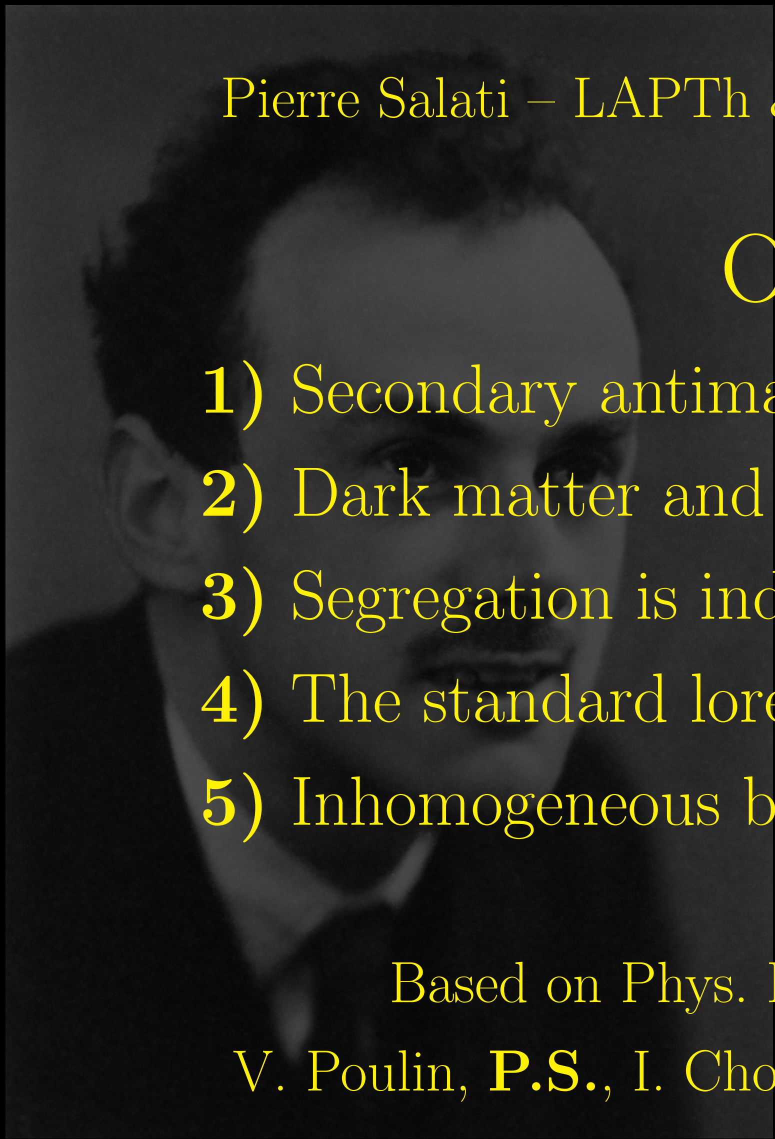
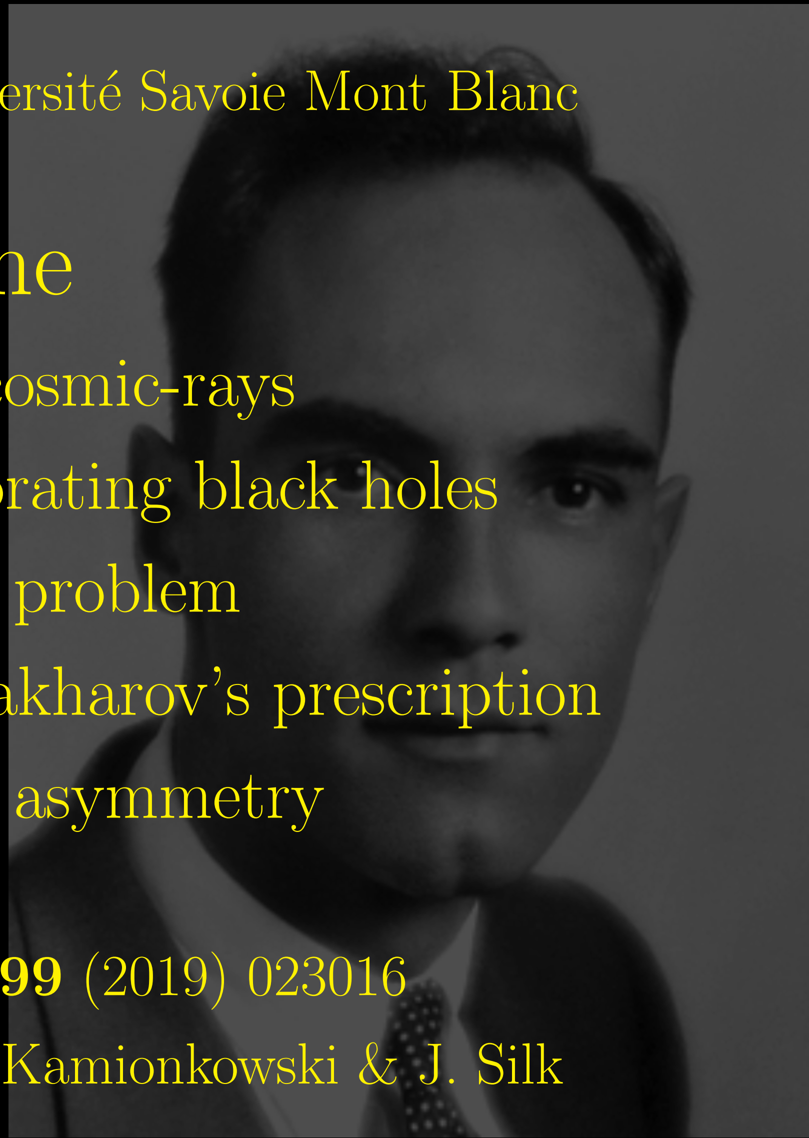
Sources of antimatter

The mundane, the exciting and the disconcerting





Pierre Salati – LAPTh & Université Savoie Mont Blanc

Outline

1) Secondary antimatter cosmic-rays

2) Dark matter and evaporating black holes

3) Segregation is indeed a problem

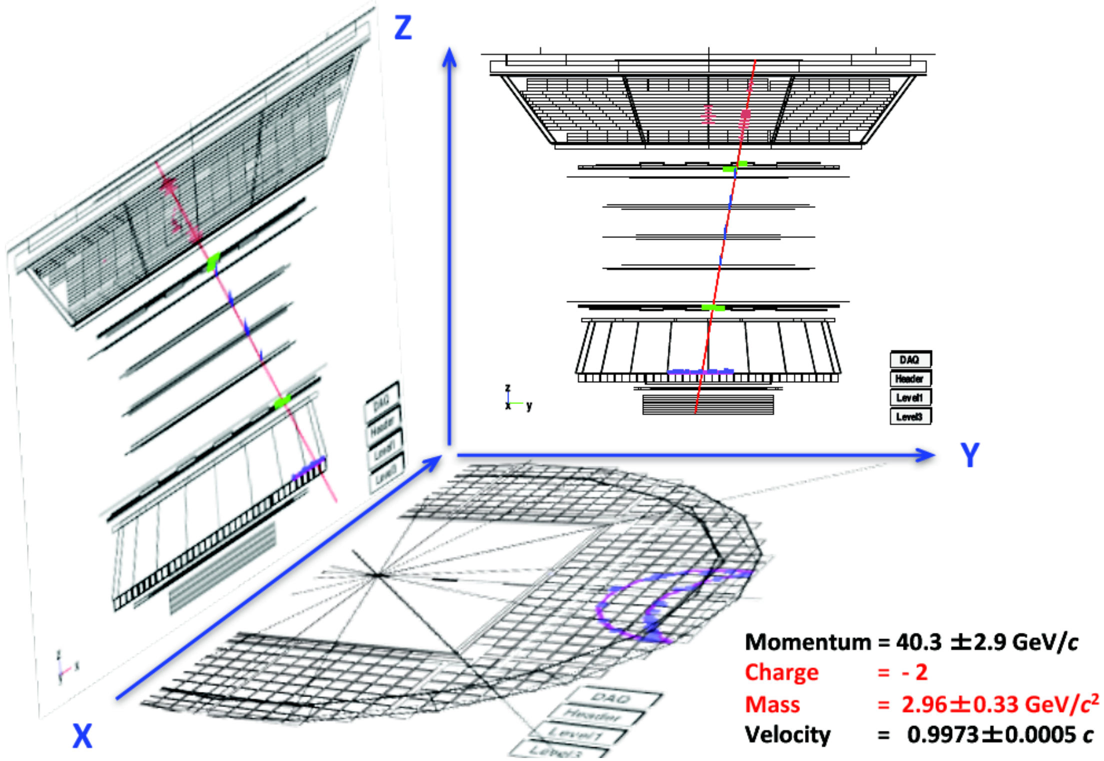
4) The standard lore or Sakharov's prescription

5) Inhomogeneous baryon asymmetry

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

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

AMS-02 and possible anti-He events

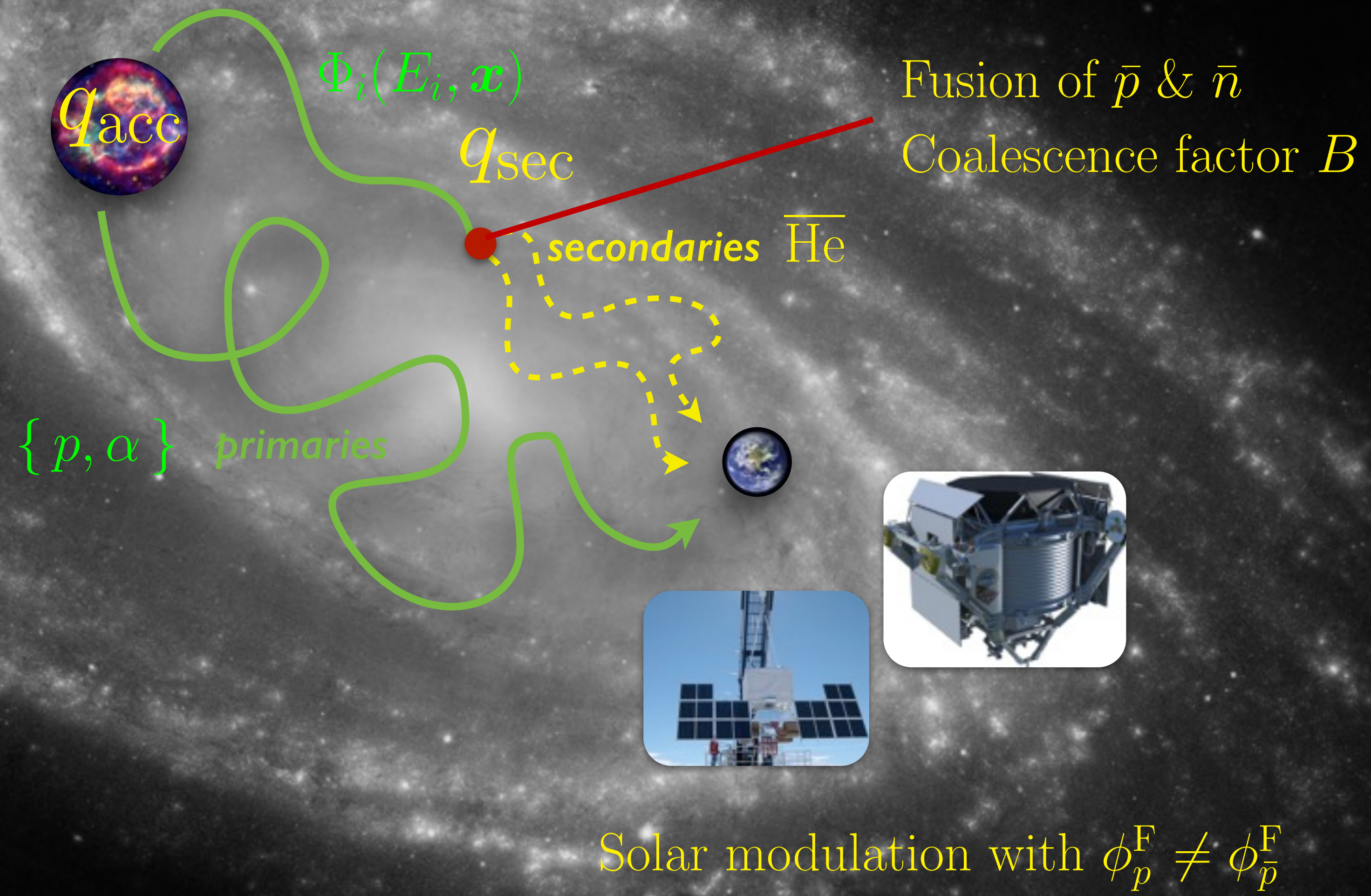


P. von Doetinchem, DSU June 18, 2018

- $^3\overline{\mathrm{He}}$ (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.

1) Secondary antimatter cosmic-rays

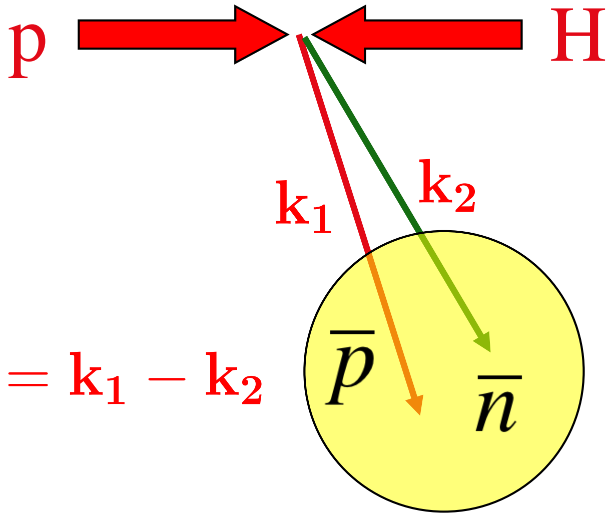
$$q_{\mathrm{sec}}(\overline{\mathrm{He}}\,|\,E_{\overline{\mathrm{He}}},\boldsymbol{x}) = \sum_{i\in \mathrm{p},\alpha}\ \sum_{j\in \mathrm{H},\mathrm{He}} 4\,\pi \int dE_i\ \Phi_i(E_i,\boldsymbol{x})\, n_j(\boldsymbol{x})\, \frac{d\sigma_{ij\to\overline{\mathrm{He}}}}{dE_{\overline{\mathrm{He}}}}(E_i,E_{\overline{\mathrm{He}}})$$



Courtesy Antje Putze, TeVPA 2015

1) Secondary antimatter cosmic-rays

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



$2\boldsymbol{\Delta} = \mathbf{k_1} - \mathbf{k_2}$

$||\boldsymbol{\Delta}|| \leq p_0$

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

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

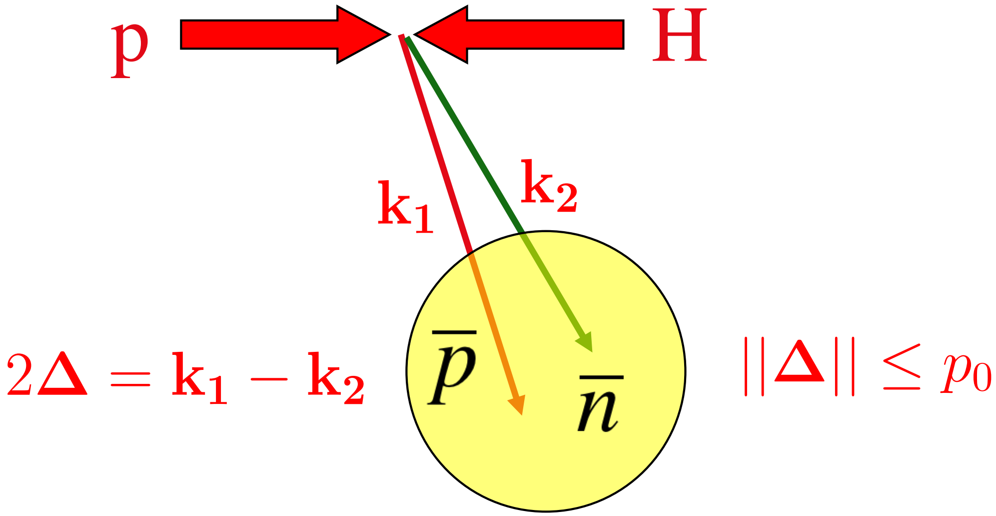
$$B_2 = \frac{E_{\bar{d}}}{E_{\bar{p}}\,E_{\bar{n}}} \int d^3\boldsymbol{\Delta}\; \mathcal{C}(\boldsymbol{\Delta}) \simeq \frac{m_{\bar{d}}}{m_{\bar{p}}\,m_{\bar{n}}} \left\{ \frac{4}{3}\pi\, p_0^3 \equiv \frac{\pi}{6}\, p_{\mathrm{coal}}^3 \right\}$$

Coalescence factor B_2

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

1) 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 $p_0 = p_{\rm coal}/2$

Production on anti-nuclei with mass A

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

Coalescence factor B_A

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

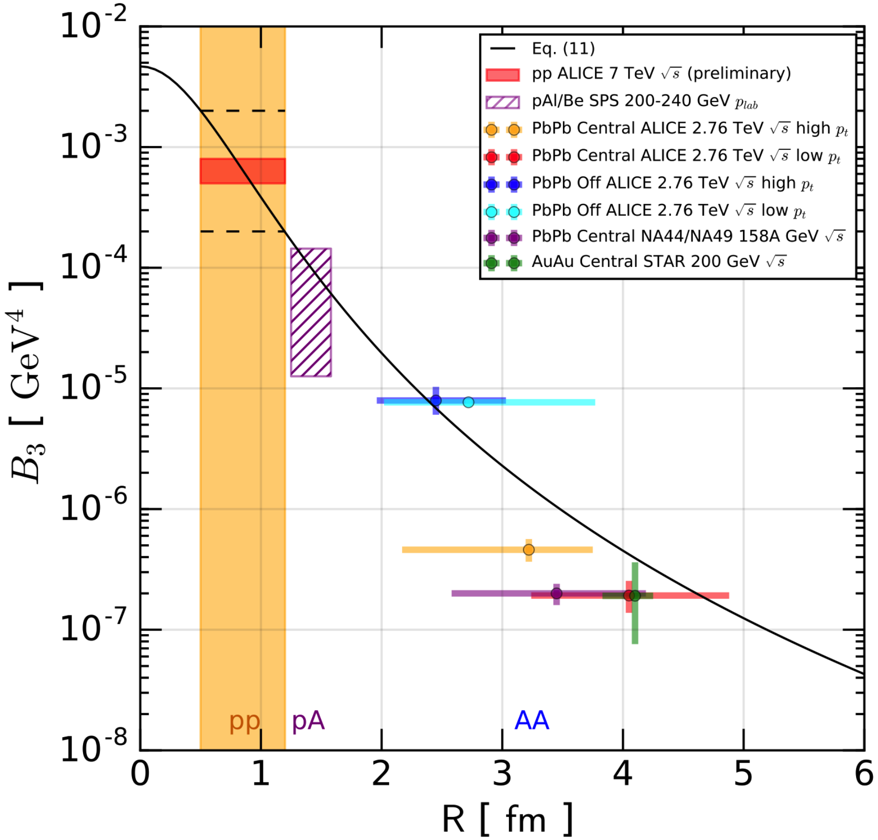
Determination of the coalescence momentum

- 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.

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

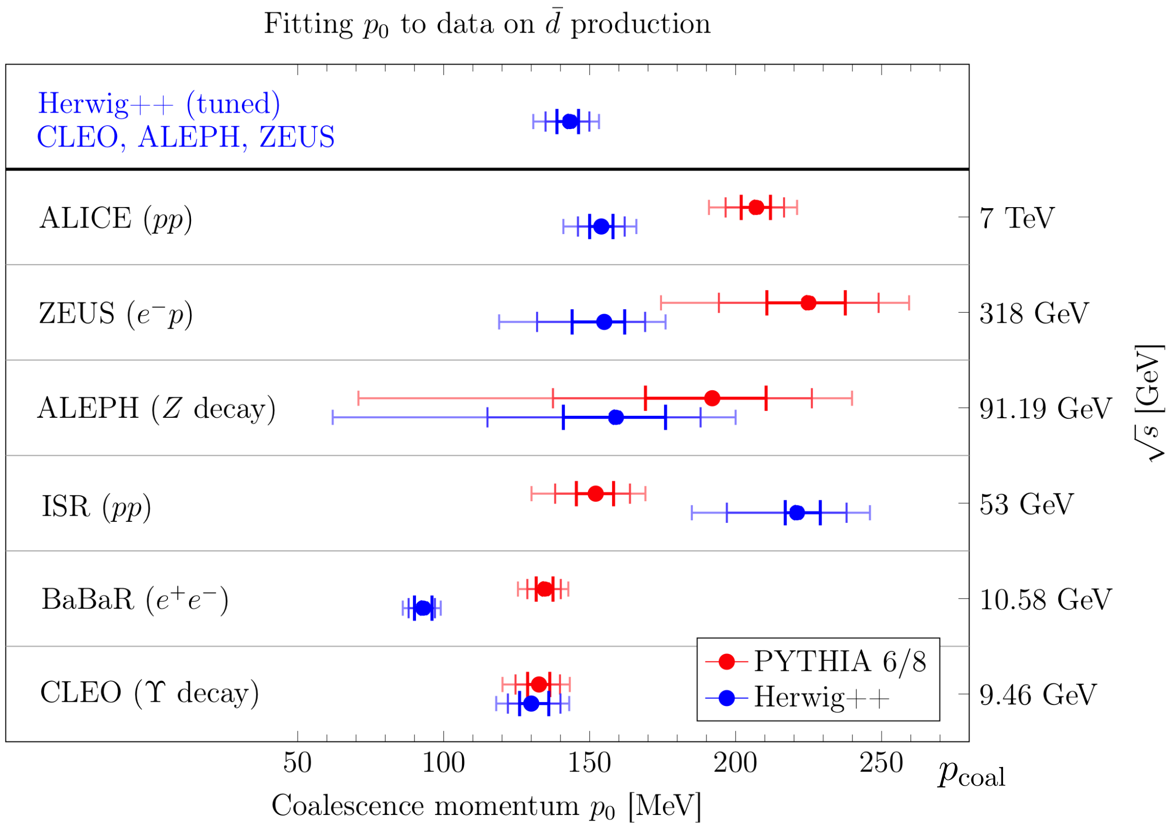
$$\frac{B_3}{\mathrm{GeV}^4} \approx 0.0024 \left(\left(\frac{R(p_t)}{1\ \mathrm{fm}} \right)^2 + 0.8 \left(\frac{b_3}{1.75\ \mathrm{fm}} \right)^2 \right)^{-3} \quad (11)$$



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 $\sqrt{s}$.



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

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

Determination of the coalescence momentum

- Monte-Carlo event-generators are not devoid of problems.
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  They yield different p_0 when adjusted to different data sets.
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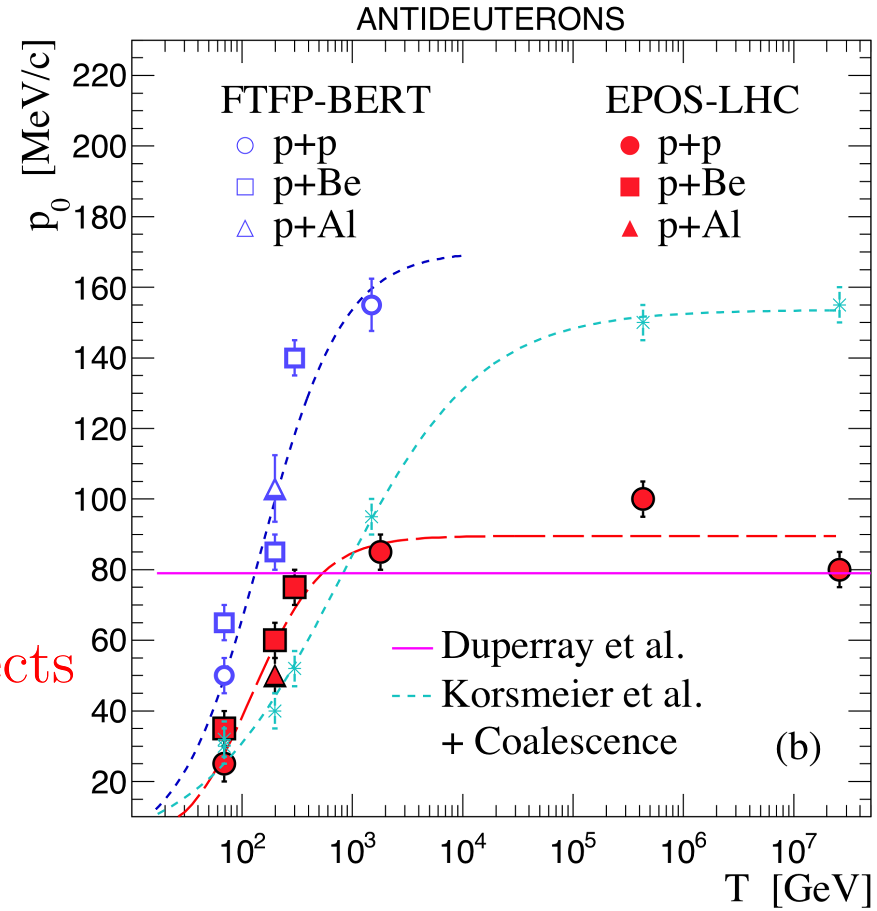
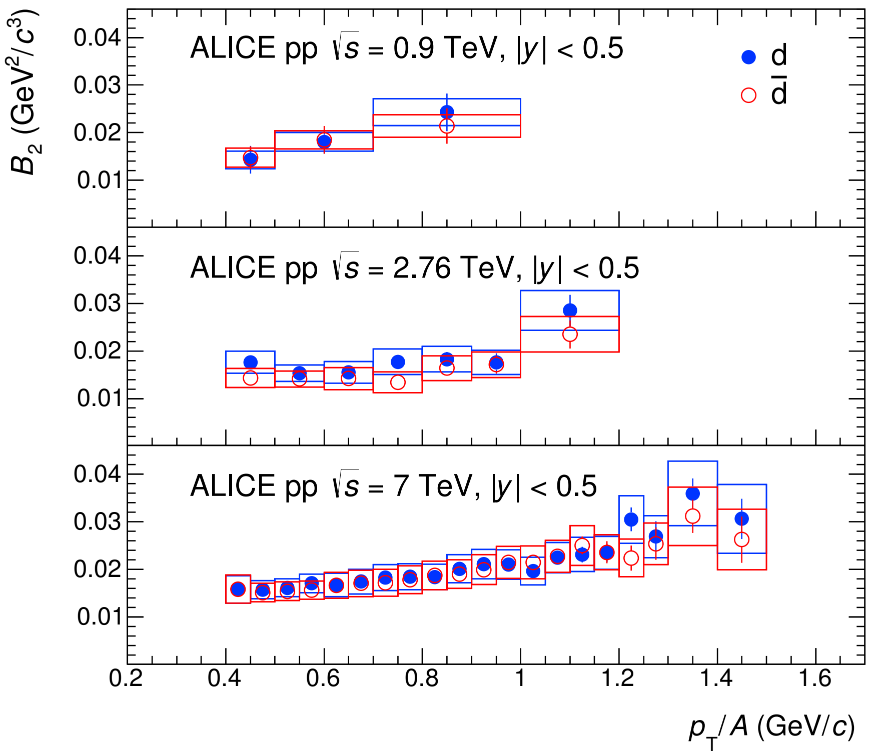
threshold effects

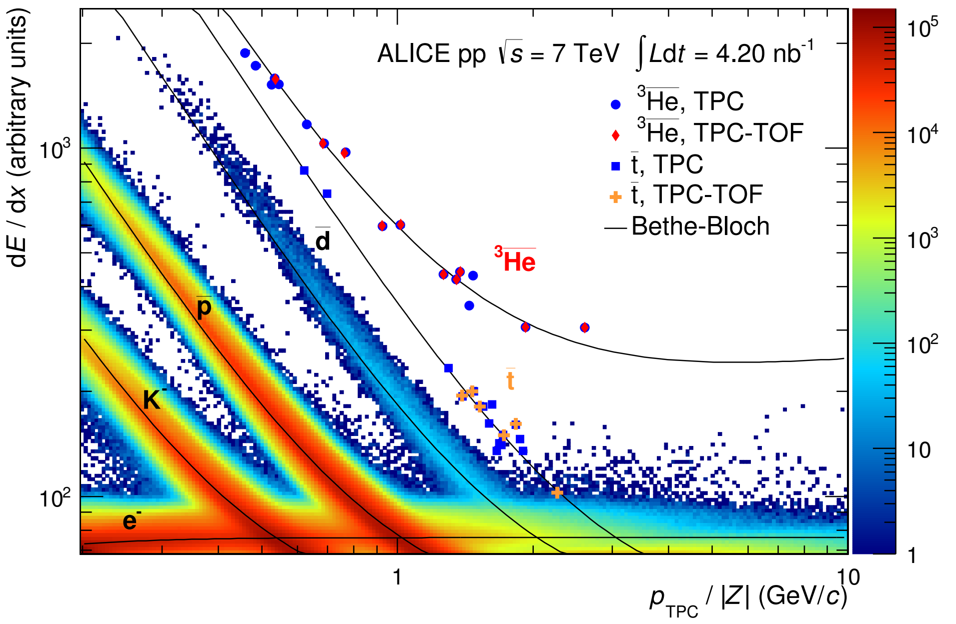


D.M. Gomez-Coral et al., Phys. Rev. **D98** (2018) 023012

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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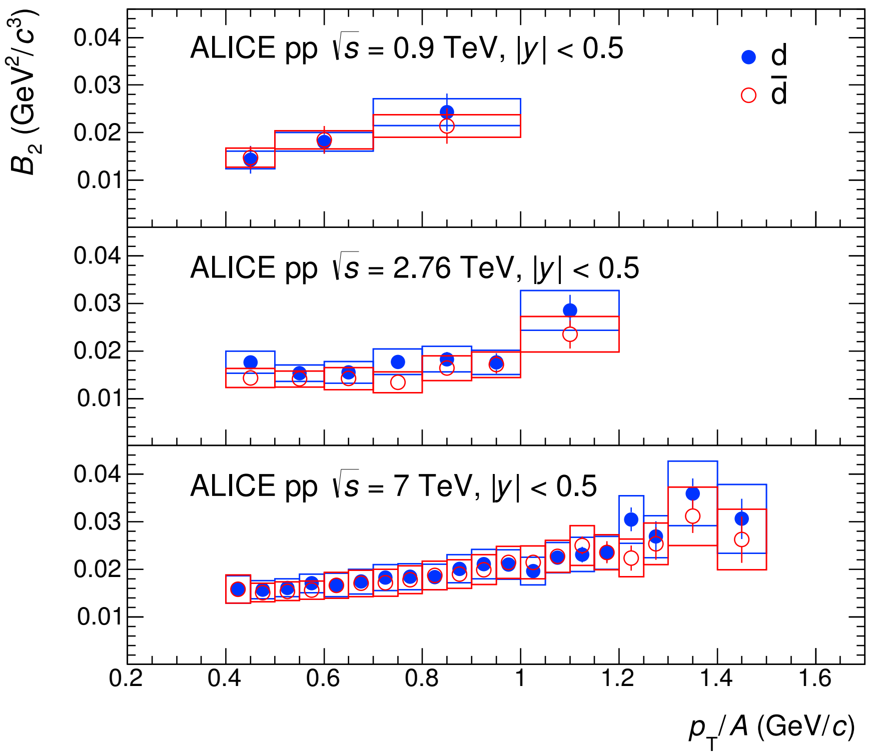
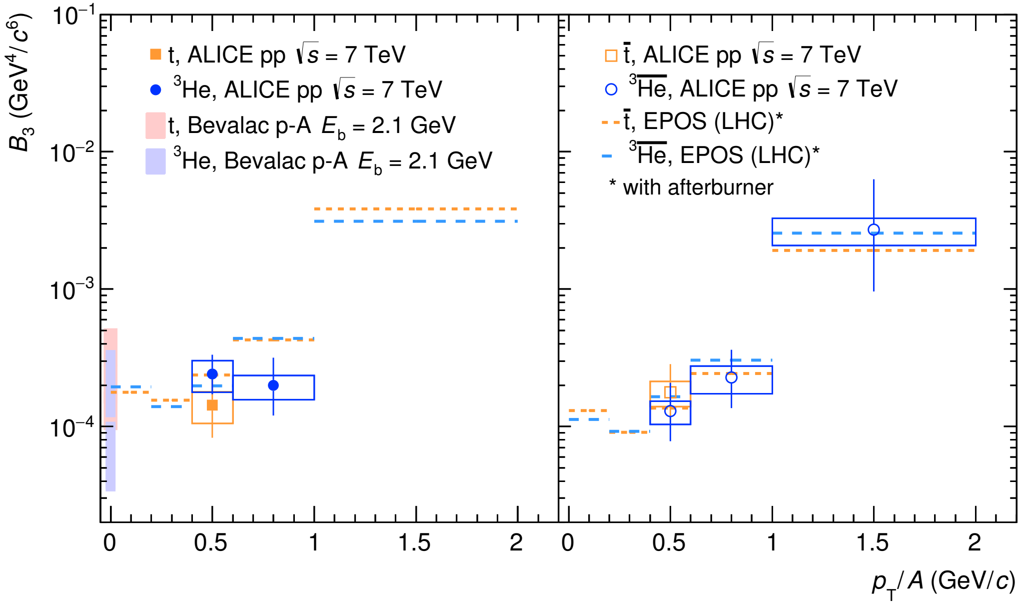


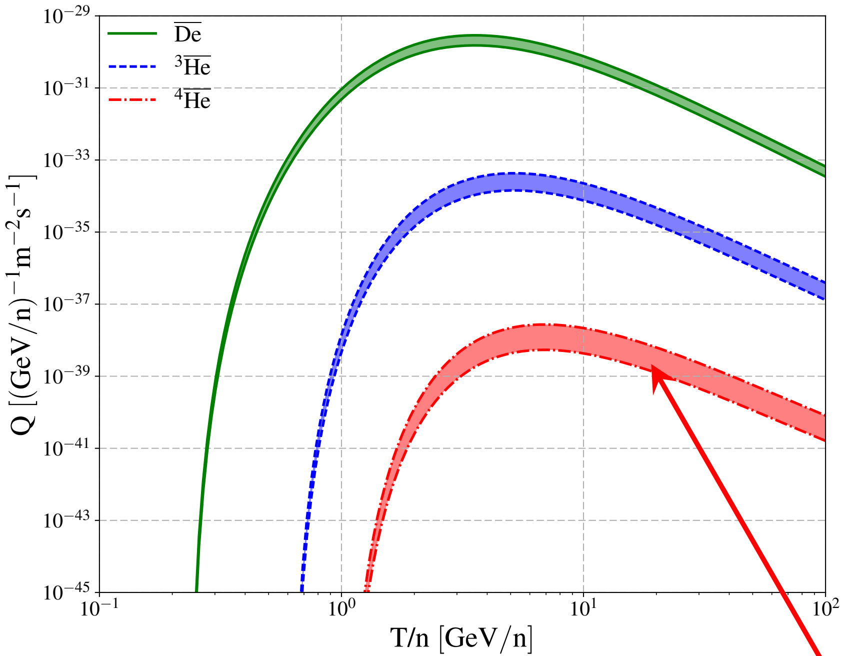


$208 \text{ MeV} \leq p_{\mathrm{coal}} \leq 262 \text{ MeV}$ $218 \text{ MeV} \leq p_{\mathrm{coal}} \leq 262 \text{ MeV}$

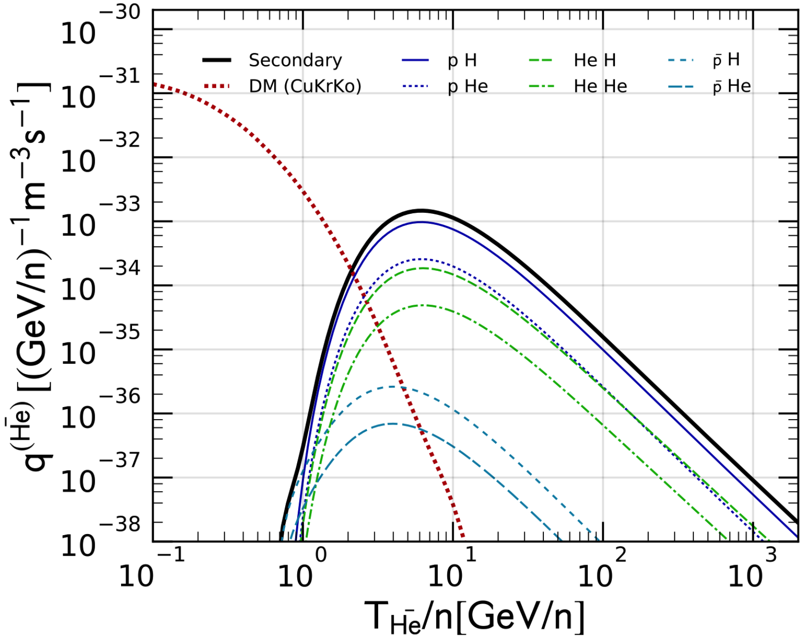
S. Acharya et al., Phys. Rev. **C97** (2018) 024615

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



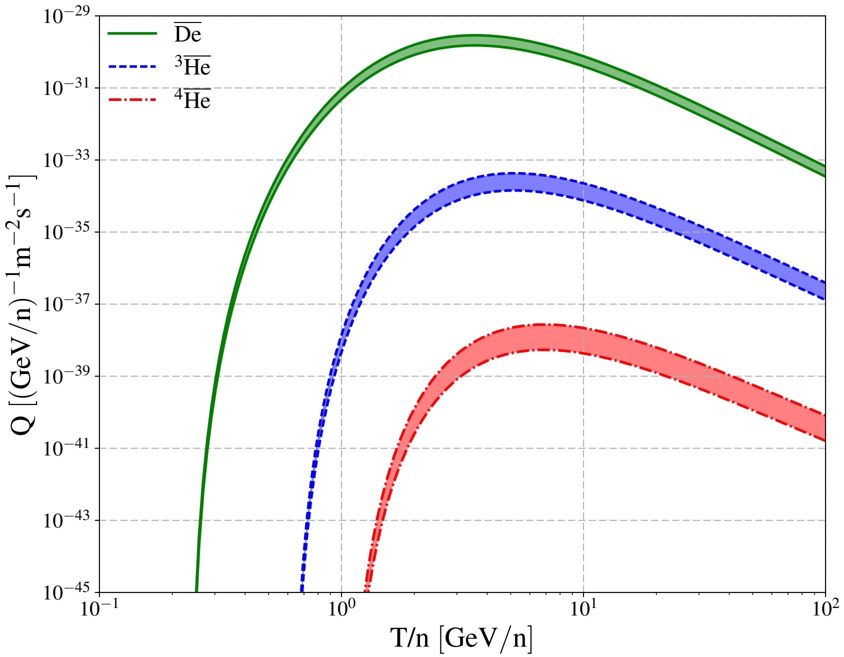
M. Korsmeier et al., Phys. Rev. **D97** (2018) 103011

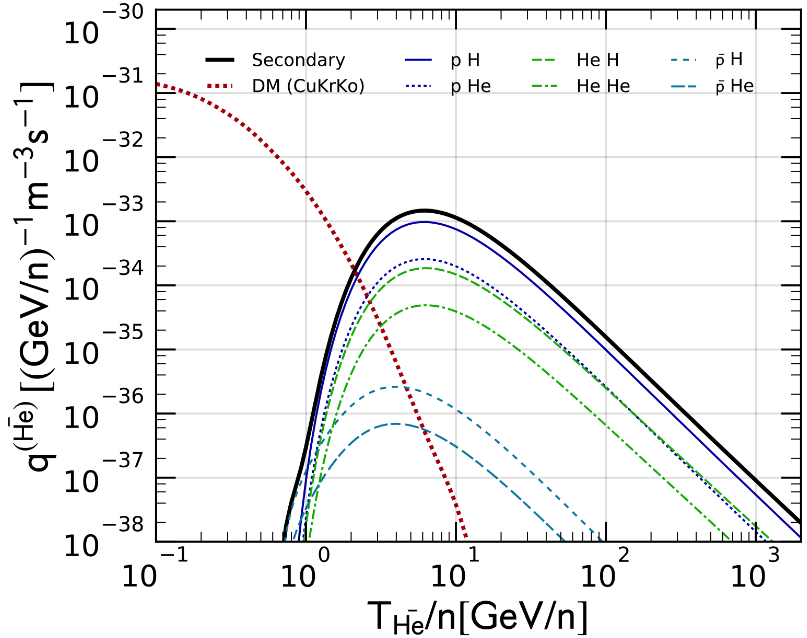
$$7.7\times 10^{-7} \le \frac{B_4}{\rm GeV^6} \le 3.9\times 10^{-6}$$

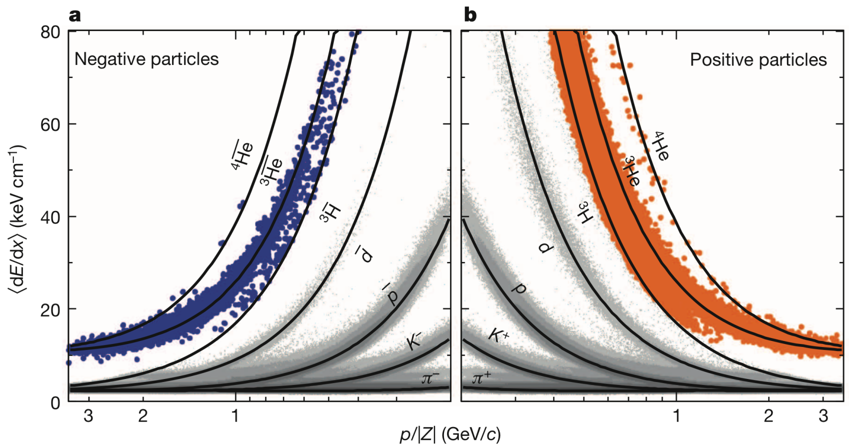
$\bar{p}$ production modeled as in
M. di Mauro et al., Phys. Rev. **D90** (2014) 085017

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

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

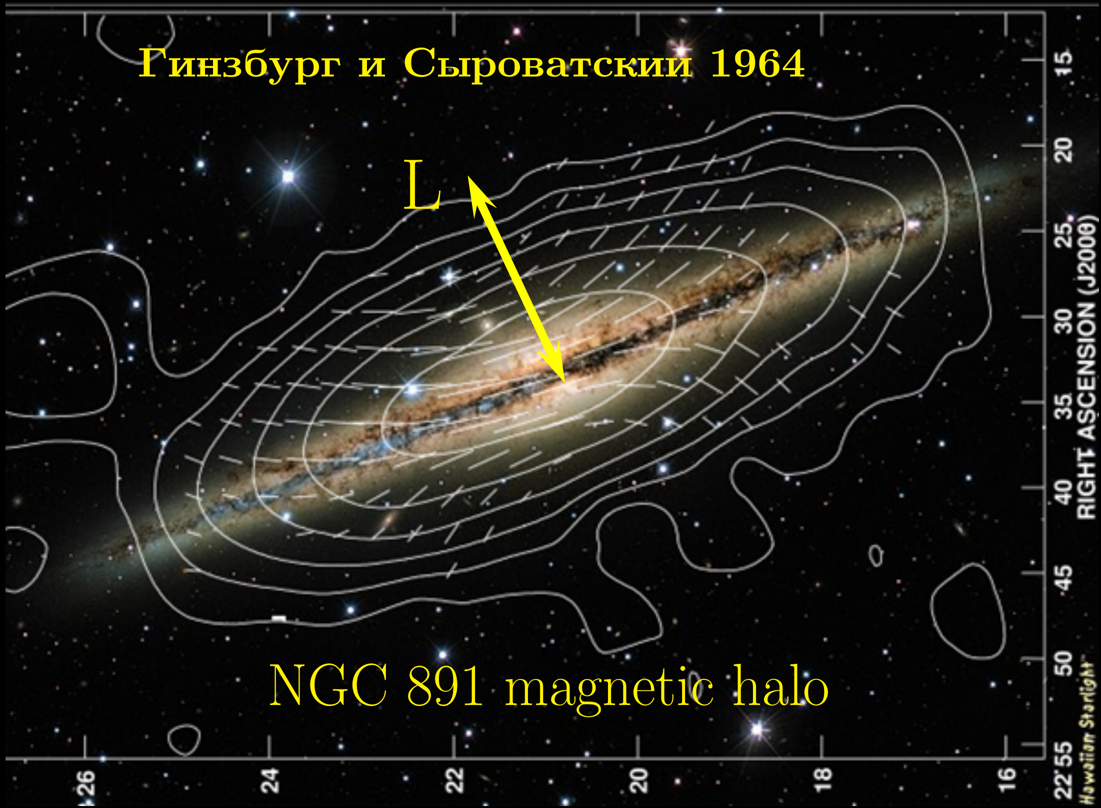


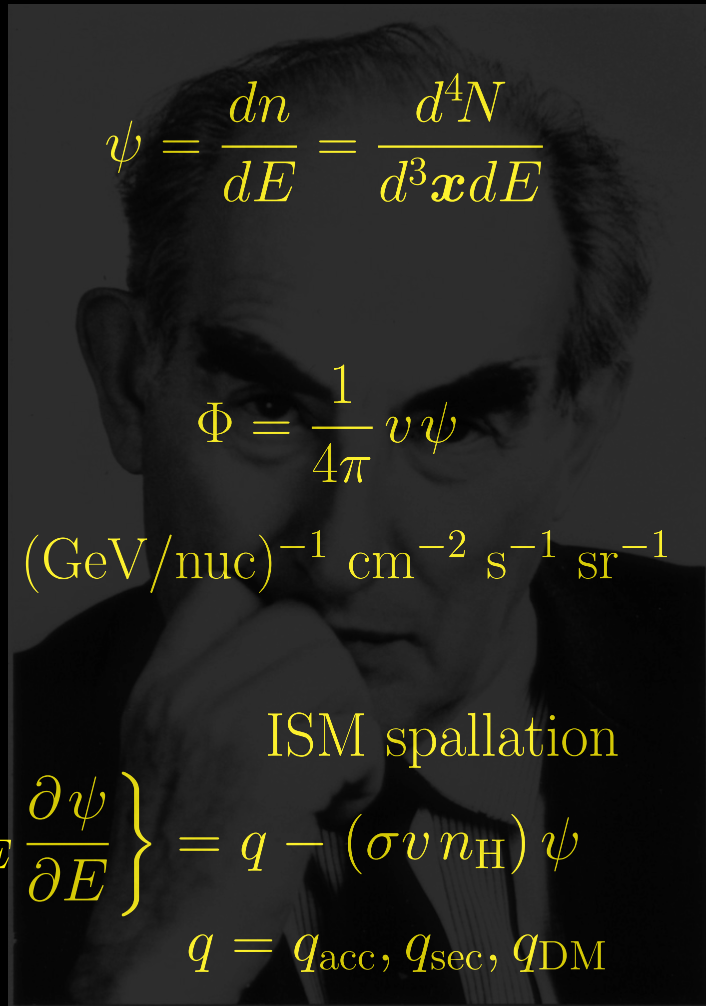




The STAR Collaboration, Nature **473** (2011) 353

Cosmic-ray anti-nuclei Galactic propagation





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

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

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

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

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

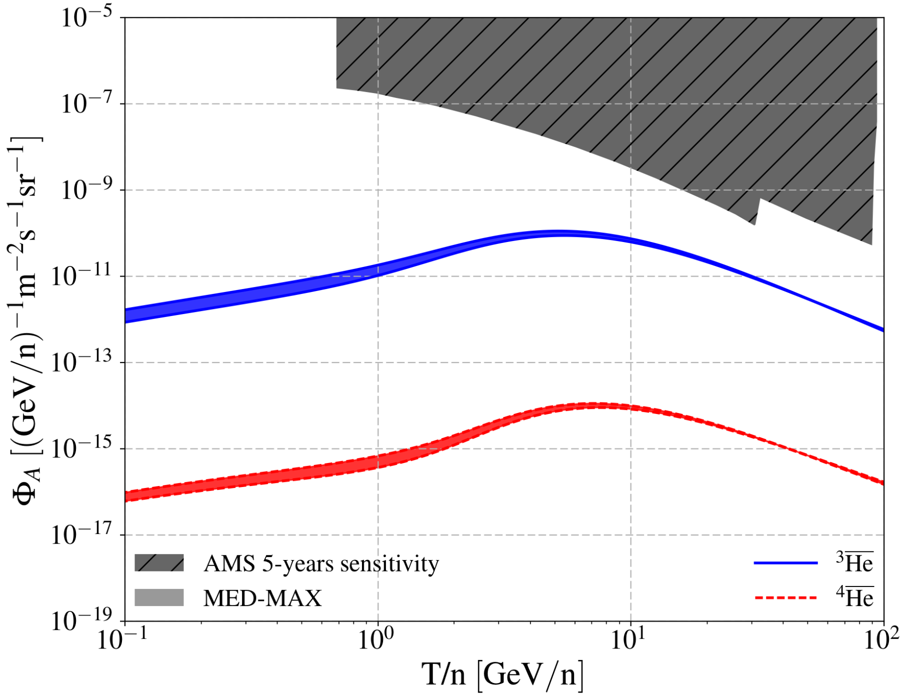
$\boldsymbol{x}$ diffusion

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

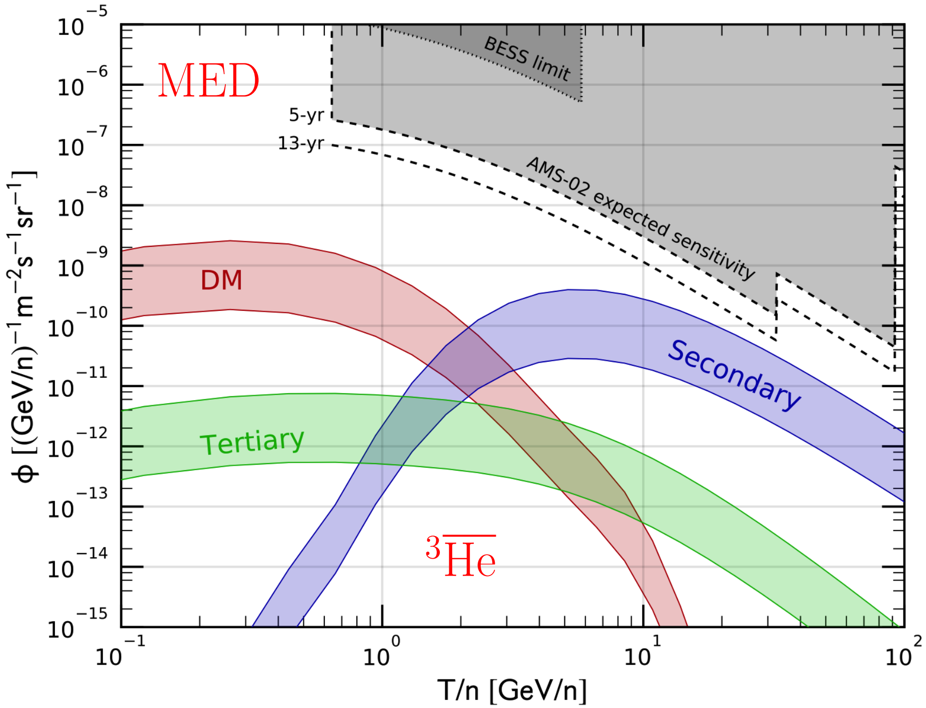
E diffusion

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

Secondary anti-helium fluxes



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

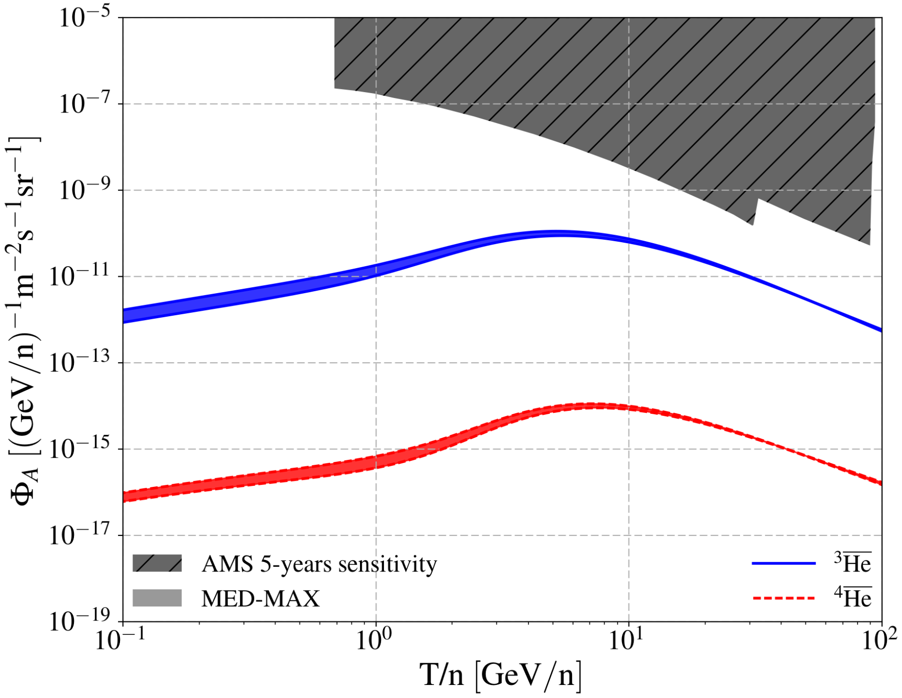


M. Korsmeier et al., Phys. Rev. **D97** (2018) 103011

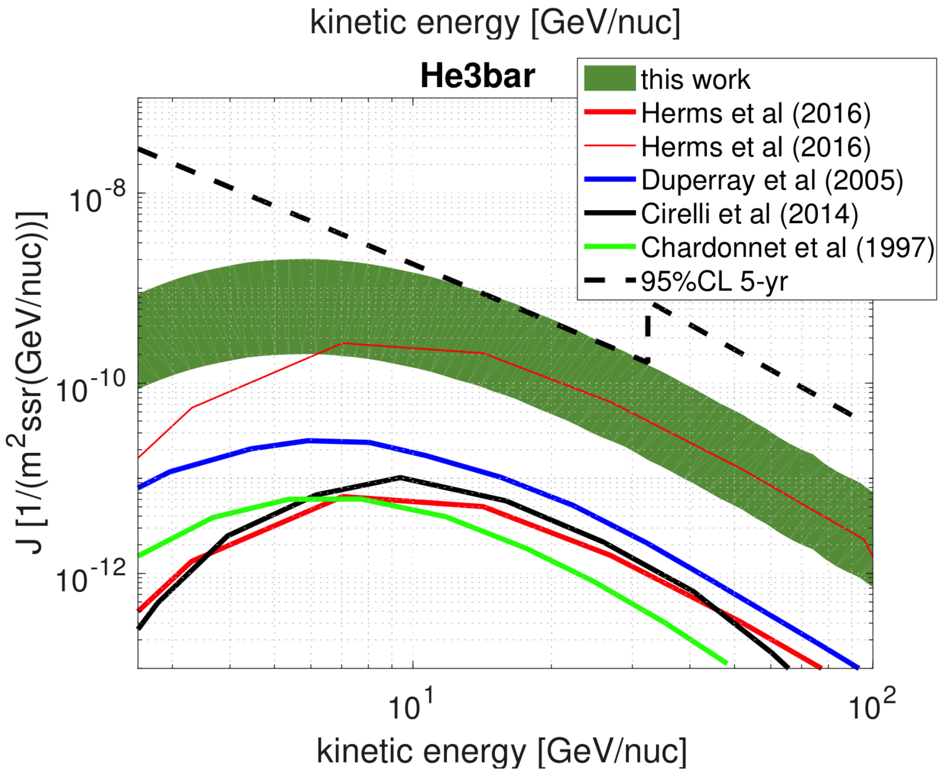
AMS-02 should not have seen $\overline{\mathrm{He}}$ events

no secondary origin $\Rightarrow$ DM, BH or else

Secondary anti-helium fluxes



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



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

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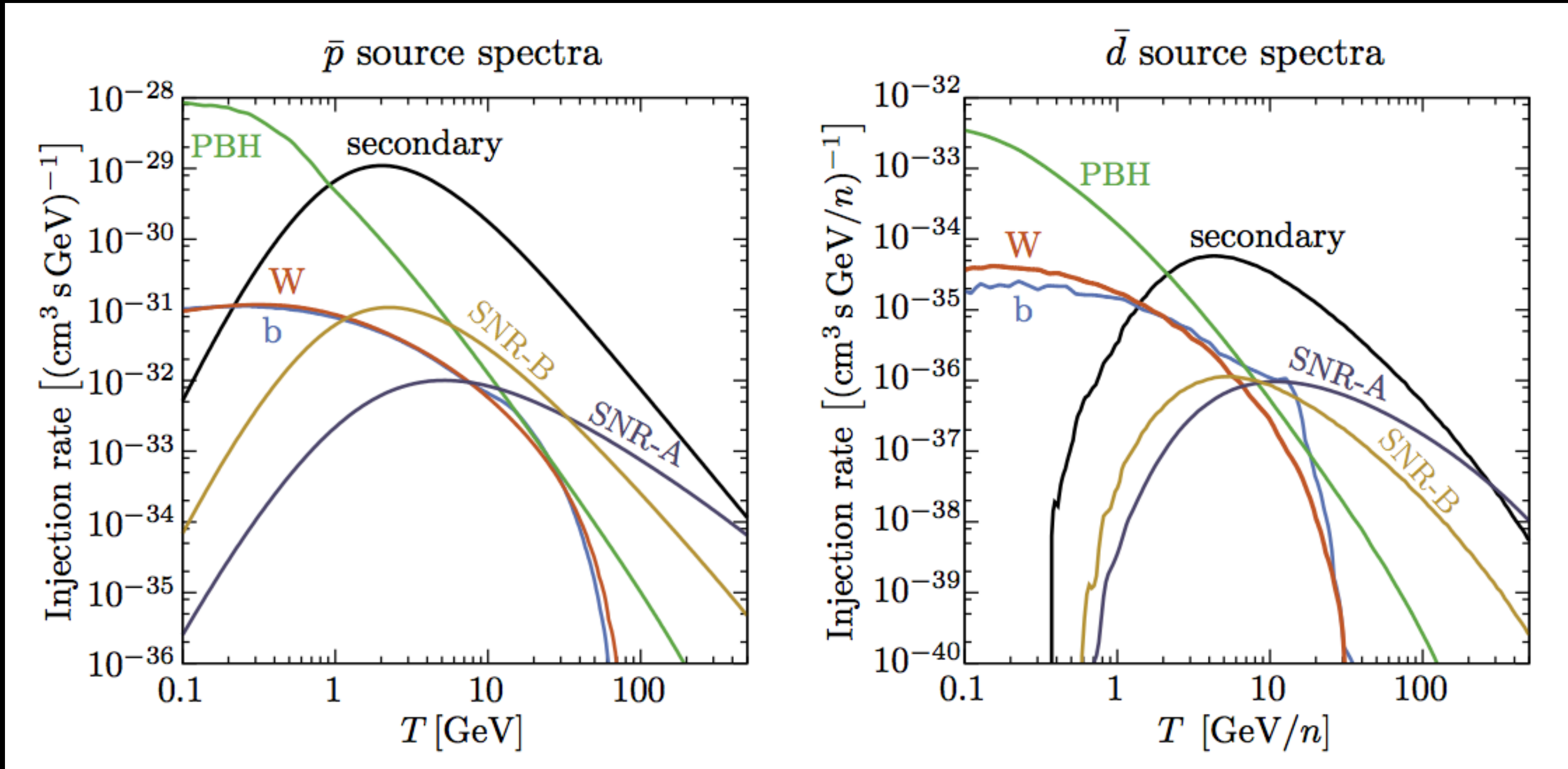
Anti-nuclei production inside SNR shock waves



$$u\frac{\partial f}{\partial x} = D\frac{\partial^2 f}{\partial x^2} + \frac{1}{3}\frac{\mathrm{d}u}{\mathrm{d}x}p\frac{\partial f}{\partial p} - \Gamma^{\mathrm{inel}} f + q$$

$$f_{\bar{N}}(x,p)\Big|_{x>0} \simeq \underbrace{f_{\bar{N},0}(p)\left(1 - \frac{\Gamma^{\mathrm{inel}}_{x>0}x}{u_2}\right)}_{\mathcal{A}} + \underbrace{\frac{q_{\bar{N}}(p)\big|_{x>0}}{u_2}x}_{\mathcal{B}}.$$

N. Tomassetti & F. Donato, Astron. & Astrophys. **544** (2012) A16

J. Herms, A. Ibarra, A. Vittino & S. Wild, JCAP **1702** (2017) 018

Anti-nuclei production inside SNR shock waves

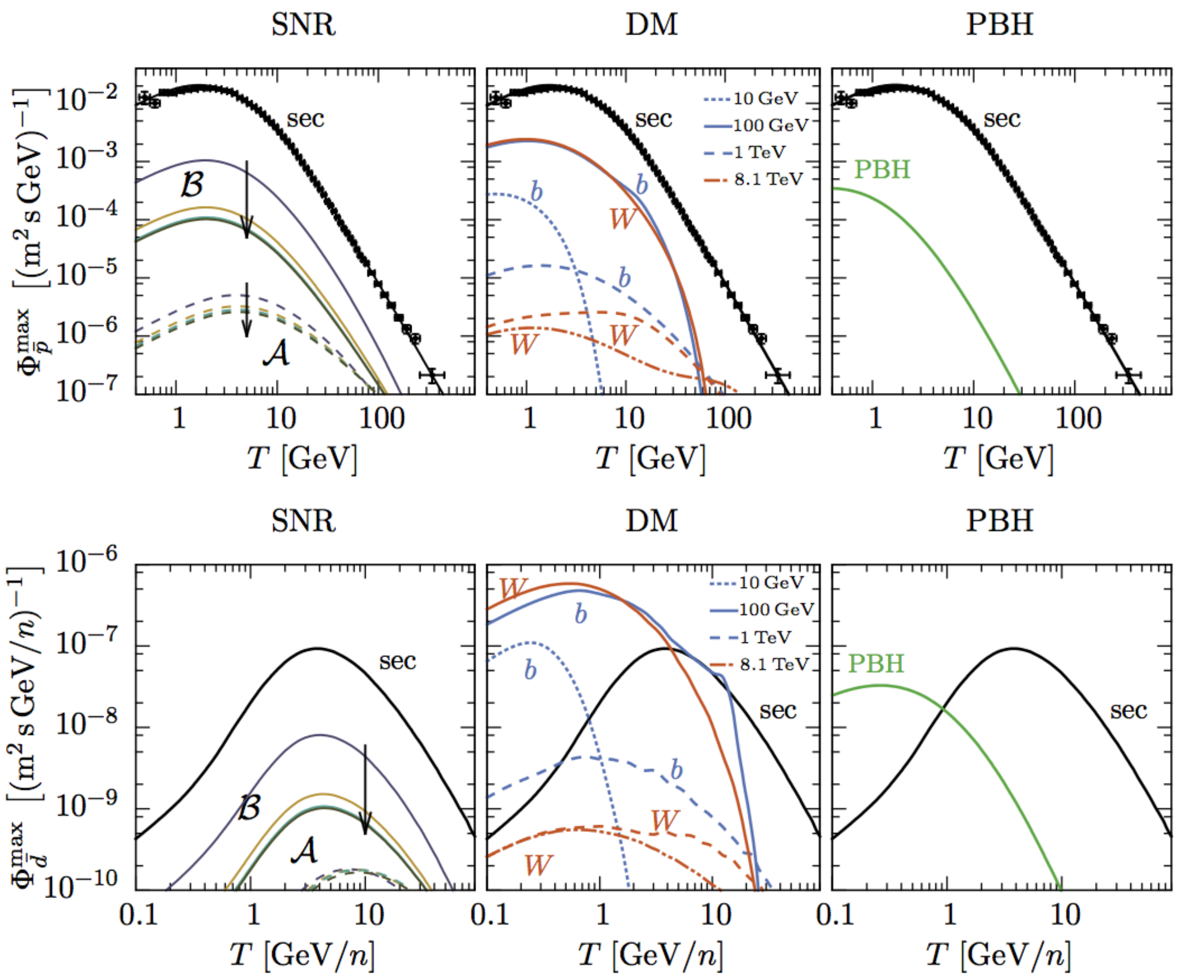


Figure 2. Maximum contribution to the antiproton flux allowed by current AMS-02 data (top panels), for the secondary contribution calculated in Section 4.1.1, and maximal antideuteron flux at Earth (lower panels) from antibaryon production in SNRs (left panels), DM annihilation (central panels) and PBH evaporation (right panels). The arrows in the SNR fluxes indicate a growing value in the cutoff momentum $p_{\rm cut} = 1$, 5, 20 and 100 TeV.

J. Herms, A. Ibarra, A. Vittino & S. Wild, JCAP **1702** (2017) 018

2) Dark matter and evaporating black holes

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

TABLE I. Summary of the propagation parameters.

Parameter	CuKrKo	MED	MAX
K_0 [kpc^2/Myr]	0.232	0.0112	0.0765
δ	0.25	0.70	0.46
V_c [km/s]	45	12	5
L [kpc]	5.4	4	15

TABLE II. Summary of the best-fit DM mass and thermally averaged cross section for various standard model final states from the analyses [14, 50].

Final state	$m_{\rm DM}$ [GeV]	$\langle\sigma v\rangle$ [10^{-26} cm^3/s]
gg	34	1.9
$b\bar{b}$	71	2.6
ZZ^*	66	2.4
hh	128	5.7
$t\bar{t}$	173	3.8

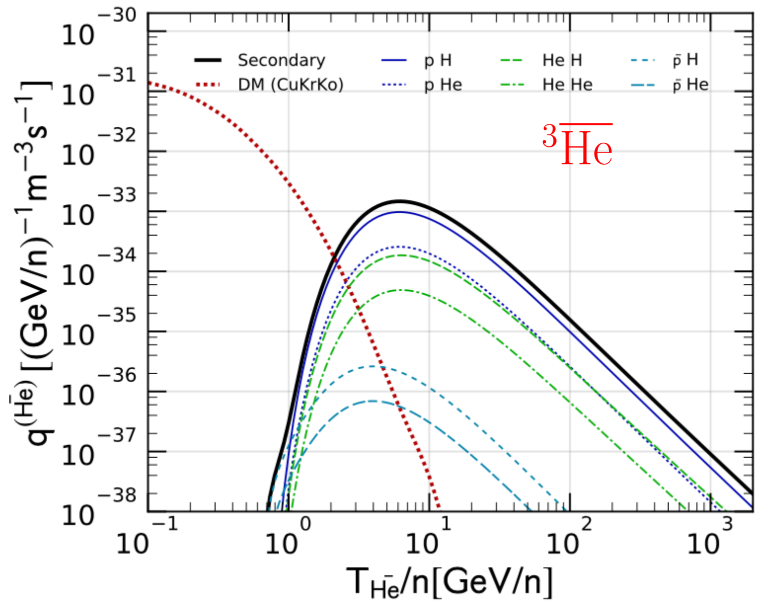


FIG. 1. Local source term for the ISM secondary and DM primary antideuteron (upper panel) and antihelium (lower panel). The secondary term is also shown in its single components given by cosmic p, He and $\bar{p}$ interacting with the ISM. The DM signal corresponds to the best fit of the antiproton excess in CuKrKo for annihilation into $b\bar{b}$, mass $m_{\rm DM} = 71$ GeV, annihilation rate $\langle\sigma v\rangle = 2.6\cdot 10^{-26}$ cm^3/s, and a local DM density of 0.43 GeV/cm^3. We use a coalescence momentum of $p_C = 160$ MeV.

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

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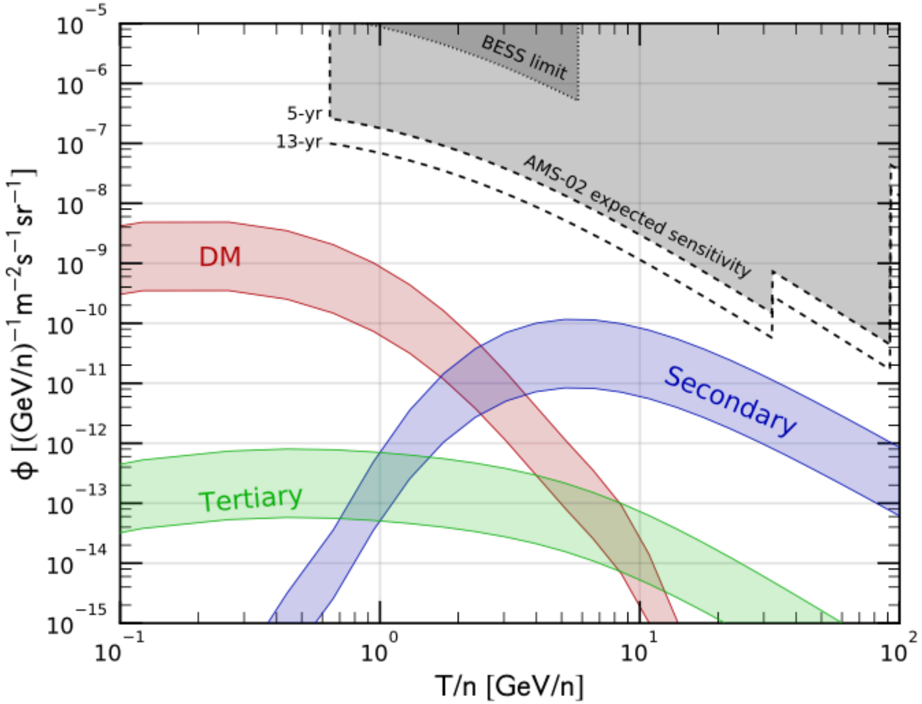

Anti-proton flux CuKrKo best-fit parameters

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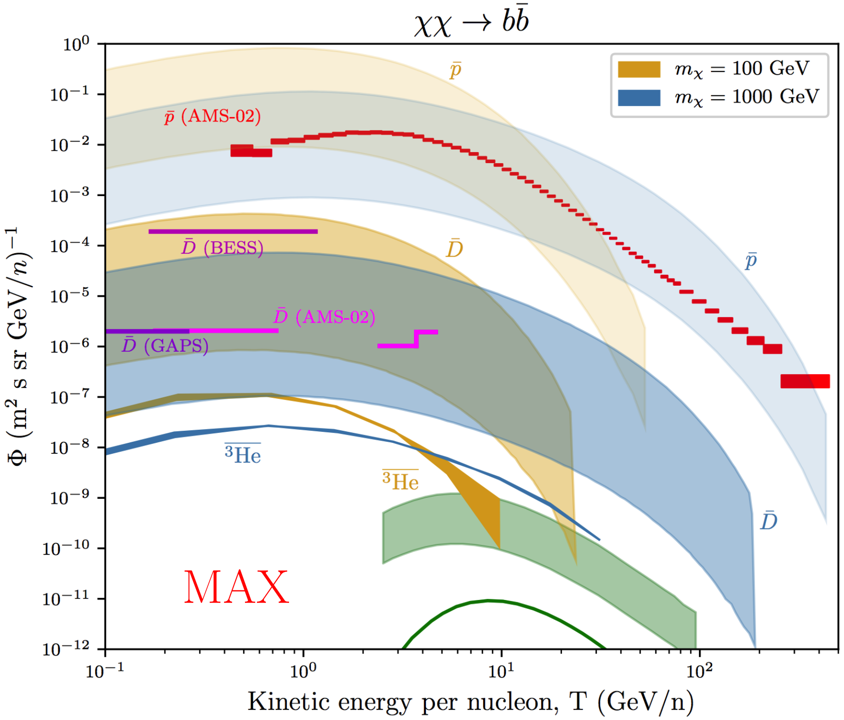
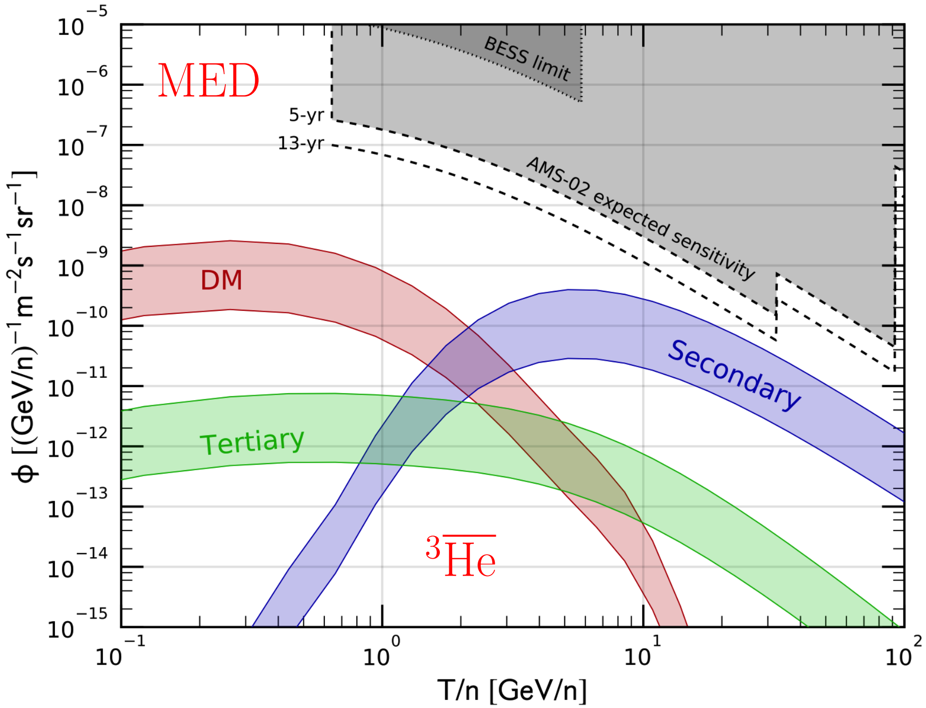


A. Coogan & S. Profumo,
Phys. Rev. **D96** (2017) 083020



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, $p_{\rm coal}$ exceedingly large.

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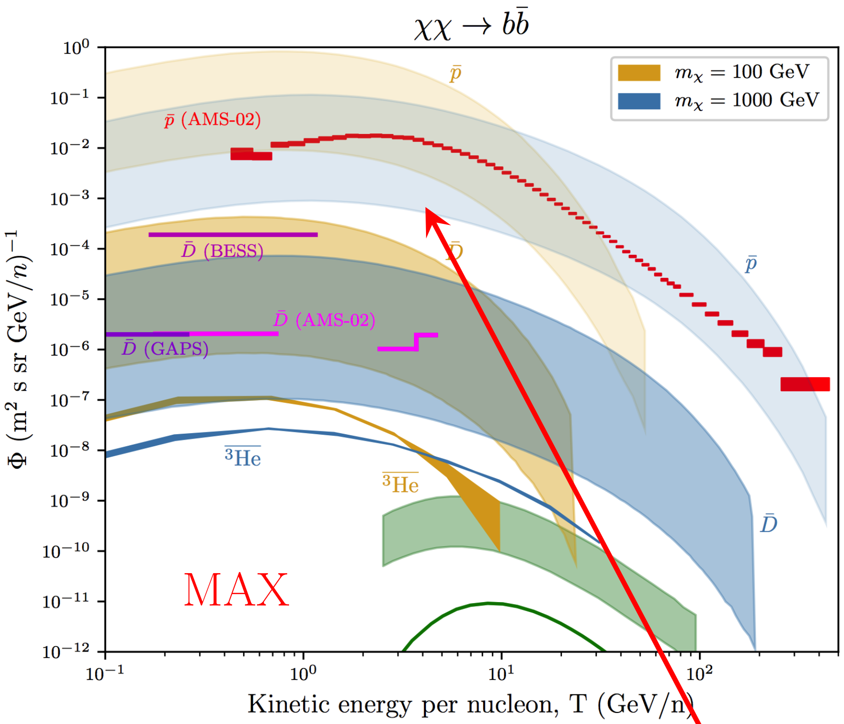
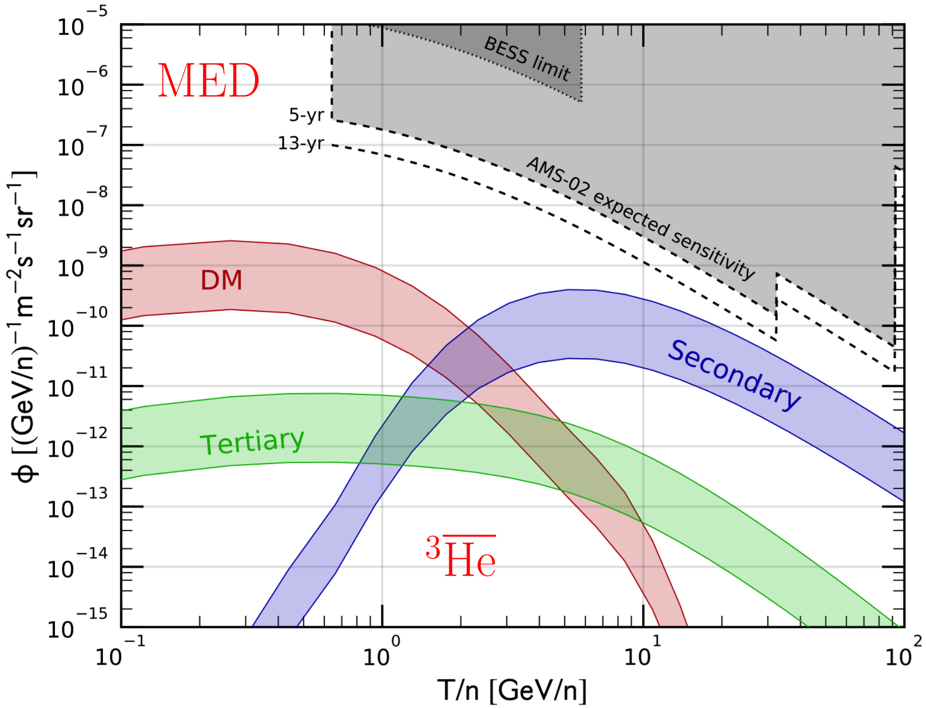




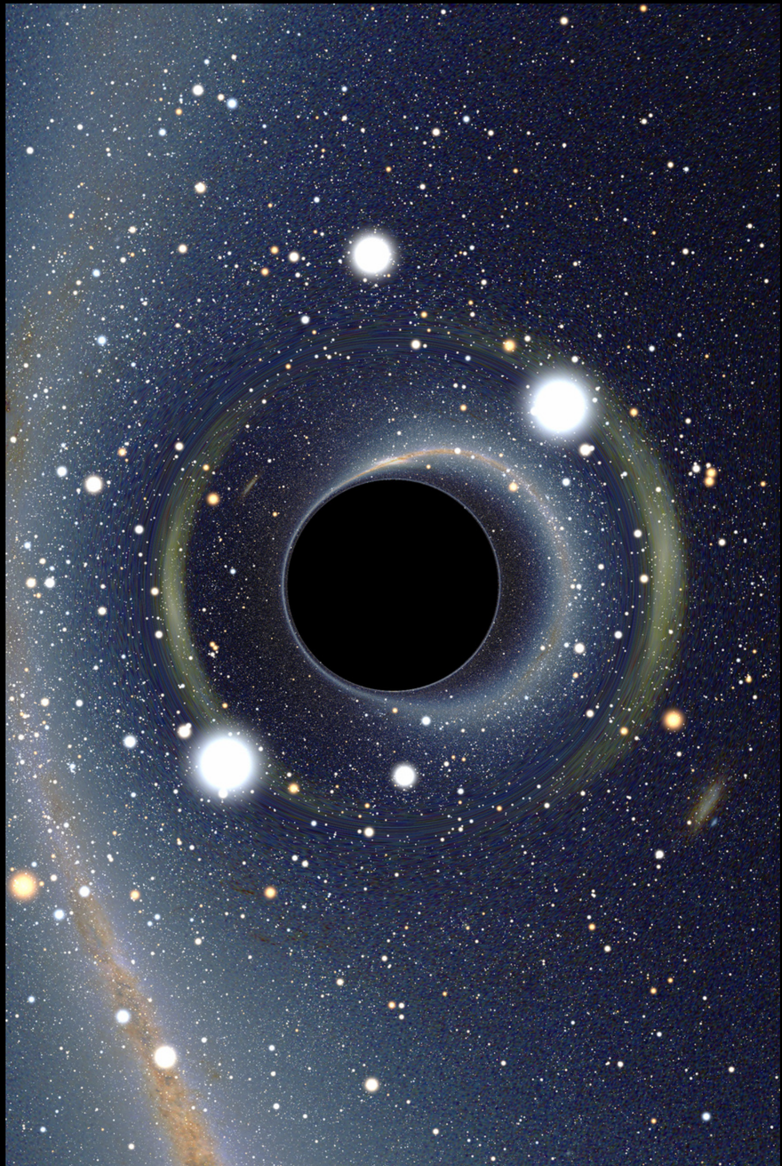
A. Coogan & S. Profumo, Phys. Rev. **D96** (2017) 083020

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

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

$$298 \text{ MeV} \leq p_{\text{coal}} \leq 416 \text{ MeV}$$

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



$$T_{\mathrm{BH}} = \frac{\hbar c^3}{8\pi k_{\mathrm{B}} G M} = 1.06\ \mathrm{GeV} \times \frac{M}{10^{13}\ \mathrm{g}}$$

$$\frac{\mathrm{d}^2 N_i}{\mathrm{d}E\mathrm{d}t} = \frac{\Gamma_i/h}{\exp(E/k_{\mathrm{B}}T) - \epsilon_i}$$

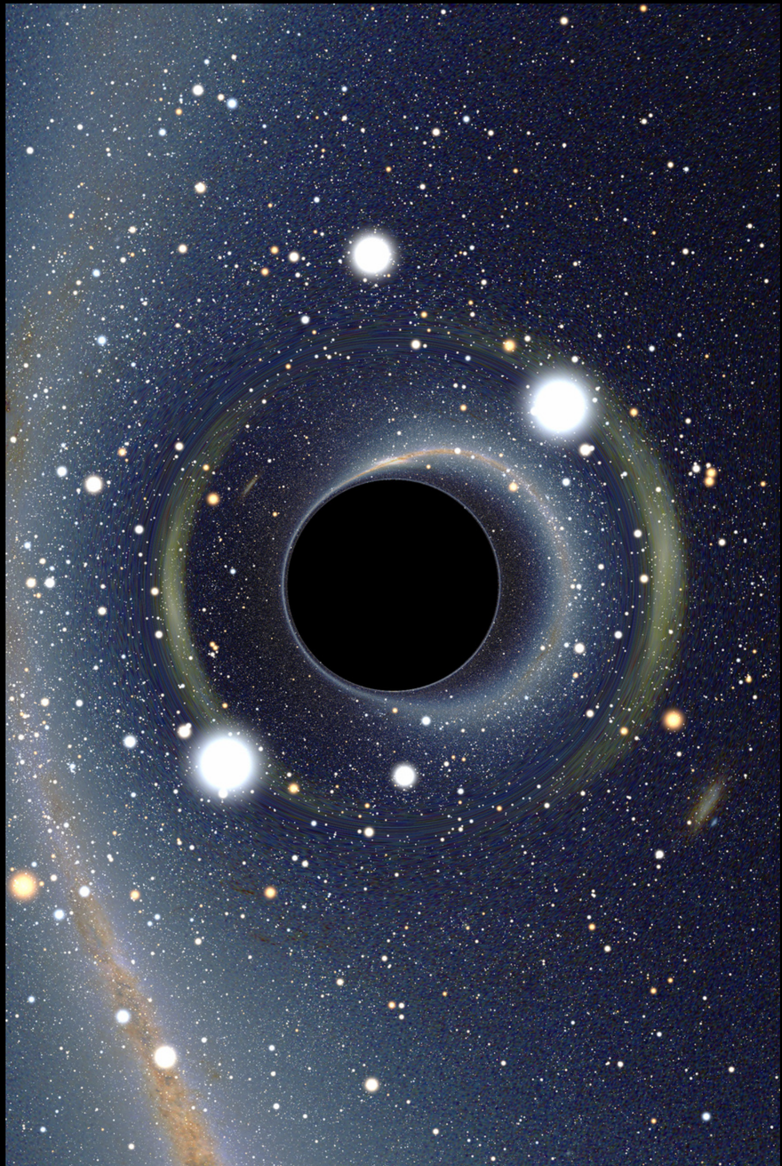
$$\Gamma_i = \frac{4\pi\sigma_i(E,M,m)}{h^2c^2}\left(E^2 - m^2\right)$$

$$\frac{\mathrm{d}^2 N_{\bar{N}}}{\mathrm{d}E\mathrm{d}t} = \sum_{i=q,g}\int_{Q=E}^{\infty} g_i \times \left.\frac{\mathrm{d}^2 N_i}{\mathrm{d}Q\mathrm{d}t}\right|_M \times \frac{\mathrm{d}\mathcal{F}}{\mathrm{d}E}(i, Q \to \bar{N}, E)$$

$$\frac{dn}{dM} \propto M^2\ (M < M_\star) \text{ while } \frac{dn}{dM} \propto M^{-5/2}\ (M > M_\star)$$

$$M_\star \simeq 5 \times 10^{14}\ \mathrm{g}$$

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



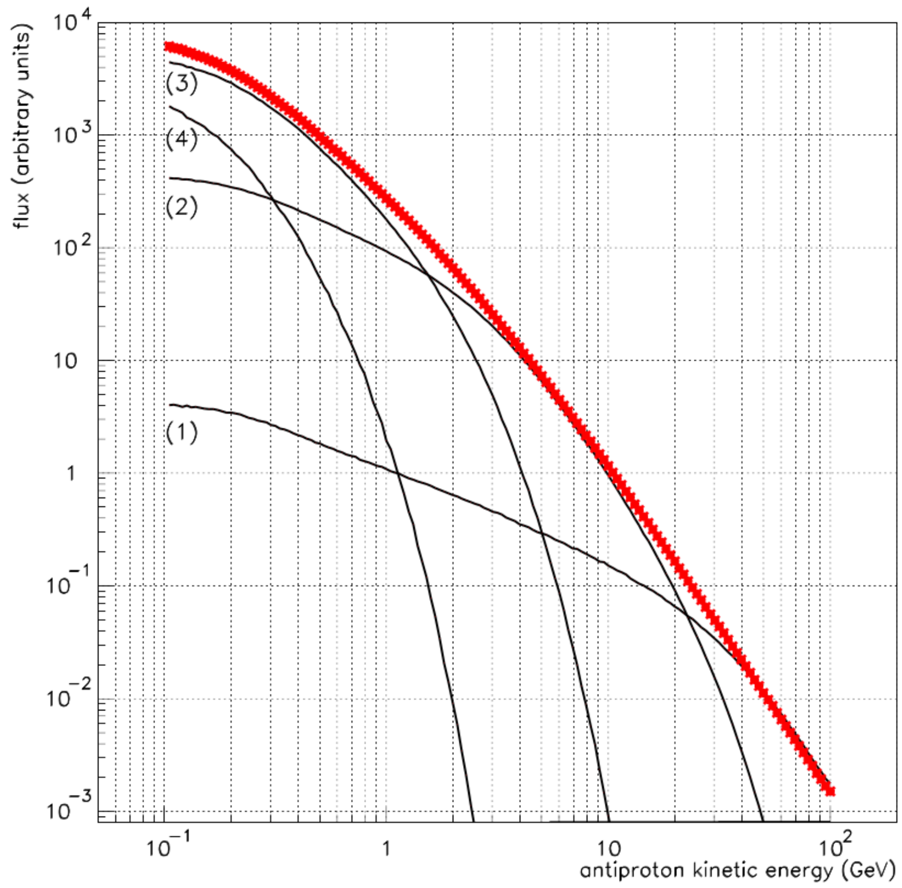


Fig. 1. Primary antiproton flux with the standard mass spectrum before propagation (in arbitrary units). Curve (1) is for $M \in [M_{Pl}, 10^{12}\mathrm{g}]$, curve (2) is for $M \in [10^{12}\mathrm{g}, 10^{13}\mathrm{g}]$, curve (3) is for $M \in [10^{13}\mathrm{g}, 5 \cdot 10^{13}\mathrm{g}]$, curve (4) is for $M > 5 \cdot 10^{13}\mathrm{g}$ and the thick line is the full spectrum.

A. Barrau et al., Astron. & Astrophys. **388** (2002) 676

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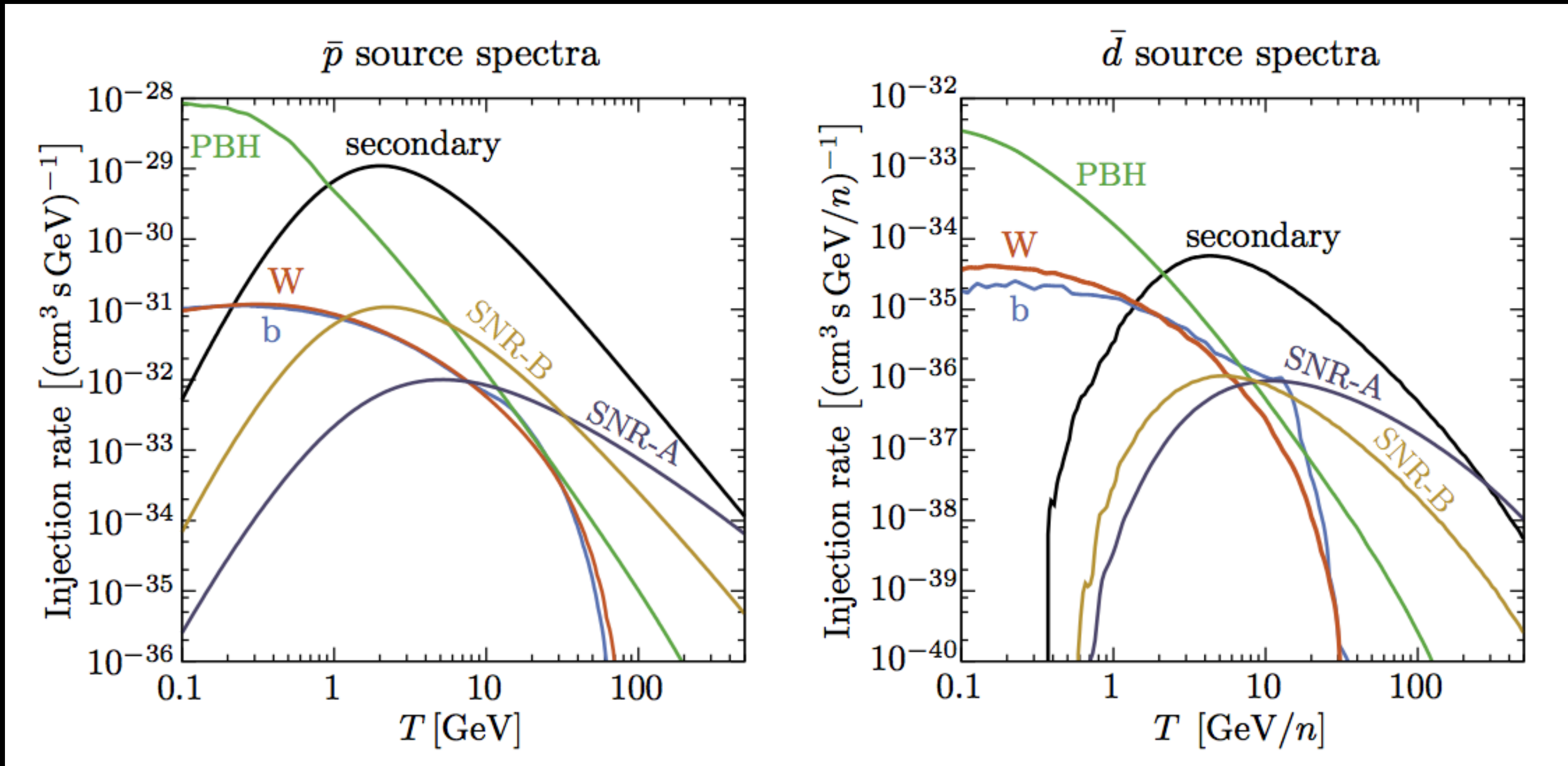

$$\rho_{\mathrm{BH}}(\odot) = 10^{-32}\ \mathrm{g\,cm^{-3}}\ \text{vs}\ \rho_{\mathrm{DM}} = 2.23 \times 10^{-30}\ \mathrm{g\,cm^{-3}}$$

J. Herms, A. Ibarra, A. Vittino & S. Wild, JCAP **1702** (2017) 018

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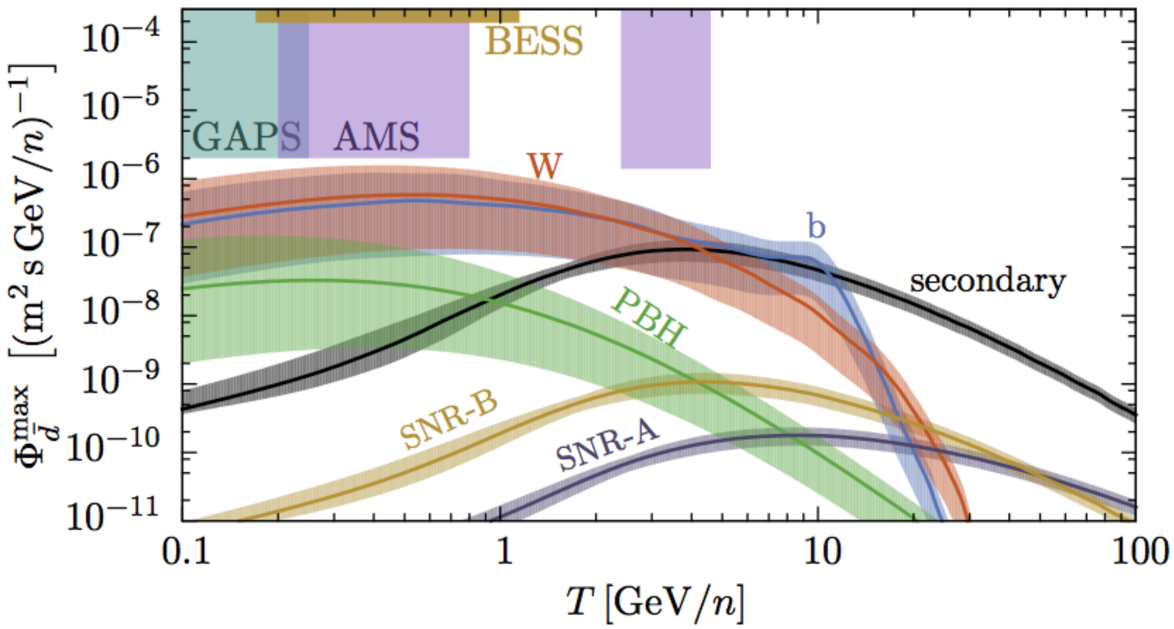

Figure 3. Maximal antideuteron flux from PBH evaporation, annihilation of DM particles with 80 GeV (102 GeV) mass into $\bar{b}b$ (W^+W^-), and production in SNRs assuming only $\mathcal{A}$−term or $\mathcal{B}$−term contributions and $p_{\mathrm{cut}} = 20$ TeV, together with the expected flux from secondary production; the bands bracket the uncertainty on the coalescence momentum and on solar modulation, as discussed in the text. For comparison we also show the current upper limit on the flux from BESS, as well as the projected sensitivities of AMS-02 and GAPS.

J. Herms, A. Ibarra, A. Vittino & S. Wild, JCAP **1702** (2017) 018

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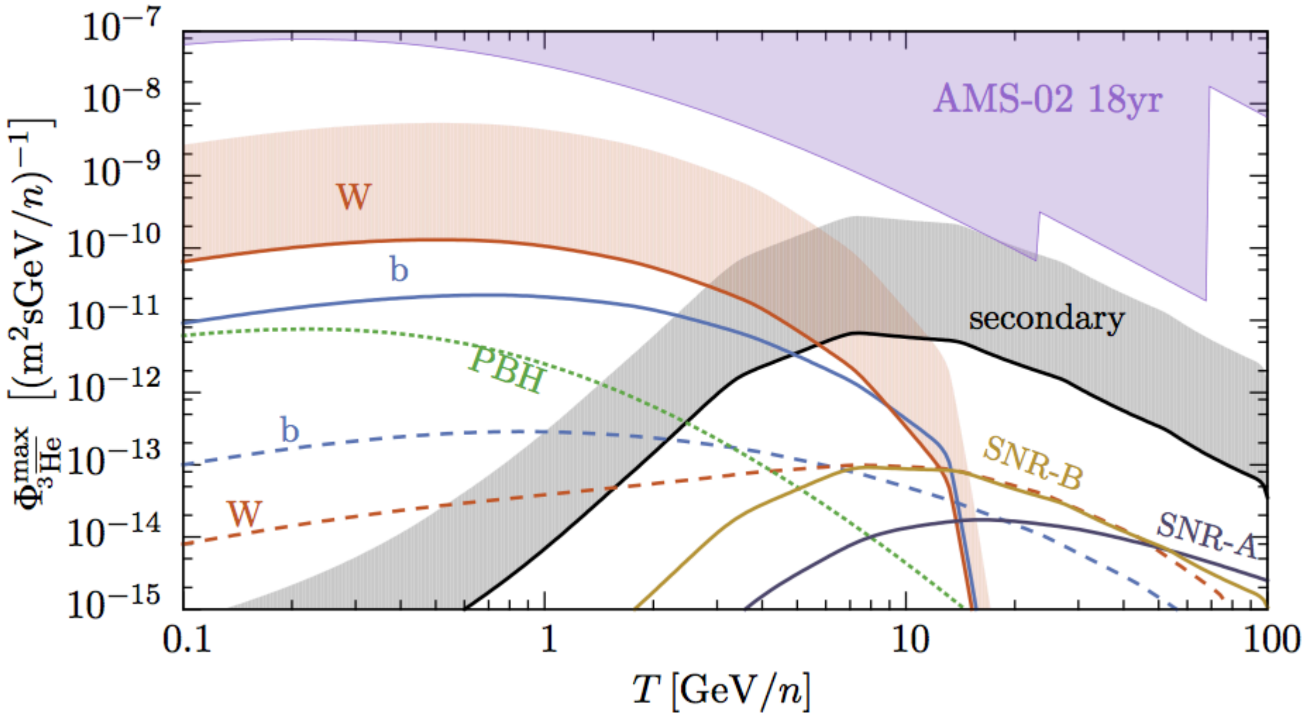


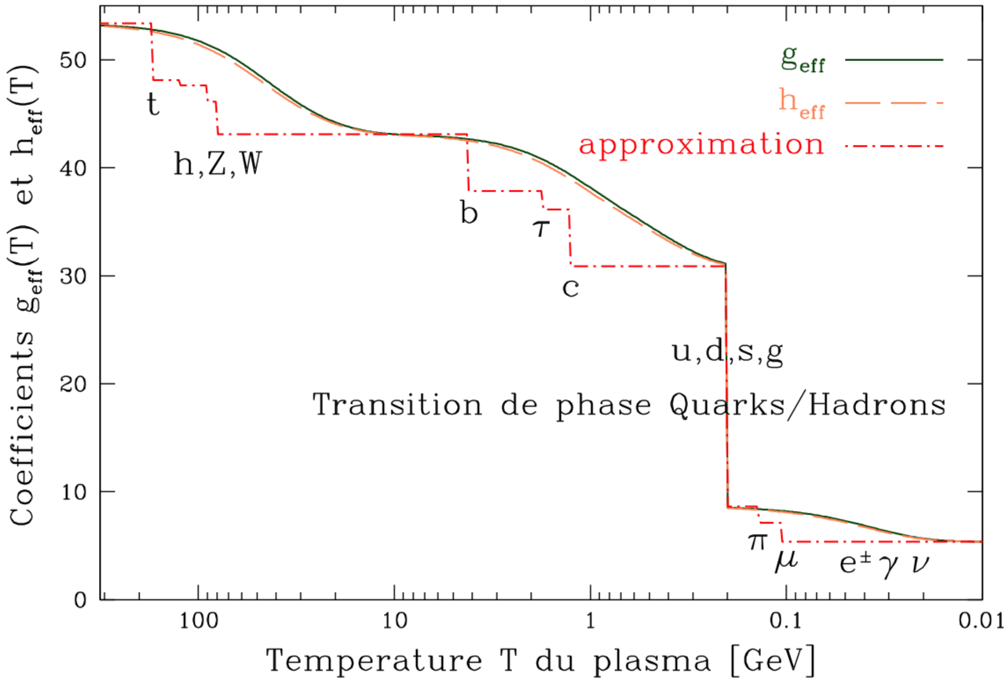
Figure 5. Maximal antihelium flux from PBH evaporation, annihilation of DM particles with 100 GeV (line) or 1 TeV (dashed) mass into $\bar{b}b$ or W^+W^-, and production in SNRs assuming only $\mathcal{A}$-term or $\mathcal{B}$-term contributions and $p_{\mathrm{cut}} = 20\,\mathrm{TeV}$, as well as the antihelium contribution from secondary production in the ISM. Lines correspond to $p_0^{\overline{\mathrm{He}}} = p_0^{\bar{d}}$, the shaded bands show the plausible range in coalescence momentum for the two most promising contributions (see text).

J. Herms, A. Ibarra, A. Vittino & S. Wild, JCAP **1702** (2017) 018

3) Segregation is indeed a problem

- The Quark/Hadron phase transition takes place between 100 and 200 MeV. Lattice QCD indicates that it might be 2nd order.

$$\mathrm{u, d, s, g} \Rightarrow \pi^0, \pi^\pm \text{ and traces of } p, n \;\&\; \bar{p}, \bar{n}$$



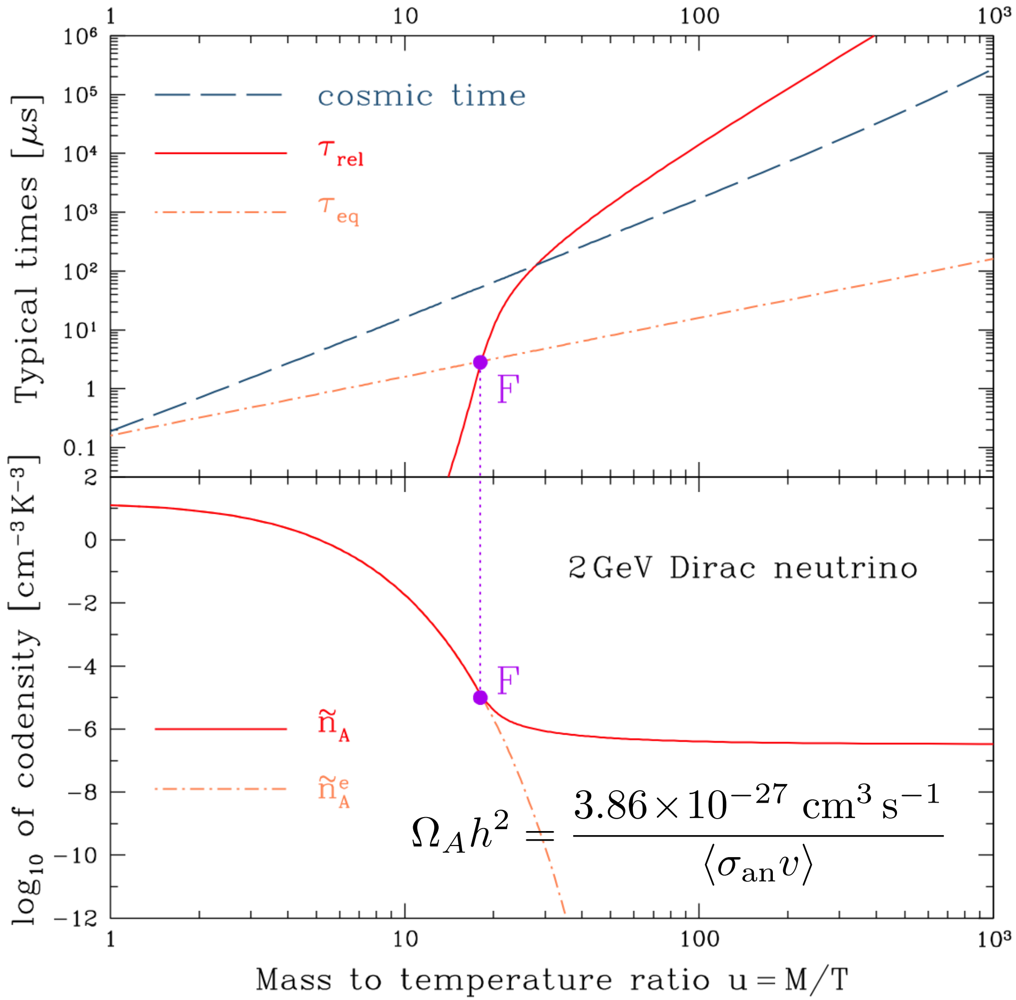
- As soon as they are formed, nucleons and antinucleons annihilate.

$$N + \bar{N} \rightleftharpoons \pi + \bar{\pi}$$

- Assuming **no asymmetry** between N & $\bar{N}$, their densities are equal. Codensities are defined as $\tilde{n}_N \equiv n_N/T^3$ and $\tilde{n}_{\bar{N}} \equiv n_{\bar{N}}/T^3$.

$$\frac{d\tilde{n}_N}{dt} + \left\{\langle\sigma_{\rm an} v\rangle n_N\right\} \tilde{n}_N = \langle\sigma_{\rm an} v\rangle T^3 \, {\tilde{n}_N^{\rm e}}^{\,2}$$

$$\tau_{\rm rel}^{-1} \equiv \Gamma_{\rm rel} = \langle\sigma_{\rm an} v\rangle n_A \qquad \tau_{\rm eq}^{-1} \equiv \Gamma_{\rm eq} = -\frac{d\ln(\langle\sigma_{\rm an} v\rangle T^3 \, {\tilde{n}_A^{\rm e}}^{\,2})}{dt}$$



- Annihilation of N & $\bar{N}$ proceeds very strongly with freeze-out at $u_{\mathrm{F}} = 41.8$ and $T_{\mathrm{F}} \simeq 22$ MeV.
  Nucleons and antinucleons are completely depleted.

$$\frac{n_N^0}{n_\gamma} \equiv \frac{\tilde{n}_N^0}{\tilde{n}_\gamma} = \frac{2\pi^2}{\zeta(3)} \left\{ \frac{1}{1+2u_{\mathrm{F}}} \right\} \left\{ \frac{u_{\mathrm{F}}}{2\pi} \right\}^{3/2} e^{-u_{\mathrm{F}}} \simeq 2.34 \times 10^{-18}$$

$$\Uparrow$$

$$\langle \sigma_{\mathrm{an}} v \rangle \simeq \left\{ \sigma_{\mathrm{an}} = 10^{-25}\ \mathrm{cm}^2 \right\} \times \left\{ v_{\mathrm{B}} = c\sqrt{3/u} \right\}$$

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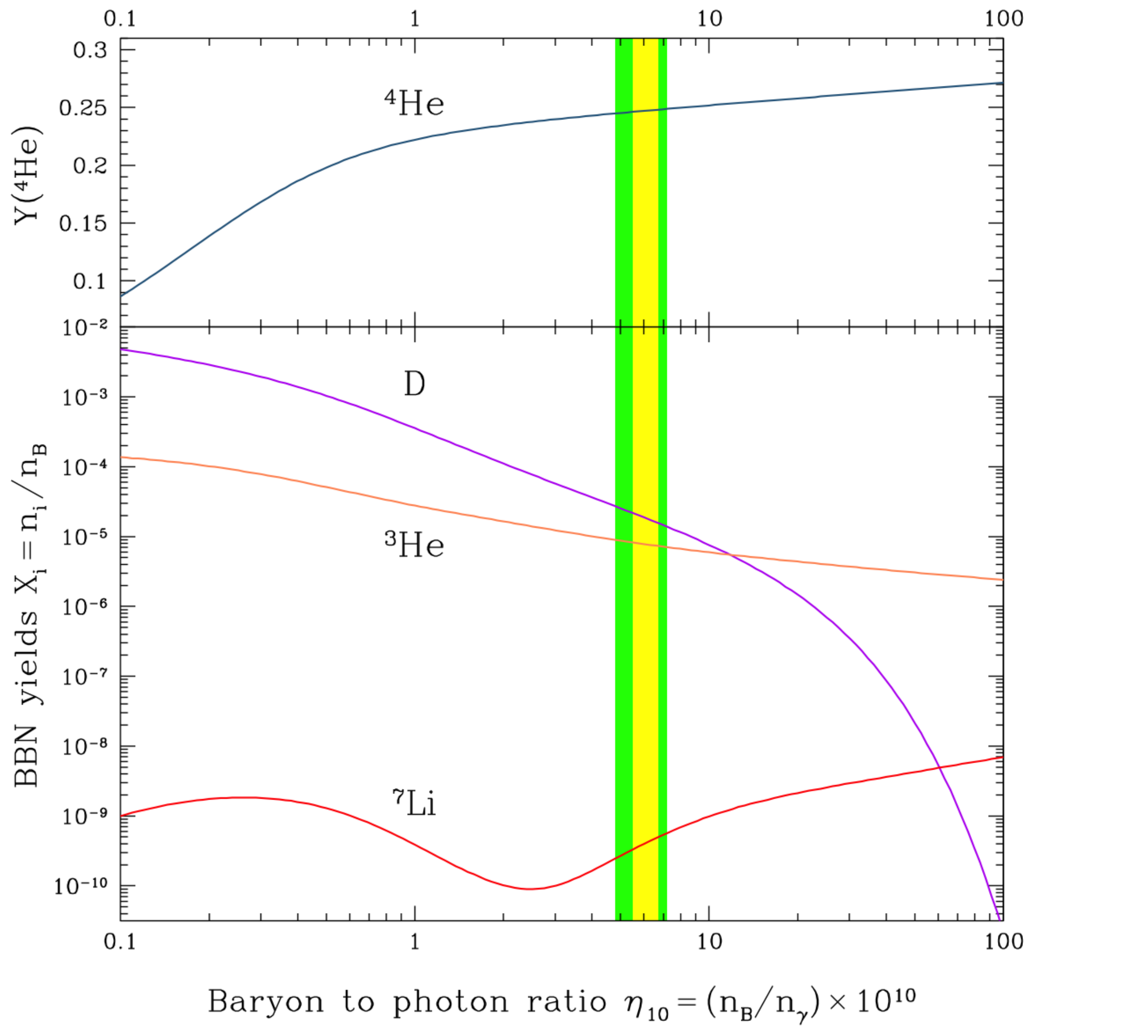

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- Segregation between N & $\bar{N}$ must take place **before** freeze-out at $u_{\mathrm{S}} = 25.1$, $T_{\mathrm{S}} \simeq 37.4$ MeV and cosmic time $t_{\mathrm{S}} \simeq 0.5$ ms.

$$\left.\frac{n_N^{\mathrm{e}}}{n_\gamma}\right|_{\mathrm{S}} \equiv \left.\frac{\tilde{n}_N^{\mathrm{e}}}{\tilde{n}_\gamma}\right|_{\mathrm{S}} = \frac{2\pi^2}{\zeta(3)} \left\{ \frac{u_{\mathrm{S}}}{2\pi} \right\}^{3/2} e^{-u_{\mathrm{S}}} \simeq 1.65 \times 10^{-9}$$

$$\Downarrow$$

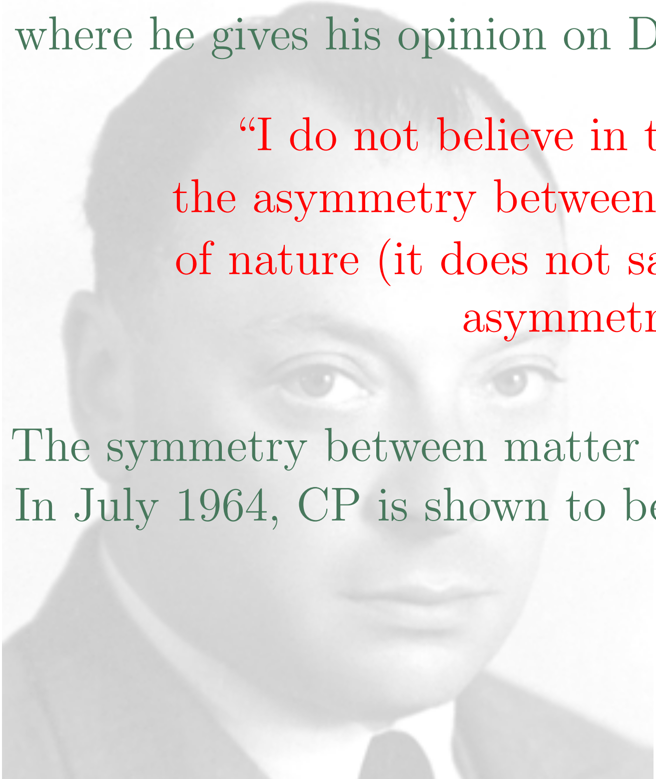
$$\mathcal{M}_N = M_p\, n_N\, R_{\mathrm{S}}^3 \simeq 1.79 \times 10^{22}\ \mathrm{kg}$$

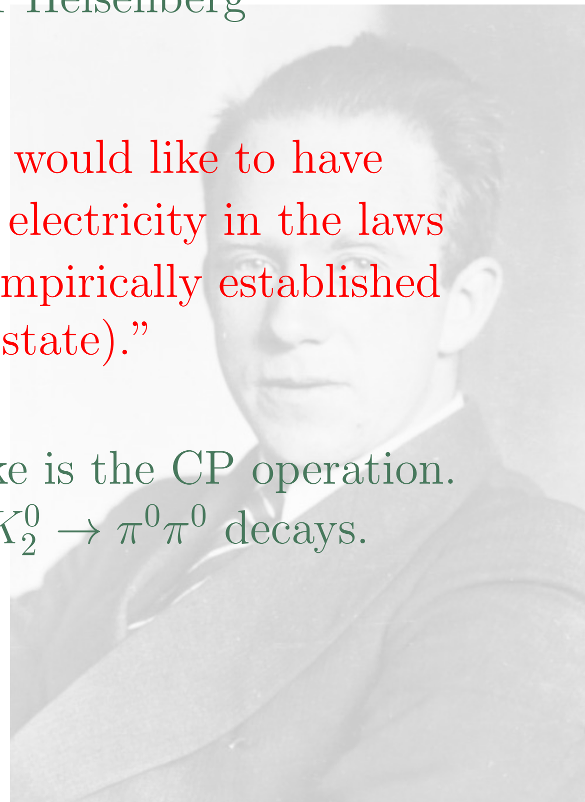
$$\Downarrow$$

Segregation active since then

We have no idea of how it proceeds

4) The standard lore or Sakharov's prescription





- In June 1933, Wolfgang Pauli sends a letter to Werner Heisenberg where he gives his opinion on Dirac's theory:

> "I do not believe in the hole theory, since I would like to have the asymmetry between positive and negative electricity in the laws of nature (it does not satisfy me to shift the empirically established asymmetry to one of the initial state)."

- The symmetry between matter and antimatter at stake is the CP operation. In July 1964, CP is shown to be violated with a few $K_2^0 \to \pi^0\pi^0$ decays.

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

4) The standard lore or Sakharov's prescription

- In June 1933, Wolfgang Pauli sends a letter to Werner Heisenberg where he gives his opinion on Dirac's theory:

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Remarque !

$$\text{sous } CP : \mathrm{u_L} \Leftrightarrow \bar{\mathrm{u}}_\mathrm{R} \text{ et } \mathrm{d_L} \Leftrightarrow \bar{\mathrm{d}}_\mathrm{R}$$

$$(1+i\varepsilon)\, \bar{\mathrm{u}}_\mathrm{R} \gamma_\mu \mathrm{d_L}\, W^\mu \xrightarrow{CP} (1+i\varepsilon)\, \bar{\mathrm{d}}_\mathrm{R} \gamma_\mu \mathrm{u_L}\, W^\mu$$

$$(1+i\varepsilon)\, \bar{\mathrm{u}}_\mathrm{R} \gamma_\mu \mathrm{d_L}\, W^\mu \xrightarrow{h.c.} (1-i\varepsilon)\, \bar{\mathrm{d}}_\mathrm{R} \gamma_\mu \mathrm{u_L}\, W^\mu$$

Si $\varepsilon \neq 0 \Rightarrow$, violation de CP !

We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As emphasized above, any alternate explanation of the effect requires highly nonphysical behavior of the three-body decays of the K_2^0. The presence of a two-pion decay mode implies that the K_2^0 meson is not a pure eigenstate of CP. Expressed as $K_2^0 = 2^{-1/2}[(K_0 - \bar{K}_0) + \epsilon(K_0 + \bar{K}_0)]$ then $|\epsilon|^2 \cong R_T \tau_1 \tau_2$ where τ_1 and τ_2 are the K_1^0 and K_2^0 mean lives and R_T is the branching ratio including decay to two π^0. Using $R_T = \frac{3}{2} R$ and the branching ratio quoted above, $|\epsilon| \cong 2.3 \times 10^{-3}$.

Baryogenesis and Sakharov's prescription

- Interactions violate the baryon number B.
- Interactions violate CP symmetry.
- Baryogenesis acts out of thermal equilibrium.

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$$\mathcal{M}(i \to j) = \mathcal{M}(\bar{j} \to \bar{\imath}), \qquad (CPT \text{ invariance})$$

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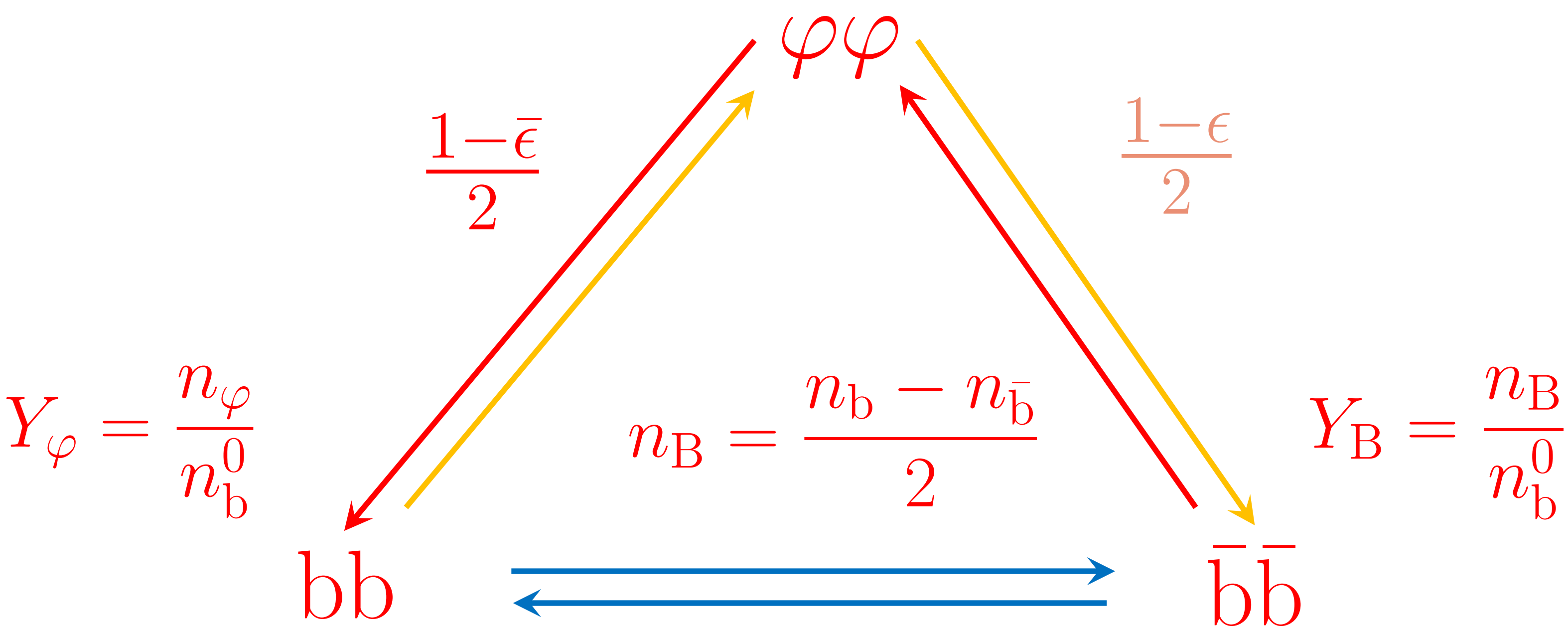
A simplistic model



$$|\mathcal{M}(\varphi\varphi \to \mathrm{bb}|^2 = \left|\mathcal{M}(\bar{\mathrm{b}}\bar{\mathrm{b}} \to \varphi\varphi\right|^2 = [\mathcal{M}_0|^2 \left(\tfrac{1-\bar{\epsilon}}{2}\right)$$

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$$k_{\bar{\mathrm{b}}} \left|\mathcal{M}(\mathrm{bb} \to \bar{\mathrm{b}}\bar{\mathrm{b}})\right|^2 + k_\varphi \left|\mathcal{M}(\mathrm{bb} \to \varphi\varphi)\right|^2 \equiv k_{\mathrm{b}} \left|\mathcal{M}(\bar{\mathrm{b}}\bar{\mathrm{b}} \to \mathrm{bb})\right|^2 + k_\varphi \left|\mathcal{M}(\bar{\mathrm{b}}\bar{\mathrm{b}} \to \varphi\varphi)\right|^2$$

$$\frac{dY_\varphi}{dt} = -\langle\sigma_0 v\rangle n_{\mathrm{b}}^0 \left\{1 - \left(\tfrac{\epsilon+\bar{\epsilon}}{2}\right)\right\} \left\{Y_\varphi^2 - \left(Y_\varphi^{\mathrm{e}}\right)^2\right\} + \langle\sigma_0 v\rangle n_{\mathrm{b}}^0 \left(\bar{\epsilon} - \epsilon\right) \left(Y_\varphi^{\mathrm{e}}\right)^2 Y_{\mathrm{B}}$$

$$\frac{dY_{\mathrm{B}}}{dt} = \langle\sigma_0 v\rangle n_{\mathrm{b}}^0 \left(\tfrac{\epsilon-\bar{\epsilon}}{4}\right) \left\{Y_\varphi^2 - \left(Y_\varphi^{\mathrm{e}}\right)^2\right\} - \langle\sigma_0 v\rangle n_{\mathrm{b}}^0 \left\{1 - \left(\tfrac{\epsilon+\bar{\epsilon}}{2}\right)\right\} \left(Y_\varphi^{\mathrm{e}}\right)^2 Y_{\mathrm{B}} - 2\langle\sigma_0 v\rangle n_{\mathrm{b}}^0 Y_{\mathrm{B}}$$

5) Inhomogeneous baryon asymmetry

In this scenario, baryogenesis is not homogeneous and leads to a very inhomogeneous distribution of $\beta \equiv (n_{\rm B} - n_{\bar{\rm B}})/(n_{\rm B} + n_{\bar{\rm B}})$ in space with small regions where $|\beta| \sim 1$ although on average β is small.

- The inflation field Φ and a complex scalar field χ evolve according to the potentials

$$U_\Phi(\Phi) = m_\Phi^2 \Phi^2/2 + \lambda_\Phi \Phi^4/4$$

$$U_\chi(\chi, \Phi) = \lambda_1 (\Phi - \Phi_1)^2 |\chi|^2 + \lambda_2 |\chi|^4 \ln \frac{|\chi|^2}{\sigma^2} + m_0^2 |\chi|^2 + m_1^2 \chi^2 + m_1^{*2} \chi^{*2}$$

- If $m_1 = |m_1| \exp(i\alpha)$ and $\chi = |\chi| \exp(i\theta)$, we can define the effective mass

$$m_{\rm eff}^2 = \lambda_1 (\Phi - \Phi_1)^2 + m_0^2 + 2|m_1|^2 \cos(2\alpha + 2\theta)$$

- The peculiar form of the potential $U_\chi(\chi, \Phi)$ leads to the non-conservation of the baryonic current which is defined as

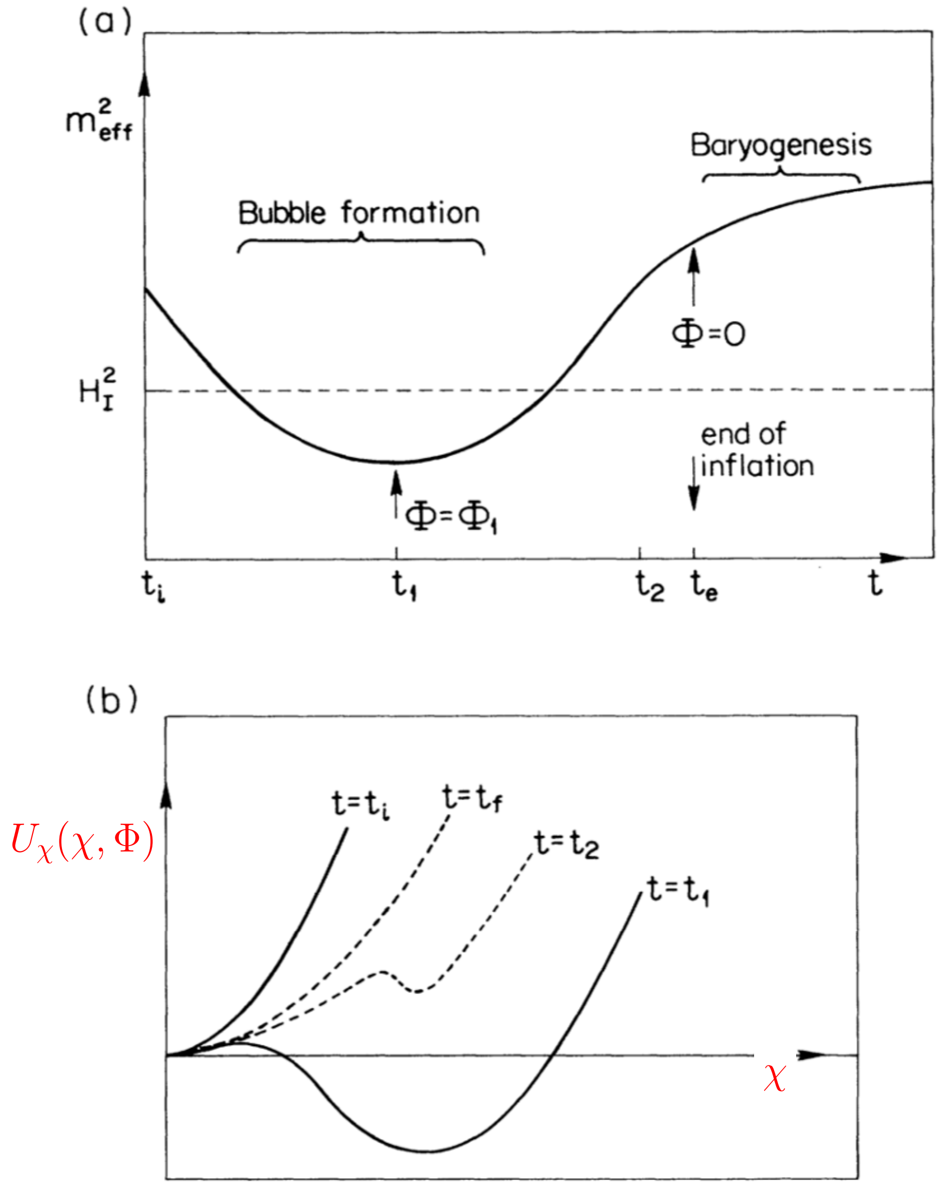
$$J_\mu^{\rm B} = i\,(\chi^* \partial_\mu \chi - \partial_\mu \chi^* \chi) = -2|\chi|^2 \partial_\mu \theta$$

while

$$\partial^\mu J_\mu^{\rm B} = 2\,i\,\left(m_1^{*2} \chi^{*2} - m_1^2 \chi^2\right) = 2|\chi|^2 |m_1|^2 \sin(2\theta + 2\alpha)$$

5) Inhomogeneous baryon asymmetry

A. Dolgov & J. Silk, Phys. Rev. **D47** (1993) 4244



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- At the beginning of inflation, $\Phi \gg \Phi_1$ so that m^2_{eff} is positive and $\langle \chi \rangle = 0$.

- When $\Phi = \Phi_1$, m^2_{eff} becomes negative and χ moves toward the true vaccum. As this is a quantum process, some regions go further than other along the χ axis.

- When $\Phi \ll \Phi_1$, m^2_{eff} is positive once again and χ migrates toward 0. But this is not an immediate process, especially when χ is large.

- Baryogenesis takes place soon after the end of inflation. A few regions have large values of β, either positive or negative. These collapse into BH or form stellar objects, hence a few anti-stars.

- In the rest of space, two possibilities have been proposed. Tuning the parameters leads to a small negative value of m^2_{eff} and a small value of β. Alternatively, $m^2_{\text{eff}} = 0$ and standard baryogenesis proceeds as in the homogeneous baryonic case.

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. But can we wait for ten more years?

- $^3\overline{\mathrm{He}}$ 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.
  DM or BH cannot explain the 6 events detected.

- $^4\overline{\mathrm{He}}$ events
  There is **absolutely** no hope to detect a single event.

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Thanks for your attention