Fundamental Physics with TeV Gamma Rays

Stockholm University

Tim Linden

The Waning of the WIMP: Endgame?

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Received: date / Accepted: date

SI DM-Nucleon Cross-section (cm^2)
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
Xenon 100 (2012)
Neutrino Fog
0.01
0.1
1
10
Dark Matter Mass (TeV)

SI DM-Nucleon Cross-section (cm^2)
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
Xenon 100 (2012)
LZ (2022)
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0.01
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DARWIN (2032)
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10
Dark Matter Mass (TeV)


VERITAS Segue I 2012
VERITAS Collaboration
1202.2144
Fermi-LAT 2013
Fermi-LAT Collaboration
1310.0828
Thermal Cross-Section
Steigman et al. 2012
1204.3622
Annihilation Cross-Section $<\sigma v>$
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10
100
1000
10^4
Energy (GeV)

Annihilation Cross-Section $< \sigma v >$
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
H.E.S.S. Reticulum II 2020
H.E.S.S. Collaboration
2008.00688
VERITAS Segue I 2012
VERITAS Collaboration
1202.2144
Fermi-LAT 2013
Fermi-LAT Collaboration
1310.0828
Fermi-LAT 2023
McDaniel et al.
2309.04982
Thermal Cross-Section
Steigman et al. 2012
1204.3622
10
100
1000
10^4
Energy (GeV)

Waning of the WIMP?

Arcadi et al. (2024; 2403.15860)

- These conclusions are strengthened when specific models are considered.
- The TeV frontier is the new home for WIMP phenomenology.

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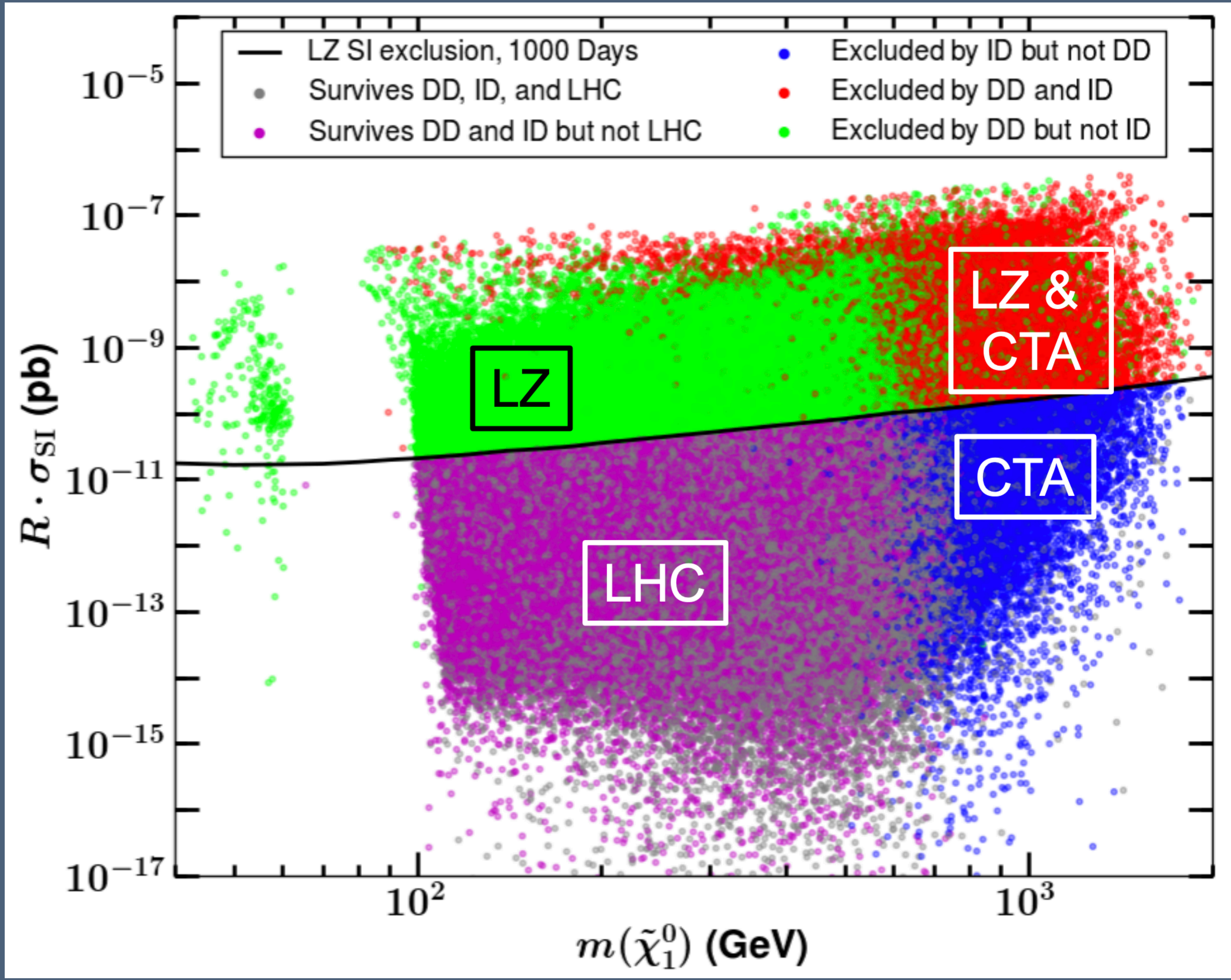
Waning of the WIMP?

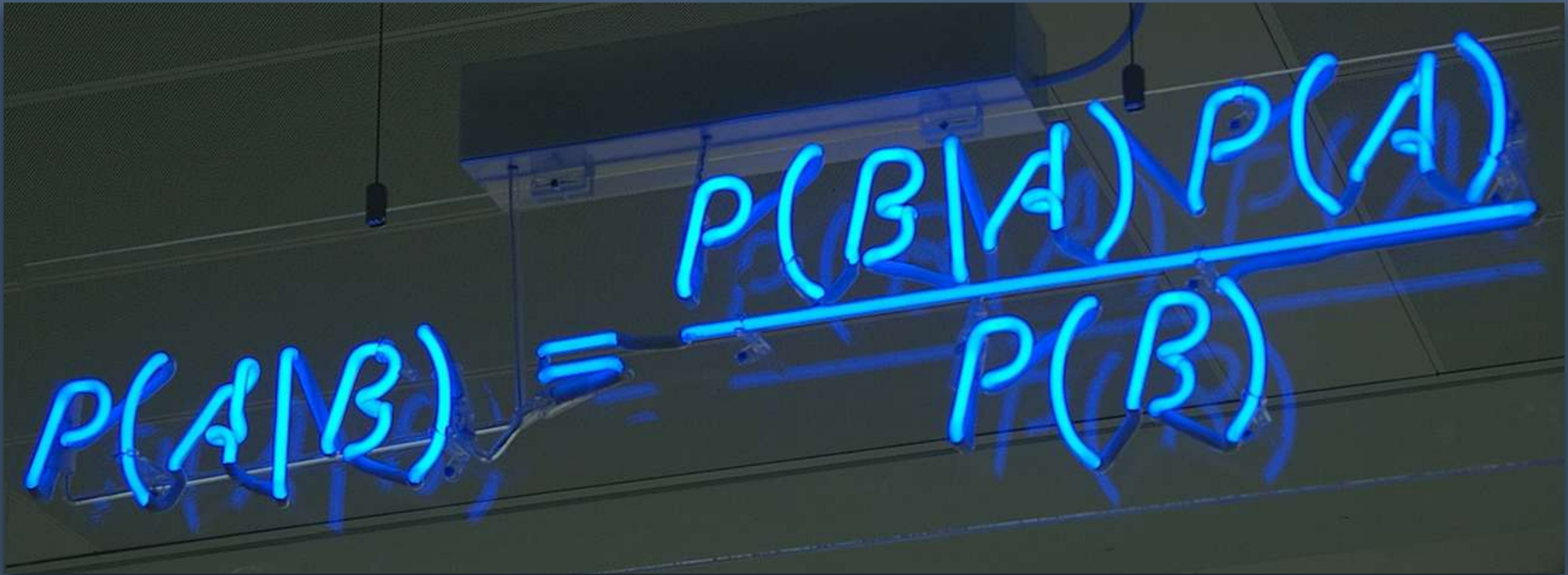
Cahill-Rawley et al. (2014; 1405.6716)

- This is also true within the context of pMSSM models. The regions where the lightest supersymmetric particle is heavy are primarily probed by CTA.

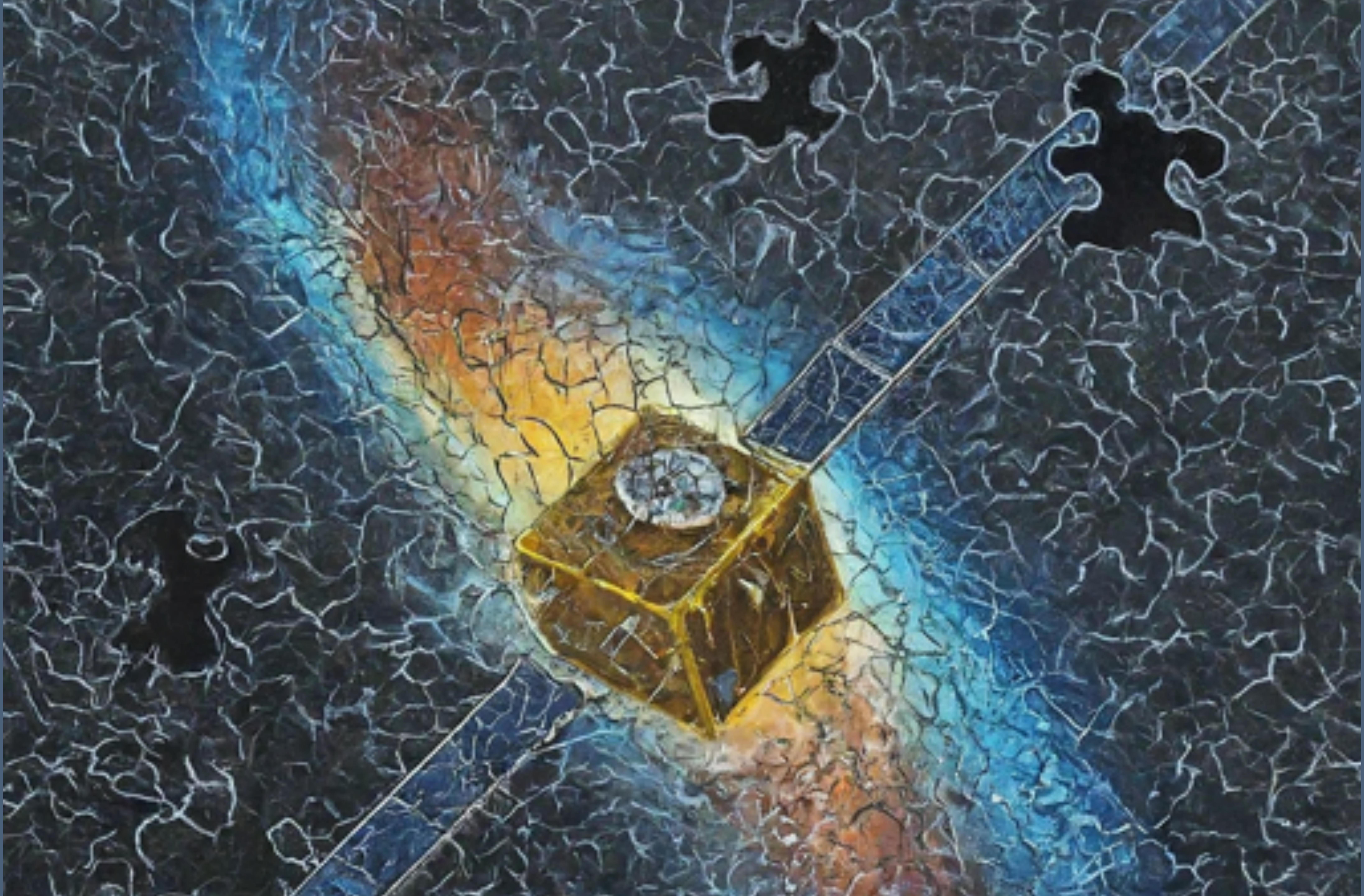
- Note: Fermi-LAT GeV searches are barely on this plot — <u>CTA is a unique DM detection instrument.</u>



Bayesian Analysis



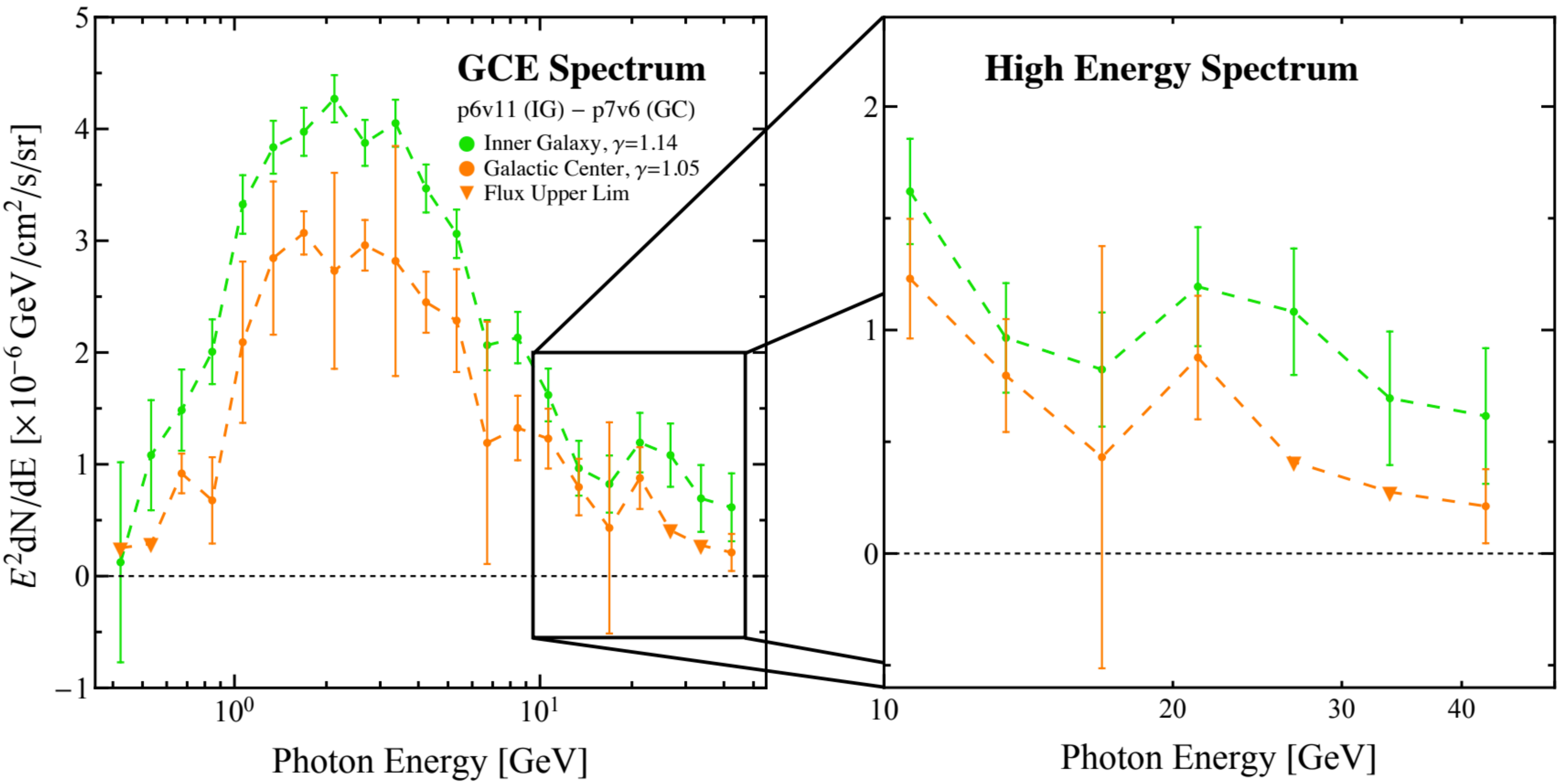
- Strong limits on GeV dark matter do two things:
  - Increase likelihood that dark matter is not a WIMP
  - Increase likelihood that dark matter is a TeV WIMP




Dark matter
annihilation
Stars in the
Galactic bulge

Galactic Center Excess

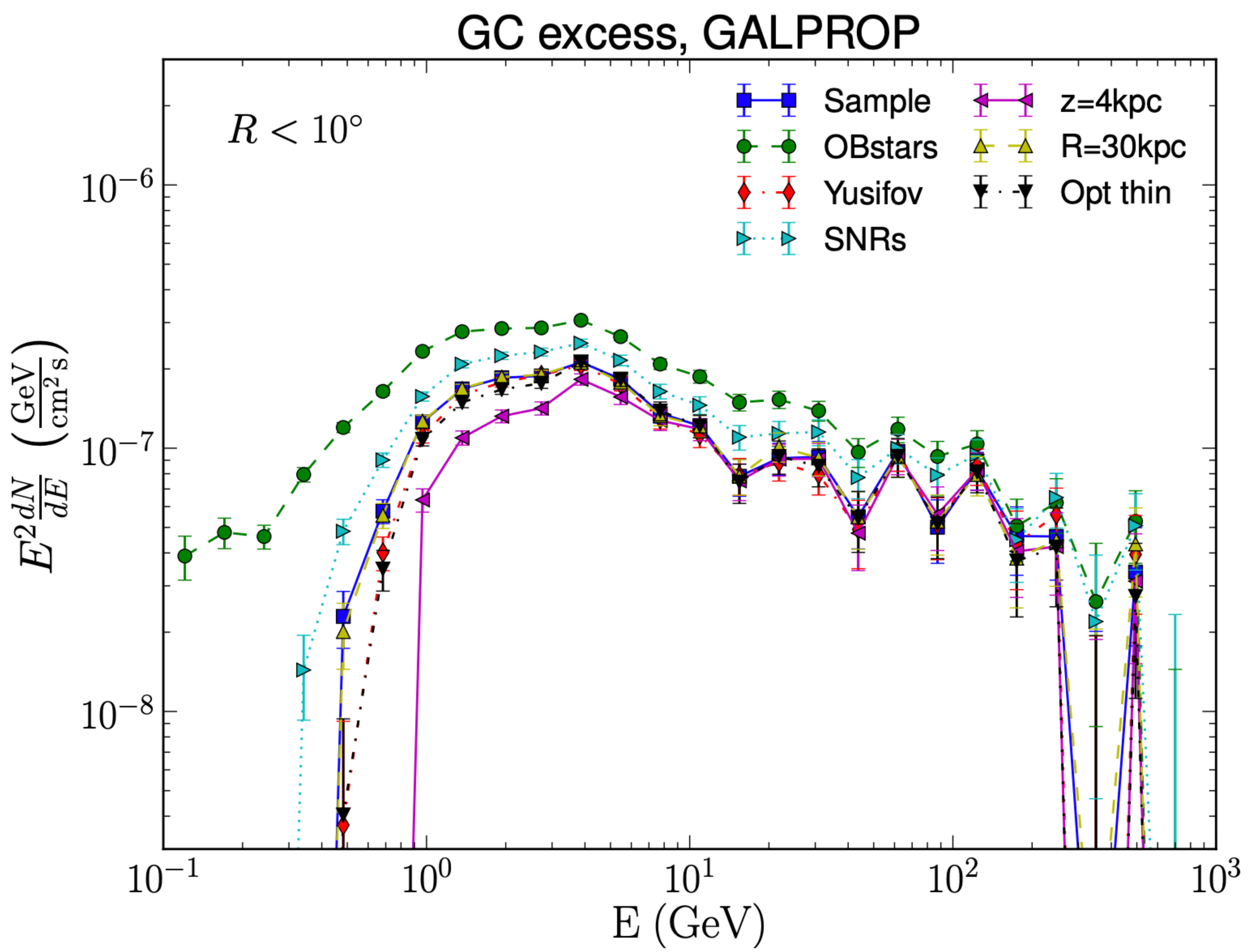
Linden et al. (2016; 1604.01026)




extragalactic gamma-ray background
interstellar emission from the galactic disk
Cygnus X
interstellar emission from the Orion molecular clouds

Galactic Center Excess

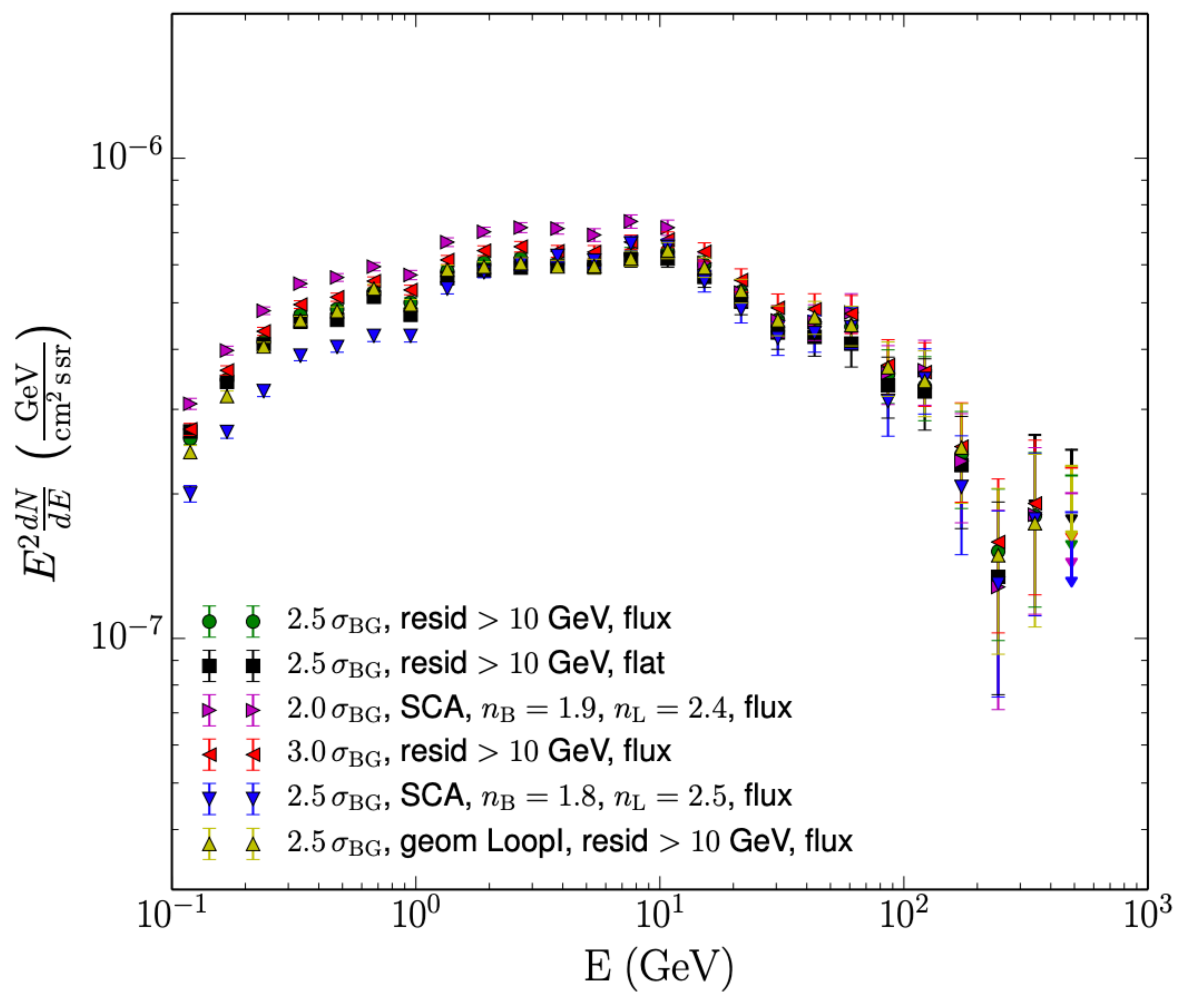
Fermi-LAT Collaboration (2017; 1704.03910)



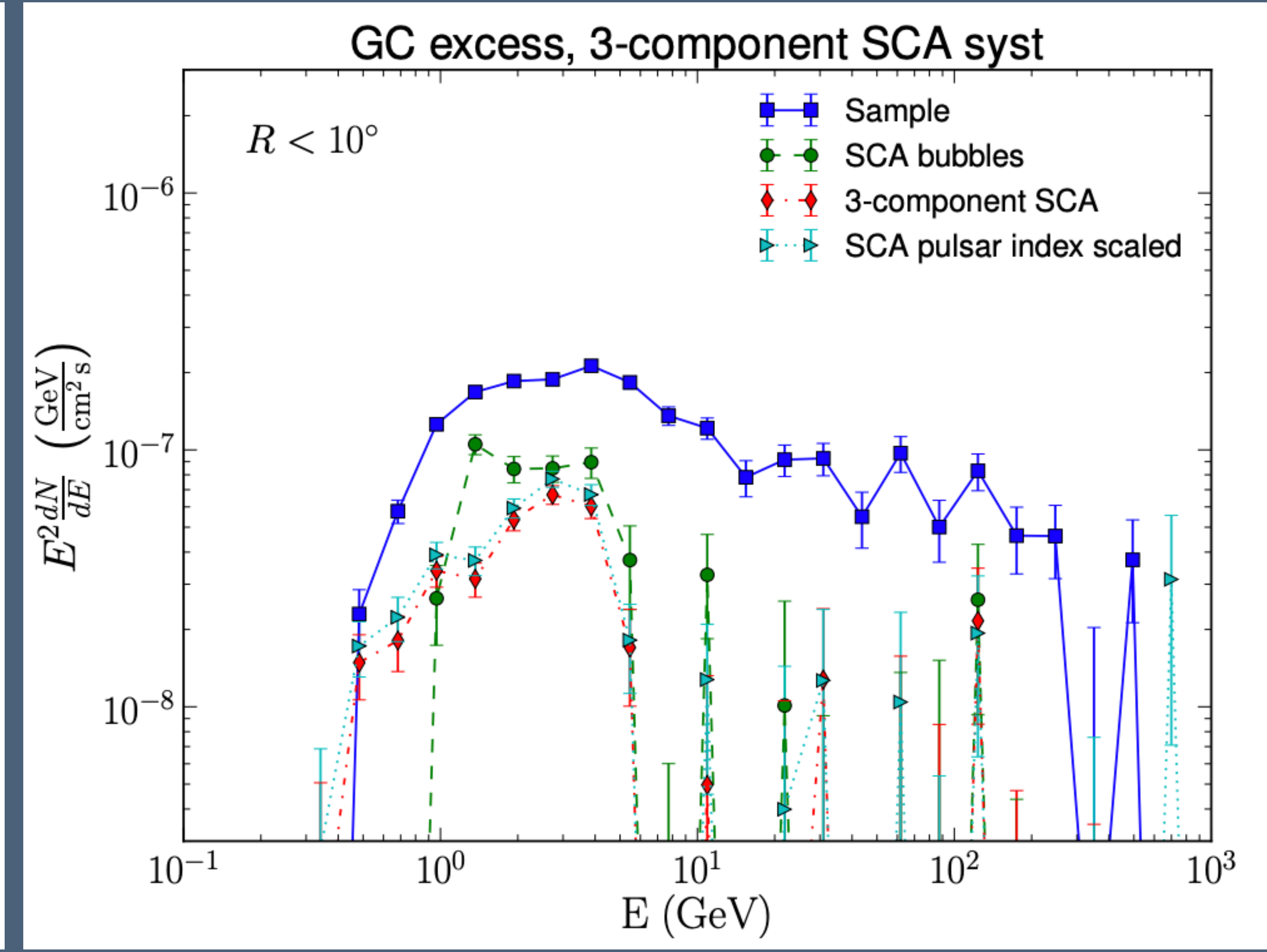
Fermi Bubbles

Fermi Bubbles

Fermi-LAT Collaboration (2014; 1407.7905)



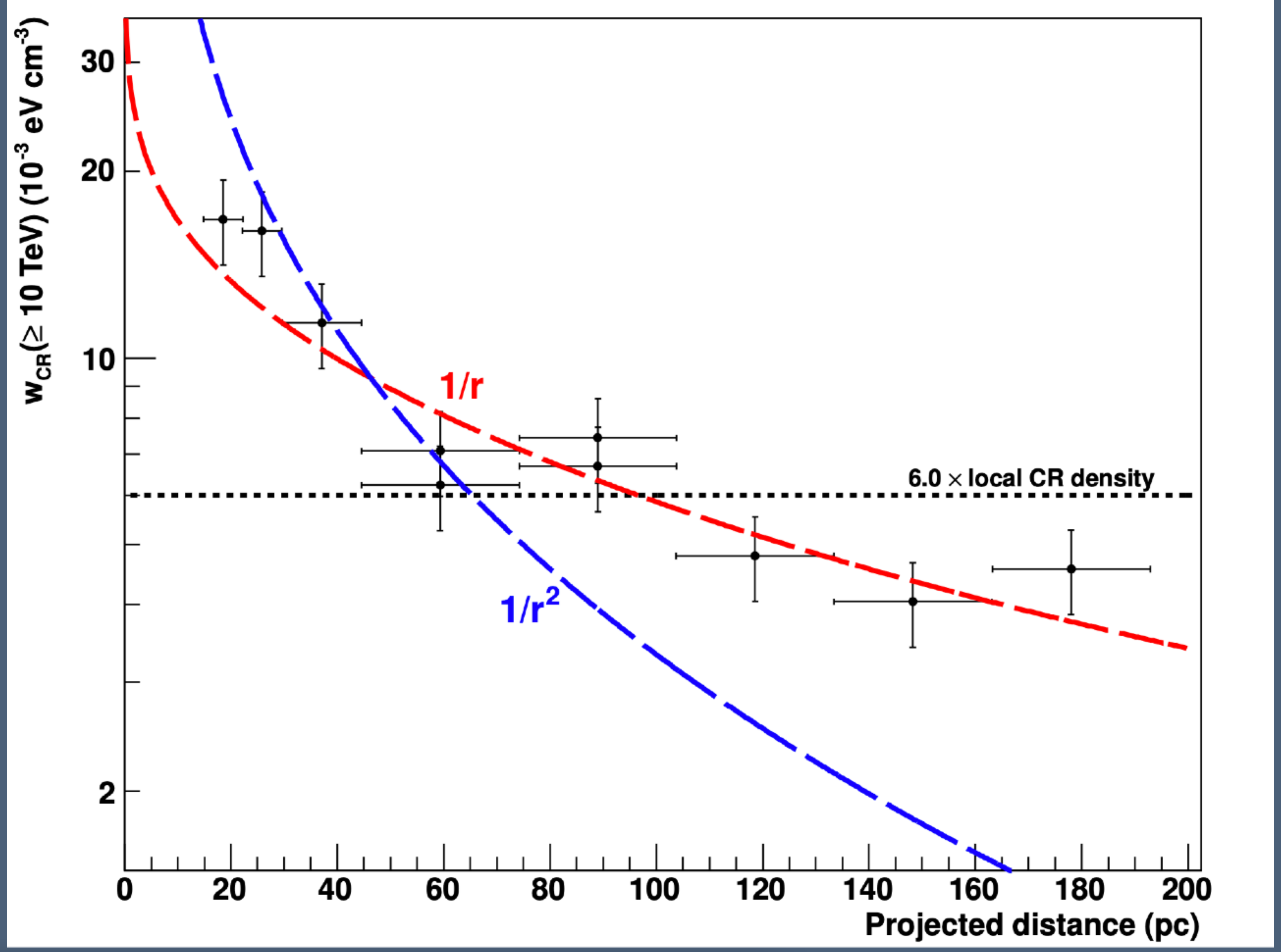
Fermi-LAT Collaboration (2017; 1704.03910)

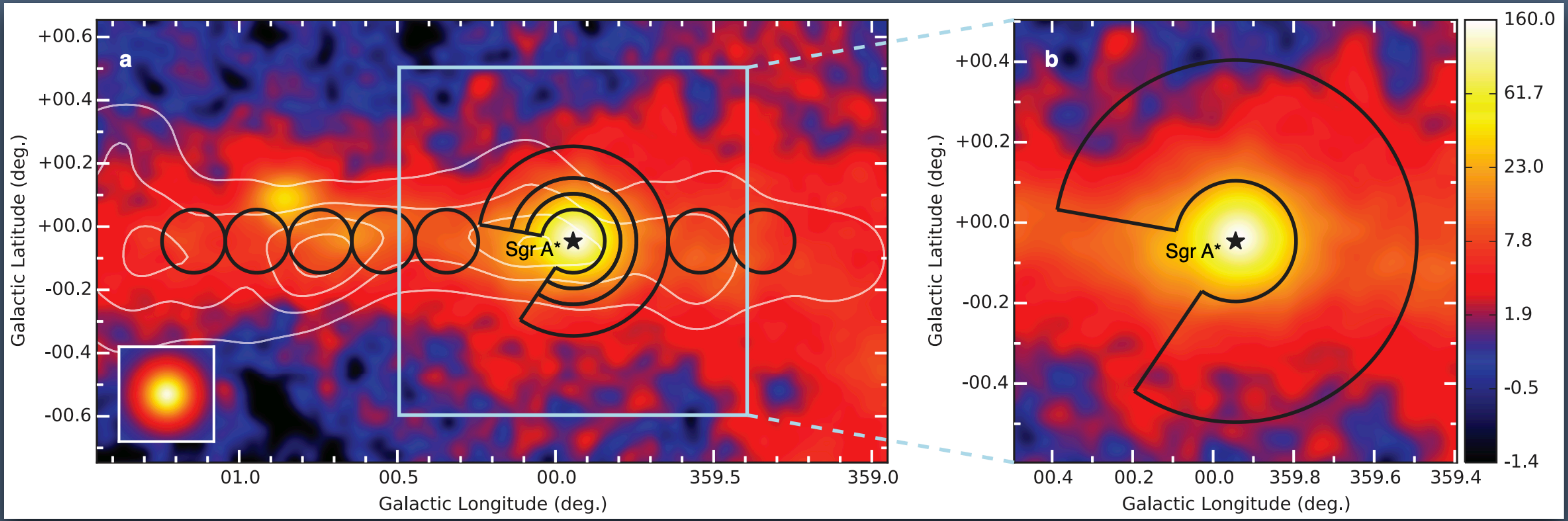


Galactic Center Excess

- Relevance of TeV Observations:
  - Potential High-Energy Tail in the GeV Excess
  - Understanding Diffuse Emission Models
  - Modeling the Fermi Bubbles
  - Star-Formation in the Galactic Center

H.E.S.S. Collaboration (2016; 1603.07730)





TeV Halos

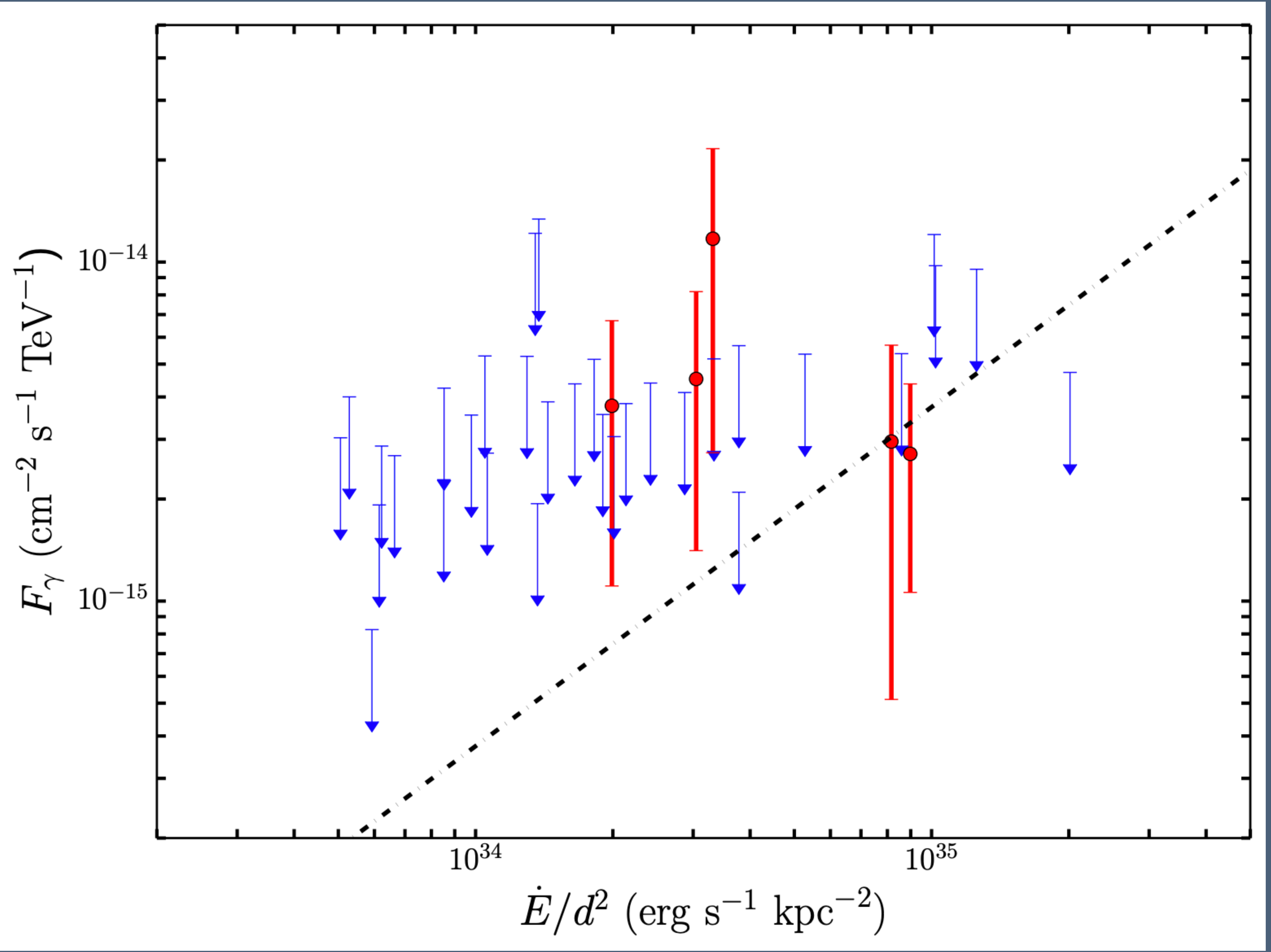

Geminga
Pulsed Emission
Fermi Collaboration
1007.1142
Fermi-LAT Halo
Di Mauro et al.
1903.05647
HAWC Halo
HAWC Collaboration
1711.06223
HESS Halo (<1°)
HESS Collaboration
2304.02631
SNR
(hadronic/leptonic)
TeV Halo
(escaped e⁺e⁻)
PWN
(confined e⁺e⁻)
E² Flux (10⁻¹⁰ erg cm⁻² s⁻¹)
Energy (GeV)

MSP halos and the GCE

Hooper & Linden (2021; 2104.00014)

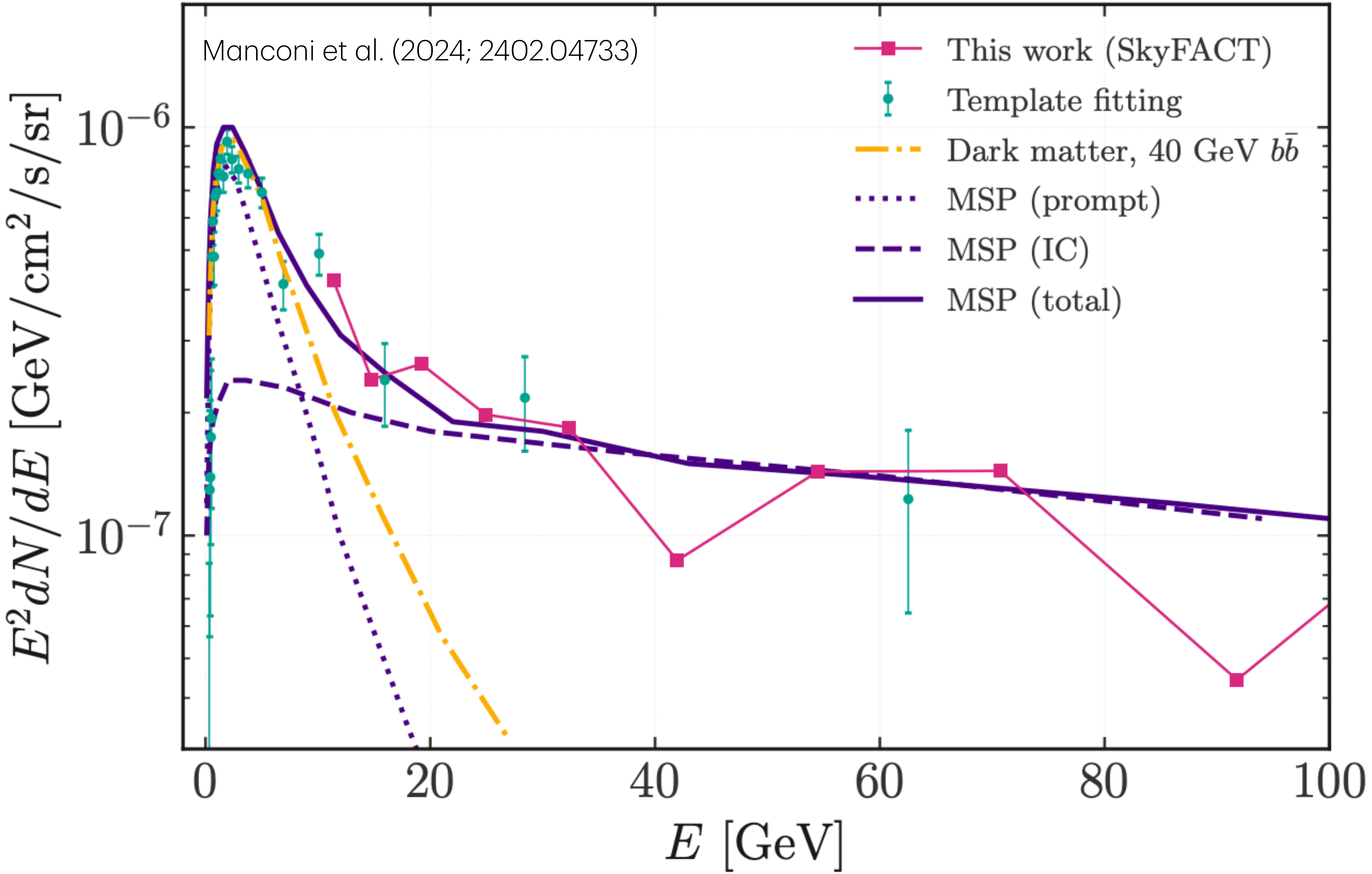
- Potential evidence that some MSPs host TeV halos
  - Important from evolutionary perspective because SNR energetics not important
  - Could produce large population of TeV halos in the Galactic Center

- **For GCE - TeV halo nature is not as important as the principle that MSPs also accelerate ~10% of spin down power into e+e- pairs.**



LHAASO Collaboration (2023; 2305.17030)

1LHAASO J0216+4237u	0.33	ATNF PSR J0218+4232	$\dot{E} = 2.44 \times 10^{35}$ erg s^{-1},$\tau_c = 476000.0$ kyr,$d = 3.15$ kpc
	0.33	4FGL J0218.1+4232	PSR J0218+4232;MSP;

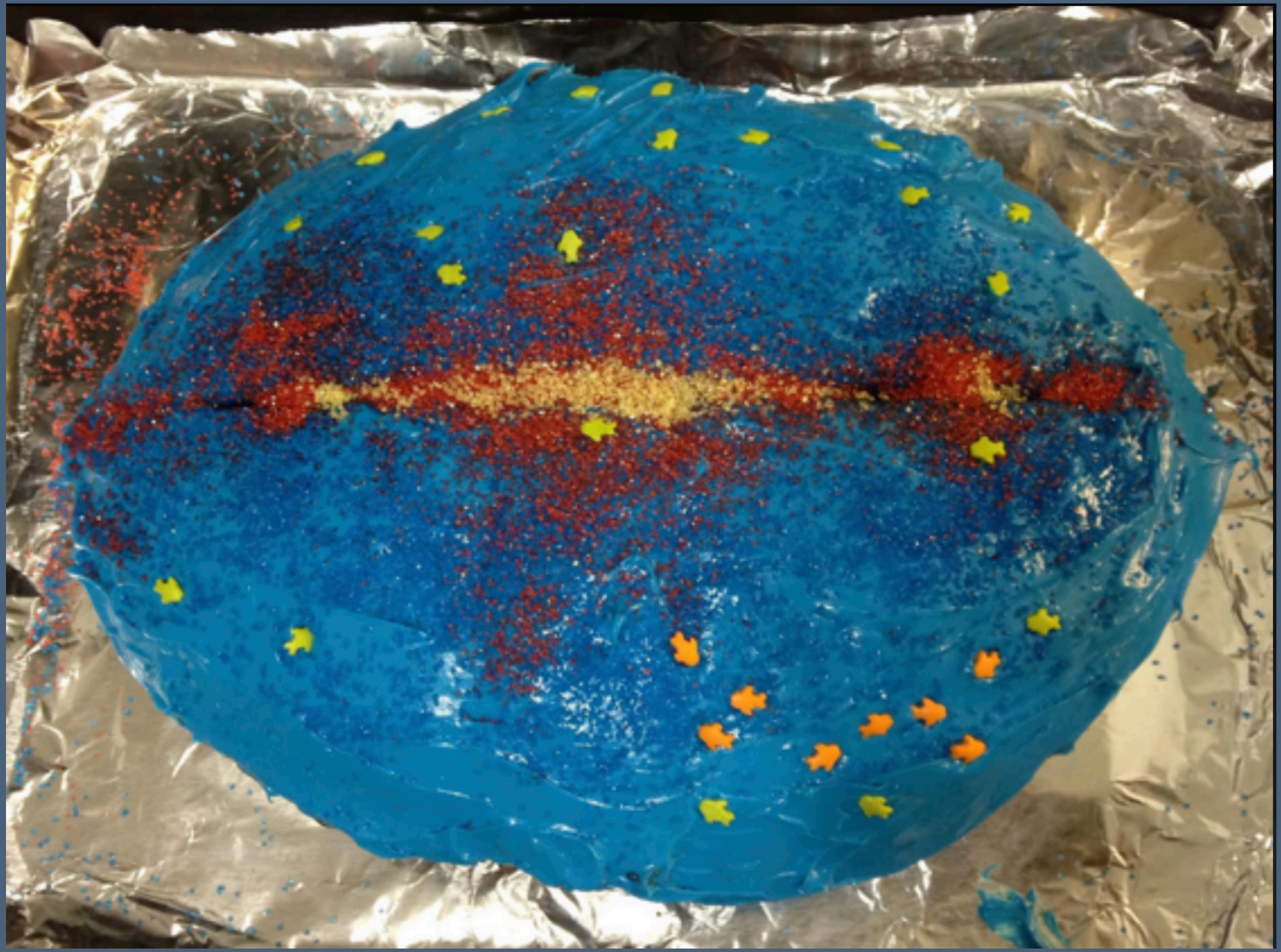


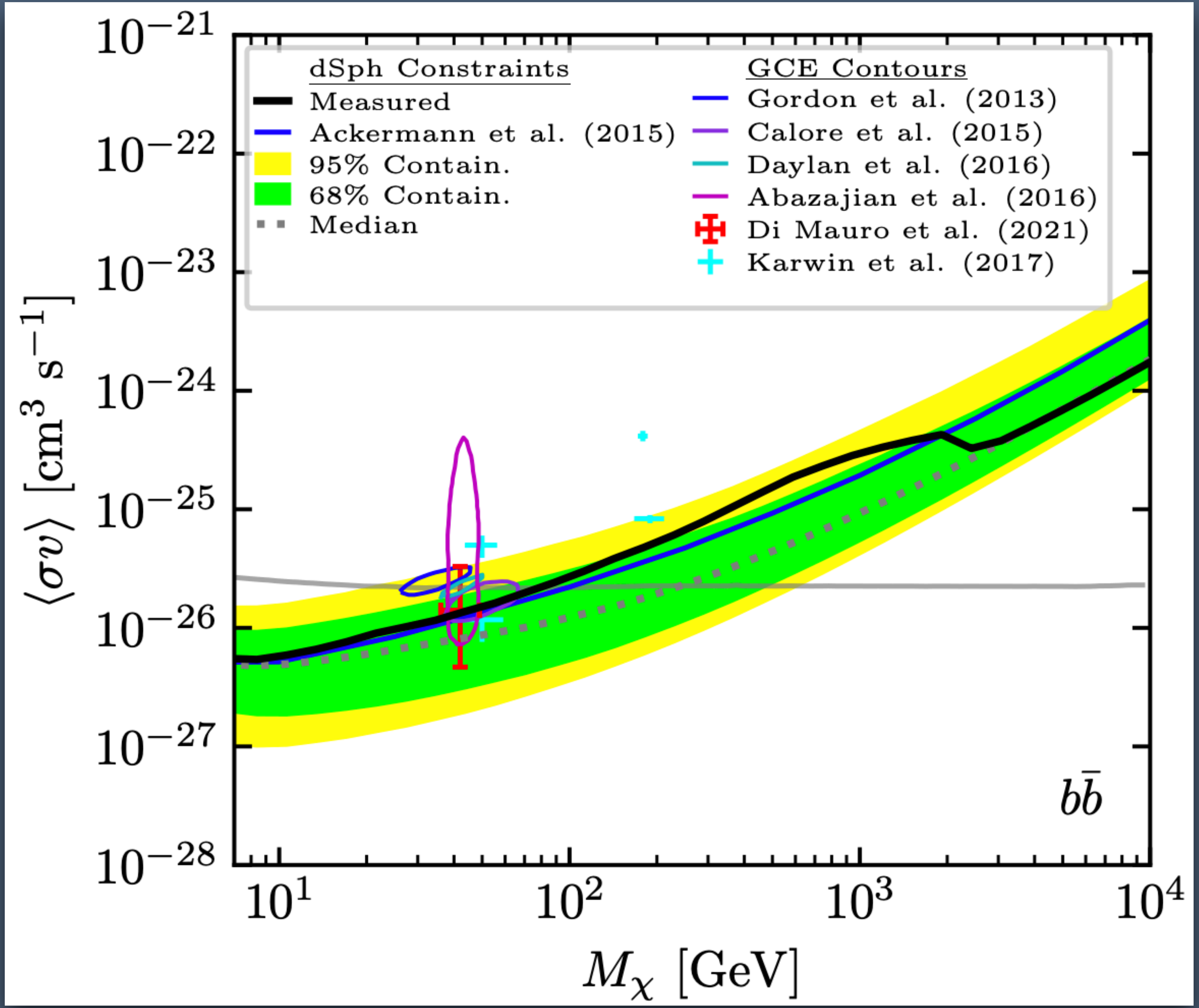
Manconi et al. (2024; 2402.04733)
This work (SkyFACT)
Template fitting
Dark matter, 40 GeV $b\bar{b}$
MSP (prompt)
MSP (IC)
MSP (total)
10^{-6}
10^{-7}
$E^2 dN/dE$ [GeV/cm^2/s/sr]
0
20
40
60
80
100
E [GeV]

Dwarf Searches

McDaniel et al. (2023; 2311.04982)

- Population of dwarf spheroidal galaxies have set strong limits on GeV dark matter annihilation.





Dwarf Searches

McDaniel et al. (2023; 2311.04982)

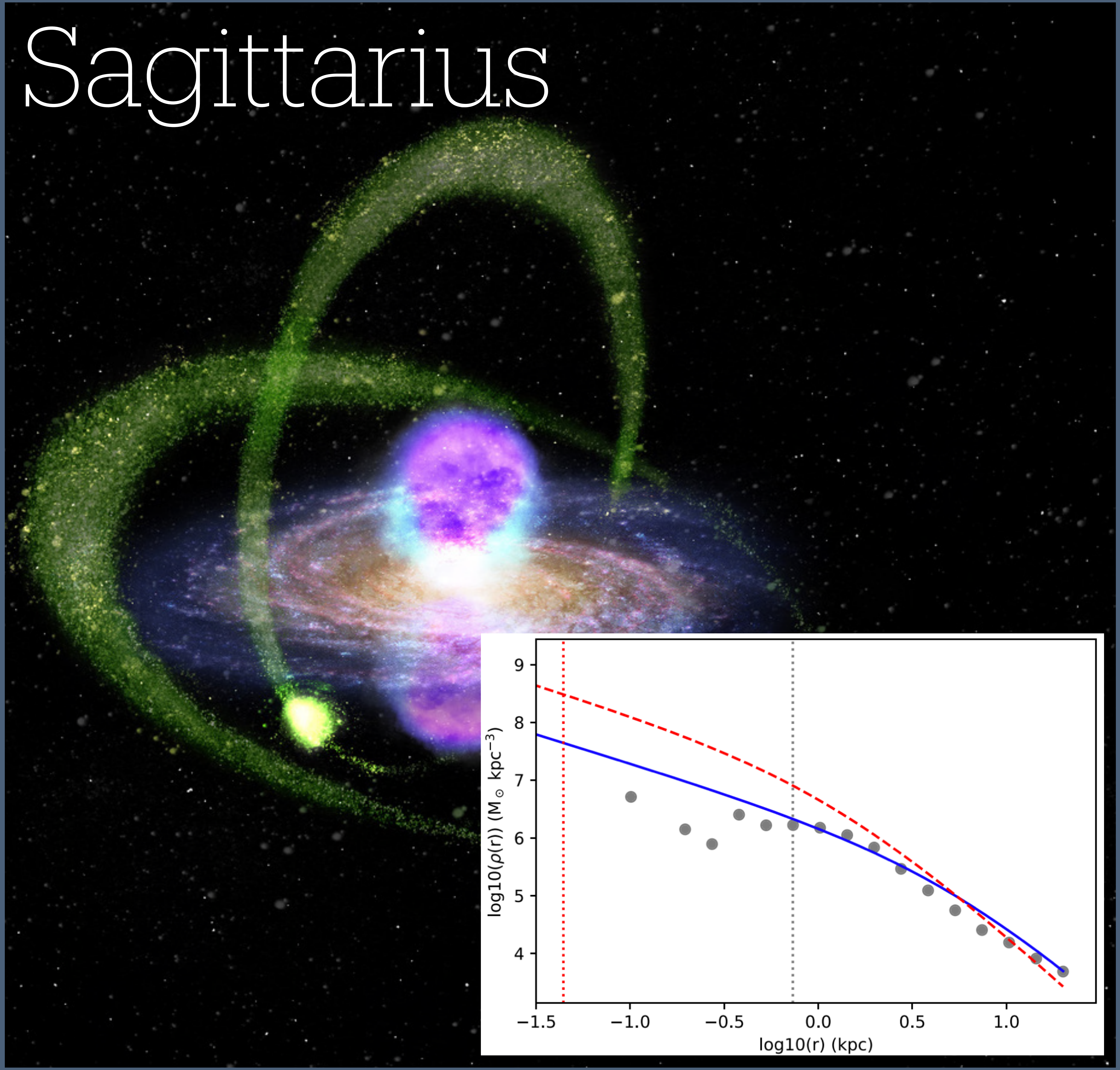
- GeV dSph constraints obtained by calculating the joint-likelihood of a simultaneous fit of a <u>single</u> dark matter model to <u>all</u> dSphs

$$\mathcal{L}_J(J) = \frac{1}{\ln(10)\sqrt{2\pi\sigma_J}J_{obs}} \times \exp\left[-\left(\frac{\log_{10}(J) - \log_{10}(J_{obs})}{\sqrt{2}\sigma_J}\right)^2\right]$$

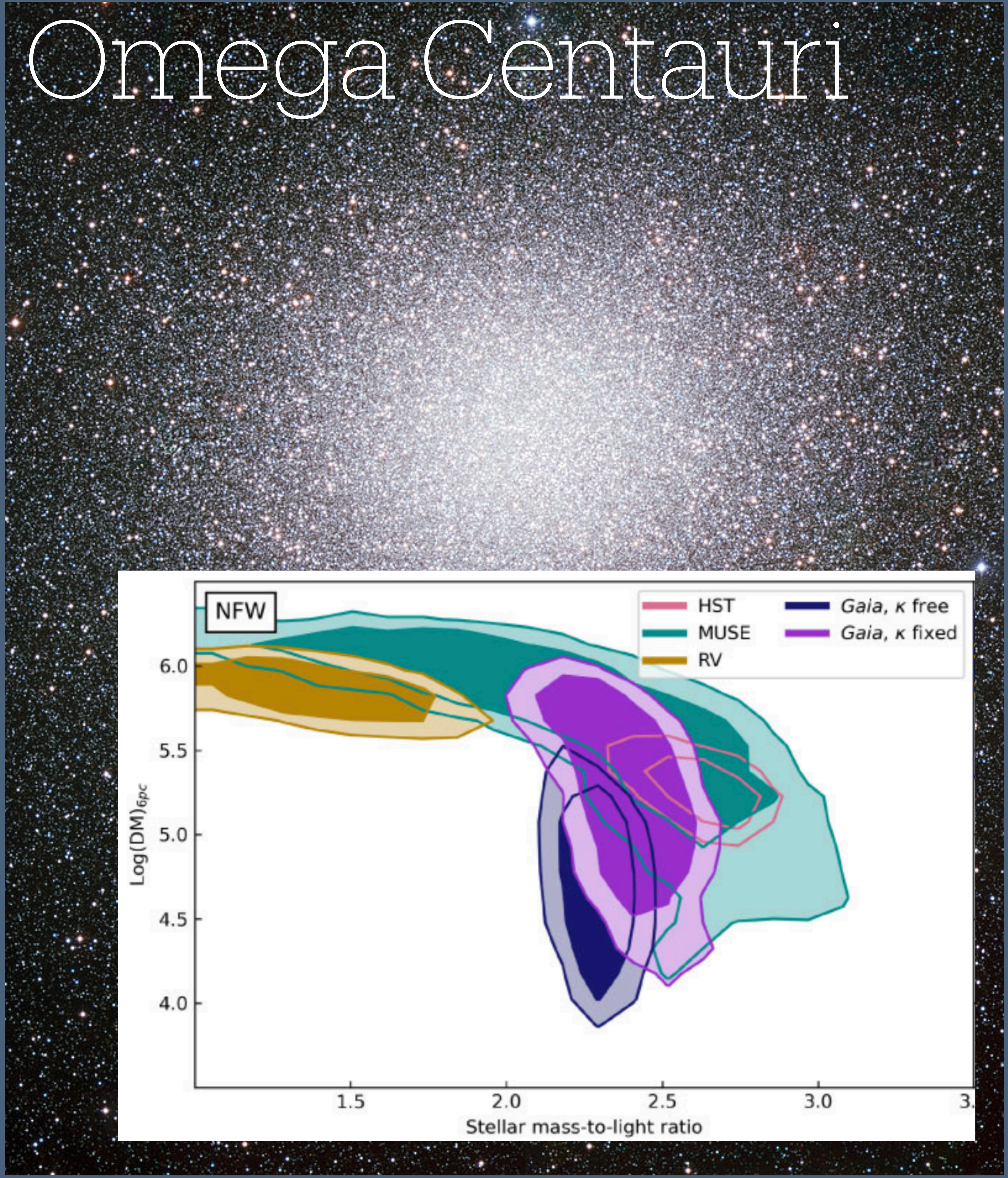
TeV Dwarf Searches

- Optimal strategy in the TeV era will change
  - Target observations add a cost to observing many dwarfs
  - LSST and updated spectroscopic measurements will decrease J-factor uncertainties
  - Increasing possibility of finding “extraordinary” high J-factor dwarf

Fortuitous Dwarfs?



Venville et al. (2023; 2308.13180)



Evans et al. (2021; 2109.10998)

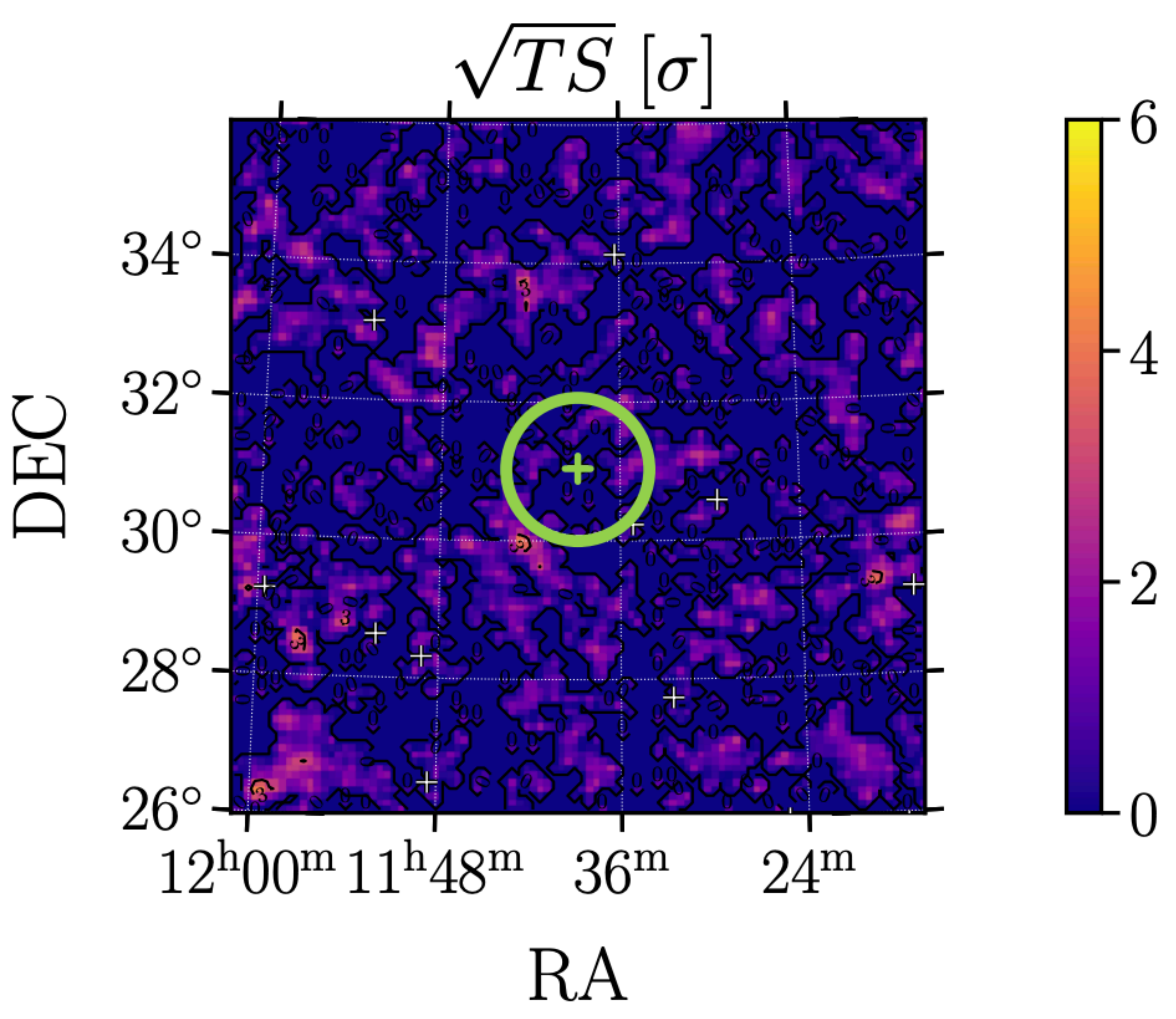
Fortuitous Dwarfs?

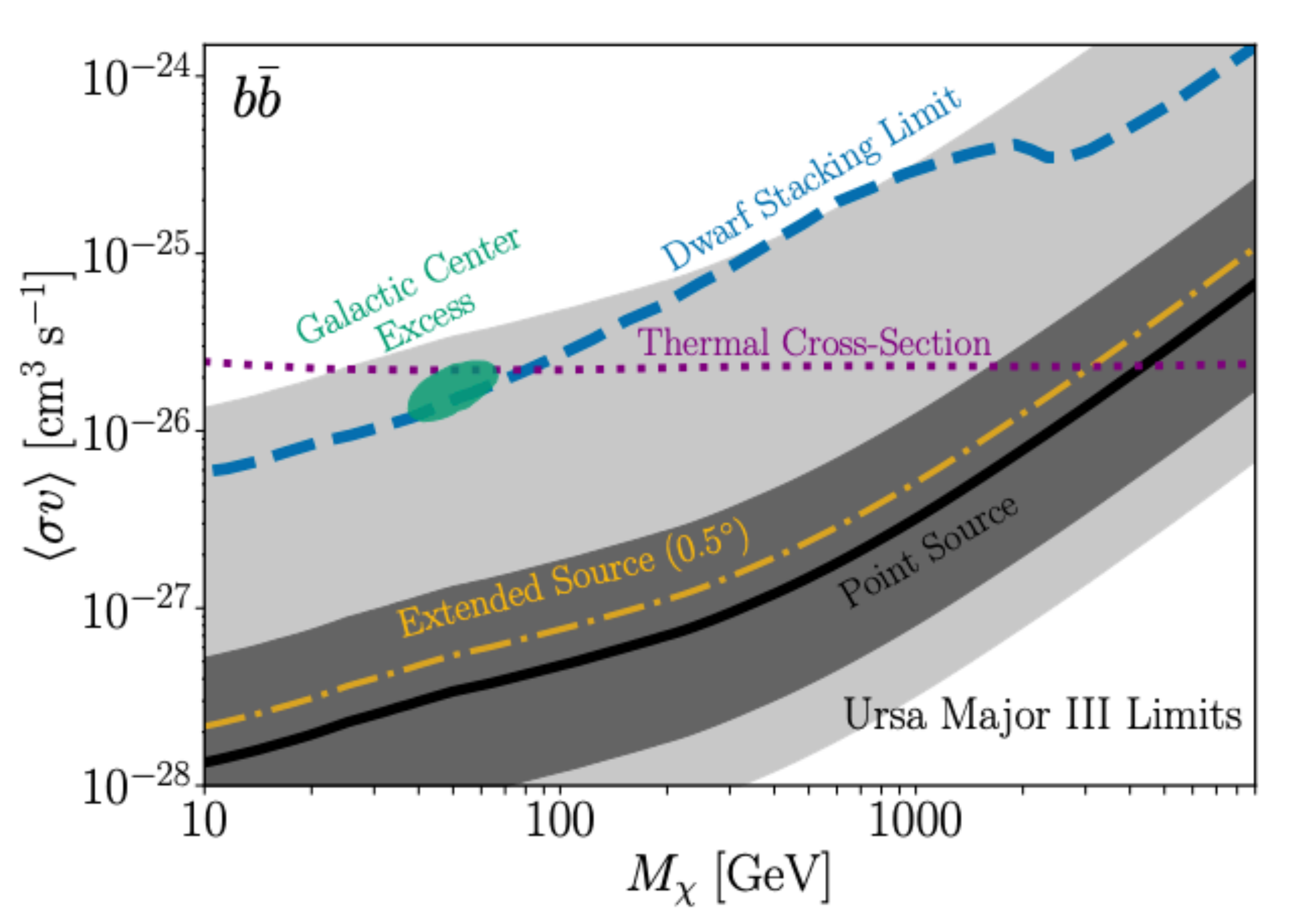
Smith et al. (2023; 2311.10147)

- Recently, a candidate dwarf Ursa Major III was discovered in UNIONS data.
- Rotation curve data, combined with proximity, indicate this may be the highest J-factor system in the galaxy.

Fortuitous Dwarfs?

Crnogorčević & Linden (2023; 2311.10147)

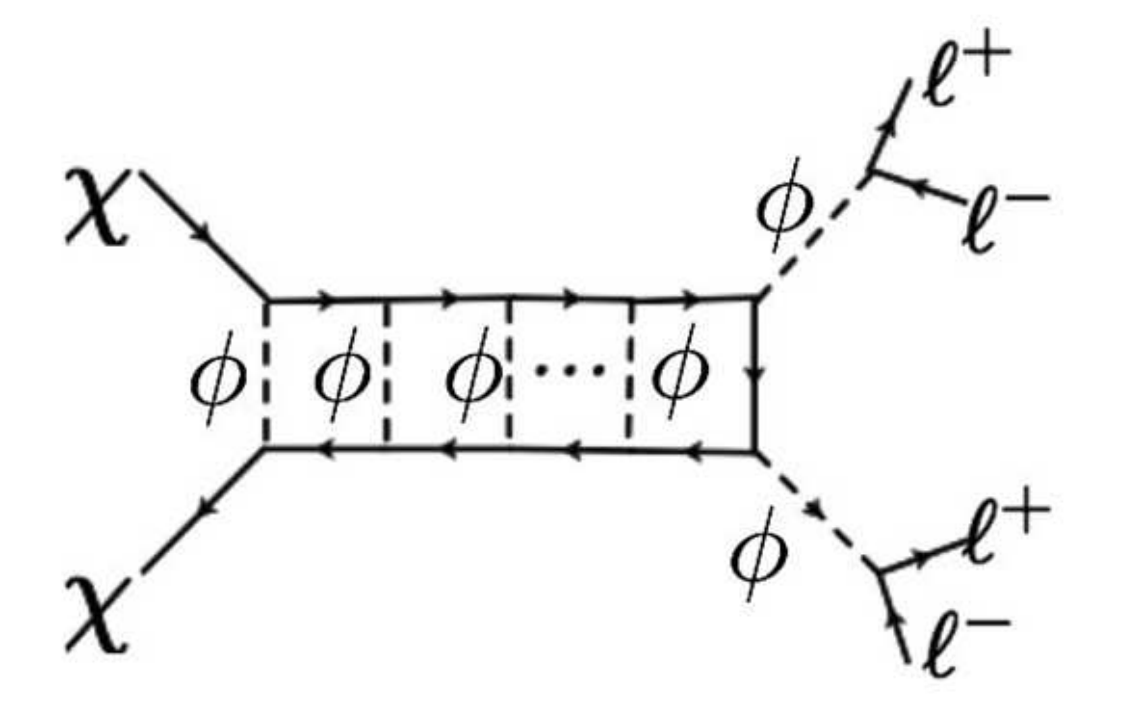


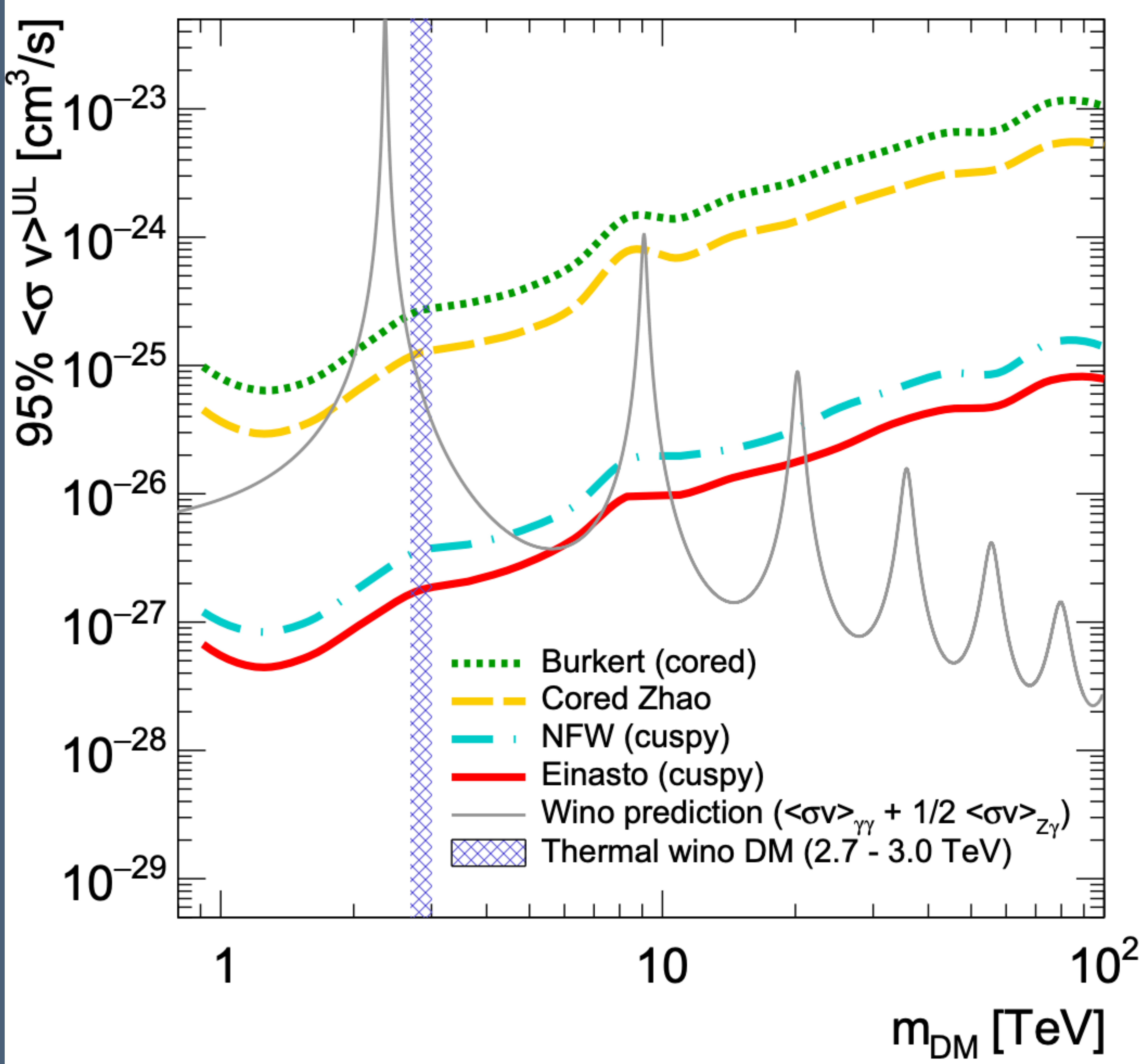


- Recently, a candidate dwarf Ursa Major III was discovered in UNIONS data.
- Rotation curve data, combined with proximity, indicate this may be the highest J-factor system in the galaxy.

TeV-Lines from WIMP Dark Matter

- Can also search for dark matter spectral features!
  - Most likely target $\chi\chi \rightarrow \gamma\gamma$
  - At TeV energies, this is always accompanied by $\chi\chi \rightarrow \gamma Z$, which has a similar energy above ~300 GeV.
  - In general, cross-section is suppressed by α^2, but models with enhanced lines are possible, especially at resonances (e.g., Sommerfeld effect)

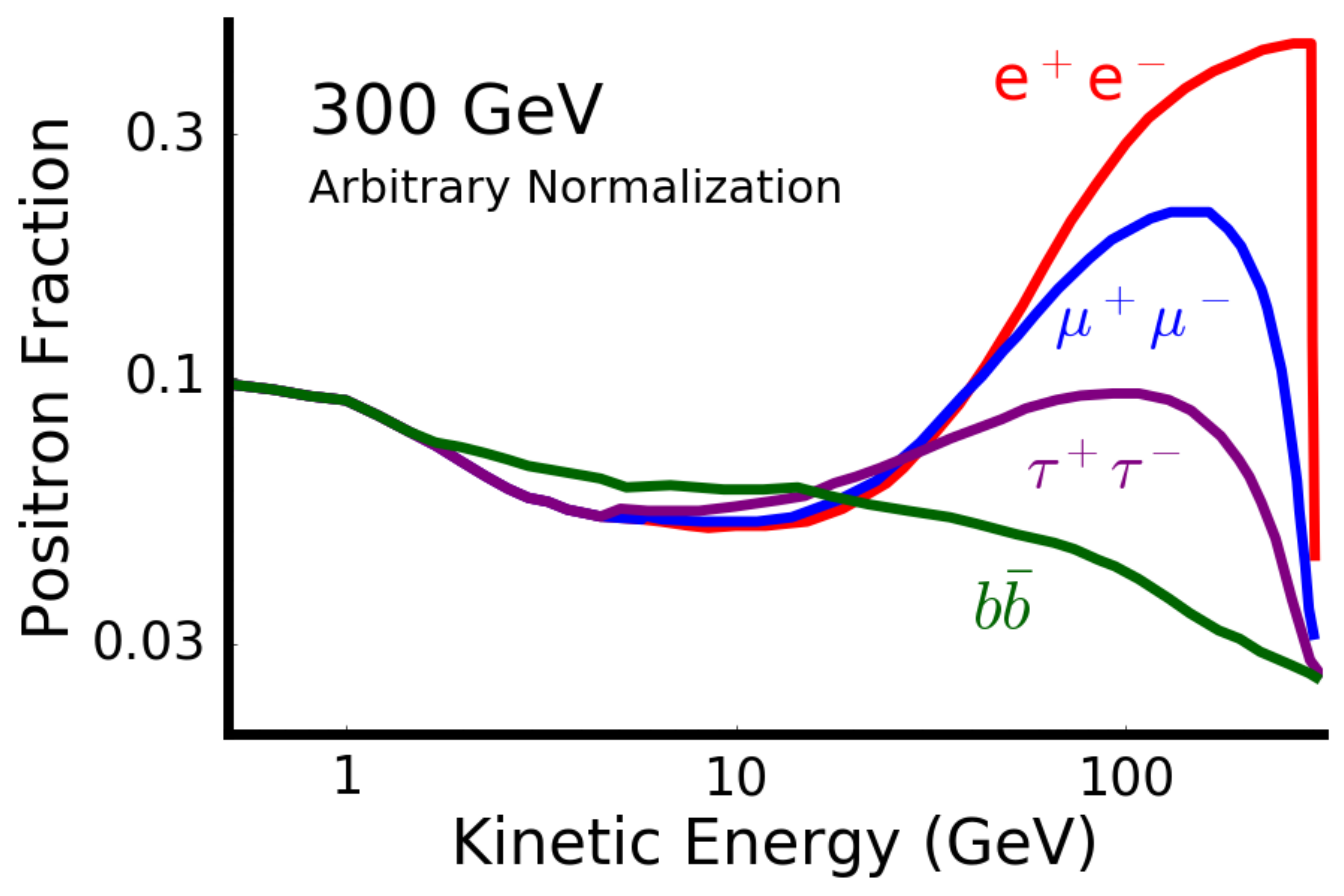


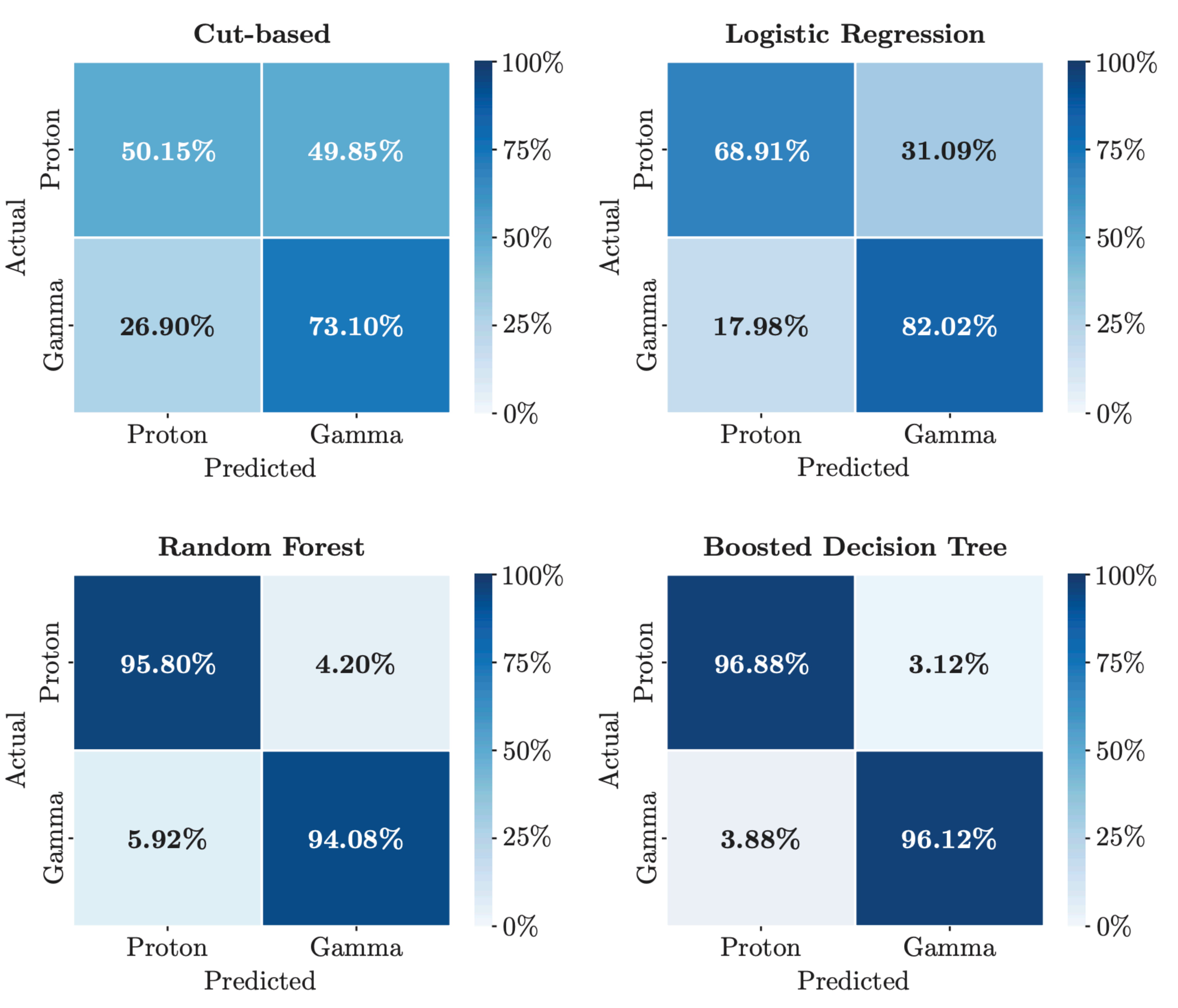


MAGIC Collaboration (2022; 2212.10527)

Electron/Positron Lines ?

Dark Matter

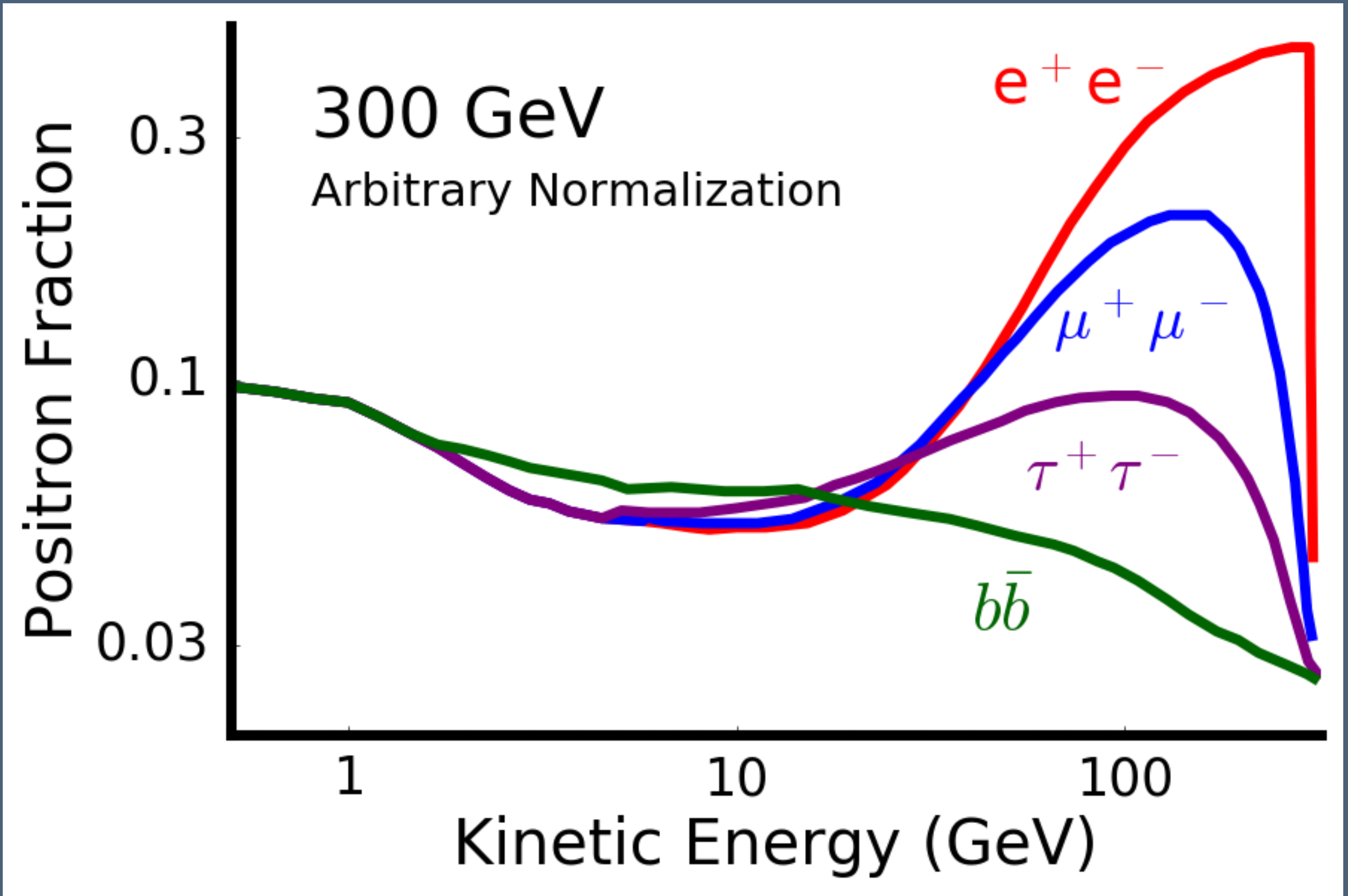




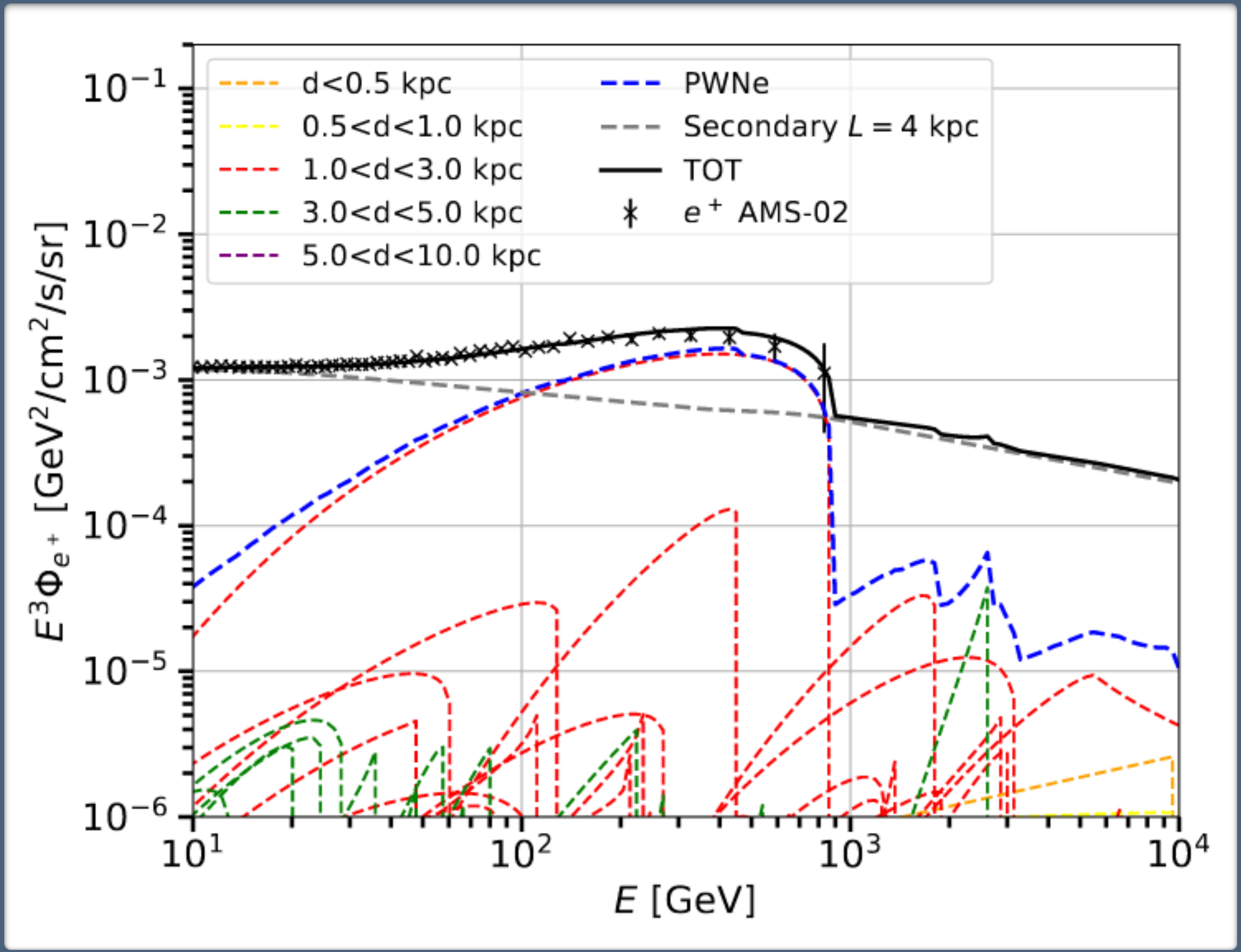
Caro (2023)

Electron/Positron Lines ?

Dark Matter



Pulsars

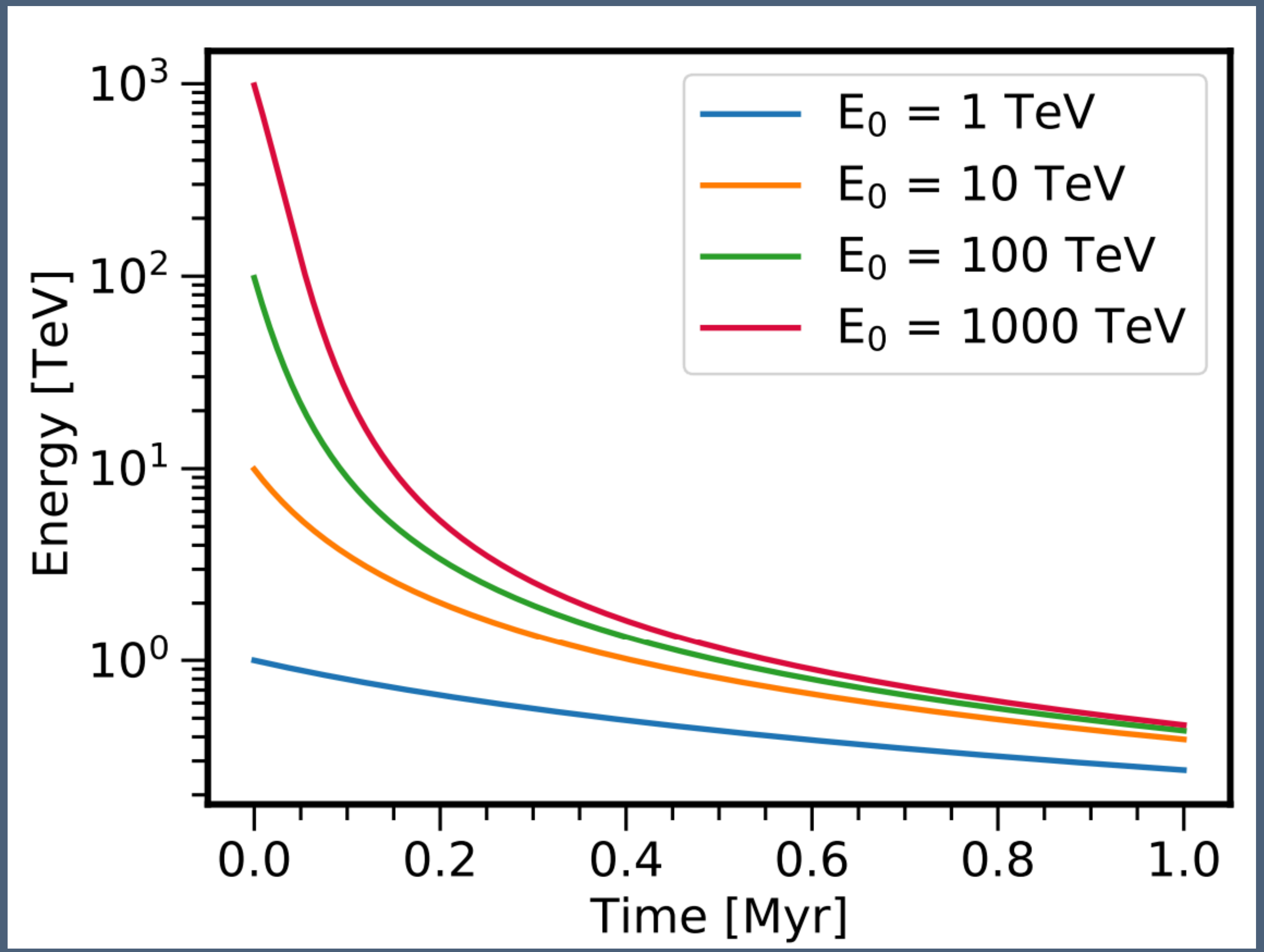


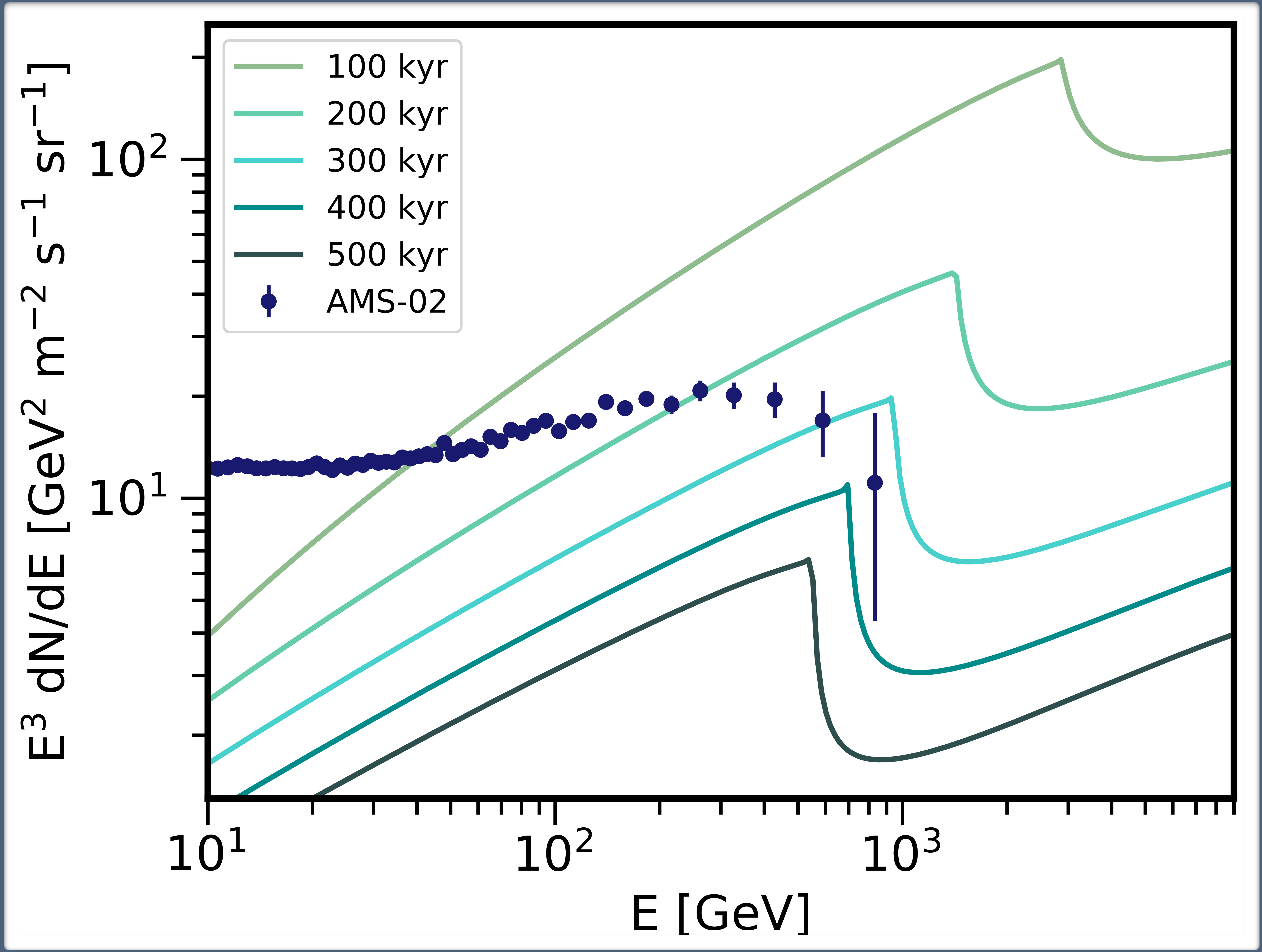
Orusa et al. (2021; 2107.06300)

Electron/Positron Lines ?

John & Linden (2022; 2206.04699)

- Pulsar Cooling Produces Sharp Lines:
  - Electrons at higher energy cool faster due to inverse-Compton scattering.
  - Pile-Up of High Energy Electrons at a specific energy that is related to the pulsar age.

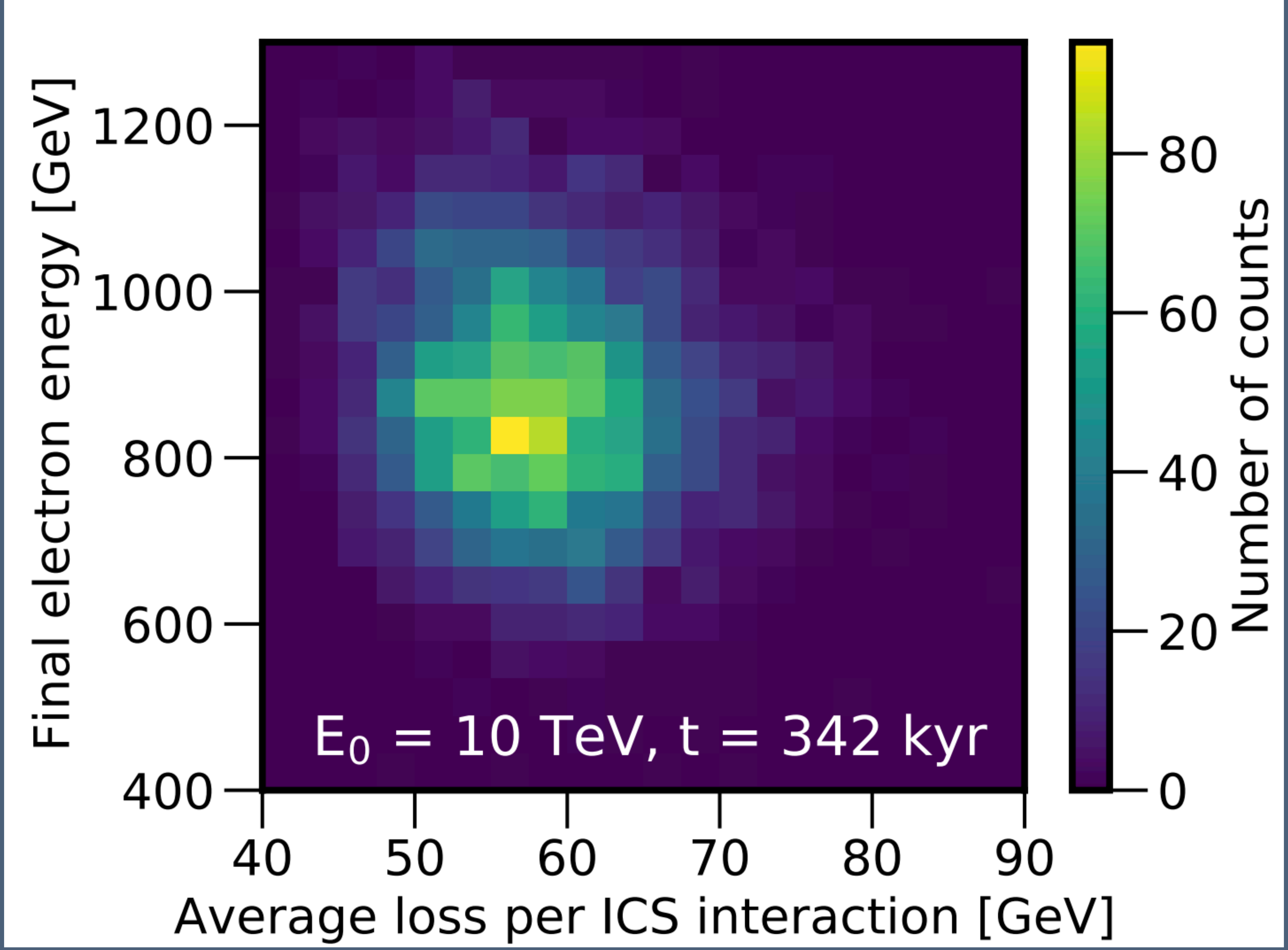




Electron/Positron Lines ?

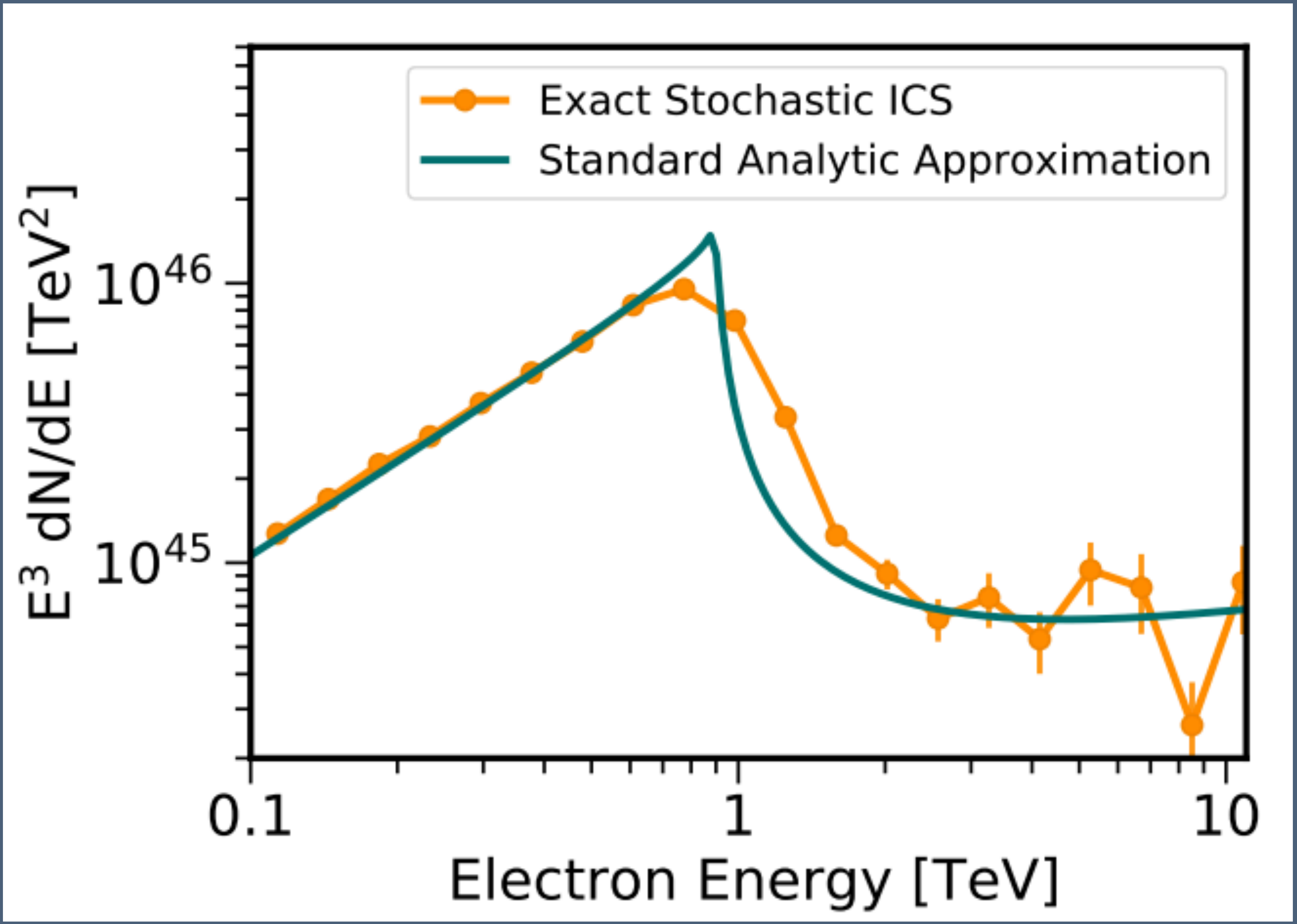
John & Linden (2022; 2206.04699)

- This story is <u>entirely wrong</u>.
- Electrons don't cool continuously, and an electron doesn't encounter the entire interstellar radiation field.
- Electrons encounter a small number of random photons at random angles, and lose random amounts of energy.
- Can't cool to a single line!



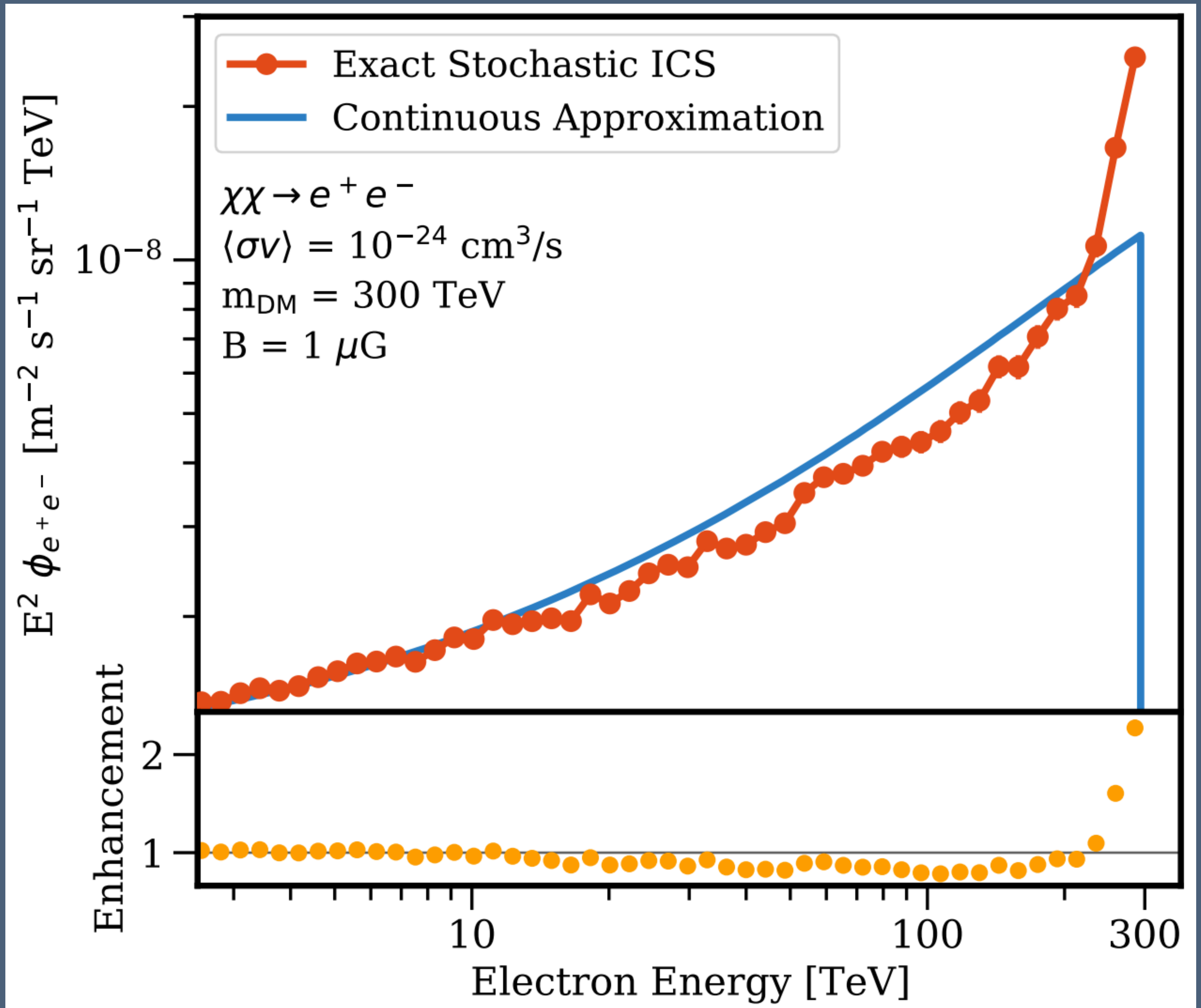
Electron/Positron Lines ?

John & Linden (2022; 2206.04699)



Pulsars don't produce lines!

John & Linden (2023; 2304.07317)



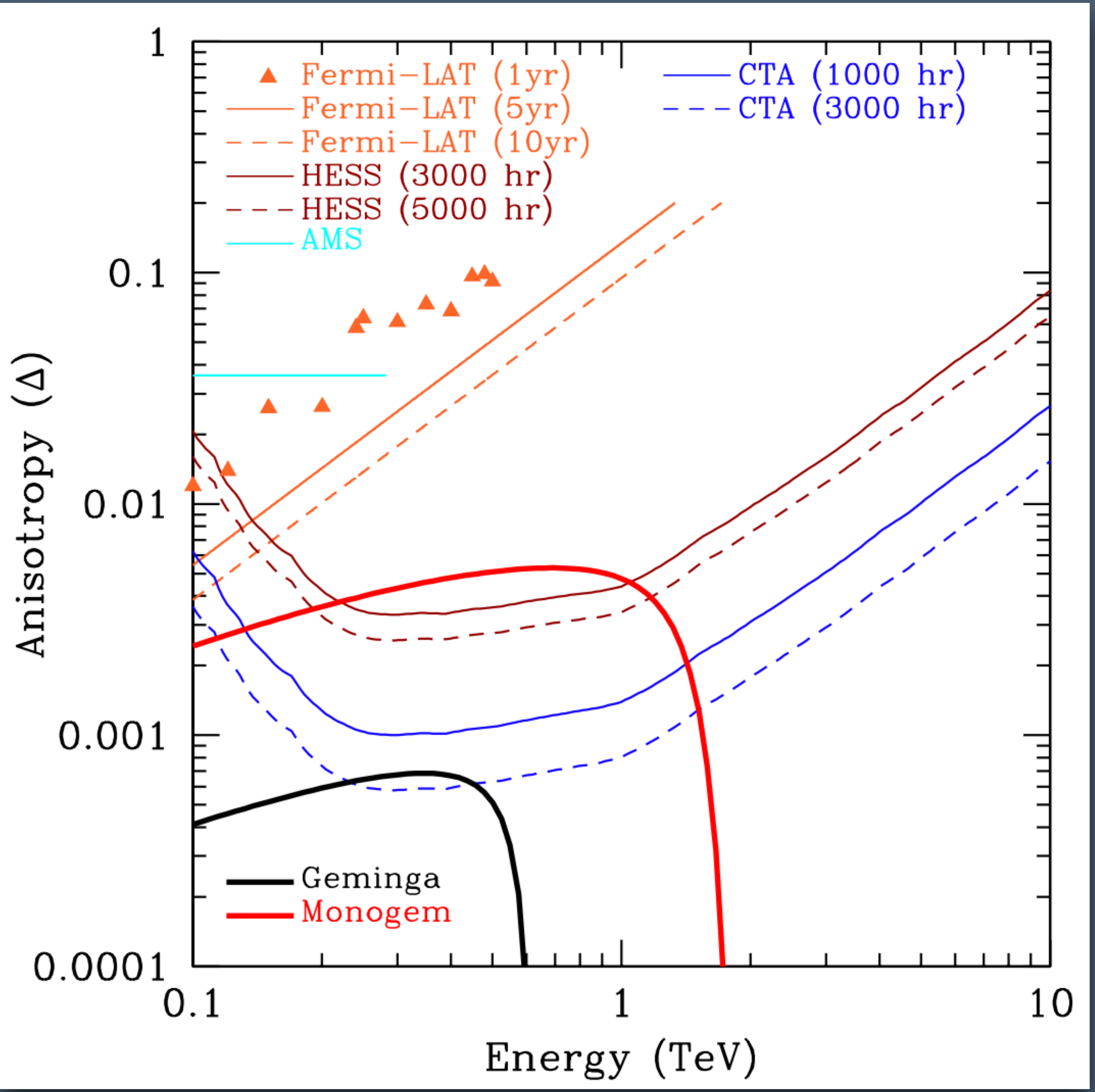
Dark Matter lines are sharper!

Electron Anisotropies ?

- Measuring electron fluxes with ACTs is difficult!
- Why? Because hadronic foregrounds dominate and hadronic/leptonic separation has large systematic errors.
- Searching for anisotropies may sound impossible?

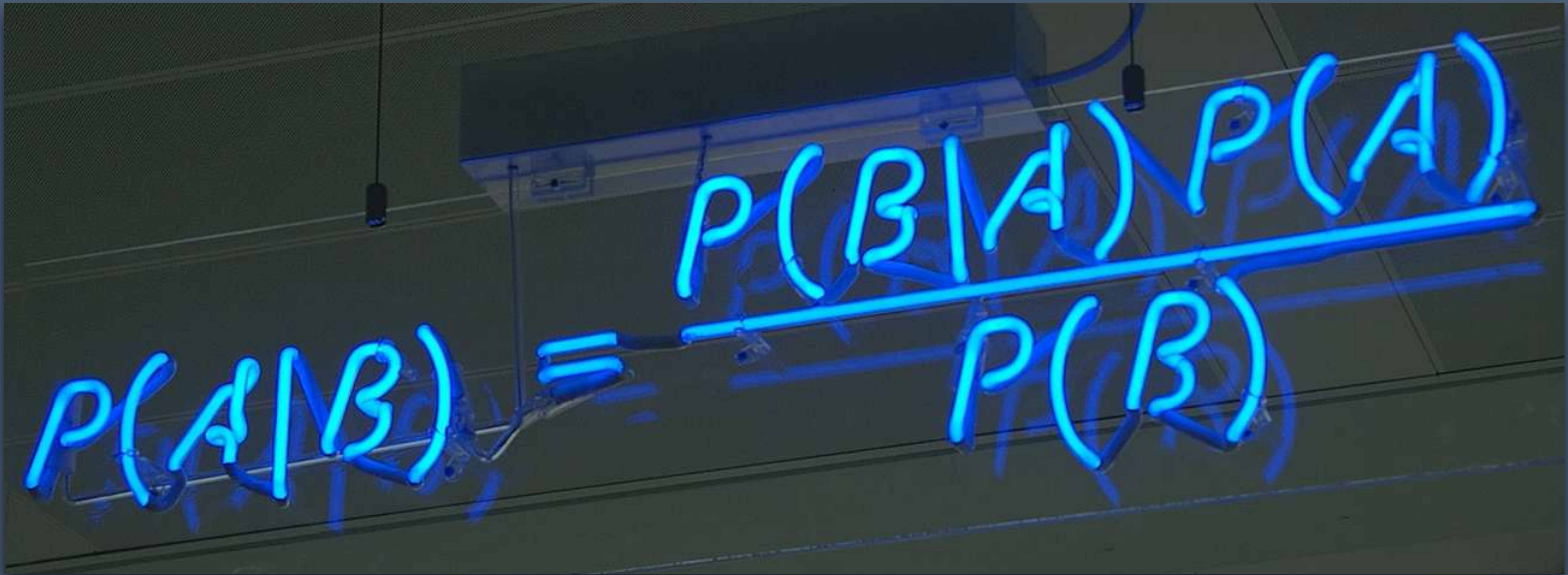
$$\Delta = \frac{3}{2c}\frac{d}{T}\frac{(1-\delta)E/E_{\rm loss}}{1-(1-E/E_{\rm loss})^{1-\delta}}\frac{N_{\rm psr}(E)}{N_{\rm tot}(E)}$$

- However - Hadronic background is known to be isotropic! It is a statistical (not systematic) error.
- CTA will observe many many hadrons, making the uncertainty small.



Linden & Profumo (2013; 1304.1791)

Bayesian Analysis



- Strong limits on GeV dark matter do two things:
  - Increase likelihood that dark matter is not a WIMP
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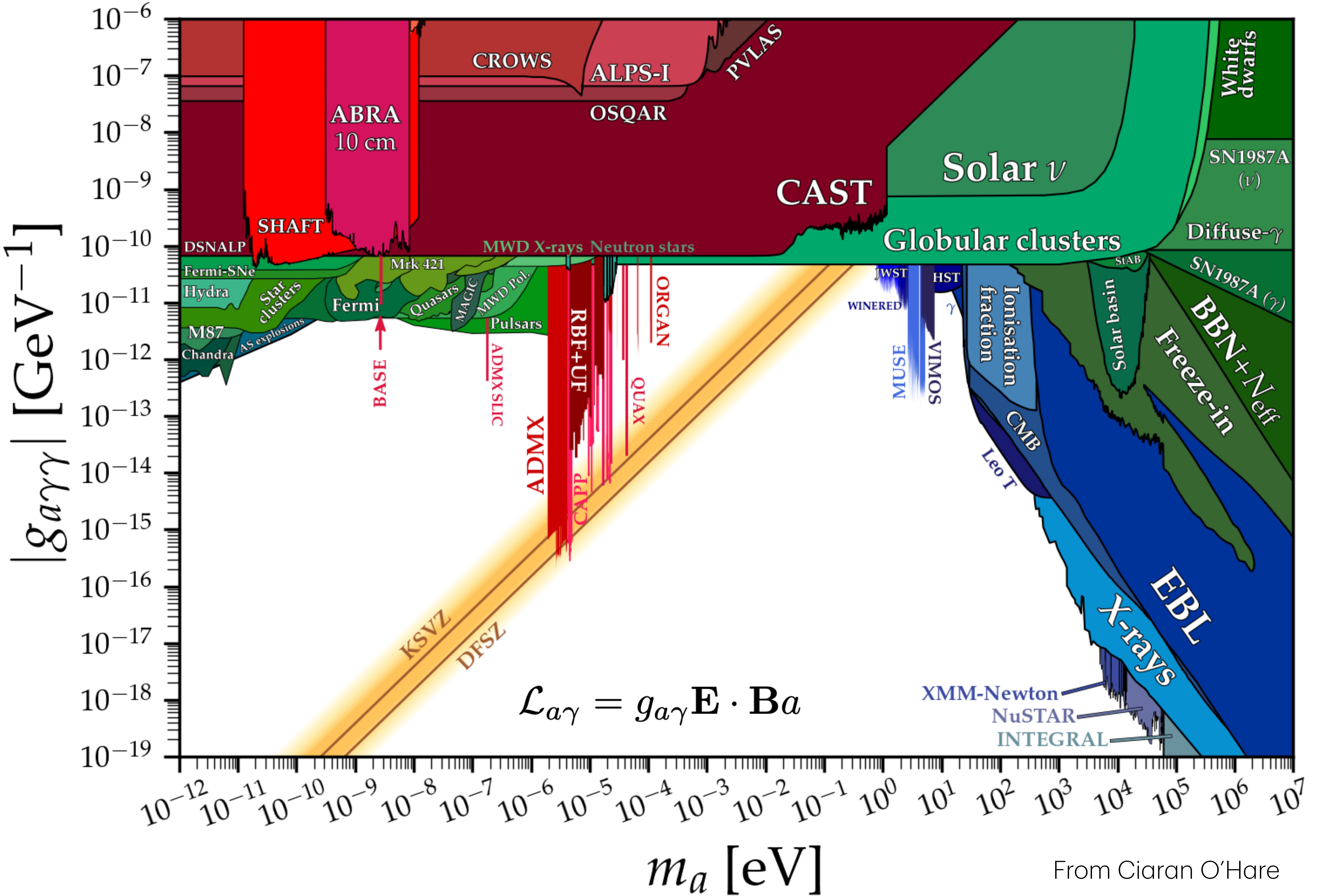
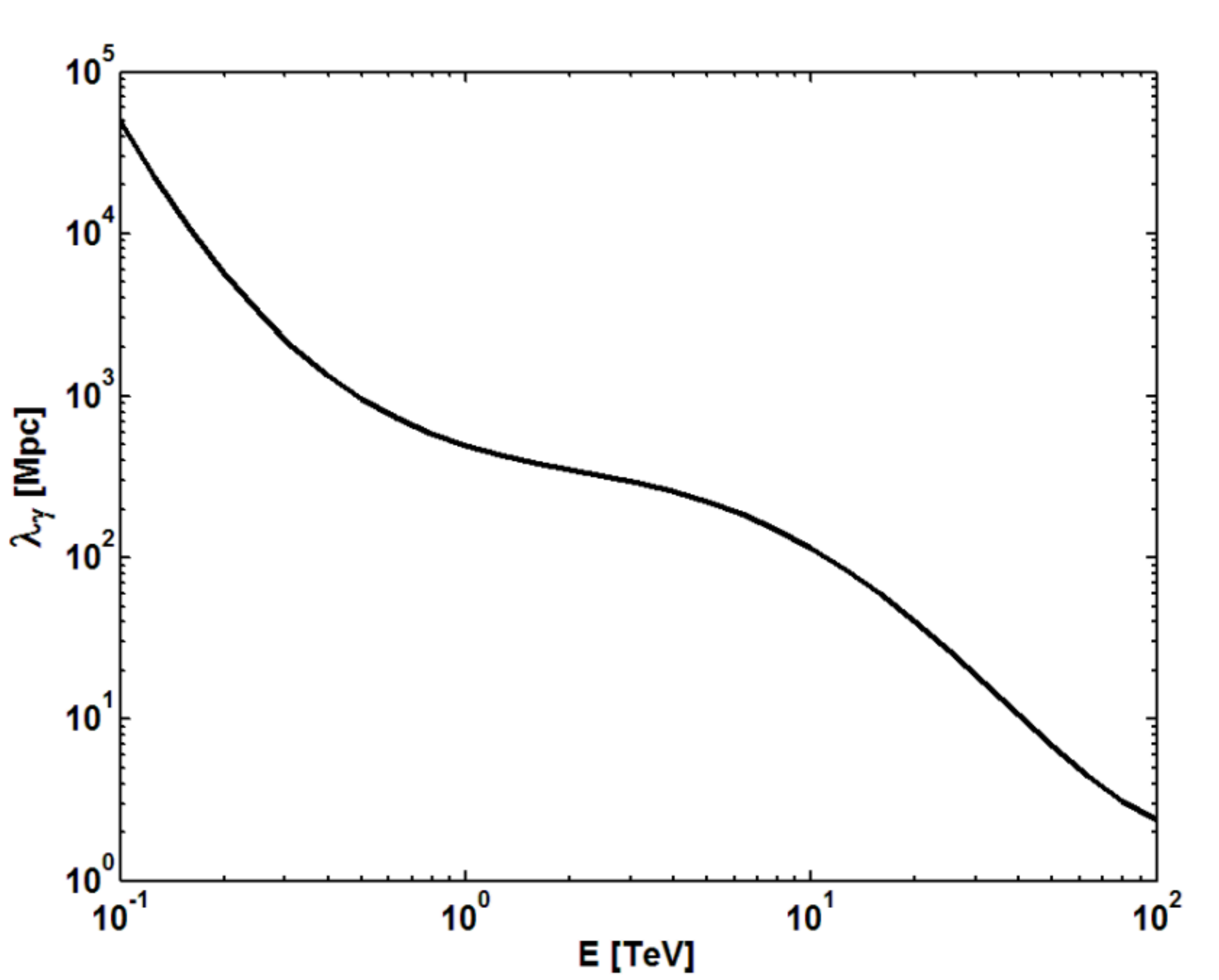


From Ciaran O'Hare

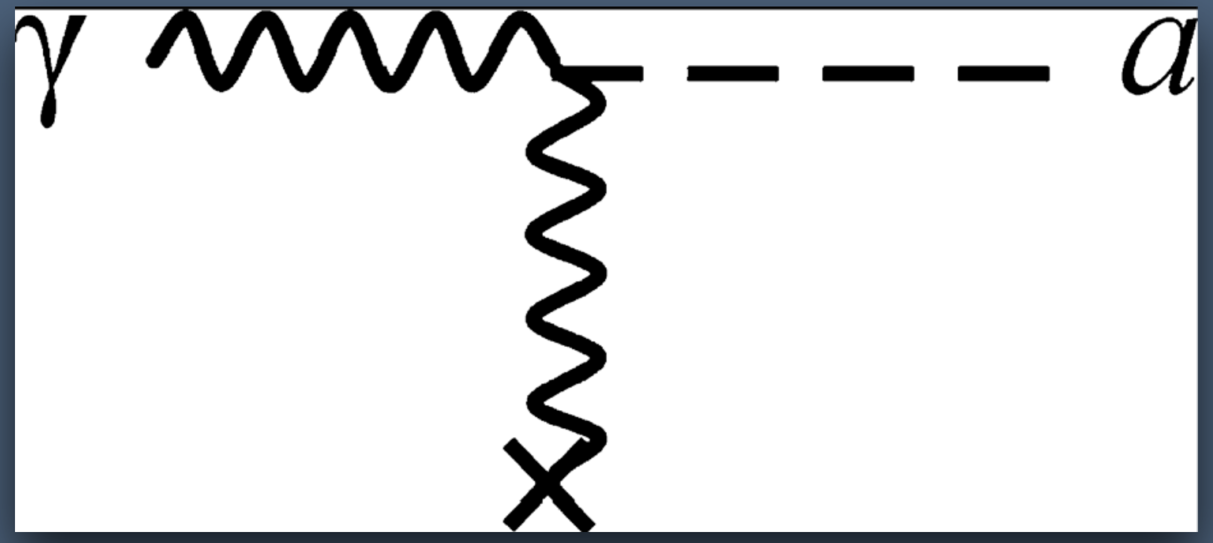
Why TeV Gamma-Rays?

De Angelis et al. 2011 (1106.1132)



- Why TeV Photons?
- While the universe is transparent to GeV photons, TeV photons can upscatter ambient light and convert to e+e- pairs.
- This produces a cascade that attenuates the TeV photon flux.
- **Light through a wall experiment.**

Why neV Axions?



- Photon to Axion Conversion kinematically forbidden in a vacuum.
- Photon must acquire an effective mass

$$\omega_{\mathrm{pl}} = \left(\frac{4\pi\alpha n_e}{m_e}\right)^{1/2}$$

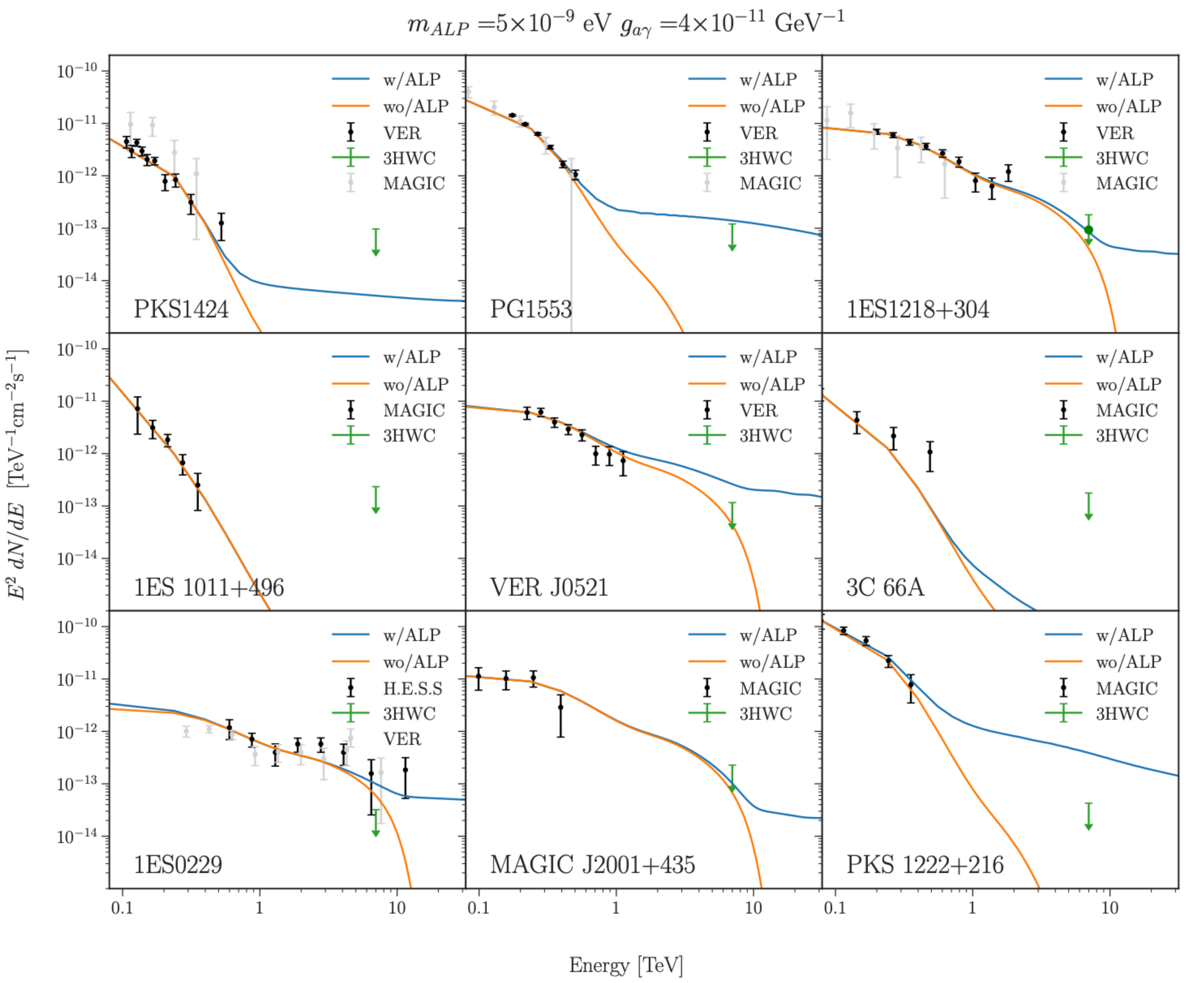
- For intergalactic magnetic field strengths and electron densities, this is order of 1-1000 neV.

- **Strong link between divergent energy scales - TeV gamma-rays uniquely tell us about neV axions!**

Axion Searches

Axion Searches

- ALPs significantly increase the transparency of the universe.
- Biggest Uncertainties:
  - Gap between Fermi GeV observations and HAWC/HESS TeV observations
  - Variability in blazers makes analyses with multiple instruments difficult
  - Constraints will significantly improve with dedicated GeV-TeV instrument

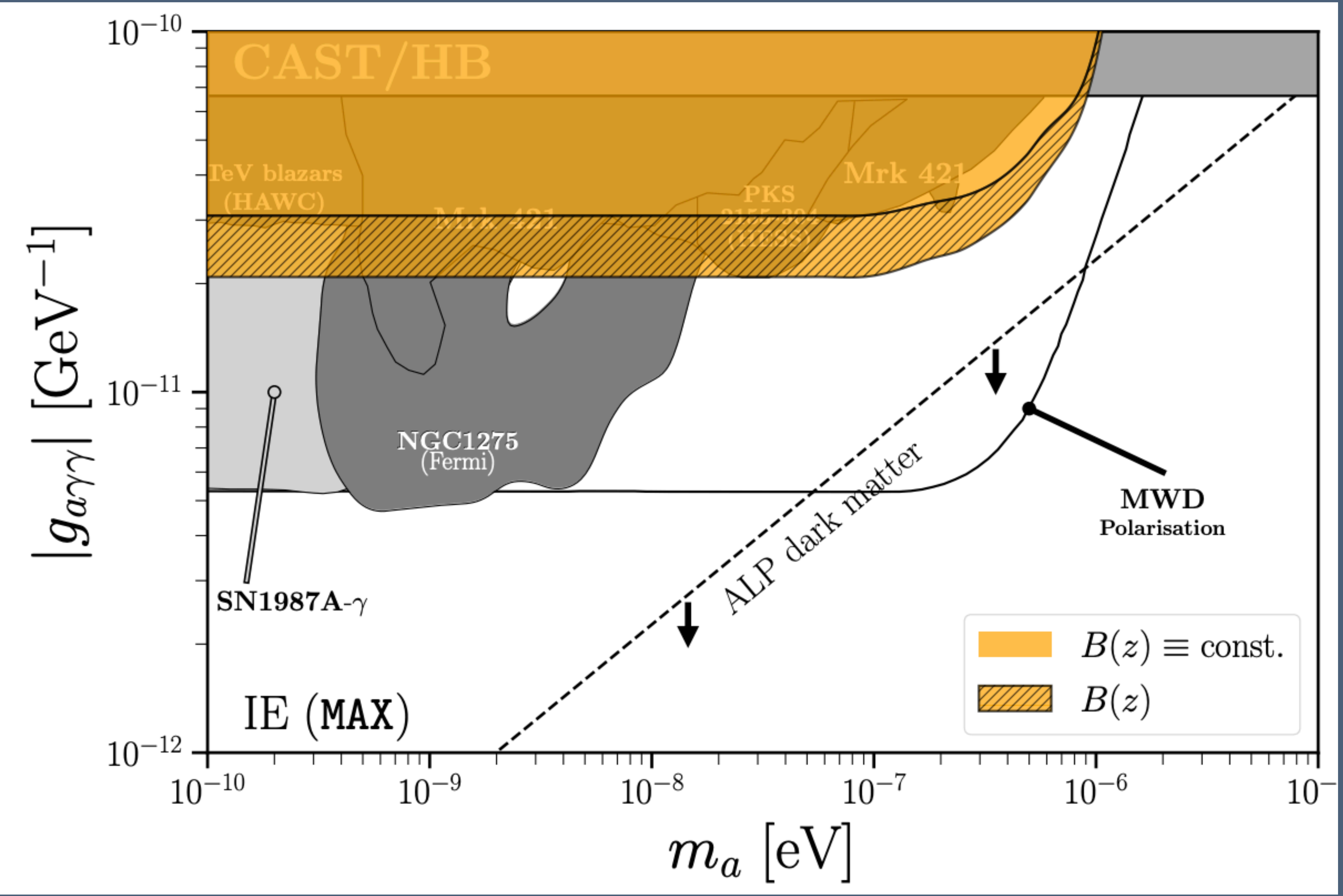


Jacobsen, Linden, Freese (2022; 2203.04332)

Axion Searches

Eckner & Calore (2022; 2204.12487)

- ALPs significantly increase the transparency of the universe.
- Can also use HAWC/Tibet data independently to look for TeV sources.
- High absorption near 1 PeV opens the avenue to using Galactic observations.
- Constraints at hundred-TeV energies extend to higher ALP masses, but sensitivity of survey telescopes lies below targeted ACTs




To be successful you don’t need to do extraordinary things, you just need to do ordinary things extraordinarily well.
Jim Rohn
quotefancy

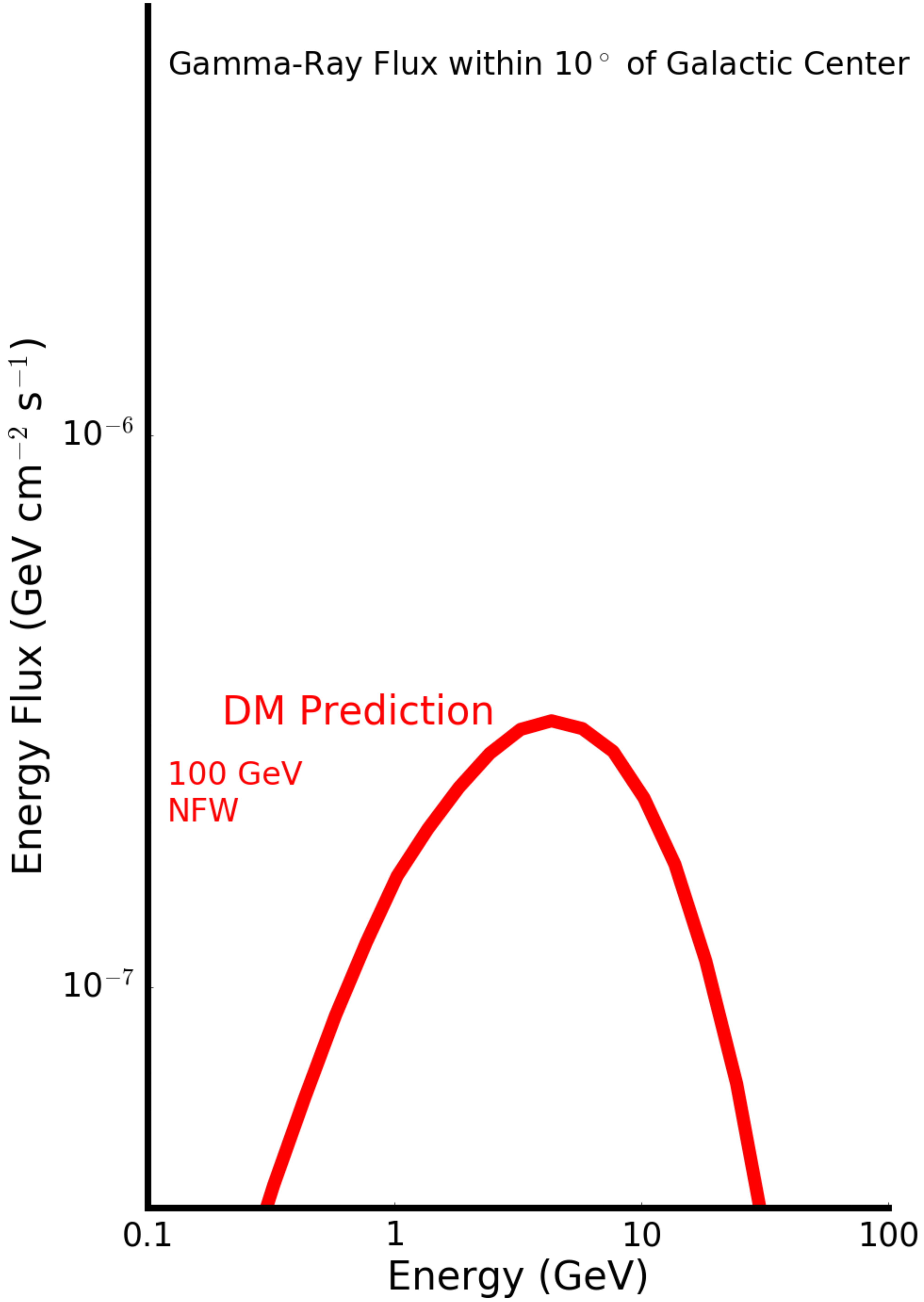
GeV WIMPs and the Story of Tantalus

NFW Profile (Mass of Milky Way)

Thermal Cross-Section (Early Universe)

Dark Matter Mass (?)

Annihilation Final State (?)



GeV WIMPs and the Story of Tantalus

NFW Profile (Mass of Milky Way)

Thermal Cross-Section (Early Universe)

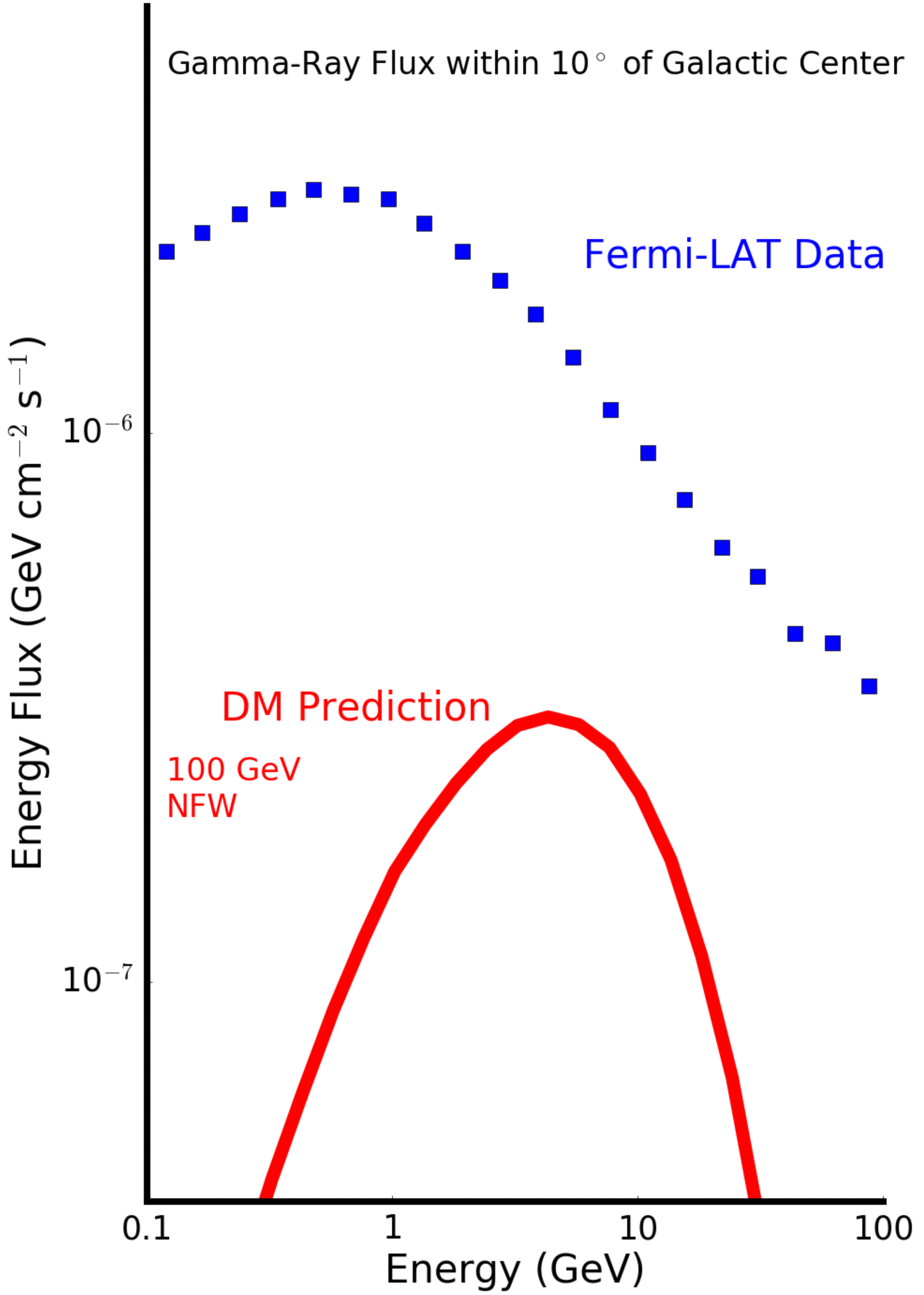
Dark Matter Mass (?)

Annihilation Final State (?)

Milky Way Star-Formation Rate (Galactic Dynamics)

Diffusion Constant in Galactic Center (Hydrodyanmics)

Activity of Supermassive Blackhole (?)



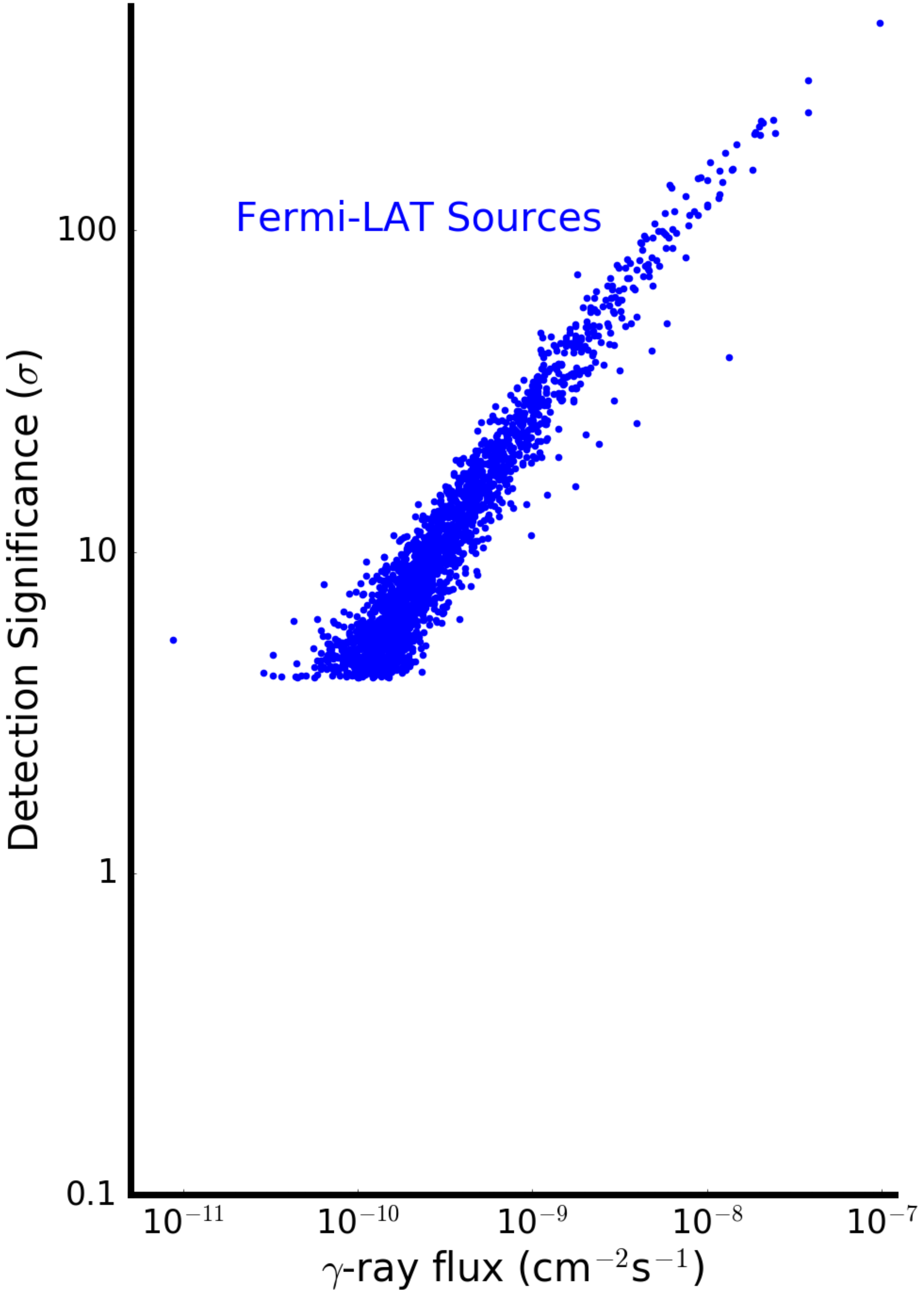
GeV WIMPs and the Story of Tantalus

SMBH Accretion Efficiency (Magnetohydrodynamics)

Blazar Acceleration Mechanisms (Leptonic? Hadronic?)

Radio Galaxy Emission Models

Star-Formation Rates in Starburst Galaxies



GeV WIMPs and the Story of Tantalus

SMBH Accretion Efficiency (Magnetohydrodynamics)

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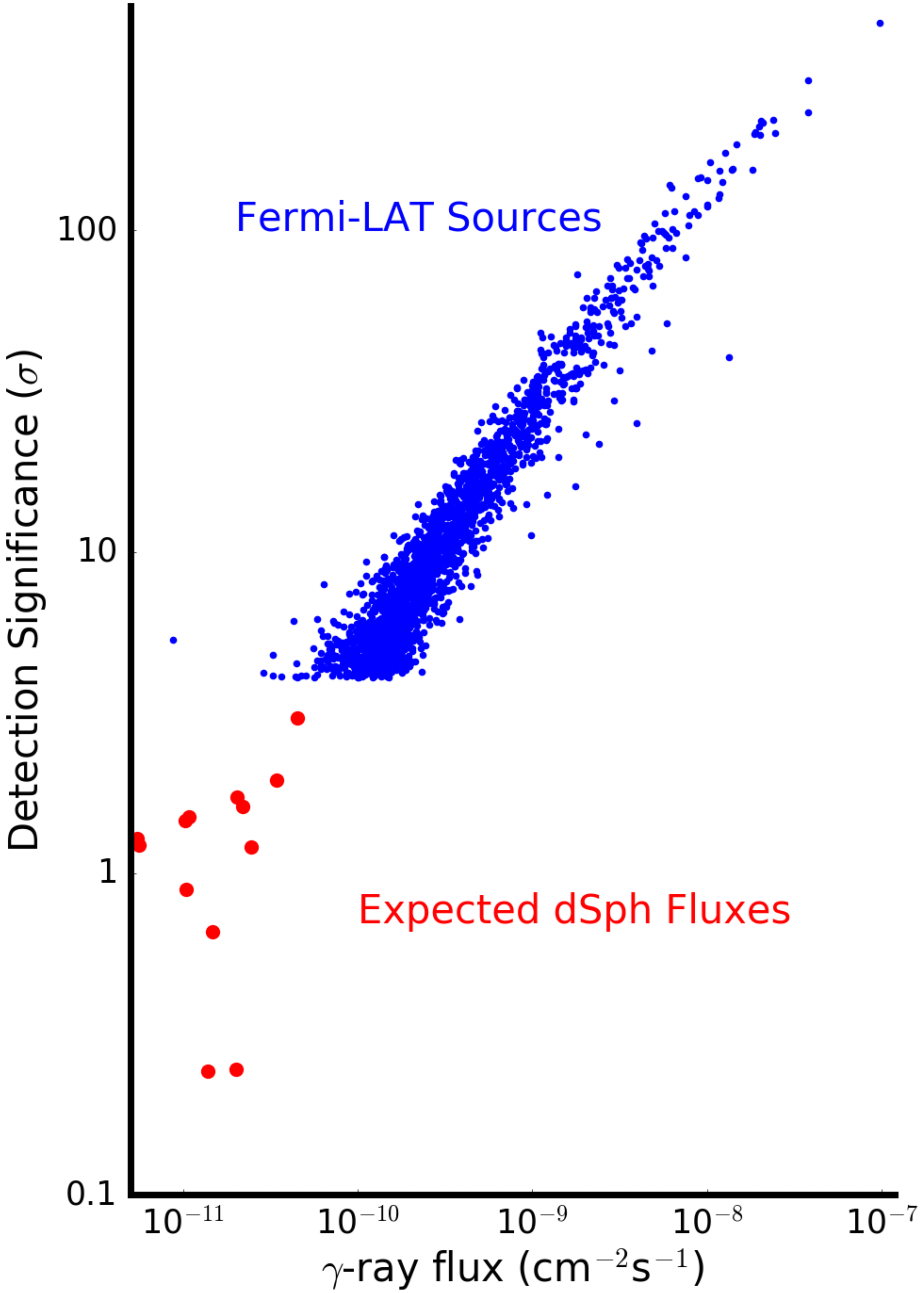
Star-Formation Rates in Starburst Galaxies

dSph Proximity

Substructure Models

Milky Way Merger History



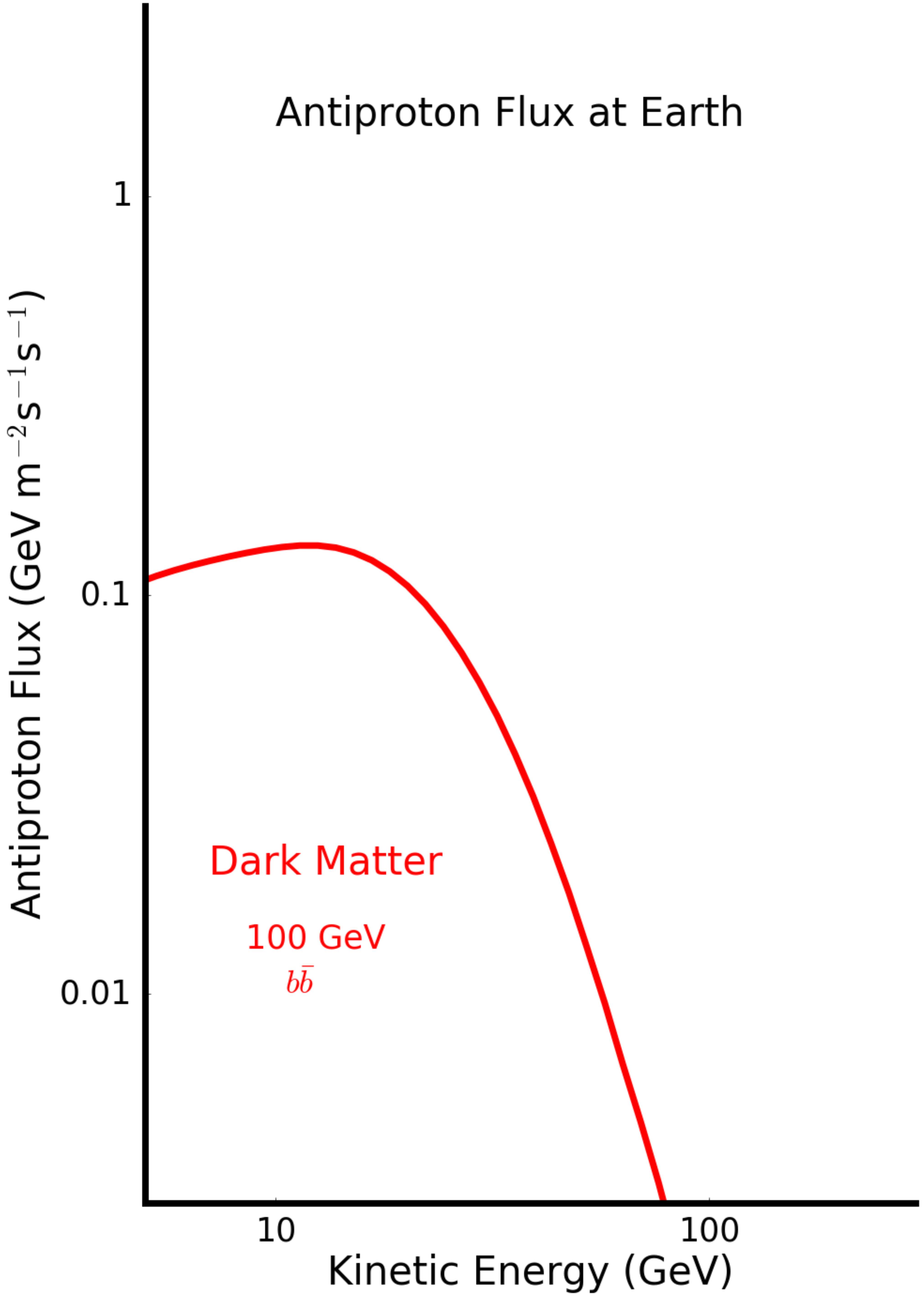
GeV WIMPs and the Story of Tantalus

Local Dark Matter Density

Thermal Cross-Section (Early Universe)

Dark Matter Mass (?)

Convection of Annihilation Products from GC (Winds?)



GeV WIMPs and the Story of Tantalus

Local Dark Matter Density

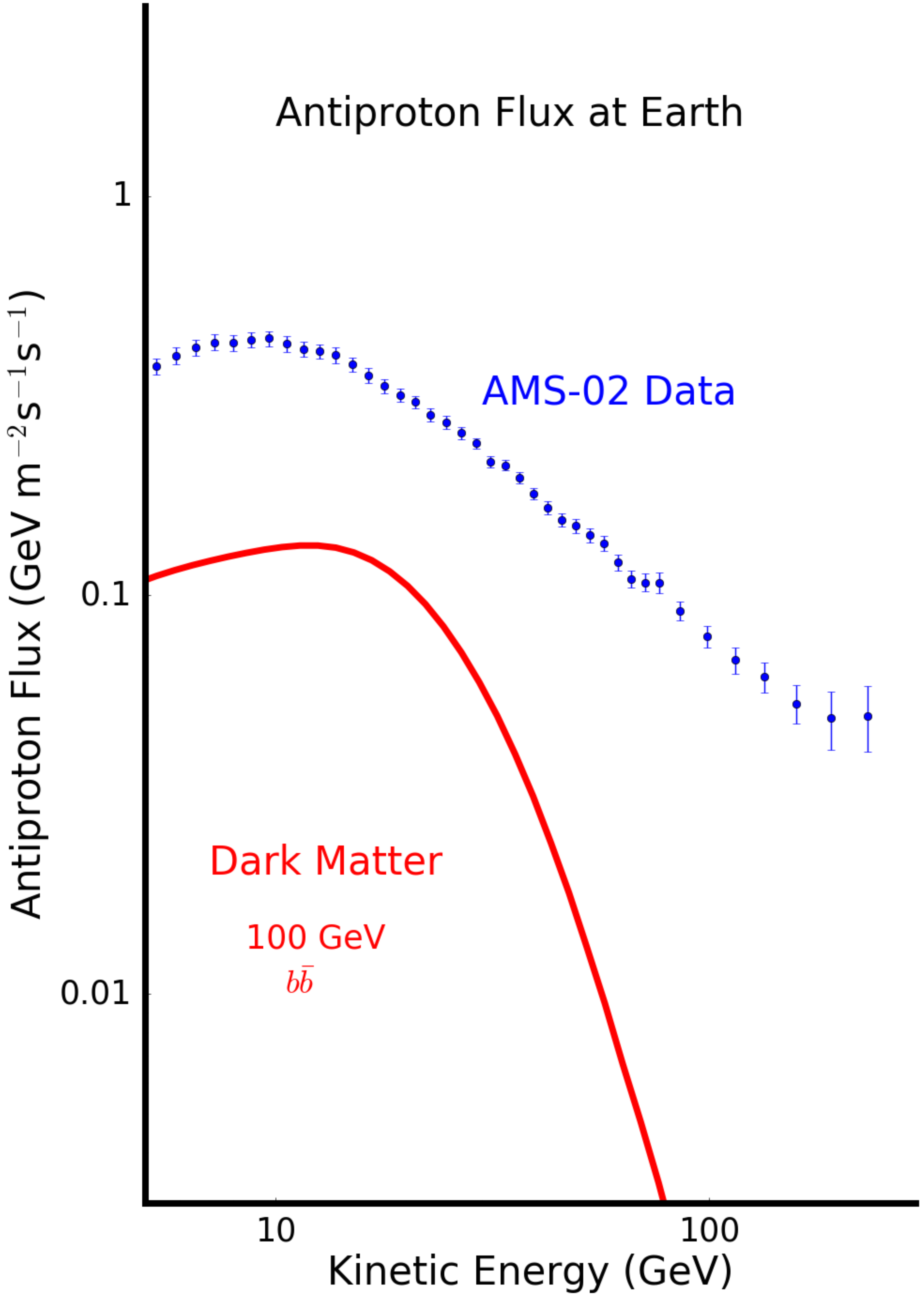
Thermal Cross-Section (Early Universe)

Hadronic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Local Gas Density

Local Supernova Rate



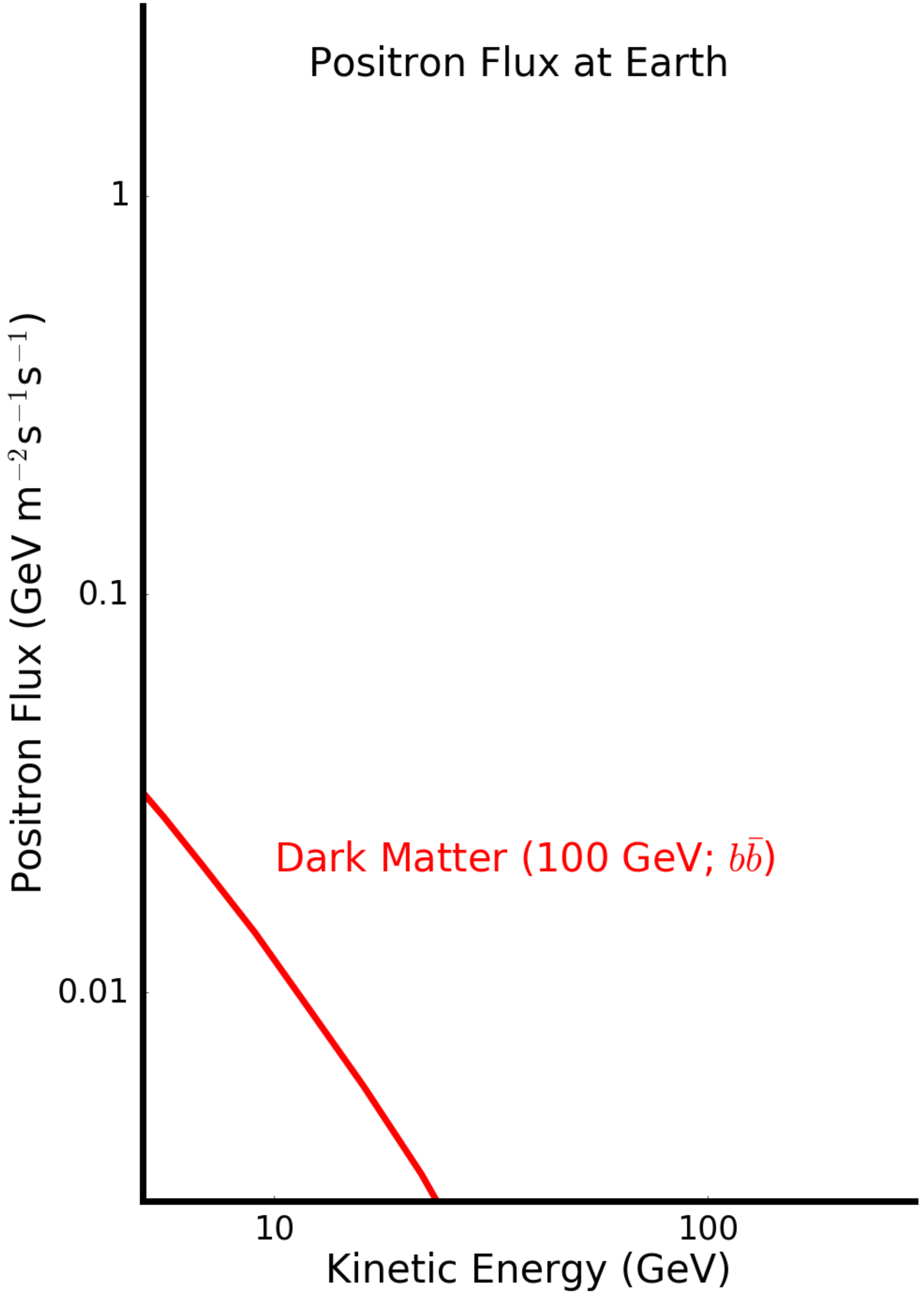
GeV WIMPs and the Story of Tantalus

Local Dark Matter Density

Thermal Cross-Section (Early Universe)

Leptonic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)



GeV WIMPs and the Story of Tantalus

Local Dark Matter Density

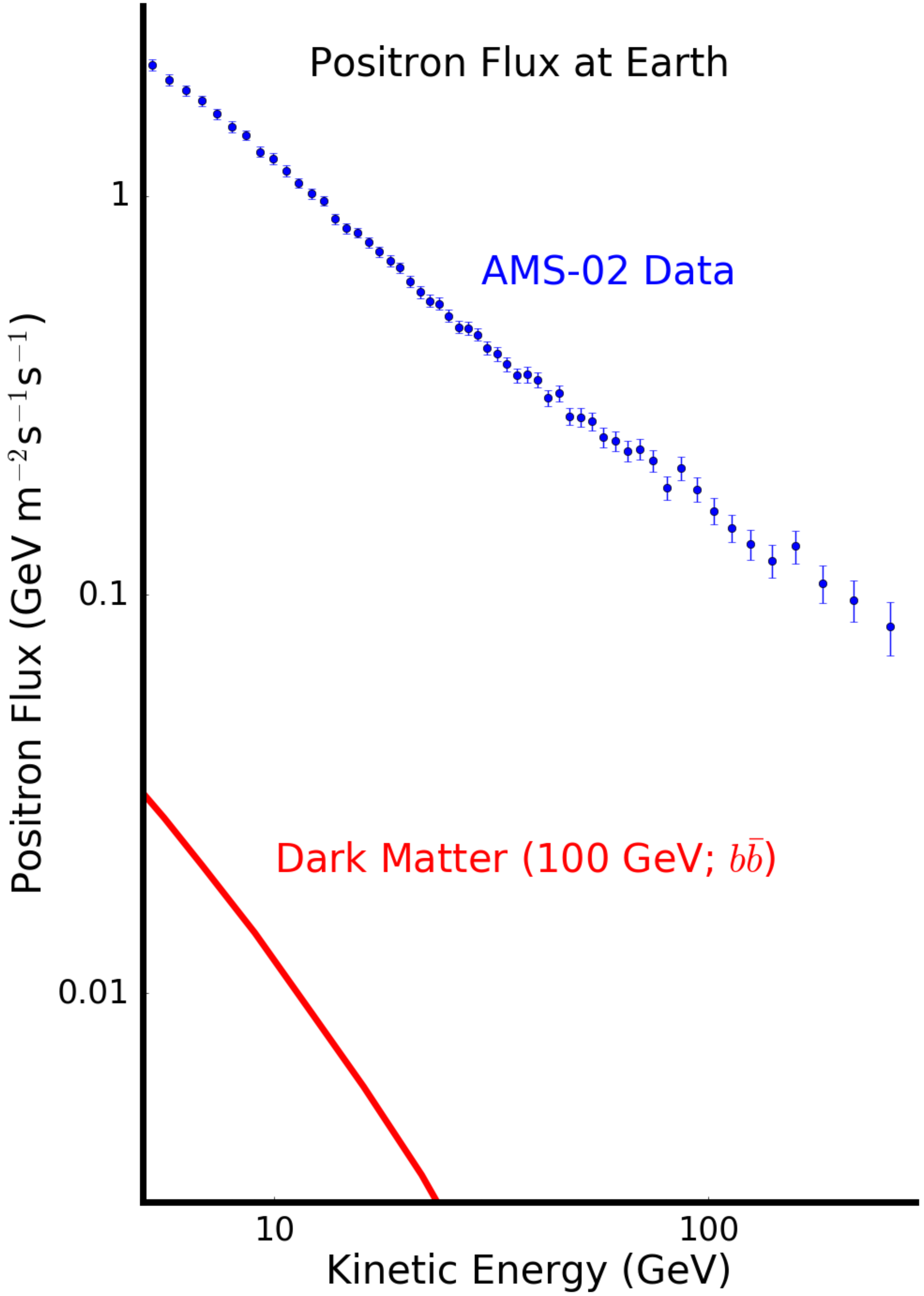
Thermal Cross-Section (Early Universe)

Leptonic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Pulsar Birth Rate

e^+e^- Acceleration Efficiency in Pulsar Magnetospheres



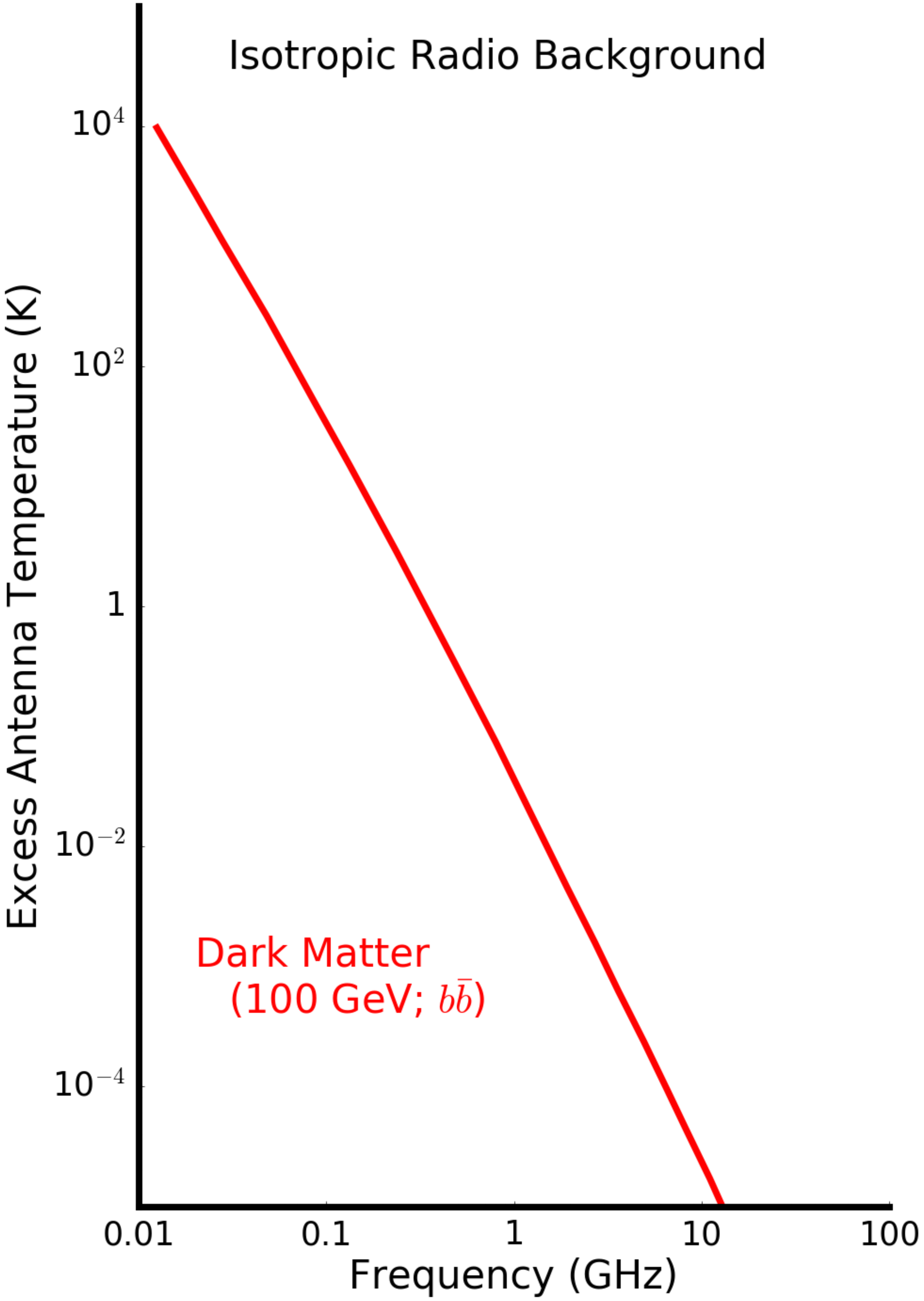
GeV WIMPs and the Story of Tantalus

Extragalactic Dark Matter Density

Thermal Cross-Section (Early Universe)

e+e- Energy Fraction in Dark Matter Annihilation

Intergalactic Magnetic Fields



GeV WIMPs and the Story of Tantalus

Extragalactic Dark Matter Density

Thermal Cross-Section (Early Universe)

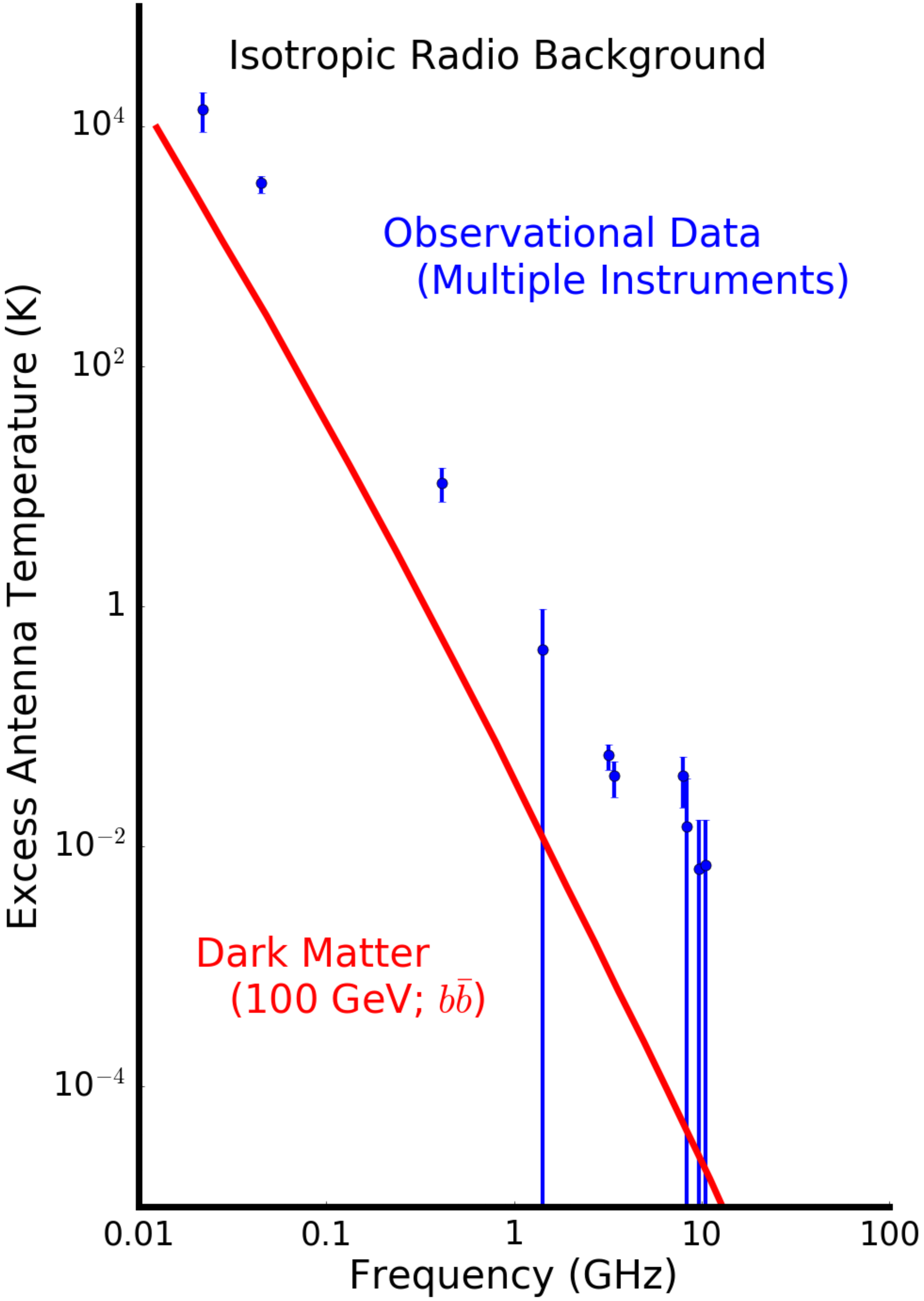
e+e- Energy Fraction in Dark Matter Annihilation

Intergalactic Magnetic Fields

Radio Luminosity in Starbursts and AGN

e+e- Reacceleration in Cluster Mergers

Redshift Dependence of Signal vs. CMB




WE HAVE MET THE ENEMY AND HE IS US.
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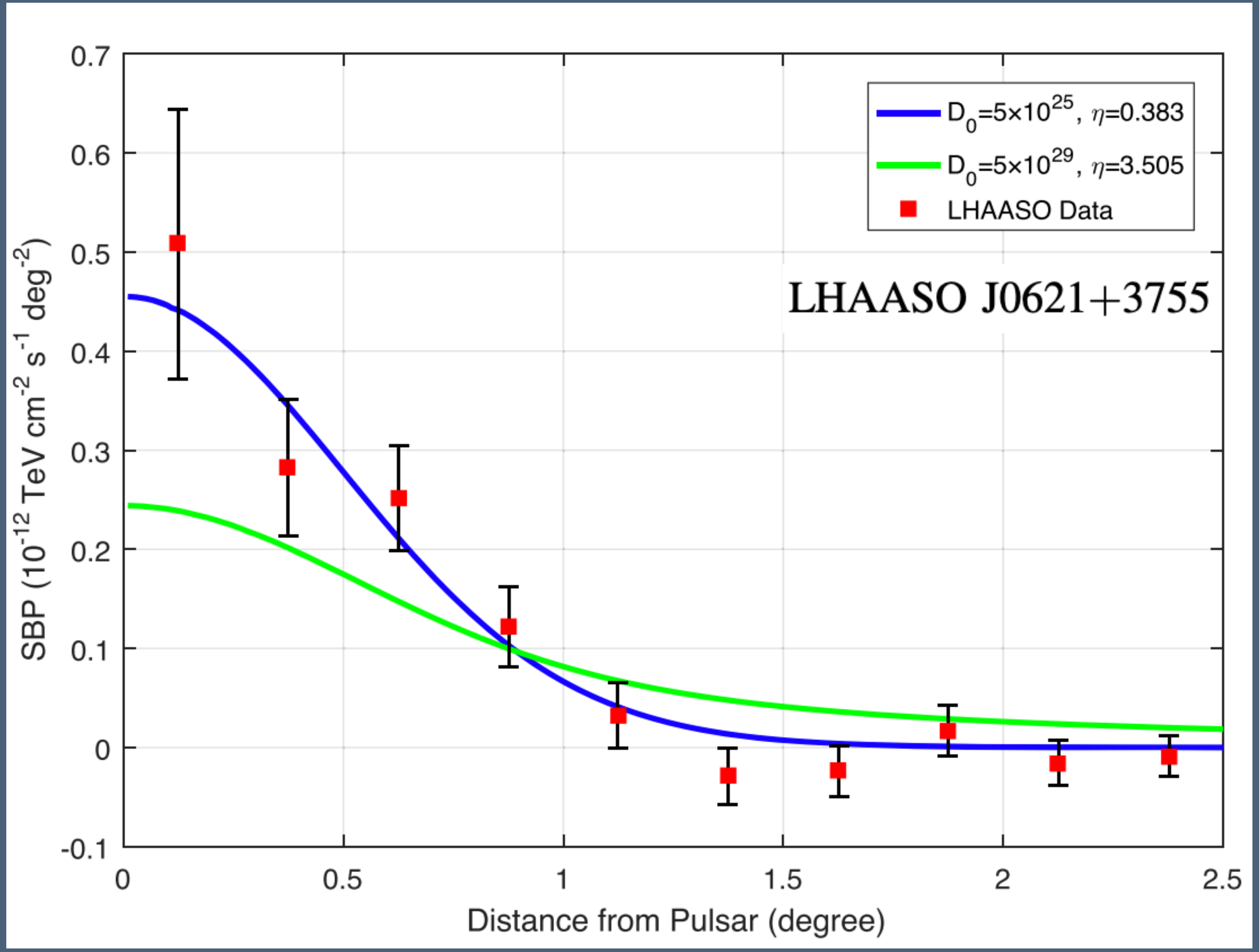
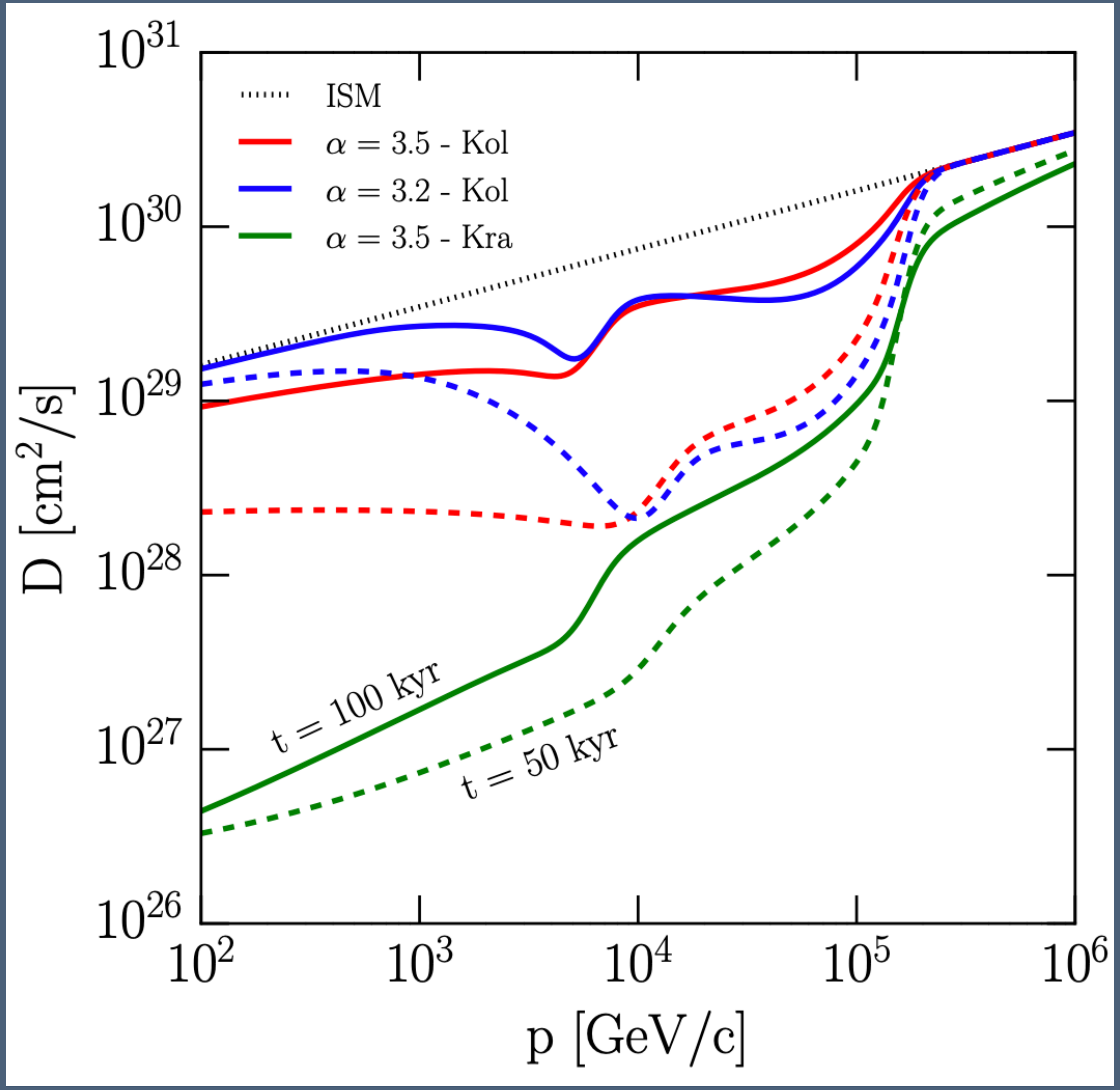
Fundamentals of Diffusion

Fundamentals of Diffusion

Bao et al. (2021; 2107.07395)



Evoli, Linden, Morlino (2018; 1807.09263)



- TeV halo observations indicate diffusion is locally suppressed near energetic pulsars.
- Models predict difference is largest near 10 TeV — TeV sky is much richer than GeV sky!

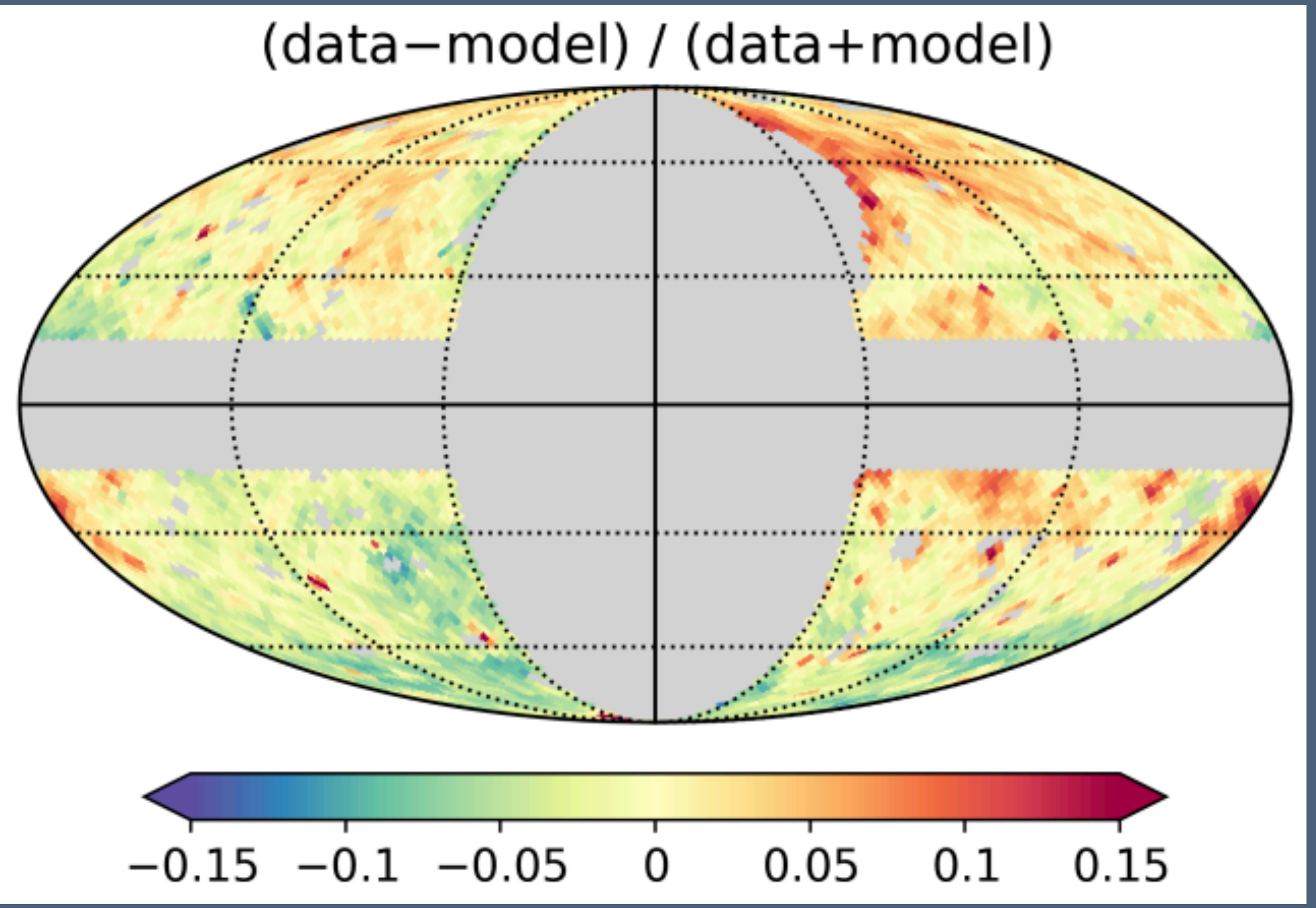
Separating Leptonic and Hadronic Emission

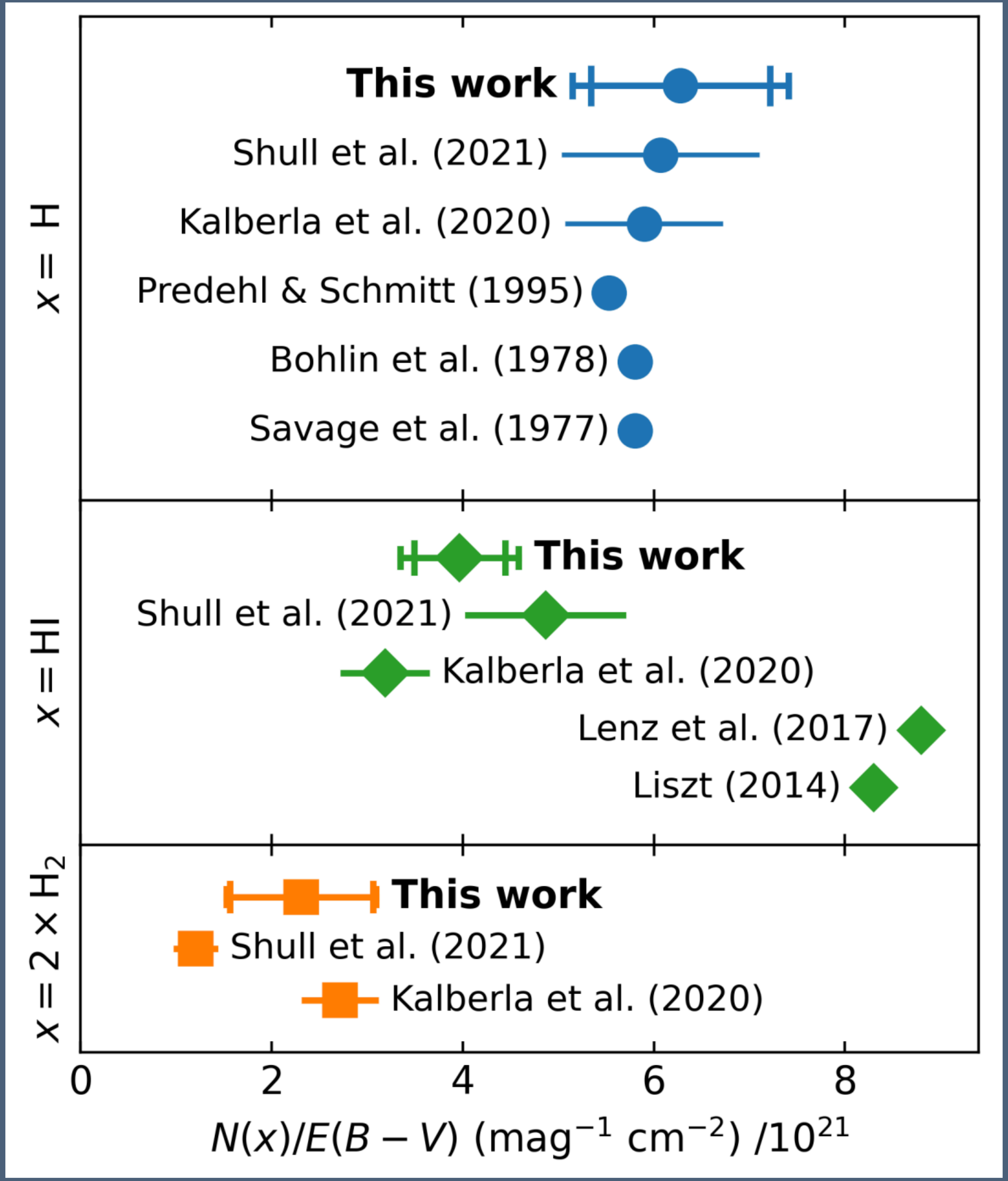
Widmark, Korsmeier, Linden (2022; 2208.11704)

Separating Leptonic and Hadronic Emission

Widmark, Korsmeier, Linden (2022; 2208.11704)

- By observing gamma-rays in the Milky Way, we can constrain the gas density within compact clouds.
- New method for understanding the dust to gas ratio of galaxies.
- Similar accuracy to radio measurements, with independent uncertainties.





Conclusions

- CTA will have an important role in understanding excesses from the Fermi-LAT era, such as the GeV excess.
- The search for dark matter from dwarf spheroidal galaxies will become increasingly focused on a few optimal dwarf targets.
- Searches for axions require an instrument with consistent, deep images spanning from ~100 GeV to 100 TeV.
- Baryons will continue to be the largest problem in dark matter searches — understanding astrophysical signatures better is the key to making any real progress.