

Cosmic-ray anti-helium nuclei or the quest for antimatter in the Universe

Pierre Salati – LAPTh & Université Savoie Mont Blanc

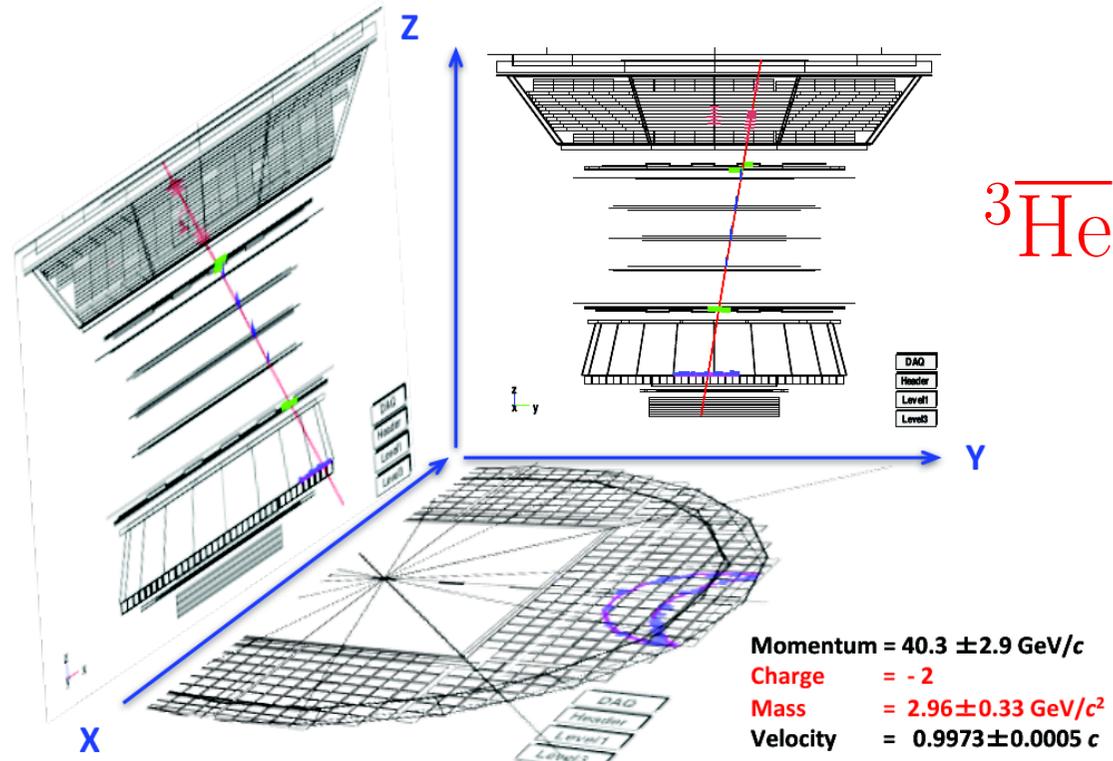
Outline

- 1) AMS-02 and possible anti-He events
- 2) Secondary cosmic-ray anti-helium
- 3) A word on Dark Matter production
- 4) Anti-clouds - general considerations
- 5) Anti-clouds – a (crazy) step further

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

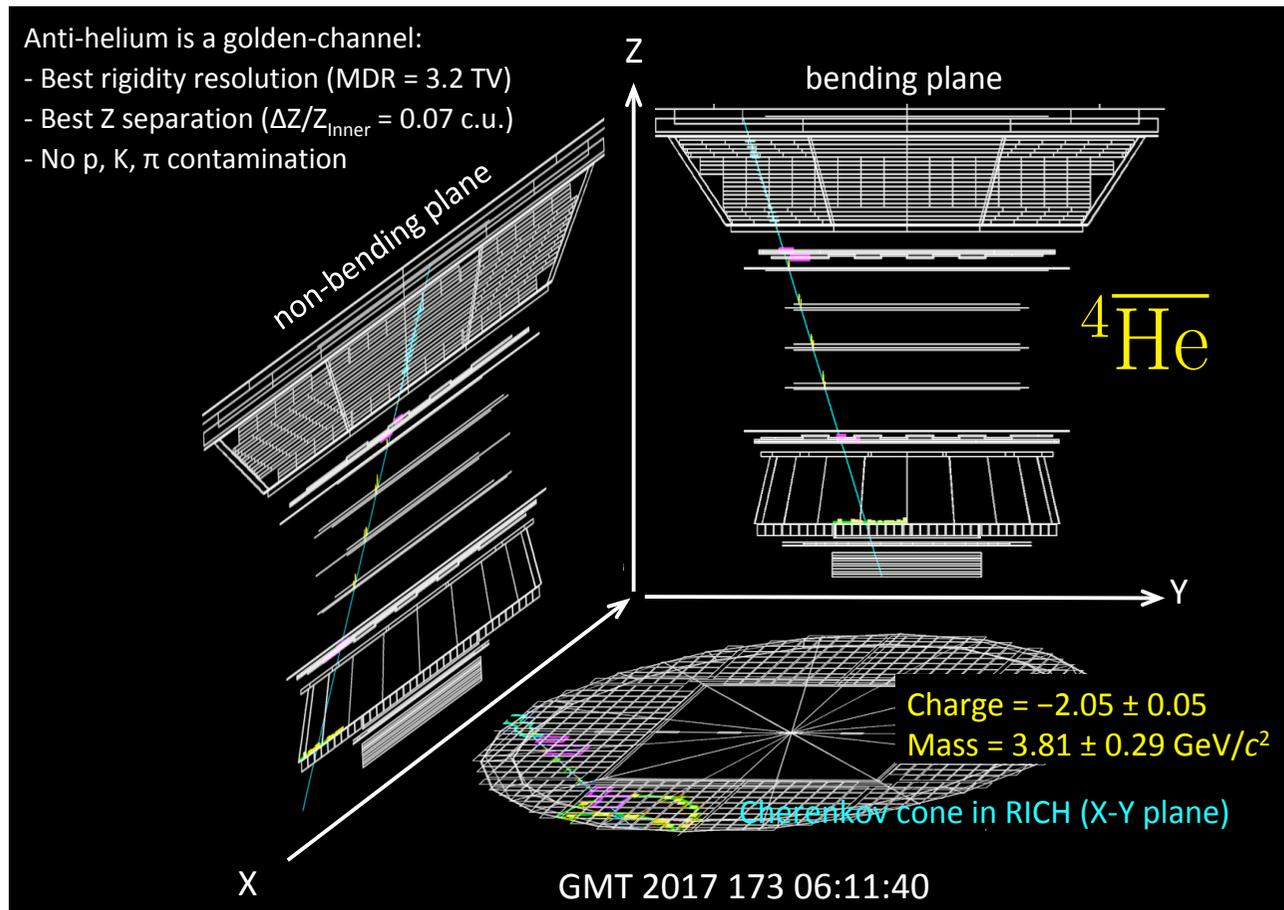
V. Poulin, **P.S.**, I. Cholis, M. Kamionkowski & J. Silk

1) AMS-02 and possible anti-He events



S. Ting, The First Five Years of AMS on the ISS, CERN, December 8, 2016

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

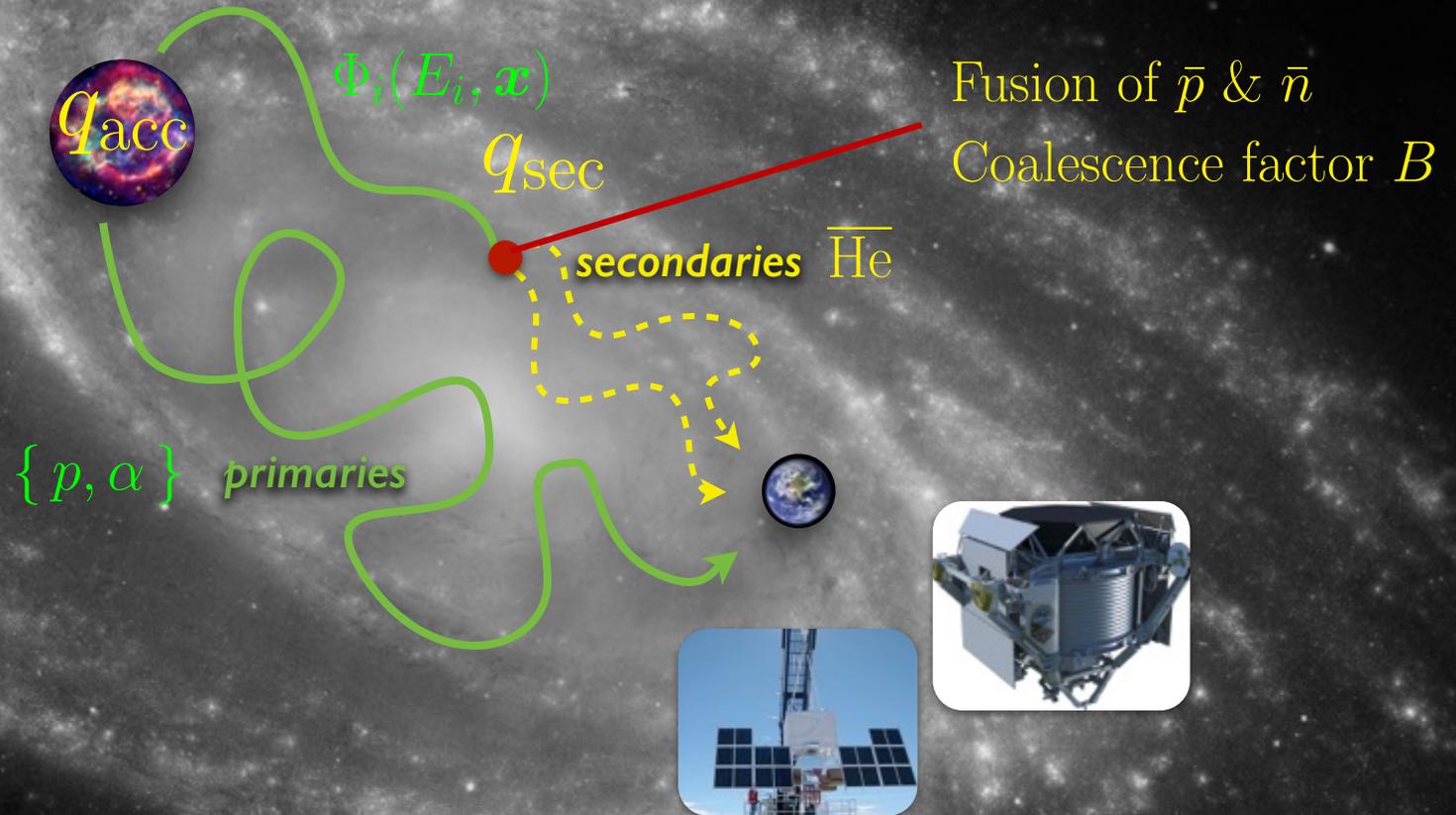


A. Oliva, Light Anti-nuclei as a Probe for New Physics, Leiden, October 15, 2019

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2) Secondary cosmic-ray anti-helium

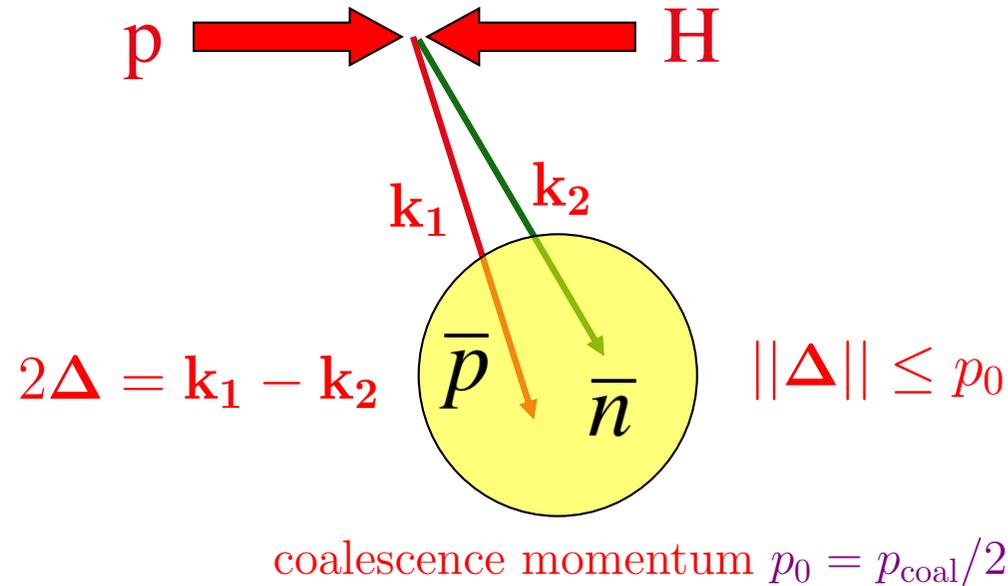
$$q_{\text{sec}}(\overline{\text{He}} | E_{\overline{\text{He}}}, \mathbf{x}) = \sum_{i \in \{p, \alpha\}} \sum_{j \in \{H, \text{He}\}} 4\pi \int dE_i \Phi_i(E_i, \mathbf{x}) n_j(\mathbf{x}) \frac{d\sigma_{ij \rightarrow \overline{\text{He}}}}{dE_{\overline{\text{He}}}}(E_i, E_{\overline{\text{He}}})$$



Solar modulation with $\phi_p^F \neq \phi_{\bar{p}}^F$

Anti-helium production and the coalescence factor

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



$$d^3\mathcal{N}_{\bar{d}}(\mathbf{K}) = \int d^6\mathcal{N}_{\bar{p},\bar{n}}\{\mathbf{k}_1, \mathbf{k}_2\} \times \mathcal{C}(\Delta) \times \delta^3(\mathbf{K} - \mathbf{k}_1 - \mathbf{k}_2)$$

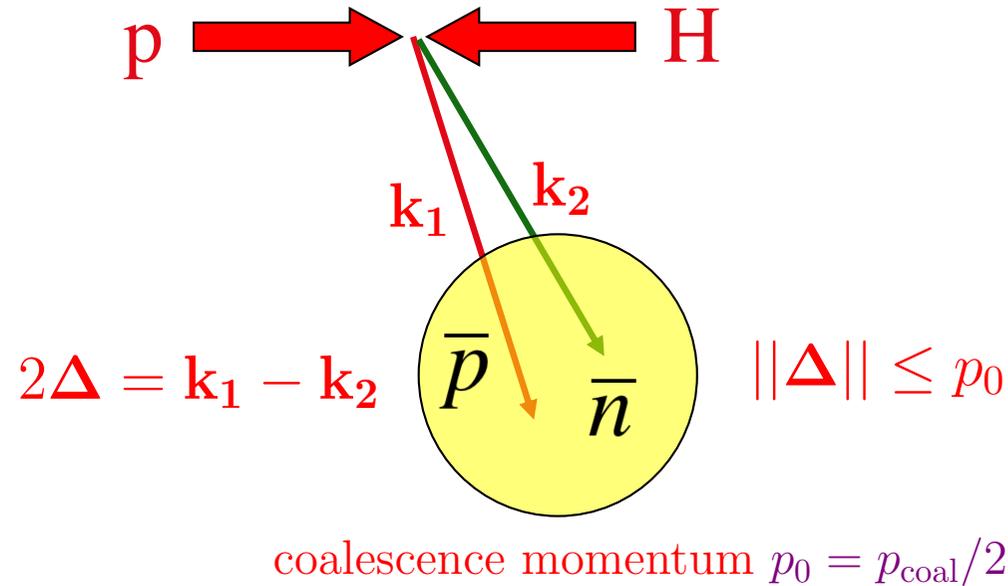
$$B_2 = \frac{E_{\bar{d}}}{E_{\bar{p}}E_{\bar{n}}} \int d^3\Delta \mathcal{C}(\Delta) \simeq \frac{m_{\bar{d}}}{m_{\bar{p}}m_{\bar{n}}} \left\{ \frac{4}{3}\pi p_0^3 \equiv \frac{\pi}{6} p_{\text{coal}}^3 \right\}$$

Coalescence factor B_2

$$\frac{E_{\bar{d}}}{\sigma_{\text{in}}} \frac{d^3\sigma_{\bar{d}}}{d^3\mathbf{K}} = B_2 \left\{ \frac{E_{\bar{p}}}{\sigma_{\text{in}}} \frac{d^3\sigma_{\bar{p}}}{d^3\mathbf{k}_1} \right\} \left\{ \frac{E_{\bar{n}}}{\sigma_{\text{in}}} \frac{d^3\sigma_{\bar{n}}}{d^3\mathbf{k}_2} \right\}$$

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Production on anti-nuclei with mass A

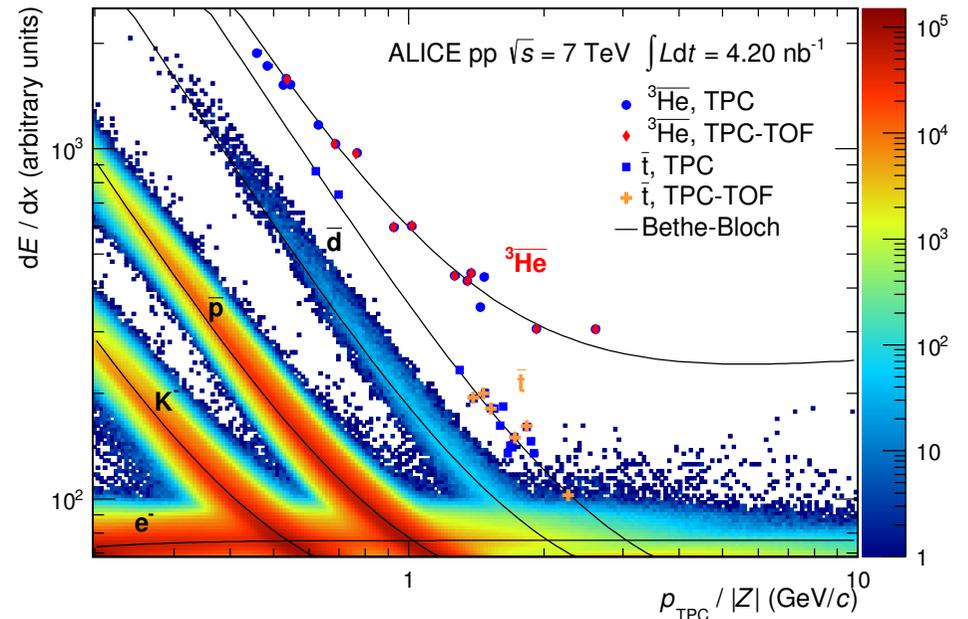
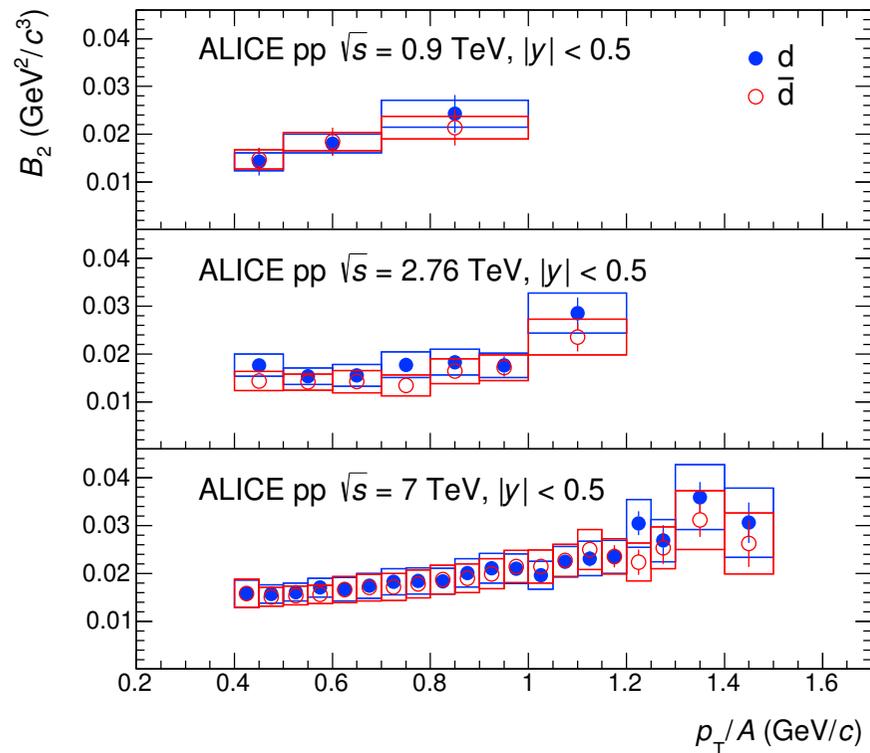
$$\frac{E_{\bar{A}}}{\sigma_{\text{in}}} \frac{d^3\sigma_{\bar{A}}}{d^3\mathbf{k}_{\bar{A}}} = B_A \left\{ \frac{E_{\bar{p}}}{\sigma_{\text{in}}} \frac{d^3\sigma_{\bar{p}}}{d^3\mathbf{k}_{\bar{p}}} \right\}^Z \left\{ \frac{E_{\bar{n}}}{\sigma_{\text{in}}} \frac{d^3\sigma_{\bar{n}}}{d^3\mathbf{k}_{\bar{n}}}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

Coalescence factor B_A

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

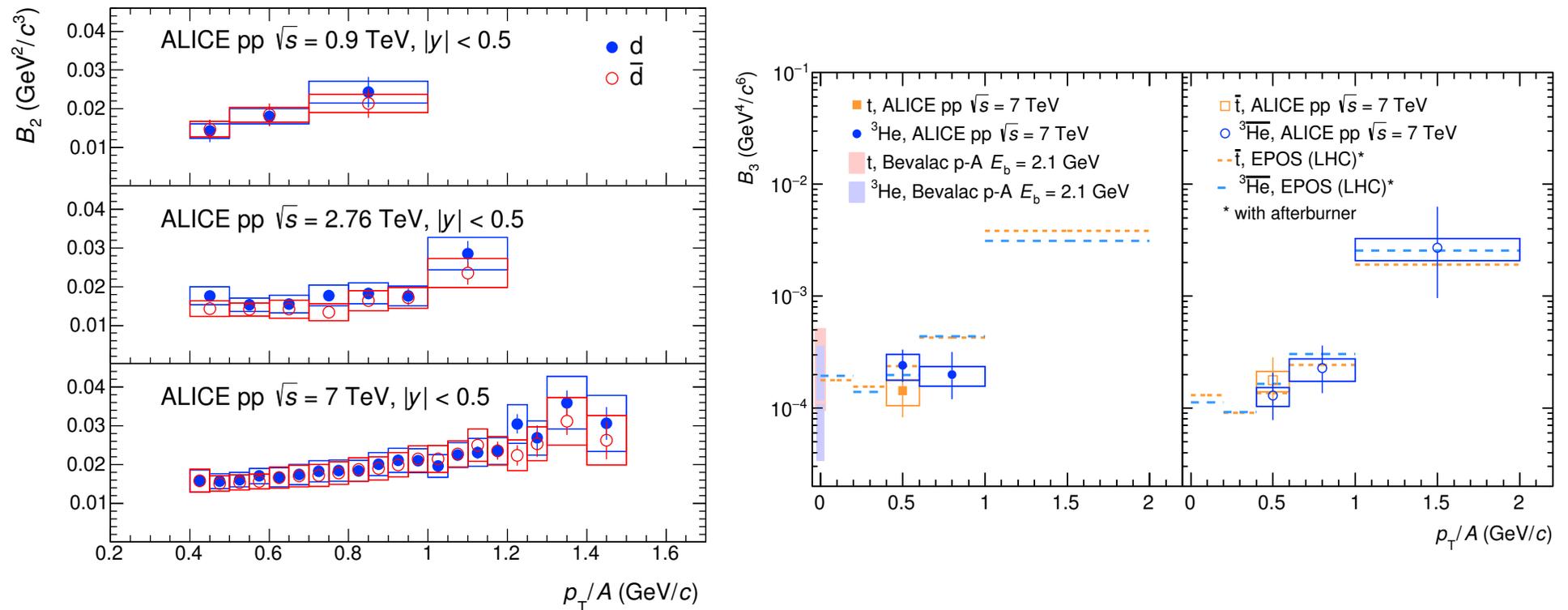
Determination of the coalescence momentum

- 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 ${}^3\overline{\text{He}}$.



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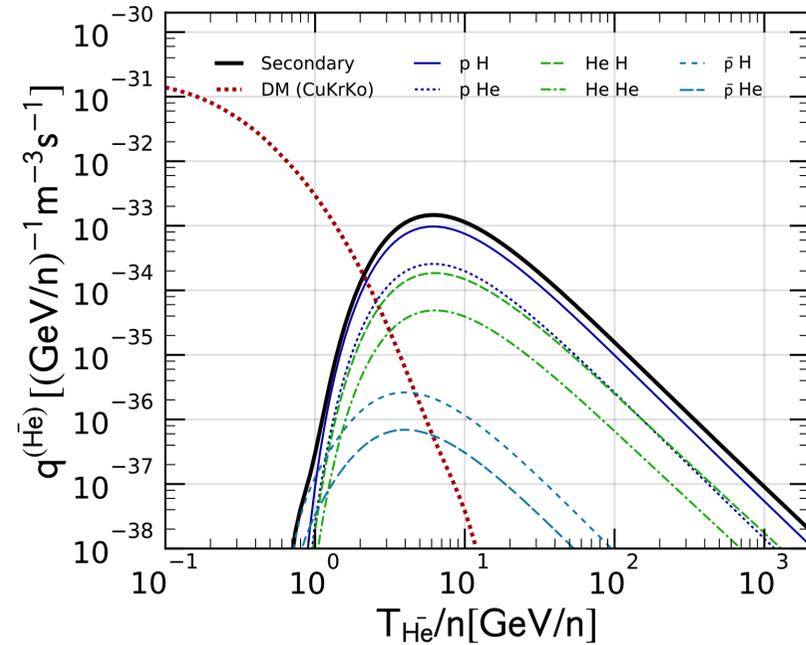
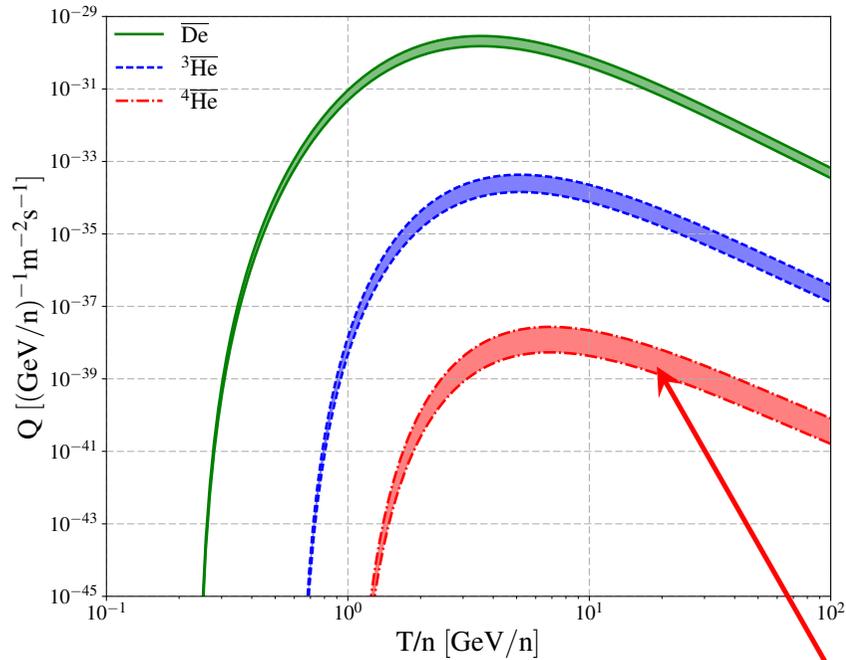


$$208 \text{ MeV} \leq p_{\text{coal}} \leq 262 \text{ MeV}$$

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

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

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



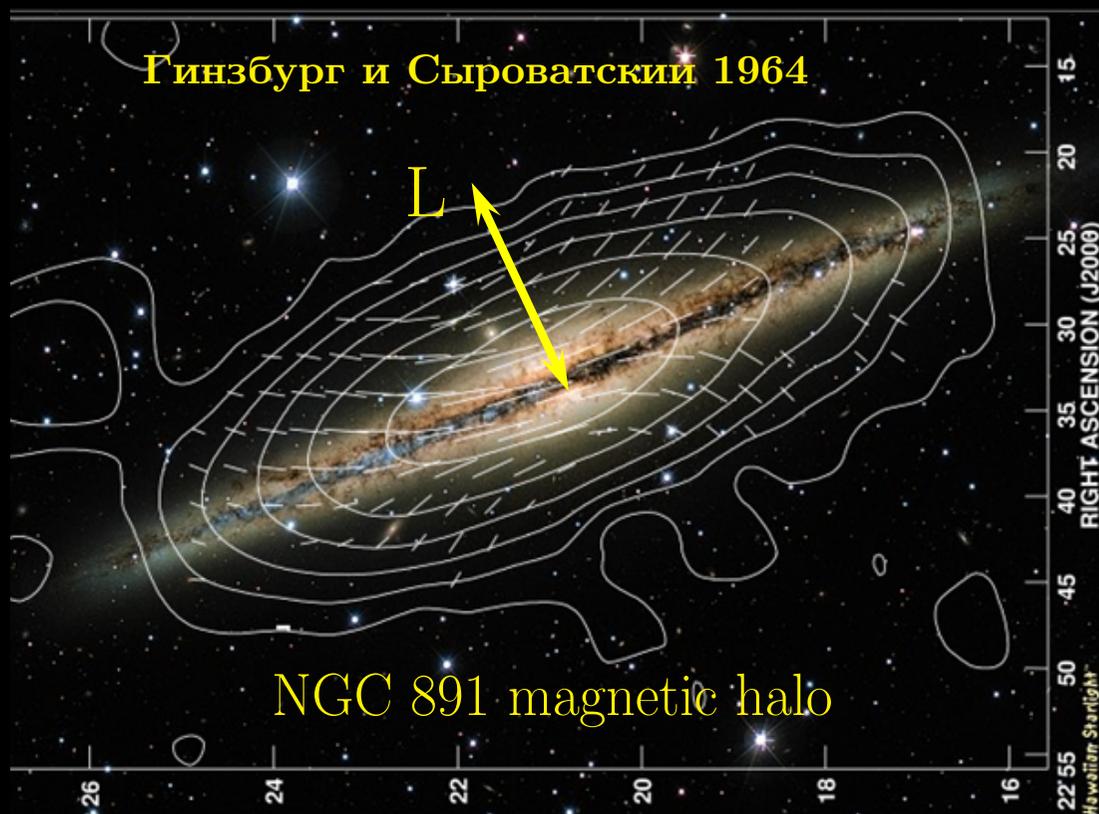
V. Poulin et al., Phys. Rev. **D99** (2019) 023016

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

$$7.7 \times 10^{-7} \leq \frac{B_4}{\text{GeV}^6} \leq 3.9 \times 10^{-6}$$

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

Charged cosmic-ray Galactic propagation



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

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

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

ISM spallation

$$\frac{\partial \psi}{\partial E} \left\{ b \psi - D_{EE} \frac{\partial \psi}{\partial E} \right\} = q - (\sigma v n_H) \psi$$

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

$$\dot{\psi} + \nabla \cdot \{ -K \nabla \psi + \psi \mathbf{V}_C \} + \frac{\partial}{\partial E} \left\{ b \psi - D_{EE} \frac{\partial \psi}{\partial E} \right\} = q - (\sigma v n_H) \psi$$

convection

E losses

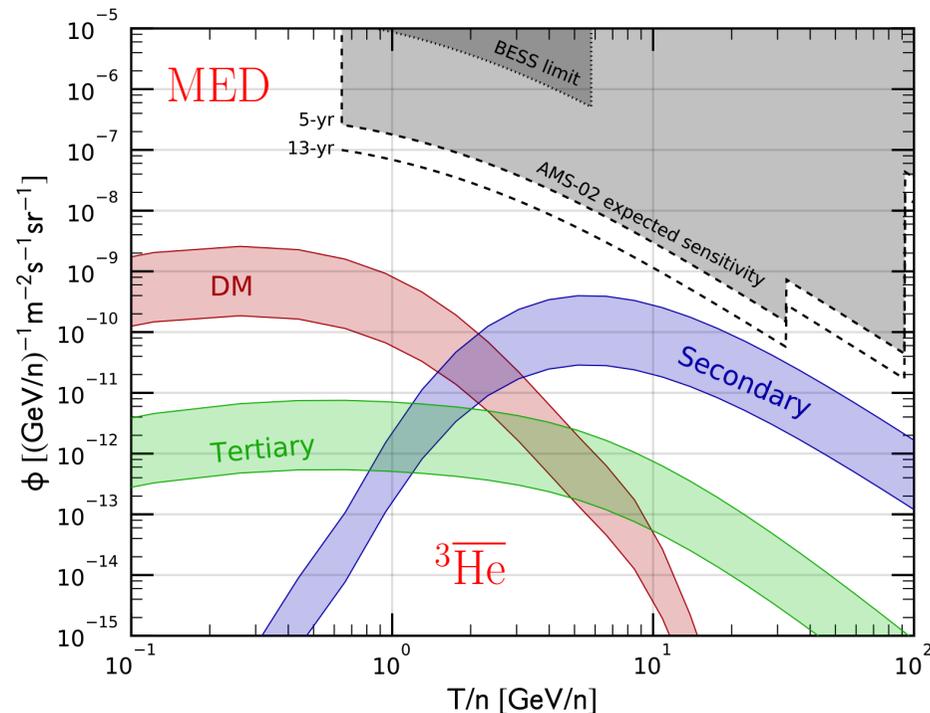
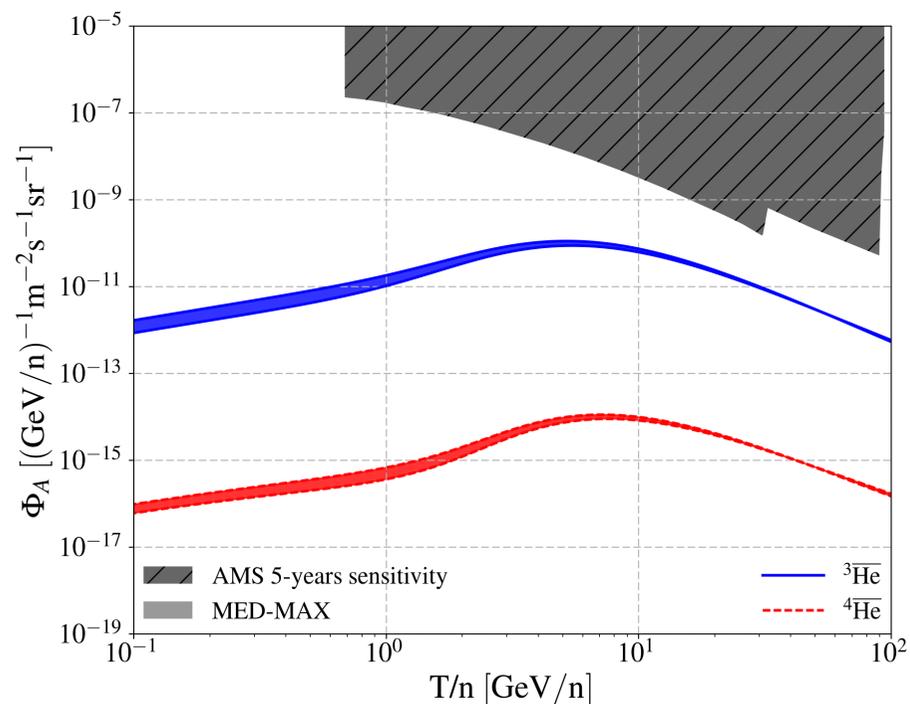
\mathbf{x} diffusion

E diffusion

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

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

Secondary anti-helium fluxes



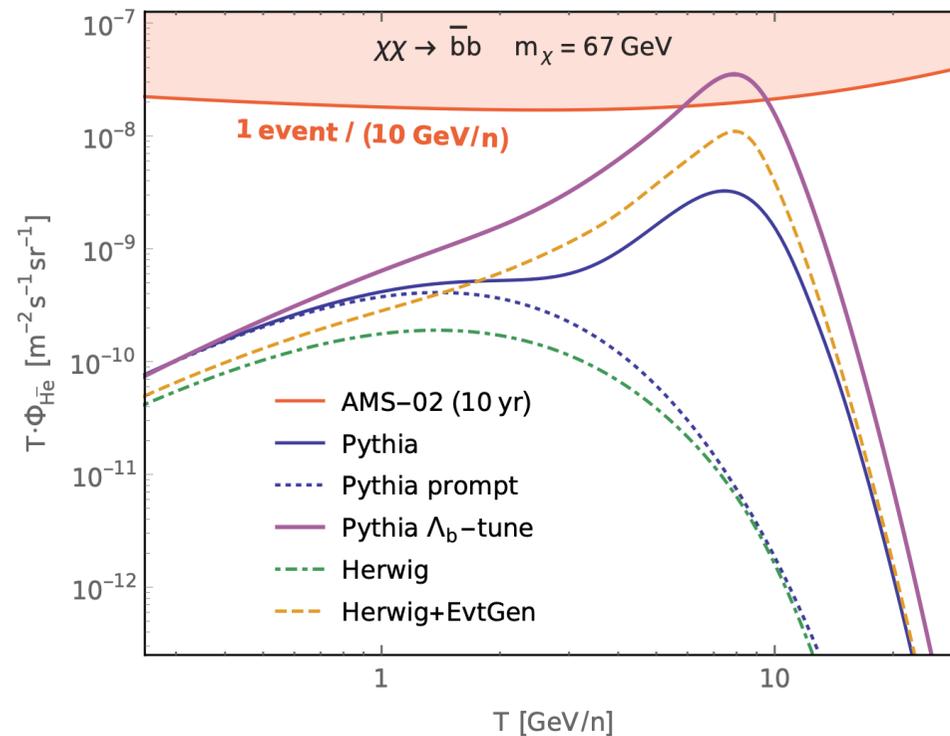
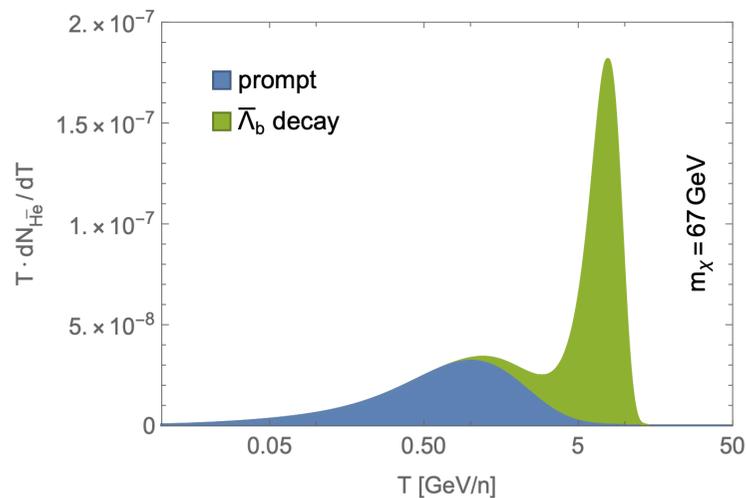
V. Poulin et al., Phys. Rev. **D99** (2019) 023016

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

- Interactions of high-energy cosmic-ray protons and helium nuclei on the ISM yield a **secondary anti-He flux** well below AMS-02 sensitivity.
- The same conclusion holds for DM decays or annihilations although M. Winkler and T. Linden have proposed a nice counter-example based on $\bar{\Lambda}_b$ production if pure $^3\bar{\text{He}}$ events – Phys. Rev. Lett. **126** (2021) 101101.
- Dark Matter has triggered a hectic activity and has been systematically hunted for. It may be time now to devote some attention to the possibility of anti-matter domains in the universe – **anti-clouds & anti-stars**.

3) A word on Dark Matter production

- In general, DM species annihilations do not produce a detectable amount of ${}^3\overline{\text{He}}$. Furthermore, since DM is at rest, the spectrum peaks at low energy $\neq \mathcal{O}(10)$ GeV/n.
- Recently, a new proposal based on DM coupling to b quarks.



4) Anti-clouds - general considerations

Domains of anti-matter gas inside the Milky Way disk and in the early universe

Two general arguments can be used irrespective of AMS-02 events. Survival time (in MW and universe) and energy deposition (in IGM) constrain matter and anti-matter mutual contaminations.

- Annihilation timescale of anti-matter $\tau_{\text{ann}} >$ age t of the anti-cloud

$n_{\bar{p}}$ inside anti-cloud is constrained

- Energy deposition in IGM after recombination is constrained by CMB

$n_{\bar{p}}$ inside matter is now constrained

The annihilation cross-section $\langle \sigma_{p\bar{p}} v \rangle$ is a key ingredient

proton-antiproton annihilation cross-section $\langle \sigma_{p\bar{p}} v \rangle$

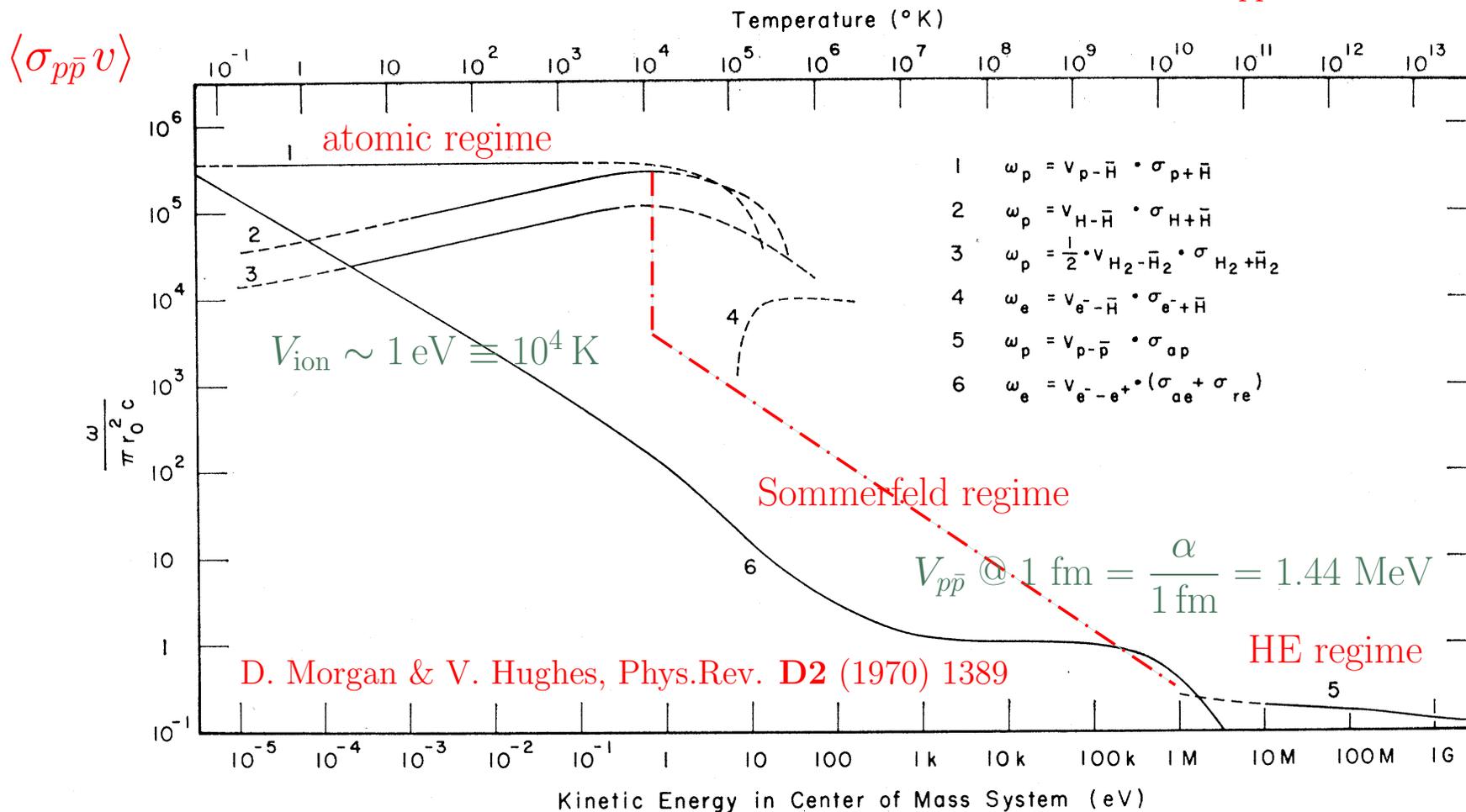


FIG. 4. Per particle per unit antiparticle number-density annihilation rates for various processes producing annihilation. The approximate temperature is shown.

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

Anti-clouds in the disk of the Milky Way (MW)

Anti-matter should survive annihilation, hence a very small density of matter inside anti-matter clouds. The survival rate depends on whether anti-matter is in the form of cold clouds, where $T \sim \mathcal{O}(30)$ K, or in hot ionized clouds, where $T \sim \mathcal{O}(10^6)$ K.

$$\tau_{\text{ann}} = \frac{1}{\langle \sigma_{p\bar{p}} v \rangle n_p} > t_{\text{MW}} \simeq 9 \times 10^9 \text{ y}$$

⇓

$$n_p^{\text{cold}} < 3.5 \times 10^{-8} \text{ cm}^{-3} \quad \text{while} \quad n_p^{\text{hot}} < 3.5 \times 10^{-5} \text{ cm}^{-3}$$

Structure of interstellar medium (ISM)

TABLE I. Descriptive parameters of the different components of the interstellar gas, according to the references quoted in the main text. T is the temperature, n is the true (as opposed to space-averaged) number density of hydrogen nuclei near the Sun, Σ_{\odot} is the azimuthally-averaged mass density per unit area at the solar circle, and \mathcal{M} is the mass contained in the entire Milky Way. Both Σ_{\odot} and \mathcal{M} include 70.4 % of hydrogen, 28.1 % of helium, and 1.5 % of heavier elements. All values were rescaled to $R_{\odot} = 8.5$ kpc, in accordance with footnote 3.

Component	T (K)	n (cm^{-3})	Σ_{\odot} ($M_{\odot} \text{ pc}^{-2}$)	\mathcal{M} ($10^9 M_{\odot}$)
Molecular	10 – 20	$10^2 - 10^6$	~ 2.5	$\sim 1.3^{\text{a}} - 2.5^{\text{b}}$
Cold atomic	50 – 100	20 – 50	~ 3.5	} $\gtrsim 6.0$
Warm atomic	6000 – 10000	0.2 – 0.5	~ 3.5	
Warm ionized	~ 8000	0.2 – 0.5	~ 1.4	$\gtrsim 1.6$
Hot ionized	$\sim 10^6$	~ 0.0065		

^aadapted from Bronfman *et al.*, 1988.

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K.M. Ferriere, Rev. Mod. Phys. **73** (2001) 1031

Segregation factor between 10^{-14} (cold) and 0.005 (hot)

Anti-clouds surviving in the early universe

The same calculation can be performed in the early universe, splitting between three periods depending on the annihilation regime. The annihilation timescale needs to be compared to the age of the universe at **redshift** z .

$$\tau_{\text{ann}} = \frac{1}{\langle \sigma_{p\bar{p}} v \rangle n_p} > t_U \simeq \begin{cases} 10^{19} \text{ s } (1+z)^{-2} & \text{radiation} \\ 3 \times 10^{17} \text{ s } (1+z)^{-3/2} & \text{matter} \end{cases}$$

⇓

Constraint on $n_p^{\text{local}}/n_p^{\text{cosmo}}$ where $n_p^{\text{cosmo}} = 2.534 \times 10^{-7} (1+z)^3 \text{ cm}^{-3}$

⇓

- Before BBN era $T > 10^{10} \text{ K}$

$$n_p^{\text{local}}/n_p^{\text{cosmo}} \leq \frac{263}{(1+z)} \text{ with } z \geq 3.5 \times 10^9$$

- After BBN and before matter-radiation equality, i.e. $10^4 \text{ K} < T < 10^{10} \text{ K}$

$$n_p^{\text{local}}/n_p^{\text{cosmo}} \leq \frac{3.25 \times 10^{-3}}{\sqrt{1+z}} \text{ with } 3.5 \times 10^3 \leq z \leq 3.5 \times 10^9$$

- During the matter domination era, i.e. $T < 10^4 \text{ K}$

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Segregation factor between $\leq 7 \times 10^{-8}$ (BBN) and 0.13 (now)

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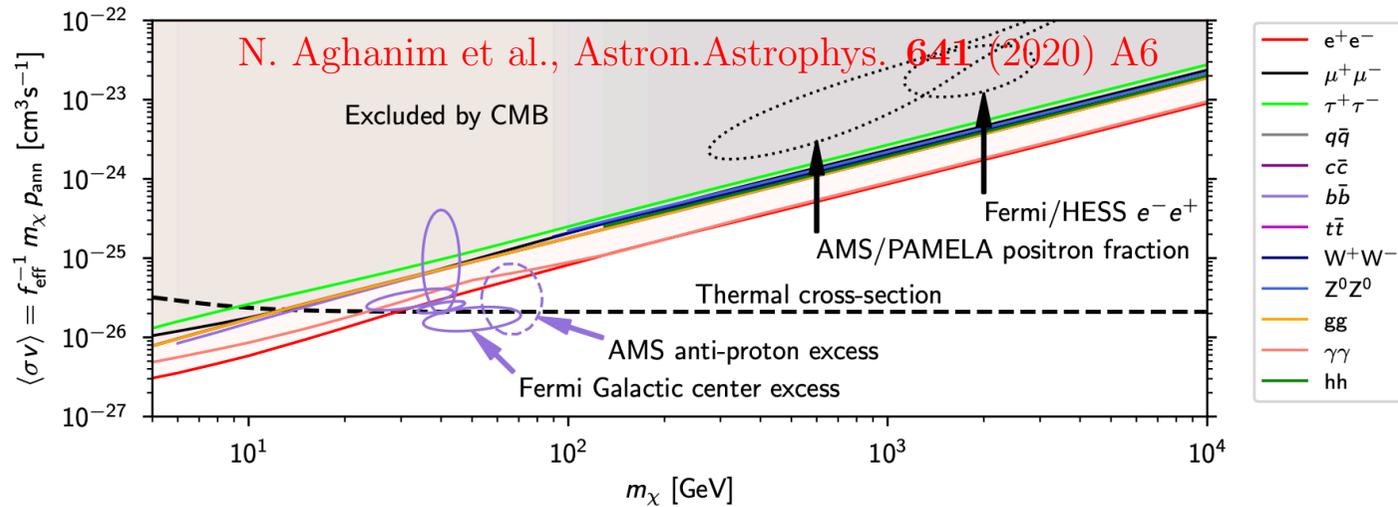
Energy injection in the intergalactic medium

Energy injected after recombination modifies the re-ionization history of the IGM and its optical depth against Thomson scattering. It eventually modifies polarization anisotropies in the CMB, hence strong constraints from Planck.

$$\left. \frac{d^2 E}{dV dt} \right|_{\text{DM}} = \frac{1}{2} \langle \sigma_{\text{ann}} v \rangle n_{\text{DM}}^2 \times 2 m_{\text{DM}} c^2 \times f_{\text{eff}}$$

⇓

$$\left. \frac{d^2 E}{dV dt} \right|_{\text{DM}} = \left\{ p_{\text{ann}} \equiv f_{\text{eff}} \frac{\langle \sigma_{\text{ann}} v \rangle}{m_{\text{DM}}} \right\} \left\{ \rho_c^0 \Omega_{\text{CDM}} c \right\}^2 (1+z)^6$$



$$p_{\text{ann}} \leq 3.2 \times 10^{-28} \text{ cm}^3 \text{ s}^{-1} \text{ GeV}^{-1}$$

⇓

$$\left. \frac{d^2 E}{dV dt} \right|_{\text{DM}} \leq 8.26 \times 10^{-44} (1+z)^6 \text{ J m}^{-3} \text{ s}^{-1}$$

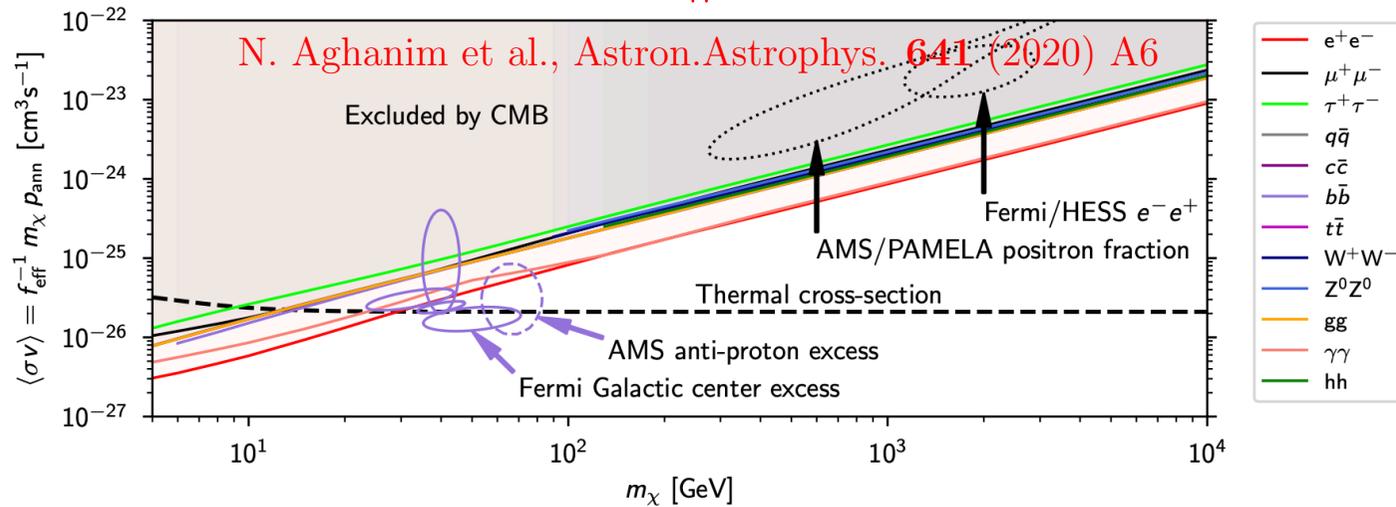
Energy injection in the intergalactic medium

$$\left. \frac{d^2 E}{dV dt} \right|_{\text{DM}} = \langle \sigma_{p\bar{p}} v \rangle n_p n_{\bar{p}} \times 2 m_p c^2 = \langle \sigma_{p\bar{p}} v \rangle n_p^0 n_{\bar{p}}^0 \times 2 m_p c^2 (1+z)^6$$



$$n_{\bar{p}}^0 \leq 1.1 \times 10^{-23} \text{ cm}^{-3} \left\{ \frac{10^{-10} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma_{p\bar{p}} v \rangle} \right\}$$

4.3×10^{-17} smaller than $n_p^0 = 2.534 \times 10^{-7} \text{ cm}^{-3}$



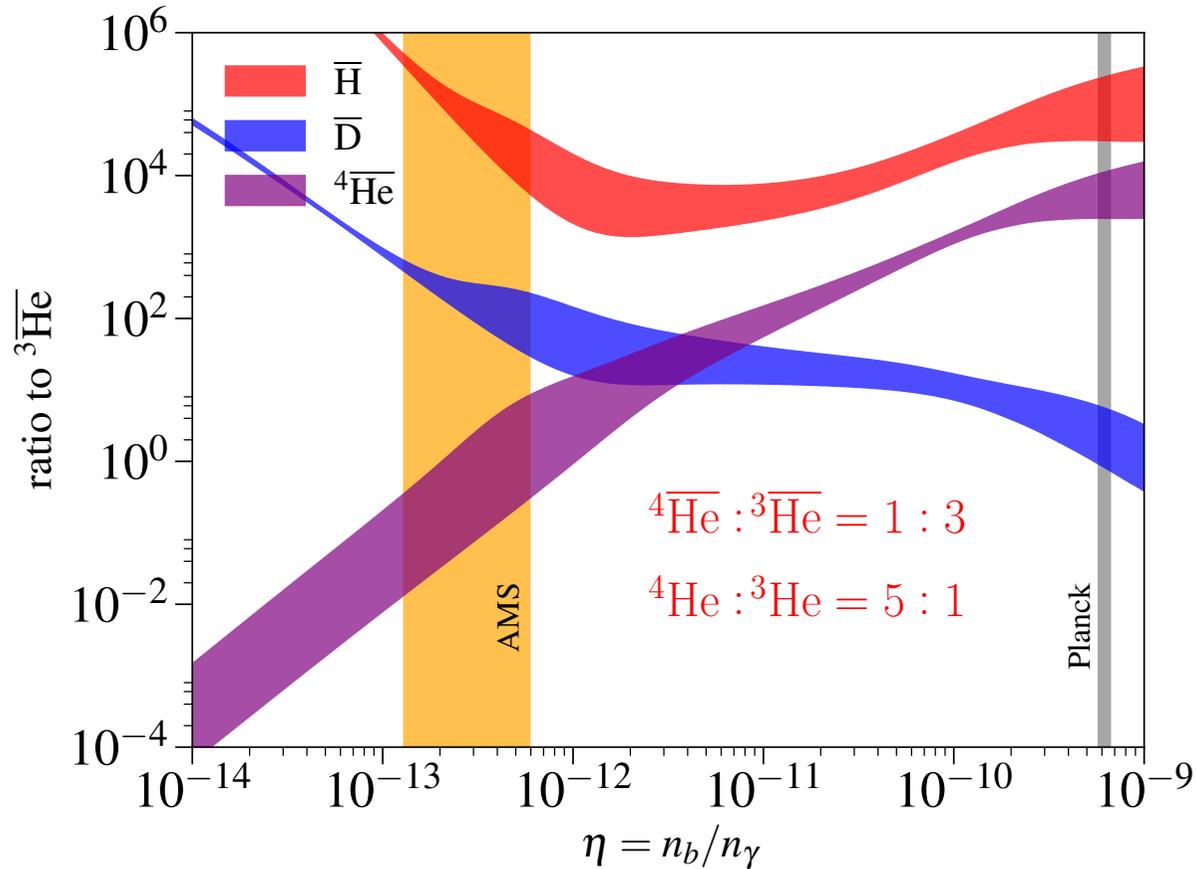
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5) Anti-clouds – a (crazy) step further

Taken at face value, the isotopic ratio of $\overline{\text{He}}$ nuclei could be explained by anisotropic BBN taking place in regions where $\bar{\eta} \sim (1.3 - 6) \times 10^{-13}$.



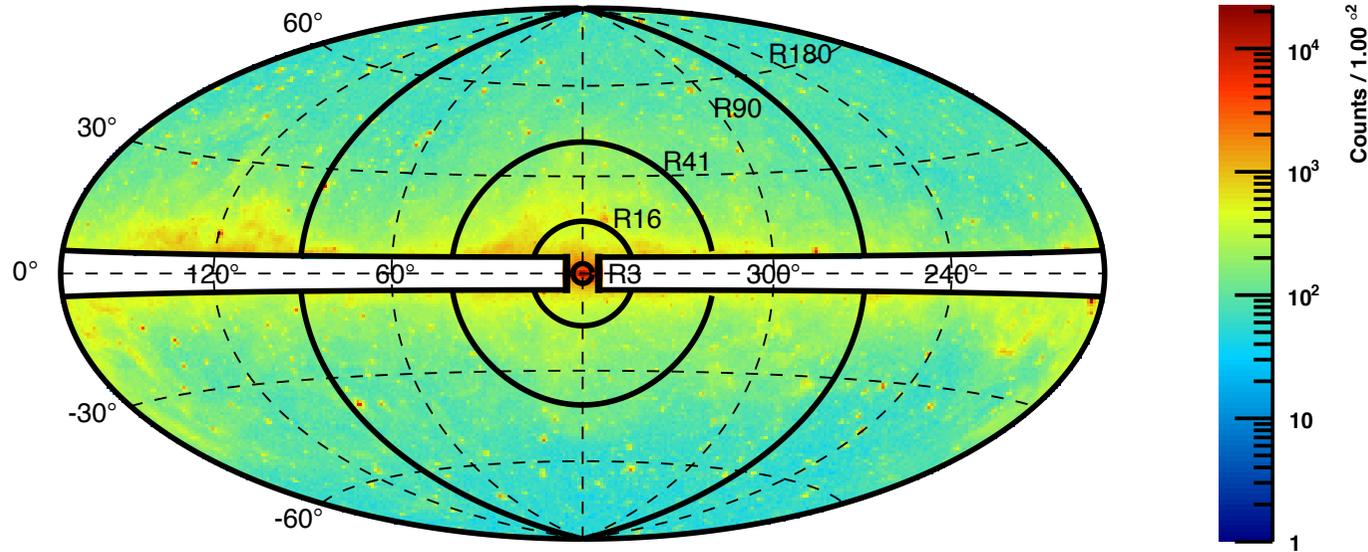
$$10^{-8} \simeq \frac{\Phi_{\overline{\text{He}}}}{\Phi_{\text{He}}} \simeq \frac{N_{\overline{\text{He}}}}{N_{\text{He}}} = \frac{V_{\overline{\text{M}}} n_{\overline{\text{He}}}}{V_{\text{M}} n_{\text{He}}} = \frac{V_{\overline{\text{M}}} n_{\overline{\text{b}}}}{V_{\text{M}} n_{\text{b}}} \frac{n_{\overline{\text{He}}}}{n_{\overline{\text{H}}}} \frac{n_{\text{H}}}{n_{\text{He}}} \text{ in ISM}$$



$$\left. \frac{V_{\overline{\text{M}}} n_{\overline{\text{b}}}}{V_{\text{M}} n_{\text{b}}} \right|_{\text{ISM}} \simeq 10^{-8} \times 10^{-1} \times (10^4 - 10^{5.5}) \simeq (10^{-5} - 10^{-3.5})$$

γ-ray line constraint at 933 MeV on n_p^{local}

Annihilations inside anti-matter domains yield γ-ray lines. We are interested here in $p\bar{p} \rightarrow \pi^0 \gamma$ at 933 MeV whose integrated flux over the MW is constrained by Fermi-LAT observations.



M. Ackermann et al. (Fermi-LAT), Phys. Rev. **D91** (2015) 122002

$$\left. \frac{d^2 N_\gamma}{dV dt} \right|_{\pi^0 \gamma} = \rho_{\pi^0 \gamma}^{\text{ISM}} = \mathcal{B}_{\pi^0 \gamma} \left\{ \frac{V_{\text{M}}}{V_{\text{M}}} \right\} n_{\bar{p}} n_p^{\text{local}} \langle \sigma_{p\bar{p}} v \rangle$$

$$\Phi_\gamma = \frac{1}{4\pi} \int^{R180} d\ell d\Omega \rho_{\pi^0 \gamma}^{\text{ISM}} \leq 6.87 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \text{ (Fermi-LAT)}$$

⇓

$$n_p^{\text{local}} \lesssim (10^{-10} - 3 \times 10^{-9}) \text{ cm}^{-3}$$

This is O(10) times better than the lifetime limit

γ -rays from cosmic-ray annihilations in close-by anti-clouds

Nothing prevents cosmic-ray protons to penetrate inside anti-clouds where they annihilate. This should yield a strong annihilation signal appearing as **(i)** a continuous emission and also as **(ii)** a point source in the sky if anti-matter domains are well localized in space.

$$\text{We start from } N_{\bar{c}} M_{\bar{c}} = M_{\bar{M}} = m_{\bar{b}} n_{\bar{b}} V_{\bar{M}}$$

and assume that $N_{\bar{c}} \times 2h D_{\bar{c}}^2 = V_M \equiv V_{\text{disk}}$ (homogeneous over MW)



$$2h D_{\bar{c}}^2 = \frac{V_M}{N_{\bar{c}}} = \frac{V_M n_b}{V_{\bar{M}} n_{\bar{b}}} \times \frac{M_{\bar{c}}}{n_b m_{\bar{b}}}$$



$$D_{\bar{c}} \simeq (1 \text{ to } 5.5) \times 860 \text{ pc} \times \left\{ \frac{M_{\bar{c}}}{10^3 M_{\odot}} \right\}^{1/2}$$

γ -rays from cosmic-ray annihilations in close-by anti-clouds

Nothing prevents cosmic-ray protons to penetrate inside anti-clouds where they annihilate. This should yield a strong annihilation signal appearing as **(i)** a continuous emission and also as **(ii)** a point source in the sky if anti-matter domains are well localized in space.

The absolute luminosity of a cloud is its production rate of photons

$$L_\gamma = \int_{E_p^{\text{inf}}}^{E_p^{\text{sup}}} \langle \sigma_{p\bar{p}} v \rangle n_{\bar{p}} \frac{dn_p}{dE_p} dE_p \times \mathcal{B}_\gamma^{\text{eff}} \times V_{\bar{c}} \propto M_{\bar{c}}$$



$$\Phi_\gamma = \frac{L_\gamma}{4\pi D_{\bar{c}}^2} = \frac{\mathcal{B}_\gamma^{\text{eff}}}{D_{\bar{c}}^2} \times \frac{M_{\bar{c}}}{m_{\bar{p}}} \times \int_{E_p^{\text{inf}}}^{E_p^{\text{sup}}} \sigma_{p\bar{p}} \Phi_p(E_p) dE_p$$

The flux does not depend on $M_{\bar{c}}$. Assuming $\mathcal{B}_\gamma^{\text{eff}} = 4 \times 4\%$ and integrating E_p from 3 to 10 GeV for photons in the 1–3 GeV energy band, we get

$$\Phi_\gamma^{\text{cloud}} \simeq (0.03 \text{ to } 1) \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$$

to be compared to $\Phi_\gamma^{\text{Fermi}} \geq 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$

Clouds may be on the verge of detection

Concluding remarks

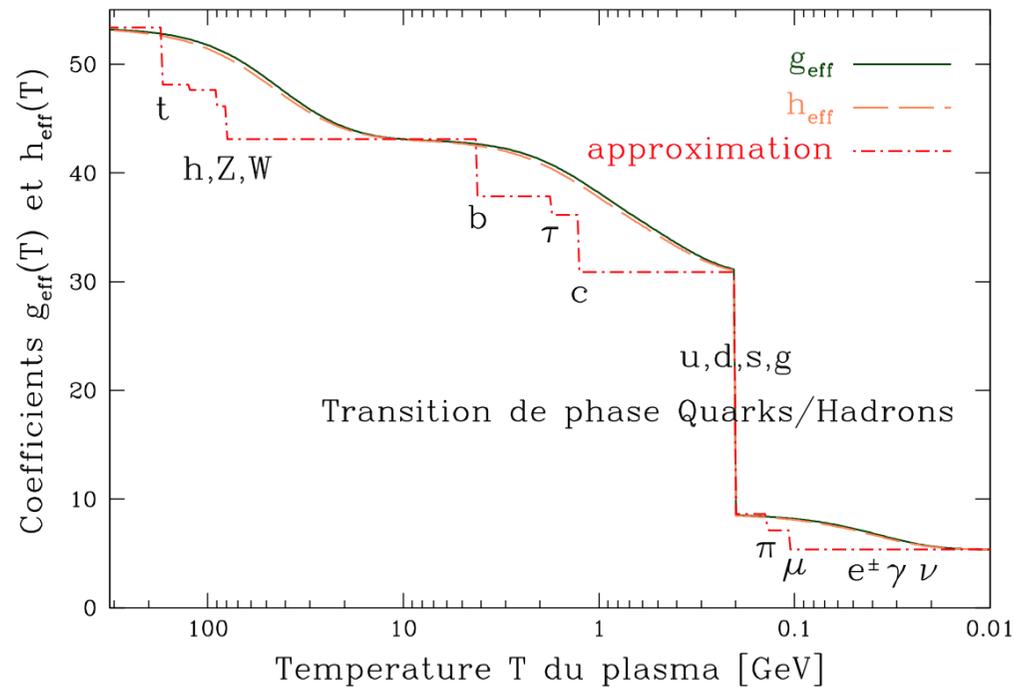
- Anti-helium-3 and anti-helium-4 candidates may have been identified by AMS-02. Massive background simulations are carried out to evaluate significance. More data are needed.
- ${}^3\overline{\text{He}}$ events
Unless CR propagation and coalescence are very different from expected, AMS-02 should **not** see secondary CR ${}^3\overline{\text{He}}$.
Interesting possibility from DM annihilating into $\bar{\Lambda}_b$ mesons – Linden & Winkler.
- ${}^4\overline{\text{He}}$ events
There is no hope to detect a single event from CR spallation or DM.
- However, the existence of anti-matter domains raises an insuperable difficulty because of segregation. It must be active at $T_S \simeq 37.4$ MeV and active since then until today.
- Could antimatter be packed inside anti-stars and be protected until today?
Stay tuned for Alexander Dolgov and Peter von Ballmoos talks.

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

6) Matter-antimatter segregation is a problem

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

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



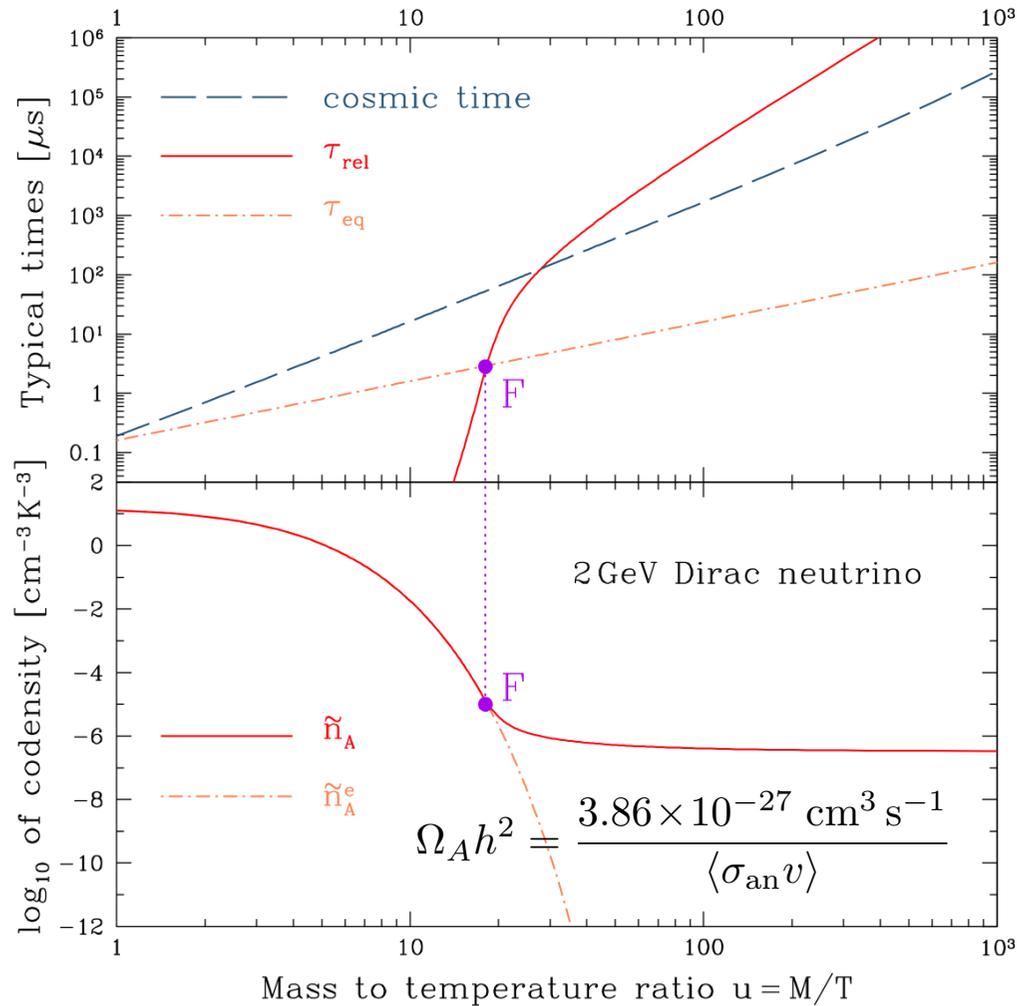
- As soon as they are formed, nucleons and antinucleons annihilate.



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

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

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



- Annihilation of N & \bar{N} proceeds very strongly with freeze-out at $u_F = 41.8$ and $T_F \simeq 22$ MeV.

Nucleons and antinucleons are completely depleted.

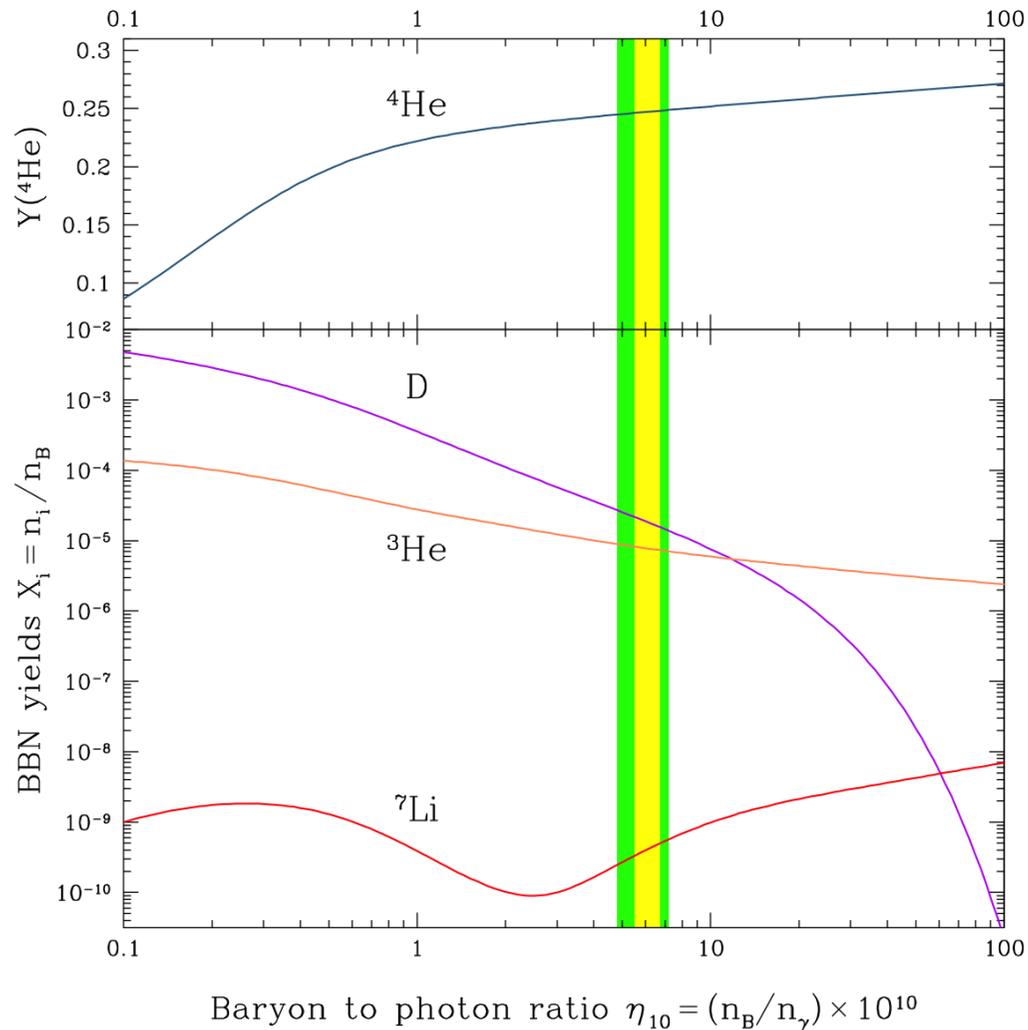
$$\frac{n_N^0}{n_\gamma} \equiv \frac{\tilde{n}_N^0}{\tilde{n}_\gamma} = \frac{2\pi^2}{\zeta(3)} \left\{ \frac{1}{1 + 2u_F} \right\} \left\{ \frac{u_F}{2\pi} \right\}^{3/2} e^{-u_F} \simeq 2.34 \times 10^{-18}$$

↑

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

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

- Segregation between N & \bar{N} must take place **before** freeze-out at $u_S = 25.1$, $T_S \simeq 37.4$ MeV and cosmic time $t_S \simeq 0.5$ ms.

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



$$\mathcal{M}_N = M_p n_N R_S^3 \simeq 1.79 \times 10^{22} \text{ kg}$$



Segregation active since then

We have no idea on how it proceeds

7) The search for anti-stars

Anti-star properties related to AMS-02 events

Anti-matter could alternatively be in the form of anti-stars. They could essentially be made of anti-helium if BBN proceeded in a high $\bar{\eta}$ medium. Matter falling at the surface would annihilate and generate energy. An Earth size body would release 10^{49} ergs and could expel a shell of $0.01 M_{\odot}$ in outer space at 10^4 km/s. Acceleration could take place in the resulting shock wave.

- Matching the $\overline{\text{He}}$ flux, i.e. $\Phi_{\overline{\text{He}}}/\Phi_{\text{He}} \sim 10^{-8}$.

$$\Phi_{\overline{\text{He}}} \simeq \frac{1}{4\pi} \frac{c}{V_{\text{gal}}} \frac{f_{\overline{\text{He}}} M_{*}}{m_{\overline{\text{He}}}} f_{\text{acc}}$$

↓

$$\Phi_{\overline{\text{He}}} \simeq 2 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1} \times \frac{M_{*}}{M_{\odot}} \times \frac{f_{\text{acc}}}{10^{-6}}$$

- Once accelerated, CR ${}^4\overline{\text{He}}$ need to cross over 20 g cm^{-2} of matter for being converted into ${}^3\overline{\text{He}}$ in order to achieve the isotopic ratio ${}^4\overline{\text{He}} : {}^3\overline{\text{He}} = 1 : 3$

Table 2

Total reaction cross section, cross section for reactions with different number of charged prongs and for ${}^3\text{He}$ production. All quantities are in mb. $\langle n_c \rangle$ is the mean number of charged prongs per event.

Number of charged prongs	σ			N_{π^-}
	19.6 MeV	48.7 MeV	179.6 MeV	
${}^3\text{He}$ production	93.2 \pm 7.9	58.6 \pm 4.1	35.7 \pm 2.8	

**Constraints on the antistar fraction in the Solar system
neighborhood from the 10-years *Fermi* Large Area Telescope
gamma-ray source catalog**

S. Dupourqué, L. Tibaldo and P. von Ballmoos, *Phys.Rev.* **D103** (2021) 083016

- extended sources are excluded since the angular size of a star is several orders of magnitude smaller than the LAT resolution at low energy, thus antistars are expected to be point-like sources;
- sources associated with objects known from other wavelengths that belong to established gamma-ray source classes (e.g., pulsars, active galactic nuclei) are excluded;
- sources with total TS summed for energy bands above 1 GeV larger than 9 (that is, emission detected at $> 3\sigma$ above 1 GeV) are excluded since the emission spectrum from proton-antiproton annihilation is null above 938 MeV (mass of the proton); the high-energy cutoff makes it possible to differentiate the matter-antimatter annihilation signal from the well-known pion-bump signal produced by interactions of cosmic rays with an approximate power-law spectrum onto the ISM and seen in the Galactic interstellar emission and a few supernova remnants [23, 24]; to our knowledge this is the first time that spectral criteria are used to select candidate antistars in gamma-ray catalogs;
- sources flagged in the catalog as potential spurious detections related to uncertainties in the background models or nearby bright sources (flags 1 to 6) are excluded.

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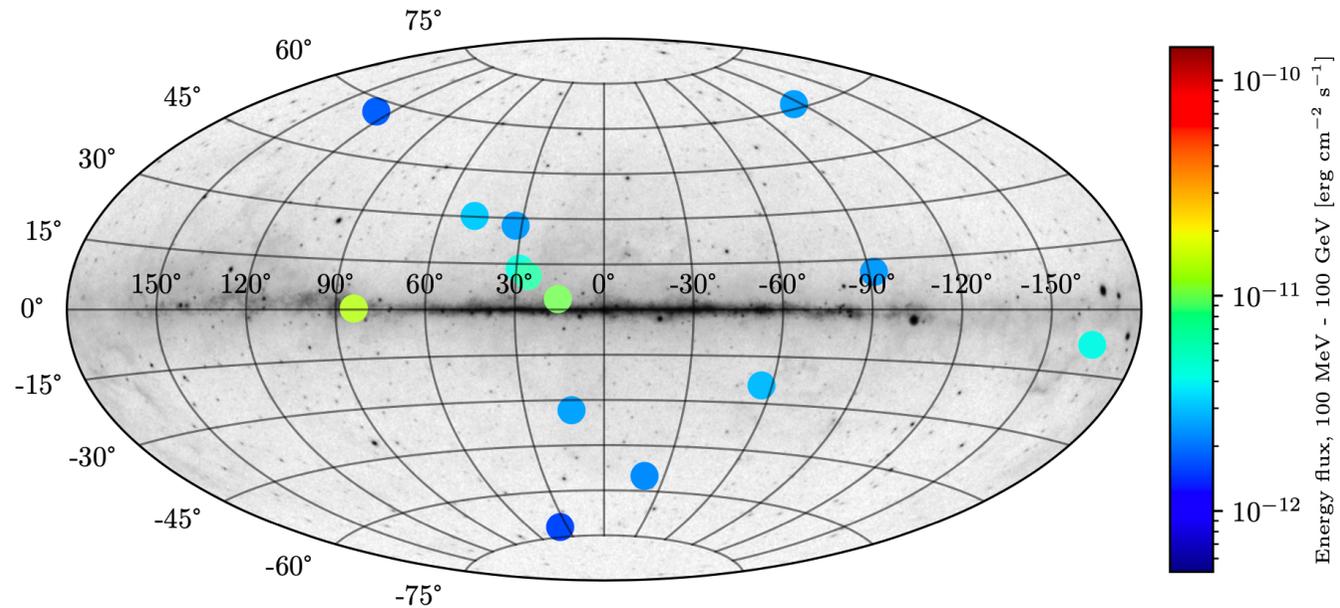


FIG. 1. Positions and energy flux in the 100 MeV - 100 GeV range of antistar candidates selected in 4FGL-DR2. Galactic coordinates. The background image shows the Fermi 5-year all-sky photon counts above 1 GeV (Image credit: NASA/DOE/Fermi LAT Collaboration)

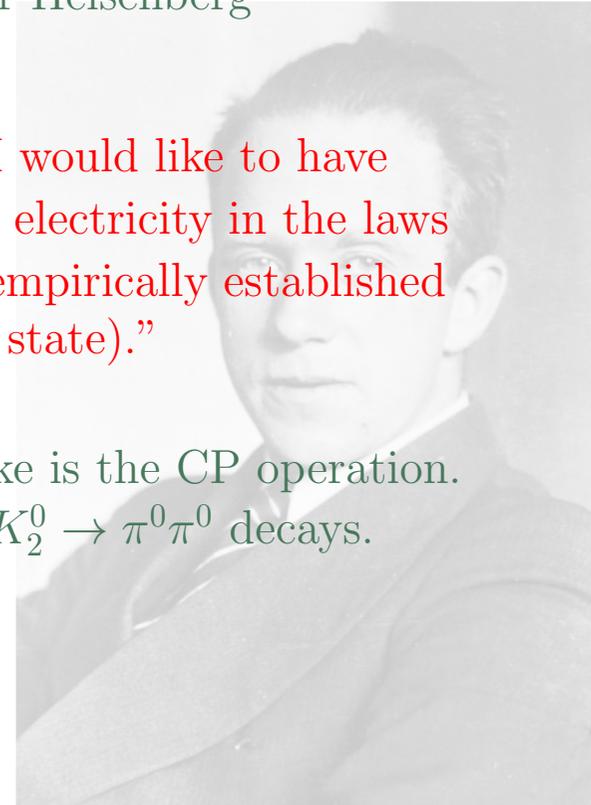
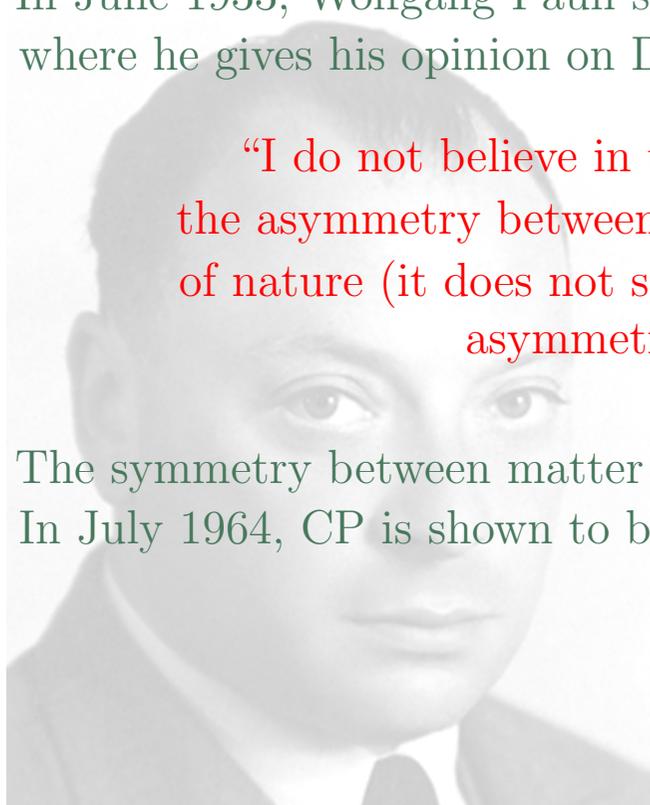
$$f_{*} \leq 2.68 \times 10^3 \left(\frac{\Phi_{\max}}{\text{cm}^{-2} \text{ s}^{-1}} \right)^{3/2} \left(\frac{\rho}{\text{m}_p \text{ cm}^{-3}} \right)^{-3/2} \left(\frac{M}{M_{\odot}} \right)^{-3} \left(\frac{\sqrt{v^2 + c^2}}{10 \text{ km s}^{-1}} \right)^{9/2}$$

8) 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 $K_2^0 \rightarrow \pi^0\pi^0$ decays.



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)

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Remarque !

sous CP : $u_L \Leftrightarrow \bar{u}_R$ et $d_L \Leftrightarrow \bar{d}_R$

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

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

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

We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2^0 \rightarrow \pi^+ + \pi^-) / (K_2^0 \rightarrow \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ 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 $K_2^0 = 2^{-1/2}[(K_0 - \bar{K}_0) + \varepsilon(K_0 + \bar{K}_0)]$ then $|\varepsilon|^2 \cong R_T \tau_1 \tau_2$ 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, $|\varepsilon| \cong 2.3 \times 10^{-3}$.

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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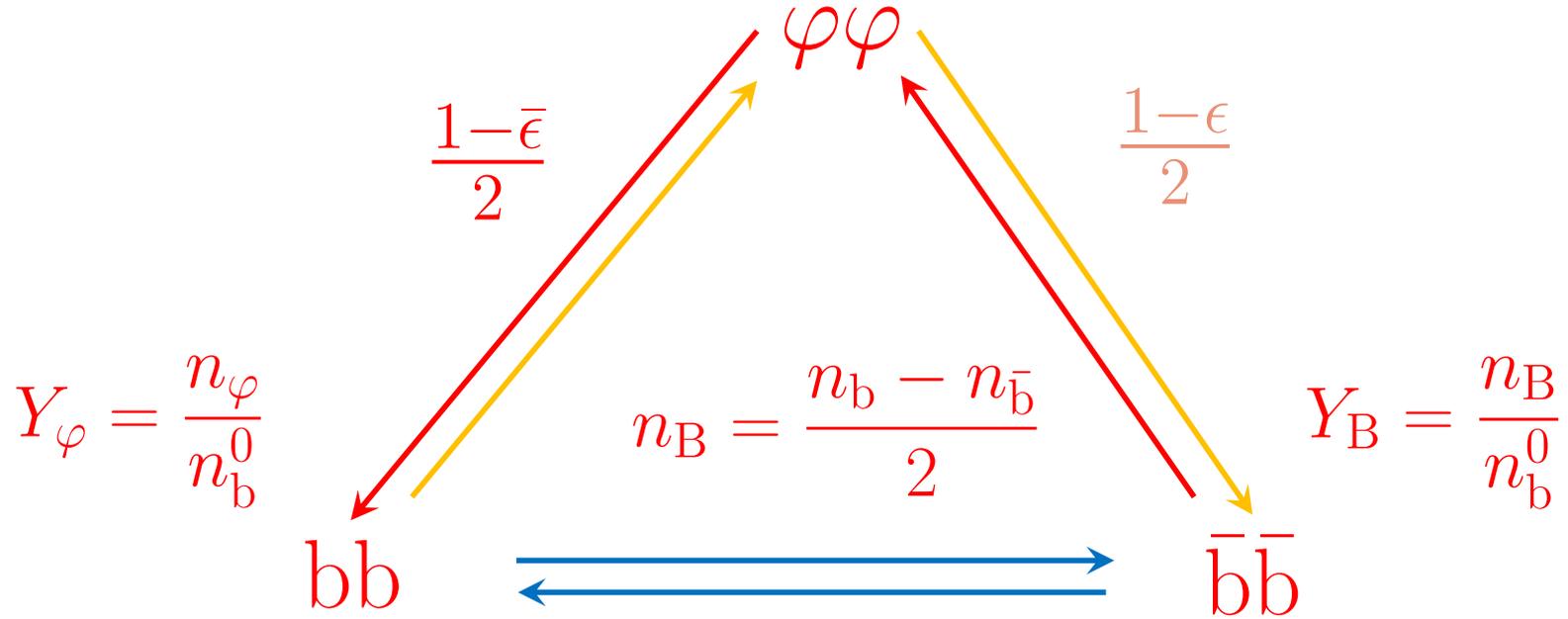
$$\mathcal{M}(i \rightarrow j) = \mathcal{M}(\bar{j} \rightarrow \bar{i}), \quad (CPT \text{ invariance})$$

$$\sum_j |\mathcal{M}(i \rightarrow j)|^2 = \sum_j |\mathcal{M}(j \rightarrow i)|^2, \quad (\text{unitarity})$$

$$\sum_j |\mathcal{M}(i \rightarrow j)|^2 = \sum_j |\mathcal{M}(j \rightarrow \bar{i})|^2 = \sum_j |\mathcal{M}(j \rightarrow i)|^2, \quad (CPT + \text{unitarity})$$

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A simplistic model



$$|\mathcal{M}(\varphi\varphi \rightarrow bb)|^2 = |\mathcal{M}(\bar{b}\bar{b} \rightarrow \varphi\varphi)|^2 = [\mathcal{M}_0]^2 \left(\frac{1-\bar{\epsilon}}{2}\right)$$

$$|\mathcal{M}(\varphi\varphi \rightarrow \bar{b}\bar{b})|^2 = |\mathcal{M}(bb \rightarrow \varphi\varphi)|^2 = [\mathcal{M}_0]^2 \left(\frac{1-\epsilon}{2}\right)$$

$$k_{\bar{b}} |\mathcal{M}(bb \rightarrow \bar{b}\bar{b})|^2 + k_\varphi |\mathcal{M}(bb \rightarrow \varphi\varphi)|^2 \equiv k_b |\mathcal{M}(\bar{b}\bar{b} \rightarrow bb)|^2 + k_\varphi |\mathcal{M}(\bar{b}\bar{b} \rightarrow \varphi\varphi)|^2$$

$$\frac{dY_\varphi}{dt} = -\langle\sigma_0 v\rangle n_b^0 \left\{1 - \left(\frac{\epsilon+\bar{\epsilon}}{2}\right)\right\} \left\{Y_\varphi^2 - (Y_\varphi^e)^2\right\} + \langle\sigma_0 v\rangle n_b^0 (\bar{\epsilon} - \epsilon) (Y_\varphi^e)^2 Y_B$$

$$\frac{dY_B}{dt} = \langle\sigma_0 v\rangle n_b^0 \left(\frac{\epsilon-\bar{\epsilon}}{4}\right) \left\{Y_\varphi^2 - (Y_\varphi^e)^2\right\} - \langle\sigma_0 v\rangle n_b^0 \left\{1 - \left(\frac{\epsilon+\bar{\epsilon}}{2}\right)\right\} (Y_\varphi^e)^2 Y_B - 2\langle\sigma_0 v\rangle n_b^0 Y_B$$