Updated secondary anti-helium cosmic ray fluxes
A first estimate for $^4\overline{\mathrm{He}}$

Pierre Salati – LAPTh & Université Savoie Mont Blanc

Outline

1) Anti-helium et advocati diaboli

2) Anti-helium production and the coalescence factor

3) Cosmic ray anti-helium Galactic propagation

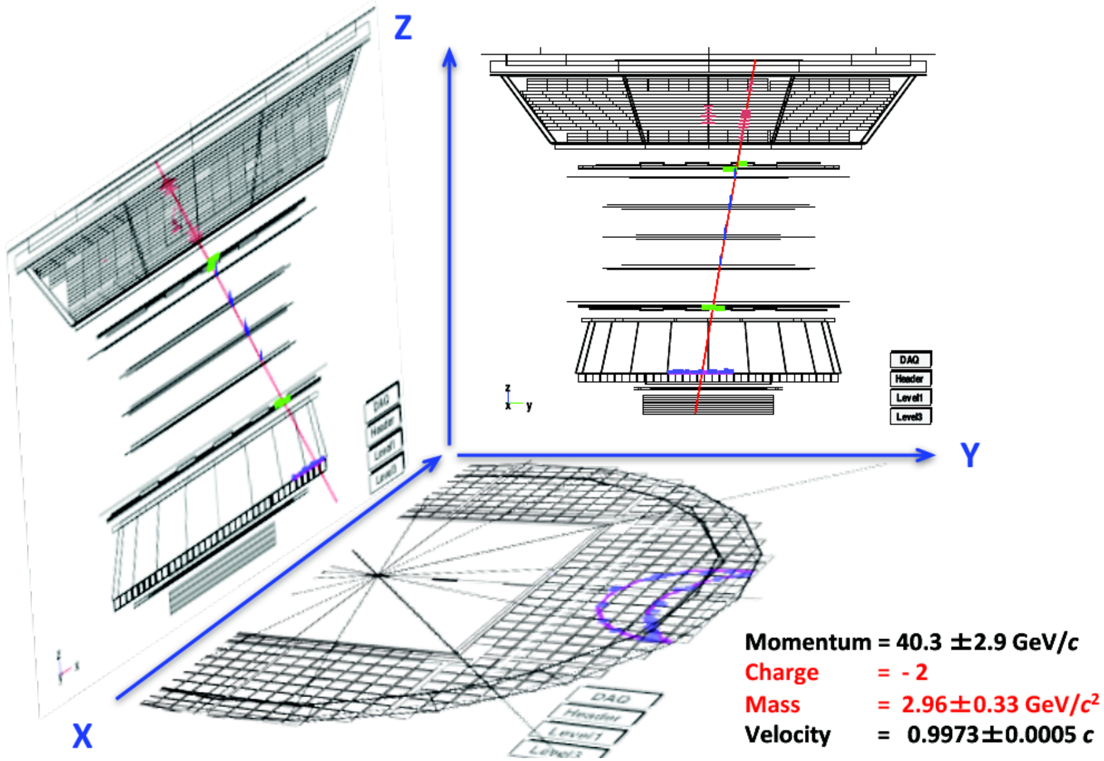
4) A word on dark matter

Based on Phys. Rev. **D99** (2019) 023016

V. Poulin, **P.S.**, I. Cholis, M. Kamionkowski & J. Silk

Antideuteron 2019 – University of California, Los Angeles – March 27, 2019

1) Anti-helium et advocati diaboli

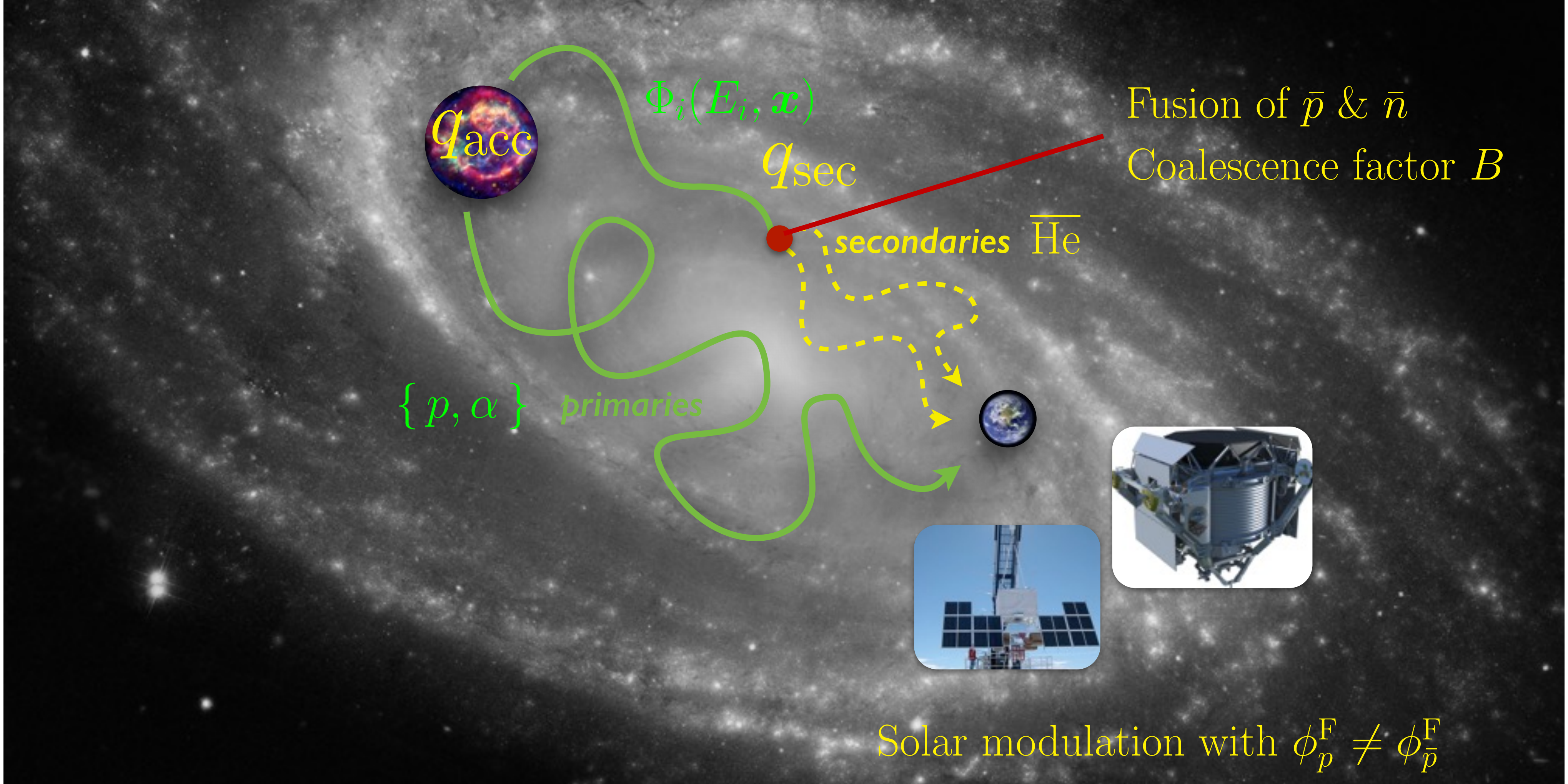


P. von Doetinchem, DSU June 18, 2018

- $^3\overline{\mathrm{He}}$ (6) and $^4\overline{\mathrm{He}}$ (2) candidates have been identified by AMS-02. The event rate is $\sim$ 1 anti-helium in 100 million helium.
- Massive background simulations are carried out to evaluate significance. The probability of a background origin for $\overline{\mathrm{He}}$ events is very small.
- More data are needed. Number of collected $\overline{\mathrm{He}}$ events should increase, while probability of background origin should decrease.

Secondary cosmic-ray anti-helium

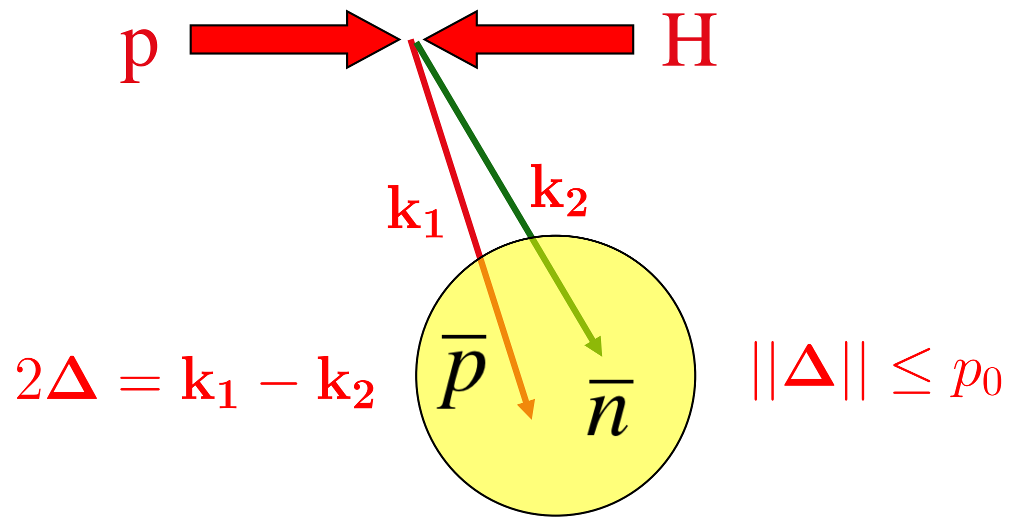
$$q_{\rm sec}(\overline{\rm He}\,|\,E_{\overline{\rm He}},\boldsymbol{x}) = \sum_{i\in {\rm p},\alpha}\ \sum_{j\in {\rm H,He}} 4\,\pi \int dE_i\ \Phi_i(E_i,\boldsymbol{x})\,n_j(\boldsymbol{x})\,\frac{d\sigma_{ij\rightarrow\overline{\rm He}}}{dE_{\overline{\rm He}}}(E_i,E_{\overline{\rm He}})$$



Courtesy Antje Putze, TeVPA 2015

2) Anti-helium production and the coalescence factor

coalescence $\equiv$ fusion of $\bar{p}$ & $\bar{n}$ into $\bar{d}$, $\overline{^3\mathrm{He}}$ or $\overline{^4\mathrm{He}}$



coalescence momentum $p_0 = p_{\mathrm{coal}}/2$

$$d^3\mathcal{N}_{\bar{d}}(\mathbf{K}) = \int d^6\mathcal{N}_{\bar{p},\bar{n}}\,\{\mathbf{k_1},\mathbf{k_2}\} \times \mathcal{C}(\boldsymbol{\Delta}) \times \delta^3(\mathbf{K} - \mathbf{k_1} - \mathbf{k_2})$$

$$B_2 = \frac{E_{\bar{d}}}{E_{\bar{p}}\,E_{\bar{n}}} \int d^3\boldsymbol{\Delta}\;\mathcal{C}(\boldsymbol{\Delta}) \simeq \frac{m_{\bar{d}}}{m_{\bar{p}}\,m_{\bar{n}}} \left\{ \frac{4}{3}\pi\,p_0^3 \equiv \frac{\pi}{6}\,p_{\mathrm{coal}}^3 \right\}$$

Coalescence factor B_2

$$\frac{E_{\bar{d}}}{\sigma_{\mathrm{in}}}\frac{d^3\sigma_{\bar{d}}}{d^3\mathbf{K}} = B_2 \left\{ \frac{E_{\bar{p}}}{\sigma_{\mathrm{in}}}\frac{d^3\sigma_{\bar{p}}}{d^3\mathbf{k_1}} \right\} \left\{ \frac{E_{\bar{n}}}{\sigma_{\mathrm{in}}}\frac{d^3\sigma_{\bar{n}}}{d^3\mathbf{k_2}} \right\}$$

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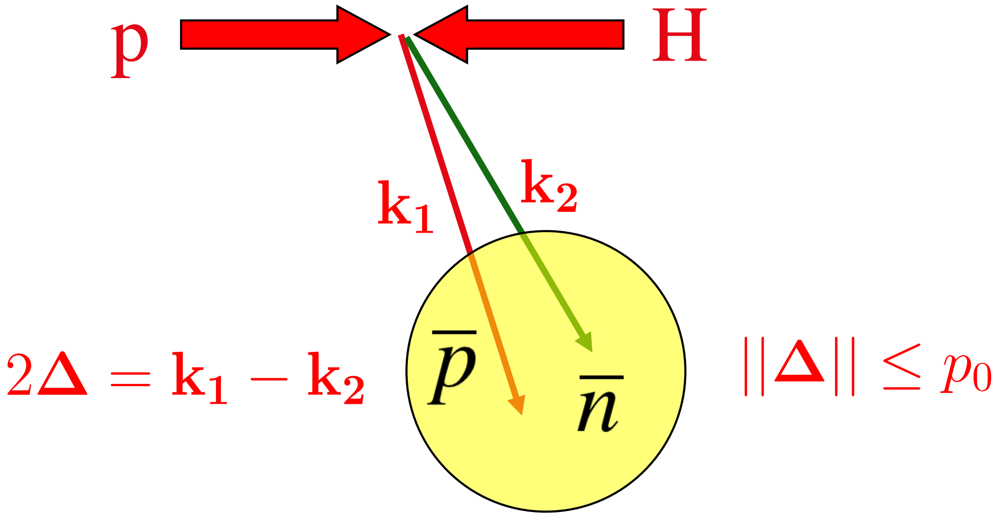


coalescence momentum $p_0 = p_{\mathrm{coal}}/2$

Production on anti-nuclei with mass A

$$\frac{E_{\bar{A}}}{\sigma_{\mathrm{in}}} \frac{d^3\sigma_{\bar{A}}}{d^3\boldsymbol{k}_{\bar{A}}} = B_A \left\{ \frac{E_{\bar{p}}}{\sigma_{\mathrm{in}}} \frac{d^3\sigma_{\bar{p}}}{d^3\boldsymbol{k}_{\bar{p}}} \right\}^Z \left\{ \frac{E_{\bar{n}}}{\sigma_{\mathrm{in}}} \frac{d^3\sigma_{\bar{n}}}{d^3\boldsymbol{k}_{\bar{n}}} \right\}^{A-Z} \quad \text{with} \quad \boldsymbol{k}_{\bar{p}} = \boldsymbol{k}_{\bar{n}} = \boldsymbol{k}_{\bar{A}}/A$$

Coalescence factor B_A

$$B_A = \frac{m_A}{m_p^Z m_n^{A-Z}} \left\{ \frac{\pi}{6} p_{\mathrm{coal}}^3 \right\}^{A-1}$$

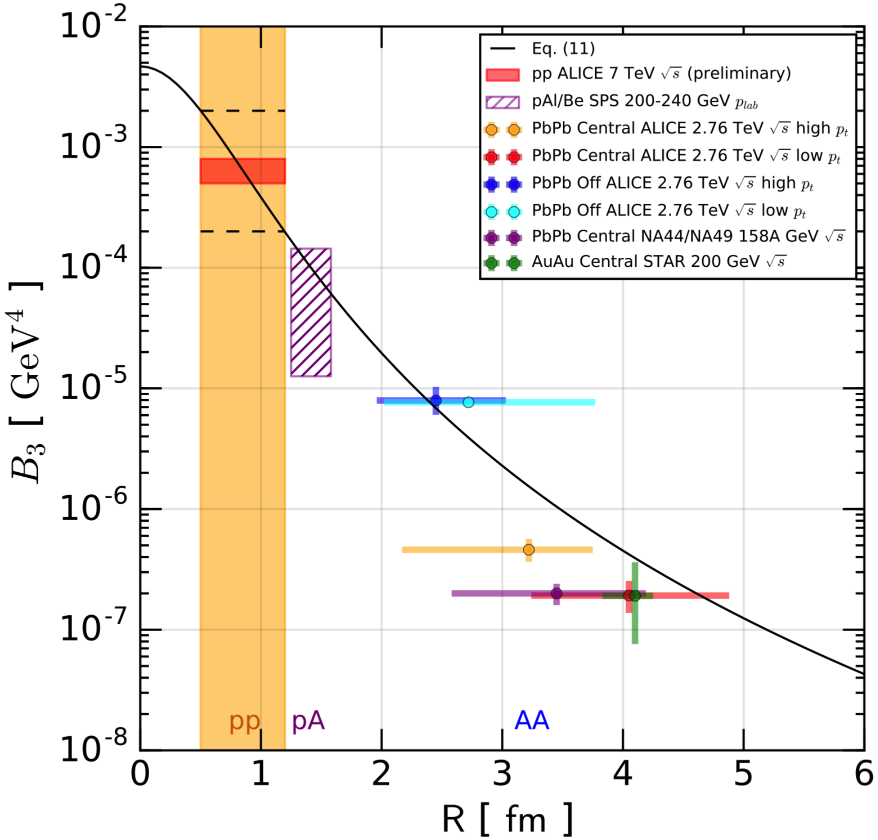
Determination of the coalescence momentum

- No ab initio determination of p_0 which needs to be fitted to data. To do so, a model is required.

  In Blum et al., $B_A \propto V^{1-A}$. The hadronic volume V is probed by the HBT two-pion correlation measurements.

$$\frac{B_2}{\mathrm{GeV}^2} \approx 0.068 \left(\left(\frac{R(p_t)}{1\ \mathrm{fm}} \right)^2 + 2.6 \left(\frac{b_2}{3.2\ \mathrm{fm}} \right)^2 \right)^{-\frac{3}{2}} \quad (12)$$

$$\frac{B_3}{\mathrm{GeV}^4} \approx 0.0024 \left(\left(\frac{R(p_t)}{1\ \mathrm{fm}} \right)^2 + 0.8 \left(\frac{b_3}{1.75\ \mathrm{fm}} \right)^2 \right)^{-3} \quad (11)$$

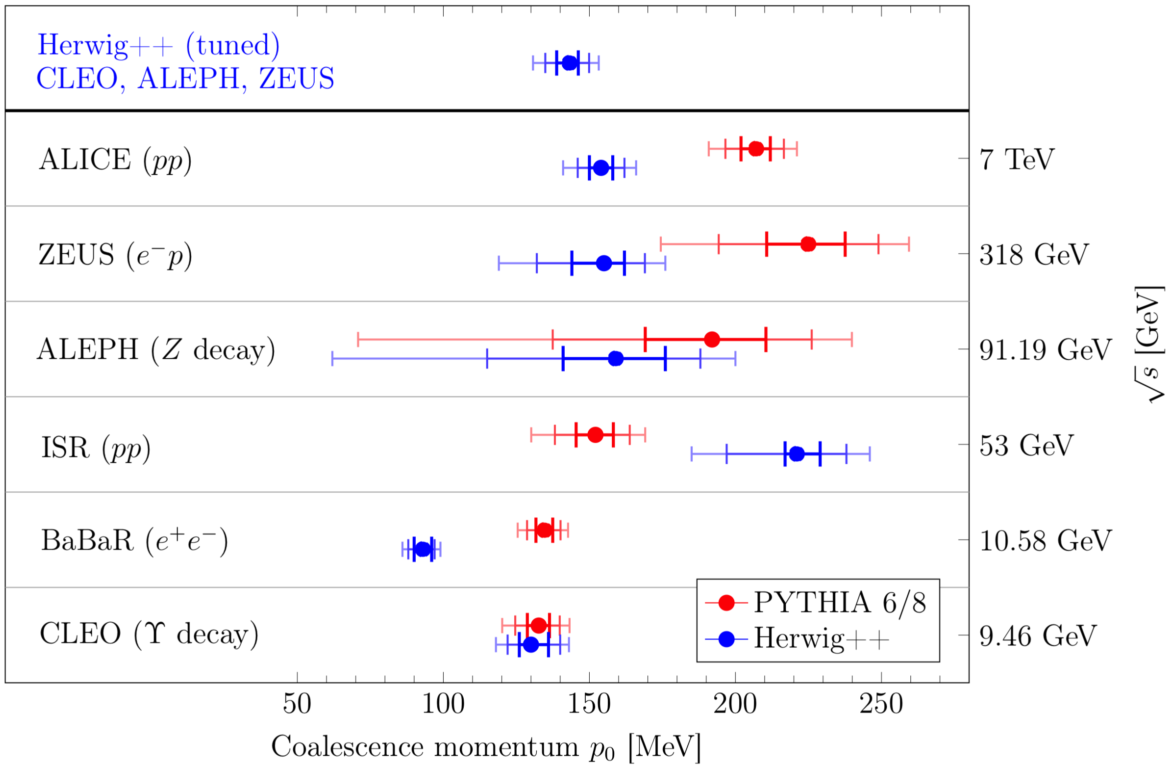


K. Blum et al., Phys. Rev. **D96** (2017) 103021

Determination of the coalescence momentum

- Monte-Carlo event-generators are not devoid of problems.
  They are tuned to specific processes $\neq$ antinucleon production.
  They yield different p_0 when adjusted to different data sets.
  p_0 depends on $\sqrt{s}$.

Fitting p_0 to data on $\bar{d}$ production



A. Ibarra & S. Wild, JCAP **1302** (2013) 021

L.A. Dal & A.R. Raklev, Phys. Rev. **D89** (2014) 103504

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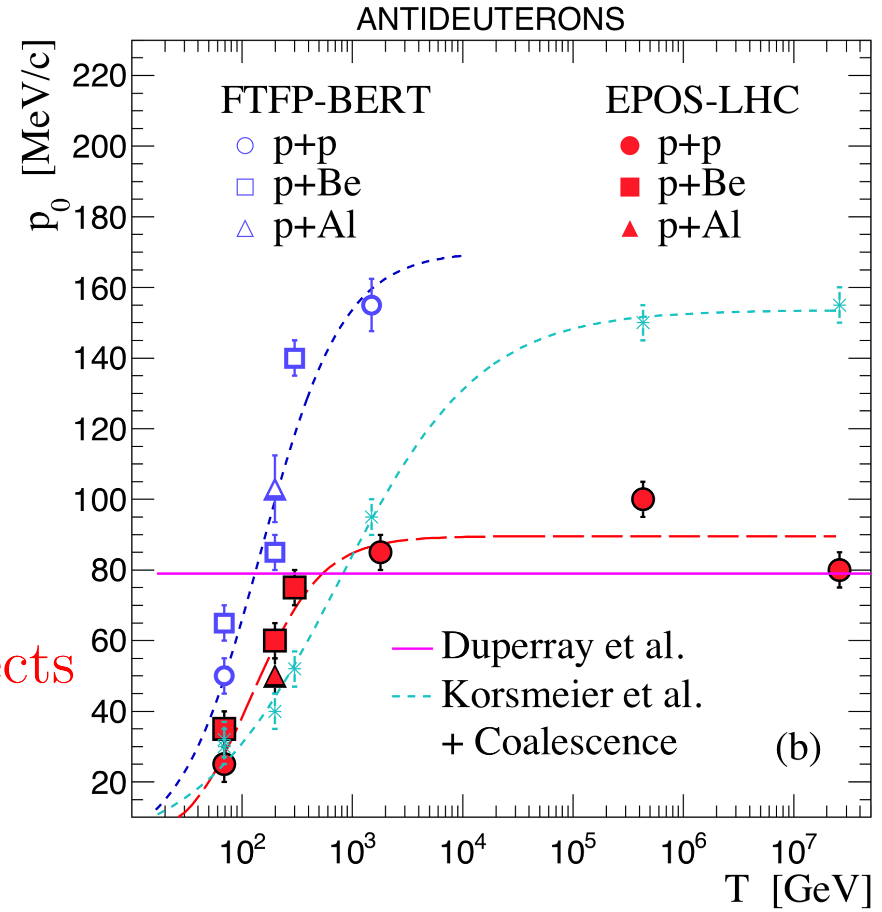
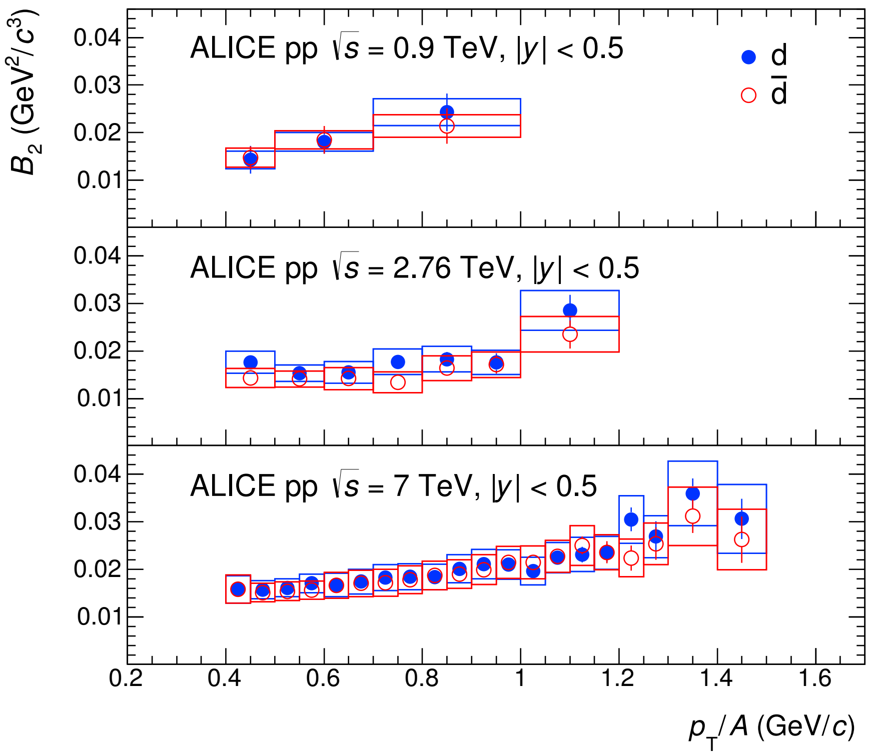
threshold effects

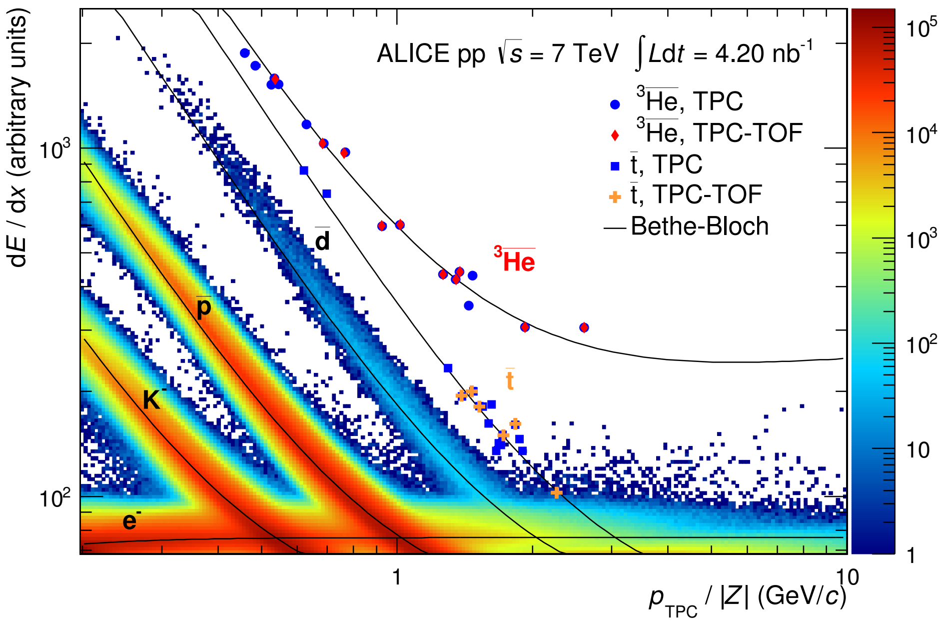


D.M. Gomez-Coral et al., Phys. Rev. **D98** (2018) 023012

Determination of the coalescence momentum

- ALICE provides an **experimental** determination of B_2 and B_3.
  $\bar{p}$ production cross-section is **measured**.
  Approximately the same value for p_0 from $\bar{d}$, $\bar{t}$ and $^3\overline{\mathrm{He}}$.





S. Acharya et al., Phys. Rev. **C97** (2018) 024615

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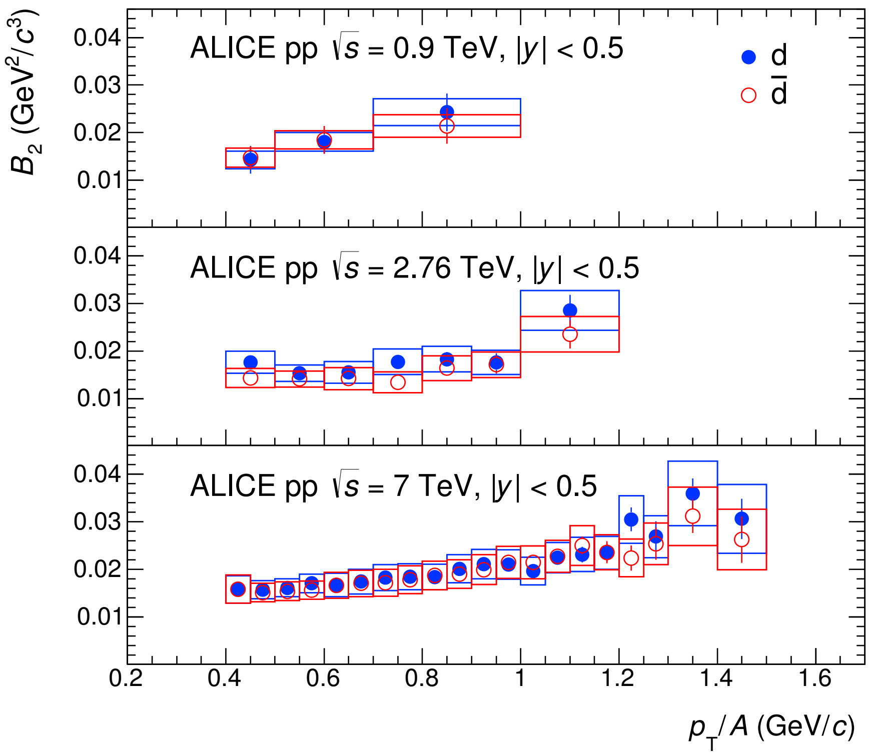
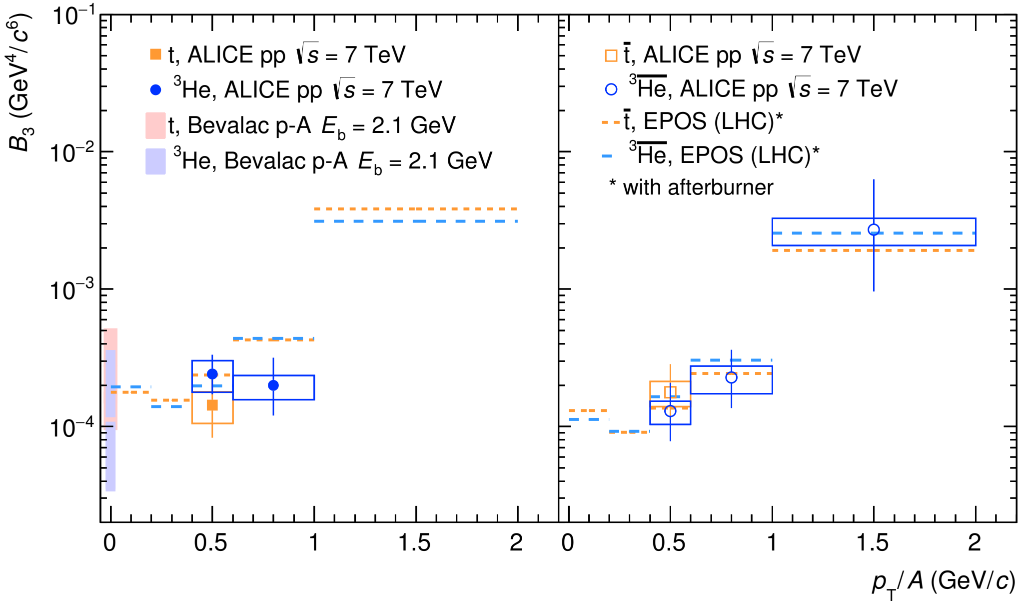




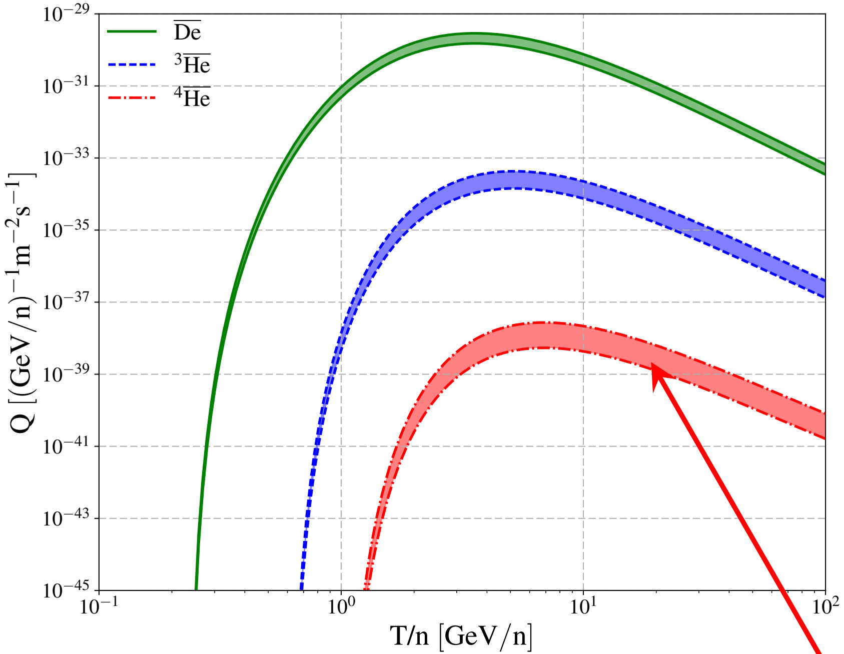
$208 \text{ MeV} \leq p_{\text{coal}} \leq 262 \text{ MeV}$

$218 \text{ MeV} \leq p_{\text{coal}} \leq 262 \text{ MeV}$

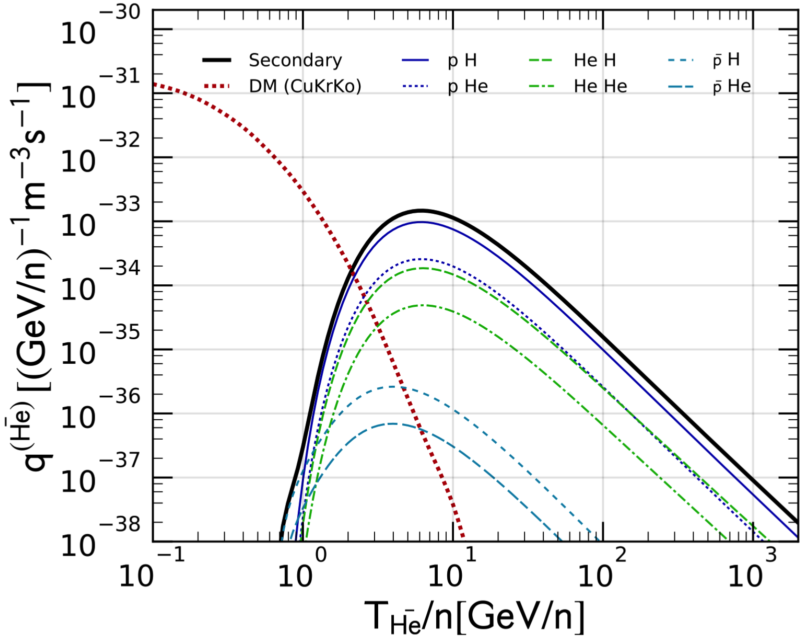
S. Acharya et al., Phys. Rev. **C97** (2018) 024615

Local source term for anti-nuclei production in cosmic-rays

$$q_{\rm sec}(\overline{\rm He}\,|\,E_{\overline{\rm He}},\boldsymbol{x}) = \sum_{i\in {\rm p},\alpha}\ \sum_{j\in {\rm H,He}} 4\pi \int dE_i\ \Phi_i(E_i,\boldsymbol{x})\, n_j(\boldsymbol{x})\, \frac{d\sigma_{ij\to\overline{\rm He}}}{dE_{\overline{\rm He}}}(E_i, E_{\overline{\rm He}})$$



V. Poulin et al., Phys. Rev. **D99** (2019) 023016



M. Korsmeier et al., Phys. Rev. **D97** (2018) 103011

$$7.7\times 10^{-7} \le \frac{B_4}{\rm GeV^6} \le 3.9\times 10^{-6}$$

$\bar{p}$ production modeled as in
M. di Mauro et al., Phys. Rev. **D90** (2014) 085017

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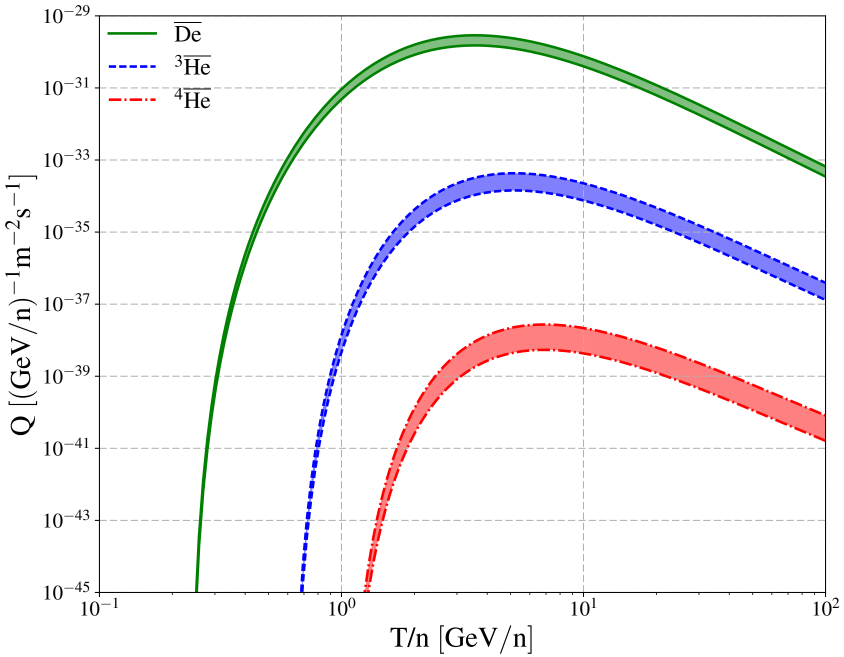
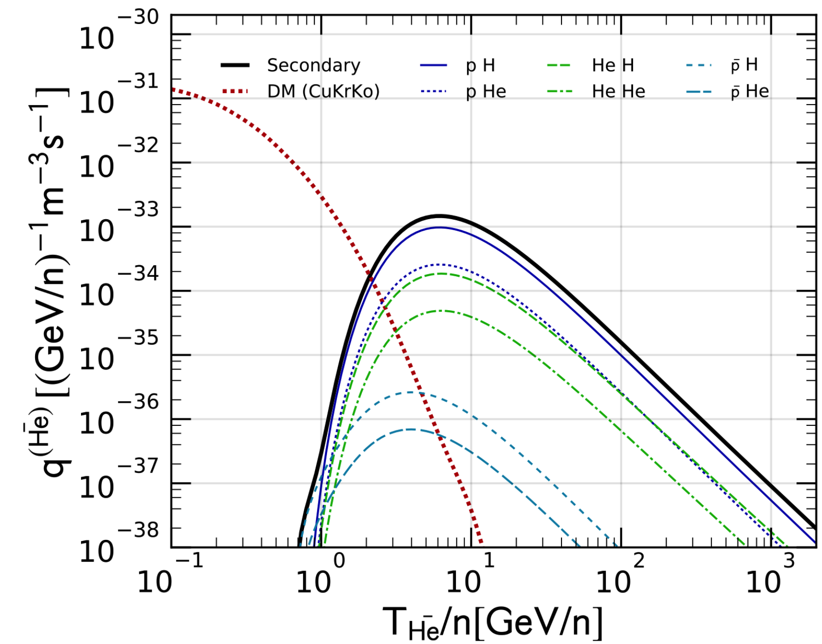
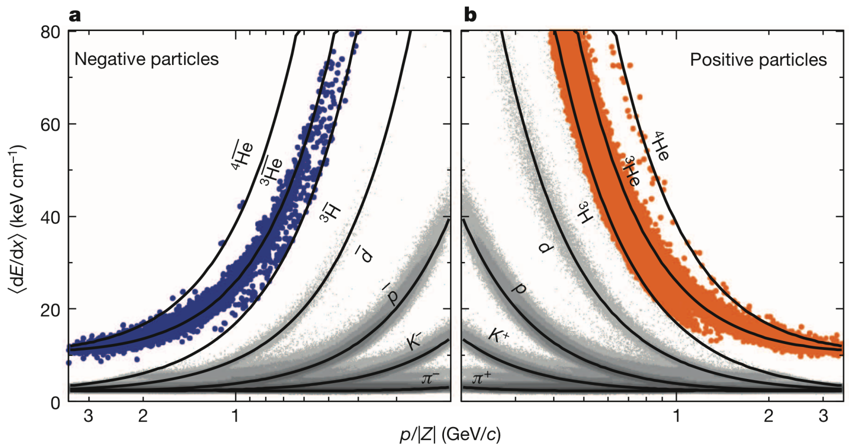
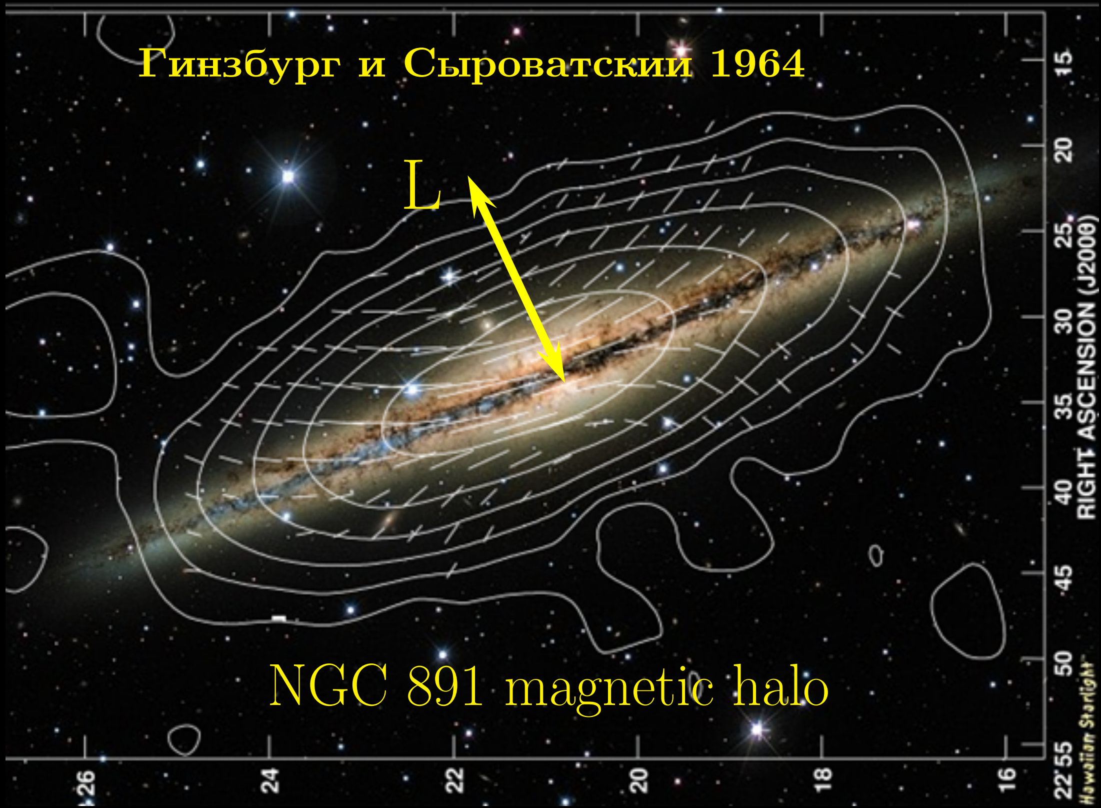


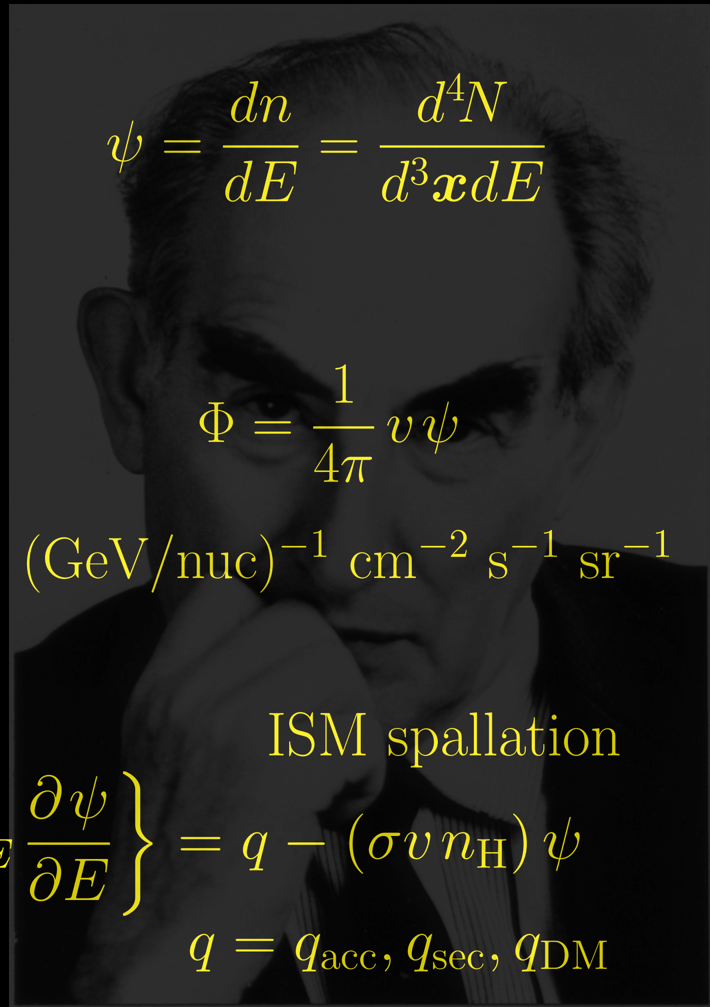




The STAR Collaboration, Nature **473** (2011) 353

3) Cosmic ray anti-helium Galactic propagation





$$\psi = \frac{dn}{dE} = \frac{d^4 N}{d^3\boldsymbol{x}\, dE}$$

$$\Phi = \frac{1}{4\pi}\, v\, \psi$$

$(\mathrm{GeV/nuc})^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$

ISM spallation

$$\dot{\psi} + \boldsymbol{\nabla}\cdot\{-K\,\boldsymbol{\nabla}\psi + \psi \boldsymbol{V}_C\} + \frac{\partial}{\partial E}\left\{b\,\psi - D_{EE}\frac{\partial \psi}{\partial E}\right\} = q - (\sigma v\, n_{\mathrm{H}})\,\psi$$

convection

E losses

$$q = q_{\mathrm{acc}},\, q_{\mathrm{sec}},\, q_{\mathrm{DM}}$$

$\boldsymbol{x}$ diffusion

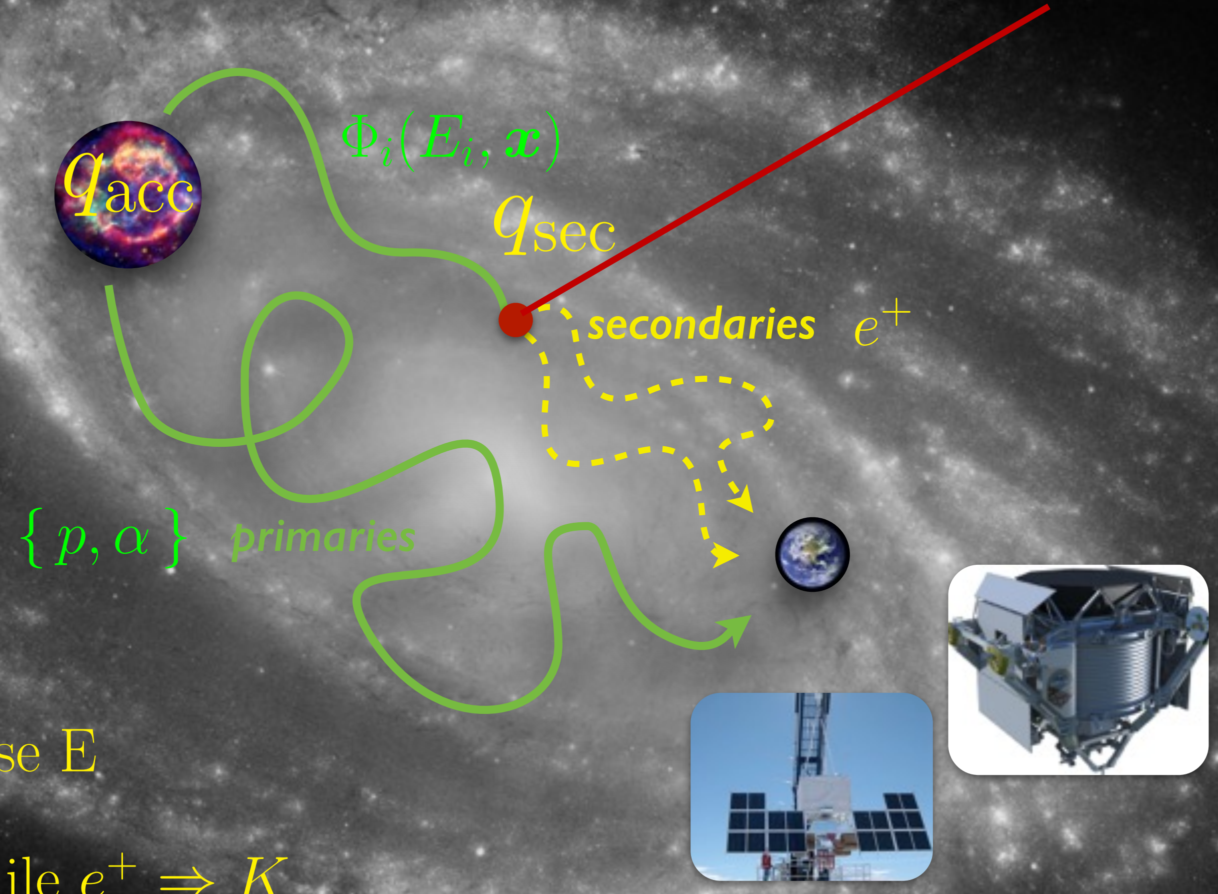
E diffusion

$$K = K_0\,\beta\,\mathcal{R}^{\delta}\left\{1 + \left(\frac{\mathcal{R}}{\mathcal{R}_b}\right)^{\Delta\delta/s}\right\}^{-s}$$

$$D_{EE} = \frac{2}{9}\,\frac{V_A^2\,\beta^4 E^2}{K}$$

Positron constraints on cosmic ray propagation

$$q_{\rm sec}(e^+ \,|\, E_e, \boldsymbol{x}) = \sum_{i \in {\rm p},\alpha} \; \sum_{j \in {\rm H,He}} 4\,\pi \int dE_i \; \Phi_i(E_i, \boldsymbol{x}) \, n_j(\boldsymbol{x}) \, \frac{d\sigma_{ij \to e^+}}{dE_e}(E_i, E_e)$$



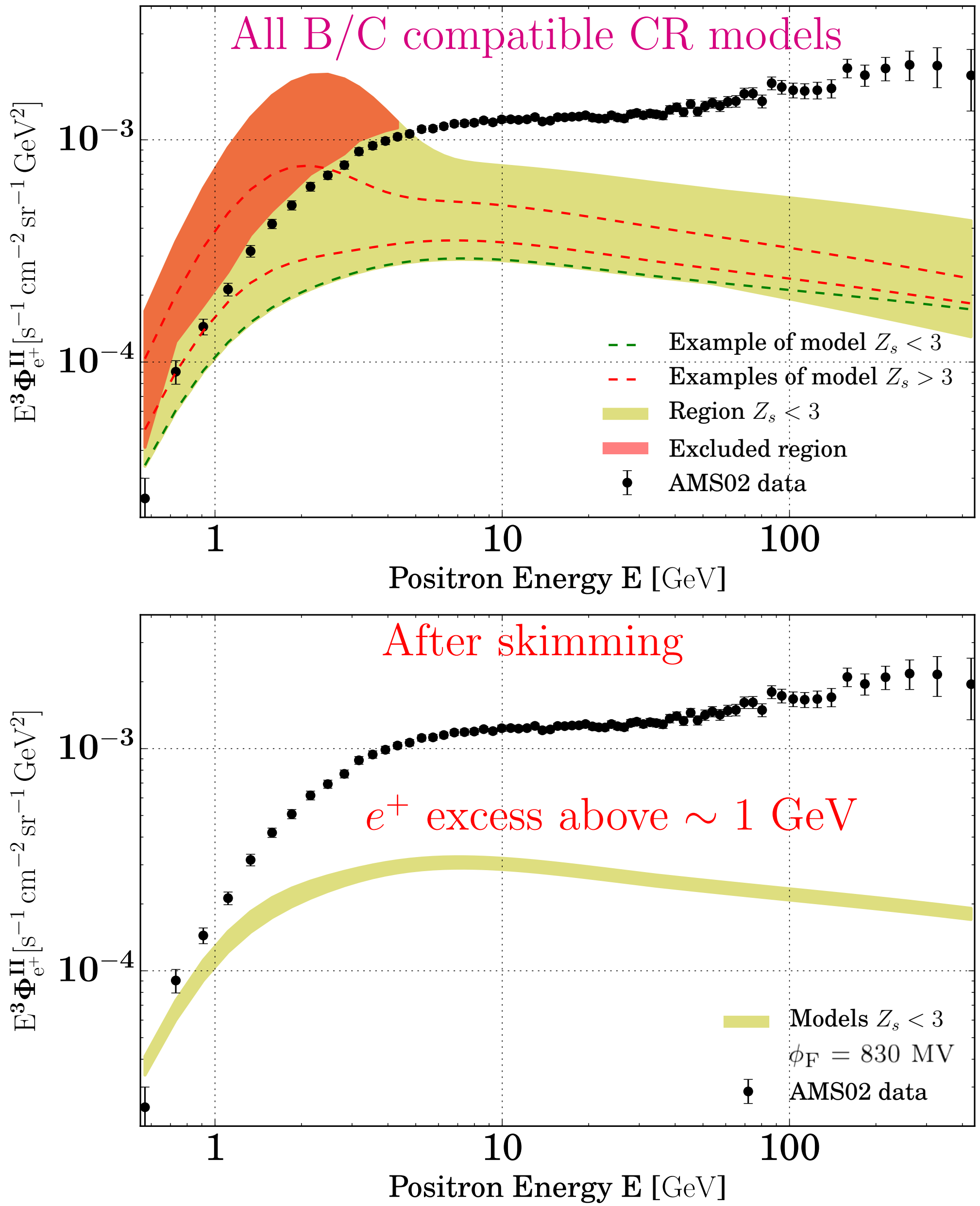
e^+ diffuse and lose E

B/C $\Rightarrow K/L$ while $e^+ \Rightarrow K$

Degeneracy between K and L can be lifted

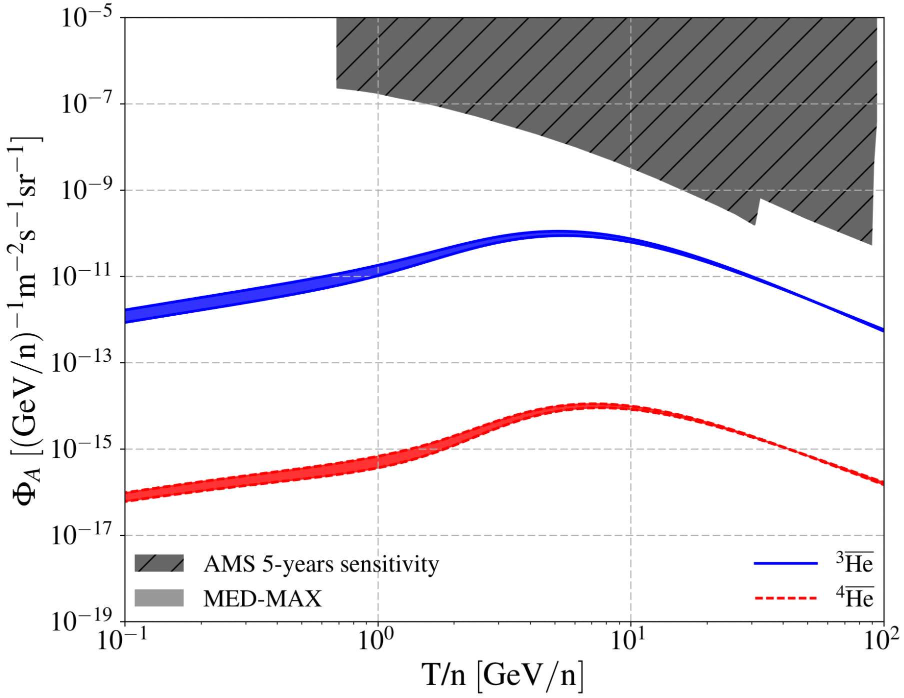
Courtesy Antje Putze, TeVPA 2015

$\Phi_{e^+}^{\rm sec}$ forces K to be large $\Rightarrow$ $L \geq L_{\rm min} \sim 8.5$ kpc

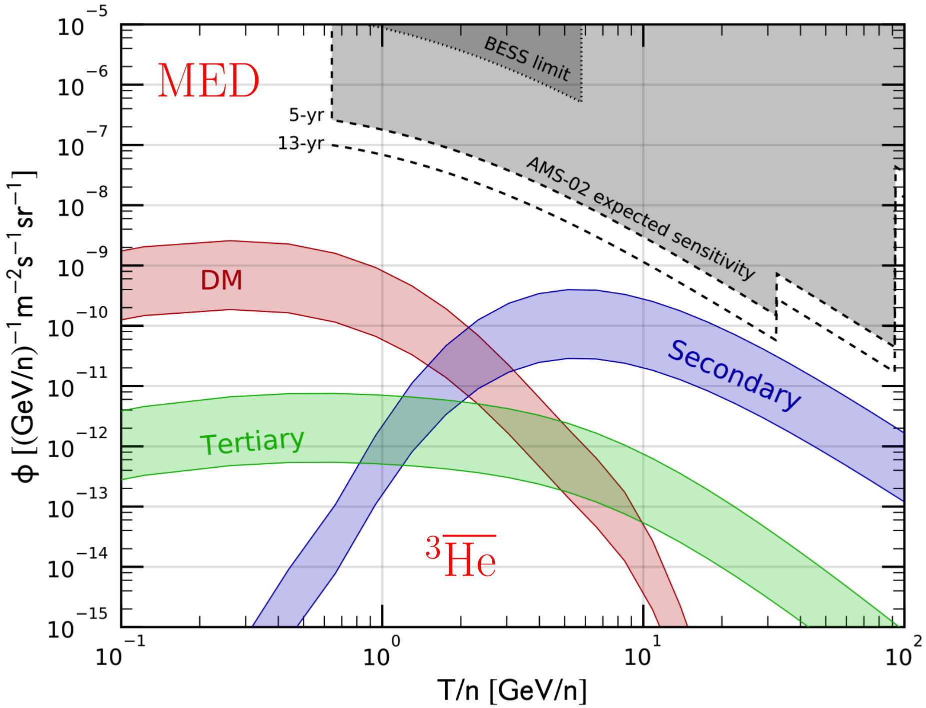


M. Boudaud et al., A&A **605** (2017) A17

Secondary anti-helium fluxes



V. Poulin et al., Phys. Rev. **D99** (2019) 023016



M. Korsmeier et al., Phys. Rev. **D97** (2018) 103011

AMS-02 should not have seen $\overline{\mathrm{He}}$ events

no secondary origin $\Rightarrow$ DM or else

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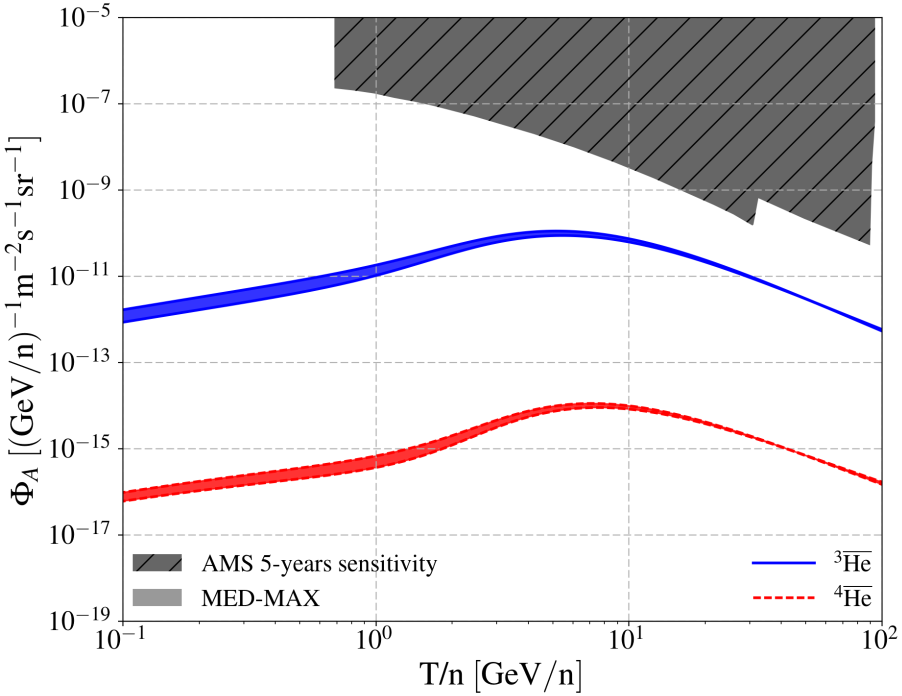

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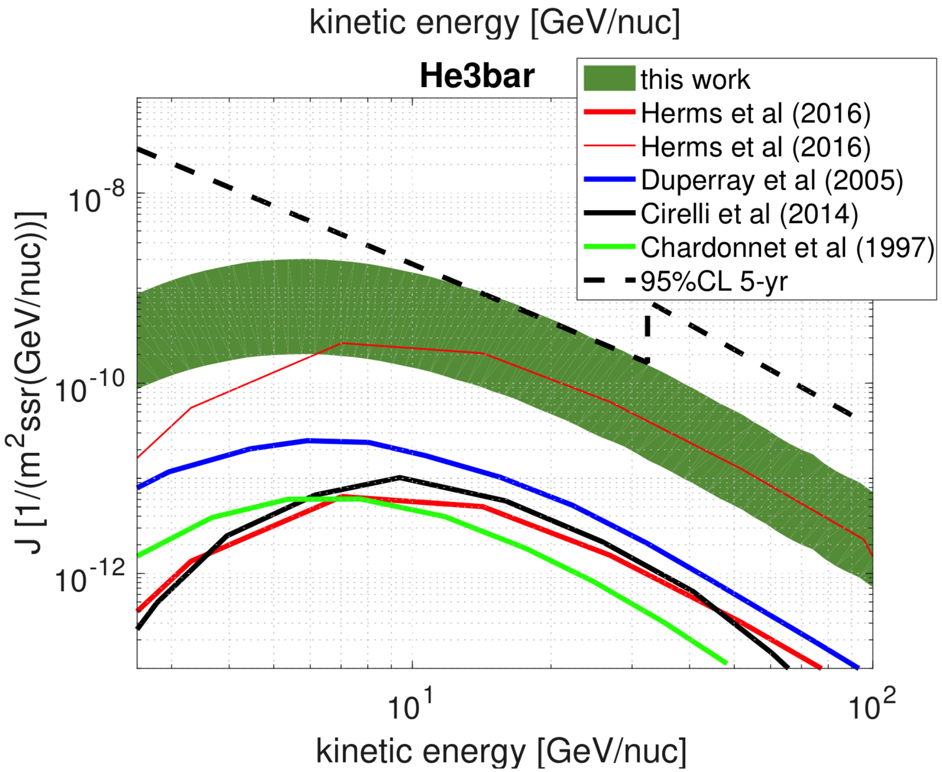

K. Blum et al., Phys. Rev. **D96** (2017) 103021

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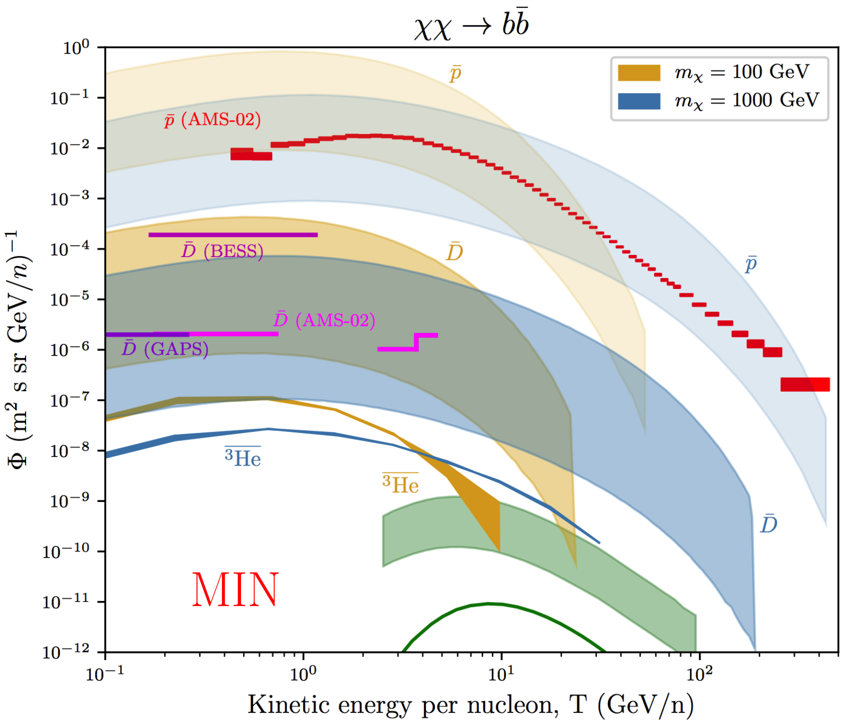
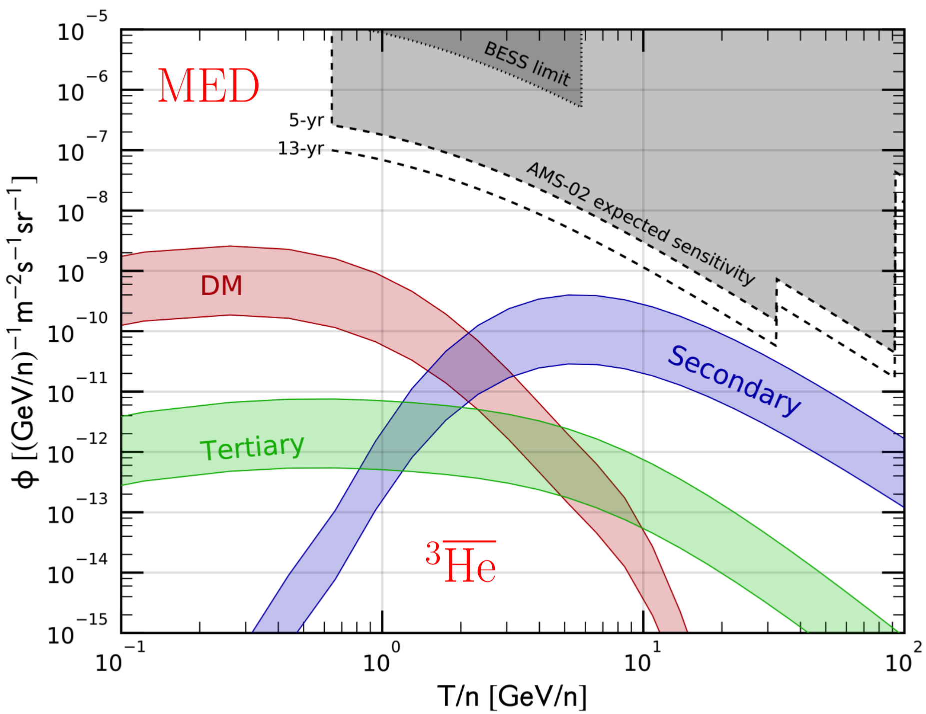
4) A word on dark matter

Could anti-helium ($^3\overline{\mathrm{He}}$) events be produced by DM?



A. Coogan & S. Profumo,
Phys. Rev. **D96** (2017) 083020



M. Korsmeier et al., Phys. Rev. **D97** (2018) 103011

- If AMS-02 $\overline{\mathrm{He}}$ events are from DM, beware of $\bar{p}$ flux.
- To evade the $\bar{p}$ constraint, p_{coal} exceedingly large.

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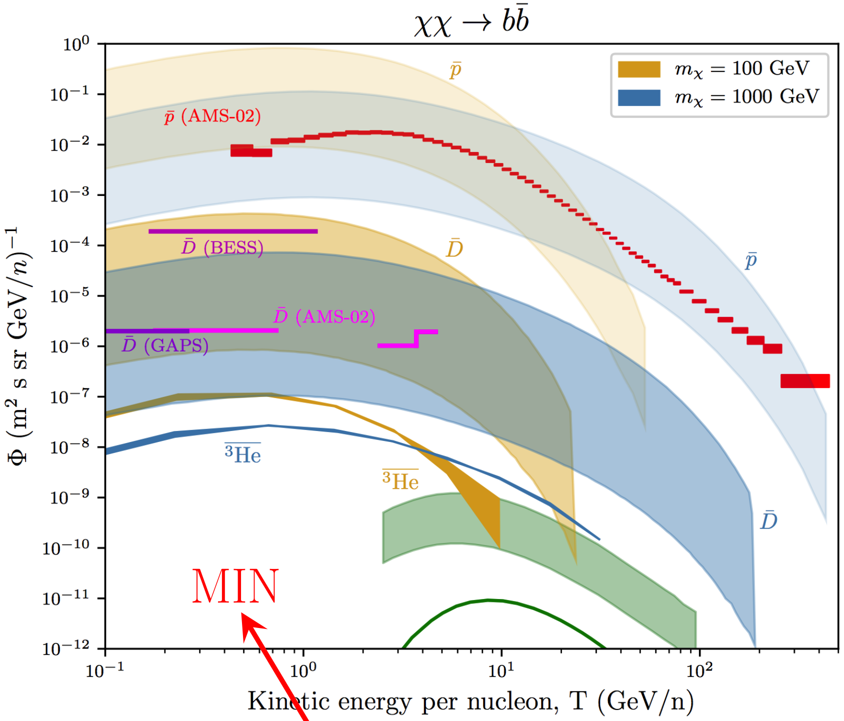
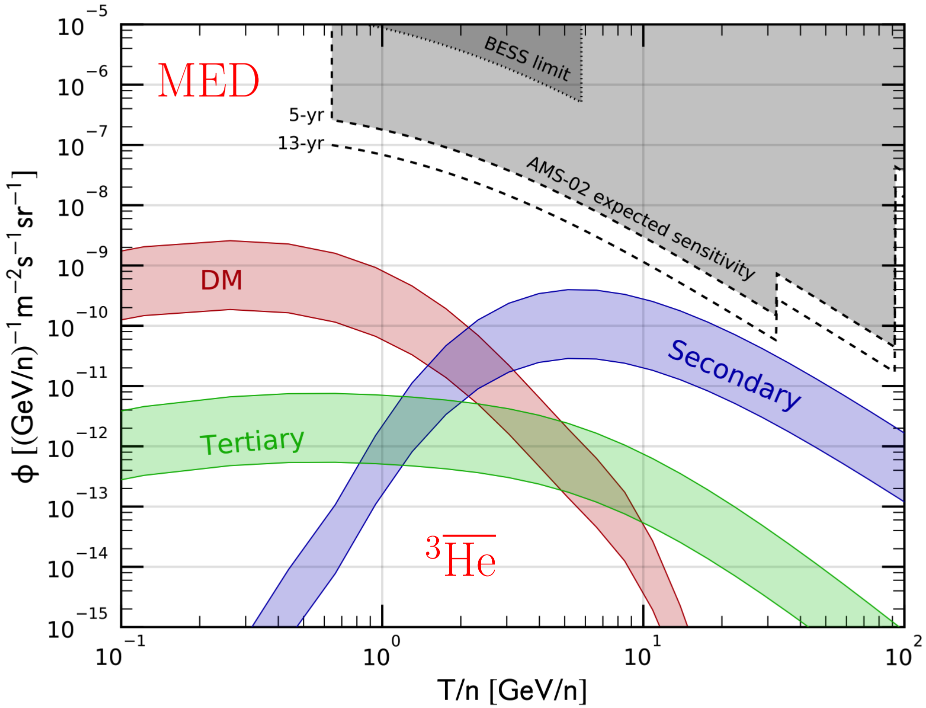
Could anti-helium ($^3\overline{\mathrm{He}}$) events be produced by DM?



A. Coogan & S. Profumo, Phys. Rev. **D96** (2017) 083020



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MIN is excluded by positrons

Concluding remarks

- Anti-helium-3 and anti-helium-4 candidates have been identified by AMS-02.
  Massive background simulations are carried out to evaluate significance.
  More data are needed.

- $^3\overline{\mathrm{He}}$ events
  AMS-02 should **not** see secondary CR $^3\overline{\mathrm{He}}$.
  If $\overline{\mathrm{He}}$ events are produced by DM, a large $\bar{p}$ excess is expected.
  Apart from a possible anomaly, no such excess is seen.

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  There is **absolutely** no hope to detect a single event.

If confirmed, a single $^4\overline{\mathrm{He}}$ would be a major discovery

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Thanks for your attention