



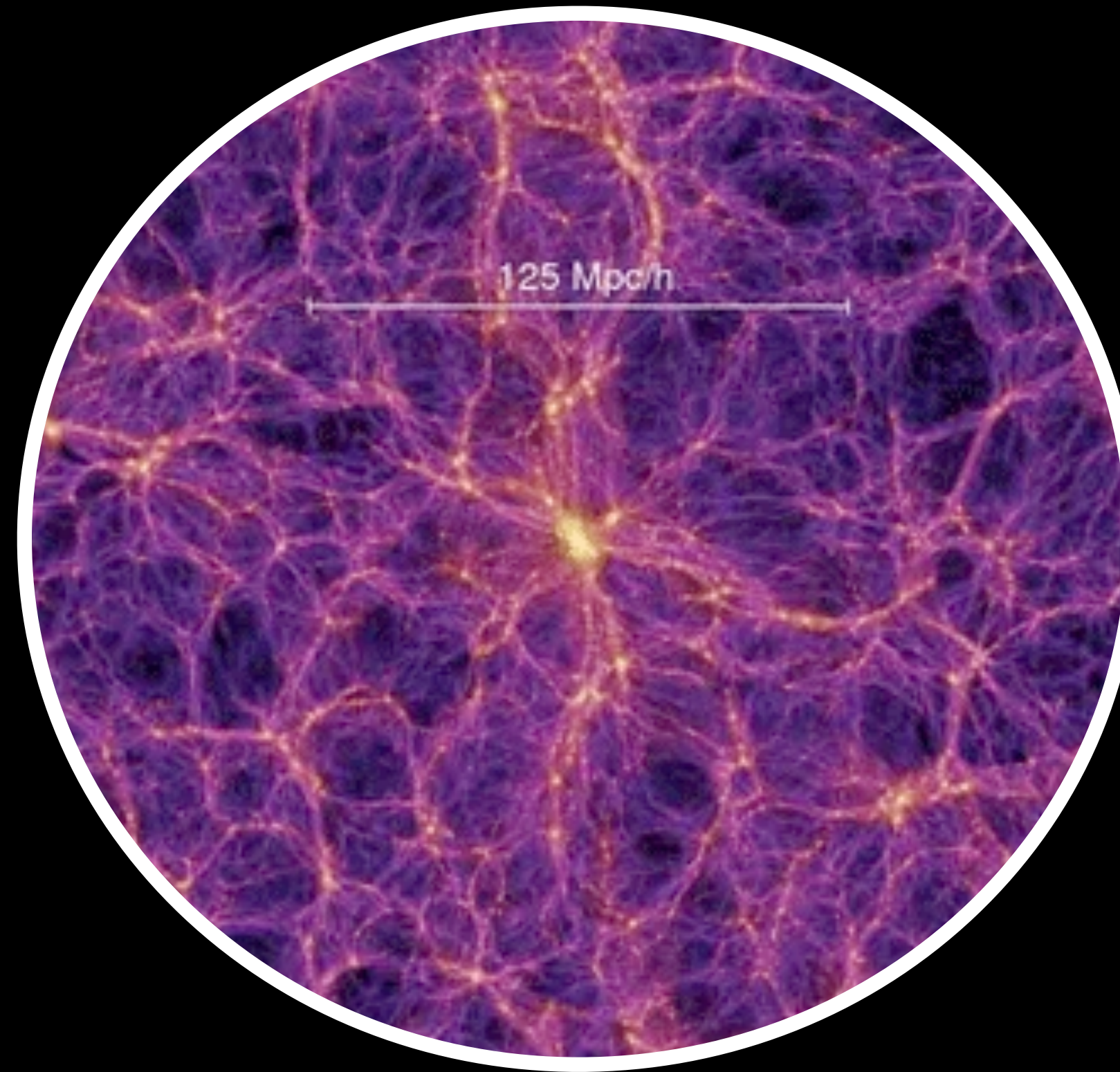
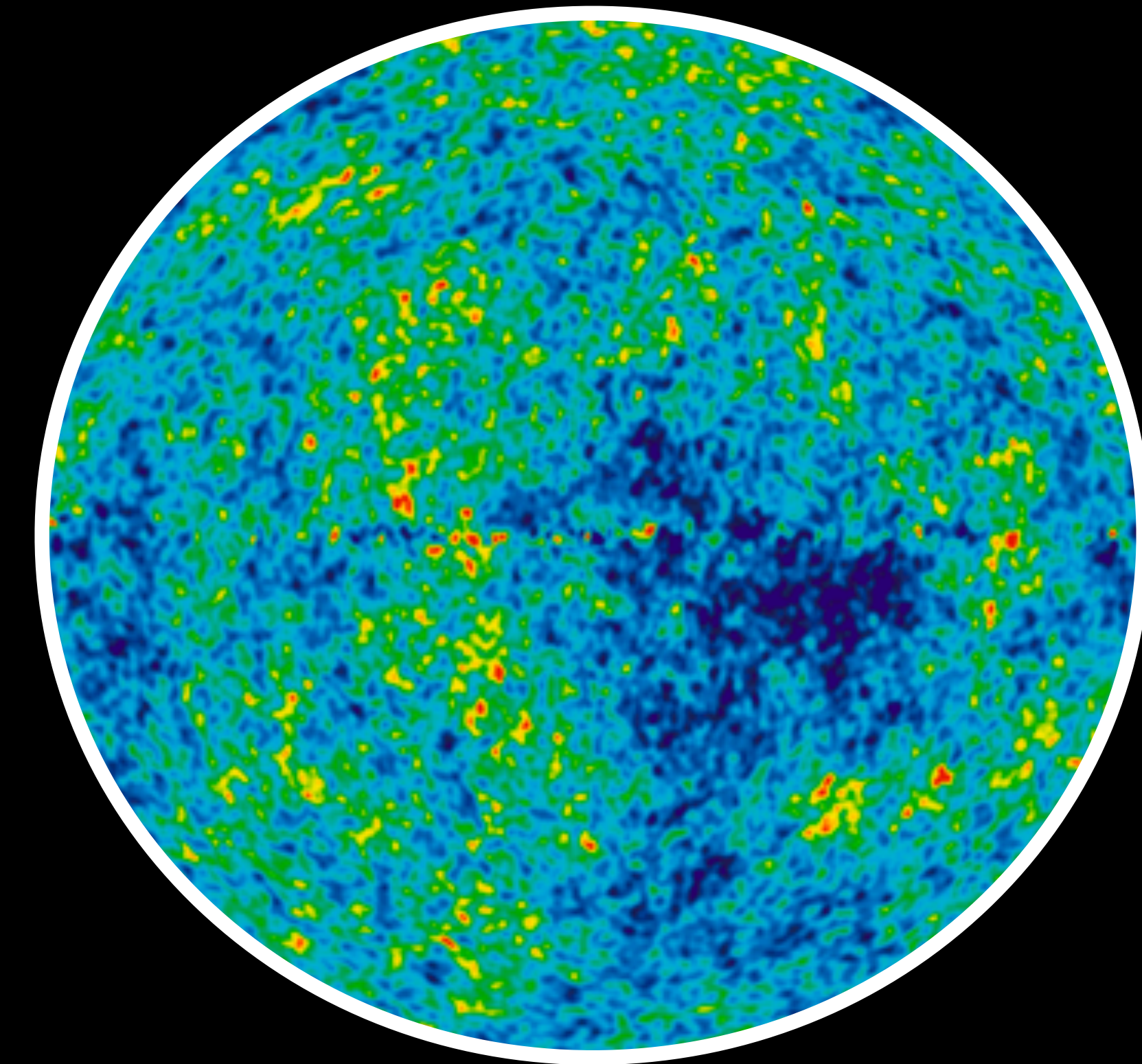
Tim Linden

Thermal WIMP Dark Matter on the Brink

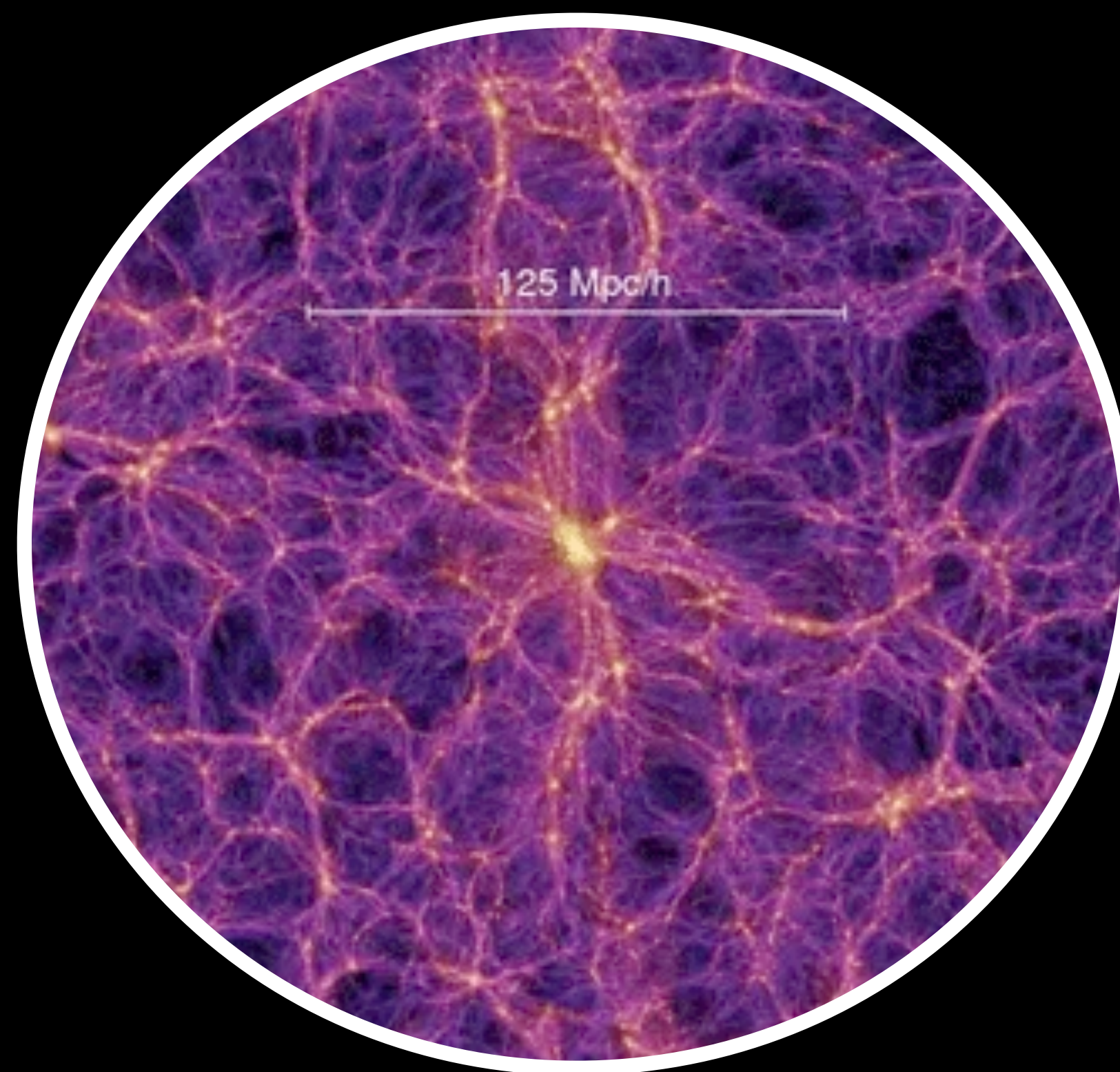
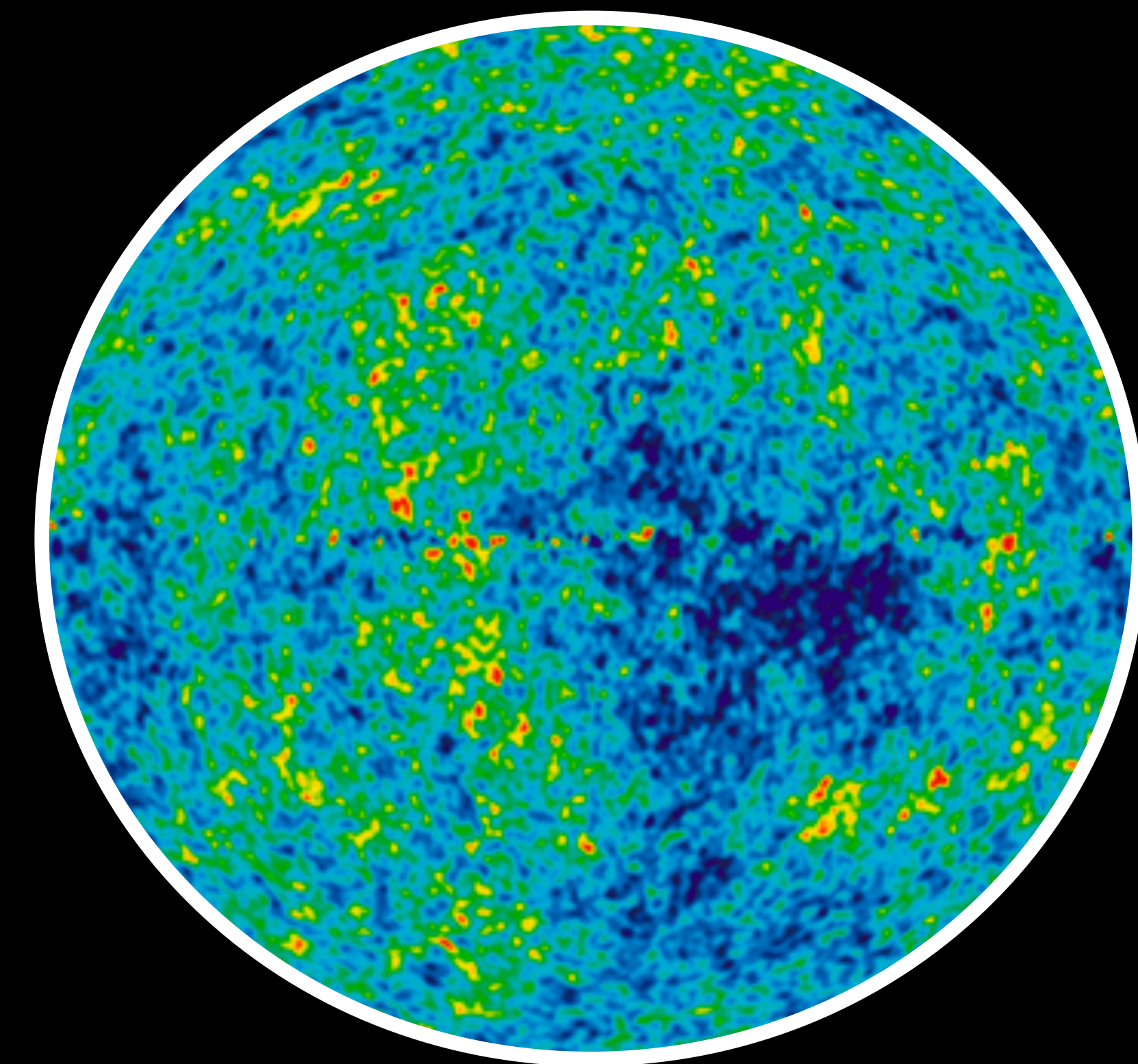


Stockholms
universitet

The Present



The Present

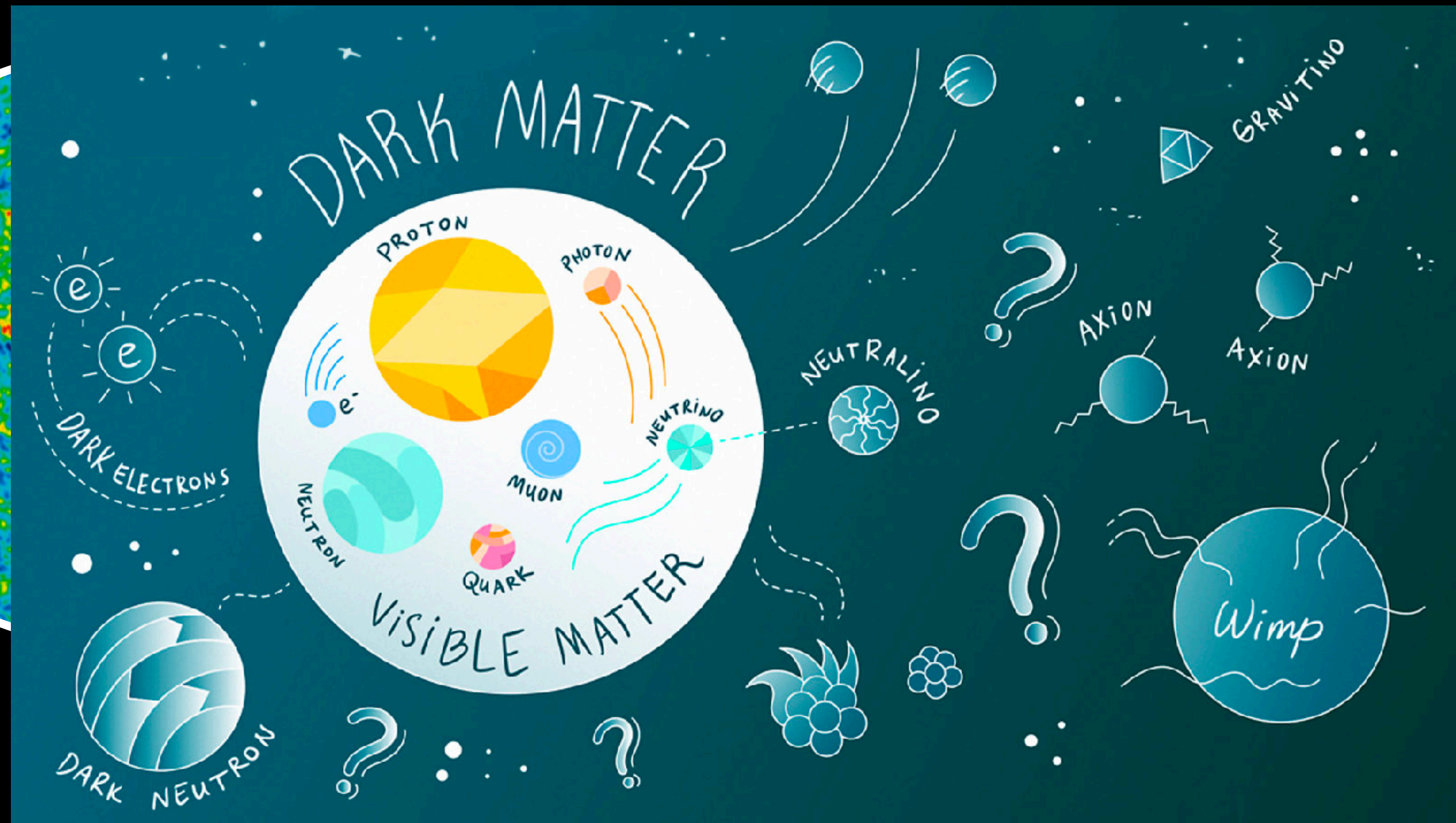


10^{-25} GeV
 $R_{DM} > R_{UFD}$

slide concept courtesy of Asher Berlin

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

The Present



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

slide concept courtesy of Asher Berlin

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



Tim Linden

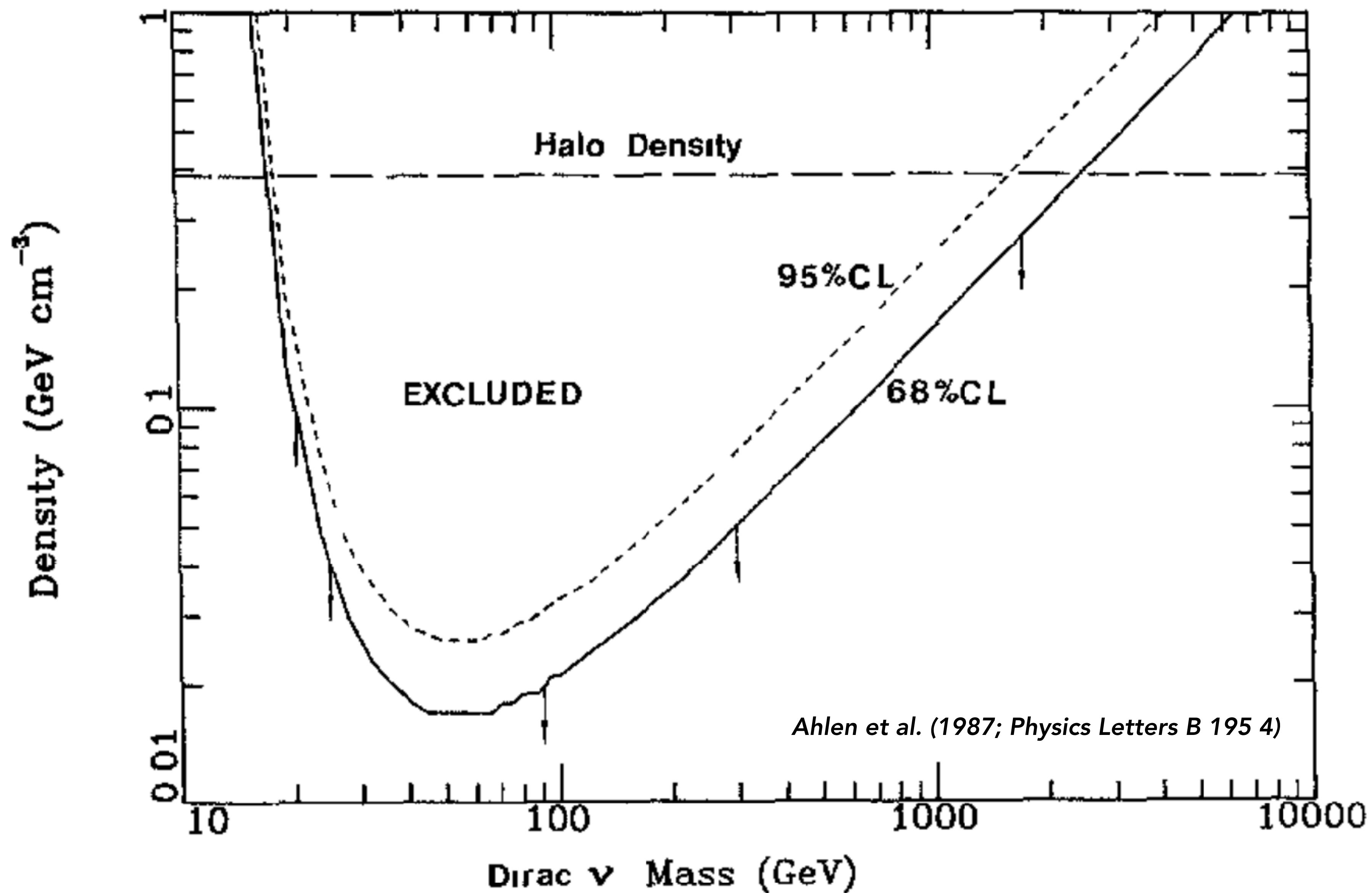
Thermal WIMP Dark Matter on the Brink



THE OHIO STATE UNIVERSITY
CENTER FOR COSMOLOGY AND
ASTROPARTICLE PHYSICS

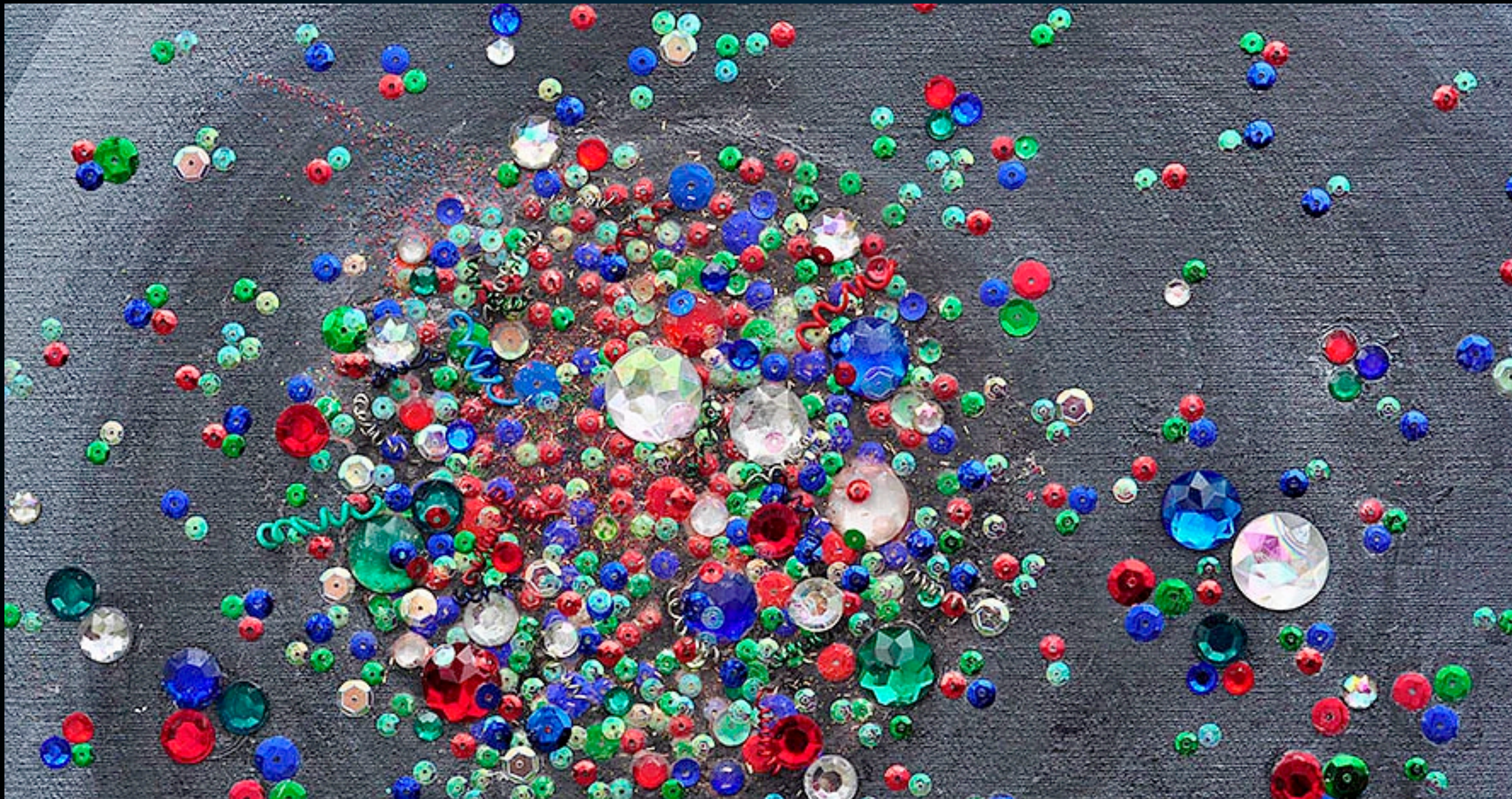
Can We Eliminate Classes of Dark Matter Models?

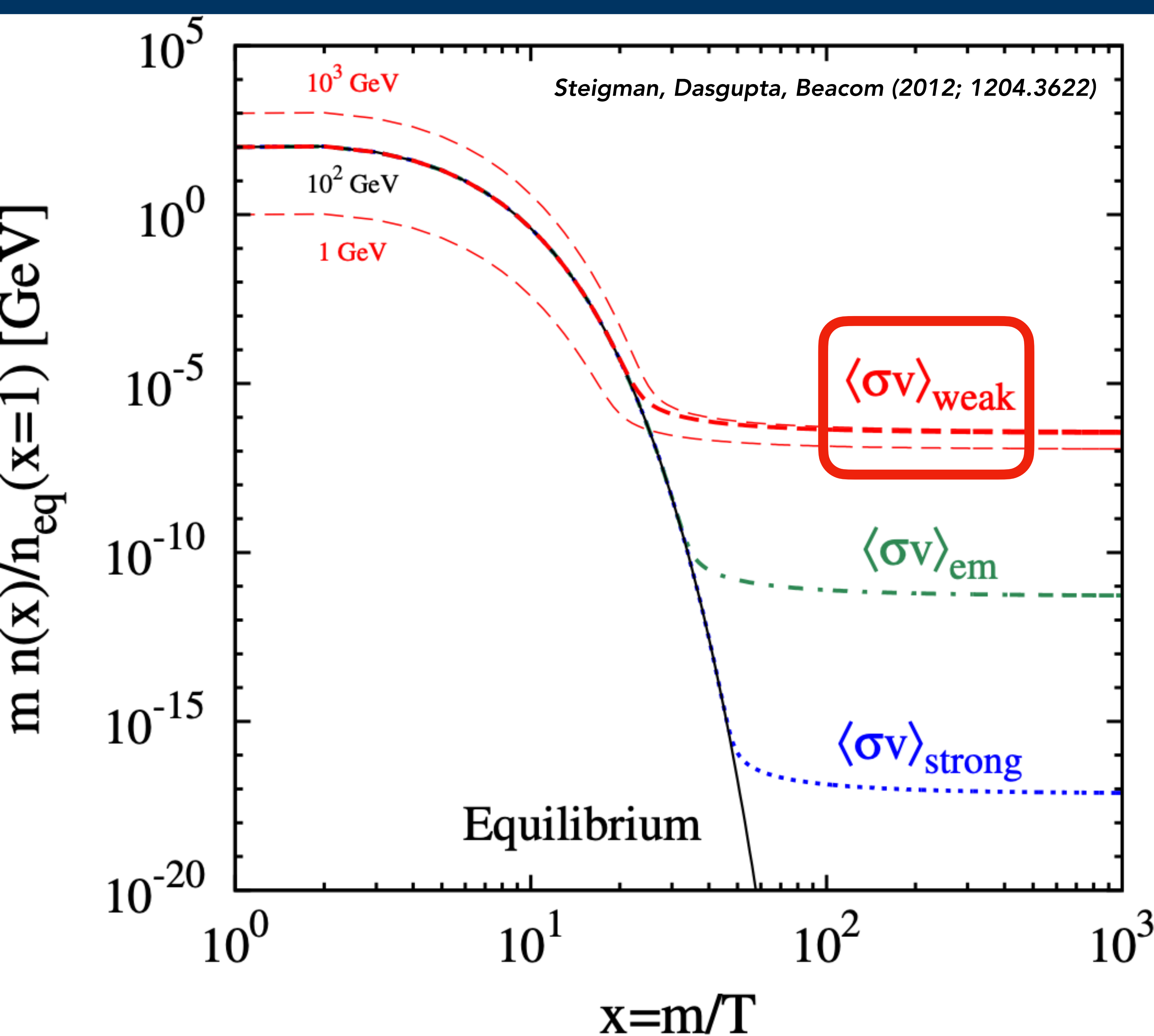
Yes!



Thermal Dark Matter

artist: Sarah Szabo



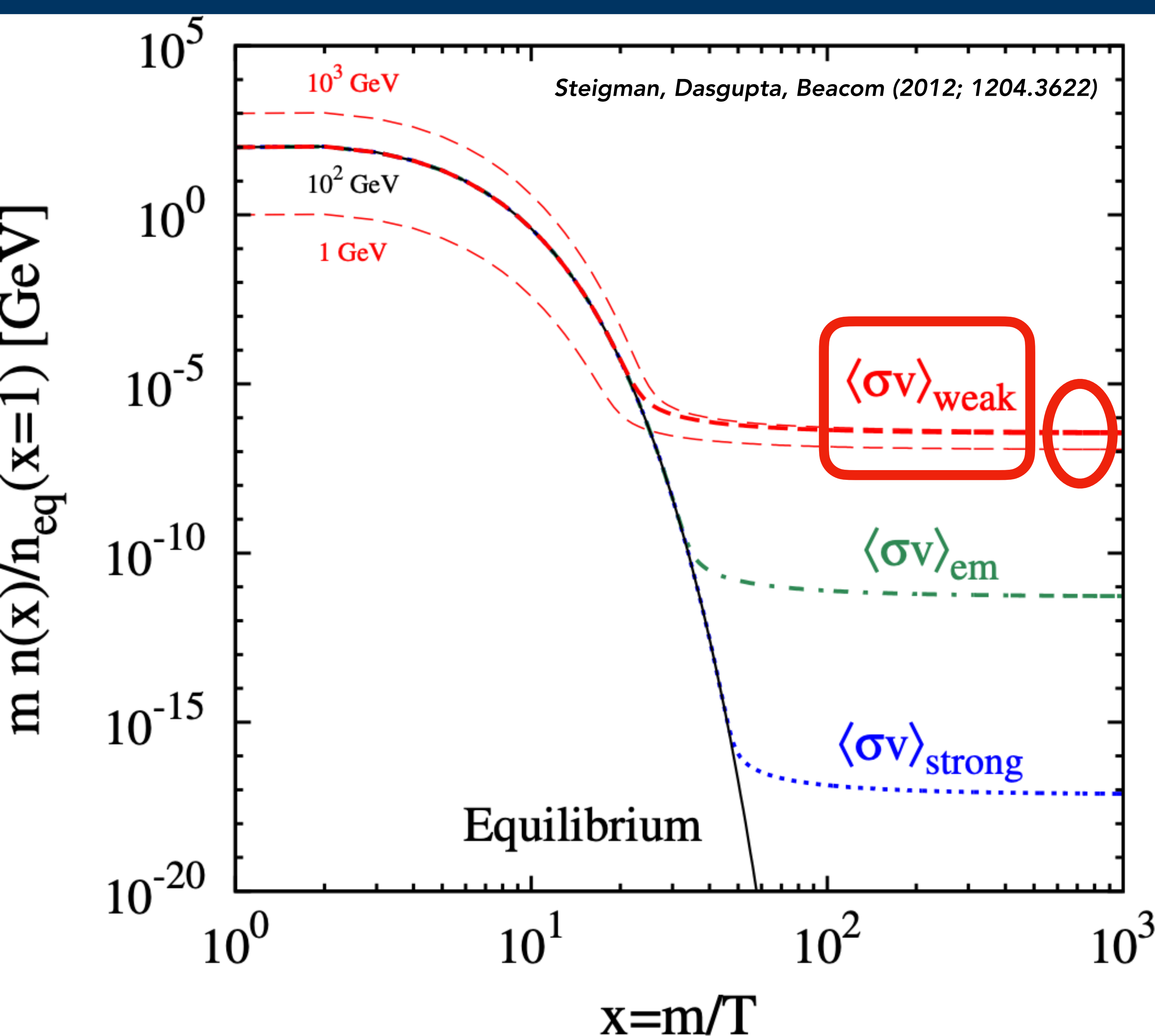


Thermal Dark Matter Density

Present density inversely proportional to the strength of the interaction.

Almost independent of particle mass.

Weak-Interaction Produces the right density!



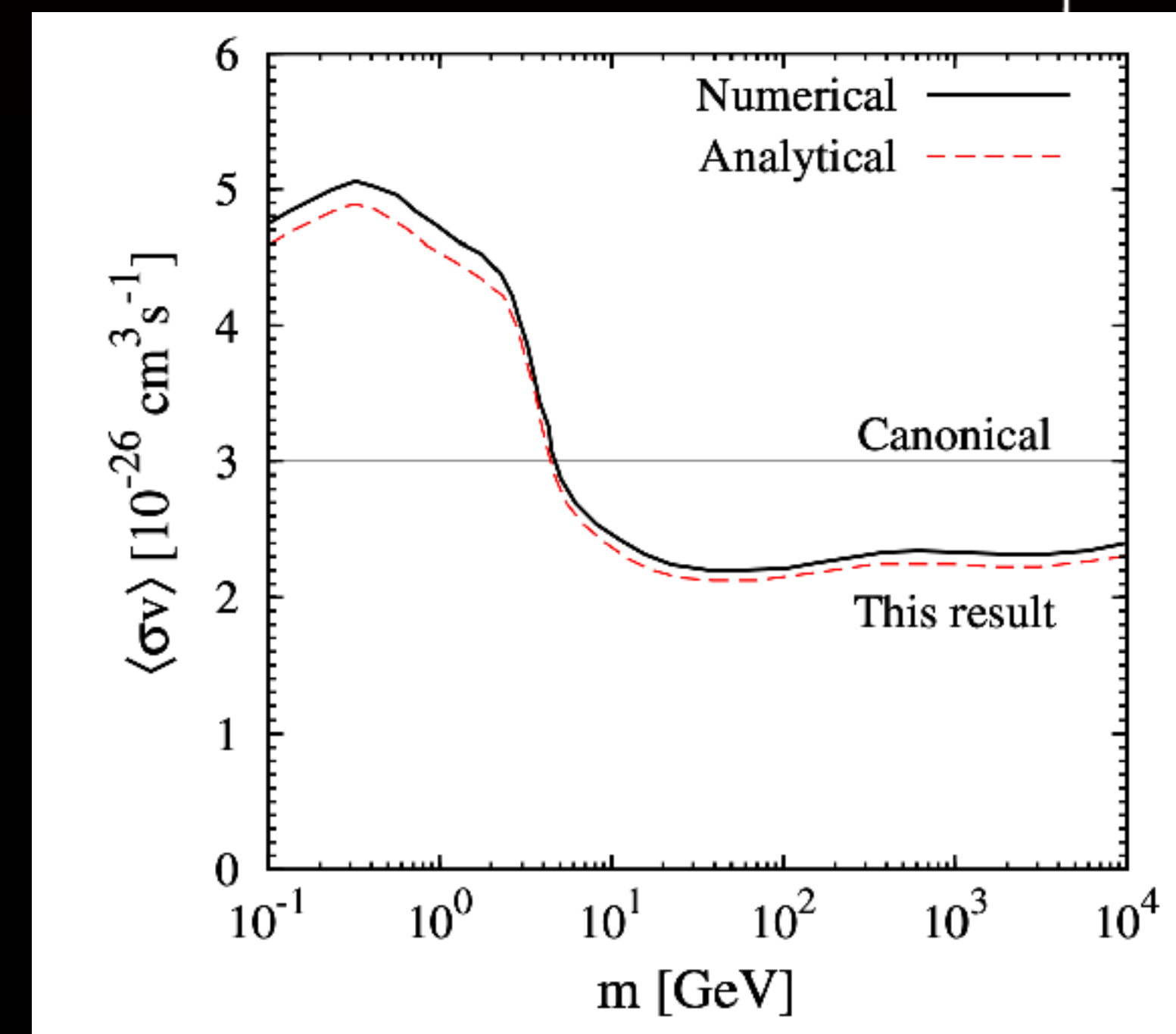
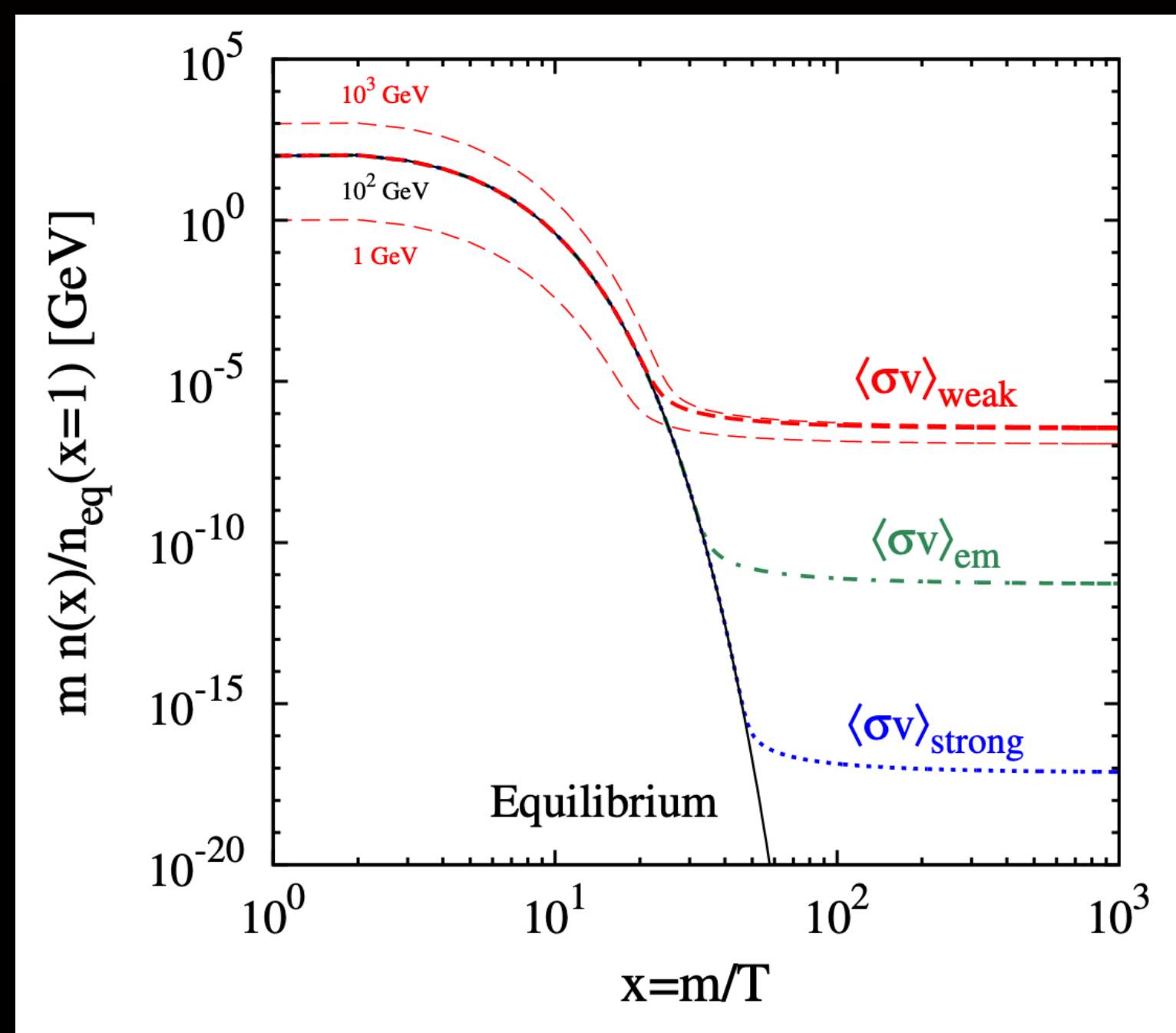
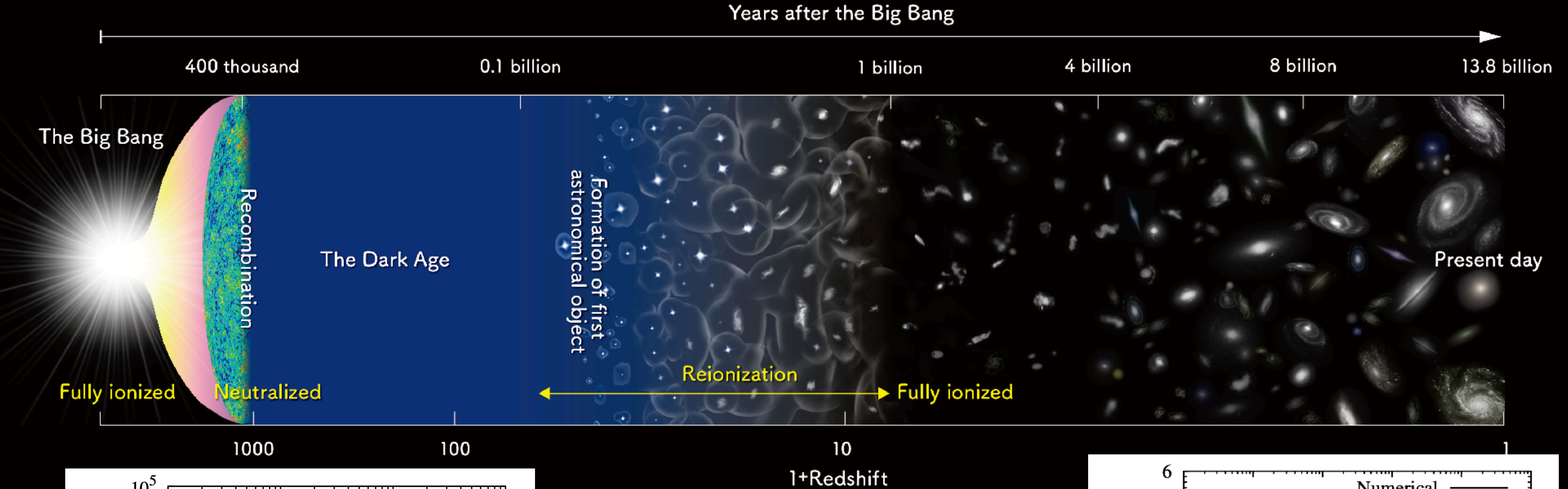
Thermal Dark Matter Density

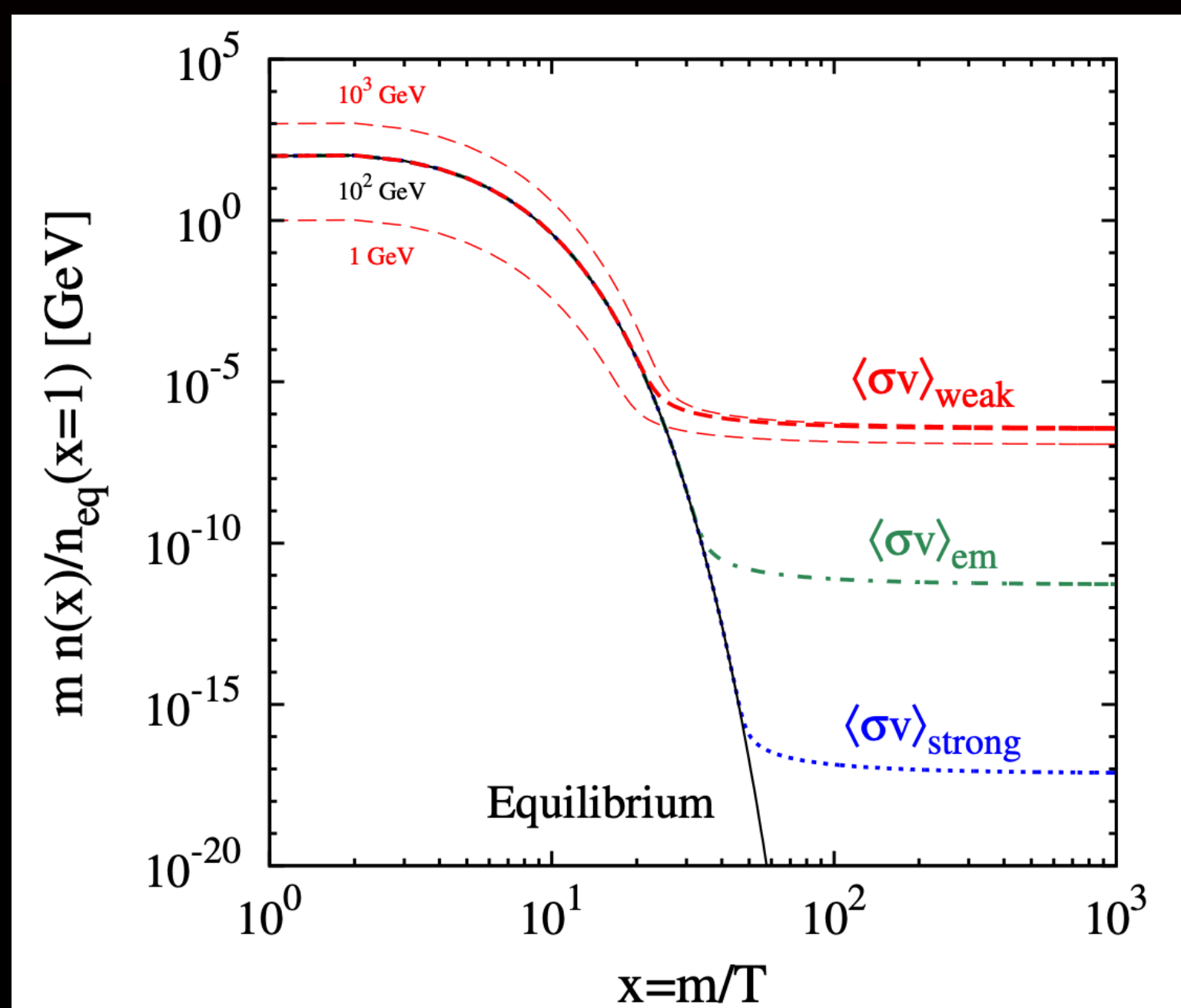
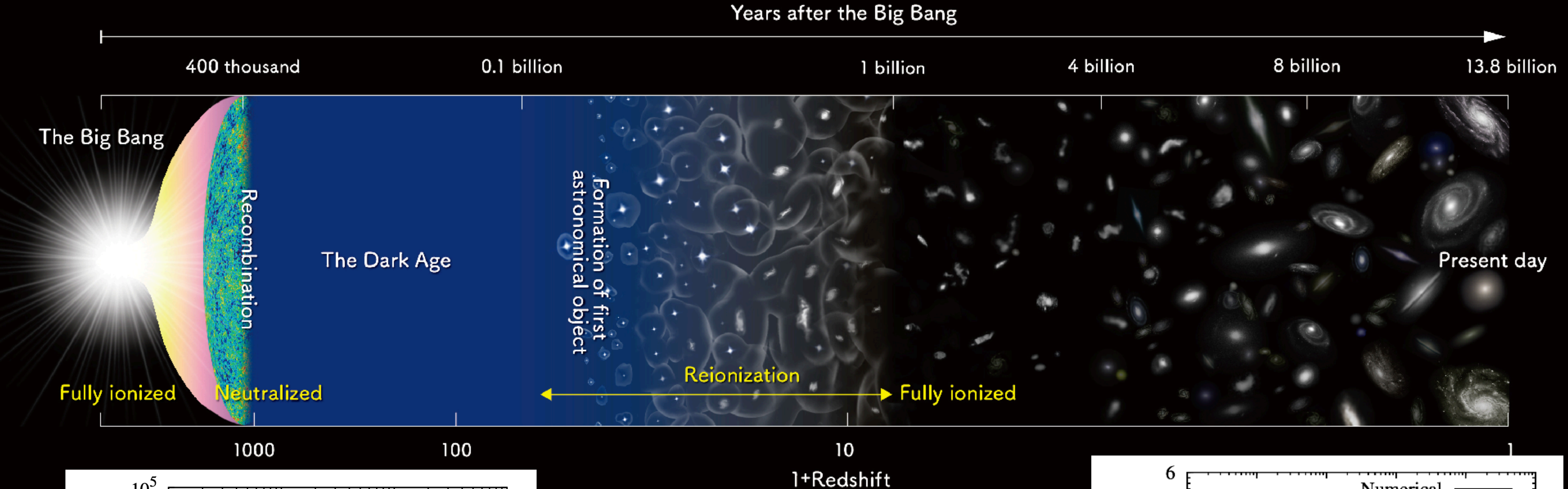
Present density inversely proportional to the strength of the interaction.

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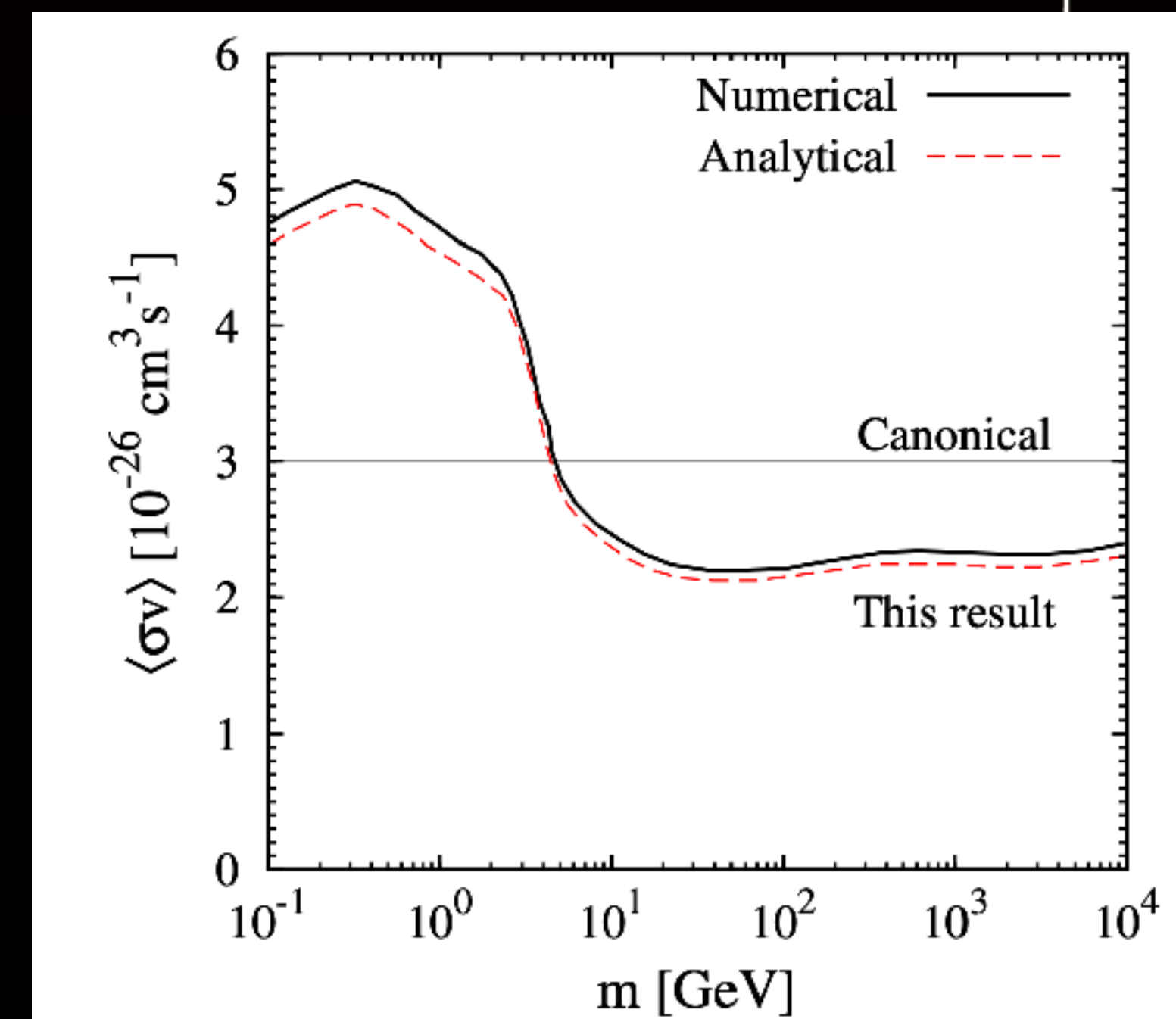
10 MeV - 100 TeV !

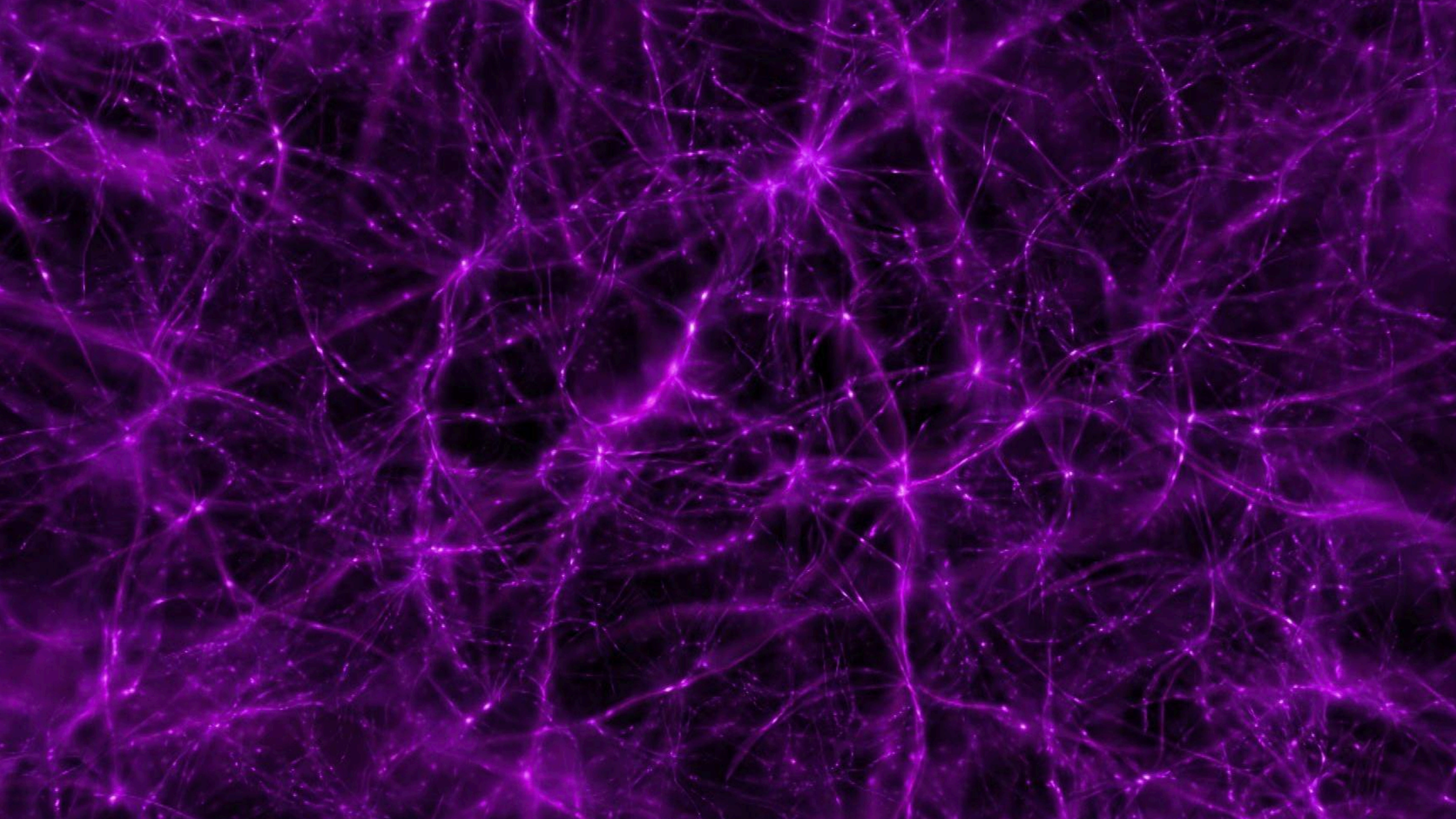


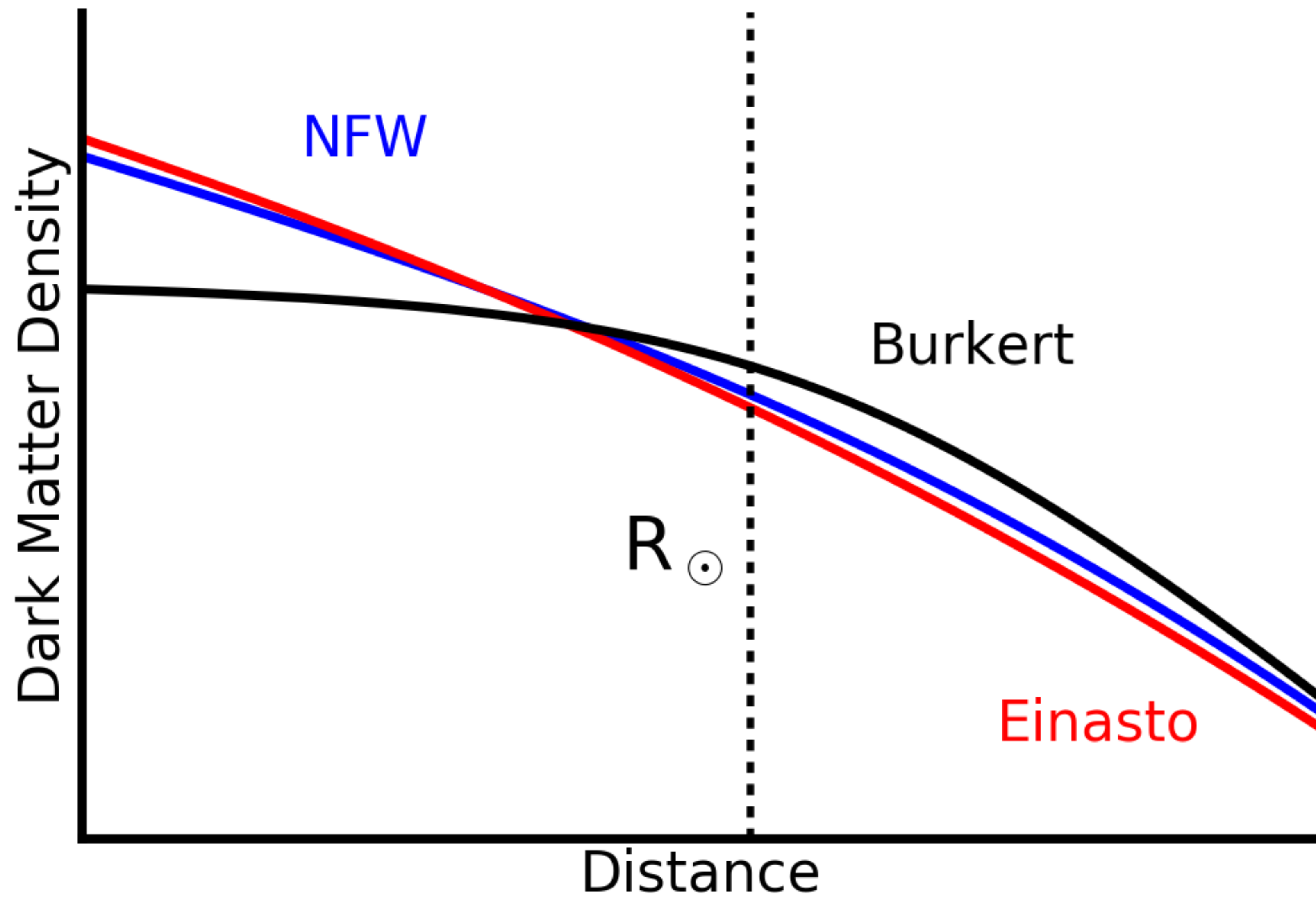


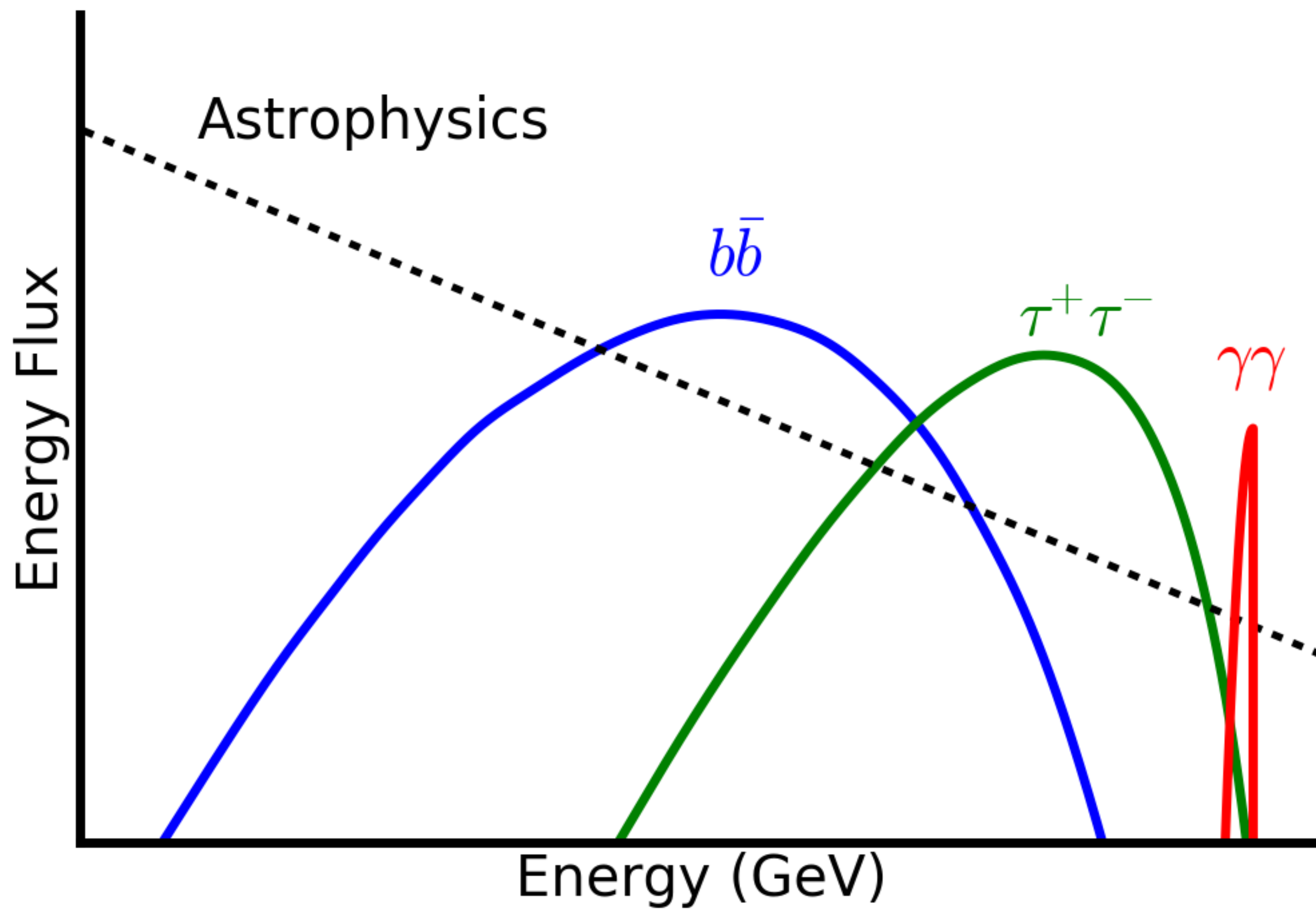
Philosophy:

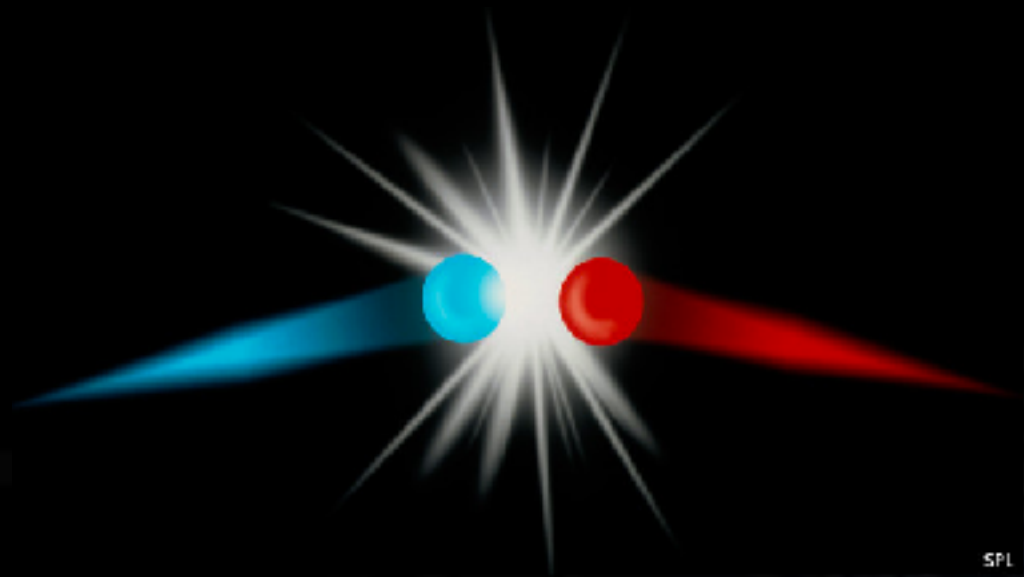
Constrain the
simplest model first





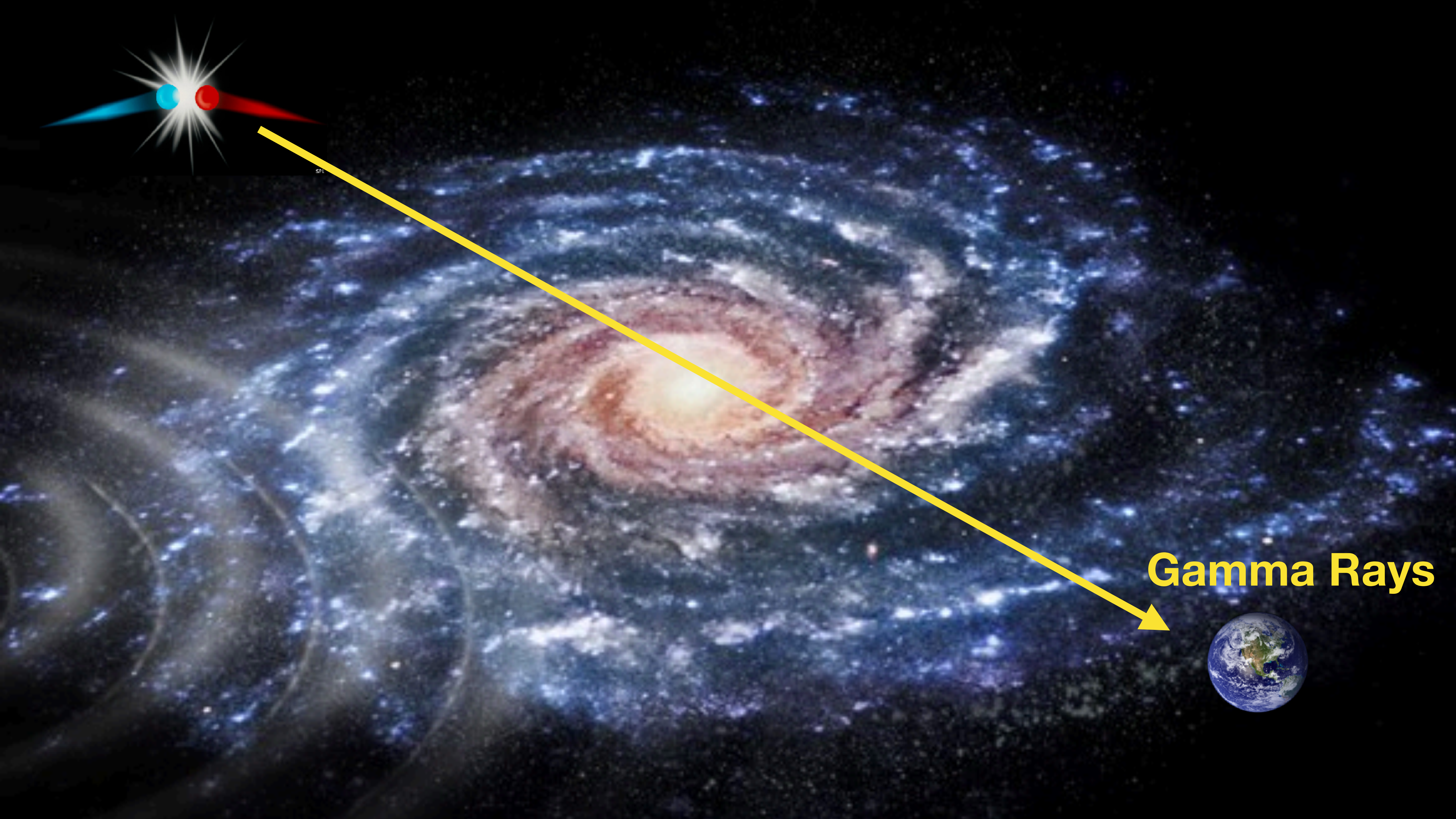






SPI



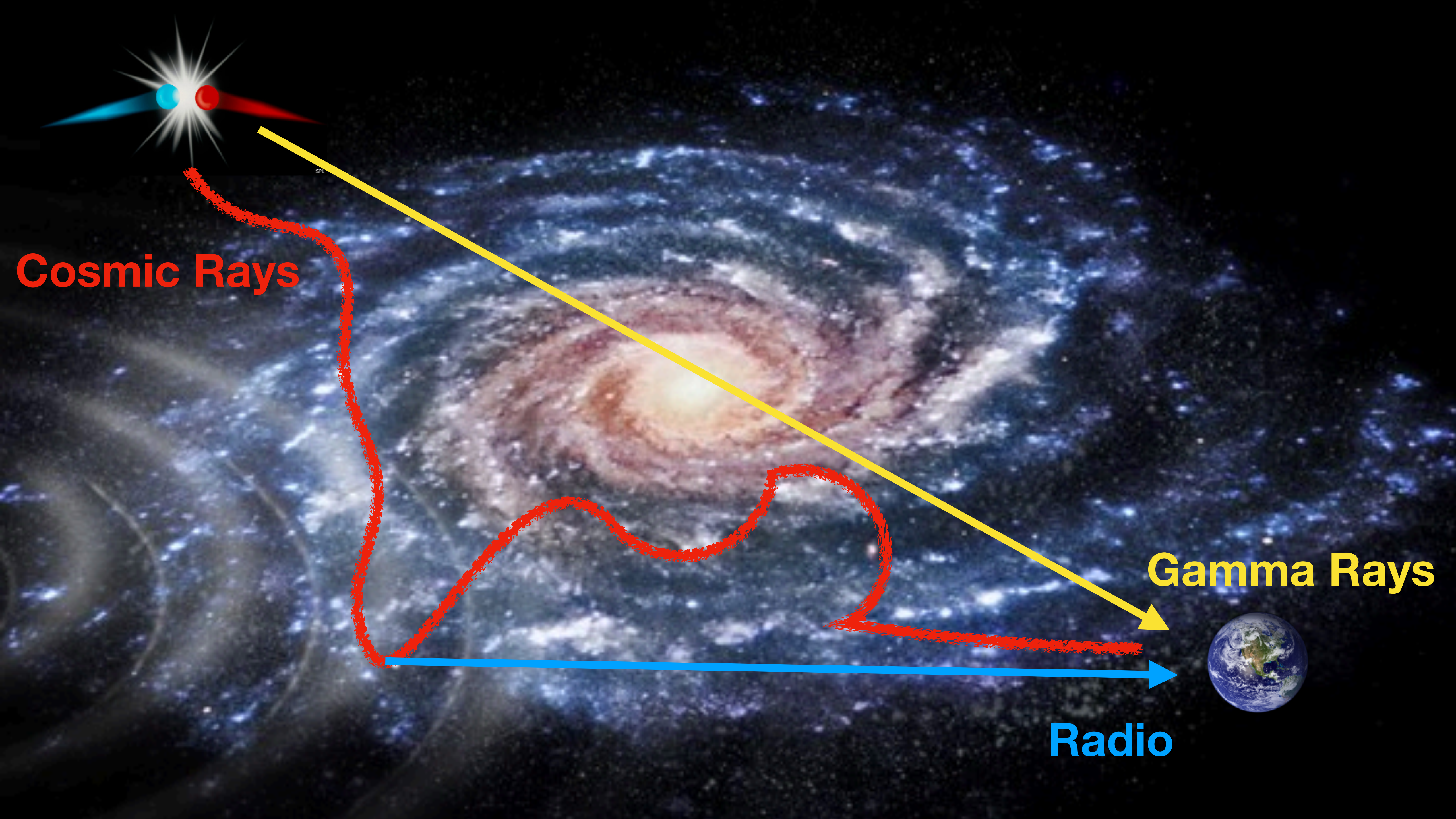


Gamma Rays



Cosmic Rays

Gamma Rays



Cosmic Rays

Gamma Rays

Radio

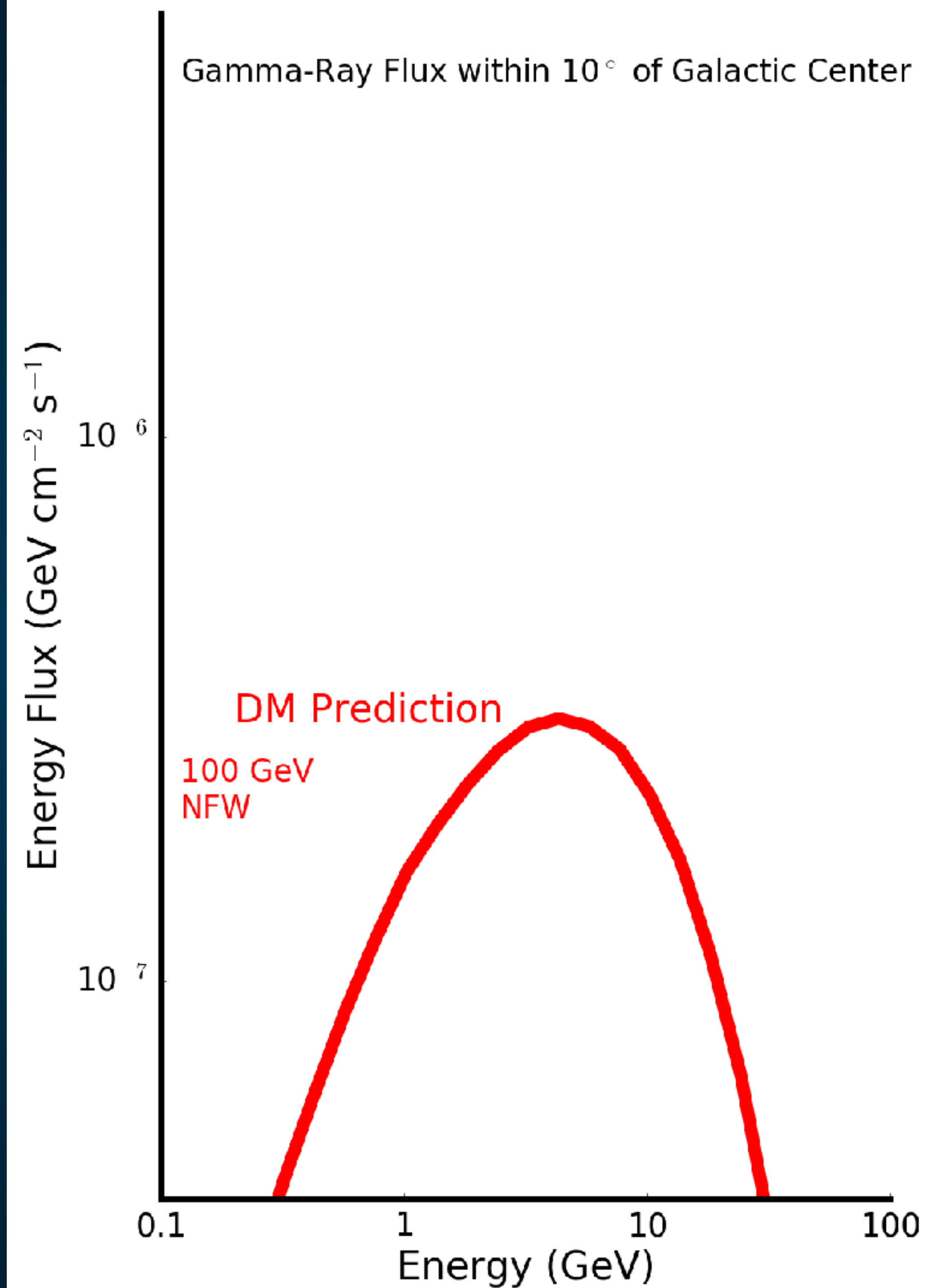
Thermal WIMPs and the Story of Tantalus

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)

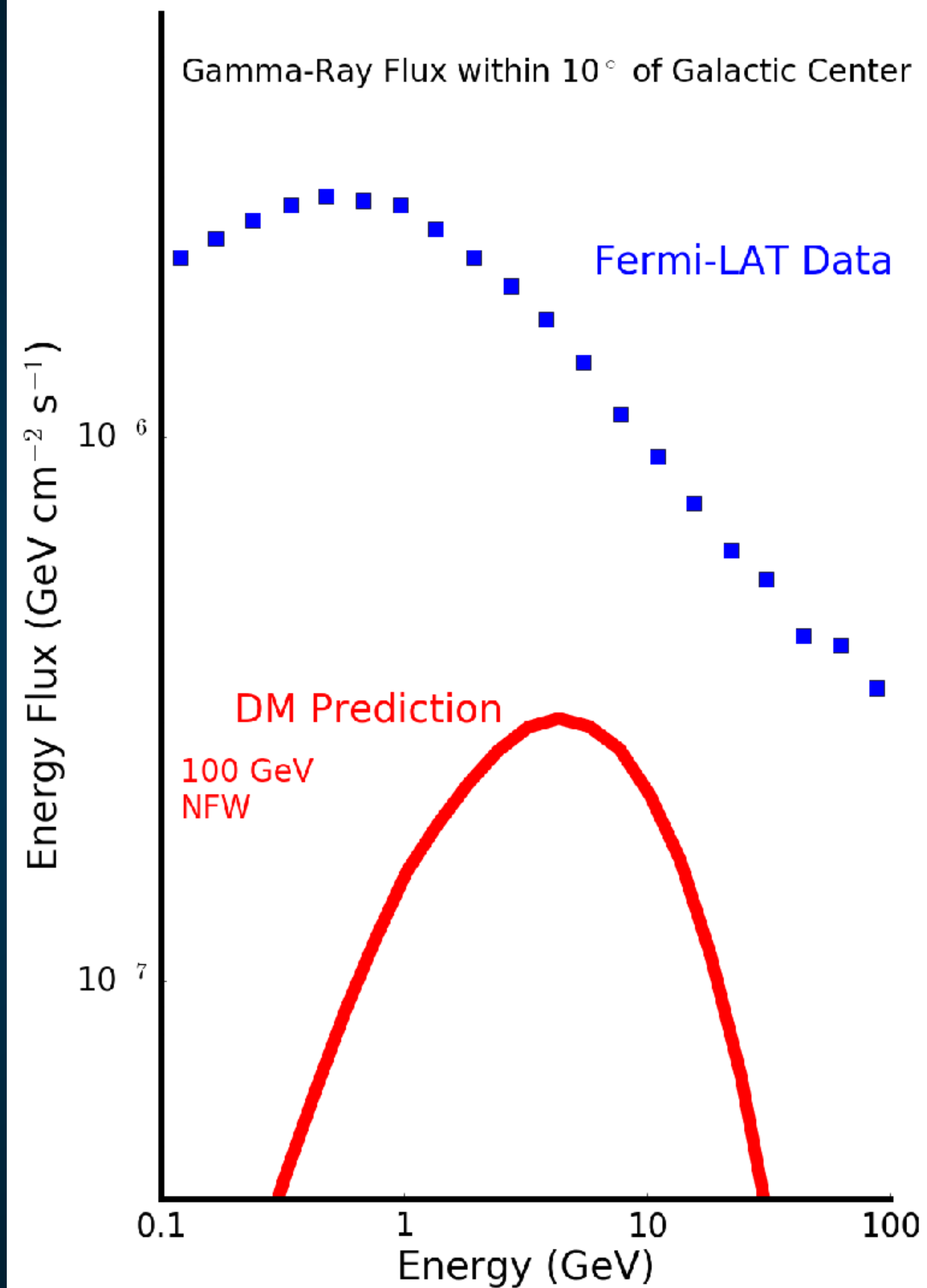
Dark Matter Mass (?)

Annihilation Final State (?)

Milky Way Star-Formation Rate (Galactic Dynamics)

Diffusion Constant in Galactic Center (Hydrodynamics)

Activity of Supermassive Blackhole (?)



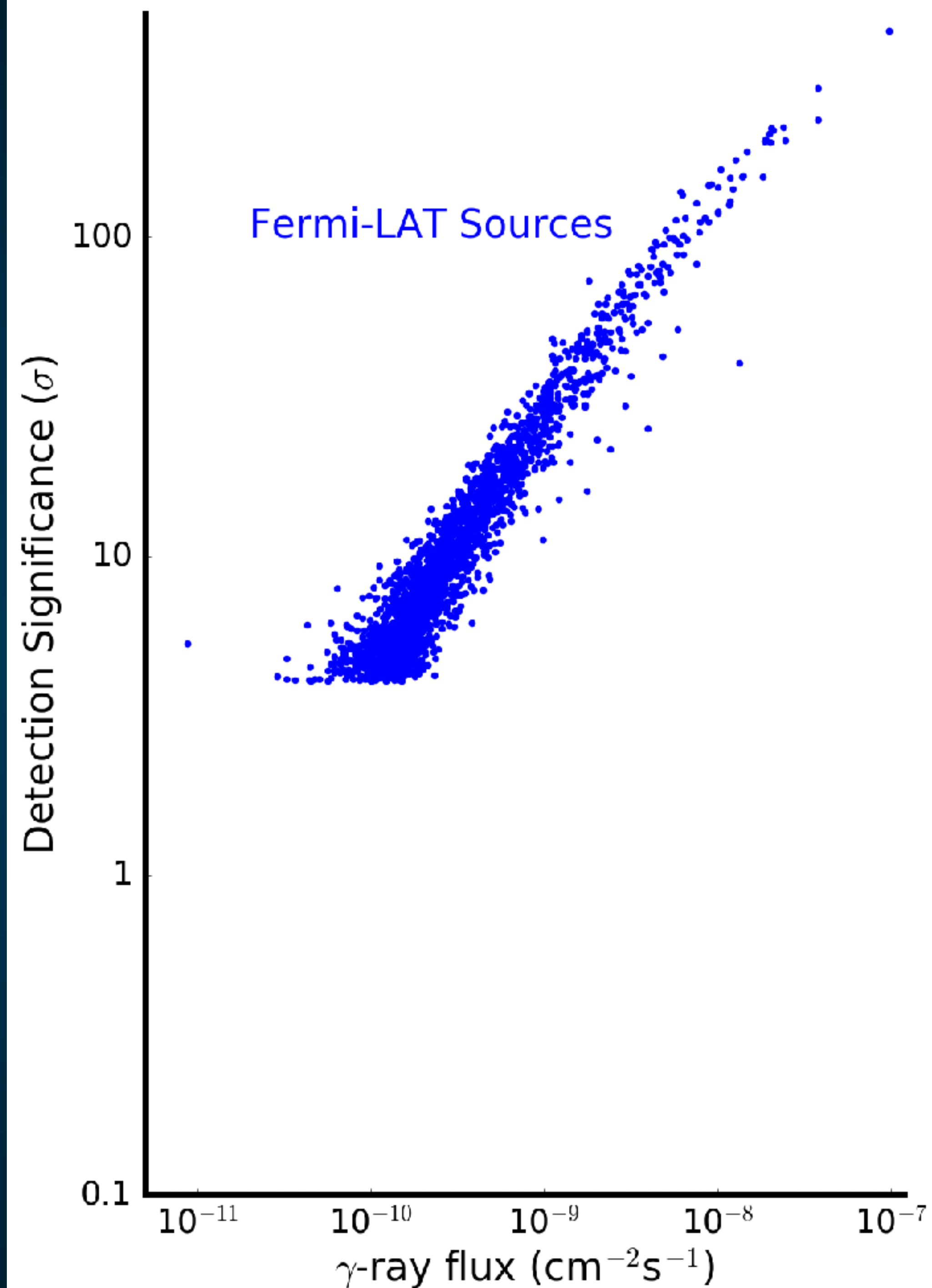
Thermal WIMPs and the Story of Tantalus

SMBH Accretion Efficiency (Magnetohydrodynamics)

Blazar Acceleration Mechanisms (Leptonic? Hadronic?)

Radio Galaxy Emission Models

Star-Formation Rates in Starburst Galaxies



Thermal WIMPs and the Story of Tantalus

SMBH Accretion Efficiency (Magnetohydrodynamics)

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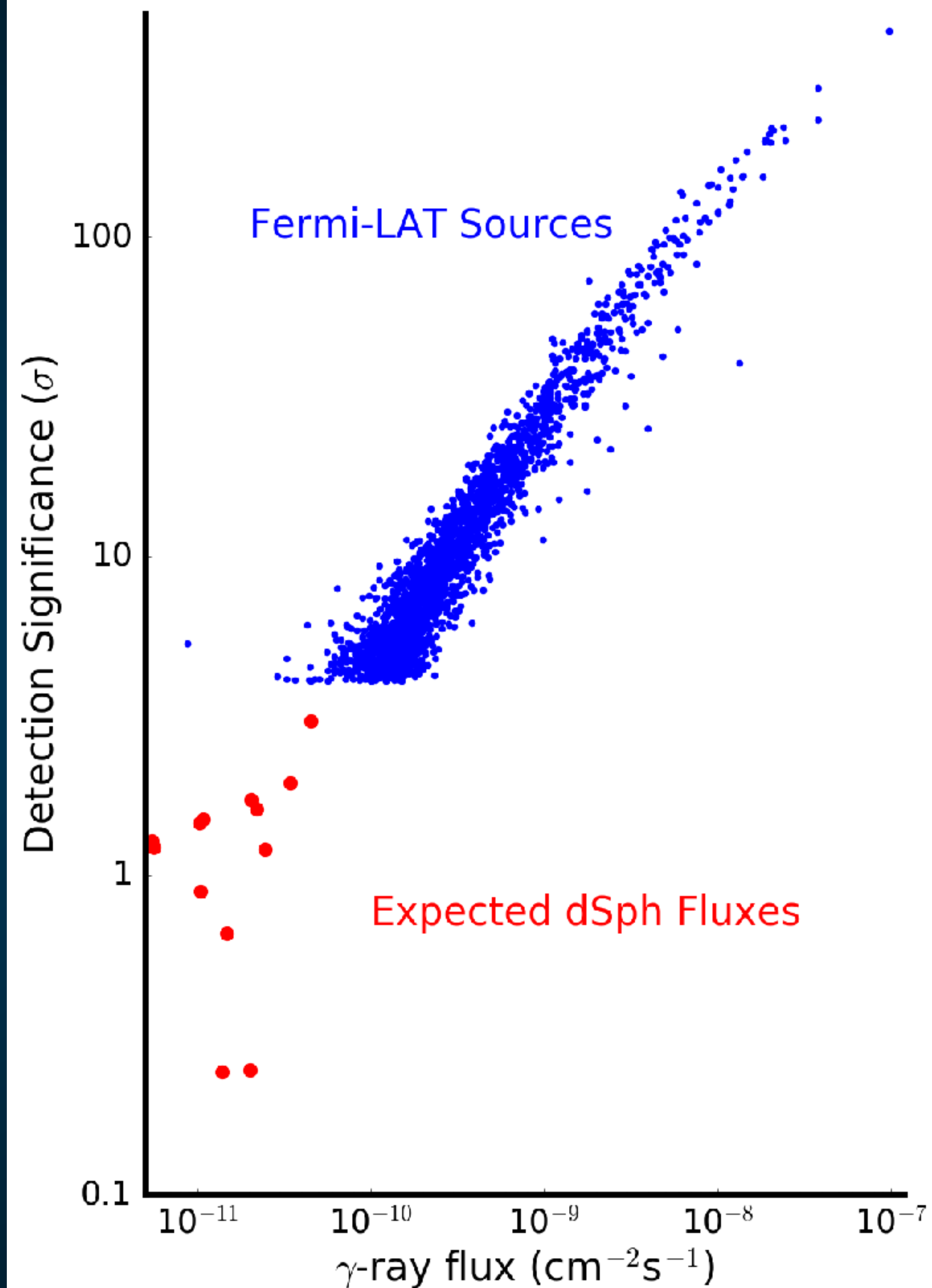
Radio Galaxy Emission Models

Star-Formation Rates in Starburst Galaxies

dSph Proximity

Substructure Models

Milky Way Merger History



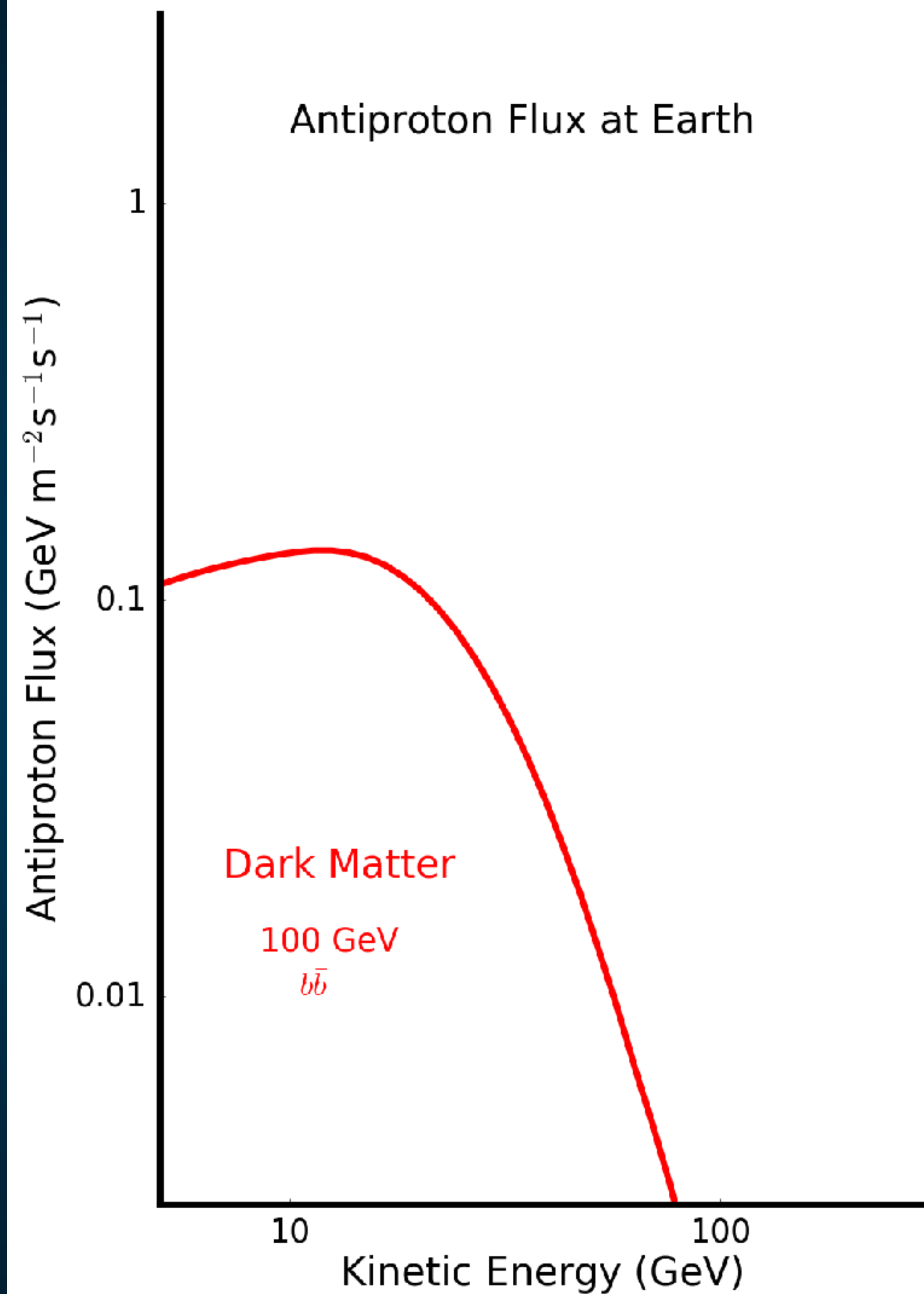
Thermal WIMPs and the Story of Tantalus

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

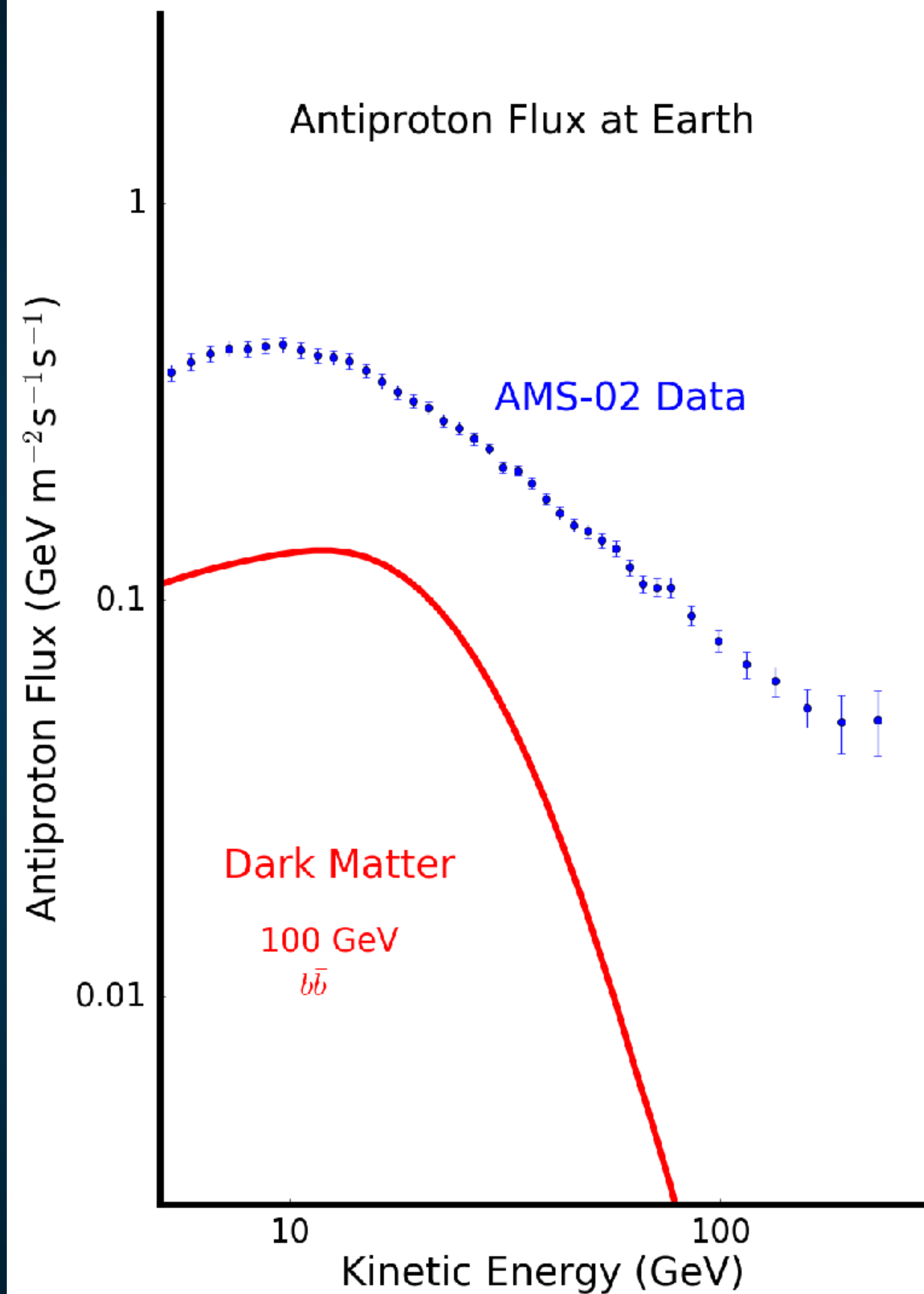
Thermal Cross-Section (Early Universe)

Hadronic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Local Gas Density

Local Supernova Rate



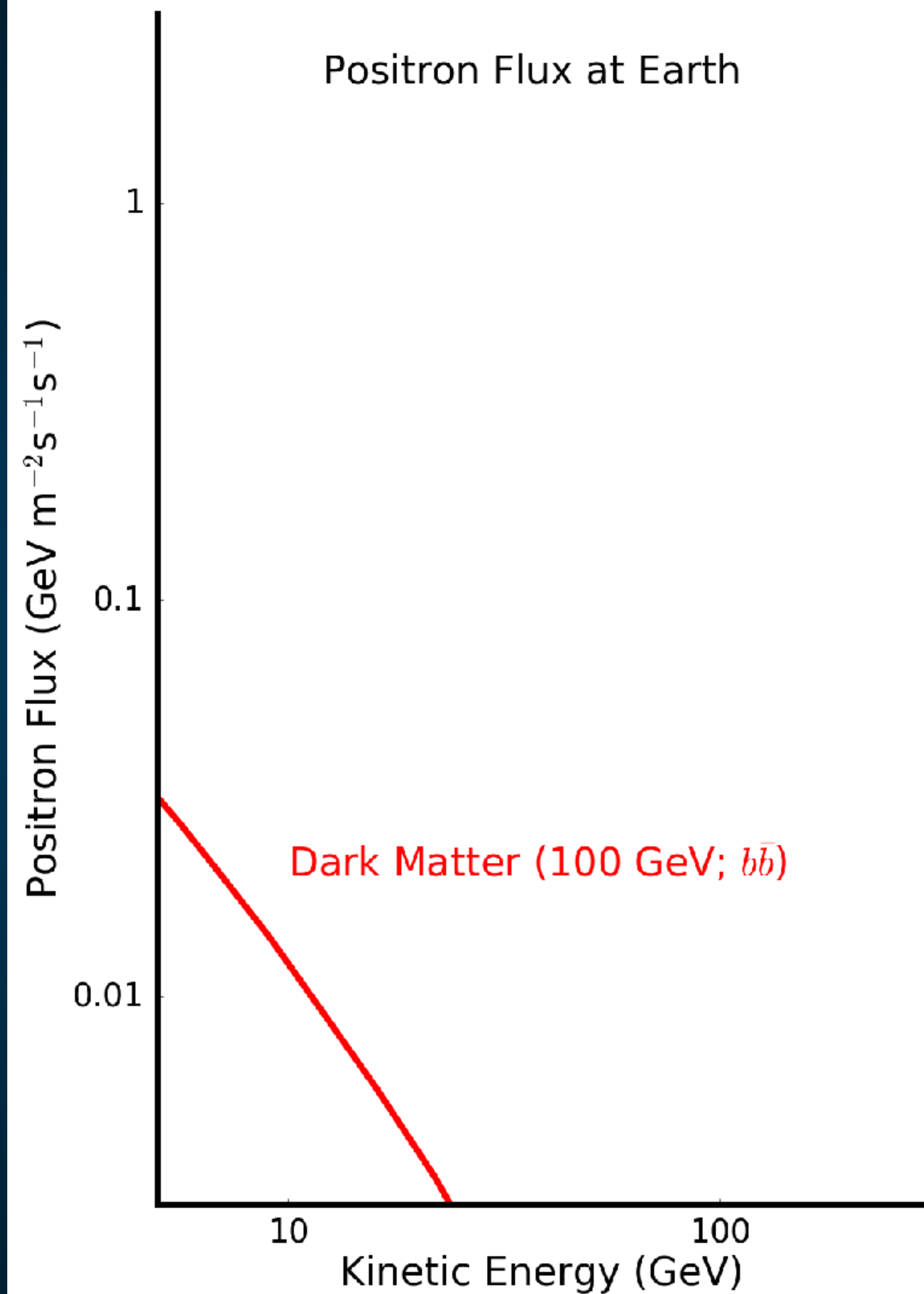
Thermal WIMPs and the Story of Tantalus

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

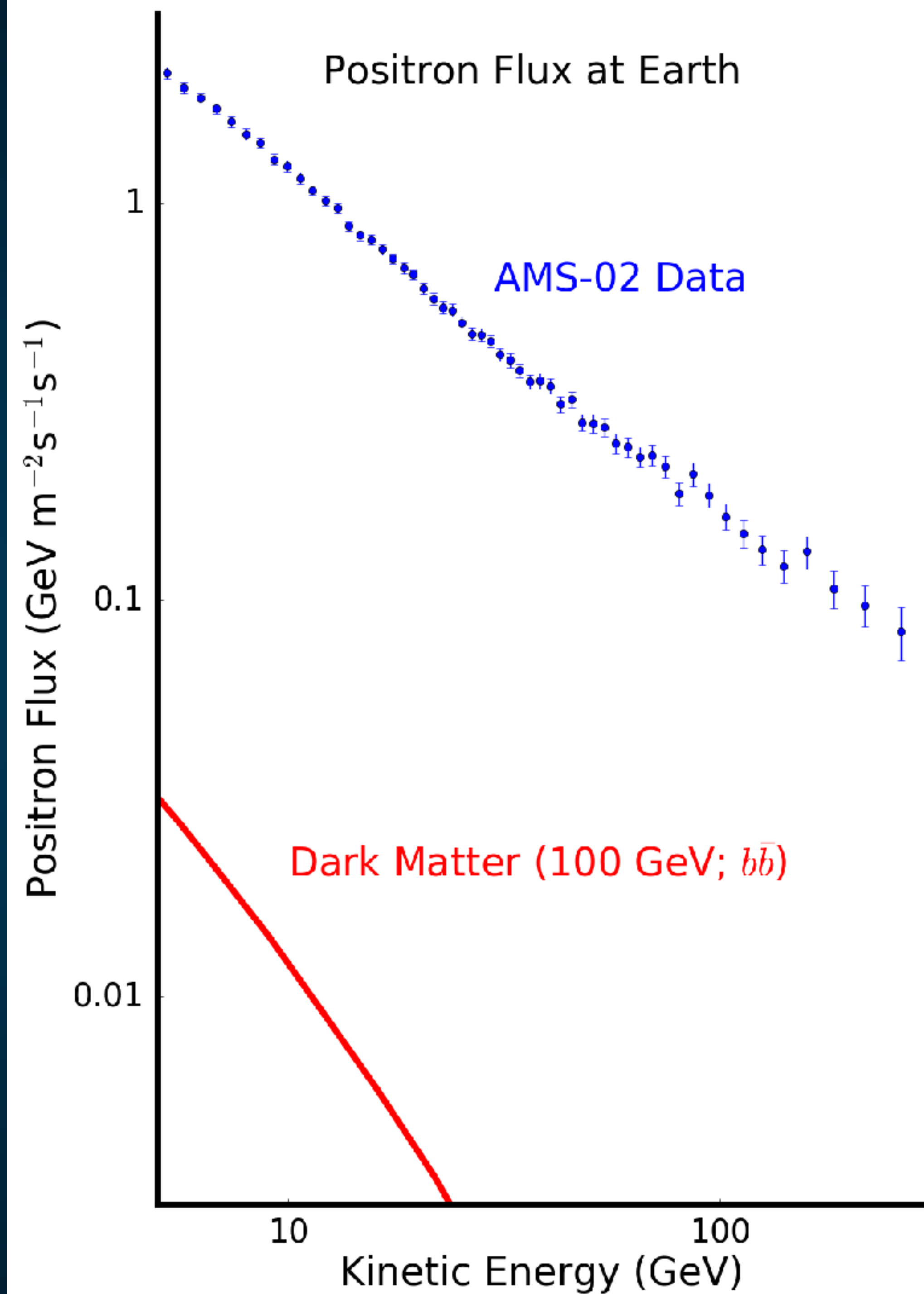
Thermal Cross-Section (Early Universe)

Leptonic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Pulsar Birth Rate

e^+e^- Acceleration Efficiency in Pulsar Magnetospheres





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

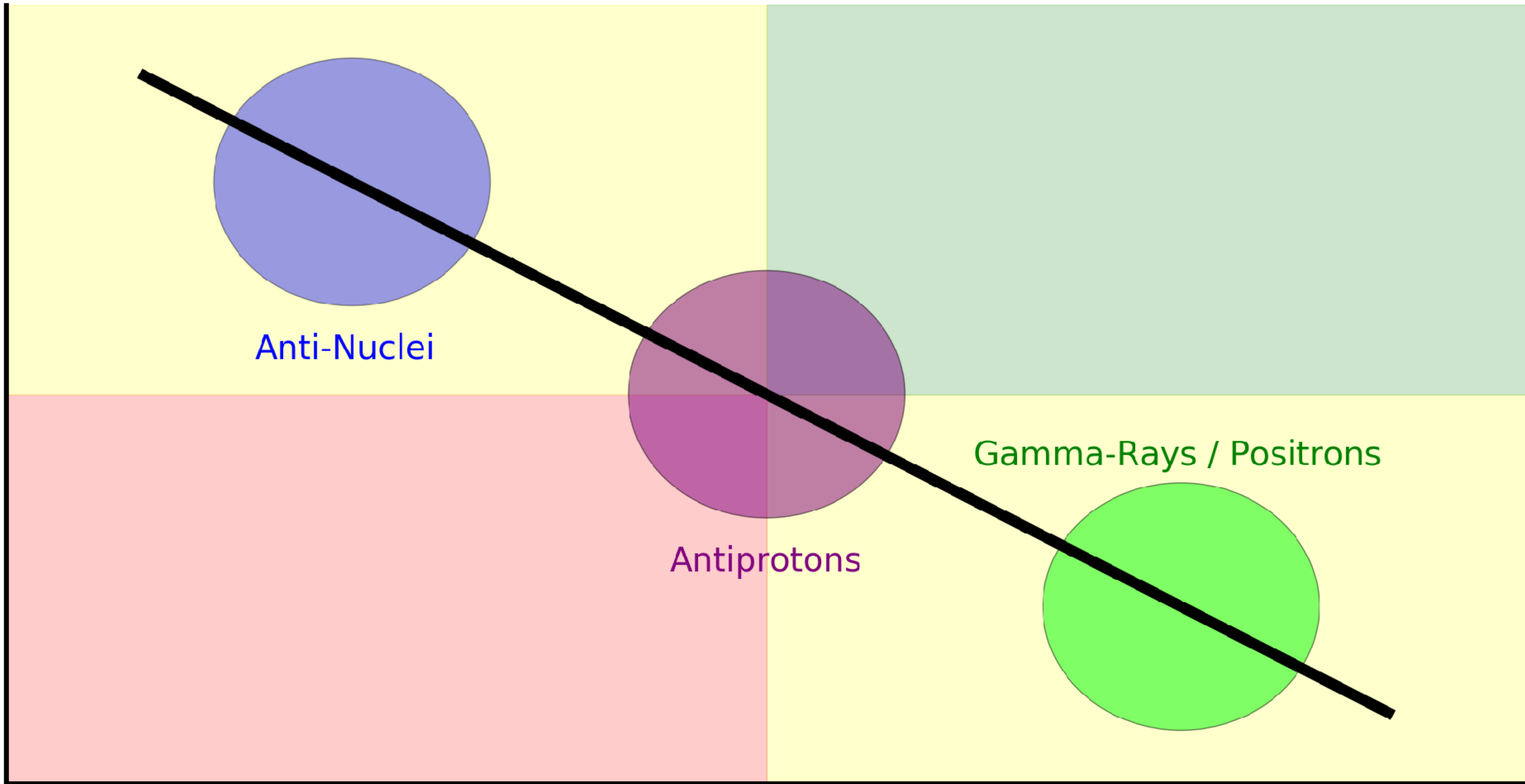
Specificity (DM Flux / Astrophysics Flux)

Anti-Nuclei

Antiprotons

Gamma-Rays / Positrons

Fraction of Dark Matter Flux



Thermal WIMPs and the Story of Tantalus



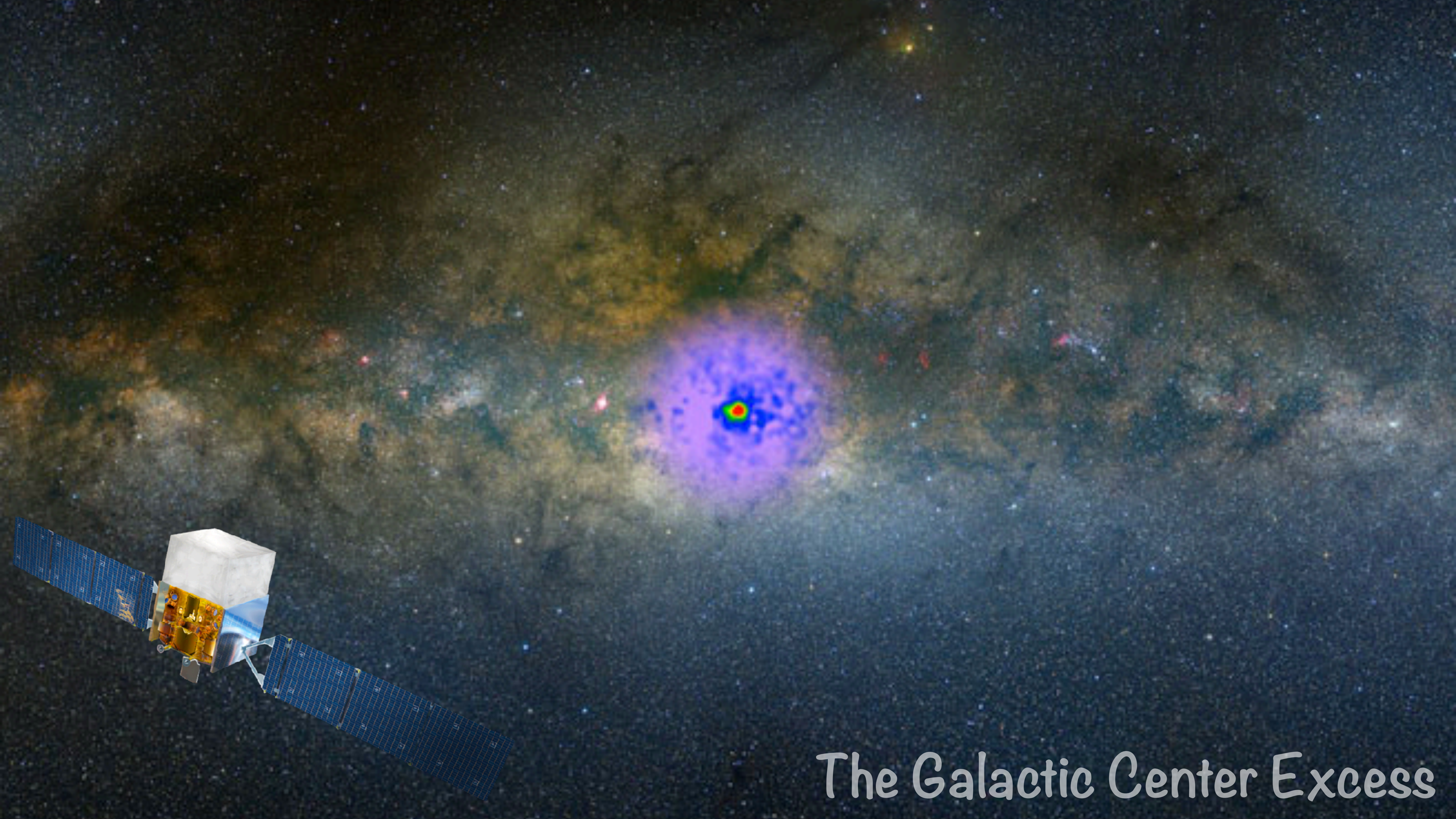
Thermal WIMPs and the Story of Tantalus



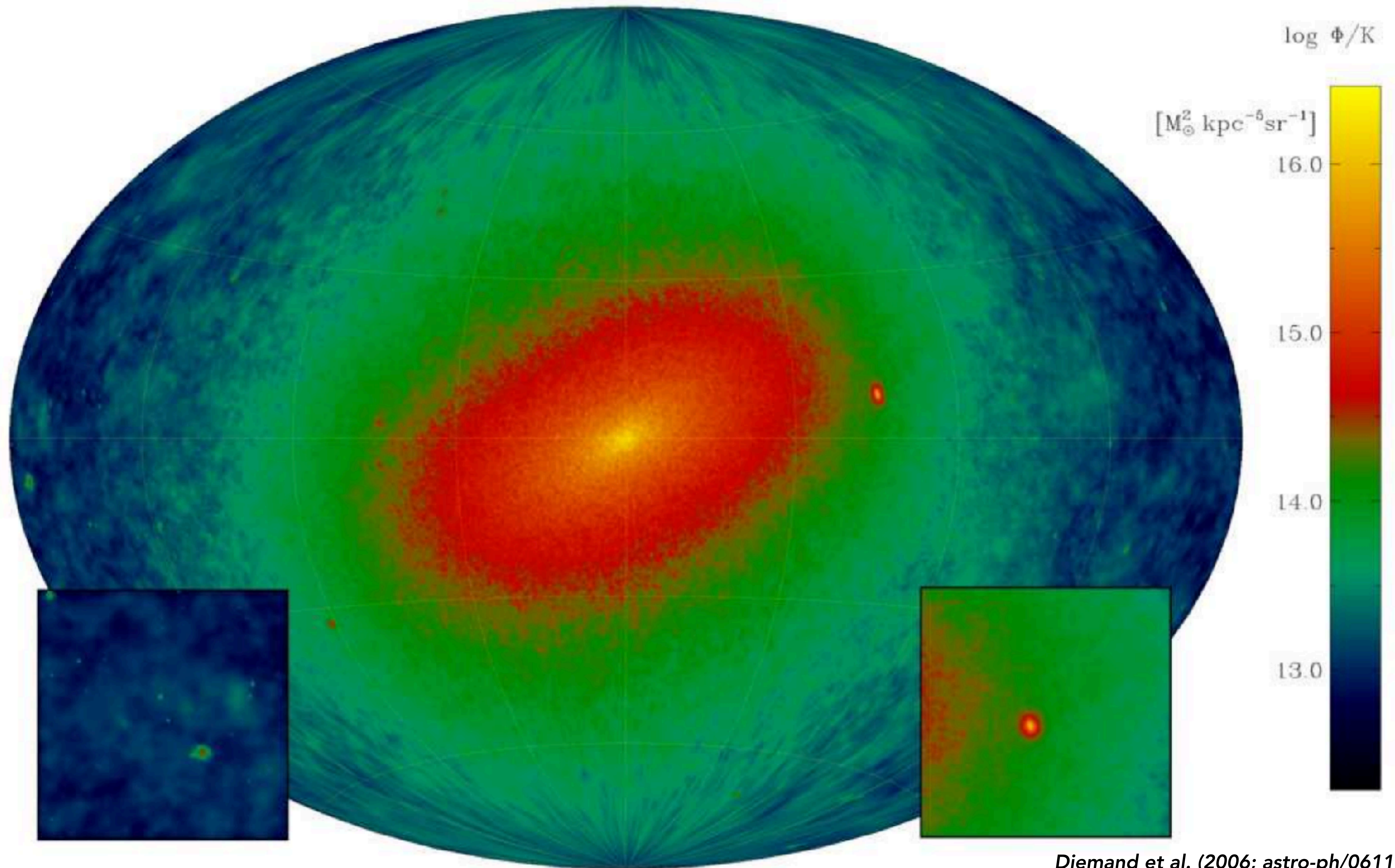
The Decade of the WIMP

Rocky Kolb
University of Chicago

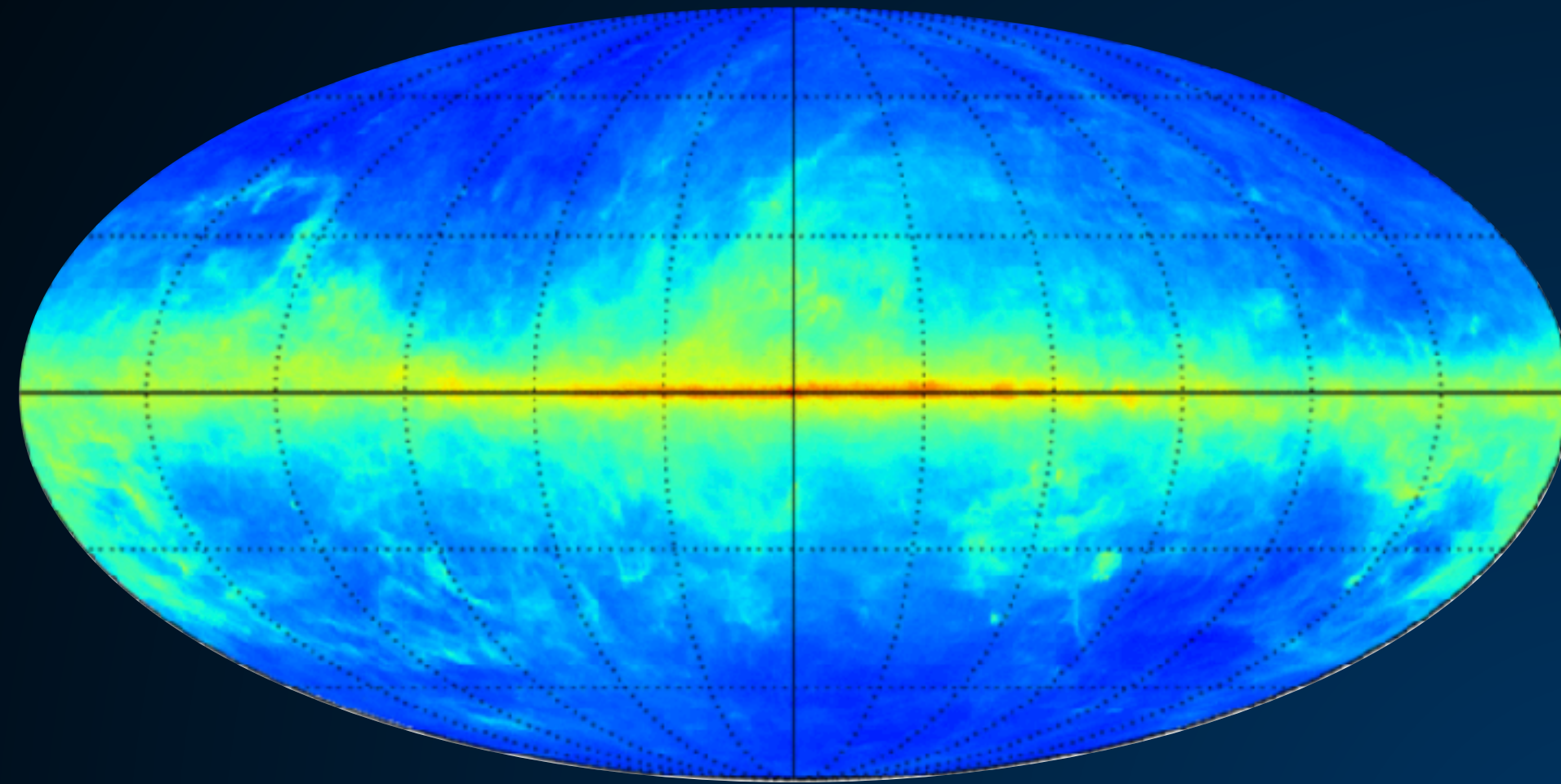
MPIK-Heidelberg
November 2012



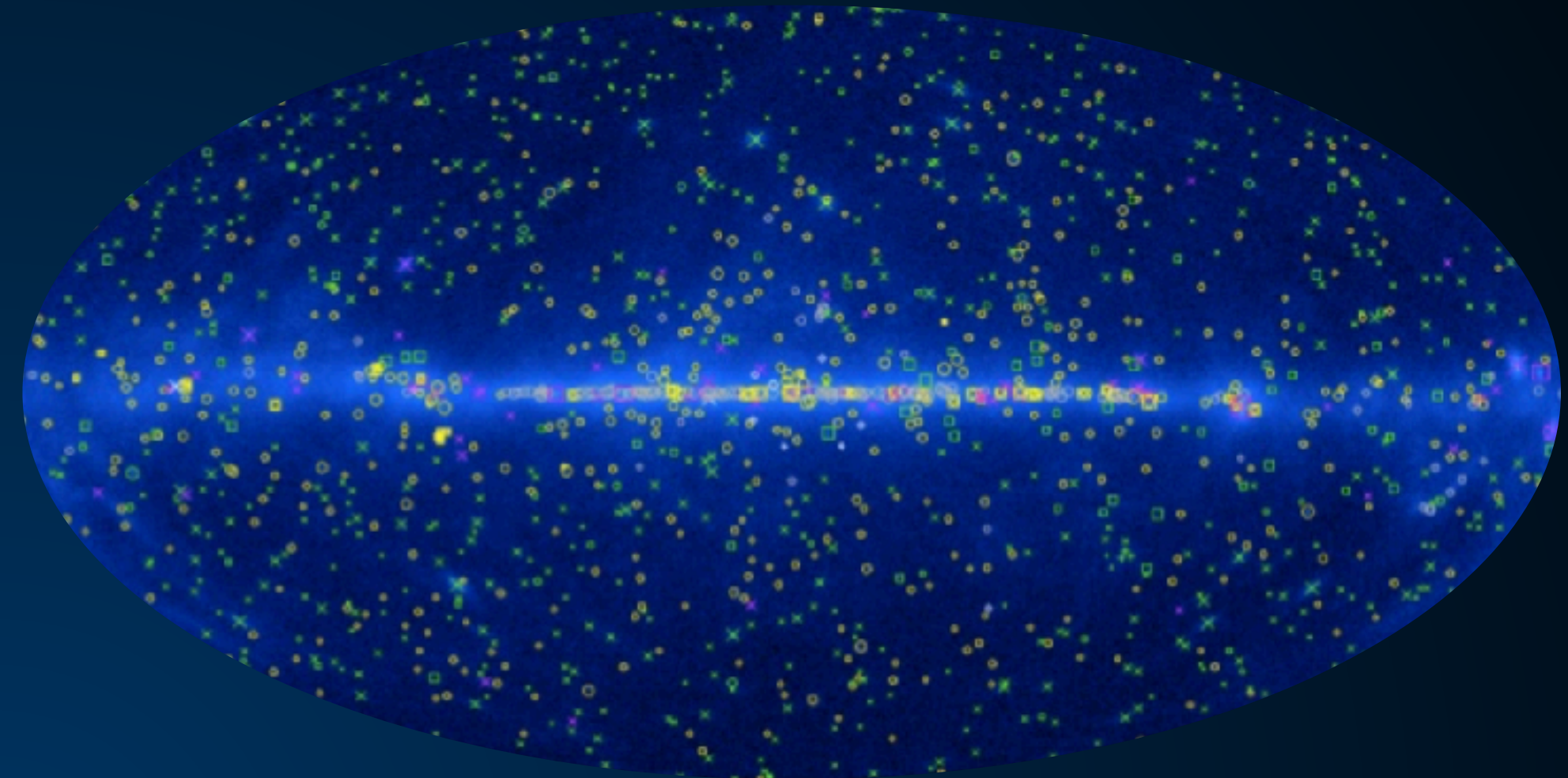
The Galactic Center Excess



The Galactic Center - Techniques



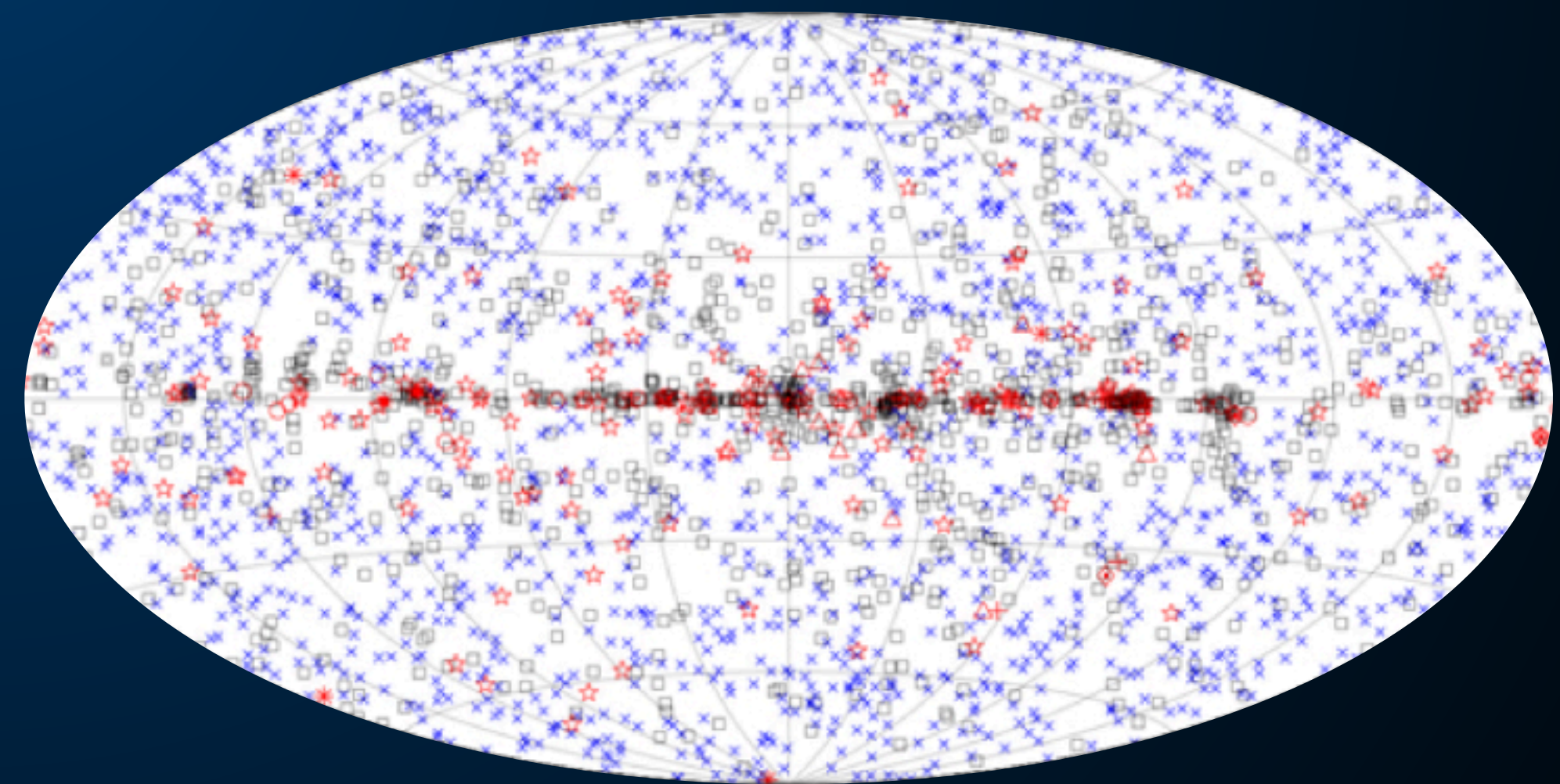
Galactic Diffuse



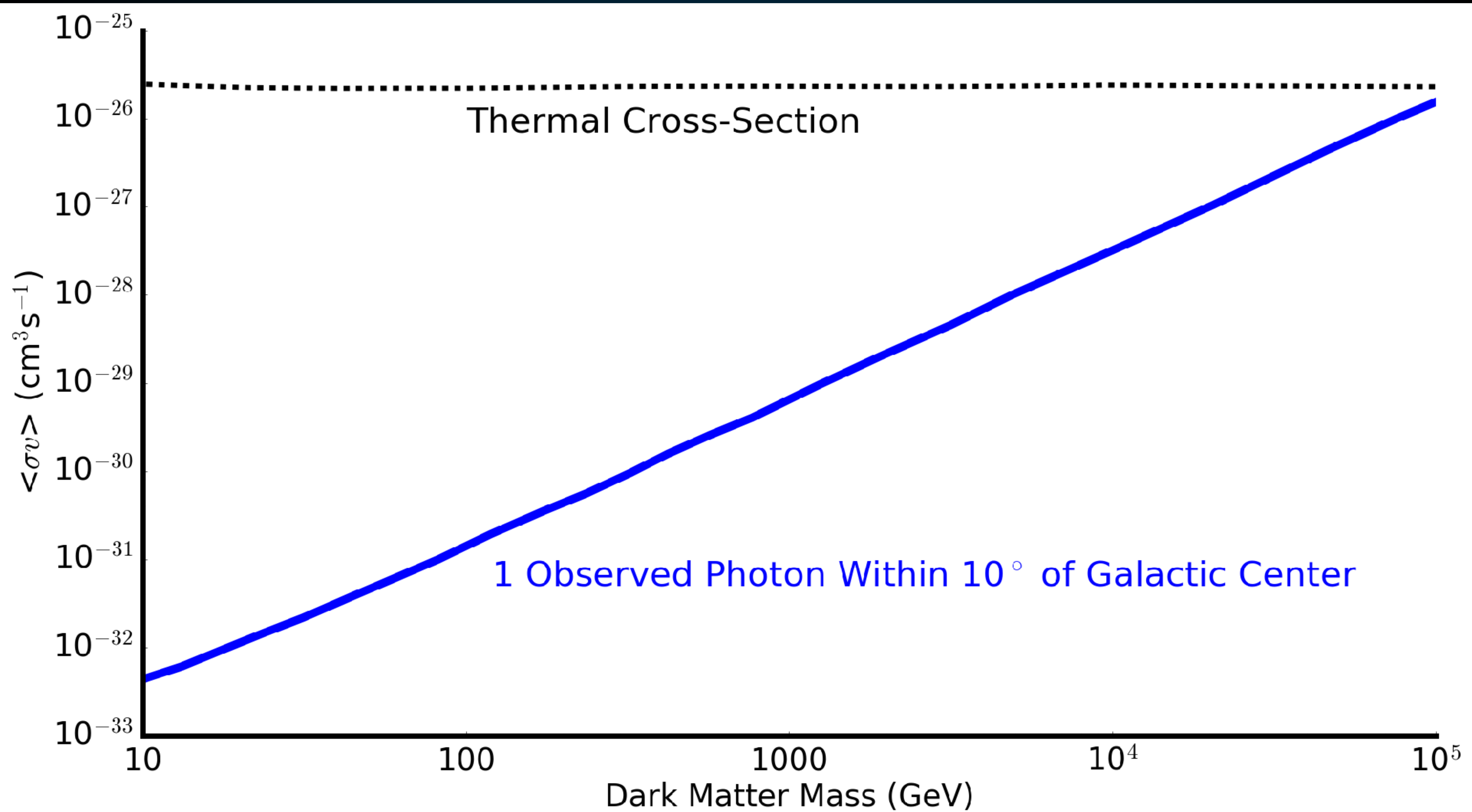
Point Sources



Isotropic Emission

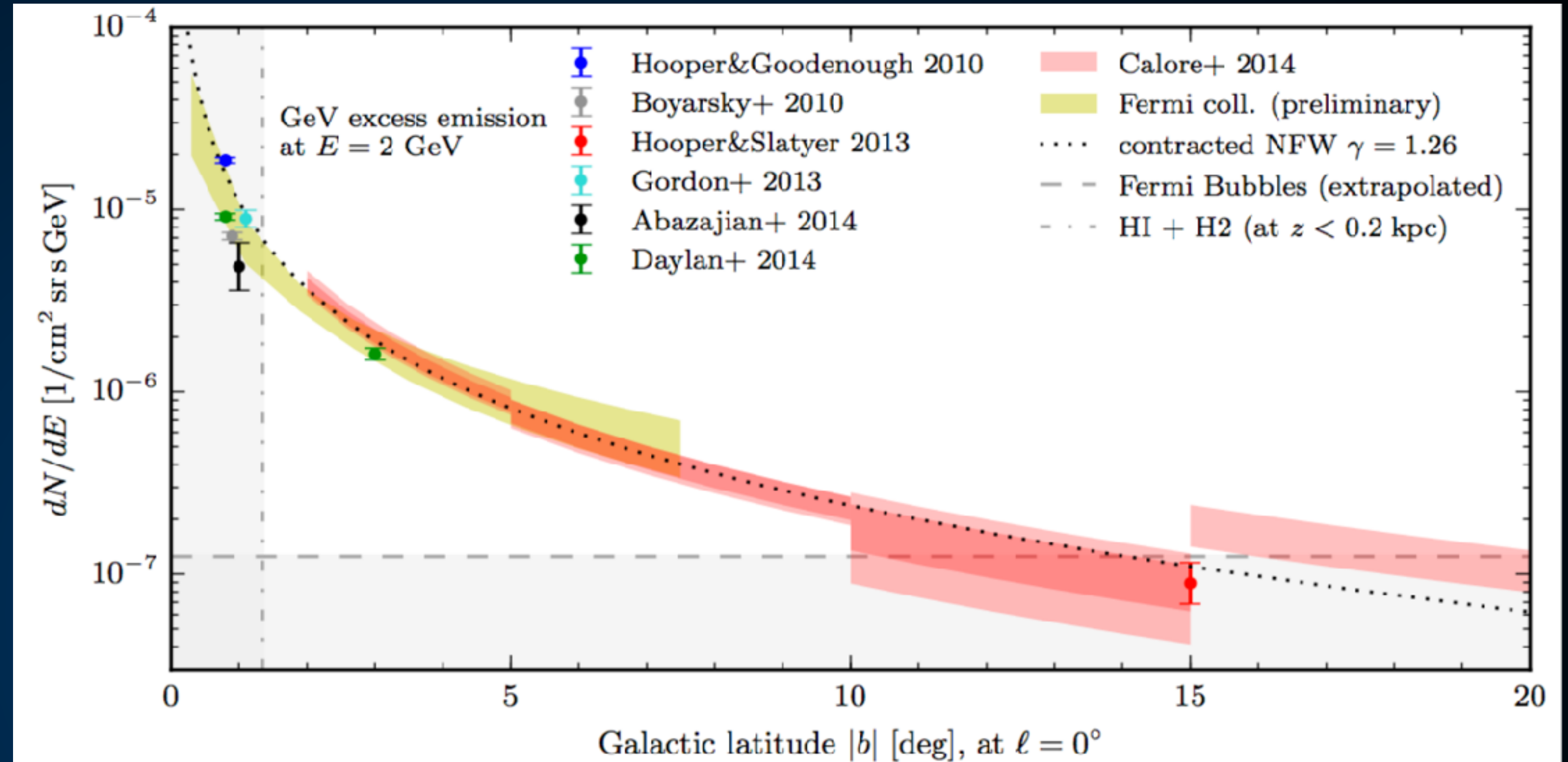
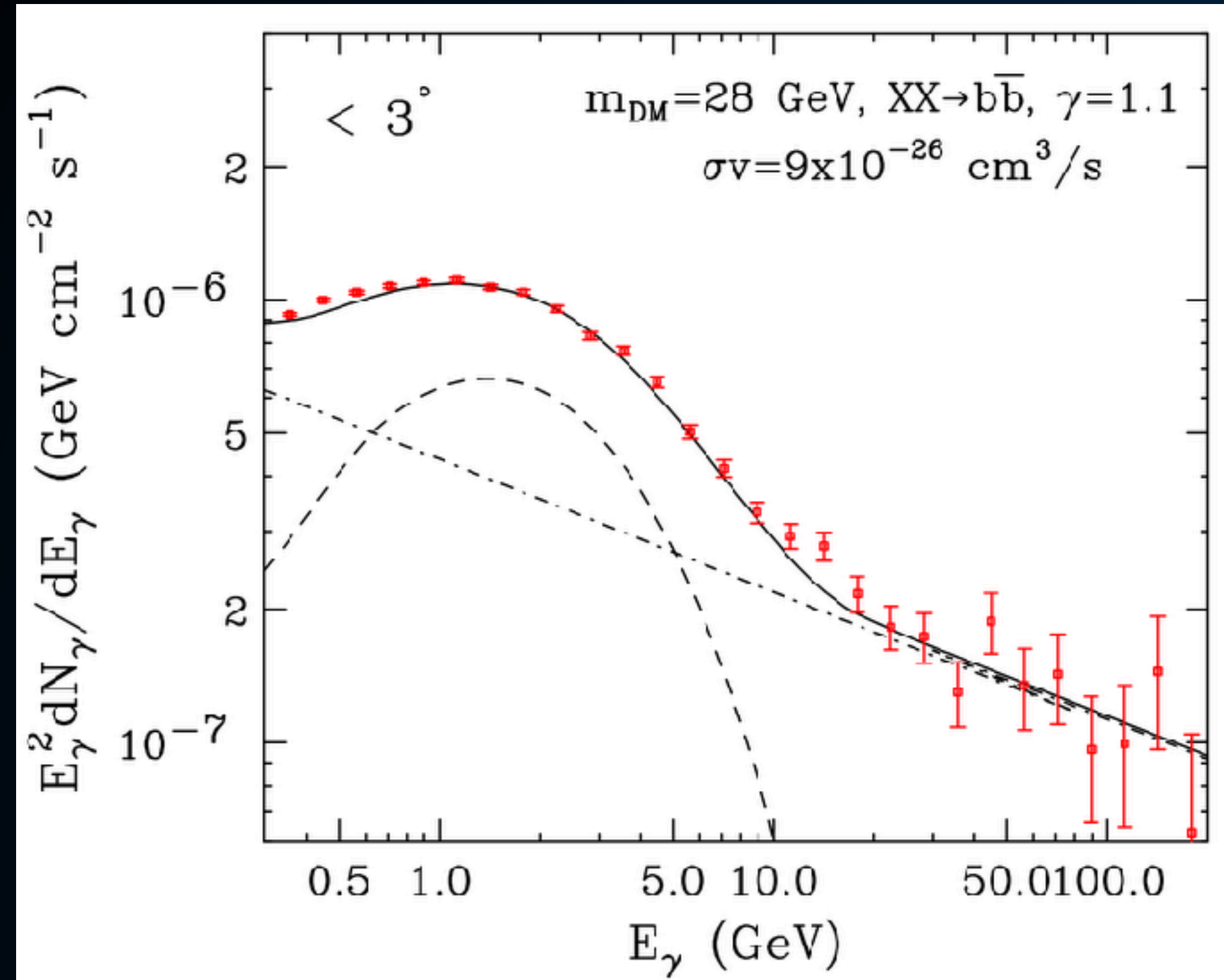


Sub-Threshold Sources



The Galactic Center Excess

Goodenough & Hooper (2009; 0910.2998)

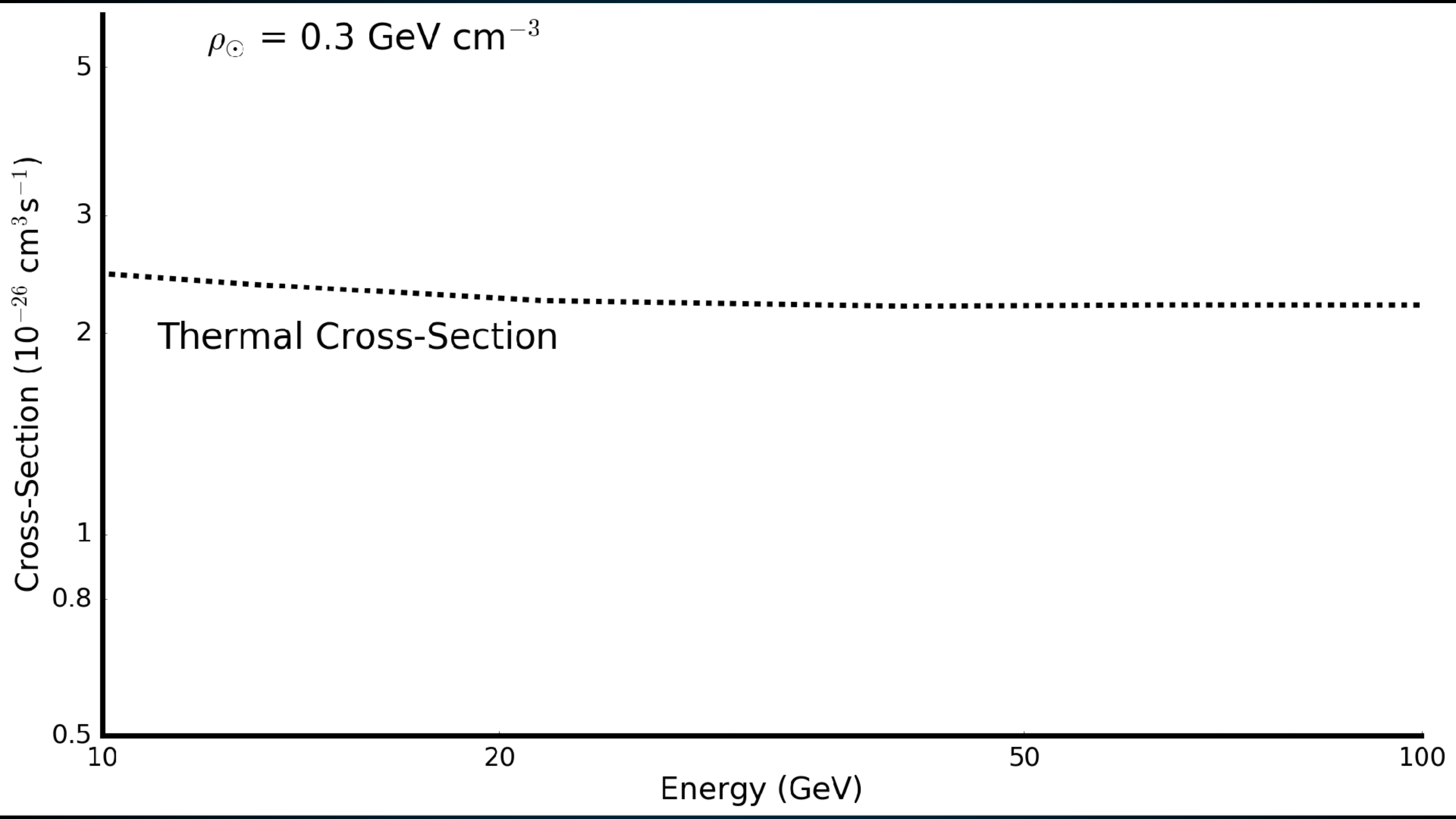


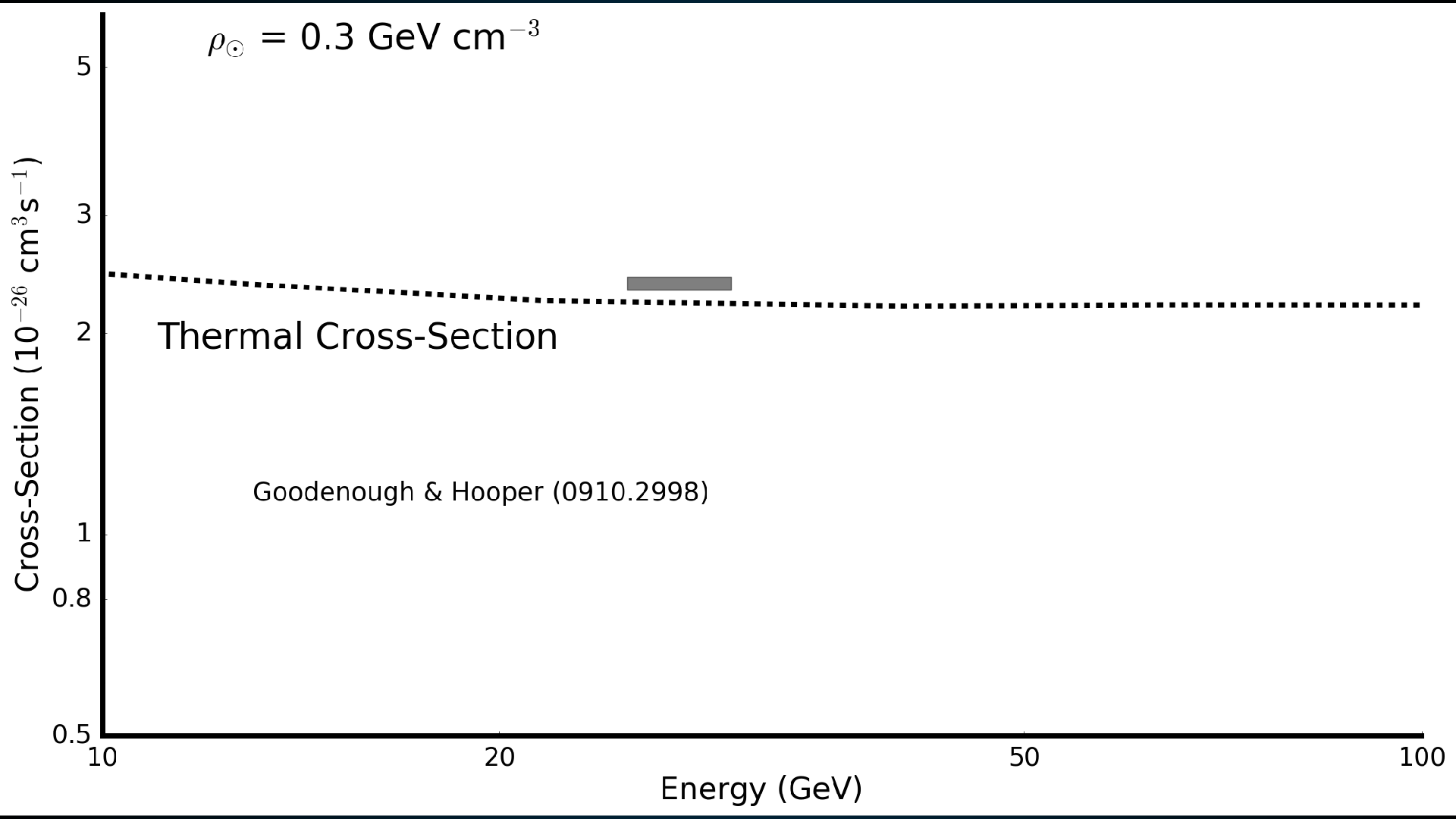
Bright *Detected at $>50\sigma$*

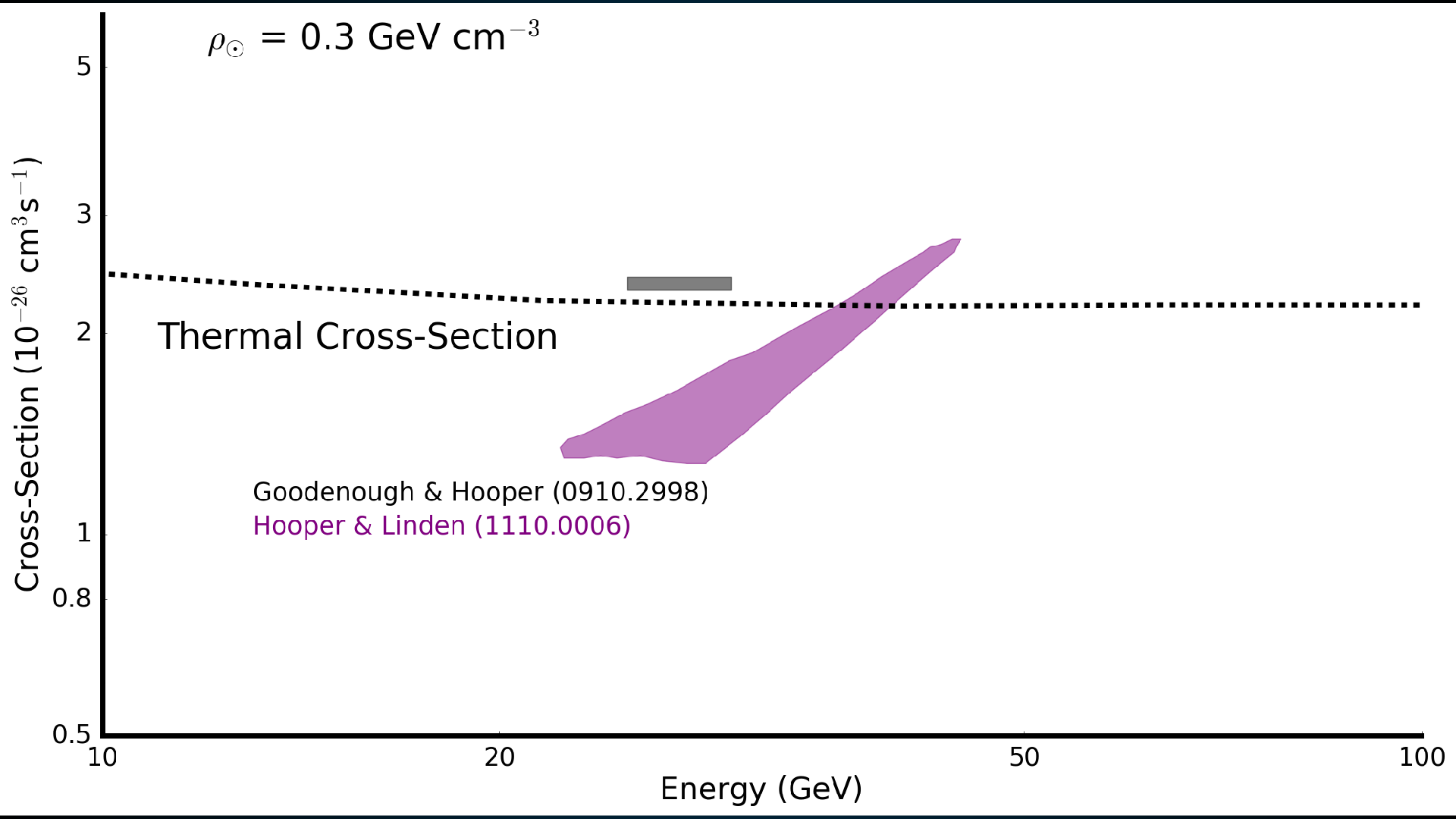
Hard-Spectrum *Incompatible with standard backgrounds*

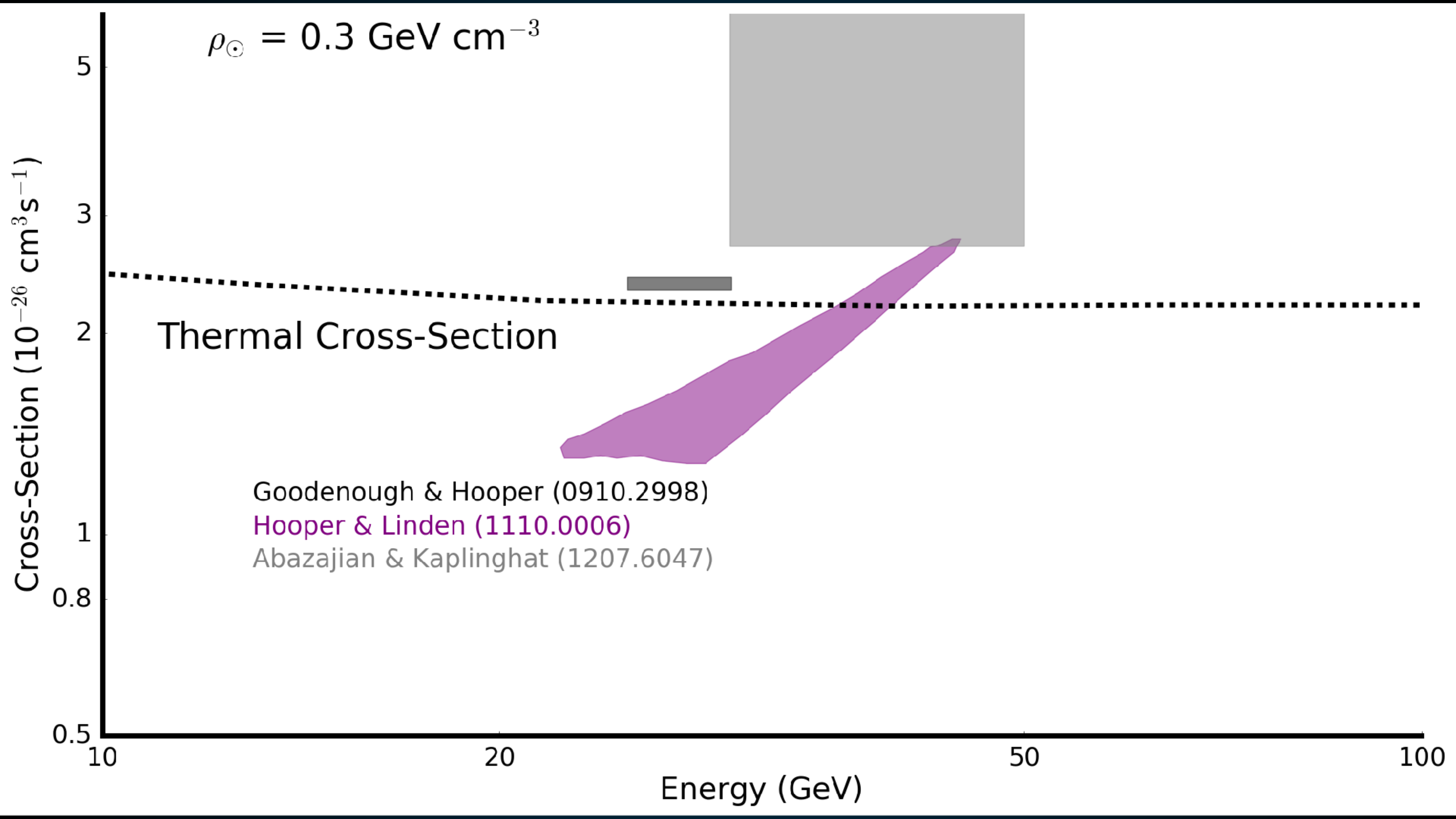
Spherically Symmetric *Expected from Dark Matter*

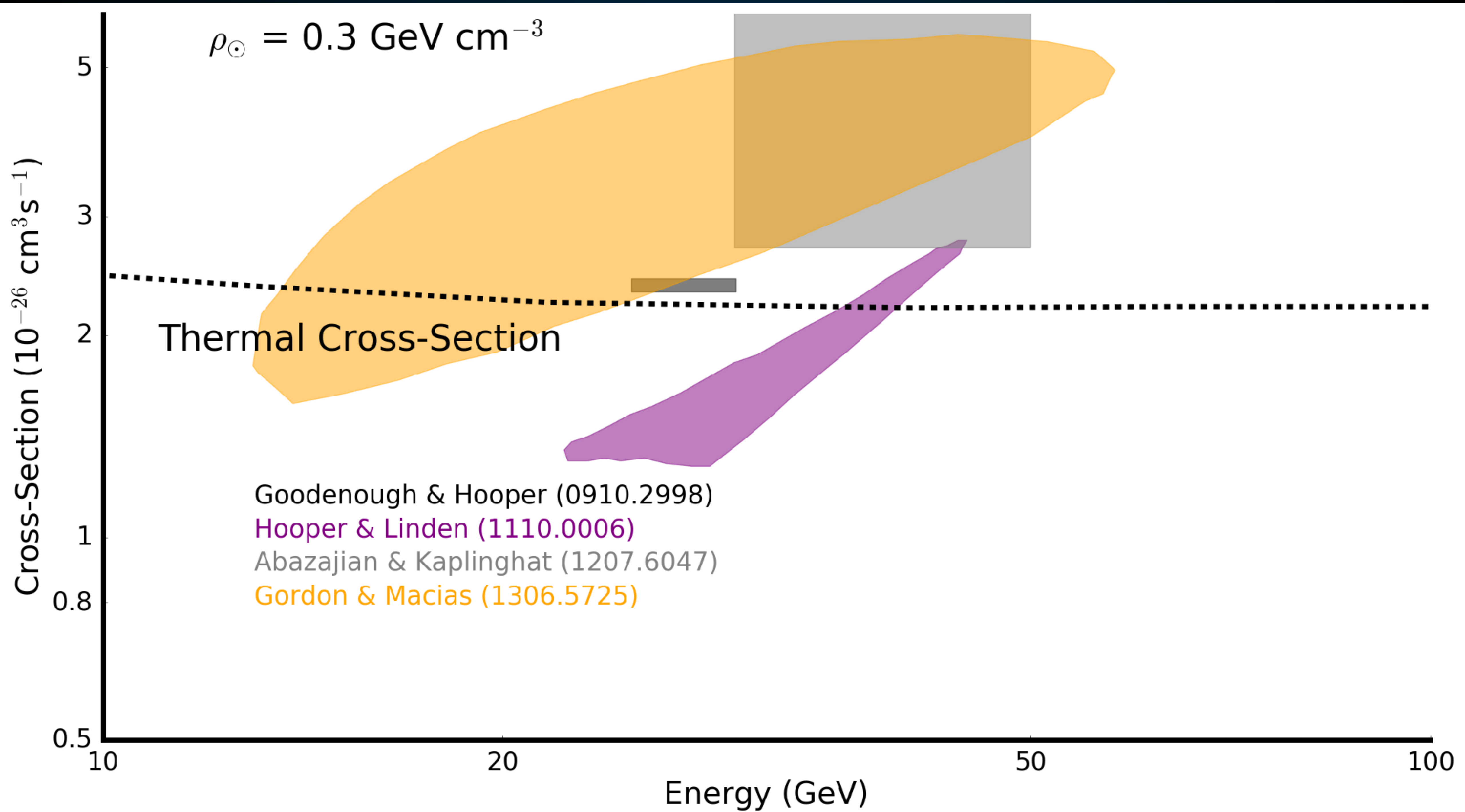
Spatially Extended *to nearly 15 degrees from Galactic center.*

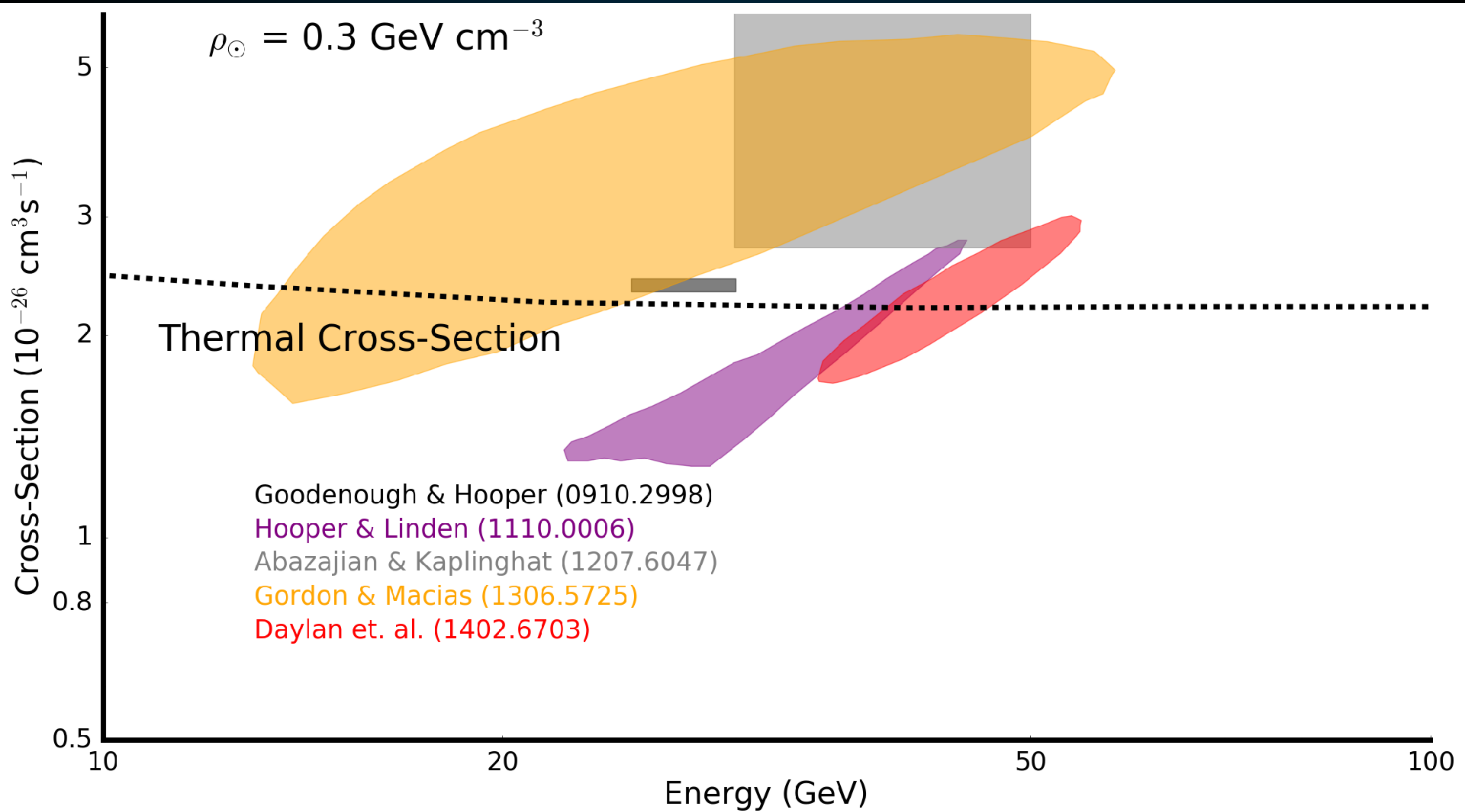


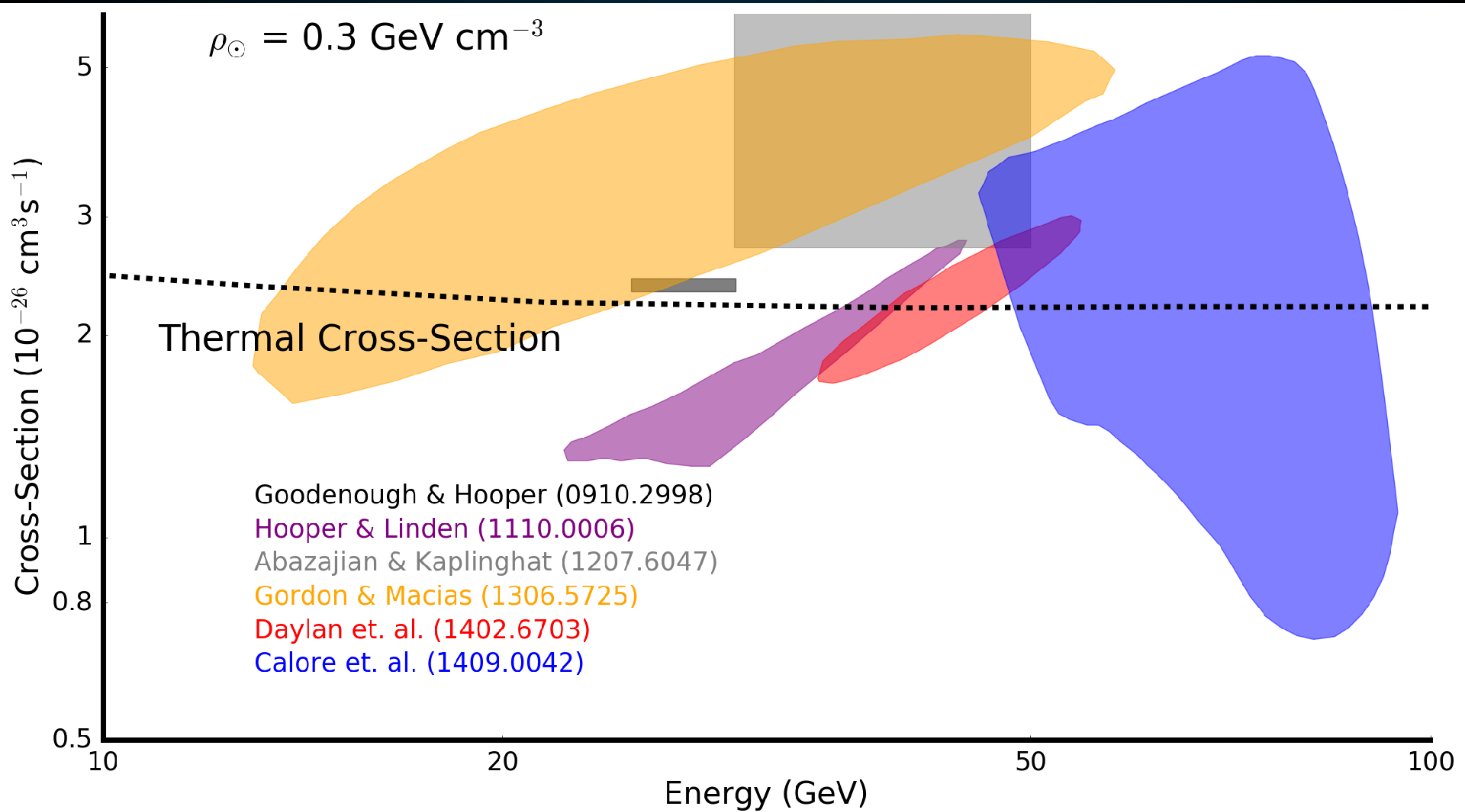


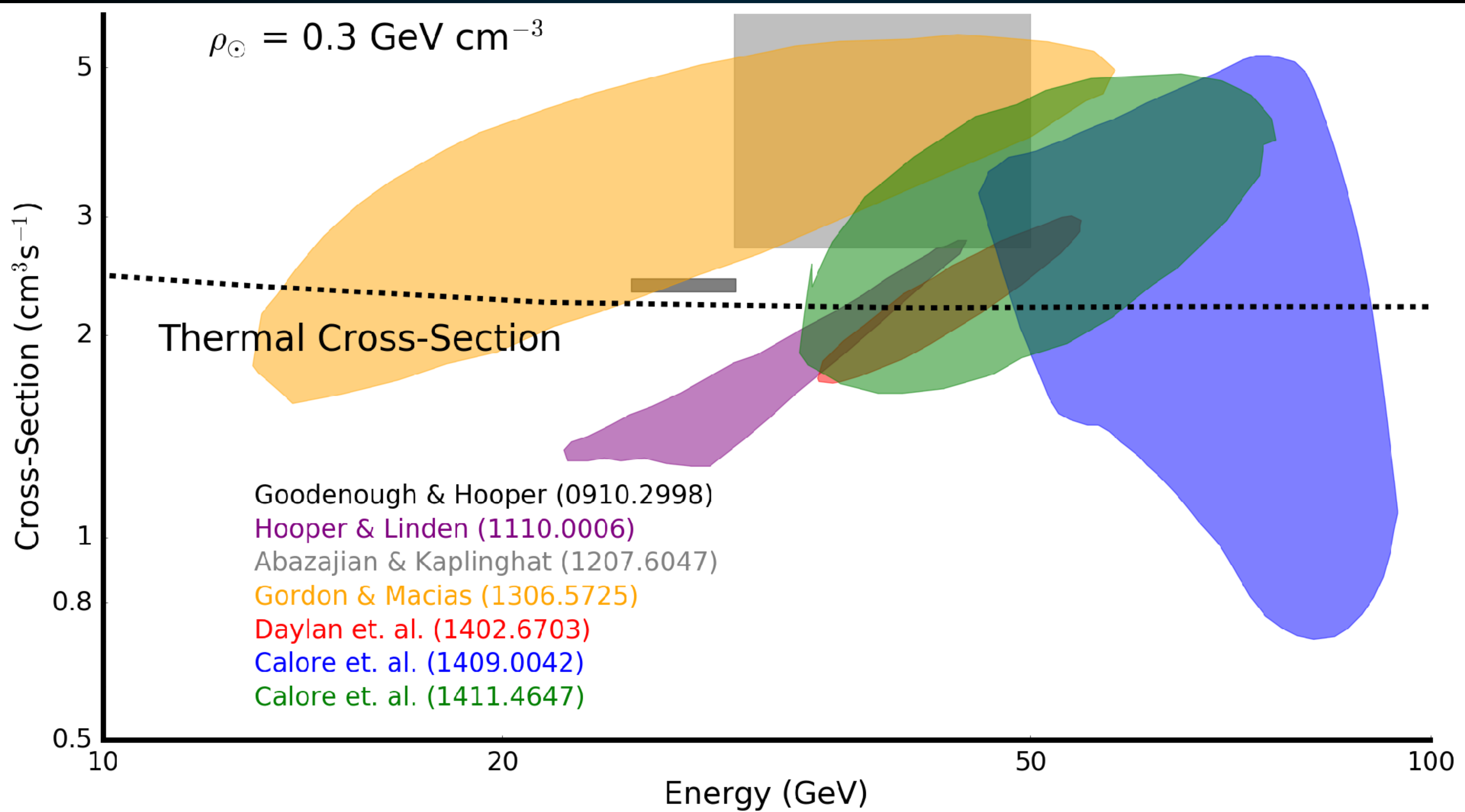




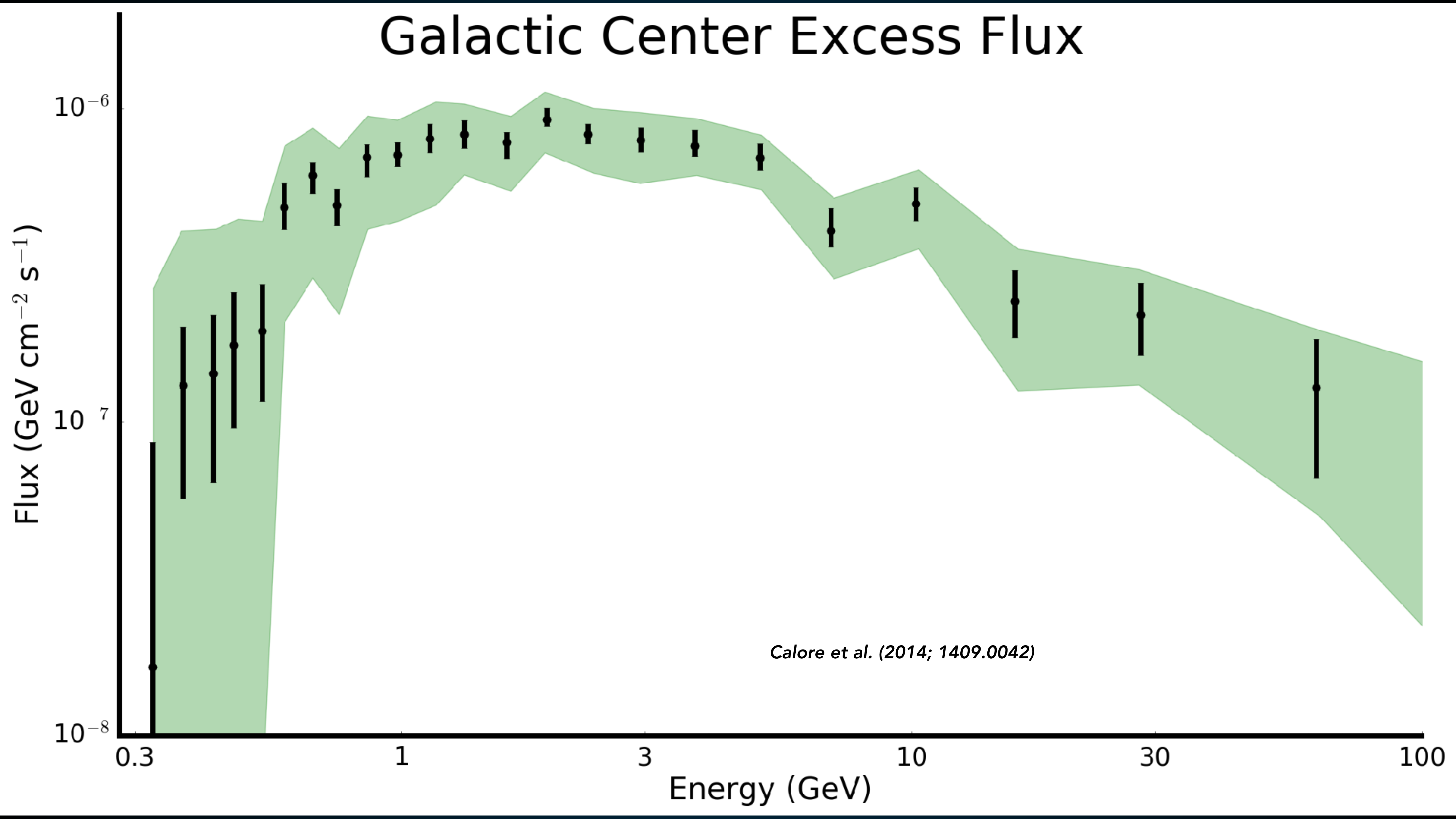




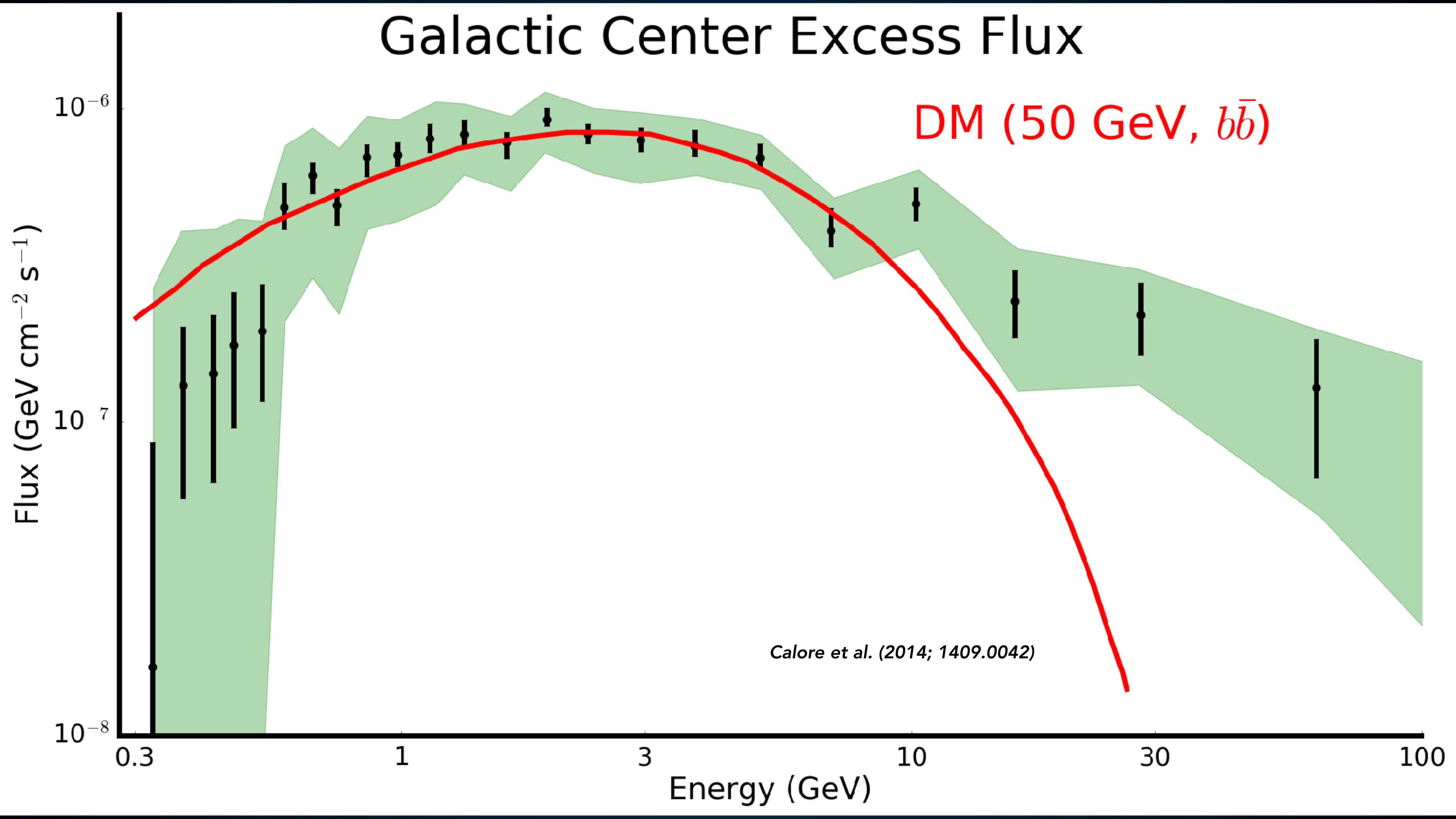




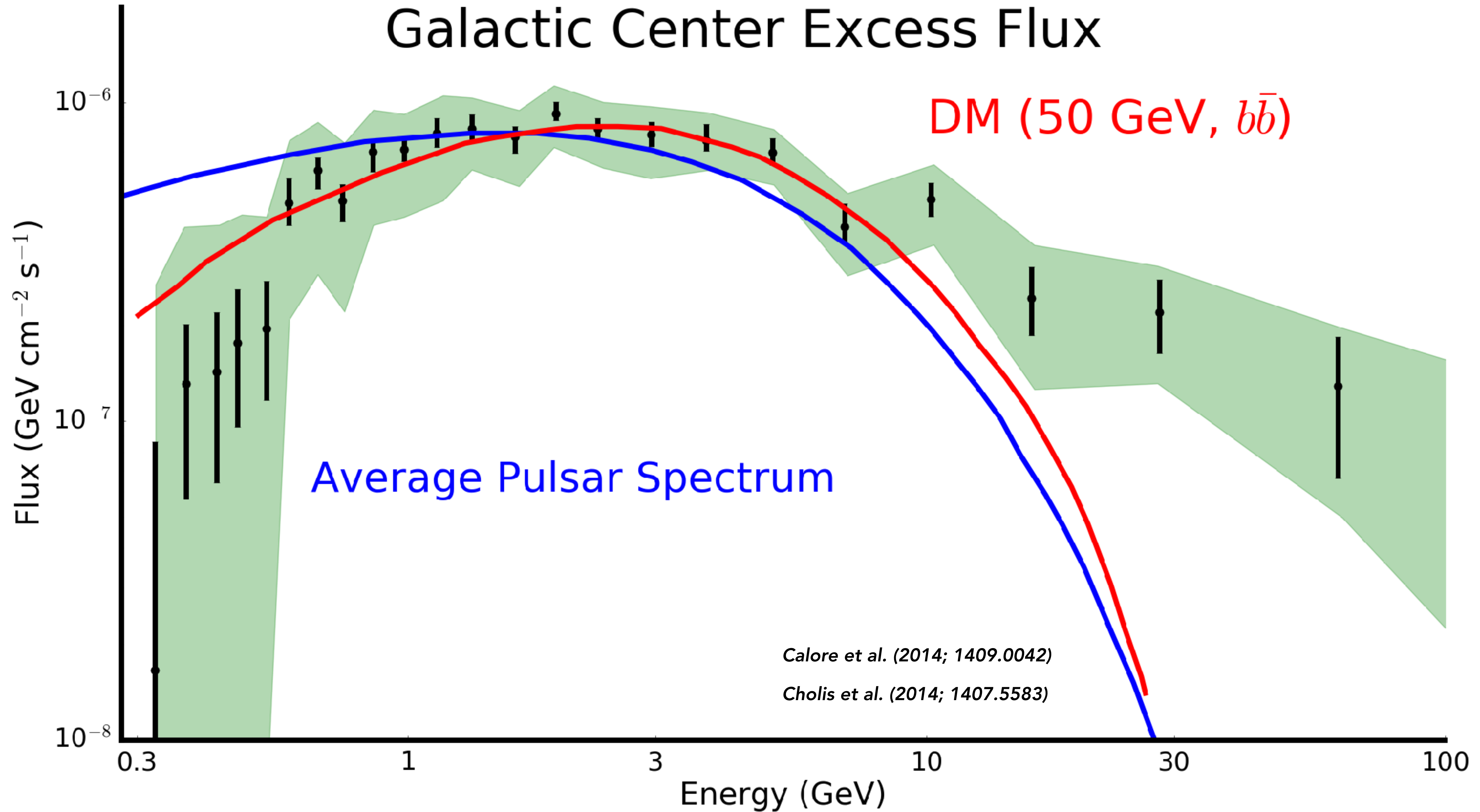
Galactic Center Excess Flux

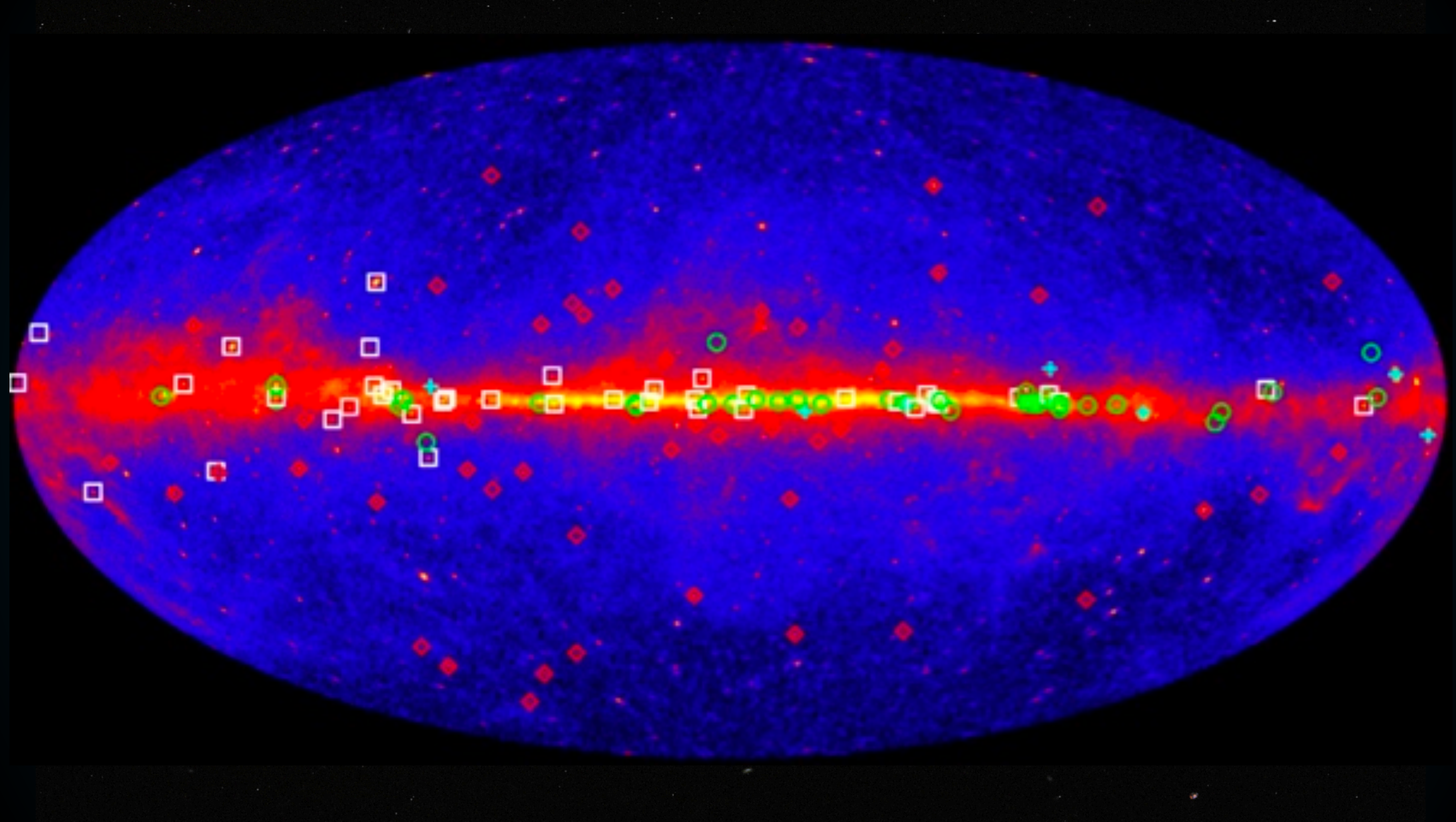


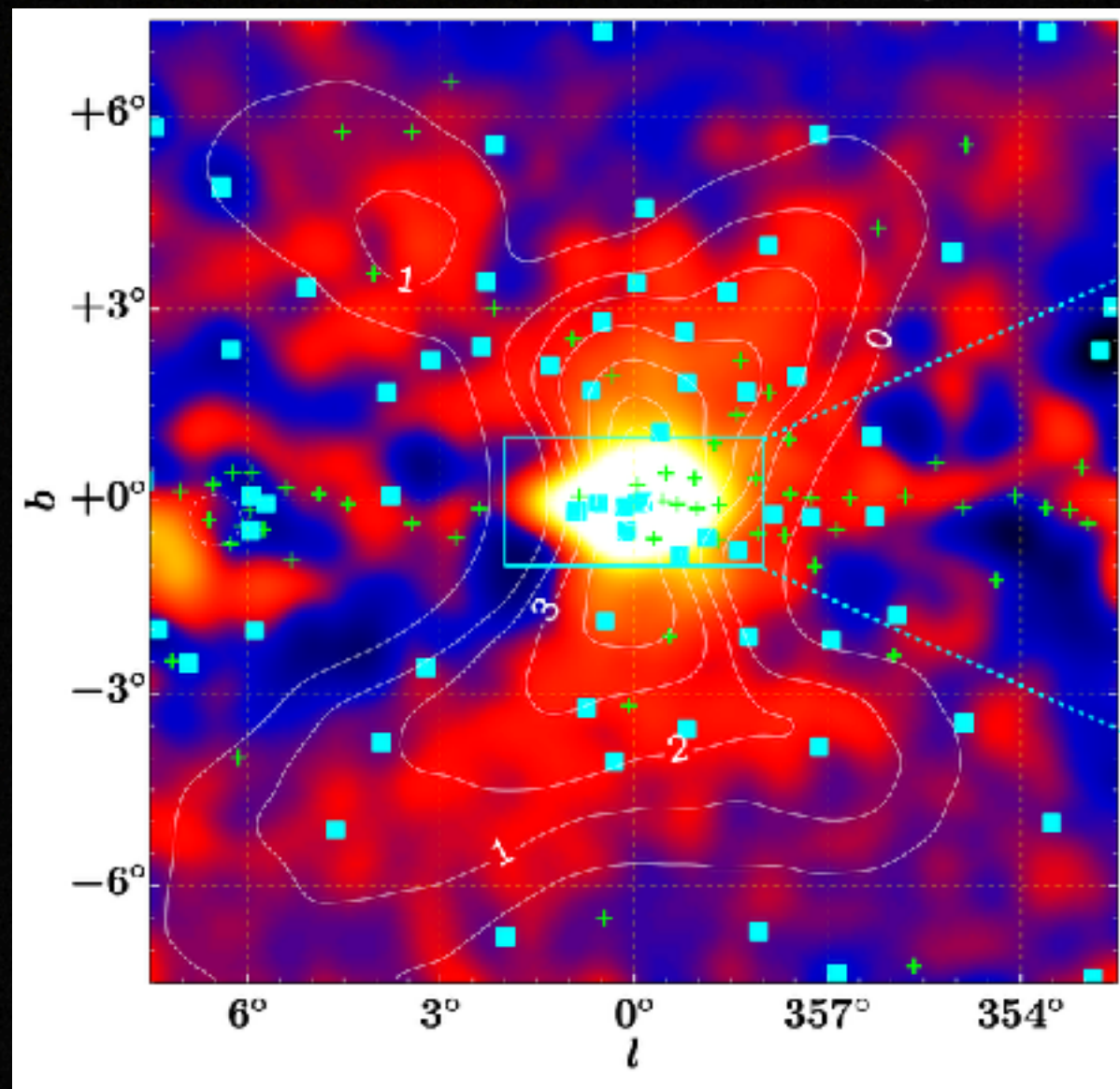
Galactic Center Excess Flux



Galactic Center Excess Flux







Macias et al. (2016; 1611.06644)

Bartels et al. (2017; 1711.04778)

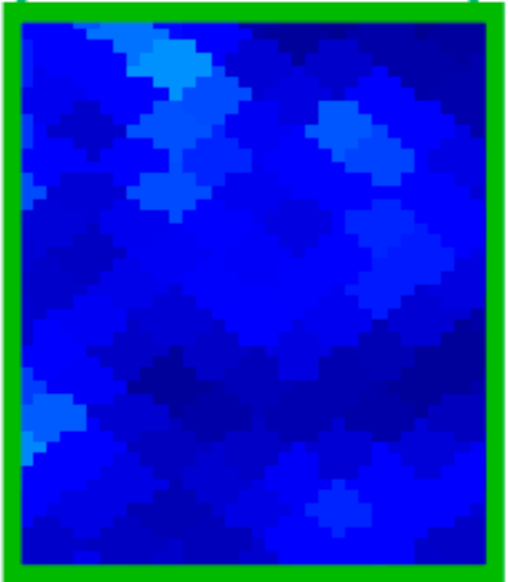
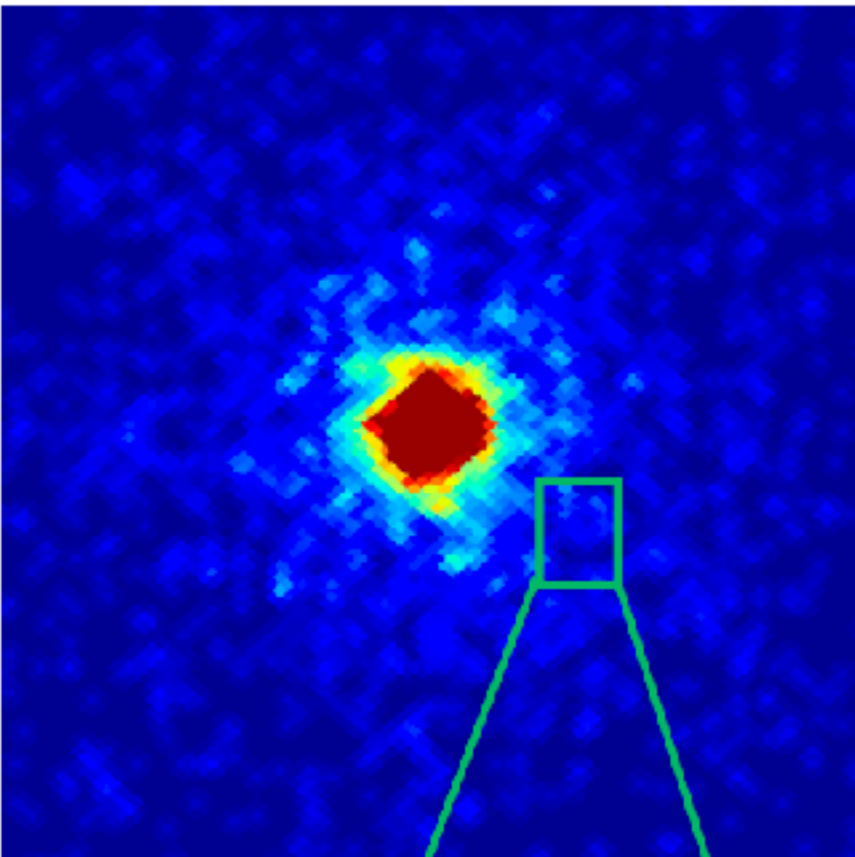
Bartels et al. (2018; 1803.04370)

Macias et al. (2019; 1901.03822)

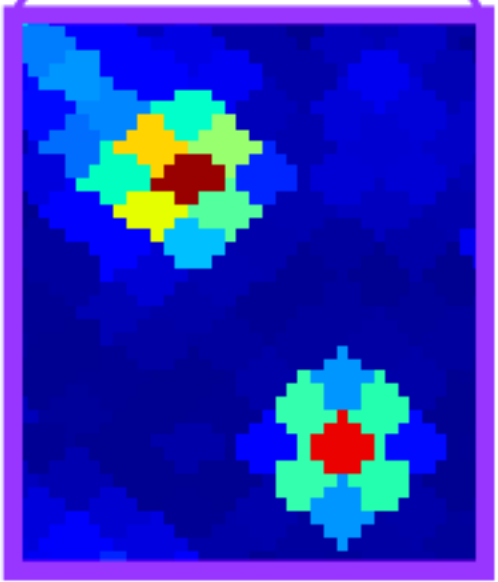
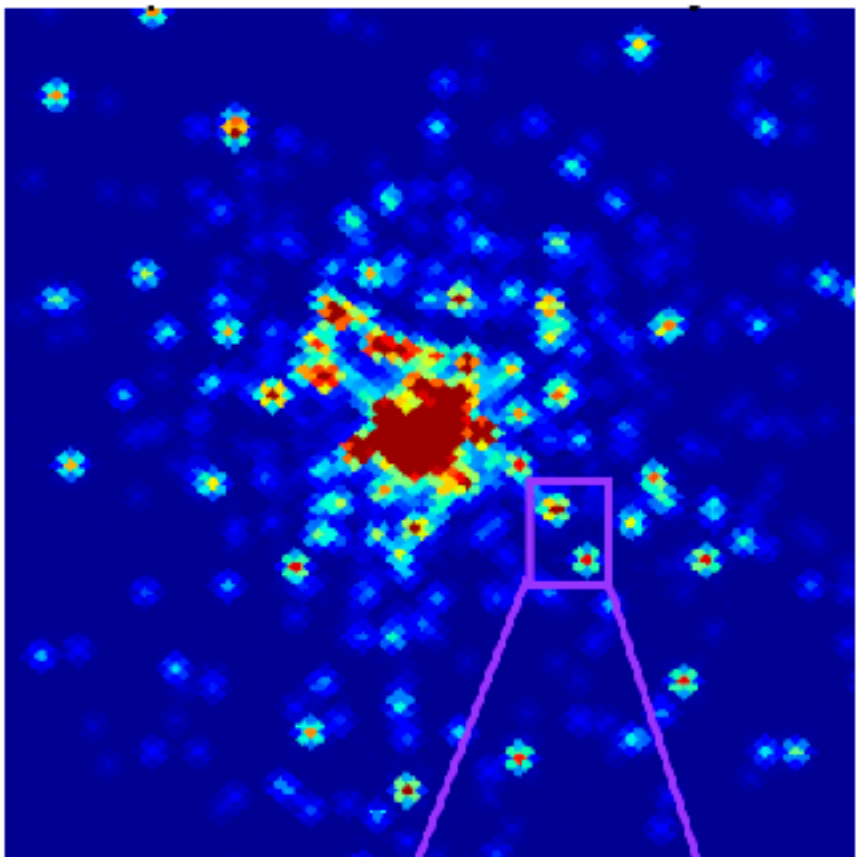
The Galactic Center Excess

No Diffuse Bkgd

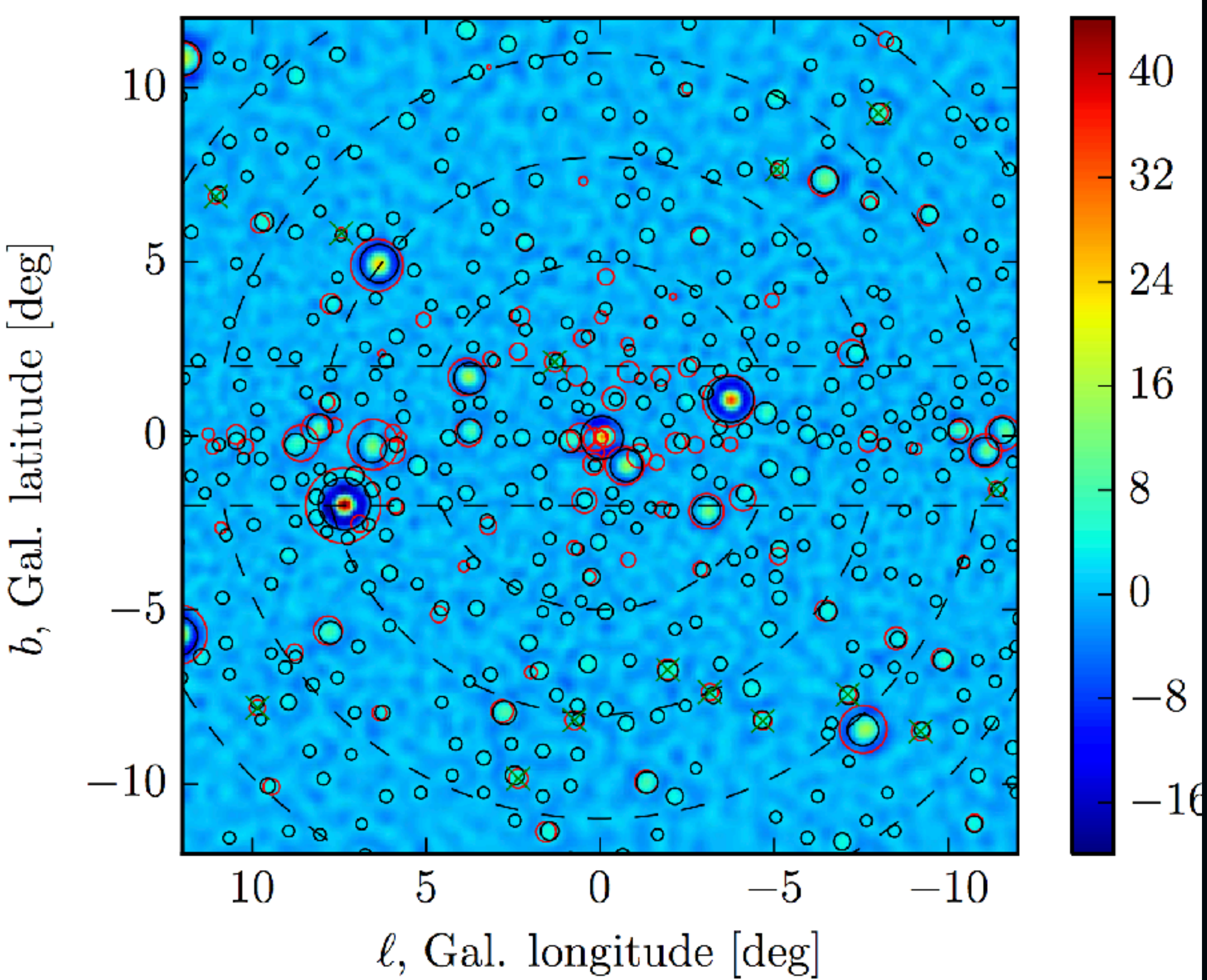
Dark Matter



Point Sources

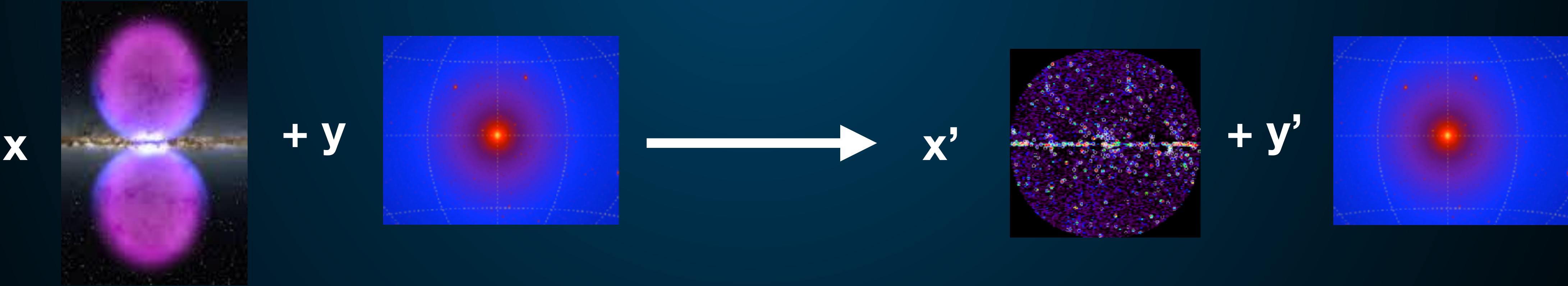
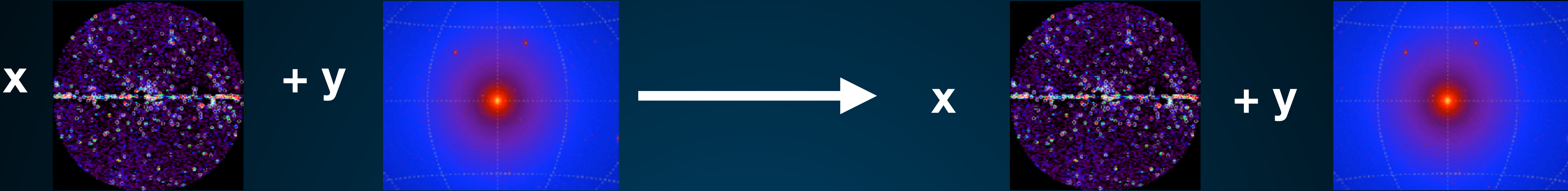


slide from Mariangela Lisanti

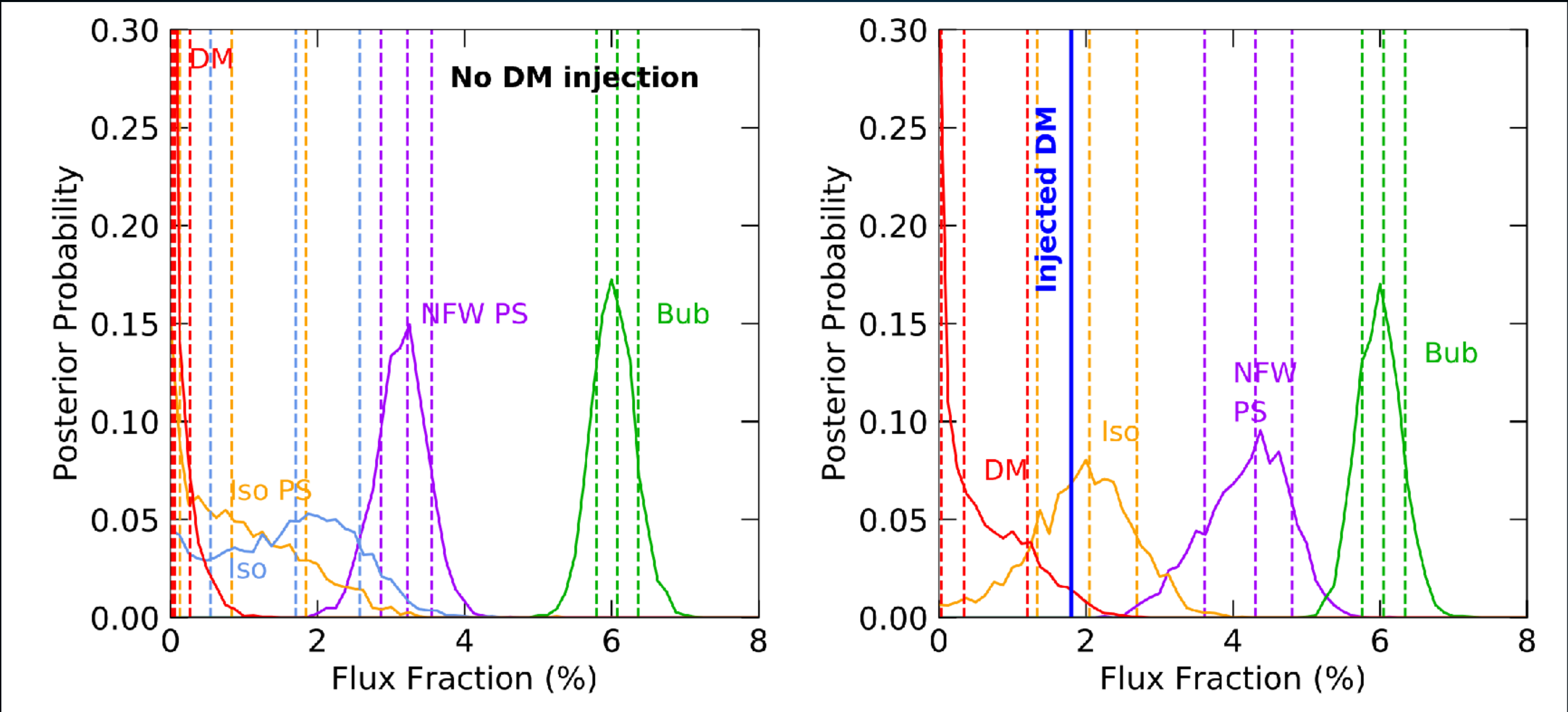


Bulletproof evidence for pulsars?

The Galactic Center Excess

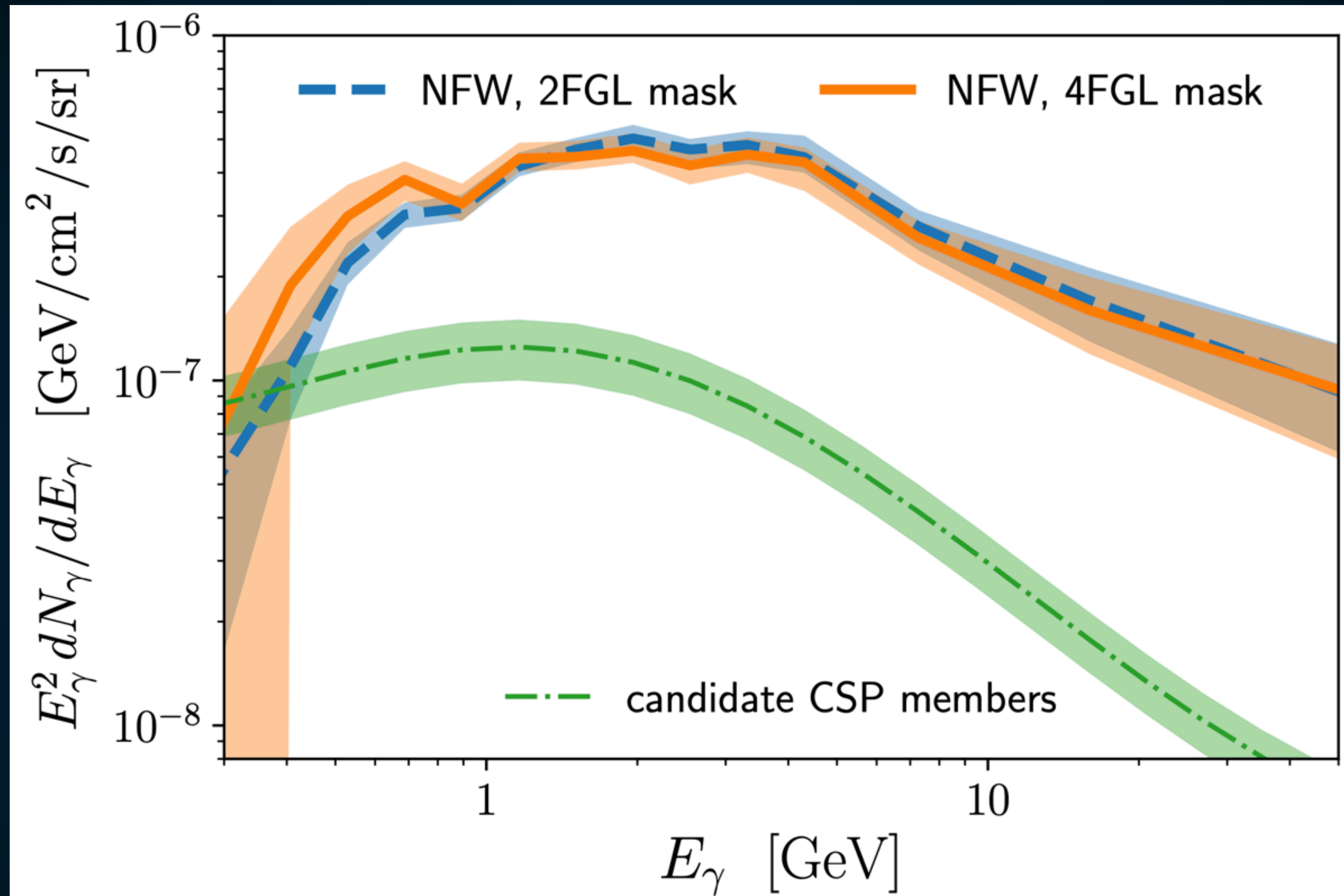


The Galactic Center Excess



Dark Matter Strikes Back at the Galactic Center

The Galactic Center Excess



New Catalogs also change the interpretation of the wavelet analysis!

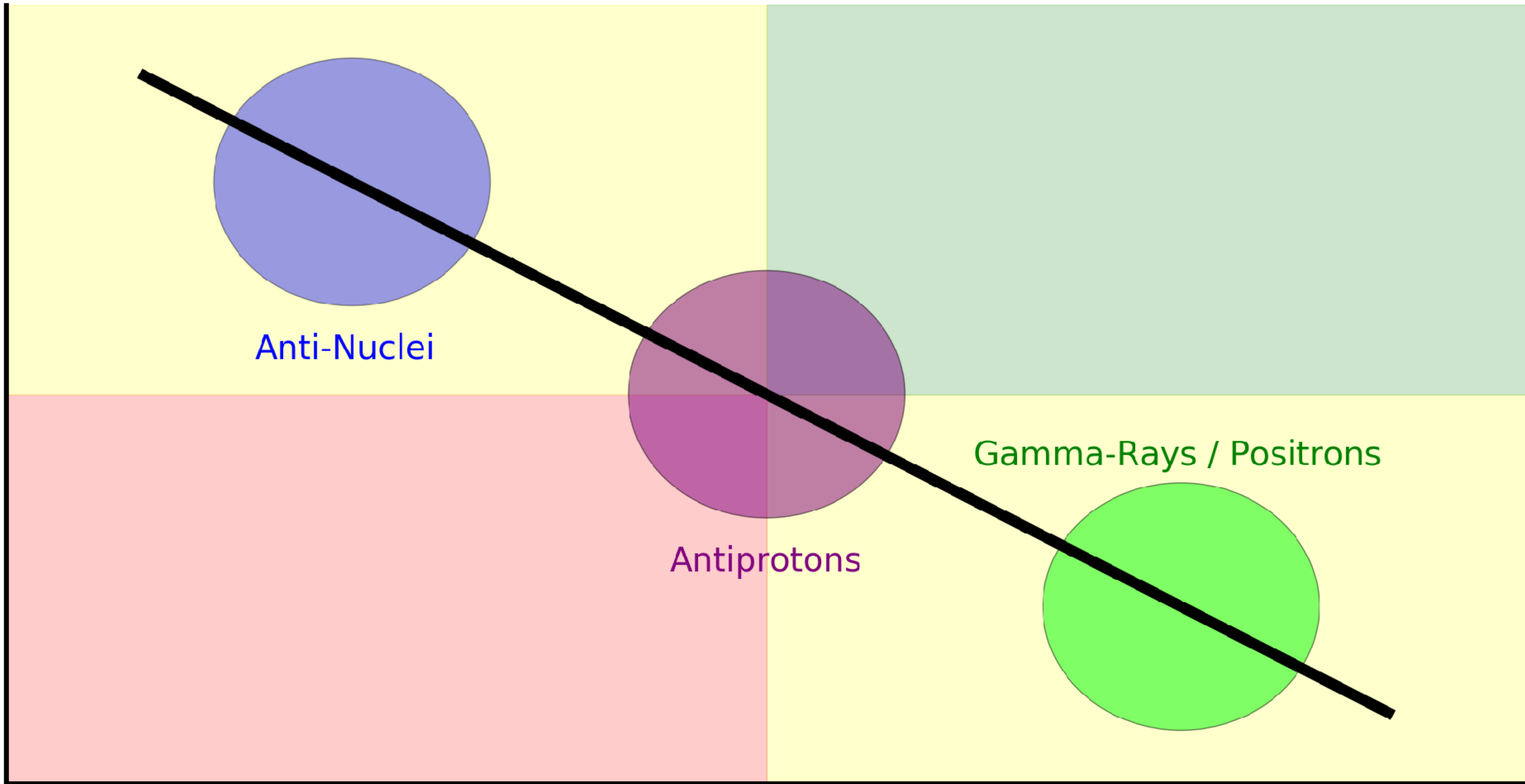
Specificity (DM Flux / Astrophysics Flux)

Anti-Nuclei

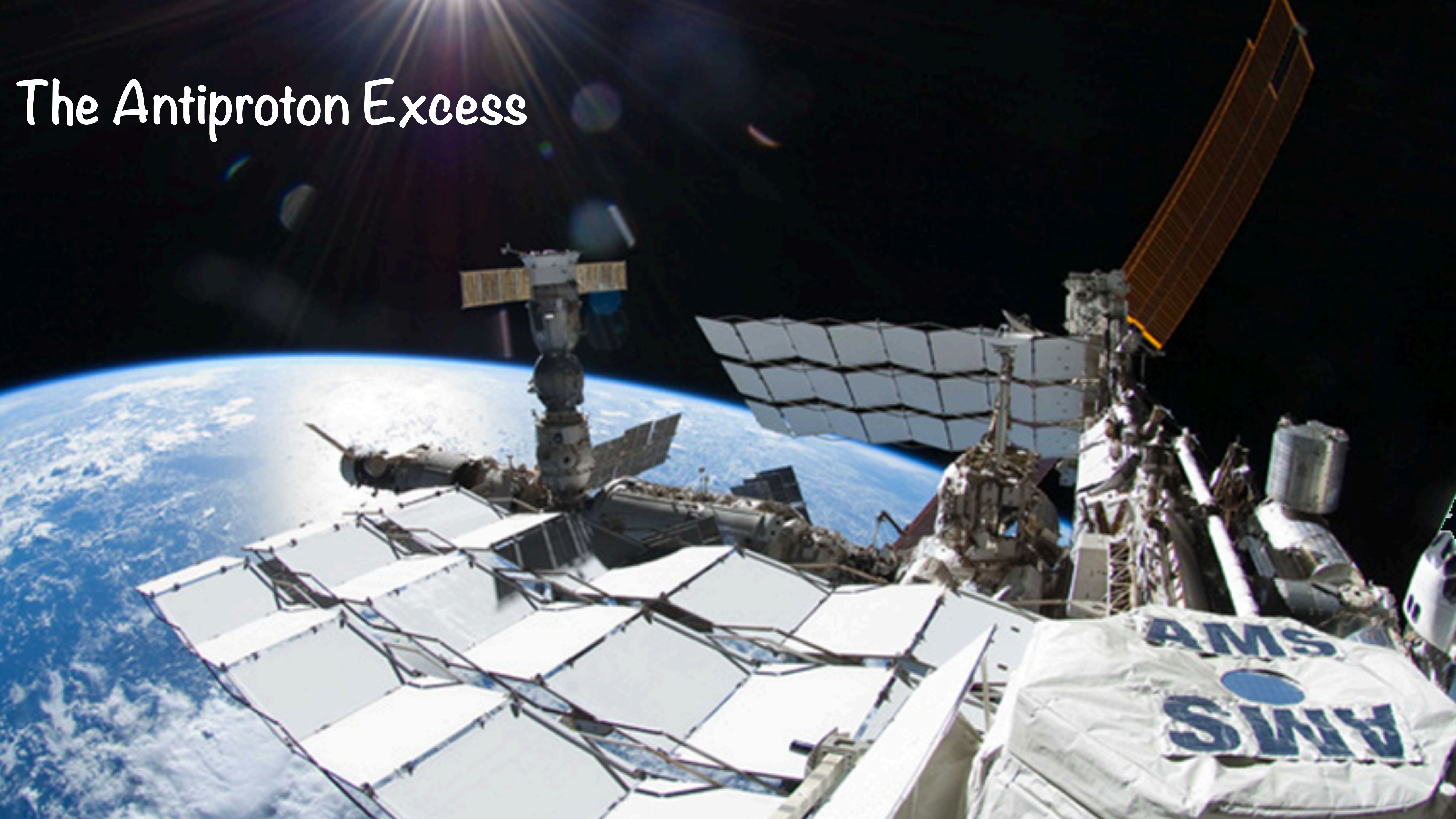
Antiprotons

Gamma-Rays / Positrons

Fraction of Dark Matter Flux



The Antiproton Excess



The Antiproton Excess

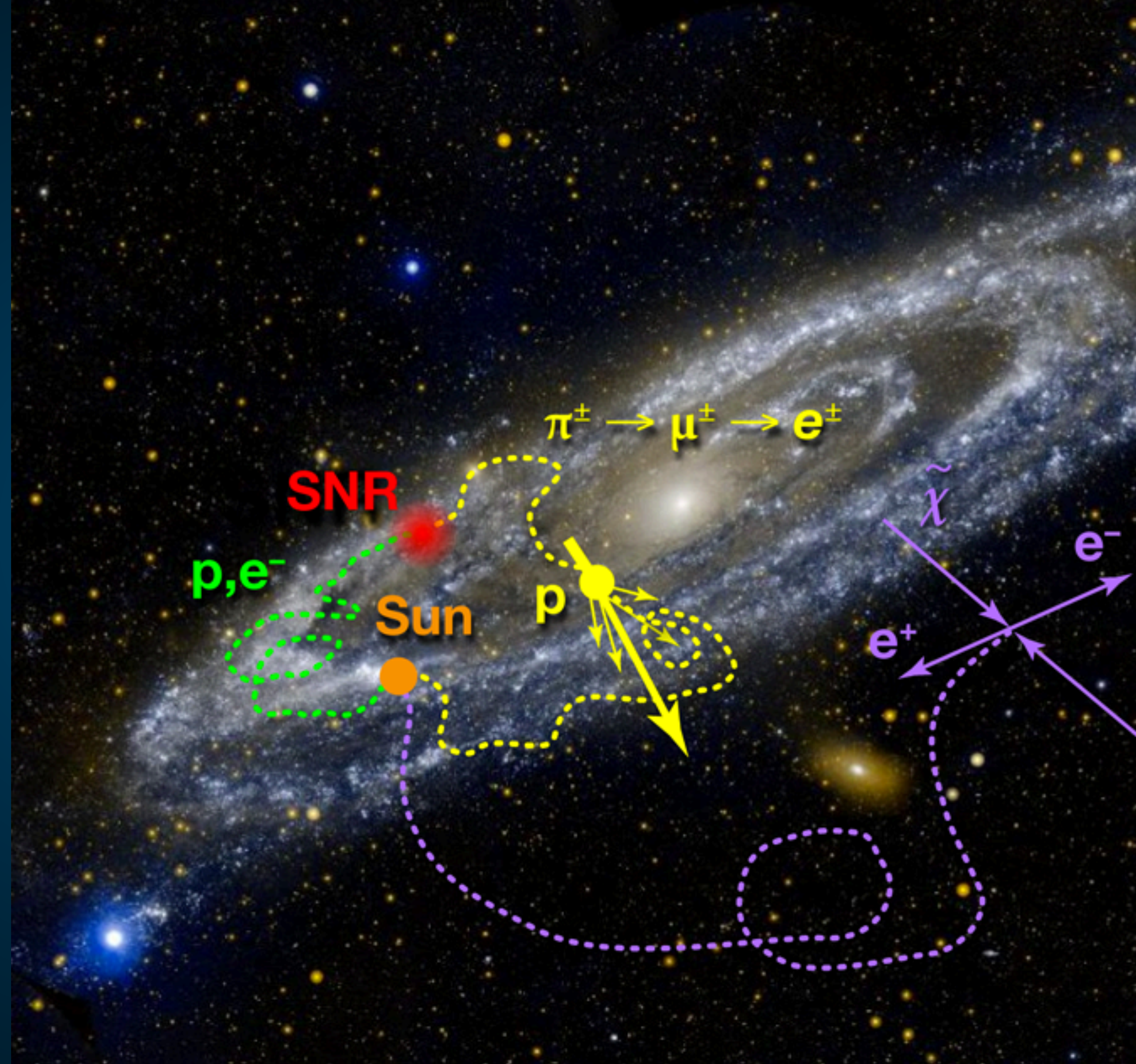
Investigate the Antiproton Fraction!

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

Two Changes:

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

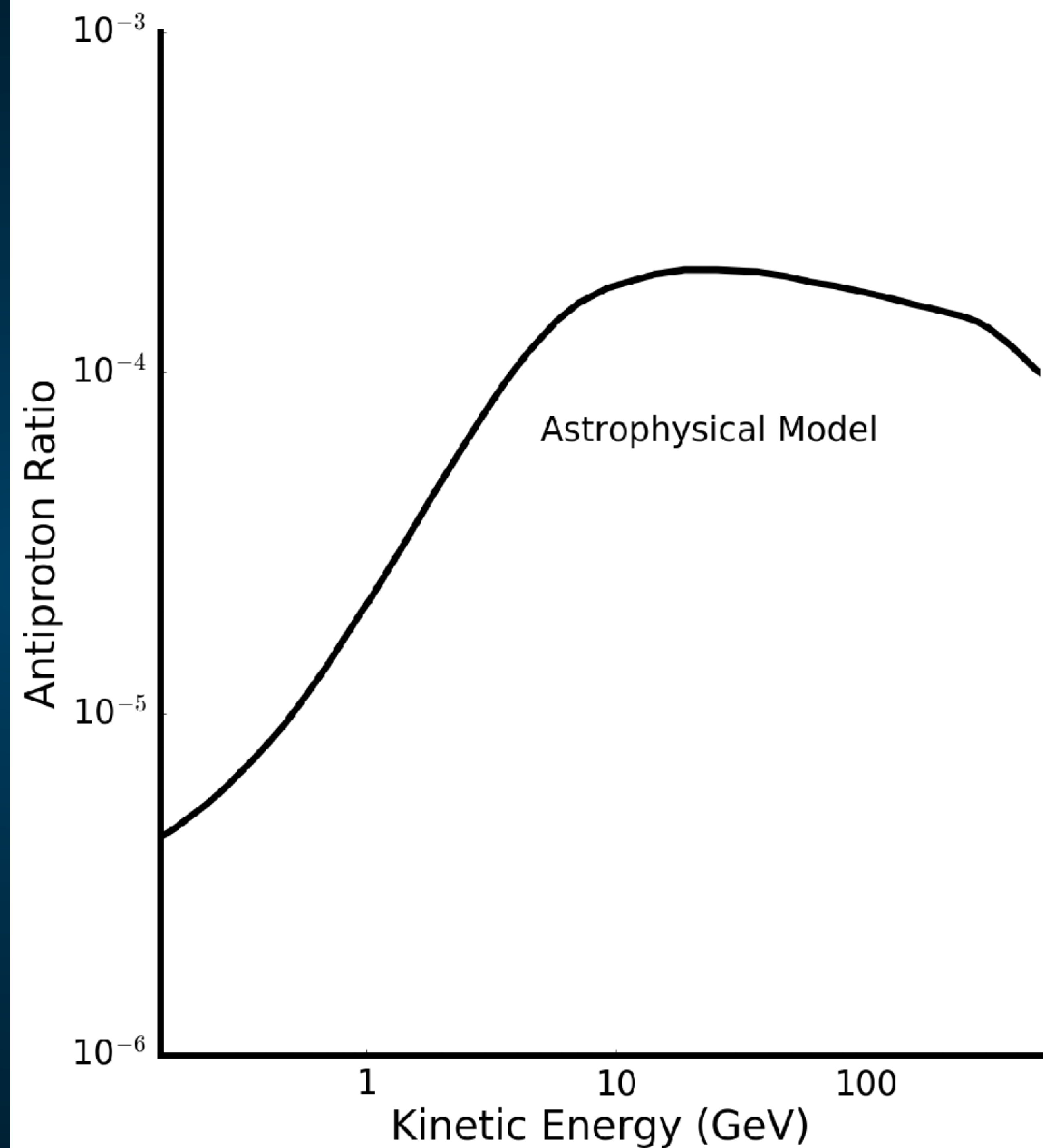
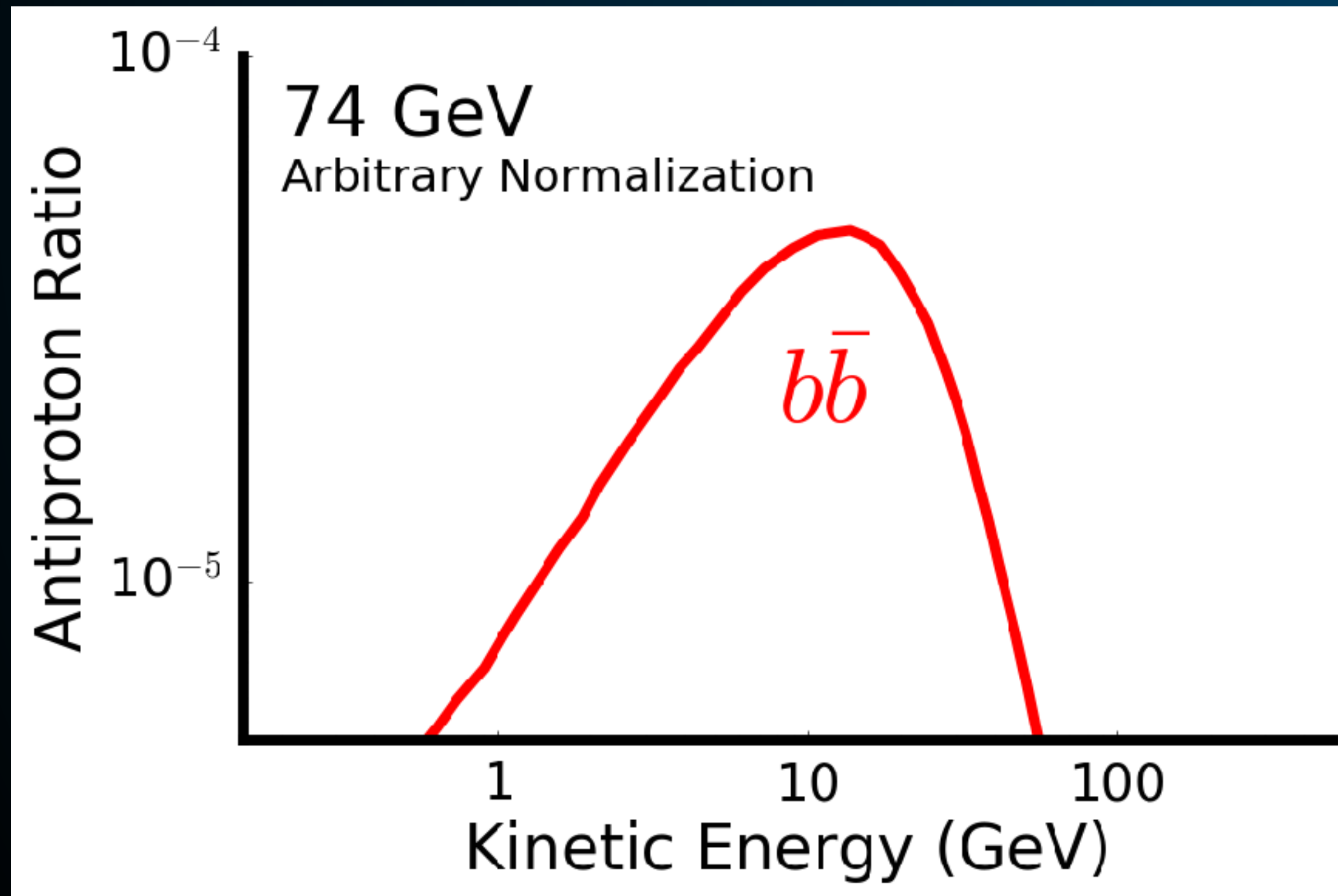
Hadronic Energy losses are slower
(sensitive to antiproton production
throughout the Galaxy)



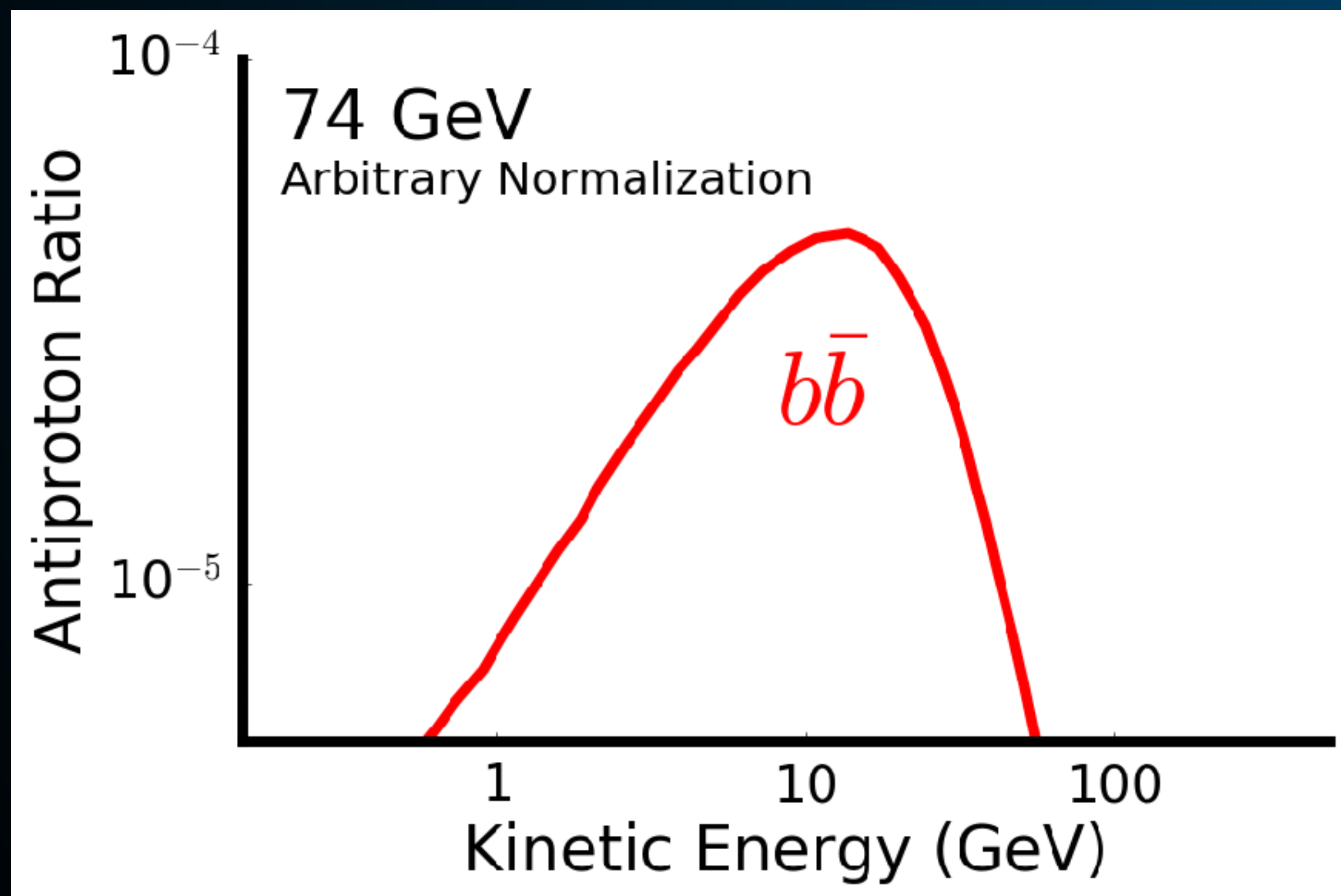
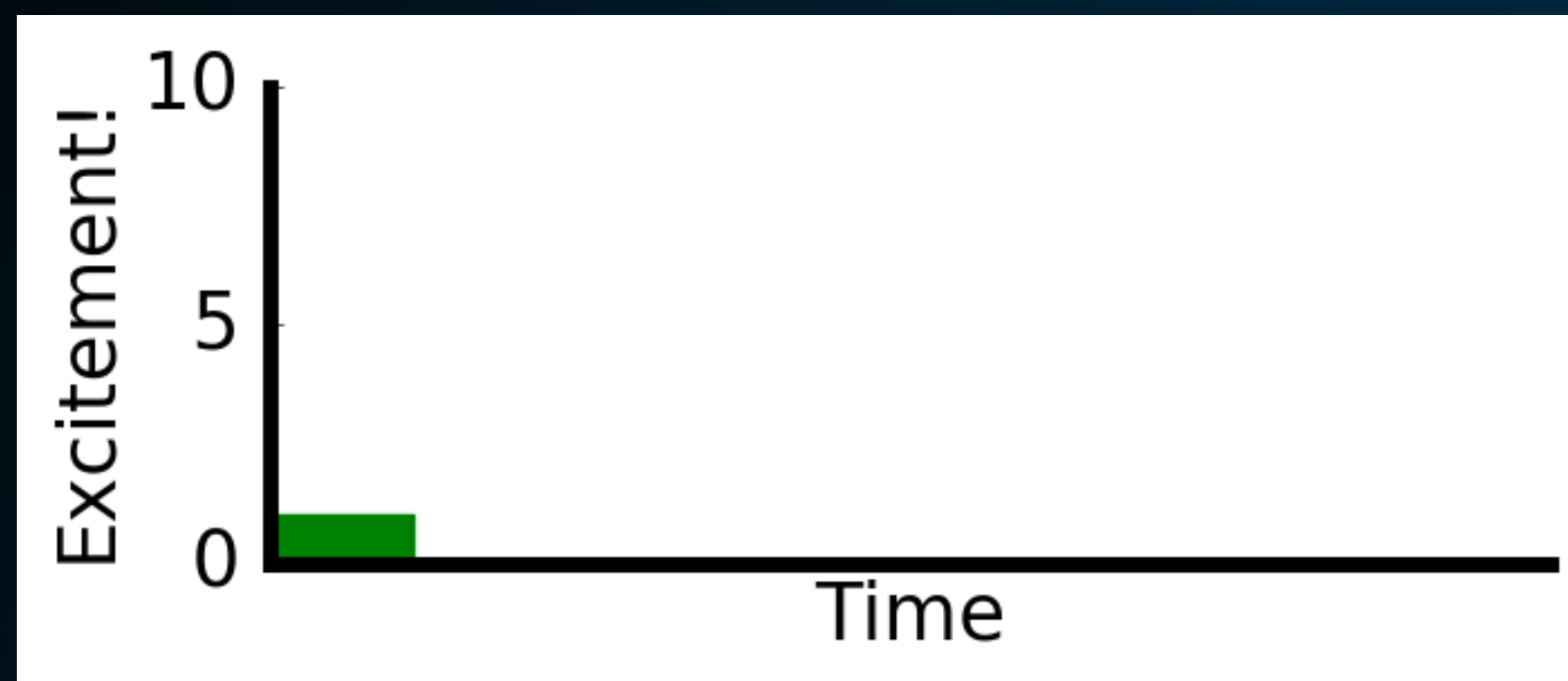
The Antiproton Excess

Astrophysics - Smooth Profile

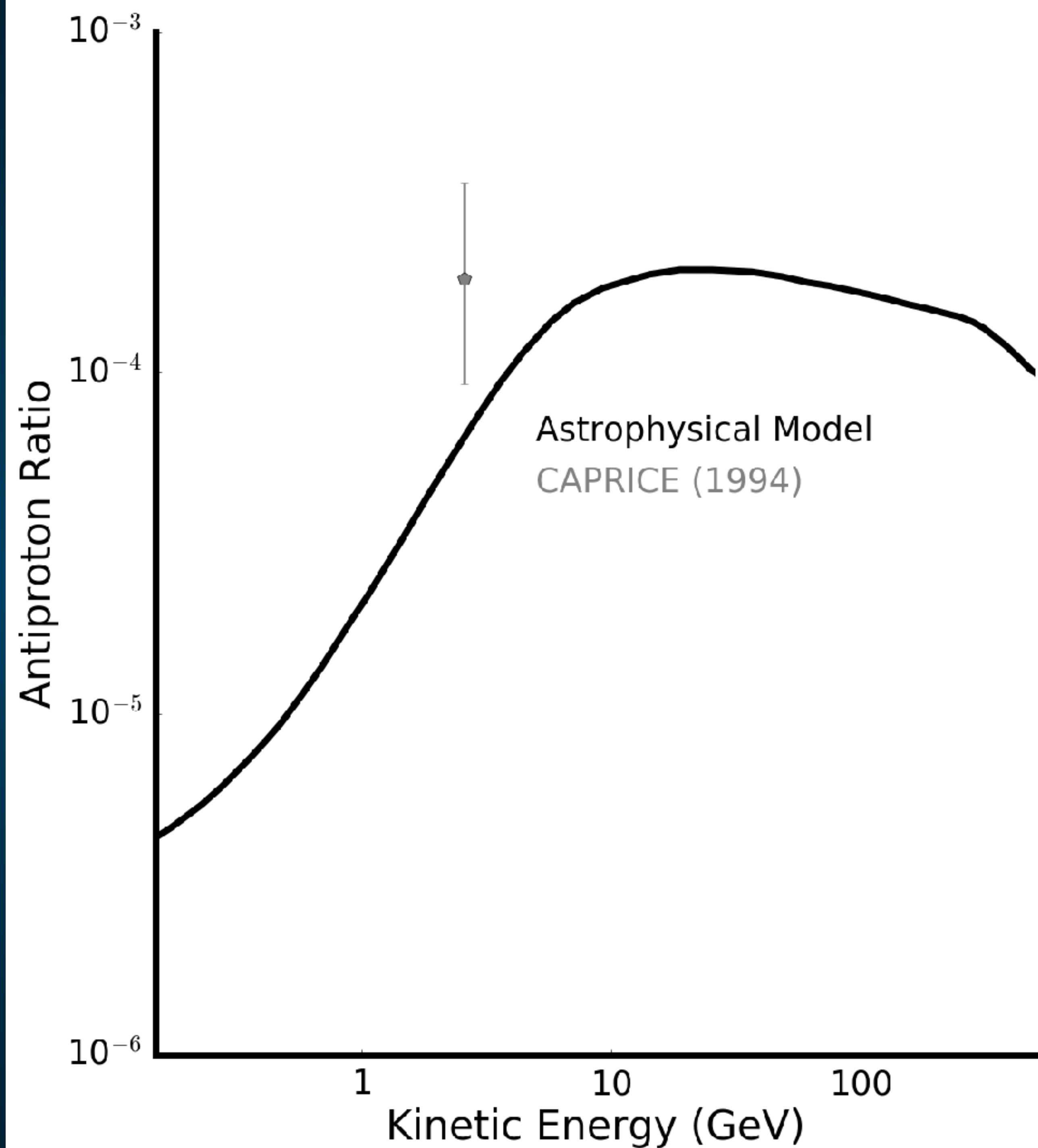
Dark Matter - Sharp Bump!



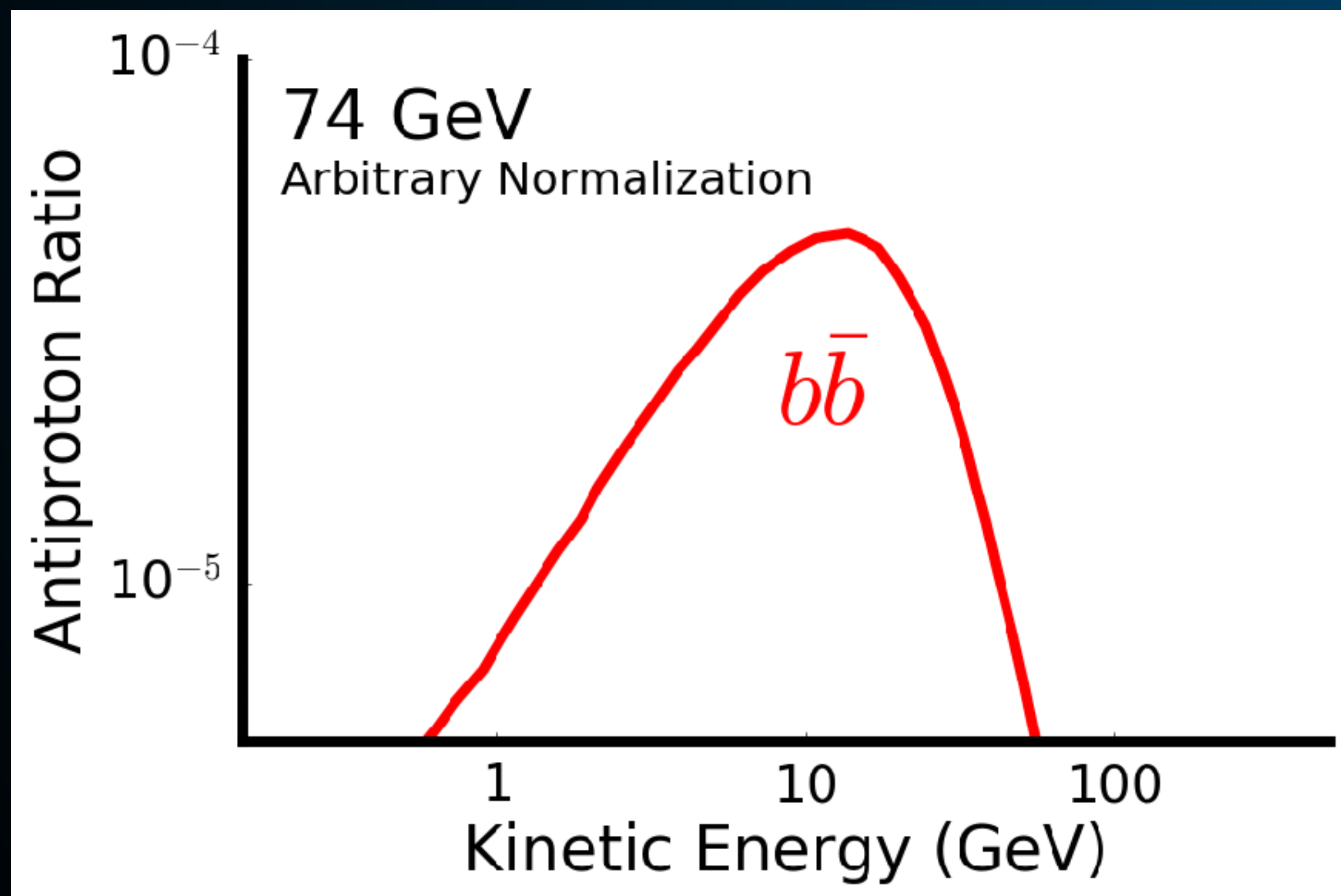
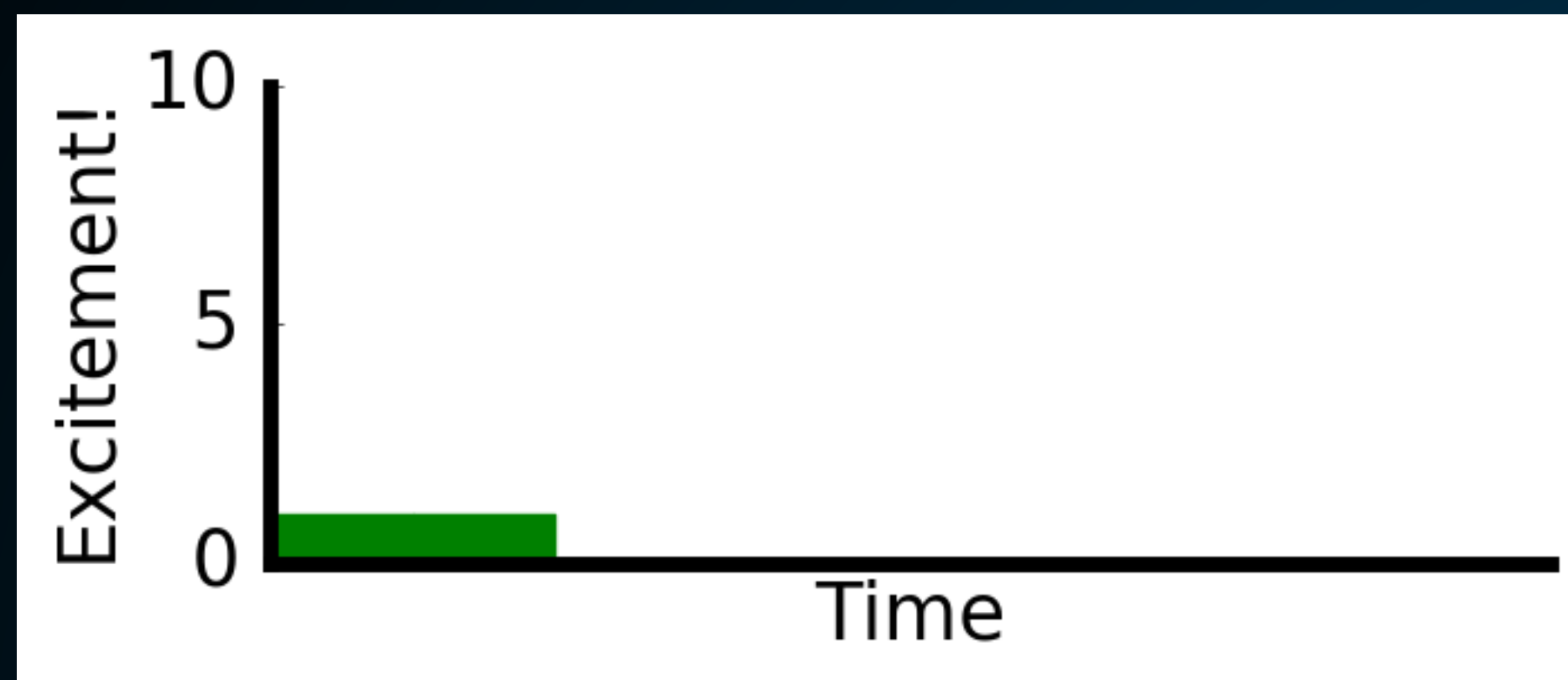
The Antiproton Excess



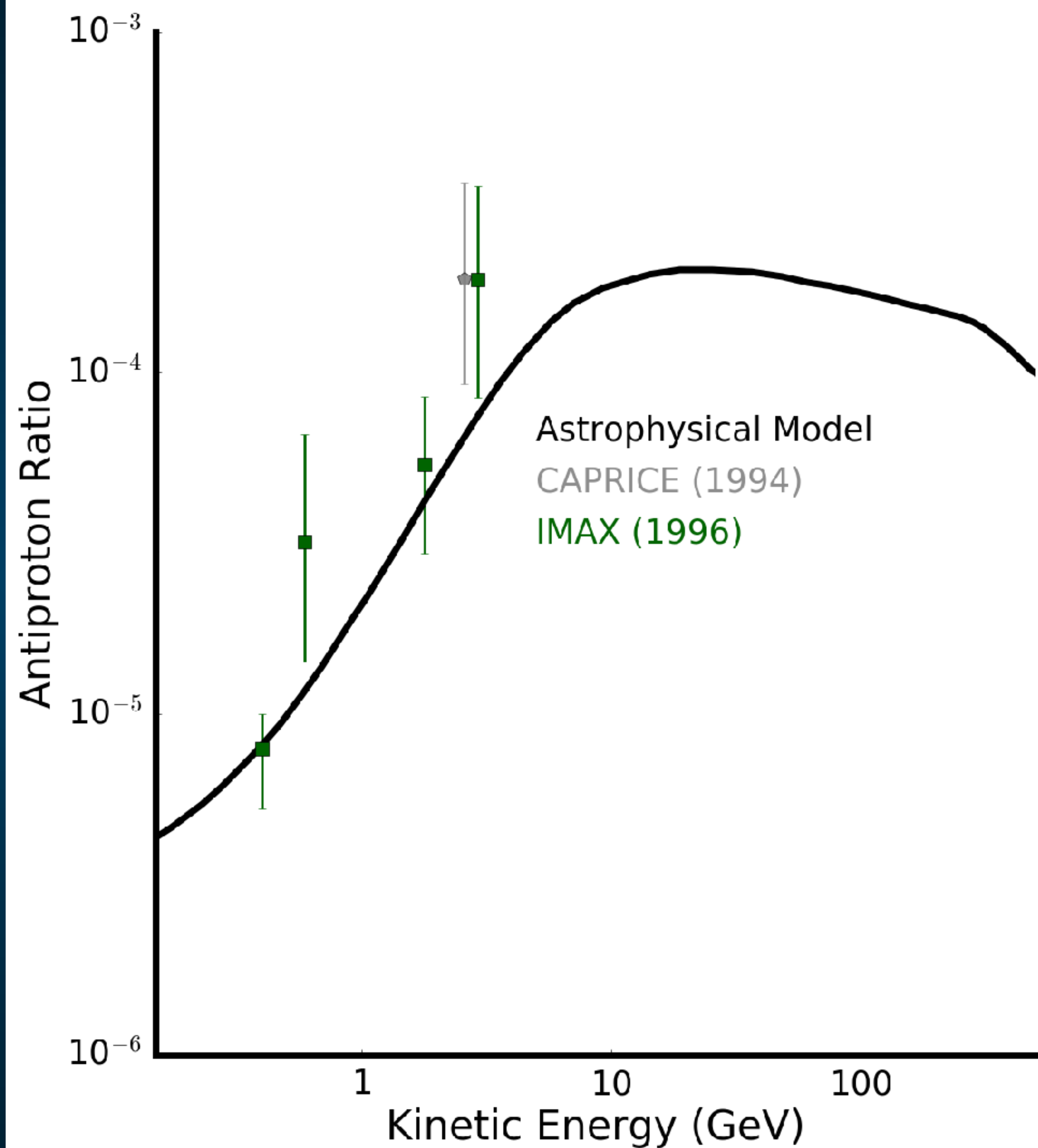
(Not an exhaustive list of observations)



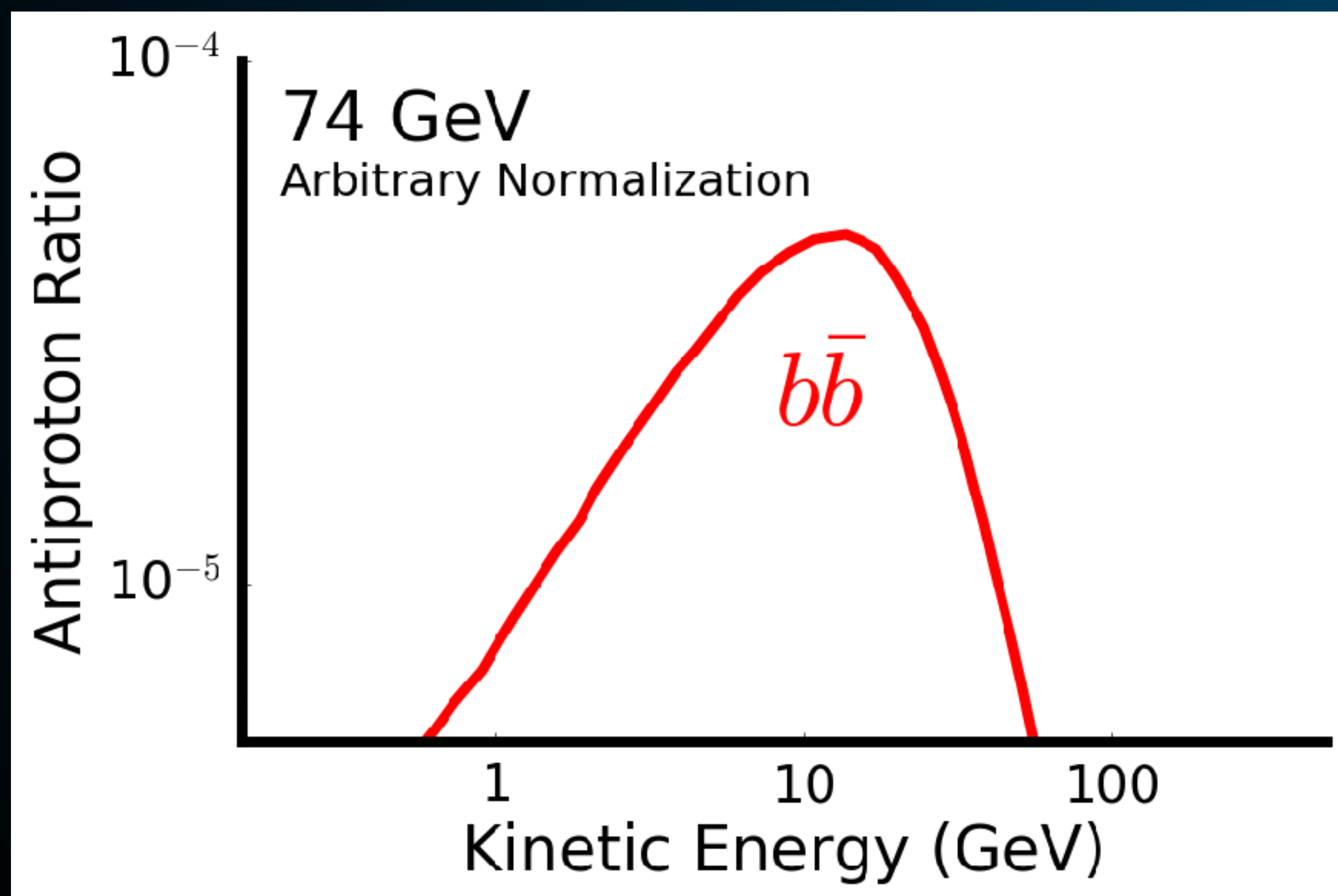
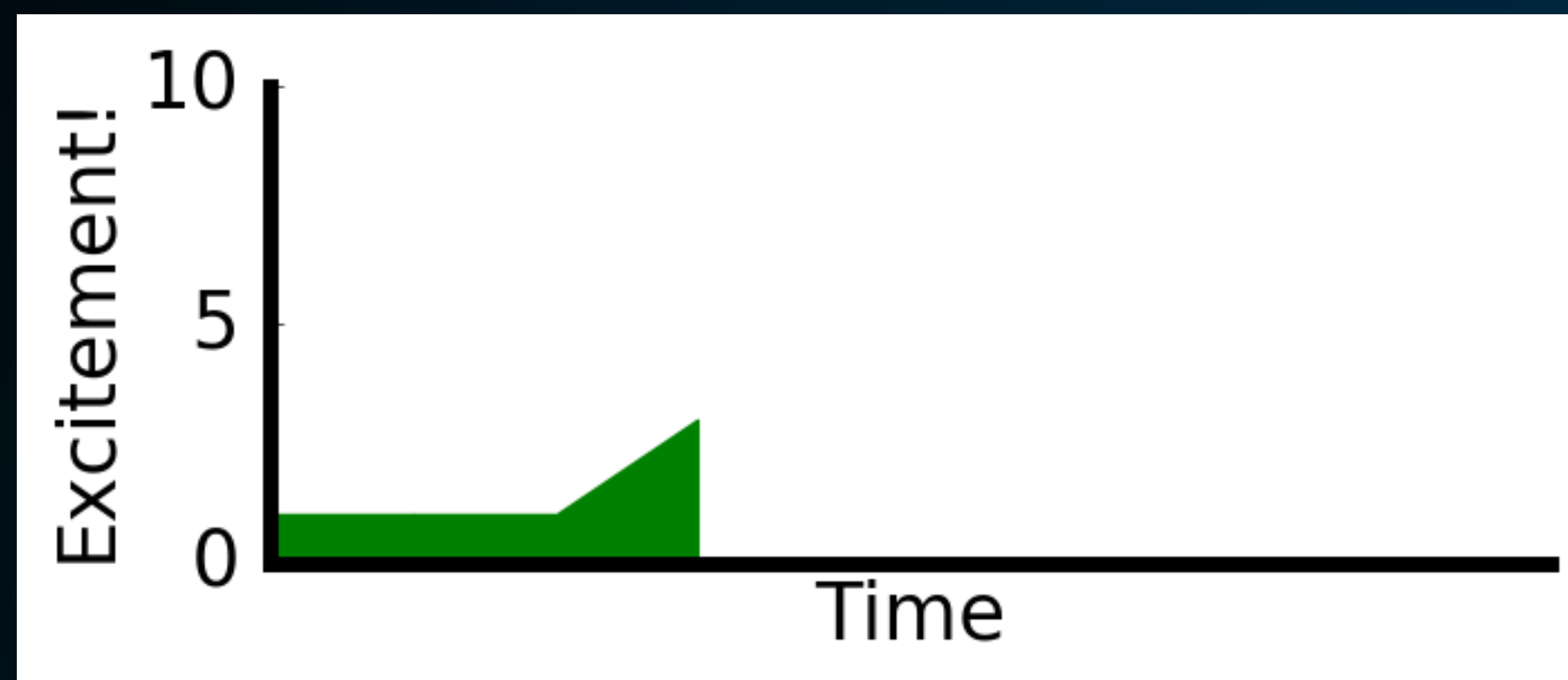
The Antiproton Excess



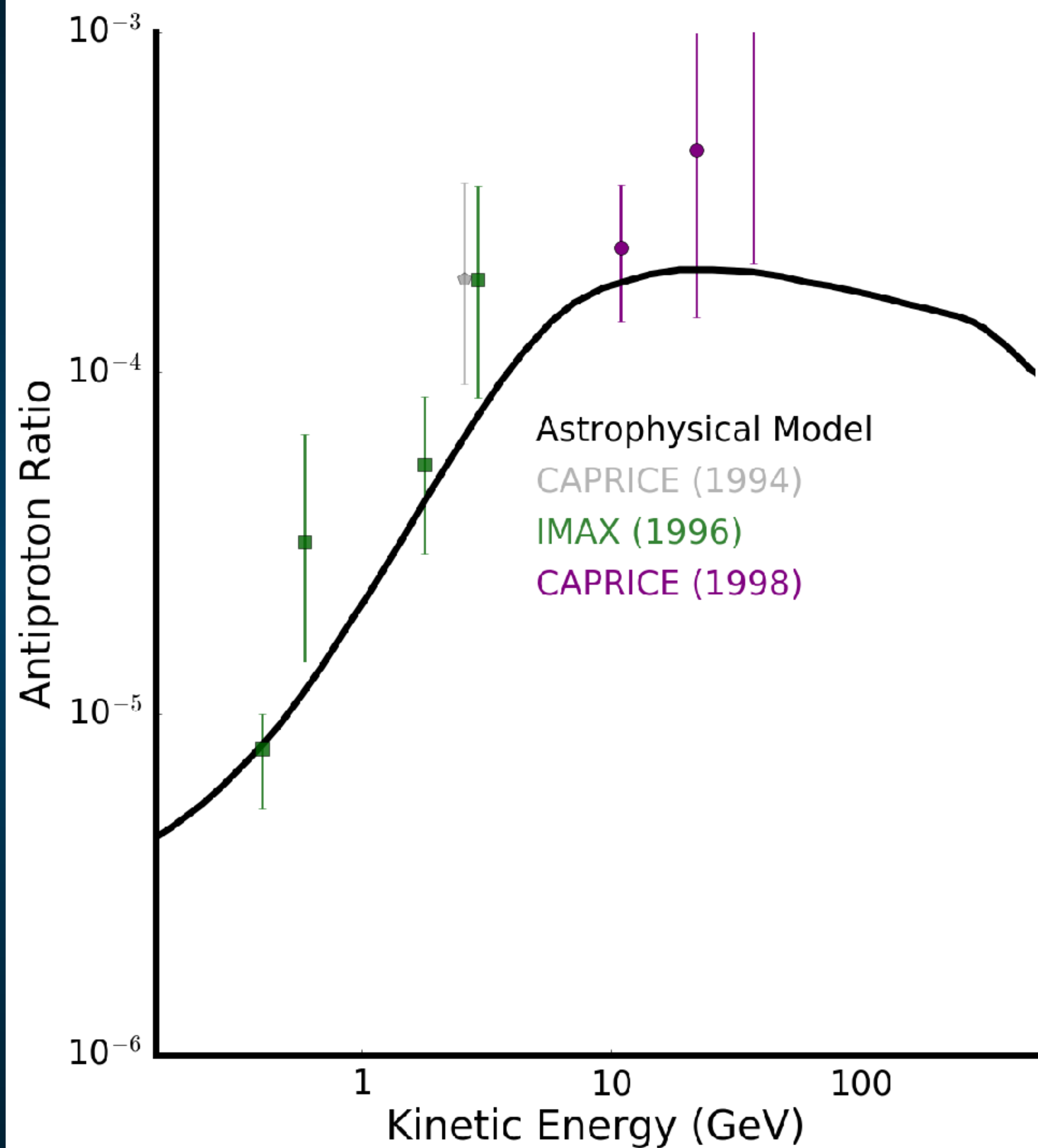
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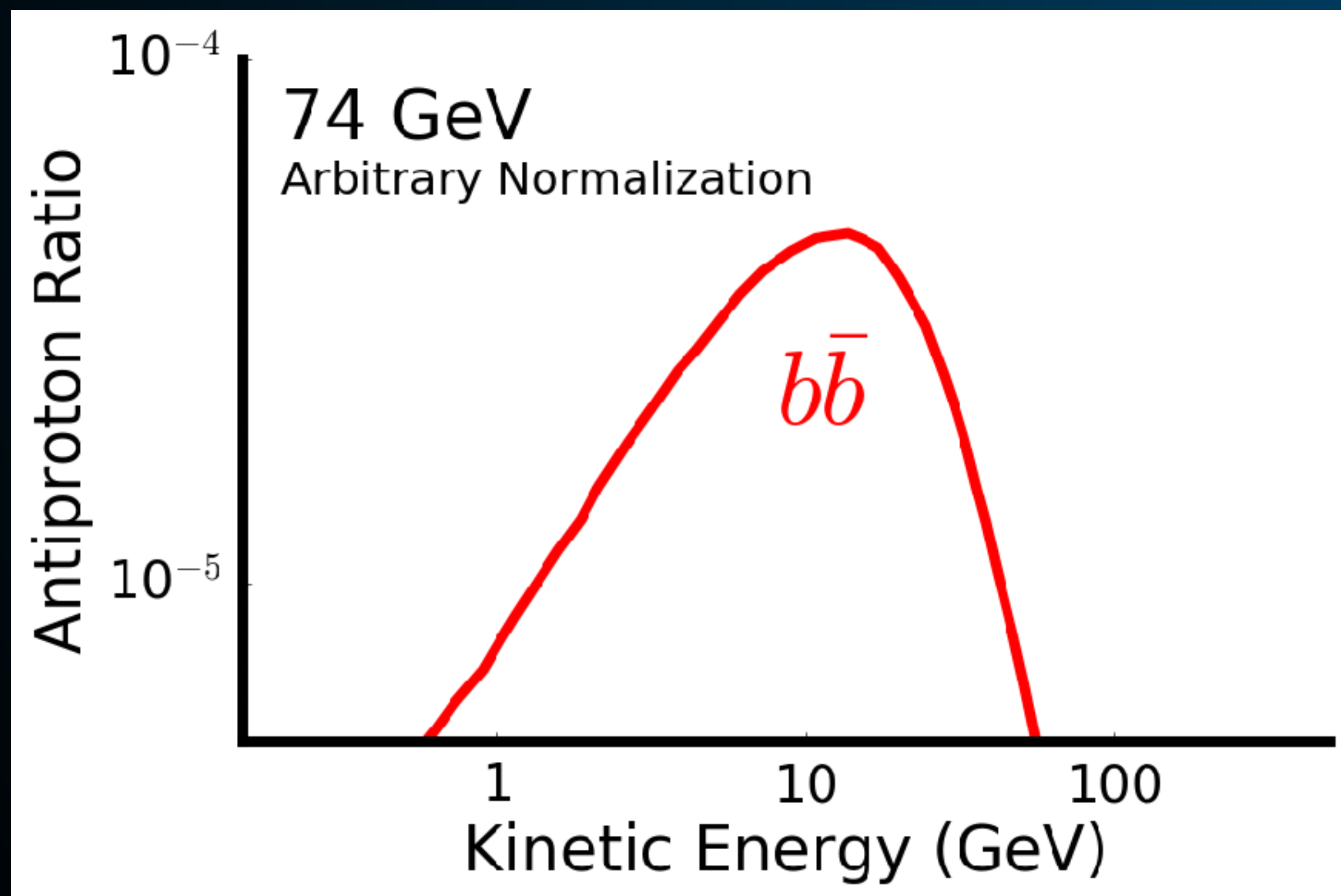
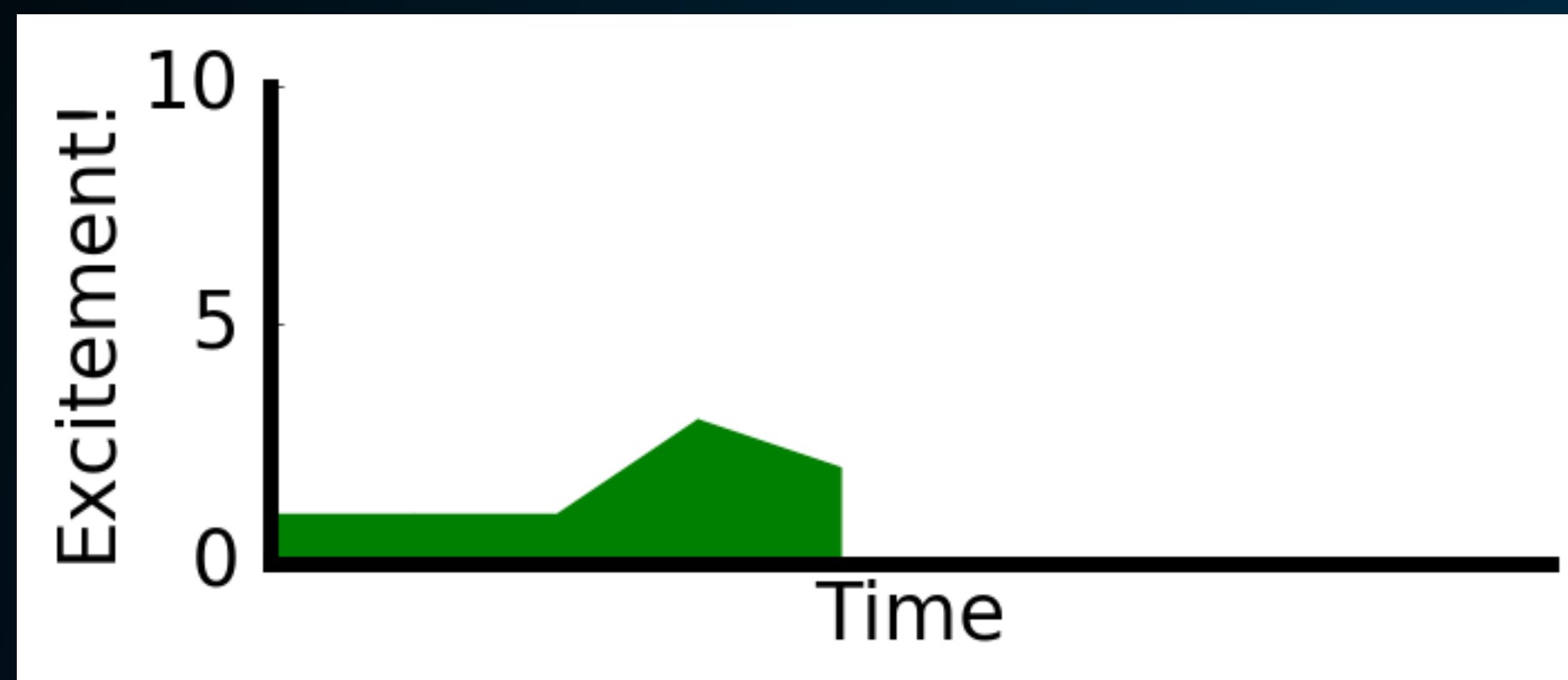
The Antiproton Excess



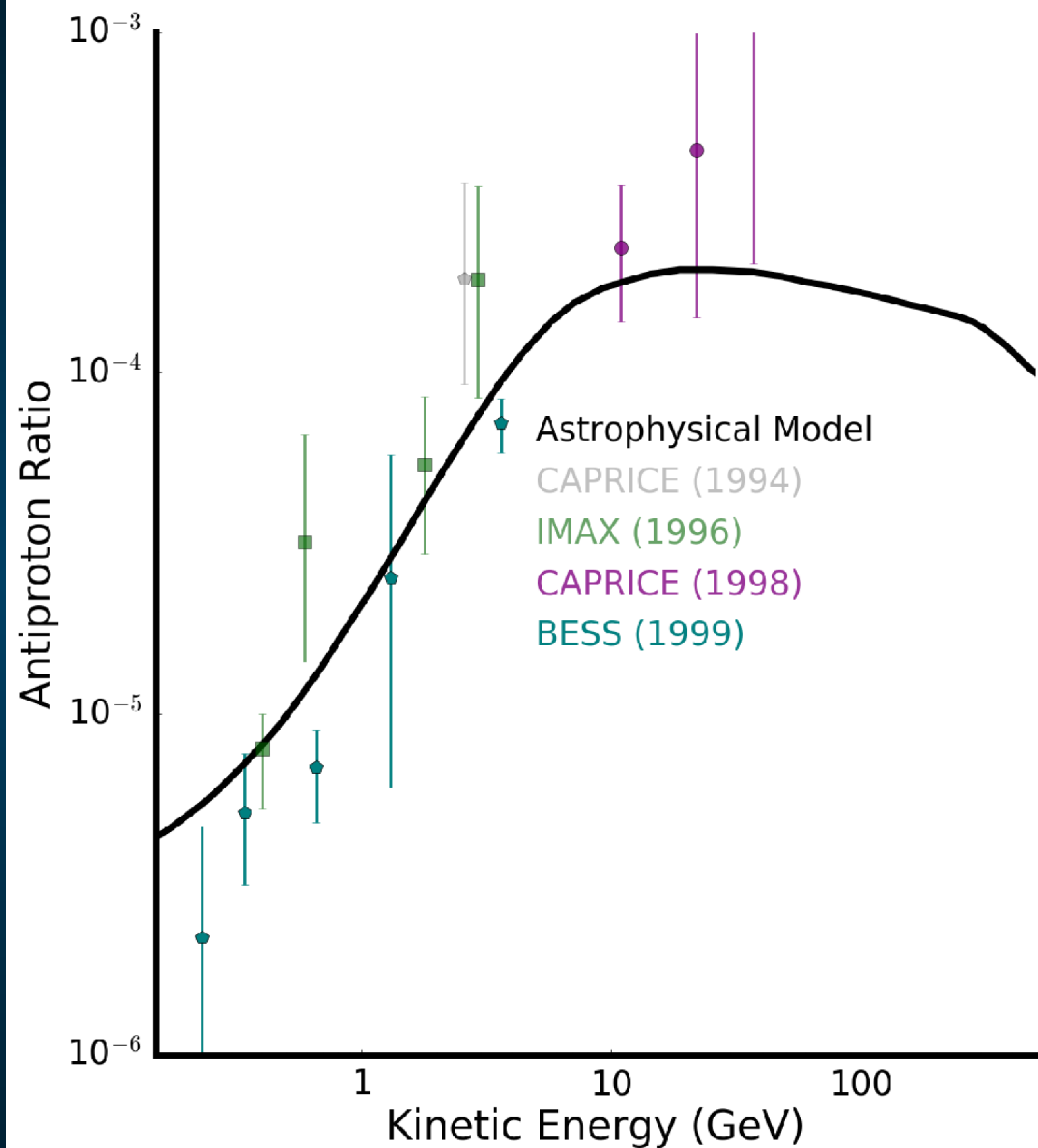
(Not an exhaustive list of observations)



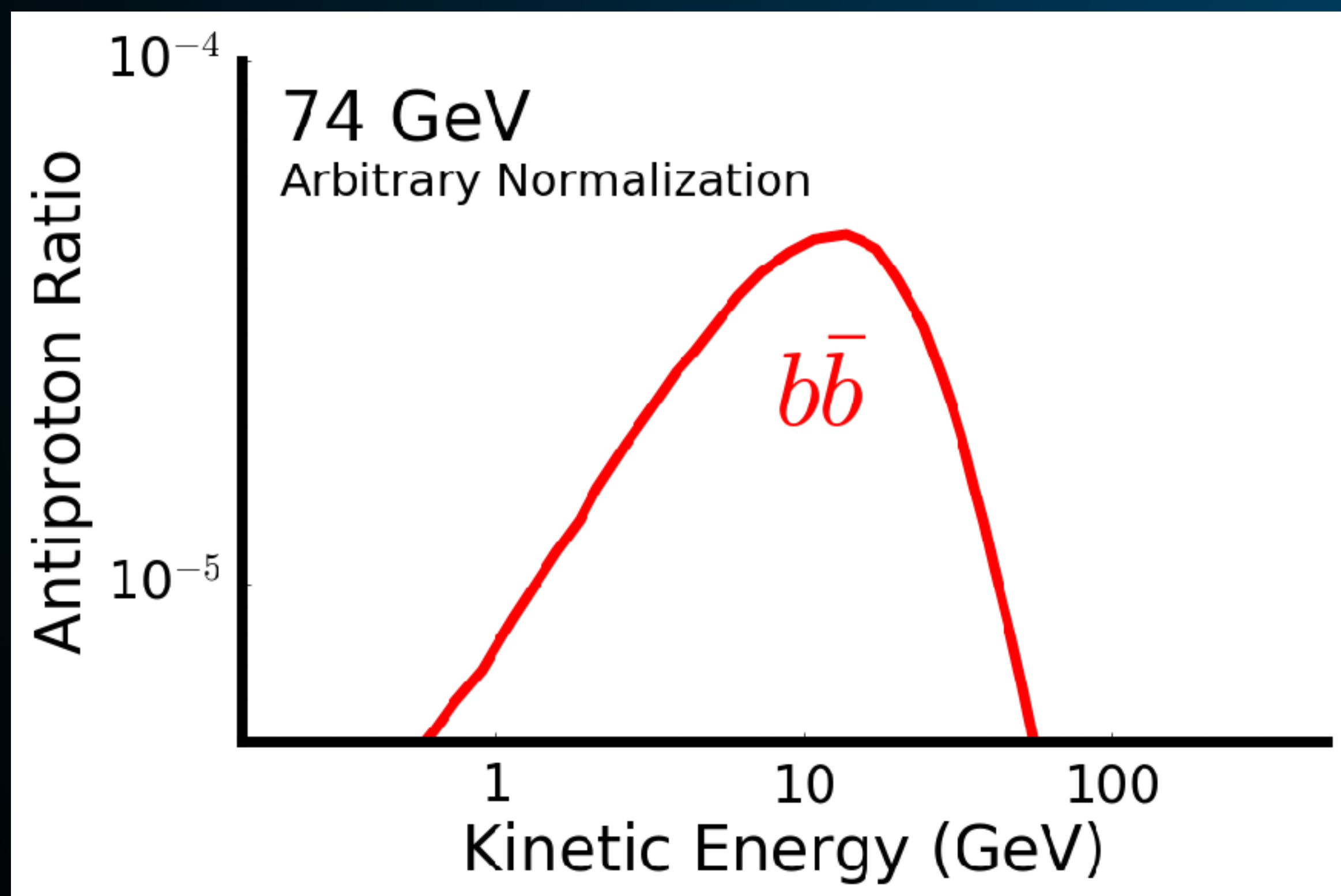
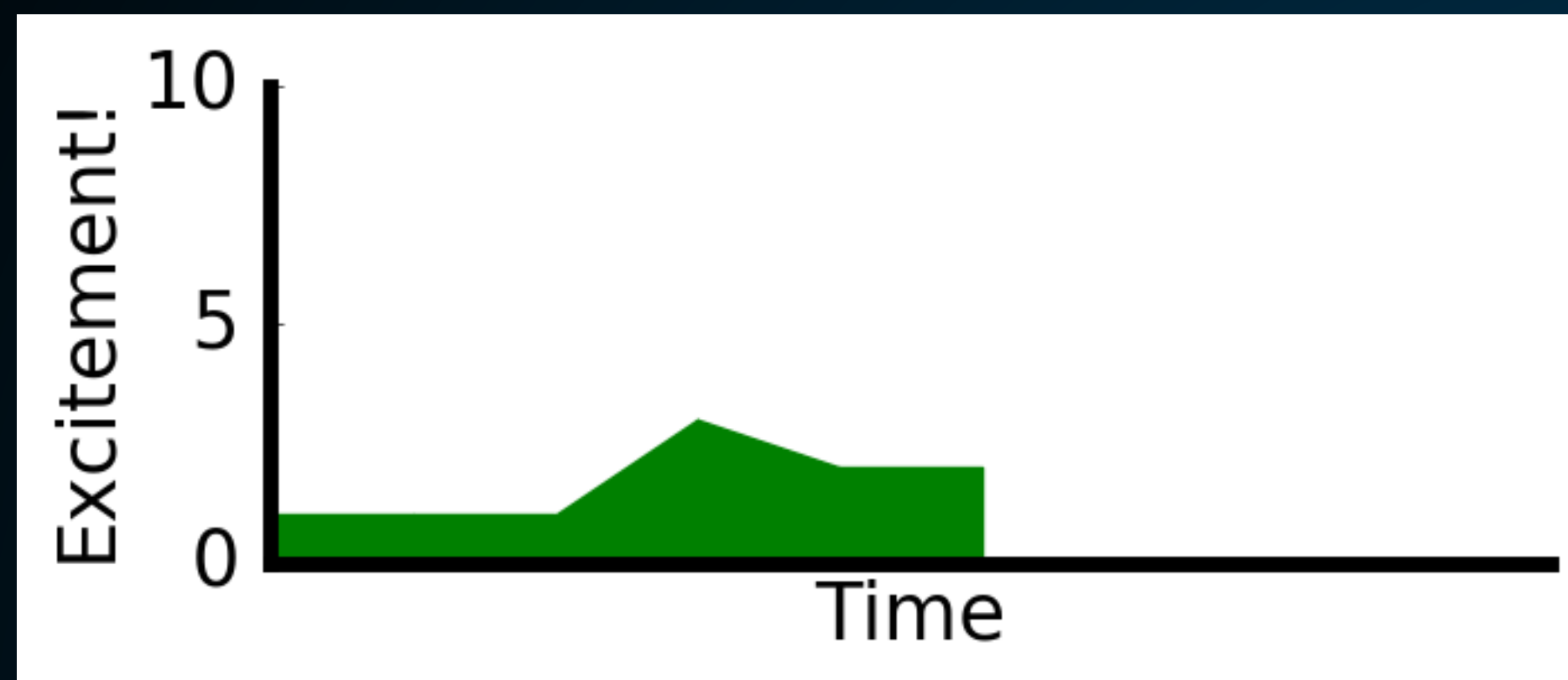
The Antiproton Excess



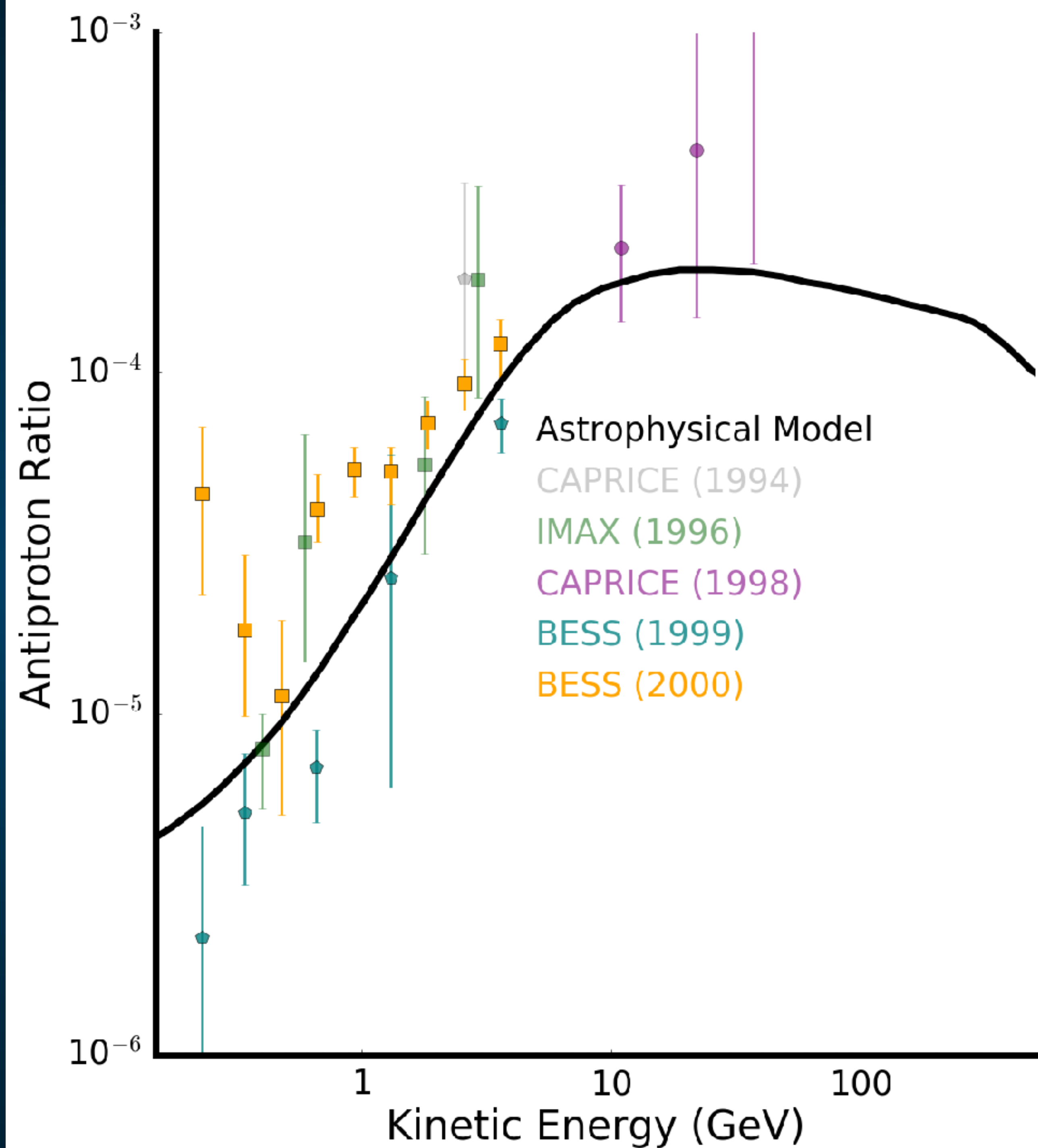
(Not an exhaustive list of observations)



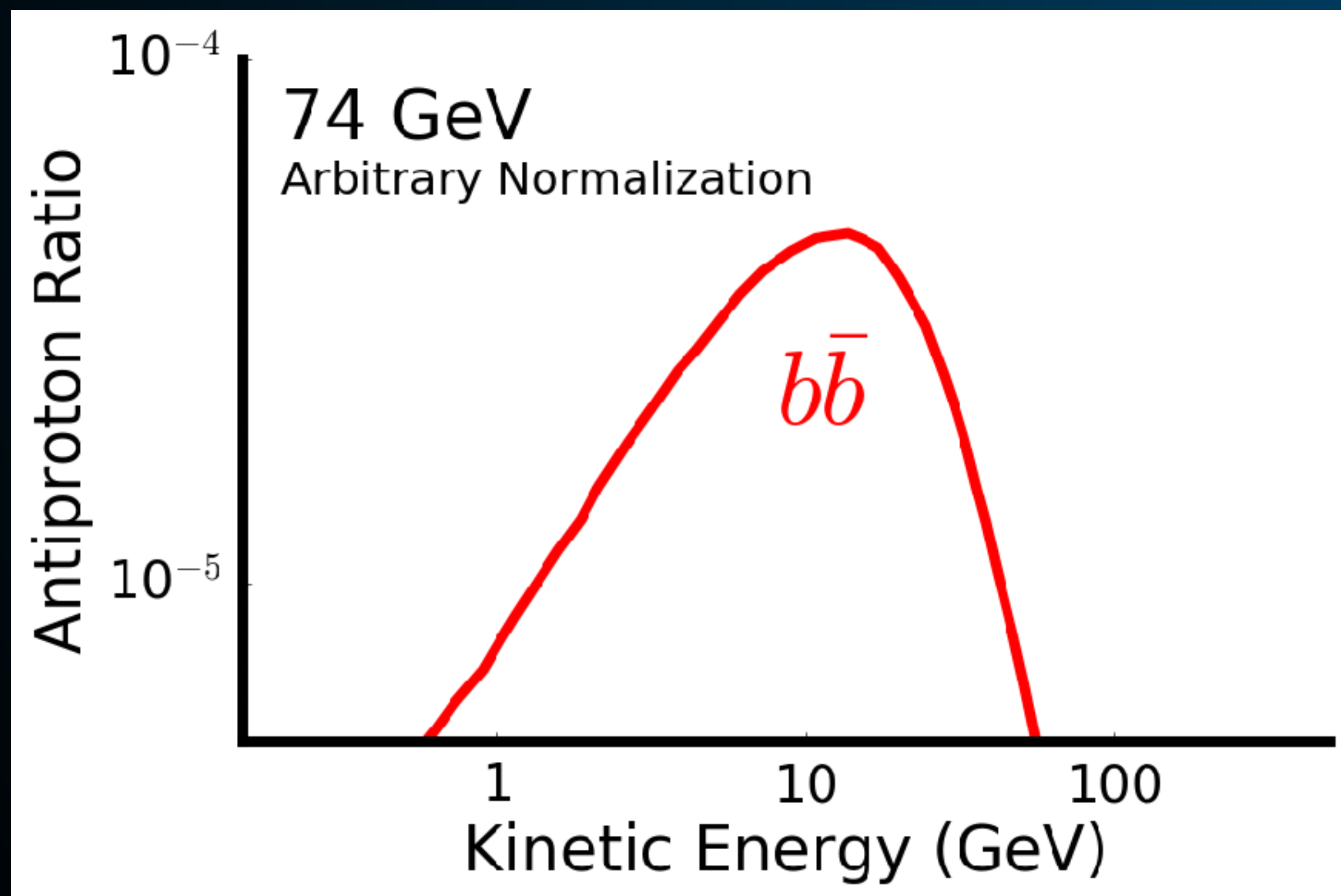
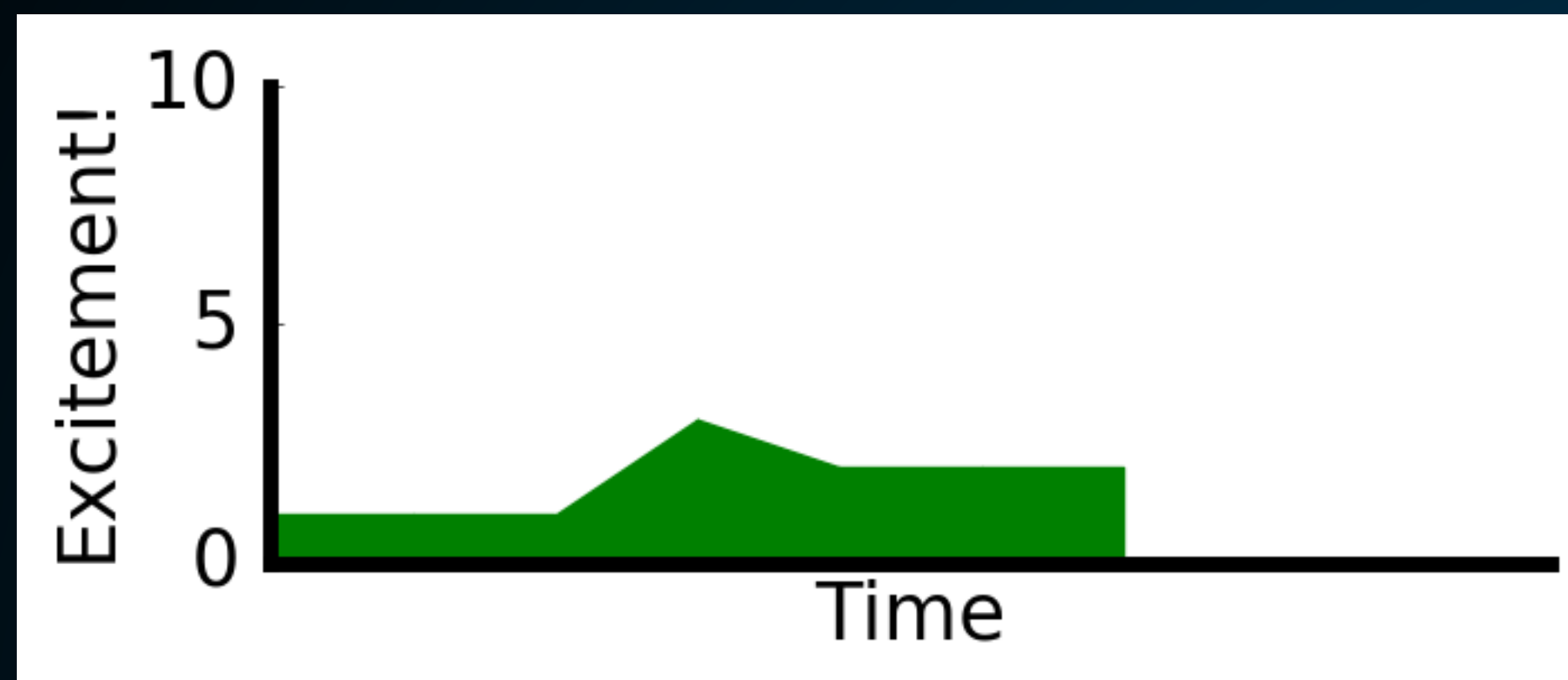
The Antiproton Excess



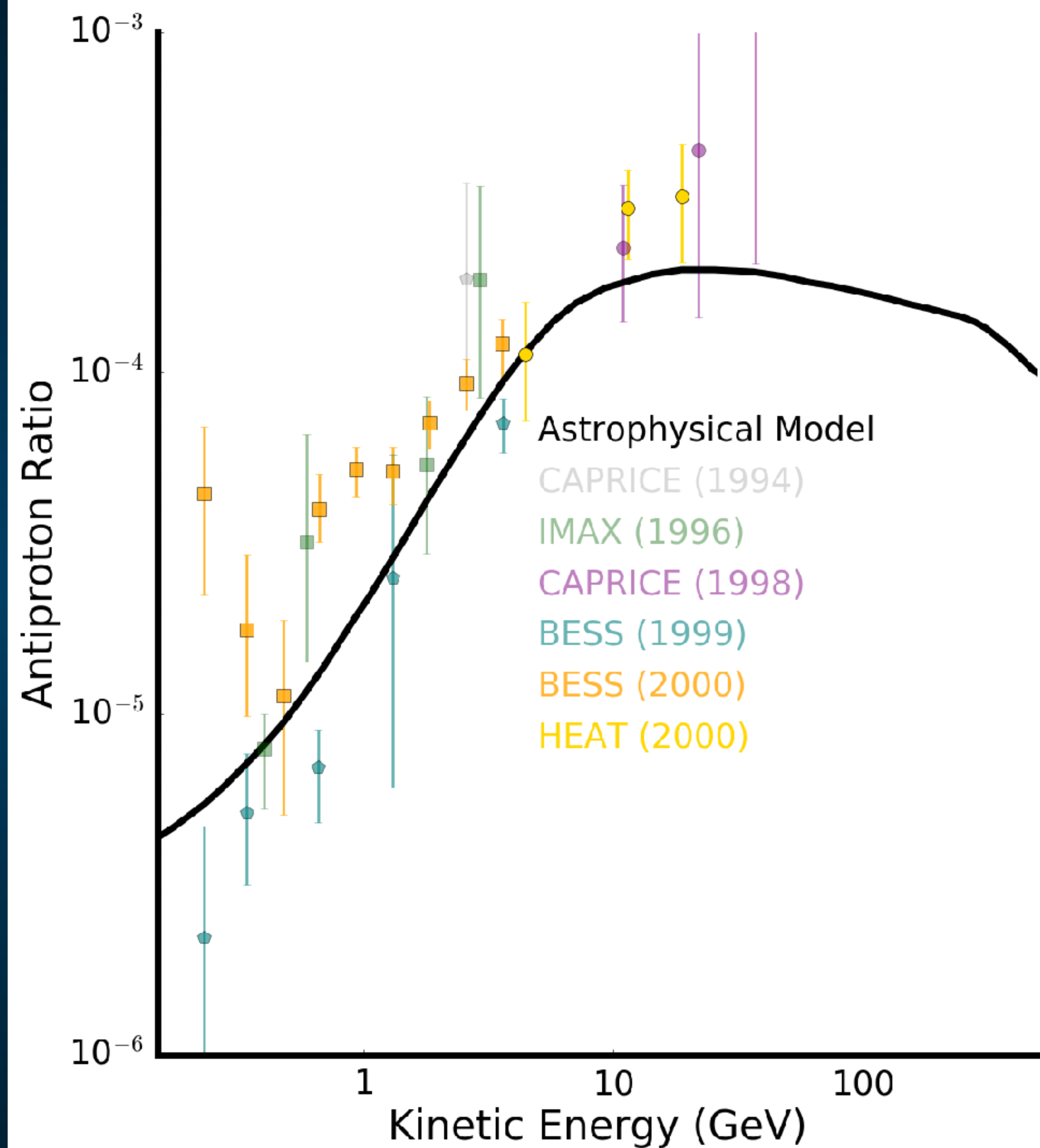
(Not an exhaustive list of observations)



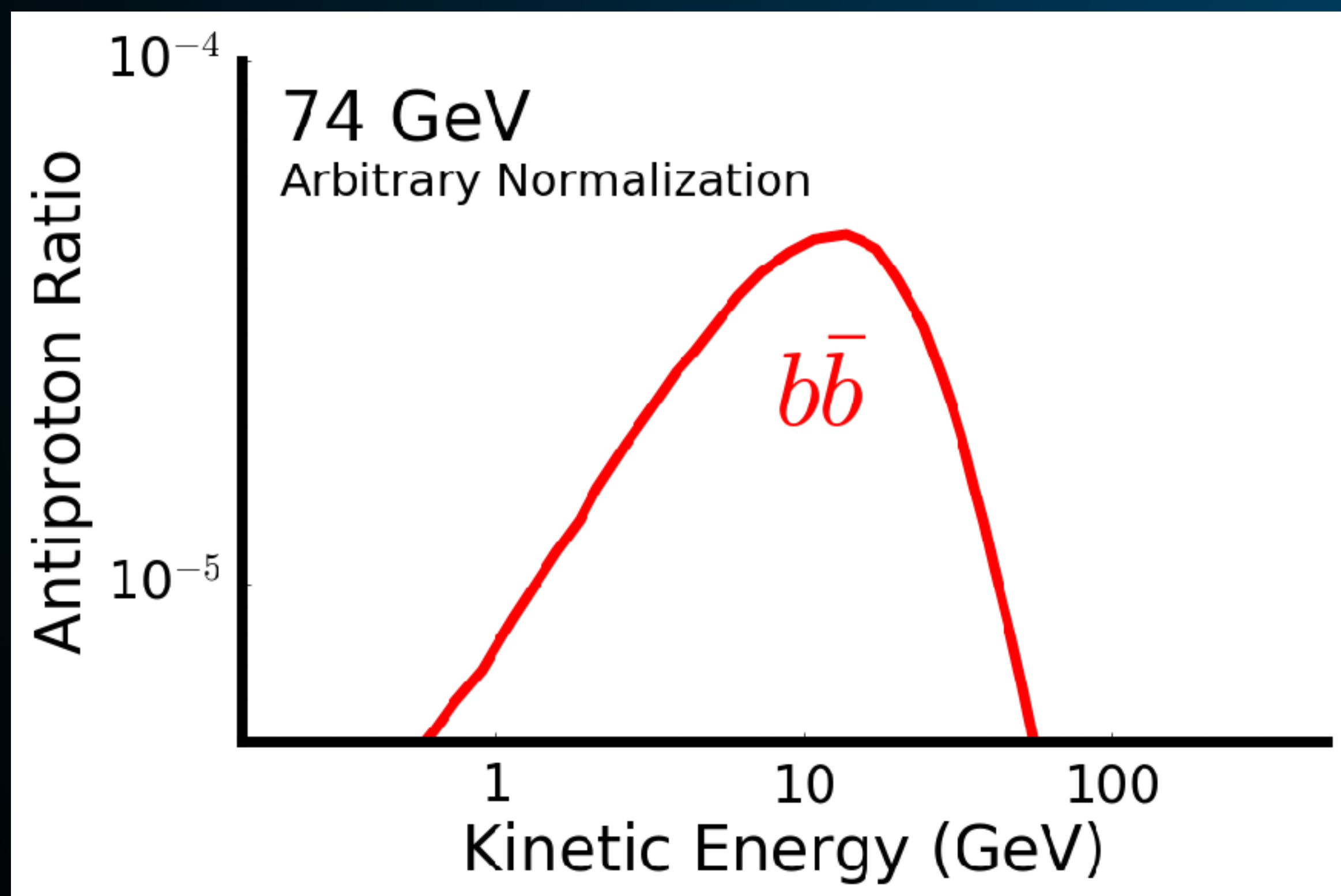
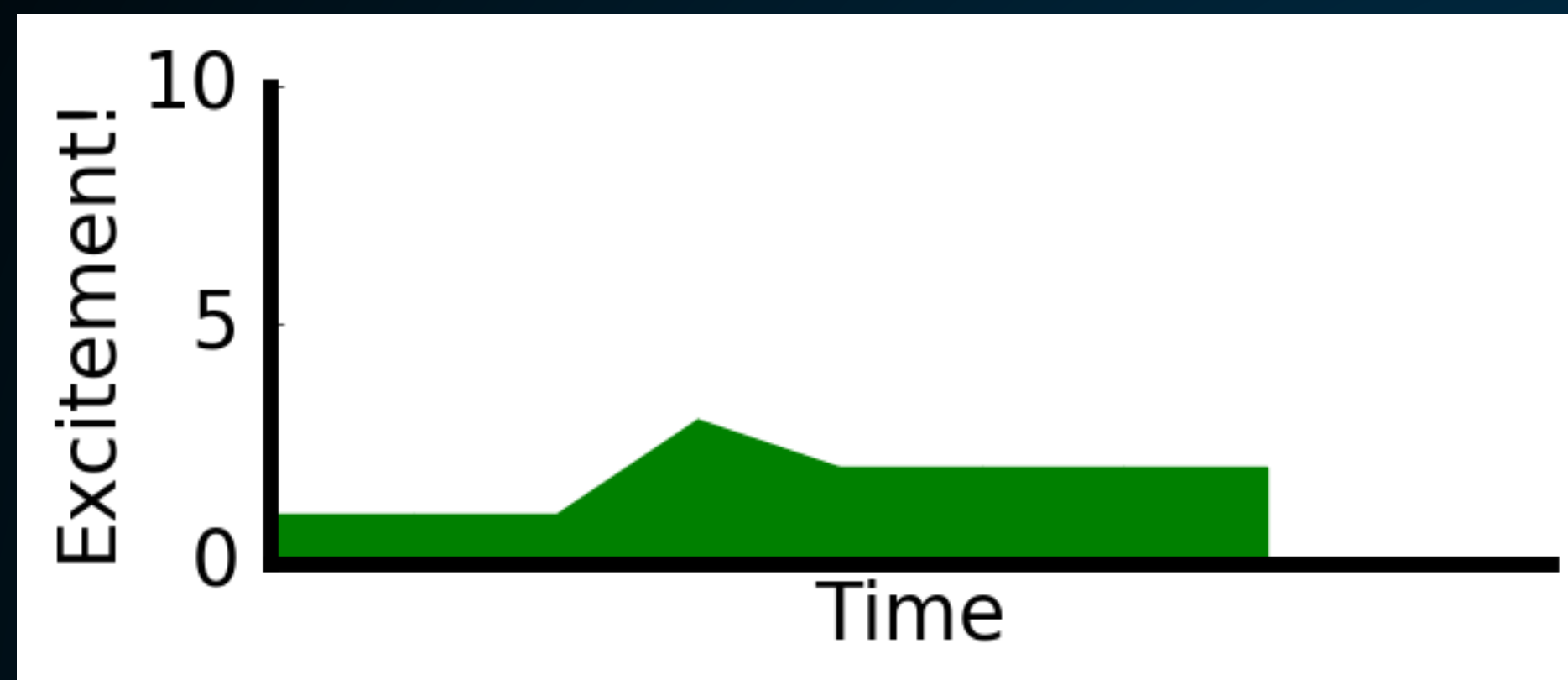
The Antiproton Excess



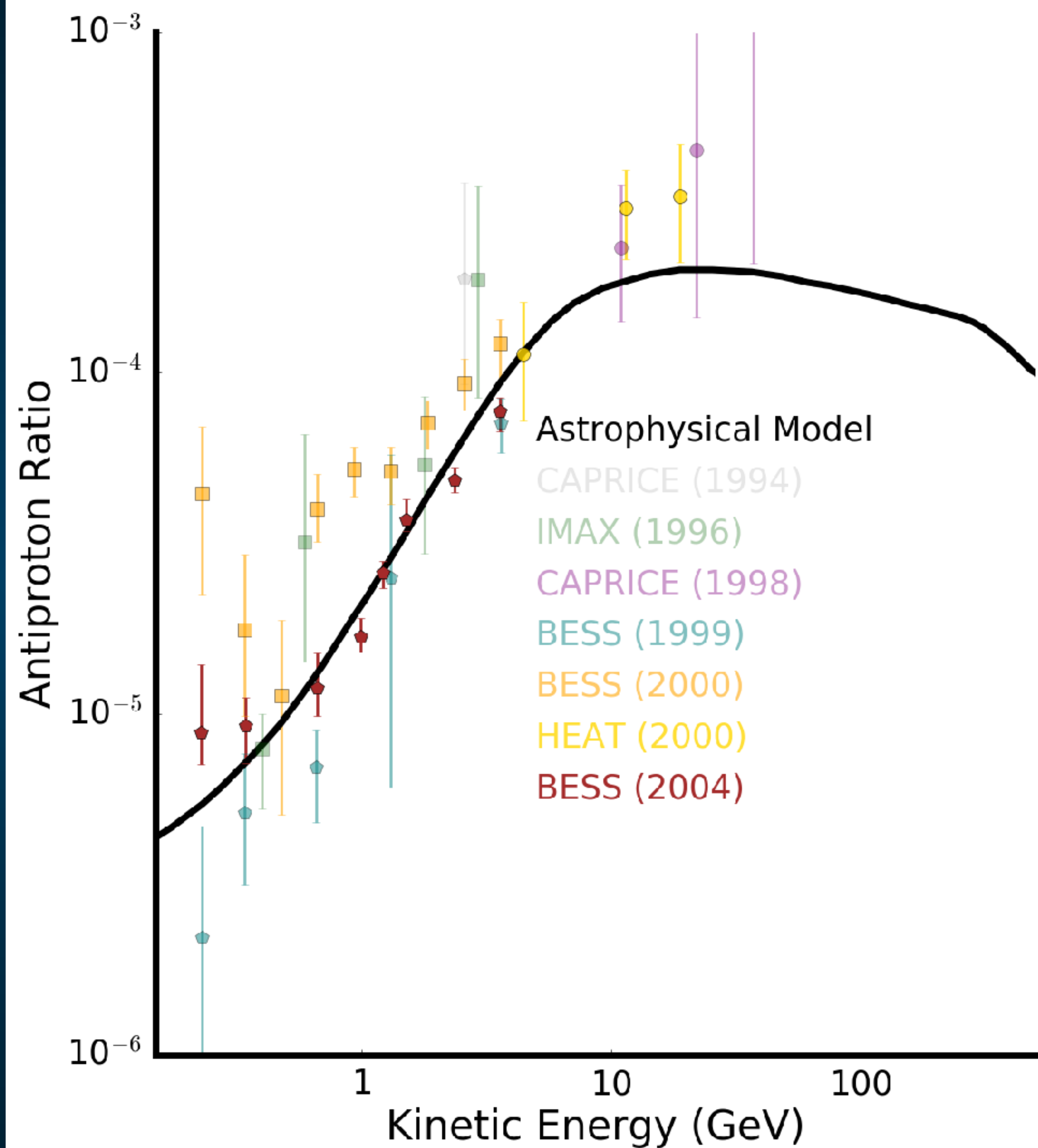
(Not an exhaustive list of observations)



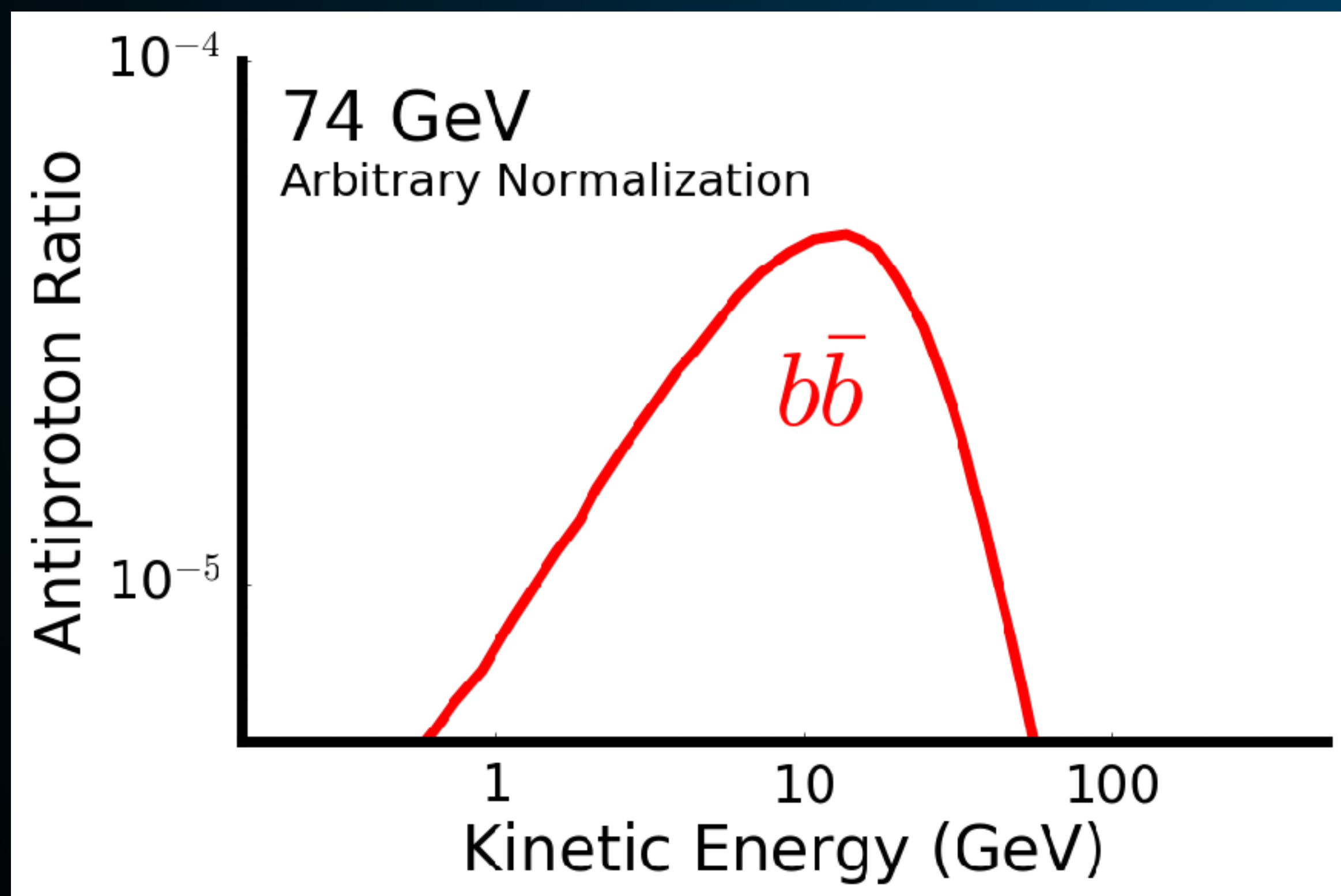
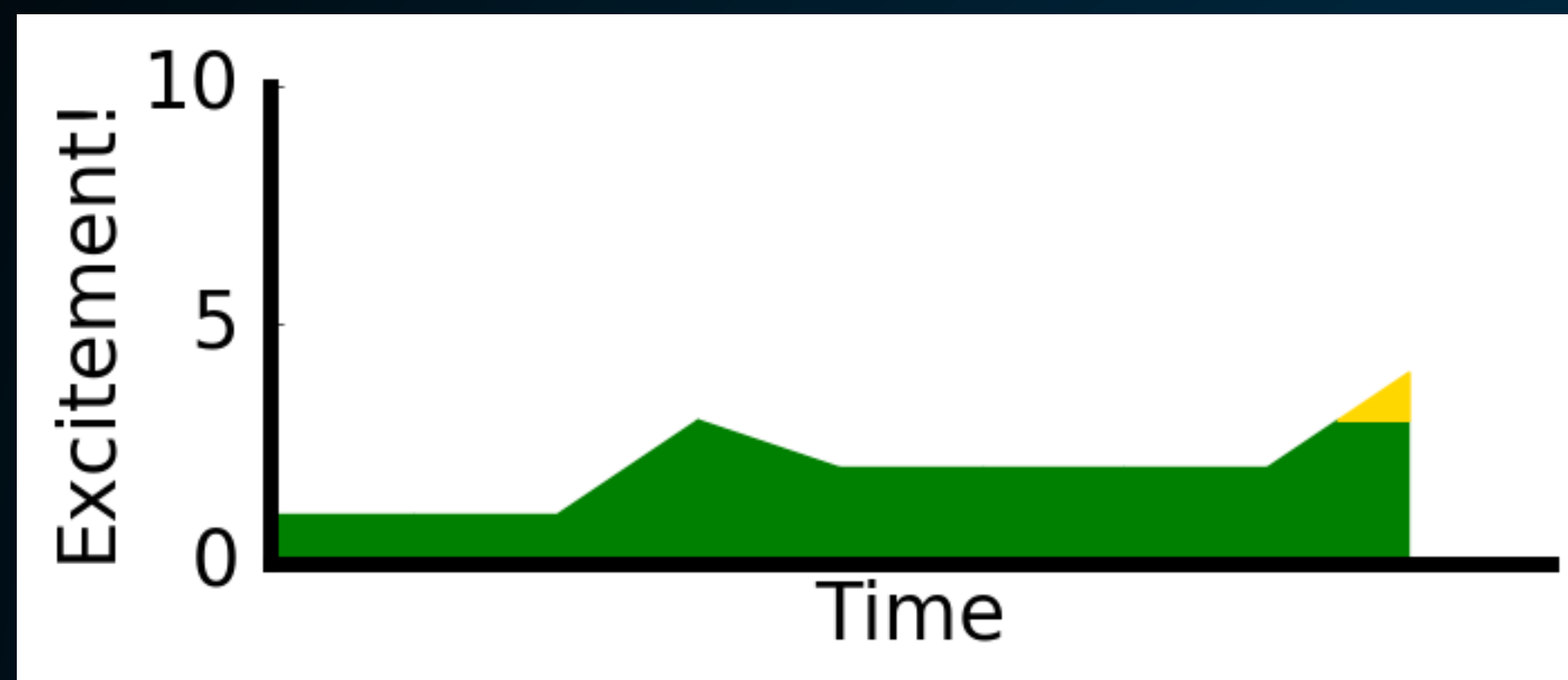
The Antiproton Excess



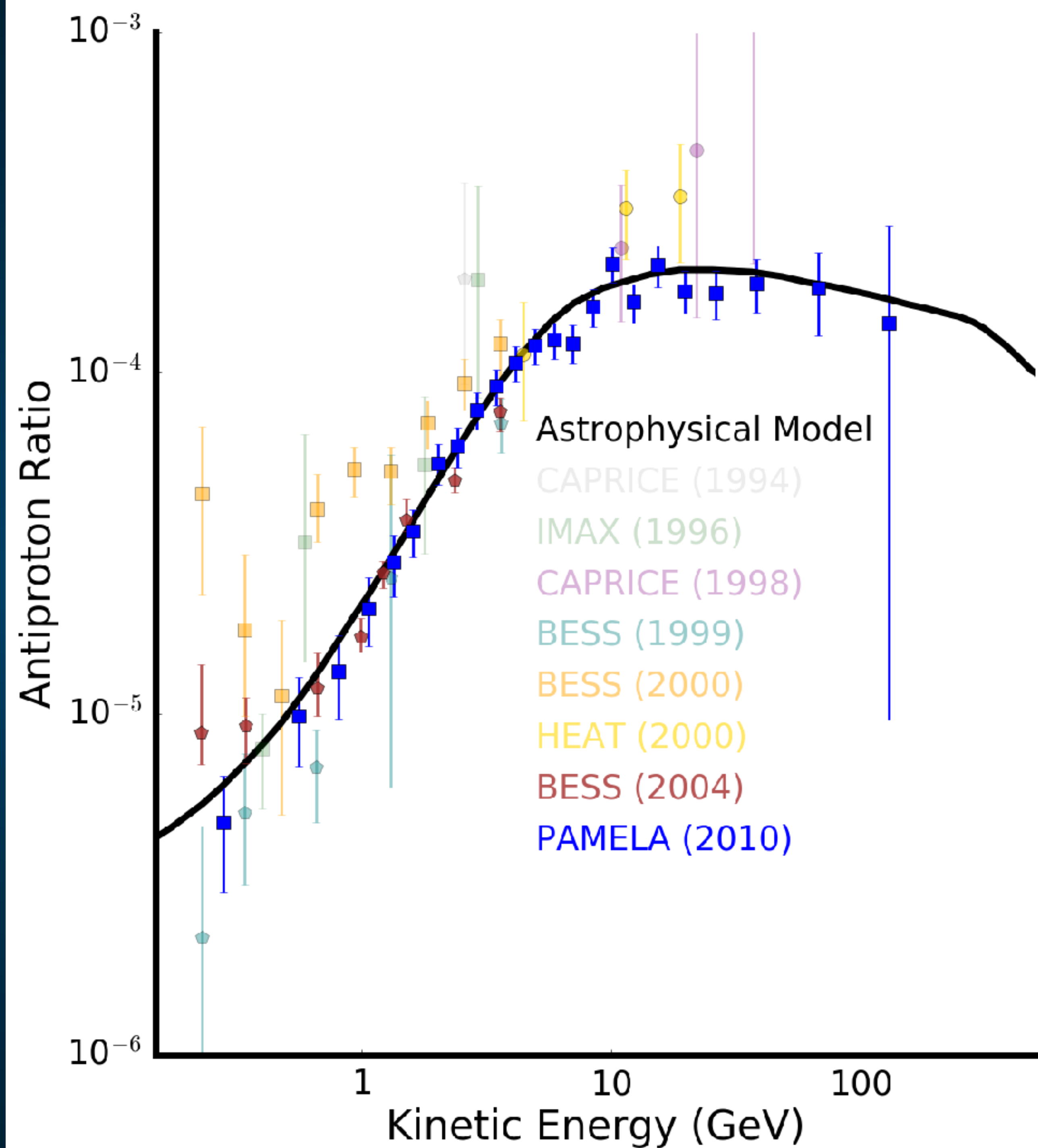
(Not an exhaustive list of observations)



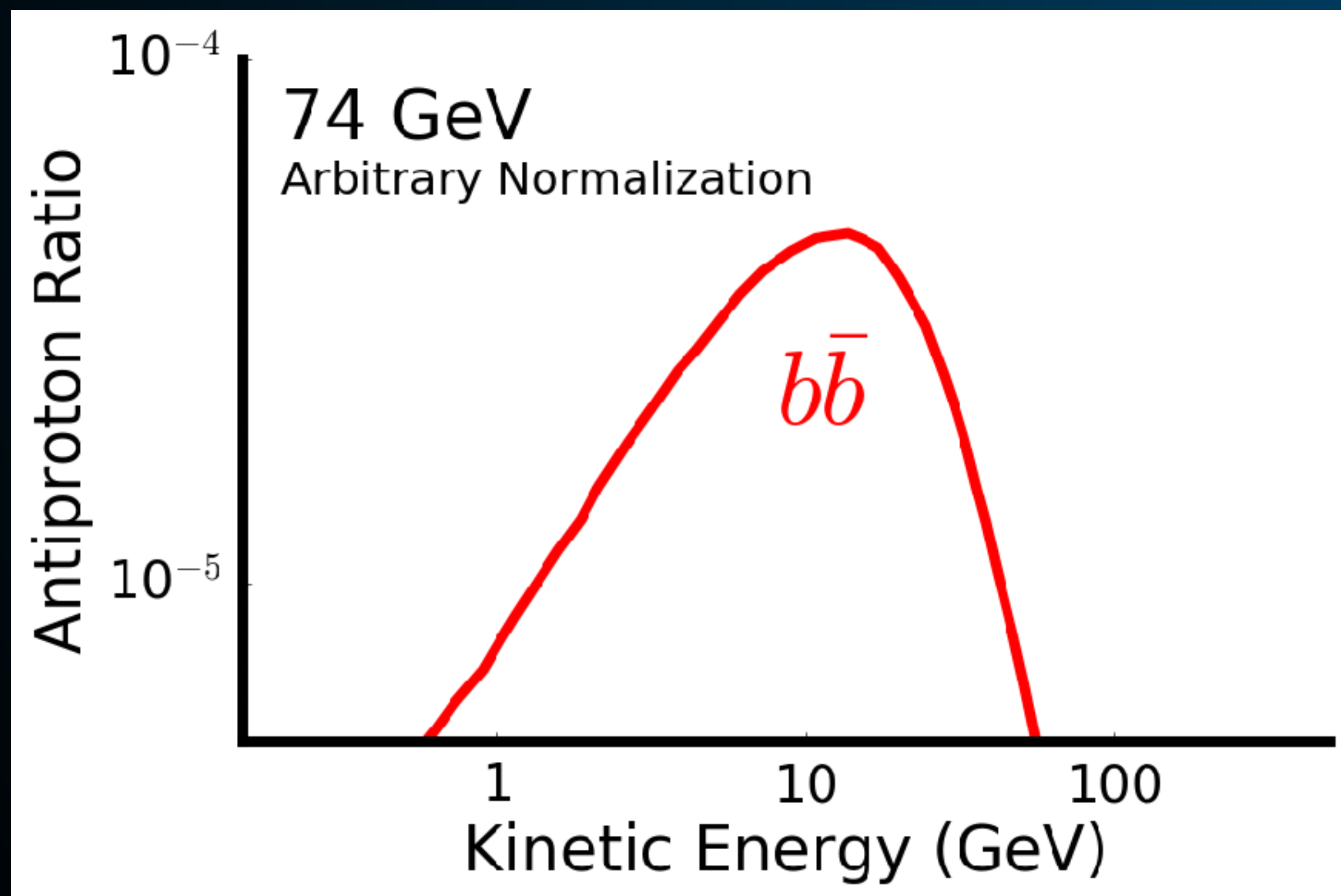
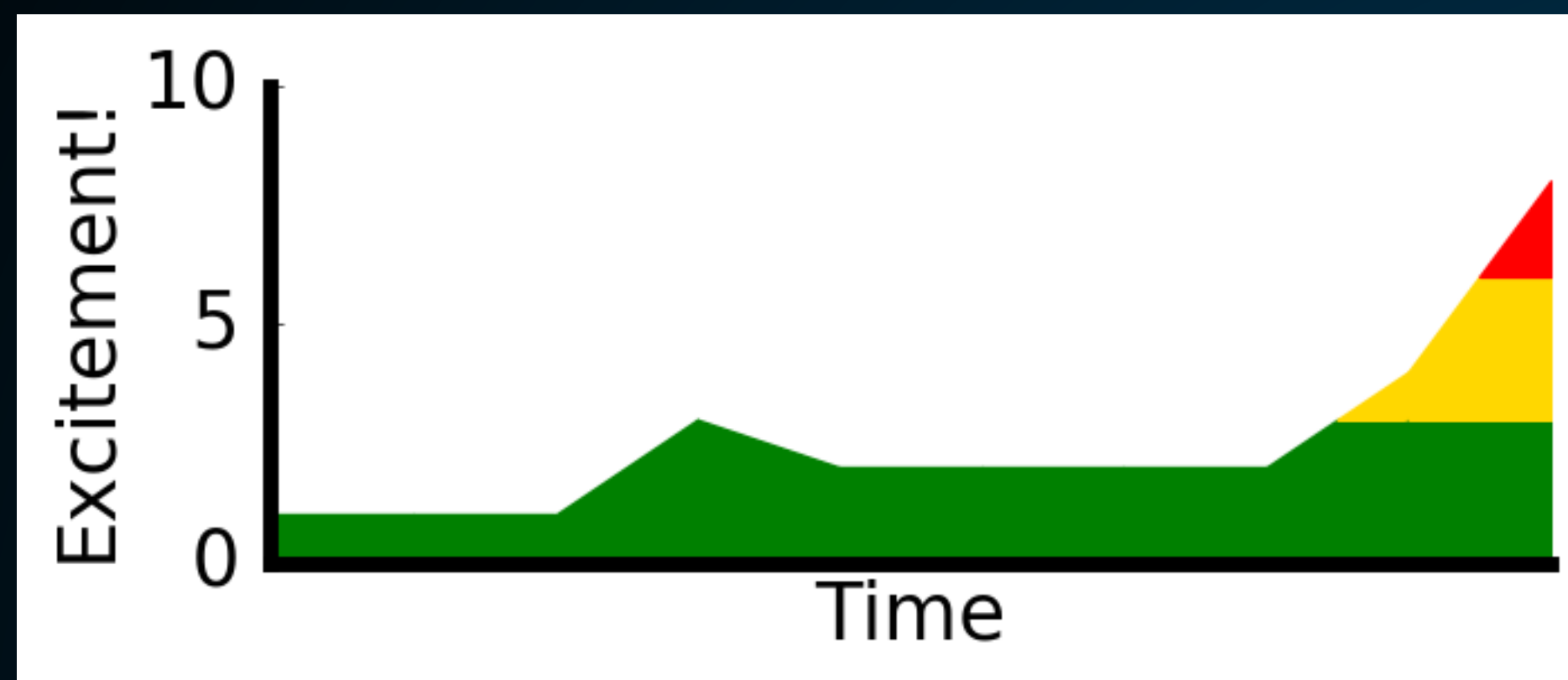
The Antiproton Excess



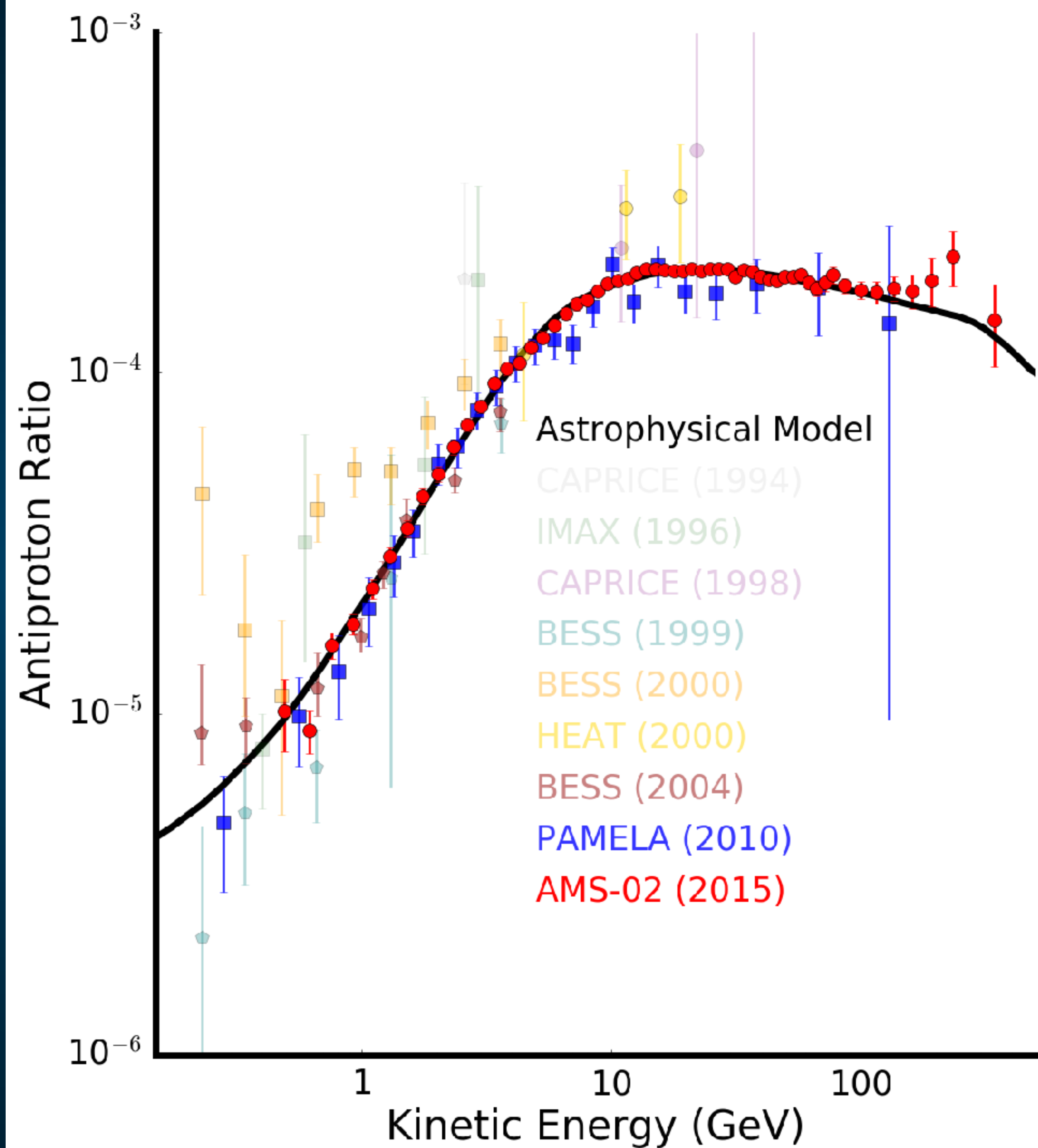
(Not an exhaustive list of observations)



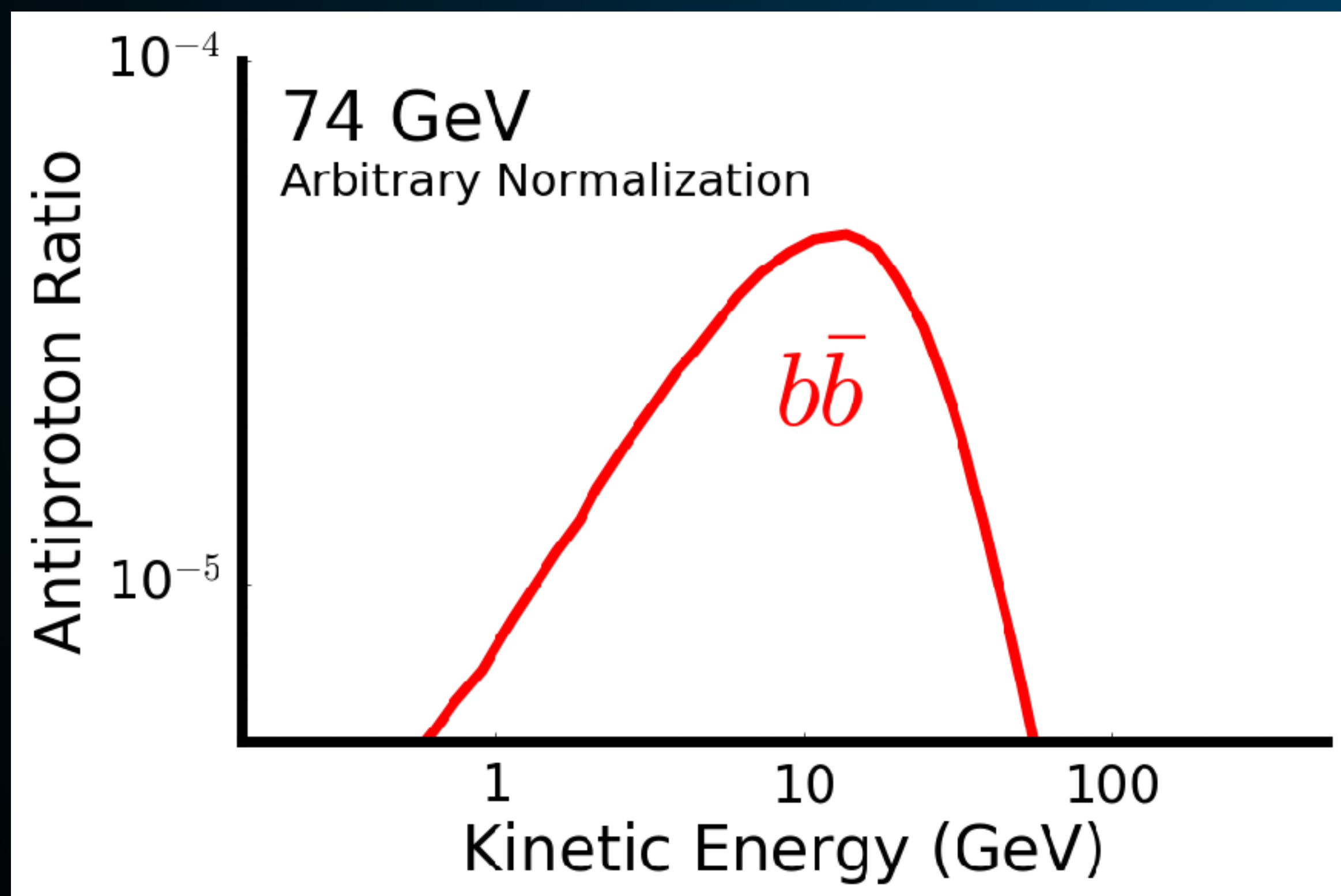
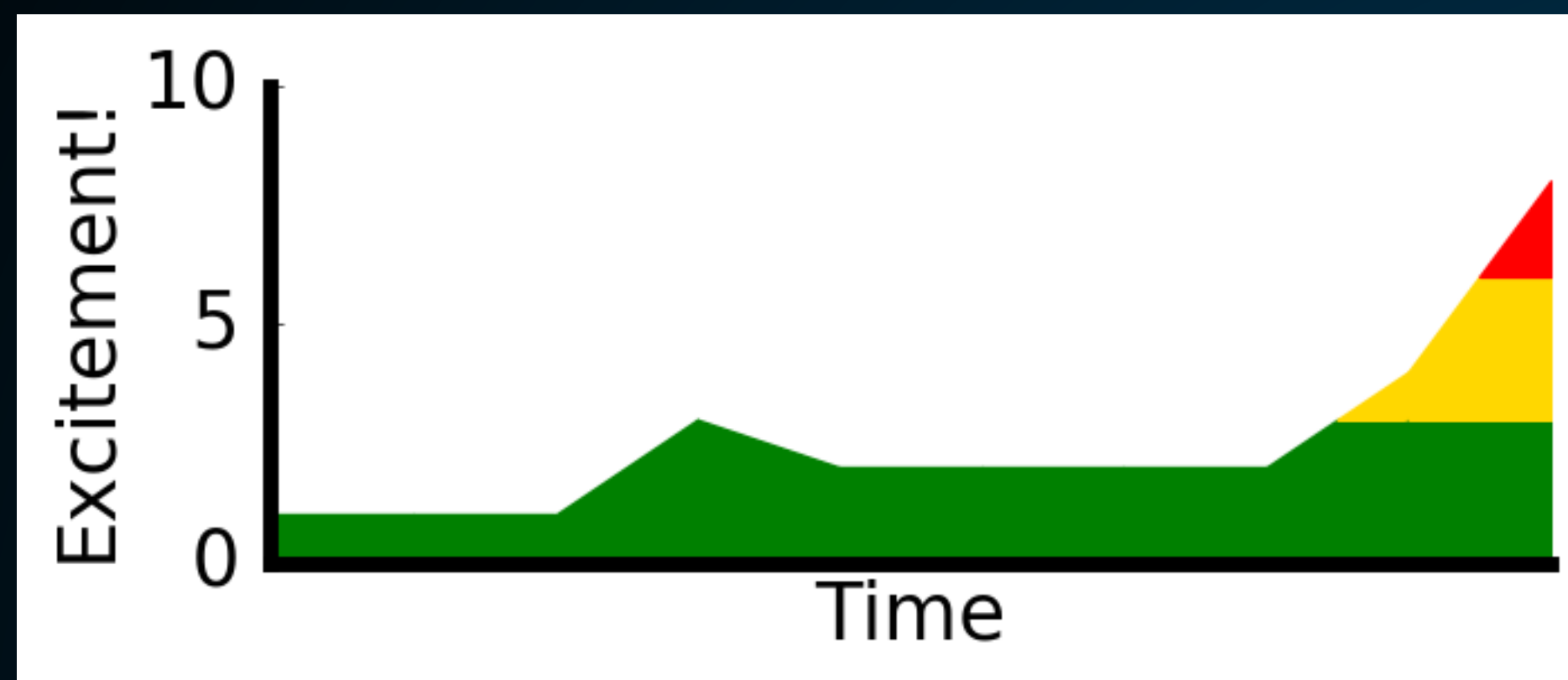
The Antiproton Excess



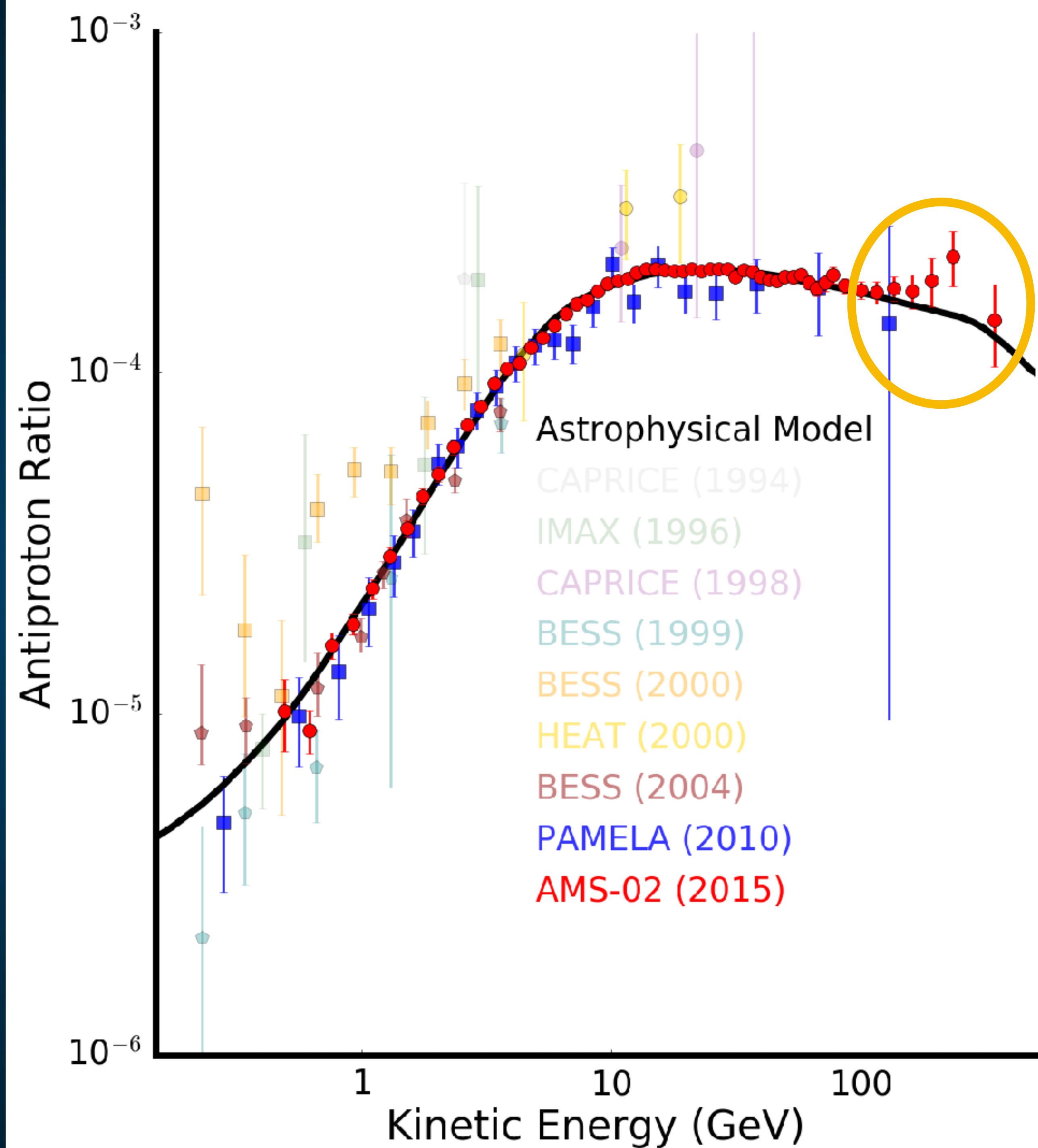
(Not an exhaustive list of observations)



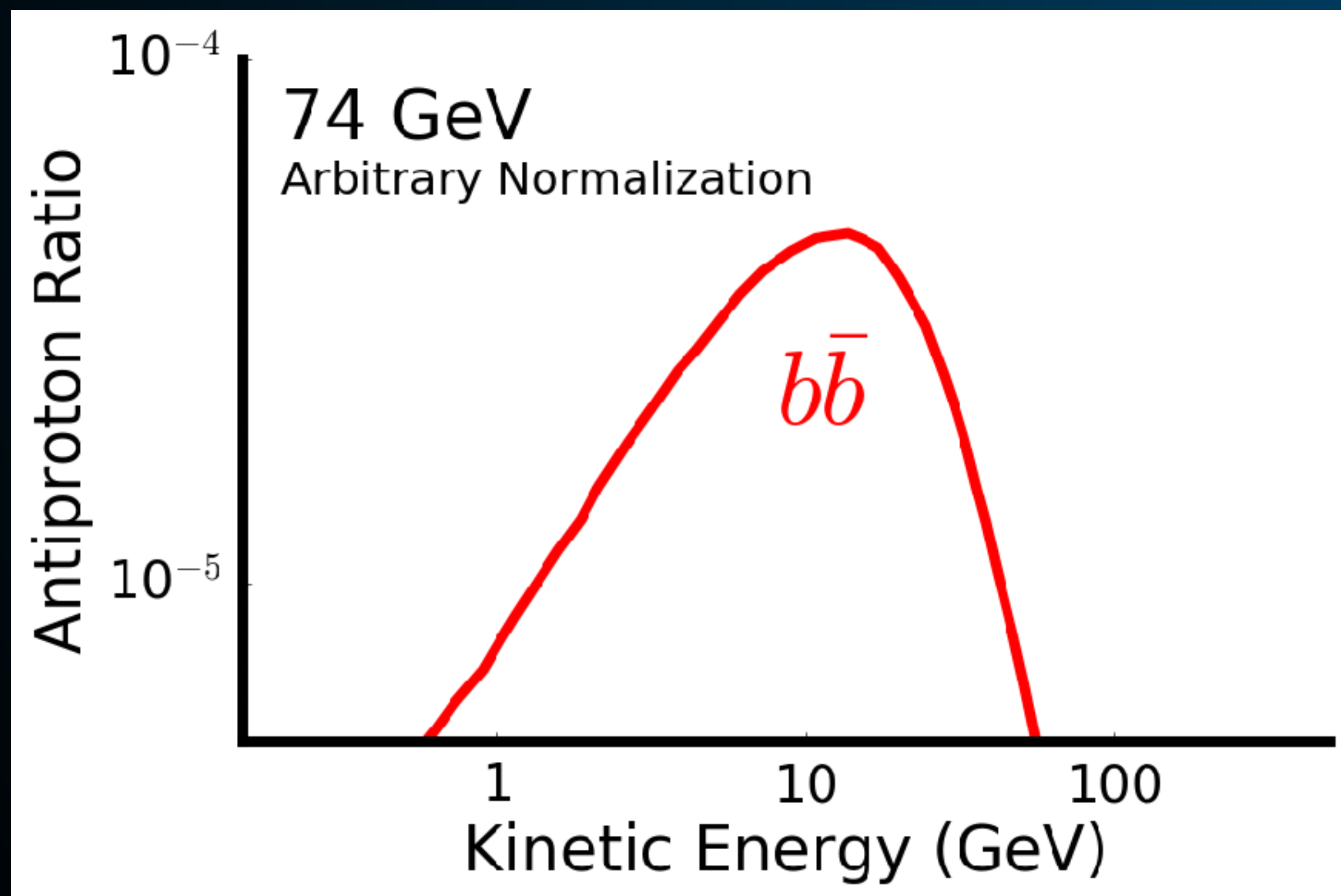
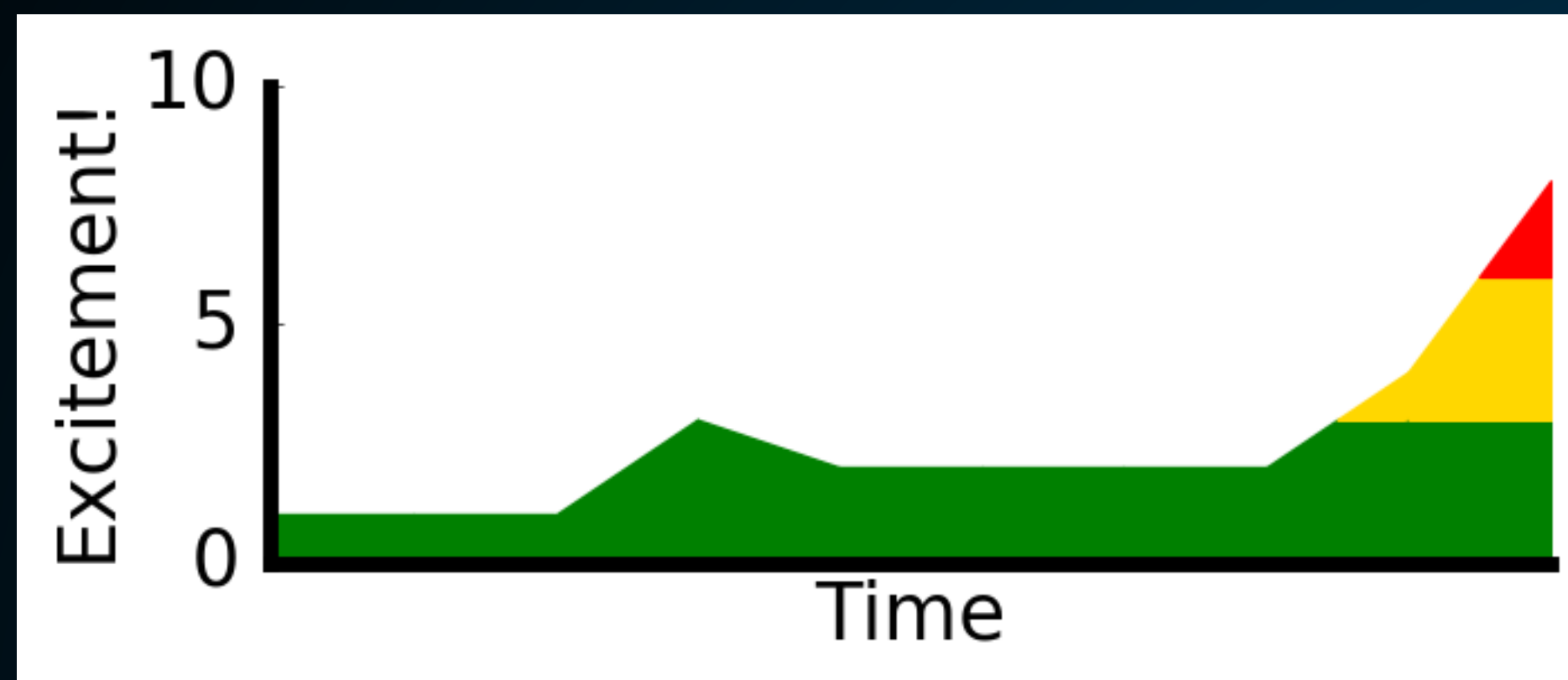
The Antiproton Excess



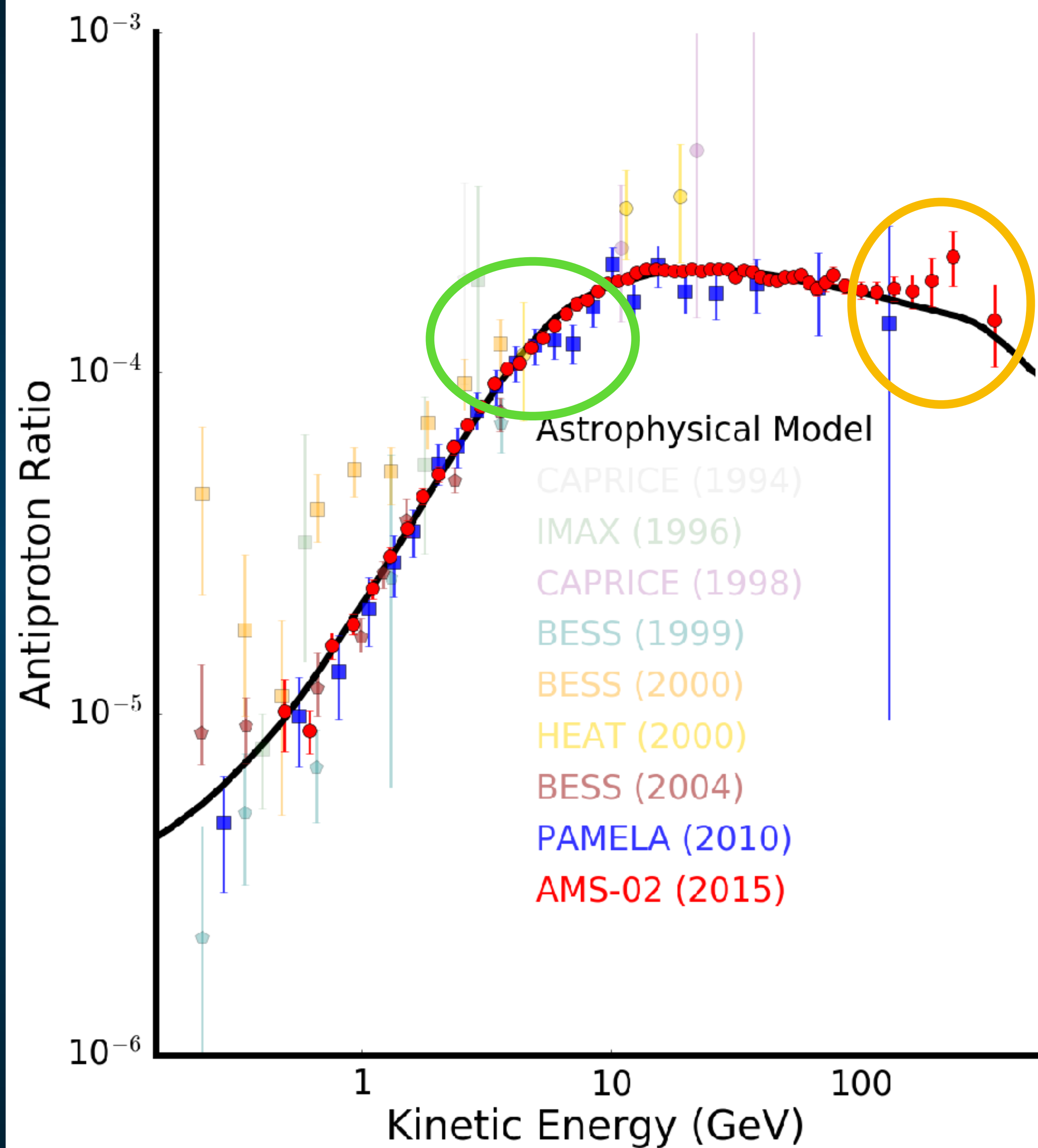
(Not an exhaustive list of observations)



The Antiproton Excess



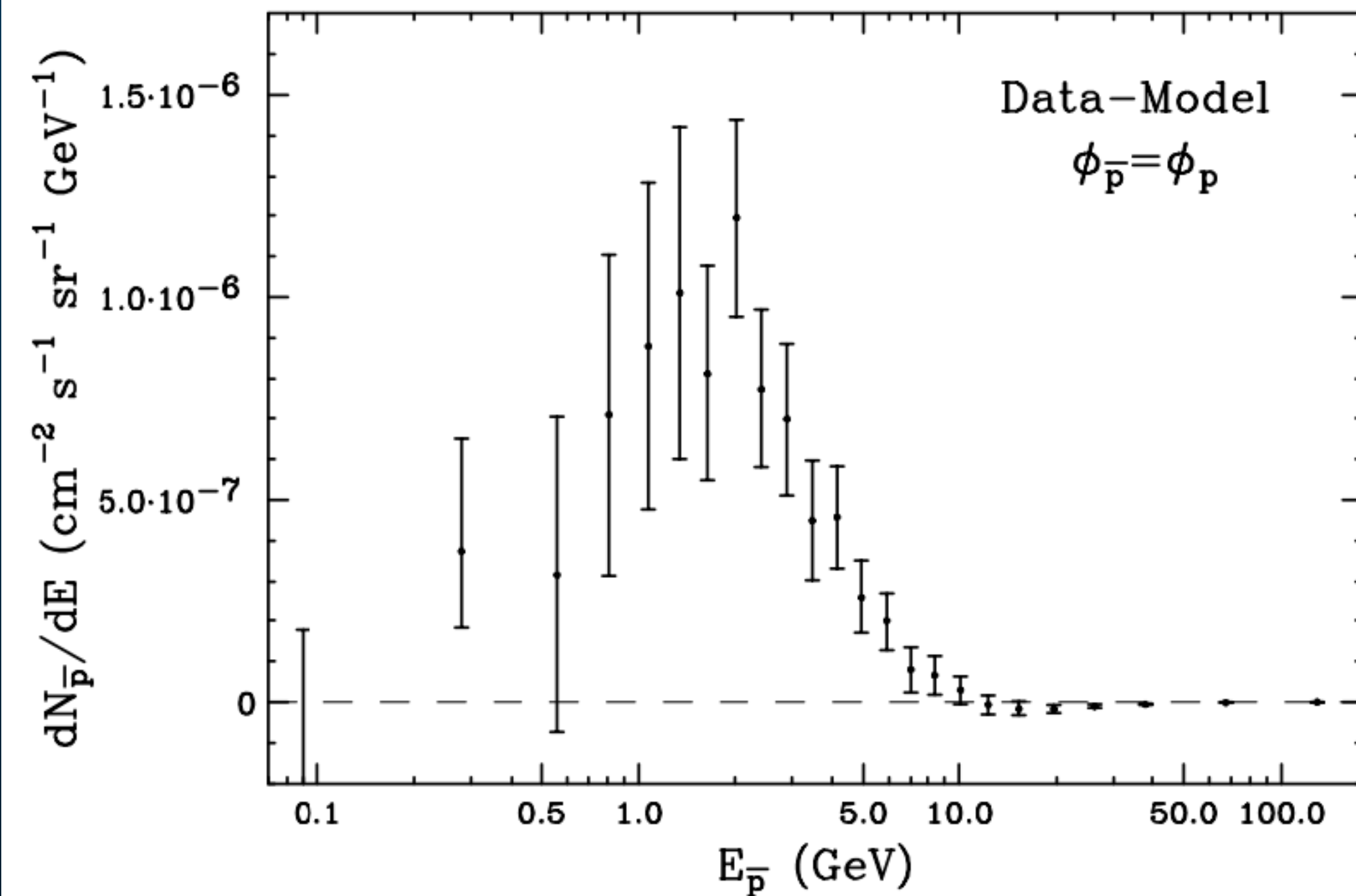
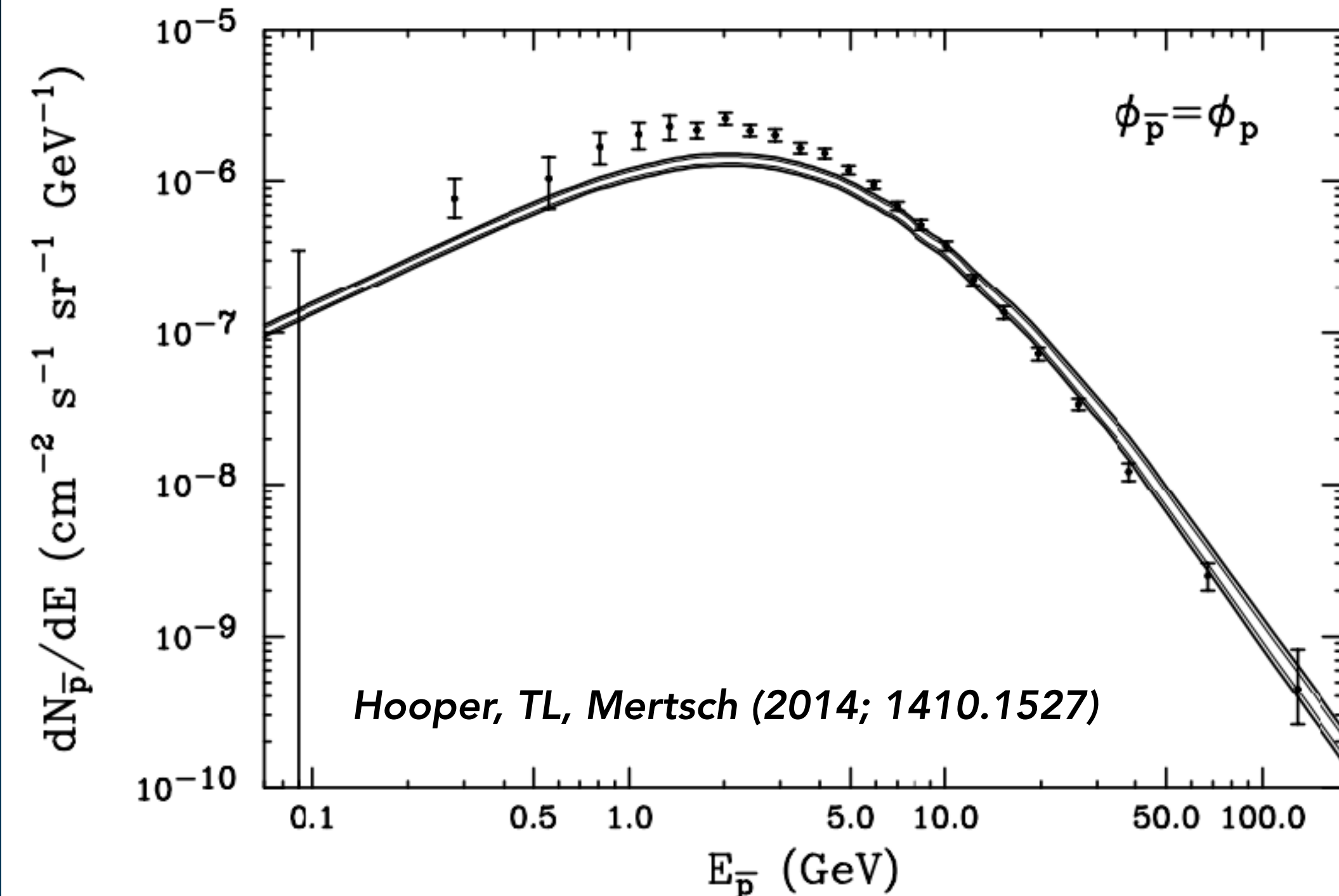
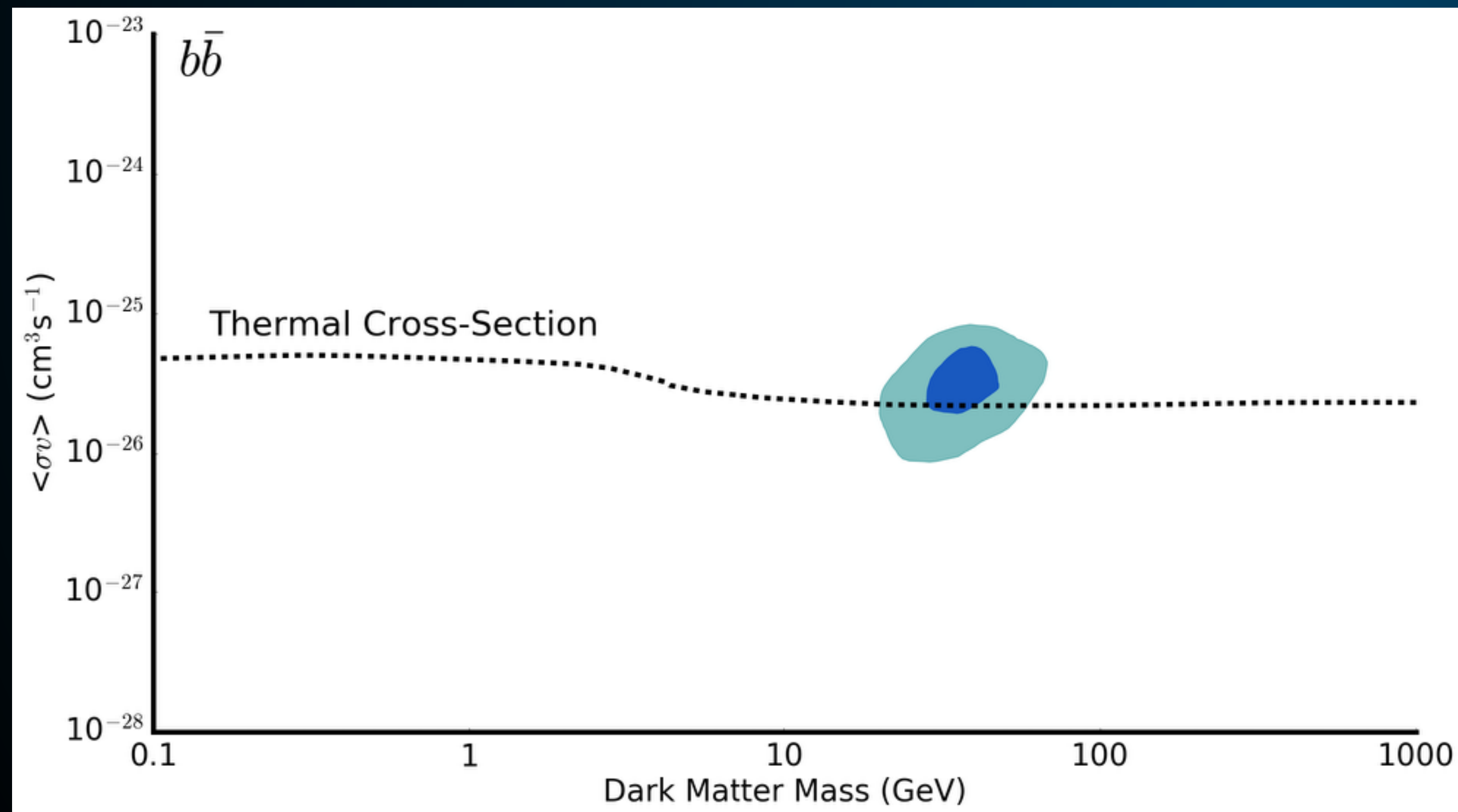
(Not an exhaustive list of observations)



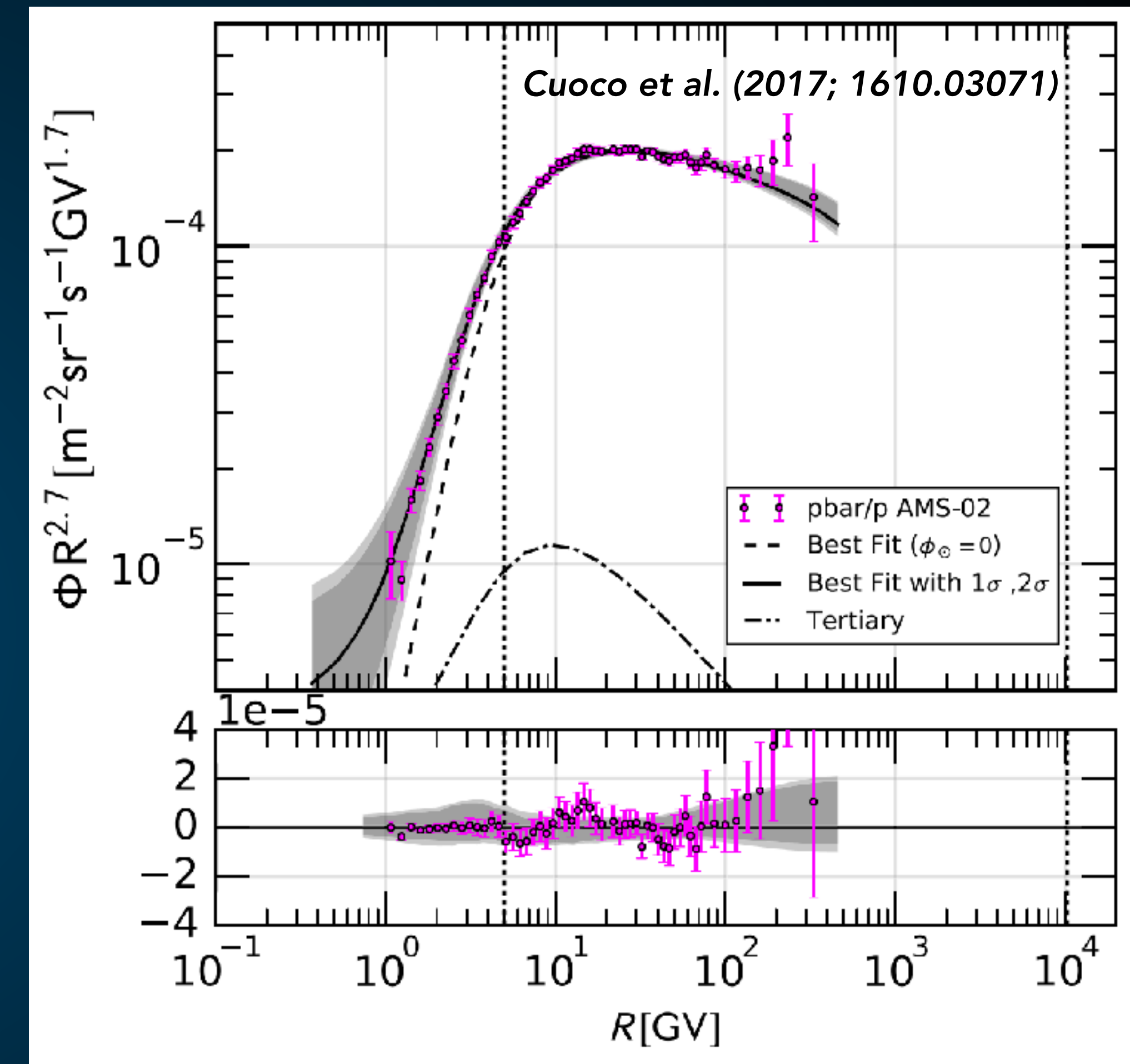
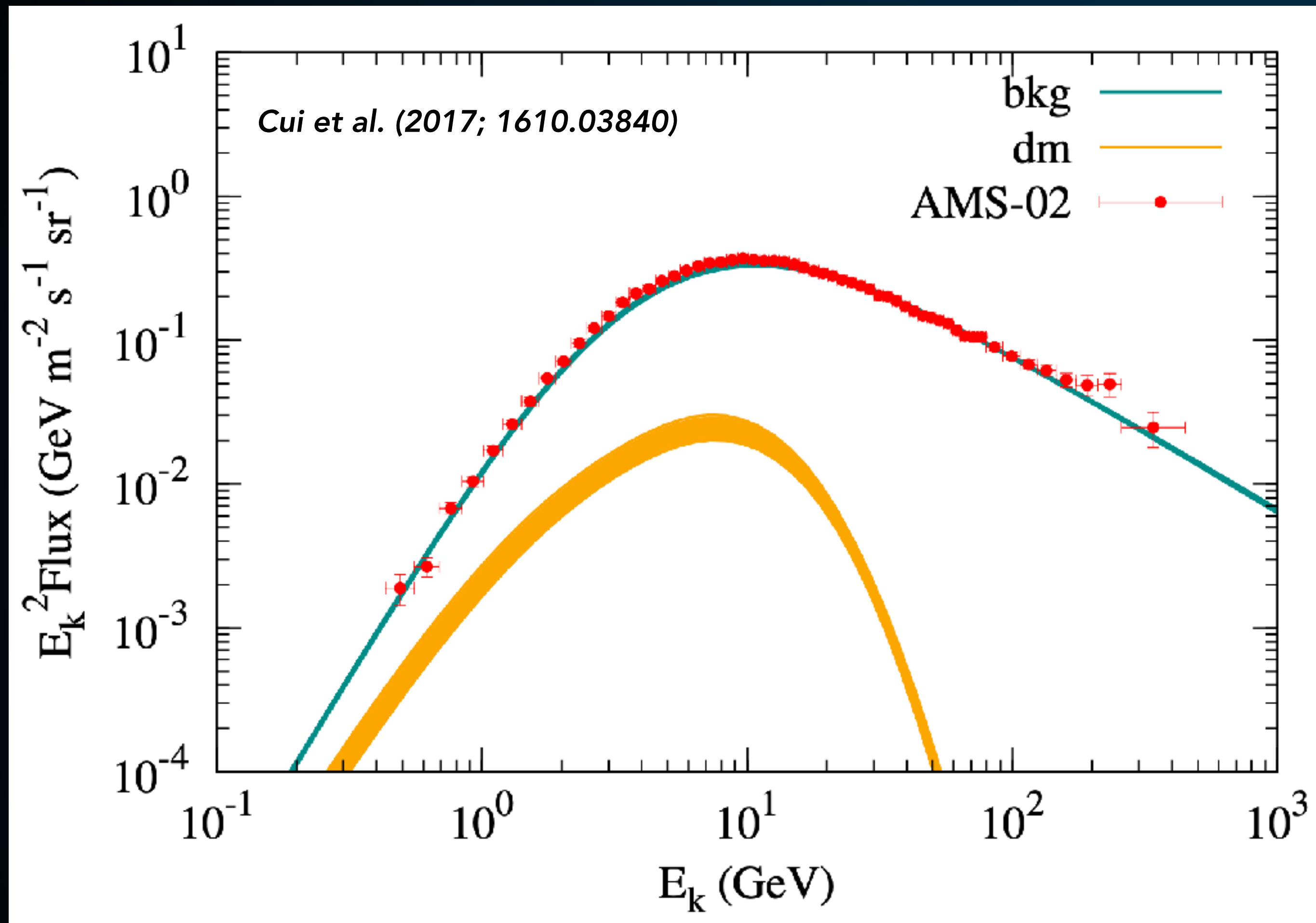
The Antiproton Excess

Hint of Excess in ~5 GeV antiprotons!

Astrophysical Uncertainties can significantly affect the signal.

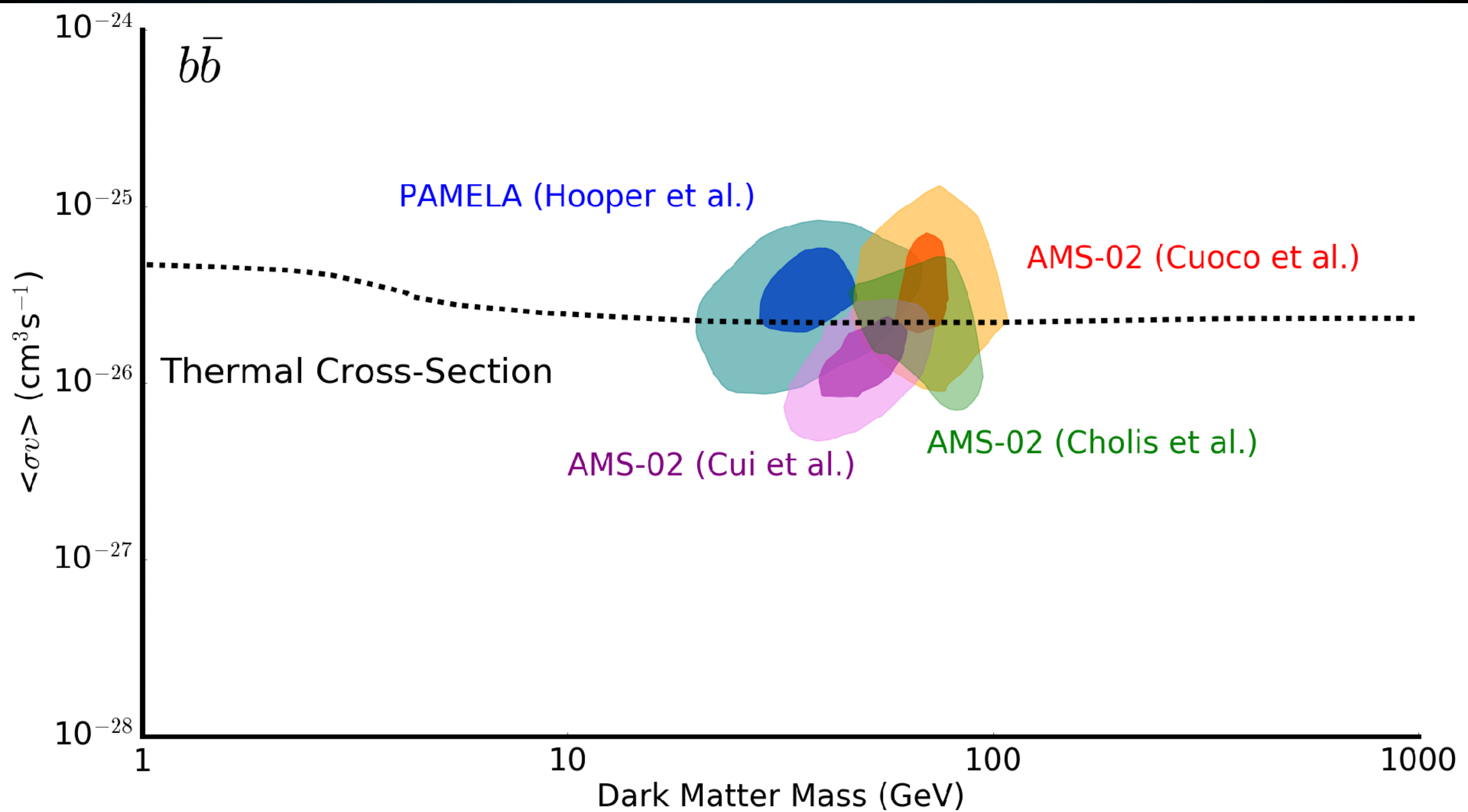


The Antiproton Excess



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)

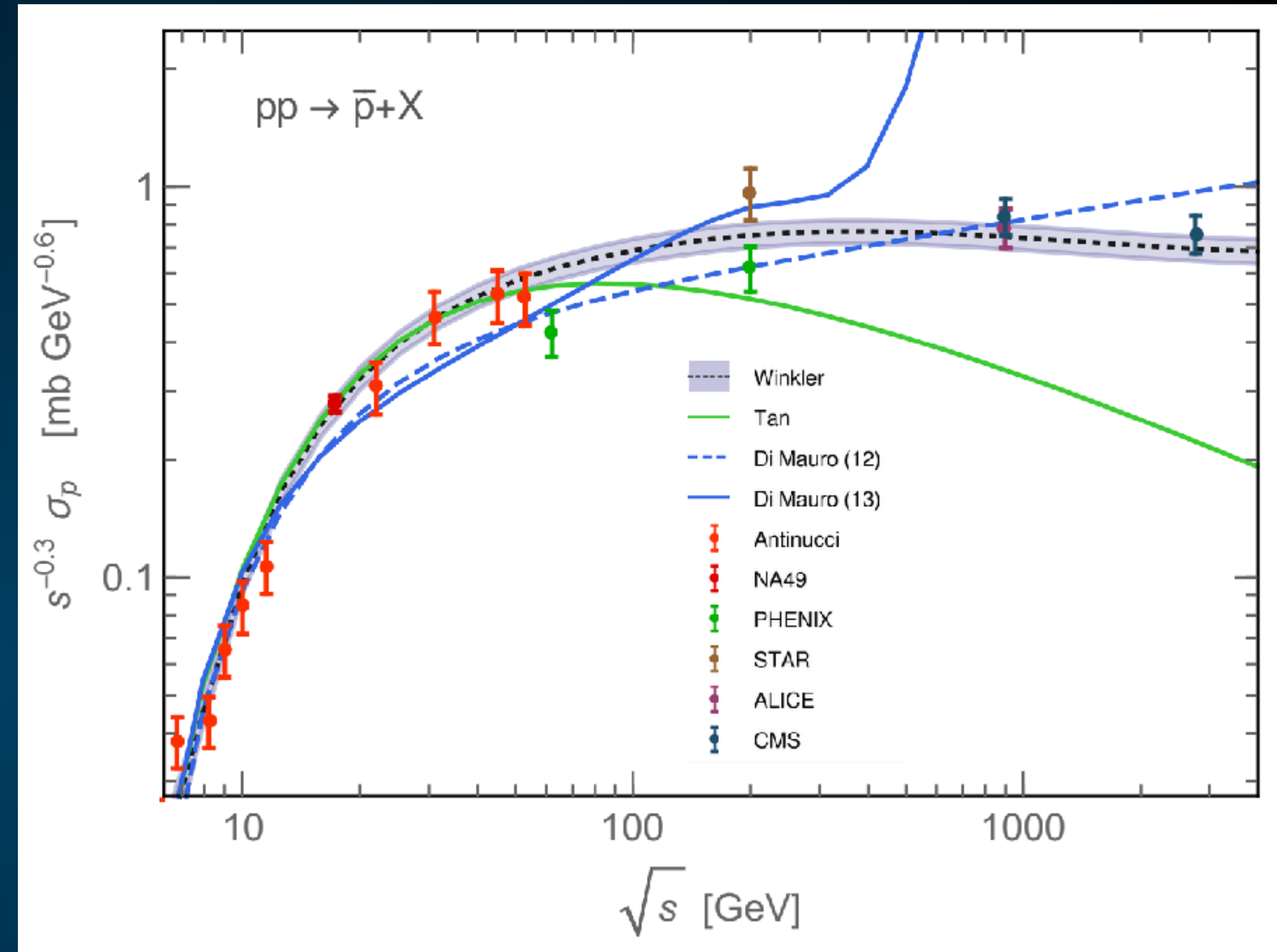
With great precision comes great responsibility:

Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

Solar Modulation

Antiproton Production Cross-Section



The Antiproton Excess - A Detection?

Reinert, Winkler (2018; 1712.00002)

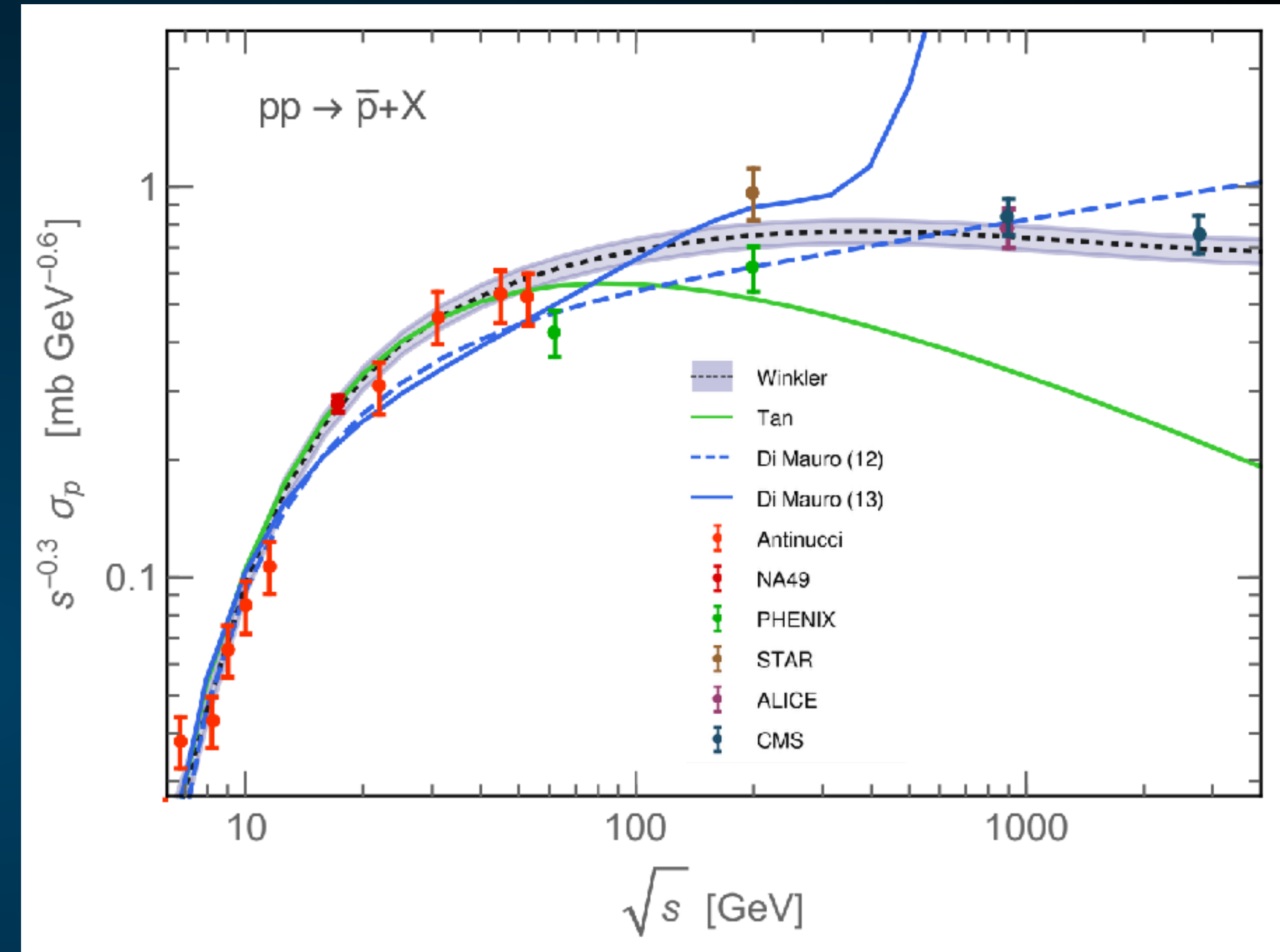
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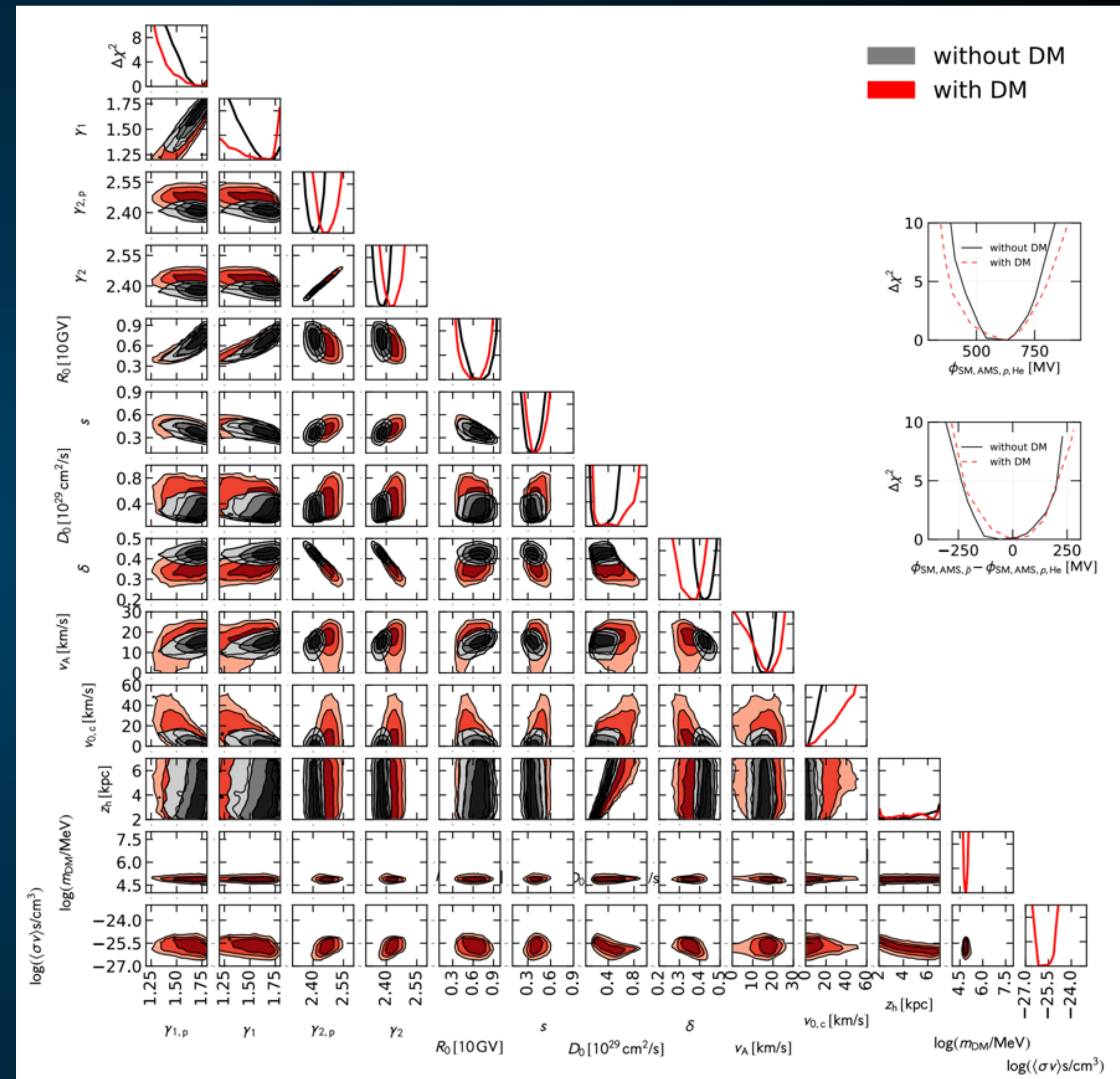
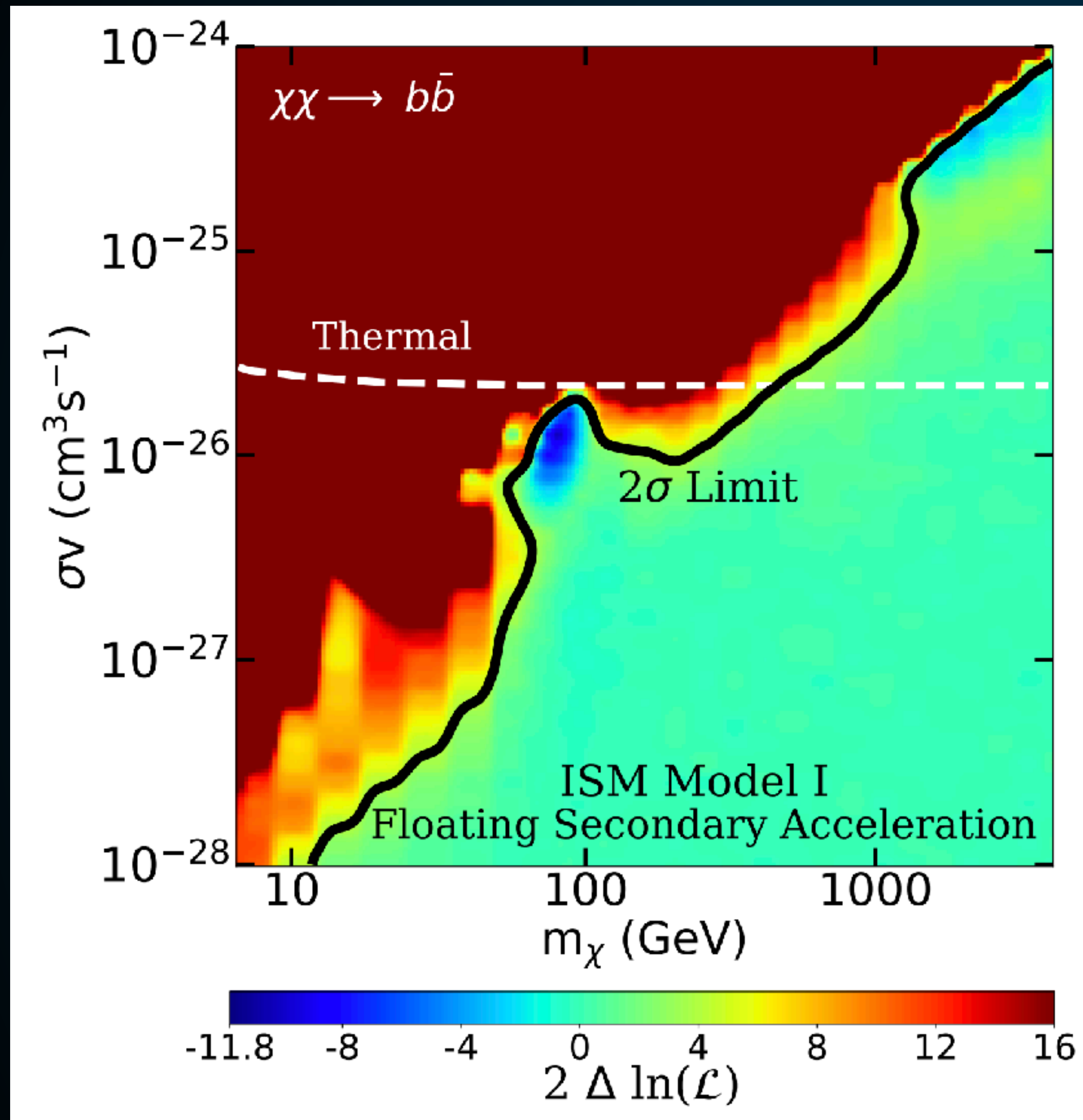
Galactic Primary to Secondary Ratios - Future AMS-02 Data!

Inhomogeneous Diffusion - TeV Halos

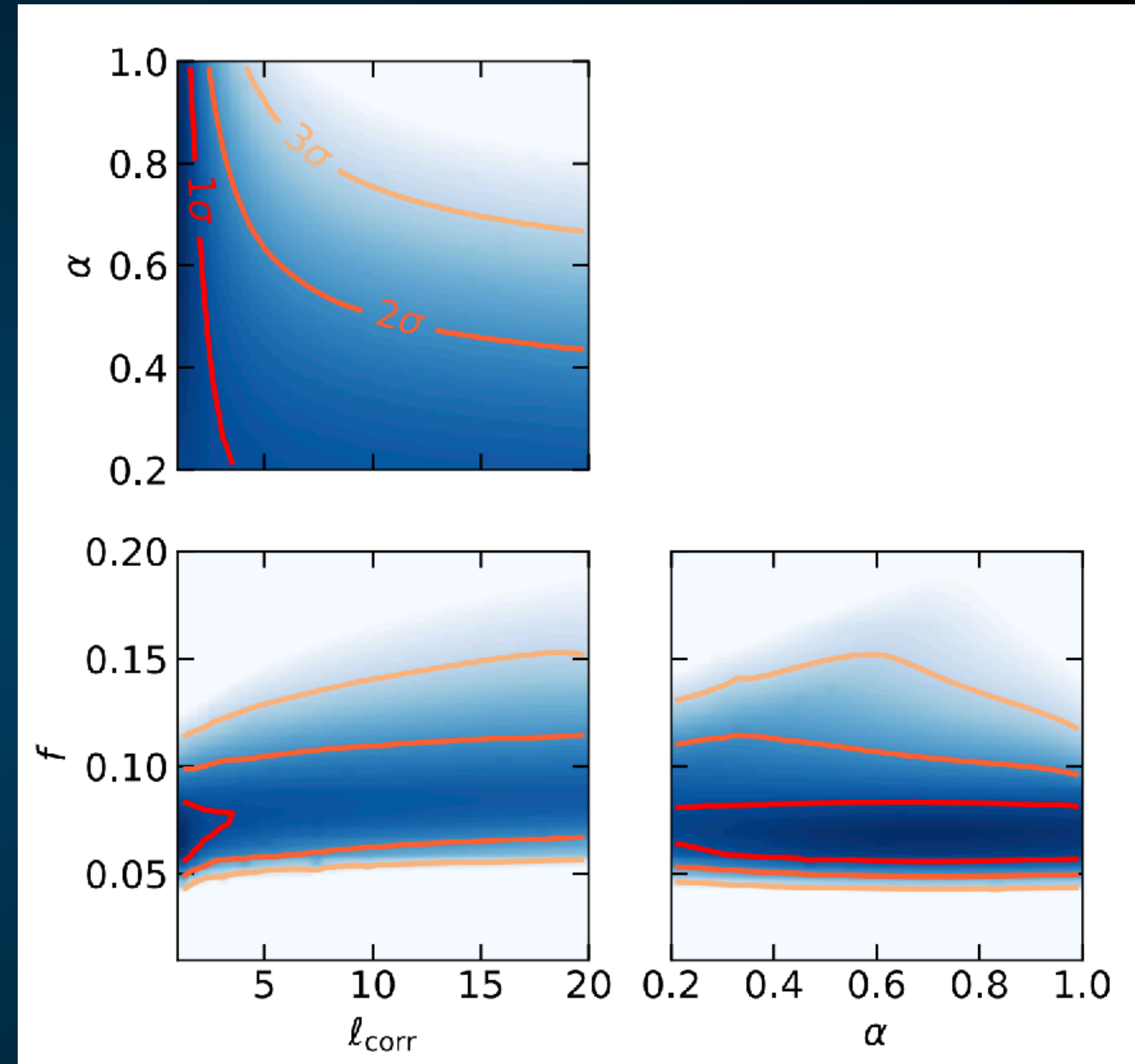
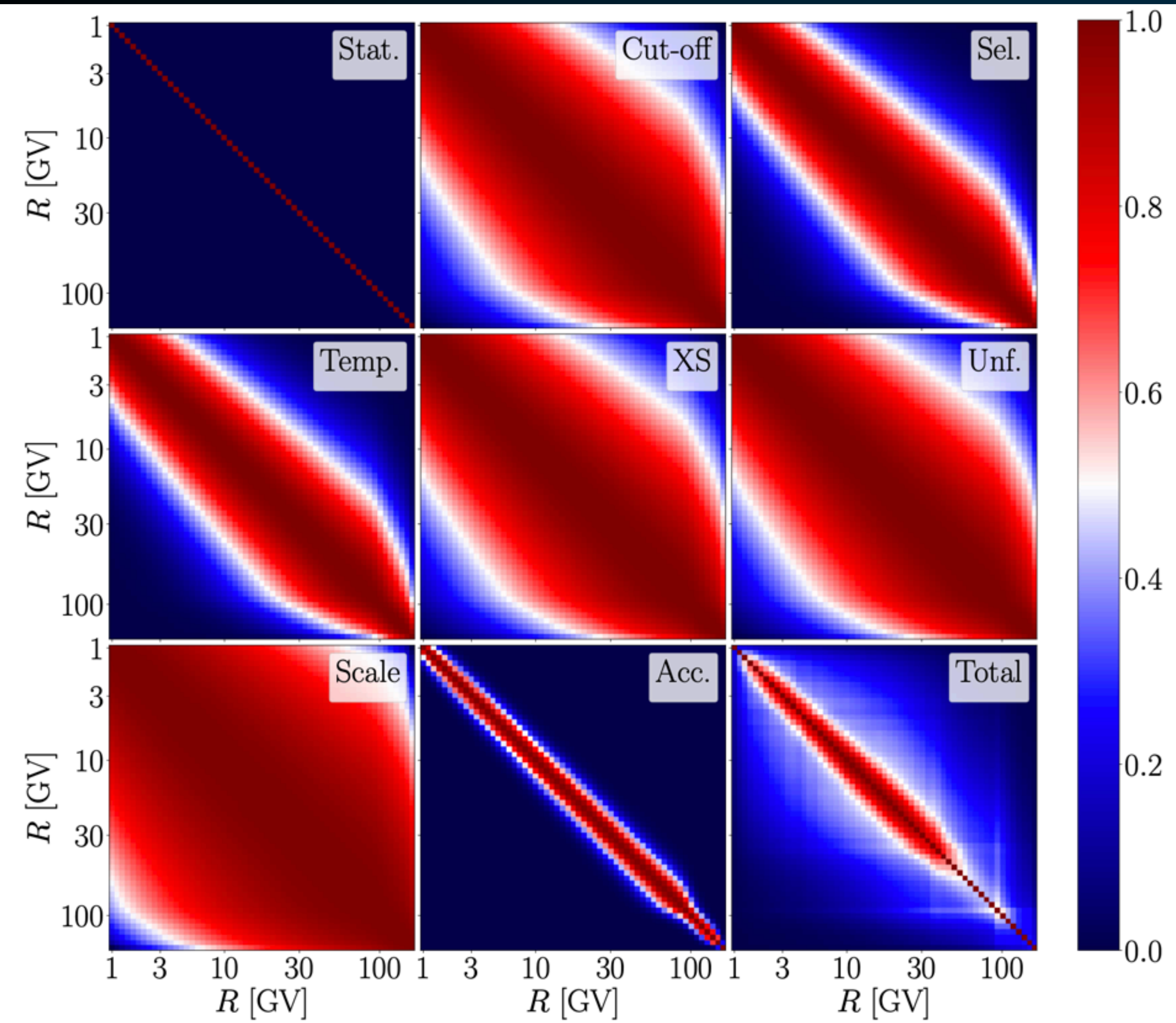
Solar Modulation - Voyager Data, Time-Dependent AMS-02 Data

Antiproton Production Cross-Section - LHCb / Laboratory Experiments

The Antiproton Excess — Robust Analyses



The Antiproton Excess — Correlation Matrices



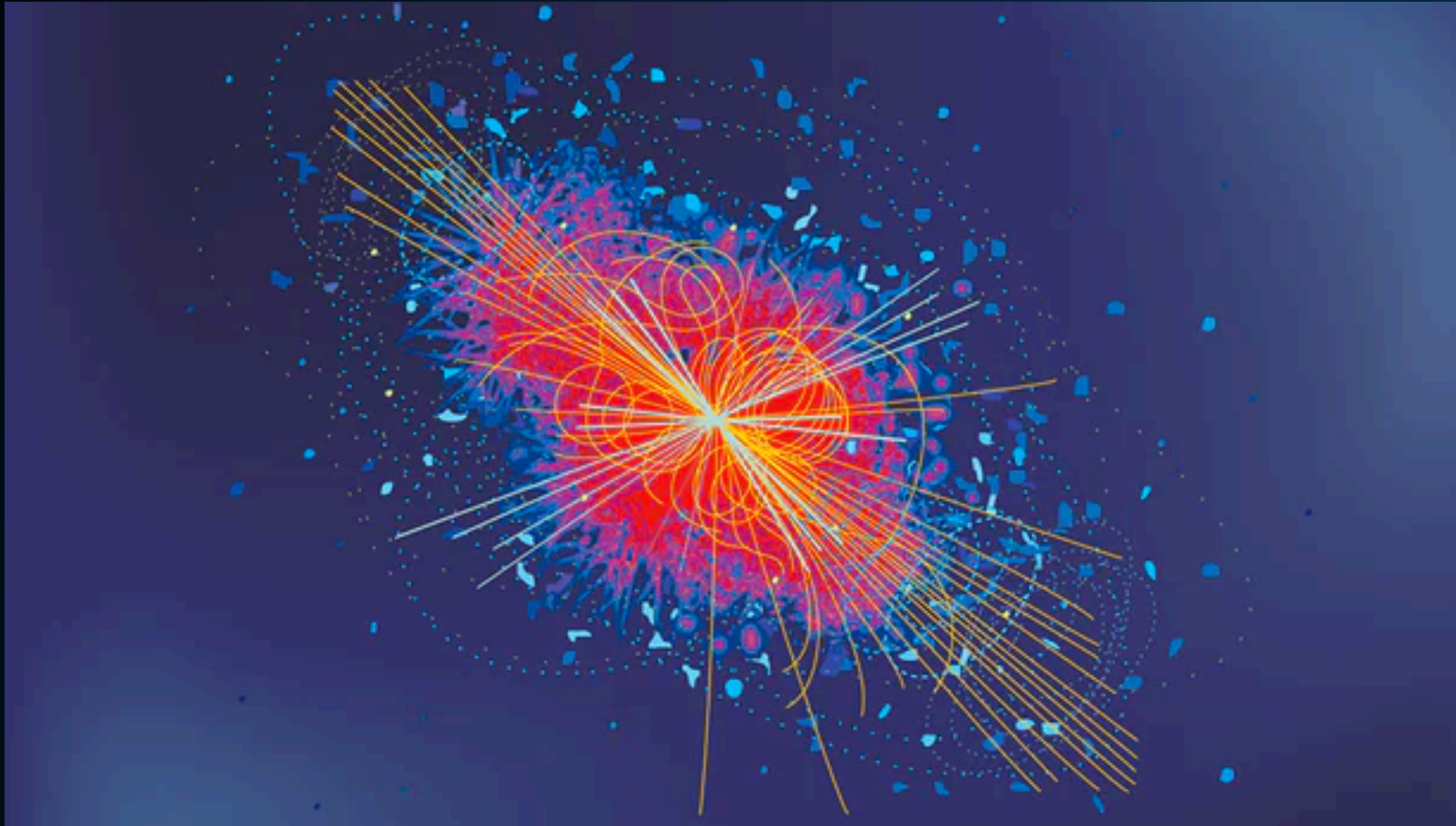
Boudaud et al. (2019; 1906.07119)

Cuoco et. al. (2019; 1903.01472)



Antinuclei !?

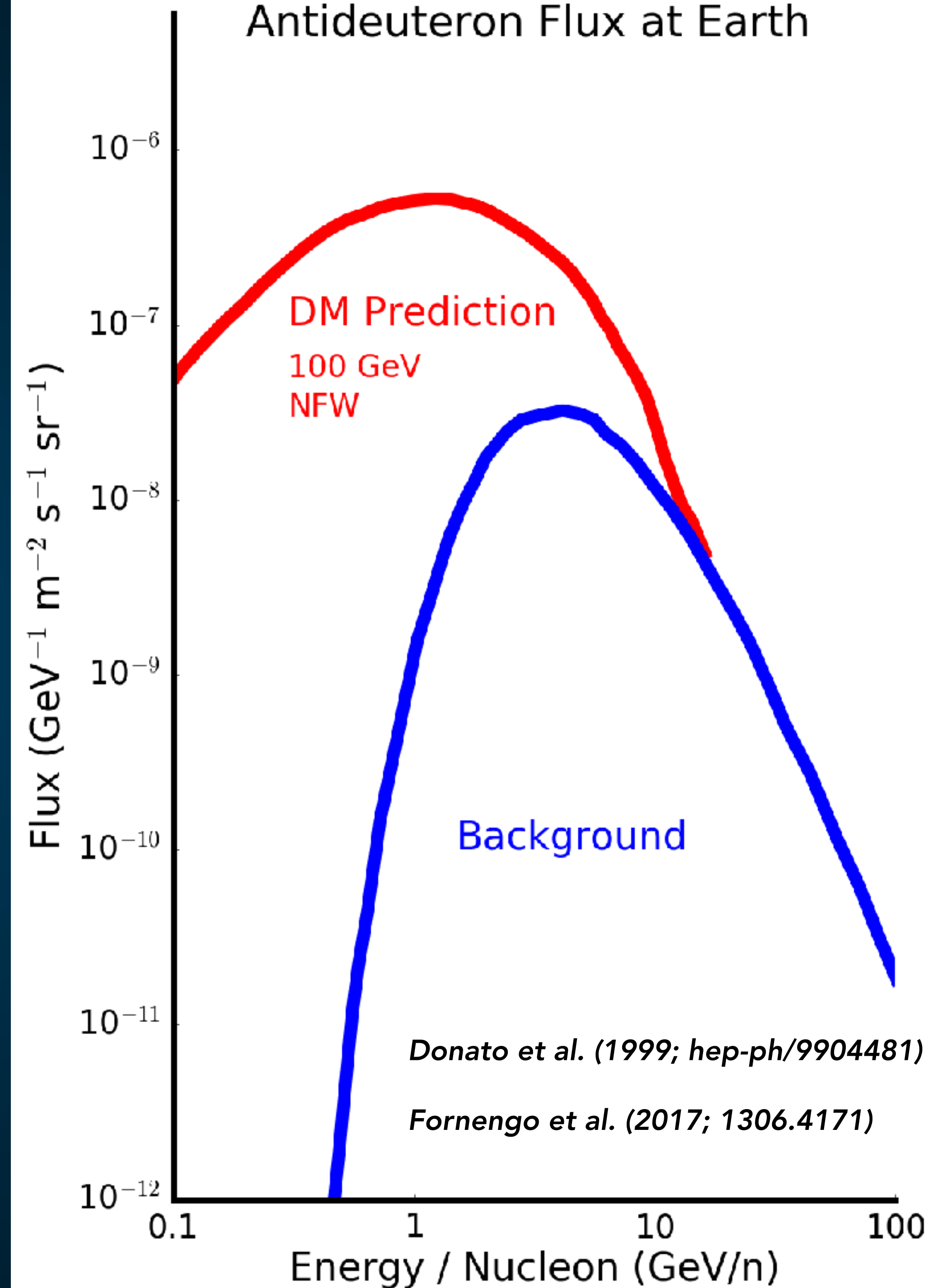
AntiNuclei - A Clean Search Strategy ?



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.

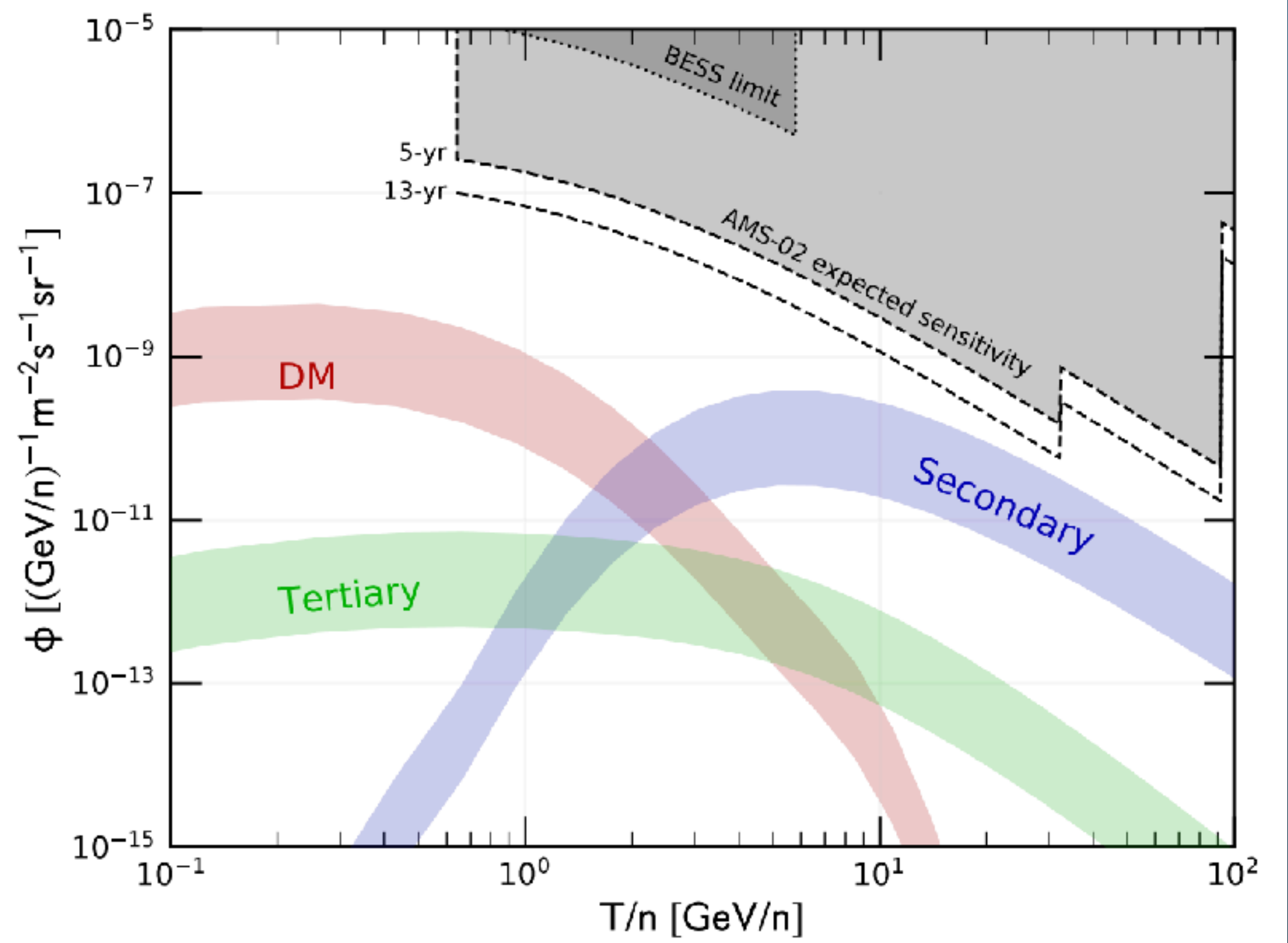
Currently (having used 50 million core hours to generate 7 times more simulated events than measured events and having found no background events from the simulation), our best evaluation of the probability of the background origin for the eight $\bar{\text{He}}$ events is **less than 3×10^{-8}** . For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

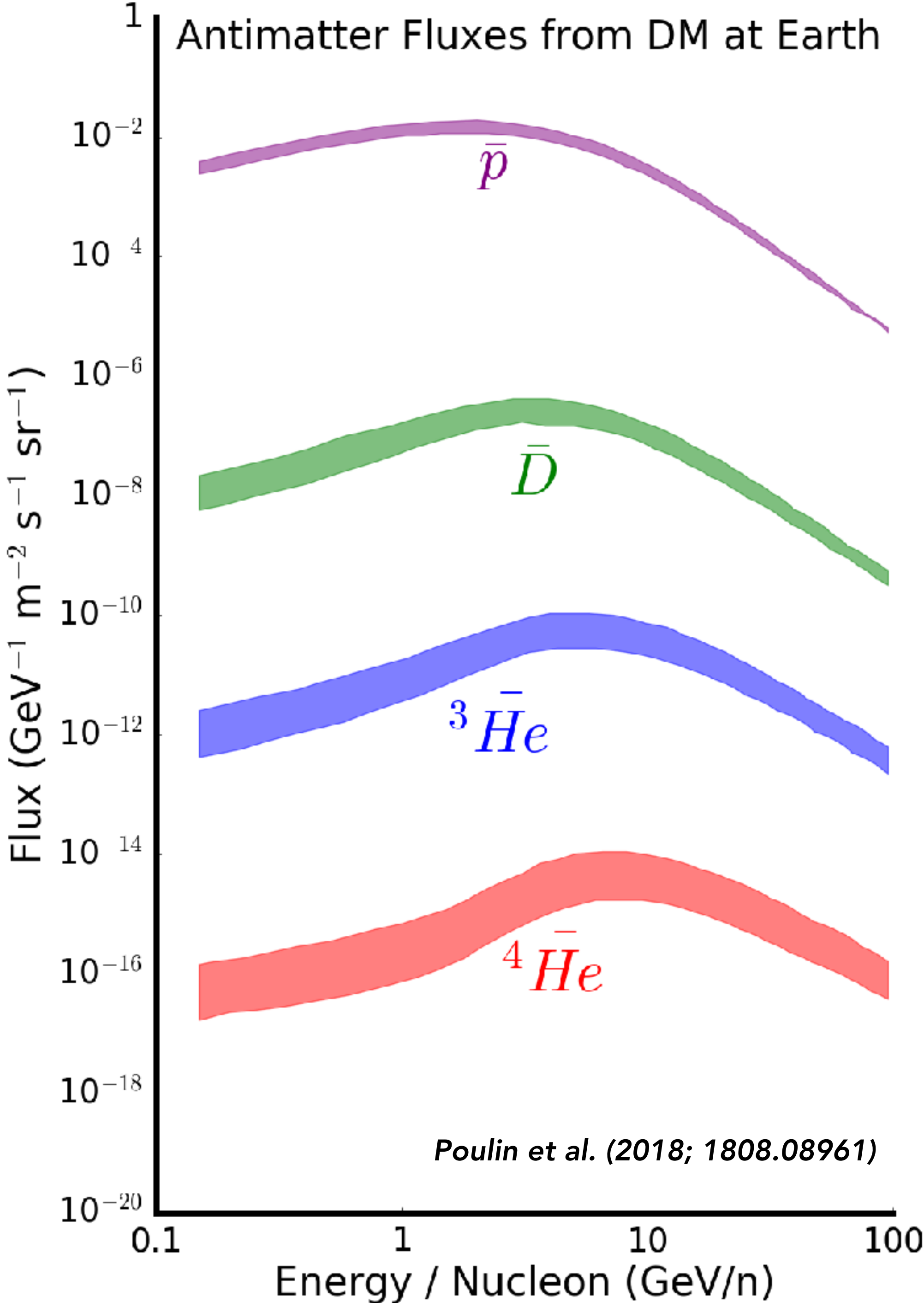
AntiNuclei - A Clean Search Strategy ?

Antihelium background even cleaner than antideuterons

But the flux is supposed to be much smaller.



Korsmeier (2017; 1711.08465)

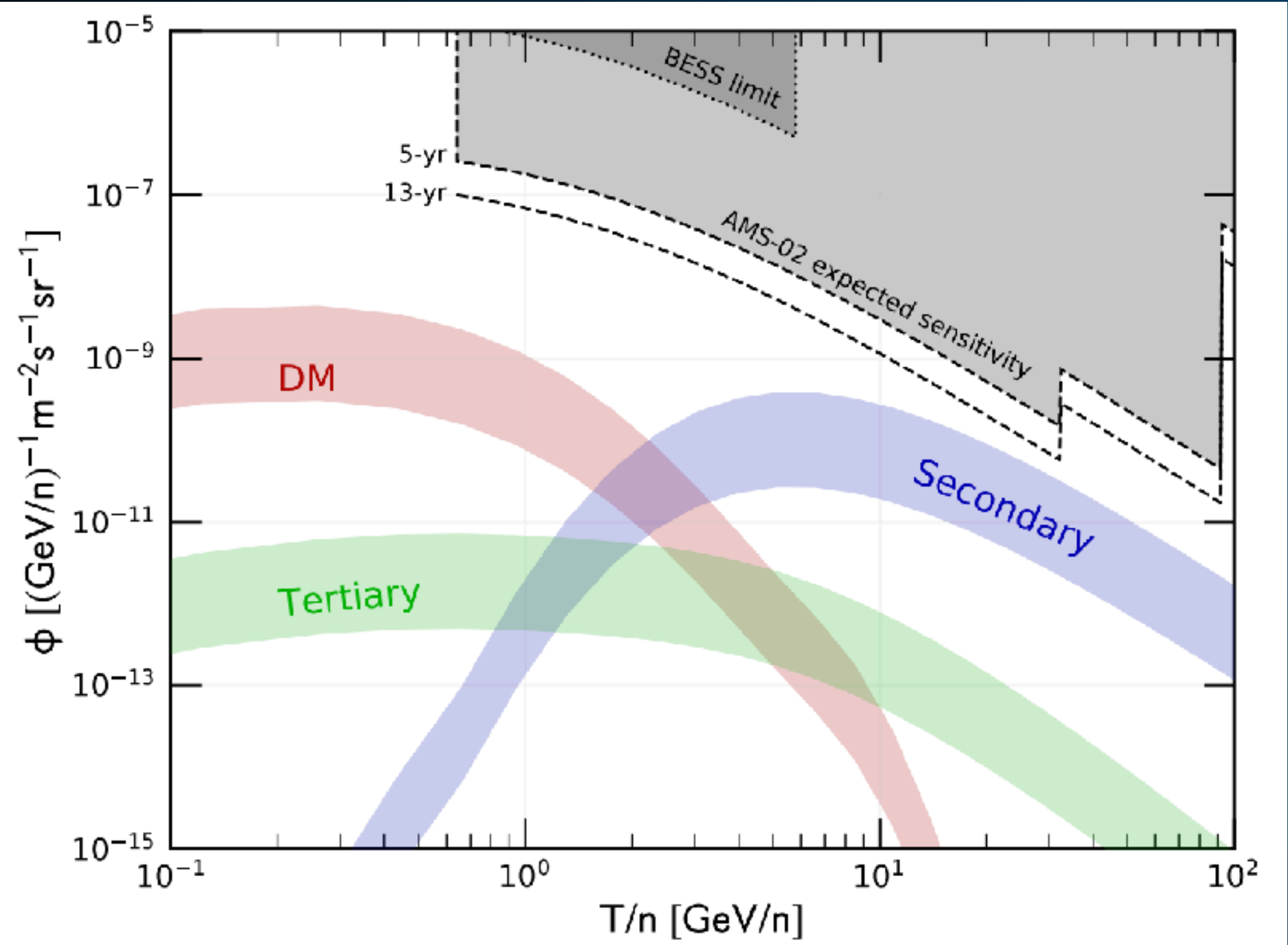


Poulin et al. (2018; 1808.08961)

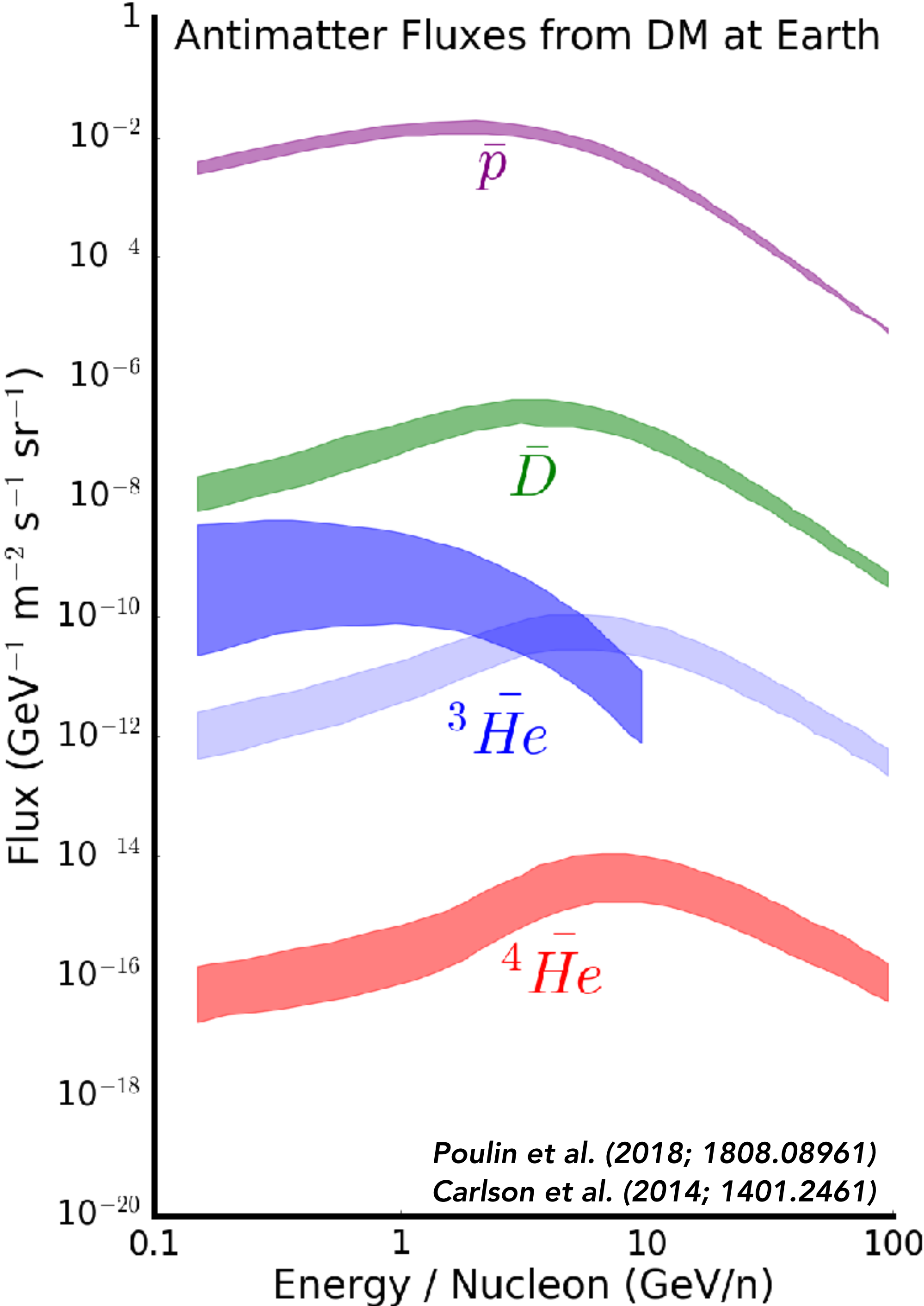
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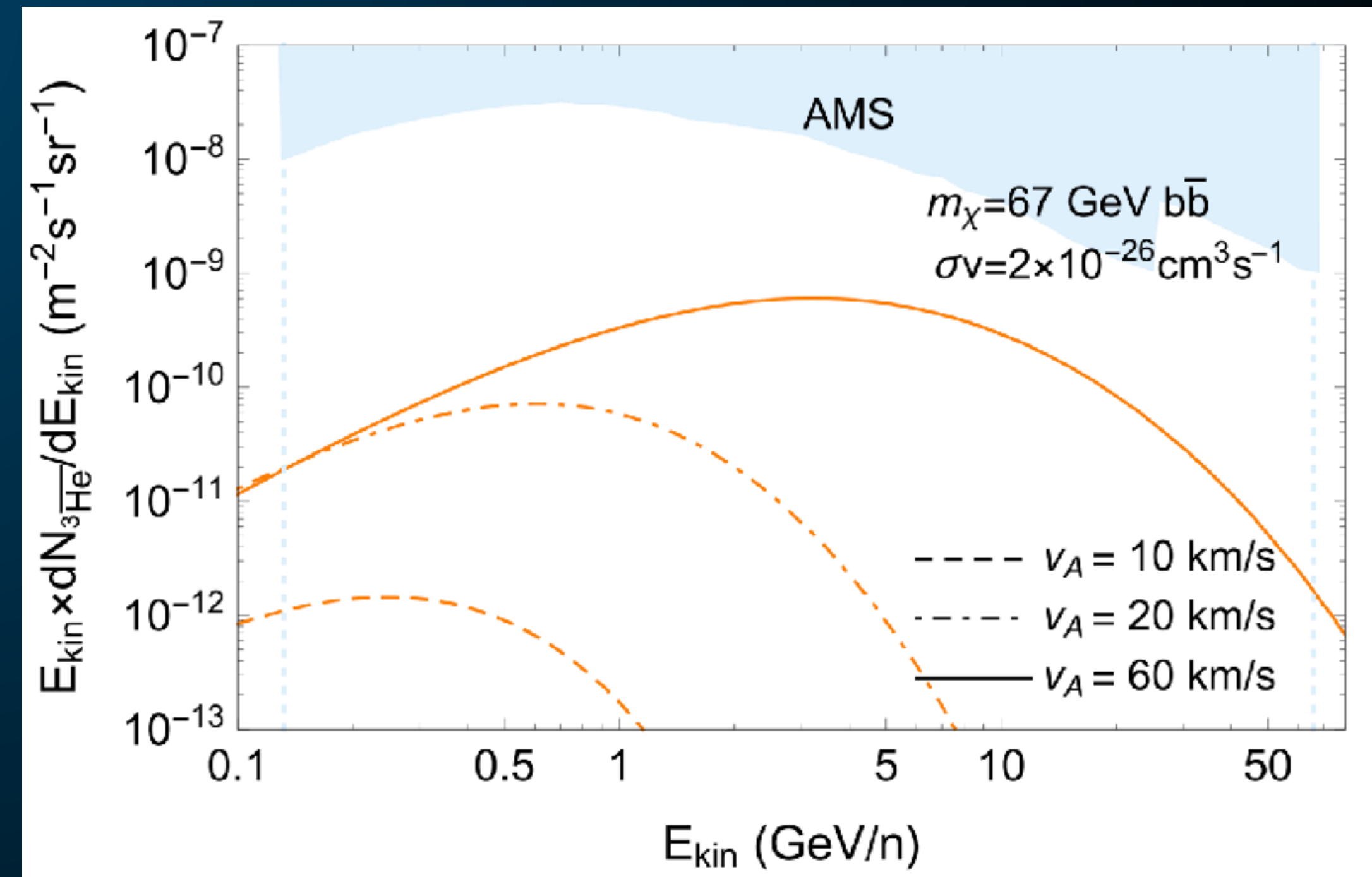
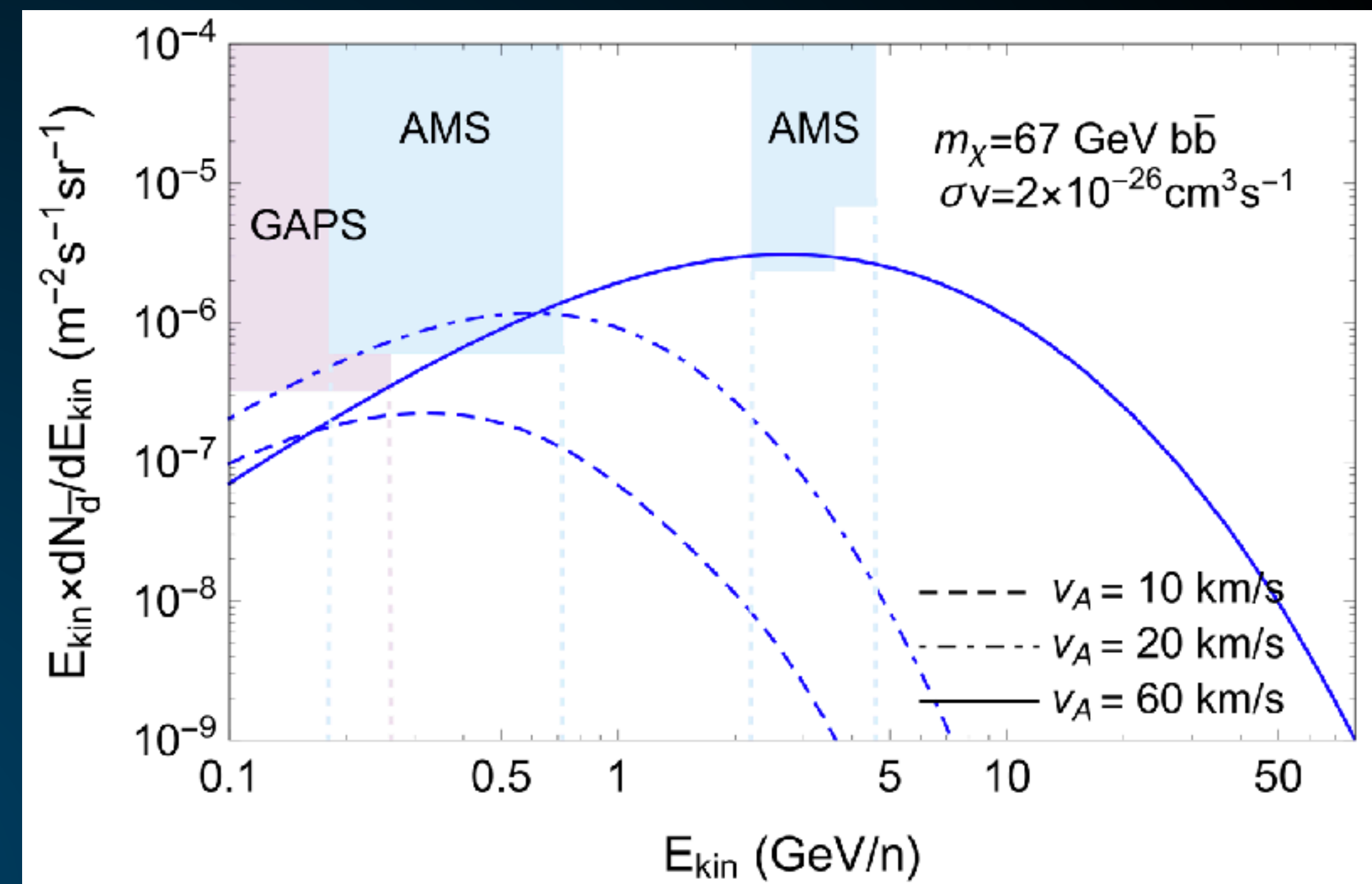


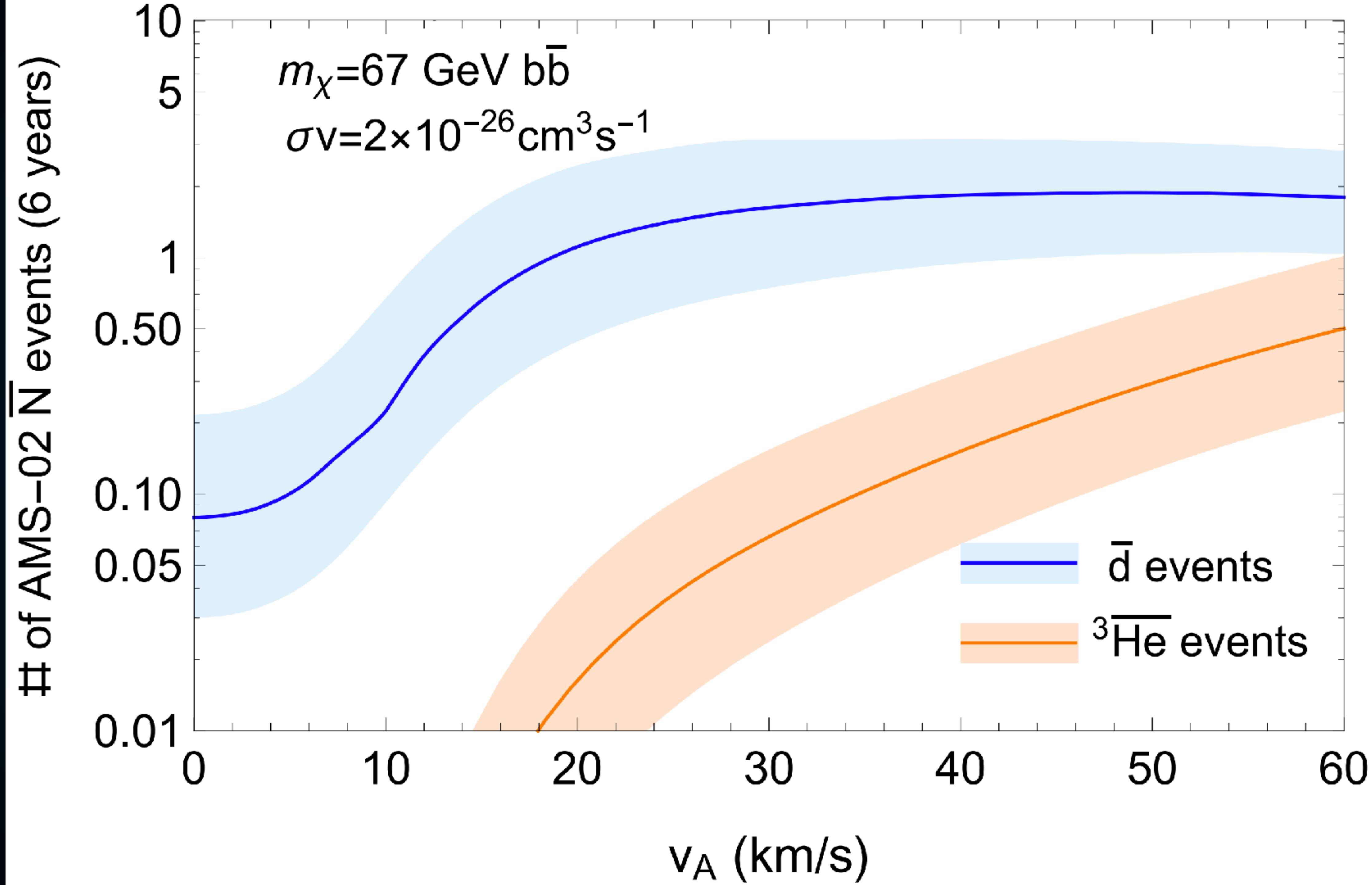
Poulin et al. (2018; 1808.08961)
Carlson et al. (2014; 1401.2461)

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!

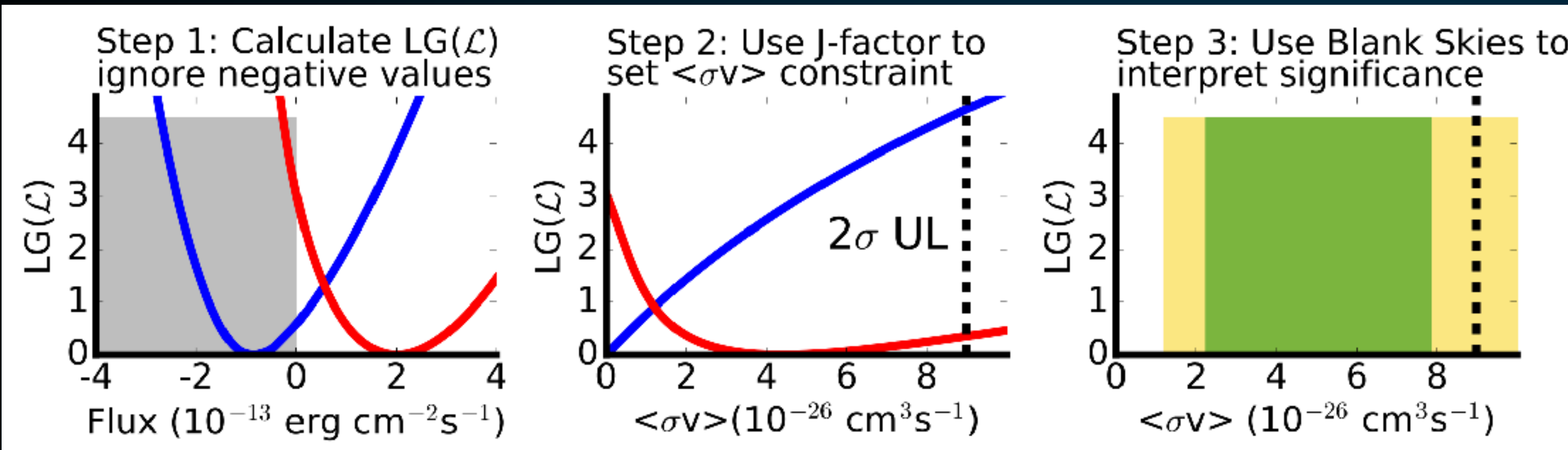






Dwarf Spheroidal Galaxies

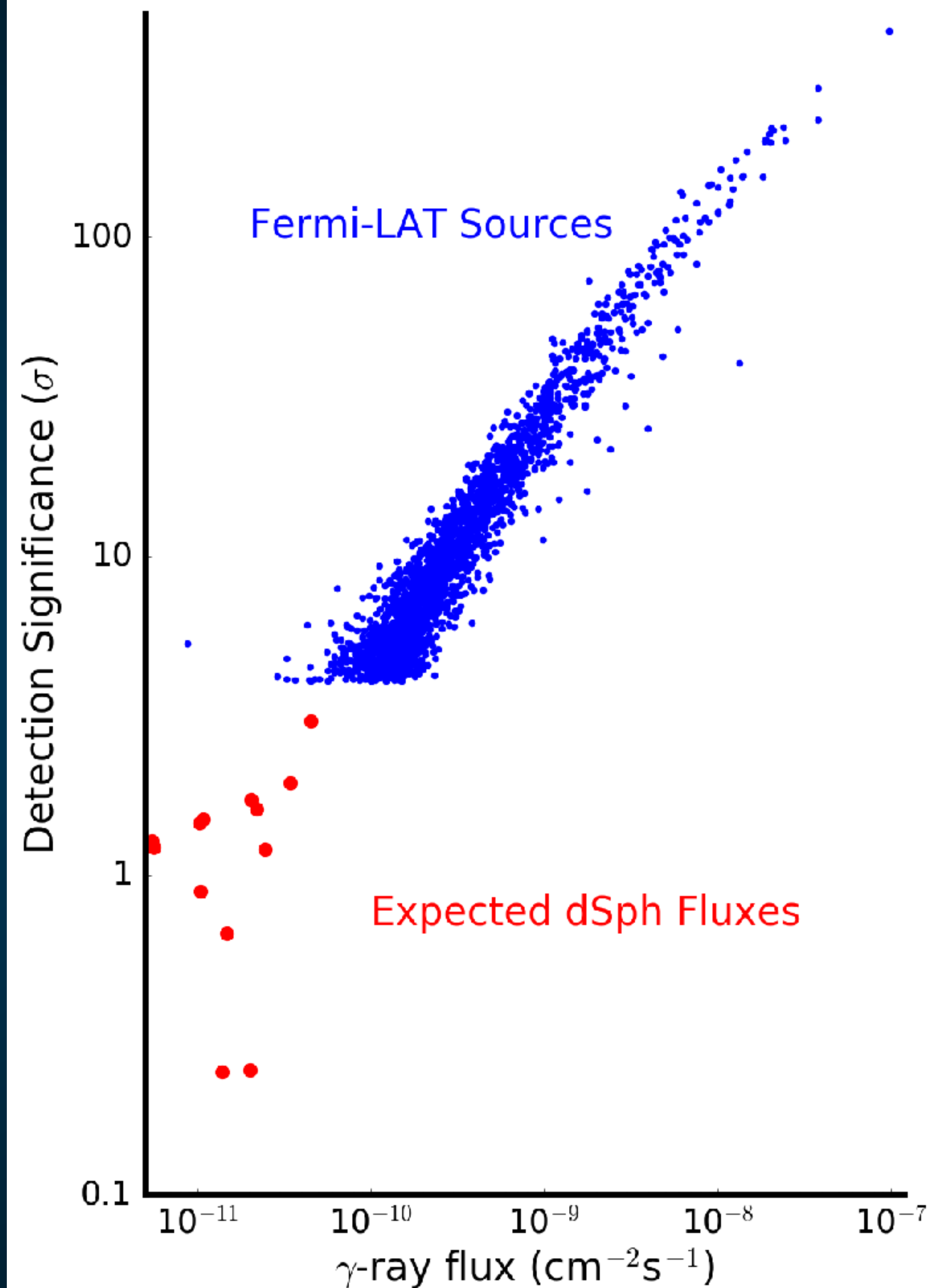
Dwarf Spheroidal Galaxies

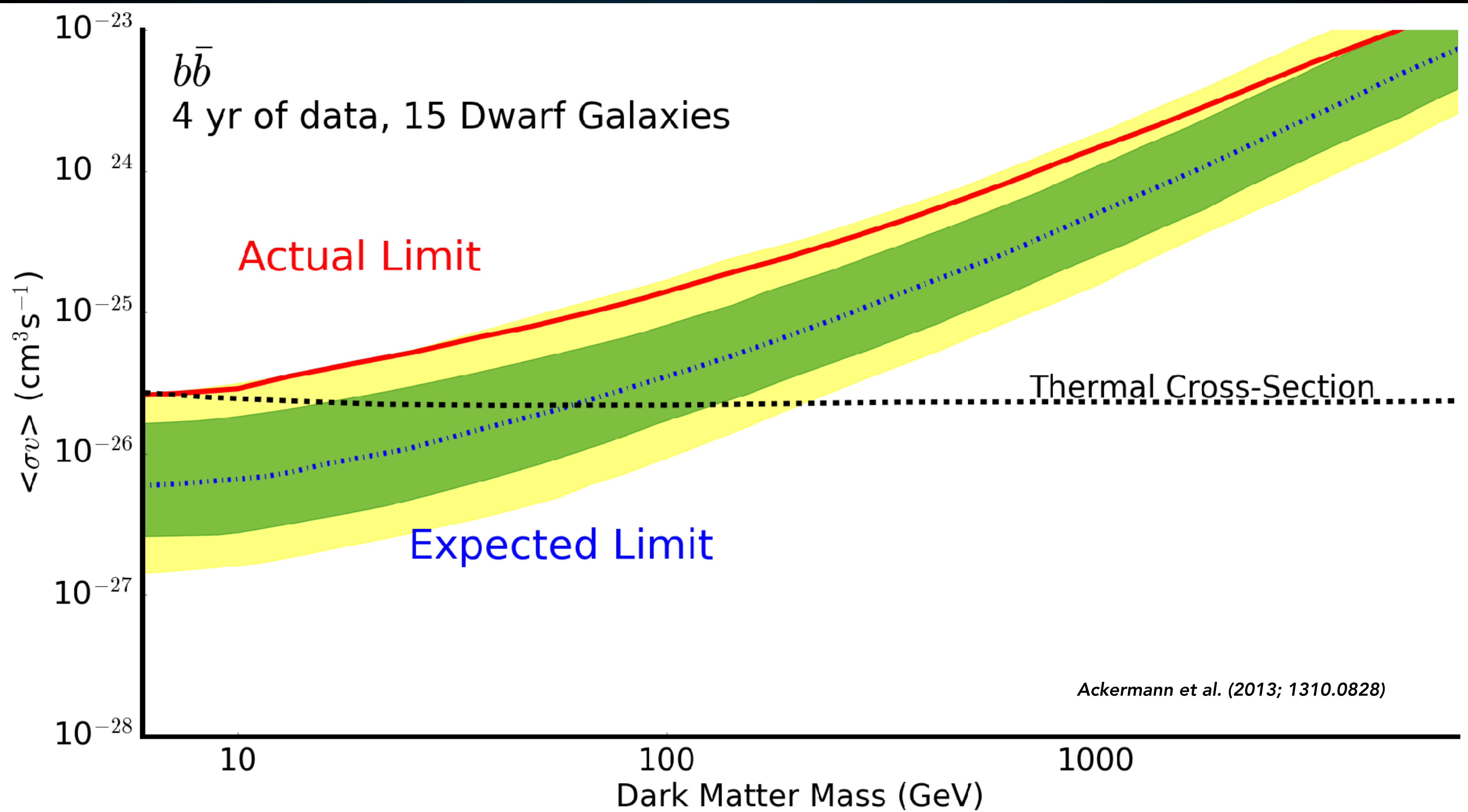


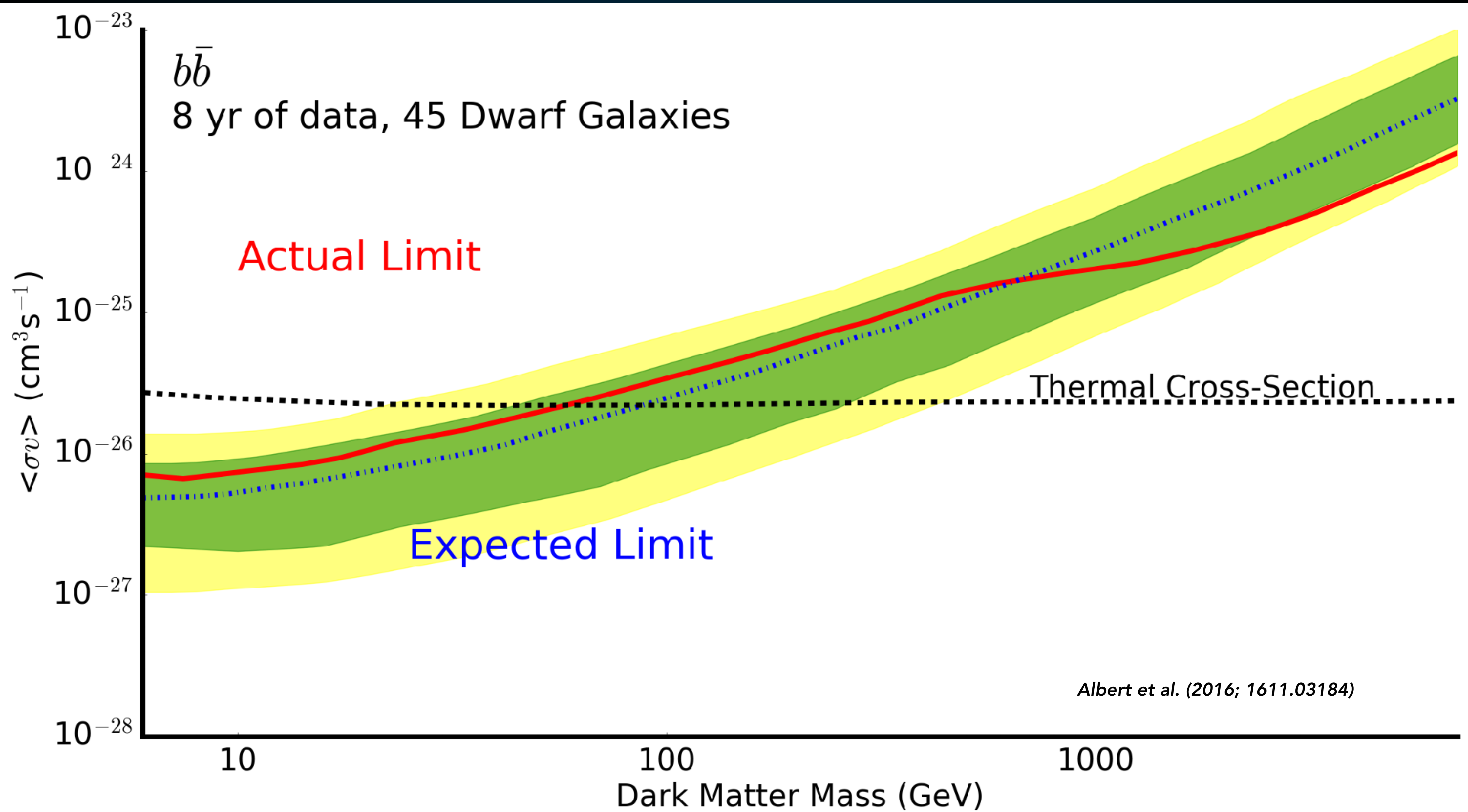
No Astrophysical Background from Dwarfs!

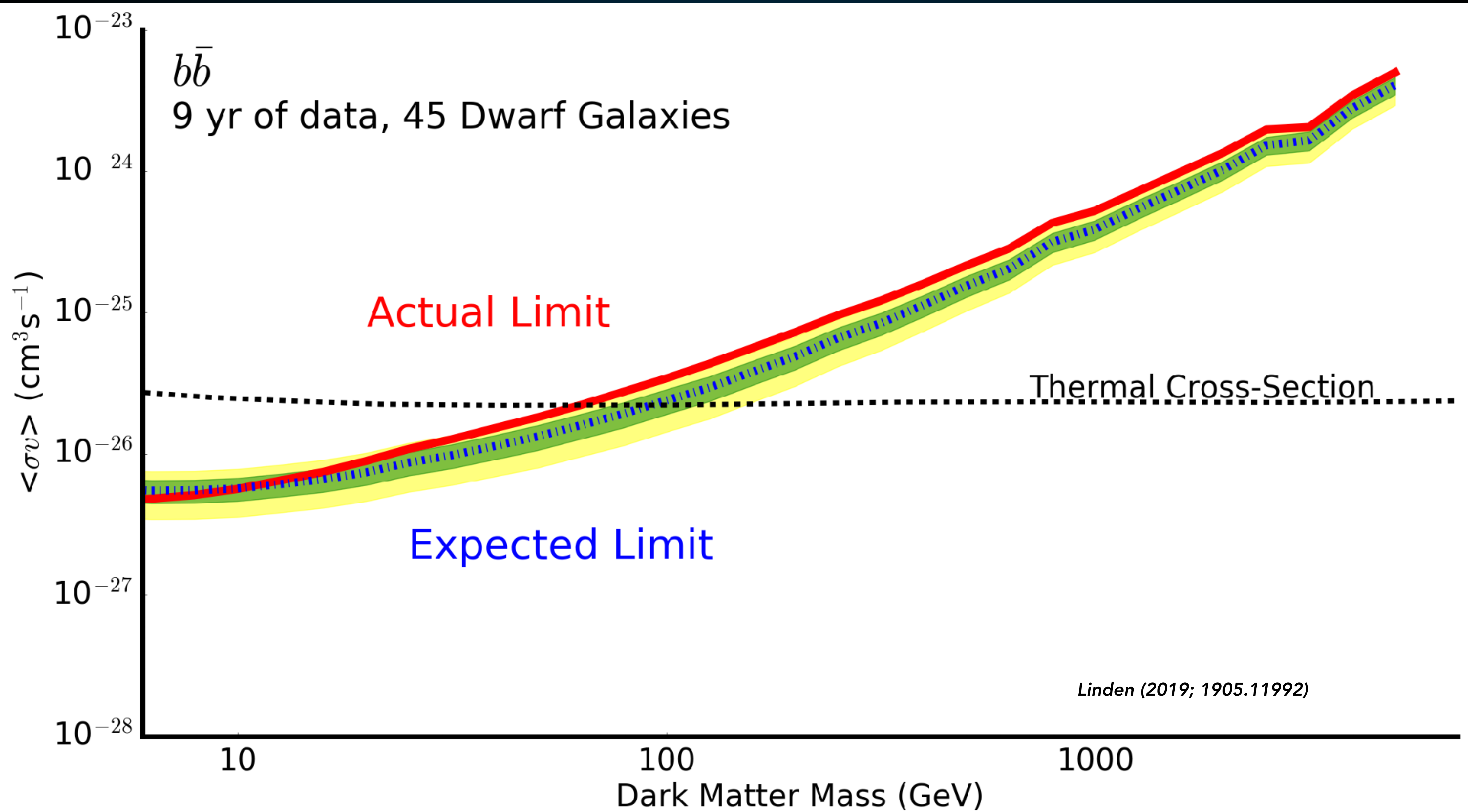
Individual dwarfs are dim

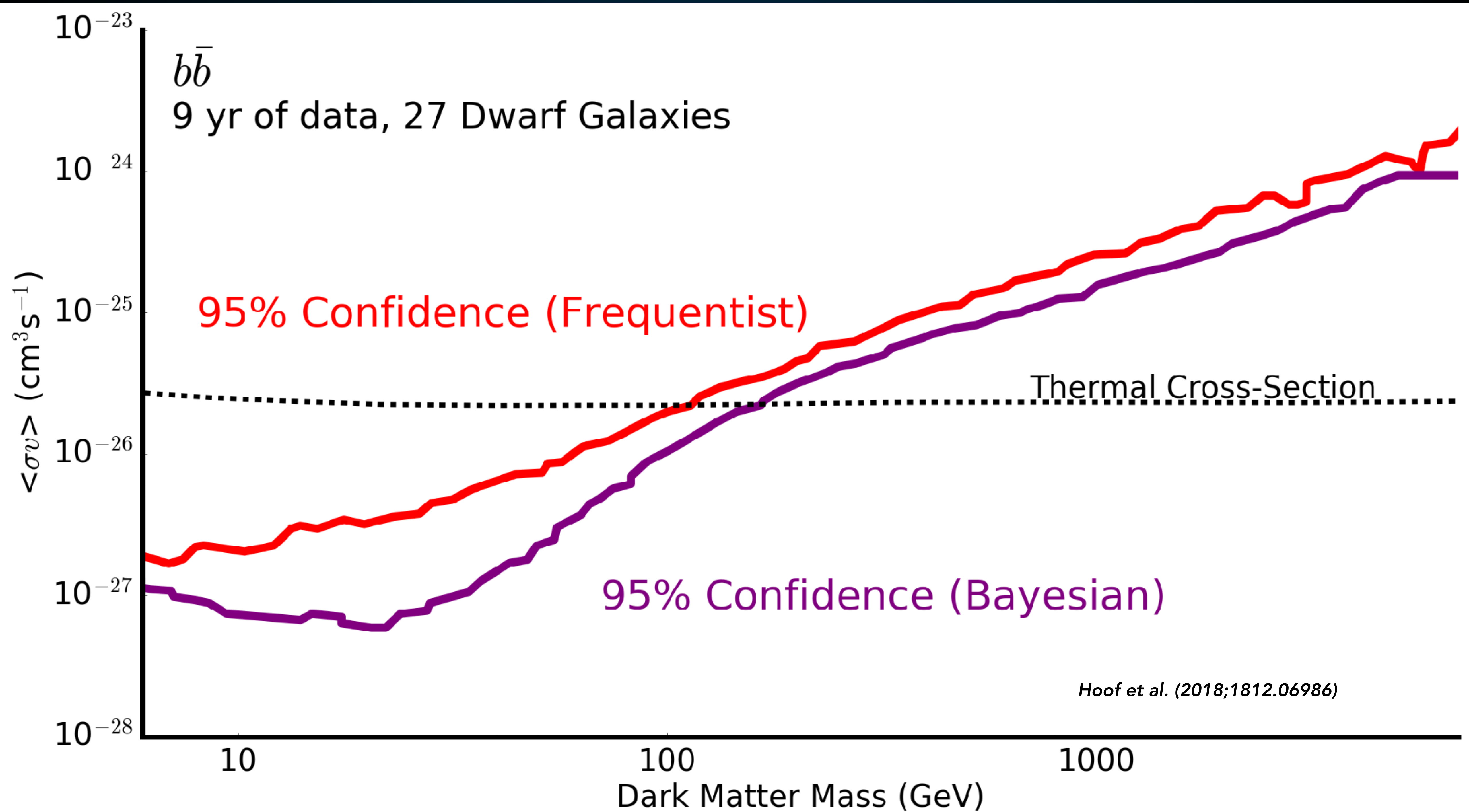
Need to combine observations of multiple dwarfs to constrain thermal cross-section











WHERE
ARE
WE NOW?

