



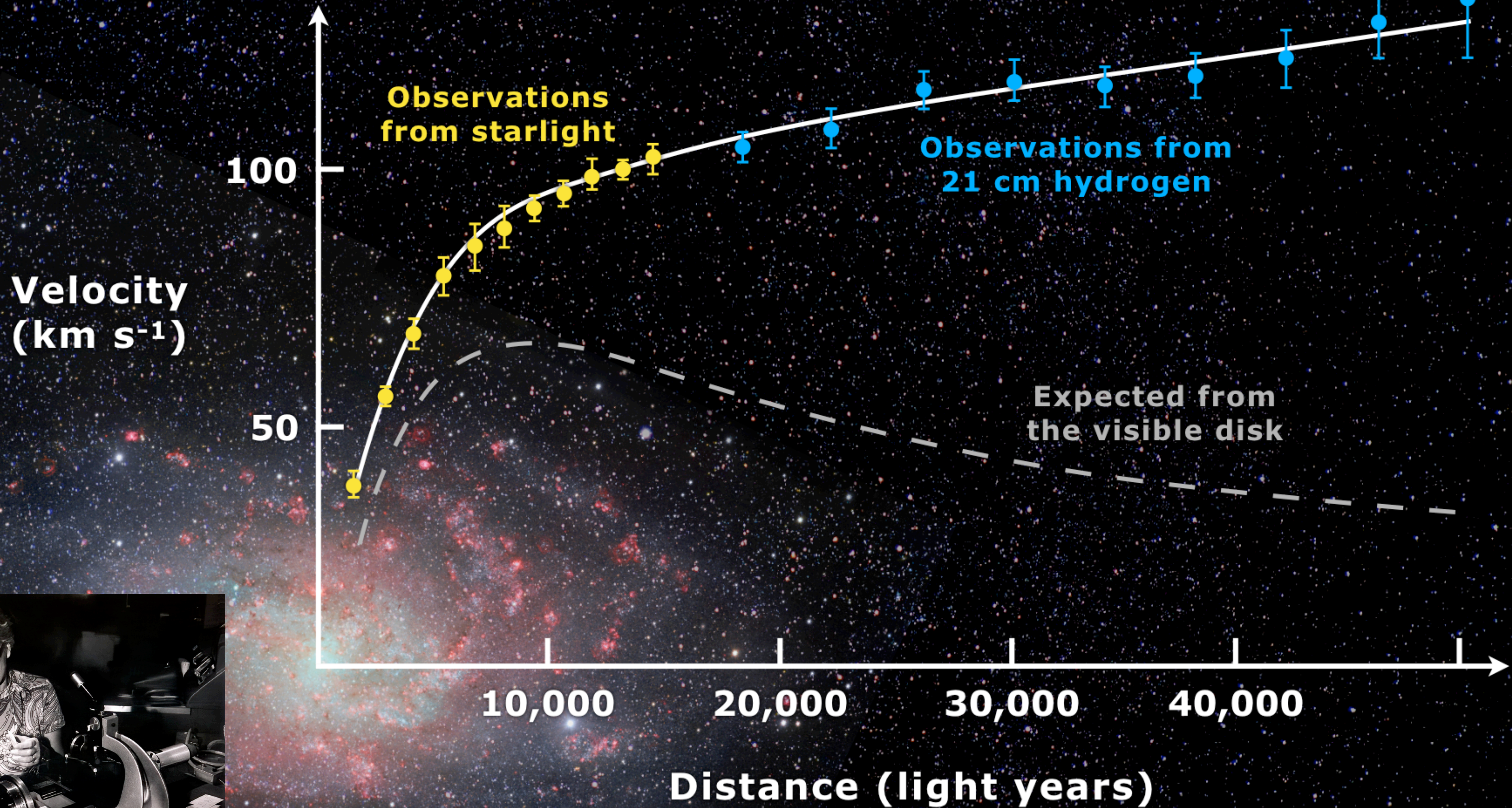
Tim Linden

Indirect Detection of Dark Matter

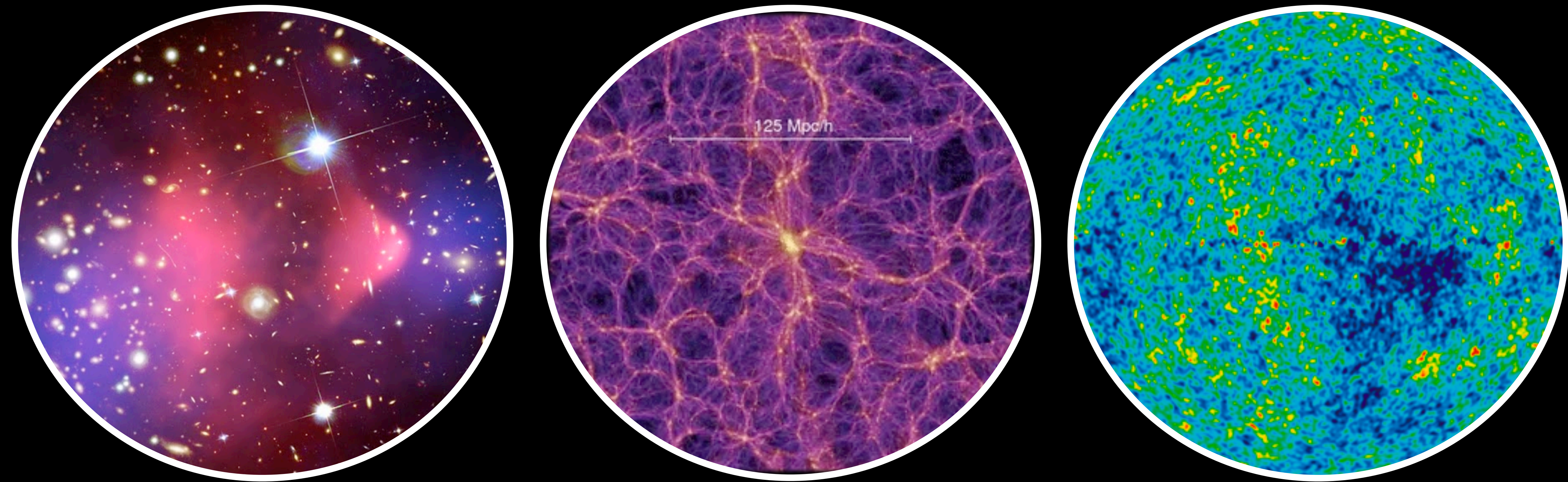


Friedrich-Alexander-Universität
Erlangen-Nürnberg

What Do We Know About Dark Matter?



What Do We Know About Dark Matter?



How a cosmologist views the evidence for dark matter.

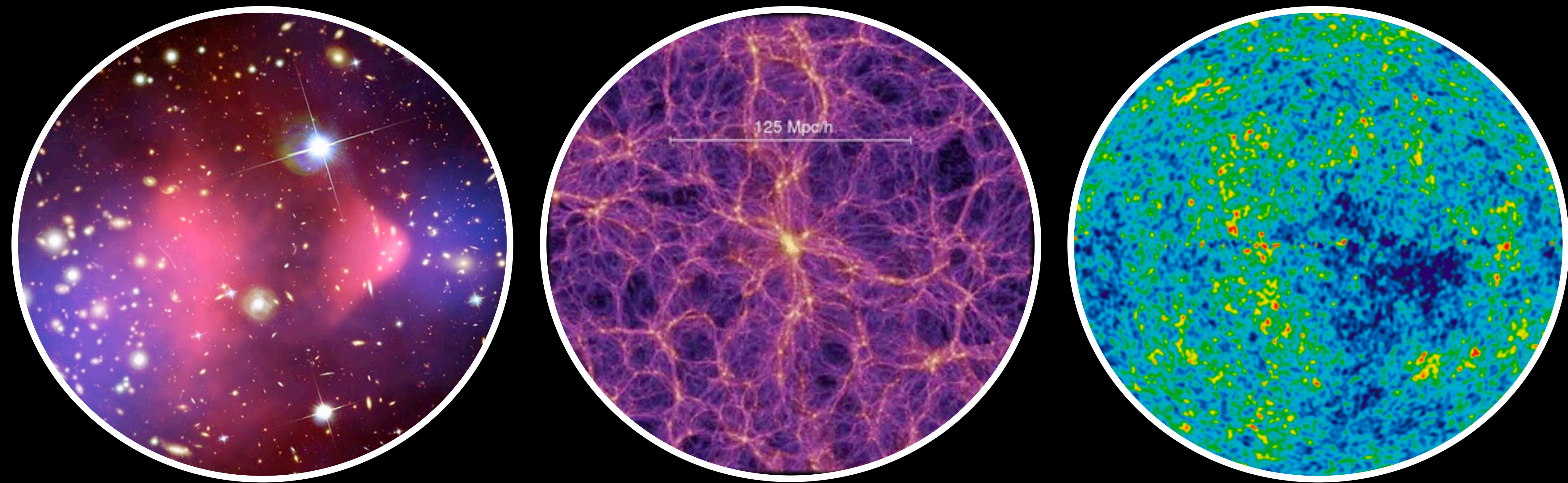
What Do We Know About Dark Matter?

Bullet Cluster

- Two galaxy clusters colliding at ~ 4000 km/s
- Hot gas stuck in the middle - stars pass through.
- Total mass distribution traces the stars, which are only $\sim 10\%$ of the baryonic content.
- Most mass must be dark!

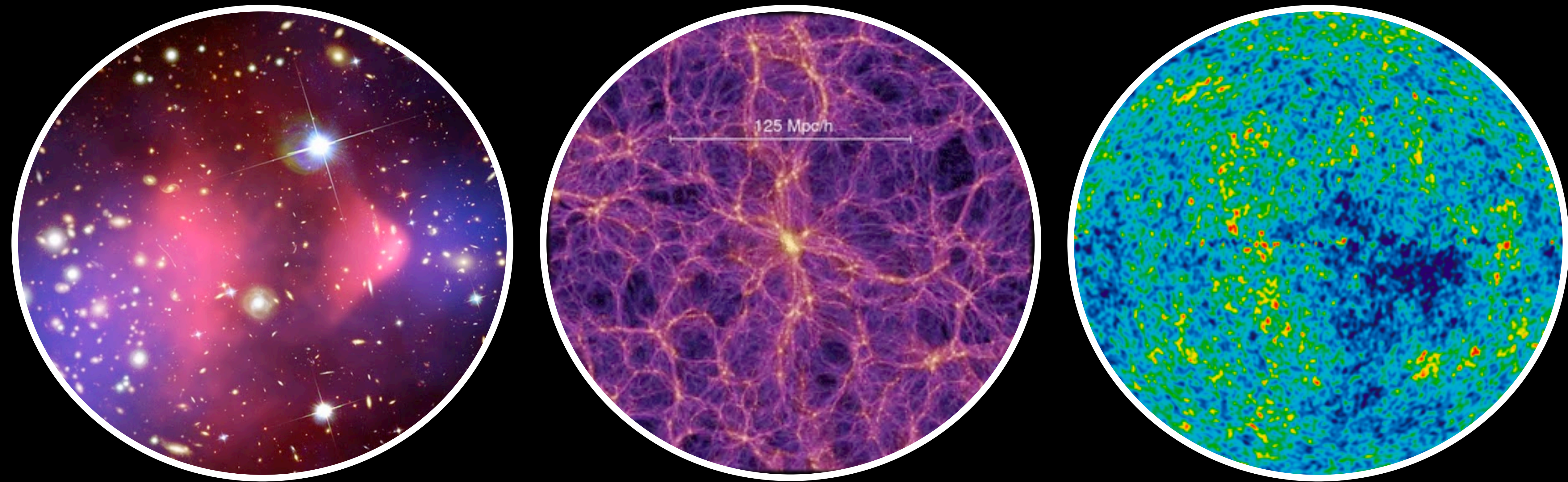


What Do We Know About Dark Matter?



How a cosmologist views the evidence for dark matter.

What Do We Know About Dark Matter?



Early Universe:

Radiation - Provides pressure that smears out over density.

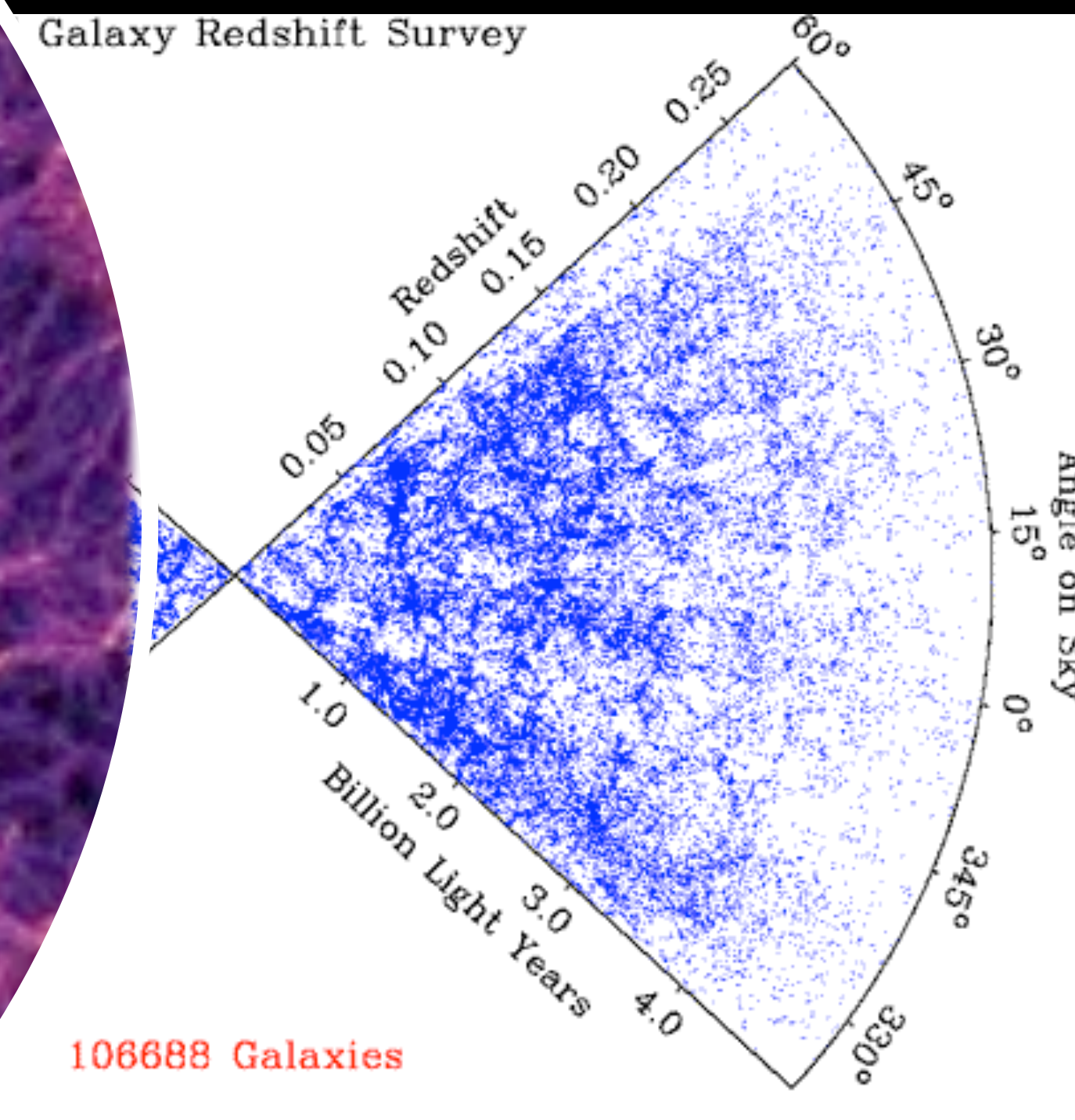
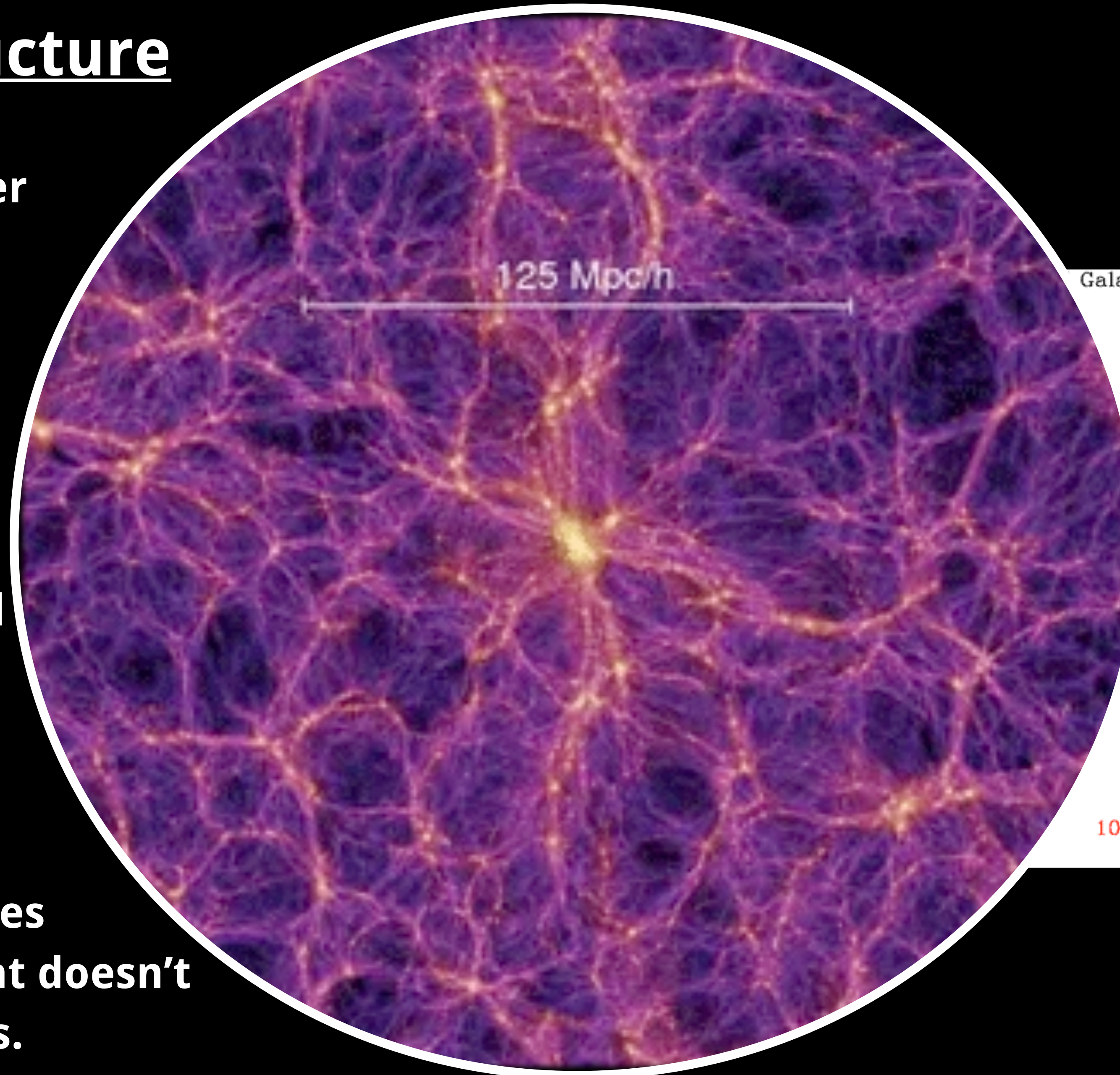
Baryonic Matter - Gravitational potential, but responds to radiation.

Dark Matter - Gravitational potential, does not respond to radiation.

What Do We Know About Dark Matter?

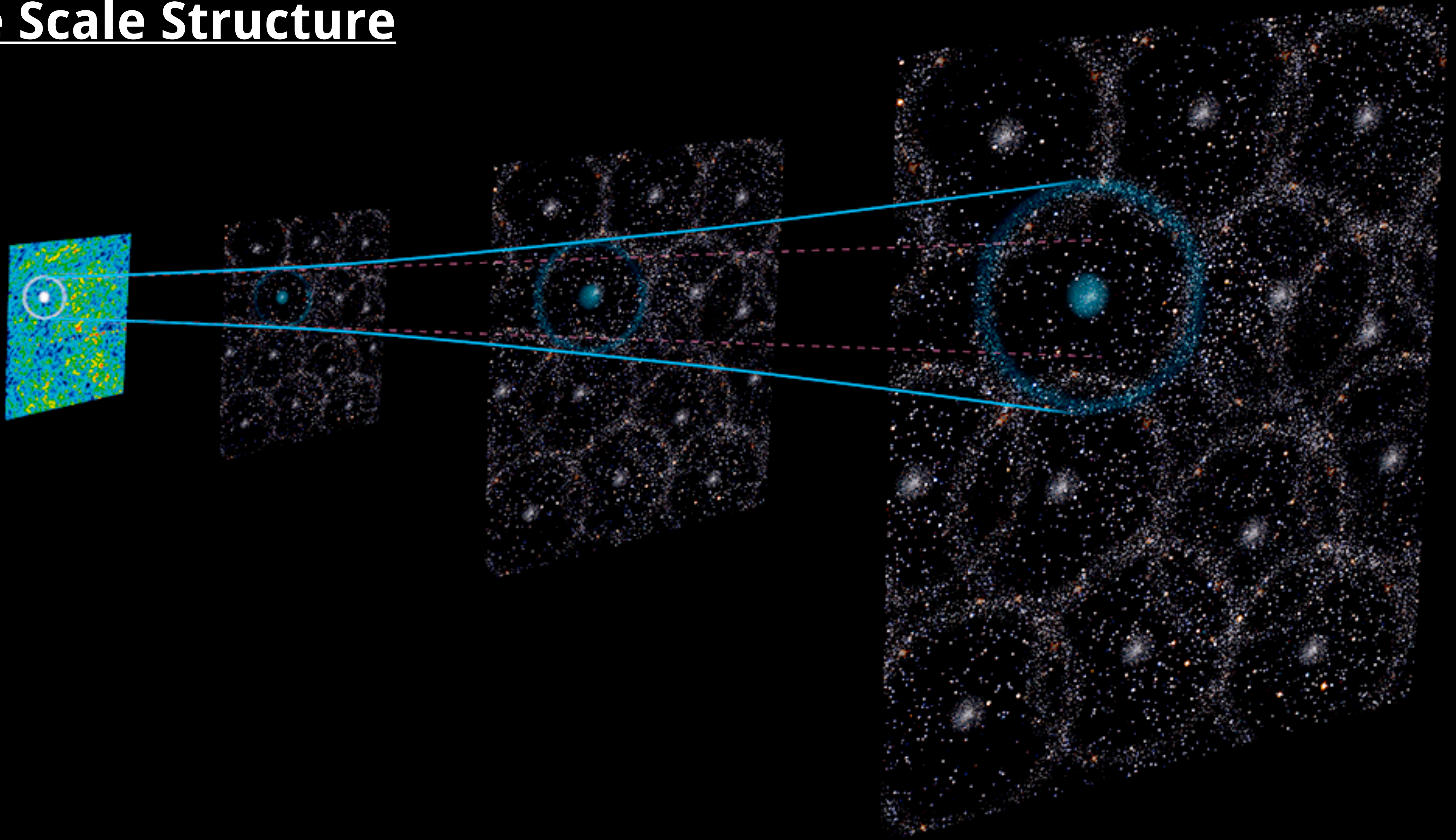
Large Scale Structure

- When baryonic matter collapse it heats up.
- This produces photons that cause the matter to expand (baryonic acoustic oscillations).
- Distribution of galaxies requires a matter that doesn't interact with photons.



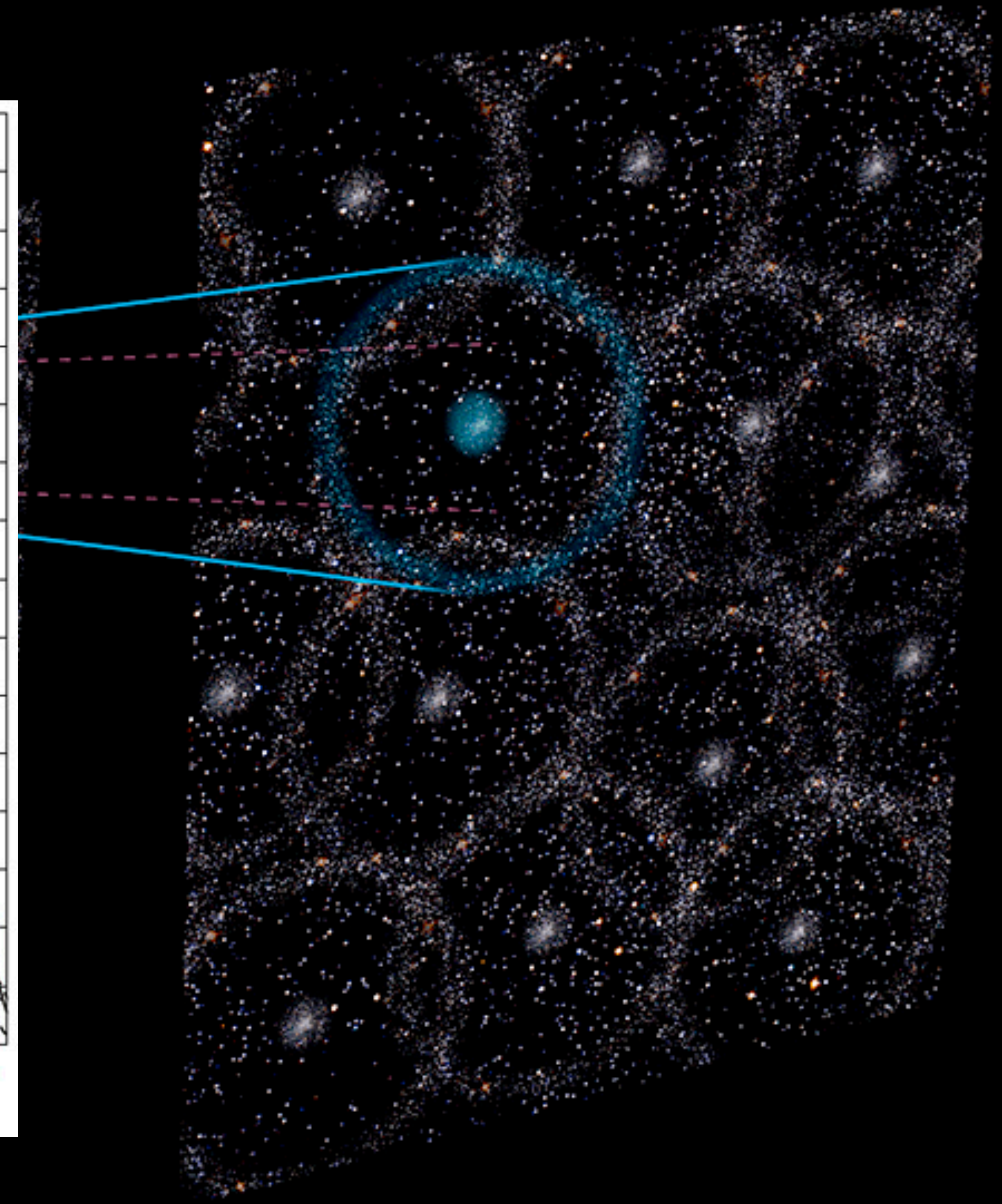
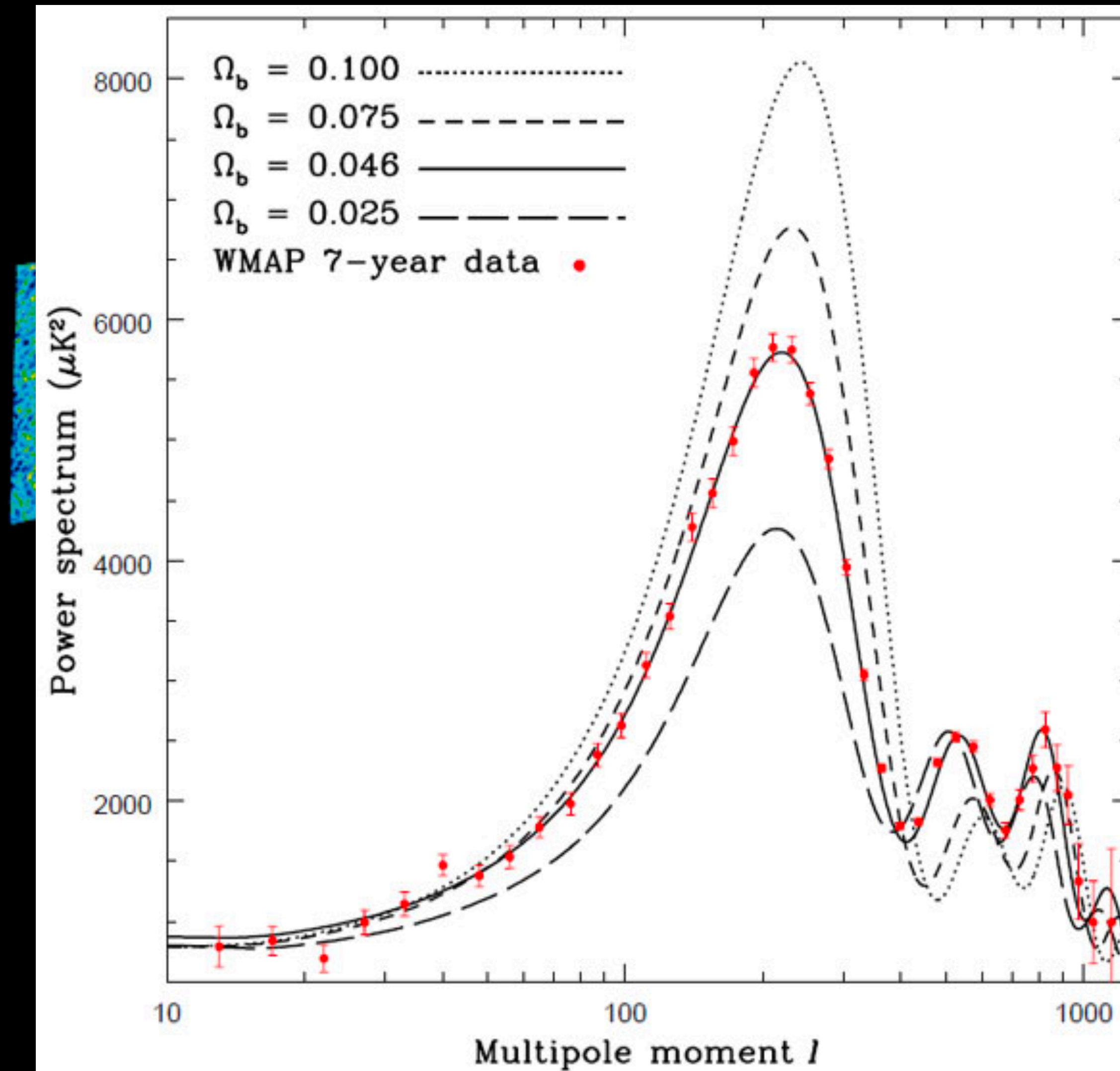
What Do We Know About Dark Matter?

Large Scale Structure

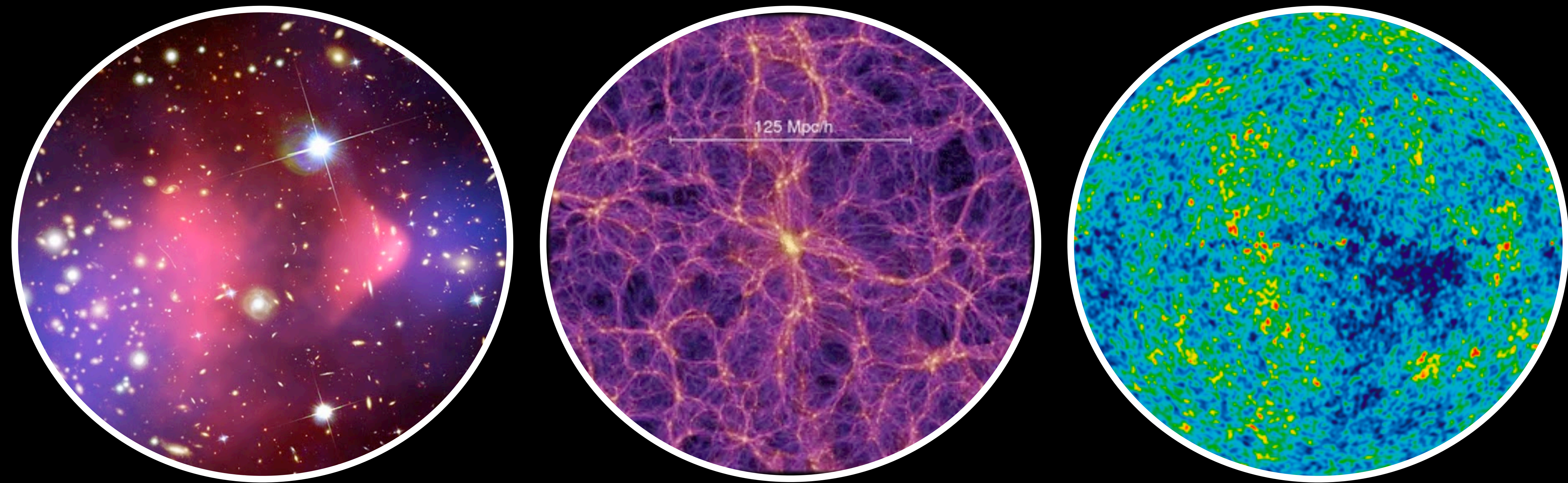


What Do We Know About Dark Matter?

Large Scale Structure



What Do We Know About Dark Matter?

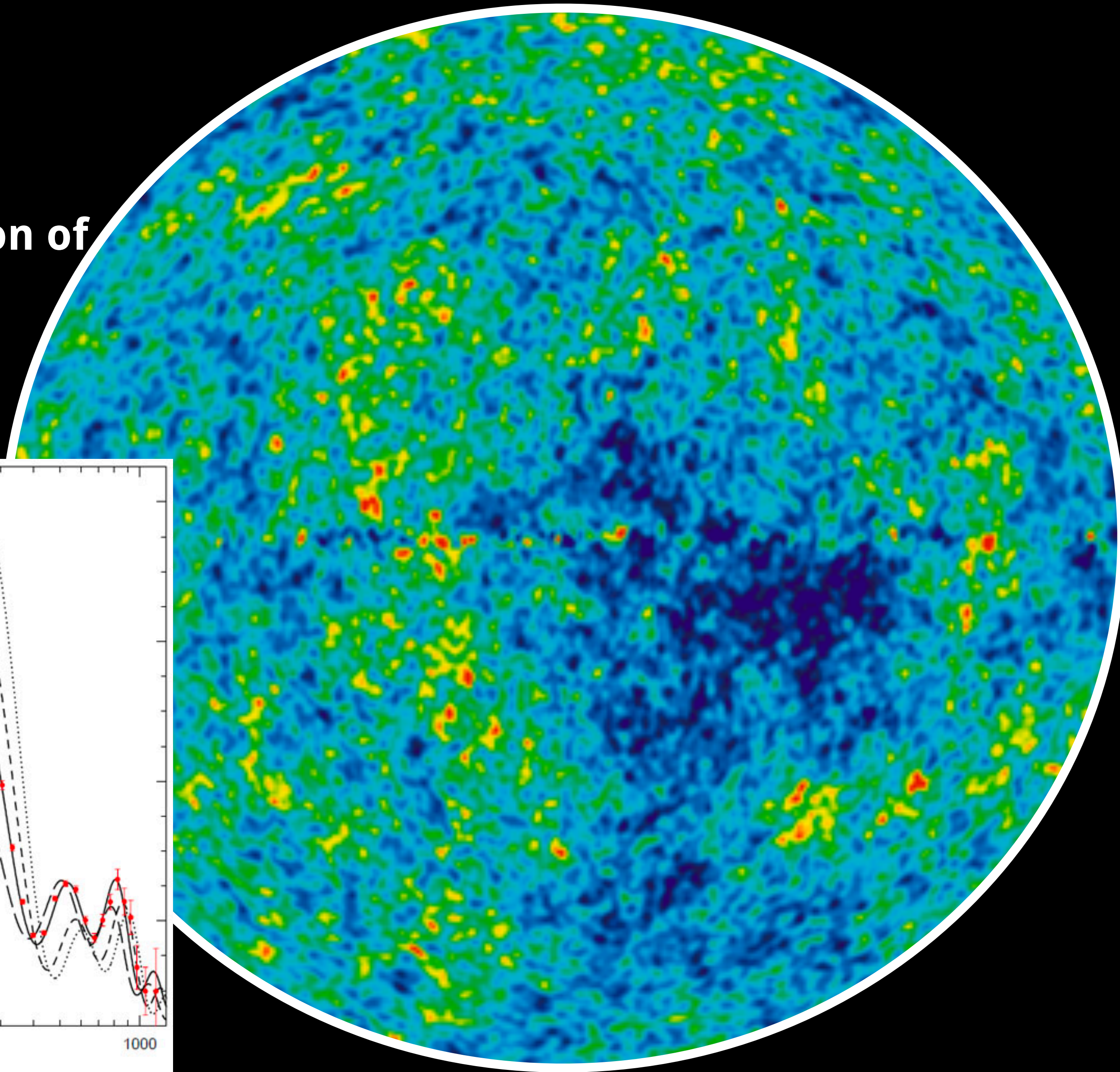
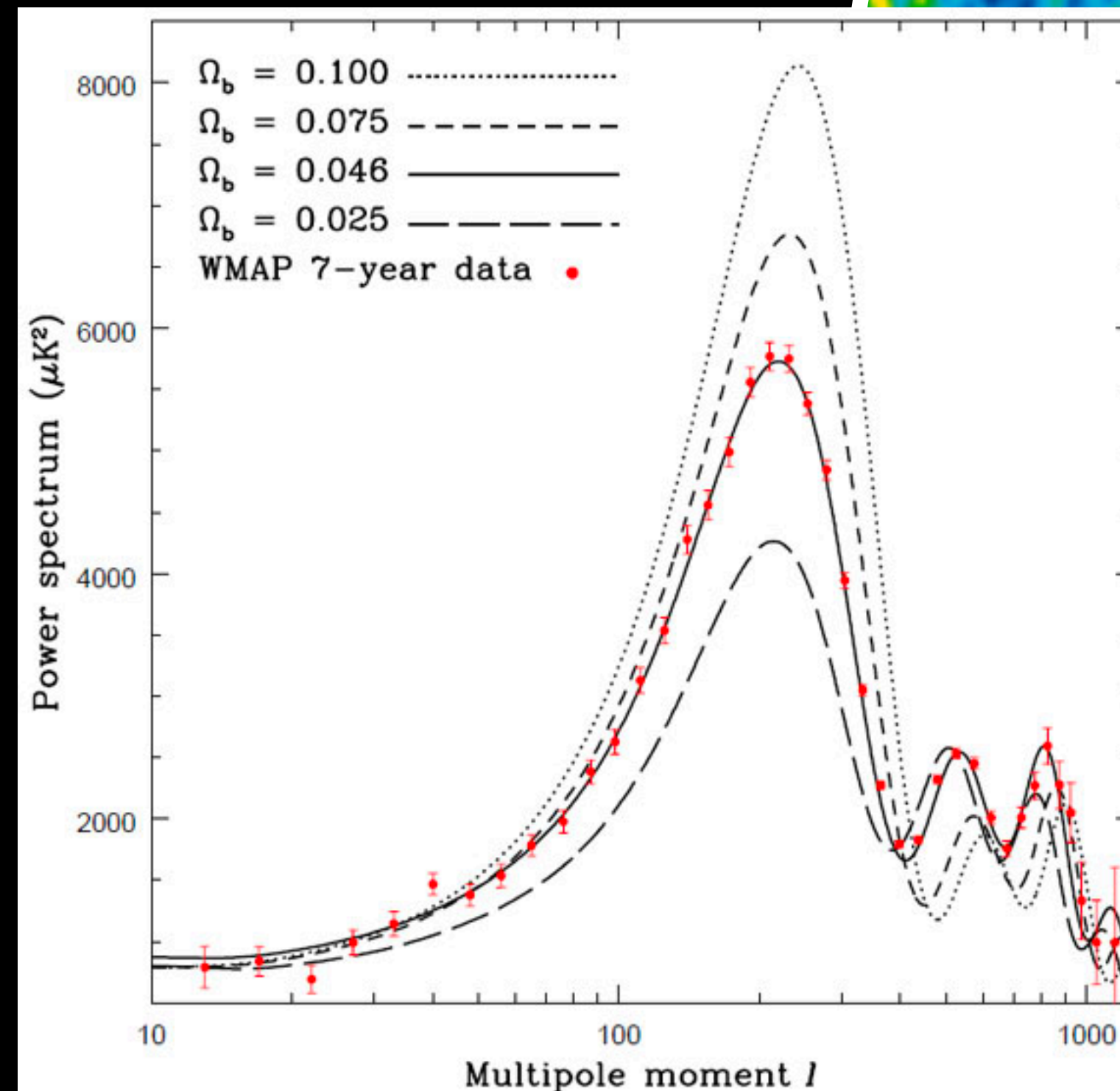


How a cosmologist views the evidence for dark matter.

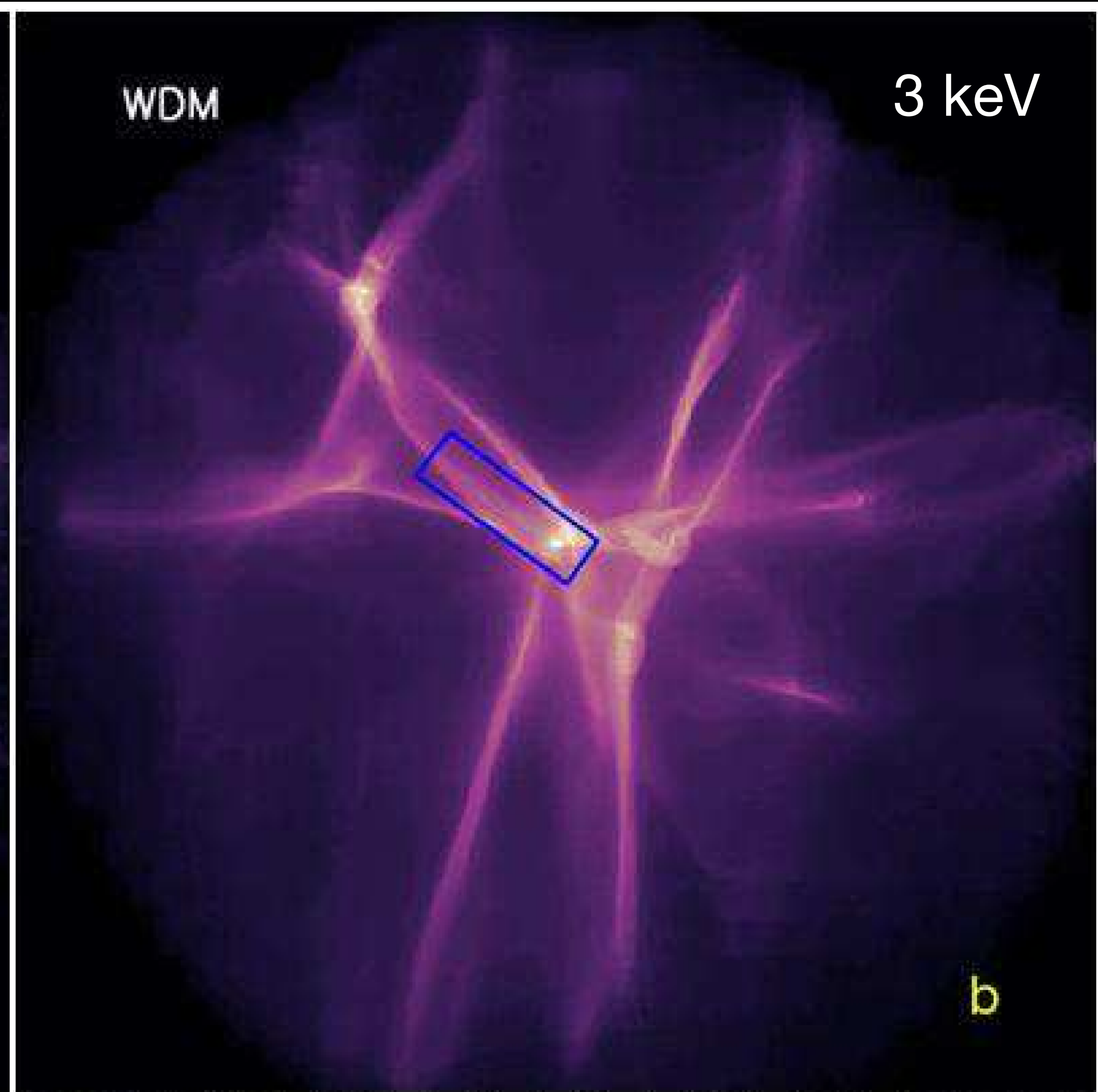
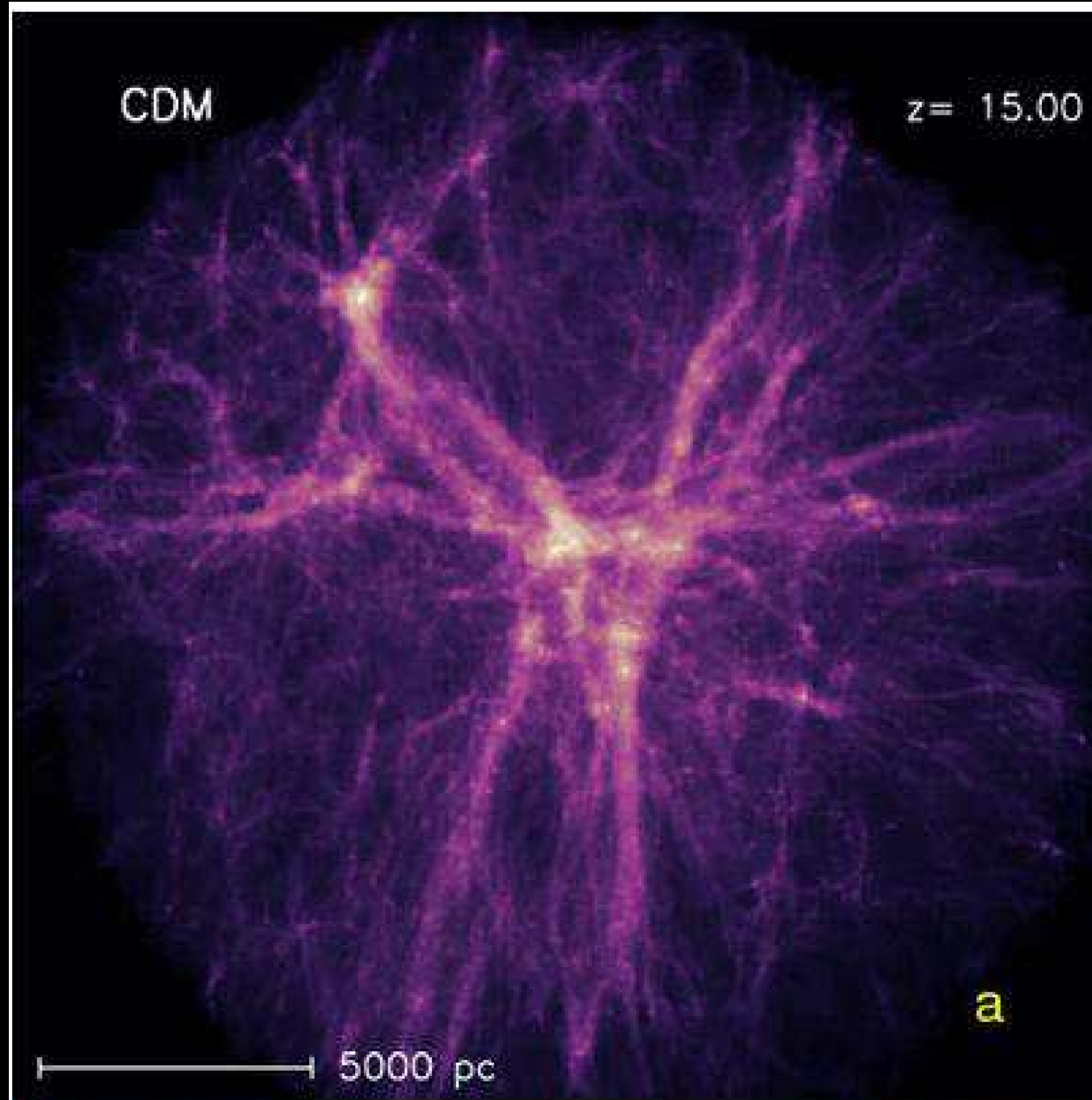
What Do We Know About Dark Matter?

Cosmic Microwave Background

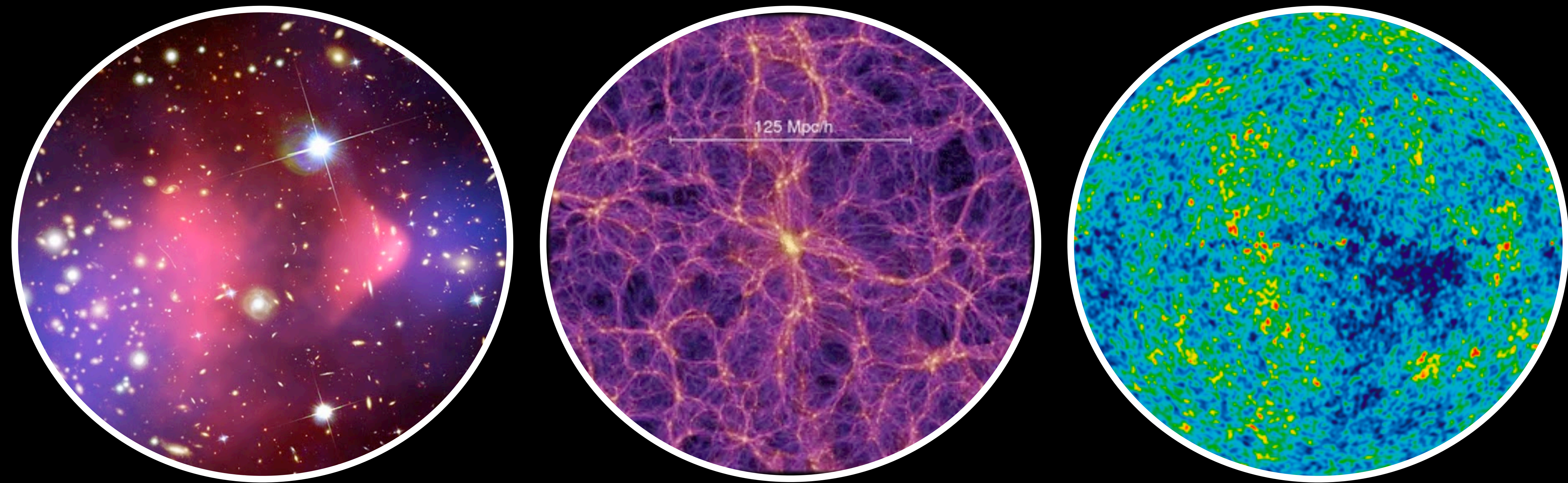
- Interaction of radiation (photons) with cold matter (baryons) controls angular distribution of structure in the early stages of the universe.
- Large component that doesn't interact with radiation is needed.



What Do We Know About Dark Matter?

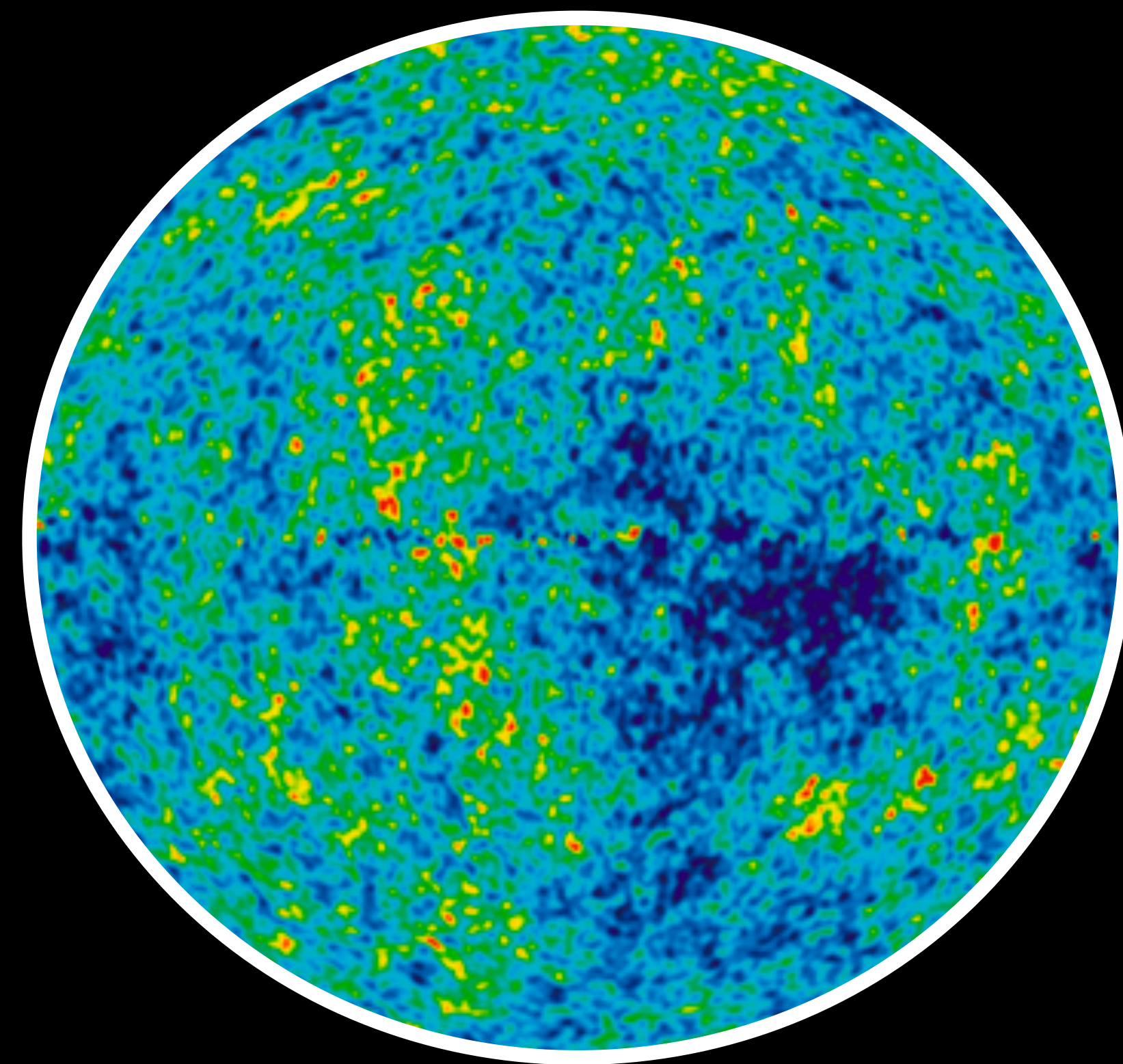
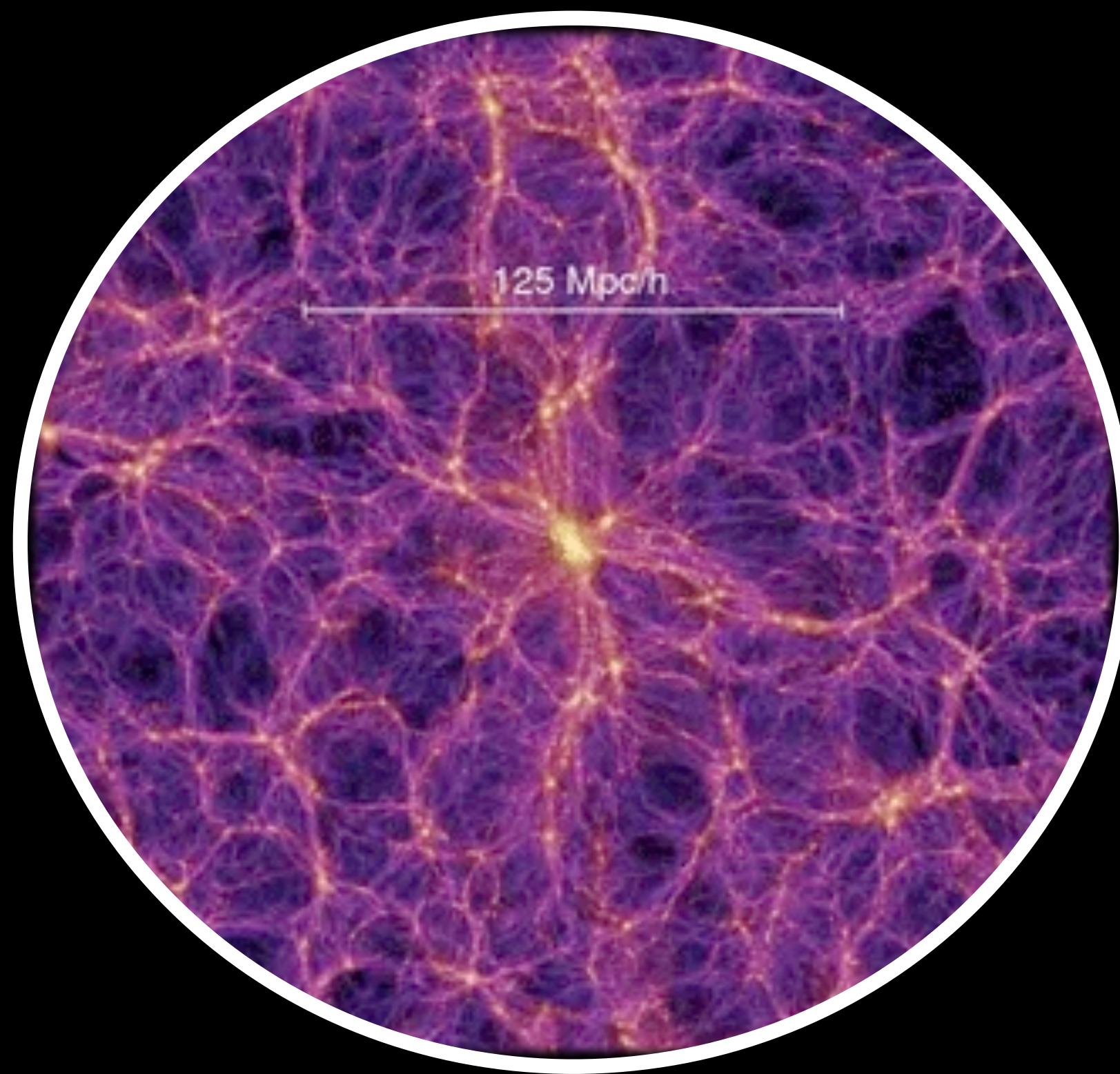


The Present



How a cosmologist views the evidence for dark matter.

The Present



10^{-22} GeV
 $R_{DM} > R_{UFD}$

slide concept courtesy of Asher Berlin

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

Maximum Mass of the Dark Matter Particle



$$M_{\text{DM}} \leq M_{\text{dSph}} = 2 \times 10^5 M_{\odot} = 10^{71} \text{ GeV}$$

Minimum Mass of the Dark Matter Particle



$$R_{\text{DM}} \leq R_{\text{dSph}} \quad \lambda = \frac{h}{p}$$

$$R_{\text{DM}} = \frac{1.2 \text{ eV } \mu\text{m}}{p}$$

$$30 \text{ pc} \approx 10^{26} \mu\text{m}$$

$$p = m_{\chi} (10 \text{ km s}^{-1})$$

$$m_{\text{min}} \approx 3 \times 10^{-22} \text{ eV}$$

Minimum Mass of the Dark Matter Particle

Pauli-Exclusionary Principle

$$f(\vec{x}, \vec{p}) = \mu$$

$$n_x \leq \int_0^{p_{\max}} \frac{d^3 p}{(2\pi)^3} f(\vec{x}, \vec{p}) = \mu p_{\max}^3$$

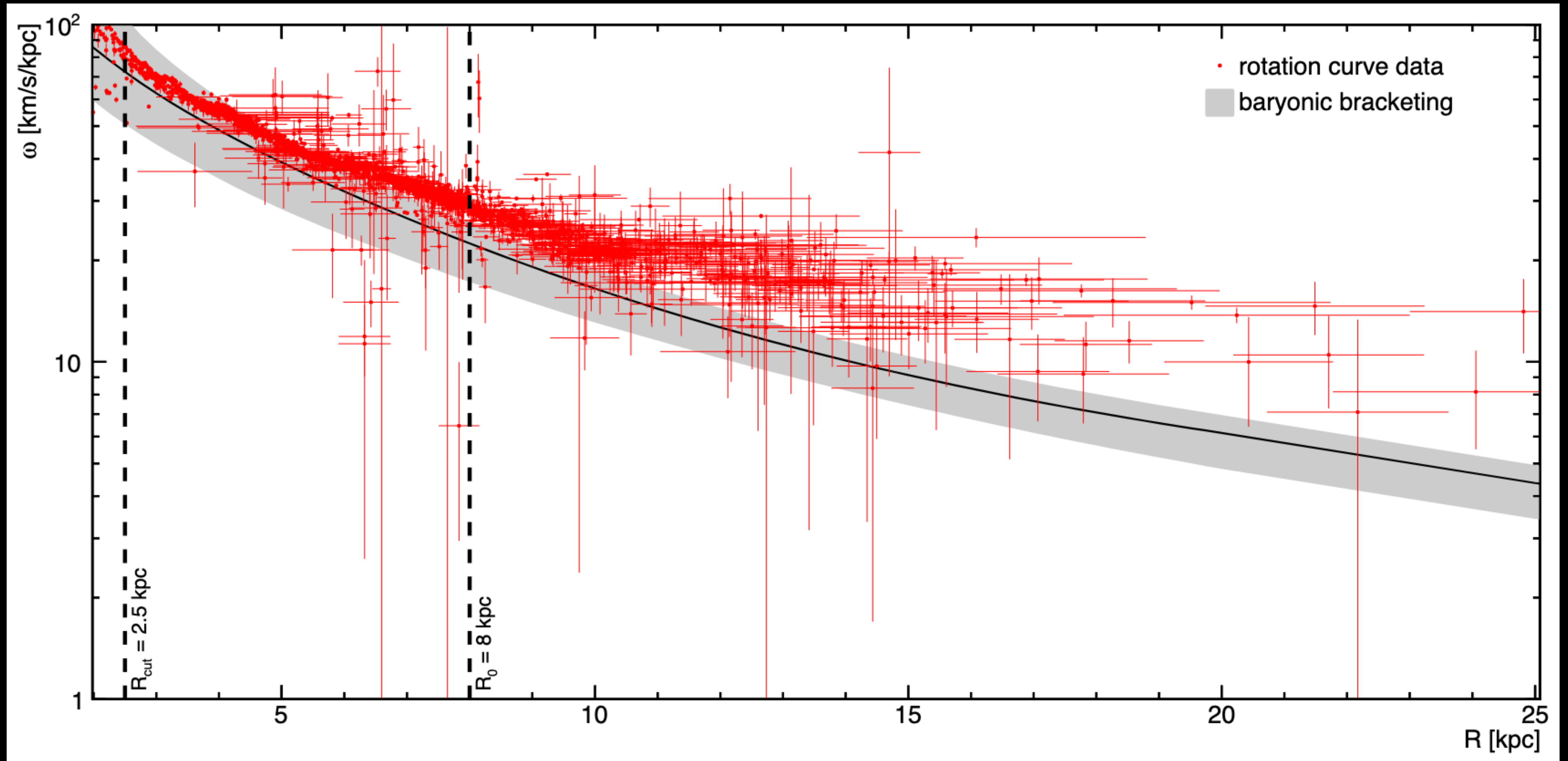
$$m_x^3 v_{\text{esc}}^3 \geq n_\chi = \frac{2 \times 10^{11} M_\odot}{4\pi (35 \text{ kpc})^3 m_\chi}$$

If dark matter is a fermion

$$m_\chi > 100 \text{ eV}$$

Where is the Dark Matter?

Local Observations

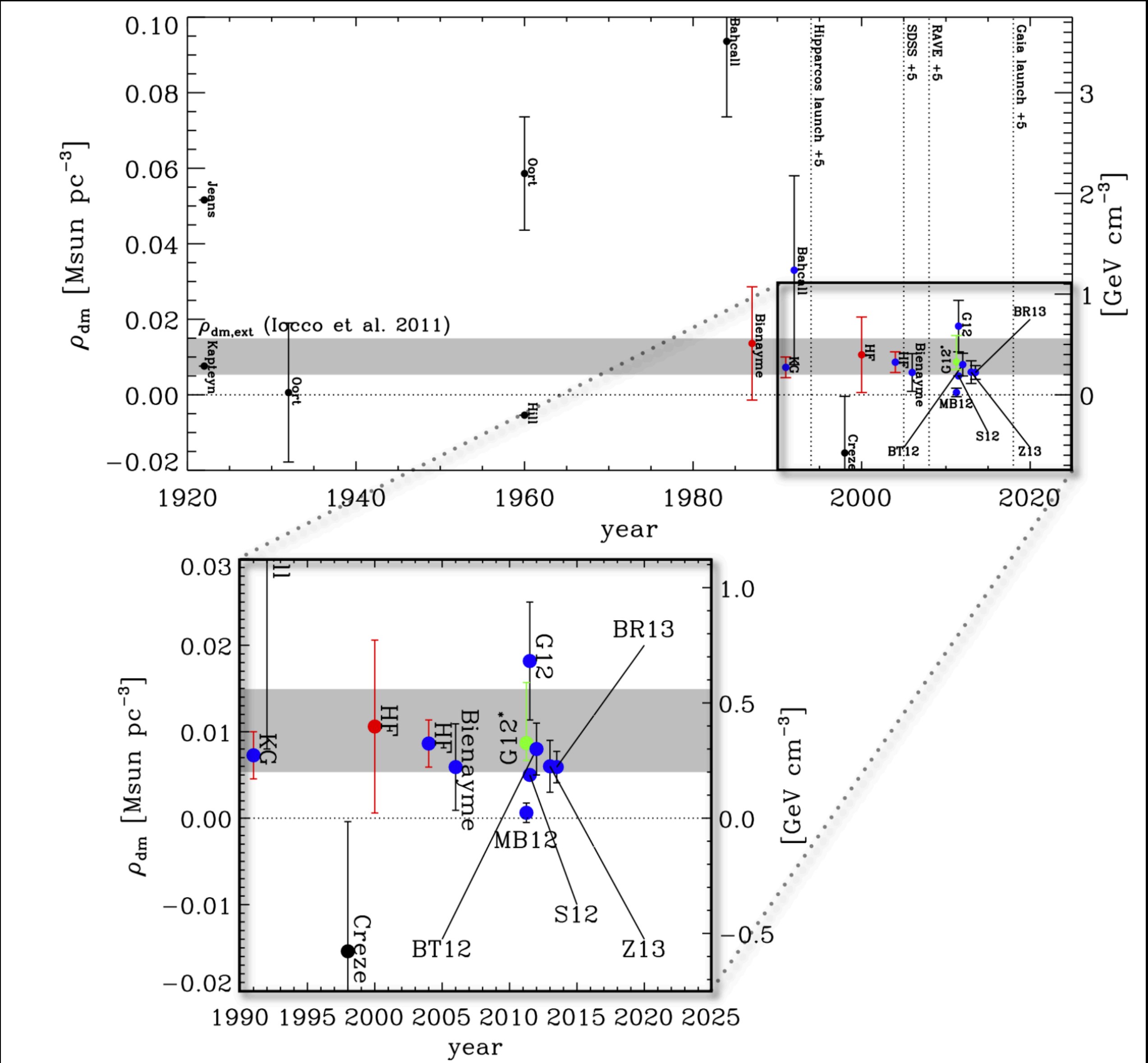


See:
Pato, Iocco (2015)

Where is the Dark Matter?

Local Observations

- Many observations of local density
- Stellar rotation curves, height distributions, GAIA data
- Still 50% uncertainties.



See:
Read (2014; 1404.1938)

Where is the Dark Matter?

Local Observations

DARK MATTER DENSITY
IN THE SOLAR SYSTEM
IS AROUND $0.3 \text{ GeV}/\text{cm}^3$

IS ... THAT A LOT?



IN TERMS OF MASS,
IT MEANS THE EARTH
CONTAINS ONE SQUIRREL
WORTH OF DARK MATTER
AT ANY GIVEN TIME.

WOW.



IS THERE ANY WAY
TO FIND OUT WHICH
SQUIRREL IT IS?

NO, IT'S NOT
LITERALLY—



OH, THAT EXPLAINS WHY
THEY WEIGH ENOUGH TO
SET OFF THOSE SPINNING
BIRD FEEDERS!

**DARK MATTER
ISN'T SQUIRRELS!**



Where is the Dark Matter?

Local Observations

- Navarro-Frenk White (NFW) Profile

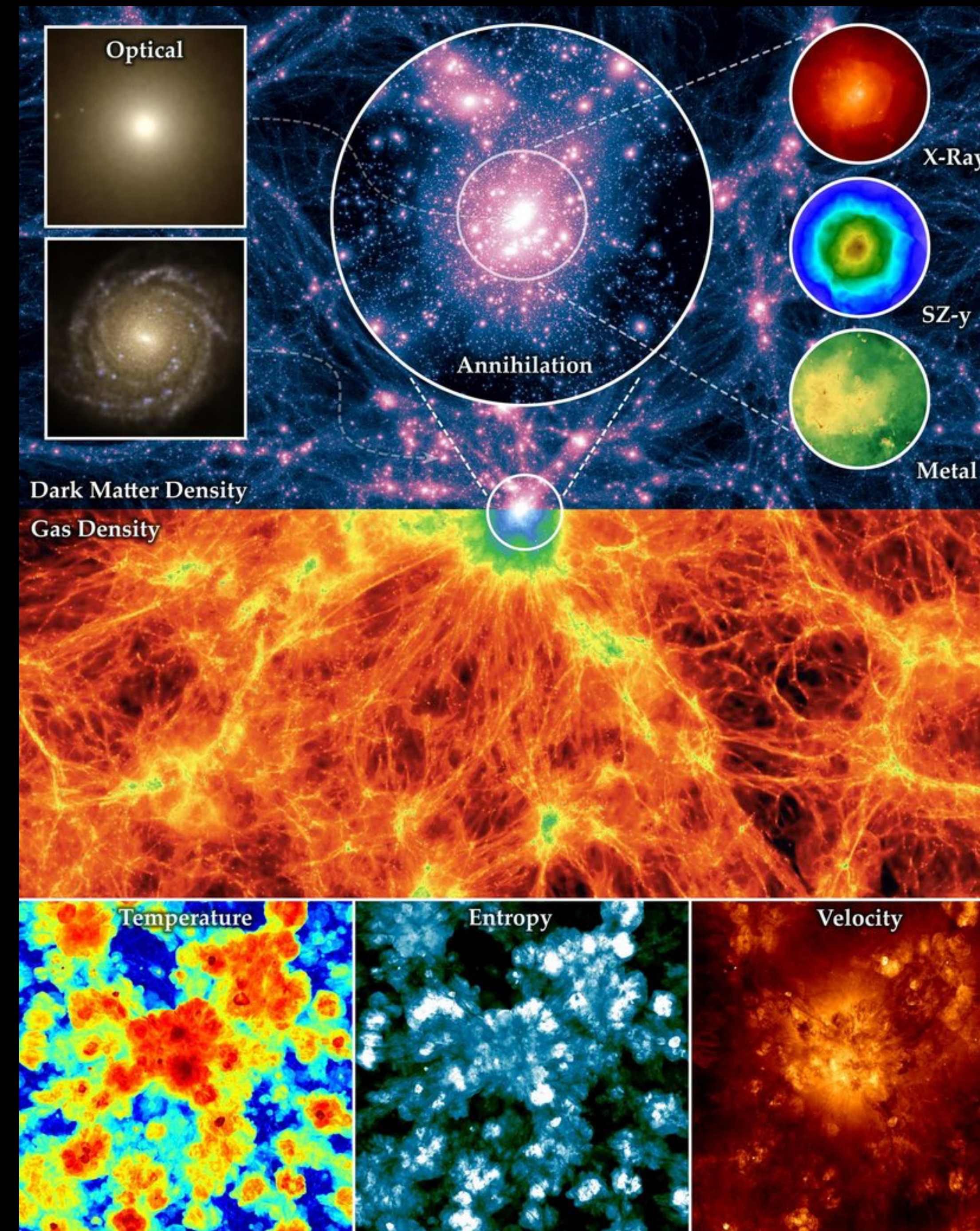
$$\rho_\chi = \rho_0 \left(\frac{r}{r_s} \right)^{-1} \left(1 + \frac{r}{r_s} \right)^{-2}$$

- Generalized NFW Profile

$$\rho_\chi = \rho_0 \left(\frac{r}{r_s} \right)^{-\alpha} \left(1 + \frac{r}{r_s} \right)^{-3+\alpha}$$

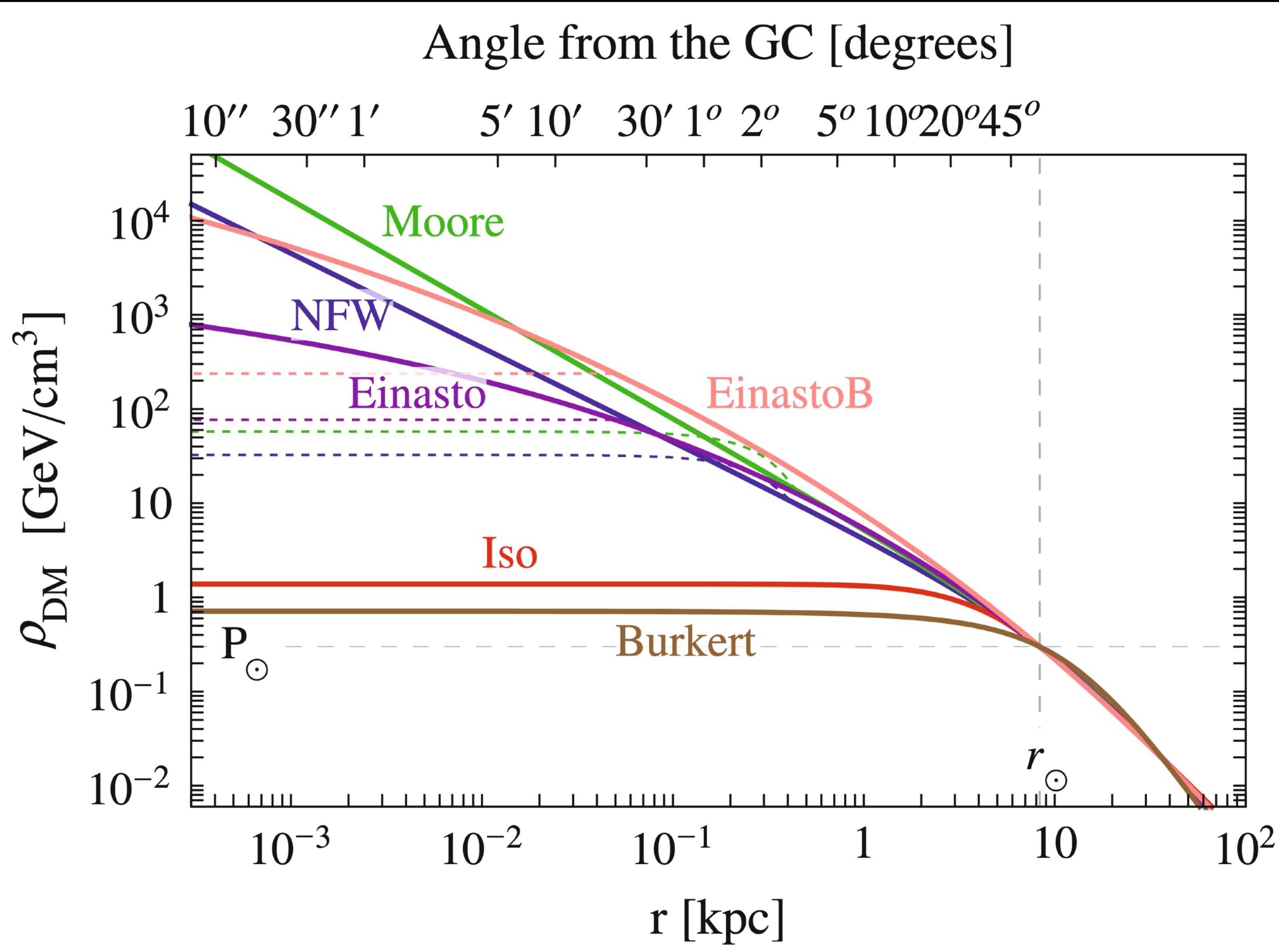
- Einasto Profile

$$\rho_\chi = \rho_0 \exp \left[-\frac{2}{\alpha} \left(\frac{r}{r_s} \right)^\alpha - 1 \right]$$



Where is the Dark Matter?

Local Observations



Where is the Dark Matter?

J-Factors

- Remember, we cannot constrain distances astrophysically.

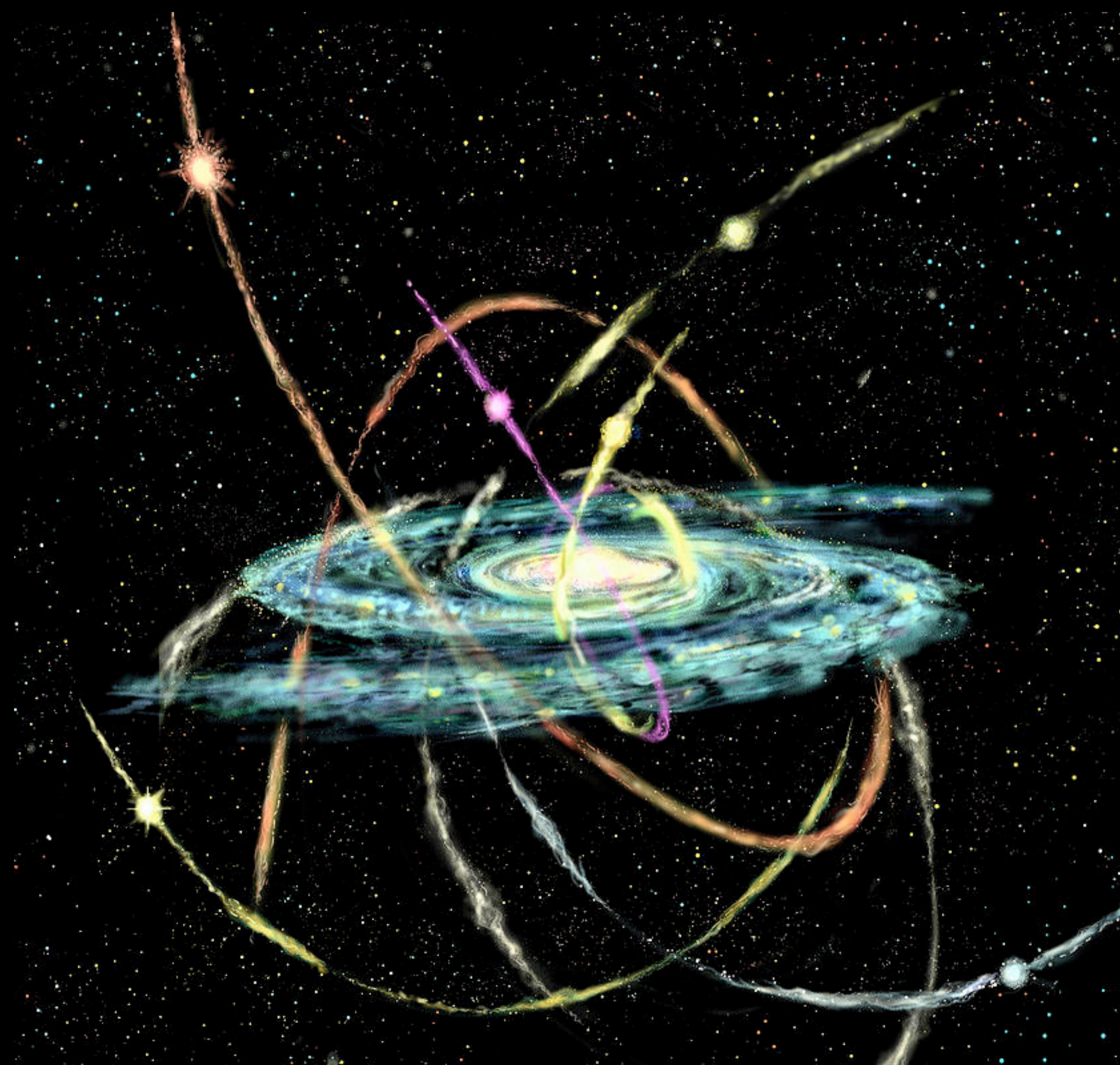
$$\underbrace{\int_{\Delta\Omega} \int_{\text{l.o.s.}} \rho_{\text{DM}}^2(\boldsymbol{r}) d\ell d\Omega'}_{\text{J-factor}}$$

- For decaying dark matter, this will depend on ρ and not ρ^2 (and is normally called the D-factor for Decay).
- Large uncertainties: The majority of the signal depends on regions near the centers of structures, where the dark matter density is maximally uncertain.

Where is the Dark Matter?

Dwarf Spheroidal Galaxies

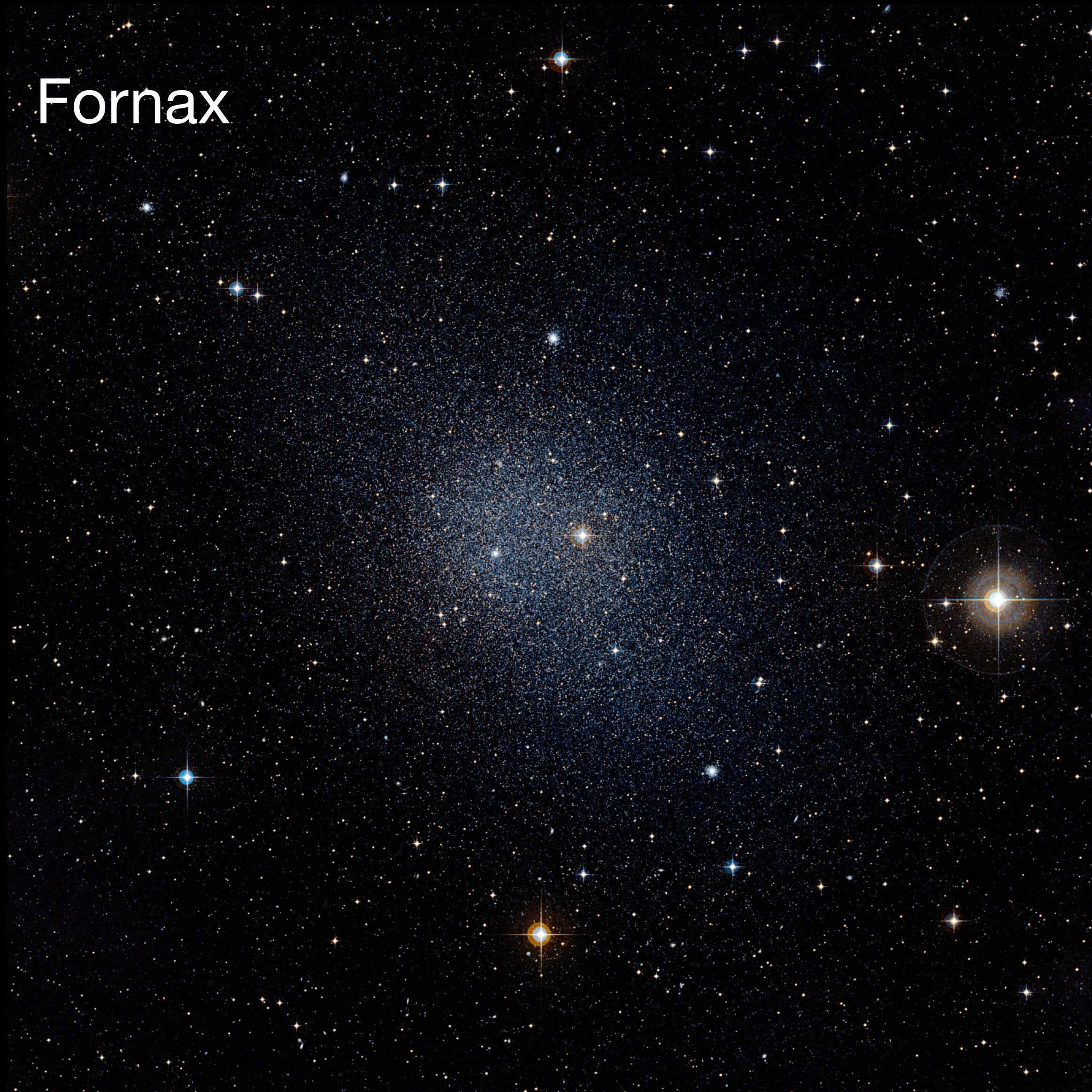
- Dark Matter dominated structures.
 - Stellar rotation curves almost always dark matter dominated.
- Single stellar population with negligible baryonic feedback, SNe, etc.



Where is the Dark Matter?

Dwarf Spheroidal Galaxies

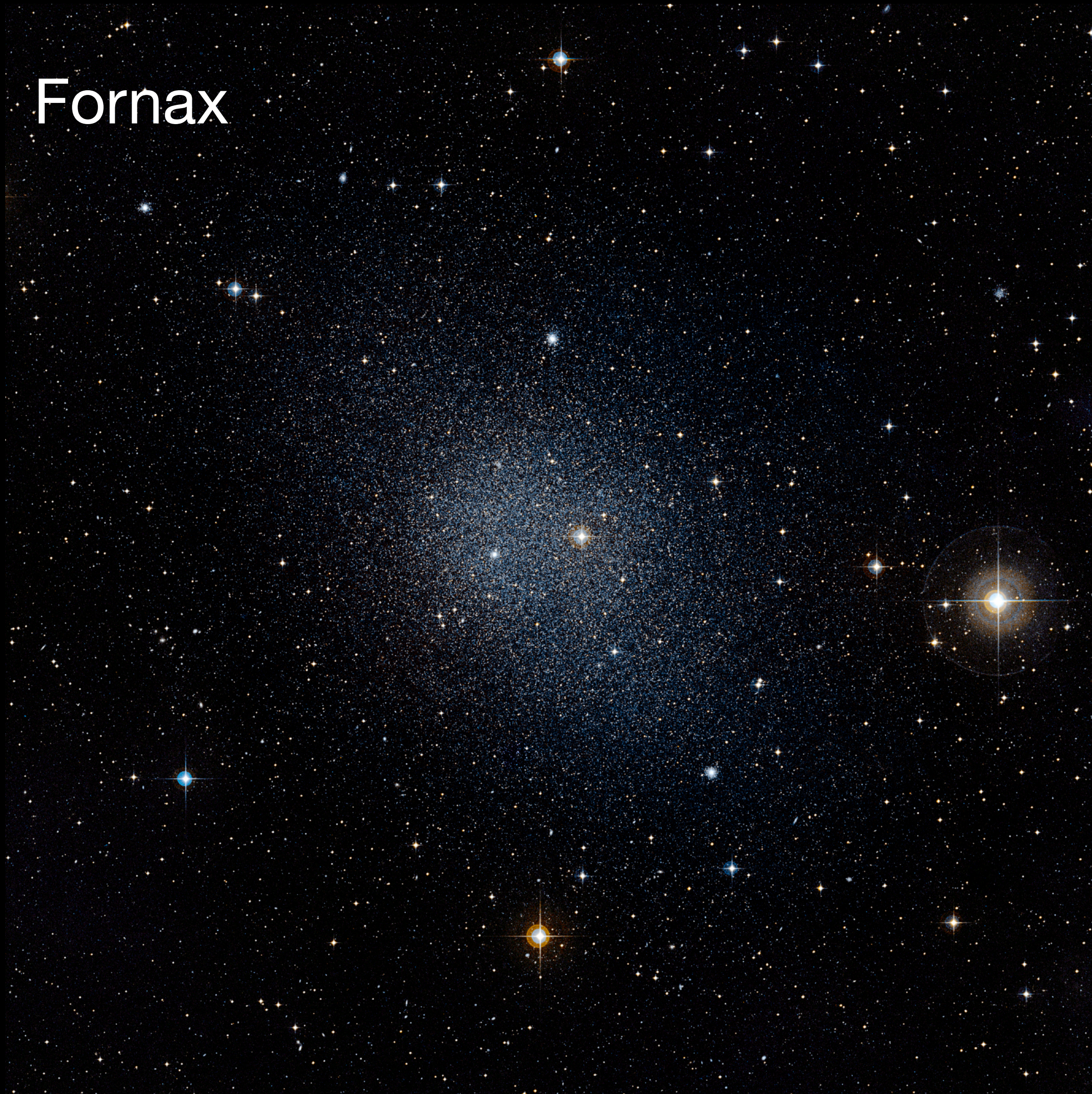
Fornax



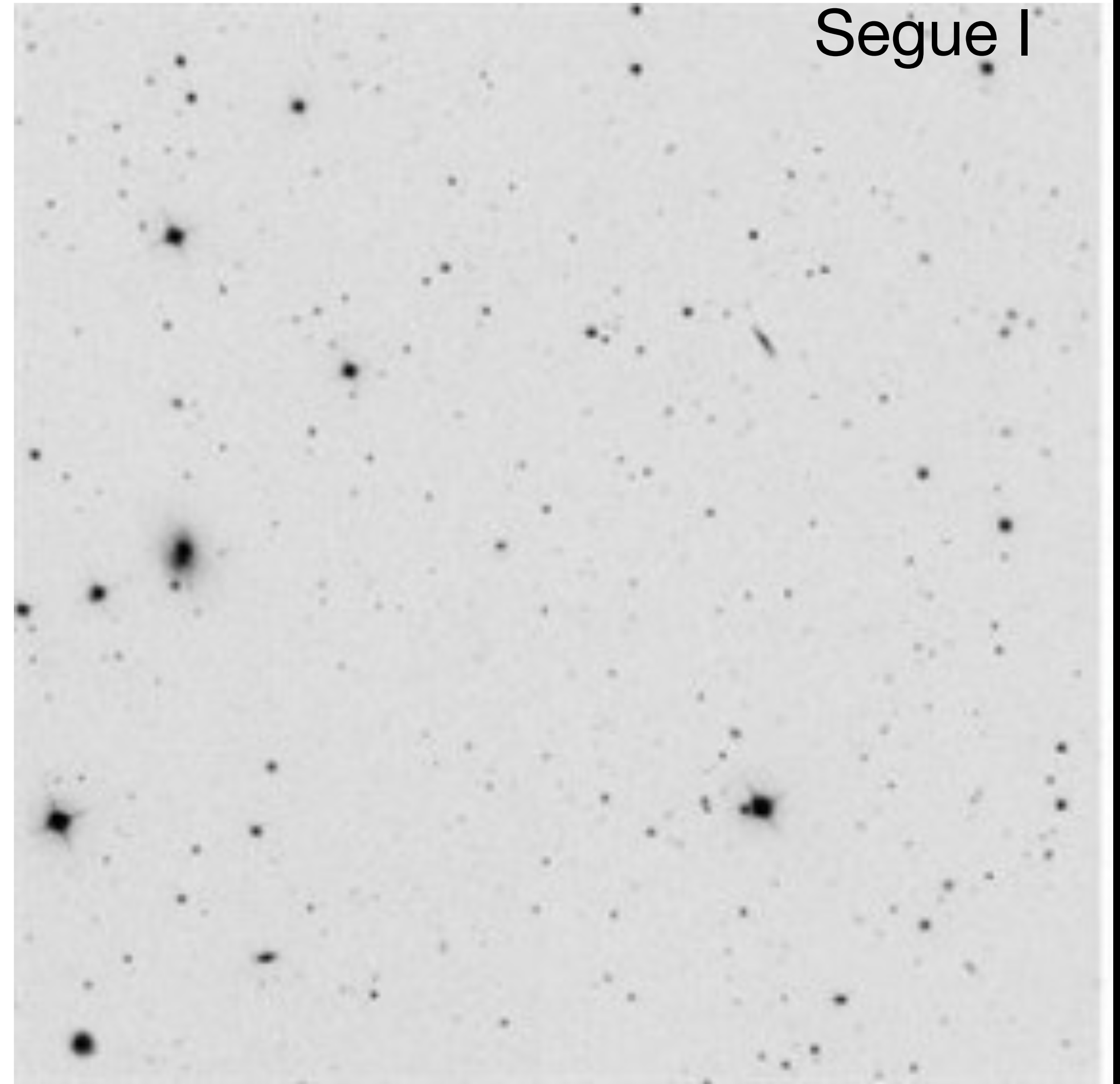
Where is the Dark Matter?

Dwarf Spheroidal Galaxies

Fornax



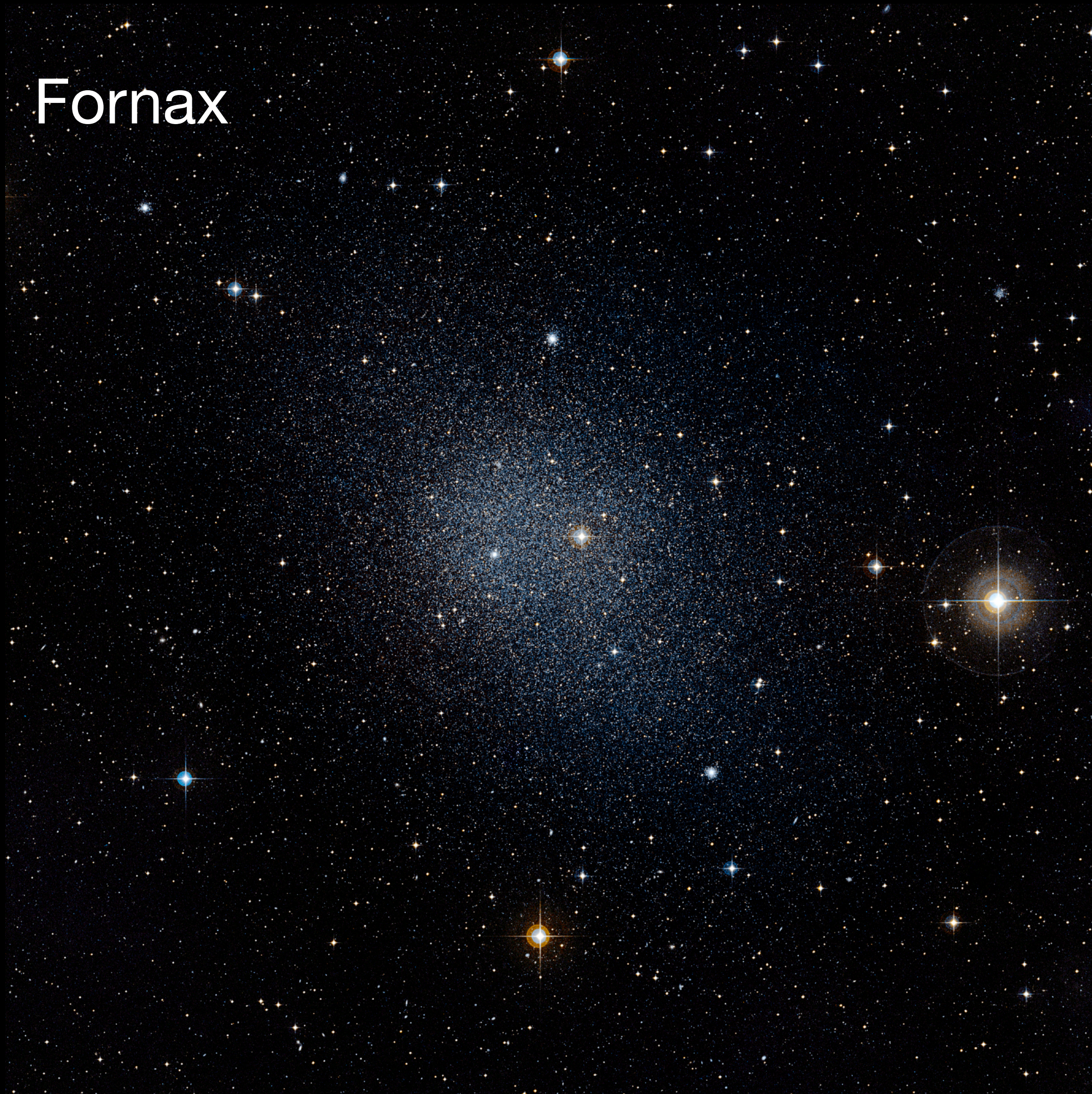
Segue I



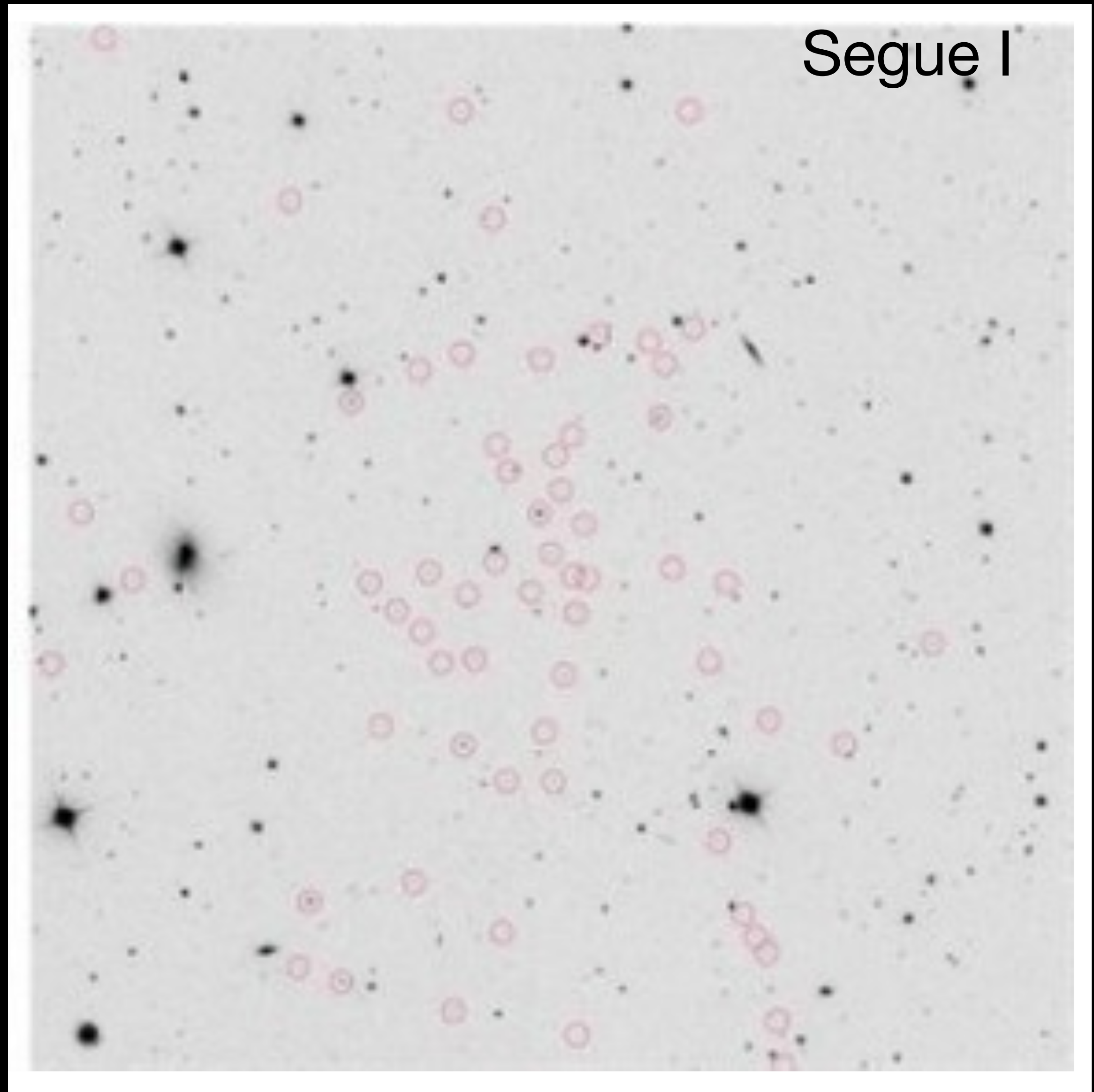
Where is the Dark Matter?

Dwarf Spheroidal Galaxies

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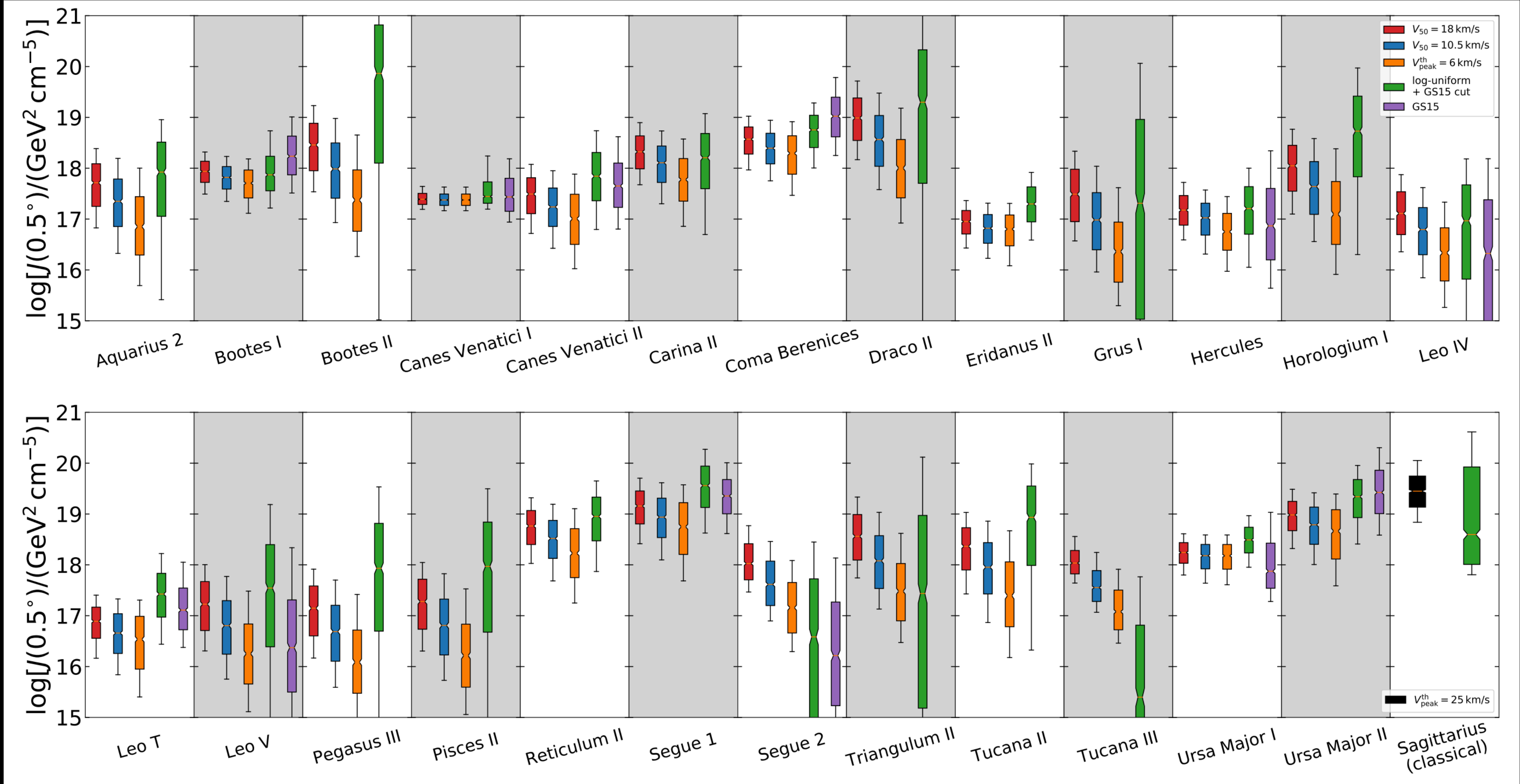


Segue I



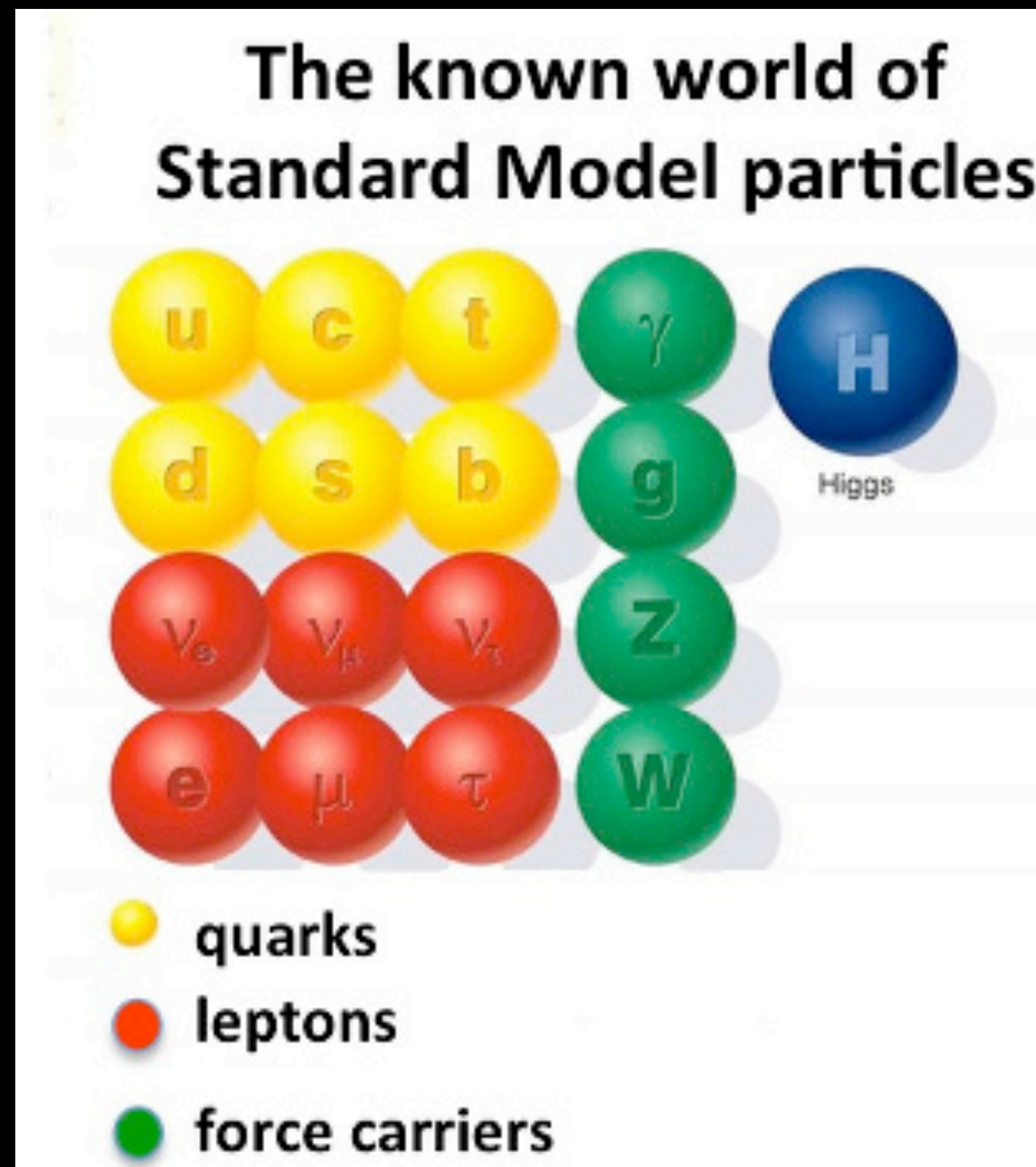
Where is the Dark Matter?

Dwarf Spheroidal Galaxies



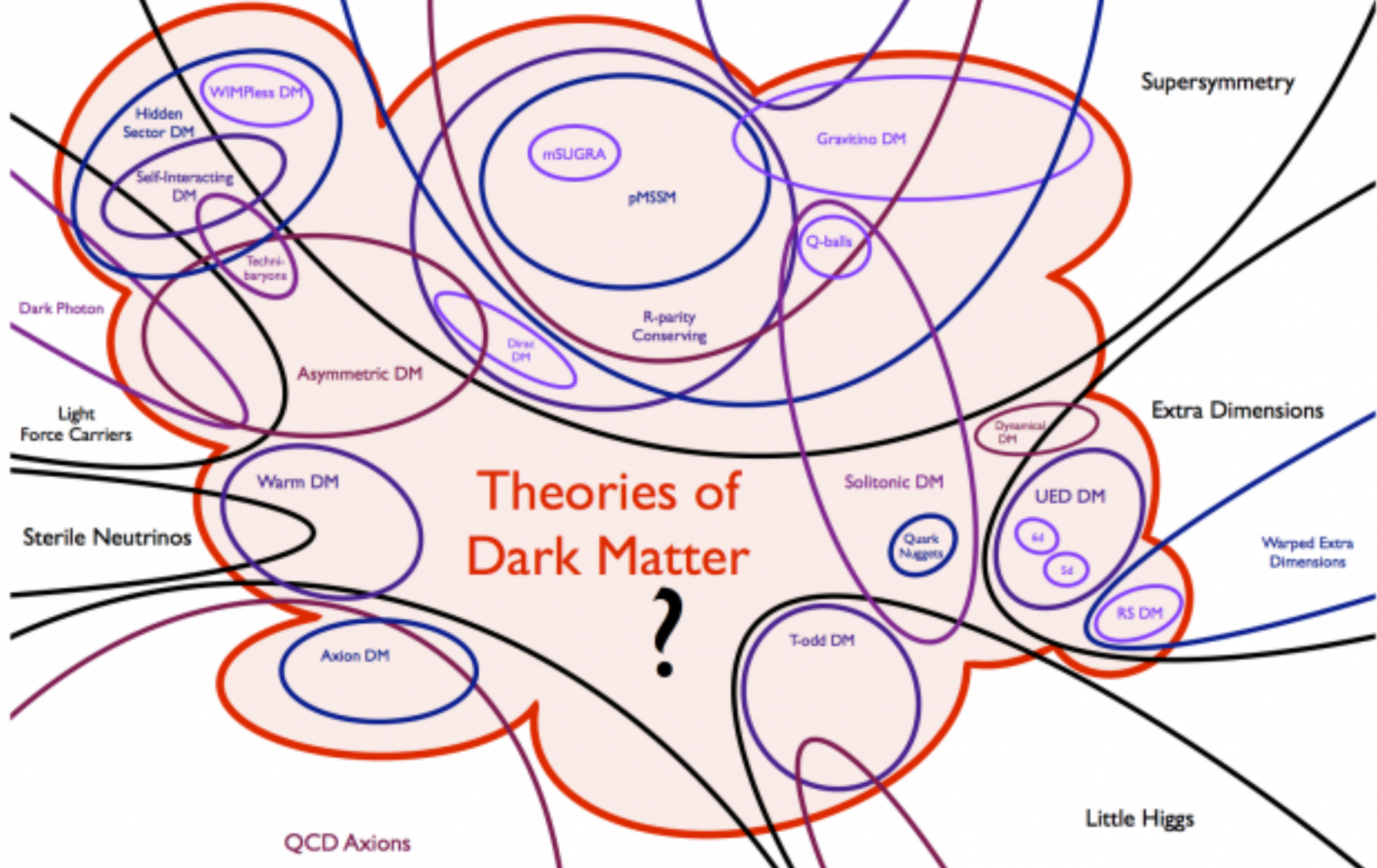
Properties of the Dark Matter Particle

- Three Key Particle Properties of Dark Matter
 - Stable
 - Does not Interact with Light (Dark)
 - Does not move relativistically throughout the Universe (Cold)



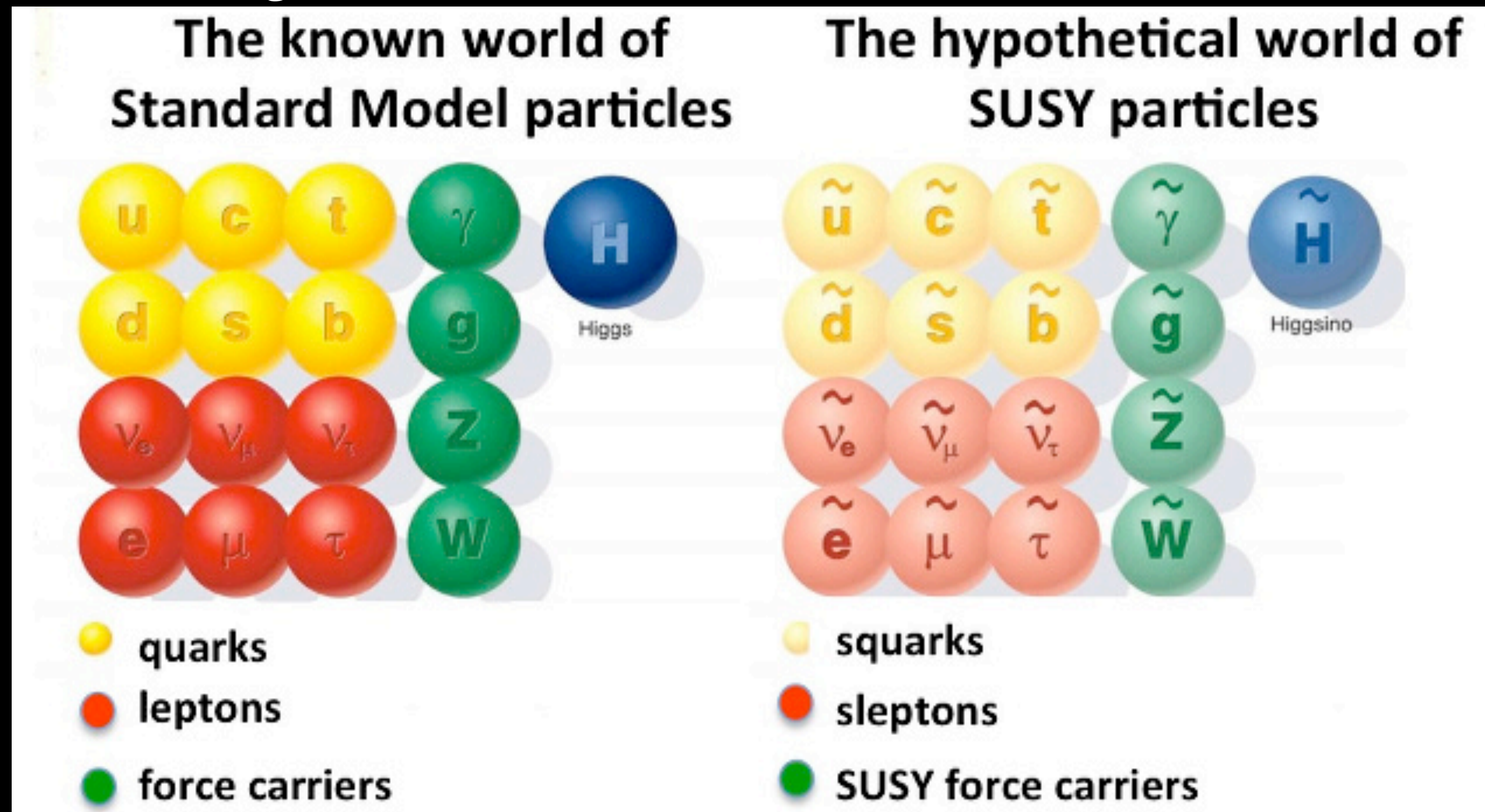
Theories of Dark Matter

?



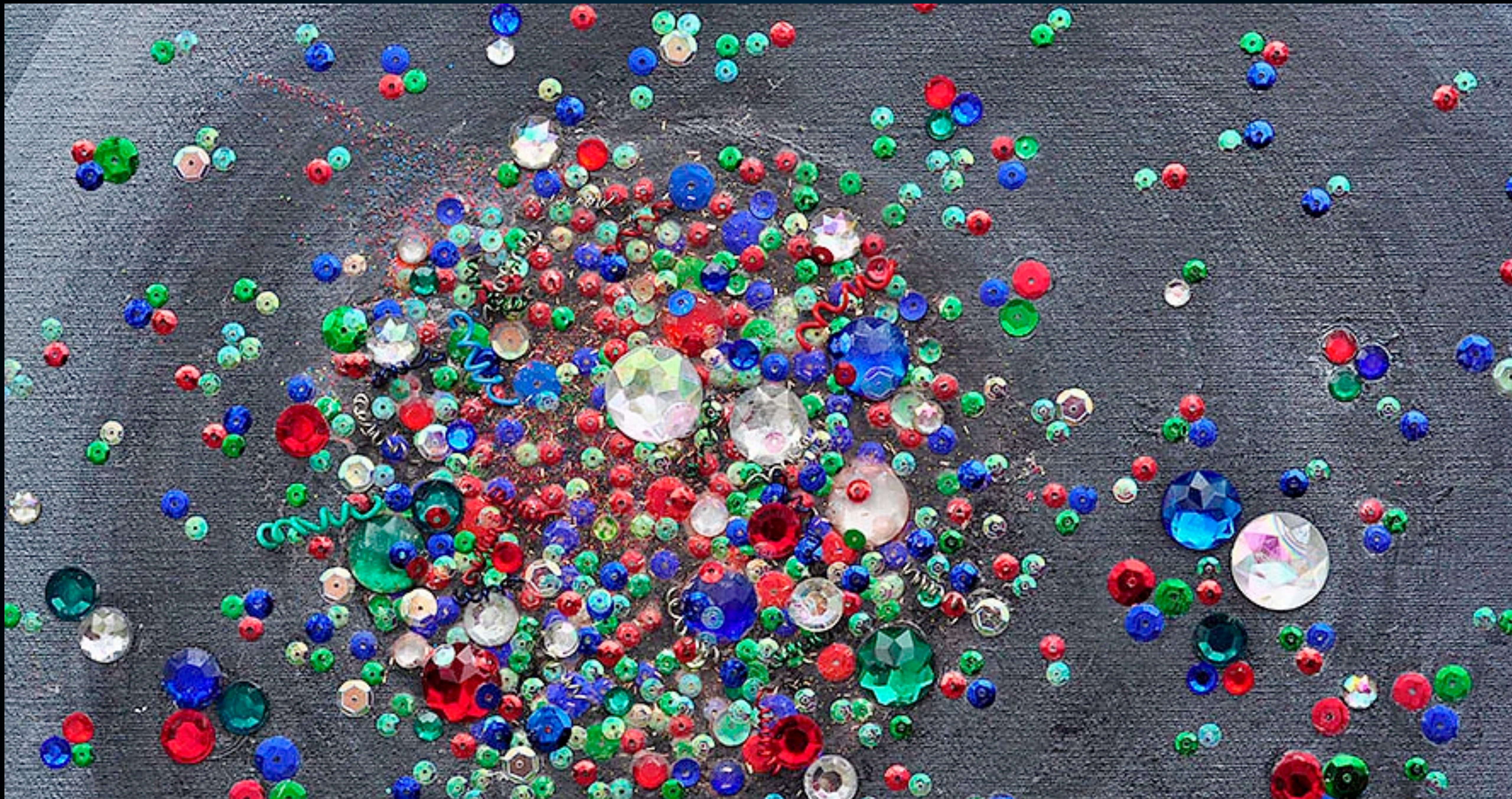
WIMP (and WIMP-like) Dark Matter

- What about the lightest supersymmetric particle?
 - R-parities can prevent decay into standard model particles (stable)
 - Likely Heavy (cold)
 - Would not interact with light if it is neutral (dark)

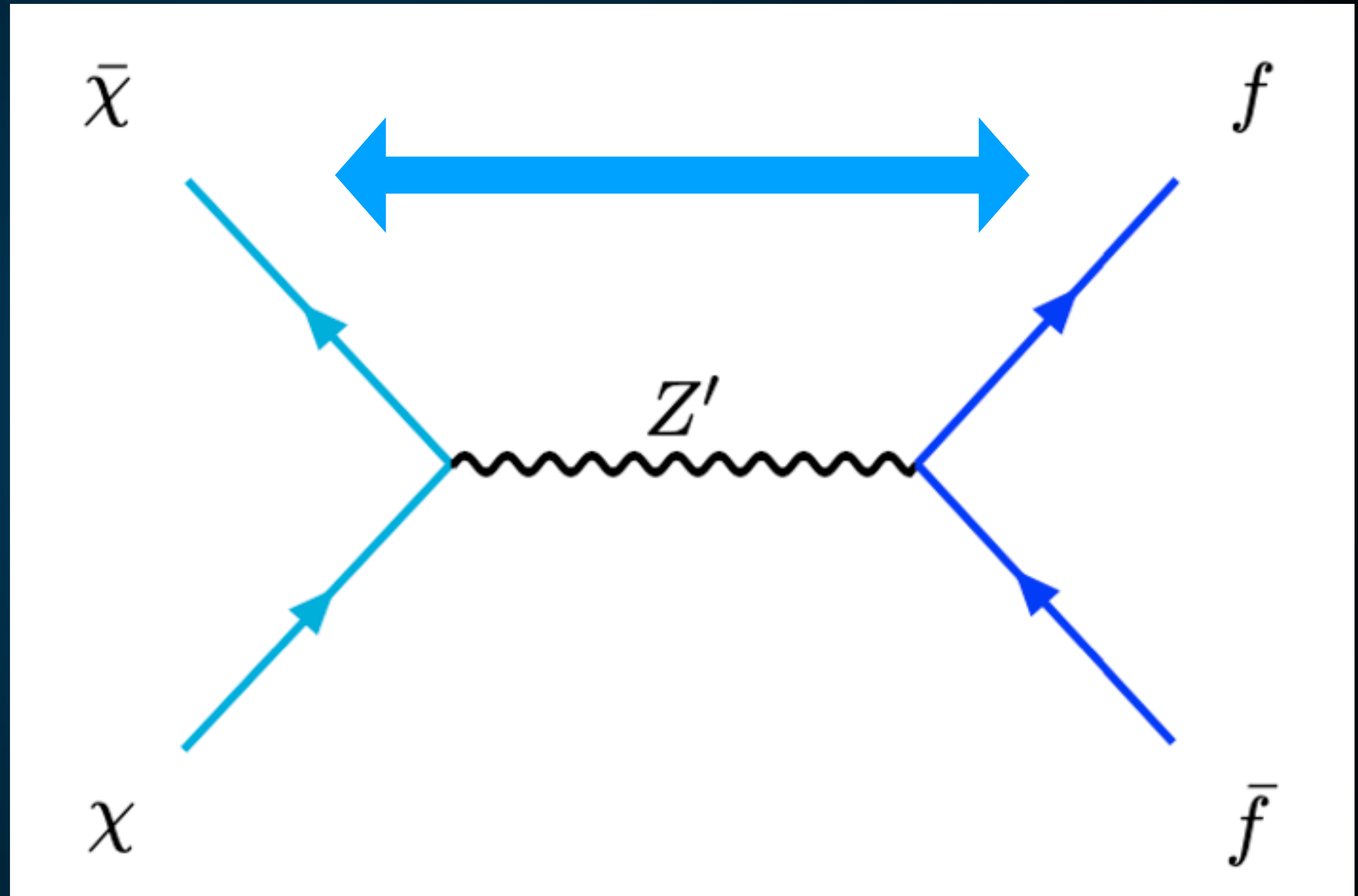


Thermal Dark Matter

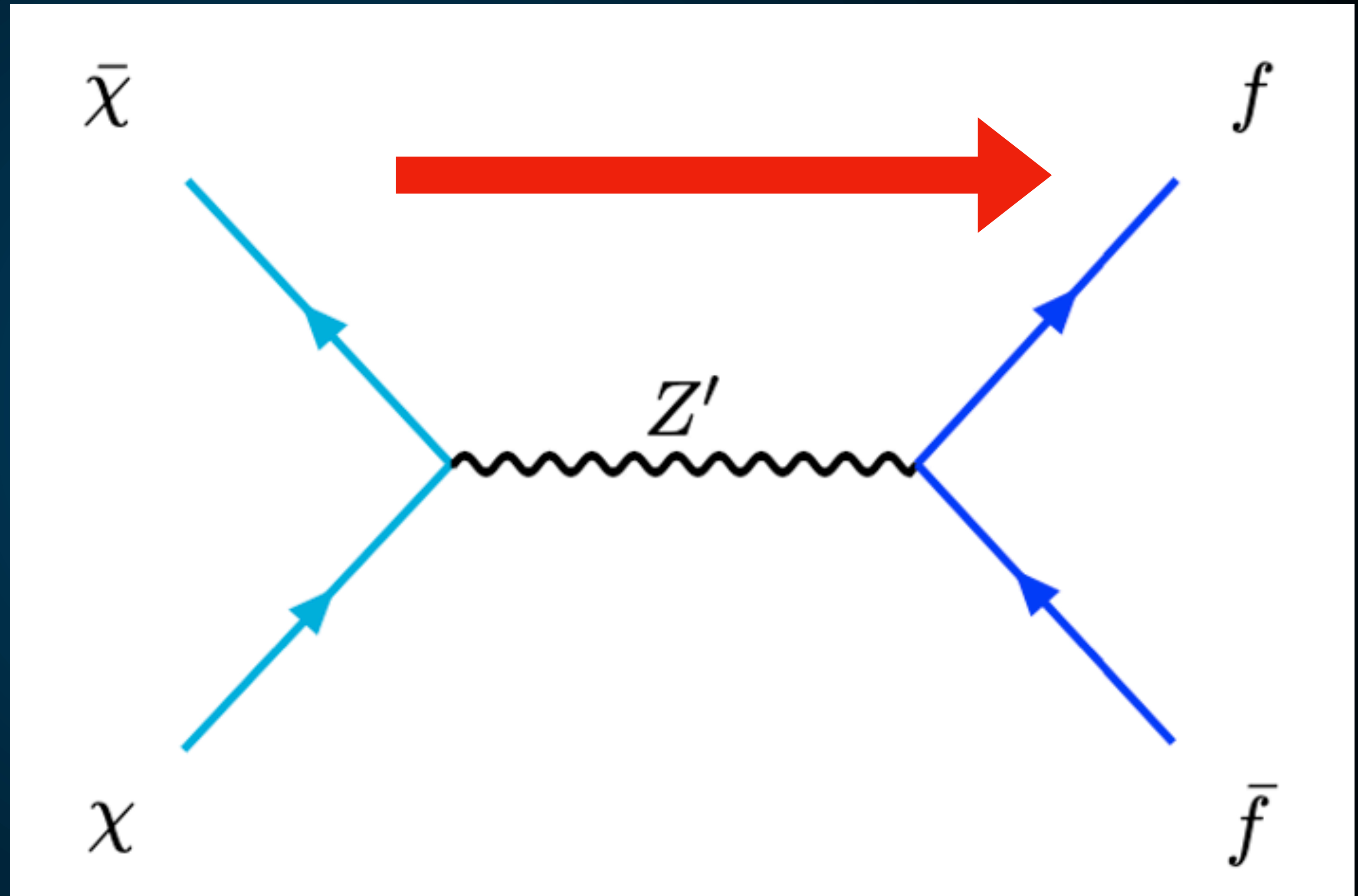
artist: Sarah Szabo



Thermal Dark Matter



Thermal Dark Matter



Thermal Freeze-Out/WIMP Miracle

- Three periods:
 - Thermal equilibrium with baryons
 - Annihilating away
 - Hubble expansion wins

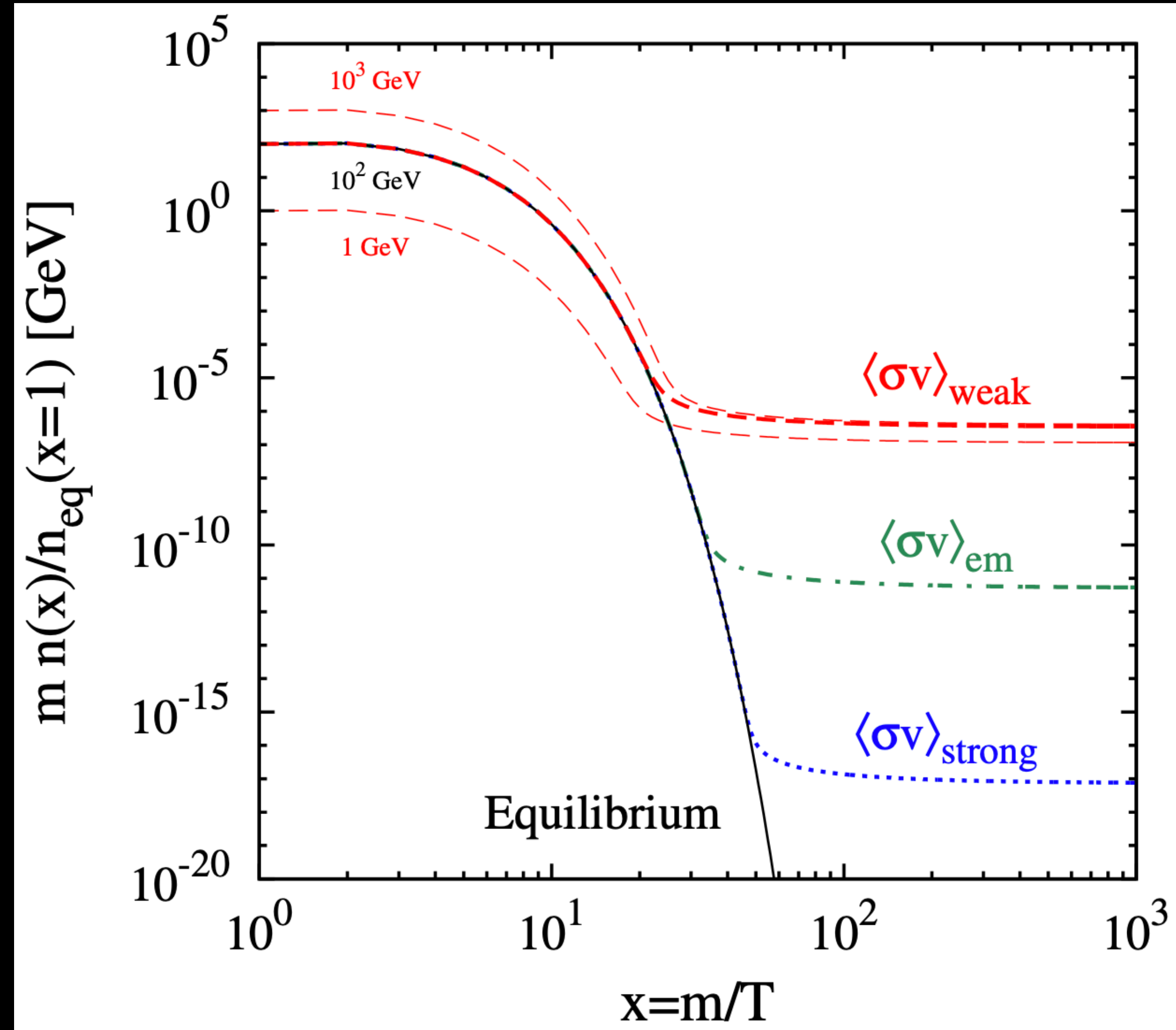
$$\frac{dn}{dt} + 3Hn = -\frac{n^2}{2} \langle \sigma v_{\text{rel}} \rangle \times 2$$

$$\frac{dn}{dt} + 3Hn = (n_{\text{eq}}^2 - n^2) \langle \sigma v_{\text{rel}} \rangle$$

- For a cold particle during freeze out

$$n \sim (m_{\chi} T)^{3/2} \exp\left(-\frac{m_{\chi}}{T}\right)$$

- If interaction has weak force strength -
current DM density = Present Density!



Thermal Freeze-Out/WIMP Miracle

- Three periods:
 - Thermal equilibrium with baryons
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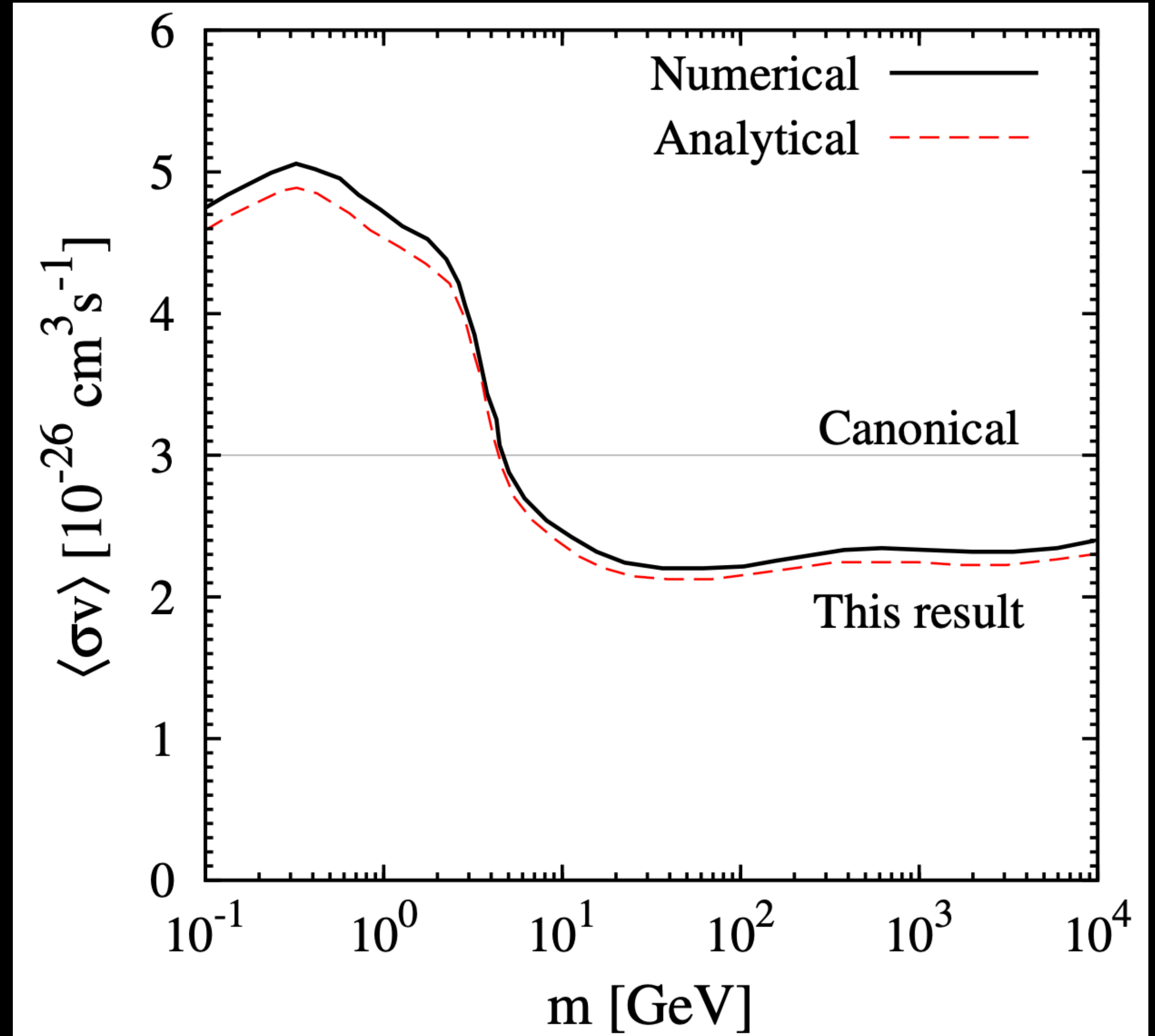
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- If interaction has weak force strength -
current DM density = Present Density!



Thermal Freeze-Out/WIMP Miracle

- What does the dark matter annihilate into?

Gaskins (1604.00014)

- Any final states are possible:

- Higgs-motivated

- To heaviest quarks, bottom/top pairs

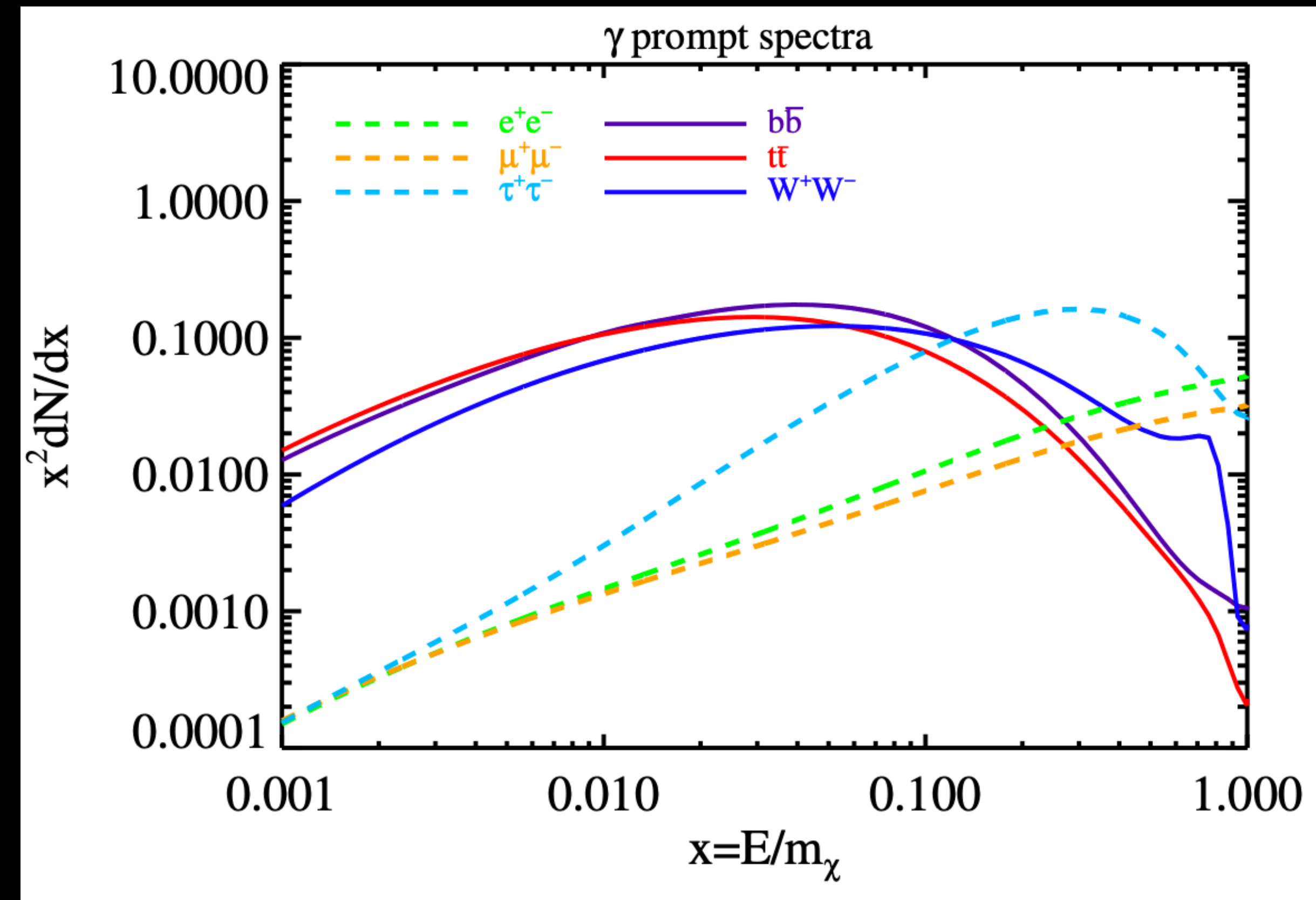
- Leptophilic

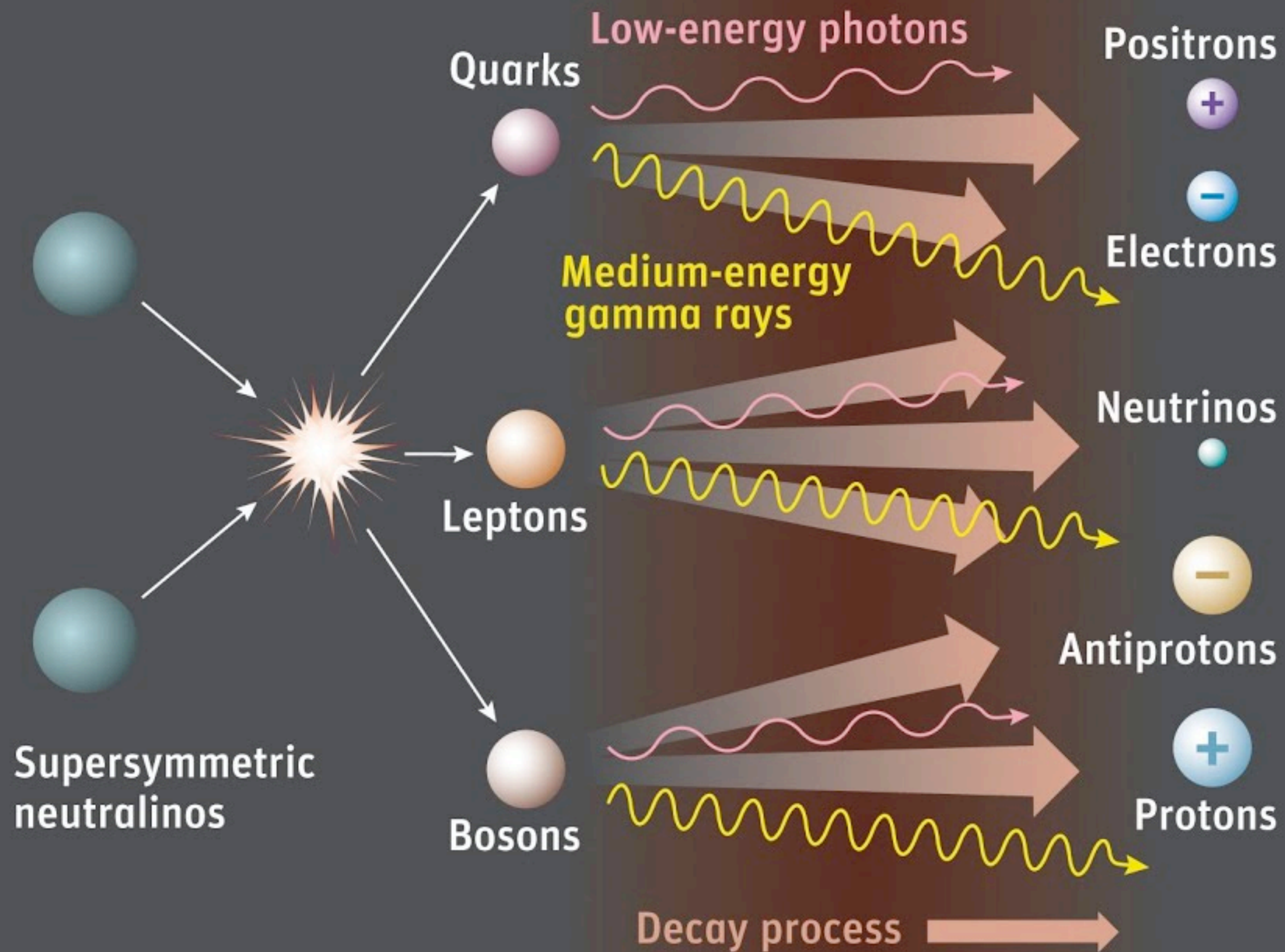
- Tau/muon/electron pairs

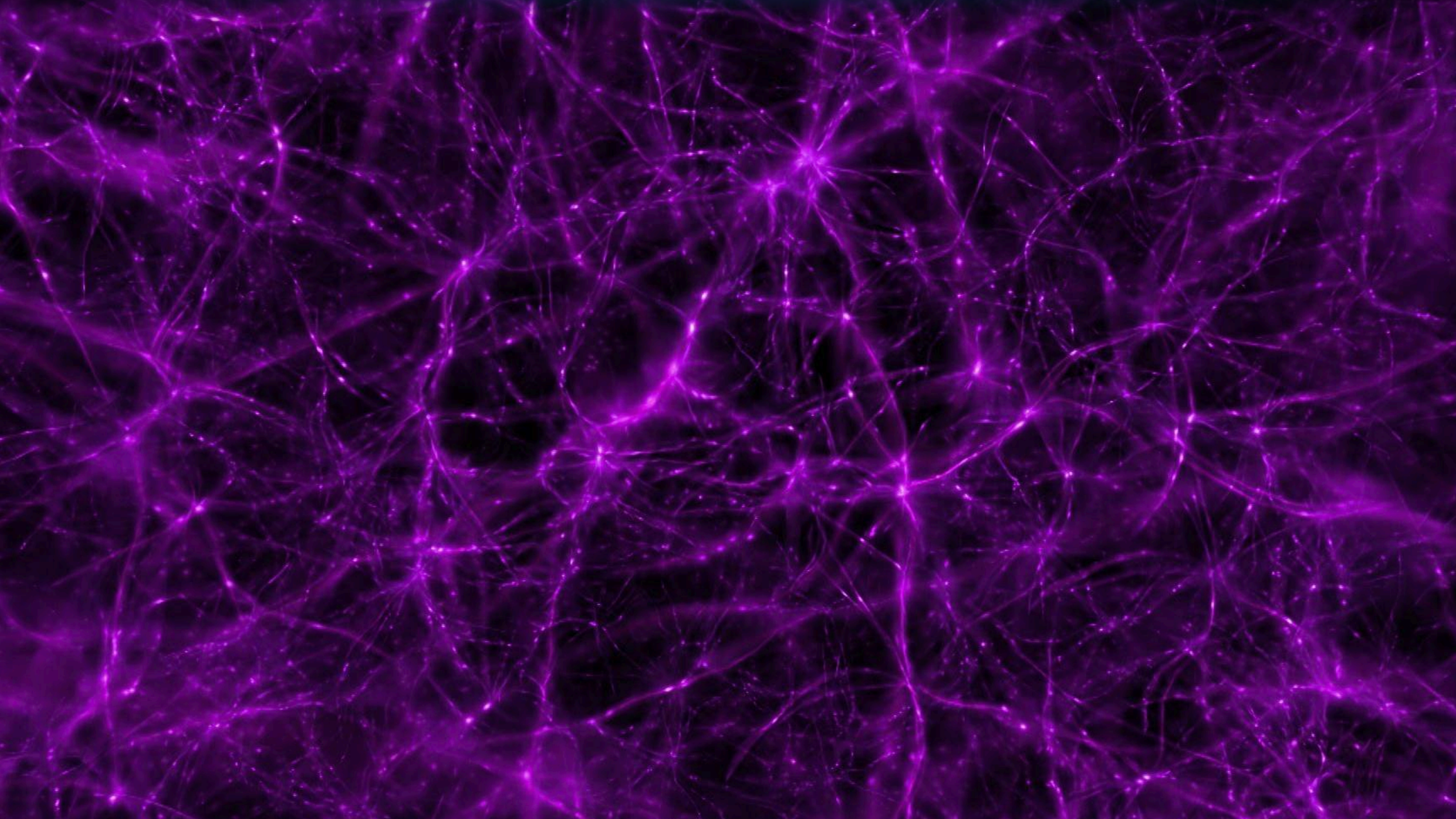
- Bosons

- W/Z or combinations

- After first baryonic particles are created, shower is formed following standard model physics to create gamma-rays, electrons/positrons/protons/neutrons







Calculation of Expected Flux

- Now we have all of the ingredients
 - J-factor
 - Annihilation Rate
 - Annihilation Final State/Spectrum

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi} \frac{\langle\sigma v\rangle}{2m_{\text{DM}}^2} \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{dN_\gamma}{dE_\gamma} dE_\gamma}_{\text{particle physics}} \times \underbrace{\int_{\Delta\Omega} \int_{\text{l.o.s.}} \rho_{\text{DM}}^2(\boldsymbol{r}) dl d\Omega'}_{\text{J-factor}}$$

Practice in Calculating Luminosity of Milky Way

$$\langle \sigma v \rangle \approx 2 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

Practice in Calculating Luminosity of Milky Way

$$\langle \sigma v \rangle \approx 2 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

$$\rho_0 = \frac{2 \times 10^{11} M_{\odot}}{\frac{4}{3} \pi (35 \text{ kpc})^3} = \frac{2 \times 10^{68} \text{ GeV}}{3 \times 10^{69} \text{ cm}^3} \sim 0.1 \text{ GeV cm}^{-3}$$

Practice in Calculating Luminosity of Milky Way

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Pick:

$$m_{\chi} = 100 \text{ GeV} \quad \frac{E}{\text{ann}} = 200 \text{ GeV}$$

Practice in Calculating Luminosity of Milky Way

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$$\Phi = \frac{E}{\text{ann}} \frac{\rho^2}{2m_{\chi}} \langle \sigma v \rangle V$$

Practice in Calculating Luminosity of Milky Way

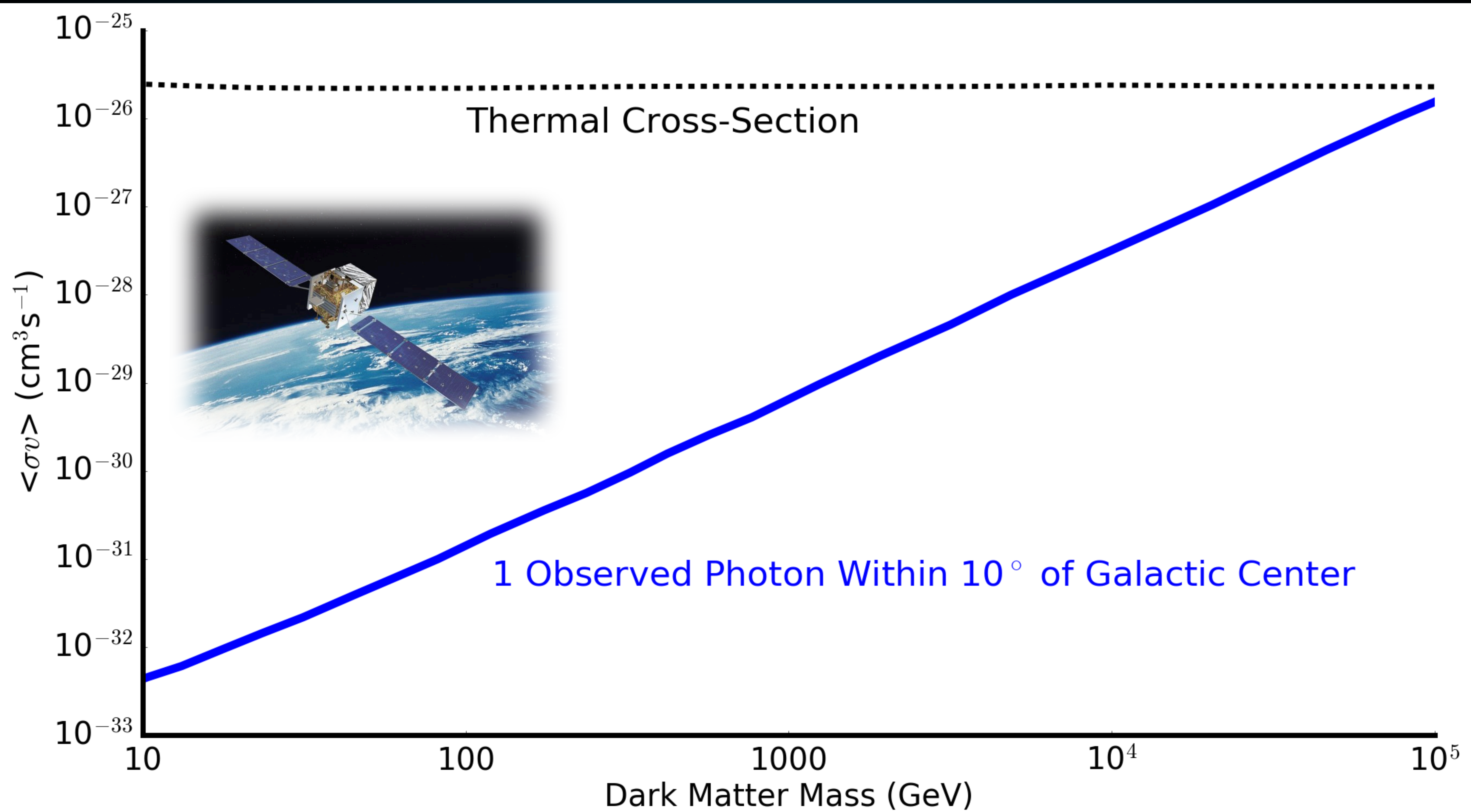
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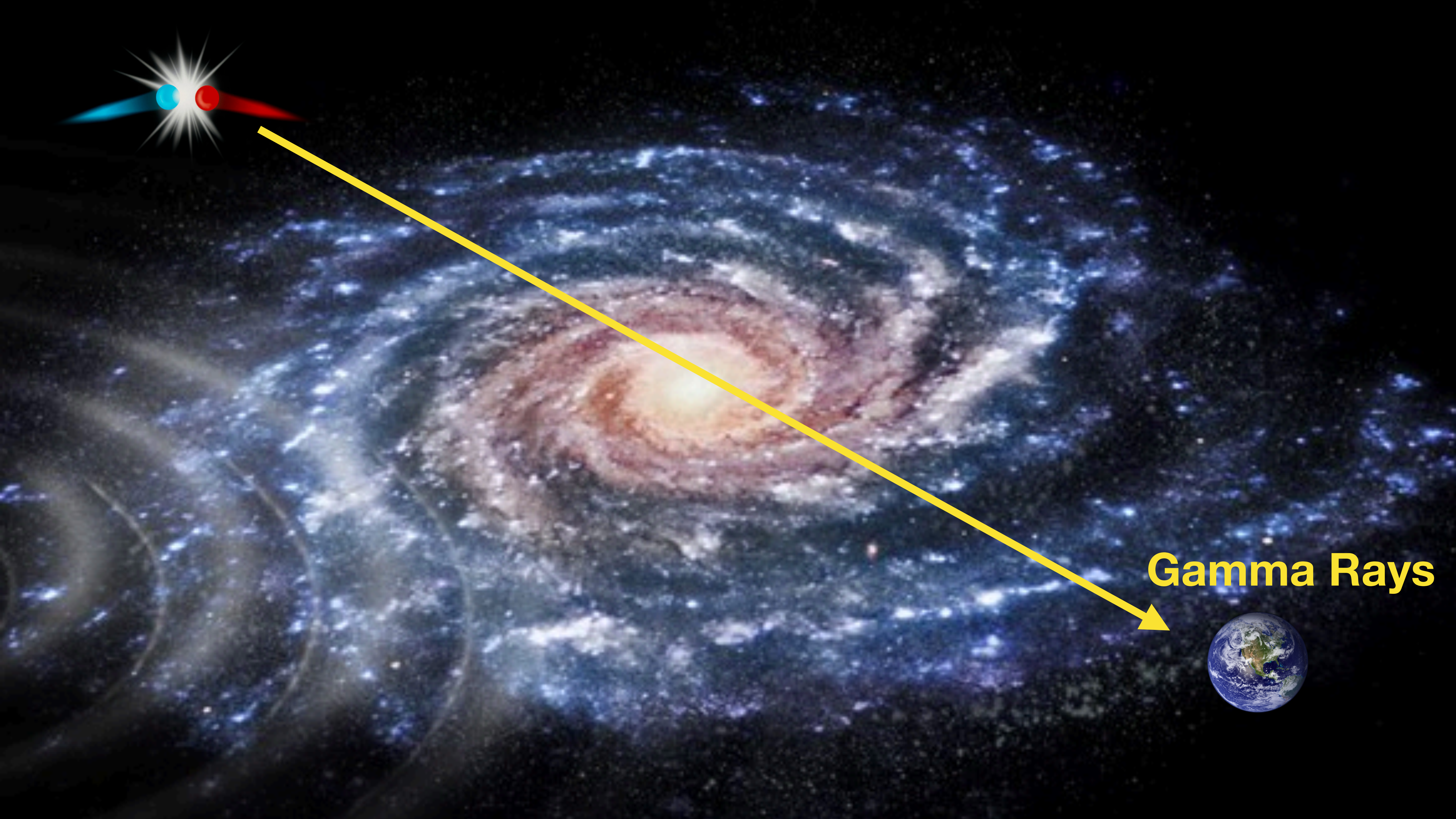
Pick:

$$m_{\chi} = 100 \text{ GeV} \quad \frac{E}{\text{ann}} = 200 \text{ GeV}$$

$$\Phi = \frac{E}{\text{ann}} \frac{\rho^2}{2m_{\chi}} \langle \sigma v \rangle V = 200 \text{ GeV} \frac{0.1 \text{ GeV cm}^{-3}}{200 \text{ GeV}} (10^{-26} \text{ cm}^3 \text{s}^{-1}) 3 \times 10^{69} \text{ cm}^3 = 3 \times 10^{39} \text{ GeV s}^{-1}$$



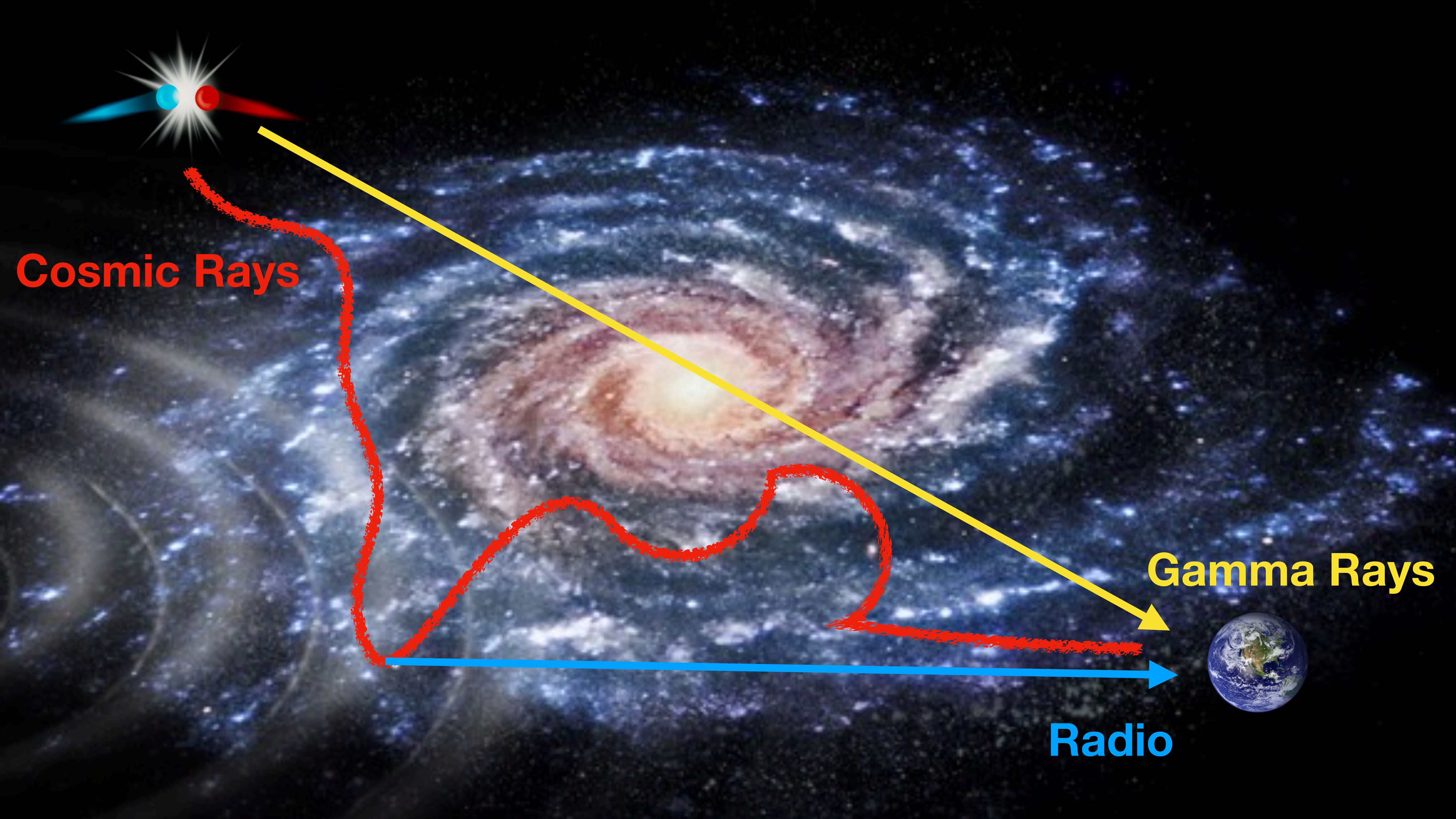






Cosmic Rays

Gamma Rays



Cosmic Rays

Gamma Rays

Radio

Gamma-Rays

Galactic Center
Dwarf Spheroidal Galaxies
Galaxy Clusters
Milky Way Subhalos
Galactic Diffuse
Sun
Jupiter
Nearby Stars
Galactic Center Stars
Andromeda
Little Galaxies
Isotropic Gamma-Ray Background
Anisotropy Searches
Cusps
511 keV line

Morphology

Cosmic-Rays

Positrons
Electron + Positron Spectrum
Antiprotons
Antineutrons
Antihelium
Cosmological Lithium Problem

Antimatter

Neutrinos

The Sun
Direct Annihilation to Neutrinos
Hidden Sources
The Earth
Ultra-Heavy Dark Matter

Messengers

Low-Energy

Galactic Center Synchrotron
Dwarf Galaxy Synchrotron
Galaxy Cluster Synchrotron
Diffuse Synchrotron
Sun
Jupiter
Isotropic Background
X-ray background from Clusters
Anisotropy Searches
Stellar Evolution
Pulsar Evolution
Planetary Heating
Thermal Scattering
Cosmic Microwave Background
CMB Absorption

Targets

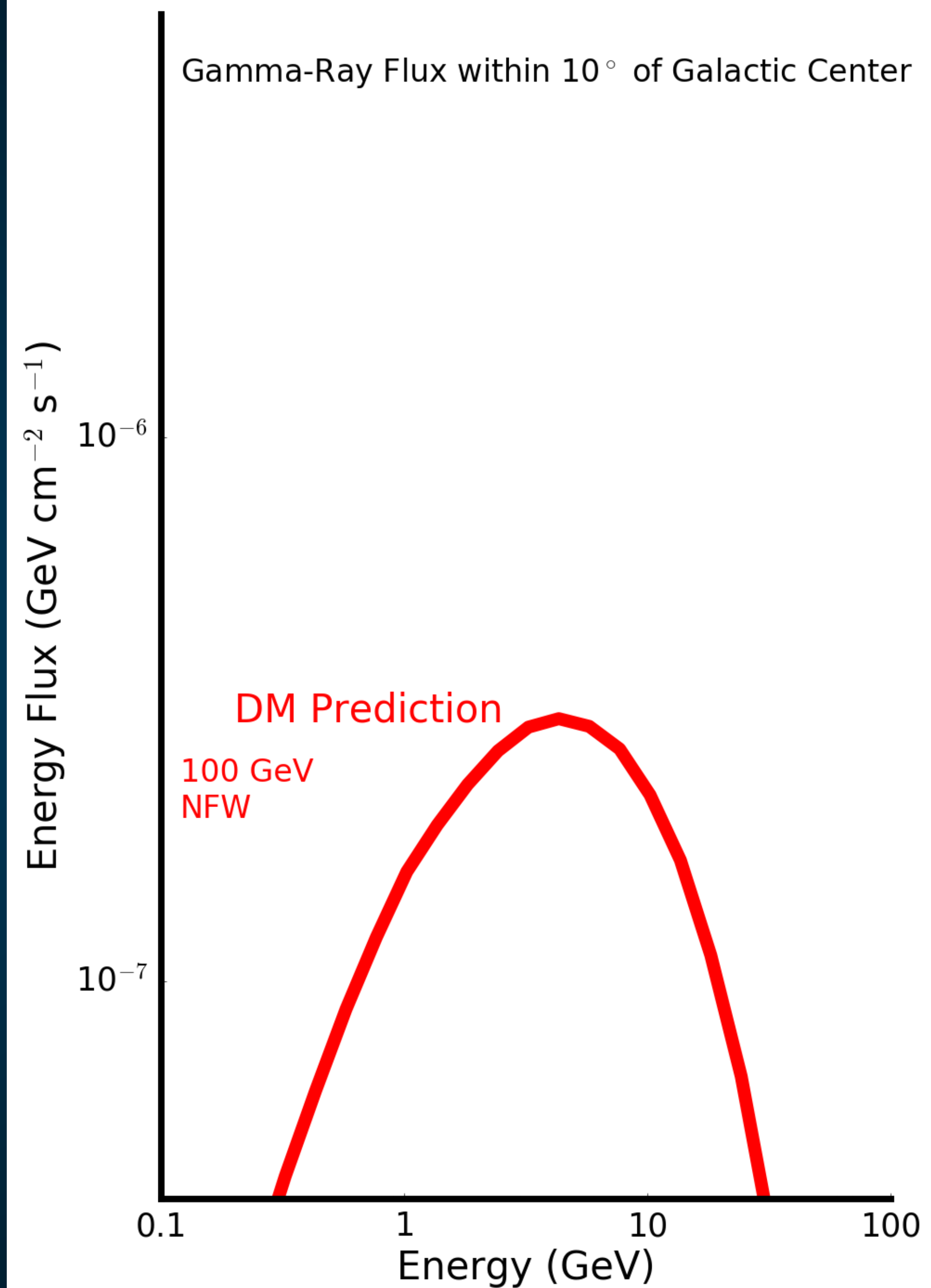
Thermal WIMPs and the Story of Tantalus

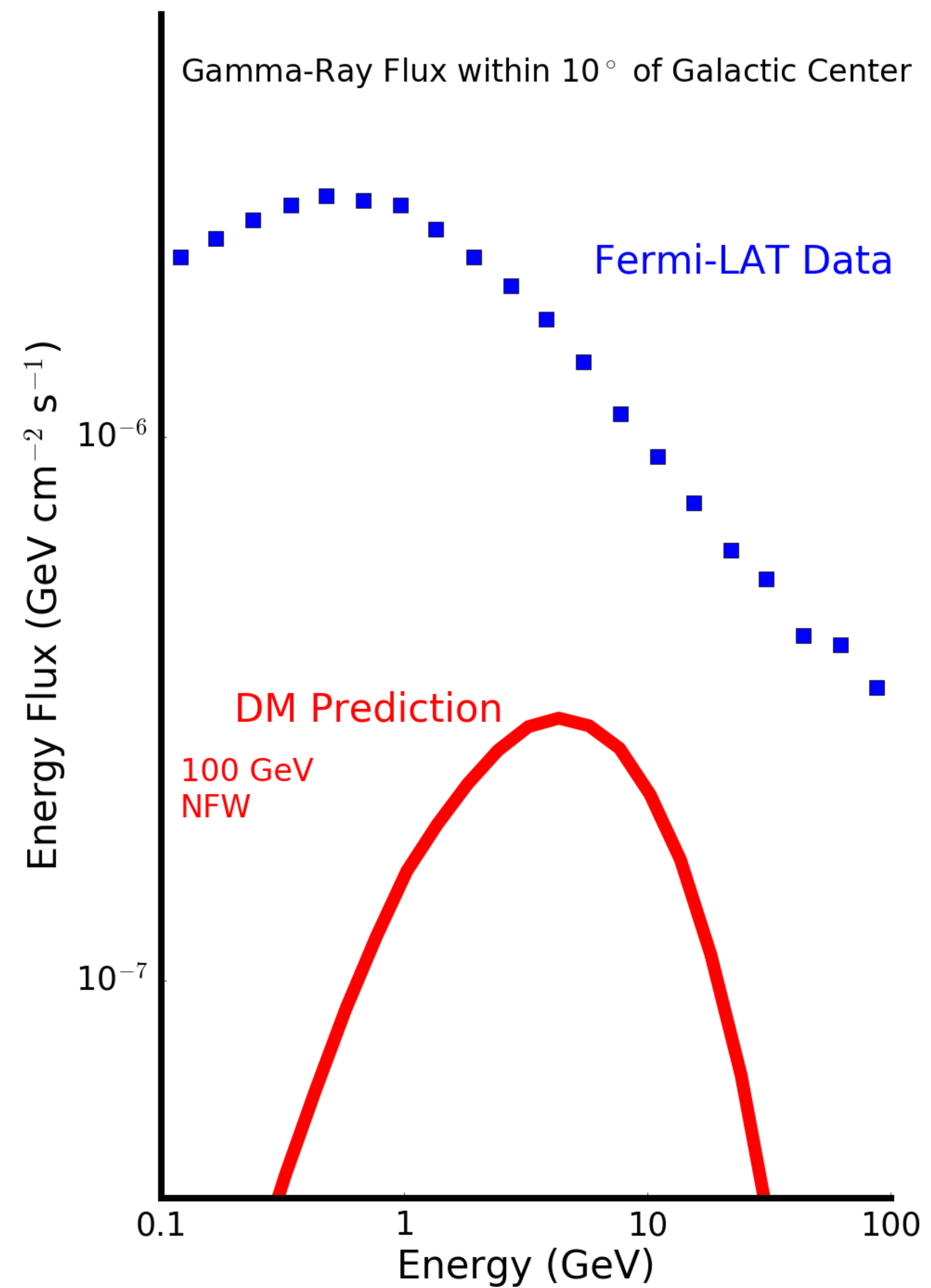
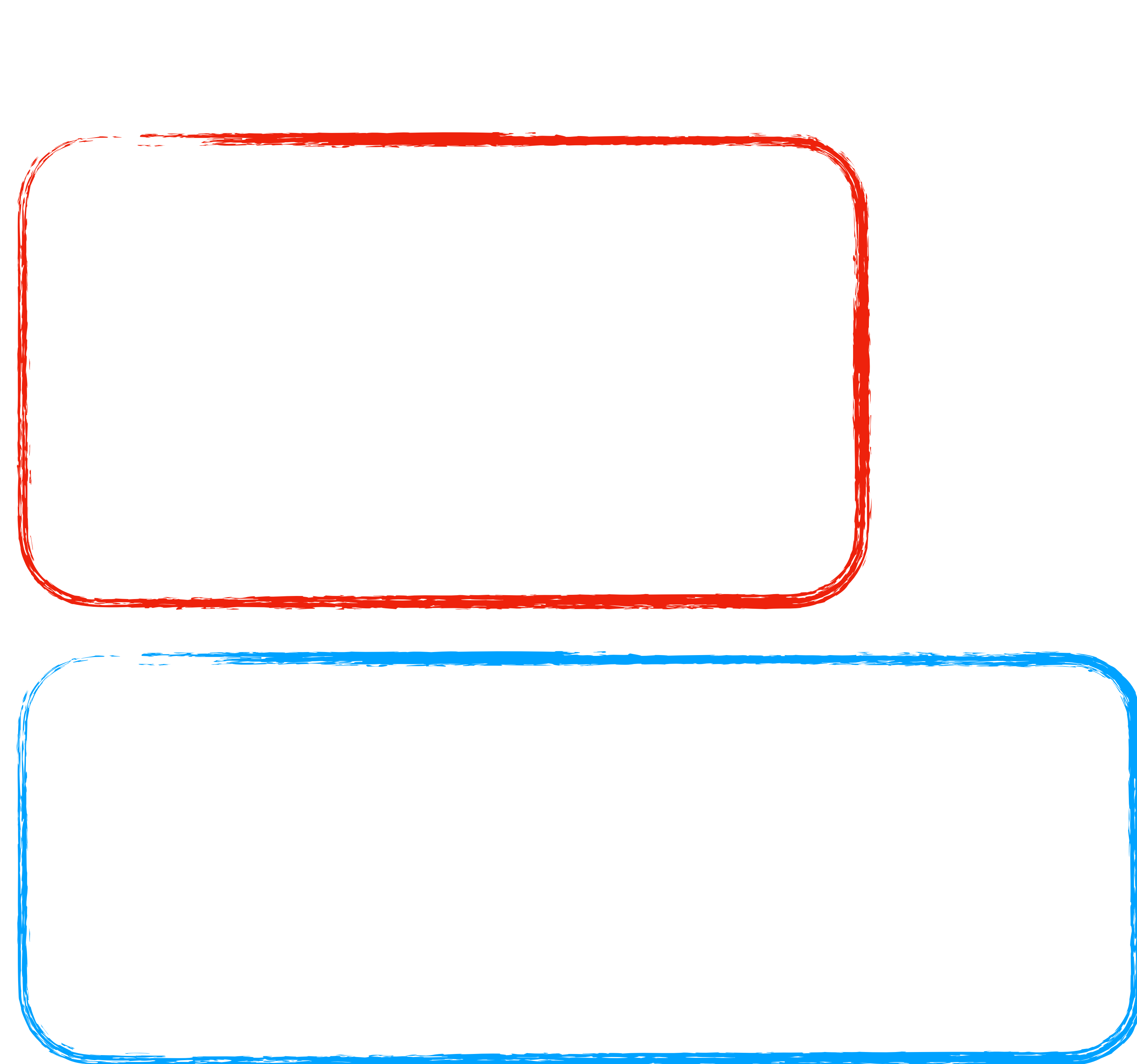
NFW Profile (Mass of Milky Way)

Thermal Cross-Section (Early Universe)

Dark Matter Mass (?)

Annihilation Final State (?)





Antiproton Flux at Earth

Antiproton Flux ($\text{GeV m}^{-2} \text{s}^{-1} \text{s}^{-1}$)

1

0.1

0.01

Dark Matter

100 GeV

$b\bar{b}$

10

100

Kinetic Energy (GeV)



Antiproton Flux at Earth

Antiproton Flux ($\text{GeV m}^{-2} \text{s}^{-1} \text{s}^{-1}$)

AMS-02 Data

Dark Matter

100 GeV

$b\bar{b}$

0.01

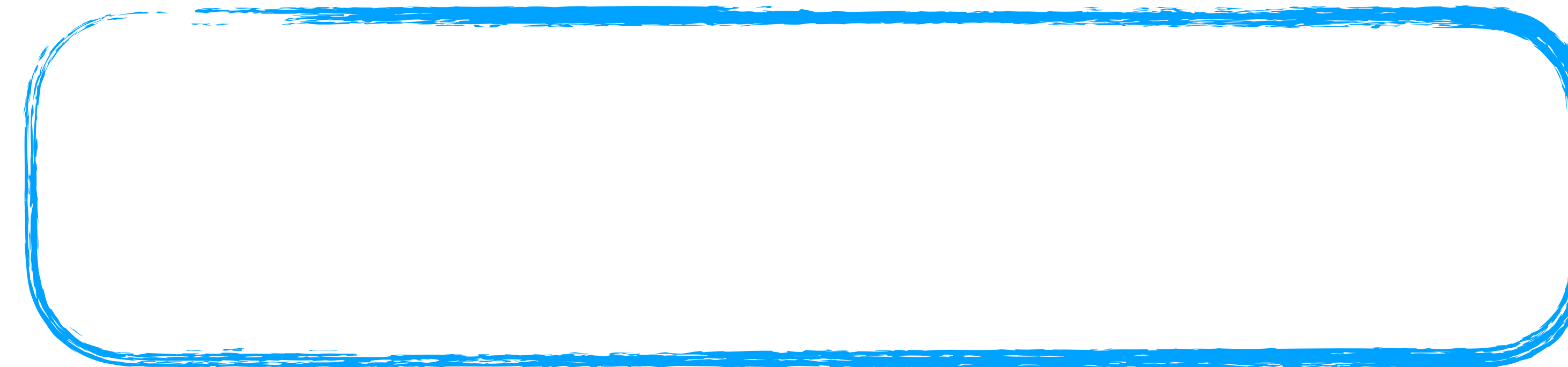
0.1

1

Kinetic Energy (GeV)

10

100



Positron Flux at Earth

Positron Flux ($\text{GeV m}^{-2} \text{s}^{-1} \text{s}^{-1}$)

1

0.1

0.01

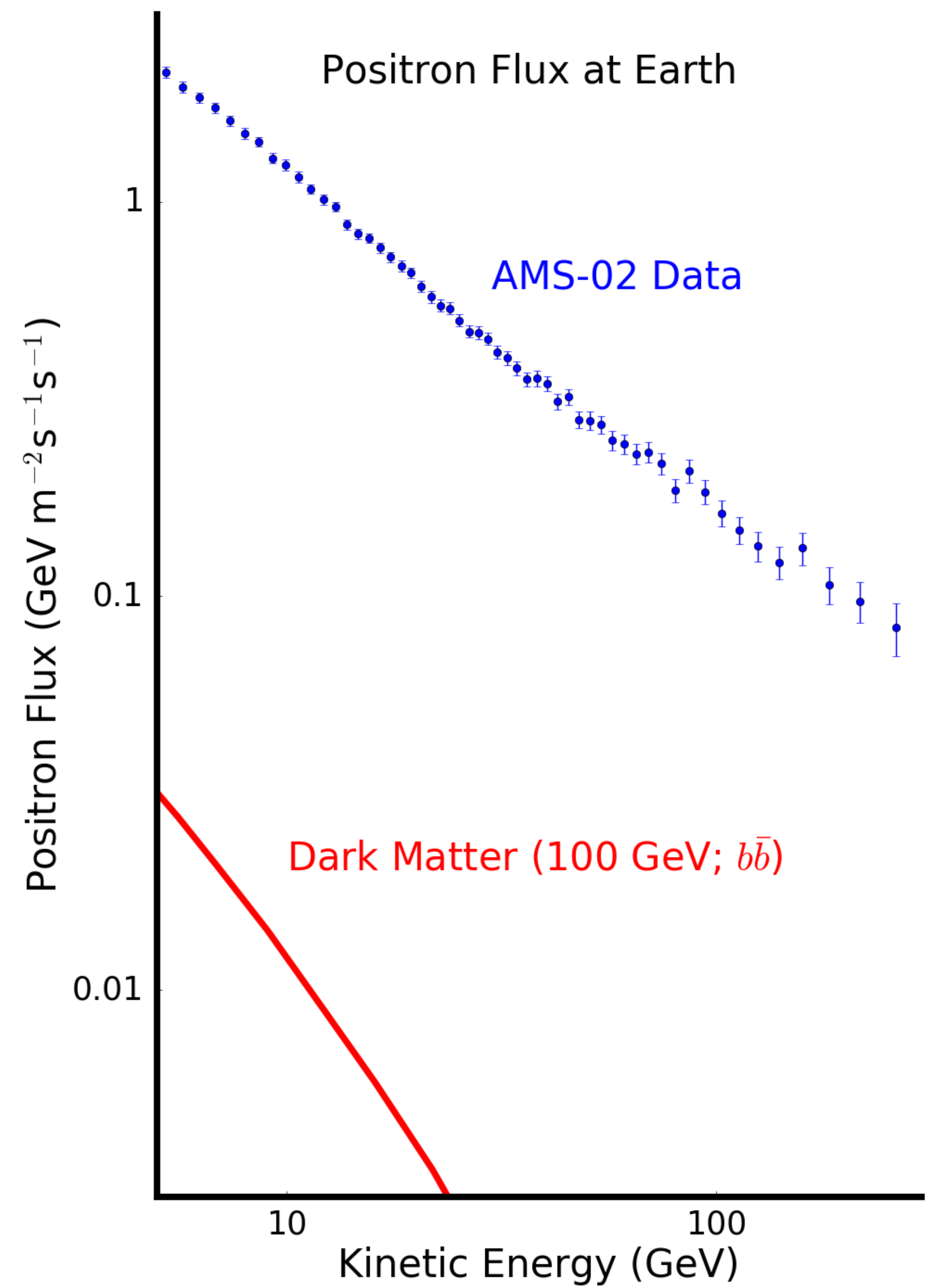
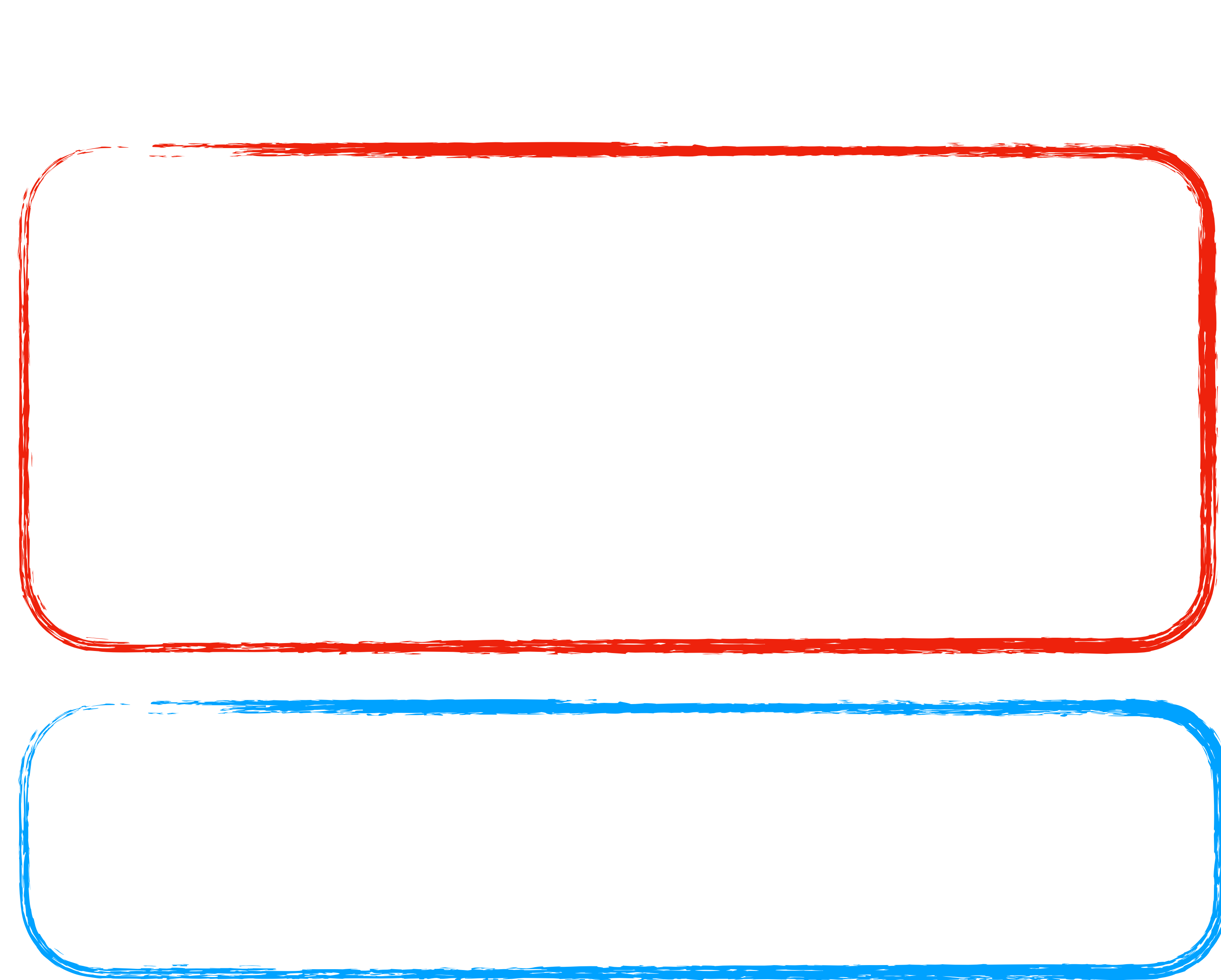
Dark Matter (100 GeV; $b\bar{b}$)

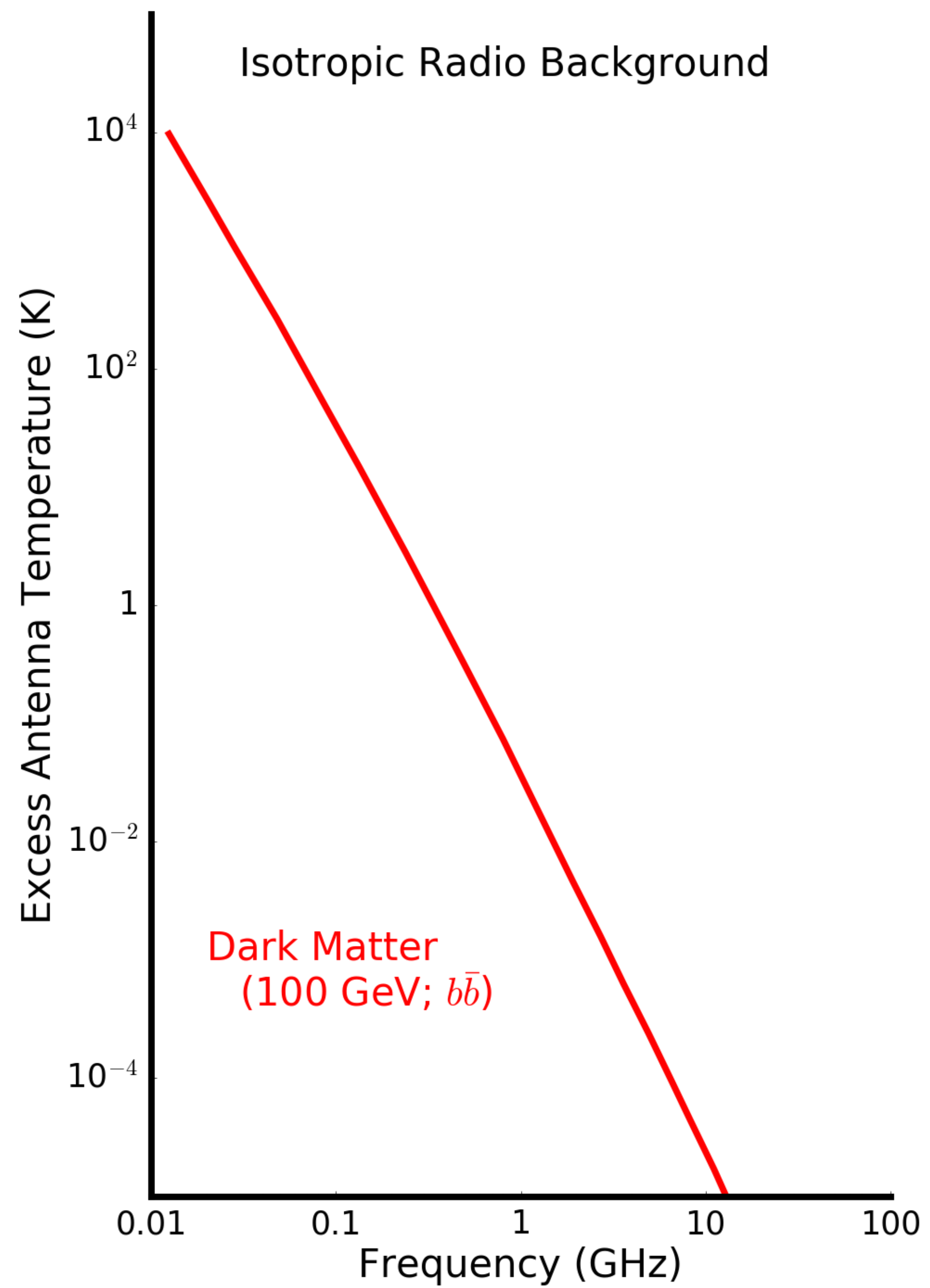
10

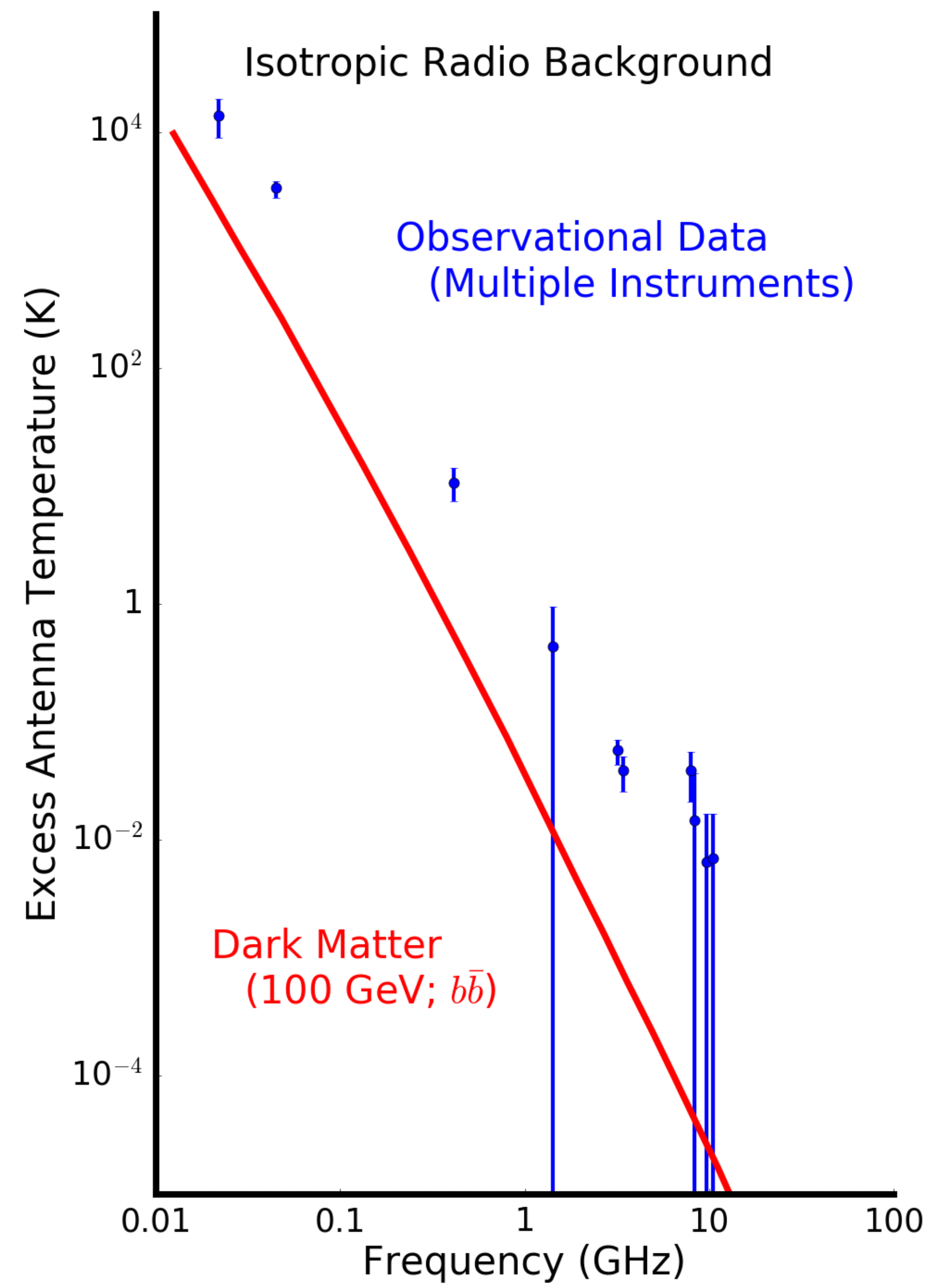
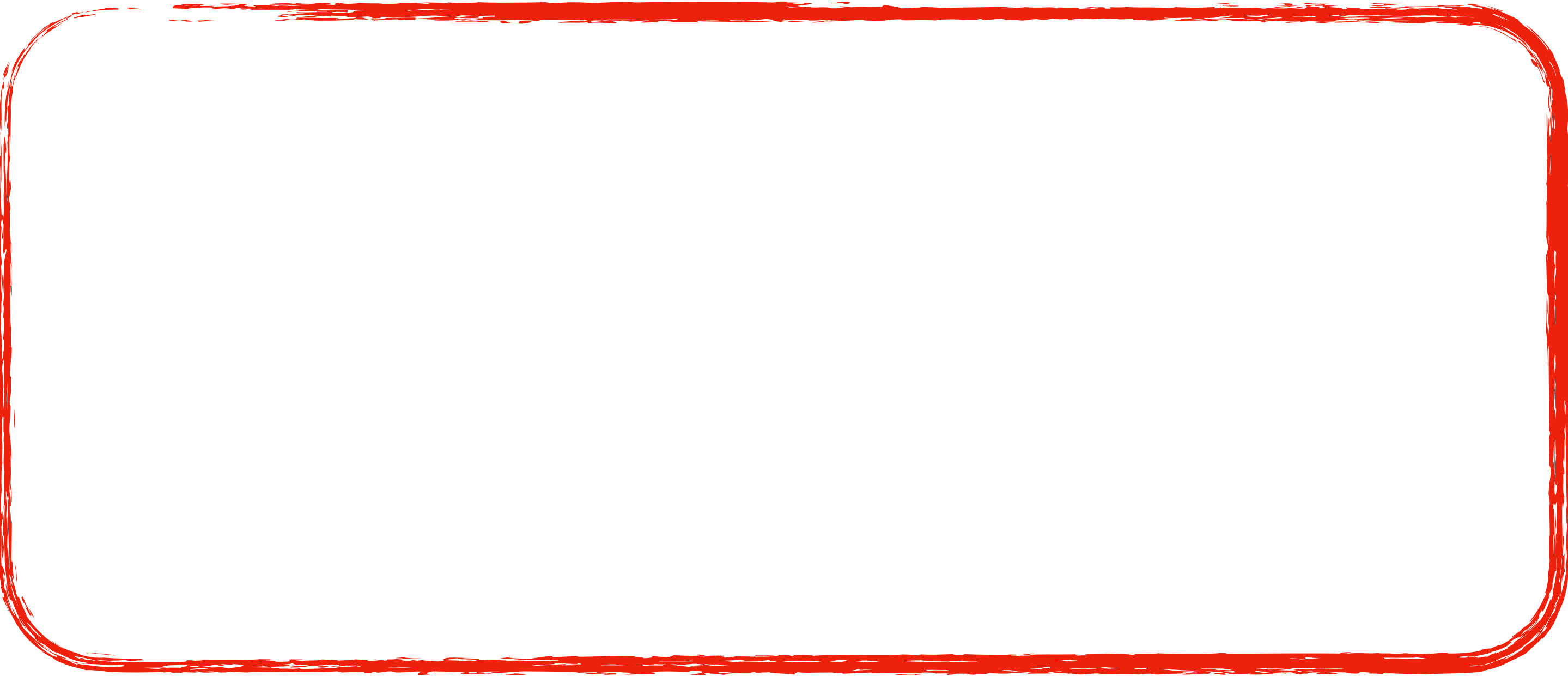
100

Kinetic Energy (GeV)











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)

Small Dark Matter Signal
Small Astrophysical Background

Large Dark Matter Signal
Small Astrophysical Background

Easy

Small Dark Matter Signal
Large Astrophysical Background

Large Dark Matter Signal
Large Astrophysical Background

Fraction of Dark Matter Flux

Specificity (DM Flux / Astrophysics Flux)

Small Dark Matter Signal
Small Astrophysical Background

Large Dark Matter Signal
Small Astrophysical Background

Easy

Easy

Small Dark Matter Signal
Large Astrophysical Background

Large Dark Matter Signal
Large Astrophysical Background

Fraction of Dark Matter Flux

Specificity (DM Flux / Astrophysics Flux)

Small Dark Matter Signal
Small Astrophysical Background

Large Dark Matter Signal
Small Astrophysical Background

Easy

Easy

Small Dark Matter Signal
Large Astrophysical Background

Hard

Large Dark Matter Signal
Large Astrophysical Background

Fraction of Dark Matter Flux

Specificity (DM Flux / Astrophysics Flux)

Small Dark Matter Signal
Small Astrophysical Background

Hard

Large Dark Matter Signal
Small Astrophysical Background

Easy

Small Dark Matter Signal
Large Astrophysical Background

Easy

Large Dark Matter Signal
Large Astrophysical Background

Hard

Fraction of Dark Matter Flux

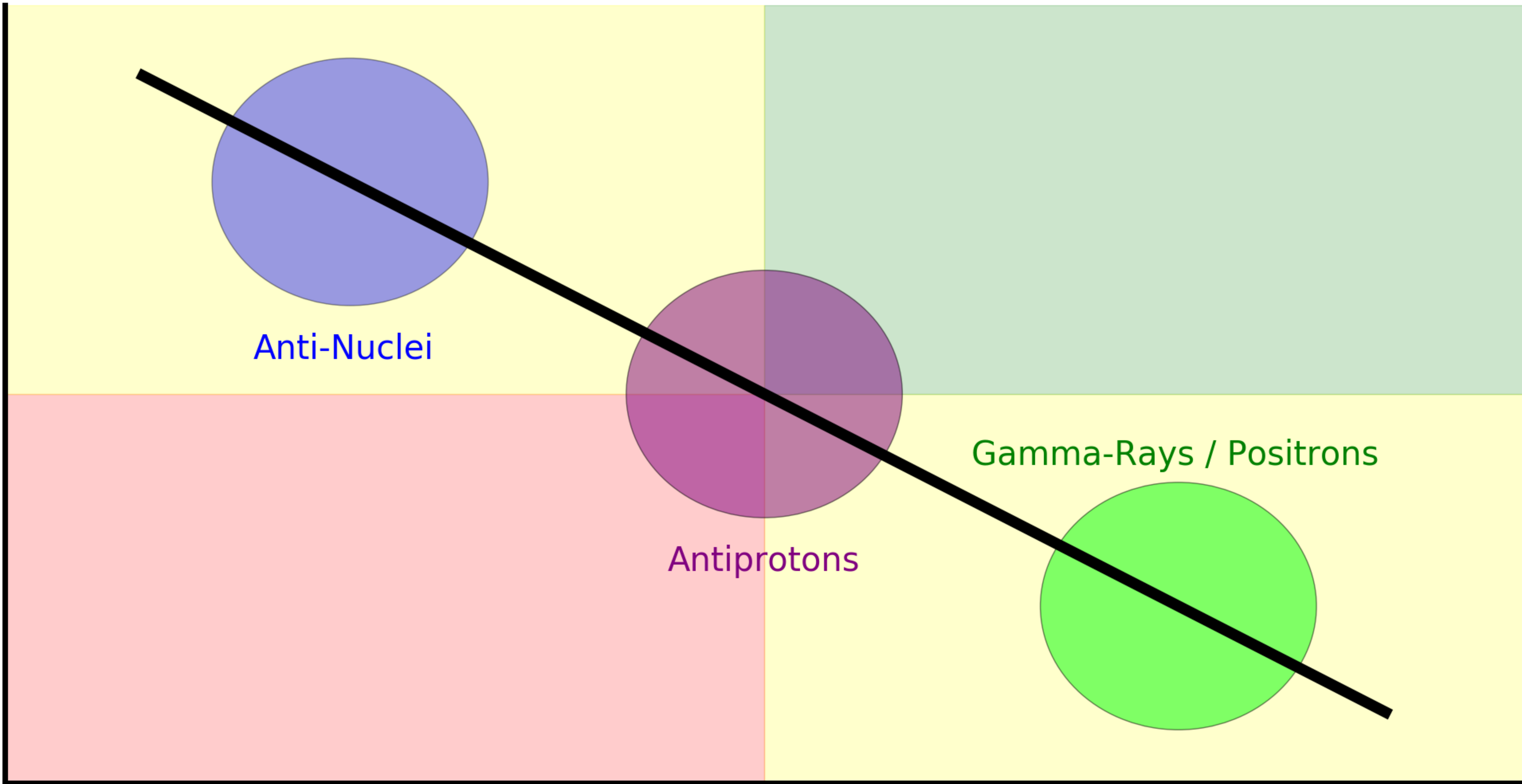
Specificity (DM Flux / Astrophysics Flux)

Anti-Nuclei

Antiprotons

Gamma-Rays / Positrons

Fraction of Dark Matter Flux





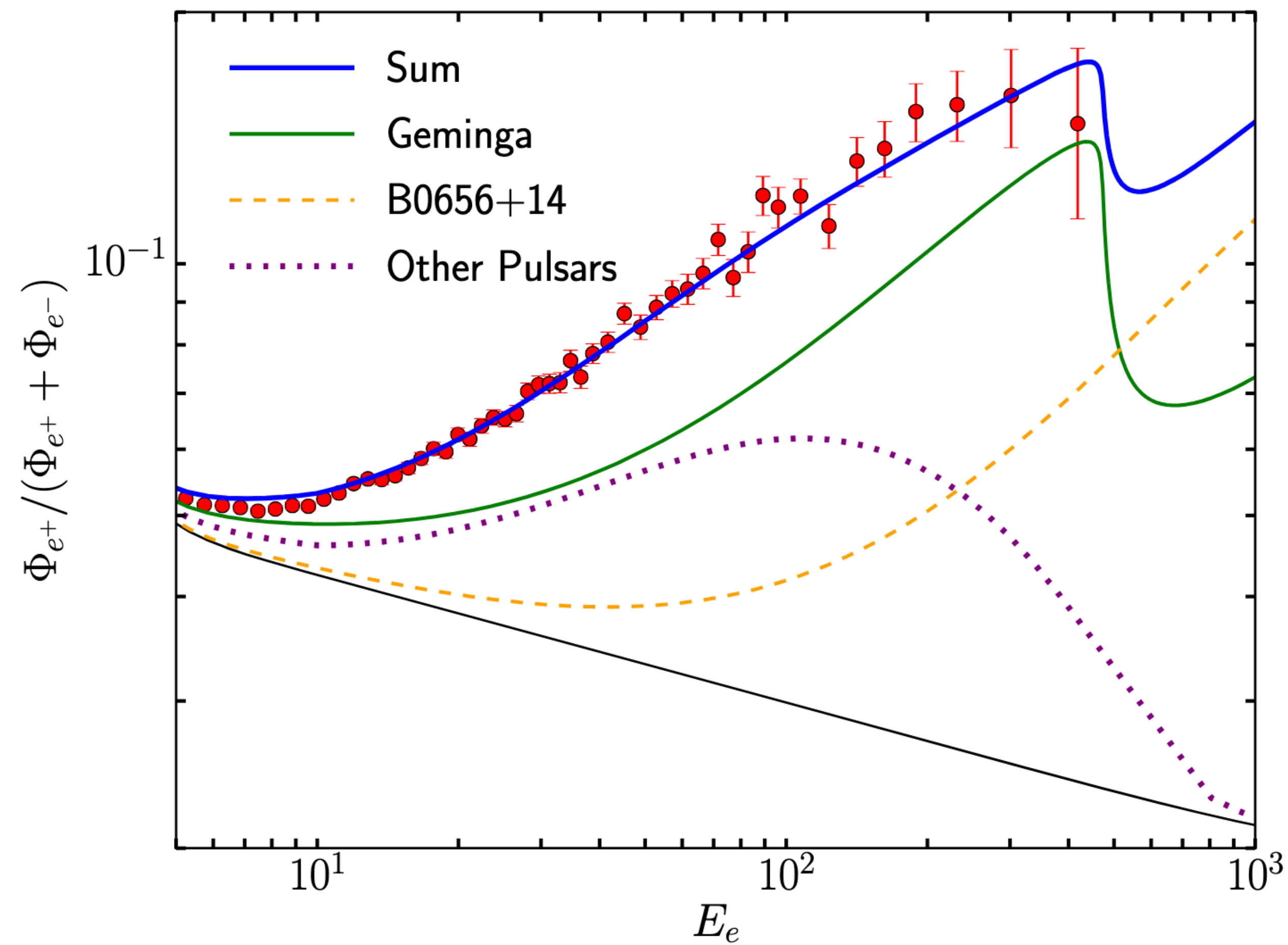
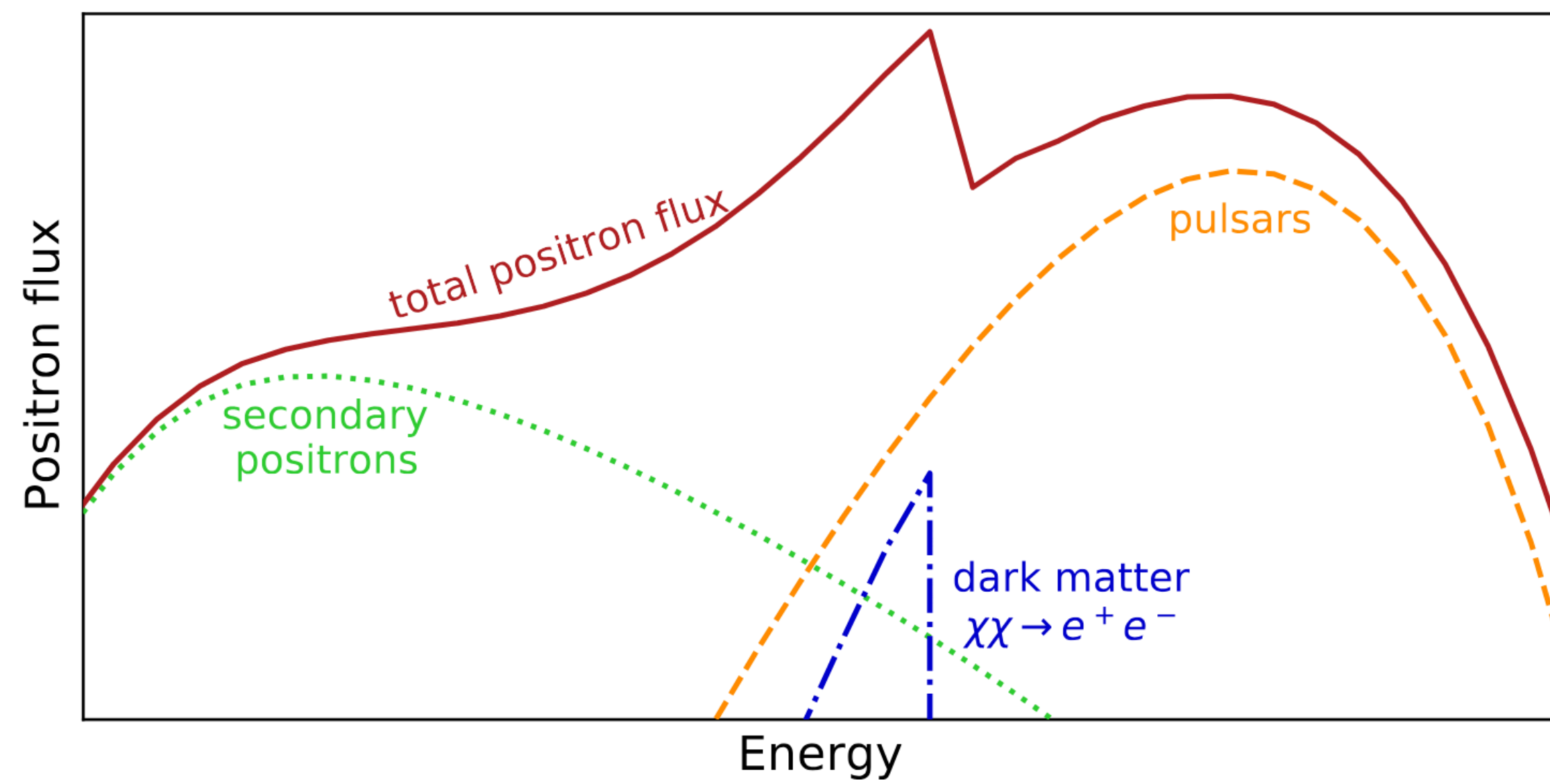
**WE HAVE MET
THE ENEMY
AND HE IS US.**





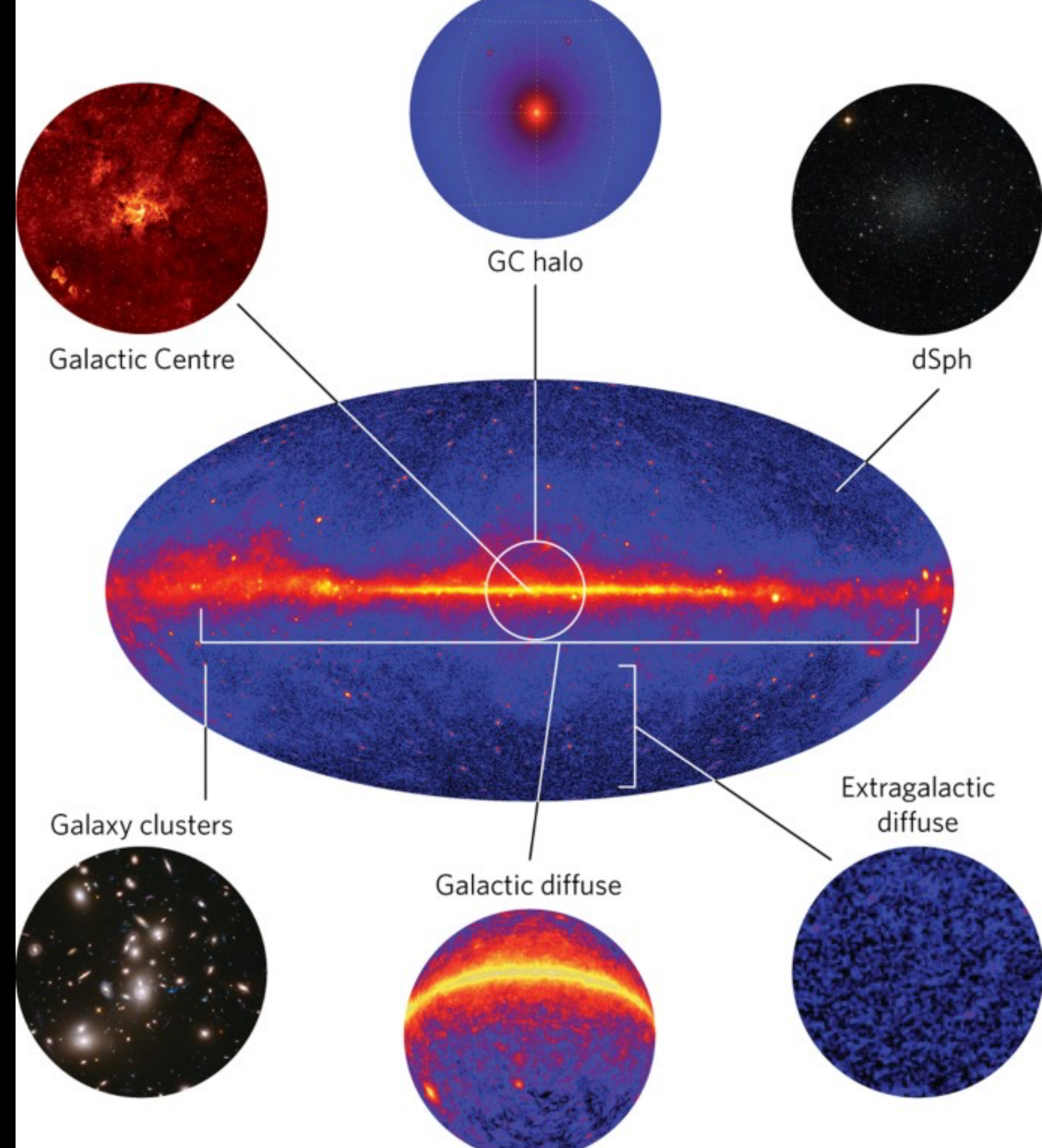
Congratulations!

You're an astrophysicist now!



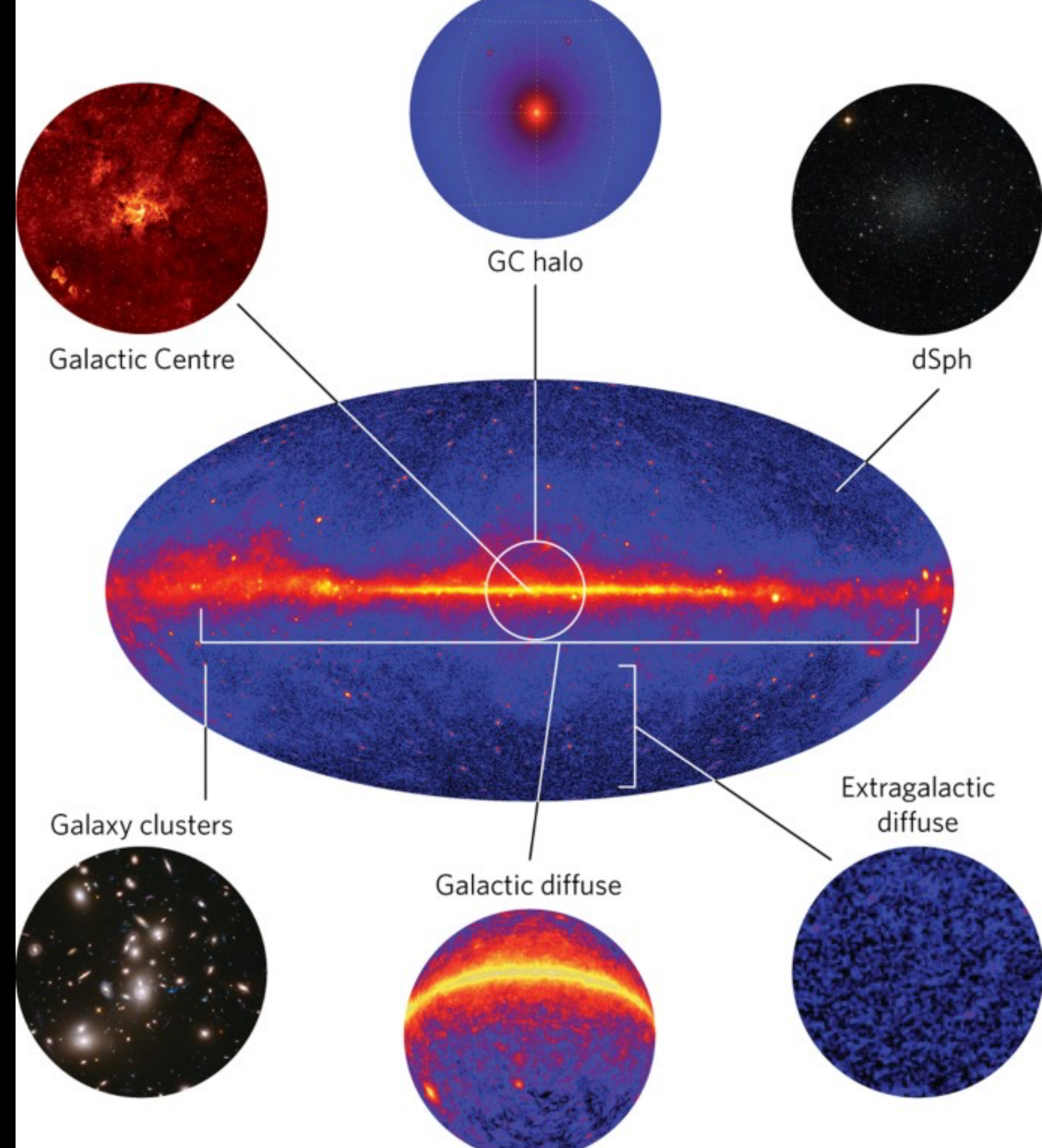
Targets

- 2008: Very uncertain which dark matter targets would be most sensitive



Targets

- 2008: Very uncertain which dark matter targets would be most sensitive
- 2023: Some consensus that most interesting targets are Galactic center and dSphs (though surprises always possible)



Gamma-Rays

Galactic Center
Dwarf Spheroidal Galaxies
Galaxy Clusters
Milky Way Subhalos
Galactic Diffuse
Sun
Jupiter
Nearby Stars
Galactic Center Stars
Andromeda
Little Galaxies
Isotropic Gamma-Ray Background
Anisotropy Searches
Cusps
511 keV line

Morphology

Cosmic-Rays

Positrons
Electron + Positron Spectrum
Antiprotons
Antineutrons
Antihelium
Cosmological Lithium Problem

Antimatter

Neutrinos

The Sun
Direct Annihilation to Neutrinos
Hidden Sources
The Earth
Ultra-Heavy Dark Matter

Messengers

Low-Energy

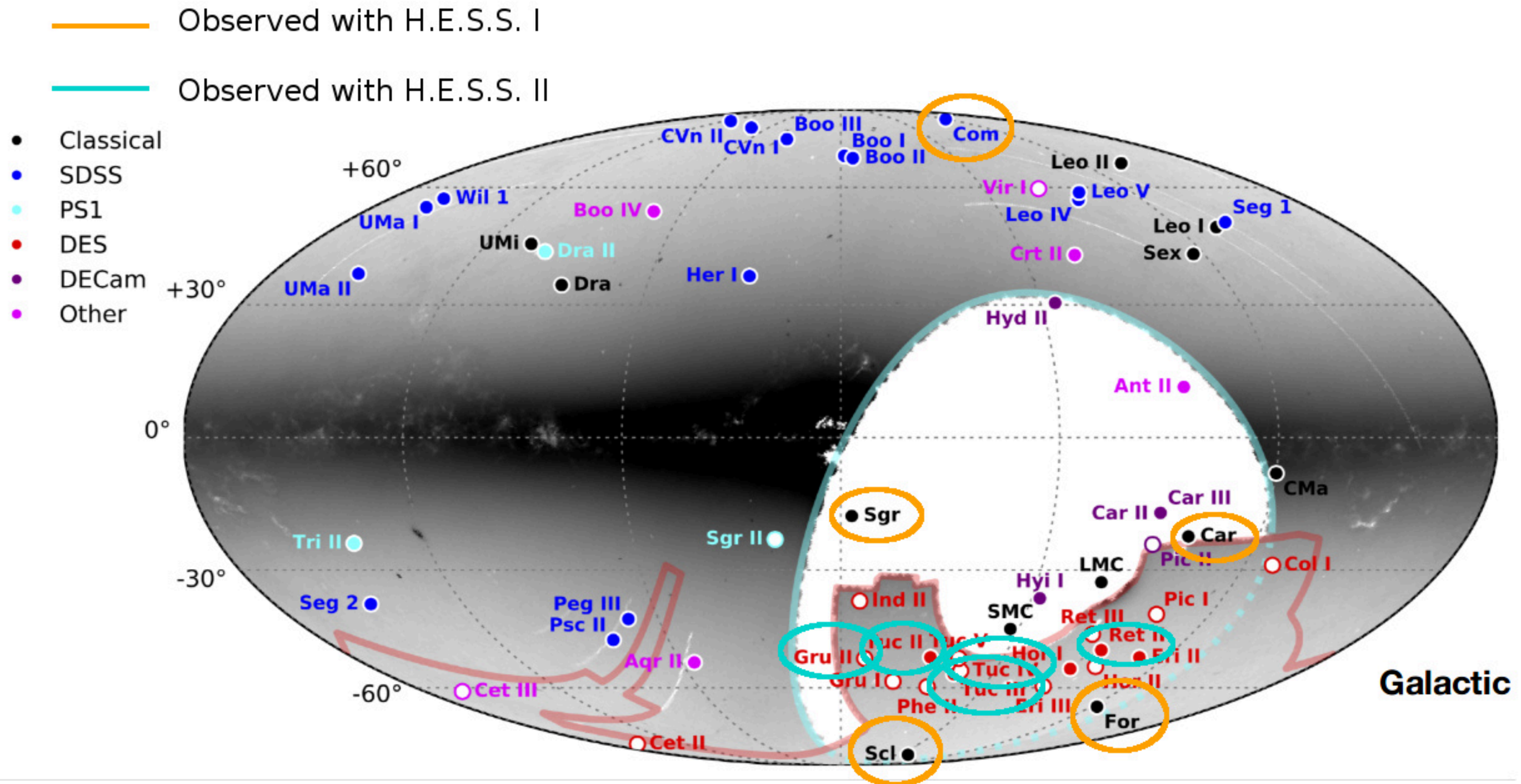
Galactic Center Synchrotron
Dwarf Galaxy Synchrotron
Galaxy Cluster Synchrotron
Diffuse Synchrotron
Sun
Jupiter
Isotropic Background
X-ray background from Clusters
Anisotropy Searches
Stellar Evolution
Pulsar Evolution
Planetary Heating
Thermal Scattering
Cosmic Microwave Background
CMB Absorption

Targets

Topics:

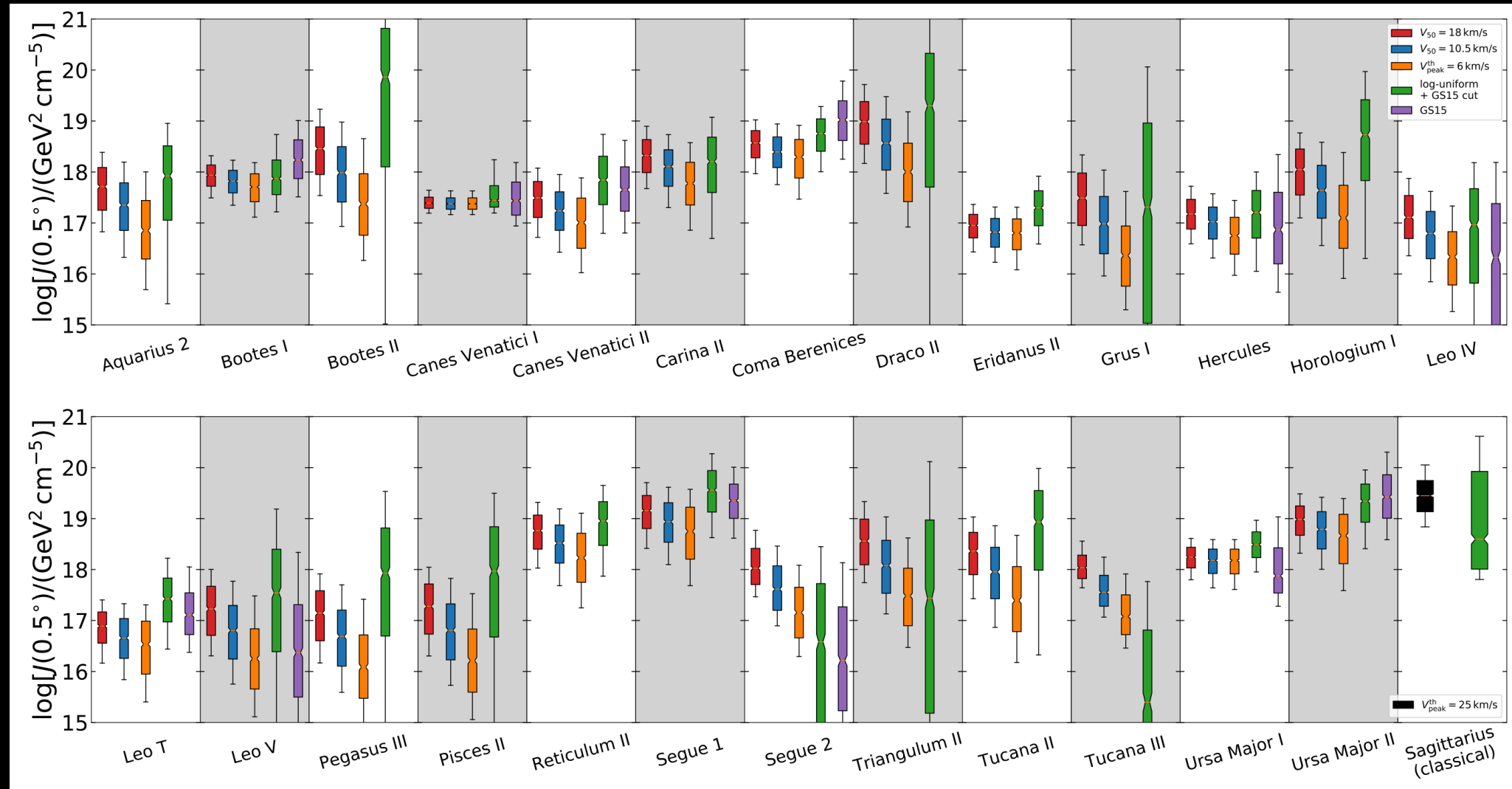
- Thermal/WIMP-like:
 - dSphs
 - Galactic Center Excess
 - Positron Excess
 - Antiproton Excess
 - Antinuclei
 - Gamma-Ray Lines
 - Neutrinos
- Axions
- Sterile Neutrinos
- Primordial Black Holes

dSphs



dSphs

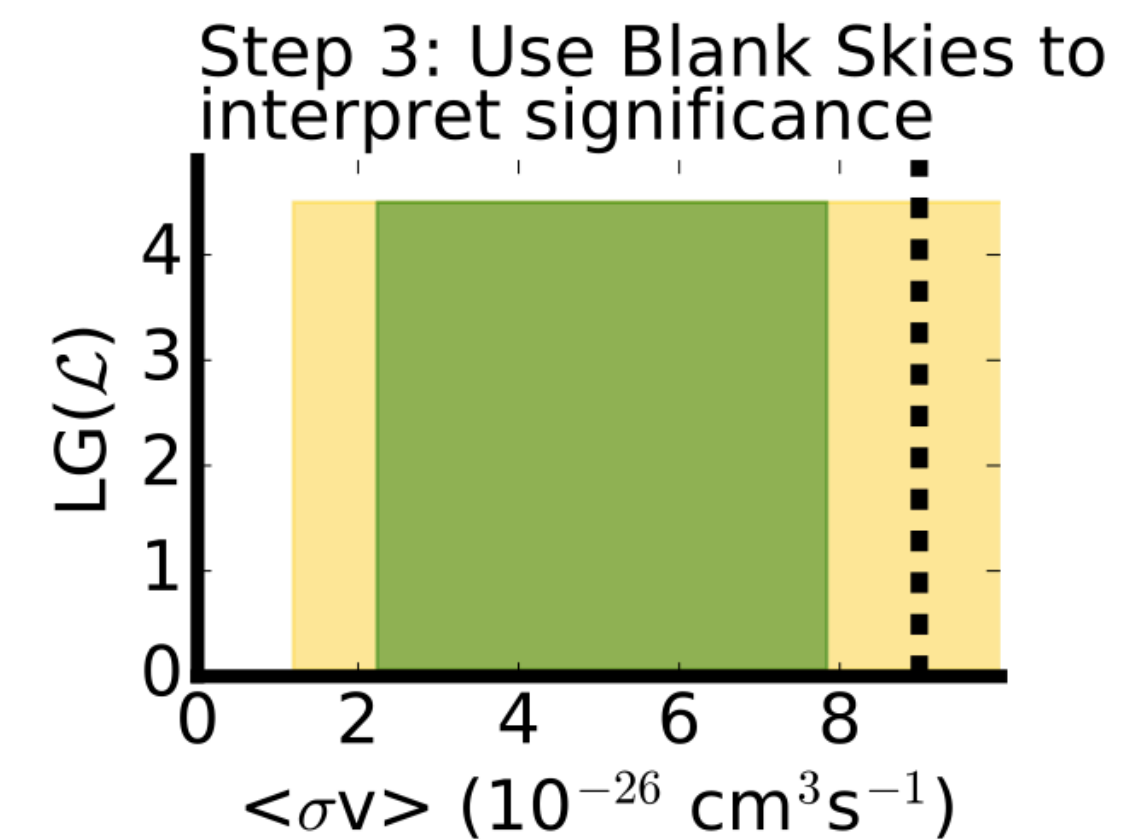
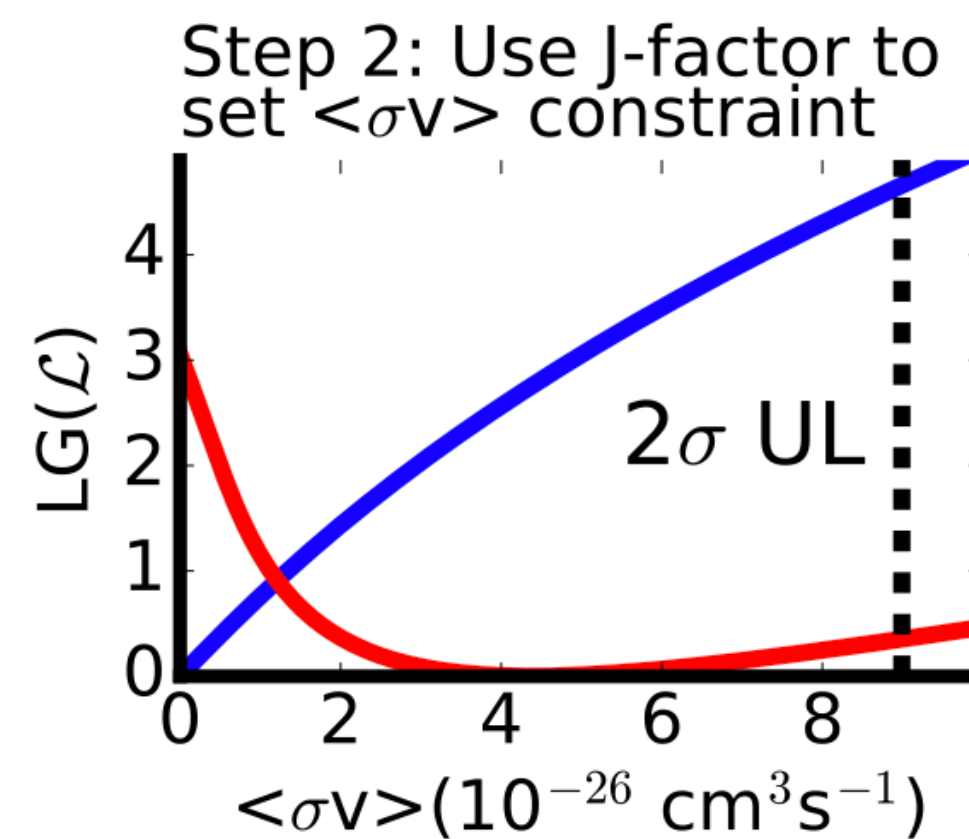
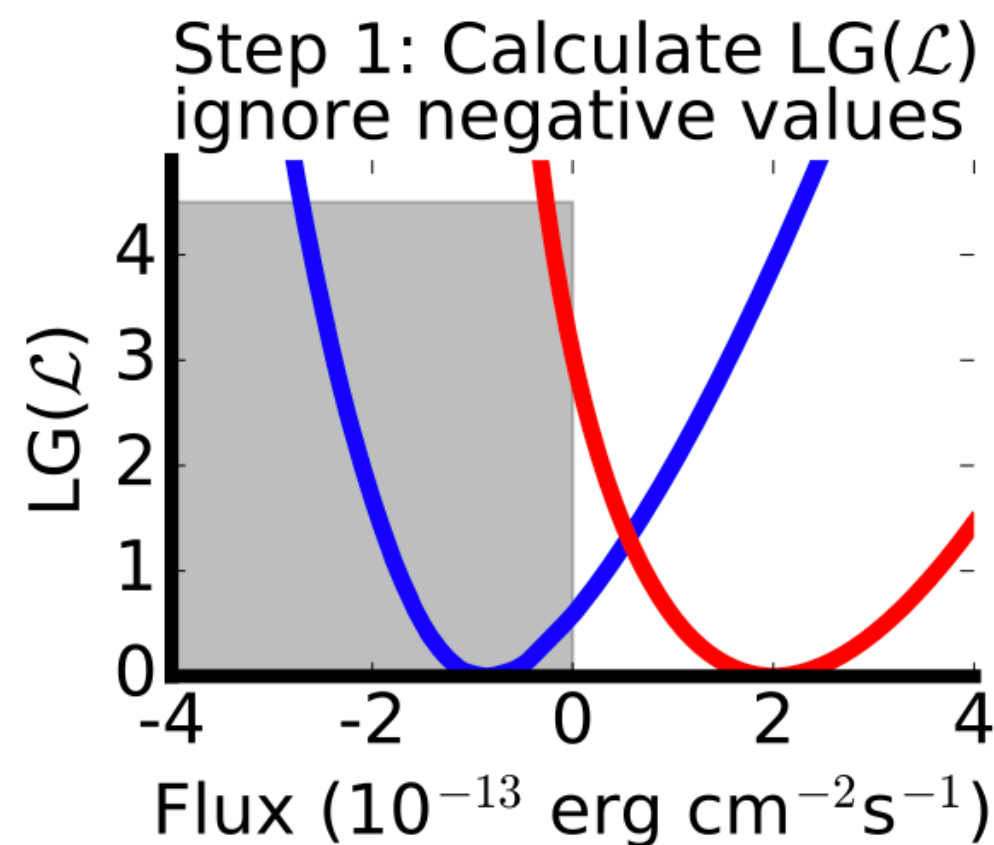
- J-factors tell us the relative flux of each dSph
- Can add the likelihood profiles of each source.
- Use Blank Sky locations to test



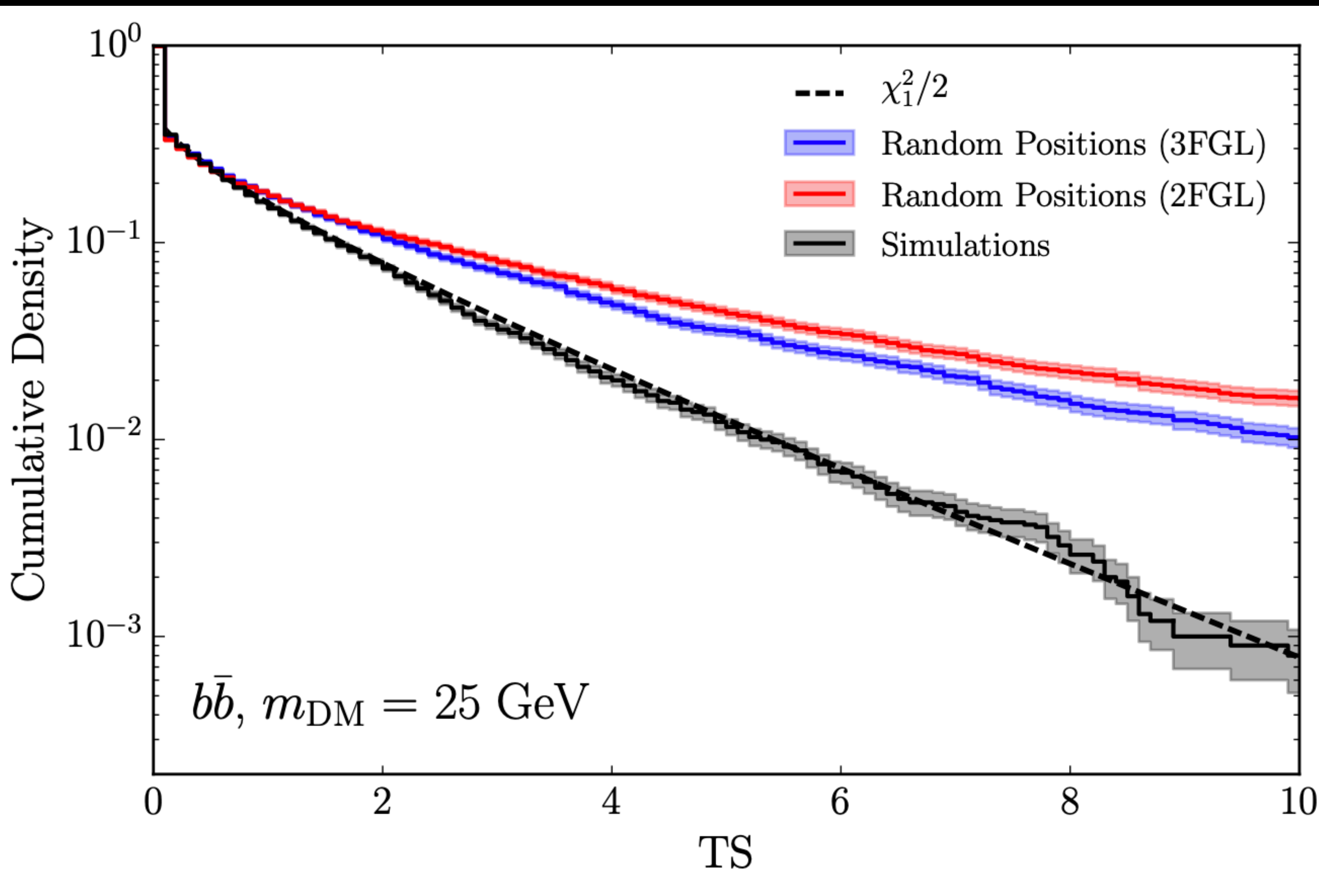
$$\mathcal{L}_J(J_i | J_{\text{obs},i}, \sigma_i) = \frac{1}{\ln(10) J_{\text{obs},i} \sqrt{2\pi} \sigma_i} \times e^{-(\log_{10}(J_i) - \log_{10}(J_{\text{obs},i}))^2 / 2\sigma_i^2}$$

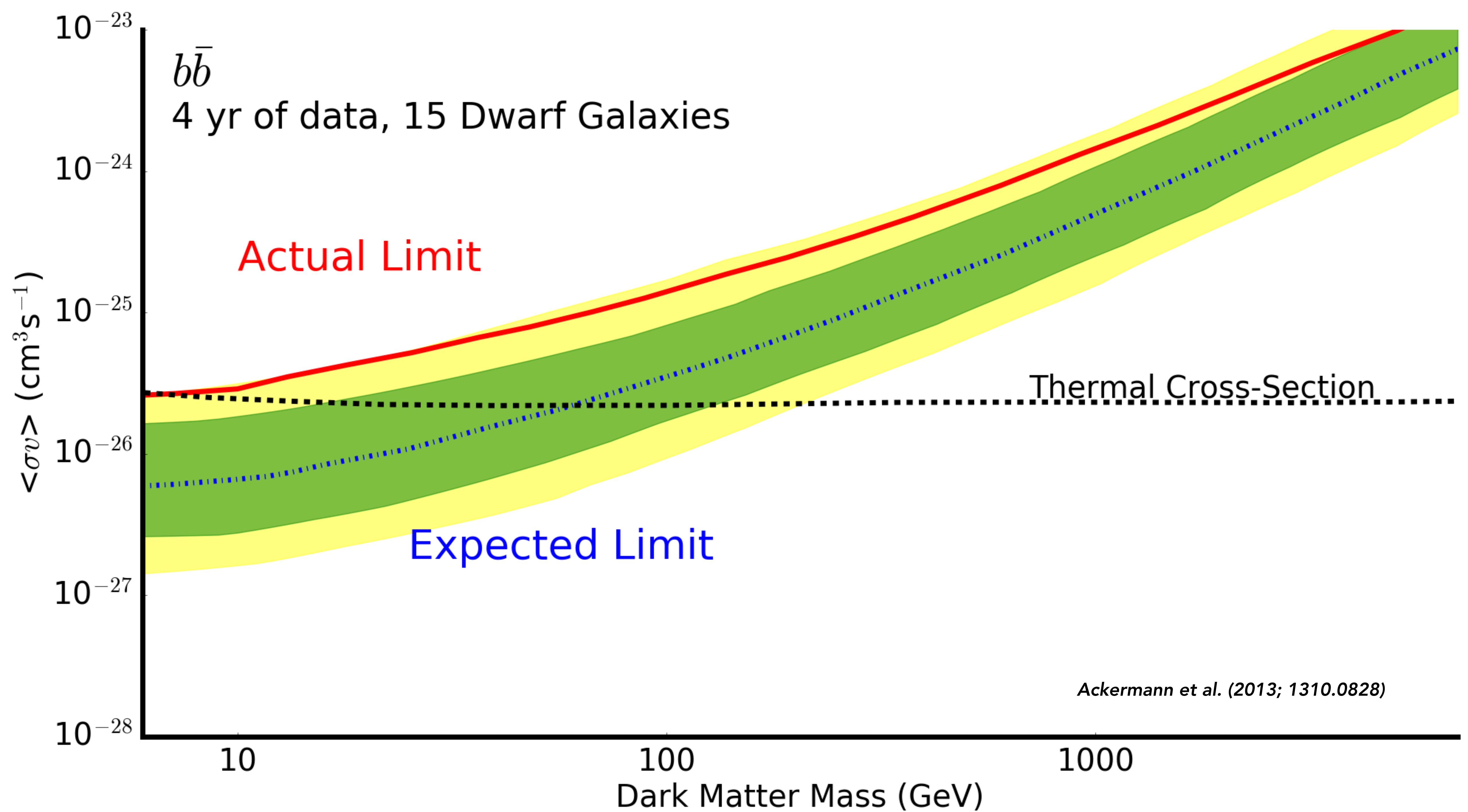
$$\mathcal{L}_i(\mu, \theta_i | \mathcal{D}_i) = \prod_j \mathcal{L}_i(\mu, \theta_i | \mathcal{D}_{i,j}).$$

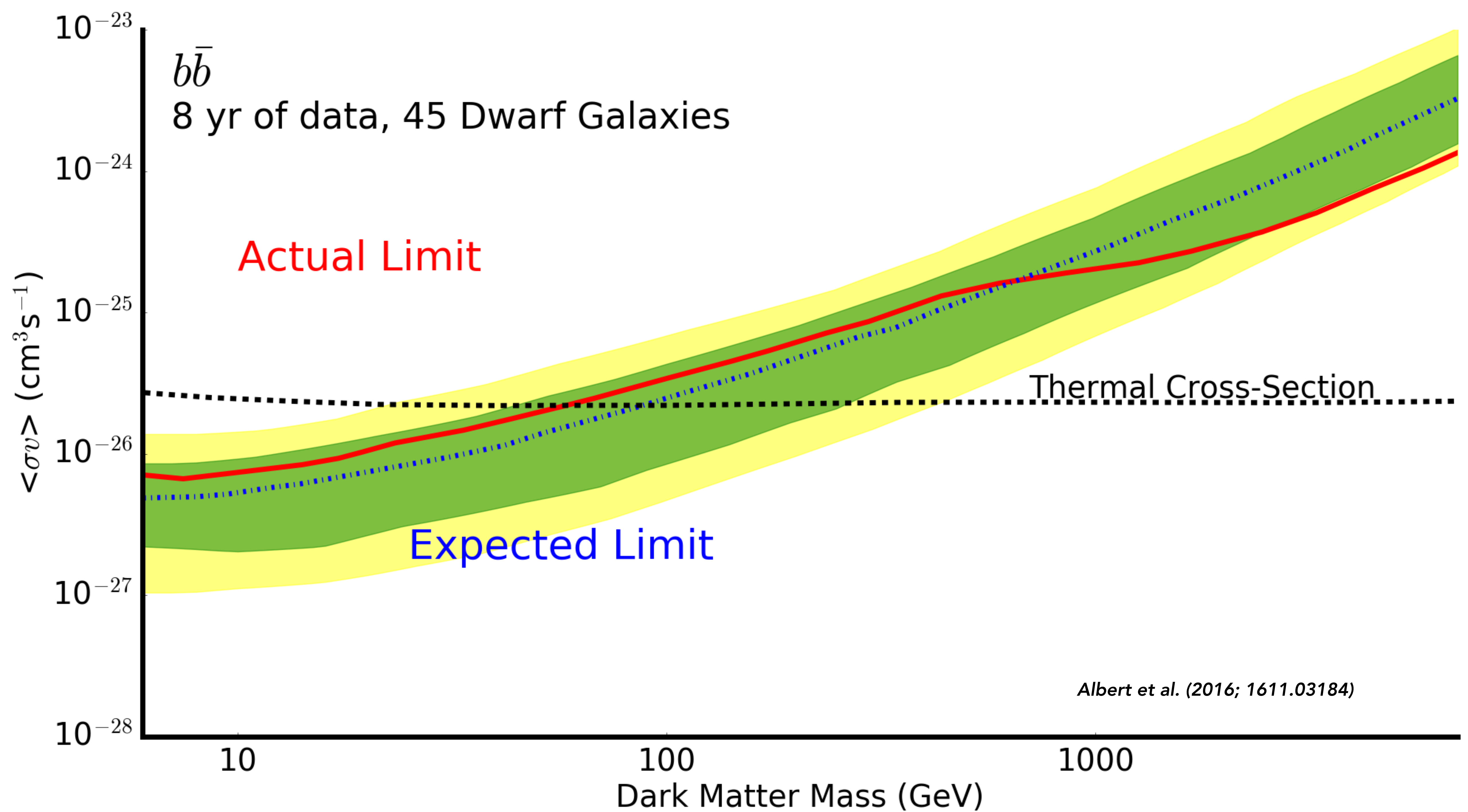
Standard Method

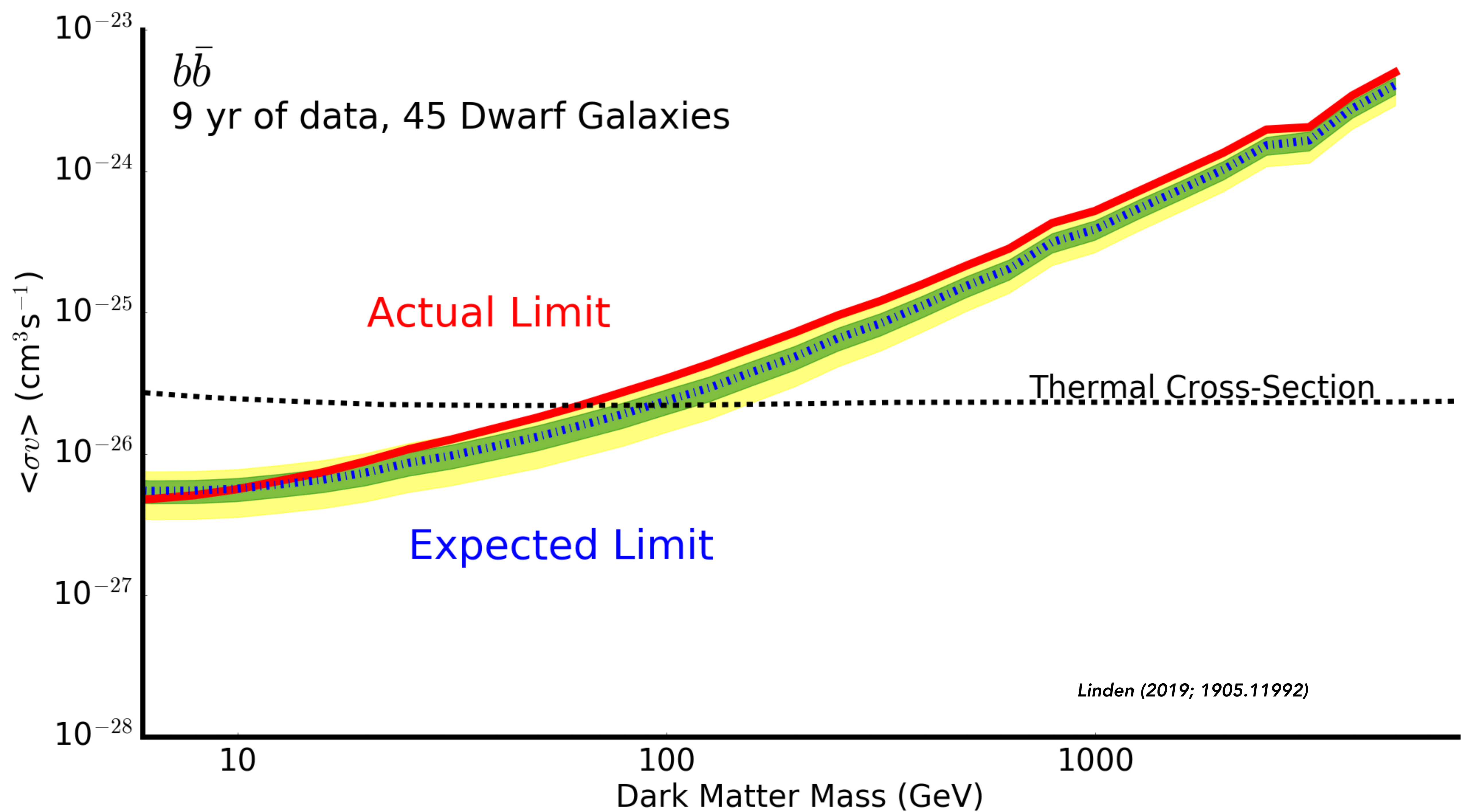


dSphs









The Galactic Center Excess

FERMILAB-PUB-09-494-A

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope

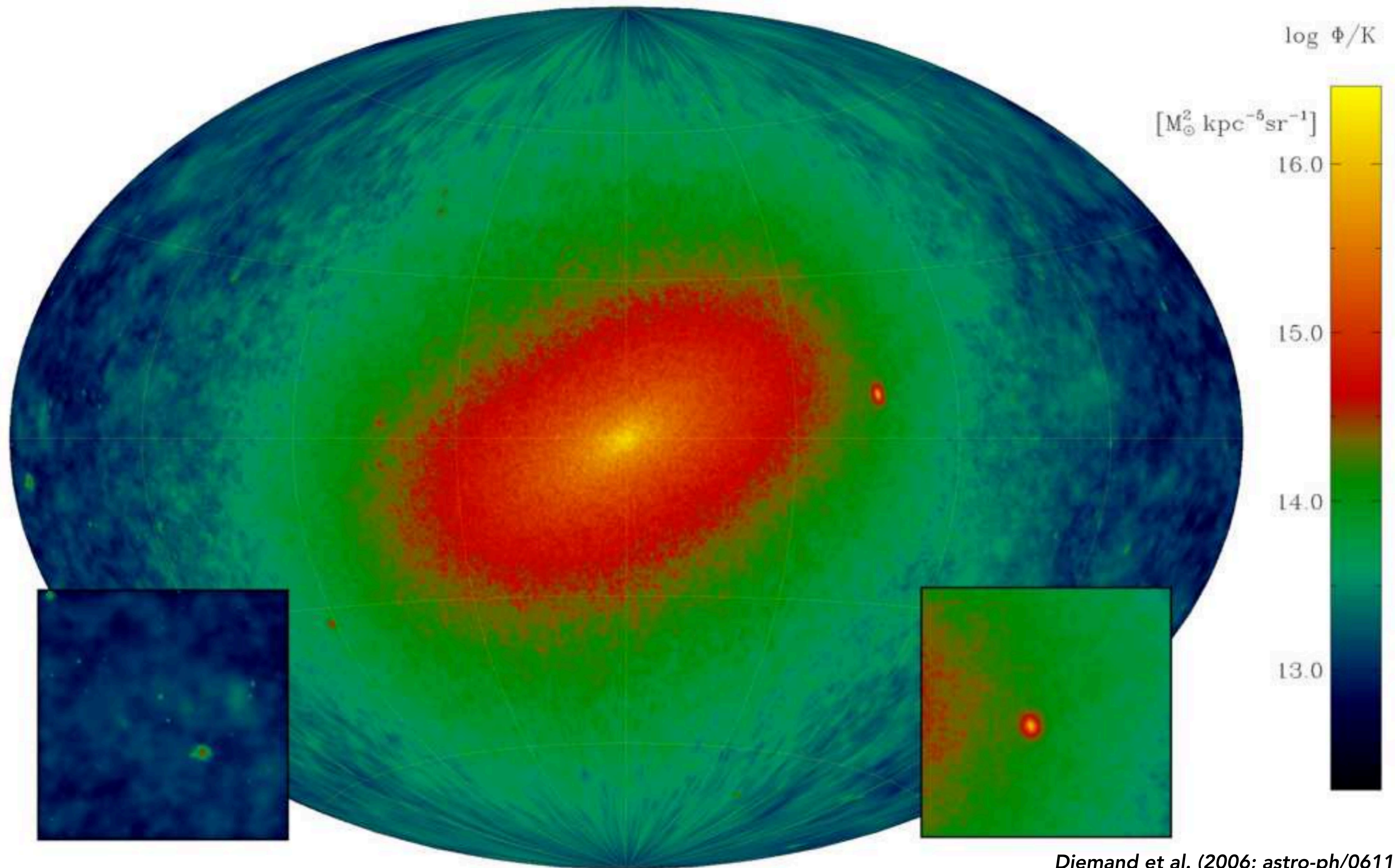
Lisa Goodenough¹ and Dan Hooper^{2,3}

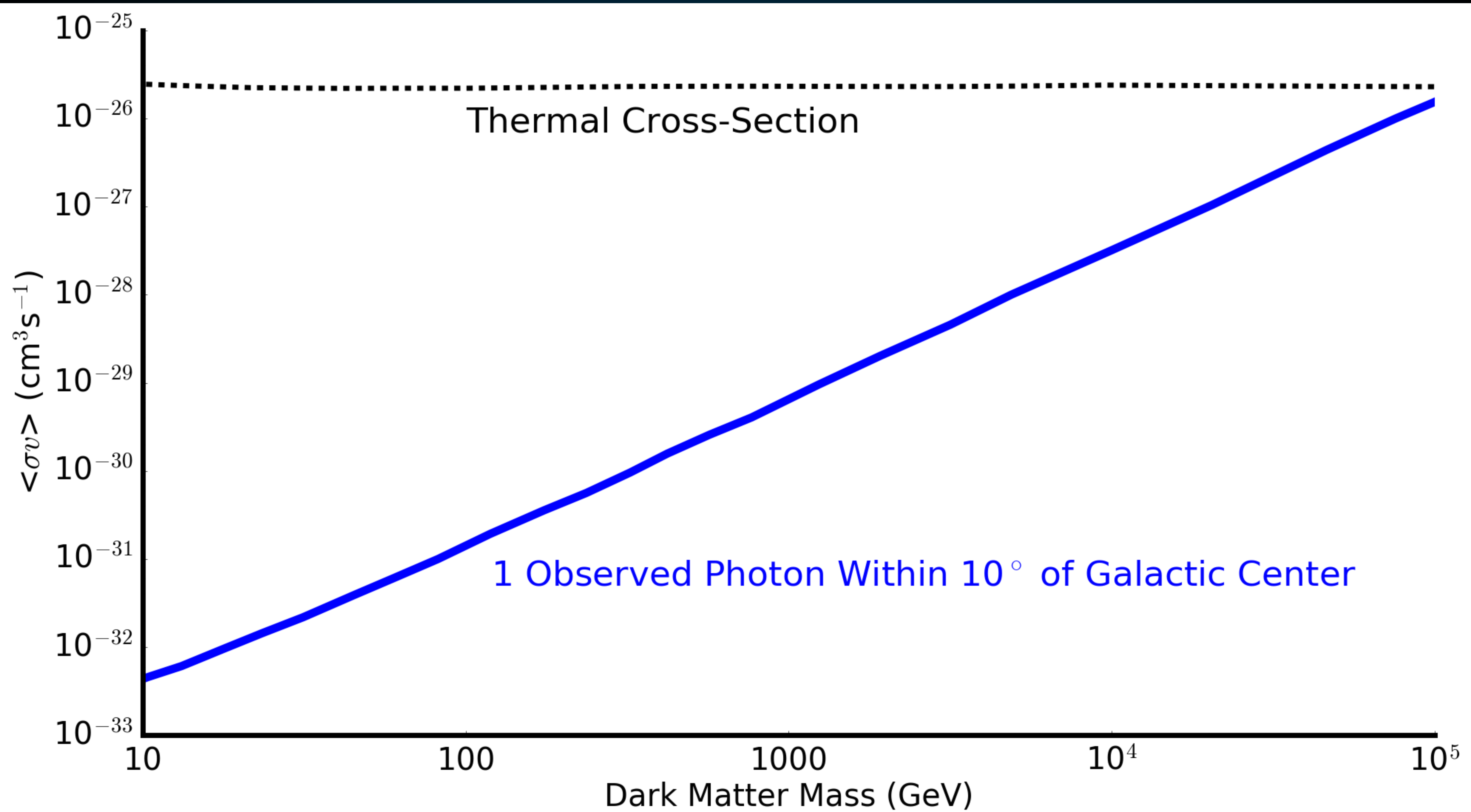
¹*Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003*

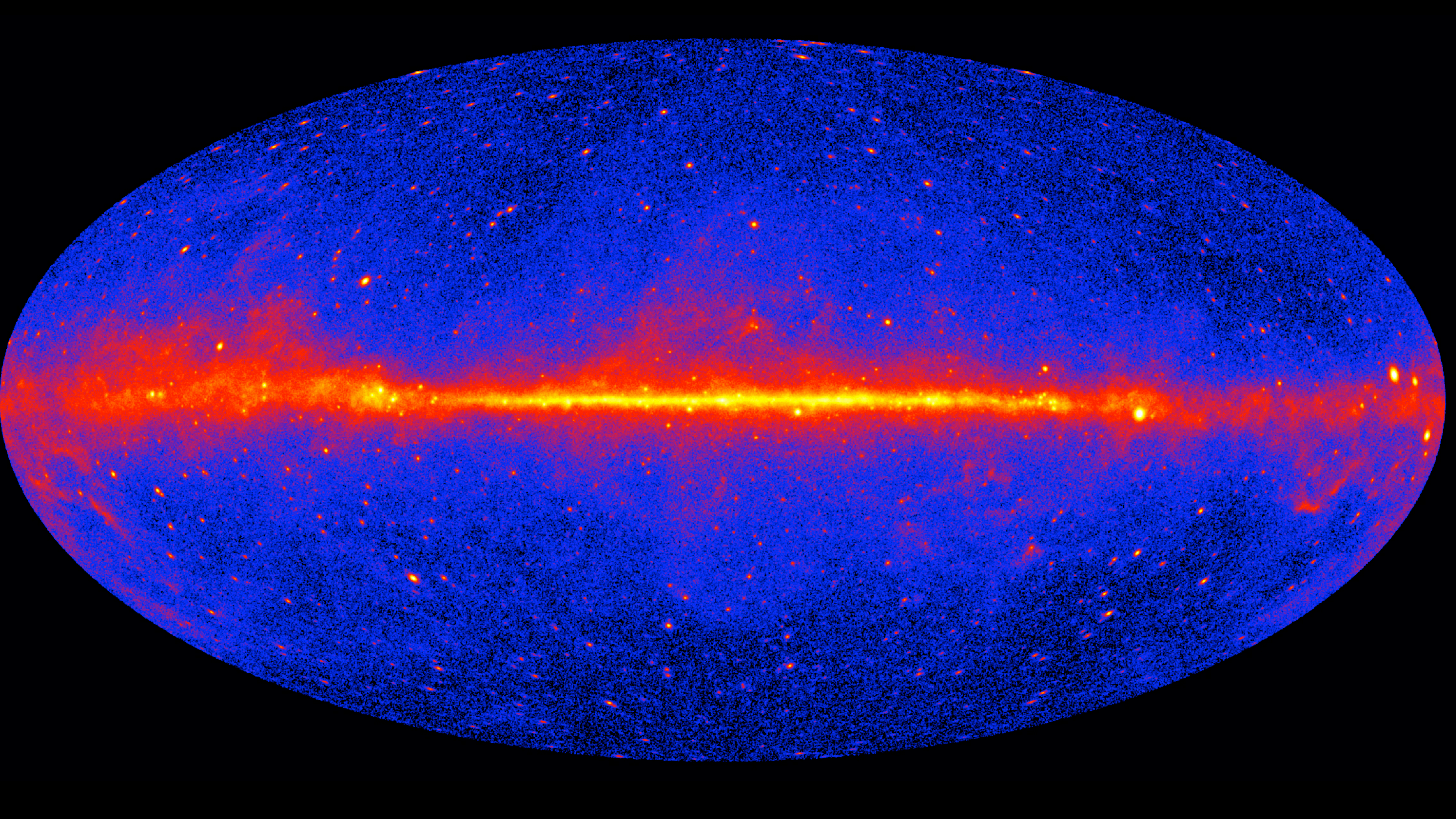
²*Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510*

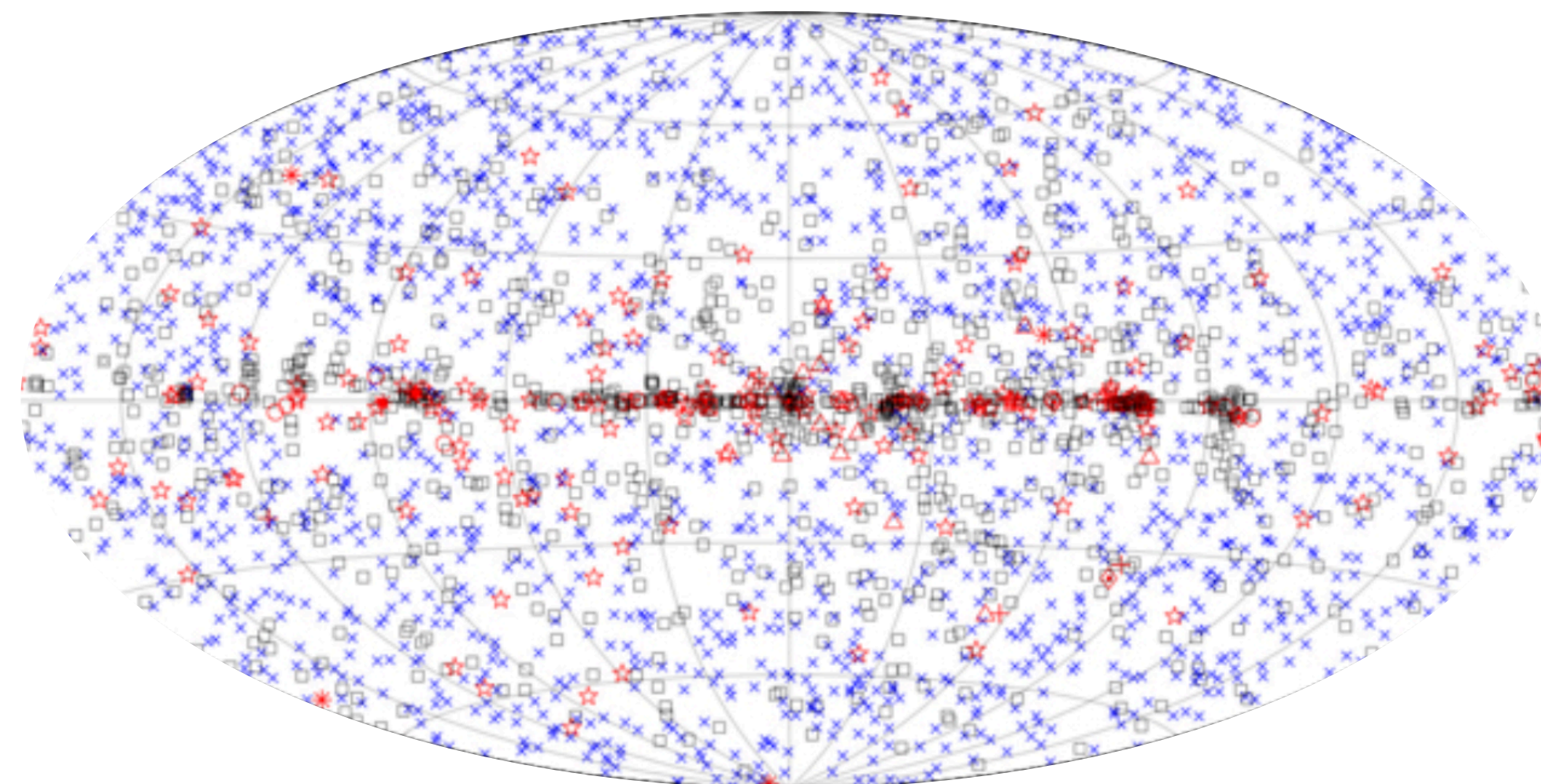
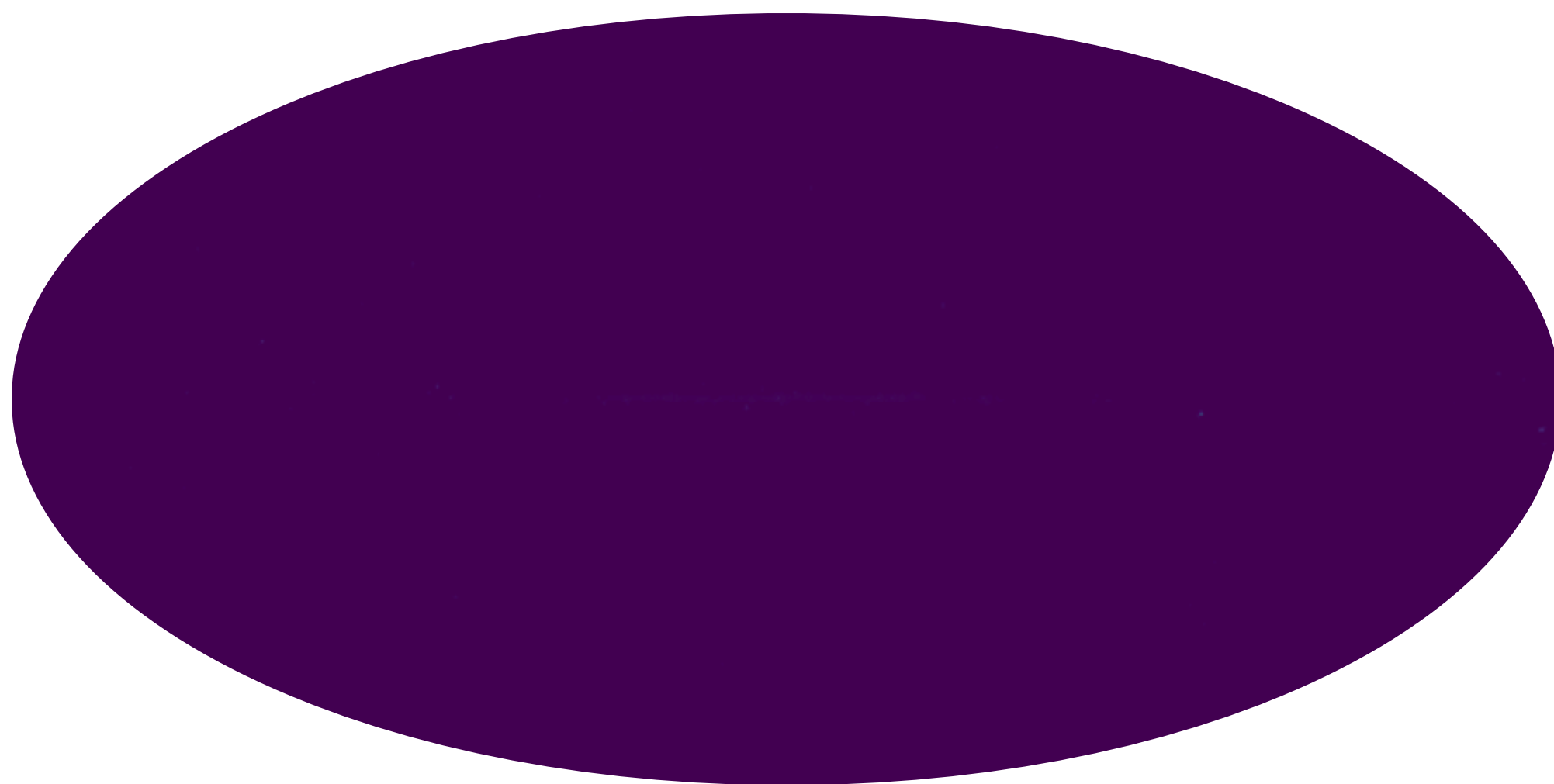
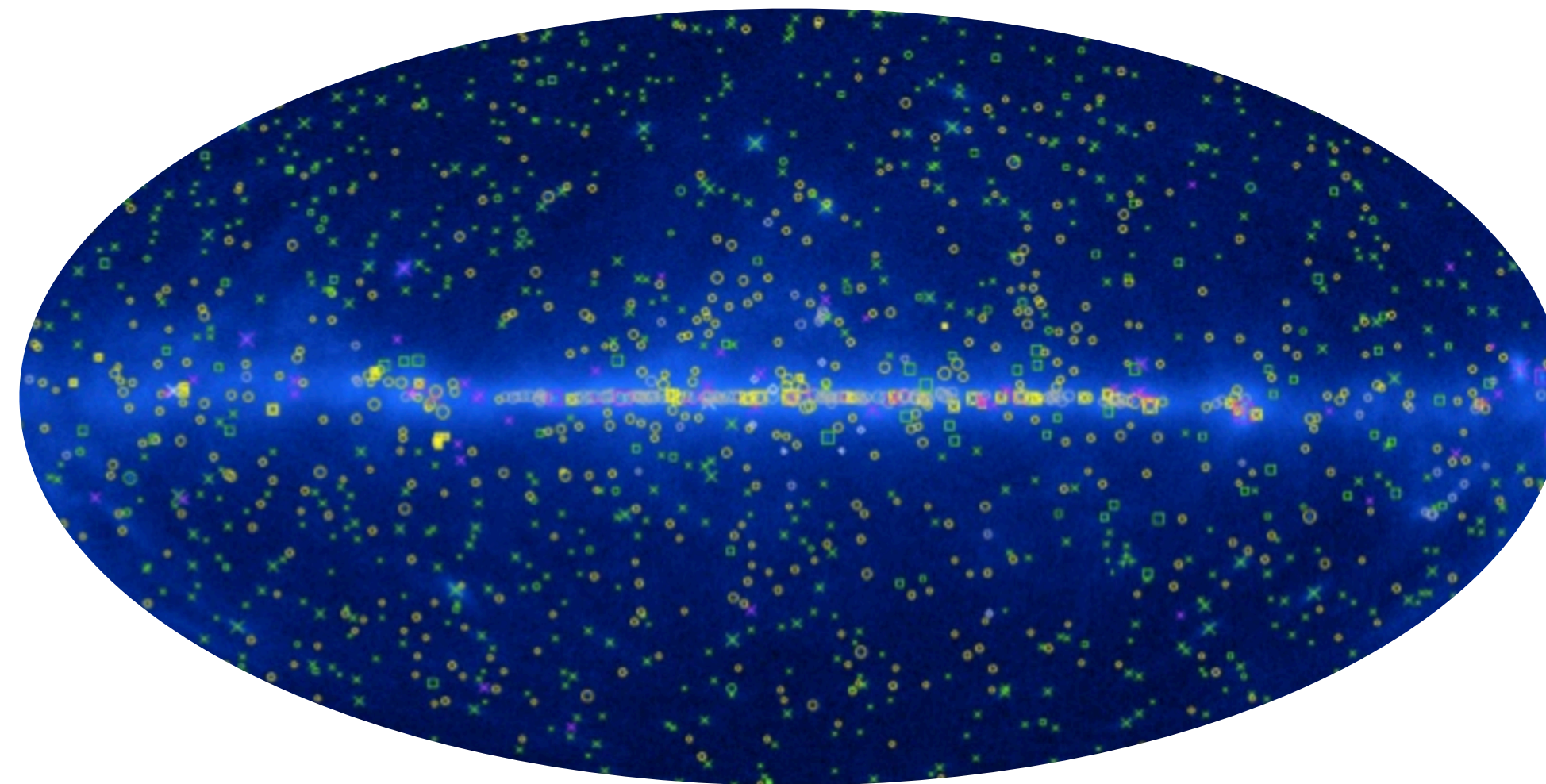
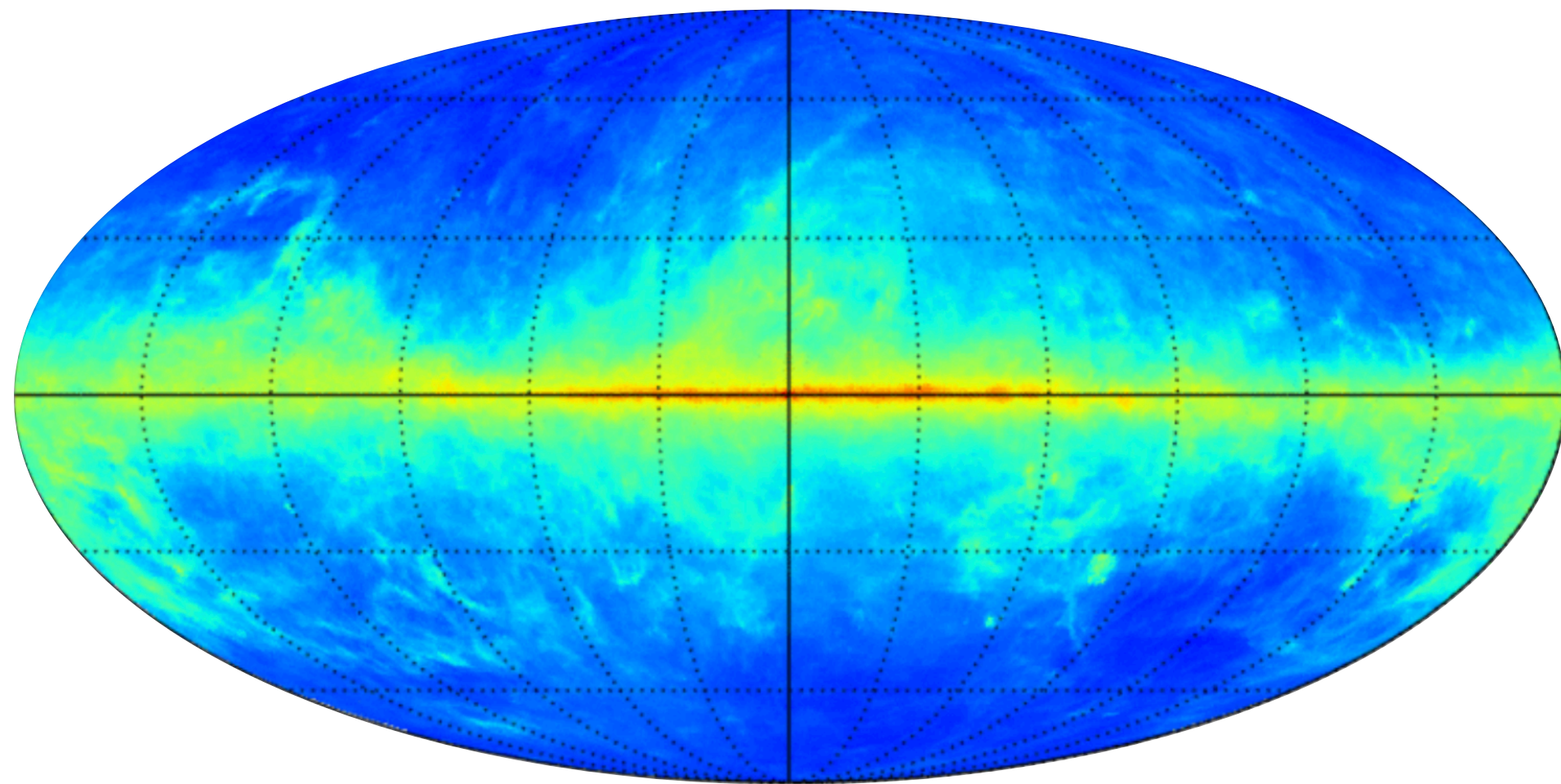
³*Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637*

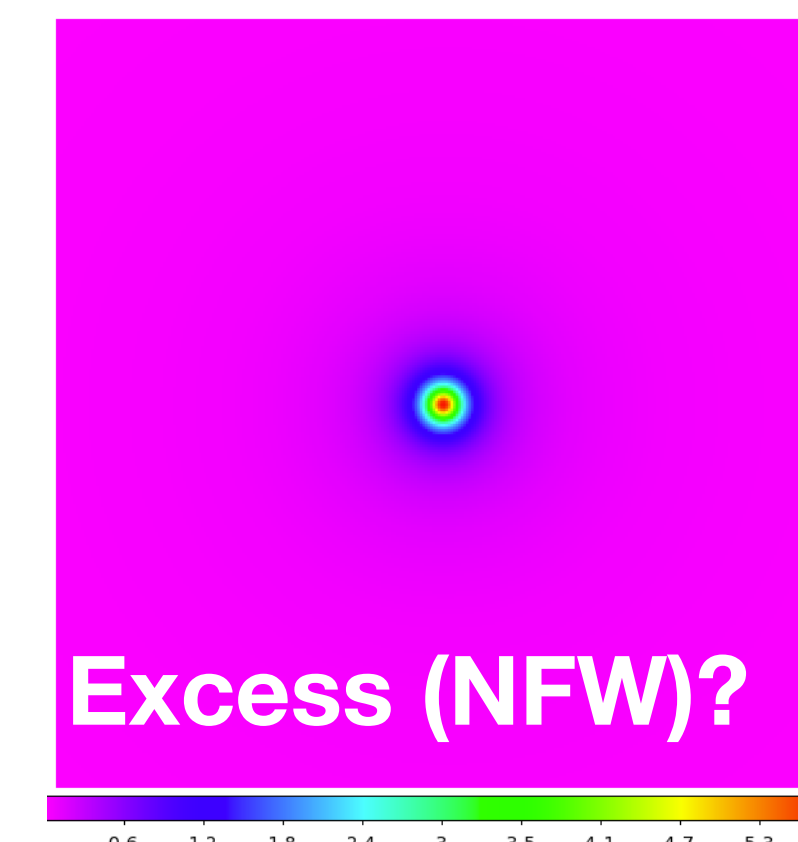
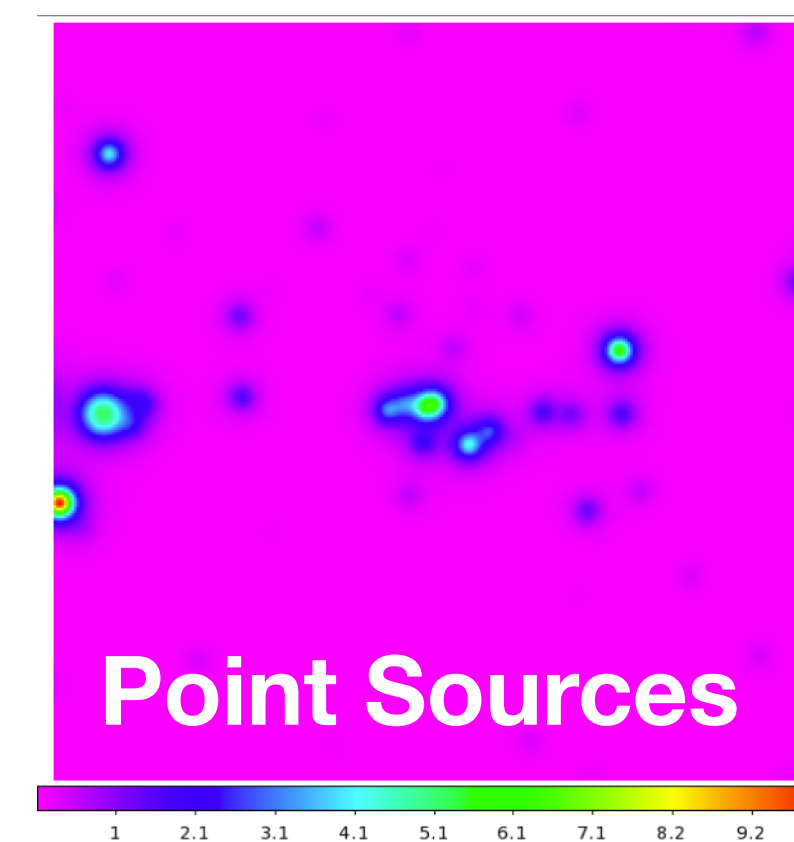
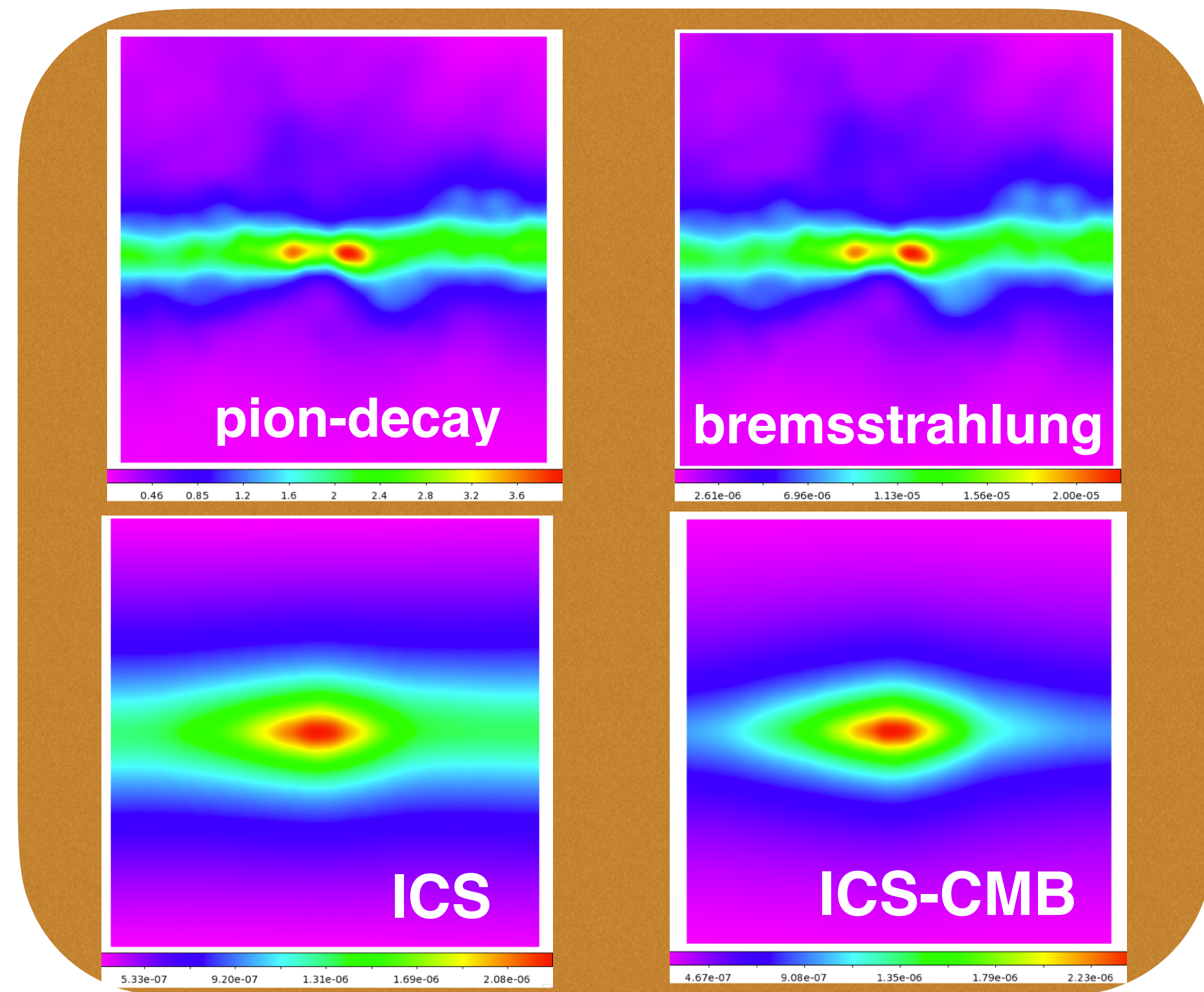
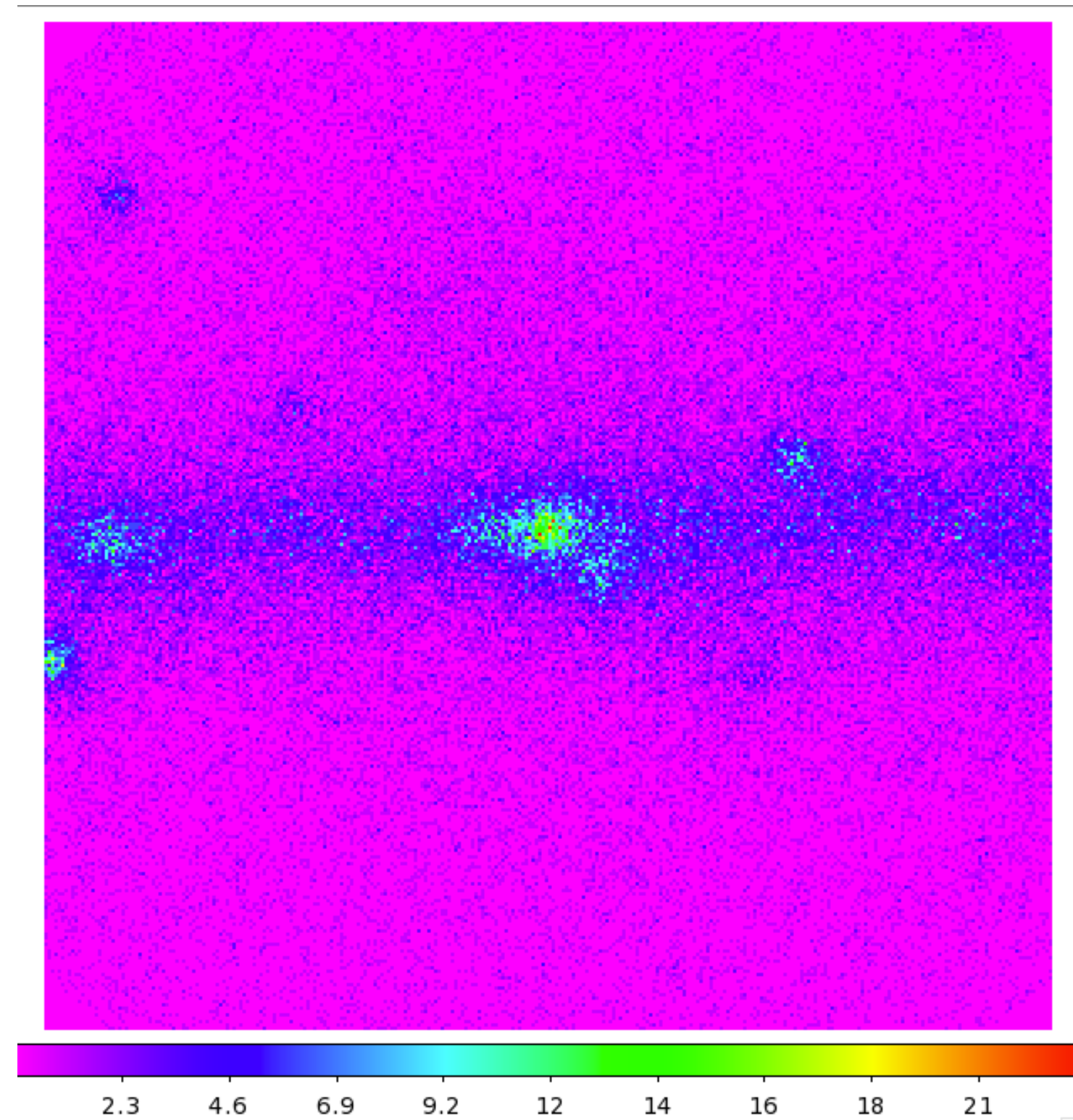
We study the gamma rays observed by the Fermi Gamma Ray Space Telescope from the direction of the Galactic Center and find that their angular distribution and energy spectrum are well described by a dark matter annihilation scenario. In particular, we find a good fit to the data for dark matter particles with a 25-30 GeV mass, an annihilation cross section of $\sim 9 \times 10^{-26} \text{ cm}^3/\text{s}$, and that are distributed with a cusped halo profile, $\rho(r) \propto r^{-1.1}$, within the inner kiloparsec of the Galaxy. We cannot, however, exclude the possibility that these photons originate from an astrophysical source or sources with a similar morphology and spectral shape to those predicted in an annihilating dark matter scenario.









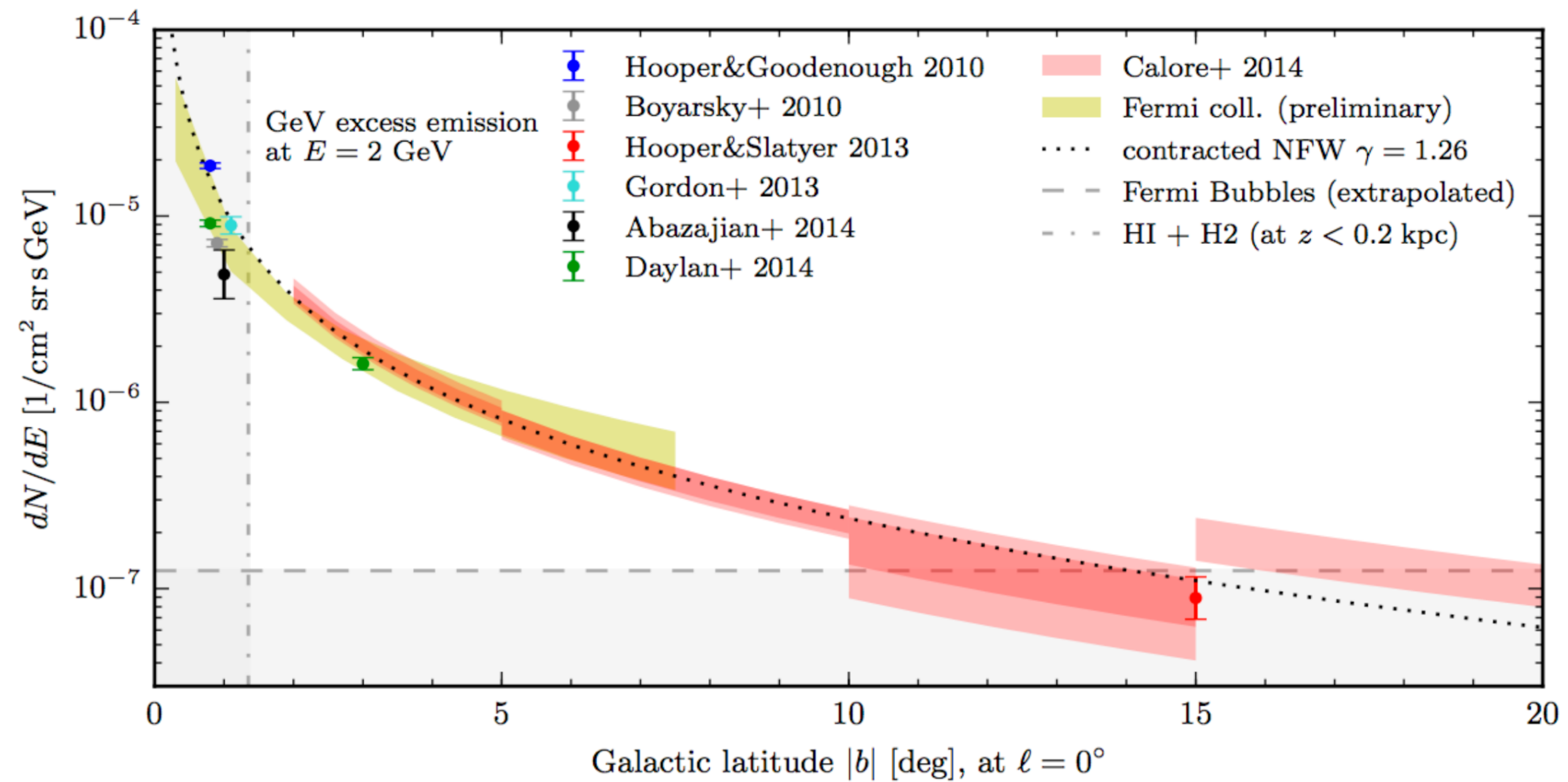
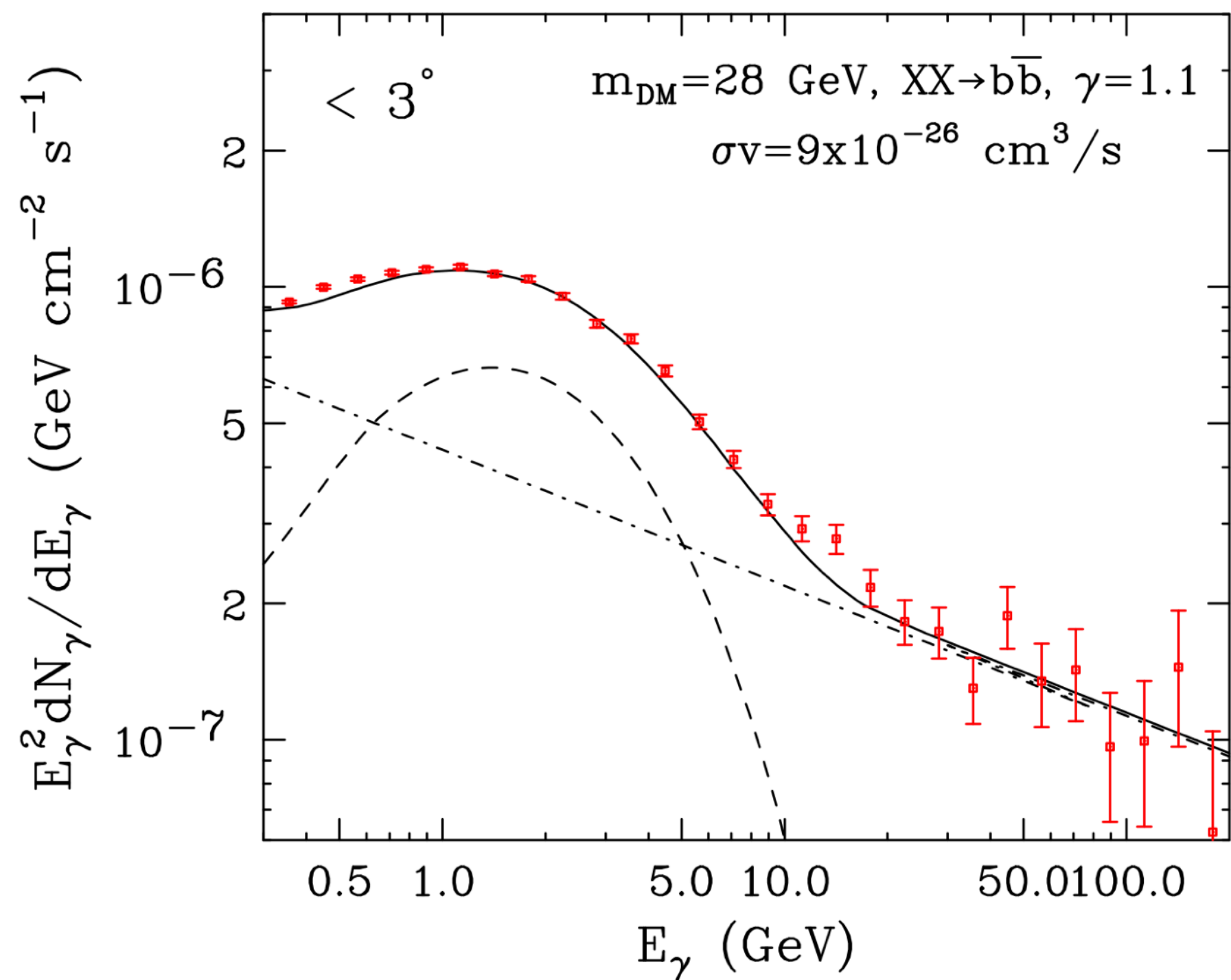


Cosmic-Ray Transport

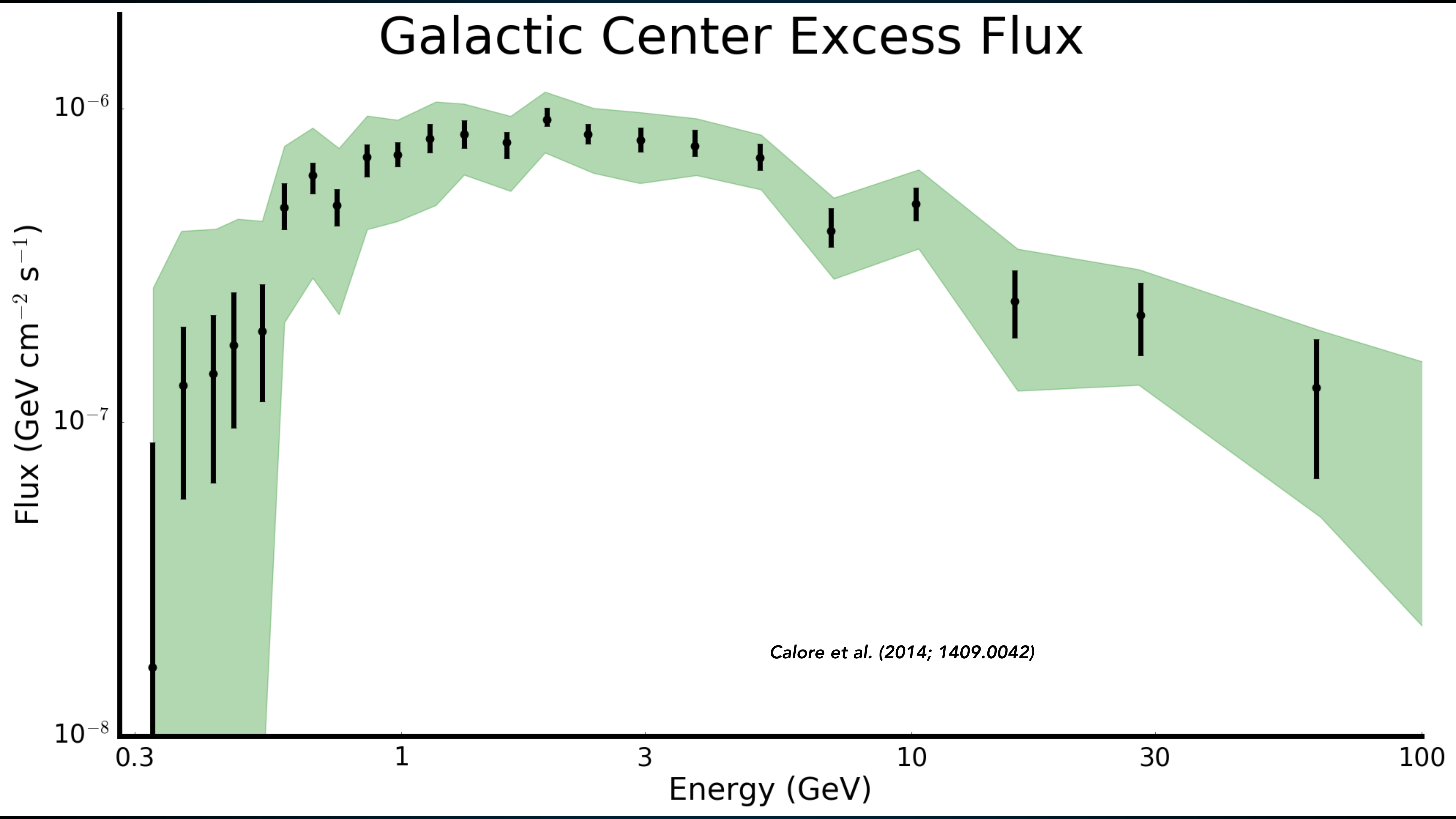
Latex by Isabelle John

$$\begin{aligned}
 \overbrace{\frac{\partial \psi(\vec{r}, p, t)}{\partial t}}^{\text{flux}} = & \overbrace{Q(\vec{r}, p, t)}^{\text{source}} + \overbrace{\vec{\nabla} \times (D_{xx} \vec{\nabla} \psi)}^{\text{diffusion}} - \overbrace{\vec{V} \psi}^{\text{convection}} + \overbrace{\frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \psi}^{\text{re-acceleration}} \\
 & - \underbrace{\frac{\partial}{\partial p} \left(\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \times \vec{V}) \psi \right)}_{\text{energy loss}} - \underbrace{\frac{\psi}{\tau_f}}_{\text{fragmentation}} - \underbrace{\frac{\psi}{\tau_r}}_{\text{radioactive decay}}
 \end{aligned}$$

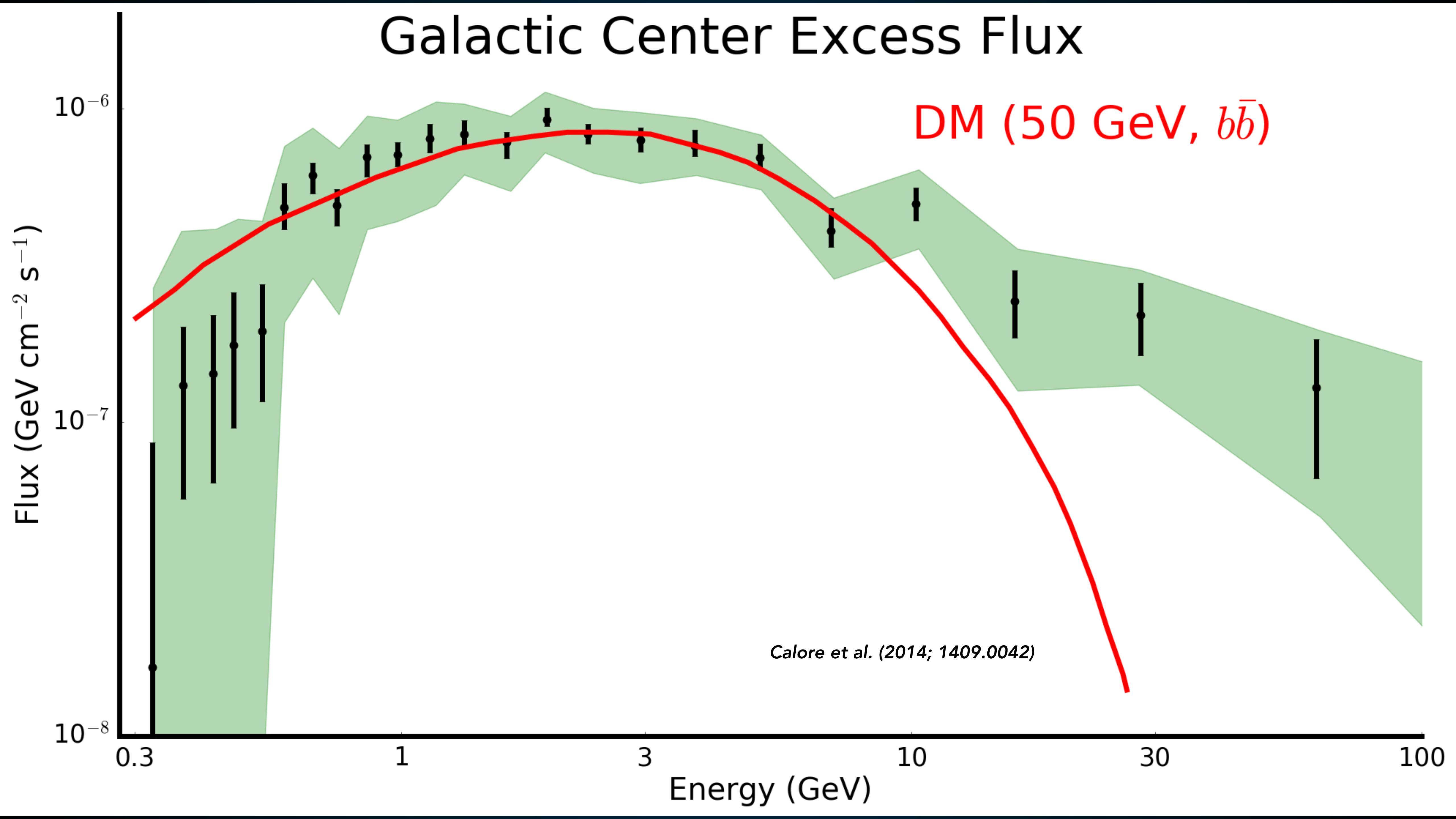
- **Convection:** Winds driven by injection of cosmic-rays and relativistic gas from the Milky Way
- **Energy Losses:** (Next Section)
- **Fragmentation:** Nuclei can be split by interactions
- **Radioactive Decay:** For radioactive nuclei

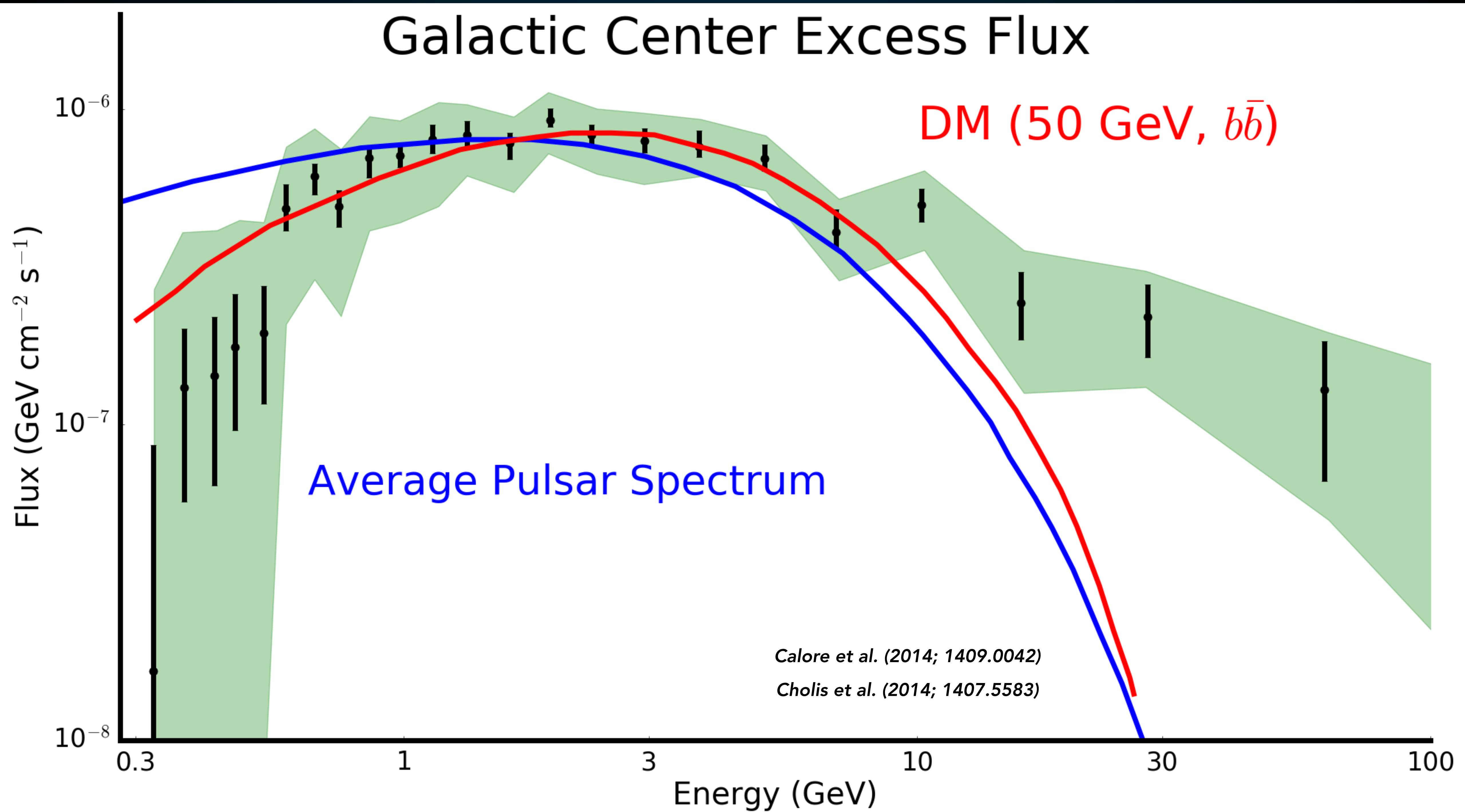


Galactic Center Excess Flux

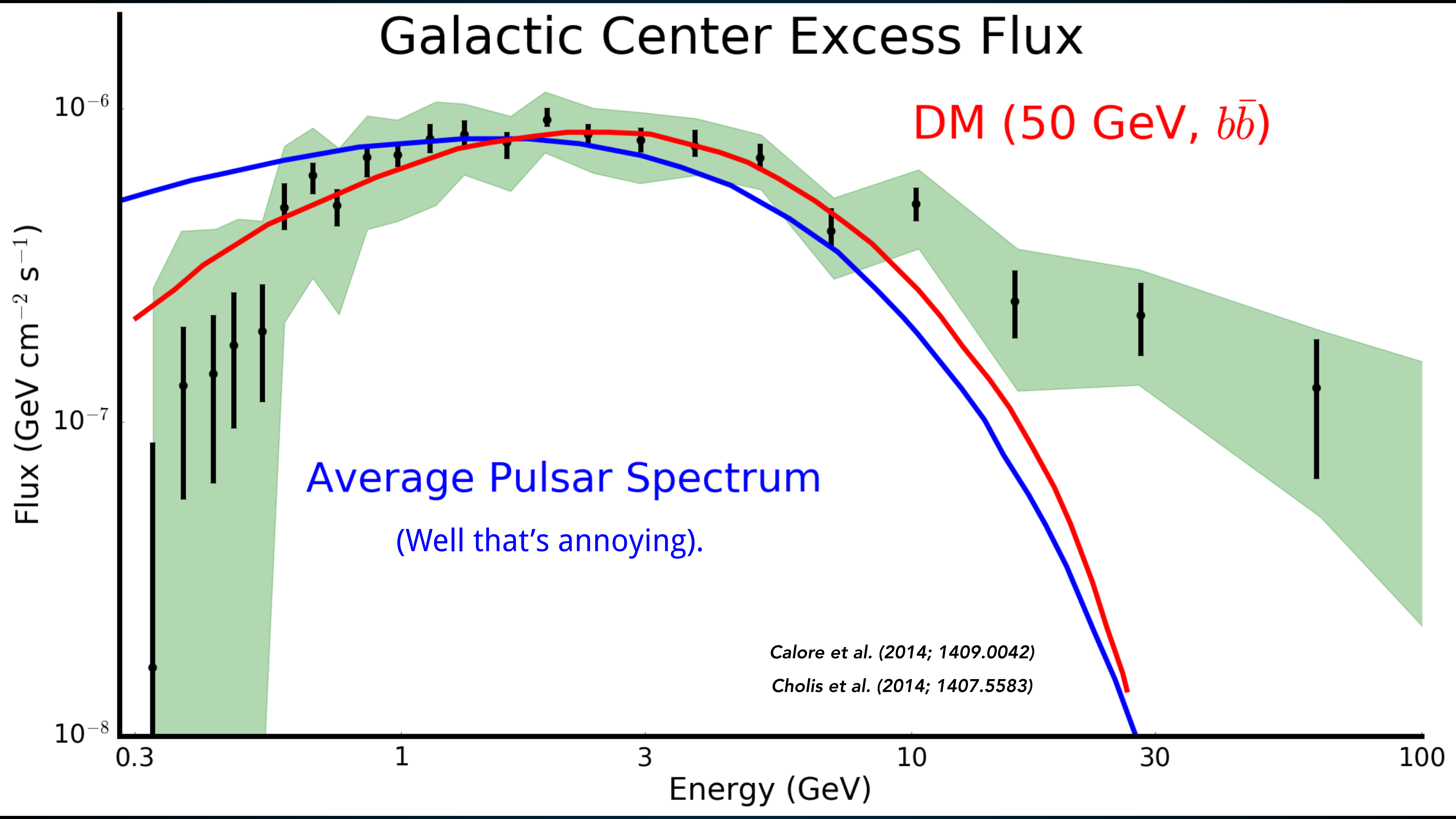


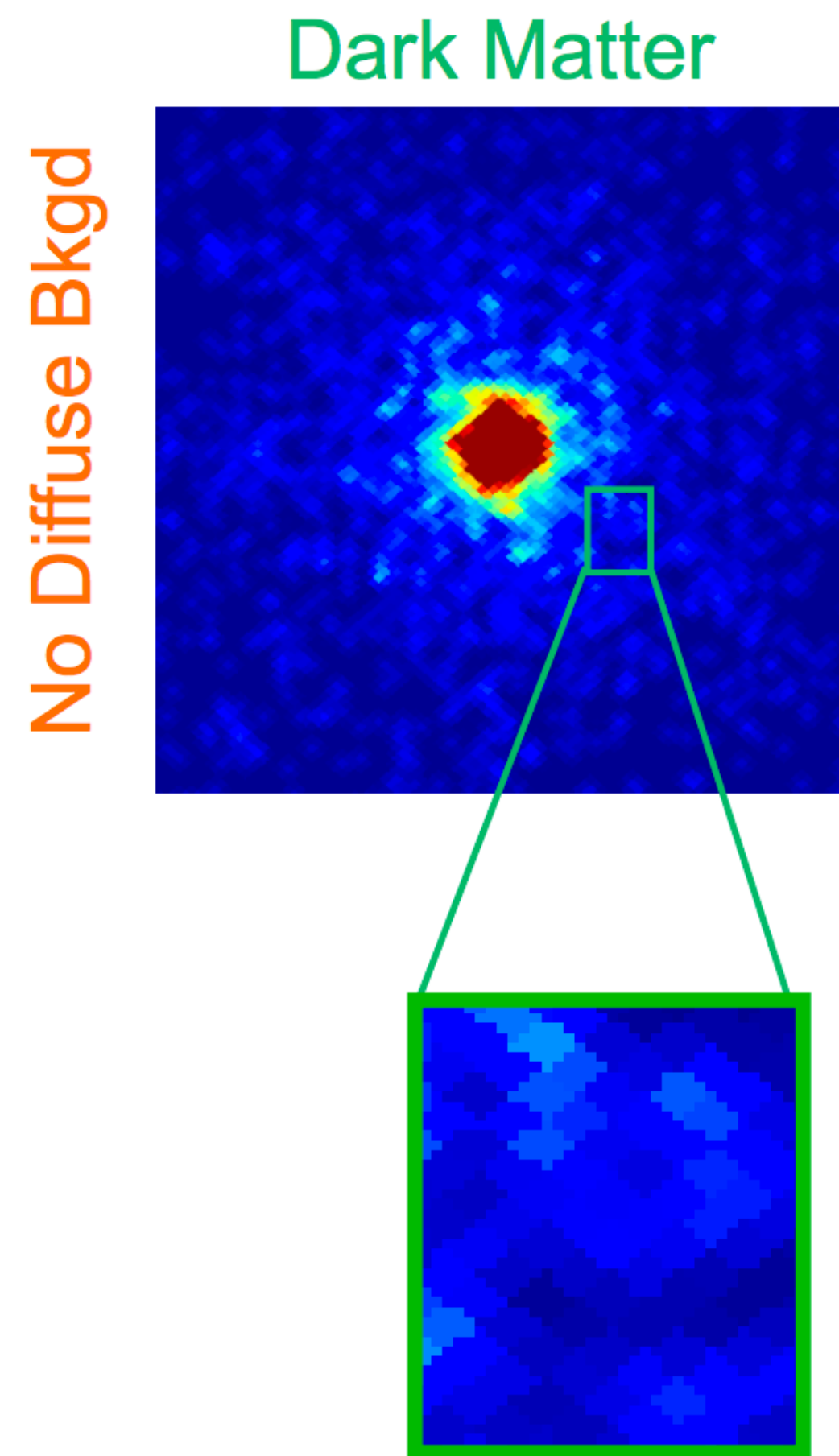
Galactic Center Excess Flux



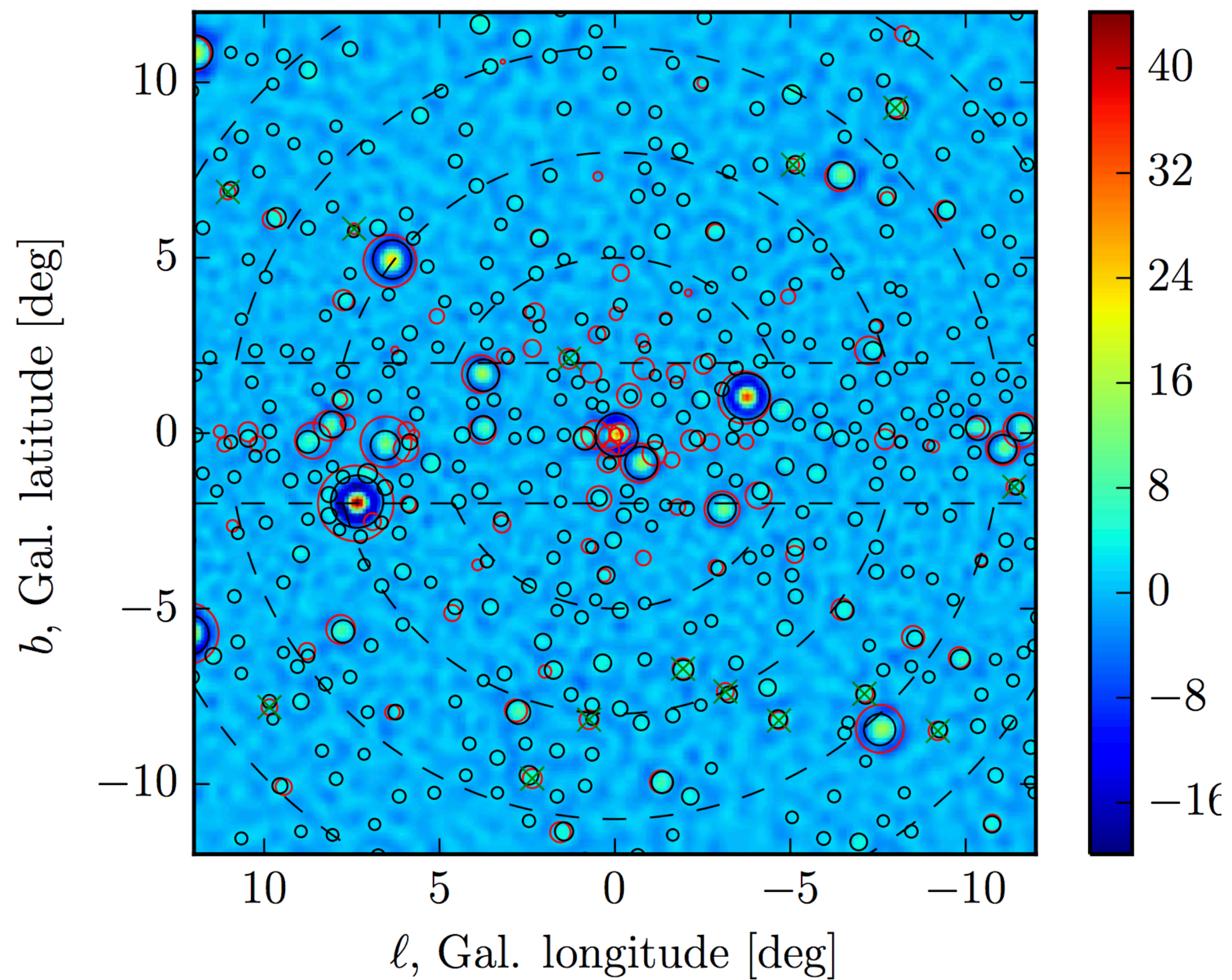
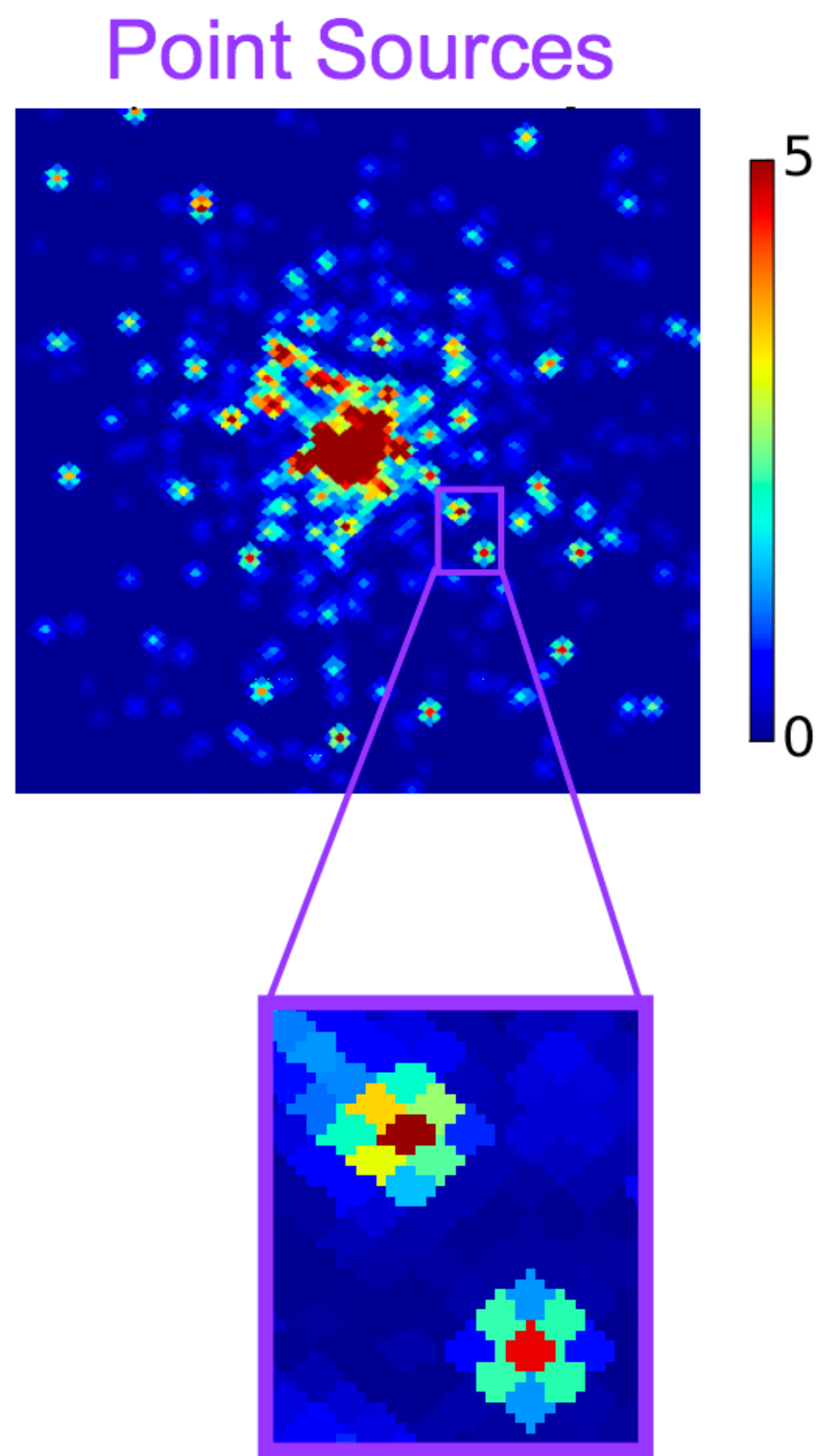


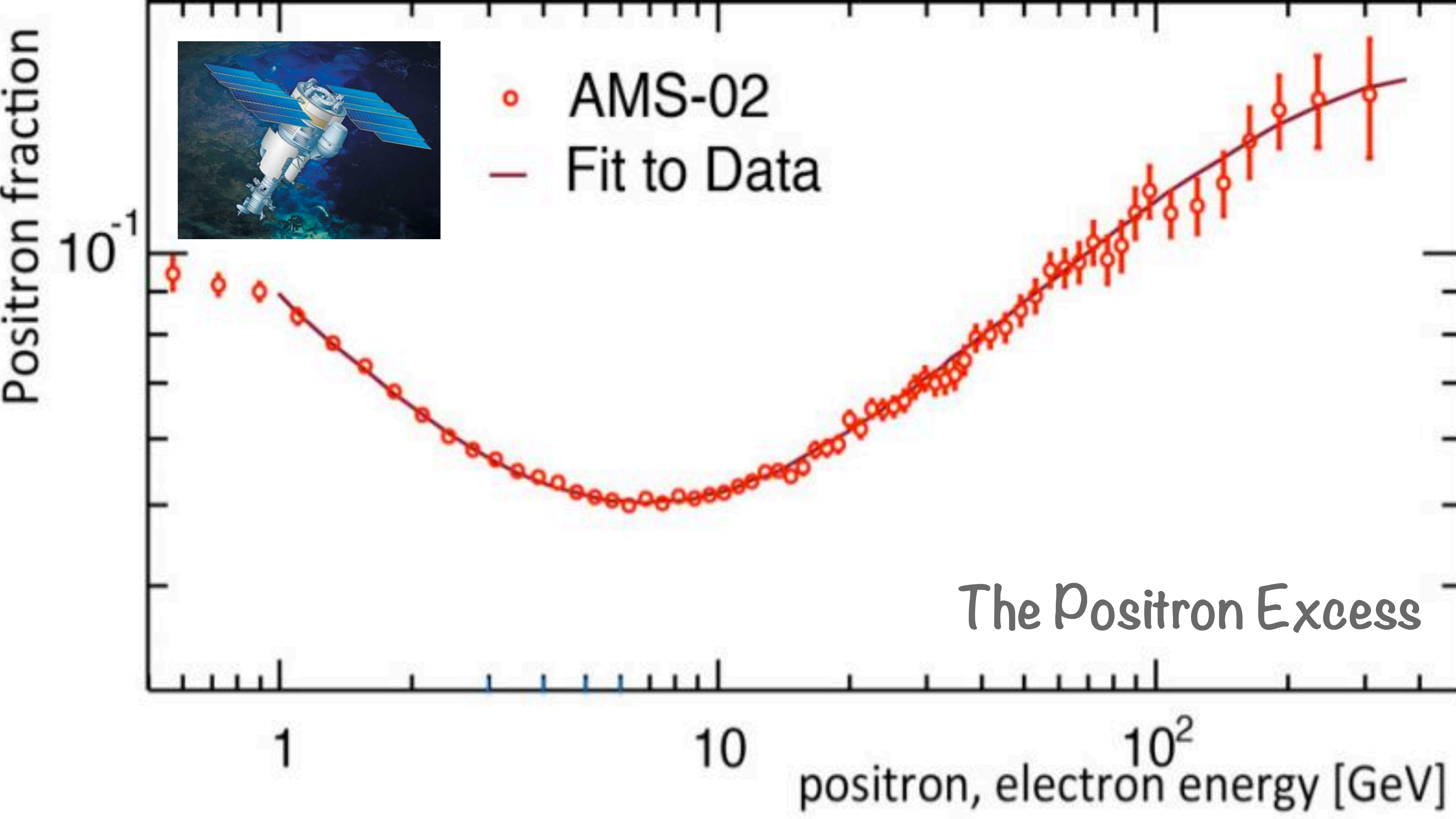
Galactic Center Excess Flux

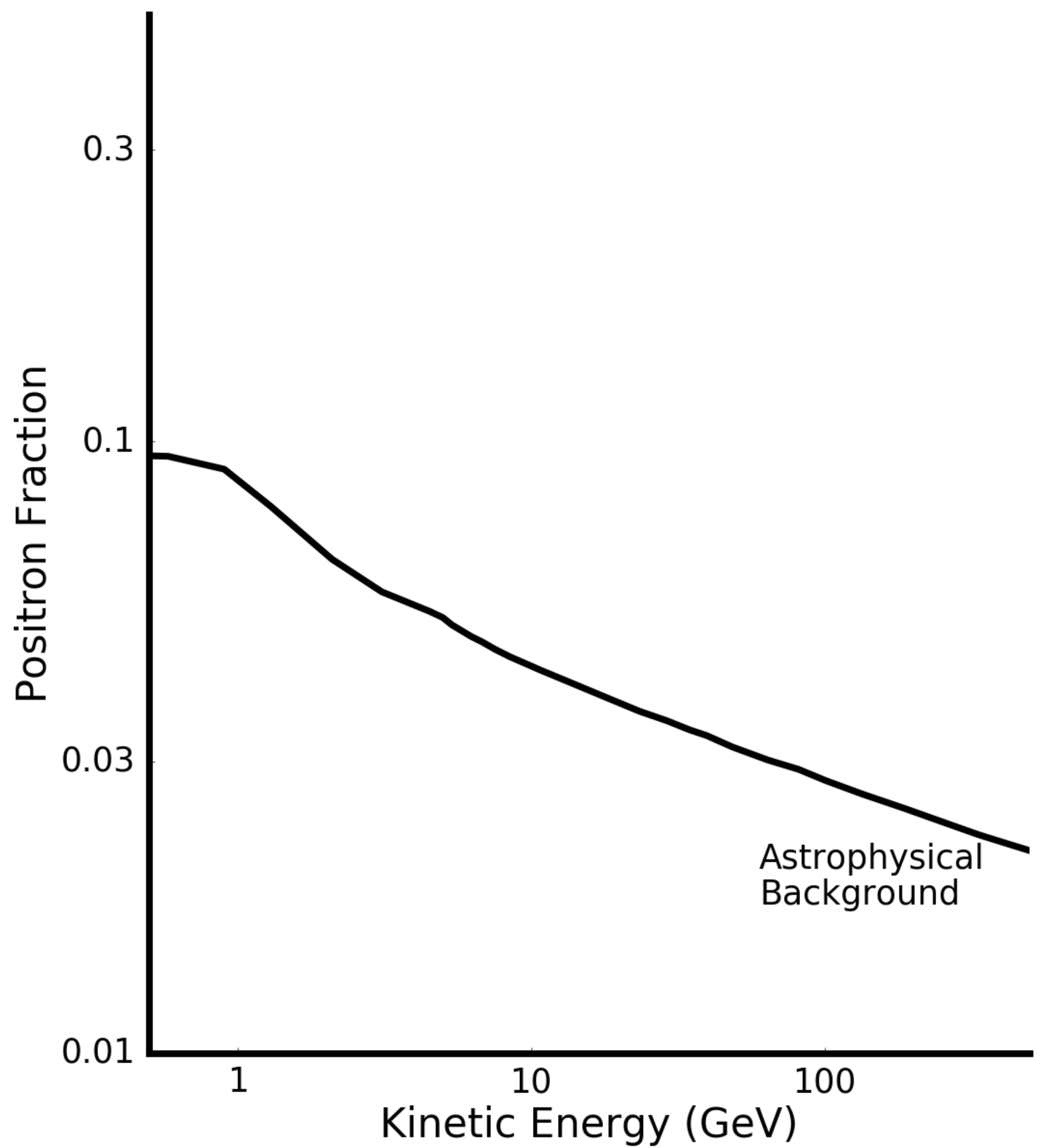
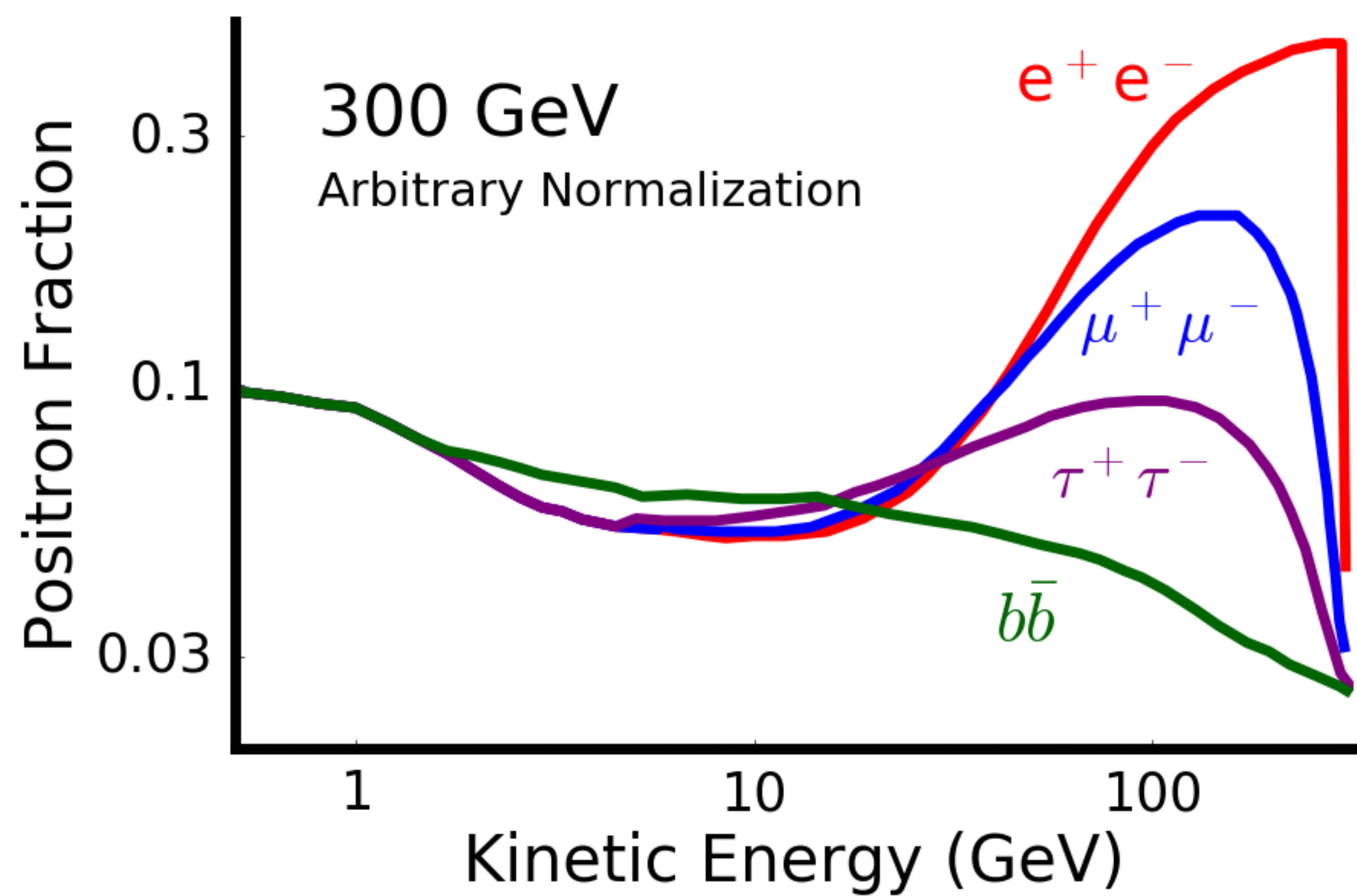


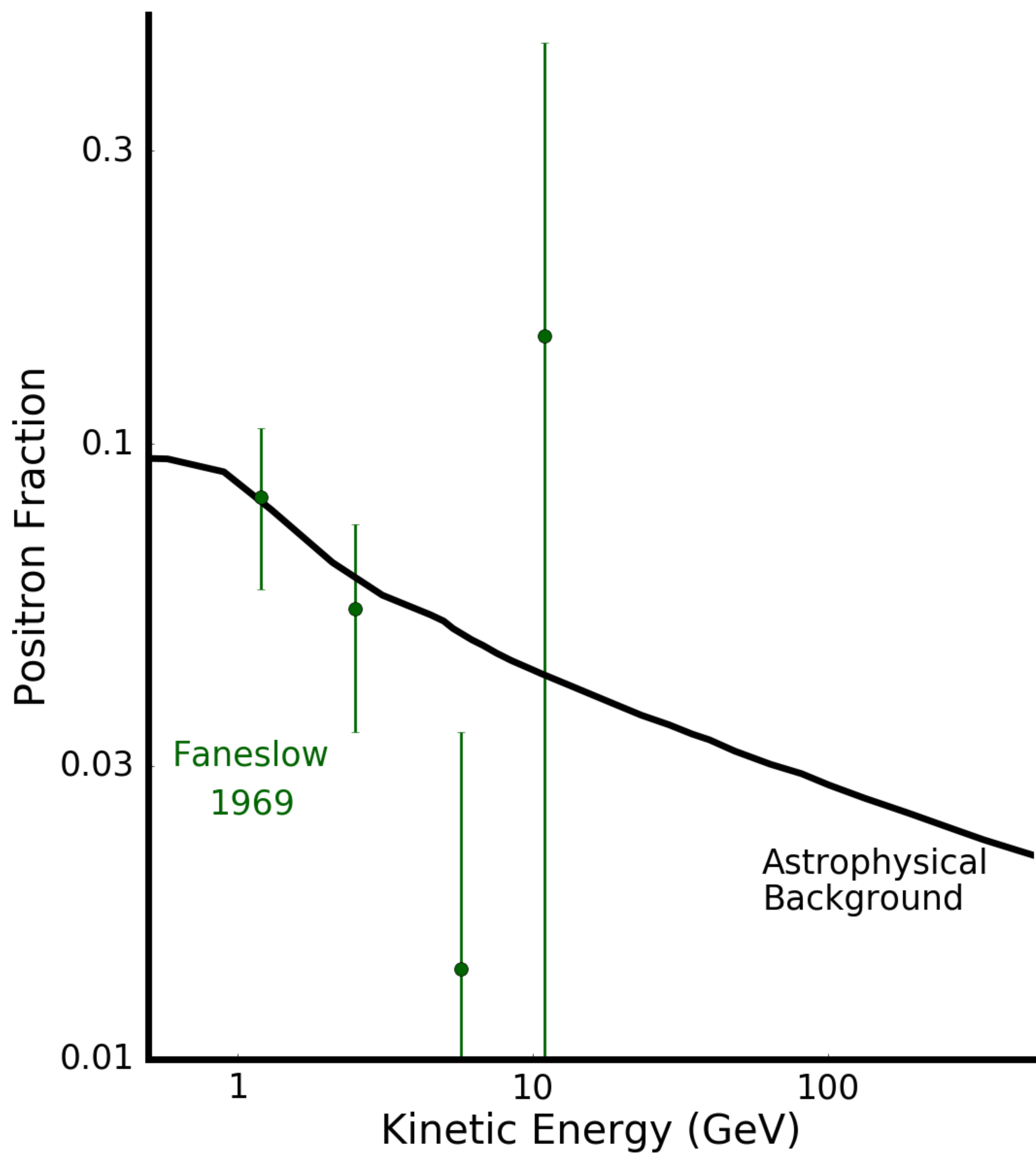
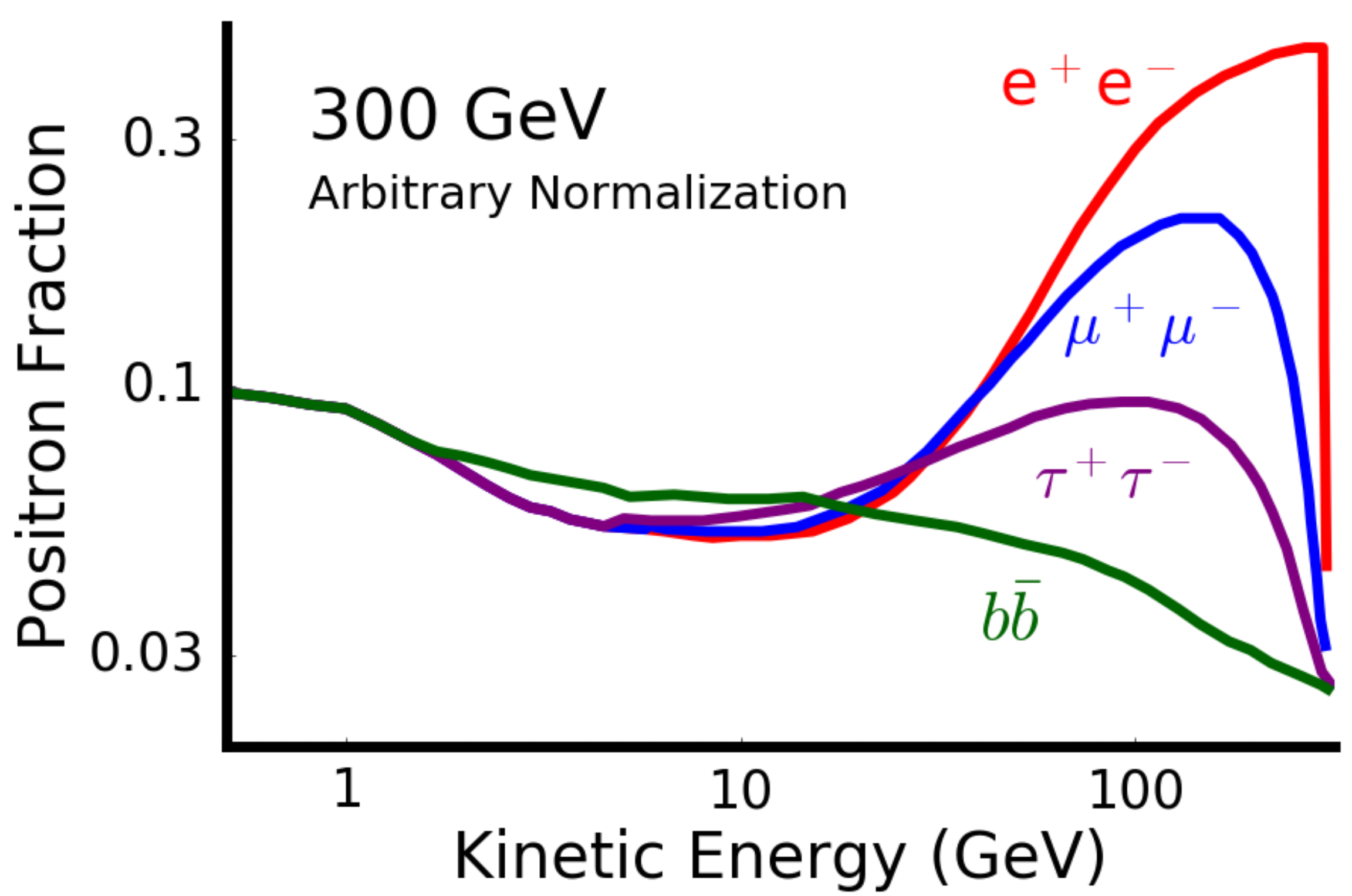
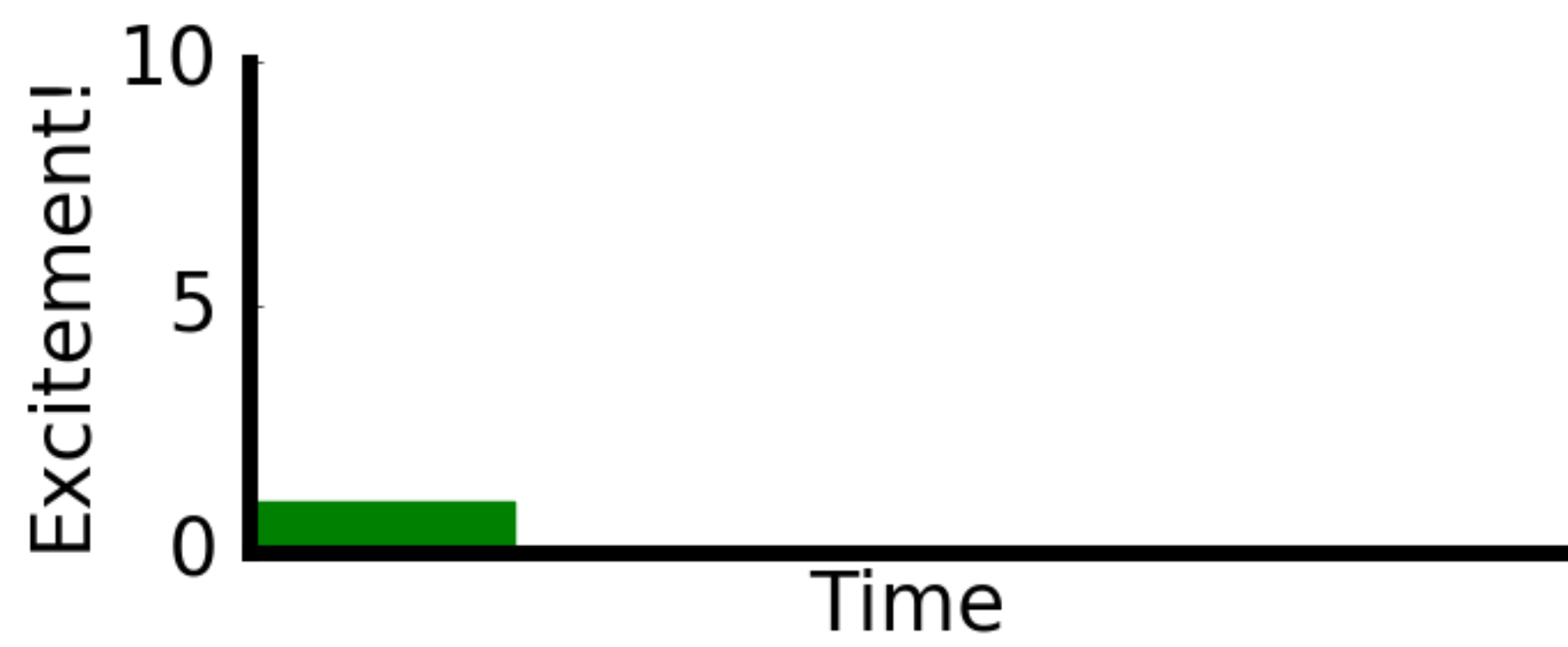


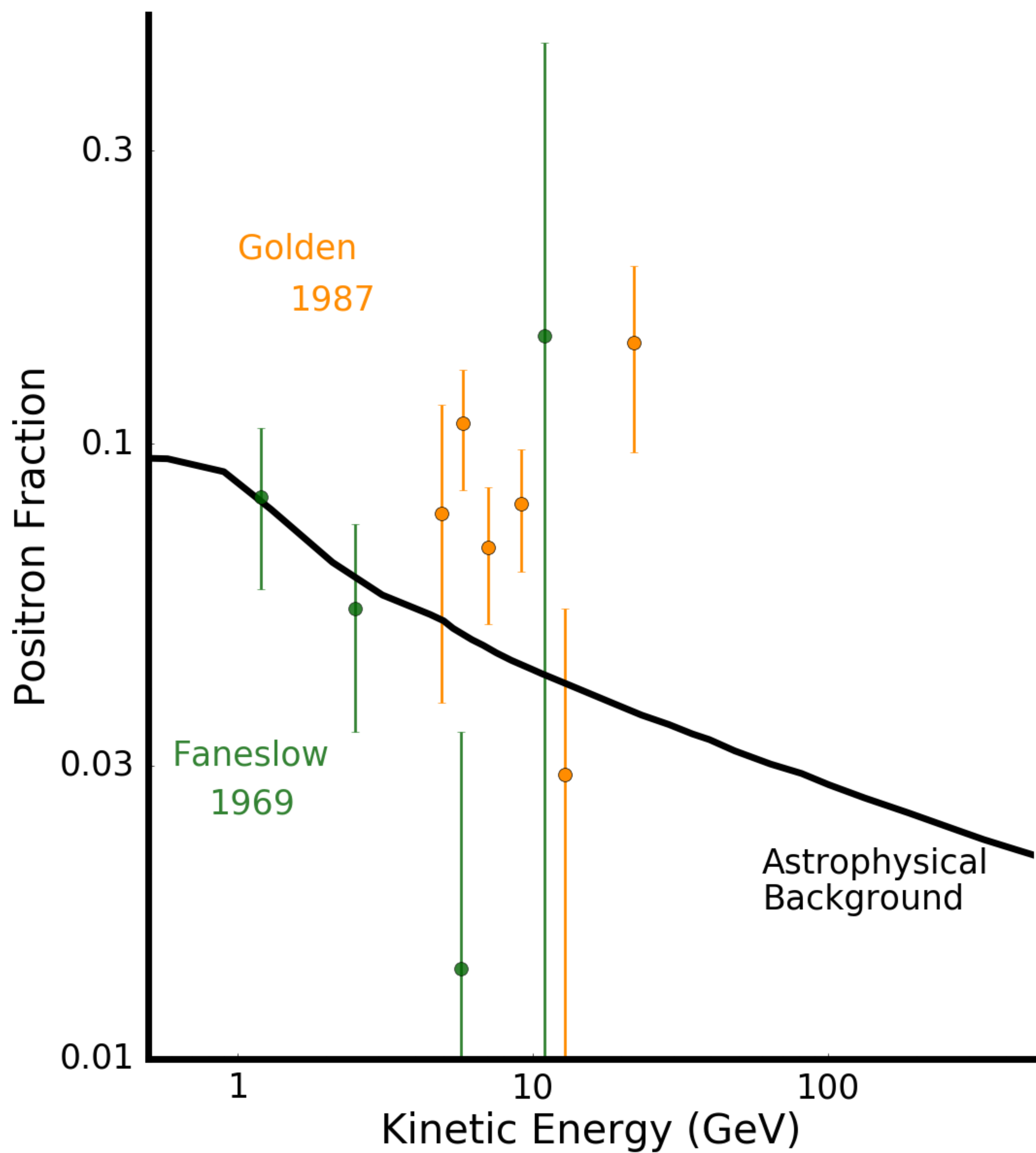
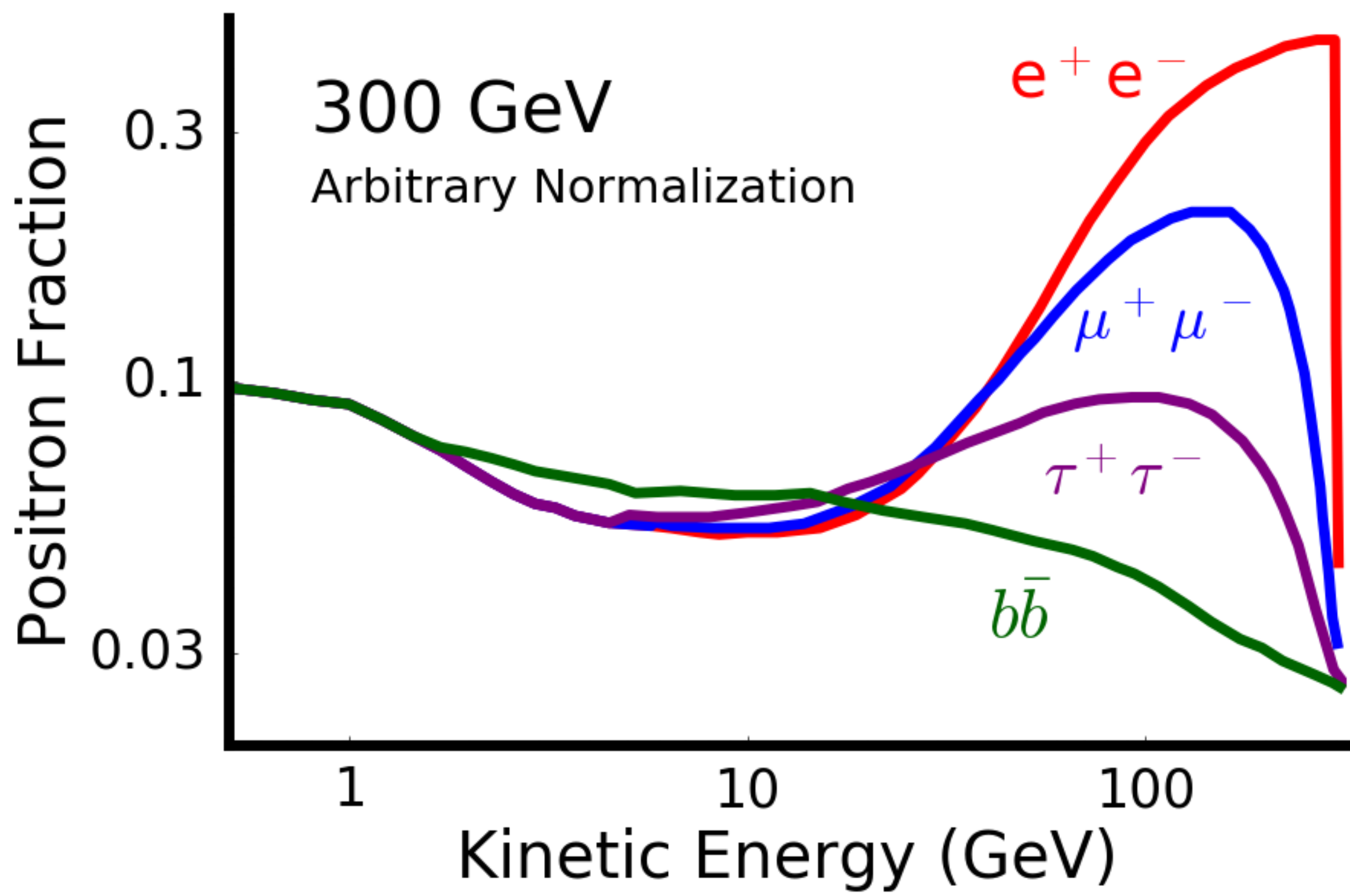
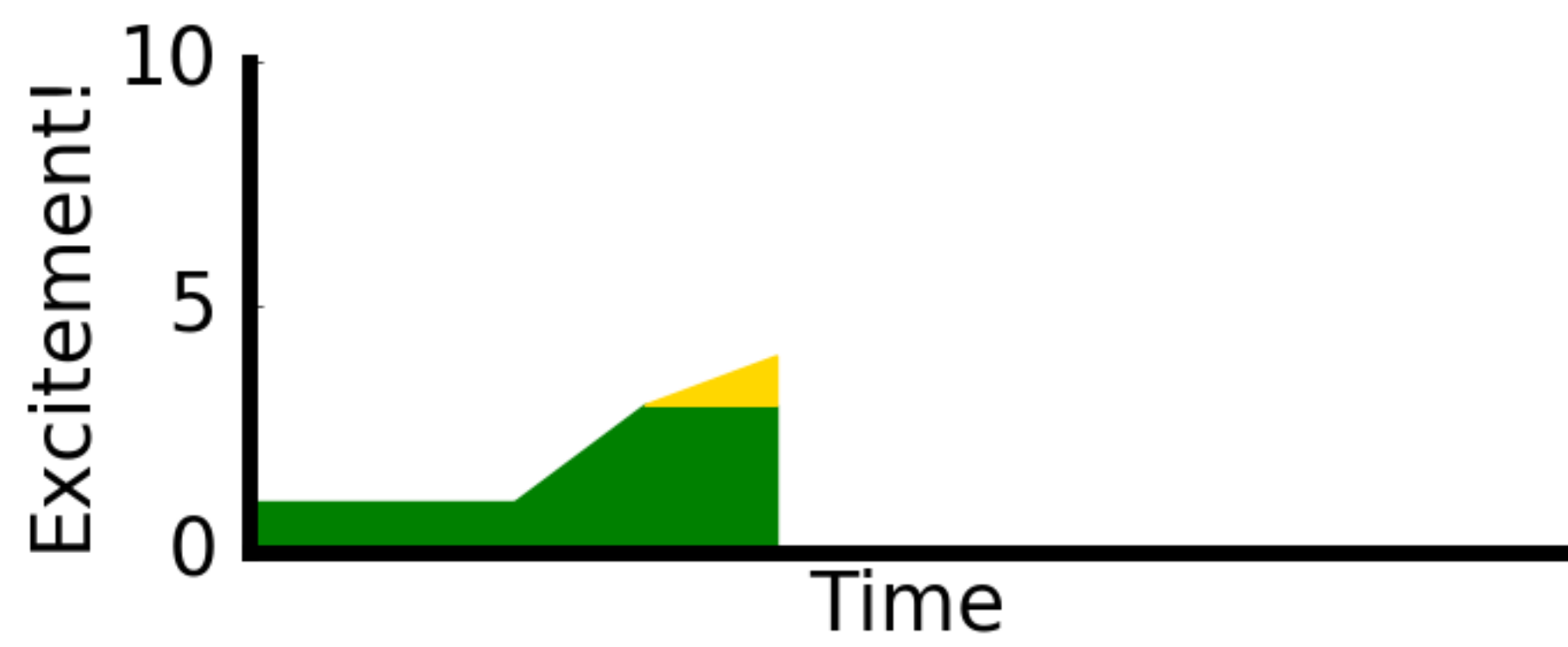
slide from Mariangela Lisanti

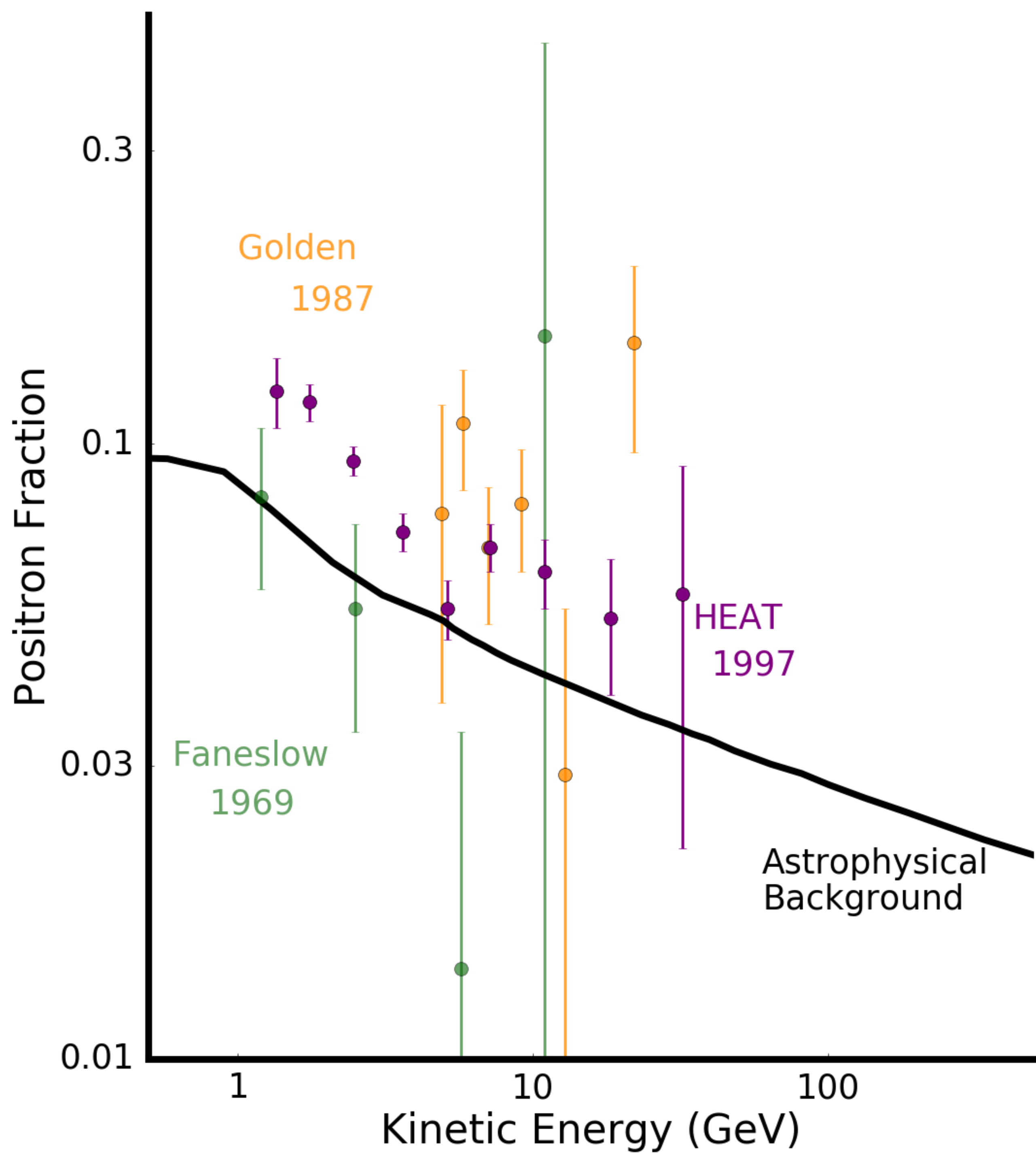
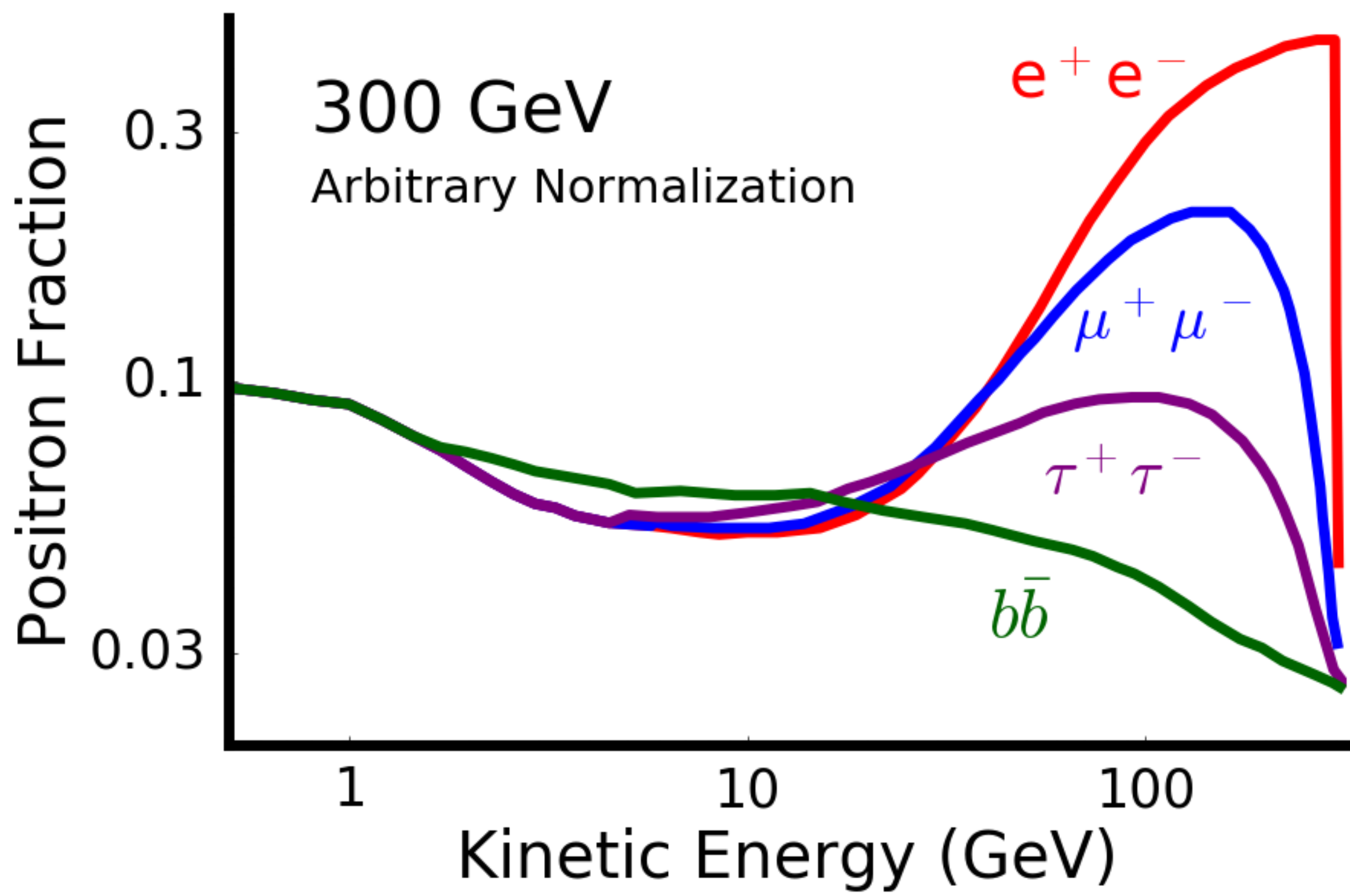
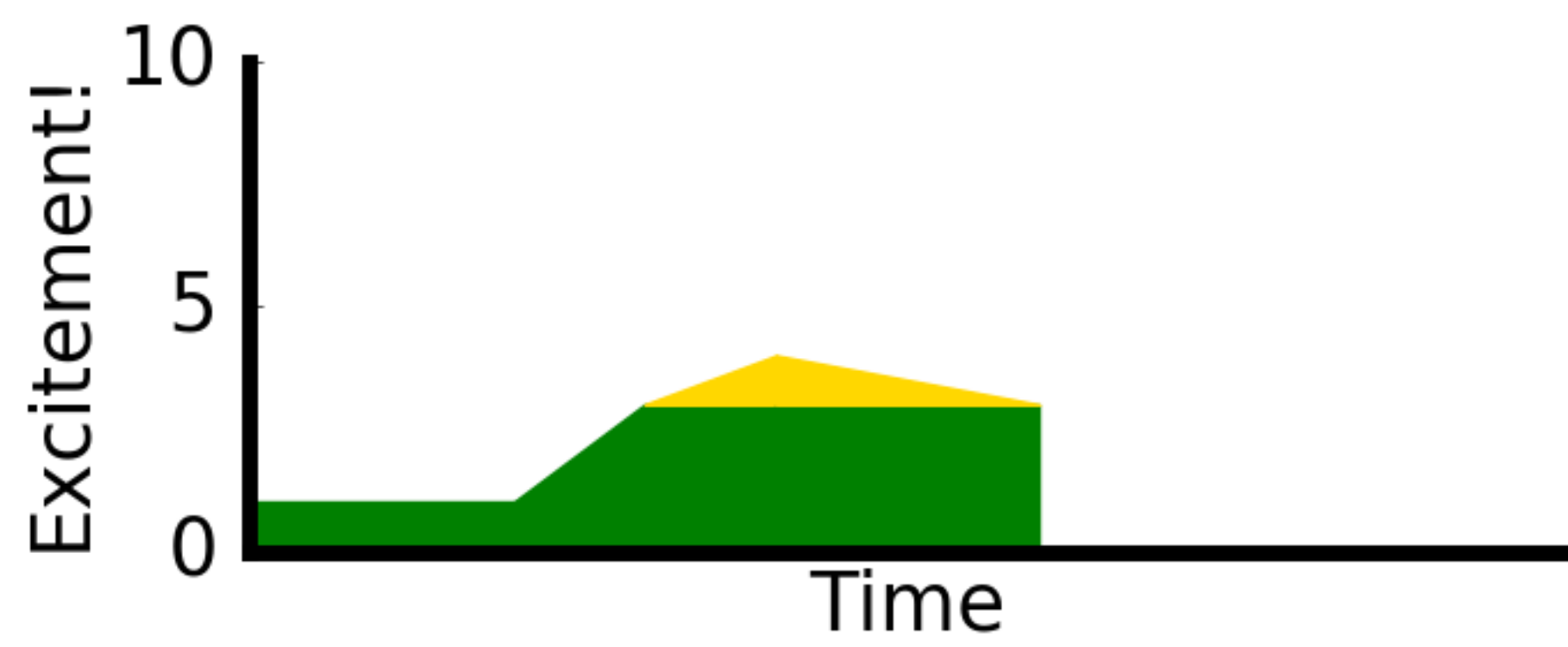


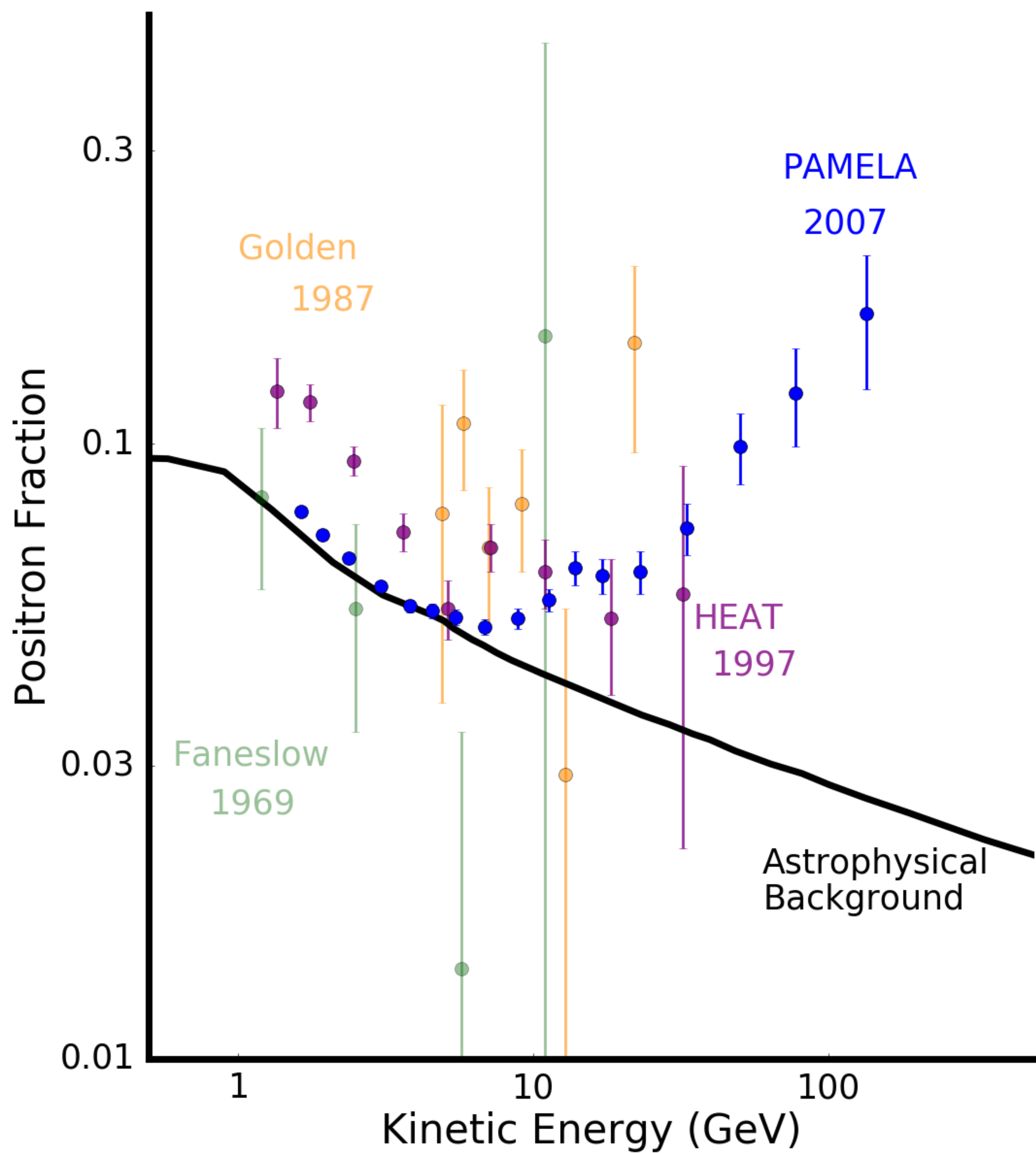
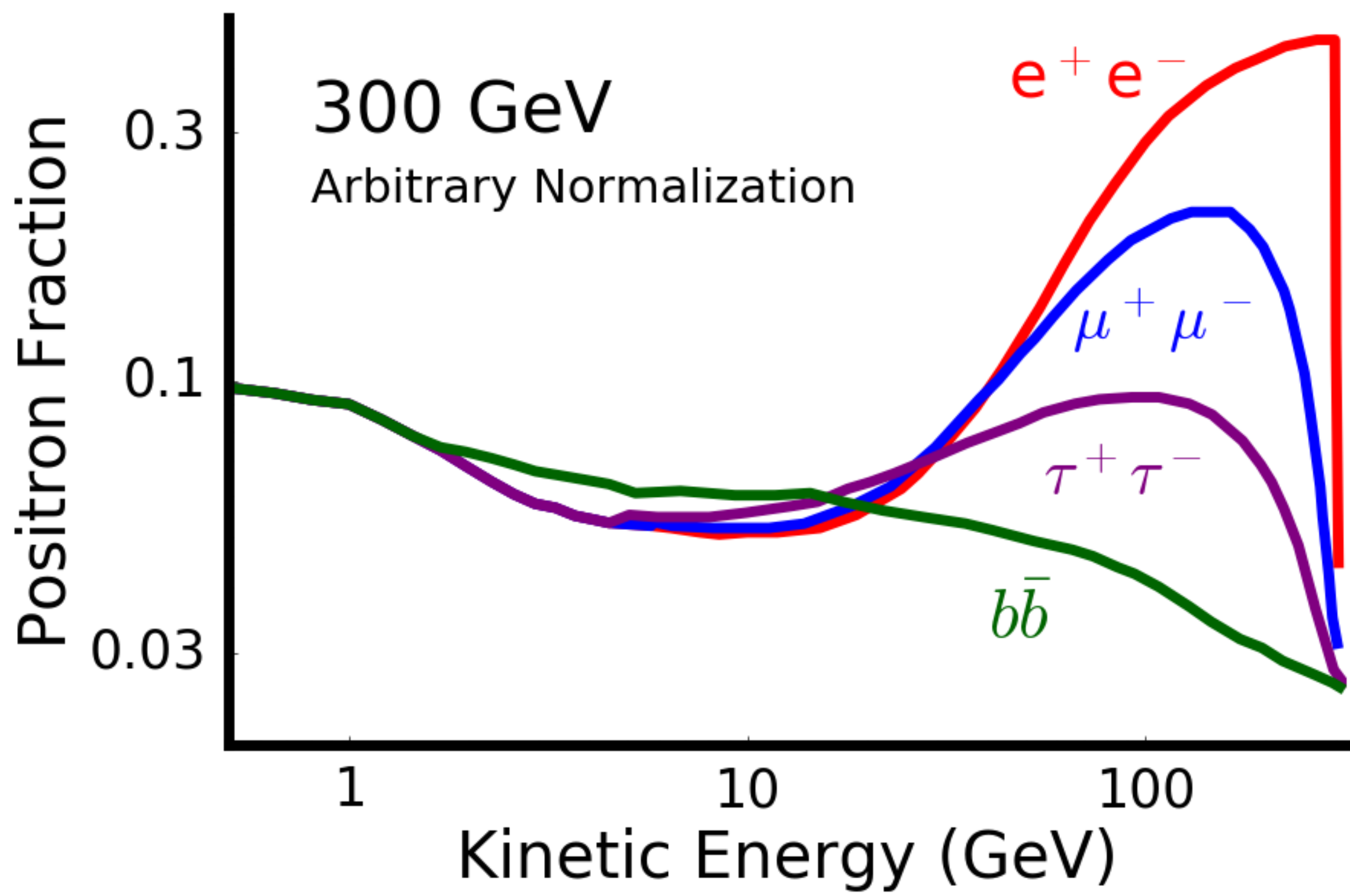
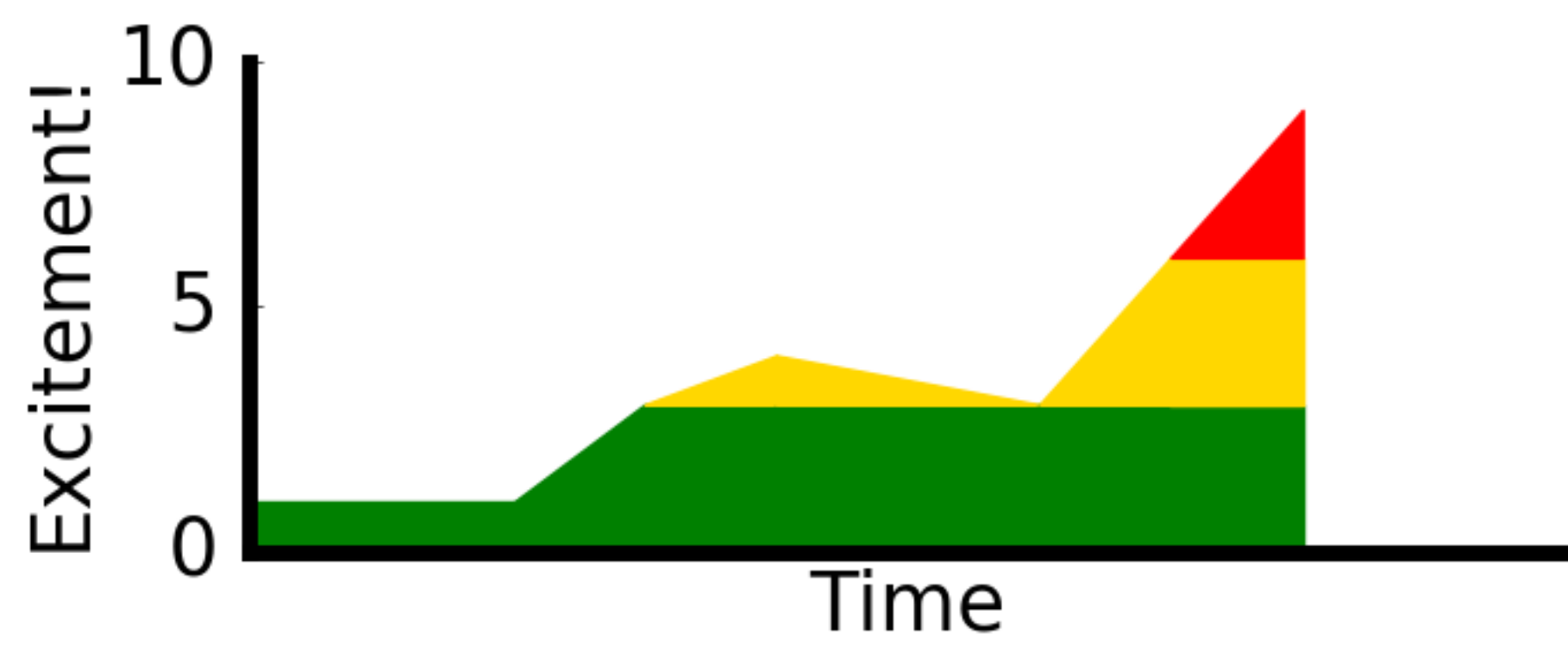


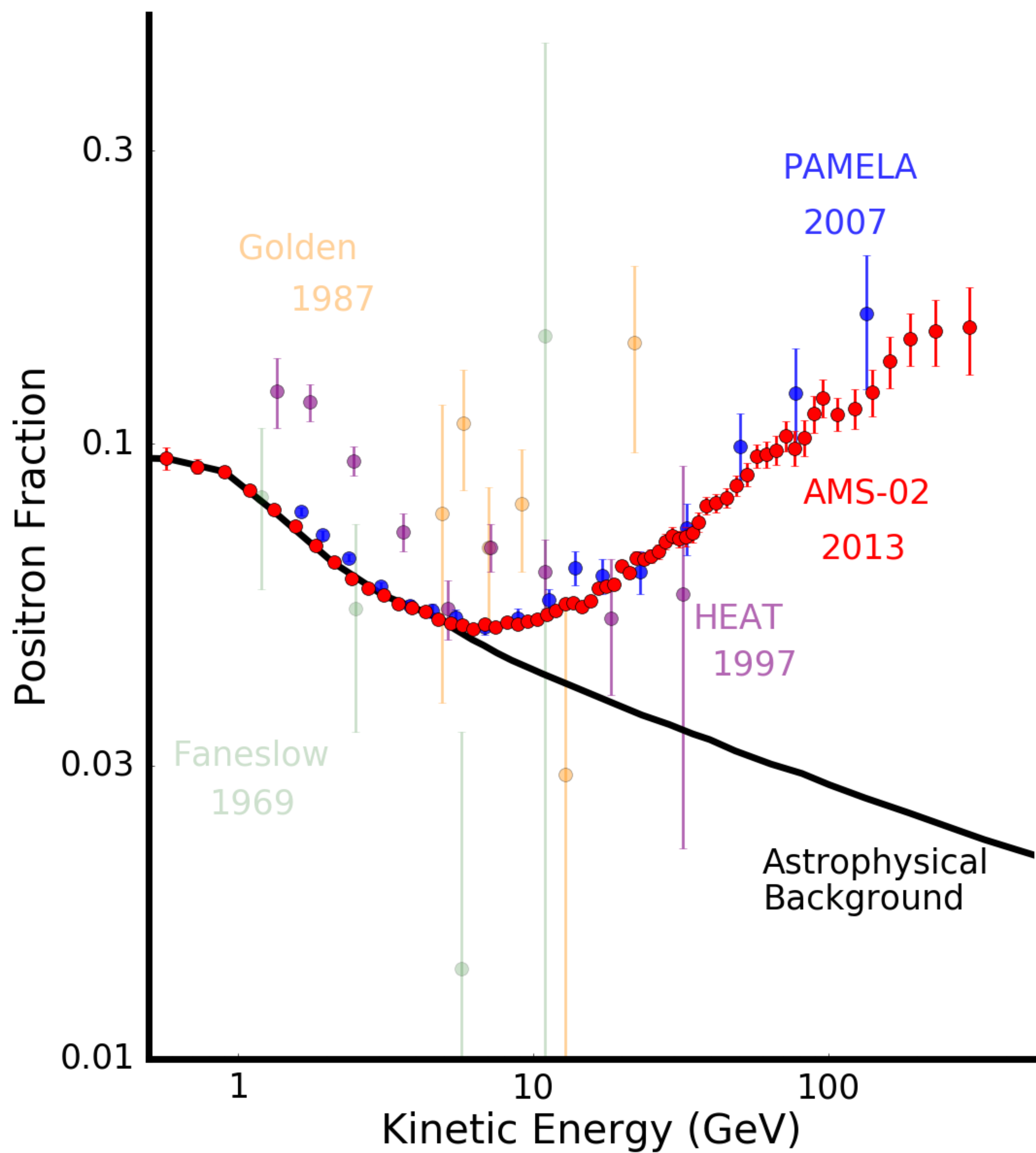
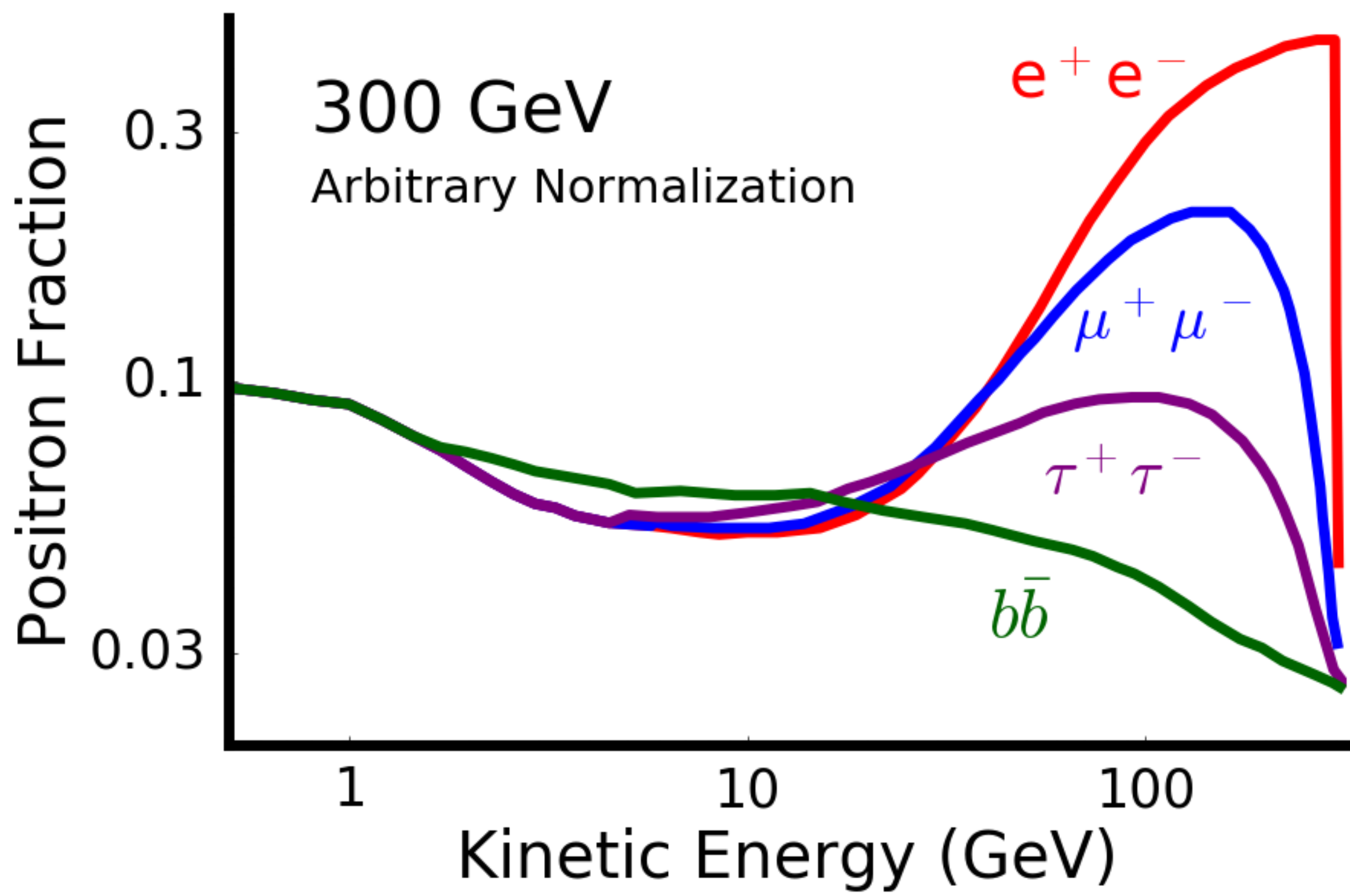
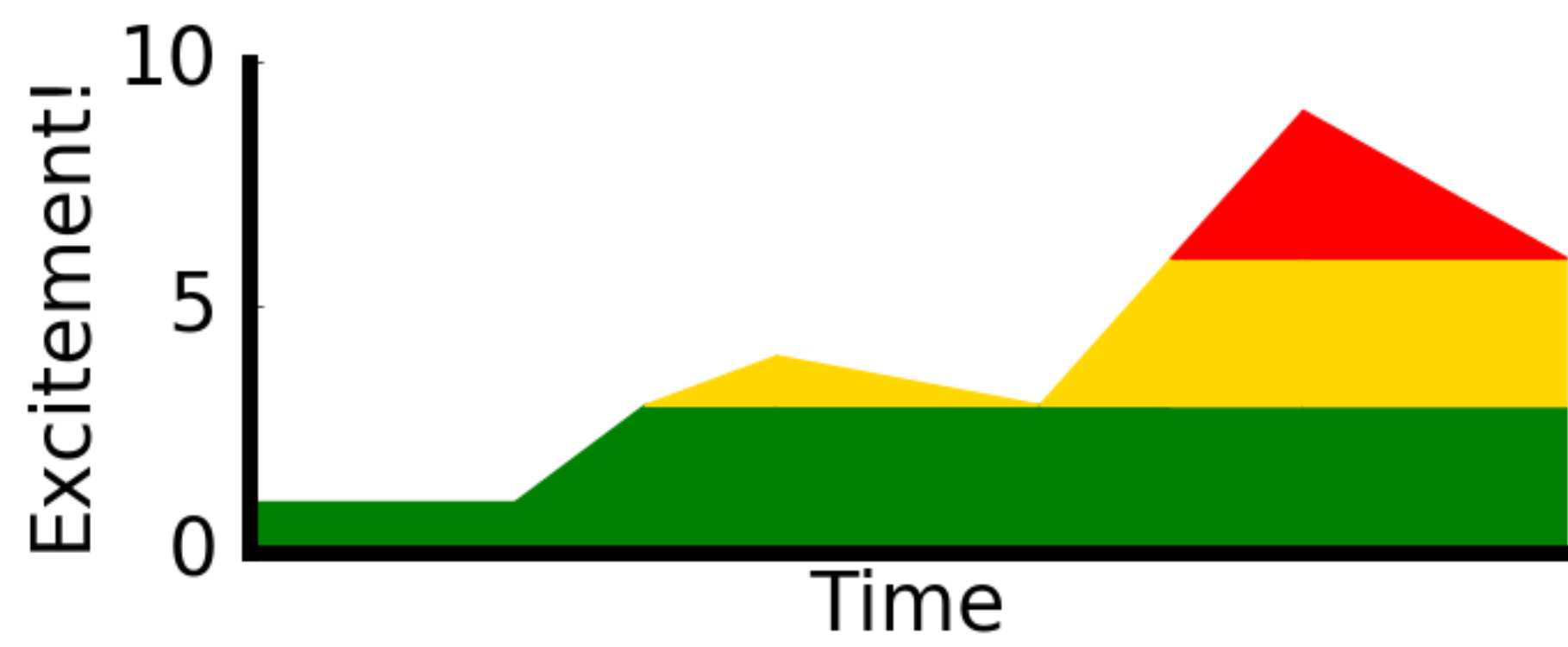


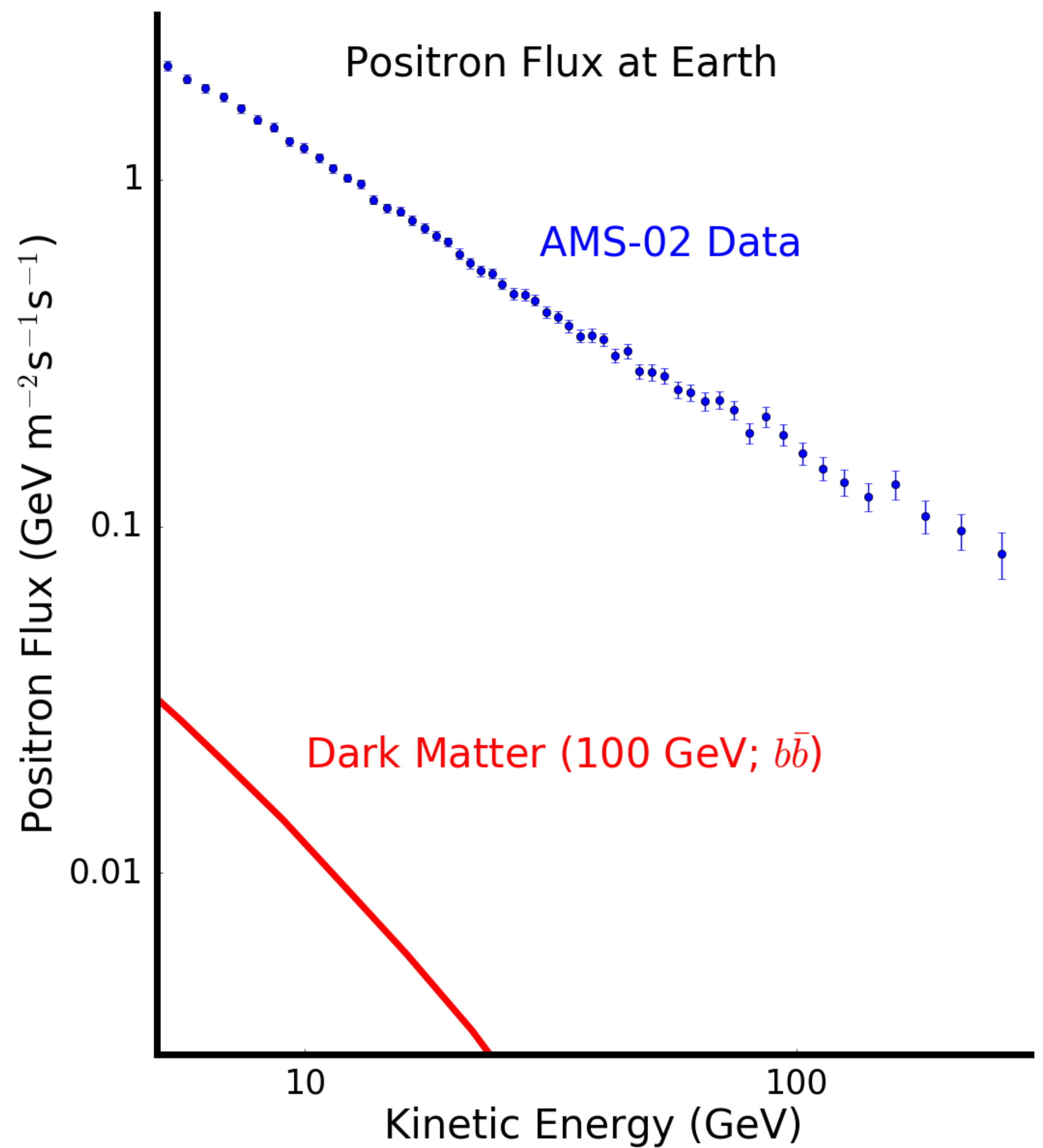
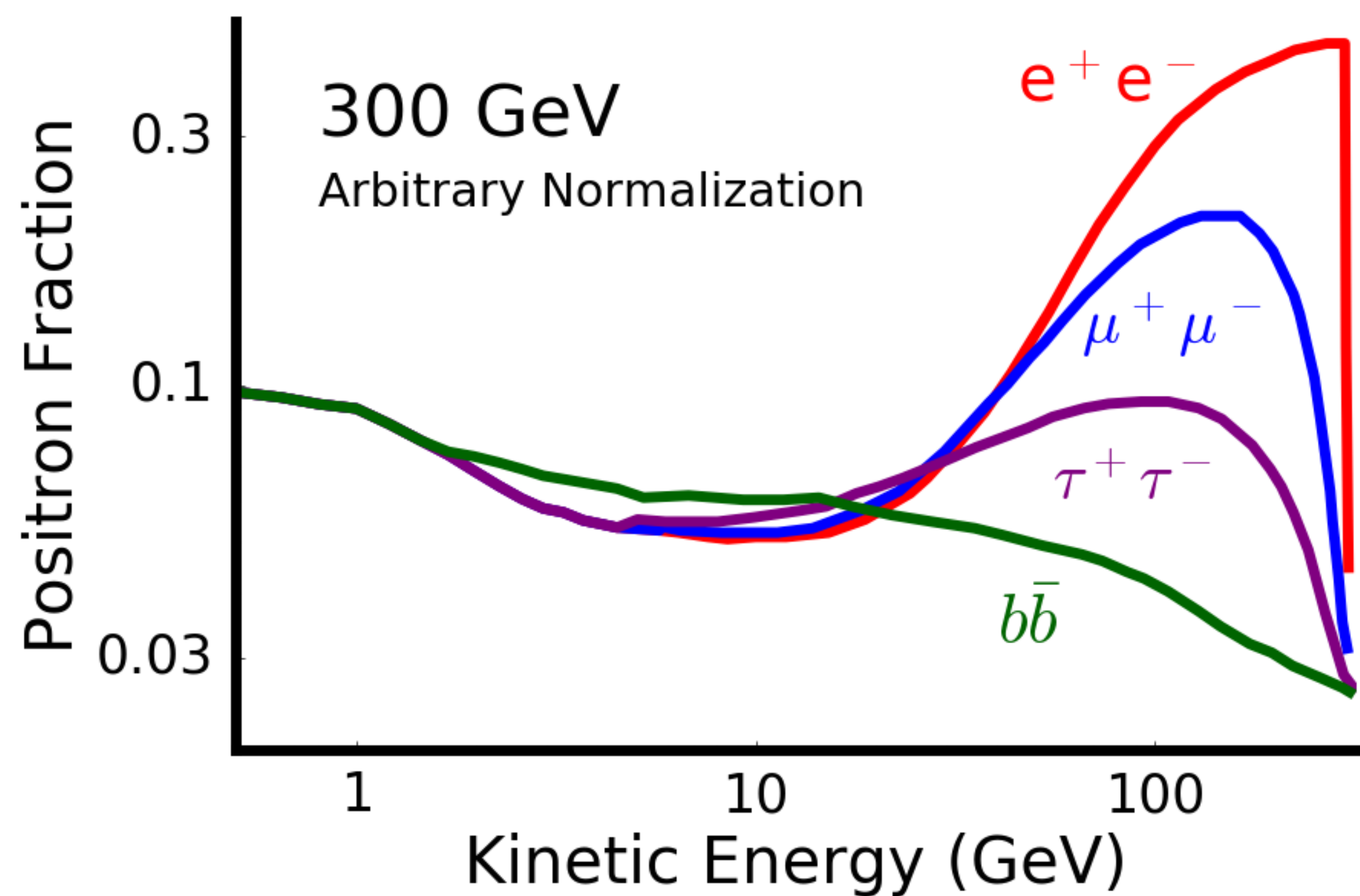




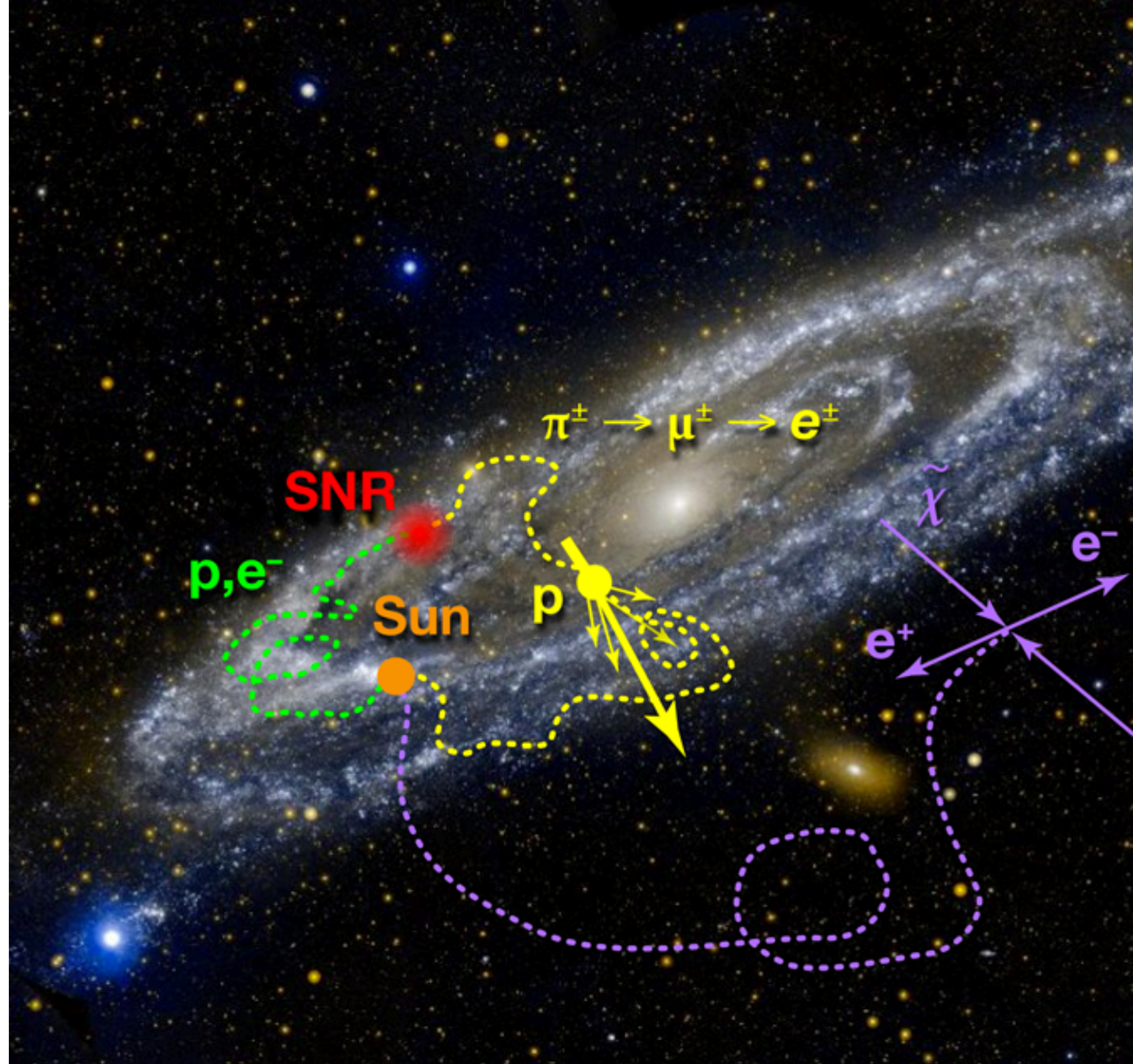
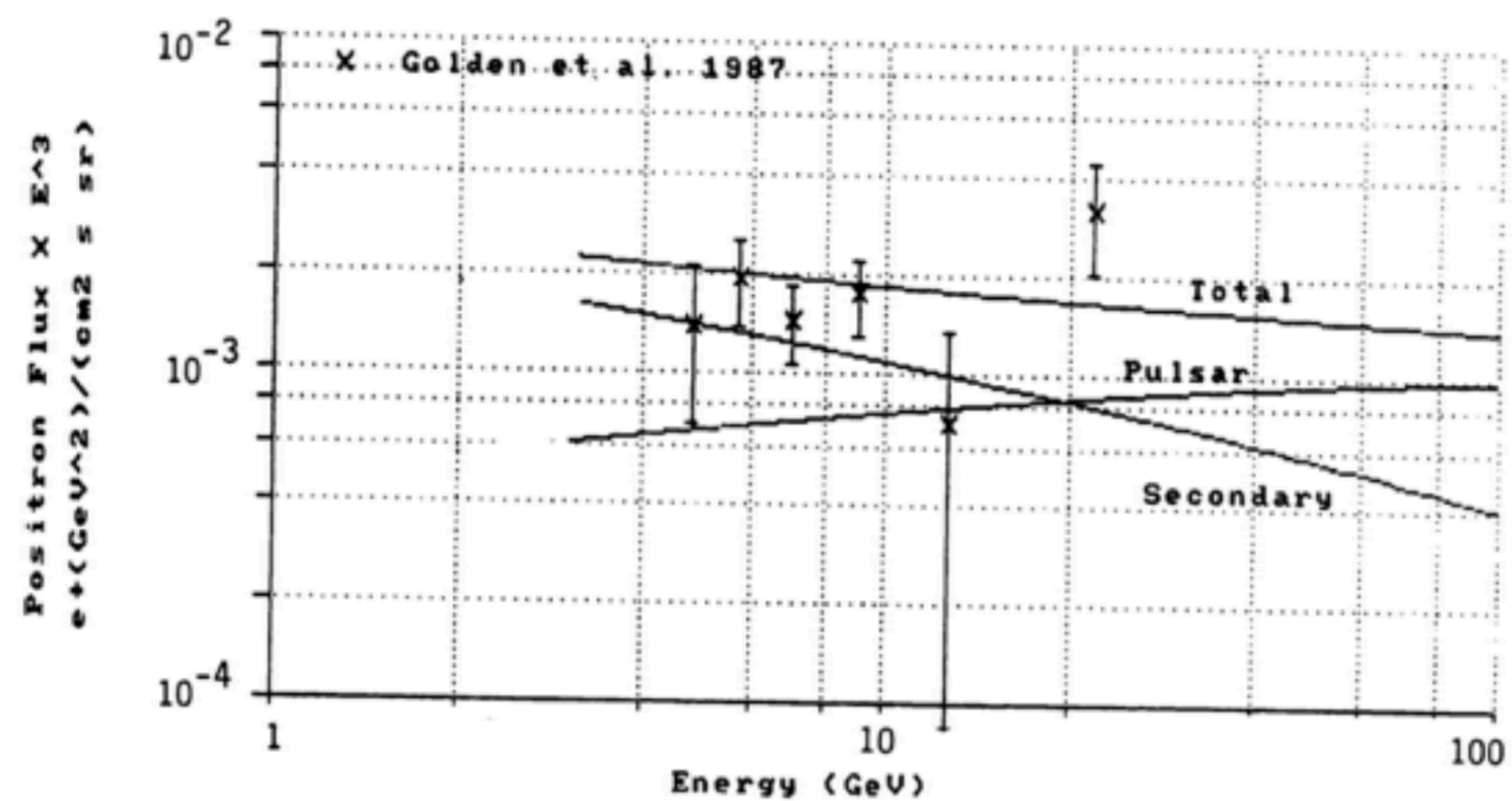


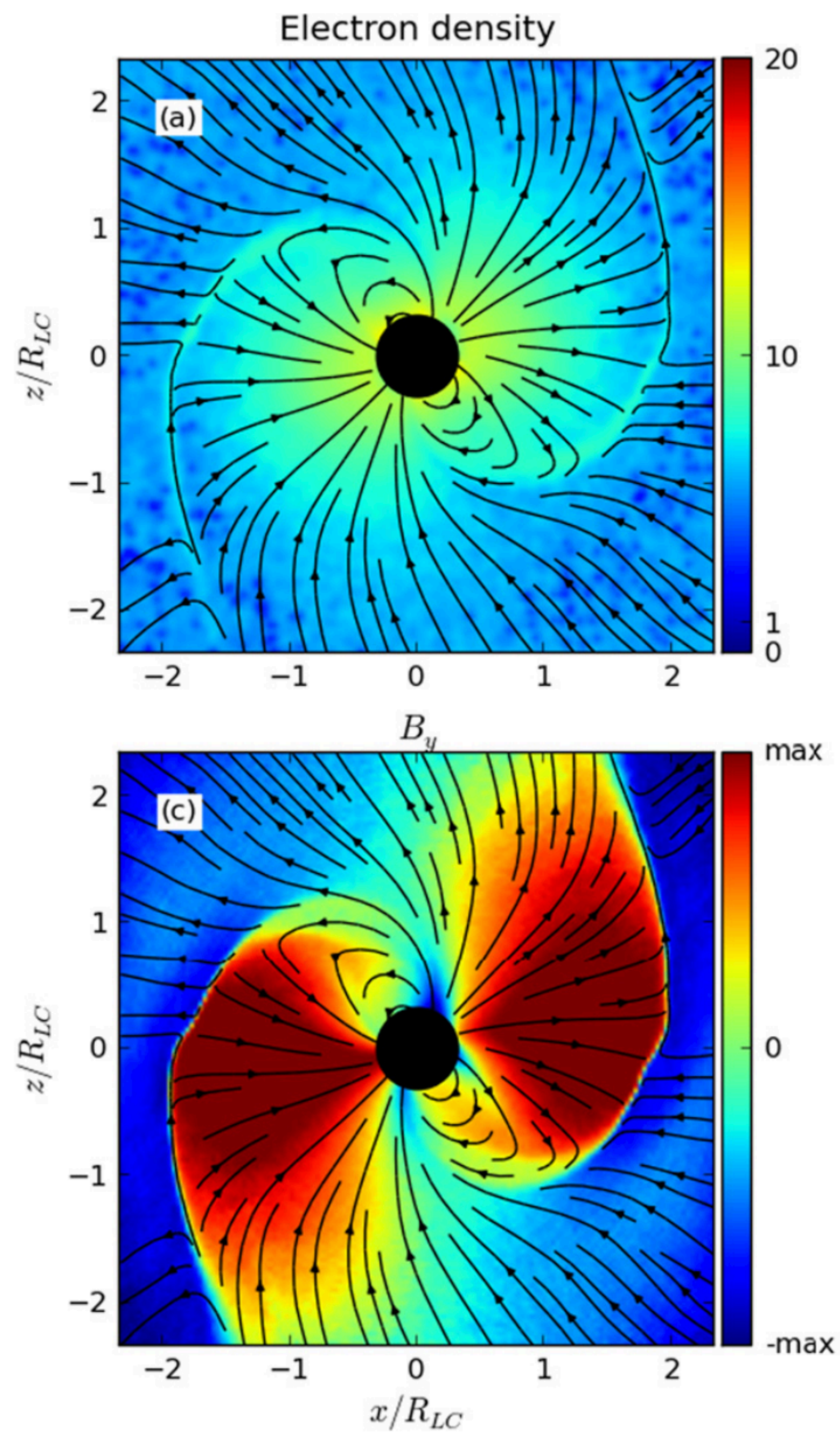
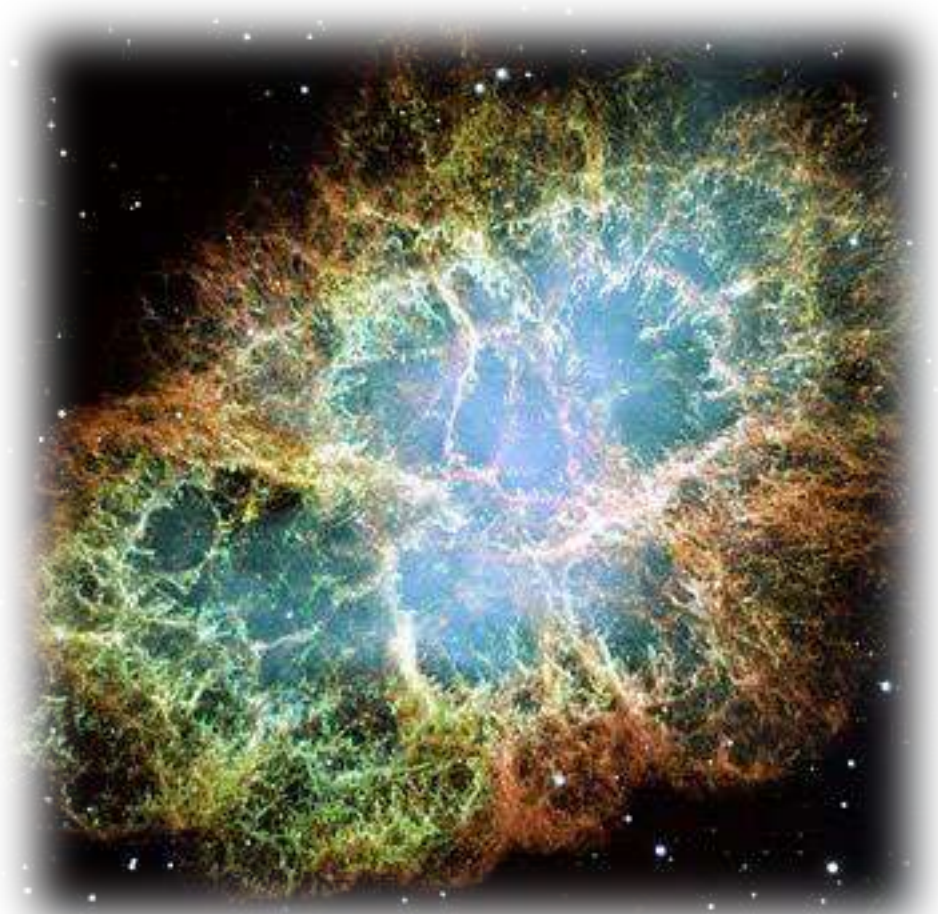


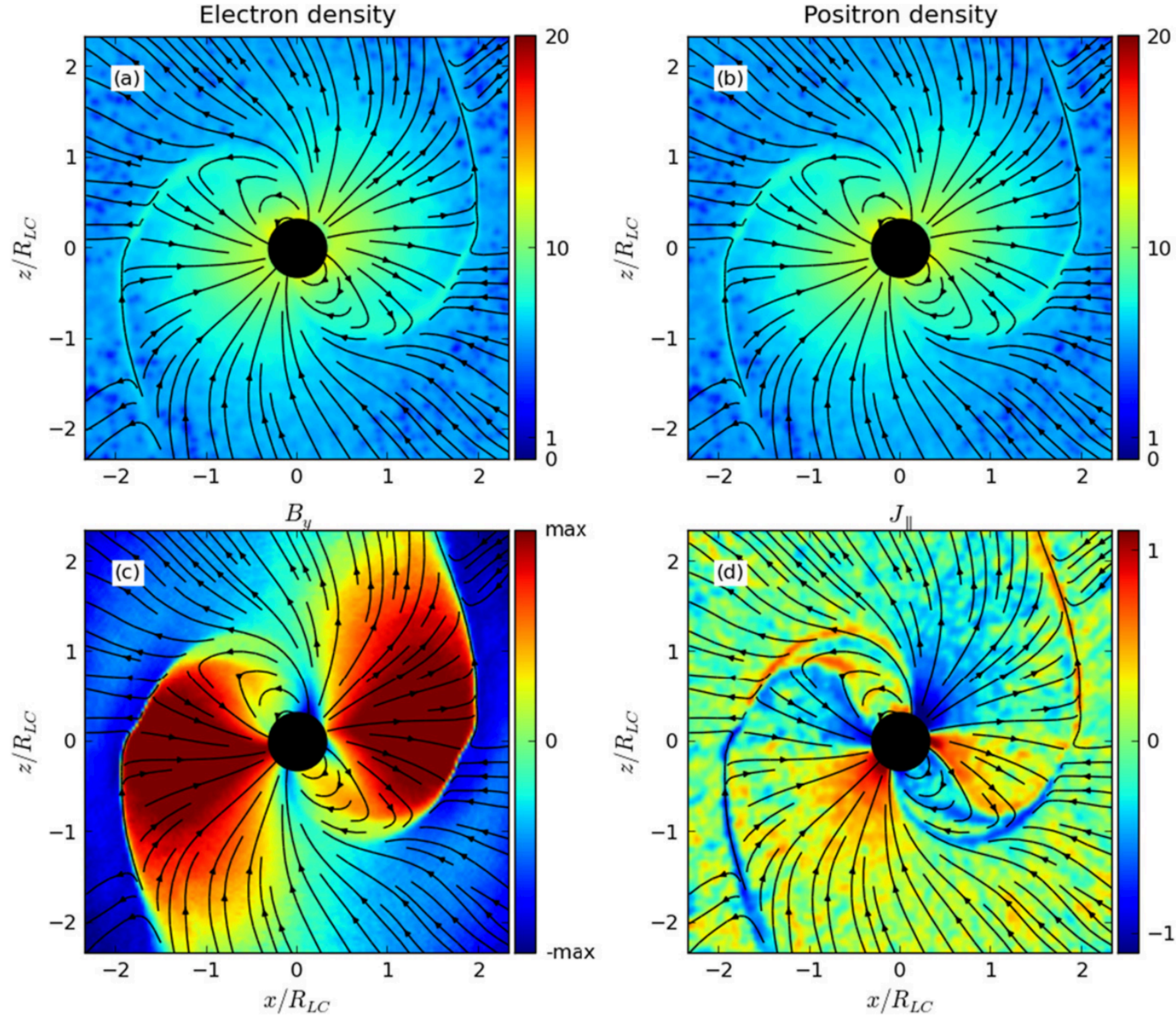




$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$







%. 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)

SNR
(hadronic/leptonic)

TeV Halo
(escaped e^+e^-)

PWN
(confined e^+e^-)

Geminga





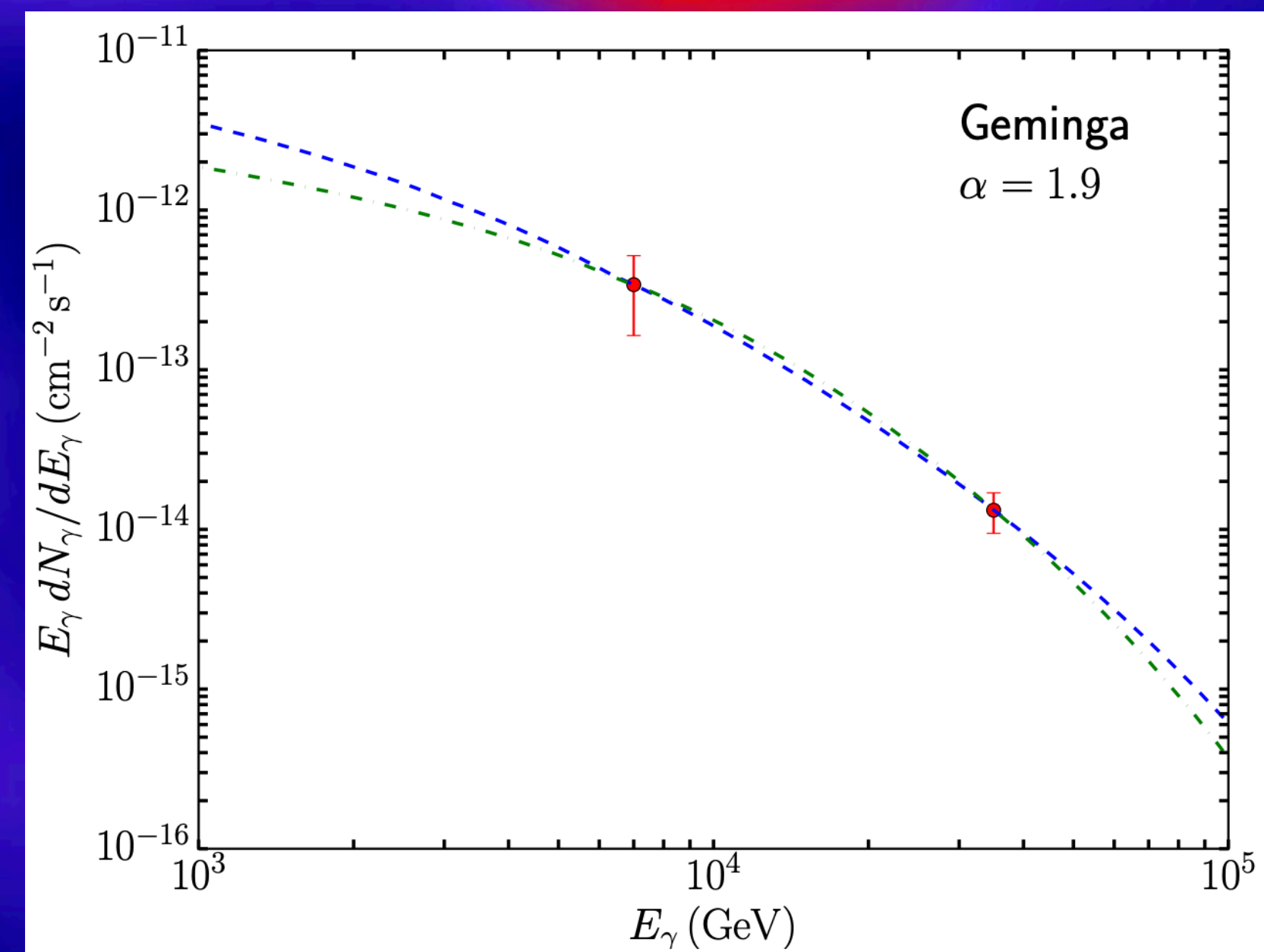
Moon (To Scale)

SNR
(hadronic/leptonic)

TeV Halo
(escaped e^+e^-)

PWN
(confined e^+e^-)

Geminga





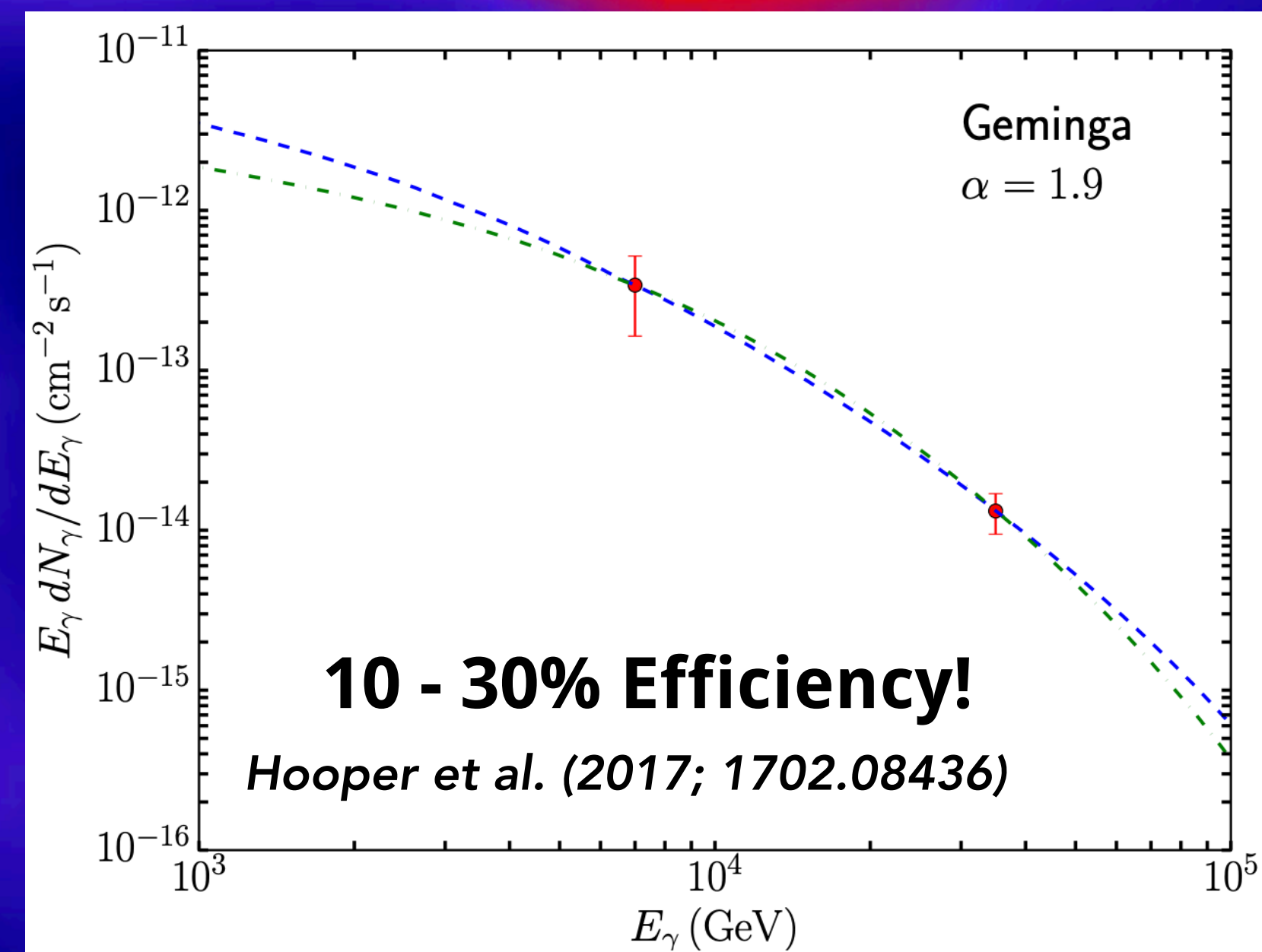
Moon (To Scale)

SNR
(hadronic/leptonic)

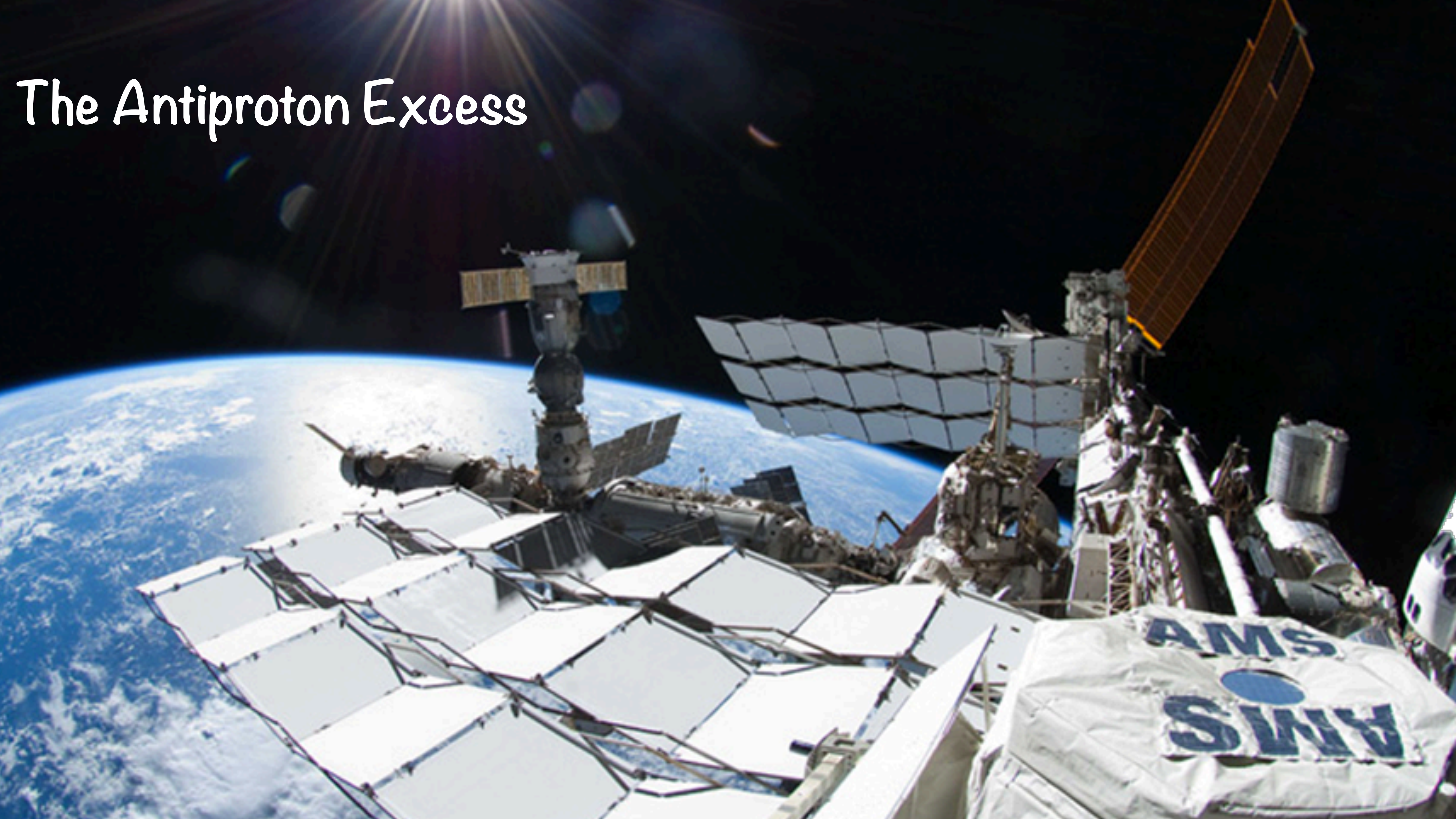
TeV Halo
(escaped e^+e^-)

PWN
(confined e^+e^-)

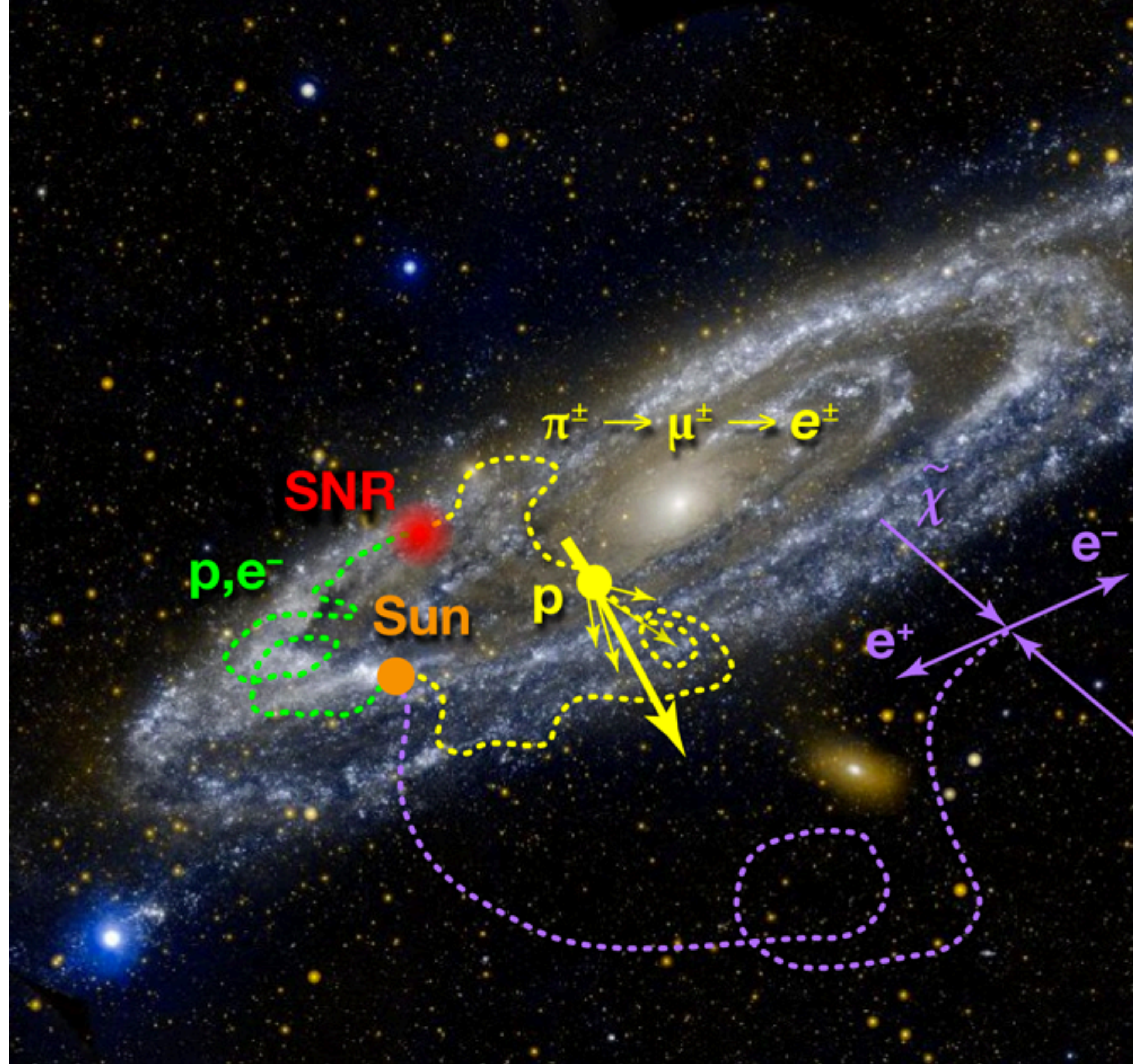
Geminga

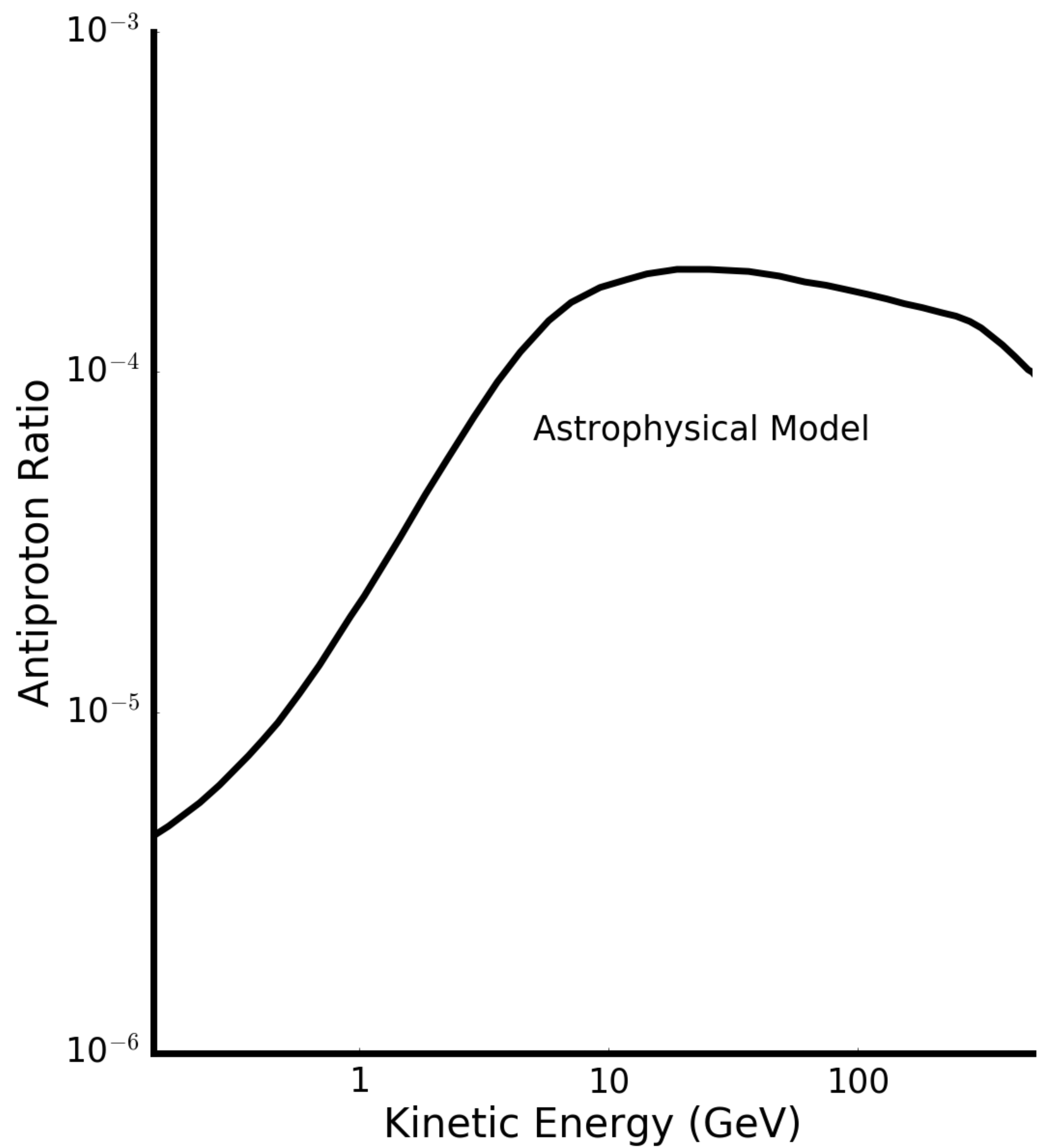
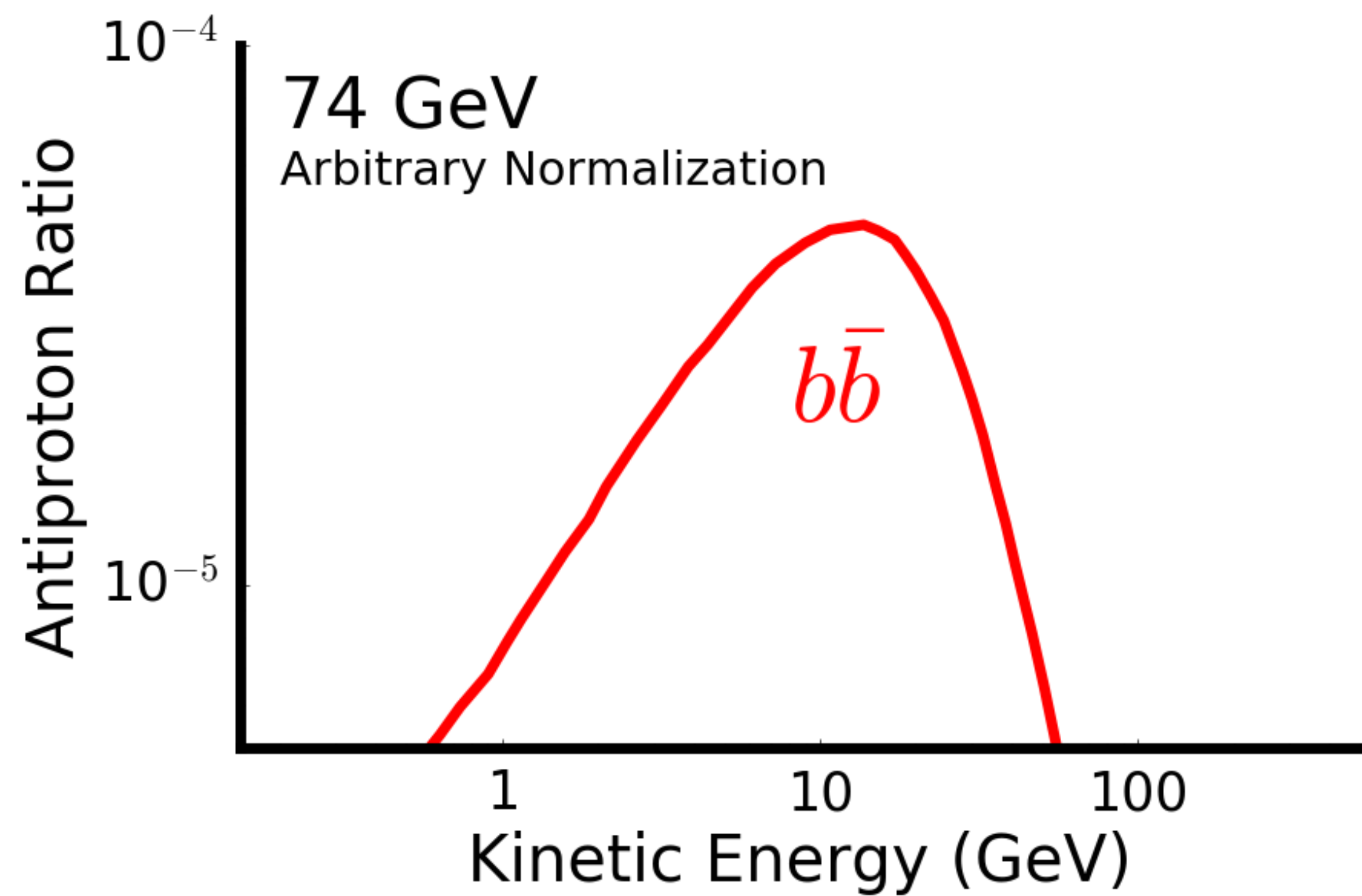


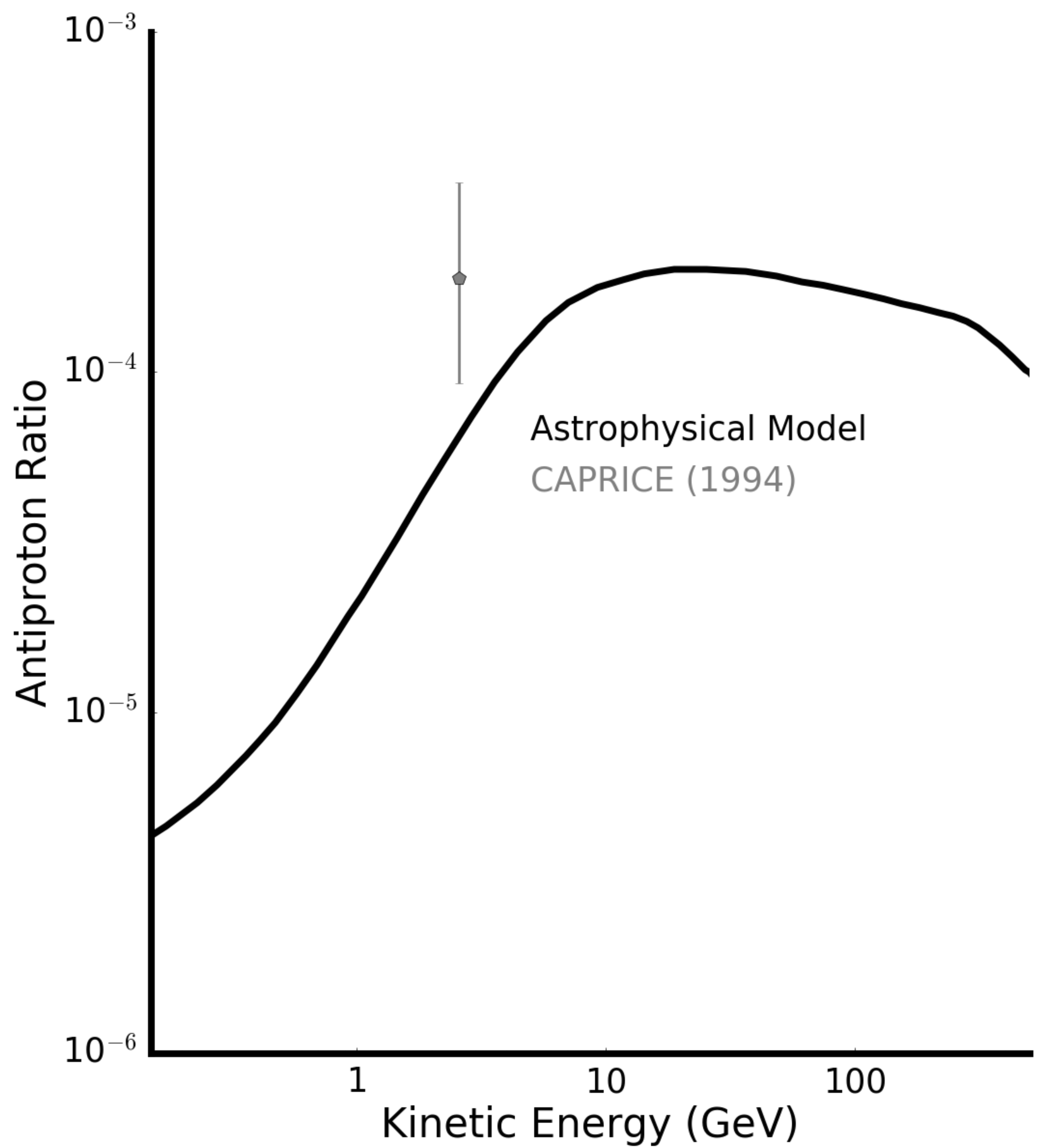
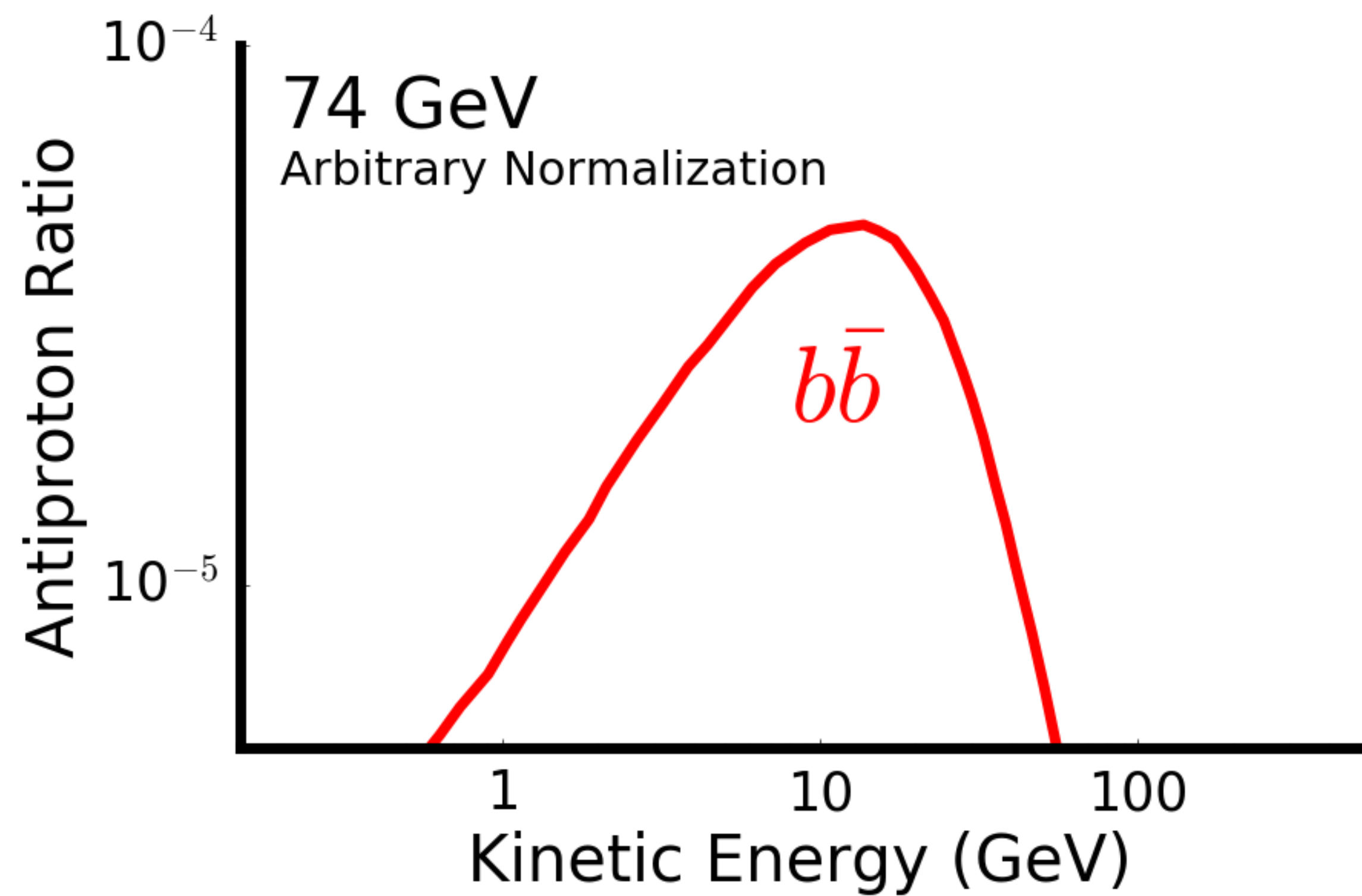
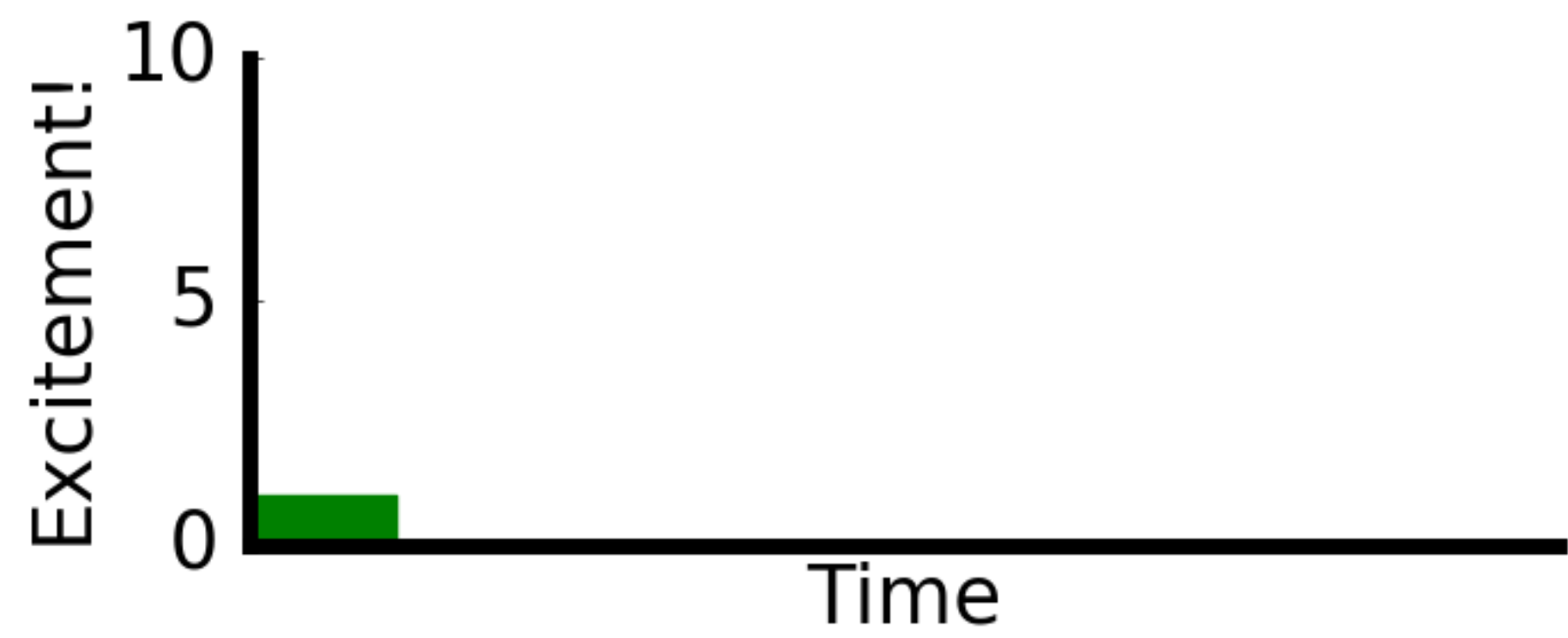
The Antiproton Excess

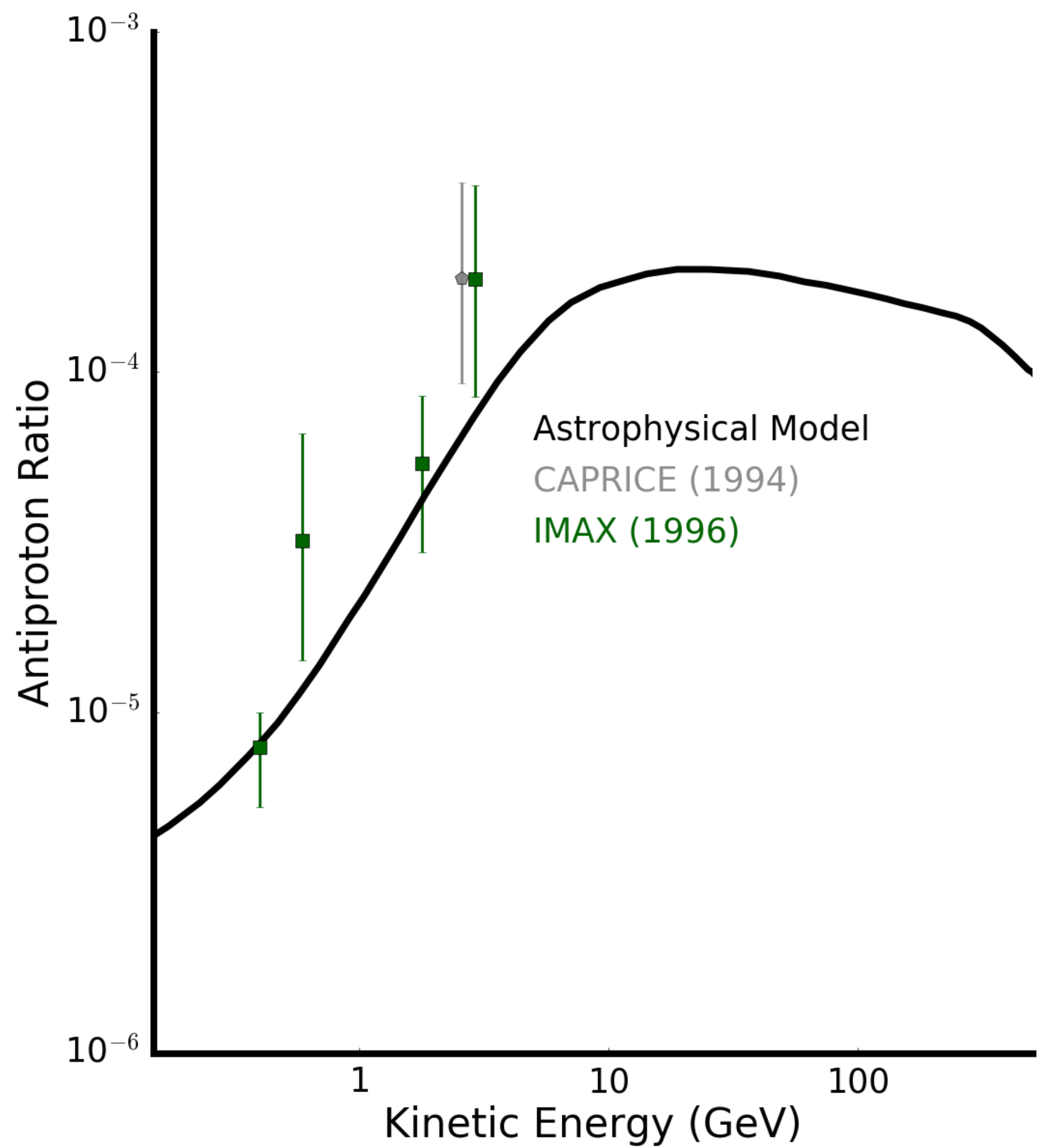
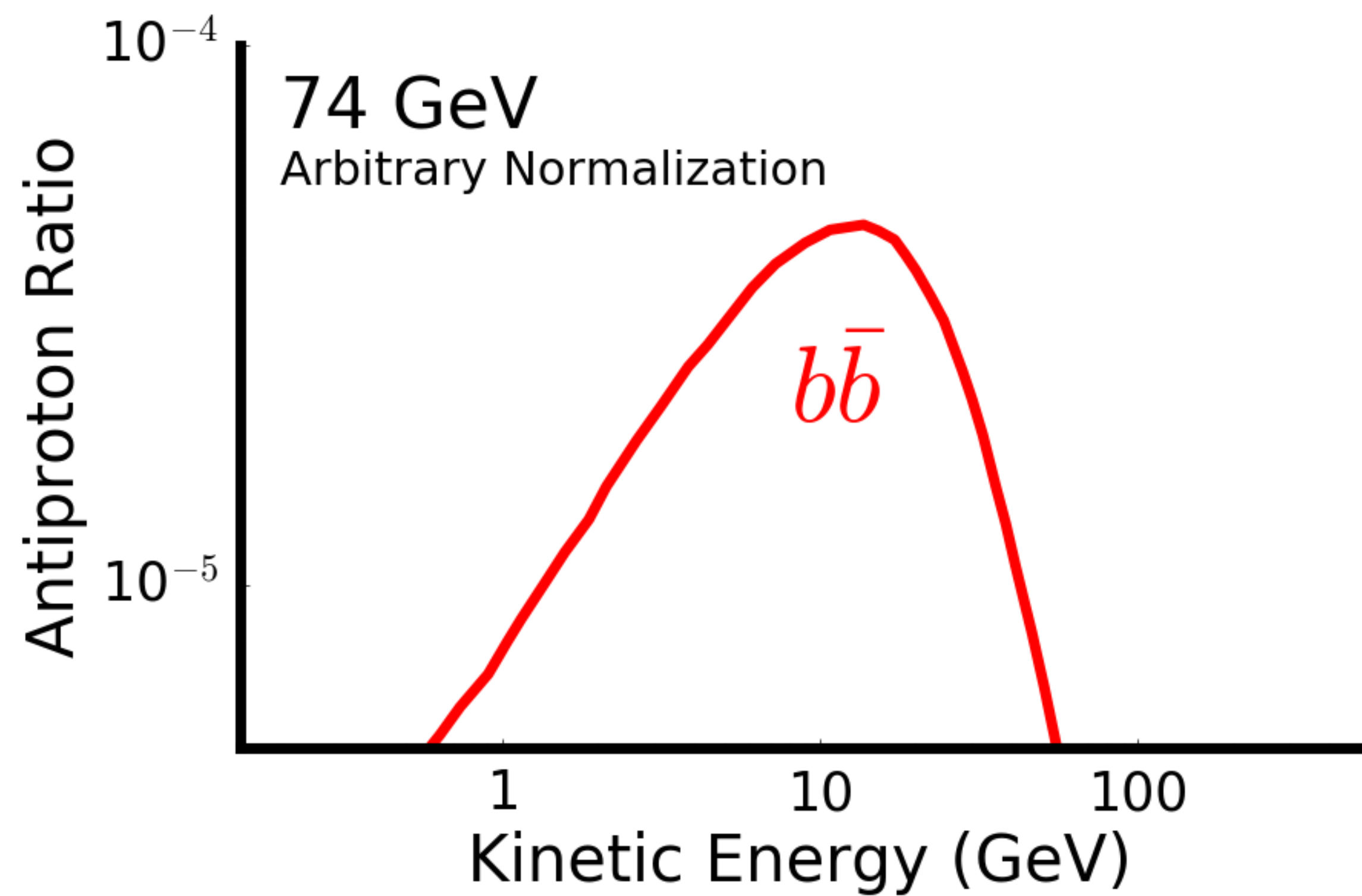
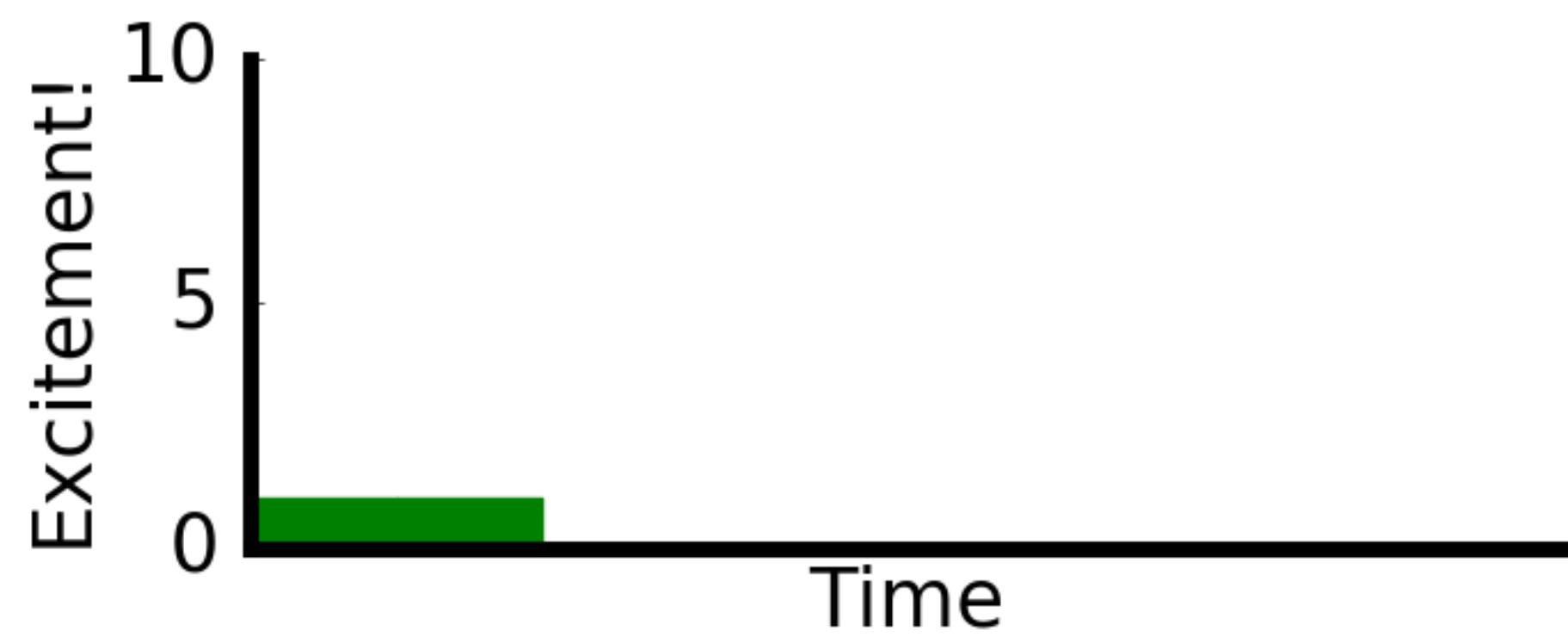


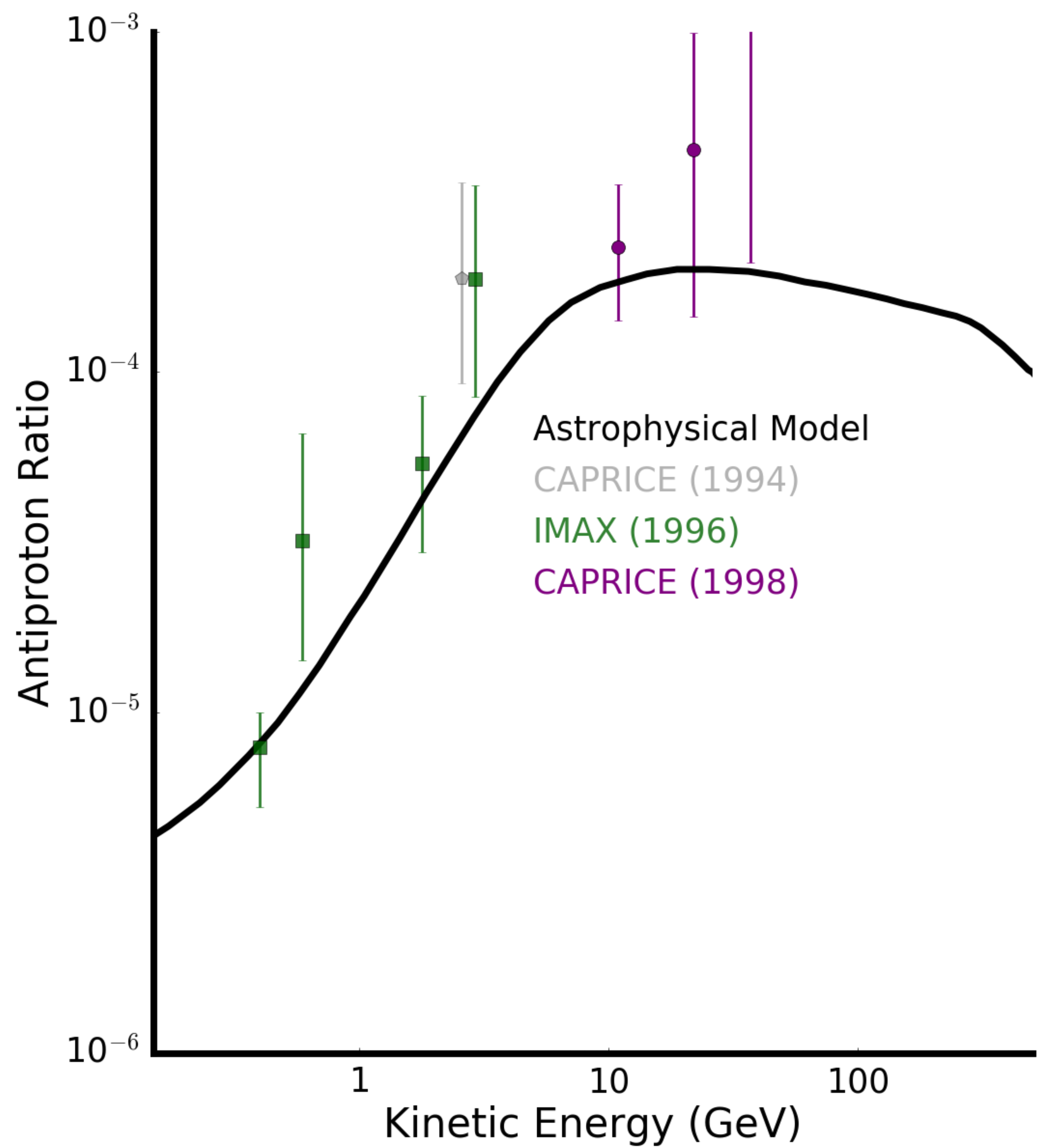
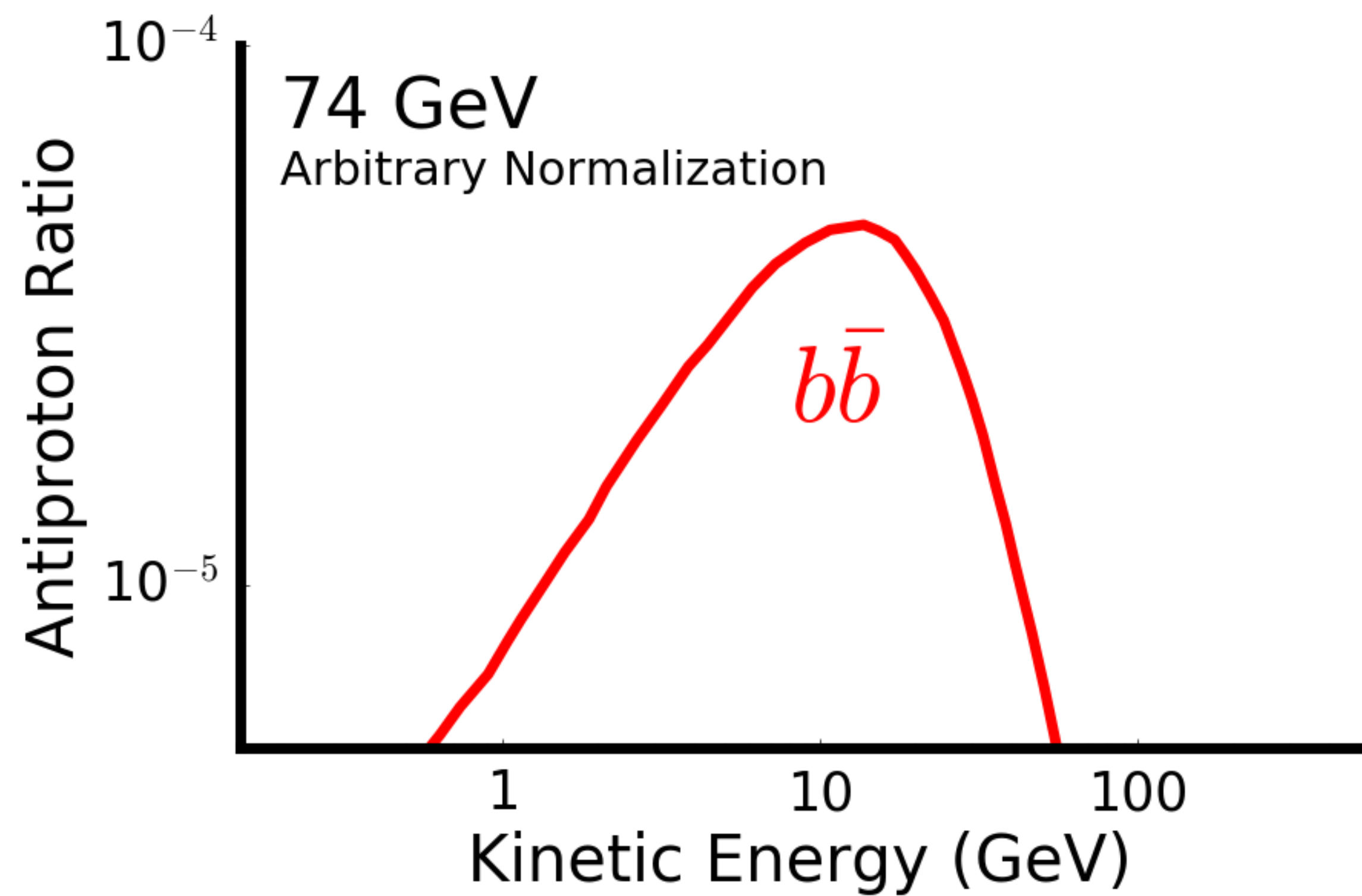
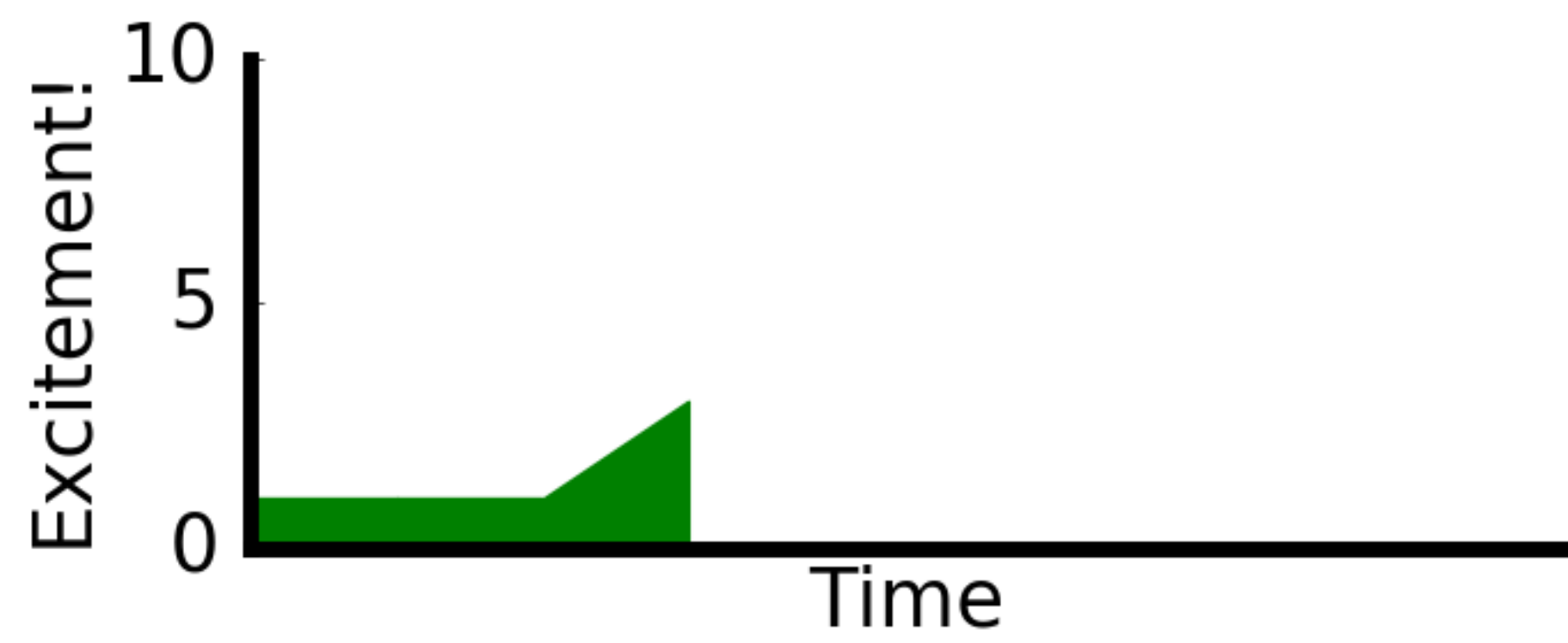
$$\frac{\phi_{\bar{p}}}{\phi_p}$$

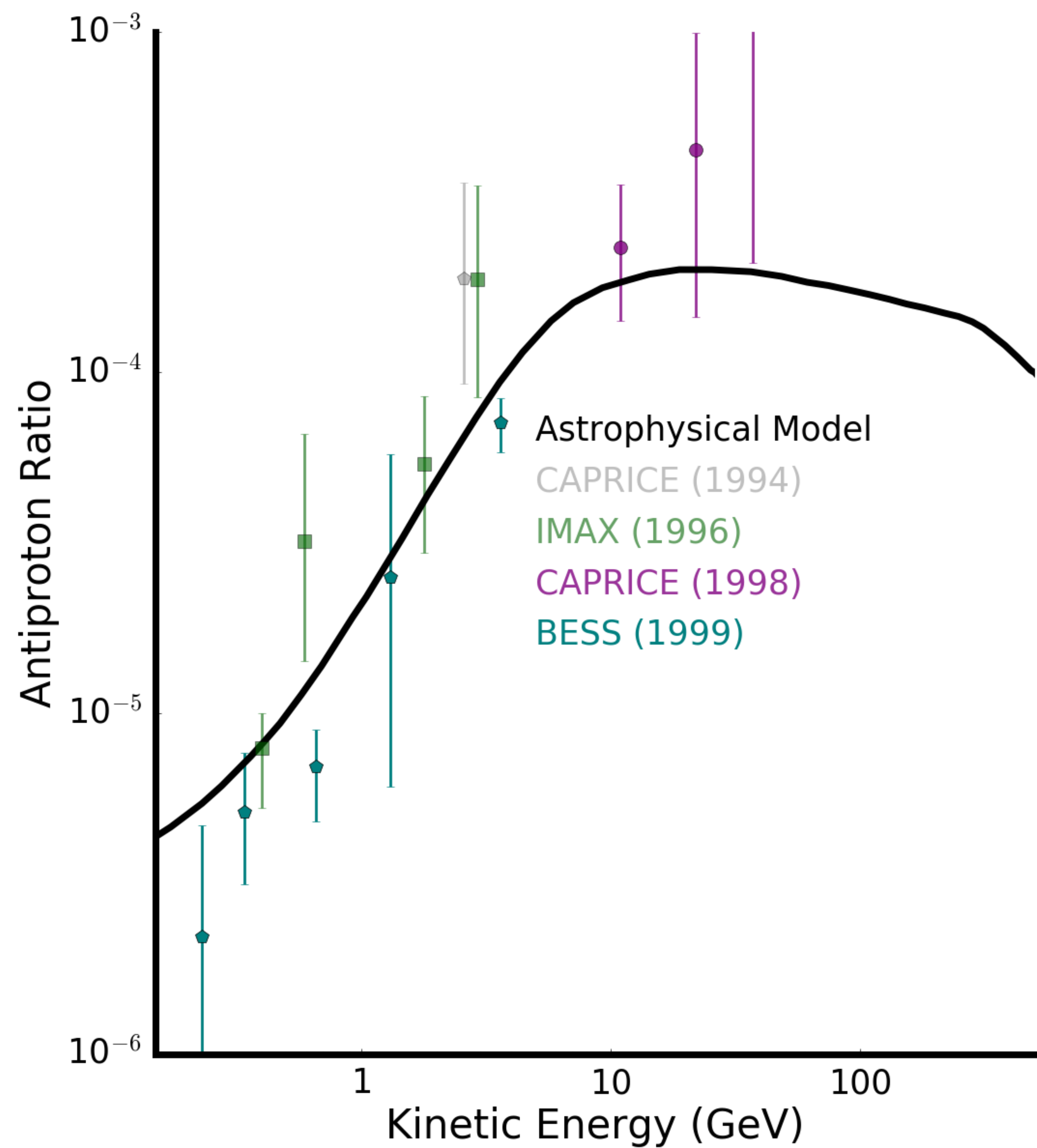
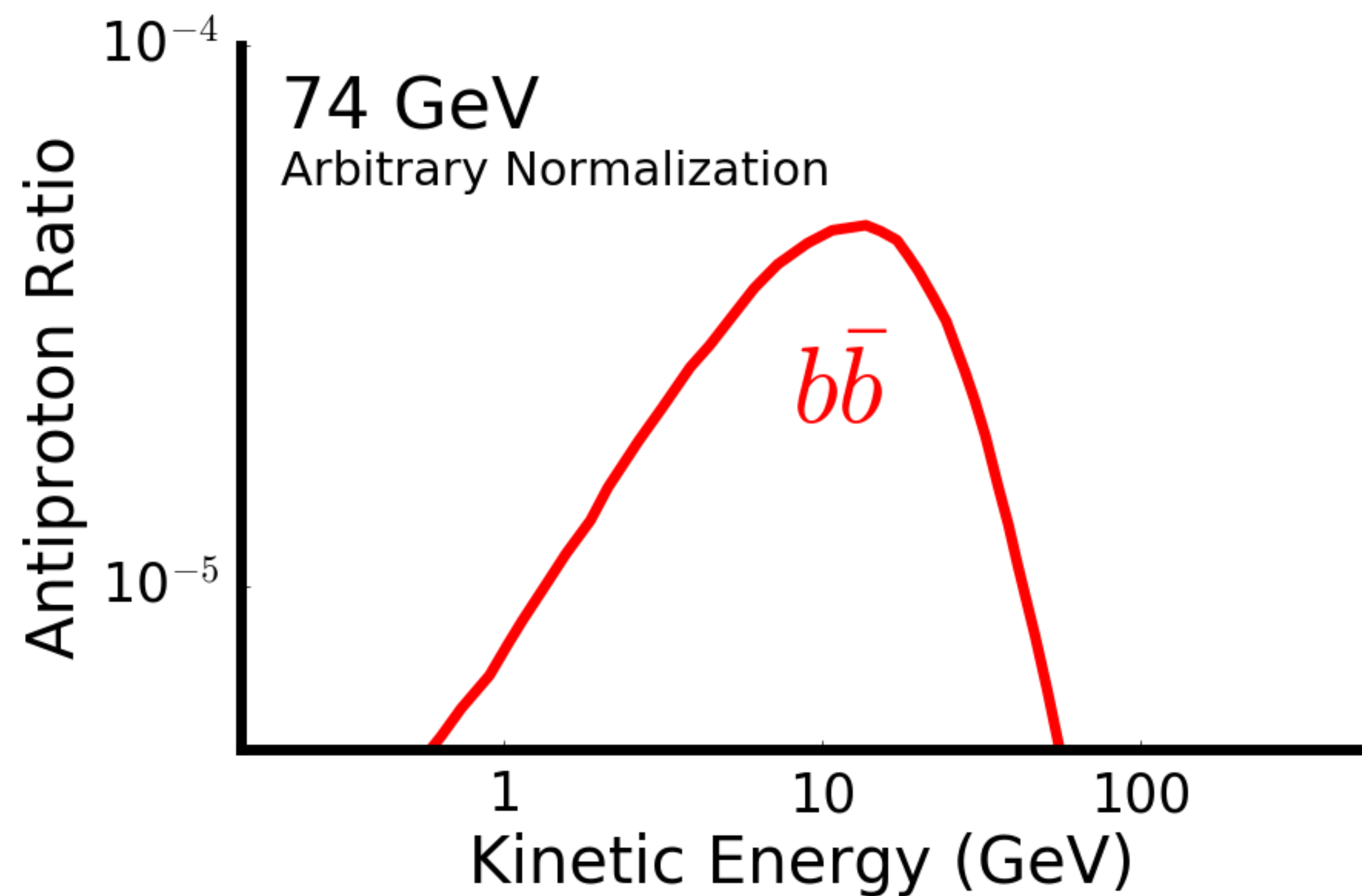
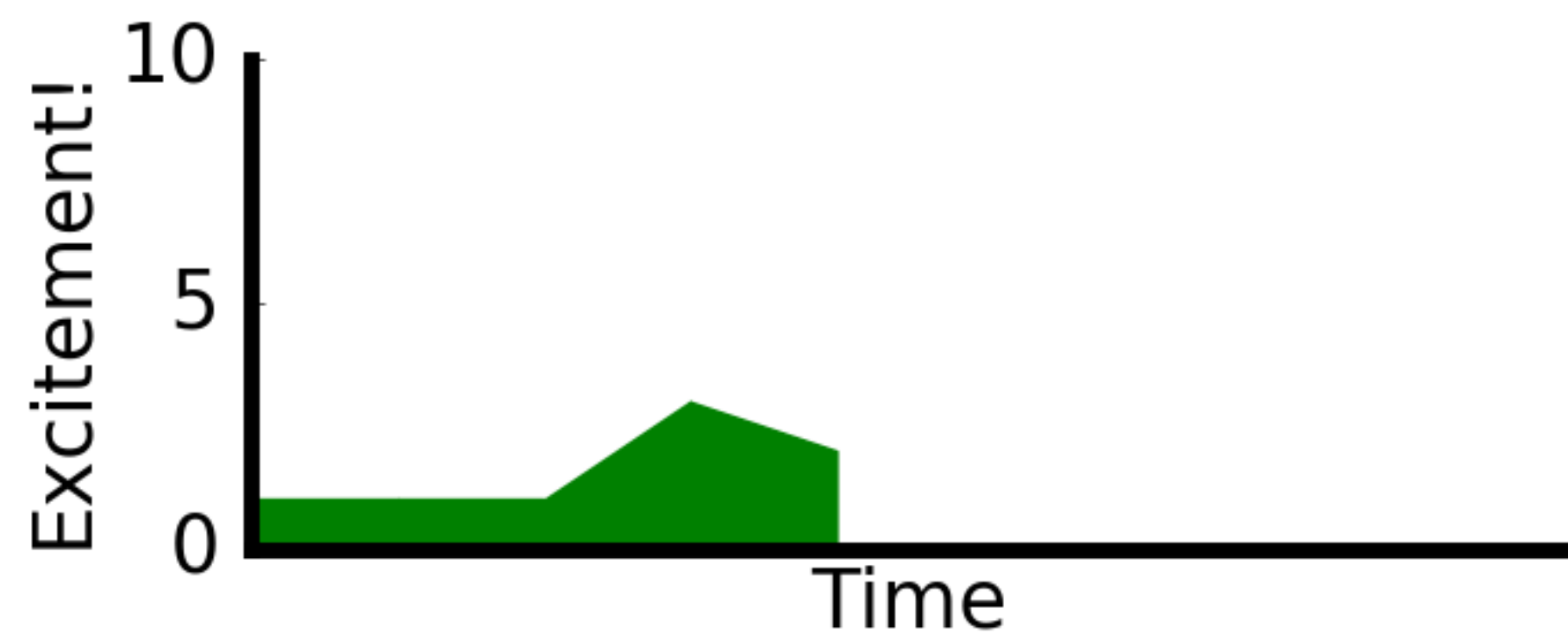


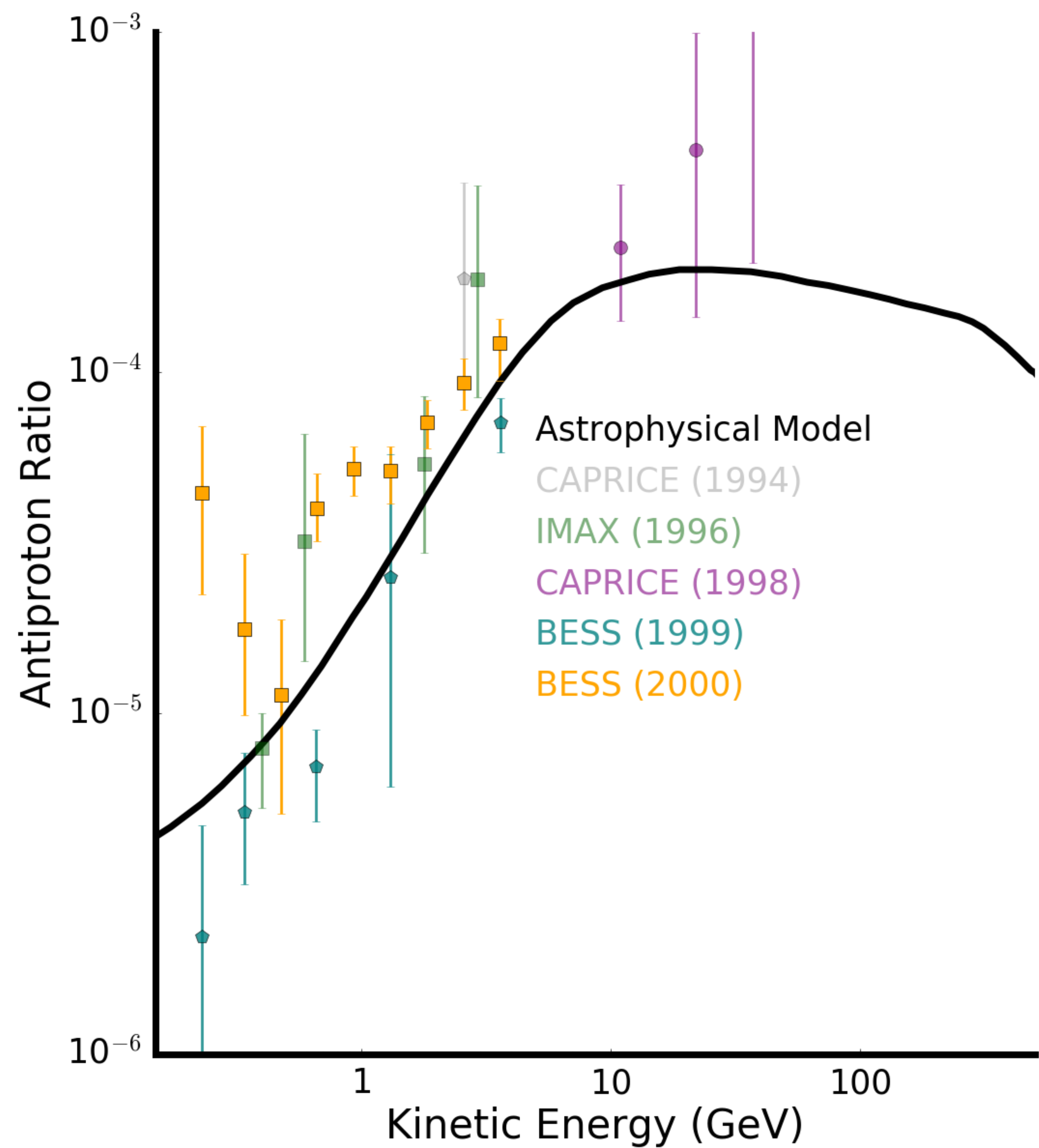
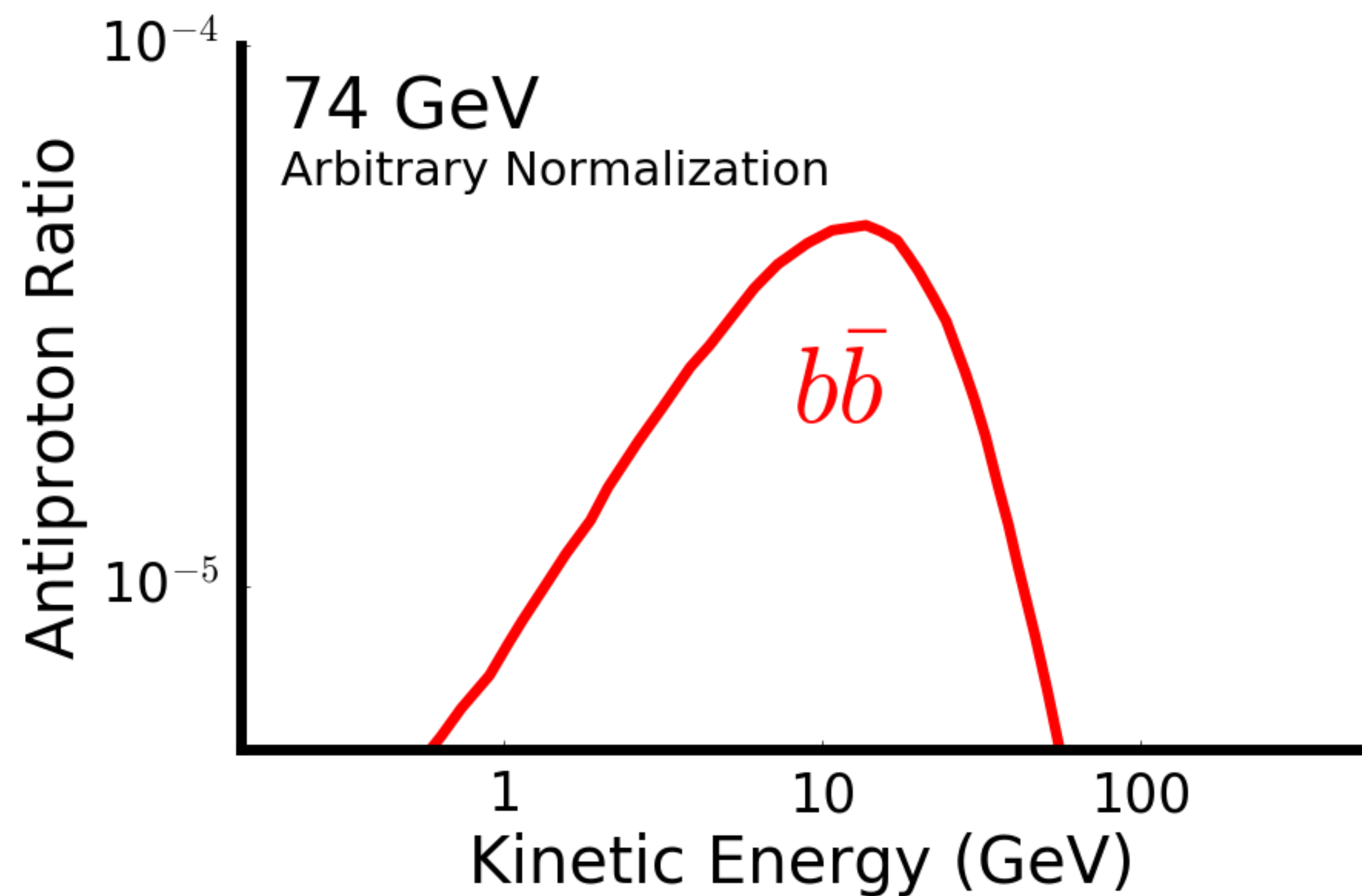
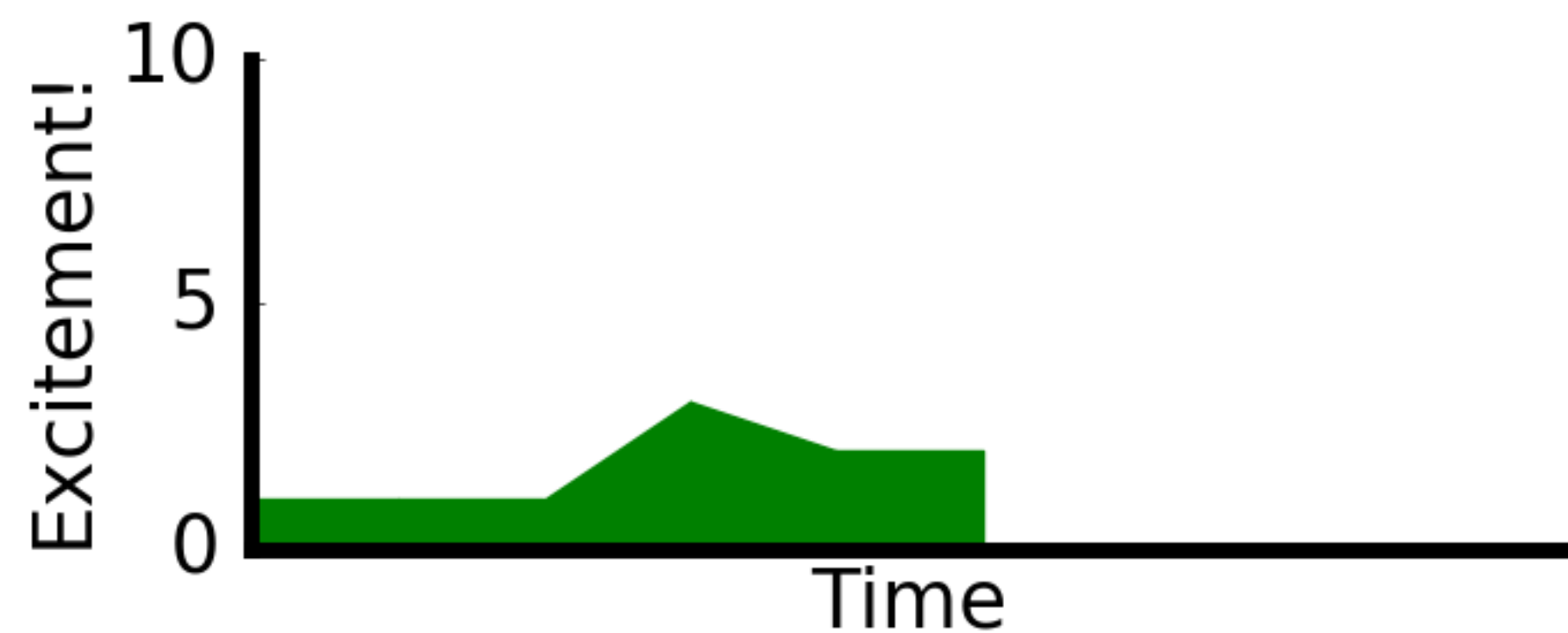


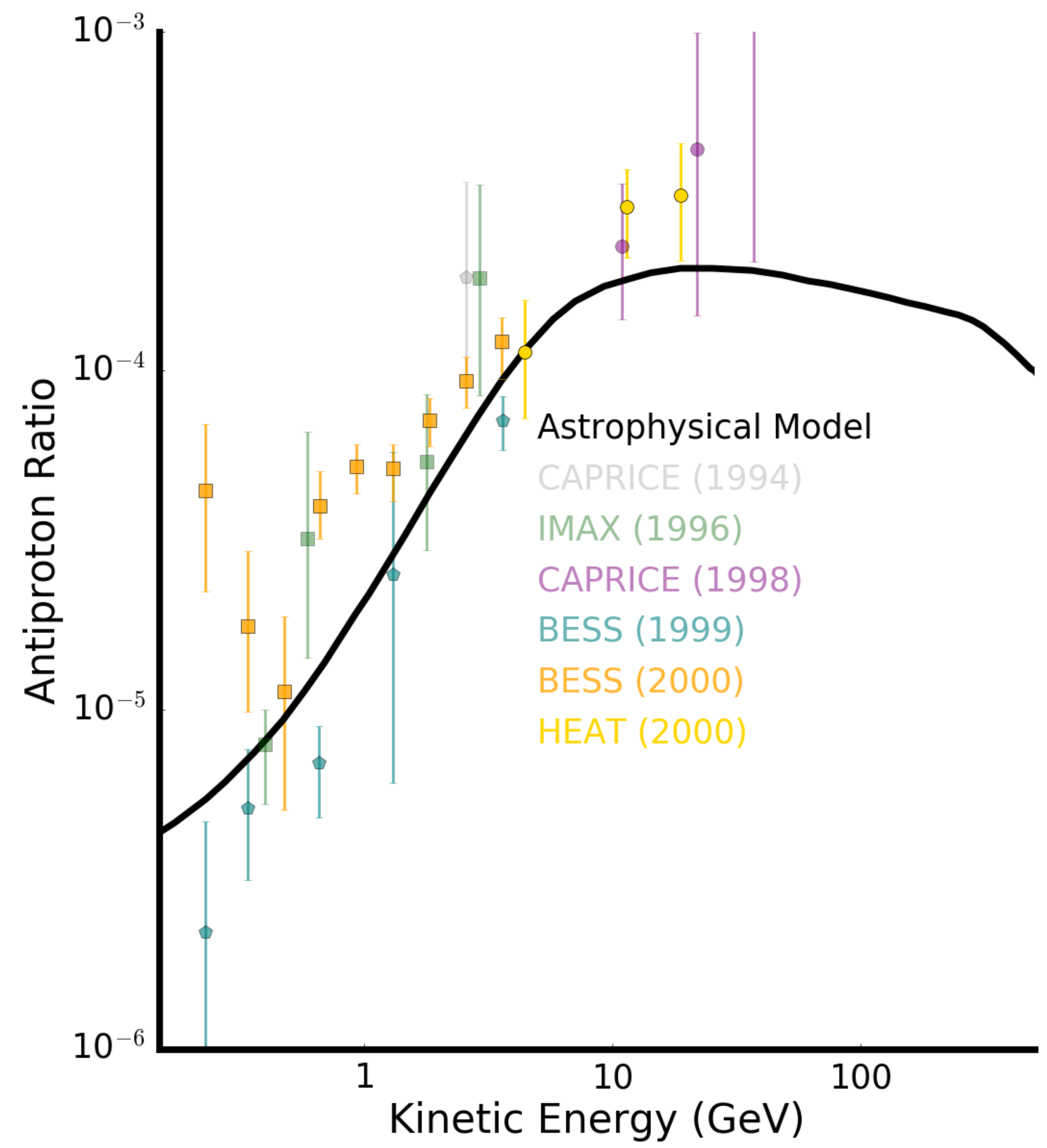
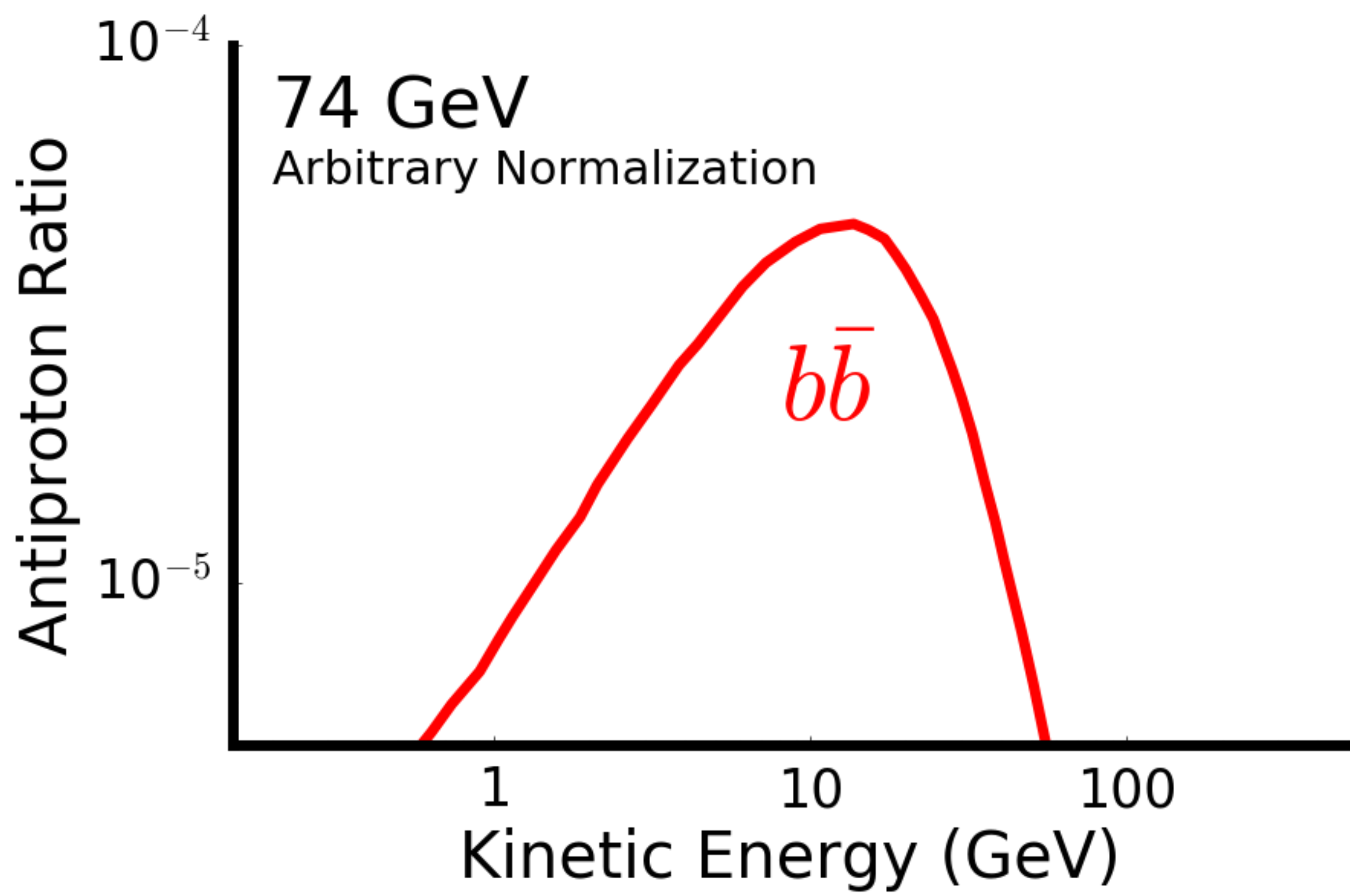
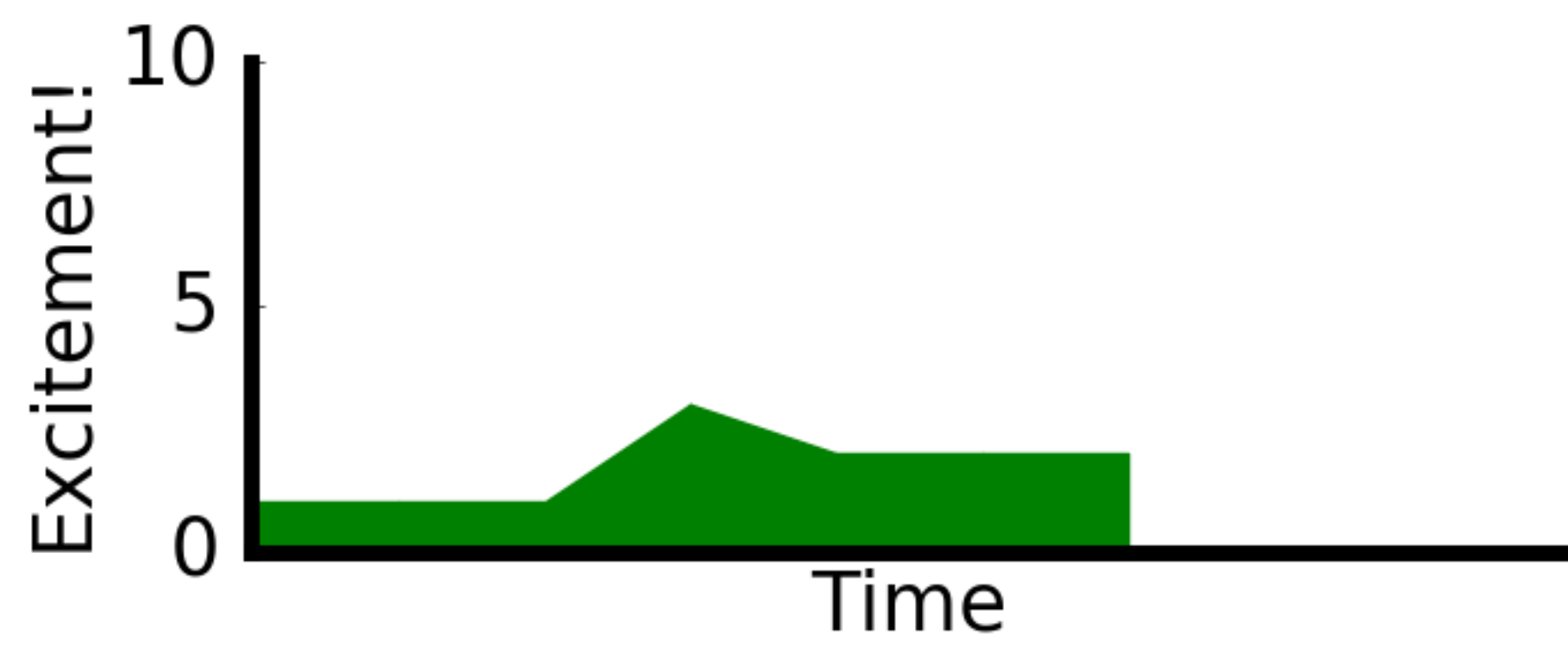


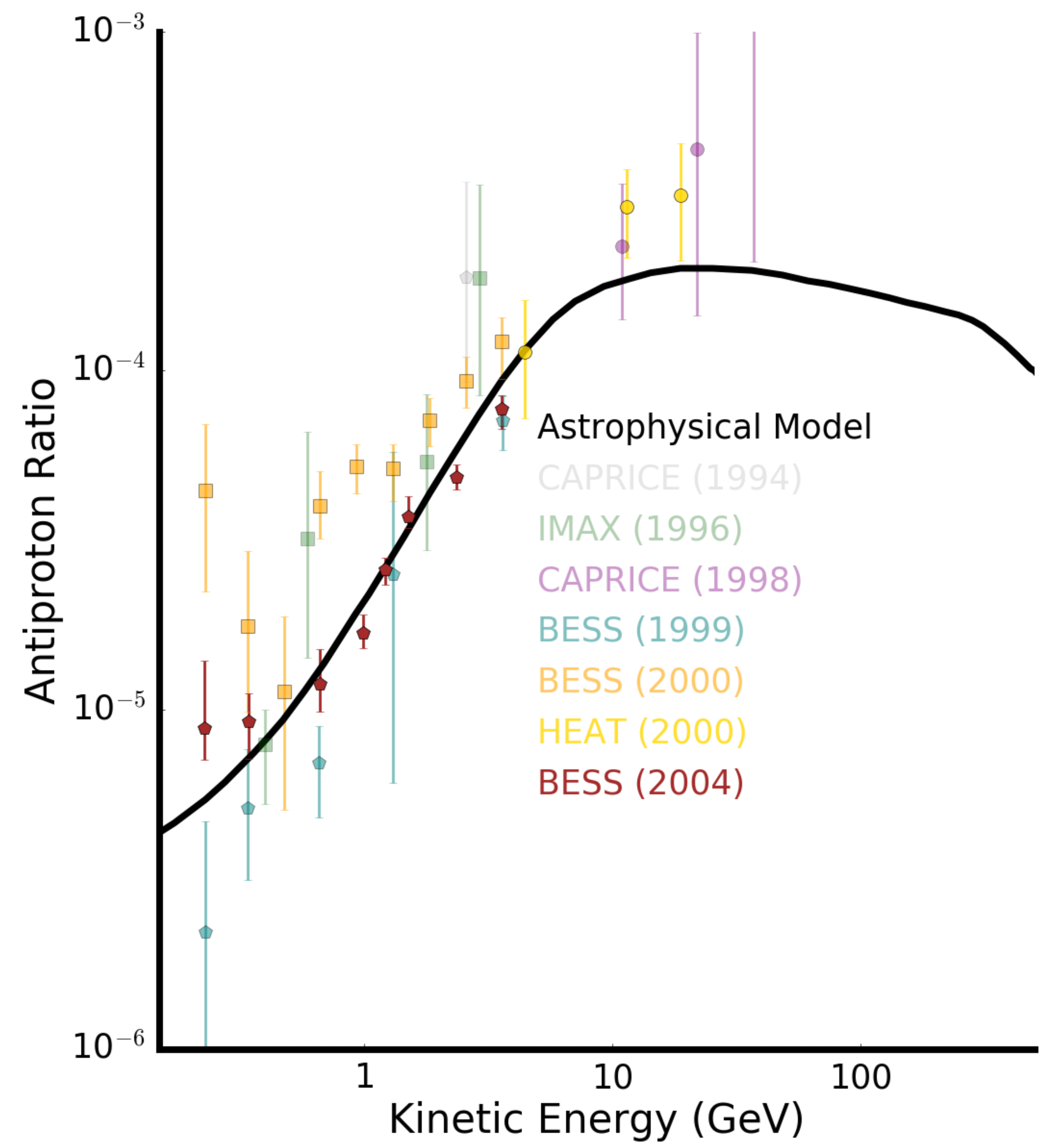
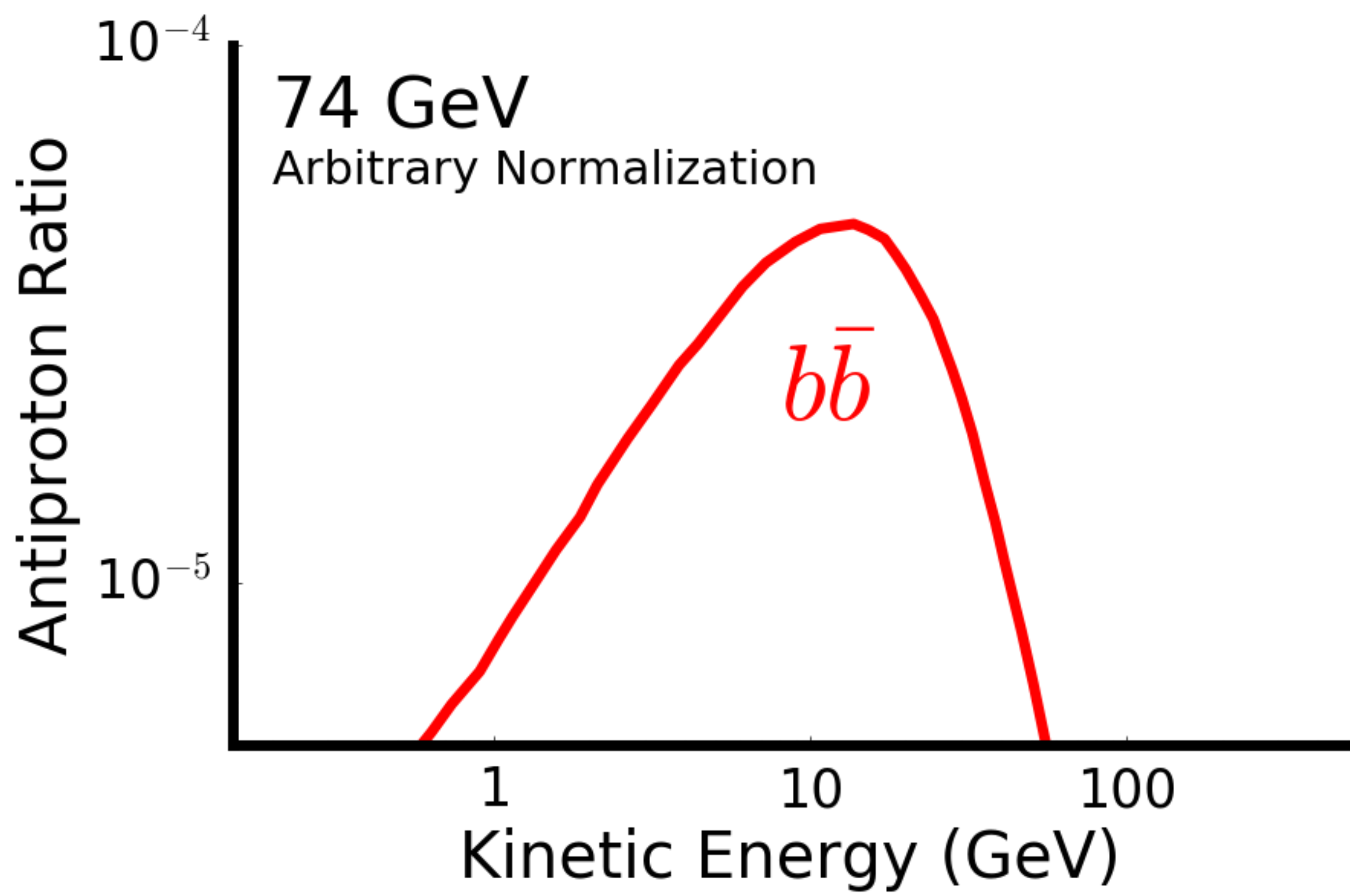
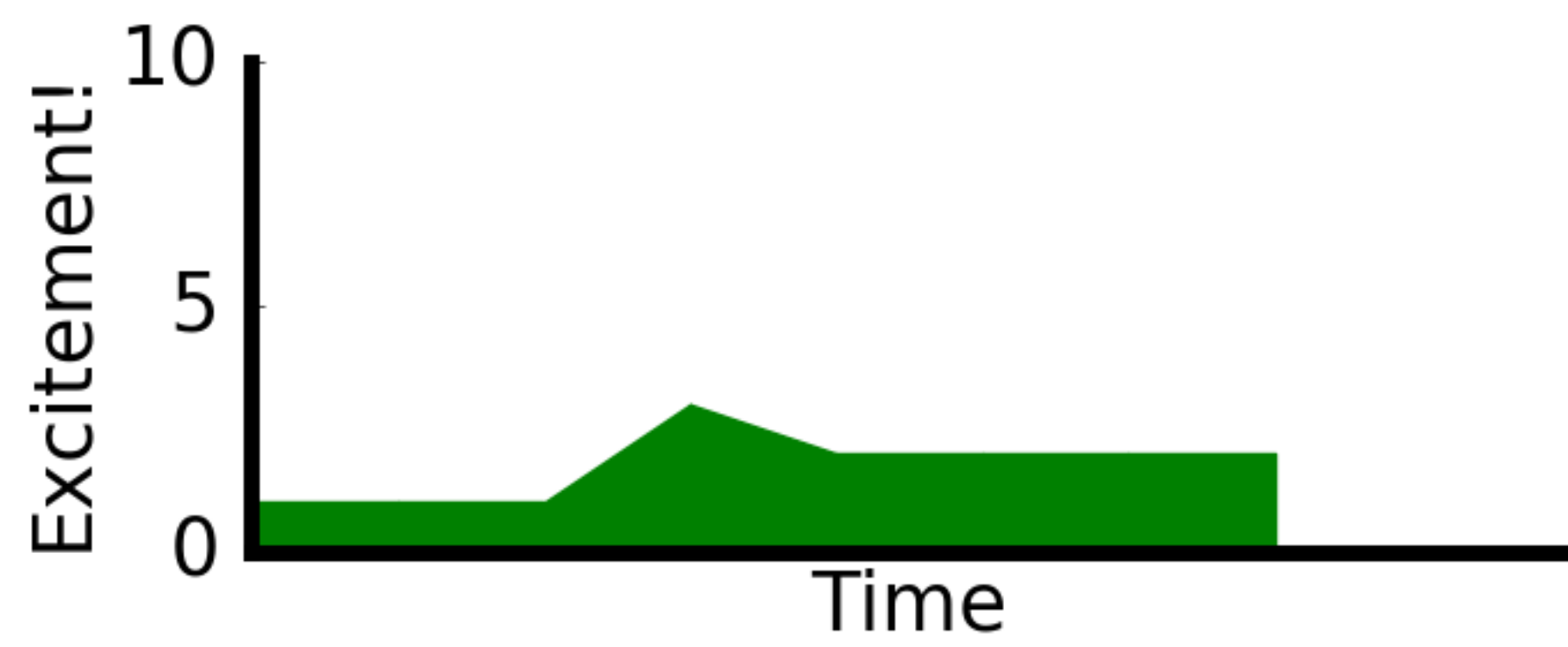


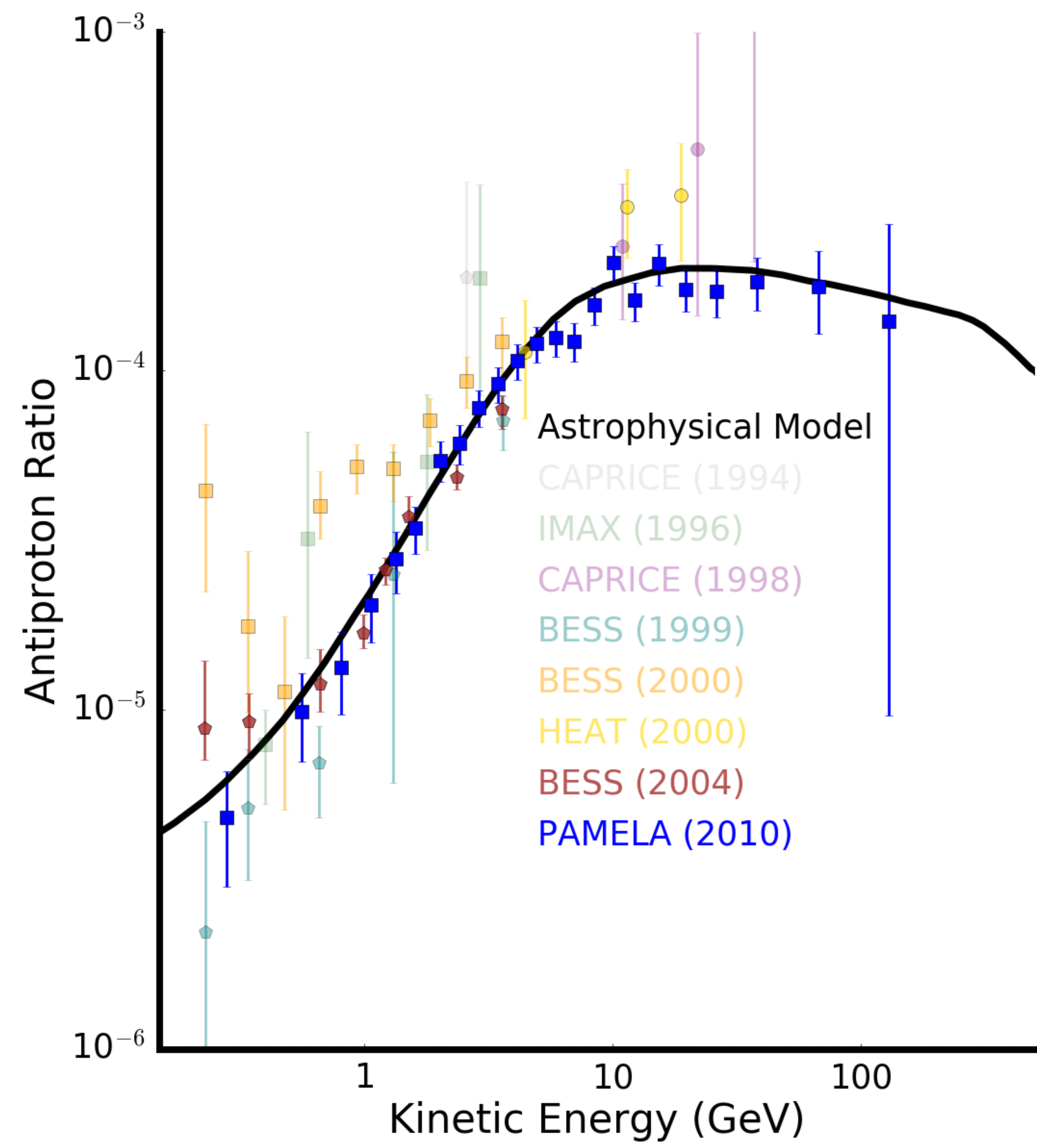
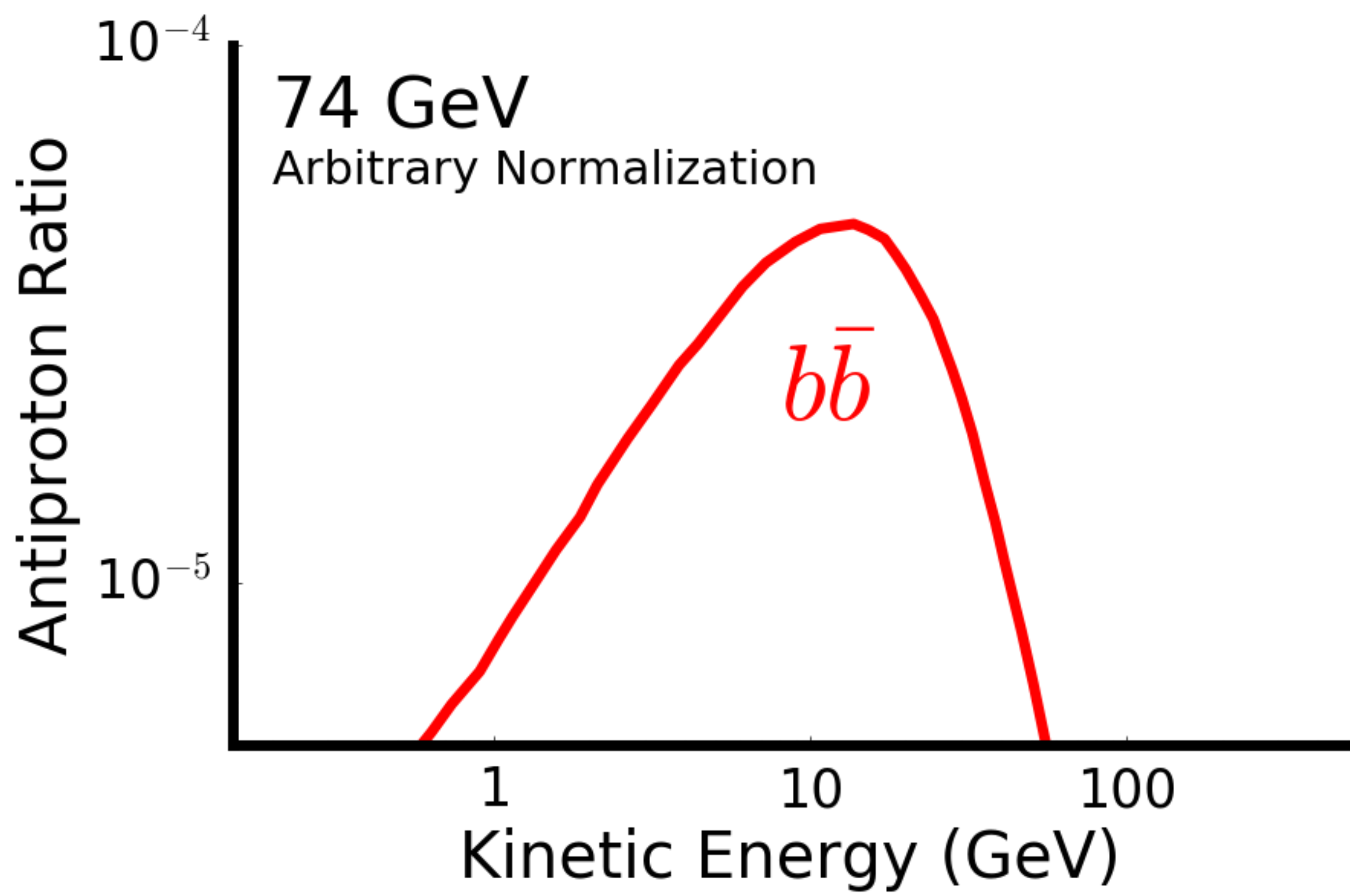
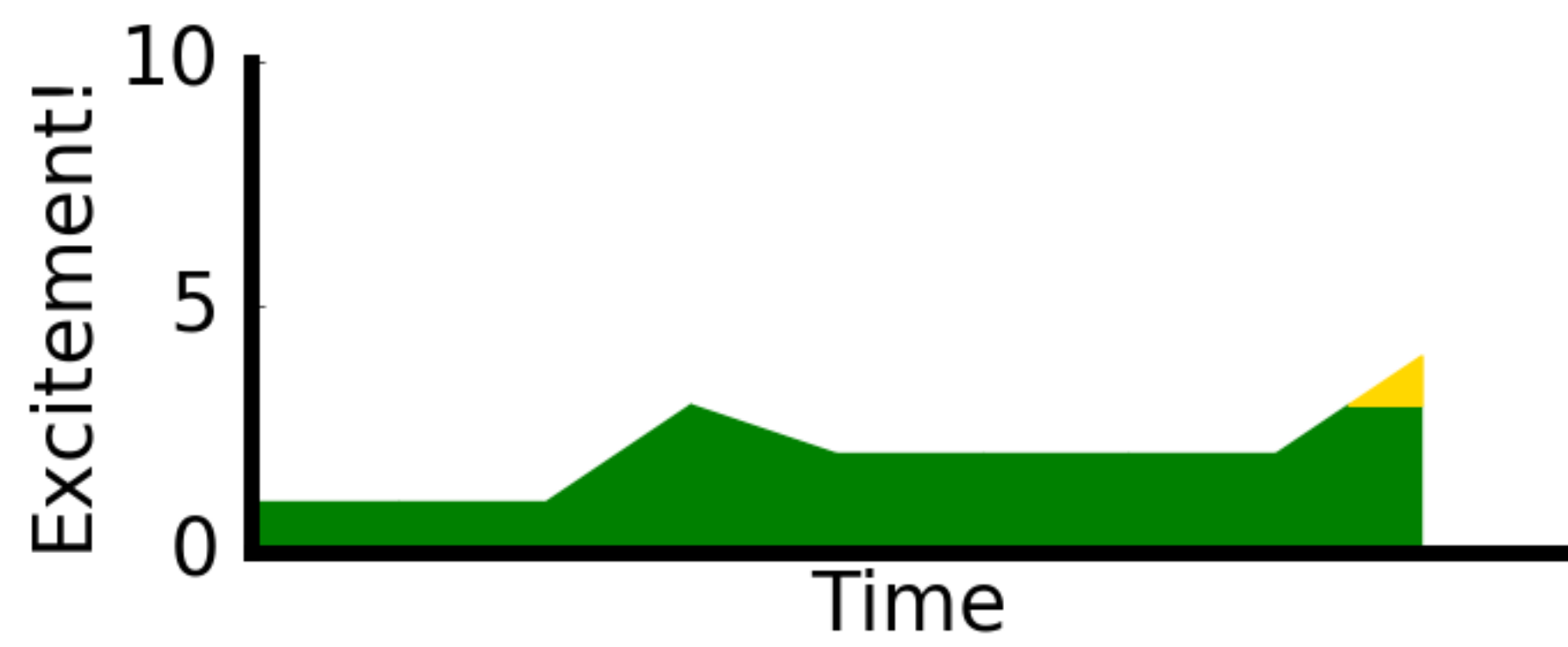


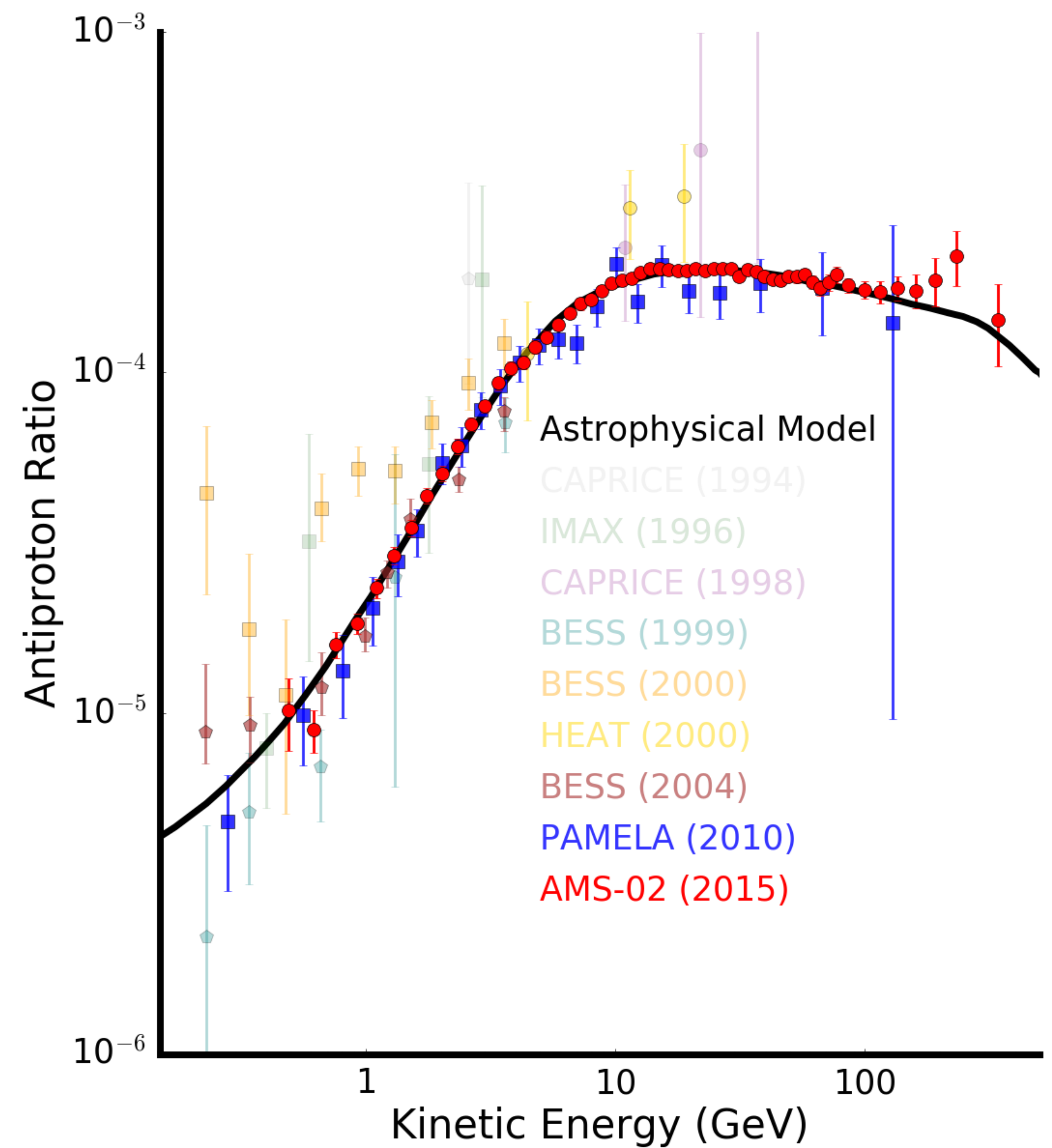
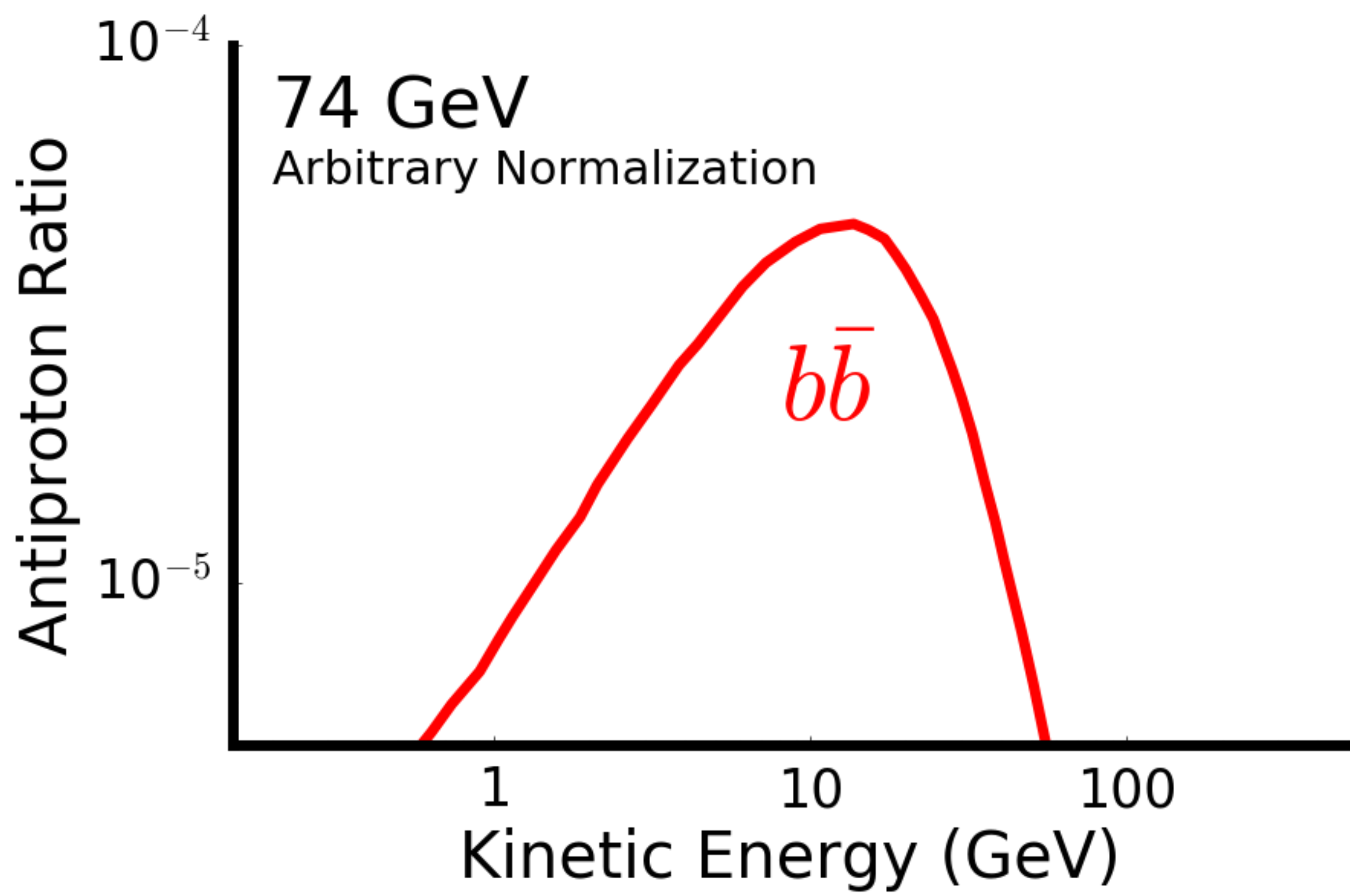
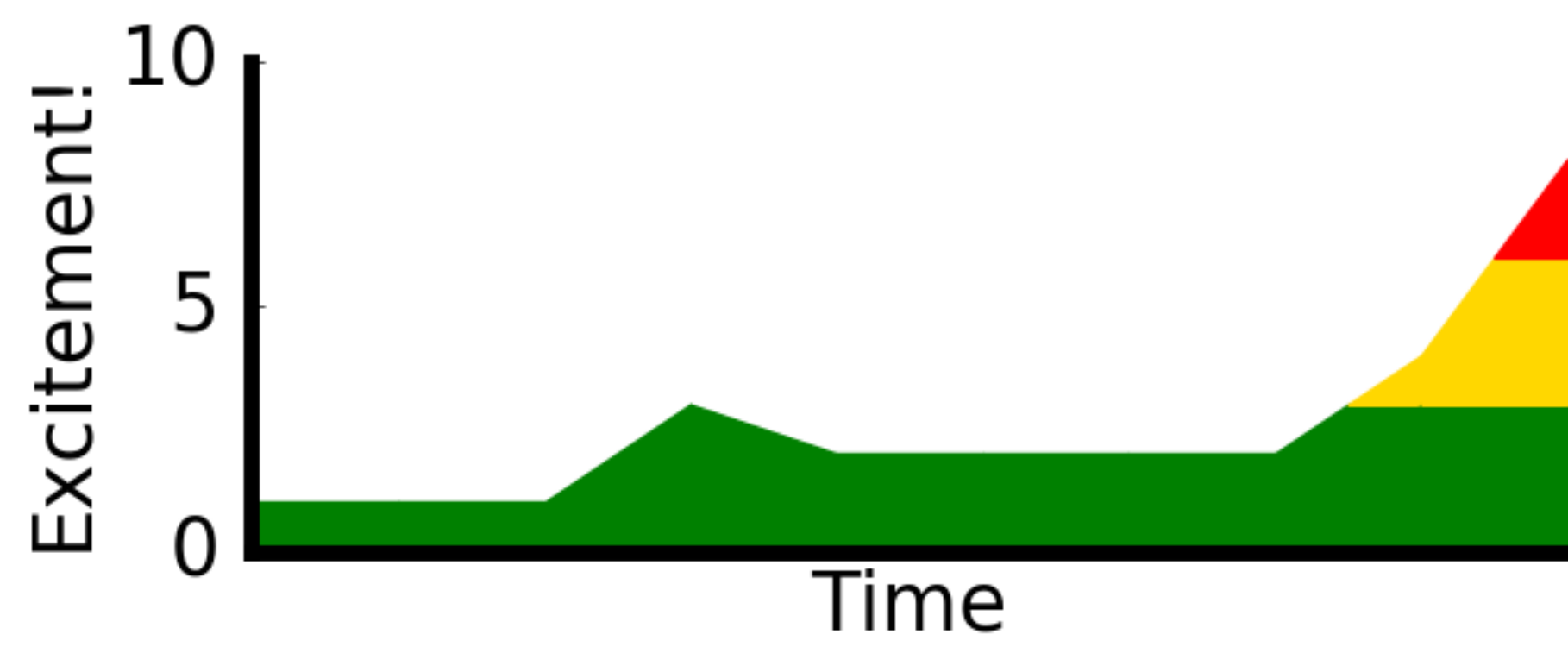


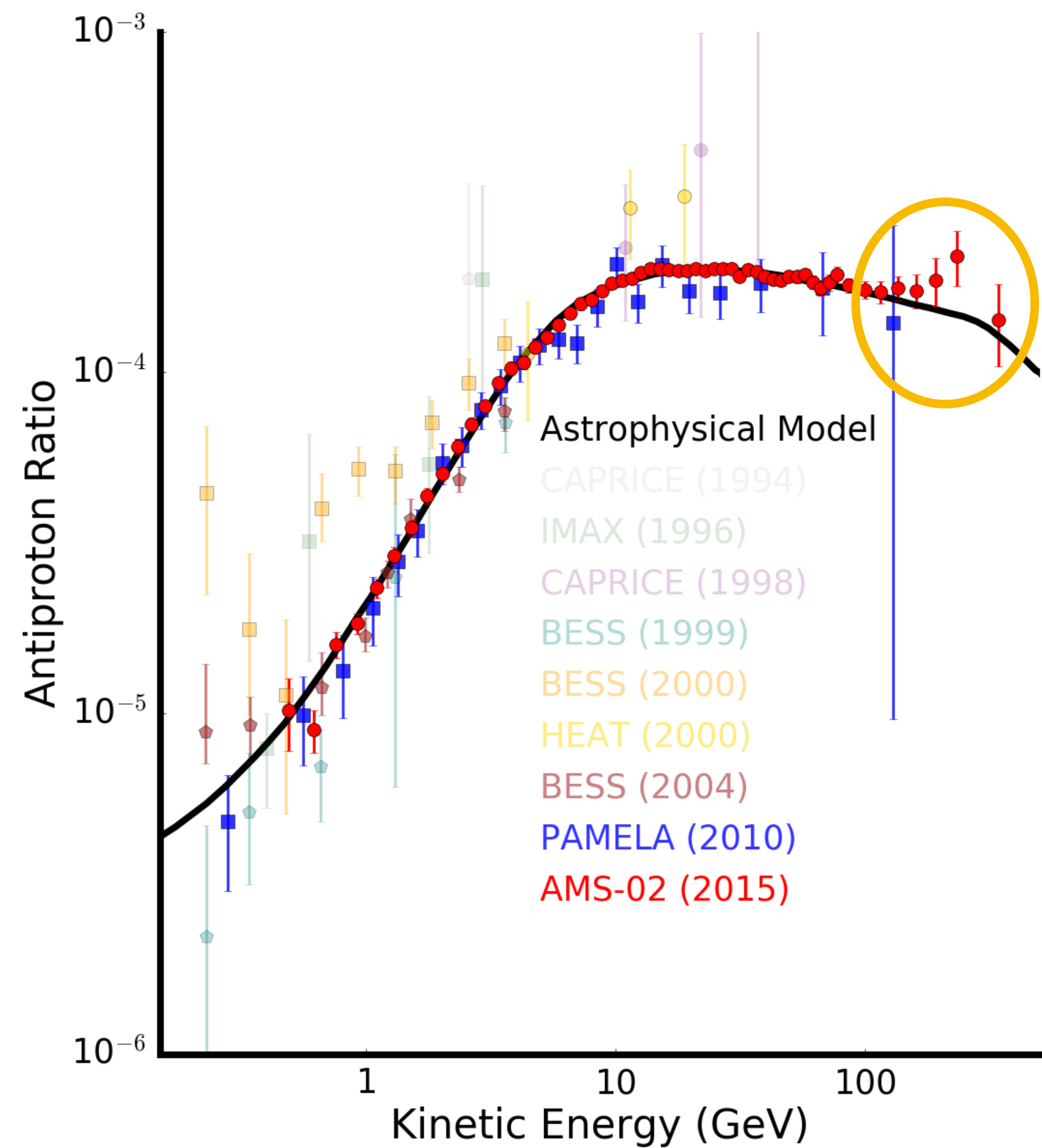
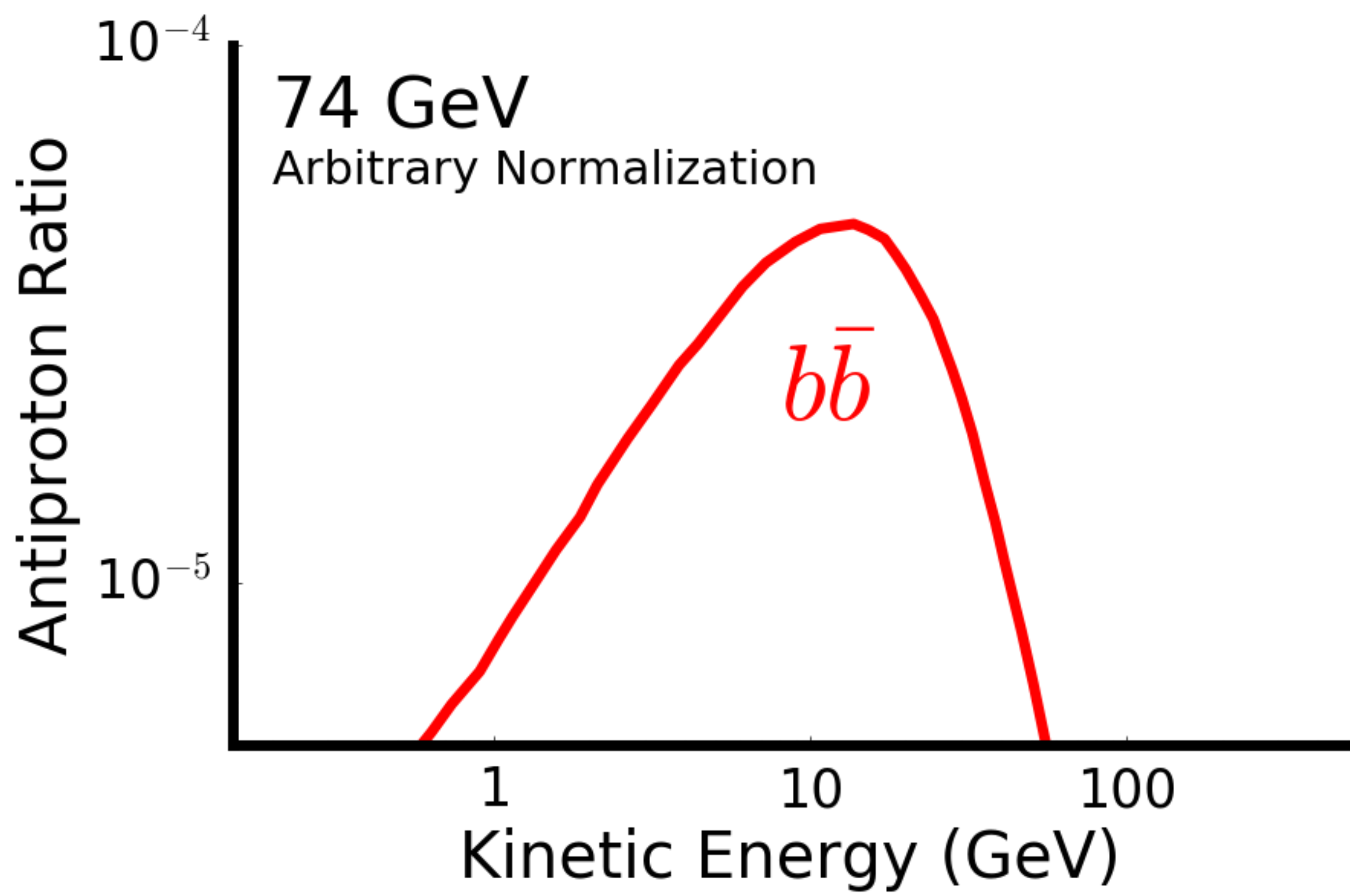
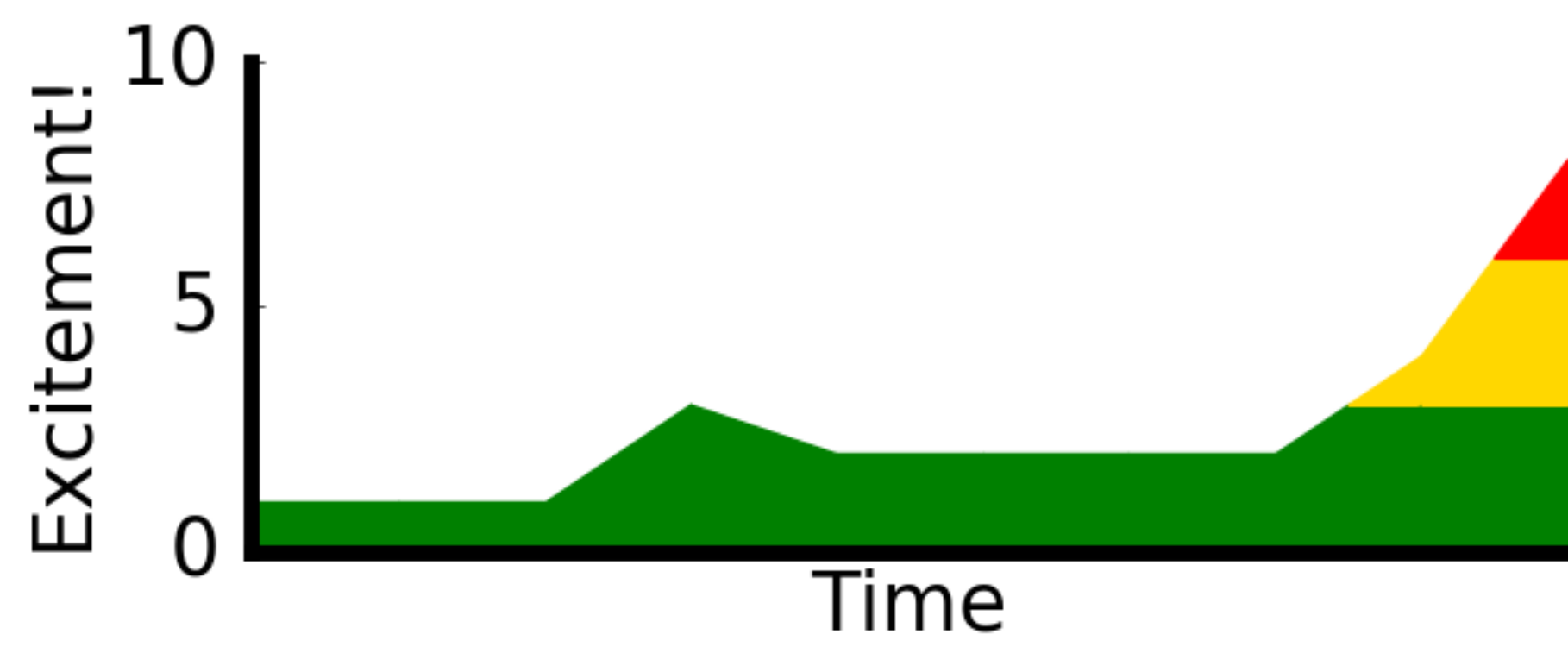


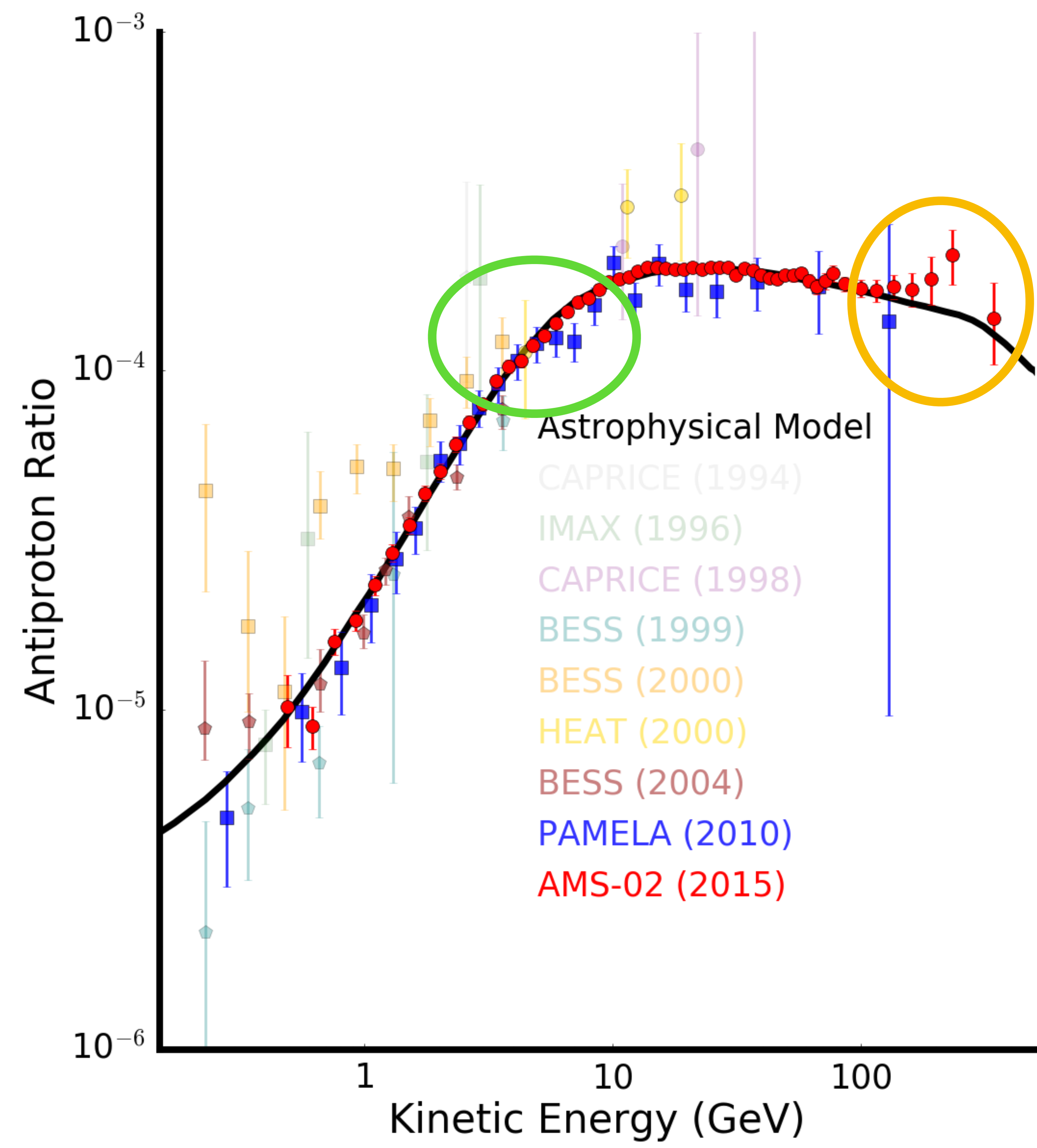
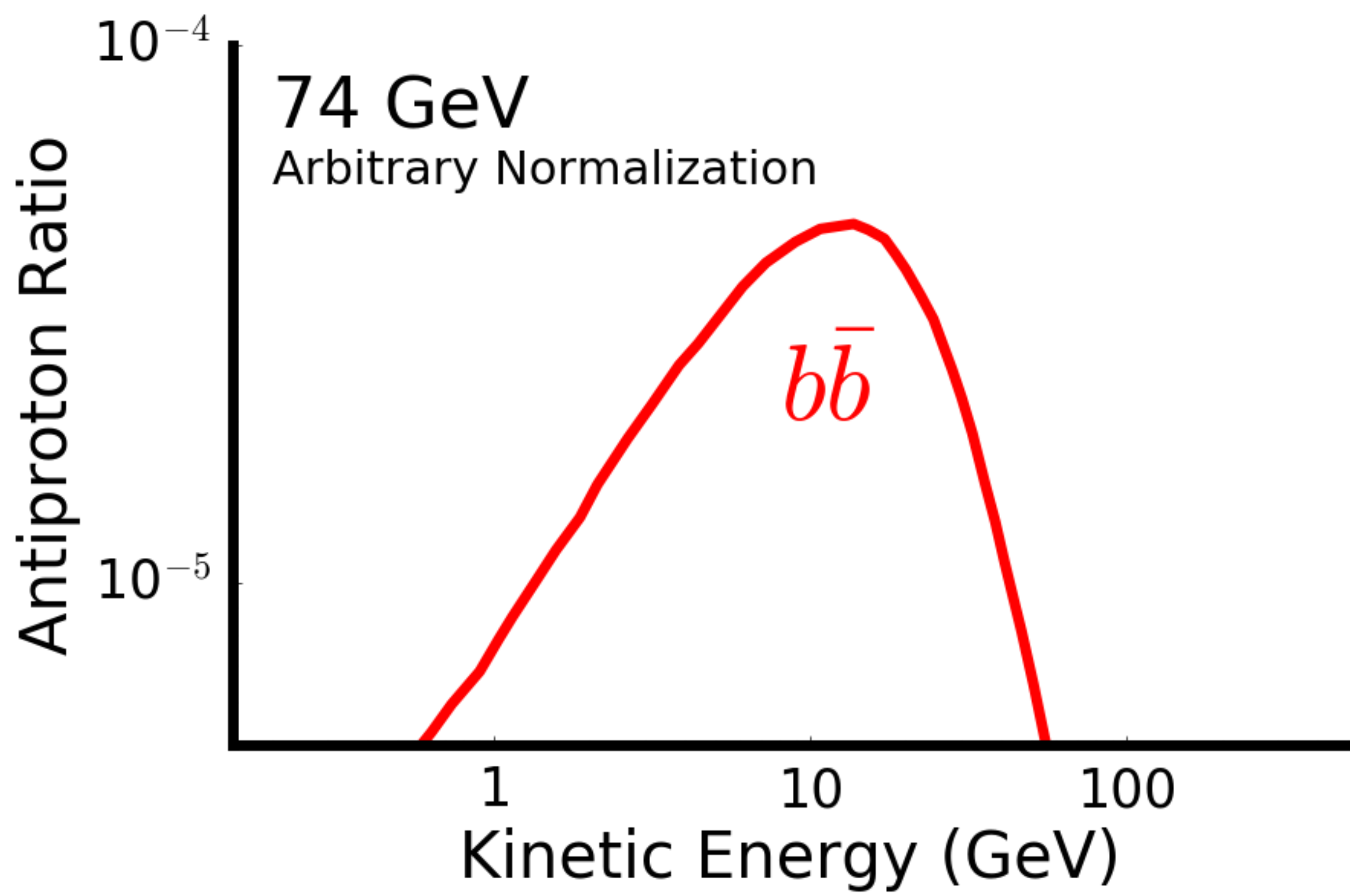
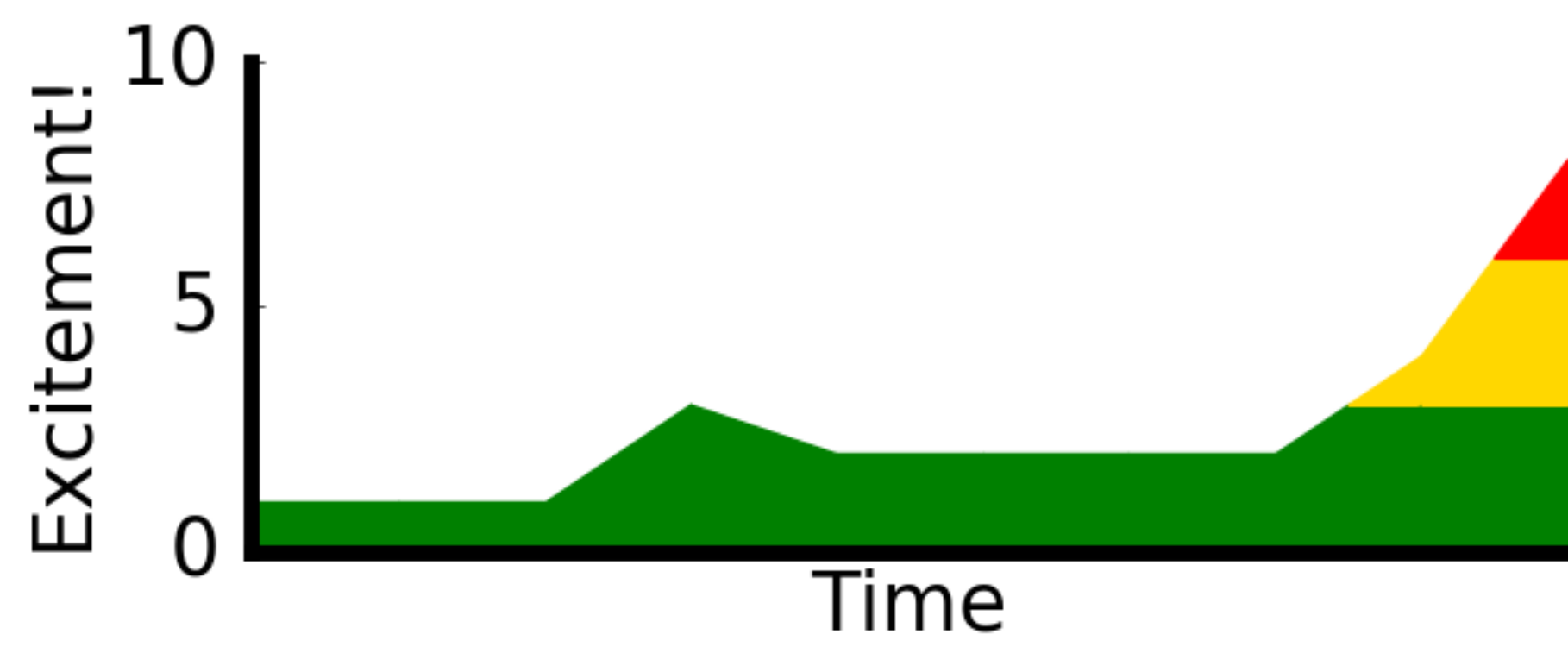


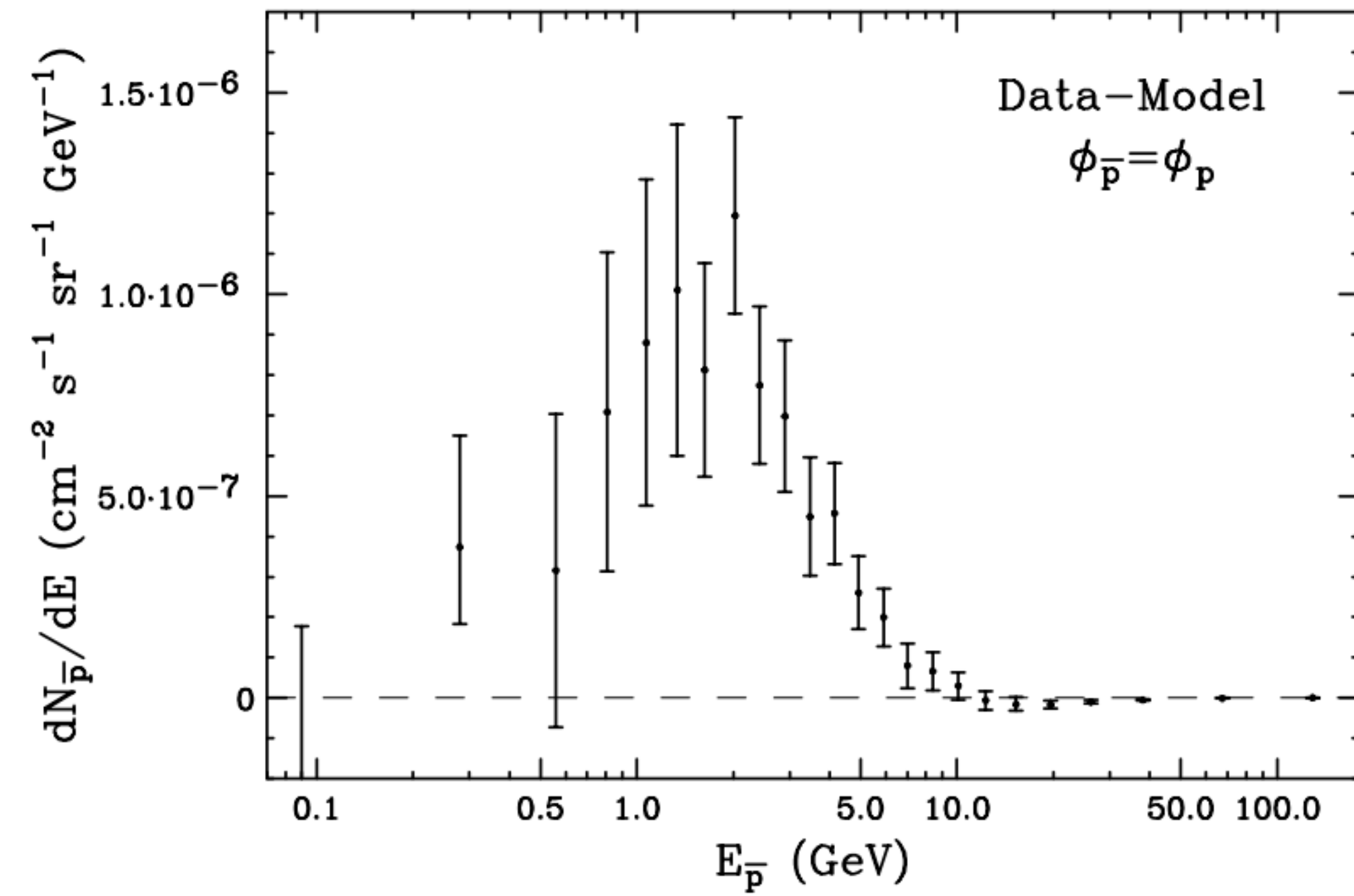
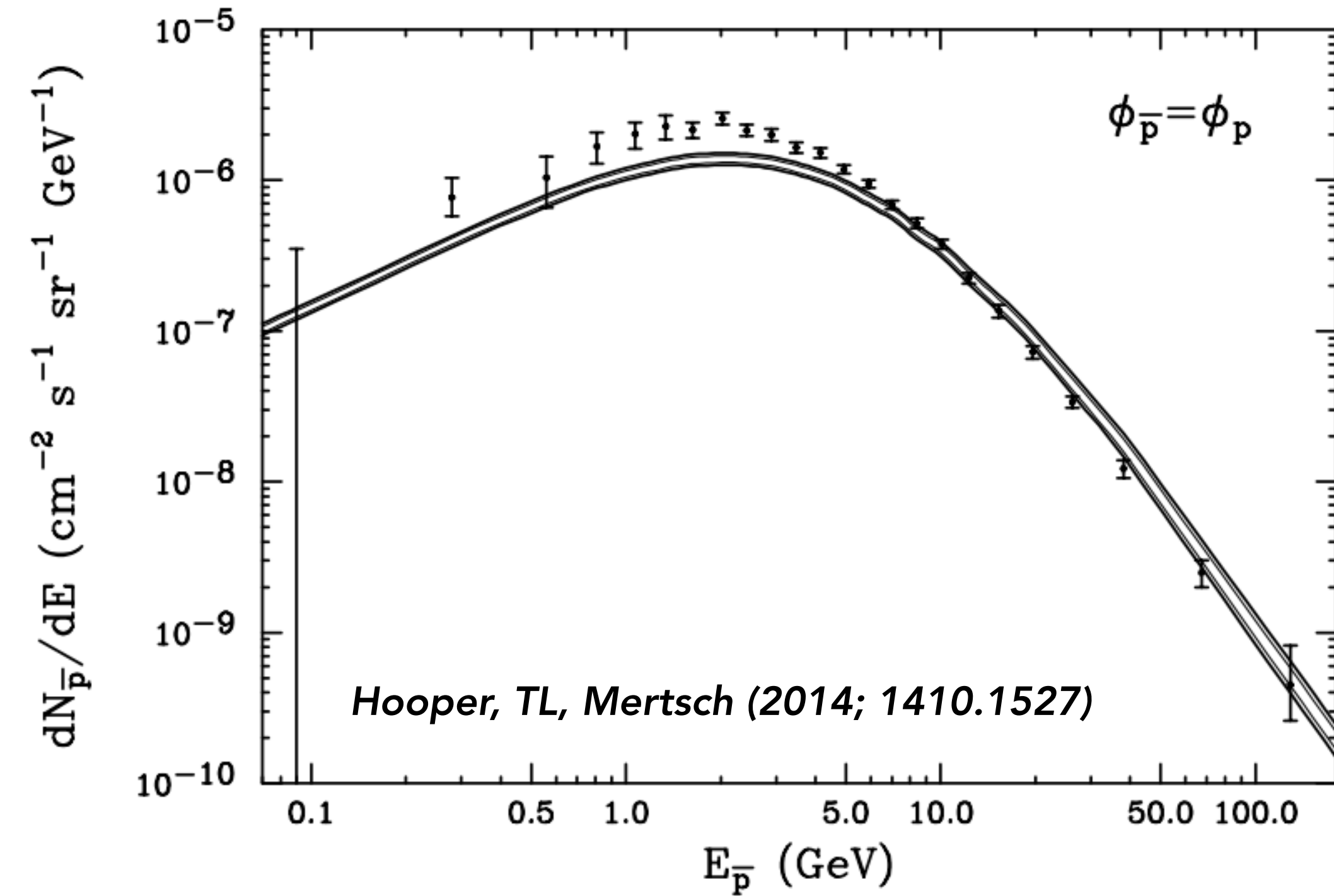
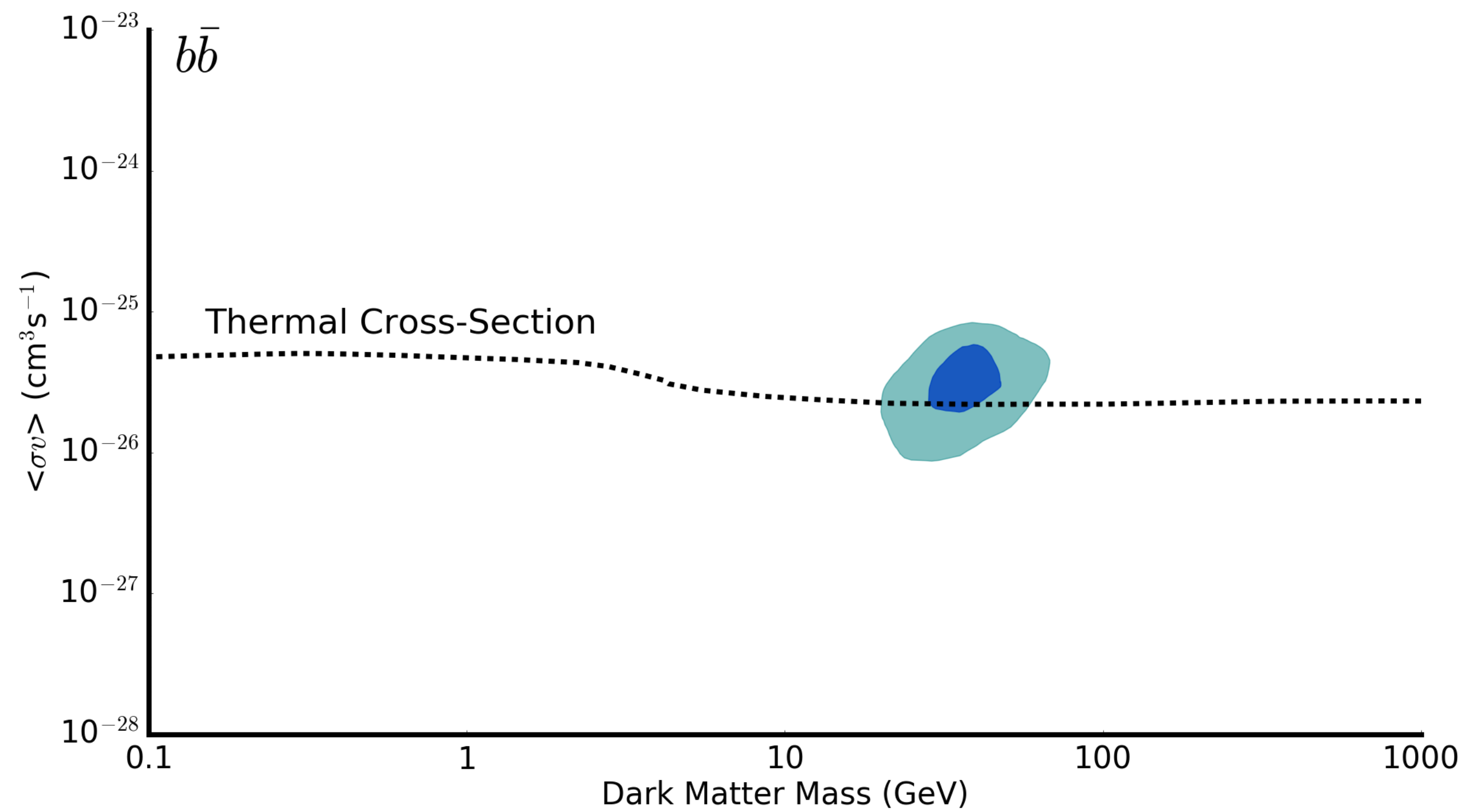


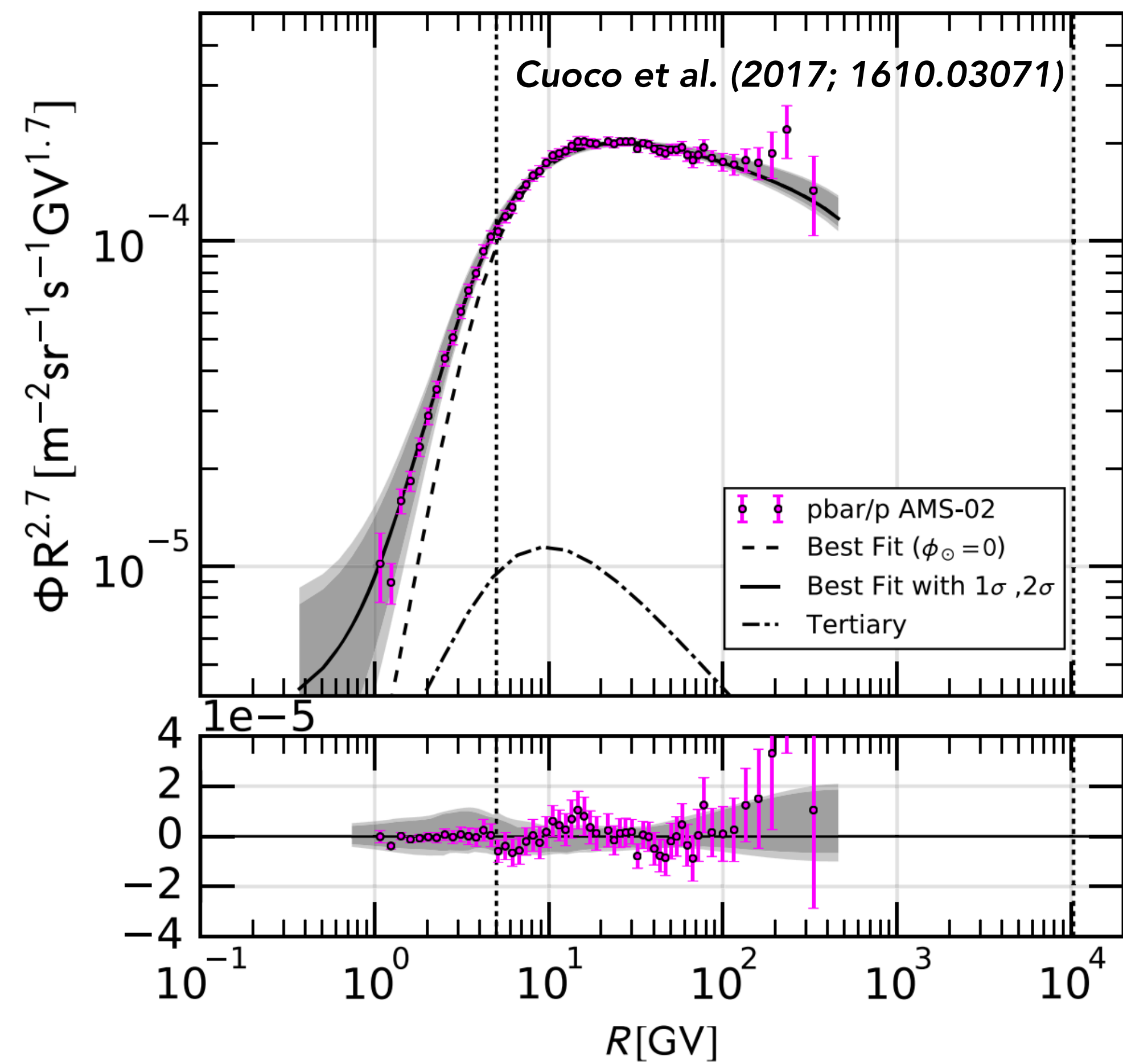
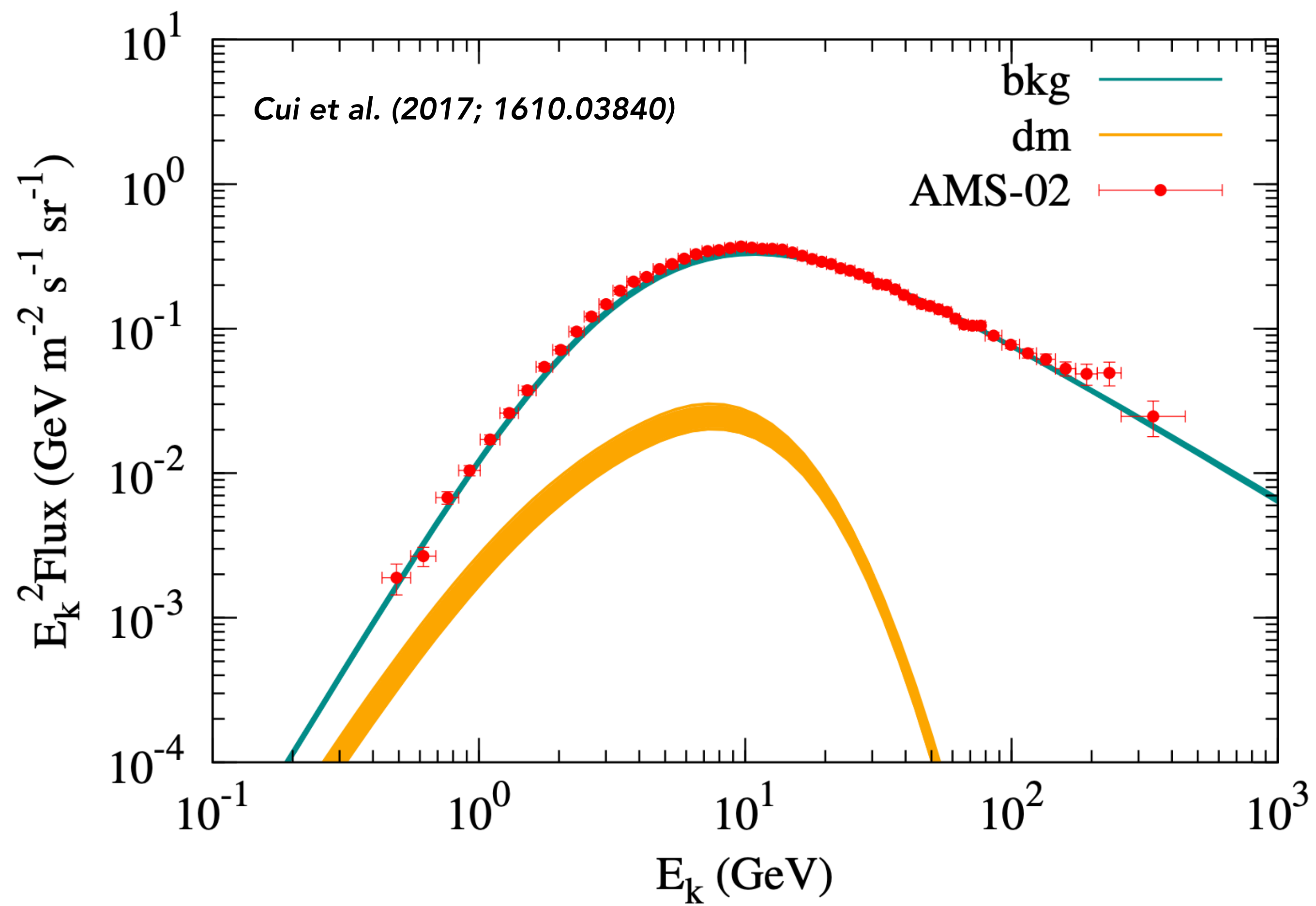




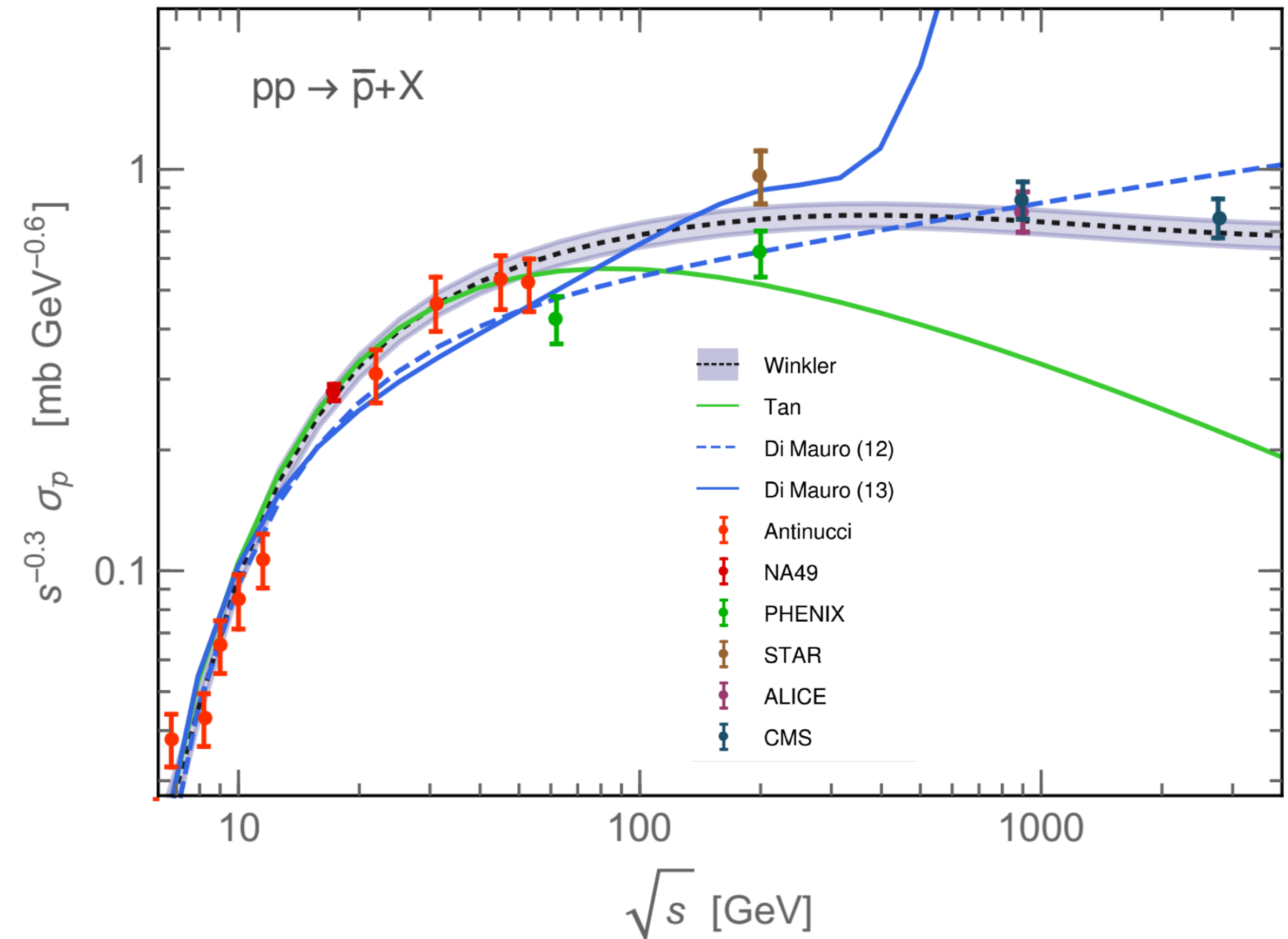








With great precision comes great responsibility:



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



Gamma-Rays

Galactic Center
Dwarf Spheroidal Galaxies
Galaxy Clusters
Milky Way Subhalos
Galactic Diffuse
Sun
Jupiter
Nearby Stars
Galactic Center Stars
Andromeda
Little Galaxies
Isotropic Gamma-Ray Background
Anisotropy Searches
Cusps
511 keV line

Morphology

Cosmic-Rays

Positrons
Electron + Positron Spectrum
Antiprotons
Antineutrons
Antihelium
Cosmological Lithium Problem

Antimatter

Neutrinos

The Sun
Direct Annihilation to Neutrinos
Hidden Sources
The Earth
Ultra-Heavy Dark Matter

Messengers

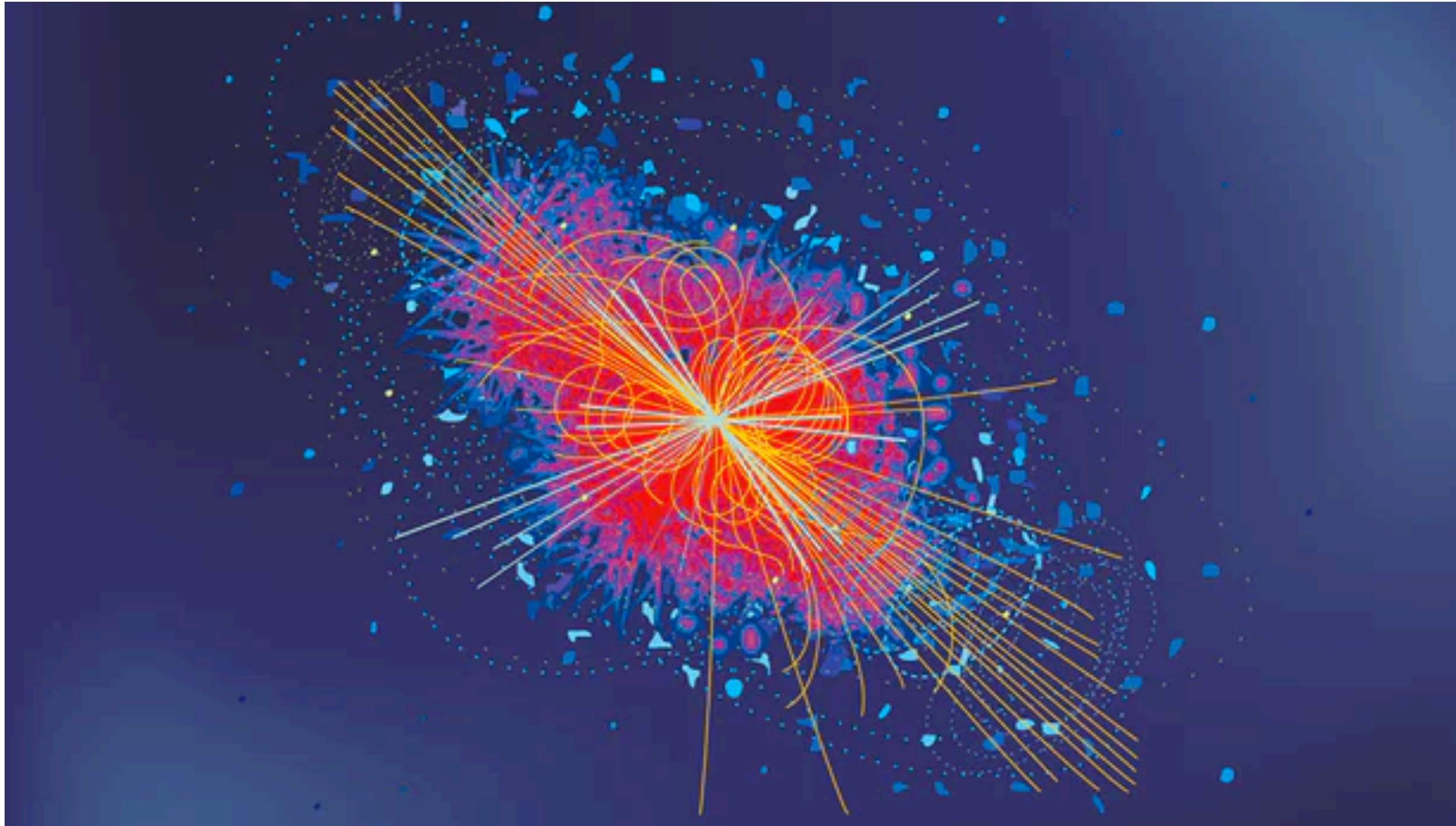
Low-Energy

Galactic Center Synchrotron
Dwarf Galaxy Synchrotron
Galaxy Cluster Synchrotron
Diffuse Synchrotron
Sun
Jupiter
Isotropic Background
X-ray background from Clusters
Anisotropy Searches
Stellar Evolution
Pulsar Evolution
Planetary Heating
Thermal Scattering
Cosmic Microwave Background
CMB Absorption

Targets

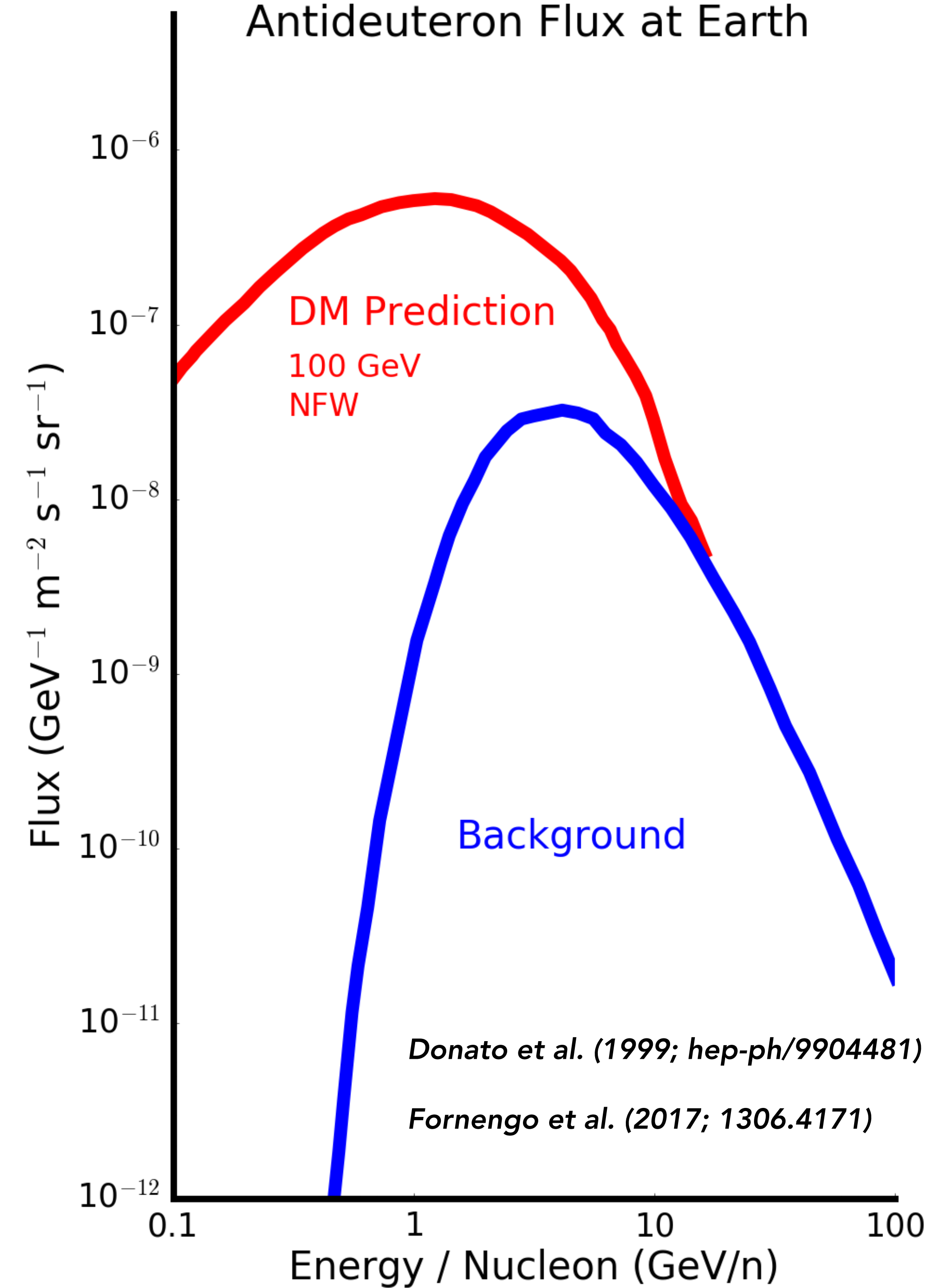
Tentative Evidence for Antinuclei

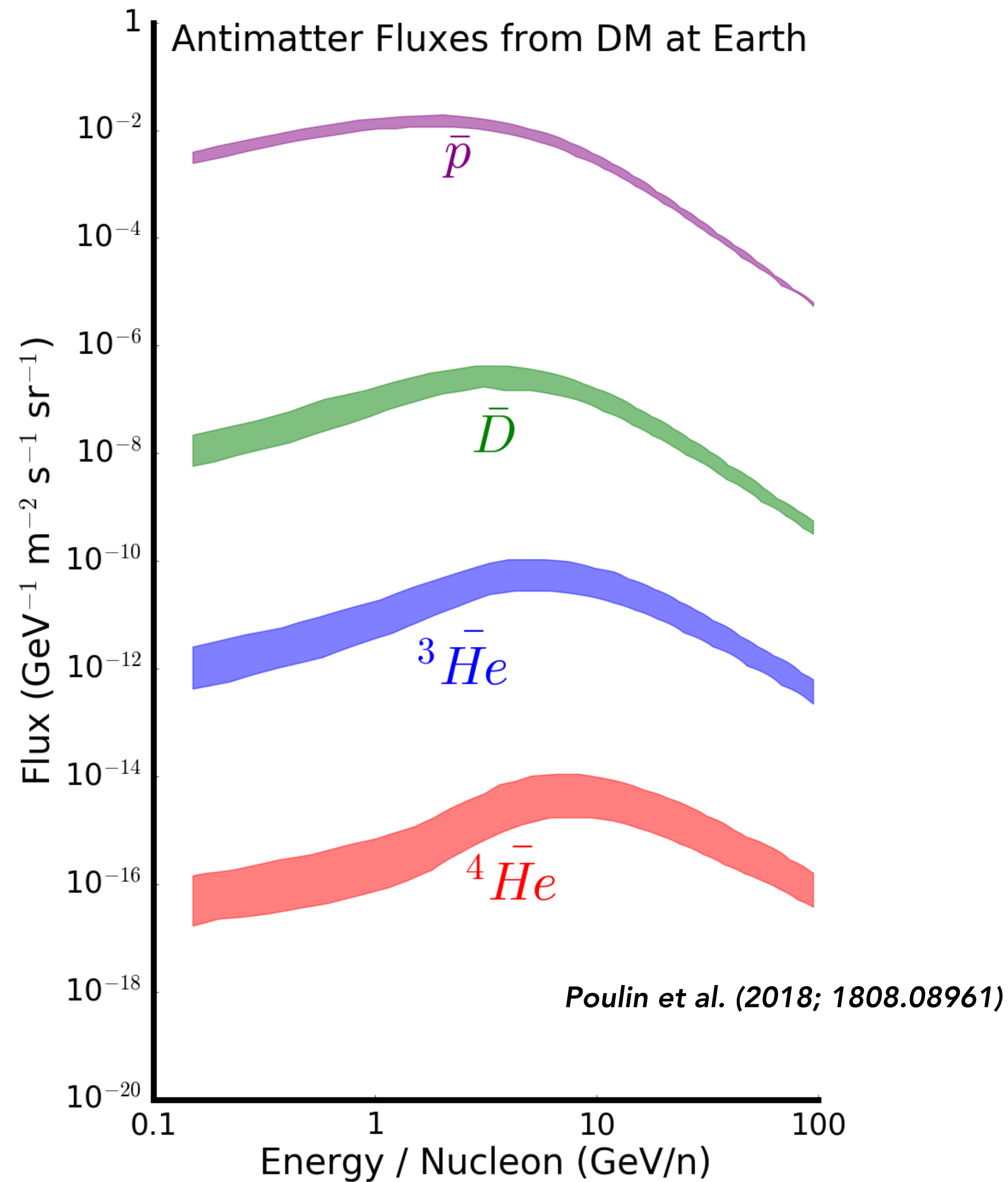
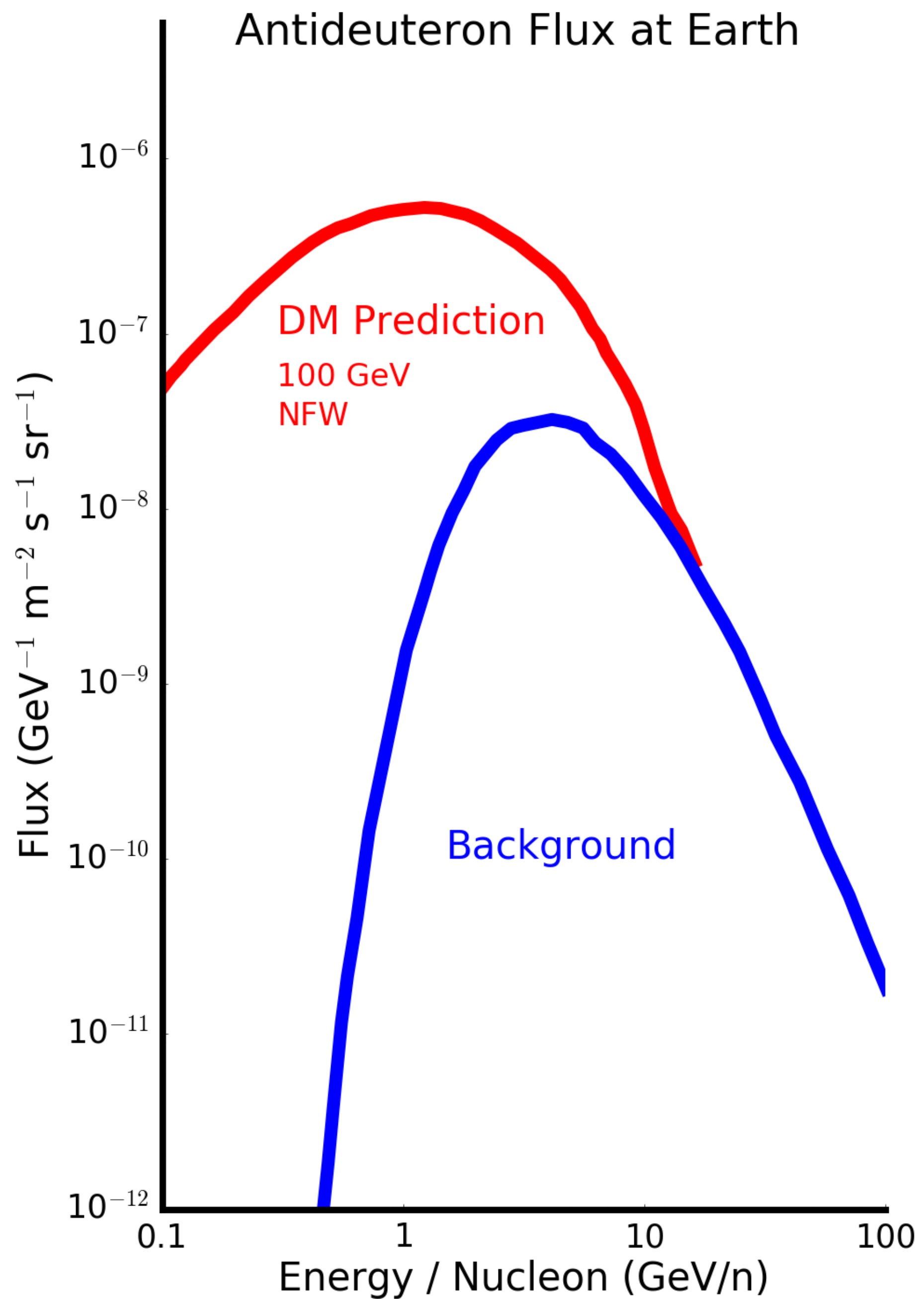




Astrophysical Antinuclei - Most be moving relativistically!

Dark Matter Antinuclei - Can be slow!





Specificity (DM Flux / Astrophysics Flux)

Small Dark Matter Signal
Small Astrophysical Background

Hard

Large Dark Matter Signal
Small Astrophysical Background

Easy

Small Dark Matter Signal
Large Astrophysical Background

Easy

Large Dark Matter Signal
Large Astrophysical Background

Hard

Fraction of Dark Matter Flux

Specificity (DM Flux / Astrophysics Flux)

Small Dark Matter Signal
Small Astrophysical Background

Acceptable?

Large Dark Matter Signal
Small Astrophysical Background

Easy

Easy

Small Dark Matter Signal
Large Astrophysical Background

Hard

Large Dark Matter Signal
Large Astrophysical Background

Fraction of Dark Matter Flux

NOT MY DEPARTMENT

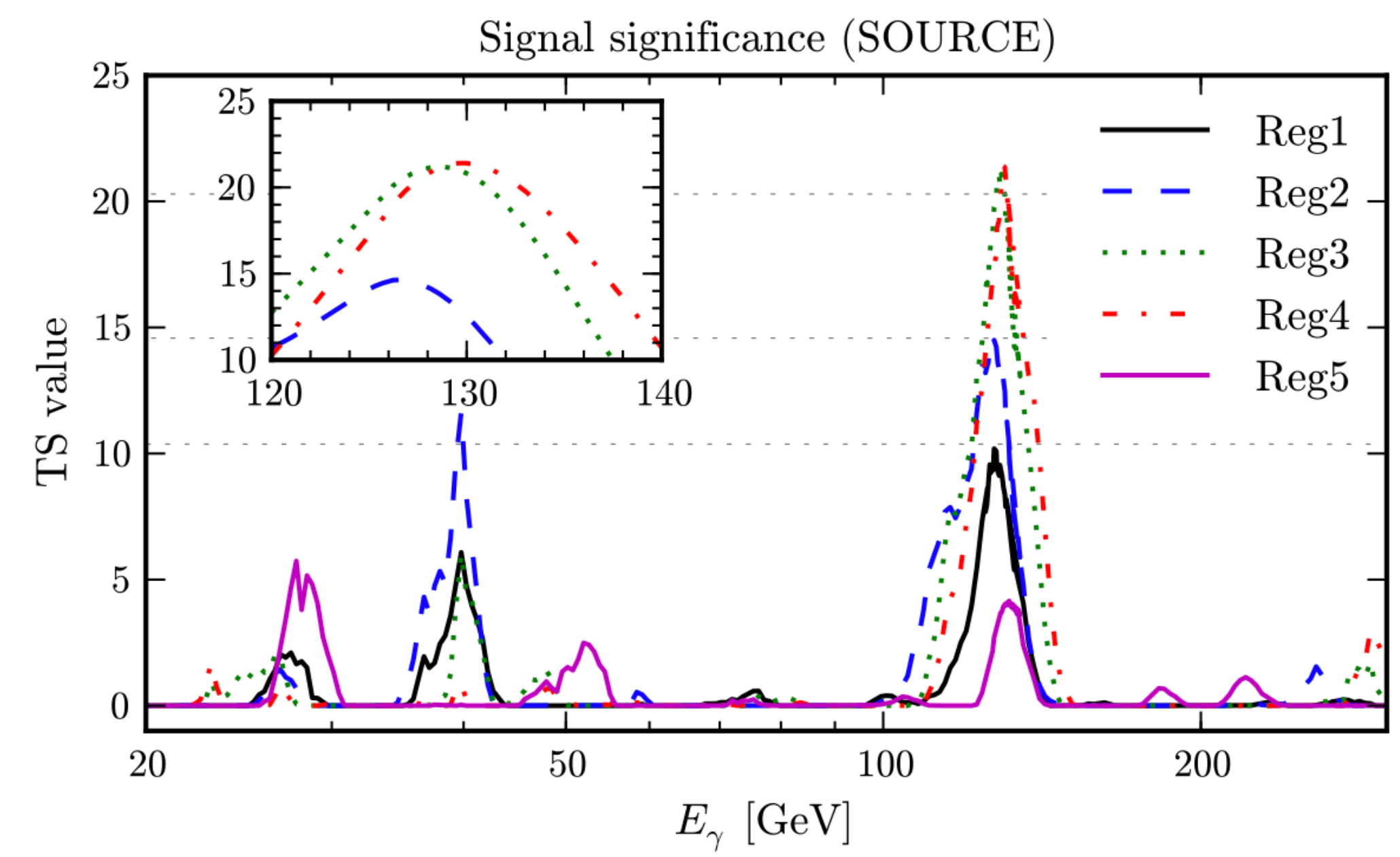
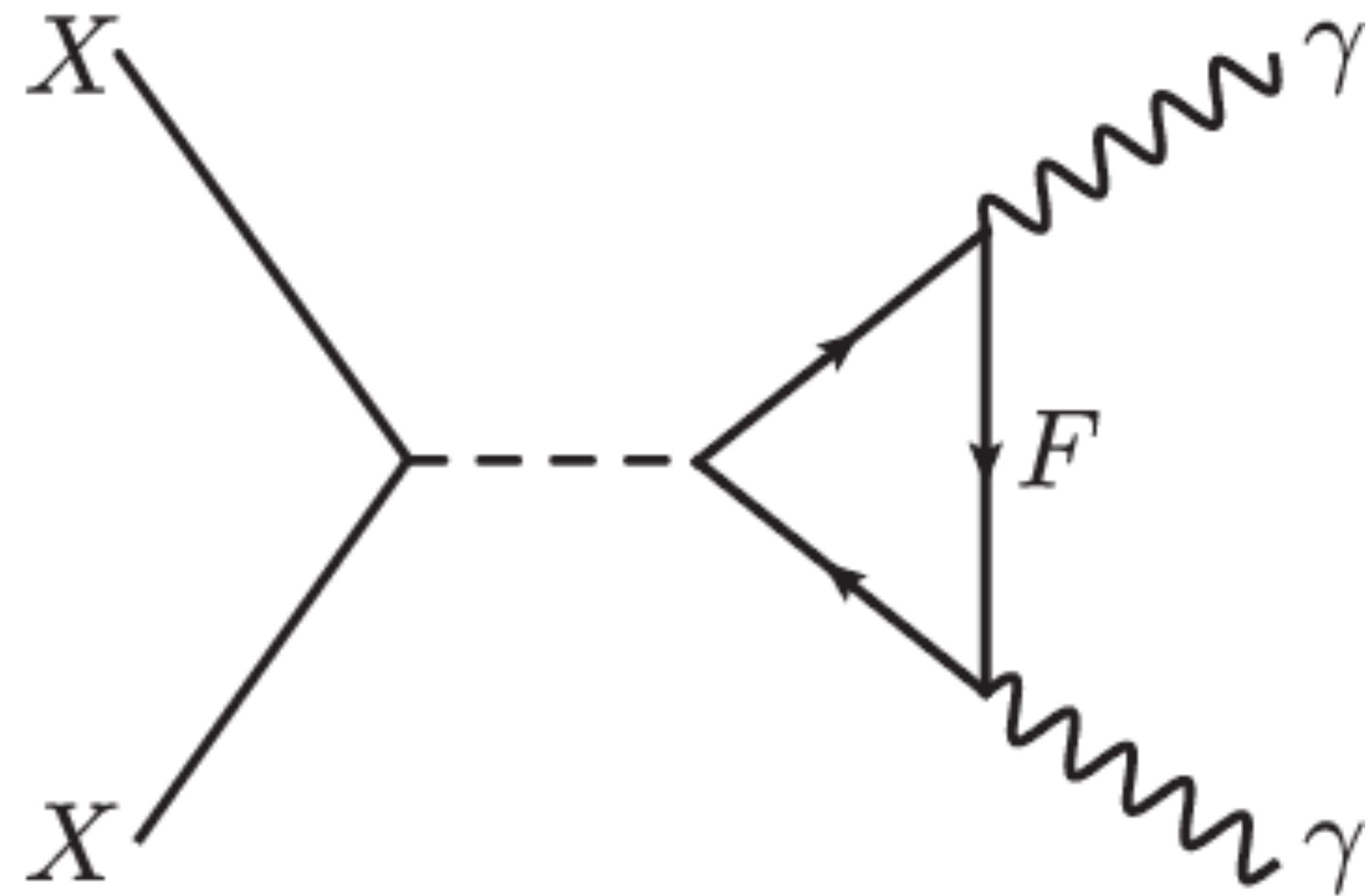


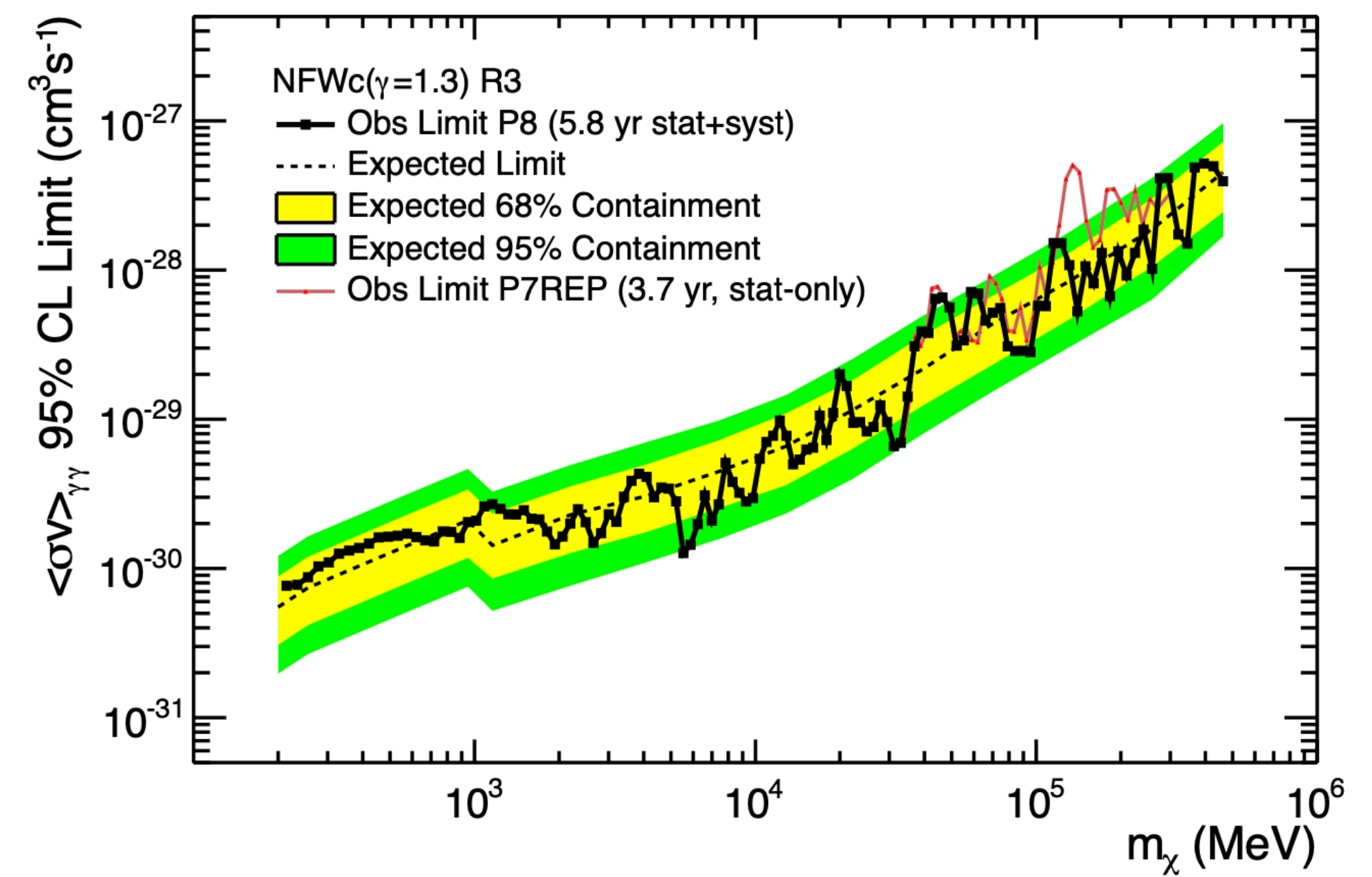
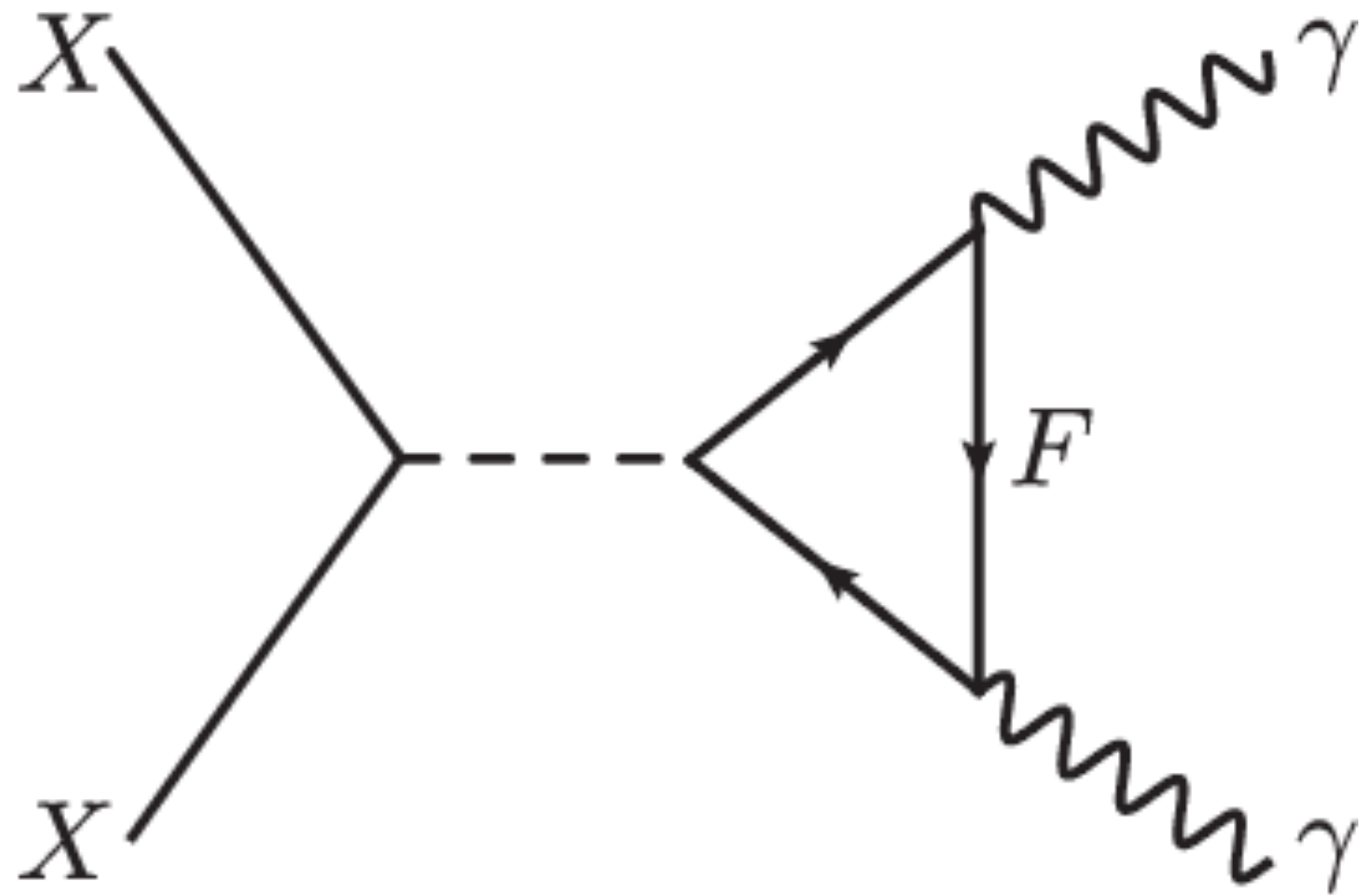
NOT MY PROBLEM

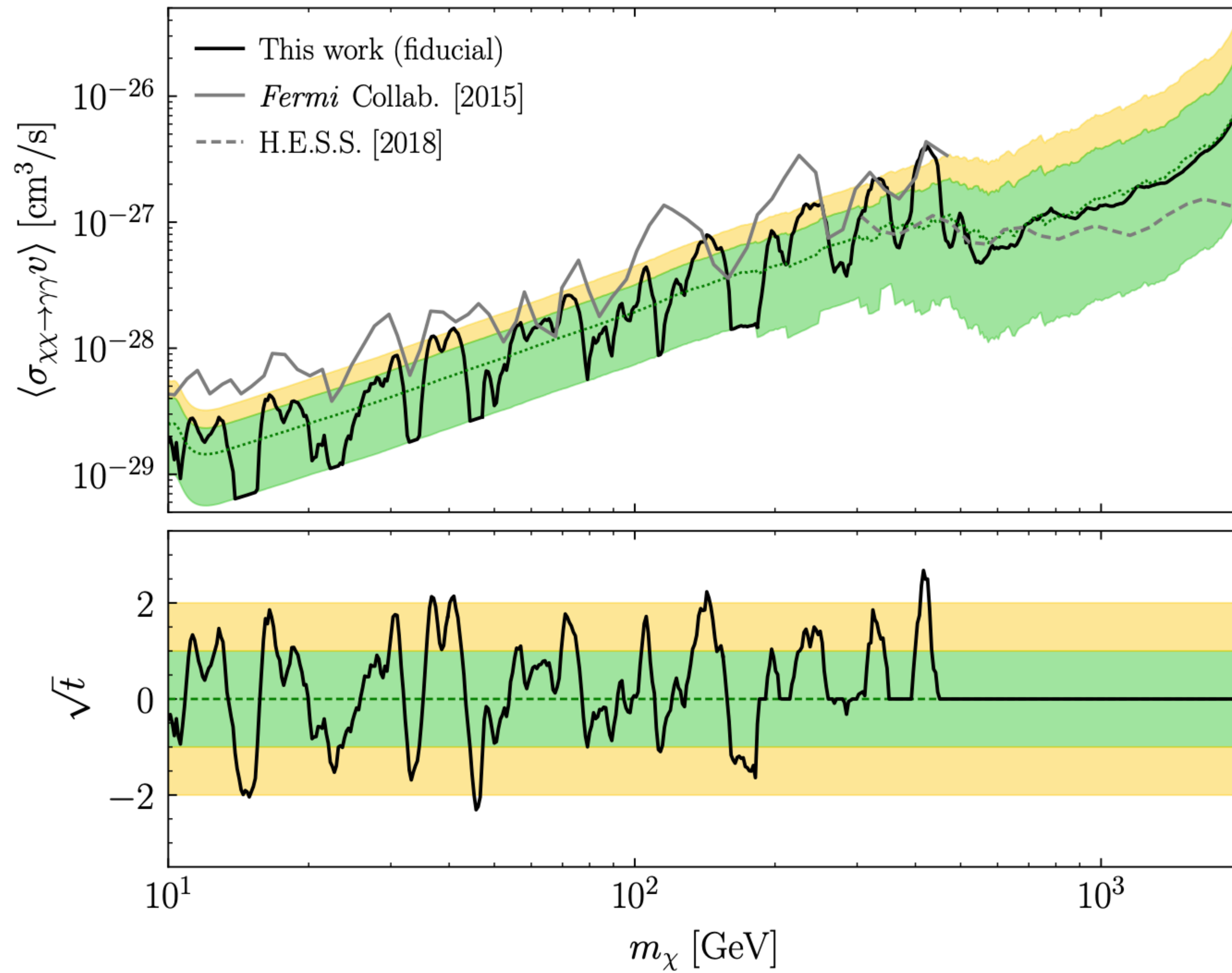
To date, we have observed eight events in the mass region from 0 to 10 GeV with $Z = -2$. All eight events are in the helium mass region.

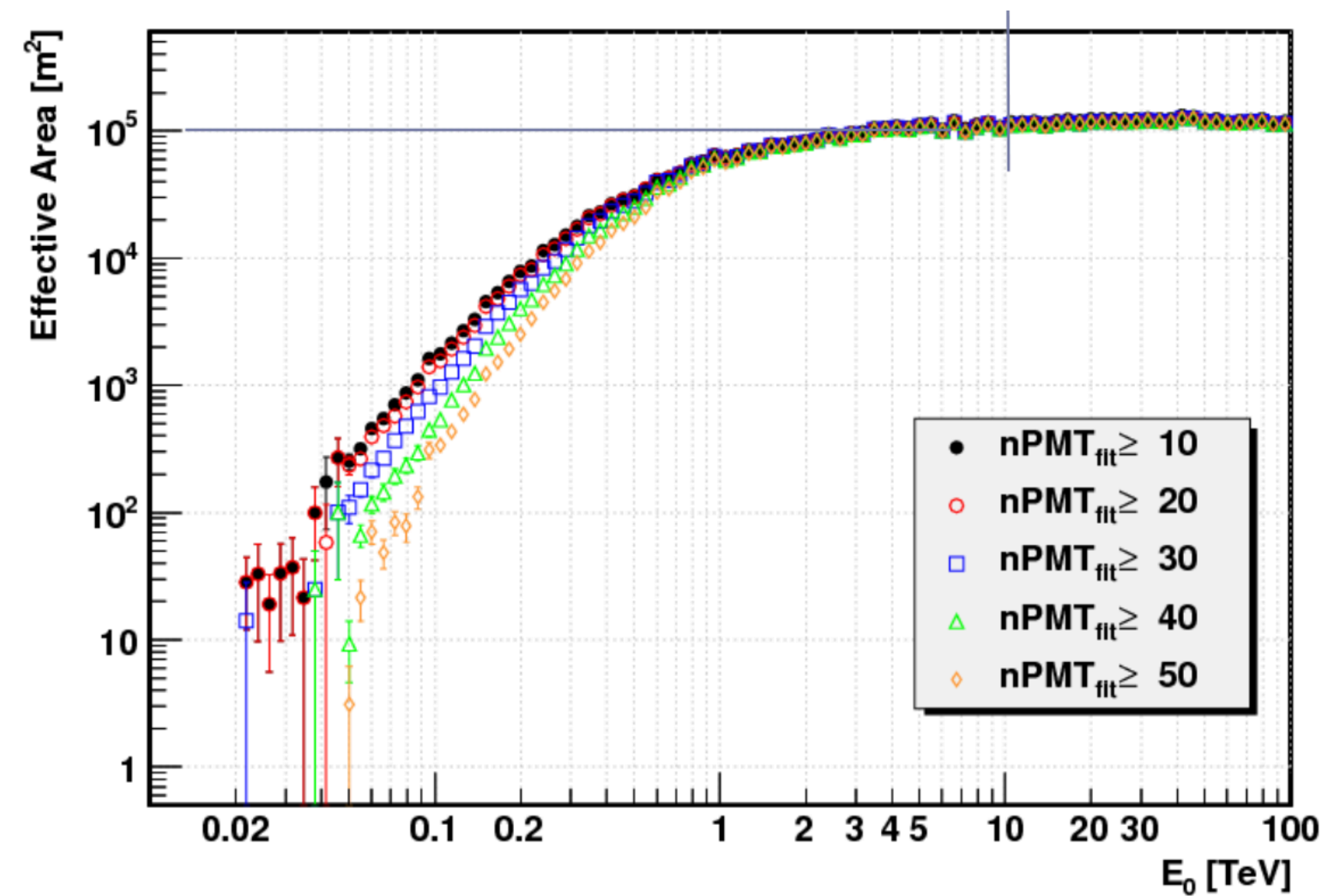
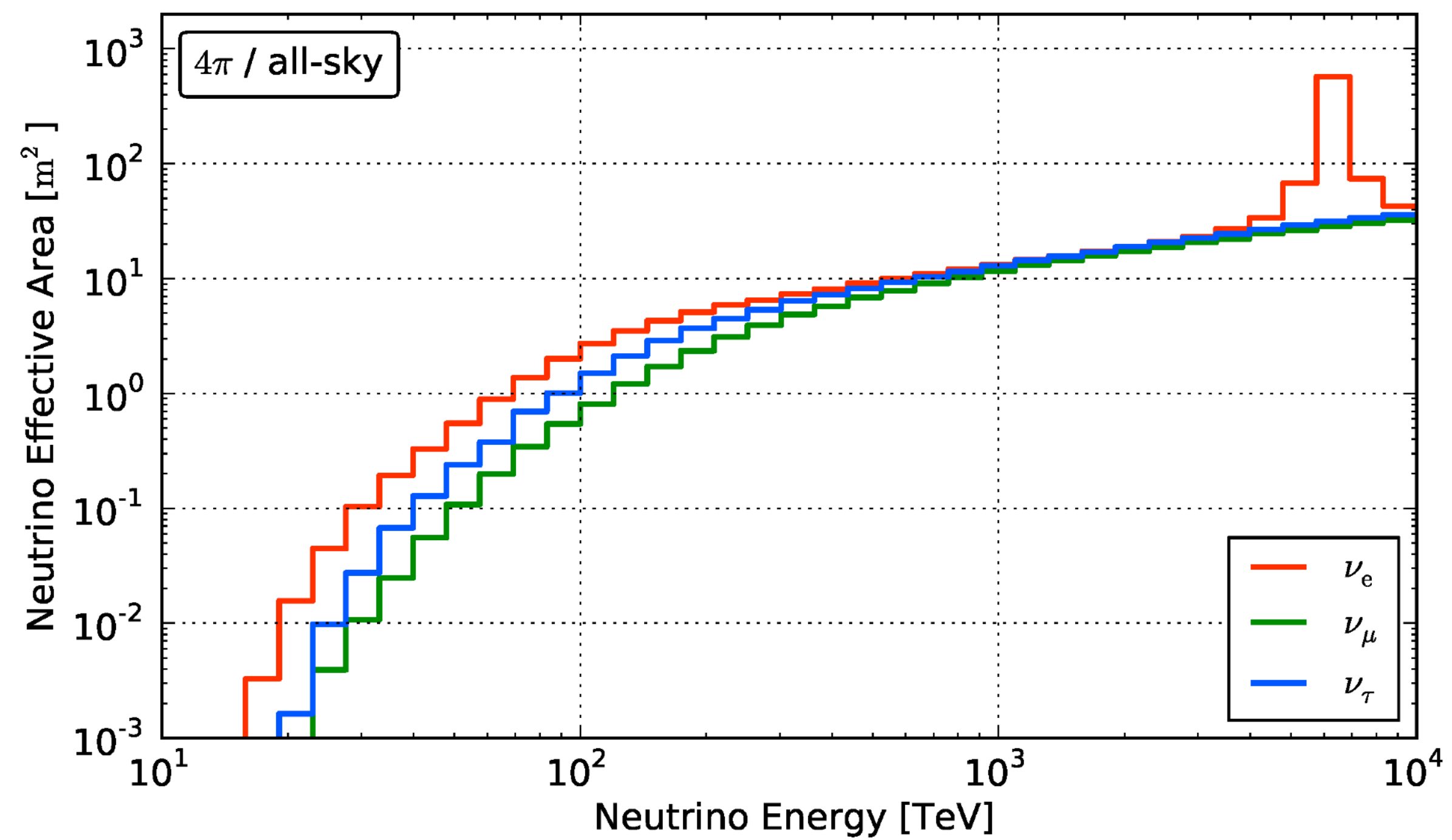
Currently (having used 50 million core hours to generate 7 times more simulated events than measured events and having found no background events from the simulation), our best evaluation of the probability of the background origin for the eight He^- events is **less than 3×10^{-8}** . For the two ${}^4\text{He}^-$ 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 ${}^4\text{He}^-$, 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 ${}^4\text{He}^-$ would be **2×10^{-7}** , i.e., greater than 5-sigma significance.



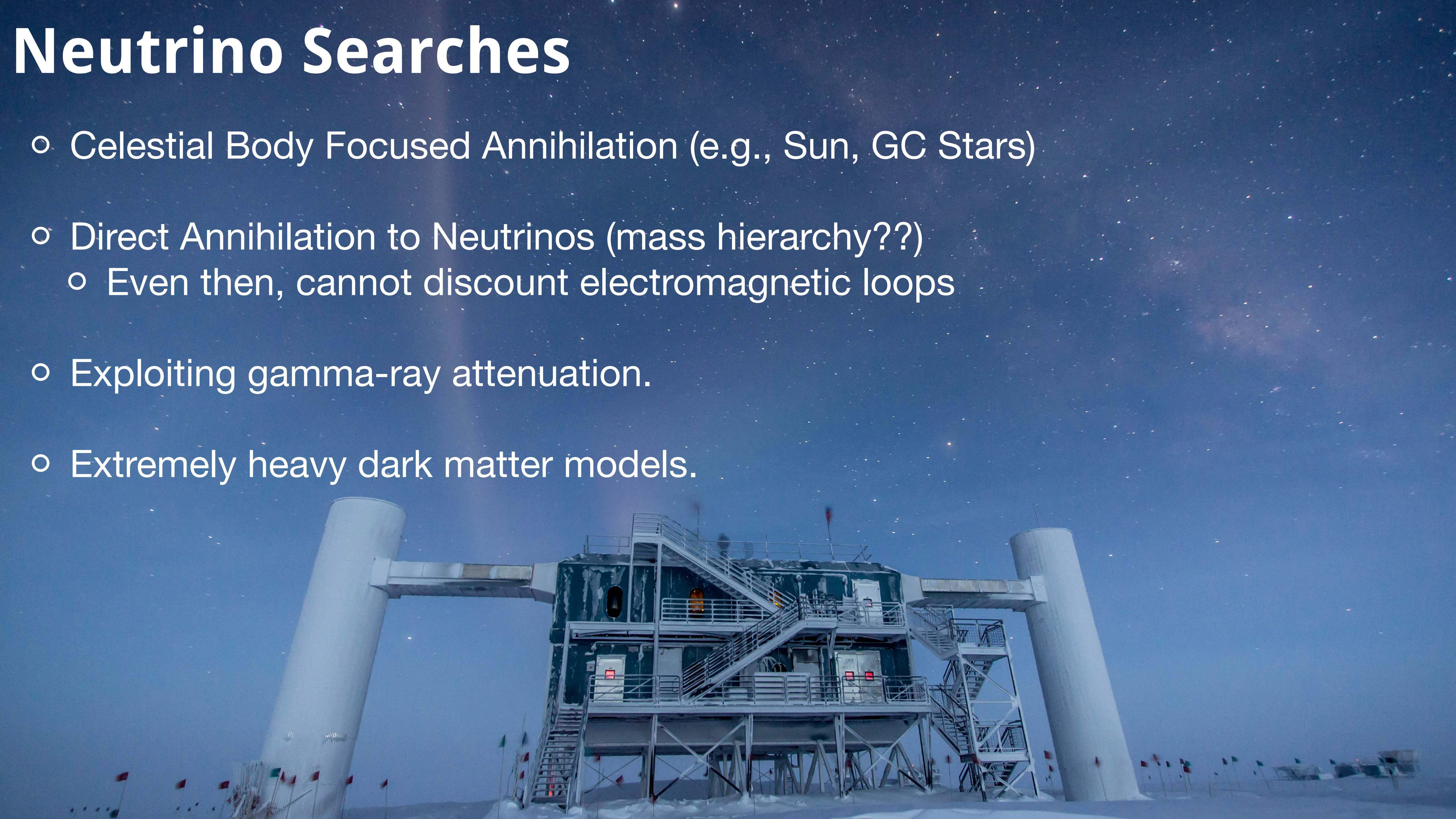






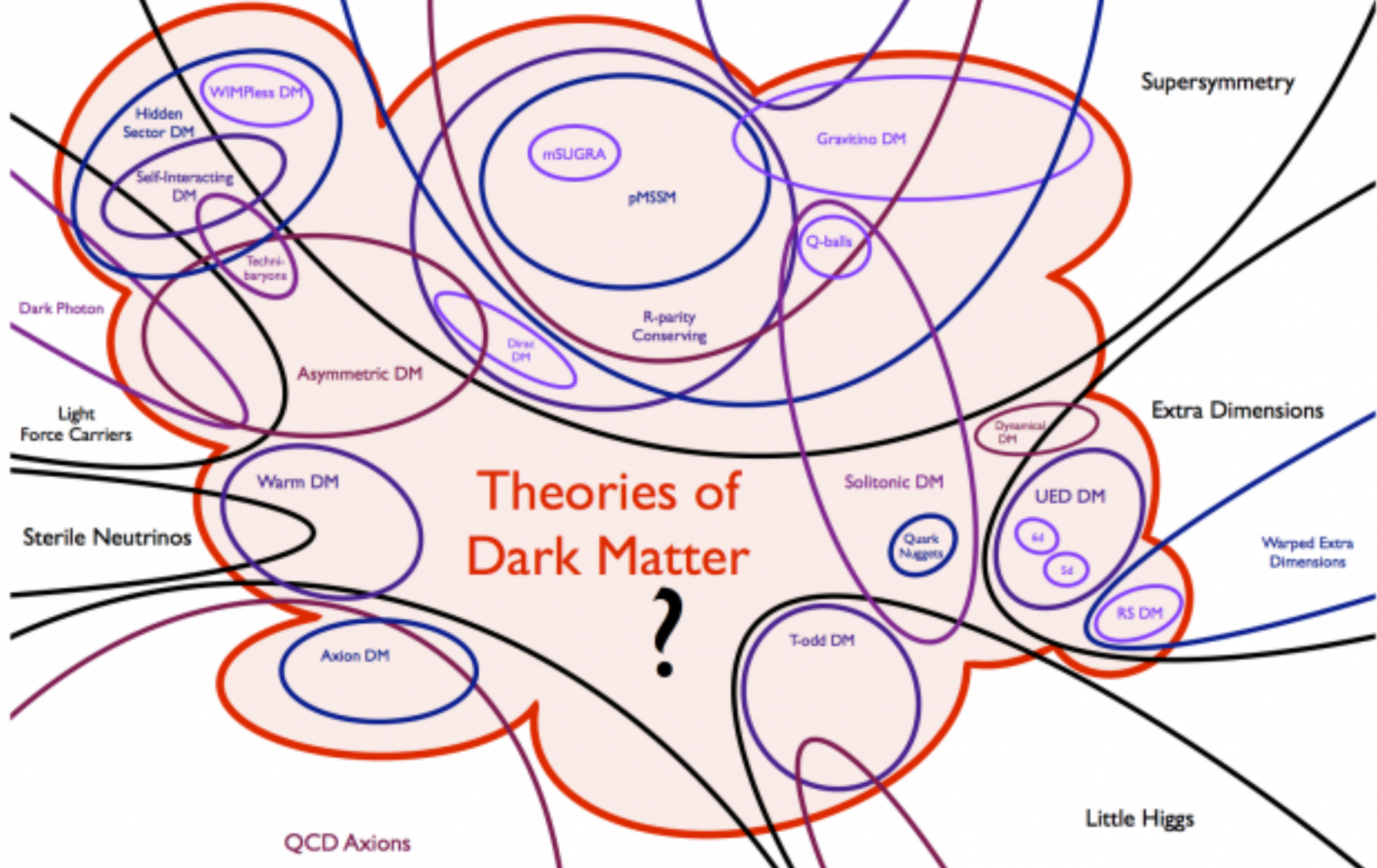
Neutrino Searches

- Celestial Body Focused Annihilation (e.g., Sun, GC Stars)
- Direct Annihilation to Neutrinos (mass hierarchy??)
 - Even then, cannot discount electromagnetic loops
- Exploiting gamma-ray attenuation.
- Extremely heavy dark matter models.



Theories of Dark Matter

?



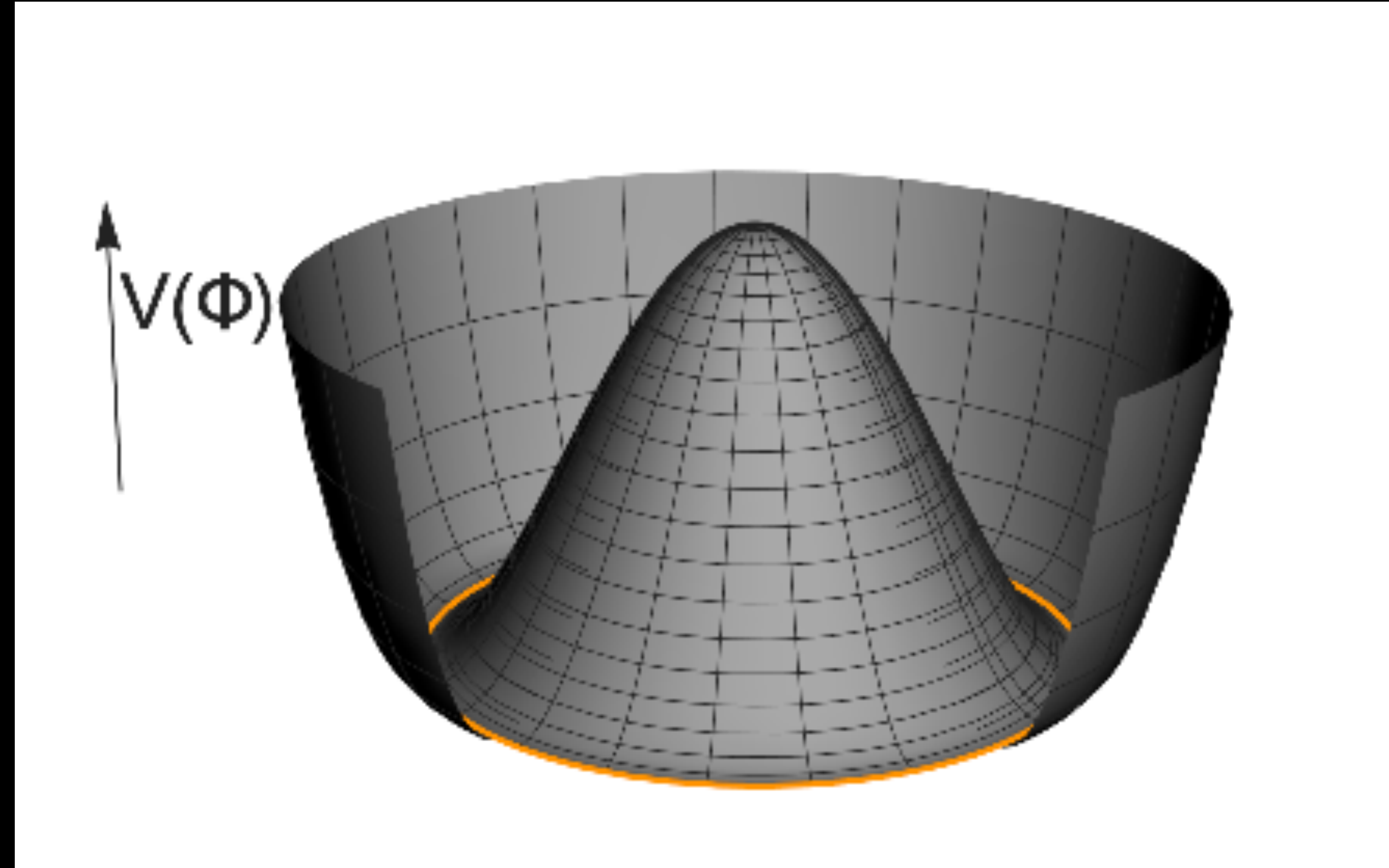
The Pecci-Quinn Mechanism

- QCD Naturally Includes the following CP-violating term:

$$\mathcal{L}_\theta = \bar{\theta} \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu}$$

- Turn theta into a dynamic variable:

$$\mathcal{L} \supset \left(\frac{a(x)}{f_a} + \bar{\theta} \right) \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu}$$



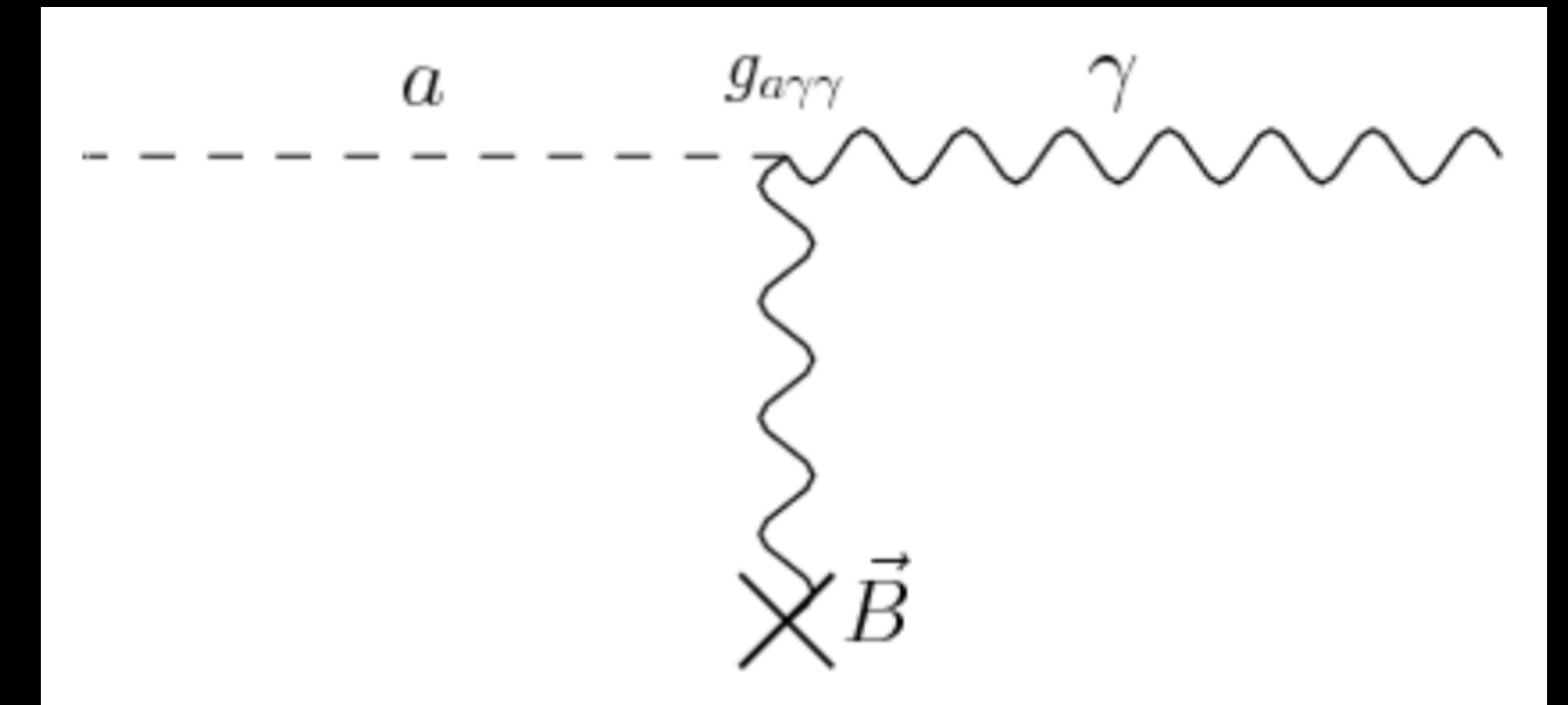
- This naturally introduces a vacuum potential, which wants to fall to 0.

$$V(a) \sim \chi \left(1 - \cos \left(\frac{a}{f_a} + \bar{\theta} \right) \right)$$

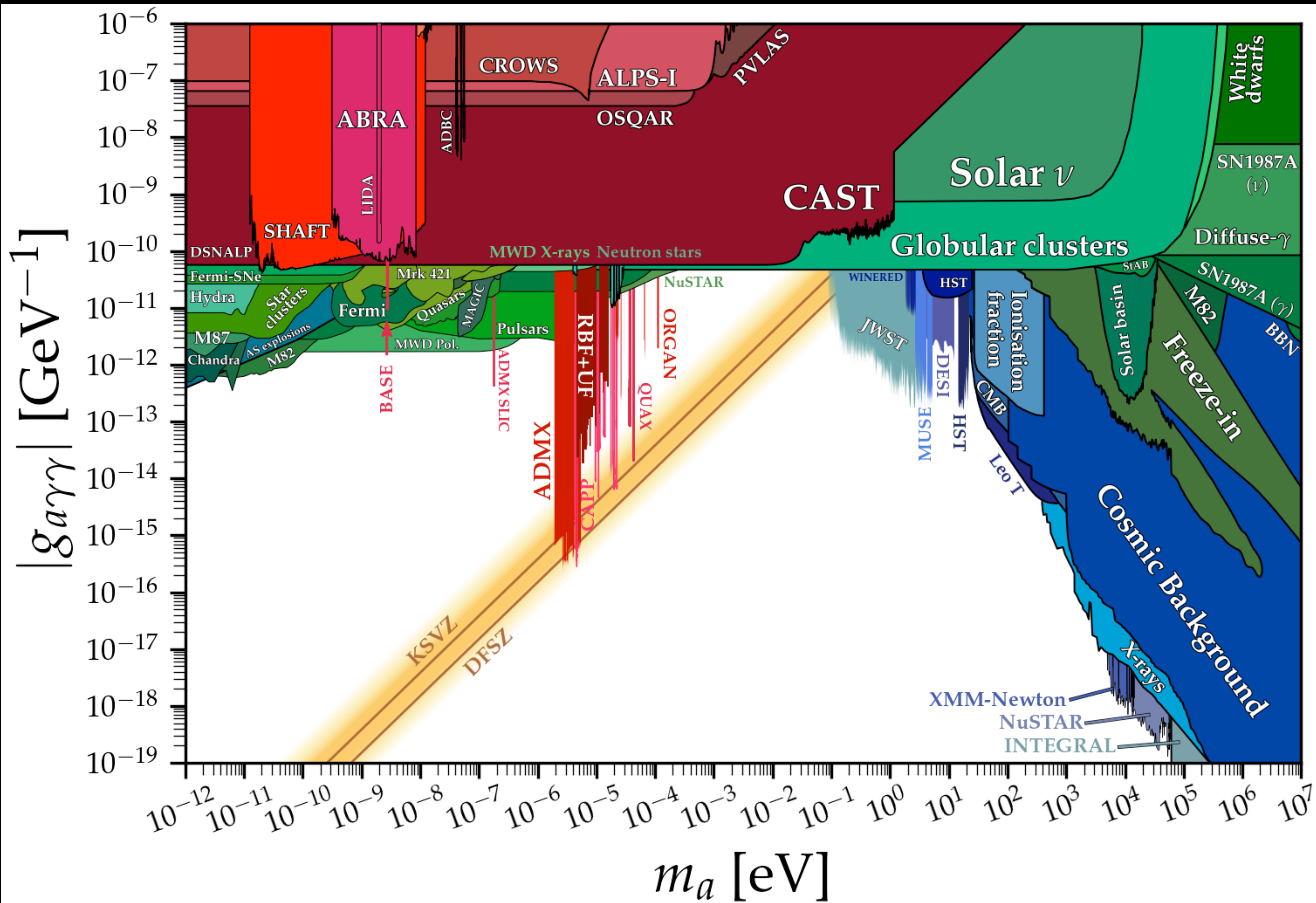
The Pecci-Quinn Mechanism

- The drawback (benefit?) is that this axion term must also couple to electromagnetic fields (photons).

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma} a \vec{E} \cdot \vec{B},$$
$$g_{a\gamma} \simeq \frac{\alpha}{2\pi f_a} \sim 10^{-12} \text{ GeV}^{-1} \left(\frac{10^9 \text{ GeV}}{f_a} \right)$$



- This makes it possible to search for axion to photon conversion in the universe today.





electron
neutrino



muon
neutrino



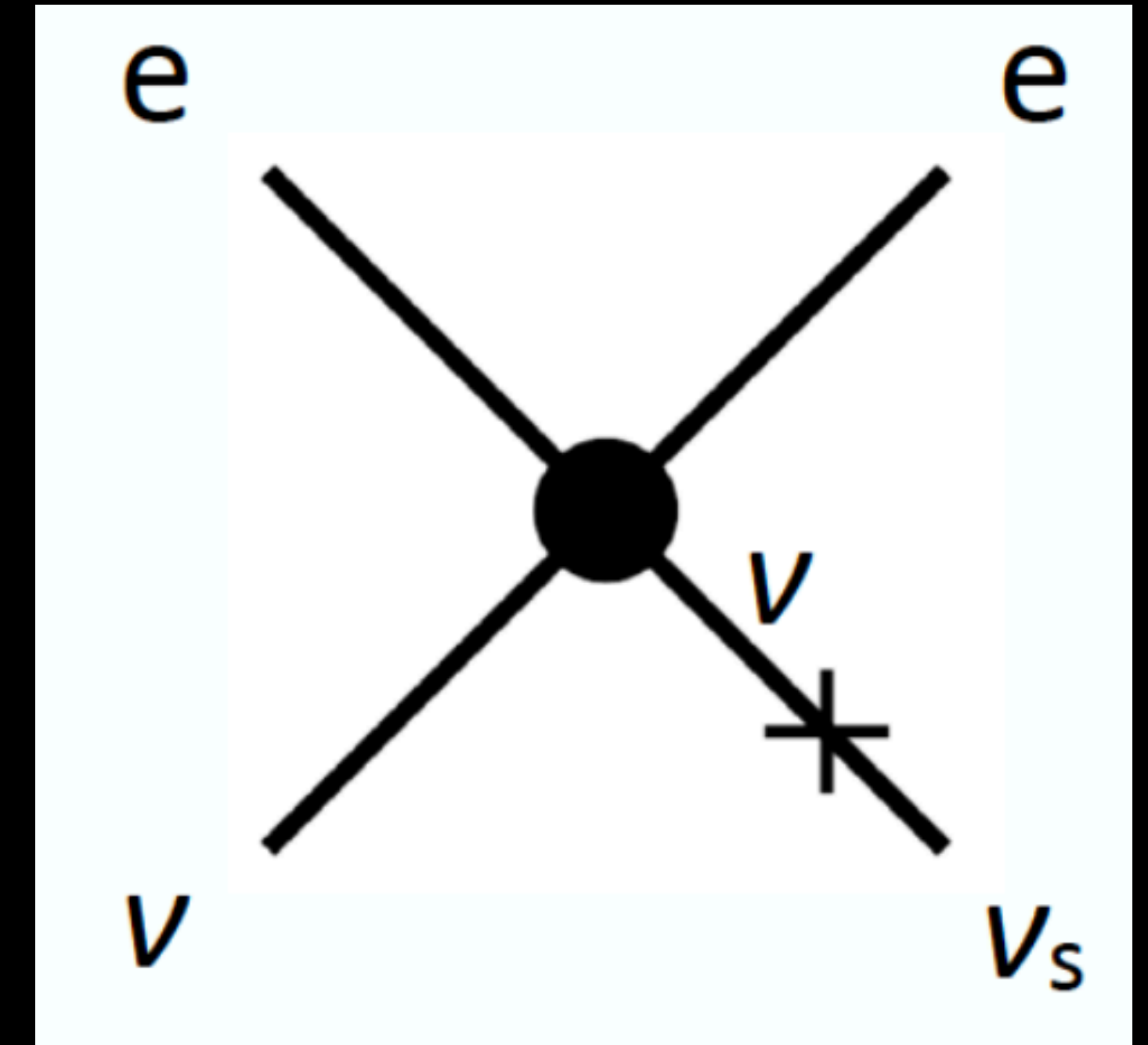
tau
neutrino



sterile
neutrino

The Dodelson-Widrow Mechanism

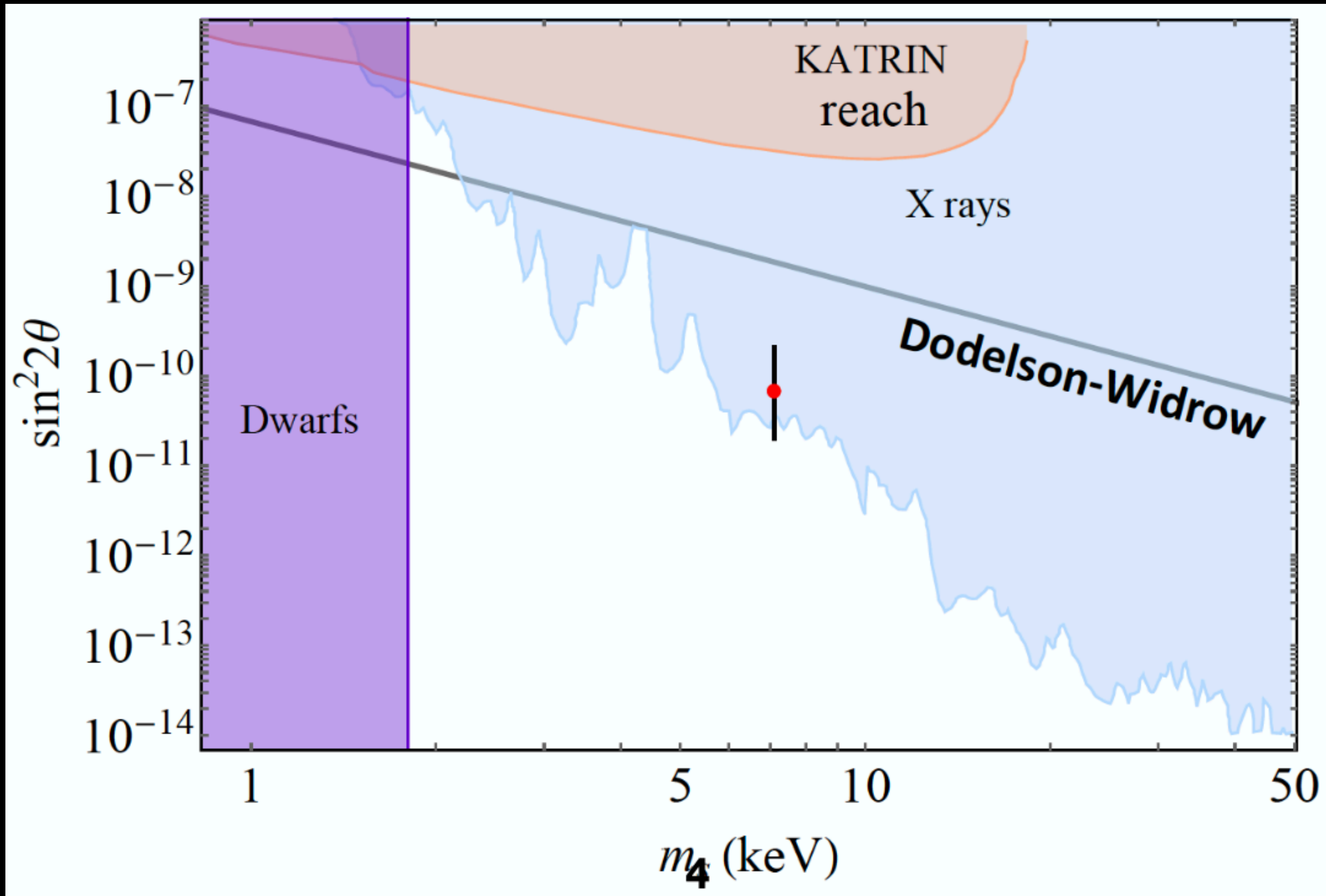
- Add a 4th generation of neutrinos (right-handed, solving the right/left handed neutrino problem).
- Can also be correlated to leptogenesis.
- Sterile neutrino cannot be in thermal equilibrium, but active neutrinos can be - and can oscillate to sterile neutrinos with amplitude $\sin^2(\theta_4)$



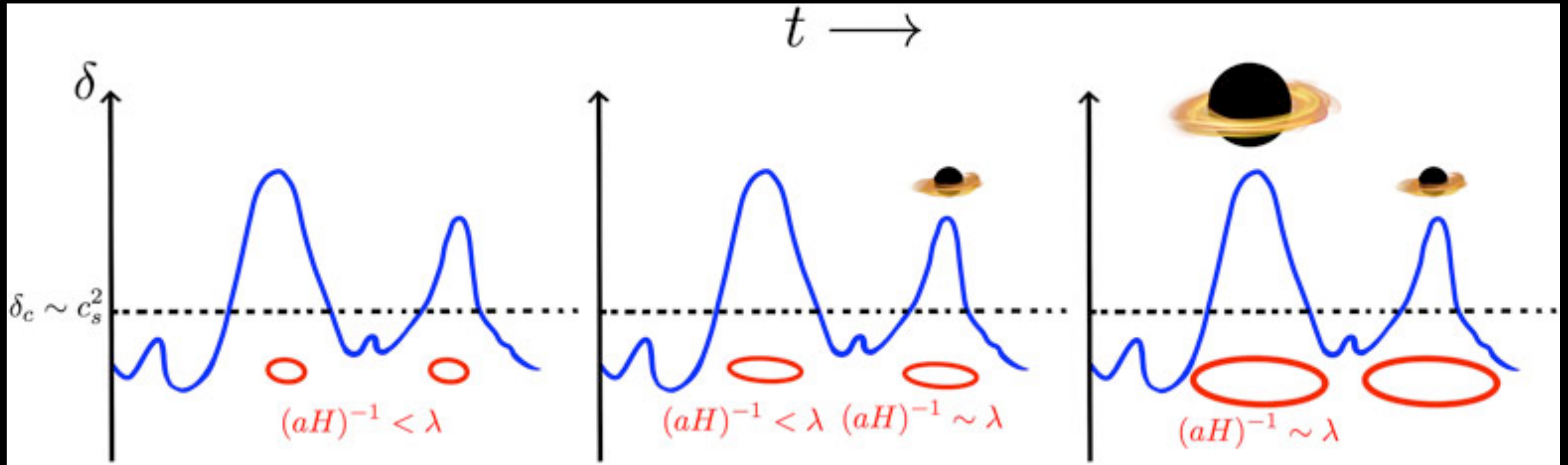
$$\langle P(\nu_a \rightarrow \nu_s) \rangle = \frac{1}{2} \frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + \frac{\Gamma_a^2}{4} + (\Delta \cos 2\theta - V)^2}$$

Averaged over one mean free path
 $\Delta = m_s^2/2E$
 Quantum Zeno damping
 Matter potential $V = V_T + V_D$

The Dodelson-Widrow Mechanism



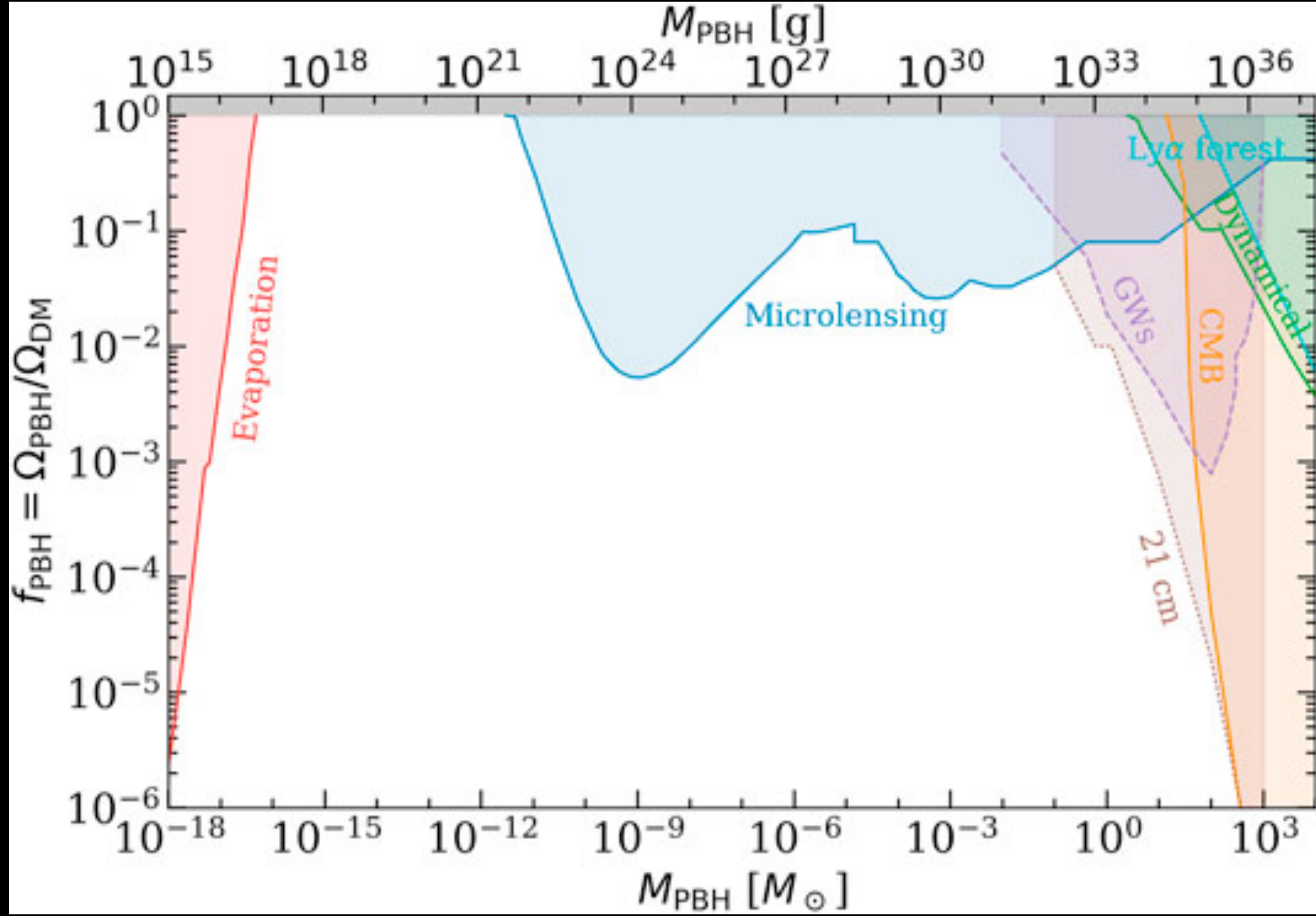
Primordial Black Holes



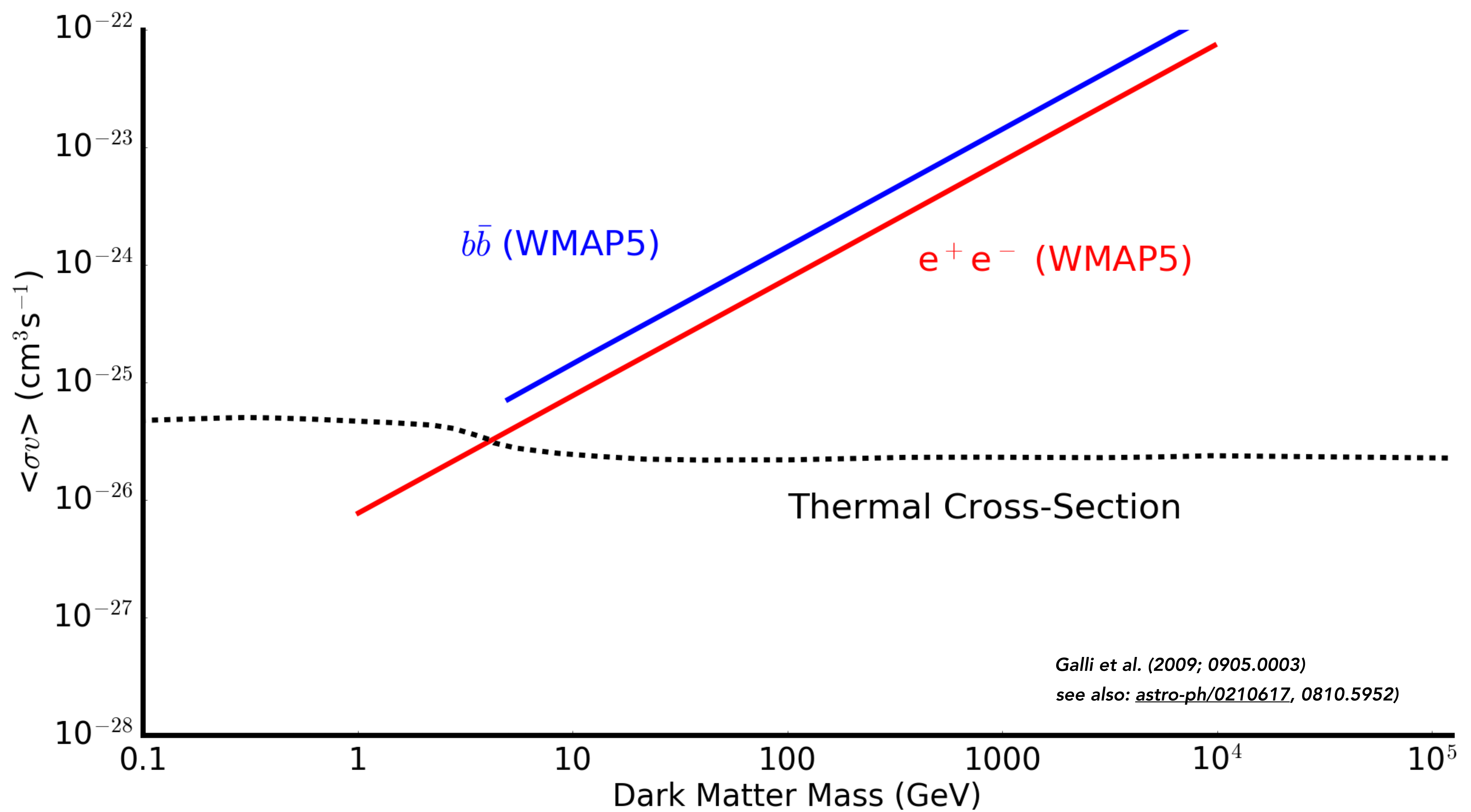
- Density Perturbations in the Early Universe Could Collapse into BHs with masses that are related to the mass inside a Hubble radius at the time of their formation:

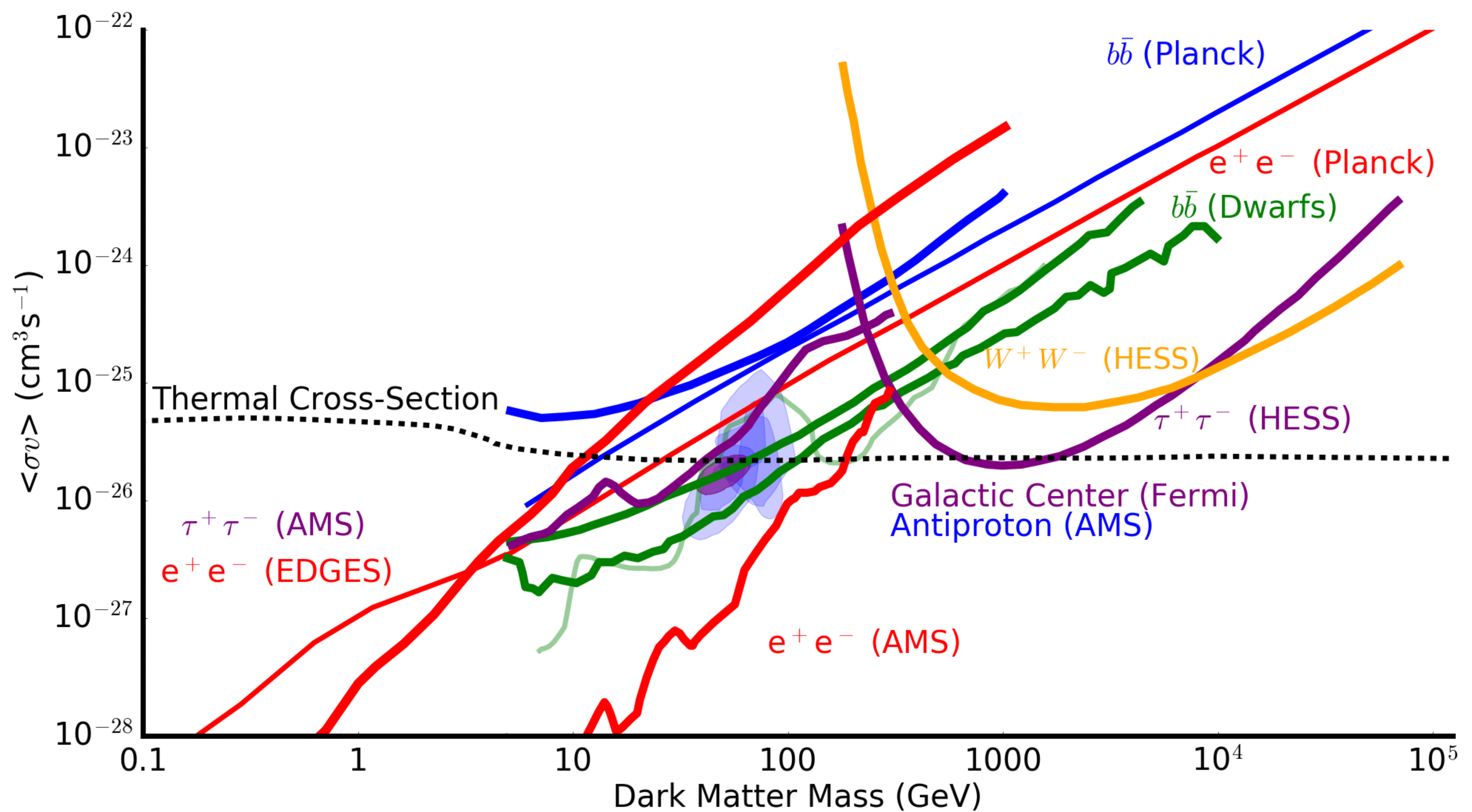
$$M_H = \frac{4}{3} \bar{\rho} \left(\frac{c}{H} \right)^3 = \frac{c^3}{2GH} \sim 10^{15} \text{ g} \left(\frac{t}{10^{-23} \text{ s}} \right)$$

- Formation details dependent on radiation/matter domination during that time.



WHERE
ARE
WE NOW?







And the (TeV) future is bright!