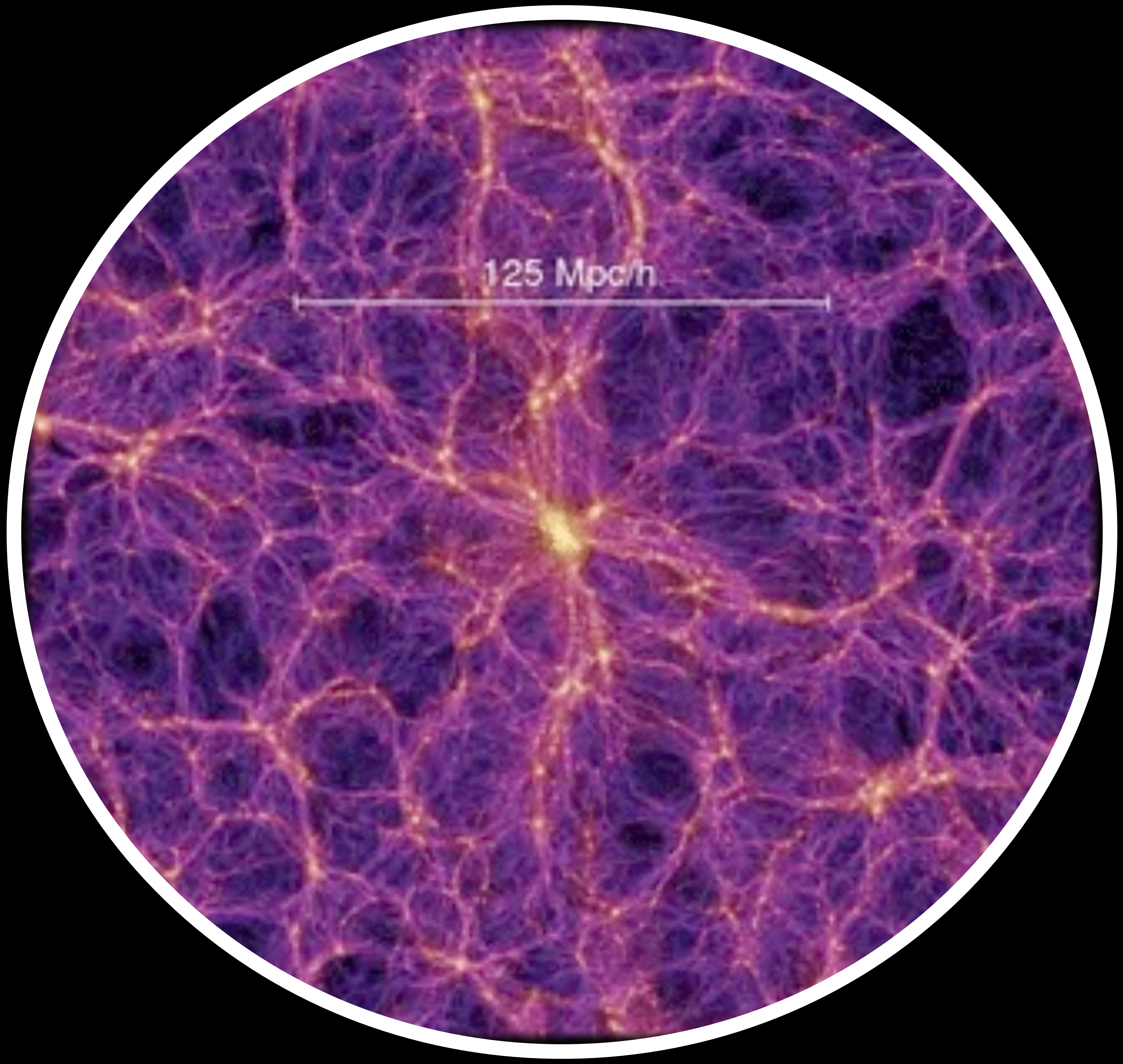
Thermal WIMP Dark Matter on the Brink

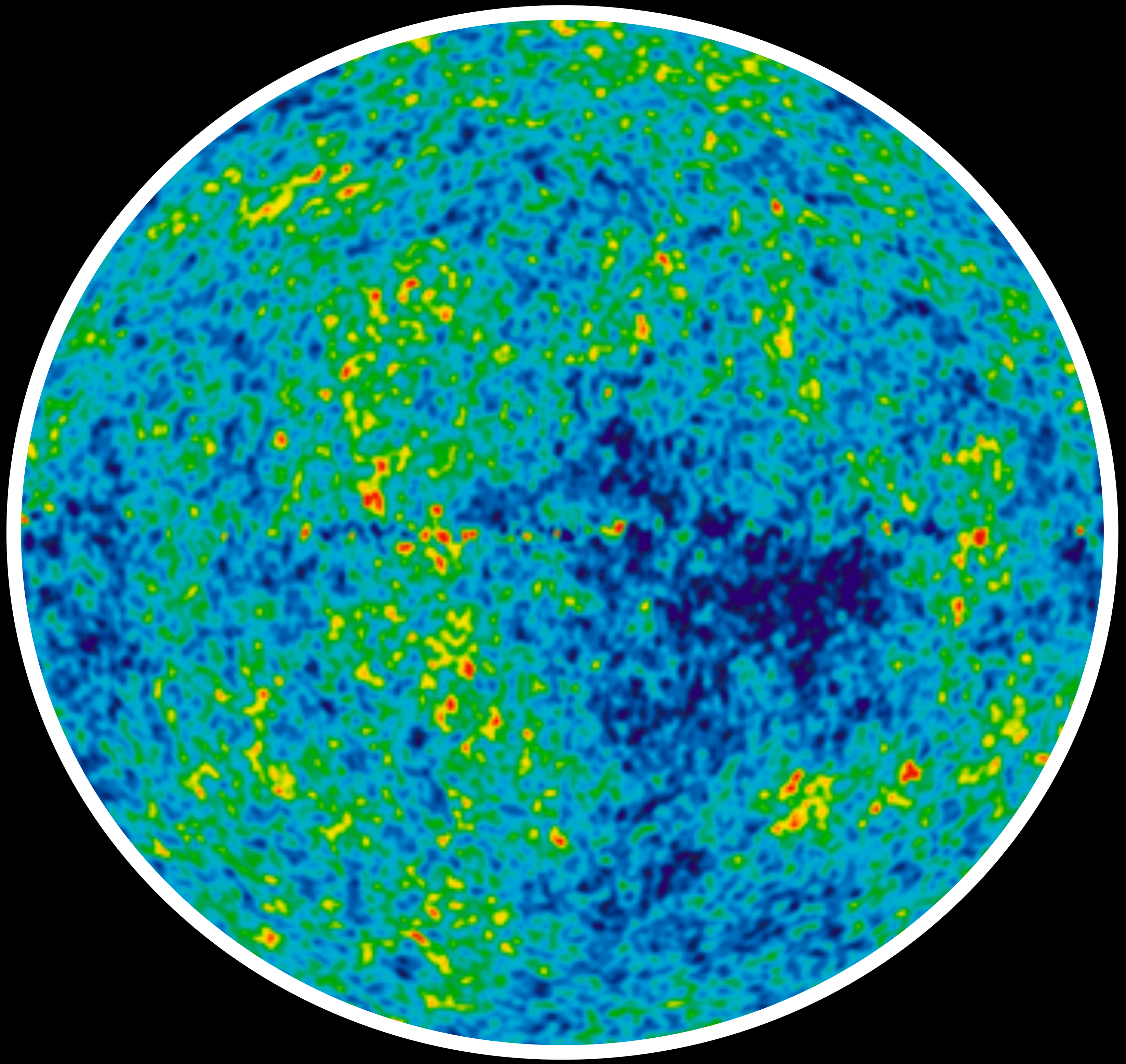
Tim Linden

Stockholm University

What Do We Know About Dark Matter?

What Do We Know About Dark Matter?





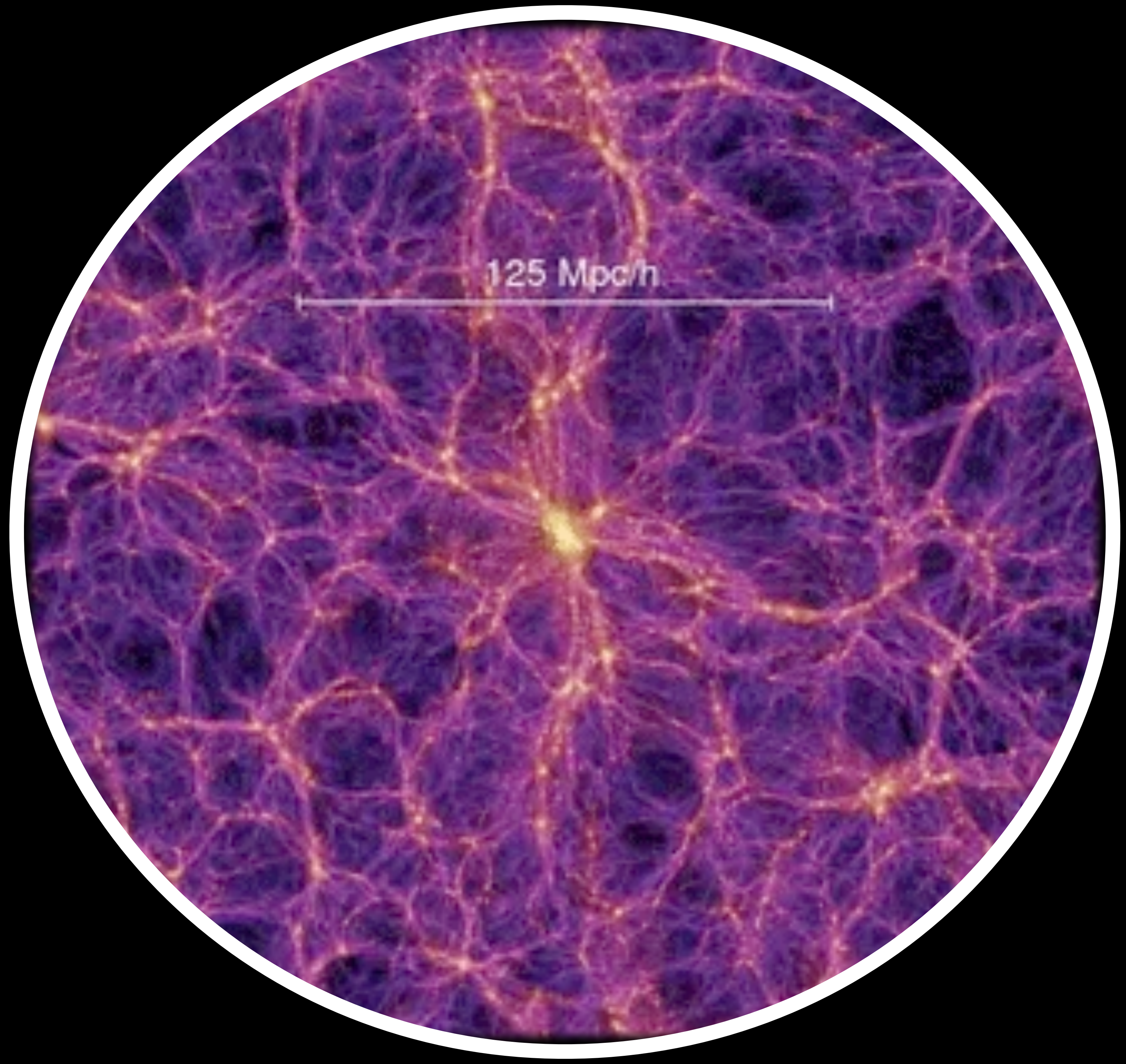
How a cosmologist views the evidence for dark matter.

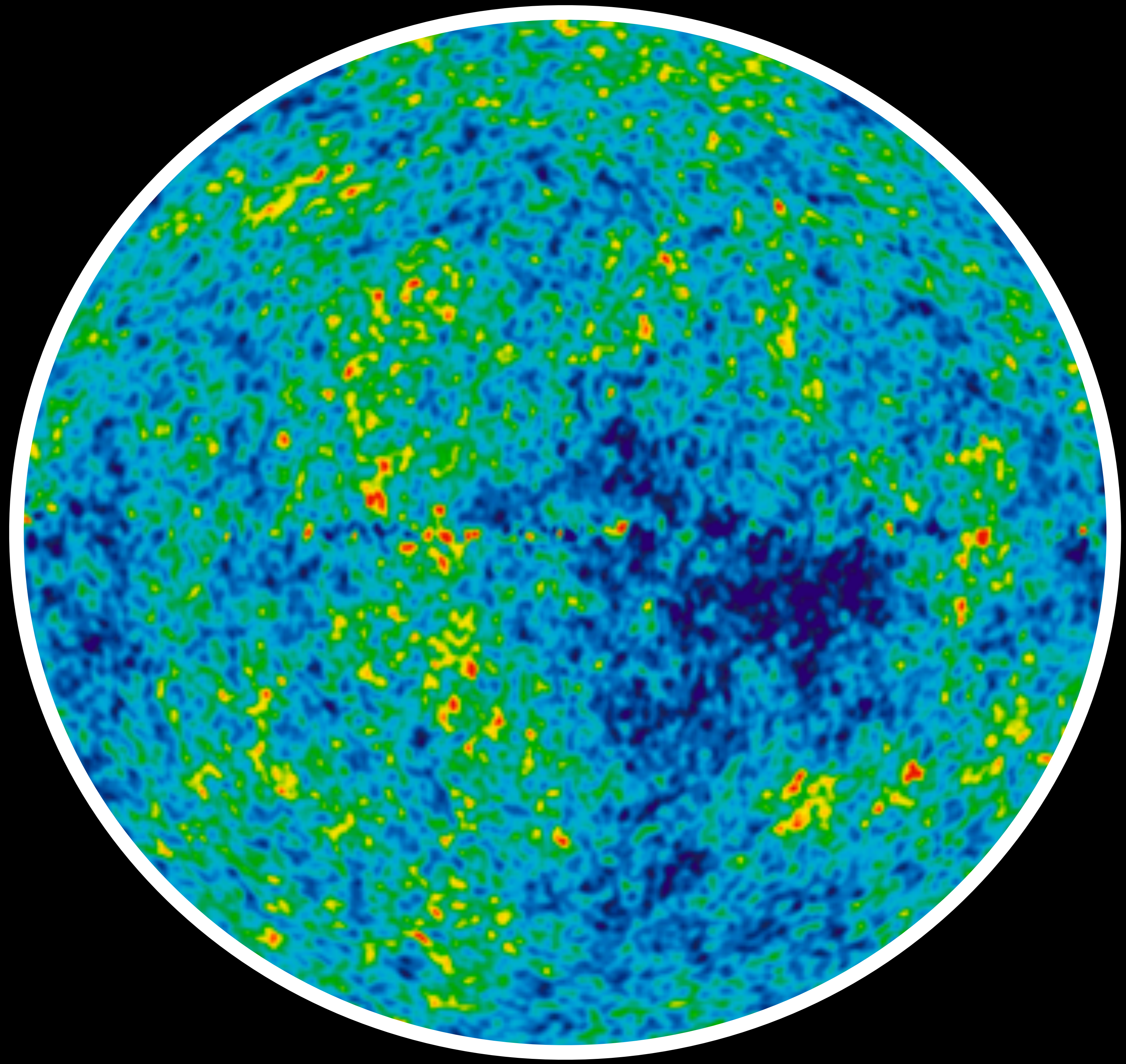
What Do We Know About Dark Matter?

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 ~10% of the baryonic content.
- Most mass must be dark!

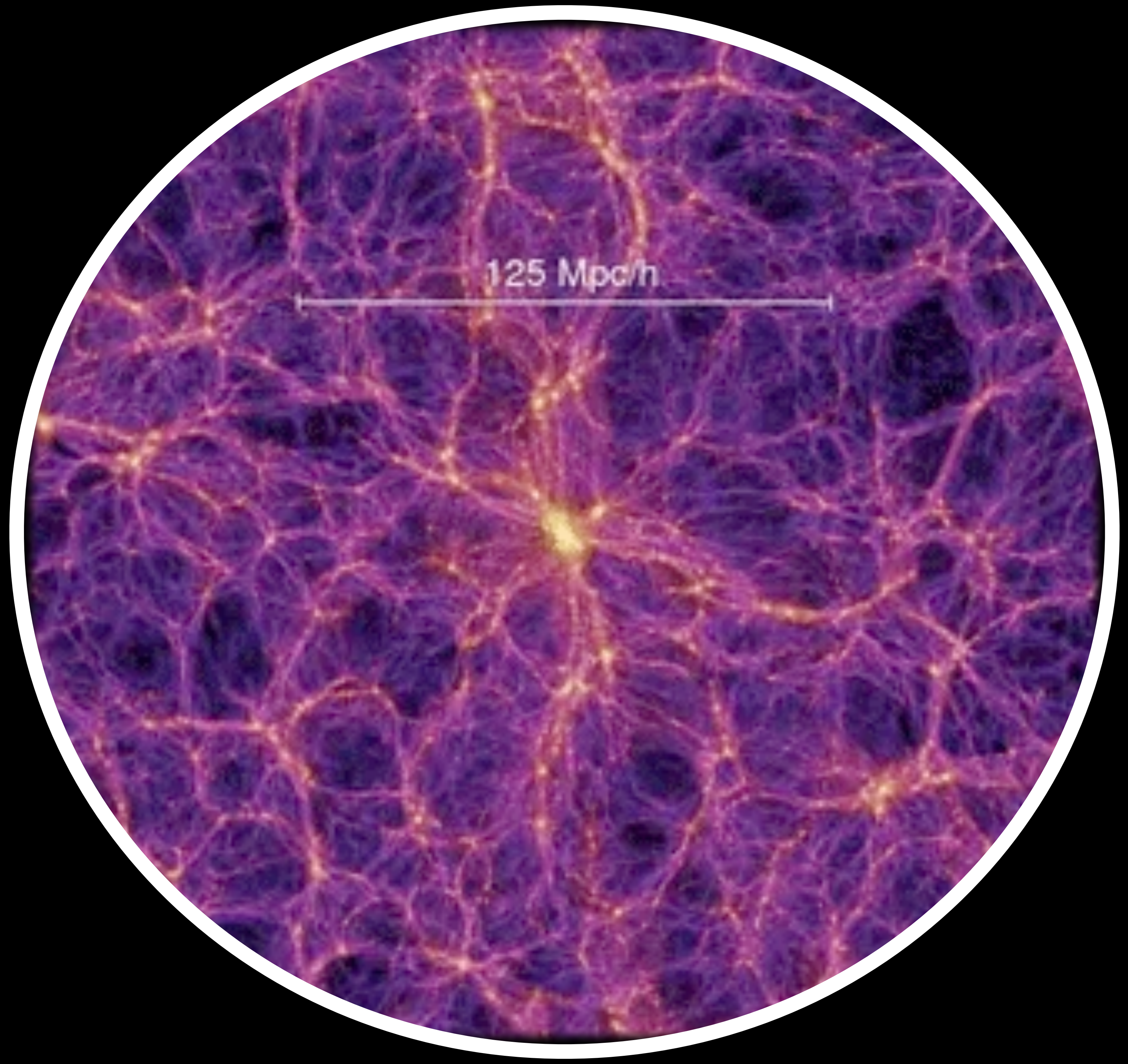
What Do We Know About Dark Matter?

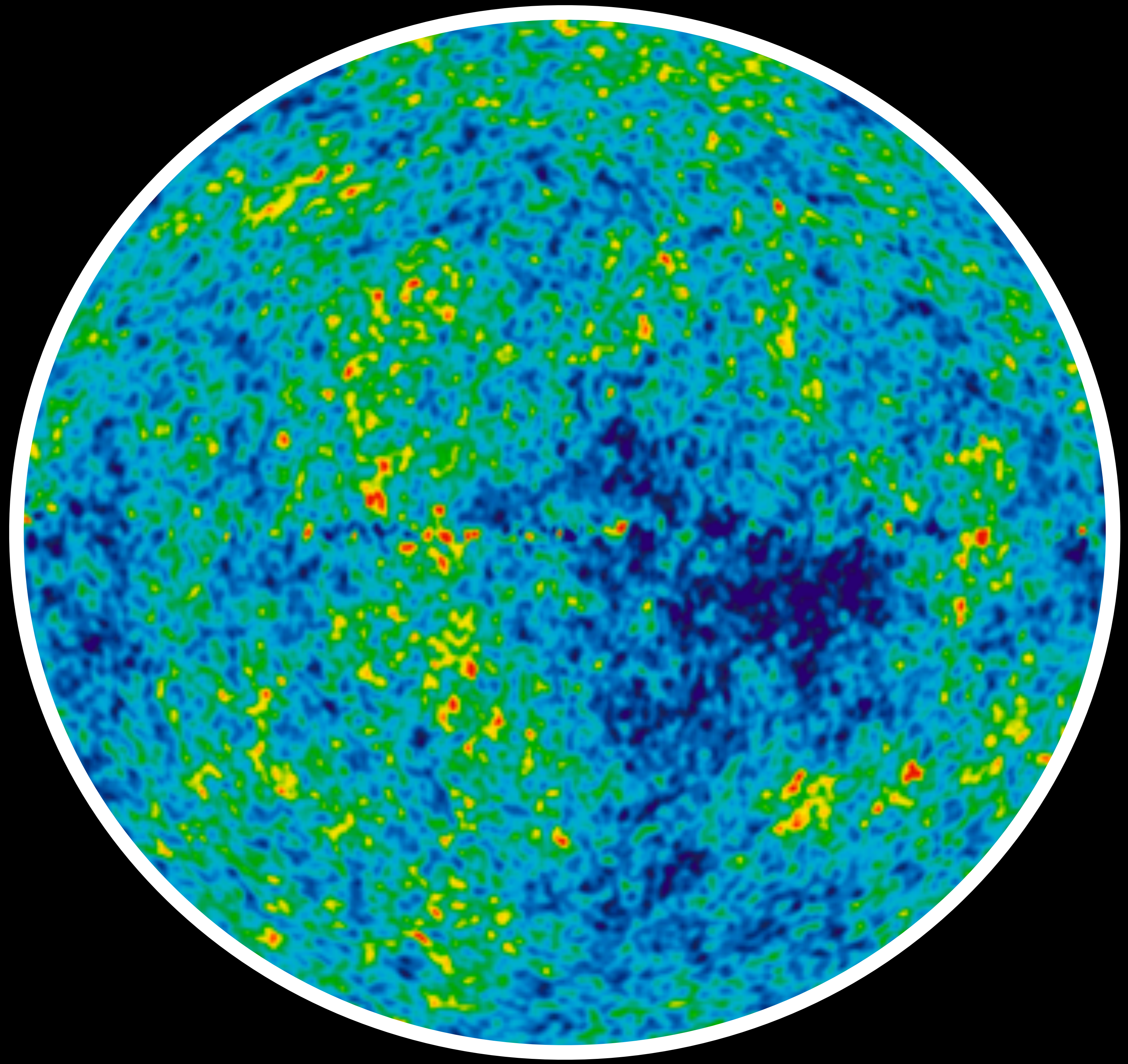




How a cosmologist views the evidence for dark matter.

What Do We Know About Dark Matter?





Early Universe:

Radiation - Provides pressure that smears out over density.

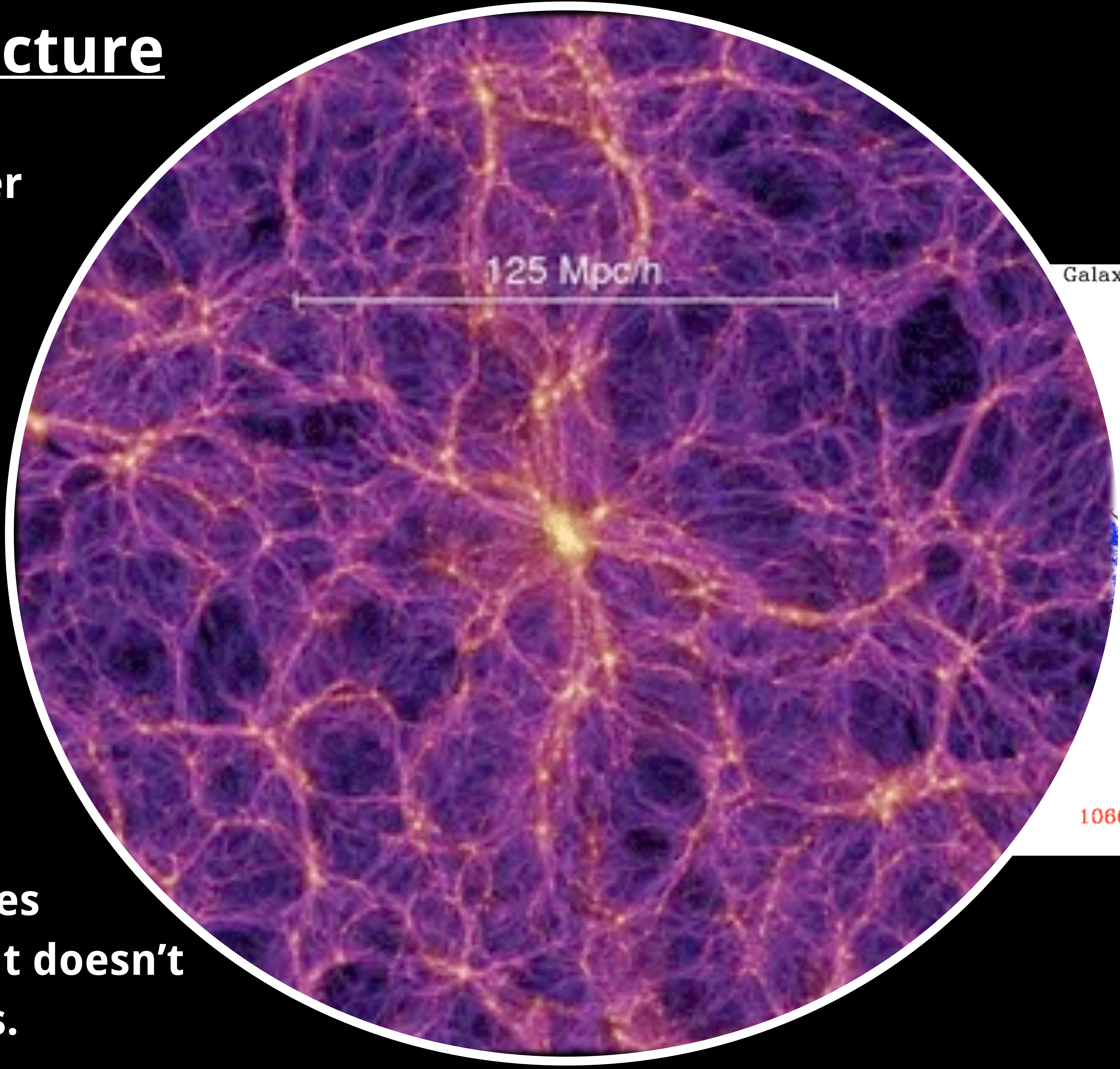
Baryonic Matter - Gravitational potential, but responds to radiation.

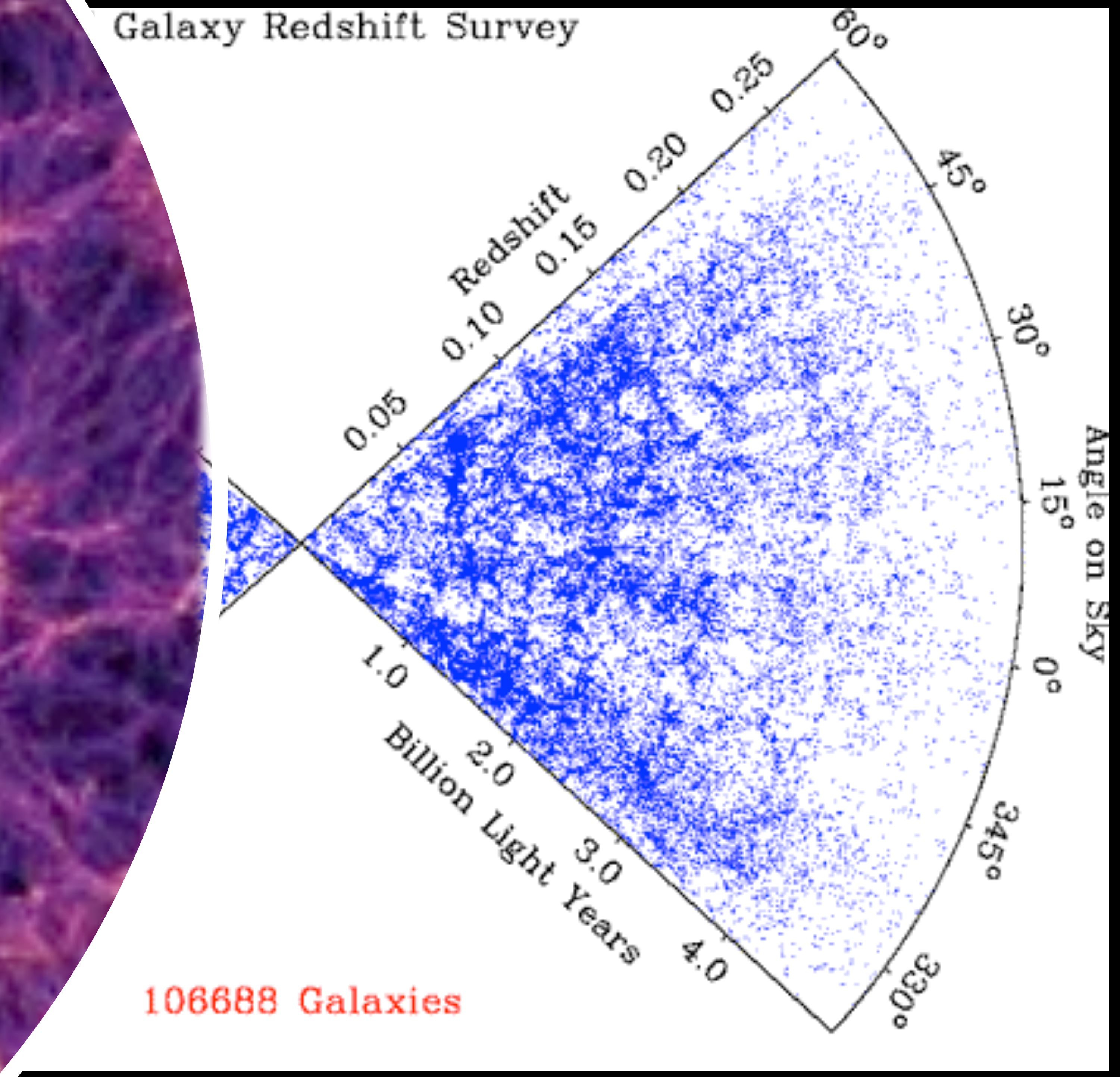
Dark Matter - Gravitational potential, does not respond to radiation.

What Do We Know About Dark Matter?

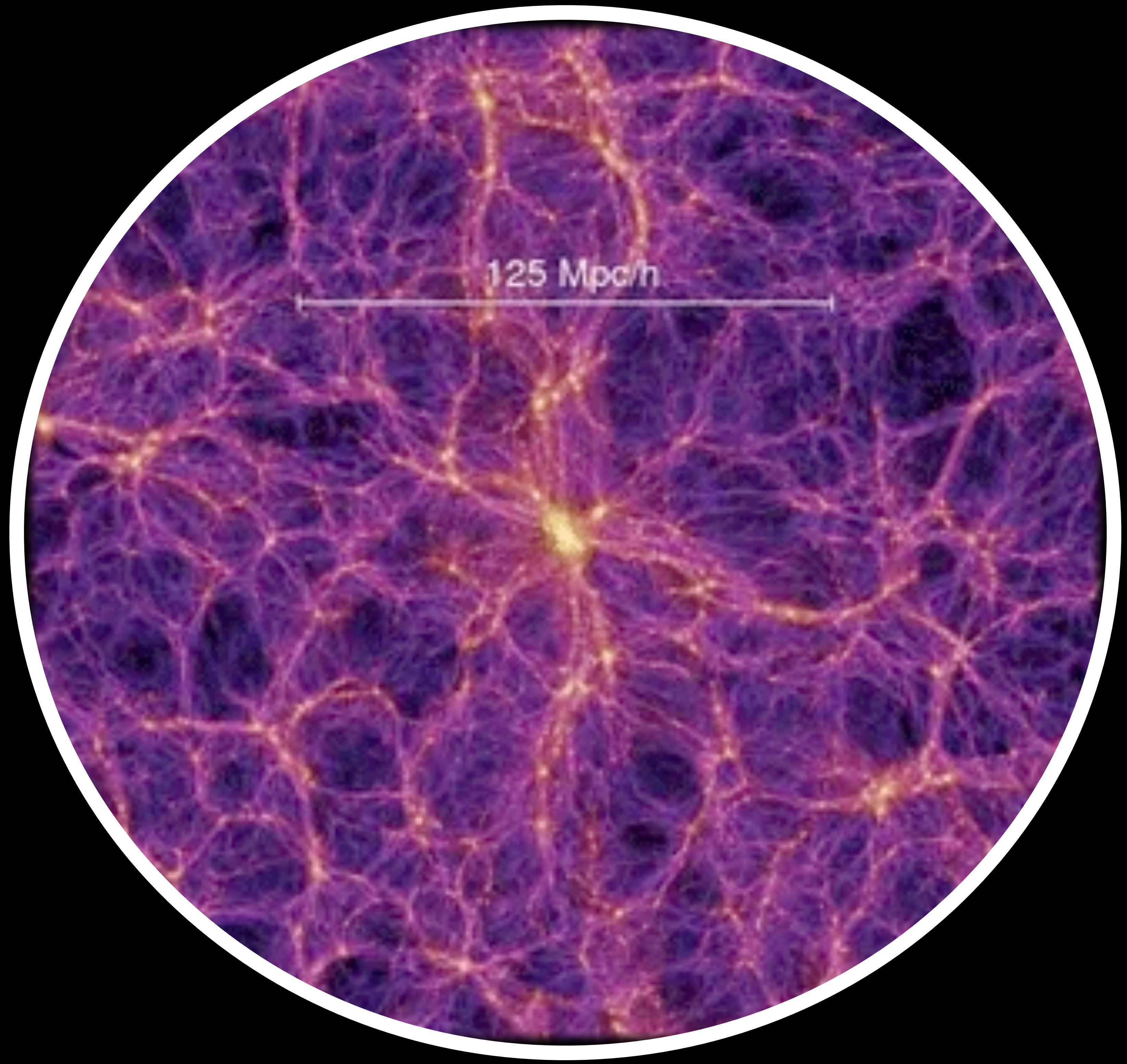
Large Scale Structure

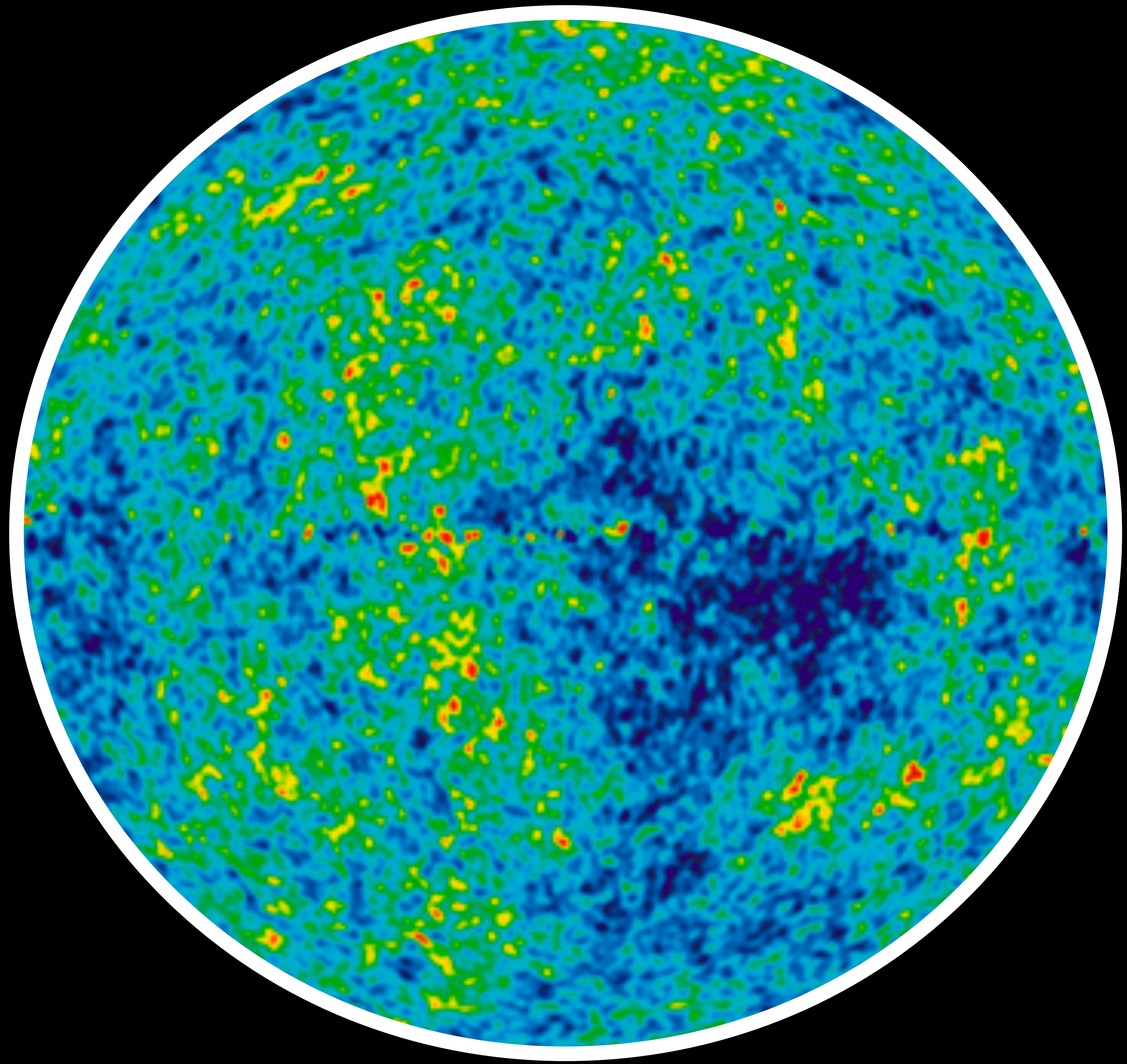
- When baryonic matter collapse it heats up.
- This produces photons that cause the matter to expand (baryonic acoustic oscillations).
- Distribution of galaxies requires a matter that doesn't interact with photons.





What Do We Know About Dark Matter?





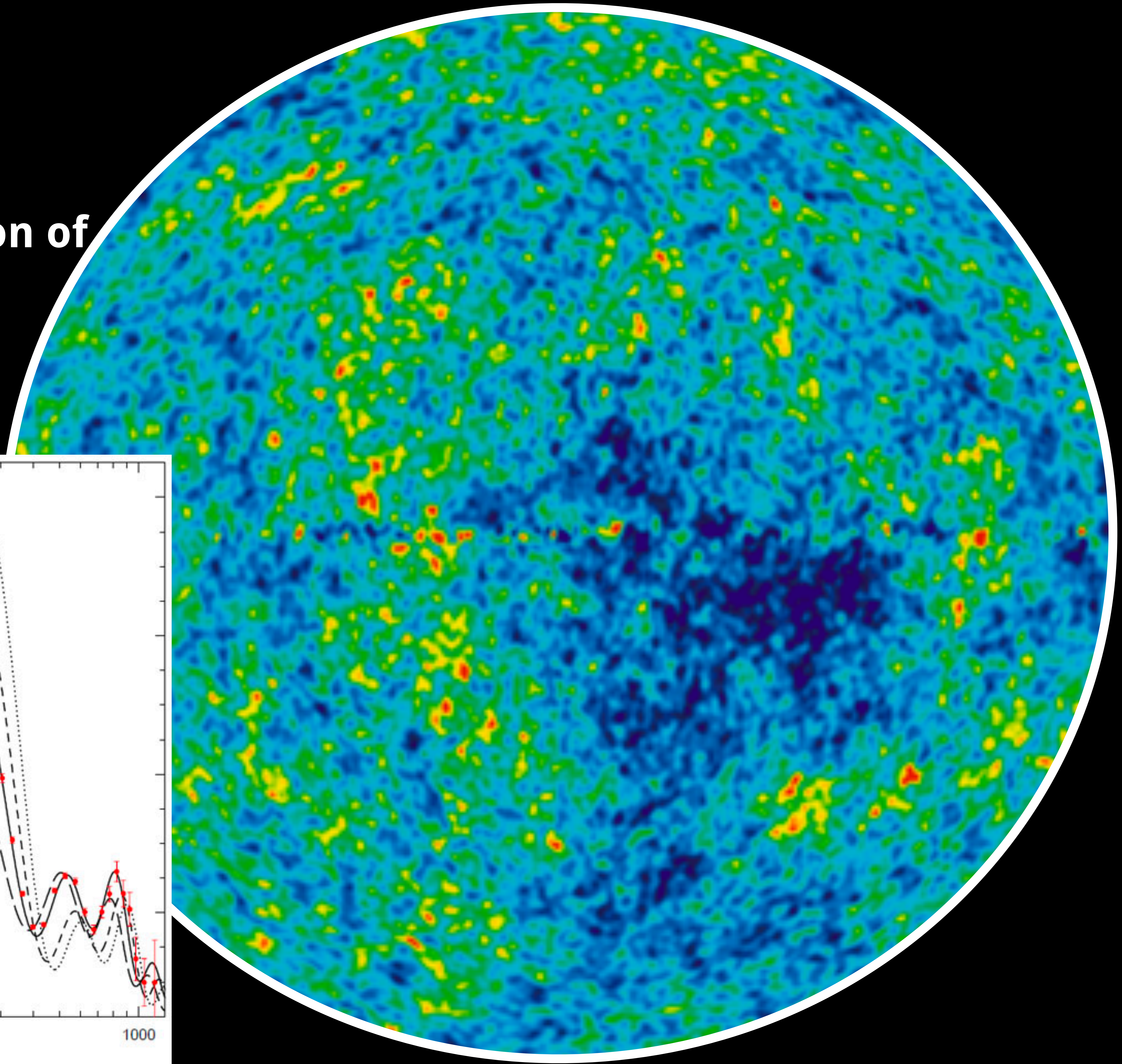
How a cosmologist views the evidence for dark matter.

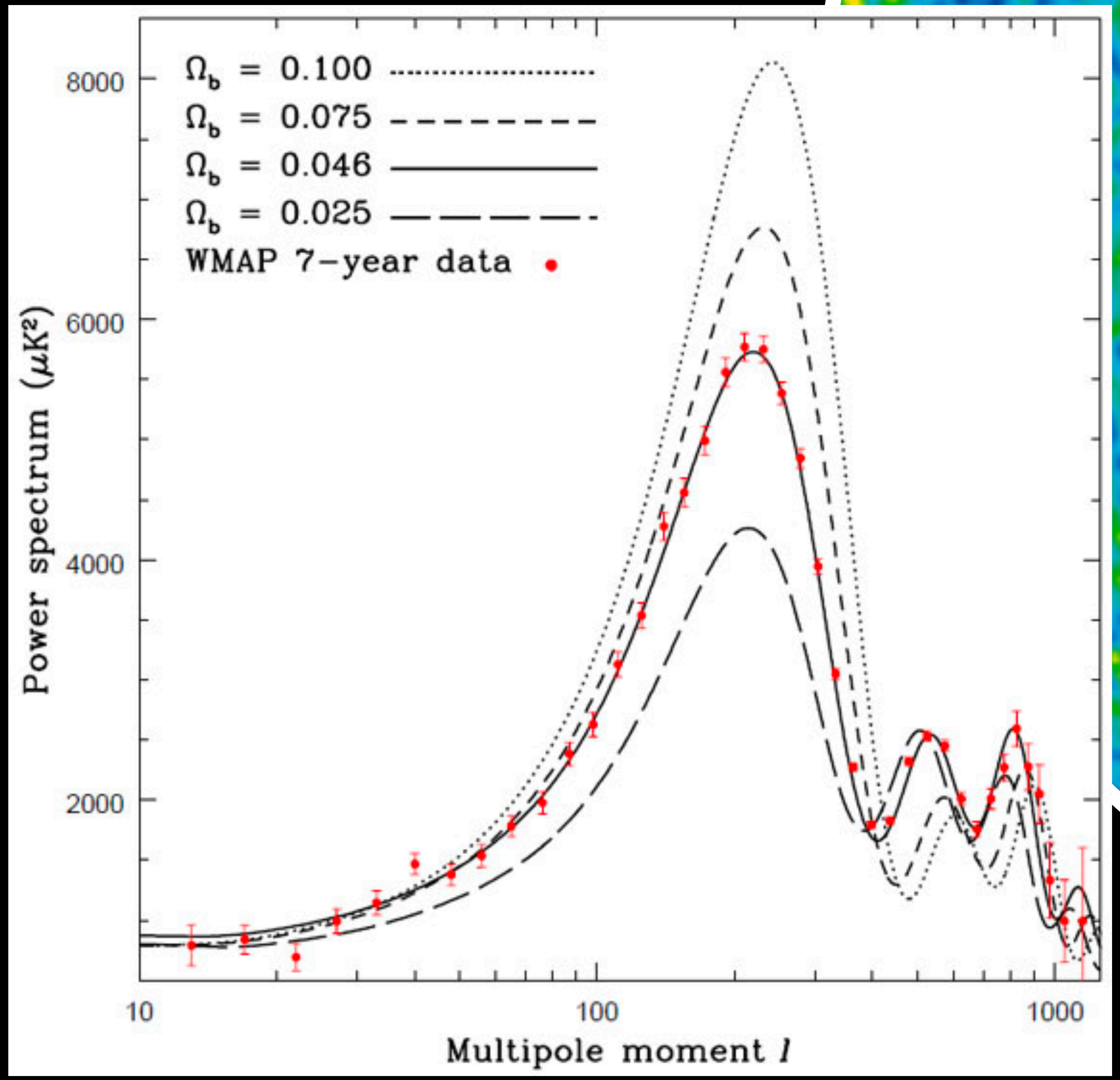
What Do We Know About Dark Matter?

Cosmic Microwave Background

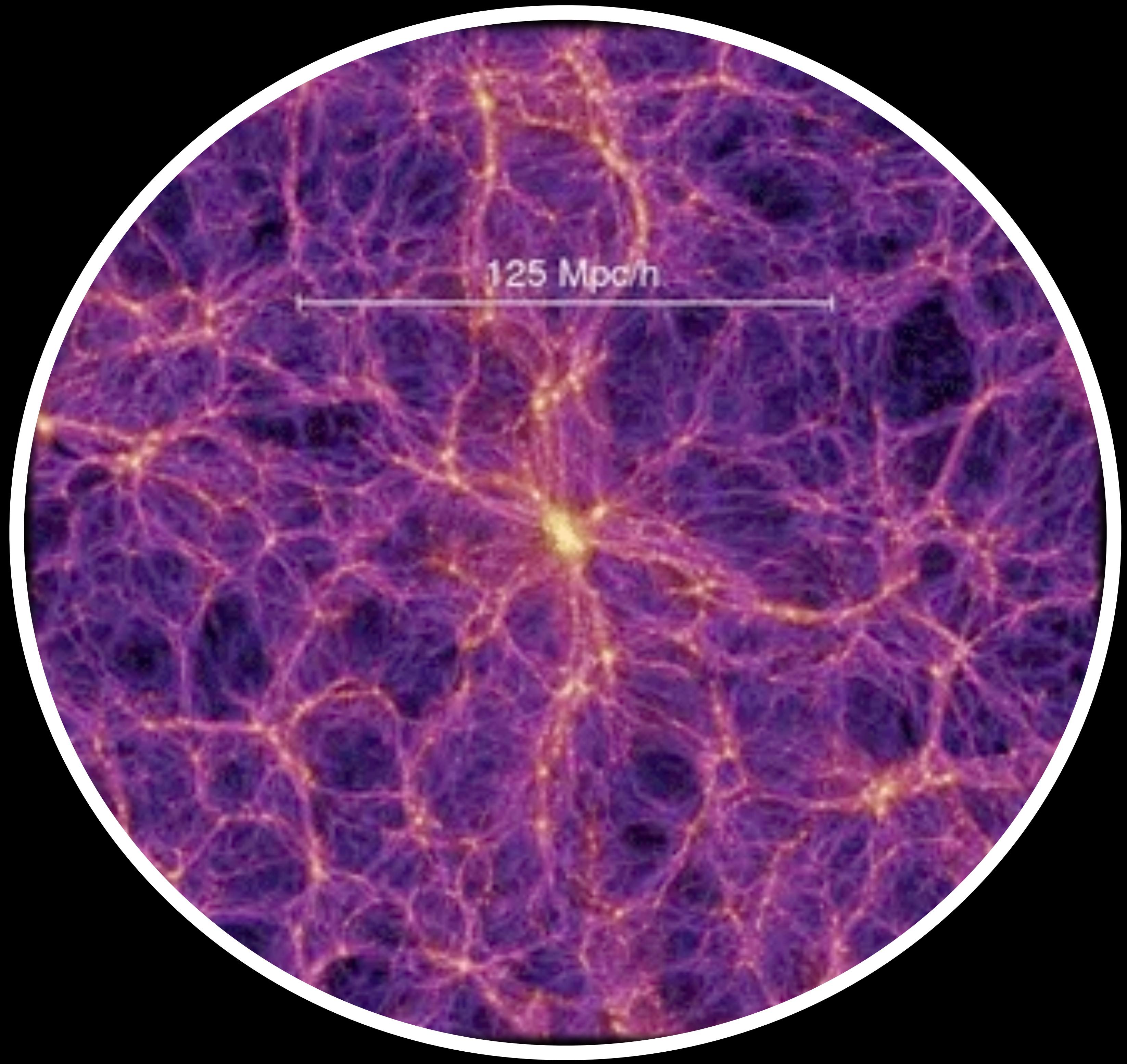
- Interaction of radiation (photons) with cold matter (baryons) controls angular distribution of structure in the early stages of the universe.

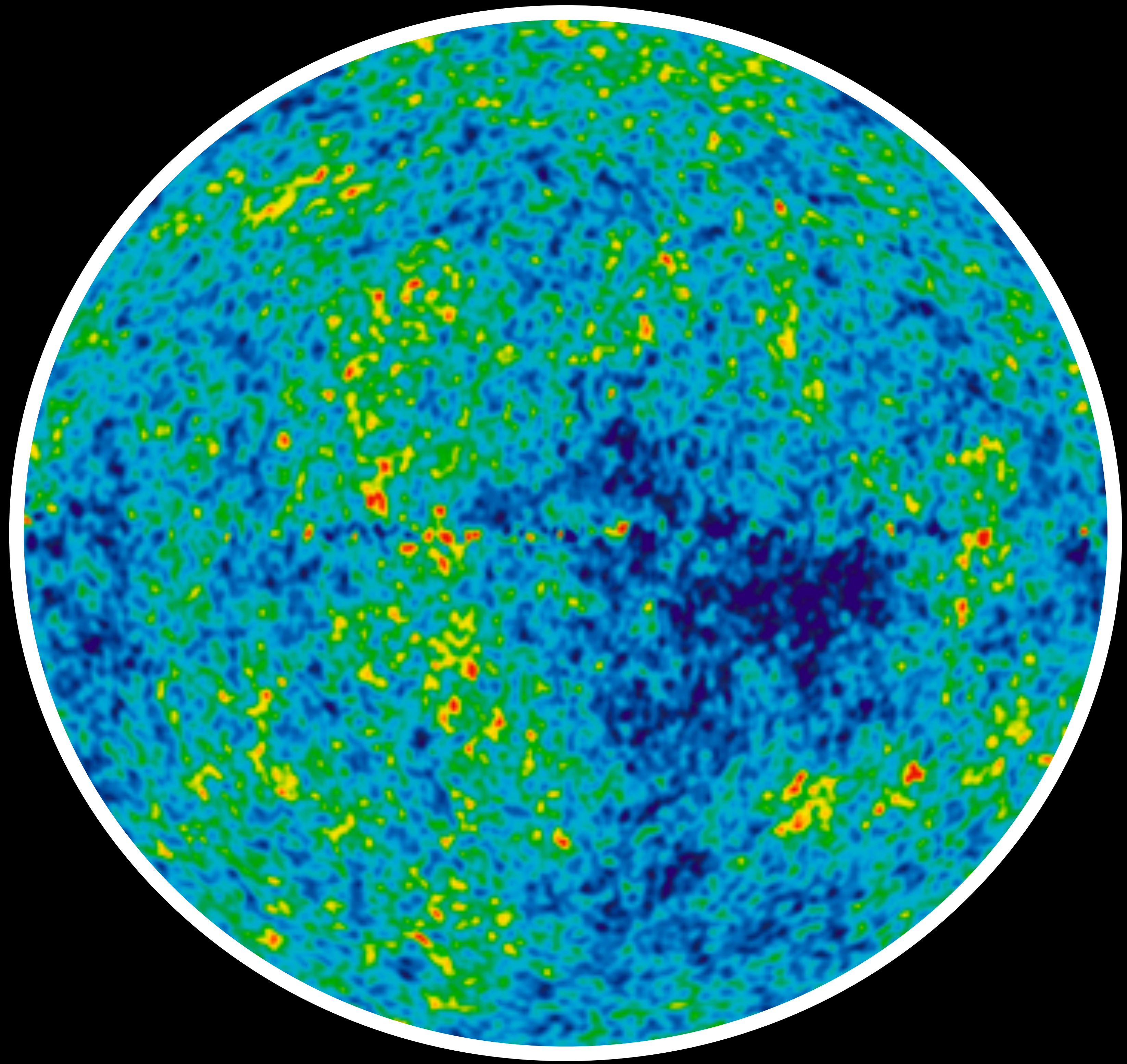
- Large component that doesn't interact with radiation is needed.





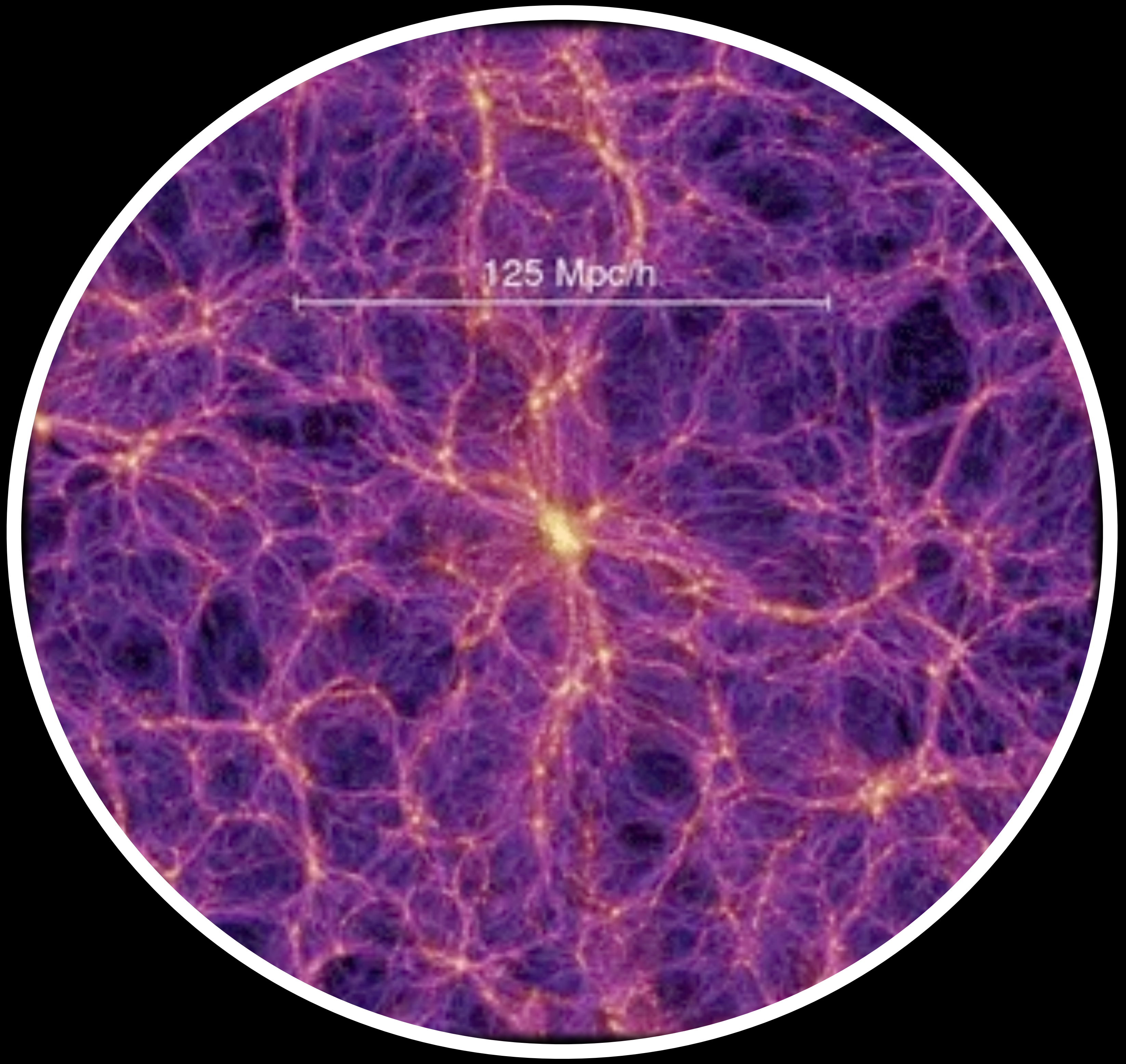
The Present

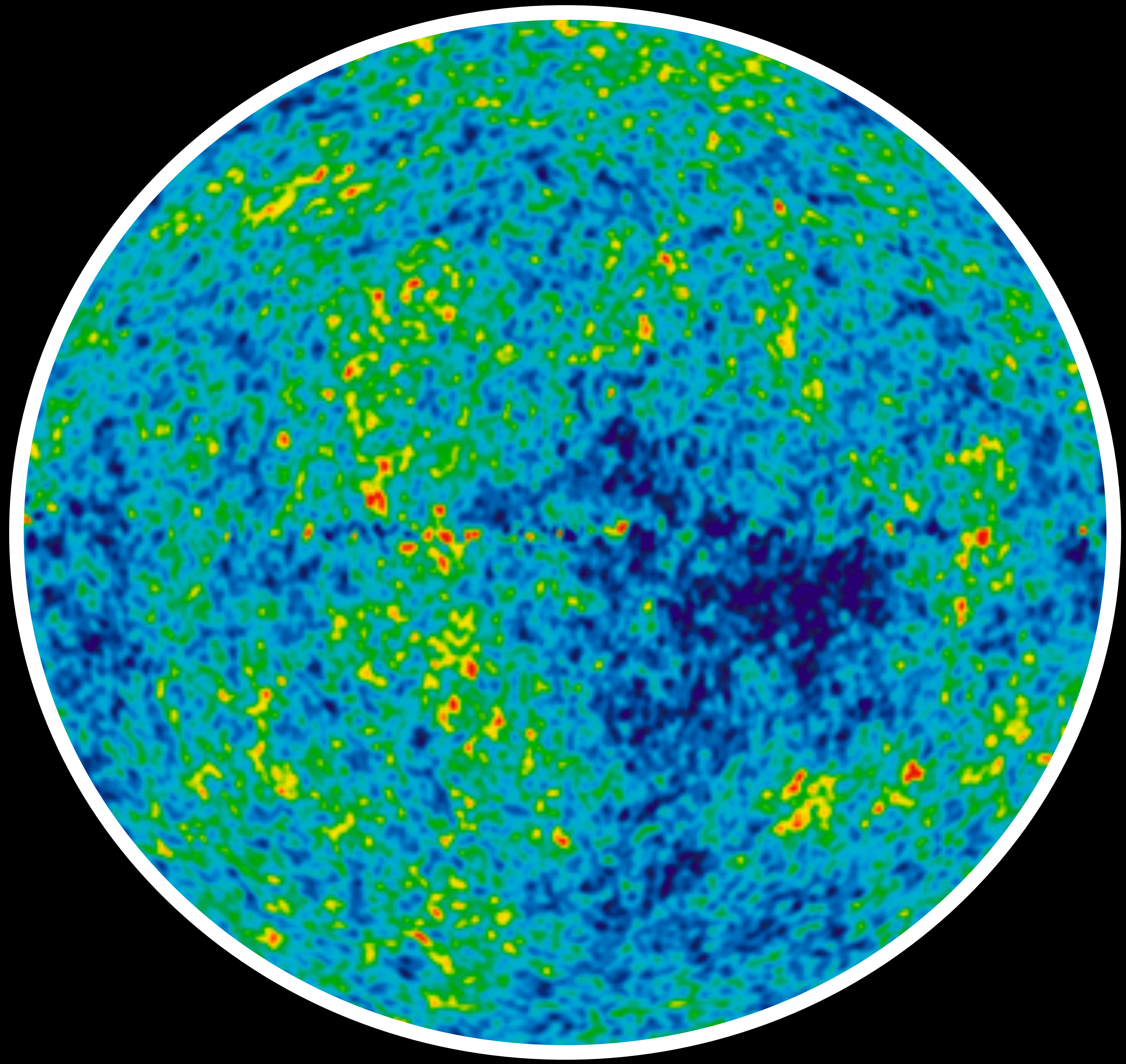




How a cosmologist views the evidence for dark matter.

The Present





10^{-22} GeV

$R_{DM} > R_{UFD}$

10^{62} GeV

$M_{DM} > M_{UFD}$

slide concept courtesy of Asher Berlin

The Present

courtesy: Tim Tait

10^{-22} GeV

$R_{DM} > R_{UFD}$

10^{62} GeV

$M_{DM} > M_{UFD}$

slide concept courtesy of Asher Berlin


topic

Tim Linden

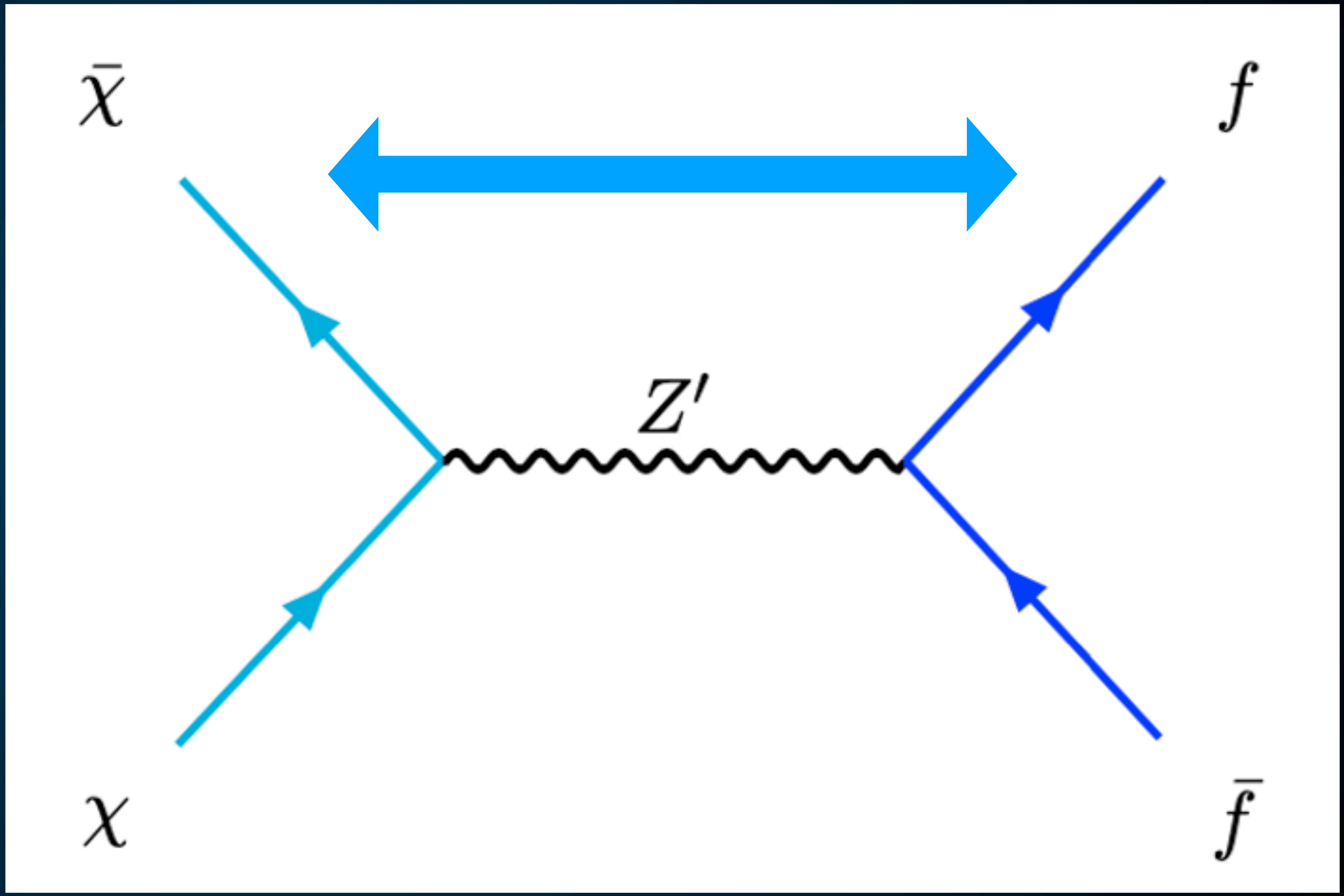
Thermal WIMP Dark Matter on the Brink

Stockholm University

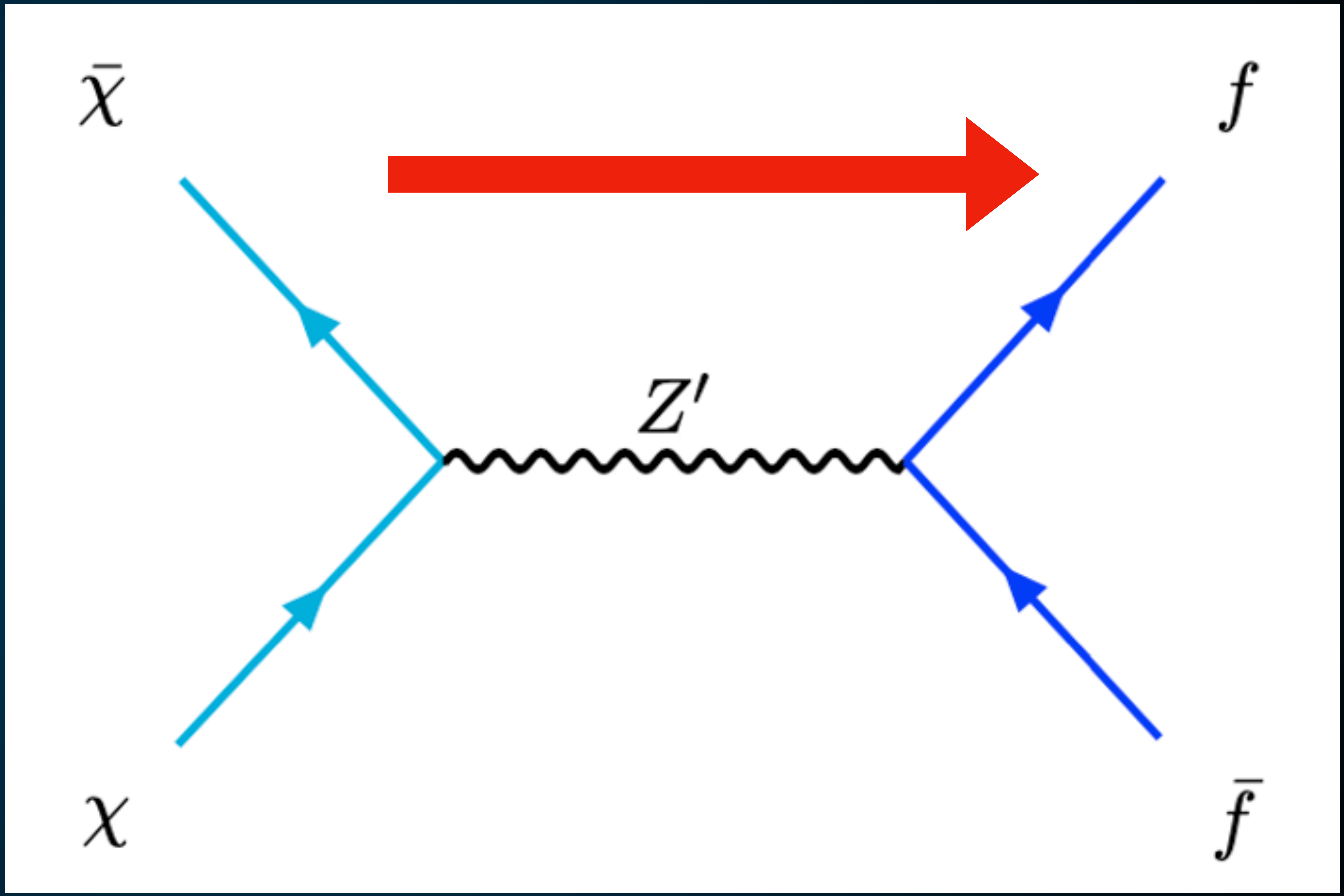
Thermal Dark Matter

artist: Sarah Szabo

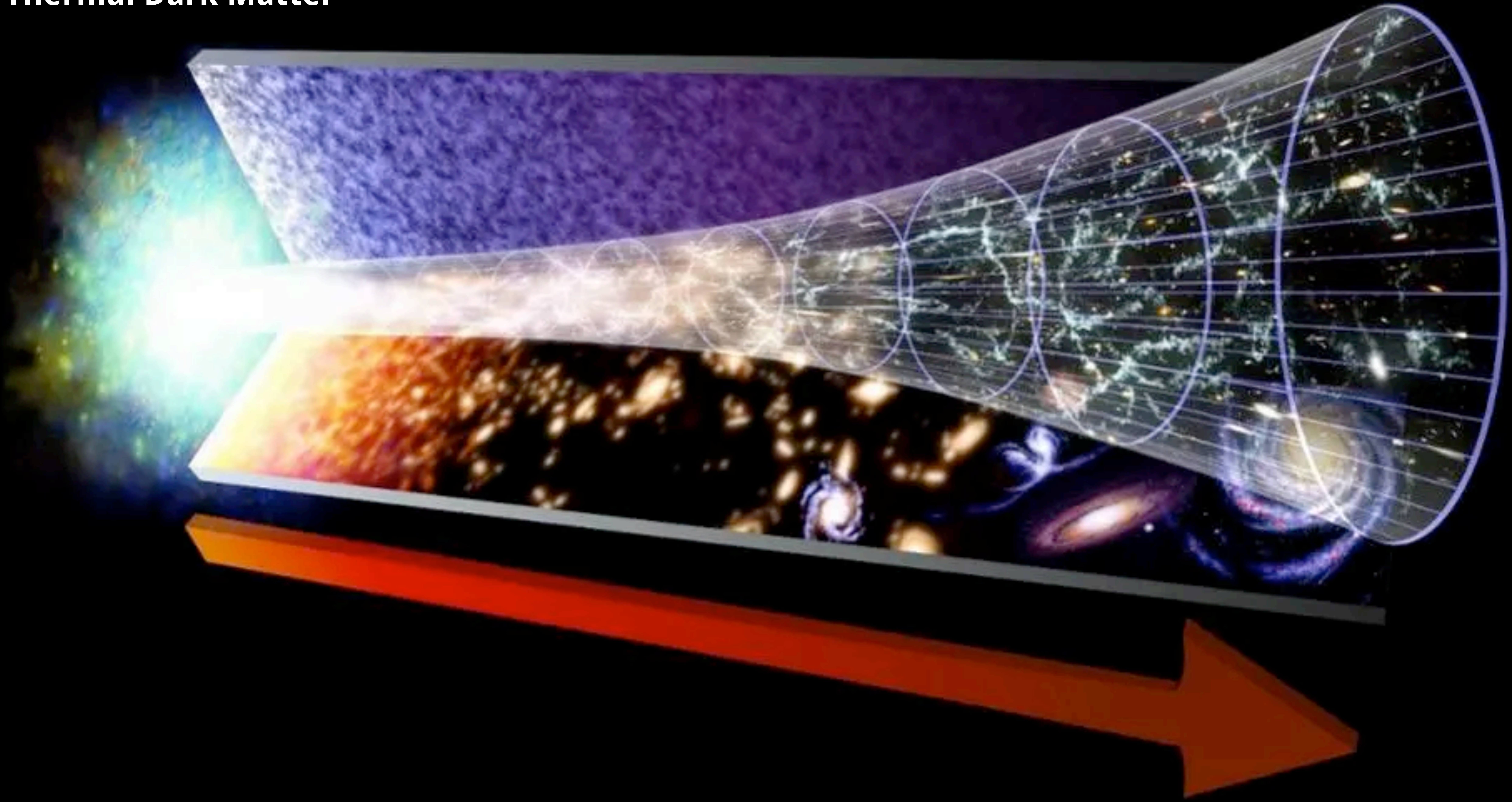
Thermal Dark Matter

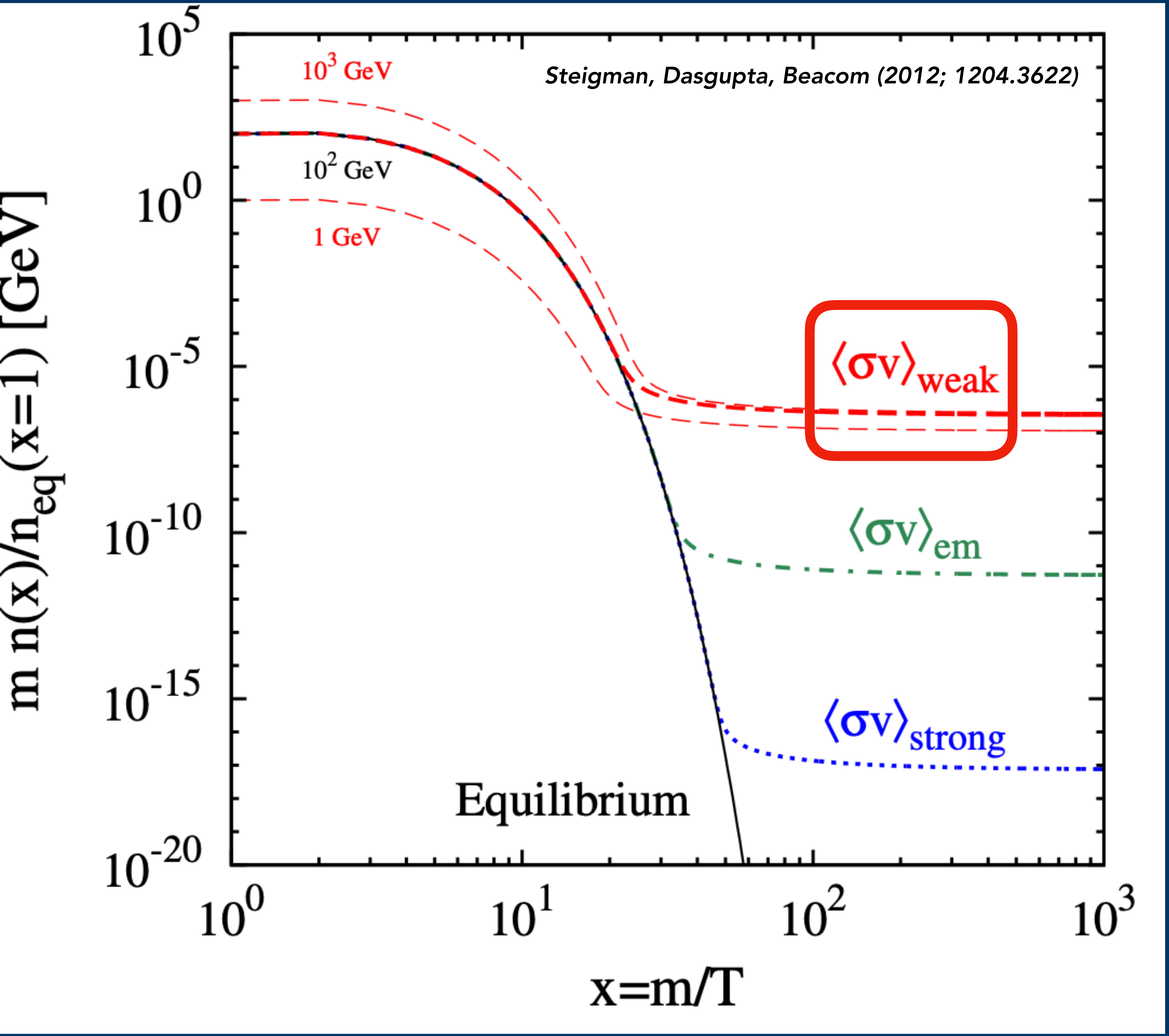


Thermal Dark Matter



Thermal Dark Matter



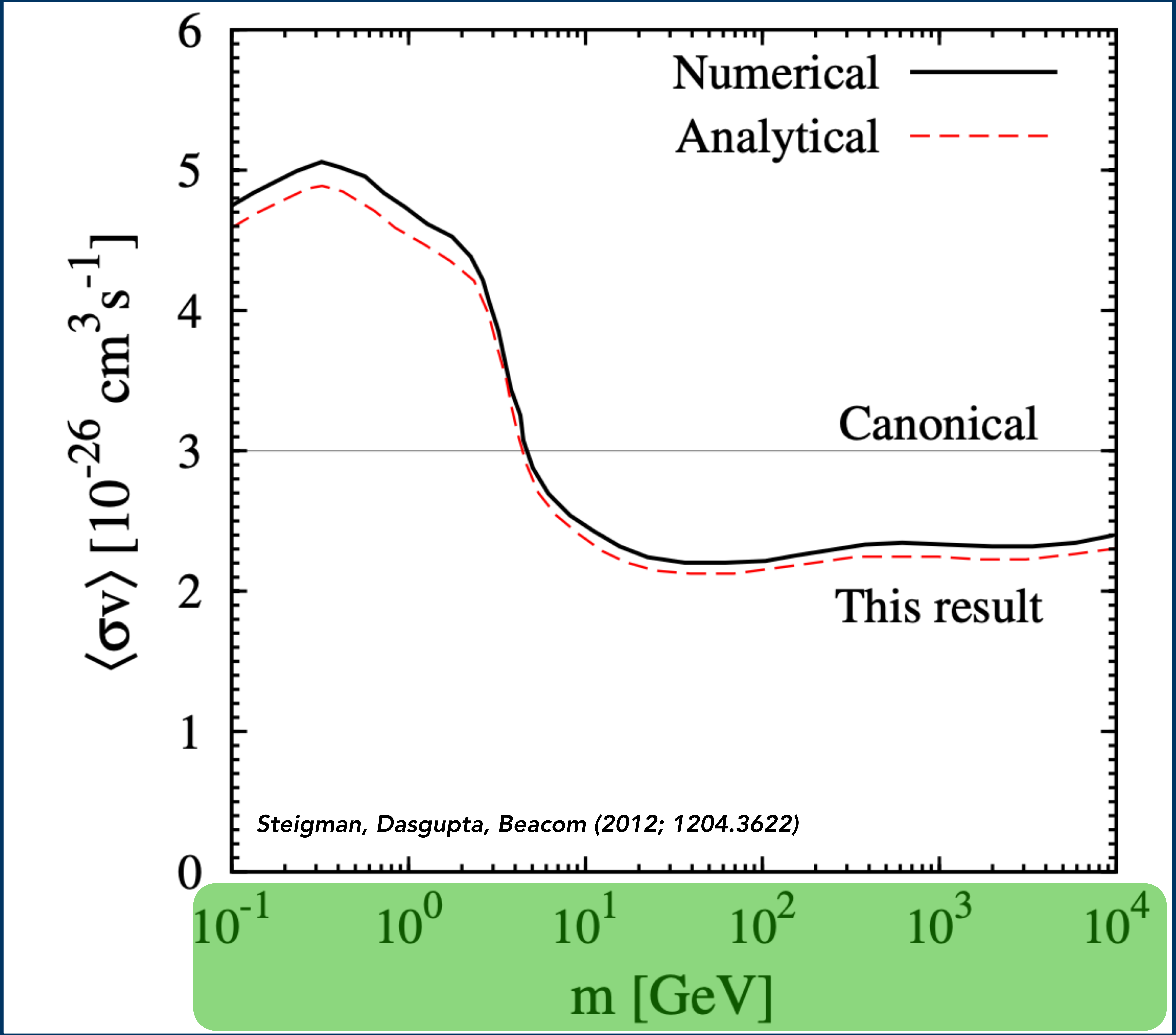


Thermal Dark Matter Density

Present density inversely proportional to the strength of the interaction.

Almost independent of particle mass.

Weak-Interaction Produces the right density!



Thermal Dark Matter

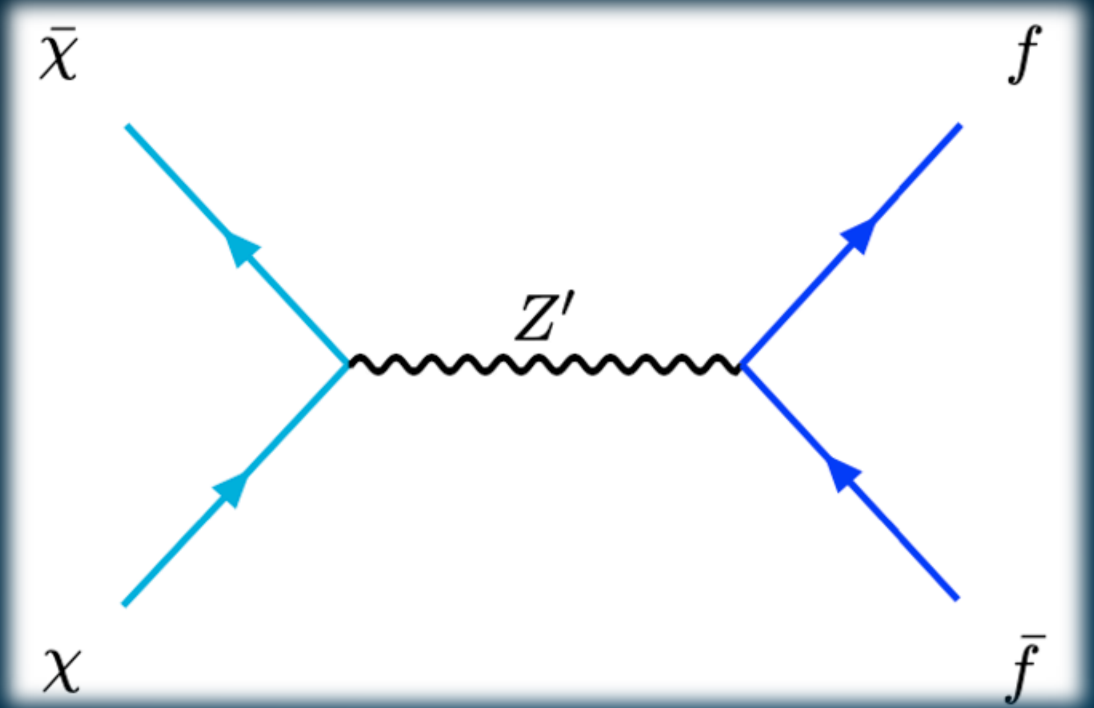
Simplest model has a known cross-section!

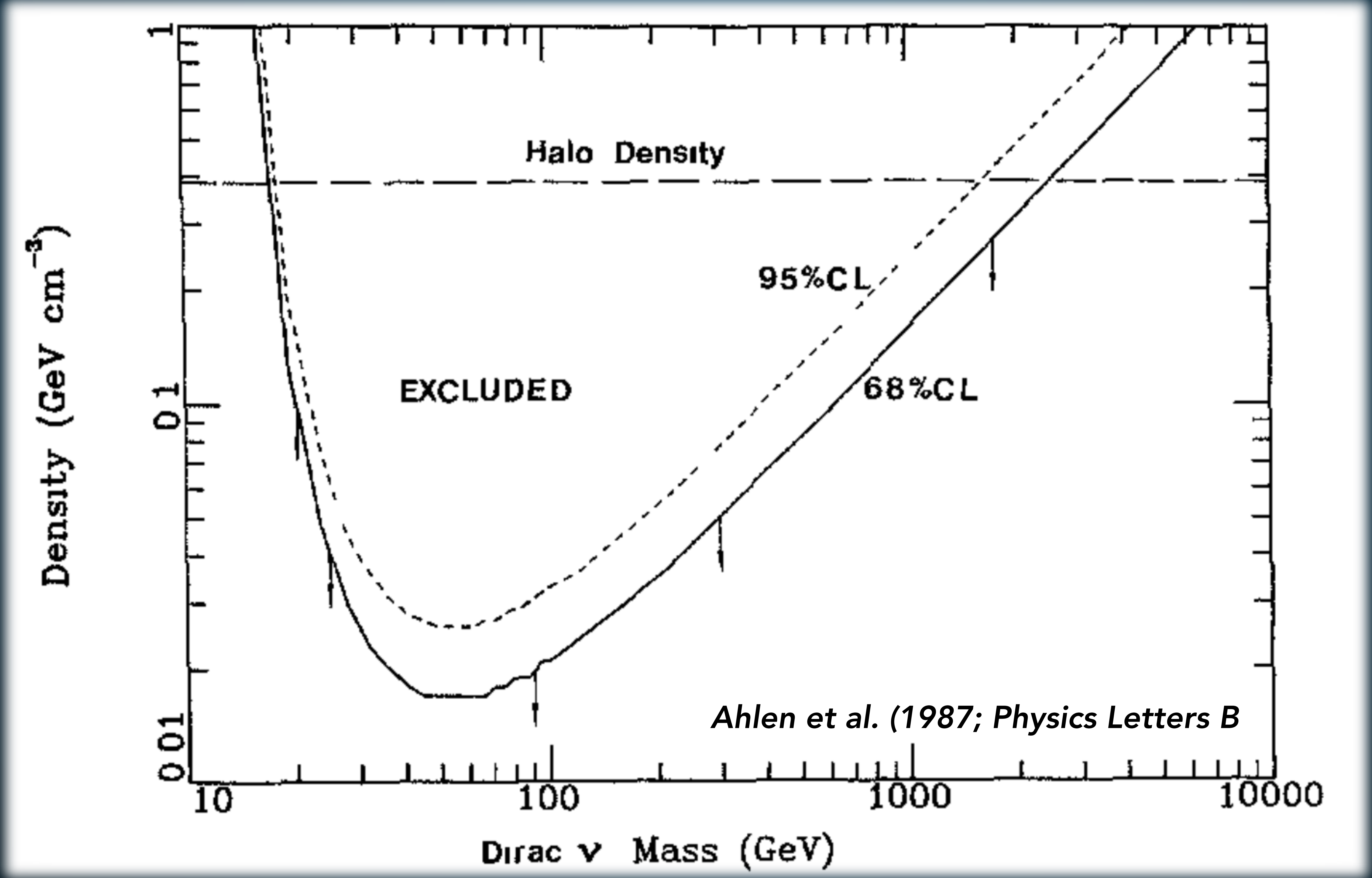
Deviations from this cross-section include complicating effects.

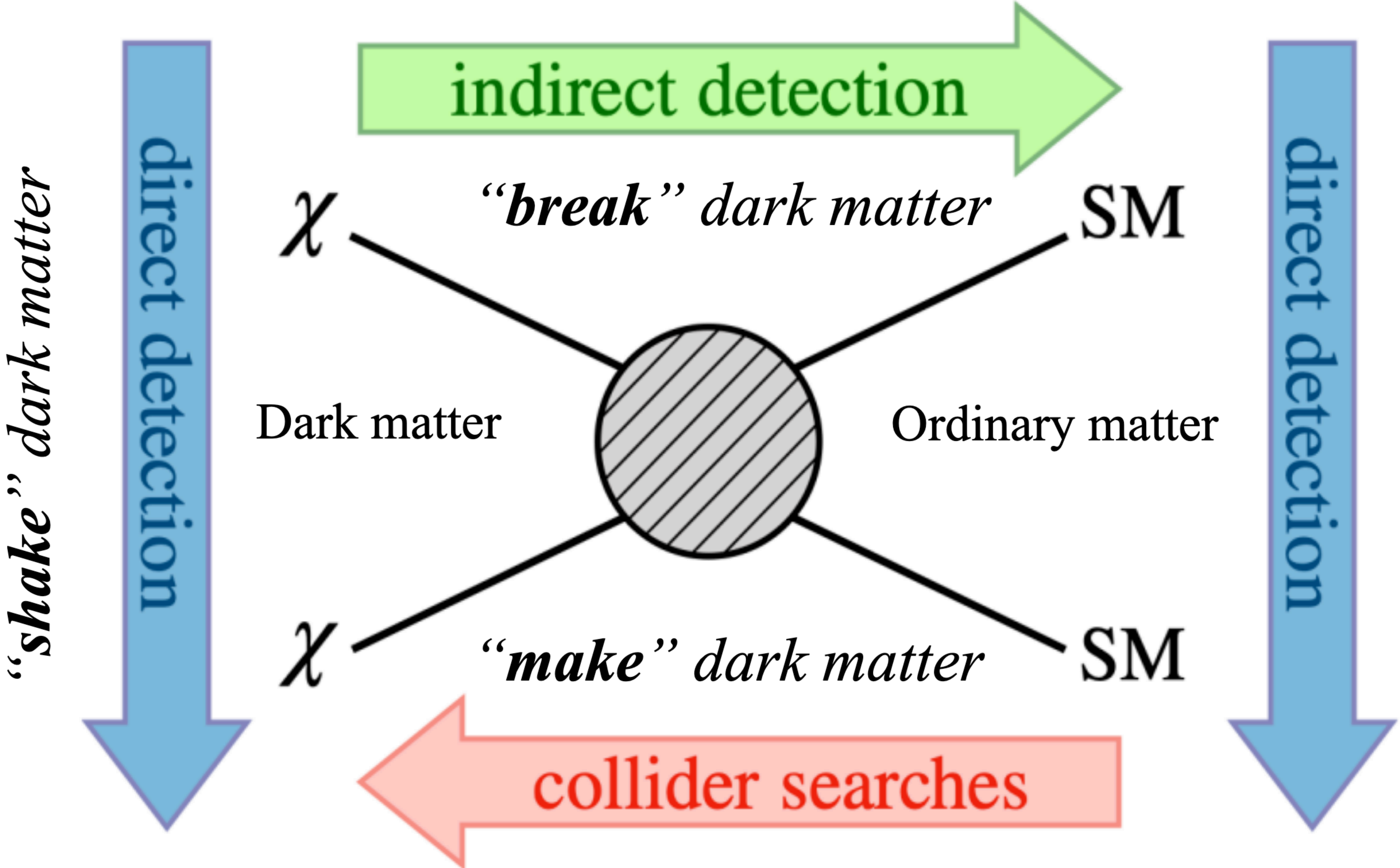
A Mass Scale!

Can We Eliminate Classes of Dark Matter Models?

Yes!

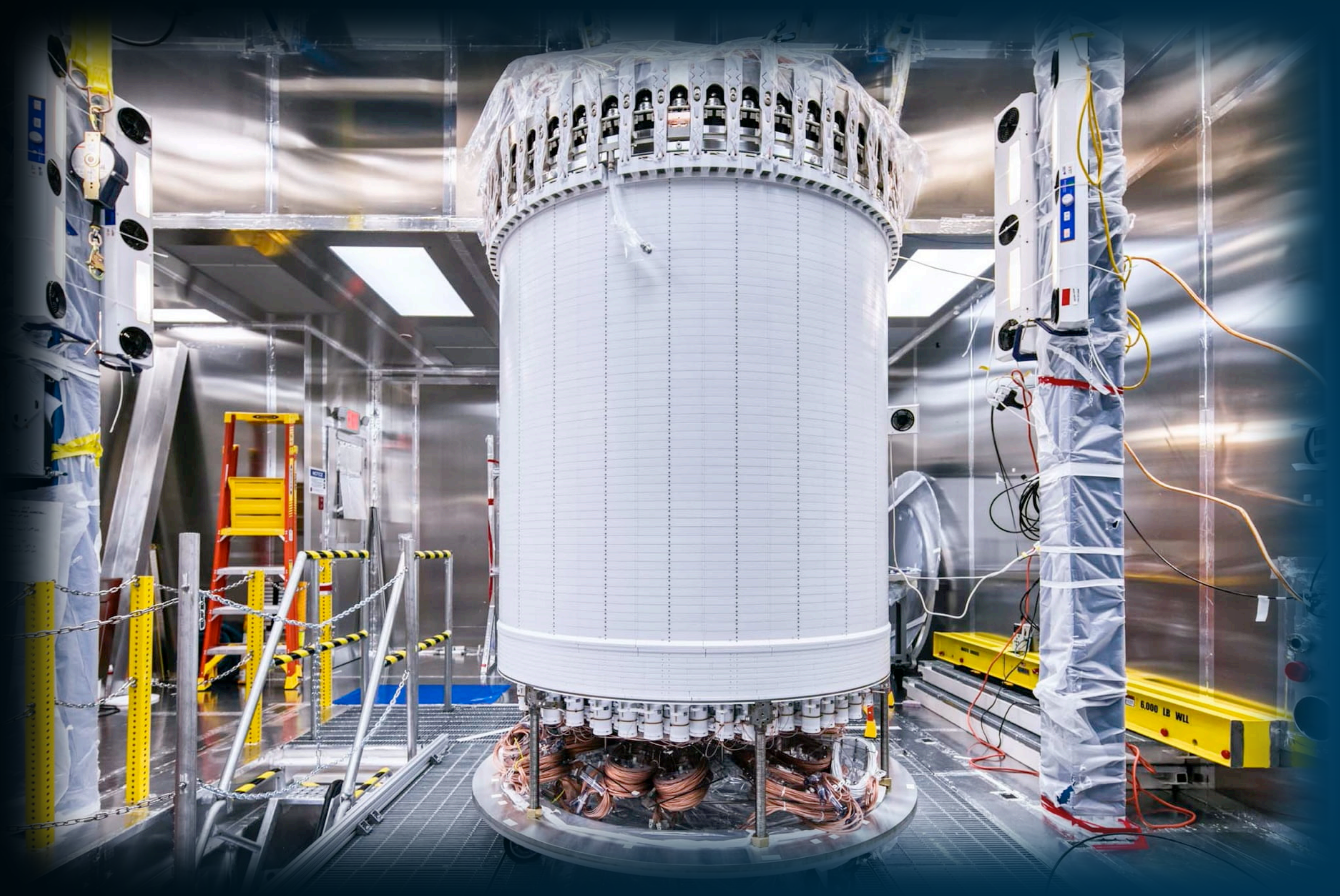


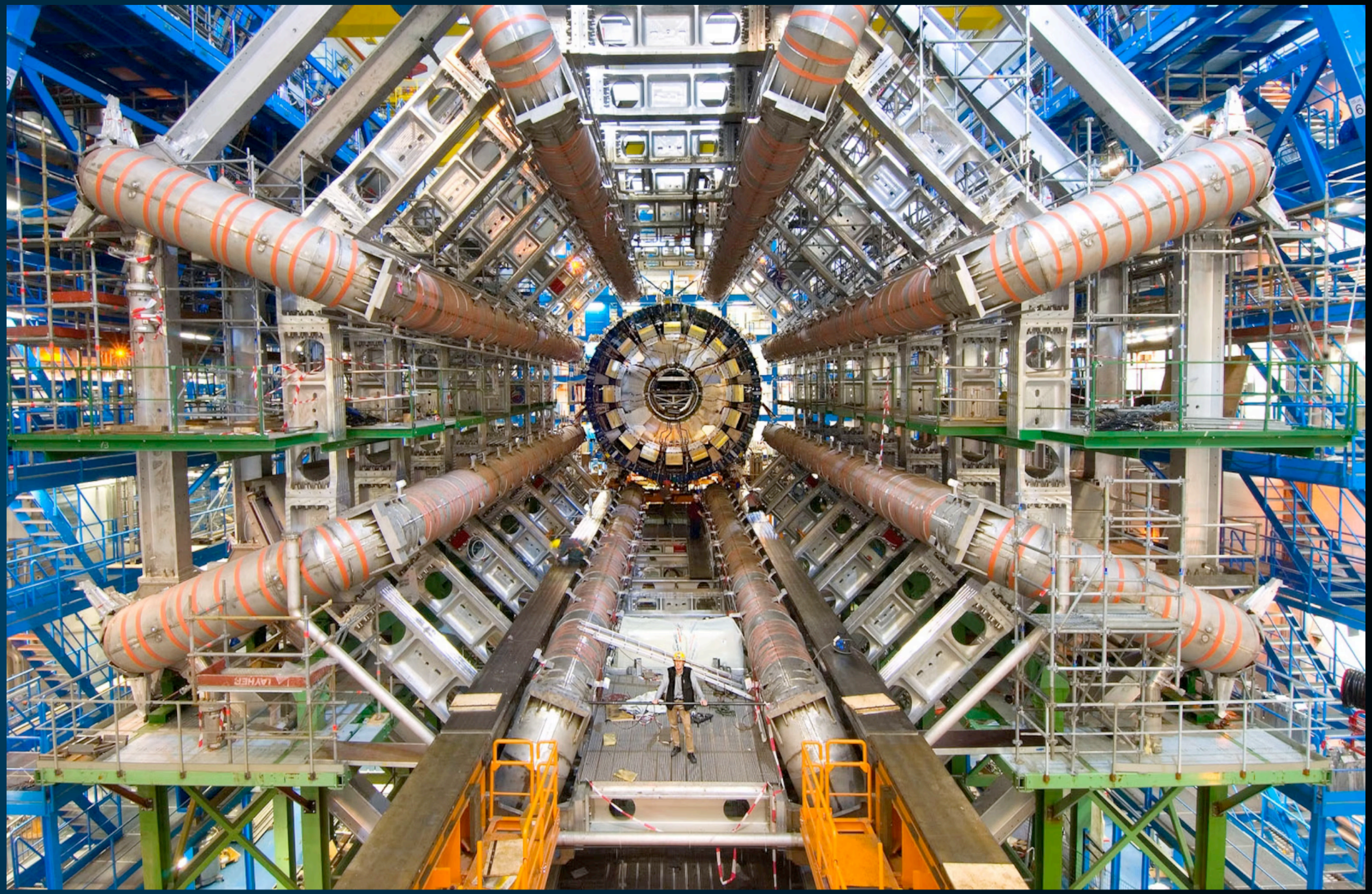


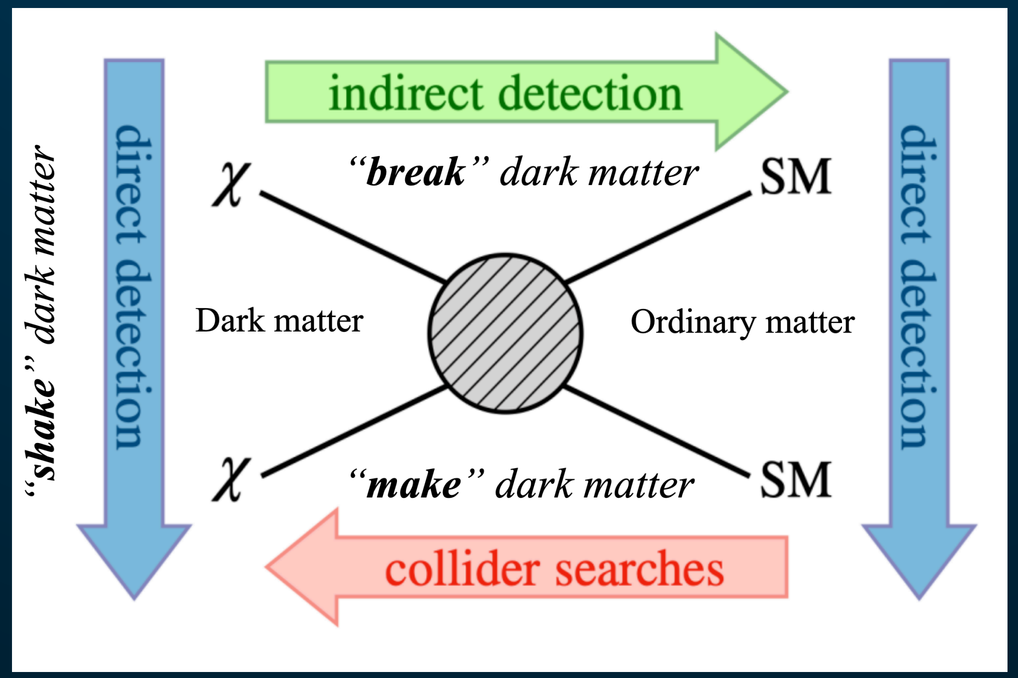


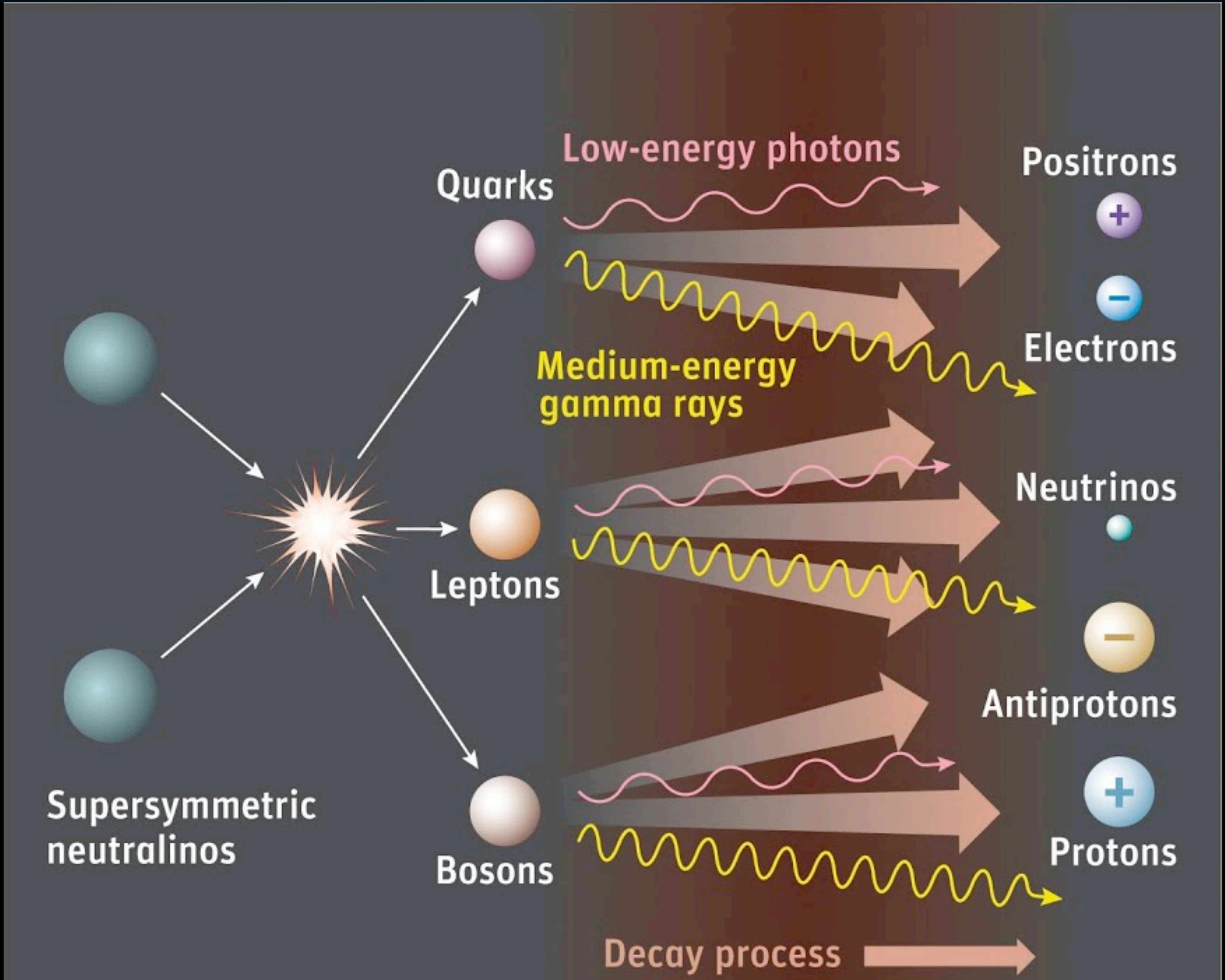
indirect detection
"break" dark matter
χ
SM
"shake" dark matter
direct detection
Dark matter
Ordinary matter
direct detection
χ
SM
"make" dark matter
collider searches

Collider and Direct Detection Searches

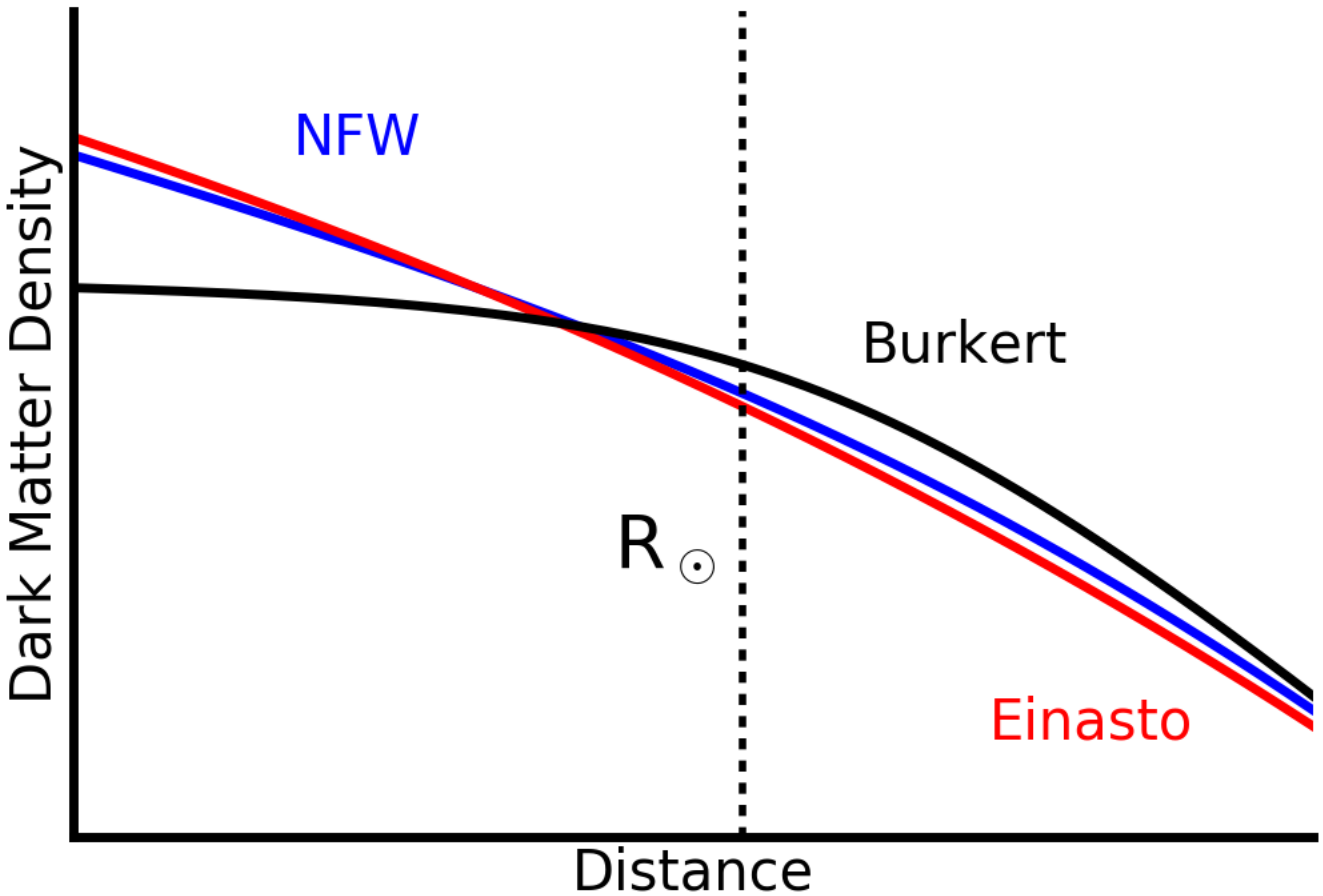








Low-energy photons
Quarks
Positrons
Medium-energy
gamma rays
Electrons
Neutrinos
Leptons
Antiprotons
Supersymmetric
neutralinos
Bosons
Protons
Decay process

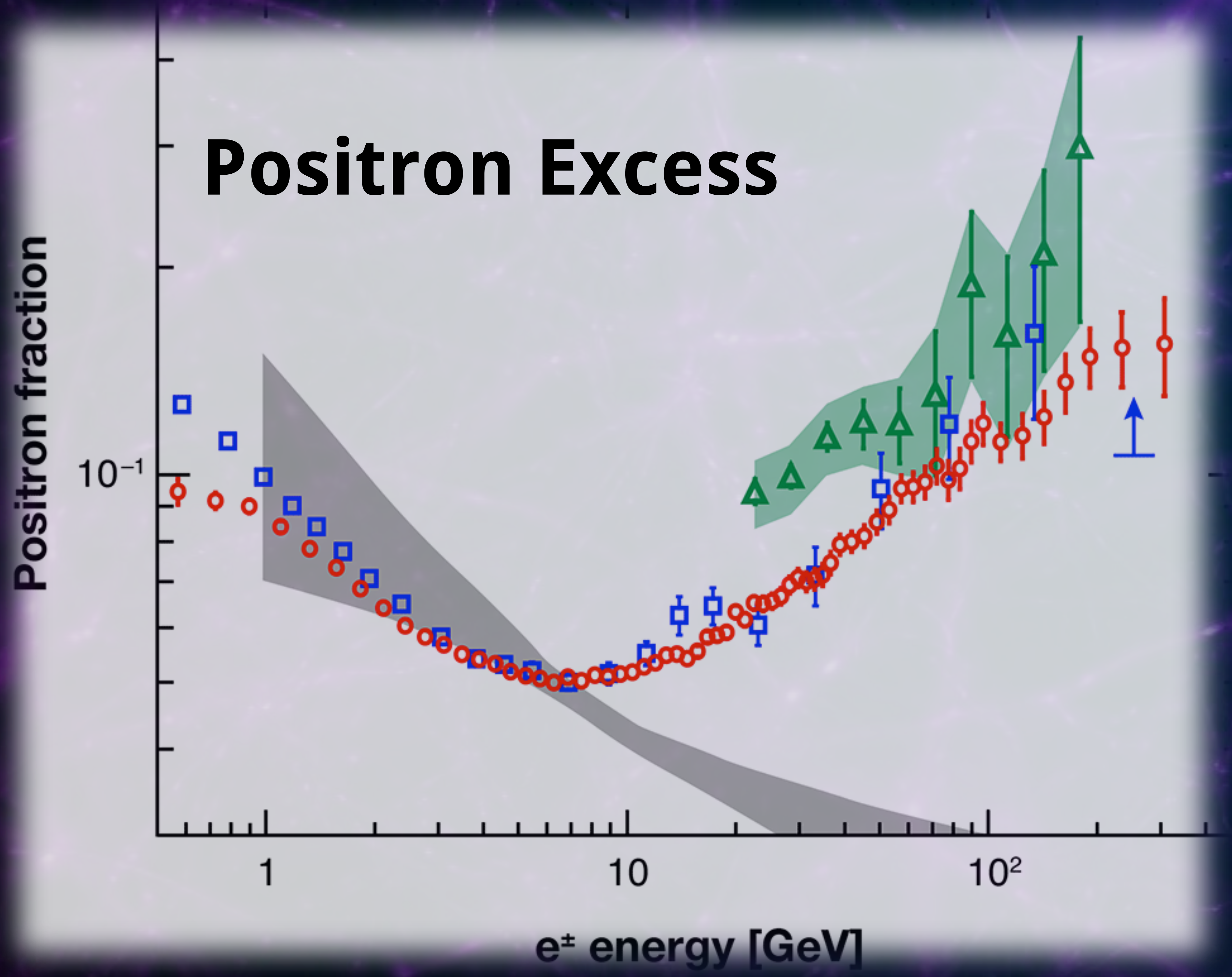

NFW
Burkert
Einasto
Dark Matter Density
Distance
R ☉

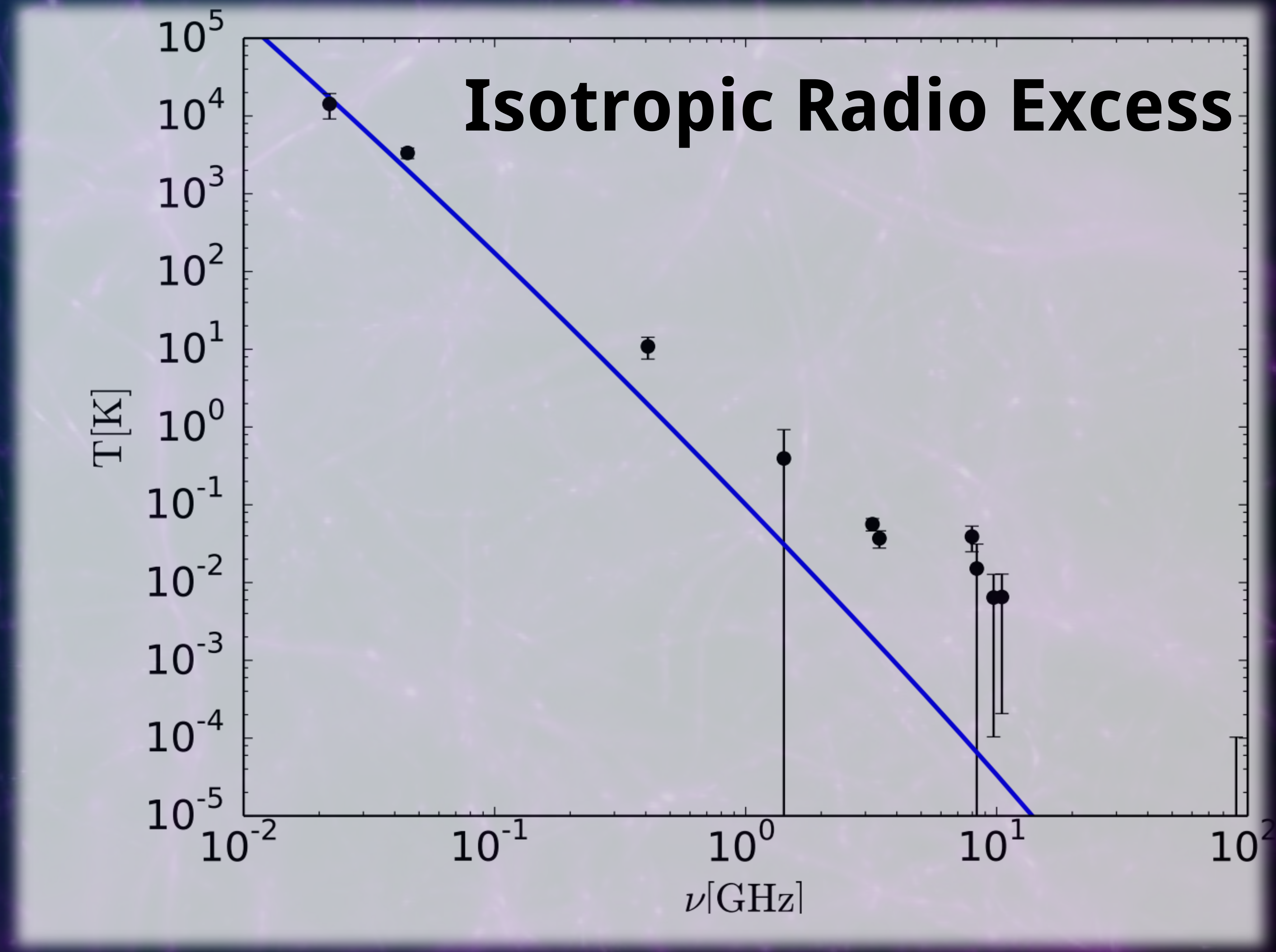

Gamma Rays


Cosmic Rays
Gamma Rays


Cosmic Rays
Gamma Rays
Radio


Galactic Center Excess


Positron Excess
Positron fraction
10⁻¹
1
10
10²
e± energy [GeV]


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

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

Indirect Detection Searches

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

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

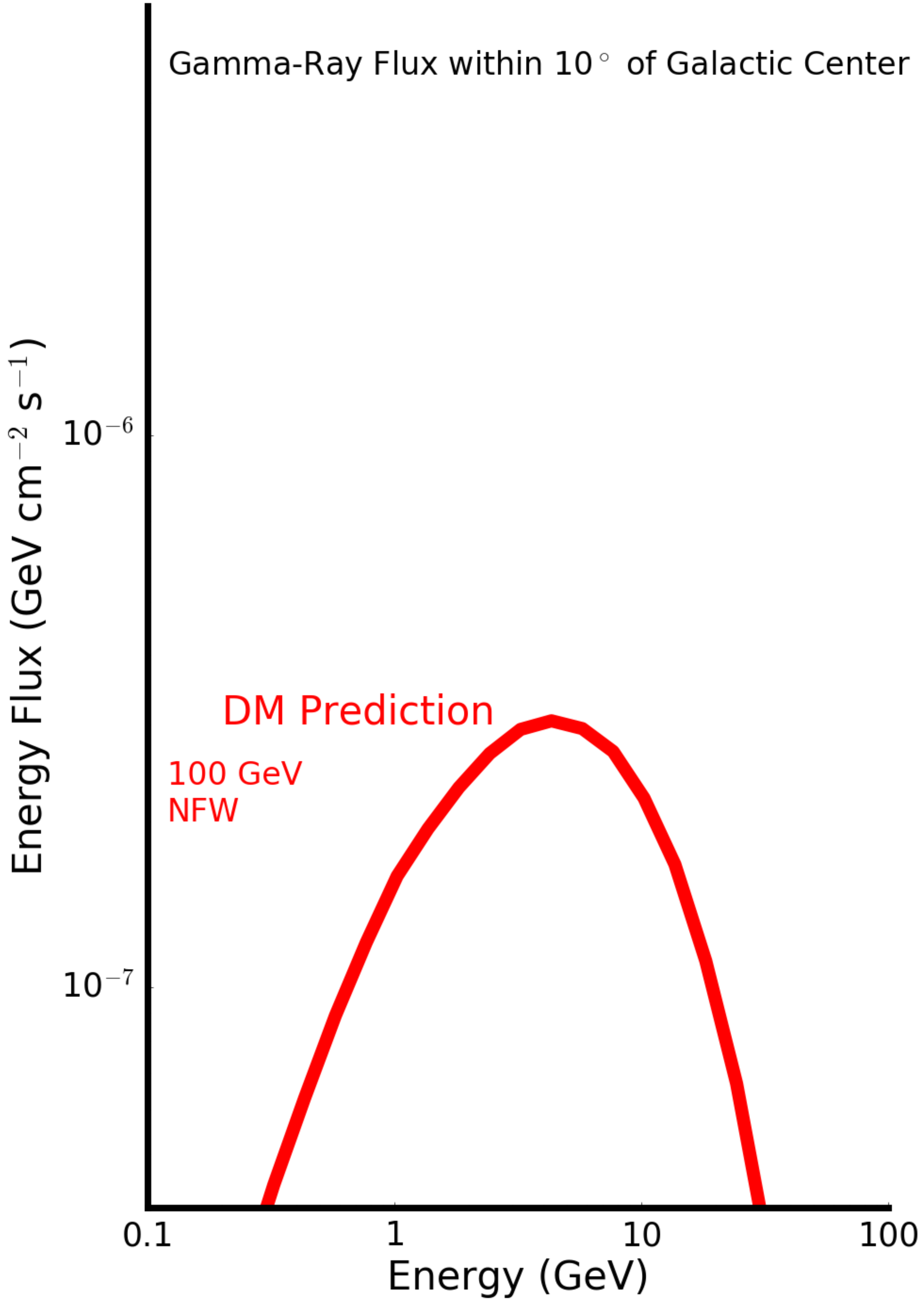
Thermal WIMPs and the Story of Tantalus

NFW Profile (Mass of Milky Way)

Thermal Cross-Section (Early Universe)

Dark Matter Mass (?)

Annihilation Final State (?)



Thermal WIMPs and the Story of Tantalus

NFW Profile (Mass of Milky Way)

Thermal Cross-Section (Early Universe)

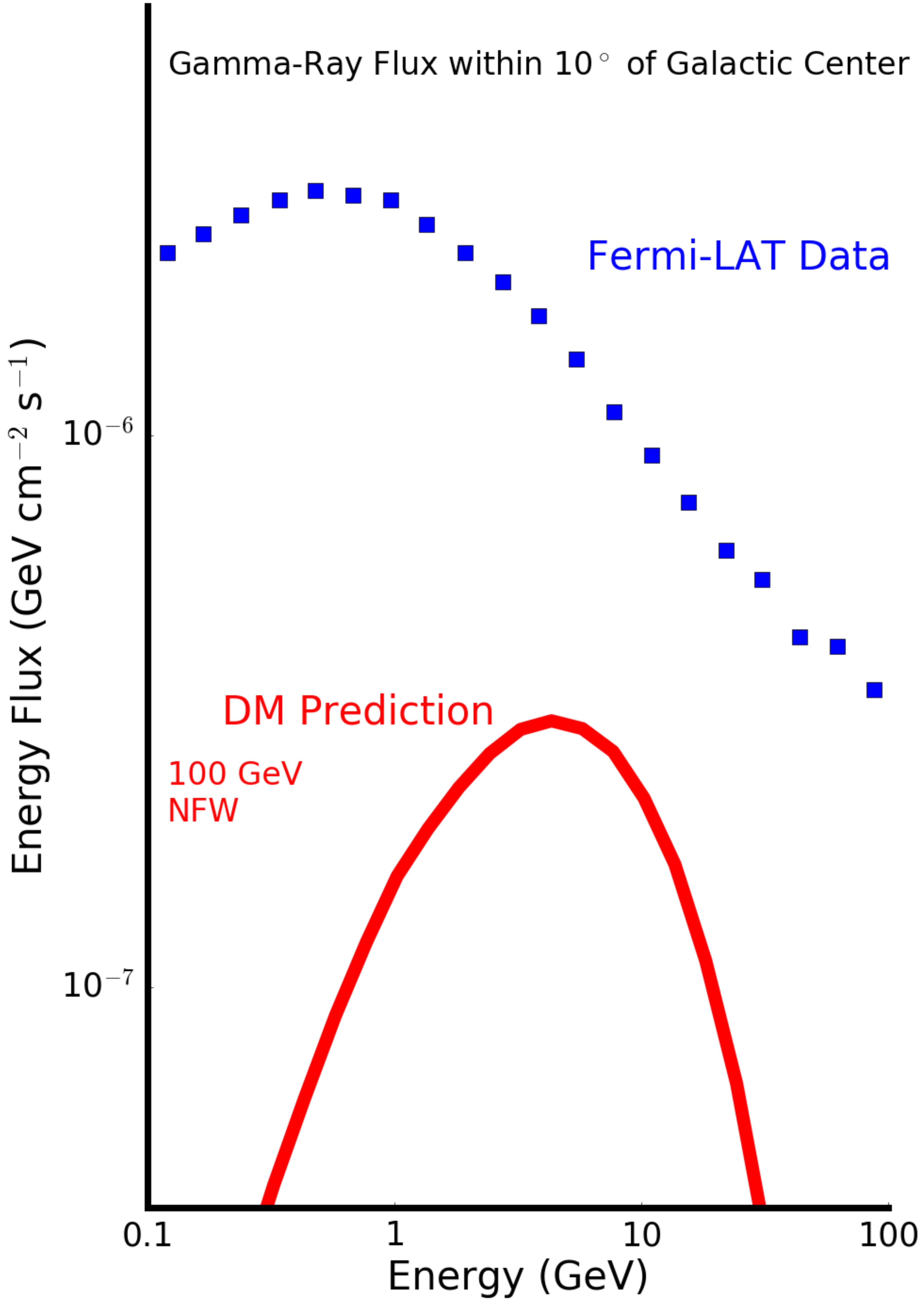
Dark Matter Mass (?)

Annihilation Final State (?)

Milky Way Star-Formation Rate (Galactic Dynamics)

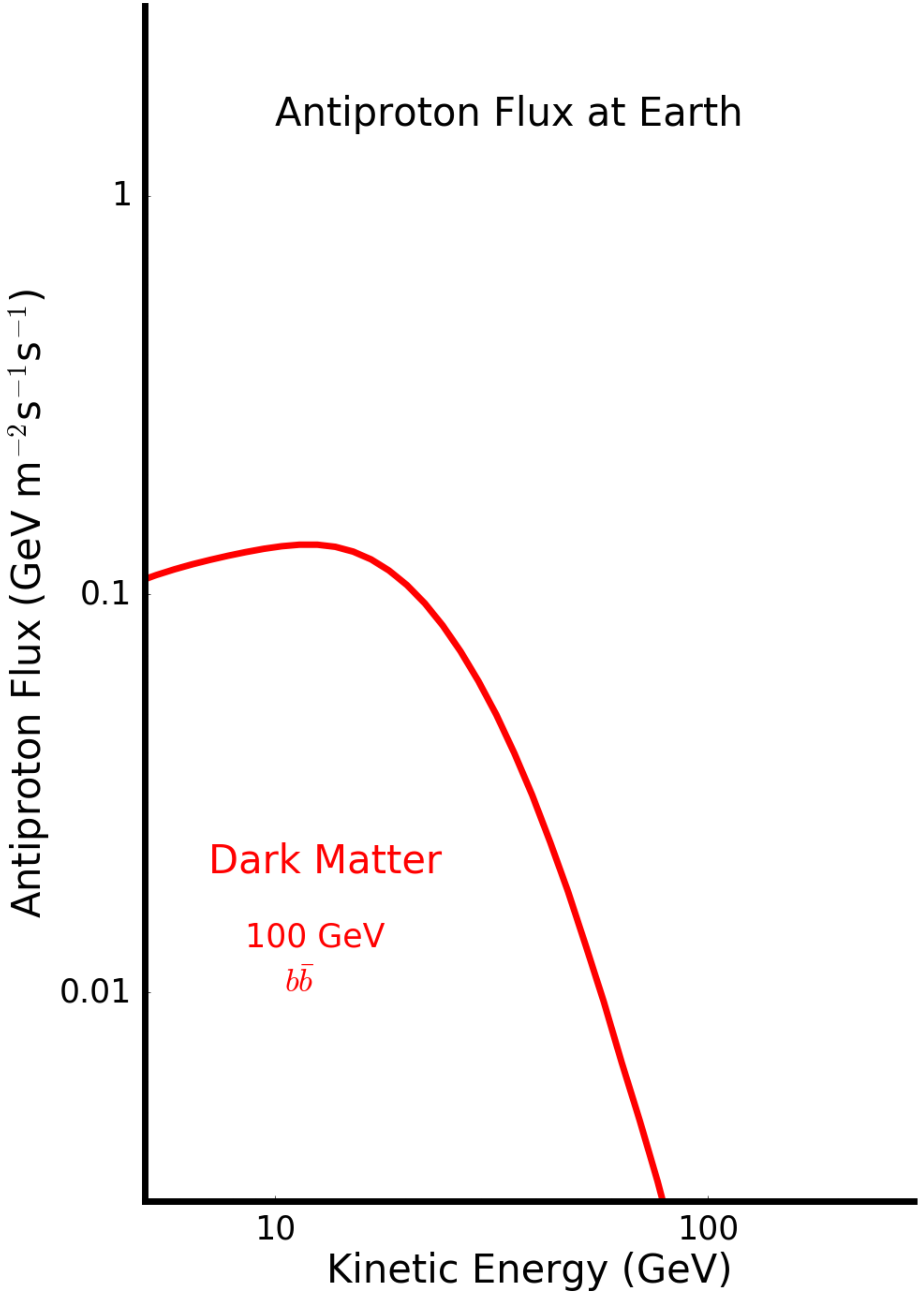
Diffusion Constant in Galactic Center (Hydrodyanmics)

Activity of Supermassive Blackhole (?)



Thermal WIMPs and the Story of Tantalus

- Local Dark Matter Density
- Thermal Cross-Section (Early Universe)
- Hadronic Component of Dark Matter Final State
- Convection of Annihilation Products from GC (Winds?)



Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

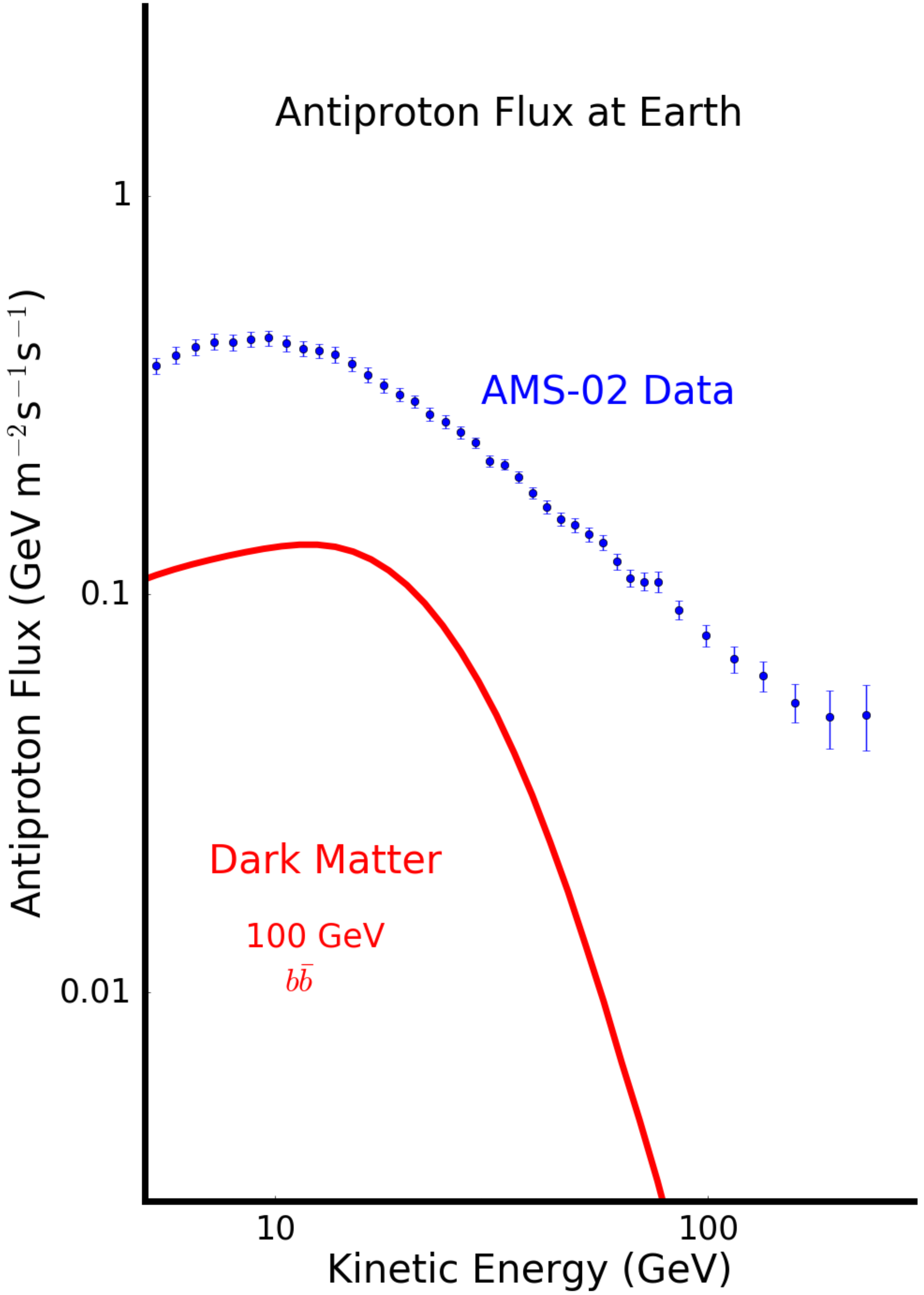
Thermal Cross-Section (Early Universe)

Hadronic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

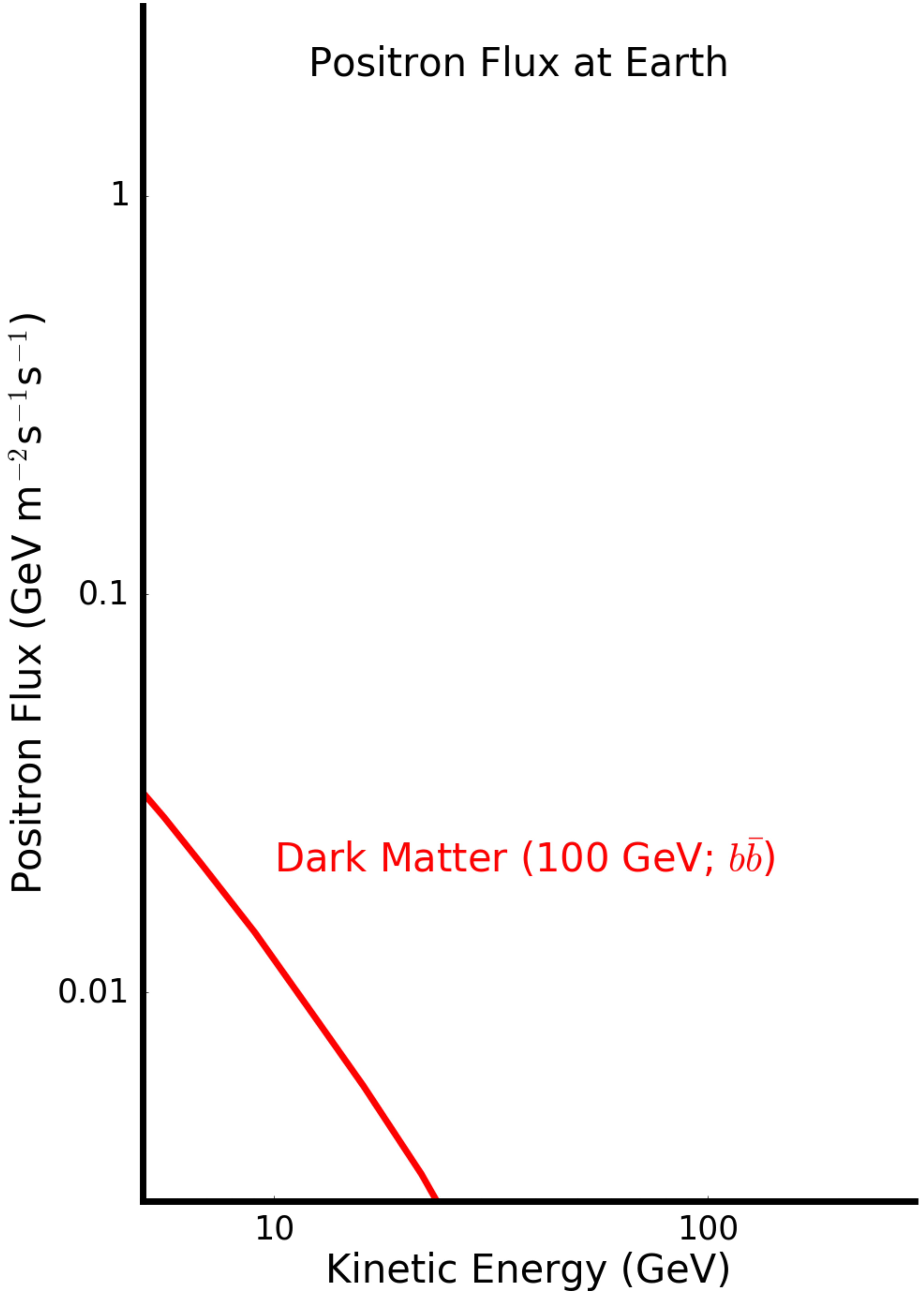
Local Gas Density

Local Supernova Rate



Thermal WIMPs and the Story of Tantalus

- Local Dark Matter Density
- Thermal Cross-Section (Early Universe)
- Leptonic Component of Dark Matter Final State
- Convection of Annihilation Products from GC (Winds?)



Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

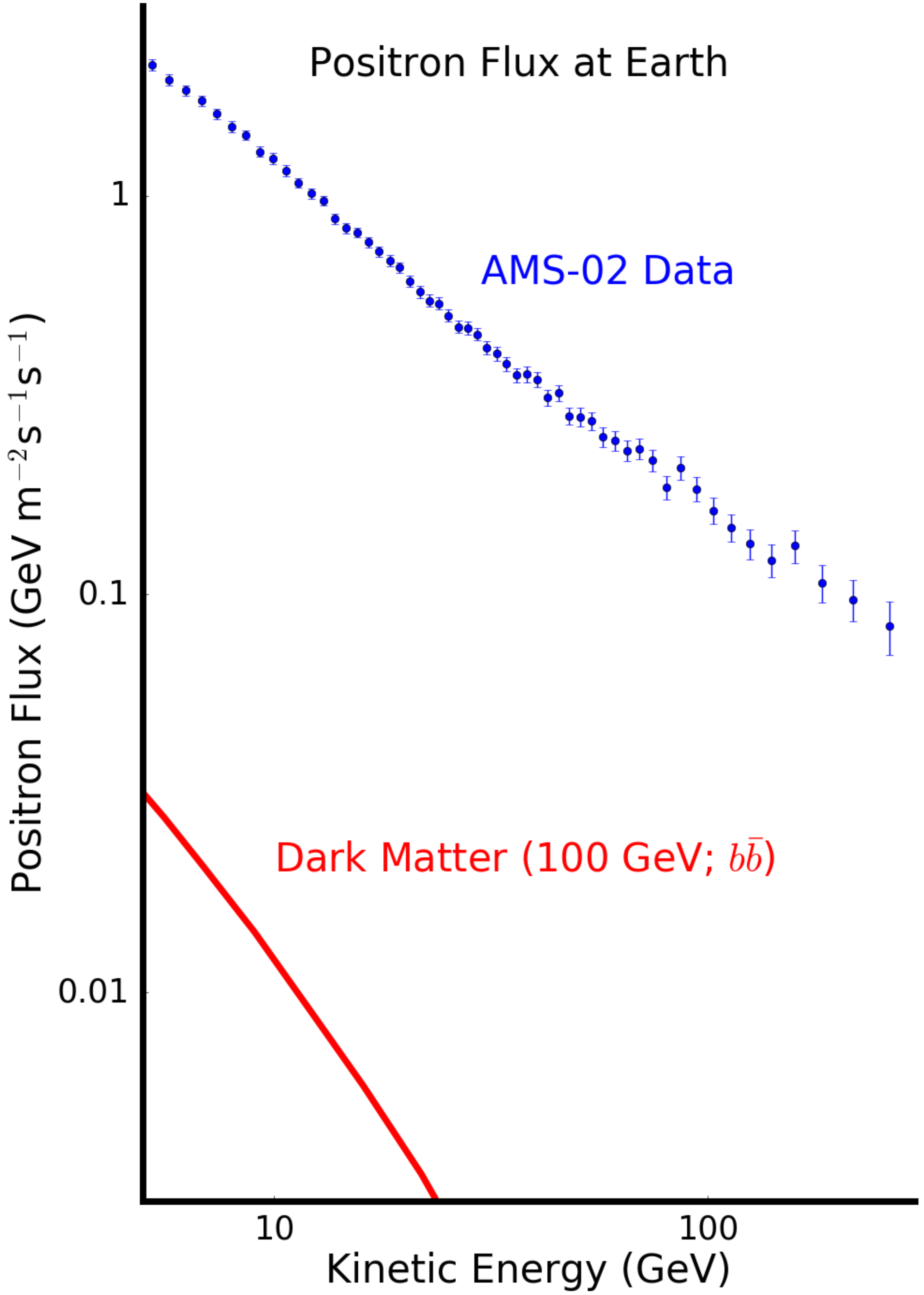
Thermal Cross-Section (Early Universe)

Leptonic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Pulsar Birth Rate

e^+e^- Acceleration Efficiency in Pulsar Magnetospheres



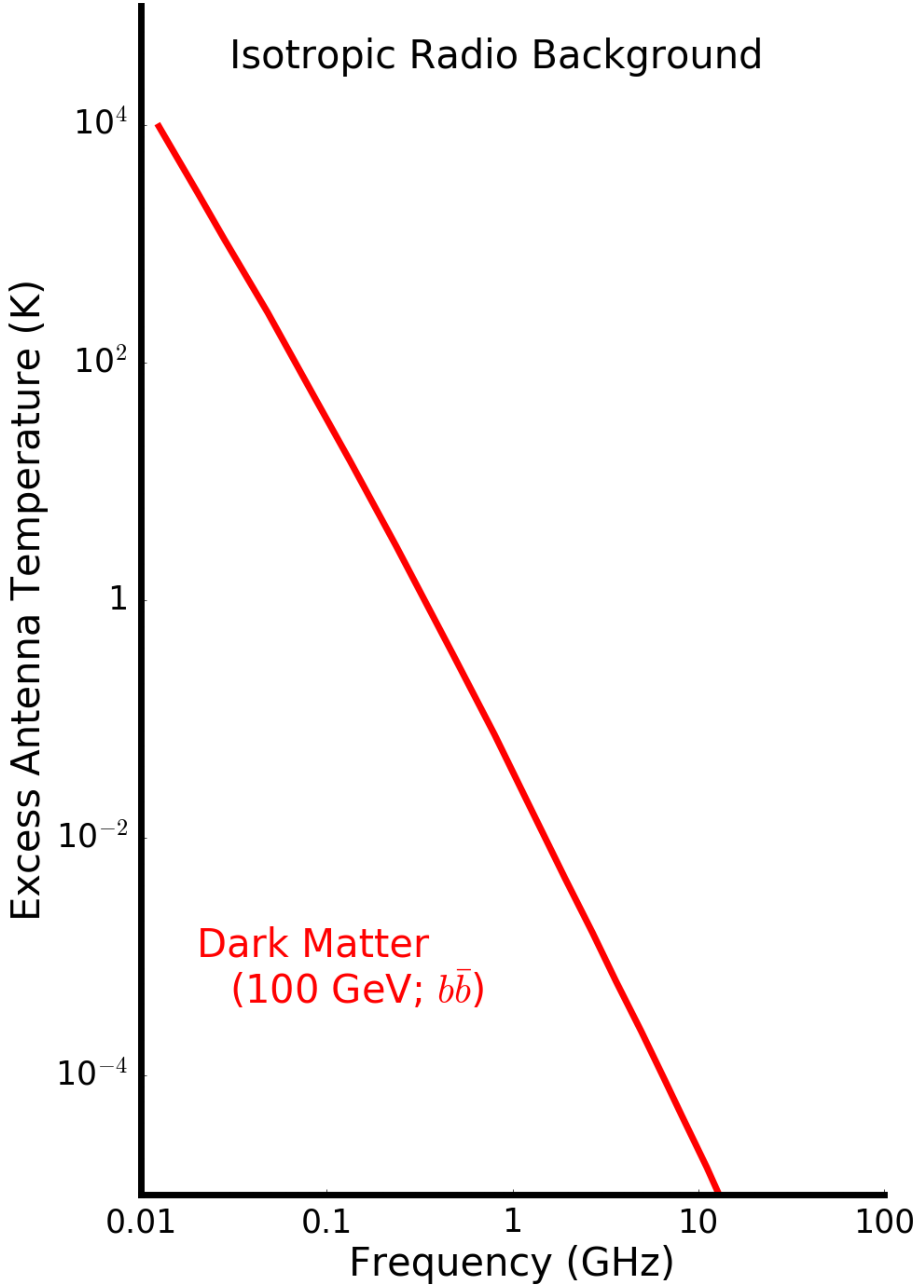
Thermal WIMPs and the Story of Tantalus

Extragalactic Dark Matter Density

Thermal Cross-Section (Early Universe)

e+e- Energy Fraction in Dark Matter Annihilation

Intergalactic Magnetic Fields



Thermal WIMPs and the Story of Tantalus

Extragalactic Dark Matter Density

Thermal Cross-Section (Early Universe)

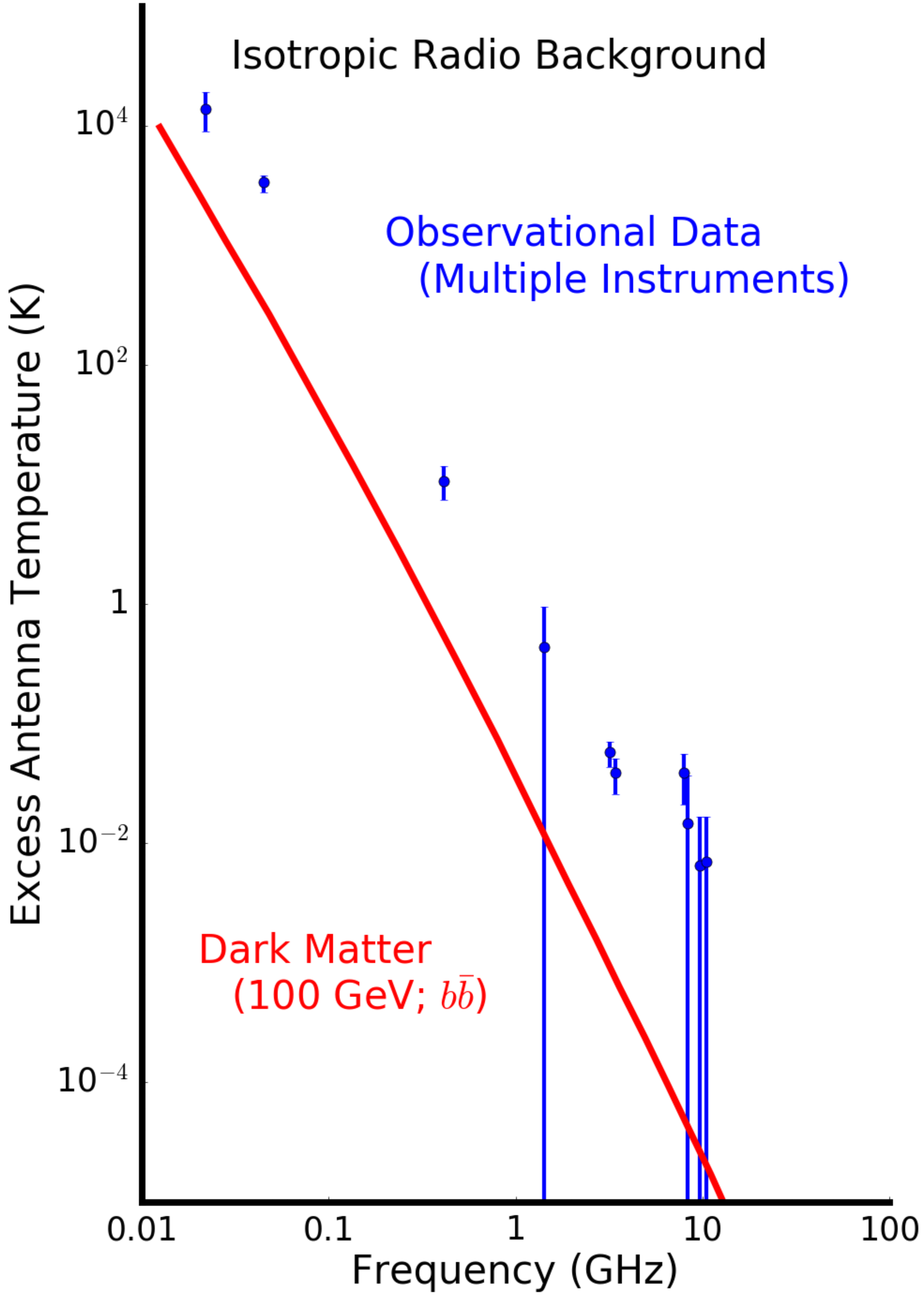
e+e- Energy Fraction in Dark Matter Annihilation

Intergalactic Magnetic Fields

Radio Luminosity in Starbursts and AGN

e+e- Reacceleration in Cluster Mergers

Redshift Dependence of Signal vs. CMB



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

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
Specificity (DM Flux / Astrophysics Flux)
Fraction of Dark Matter 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
Specificity (DM Flux / Astrophysics Flux)
Fraction of Dark Matter Flux


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

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

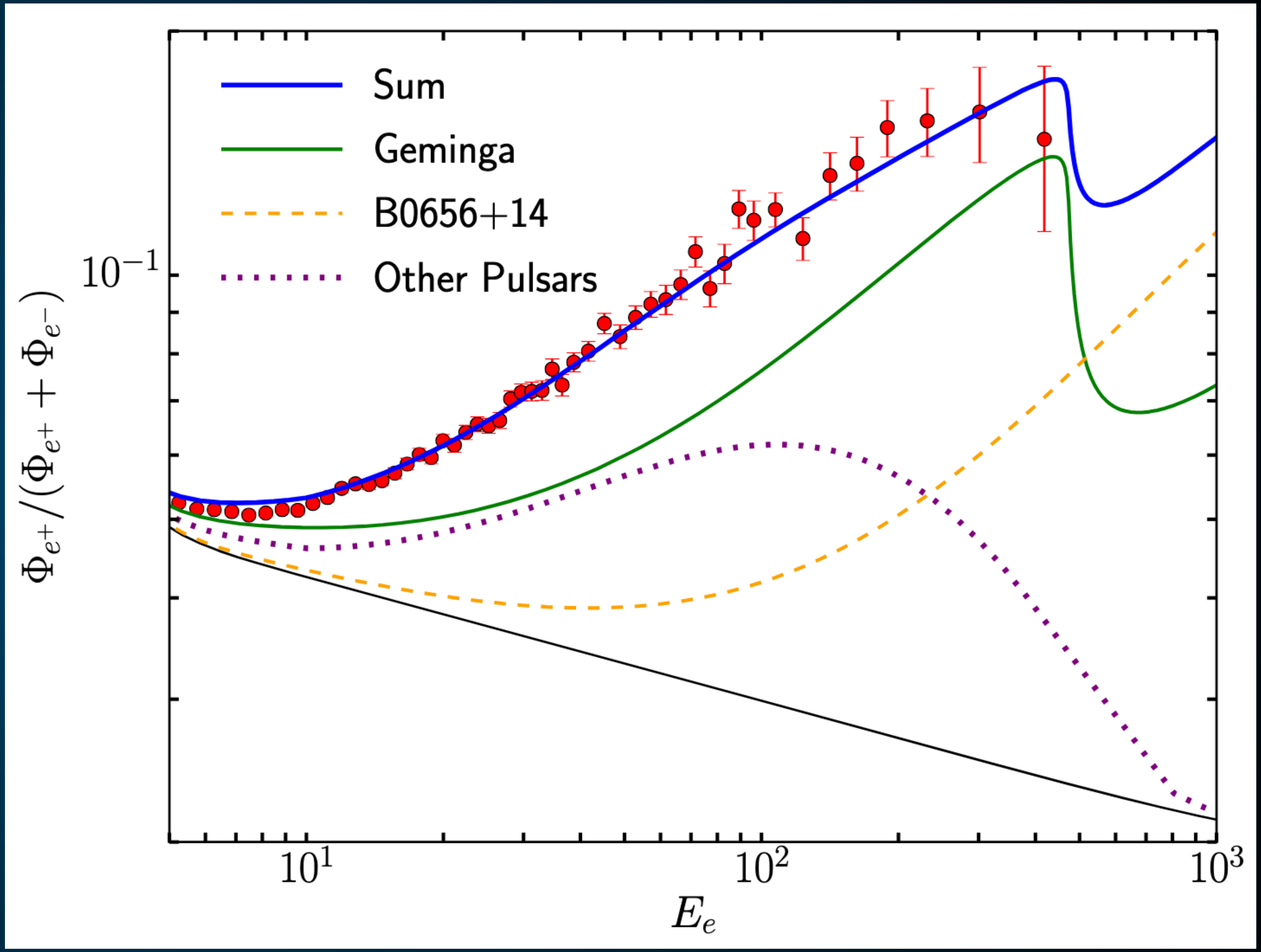
Thermal WIMPs and the Story of Tantalus

Thermal WIMPs and the Story of Tantalus


Congratulations!
You’re an astrophysicicist now!

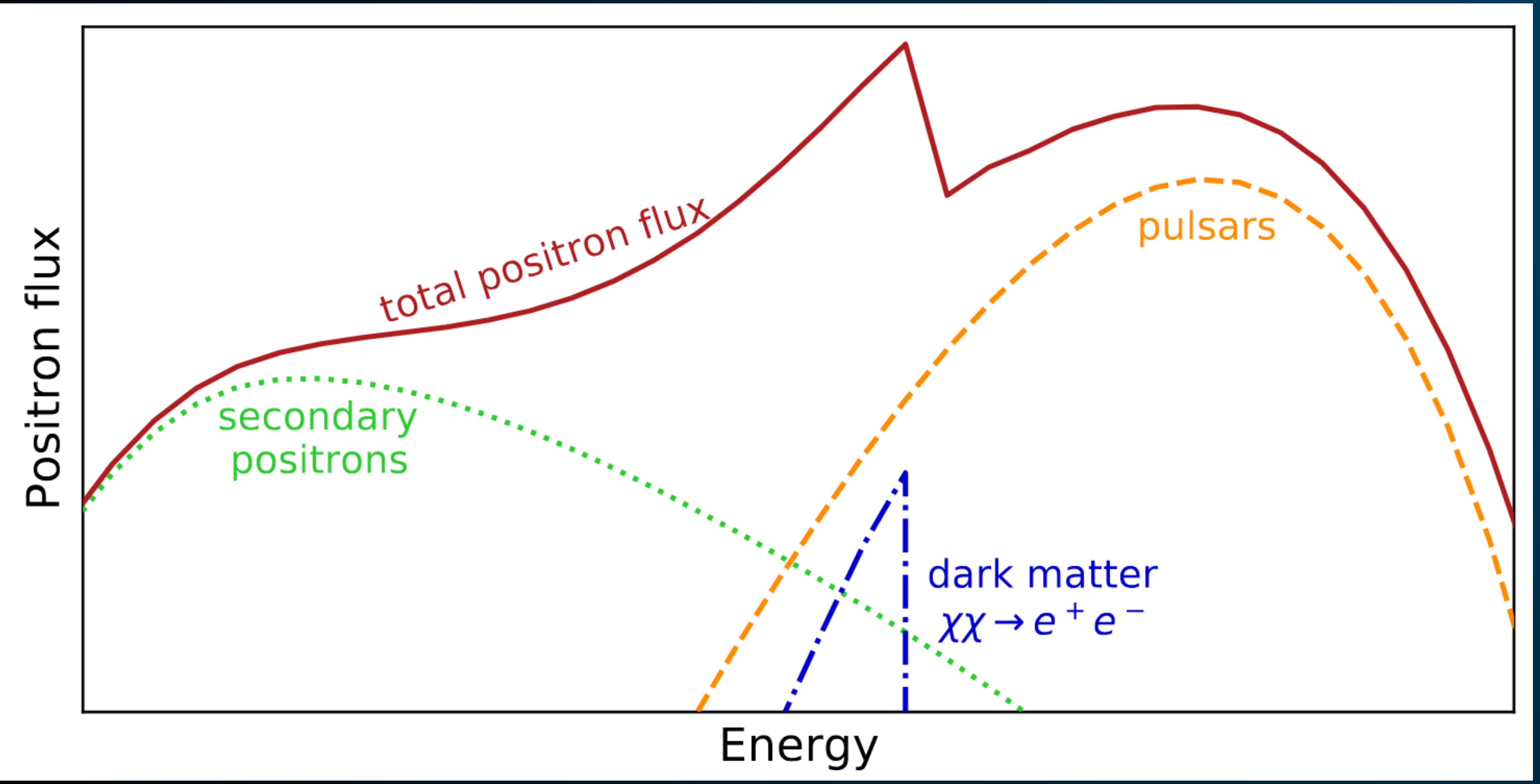
Can Still Set Limits

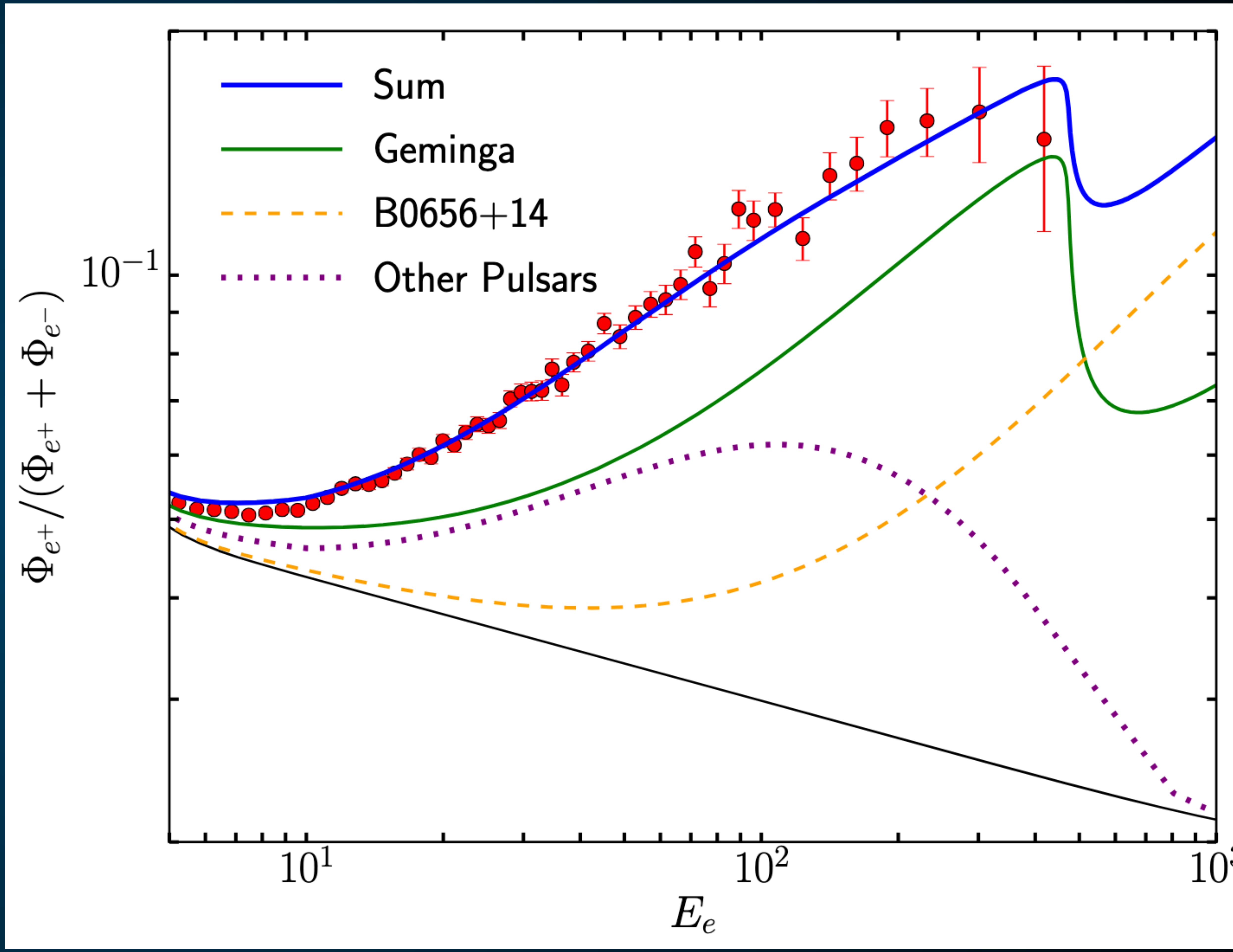
Look for subdominant dark matter contributions!



Can Still Set Limits

Look for subdominant dark matter contributions!

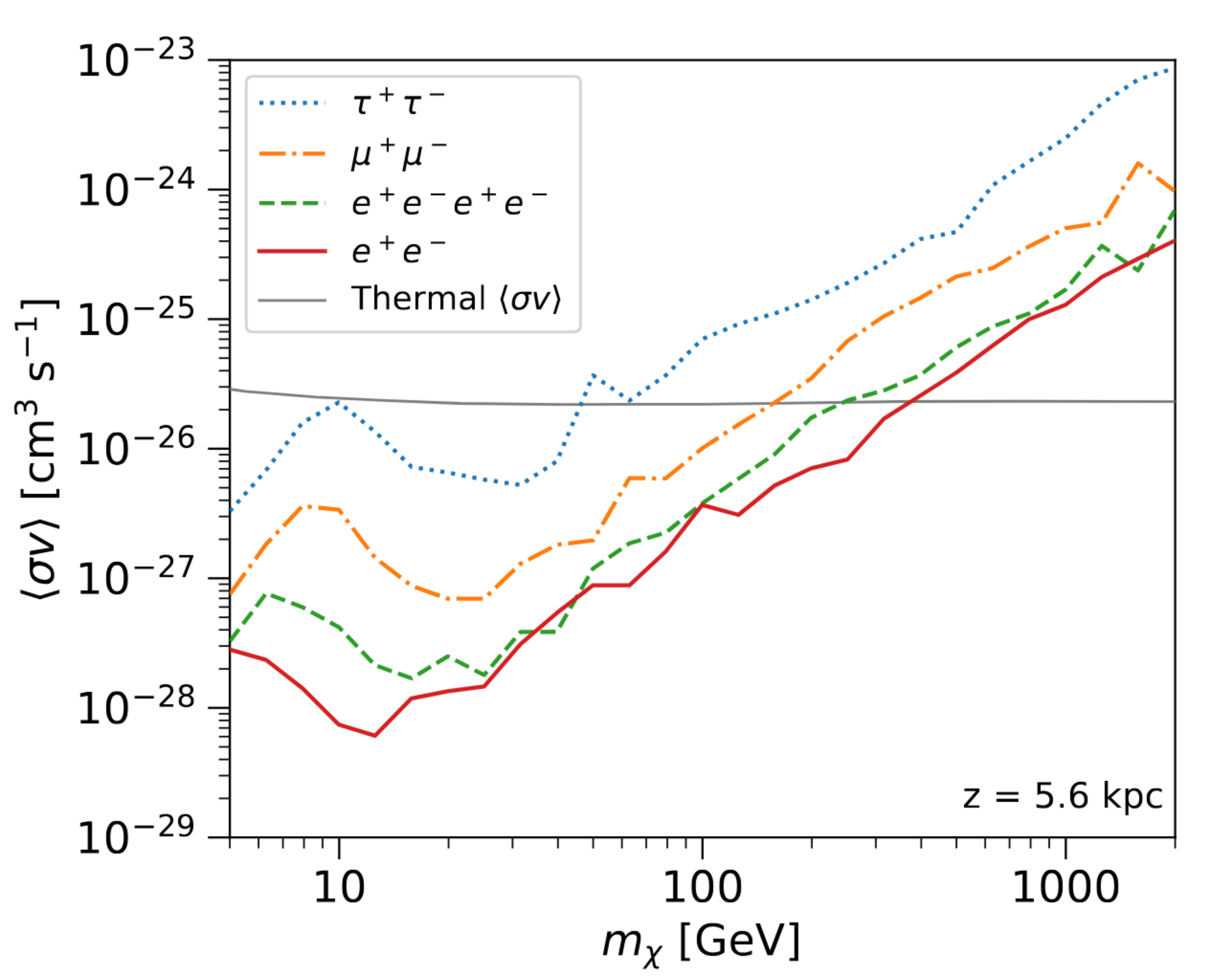




(Not an exhaustive list of observations)

Can Still Set Limits

John & TL (2107.10261)




topic

Indirect Detection Searches

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

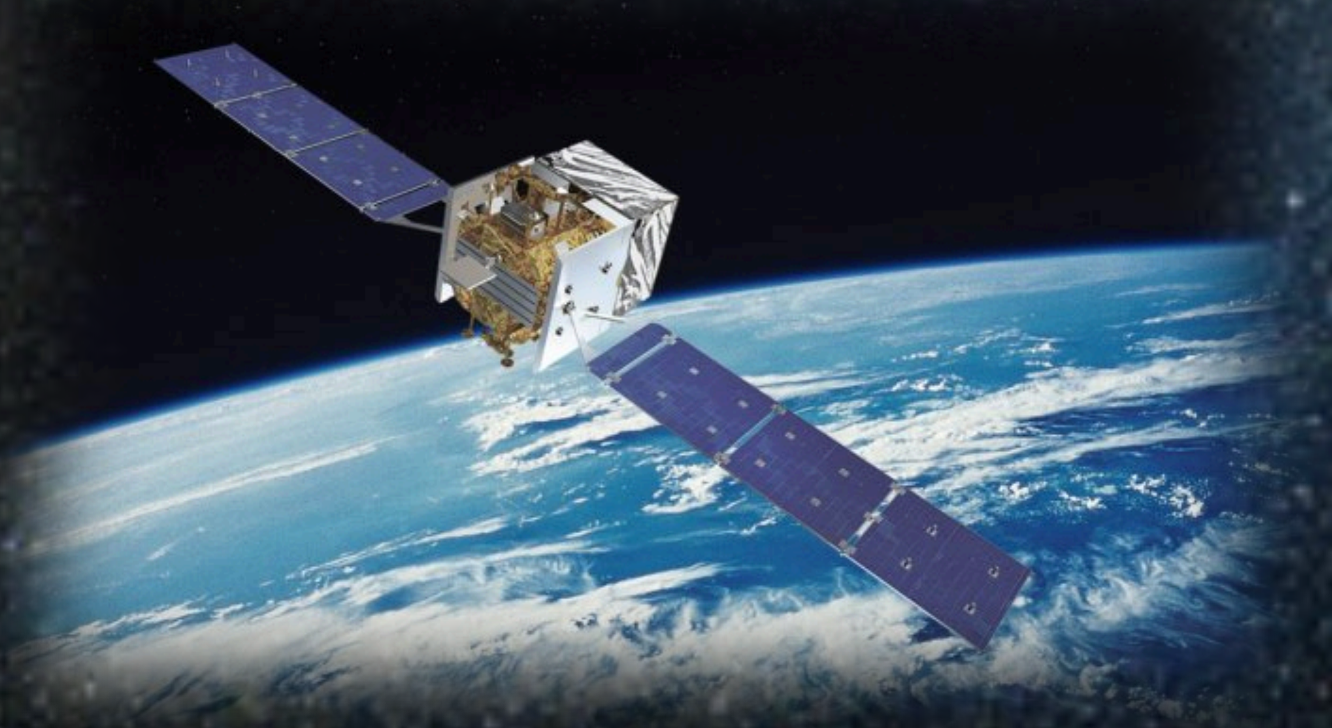
Cosmic-Rays

Positrons
Electron + Positron Spectrum
Antiprotons
Antineutrons
Antihelium
Cosmological Lithium Problem

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

The Galactic Center Excess



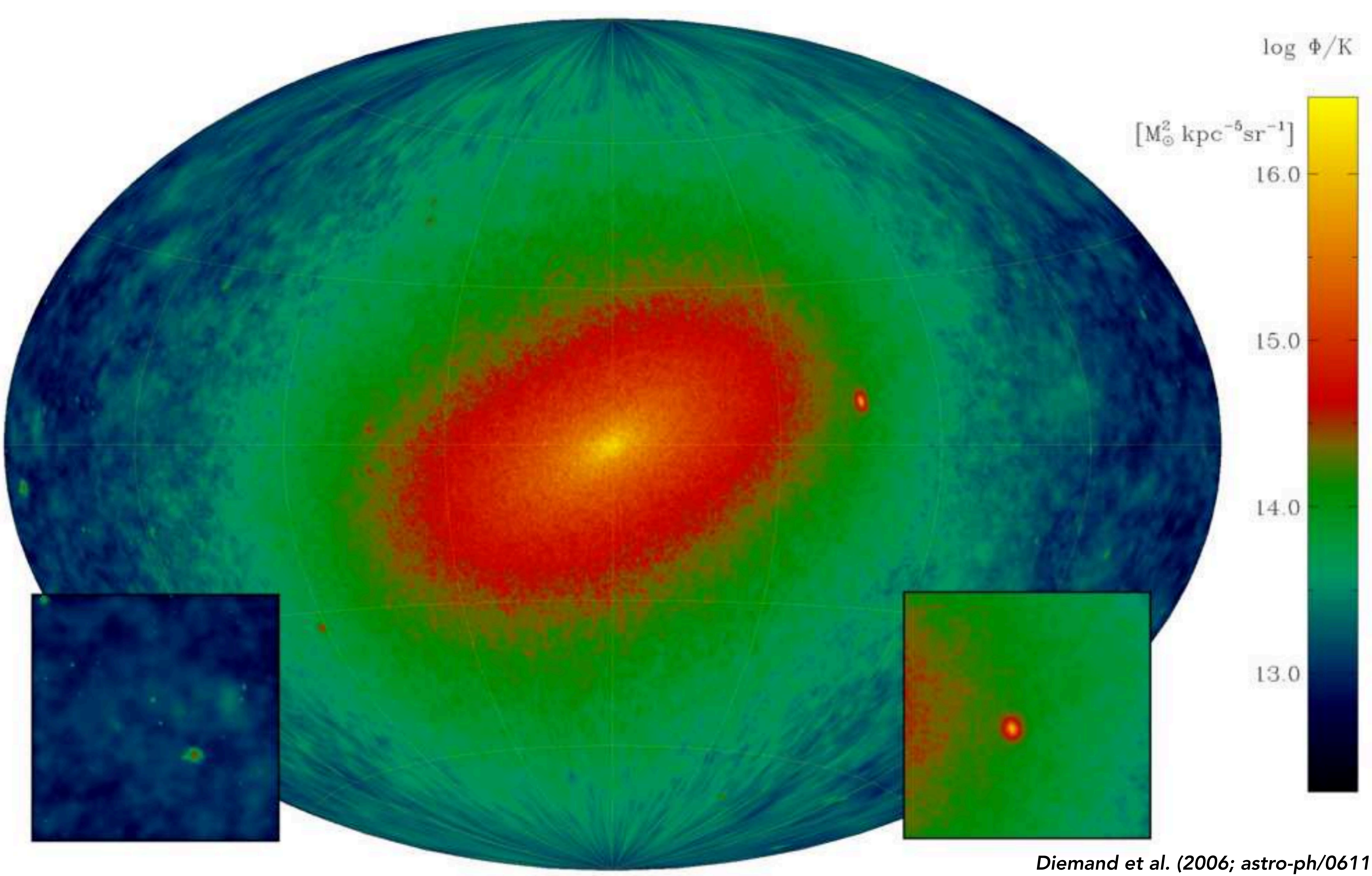
FERMILAB-PUB-09-494-A

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

Lisa Goodenough[1] 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*

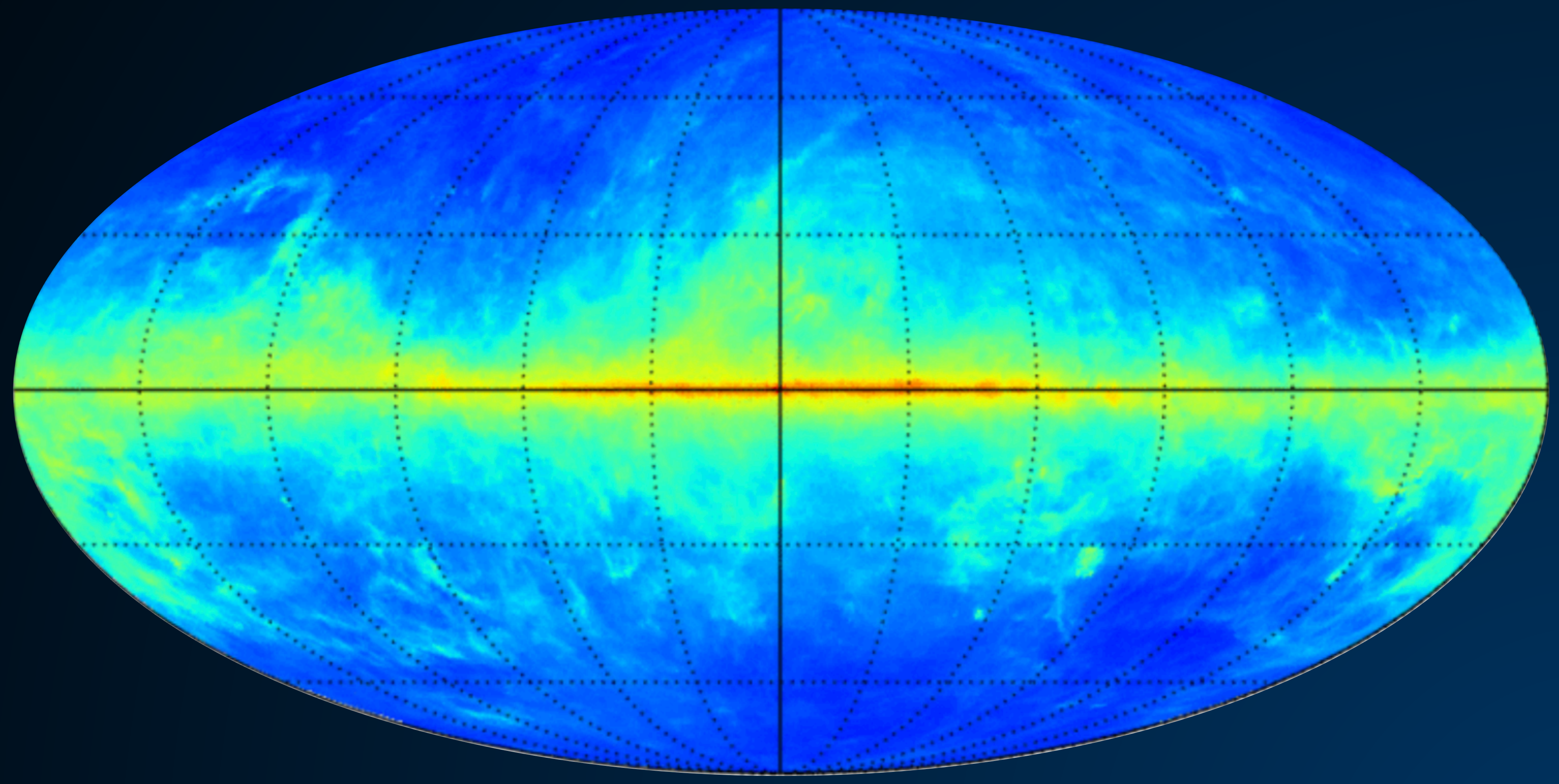
We study the gamma rays observed by the Fermi Gamma Ray Space Telescope from the direction of the Galactic Center and find that their angular distribution and energy spectrum are well described by a dark matter annihilation scenario. In particular, we find a good fit to the data for dark matter particles with a 25-30 GeV mass, an annihilation cross section of $\sim 9 \times 10^{-26}$ cm^3/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.



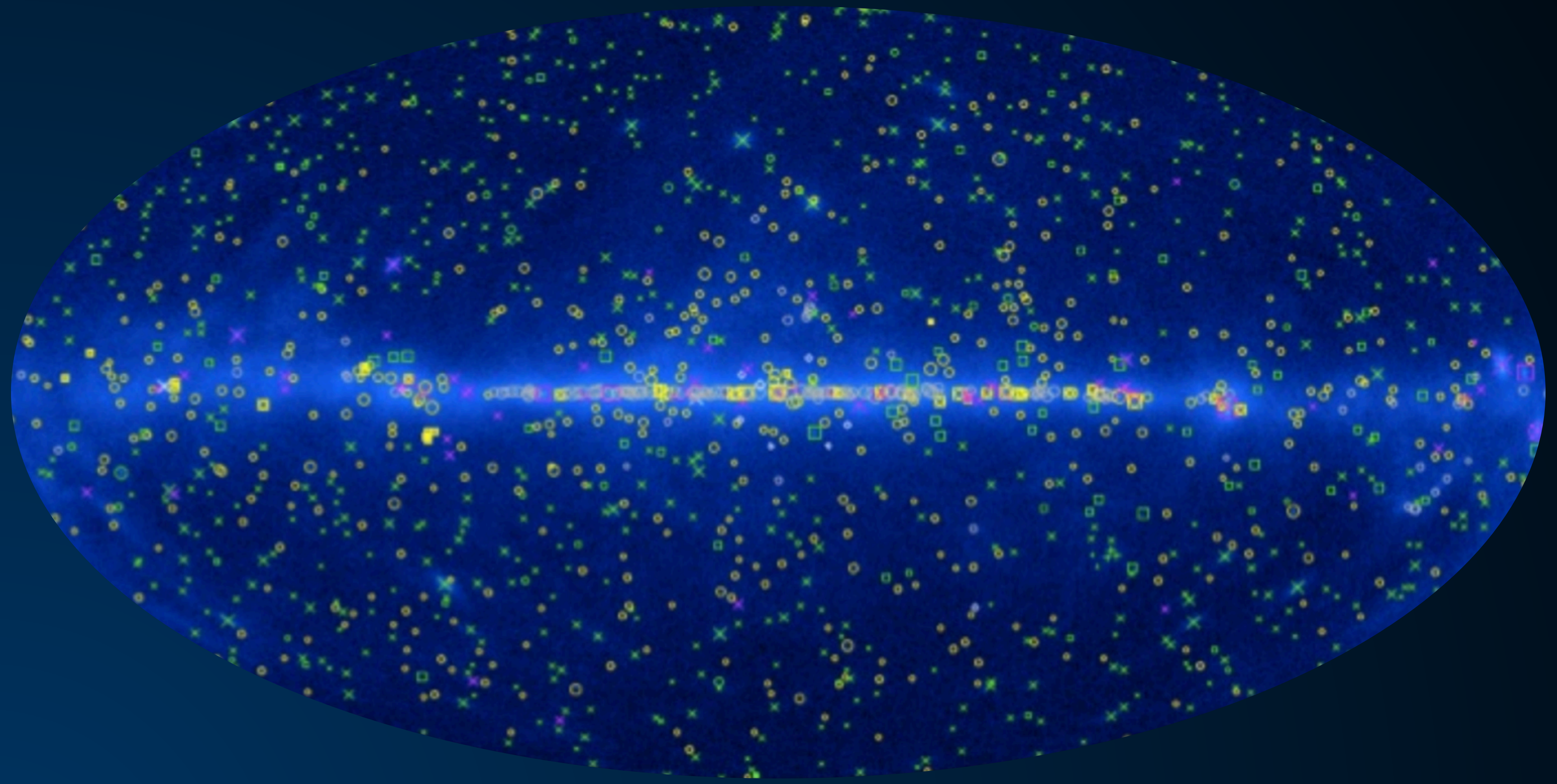
Diemand et al. (2006; astro-ph/0611370)

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

Gamma-Ray Searches Techniques

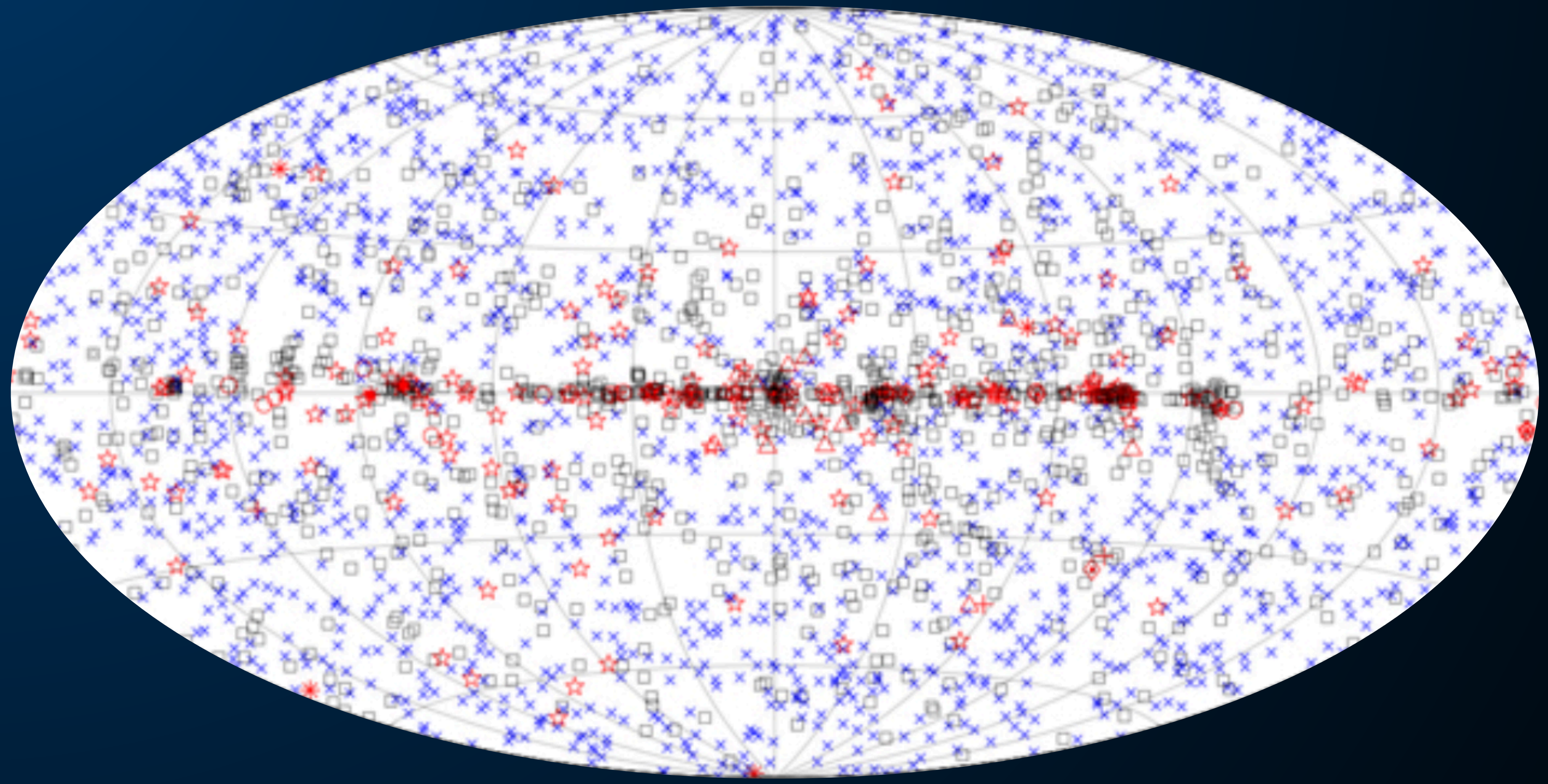


Galactic Diffuse



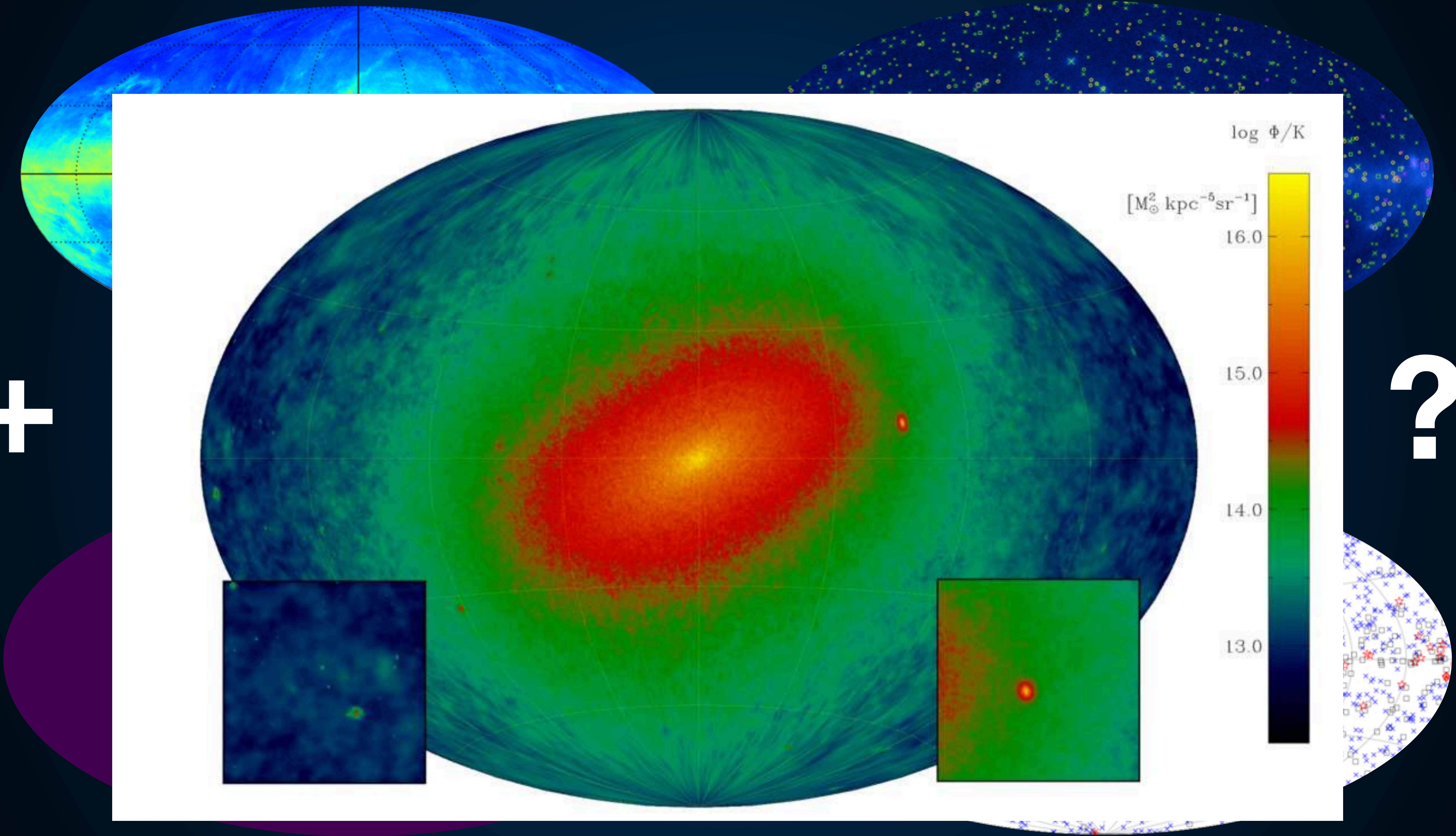
Point Sources

Isotropic Emission



Sub-Threshold Sources

Gamma-Ray Searches Techniques



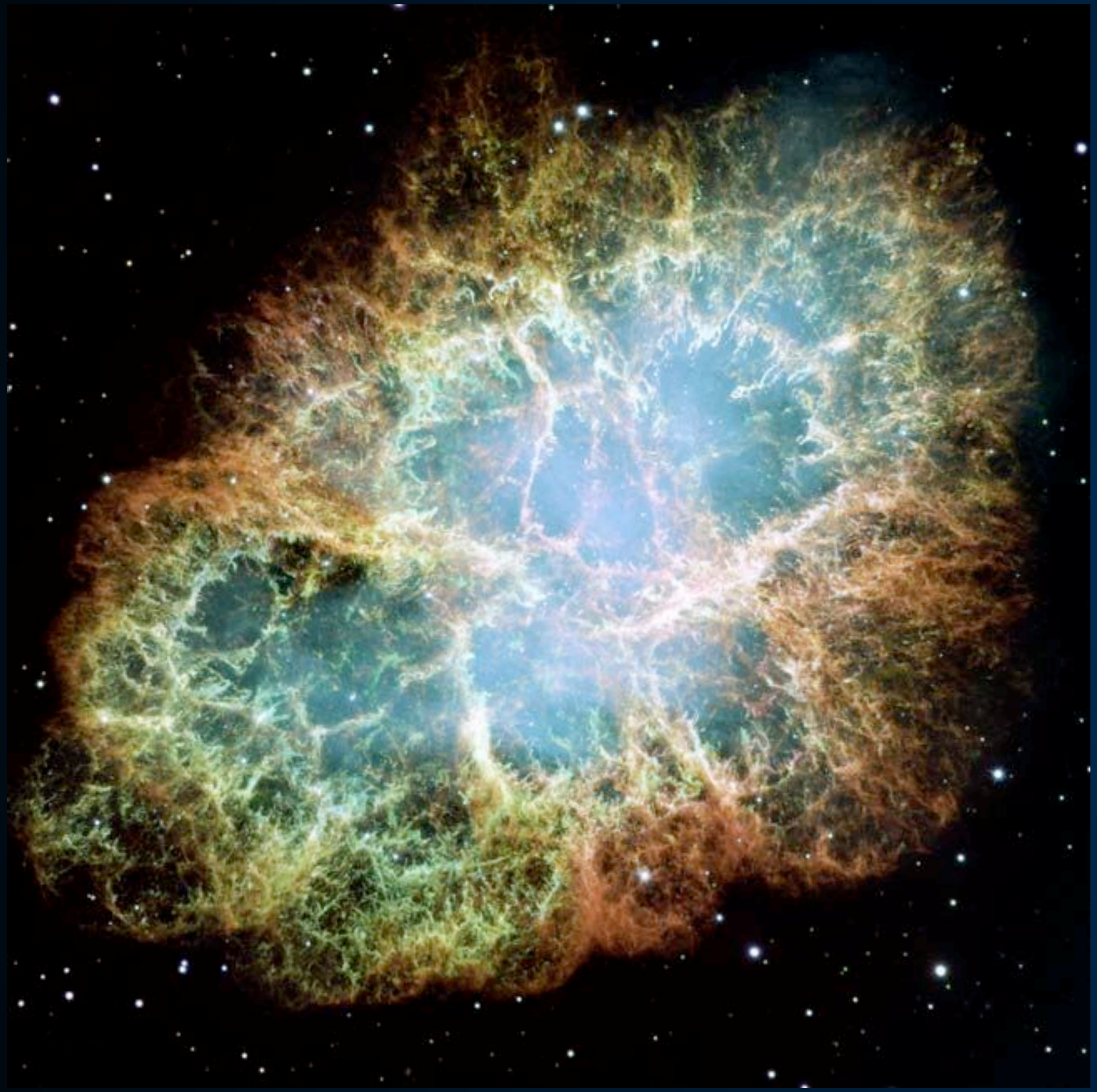
+

?

Isotropic Emission

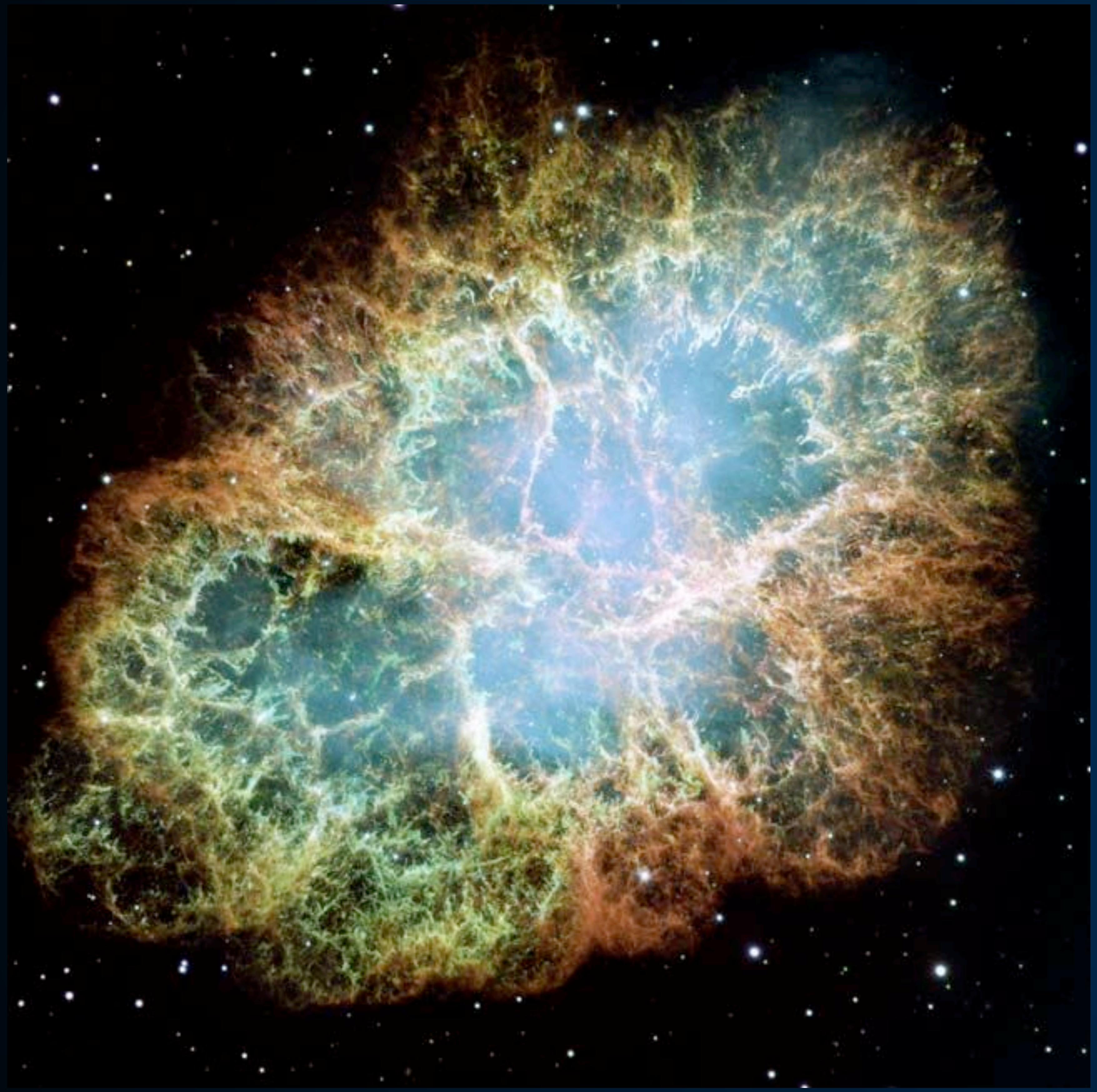
Sub-Threshold Sources

Gamma-Ray Angular Resolution is …. Poor

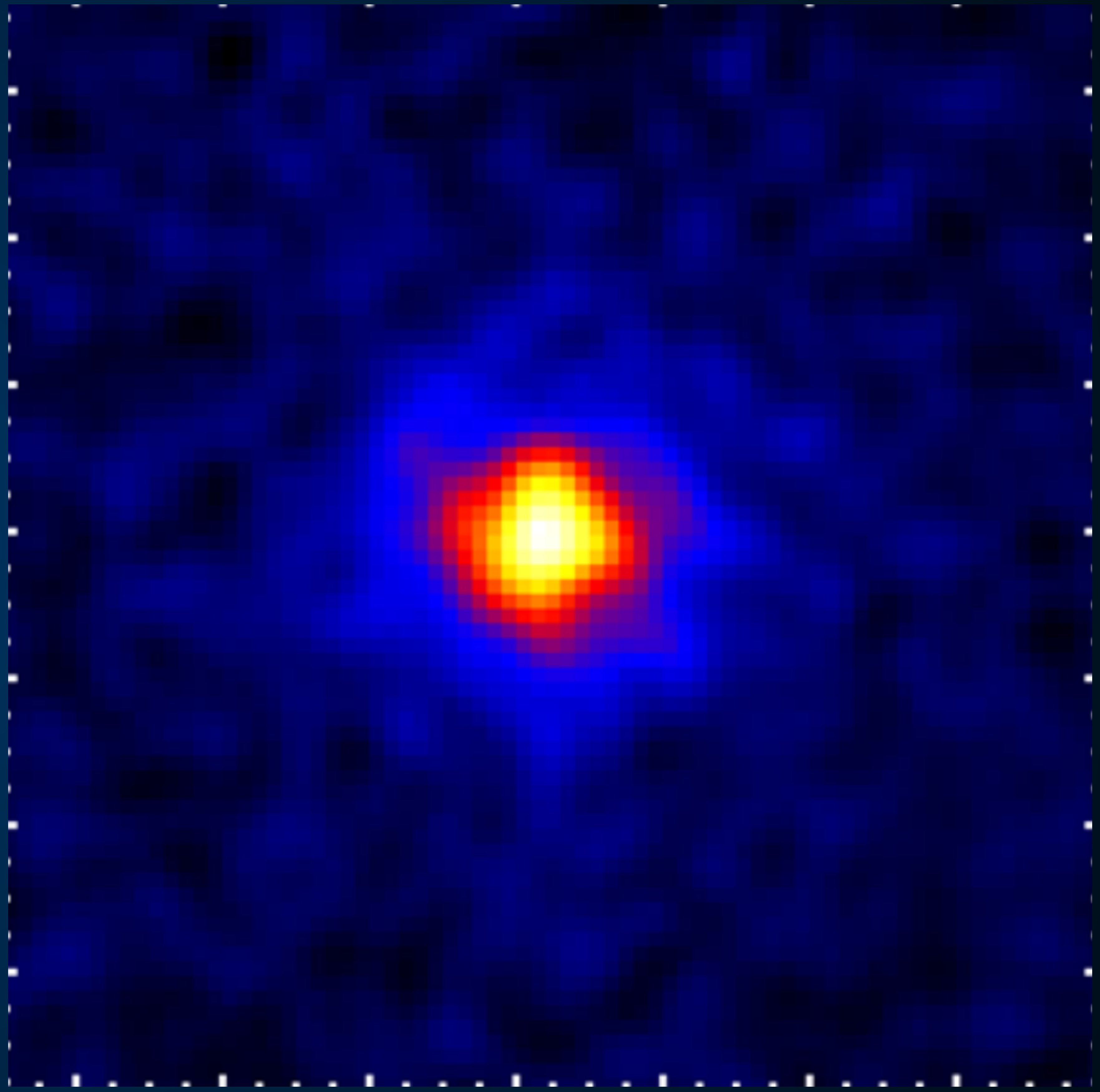


Hubble Space Telescope

Gamma-Ray Angular Resolution is .... Poor

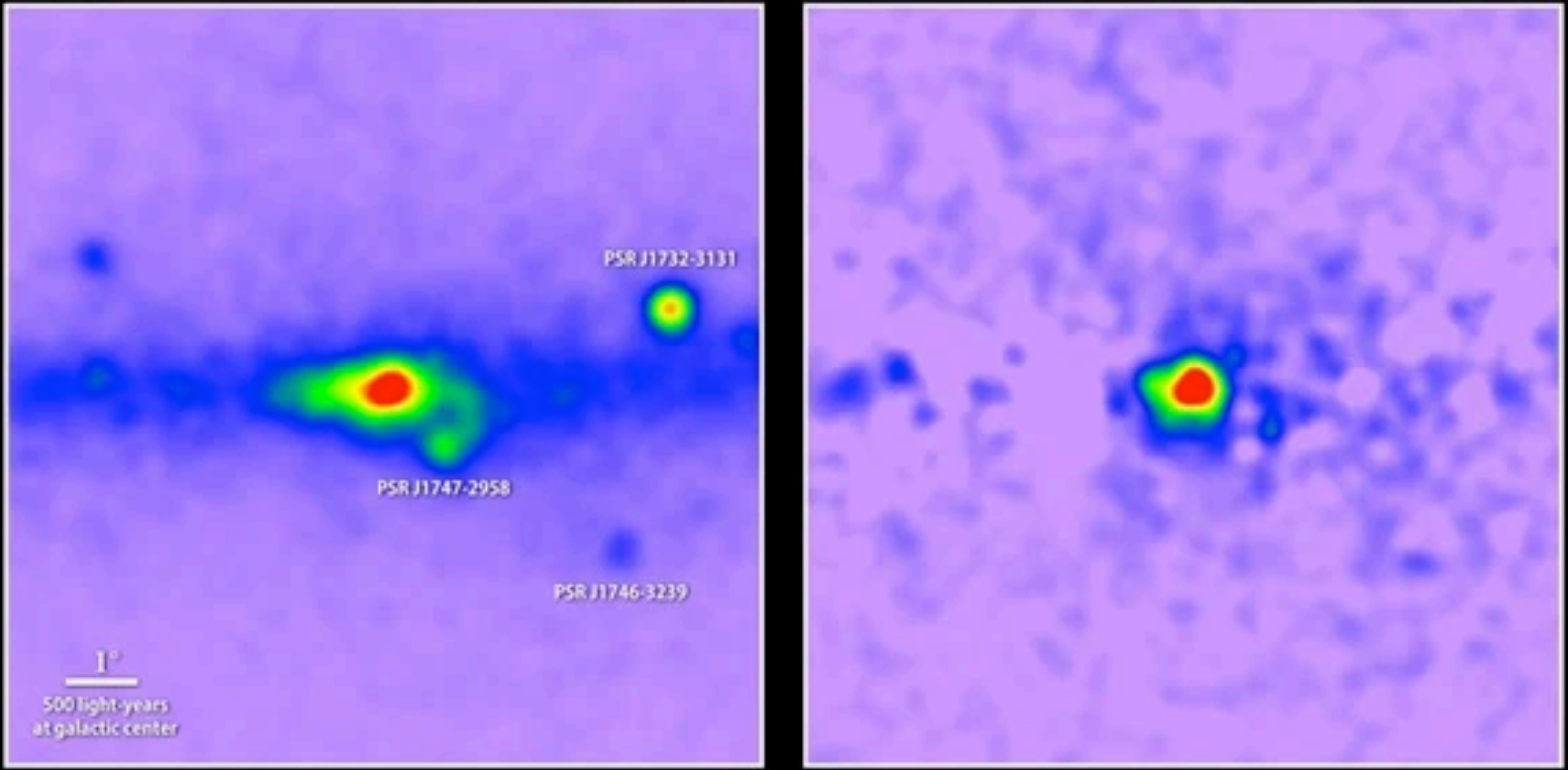


Hubble Space Telescope



Fermi-LAT

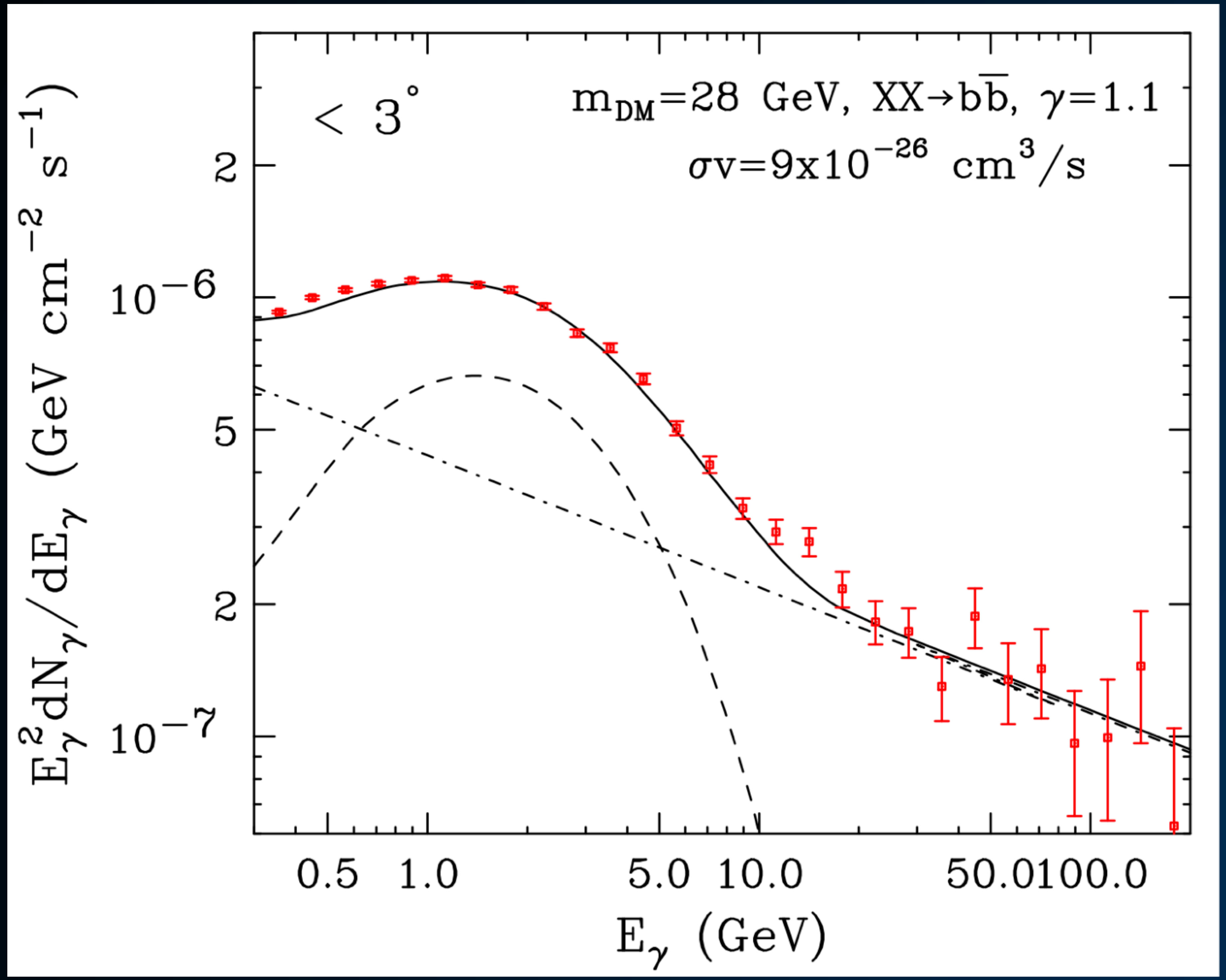
Uncovering a gamma-ray excess at the galactic center

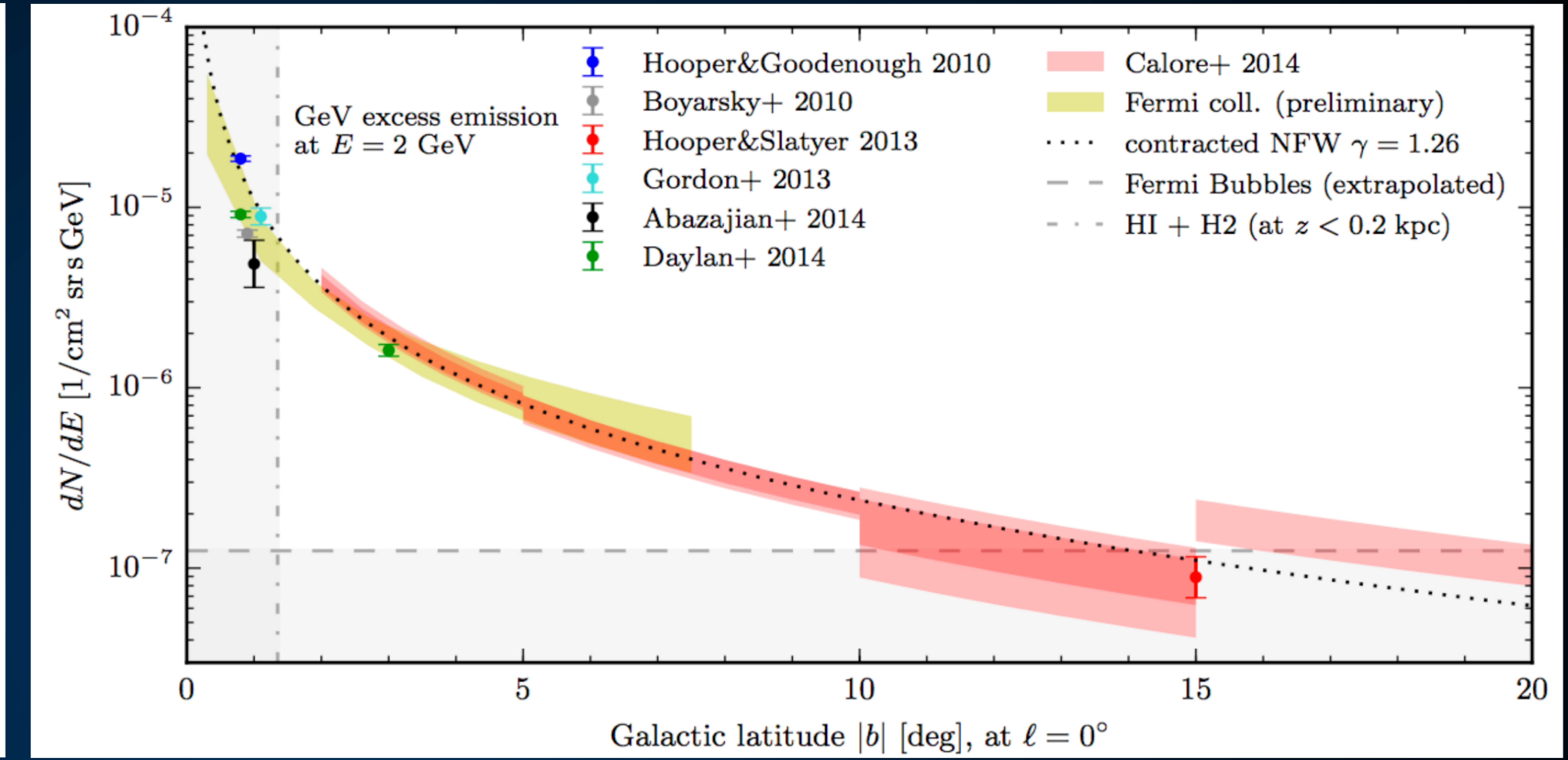


Unprocessed map of 1.0 to 3.16 GeV gamma rays | **Known sources removed**

The Galactic Center Excess

Goodenough & Hooper (2009; 0910.2998)





Bright *Detected at >50σ*

Hard-Spectrum *Incompatible with standard backgrounds*

Spherically Symmetric *Expected from Dark Matter*

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

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

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

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

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

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


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

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

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

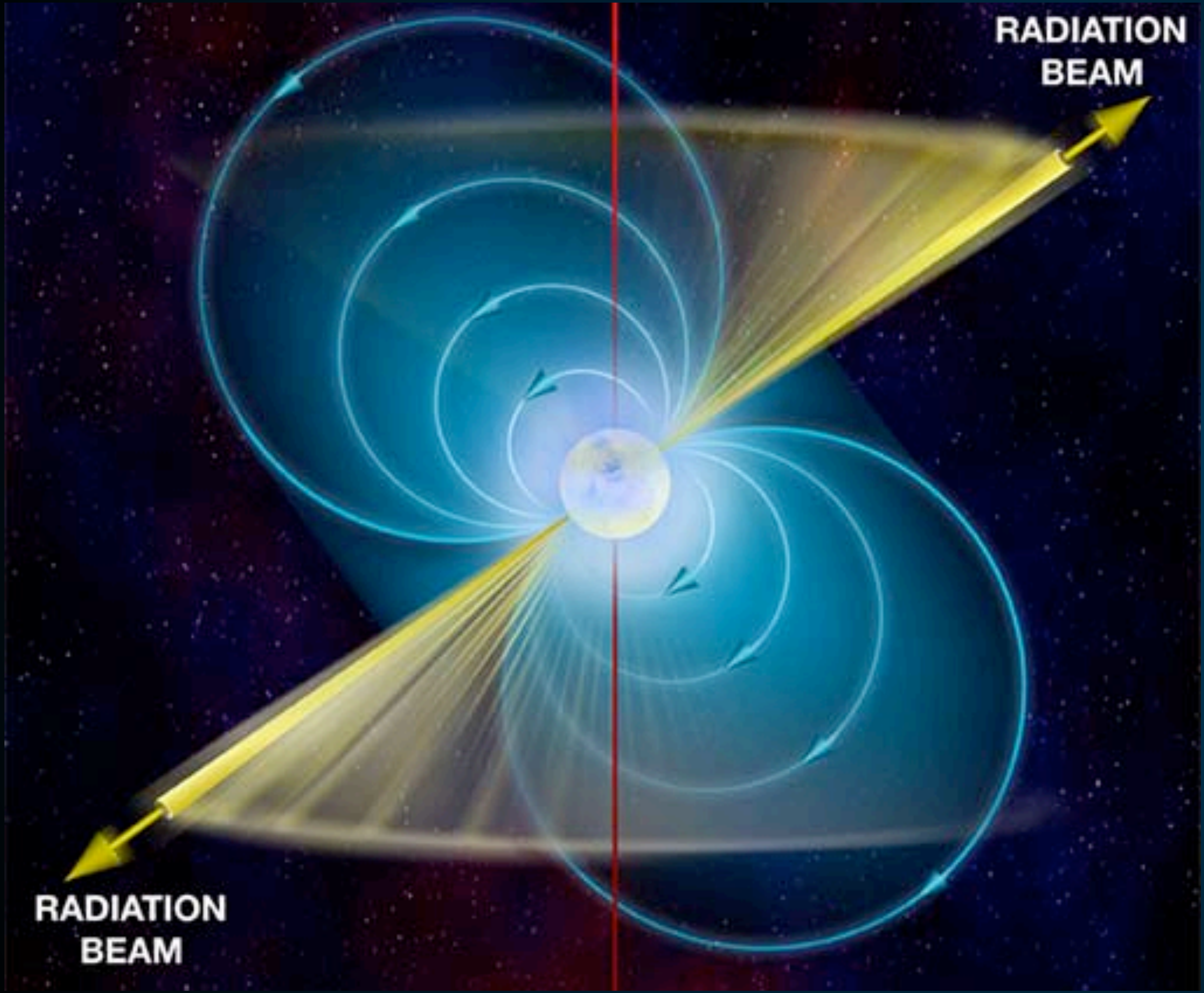

Galactic Center Excess Flux
Flux (GeV cm^{-2} s^{-1})
10^{-6}
10^{-7}
10^{-8}
0.3
1
3
10
30
100
Energy (GeV)
Calore et al. (2014; 1409.0042)


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

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

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

What is a Pulsar?



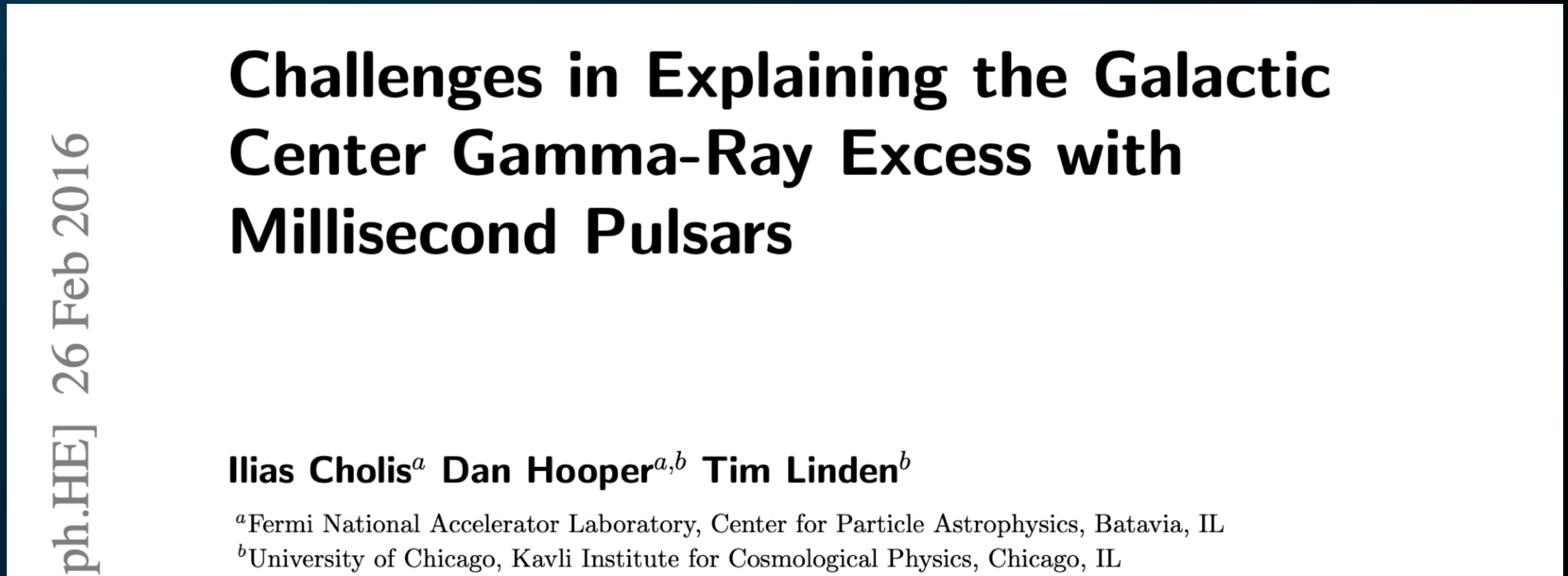
Pulsar

- Rapidly rotating neutron star
- Misalignment between 10^{10} T magnetic field and ~ms rotation period produces huge electromagnetic fields.
- Accelerates e^+e^- pairs to TeV or even PeV energies

What is a Pulsar?

Millisecond Pulsars

- “Recycled” pulsar spun up again via accretion by binary companion.
- Young pulsars in plane, but millisecond pulsars can be in the galactic bulge.
- To explain the excess, we need 10000 - 10000 pulsars

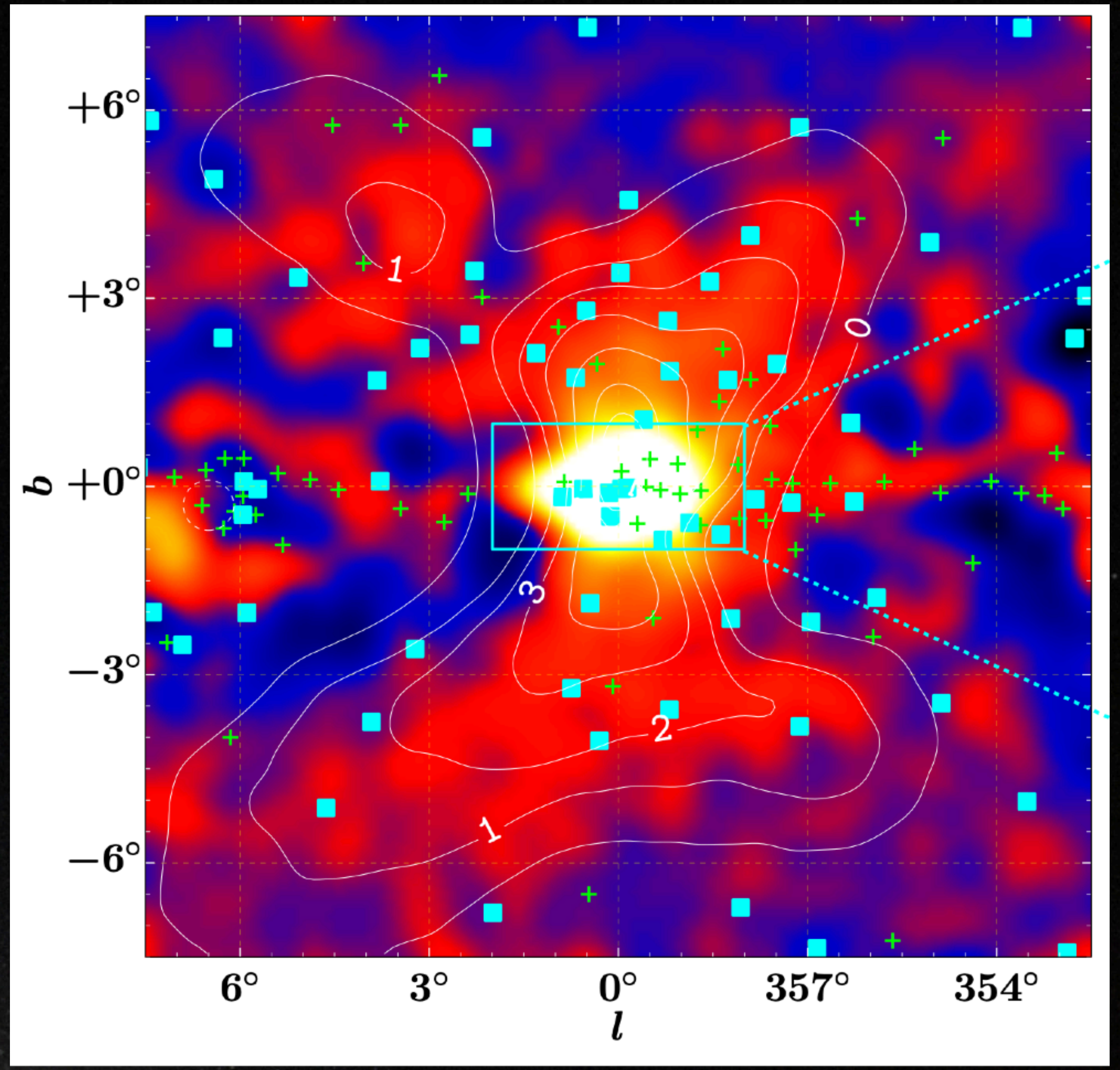


ph.HE] 26 Feb 2016

Challenges in Explaining the Galactic Center Gamma-Ray Excess with Millisecond Pulsars

Ilias Cholis[a] **Dan Hooper**[a,b] **Tim Linden**[b]

[a]Fermi National Accelerator Laboratory, Center for Particle Astrophysics, Batavia, IL
[b]University of Chicago, Kavli Institute for Cosmological Physics, Chicago, IL



Macias et al. (2016; 1611.06644)

Bartels et al. (2017; 1711.04778)

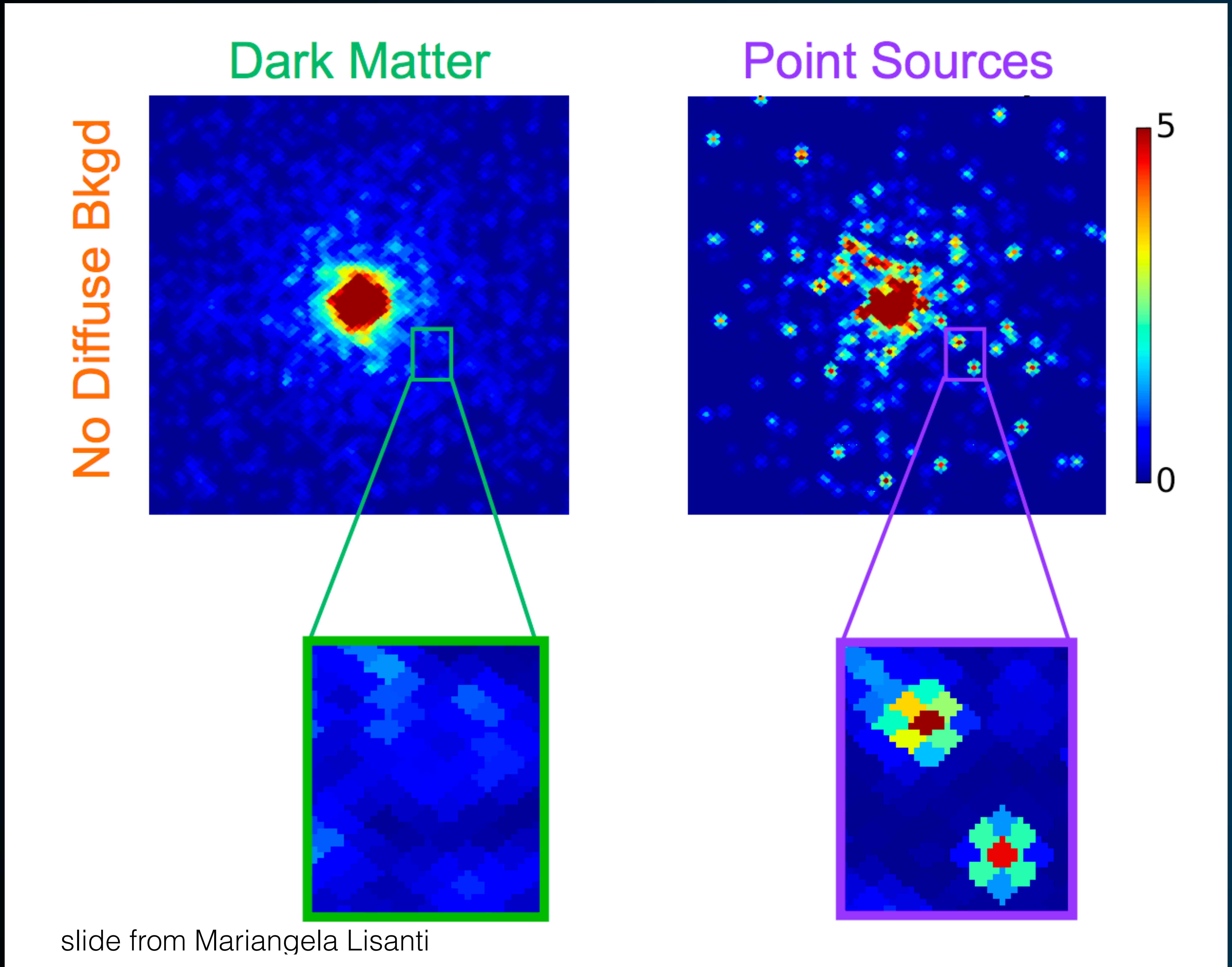
Bartels et al. (2018; 1803.04370)

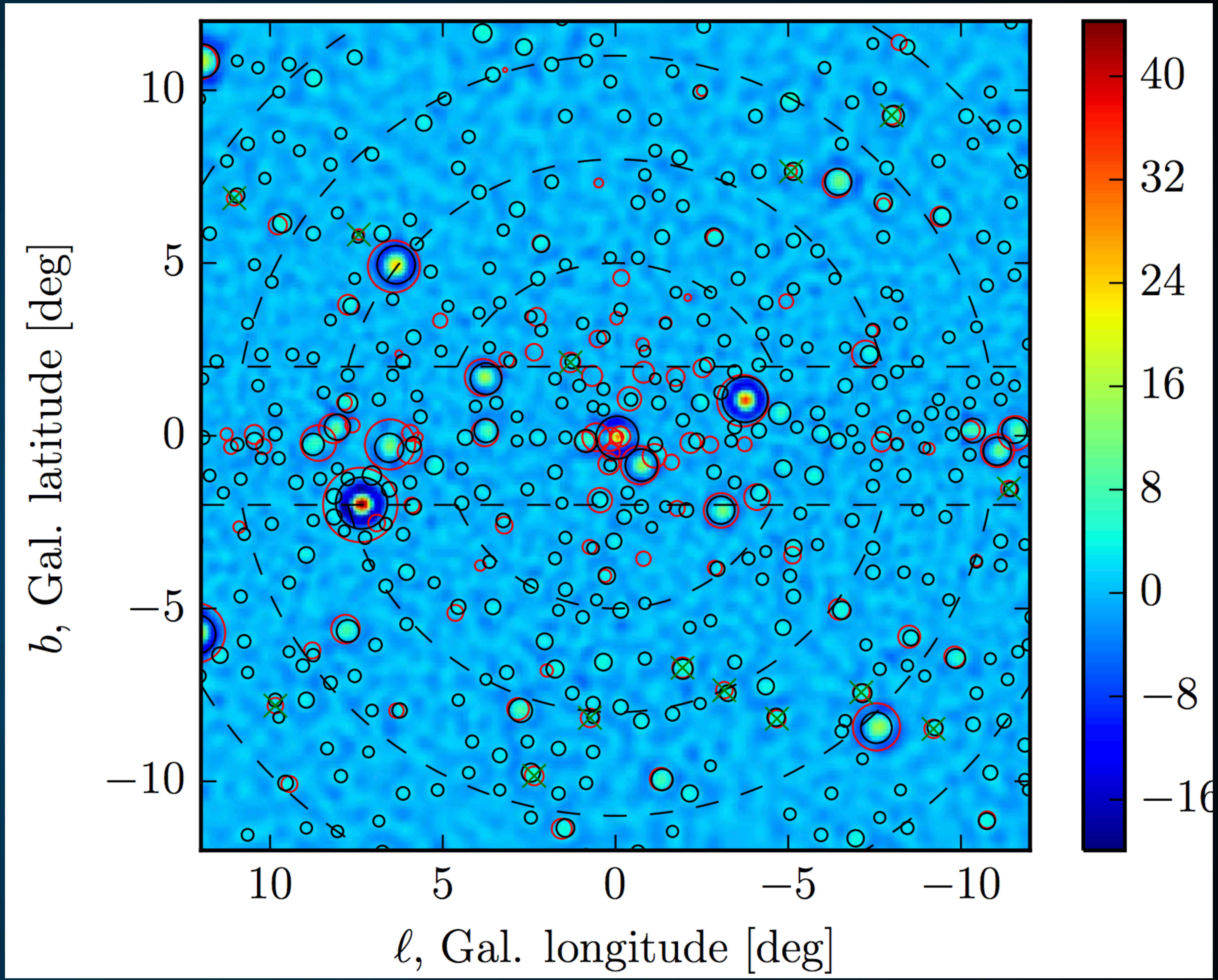
Macias et al. (2019; 1901.03822)

The Galactic Center Excess

Bartels et al. (2015; 1506.05104)

Lee et al. (2015; 1506.05124)





Bulletproof evidence for pulsars?

The Galactic Center Excess

1 (1 of 39) Automatic Zoom

Back at

emplate

an
ing
n

esolved

terest
ates
e with

igures

rom
ta
ry

int
e Fermi

real
tary

MIT-CTP/5104

Dark Matter Strikes Back at the Galactic Center

Rebecca K. Leane[1,*] and Tracy R. Slatyer[1,2,†]

[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2] *School of Natural Sciences, Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA*

(Dated: April 19, 2019)

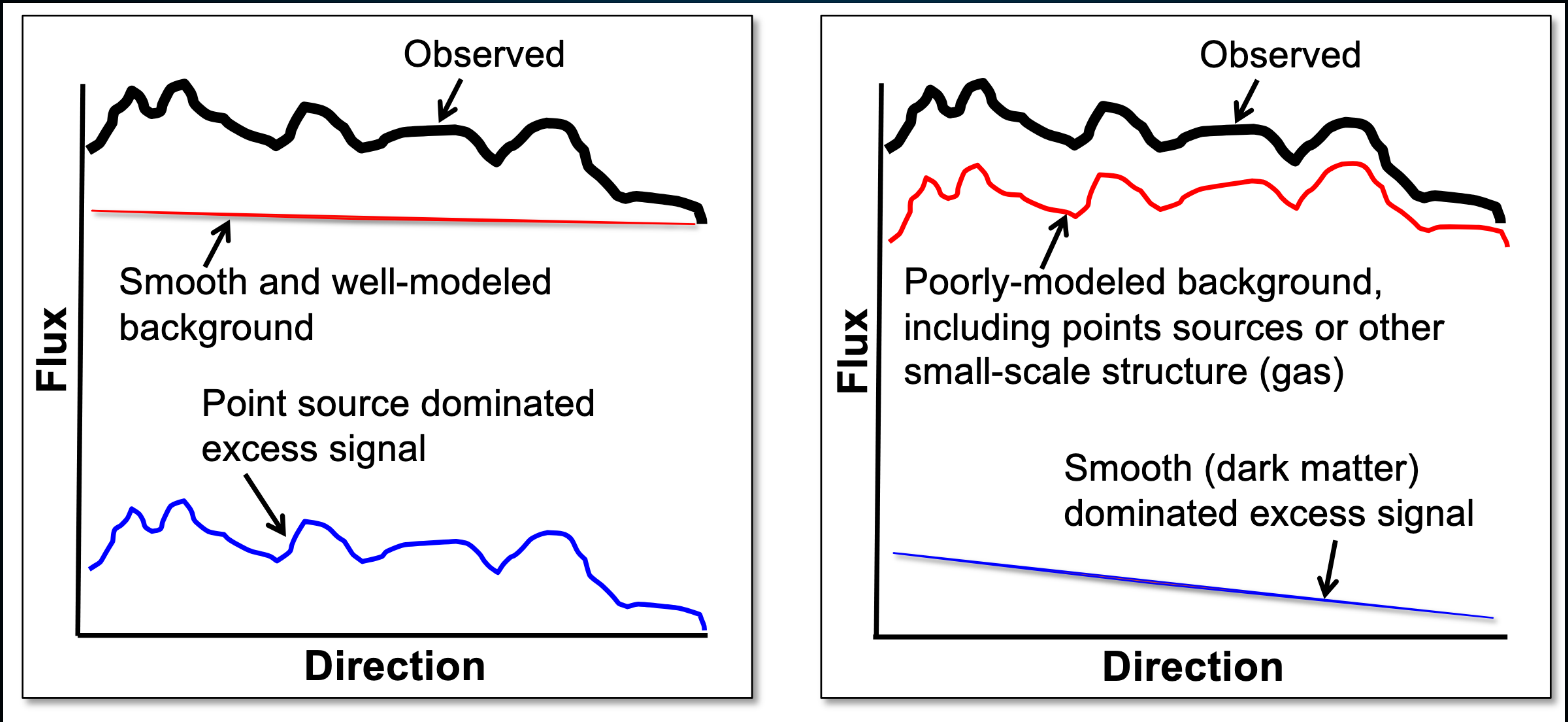
Statistical evidence has previously suggested that the Galactic Center GeV Excess (GCE) originates largely from point sources, and not from annihilating dark matter. We examine the impact of unmodeled source populations on identifying the true origin of the GCE using non-Poissonian template fitting (NPTF) methods. In a proof-of-principle example with simulated data, we discover that unmodeled sources in the *Fermi* Bubbles can lead to a dark matter signal being misattributed to point sources by the NPTF. We discover striking behavior consistent with a mismodeling effect in the real *Fermi* data, finding that large artificial injected dark matter signals are completely misattributed to point sources. Consequently, we conclude that dark matter may provide a dominant contribution to the GCE after all.

Introduction. There has been an extensive debate in the literature over the origins of the Galactic Center Excess (GCE), an extended and roughly spherically symmetric gamma-ray source filling the region within ~ 1.5 kpc of the Galactic Center (GC), with energy spectrum peaking at $1-3$ GeV [1–7]. The leading hypotheses are a new population of unresolved gamma-ray pulsars, individually too faint to be detected but in aggregate yielding the excess [8–19], or alternatively a signal from annihi-

function" (SCF), which describes the probability that a given source has a certain brightness (i.e. produces a certain expected number of photons). It is then possible to calculate the probability to observe a certain number of photons in each pixel, as a function of the coefficients of the various templates and the source-count function parameters, and to study the resulting overall likelihood as a function of these parameters. This approach is called non-Poissonian template fitting (NPTF) [21, 22, 24].

The Galactic Center Excess

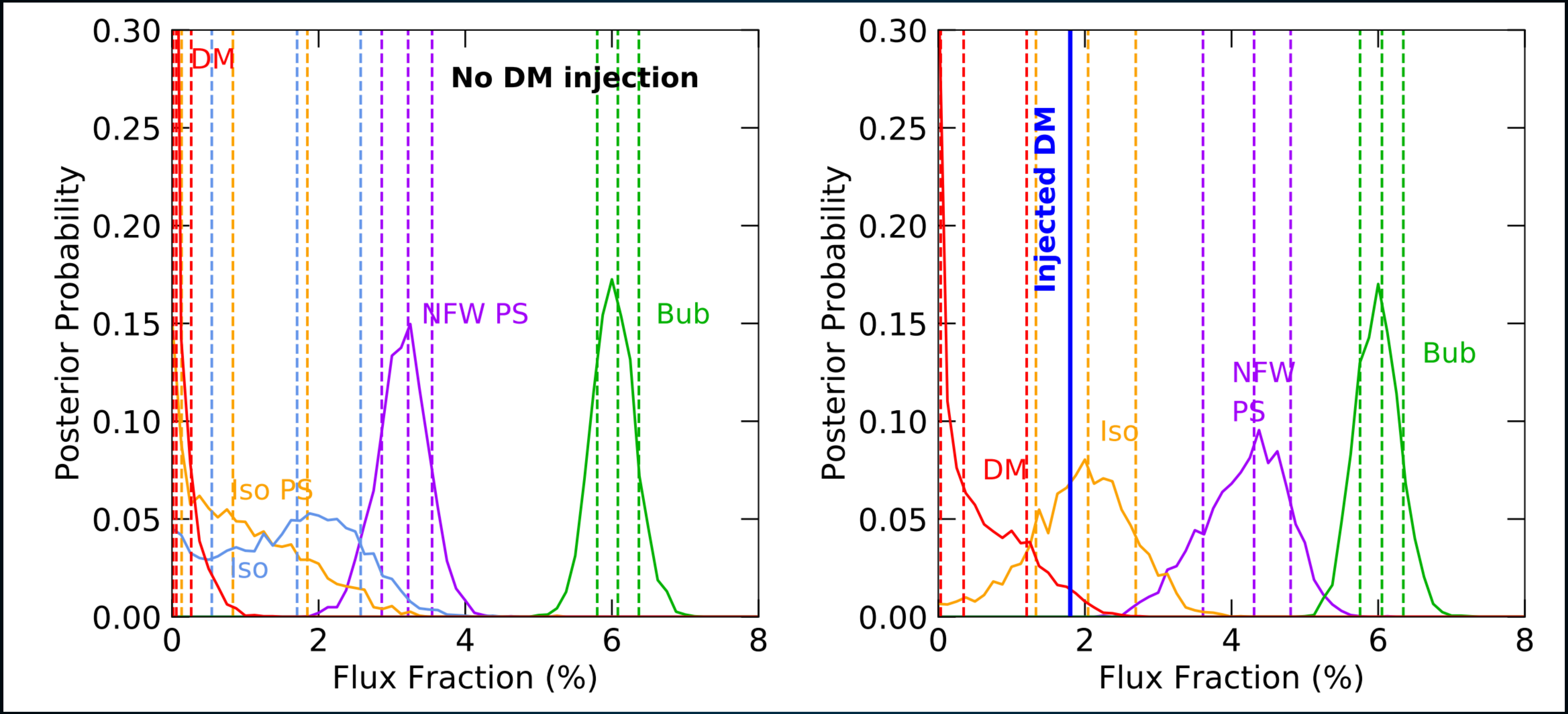
Leane & Slatyer (2019; 1904.08430)



Slide from Dan Hooper

The Galactic Center Excess

Leane & Slatyer (2019; 1904.08430)



Dark Matter Strikes Back at the Galactic Center

The Galactic Center Excess

Back at
emplate
an
ing
n
esolved
terest
ates
e with
igures
rom
ta
ry
int
e Fermi
real
tary

MIT-CTP/5104

Dark Matter Strikes Back at the Galactic Center

No!

Rebecca K. Leane[1,*] and Tracy R. Slatyer[1,2,†]

[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2] *School of Natural Sciences, Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA*

(Dated: April 19, 2019)

Statistical evidence has previously suggested that the Galactic Center GeV Excess (GCE) originates largely from point sources, and not from annihilating dark matter. We examine the impact of unmodeled source populations on identifying the true origin of the GCE using non-Poissonian template fitting (NPTF) methods. In a proof-of-principle example with simulated data, we discover that unmodeled sources in the *Fermi* Bubbles can lead to a dark matter signal being misattributed to point sources by the NPTF. We discover striking behavior consistent with a mismodeling effect in the real *Fermi* data, finding that large artificial injected dark matter signals are completely misattributed to point sources. Consequently, we conclude that dark matter may provide a dominant contribution to the GCE after all.

ph.HE] 17 Apr 2019

Introduction. There has been an extensive debate in the literature over the origins of the Galactic Center Excess (GCE), an extended and roughly spherically symmetric gamma-ray source filling the region within ∼ 1.5 kpc of the Galactic Center (GC), with energy spectrum peaking at 1 − 3 GeV [1–7]. The leading hypotheses are a new population of unresolved gamma-ray pulsars, individually too faint to be detected but in aggregate yielding the excess [8–19], or alternatively a signal from annihi-

function" (SCF), which describes the probability that a given source has a certain brightness (i.e. produces a certain expected number of photons). It is then possible to calculate the probability to observe a certain number of photons in each pixel, as a function of the coefficients of the various templates and the source-count function parameters, and to study the resulting overall likelihood as a function of these parameters. This approach is called non-Poissonian template fitting (NPTF) [21, 22, 24].

The Galactic Center Excess

LCTP-20-02

Foreground Mismodeling and the Point Source Explanation of the *Fermi* Galactic Center Excess

Yes!

Malte Buschmann,[1] Nicholas L. Rodd,[2,3] Benjamin R. Safdi,[1] Laura J. Chang,[4] Siddharth Mishra-Sharma,[5] Mariangela Lisanti,[4] and Oscar Macias[6,7]

[1] *Leinweber Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, MI 48109 USA*
[2] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, USA*
[3] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[4] *Department of Physics, Princeton University, Princeton, NJ 08544, USA*
[5] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA*
[6] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa, Chiba 277-8583, Japan*
[7] *GRAPPA Institute, University of Amsterdam, 1098 XH Amsterdam, The Netherlands*

(Dated: March 2, 2020)

The *Fermi* Large Area Telescope has observed an excess of ∼GeV energy gamma rays from the center of the Milky Way, which may arise from near-thermal dark matter annihilation. Firmly establishing the dark matter origin for this excess is however complicated by challenges in modeling diffuse cosmic-ray foregrounds as well as unresolved astrophysical sources, such as millisecond pulsars. Non-Poissonian Template Fitting (NPTF) is one statistical technique that has previously been used to show that at least some fraction of the GeV excess is likely due to a population of dim point sources. These results were recently called into question by Leane and Slatyer (2019), who showed that a synthetic dark matter annihilation signal injected on top of the real *Fermi* data is not recovered by the NPTF procedure. In this work, we perform a dedicated study of the *Fermi* data and explicitly show that the central result of Leane and Slatyer (2019) is likely driven by the fact that their choice of model for the Galactic foreground emission does not provide a sufficiently

The Galactic Center Excess

Nature
oint
ctic
ematic
edure
Data
Source-
nd the
-Only
Dark
ery
tion
te
deling
e
ery
Signal

LCTP-19-20

Characterizing the Nature of the Unresolved Point Sources in the Galactic Center: An Assessment of Systematic Uncertainties

Yes!

Laura J. Chang,[1] Siddharth Mishra-Sharma,[2] Mariangela Lisanti,[1]
Malte Buschmann,[3] Nicholas L. Rodd,[4,5] and Benjamin R. Safdi[3]

[1] *Department of Physics, Princeton University, Princeton, NJ 08544, USA*
[2] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA*
[3] *Leinweber Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA*
[4] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, USA*
[5] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

(Dated: March 4, 2020)

The Galactic Center Excess (GCE) of GeV gamma rays can be explained as a signal of annihilating dark matter or of emission from unresolved astrophysical sources, such as millisecond pulsars. Evidence for the latter is provided by a statistical procedure—referred to as Non-Poissonian Template Fitting (NPTF)—that distinguishes the smooth distribution of photons expected for dark matter annihilation from a "clumpy" photon distribution expected for point sources. In this paper, we perform an extensive study of the NPTF on simulated data, exploring its ability to recover the flux and luminosity function of unresolved sources at the Galactic Center. When astrophysical background emission is perfectly modeled, we find that the NPTF successfully distinguishes between the dark matter and point source hypotheses when either component makes up the entirety of the GCE. When the GCE is a mixture of dark matter and point sources, the NPTF may fail to reconstruct the correct contribution of each component. These results are related to the fact that in the ultra-faint limit, a population of unresolved point sources is exactly degenerate with Poissonian emission. We further study the impact of mismodeling the Galactic diffuse backgrounds, finding that while a

The Galactic Center Excess

MIT-CTP/5170

Spurious Point Source Signals in the Galactic Center Excess

No!

Rebecca K. Leane[1,*] and Tracy R. Slatyer[1,†]

[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

(Dated: September 18, 2020)

We re-examine evidence that the Galactic Center Excess (GCE) originates primarily from point sources (PSs). We show that in our region of interest, non-Poissonian template fitting (NPTF) evidence for GCE PSs is an artifact of unmodeled north-south asymmetry of the GCE. This asymmetry is strongly favored by the fit (although it is unclear if this is physical), and when it is allowed, the preference for PSs becomes insignificant. We reproduce this behavior in simulations, including detailed properties of the spurious PS population. We conclude that NTPF evidence for GCE PSs is highly susceptible to certain systematic errors, and should not at present be taken to robustly disfavor a dominantly smooth GCE.

Data from the *Fermi* Gamma-Ray Space Telescope have revealed an intriguing excess of GeV-scale gamma rays from the region around the Galactic Center [1–4]. The origin of this Galactic Center Excess (GCE) has been an active controversy for some years, with much interest in the possibility that it might be the first detected signal of annihilating dark matter (DM). In 2015, two papers made data-driven arguments that the GCE was likely to represent a previously-undetected population of point sources (PSs) in the inner Galaxy, most likely pulsars [5, 6]; subsequent analyses have argued for a stellar

generate posterior probability distributions for the model parameters. Ref. [6] found a strong statistical preference for a GCE PS template with flux sufficient to explain the entire GCE, and interpreted this as evidence for a new GCE-correlated PS population.

In this *Letter* we will explicitly demonstrate that the NPTF preference for PSs can change dramatically as a result of a simple perturbation to the signal model. Working in a 10° radius region of interest (ROI), we show that when the northern and southern halves of the GCE are allowed to float independently, their coefficients are

The Galactic Center Excess

Automatic Zoom

ctic
rious
ignal

nd Data

elected
f the

f
ults
l (2016)
5fea)

f
ults
t al

y)
f
ults
t al

rs)
f Relevai
Leane et

125.1211(
as a

MIT-CTP/5178

The Enigmatic Galactic Center Excess: Spurious Point Sources and Signal Mismodeling

No!

Rebecca K. Leane* and Tracy R. Slatyer†

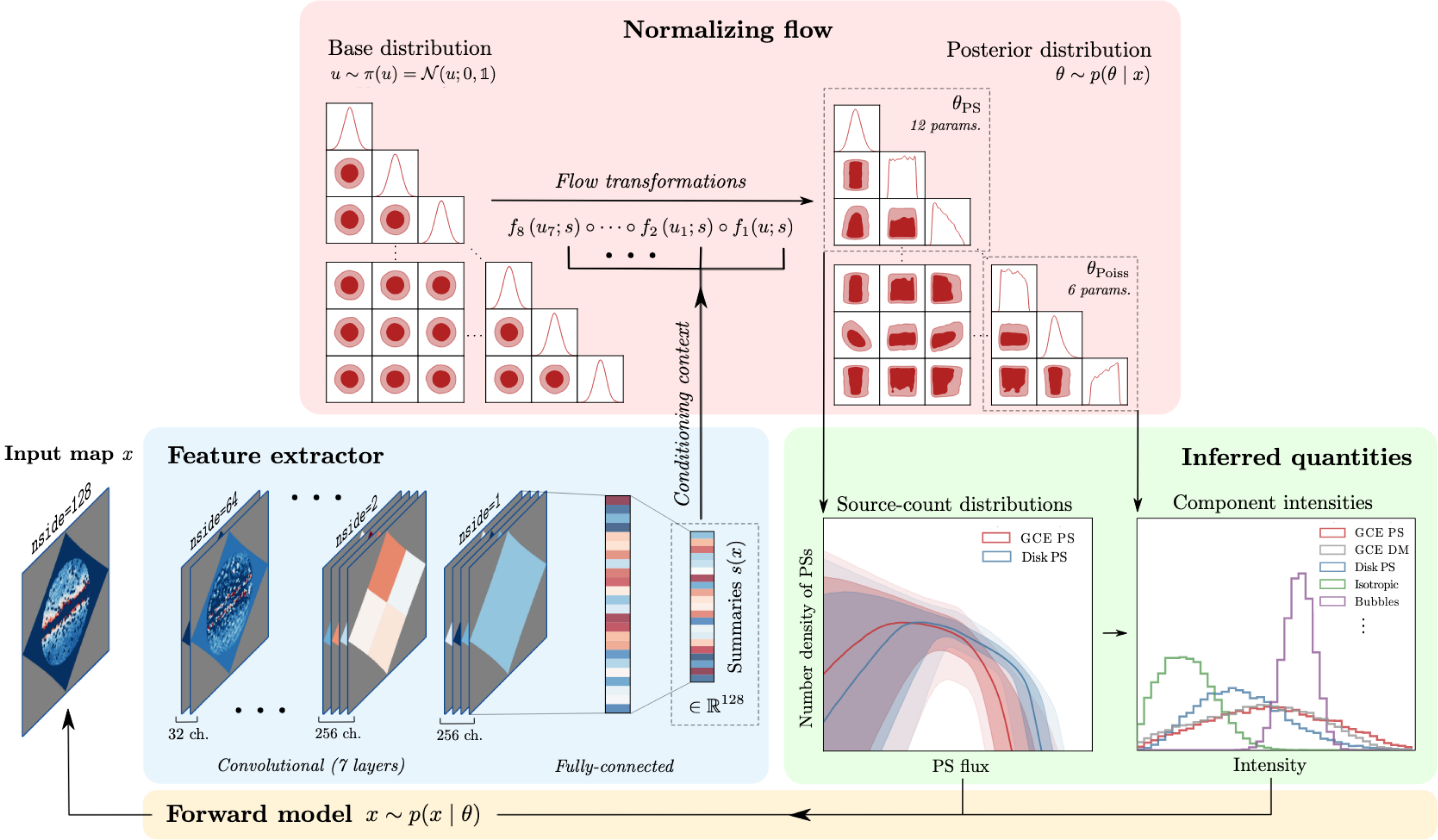
Center for Theoretical Physics
Massachusetts Institute of Technology
Cambridge, MA 02139, USA

(Dated: September 18, 2020)

Abstract

The Galactic Center GeV excess (GCE) has garnered great interest as a possible signal of either dark matter annihilation or some novel astrophysical phenomenon, such as a new population of gamma-ray emitting pulsars. In a companion paper, we showed that in a 10° radius region of interest (ROI) surrounding the Galactic Center, apparent evidence for GCE point sources (PSs) from non-Poissonian template fitting (NPTF) is actually an artifact of unmodeled north-south asymmetry of the GCE. In this work, we develop a simplified analytic description of how signal mismodeling can drive an apparent preference for a PS population, and demonstrate how the behavior pointed out in the companion paper also appears in simpler simulated datasets that


lokal. max;
lim min
lok. min
N→R
x_n:N→R
n∈N, A>0,⇒



Normalizing flow
Base distribution
$u \sim \pi(u) = \mathcal{N}(u; 0, \mathbb{1})$
Posterior distribution
$\theta \sim p(\theta \mid x)$
θ_{PS}
12 params.
θ_{Poiss}
6 params.
Flow transformations
$f_8(u_7; s) \circ \cdots \circ f_2(u_1; s) \circ f_1(u; s)$
Conditioning context
Input map x
nside=128
Feature extractor
nside=64
nside=2
nside=1
32 ch.
256 ch.
256 ch.
Convolutional (7 layers)
Fully-connected
Summaries $s(x)$
$\in \mathbb{R}^{128}$
Inferred quantities
Source-count distributions
GCE PS
Disk PS
Number density of PSs
PS flux
Component intensities
GCE PS
GCE DM
Disk PS
Isotropic
Bubbles
Intensity
Forward model $x \sim p(x \mid \theta)$

The GCE in a New Light: Disentangling the γ-ray Sky with Bayesian Graph Convolutional Neural Networks

Maybe!

Florian List,[1,*] Nicholas L. Rodd,[2,3] Geraint F. Lewis,[1] and Ishaan Bhat[4]

[1] *Sydney Institute for Astronomy, School of Physics, A28, The University of Sydney, NSW 2006, Australia*
[2] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, USA*
[3] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[4] *UMC Utrecht, Image Sciences Institute, 3508 GA Utrecht, The Netherlands*

(Dated: October 29, 2020)

A fundamental question regarding the Galactic Center Excess (GCE) is whether the underlying structure is point-like or smooth. This debate, often framed in terms of a millisecond pulsar or annihilating dark matter (DM) origin for the emission, awaits a conclusive resolution. In this work we weigh in on the problem using Bayesian graph convolutional neural networks. In simulated data, our neural network (NN) is able to reconstruct the flux of inner Galaxy emission components to on average $\sim$0.5%, comparable to the non-Poissonian template fit (NPTF). When applied to the actual *Fermi*-LAT data, we find that the NN estimates for the flux fractions from the background templates are consistent with the NPTF; however, the GCE is almost entirely attributed to smooth emission. While suggestive, we do not claim a definitive resolution for the GCE, as the NN tends to underestimate the flux of point-sources peaked near the 1σ detection threshold. Yet the technique displays robustness to a number of systematics, including reconstructing injected DM, diffuse mismodeling, and unmodeled north-south asymmetries. So while the NN is hinting at a smooth origin for the GCE at present, with further refinements we argue that Bayesian Deep Learning is

] 28 Oct 2020

Dim but not entirely dark: Extracting the Galactic Center Excess' source-count distribution with neural nets

Maybe!

Florian List,[1,2,*] Nicholas L. Rodd,[3] and Geraint F. Lewis[1]
[1] *Sydney Institute for Astronomy, School of Physics, A28, The University of Sydney, NSW 2006, Australia*
[2] *Department of Astrophysics, University of Vienna, Türkenschanzstraße 17, 1180 Vienna, Austria*
[3] *CERN, Theoretical Physics Department, Geneva 1211, Switzerland*

The two leading hypotheses for the Galactic Center Excess (GCE) in the *Fermi* data are an unresolved population of faint millisecond pulsars (MSPs) and dark-matter (DM) annihilation. The dichotomy between these explanations is typically reflected by modeling them as two separate emission components. However, point-sources (PSs) such as MSPs become statistically degenerate with smooth Poisson emission in the ultra-faint limit (formally where each source is expected to contribute much less than one photon on average), leading to an ambiguity that can render questions such as whether the emission is PS-like or Poissonian in nature ill-defined. We present a conceptually new approach that describes the PS and Poisson emission in a unified manner and only afterwards derives constraints on the Poissonian component from the so obtained results. For the implementation of this approach, we leverage deep learning techniques, centered around a neural network-based method for histogram regression that expresses uncertainties in terms of quantiles. We demonstrate that our method is robust against a number of systematics that have plagued previous approaches, in particular DM / PS misattribution. In the *Fermi* data, we find a faint GCE described by a median source-count distribution (SCD) peaked at a flux of $\sim 4 \times 10^{-11}$ counts cm^{-2} s^{-1} (corresponding to $\sim 3-4$ expected counts per PS), which would require $N \sim \mathcal{O}(10^4)$ sources to explain the entire excess (median value $N = 29{,}300$ across the sky). Although faint, this SCD allows us to derive the constraint $\eta_P \leq 66\%$ for the Poissonian fraction of the GCE flux η_P at 95% confidence, suggesting that a substantial amount of the GCE flux is due to PSs.

I. INTRODUCTION

DM annihilation [16, 26–30], although a recent study in Refs. [31, 32] found that with a different modeling of the

MIT-CTP/5337

A neural simulation-based inference approach for characterizing the Galactic Center γ-ray excess

Maybe!

Siddharth Mishra-Sharma[1,2,3,4,5,*] and Kyle Cranmer[5,6,†]

[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2] *The NSF AI Institute for Artificial Intelligence and Fundamental Interactions*
[3] *Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[4] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[5] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA*
[6] *Center for Data Science, New York University, 60 Fifth Ave, New York, NY 10011, USA*

(Dated: March 29, 2022)

The nature of the *Fermi* γ-ray Galactic Center Excess (GCE) has remained a persistent mystery for over a decade. Although the excess is broadly compatible with emission expected due to dark matter annihilation, an explanation in terms of a population of unresolved astrophysical point sources *e.g.*, millisecond pulsars, remains viable. The effort to uncover the origin of the GCE is hampered in particular by an incomplete understanding of diffuse emission of Galactic origin. This can lead to spurious features that make it difficult to robustly differentiate smooth emission, as expected for a dark matter origin, from more "clumpy" emission expected from a population of relatively bright, unresolved point sources. We use recent advancements in the field of simulation-based inference, in particular density estimation techniques using normalizing flows, in order to characterize the contribution of modeled components, including unresolved point source populations, to the GCE. Compared to traditional techniques based on the statistical distribution of photon counts, our machine learning-based method is able to utilize more of the information contained in a given model of the Galactic Center emission, and in particular can perform posterior parameter estimation while accounting for pixel-to-pixel spatial correlations in the γ-ray map. This makes the method demonstrably more resilient to certain forms of model misspecification. On application to *Fermi* data, the method generically attributes a smaller fraction of the GCE flux to unresolved point sources when compared to traditional approaches. We nevertheless infer such a contribution to make up a non-negligible fraction of the GCE across all analysis variations considered, with at least $38^{+9}_{-19}\%$ of the excess attributed to unresolved point sources in our baseline analysis.

MIT-CTP/5390

Characterizing the Expected Behavior of Non-Poissonian Template Fitting

You Can't Tell!

Luis Gabriel C. Bariuan[1,*] and Tracy R. Slatyer[1,2,†]

[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A.*
[2] *The NSF AI Institute for Artificial Intelligence and Fundamental Interactions*

We have performed a systematic study of the statistical behavior of non-Poissonian template fitting (NPTF), a method designed to analyze and characterize unresolved point sources in general counts datasets. In this paper, we focus on the properties and characteristics of the *Fermi*-LAT gamma-ray data set. In particular, we have simulated and analyzed gamma-ray sky maps under varying conditions of exposure, angular resolution, pixel size, energy window, event selection, and source brightness. We describe how these conditions affect the sensitivity of NPTF to the presence of point sources, for inner-galaxy studies of point sources within the Galactic Center excess, and for the simplified case of isotropic emission. We do not find opportunities for major gains in sensitivity from varying these choices, within the range available with current *Fermi-LAT* data. We provide an analytic estimate of the NPTF sensitivity to point sources for the case of isotropic emission and perfect angular resolution, and find good agreement with our numerical results for that case.

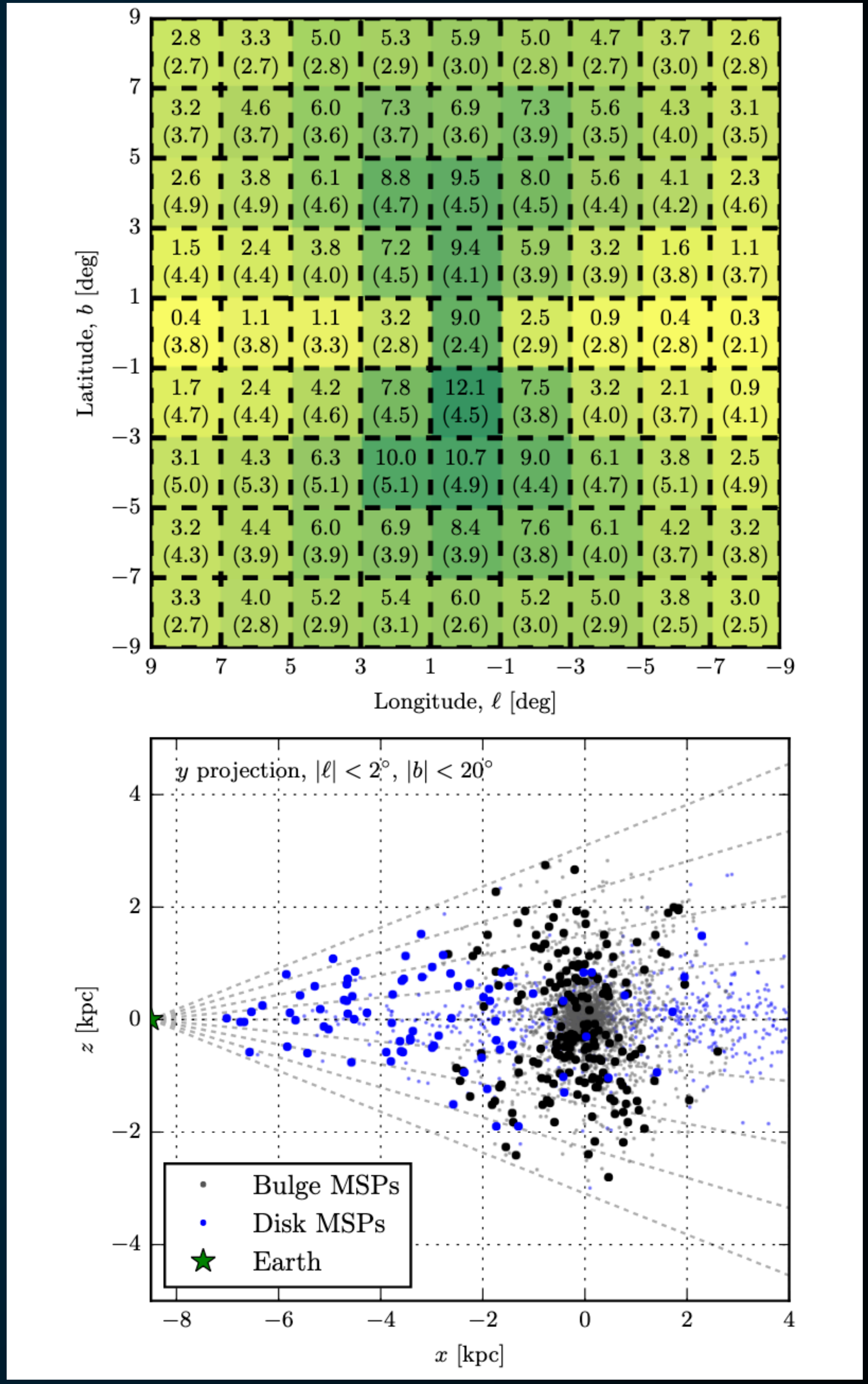
I. INTRODUCTION

Recent years have seen a number of efforts to apply photon pixel count statistics to gamma-ray data, in order to characterize populations of point sources (PSs) too faint to be individually detected at high significance (e.g. [1–11]). The general idea of these methods is to exploit the fact that an unmodeled PS population gives rise to non-Poissonian fluctuations in the number of photons per pixel, with "hot spots" corresponding to the locations

controversy for the past decade, with two explanations receiving the most attention. One possibility is that the GCE originates from diffuse particle dark matter (DM) undergoing annihilation (e.g. [15, 19, 22]), as the flux, energy spectrum, and spatial morphology of the GCE appear broadly consistent with a DM origin. If this hypothesis were confirmed, it would be a discovery of profound importance, representing the first evidence of non-gravitational interactions between DM and visible particles. However, the energy spectrum of the GCE also

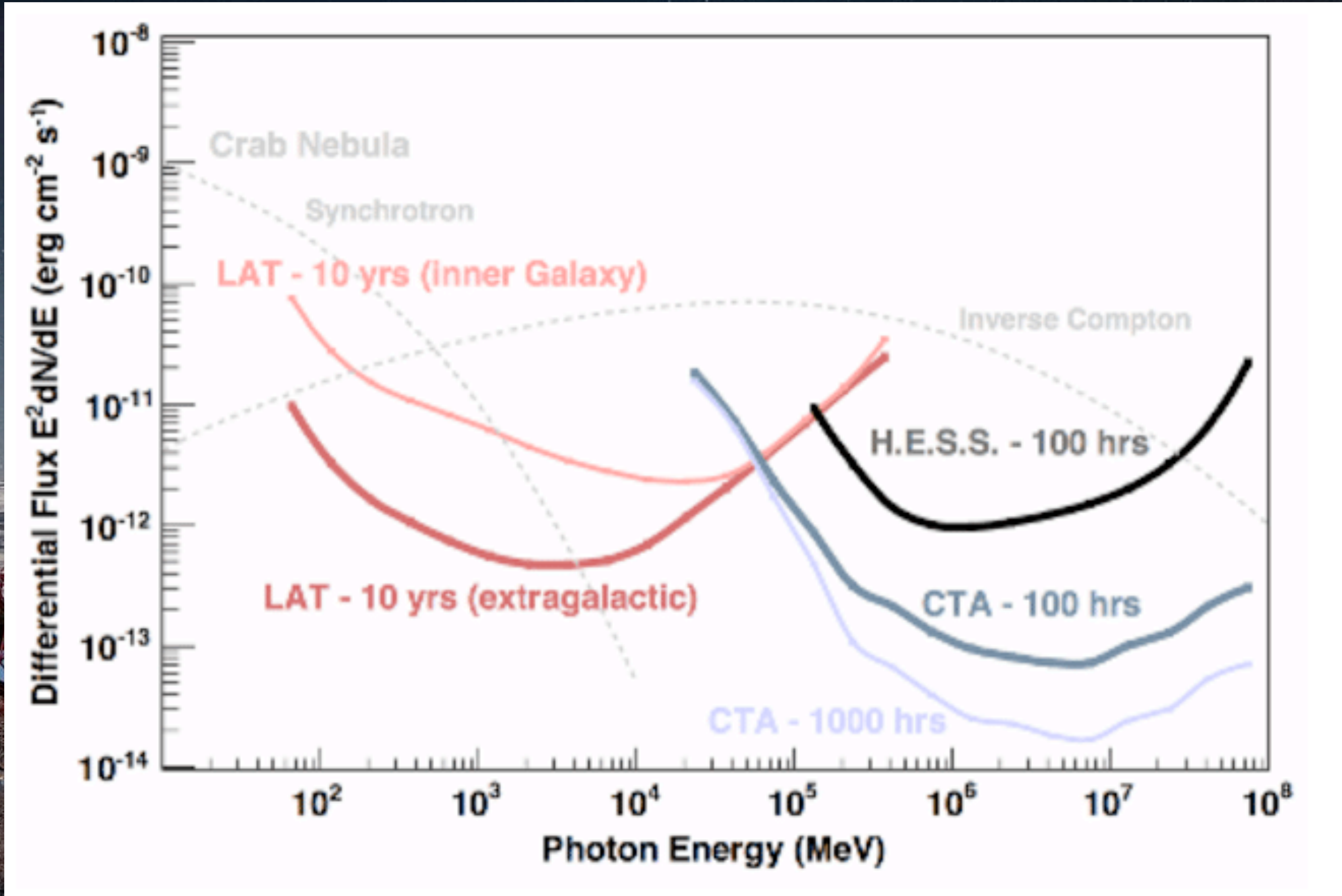
The (Low-Energy) Path Forward

Calore et al. (1512.06825)

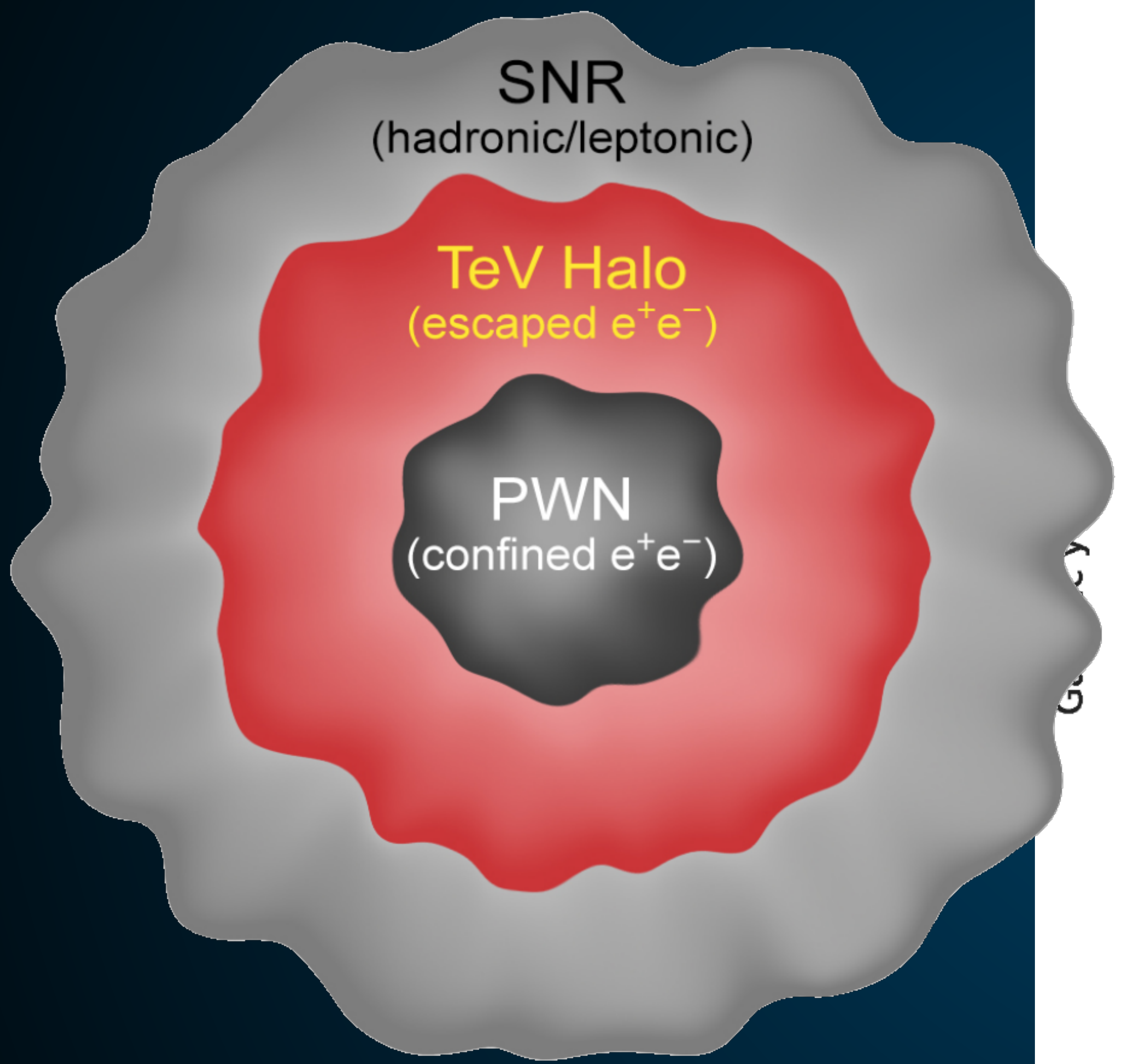


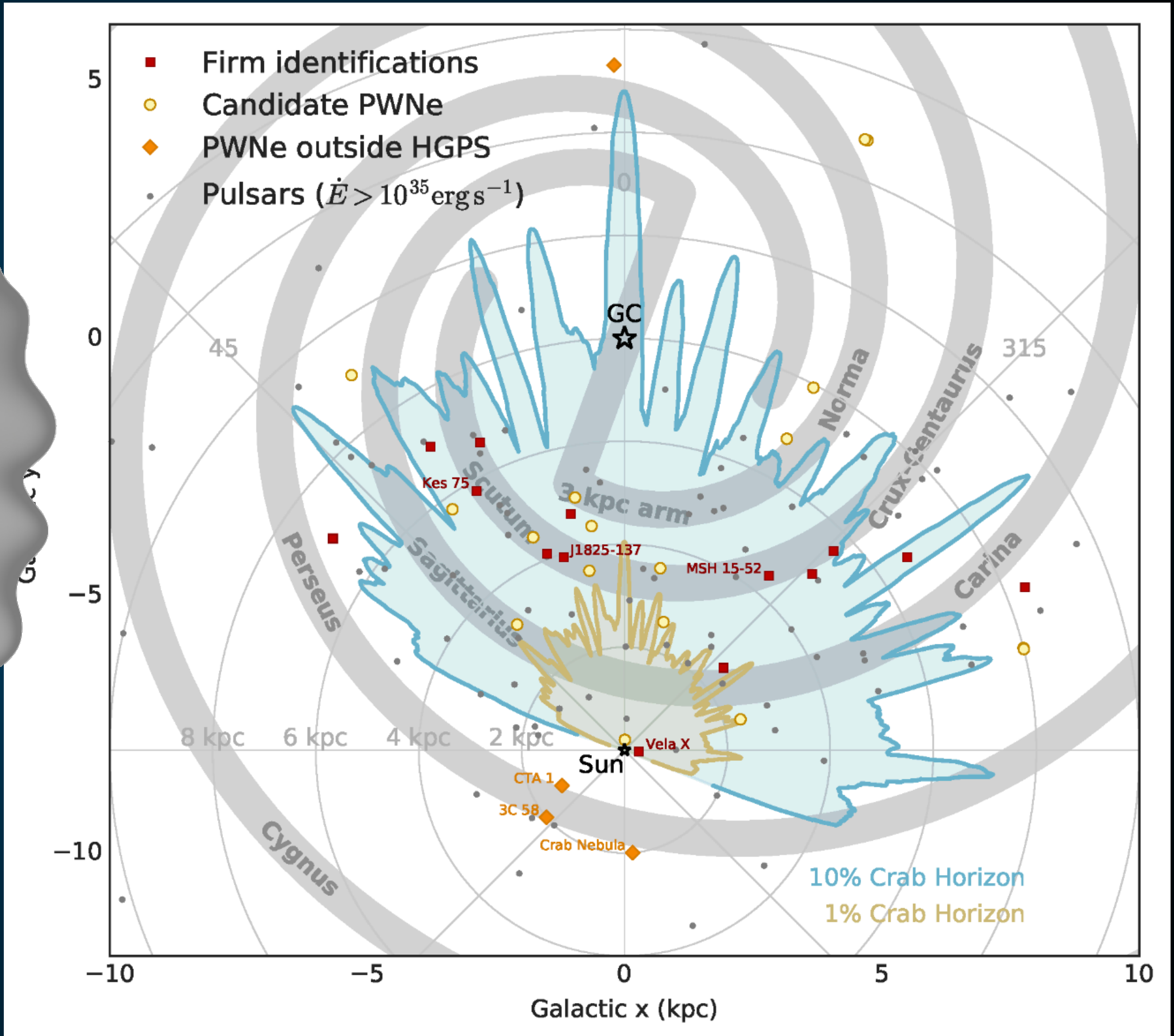
The (High-Energy) Path Forward

The (High-Energy) Path Forward



The Positron Excess

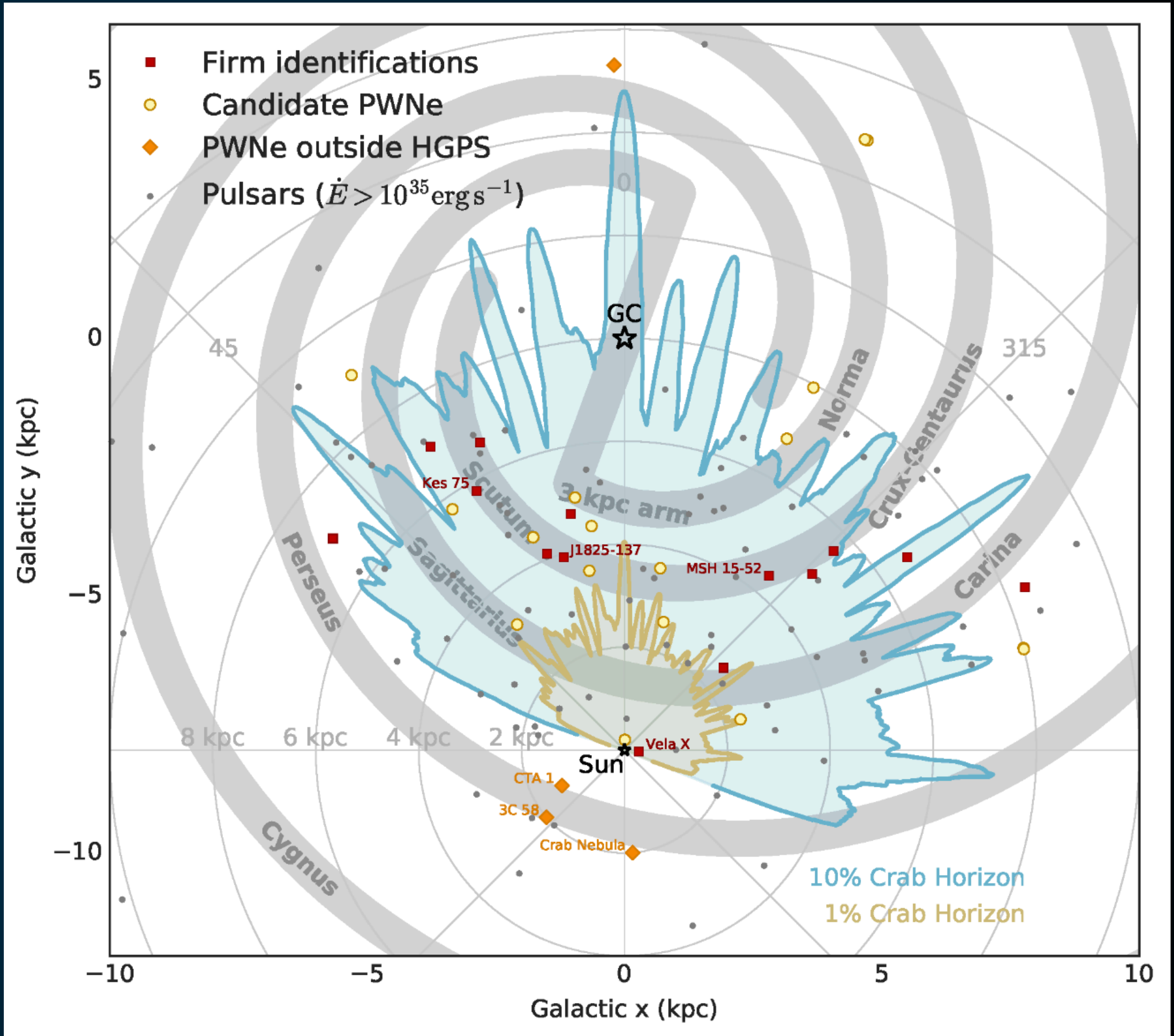




TeV Pulsar Wind Nebulae

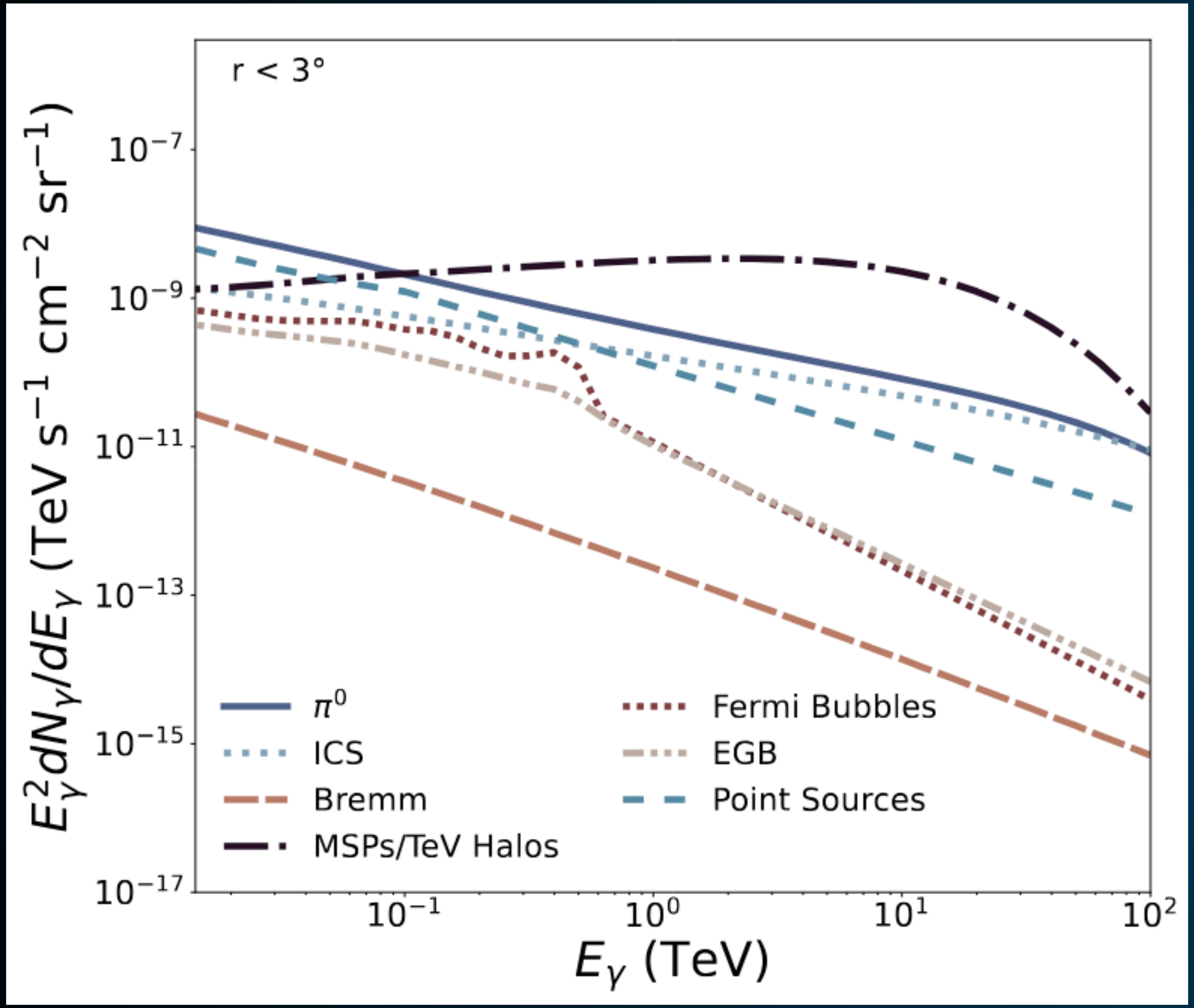
H.E.S.S. has found dozens of pulsar wind nebulae at TeV energies.

Emission from the inverse-Compton of TeV to PeV electrons accelerated by the pulsar and pulsar wind.




Moon (To Scale)
Geminga
PSR B0656+14
TeV Halos

The (High-Energy) Path Forward



FERMILAB-PUB-22-923-T

The Cherenkov Telescope Array Will Test Whether Pulsars Generate the Galactic Center Gamma-Ray Excess

Celeste Keith[a,b,*] Dan Hooper[a,b,c,†] and Tim Linden[d,‡]

[a] University of Chicago, Kavli Institute for Cosmological Physics, Chicago IL, USA
[b] University of Chicago, Department of Astronomy and Astrophysics, Chicago IL, USA
[c] Fermi National Accelerator Laboratory, Theoretical Astrophysics Group, Batavia, IL, USA and
[d] ... University and The Oskar Klein Centre for Cosmoparticle Physics, AlbaNova, 10691 Stockholm, Swe...

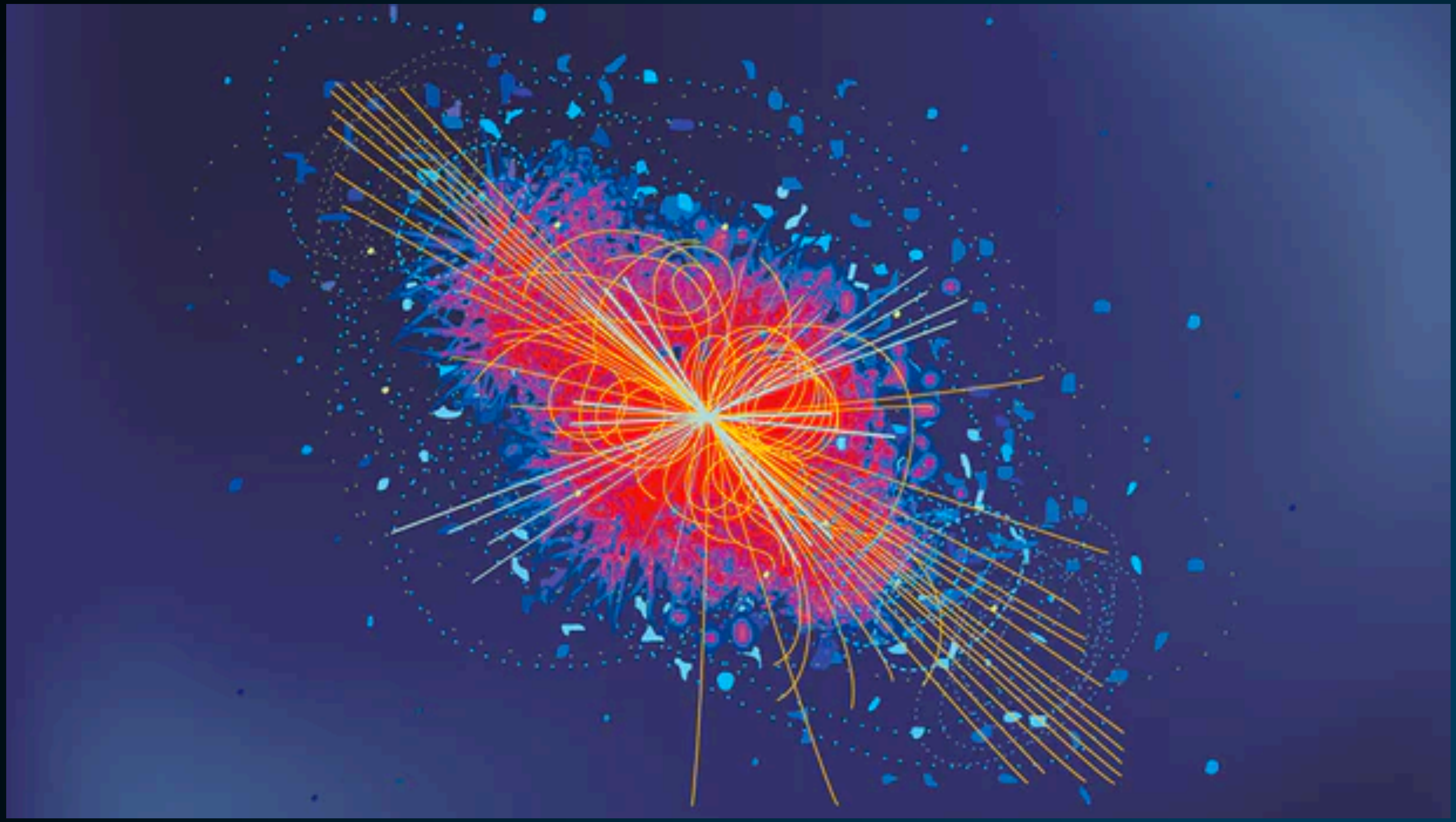
(Dated: December 21, 2022)

...le gamma-ray excess observed from the region surrounding the Galactic Center has ...
... either the products of annihilating dark matter particles, or as the emission...
... of faint and centrally-located millisecond pulsars. If pulsars are responsibl...
... also produce detectable levels of TeV-scale emission. In this study, ...
... of simulated data in an effort to assess the ability of the Cheren...
... constrain the presence of this emission, providing a ne...
... and pulsars are responsible for the observed exce...
... of the Inner Galaxy, CTA will be able to de...
... the source of the Galactic Center Ga...


topic

Tentative Evidence for Antinuclei

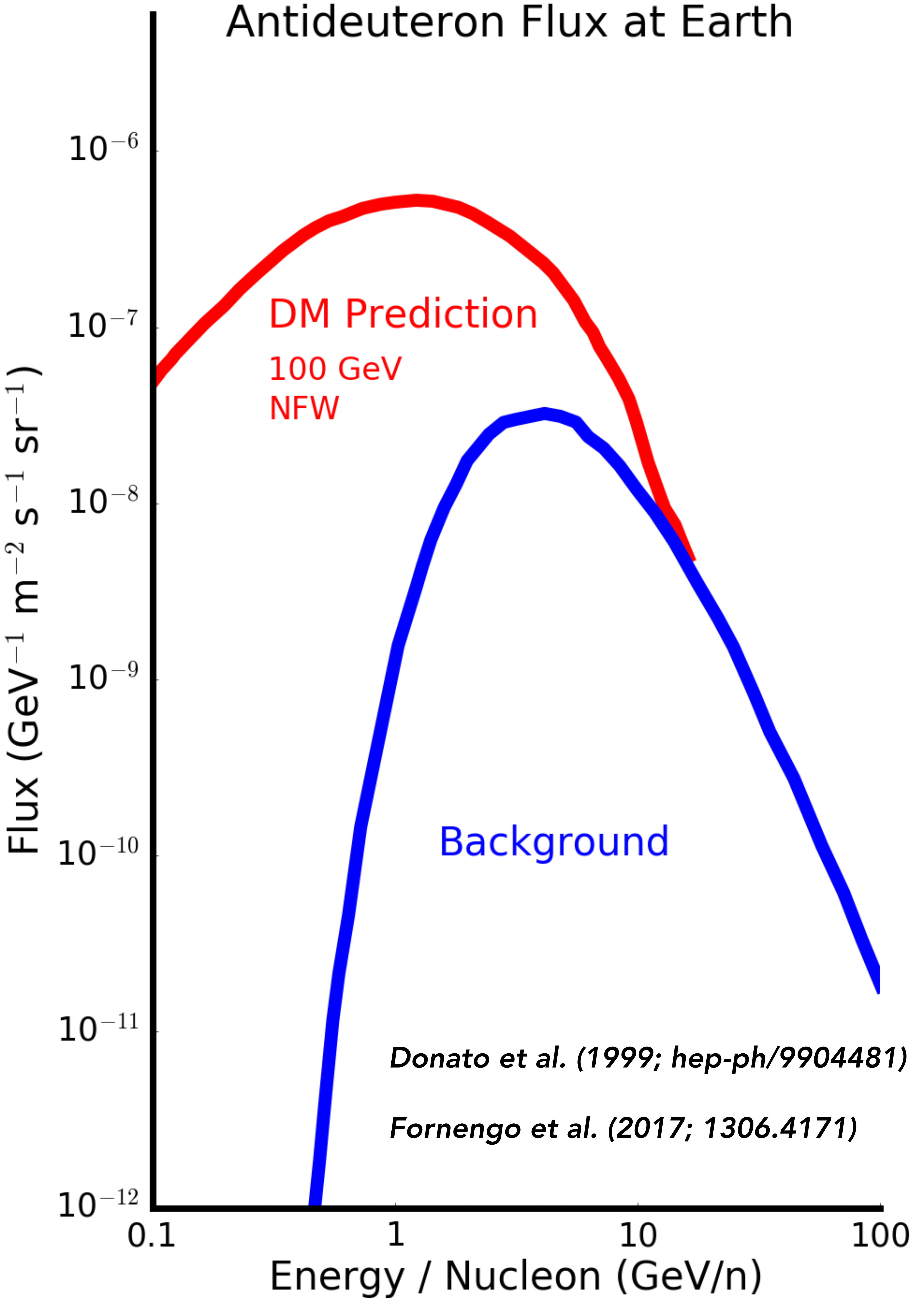
AntiNuclei - A Clean Search Strategy ?



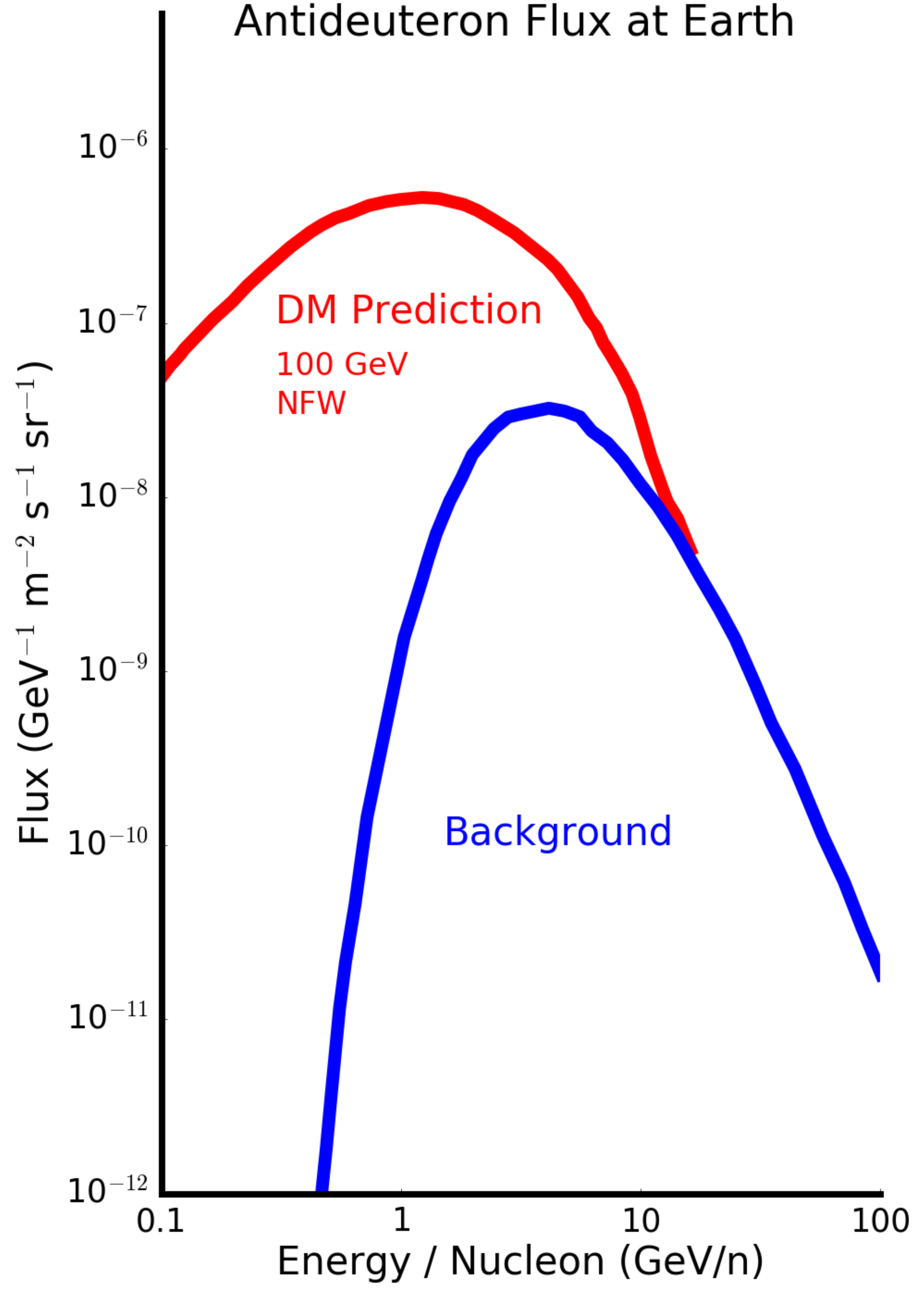
Antinuclei carry away a significant fraction of the total momentum in a particle collision.

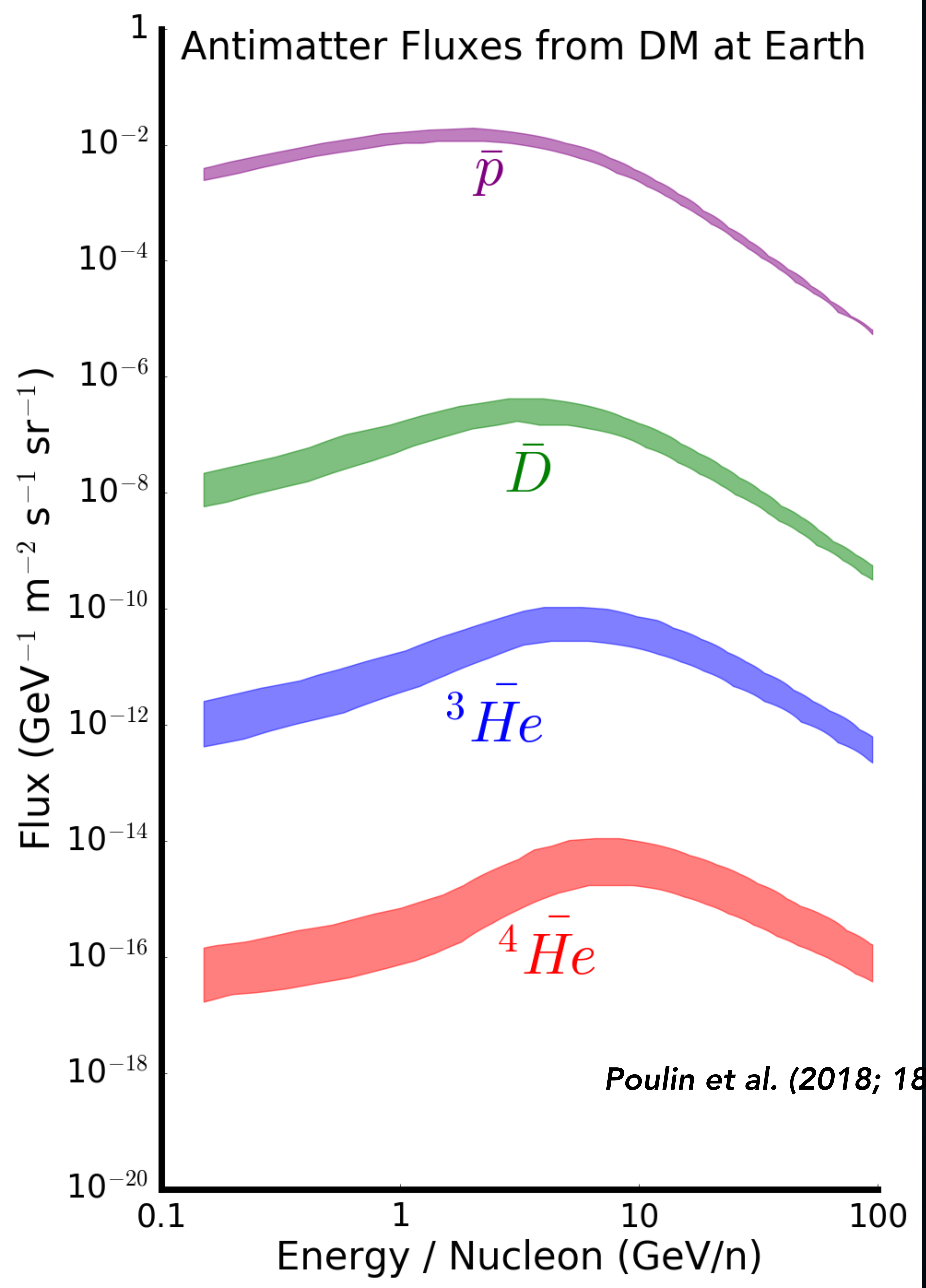
Astrophysical Antinuclei - Most be moving relativistically!

Dark Matter Antinuclei - Can be slow!



AntiNuclei: A Clean Search Strategy





Poulin et al. (2018; 1808.08961)


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

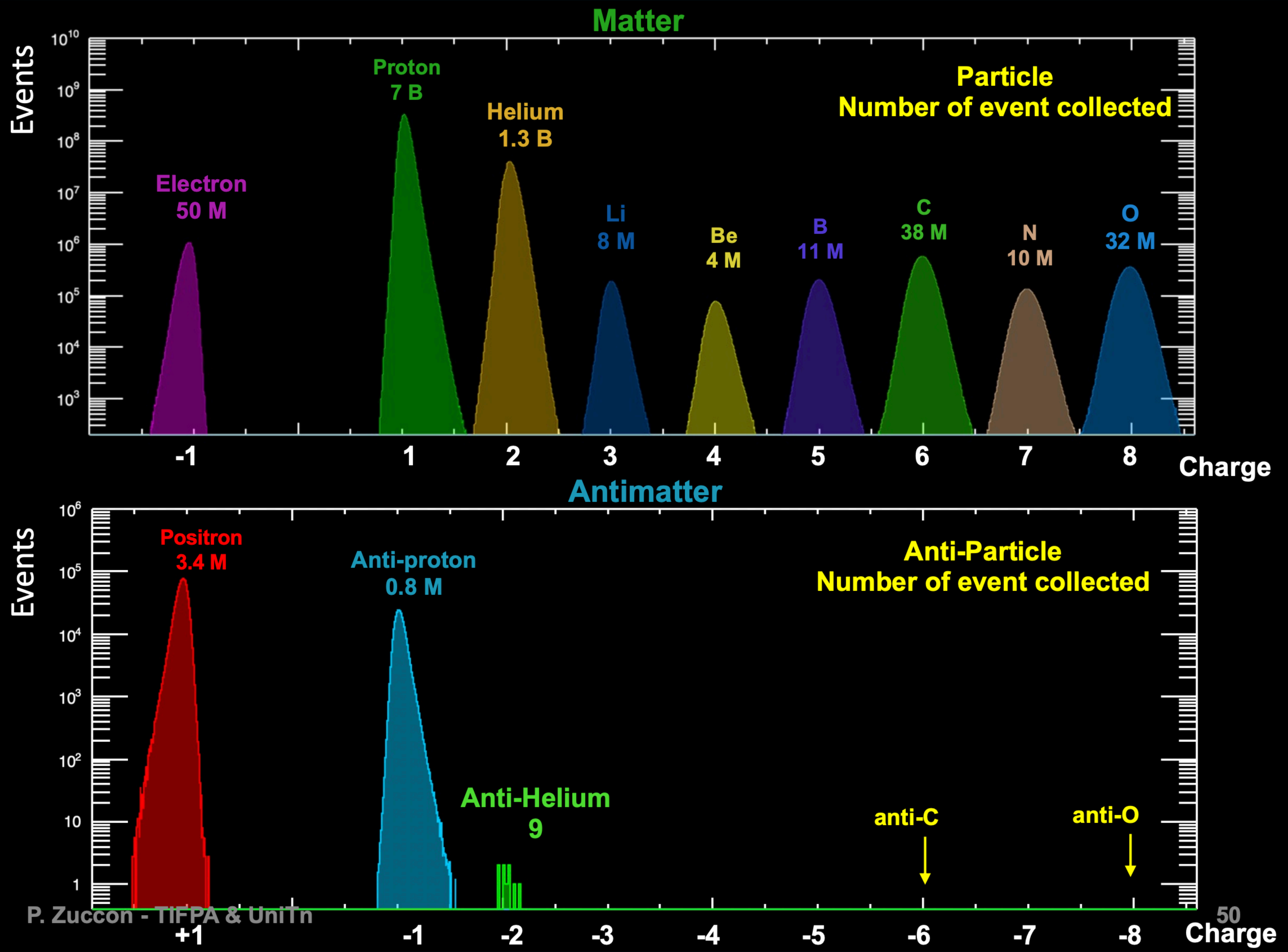

NOT MY DEPARTMENT
BRILLIANT!
NOT MY PROBLEM

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 $\overline{He}$ events is less than 3×10^{-8}. For the two $^{4}\overline{He}$ events our best evaluation of the probability (upon completion of the current 100 million core hours of simulation) will be less than 3×10^{-3}.

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

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



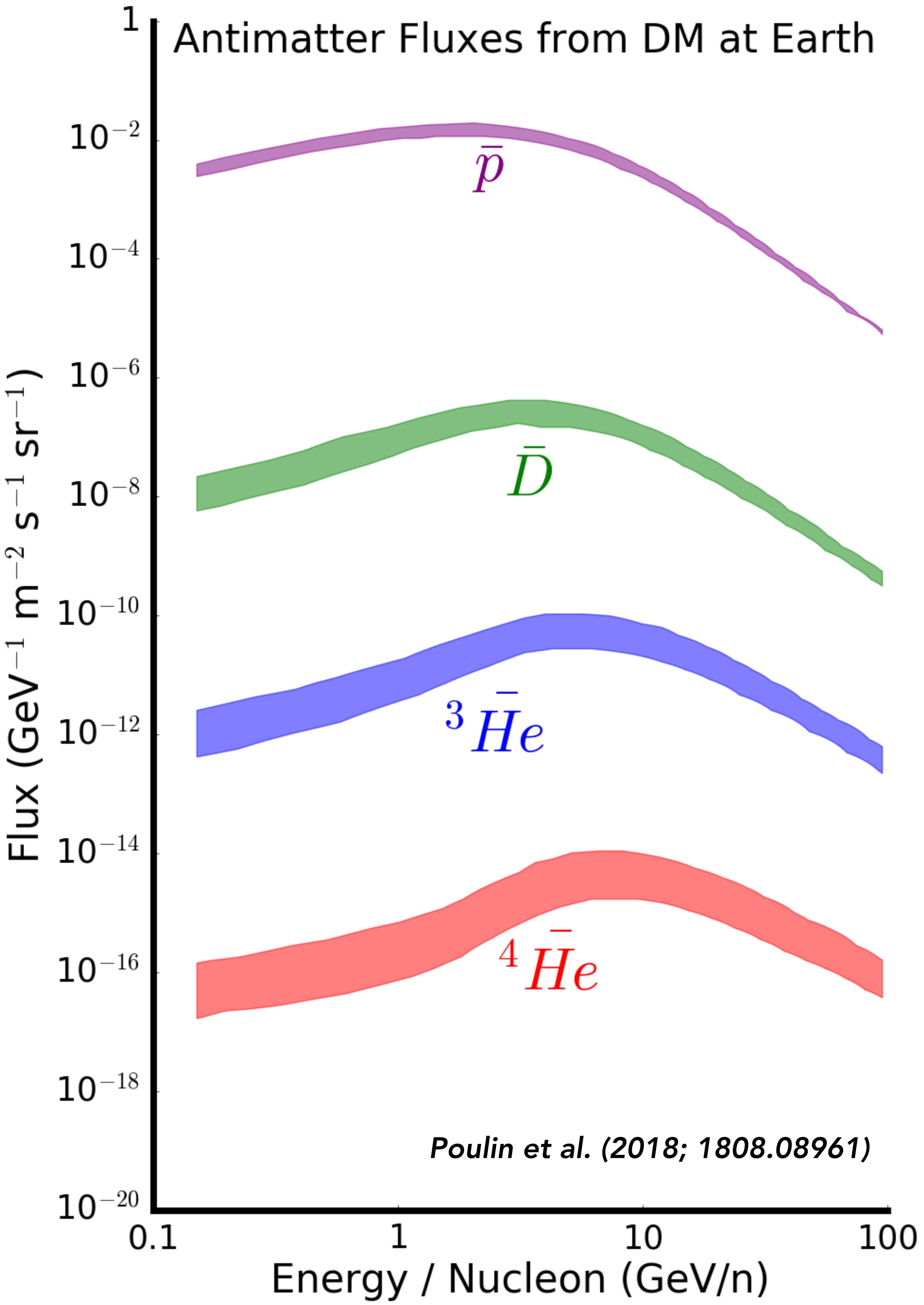
P. Zuccon - TIFPA & UniTn

Chasing an AntiHelium Signal

1.) Coalescence Rates (1401.2461)

2.) Lambda_b Enhancement (2006.16251, 2106.00053)

3.) Strongly Coupled Dark Sectors (2211.00025)



$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_{\bar{\mathrm{p}}} \frac{d^3 N_{\bar{\mathrm{p}}}}{dp_{\bar{\mathrm{p}}}^3} \right)^Z \left(E_{\bar{\mathrm{n}}} \frac{d^3 N_{\bar{\mathrm{n}}}}{dp_{\bar{\mathrm{n}}}^3} \right)^{A-Z}$$

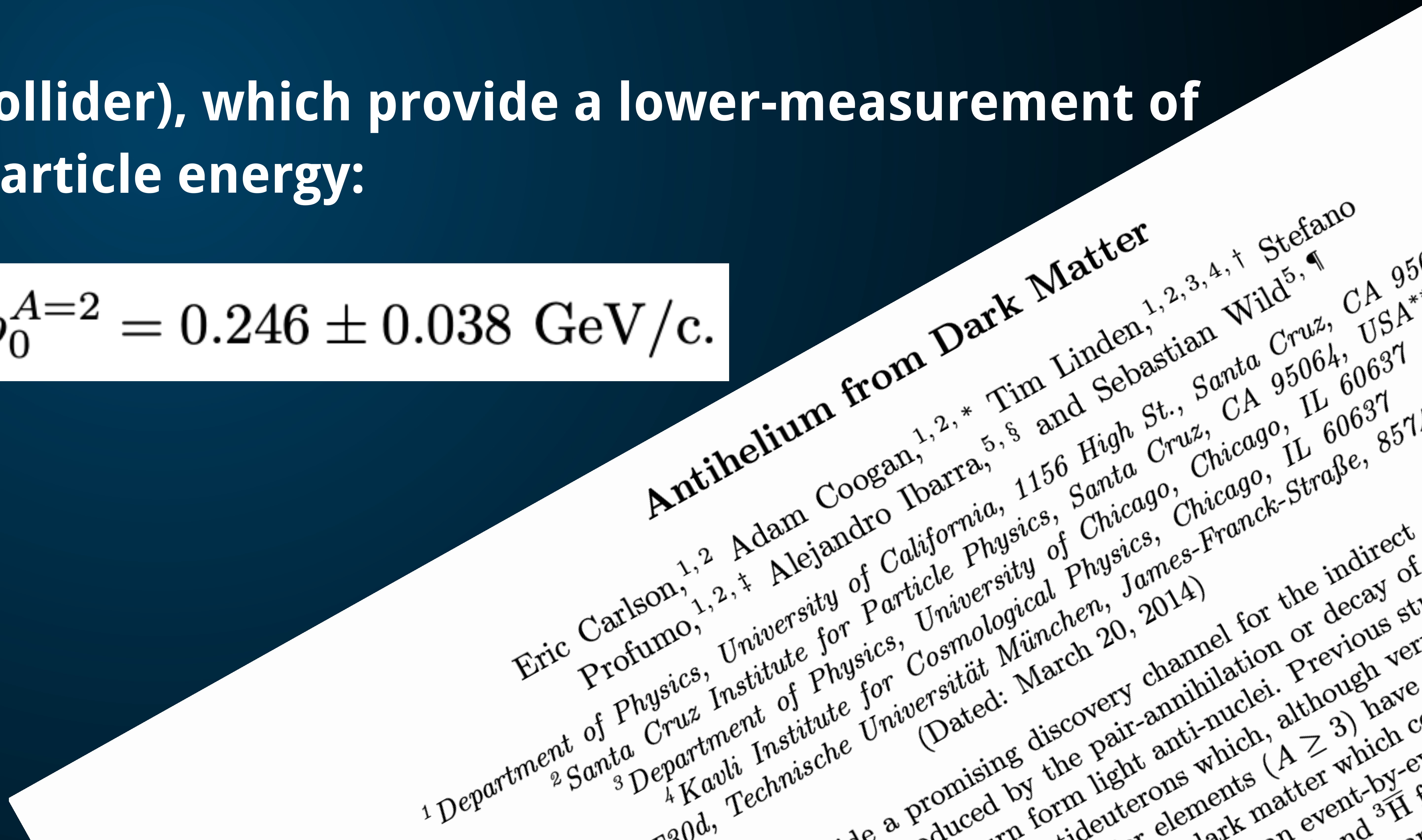
Key Insight - Coalescence Momentum for Antihelium Should Be Larger

While particle coalescence is hard to measure, the inverse process (fragmentation) is easier to measure. Helium's binding energy significantly exceeds deuteriums

$$p_0^{A=3} = \sqrt{B_{^3\overline{He}}/B_{\bar{D}}}\; p_0^{A=2} = 0.357 \pm 0.059 \text{ GeV/c.}$$

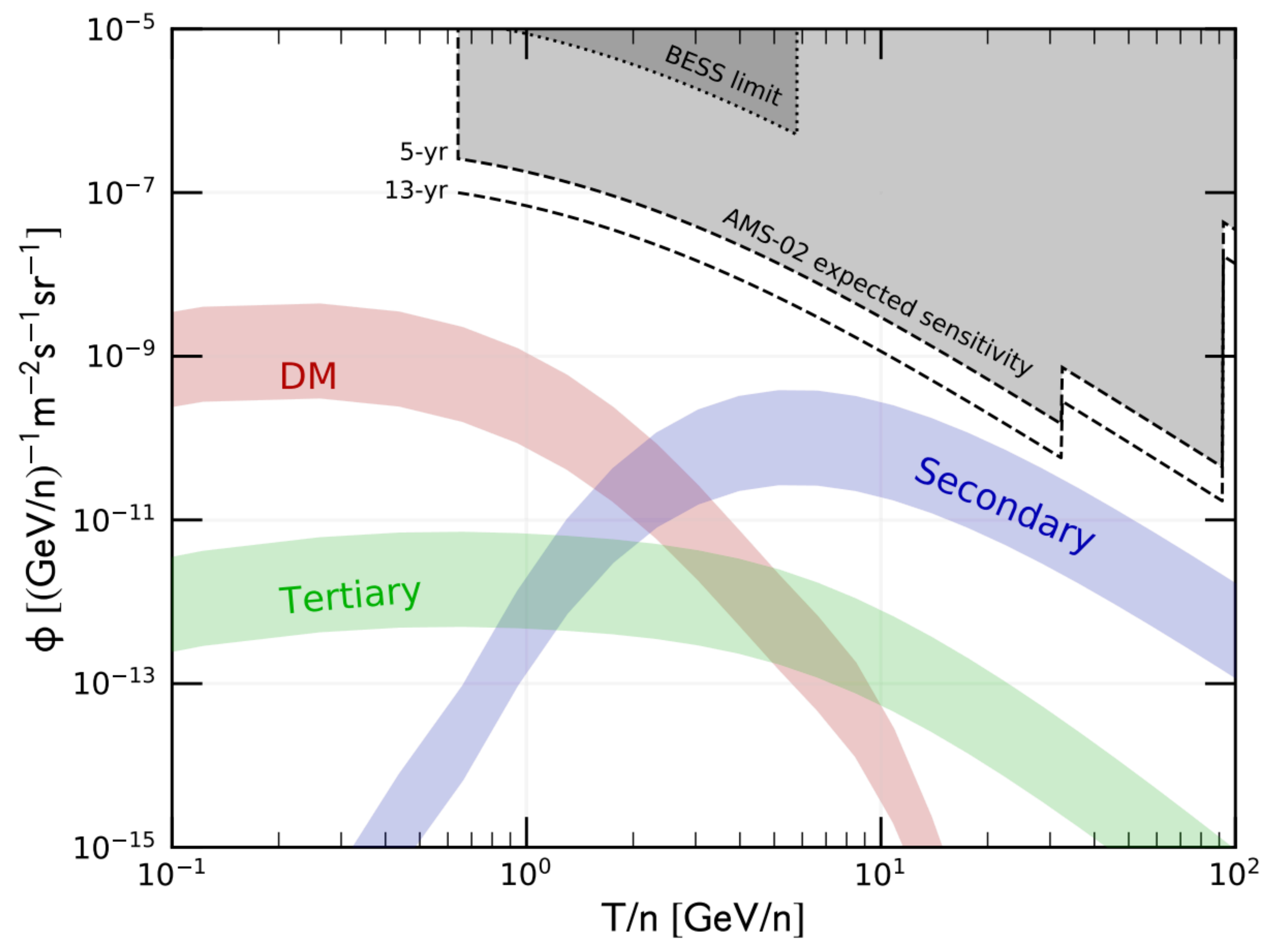
Can also use Heavy ion results (Berkeley Collider), which provide a lower-measurement of the coalescence momentum at a specific particle energy:

$$p_0^{A=3} = 1.28\; p_0^{A=2} = 0.246 \pm 0.038 \text{ GeV/c.}$$

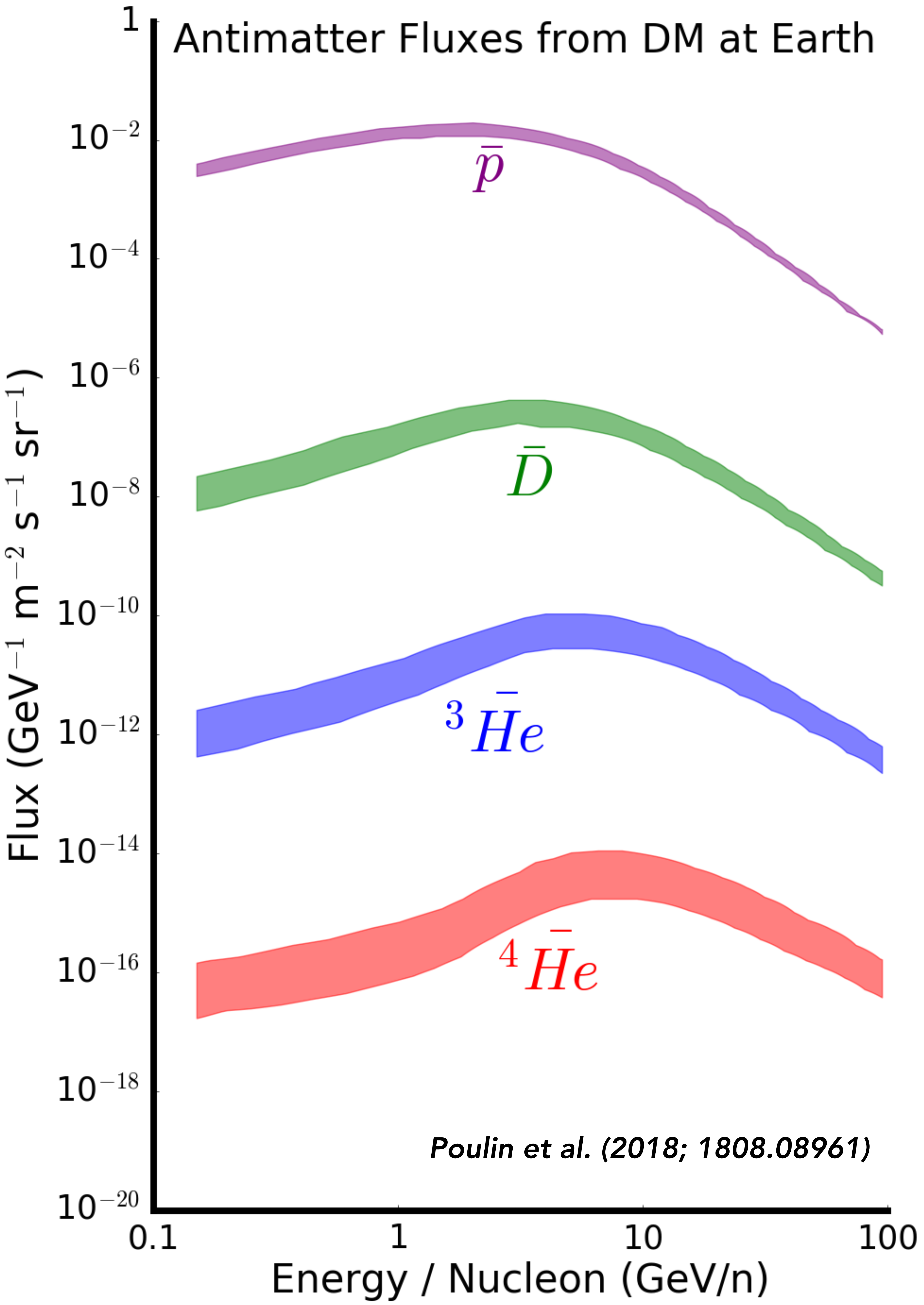


Coalescence Models - Expected Helium Flux

Using more realistic estimates for the anti helium coalescence momentum produces a boosted anti helium flux, especially at low energies.

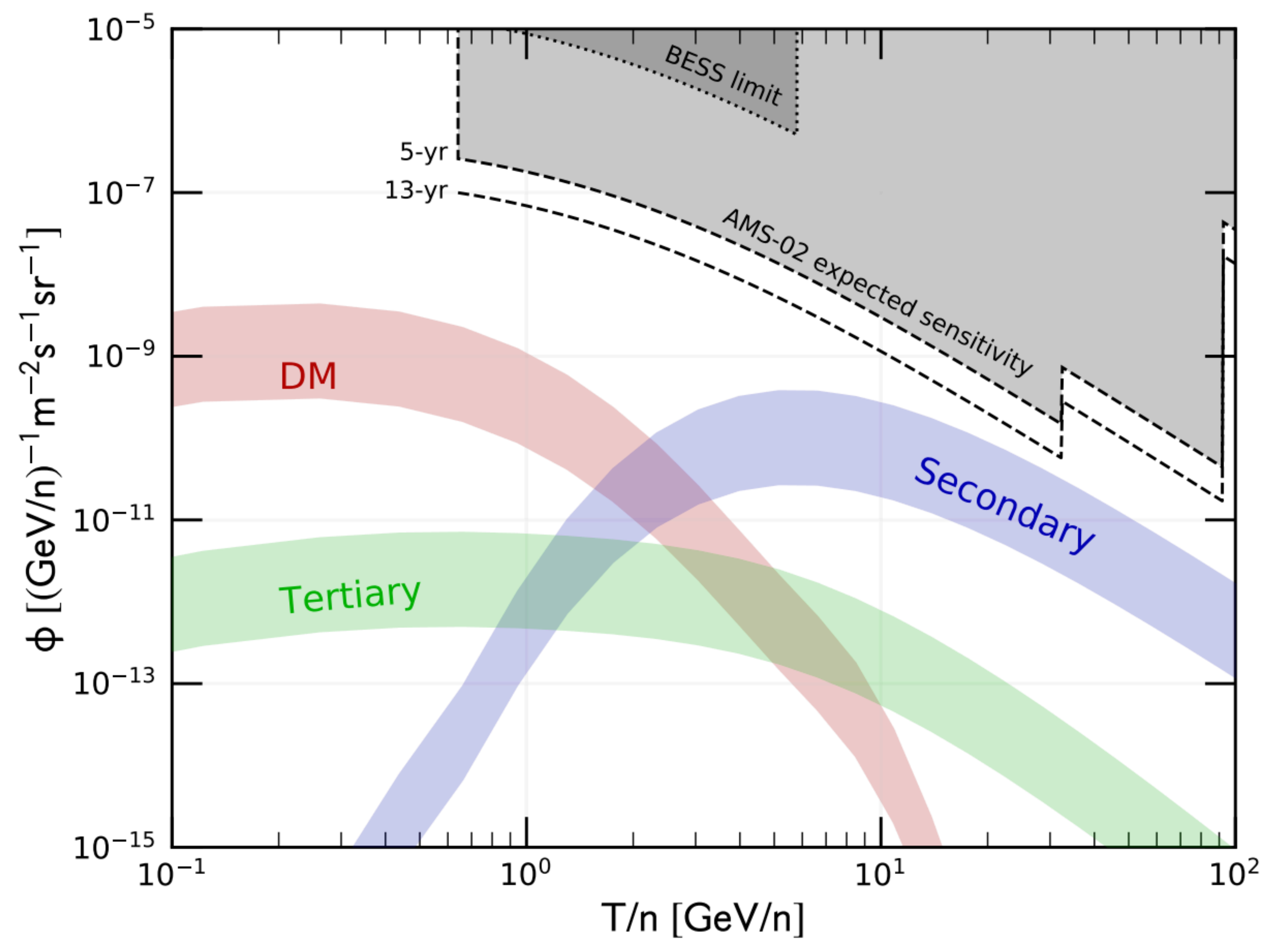


Korsmeier (2017; 1711.08465)

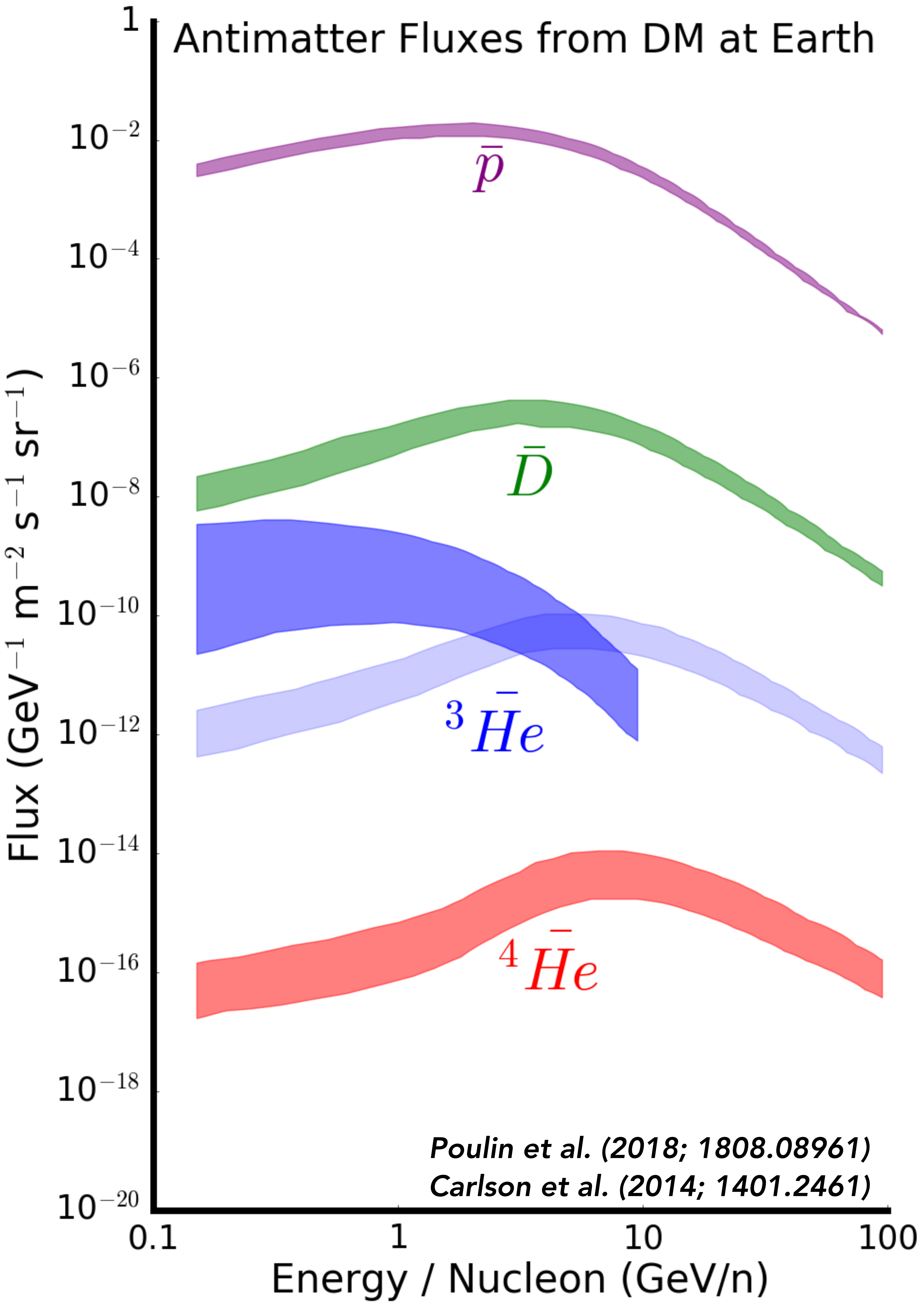


Coalescence Models - Expected Helium Flux

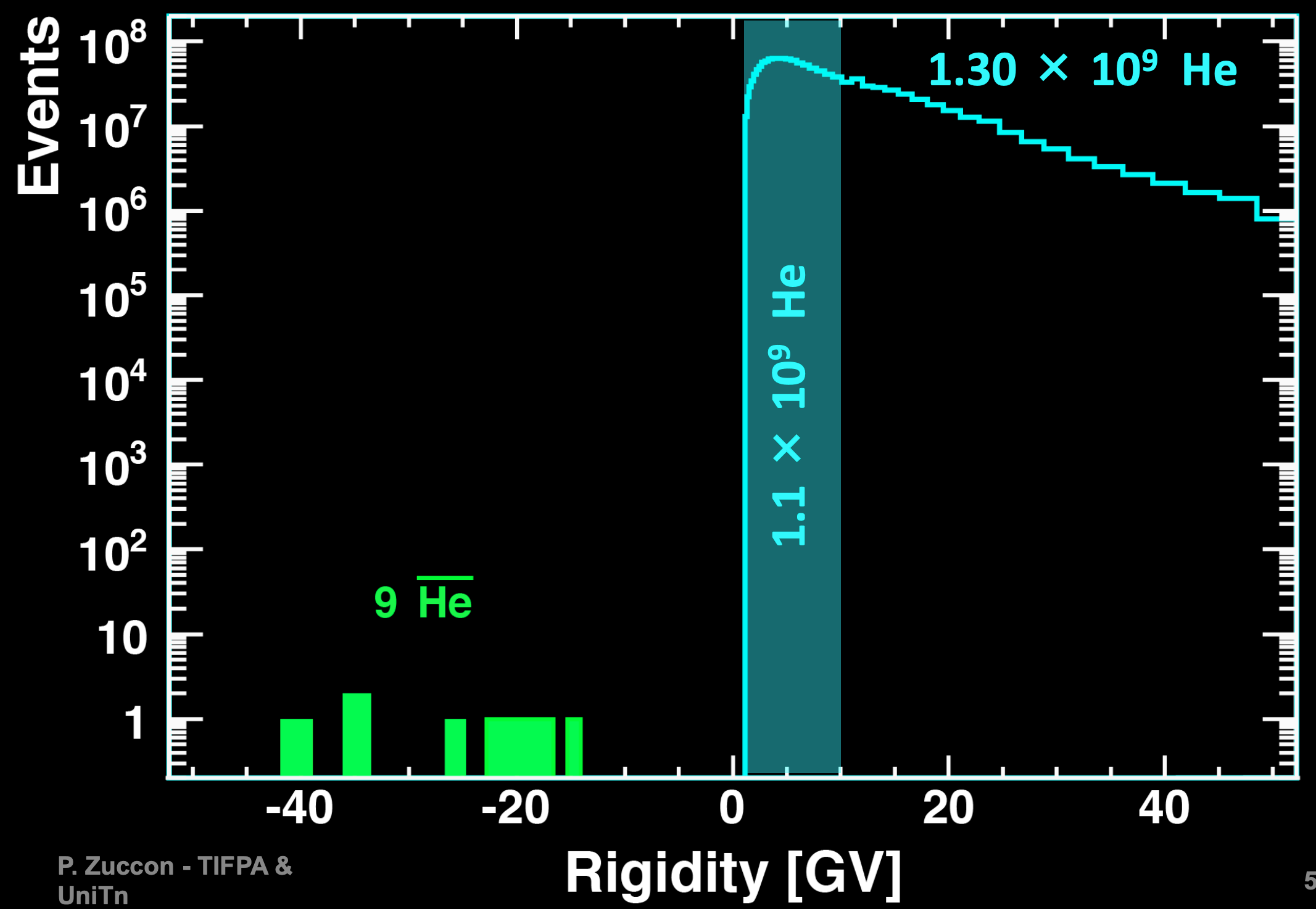
Using more realistic estimates for the anti helium coalescence momentum produces a boosted anti helium flux, especially at low energies.



Korsmeier (2017; 1711.08465)



However the Rigidity of these Antihelium Events is High



Idea 2: A New Method for Producing Antihelium

Dark Matter Annihilation Can Produce a Detectable Antihelium Flux through $\bar{\Lambda}_b$ Decays

Martin Wolfgang Winkler[1, *] and Tim Linden[1, †]

[1]*Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden*

Recent observations by the Alpha Magnetic Spectrometer (AMS-02) have tentatively detected a handful of cosmic-ray antihelium events. Such events have long been considered as smoking-gun evidence for new physics, because astrophysical antihelium production is expected to be negligible. However, the dark-matter-induced antihelium flux is also expected to fall below current sensitivities, particularly in light of existing antiproton constraints. Here, we demonstrate that a previously neglected standard model process — the production of antihelium through the displaced-vertex decay of $\bar{\Lambda}_b$-baryons — can significantly boost the dark matter induced antihelium flux. This process can triple the standard prompt-production of antihelium, and more importantly, entirely dominate the production of the high-energy antihelium nuclei reported by AMS-02.

I. INTRODUCTION

The detection of massive cosmic-ray antinuclei has long been considered a holy grail in searches for WIMP dark matter [1, 2]. Primary cosmic-rays from astrophysical sources are matter-dominated, accelerated by nearby supernova, pulsars, and other extreme objects. The secondary cosmic-rays produced by the hadronic interactions of primary cosmic-rays can include an antinuclei component, but the flux is highly suppressed by baryon number conservation and kinematic constraints [3, 4]. Dark matter annihilation, on the other hand, occurs within the rest frame of the Milky Way and produces equal baryon and antibaryon fluxes [1, 5–7]

In this *letter*, we challenge the current understanding that standard dark matter annihilation models cannot produce a measurable antihelium flux. Our analysis examines a known, and potentially dominant, antinuclei production mode which has been neglected by previous literature – the production of antihelium through the off-vertex decays of the $\bar{\Lambda}_b$. Such bottom baryons are generically produced in dark matter annihilation channels involving b quarks. Their decays efficiently produce heavy antinuclei due to their antibaryon number and 5.6 GeV rest-mass, which effectively decays to multi-nucleon states with small relative momenta. Intriguingly, because any $^3\overline{\text{He}}$ produced by $\bar{\Lambda}_b$ inherits its boost factor, these nuclei can obtain the large center-of-mass momenta necessary to fit AMS-02 data [13].

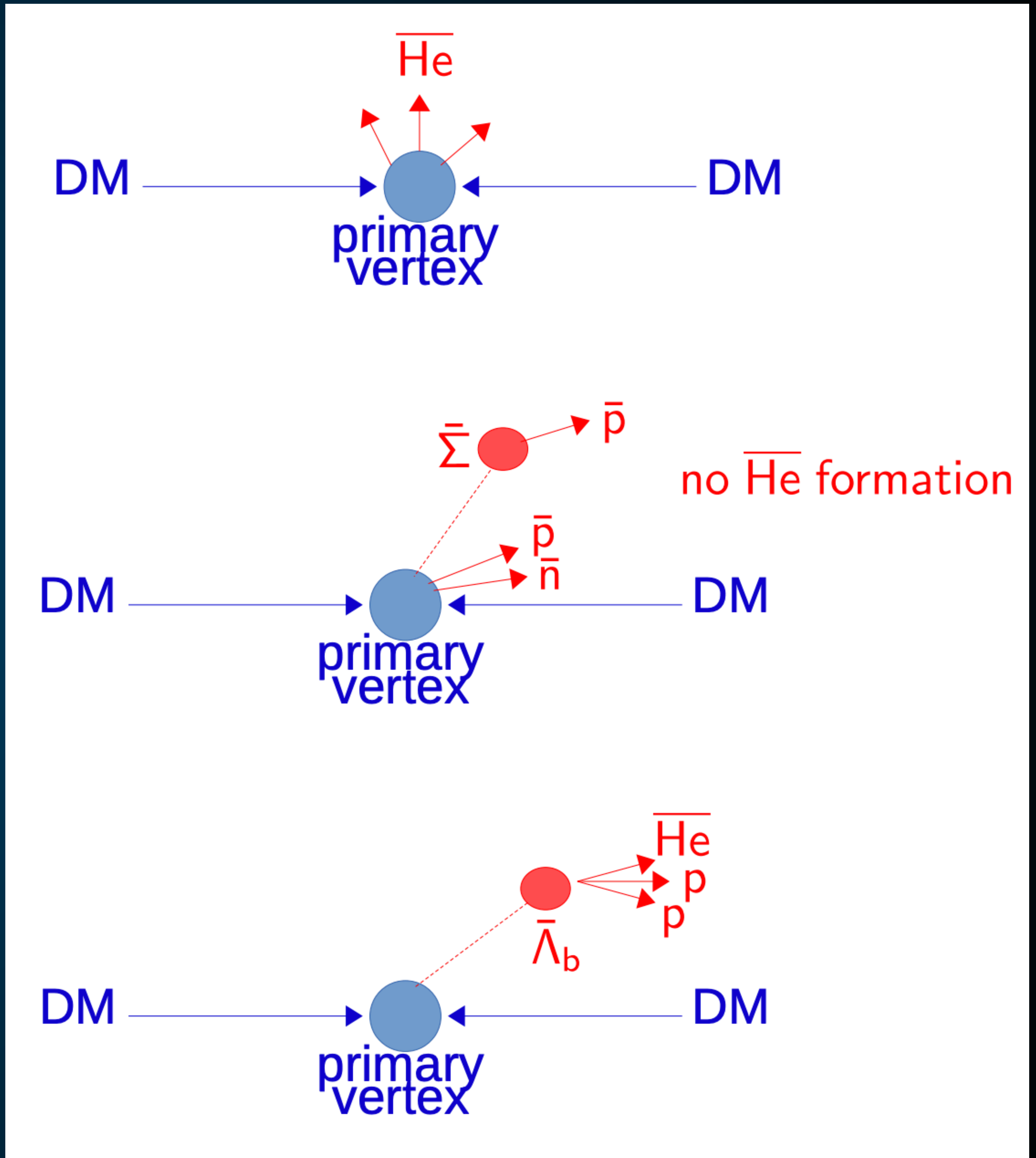
A Standard Model Resonance to Enhance Antihelium

Previous analyses have missed the (potentially) dominant contribution to anti-Helium production.

$\overline{\Lambda_b}$ **has correct parameters to produce** $^3\overline{He}$**:**

- **Antibaryon number of 1**
  - **Mass: 5.6 GeV** $(\bar{p}, \bar{p}, \bar{n}, p, p)$
  - **Or:** $\bar{p}, \bar{n}, \bar{n}, p, p$ **because** $^3H \rightarrow {}^3He$

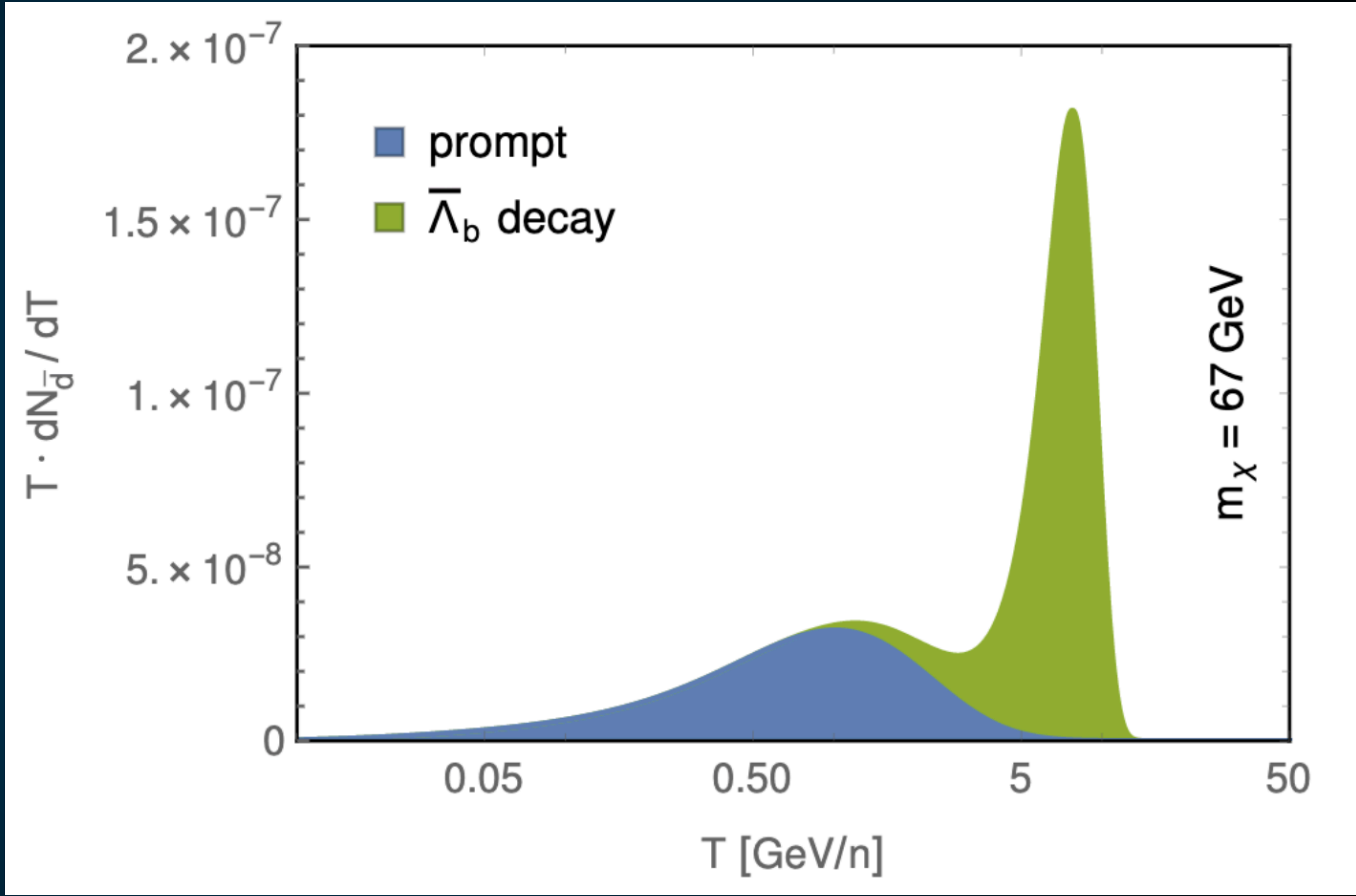
$$R \propto p_0^{3(A-1)} \qquad R \propto \exp[-(\mathrm{p_i} - \mathrm{p_f})]$$



From: Martin Winkler

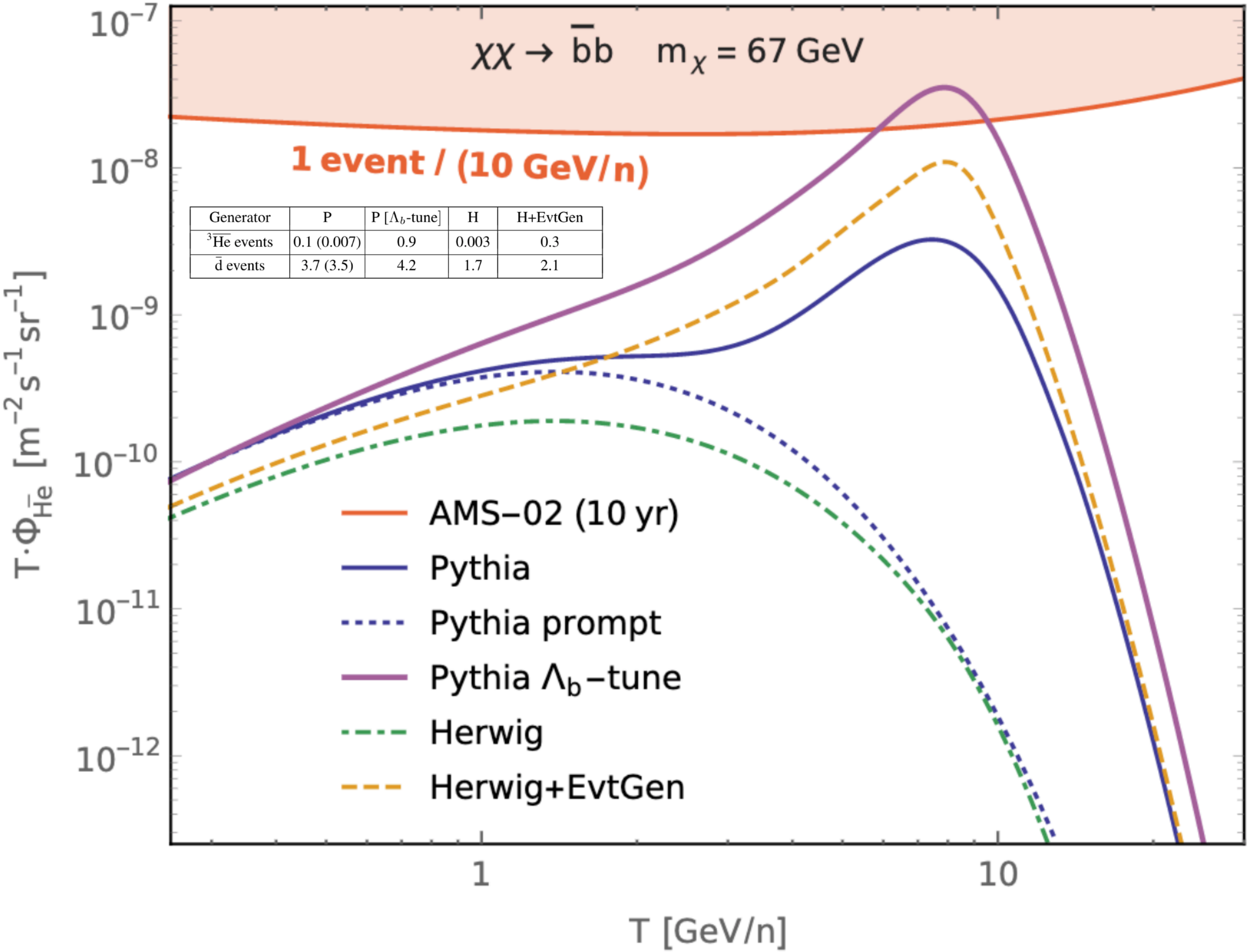
A High-Momentum Bump!

Can produce a significant enhancement of the total anti helium flux.



Moreover, the enhancement is at high-energies - matching the data.

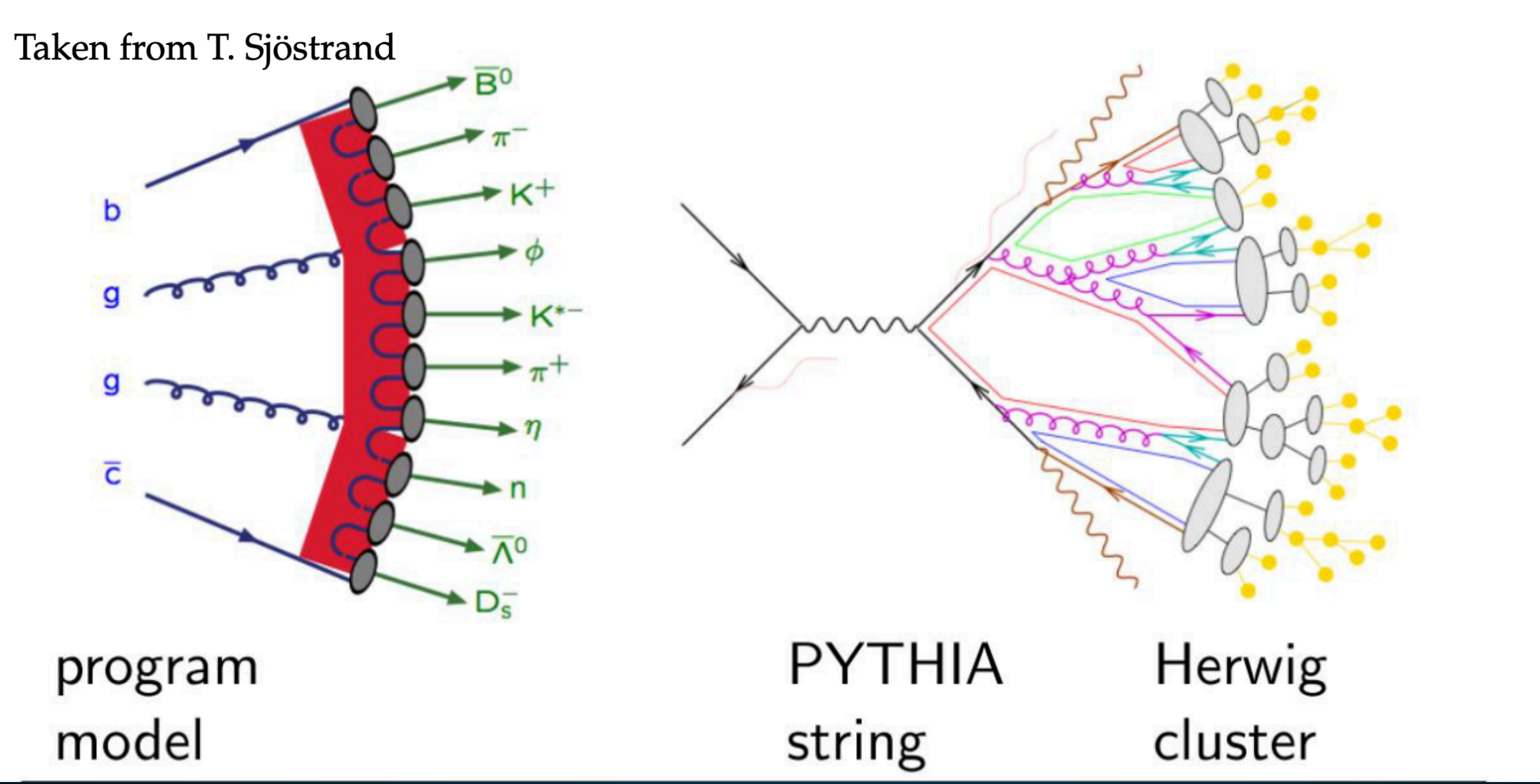
Winkler & Linden (2020; 2020.16251)



Generator	P	P [Λ_b-tune]	H	H+EvtGen
$^3\overline{He}$ events	0.1 (0.007)	0.9	0.003	0.3
$\bar{d}$ events	3.7 (3.5)	4.2	1.7	2.1

Uncertainties in the Rate

$\overline{\Lambda_b} \rightarrow {}^3\text{He}$ rate



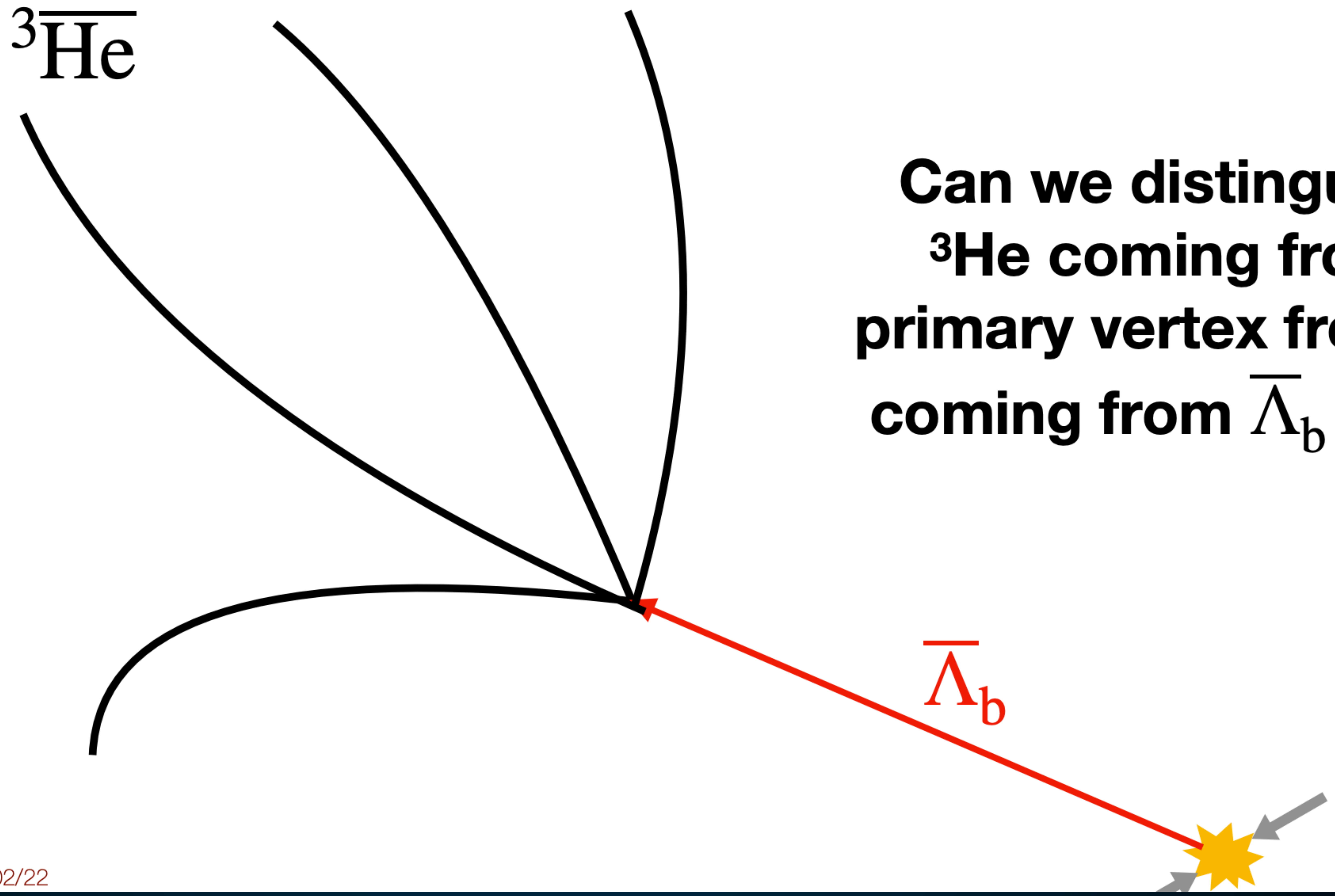
Pythia:

$$P(\overline{\Lambda_b} \rightarrow {}^3\overline{\text{He}} + X) \sim 10^{-6}$$

Herwig:

$$P(\overline{\Lambda_b} \rightarrow {}^3\overline{\text{He}} + X) \sim 10^{-9}$$

Can We Find this At Particle Accelerators?



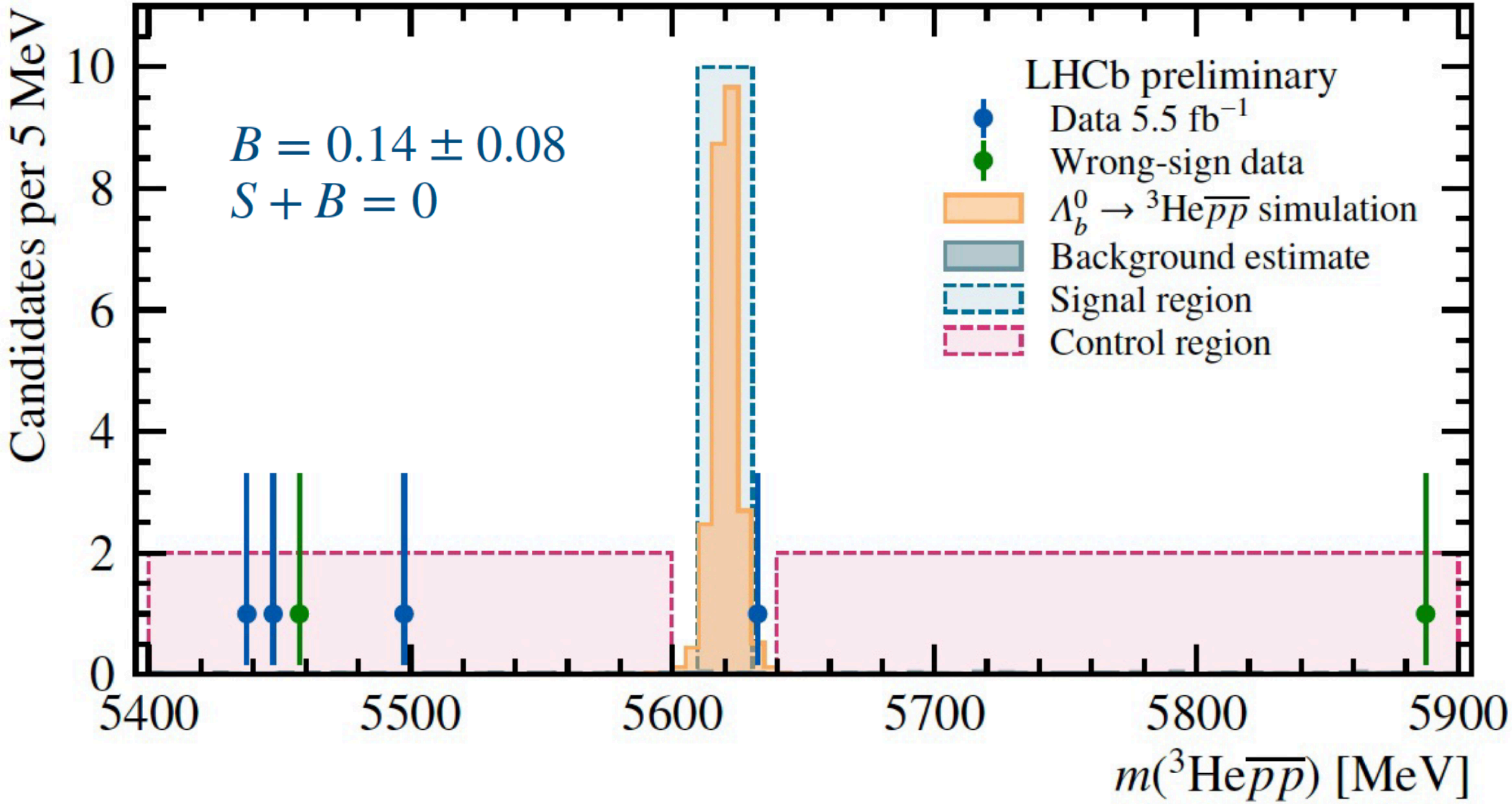
$c\tau$ ~ 450 µm

Can we distinguish the ^{3}He coming from the primary vertex from those coming from $\overline{\Lambda}_b$ decays?

Search for antihelium from $\overline{\Lambda}_b^0$ decays: Invariant-mass spectra

$\overline{\Lambda}_b^0 \rightarrow {}^3\overline{\mathrm{He}} + \mathrm{p} + \mathrm{p}$ (exclusive mode)

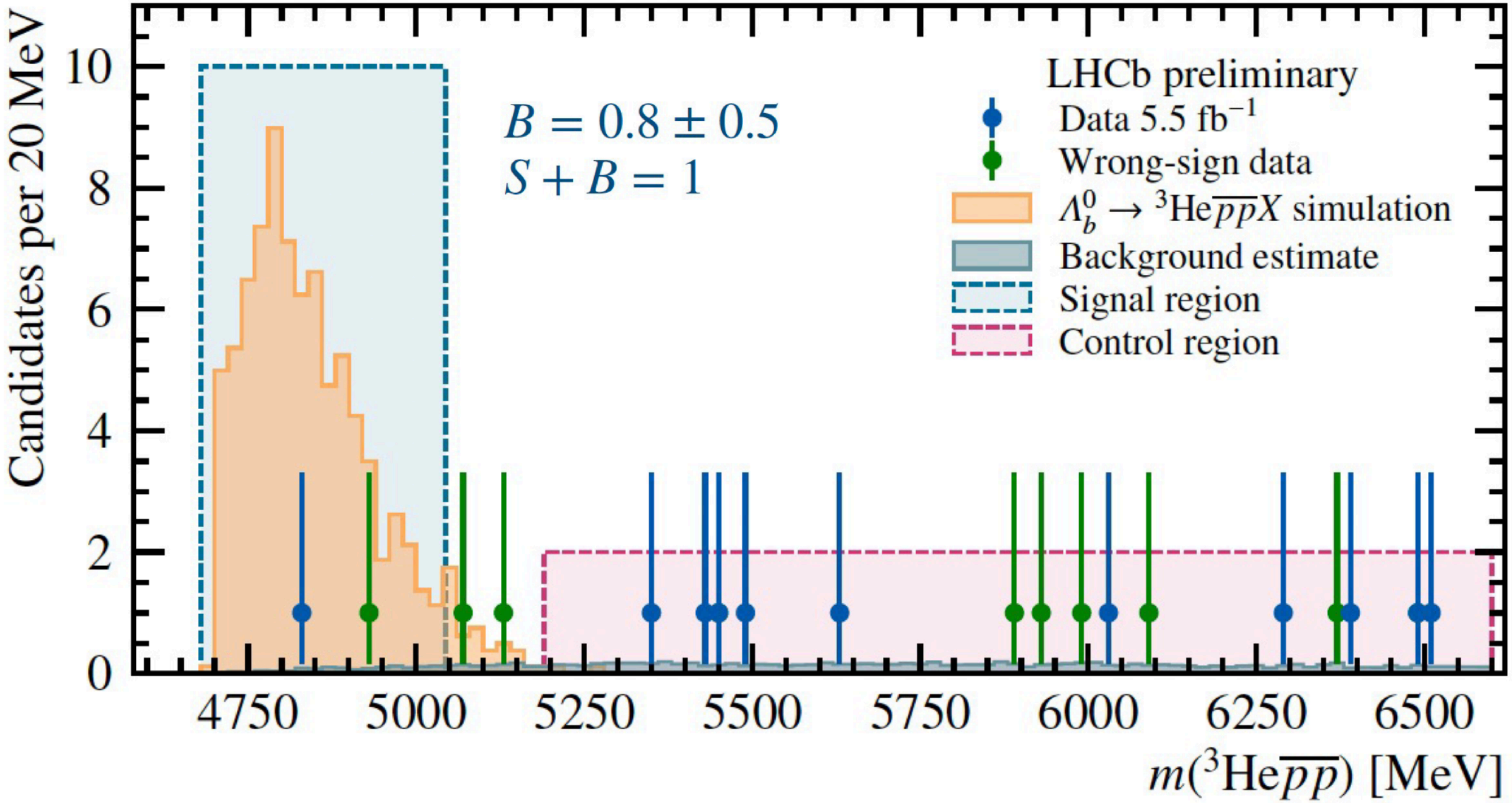
LHCb-CONF-2024-005



Search for antihelium from $\overline{\Lambda}_b^0$ decays: Invariant-mass spectra

$\overline{\Lambda}_b^0 \rightarrow {}^3\overline{\text{He}} + \text{p} + \text{p} + \text{X}$ (inclusive mode)

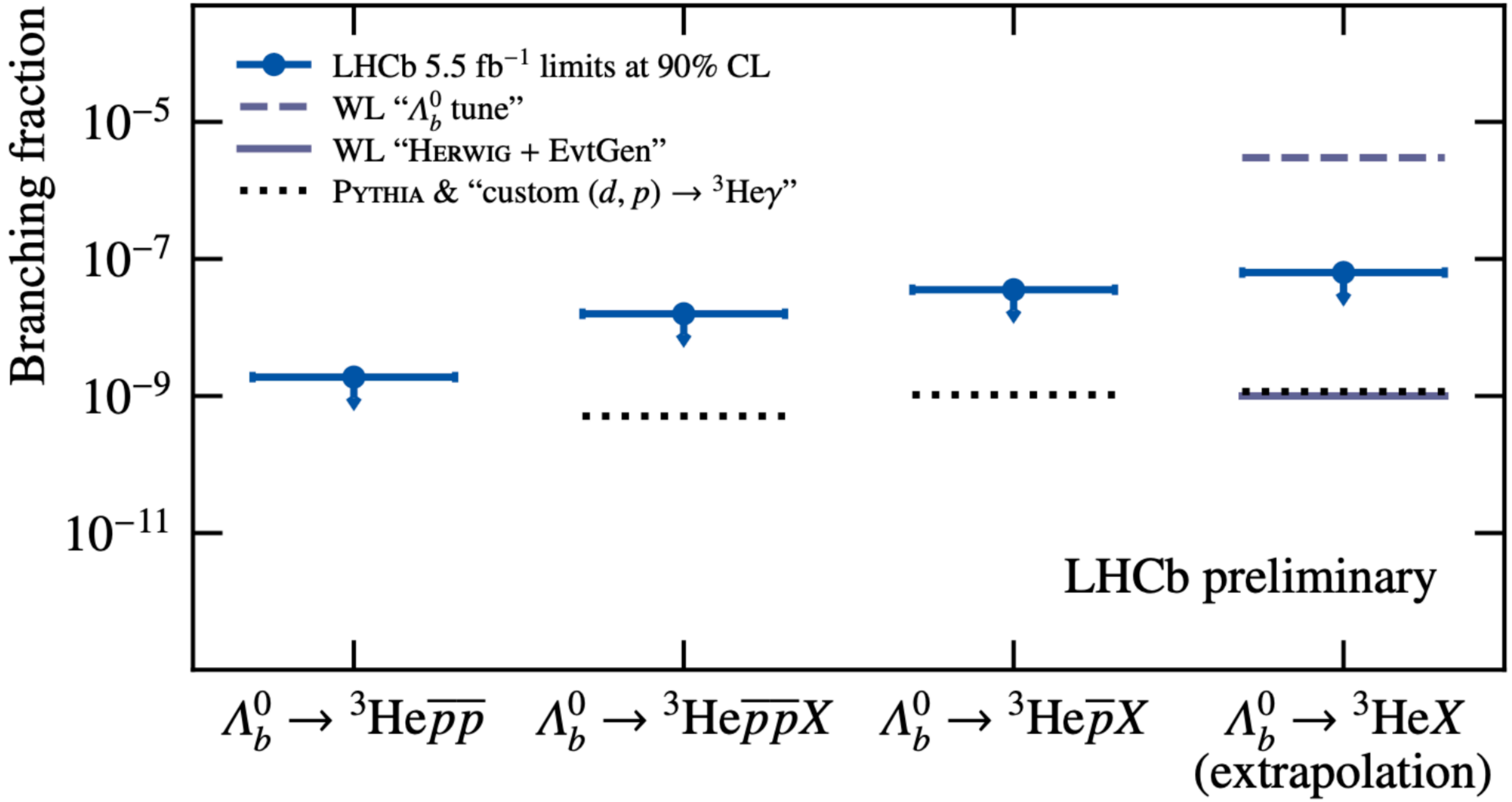
LHCb-CONF-2024-005



Search for antihelium from $\overline{\Lambda}_b^0$ decays: Extrapolation to $\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}X)$

Conservative extrapolation assuming isospin symmetric production of nucleons

LHCb-CONF-2024-005



$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}X) < 6.3 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

Some Caveats

1.) LHCb results are preliminary

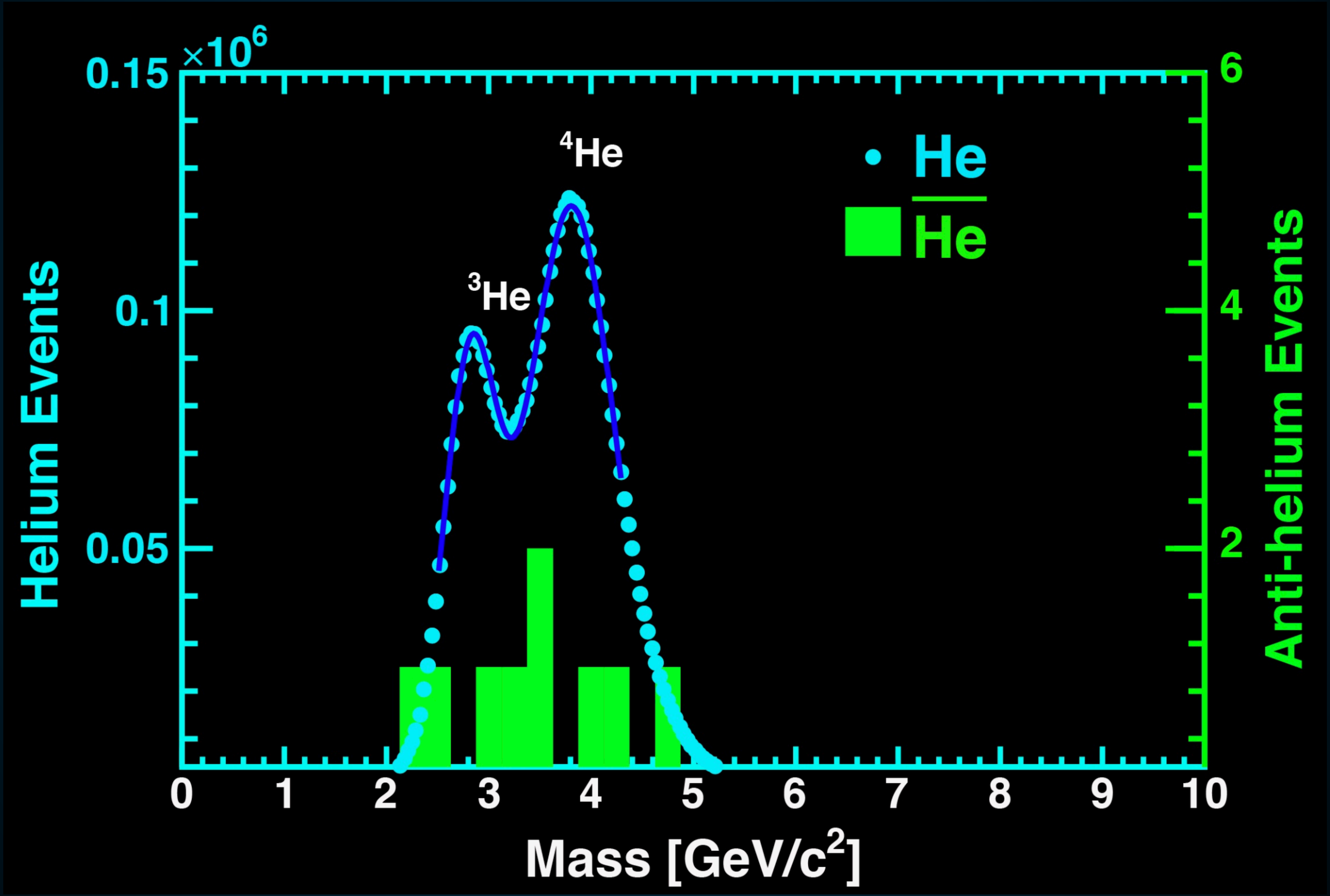
2.) There is a factor of two offset, because tritium decays to $^3\mathrm{He}$ in space.

- This can potentially be larger, because $\overline{p} + \overline{n} + \overline{n} + p + n$ has smaller kinetic energy (117 anti-tritium detected by LHCb, but no spectrum)

3.) Unclear how inclusive cross-sections are calculated with additional pions (which may make the momentum of the $\overline{^3\mathrm{He}}$ and p harder to distinguish).

4.) No searches for $\overline{^3\mathrm{H}} + n + n + \pi^+$. This could dominate, for example, if the proton and $\overline{^3\mathrm{He}}$ quickly re-annihilate due to Coulomb attraction.

Problem: Are We Actually Observing Antihelium 4?

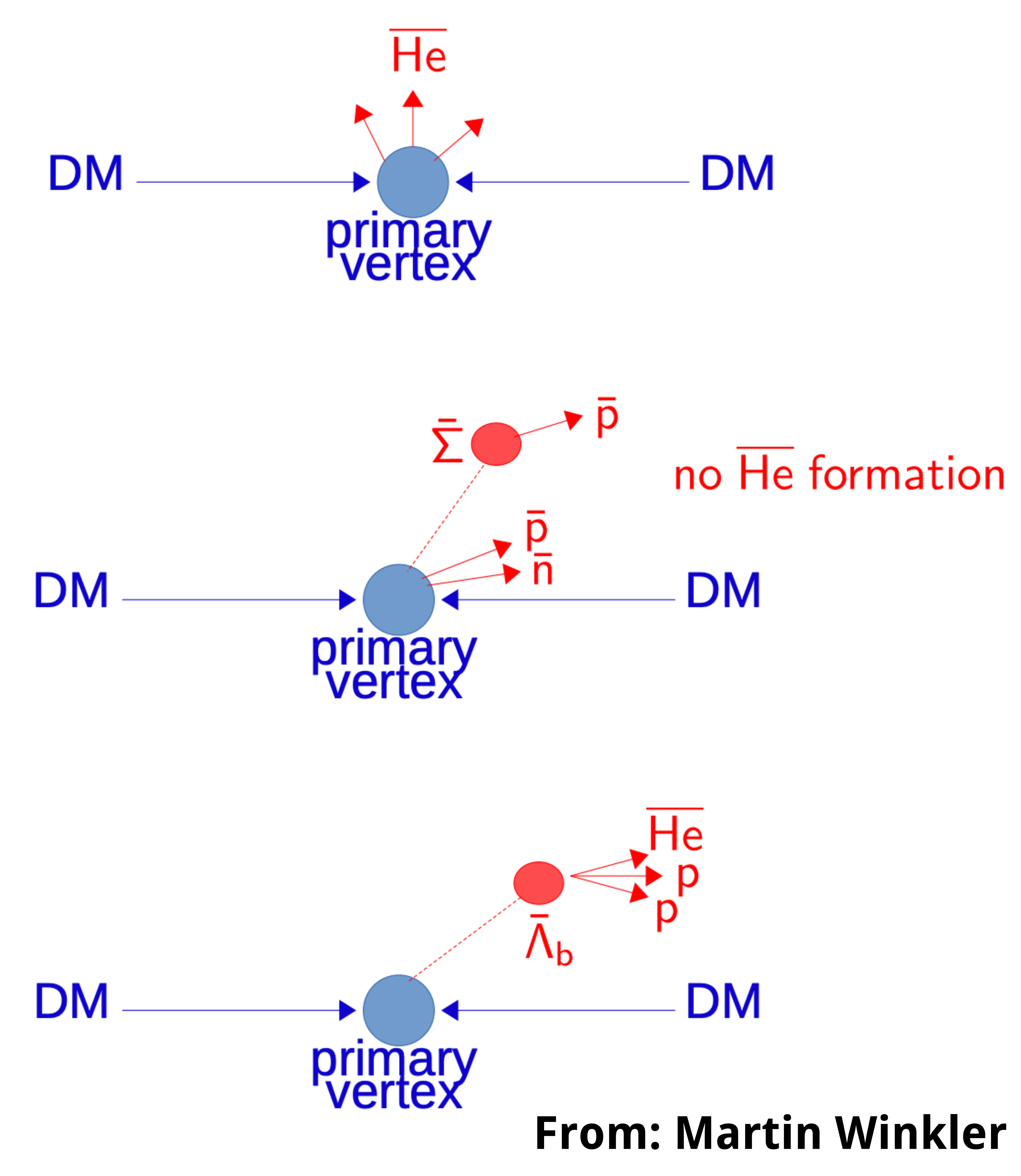


Cannot Enhance Antihelium-4 with Λ_b

$\overline{\Lambda_b}$ has correct parameters to produce $^3\overline{\mathrm{He}}$:

- Antibaryon number of 1
- Mass: 5.6 GeV

Too light to produce $^4\overline{\mathrm{He}}$!



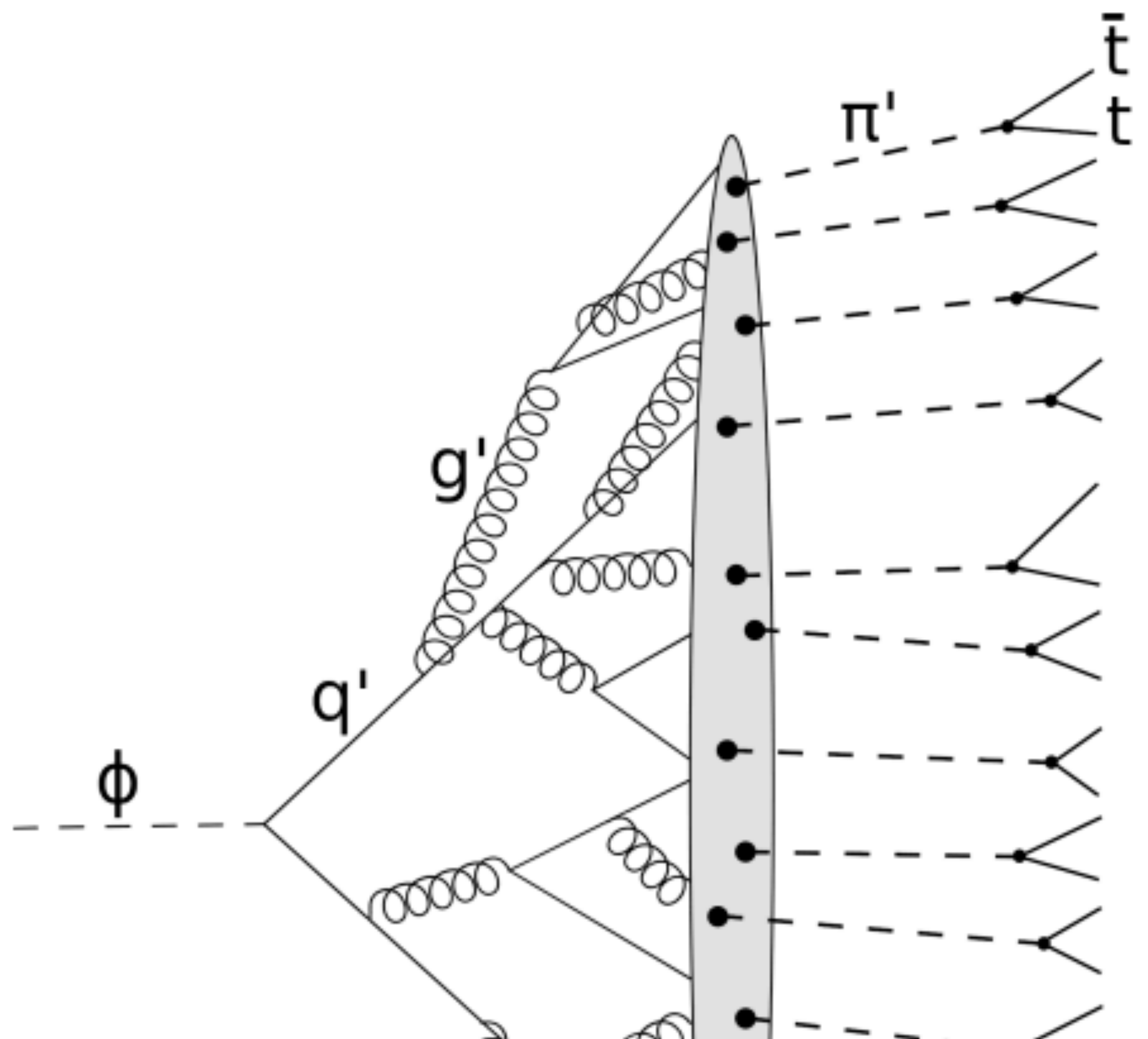
Cosmic Ray Antihelium from a Strongly Coupled Dark Sector

Martin Wolfgang Winkler,[1,2,*] Pedro De La Torre Luque,[2,†] and Tim Linden[2,‡]
[1]*Department of Physics, The University of Texas at Austin, Austin, 78712 TX, USA*
[2]*The Oskar Klein Centre, Department of Physics, Stockholm University, AlbaNova, SE-10691 Stockholm, Sweden*

Standard Model extensions with a strongly coupled dark sector can induce high-multiplicity states of soft quarks. Such final states trigger extremely efficient antinucleus formation. We show that dark matter annihilation or decay into a strongly coupled sector can dramatically enhance the cosmic-ray antinuclei flux – by six orders of magnitude in the case of $^4\overline{\mathrm{He}}$. In this work, we argue that the tentative $^3\overline{\mathrm{He}}$ and $^4\overline{\mathrm{He}}$ events reported by the AMS-02 collaboration could be the first sign of a strongly coupled dark sector observed in nature.

I. INTRODUCTION

Cosmic-ray (CR) antinuclei are among the most promising targets in the indirect search for particle dark matter (DM). While the formation of antinuclei by DM annihilation or decay is strongly suppressed compared to *e.g.* gamma rays, the astrophysical antinuclei backgrounds – which arise from interactions of cosmic ray protons and helium with the interstellar gas – are extremely low. Therefore, the unambiguous discovery of even a single cosmic-ray antinucleus could provide smoking-gun evidence for particle DM [1, 2].



Strongly Coupled Dark Sectors

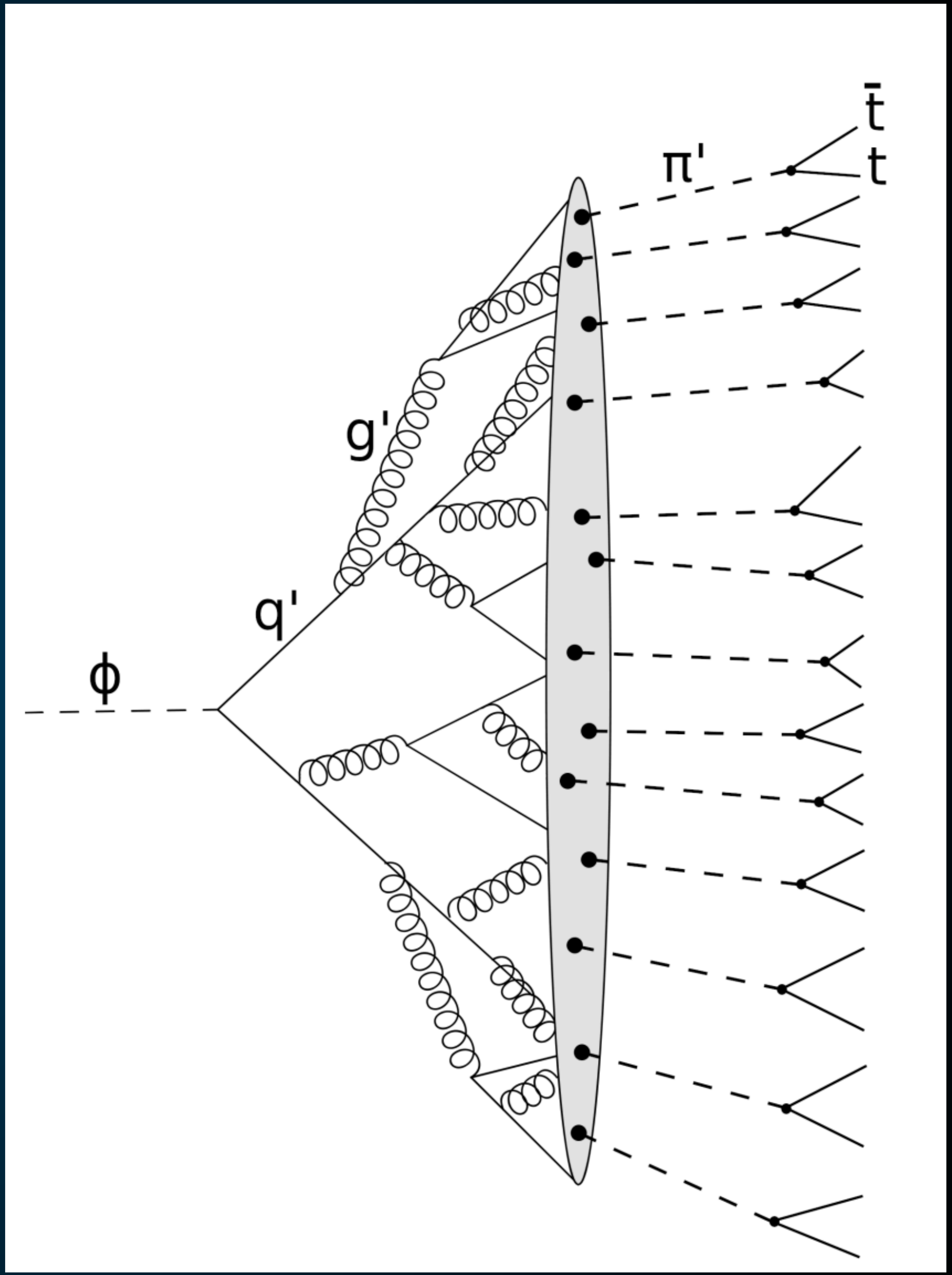
Just make a ton of quarks.

The production of heavy nuclei scales strongly with the number of quarks in the final state.

In QCD, a single 100 GeV annihilation produces O(100) pions

The dark matter model looks like a dark version of QCD.

$$\mathcal{L} \supset -\frac{1}{2}\,\mathrm{Tr}\,G'_{\mu\nu}G'^{\mu\nu} - \bar{q}'(i\not{D} - m_{q'})q'$$



Strongly Coupled Dark Sectors

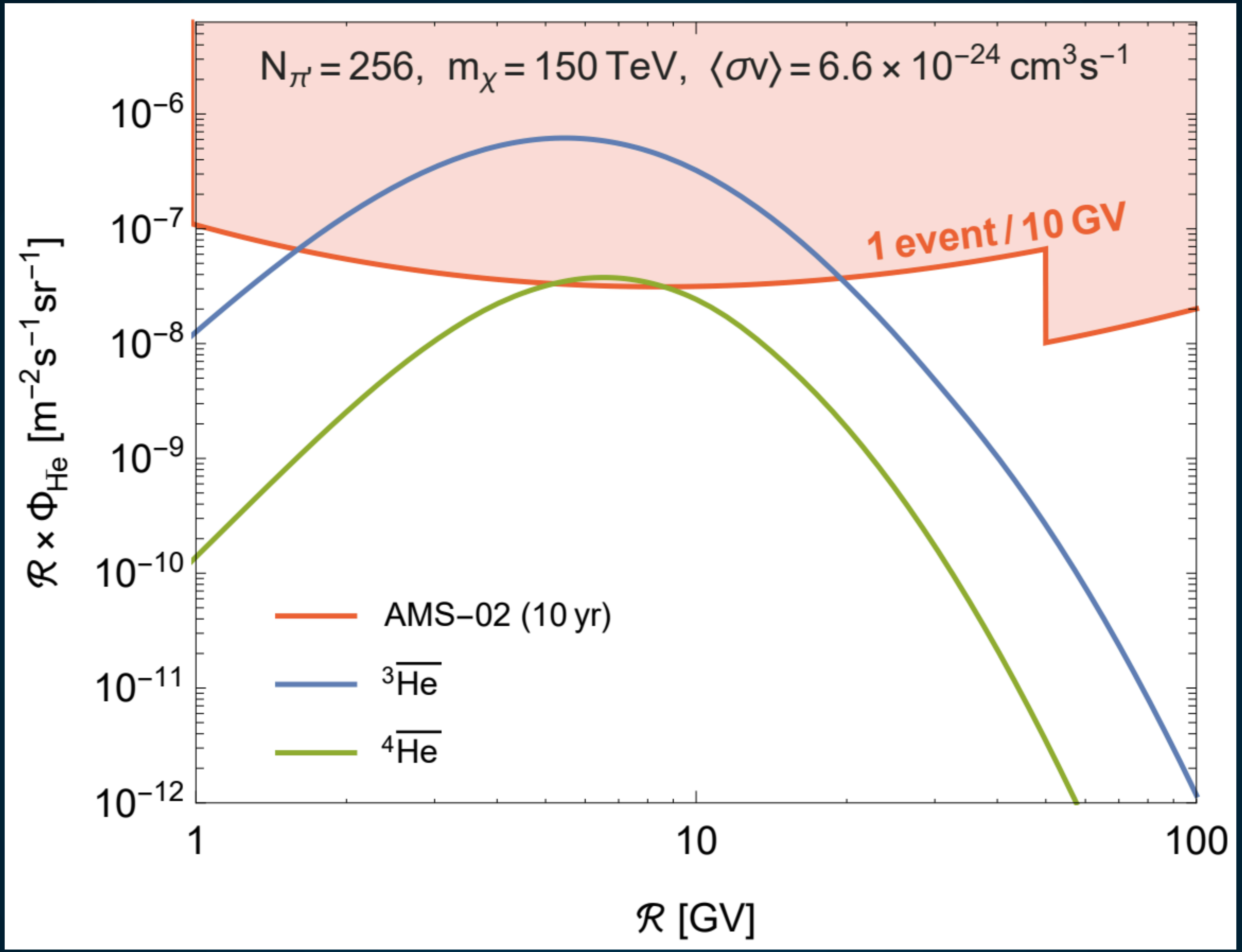
The dark pions need to be very heavy — so the dark matter also has to be very heavy.

For annihilating dark matter — we are limited by unitarity.

For decaying dark matter, we are not.

DM type	Annihilating
Input Parameters	
m_χ [TeV]	150
m_ϕ [TeV]	50.4
$m_{\pi'}$ [GeV]	380
$N_{\pi'}$	256
$\langle\sigma v\rangle$ [cm^{3}s^{-1}]	6.6×10^{-24}
Γ [s^{-1}]	–
Antinuclei Events at AMS-02	
$^3\overline{\mathrm{He}}$	15.6
$^4\overline{\mathrm{He}}$	1.0
$\bar{\mathrm{d}}$	19.3
Antinuclei Events at GAPS	
$\bar{\mathrm{d}}$	0.7

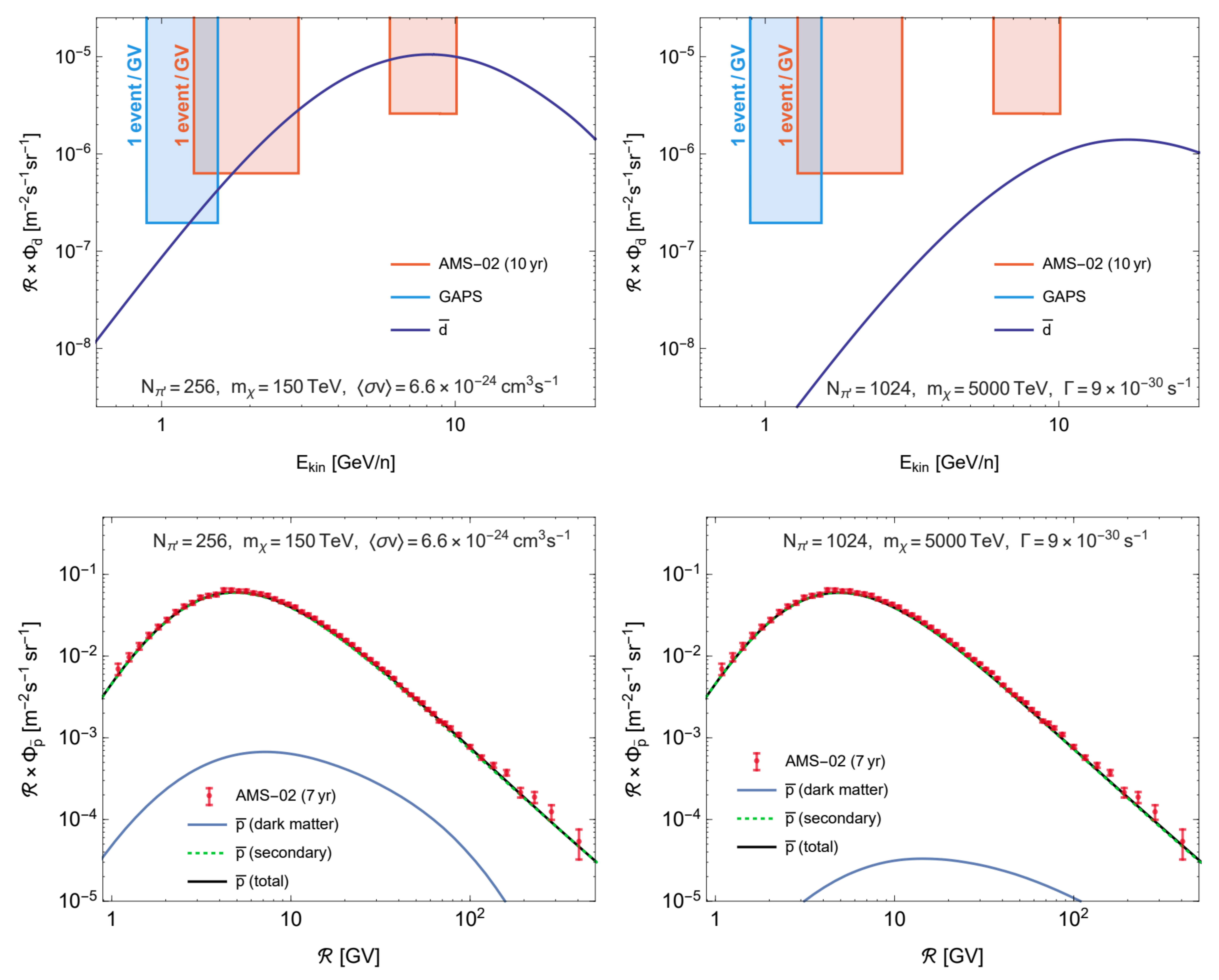
Strongly Coupled Dark Sectors



This significantly boosts the anti helium production rate:

By a factor of n^9 for $^3\overline{He}$ and n^{12} for $^4\overline{He}$

Strongly Coupled Dark Sectors



WHERE ARE WE NOW?

$b\bar{b}$ (WMAP5)
e^+e^- (WMAP5)
Thermal Cross-Section
$<\sigma v>$ (cm^3s^{-1})
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
0.1
1
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)
Galli et al. (2009; 0905.0003)
see also: astro-ph/0210617, 0810.5952)

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


And the (TeV) future is bright!