

Enhanced Cosmic-Ray Antinuclei Fluxes with Dark Matter Annihilation into SUEPs

Based on 2602.15132 (with M. Di Mauro, A. Batz, D. Curtin,
F. Donato, N. Fornengo, G. Kribs)

Caleb Gemmell
Phenomenology Symposium
University of Pittsburgh, 12th May 2026



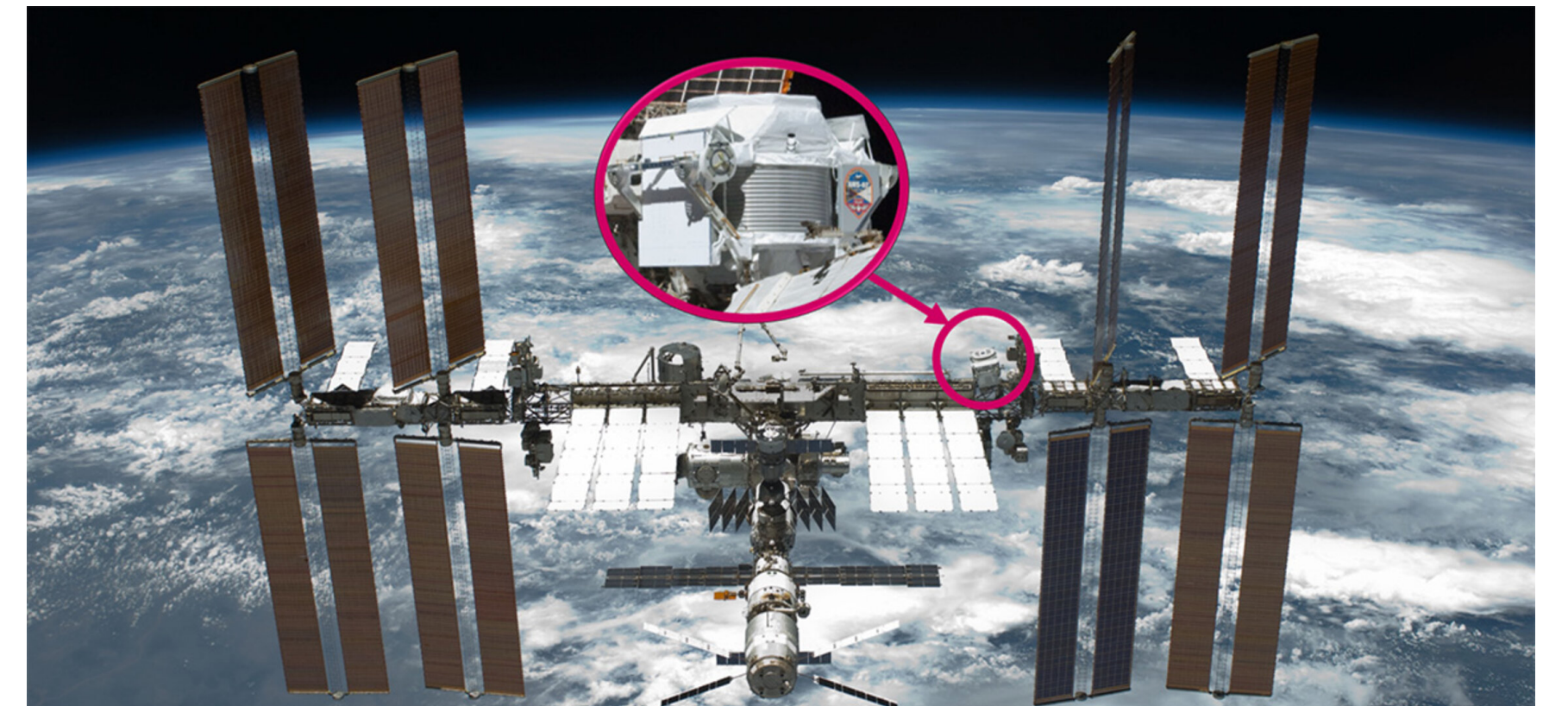
- **The AMS-02 Antinuclei “Anomaly”**
- **Antinuclei production and Coalescence**
- **Soft Unclustered Energy Patterns (SUEPs)**
- **Observational Enhancement**
 - **AMS-02**
 - **GAPS**



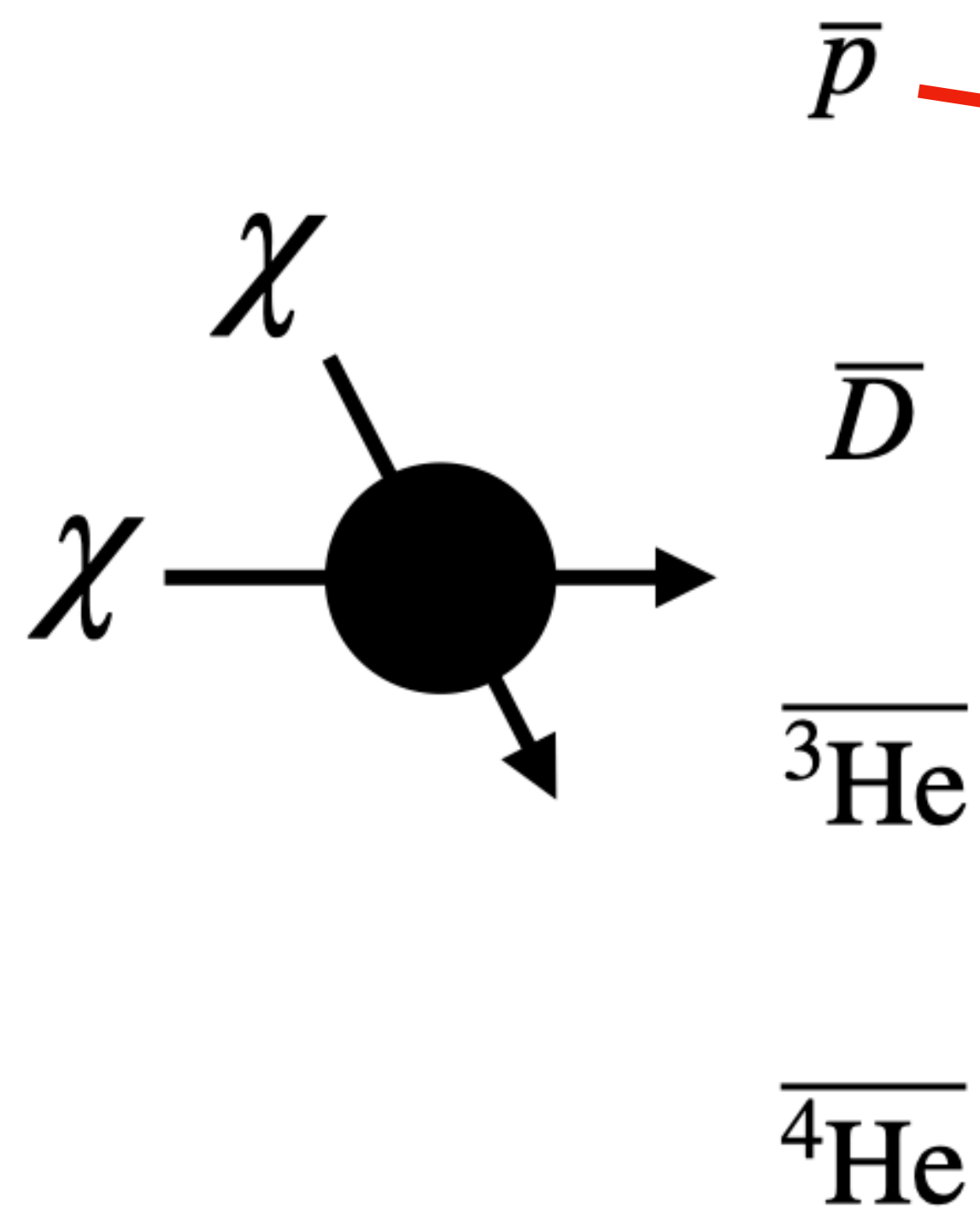
The AMS-02 Antinuclei “Anomaly”

AMS-02

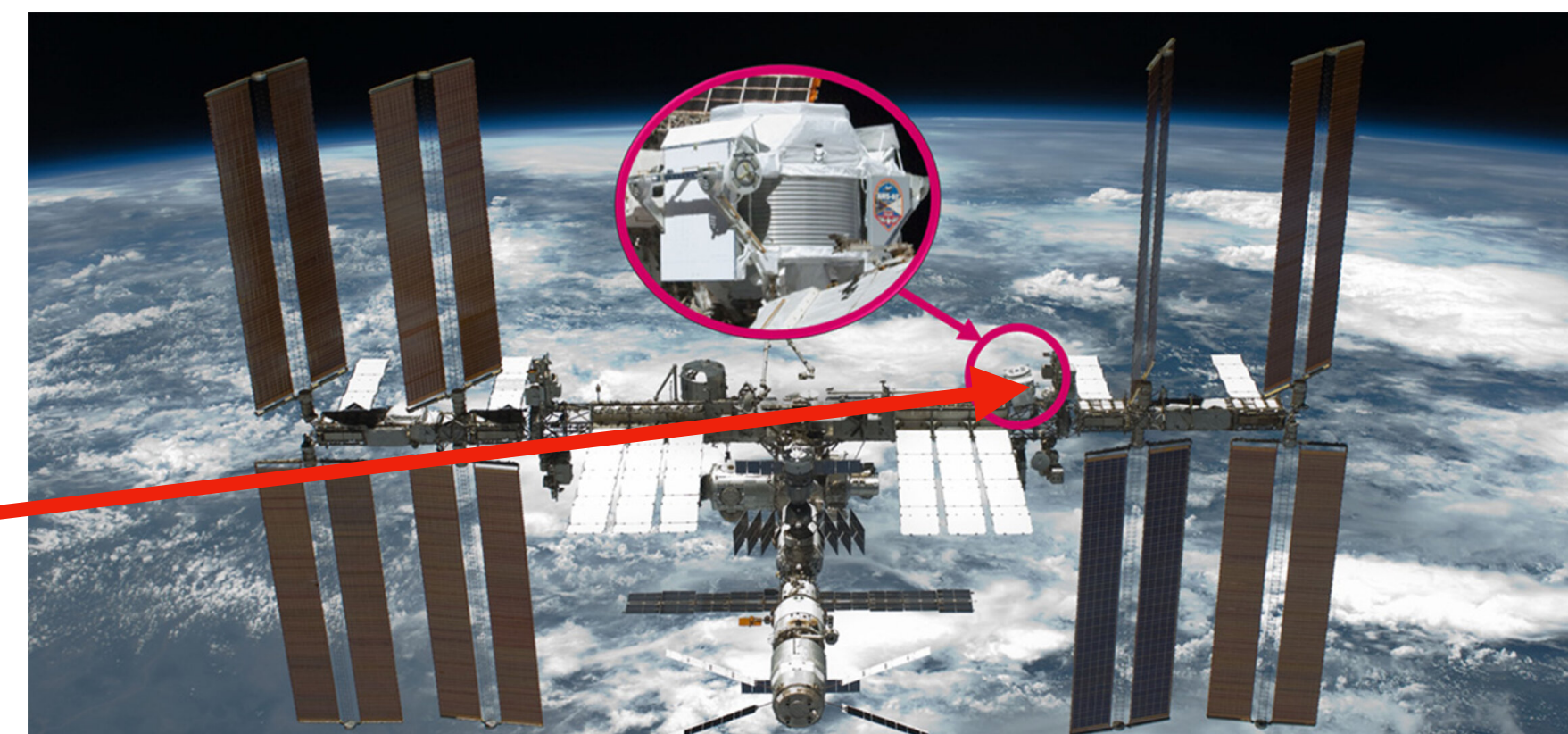
Cosmic Ray Detector on the ISS



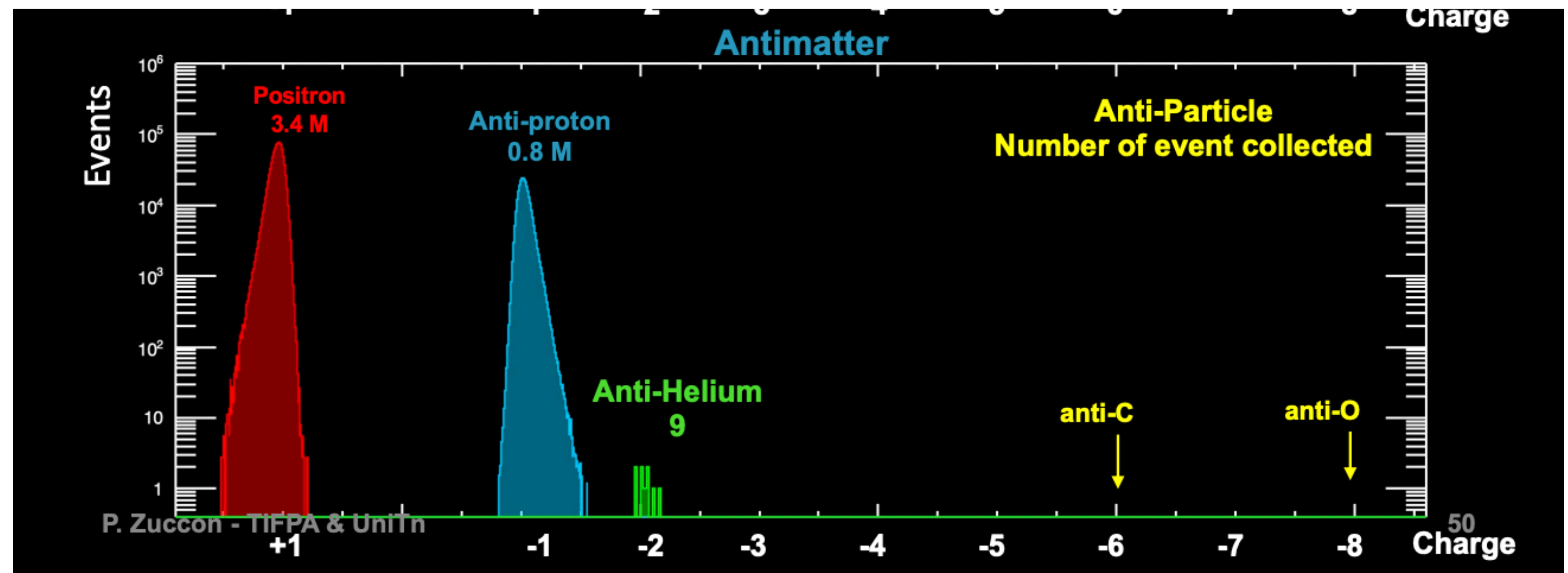
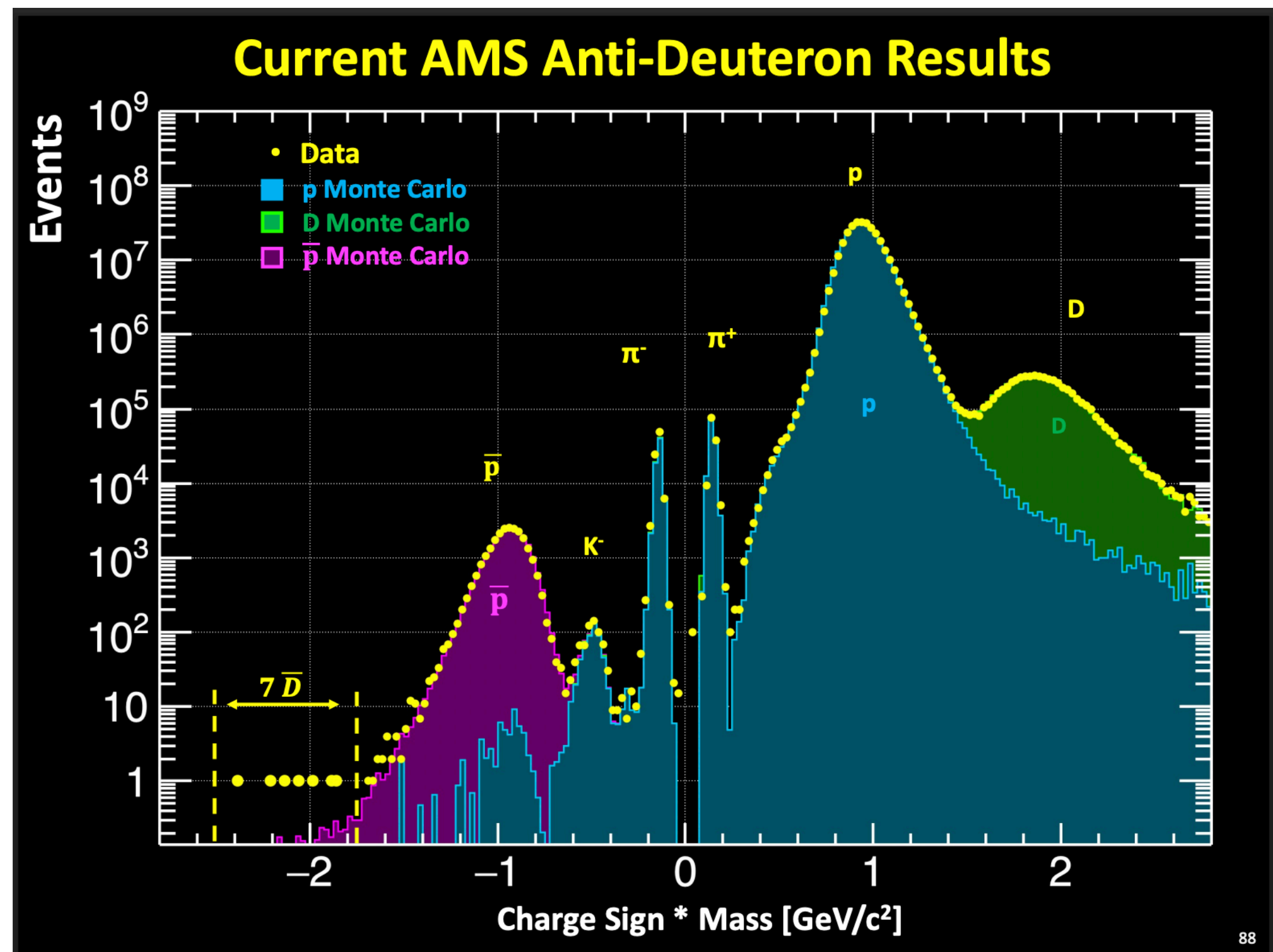
AMS-02



Cosmic Ray Detector on the ISS



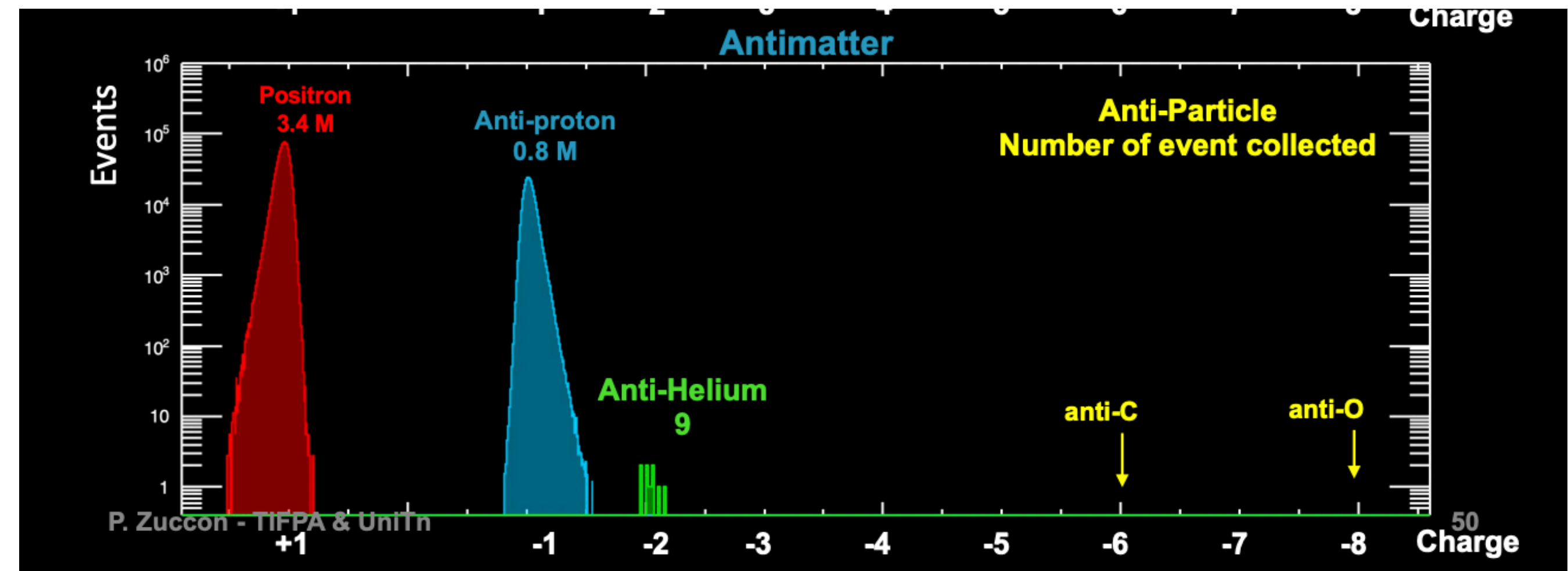
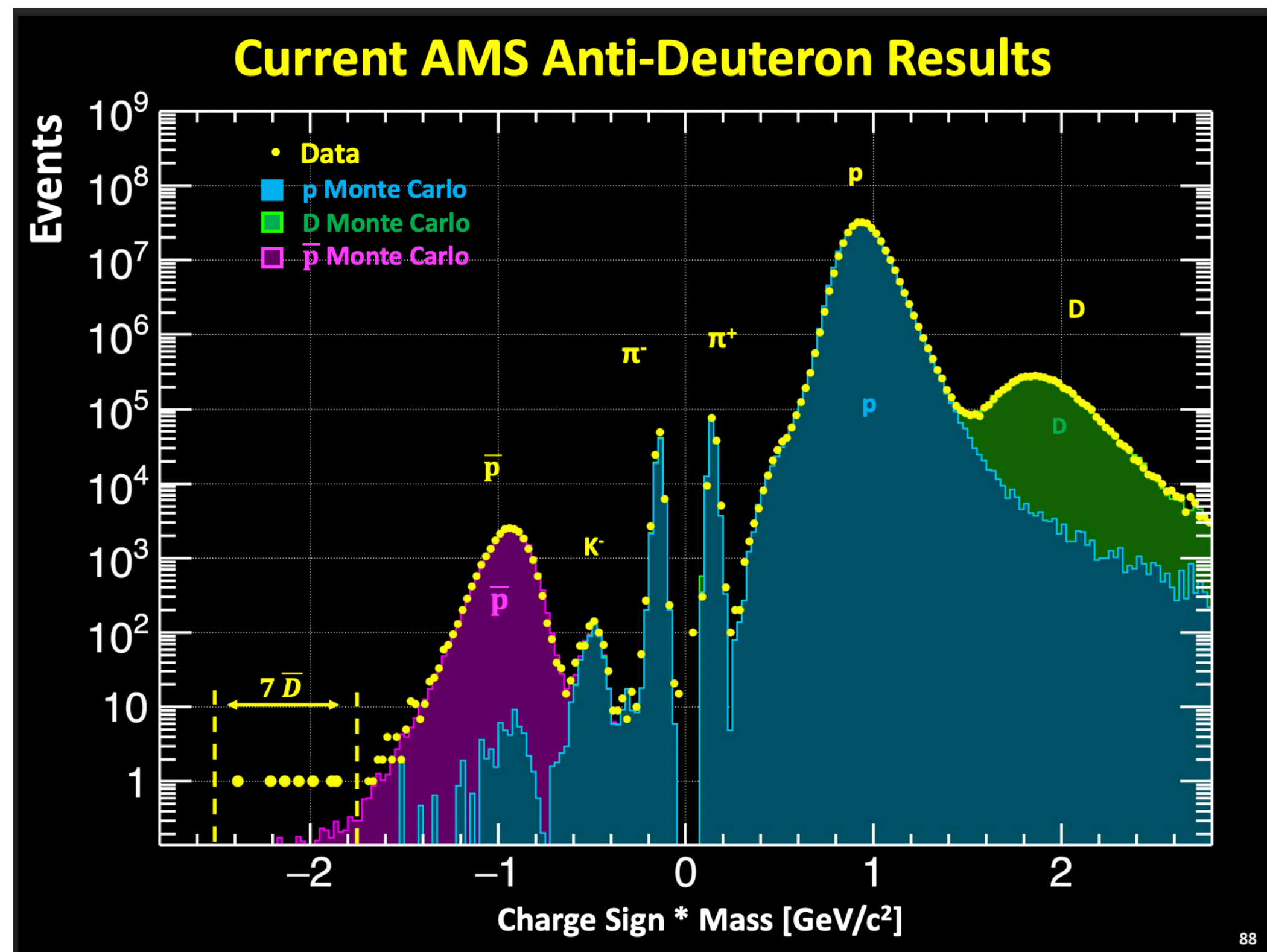
AMS-02 Antinuclei “Anomaly”



P. Zuccon, AMS-02 results & upgrade, conference presentation at MIAPbP conference ‘Antinuclei in the Universe?’, February 28, 2022

S. Ting, Latest Results from the AMS Experiment on the International Space Station, CERN colloquium presentation, June 8, 2023

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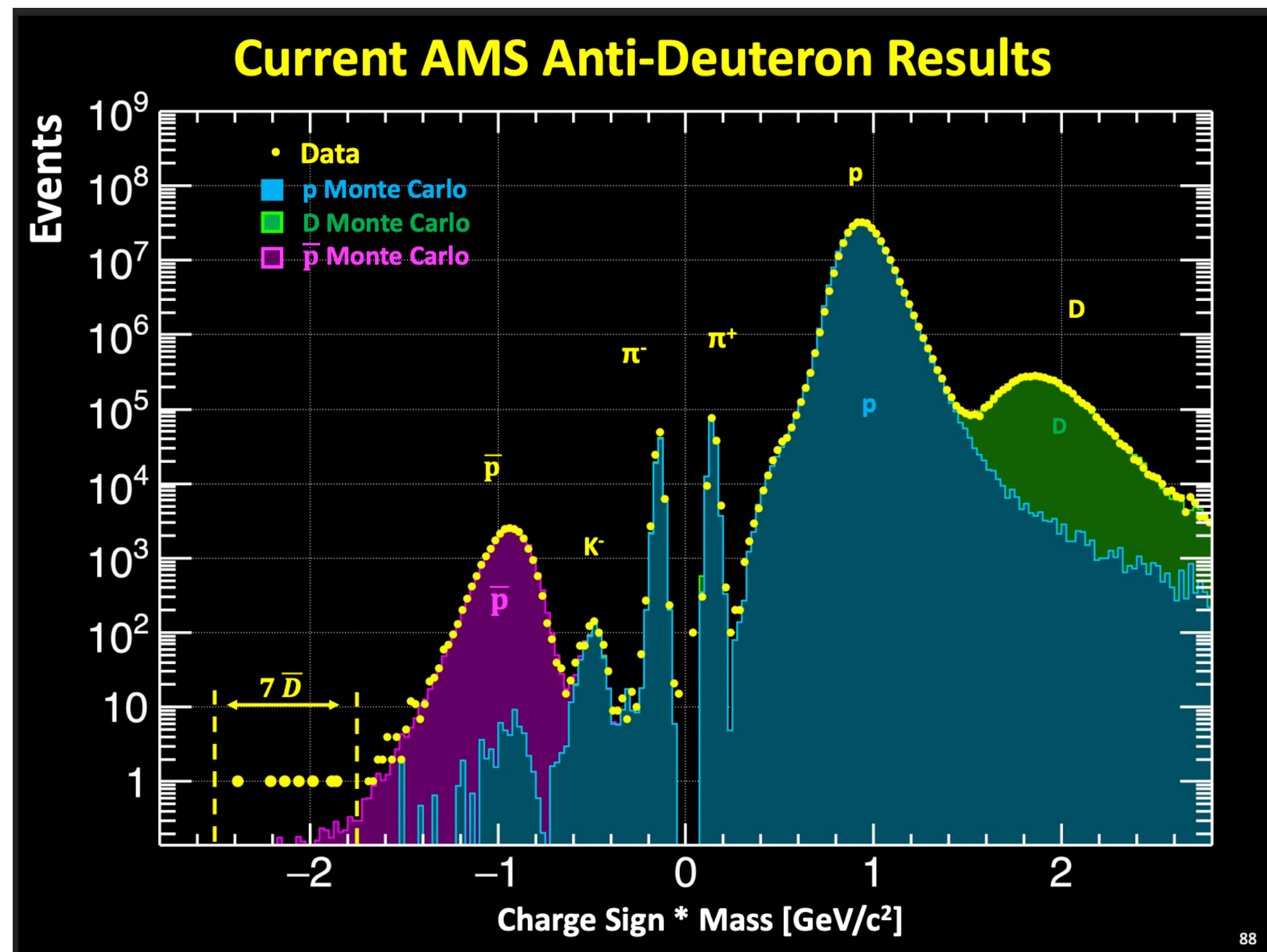


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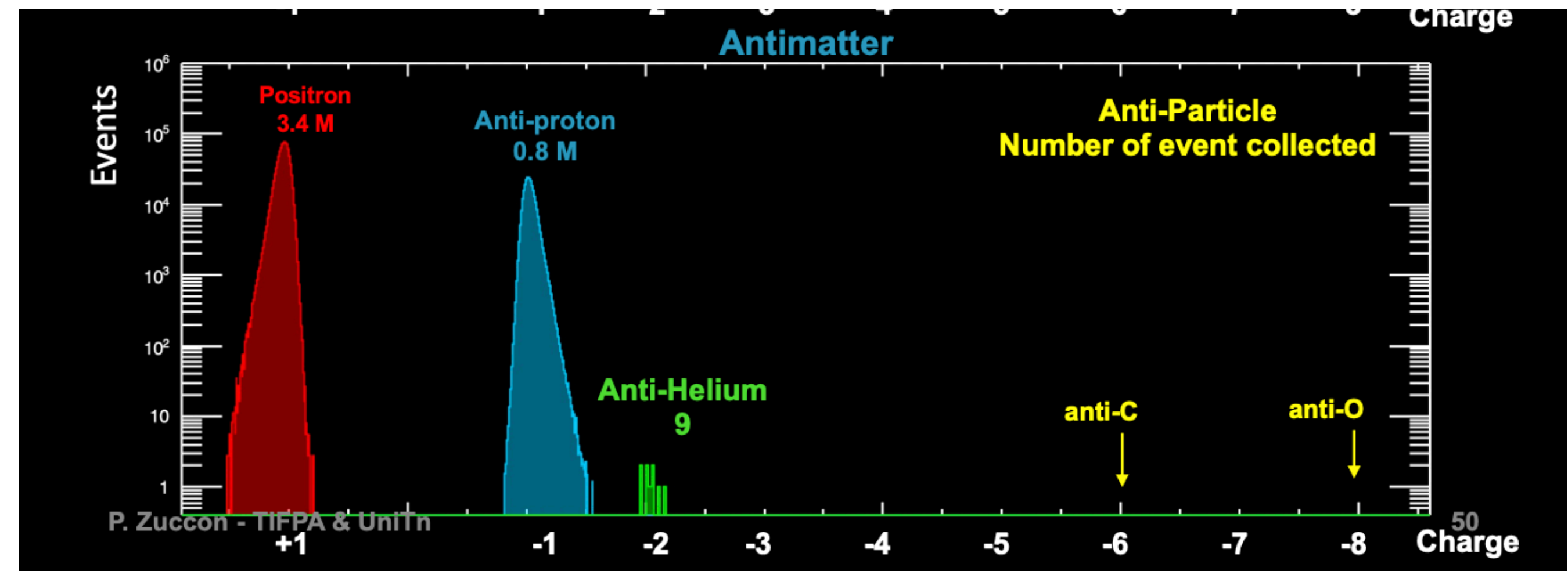
- **Very hard to explain these events with standard astrophysical backgrounds, spallation off interstellar medium**

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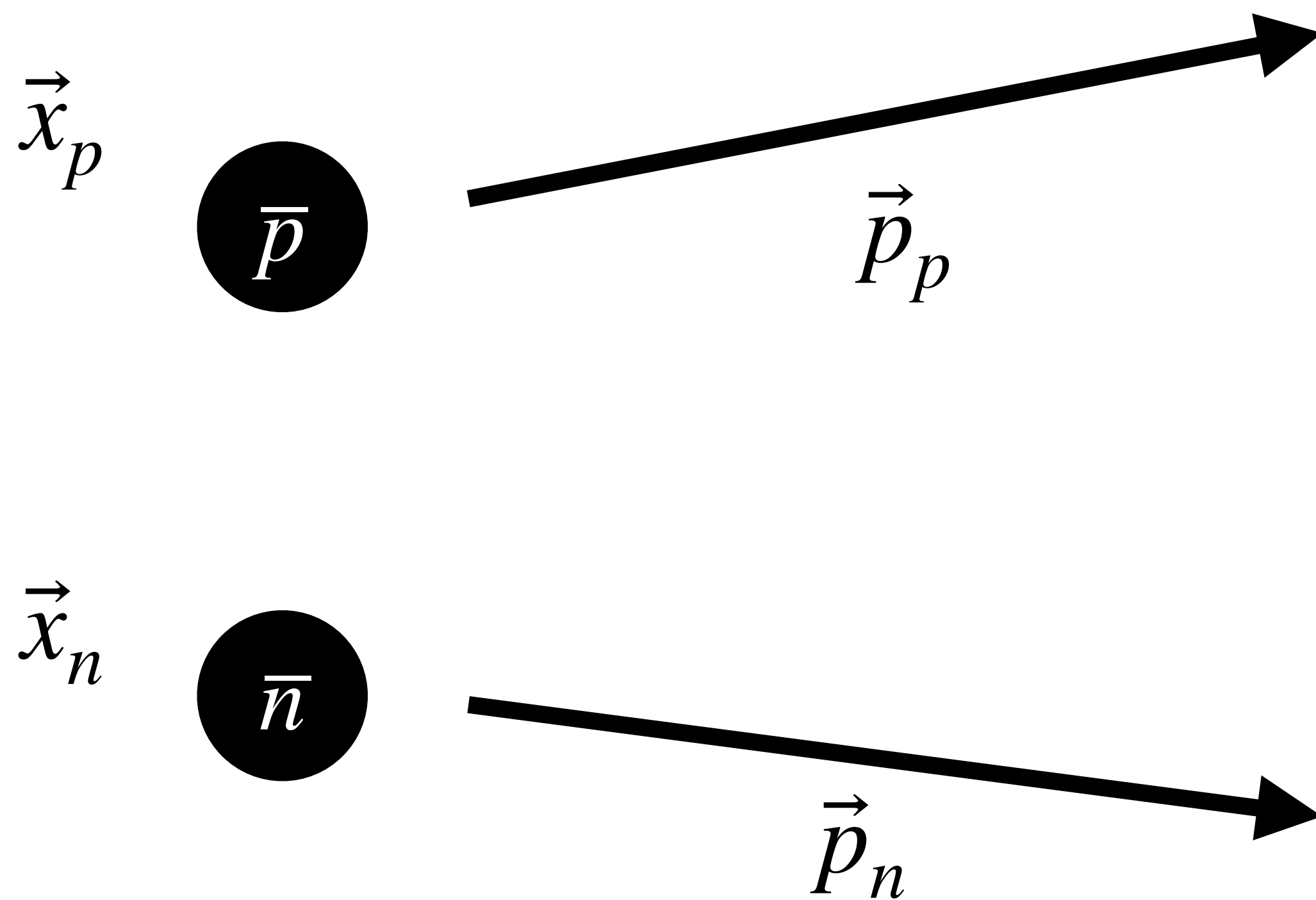
- **Very hard to explain these events with standard astrophysical backgrounds, spallation off interstellar medium**
- **Also hard to explain these events with standard DM annihilation... relative multiplicities $\sim 10^{-4}$ due to phase space**



Antinuclei production and Coalescence

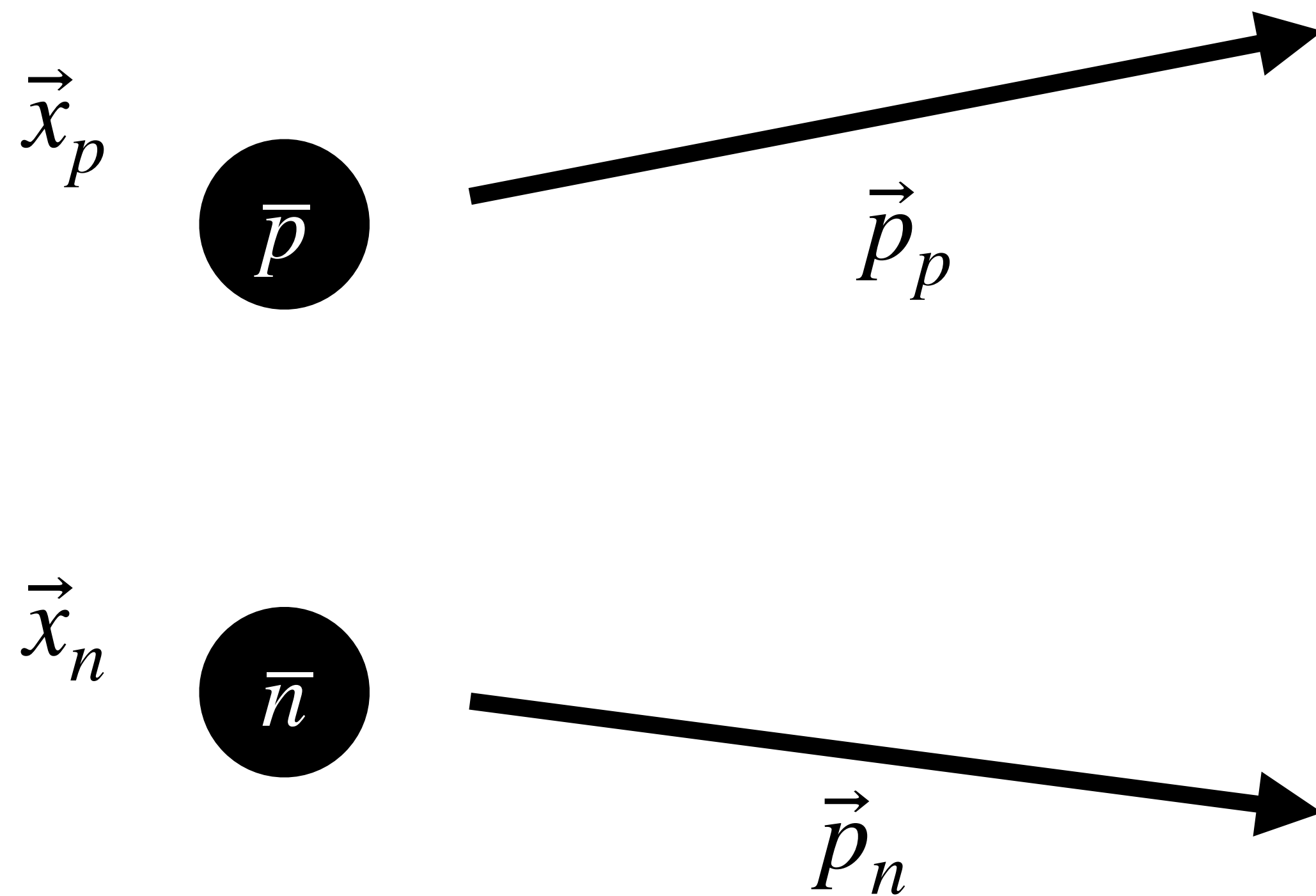
Coalescence Model

* in antideuteron frame



Coalescence Model

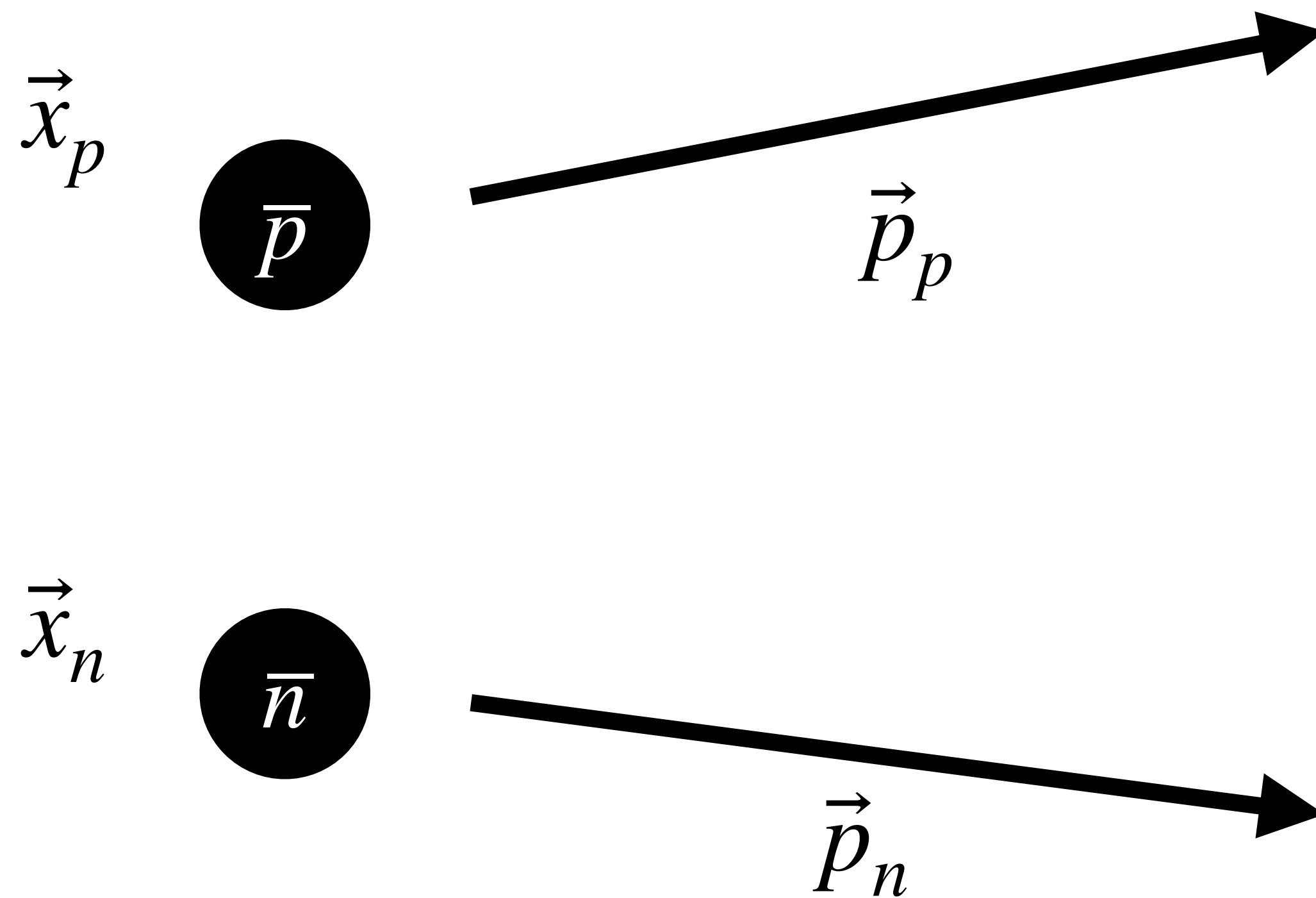
* in antideuteron frame



$$|\vec{x}_p - \vec{x}_n| < 3 \text{ fm}$$

Coalescence Model

* in antideuteron frame

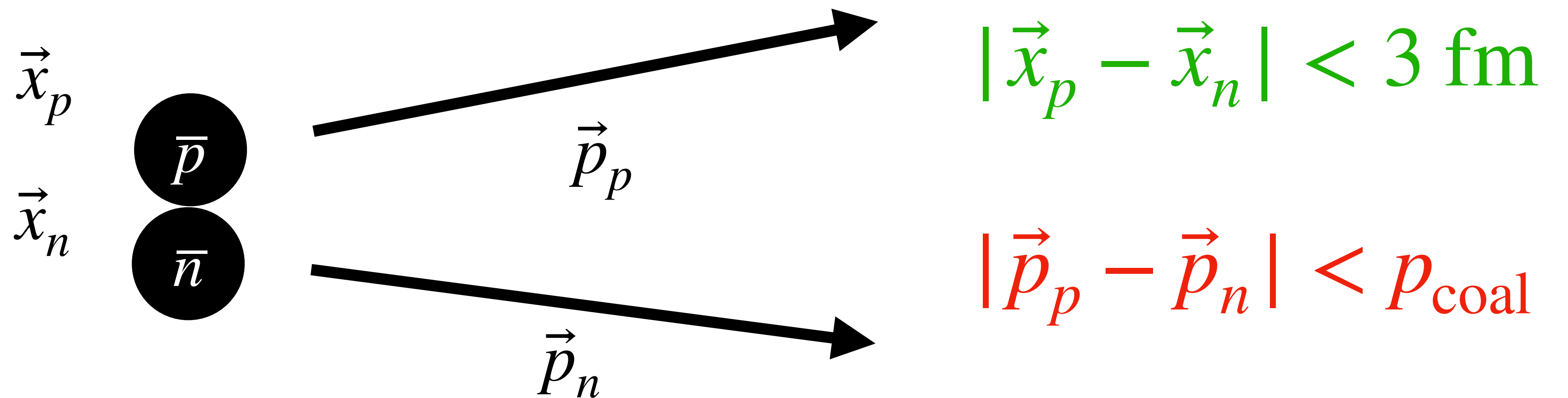


$$|\vec{x}_p - \vec{x}_n| < 3 \text{ fm}$$

$$|\vec{p}_p - \vec{p}_n| < p_{\text{coal}}$$

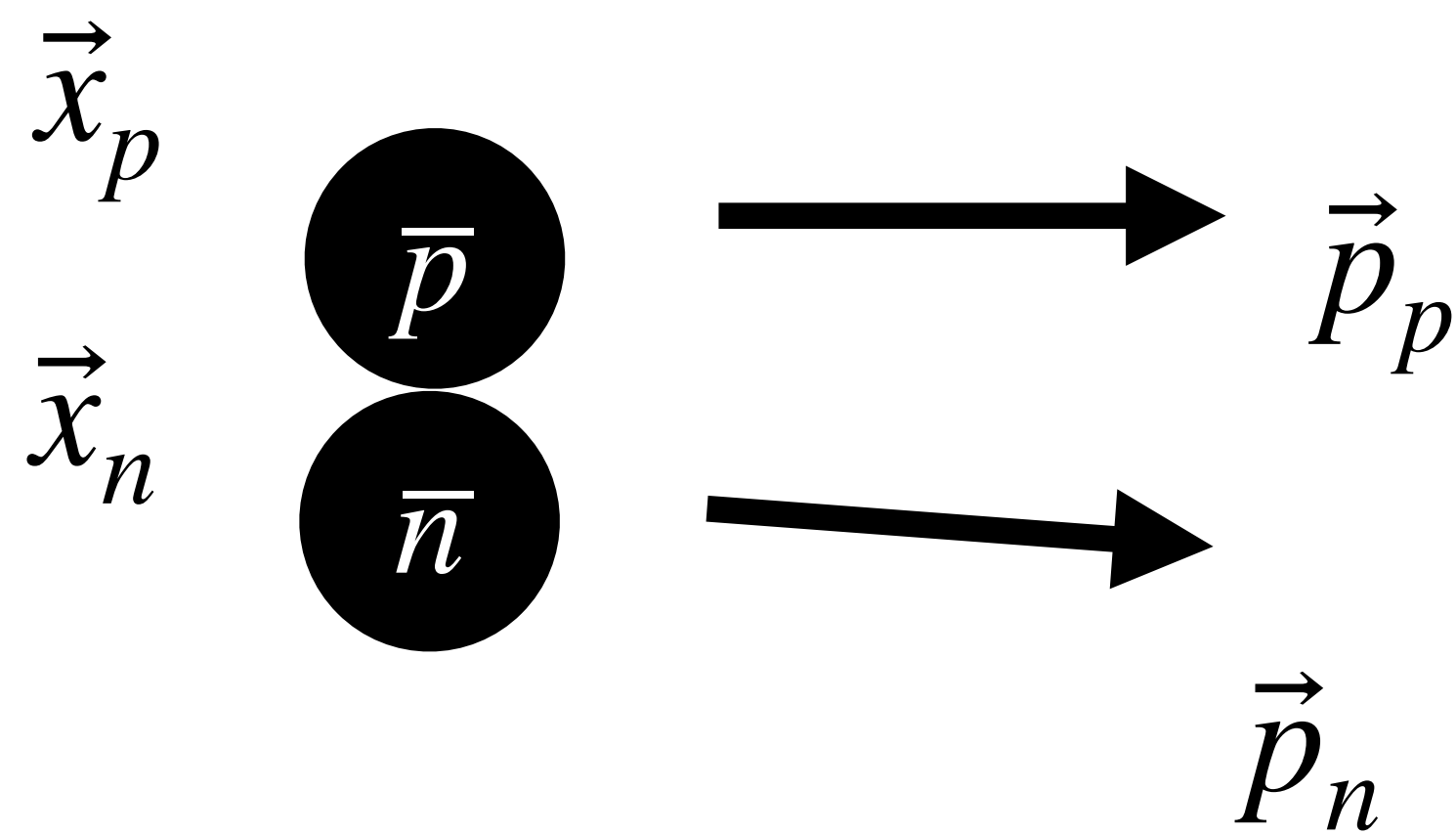
Coalescence Model

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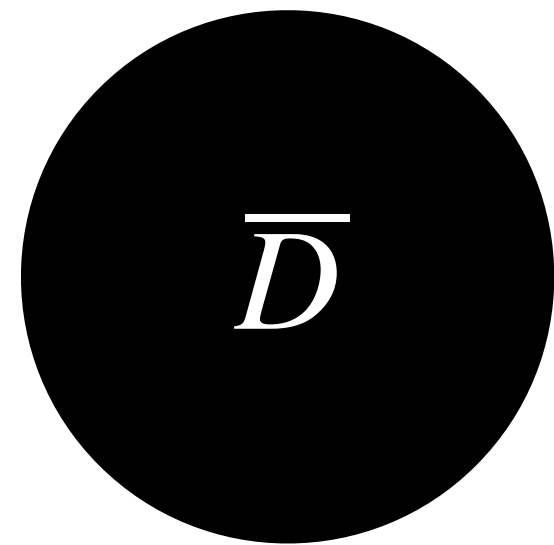


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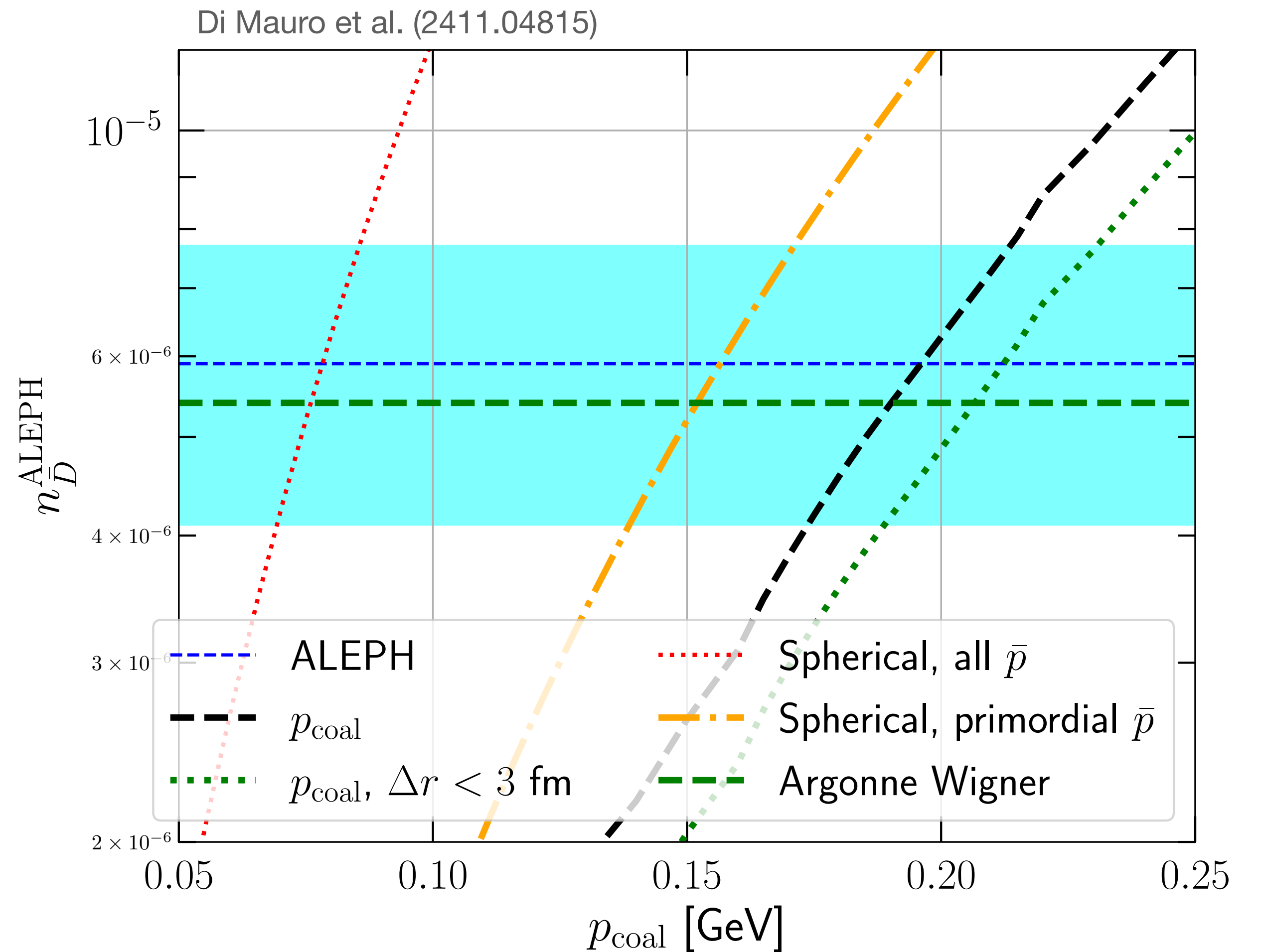


$$|\vec{x}_p - \vec{x}_n| < 3 \text{ fm}$$

$$|\vec{p}_p - \vec{p}_n| < p_{\text{coal}}$$

Coalescence Model

- **Tuned to data by selecting cutoff coalescence momentum**
- **Can boost antinuclei production by:**
 - **softening antinucleon momenta**
 - **reducing interparticle distances (increase number of antinucleons)**

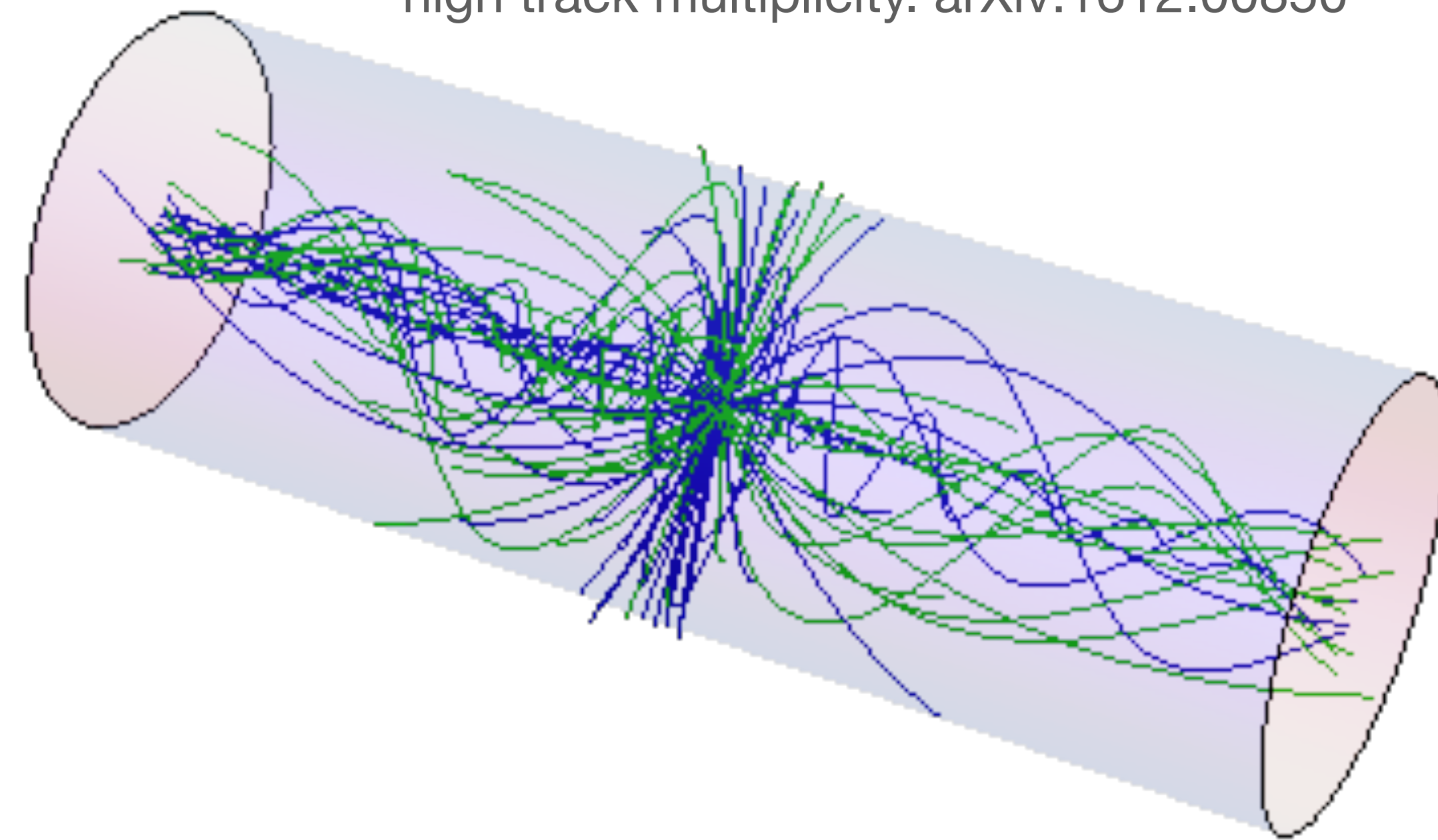


Soft Unclustered Energy Patterns

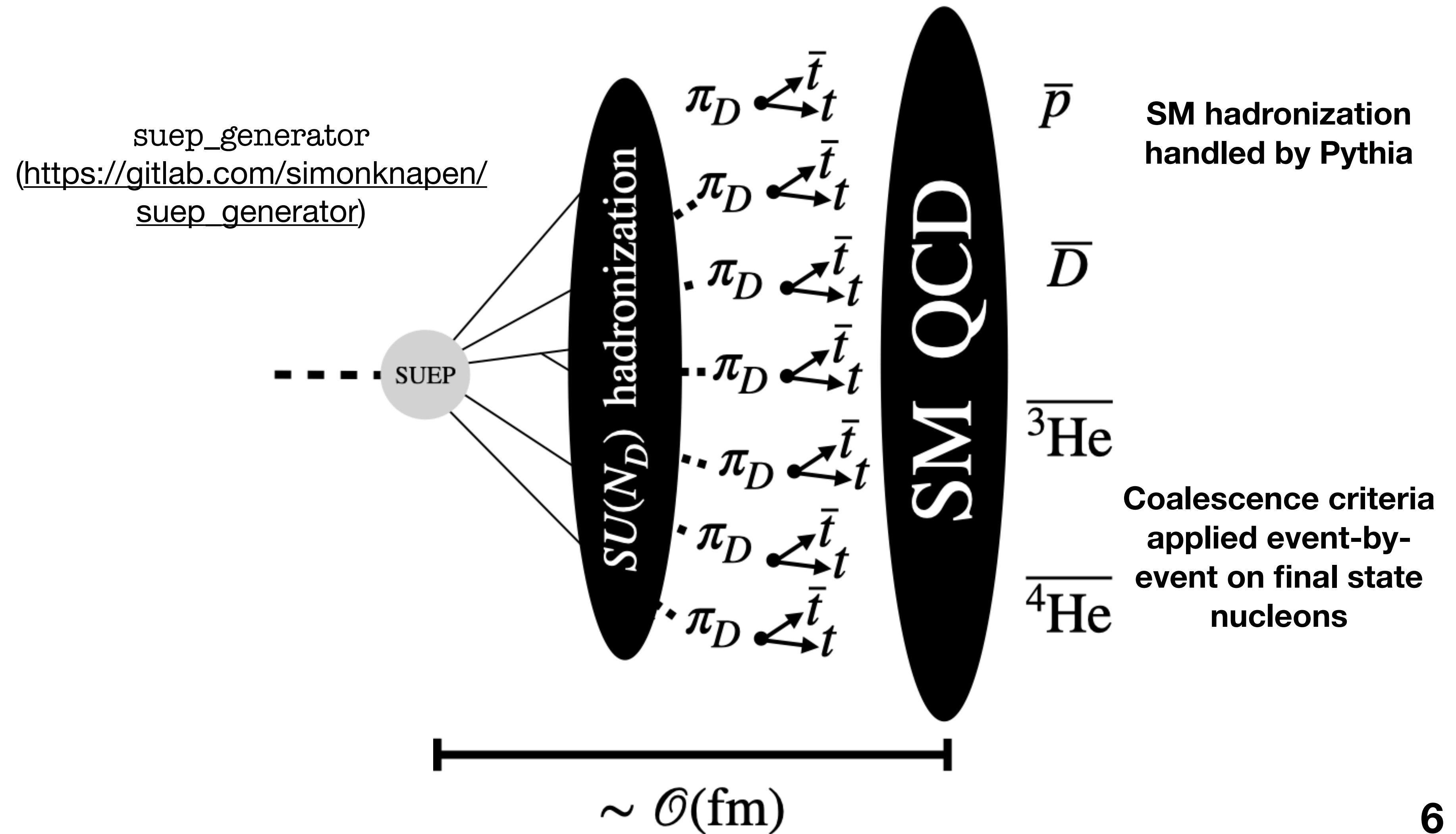
Soft Unclustered Energy Patterns (SUEPs)

- Characterised by a high multiplicity of final state dark hadrons, resulting in soft momenta and an isotropic distribution
- Arise in confining theories with large 't Hooft coupling, $\lambda = g^2 N_c > 1$
- Unsuppressed soft and collinear emission
- An example of a non-QCD-like dark sector that can arise in theories of neutral naturalness

Example SUEP event in a collider, high track multiplicity. arXiv:1612.00850



Soft Unclustered Energy Patterns (SUEPs)

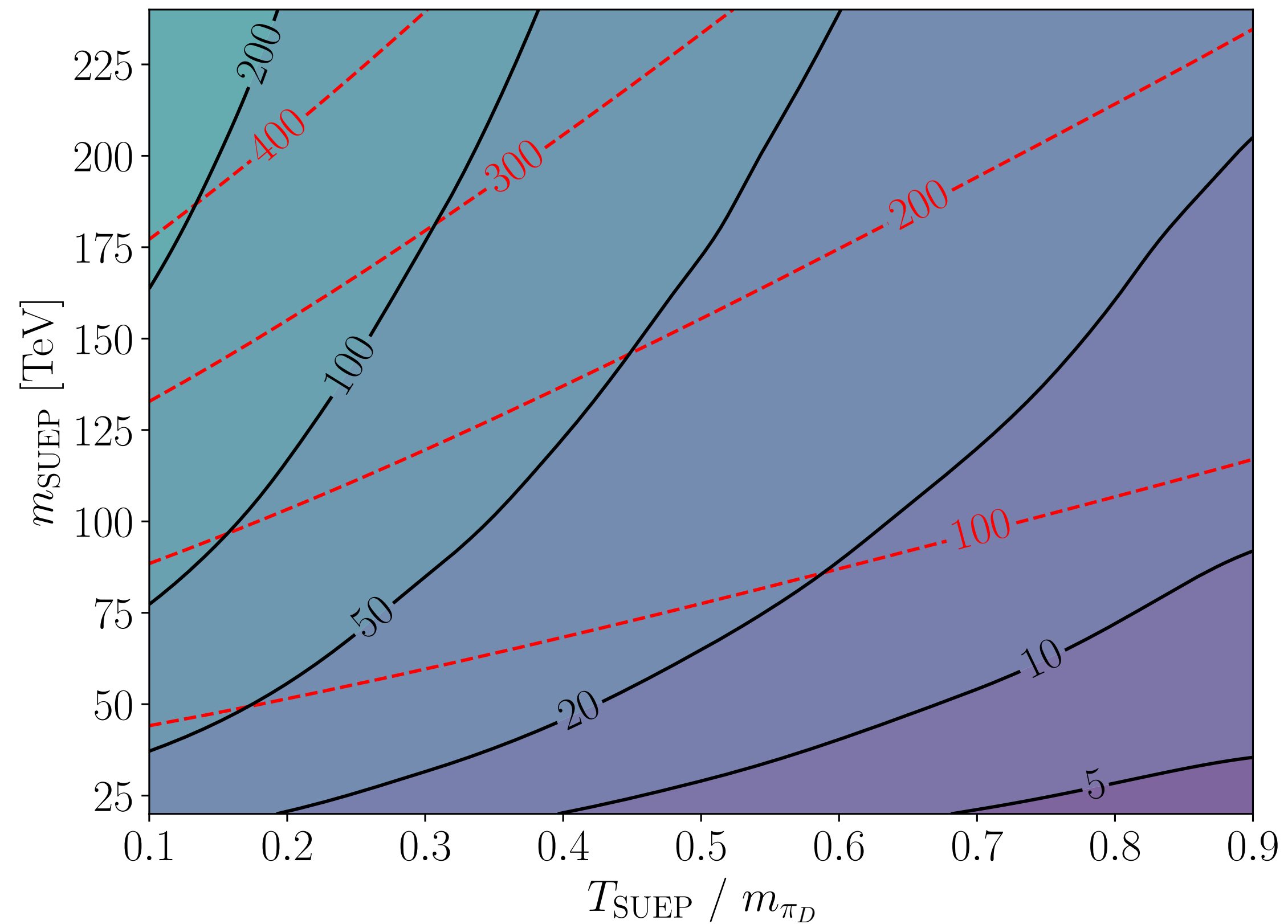


Parameters:

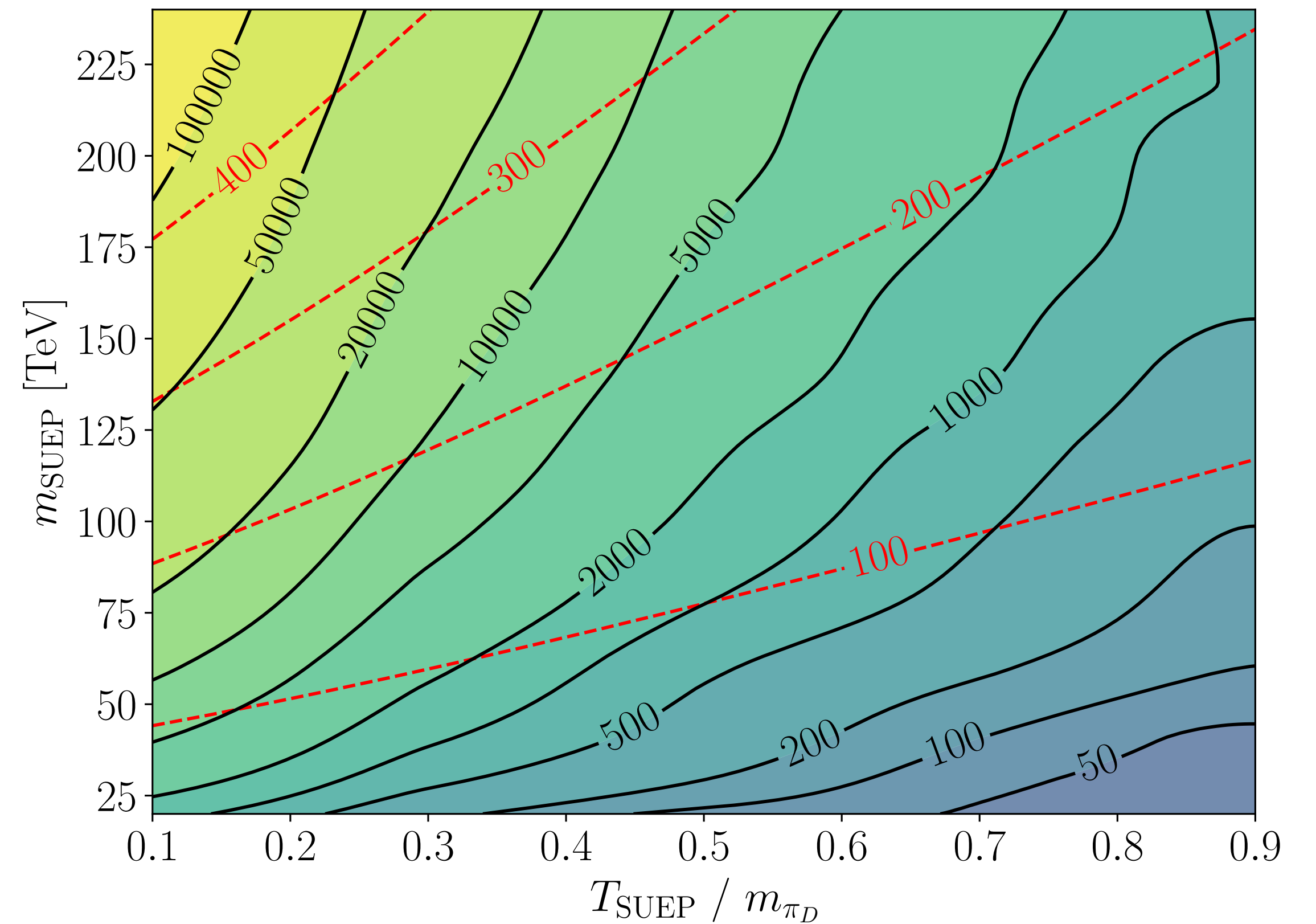
$$\{ m_{\text{SUEP}}, T_{\text{SUEP}} \}$$

Soft Unclustered Energy Patterns (SUEPs)

Antideuteron



Antihelium-3



Large SUEP mass / small SUEP temperature \rightarrow Large dark pion multiplicity \rightarrow Large antinuclei enhancement

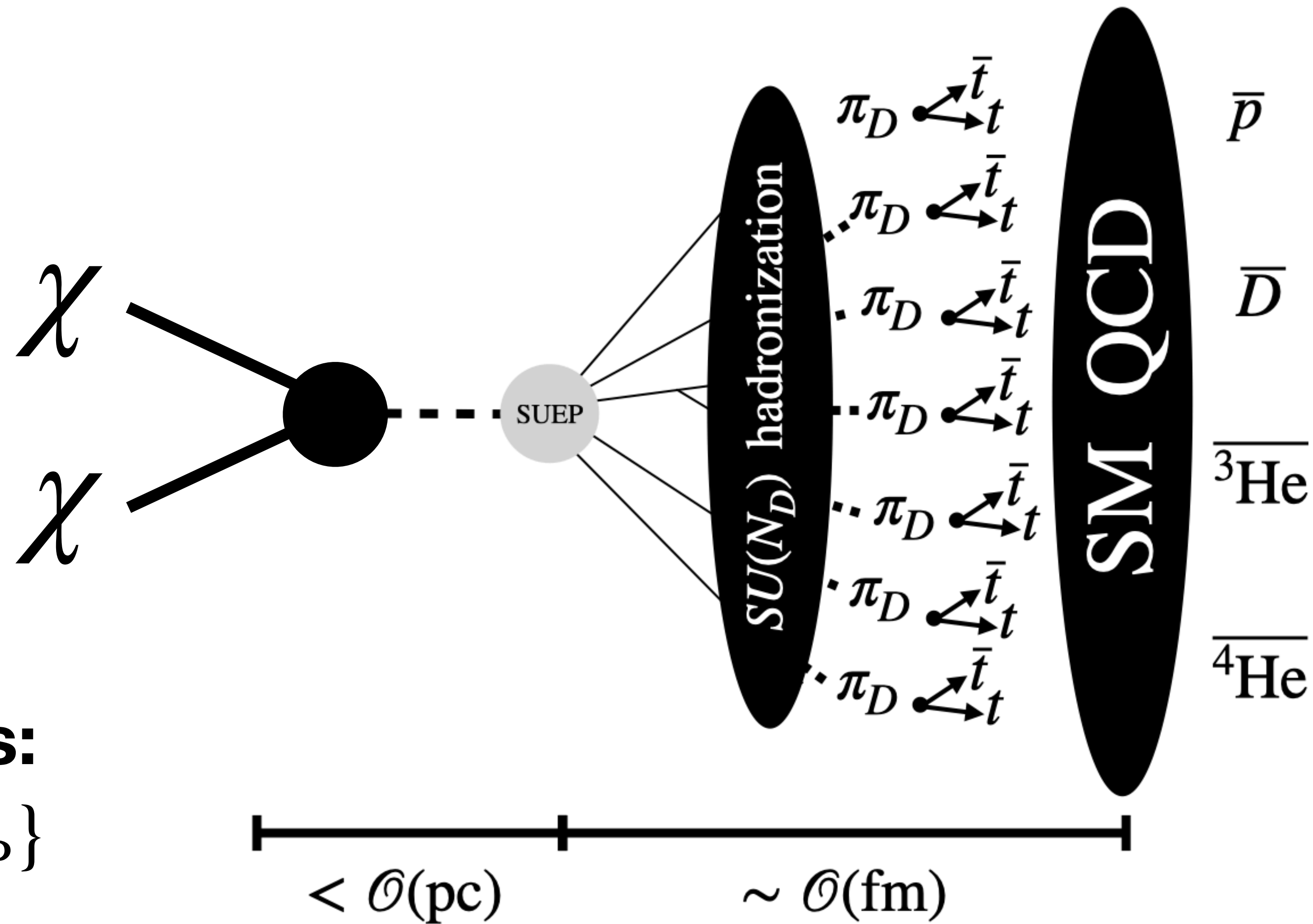
Soft Unclustered Energy Patterns (SUEPs)

Consider two cases:

1. One SUEP

- **DM annihilates to an off-shell SUEP mediator, $m_{\text{DM}} < m_{\text{SUEP}}$**
- **Large multiplicity set by DM mass**

Soft Unclustered Energy Patterns (SUEPs)



Soft Unclustered Energy Patterns (SUEPs)

Consider two cases:

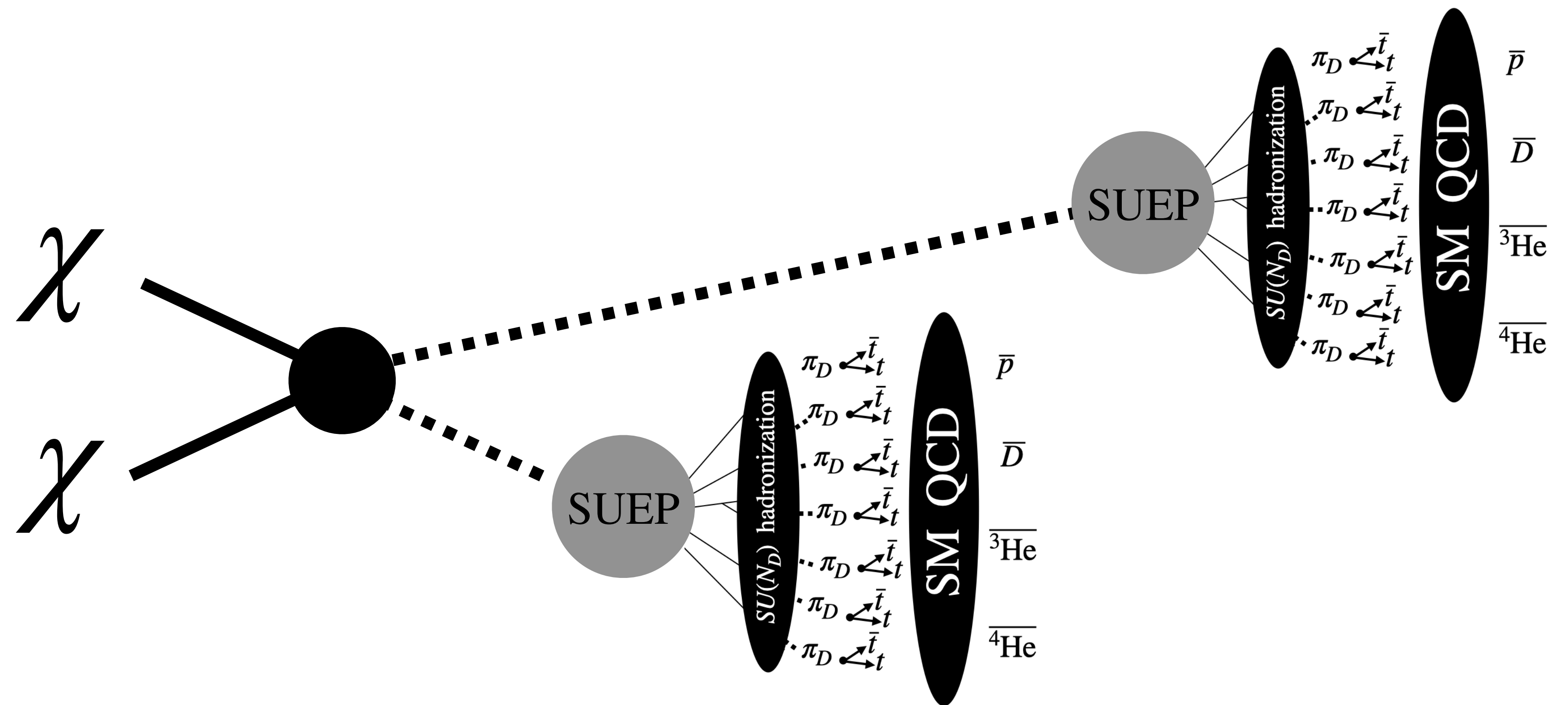
1. One SUEP

- **DM annihilates to an off-shell SUEP mediator, $m_{\text{DM}} < m_{\text{SUEP}}$**
- **Large multiplicity set by DM mass**

2. Two SUEP

- **DM annihilates to two on-shell SUEP particles which then decay, $m_{\text{SUEP}} \leq m_{\text{DM}}$**
- **Comparatively boosted final spectra, multiplicity set by SUEP mass**

Soft Unclustered Energy Patterns (SUEPs)



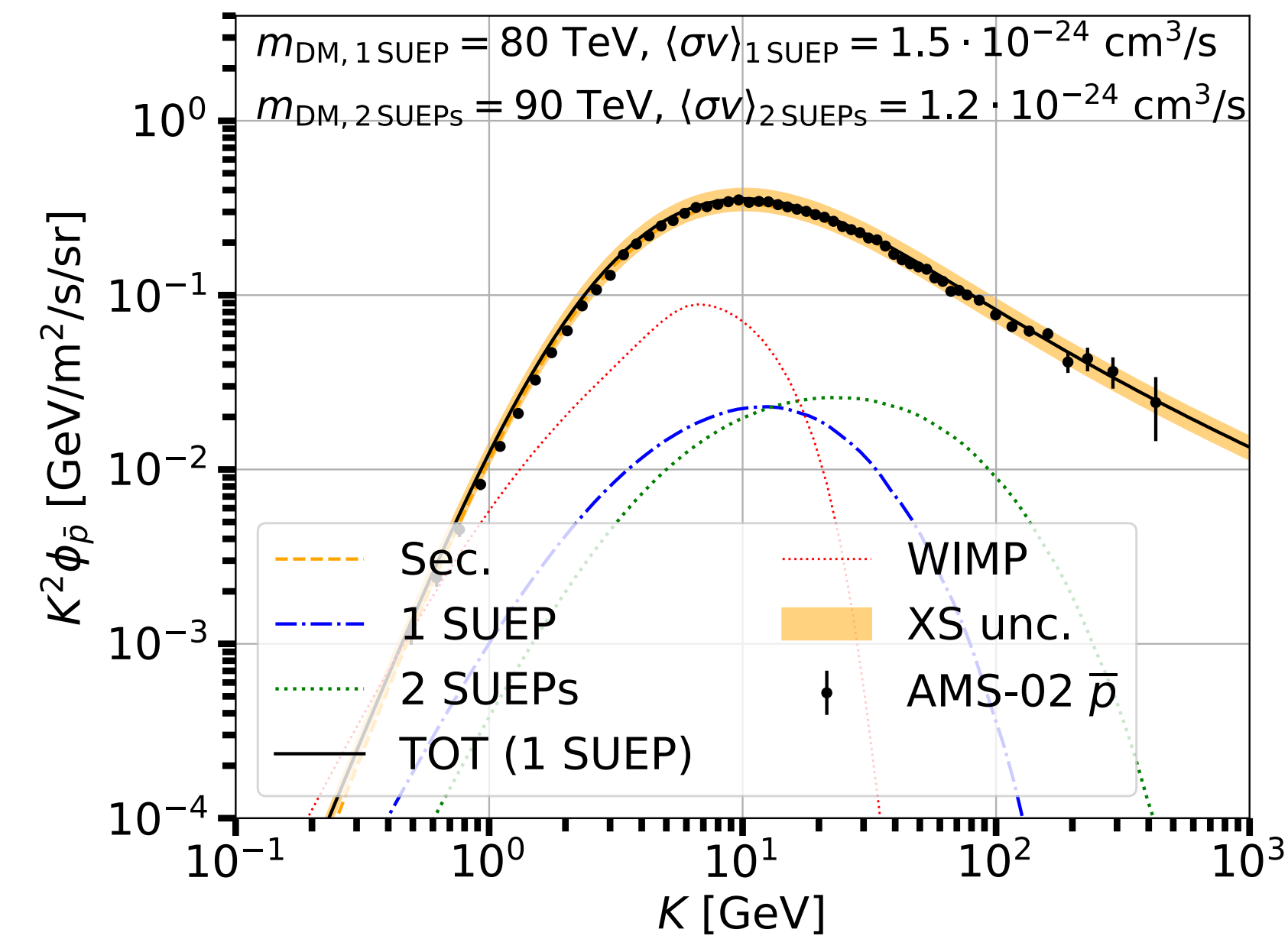
Parameters:

$$\{m_{\text{DM}}, m_{\text{SUEP}}, T_{\text{SUEP}}\}$$

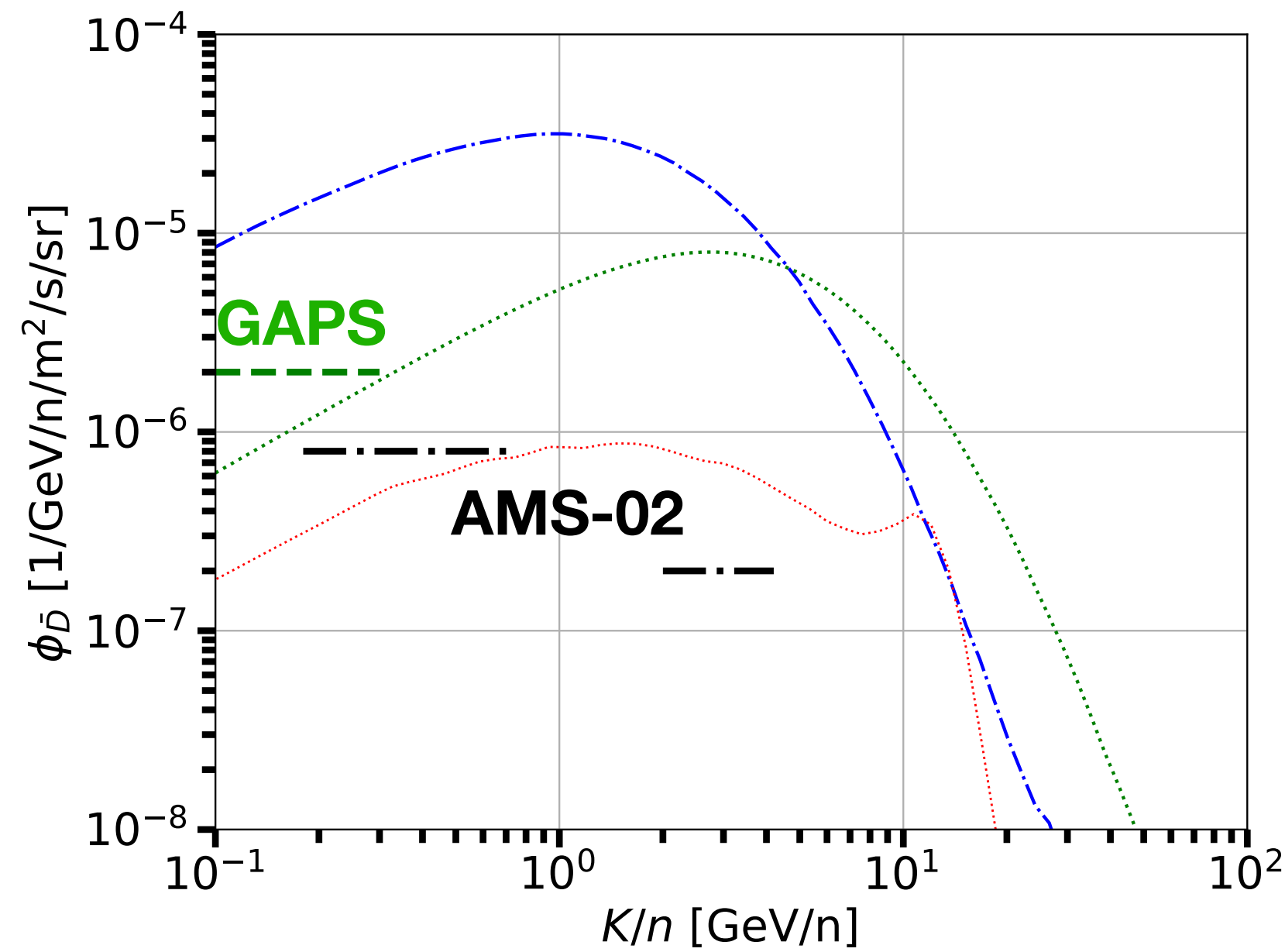
Antinuclei Enhancement at AMS-02

Antinuclei Spectra

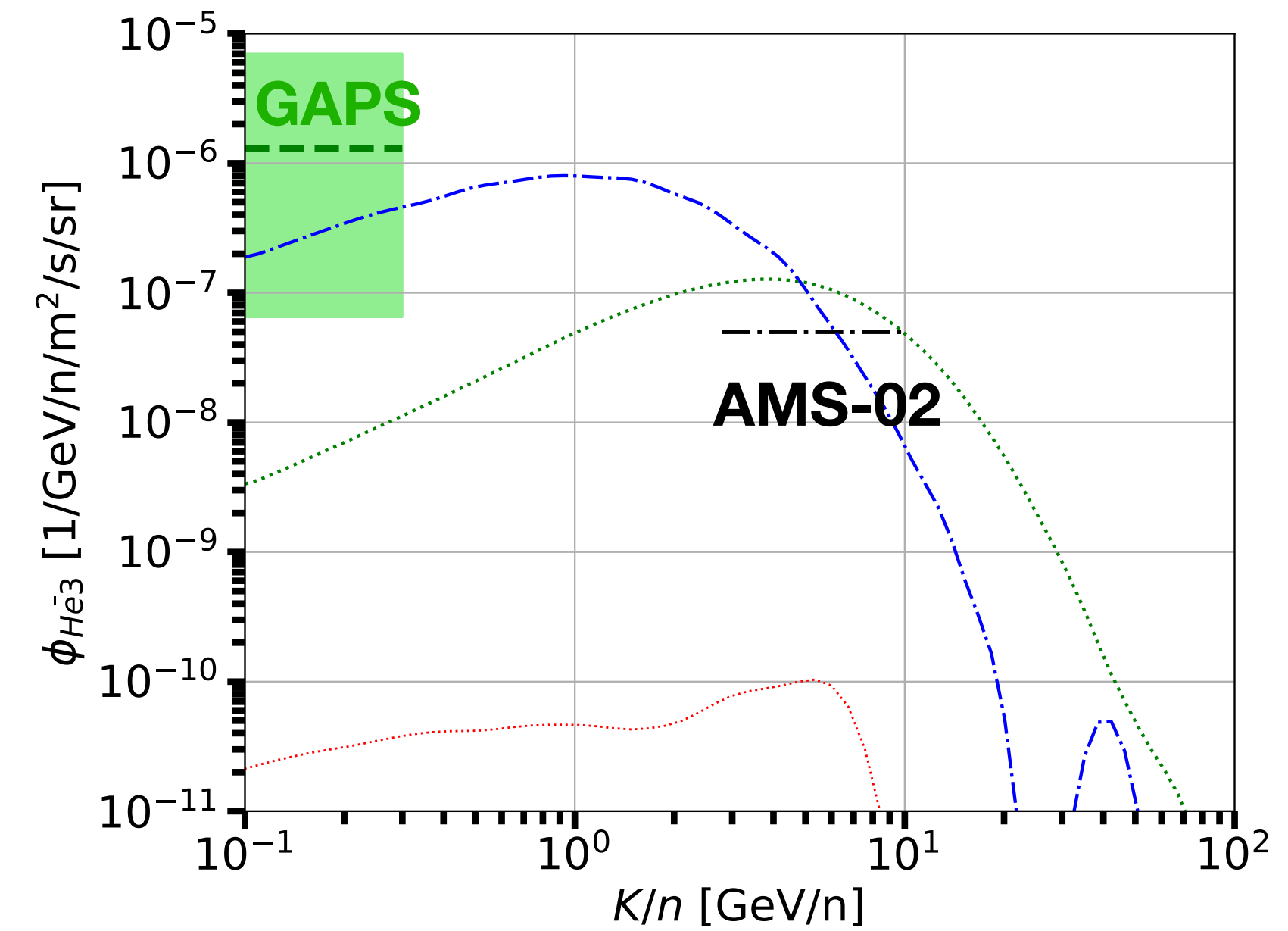
Antiproton



Antideuteron



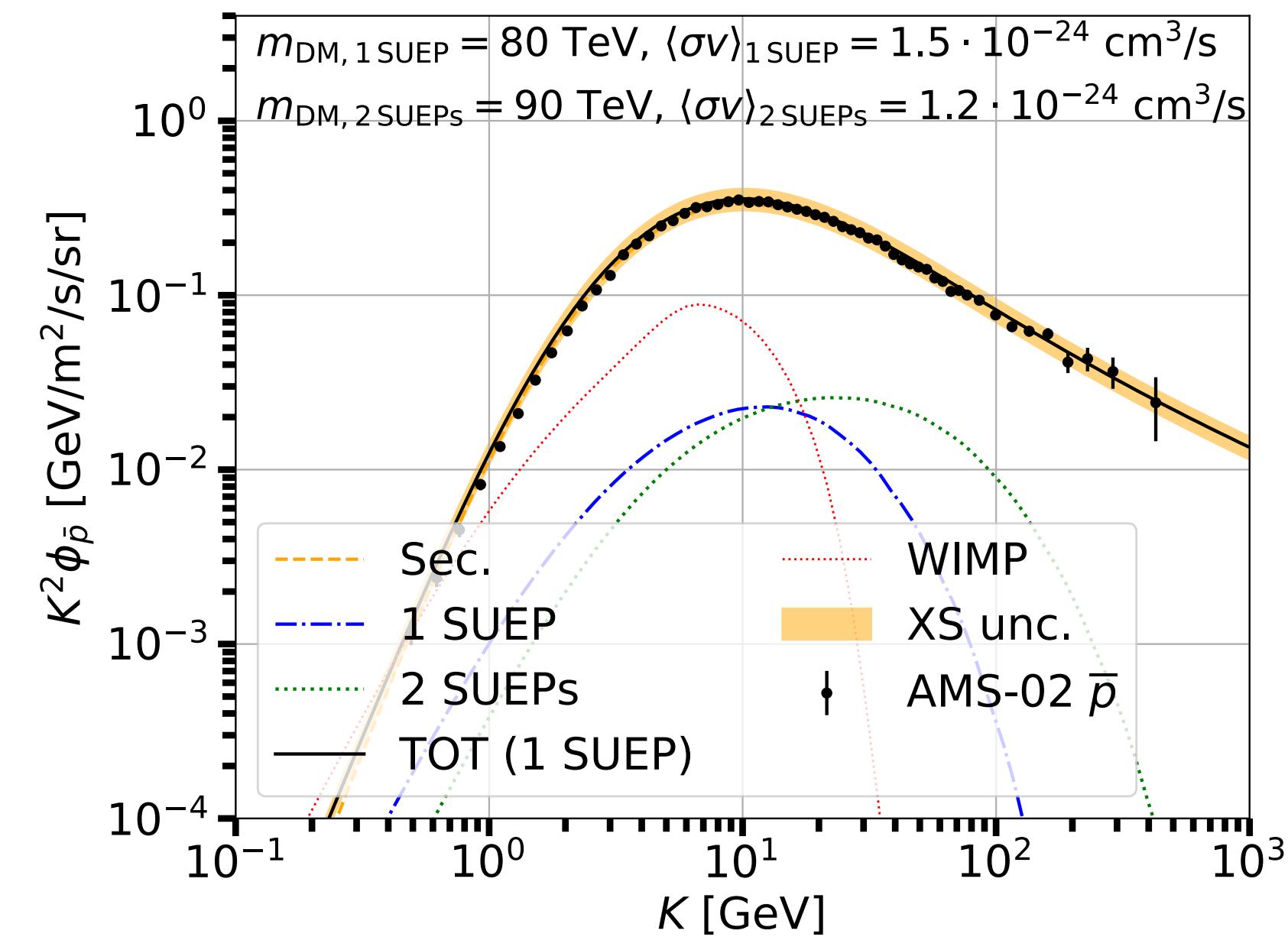
Antihelium-3



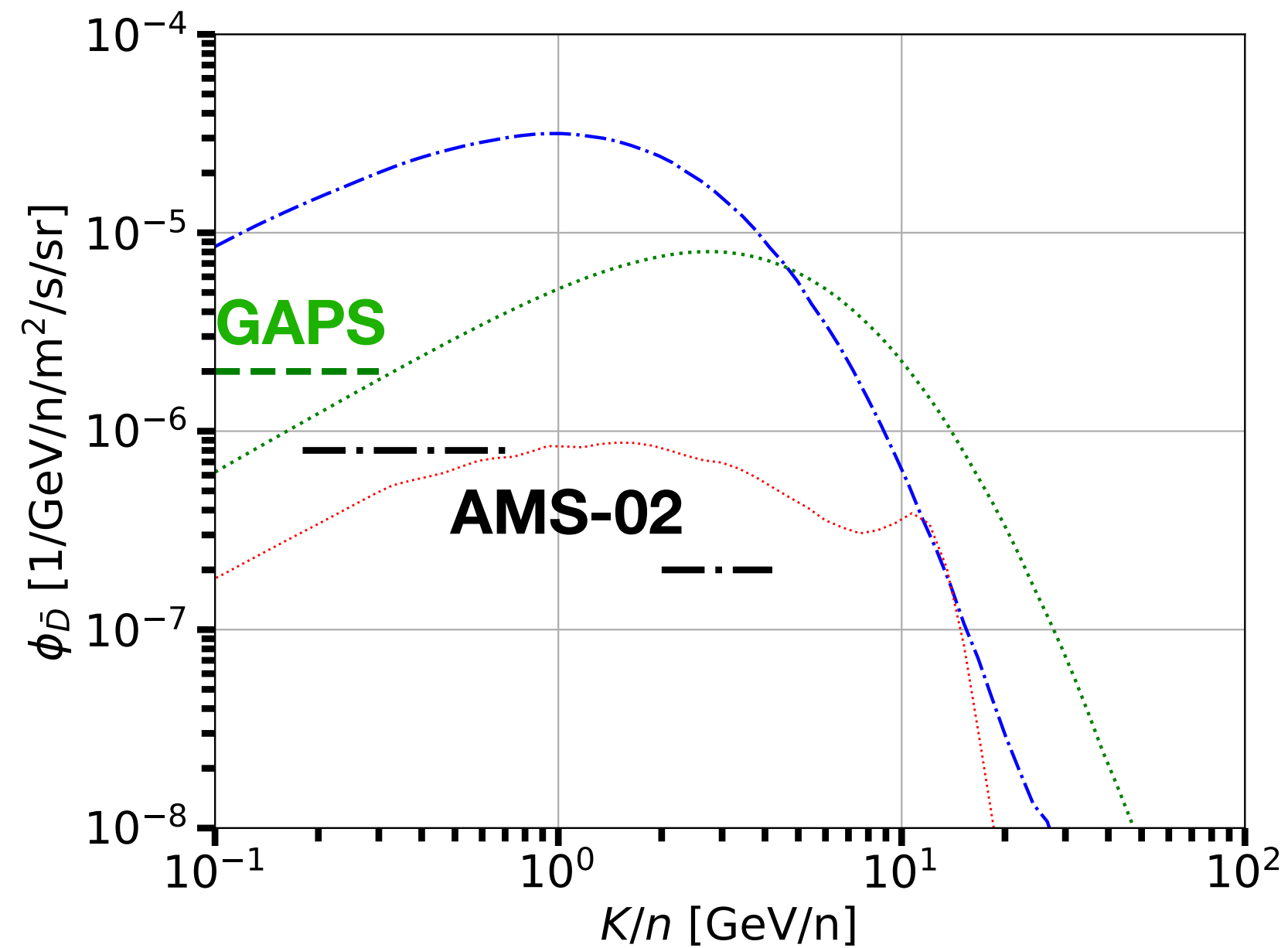
- Use analytic solution of the cosmic-ray transport equation to propagate antinuclei spectra (astro-ph/0112486)
- Cross-section is taken to be the unitarity bound (1904.11503) until it produces an observable antiproton flux, then its value is fixed to ensure antiproton flux is at most 15% AMS-02 antiproton flux

Antinuclei Spectra

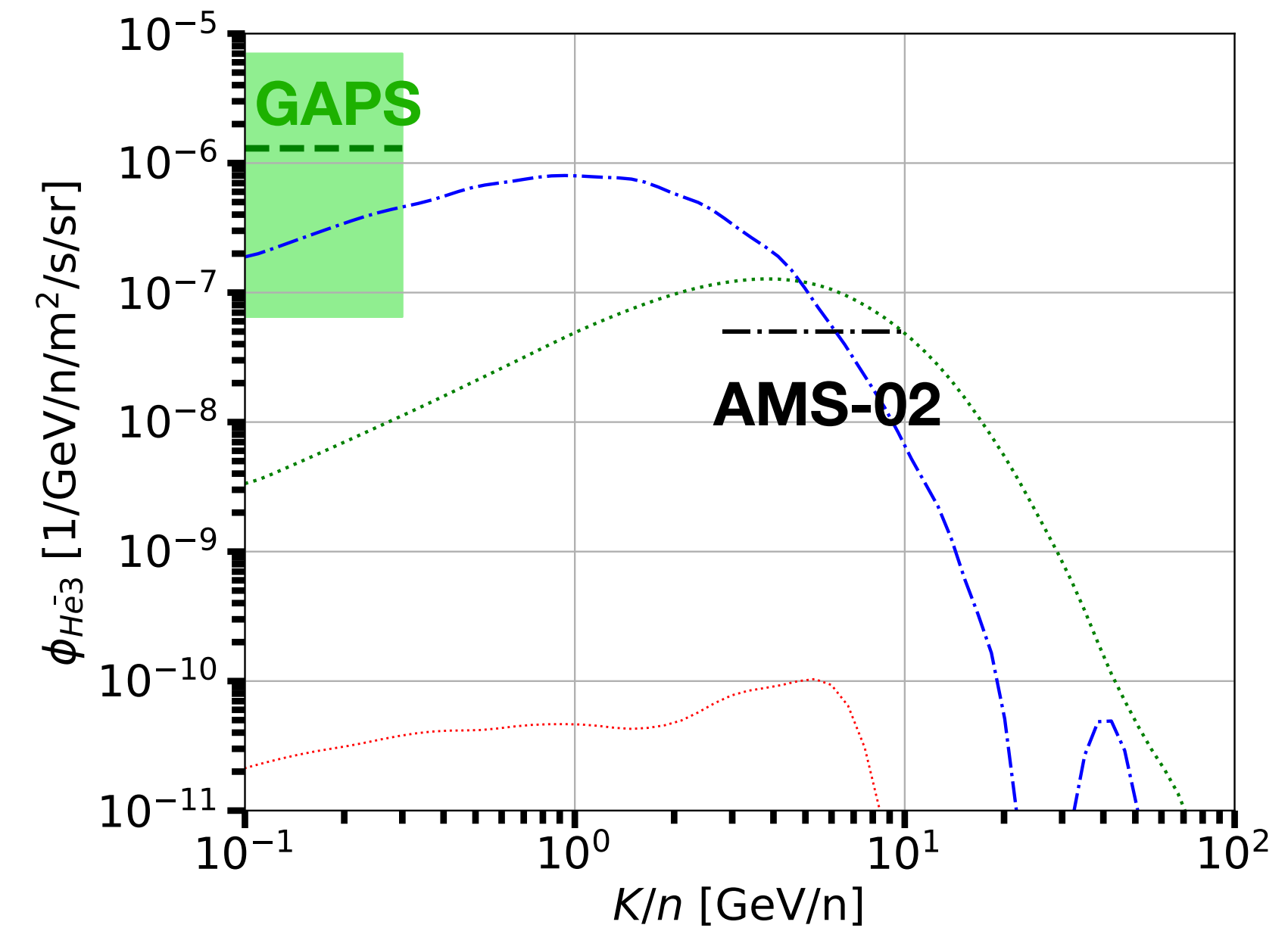
Antiproton



Antideuteron

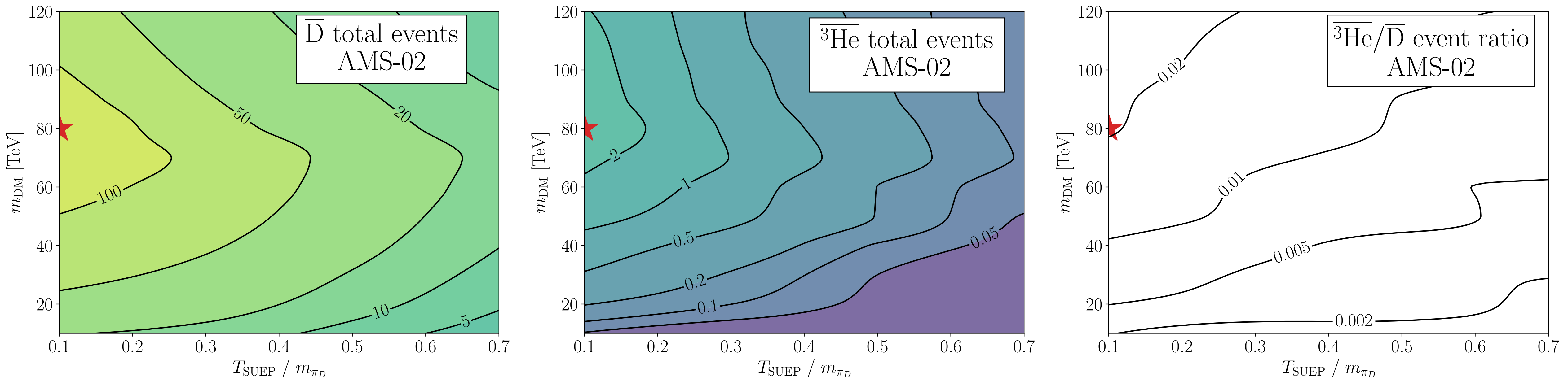


Antihelium-3



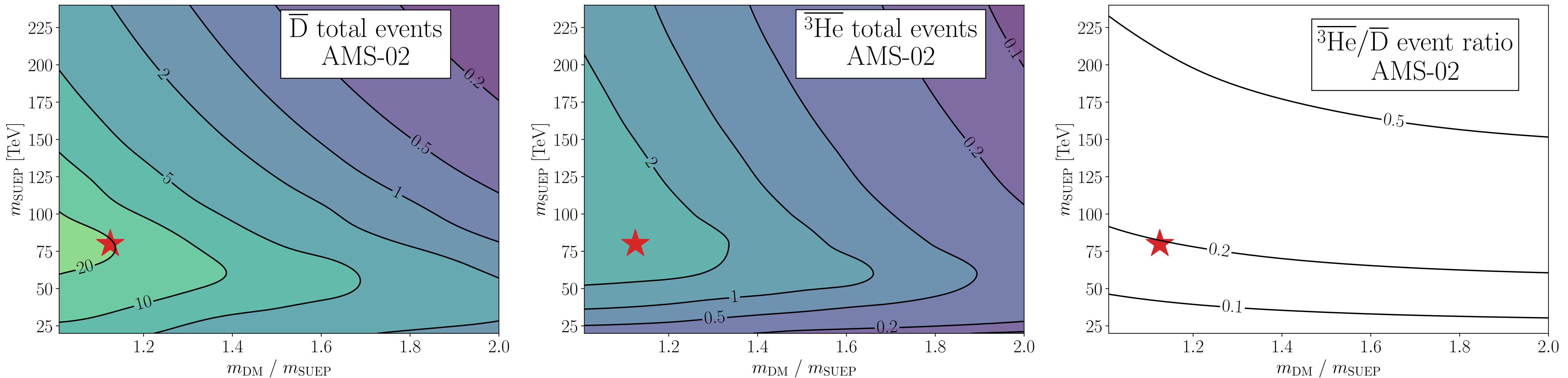
- Observable fluxes for both **One SUEP**, and **Two SUEP** cases
 - One SUEP allows larger multiplicities at smaller energies compared to the boosted Two SUEPs
- Orders of magnitude enhancement over **WIMP DM benchmark** ($b\bar{b}$, 50 GeV, thermal cross section)

Fluxes at AMS-02 (One SUEP)



- Fluxes maximized for smaller SUEP temperatures (~larger dark pion multiplicities at fixed mass)
- Antihelium/antideuteron flux ratio enhanced relative to WIMP DM

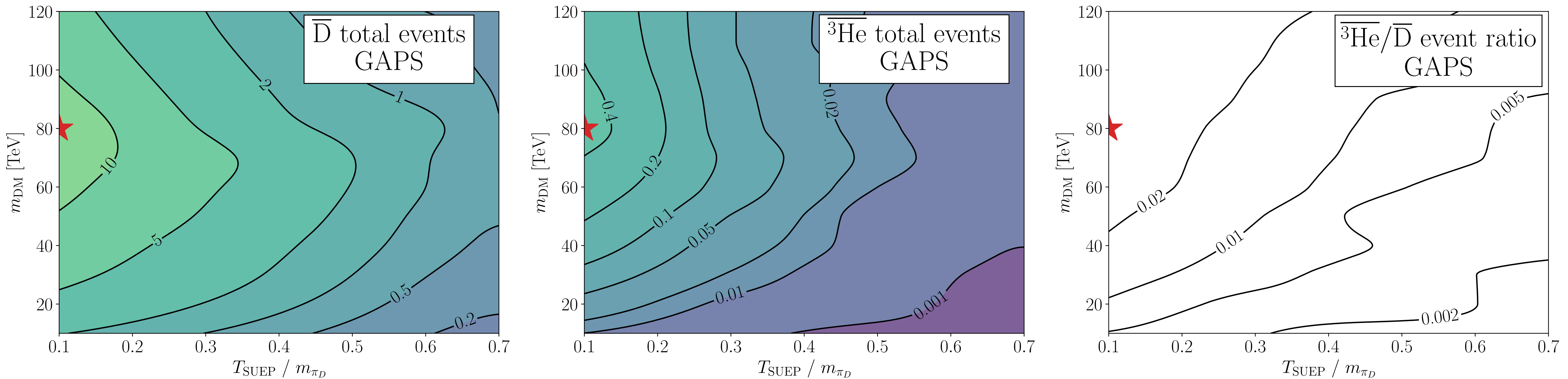
Fluxes at AMS-02 (Two SUEP)



- **Fix $T_{\text{SUEP}} \sim 0.1$ for maximum fluxes**
- **Scan m_{DM} , controls boost in galactic rest frame**
- **Antihelium/antideuteron flux ratio enhanced relative to WIMP DM, reaches almost $\mathcal{O}(1)$ value potentially seen at AMS-02**

Antinuclei Enhancement at GAPS

Fluxes at GAPS (One SUEP)



- Prediction to see a handful of antideuteron events at GAPS, antihelium-3 fluxes are marginal and dependent on final sensitivity
- Two SUEP case unobservable as GAPS focusses on low-energy antinuclei

Conclusions

The background of the slide is a deep purple and blue starry night sky. Numerous stars of varying sizes and colors, including bright orange and yellow, are scattered across the field. The overall effect is a rich, textured celestial scene.

Conclusions:

- **If confirmed, the AMS-02 antinuclei fluxes poses a challenge to both SM astrophysics and WIMP-like DM theories**
- **SUEPs are an example of a dark sector motivated by neutral naturalness that can enhance antinuclei fluxes by many orders of magnitude**
- **GAPS first flight has already been completed, upcoming data release could shed new light on the cosmic ray antinuclei fluxes**

**Stick around for Fabri Vassallo's
talk:**

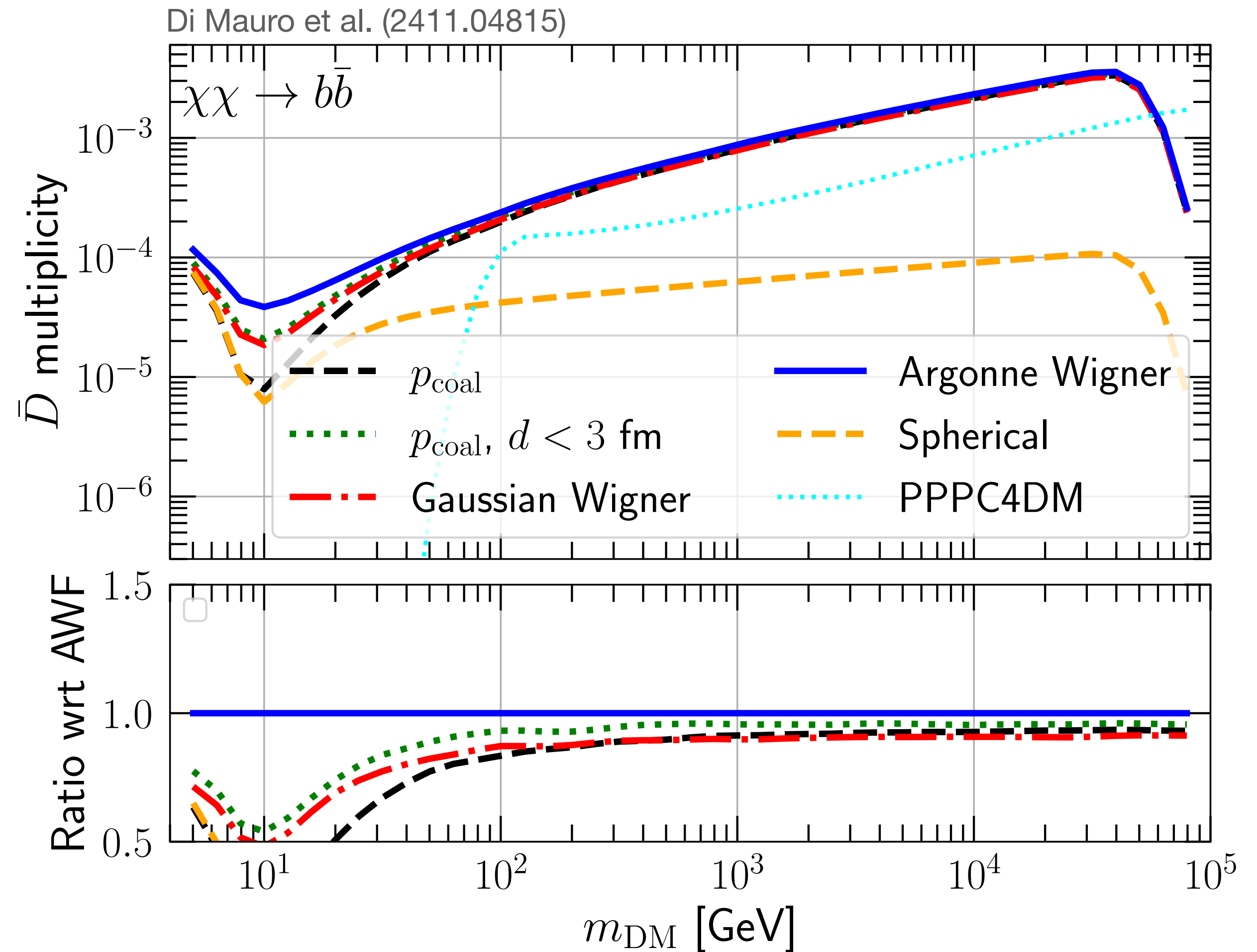


**“Enhancing Cosmic-Ray
Antinuclei Fluxes from Dark
Matter using Baryon Number”**

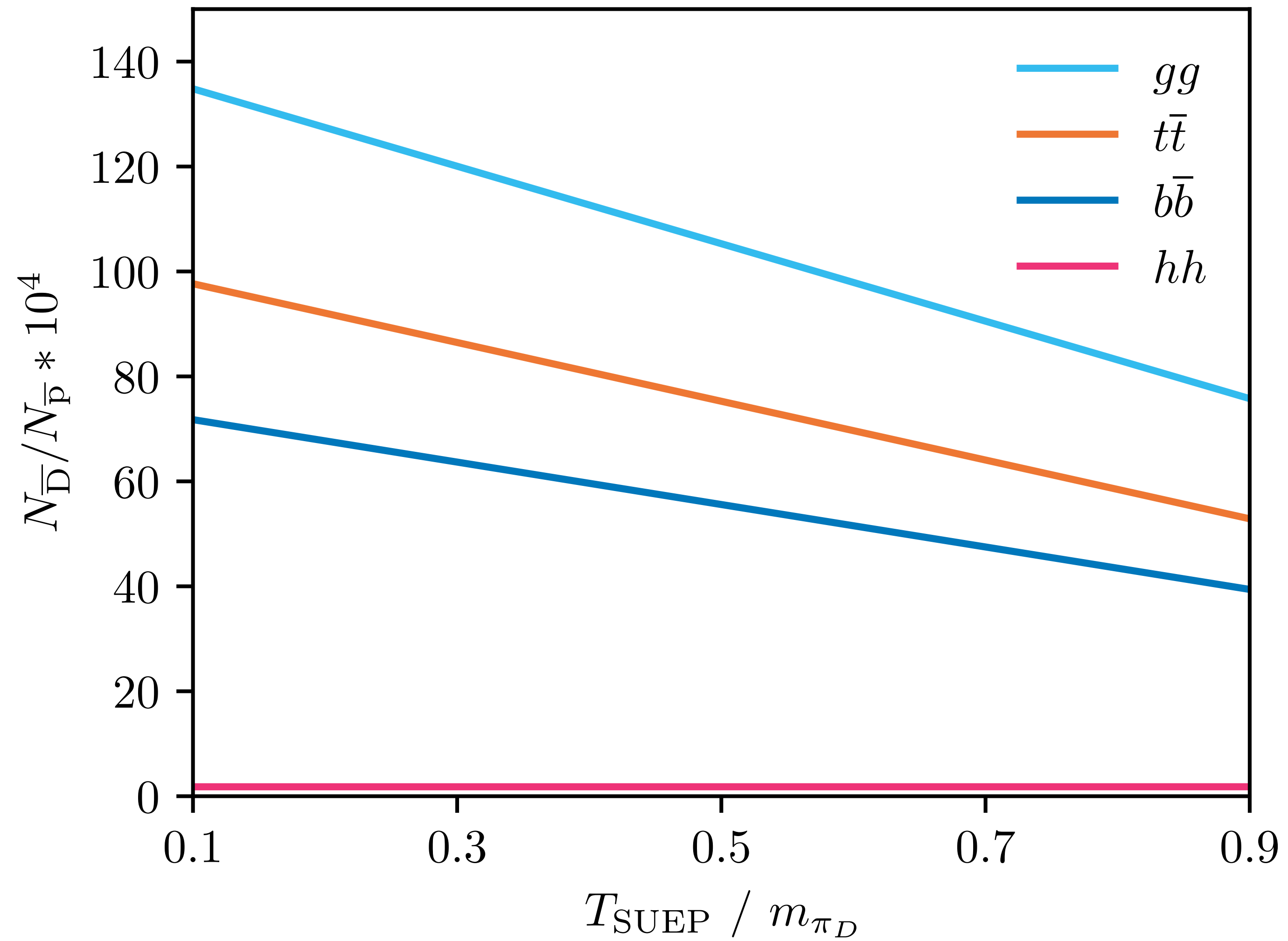
Supplementary Material

Coalescence Model

- **Simple idea:**
Antinucleons that are close in both physical distance and momentum can ‘coalesce’ into heavier antinuclei
- **Tuned to data by selecting cutoff coalescence momentum**
- **Boost antinuclei production by softening antinucleon momenta, reducing inter particle distances**



Branching Ratios



Branching Ratios

arXiv: <https://arxiv.org/pdf/1809.10184>

