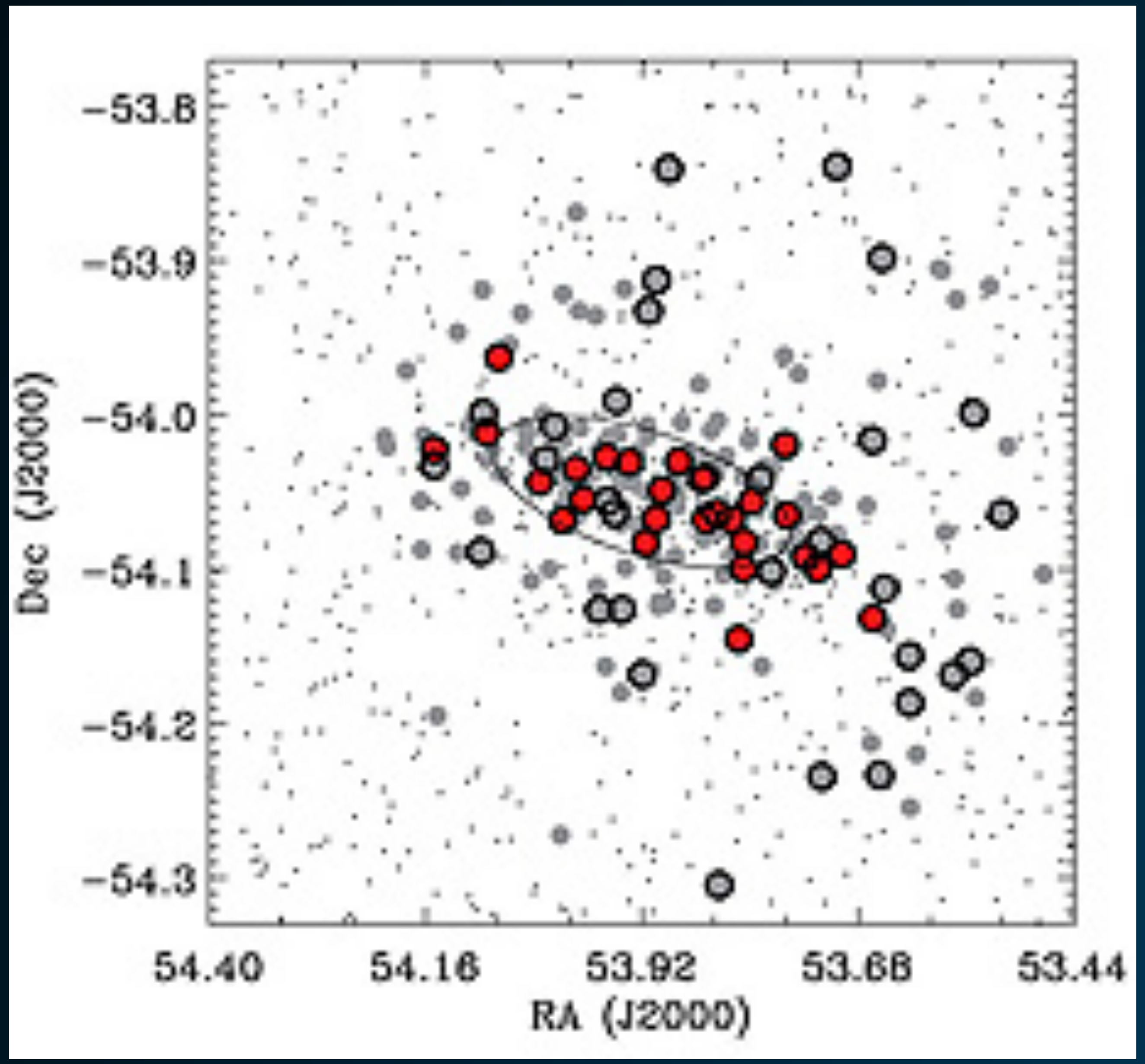
$b\bar{b}$ (Planck)
e^+e^- (Planck)
$b\bar{b}$ (Dwarfs)
W^+W^- (HESS)
$\tau^+\tau^-$ (HESS)
Thermal Cross-Section
Galactic Center (Fermi)
Antiproton (AMS)
$\tau^+\tau^-$ (AMS)
e^+e^- (EDGES)
e^+e^- (AMS)
$<\sigma v>$ (cm^3s^{-1})
Dark Matter Mass (GeV)
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
0.1
1
10
100
1000
10^4
10^5

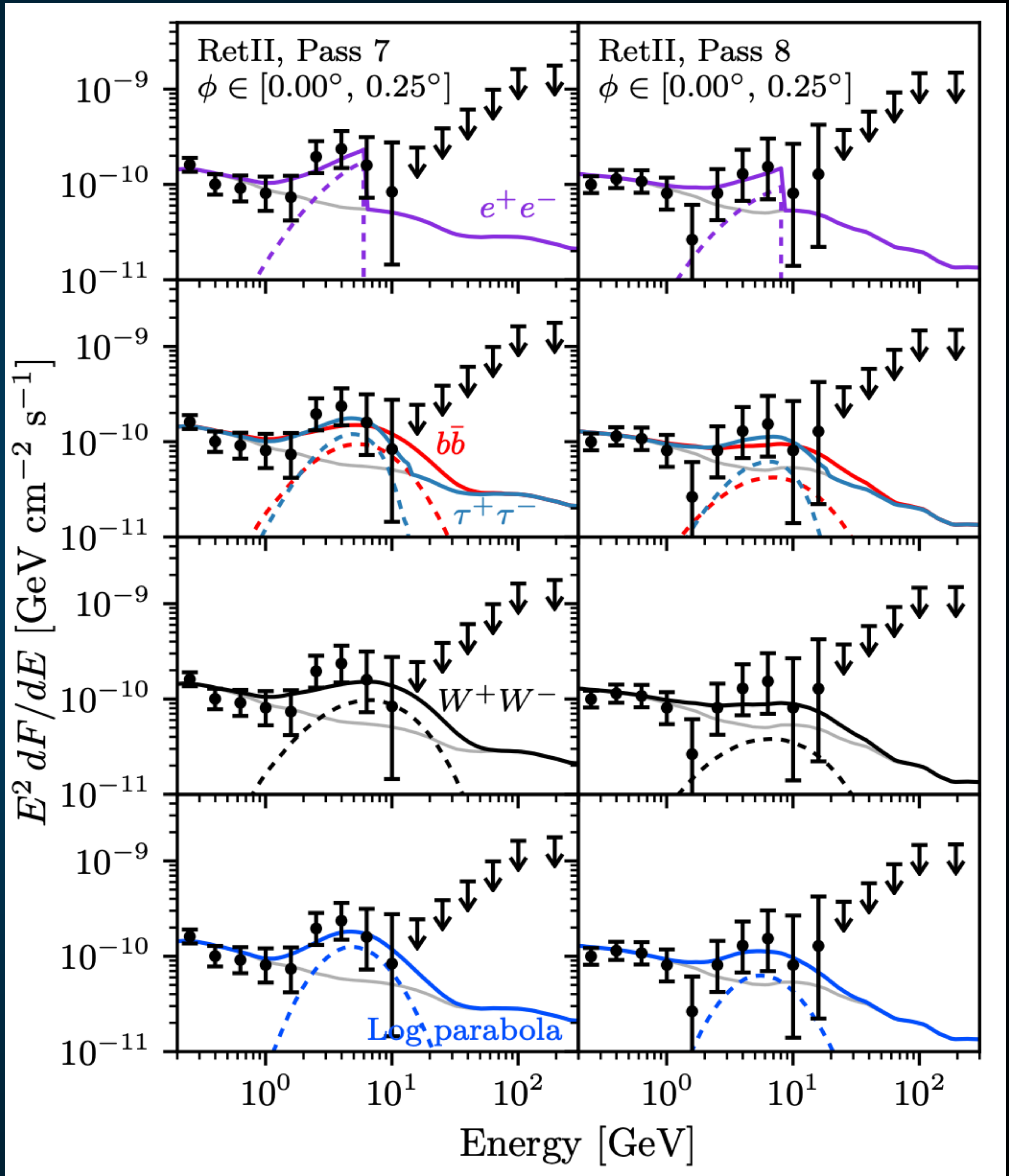
Extra Slides

Or Maybe A Surprise !

Weniger (2012; 1204.2797)

Reticulum II - The Story of 2015





Dense and Nearby dSph!

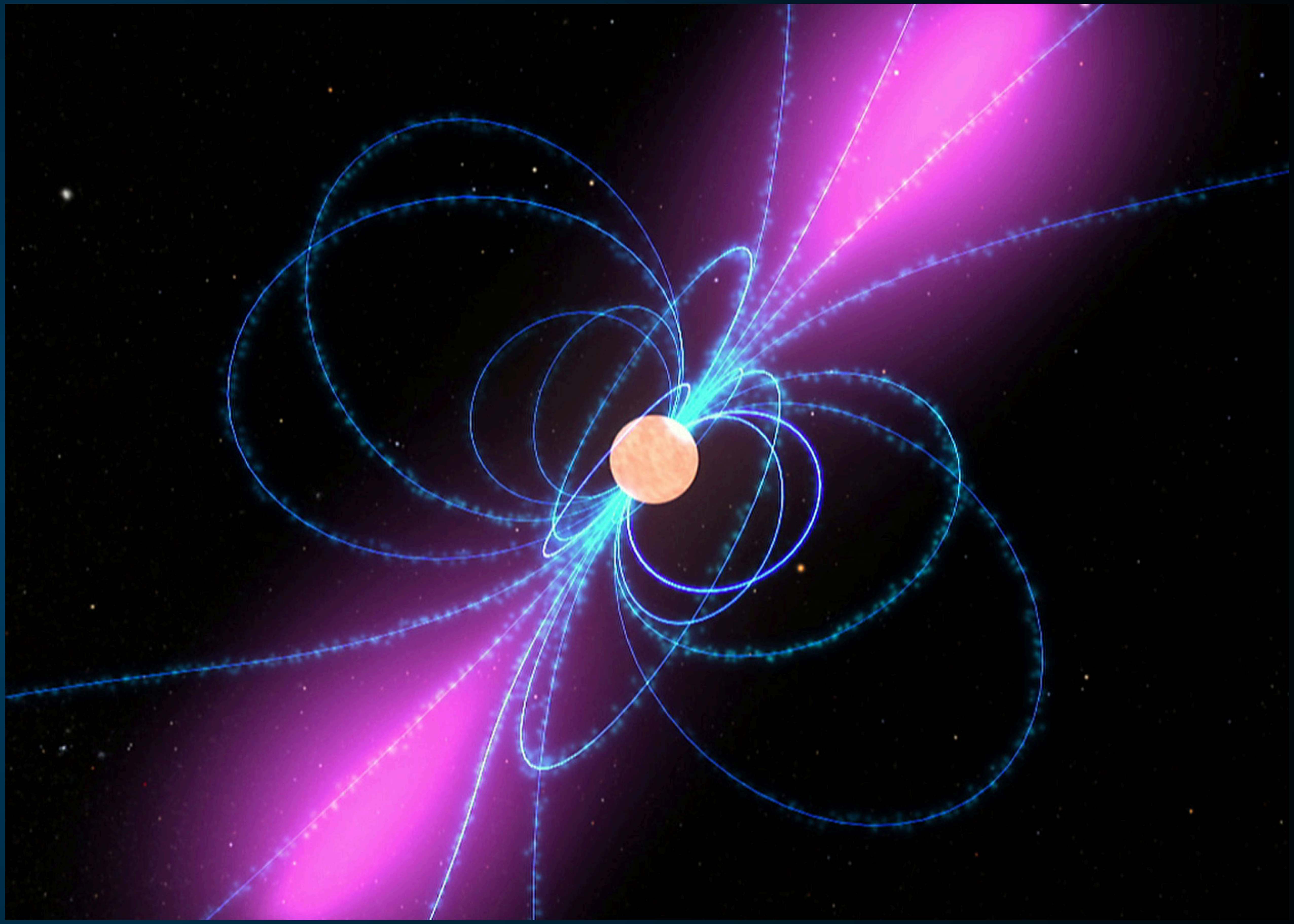
Gamma-Ray Excess!

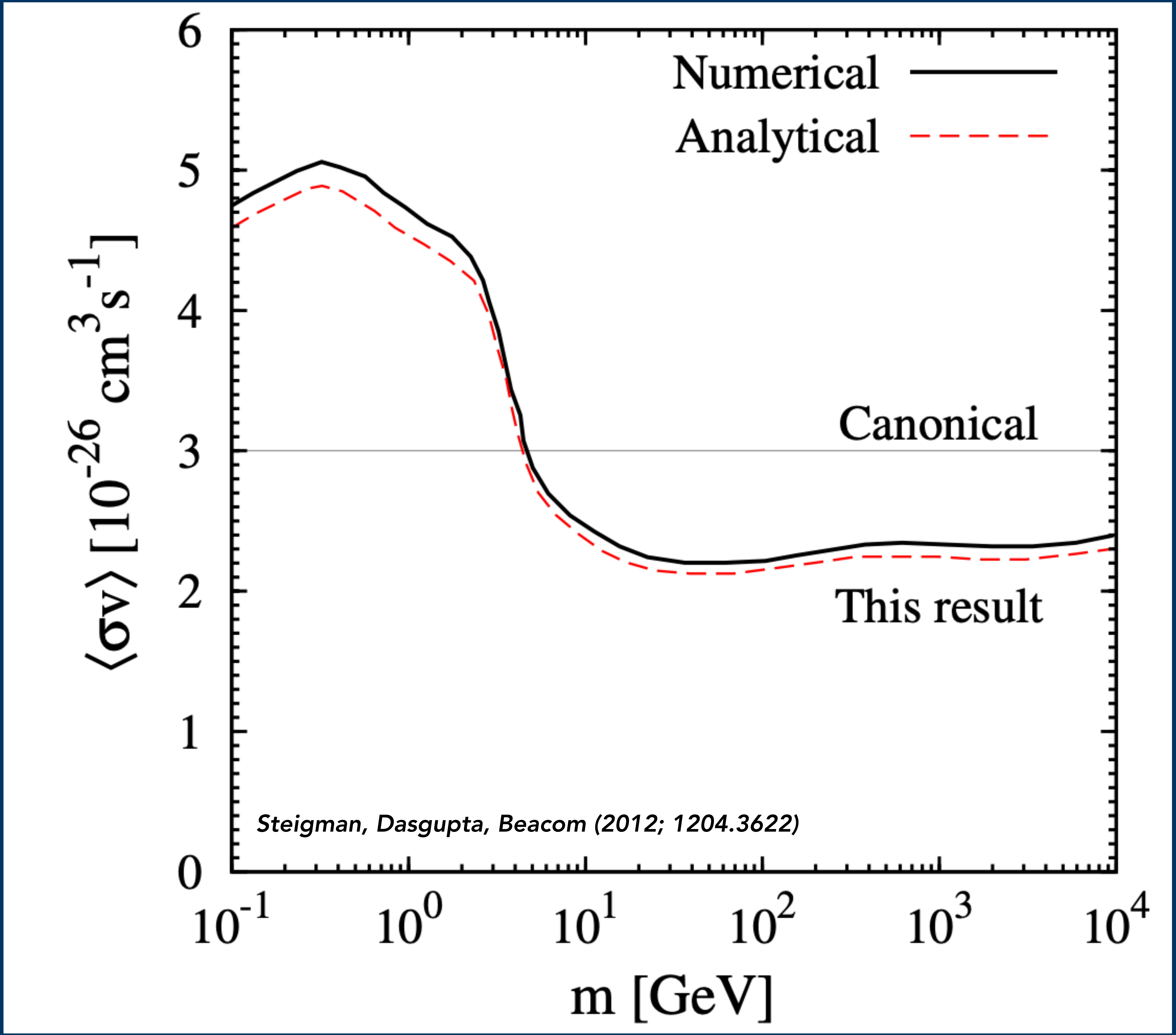
Significance has decreased from ~3.2σ to ~2.5σ in updated datasets.

Still interesting!

$b\bar{b}$
9 yr of data, 45 Dwarf Galaxies
Actual Limit
Expected Limit
Thermal Cross-Section
Linden (2019; 1905.11992)
$<\sigma v>$ ($\mathrm{cm^3 s^{-1}}$)
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10
100
1000
Dark Matter Mass (GeV)

The Galactic Center: The Easiest Place to Find Dark Matter





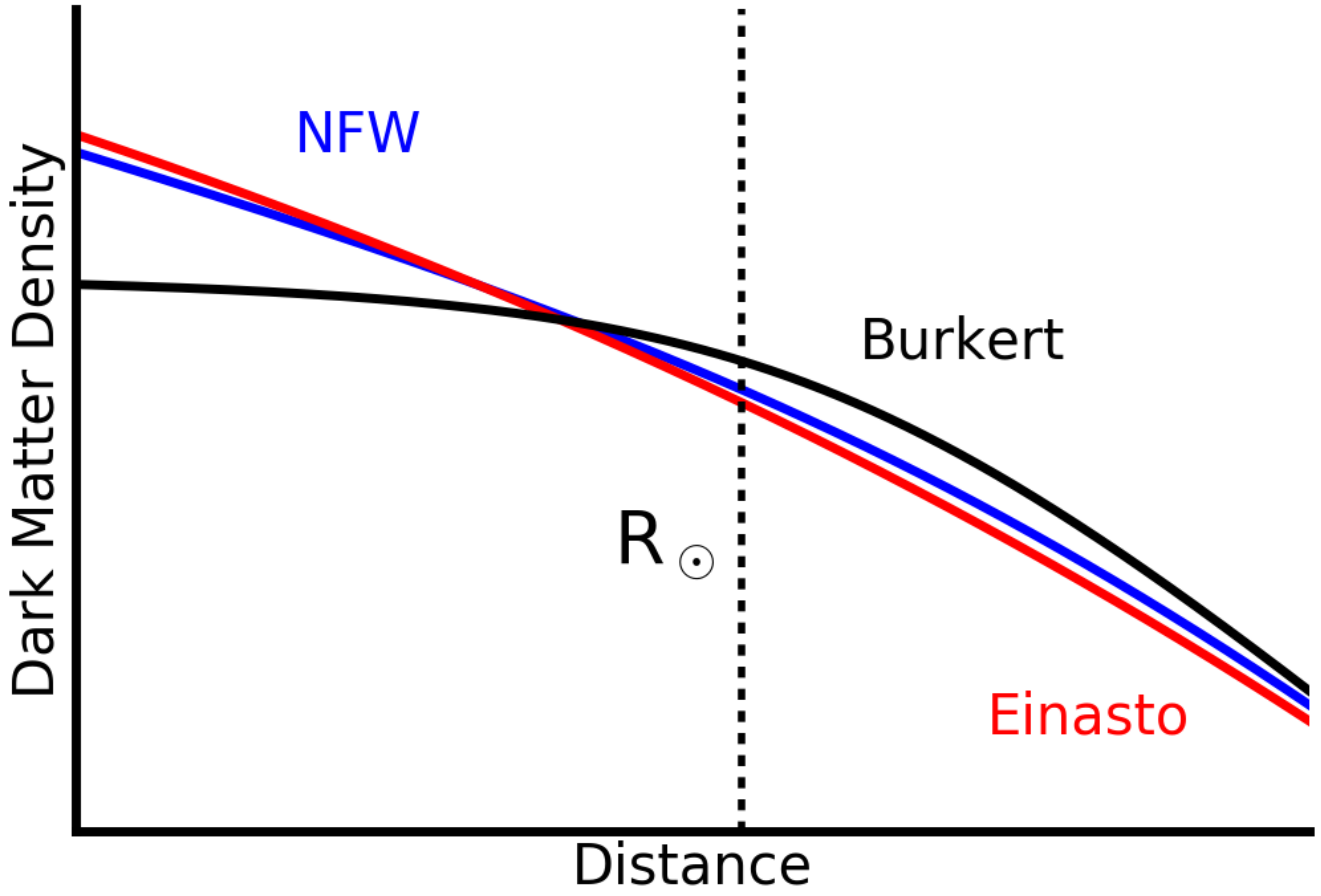
Thermal Dark Matter Density

Simplest model has a known cross-section!

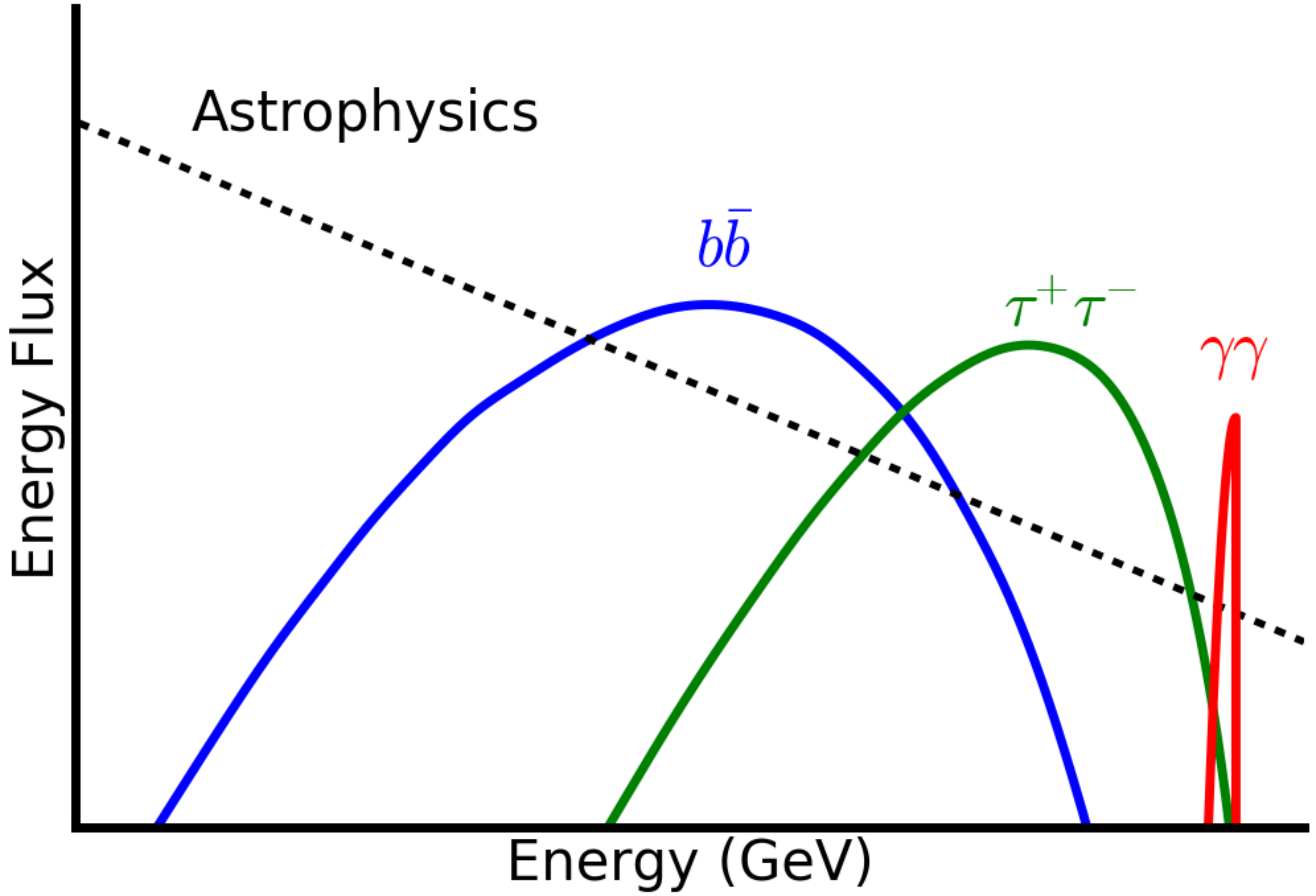
Deviations from this cross-section include complicating effects.

Philosophy:

Constrain the simplest model first



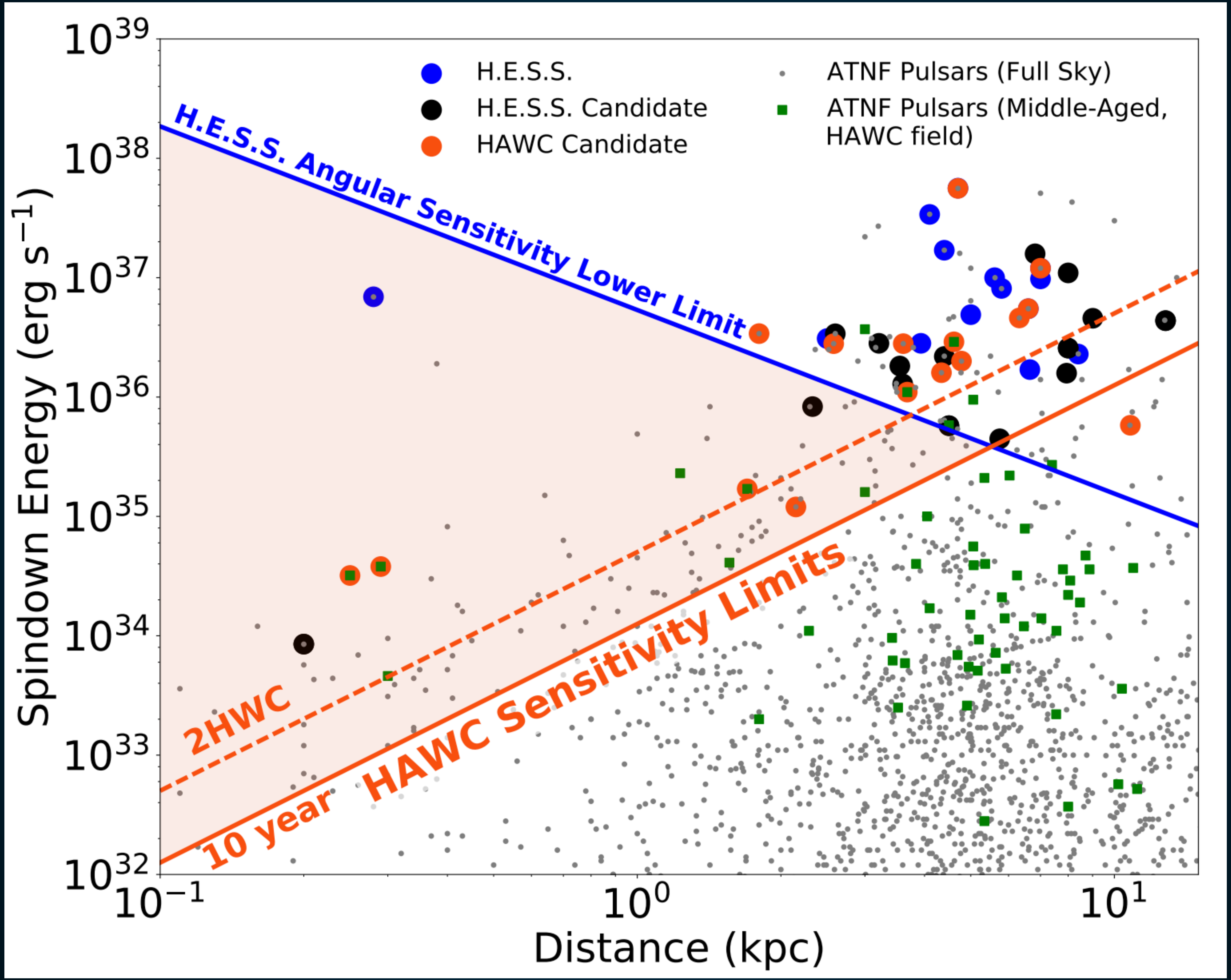
NFW
Burkert
Einasto
$R_\odot$
Dark Matter Density
Distance



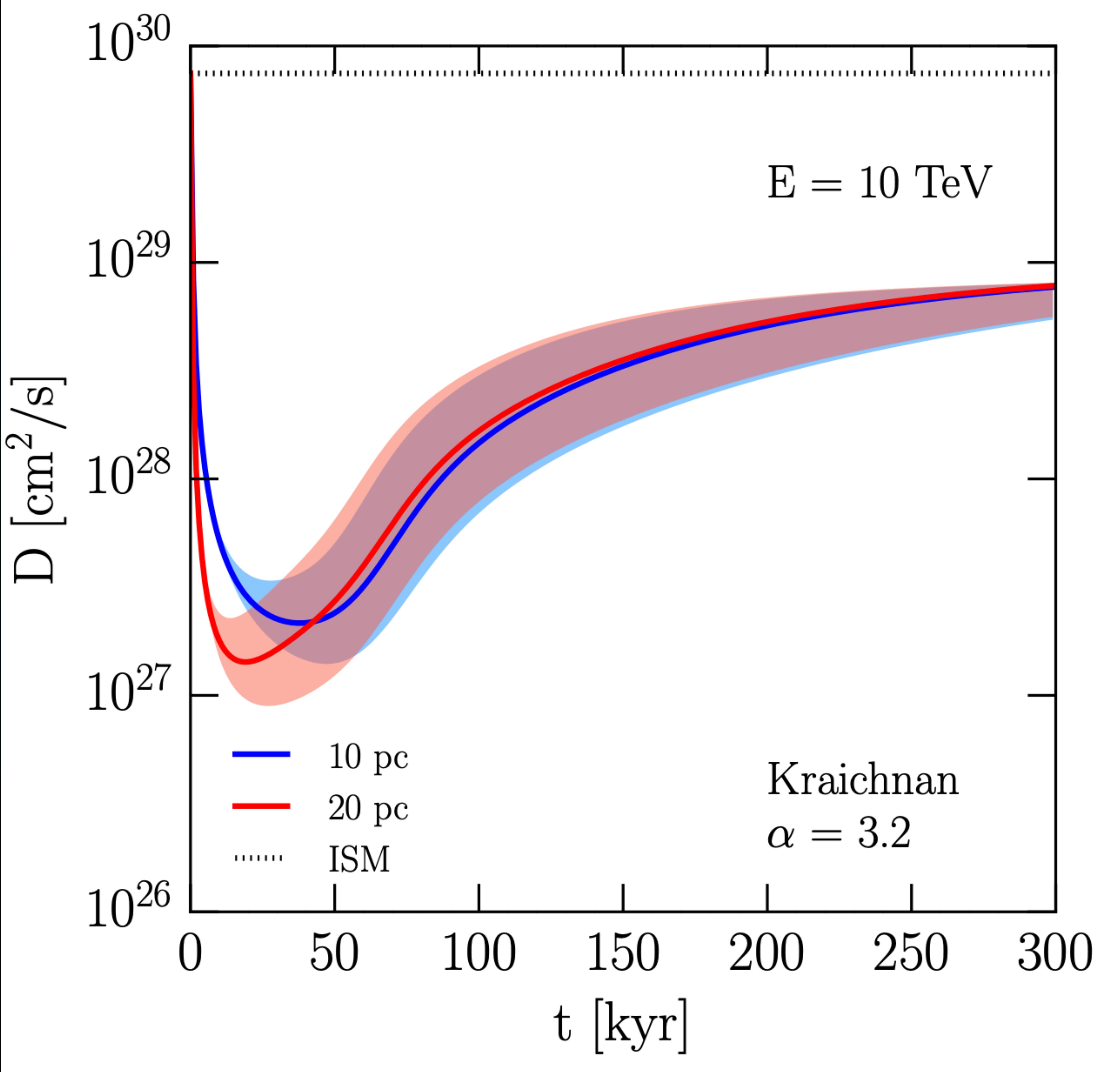
Astrophysics
$b\bar{b}$
$\tau^+\tau^-$
$\gamma\gamma$
Energy Flux
Energy (GeV)

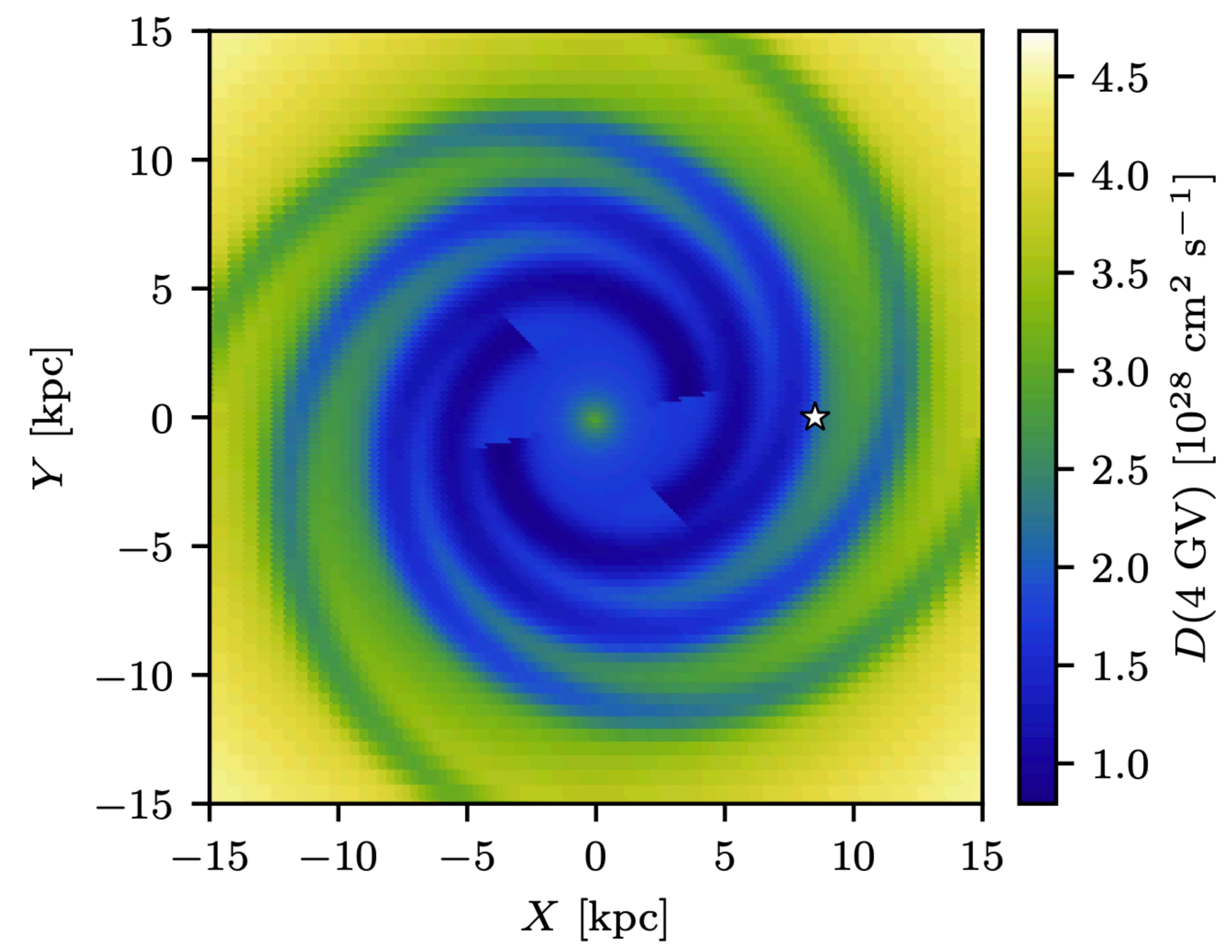
Specificity (DM Flux / Astrophysics Flux)
Anti-Nuclei
Antiprotons
Gamma-Rays / Positrons
10^{-8}
10^{-3}
0.1
Fraction of Dark Matter Flux

New Discoveries!



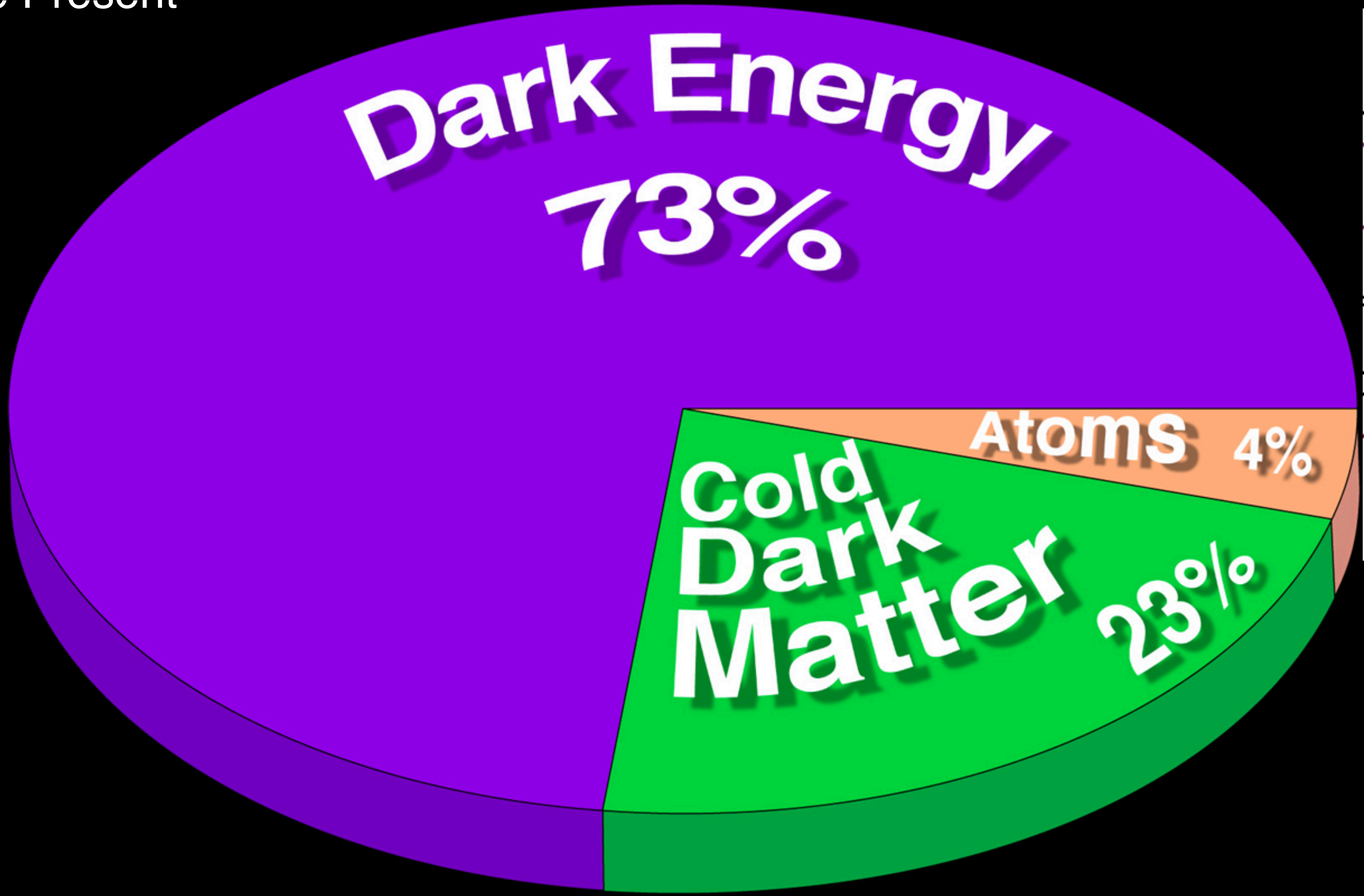
New Discoveries!

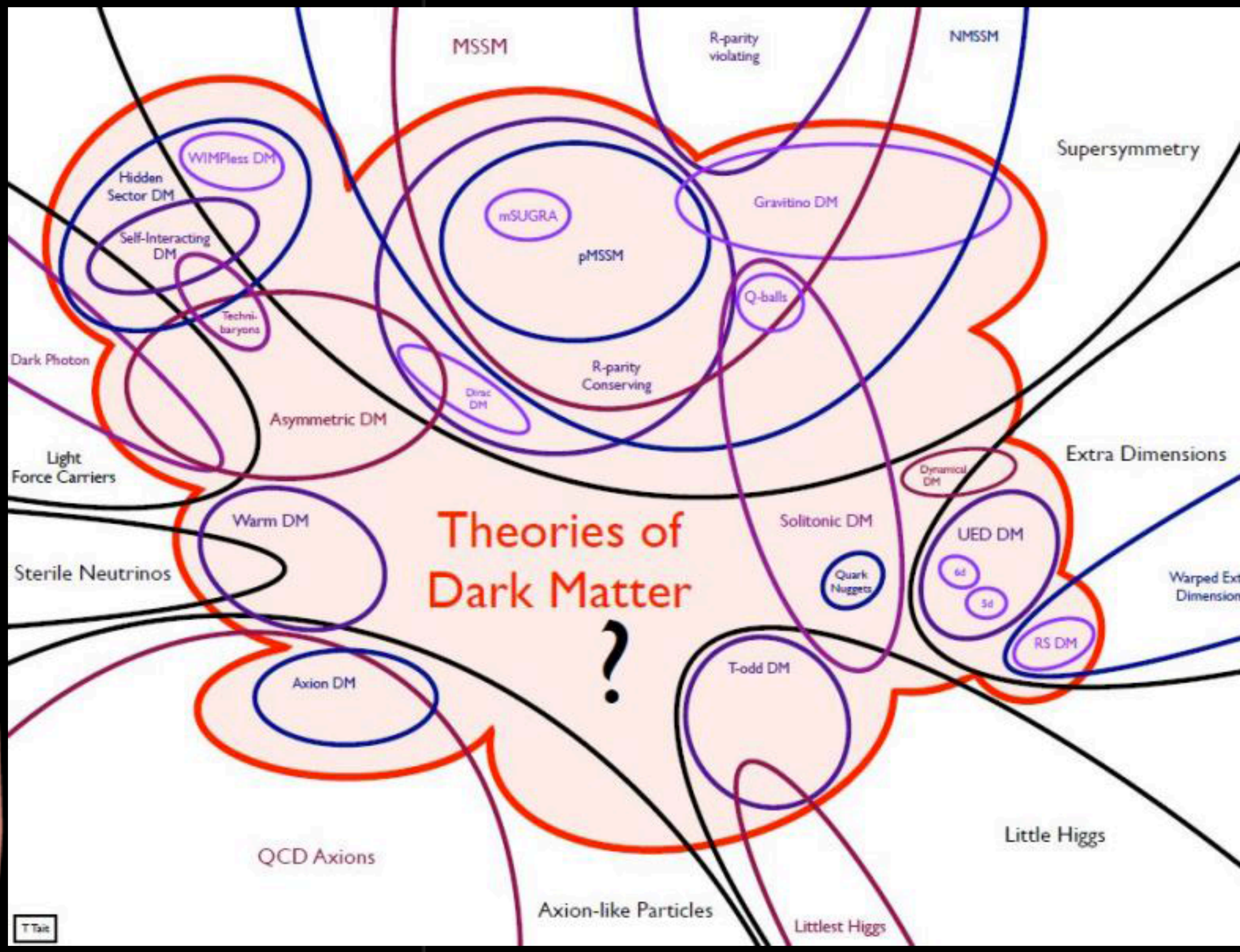




The Present

courtesy: *Tim Tait*



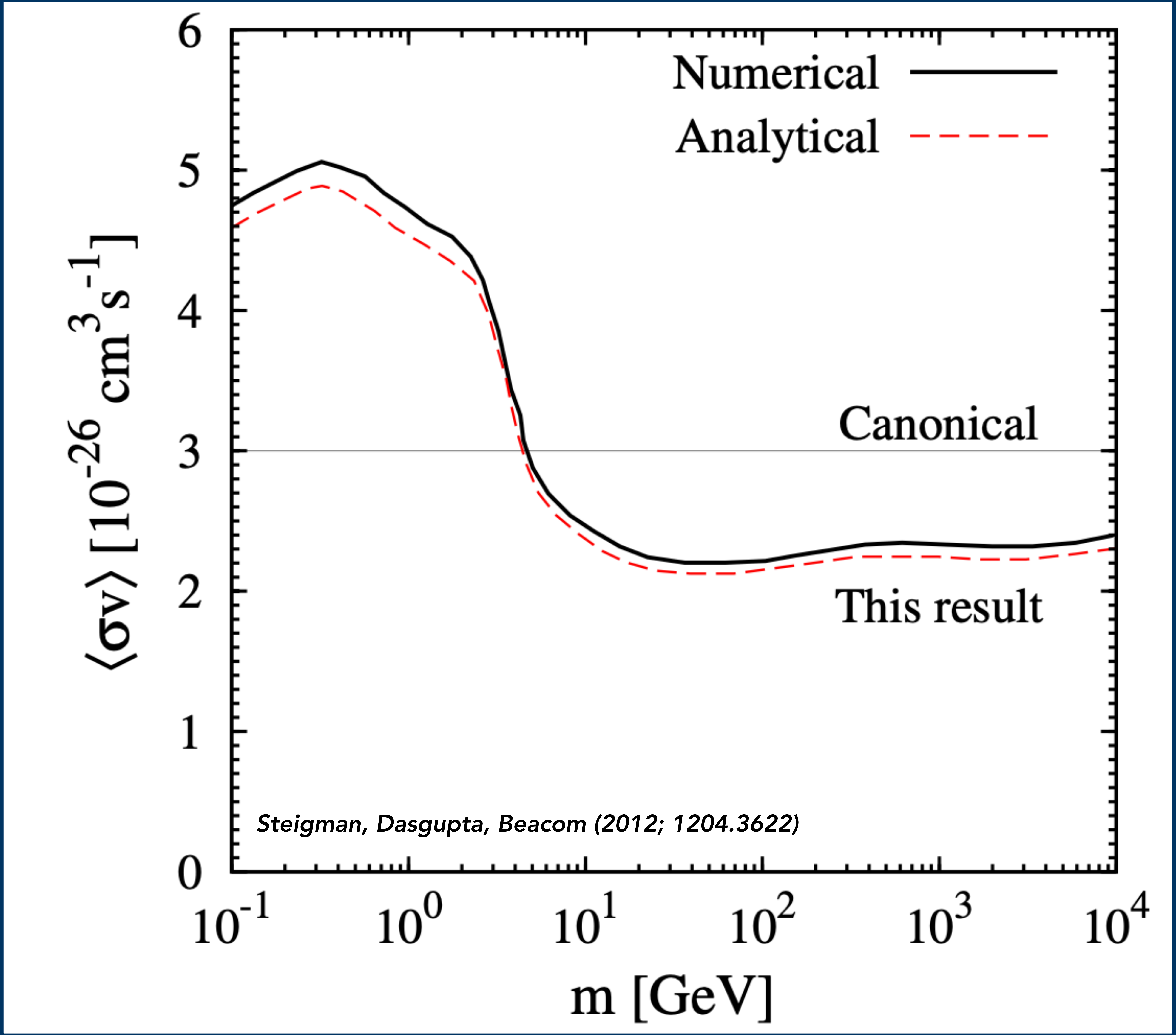


10^{-25} GeV

$R_{DM} > R_{UFD}$

10^{62} GeV

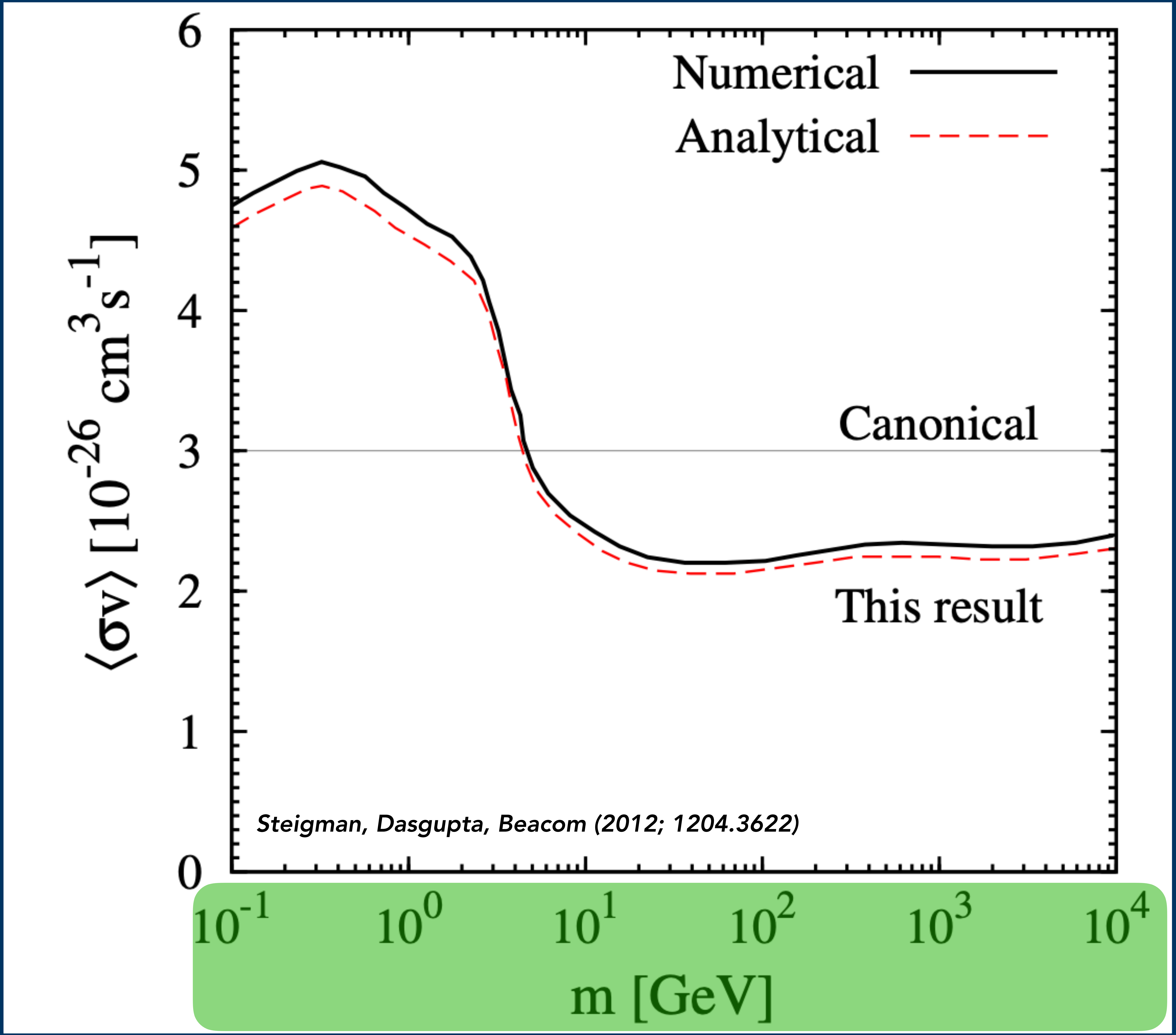
$M_{DM} > M_{UFD}$



Thermal Dark Matter Density

Simplest model has a known cross-section!

Deviations from this cross-section include complicating effects.



Thermal Dark Matter Density

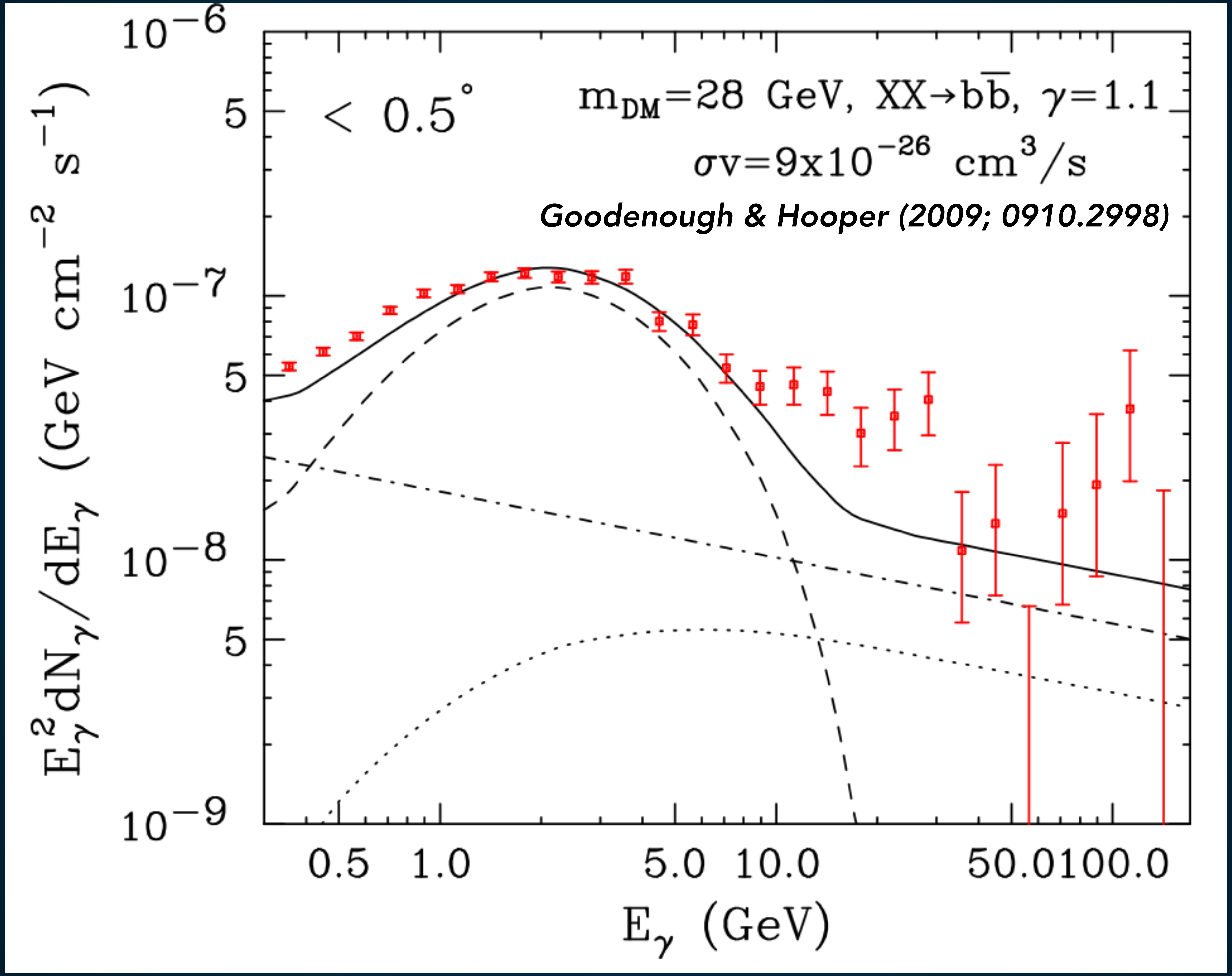
Simplest model has a known cross-section!

Deviations from this cross-section include complicating effects.

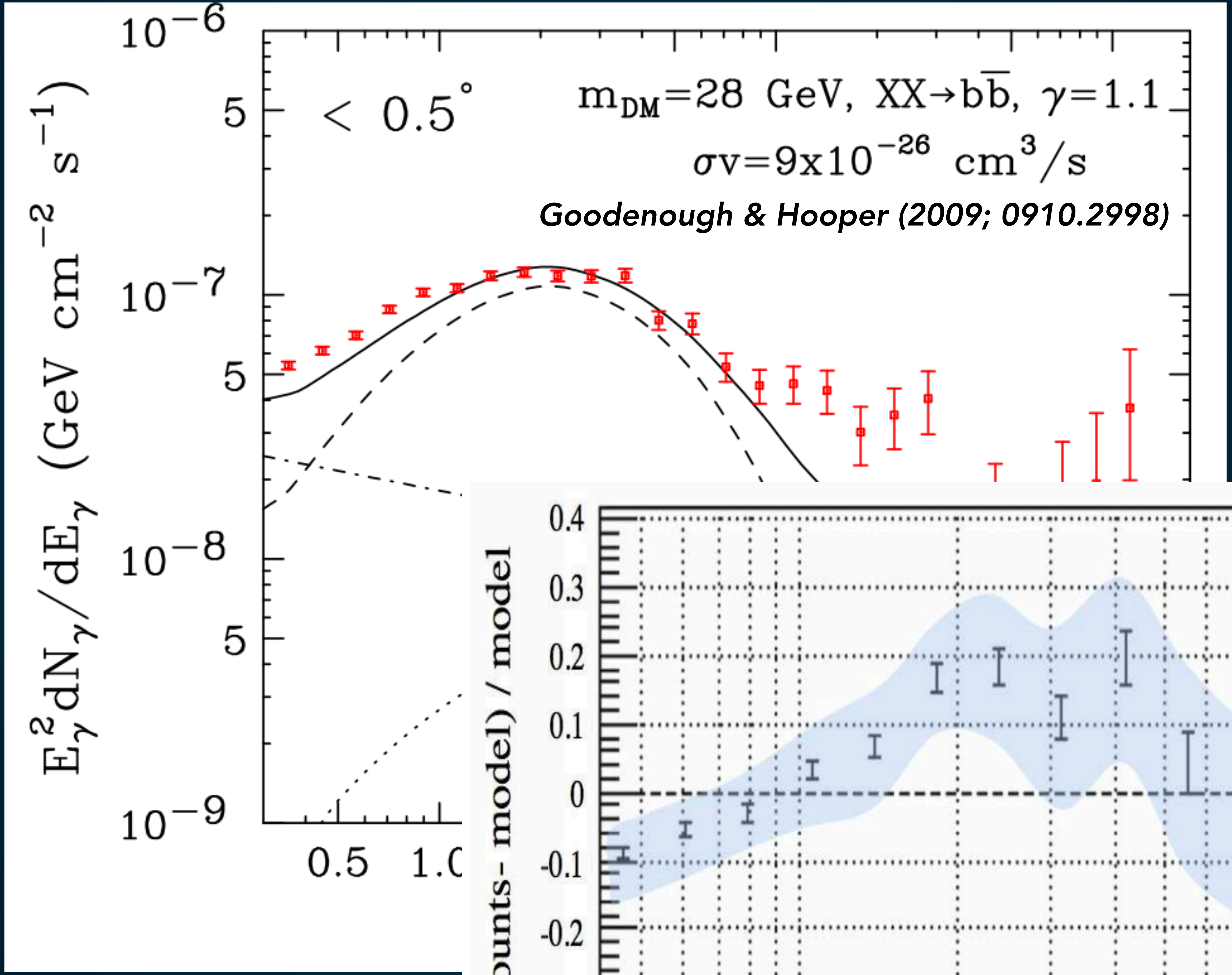
A Mass Scale!

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

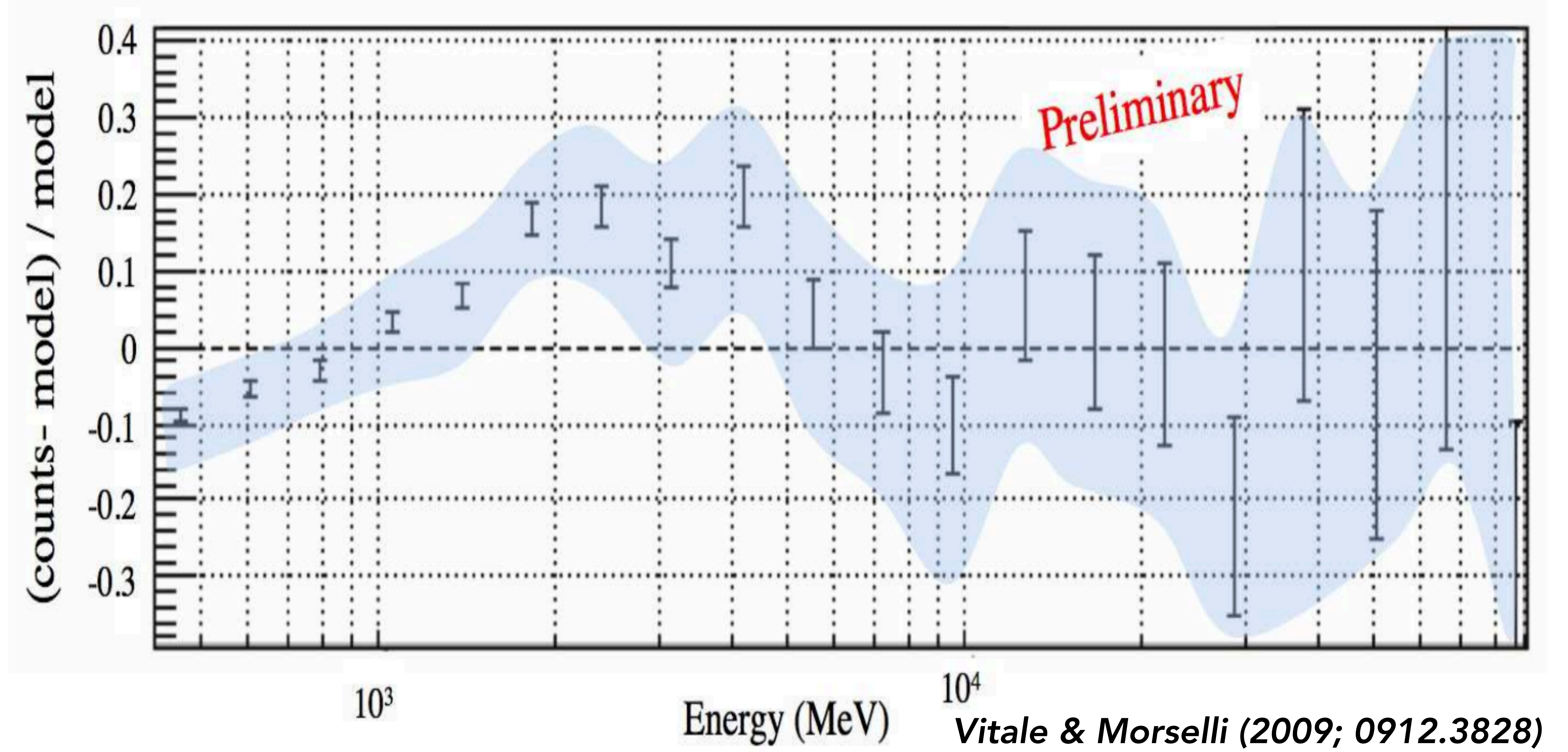
The Galactic Center: The Easiest Place to Find Dark Matter



The Galactic Center: The Easiest Place to Find Dark Matter



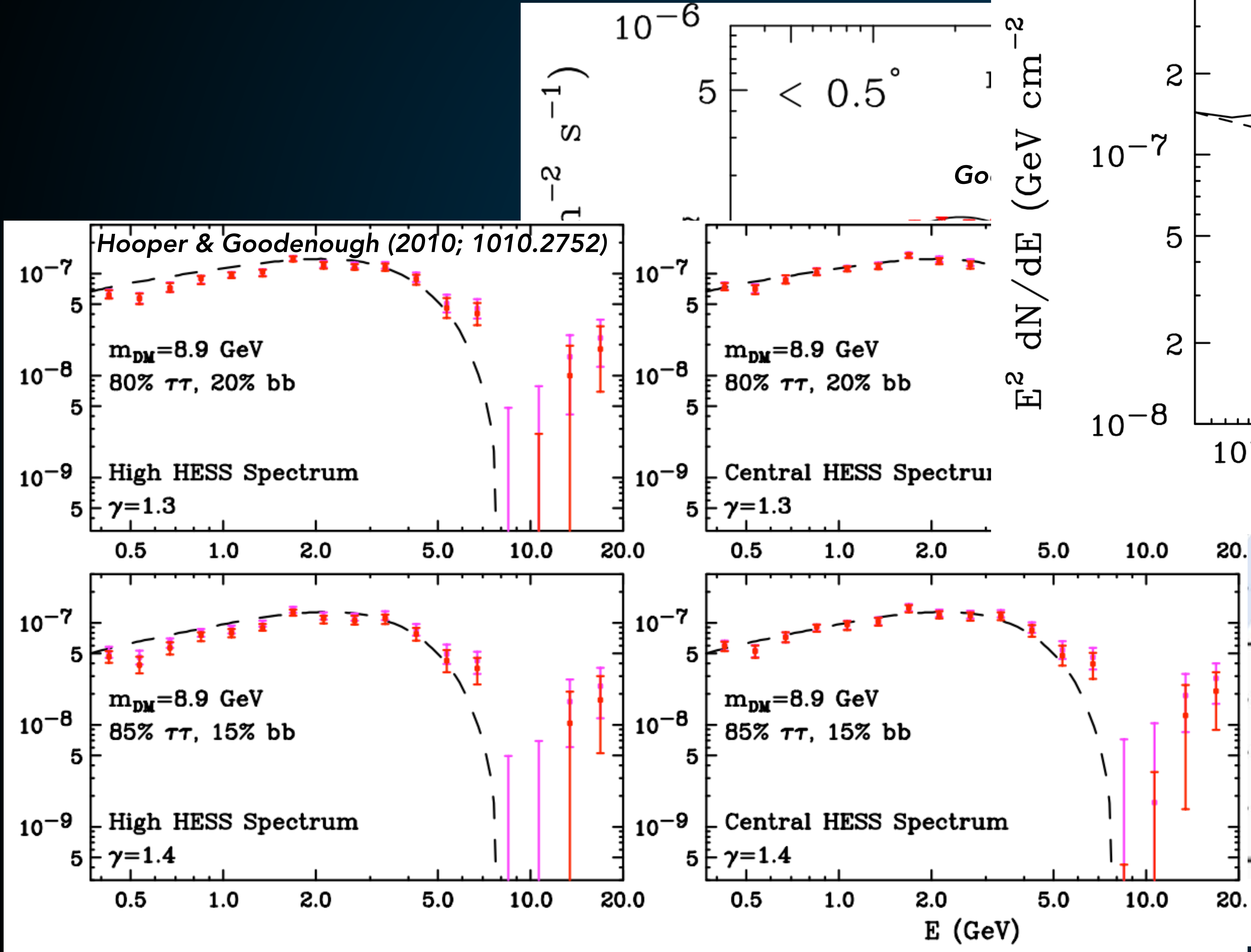
Goodenough & Hooper (2009; 0910.2998)

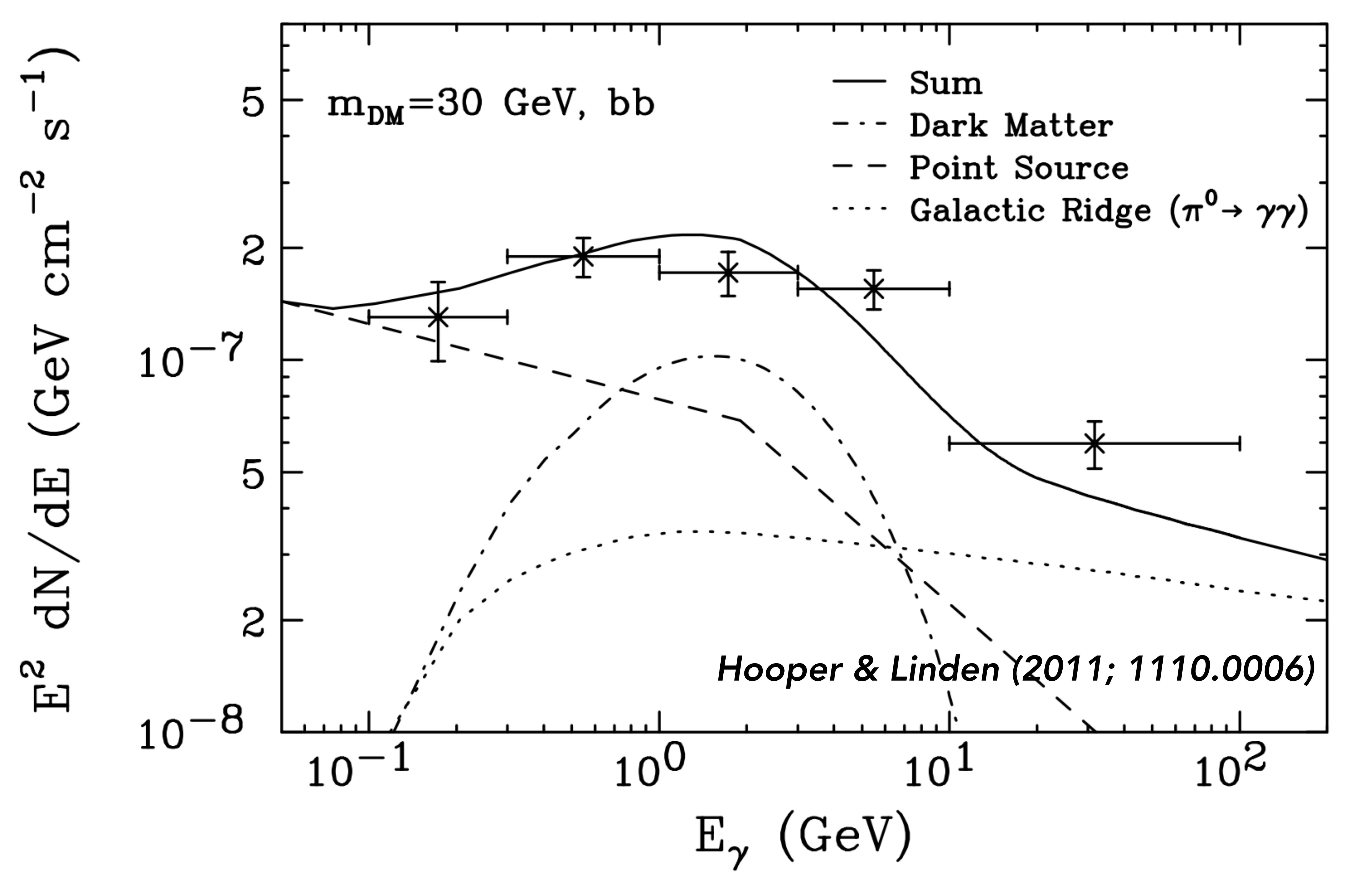


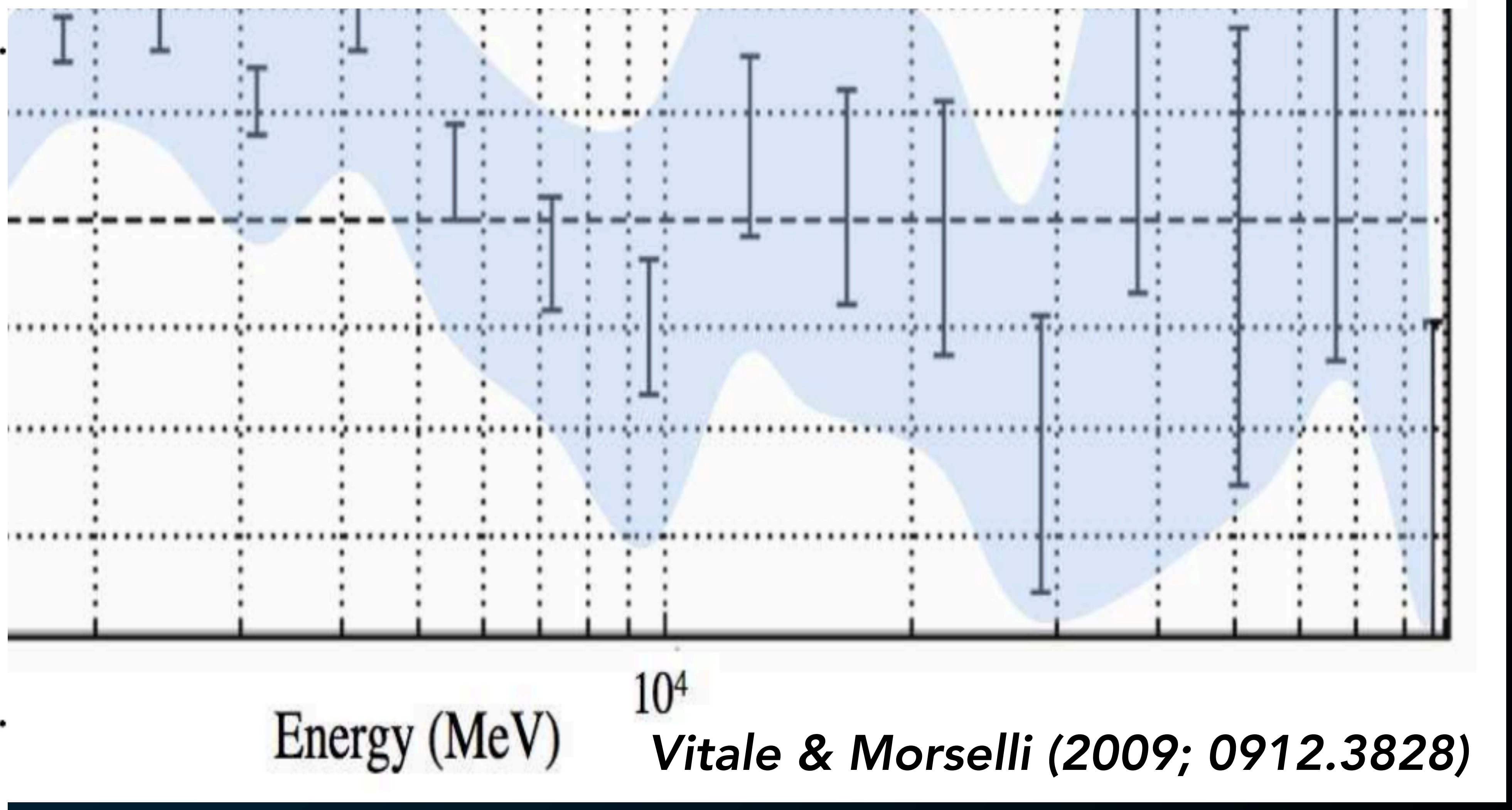
Vitale & Morselli (2009; 0912.3828)

The Galactic Center: The Easiest Place to Find Dark Matter

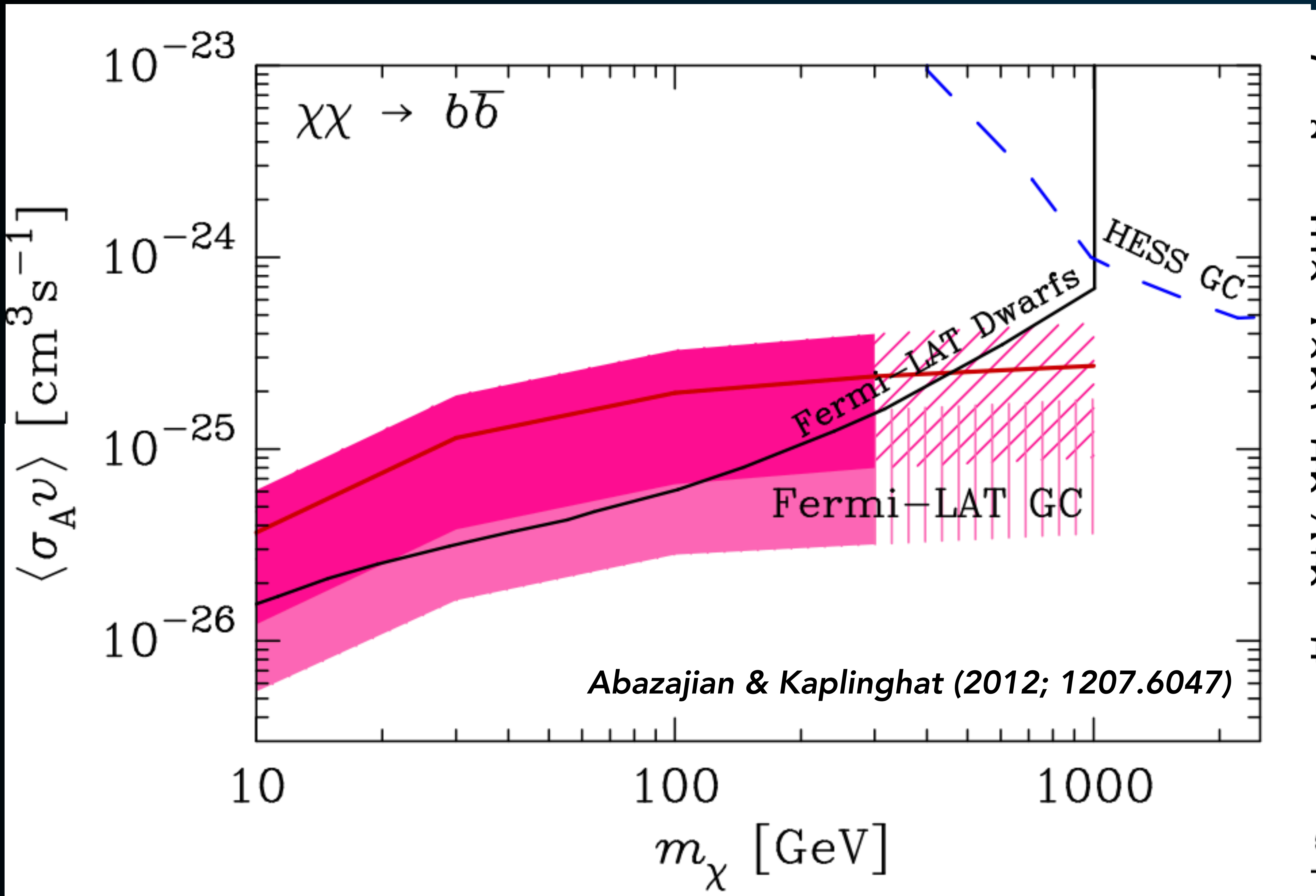
The Galactic Center: The Easiest Place to Find Dark Matter

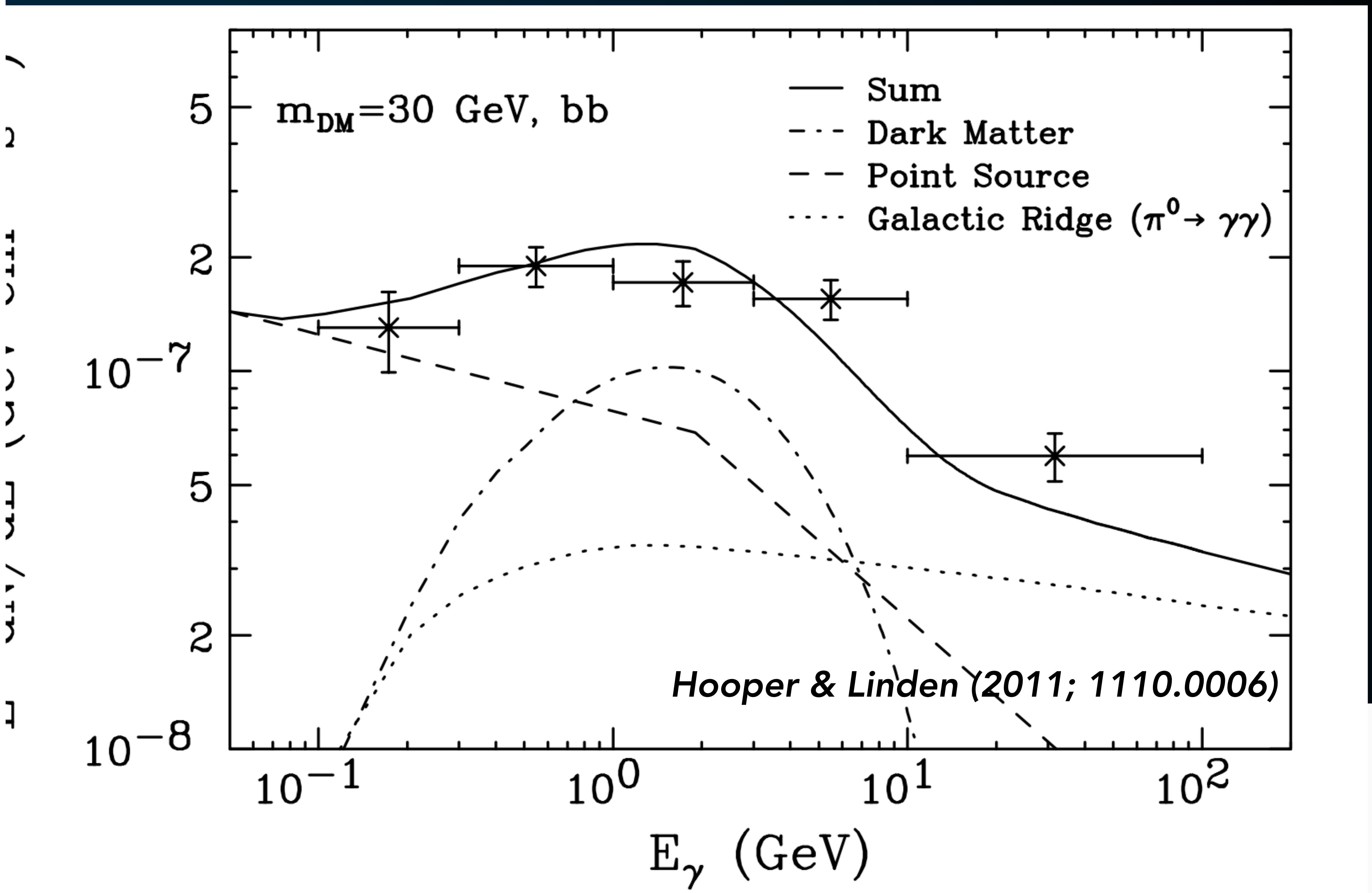


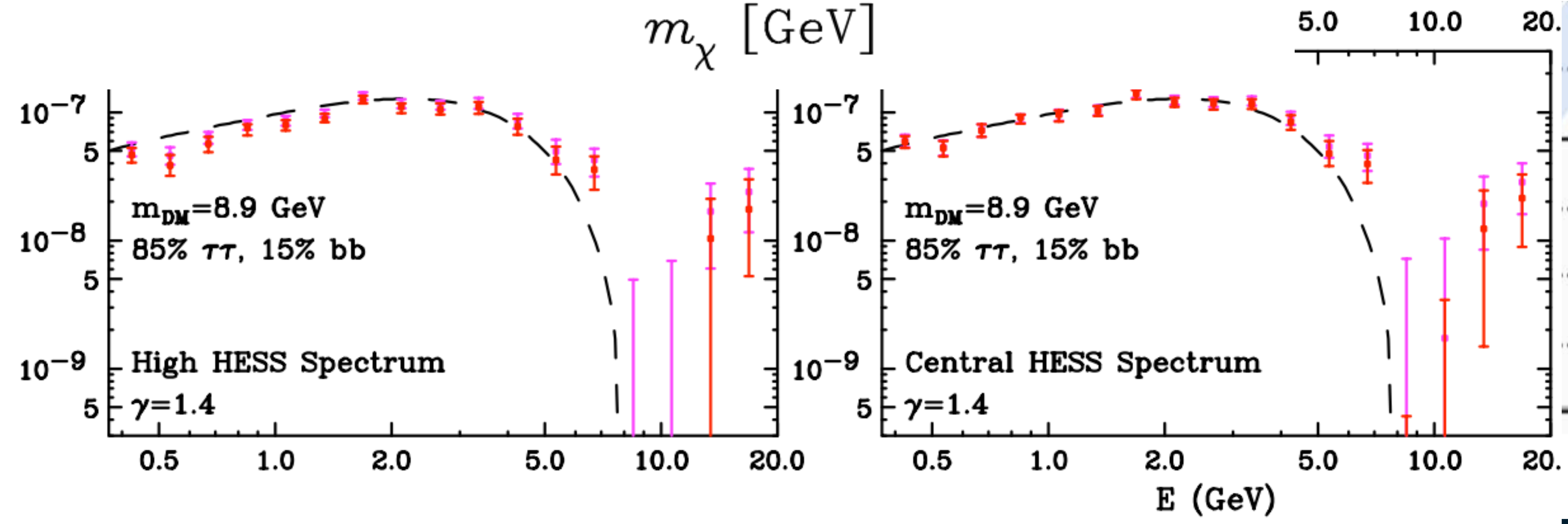


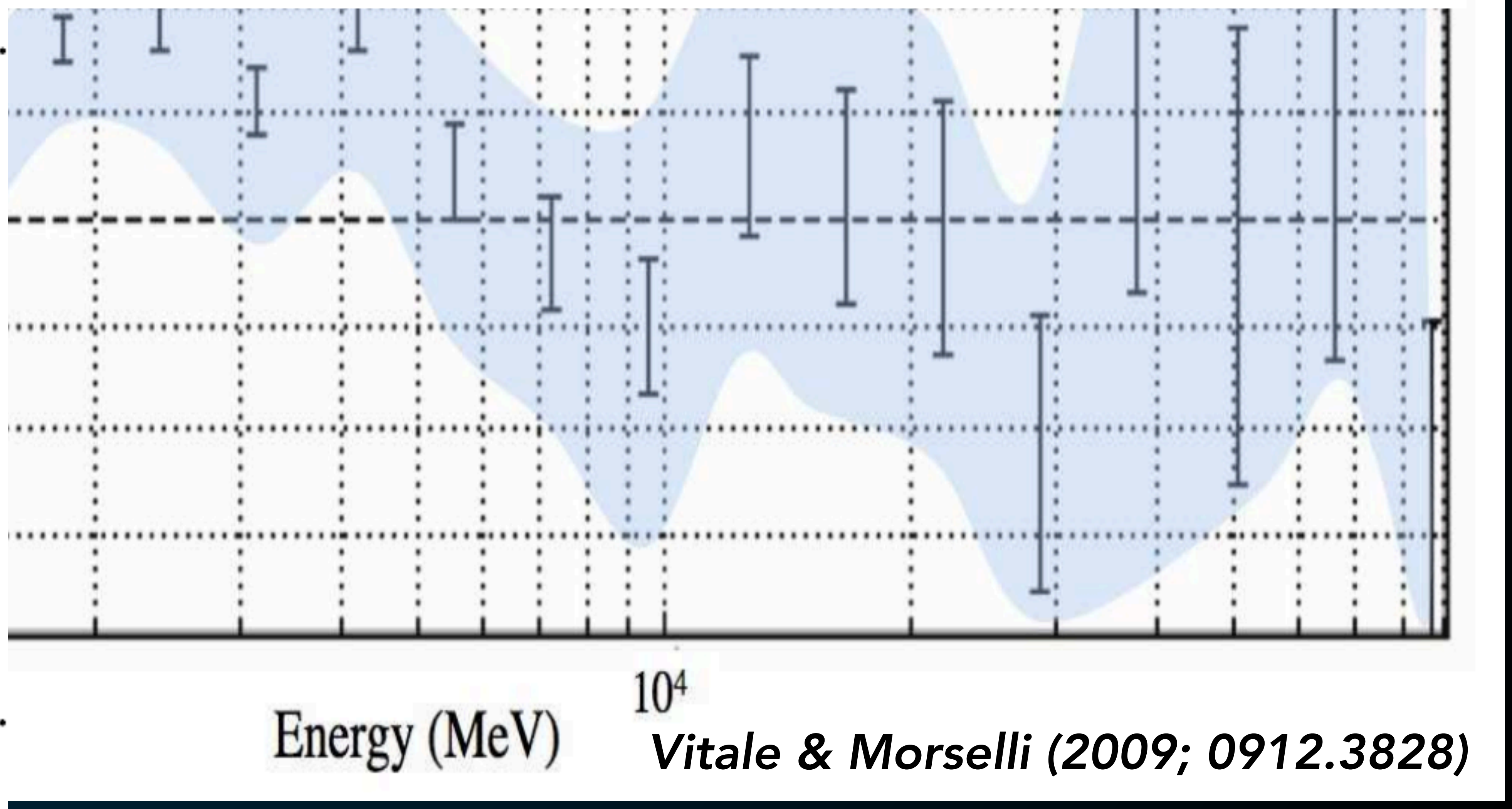


The Galactic Center: The Easiest Place to Find Dark Matter

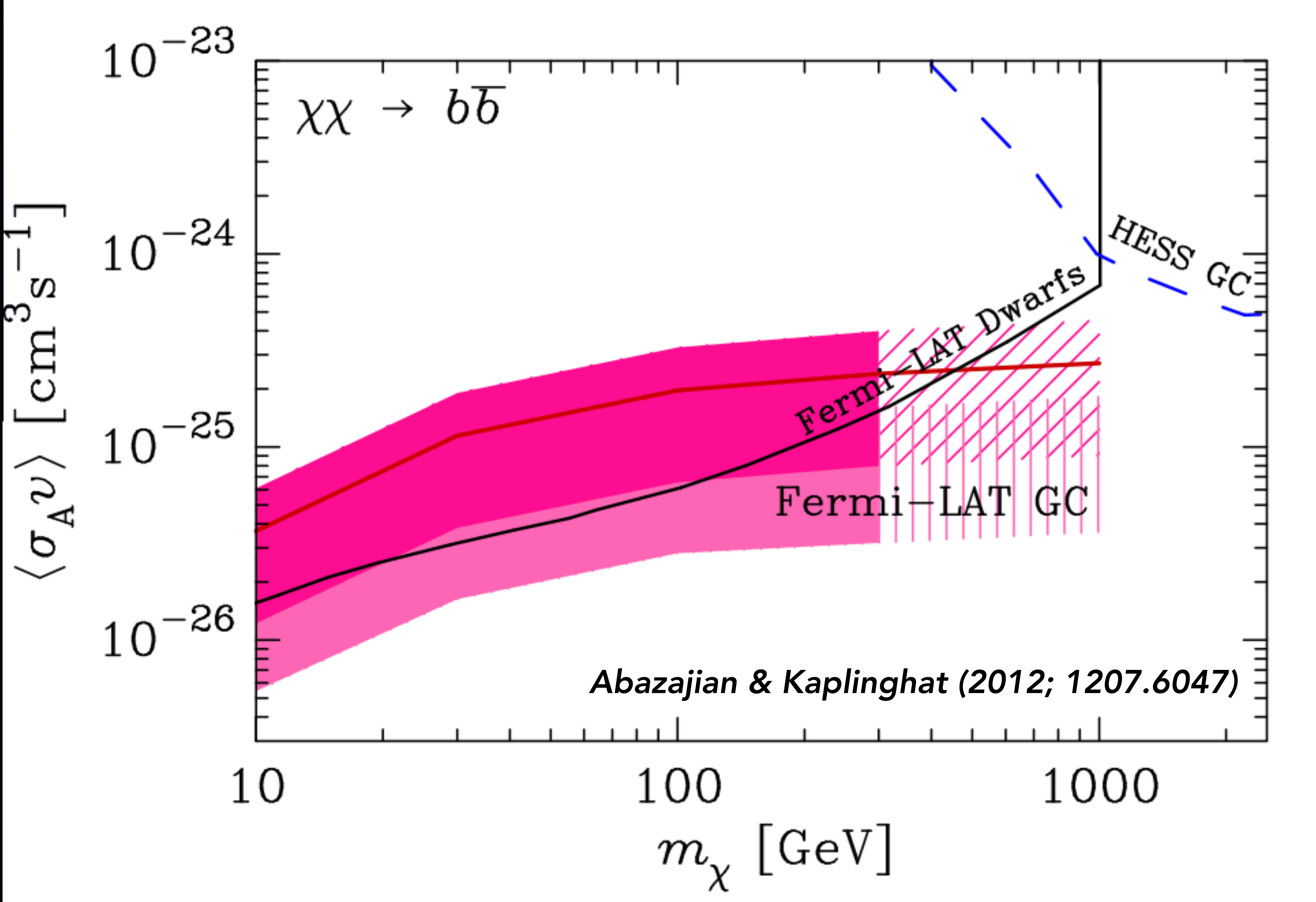


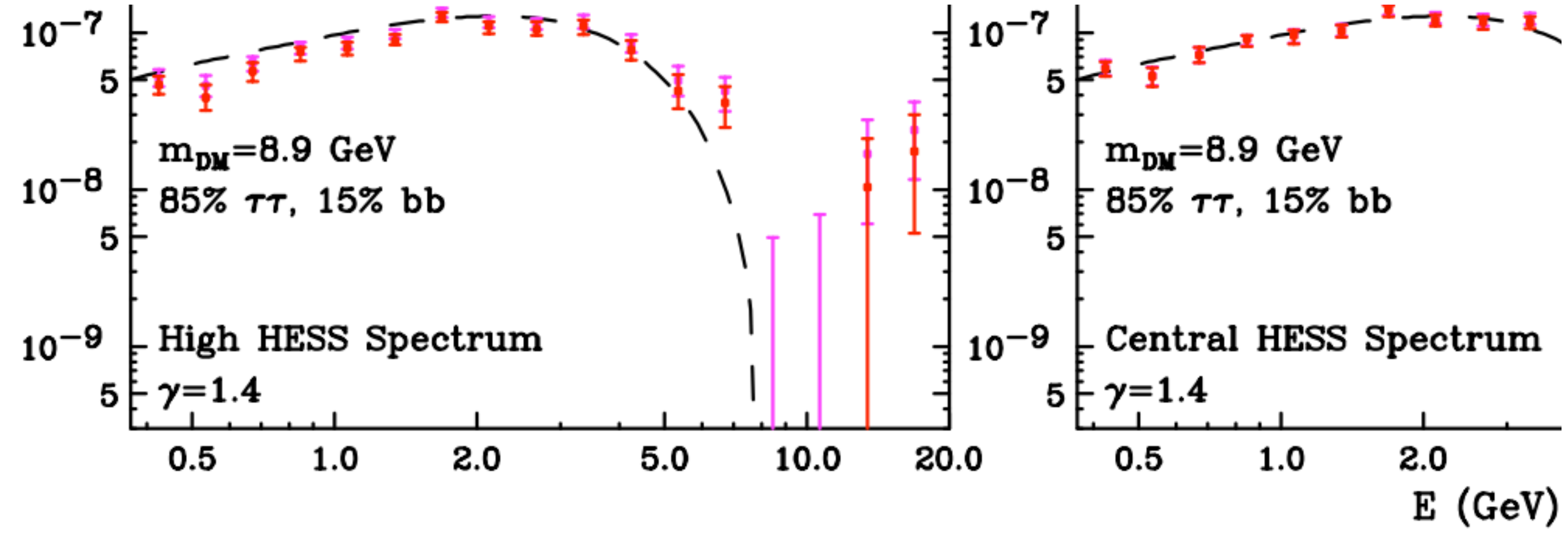


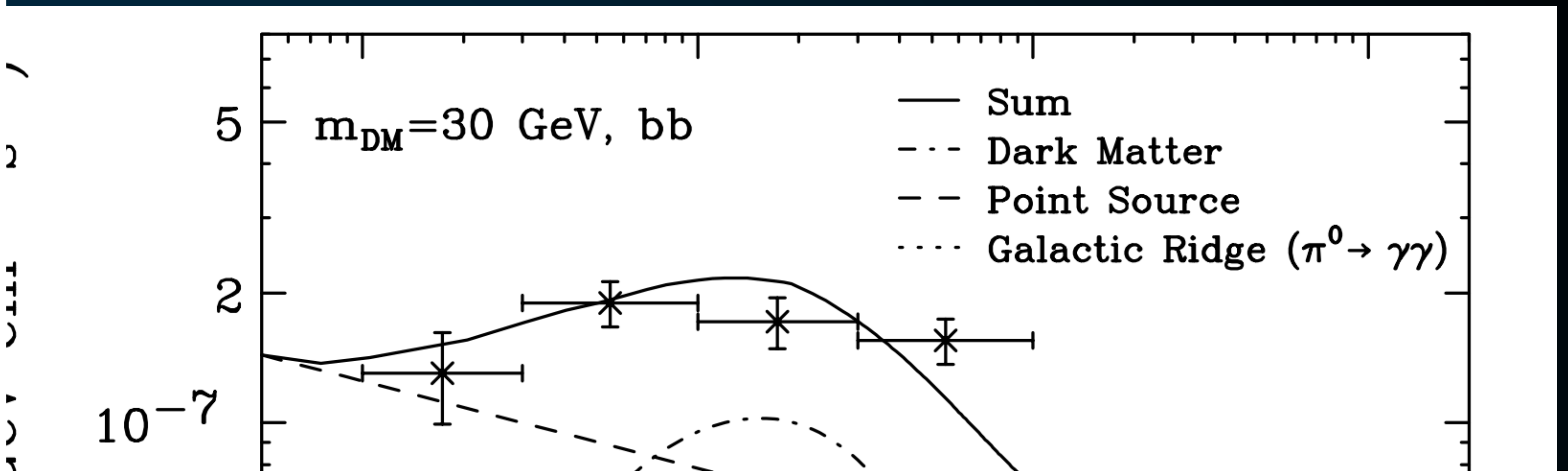


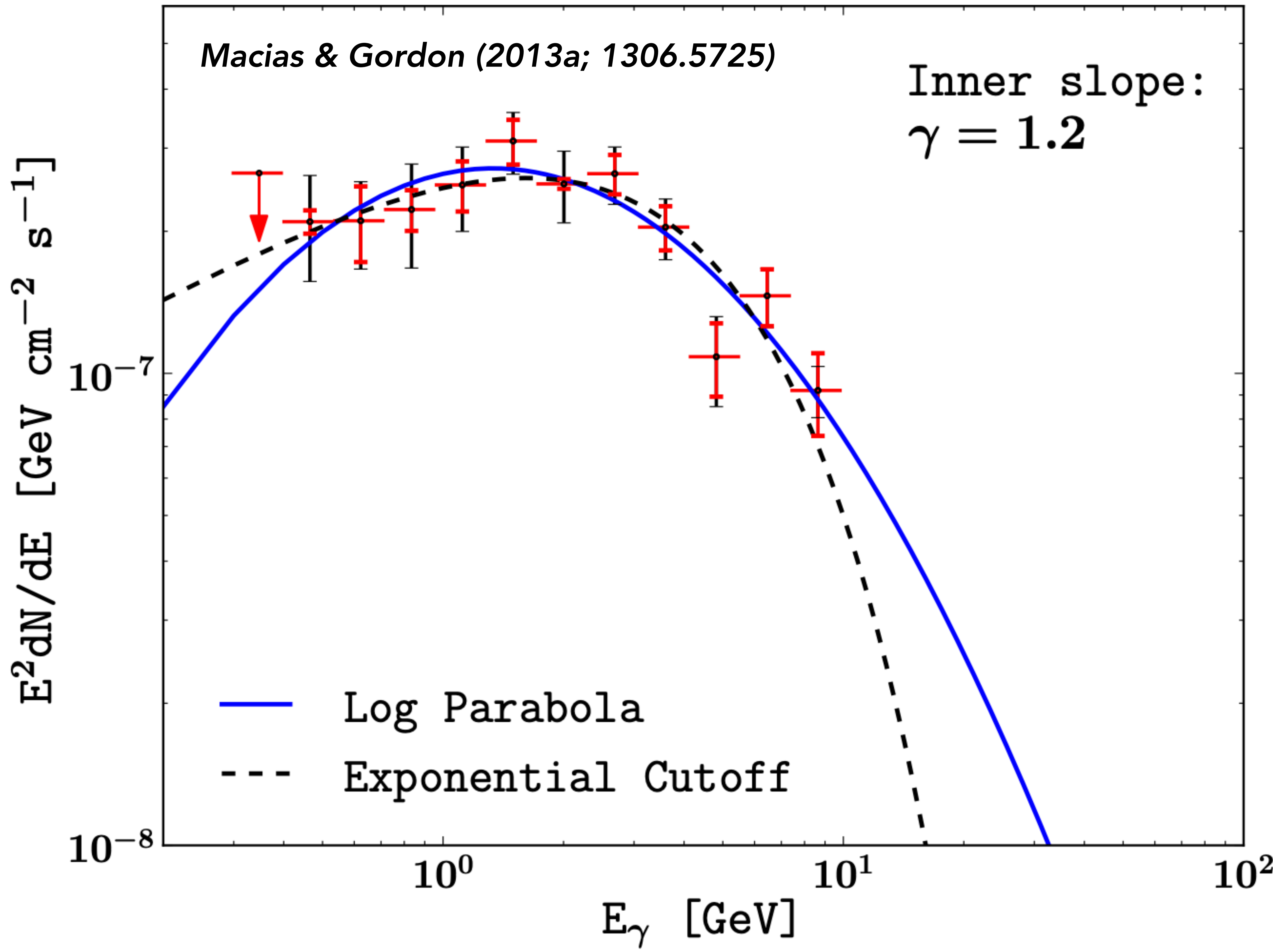


The Galactic Center: The Easiest Place to Find Dark Matter

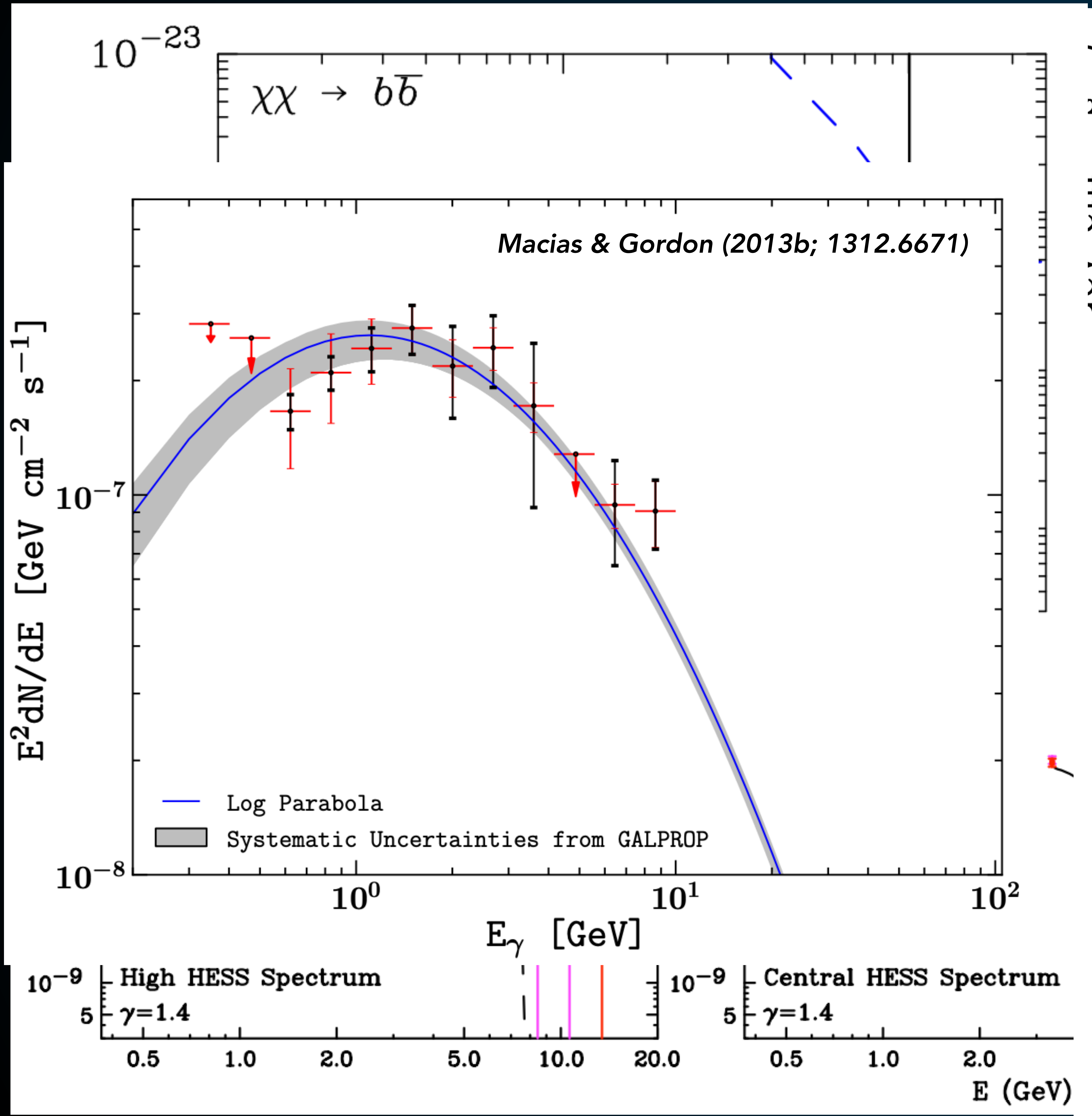


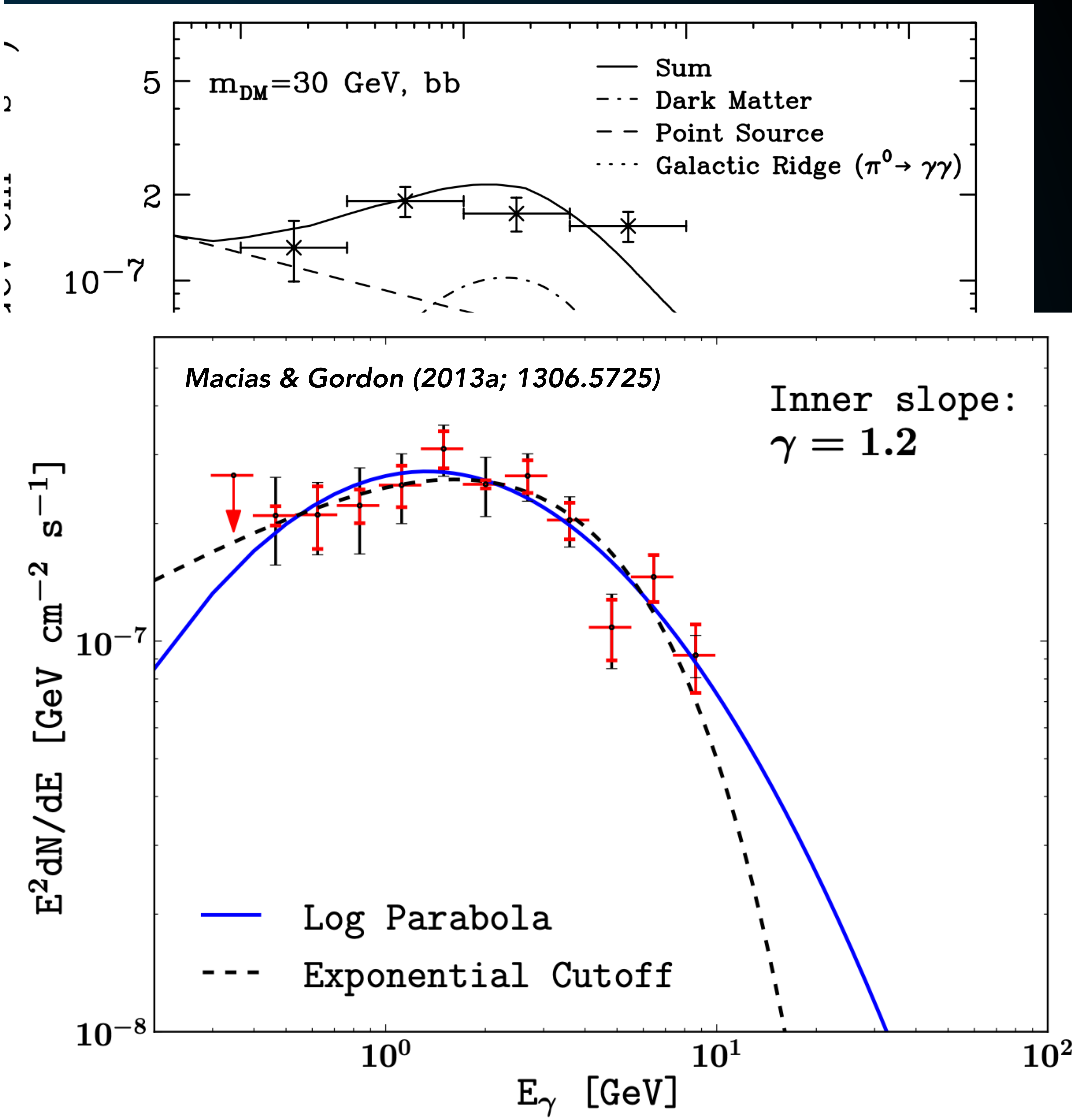






The Galactic Center: The Easiest Place to Find Dark Matter





The Galactic Center: The Easiest Place to Find Dark Matter

The Galactic Center: The Easiest Place to Find Dark Matter

The Galactic Center: The Easiest Place to Find Dark Matter

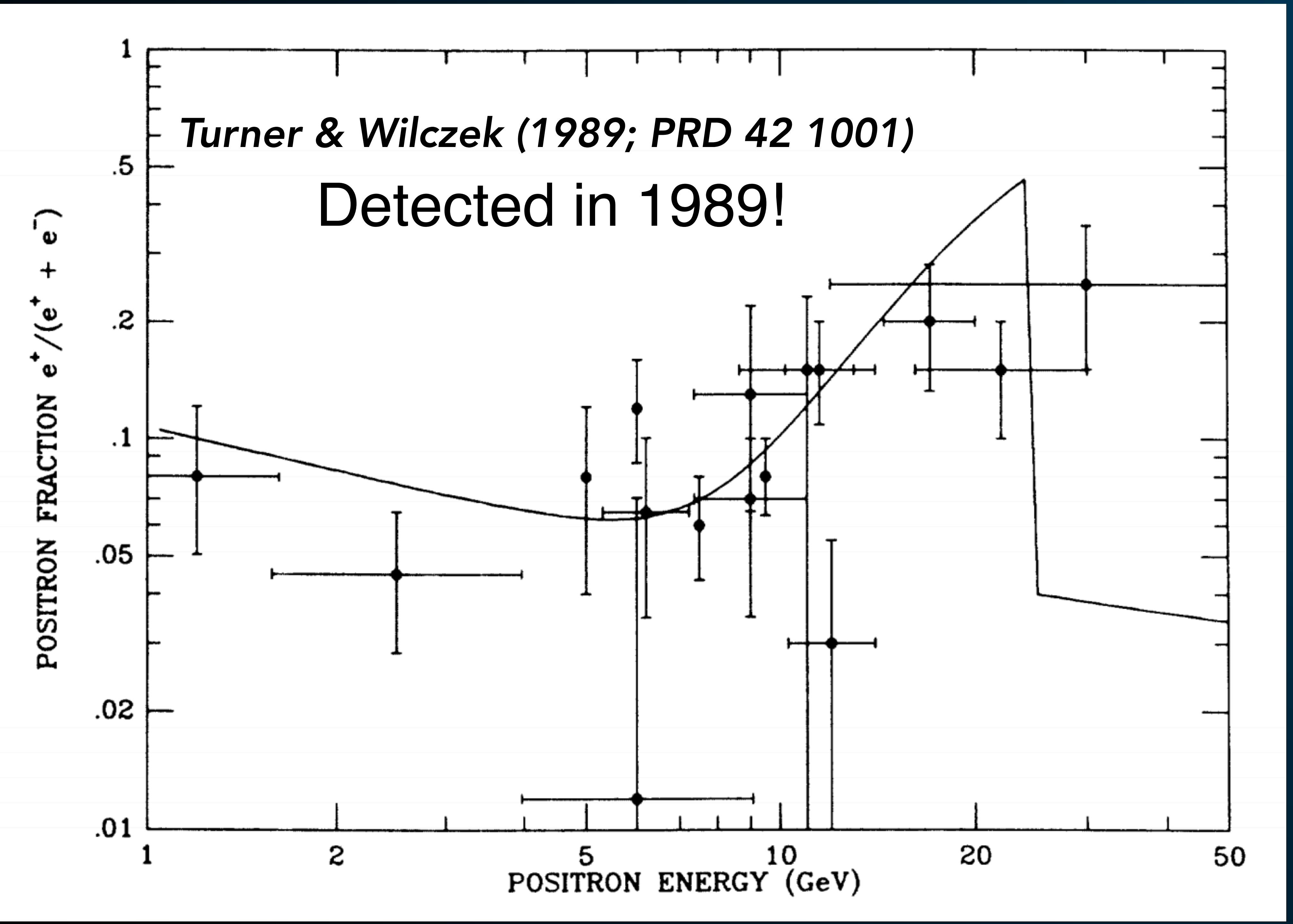
The Galactic Center: The Easiest Place to Find Dark Matter

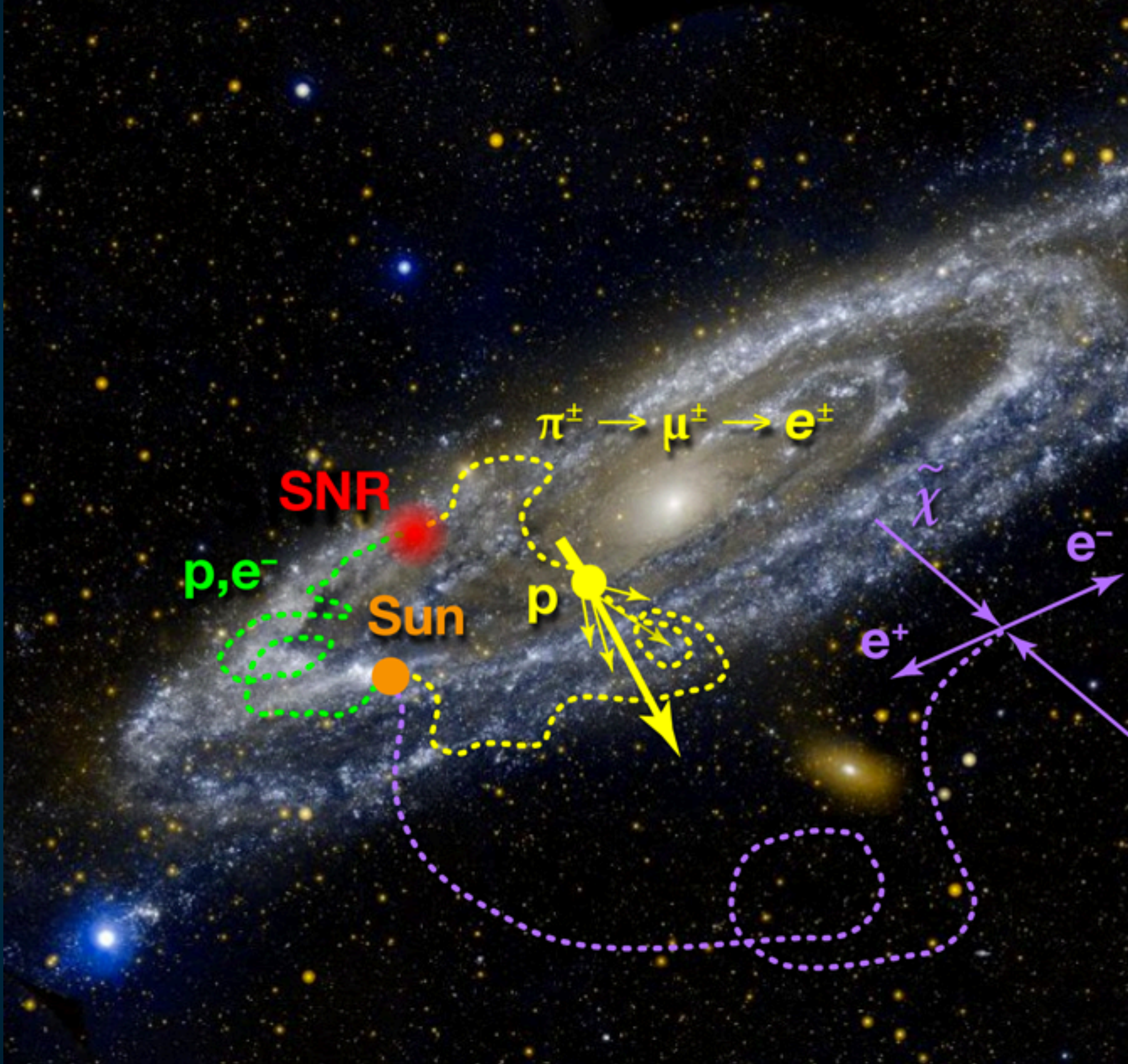

AMS-02
Fit to Data
The Positron Excess
Positron fraction
10^-1
1
10
10^2
positron, electron energy [GeV]

The Positron Excess

Key Idea: Investigate the Positron Fraction!

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

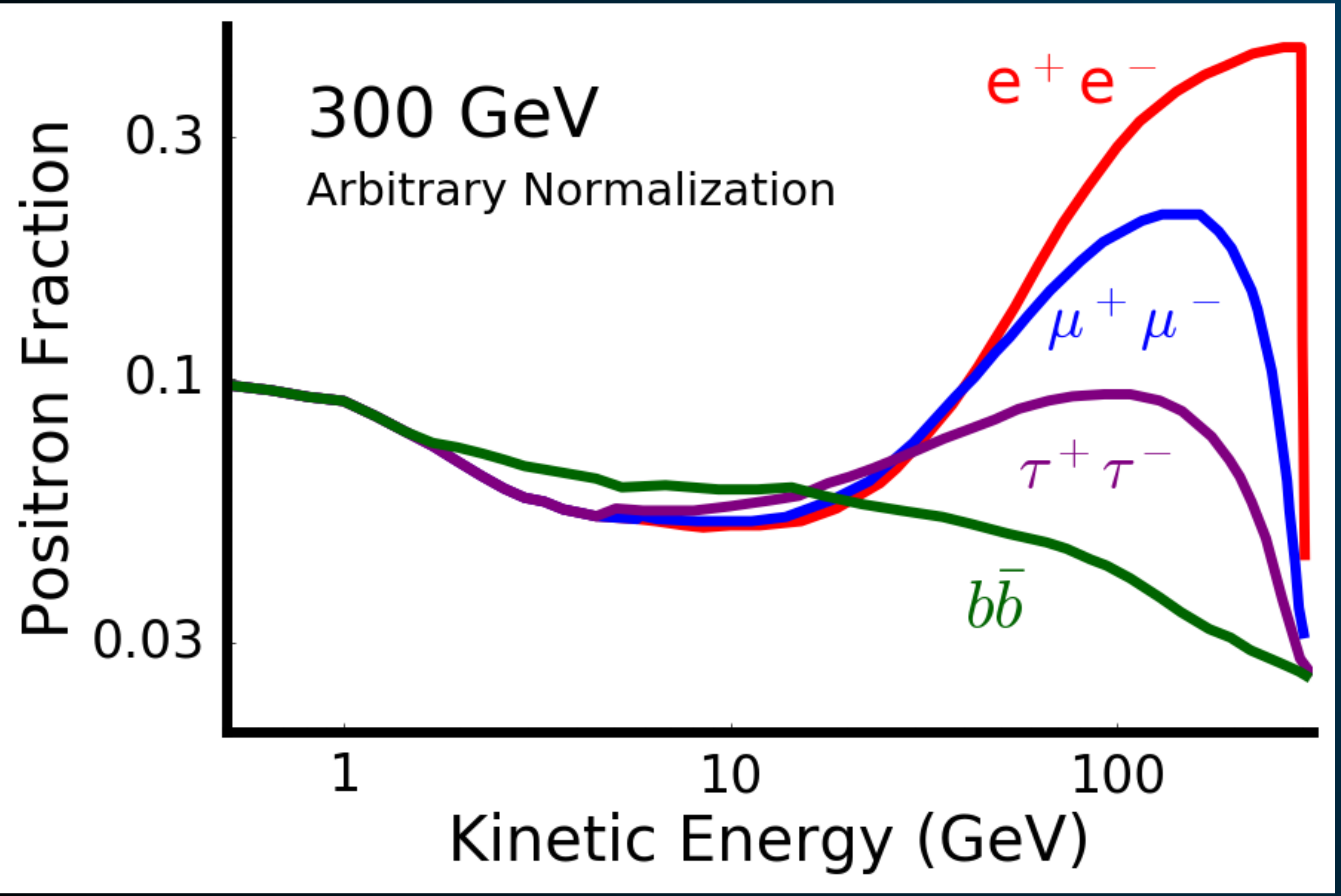


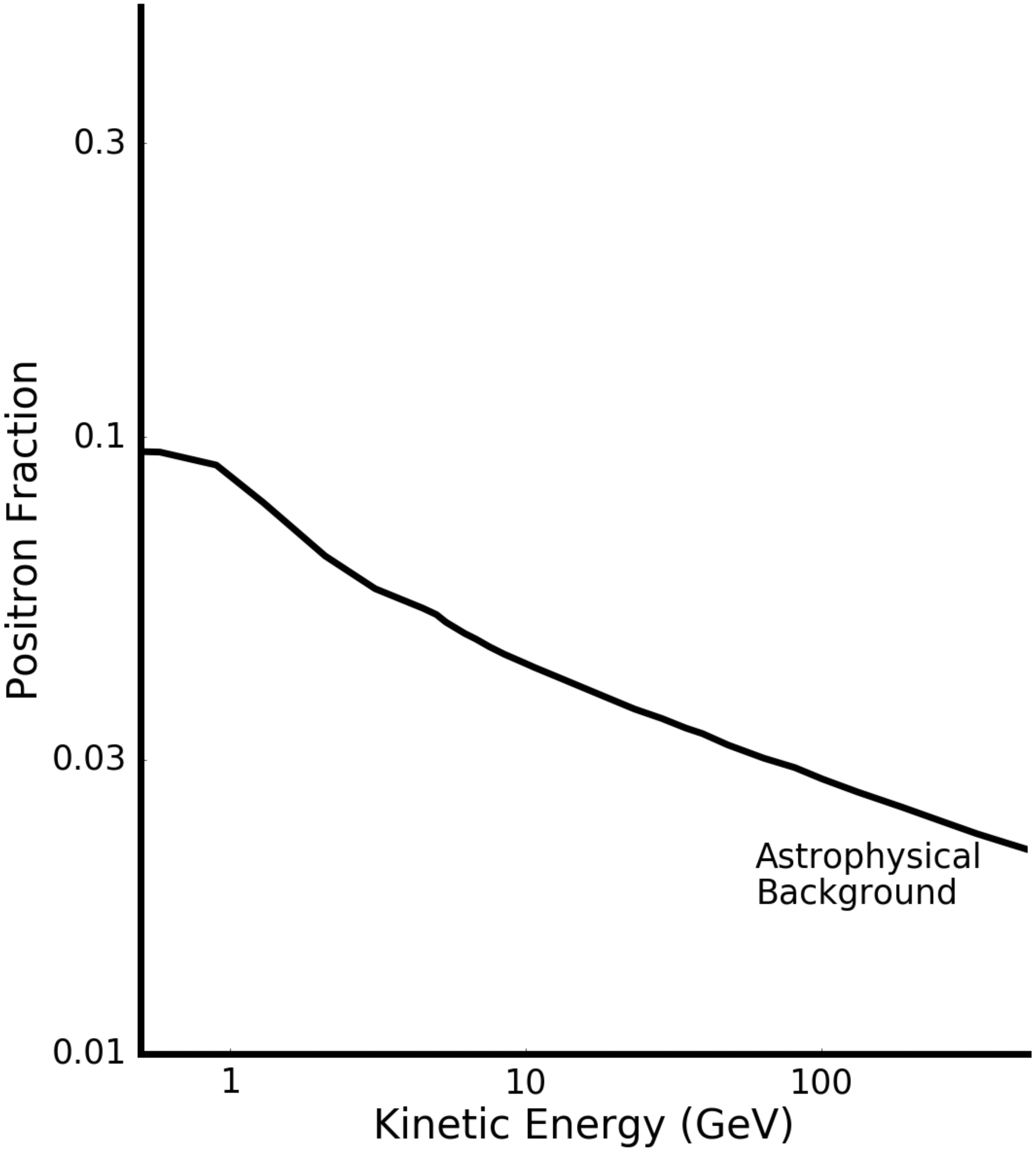


The Positron Excess

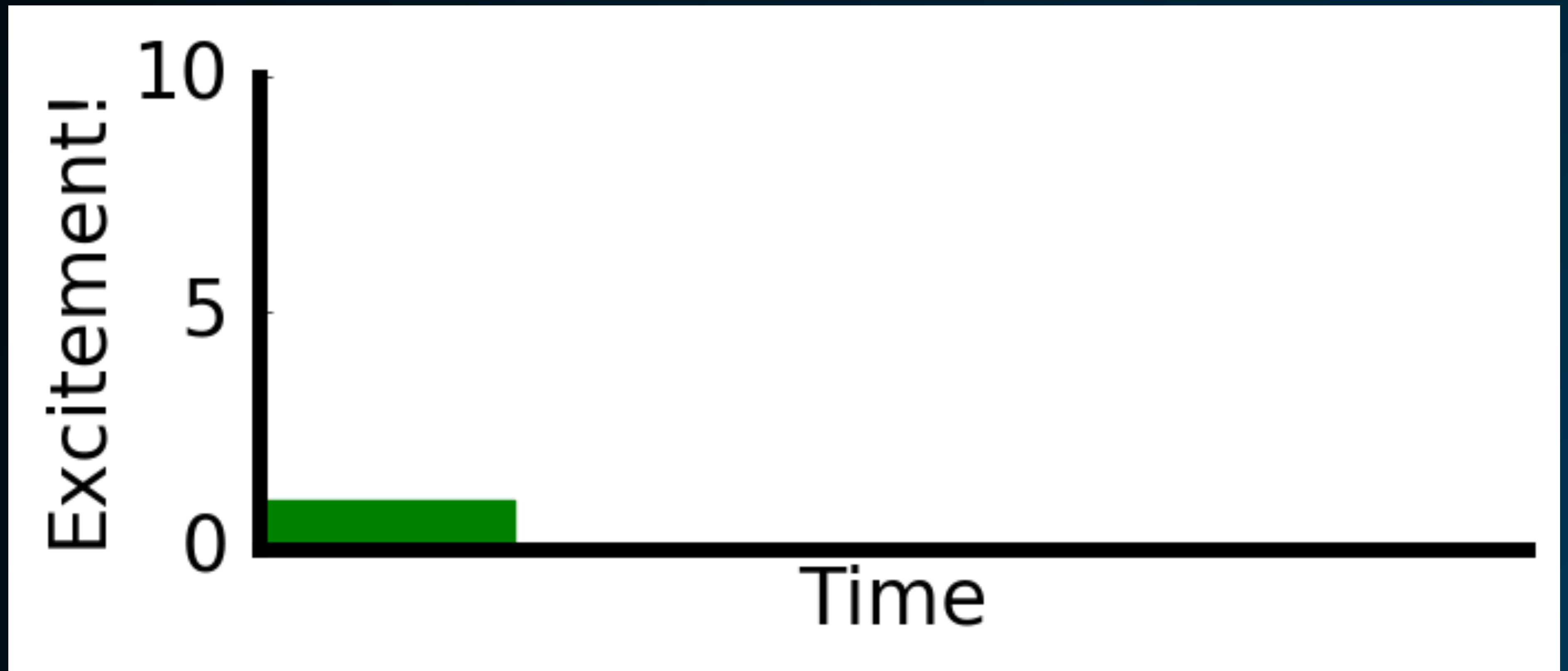
Astrophysics - Slowly Decreasing

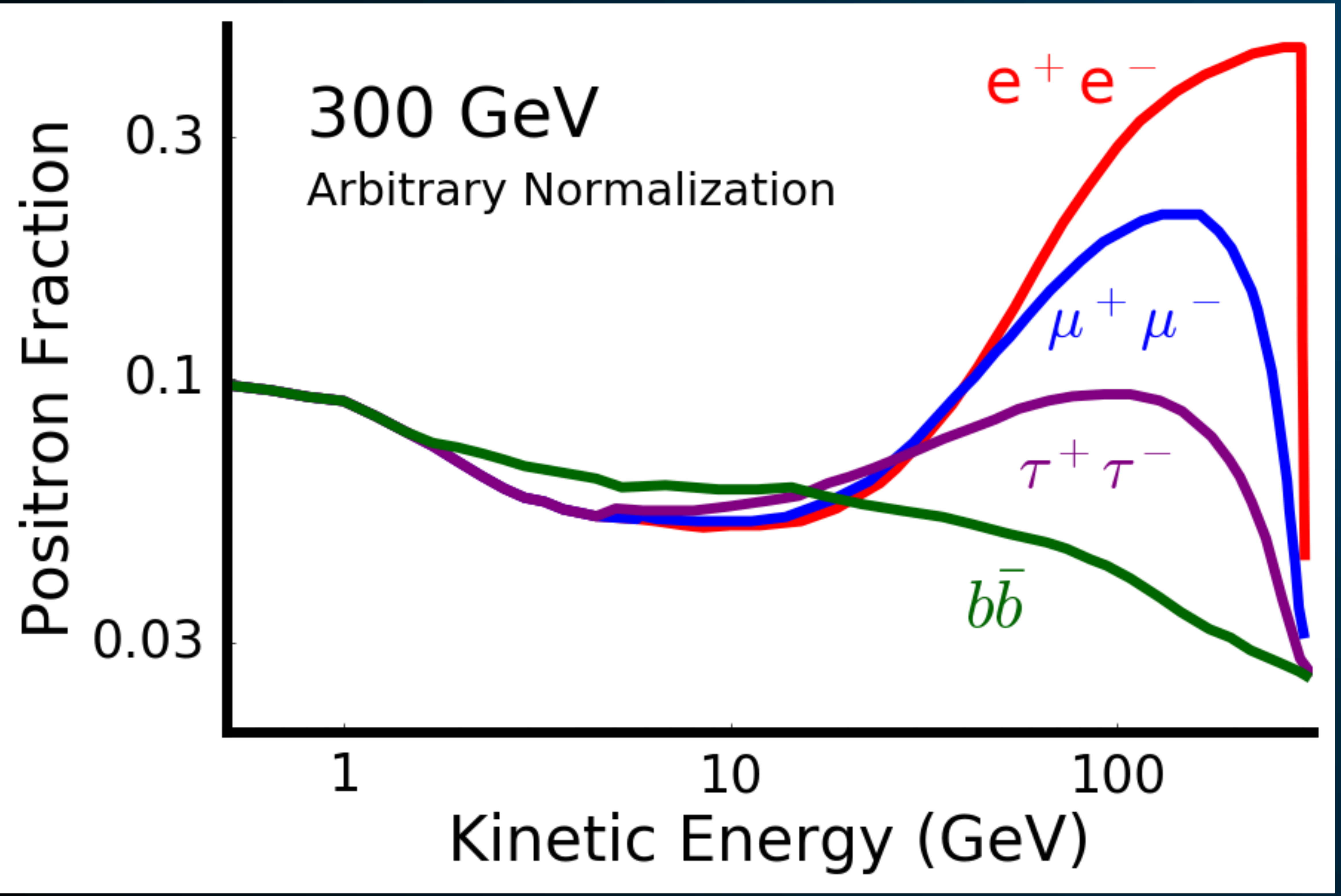
Dark Matter - Sharp Bump!



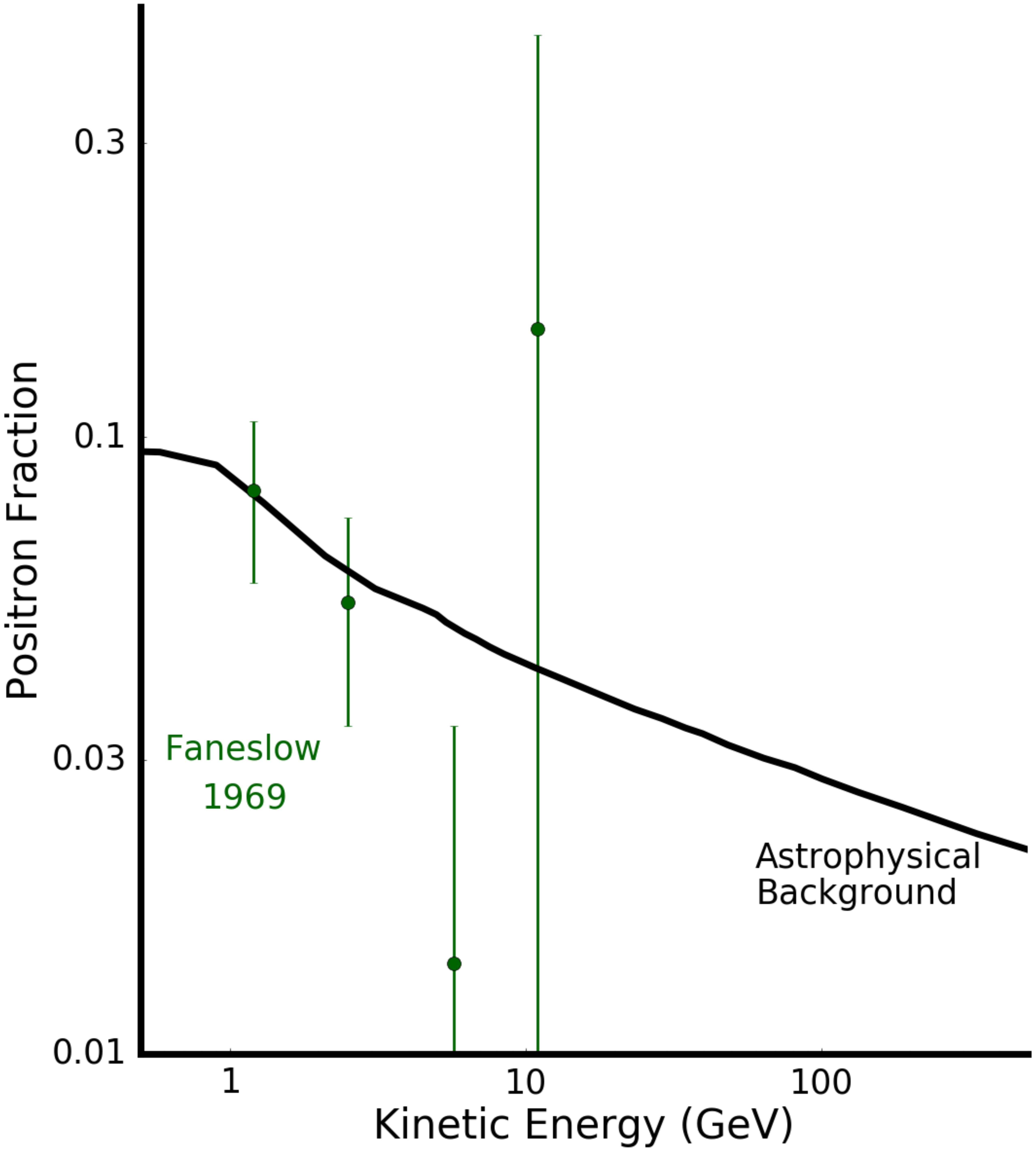


The Positron Excess

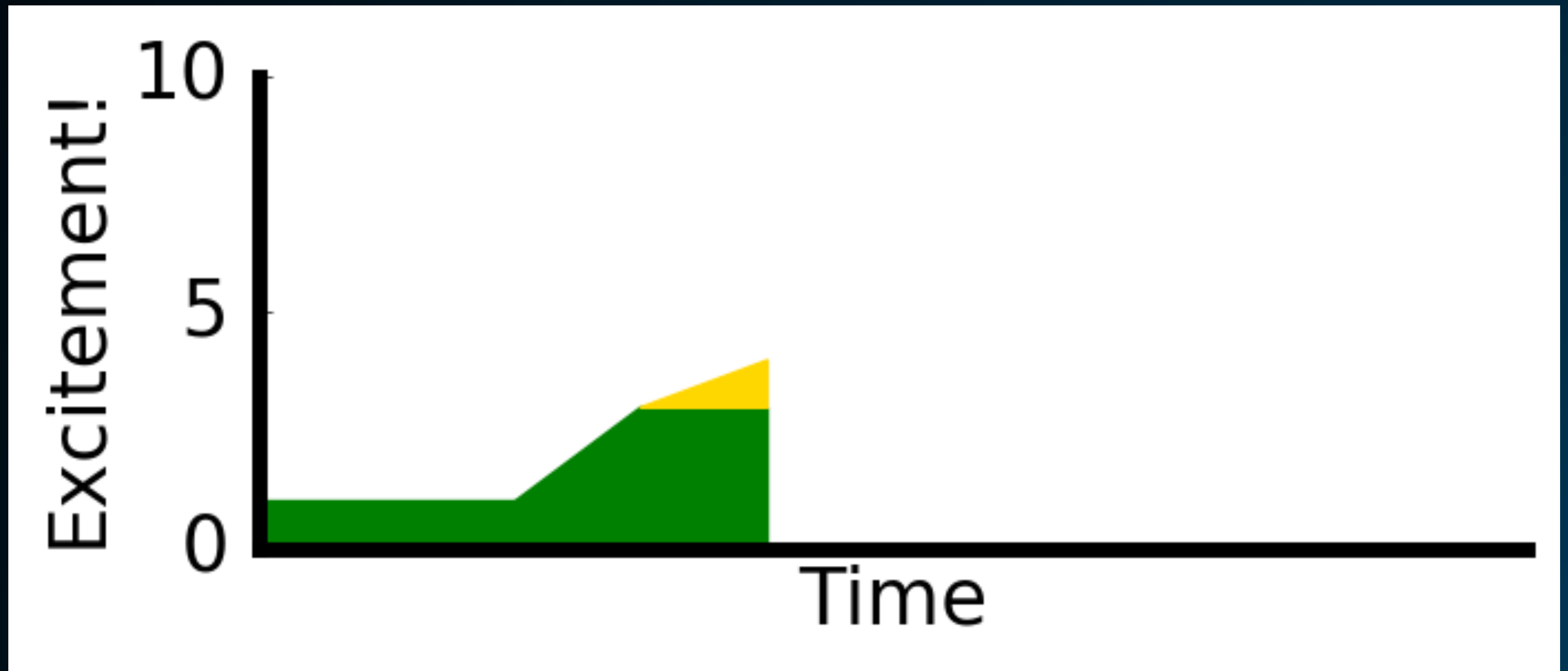


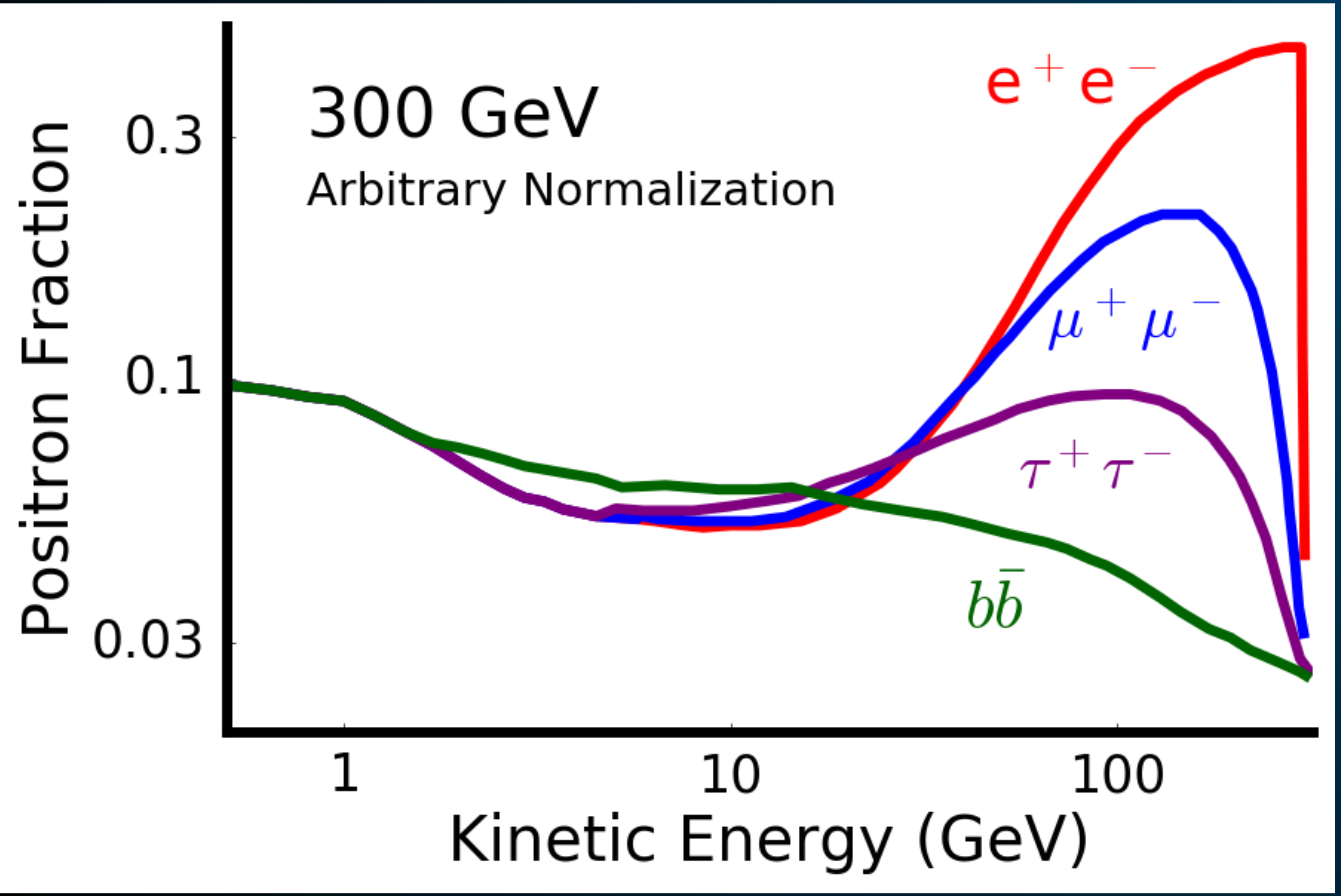


(Not an exhaustive list of observations)

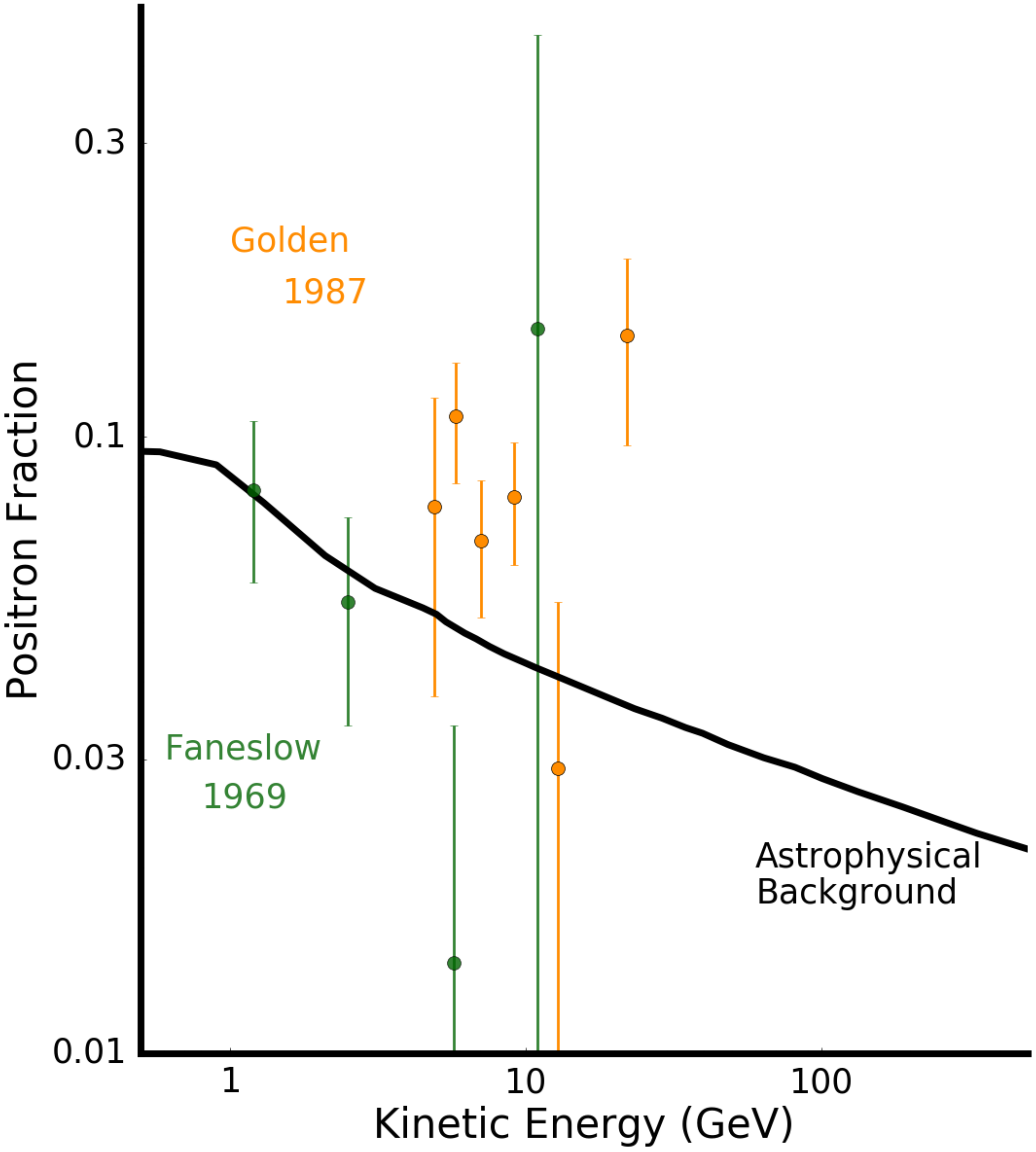


The Positron Excess

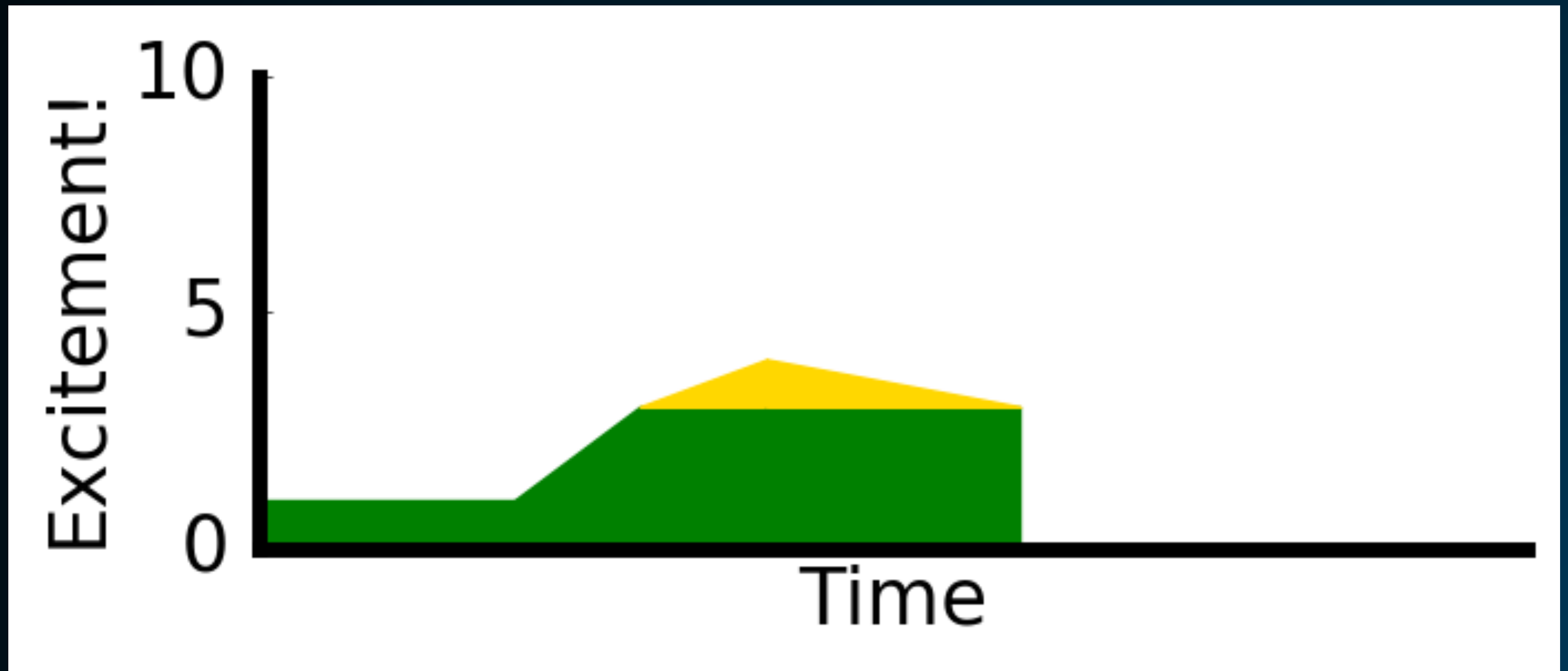


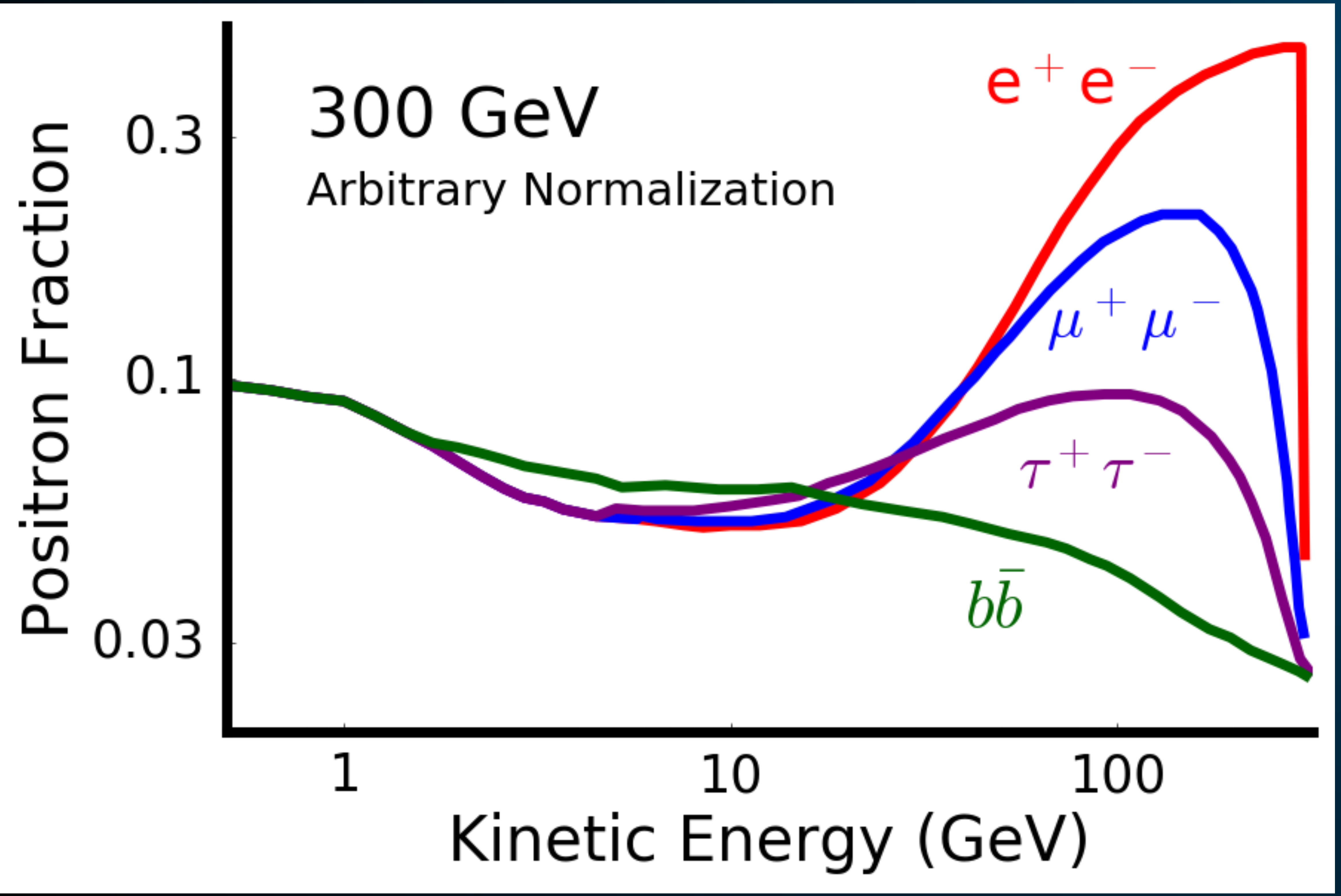


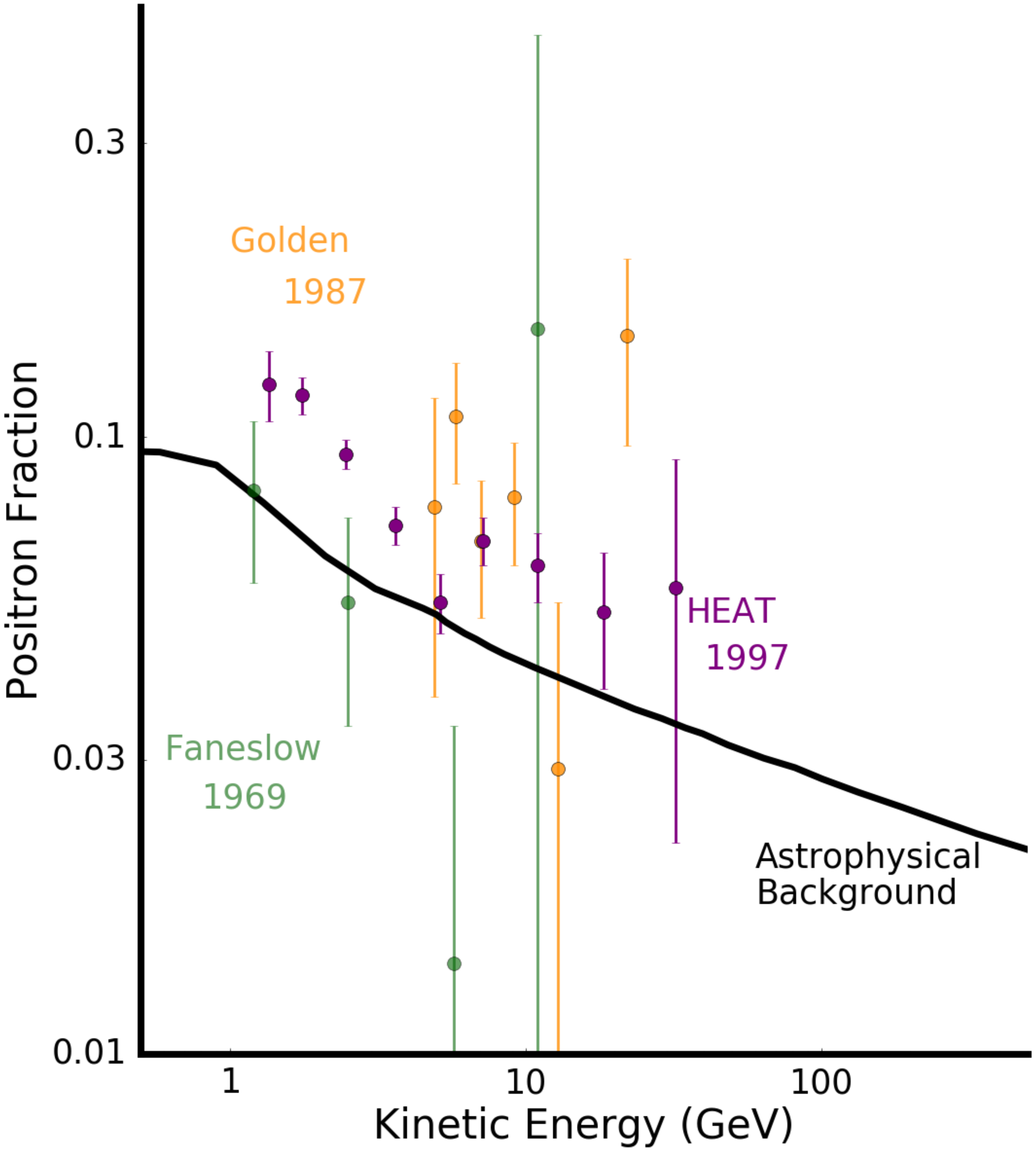
(Not an exhaustive list of observations)



The Positron Excess

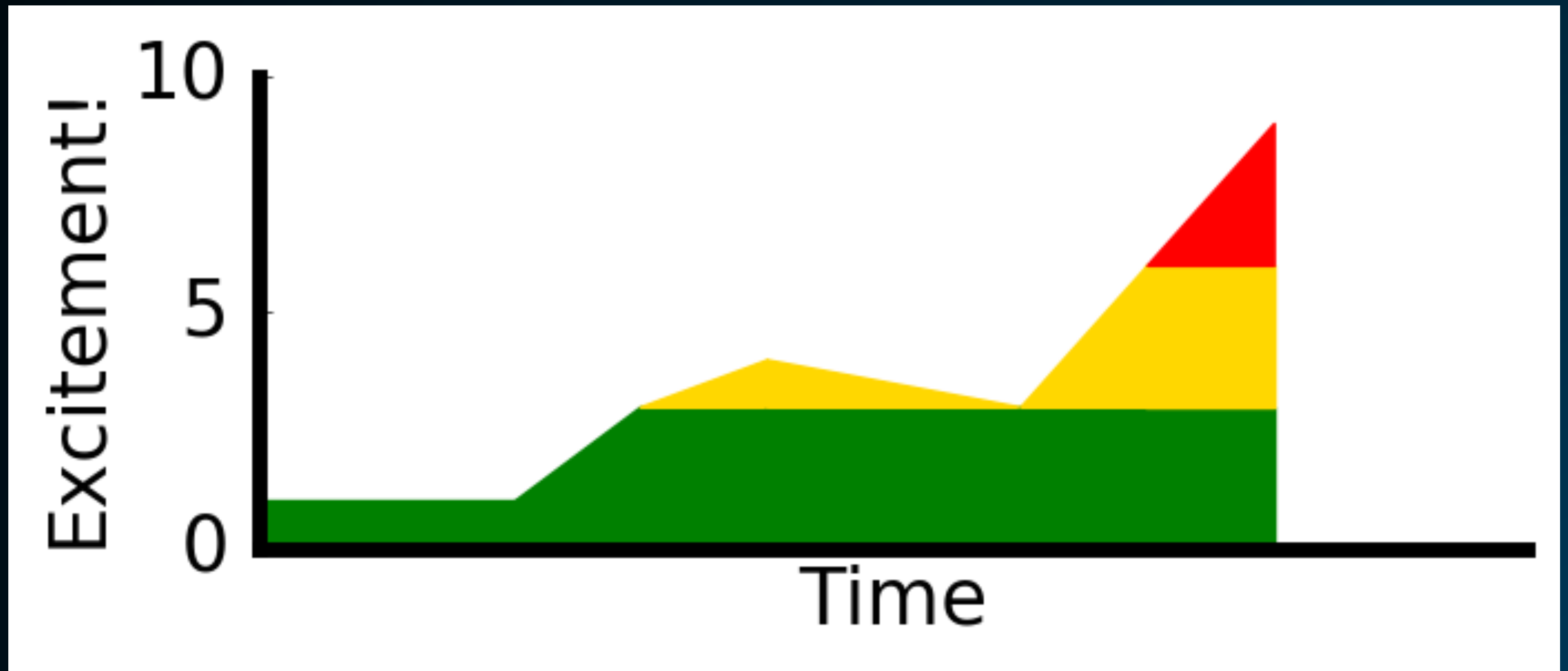


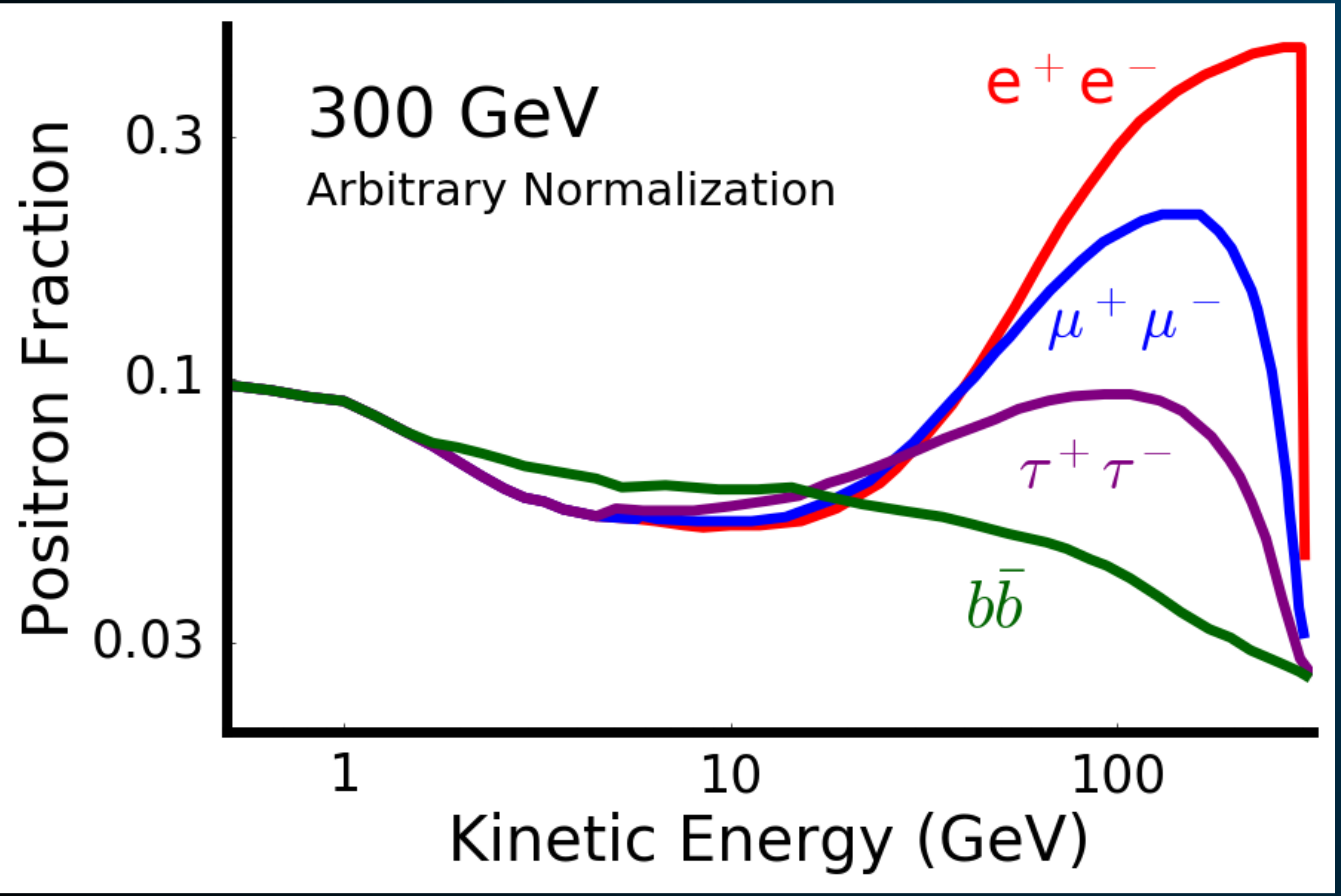




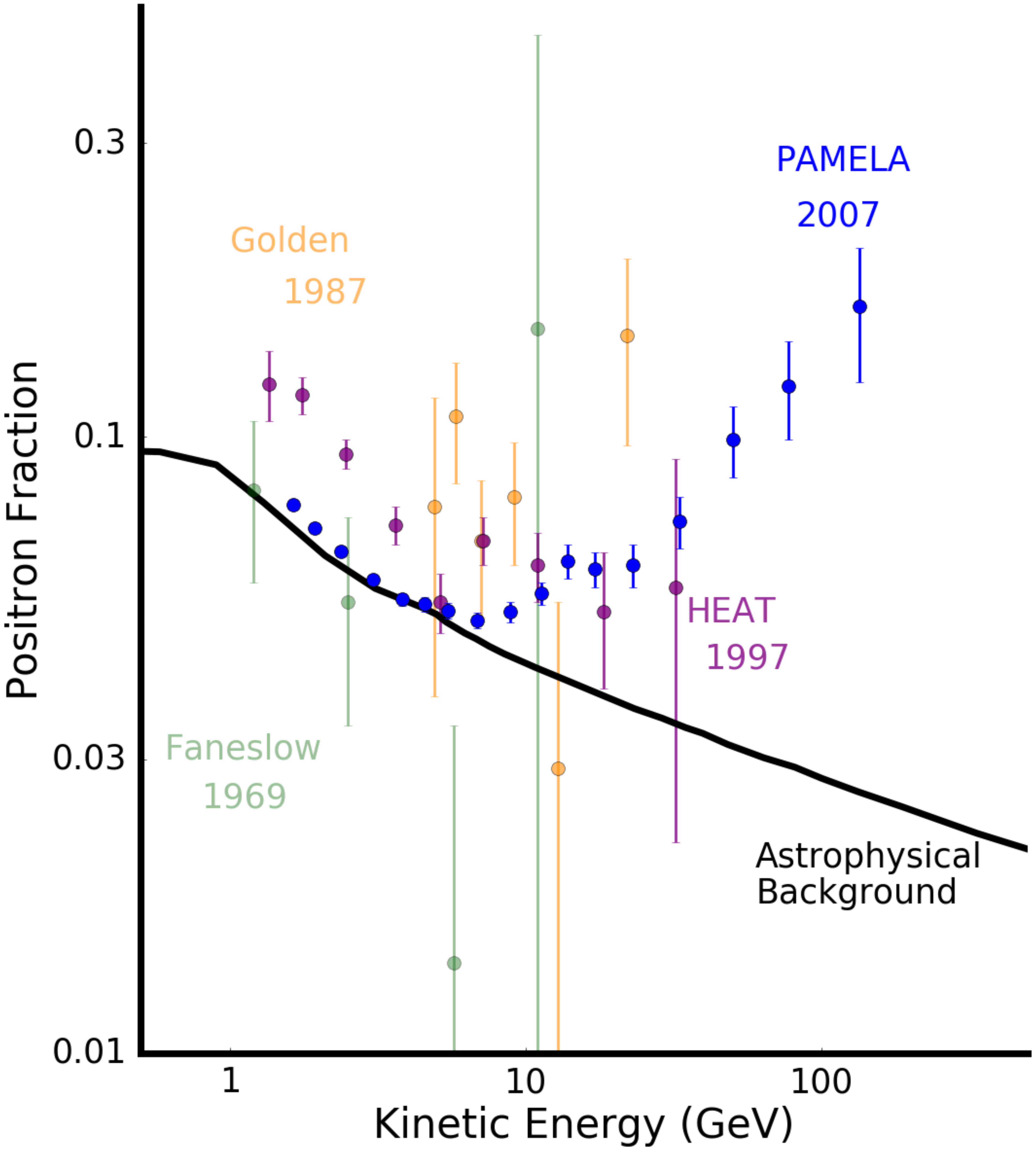
(Not an exhaustive list of observations)

The Positron Excess

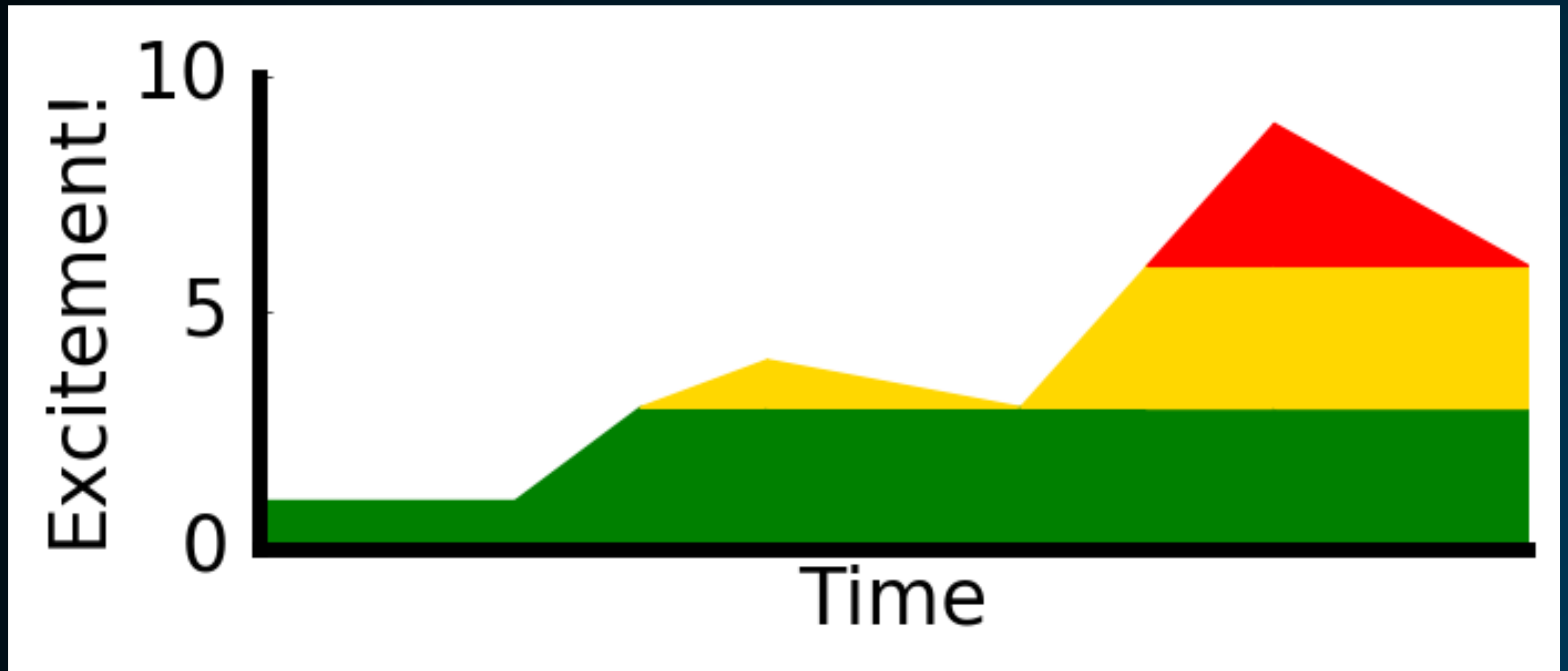


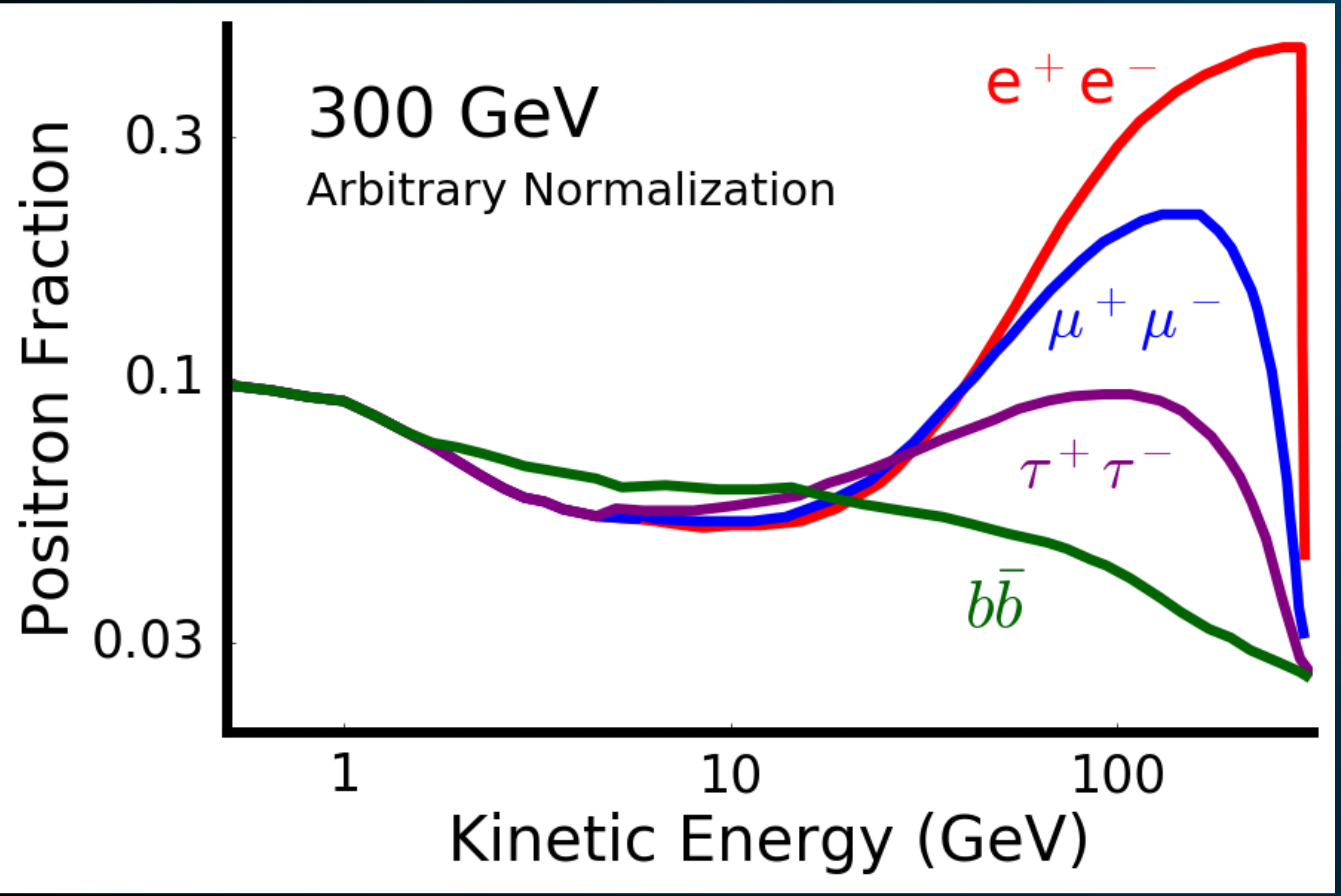


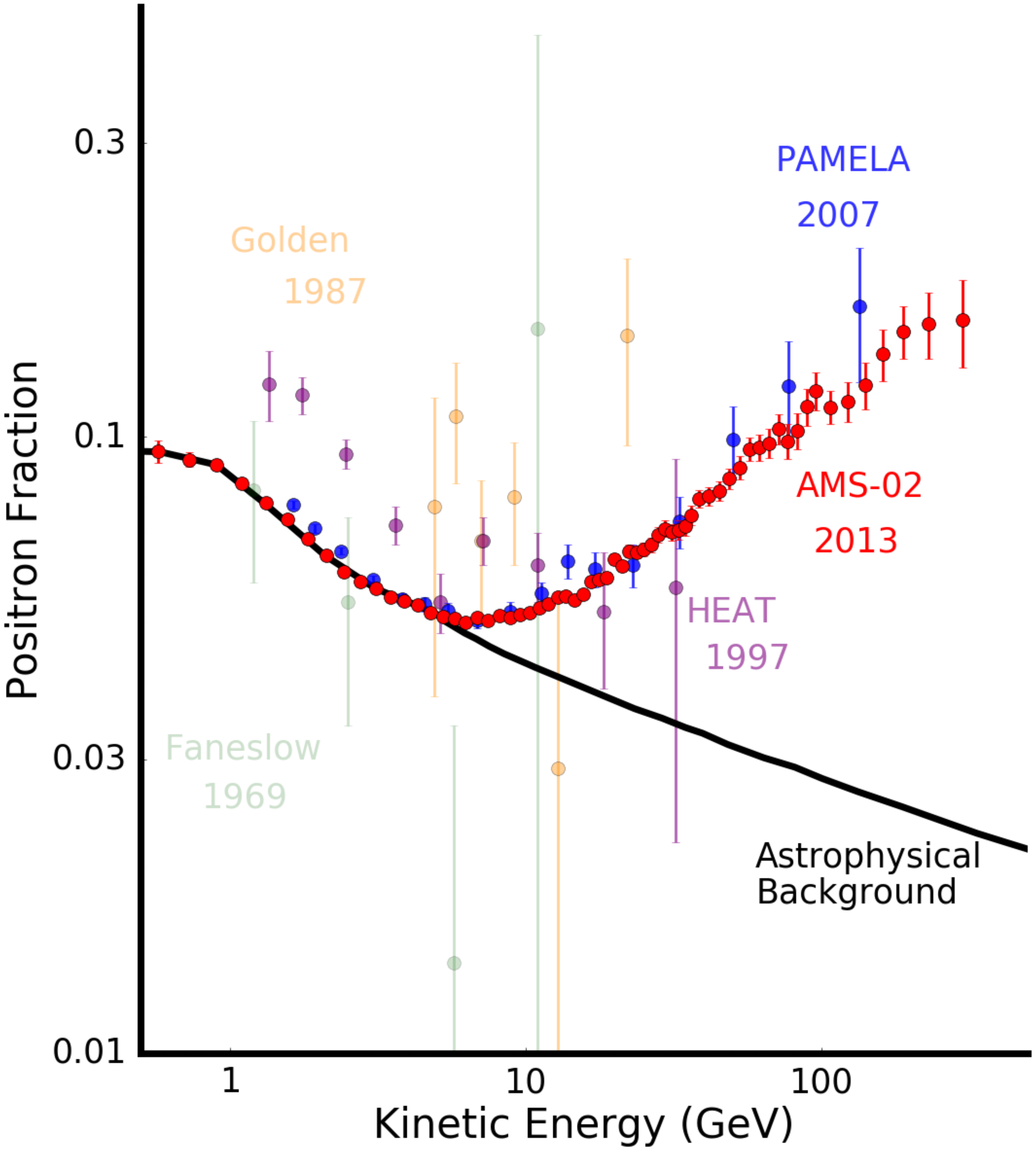
(Not an exhaustive list of observations)



The Positron Excess





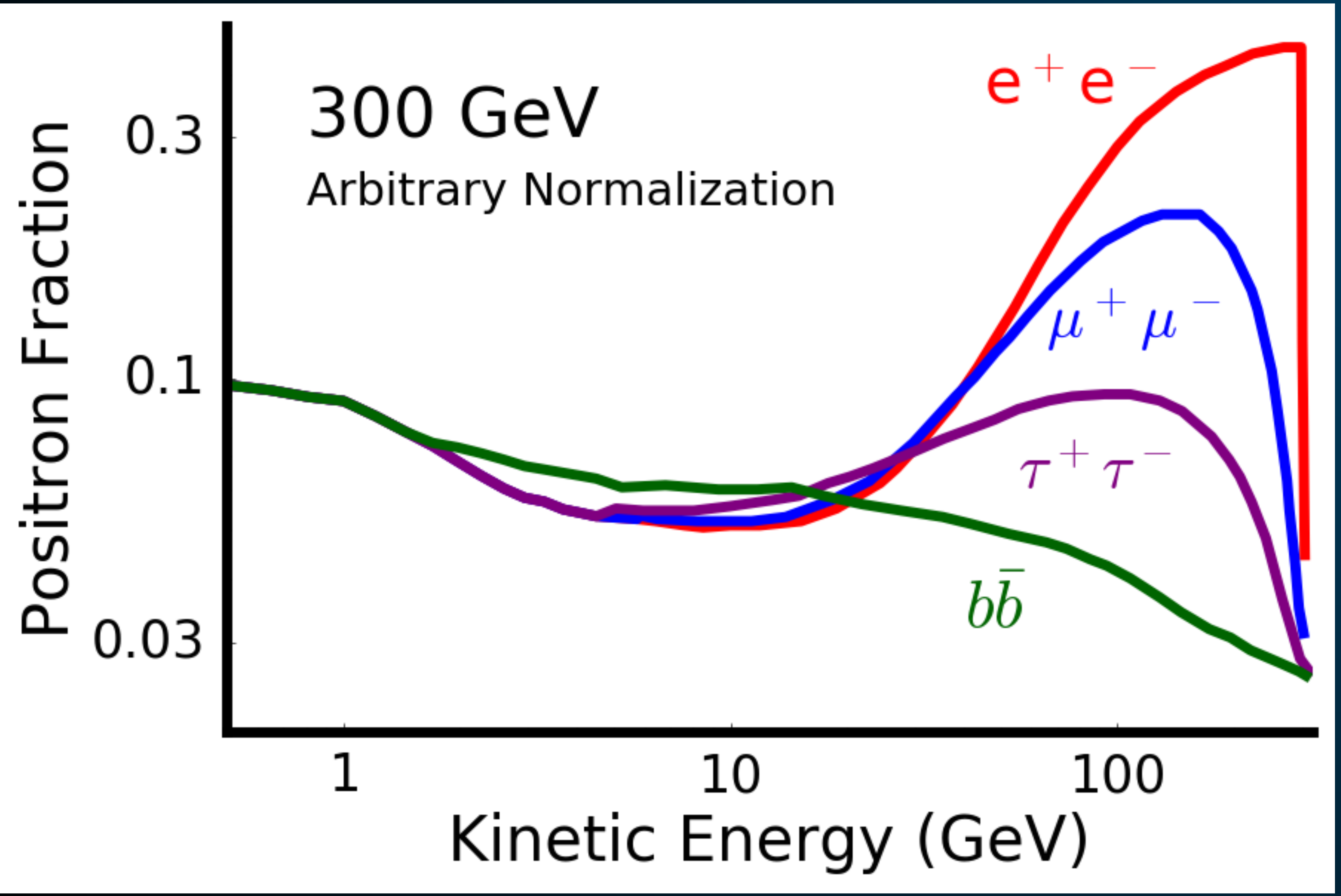


(Not an exhaustive list of observations)

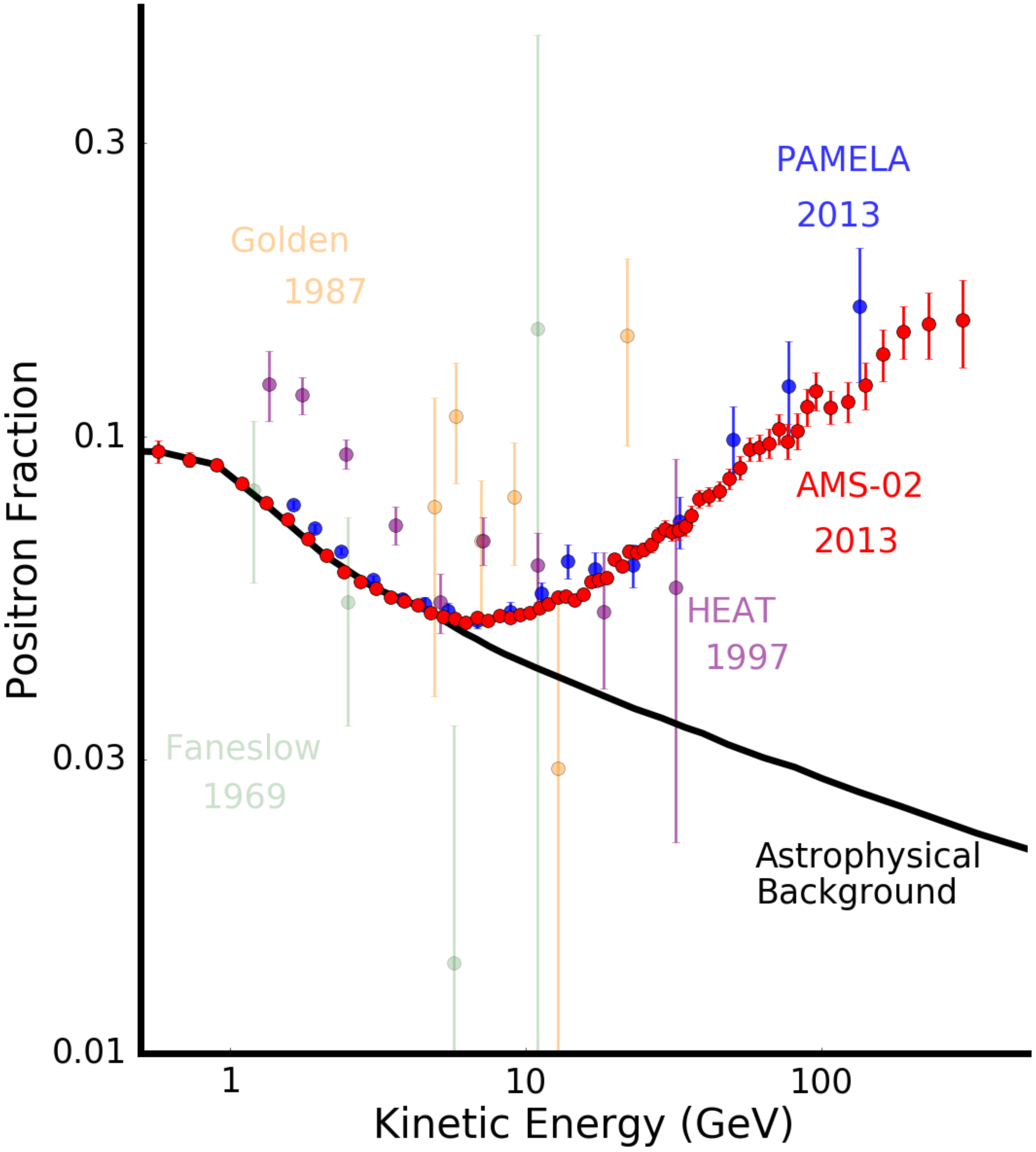
The Positron Excess

Why Less Excitement?

- Continues to Higher Mass
- Spectrum Relatively Smooth



(Not an exhaustive list of observations)

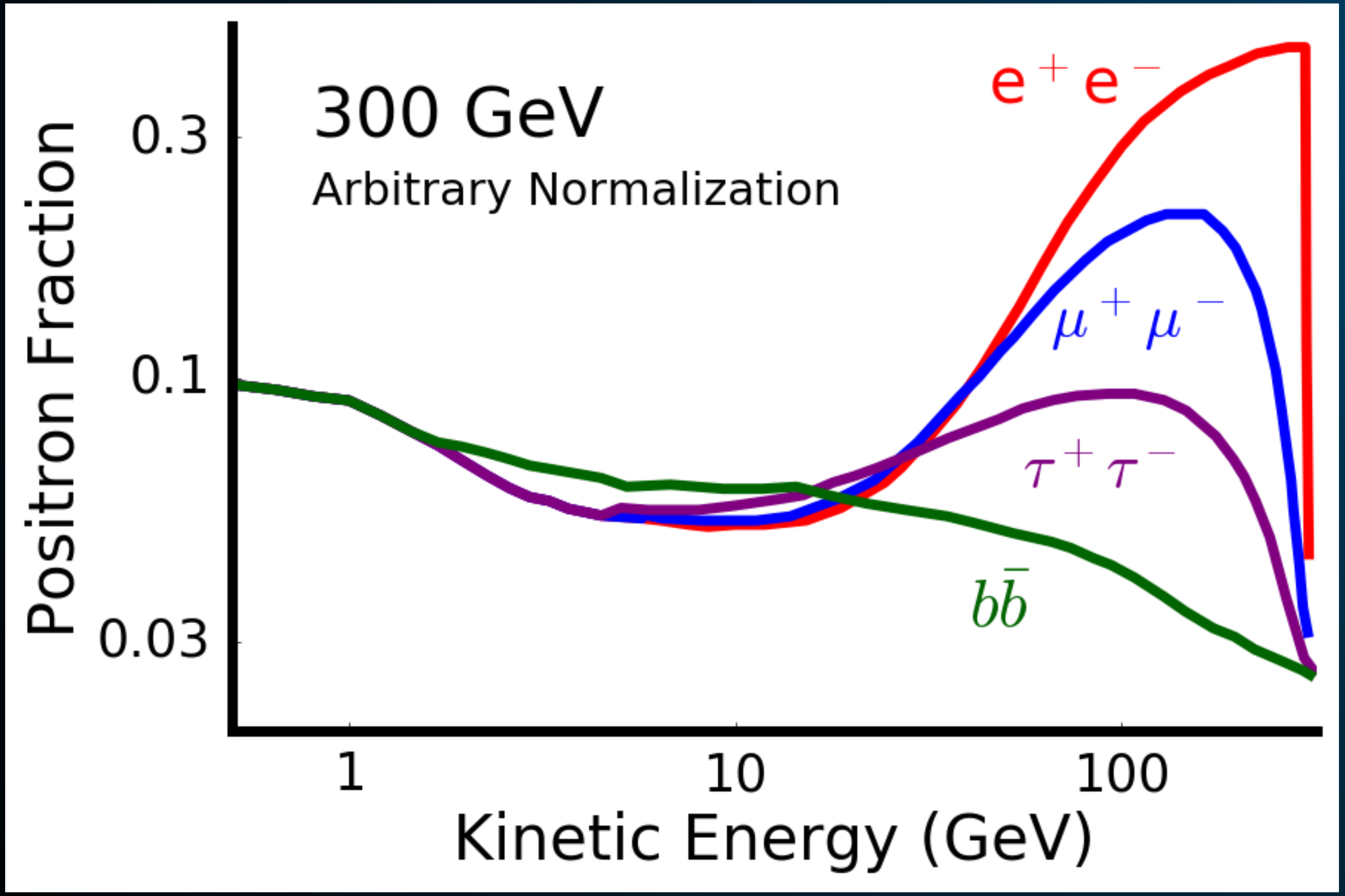


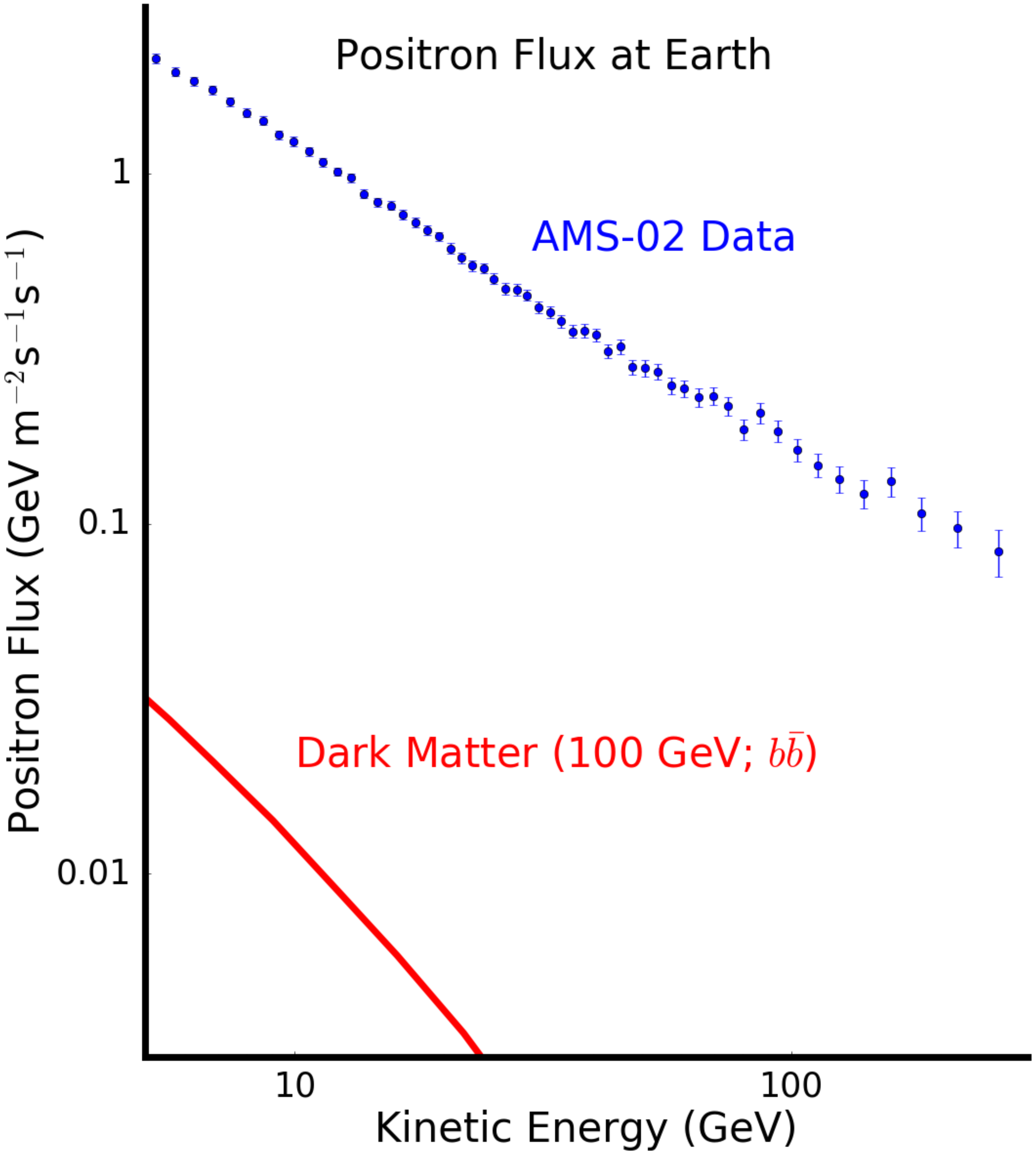
The Positron Excess

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^3s^{-1})
Dark Matter Mass (GeV)
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

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

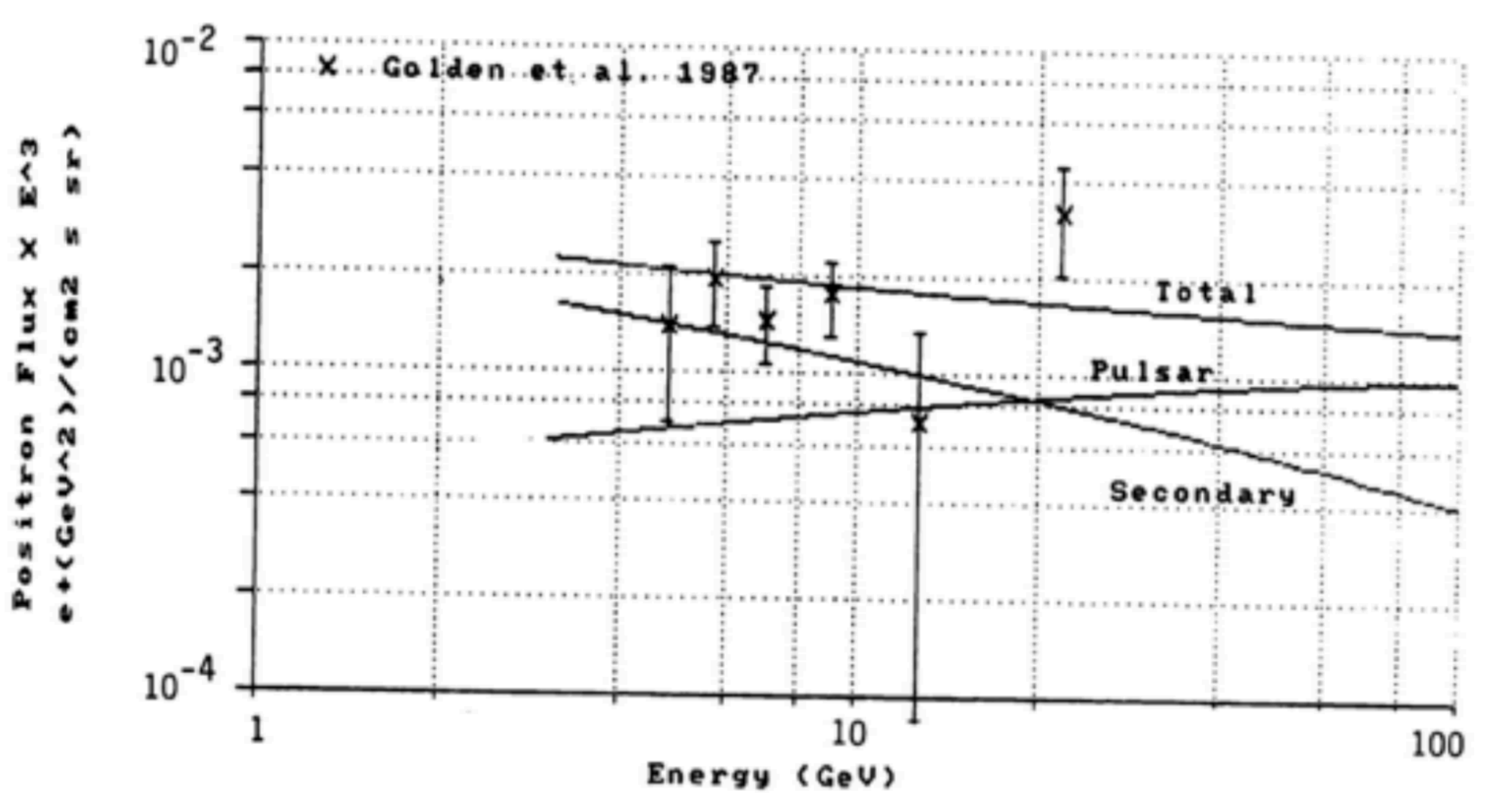

Not a Thermal WIMP!
$b\bar{b}$
e^+e^-
$b\bar{b}$ Limit (Planck)
e^+e^- Limit (Planck)
Thermal Cross-Section
Strong Gamma-Ray Constraints too!
$<\sigma v>$ ($cm^3 s^{-1}$)
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
0.1
1
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

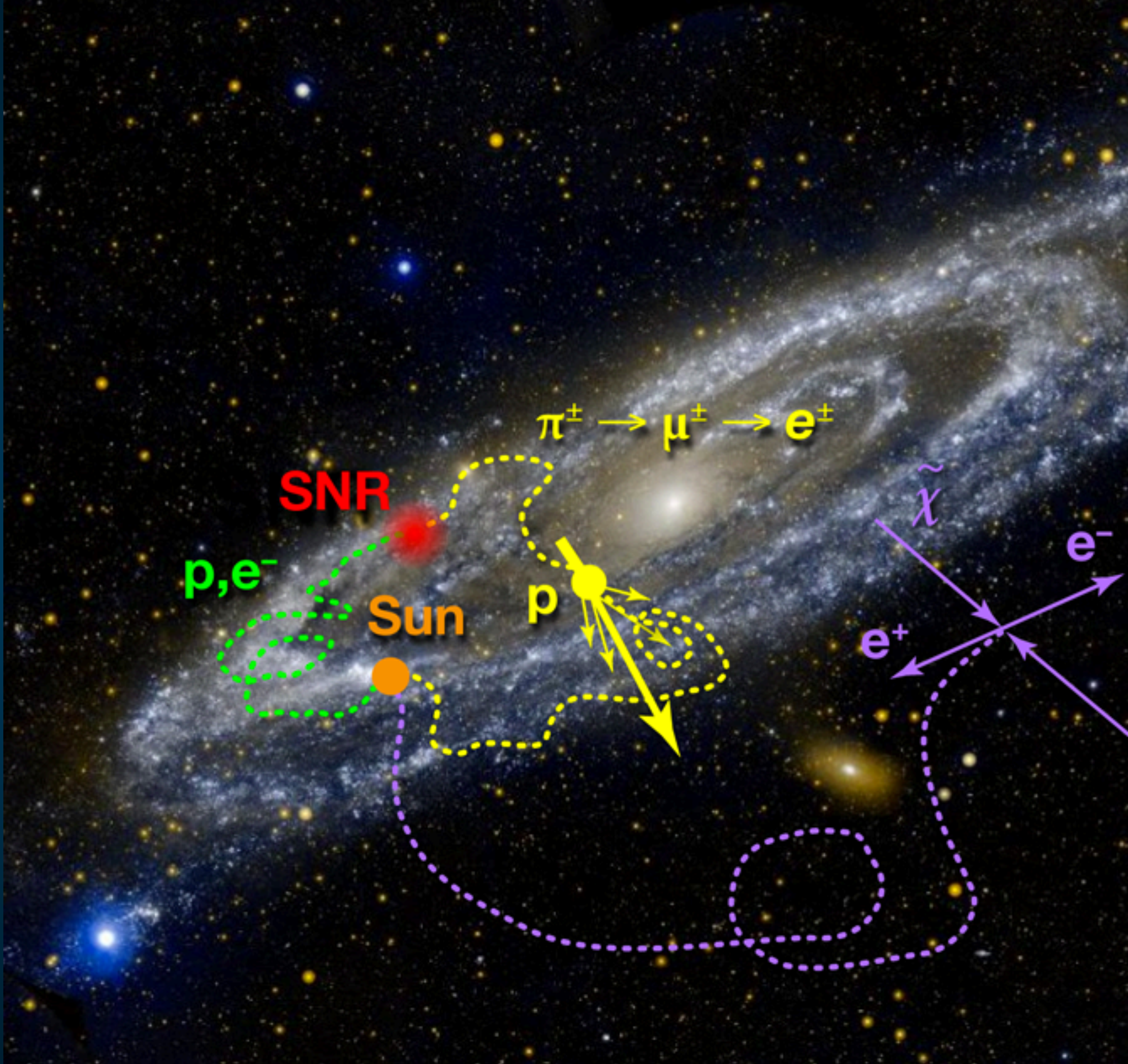
The Positron Excess

Key Idea: Investigate the Positron Fraction!

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

Harding & Ramaty (ICRC! 1987)

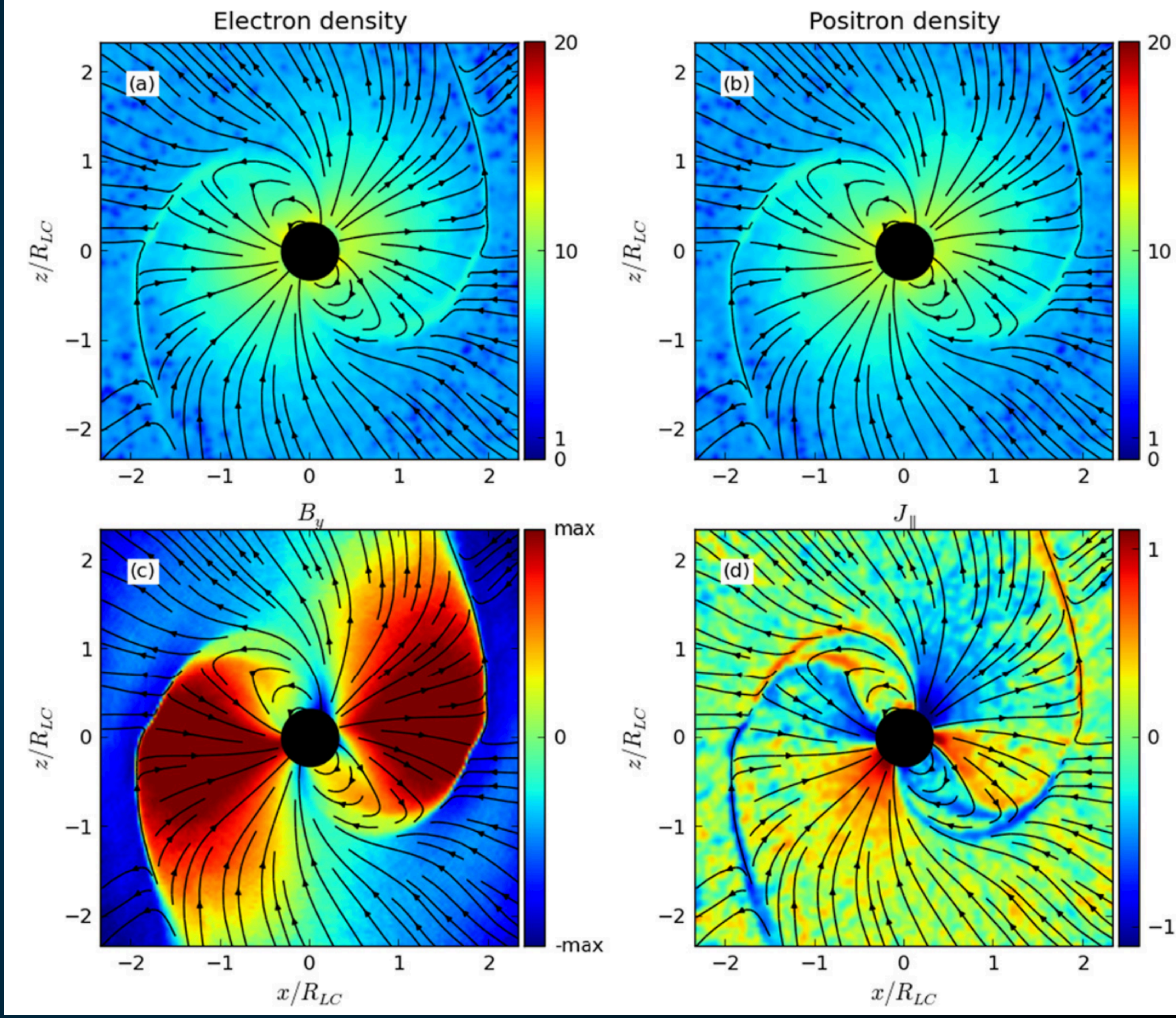




The Positron Excess

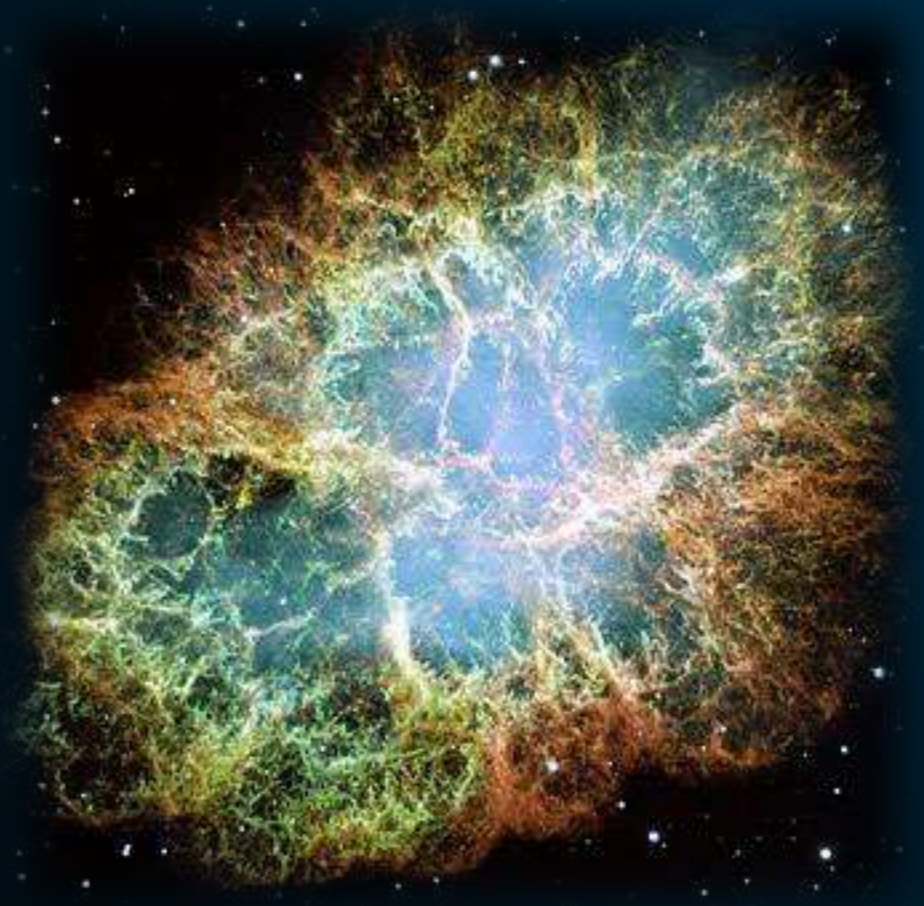
Philippov et al. (2015; 1412.0673)

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

Philippov et al. (2015; 1412.0673)

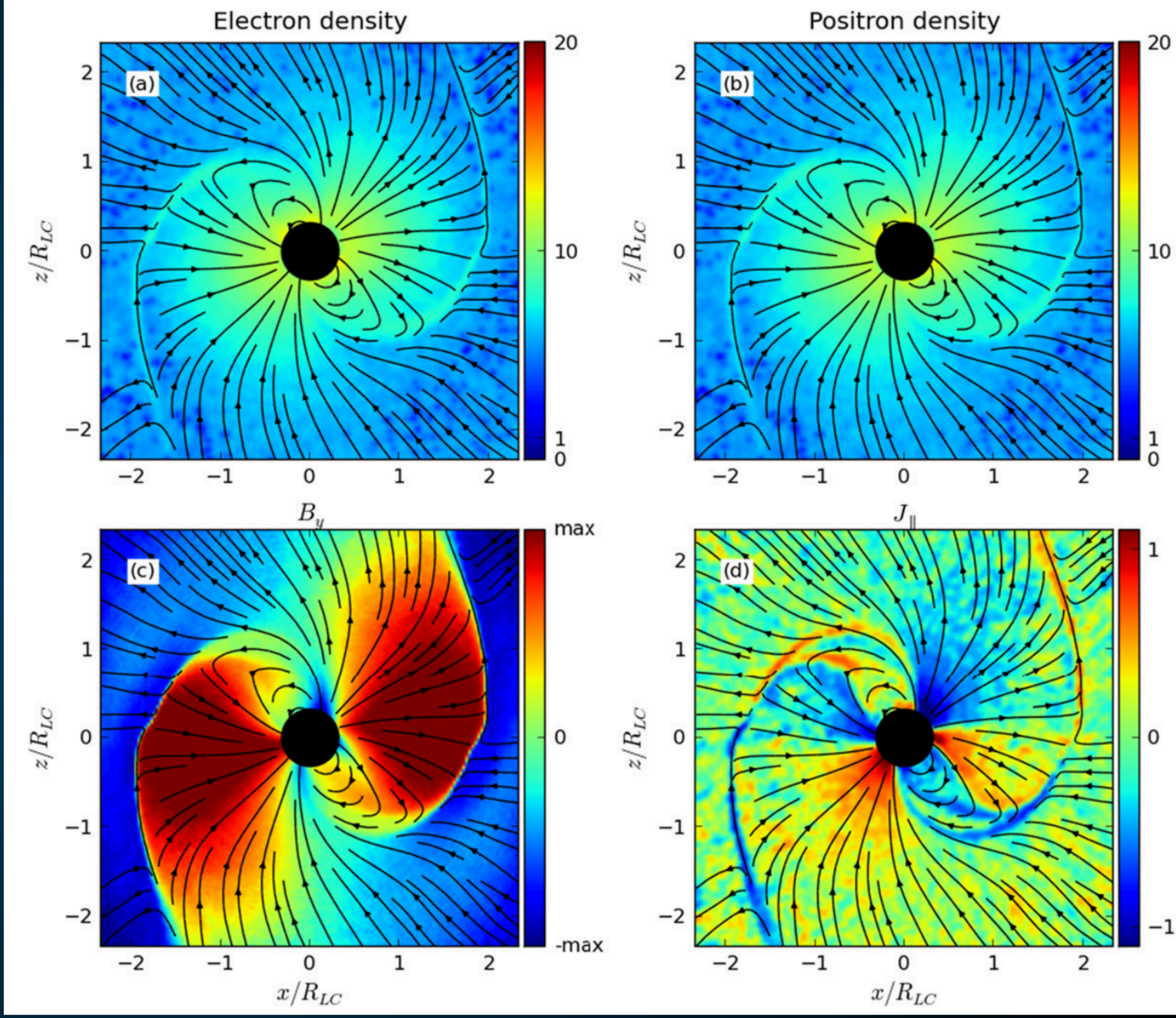
Simulations indicate that pulsars accelerate a significant e^+e^- population.

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

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

%. 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−)

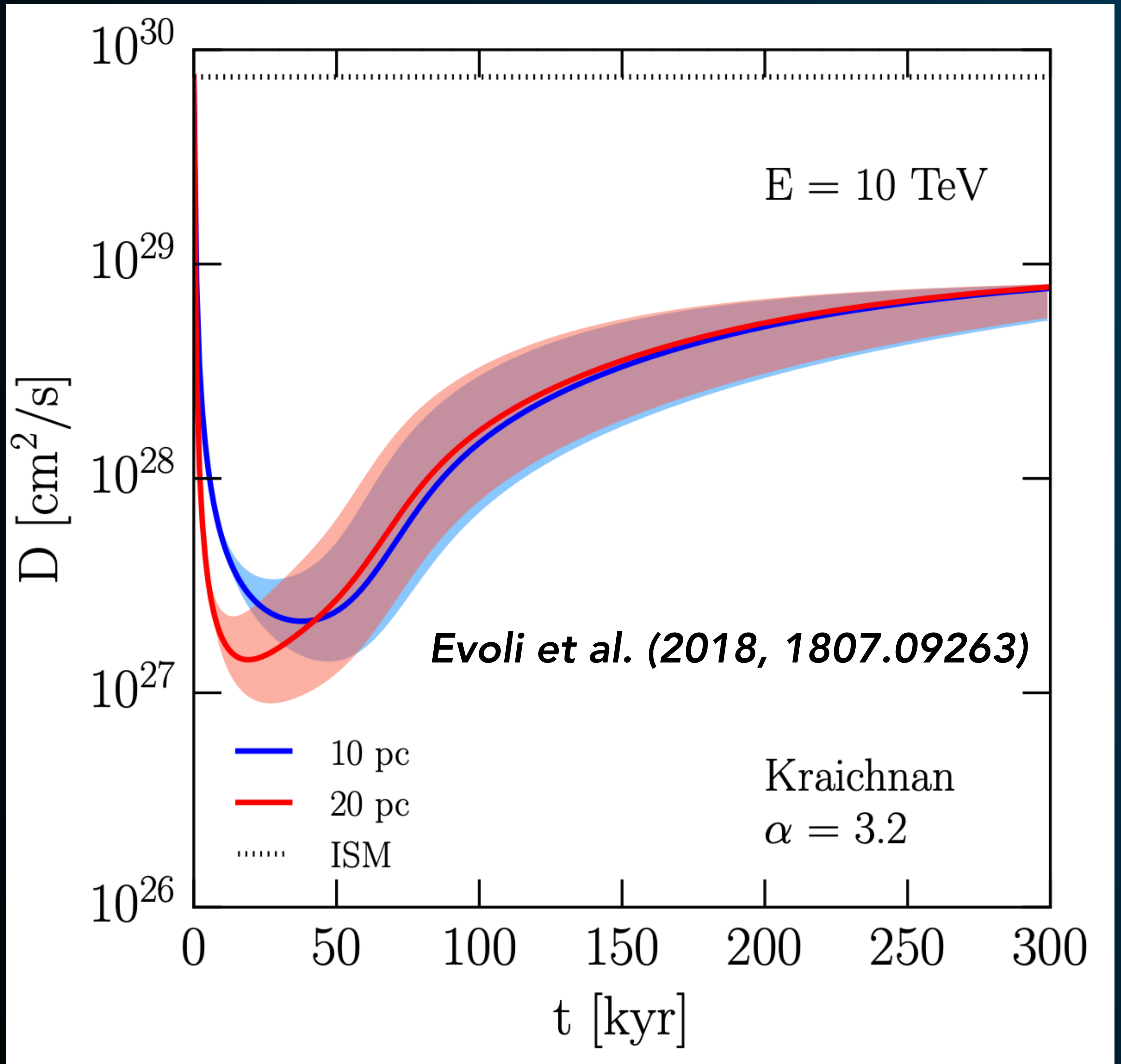
Moon (To Scale)
Geminga
SNR
(hadronic/leptonic)
TeV Halo
(escaped e⁺e⁻)
PWN
(confined e⁺e⁻)
Geminga
$\alpha = 1.9$
$E_\gamma\, dN_\gamma/dE_\gamma\ (\mathrm{cm^{-2}\,s^{-1}})$
E_γ (GeV)
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{3}
10^{4}
10^{5}

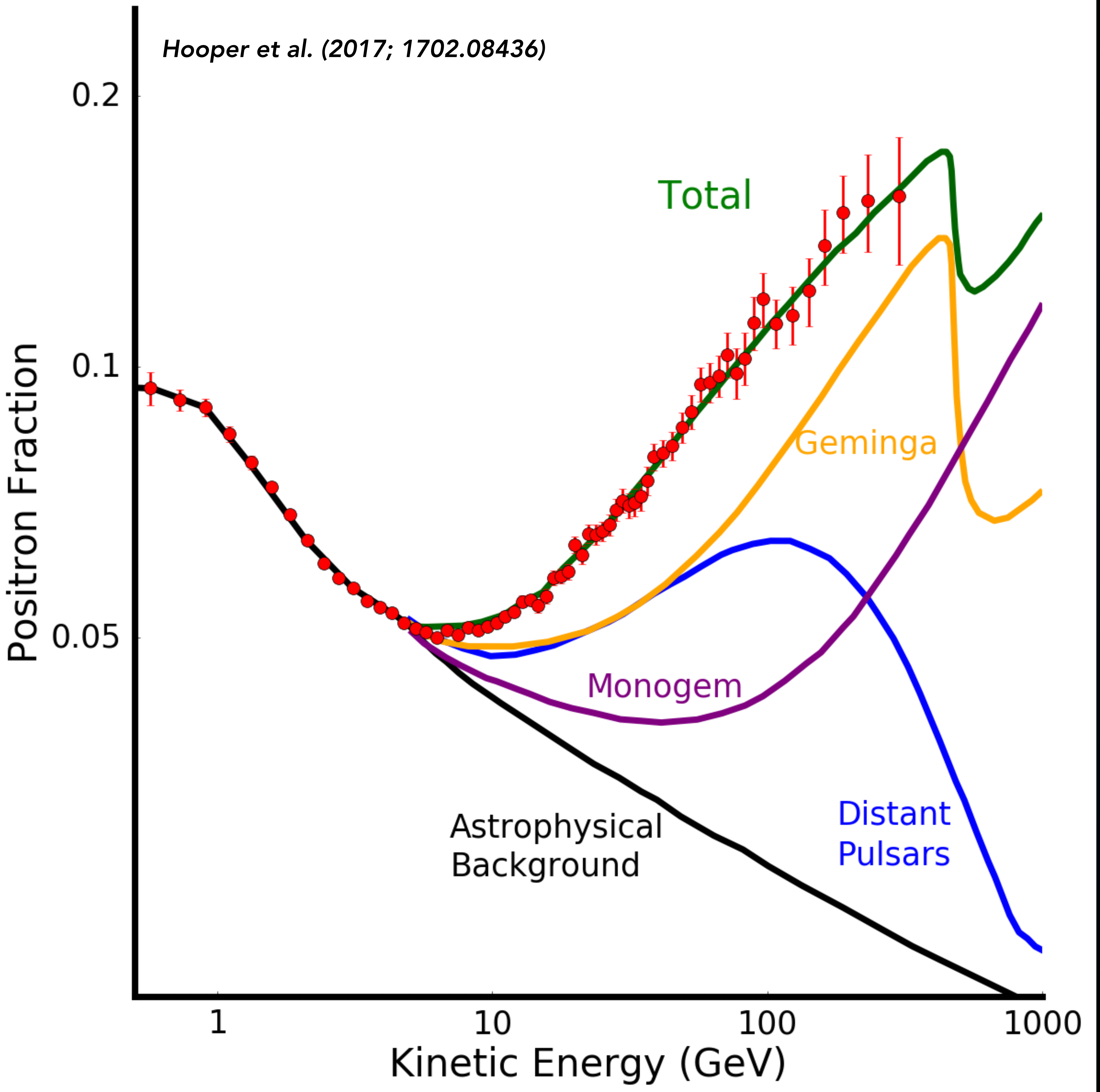

Moon (To Scale)
Geminga
SNR
(hadronic/leptonic)
TeV Halo
(escaped e⁺e⁻)
PWN
(confined e⁺e⁻)
Geminga
$\alpha = 1.9$
$E_\gamma \, dN_\gamma/dE_\gamma \, (\mathrm{cm^{-2}\,s^{-1}})$
E_γ (GeV)
10 - 30% Efficiency!
Hooper et al. (2017; 1702.08436)

The Positron Excess

This can easily match the positron fraction

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





300 GeV
Arbitrary Normalization
Positron Fraction
0.3
0.1
0.03
1
10
100
Kinetic Energy (GeV)
e^+e^-
$\mu^+\mu^-$
$\tau^+\tau^-$
$b\bar{b}$
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma v>$ (cm^3s^{-1})
$b\bar{b}$
e^+e^-
$b\bar{b}$ Limit (Planck)
e^+e^- Limit (Planck)
Thermal Cross-Section
$\tau^+\tau^-$
e^+e^-
Bergström et al. (2013; 1306.3983)
0.1
1
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)


What About TeV WIMPS?

W^+W^- (HESS GC 224h)
$b\bar{b}$ (Planck)
$b\bar{b}$ (dSphs)
$\tau^+\tau^-$ (HESS GC 224h)
$b\bar{b}$ (AMS)
$\tau^+\tau^-$ (AMS)
Thermal Cross-Section
Abdallah et al. (2016, 1607.08142)
$<\sigma v>$ (cm^{3}s^{-1})
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

W^+W^- (HESS GC 224h)
$b\bar{b}$ (Planck)
$b\bar{b}$ (dSphs)
$\tau^+\tau^-$ (HESS GC 224h)
$b\bar{b}$ (CTA GC 200h)
Thermal Cross-Section
$b\bar{b}$ (AMS)
$\tau^+\tau^-$ (CTA GC 200h)
$\tau^+\tau^-$ (AMS)
Pierre et al. (2014; 1401.7330)
$<\sigma v>$ (cm^3s^{-1})
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

$\tau^+\tau^-$ (CTA GC 200h)
NFW (γ=0.5)
NFW (γ=0.75)
NFW (γ=1.0)
Einasto
Thermal Cross-Section
Pierre et al. (2014; 1401.7330)
$<\sigma v>$ ($\mathrm{cm^3 s^{-1}}$)
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

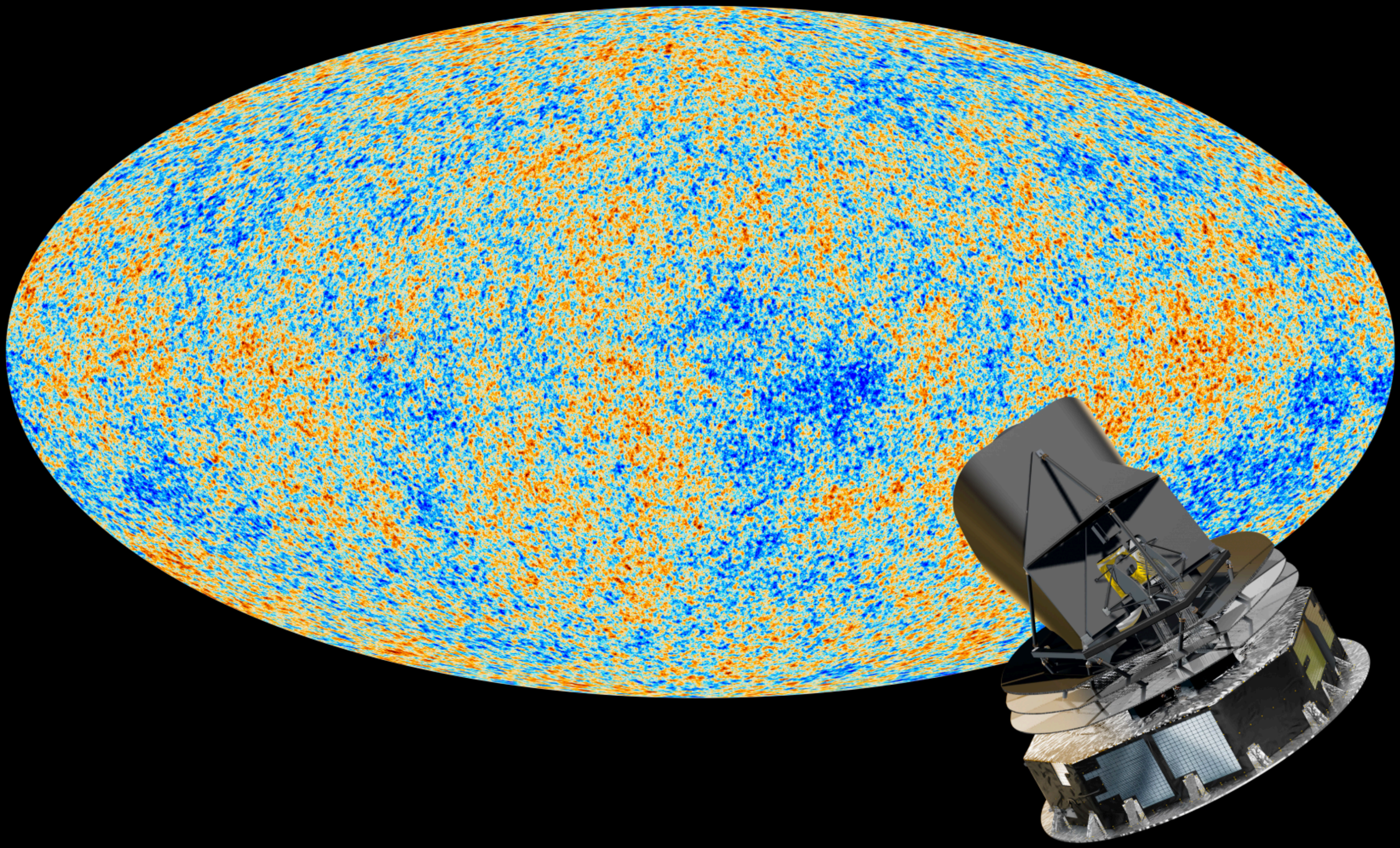
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
<σv> ($\mathrm{cm^3 s^{-1}}$)
$b\bar{b}$ (Planck)
$\tau^+\tau^-$ (CTA Draco 500h)
$b\bar{b}$ (dSphs)
Thermal Cross-Section
$b\bar{b}$ (AMS)
$\tau^+\tau^-$ (AMS)
Lefranc et al. (2016; 1605.02793)
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

What About Radio Searches?

10^{-24}
10^{-25}
10^{-26}
10^{-27}
$<\sigma v>$ (cm^{3}s^{-1})
10
100
1000
Dark Matter Mass (GeV)
$b\bar{b}$ LOFAR (Coma, Low-B)
$b\bar{b}$ (Planck)
$b\bar{b}$ (dSphs)
$b\bar{b}$ (AMS)
Thermal Cross-Section
$b\bar{b}$ SKA (Coma, Default)
$b\bar{b}$ LOFAR (Coma, High-B)
Storm et al. (2016; 1607.01049)


21 cm !

10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
$<\sigma v>$ (cm^3s^{-1})
e^+e^- (Planck)
Thermal Cross-Section
e^+e^- (EDGES)
Liu & Slatyer (2018; 1803.09739)
0.1
1
10
100
1000
10^4
Dark Matter Mass (GeV)



Slatyer (2015; 1506.03811)
$b\bar{b}$ Limit (Planck)
e^+e^- Limit (Planck)
Thermal Cross-Section
$<\sigma v>$ (cm^{3}s^{-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)

Madhavacheril et al. (2013; 1310.3815)
$b\bar{b}$ Limit (Cosmic Variance)
e^+e^- Limit (Cosmic Variance)
Thermal Cross-Section
$<\sigma v>$ (cm^{3}s^{-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)


Thermal Cross-Section
1 Observed Photon Within 10° of Galactic Center
$<\sigma v>$ (cm^3s^{-1})
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

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