Tim Linden

Excesses in Cosmic-Ray Antinuclei

Stockholms universitet

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

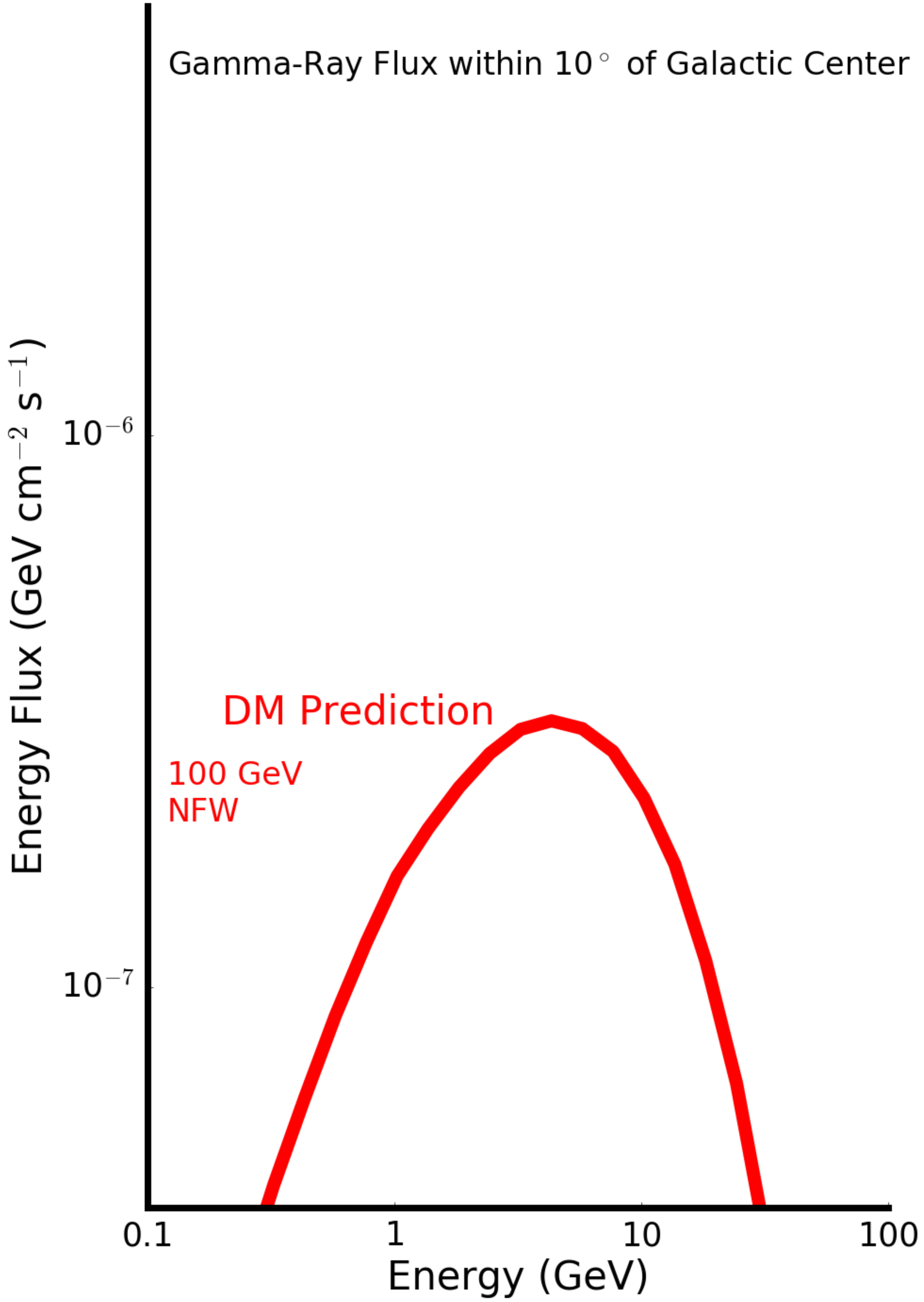
Thermal WIMPs and the Story of Tantalus

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)

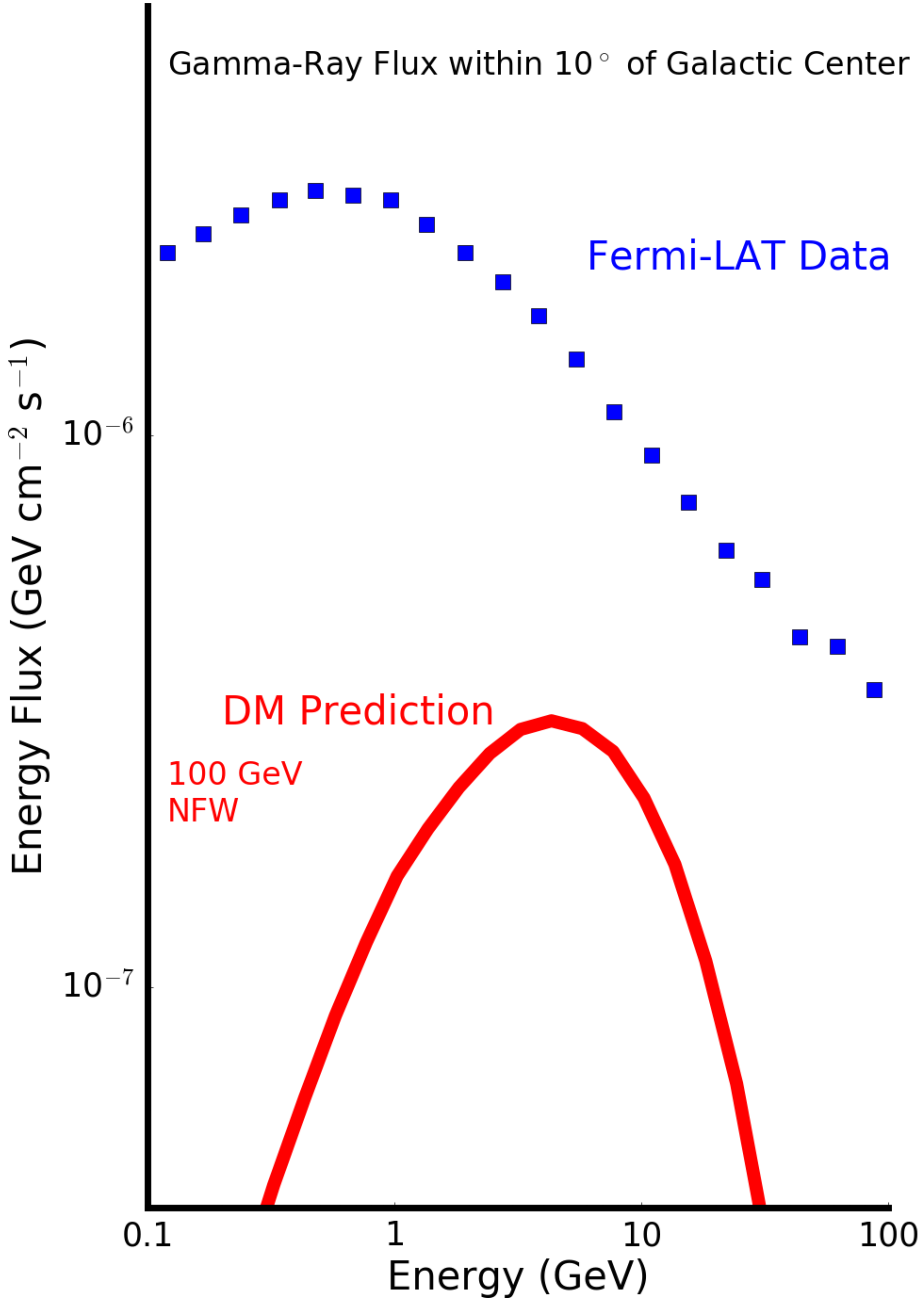
Dark Matter Mass (?)

Annihilation Final State (?)

Milky Way Star-Formation Rate (Galactic Dynamics)

Diffusion Constant in Galactic Center (Hydrodyanmics)

Activity of Supermassive Blackhole (?)



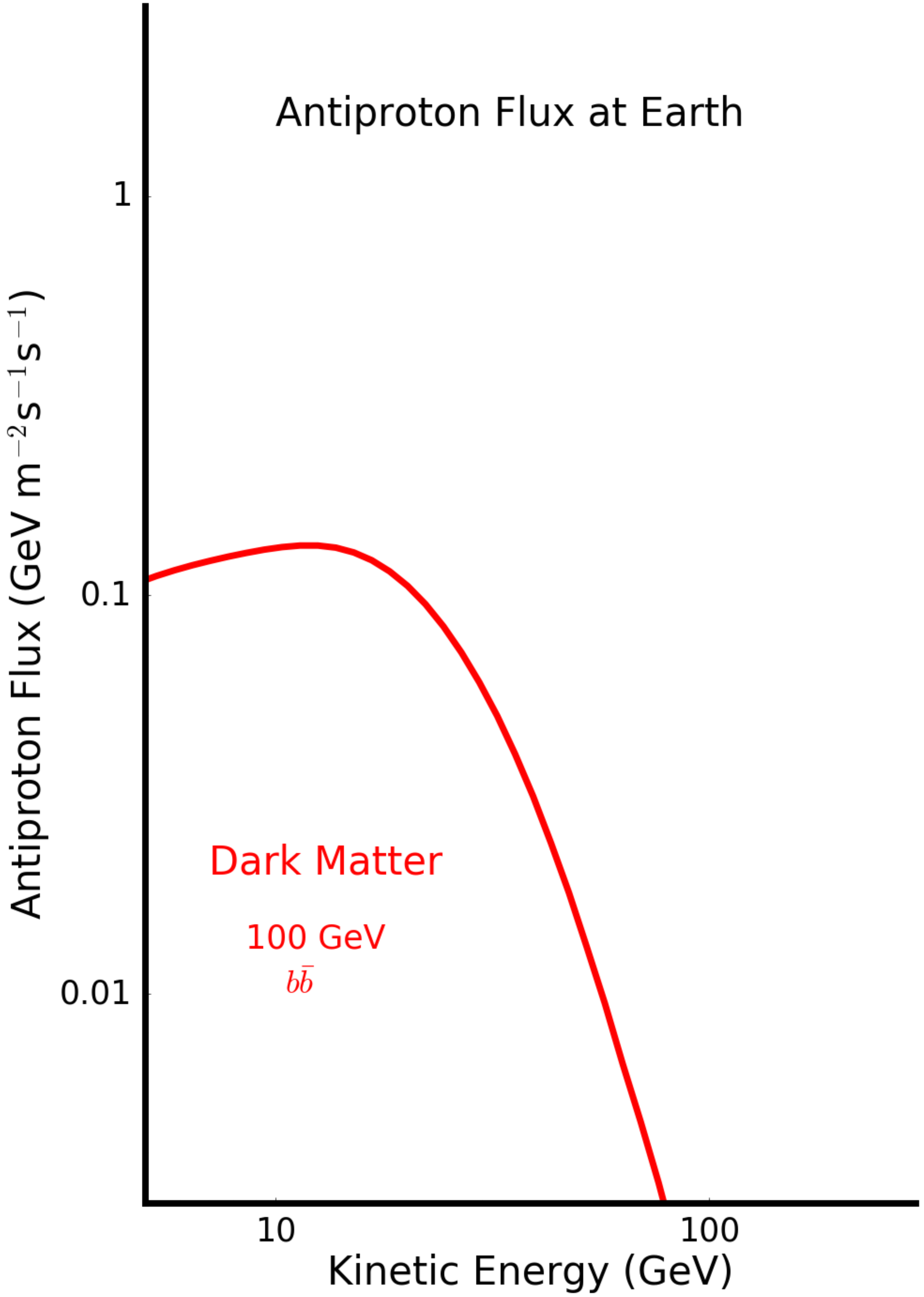
Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

Thermal Cross-Section (Early Universe)

Dark Matter Mass (?)

Convection of Annihilation Products from GC (Winds?)



Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

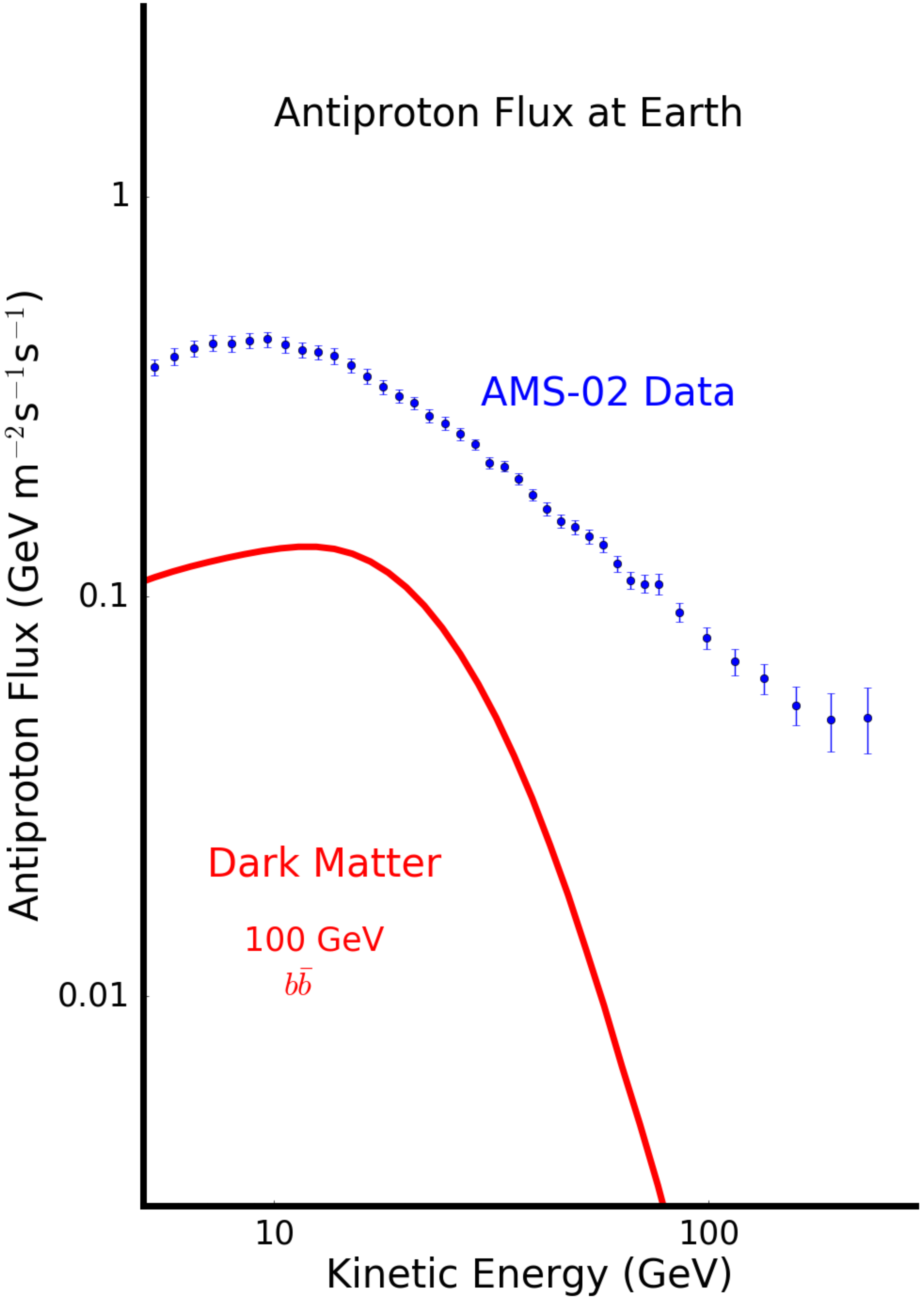
Thermal Cross-Section (Early Universe)

Hadronic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Local Gas Density

Local Supernova Rate



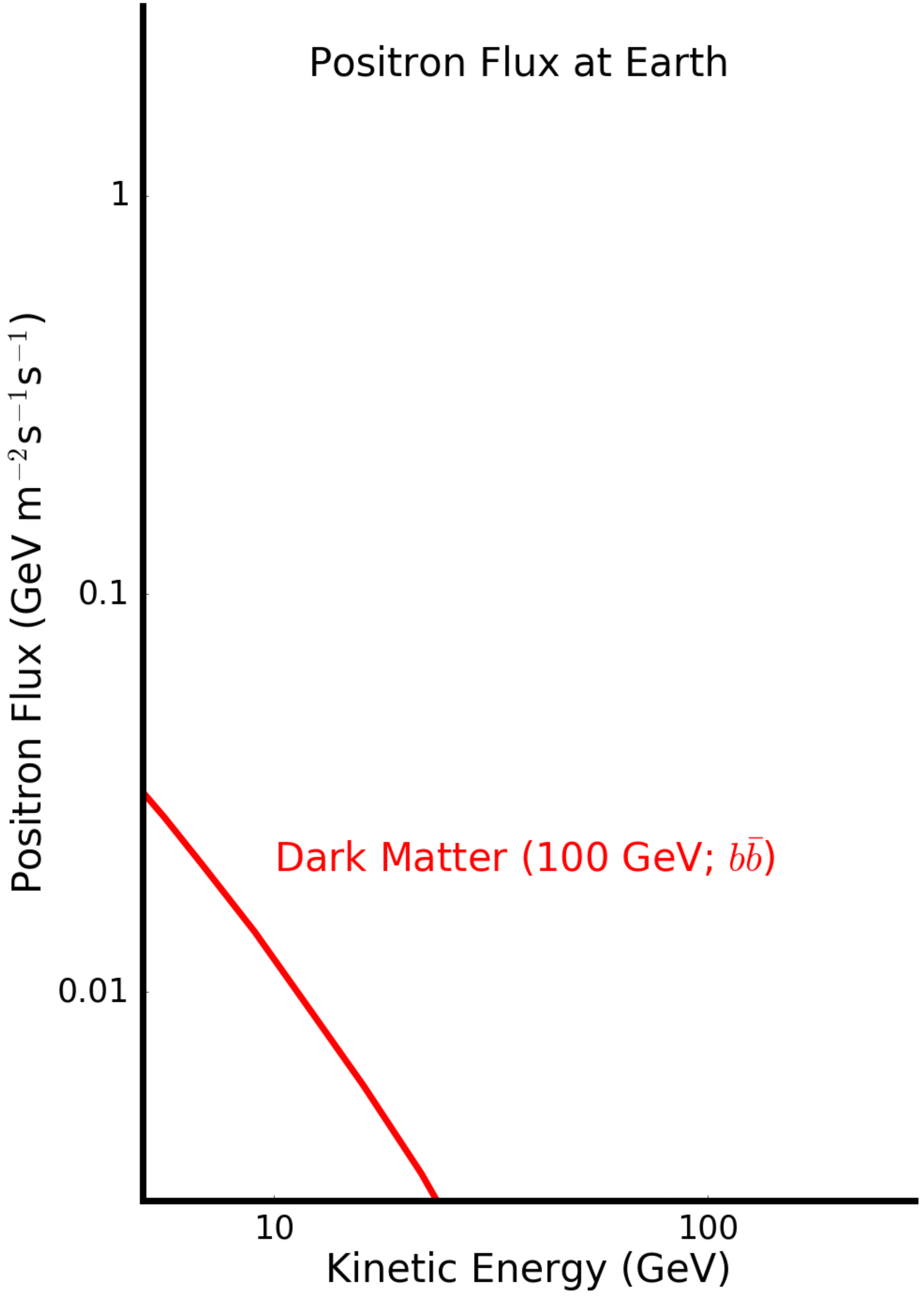
Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

Thermal Cross-Section (Early Universe)

Leptonic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)



Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

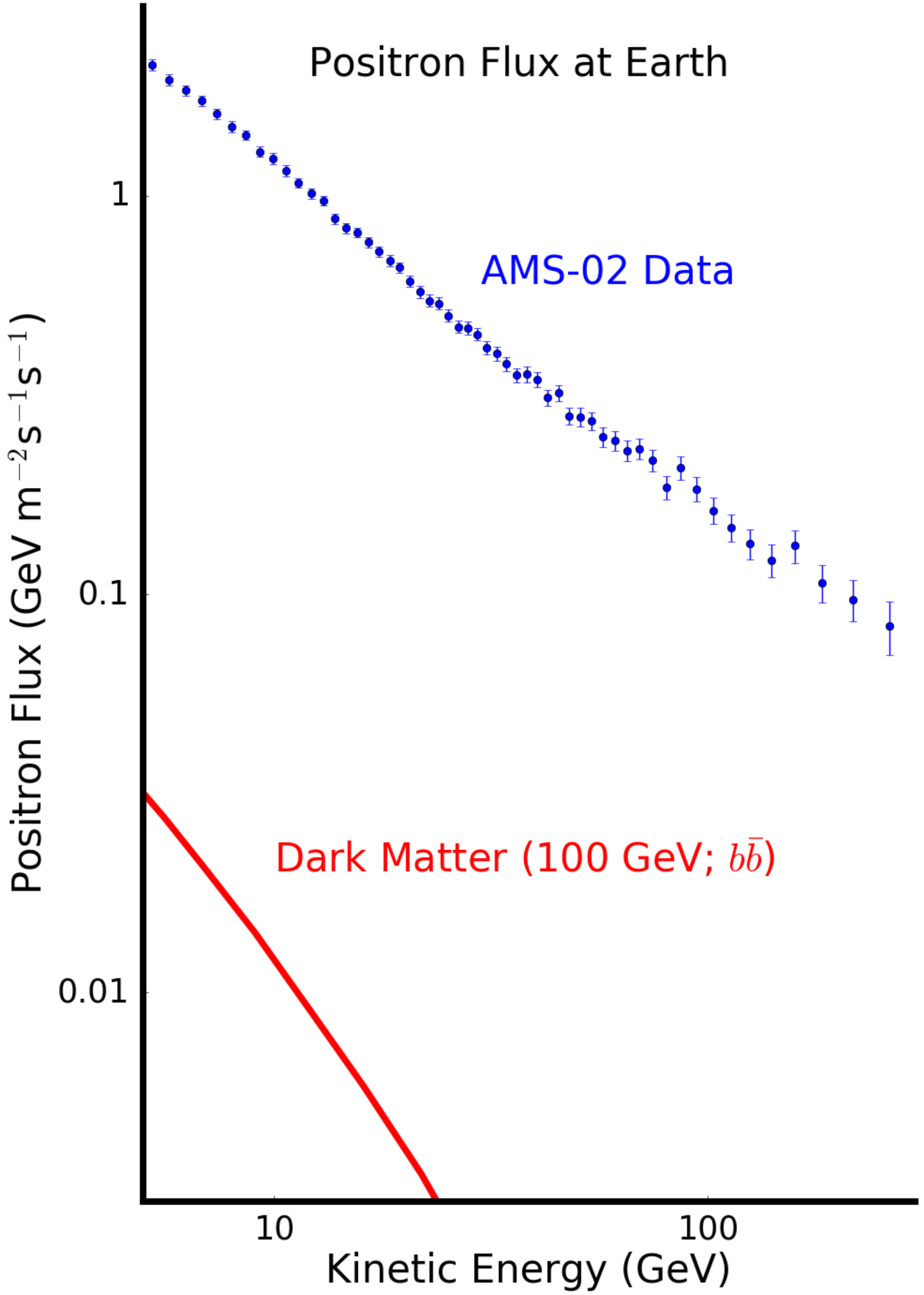
Thermal Cross-Section (Early Universe)

Leptonic Component of Dark Matter Final State

Convection of Annihilation Products from GC (Winds?)

Pulsar Birth Rate

e^+e^- Acceleration Efficiency in Pulsar Magnetospheres



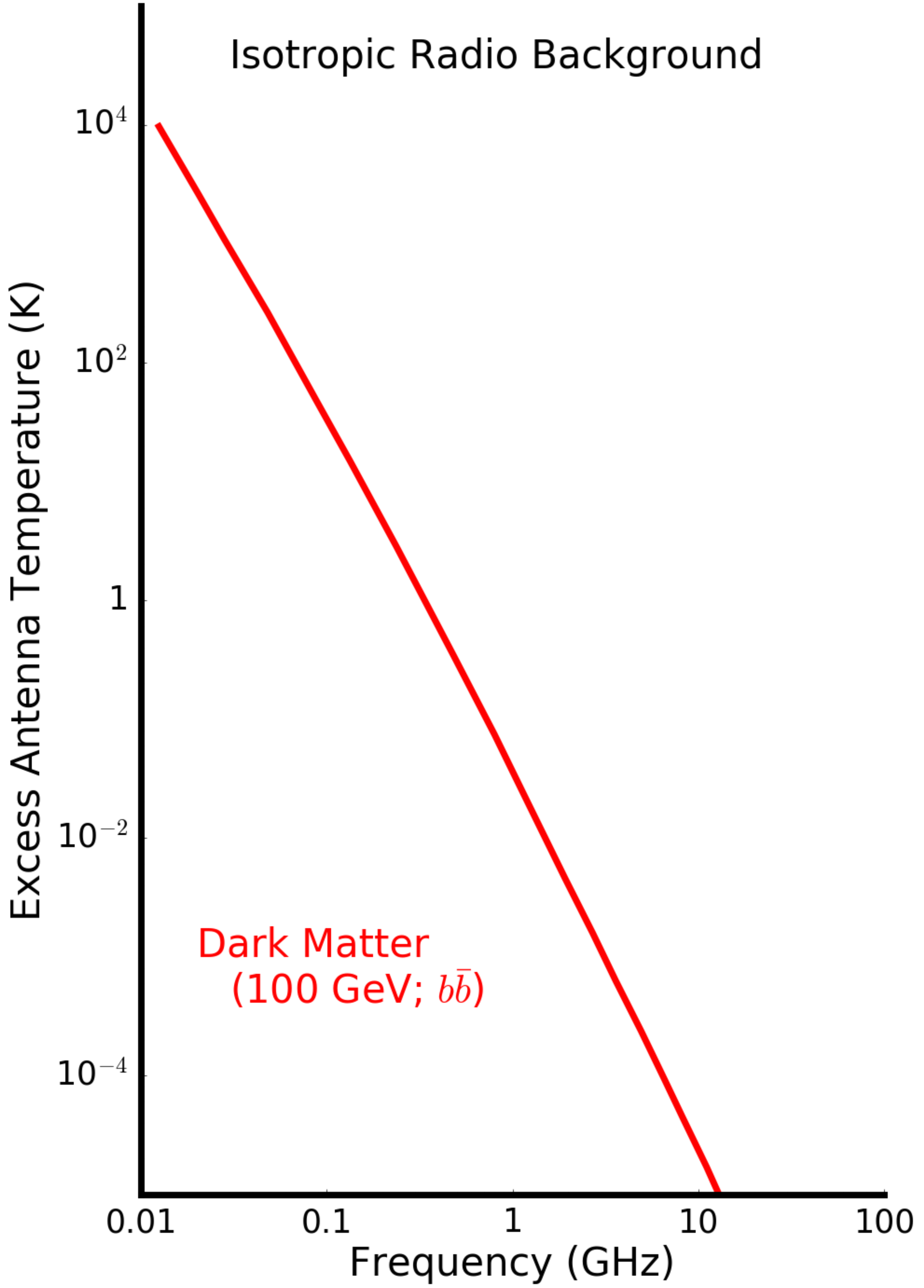
Thermal WIMPs and the Story of Tantalus

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)

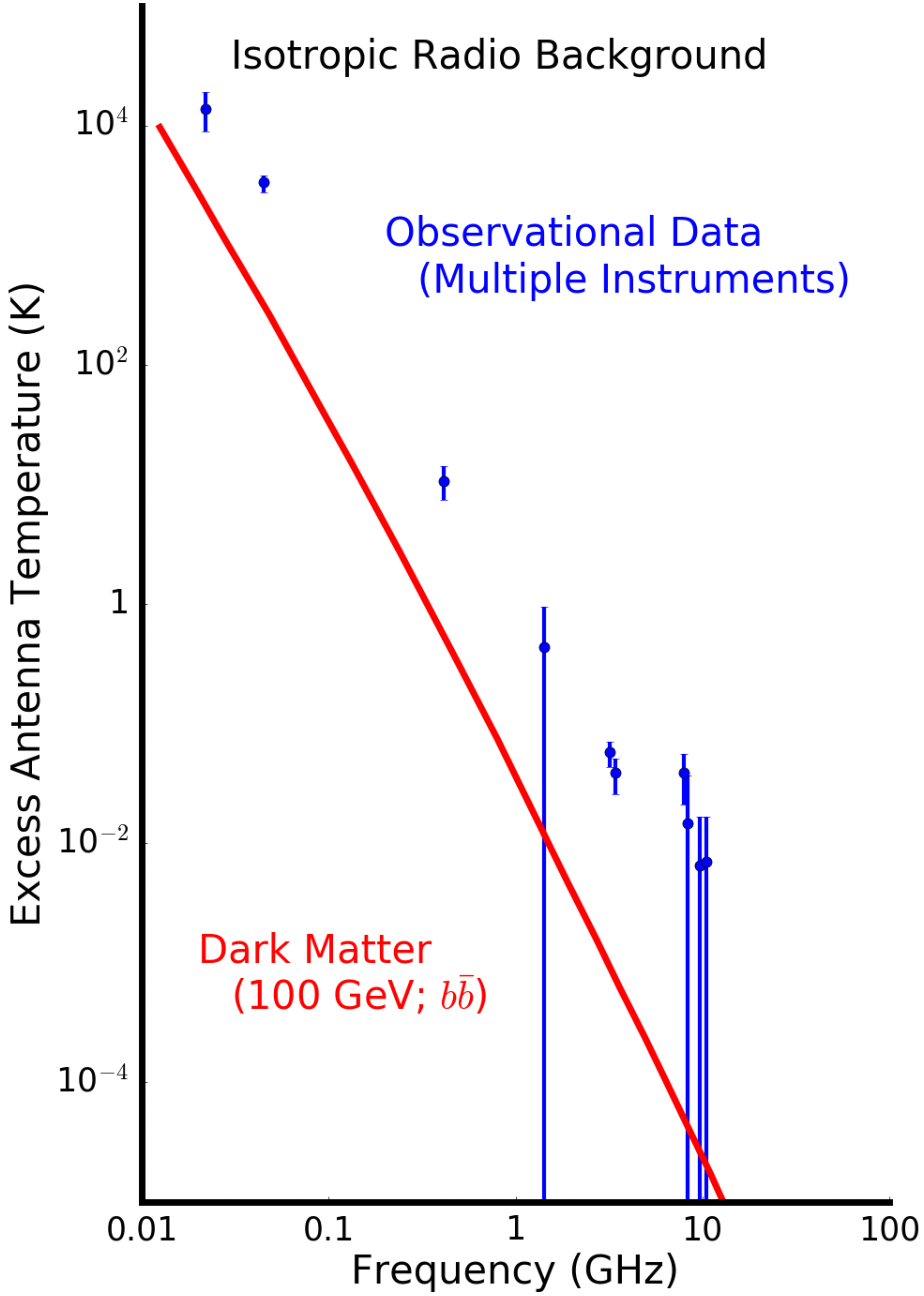
e+e- Energy Fraction in Dark Matter Annihilation

Intergalactic Magnetic Fields

Radio Luminosity in Starbursts and AGN

e+e- Reacceleration in Cluster Mergers

Redshift Dependence of Signal vs. CMB



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,§]

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[3] Department of Physics, 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.


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

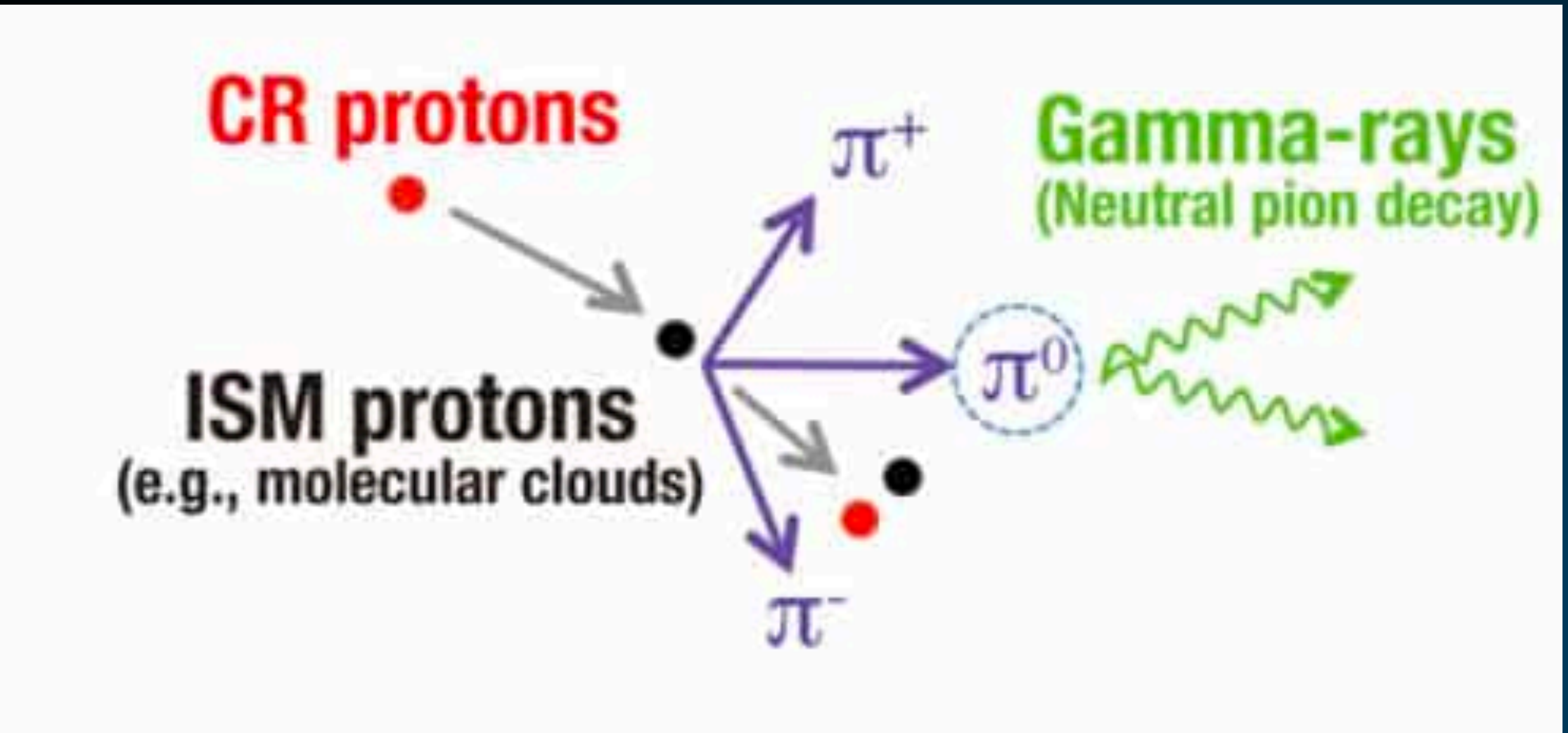

Small Dark Matter Signal
Small Astrophysical Background
Large Dark Matter Signal
Small Astrophysical Background
Easy
Hard
Small Dark Matter Signal
Large Astrophysical Background
Large Dark Matter Signal
Large Astrophysical Background
Specificity (DM Flux / Astrophysics Flux)
Fraction of Dark Matter Flux

Small Dark Matter Signal
Small Astrophysical Background
Large Dark Matter Signal
Small Astrophysical Background
Easy
Easy
Hard
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
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


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

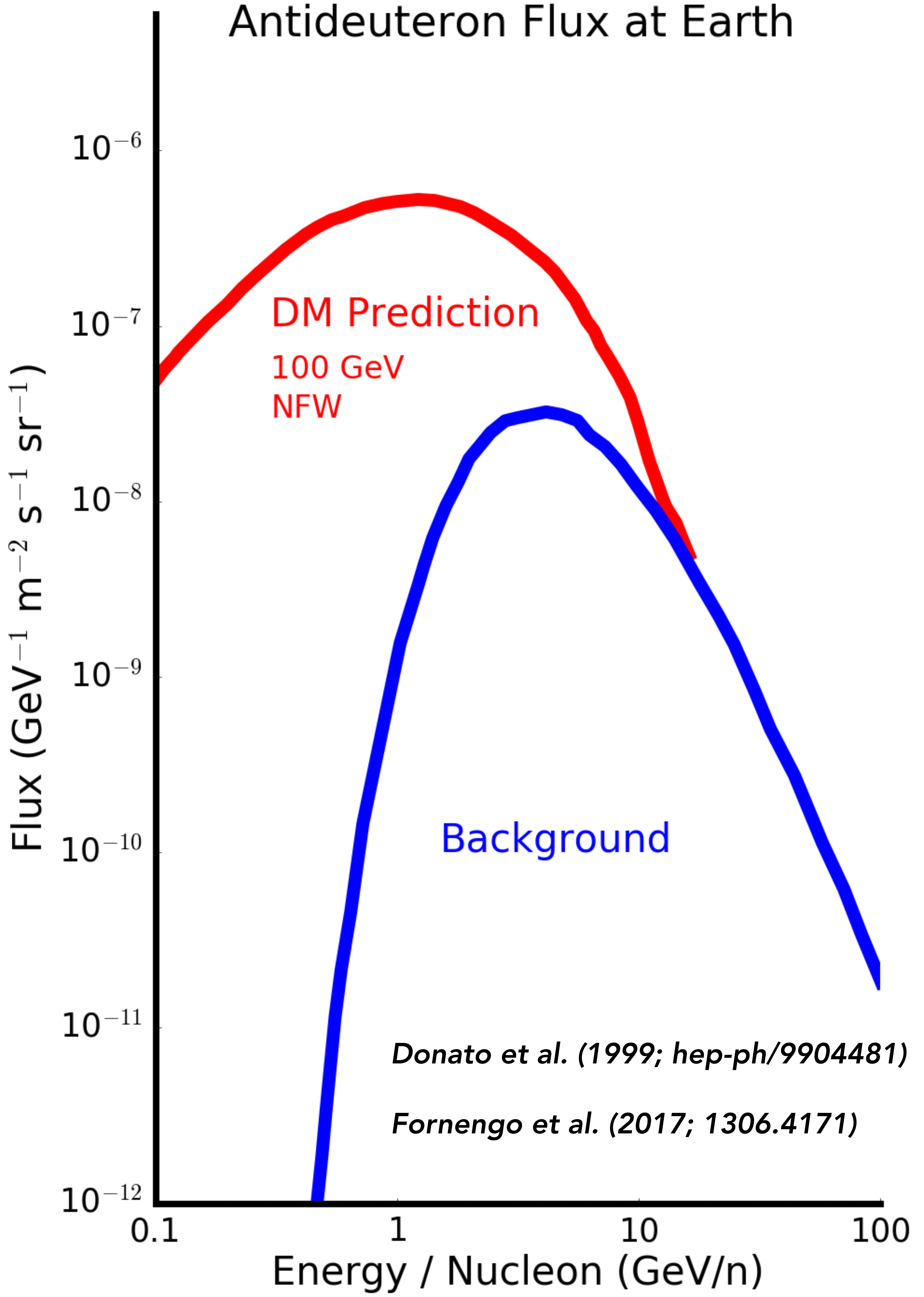
AntiNuclei: A Clean Search Strategy



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

Astrophysical Antinuclei - Most be moving relativistically!

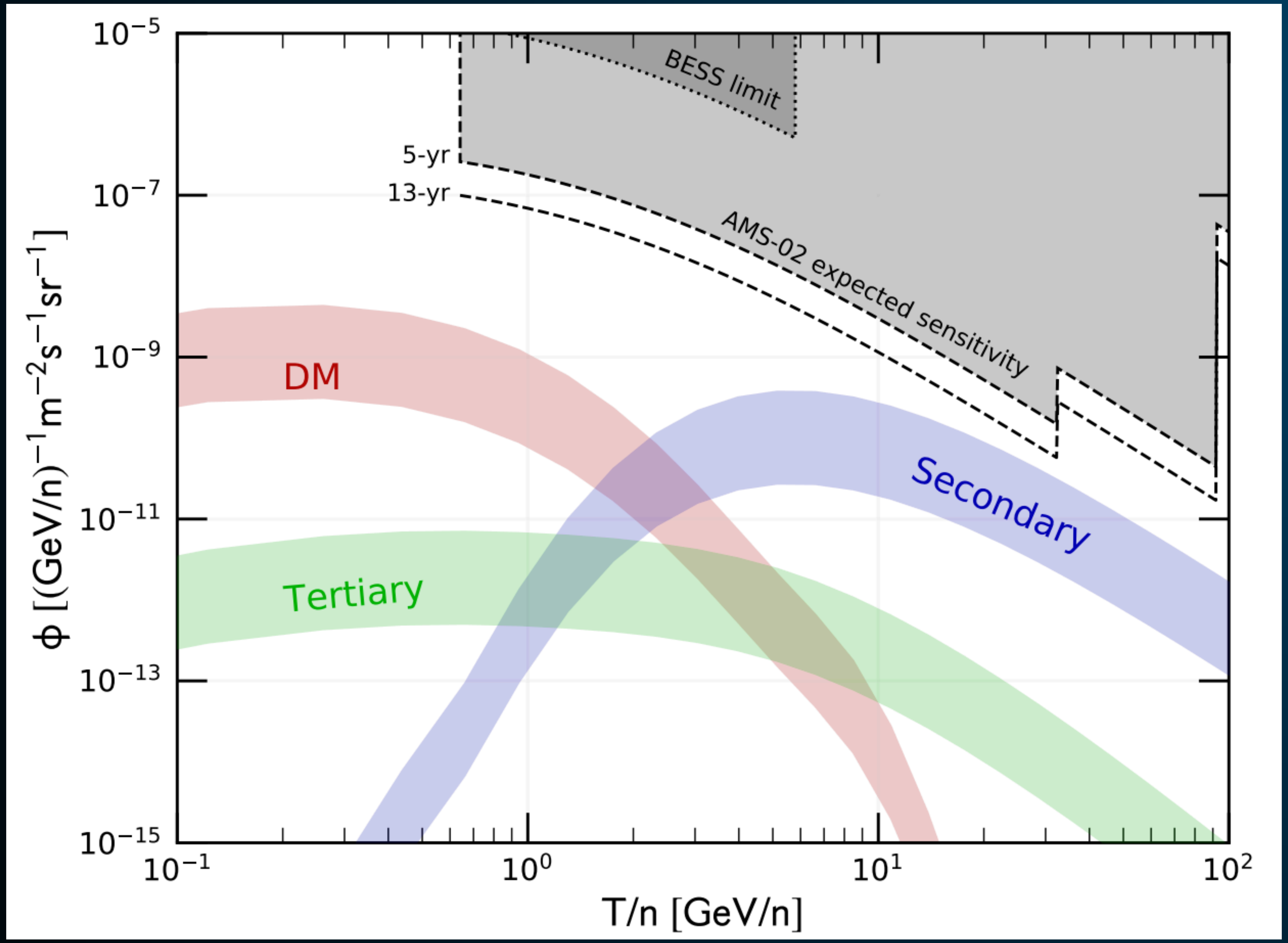
Dark Matter Antinuclei - Can be slow!



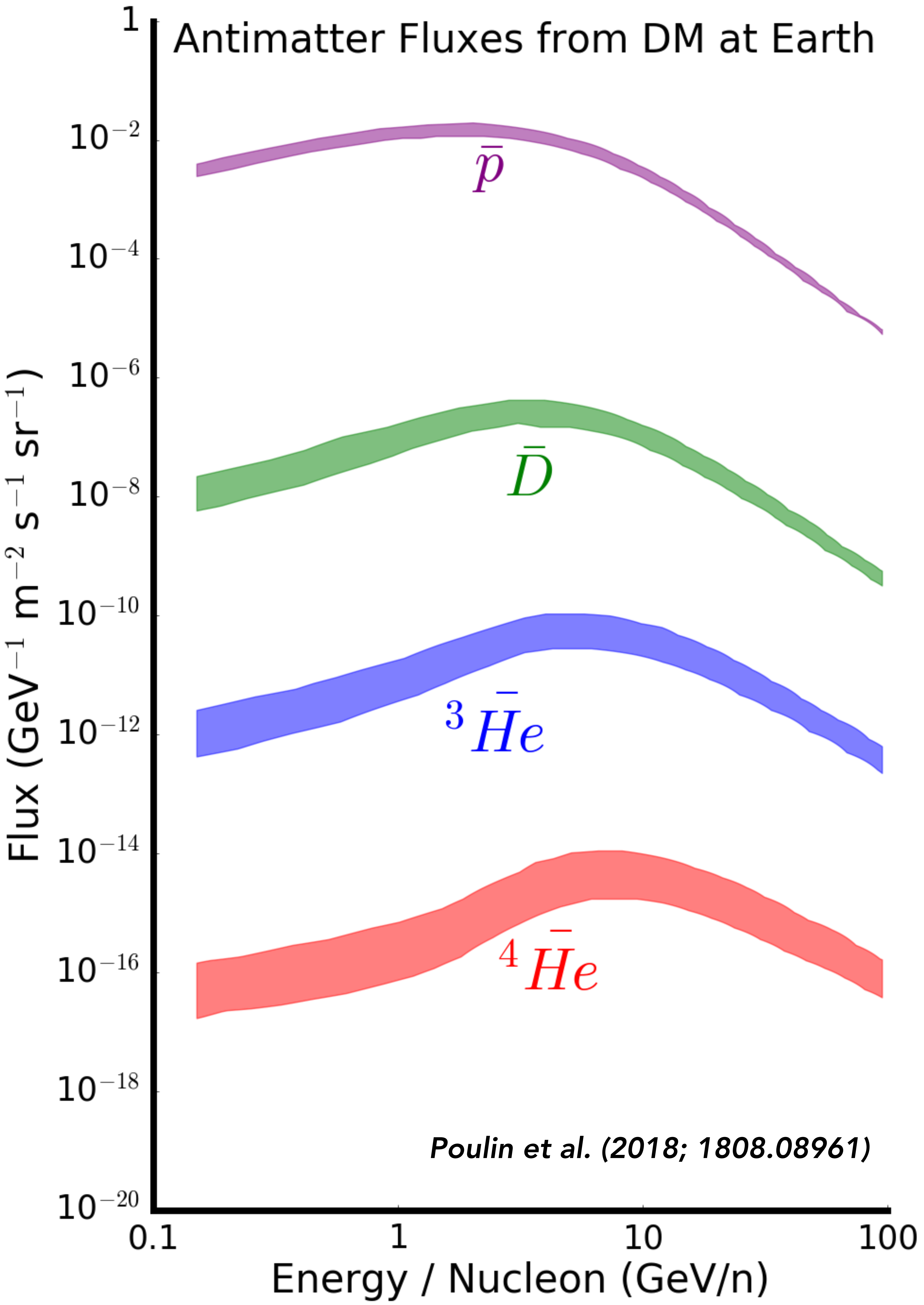
AntiNuclei: A Clean Search Strategy

Antihelium background even cleaner than antideuterons

But the flux is supposed to be <u>much</u> smaller.



Korsmeier (2017; 1711.08465)



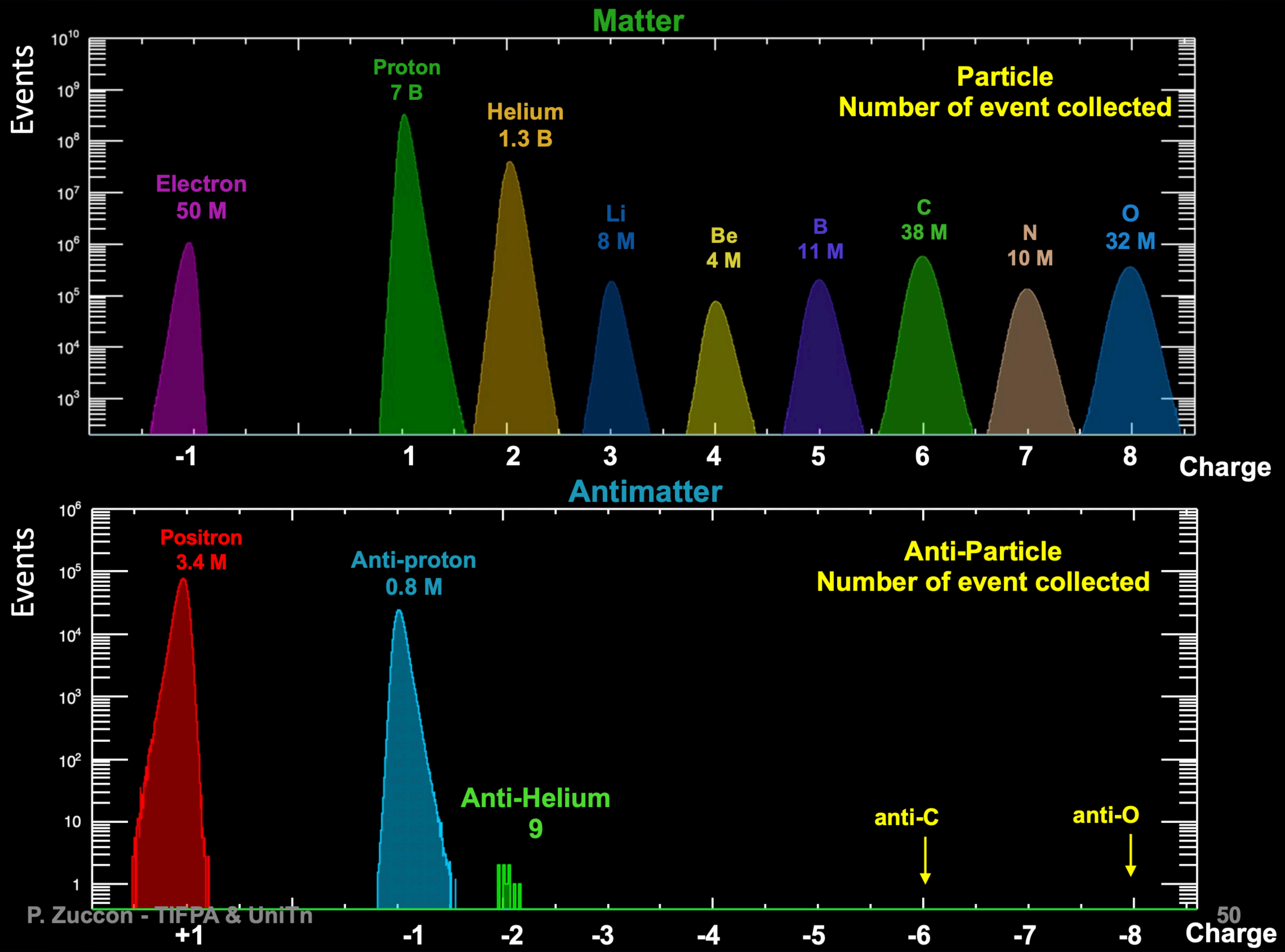
Tentative Evidence for Antinuclei

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)



Matter
Events
Particle
Number of event collected
Electron
50 M
Proton
7 B
Helium
1.3 B
Li
8 M
Be
4 M
B
11 M
C
38 M
N
10 M
O
32 M
Charge
Antimatter
Anti-Particle
Number of event collected
Positron
3.4 M
Anti-proton
0.8 M
Anti-Helium
9
anti-C
anti-O

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

Vivian Poulin,[1] Pierre Salati,[2] Ilias Cholis,[3,1] Marc Kamionkowski,[1] and Joseph Silk[1,4,5]

[1] *Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA*
[2] *LAPTh, Université Savoie Mont Blanc & CNRS, 74941 Annecy Cedex, France*
[3] *Department of Physics, Oakland University, Rochester, MI 48309, USA*
[4] *Sorbonne Universités, UPMC Univ. Paris 6 et CNRS, UMR 7095, Institut dAstrophysique de Paris, 98 bis bd Arago, 75014 Paris, France*
[5] *Beecroft Institute of Particle Astrophysics and Cosmology, Department of Physics, University of Oxford, Denys Wilkinson Building, 1 Keble Road, Oxford OX1 3RH, UK*

(Dated: March 26, 2019)

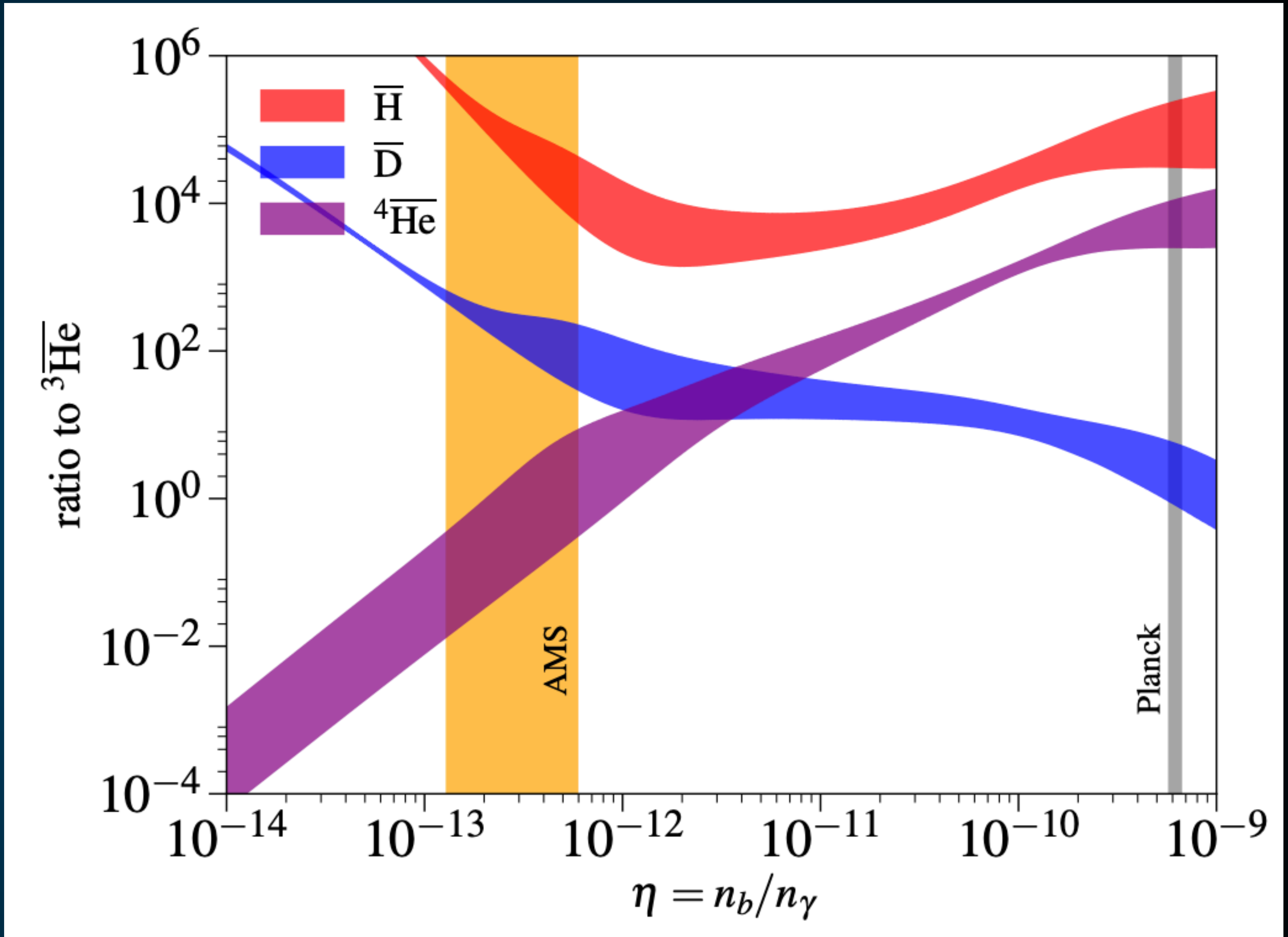
We discuss the origin of the anti-helium-3 and -4 events possibly detected by *AMS-02*. Using up-to-date semi-analytical tools, we show that spallation from primary hydrogen and helium nuclei onto the ISM predicts a $\overline{^{3}\mathrm{He}}$ flux typically one to two orders of magnitude below the 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.

Antihelium Production in Antidomains

If the big bang is asymmetric - different regions may have inverted antiparticle/ particle dominance.

Anticlouds (and potentially antistars will form), undergoing BBN and later stellar fusion.

Can produce a significant (low-energy anti helium abundance)



Poulin et al. (2018; 1808.08961)

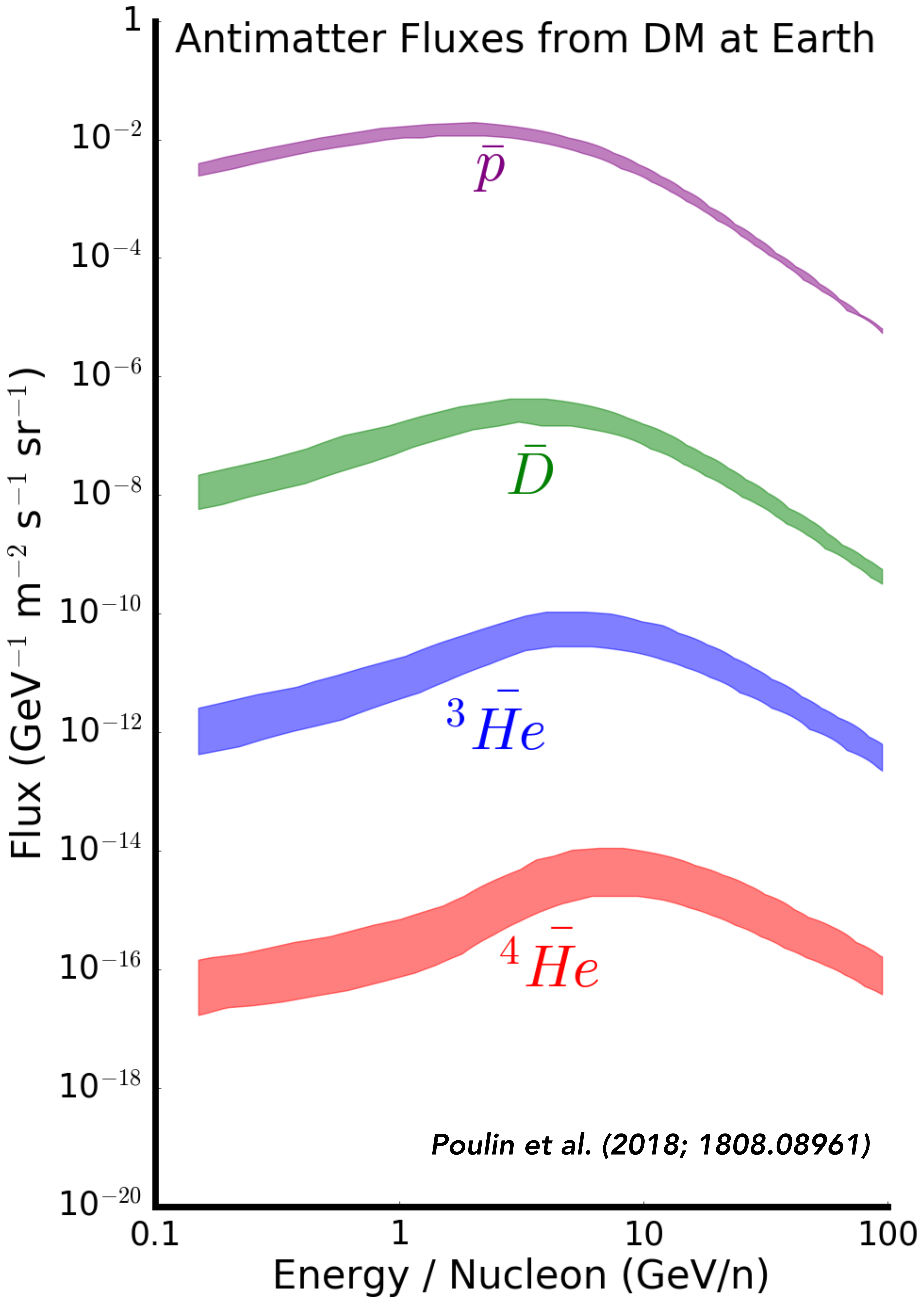
Boosting this Signal to Meet the Challenge?

1.) Coalescence Rates (1401.2461)

2.) Lambda_b Enhancement (2006.16251, 2106.00053)

3.) Strongly Coupled Dark Sectors (2211.00025)

4.) Astrophysical Acceleration (2001.08749)



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

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

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

This is a general result for many enhancements - we need to either get more particles into the same momentum space - or make the momentum space for coalescence larger.

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

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

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

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

Key Insight - Coalescence Momentum for Antihelium Should Be Larger

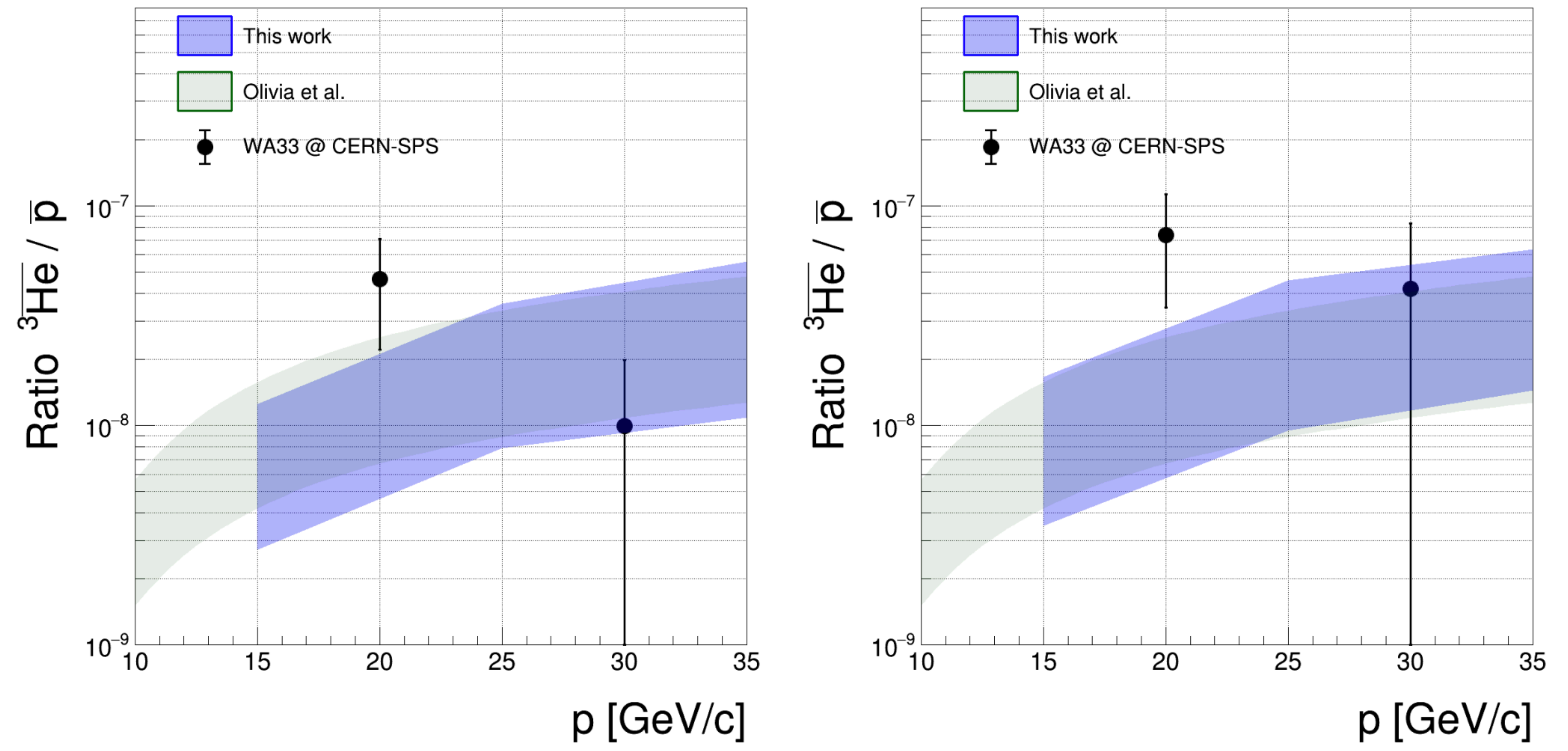
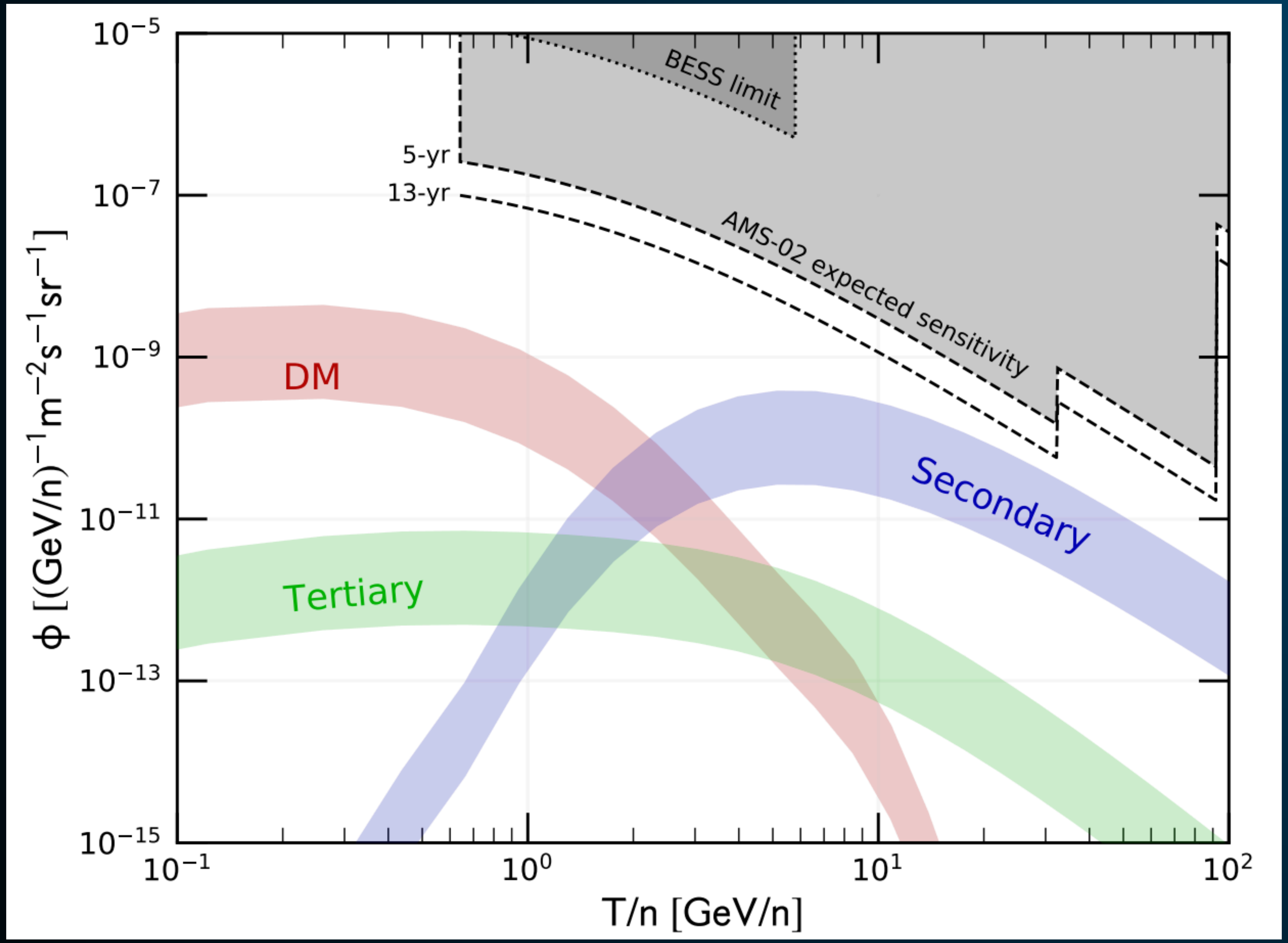


FIG. 4. The invariant production cross section ratio $^3\overline{\mathrm{He}}/\overline{p}$ as function of momentum p [GeV/c] in the laboratory frame for (left) p-Be at $p_{\mathrm{lab}} = 200\,\mathrm{GeV}/c$ and (right) p–Al at $p_{\mathrm{lab}} = 200\,\mathrm{GeV}/c$. The uncertainty bands for this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

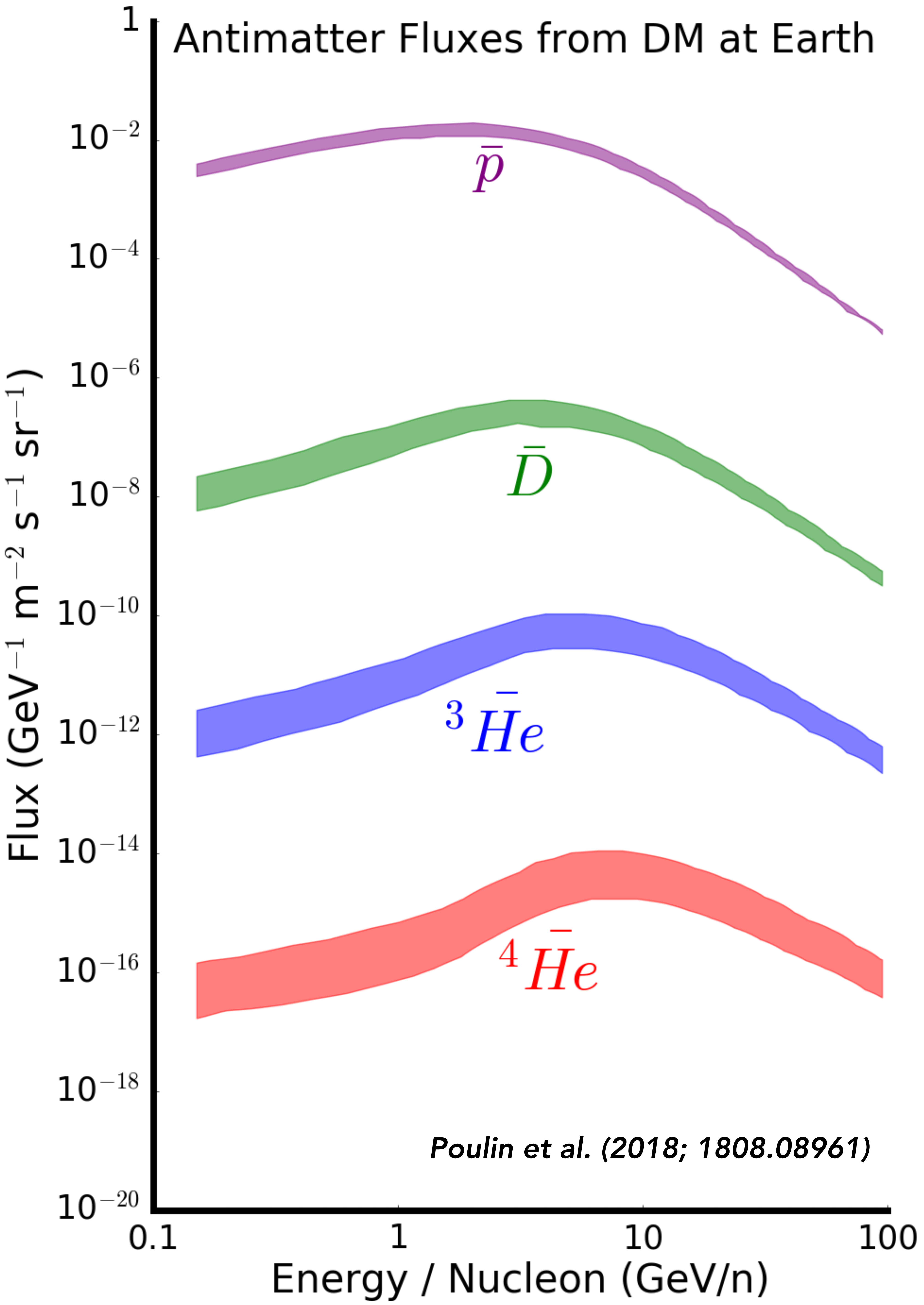
Shukla et al. (2006.12707)

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.

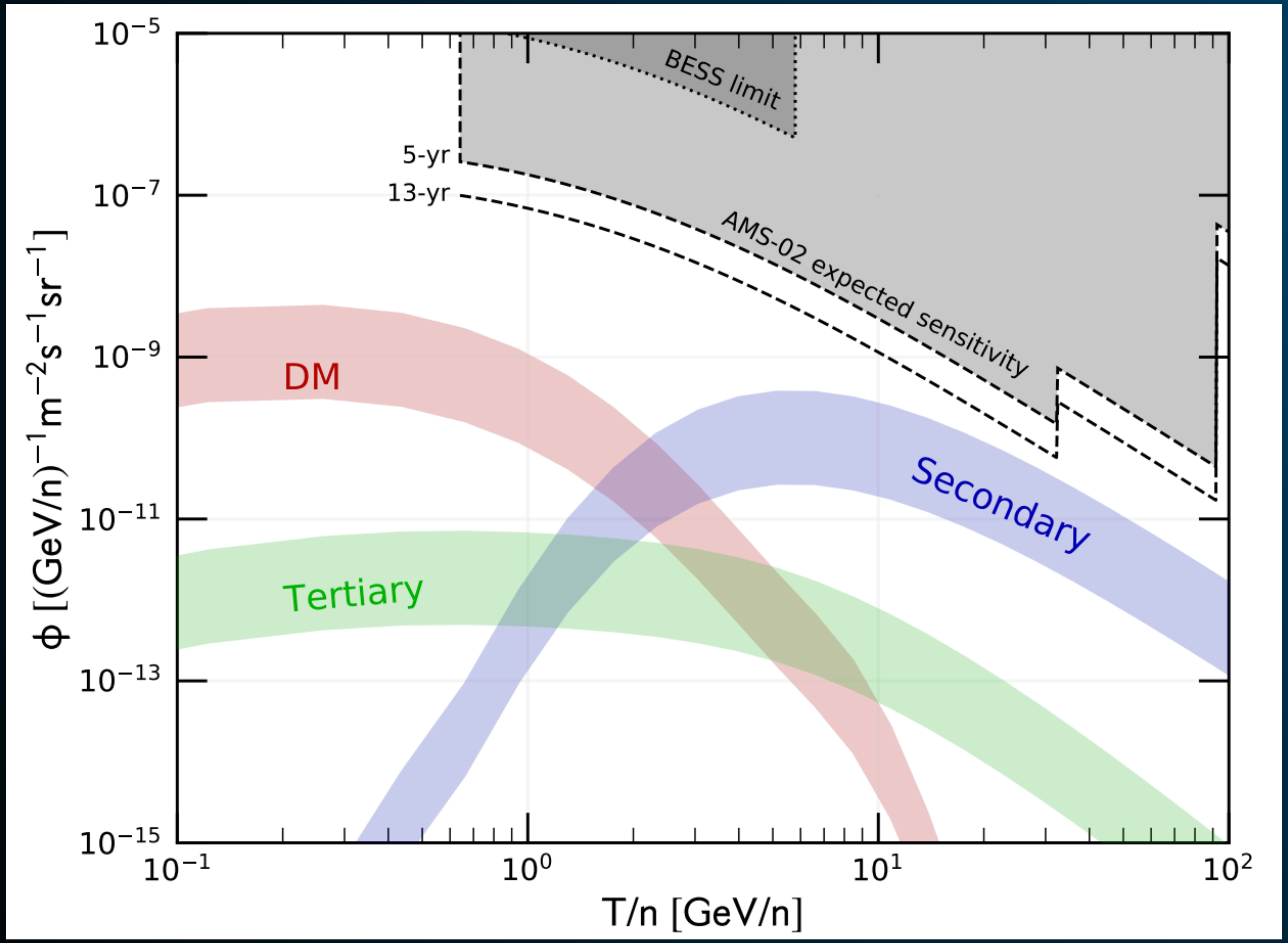


Korsmeier (2017; 1711.08465)

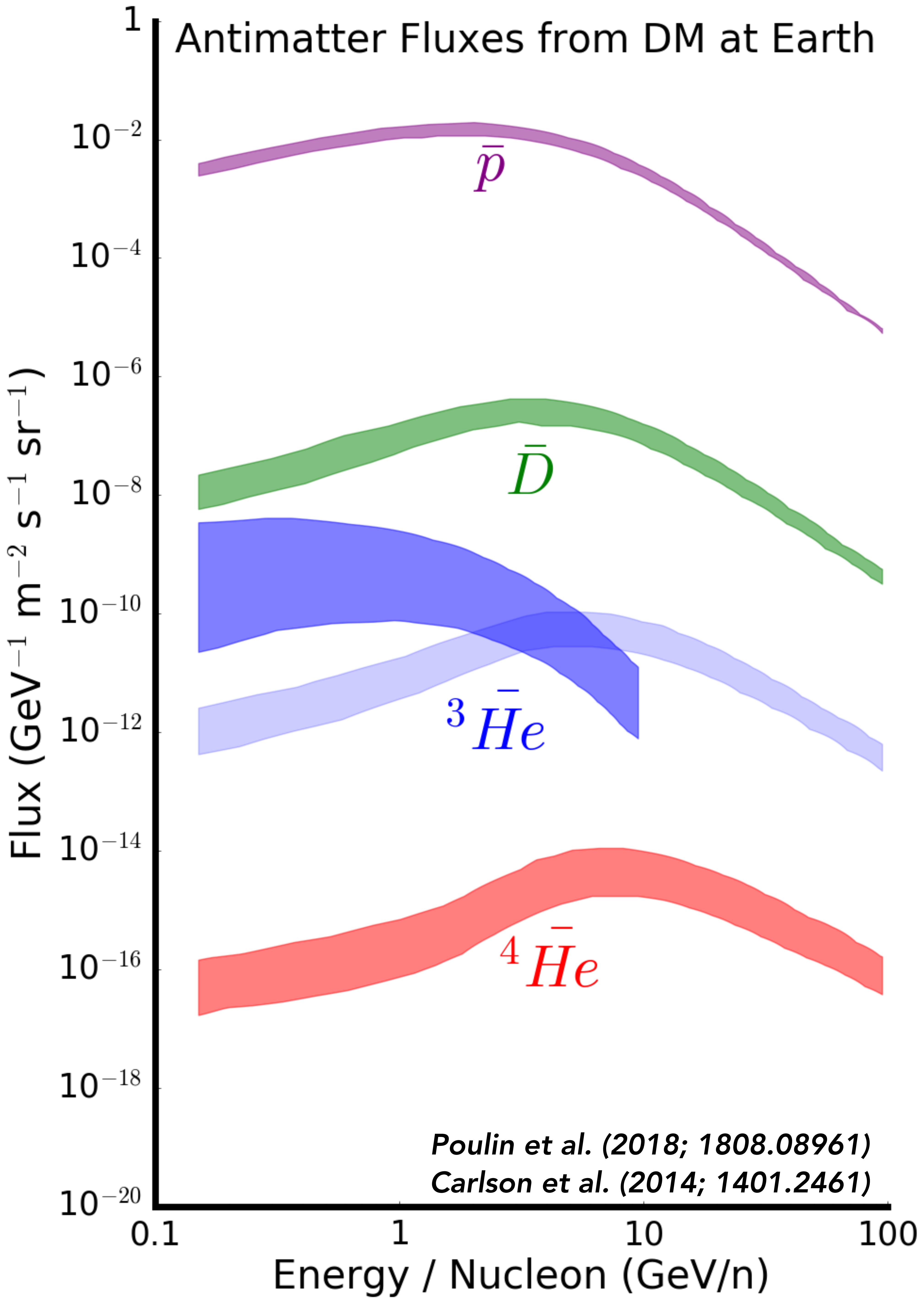


Coalescence Models - Expected Helium Flux

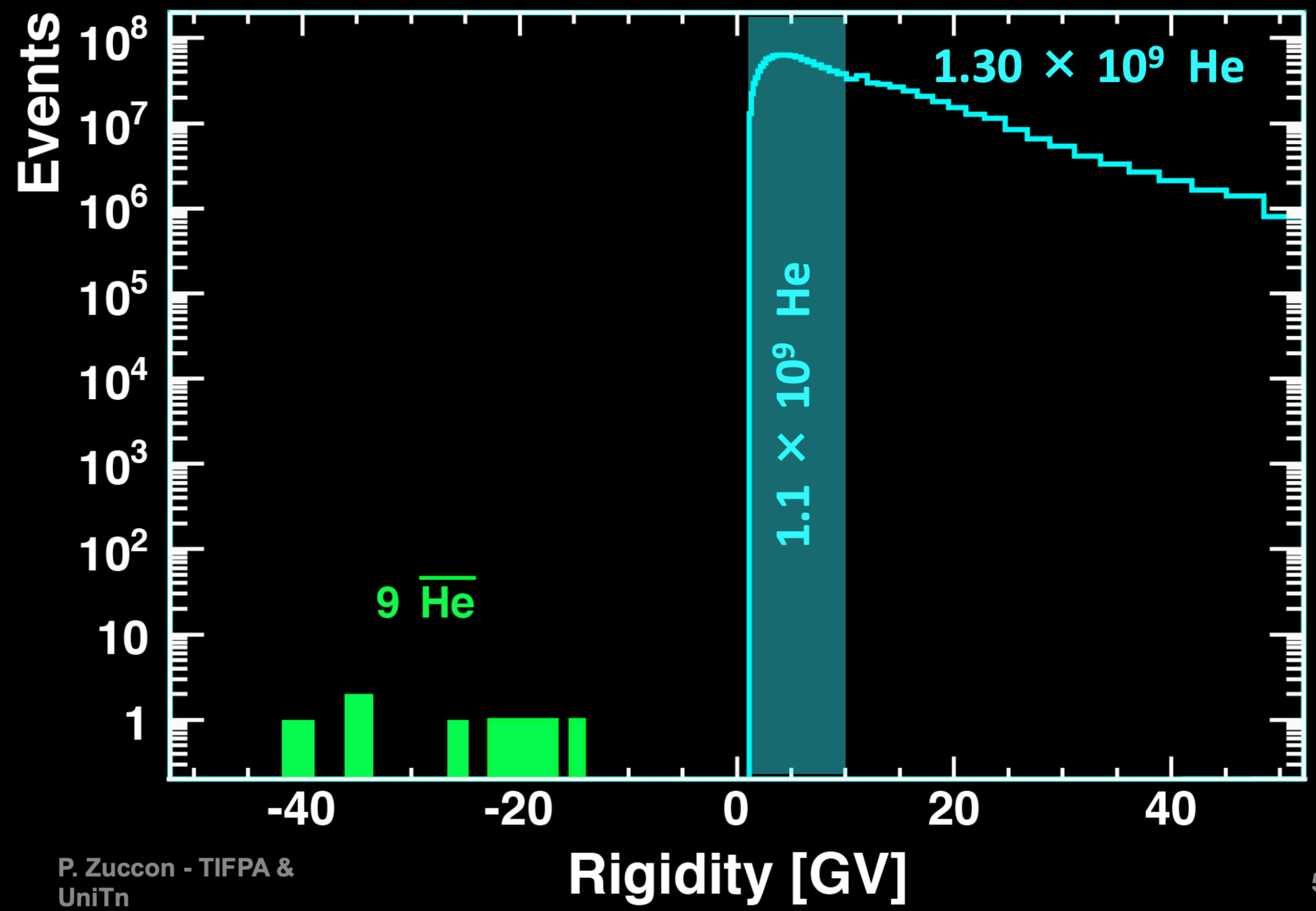
Using more realistic estimates for the anti helium coalescence momentum produces a boosted anti helium flux, especially at low energies.



Korsmeier (2017; 1711.08465)



However the Rigidity of these Antihelium Events is High



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]

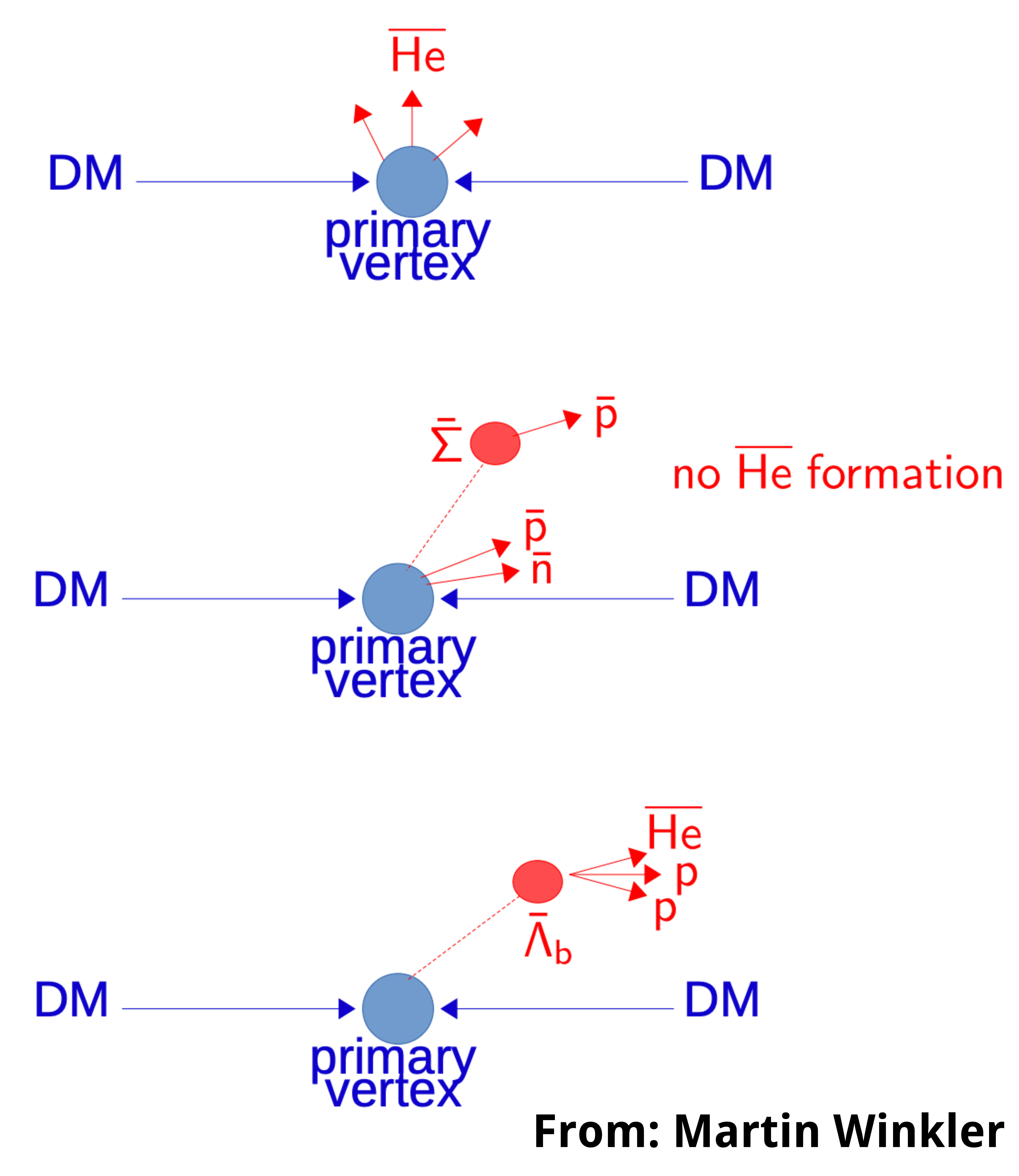
In this *letter*, we challenge the current understanding that standard dark matter annihilation models cannot produce a measurable antihelium flux. Our analysis examines a known, and potentially dominant, antinuclei production mode which has been neglected by previous literature – the production of antihelium 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 $^3\overline{\mathrm{He}}$ 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.

Lambda_b antibaryon has correct parameters to produce anti helium:

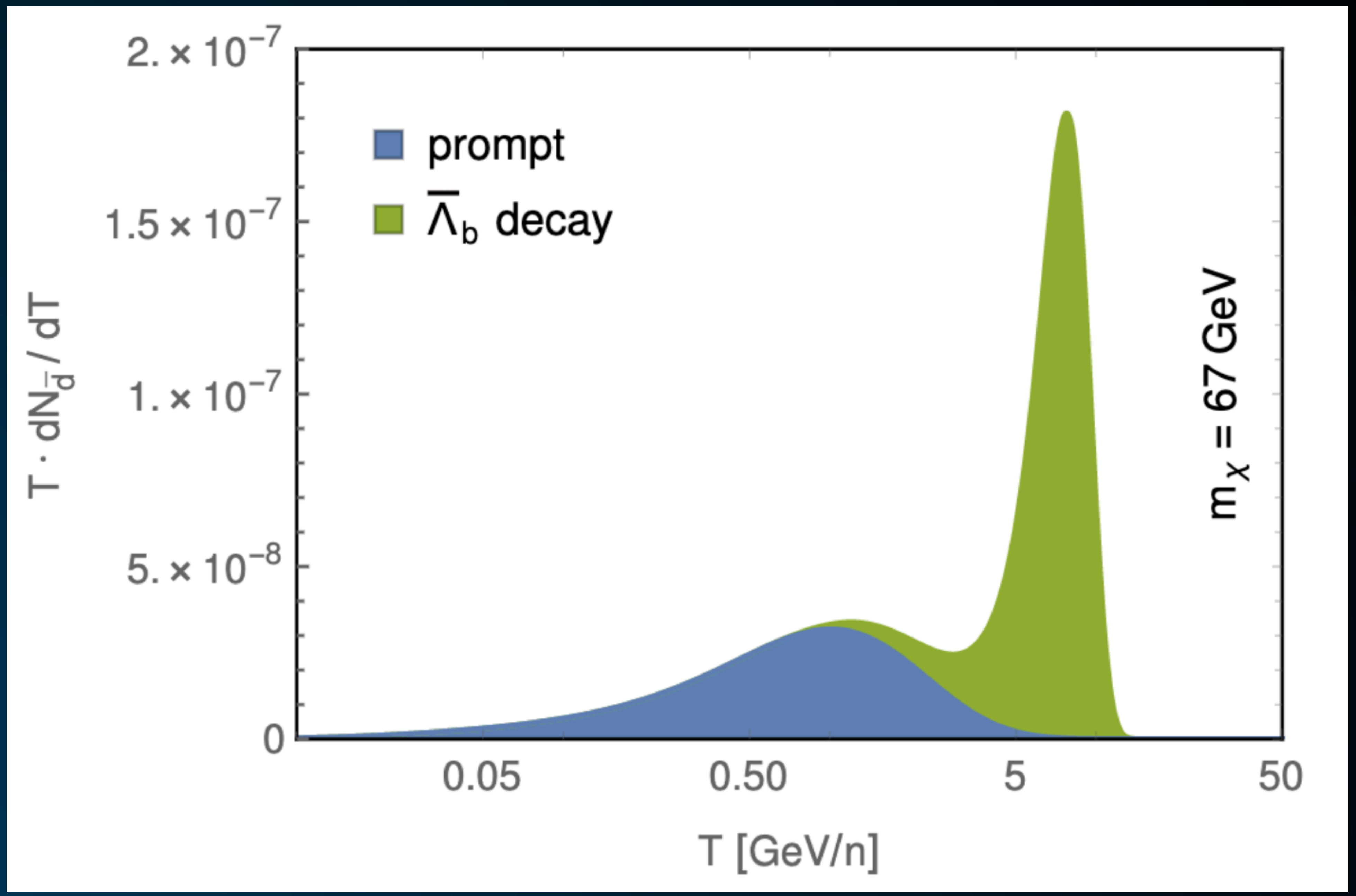
- **Antibaryon number of 1**
- **Mass: 5.6 GeV (pbar, nbar, pbar, p, p)**

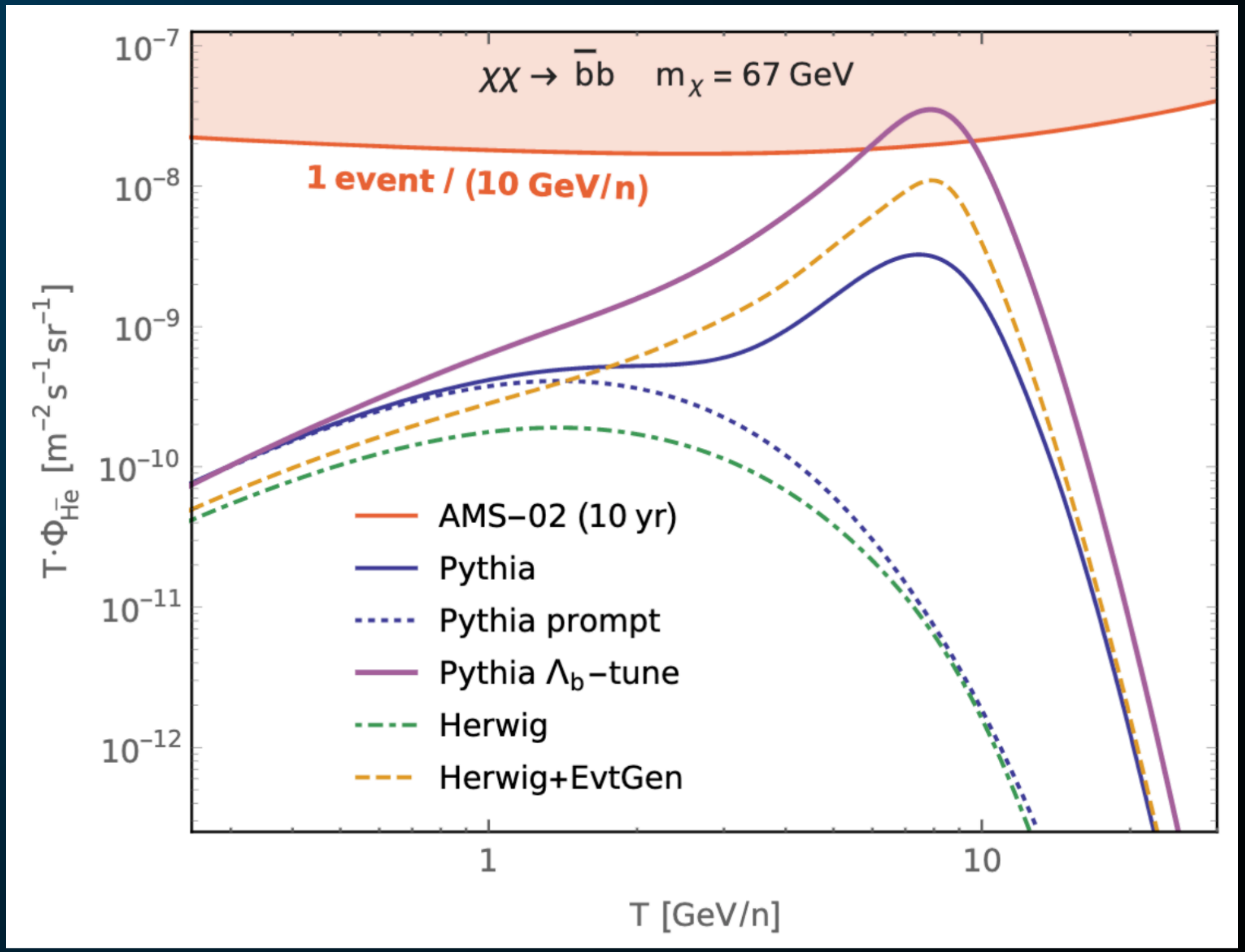


A New Method for Producing Antihelium

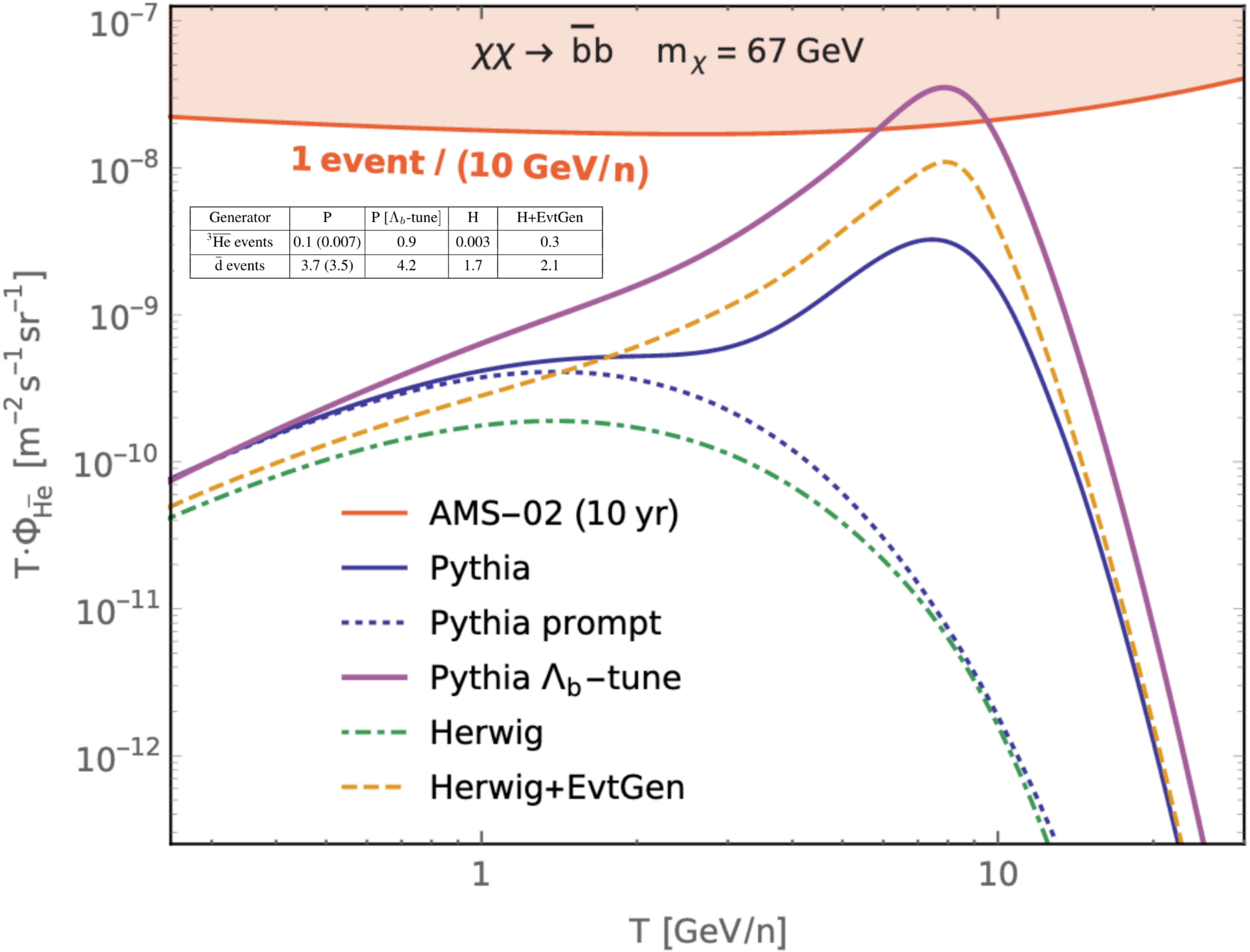
Can produce a significant enhancement of the total anti helium flux.

Moreover, the enhancement is at high-energies - producing an observable spectral feature.





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

Making These Predictions More Robust

Antiproton Bounds on Dark Matter Annihilation from a Combined Analysis Using the DRAGON2 Code

Pedro De La Torre Luque[a,b] **Martin Wolfgang Winkler**[c] **Tim Linden**[b]

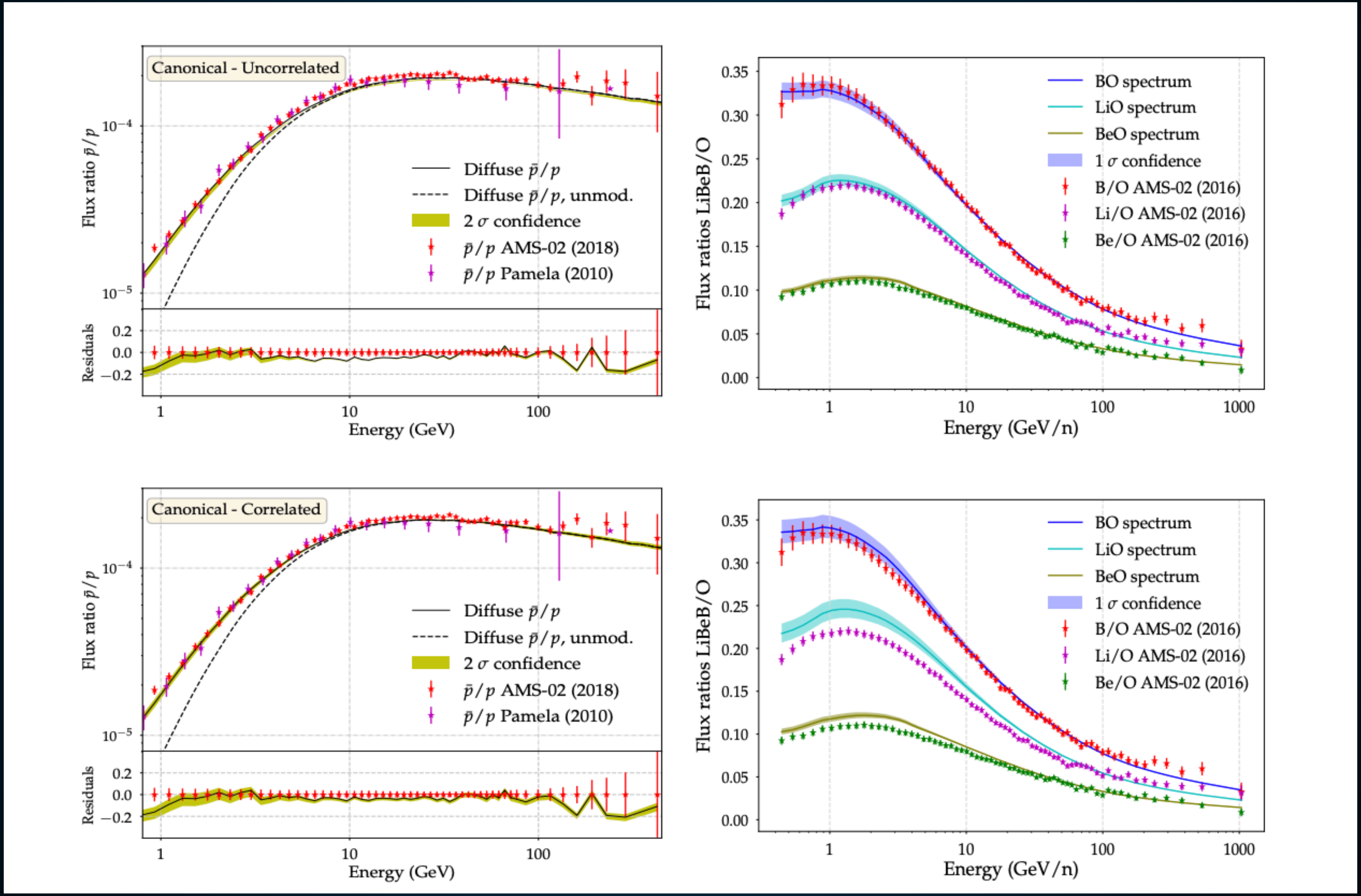
[a]Instituto de Física Teórica, IFT UAM-CSIC, Departamento de Física Teórica, Universidad Autónoma de Madrid, ES-28049 Madrid, Spain

[b]The Oskar Klein Centre, Department of Physics, Stockholm University, AlbaNova SE-10691 Stockholm, Sweden

[c]Department of Physics, The University of Texas at Austin, Austin, 78712 TX, USA

E-mail: pedro.delatorre@uam.es, martin.winkler@austin.utexas.edu, linden@fysik.su.se

Making These Predictions More Robust



Making These Predictions More Robust

This sets strong constraints on dark matter annihilation, that can be used to constrain the antihelium flux.

Making These Predictions More Robust

Cosmic-Ray Propagation Models Elucidate the Prospects for Antinuclei Detection

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Robust Calculations Utilizing Antiproton-Motivated Models

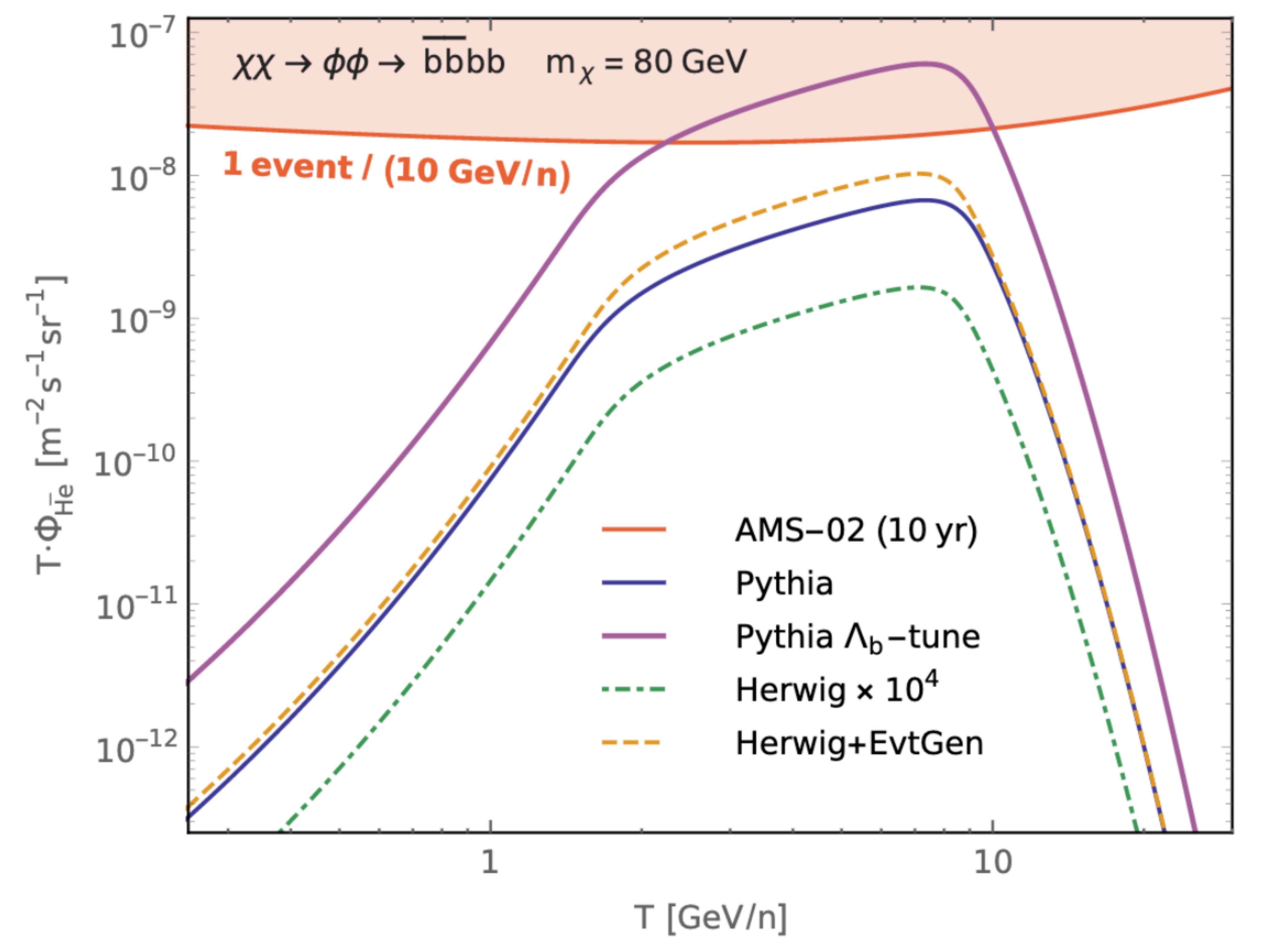
Include uncertainties from cosmic-ray propagation and coalescence models

Predicts observation of roughly 1 anti helium nuclei.

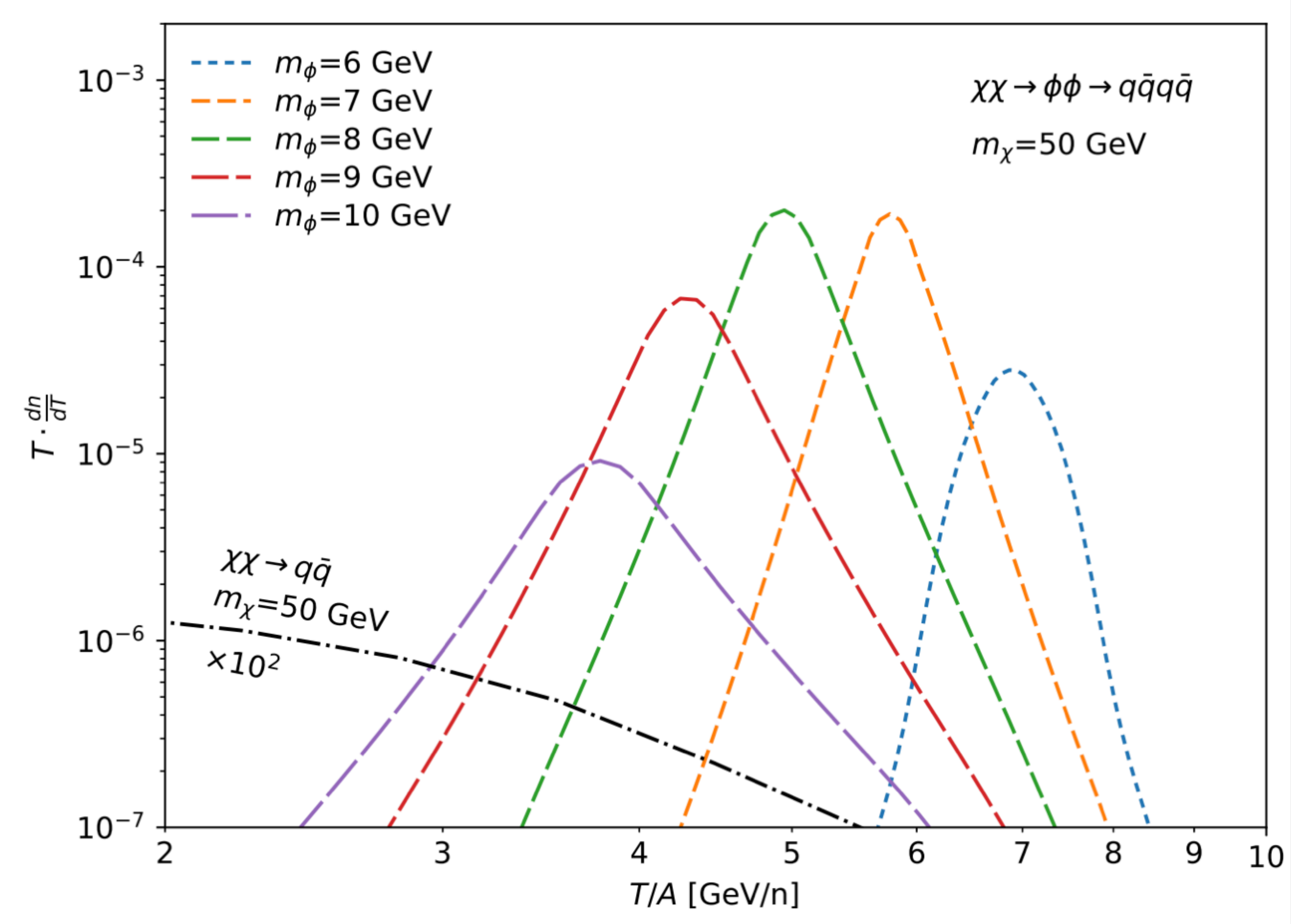
De la Torre Luque, Winkler, Linden (TBS; 2402.XXXXX)

Building a Specific Dark Particle

Can further boost antihelium formation through the inclusion of a dark mediator that lies just above above the antihelium mass.



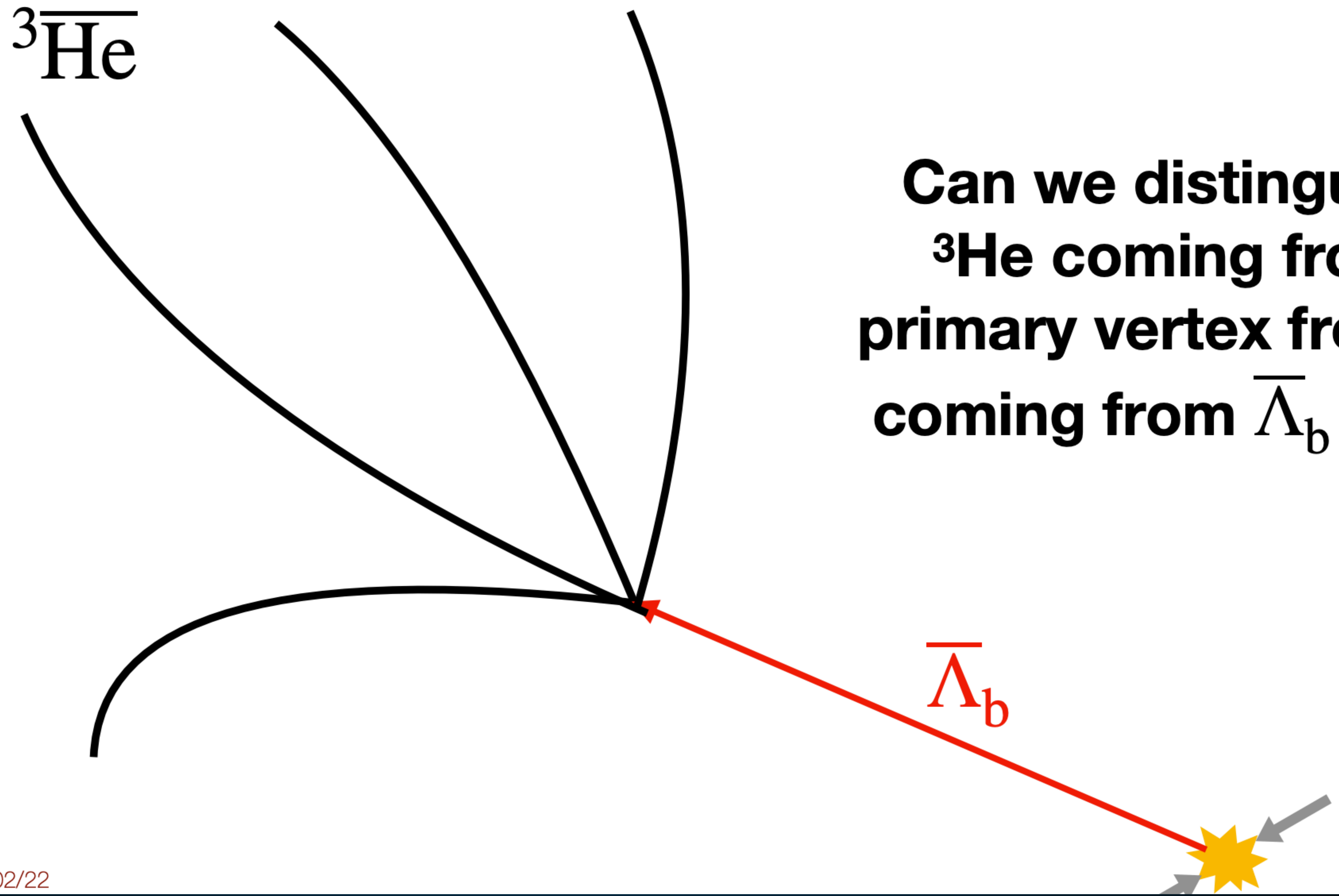
Best fit 14 GeV (but maybe lighter).



Winkler & Linden (2020; 2020.16251)

Ding, Li, & Zhou (2022; 2212.05239)

Can We Find this At Particle Accelerators?

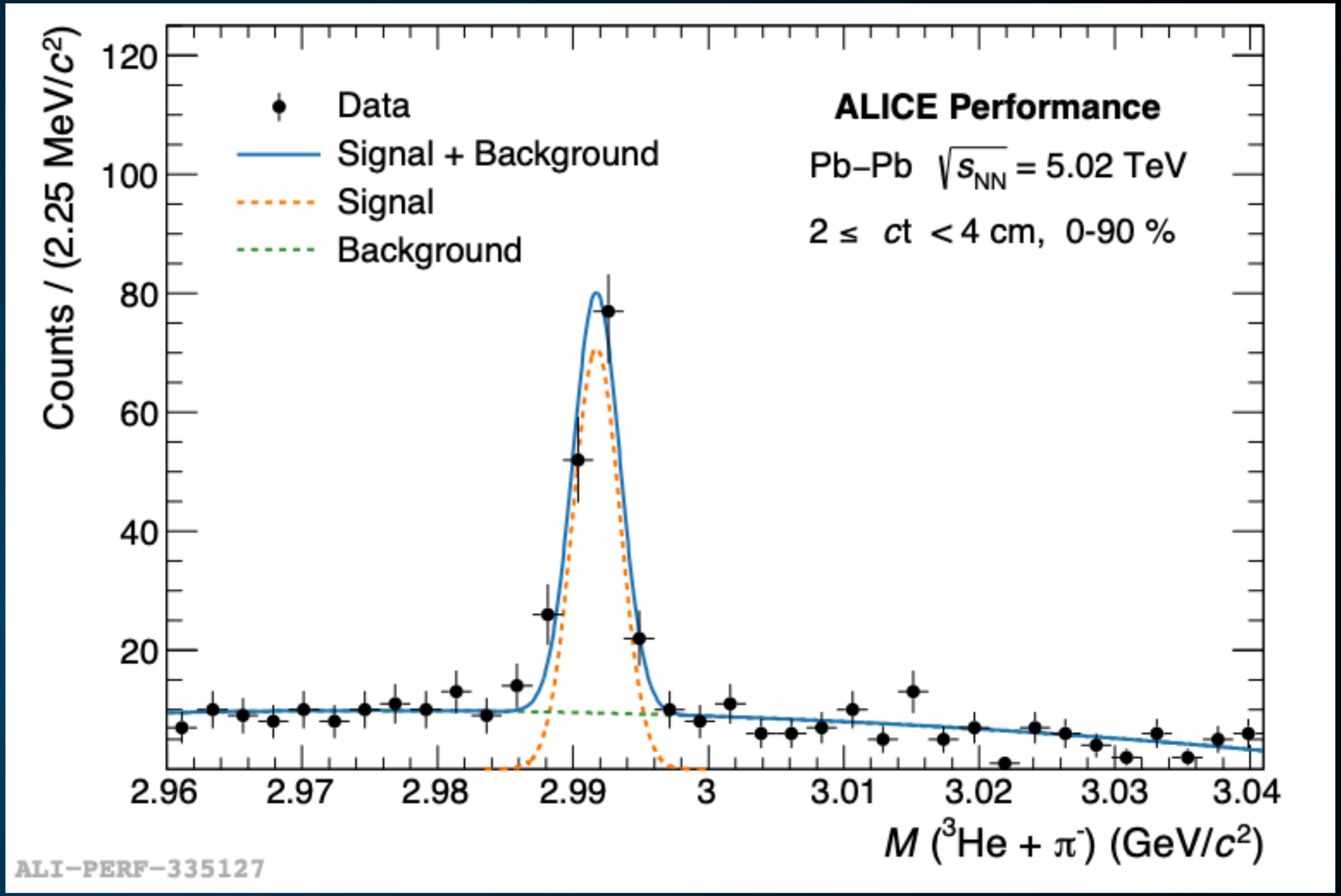


Can we distinguish the ^{3}He coming from the primary vertex from those coming from $\overline{\Lambda}_b$ decays?

$c\tau$ ~ 450 µm

Can We Find this At Particle Accelerators?

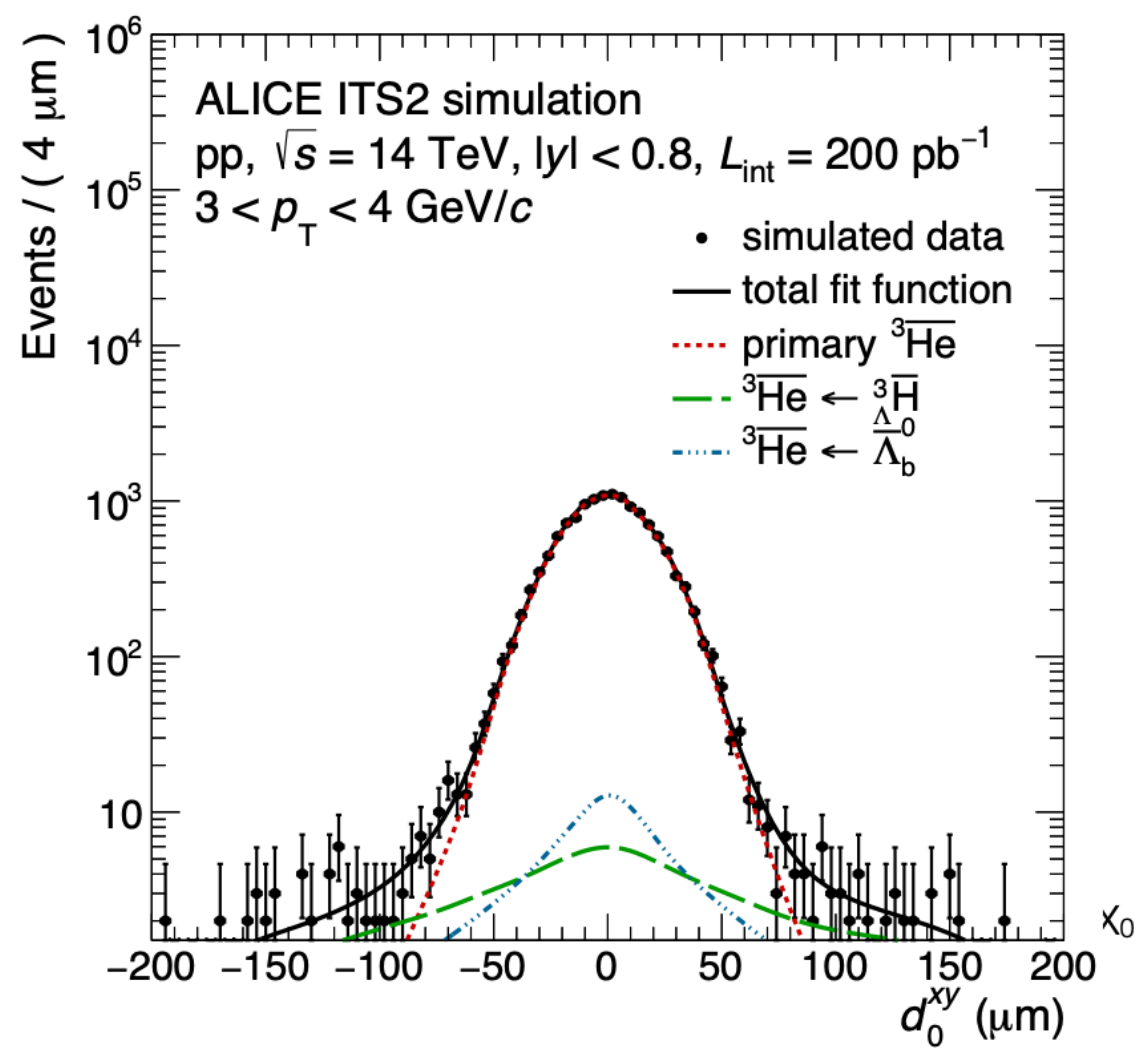
Current observations are not sensitive to this offset



Can We Find this At Particle Accelerators?

Current observations are not sensitive to this offset

The ITS2 run of ALICE is unlikely to be able to detect the signal, but may provide a hint if the antihelium production rate is near the upper limits of our predictions.

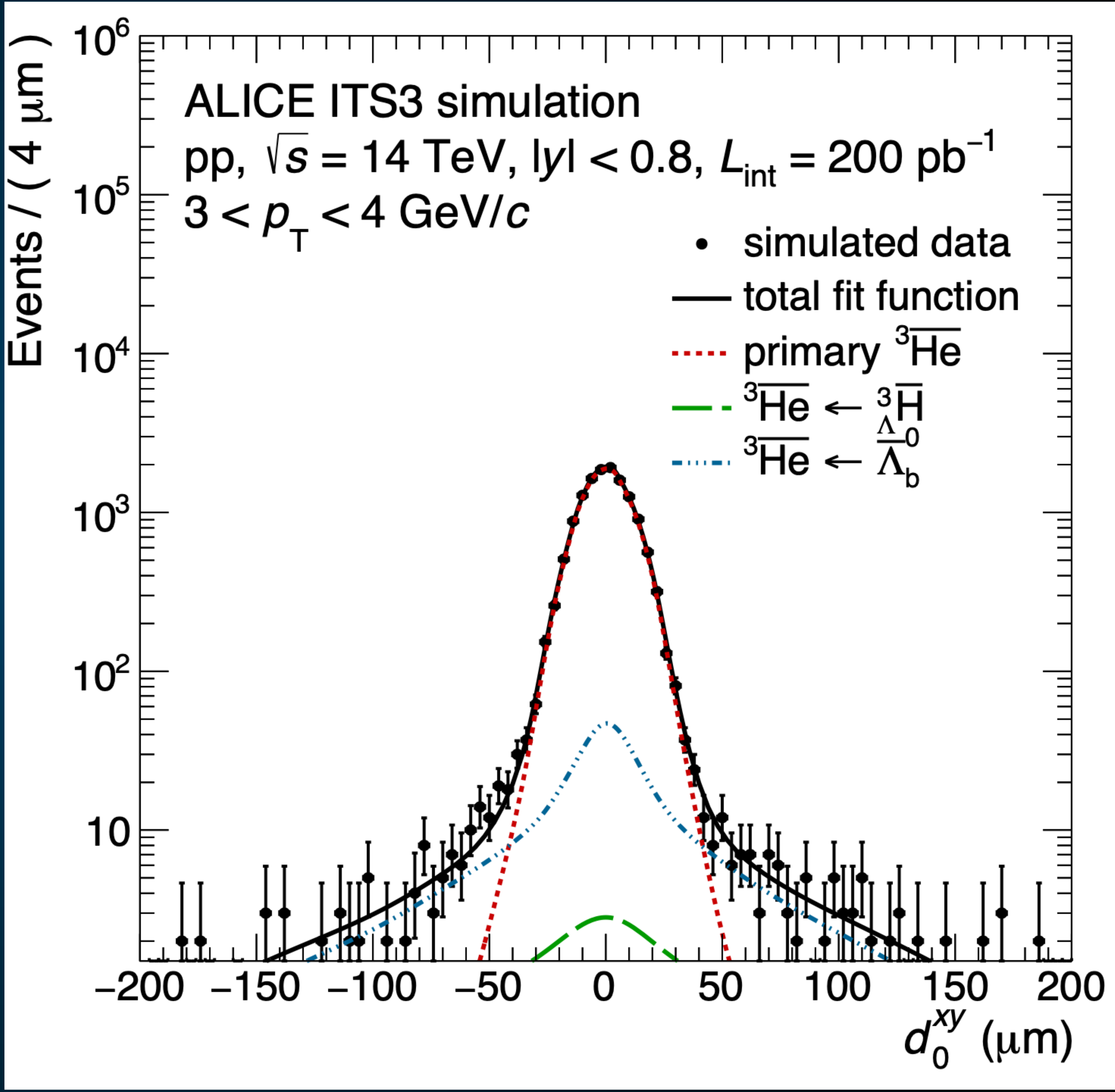


Can We Find this At Particle Accelerators?

Current observations are not sensitive to this offset

The ITS2 run of ALICE is unlikely to be able to detect the signal, but may provide a hint if the antihelium production rate is near the upper limits of our predictions.

The upcoming ITS3 experiment from ALICE will be able to differentiate the Lambda_b channel for anti helium creation.



Synergy between Indirect Detection and Colliders

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE

CERN

CERN-EP-2022-023
03 February 2022

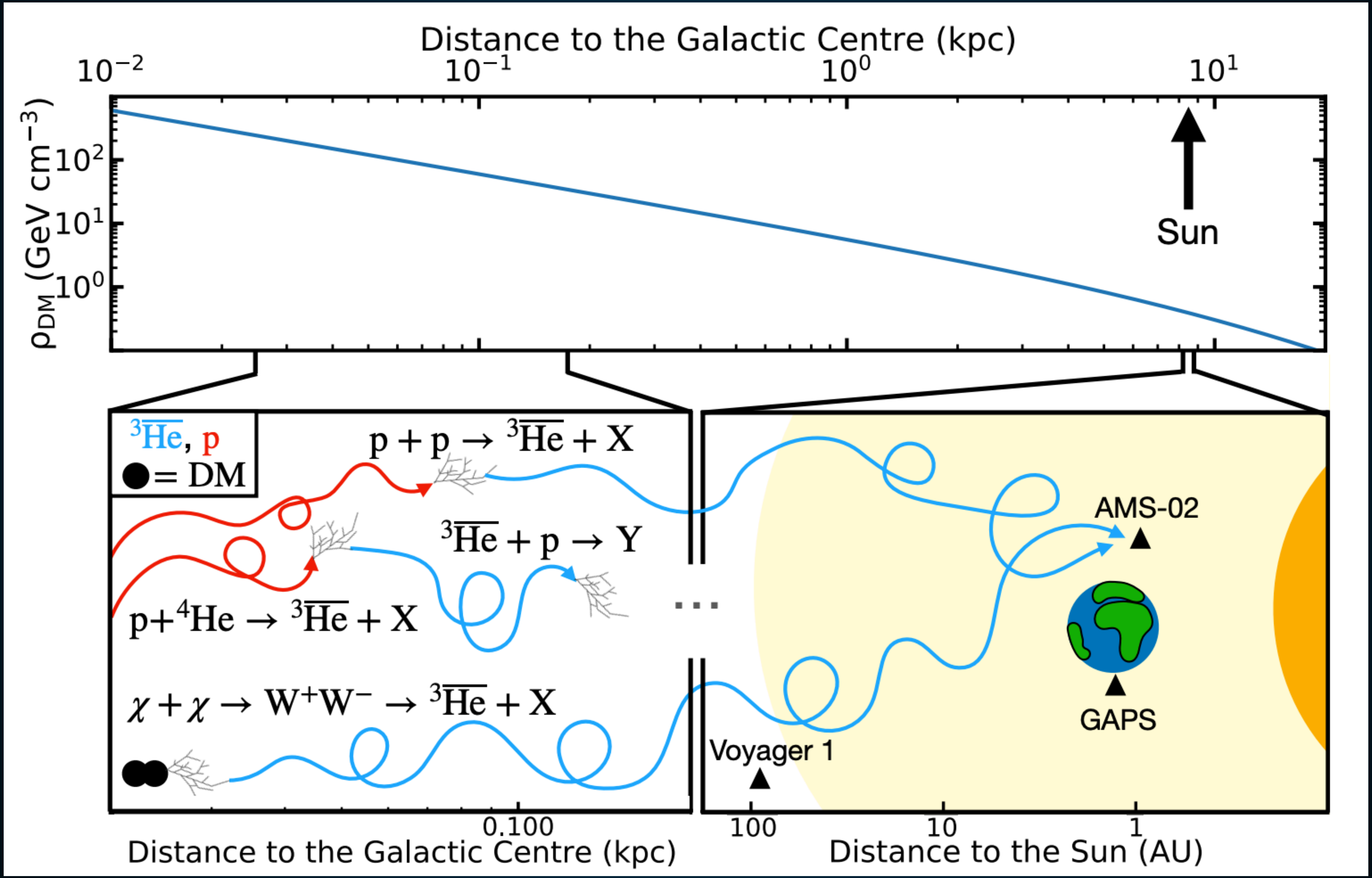
Measurement of $^{3}\overline{\mathrm{He}}$ nuclei absorption in matter and impact on their propagation in the Galaxy

ALICE Collaboration

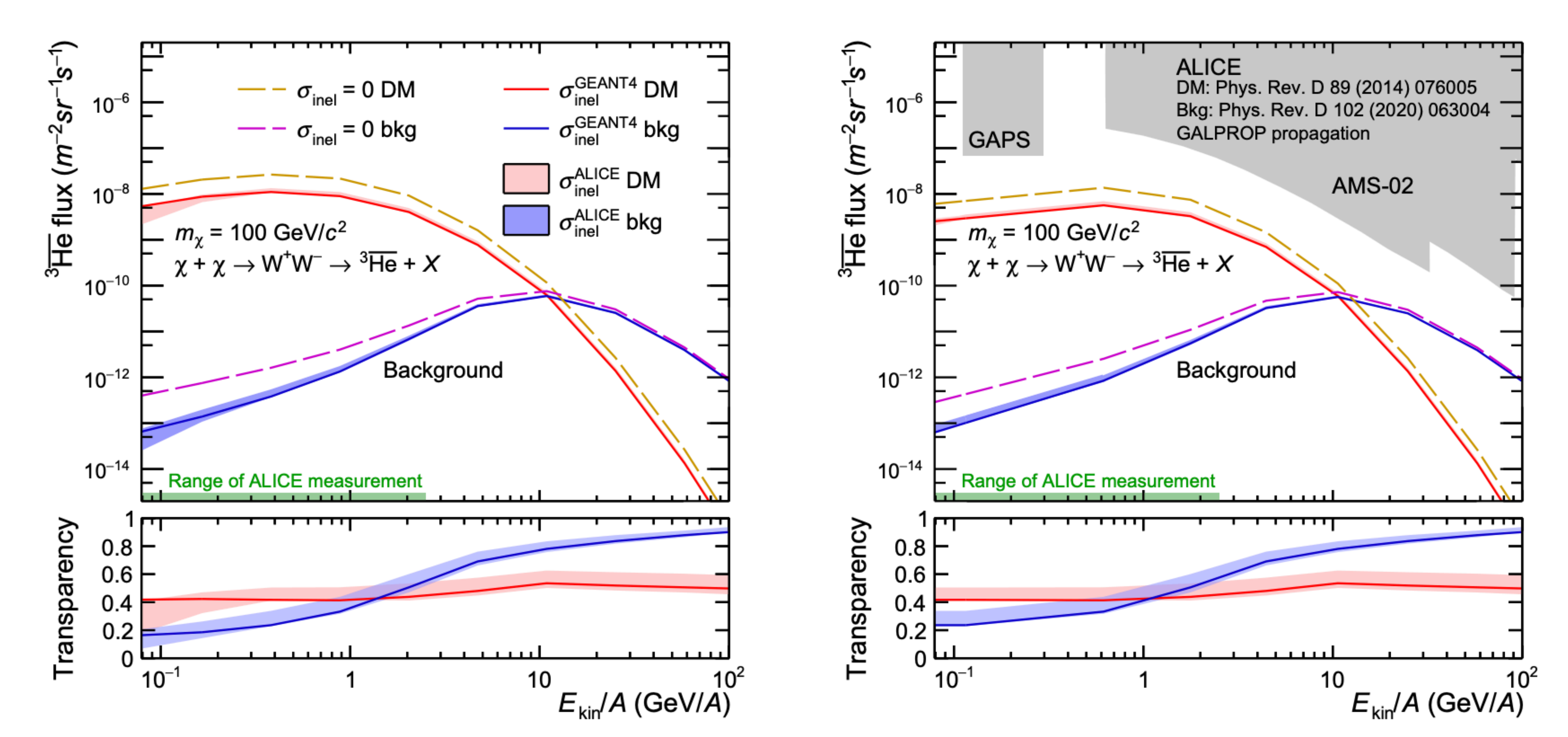
Abstract

In our Galaxy, light antinuclei composed of antiprotons and antineutrons can be produced through high-energy cosmic-ray collisions with the interstellar medium or could also originate from the annihilation of dark-matter particles that have not yet been discovered. On Earth, the only way to produce and study antinuclei with high precision is to create them at high-energy particle accelerators. Although the properties of elementary antiparticles have been studied in detail, the knowledge of the interaction of light antinuclei with matter is limited. We determine the disappearance probability of $^{3}\overline{\mathrm{He}}$ when it encounters matter particles and annihilates or disintegrates within the ALICE detector at the Large Hadron Collider. We extract the inelastic interaction cross section, which is then used as input to calculations of the transparency of our Galaxy to the propagation of $^{3}\overline{\mathrm{He}}$ stemming from dark-matter annihilation and cosmic-ray interactions within the interstellar medium. For a specific dark-matter profile, we estimate a transparency of about 50%, whereas it varies with increasing $^{3}\overline{\mathrm{He}}$ momentum from 25% to 90% for cosmic-ray sources. The results indicate that $^{3}\overline{\mathrm{He}}$ nuclei can travel long distances in the Galaxy, and can be used to study cosmic-ray interactions and dark-matter

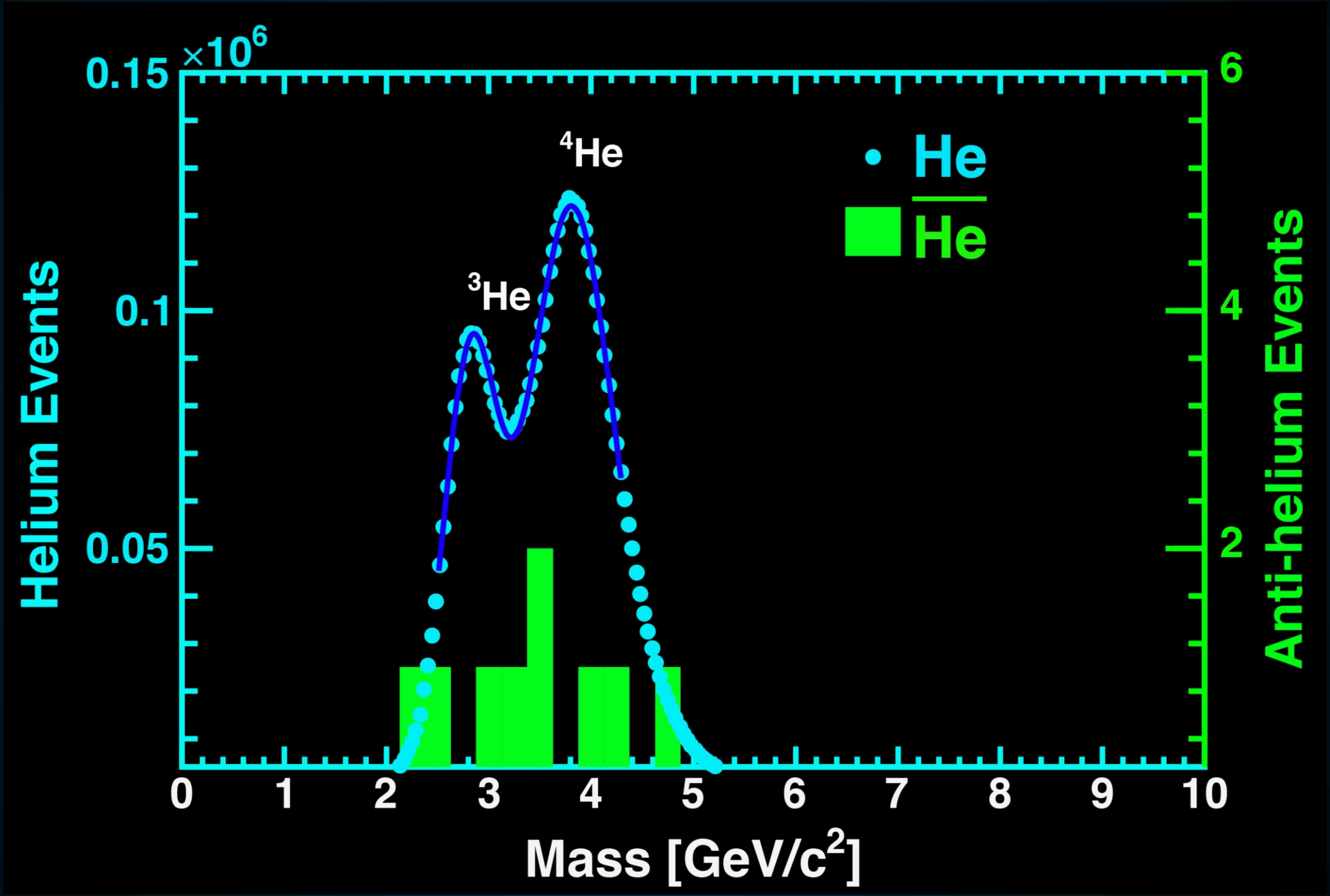
Synergy between Indirect Detection and Colliders



Synergy between Indirect Detection and Colliders



Problem: Are We Actually Observing Antihelium 4?

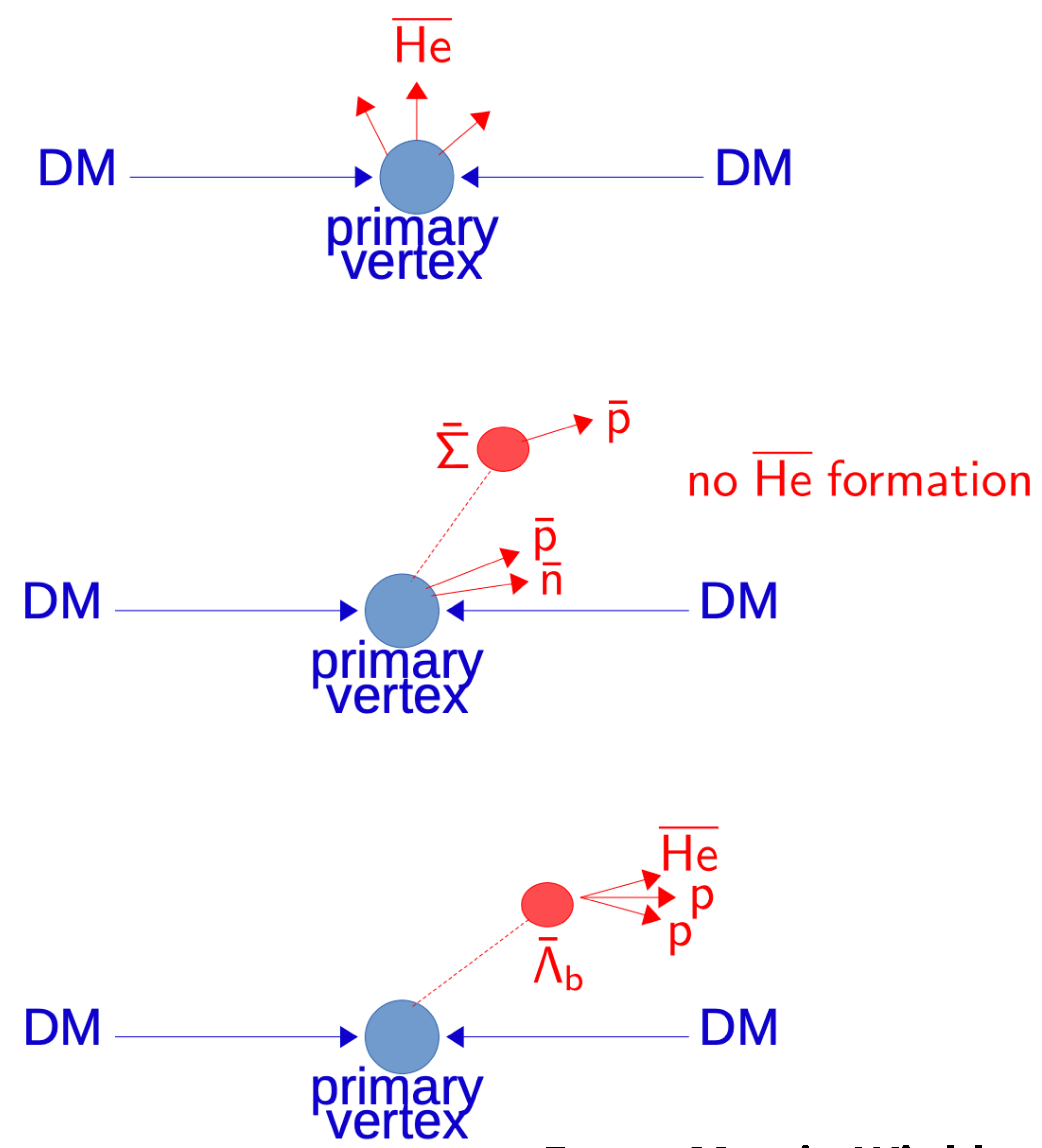


Cannot Enhance Antihelium-4 with Λ_b

Λ_b antibaryon has correct parameters to produce anti helium:

- Antibaryon number of 1
- Mass: 5.6 GeV (pbar, nbar, pbar, p, p)

Too light to produce antihelium-4!



From: Martin Winkler

Strongly Coupled Dark Sectors

Cosmic Ray Antihelium from a Strongly Coupled Dark Sector

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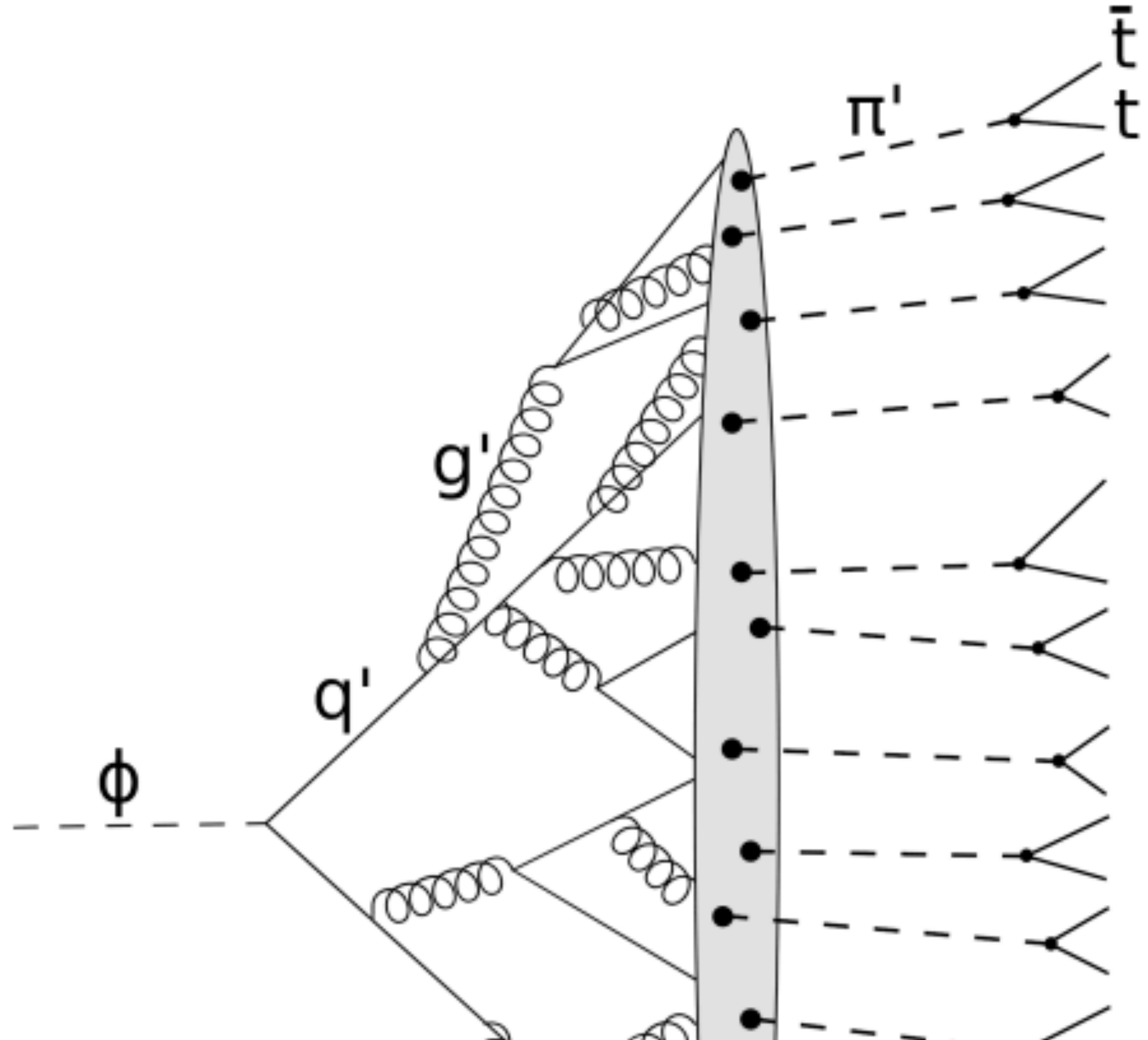
Standard Model extensions with a strongly coupled dark sector can induce high-multiplicity states of soft quarks. Such final states trigger extremely efficient antinucleus formation. We show that dark matter annihilation or decay into a strongly coupled sector can dramatically enhance the cosmic-ray 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].

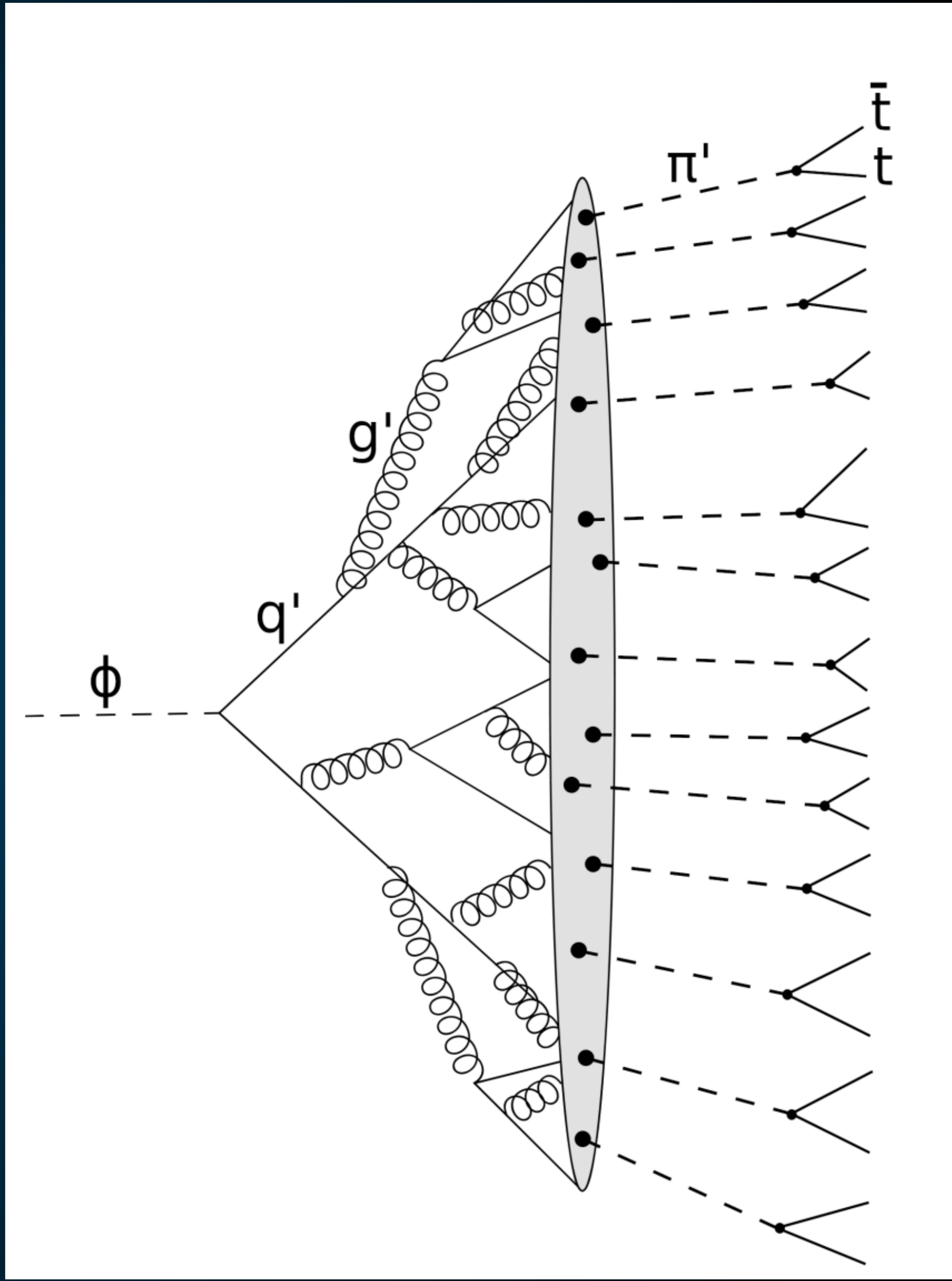


Strongly Coupled Dark Sectors

Just make a ton of quarks.

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

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



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 the unitarity limit

For decaying dark matter, we are not.

DM type	Annihilating	Decaying
Input Parameters		
m_χ [TeV]	150	5000
m_ϕ [TeV]	50.4	375
$m_{\pi'}$ [GeV]	380	700
$N_{\pi'}$	256	1024
$\langle \sigma v \rangle$ [cm^{3}s^{-1}]	6.6×10^{-24}	–
Γ [s^{-1}]	–	9×10^{-30}
Antinuclei Events at AMS-02		
$^3\overline{\mathrm{He}}$	15.6	20.3
$^4\overline{\mathrm{He}}$	1.0	3.1
$\bar{\mathrm{d}}$	19.3	1.2
Antinuclei Events at GAPS		
$\bar{\mathrm{d}}$	0.7	0

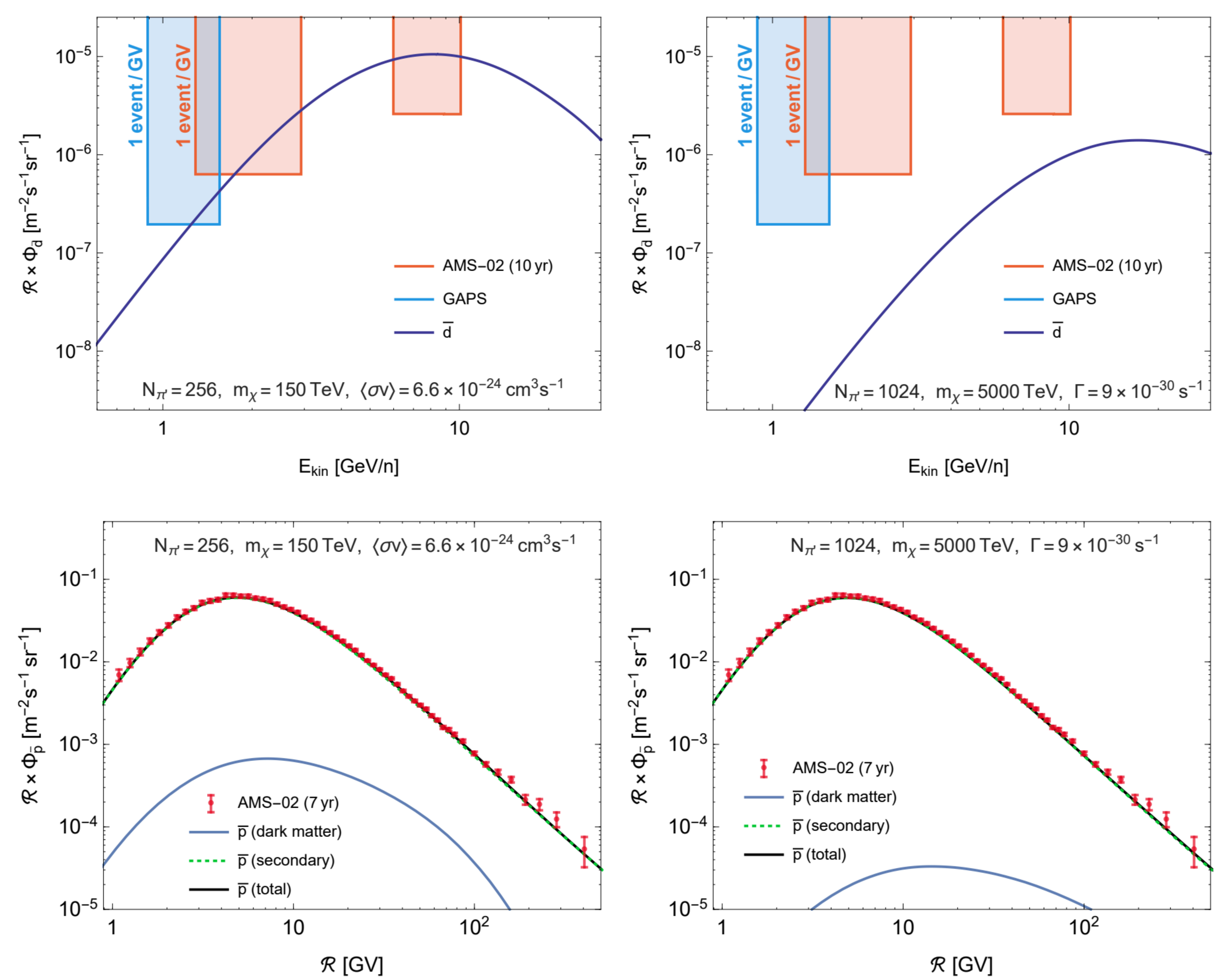
Strongly Coupled Dark Sectors

This significantly boosts the anti helium production rate — by a factor of n^9 for antihelium 3 and n^{12} for antihelium 4

Strongly Coupled Dark Sectors

Can accomplish this without producing too many antideuterium or antiprotons.

May be compatible with a 2-sigma excess in collider experiments.



Idea 4: Move the Excess to High Energies

1.) Changing the coalescence model primarily affects the Helium yield when the total center of mass energy is small.

2.) Very good for predicted rates with GAPS, or low-energy AMS-02 observations.

3.) But AMS-02 antihelium are (generally reported) at energies of ~10 GeV/n.

Astrophysical Enhancements!

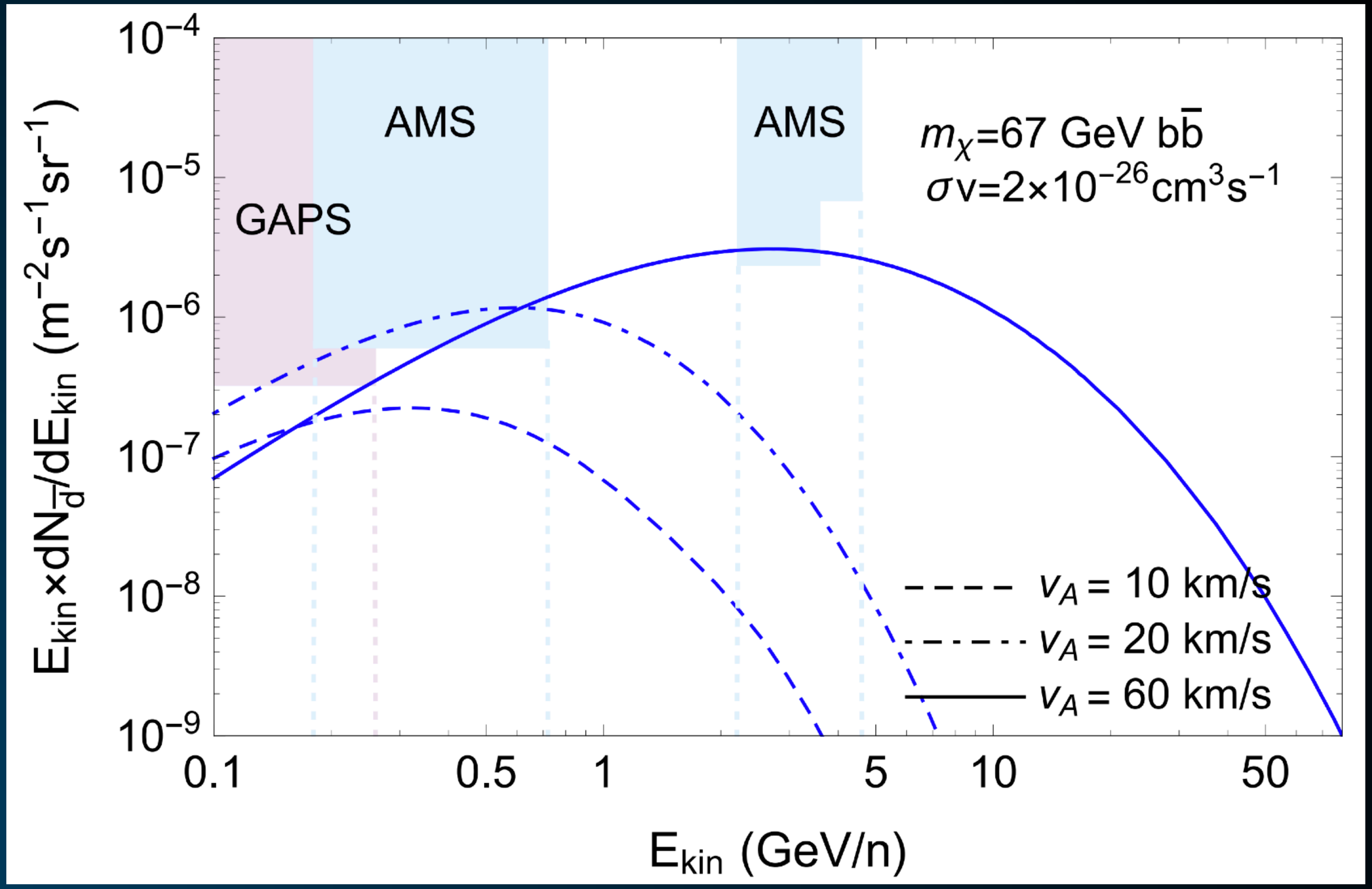
The current event rates depend on the detector sensitivity to anti-Helium.

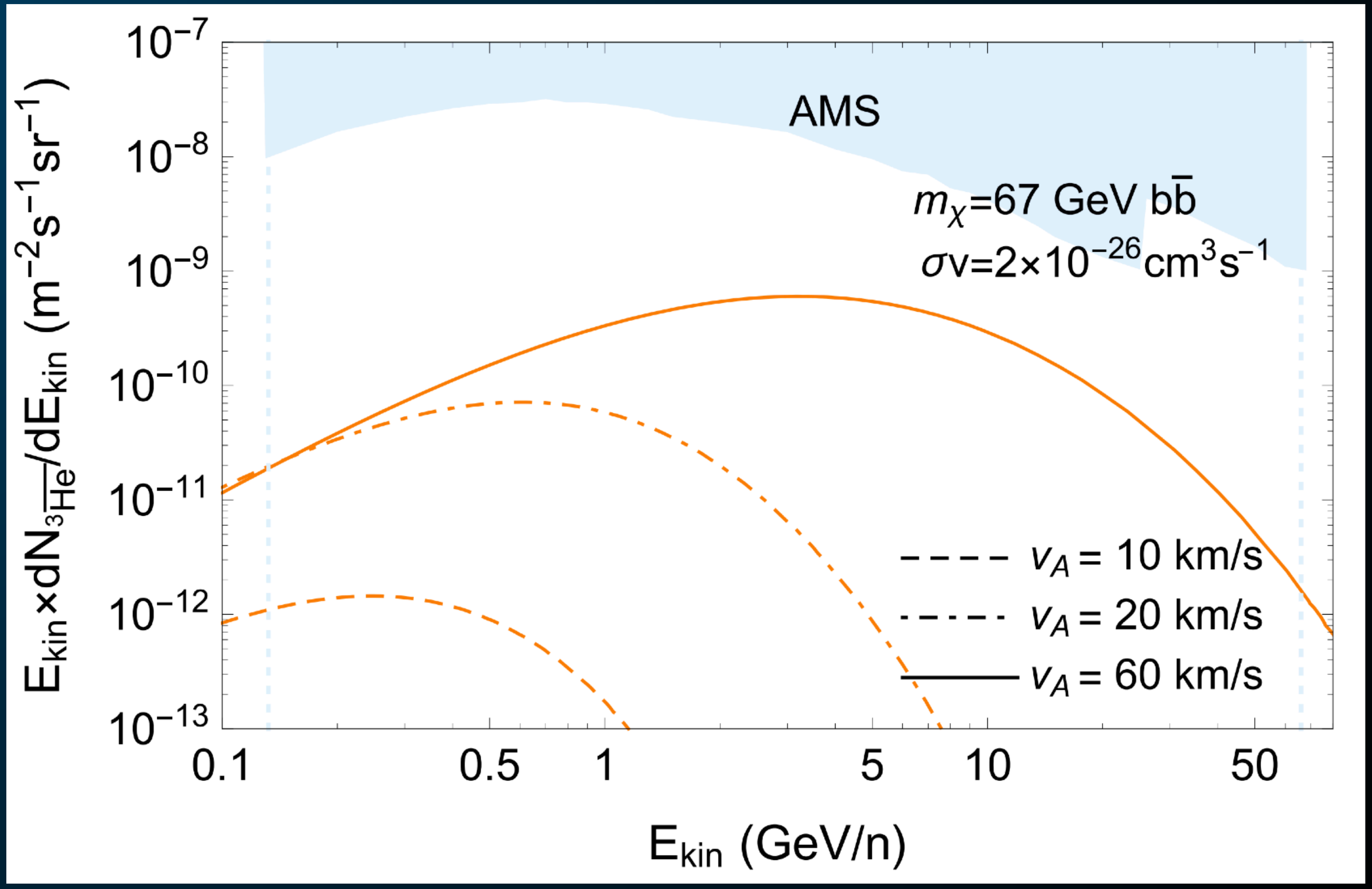
We lose many events because most anti-He are produced at energies that are too small to be detected.

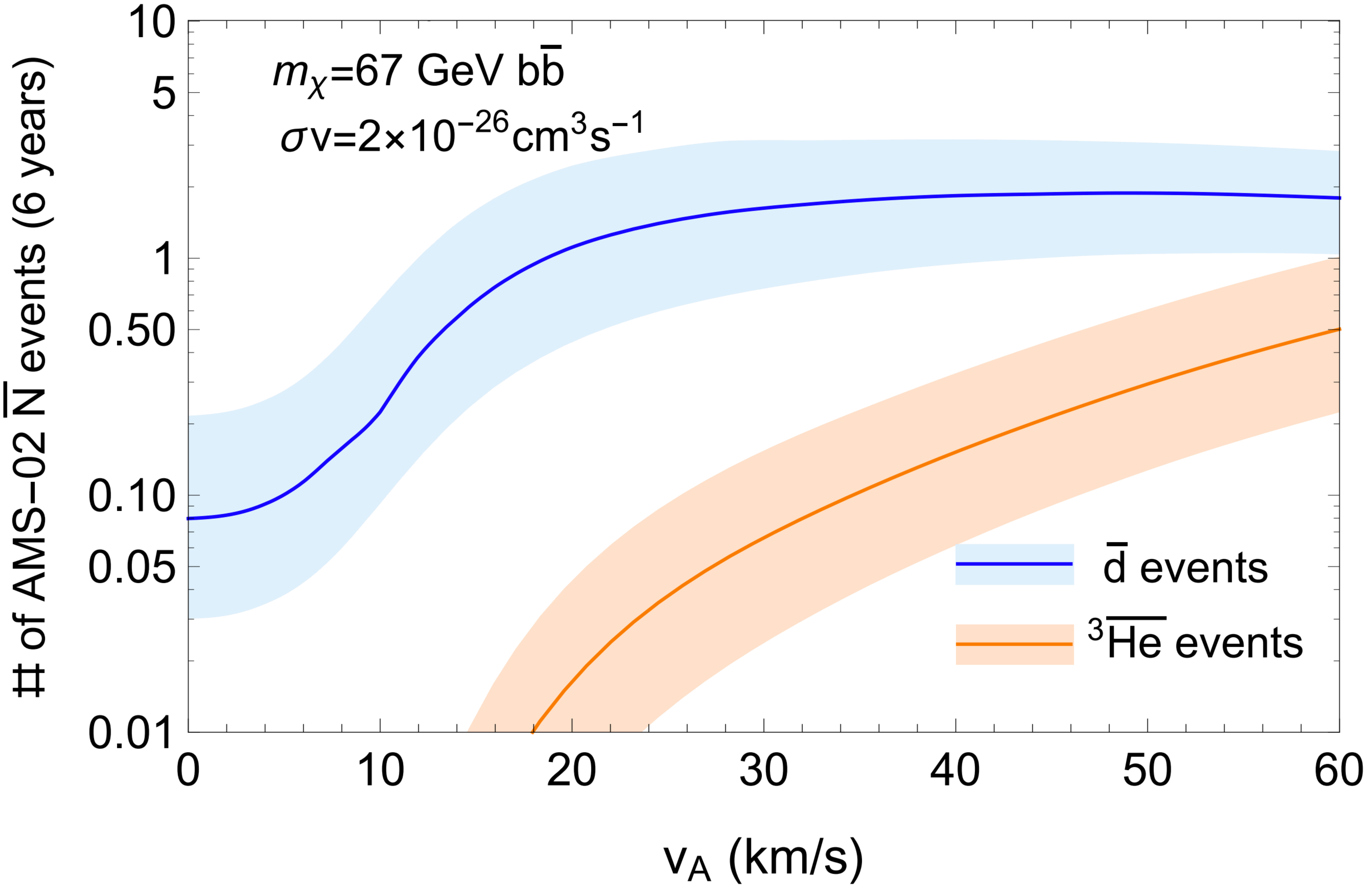
Use re-acceleration to boost the anti-He energies into the detectable range!

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

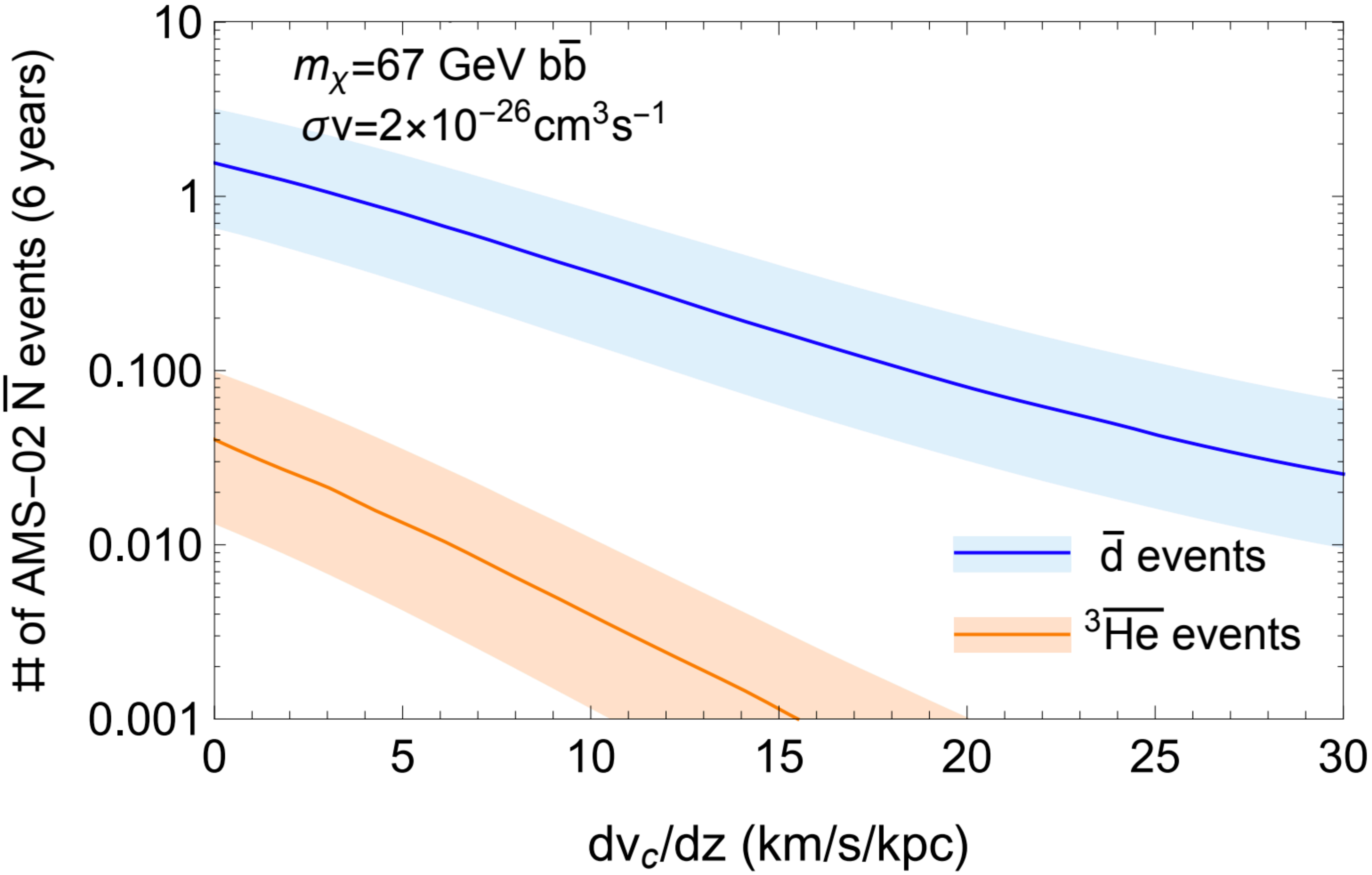
Cholis, Linden, Hooper (2020; 2001.08749)







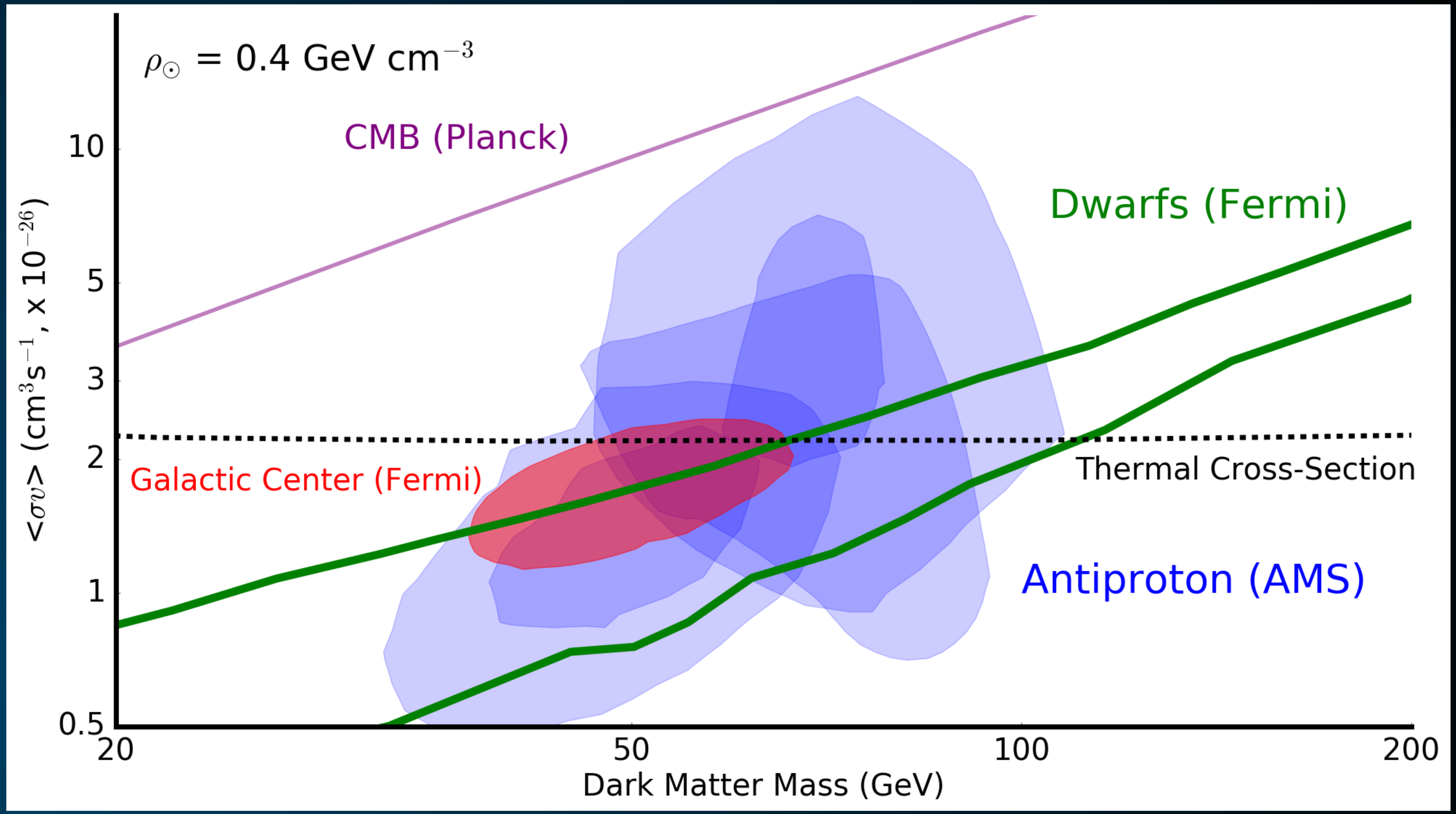
m_χ=67 GeV $b\bar{b}$
σv=2×10^{-26}cm^{3}s^{-1}
# of AMS–02 $\overline{\mathrm{N}}$ events (6 years)
10
5
1
0.50
0.10
0.05
0.01
0
10
20
30
40
50
60
$\bar{d}$ events
$^3\overline{\mathrm{He}}$ events
v_A (km/s)



m_χ=67 GeV $b\bar{b}$
$\sigma v = 2\times10^{-26} cm^3 s^{-1}$
$\bar{d}$ events
$^3\overline{He}$ events
# of AMS−02 $\overline{N}$ events (6 years)
dv_c/dz (km/s/kpc)
10
1
0.100
0.010
0.001
0
5
10
15
20
25
30

$\rho_\odot$ = 0.4 GeV cm^{-3}
CMB (Planck)
Dwarfs (Fermi)
Galactic Center (Fermi)
Thermal Cross-Section
Antiproton (AMS)
<σv> (cm^{3}s^{-1}, x 10^{-26})
Dark Matter Mass (GeV)
10
5
3
2
1
0.5
20
50
100
200

Why are these Methods Important for Antihelium



Coalescence - Essentially predicts the number of quarks that will fuse into anti helium

Λ_b - Antiproton decays were already accounted for by standard models, ability to produce antihelium was not known.

Dark Sectors - Antiproton production is small due to heavy DM mass. Antihelium is enhanced (compared to typical rates for heavy dark matter, ~O(10^6).

Reacceleration - Important when the particle is very low energy (from coalescence) and also has charge +2 (antihelium specific)

Courtesy NASA/JPL-Caltech

ANTINUCLEI IN THE UNIVERSE?

7 February - 4 March 2022

Kfir Blum, Laura Fabbietti, Alejandro Ibarra, Stephan Paul, Stefan Schael

- Slides (and even many talks) are online.

Synergy between Indirect Detection and Colliders

Cross section measurements at NA61

Anirvan Shukla
University of Hawaii at Manoa

MIAPP - Antinuclei in the Universe

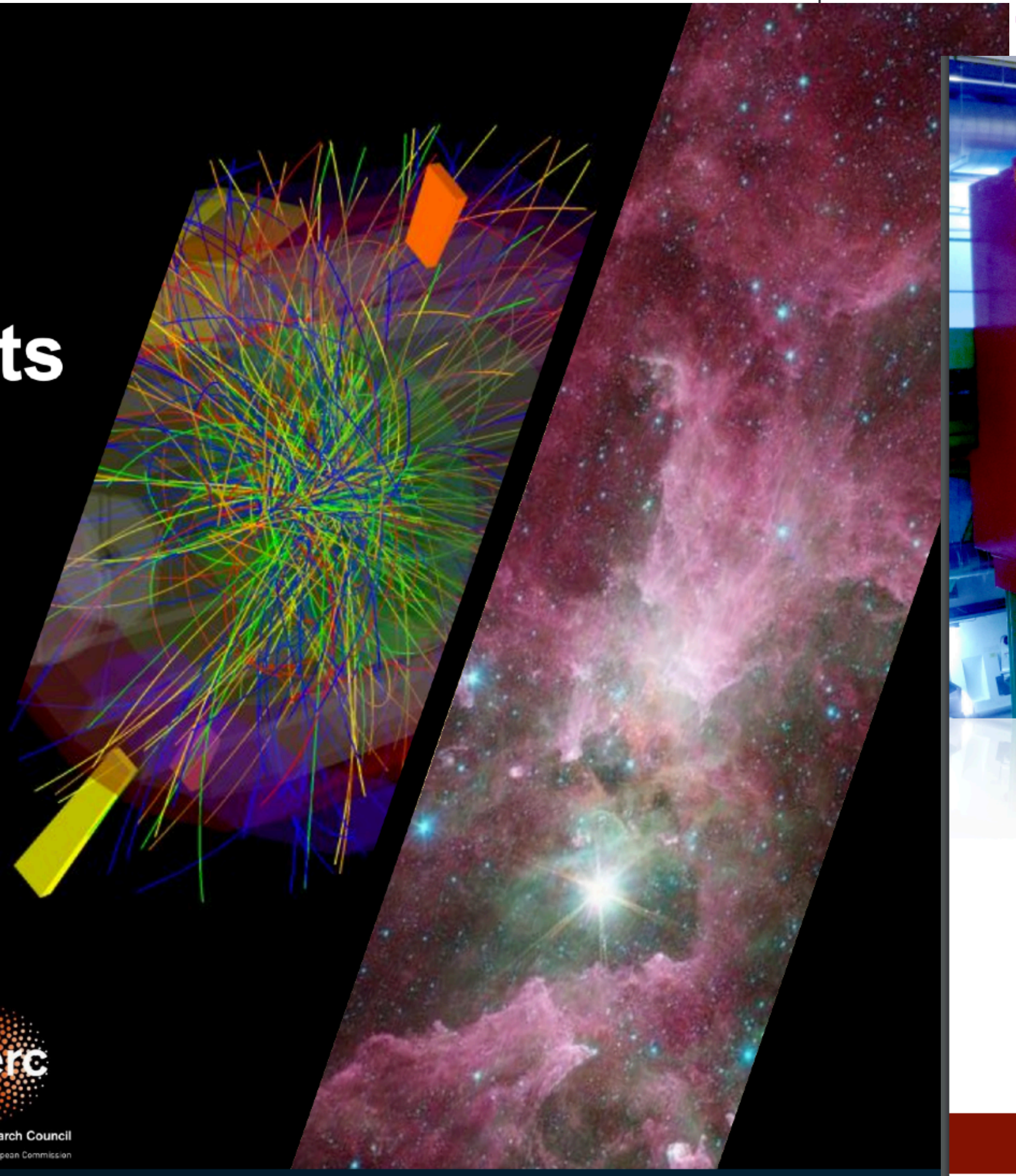
INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

(some plots about) detecting $\bar{\mathrm{d}}$ at BelleII

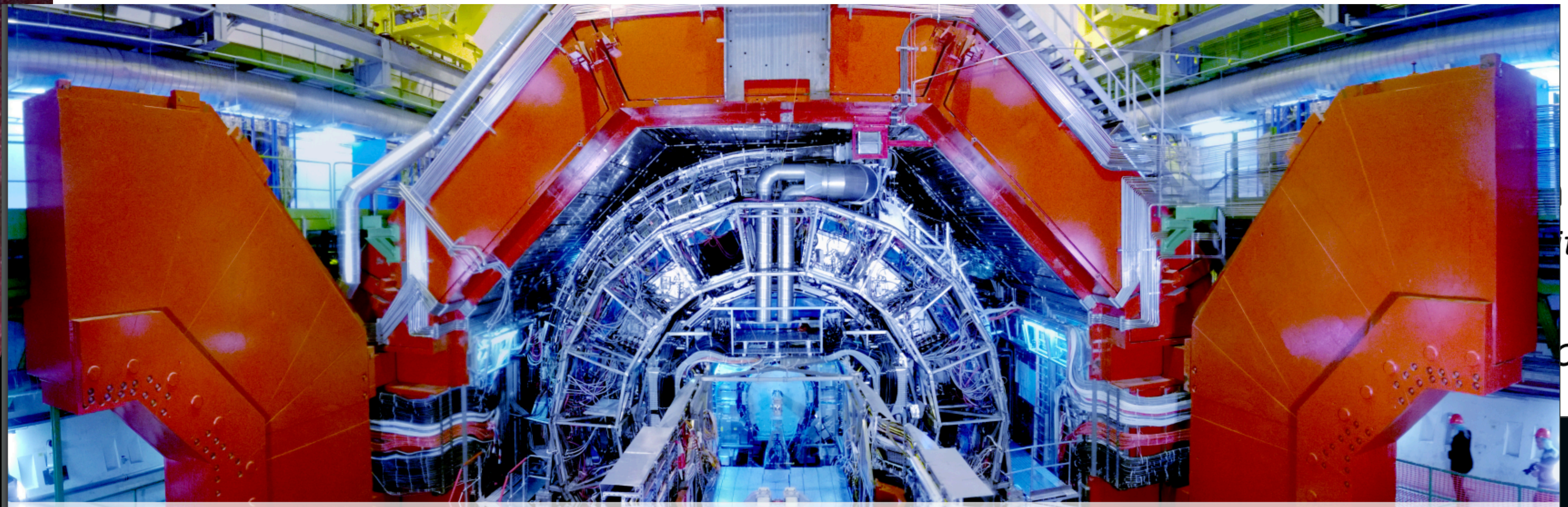
(Anti)nuclei measurements at accelerators

F. Bellini (University of Bologna and INFN)

MIAPP's "Antinuclei in the Universe?"
8th February 2022



ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA · INFN · CosmicAntiNuclei · erc European Research Council



Measuring non-prompt antinuclei production in high energy collisions

Maximiliano Puccio (CERN)
with huge help and inputs by A. Kalweit and F. Grosa

MIAPP Antinuclei in the universe — 9th February 2022

Conclusions

These are non-standard approaches. Even if dark matter is a WIMP, it may not produce antihelium.

However, if antihelium is detected, these are among the most reasonable methods for producing such an exotic particle.

All of these avenues are experimentally testable with upcoming colliders.