



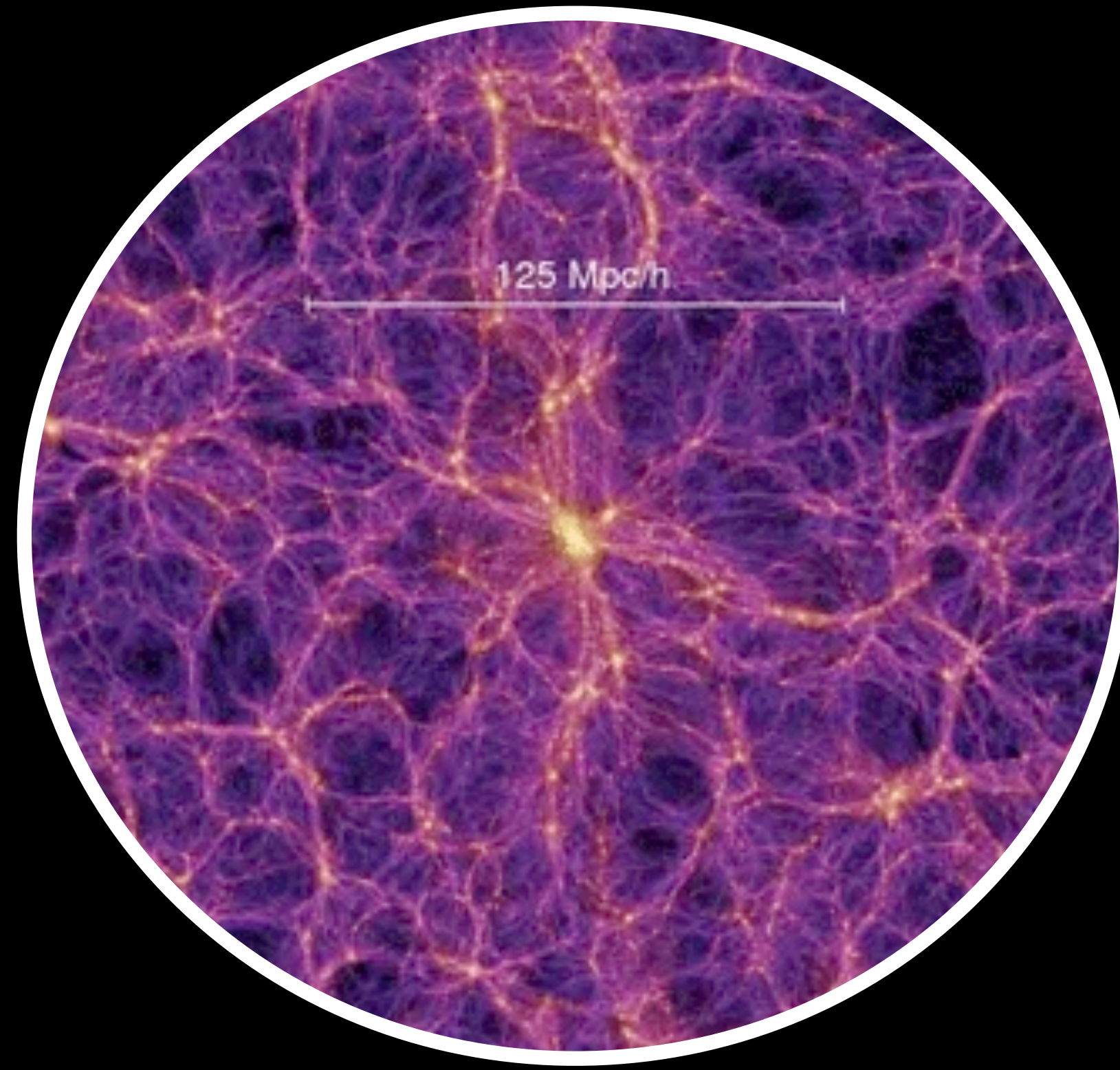
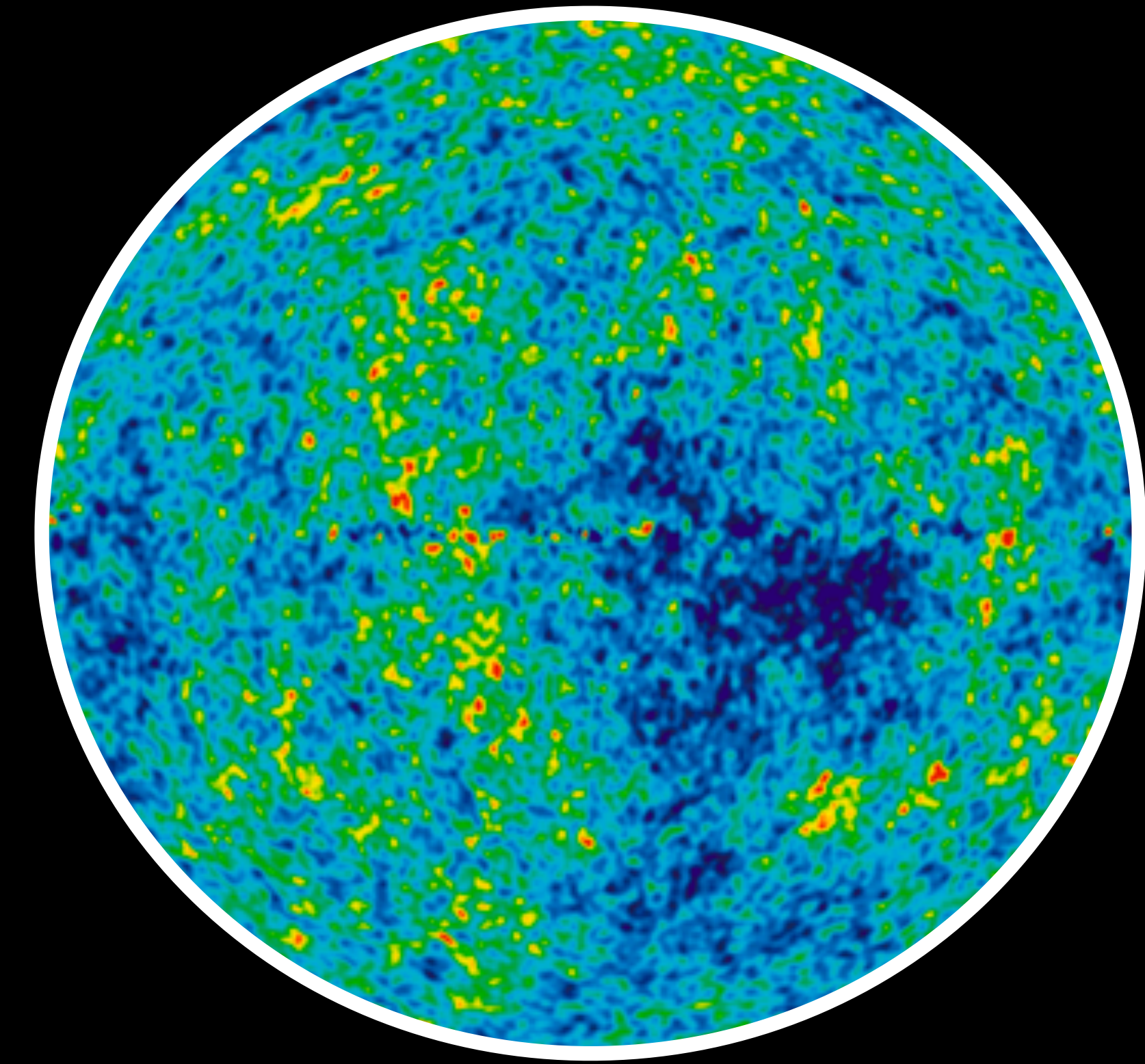
Tim Linden

Thermal WIMP Dark Matter on the Brink

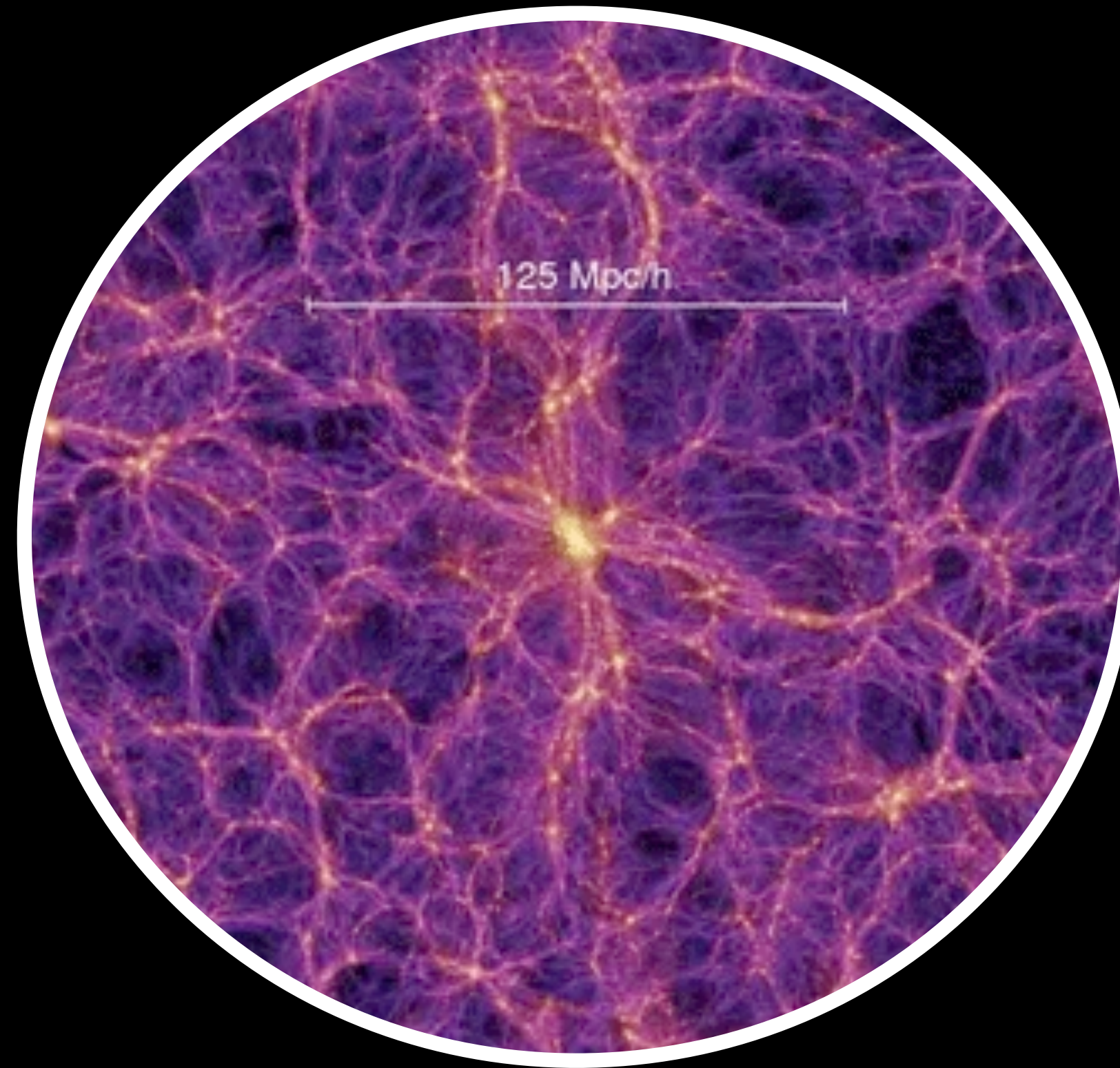
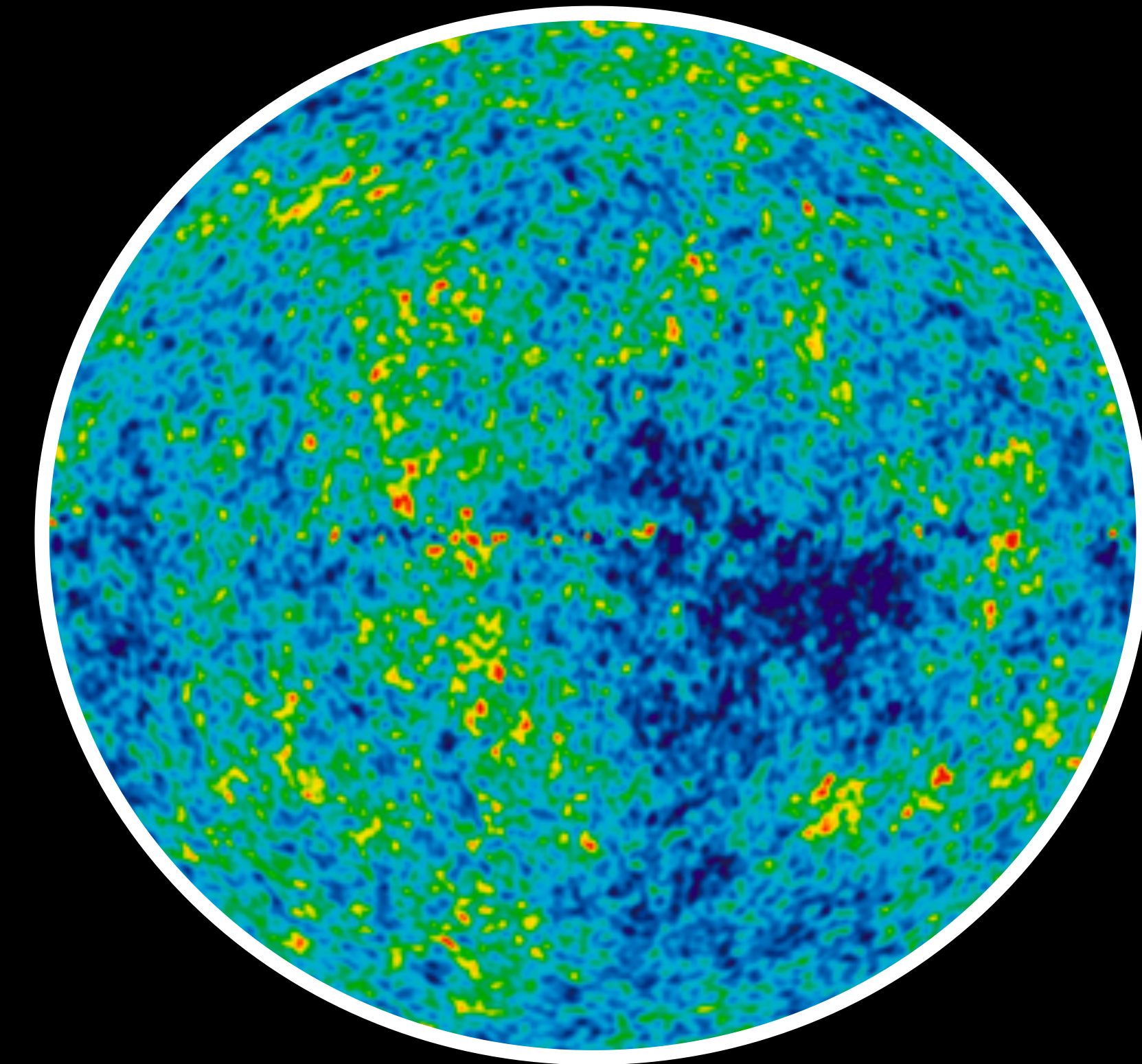


THE OHIO STATE UNIVERSITY
CENTER FOR COSMOLOGY AND
ASTROPARTICLE PHYSICS

The Present



The Present



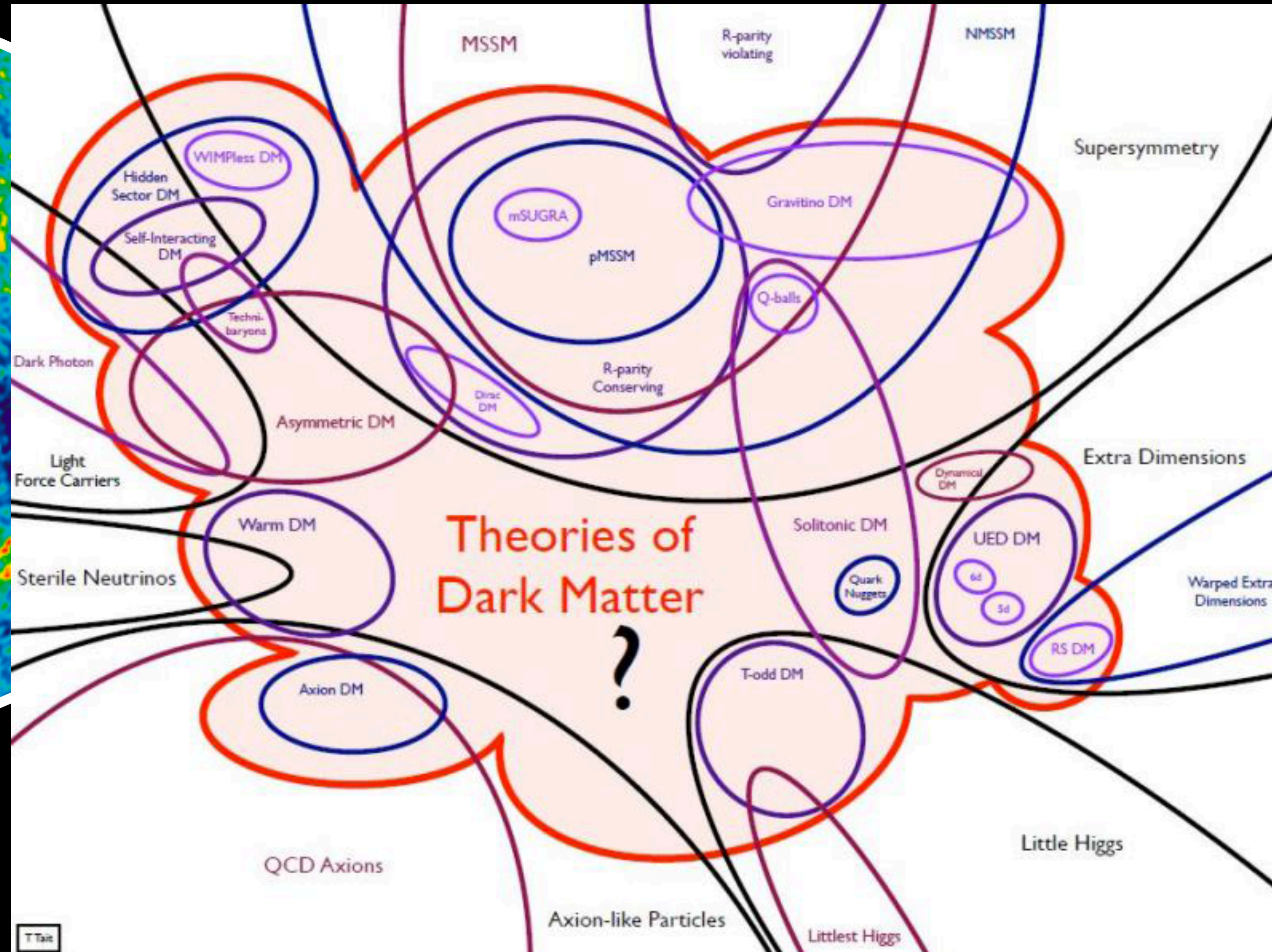
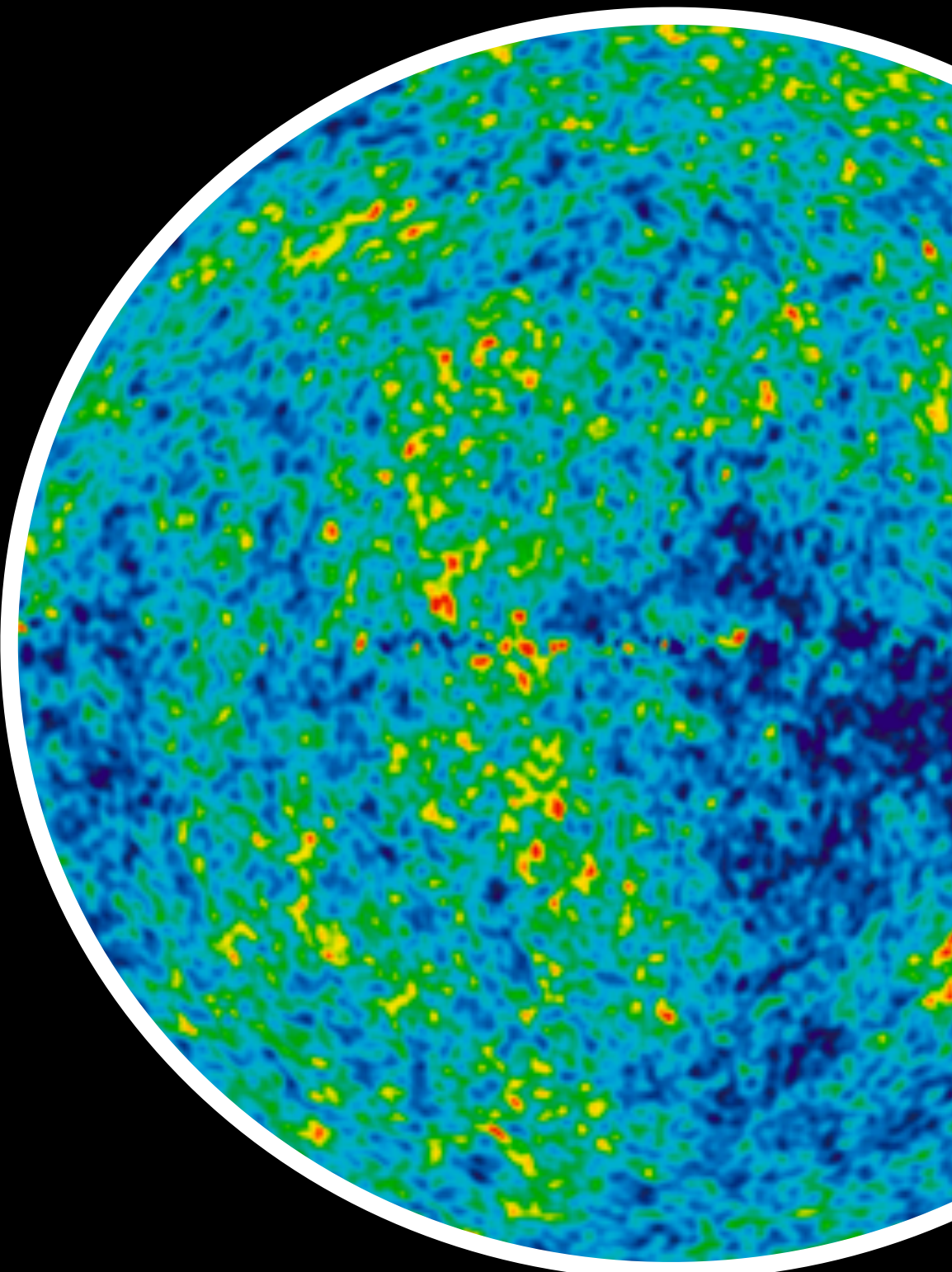
10^{-25} GeV
 $R_{DM} > R_{UFD}$

slide concept courtesy of Asher Berlin

10^{62} GeV
 $M_{DM} > M_{UFD}$

The Present

courtesy: Tim Tait



10^{-25} GeV
 $R_{DM} > R_{UFD}$

10^{62} GeV
 $M_{DM} > M_{UFD}$

slide concept courtesy of Asher Berlin



Tim Linden

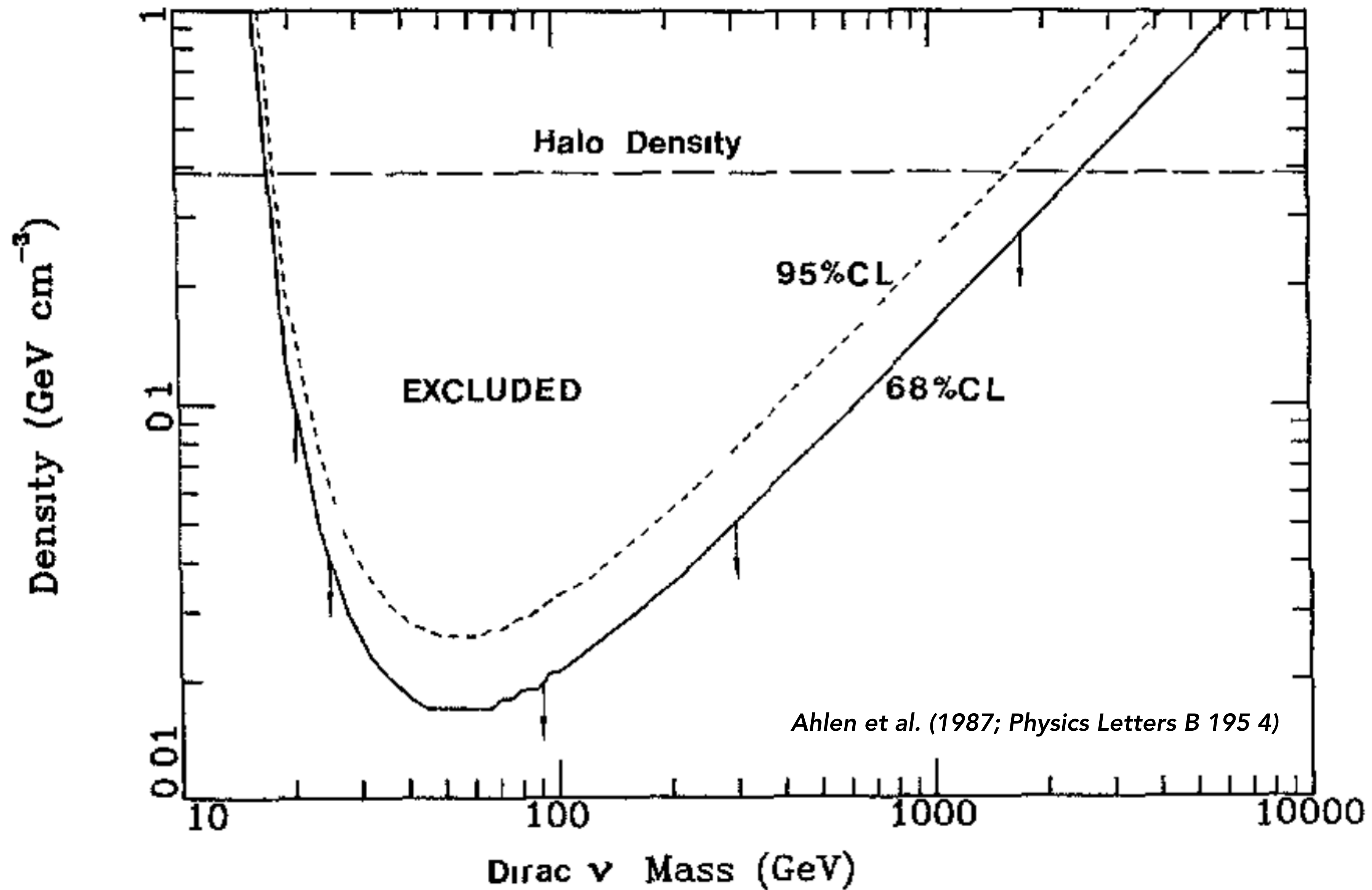
Thermal WIMP Dark Matter on the Brink



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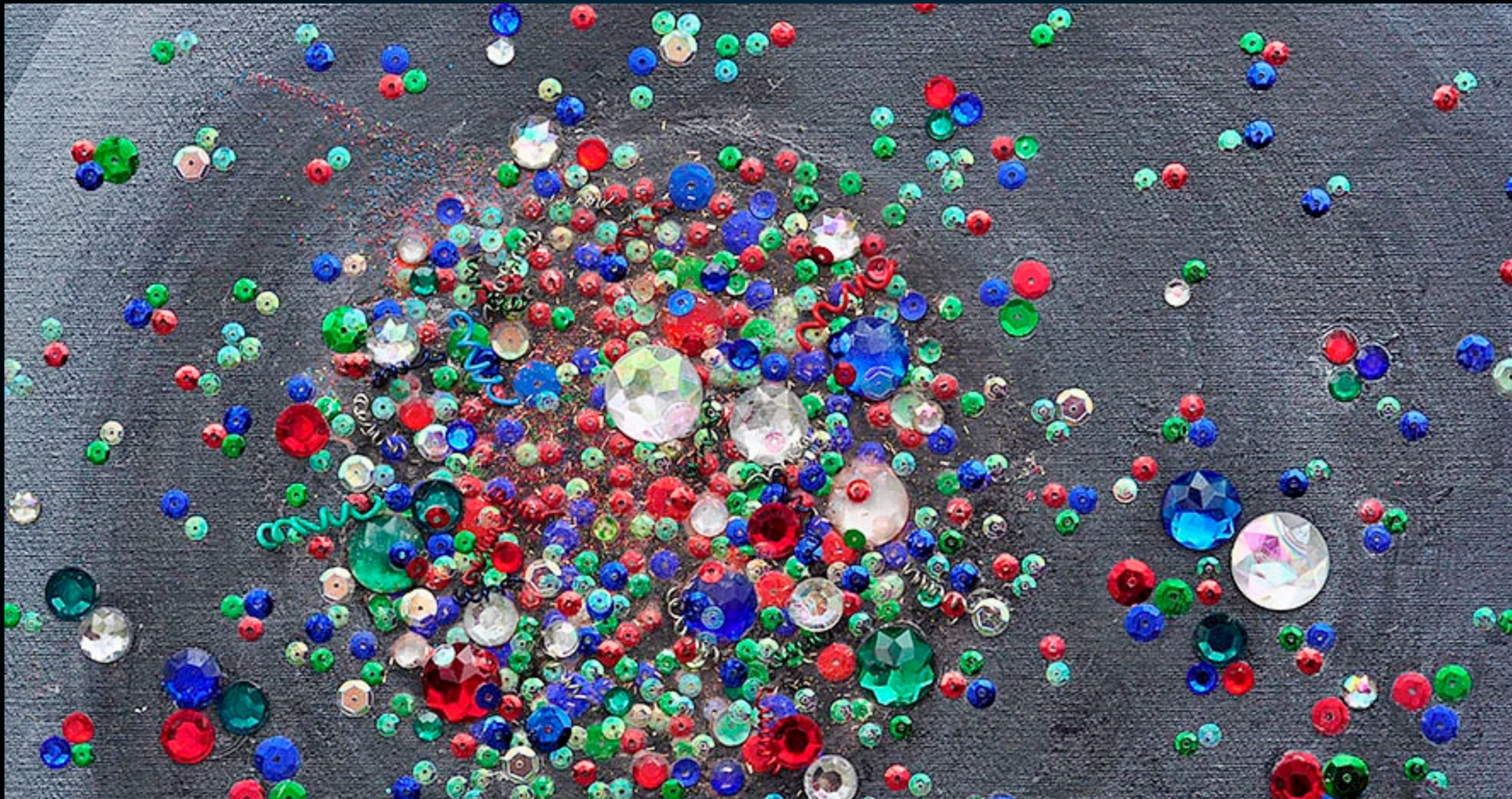
Can We Eliminate Classes of Dark Matter Models?

Yes!

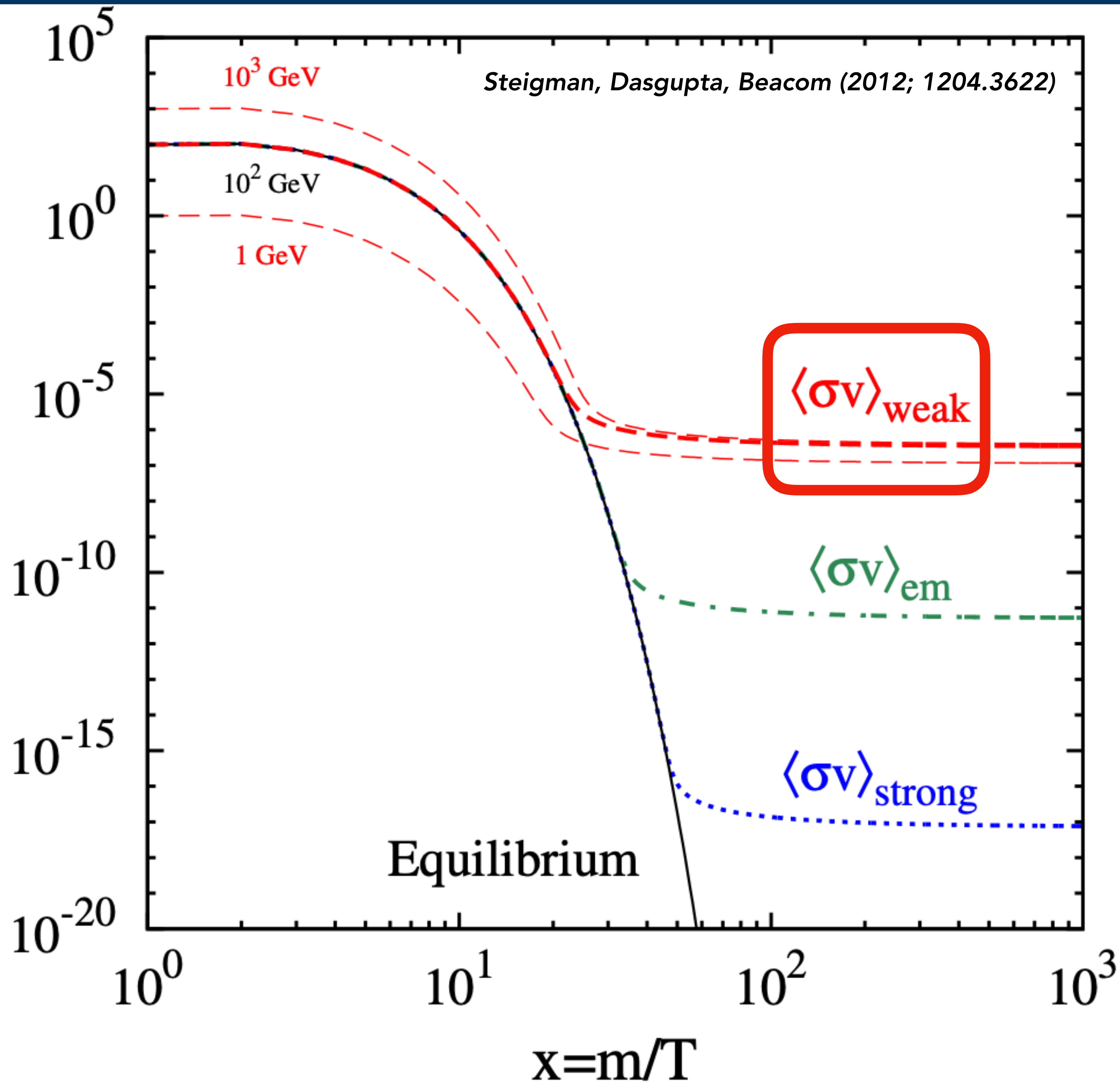


Thermal Dark Matter

artist: Sarah Szabo



$m n(x)/n_{\text{eq}}(x=1)$ [GeV]



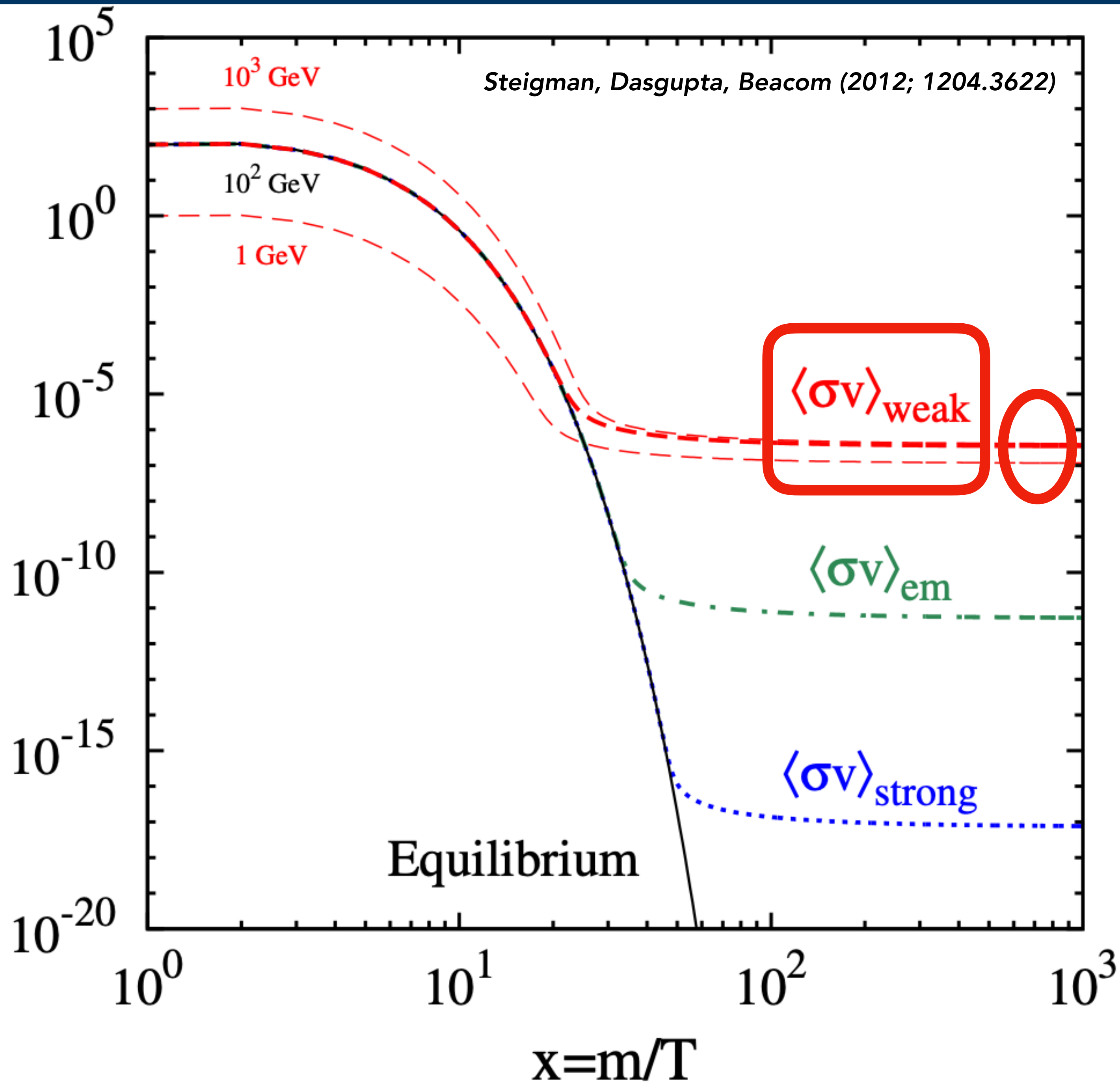
Thermal Dark Matter Density

Present density inversely proportional to the strength of the interaction.

Almost independent of particle mass.

Weak-Interaction Produces the right density!

$m n(x)/n_{eq}(x=1)$ [GeV]



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

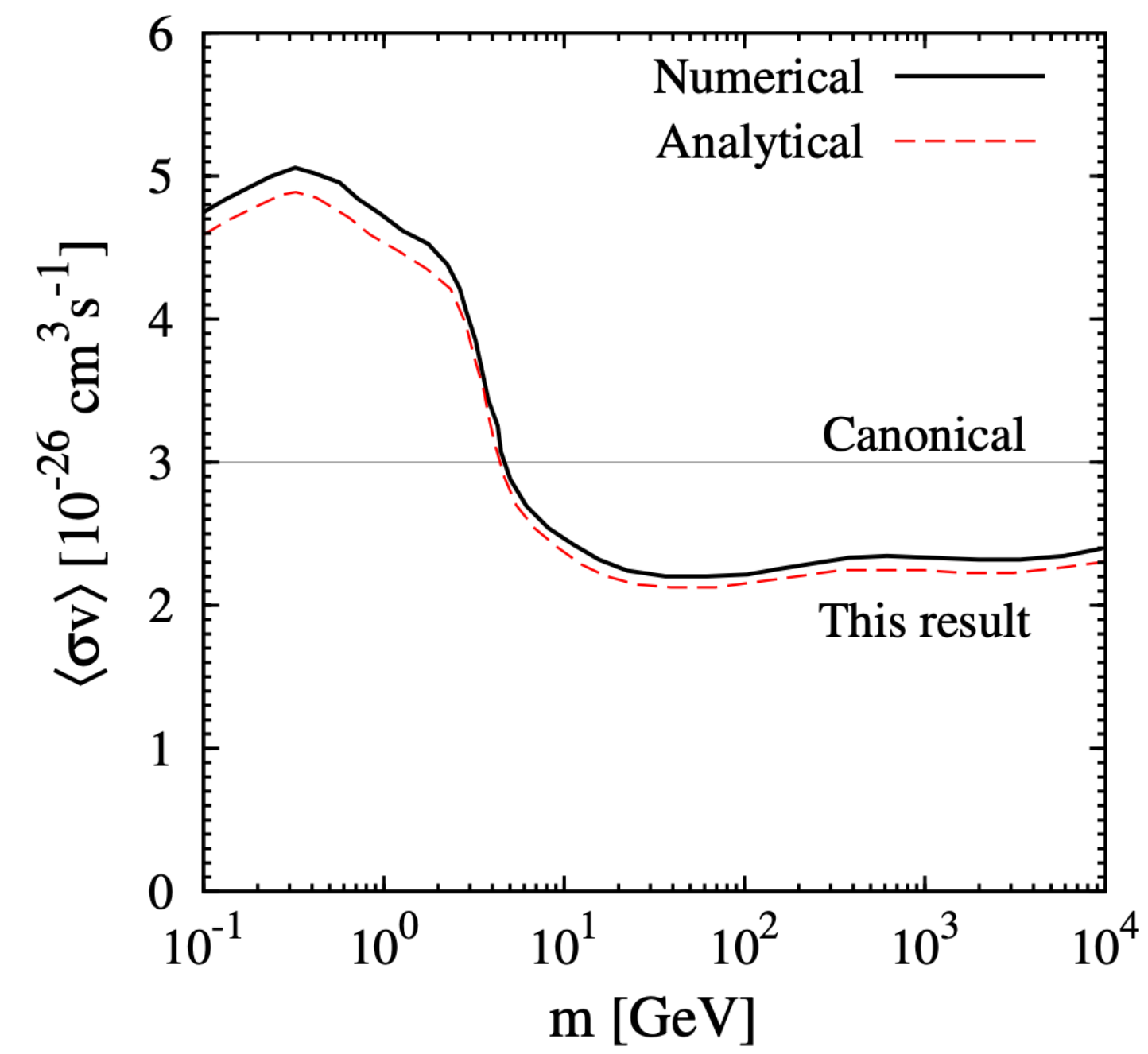
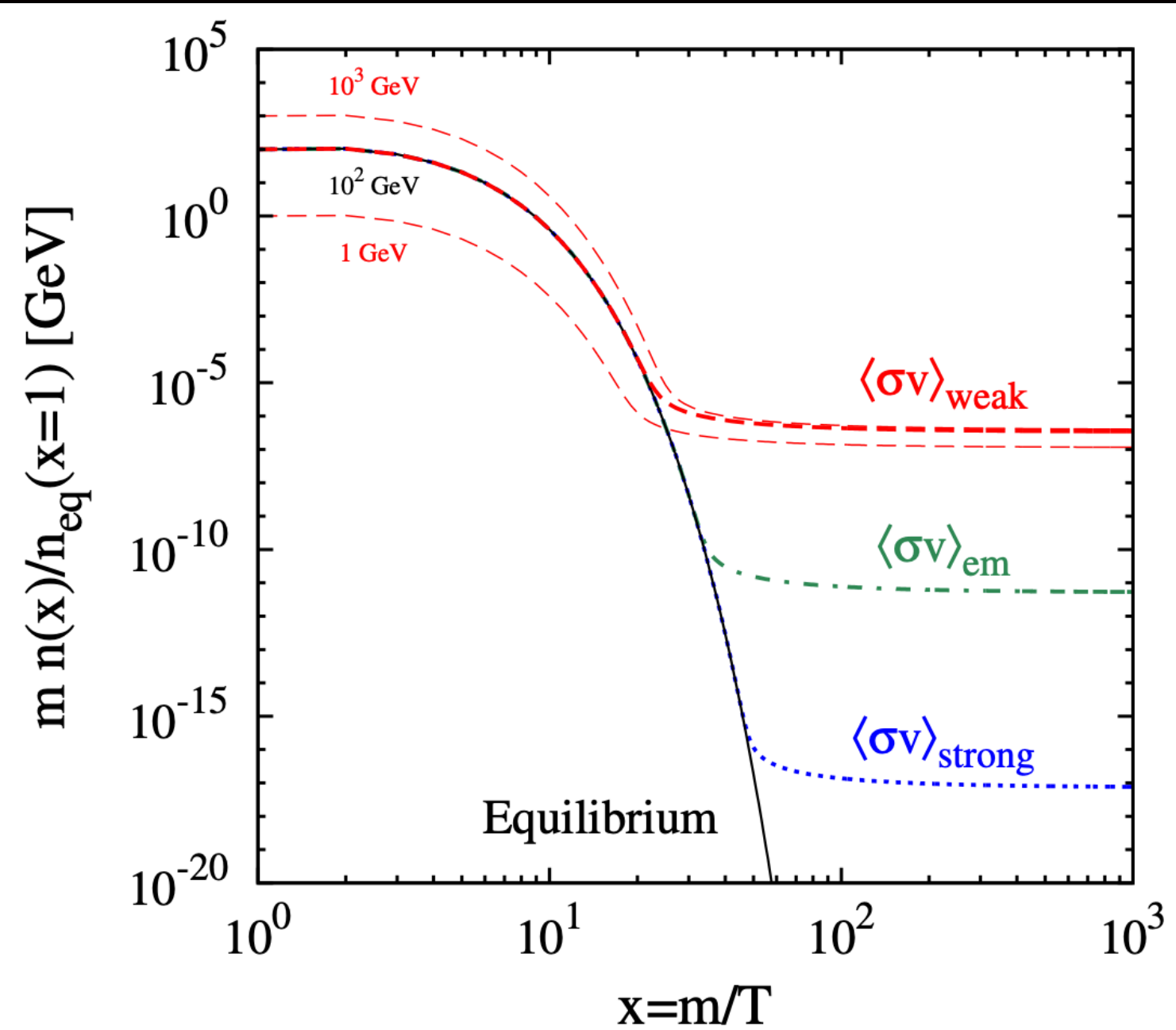
1000

100

10

1

1+Redshift



Years after the Big Bang

400 thousand

0.1 billion

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The Big Bang

Recombination

The Dark Age

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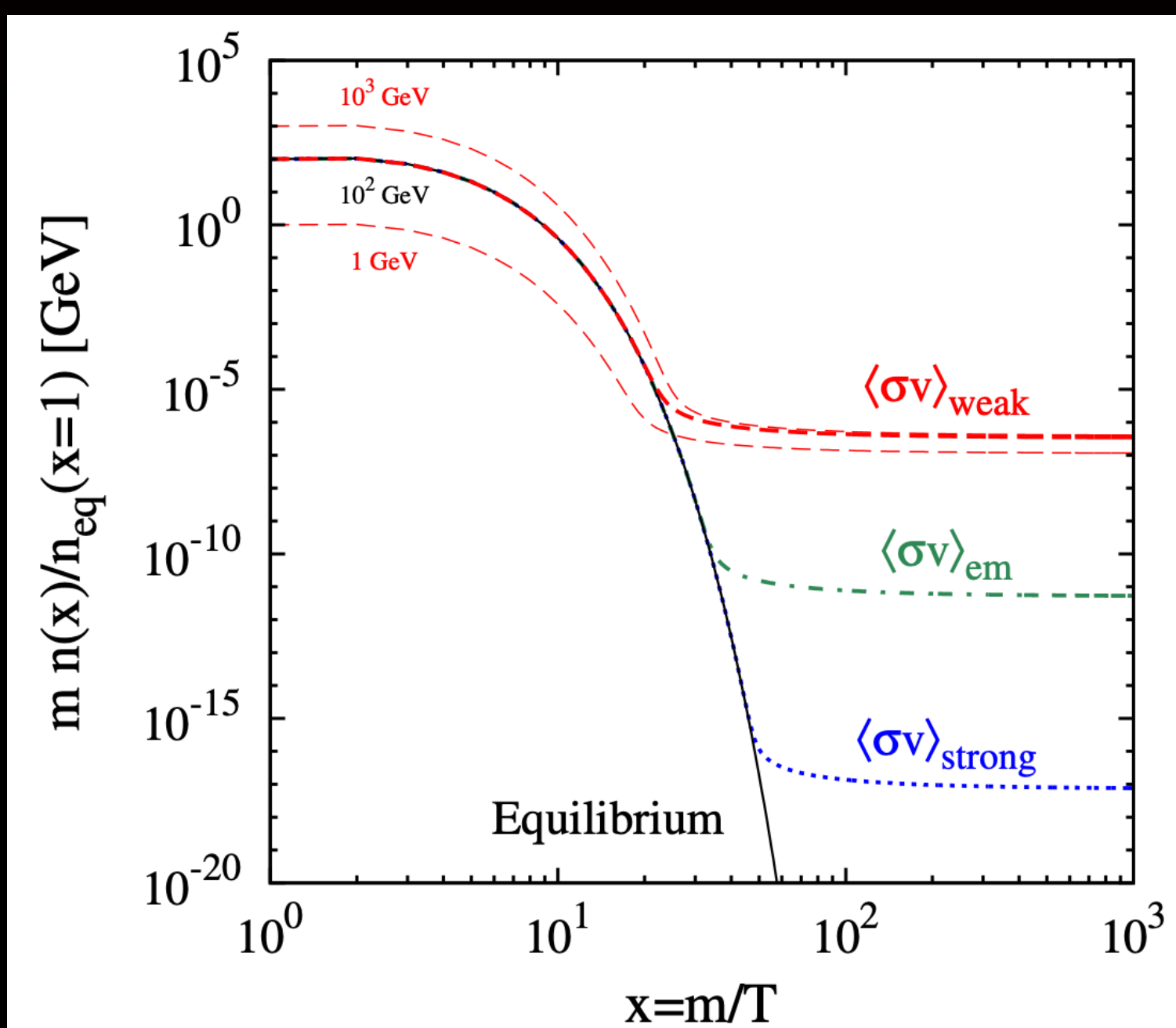
Fully ionized

1000

100

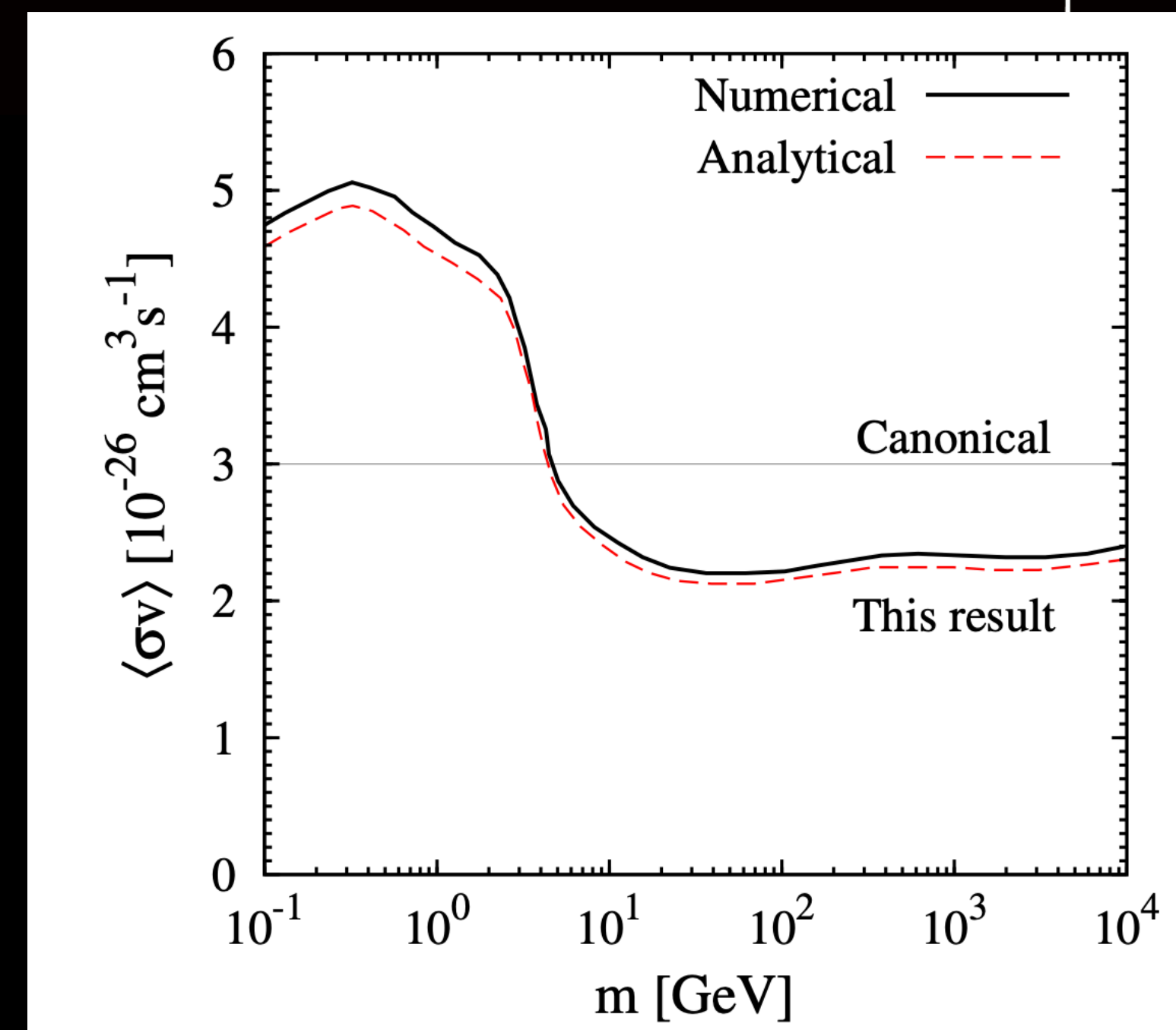
10

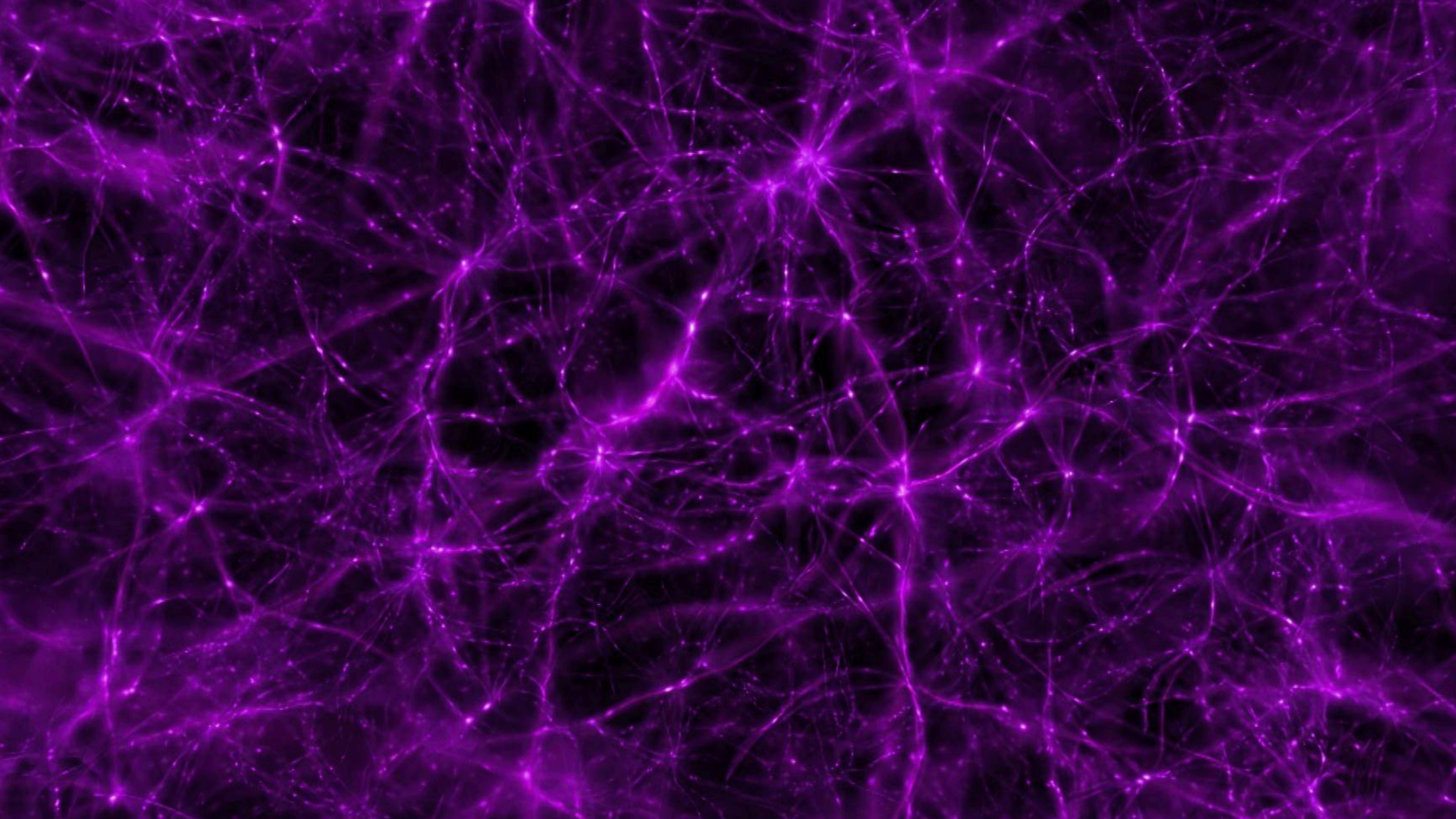
1+Redshift

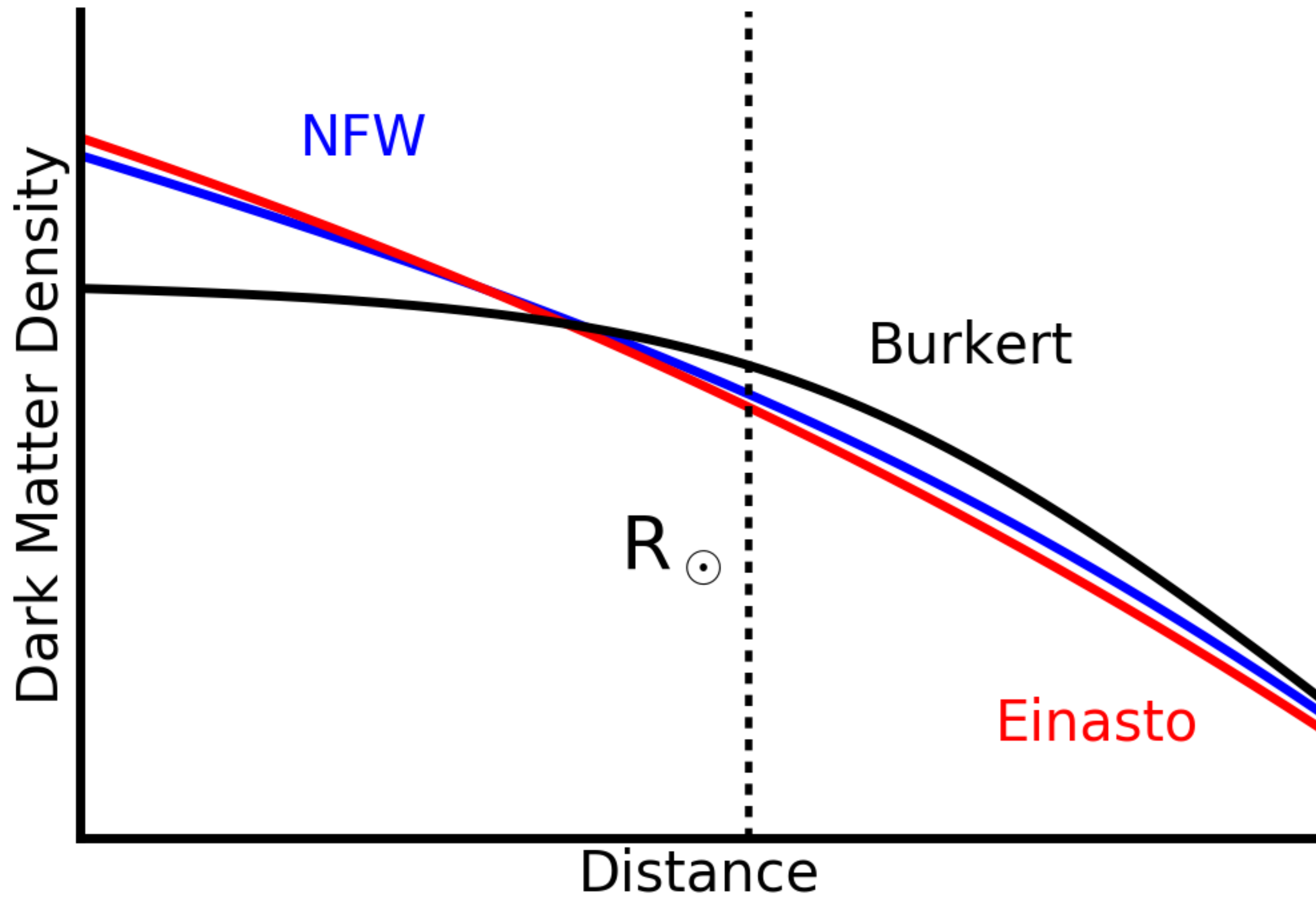


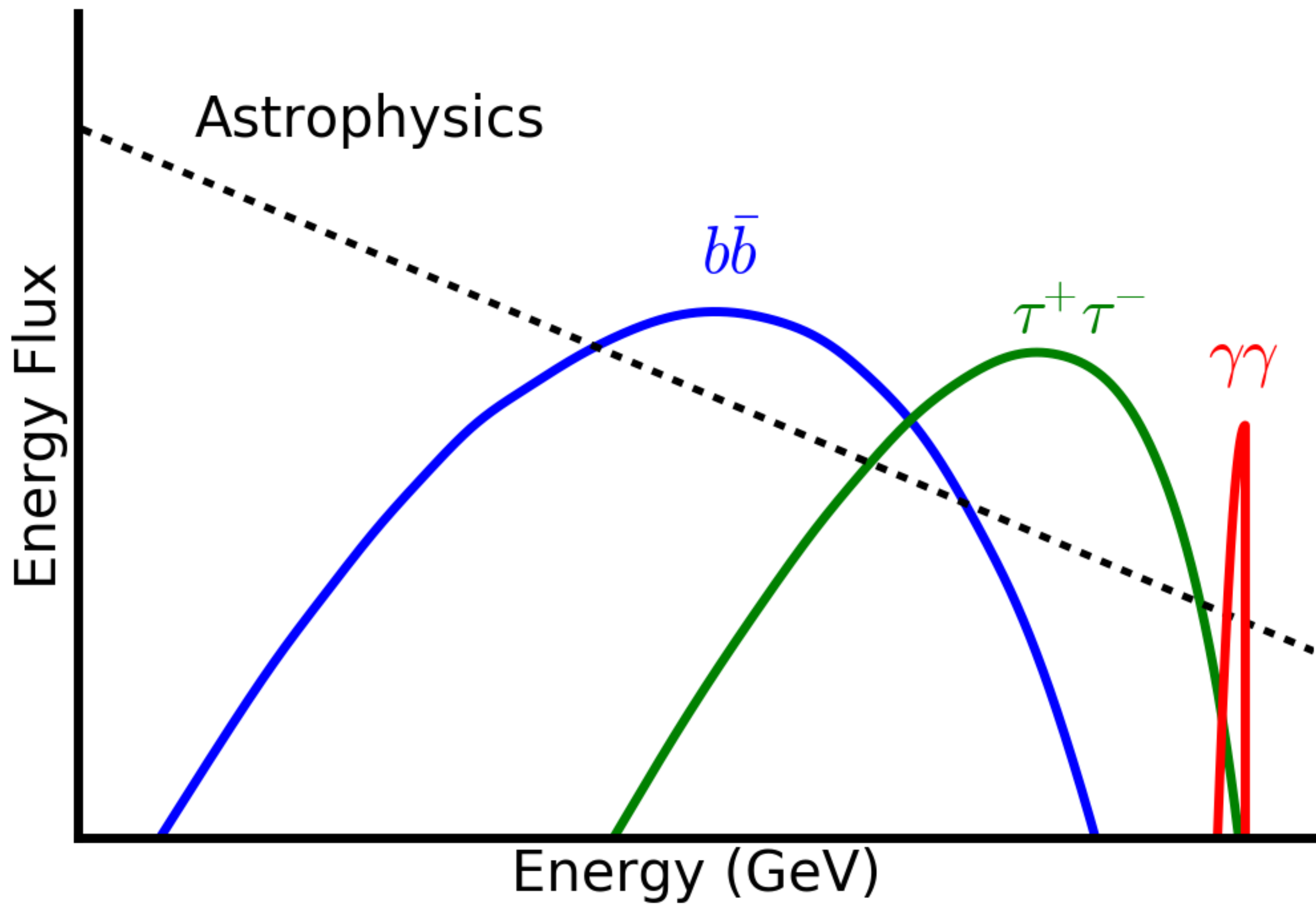
Philosophy:

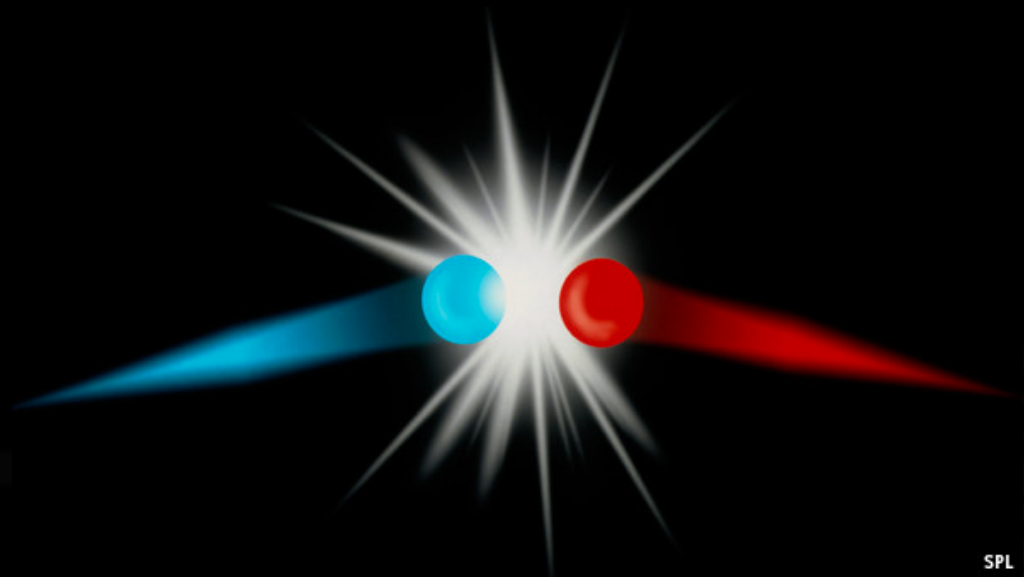
Constrain the simplest model first





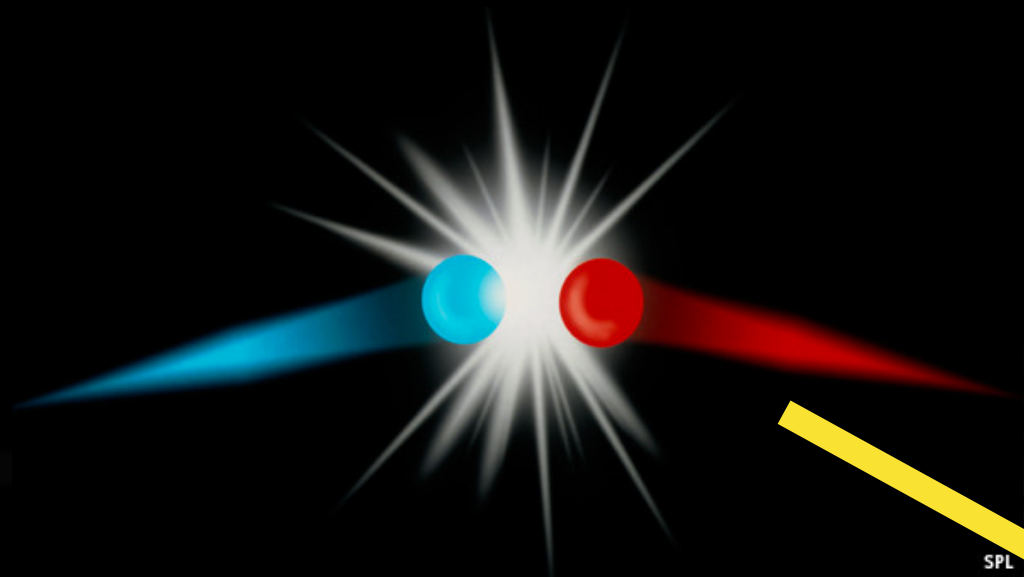




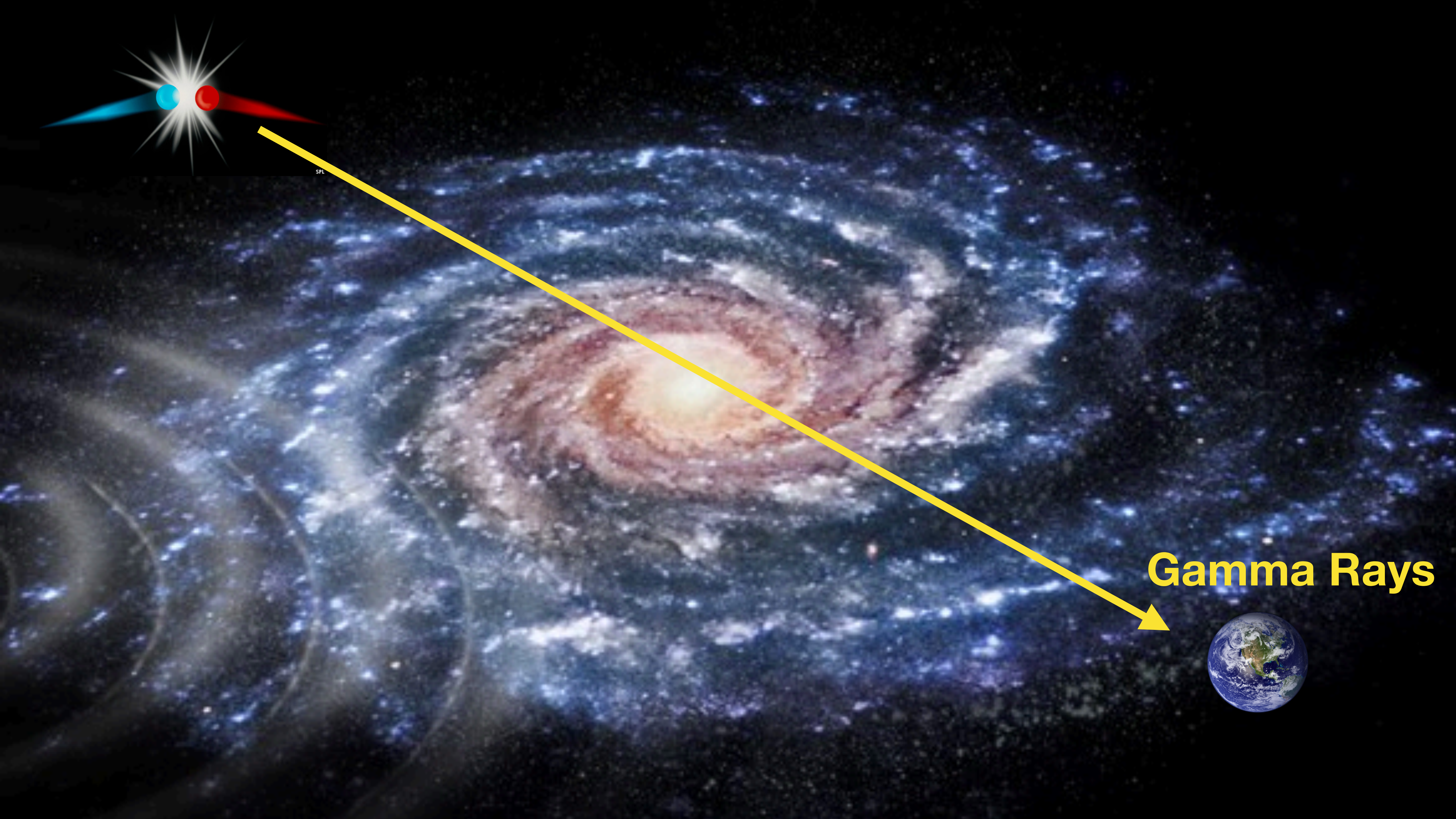


SPL





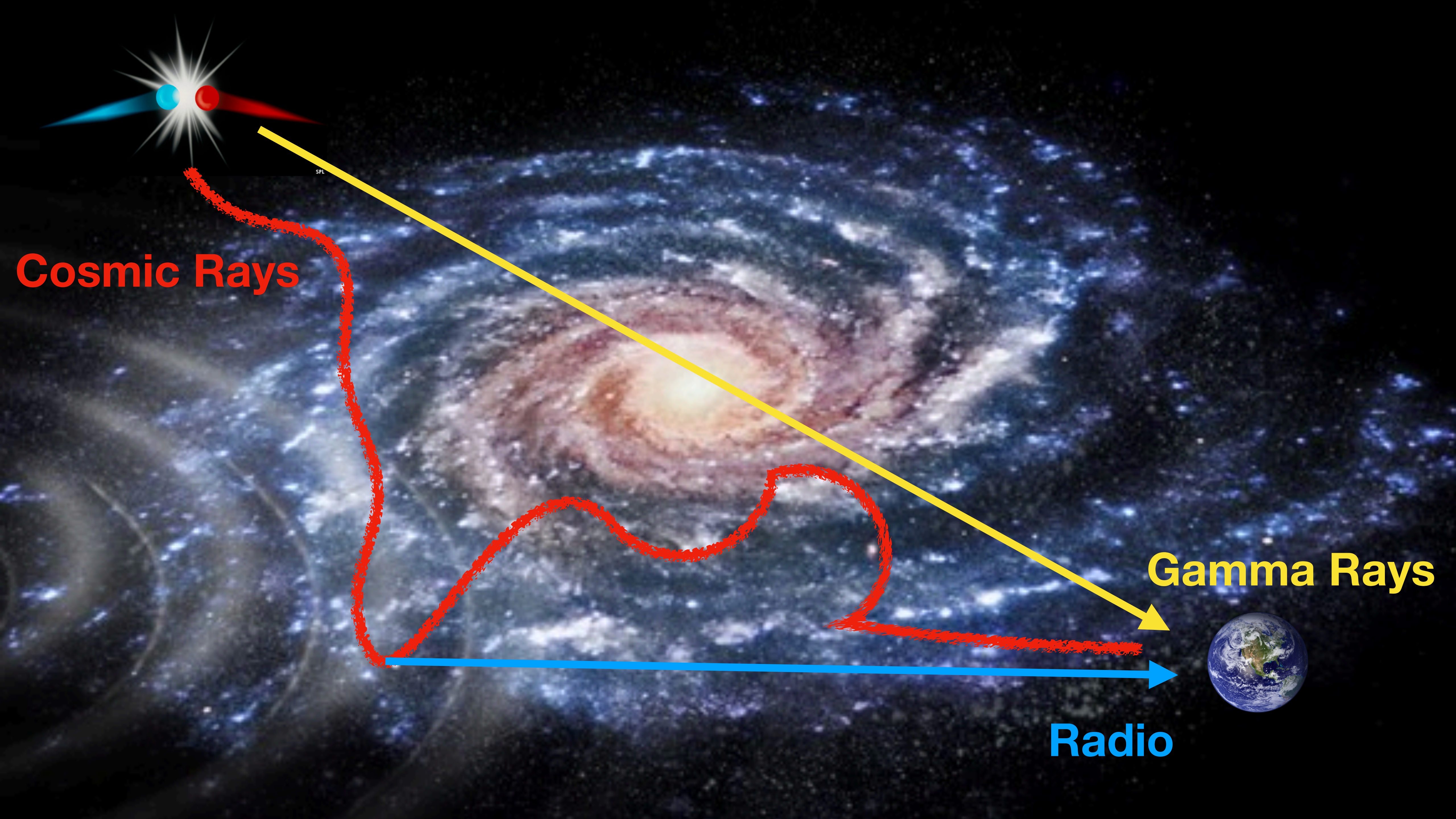
Gamma Rays





Cosmic Rays

Gamma Rays



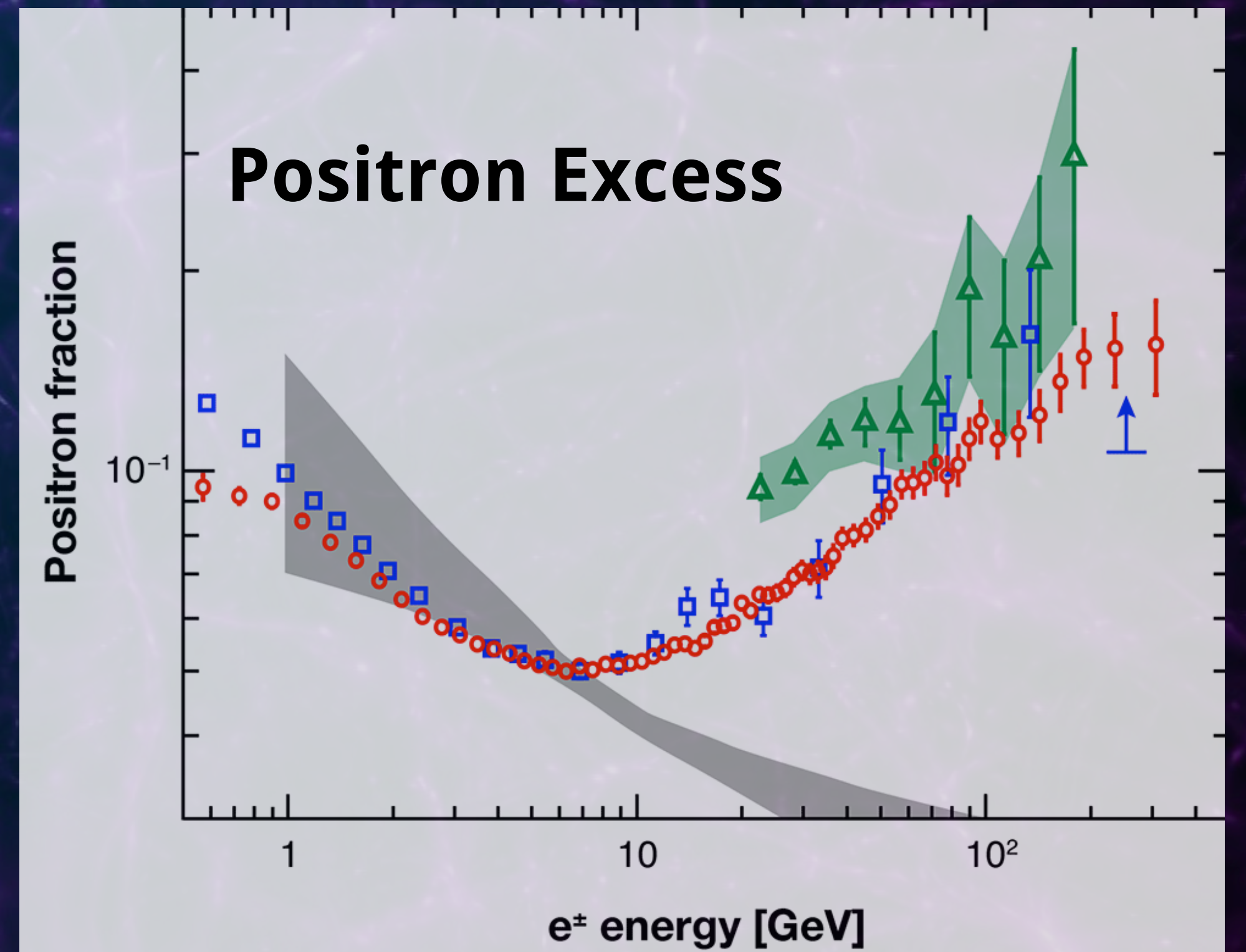
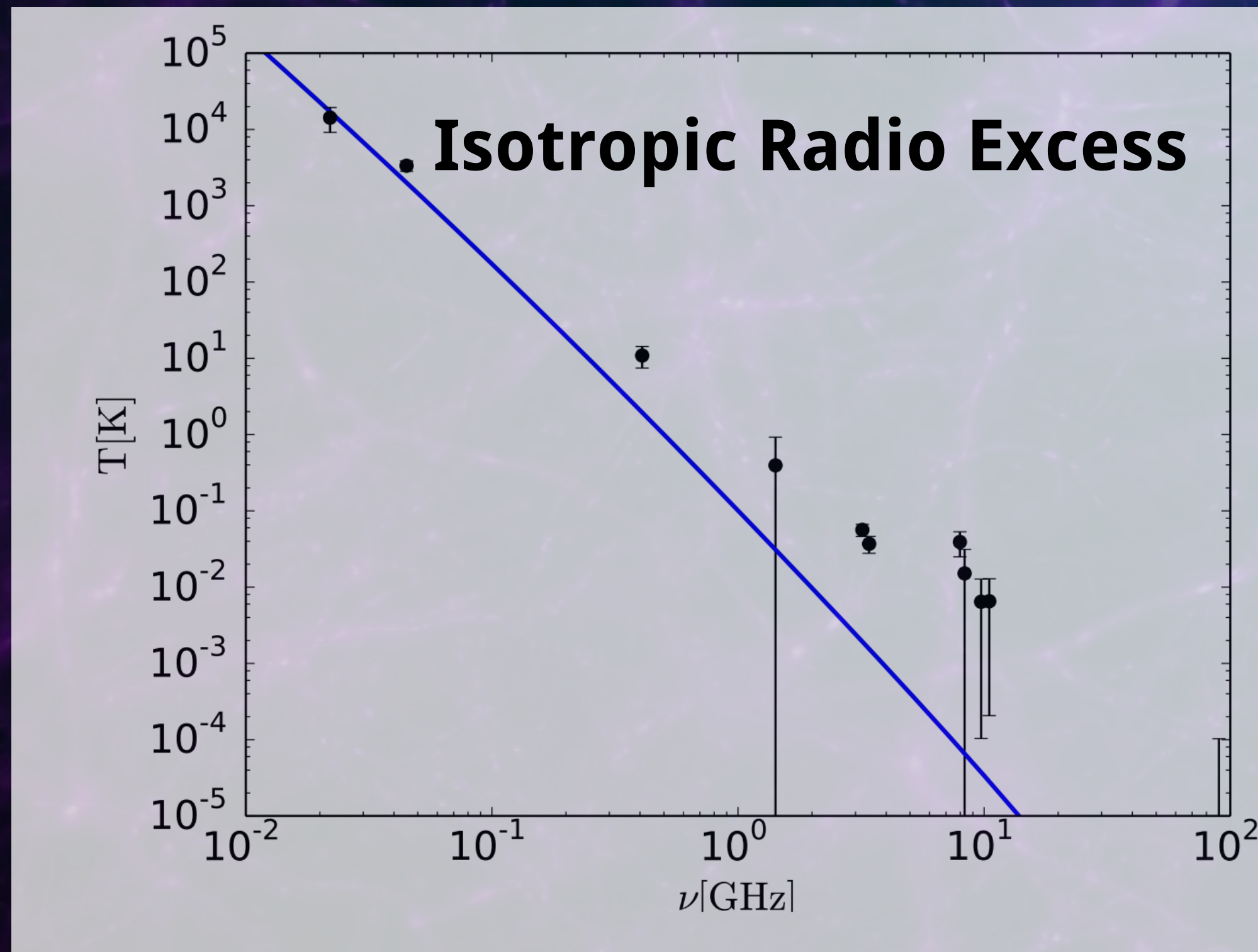
Cosmic Rays

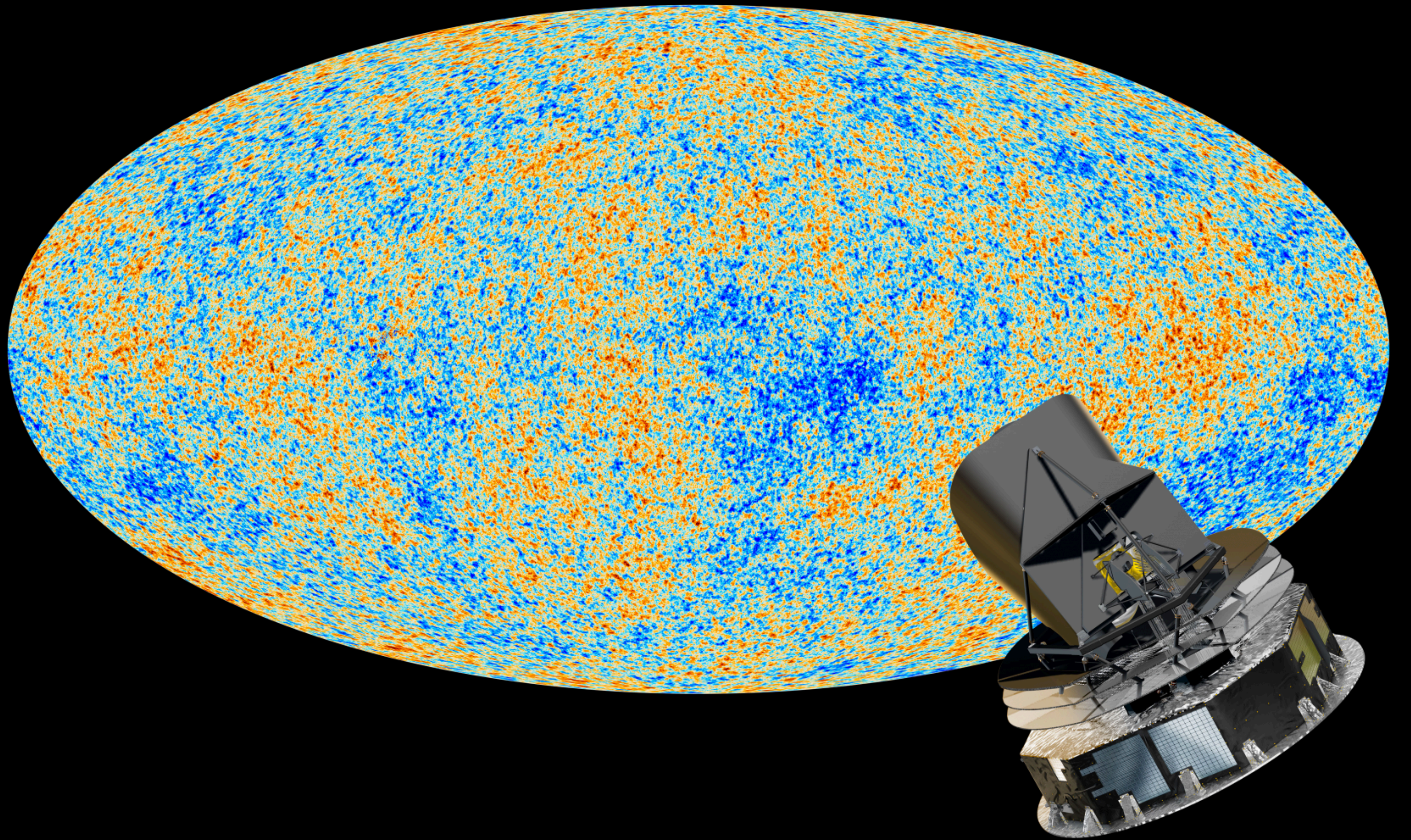
Gamma Rays

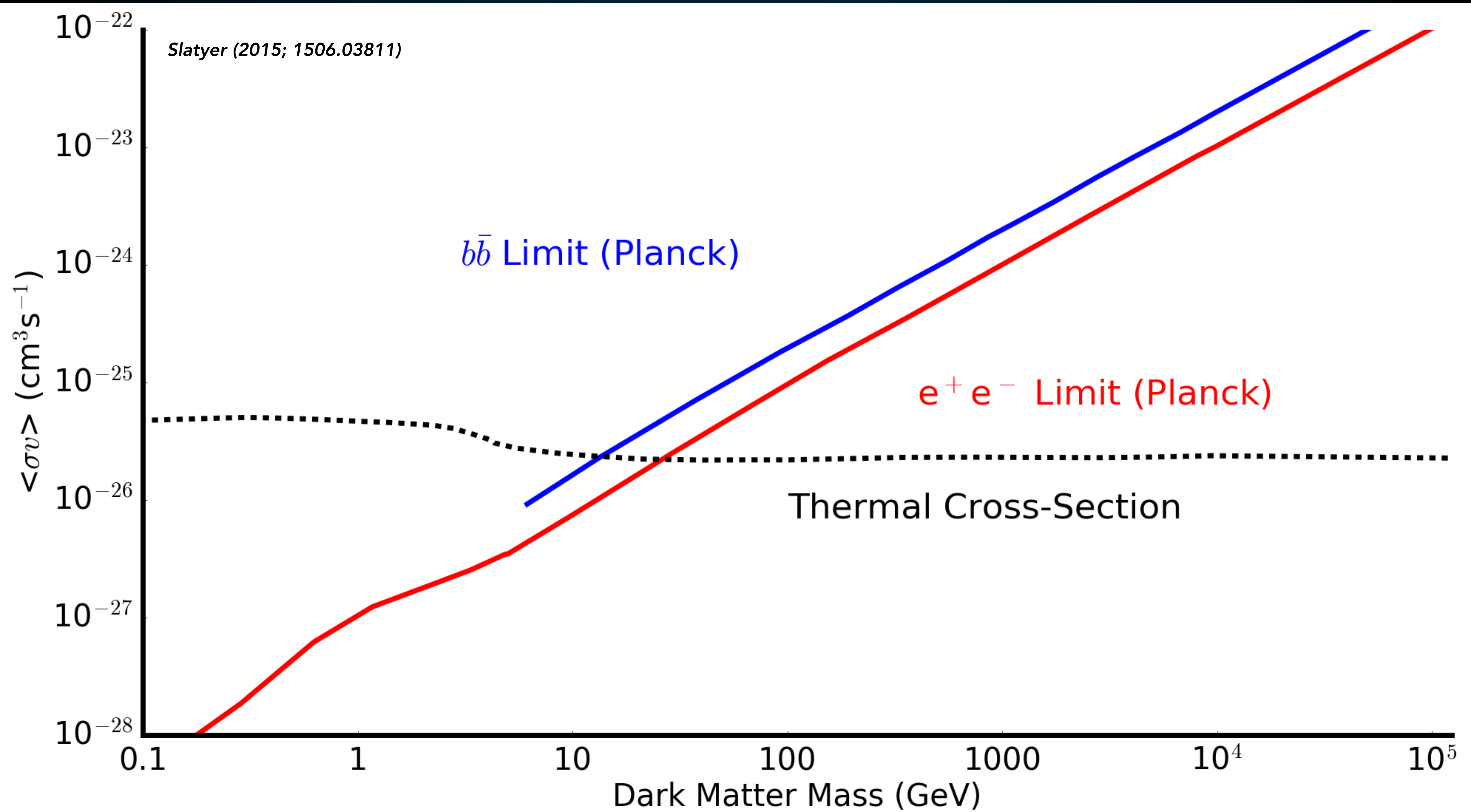
Radio



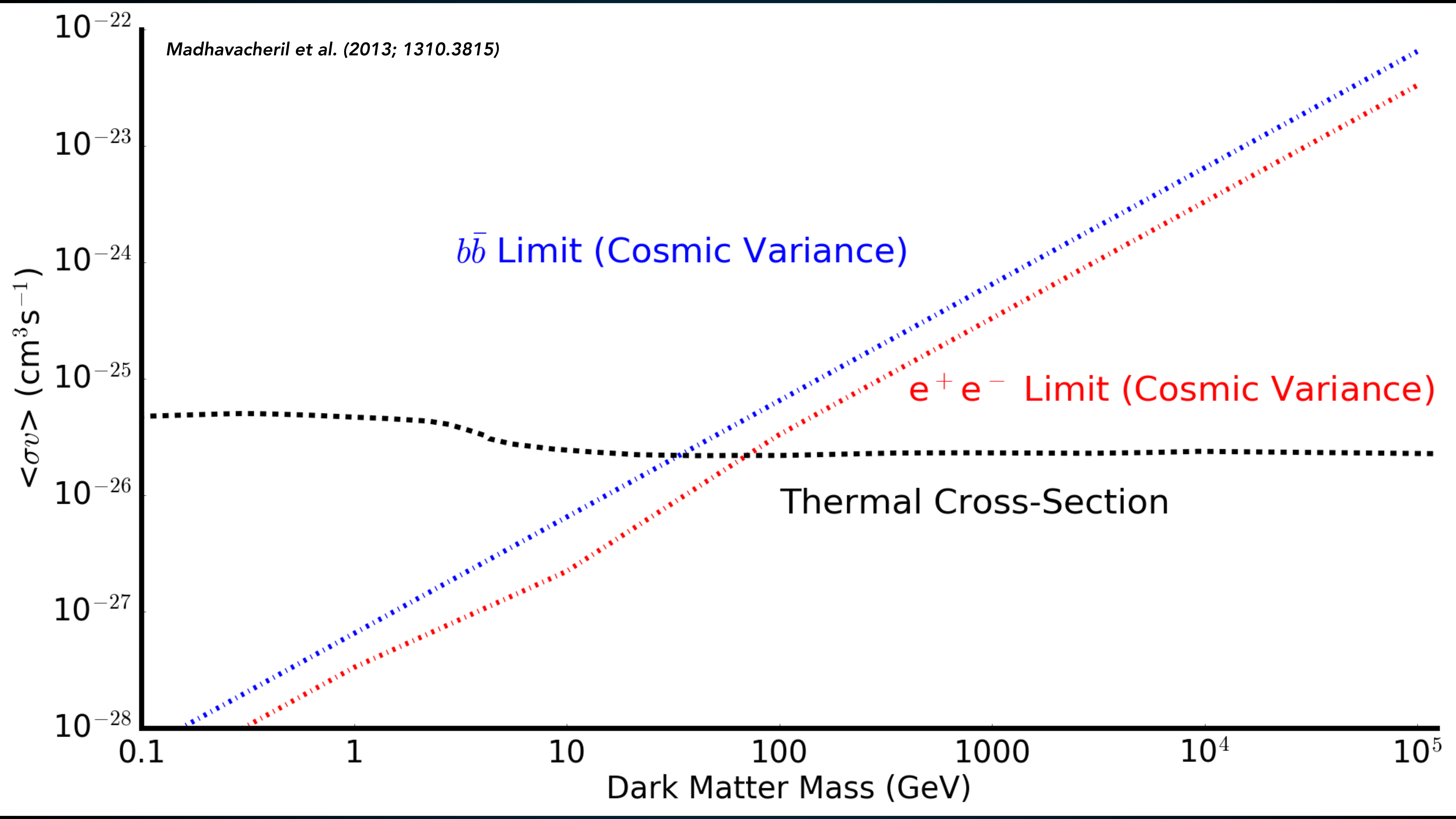
Galactic Center Excess







Madhavacheril et al. (2013; 1310.3815)



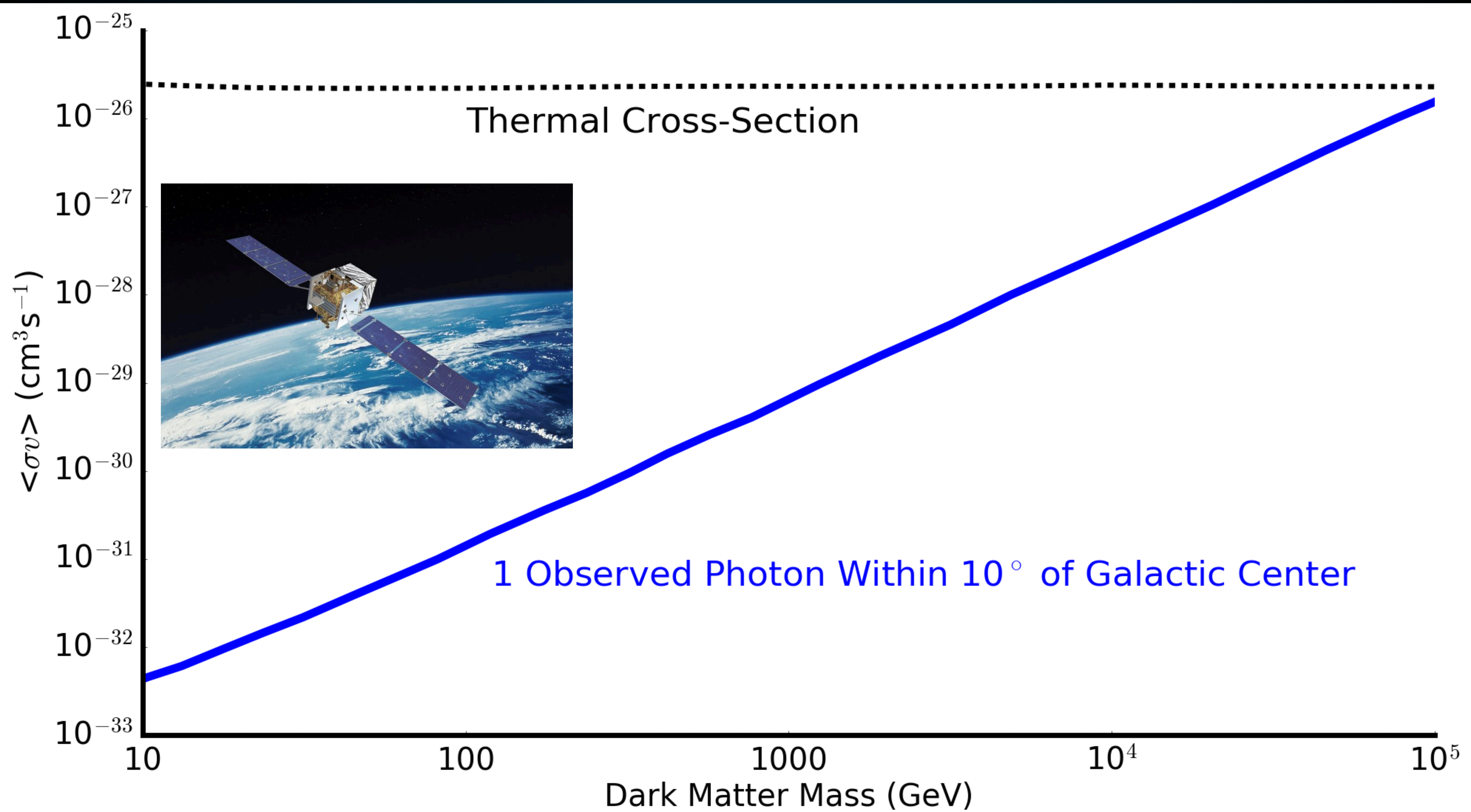
$b\bar{b}$ Limit (Cosmic Variance)

e^+e^- Limit (Cosmic Variance)

Thermal Cross-Section

$\langle\sigma v\rangle$ (cm^3s^{-1})

Dark Matter Mass (GeV)



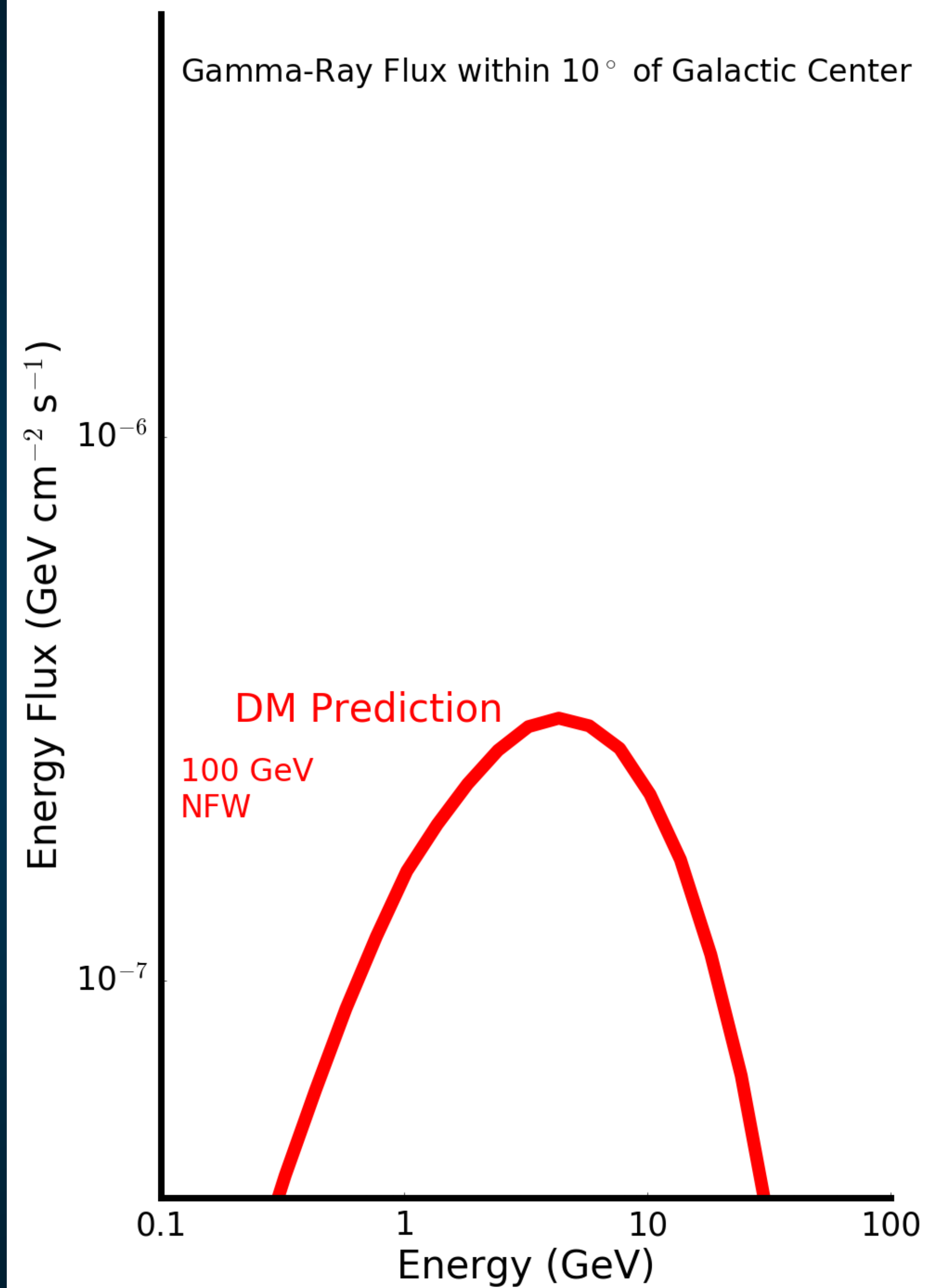
Thermal WIMPs and the Story of Tantalus

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)

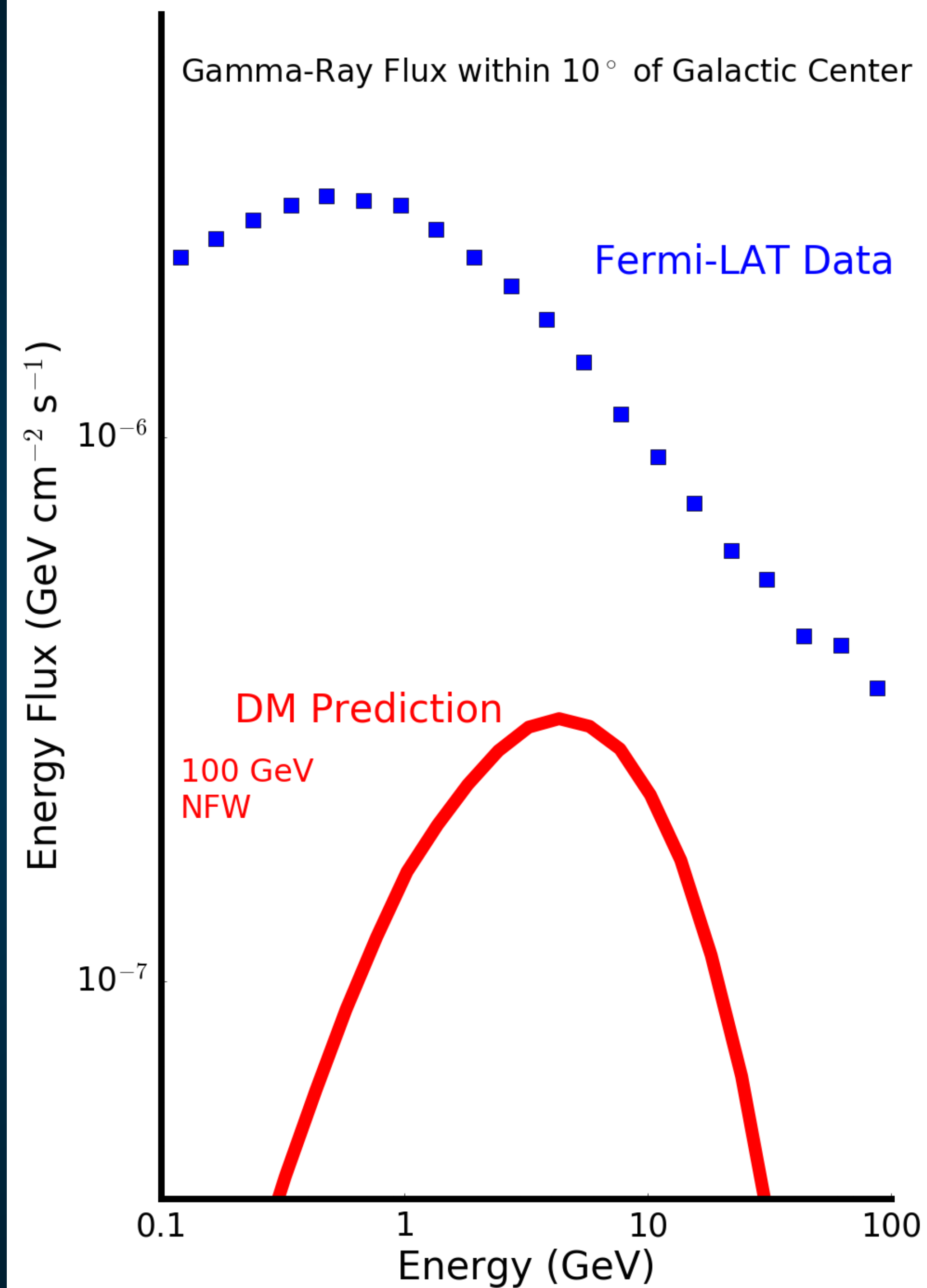
Dark Matter Mass (?)

Annihilation Final State (?)

Milky Way Star-Formation Rate (Galactic Dynamics)

Diffusion Constant in Galactic Center (Hydrodynamics)

Activity of Supermassive Blackhole (?)



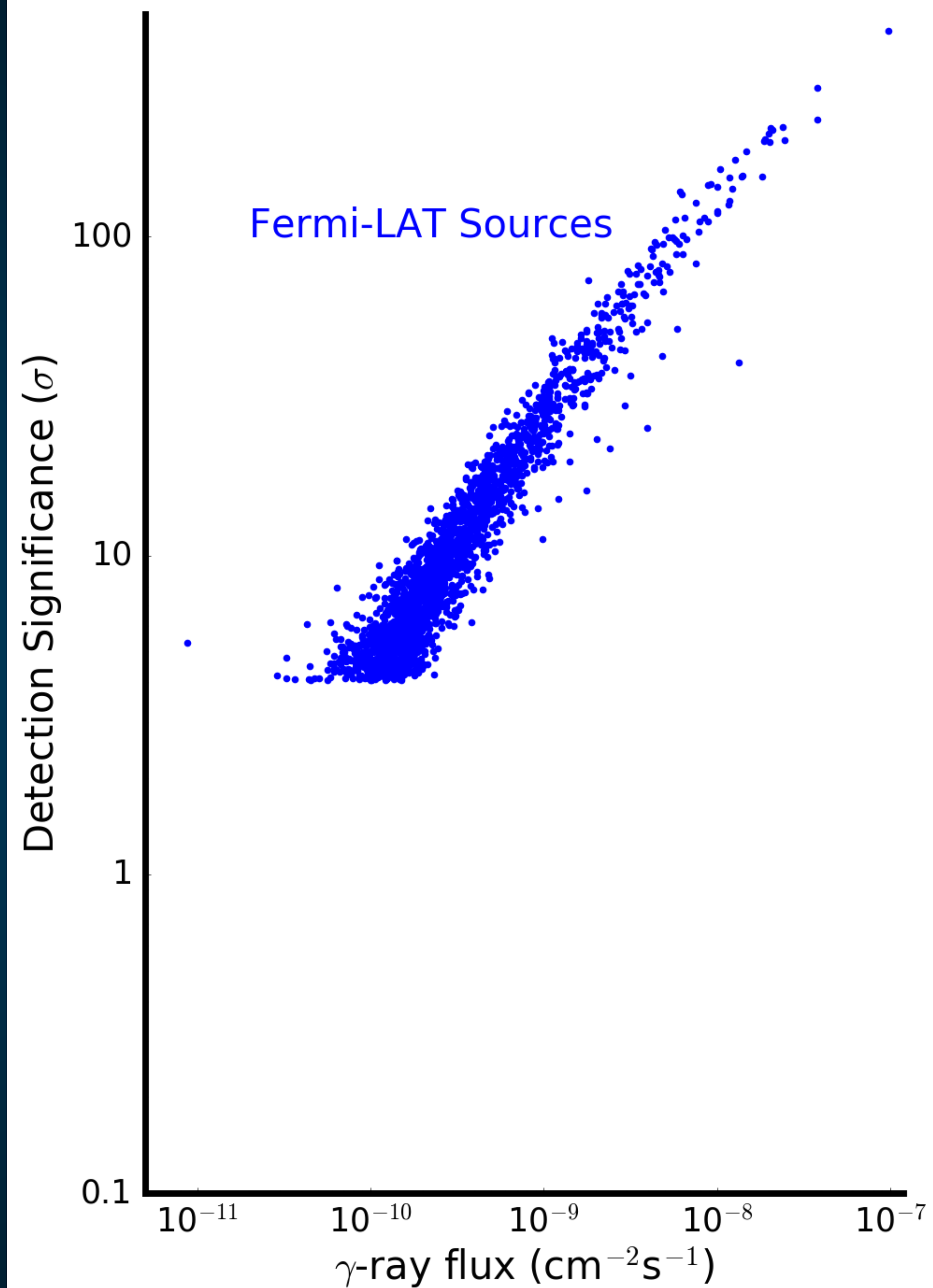
Thermal WIMPs and the Story of Tantalus

SMBH Accretion Efficiency (Magnetohydrodynamics)

Blazar Acceleration Mechanisms (Leptonic? Hadronic?)

Radio Galaxy Emission Models

Star-Formation Rates in Starburst Galaxies



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SMBH Accretion Efficiency (Magnetohydrodynamics)

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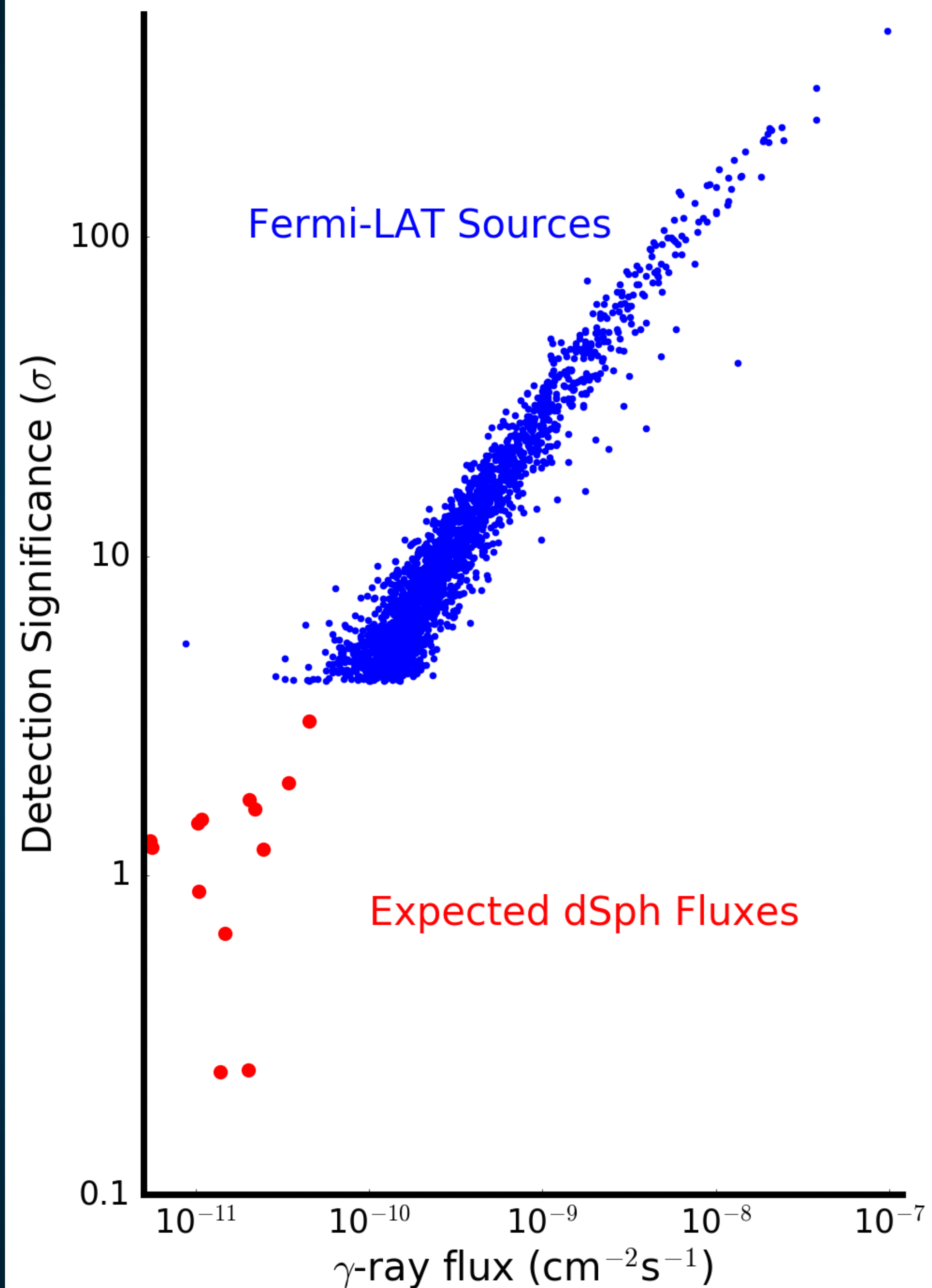
Radio Galaxy Emission Models

Star-Formation Rates in Starburst Galaxies

dSph Proximity

Substructure Models

Milky Way Merger History



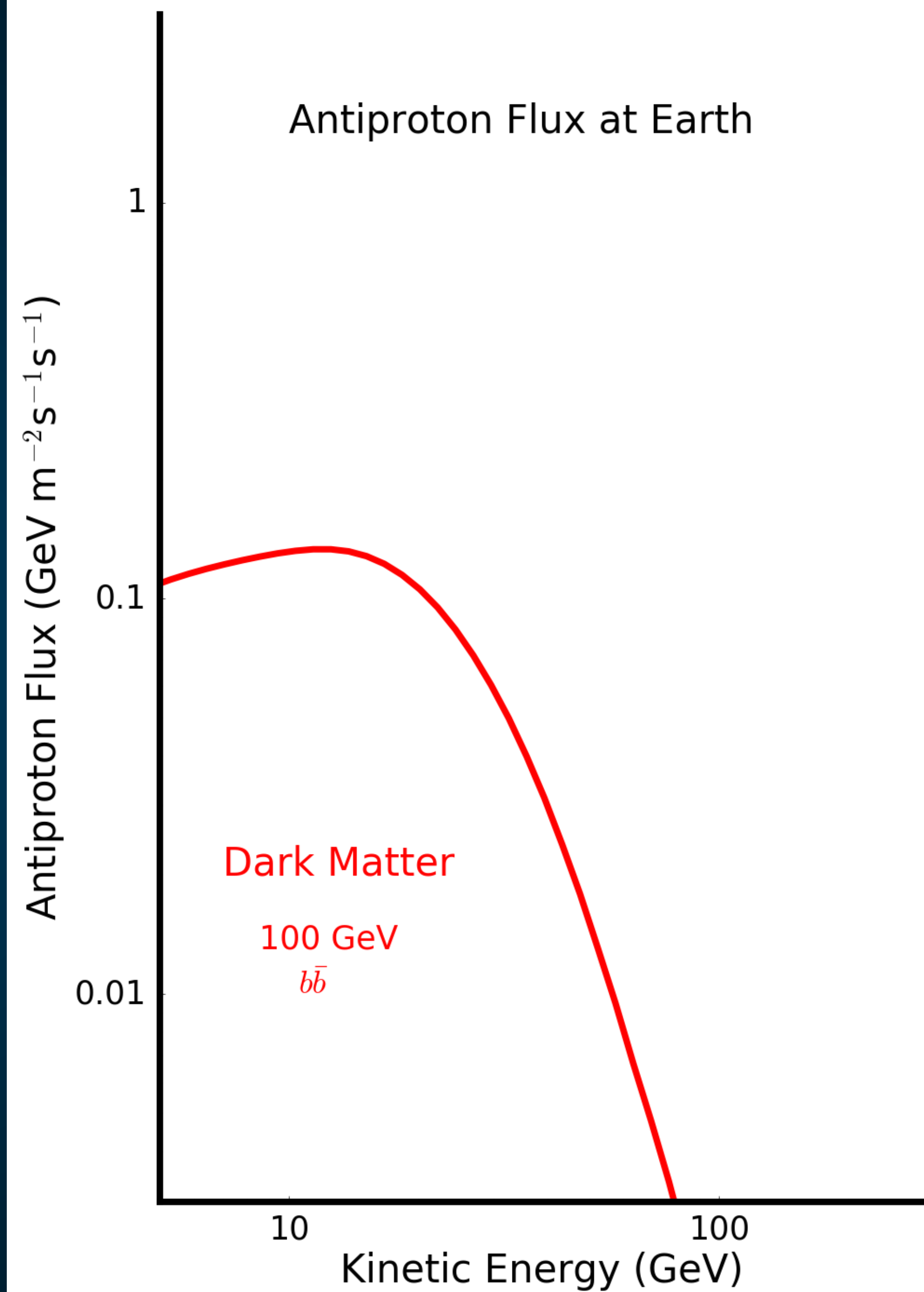
Thermal WIMPs and the Story of Tantalus

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

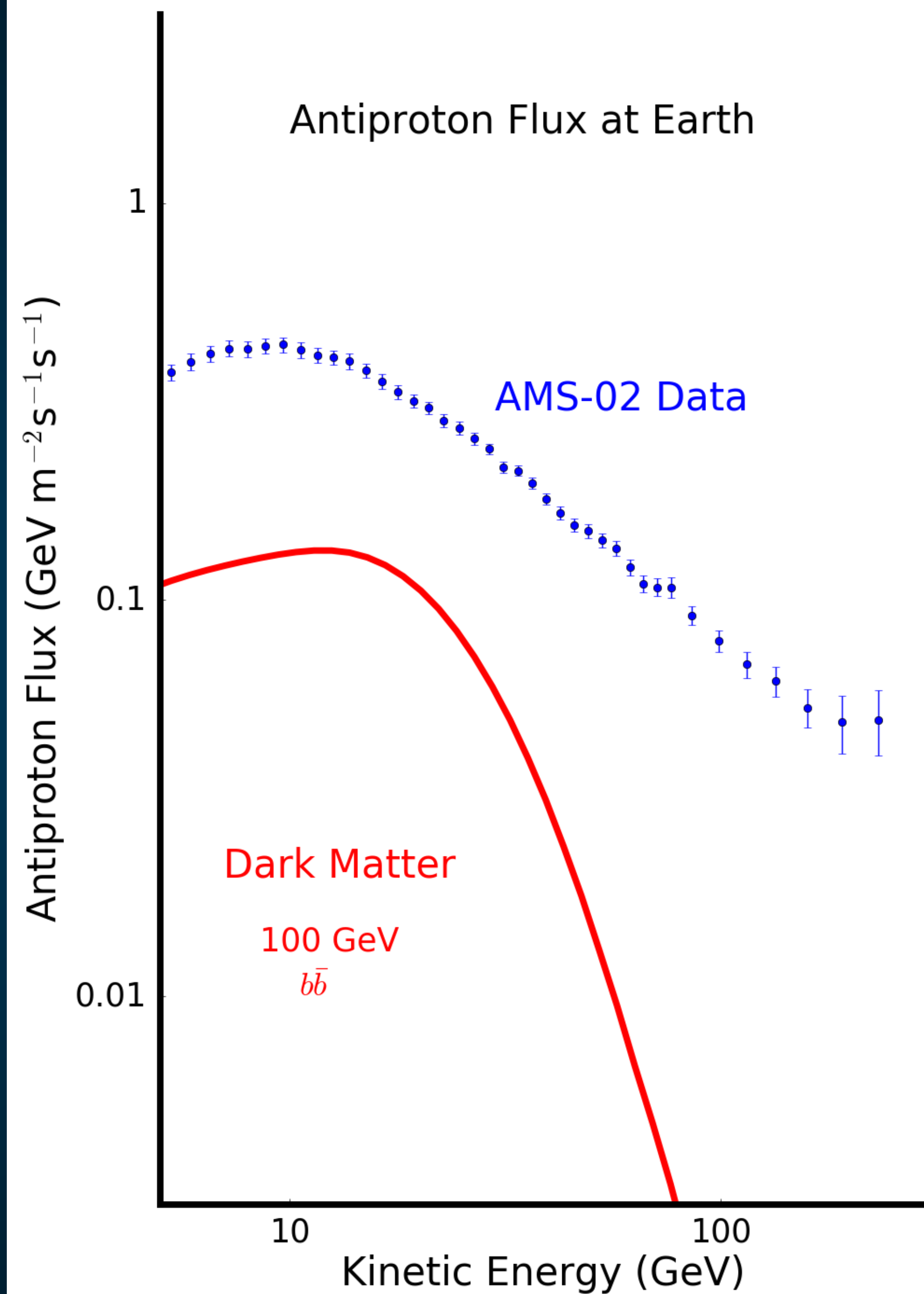
Thermal Cross-Section (Early Universe)

Hadronic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Local Gas Density

Local Supernova Rate



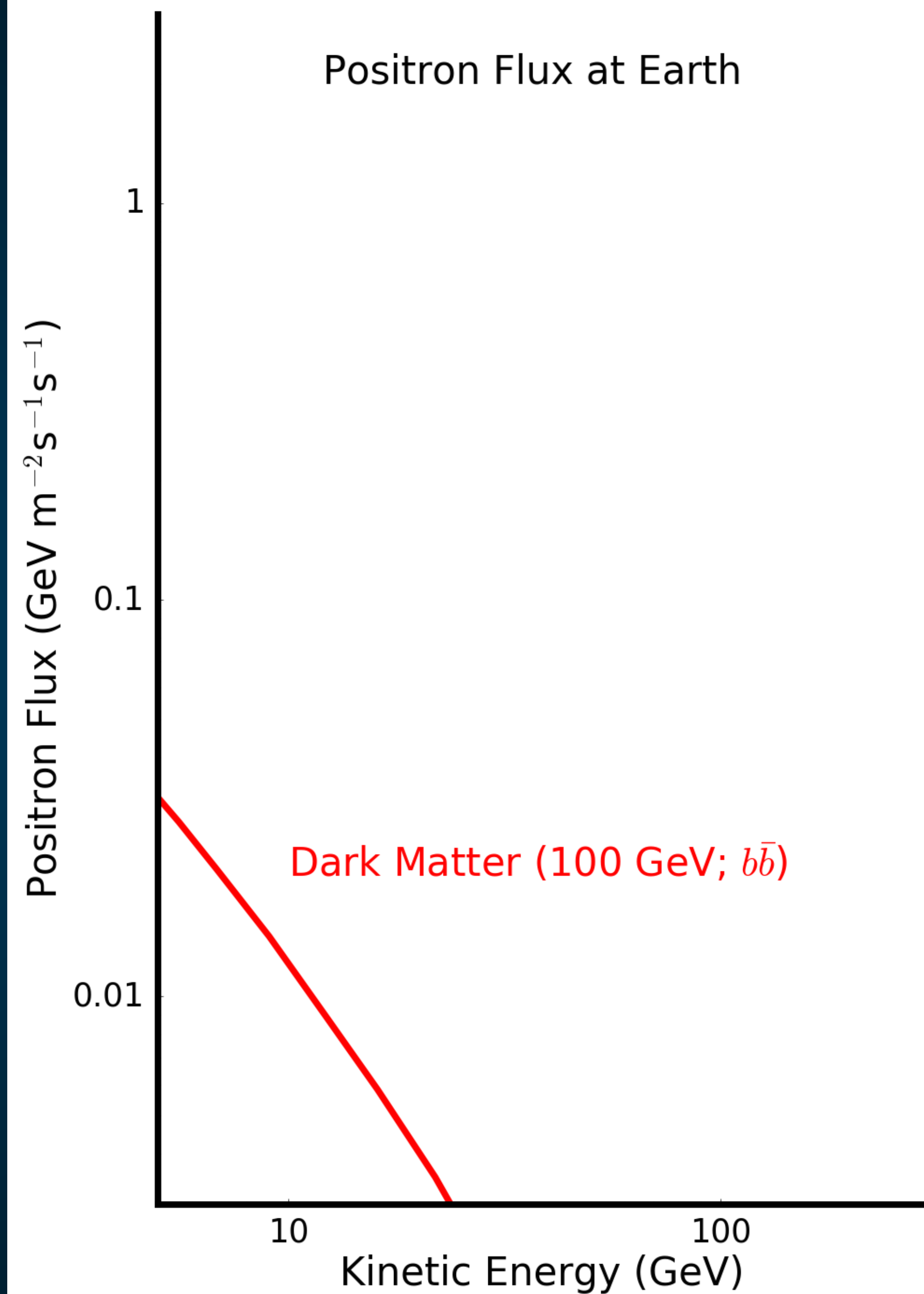
Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

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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

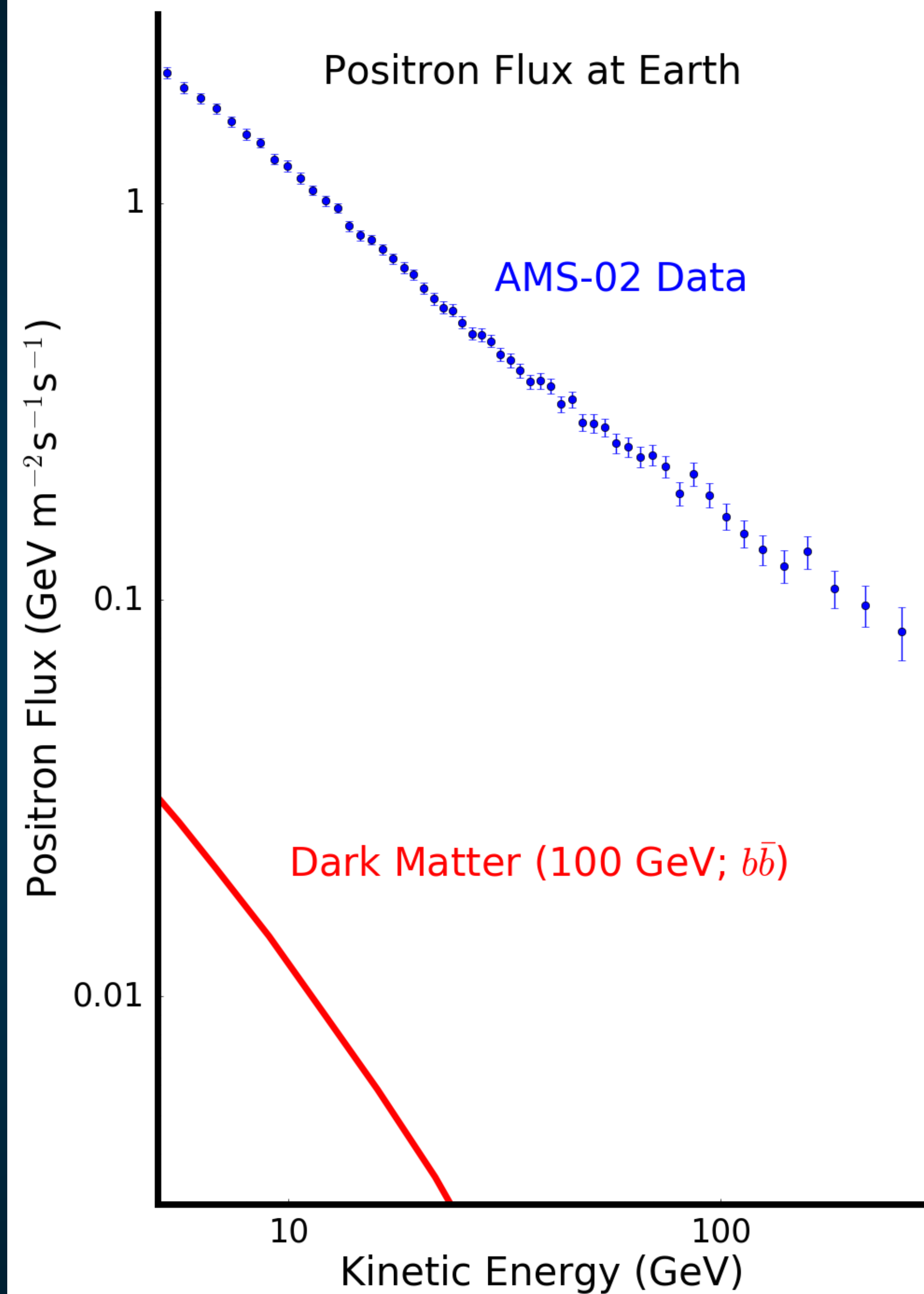
Thermal Cross-Section (Early Universe)

Leptonic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Pulsar Birth Rate

e^+e^- Acceleration Efficiency in Pulsar Magnetospheres



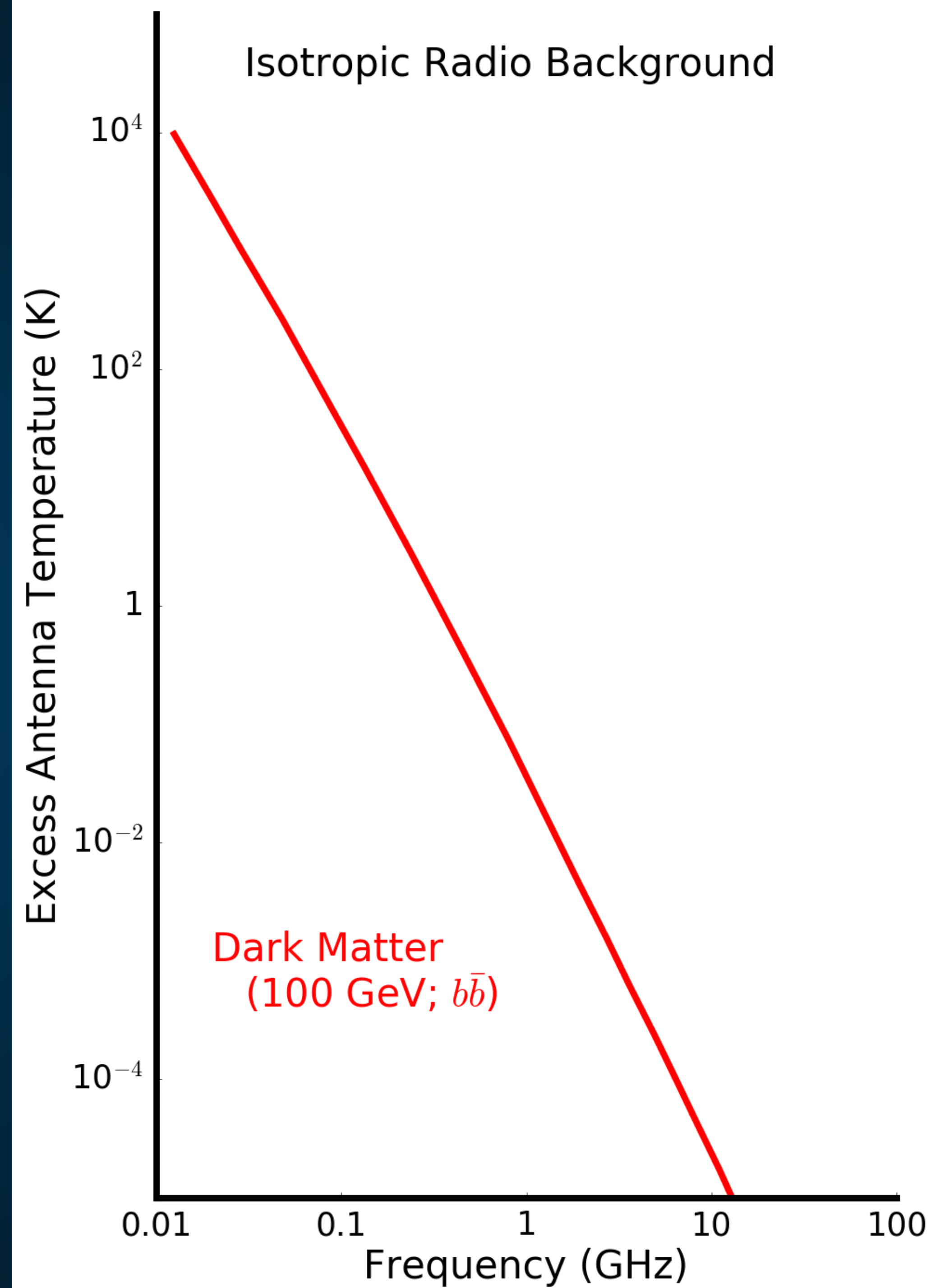
Thermal WIMPs and the Story of Tantalus

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)

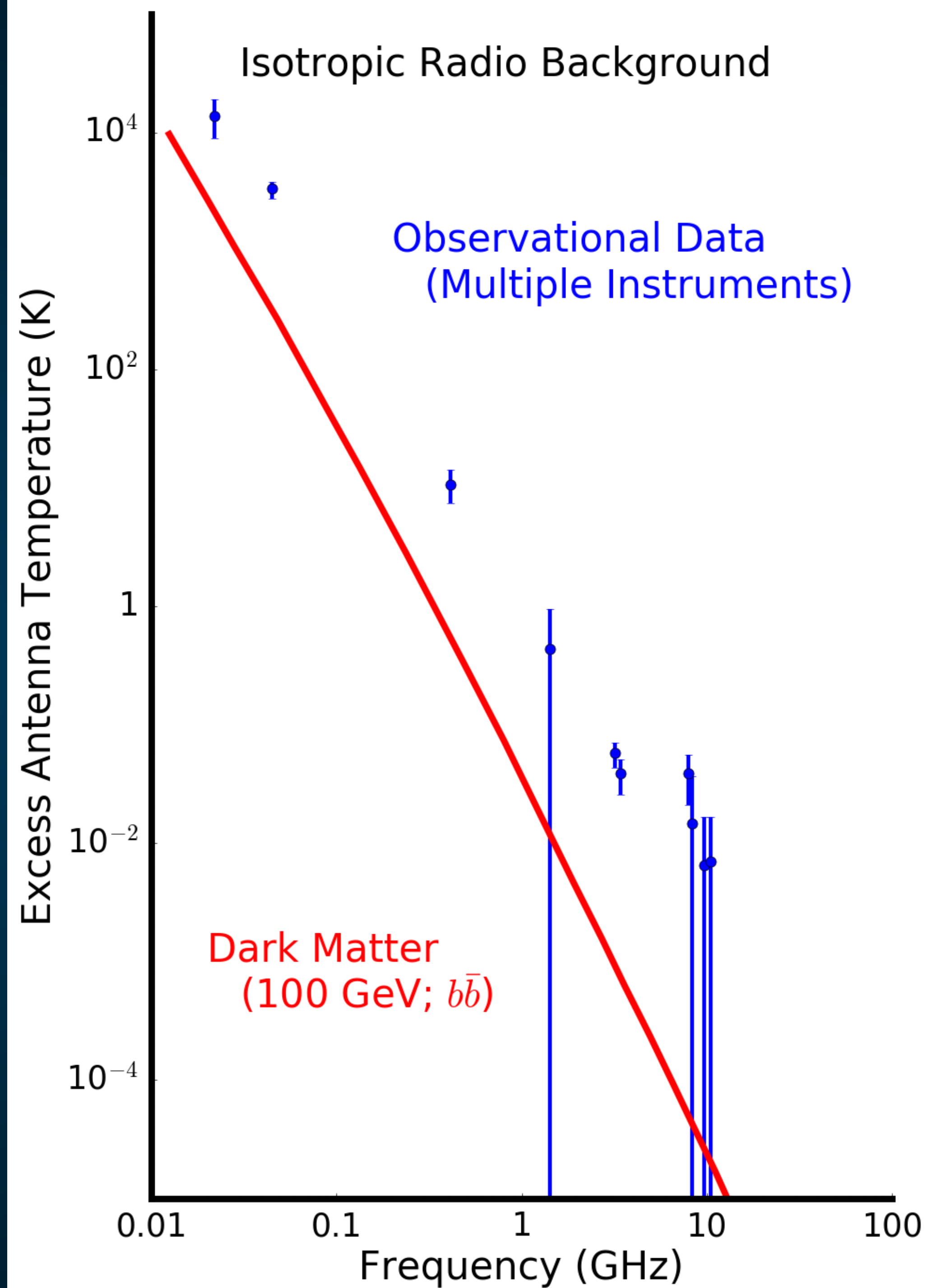
e^+e^- Energy Fraction in Dark Matter Annihilation

Intergalactic Magnetic Fields

Radio Luminosity in Starbursts and AGN

e^+e^- Reacceleration in Cluster Mergers

Redshift Dependence of Signal vs. CMB





Specificity (DM Flux / Astrophysics Flux)

Small Dark Matter Signal
Small Astrophysical Background

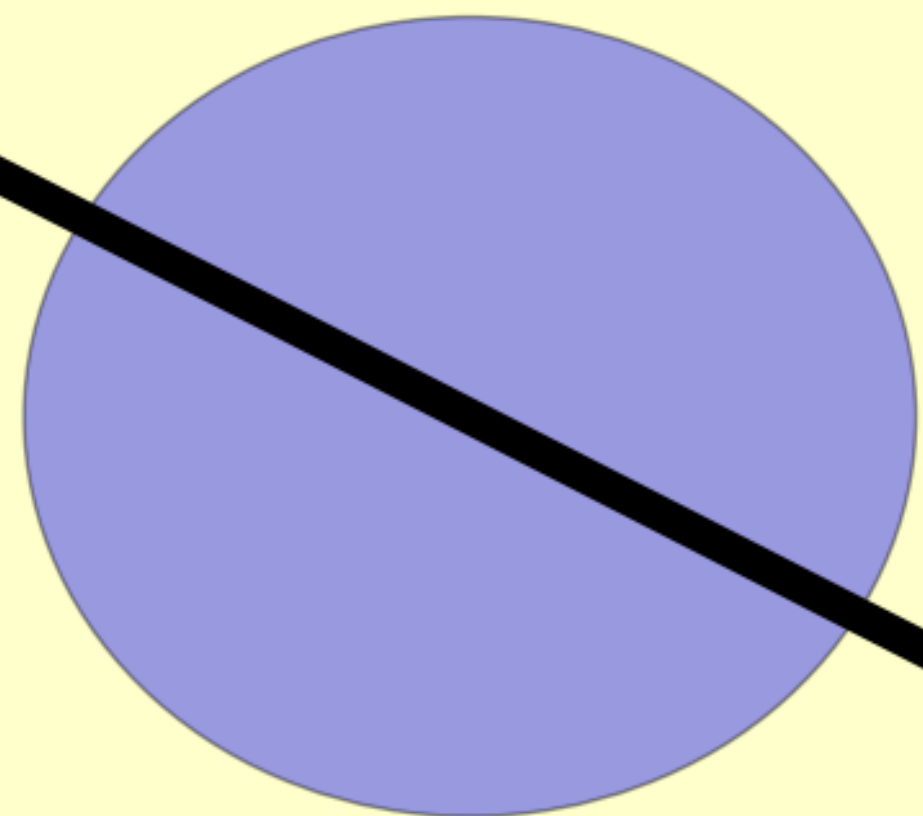
Large Dark Matter Signal
Small Astrophysical Background

Small Dark Matter Signal
Large Astrophysical Background

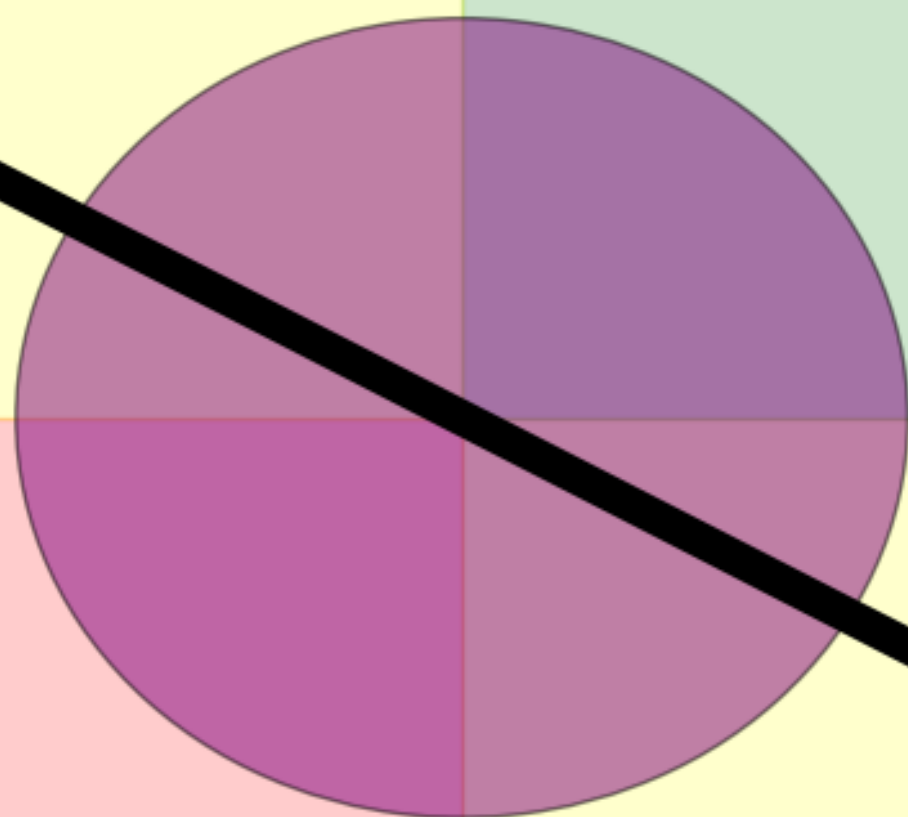
Large Dark Matter Signal
Large Astrophysical Background

Fraction of Dark Matter Flux

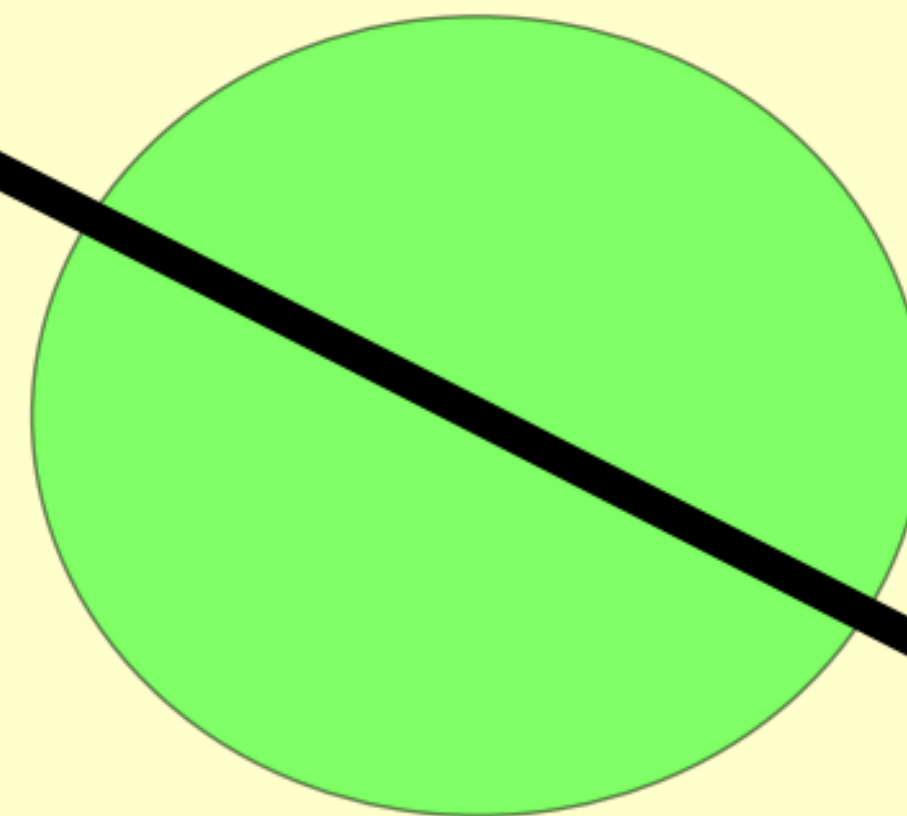
Specificity (DM Flux / Astrophysics Flux)



Anti-Nuclei

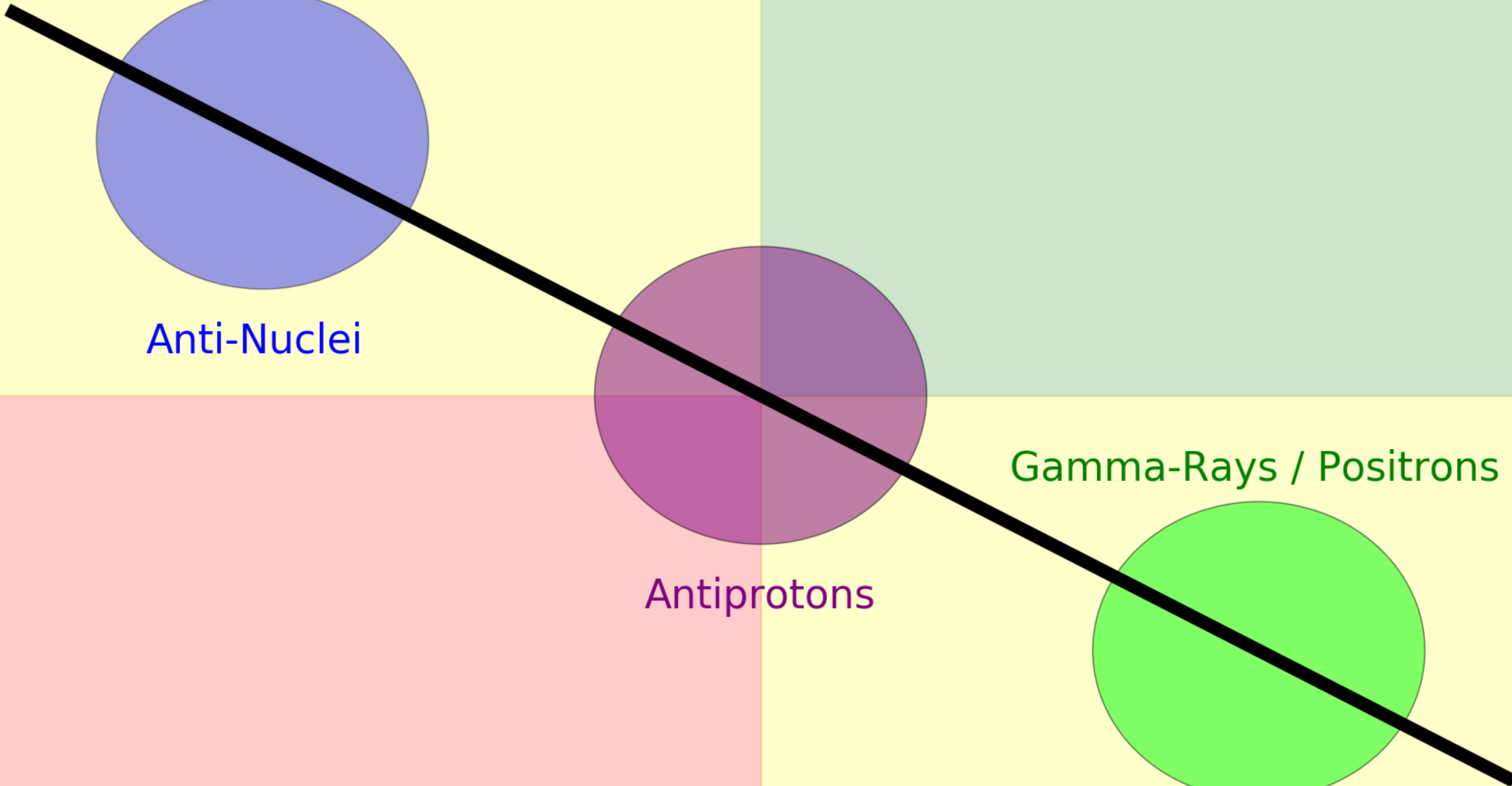


Antiprotons



Gamma-Rays / Positrons

Fraction of Dark Matter Flux

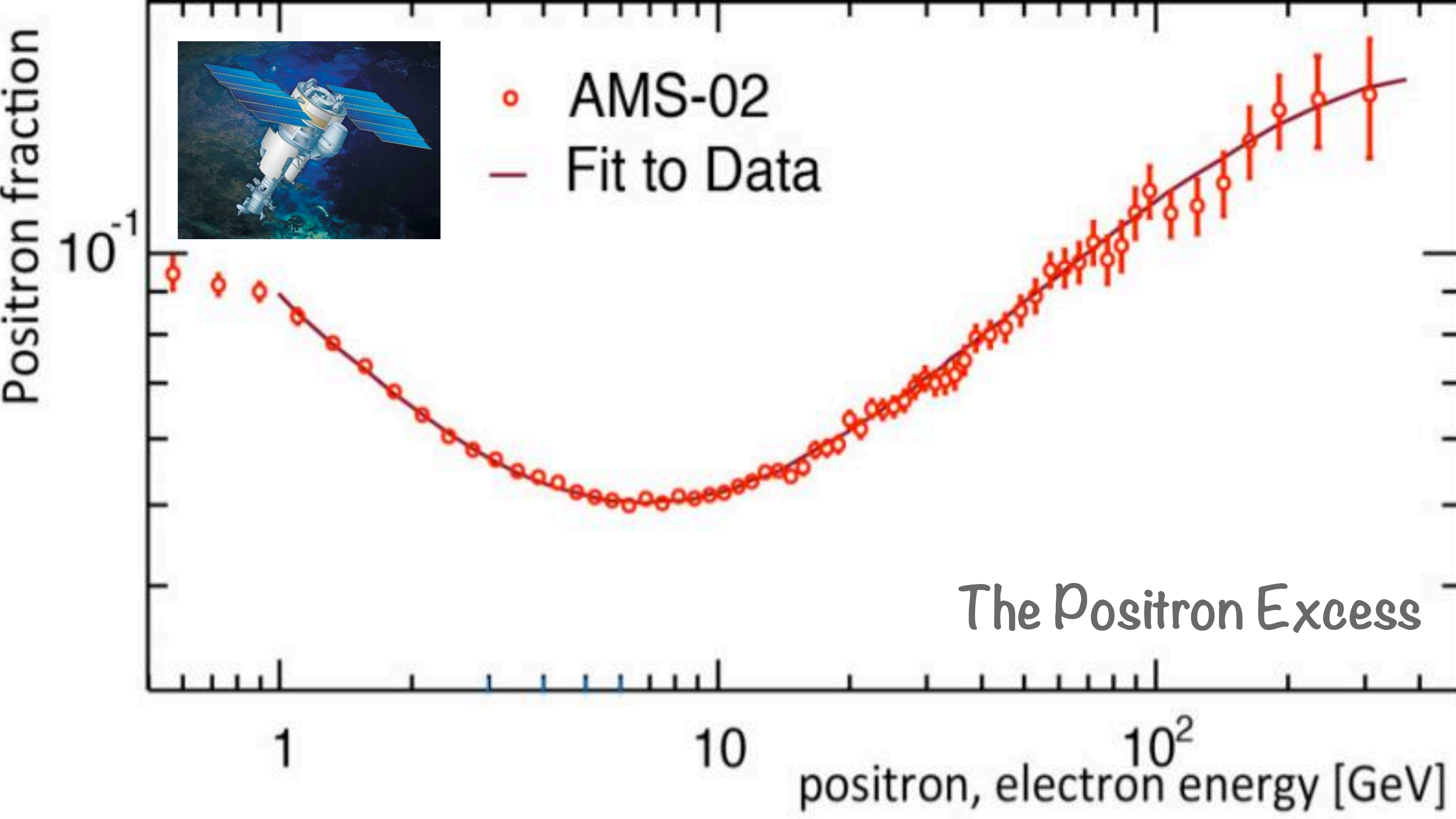


Thermal WIMPs and the Story of Tantalus



Thermal WIMPs and the Story of Tantalus

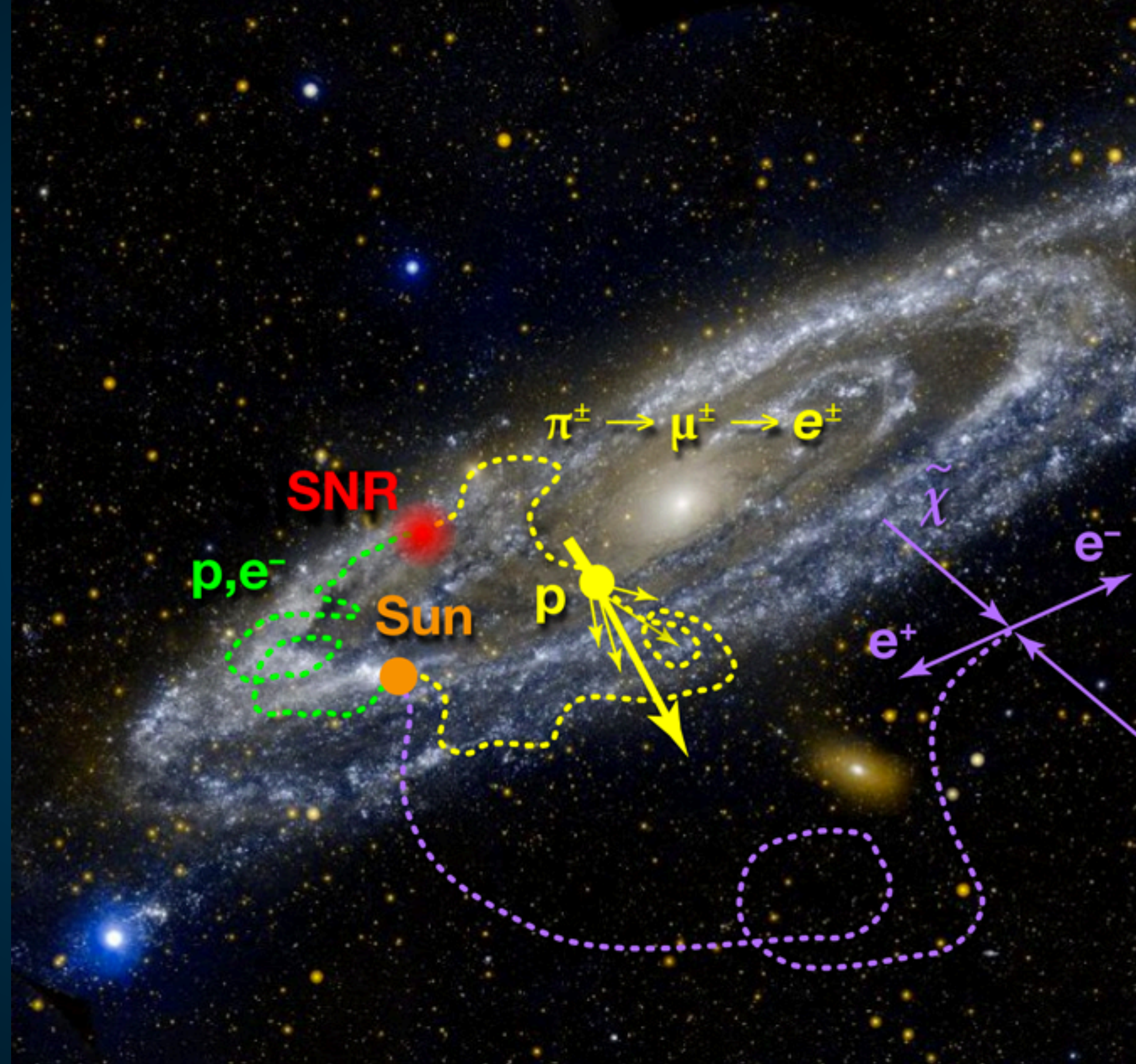
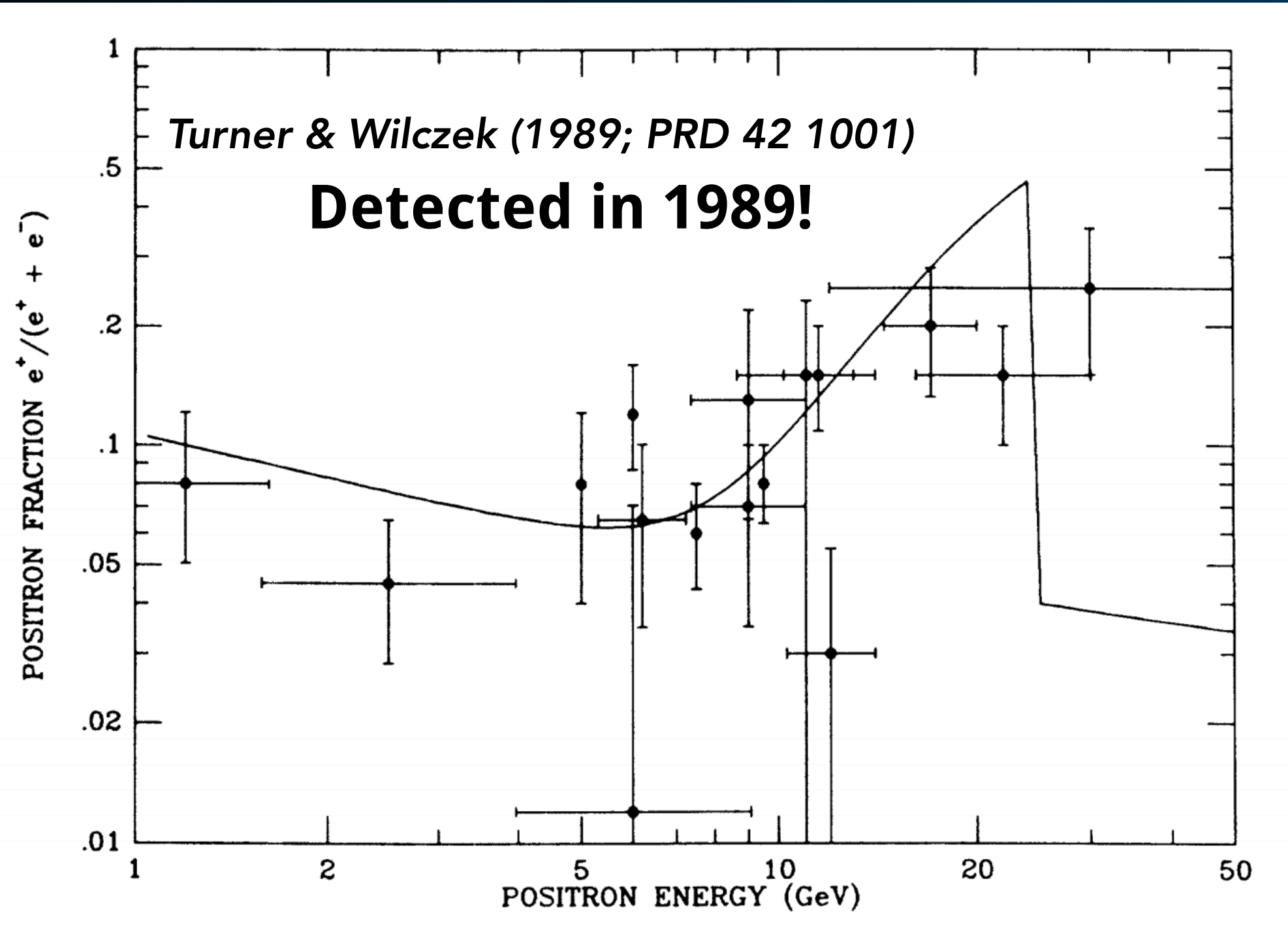




The Positron Excess

Key Idea: Investigate the Positron Fraction!

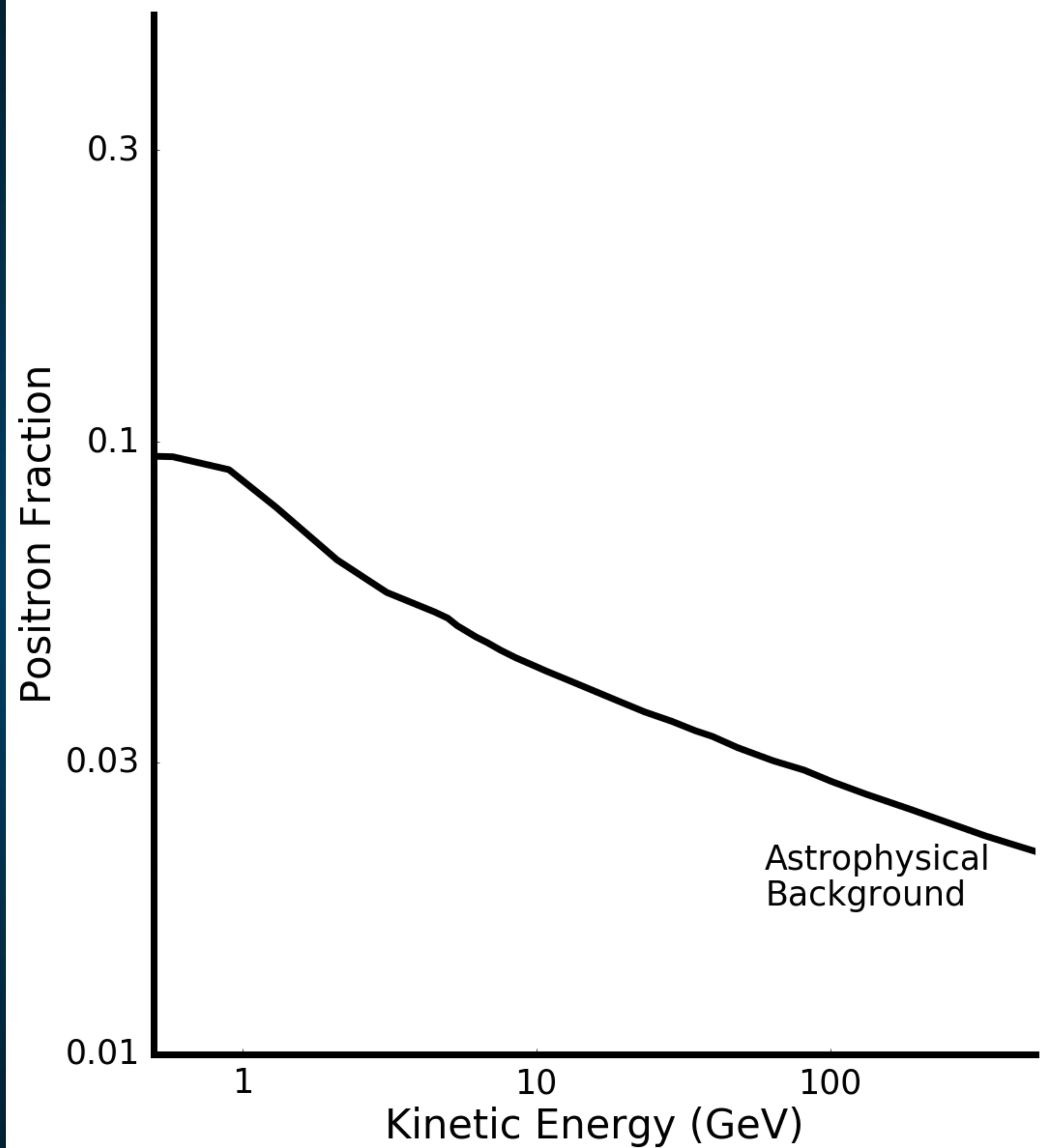
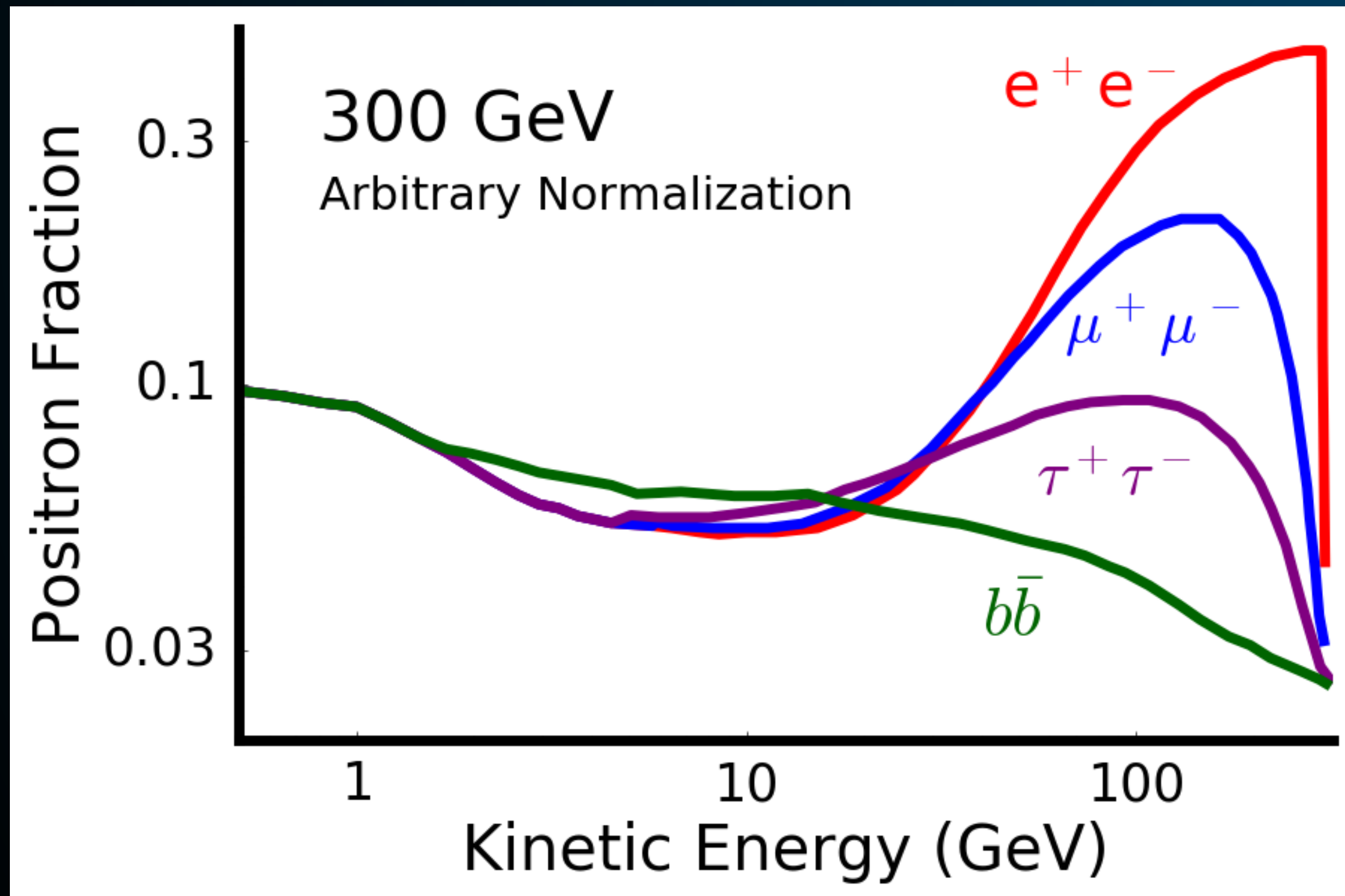
$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$



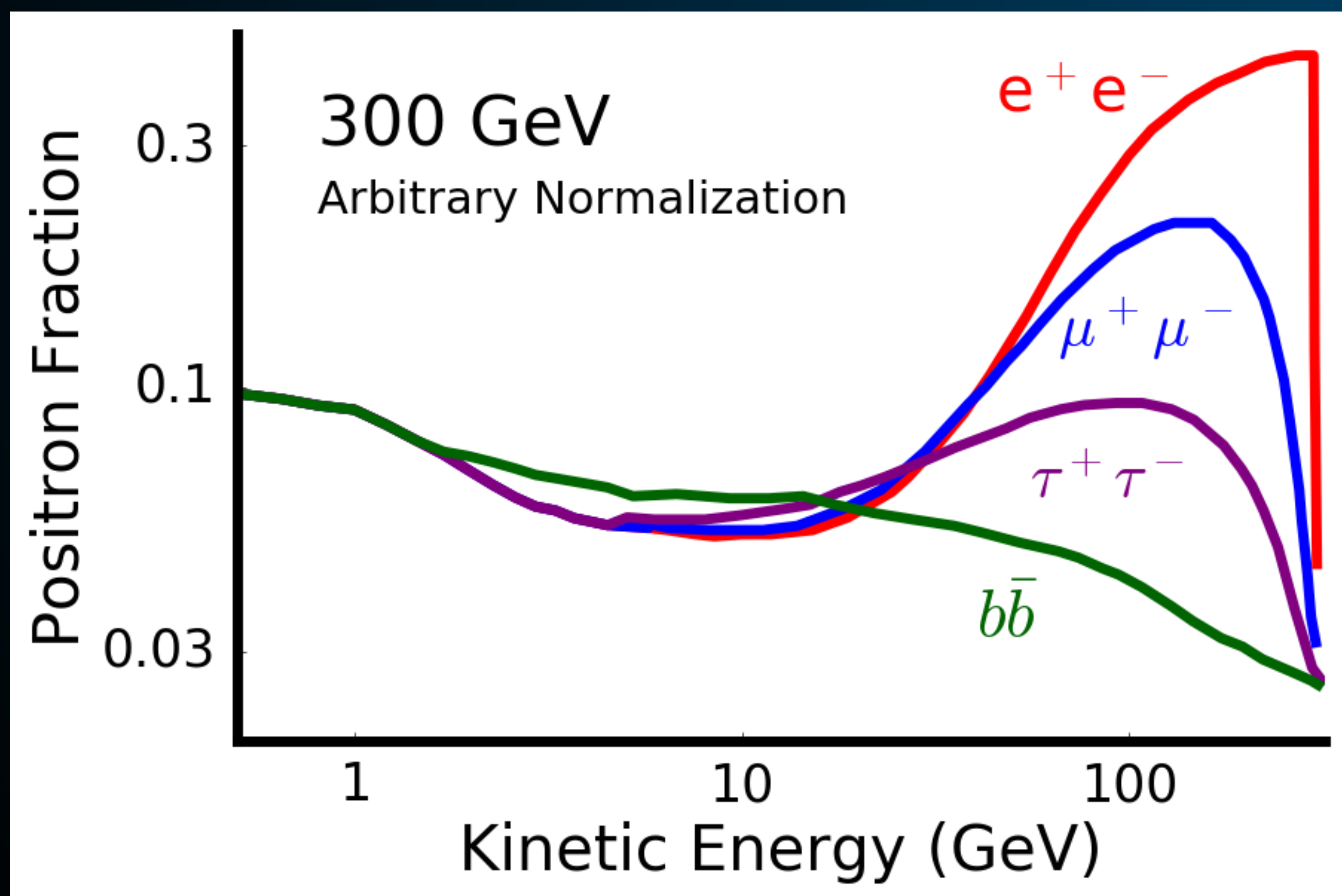
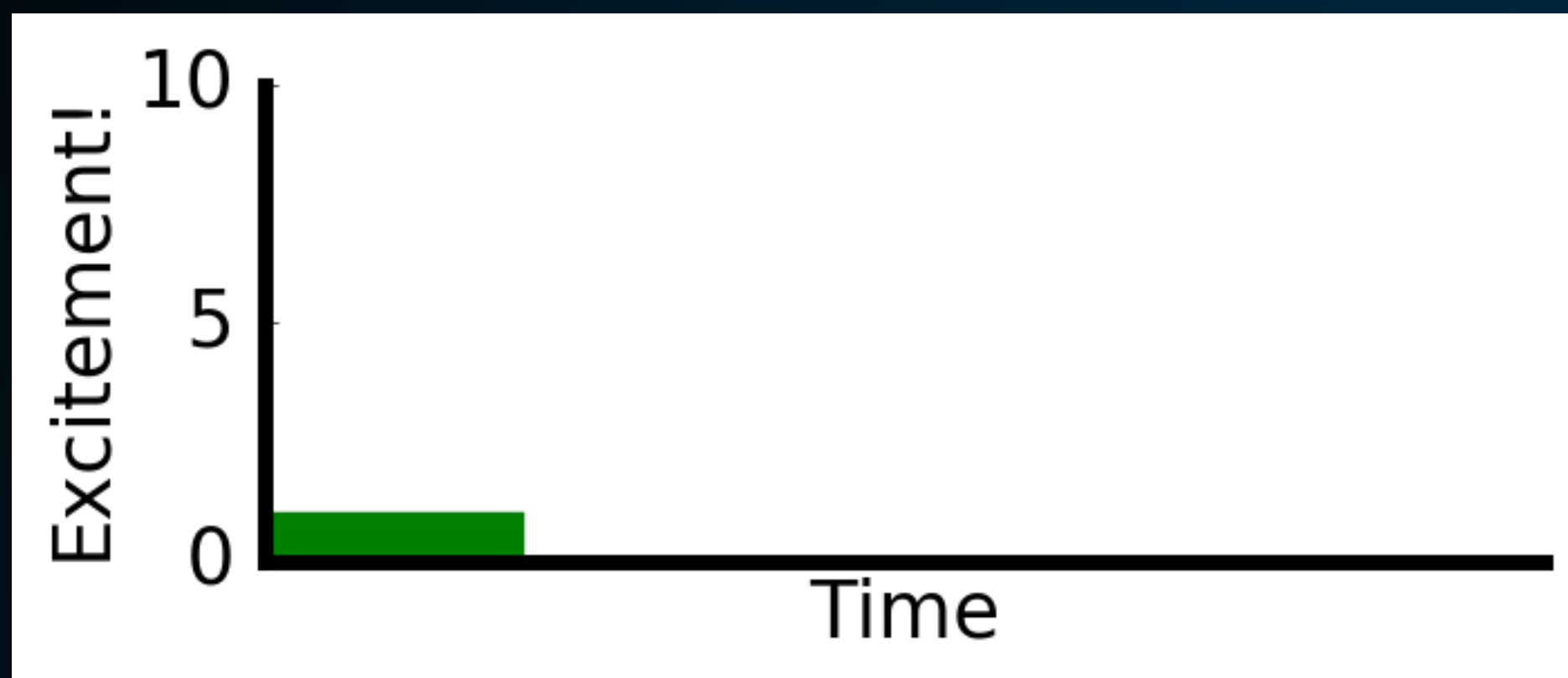
The Positron Excess

Astrophysics - Slowly Decreasing

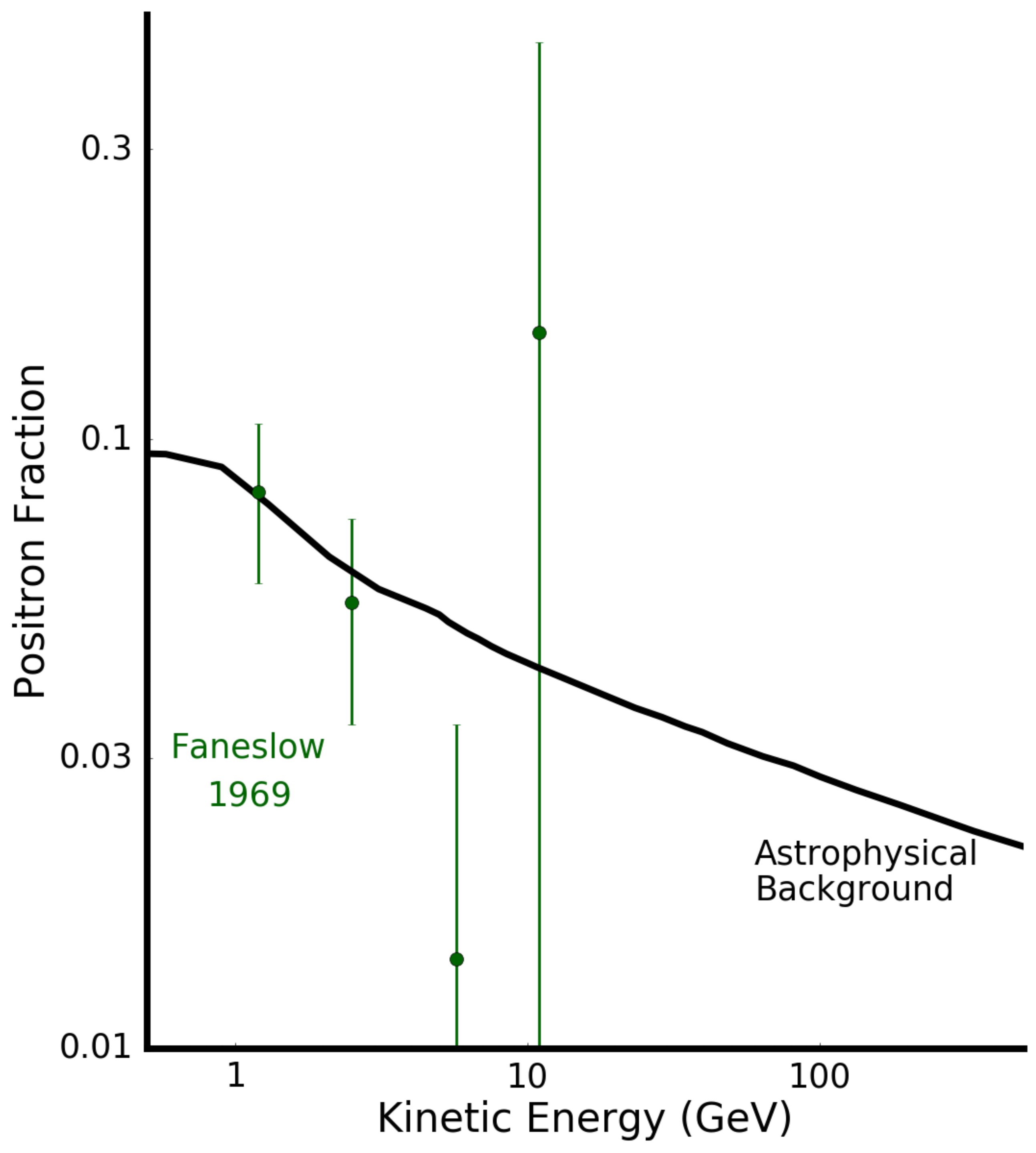
Dark Matter - Sharp Bump!



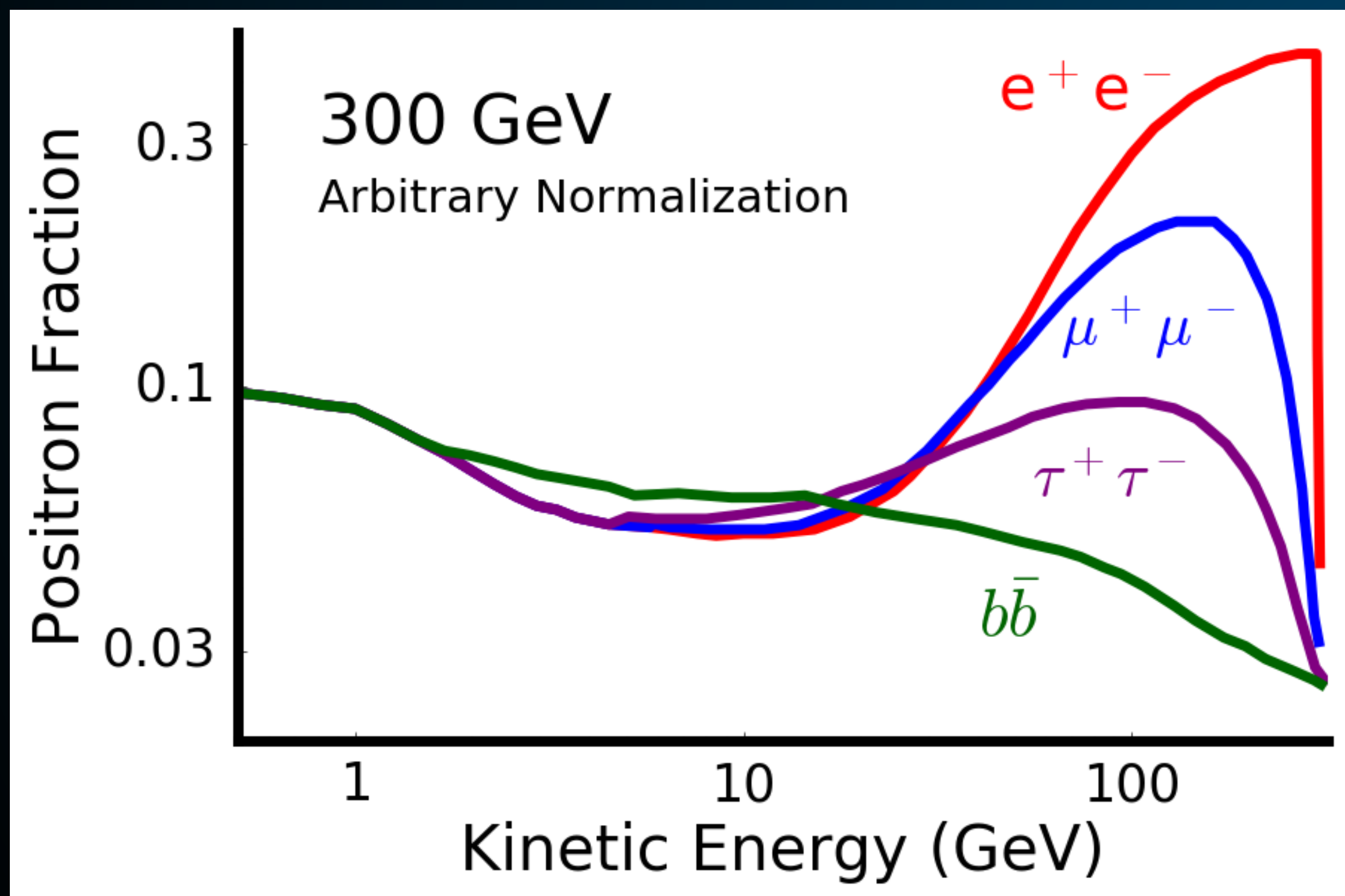
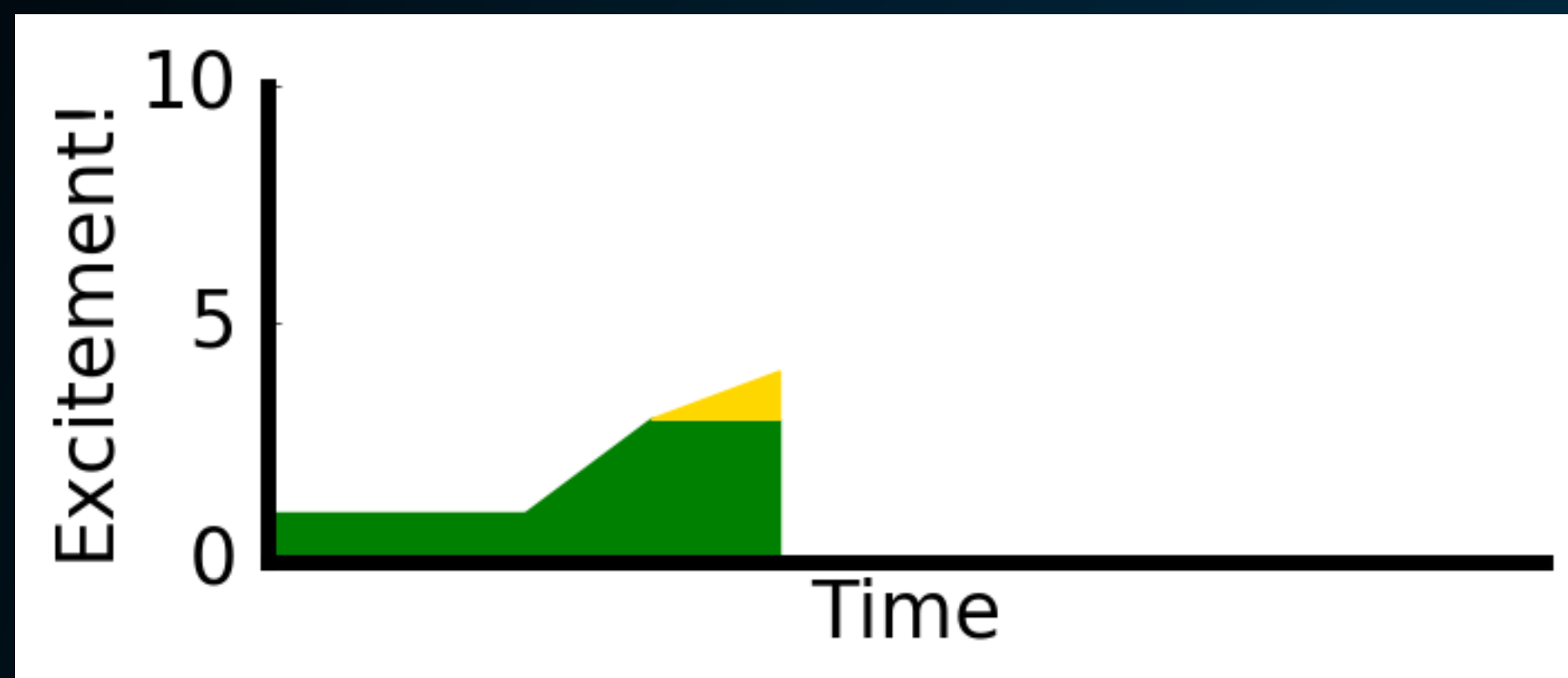
The Positron Excess



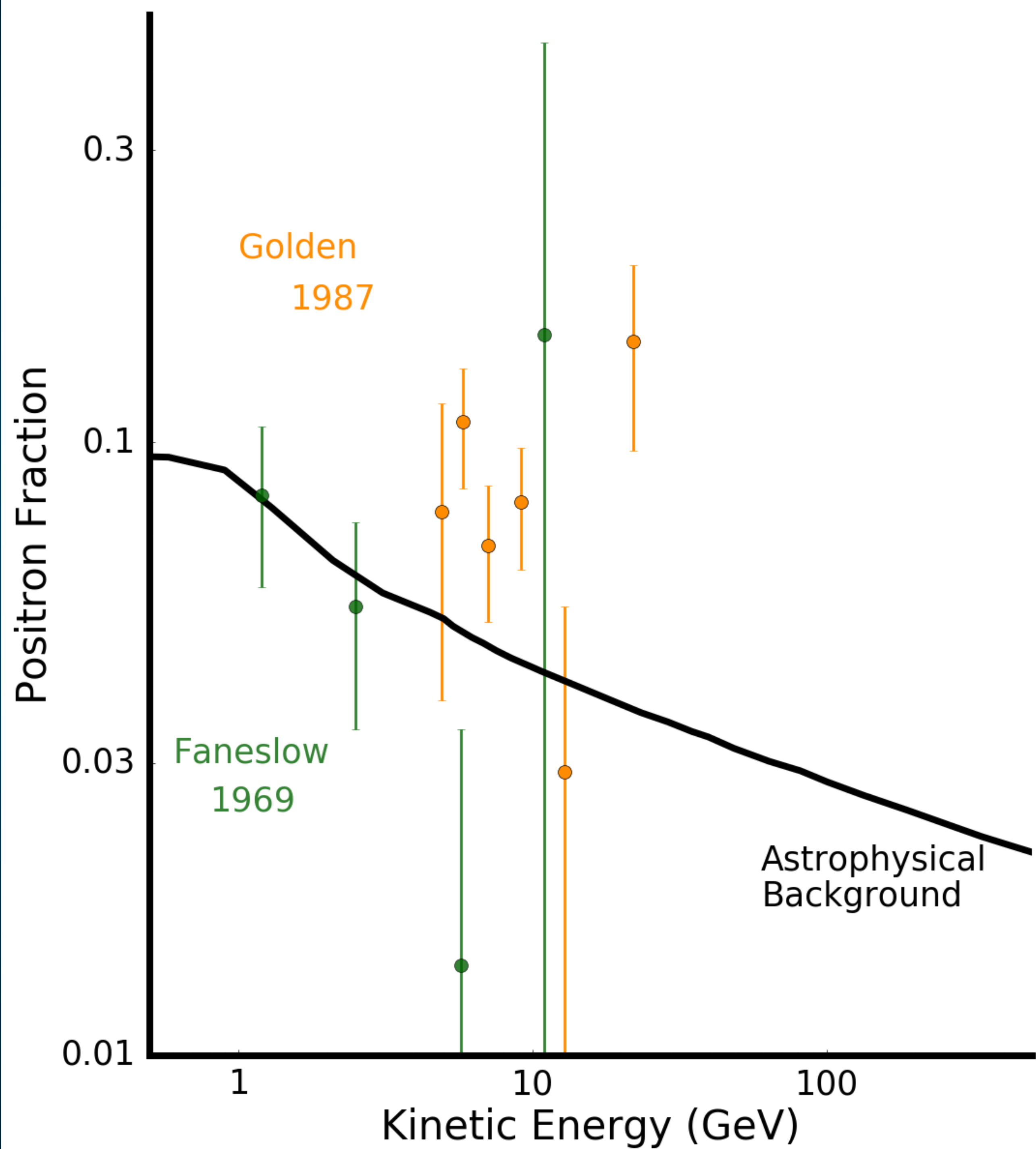
(Not an exhaustive list of observations)



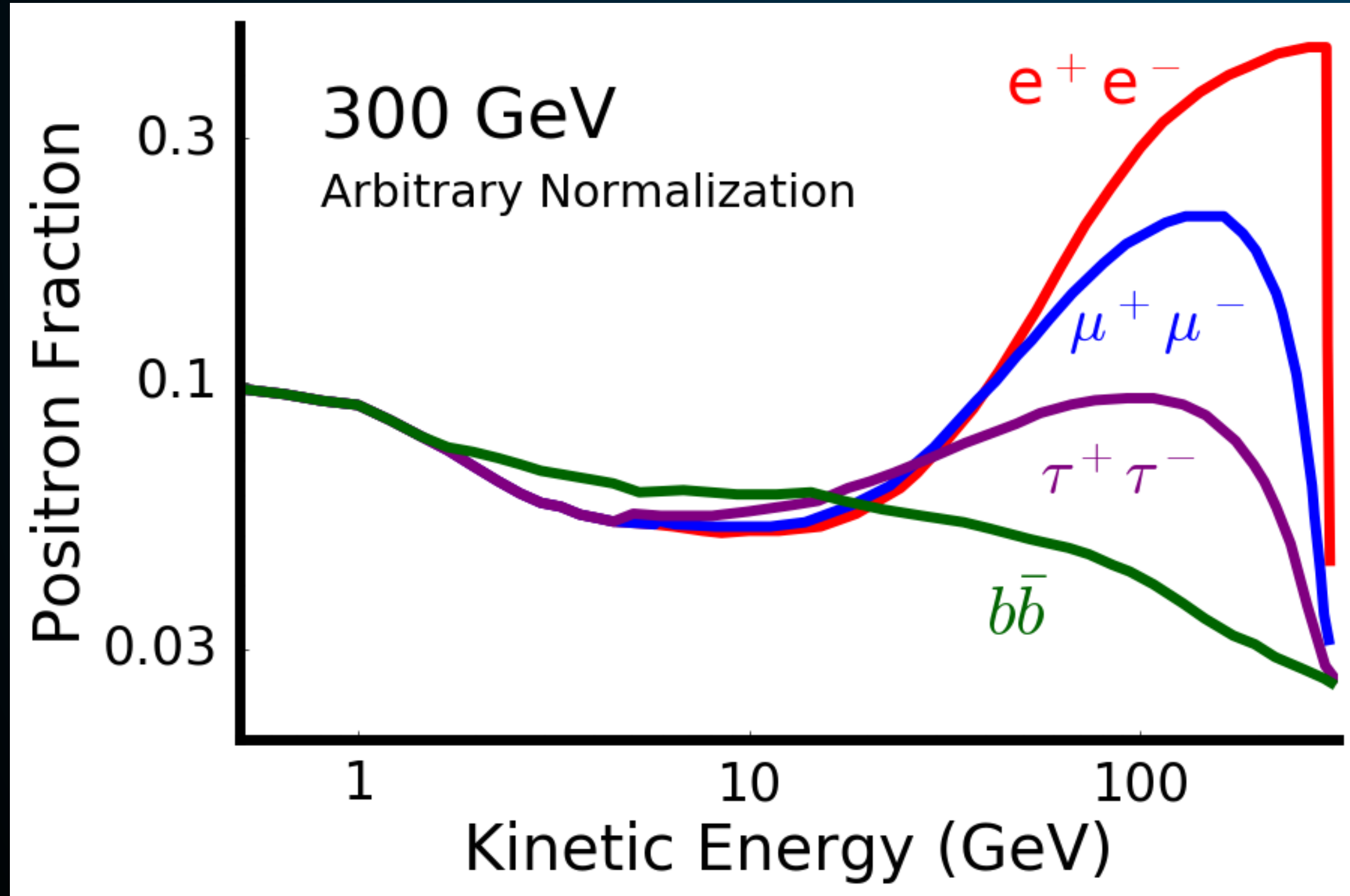
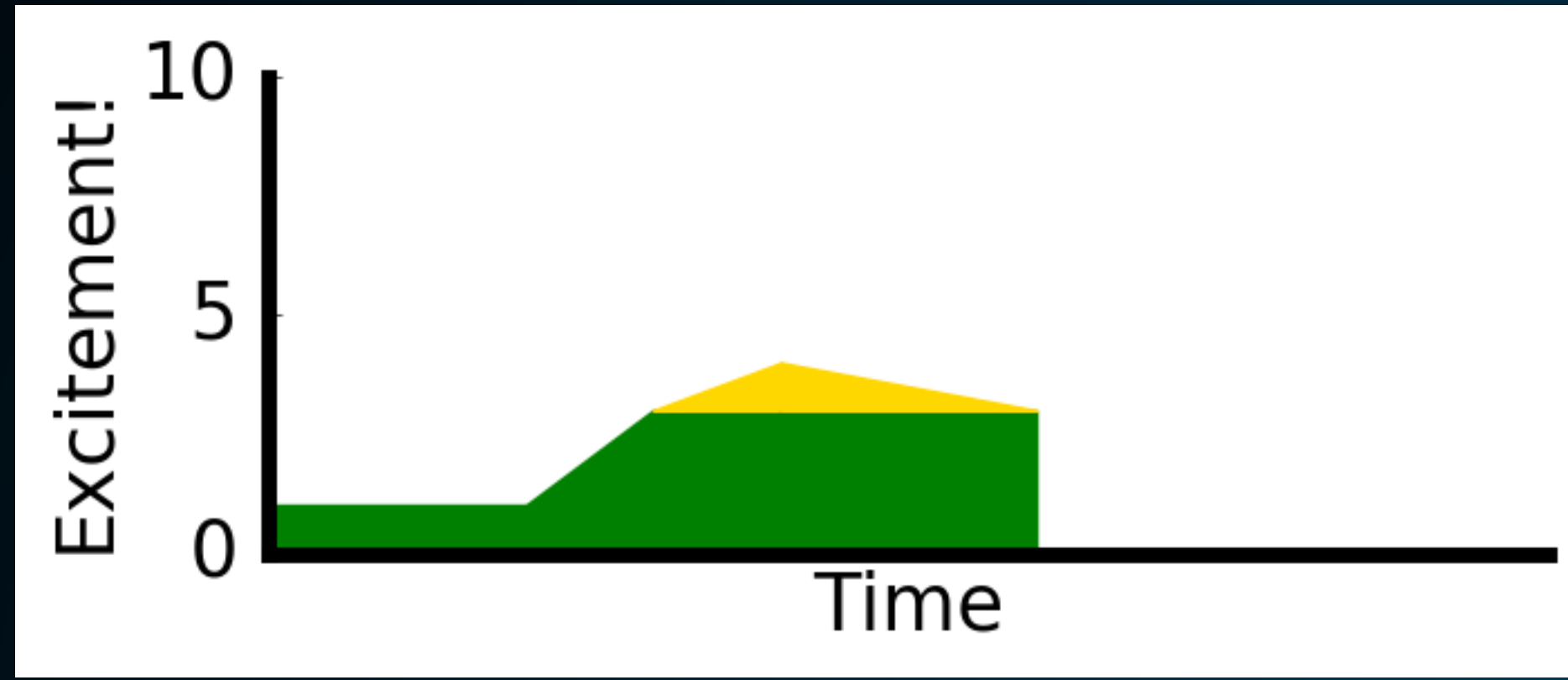
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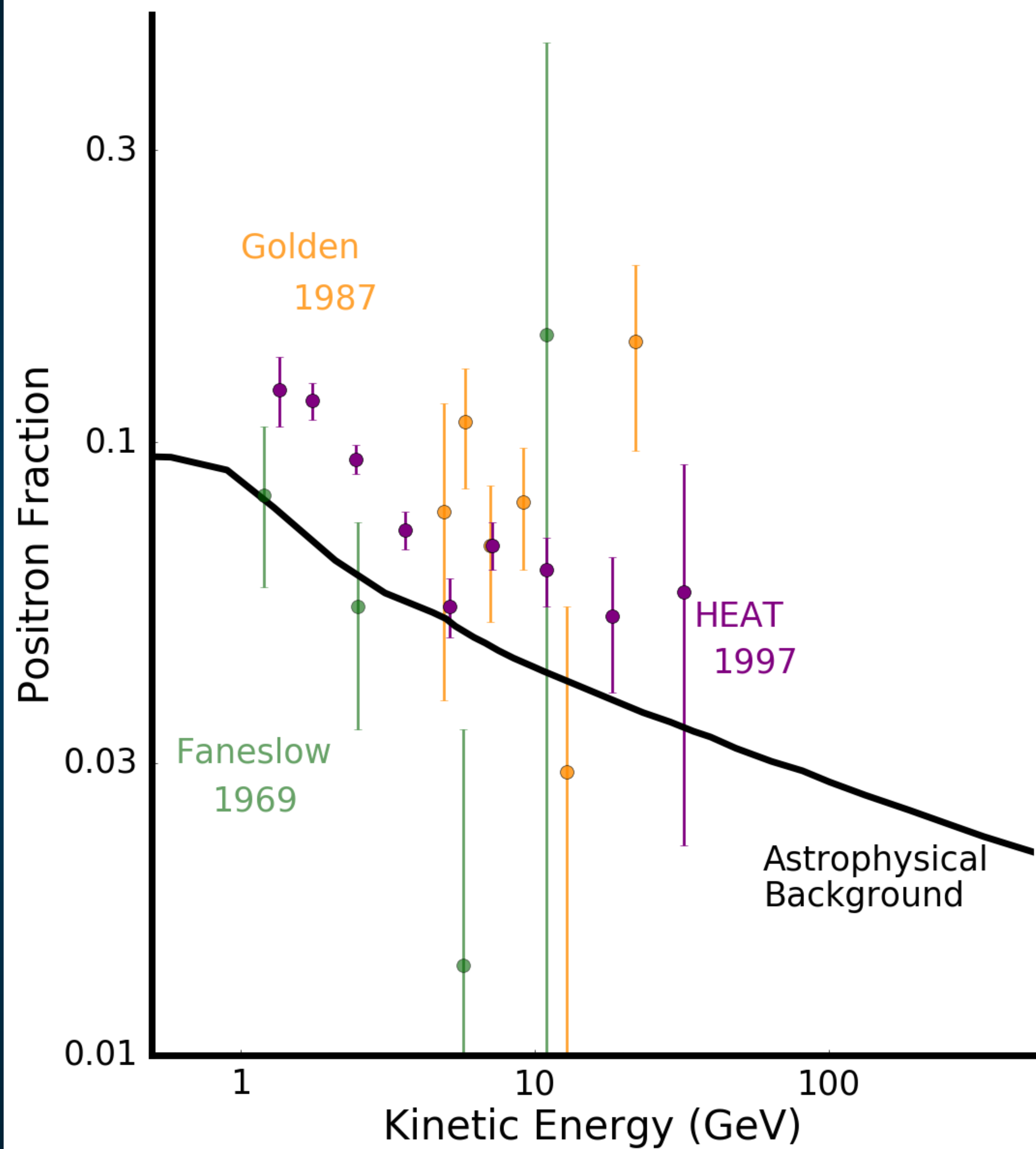
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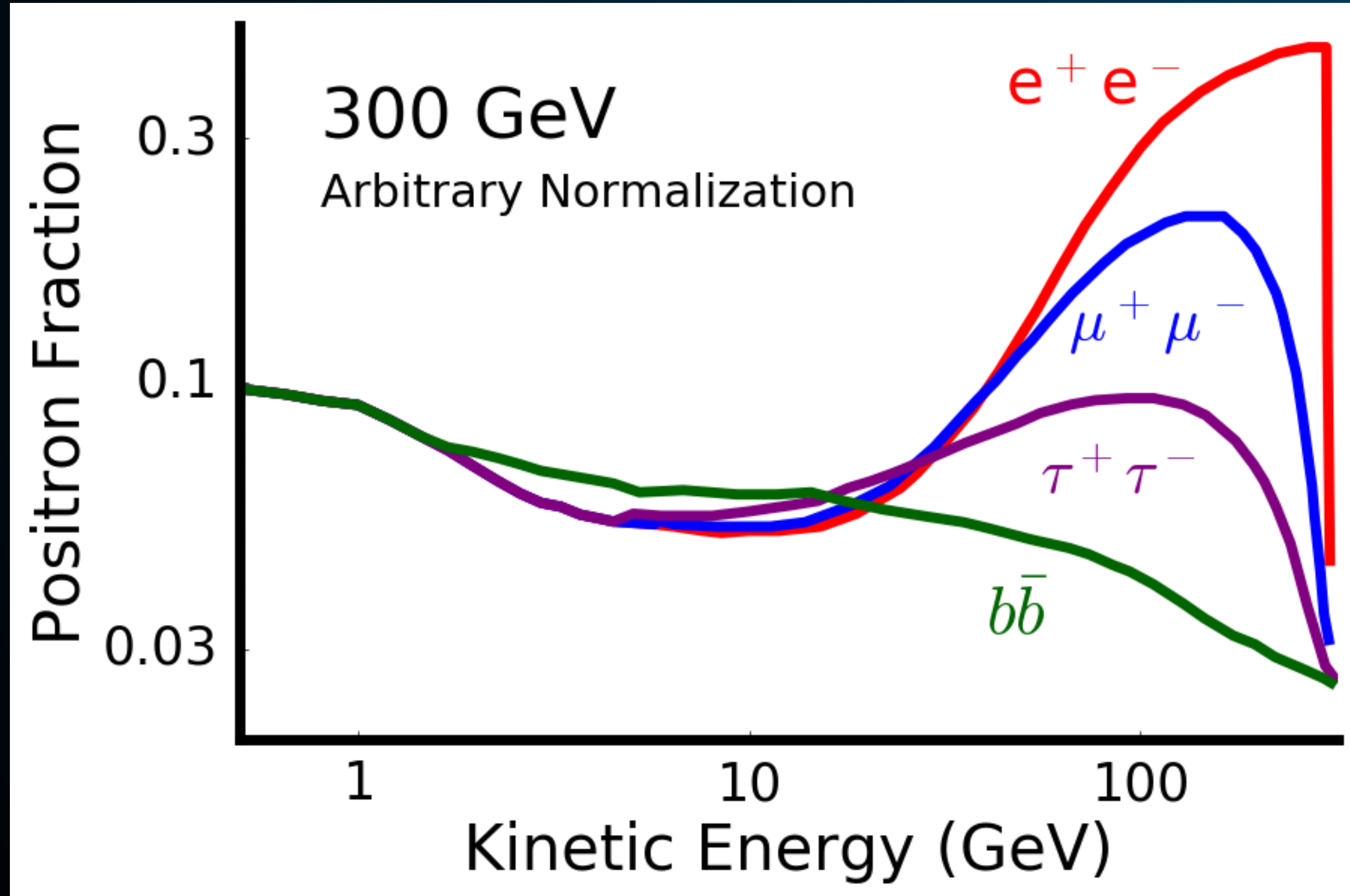
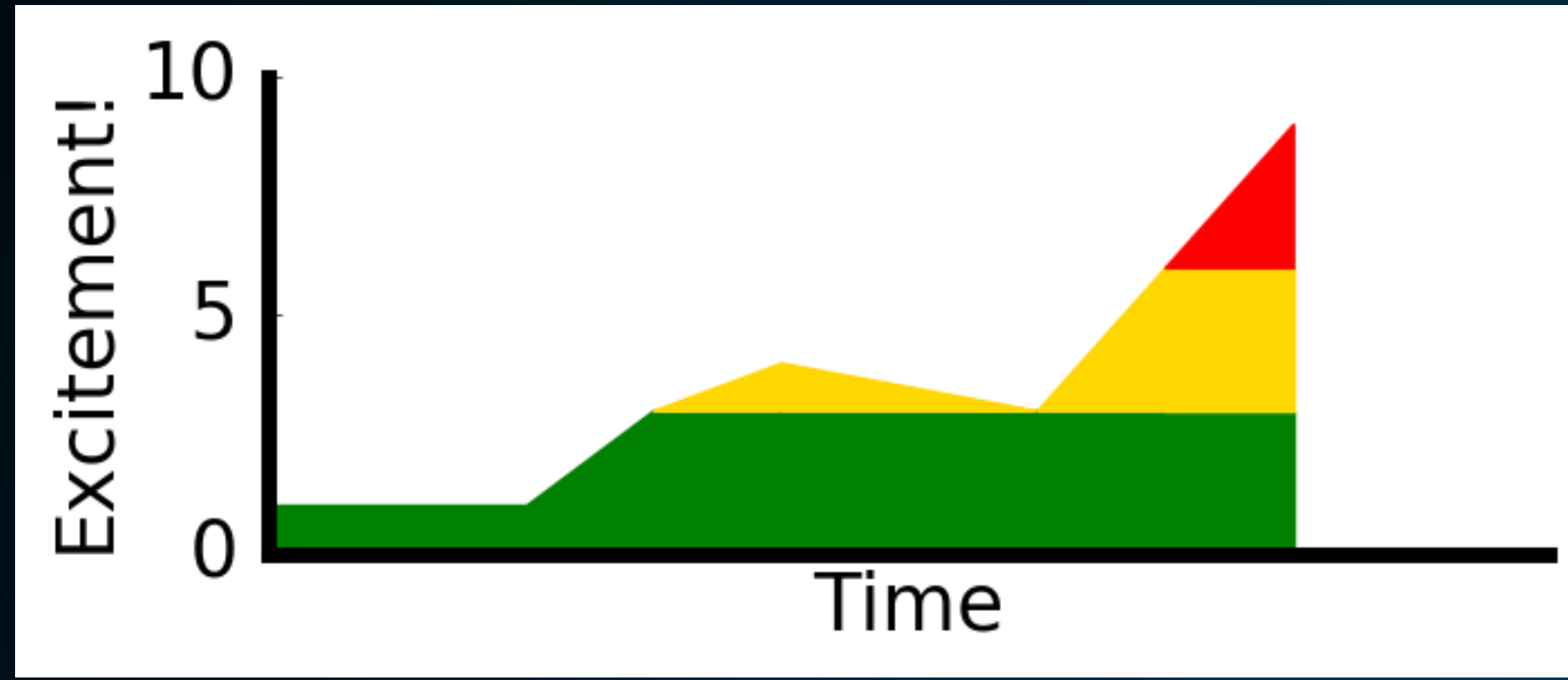
The Positron Excess



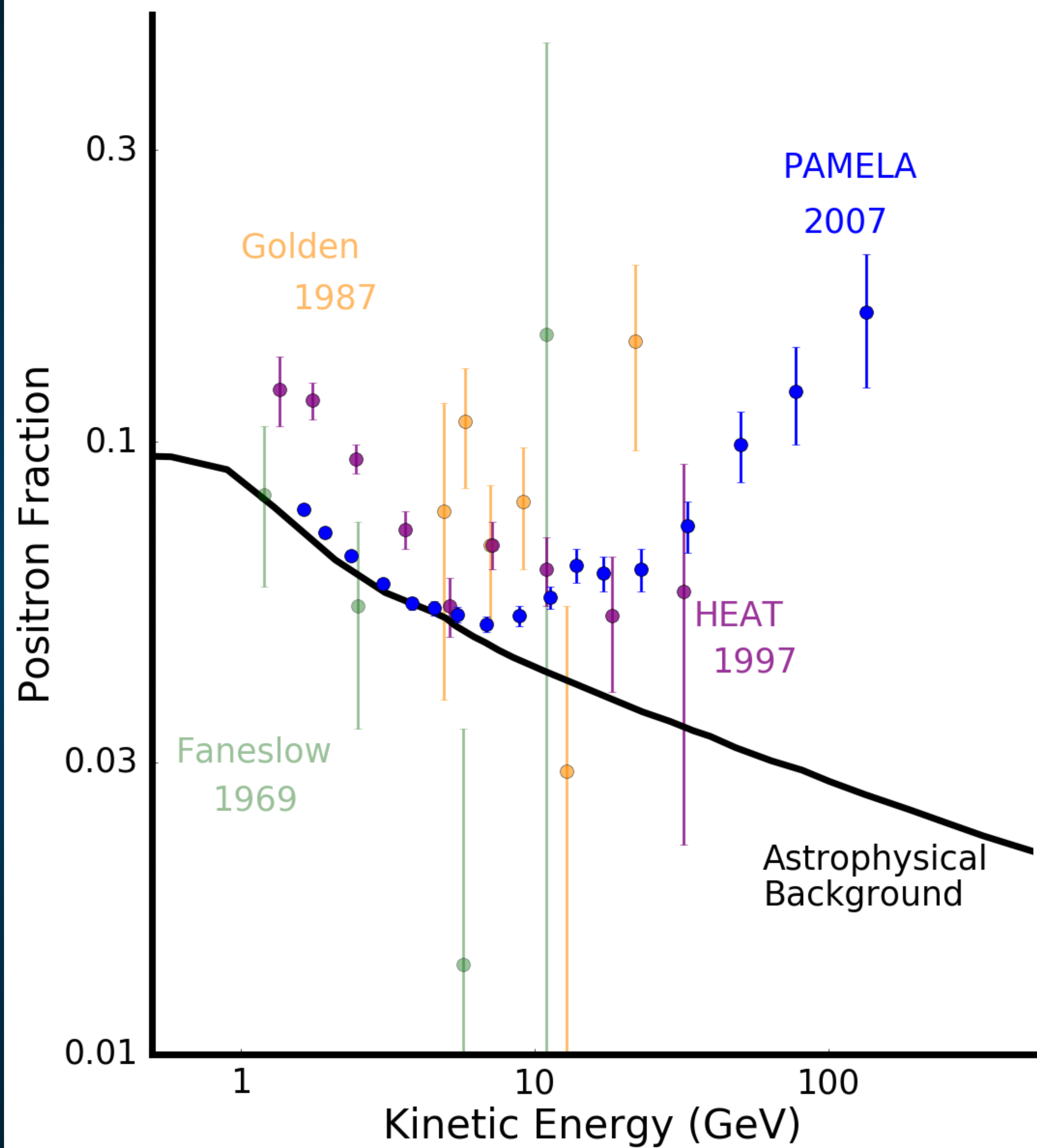
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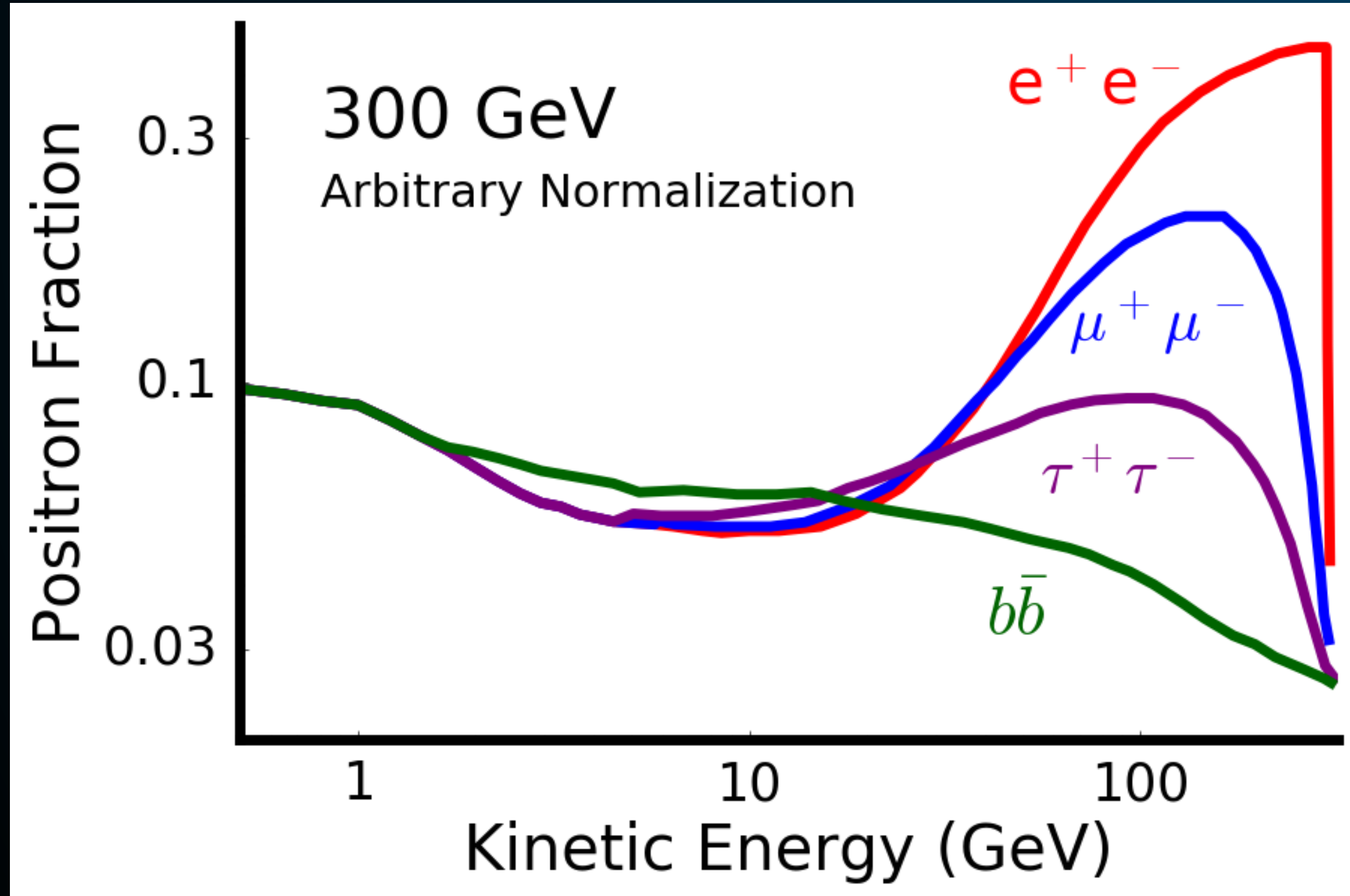
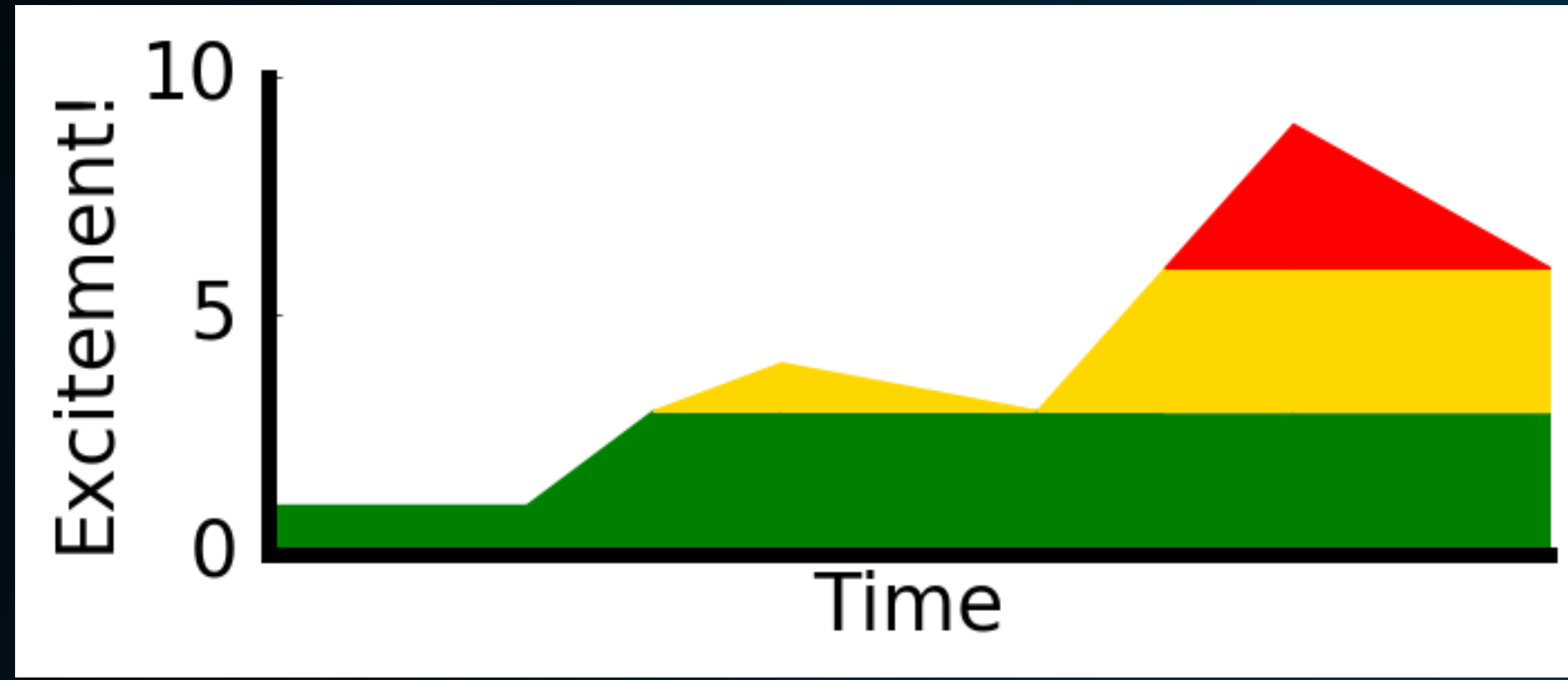
The Positron Excess



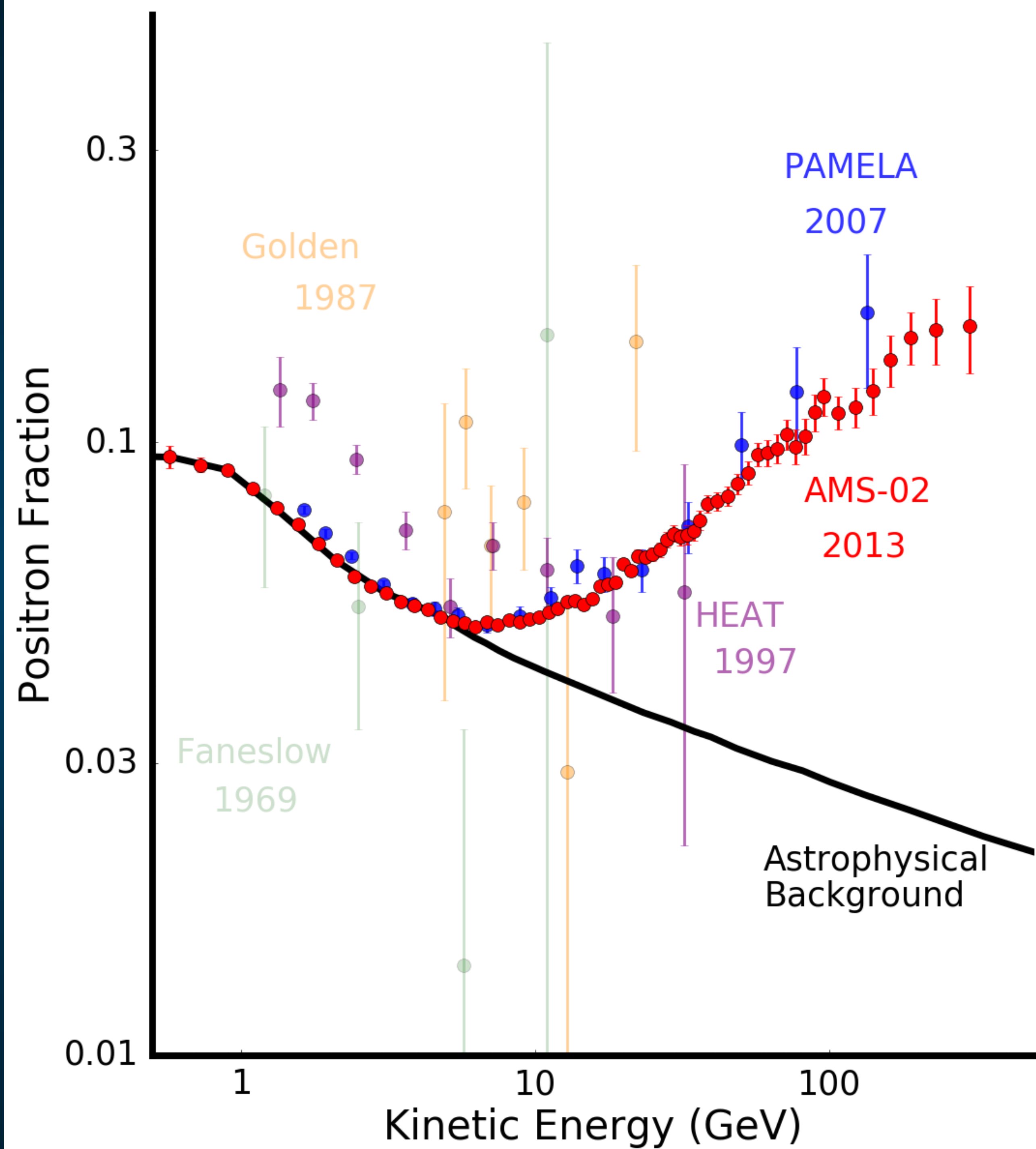
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The Positron Excess



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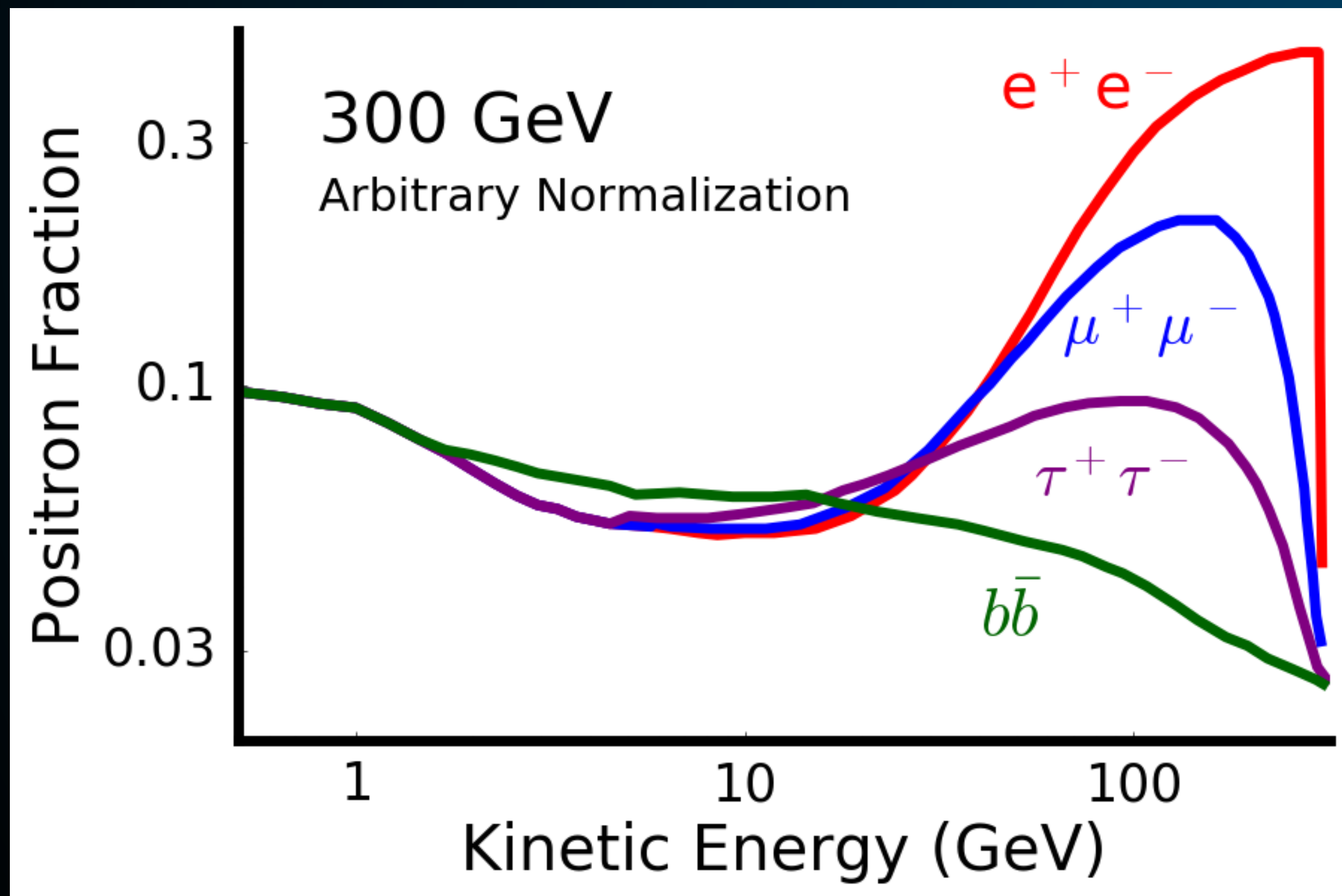


The Positron Excess

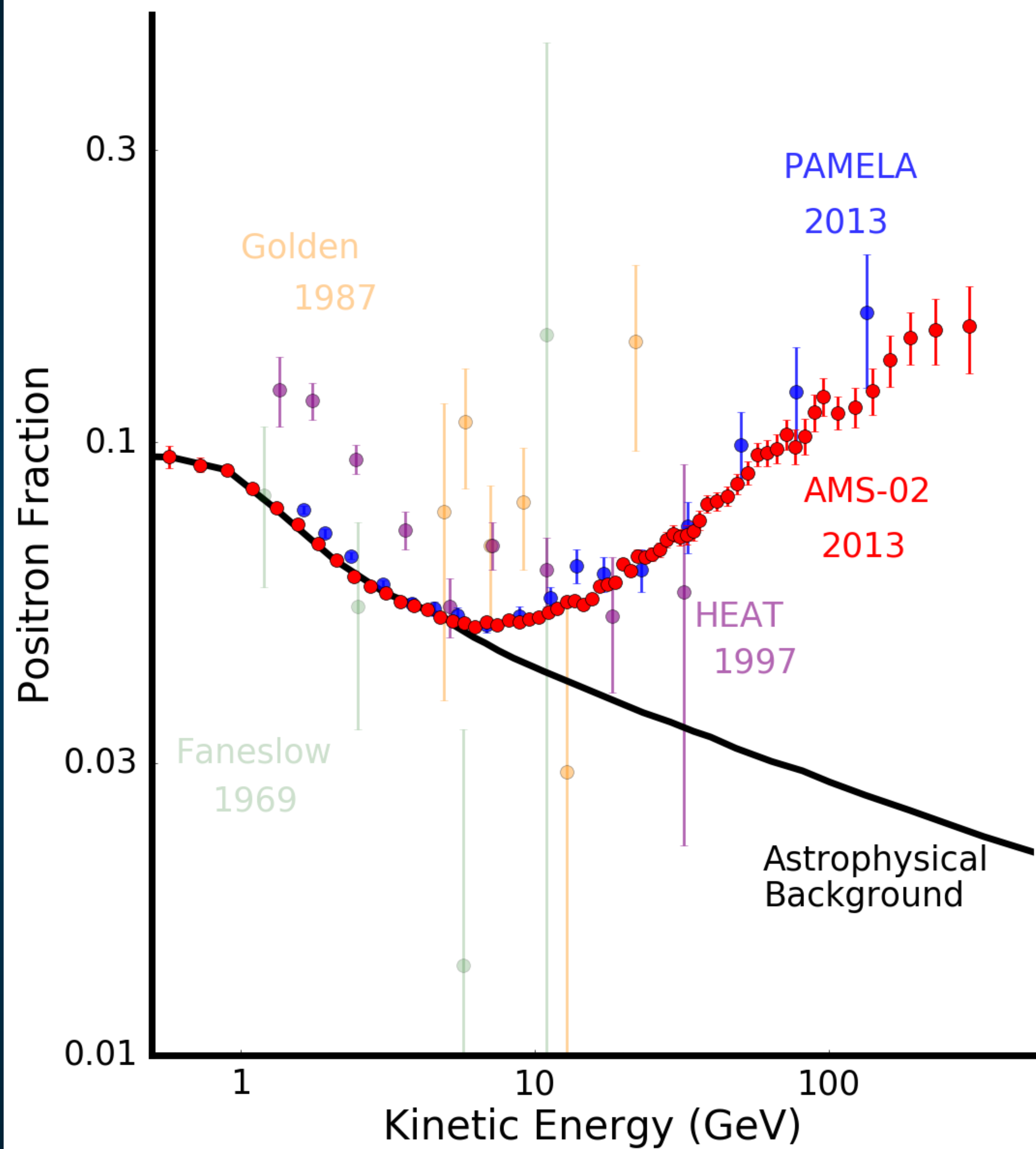
Why Less Excitement?

Continues to Higher Mass

Spectrum Relatively Smooth



(Not an exhaustive list of observations)

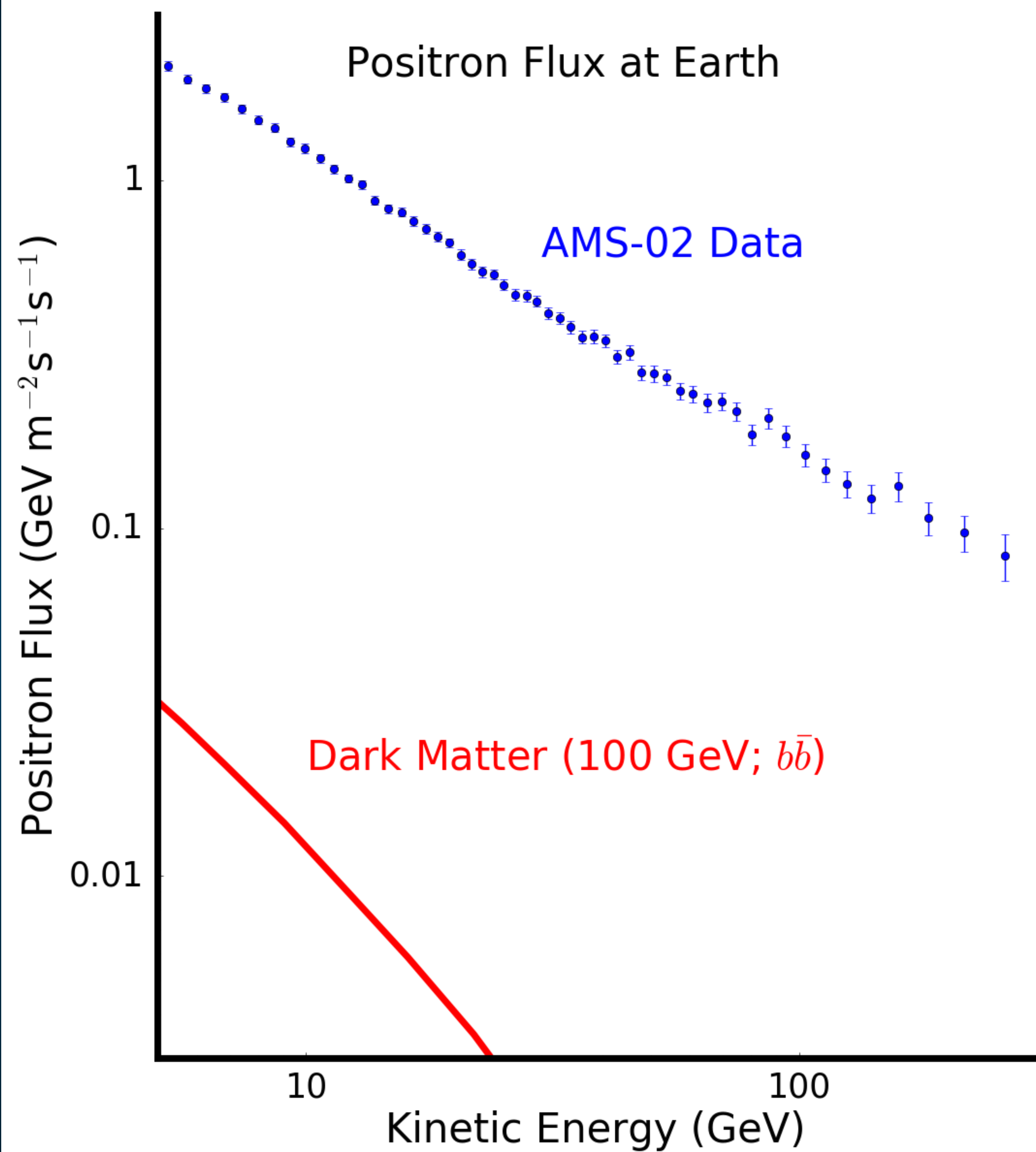
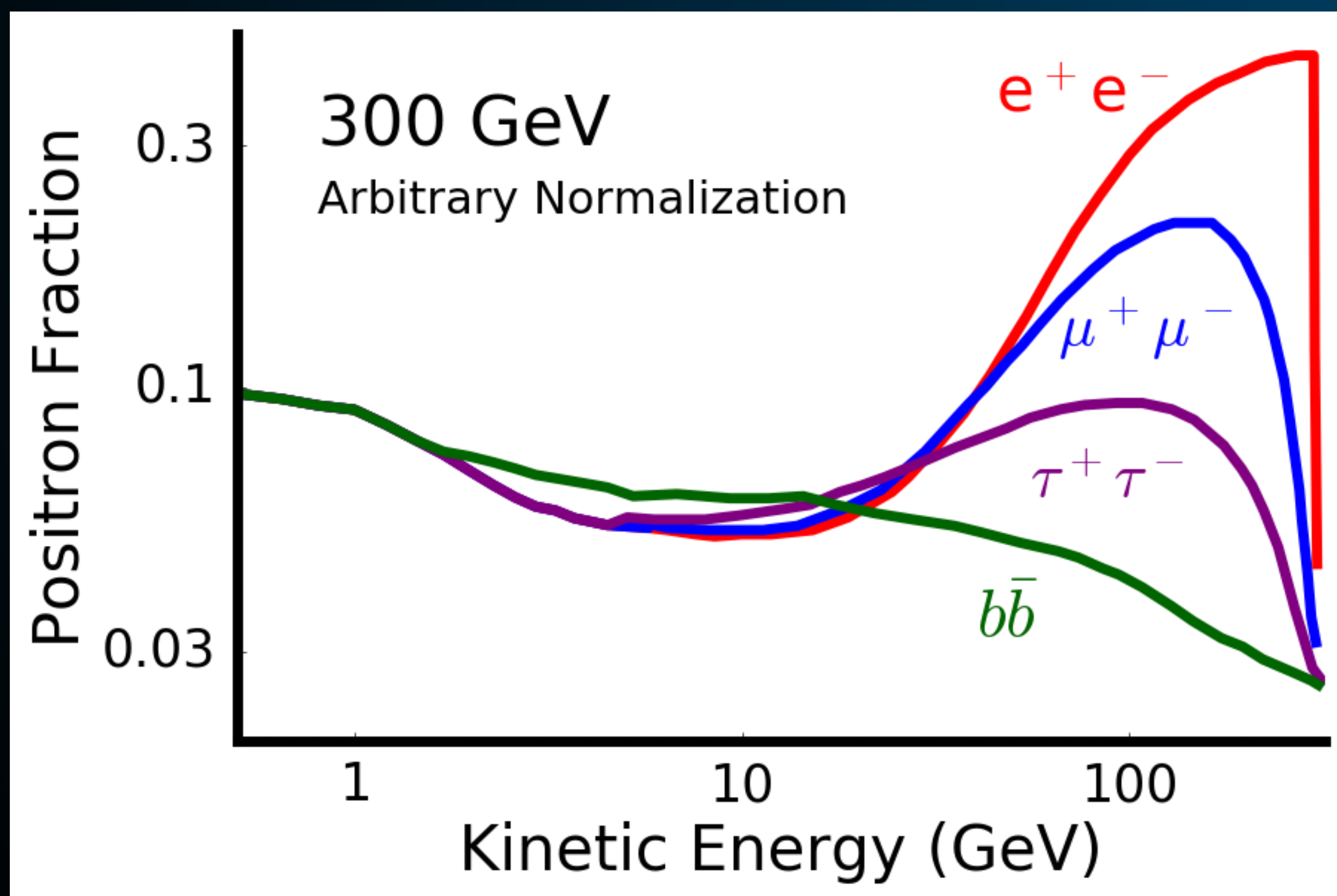


The Positron Excess

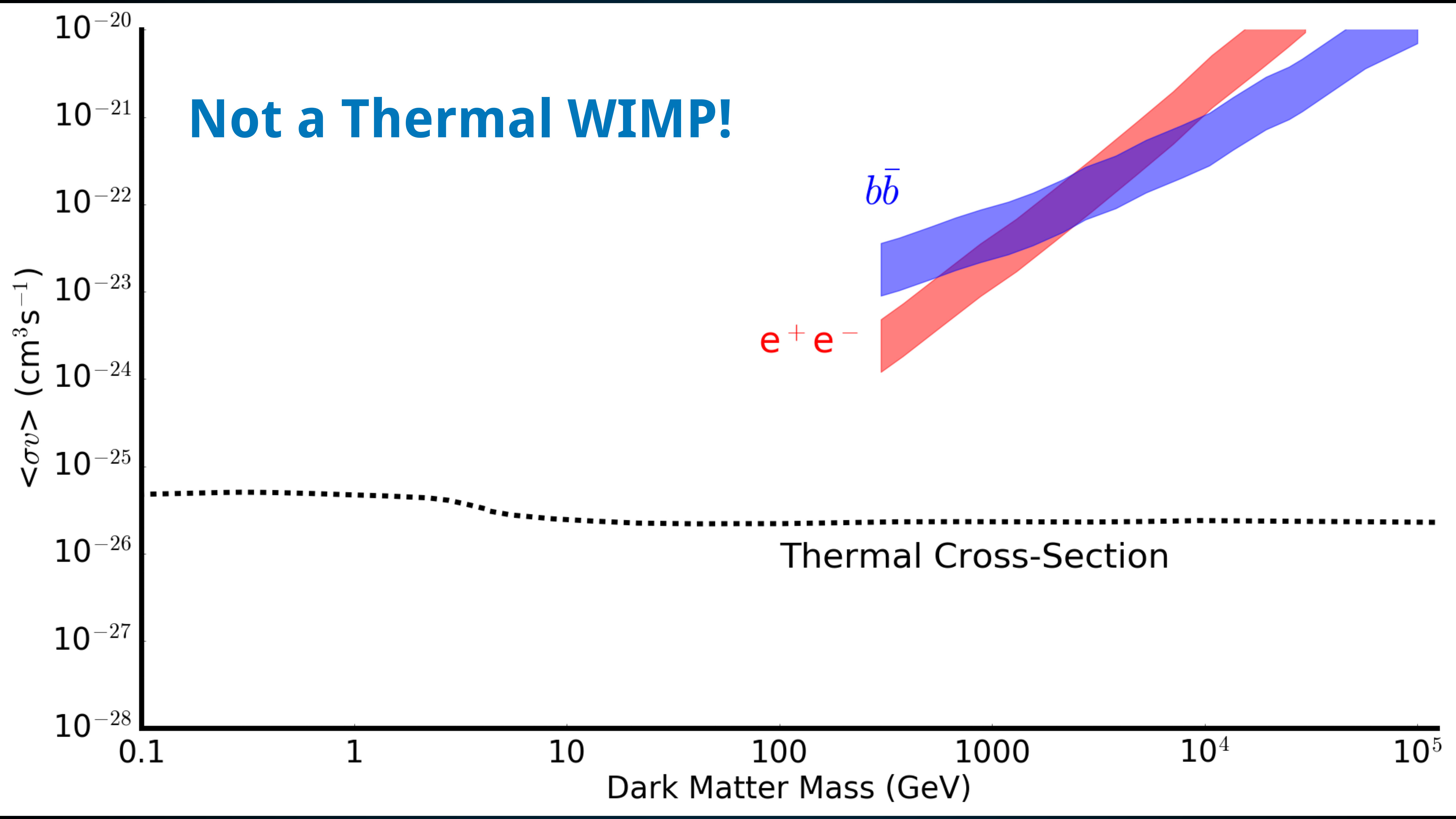
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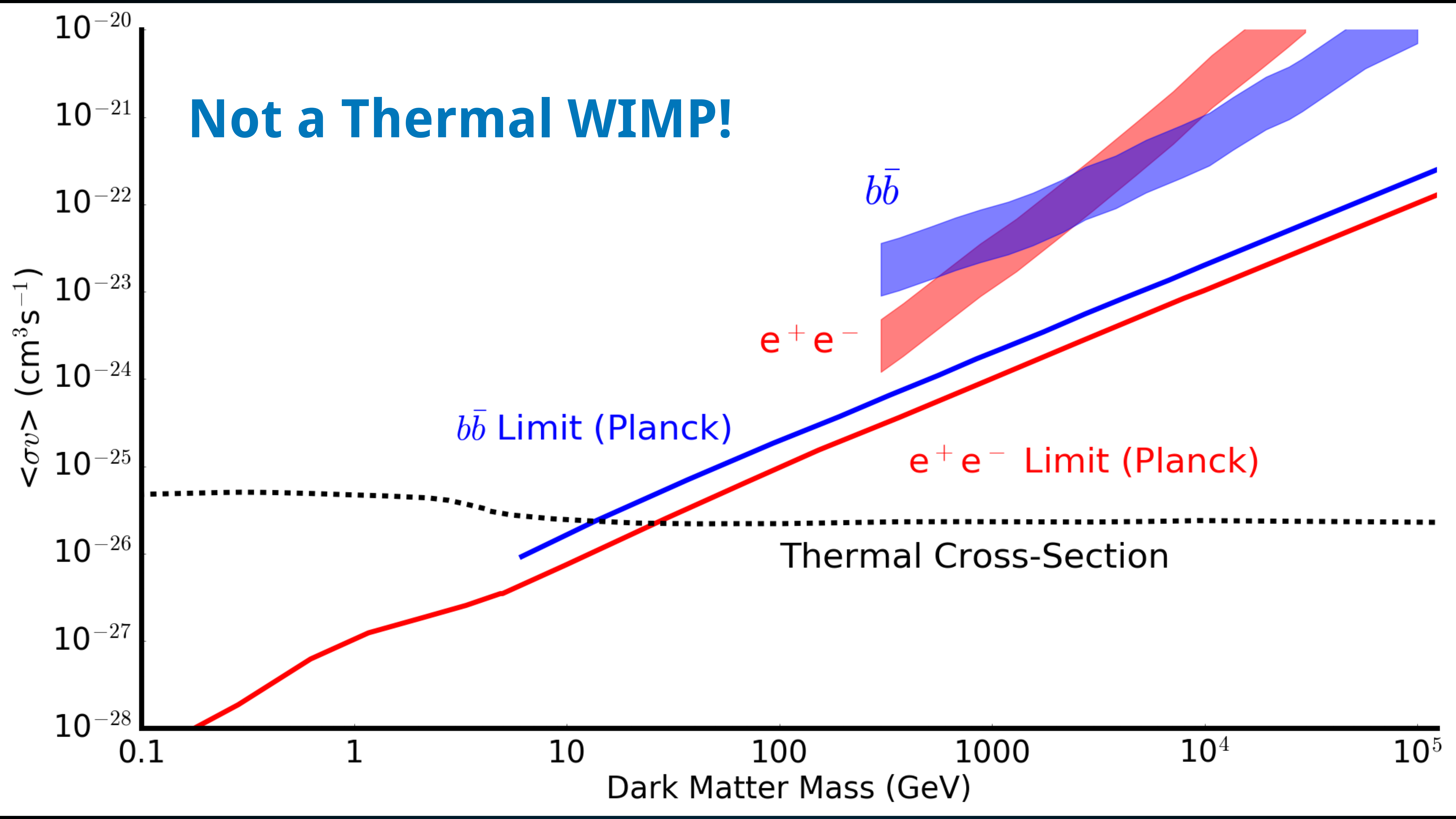
Spectrum Relatively Smooth

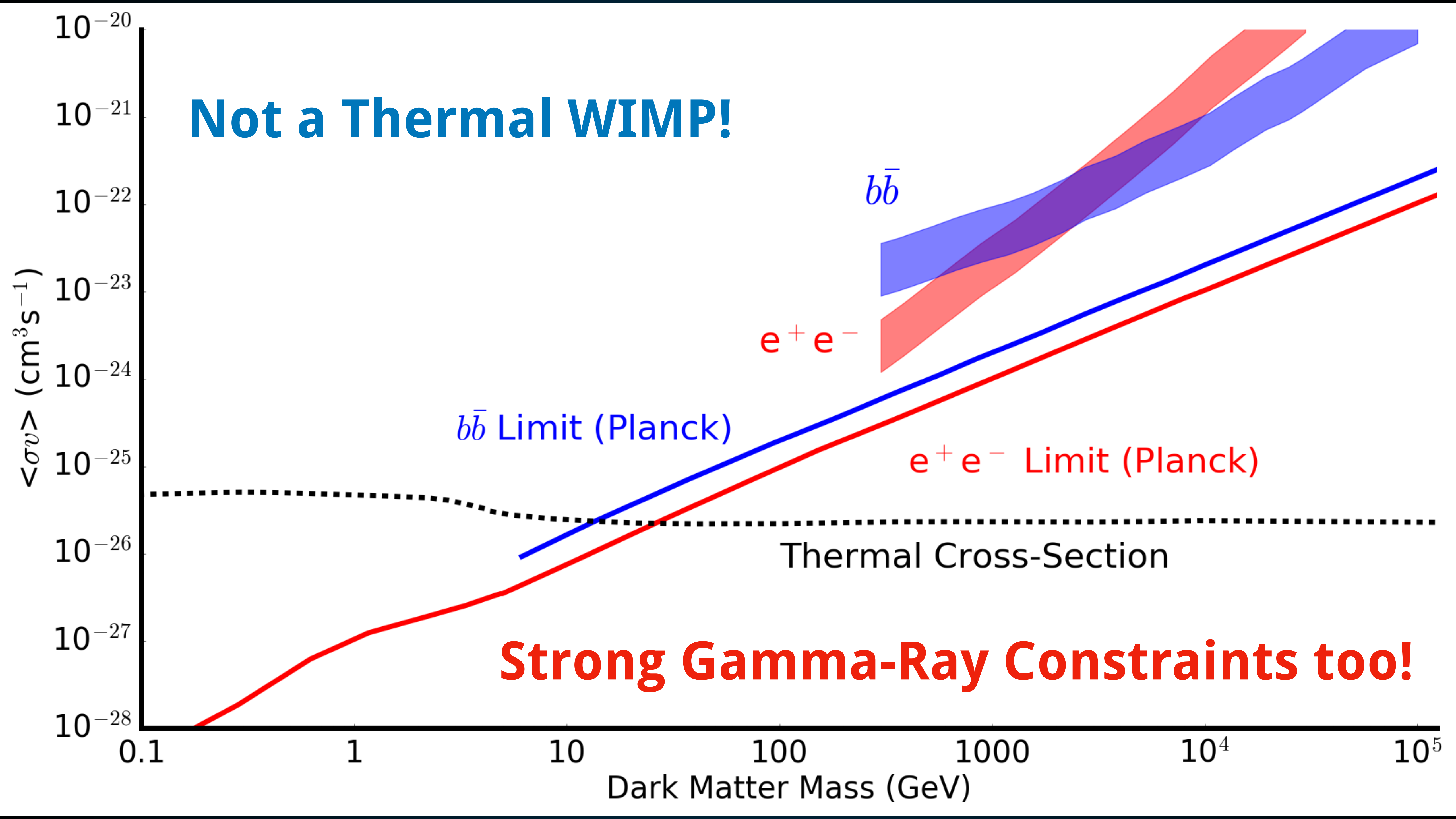


Not a Thermal WIMP!



Not a Thermal WIMP!



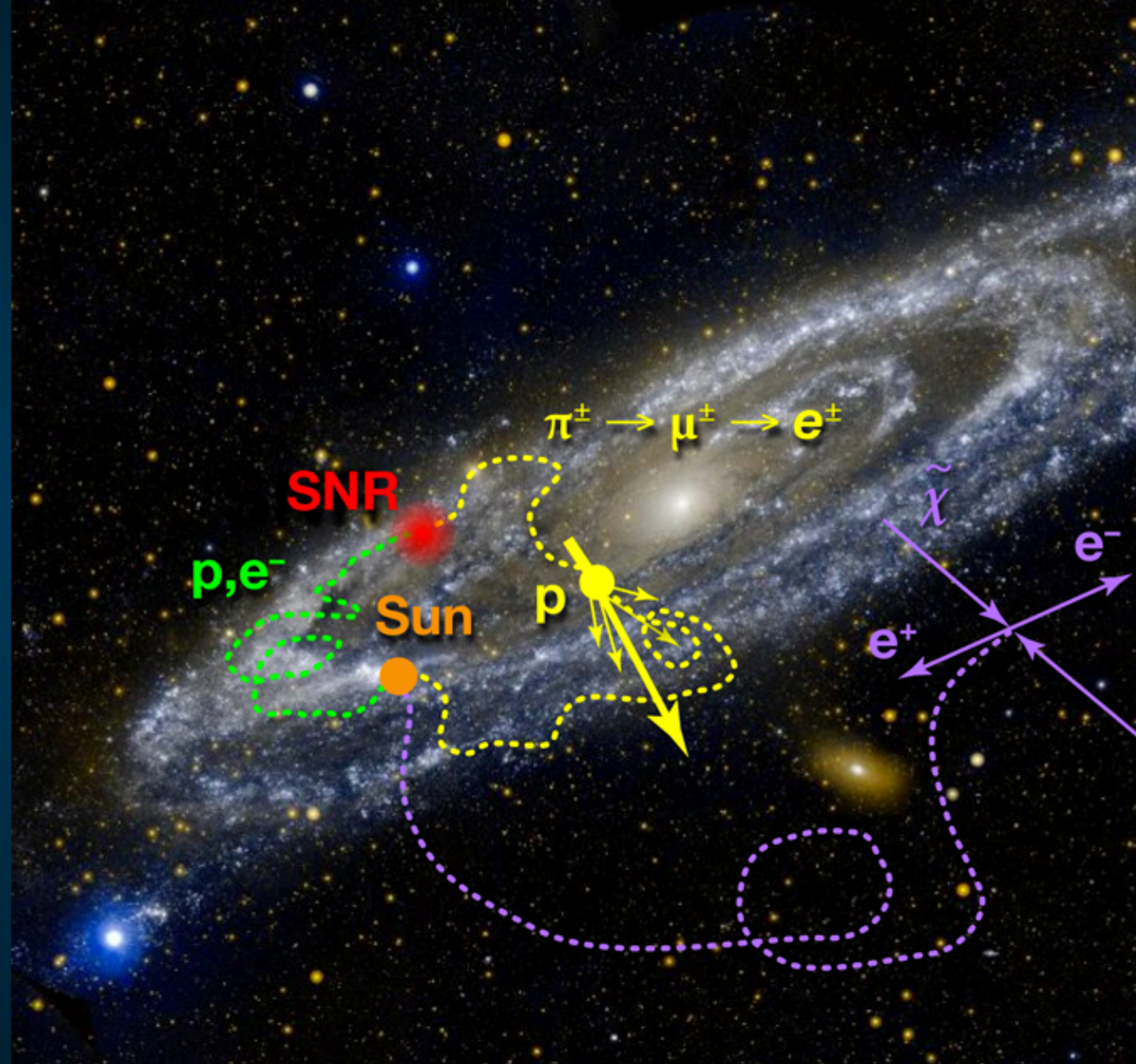
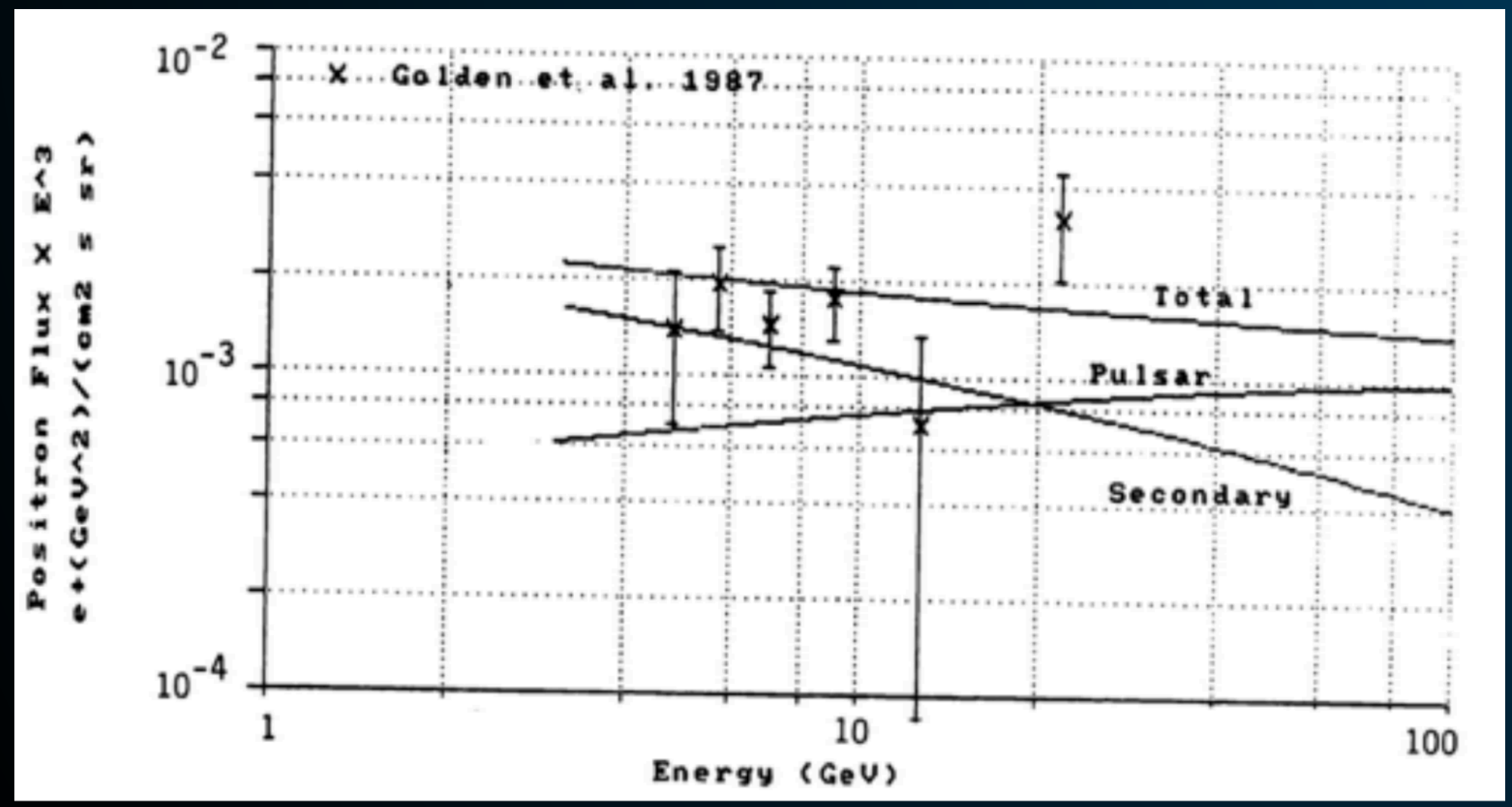


The Positron Excess

Key Idea: Investigate the Positron Fraction!

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

Harding & Ramaty (ICRC! 1987)



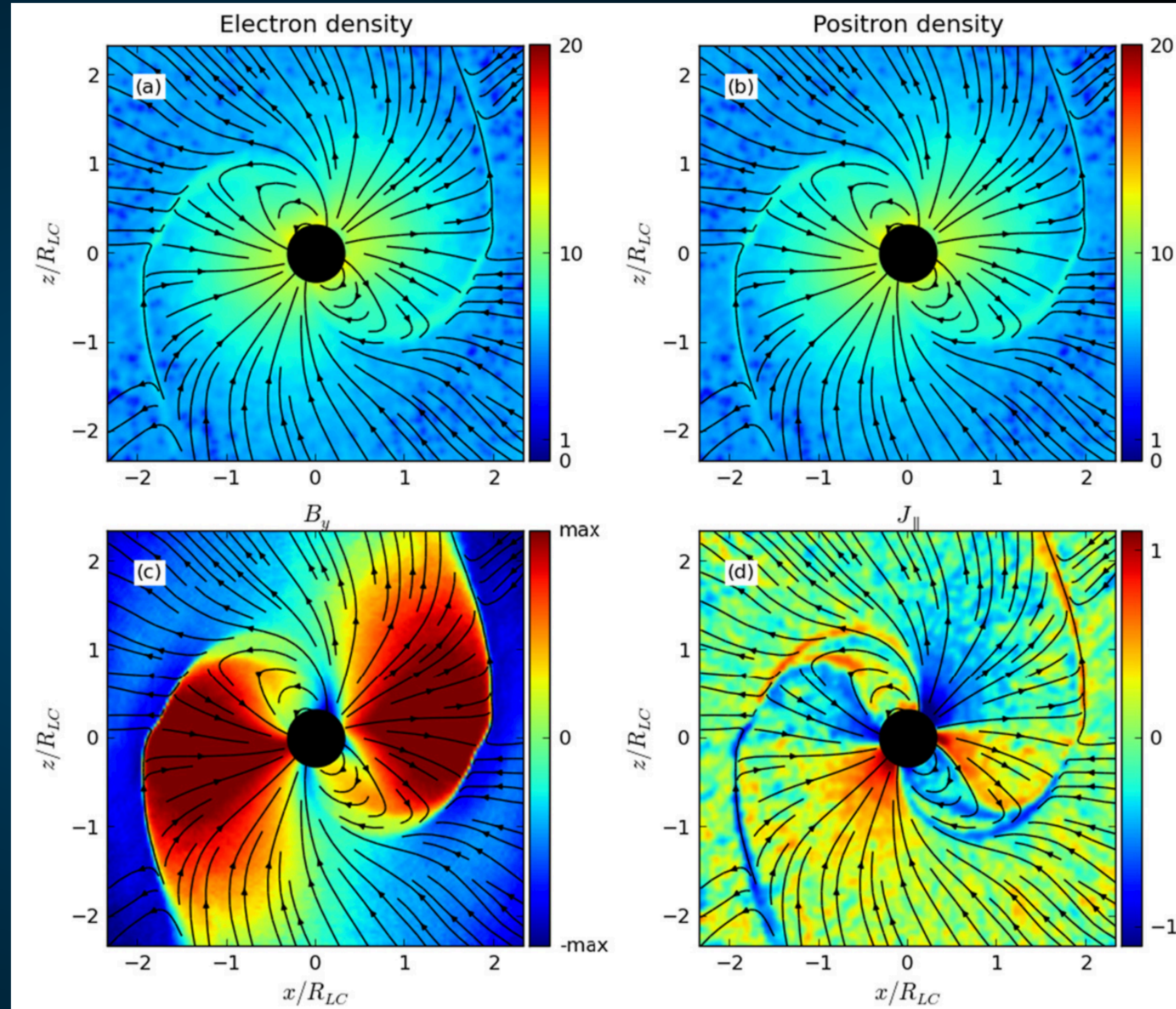
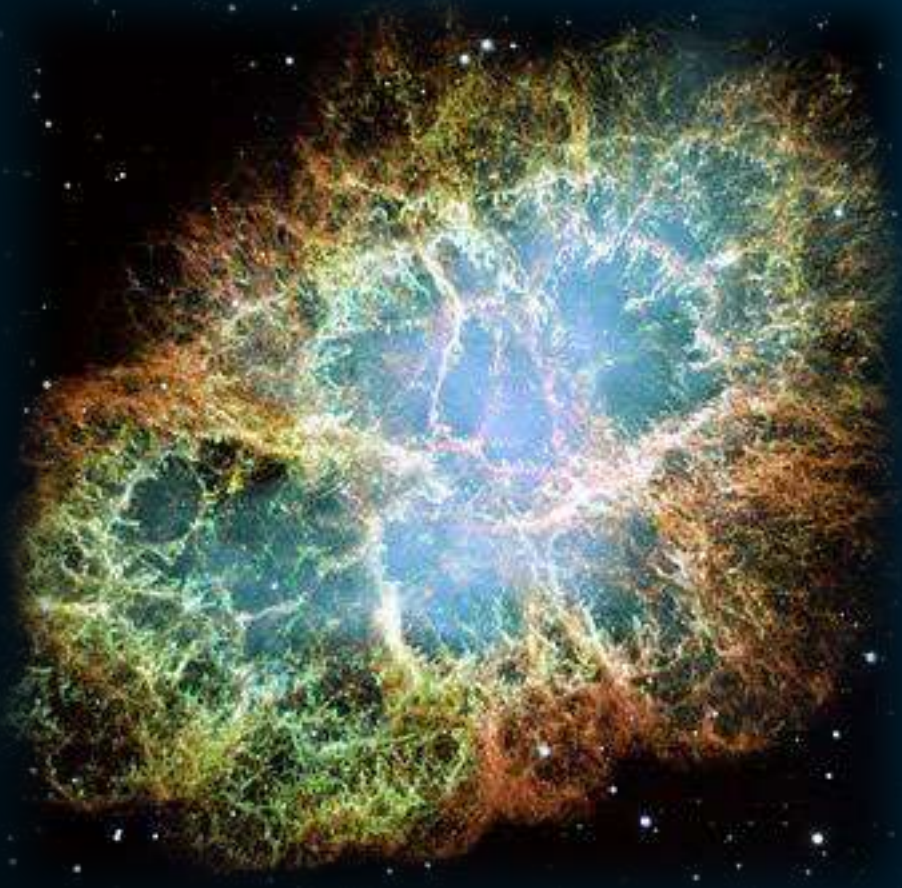
The Positron Excess

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

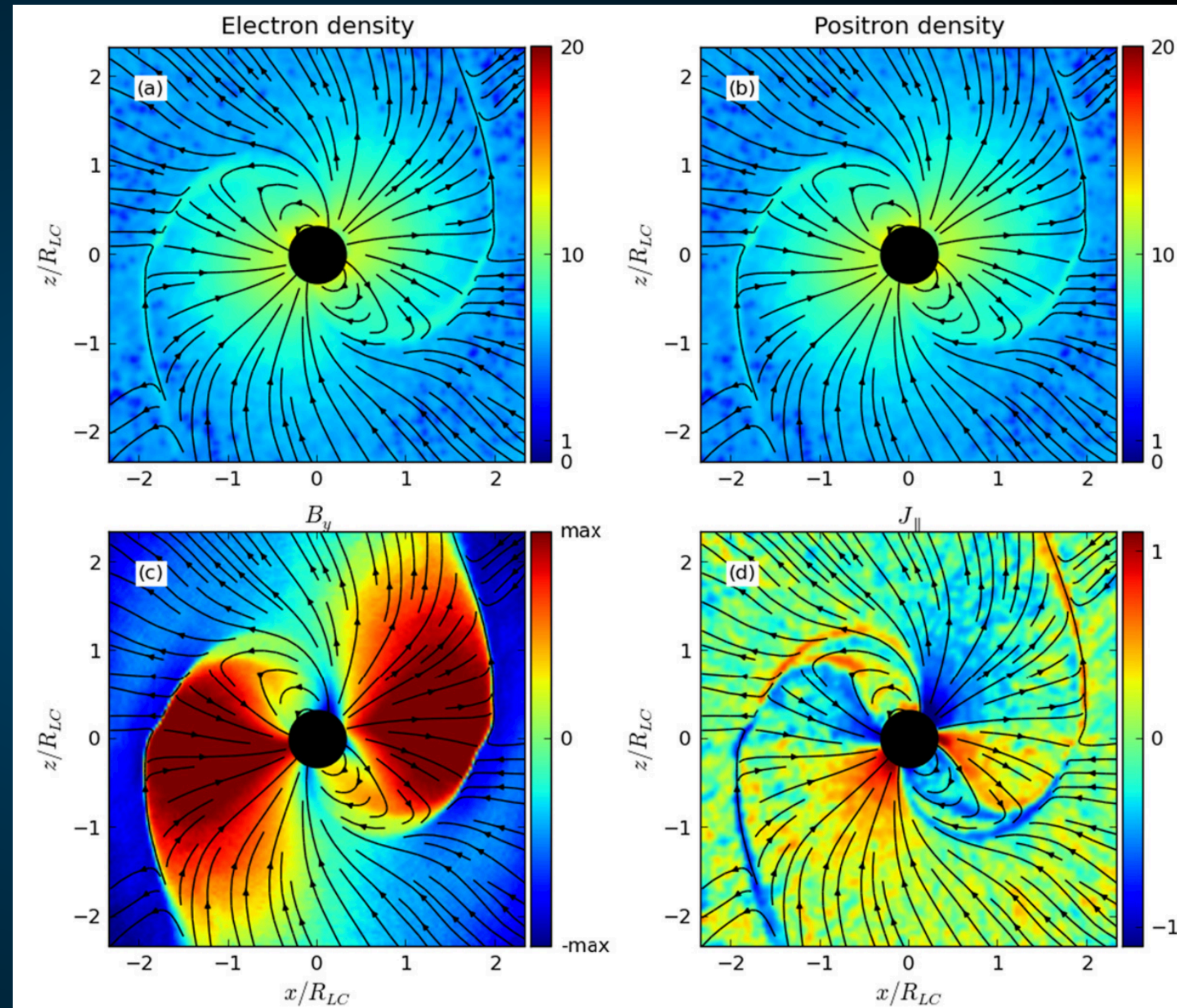
Philippov et al. (2015; 1412.0673)

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%.





Moon (To Scale)

Geminga



PSR B0656+14





Moon (To Scale)

SNR
(hadronic/leptonic)

TeV Halo
(escaped e^+e^-)

PWN
(confined e^+e^-)

Geminga





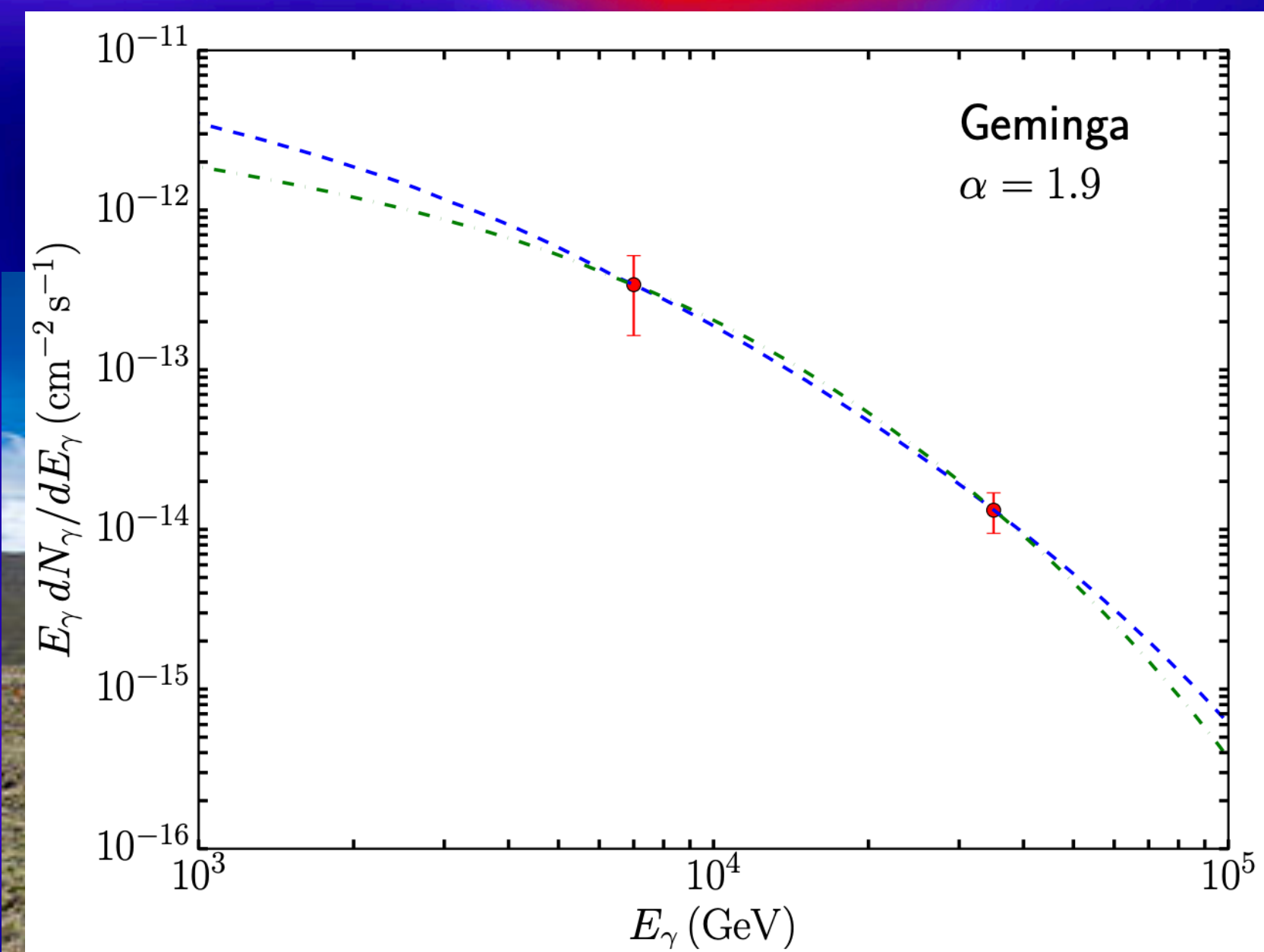
Moon (To Scale)

SNR
(hadronic/leptonic)

TeV Halo
(escaped e^+e^-)

PWN
(confined e^+e^-)

Geminga





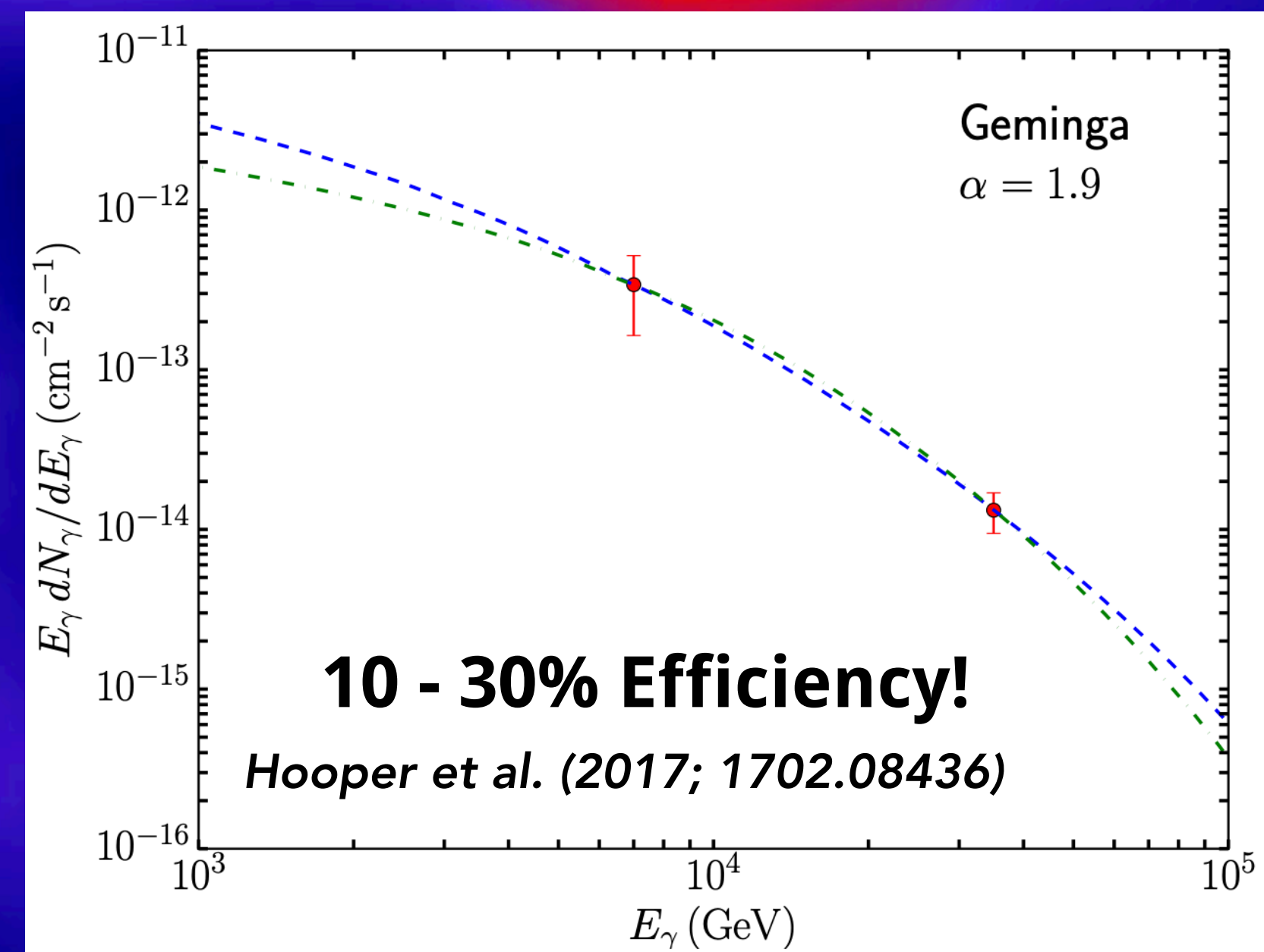
Moon (To Scale)

SNR
(hadronic/leptonic)

TeV Halo
(escaped e^+e^-)

PWN
(confined e^+e^-)

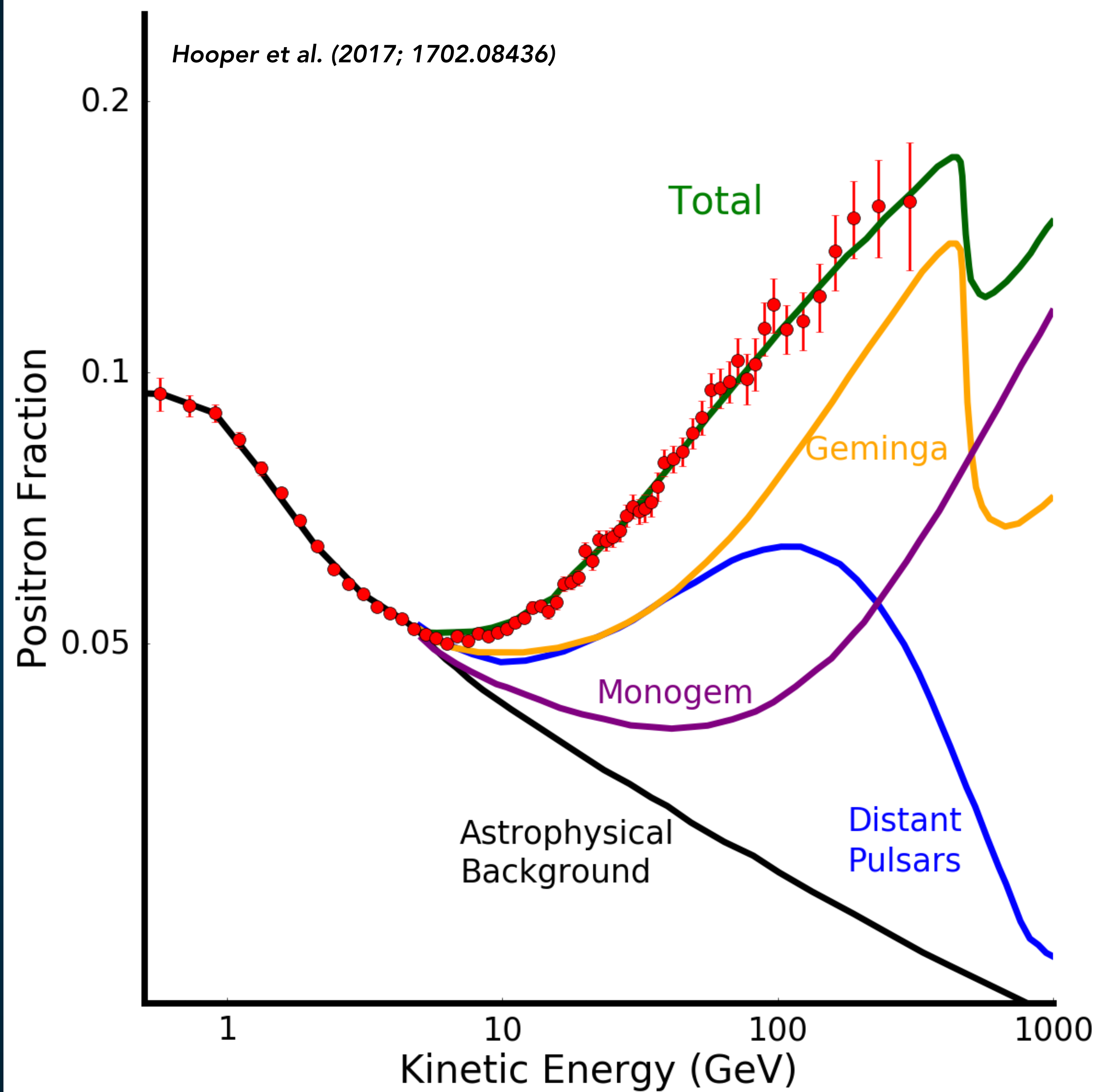
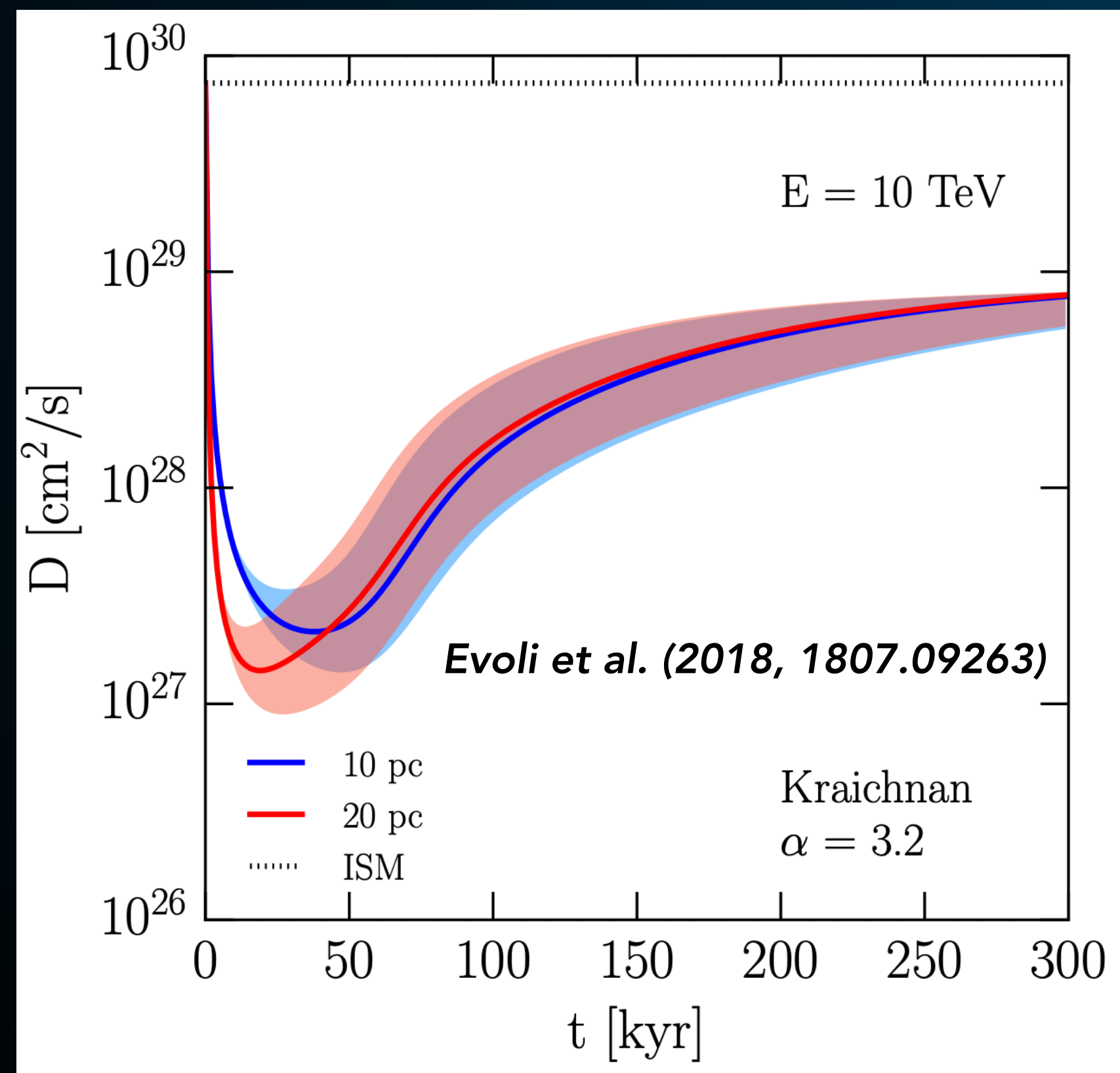
Geminga

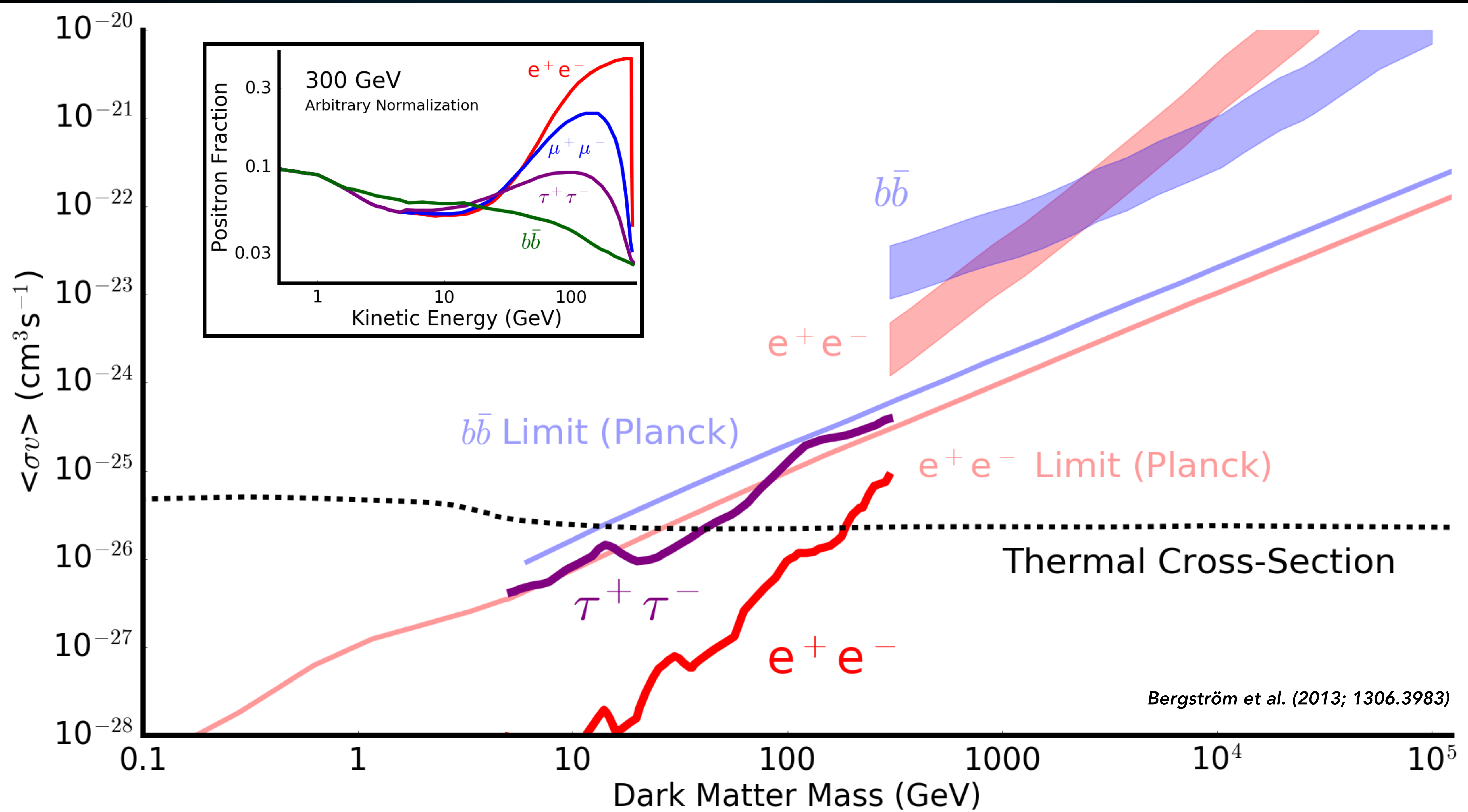


The Positron Excess

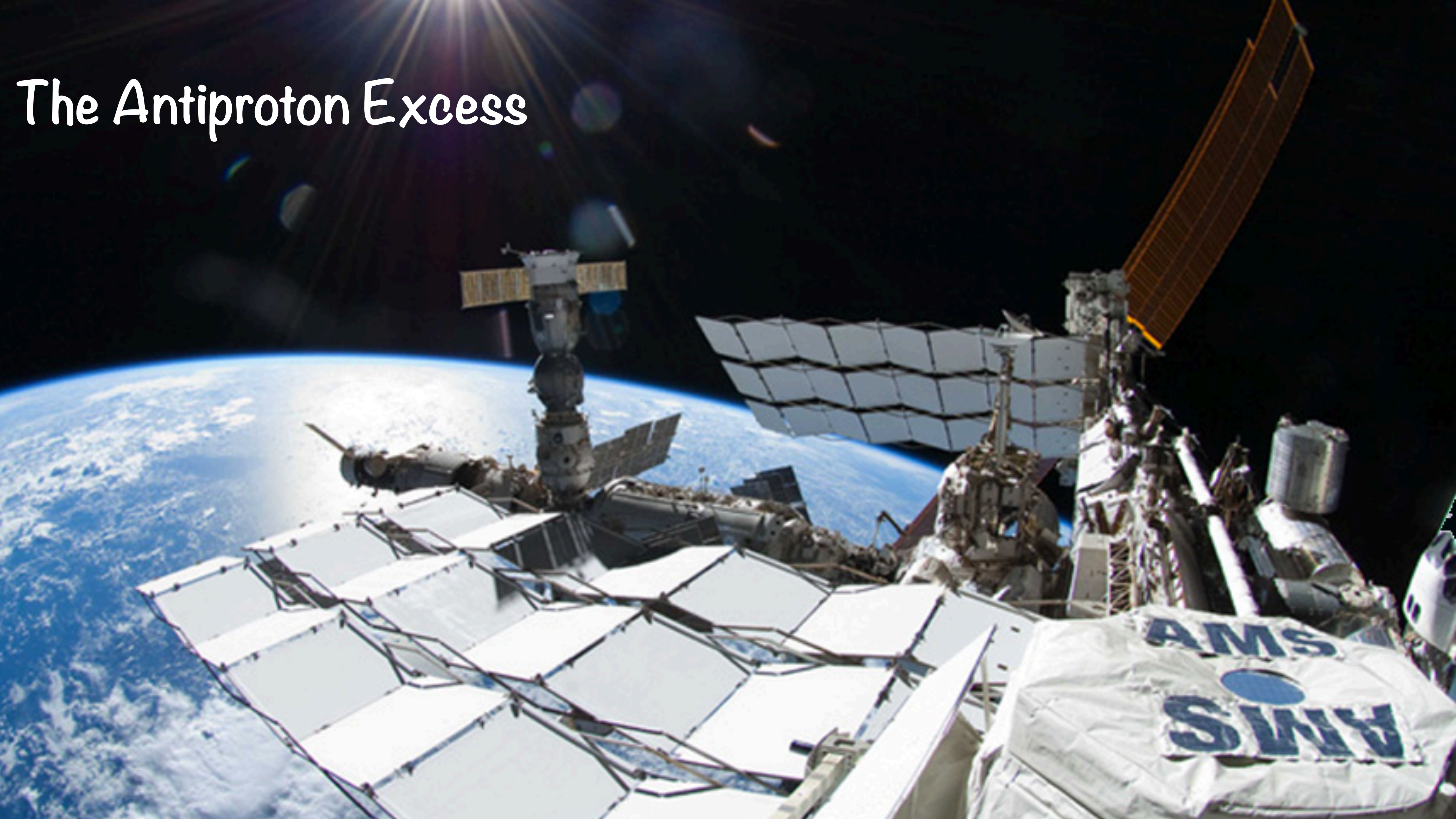
This can easily match the positron fraction

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





The Antiproton Excess



The Antiproton Excess

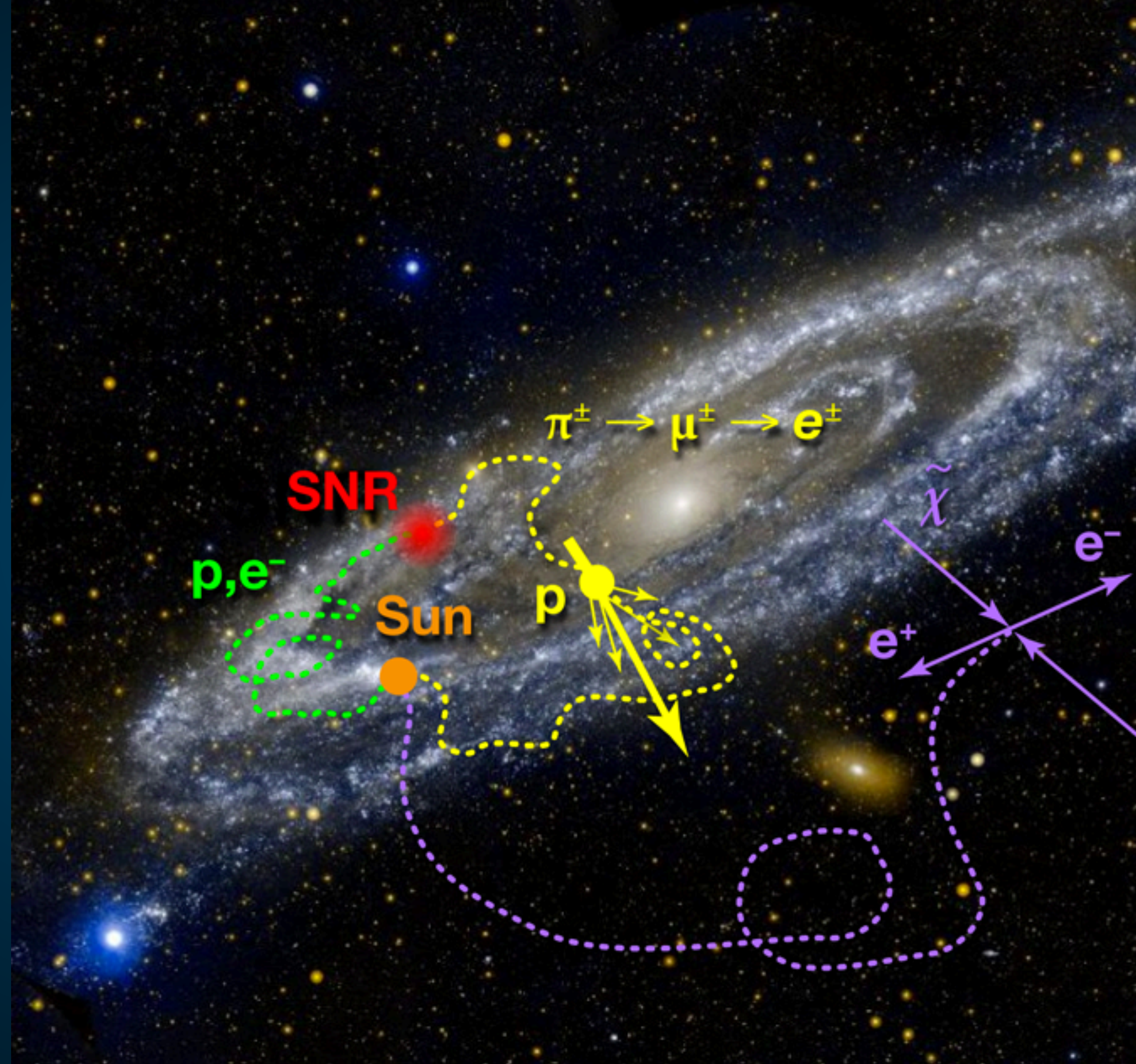
Investigate the Antiproton Fraction!

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

Two Changes:

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

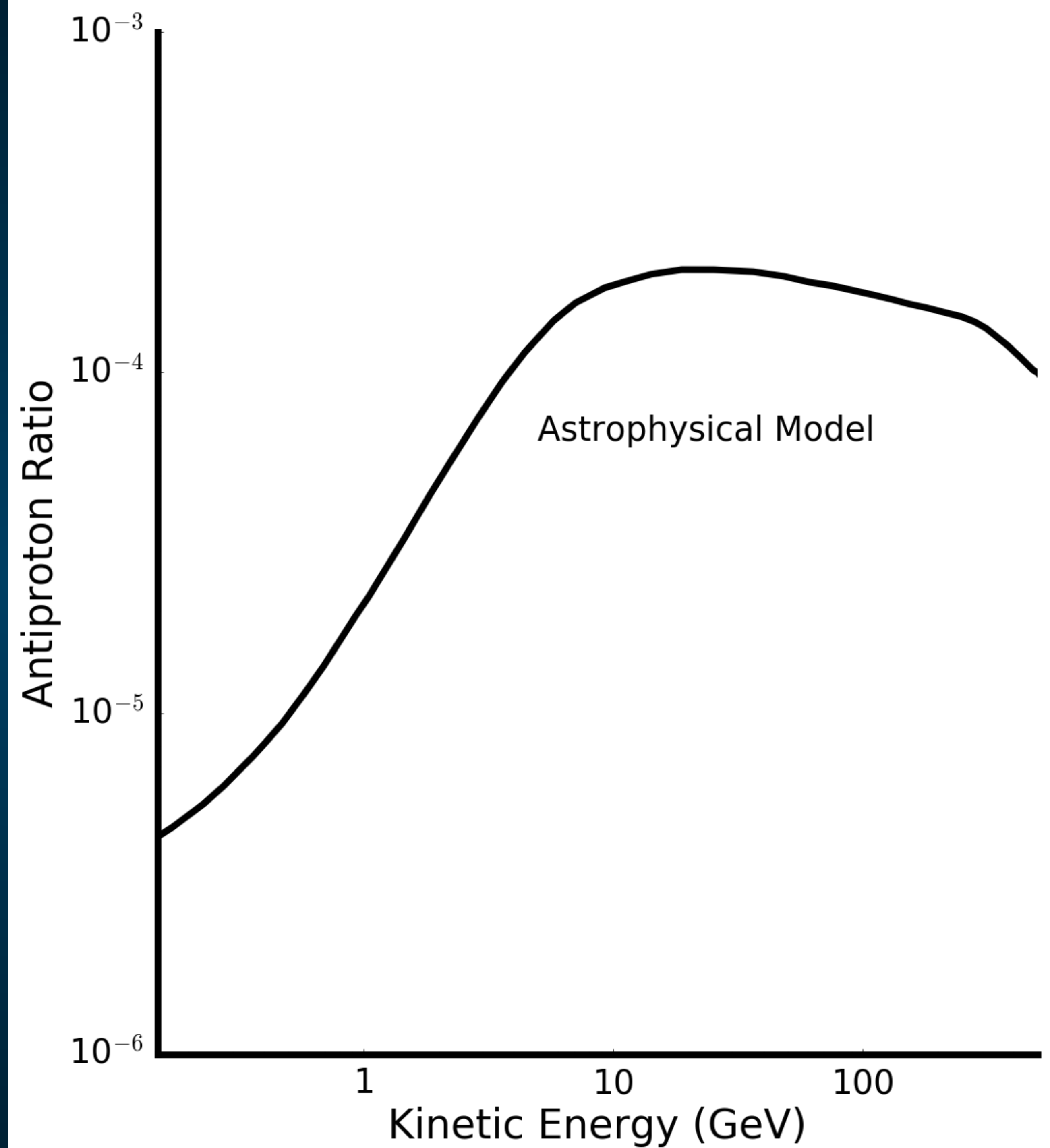
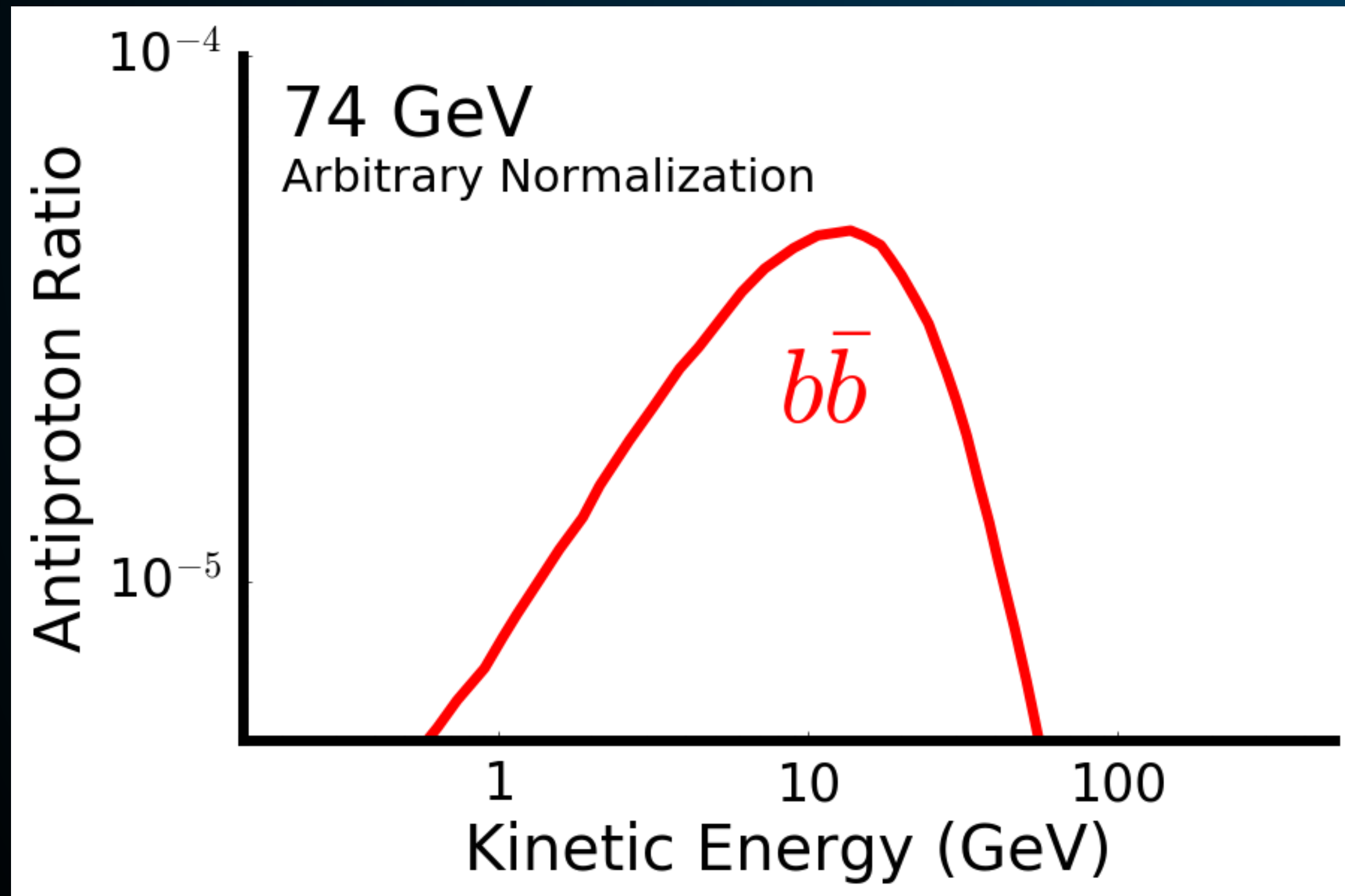
Hadronic Energy losses are slower (sensitive to antiproton production throughout the Galaxy)



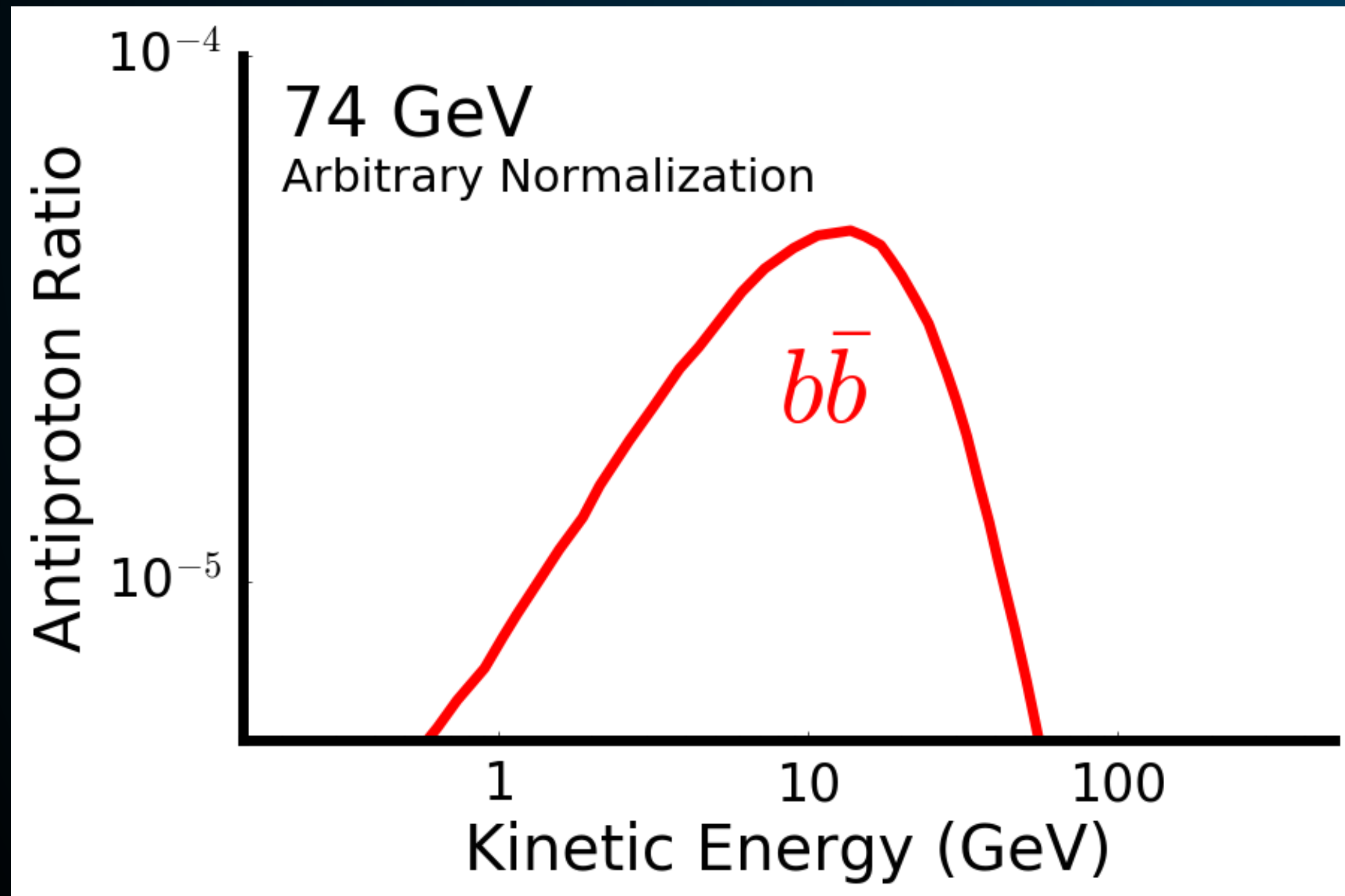
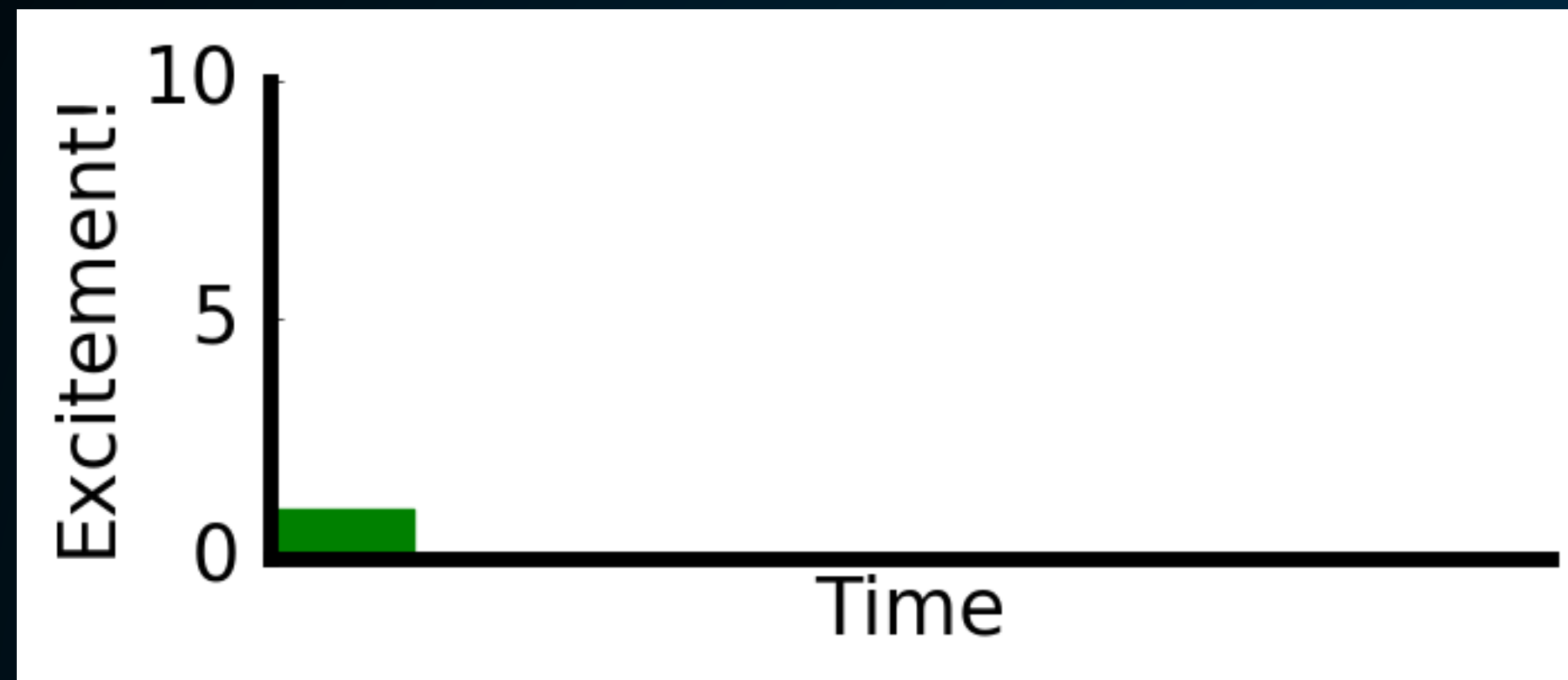
The Antiproton Excess

Astrophysics - Smooth Profile

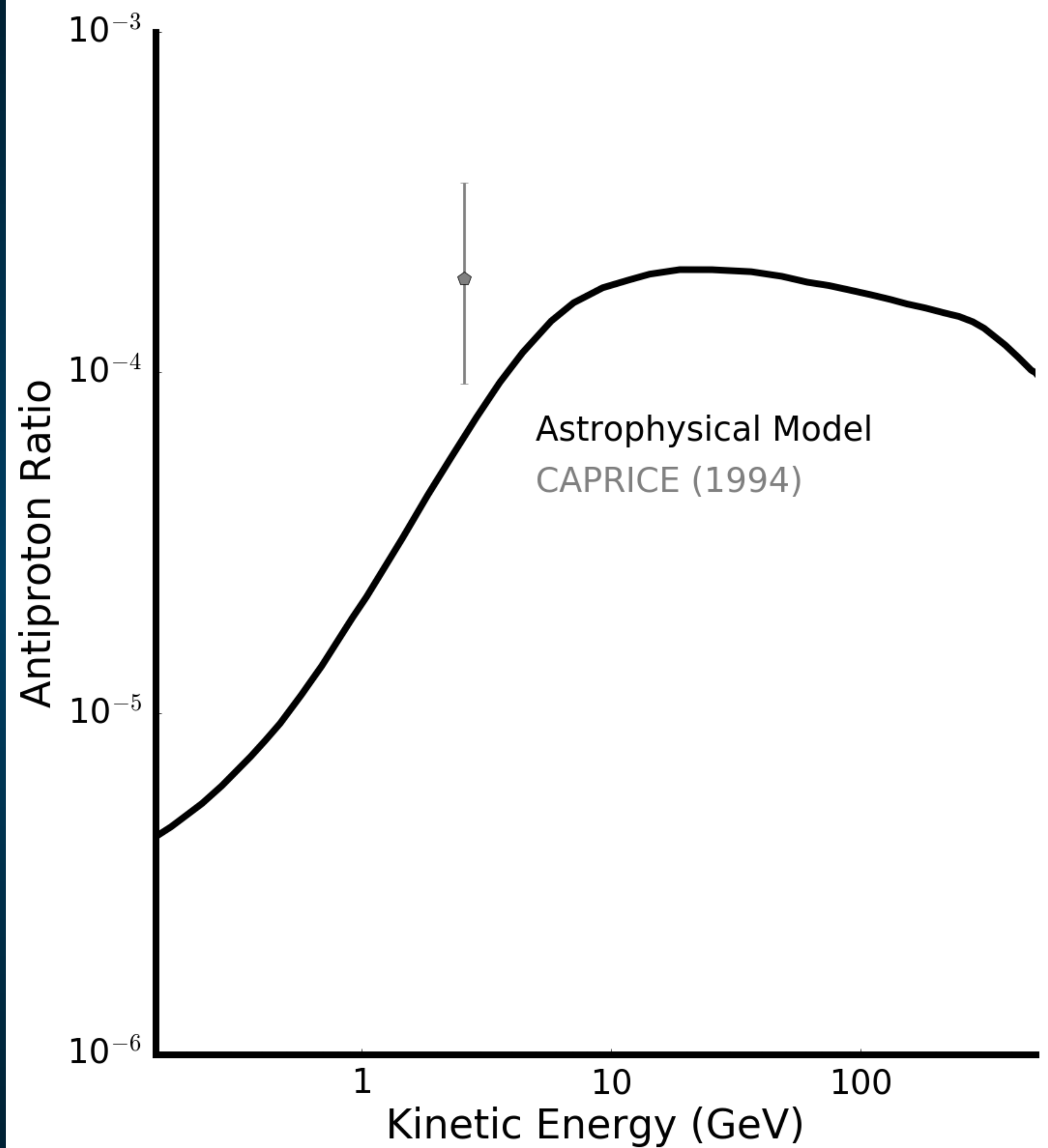
Dark Matter - Sharp Bump!



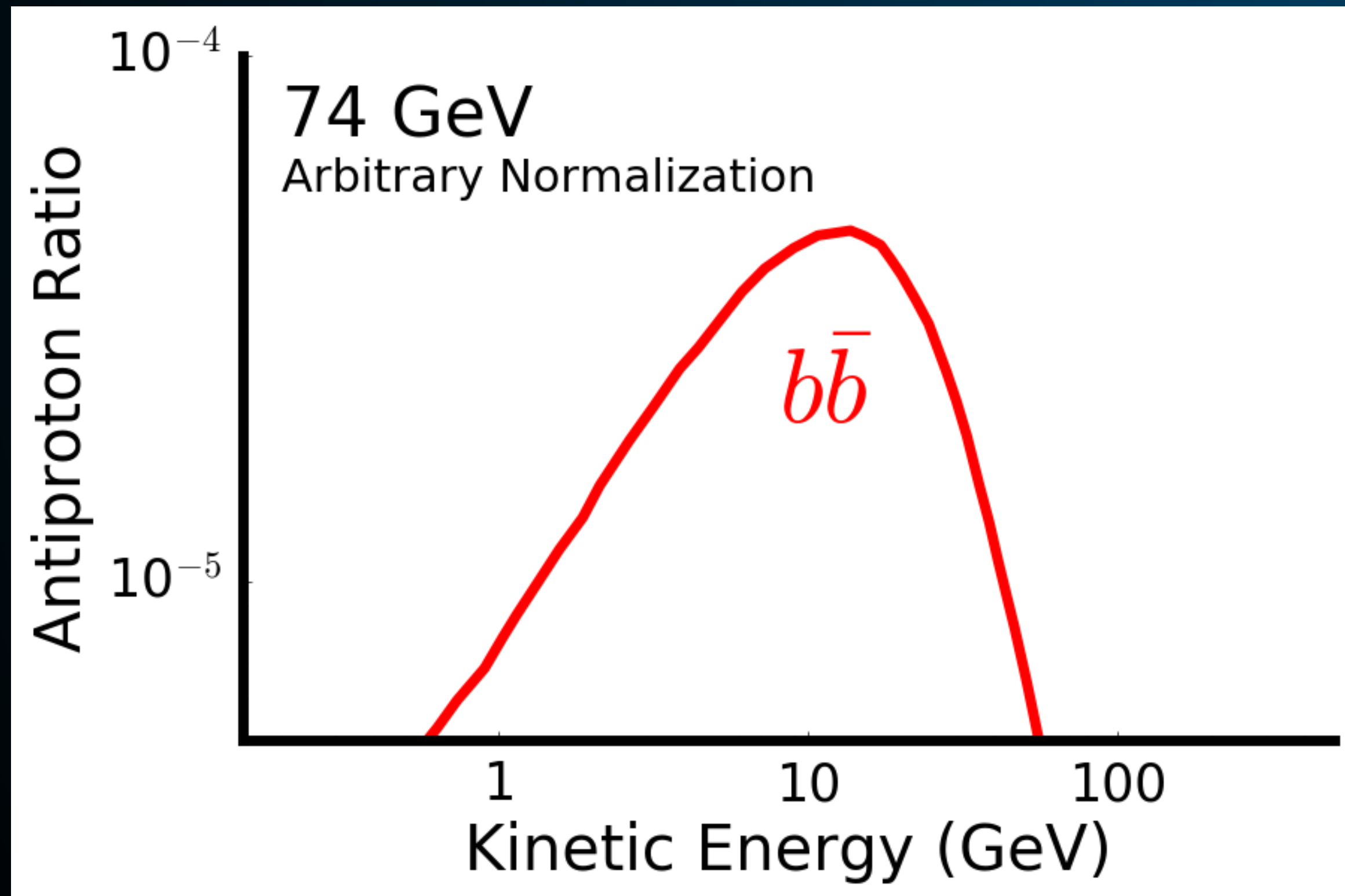
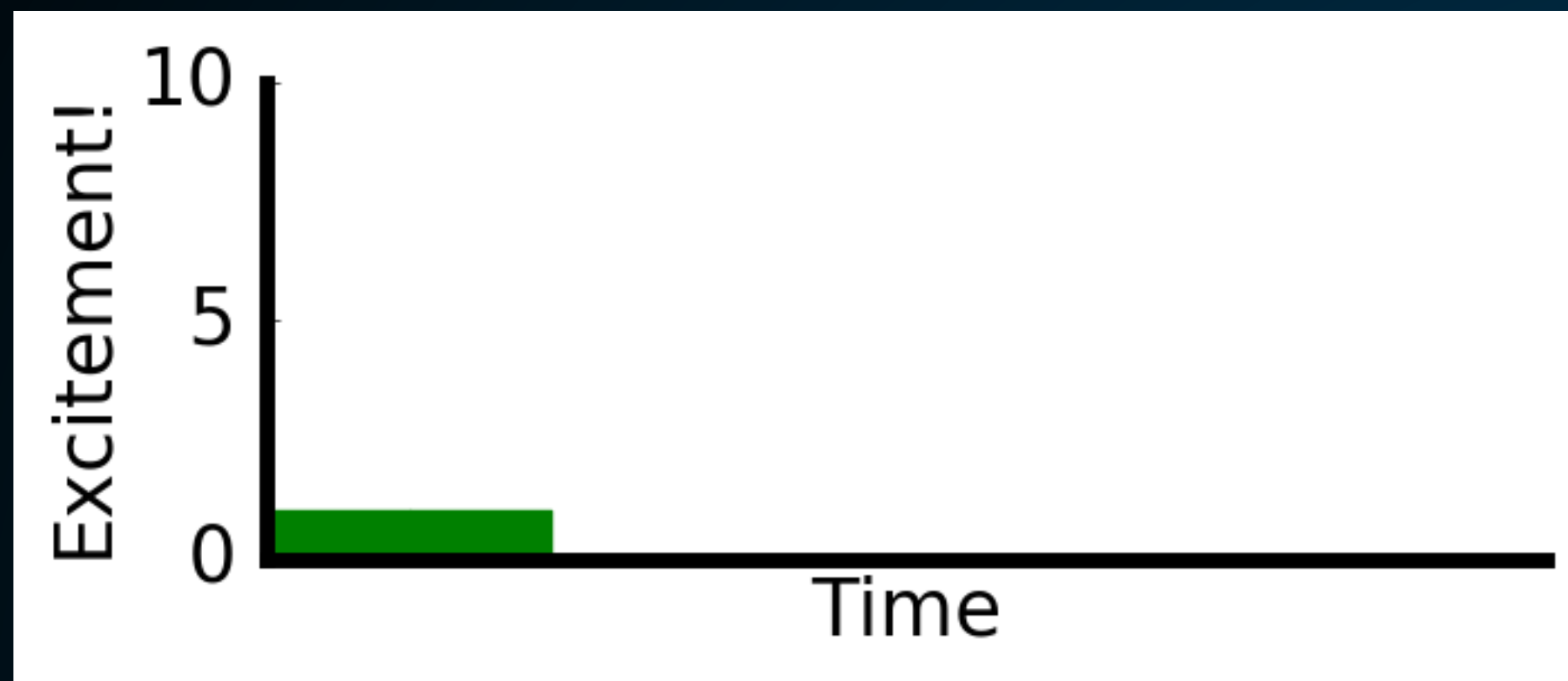
The Antiproton Excess



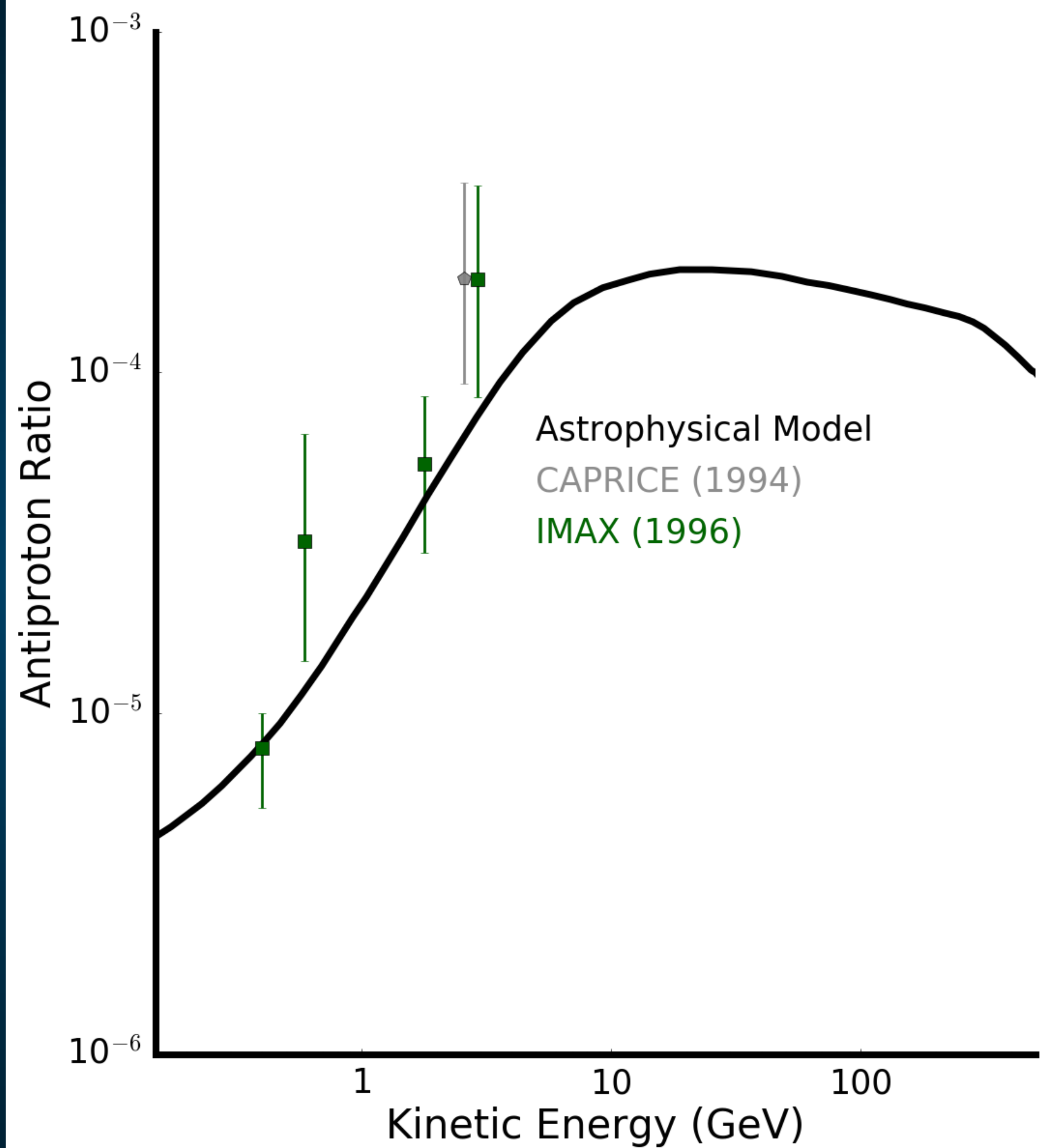
(Not an exhaustive list of observations)



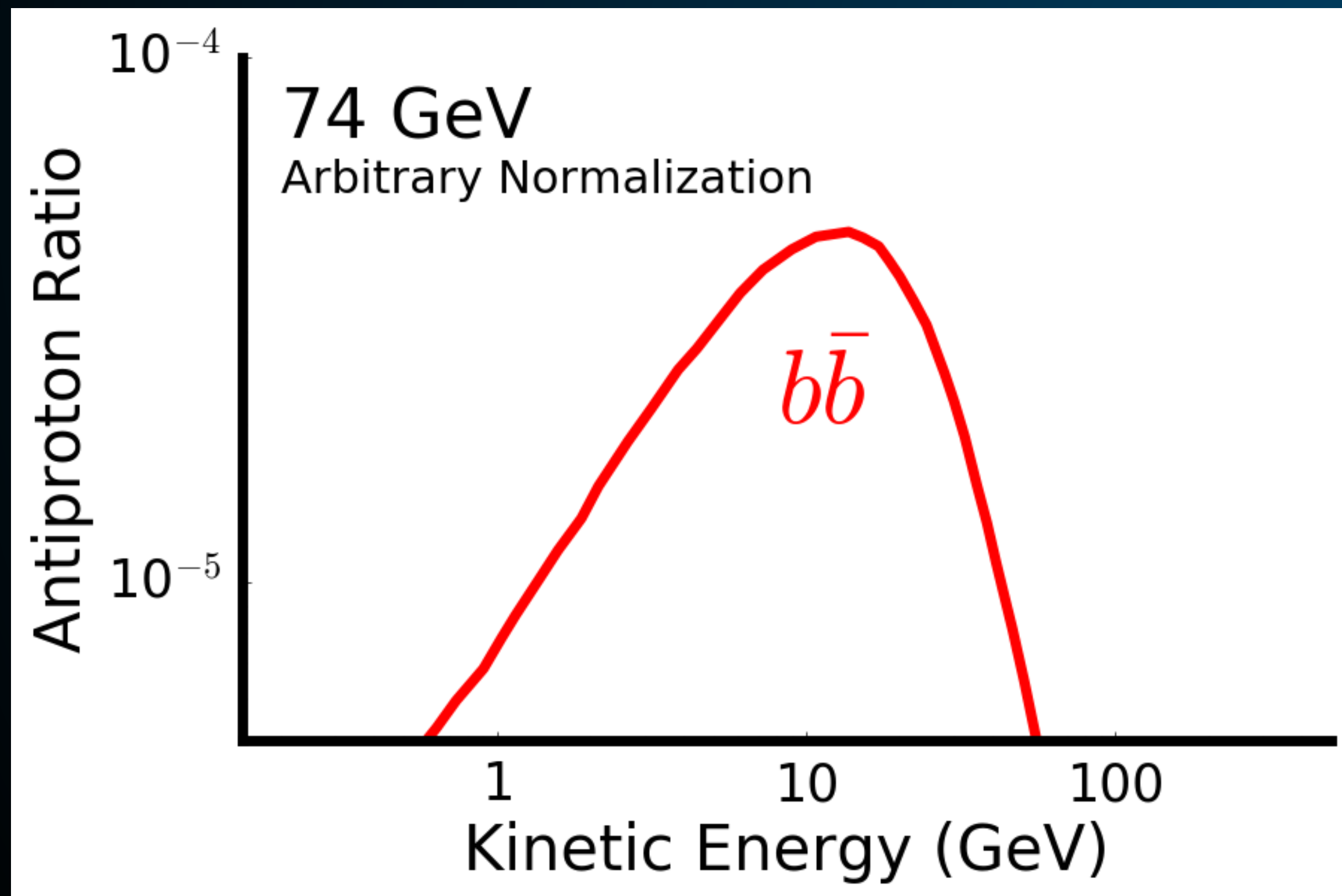
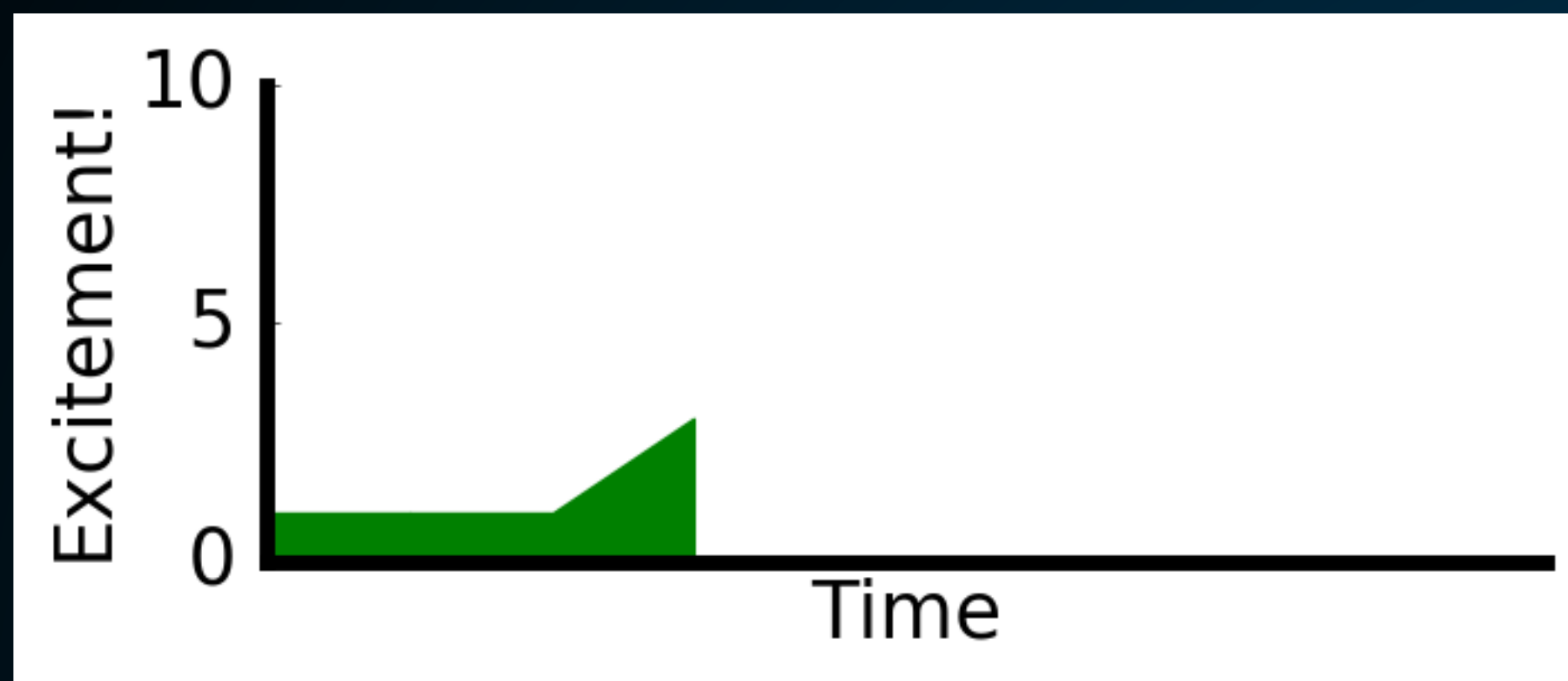
The Antiproton Excess



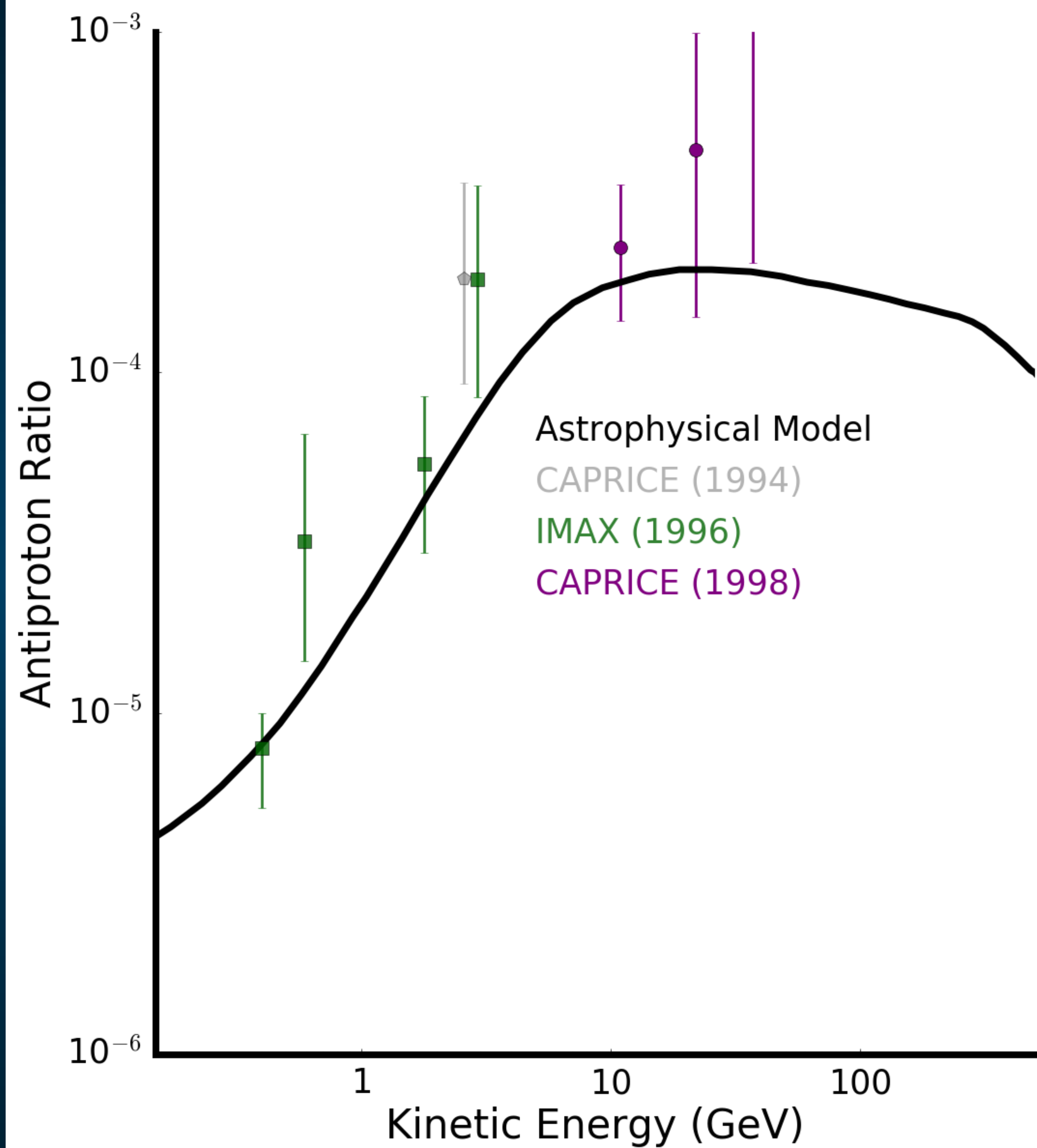
(Not an exhaustive list of observations)



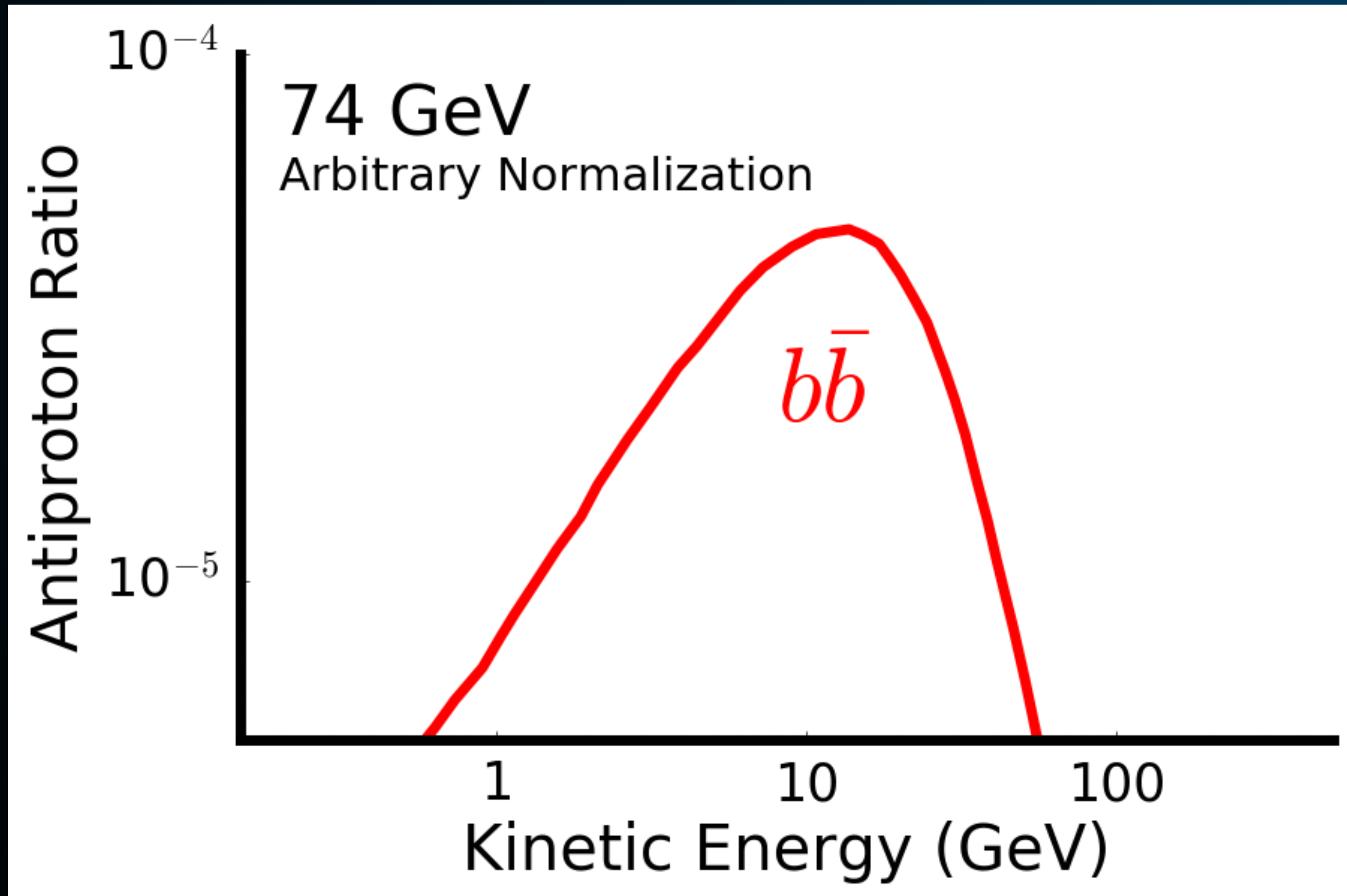
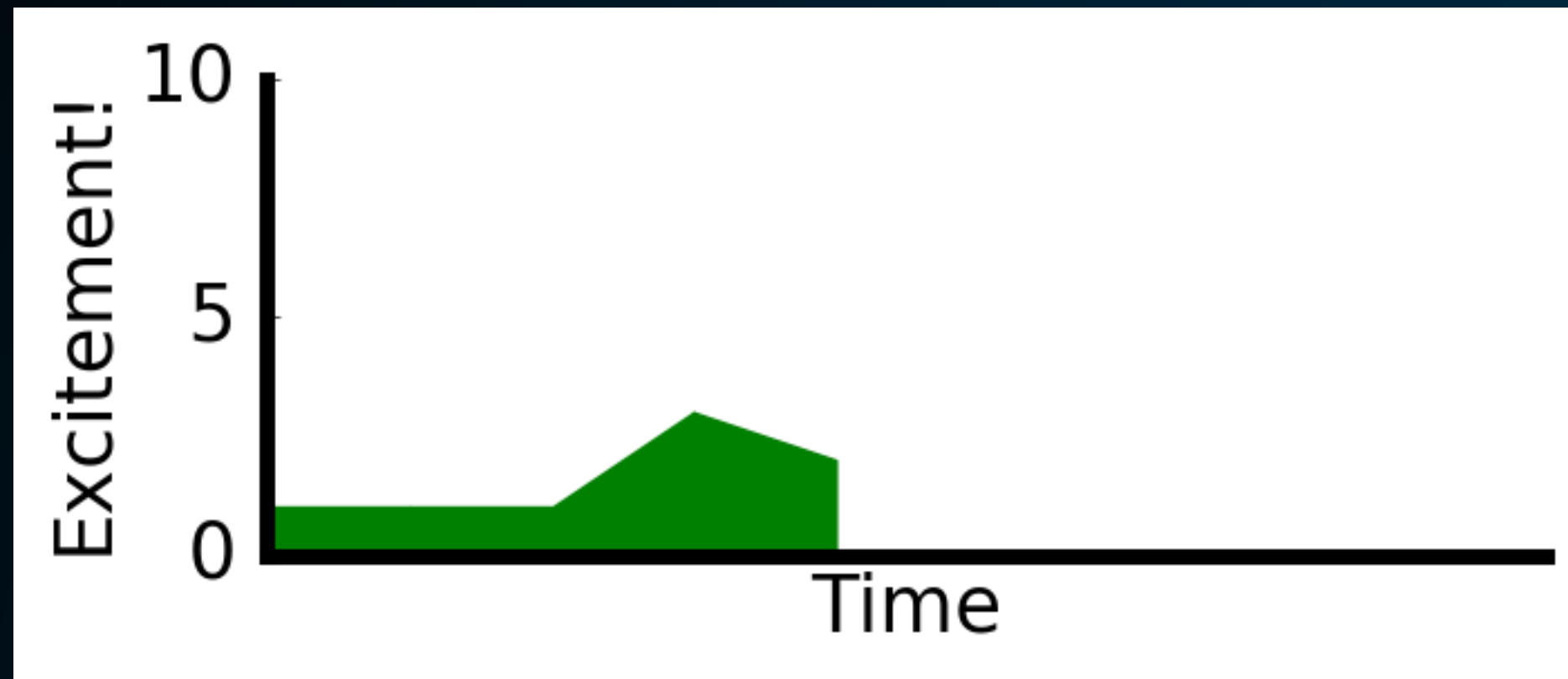
The Antiproton Excess



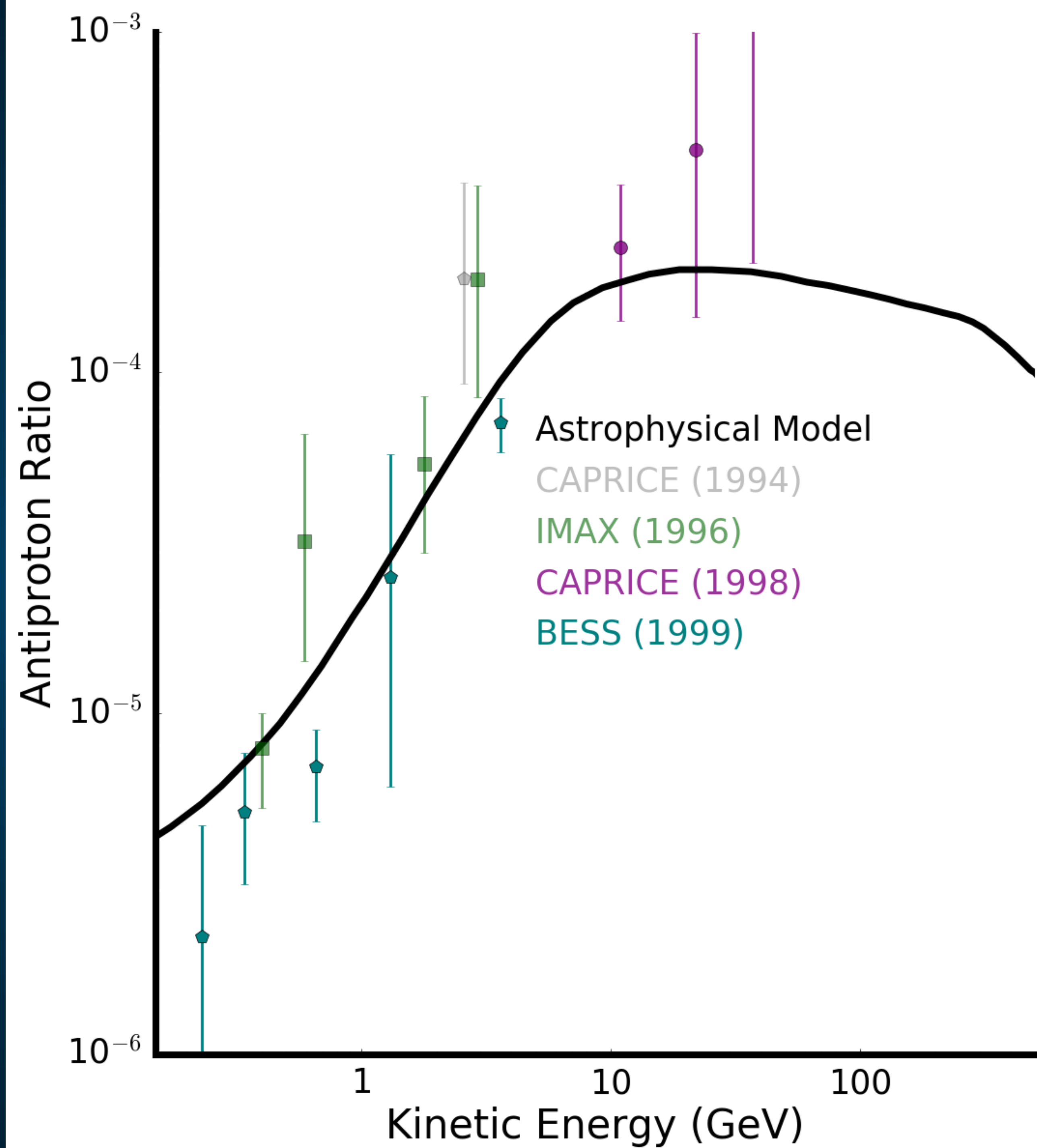
(Not an exhaustive list of observations)



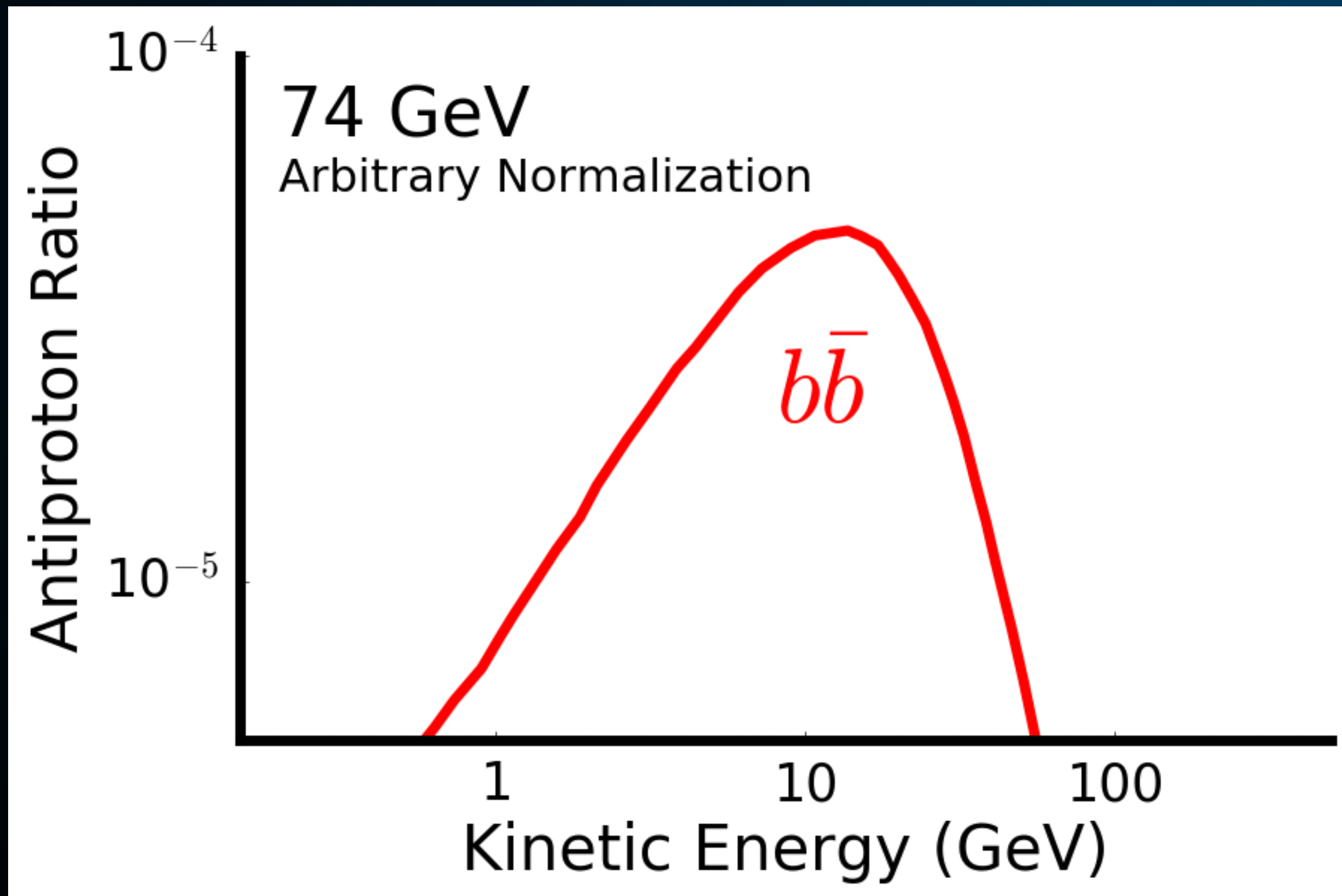
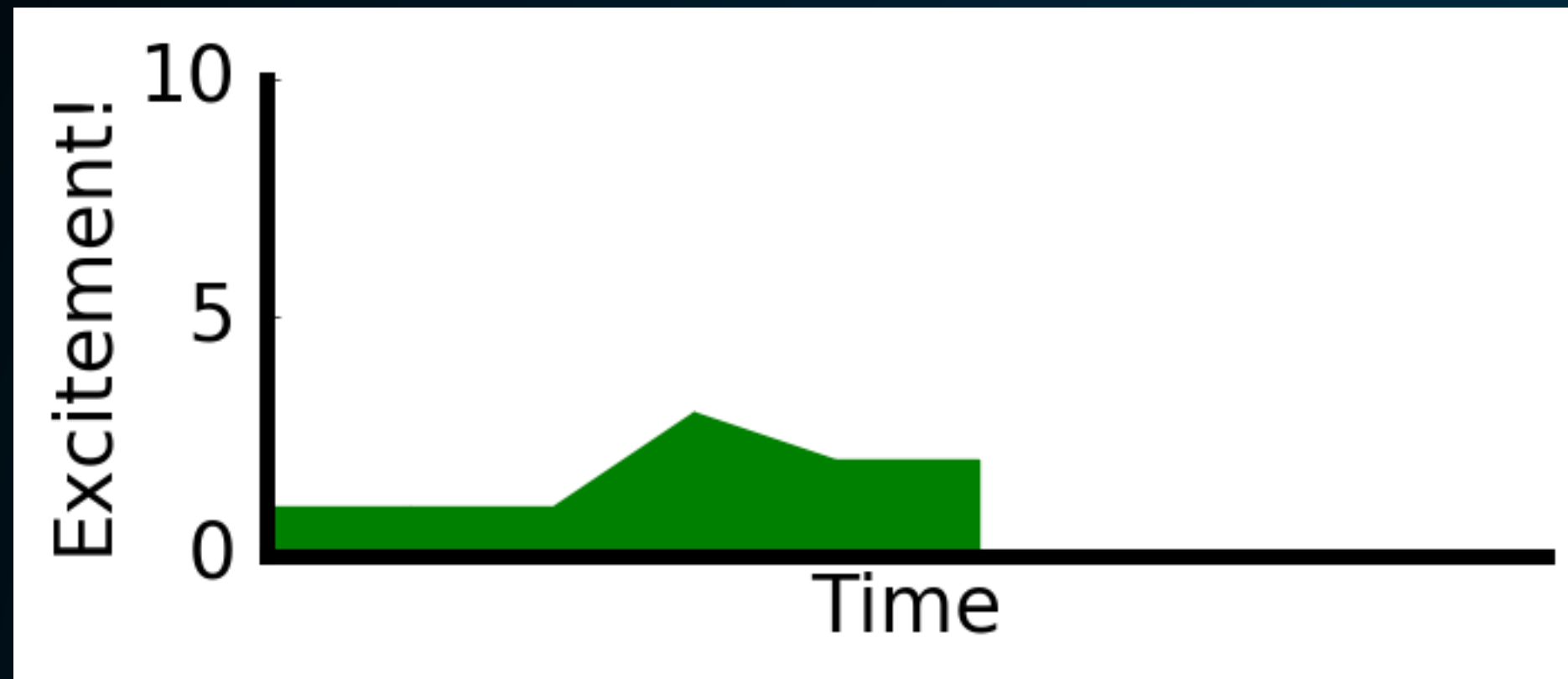
The Antiproton Excess



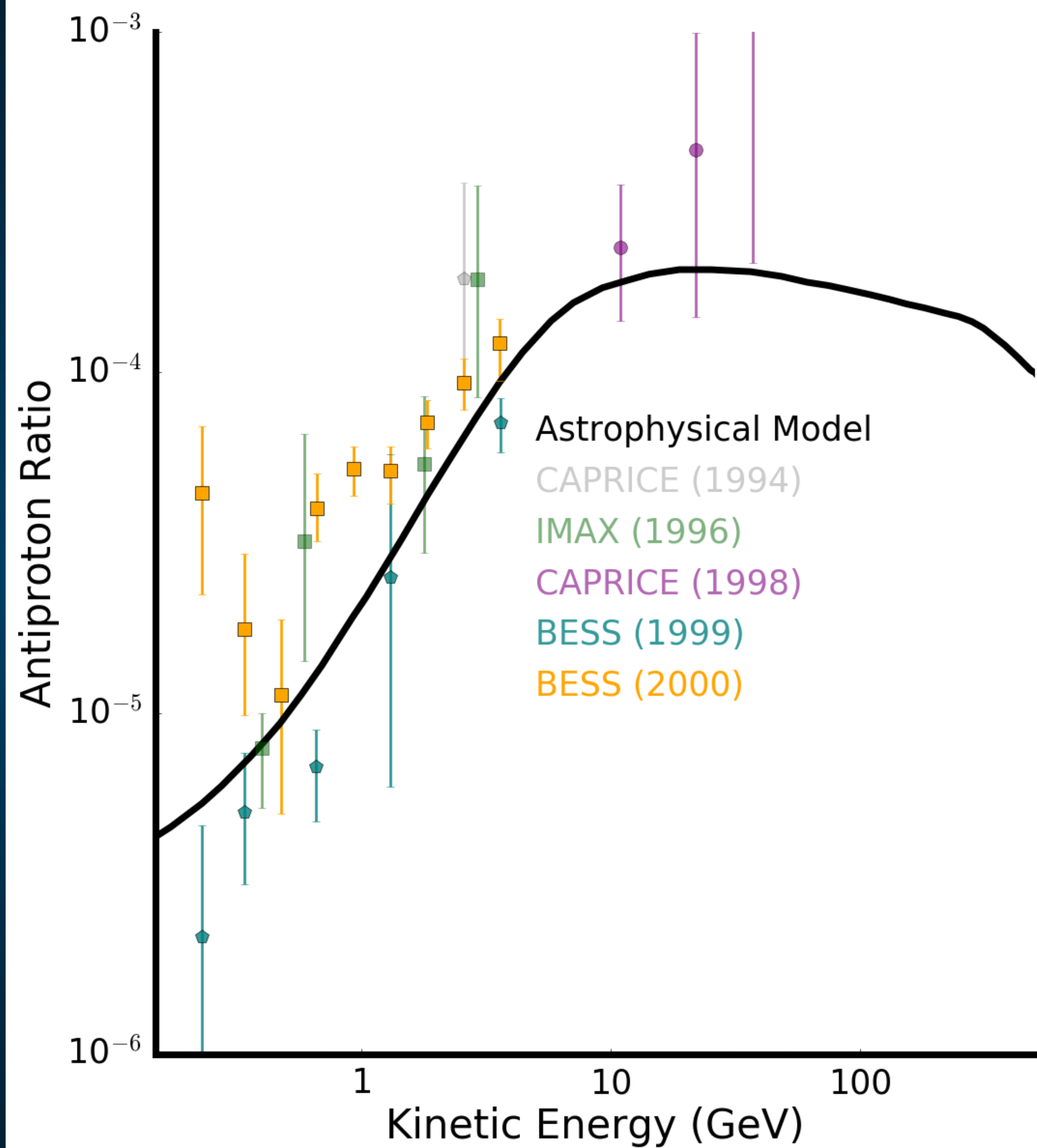
(Not an exhaustive list of observations)



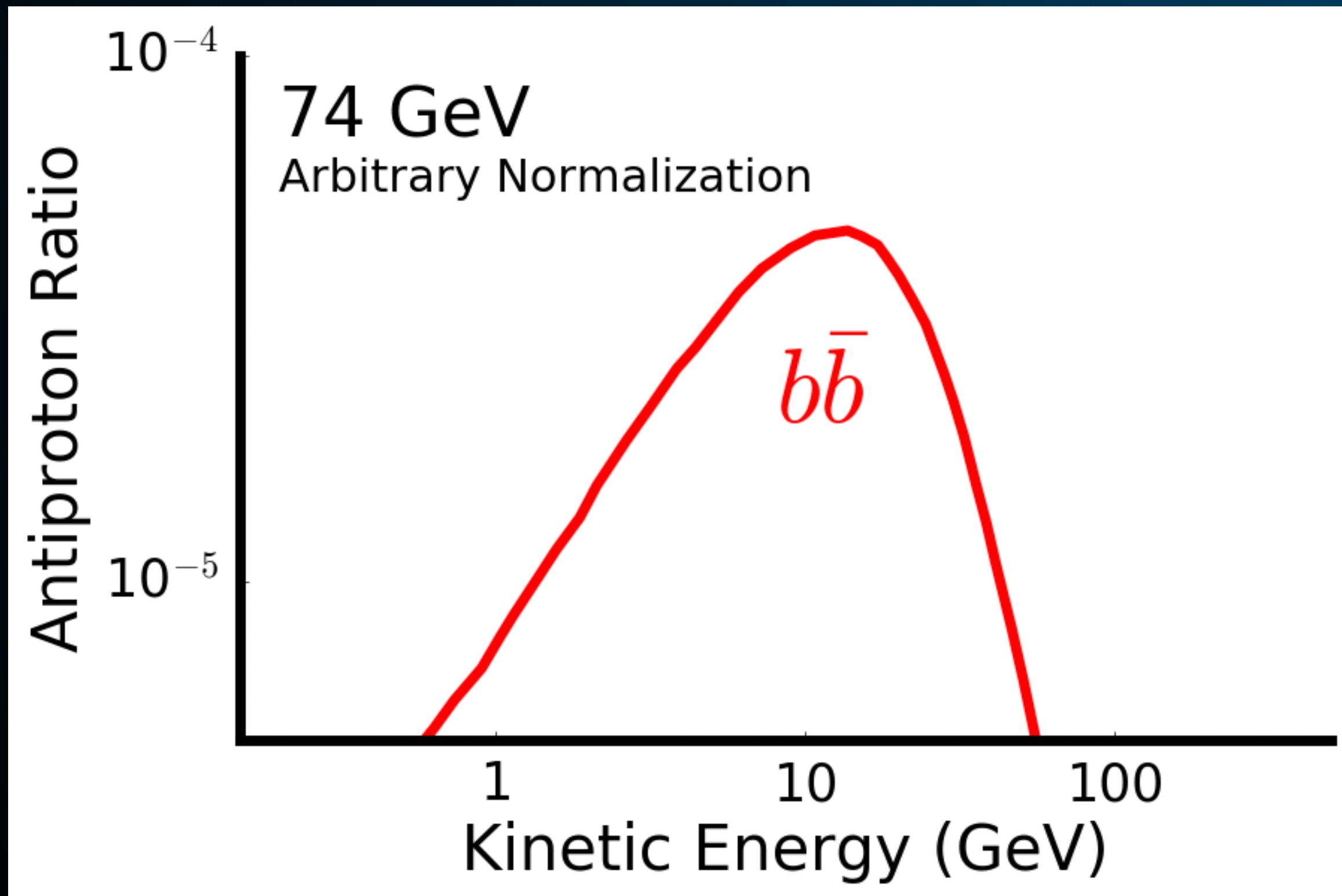
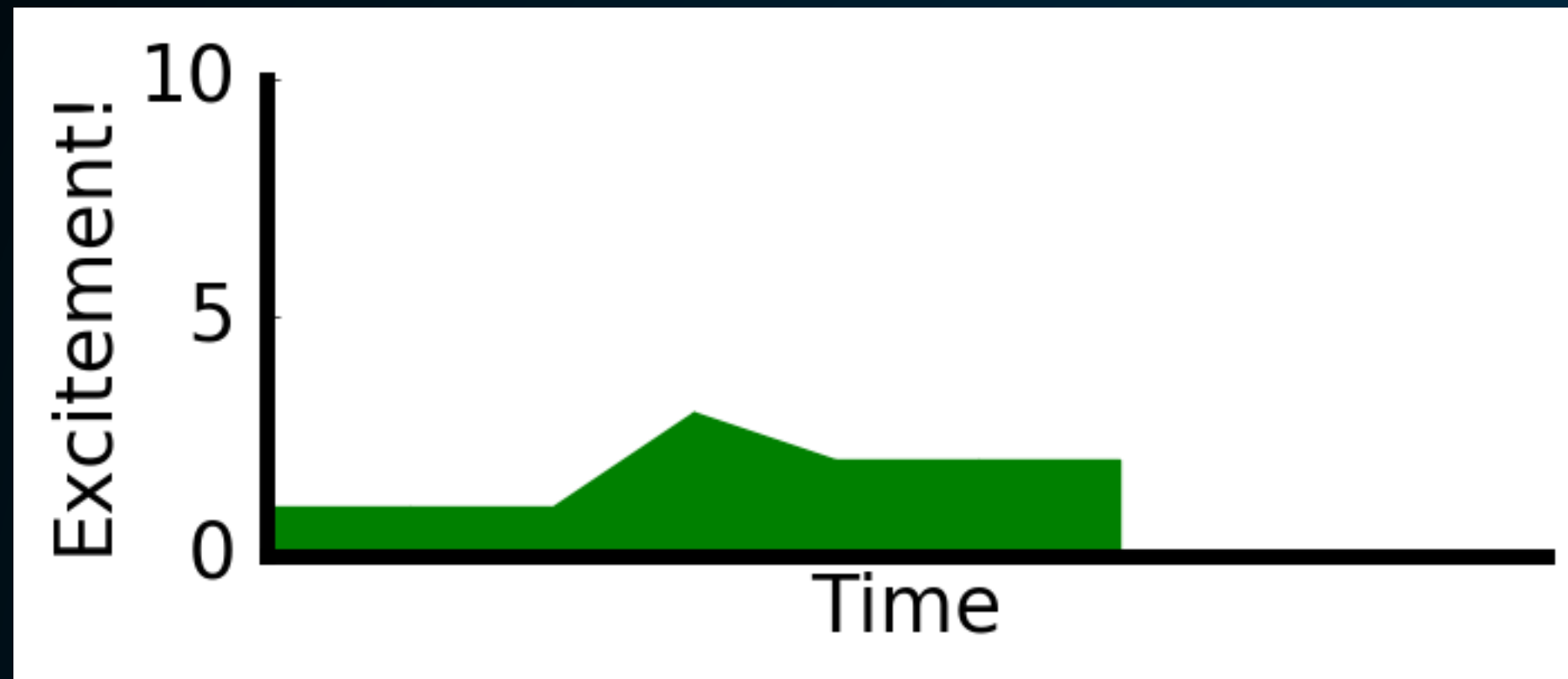
The Antiproton Excess



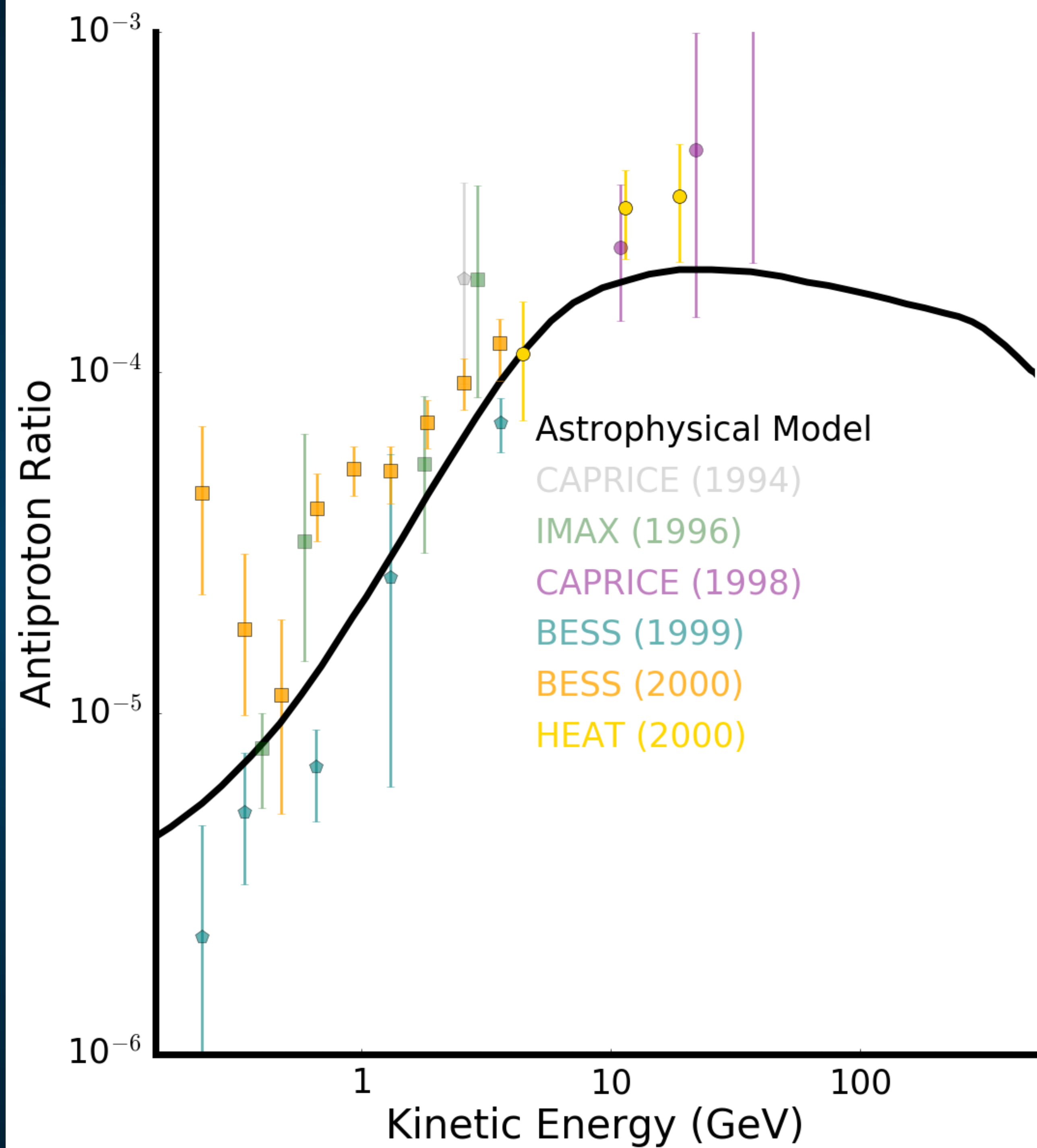
(Not an exhaustive list of observations)



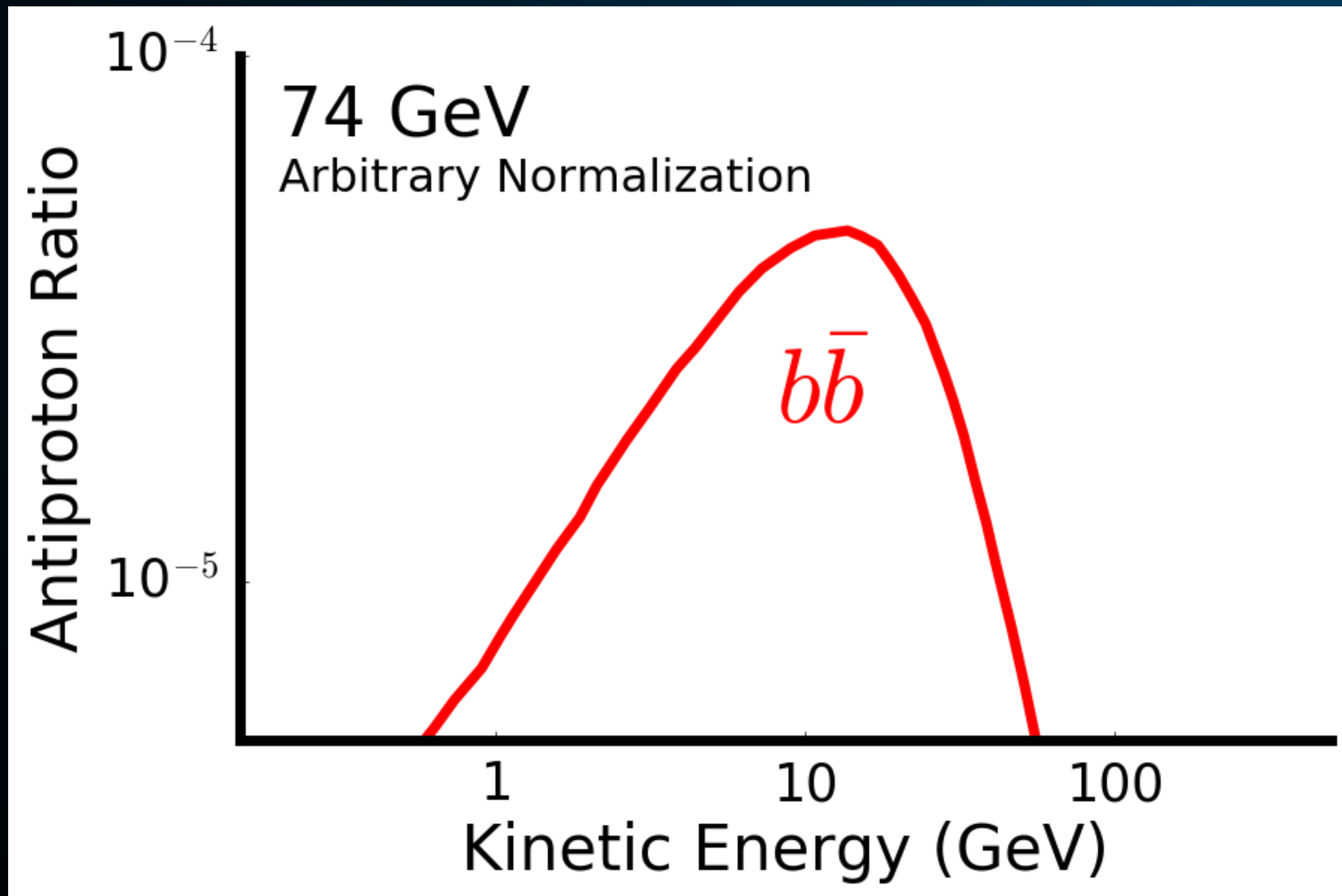
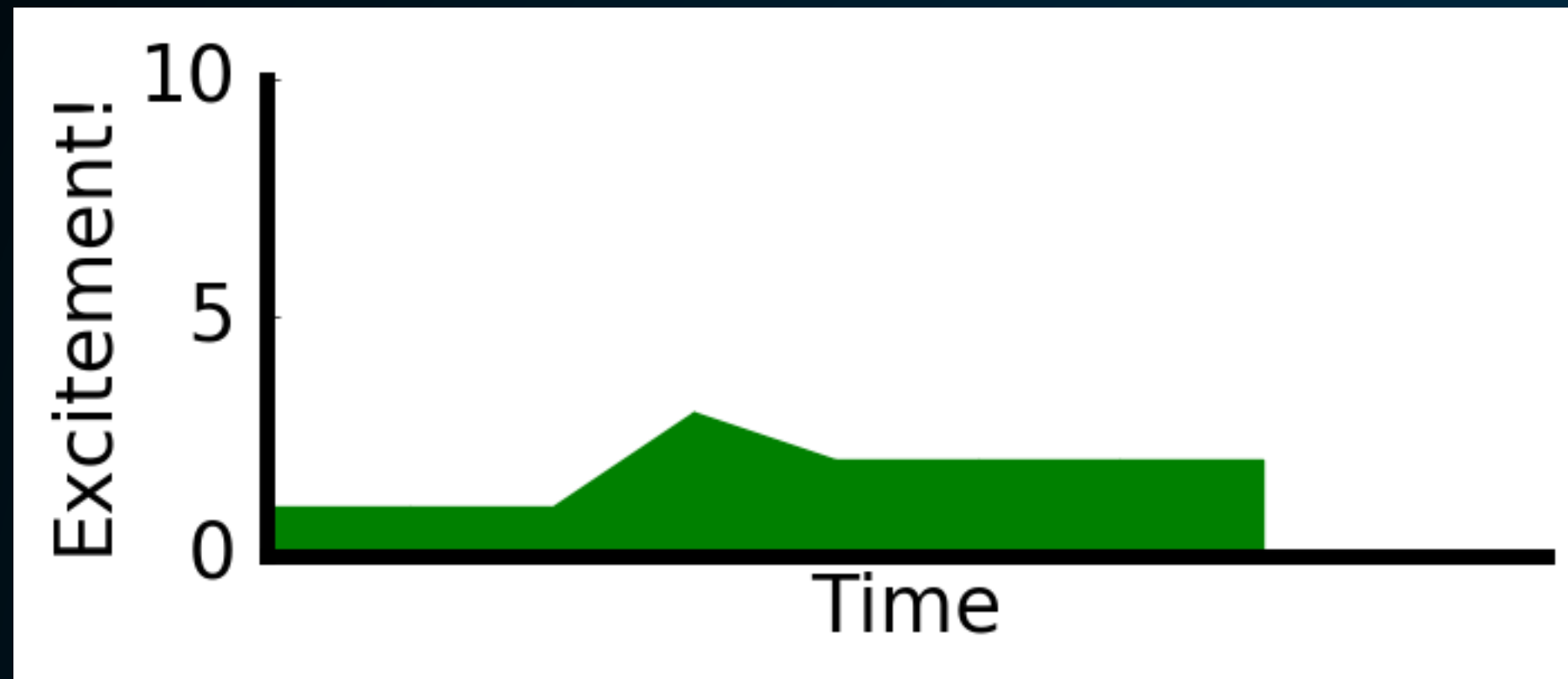
The Antiproton Excess



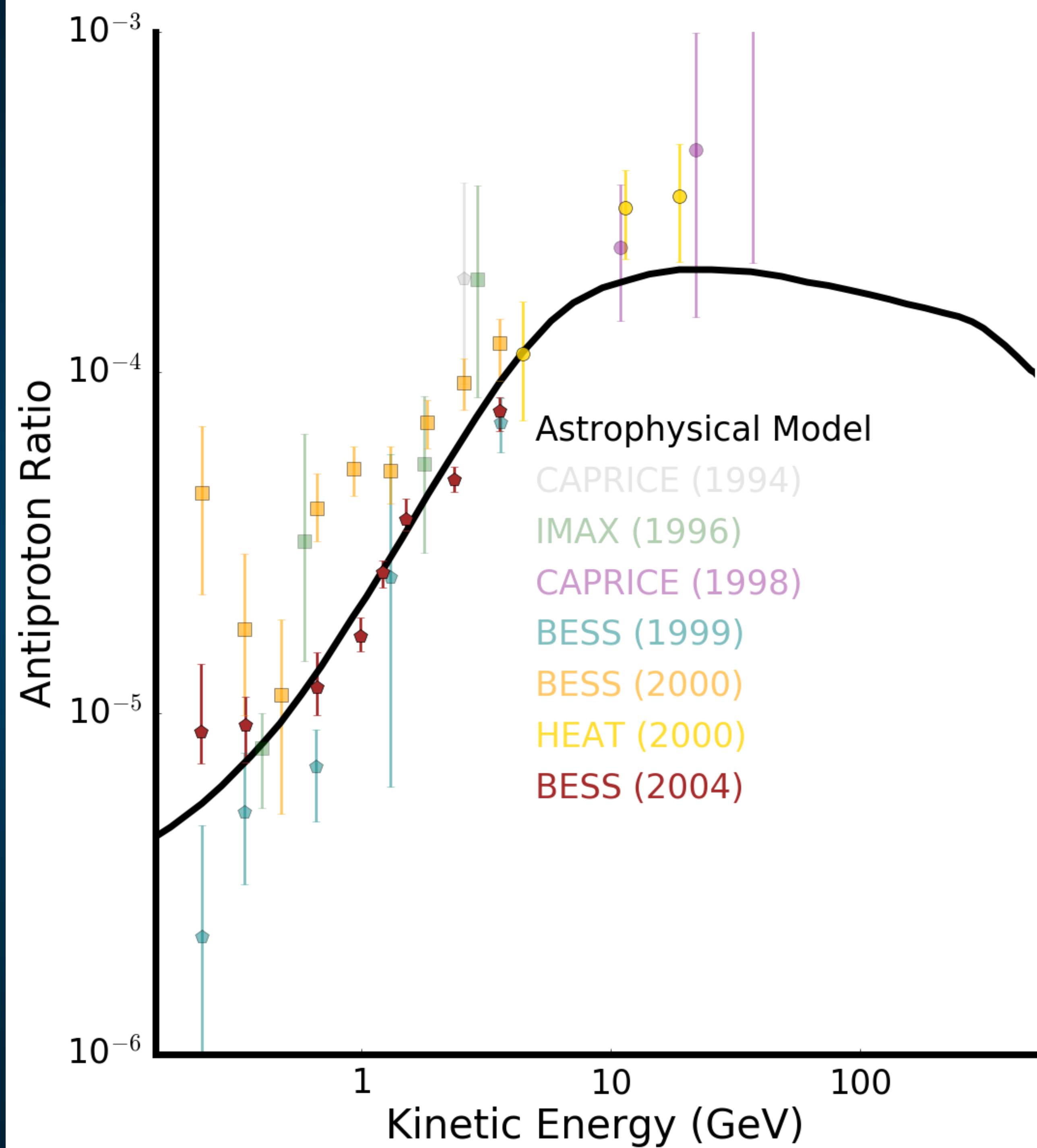
(Not an exhaustive list of observations)



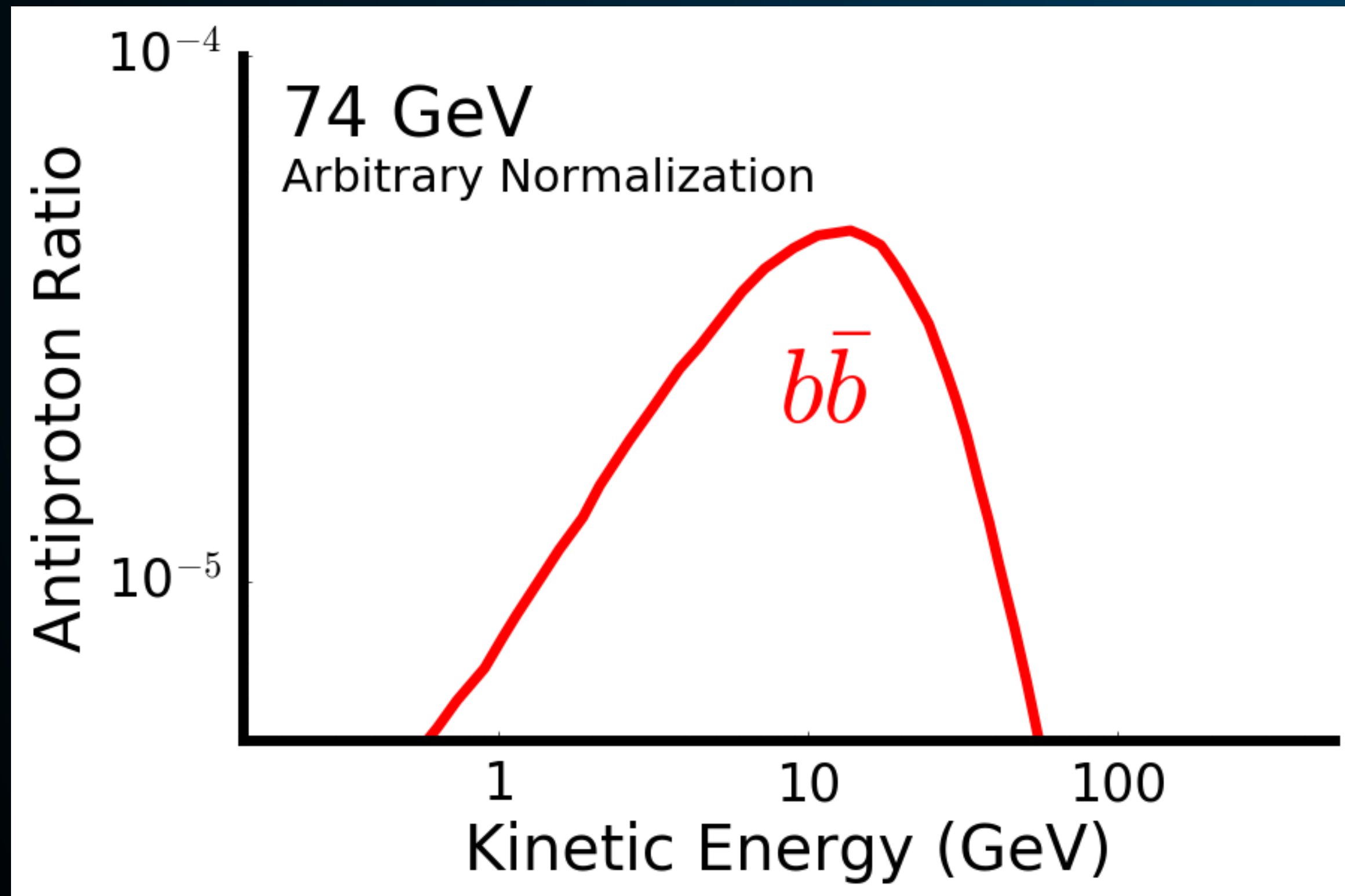
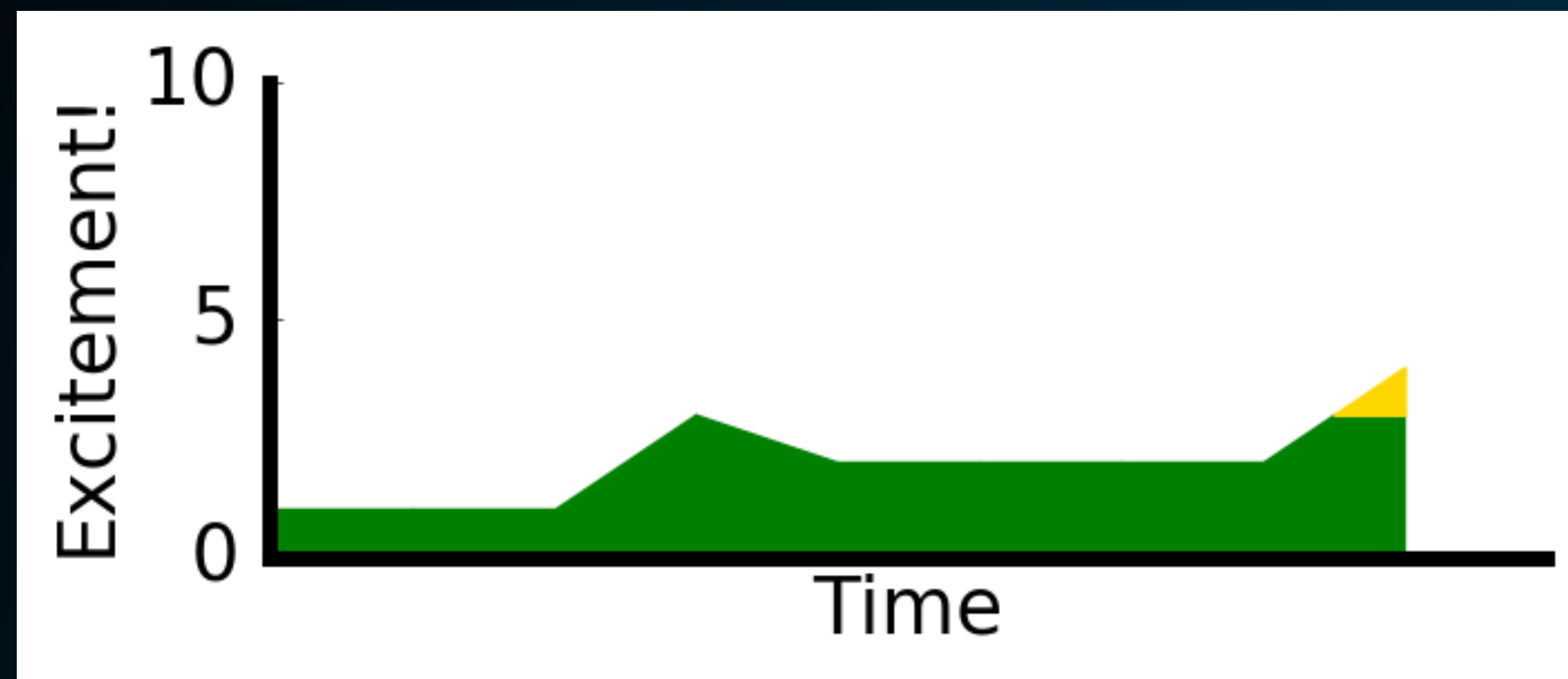
The Antiproton Excess



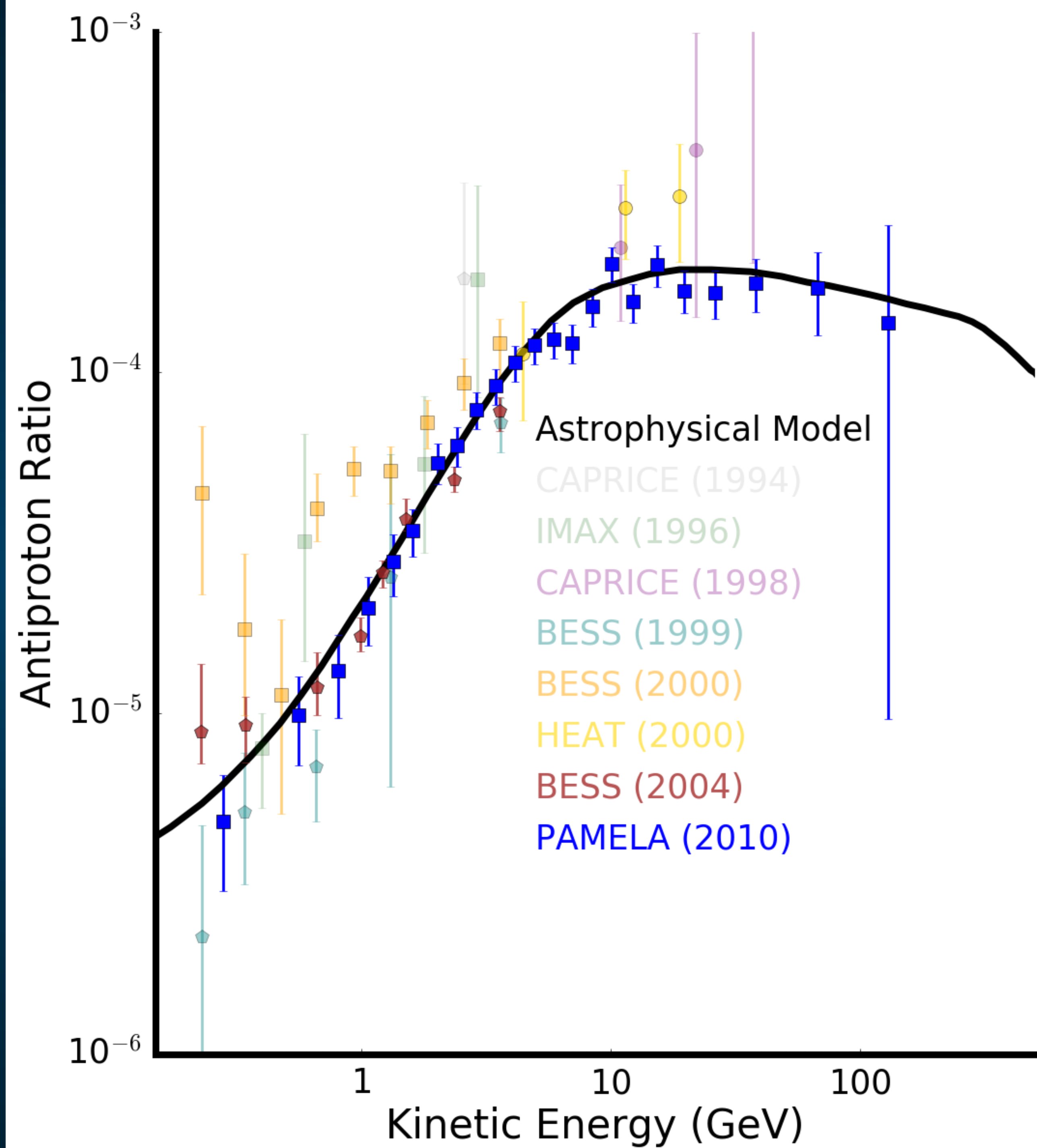
(Not an exhaustive list of observations)



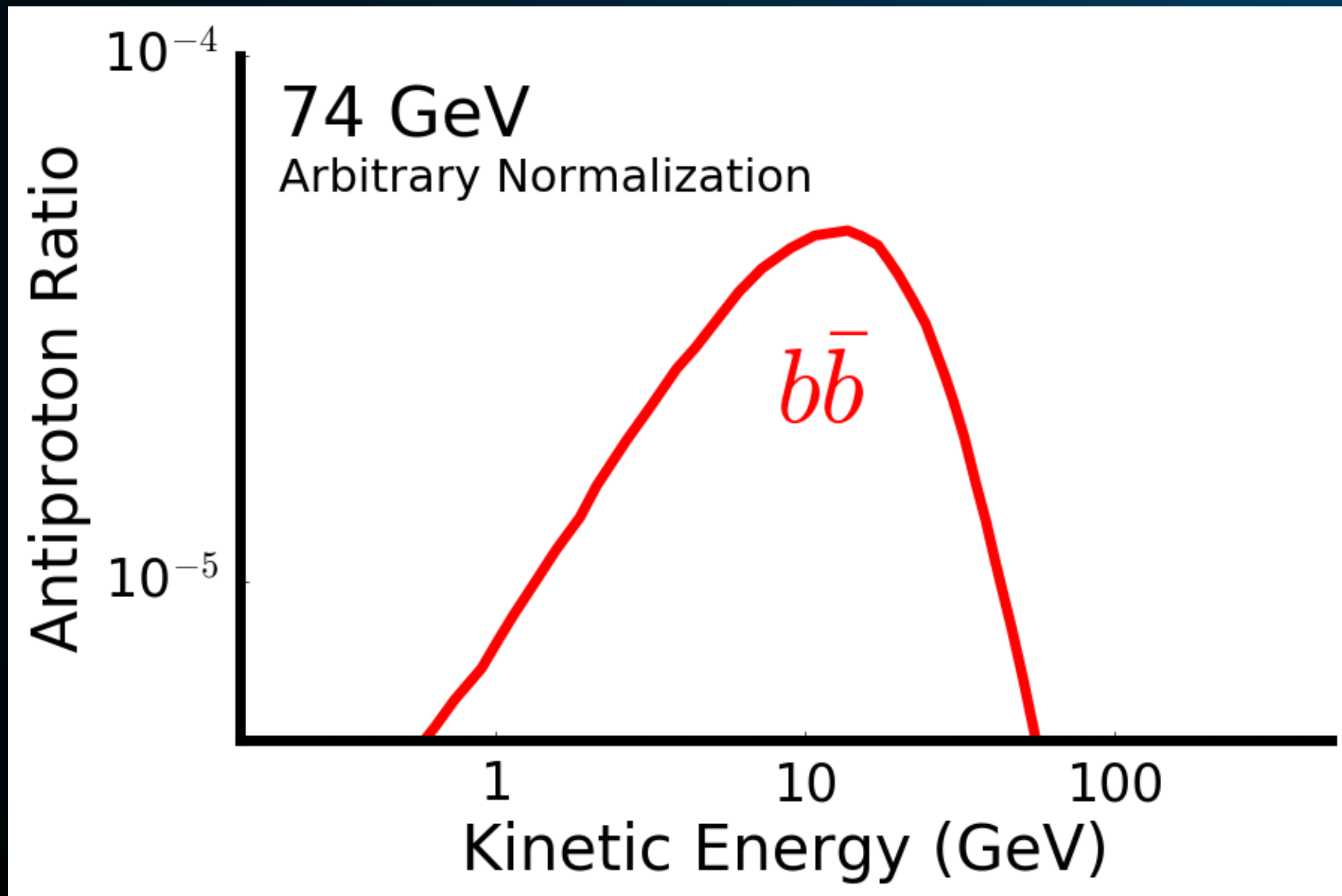
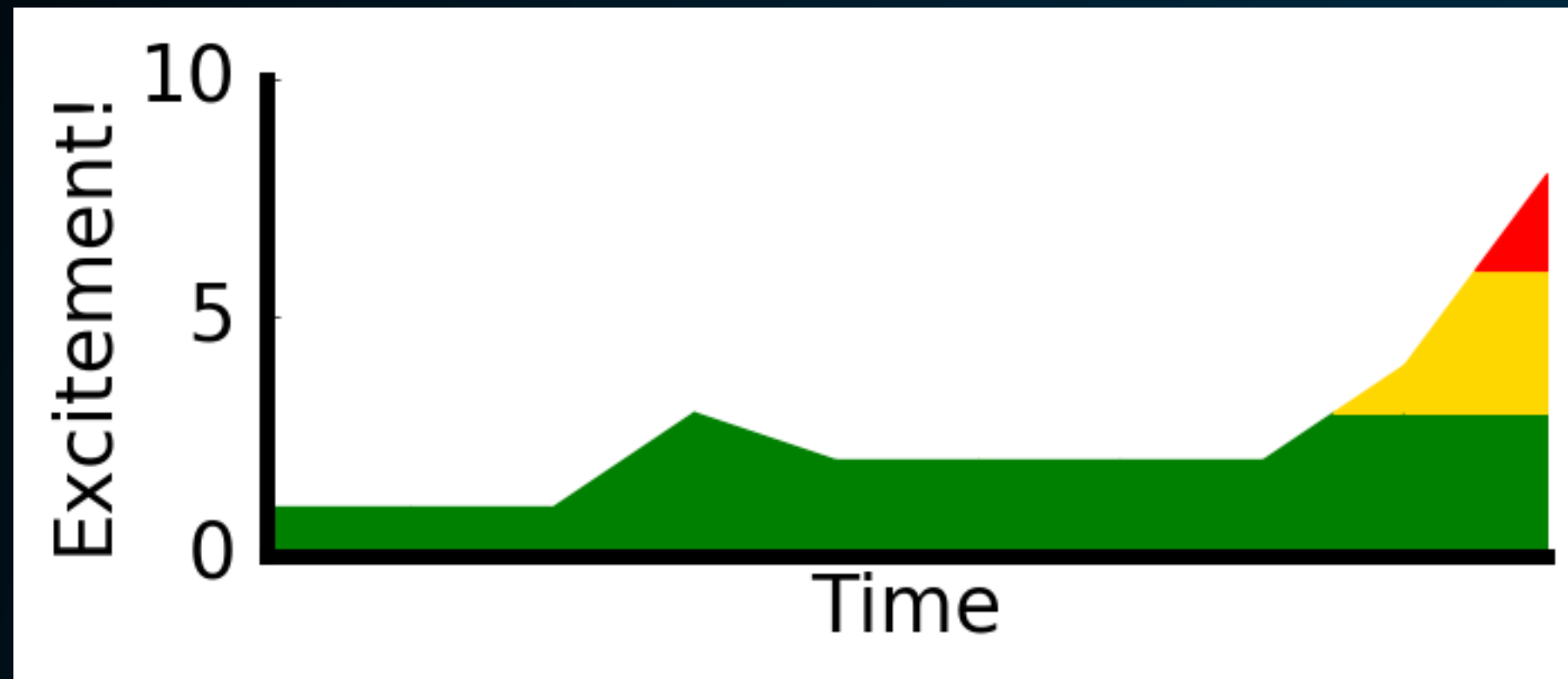
The Antiproton Excess



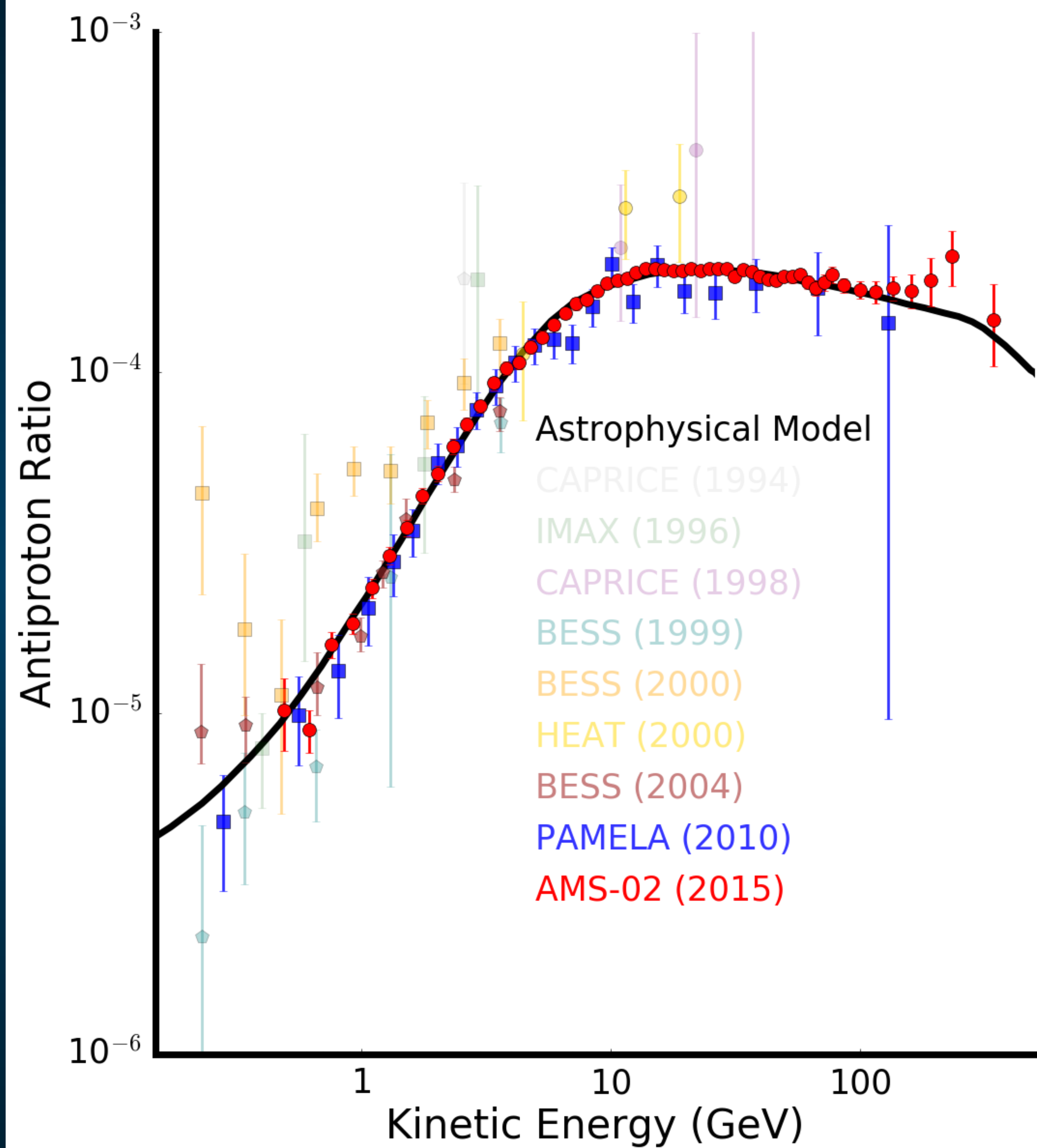
(Not an exhaustive list of observations)



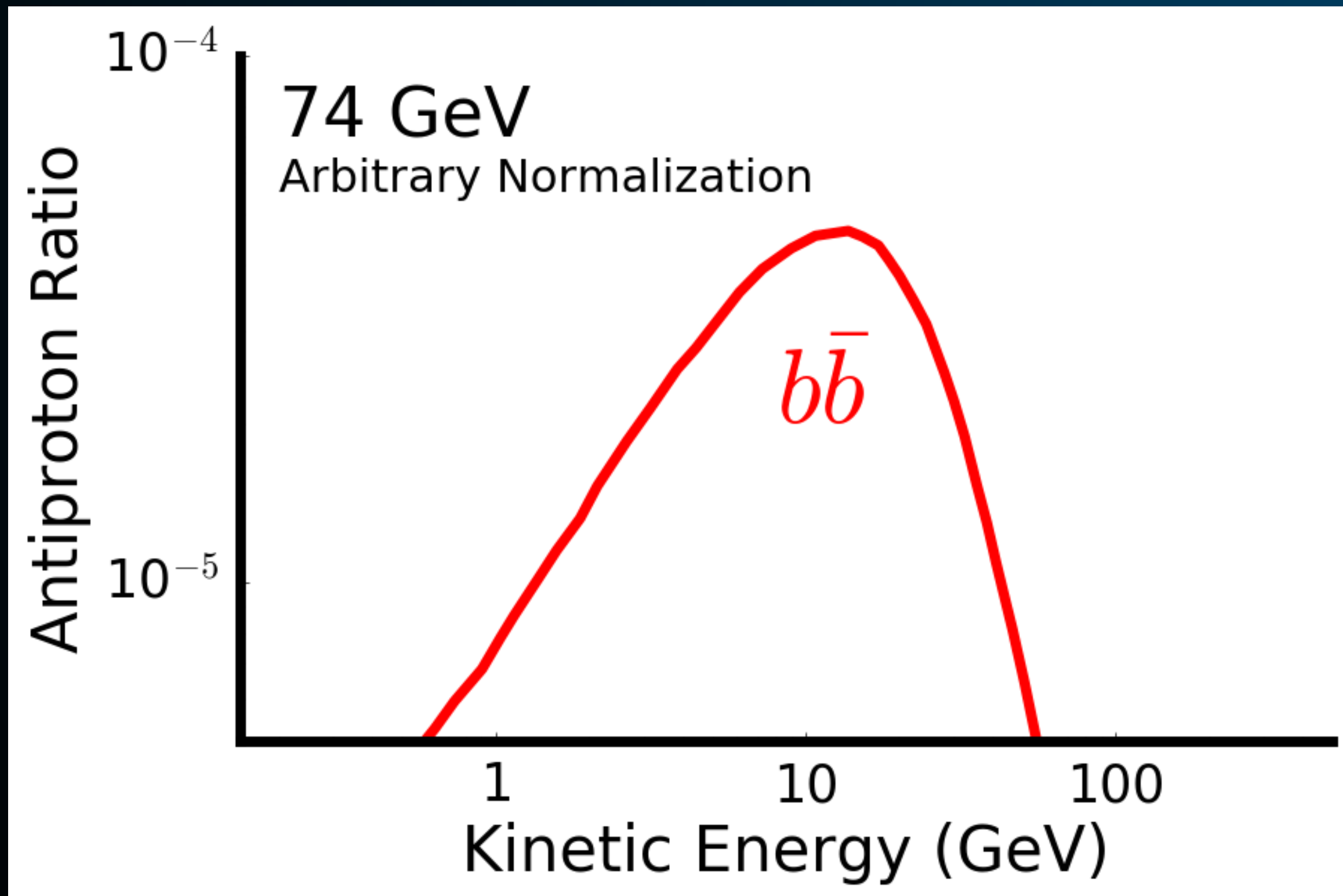
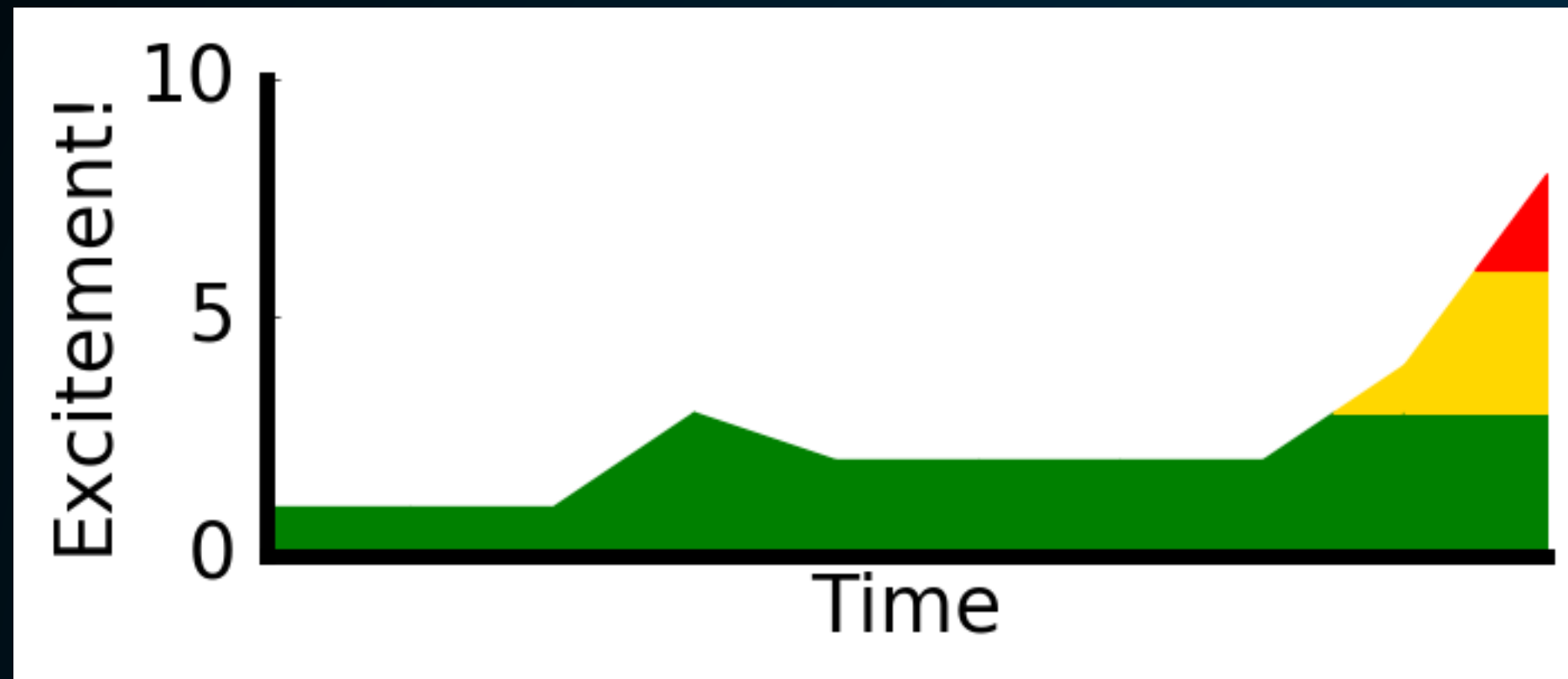
The Antiproton Excess



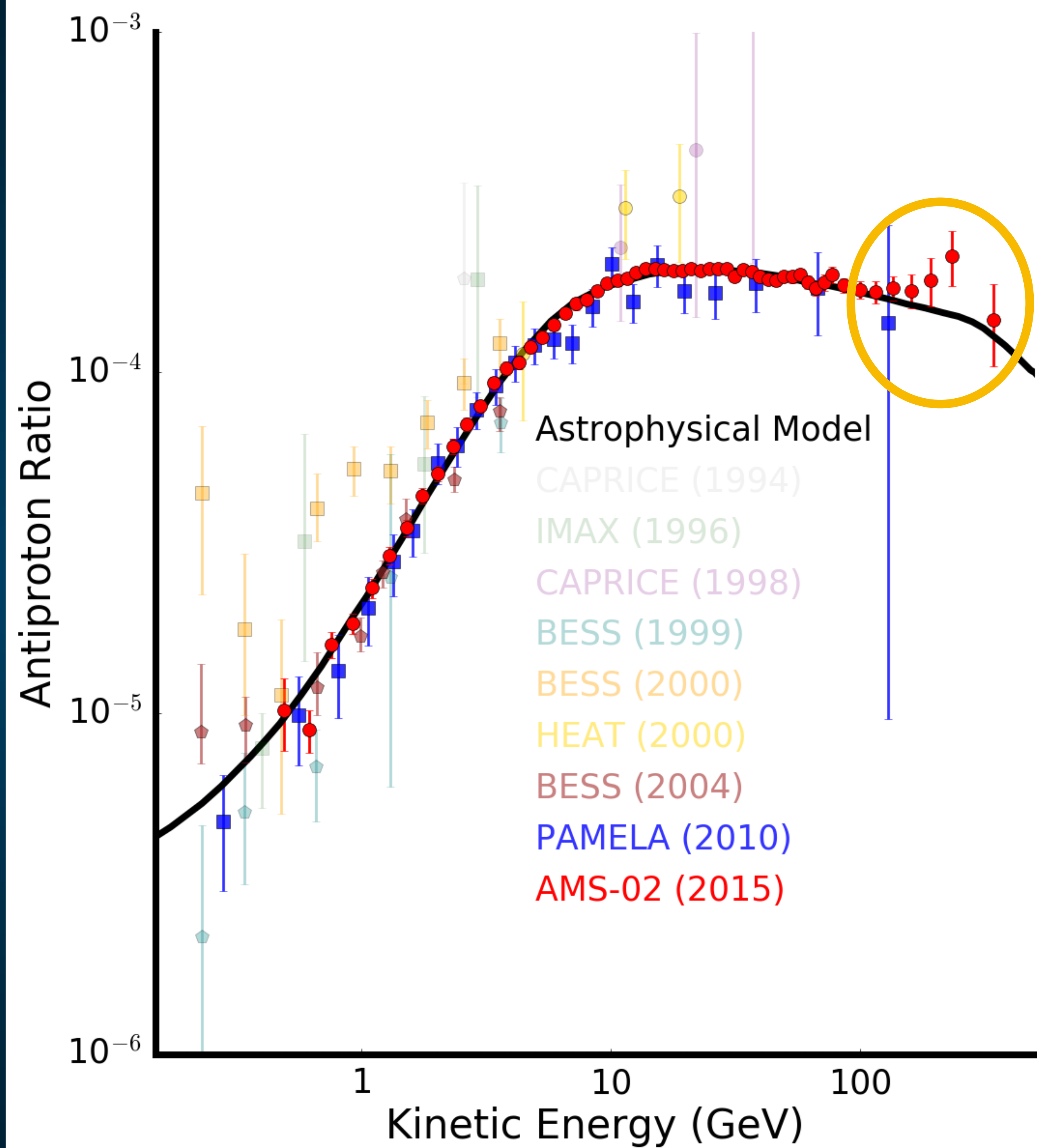
(Not an exhaustive list of observations)



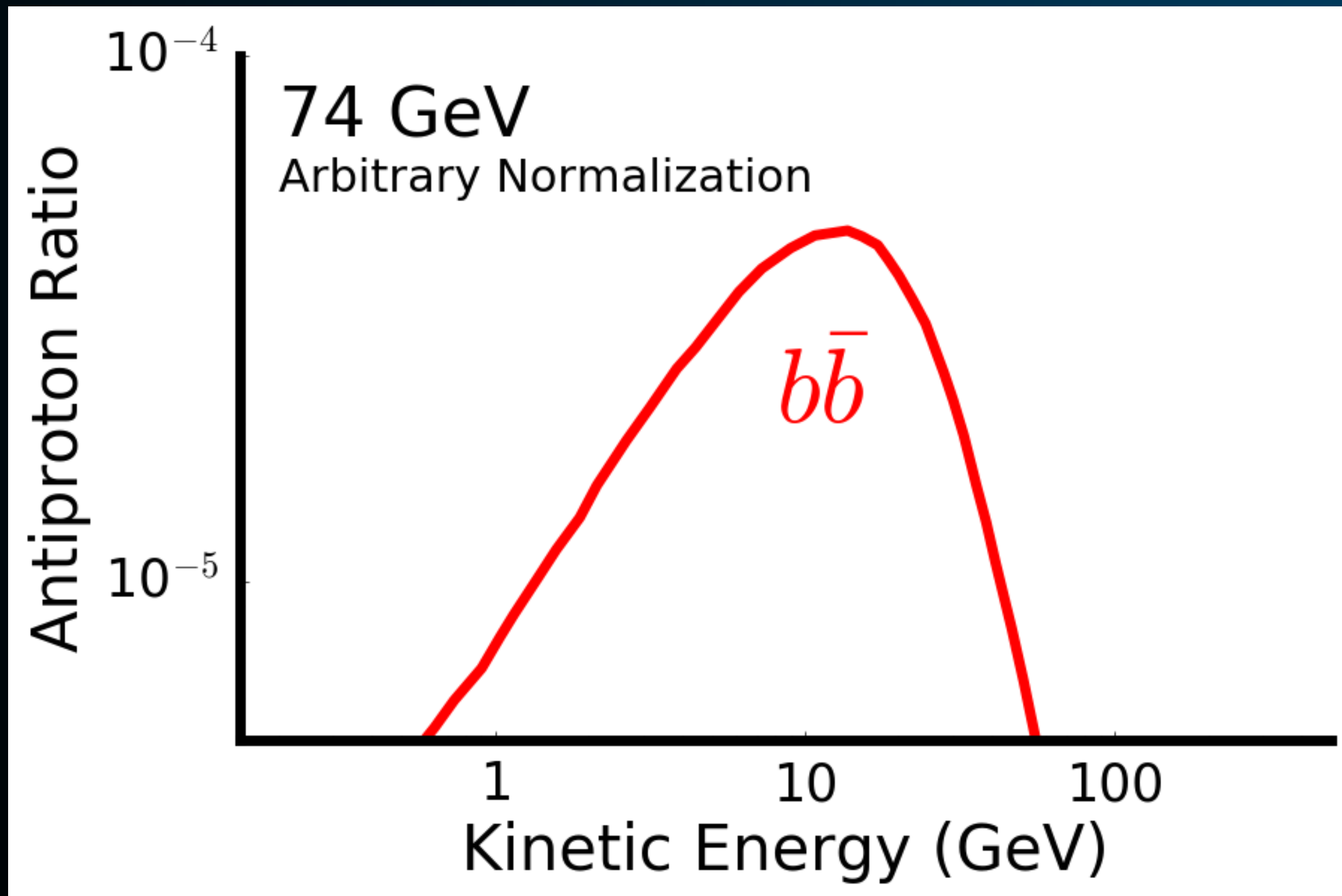
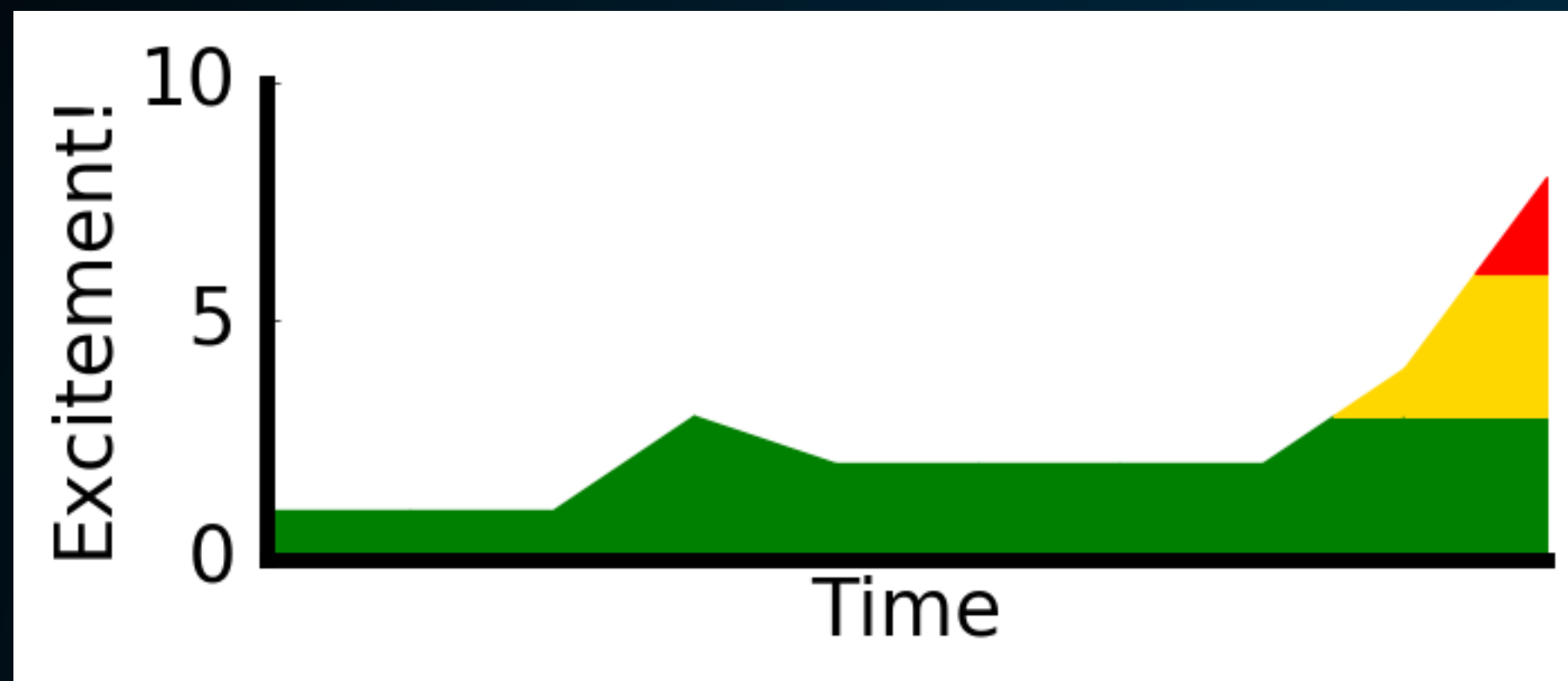
The Antiproton Excess



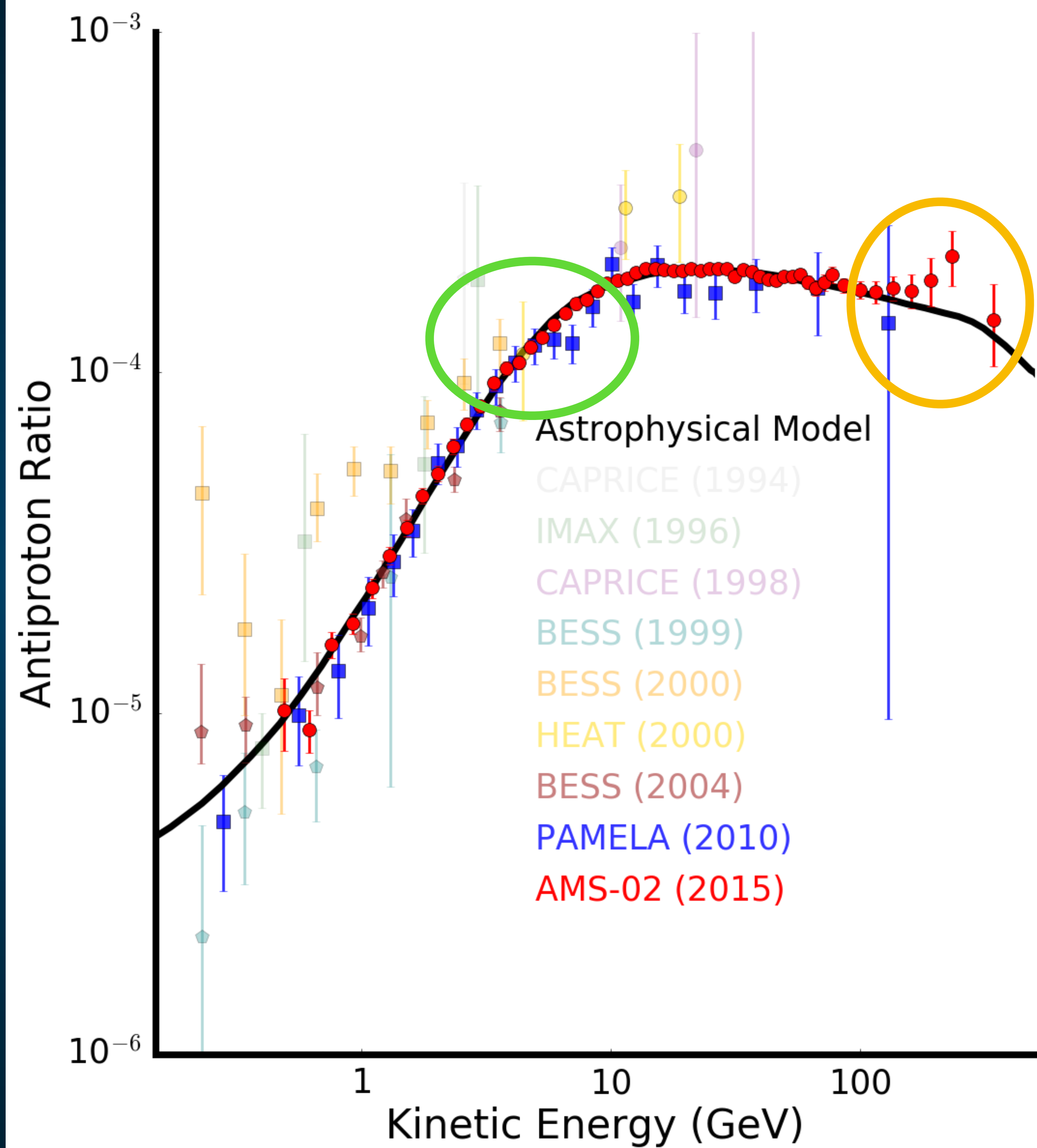
(Not an exhaustive list of observations)



The Antiproton Excess



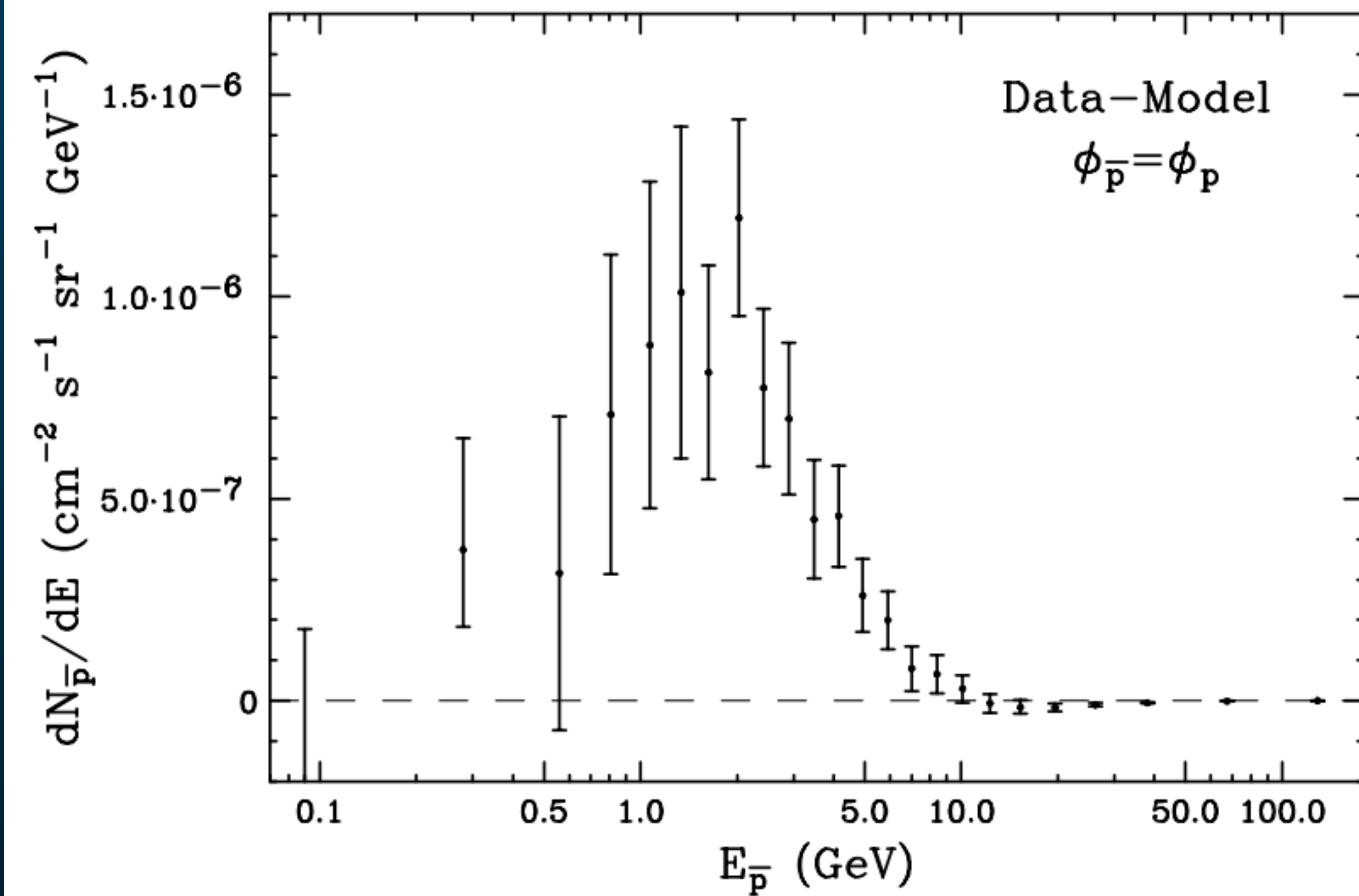
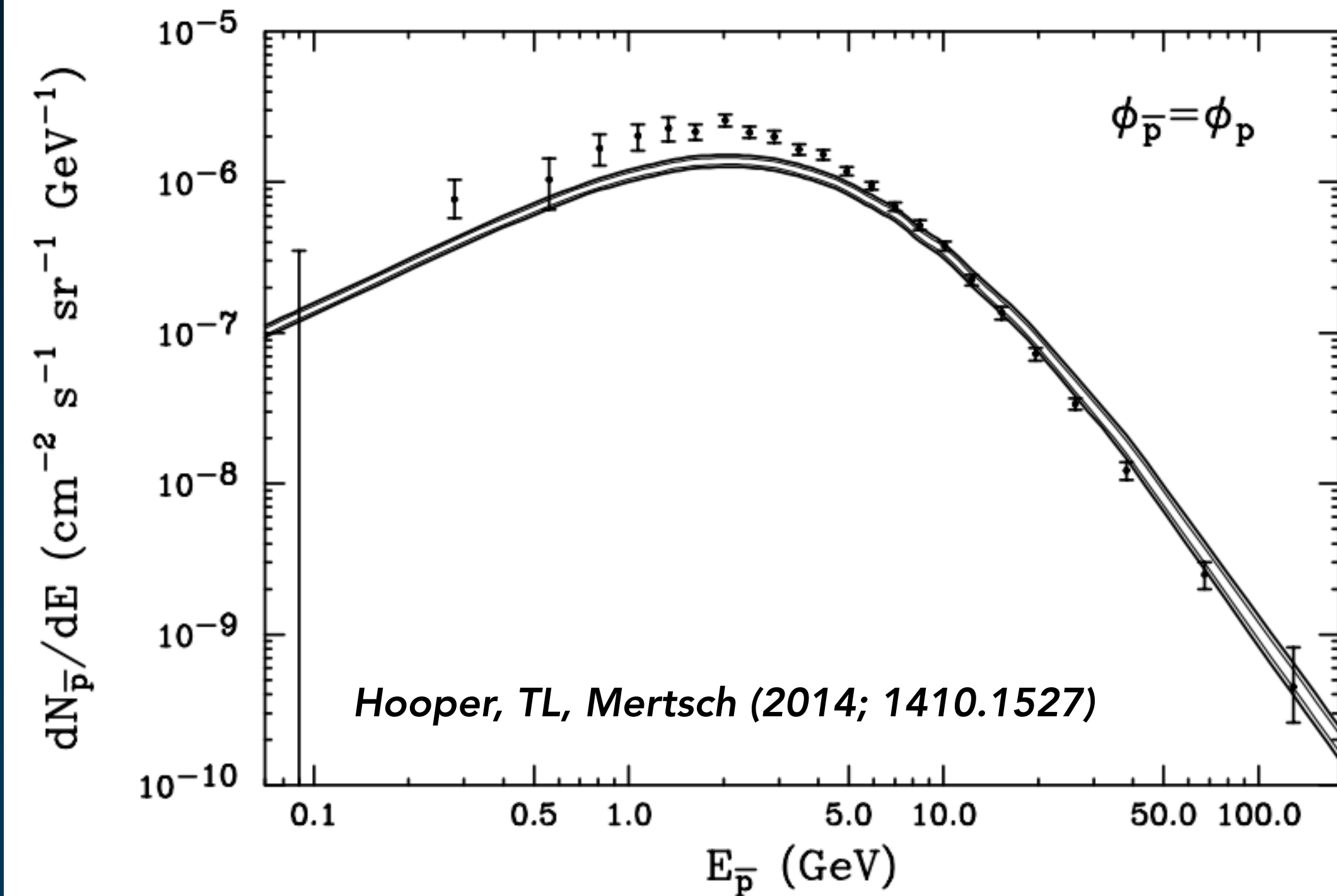
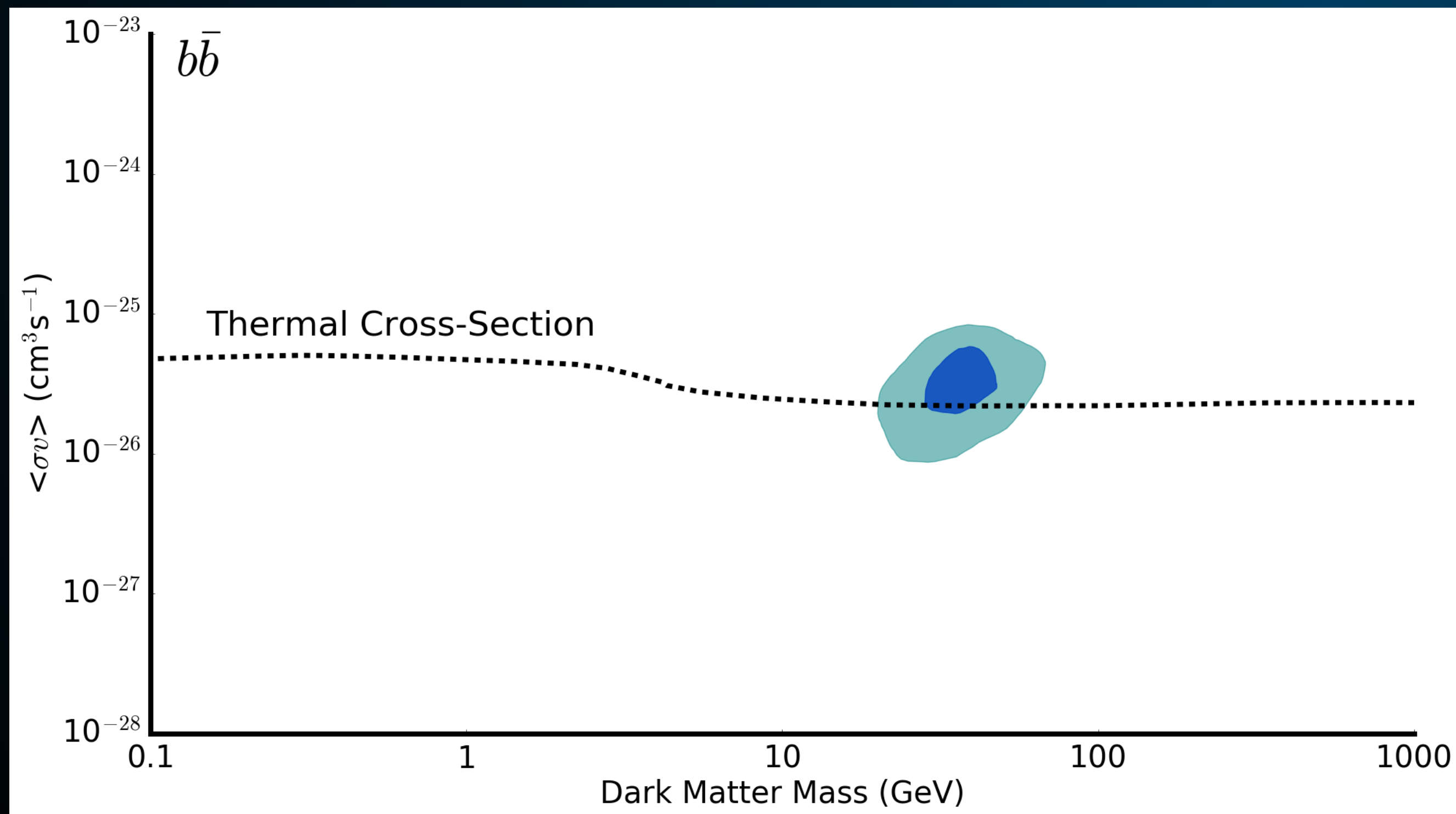
(Not an exhaustive list of observations)



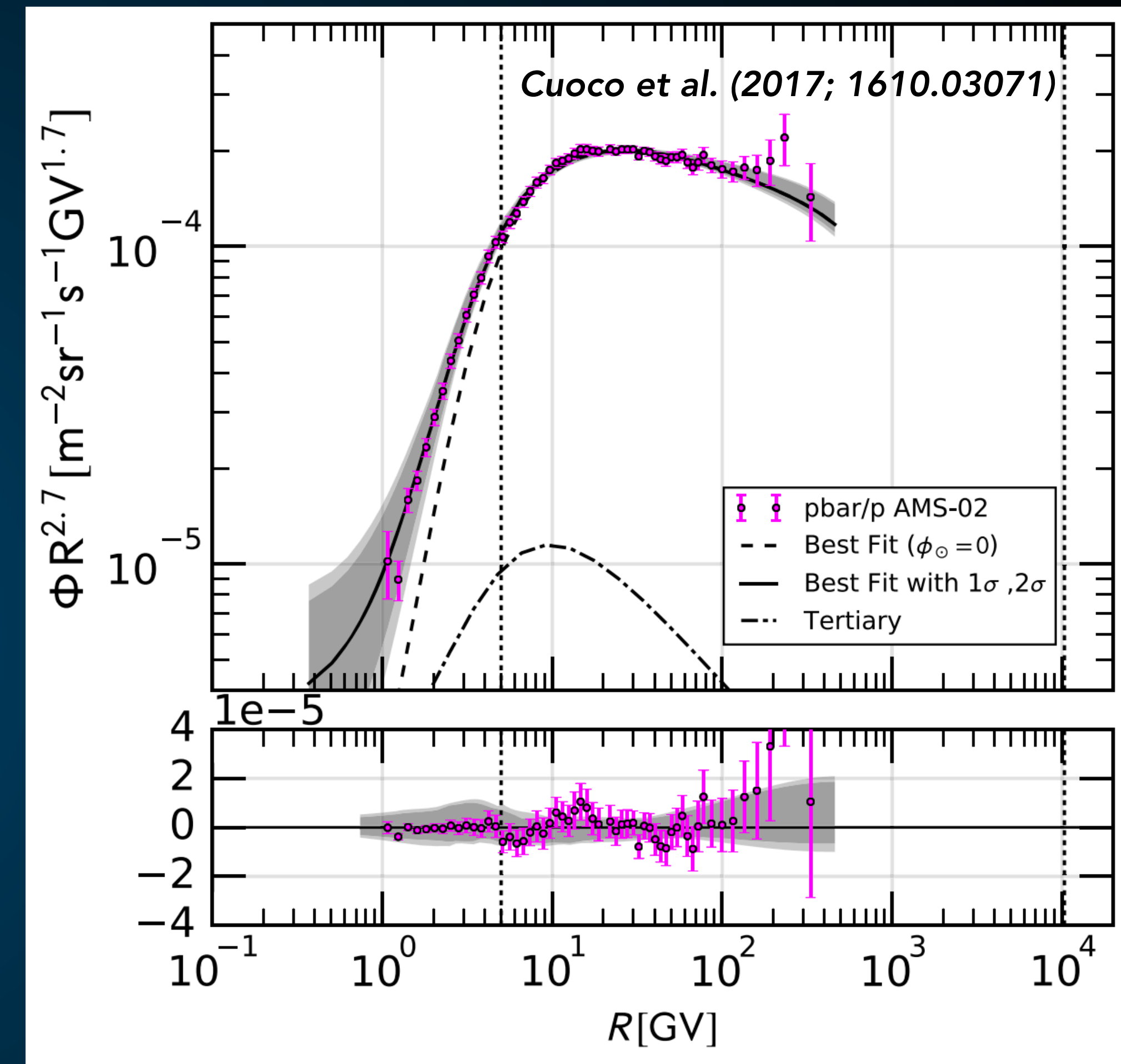
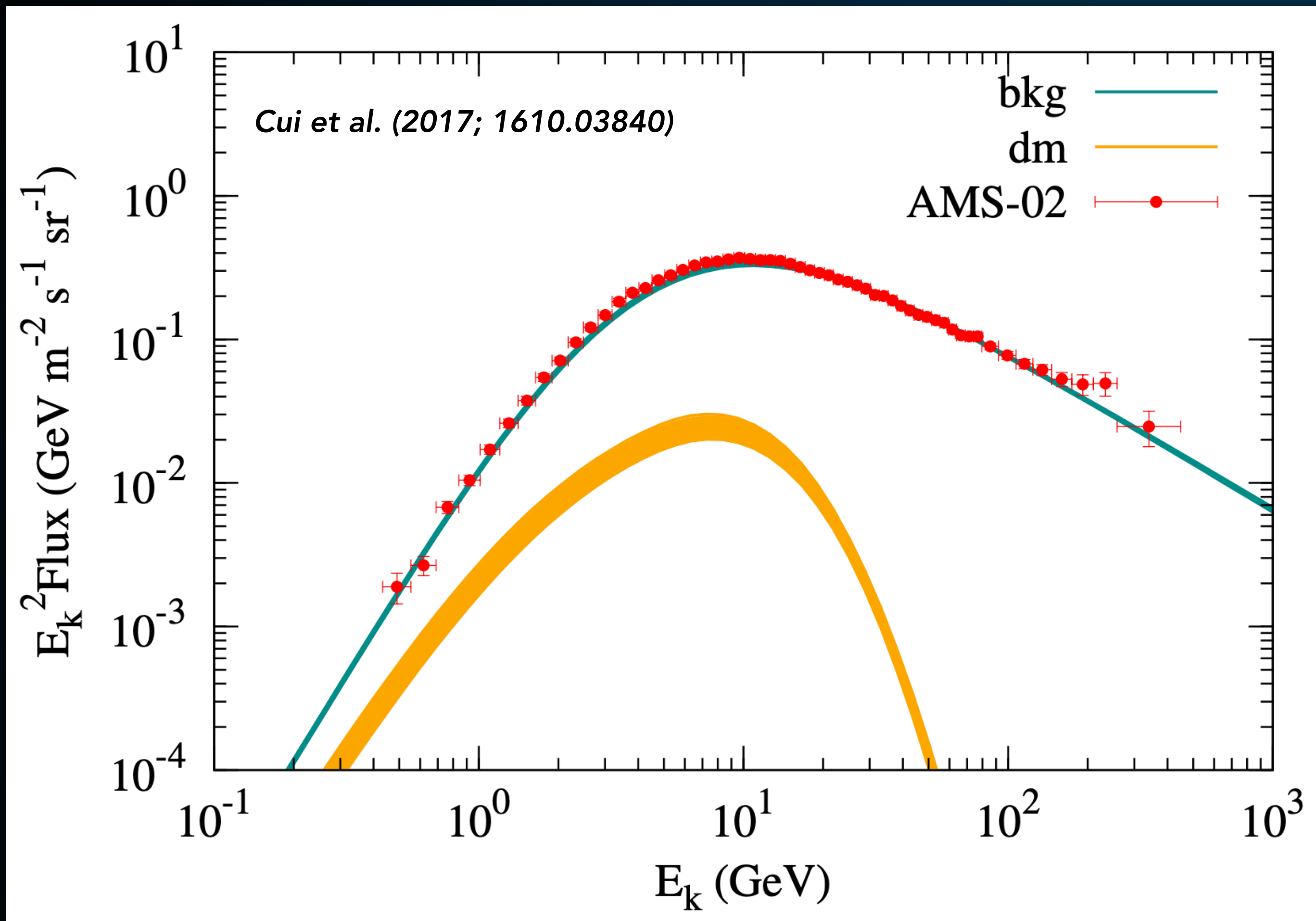
The Antiproton Excess

Hint of Excess in ~5 GeV antiprotons!

Astrophysical Uncertainties can significantly affect the signal.

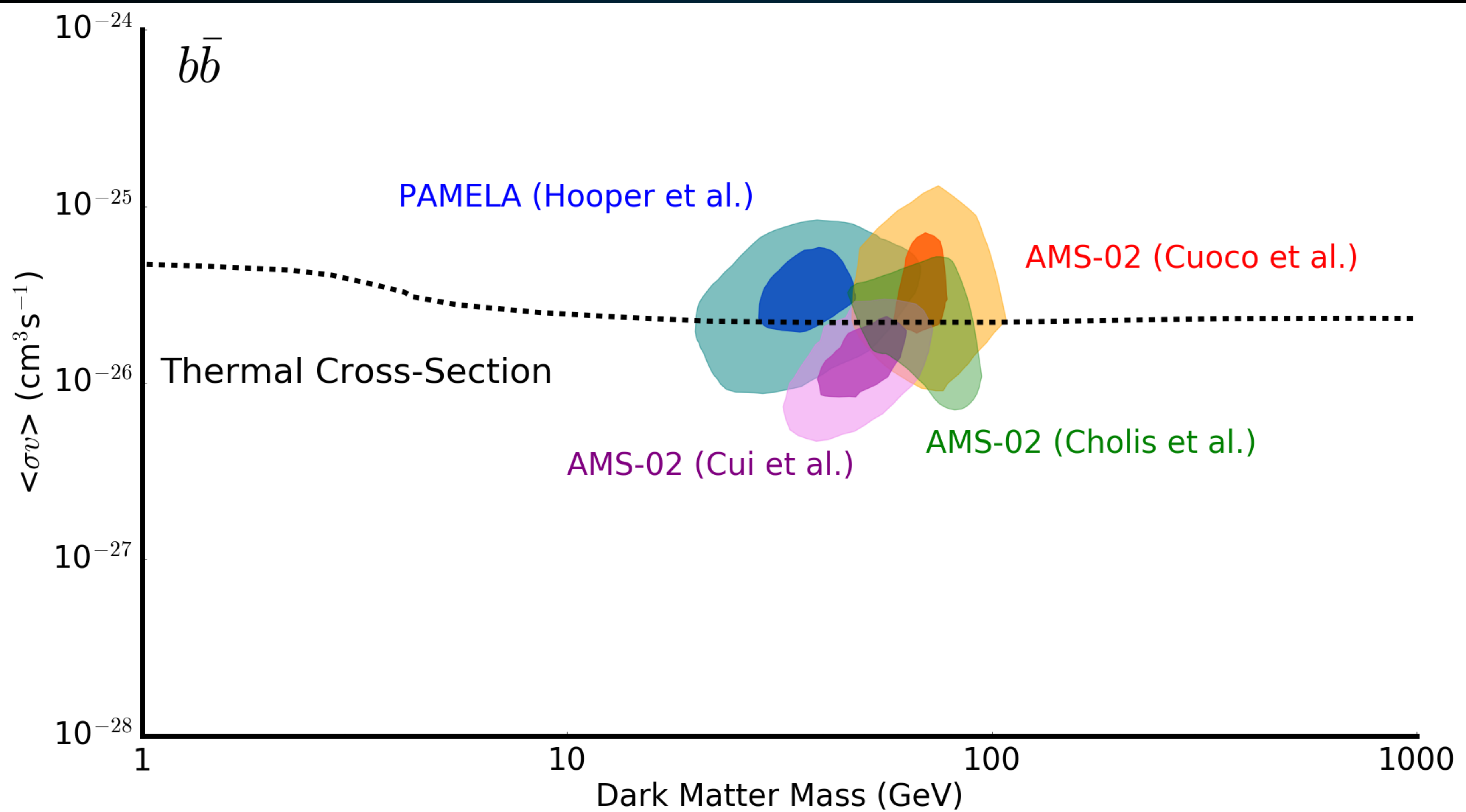


The Antiproton Excess



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

Significance approaching (or past) 5σ !



The Antiproton Excess - A Detection?

Reinert, Winkler (2018; 1712.00002)

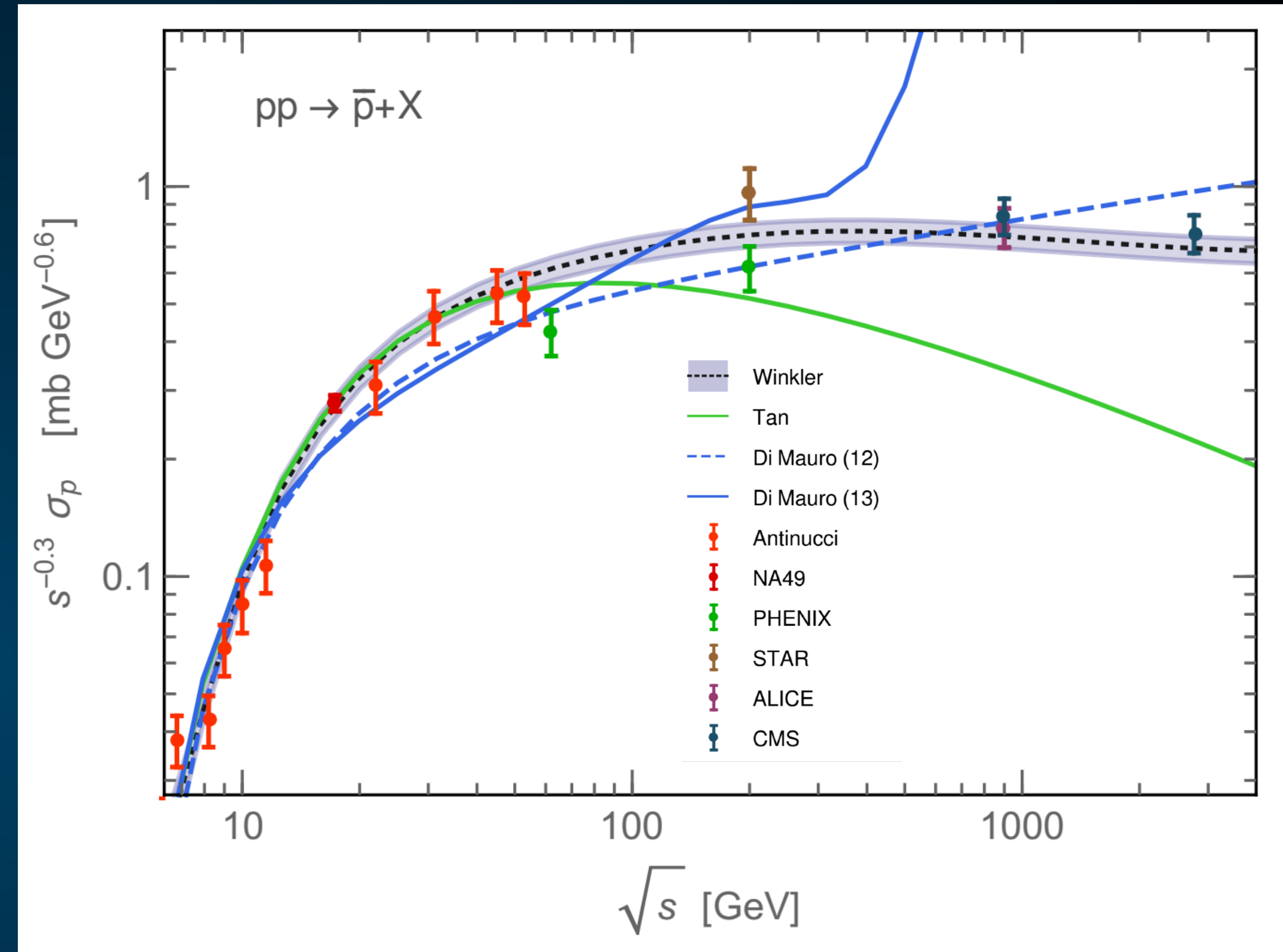
With great precision comes great responsibility:

Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

Solar Modulation

Antiproton Production Cross-Section



The Antiproton Excess - A Detection?

Reinert, Winkler (2018; 1712.00002)

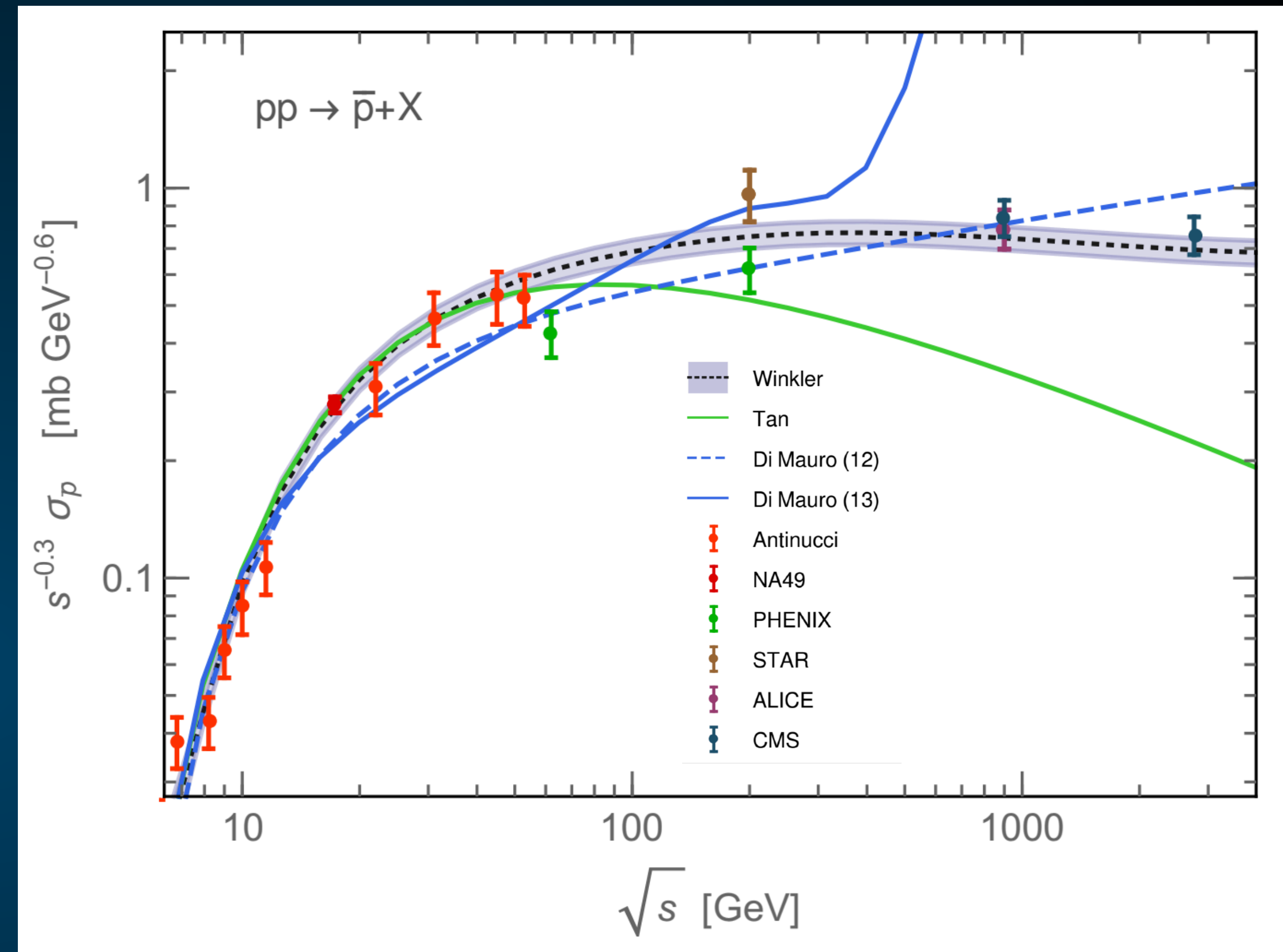
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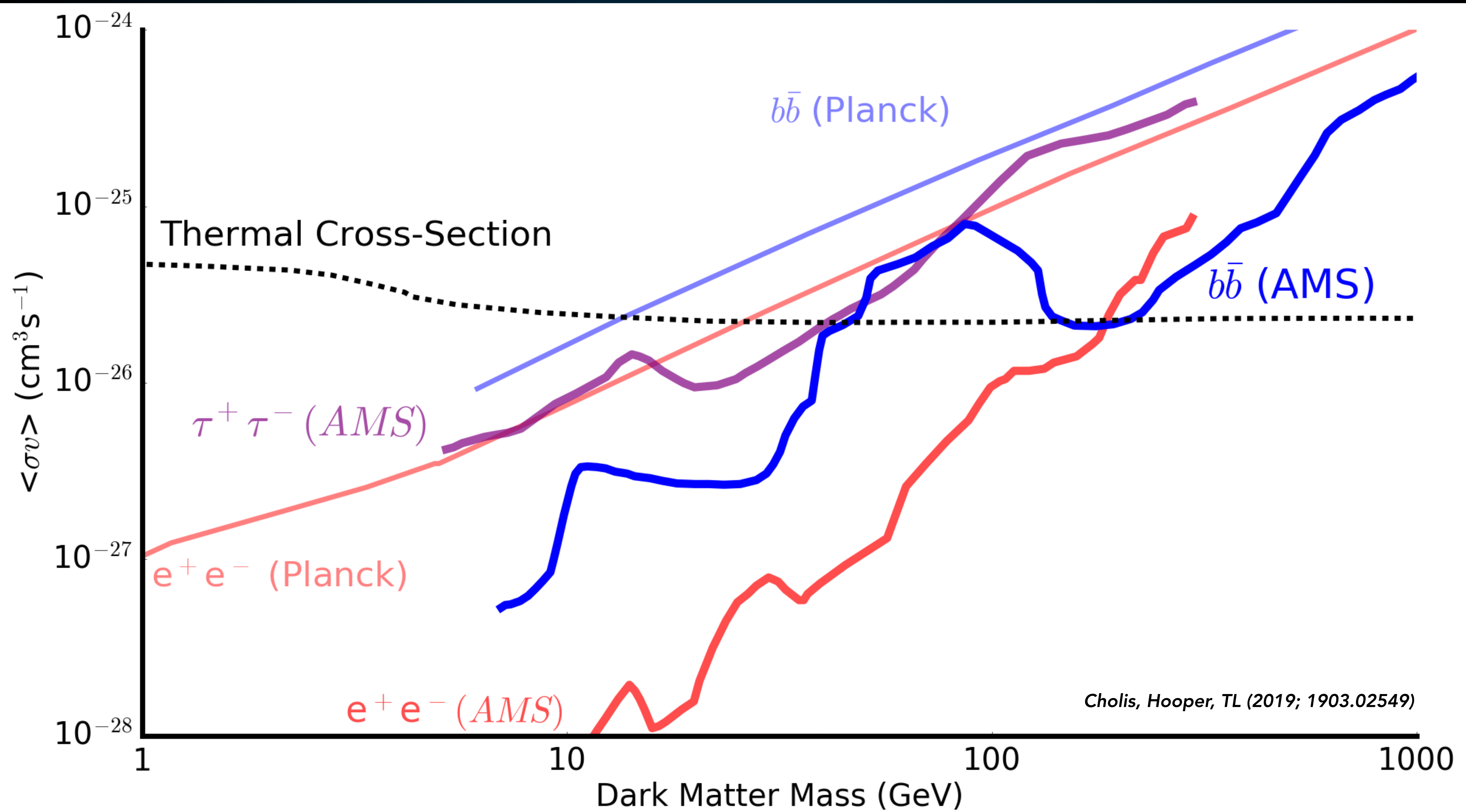


Galactic Primary to Secondary Ratios - Future AMS-02 Data!

Inhomogeneous Diffusion - TeV Halos

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

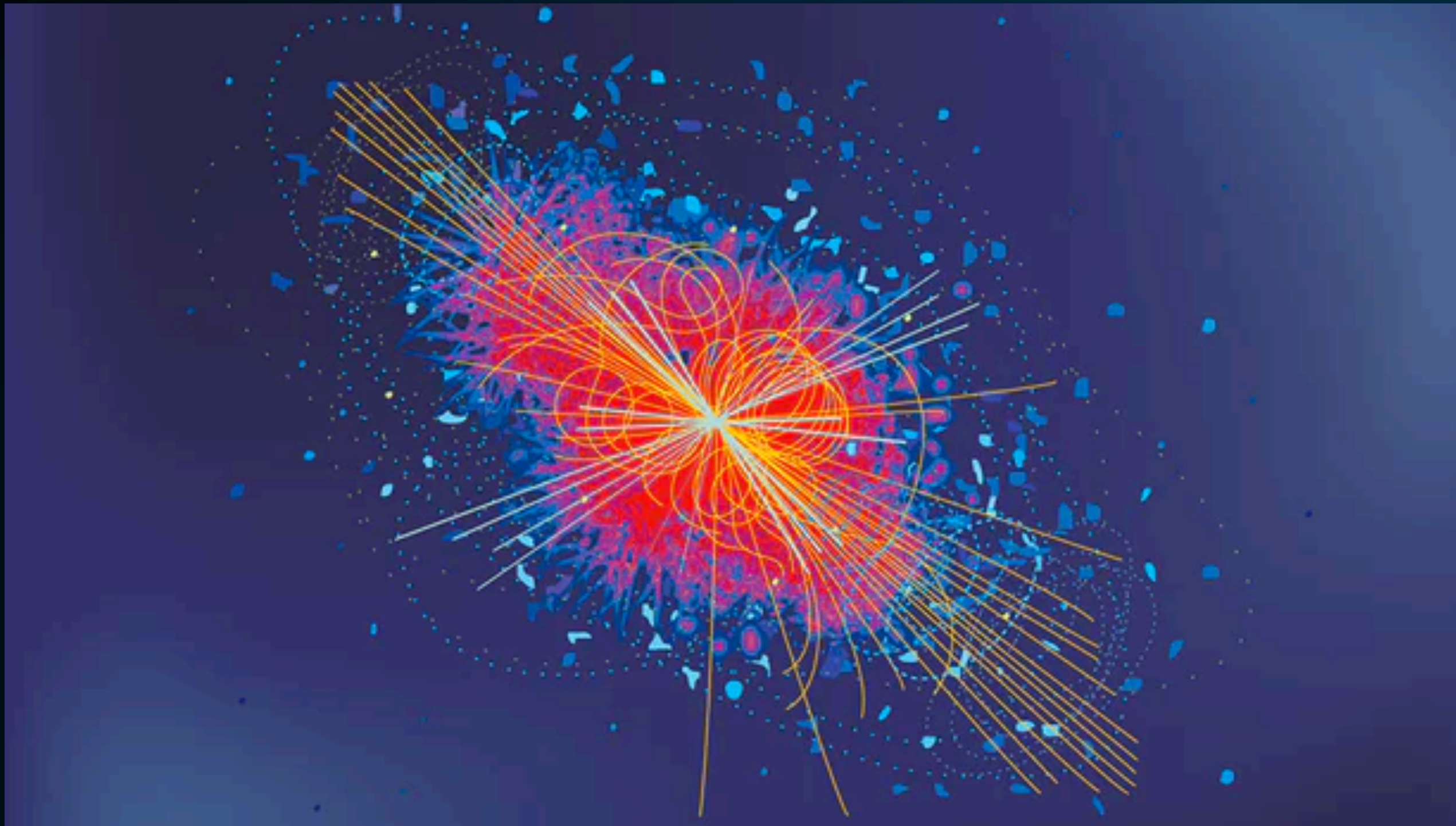
Antiproton Production Cross-Section - LHCb / Laboratory Experiments



Antinuclei!?



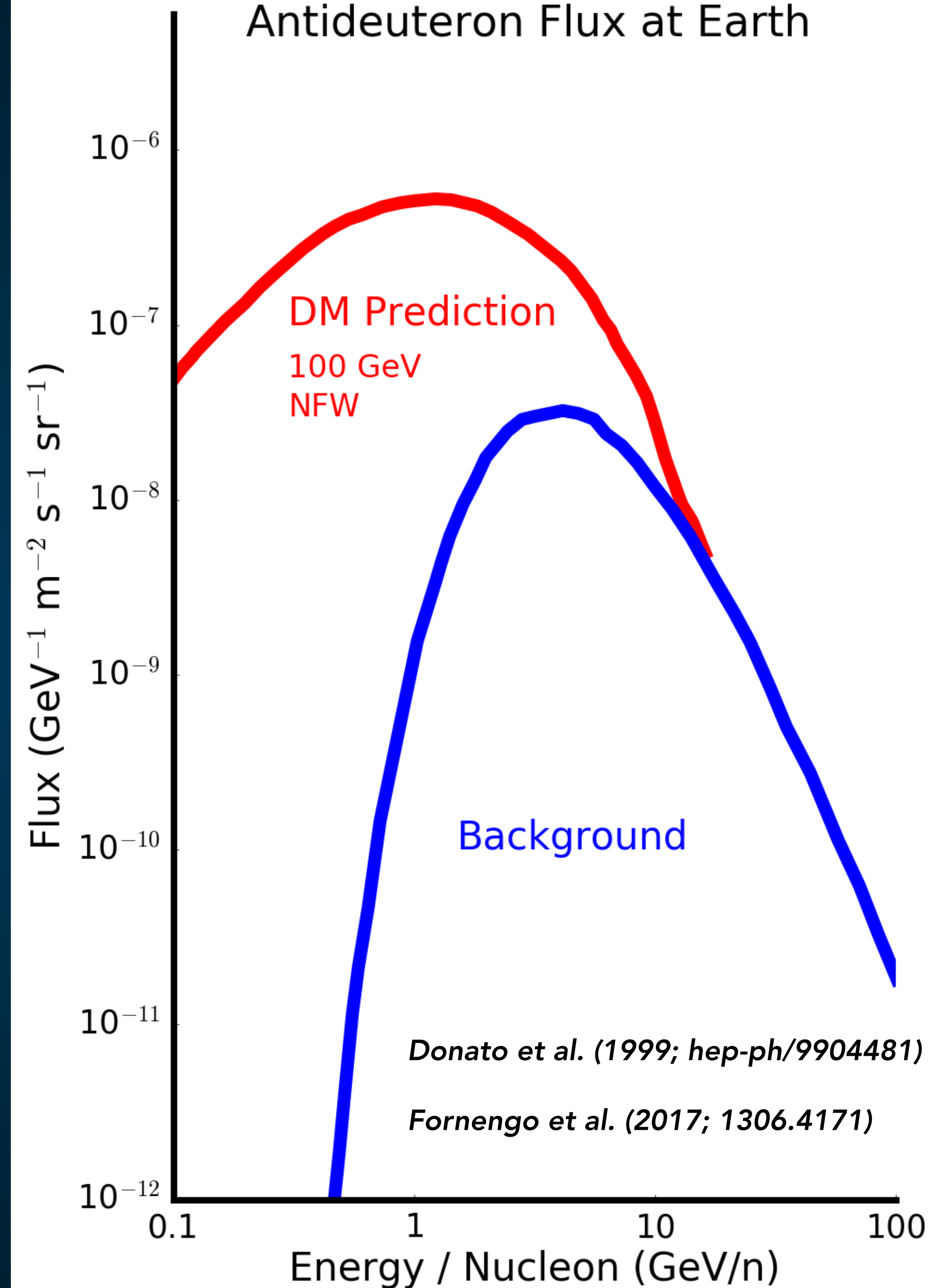
AntiNuclei - A Clean Search Strategy ?



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

Astrophysical Antinuclei - Most be moving relativistically!

Dark Matter Antinuclei - Can be slow!



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

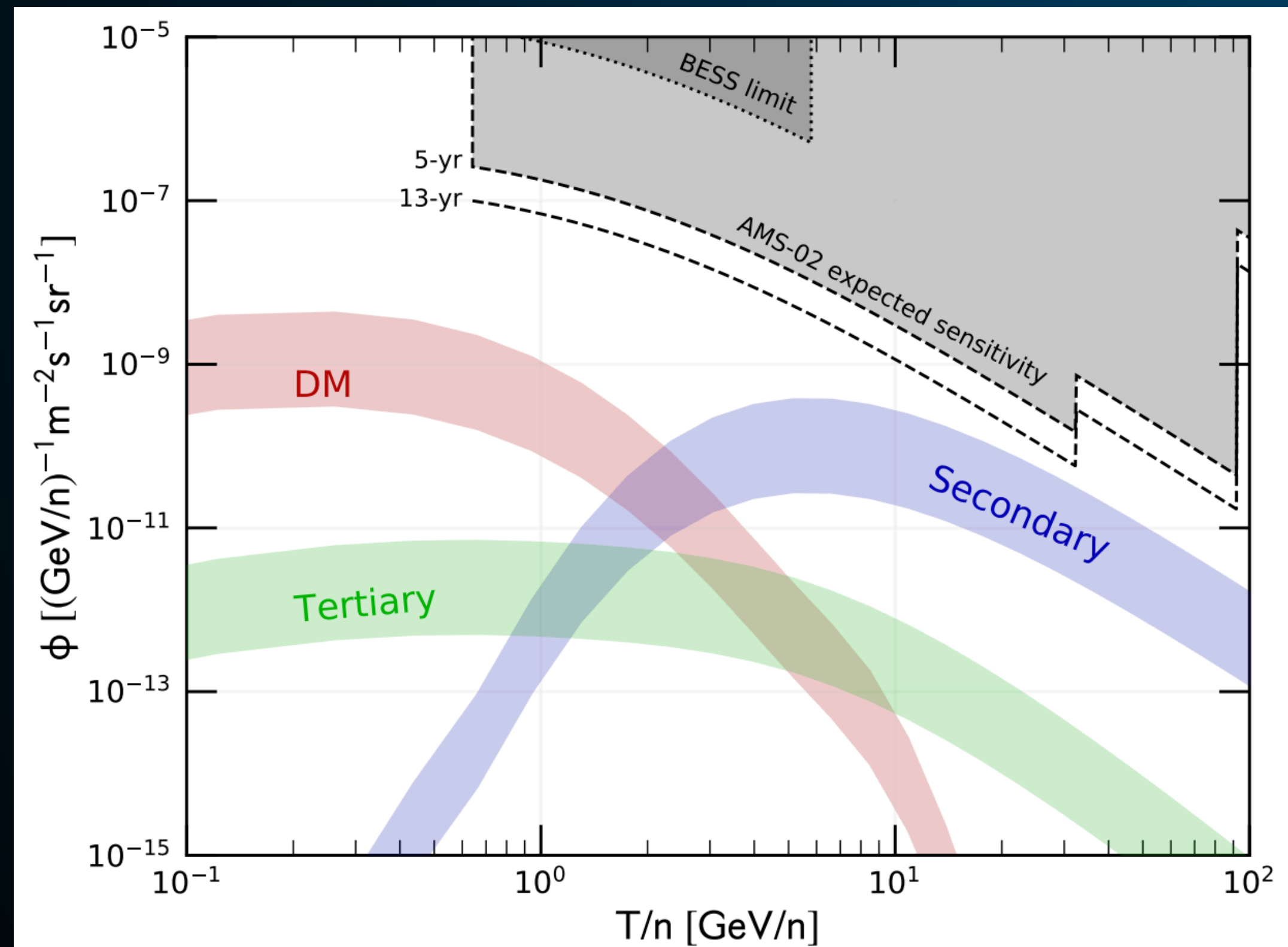
Currently (having used 50 million core hours to generate 7 times more simulated events than measured events and having found no background events from the simulation), our best evaluation of the probability of the background origin for the eight $\bar{\text{He}}$ events is **less than 3×10^{-8}** . For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

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

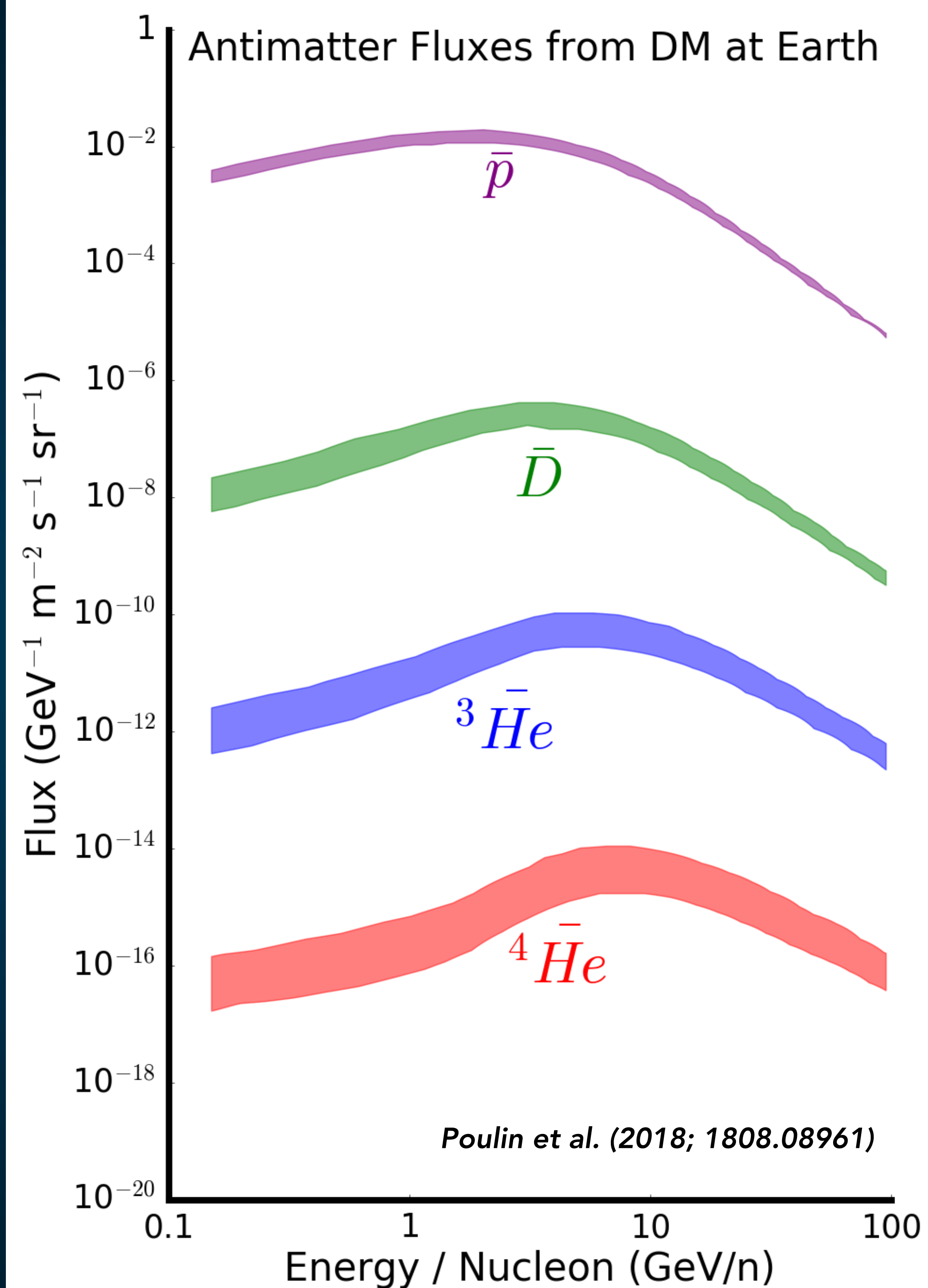
AntiNuclei - A Clean Search Strategy ?

Antihelium background even cleaner than antideuterons

But the flux is supposed to be much smaller.



Korsmeier (2017; 1711.08465)

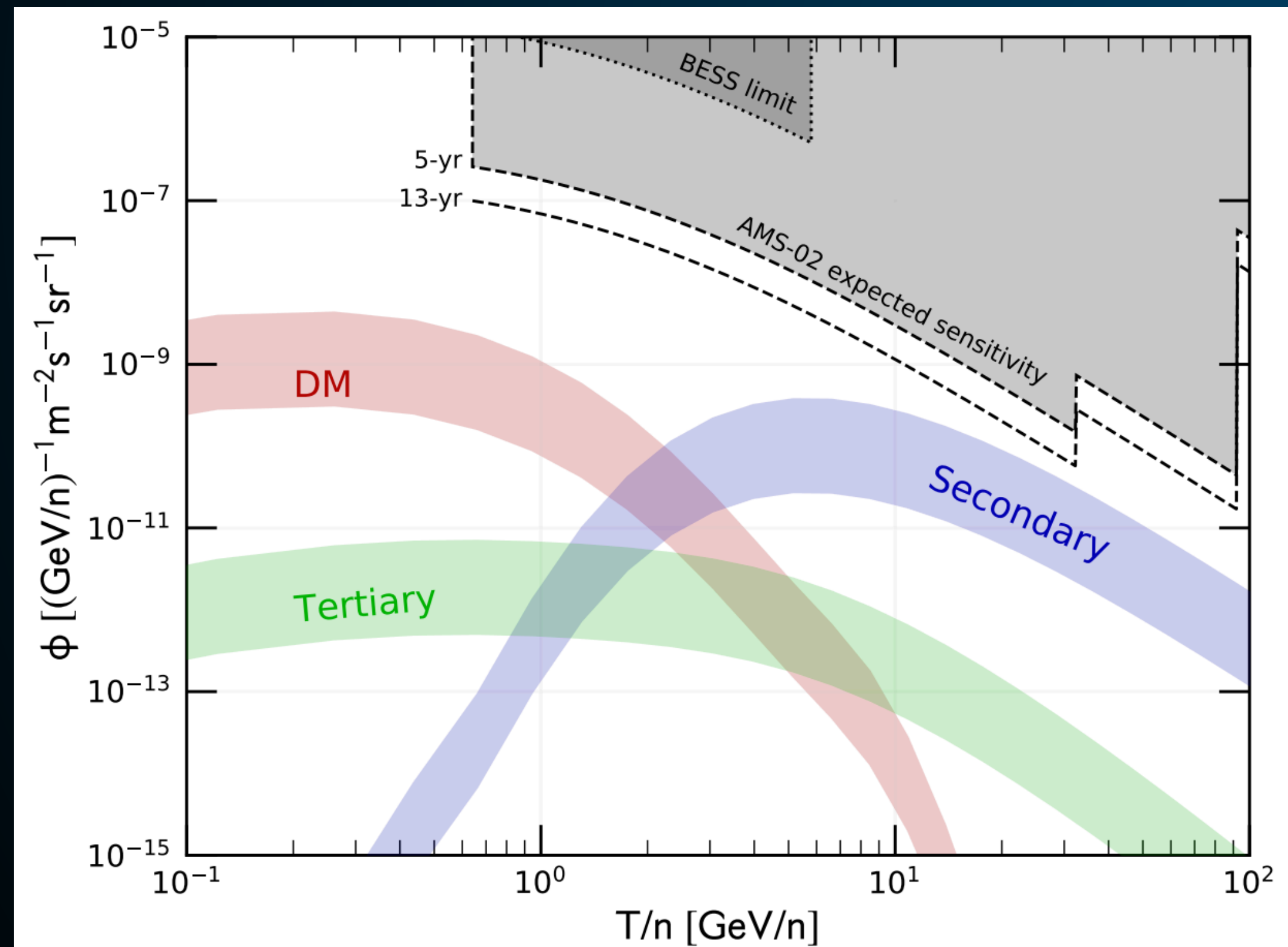


Poulin et al. (2018; 1808.08961)

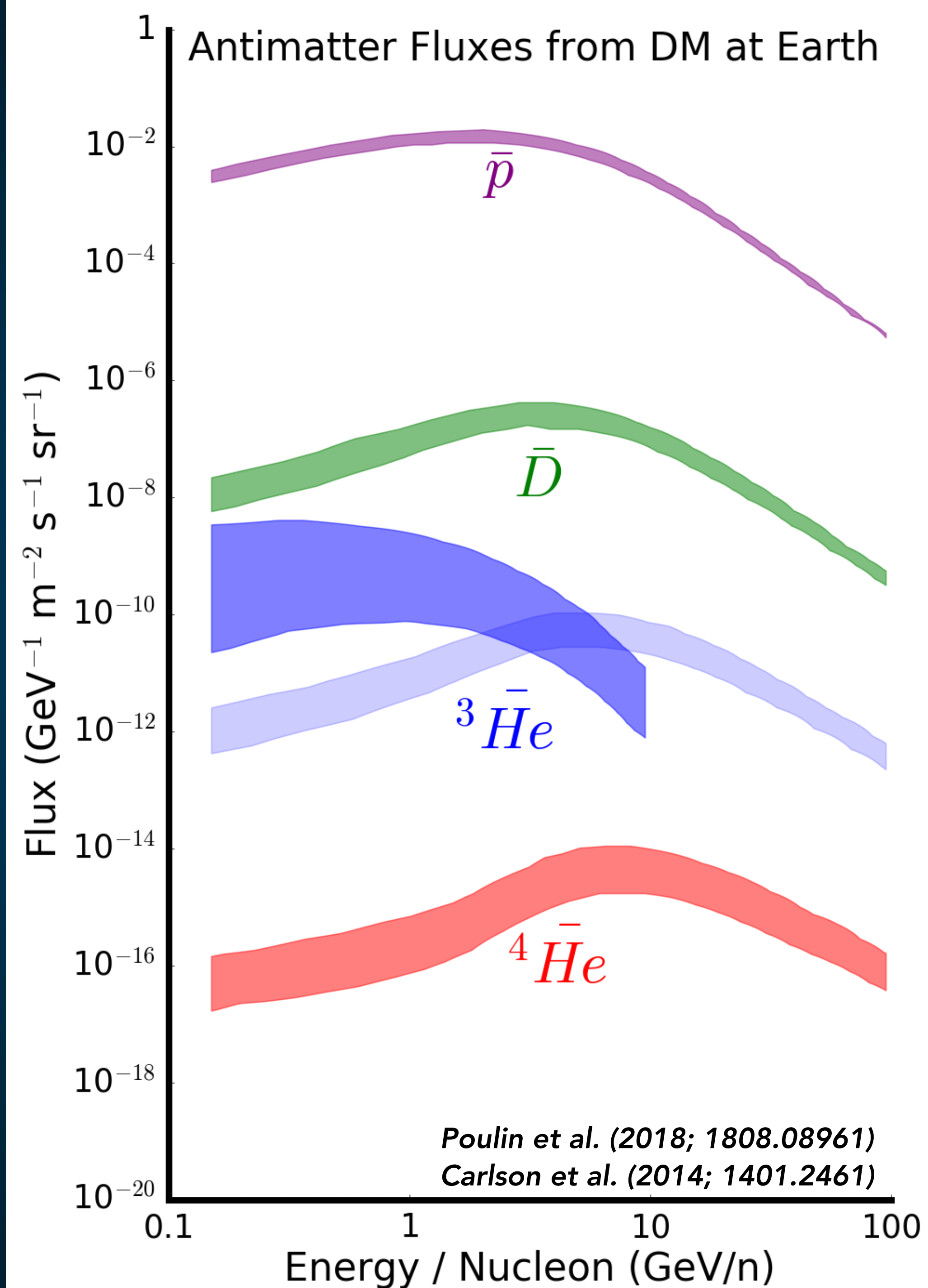
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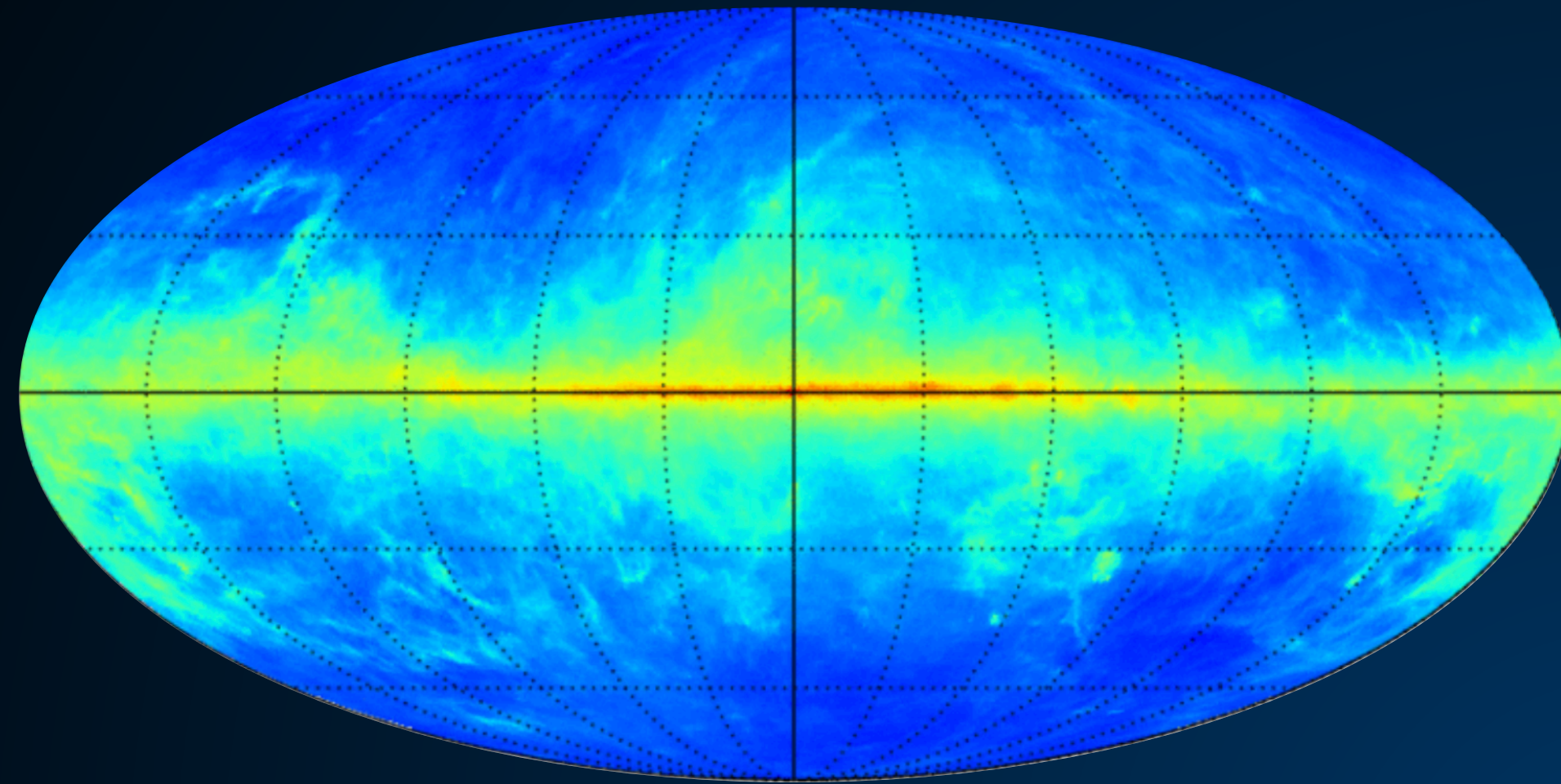


Poulin et al. (2018; 1808.08961)
Carlson et al. (2014; 1401.2461)

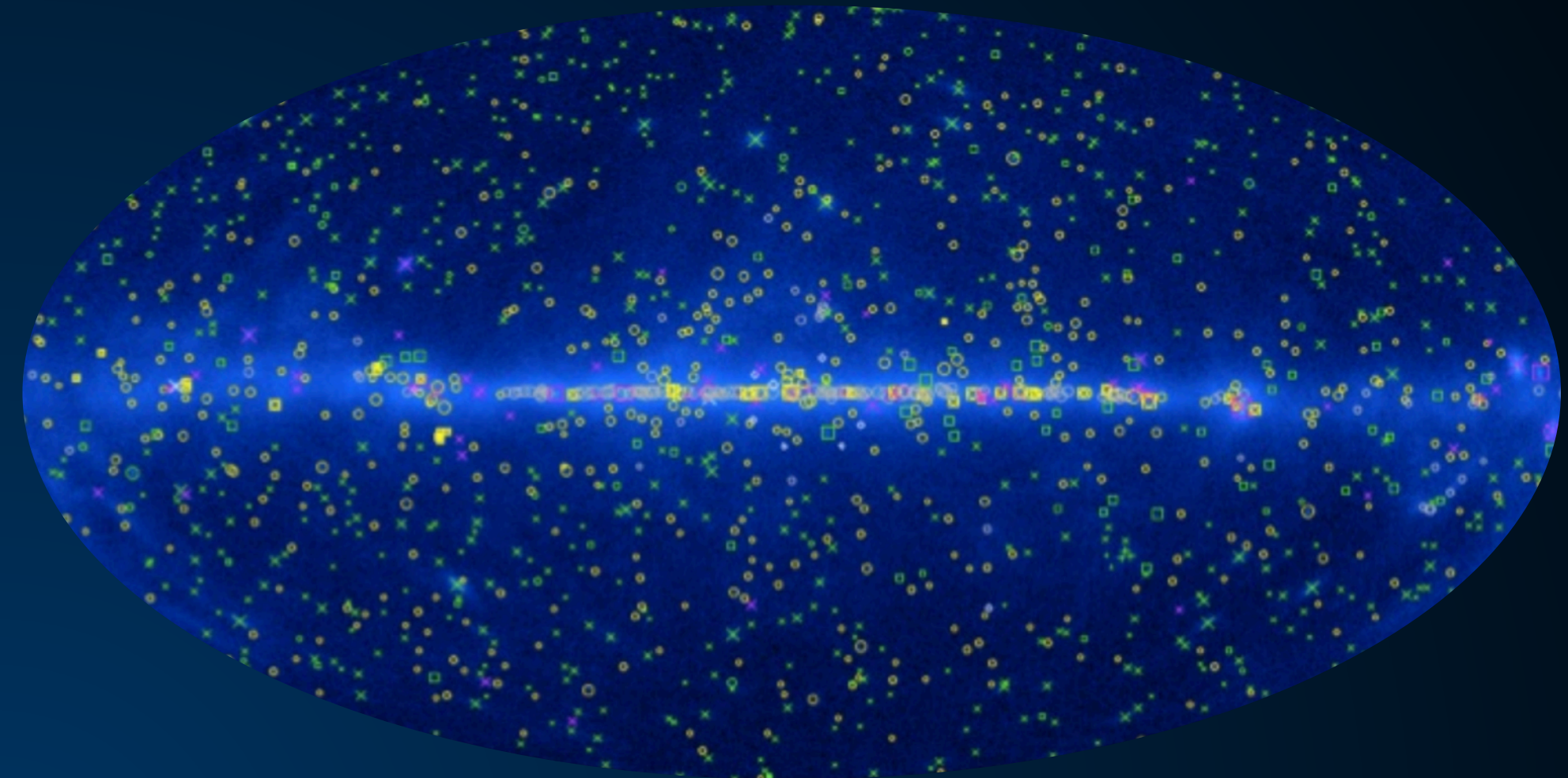


The Galactic Center Excess

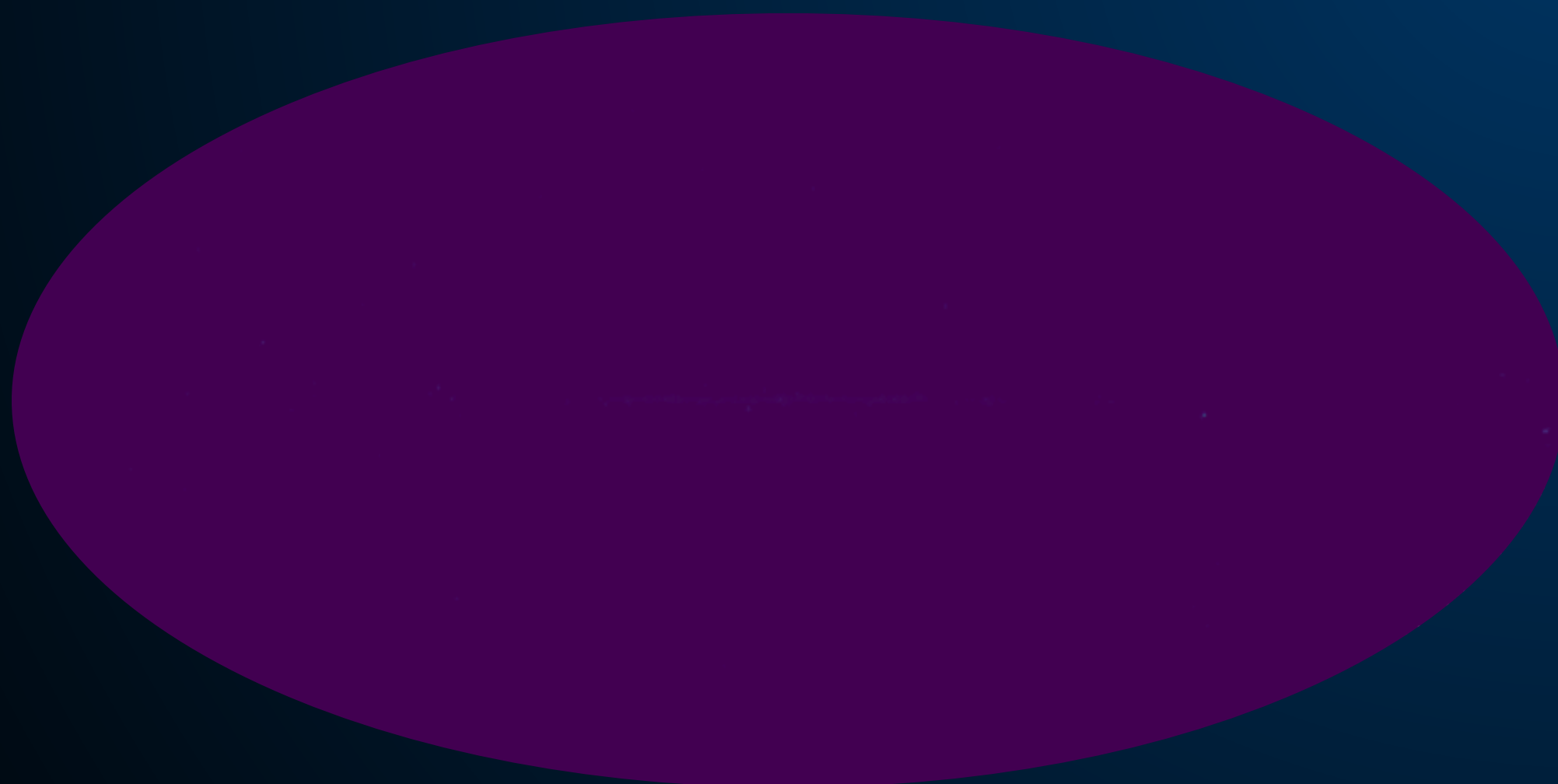
The Galactic Center - Techniques



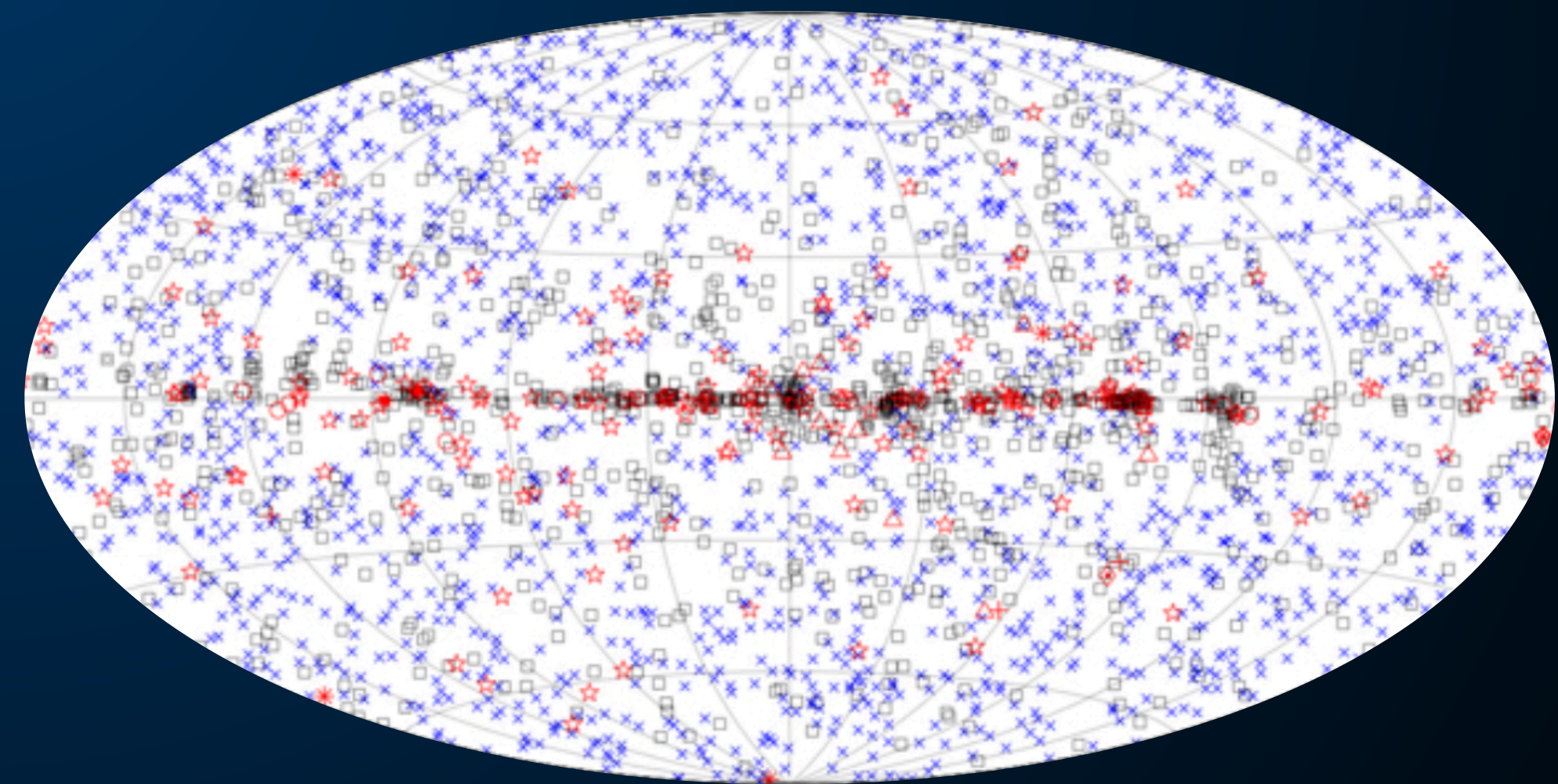
Galactic Diffuse



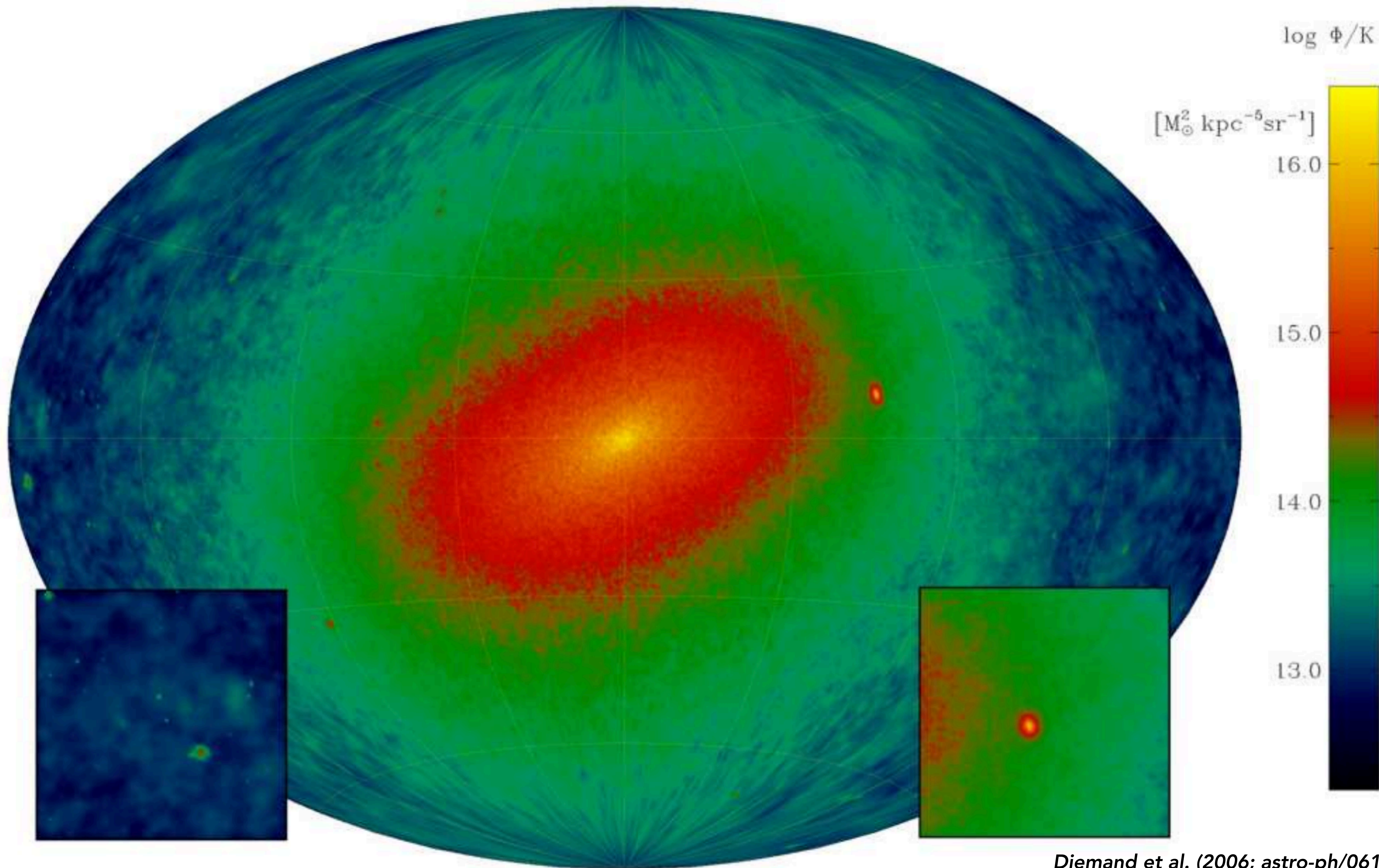
Point Sources

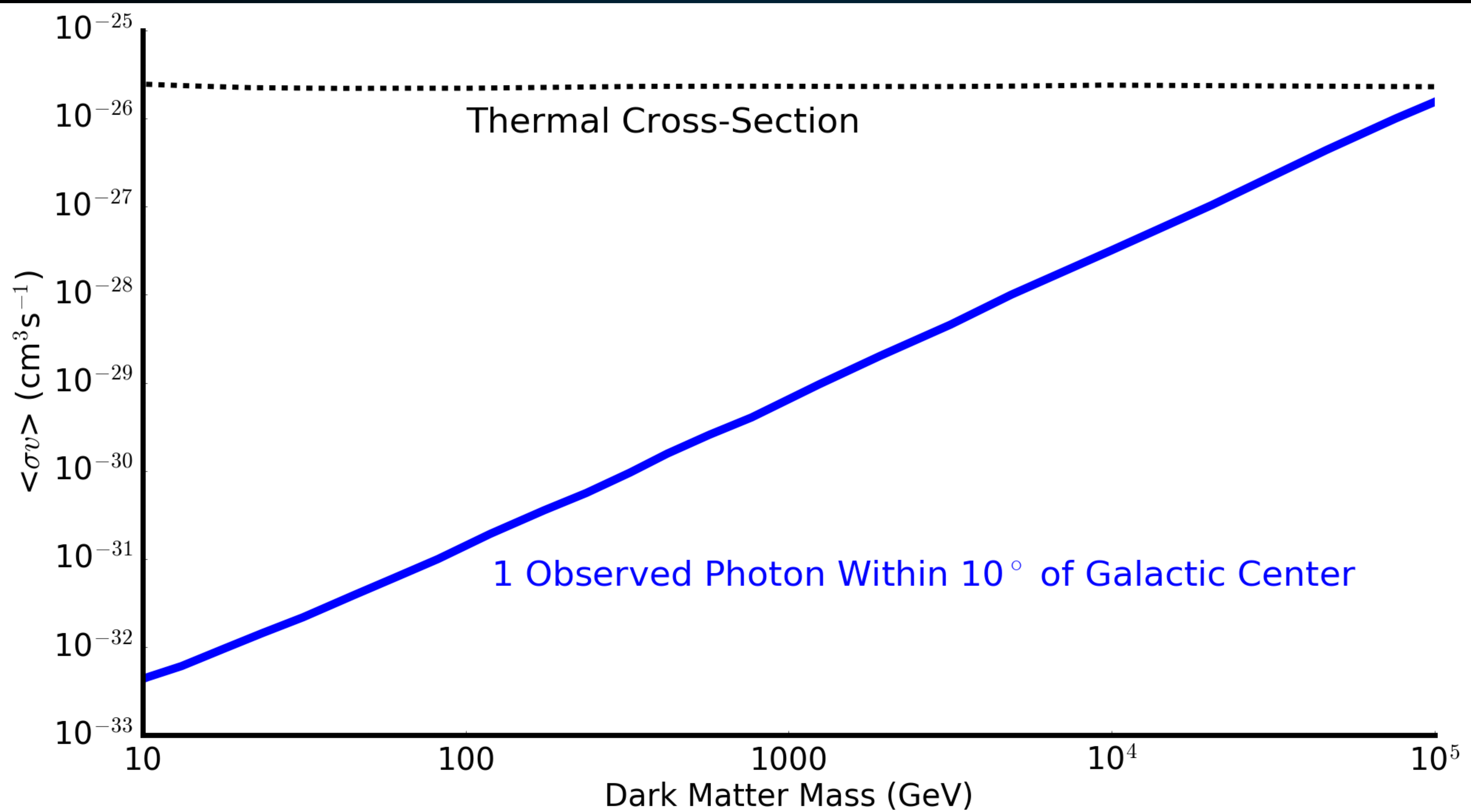


Isotropic Emission



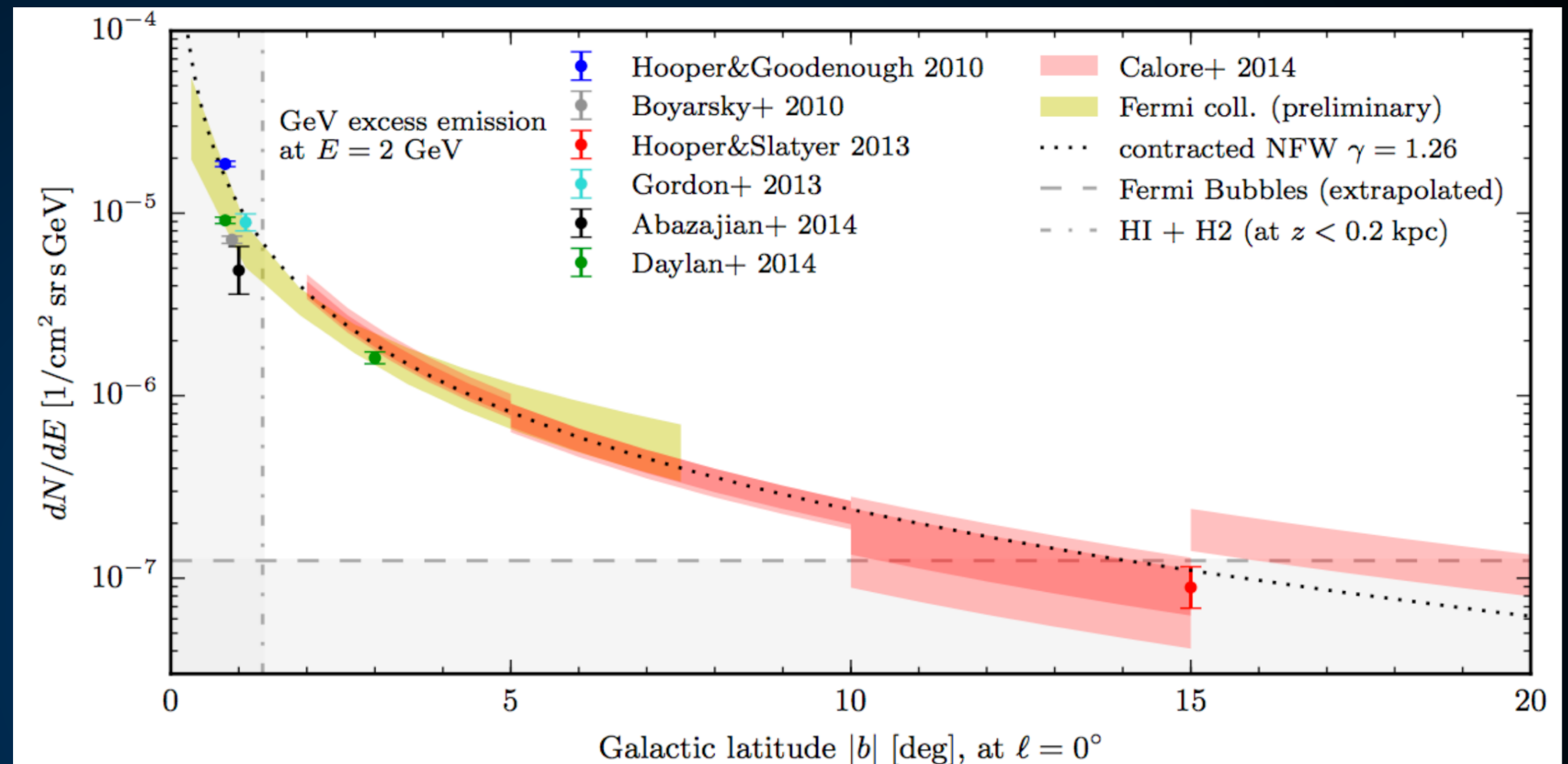
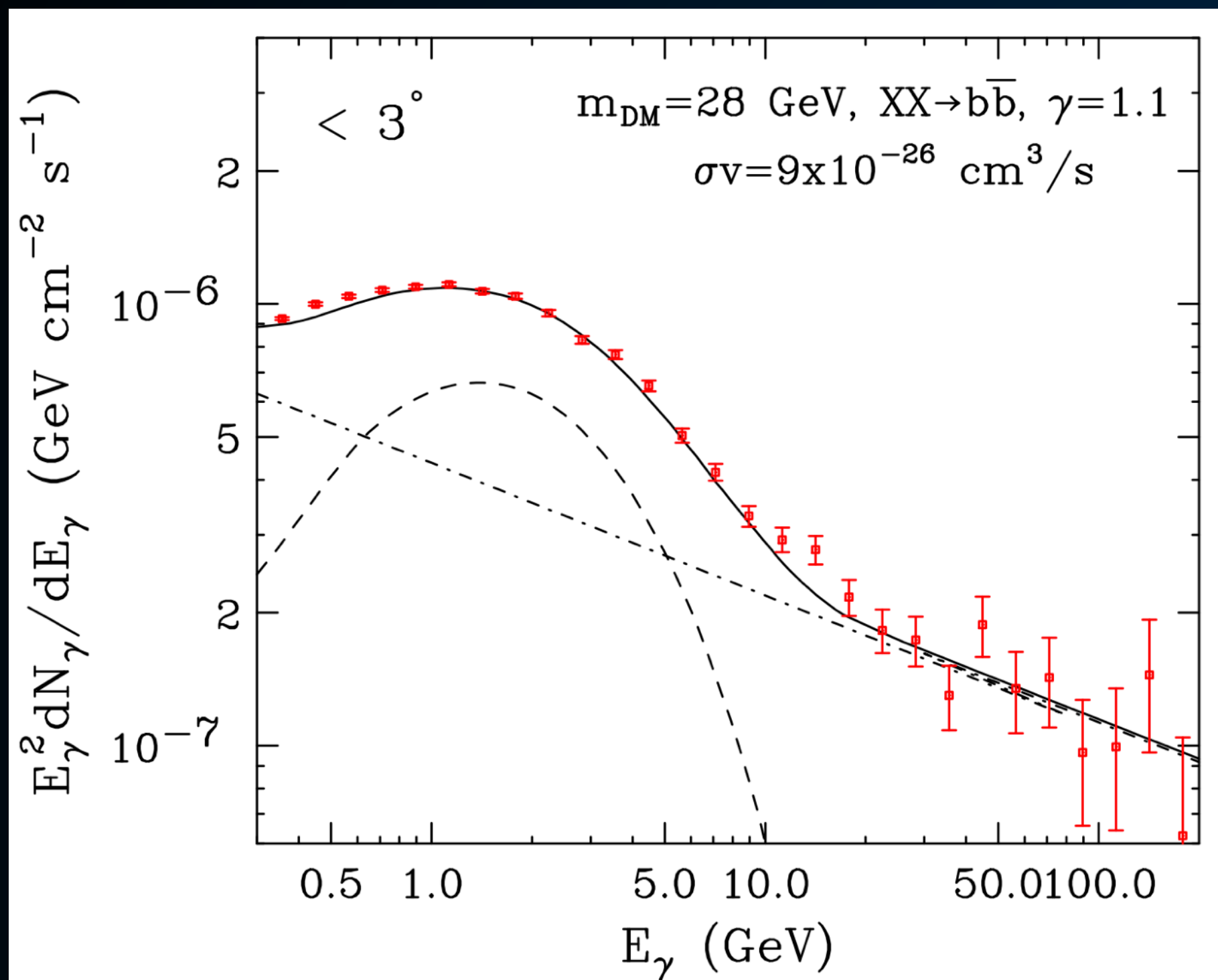
Sub-Threshold Sources





The Galactic Center Excess

Goodenough & Hooper (2009; 0910.2998)



Bright *Detected at $>50\sigma$*

Hard-Spectrum *Incompatible with standard backgrounds*

Spherically Symmetric *Expected from Dark Matter*

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

$$\rho_{\odot} = 0.3 \text{ GeV cm}^{-3}$$

Cross-Section ($10^{-26} \text{ cm}^3 \text{ s}^{-1}$)

Thermal Cross-Section

0.5

0.8

1

2

3

5

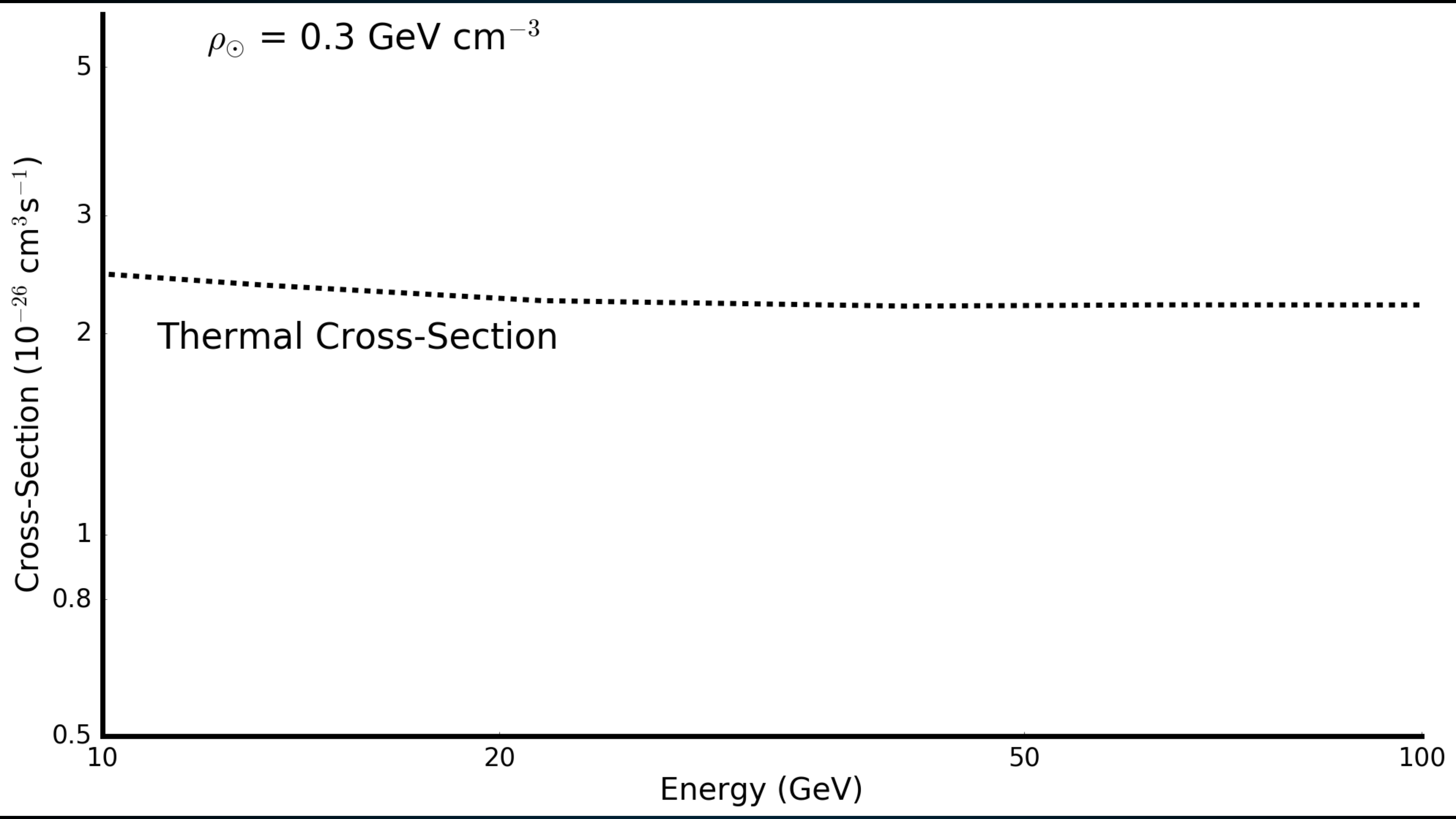
10

20

50

100

Energy (GeV)



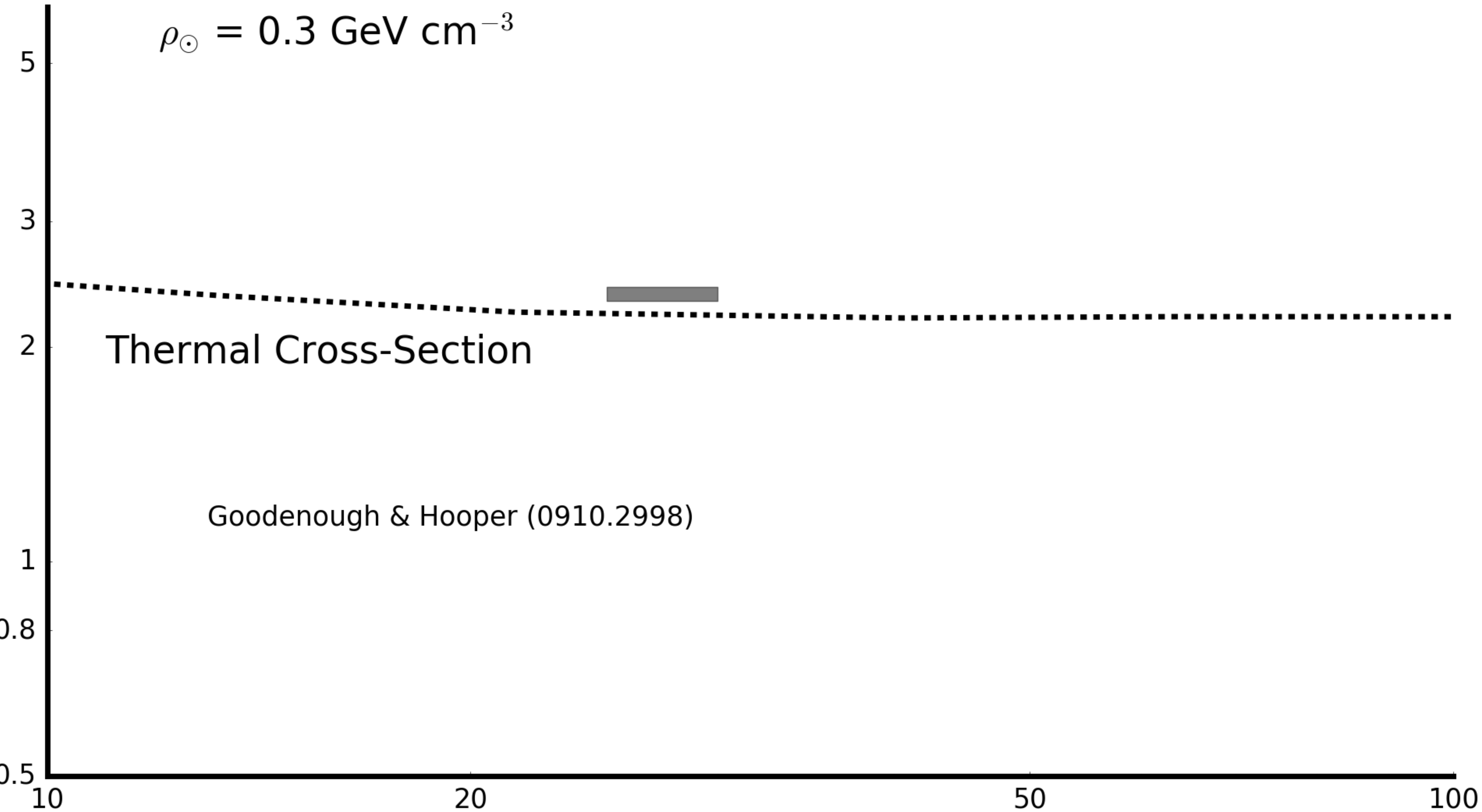
$$\rho_{\odot} = 0.3 \text{ GeV cm}^{-3}$$

Cross-Section ($10^{-26} \text{ cm}^3 \text{ s}^{-1}$)

Thermal Cross-Section

Goodenough & Hooper (0910.2998)

Energy (GeV)



$$\rho_{\odot} = 0.3 \text{ GeV cm}^{-3}$$

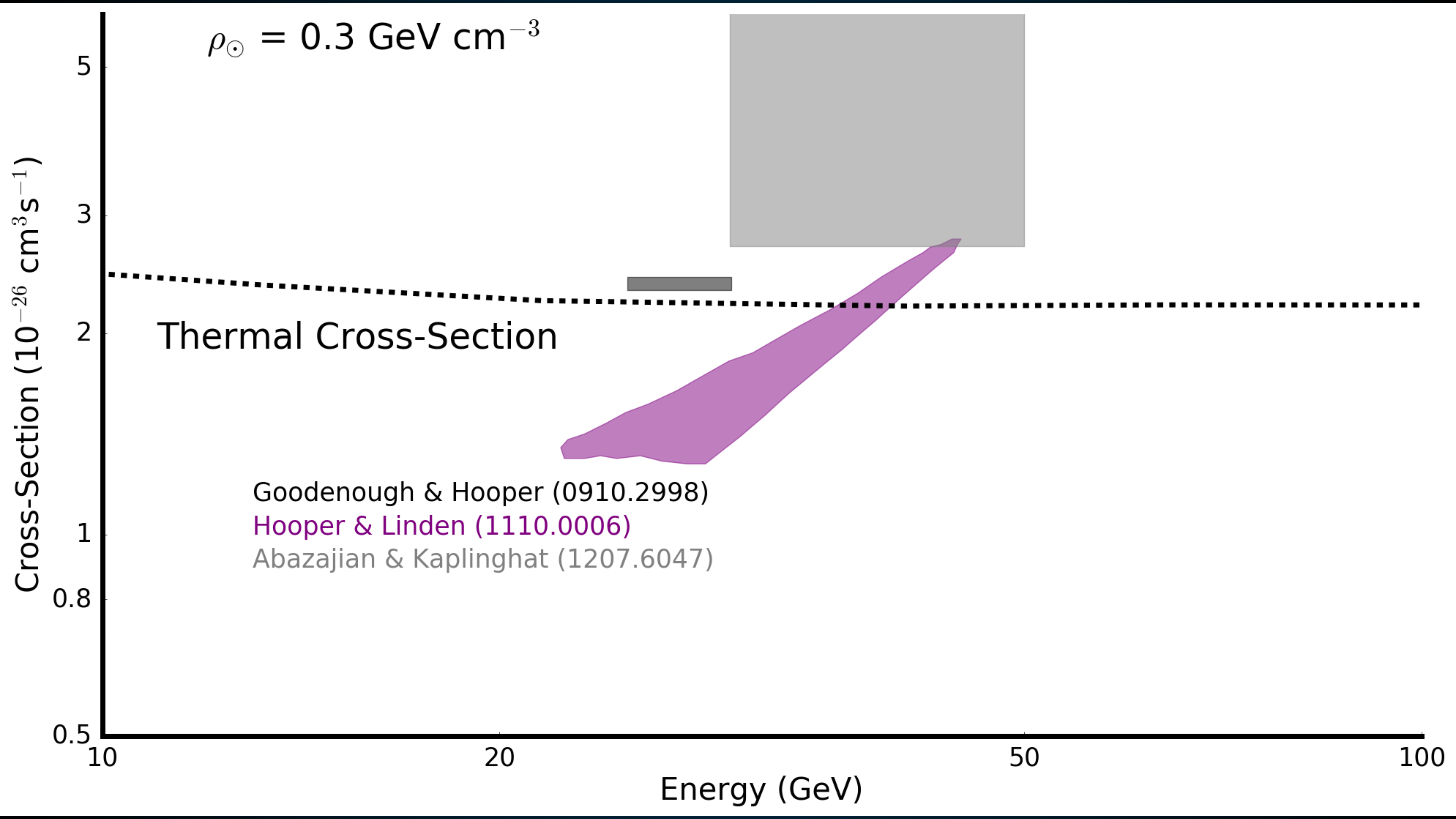
Cross-Section ($10^{-26} \text{ cm}^3 \text{ s}^{-1}$)

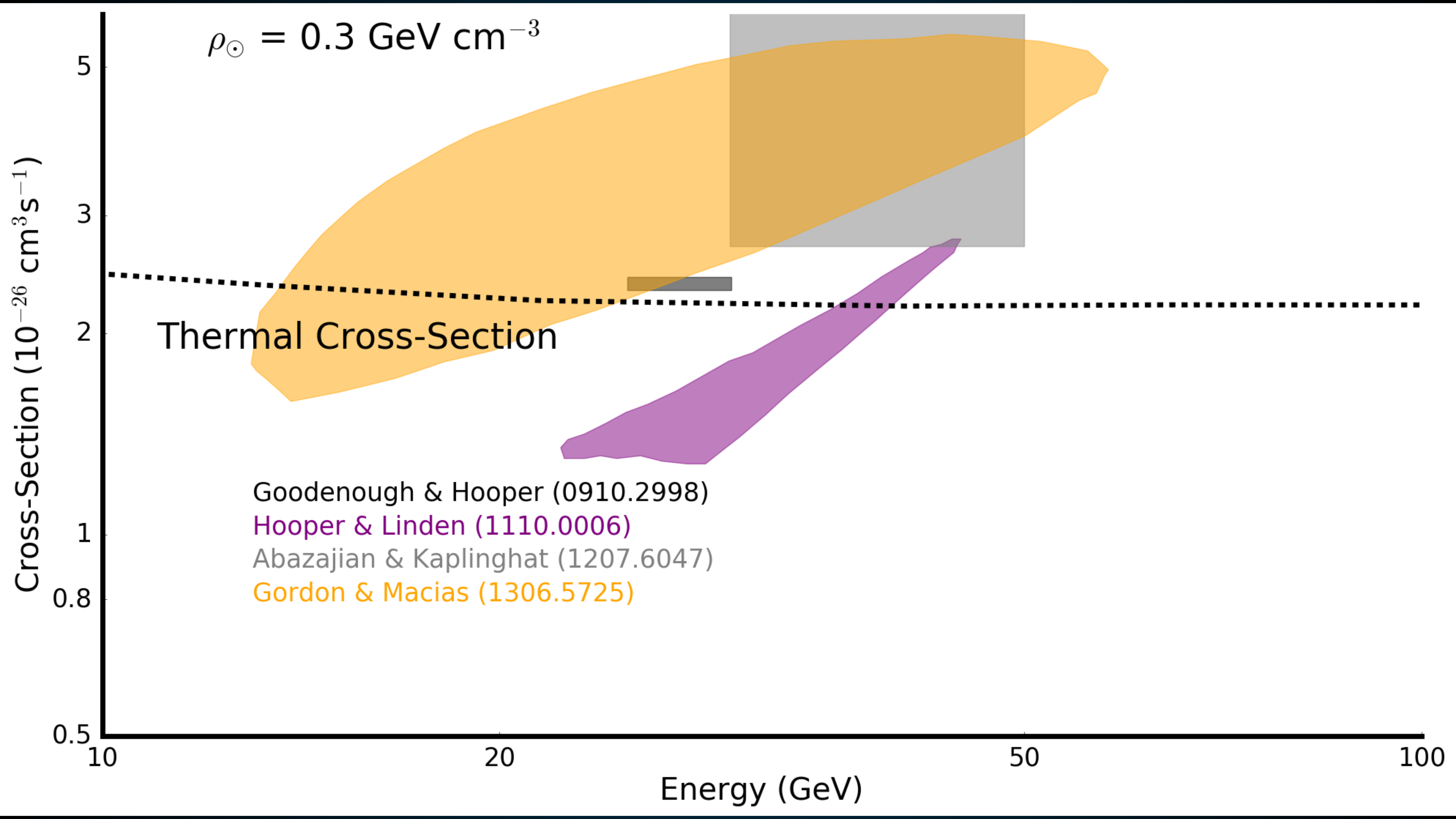
Thermal Cross-Section

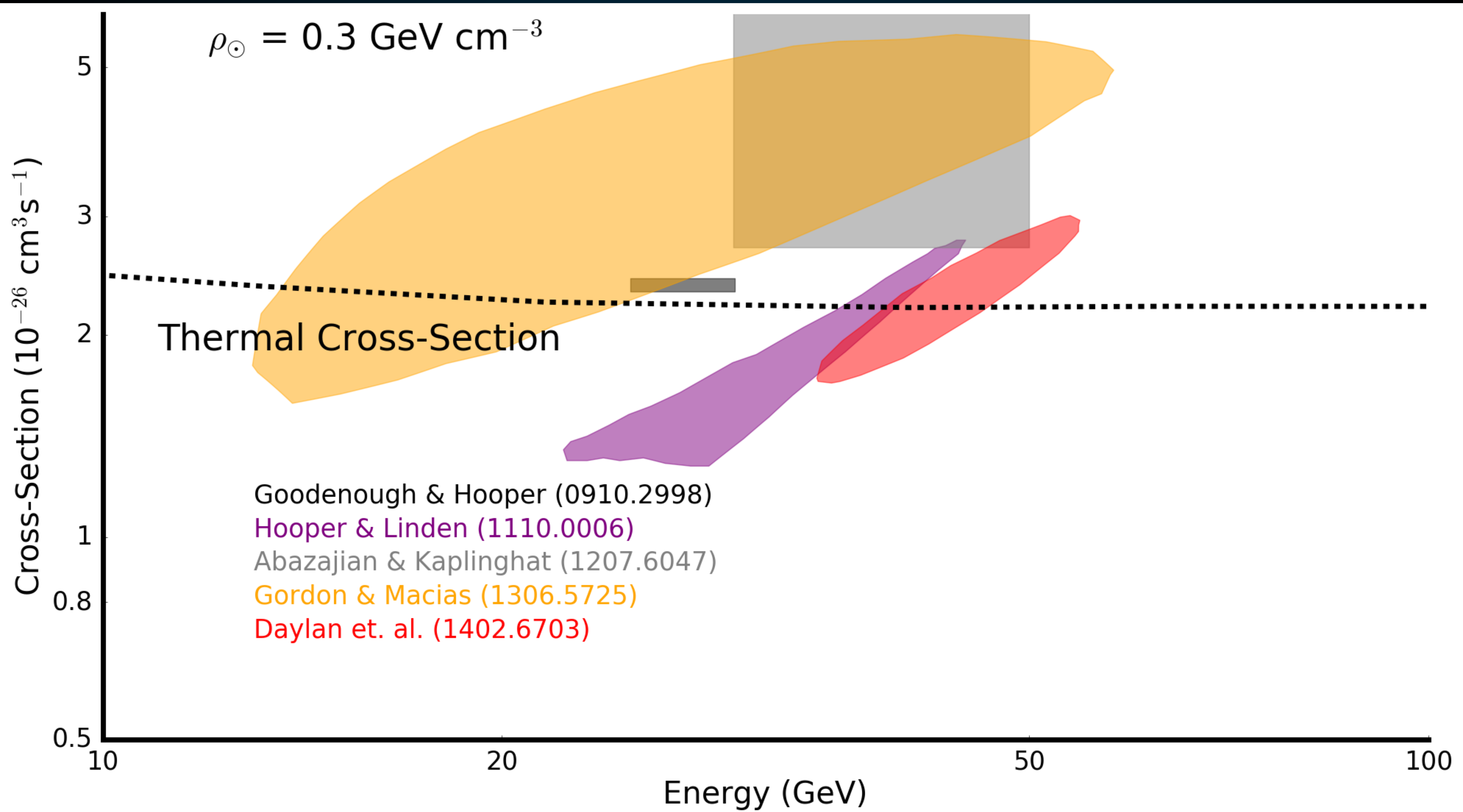
- Goodenough & Hooper (0910.2998)
- Hooper & Linden (1110.0006)
- Abazajian & Kaplinghat (1207.6047)

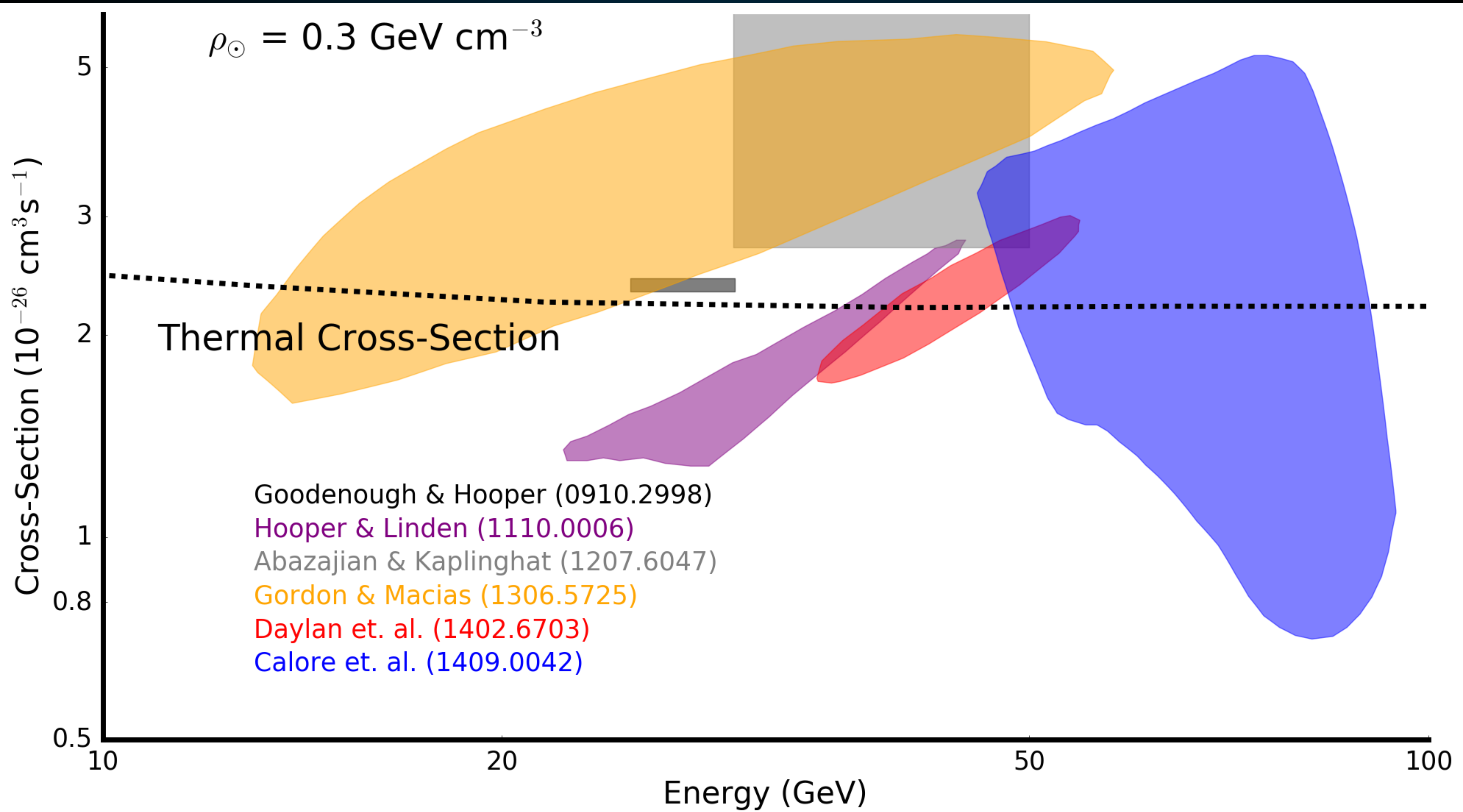
Energy (GeV)

10 20 50 100

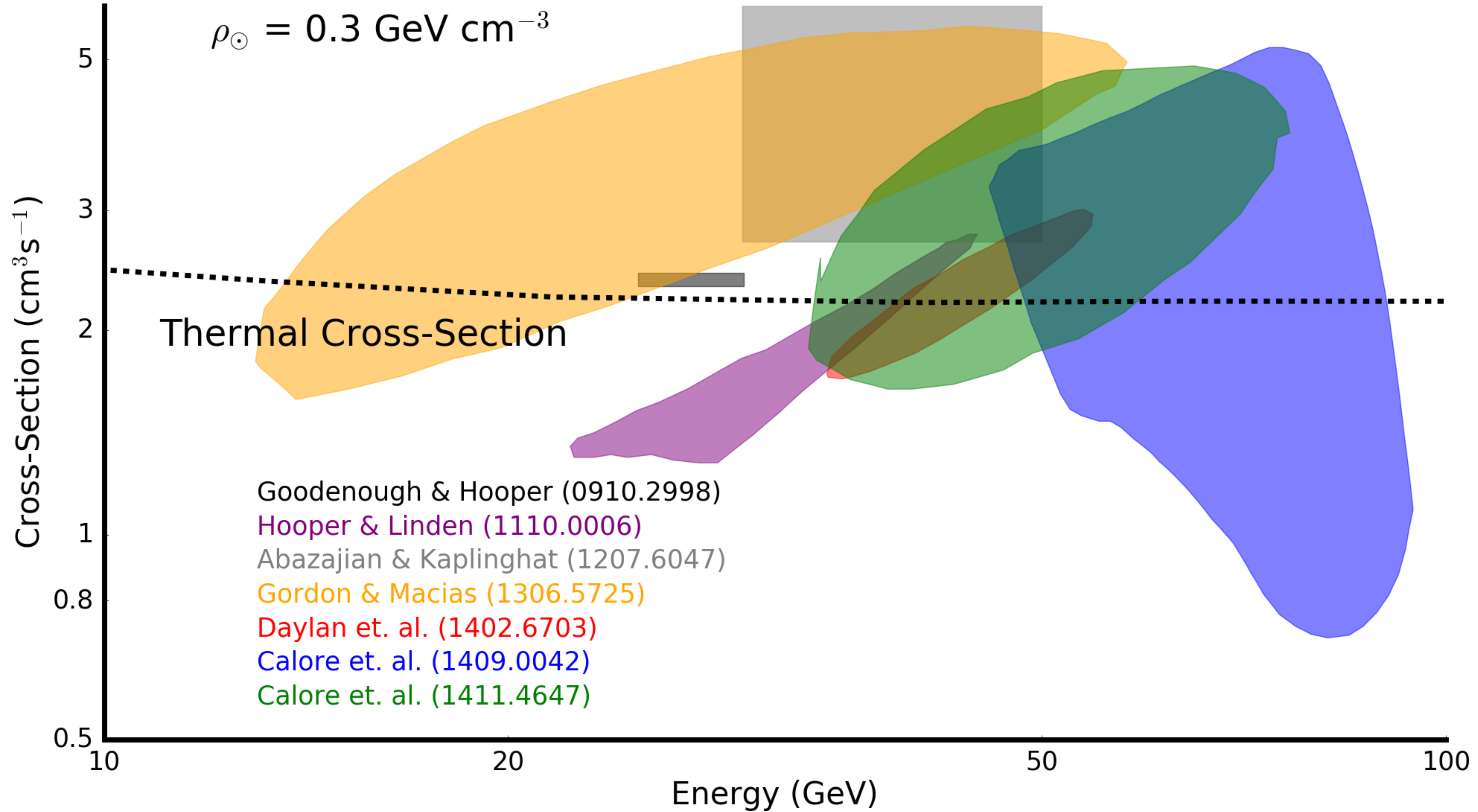




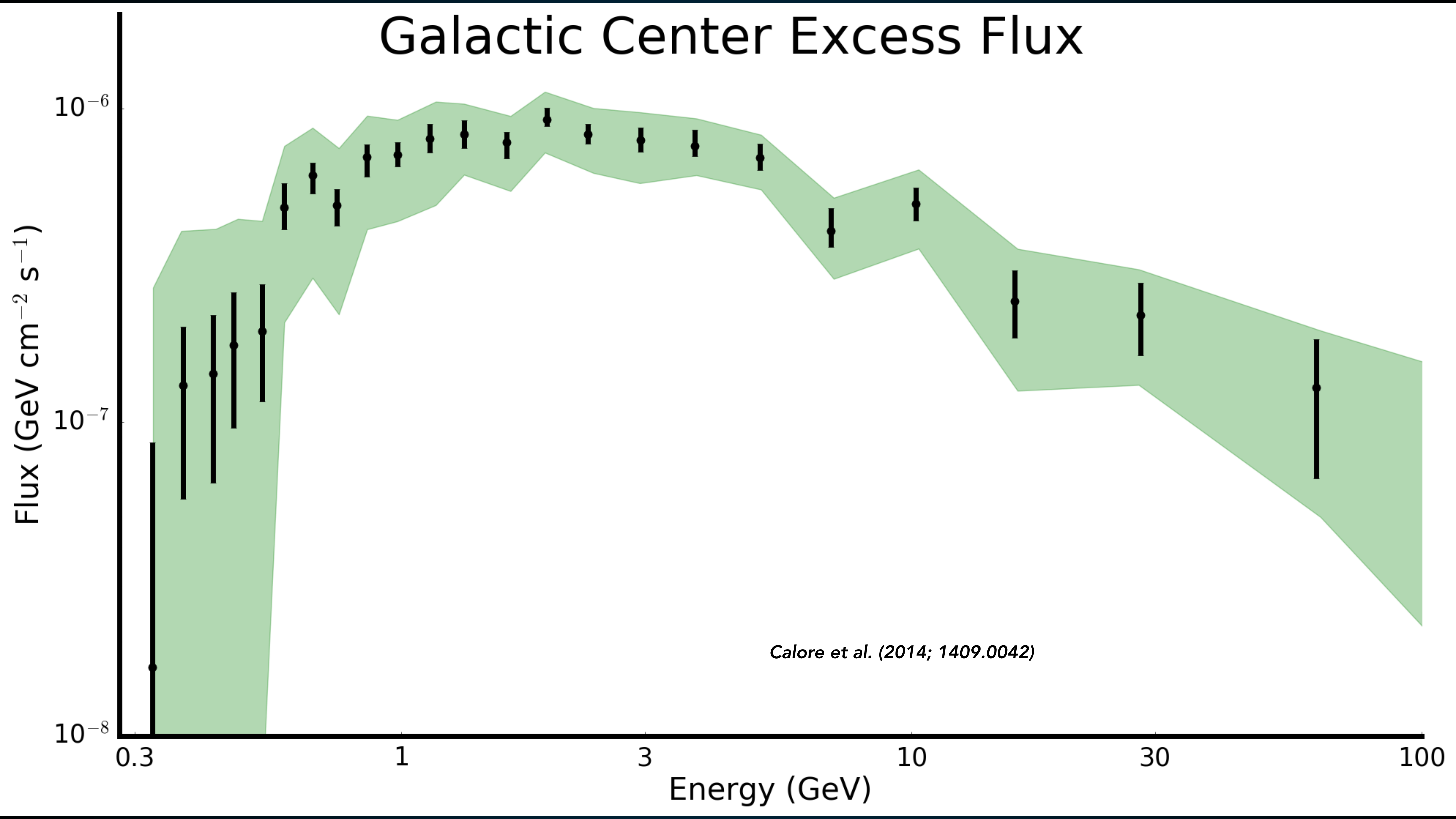




$$\rho_{\odot} = 0.3 \text{ GeV cm}^{-3}$$

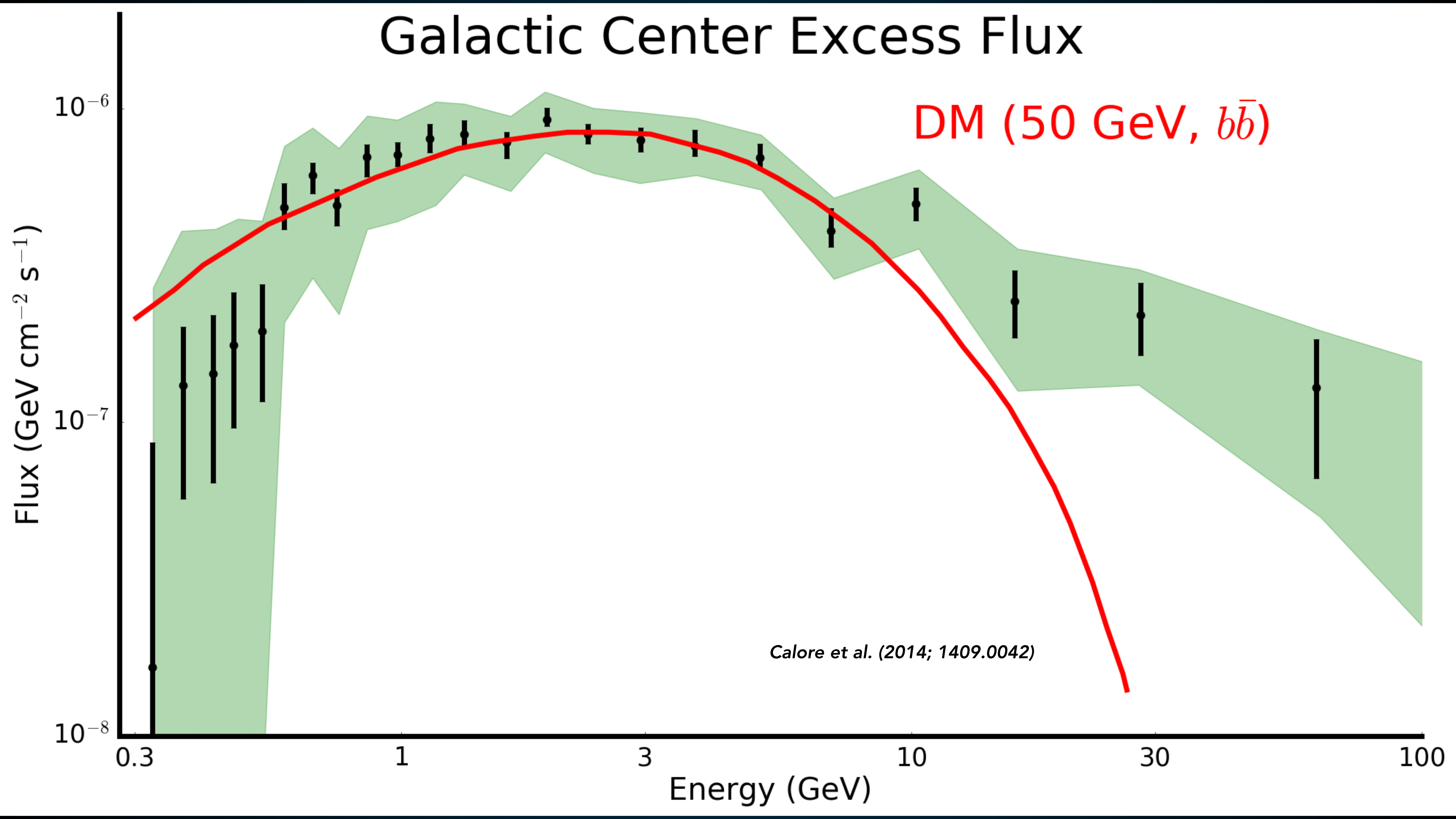


Galactic Center Excess Flux

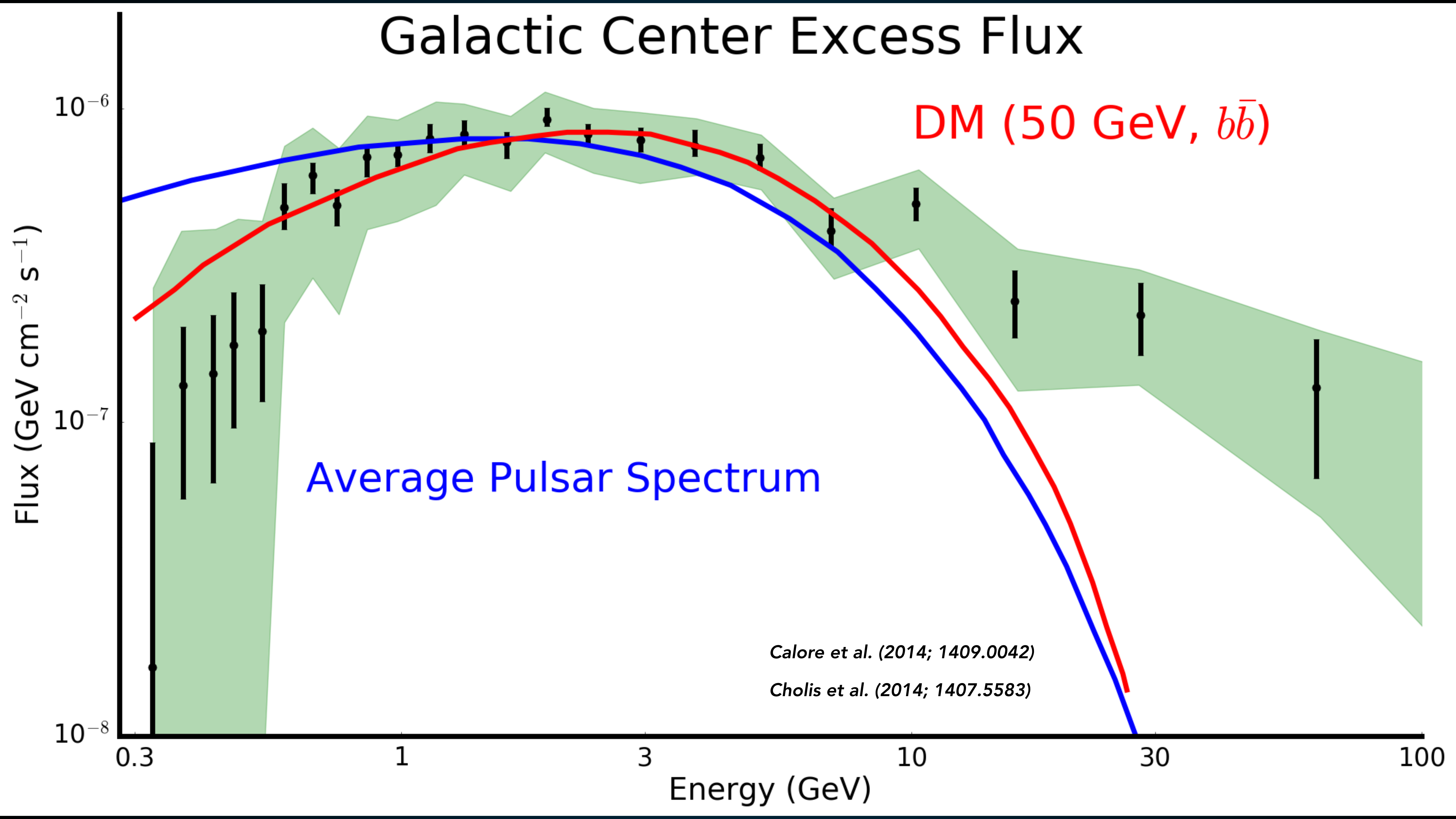


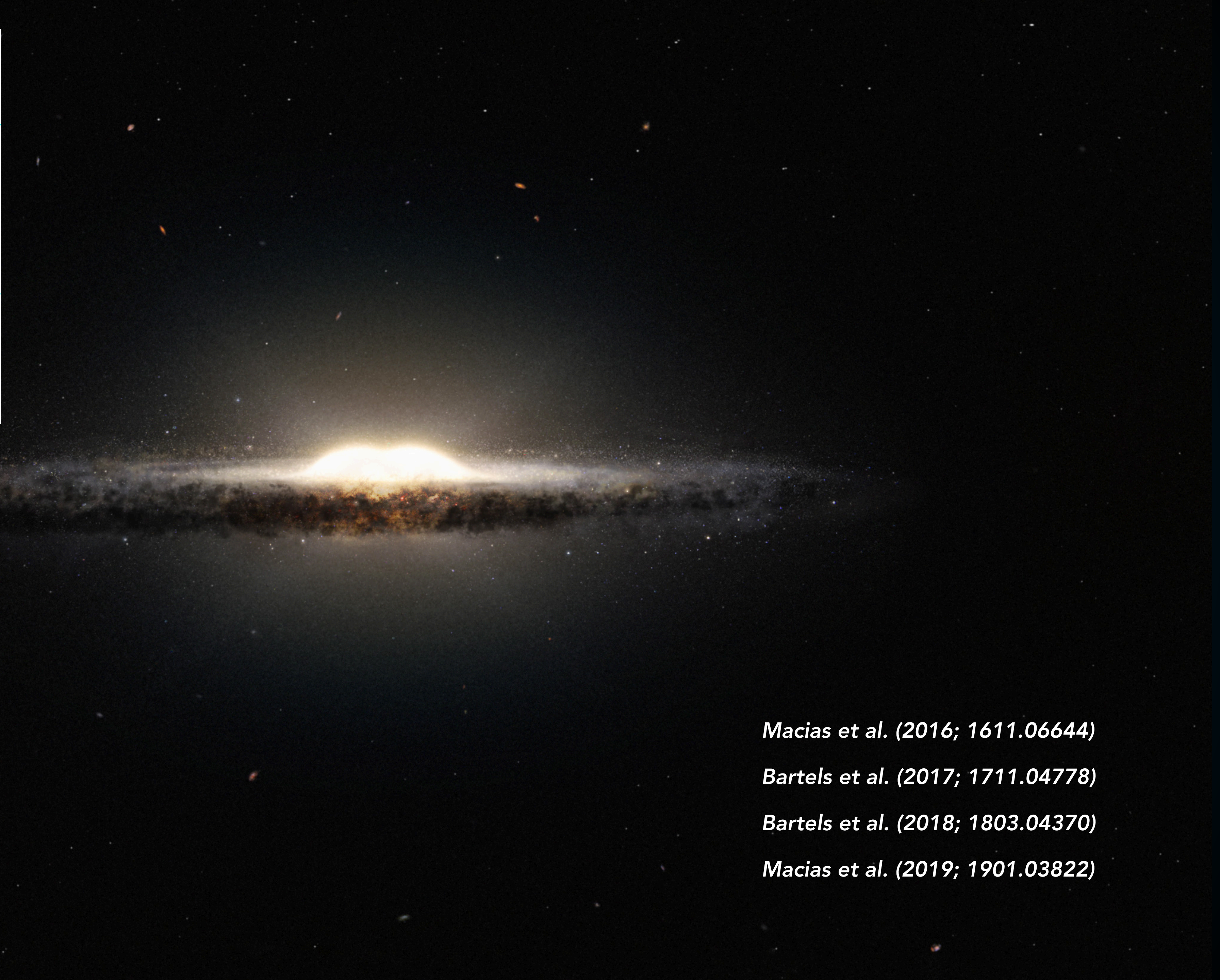
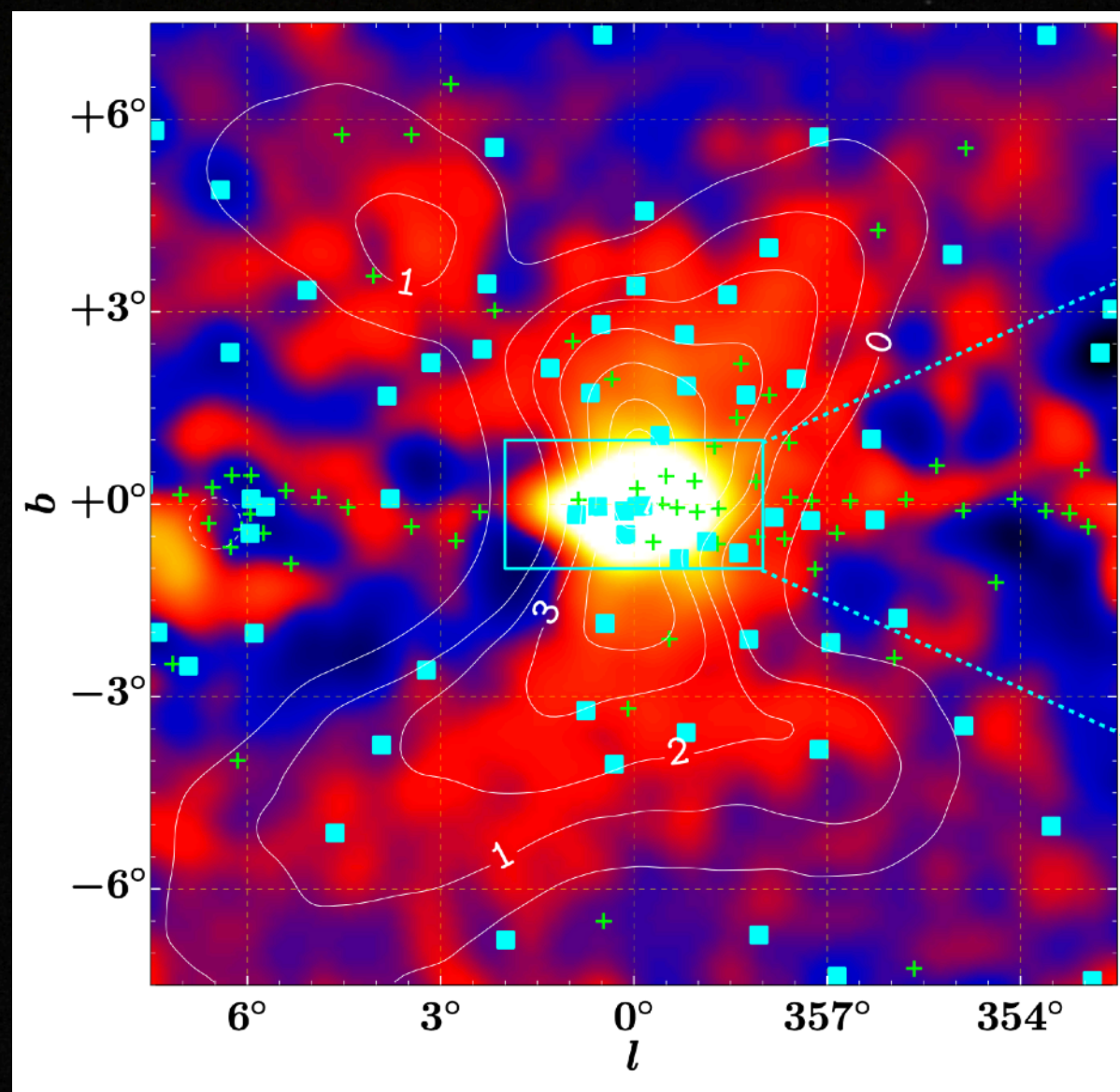
Calore et al. (2014; 1409.0042)

Galactic Center Excess Flux



Galactic Center Excess Flux





Macias et al. (2016; 1611.06644)

Bartels et al. (2017; 1711.04778)

Bartels et al. (2018; 1803.04370)

Macias et al. (2019; 1901.03822)

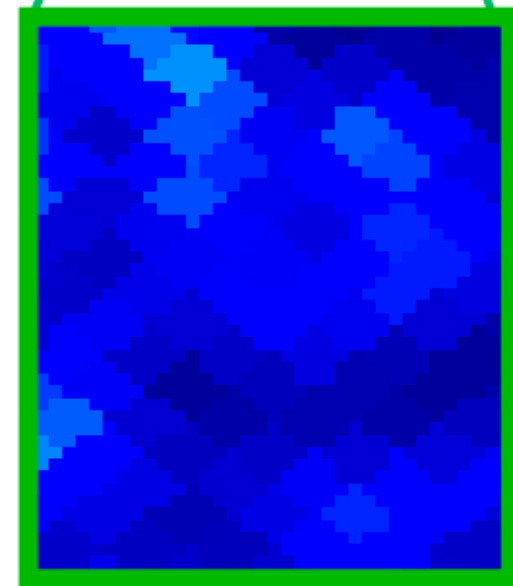
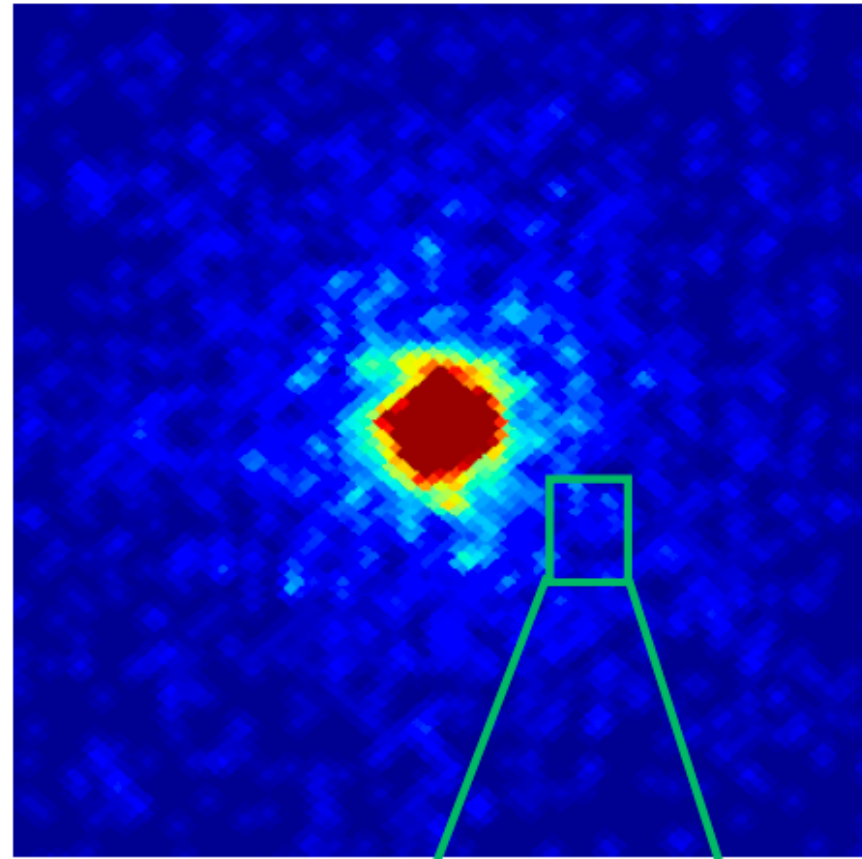
The Galactic Center Excess

Bartels et al. (2015; 1506.05104)

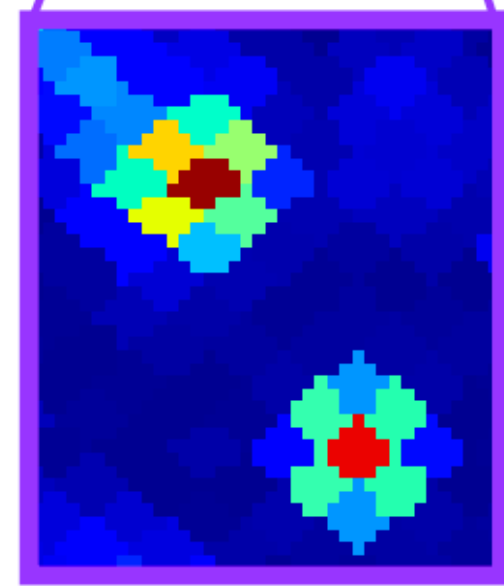
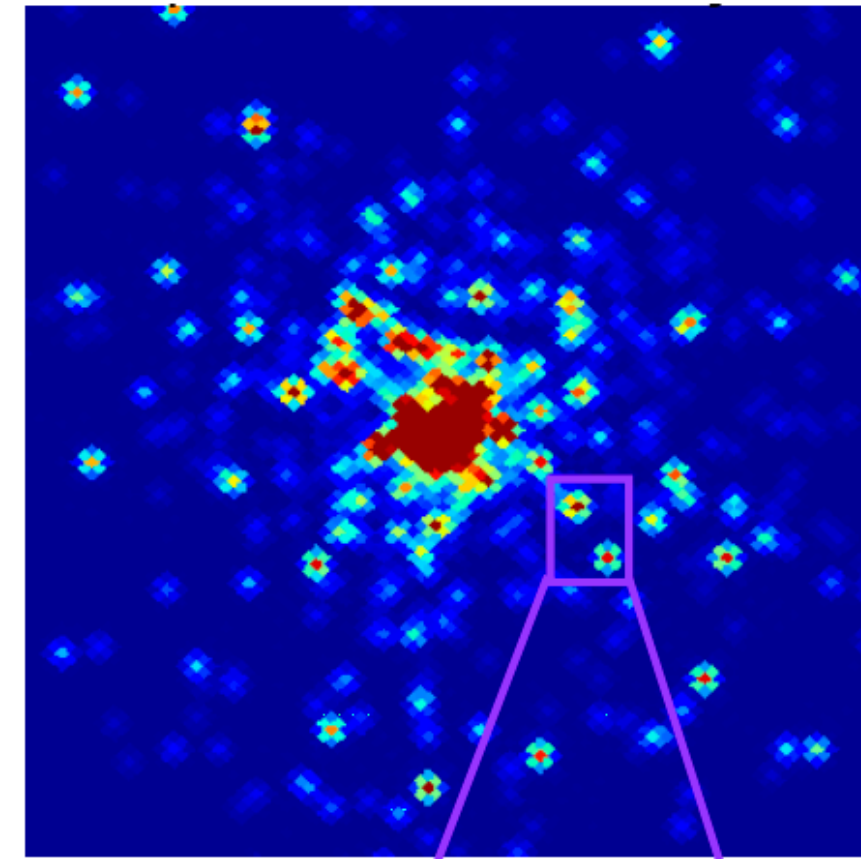
Lee et al. (2015; 1506.05124)

No Diffuse Bkgd

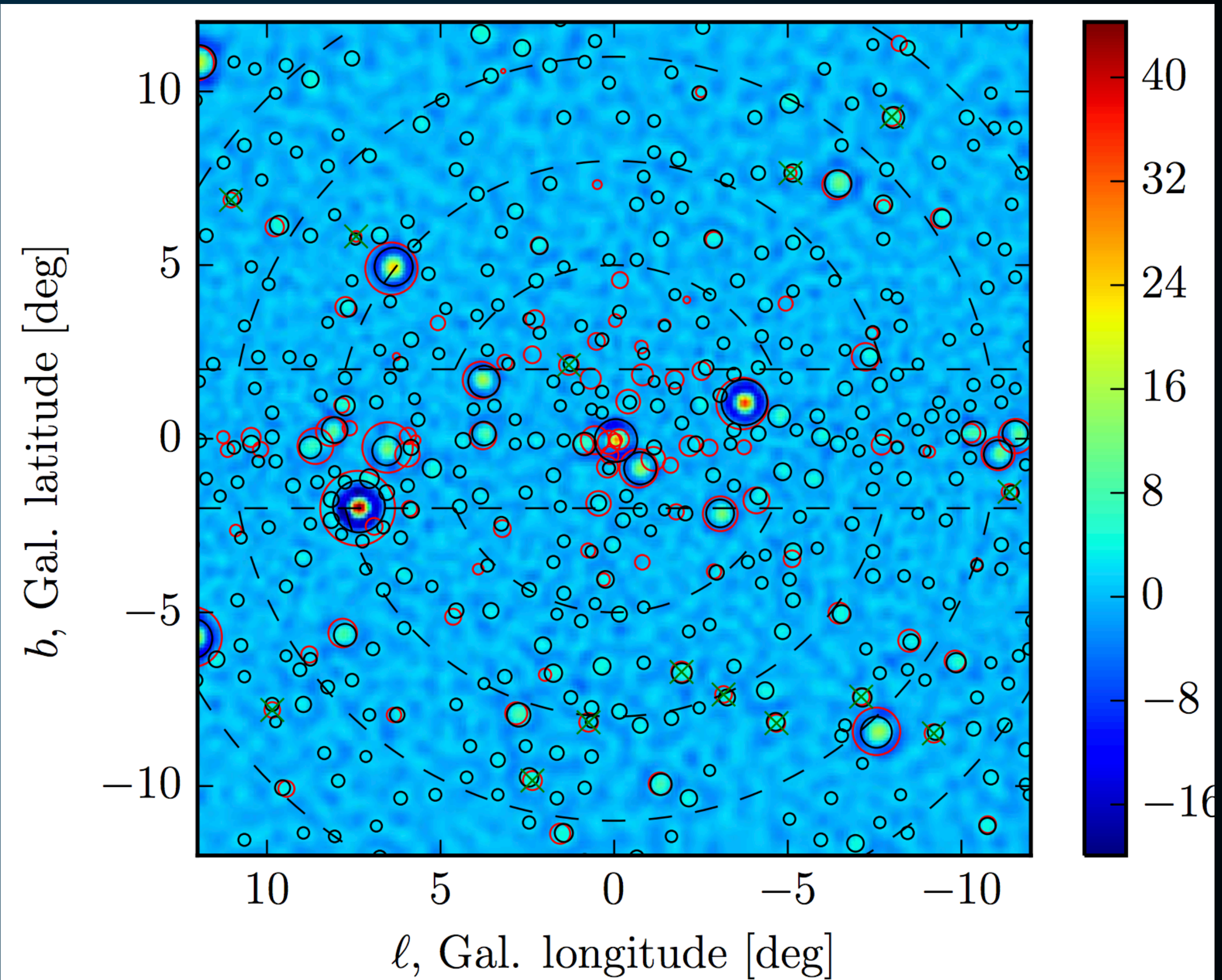
Dark Matter



Point Sources

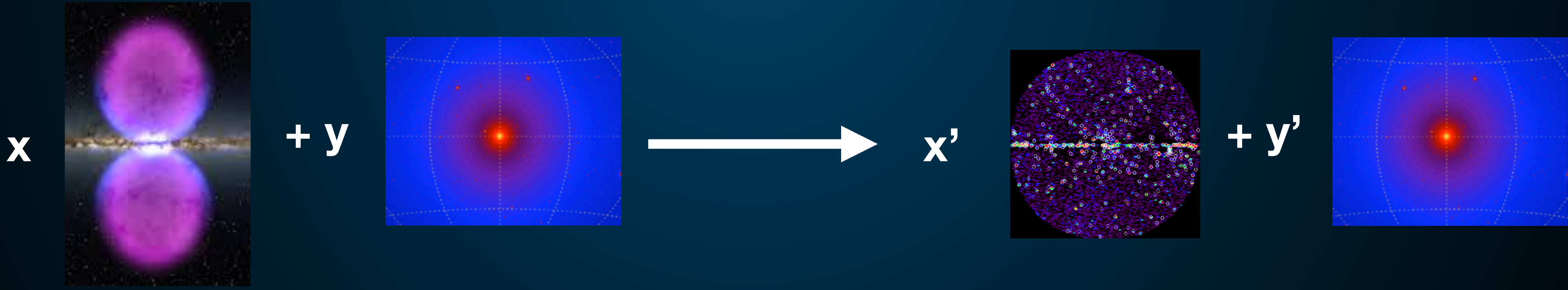
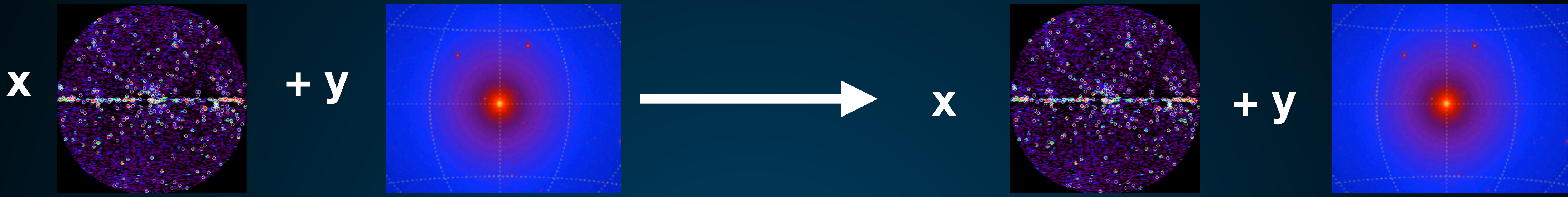


slide from Mariangela Lisanti

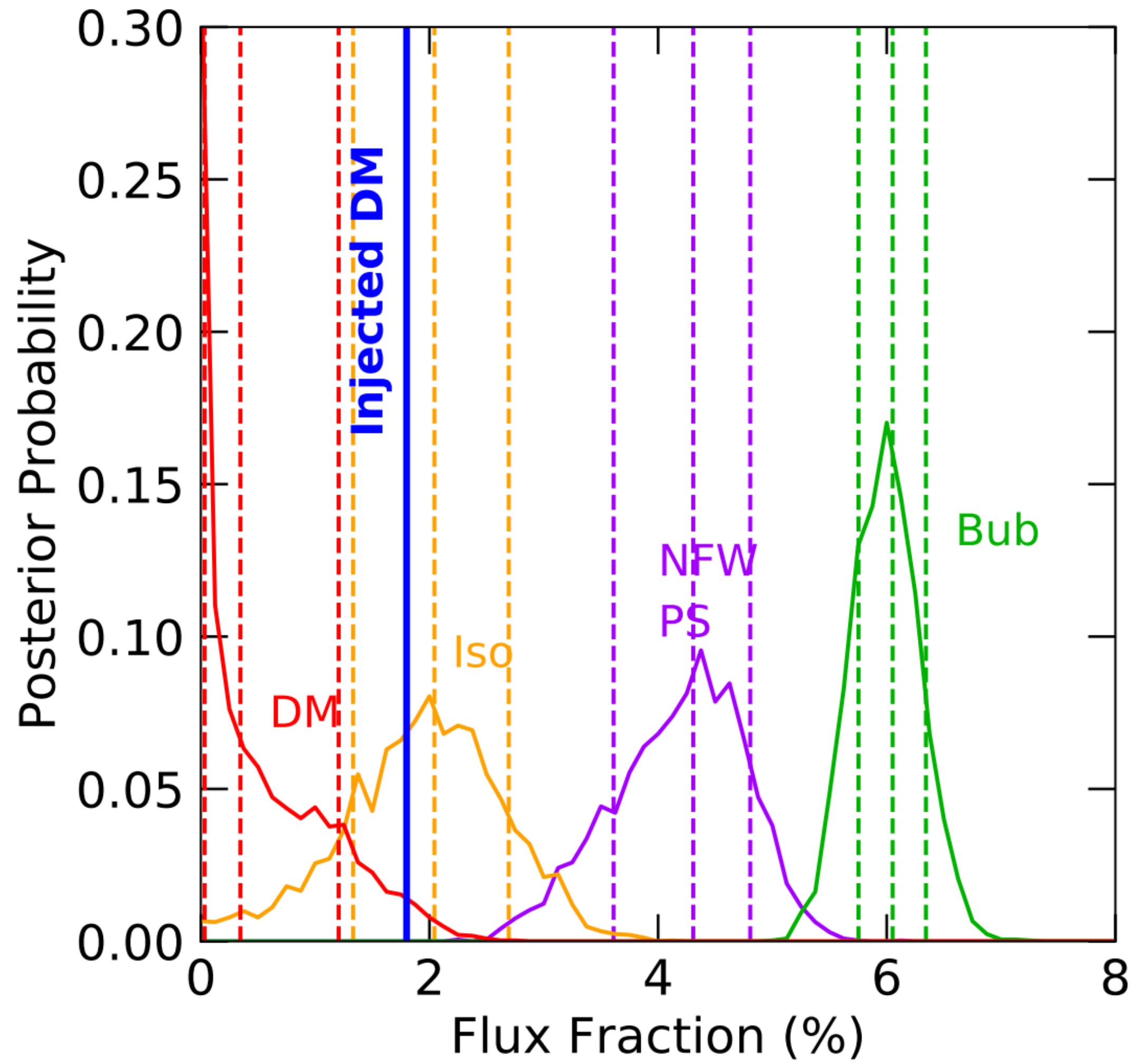
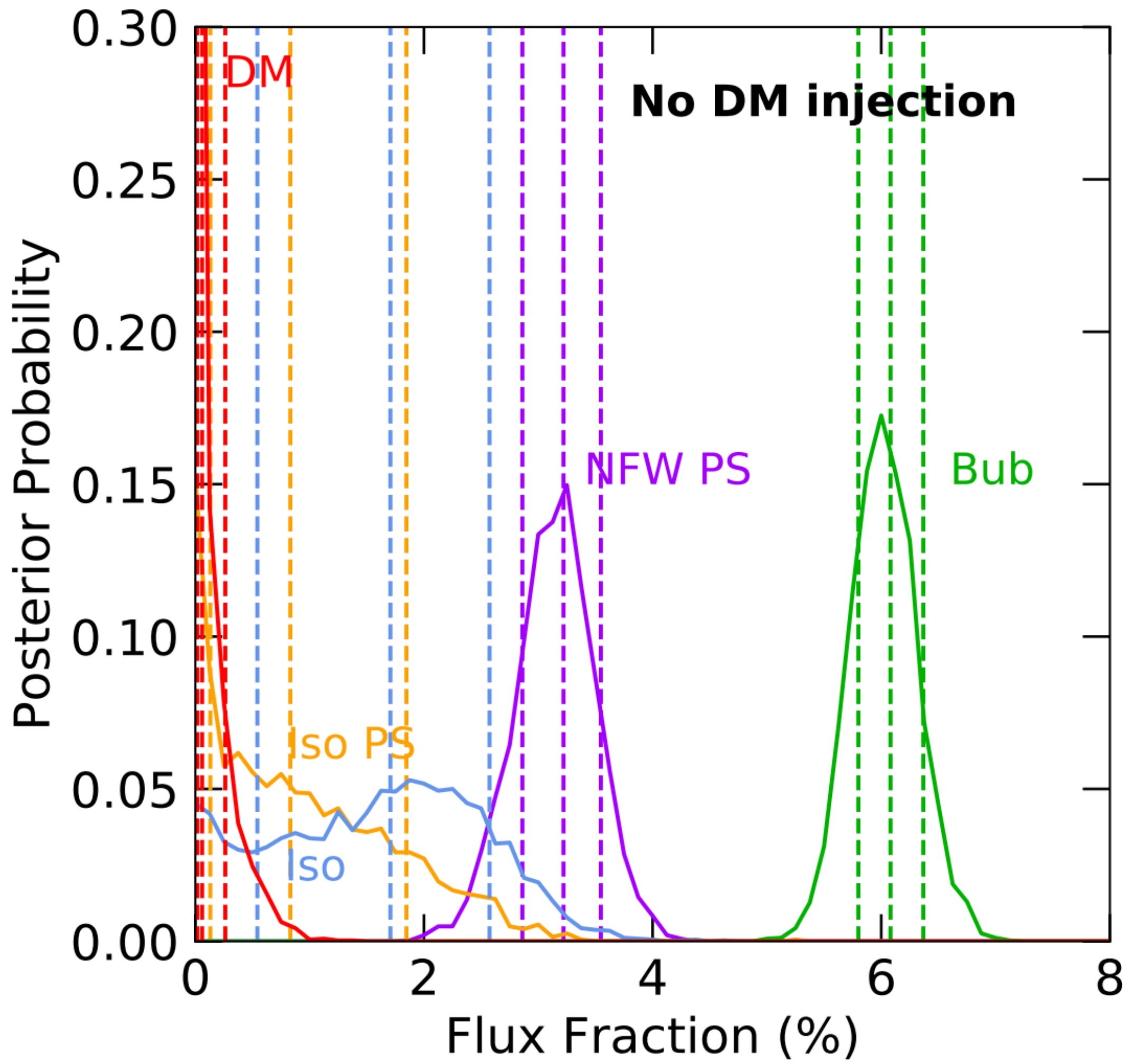


Bulletproof evidence for pulsars?

The Galactic Center Excess



The Galactic Center Excess



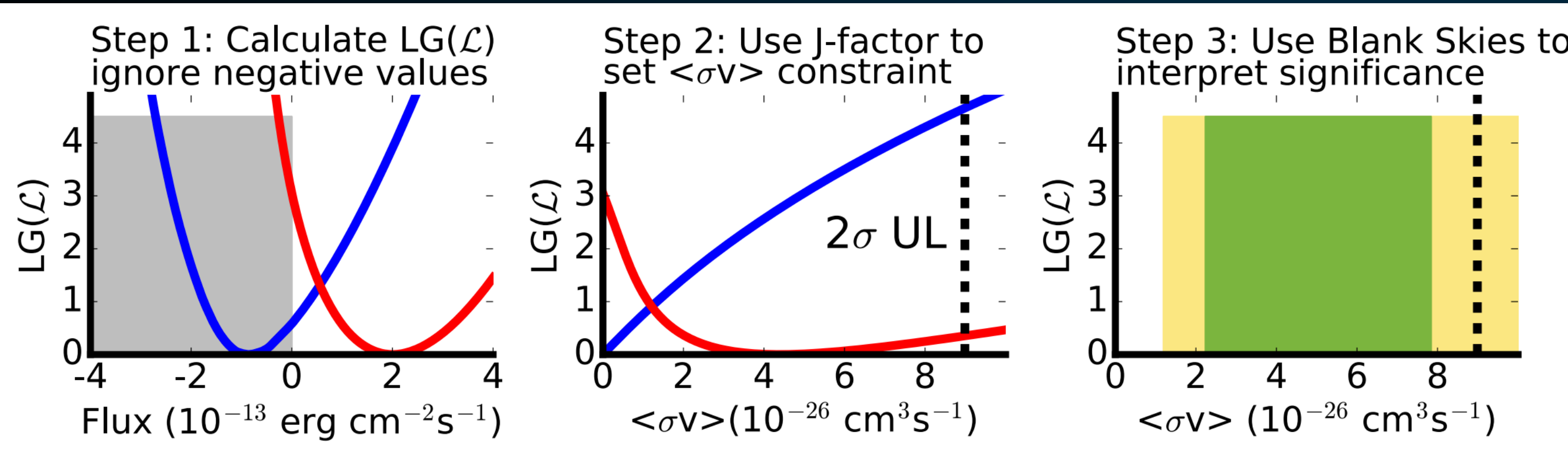
Dark Matter Strikes Back at the Galactic Center





Dwarf Spheroidal Galaxies

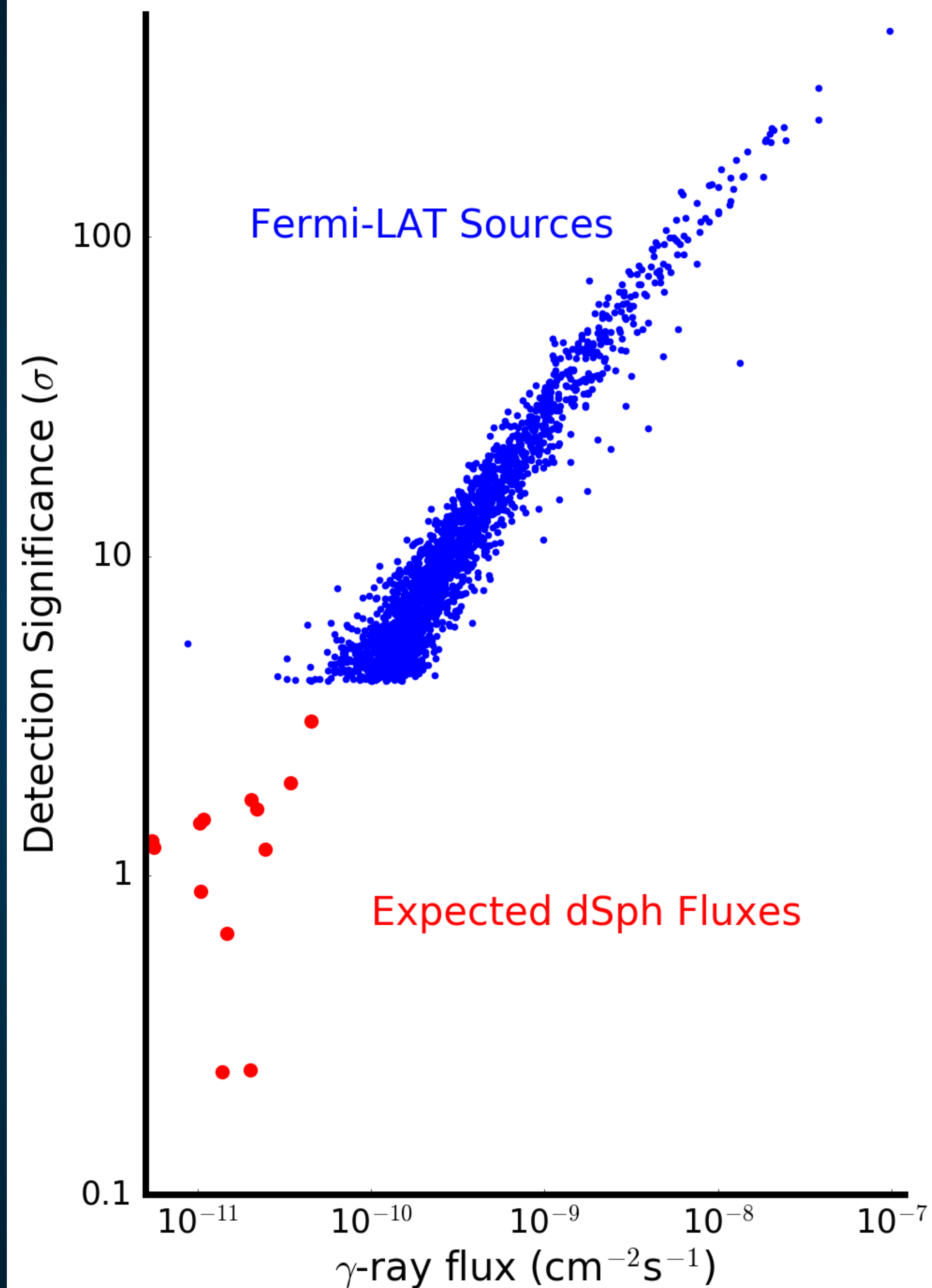
Dwarf Spheroidal Galaxies

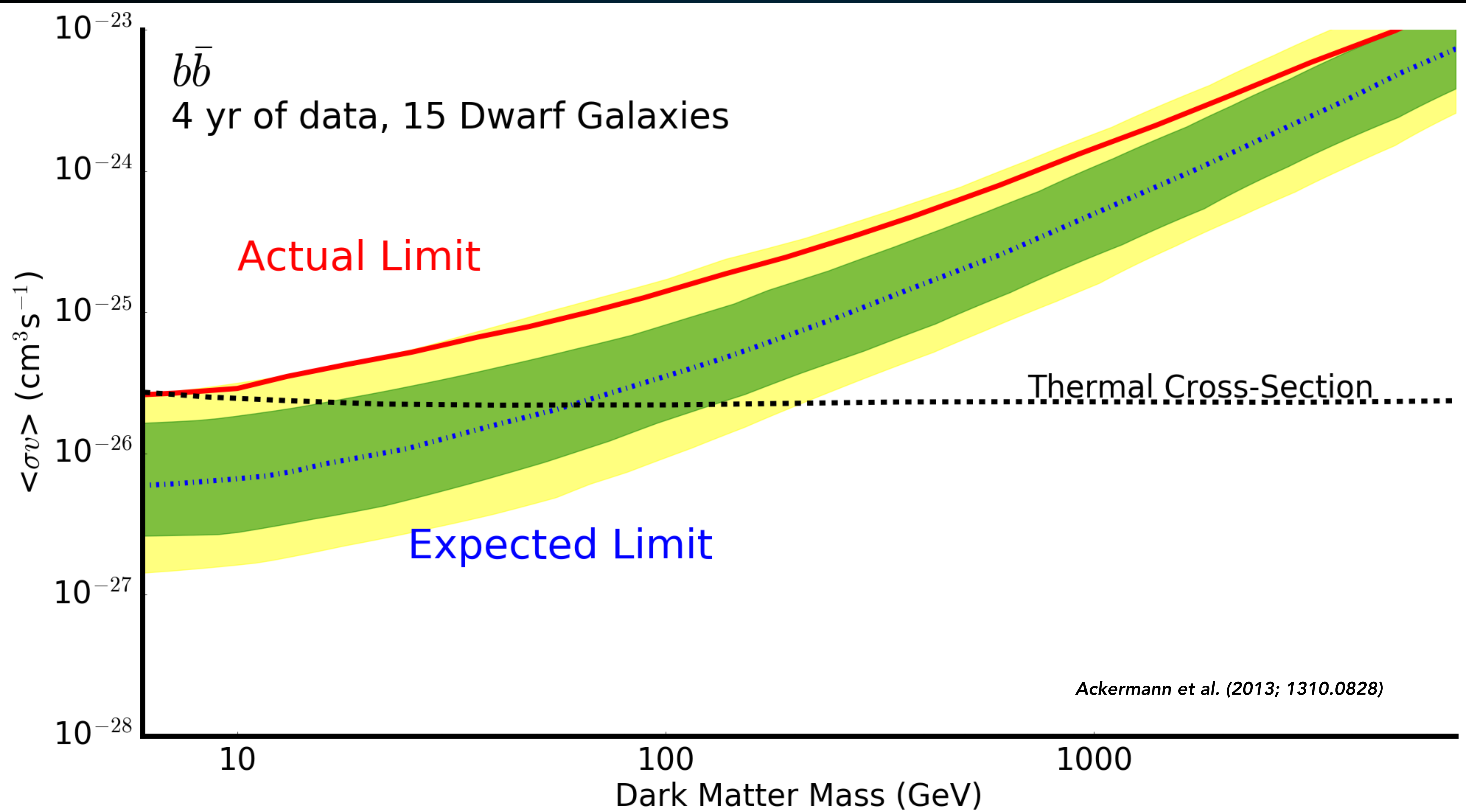


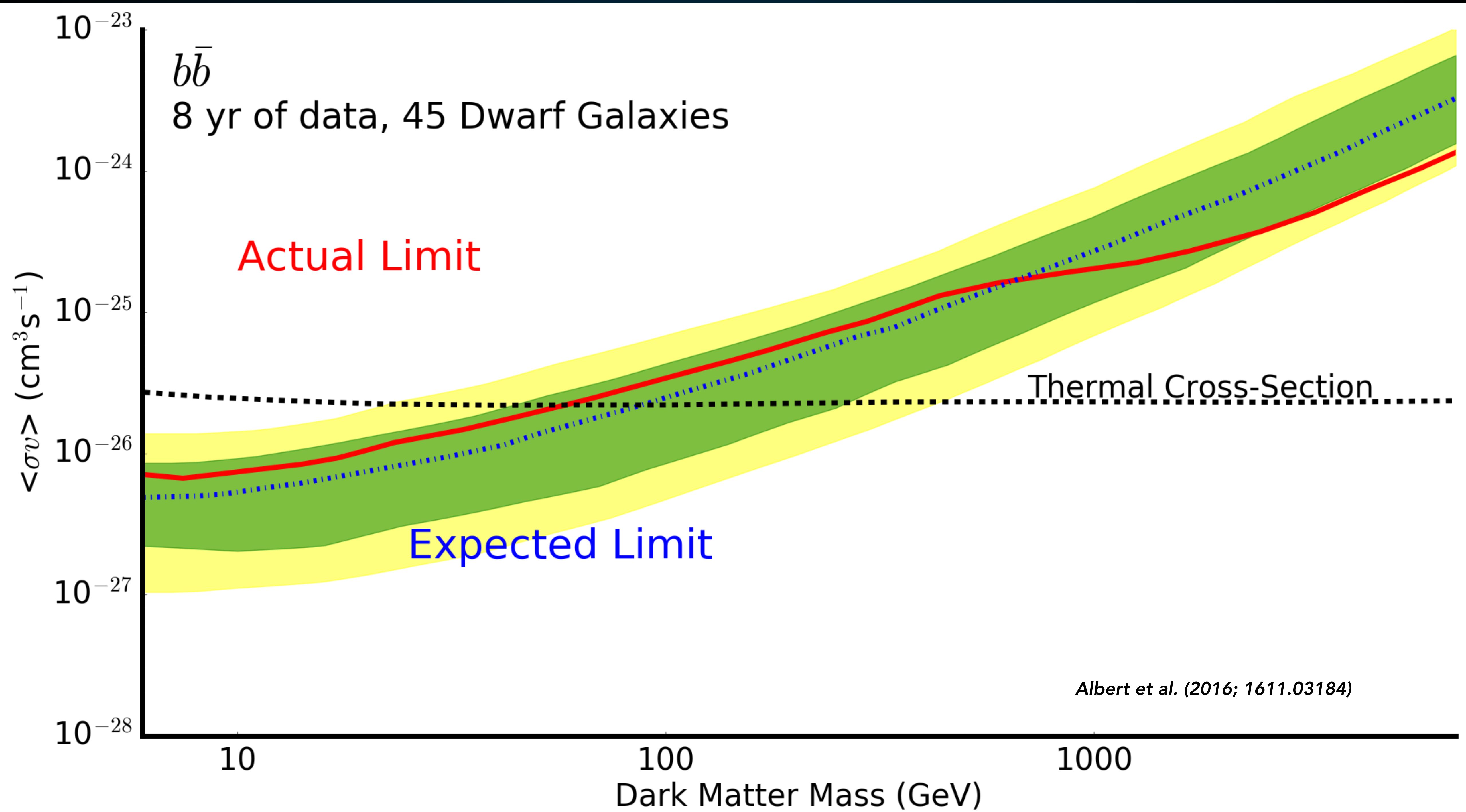
No Astrophysical Background from Dwarfs!

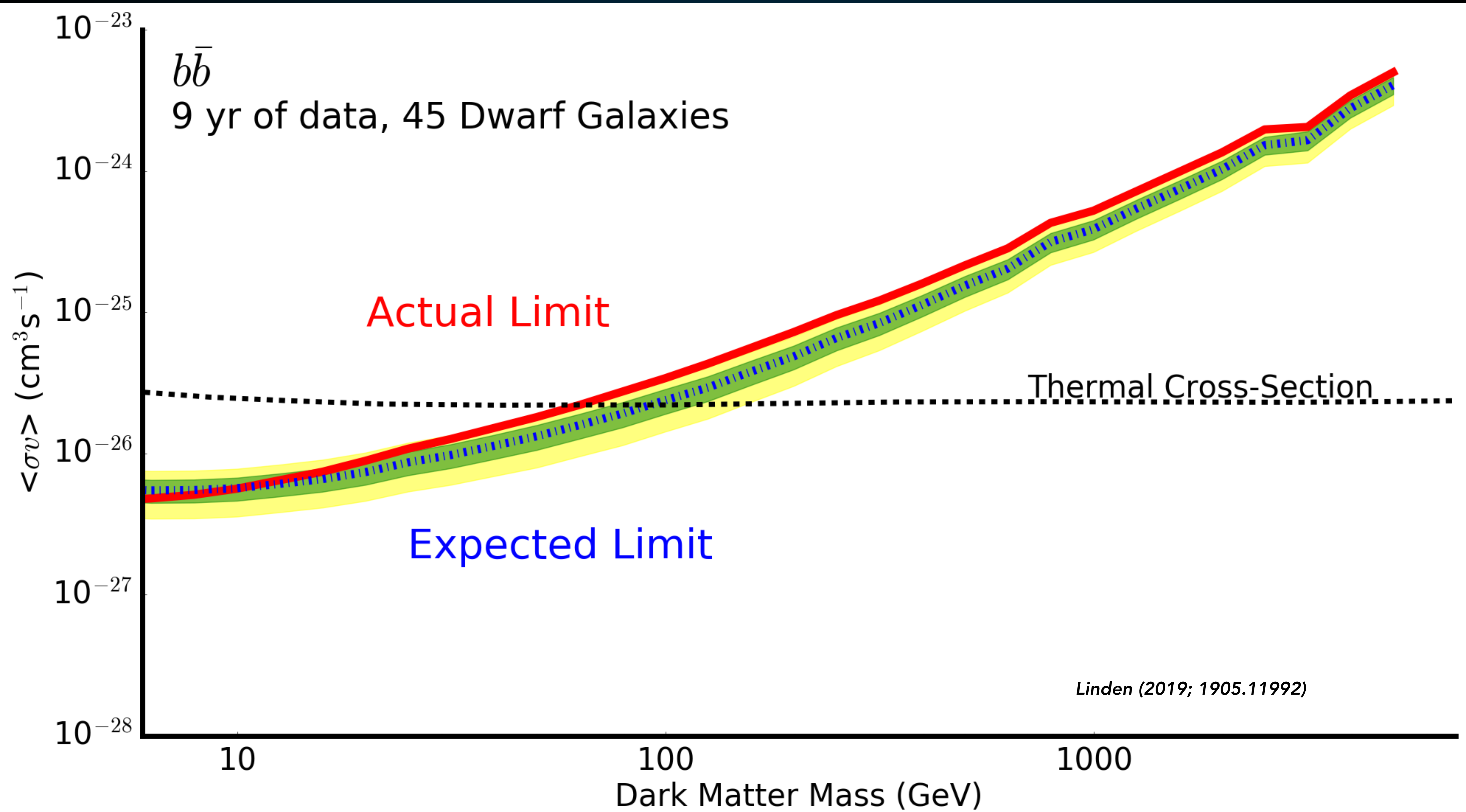
Individual dwarfs are dim

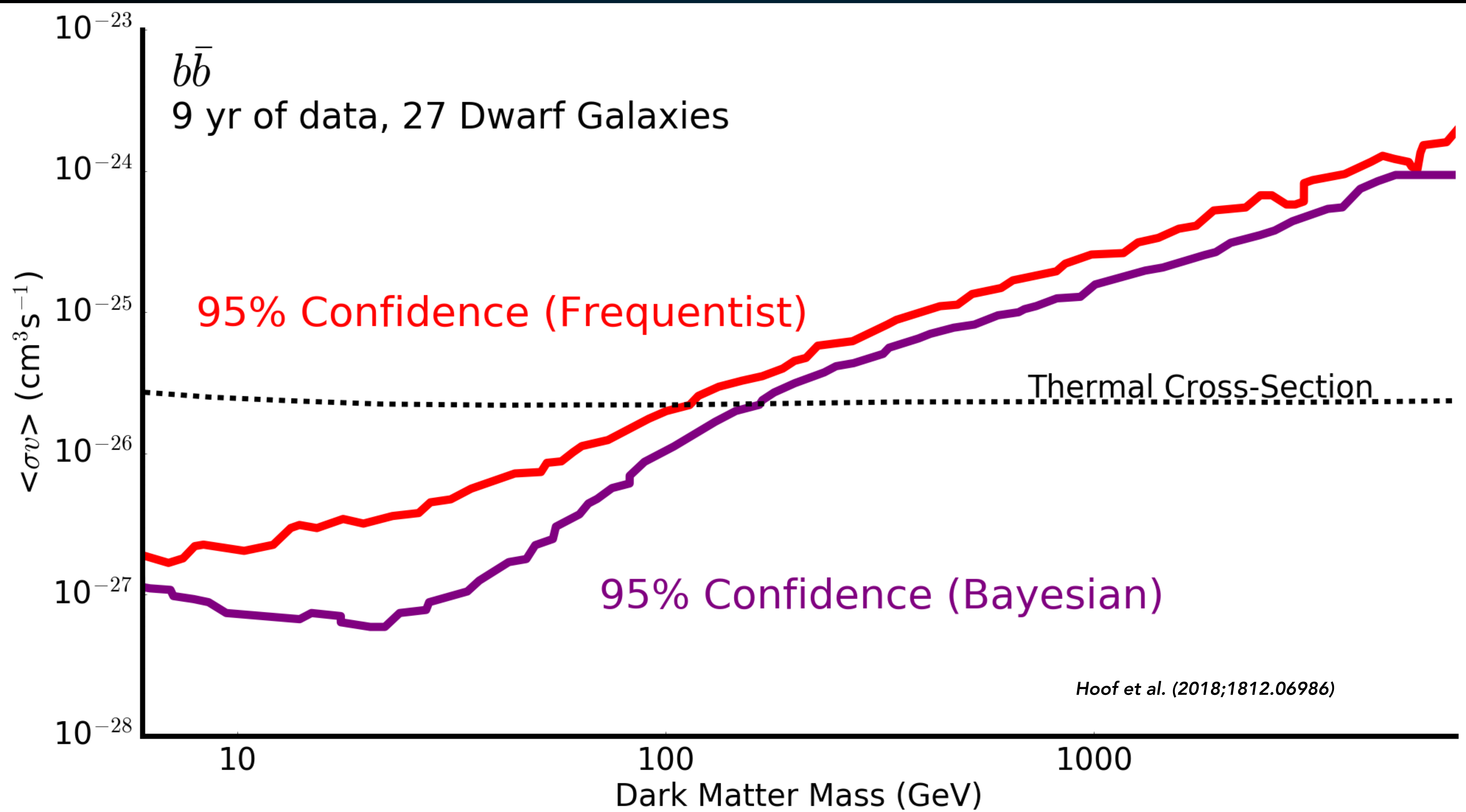
Need to combine observations of multiple dwarfs to constrain thermal cross-section



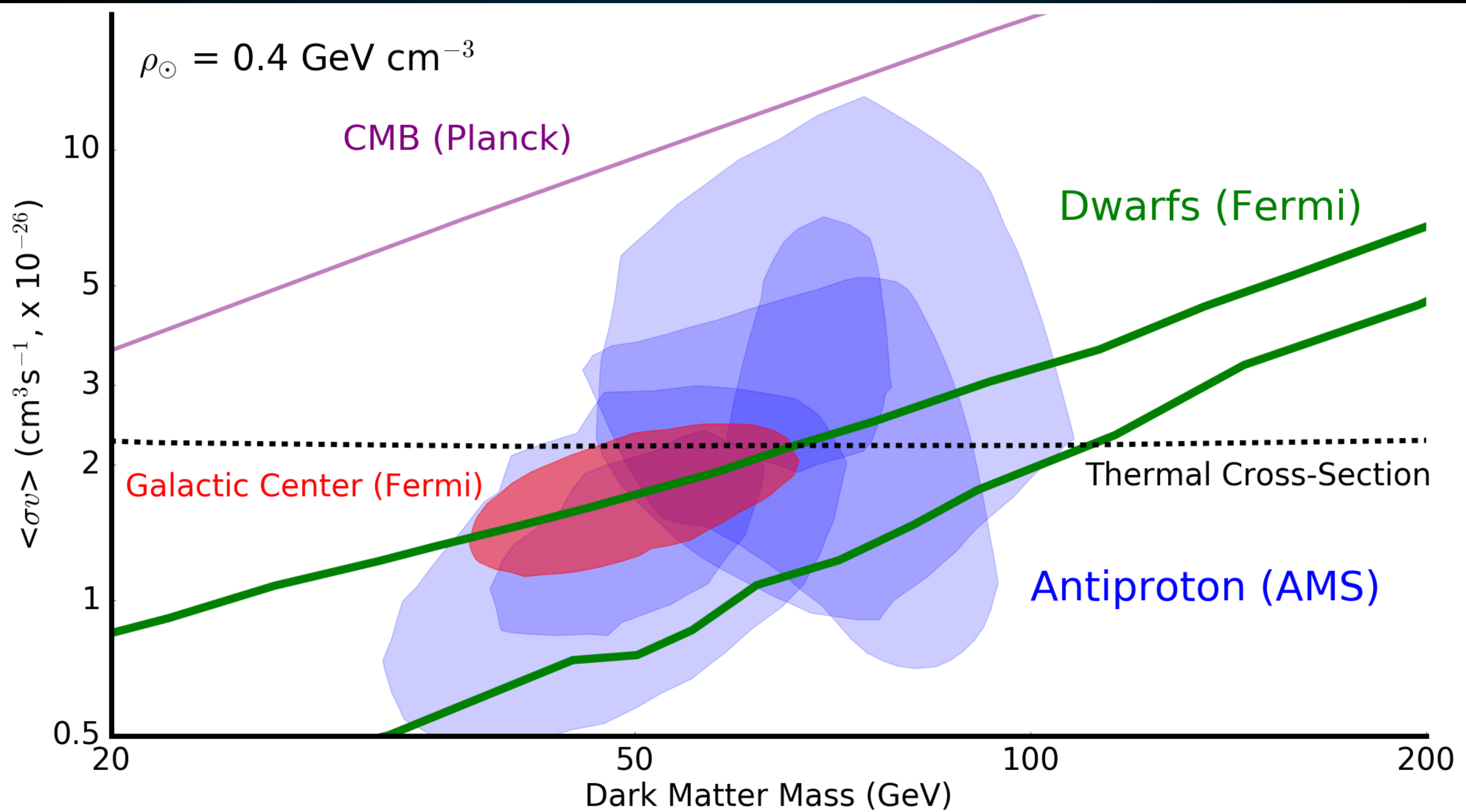




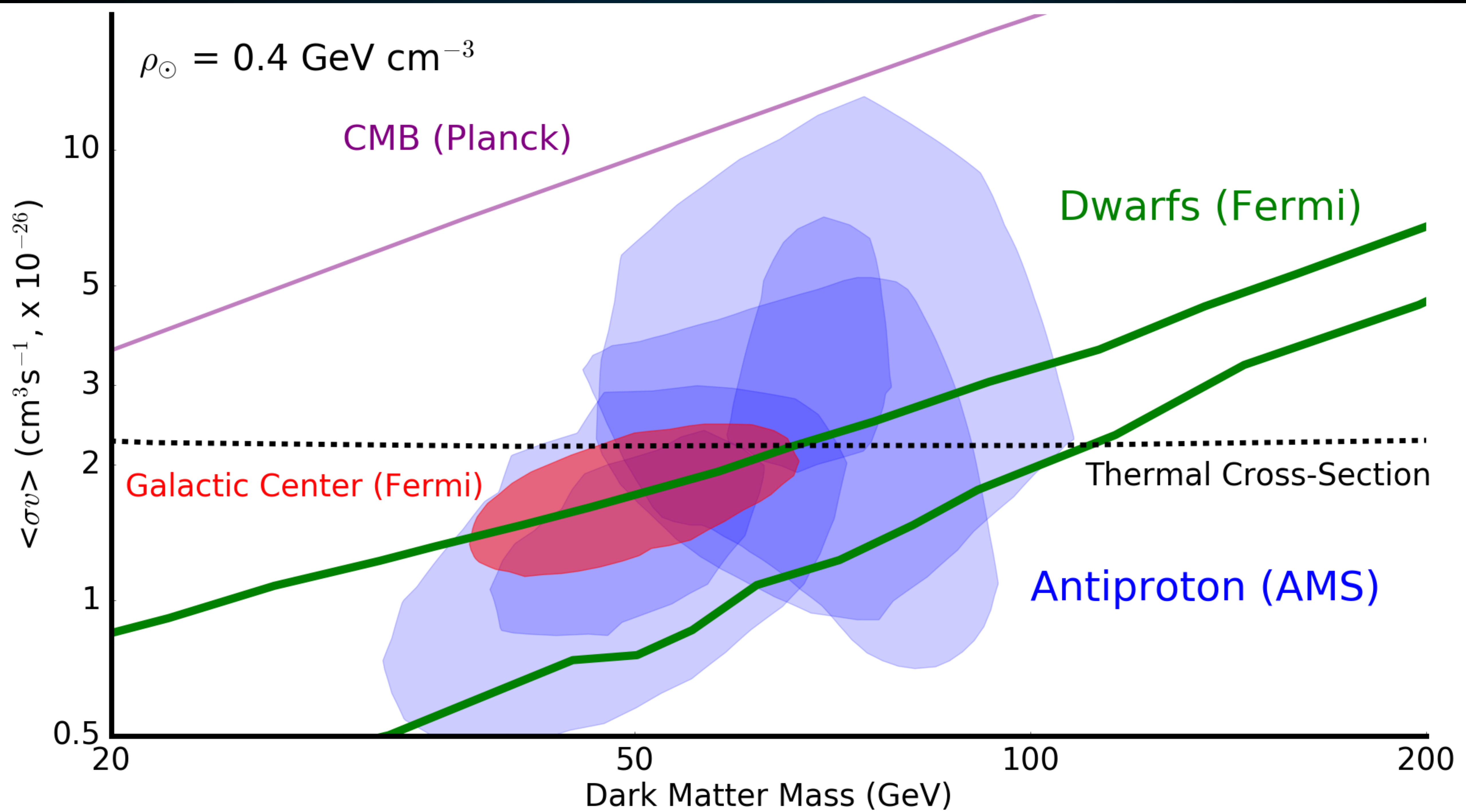


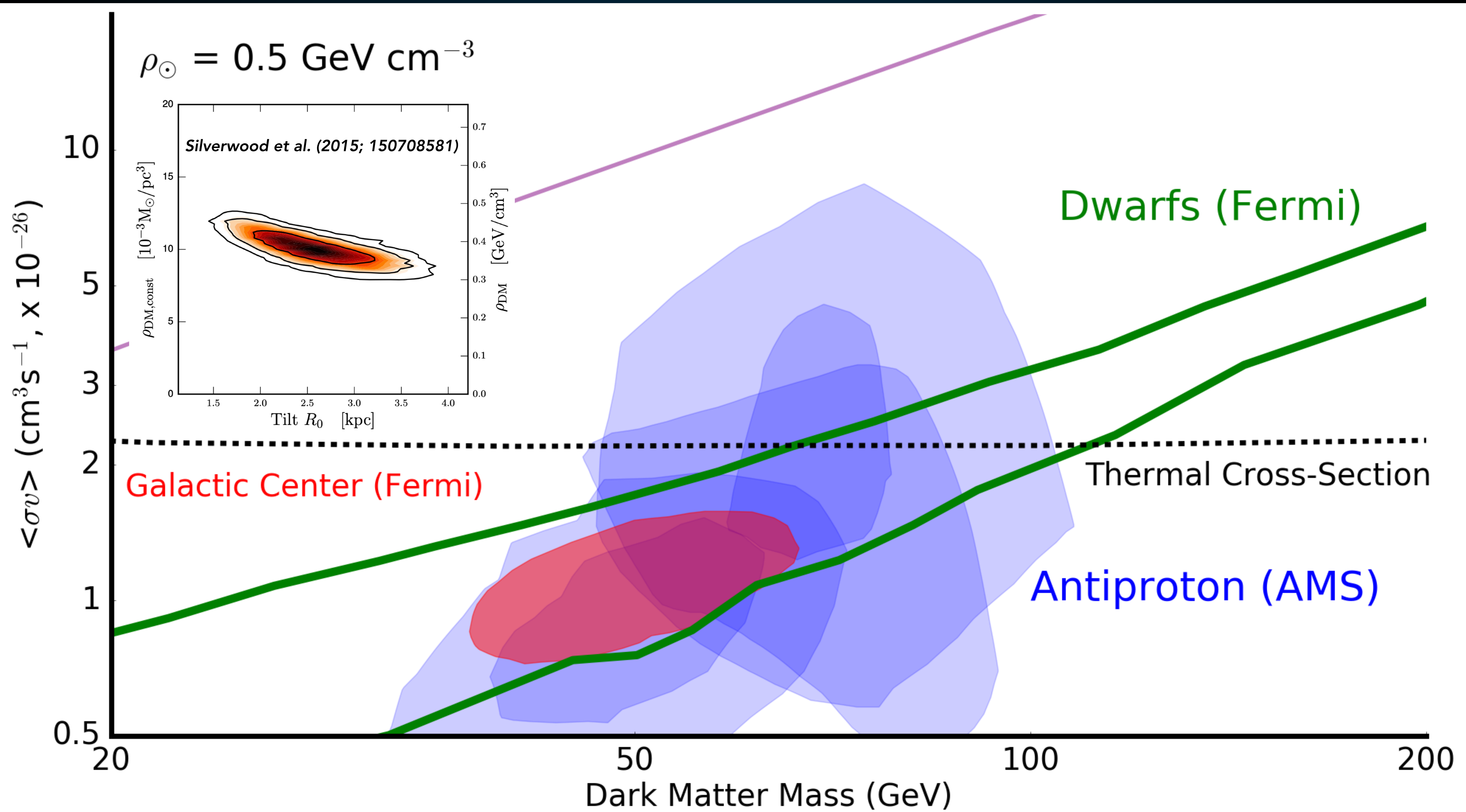


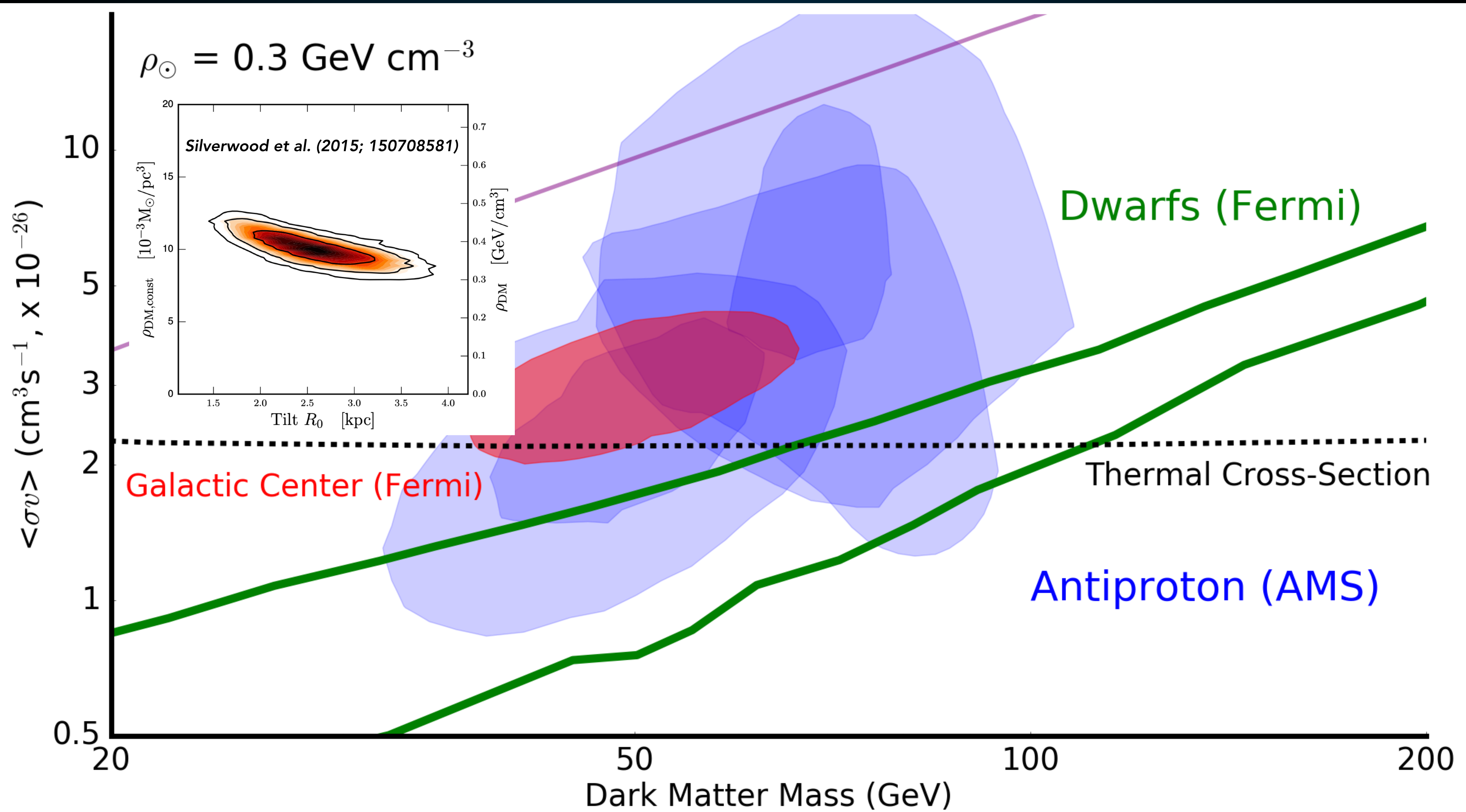
WHERE
ARE
WE NOW?

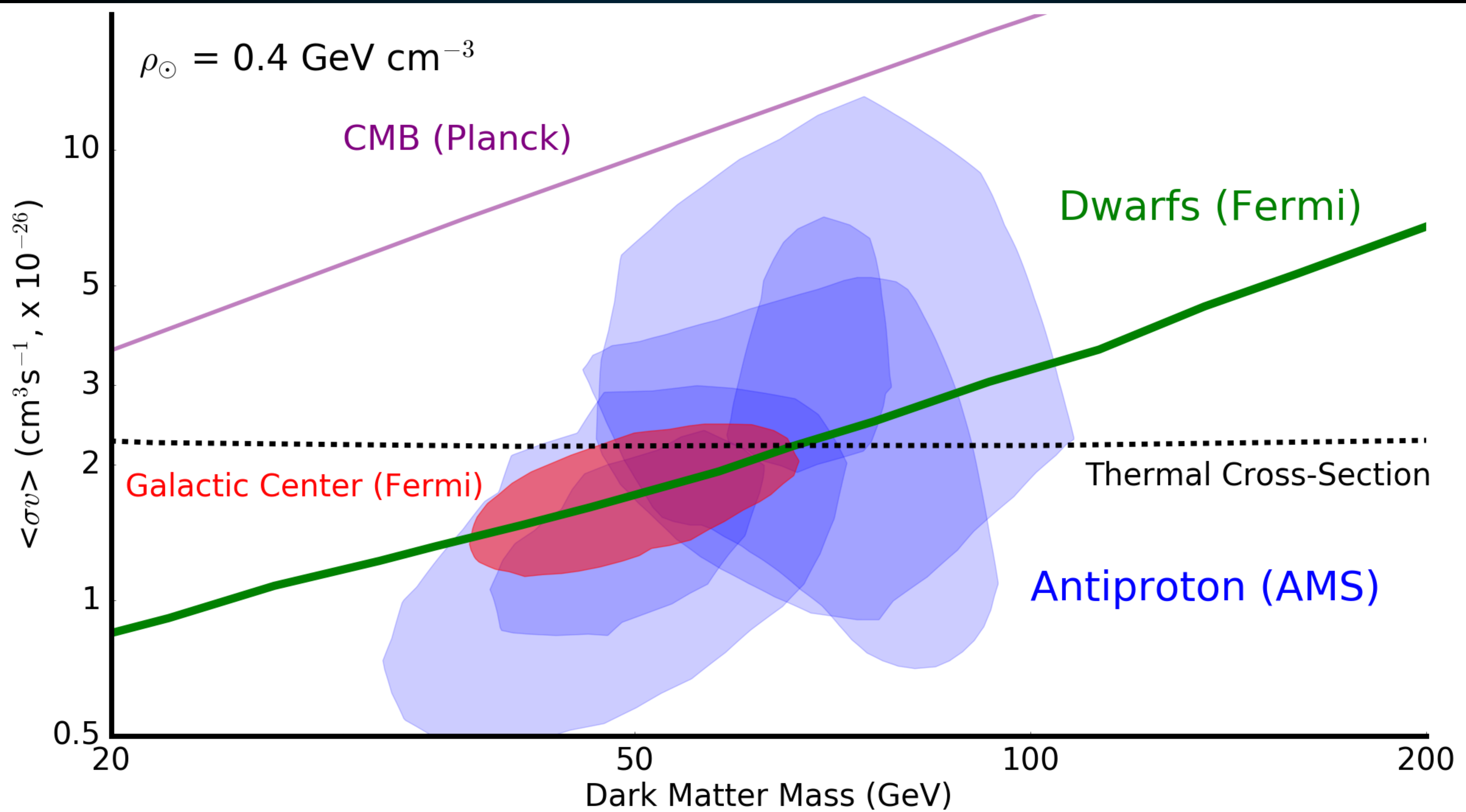


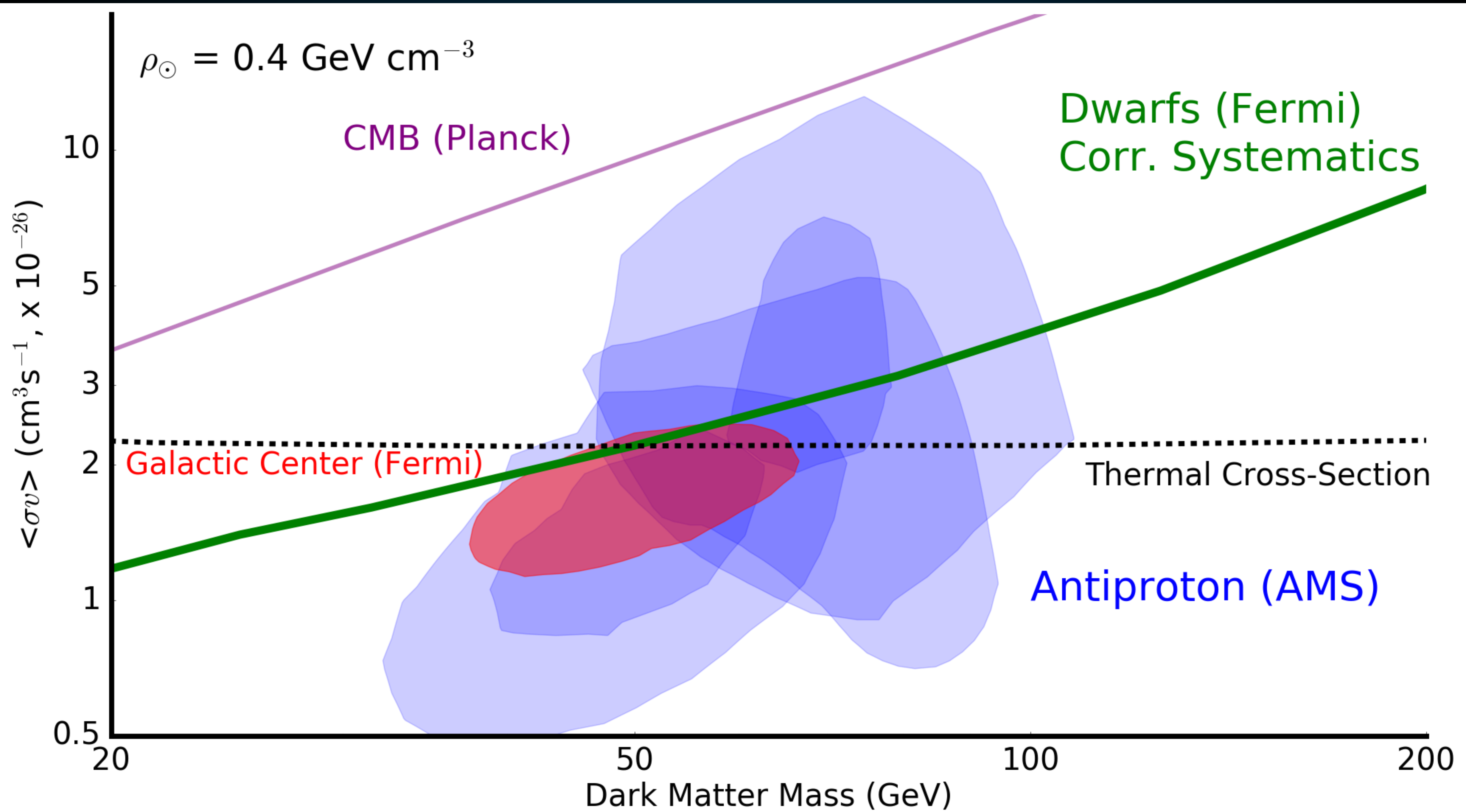


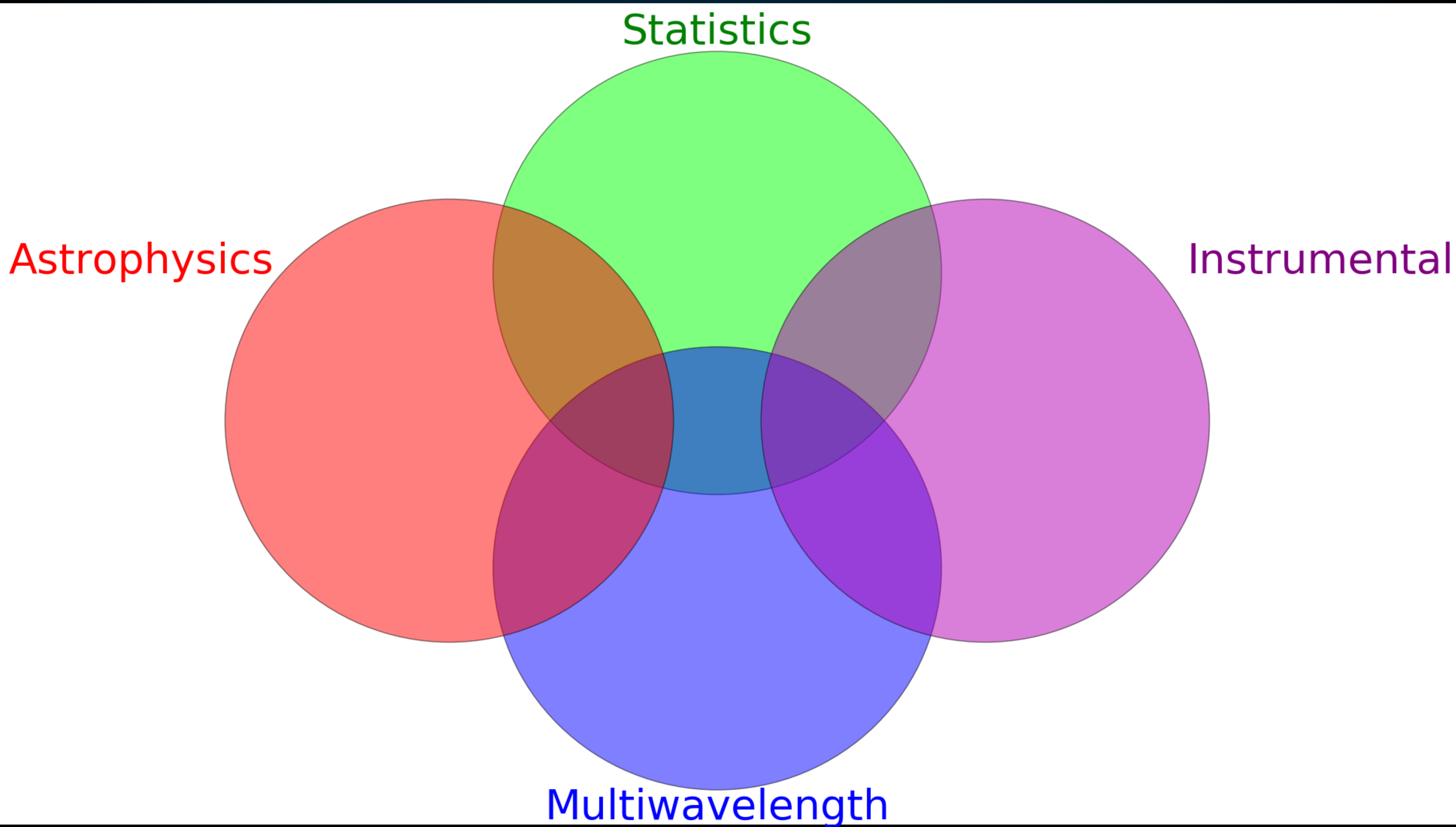




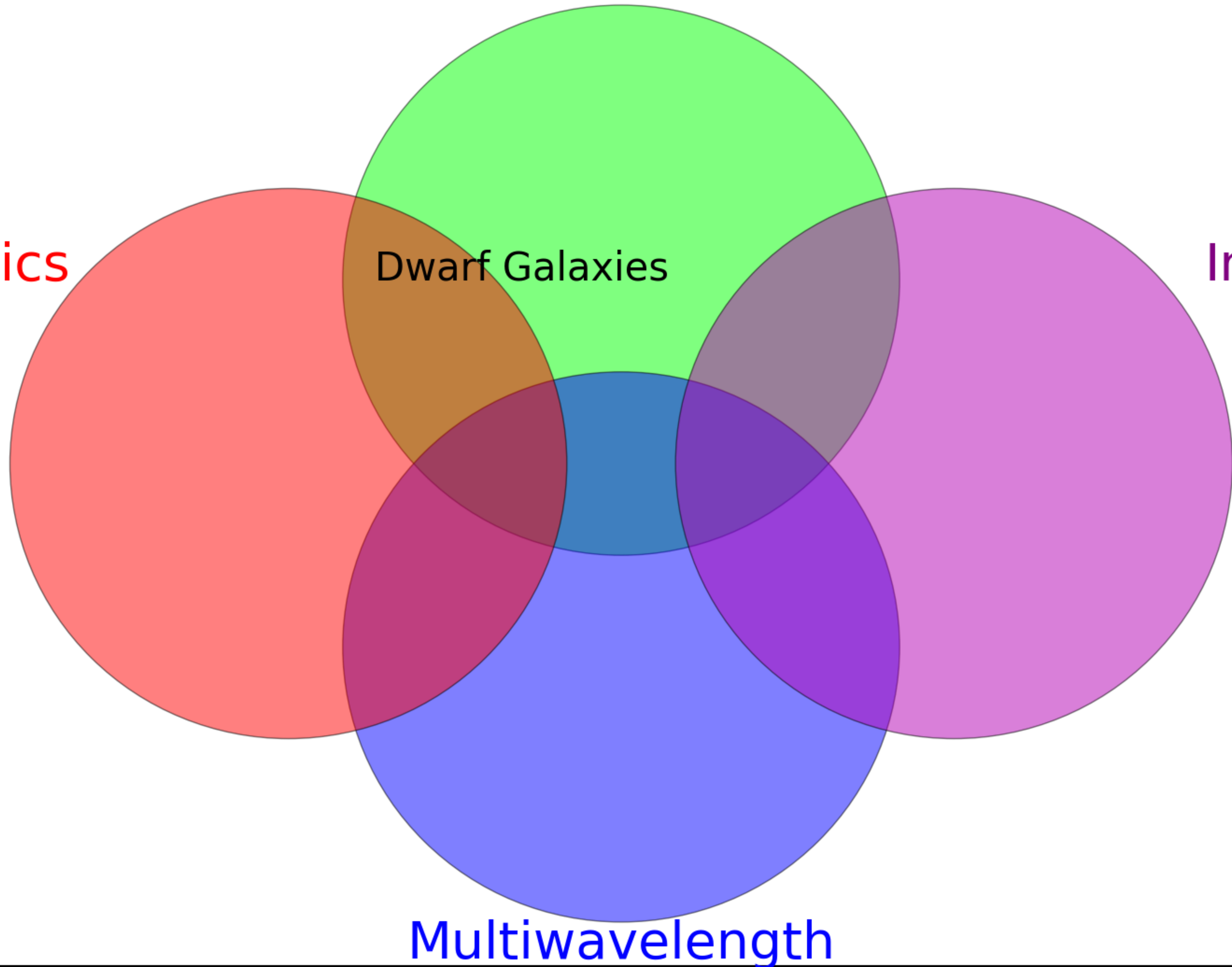








Astrophysics



Statistics

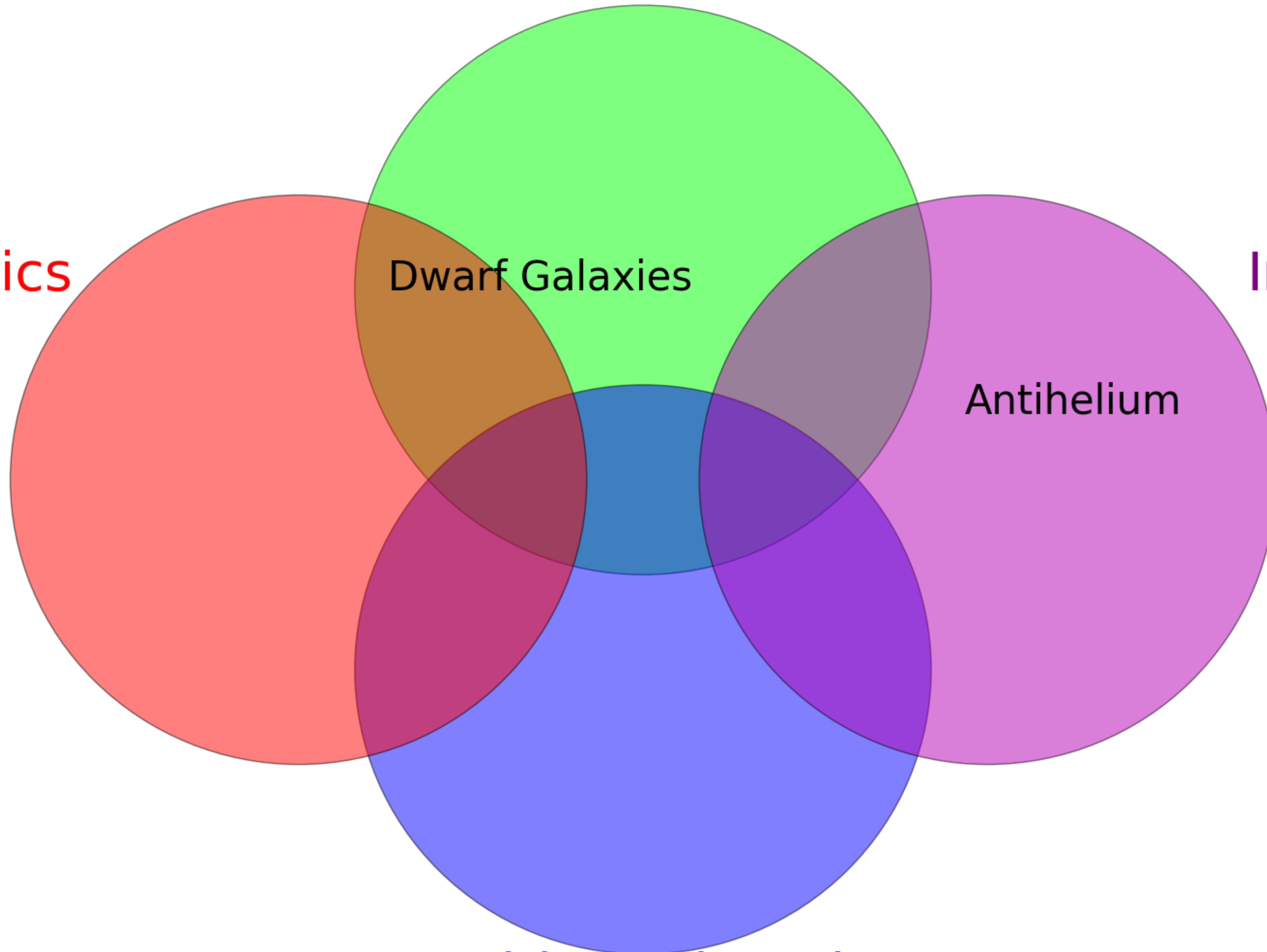
Instrumental

Multiwavelength

Astrophysics

Statistics

Instrumental

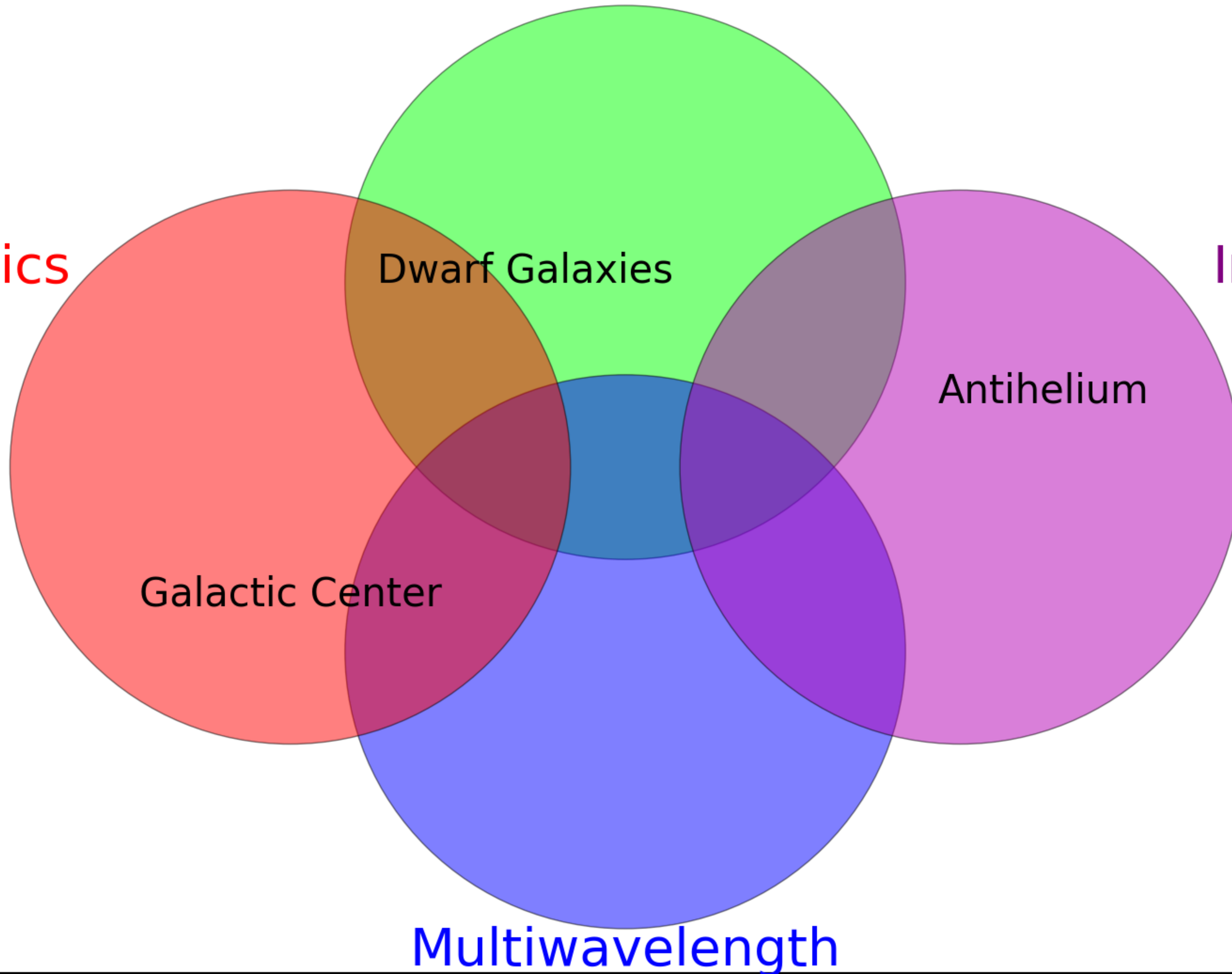


Dwarf Galaxies

Antihelium

Multiwavelength

Astrophysics



Statistics

Dwarf Galaxies

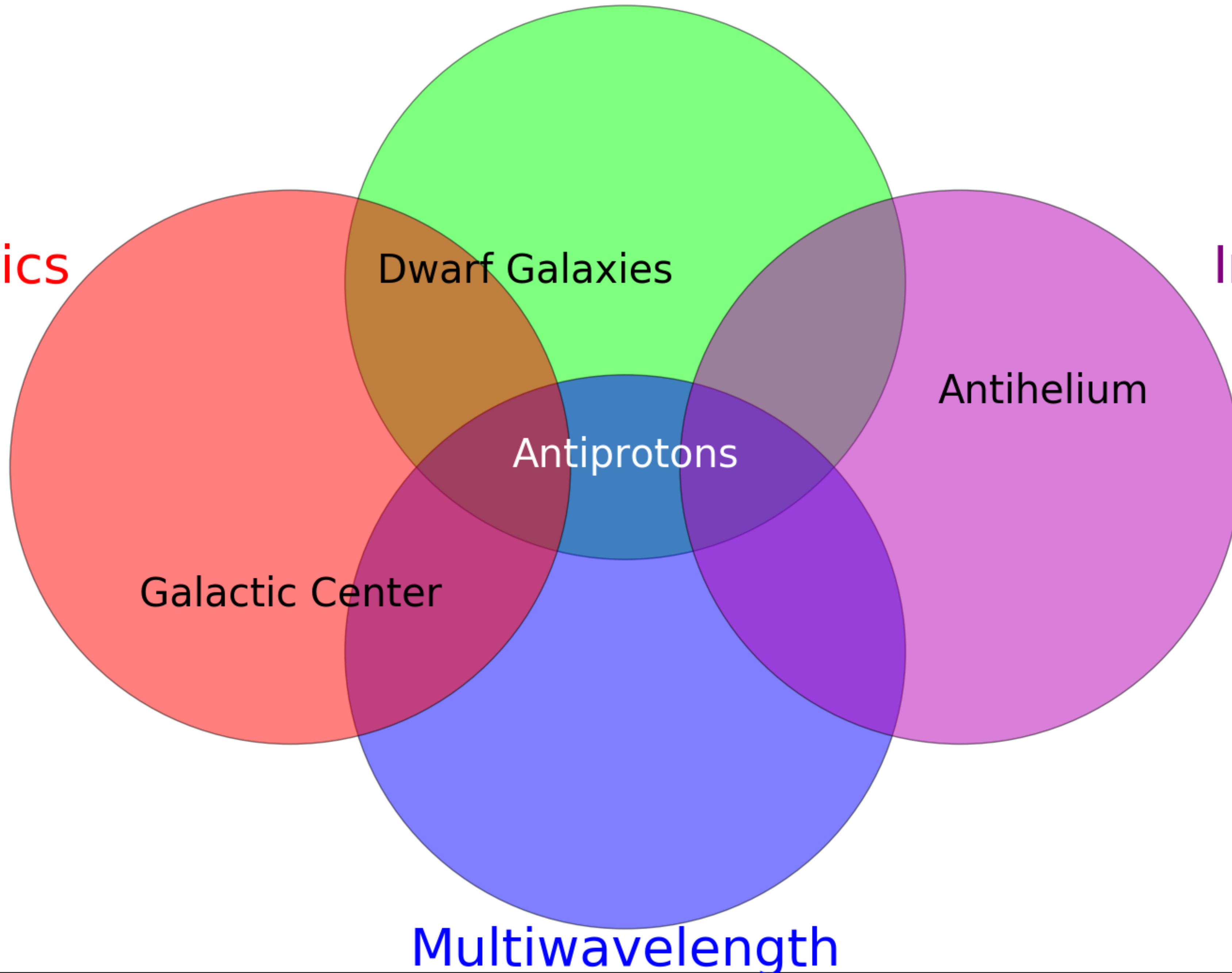
Instrumental

Antihelium

Galactic Center

Multiwavelength

Astrophysics



Dwarf Galaxies

Instrumental

Antihelium

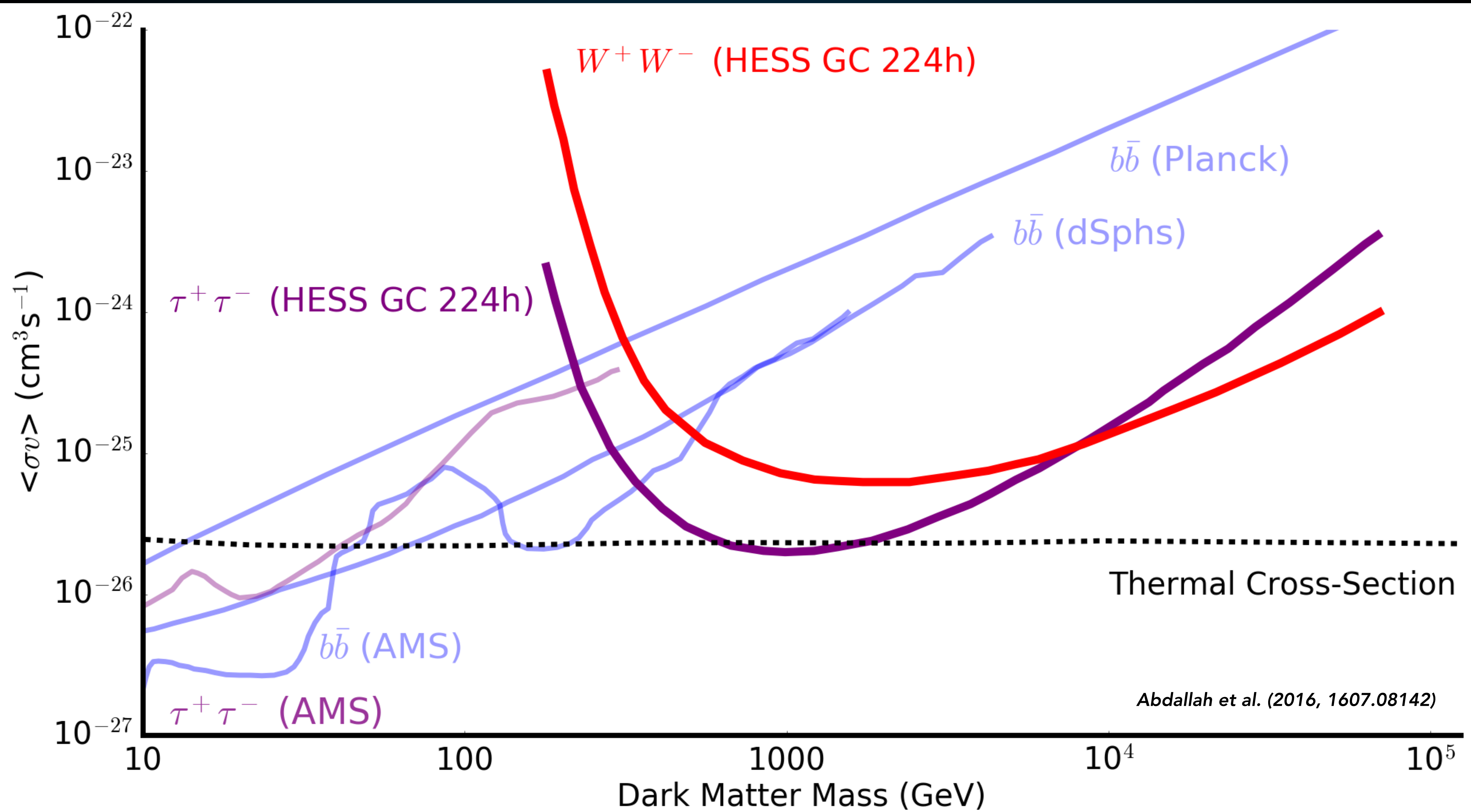
Antiprotons

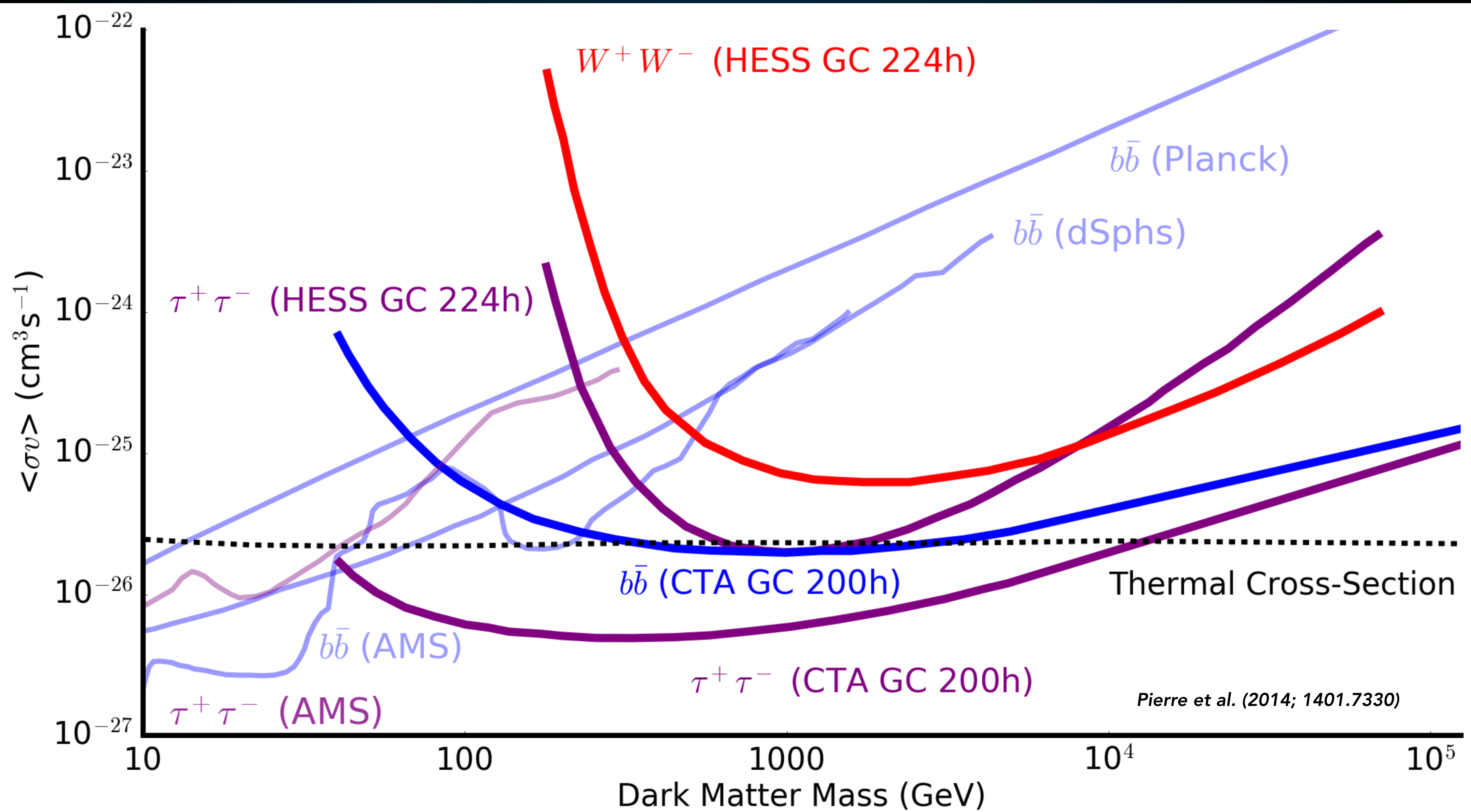
Galactic Center

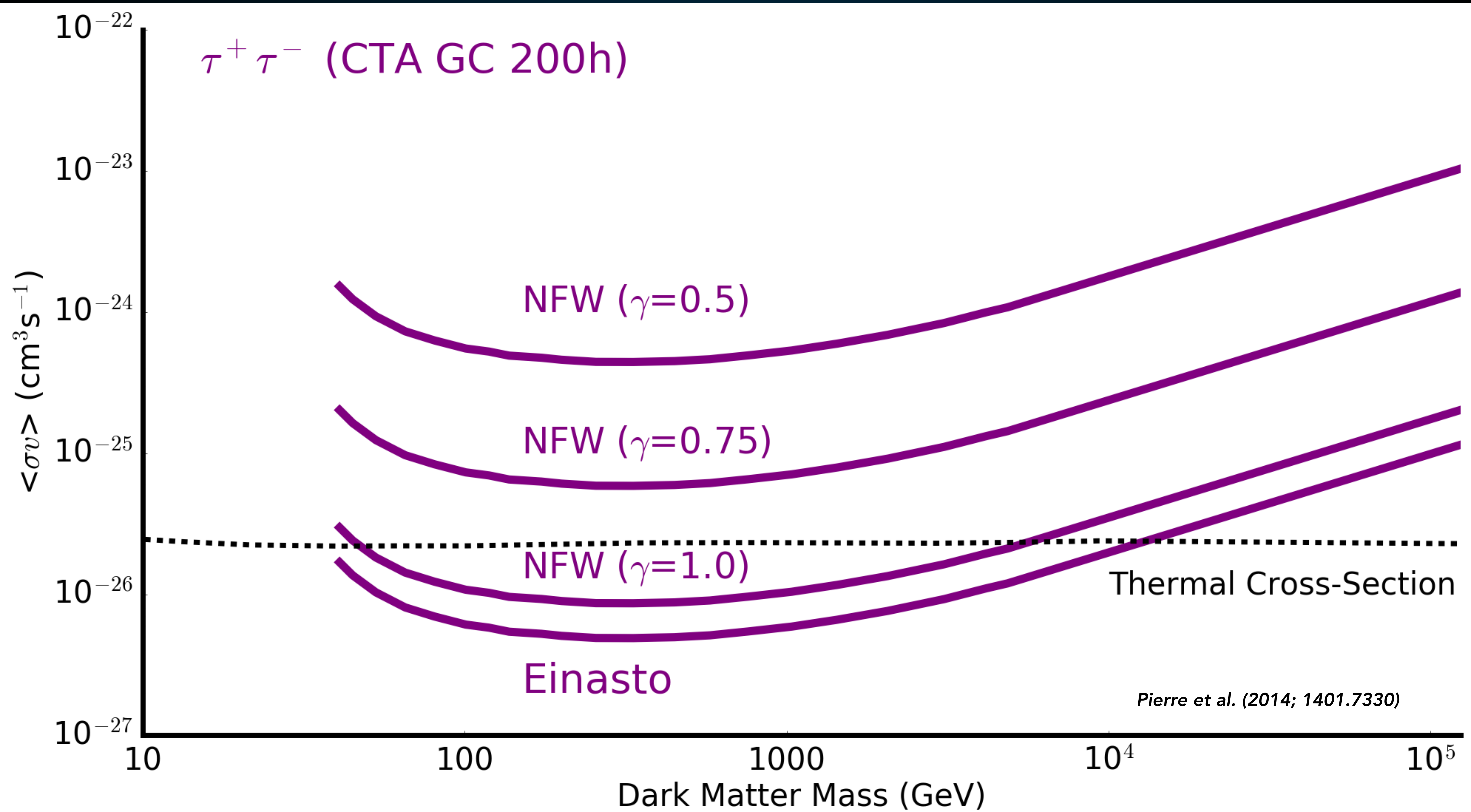
Multiwavelength

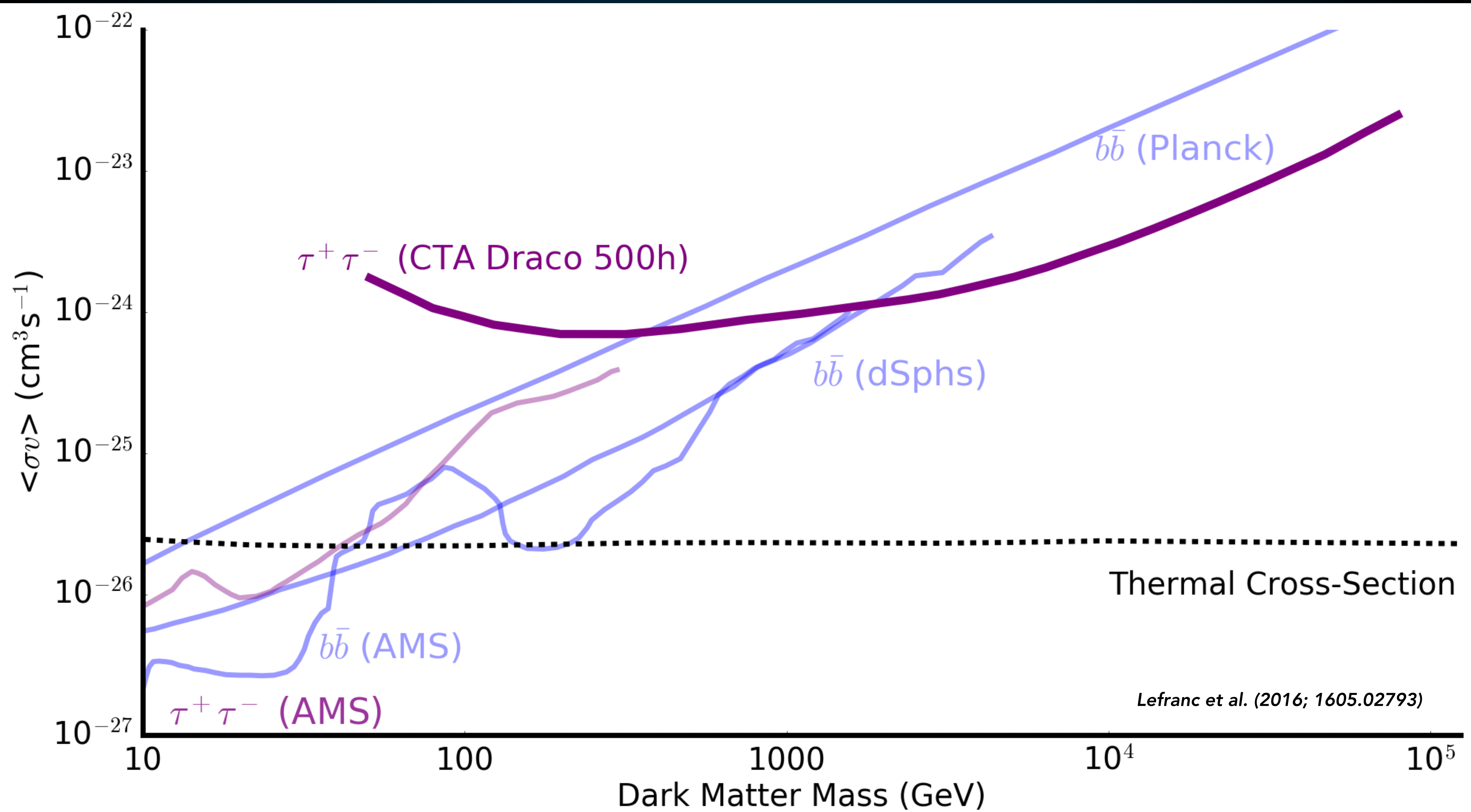


What About TeV WIMPS?



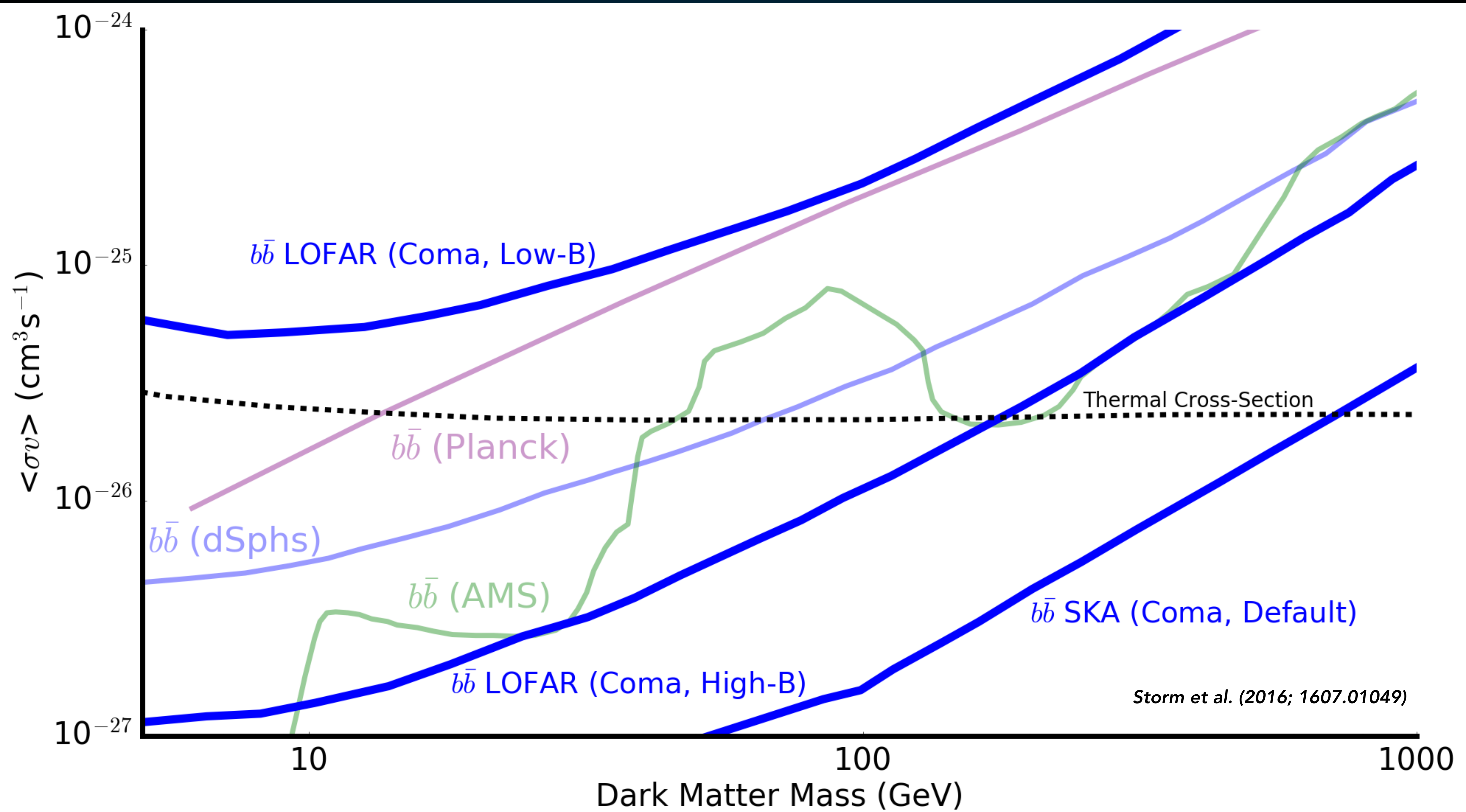






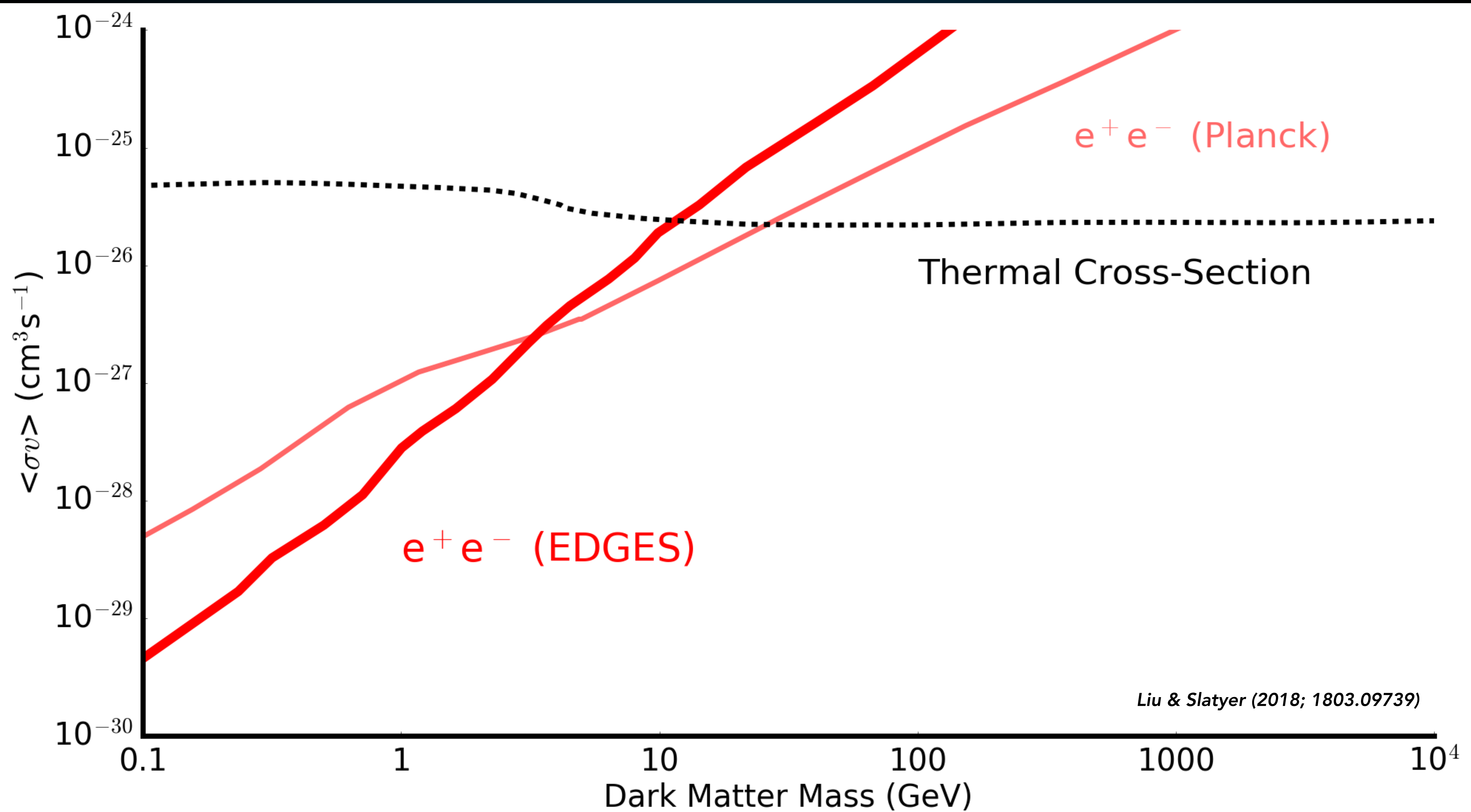
What About Radio Searches?



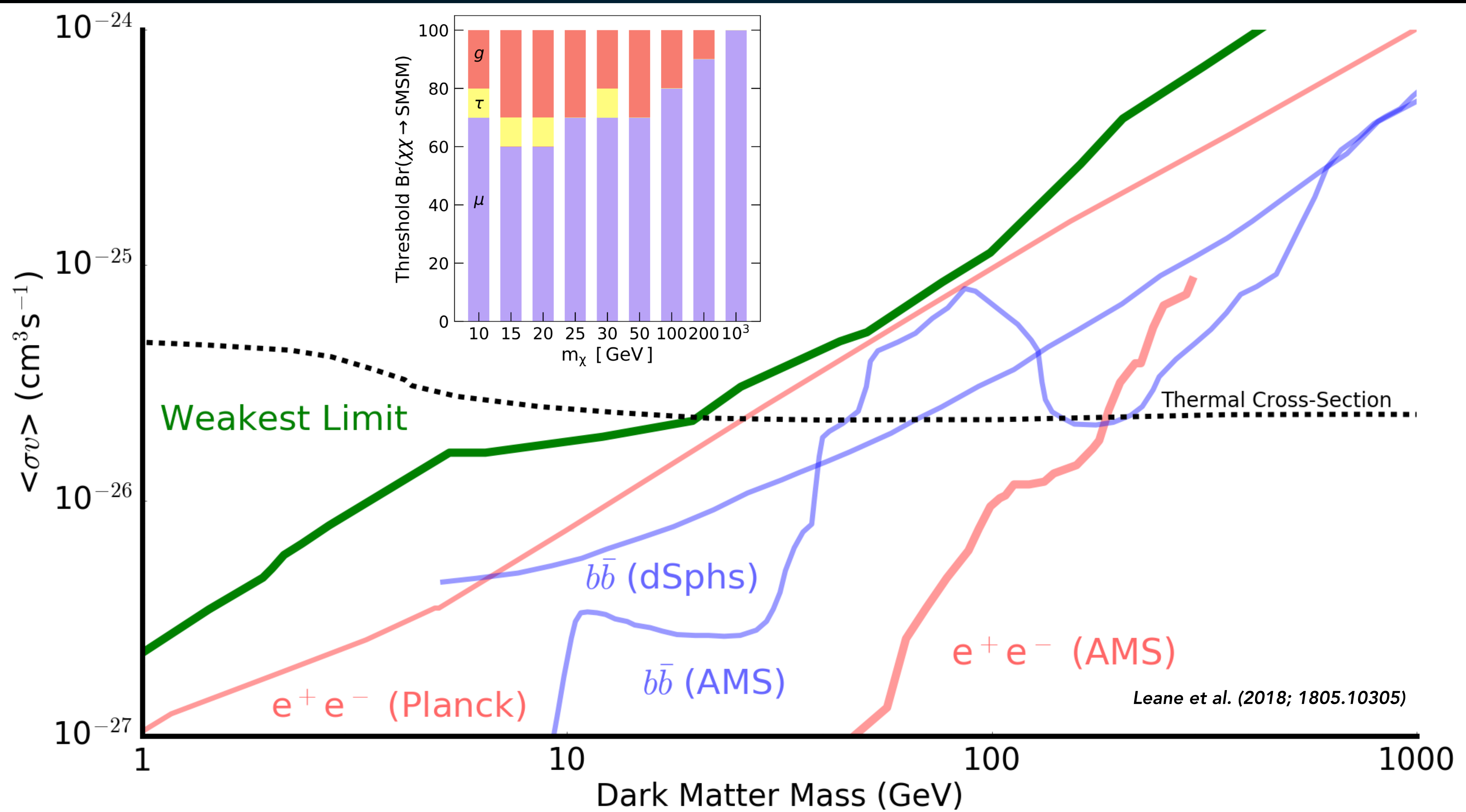




21 cm!







Or Maybe A Surprise !

