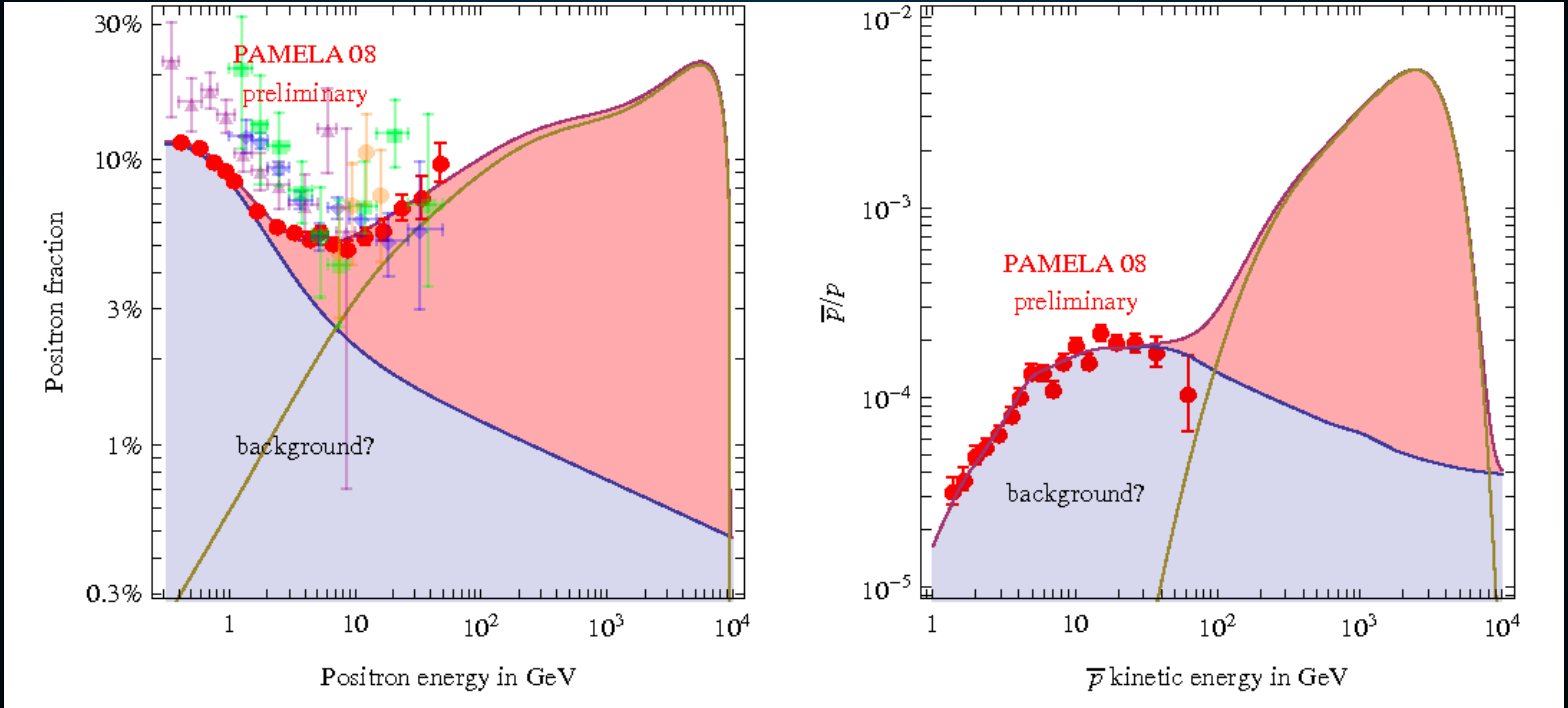
Tim Linden

Excesses in Cosmic-Ray Antinuclei

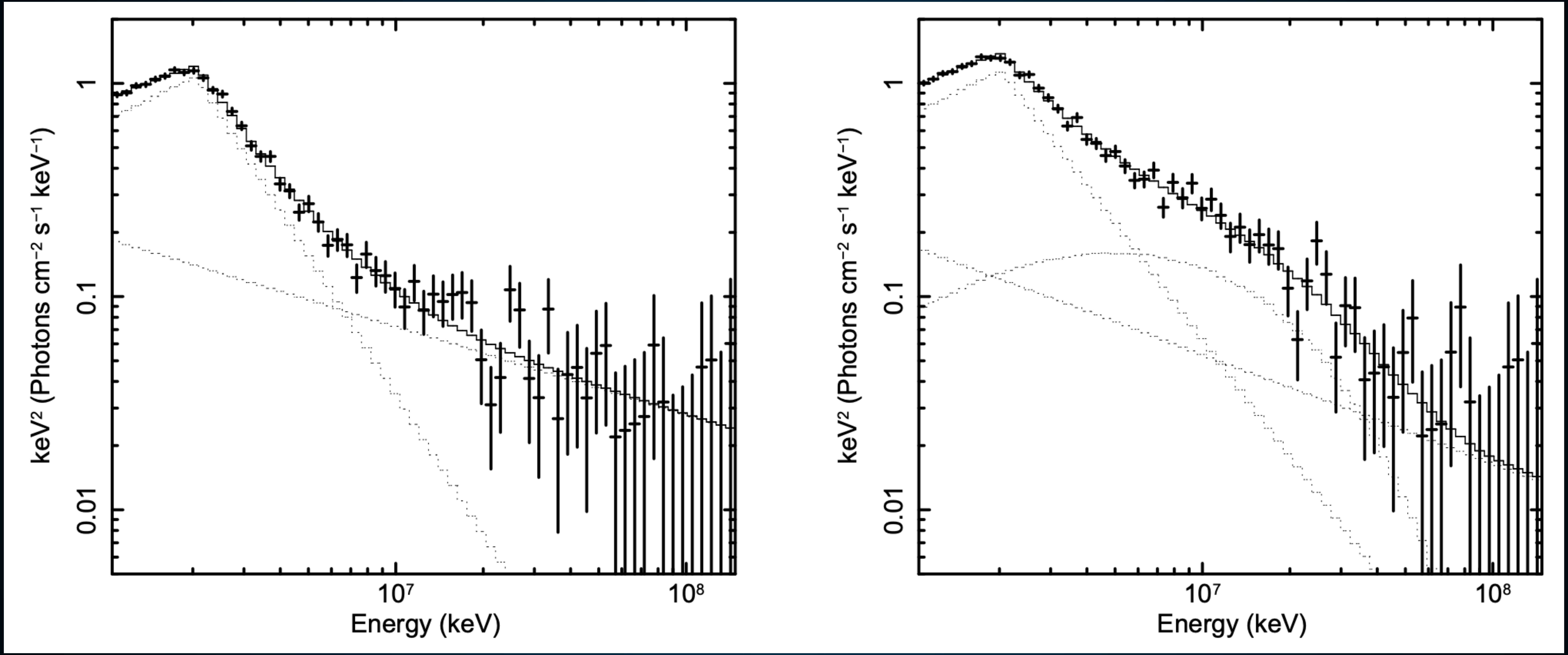
Stockholms universitet

Reflections on the State of Indirect Detection



Cirelli et al. 2008

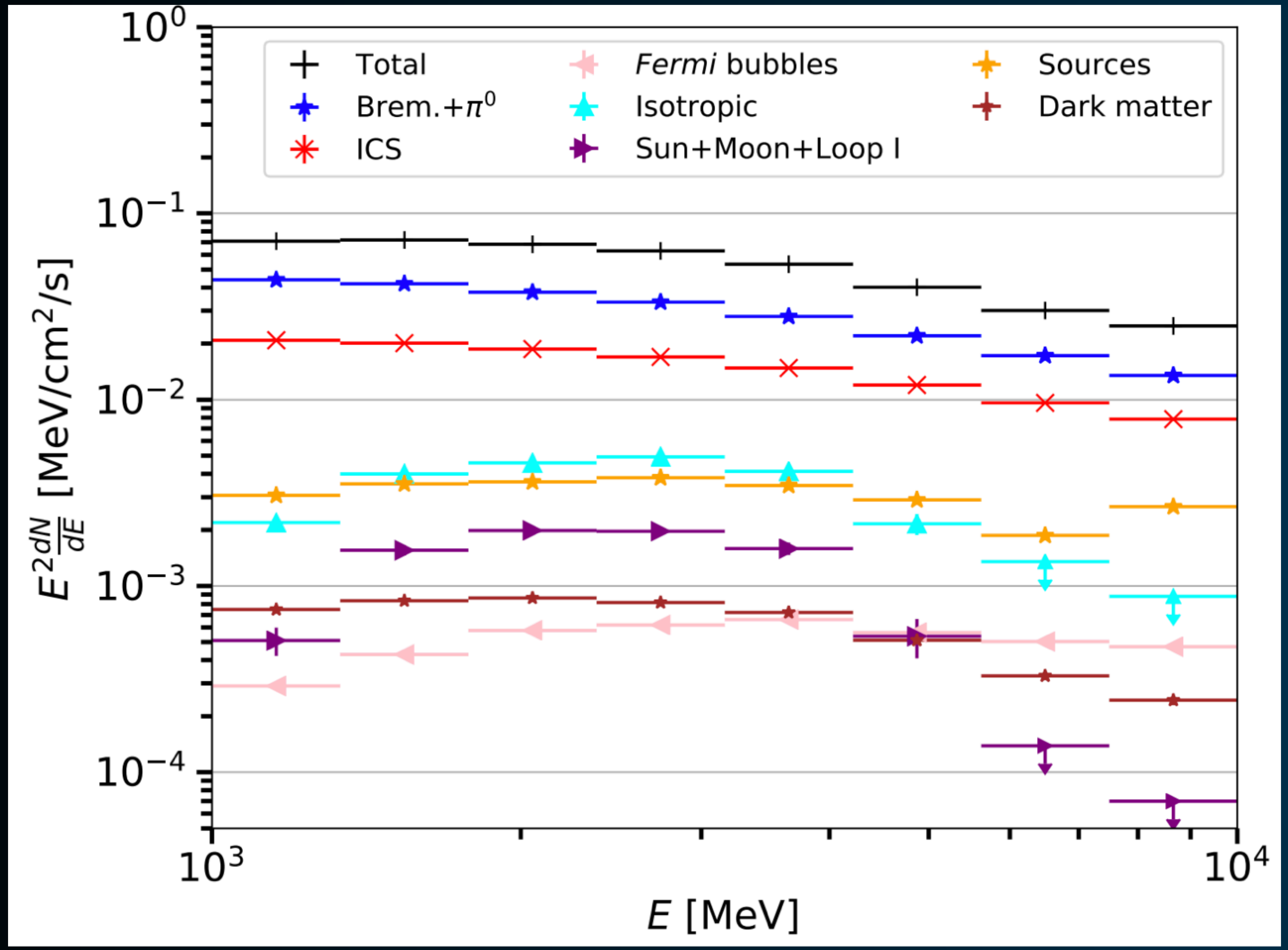
Reflections on the State of Indirect Detection



Jeltema & Profumo (0808.2641)

Reflections on the State of Indirect Detection

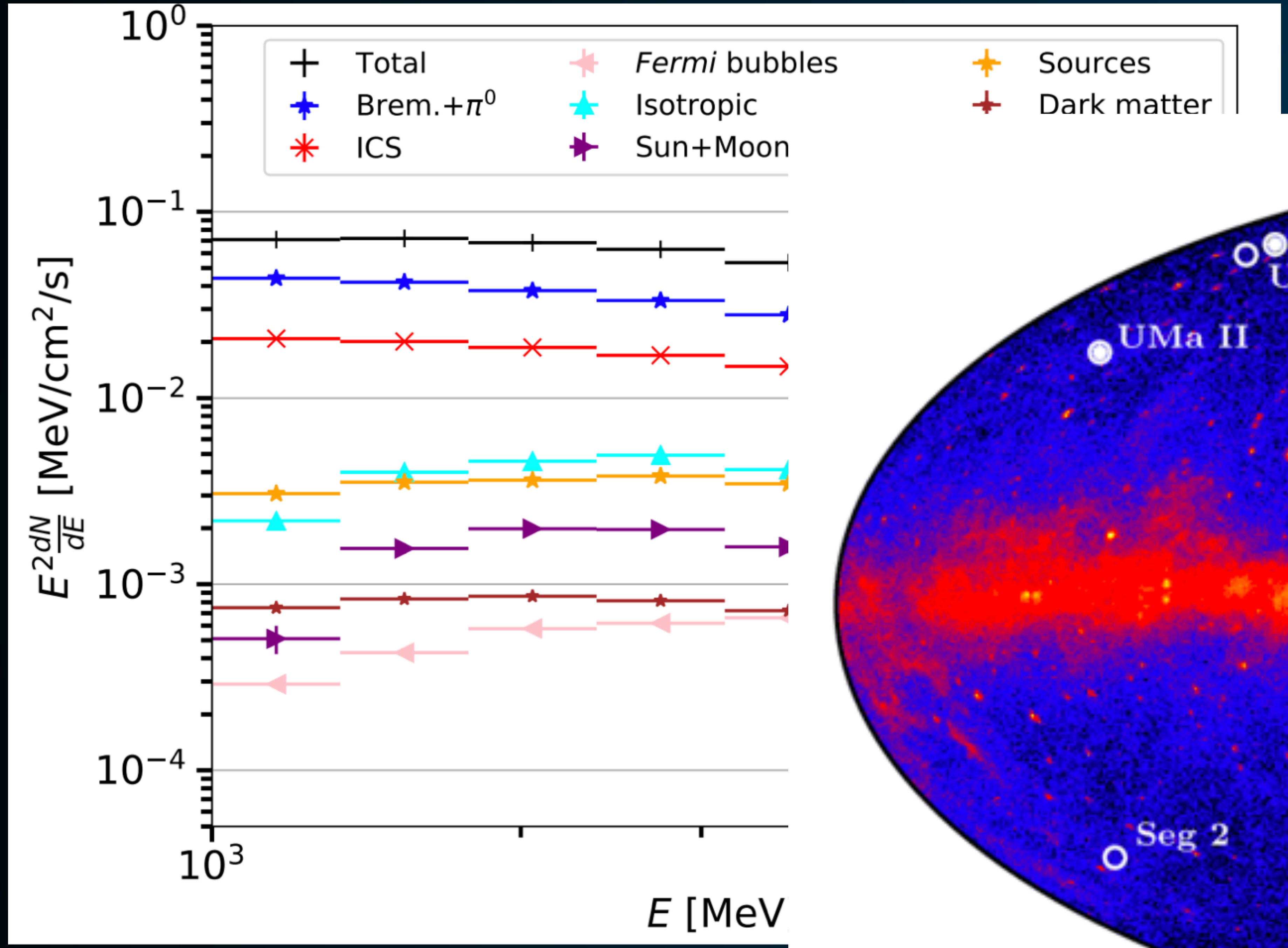
Galactic Center



Di Mauro 2021 (2101.04694)

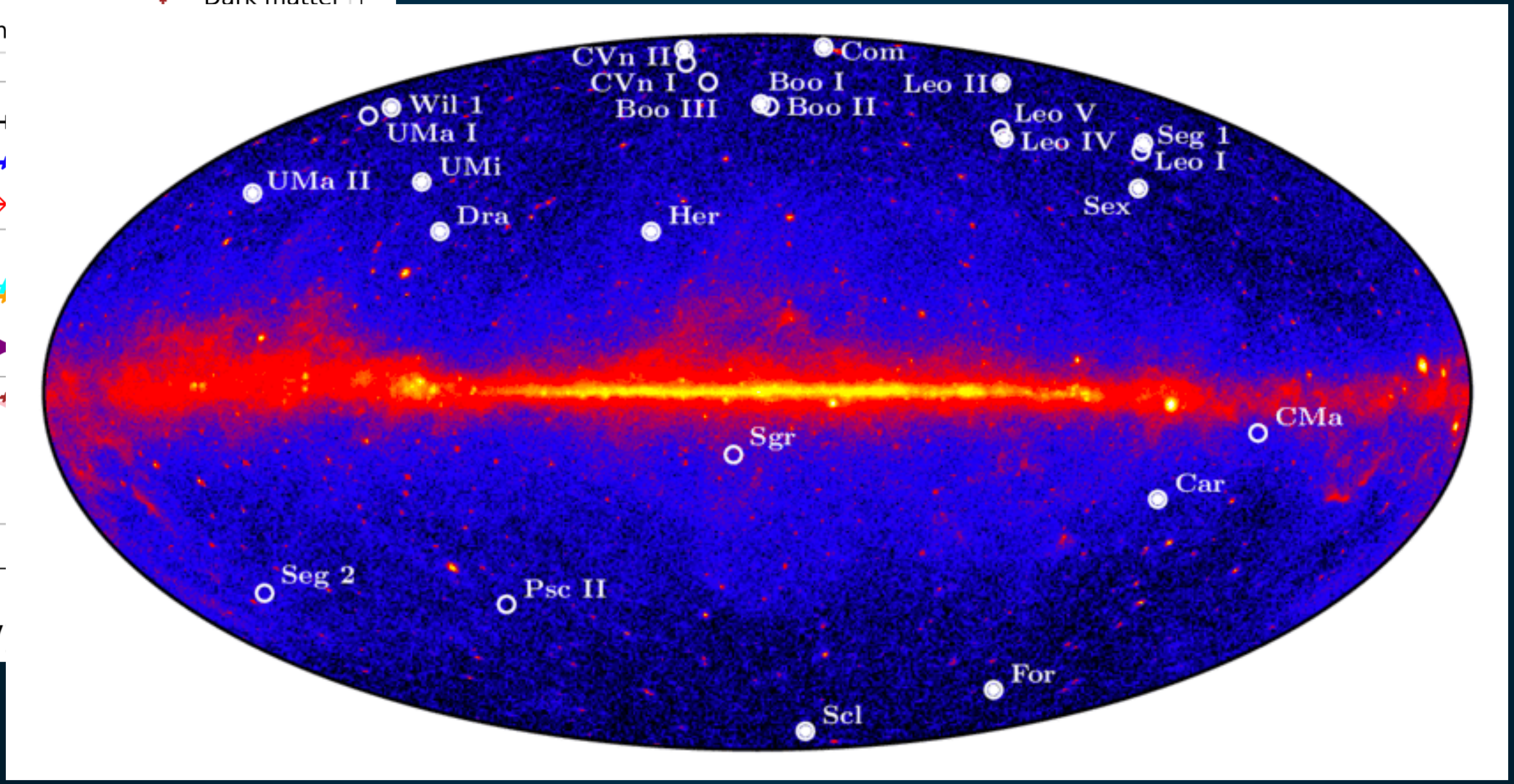
Reflections on the State of Indirect Detection

Galactic Center



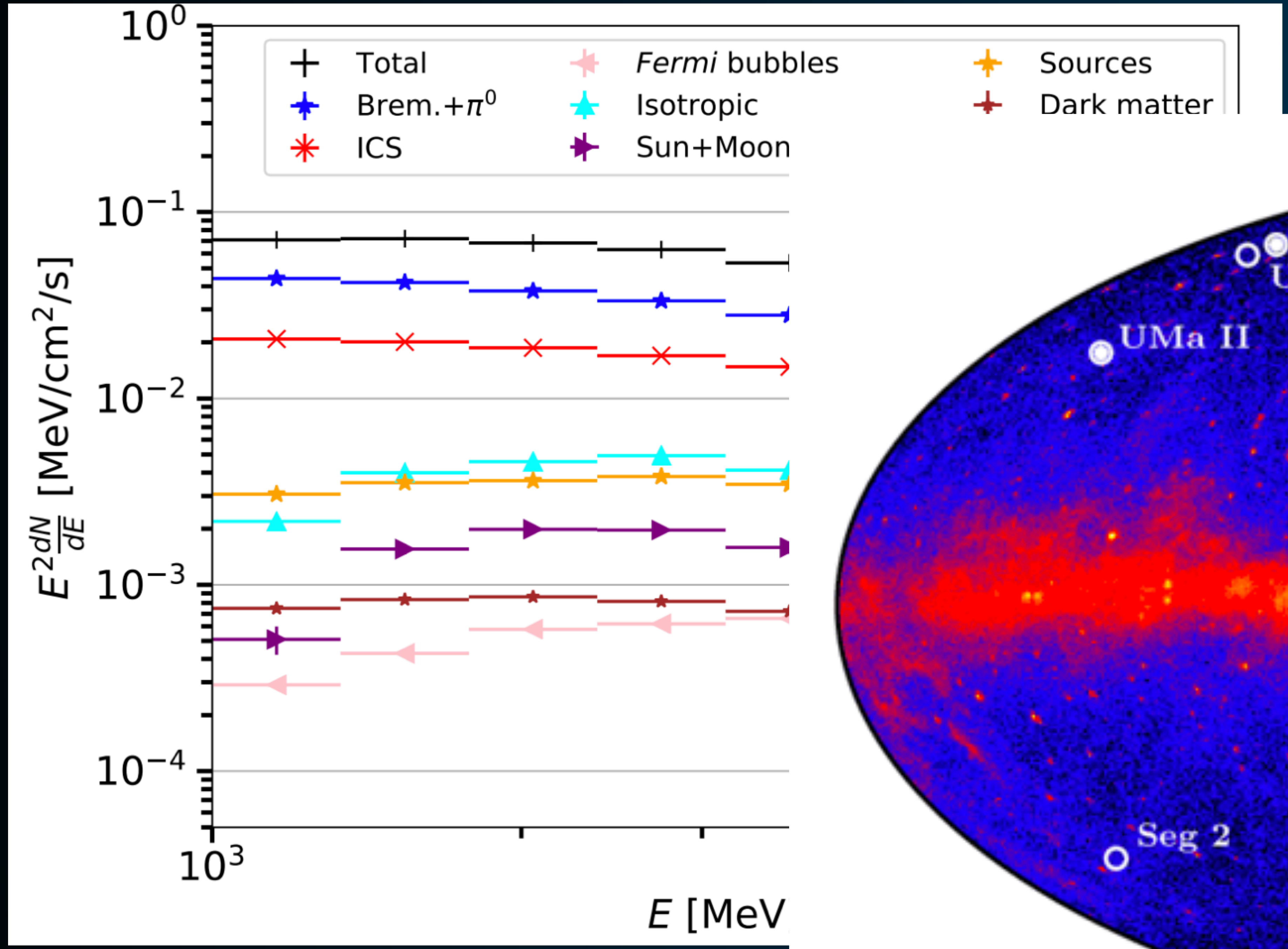
Di Mauro 2021 (2101.04694)

Dwarf Spheroidal Galaxies



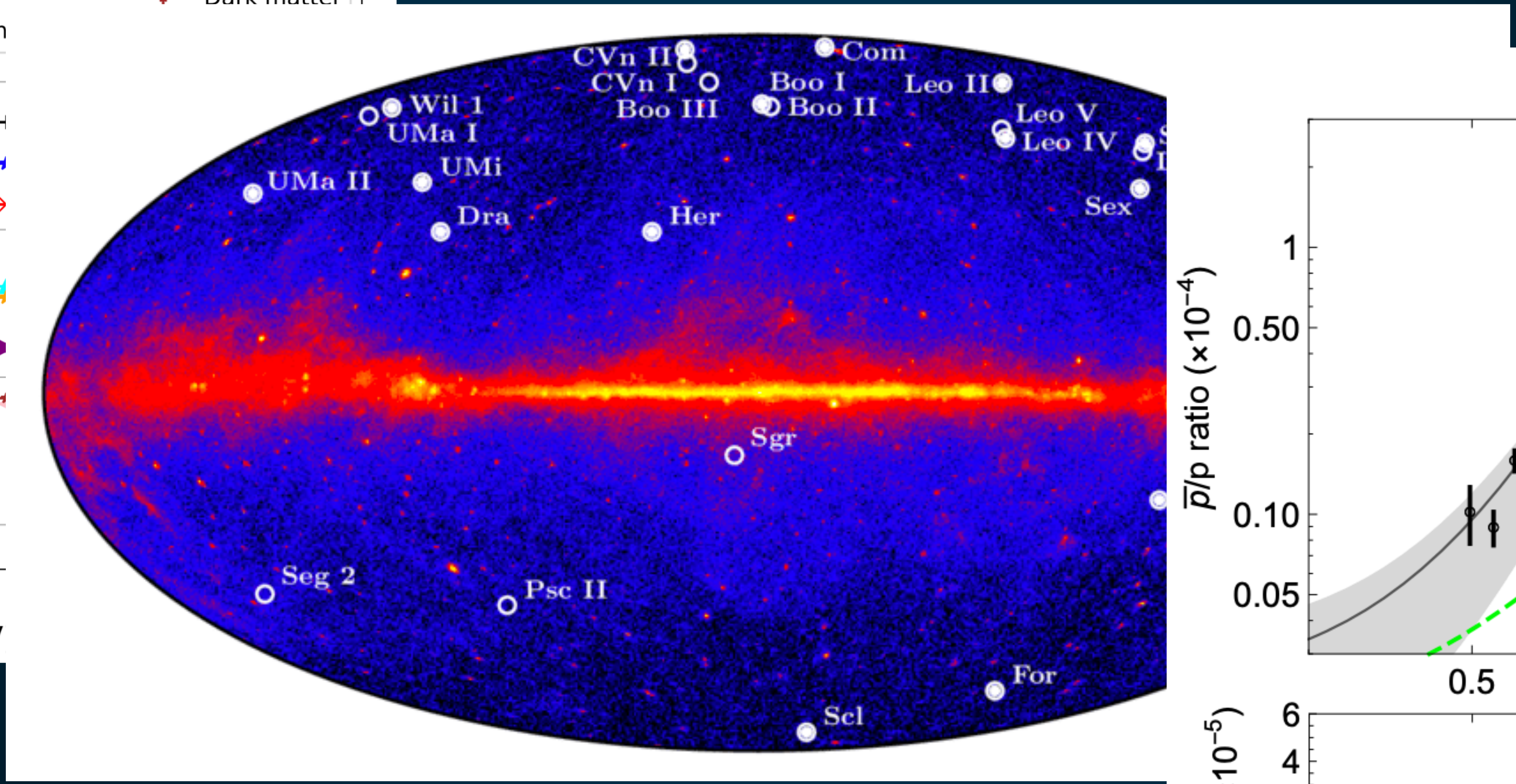
Reflections on the State of Indirect Detection

Galactic Center

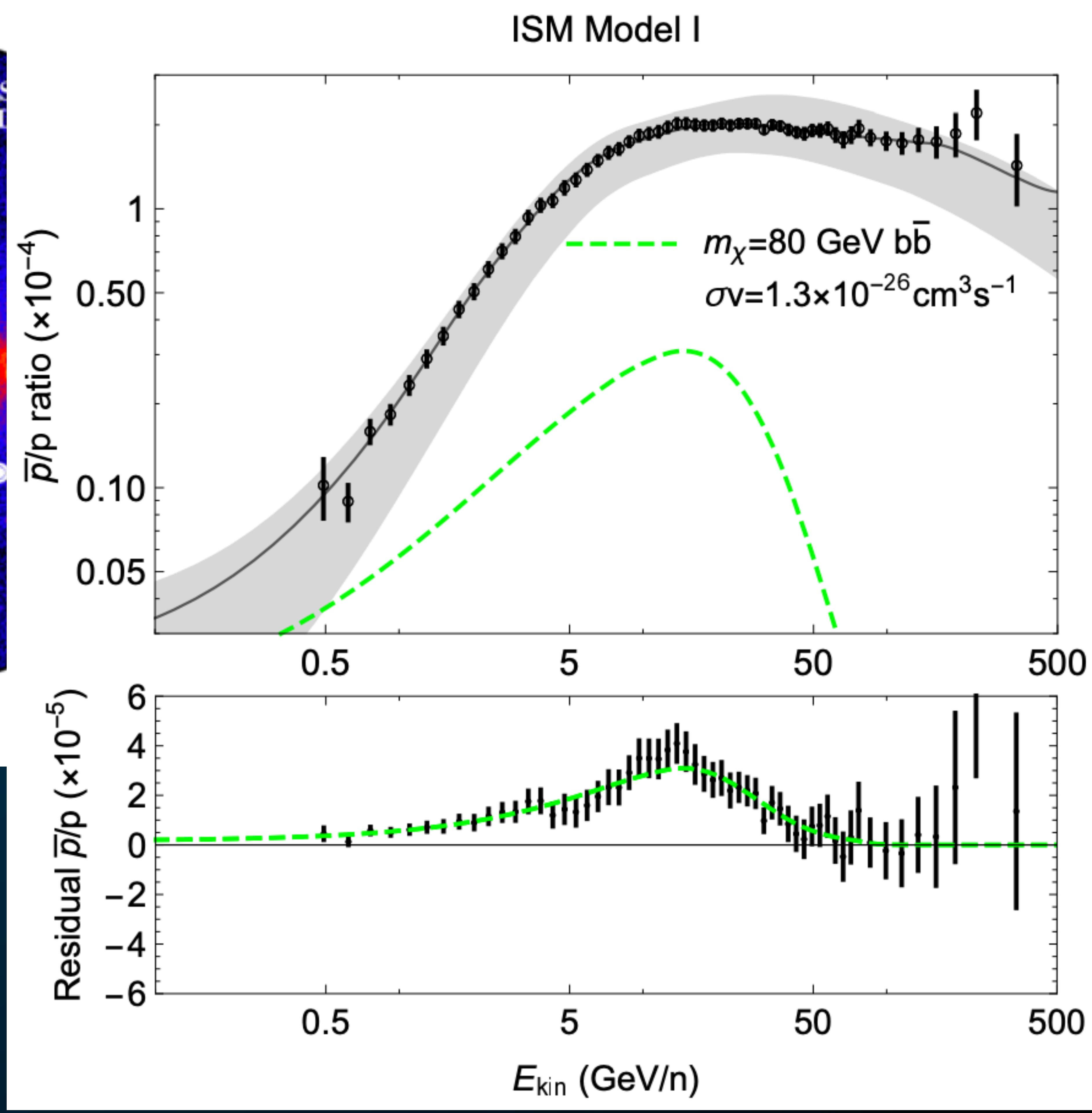


Di Mauro 2021 (2101.04694)

Dwarf Spheroidal Galaxies



Antiprotons



Cholis et al. (1902.02549)

Reflections on the State of Indirect Detection

MIT-CTP/5020

GeV-Scale Thermal WIMPs: Not Even Slightly Dead

Rebecca K. Leane,[1,*] Tracy R. Slatyer,[1,†] John F. Beacom,[2,3,4,‡] and Kenny C. Y. Ng[5,§]

[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2] *Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, OH 43210, USA*
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[5] *Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 76100, Israel*

(Dated: July 13, 2018)

Weakly Interacting Massive Particles (WIMPs) have long reigned as one of the leading classes of dark matter candidates. The observed dark matter abundance can be naturally obtained by freeze-out of weak-scale dark matter annihilations in the early universe. This "thermal WIMP" scenario makes direct predictions for the total annihilation cross section that can be tested in present-day experiments. While the dark matter mass constraint can be as high as $m_\chi \gtrsim 100$ GeV for particular annihilation channels, the constraint on the *total* cross section has not been determined. We construct the first model-independent limit on the WIMP total annihilation cross section, showing that allowed combinations of the annihilation-channel branching ratios considerably weaken the sensitivity. For thermal WIMPs with s-wave $2 \to 2$ annihilation to visible final states, we find the dark matter mass is only known to be $m_\chi \gtrsim 20$ GeV. This is the strongest largely model-independent lower limit on the mass of thermal-relic WIMPs; together with the upper limit on the mass from the unitarity bound ($m_\chi \lesssim 100$ TeV), it defines what we call the "WIMP window". To probe the remaining mass range, we outline ways forward.

I. INTRODUCTION

scenarios. The branching ratios, coupling types and signals are model-dependent, and so the lack of observations

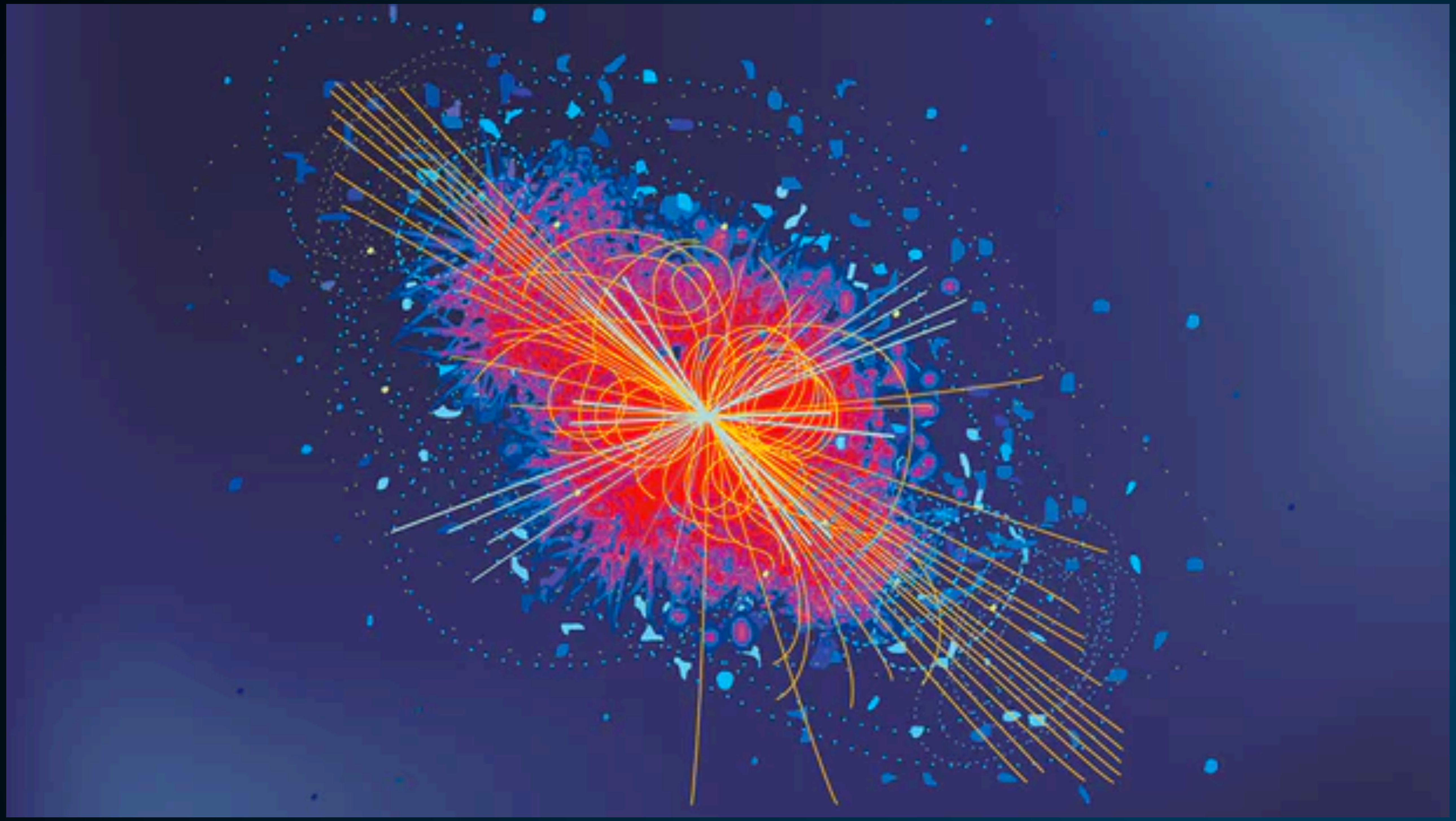
Reflections on the State of Indirect Detection

But is our (practical) ability to search for them ruled out?

i.e., In 2008, it was possible that WIMP dark matter was the dominant energetic component in some GeV gamma-ray or cosmic-ray channel. However, it appears that astrophysics is unfortunately bright - and that will not change.


Specificity (DM Flux / Astrophysics Flux)
Anti-Nuclei
Antiprotons
Gamma-Rays / Positrons
10^{-8}
10^{-3}
0.1
Fraction of Dark Matter Flux

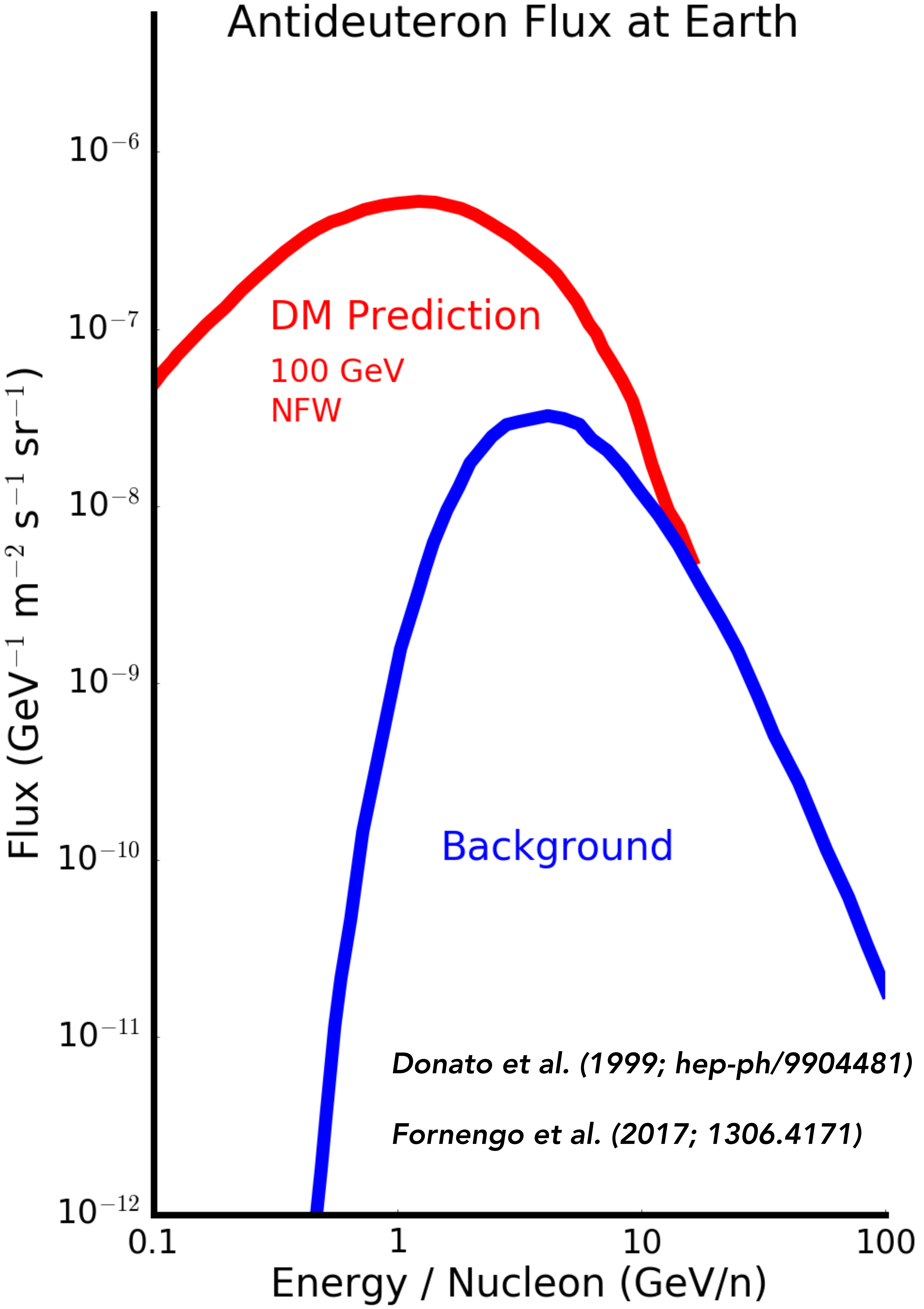
AntiNuclei - A Clean Search Strategy ?



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

Astrophysical Antinuclei - Most be moving relativistically!

Dark Matter Antinuclei - Can be slow!



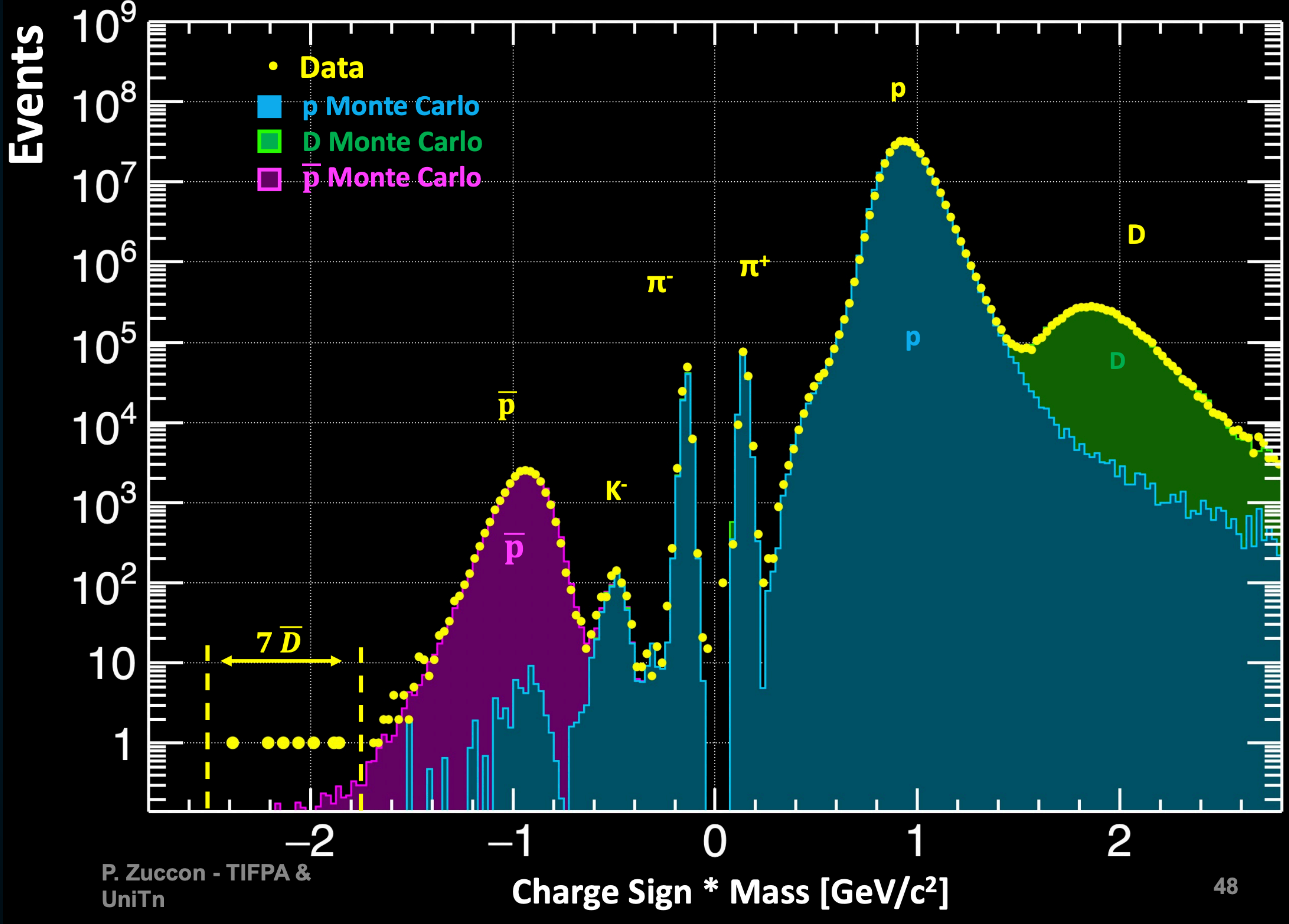
To date, we have observed eight events in the mass region from 0 to 10 GeV with Z= –2. All eight events are in the helium mass region.

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

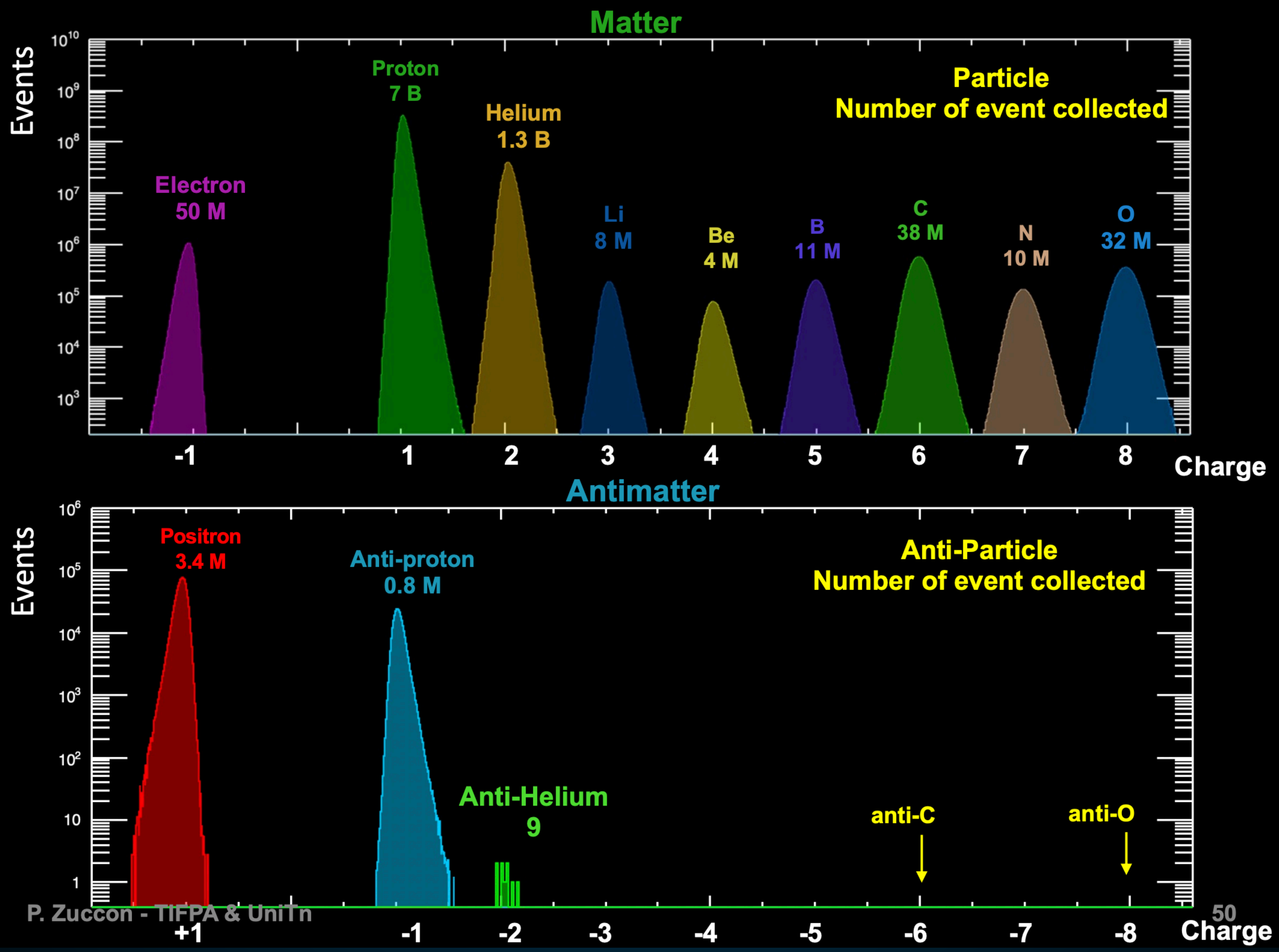
Note that for $^{4}\overline{\mathrm{He}}$, projecting based on the statistics we have today, by using an additional 400 million core hours for simulation the background probability would be 10^{-4}. Simultaneously, continuing to run until 2023, which doubles the data sample, the background probability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

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

Current AMS Anti-Deuteron Status



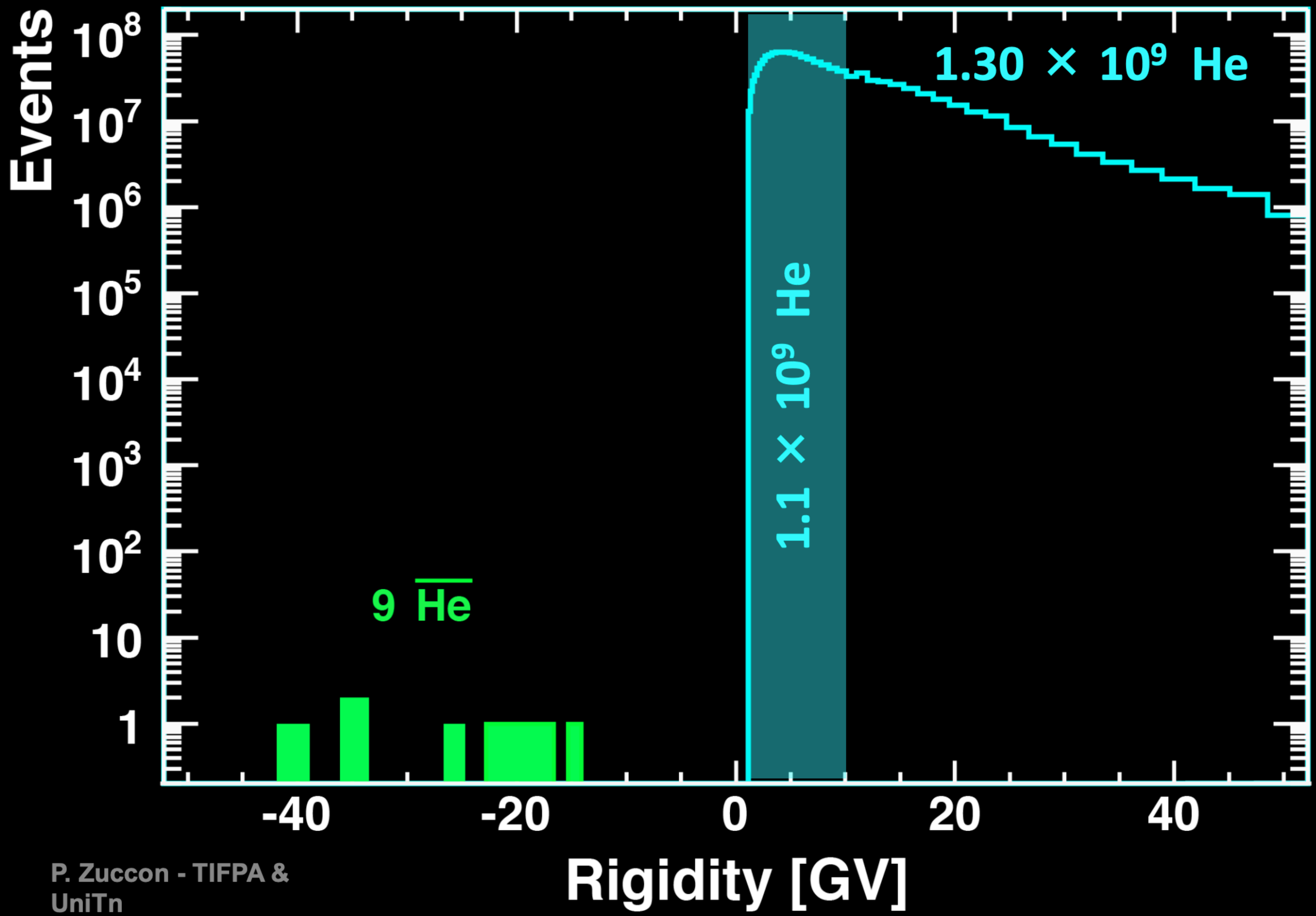
AMS Measurements of Matter and Antimatter



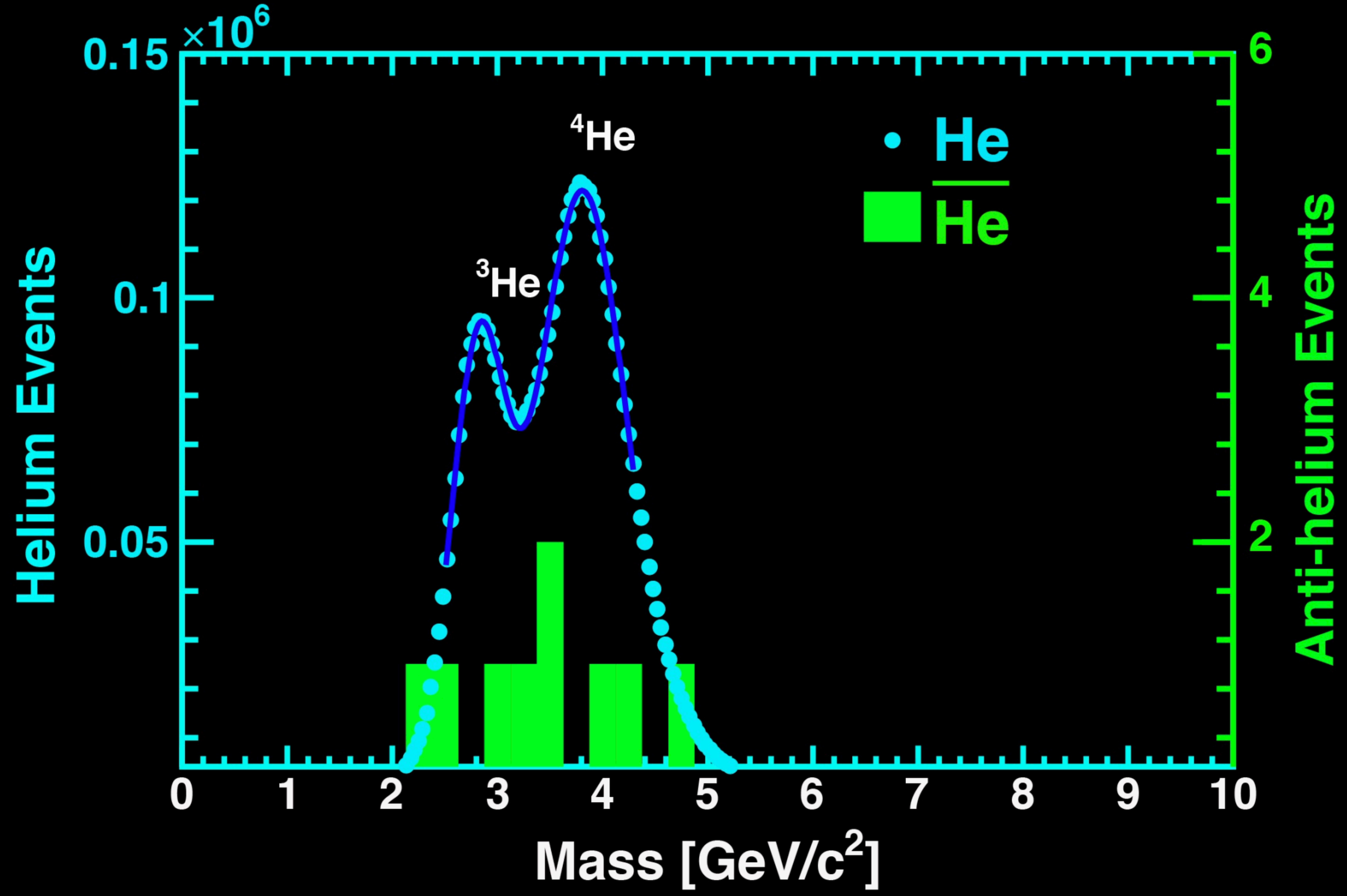
P. Zuccon - TIFPA & UniTn

Identification of antihelium

Rigidity) resolution



AMS Anti-Helium Mass Spectrum

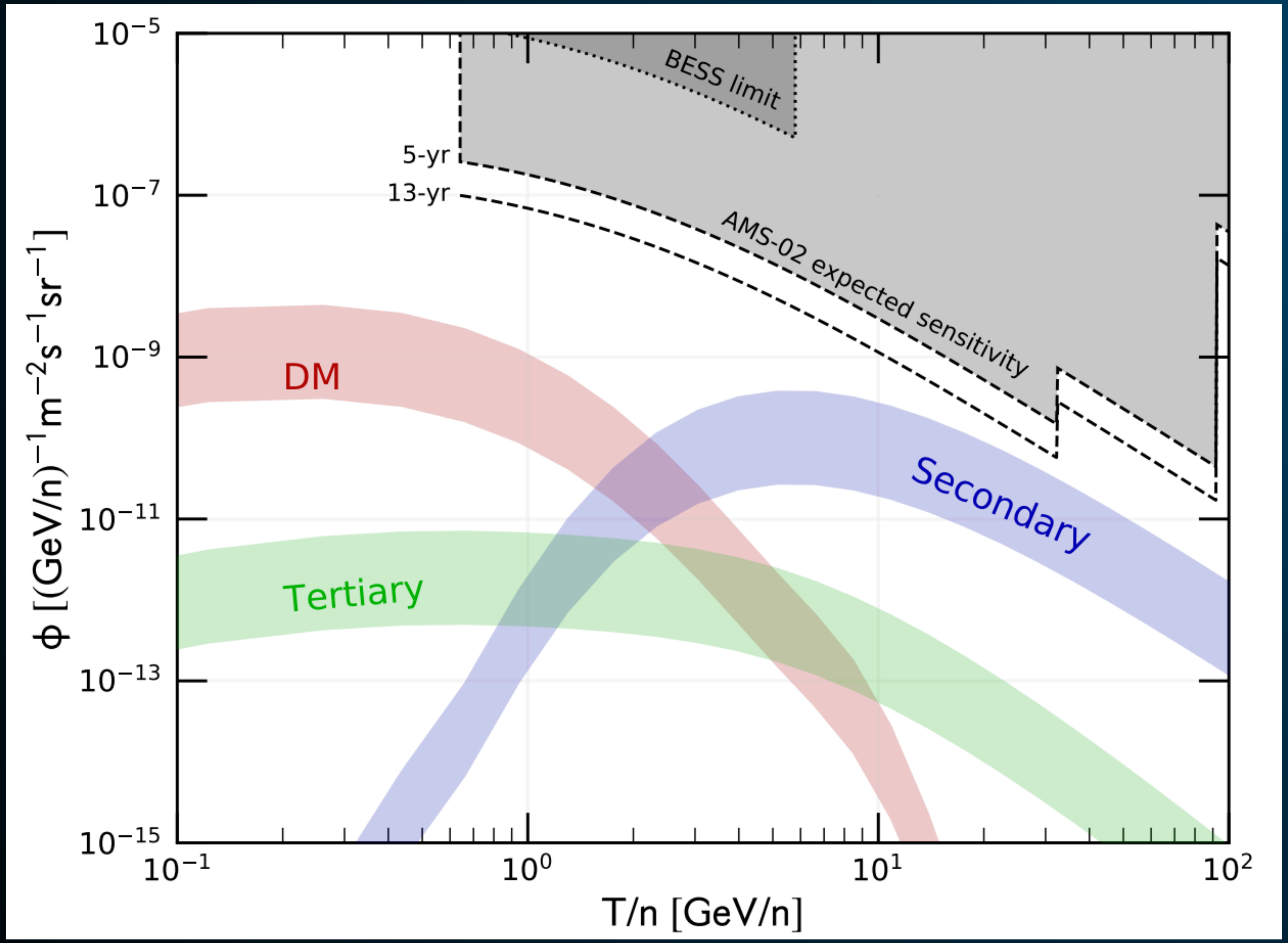


from 0 to 10 GeV/c^2 there are no other signals

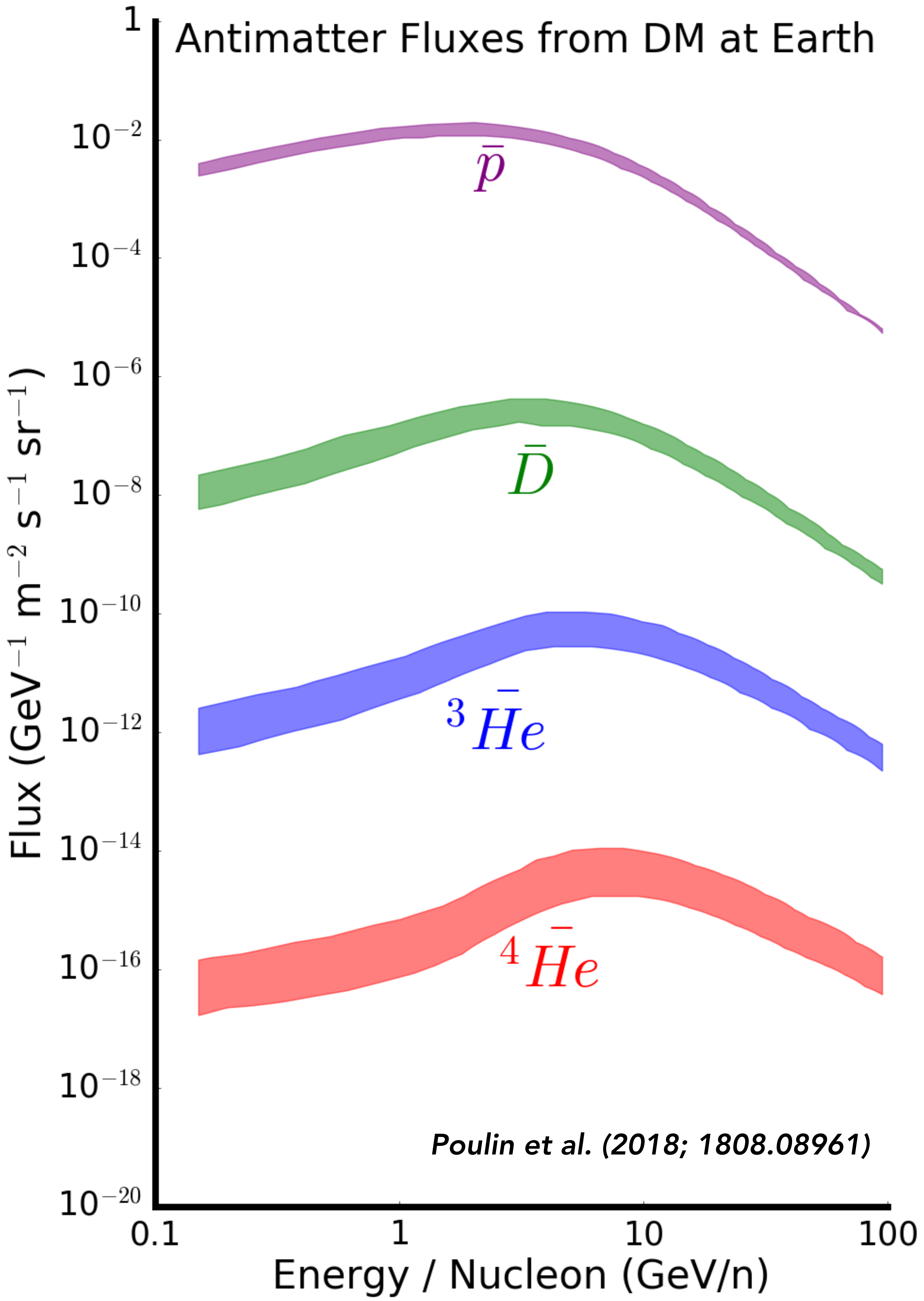
AntiNuclei - A Clean Search Strategy ?

Antihelium background even cleaner than antideuterons

But the flux is supposed to be much smaller.



Korsmeier (2017; 1711.08465)



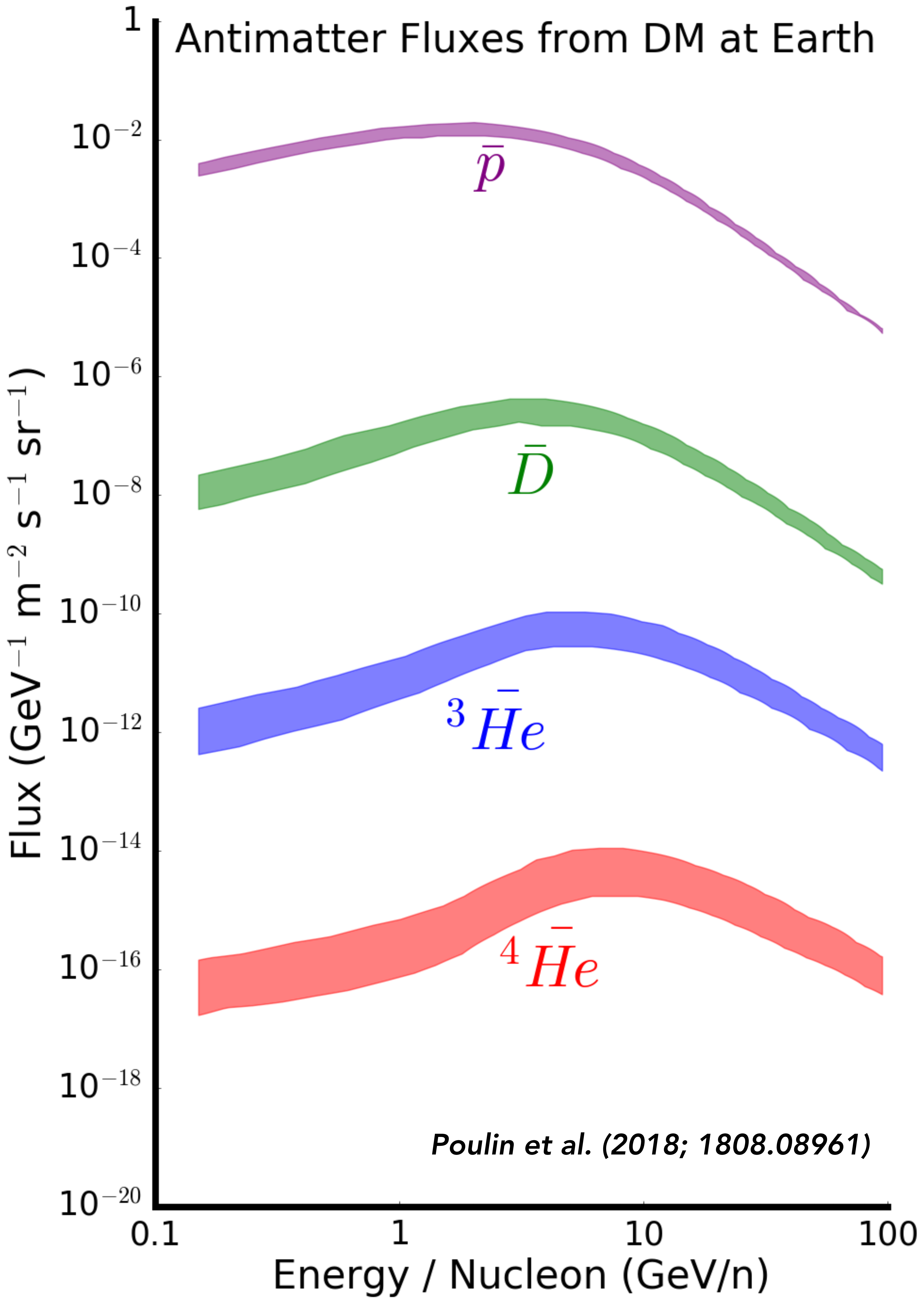
Boosting this Signal to Meet the Challenge?

1.) Hadronic Interaction Rates (should affect Antiprotons)

2.) Coalescence Rates

3.) Astrophysical Acceleration

4.) New Channels



$$R \propto p_0^{3(A-1)}$$

Antihelium from Dark Matter

Eric Carlson,[1,2] Adam Coogan,[1,2,*] Tim Linden,[1,2,3,4,†] Stefano Profumo,[1,2,‡] Alejandro Ibarra,[5,§] and Sebastian Wild[5,¶]

[1]*Department of Physics, University of California, 1156 High St., Santa Cruz, CA 95064, USA*
[2]*Santa Cruz Institute for Particle Physics, Santa Cruz, CA 95064, USA***
[3]*Department of Physics, University of Chicago, Chicago, IL 60637*
[4]*Kavli Institute for Cosmological Physics, Chicago, IL 60637*
[5]*Physik-Department T30d, Technische Universität München, James-Franck-Straße, 85748 Garching, Germany*

(Dated: March 20, 2014)

Cosmic-ray anti-nuclei provide a promising discovery channel for the indirect detection of particle dark matter. Hadron showers produced by the pair-annihilation or decay of Galactic dark matter generate anti-nucleons which can in turn form light anti-nuclei. Previous studies have only focused on the spectrum and flux of low energy antideuterons which, although very rarely, are occasionally also produced by cosmic-ray spallation. Heavier elements ($A \geq 3$) have instead entirely negligible astrophysical background and a primary yield from dark matter which could be detectable by future experiments. Using a Monte Carlo event generator and an event-by-event phase space analysis, we compute, for the first time, the production spectrum of $^3\overline{\mathrm{He}}$ and $^3\overline{\mathrm{H}}$ for dark matter annihilating or decaying to $b\bar{b}$ and W^+W^- final states. We then employ a semi-analytic model of interstellar and heliospheric propagation to calculate the $^3\overline{\mathrm{He}}$ flux as well as to provide tools to relate the anti-helium spectrum corresponding to an arbitrary antideuteron spectrum. Finally, we discuss prospects for current and future experiments, including GAPS and AMS-02.

I. INTRODUCTION

Within the paradigm of Weakly Interacting Massive Particle (WIMP) dark matter, the pair-annihilation or decay of dark matter particles generically yields high-energy matter and antimatter cosmic rays. While the former are usually buried under large fluxes of cosmic rays of more ordinary astrophysical origin, antimatter is rare enough that a signal from dark matter might be distinguishable and detectable with the current generation of experiments. While astrophysical accelerators of high-energy positrons such as pulsars' magnetospheres are well-known, observations of cosmic anti-nuclei might provide a unique window into physics beyond the Stan-

cal backgrounds often prohibit the clean disentanglement of exotic sources, a recent analysis projects that the 1-year AMS-02 data will produce robust constraints on WIMP annihilation to heavy quarks below the thermal-relic cross-section for dark matter masses $30 \leq m_\chi \leq 200$ GeV [10].

In addition to antiprotons, Ref. [13] proposed new physics searches using heavier anti-nuclei such as antideuteron ($\overline{\mathrm{D}}$), antihelium-3 ($^3\overline{\mathrm{He}}$), or antitritium ($^3\overline{\mathrm{H}}$) forming from hadronic neutralino annihilation products. Although such production is of course highly correlated with the antiproton spectrum, the secondary astrophysical background decreases much more rapidly than the expected signal as the atomic number A is increased [14].

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:

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

Key Insight - Coalescence Momentum for Antihelium Should Be Larger

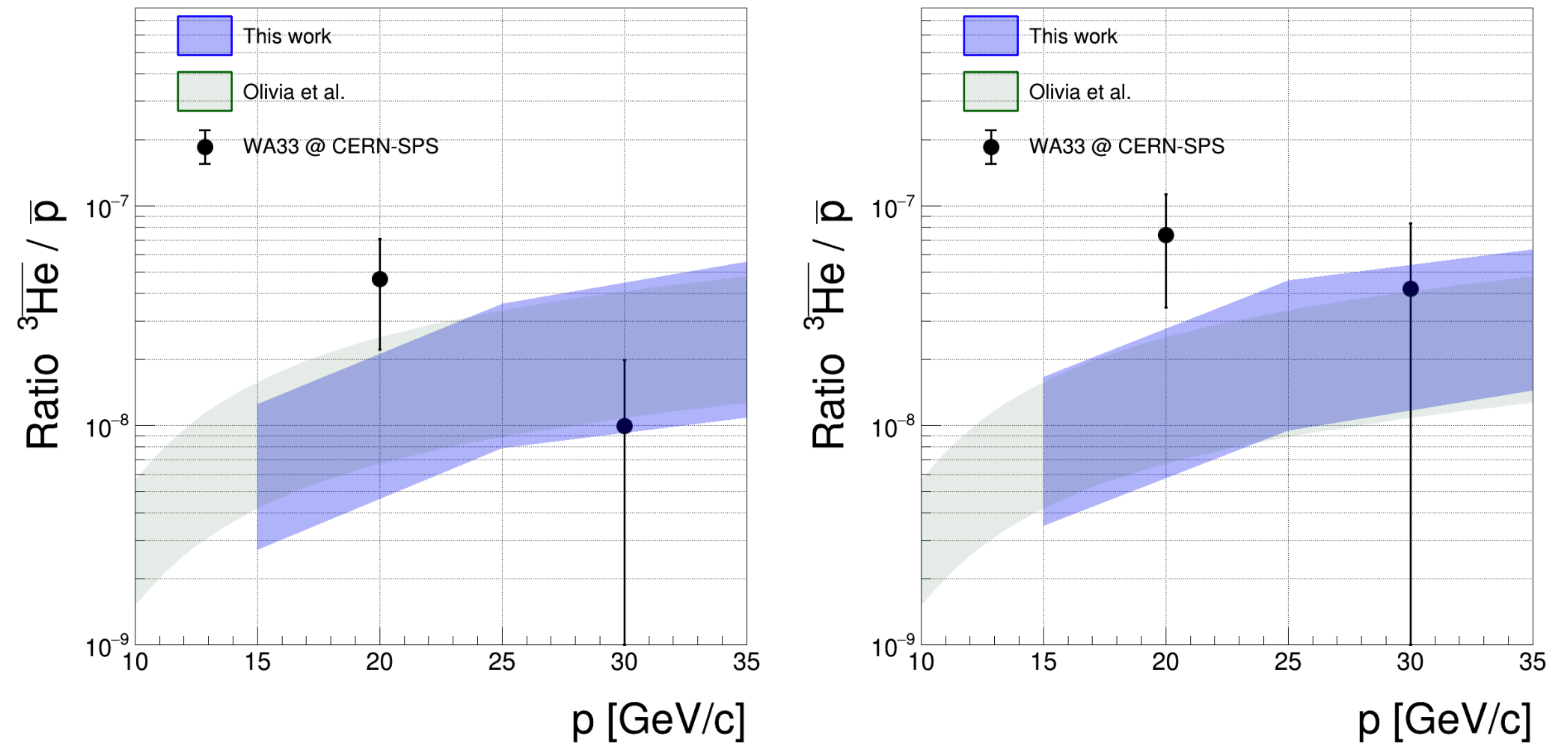
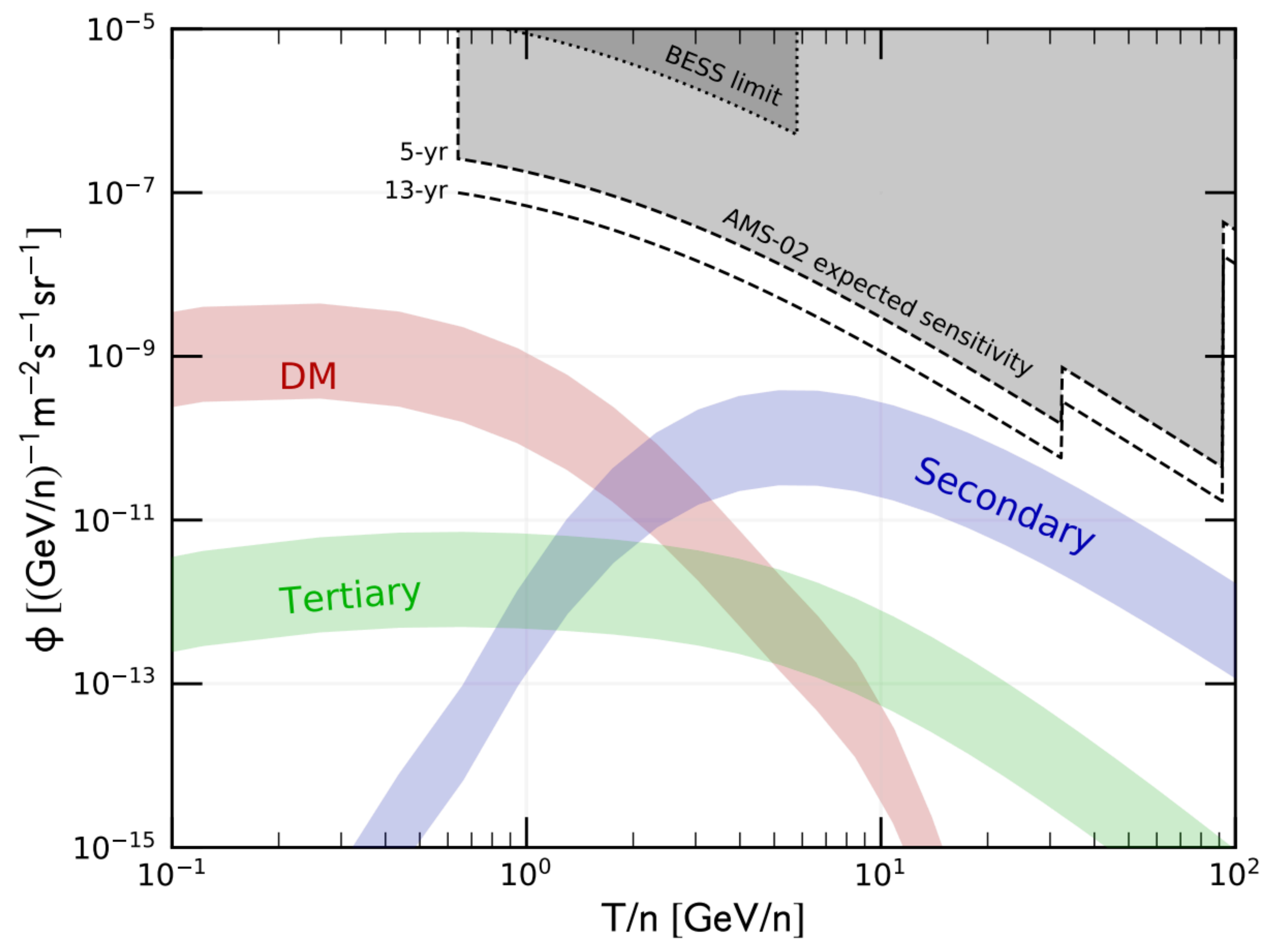


FIG. 4. The invariant production cross section ratio $^3\overline{\mathrm{He}}/\overline{p}$ as function of momentum p [GeV$/c$] in the laboratory frame for (left) p-Be at $p_{\mathrm{lab}} = 200\,\mathrm{GeV}/c$ and (right) p–Al at $p_{\mathrm{lab}} = 200\,\mathrm{GeV}/c$. The uncertainty bands for this work were estimated by varying the coalescence parameter from $p_{0,G}$ (59 MeV$/c$) to 130% of $p_{0,G}$ (77 MeV$/c$).

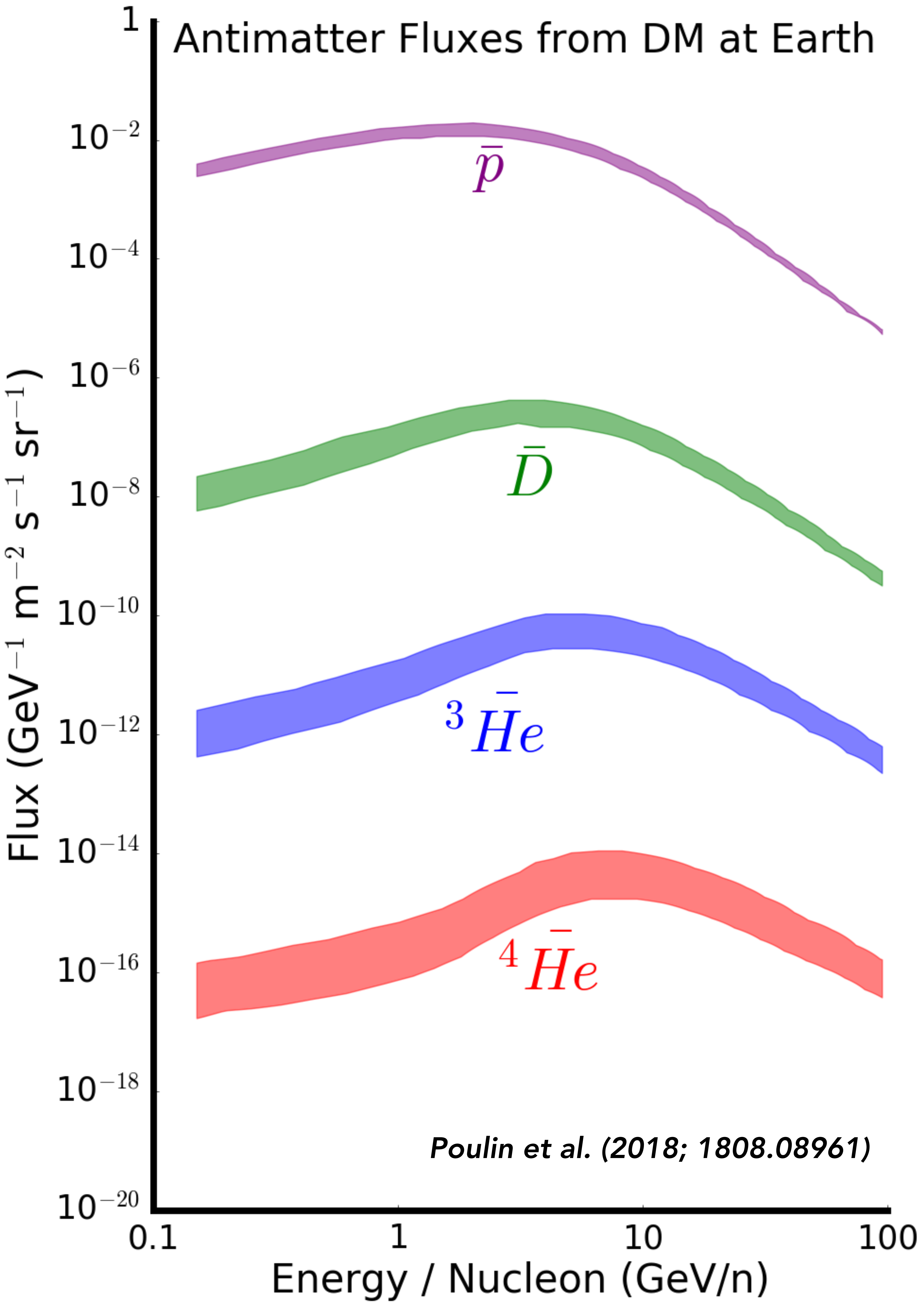
Shukla et al. (2006.12707)

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

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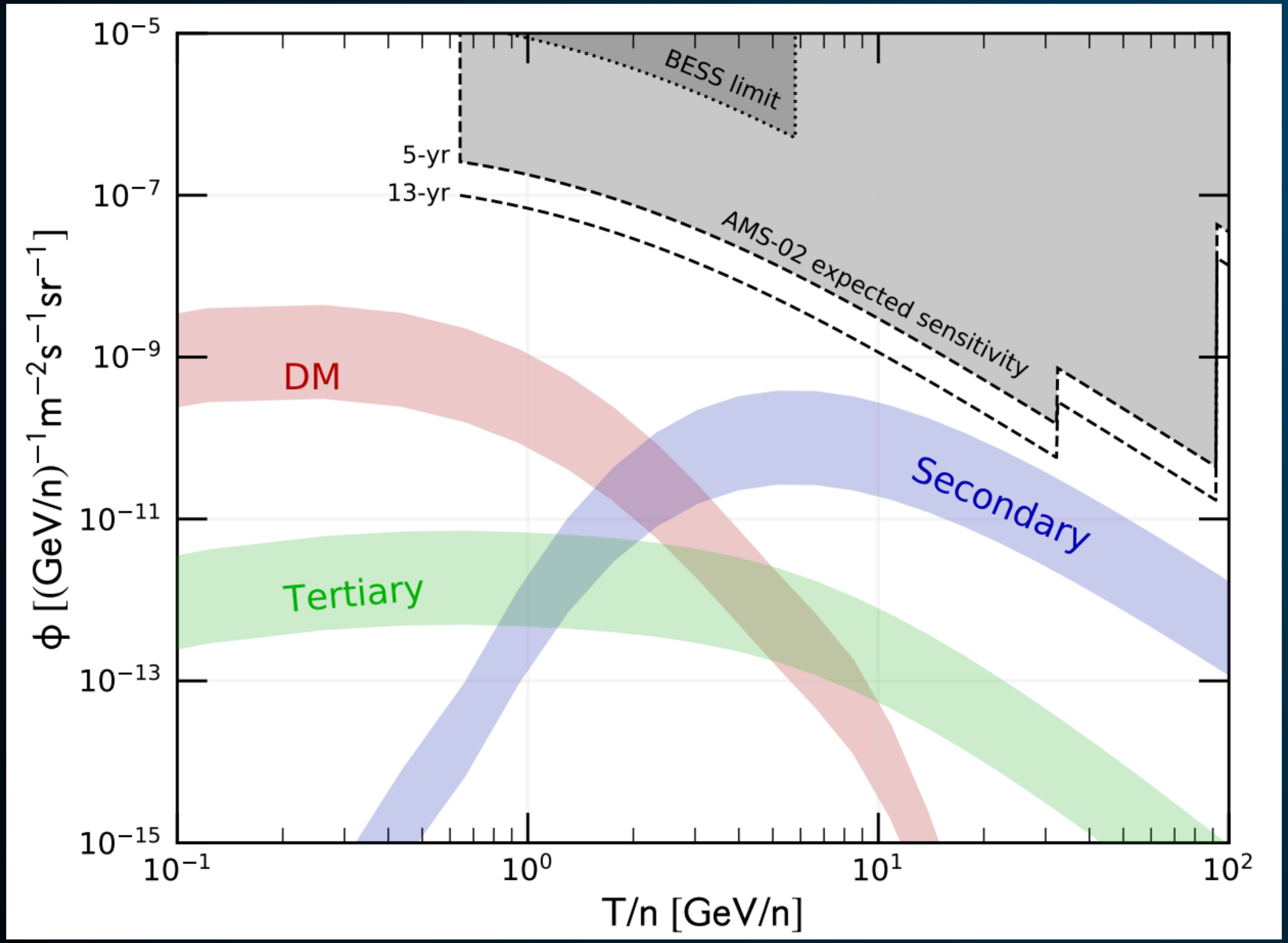
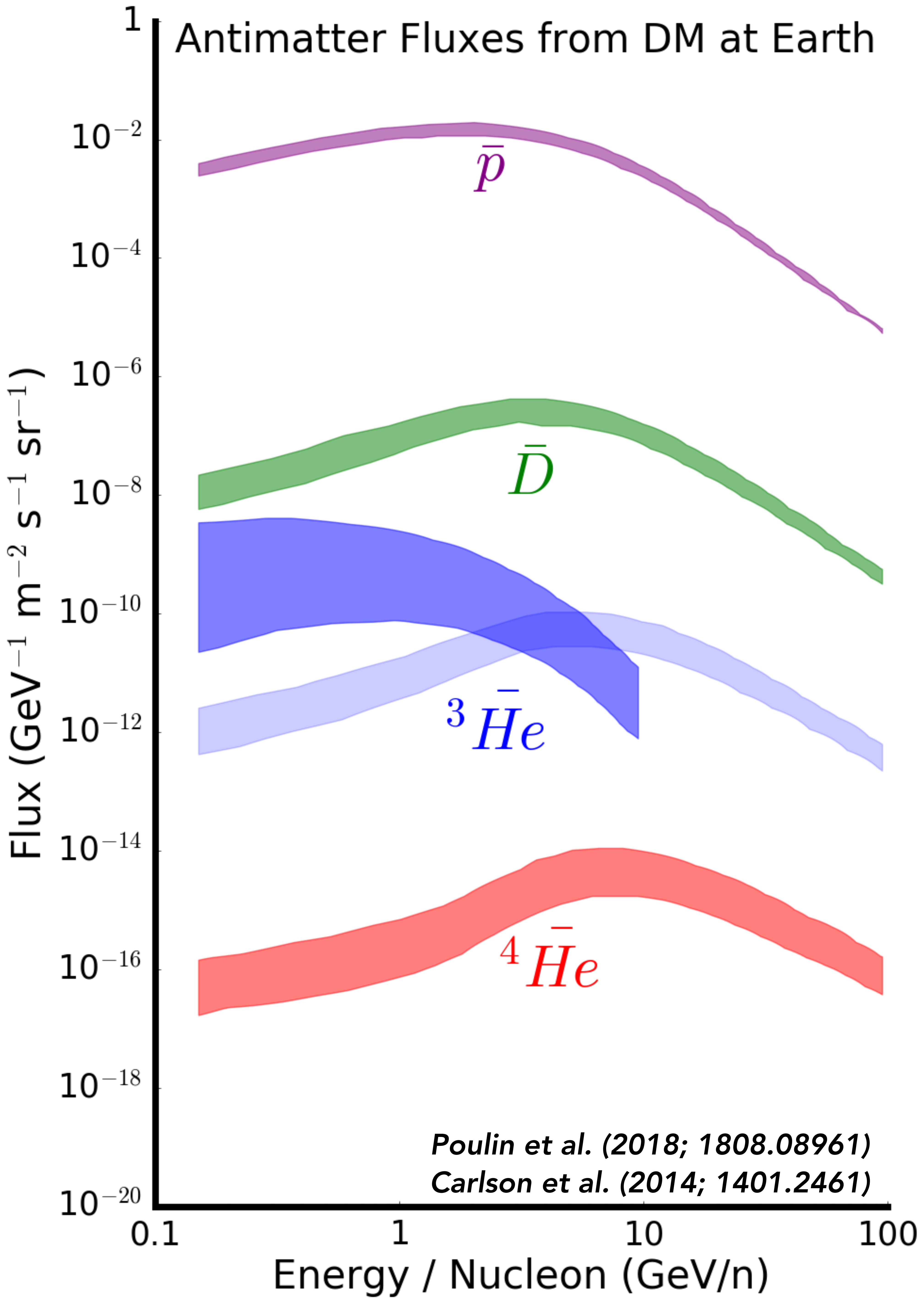


Korsmeier (2017; 1711.08465)



Problem: The AMS-02 Antihelium Excess is not at low energies

FERMILAB-PUB-20-021-A

Anti-Deuterons and Anti-Helium Nuclei from Annihilating Dark Matter

Ilias Cholis,[1,*] Tim Linden,[2,3,†] and Dan Hooper[4,5,‡]

[1] *Department of Physics, Oakland University, Rochester, Michigan, 48309, USA*
[2] *Stockholm University and the Oskar Klein Centre, Stockholm, Sweden*
[3] *Center for Cosmology and AstroParticle Physics (CCAPP) and Department of Physics, The Ohio State University Columbus, Ohio, 43210*
[4] *Theoretical Astrophysics Group, Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA*
[5] *Department of Astronomy and Astrophysics and the Kavli Institute for Cosmological Physics (KICP), University of Chicago, Chicago, Illinois, 60637, USA*

(Dated: August 27, 2020)

Recent studies of the cosmic-ray antiproton-to-proton ratio have identified an excess of ∼10–20 GeV antiprotons relative to the predictions of standard astrophysical models. Intriguingly, the properties of this excess are consistent with the same range of dark matter models that can account for the long-standing excess of γ-rays observed from the Galactic Center. Such dark matter candidates can also produce significant fluxes of anti-deuterium and anti-helium nuclei. Here we study the production and transport of such particles, both from astrophysical processes as well as from dark matter annihilation. Importantly, in the case of *AMS-02*, we find that Alfvénic reacceleration (i.e., diffusion in momentum space) can boost the expected number of $\bar{\mathrm{d}}$ and $^3\overline{\mathrm{He}}$ events from annihilating dark matter by an order of magnitude or more. For relatively large values of the Alfvén speed, and for dark matter candidates that are capable of producing the antiproton and γ-ray excesses, we expect annihilations to produce a few anti-deuteron events and about one anti-helium event in six years of *AMS-02* data. This is particularly interesting in light of recent reports from the *AMS-02* Collaboration describing the detection of a number of anti-helium candidate events.

Astrophysical Enhancements!

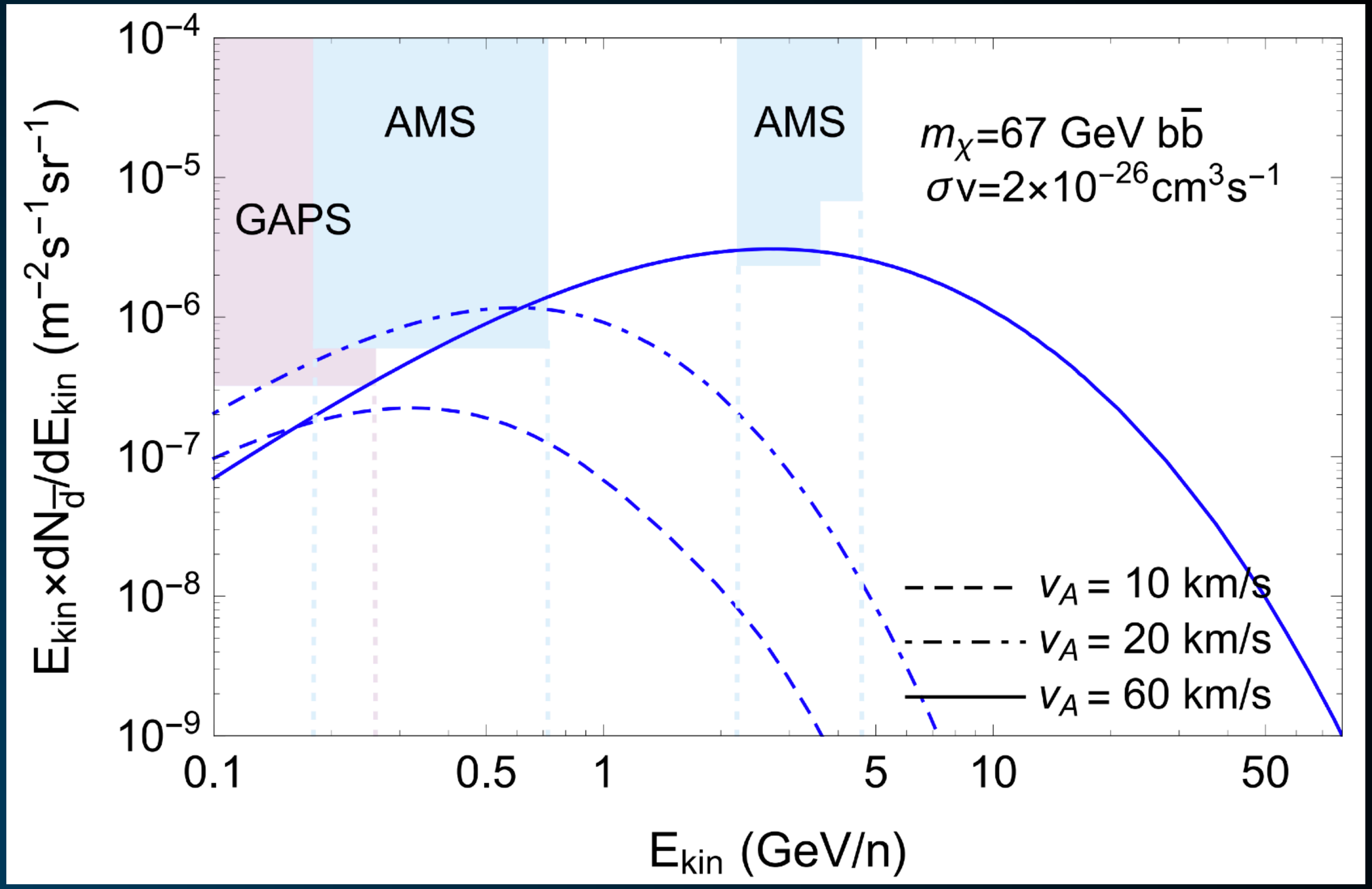
The current event rates depend on the detector sensitivity to anti-Helium.

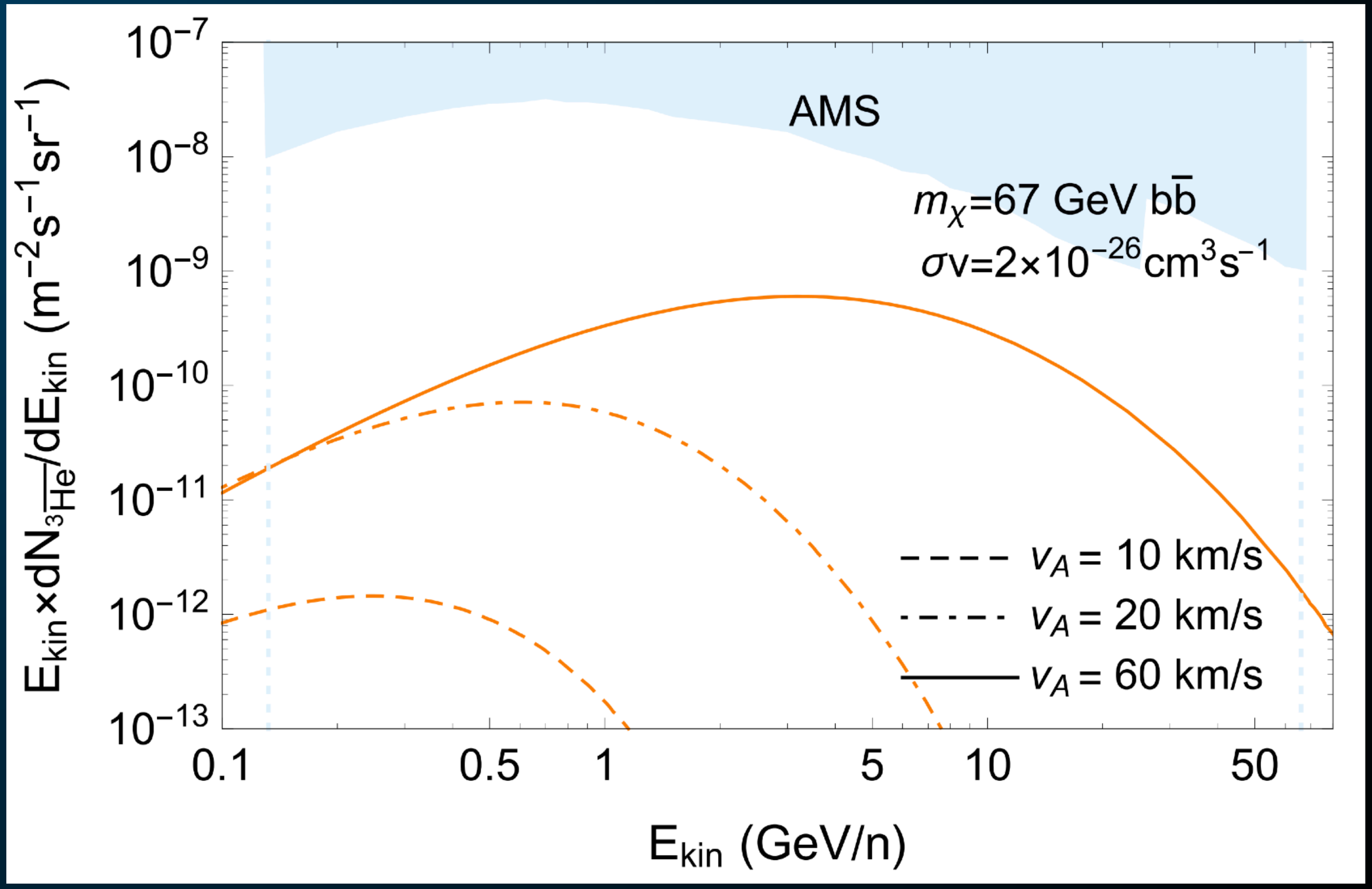
We lose many events because most anti-He are produced at energies that are too small to be detected.

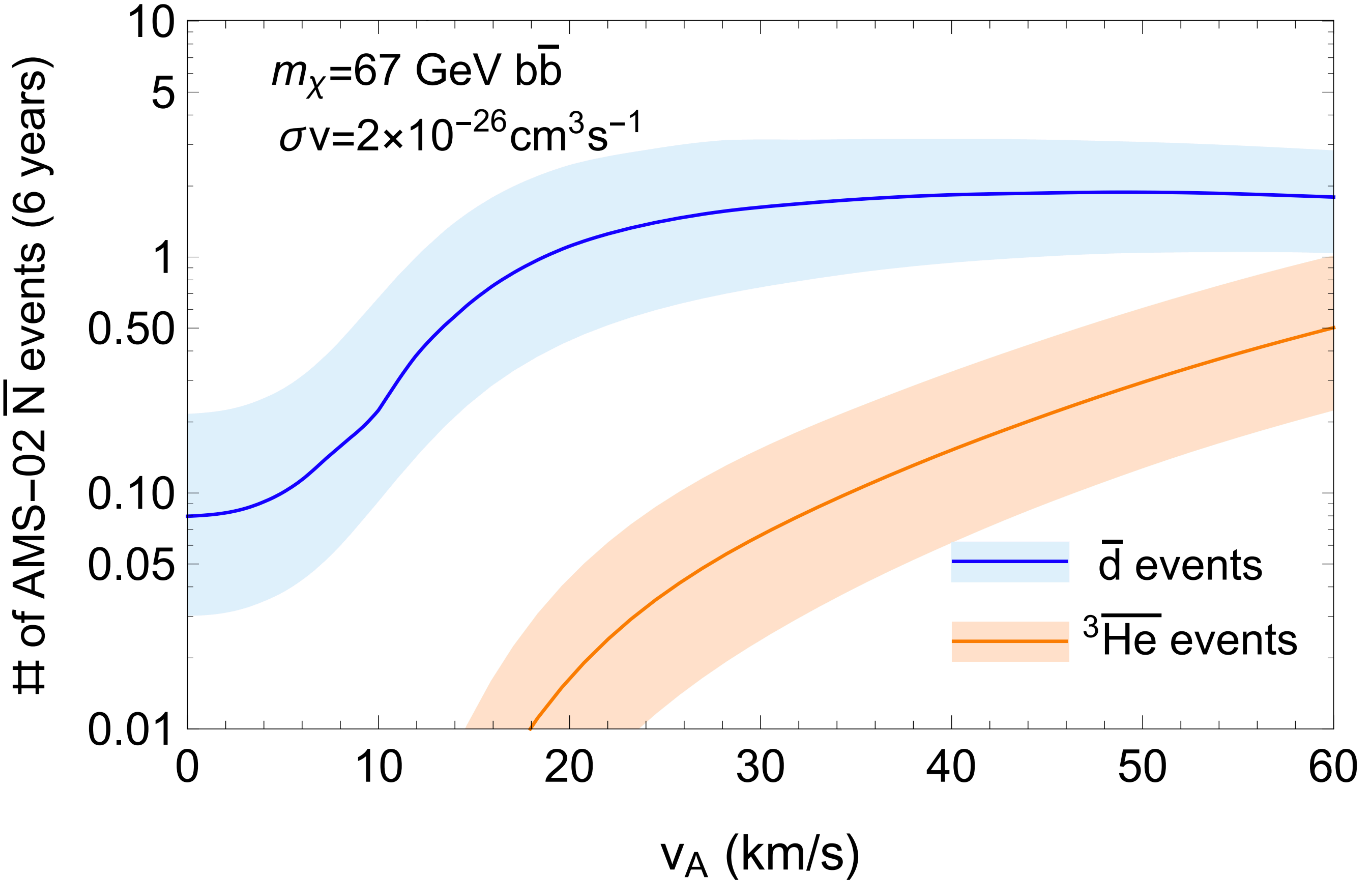
Use re-acceleration to boost the anti-He energies into the detectable range!

$$D_{pp}(R) = \frac{4}{3\delta(2-\delta)(4-\delta)(2+\delta)} \frac{R^2 v_A^2}{D_{xx}(R)}$$

Cholis, Linden, Hooper (2020; 2001.08749)







m_χ=67 GeV b$\bar{b}$
σv=2×10^{-26}cm^{3}s^{-1}
# of AMS−02 $\overline{N}$ events (6 years)
$\bar{d}$ events
$^3\overline{He}$ events
v$_A$ (km/s)
10
5
1
0.50
0.10
0.05
0.01
0
10
20
30
40
50
60

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.

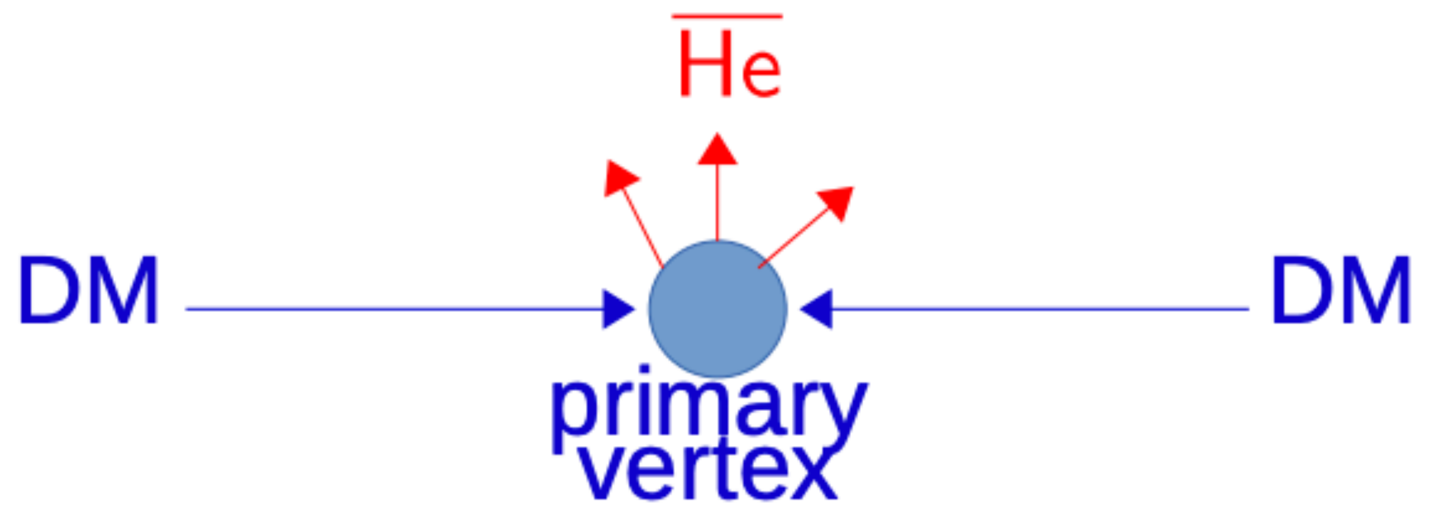
I. INTRODUCTION

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]

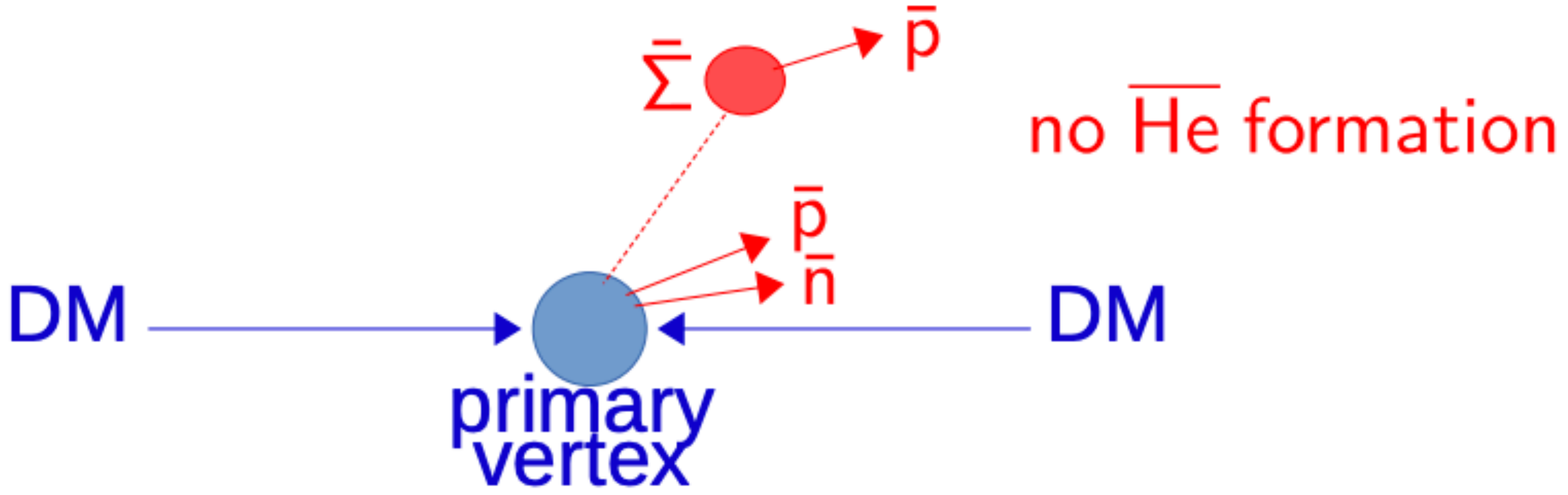
In this *letter*, we challenge the current understanding that standard dark matter annihilation models cannot produce a measurable antihelium flux. Our analysis examines a known, and potentially dominant, antinuclei production mode which has been neglected by previous literature – the production of antihelium 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].

Displaced Antihelium from Dark Matter

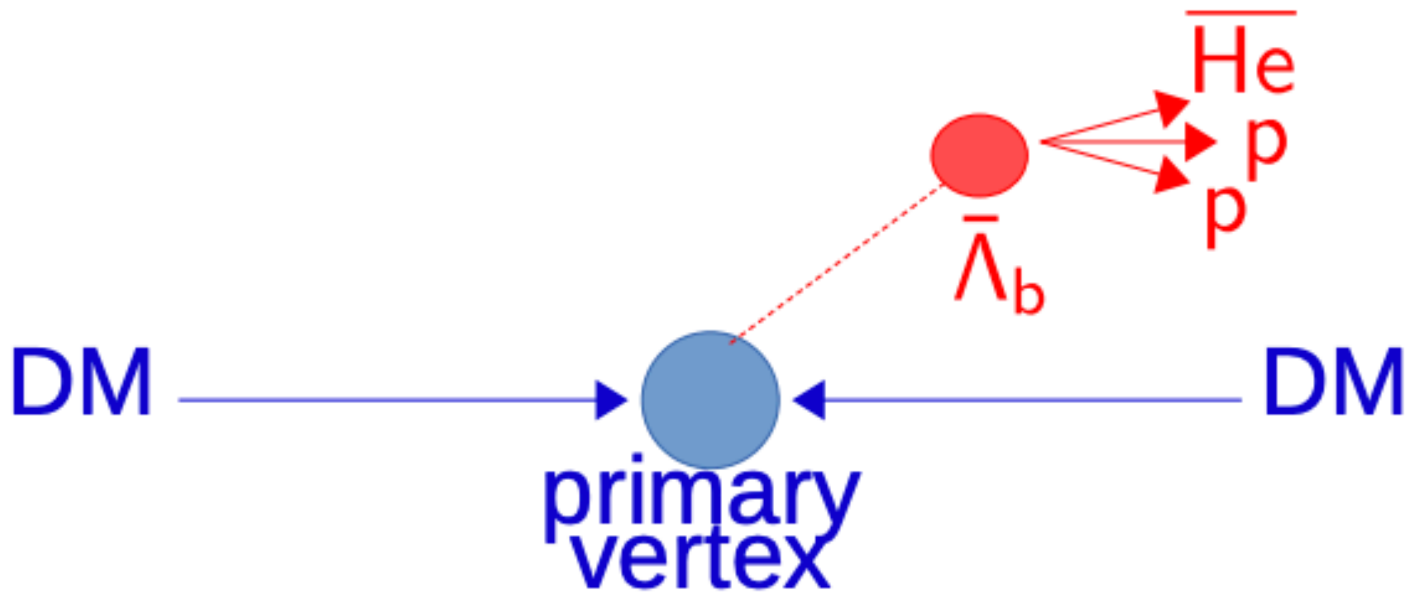
- previous analyses derived $\overline{\text{He}}$ emission by prompt antinucleons



- <u>Idea:</u> prompt antinuc-leons cannot merge with displaced antinucleons



- potentially **dominant** $\overline{\text{He}}$ production mode has been missed

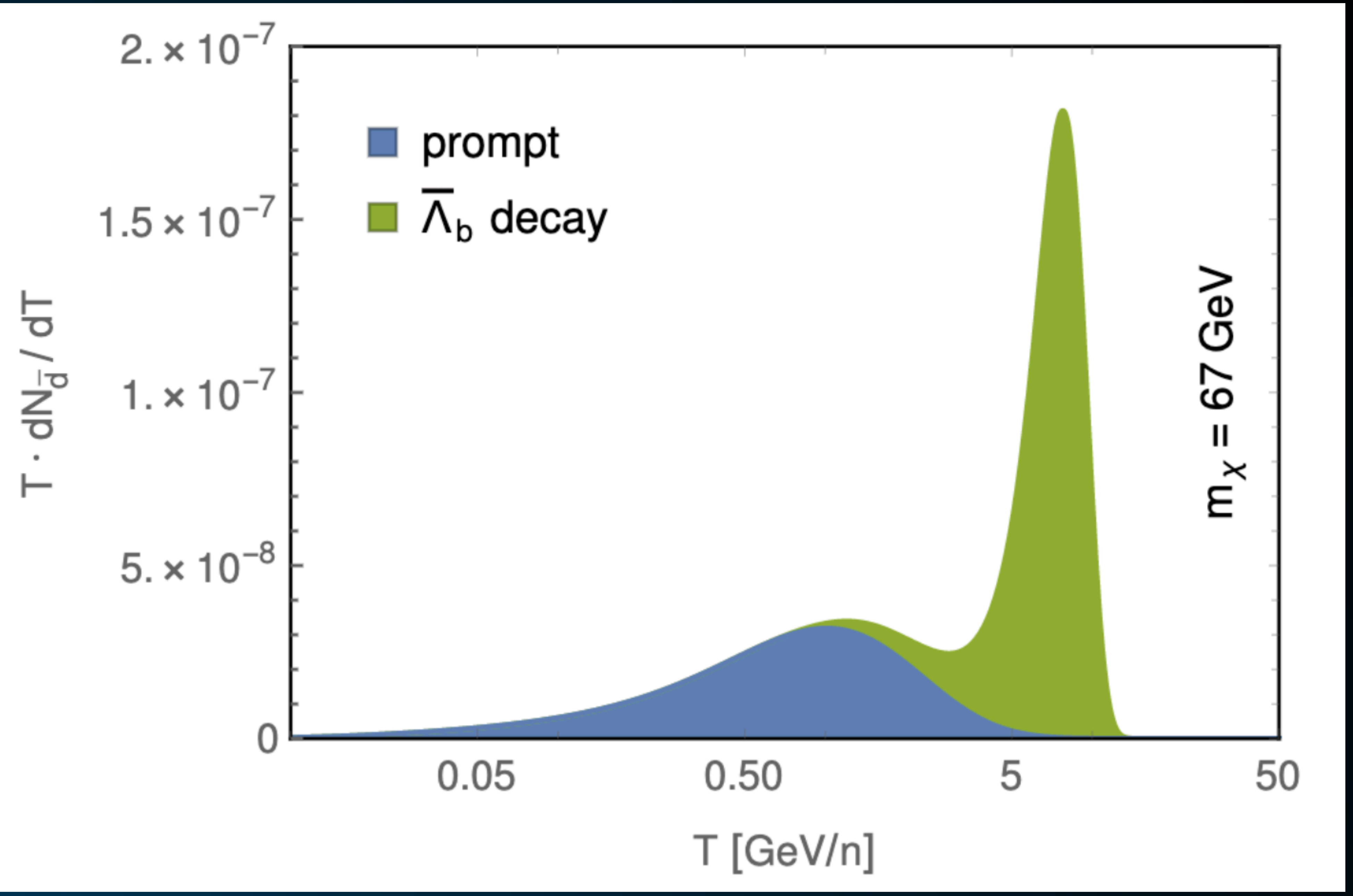


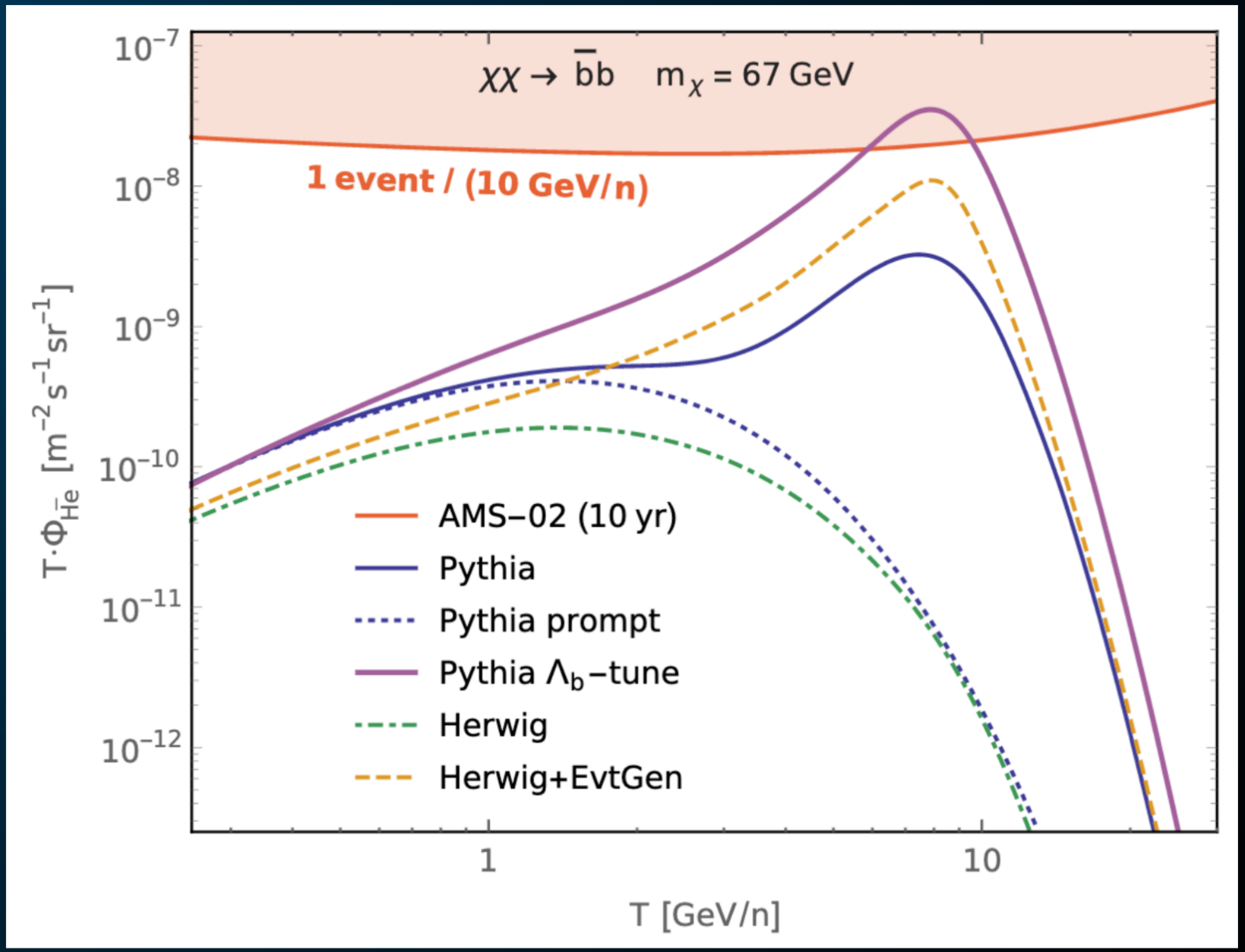
Particle Physics Enhancements!

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

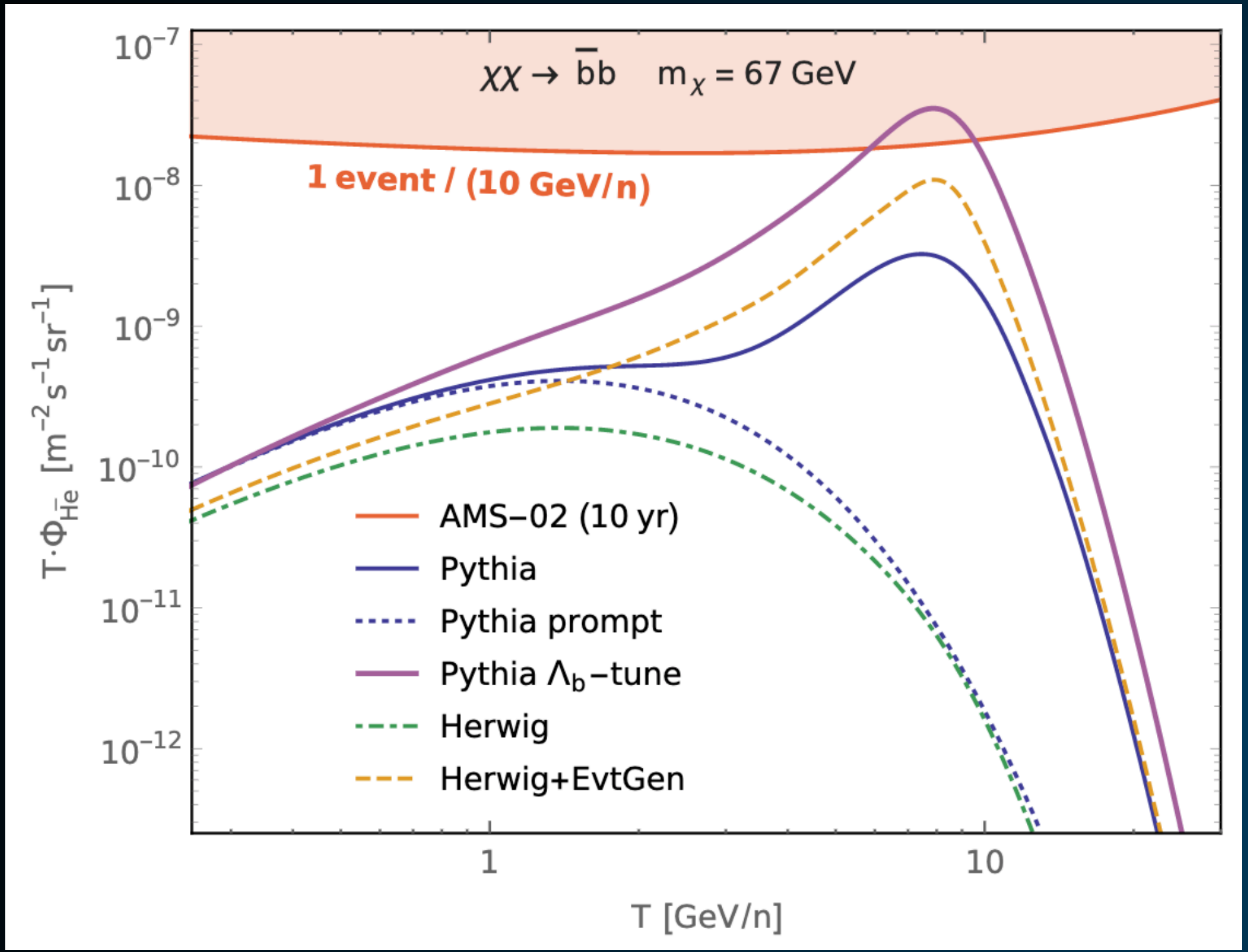
The displaced-vertex decays of Lambda_b baryons potentially boosts the detectable AMS-02 signal by orders of magnitude!

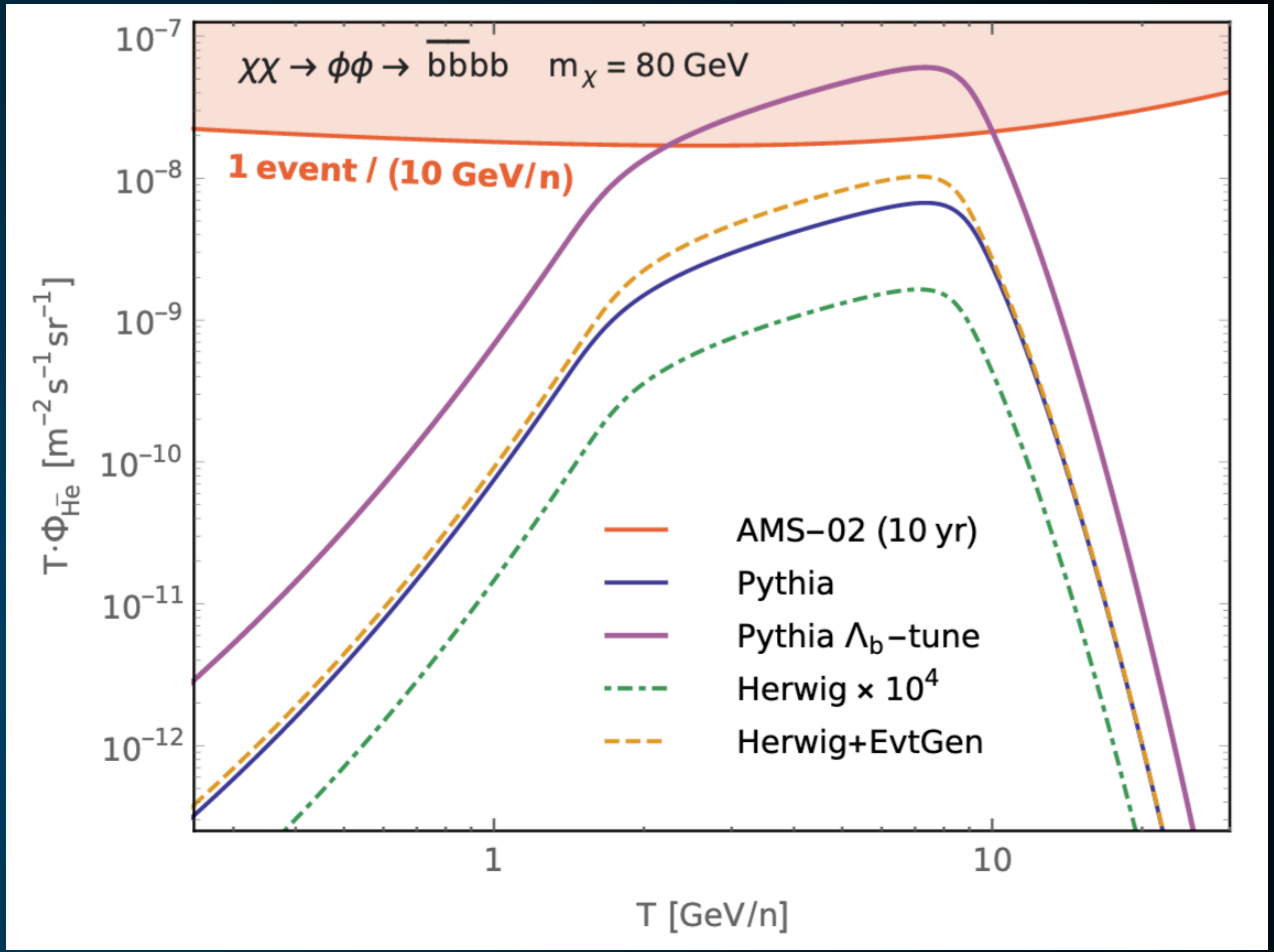
Winkler & Linden (2020; 2020.16251)





Particle Physics Enhancements!

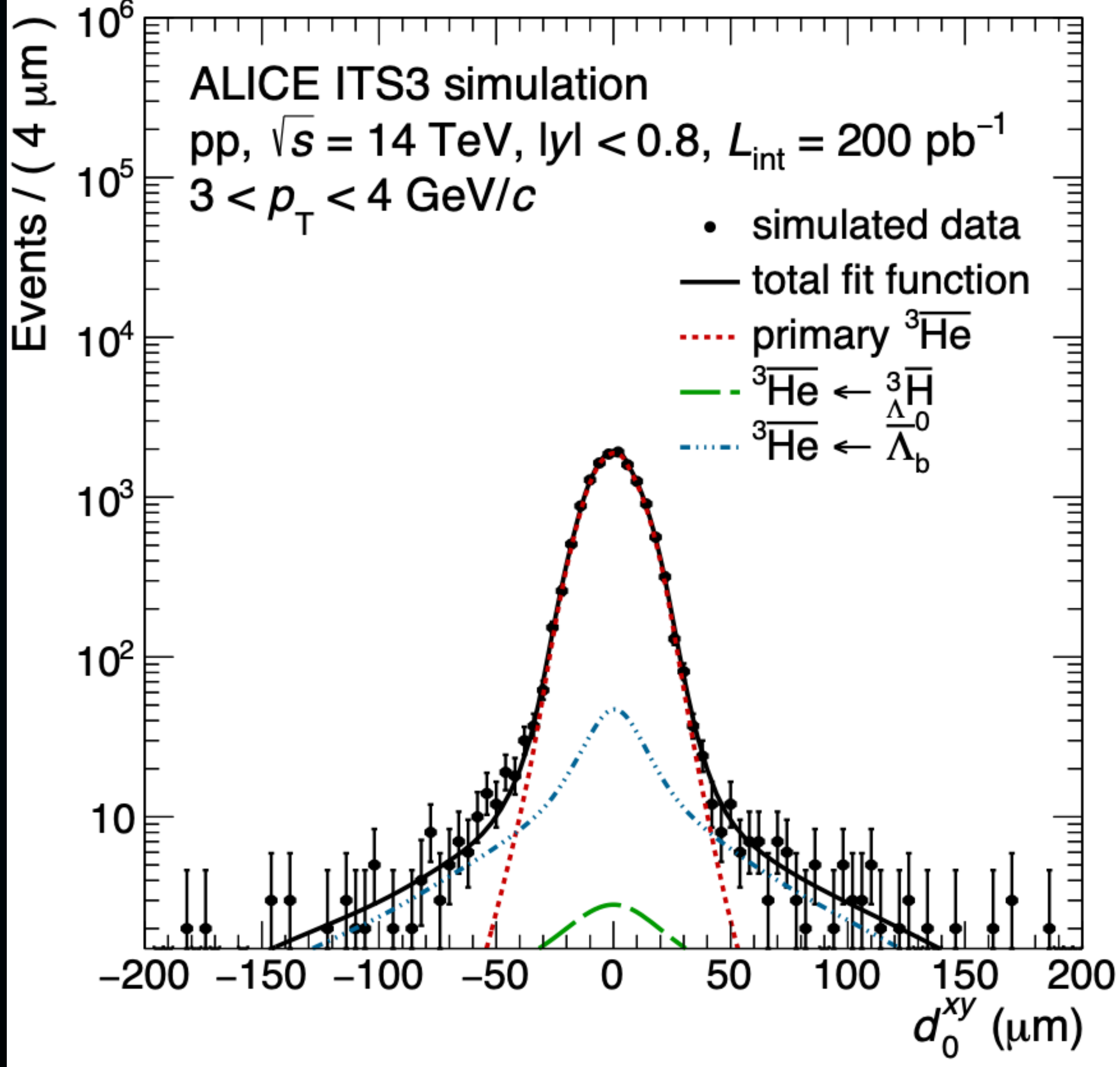


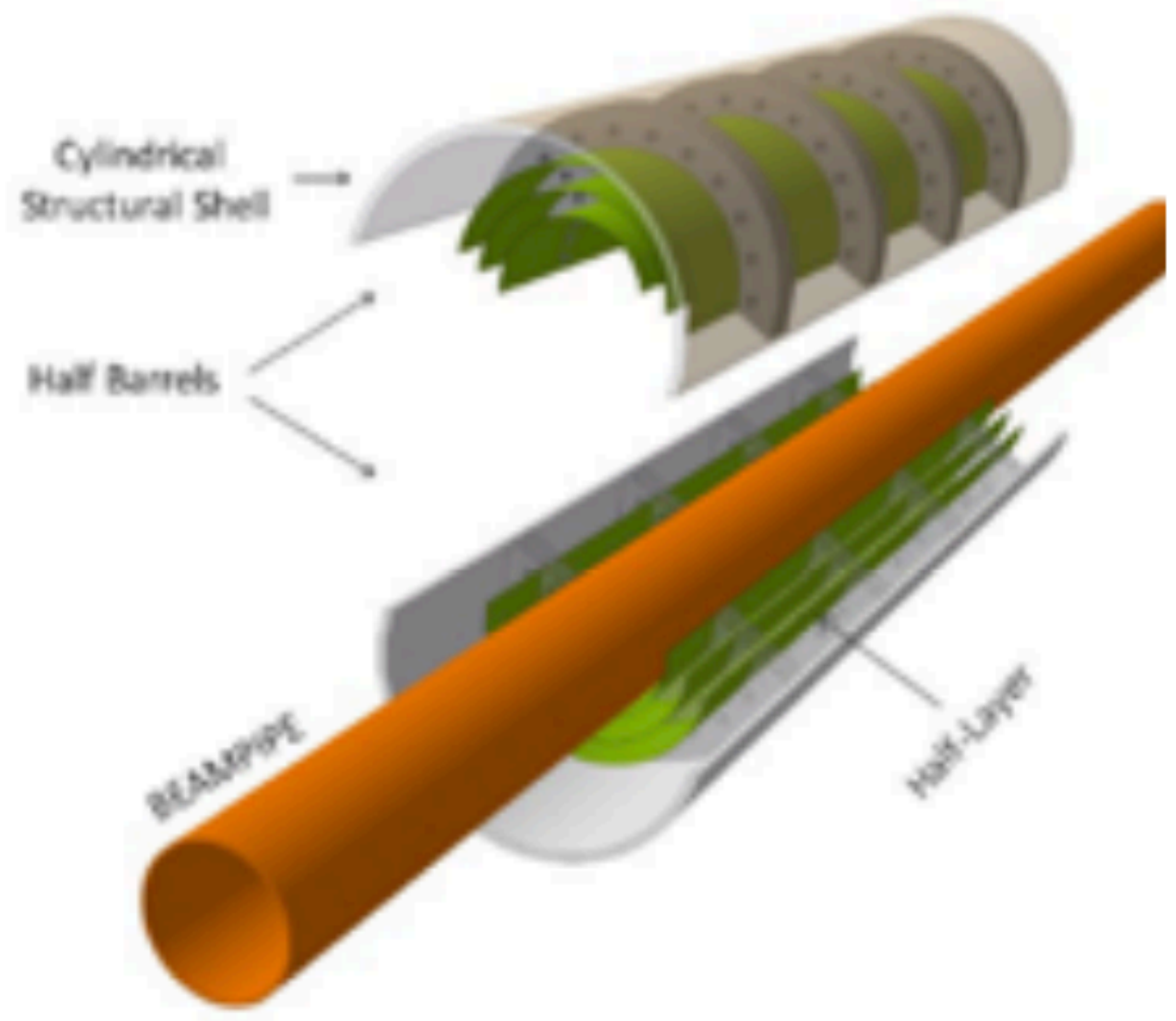


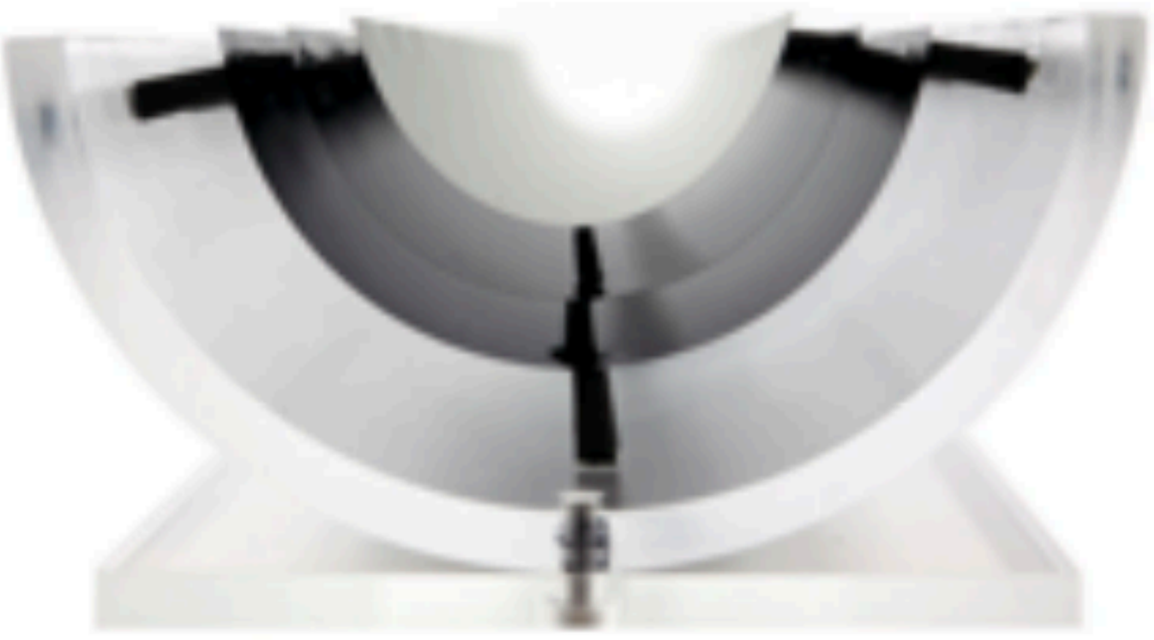
Generator	P	P [Λ_b-tune]	H	H+EvtGen
$^3\overline{\text{He}}$ events	0.1 (0.007)	0.9	0.003	0.3
$\bar{d}$ events	3.7 (3.5)	4.2	1.7	2.1

Winkler & Linden (2020; 2020.16251)

The evolution of the ALICE experiment: ITS3







Engineering model

Replacement of the innermost 3 layers of the ITS2

- Fully cylindrical and almost without support structures and services
- innermost layer is closer to the IP: 22 mm → 18 mm
- less material budget: 0.35% X/X_0 -> 0.05% X/X_0
- Possibly pixel size reduced even further: from (30×30 μm^2) to (15×15 μm^2)

Particle Physics Enhancements!

Major Issues:

1.) Anti-deuterium to Anti-Helium Ratio?

2.) Anti-Helium 4 ??

UCI-TR-2019-14

How to produce antinuclei from dark matter

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We show how to produce antideuteron, antihelium, and other antinuclei in large fractions from the decays of a new particle ϕ that carries baryon number. Close to threshold, the production of nuclear bound states is preferred over the decay into individual nucleons, effectively decoupling antinuclei and antiproton fluxes and allowing the former to dominate, in clear contrast to antimatter production via coalescence. ϕ can either form dark matter itself or be produced by it, and can give rise to a potentially testable amount of antinuclei.

I. INTRODUCTION

Most of our universe is composed of matter, with only a tiny fraction of antimatter produced in highly energetic cosmic events, measured at experiments such as PAMELA [1] and AMS-02 [2]. These experiments also probe Dark Matter (DM) models that can lead to an enhanced number of positron and antiproton events [3], and even antideuteron $\overline{\mathrm{d}}$ has become a promising target [4–6]. Future experiments such as GAPS [7] have the potential to improve these measurements significantly.

Any anomalies in such measurements would be hard to reconcile with known astrophysics and even most physics beyond the Standard Model (SM). This is because heavier antimatter is generally thought to be impossible to produce in such large numbers from astrophysics or DM, owing to the underlying coalescence models that predict a strong hierarchy of antinuclei fluxes and numbers, very roughly given by [8]

conserved, every decay mode of ϕ must contain k antinucleons. For a ϕ mass close to the decay threshold, the outgoing antibaryons will be non-relativistic and will have a significant probability of forming antinuclei with a large mass number $A \leq k$.

We will explore this basic idea and show that we can indeed build models of new physics where a new particle ϕ decays with detectable production rates for antinuclei. We will focus mostly on producing $\overline{\mathrm{d}}$ and $\overline{\mathrm{He}}$ but these models could easily be generalized to the production of other antiparticles.

The rest of this article is organized as follows: in Sec. II we discuss models that lead to $\overline{\mathrm{d}}$ and the possible relation to DM. In Sec. III we perform an analogous discussion for the production of $^3\overline{\mathrm{He}}$ that does not require knowledge of Sec. II. We conclude in Sec. IV. In appendix A we provide a discussion of models that produce $^4\overline{\mathrm{He}}$, which is technically more involved.

Where do the *AMS-02* anti-helium events come from?

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We discuss the origin of the anti-helium-3 and -4 events possibly detected by *AMS-02*. Using up-to-date semi-analytical tools, we show that spallation from primary hydrogen and helium nuclei onto the ISM predicts a $\overline{^3\mathrm{He}}$ flux typically one to two orders of magnitude below the sensitivity of *AMS-02* after 5 years, and a $\overline{^4\mathrm{He}}$ flux roughly 5 orders of magnitude below the *AMS-02* sensitivity. We argue that dark matter annihilations face similar difficulties in explaining this event. We then entertain the possibility that these events originate from anti-matter-dominated regions in the form of anti-clouds or anti-stars. In the case of anti-clouds, we show how the isotopic ratio of anti-helium nuclei might suggest that BBN has happened in an inhomogeneous manner, resulting in anti-regions with a anti-baryon-to-photon ratio $\bar{\eta} \simeq 10^{-3}\eta$. We discuss properties of these regions, as well as relevant constraints on the presence of anti-clouds in our Galaxy. We present constraints from the survival of anti-clouds in the Milky-Way and in the early Universe, as well as from CMB, gamma-ray and cosmic-ray observations. In particular, these require the anti-clouds to be almost free of normal matter. We also discuss an alternative where anti-domains are dominated by surviving anti-stars. We suggest that part of the unindentified sources in the 3FGL catalog can originate from anti-clouds or anti-stars. *AMS-02* and *GAPS* data could further probe this scenario.

I. INTRODUCTION

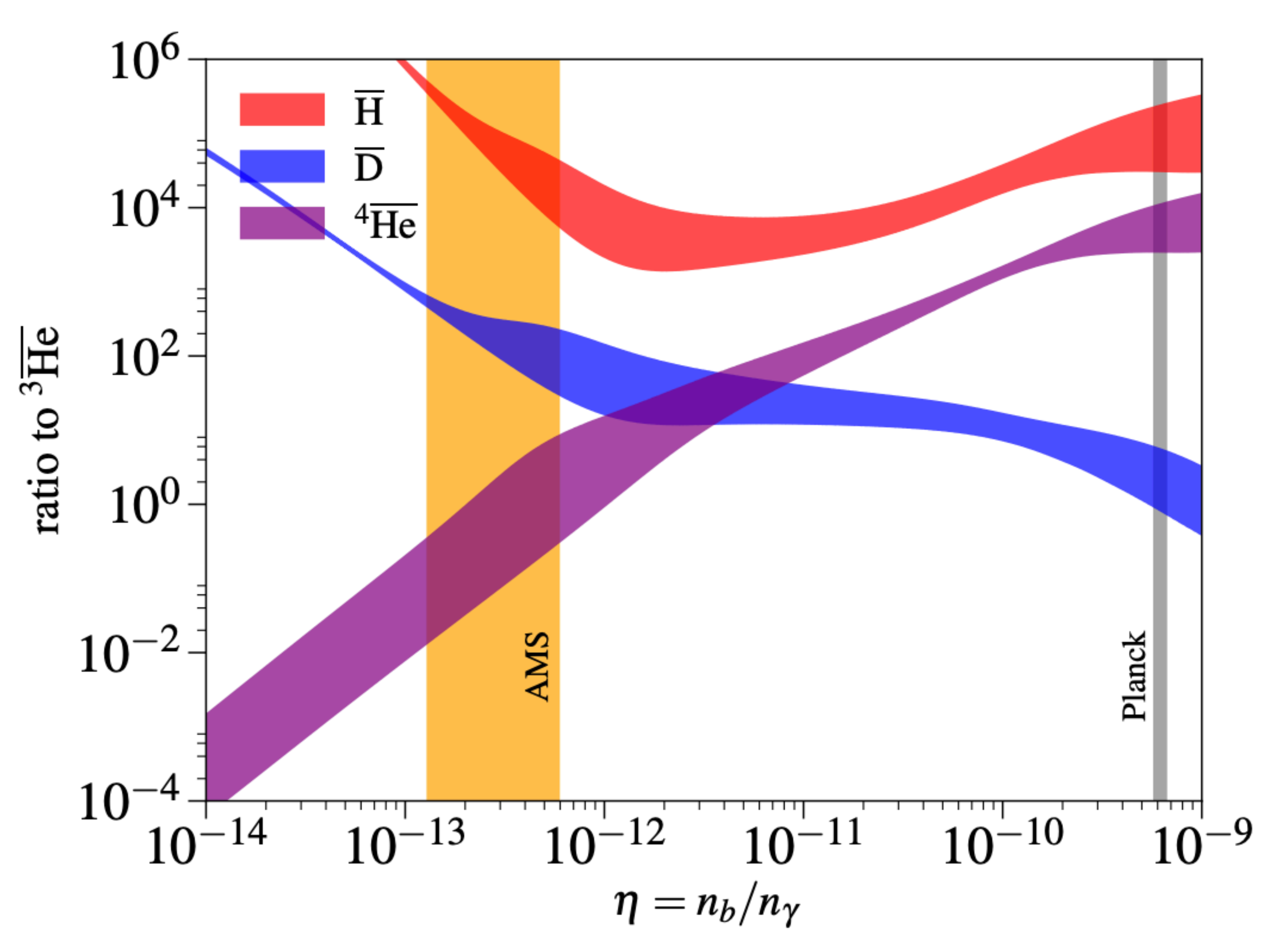
ment of the anti-helium nuclei CR flux is a very promising

Anti-Chemistry?

<u>**Major Issues:**</u>

1.) Anti-Stars or Anti-Gas can undergo nuclear and chemical processes that make the Anti-baryon ratios more similar.

2.) How are these regions separated from the matter of our universe?



Anihelium flux from antimatter globular cluster

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Abstract

Macroscopic cosmic antimatter objects are predicted in baryon asymmetrical Universe in the models of strongly nonhomogeneous baryosynthesis. We test the hypothesis of the existence of an old globular cluster of anti-stars in the galactic halo by evaluating the flux of helium anti-nuclei in galactic cosmic rays. Due to the symmetry of matter and antimatter we assume that the antimatter cluster evolves in a similar way as a matter cluster. The energy density of antiparticles in galactic cosmic rays from antimatter globular cluster is estimated. We propose a method for the propagation of a flux of antinuclei in a galactic magnetic field from the globular cluster of antistars in the Galaxy.

Conclusions

If AMS-02 results are not wrong, we have some major model building problems/opportunities.