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LUPM LABORATOIRE UNIVERS & PARTICULES MONTPELLIER

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

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w/ P. Salati, I. Cholis, M. Kamionkowski and J. Silk

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Secondaries cannot explain anti-^{4}He

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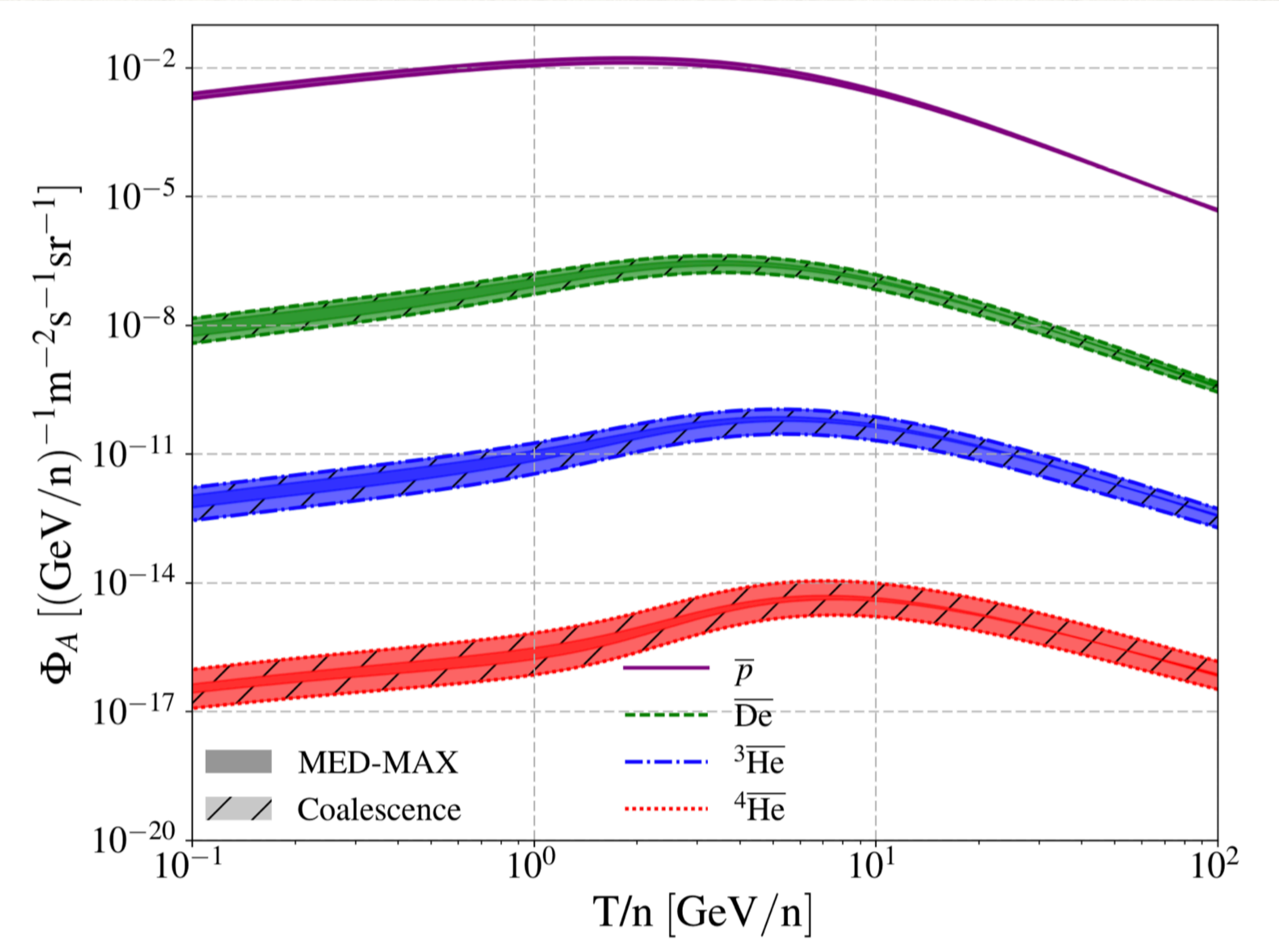

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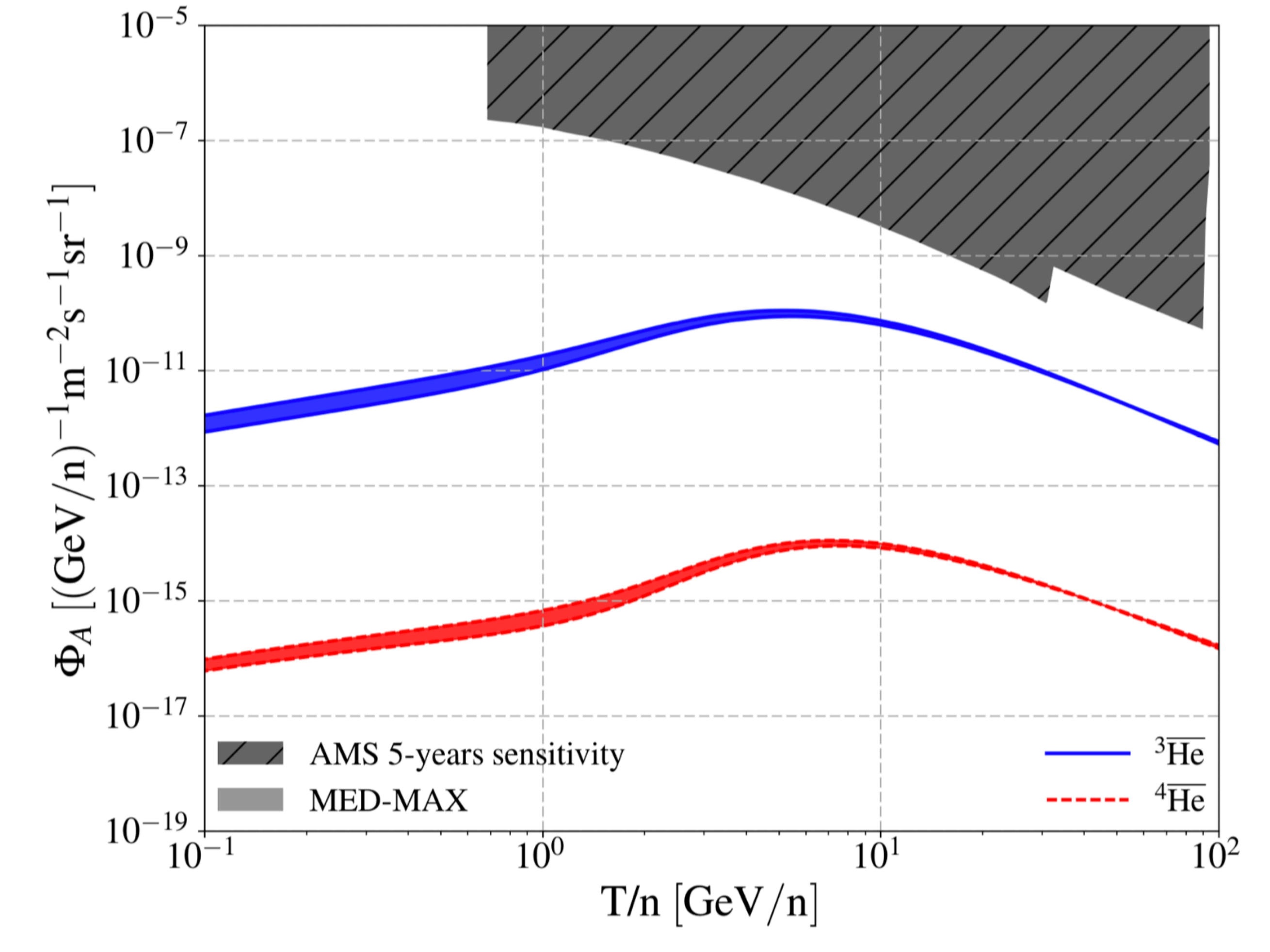
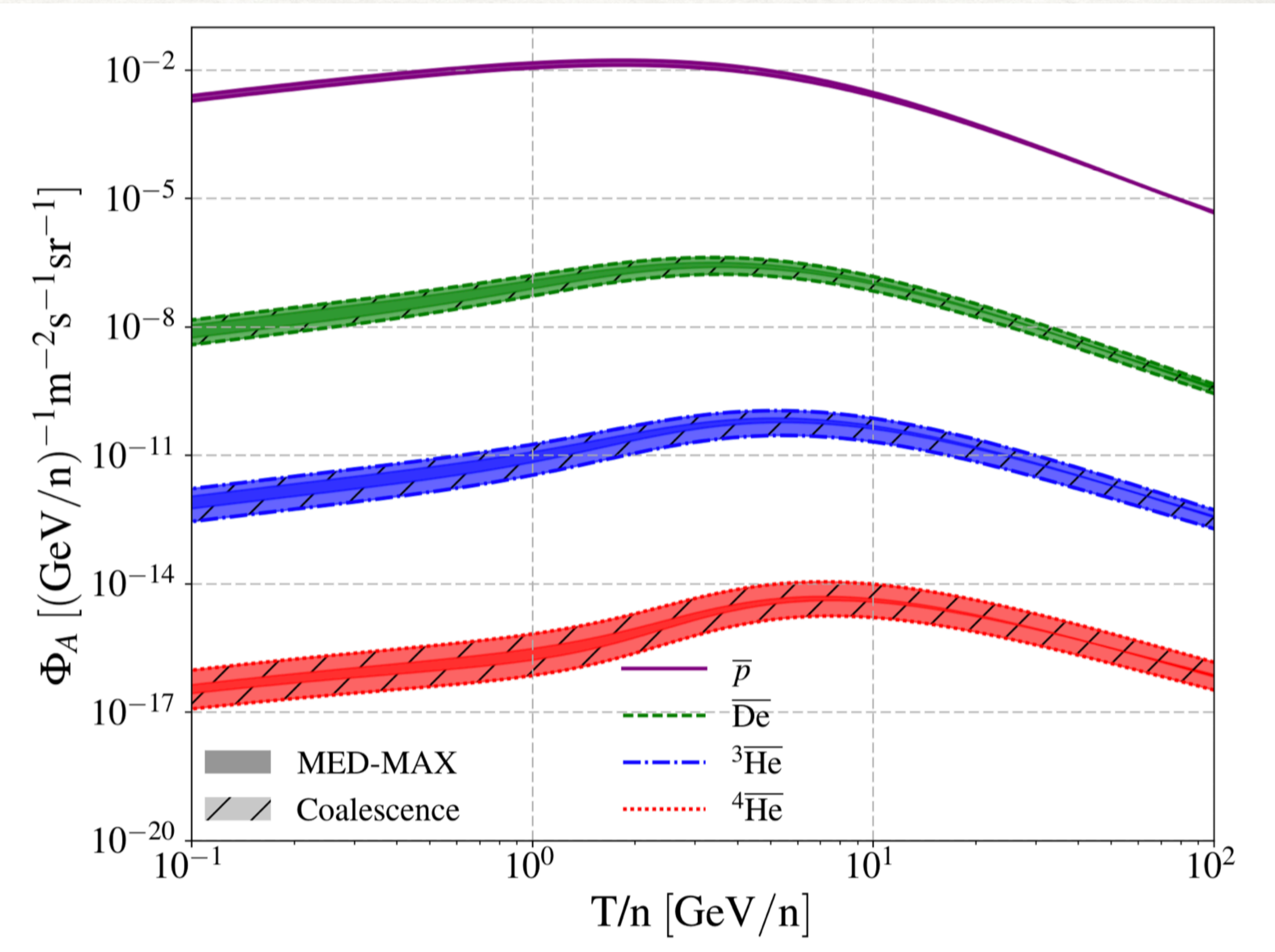
- The coalescence scenario predicts a hierarchy in the flux of anti-nuclei $\phi_{A+1} \approx 10^{-4}\phi_A$
- AMS measured no anti-De, 6 anti-^{3}He and 2 anti-^{4}He.
- AMS sensitivity after 18yrs: ϕ(anti-He) /ϕ(He) ~ $5*10^{-10}$ *Kounine, ICRC 2011*
- AMS measurement: ϕ(anti-He) /ϕ(He) ~ 10^{-8}: 20 times above the claimed sensitivity!





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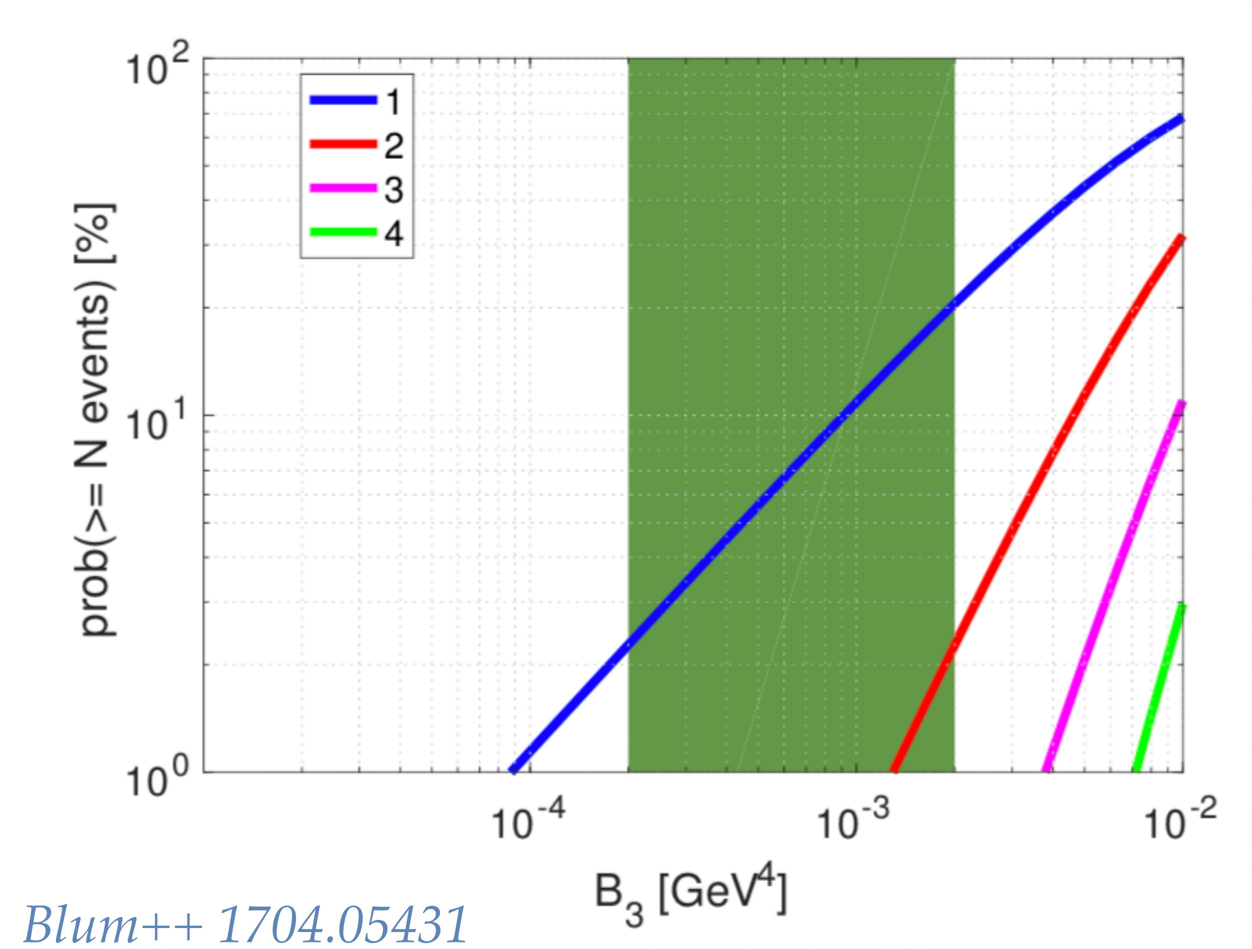

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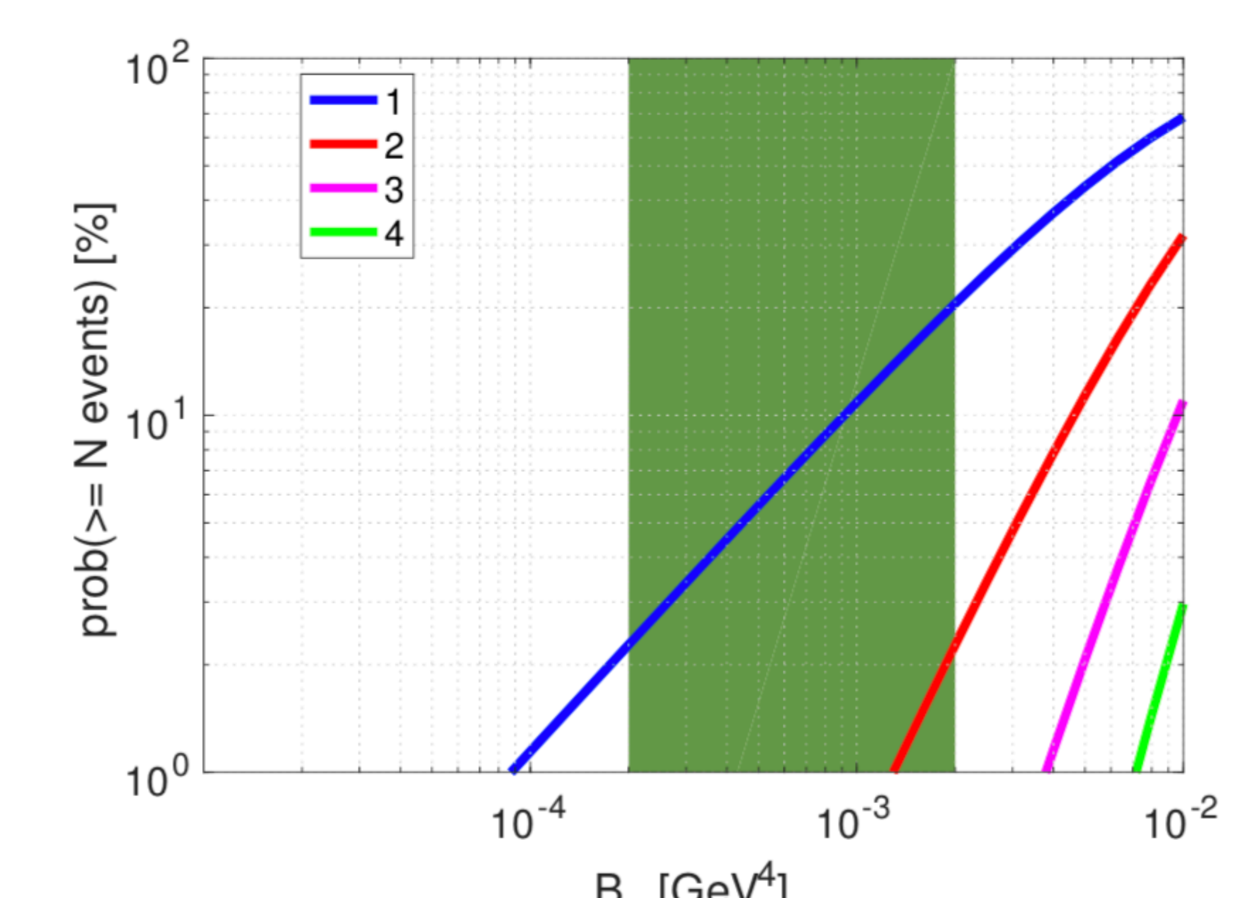

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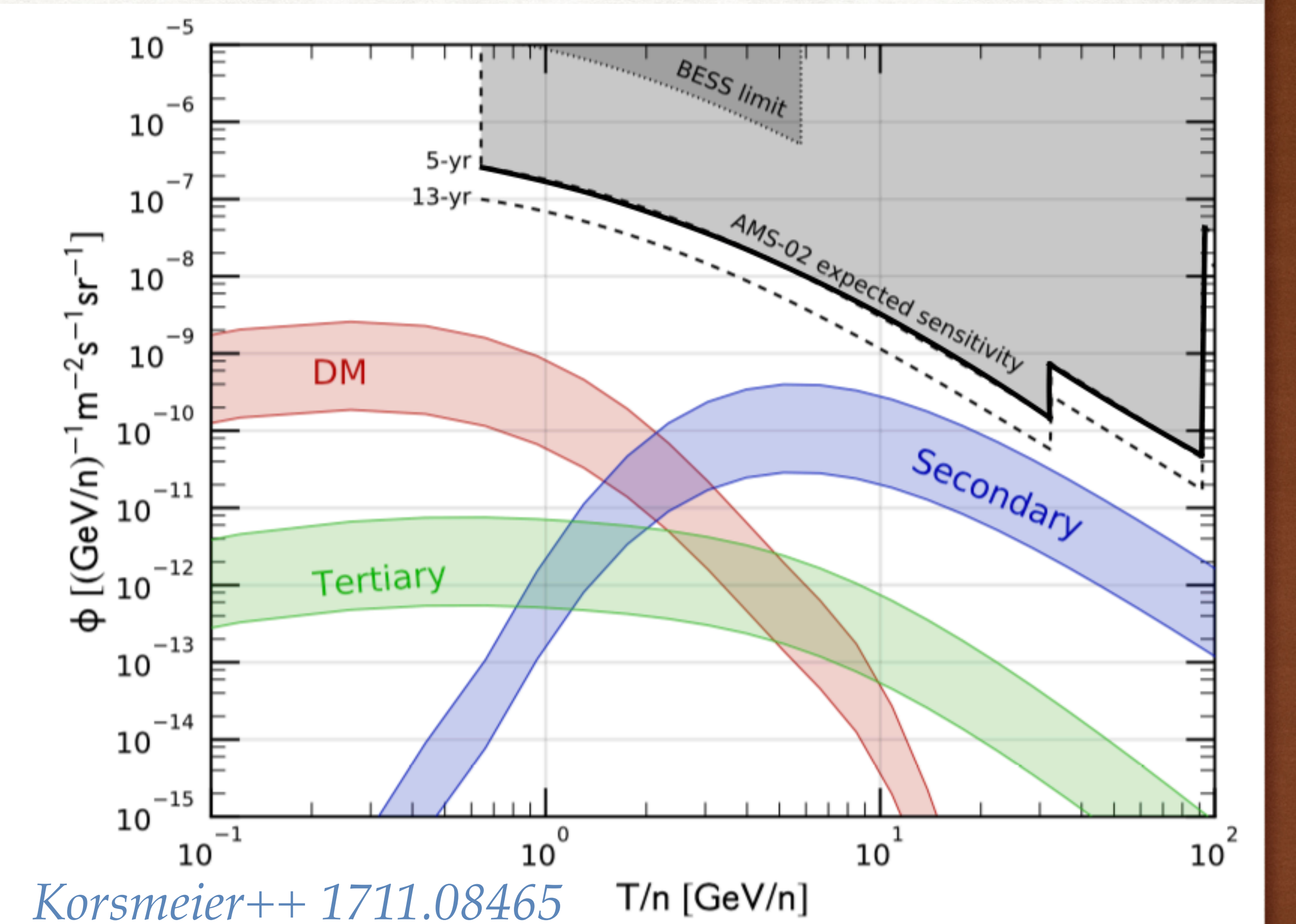

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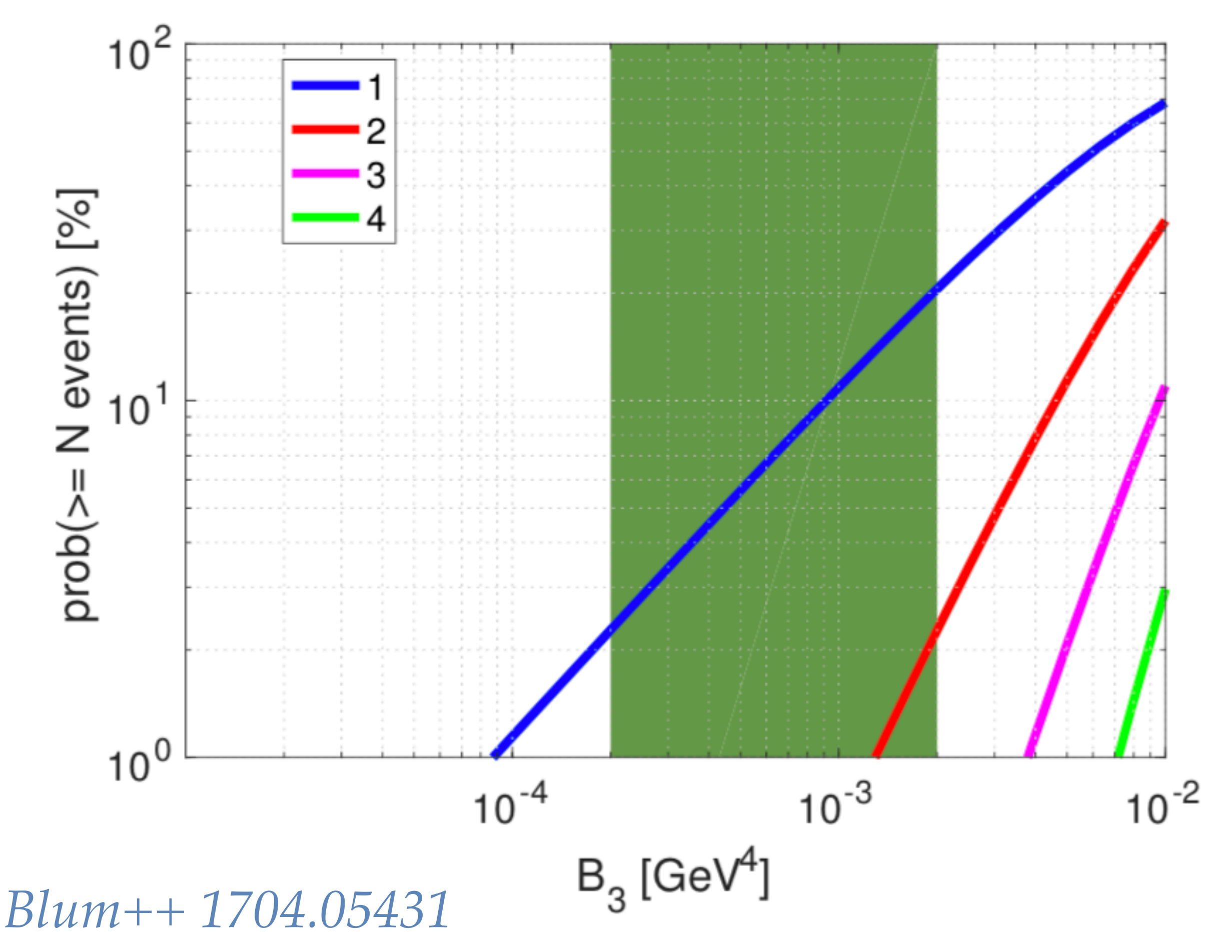

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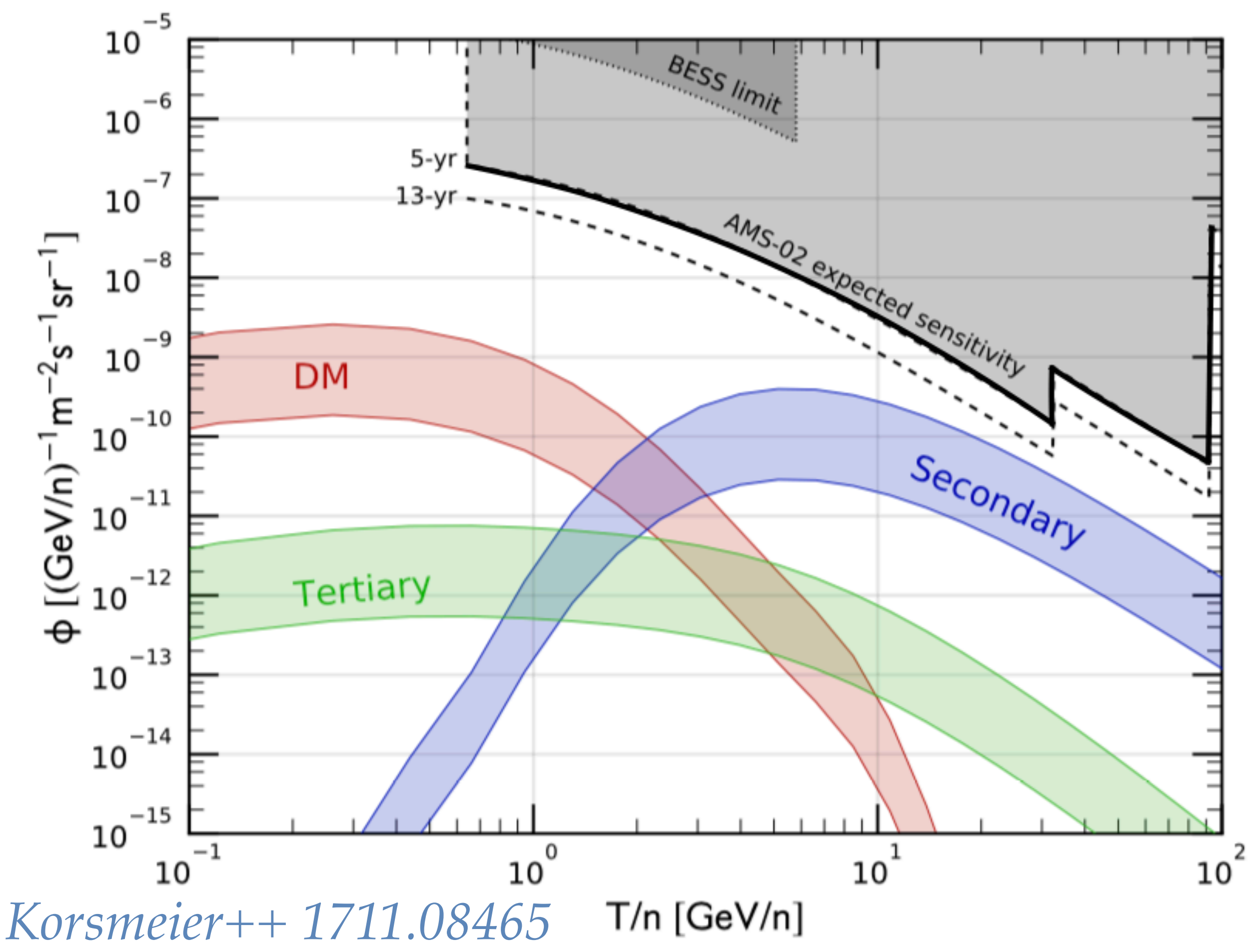

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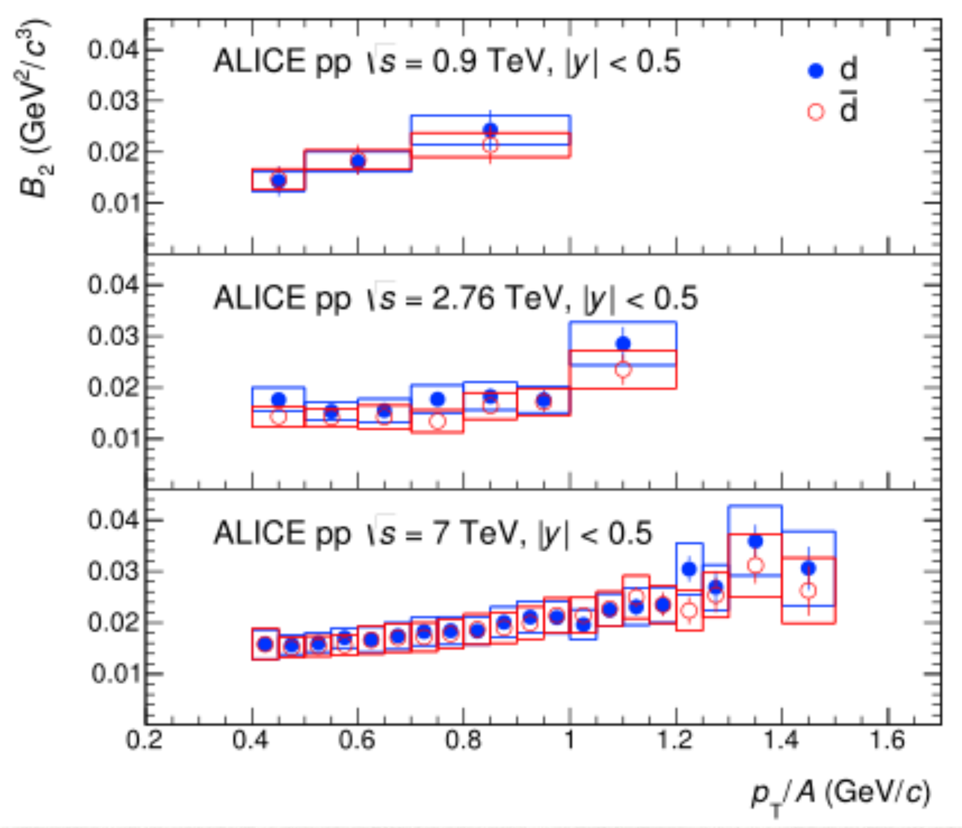
- Korsmeier++ 2017: ~1-2 orders of magnitude below measurement.
- Same conclusions in Cirelli++ 1401.4017, Herms++1610.00699 etc…

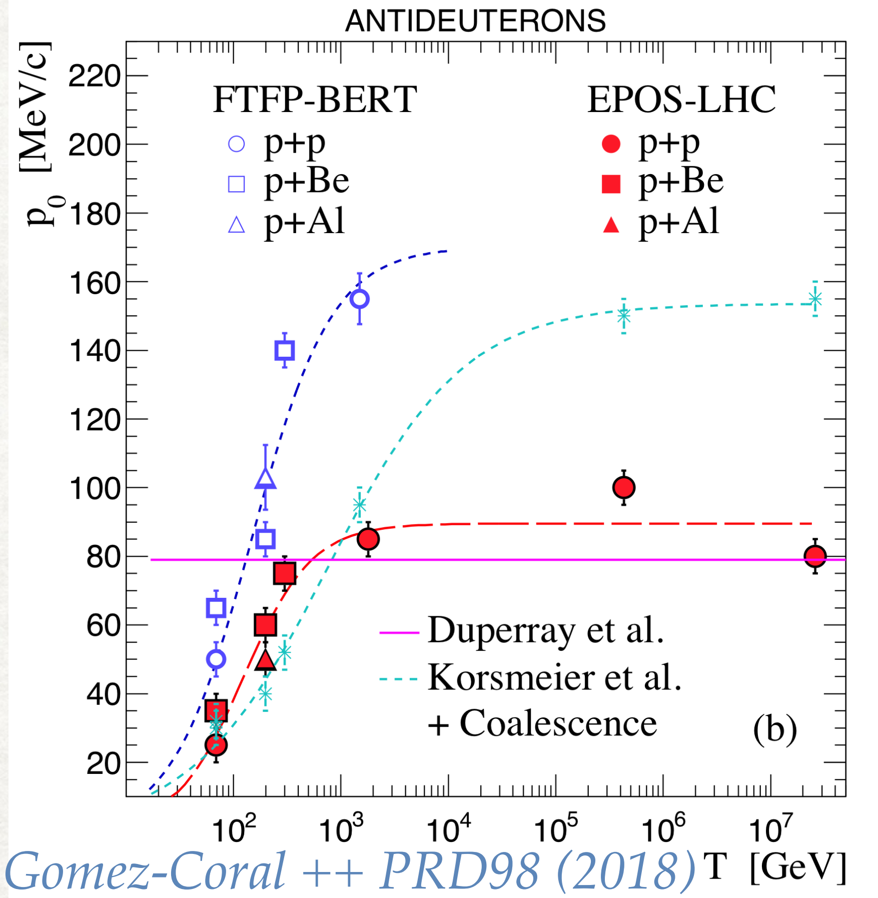
What could be wrong? (1)

- The coalescence scenario could be wrong:
  - Using the anti-De measurements we can predict what the anti-3He coalescence factor should be: very good agreement with what is measured by ALICE

$$p_{\rm coal}^{\rm De} \in [0.218, 0.262]\ {\rm GeV} \qquad p_{\rm coal}^{\rm He} \in [0.208, 0.262]\ {\rm GeV}$$

  - We have assumed a constant coalescence factor: could there be resonances?



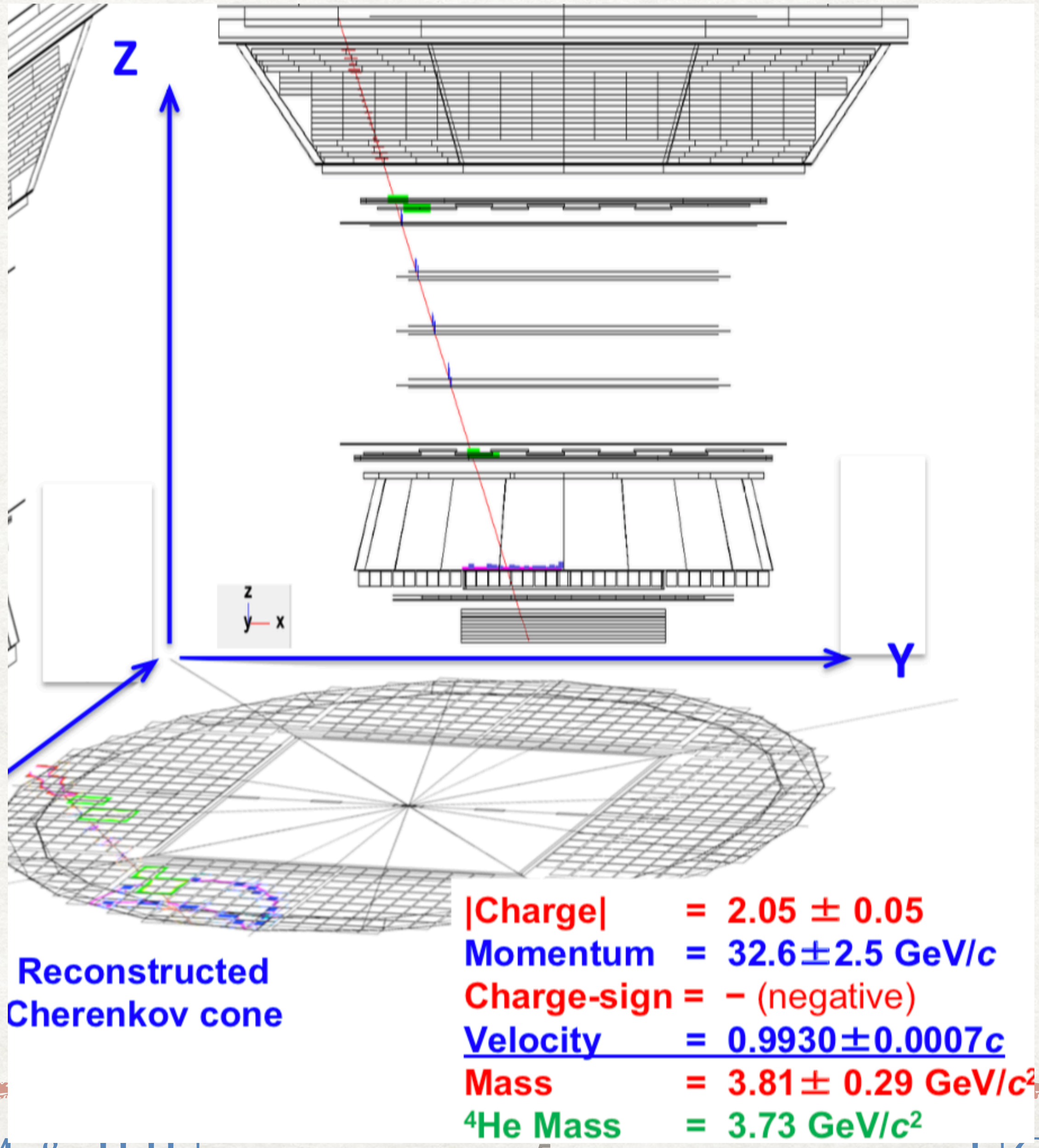


Gomez-Coral ++ PRD98 (2018)

no resonances observed in Alice data nor in MonteCarlo

What could be wrong? (2)

- The measurements could be problematic:
  - Sensitivity to anti-De is much worse than that to anti-^{3}He: did we miss them?
  - The mass of the anti-^{4}He could have been mis-reconstructed.
  - Of course, the sign could be wrong…



What about Dark Matter?

- The Dark Matter explanation suffers from very similar issues! Anti-He produced via coalescence of anti-proton and anti-neutron.

$$q_{\rm DM}(E_{\bar{D}},\vec{x}) = \frac{1}{2}\left(\frac{\rho(\vec{x})}{m_{\rm DM}}\right)^2 \langle\sigma v\rangle_{b\bar{b}} \frac{dN^{b\bar{b}}_{\bar{D}}}{dE_{\bar{D}}}.$$

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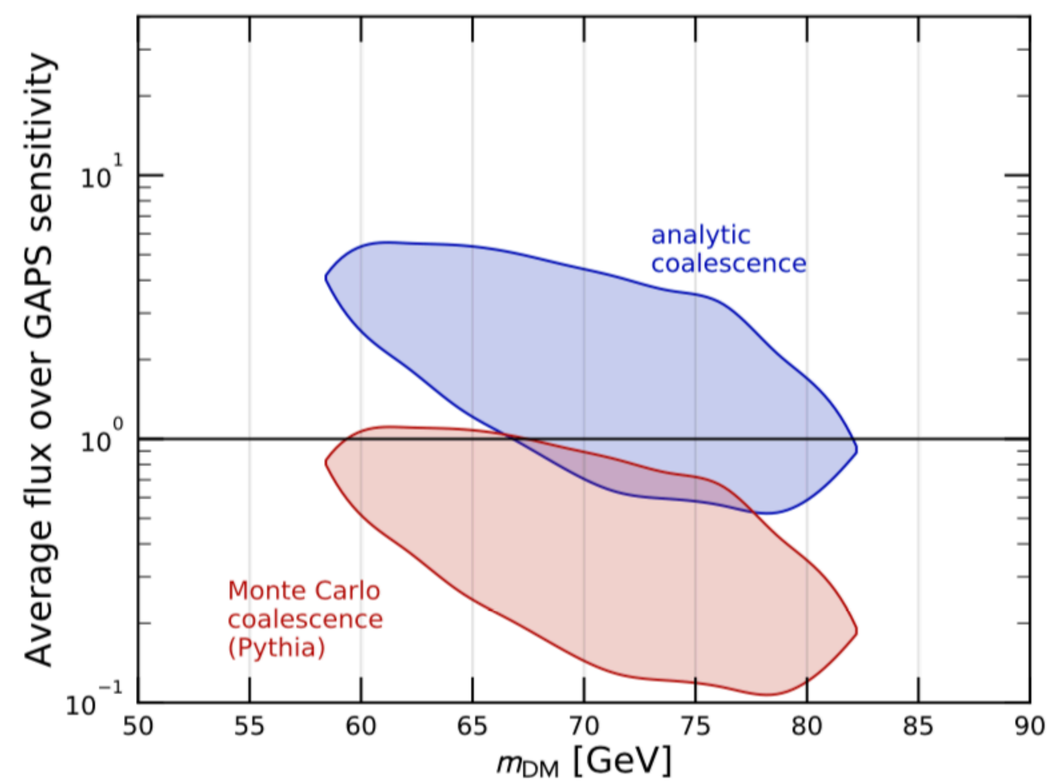
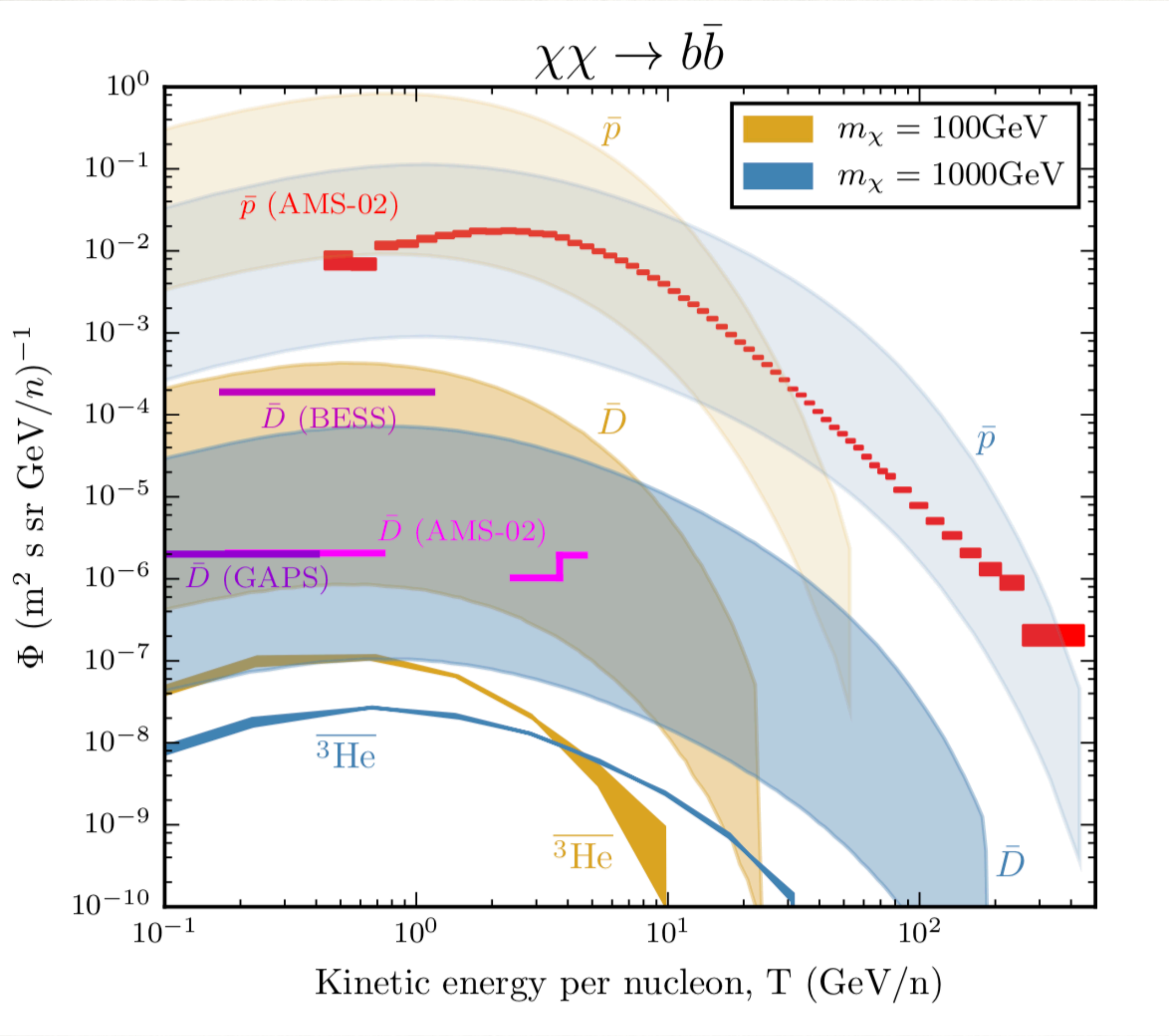
- Coalescence factor can change: very different kinematic + non-nuclear material. It leads to typically smaller values of B_A.

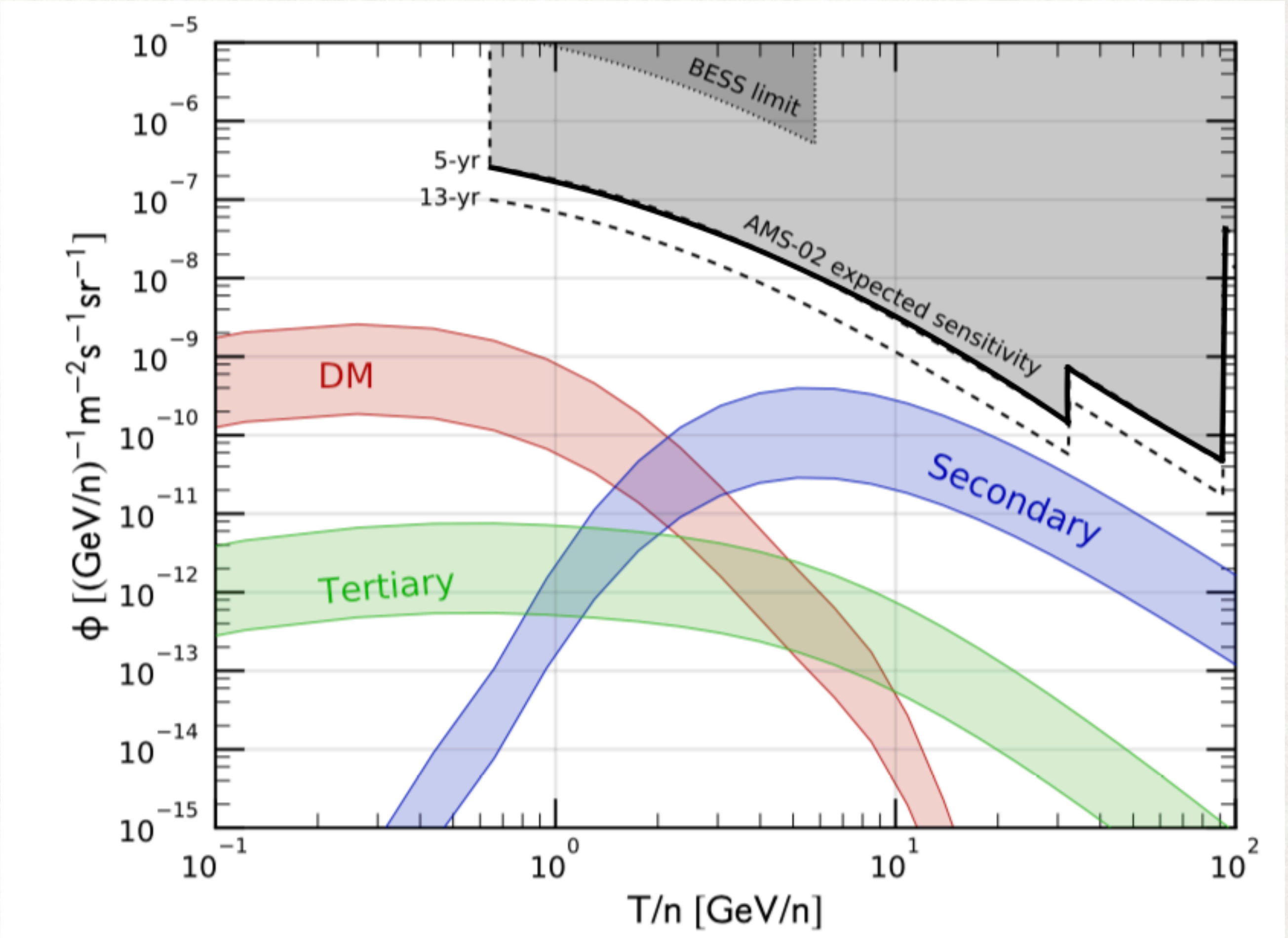


(a) Coalescence model

Korsmeier++ 1711.08465

Dark Matter is at odds with AMS02 events





- The Dark Matter flux peaks at low kinetic energy compared to background.
- AMS should see associated anti-De and anti-proton: Most of the parameter space is ruled out by anti-proton.

-> see talk by M. Korsmeier

- anti-^{4}He??

Anti-helium as a probe of an anti-world

"Production of anti-helium or heavier anti-nuclei in the interaction of ordinary matter in space is totally negligible; therefore observation of single anti-helium in space would constitute a strong argument in favor of such anti-matter domains."

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- Questions: i) How can such objects be produced?
  ii) Can such objects survive in our galaxy and in the early universe?
  iii) How many of these objects do we need to explain the measurements?
  iv) What are the constraints on the presence of such objects?

e.g. Dolgov&Silk 1993, Bambi&Dolgov 2007, Dolgov++ 0806.2986, Dolgov++ 1309.2746, Blinnikov++ 1409.5736

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Today I will discuss points ii), iii) and iv)

Anti-matter in the universe

- From BBN and CMB we know

$$\beta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \cdot 10^{-10}$$

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Where does the observed baryon asymmetry comes from?

- Three types of cosmological baryon asymmetry:
  i) β is homogeneous, the universe is 100% matter dominated;
  ii) average β is 0 but there are very large domains of matter and anti-matter;
  iii) β is not spatially constant: there are lumps of antimatter in a matter dominated universe.

e.g. Bambi&Dolgov 2007

Given the large anti-matter flux measured by AMS-02 in our galaxy, we focus on scenario iii)

Clouds of anti-matter in our galaxy?

- Anti-clouds in our galaxy could explain AMS-02 events.
- How many of them? What are their densities? What volume would they occupy?
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- Are there small, very dense objects or large, very dilute anti-domains?

Anisotropic BBN and the isotopic ratio

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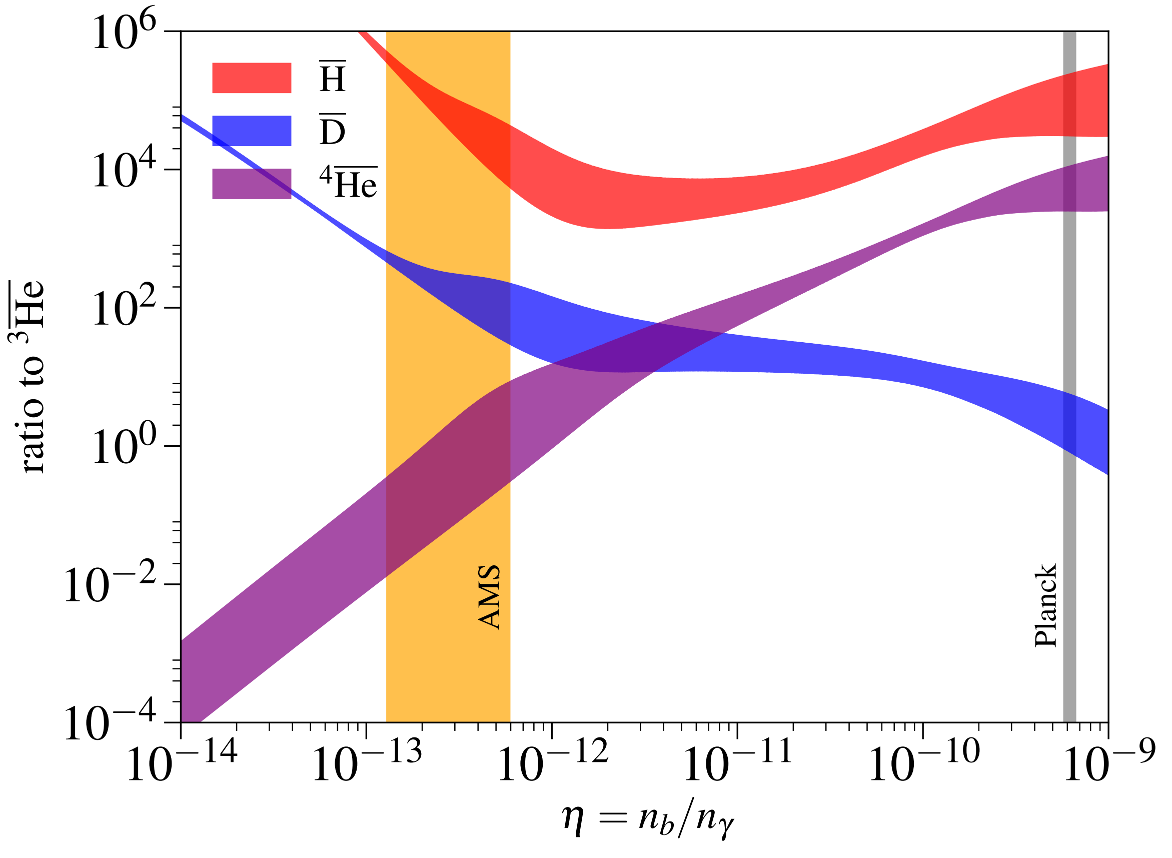

produced with AlterBBN
Arbey 1106.1363

Correct isotopic ratio if anti-η = 10^{-3} η

Some implications of the BBN calculation

- This immediately predicts density ratio: $\frac{N(^4\overline{\rm He})}{N(^3\overline{\rm He})} \simeq 0.3 \Rightarrow \frac{N(\overline{\rm p})}{N(^3\overline{\rm He})} \simeq 10^5$
- We predict ~ 10^4 primary anti-proton and ~0.1 De event.

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$$n_{\bar{p}} \simeq 10^5 - 10^{6.5} N_{\bar{c}}^{-1} \left(\frac{n_p}{1\ \mathrm{cm}^{-3}}\right)\left(\frac{r_{\bar{c}}}{1\ \mathrm{pc}}\right)^{-3} \mathrm{cm}^{-3}\,.$$

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- Question: can such objects survive in our galaxy? can we see them in γ-rays?

Survival rate in our Galaxy

- Our Galaxy exists since roughly $t_{\rm gal} \simeq 2.8 \times 10^{17}$ s .
- antiproton can annihilate with proton in the ISM at a rate: $\tau_{\rm ann}^{-1} = (n_p \langle \sigma_{p\bar{p}} v \rangle)$

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$$\langle \sigma_{p\bar{p}}\, v \rangle \simeq \begin{cases} 1.5 \times 10^{-15}\ \mathrm{cm}^3/\mathrm{s} & T > 10^{10}\ \mathrm{K}\,, \\ 10^{-10} \left(\frac{\mathrm{K}}{T}\right)^{1/2}\ \mathrm{cm}^3/\mathrm{s} & 10^{10}\ \mathrm{K} > T > 10^4\ \mathrm{K}\,, \\ 10^{-10}\ \mathrm{cm}^3/\mathrm{s} & 10^4\ \mathrm{K} > T\,. \end{cases}$$

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- Are anti-clouds cold ($T<10^4$K) or hot and ionized ($T>10^{10}$)?

- Requiring $t_{\rm ann} > t_{\rm gal}$ leads to

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Anti-clouds cannot survive unless there is a segregation between matter and anti-matter

Survival rate in the Early Universe

- In many scenarios, anti-regions will be produced in the early universe. The same calculation can be performed at that epoch.
- The hubble time before matter-radiation equality (z_{eq}>3500) is $t_H \simeq 5 \times 10^{19}(1+z)^{-2}$ s
- Before BBN ($z>10^6$), annihilation happens in the relativistic regime. The constraint on the local proton density from requiring $t_{ann}>t_H$ is:

$$\frac{n_p^{\rm local}}{n_p^{\rm cosmo}}(z > z_{\rm BBN}) < \left(\frac{67}{1+z}\right) \Rightarrow n_p^{\rm local}(z_{\rm BBN}) < 1.9 \times 10^{-8}\, n_p^{\rm cosmo}(z_{\rm BBN})$$

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If anti-domains were formed before BBN,
there must be less than 1 baryon per 10^8 anti-baryons within them!

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- Type i) and iii) can provide very strong constraints on the overlap of matter/anti-matter region. Type ii) could explain some unassociated sources in the 3FGL catalog.

Constraints from a γ-ray line

- γ-ray constraints can be much stronger than the survival rate. Let's see for instance the case of a line from $p\bar{p} \to \pi^0\gamma,\ \eta\gamma,\ \omega\gamma,\ \eta'\gamma,\ \phi\gamma,\ \gamma\gamma$.

Ackermann++ 1506.00013

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$$\Phi^{m_p}_{\pi^0\gamma} = \frac{\int^{R180} d\ell\ d\Omega\ \rho^{\rm MW}_{\pi^0\gamma}}{\int^{R180} d\Omega} < 6.8 \times 10^{-7}{\rm cm}^{-2}{\rm s}^{-1}$$

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FermiLAT can be used to improve constraints by 2 orders of magnitude!

Anti-stars in the galaxy?

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- The anti-cloud scenario is very predictive but severely constrained: it requires anisotropic BBN and strong segregation mechanism that persists today.
- Alternatively, anti-domains could have formed compact objects: naturally free of normal matter! Annihilations only occur at the surface of these objects.

An object of one solar-mass would survive if formed at $z < 10^{16}$

- Moreover, anti-stars could lead to high-energy cosmic rays (anti-SN? Flares?).
- How many of them? What mass & composition? What is the acceleration mechanism?
- Additionally we wish to know how these are formed, and what are the constraints on such objects.

AMS02 anti-stars must be primordial

- Normal stars and anti-stars seem to have very different properties: one cannot simply re-scale the anti-helium flux to deduce the typical population of anti-stars.
- Normal stars form from a helium-4 rich medium and have little helium-3.
- Very light stars (sub-solar mass) formed from a medium poor in anti-helium-4, could explain the isotopic ratio. Another sign of anisotropic BBN?

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- Primordial anti-stars could form from very dense clumps in anti-matter dominated region. Such object

- Idea similar to the formation of primordial black holes but now from strong iso-curvature perturbations at small scales: almost no constraints!

- This scenario was already suggested over 25 years ago! *Dolgov&Silk 1993*

High-energy cosmic rays from anti-stars

- Even if such objects were created in the early universe, it is unclear how they can lead to high-energy cosmic rays.

- Do they lead to supernovae explosion that accelerate the surrounding medium? Do they experience solar flares? Could there be thermo-nuclear explosions from annihilations at the surface?

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- Helium would escape the galaxy in 10^8 yrs ~ $10^{-3} t_{gal}$: there might be a population of stars!

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- We can compute the grammage required to inverse the isotopic ratio from the result of the LEAR collaboration measuring $\bar{p}\,{}^4\mathrm{He} \to {}^3\mathrm{He} + X$

  Balestra++ 1985

- We find that it requires 20g/cm^2. For comparison: this represents 1/50th of our atmosphere.

How to see an anti-star

- Normal matter falling onto the anti-star could lead to characteristic annihilation spectra (line and continuum below the proton mass).

- Within 150 pc from the Sun, non-observation of such event from Bondi accretion leads to $N_{\bar{*}} < 4 \times 10^{-5} N_{*}$.

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There could be an anti-star at ~ 1pc from us!

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- Anti-clouds with a different anti-BBN can produce the correct isotopic ratio.

- These clouds cannot survive unless they are almost free of normal matter along cosmic history: segregation mechanism?

- Alternatively, primordial anti-stars could be formed in the early universe from strong iso-curvature perturbations at small scales.

- Depending on the (unknown) acceleration mechanism, it is conceivable that a single near-by (~1pc) anti-star contributes to the AMS-02 observation.

Back-up

CMB constraints

- From Planck data we have: $\left.\frac{\mathrm{d}^2E}{\mathrm{d}V\mathrm{d}t}\right|_{\mathrm{ann}} < 8.1\times10^{-31}\,(1+z)^6\,\mathrm{J\ m^{-3}\ s^{-1}}\,.$

- The annihilation rate is: $\left.\frac{\mathrm{d}^2E}{\mathrm{d}V\mathrm{d}t}\right|_{b\bar{b}-\mathrm{ann}} = \langle\sigma_{p\bar{p}}v\rangle n_p n_{\bar{p}} 2m_p c^2$

- This leads to $n_{\bar{p}}^0 < 1.35\times10^{-10}\mathrm{cm}^{-3}$ on cosmological scales: ok for AMS02.

- Similarly, for anti-stars we find (assuming annihilation to pion injects energy).

$$\left.\frac{\mathrm{d}^2E}{\mathrm{d}V\mathrm{d}t}\right|_{\bar{\star}} = 8\pi R_{\bar{*}}^2 v n_p m_p c^2 n_{\bar{\star}} \simeq 10^{13} n_{\bar{\star}}\ \mathrm{J\ s^{-1}} \times \left(\frac{R_{\bar{*}}}{10^{11}\ \mathrm{cm}}\right)\left(\frac{v}{30\mathrm{km\ s^{-1}}}\right)\left(\frac{n_p^0}{2\times10^{-7}\mathrm{cm}^{-3}}\right).$$

- And therefore $n_{\bar{\star}} \lesssim 10^{24}(1+z)^3\mathrm{Mpc}^{-3}$