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

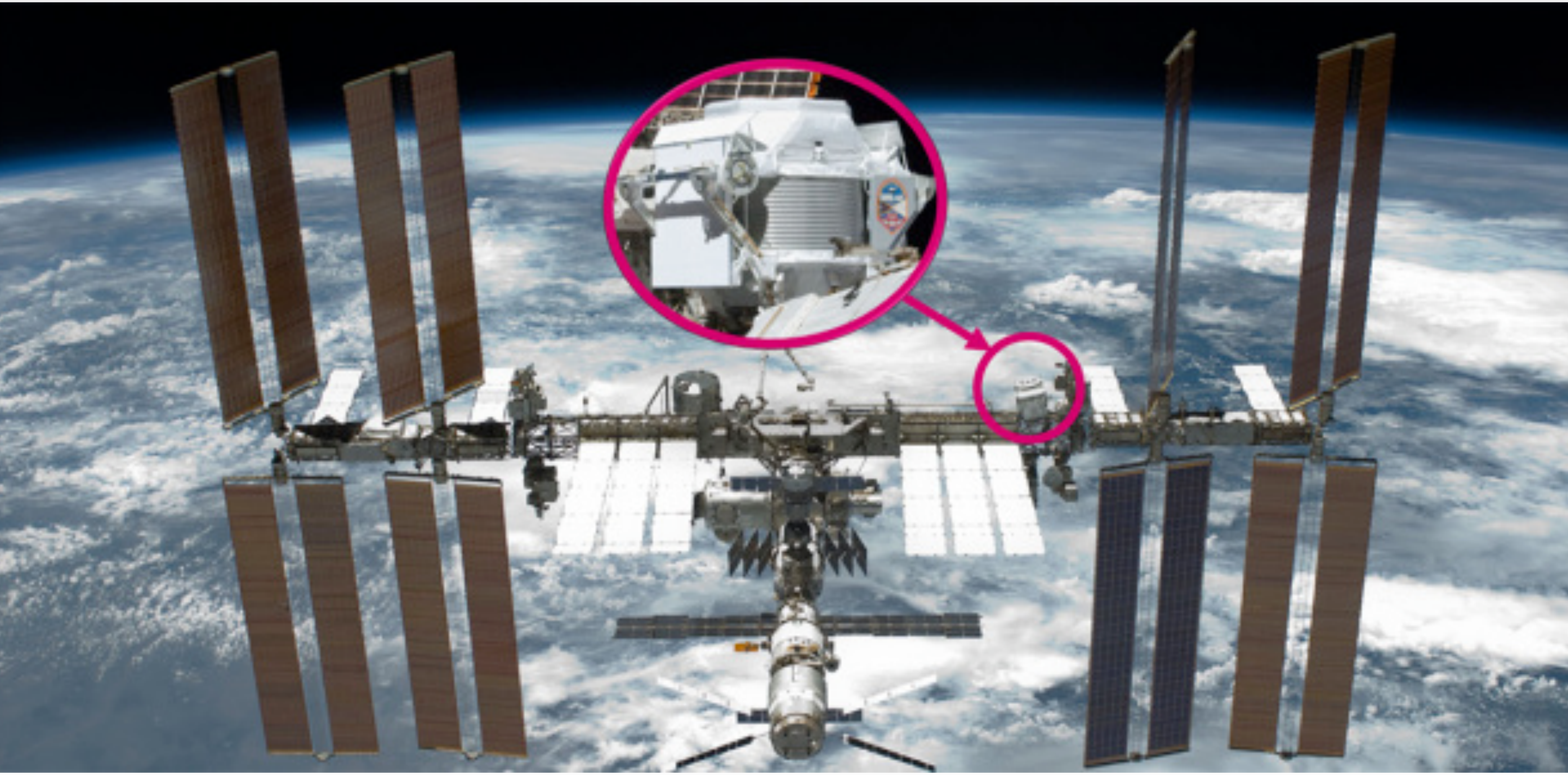
Vivian Poulin

Laboratoire Univers et Particules de Montpellier
CNRS & Université de Montpellier

*w/ P. Salati, I. Cholis, M. Kamionkowski and J. Silk*
*Phys.Rev. D99 (2019) no.2, 023016*

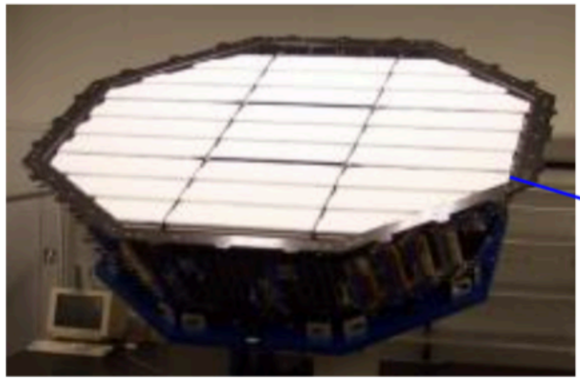
*GReCO seminar series*
*IAP, 27/01/2020*

# AMS: A particle physics detector on the ISS

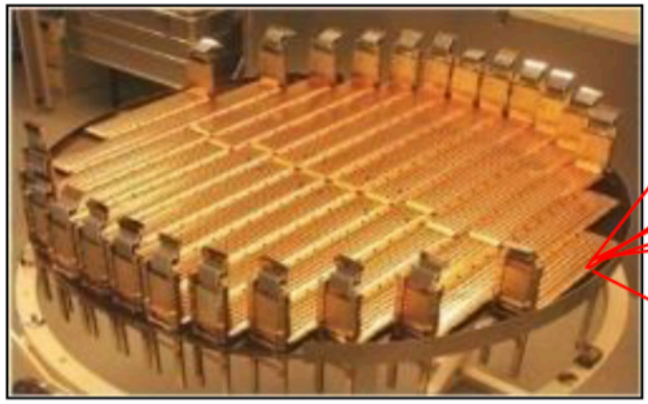


# AMS: A TeV precision, magnetic spectrometer

**Transition Radiation Detector**
Identify $e^+$, $e^-$

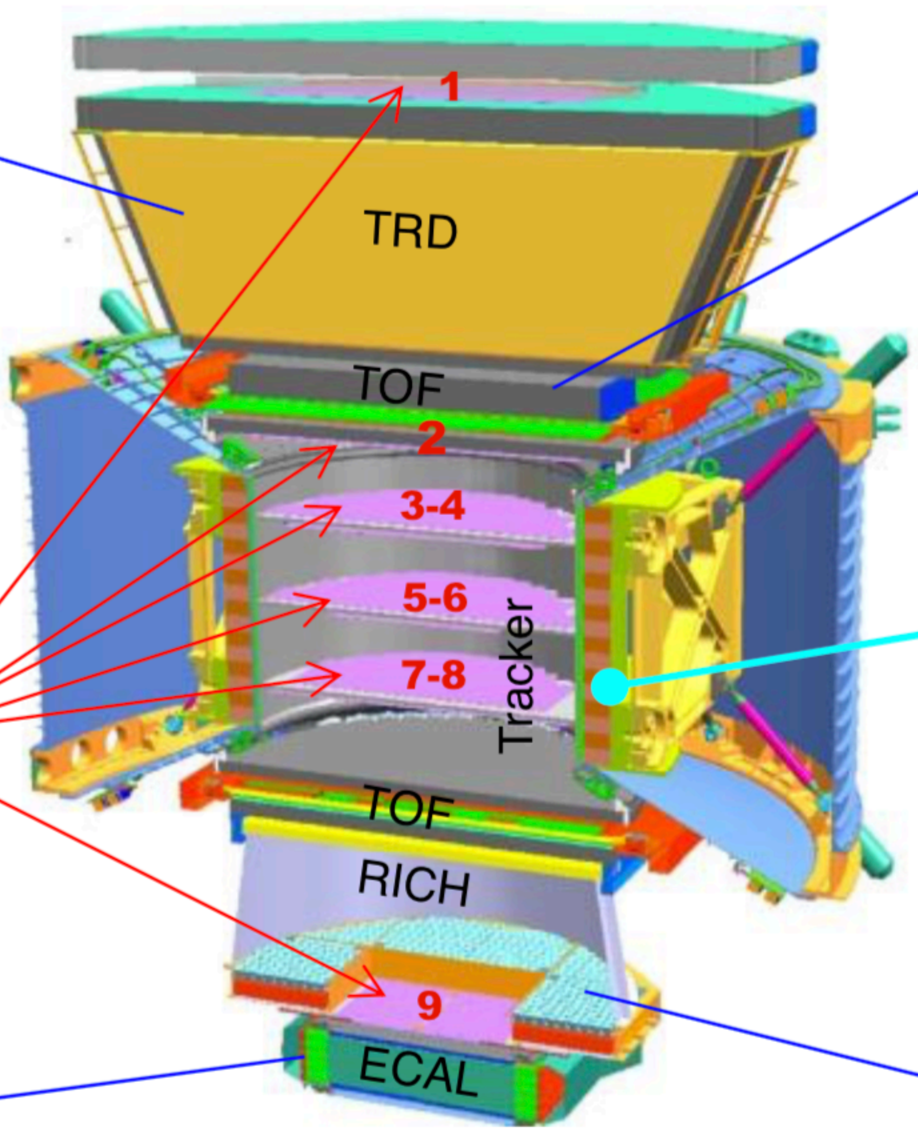


**Silicon Tracker**
Z, R



**Electromagnetic Calorimeter**
E of $e^+$, $e^-$

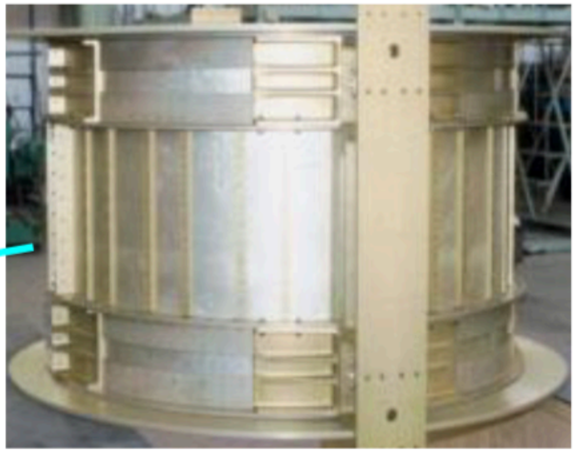
Particles and nuclei are defined by their
charge (Z) and
energy (E) or rigidity (R=p/Z)



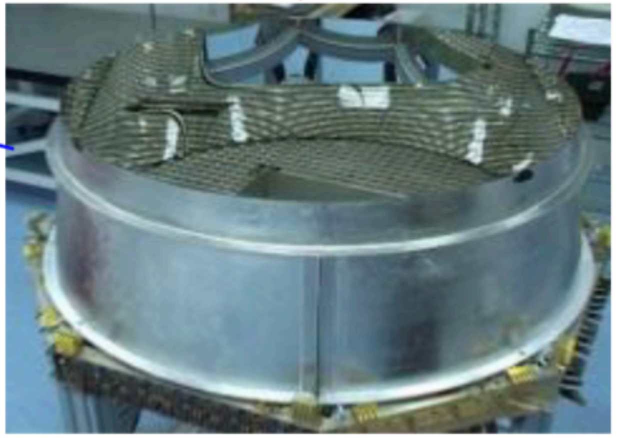
***The Charge and Energy are measured independently by many detectors***

**Time of Flight**
Z, E

**Magnet**
±Z, R



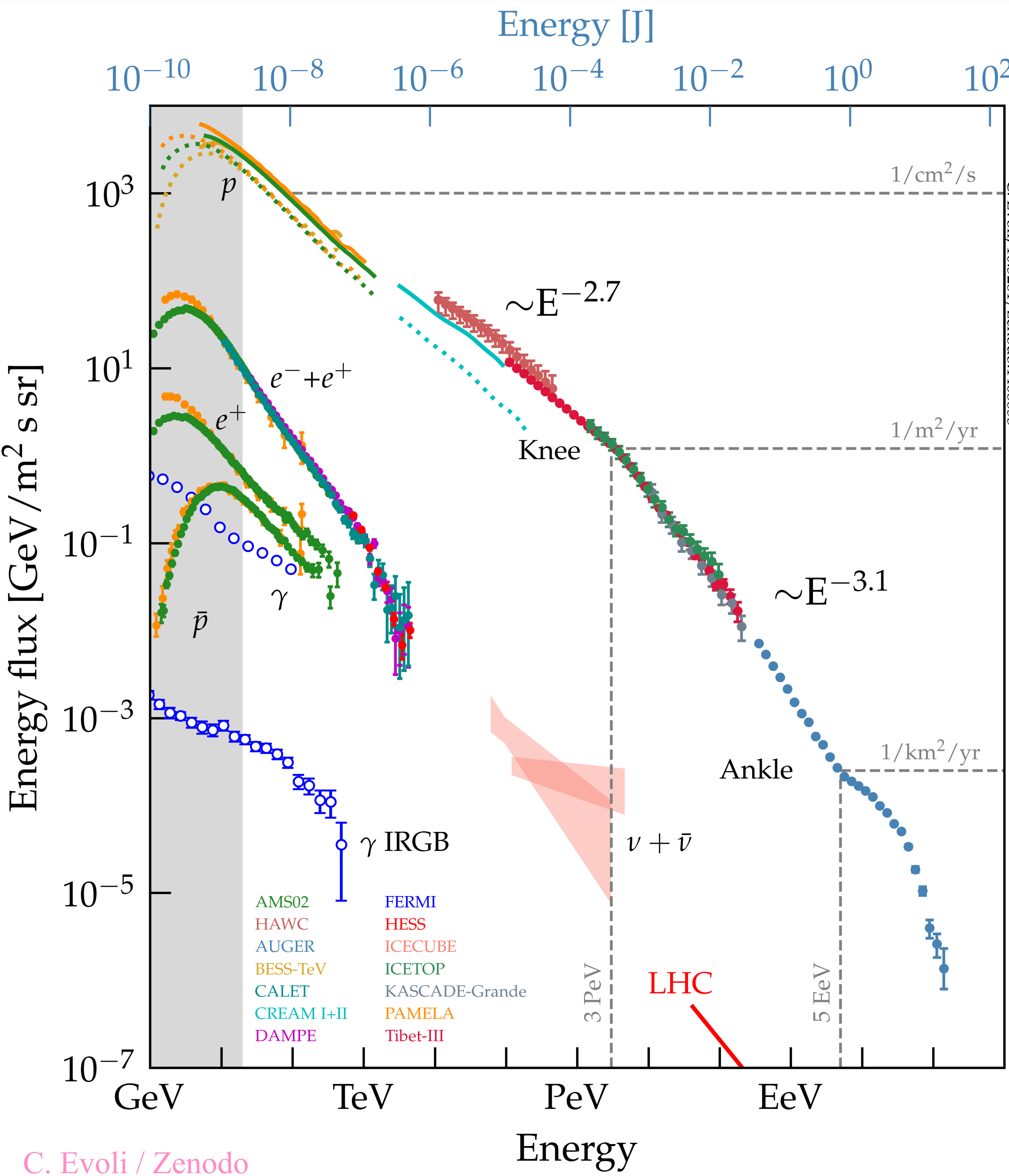
**Ring Imaging Cherenkov**
Z, E



Slide from V. Choutko

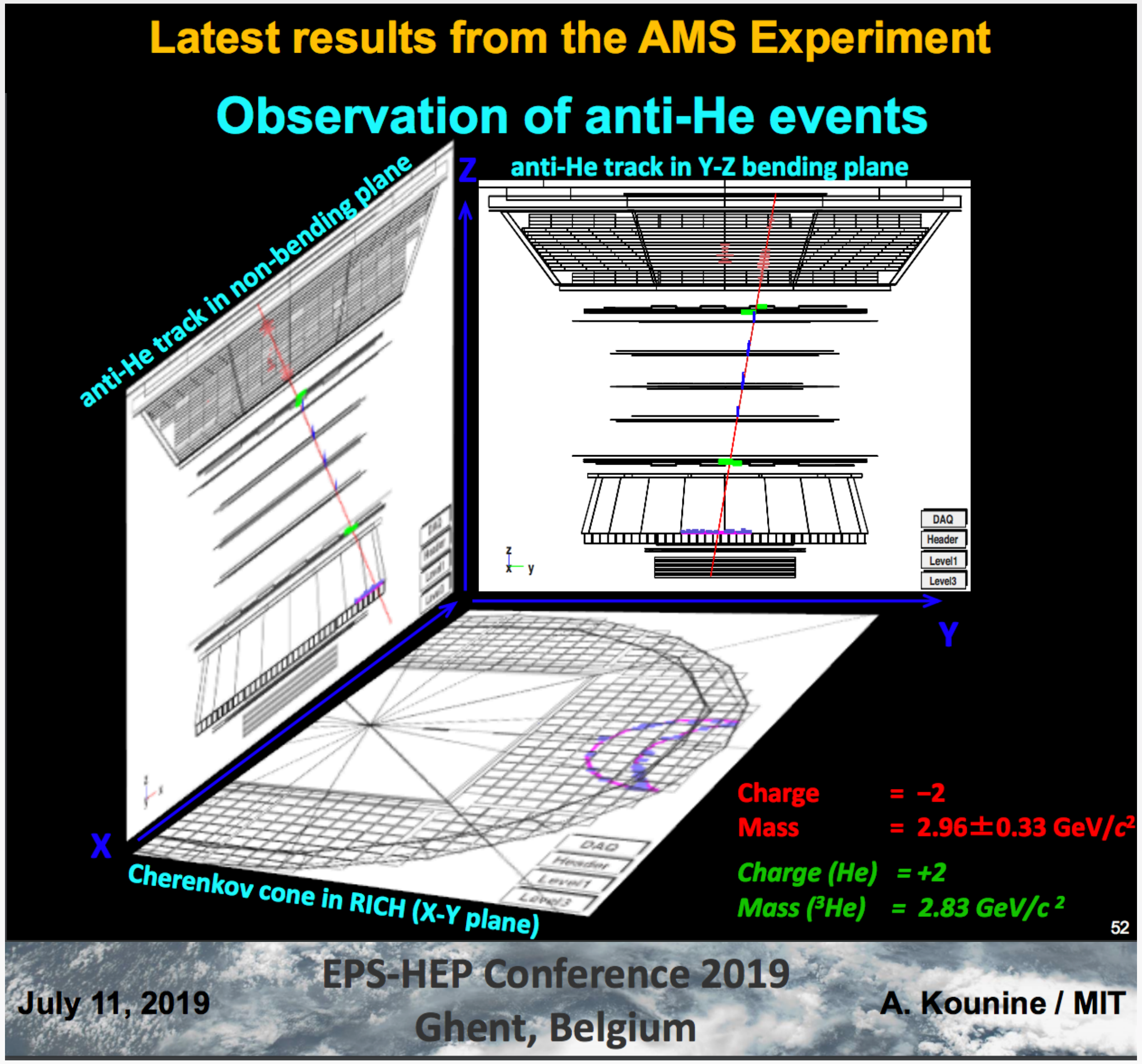
# The CR spectrum

- Largely dominated by protons
  $100p : 10\text{He} : 1e^- : 10^{-2}e^+ : 10^{-3}\bar{p}$
- AMS measures at MeV-TeV energies
  => Galactic sources.
- AMS provides the most accurate measurement of CR fluxes to date in the MeV-TeV range.
- AMS can teach us about astrophysical sources (e.g. pulsars), Dark Matter and other exotic sources of antimatter.



C. Evoli / Zenodo

# Did AMS see anti-helium events?



**Latest results from the AMS Experiment**

**Observation of anti-He events**

anti-He track in non-bending plane

anti-He track in Y-Z bending plane

Cherenkov cone in RICH (X-Y plane)

Charge = −2
Mass = 2.96±0.33 GeV/c²

*Charge (He) = +2*
*Mass ($^3$He) = 2.83 GeV/c²*

52

July 11, 2019

EPS-HEP Conference 2019
Ghent, Belgium

A. Kounine / MIT

- AMS-02 might have identified 6 $^3\overline{\mathrm{He}}$ and 2 $^4\overline{\mathrm{He}}$. The event rate is ~ 1$\overline{\mathrm{He}}$ for $10^8$He.
- Massive Monte Carlo simulations are carried out to evaluate significance.
- Current event rate is ~ 20 times above the claimed sensitivity.

*Kounine, ICRC 2011*

# Anti-matter in the universe

- Baryon asymmetry in the universe is defined: $B \equiv \frac{n_B - n_{\bar{B}}}{s_\gamma} \sim \eta \equiv \left.\frac{n_B}{n_\gamma}\right|_{\text{today}}$ *e.g. Kolb&Turner's book*
- Assuming homogeneous, baryon-symmetric universe and no B-violation processes

$$\frac{n_B}{n_\gamma} = \frac{n_{\bar{B}}}{n_\gamma} \sim 10^{-17}$$

- From BBN and CMB we know $\eta \equiv \frac{n_B}{n_\gamma} \sim 6 \cdot 10^{-10} \Rightarrow B > 0$
- In our vicinity: $n_{\bar{p}} \sim 10^{-5} n_p$ in cosmic rays, most likely purely secondaries.
- Why is there so much more matter than this naive prediction? Where is the antimatter?
- AMS has detected anti-helium: How can such objects be created? anti-BBN? anti-stars?

# Summary

A single $^4\overline{\mathrm{He}}$ could indicate the presence of anti-objects.

I/ Anti-helium flux from standard astrophysical processes

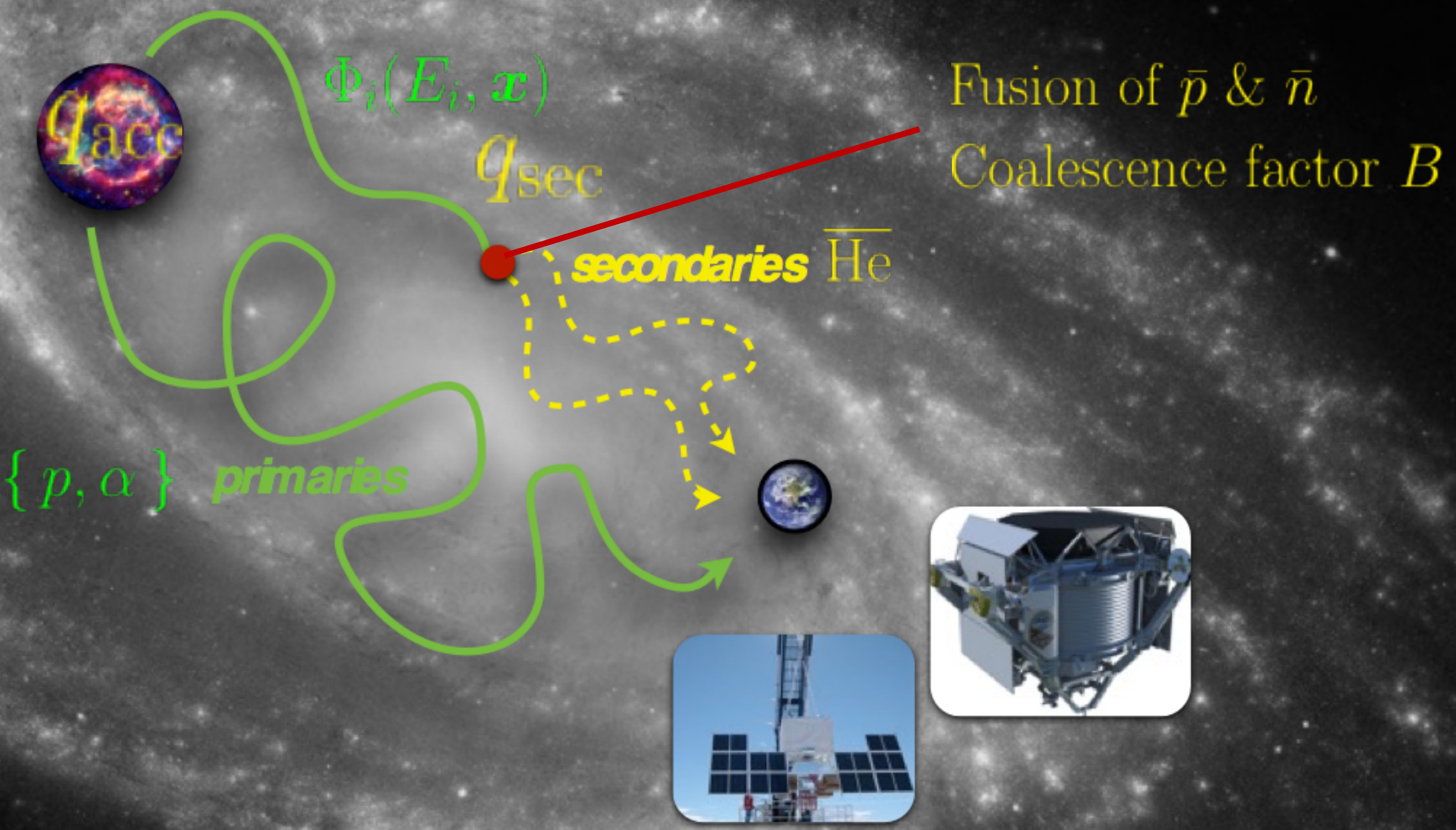
II/ Basics of baryogenesis: How to produce an anti-world?

III/ Constraining the population of anti-objects in the Galaxy / Universe

# I/ Anti-helium flux from standard astrophysical processes

# Secondary cosmic-ray anti-helium

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



$q_{\rm acc}$

$\Phi_i(E_i,\boldsymbol{x})$

$q_{\rm sec}$

Fusion of $\bar{p}$ & $\bar{n}$

Coalescence factor $B$

**secondaries** $\overline{\rm He}$

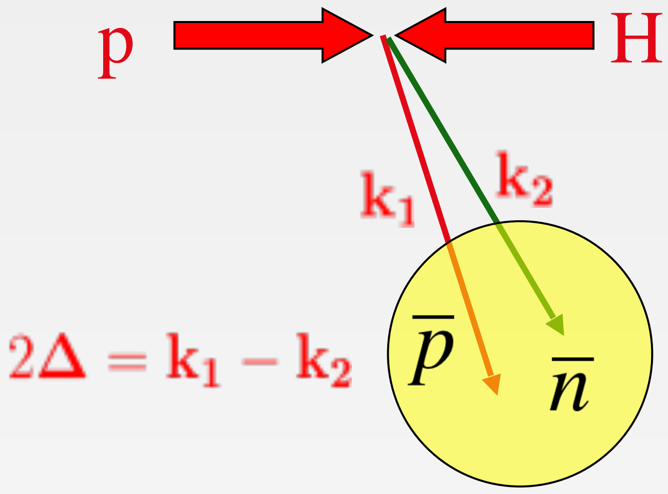
$\{\,p,\alpha\,\}$ **primaries**

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

Courtesy Antje Putze & Pierre Salati

# 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 $B_2$

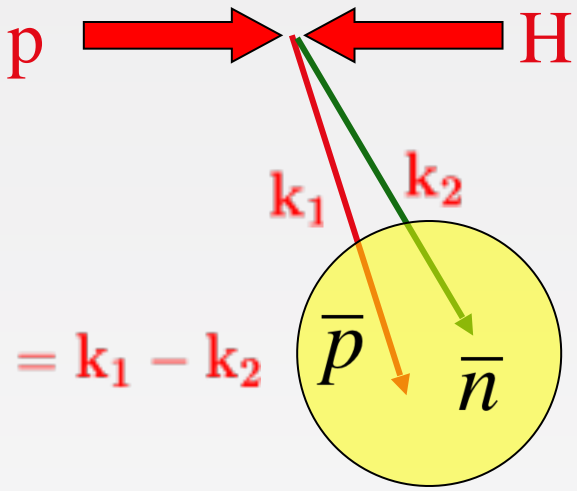
$$\frac{E_{\bar{d}}}{\sigma_{\mathrm{in}}}\frac{d^3\sigma_{\bar{d}}}{d^3\mathbf{K}} = B_2 \left\{ \frac{E_{\bar{p}}}{\sigma_{\mathrm{in}}}\frac{d^3\sigma_{\bar{p}}}{d^3\mathbf{k_1}} \right\} \left\{ \frac{E_{\bar{n}}}{\sigma_{\mathrm{in}}}\frac{d^3\sigma_{\bar{n}}}{d^3\mathbf{k_2}} \right\}$$

Courtesy Pierre Salati

*Chardonnet, Orloff, Salati, Phys.Lett. B409 (1997) 313-320*

# The coalescence factor

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



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

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 $B_A$

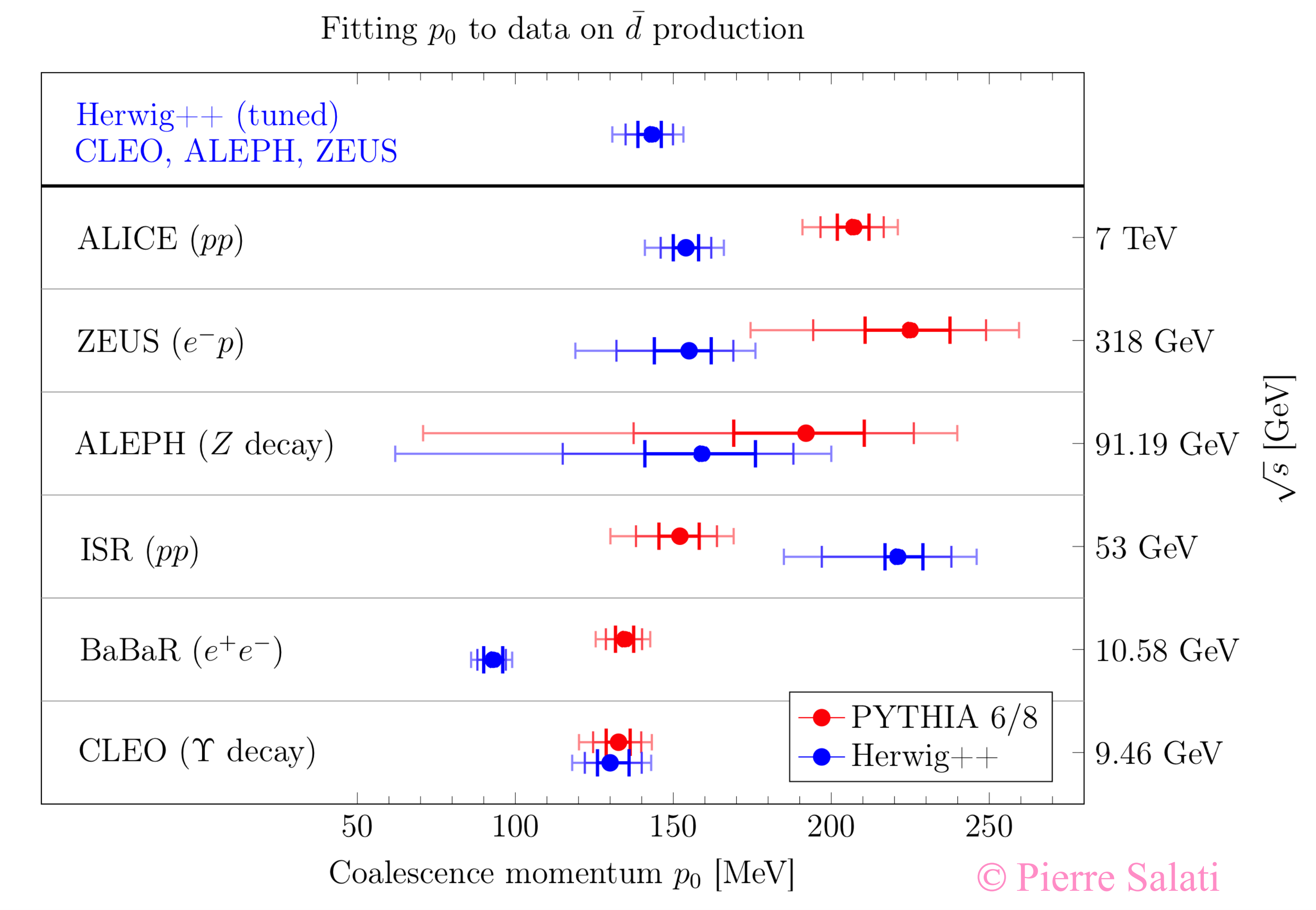
$$B_A = \frac{m_A}{m_p^Z m_n^{A-Z}} \left\{\frac{\pi}{6} p_{\mathrm{coal}}^3\right\}^{A-1}$$

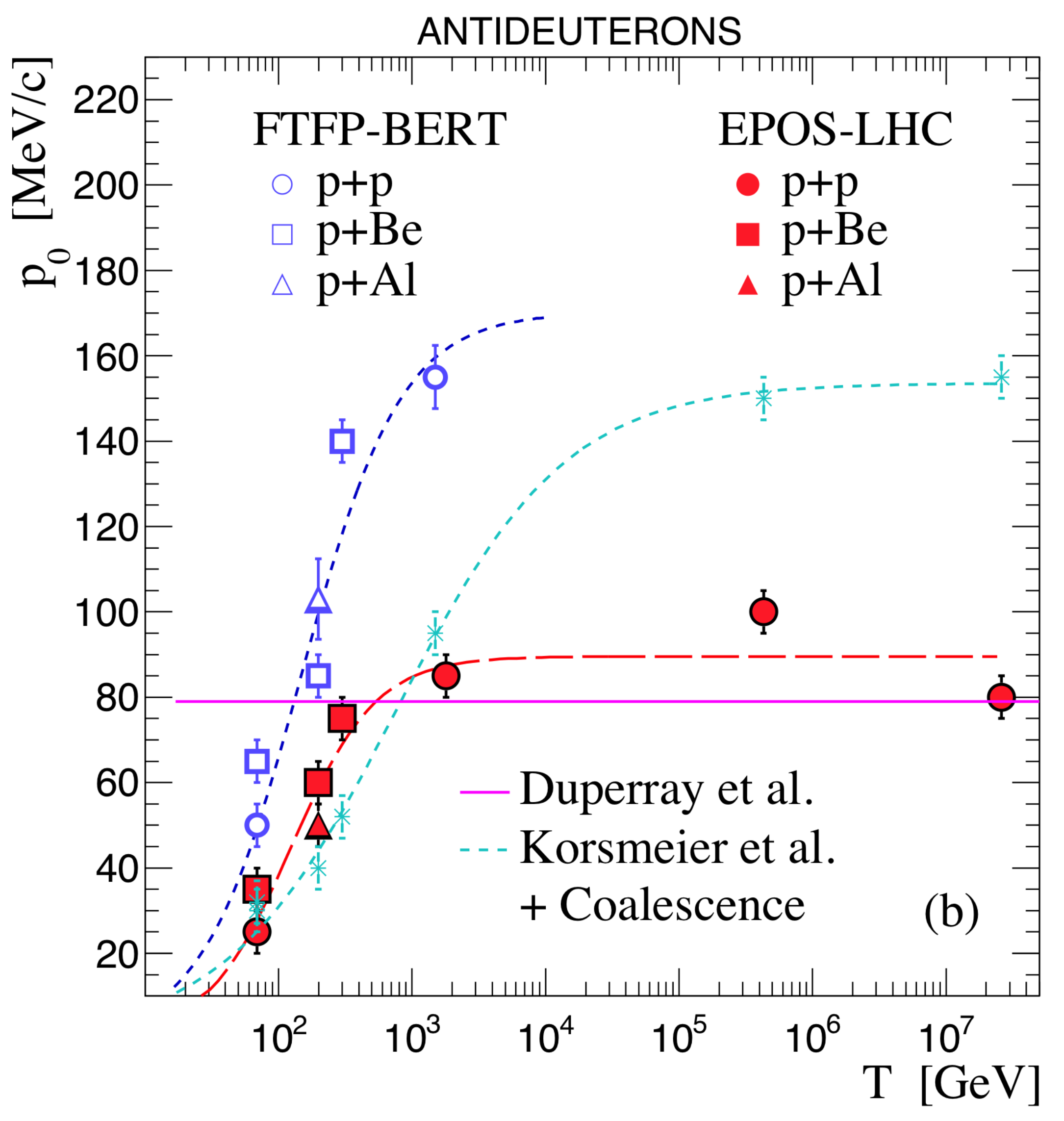
Courtesy Pierre Salati

*Chardonnet, Orloff, Salati, Phys.Lett. B409 (1997) 313-320*

# Determination of the coalescence momentum

- Monte Carlo simulations show different results depending on simulator / data sets / $\sqrt{s}$





*Ibarra & Wild, JCAP 1302 (2013)*

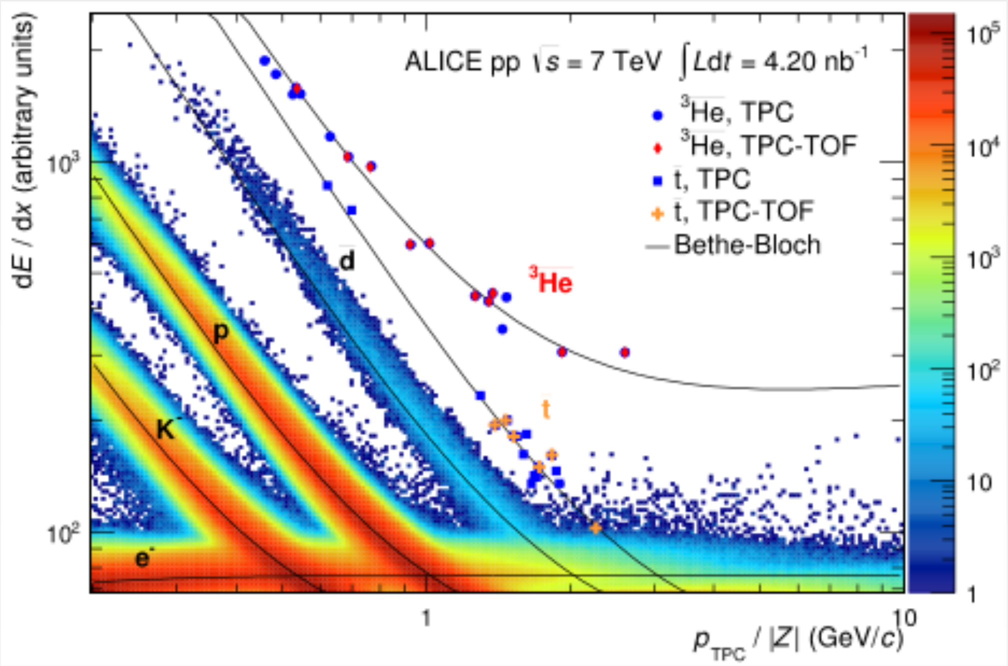
*Dal & Raklev, PRD89 (2014)*

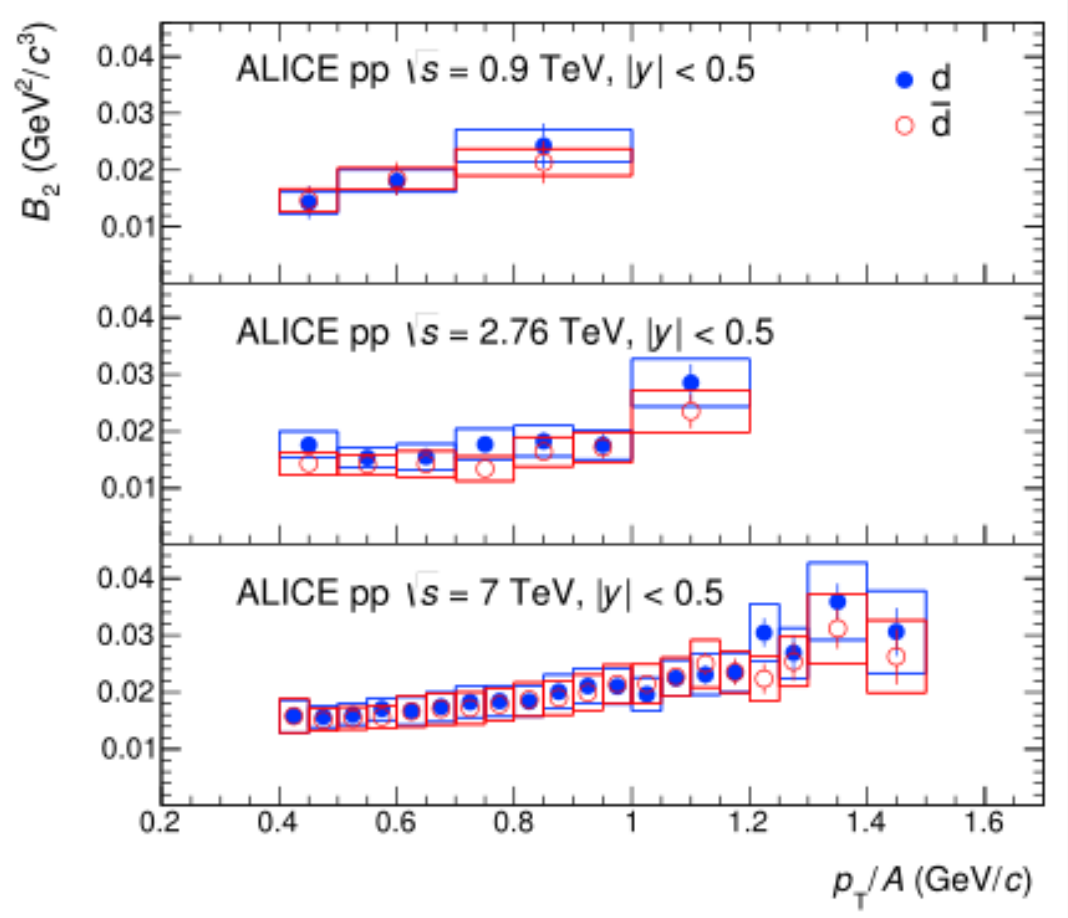
*Gomez-Coral ++ PRD98 (2018)*

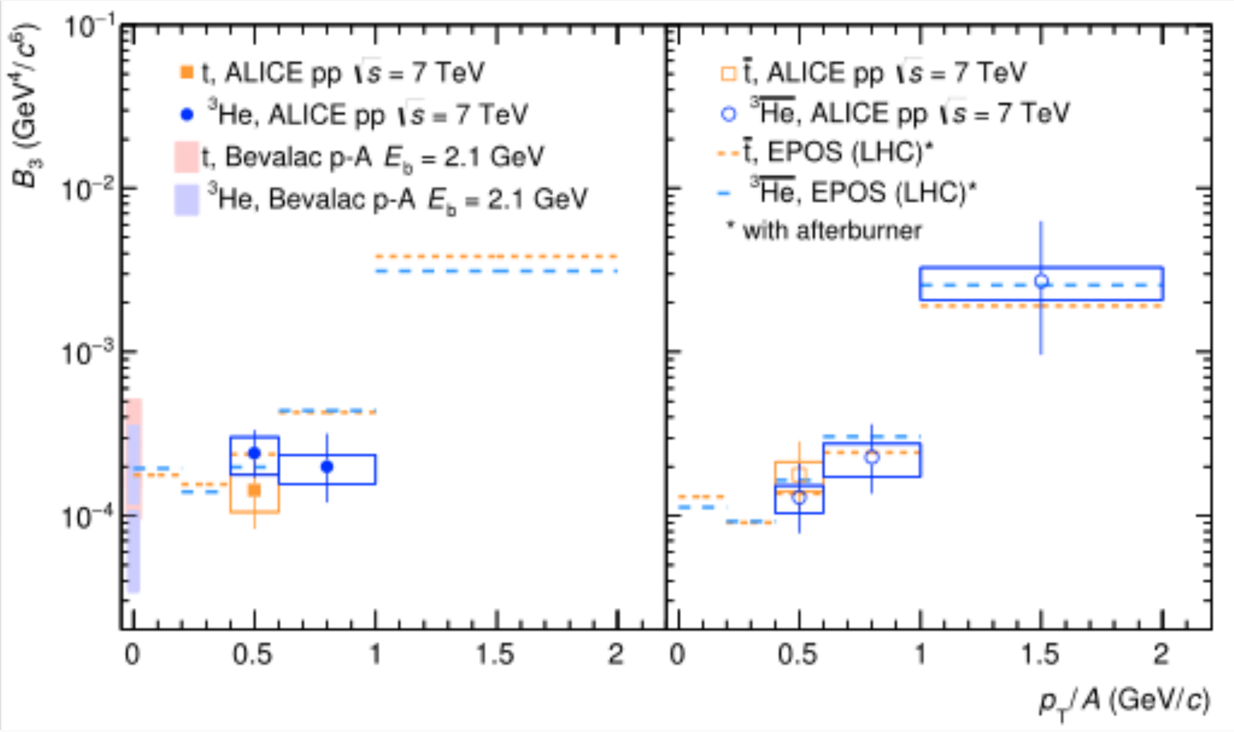
# Alice can measure the coalescence factor

- Collaborations (e.g. Alice) provide us with measurements of the coalescence factor B

$$E_A\frac{d^3N_A}{dp_A^3} = B_A\left(E_p\frac{d^3N_p}{dp_p^3}\right)^Z\left(E_n\frac{d^3N_n}{dp_n^3}\right)^N$$



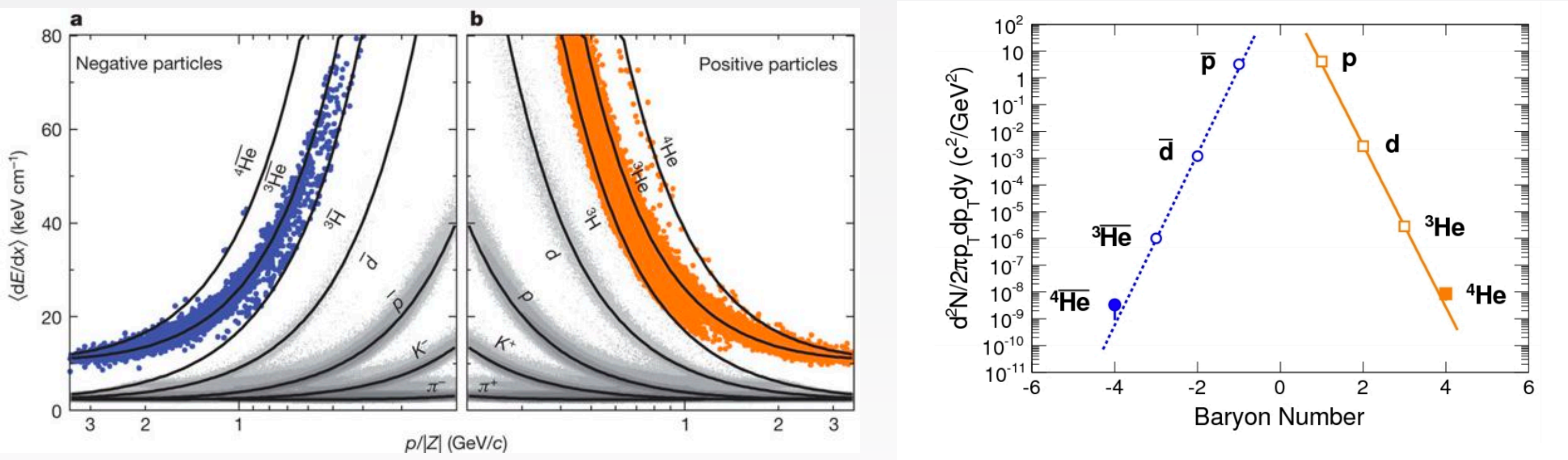




*Acharya++ PRDC97 (2018)*

# What about $^4\overline{\text{He}}$?

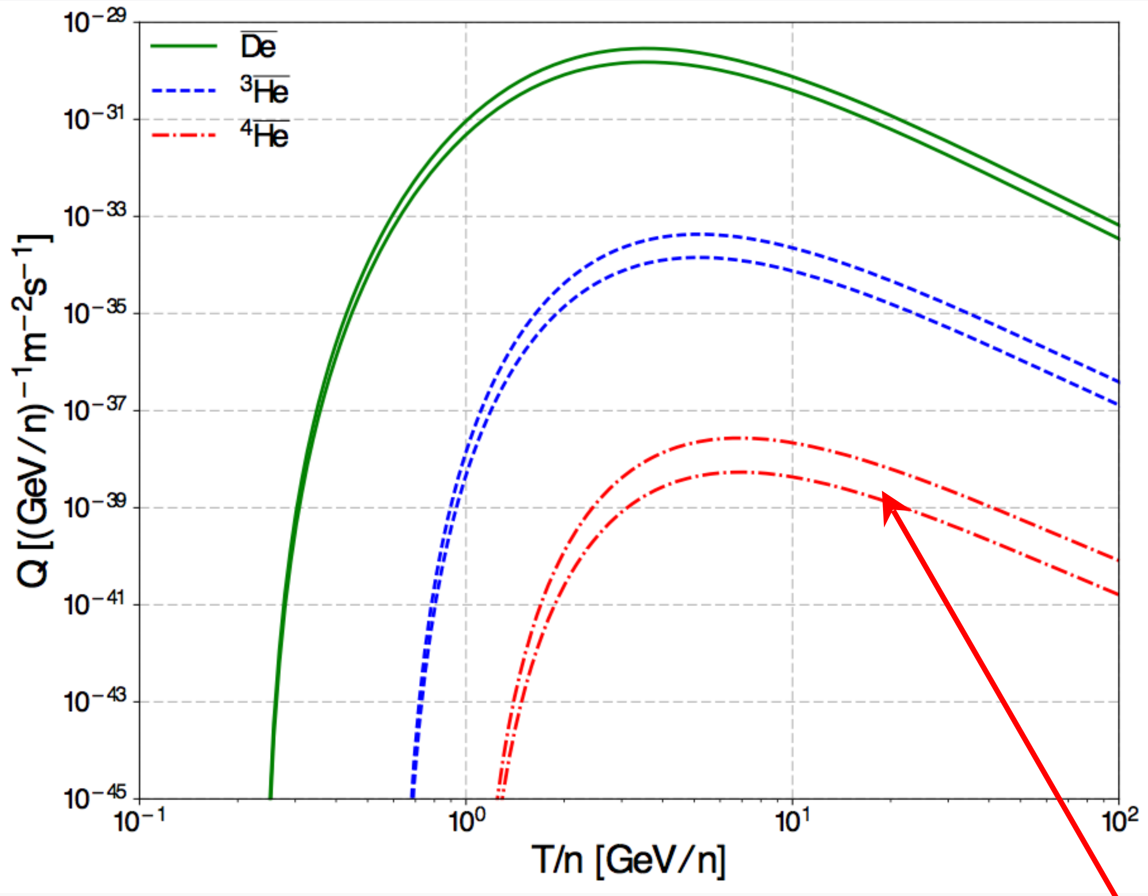
- First measurement of $^4\overline{\text{He}}$ by the STAR collaboration in Au-Au collision at $\sqrt{s} = 200$ GeV/n
- $^4\overline{\text{He}}/^3\overline{\text{He}} \simeq 10^{-3}$



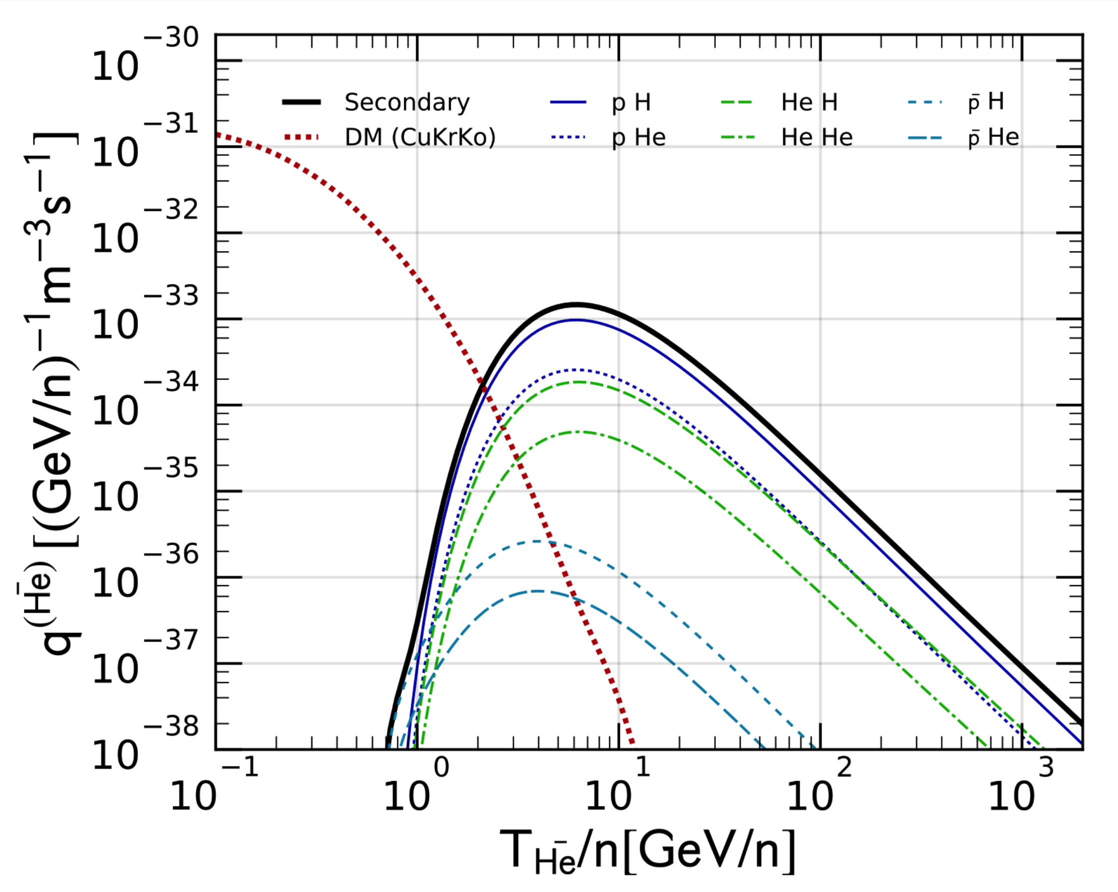
*STAR Collaboration, Nature 473 (2011)*

# Source term for production by spallation

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



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

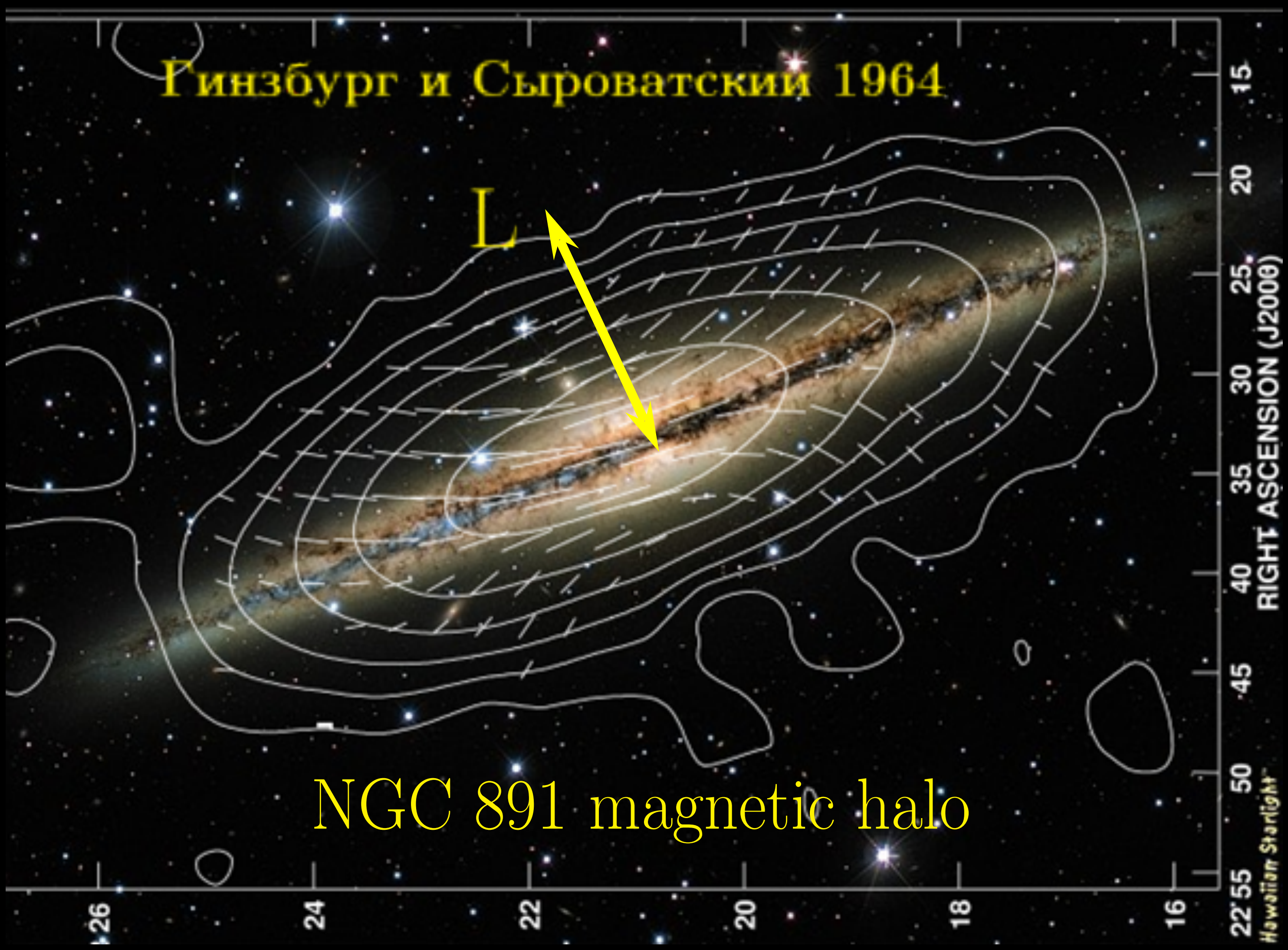


M. Korsmeier et al., Phys. Rev. **D97** (2018) 103011

$$7.7\times10^{-7}\leq\frac{B_4}{{\rm GeV}^6}\leq3.9\times10^{-6}$$

Courtesy Pierre Salati

# Cosmic-ray anti-nuclei Galactic propagation



Based on code by M. Boudaud

e.g. Genolini, Boudaud et al. 2019

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

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

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

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

E diffusion

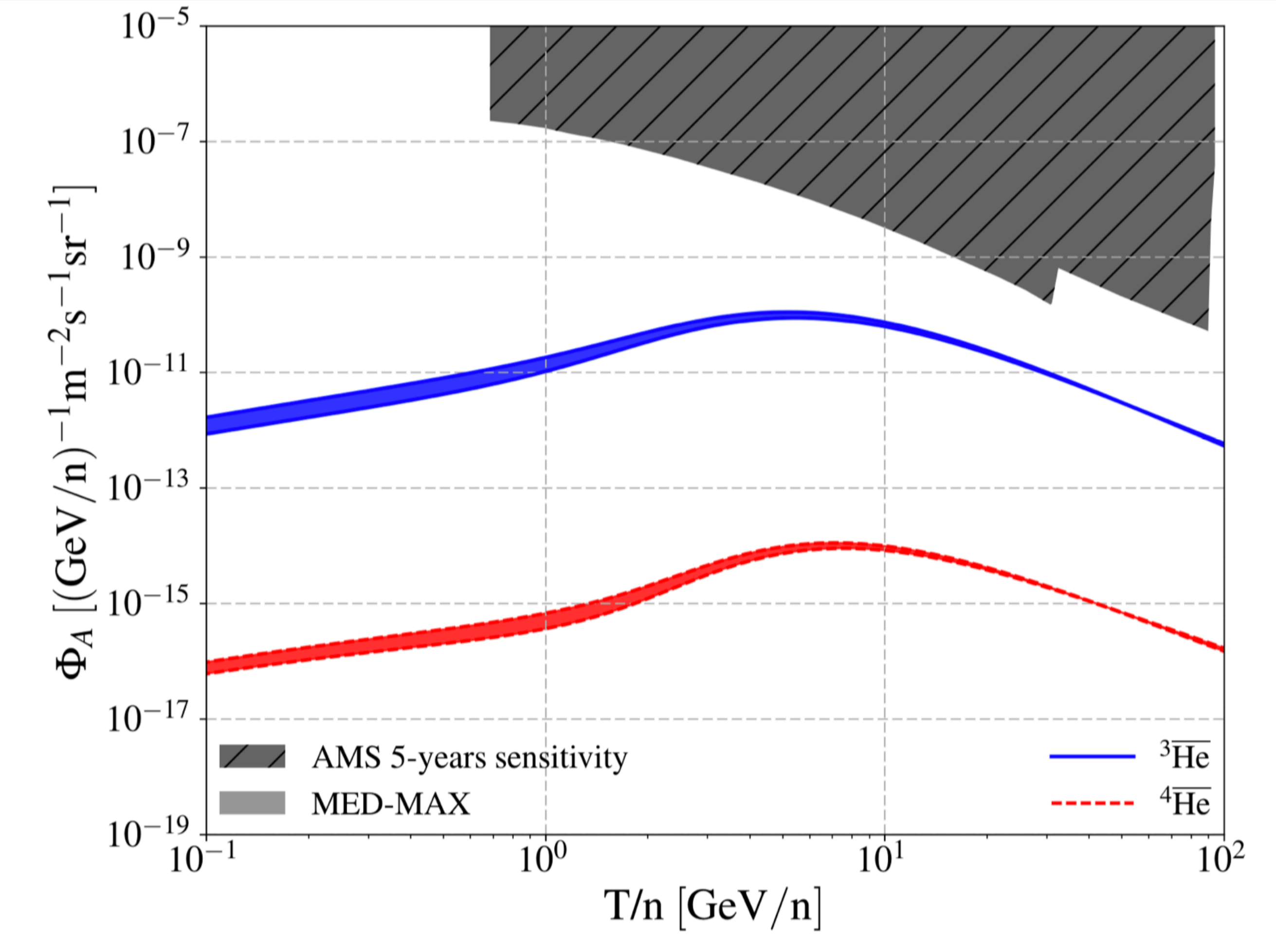
$$K = K_0\,\beta\,\mathcal{R}^{\delta}\left\{1 + \left(\frac{\mathcal{R}}{\mathcal{R}_b}\right)^{\Delta\delta/s}\right\}^{-s}$$

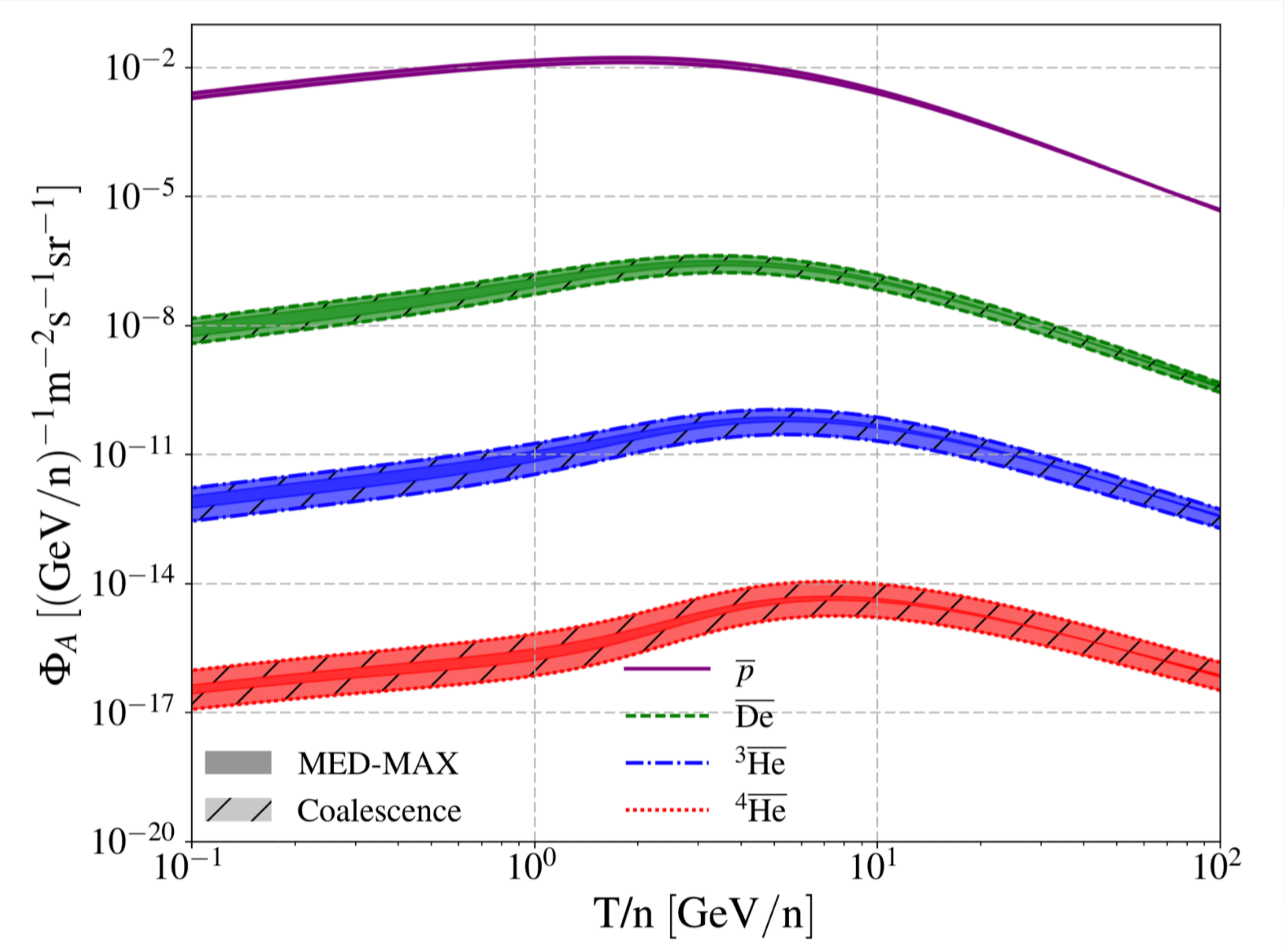
$$D_{EE} = \frac{2}{9}\,\frac{V_A^2\,\beta^4\,E^2}{K}$$

Courtesy Pierre Salati

# Secondaries cannot explain $^4\overline{\mathrm{He}}$

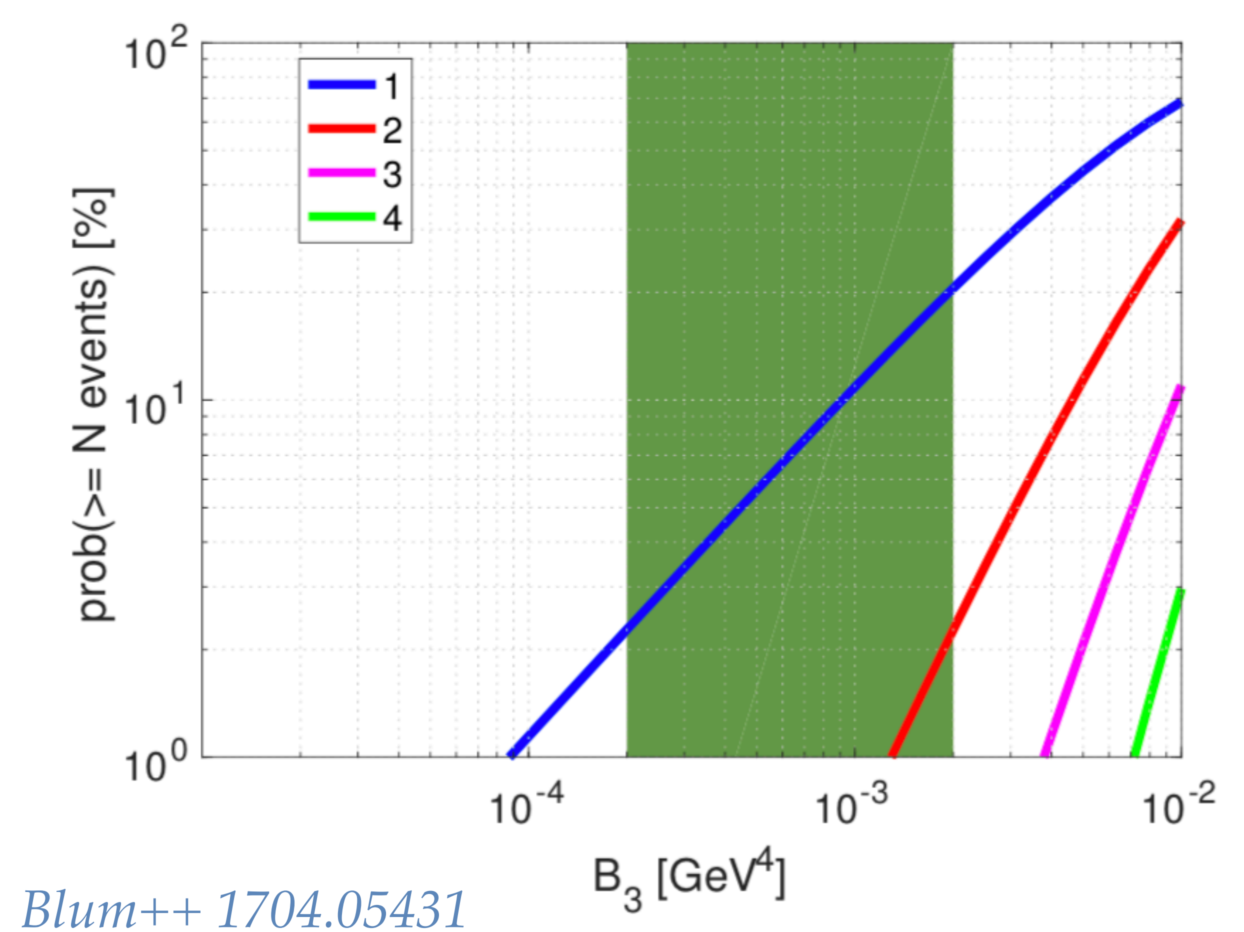
- The coalescence scenario predicts a hierarchy in the flux of anti-nuclei $\phi_{A+1} \approx 10^{-3}\text{-}10^{-4}\phi_A$
- AMS measurement is ~ 6 orders of magnitude above $^4\overline{\mathrm{He}}$ "secondary" prediction
- Where is the anti-De???



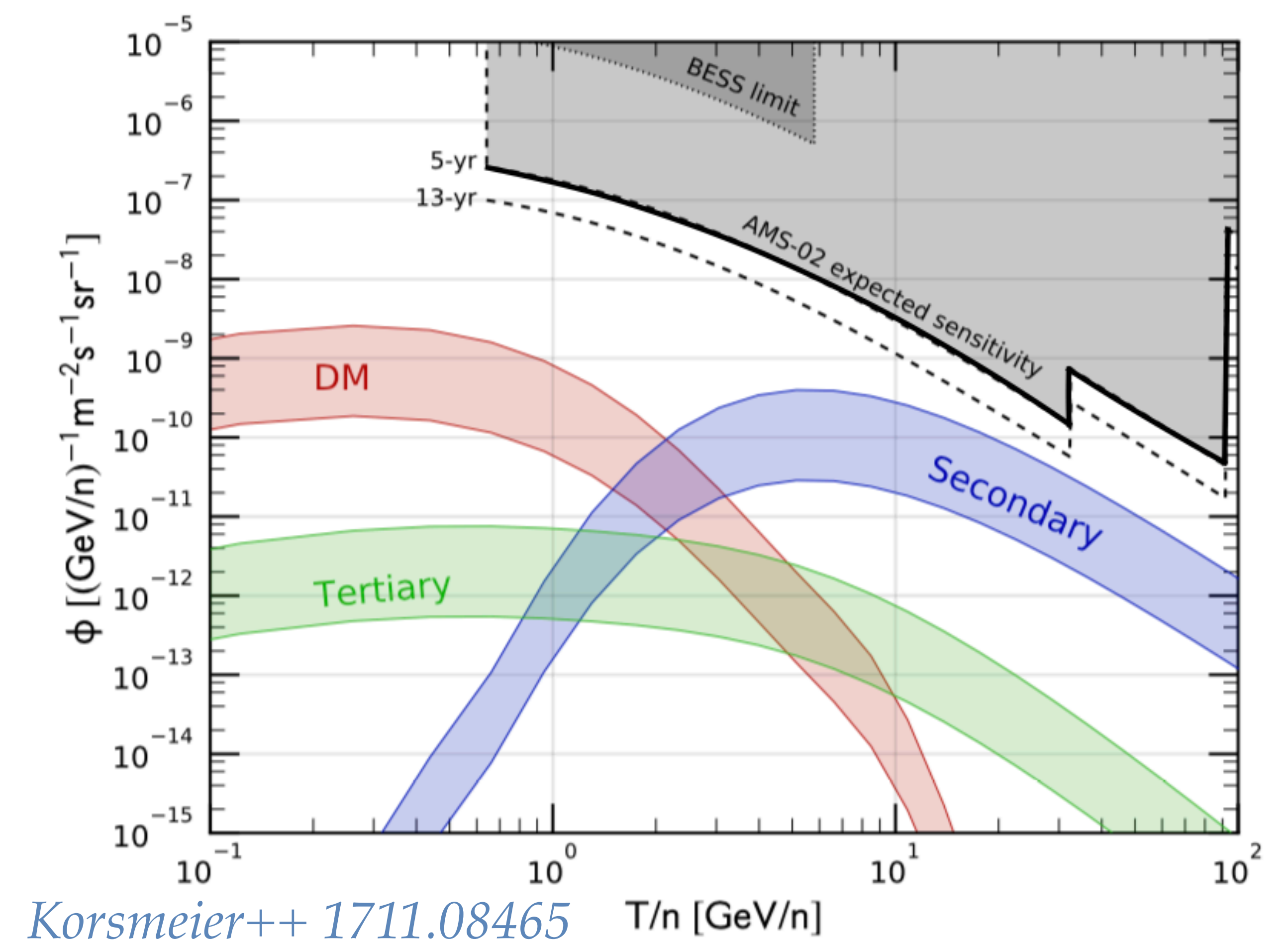


*VP, Salati++ PRD99 (2019)*

# All (recent) predictions agree!



*Blum++ 1704.05431*



*Korsmeier++ 1711.08465*

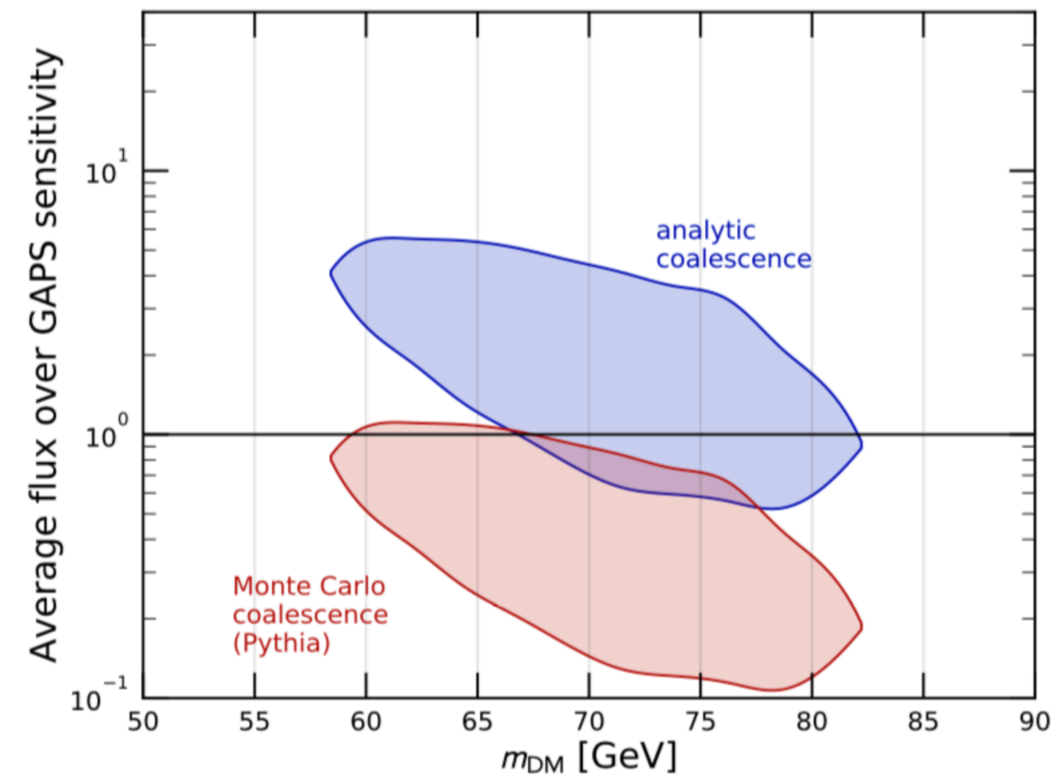
- Blum++ 2017: AMS (5yrs) could detect~1 or 2 events if B3 = 10*B3 from Alice! AMS has detected ~6 events. probability -> 0.
- Korsmeier++ 2017: ~1-2 orders of magnitude below measurement.
- Same conclusions in Cirelli++ 2014, Herms++2016 etc…

# What about Dark Matter?

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

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

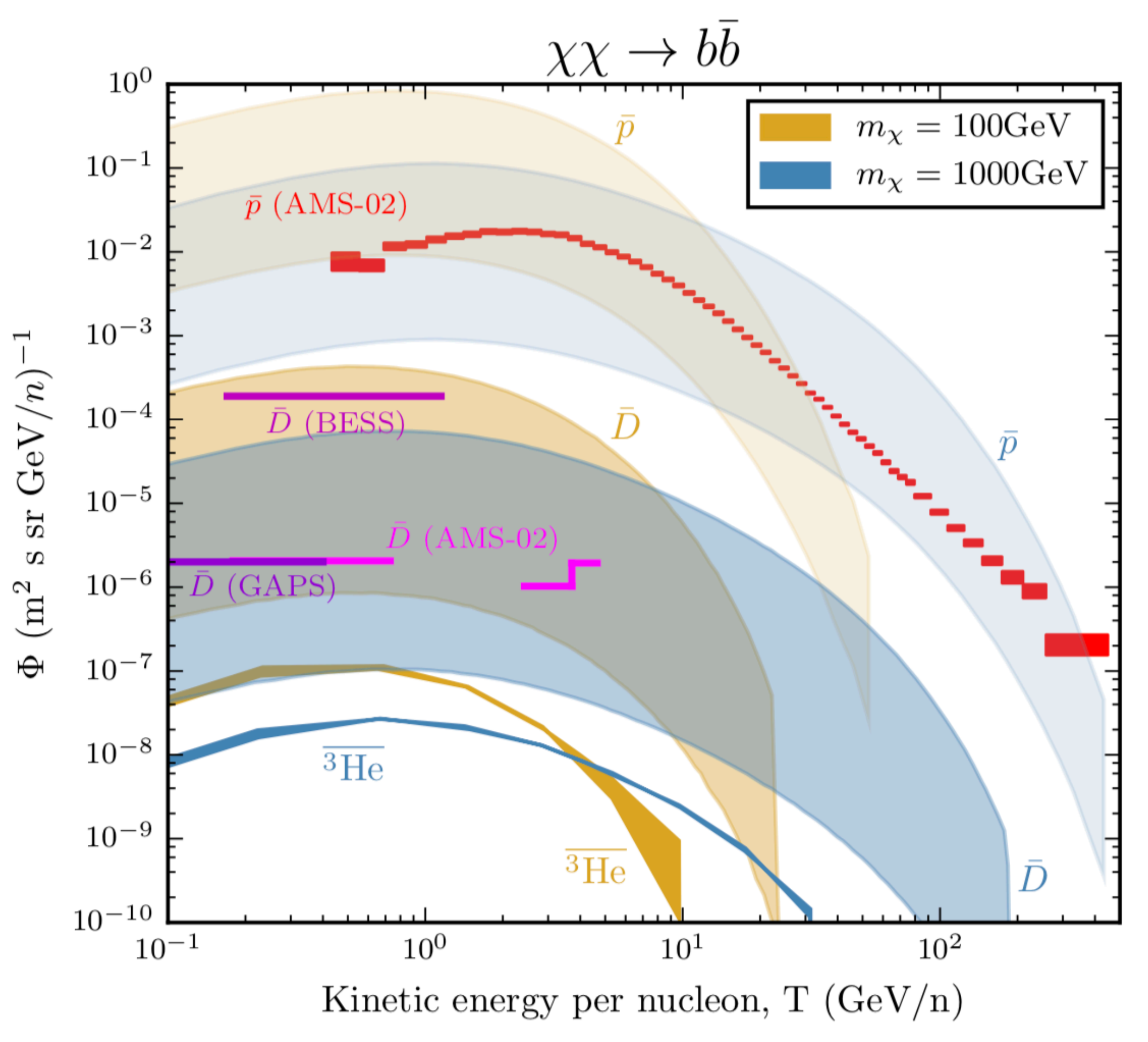
- Coalescence factor can change: very different kinematic + non-nuclear material. It leads to typically smaller values of $B_A$.



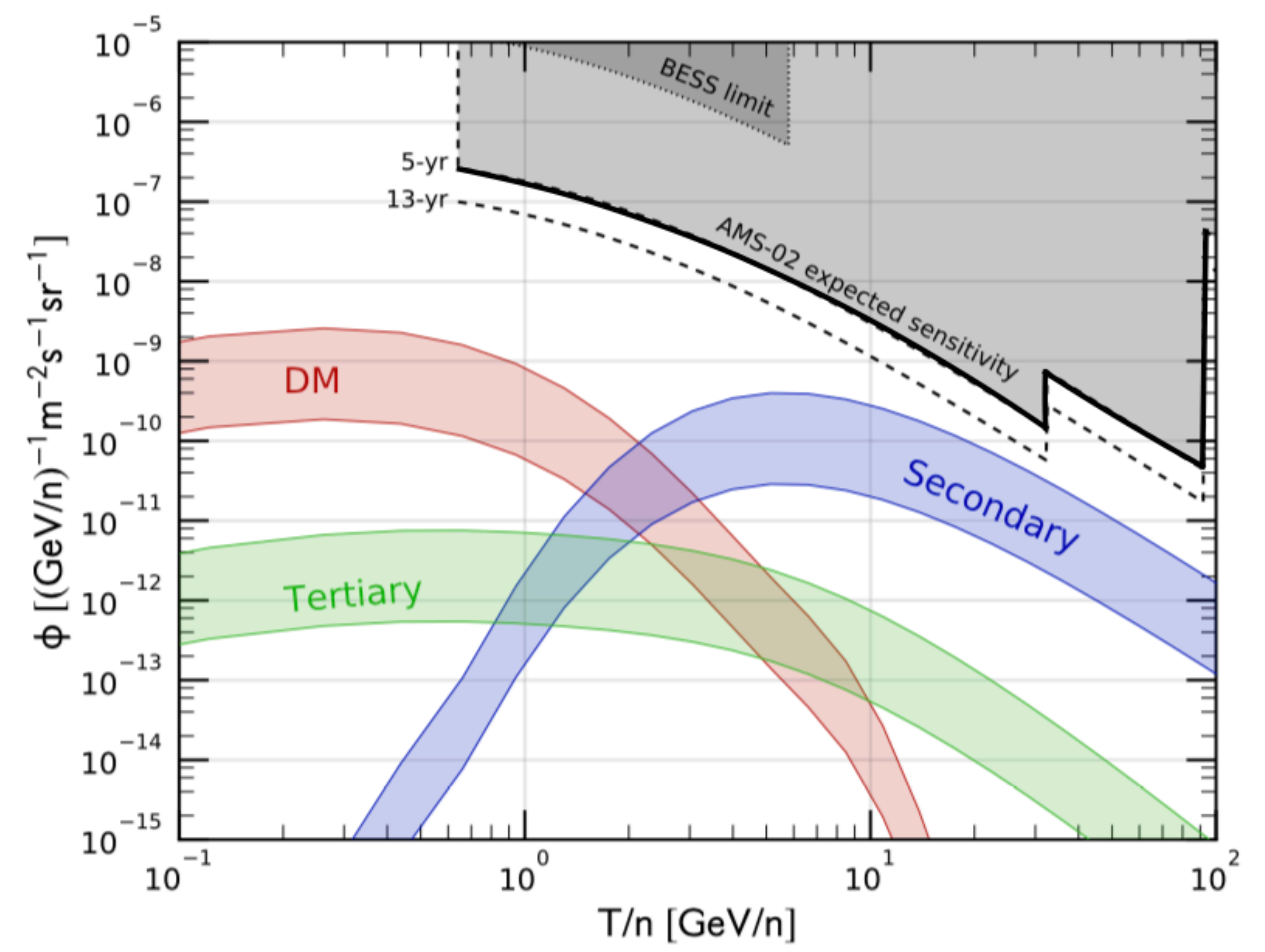
(a) Coalescence model

Korsmeier++ 1711.08465

# Dark Matter is at odds with AMS-02 events



*Coogan&Profumo, PRD96 (2017)*



*Korsmeier++ 1711.08465*

- The Dark Matter flux peaks at low kinetic energy compared to the background.
- AMS should see associated $\overline{\text{De}}$ and $\bar{p}$: Most of the parameter space is ruled out by $\bar{p}$.
- Dark Matter models cannot produce $^4\overline{\text{He}}$ via coalescence.

# II/ Basics of baryogenesis: how to produce an anti-world

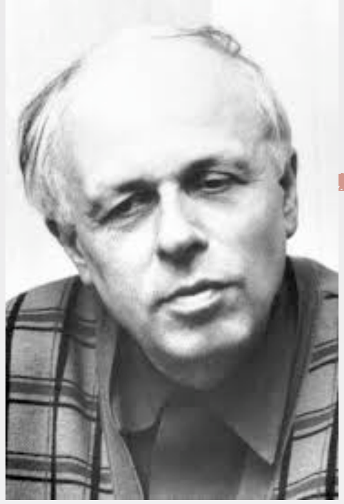
# Three types of cosmological baryon asymmetry

*e.g. Bambi&Dolgov 2007*

- $\eta$ is homogeneous, the universe is 100% matter dominated;
- average $\eta$ is 0 but there are very large domains of matter and anti-matter;
- $\eta$ is not spatially constant: there are lumps of antimatter in a matter dominated universe.

AMS-02 can typically probe scenario iii)

# Sakharov Conditions



Sakharov 1967

*See Kolb&Turner for pedagogic discussion*

**A successful baryogenesis requires**

- Baryon number violation: if $B = 0$ at an initial time, and there are not $B$-violating processes, non-zero $B$ cannot be generated.

*nb: inflation makes sure that B = 0 initially.*

- P and CP violation: ensure that opposite $B$-violating processes do not take place with an equal rate, resulting in no net Baryon asymmetry.

$$\Gamma(i \to f; p_i, s_i; p_f, s_f) \neq \Gamma(f \to i; -p_f, -s_f; -p_i, -s_i).$$

- Departure from equilibrium (or CPT violation): at equilibrium distribution are Fermi-Dirac or Bose-Einstein at temperature $T$. $B$-violating processes leads to $\mu = 0$. Because CPT ensure that $m_B = m_{\bar{B}}$, there cannot be any net Baryon asymmetry.

$$f_\pm = \frac{1}{e^{(E-\mu)/T} \pm 1}$$

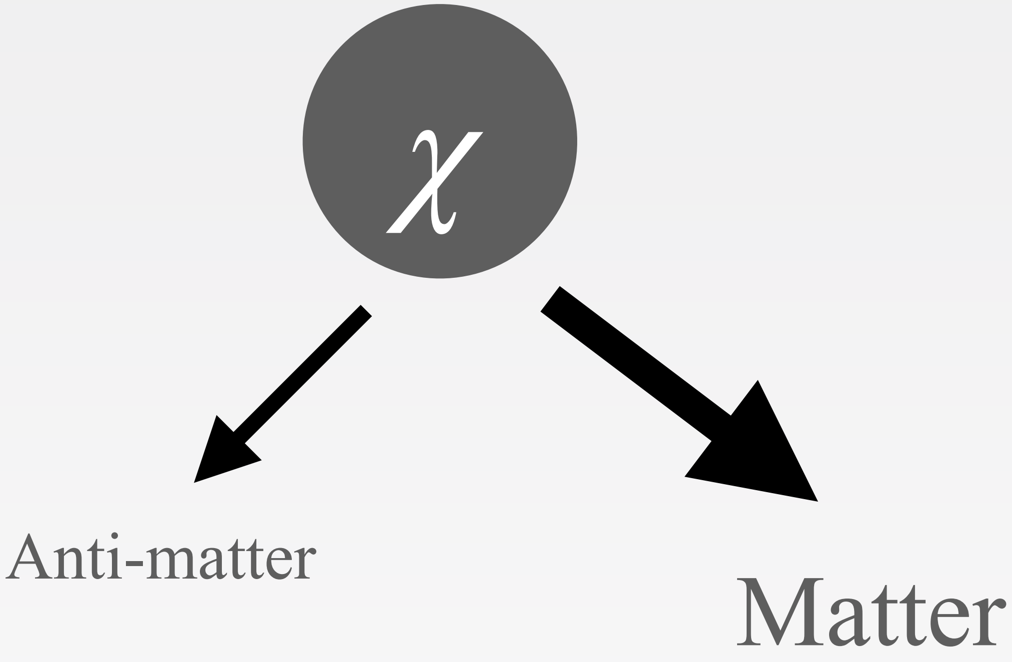
$$n(t) = \frac{g}{(2\pi)^3} \int d^3p f_s(t,p)$$

# Two types of scenarios

- Cosmic phase transition

Electroweak baryogenesis,…

- Decay of new particles



GUT baryogenesis, leptogenesis…

**Standard scenario predicts homogeneous baryon number, no anti-objects**

# Baryogenesis in the standard model

- Maximal P violation: SM is a chiral theory! Right-handed fermions (Left-handed anti-fermions) are gauge singlets w/r to $SU(2)_L$.

- CP violation:
  - first detected in observing neutral K meson decay, now also established in B meson decays.
  - *All* CP-breaking effects in the quark sector can be understood in terms of the phase δ which appears in the CKM matrix.
  - What about the neutrino sector?

*Christensen et al, 1964*

- B-violation: *B*- and *L*-number global symmetry are *accidental* in the SM. Only violated via non-perturbative effects: 'instantons' and 'sphalerons'. Rate is negligible today huge before EWPT.

$$\emptyset \leftrightarrow 2u + d + 2c + s + t + 2b + e^- + \nu_\mu + \tau^-$$

*'t Hooft 1976*

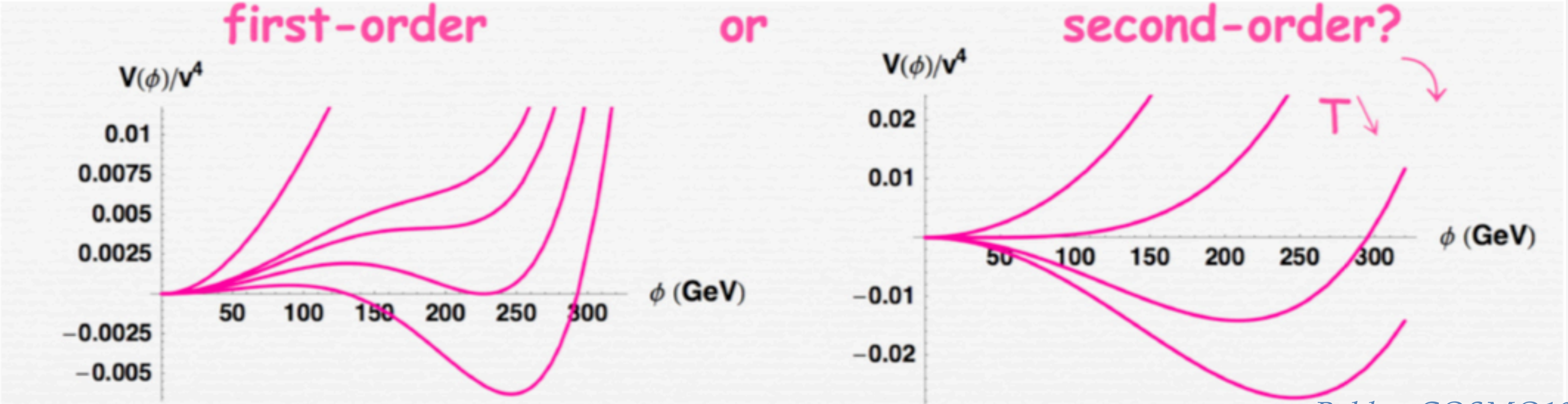
*nb: $B + L$ violated, but $B - L$ still a symmetry*

- Out-of-equilibrium: Provided by the expansion of the universe, when H > Γ.

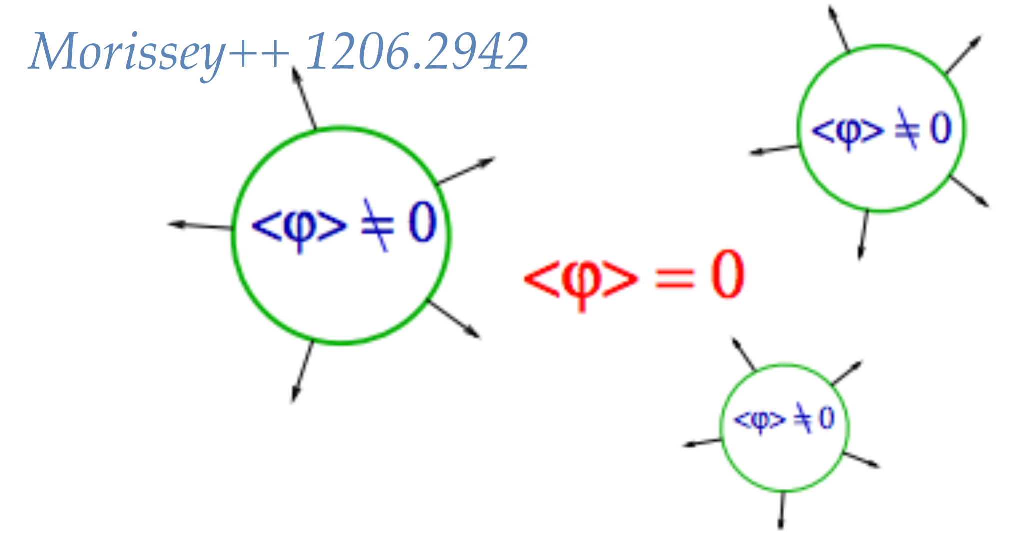
# Electro-Weak baryogenesis

- Occurs during the EW phase-transition, i.e., when $SU(2)_L \times U(1)_Y$ is broken to $U(1)_{em}$ at T~100 GeV.

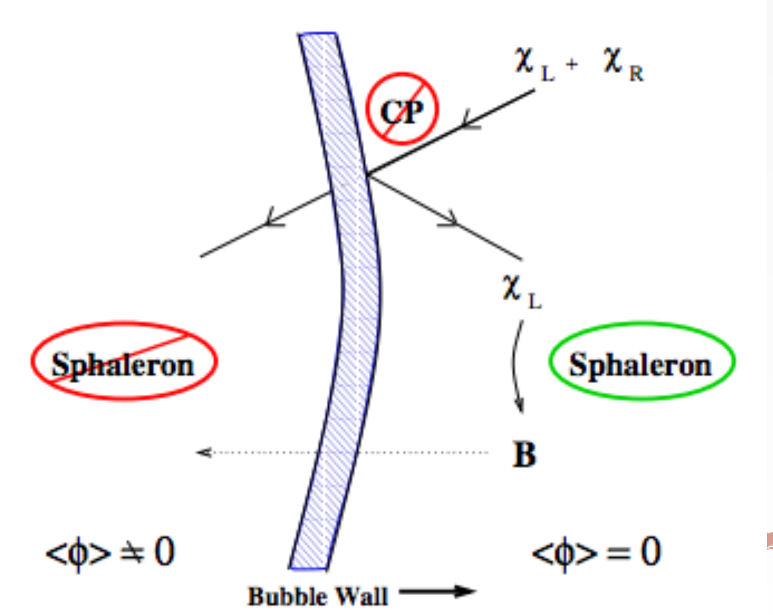
$$V_{eff}(\phi, T) \simeq D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\bar{\lambda}}{4}\phi^4$$



*Baldes, COSMO19*



*Morissey++ 1206.2942*



# Problems with SM EW Baryogenesis

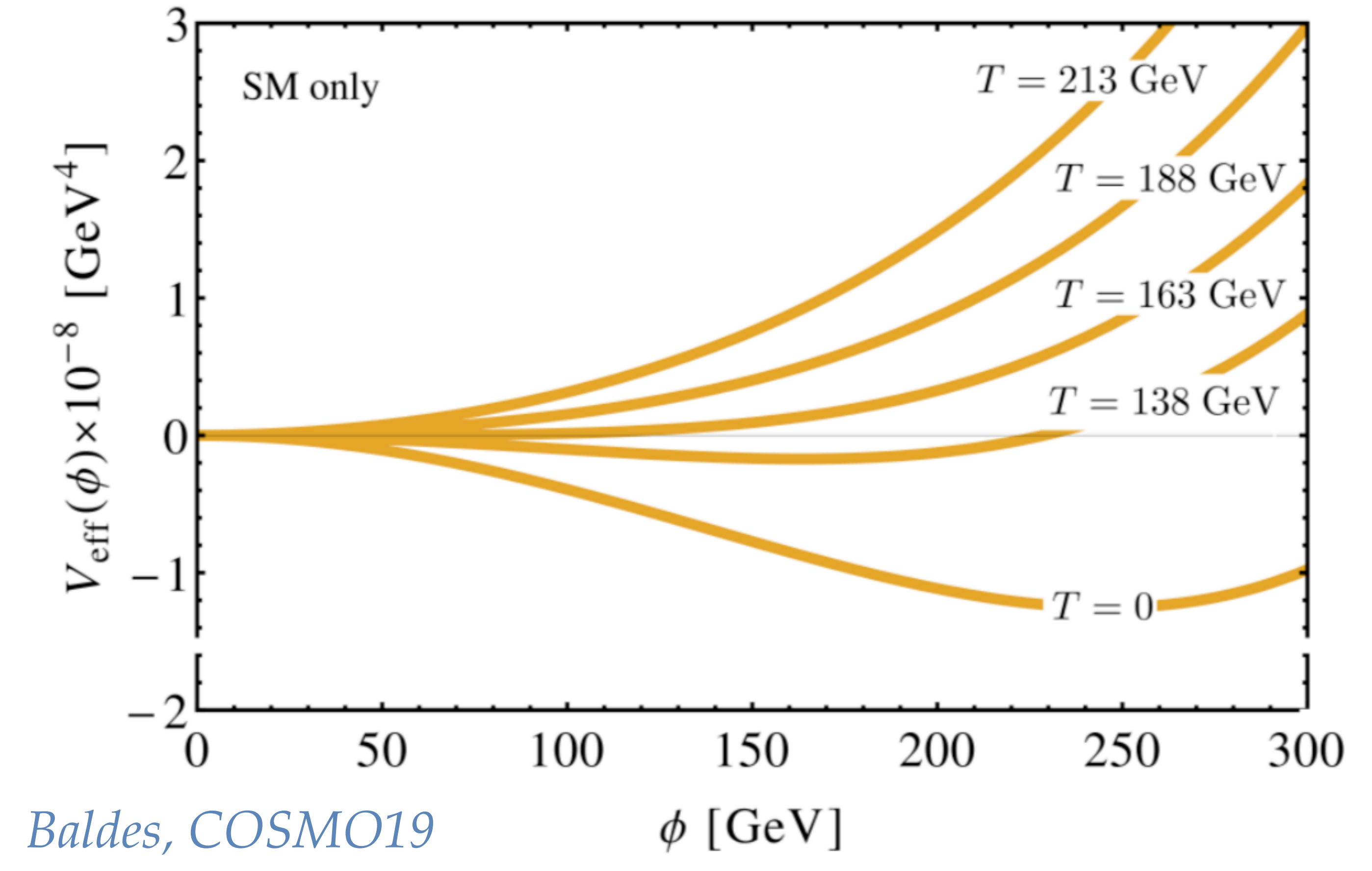
- Too little CP violation: $\epsilon_{CP} \sim 10^{-20} \ll \eta$

$$\epsilon_{CP} \sim J \frac{(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)}{E^{12}},$$

$$J = -\mathrm{Im}\left[V_{us} V_{cd} V_{cs}^* V_{ud}^*\right] = c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} s_\delta \sim 3 \times 10^{-5}.$$

$$E_{EW} \sim v \sim 10^2\ \mathrm{GeV}$$

- Too strong Sphaleron rate in the broken phase: EWPT is not strongly first order (crossover), Higgs is too heavy.

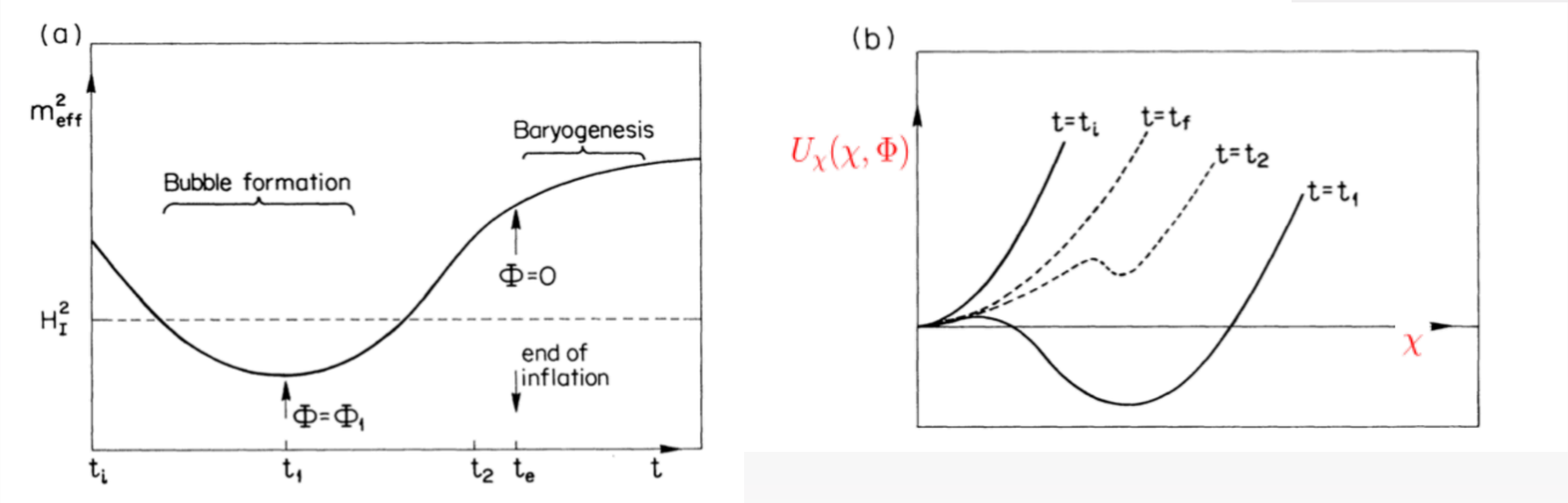


*Baldes, COSMO19*

# Inhomogeneous baryon number

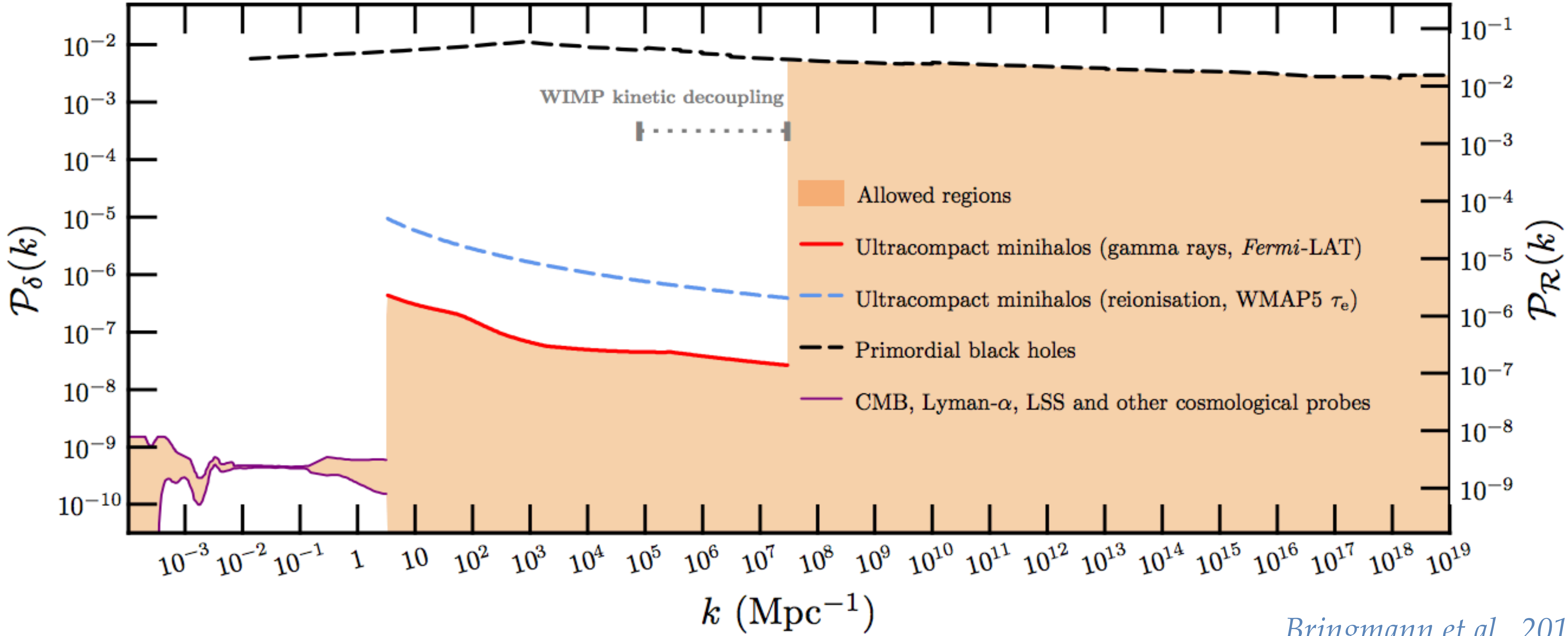
*Dolgov&Silk 1994*

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



- Modified “Affleck-Dine” baryogenesis: a complex scalar field carrying a non-zero baryon number coupled to the inflaton.
- Time-dependent effective mass allows for formation of `bubbles’ with high baryon number in some regions of space + overall homogeneous baryon number.
- After inflation, at horizon re-entry bubble collapse into compact objects (black holes, stars…)

# We know almost nothing about small scales

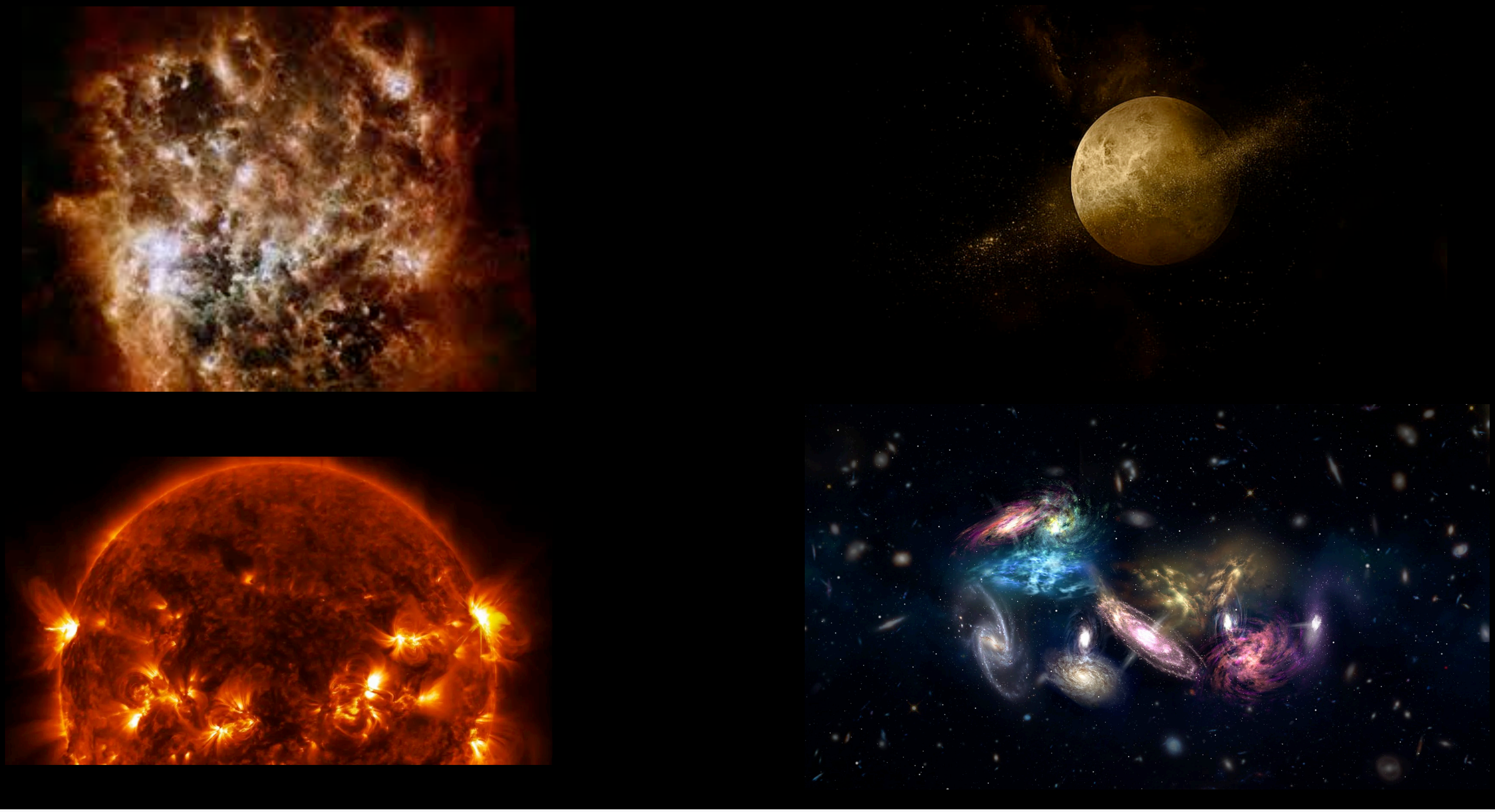


*Bringmann et al., 2012*

- Could there be pocket of antimatter at small scales?
- AMS probes antimatter at sub-galactic scales (i.e, $k > 10^2$Mpc$^{-1}$).

# III/ Constraining the population of anti-objects

# What can we learn from current data?



- AMS-02 might have identified 6 $^{3}\overline{\text{He}}$ and 2 $^{4}\overline{\text{He}}$. The event rate is ~ 1$\overline{\text{He}}$ for $10^{8}$He.
- Questions: i) what population do we need to explain the measurements?
  ii) Can such objects survive over cosmological timescale?
  iii) How can such objects accelerate CRs?

# Clouds of anti-matter in our Galaxy?

- How many of them? What are their densities? What volume would they occupy?
- AMS-02 measurements can help us answer these questions.

Assumption: acceleration and propagation of Cosmic Rays are identical for matter and anti-matter.

$$\frac{\phi_{\overline{\mathrm{He}}}}{\phi_{\mathrm{He}}} \simeq \frac{N_{\overline{\mathrm{He}}}}{N_{\mathrm{He}}} = \left(\frac{n_{\overline{\mathrm{He}}}V_{\overline{\mathrm{He}}}}{n_{\mathrm{He}}V_{\mathrm{He}}}\right) \Rightarrow n_{\overline{\mathrm{He}}}V_{\overline{\mathrm{He}}} \simeq 10^{-8}(n_{\mathrm{He}}V_{\mathrm{He}})$$

- Measured by AMS-02: $10^{-8}$
- what we want to learn

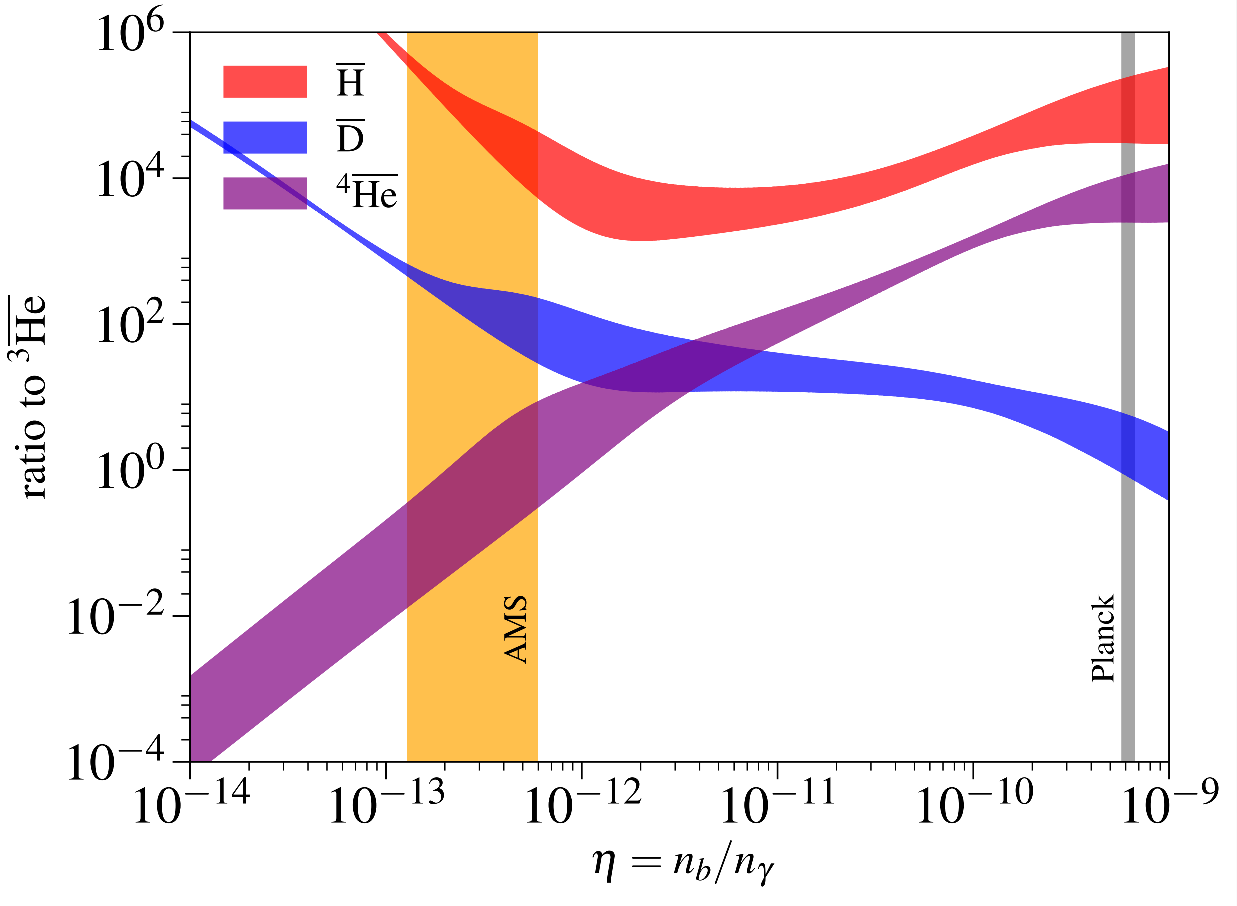
- Are there small, very dense objects or large, very dilute anti-domains?

# Anisotropic BBN and the isotopic ratio

- Standard BBN predicts in the ISM: $^4He/^3He$ ~$10^4$. Within CRs, spallation leads to $^4He/^3He$~5.

Problem: observed isotopic ratio is 0.3.

- Solution: anisotropic BBN! if η is not homogeneous, there could be pockets dominated by antimatter with very low density.



*produced with* AlterBBN
*Arbey 1106.1363*

*Checked with PRIMAT*
*Pitrou++ 1909.12046*

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

# Some implications of the BBN calculation

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

This is potentially detectable with AMS-02!

- Moreover, we know in the ISM: $n_p = 10 n_{He}$. AMS-02 therefore implies:

$$\frac{\phi_{\overline{\mathrm{He}}}}{\phi_{\mathrm{He}}} \simeq \frac{n_{\overline{\mathrm{He}}} V_{\overline{\mathrm{He}}}}{n_{\mathrm{He}} V_{\mathrm{He}}} \simeq 10^{-8} \Rightarrow \left(\frac{n_{\bar{p}}}{n_p}\right)\left(\frac{V_{\overline{\mathrm{M}}}}{V_{\mathrm{M}}}\right) \simeq 10^{-4}$$

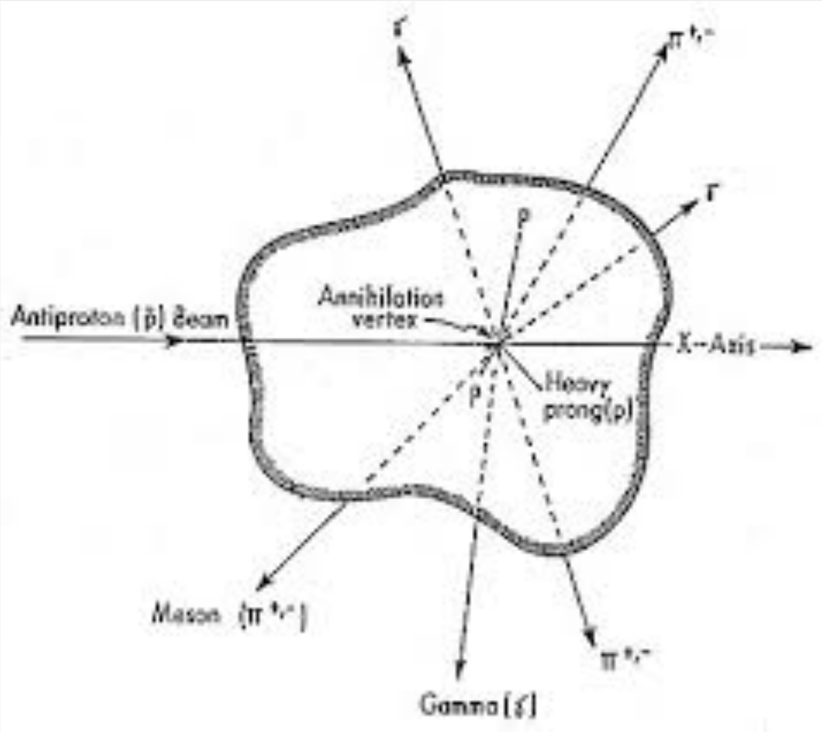
- If we assume anti-clouds are spherical with radius 1 parsec (arbitrary)

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

A few, very dense anti-clouds could explain AMS events!

- Question: can such objects survive in our galaxy? can we see them in $\gamma$-rays?

# Anti-cloud cannot survive in our Galaxy



- $\bar{p}$ can annihilate with $p$ in the ISM at a rate: $\tau_{\rm ann}^{-1} = (n_p\langle\sigma_{p\bar{p}}v\rangle)$

$$\langle\sigma_{p\bar{p}}\,v\rangle \simeq \begin{cases} 1.5\times10^{-15}\ \mathrm{cm}^3/\mathrm{s} & T > 10^{10}\ \mathrm{K}\,, \\ 10^{-10}\left(\frac{\mathrm{K}}{T}\right)^{1/2}\ \mathrm{cm}^3/\mathrm{s} & 10^{10}\ \mathrm{K} > T > 10^4\ \mathrm{K}\,, \\ 10^{-10}\ \mathrm{cm}^3/\mathrm{s} & 10^4\ \mathrm{K} > T\,. \end{cases}$$

*Steigman 1976*

- Our Galaxy exists since roughly $t_{\rm gal} \simeq 2.8\times10^{17}$ s and $n_p^{\rm ism} = 1\ \mathrm{cm}^{-3}$
- Requiring $t_{\rm ann} > t_{\rm gal}$ leads to $n_p^{\rm cold} < 3.5\times10^{-8}\ \mathrm{cm}^{-3}$ $n_p^{\rm hot} < 6.1\times10^{-5}\ \mathrm{cm}^{-3}$.

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

# Survival rate in the Early Universe

- In the early universe, larger densities lead to larger annihilation rate and stronger constraints.
- The hubble time before matter-radiation equality ($z_{eq}$>3500) is $t_H \simeq 5 \times 10^{19}(1+z)^{-2}$ s
- Before BBN ($z \sim 10^9$), annihilation happens in the relativistic regime. The constraint on the local proton density from requiring $t_{ann} > t_H$ is:

$$n_p^{\rm local}(z_{\rm BBN}) < 1.9 \times 10^{-8}\, n_p^{\rm cosmo}(z_{\rm BBN})$$

- Below $z_{eq}$, the constraint relaxes to

$$\frac{n_p^{\rm local}}{n_p^{\rm cosmo}}(z < z_{\rm eq}) < \frac{6.3 \times 10^{-2}}{(1+z)^{3/2}}$$

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

# $\gamma$-Ray constraints

- Annihilations lead to $\gamma$-rays that can be detected.

- There are three types of searches that can provide strong constraints:

  i) searches for distinctive spectral features such as a gamma-ray line;

  ii) searches for morphological features localized on the sky, either from extended or point sources;

  iii) searches for a continuous spectrum of gamma-rays extending over large area on the sky (e.g. extragalactic $\gamma$-ray background).

- 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.

- Line search in FermiLAT allows to set (for a cold cloud) $n_p^{\mathrm{local}} \lesssim 10^{-10} - 2\times 10^{-9}\ \mathrm{cm}^{-3}$.

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

# Anti-stars in the galaxy?

- Alternatively, anti-domains could have formed compact objects: naturally free of normal matter! Annihilations only occur at the surface of these objects.

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

Anti-stars cannot form from a anti-cloud because it would not survive in the early universe: they have to be primordial!

- The Dolgov & Silk scenario could produce such objects. How many of them? What mass & composition? What is the acceleration mechanism?

- Massive stars are short-lived compared to $t_{gal}$: they would require anti-stars to form again from a cloud. This is excluded!

# 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?

- Parametrically we can estimate that from a single event occurring at a given time:

$$\Phi_{\overline{\mathrm{He}}} = \left(\frac{c}{V_{\mathrm{gal}}}\right)\left(\frac{f_{\overline{\mathrm{He}}} M_{\bar{*}}}{m_{\overline{\mathrm{He}}}}\right) f_{\mathrm{acc}} = 10^{-9}\left(\frac{(4\pi/3)(10\ \mathrm{kpc})^3}{V_{\mathrm{gal}}}\right)\left(\frac{M_{\bar{*}}}{M_{\odot}}\right)\left(\frac{f_{\mathrm{acc}}}{10^{-8}}\right)\left(\frac{f_{\overline{\mathrm{He}}}}{1}\right) \overline{\mathrm{He}}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

If $10^{-8}$ of the mass of a *single* anti-helium star with $M = M_{\odot}$ is ejected in the galaxy,
it can explain AMS-02 events!

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

# A coherent scenario for AMS-02 anti-stars

- One possible scenario: White dwarf anti-stars were form in the early universe in clusters.
- Binary of (long-lived) white dwarfs can lead to type Ia supernovae! Measurements of such events indicate a rate: $1.4 \times 10^{-13}\mathrm{yr}^{-1} M_{\odot}^{-1}$

*Badenes&maoz 1202.5472*

- Requiring one such event over one CR diffusion time scale leads to a total anti-star mass of

$$\sum M_{\bar{*}} = 10^{-5} - 10^{-6} \sum M_{*}$$

- If anti-stars are heavier than 0.6Msun, producing the correct isotopic ratio requires spallation around the anti-star.
- We can compute the grammage required to inverse the isotopic ratio from the result of the LEAR collaboration measuring $\bar{p}\,{}^4\mathrm{He} \rightarrow {}^3\mathrm{He} + X$

*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 $N_{\bar{*}} < 4 \times 10^{-5} N_{*}\,.$ *Von Ballmoos, 1401.7258*

- We can check the 3FGL catalog for un-associated sources: the brightest source can be used to estimate the closest distance at which an anti-star could be.

- Luminosity from annihilations to pions and subsequent decay

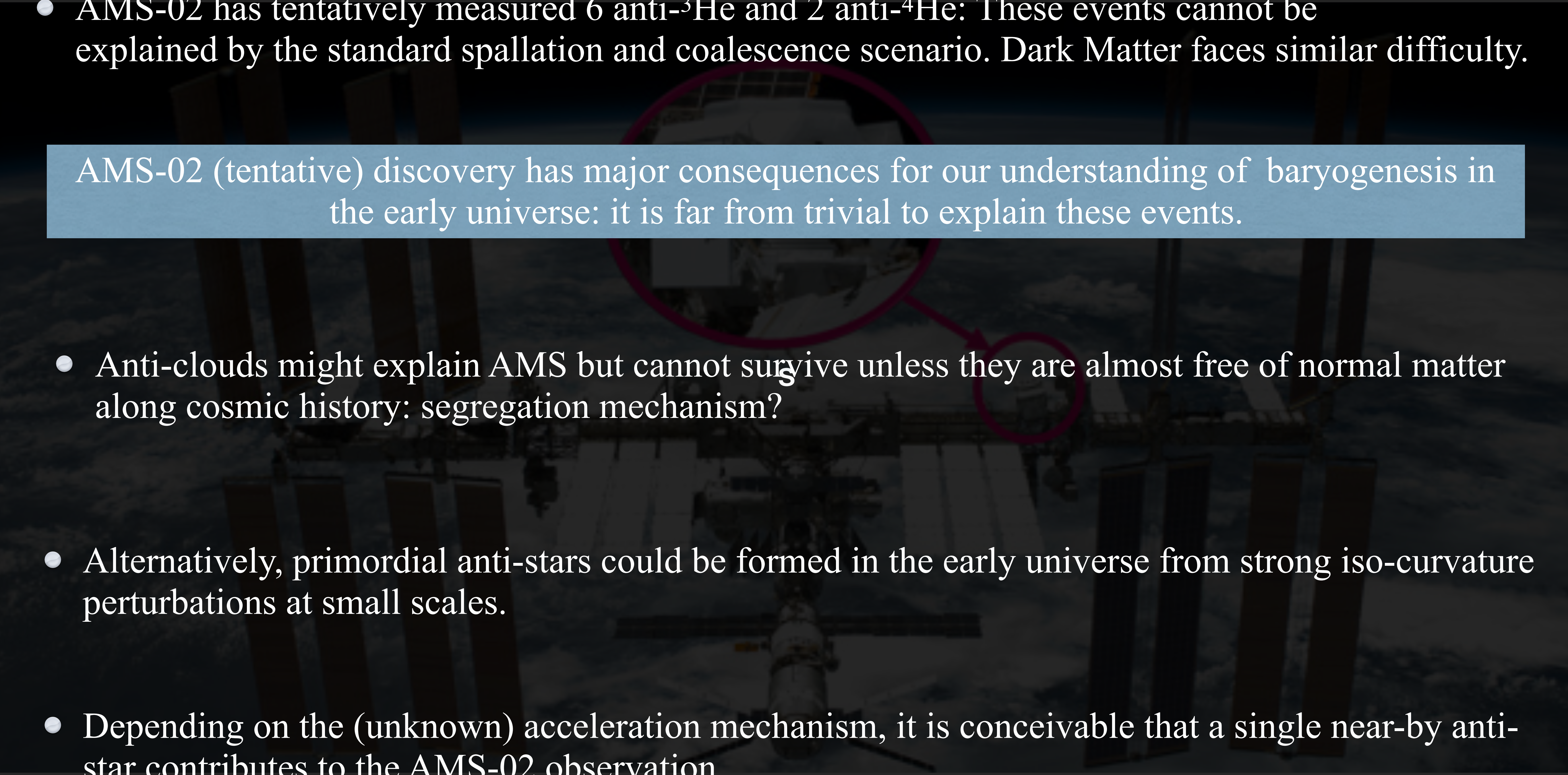
$$L_{\bar{*}} = 8\pi R_{\bar{*}}^2 v n_p \simeq 10^{31}\left(\frac{R_{\bar{*}}}{10^{11}\ \mathrm{cm}}\right)^2\left(\frac{v}{300\mathrm{km\ s}^{-1}}\right)\left(\frac{n_p}{1\mathrm{cm}^{-3}}\right)\#\gamma\ \mathrm{s}^{-1}$$

- Assuming isotropic emission, the 3FGL constrains: $\frac{L_{\bar{*}}}{4\pi d_{\bar{*}}^2} \leq 2 \times 10^{-8} \#\gamma\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

- And therefore: $d_{\bar{*}} \geq 6 \times 10^{18}\sqrt{\left(\frac{R_{\bar{*}}}{10^{11}\ \mathrm{cm}}\right)\left(\frac{v}{300\mathrm{km\ s}^{-1}}\right)\left(\frac{n_p}{1\mathrm{cm}^{-3}}\right)}\ \mathrm{cm}$

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

# Conclusions



- AMS-02 has tentatively measured 6 anti-$^3$He and 2 anti-$^4$He: These events cannot be explained by the standard spallation and coalescence scenario. Dark Matter faces similar difficulty.

AMS-02 (tentative) discovery has major consequences for our understanding of baryogenesis in the early universe: it is far from trivial to explain these events.

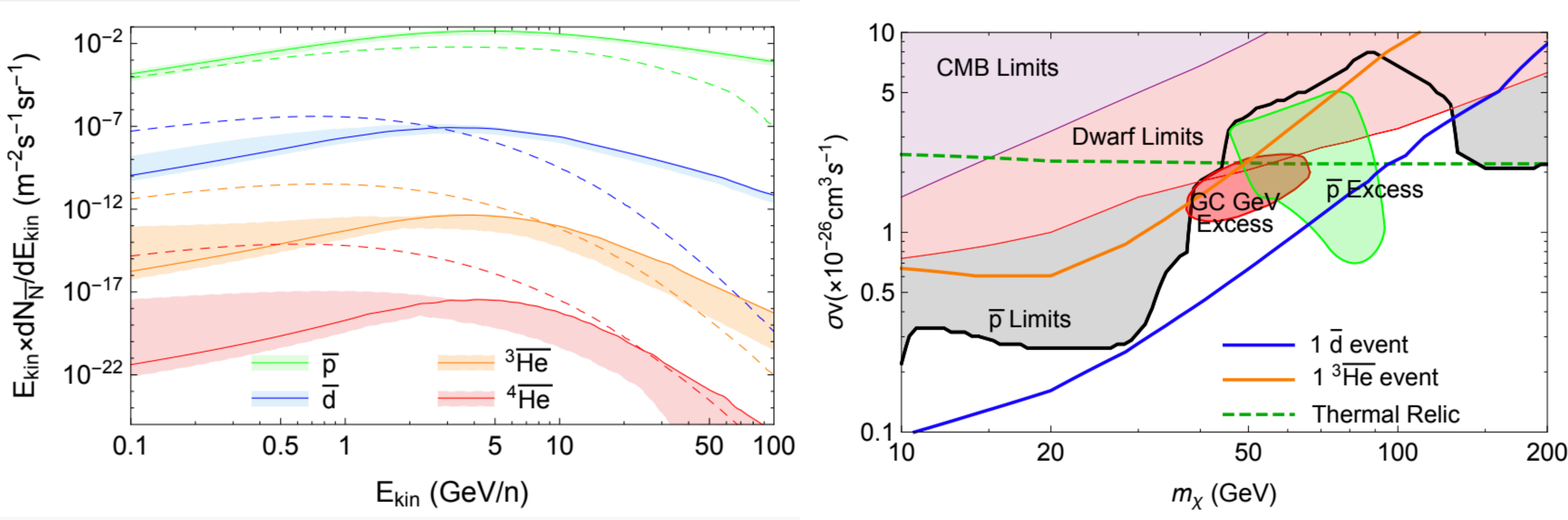
- Anti-clouds might explain AMS but cannot survive unless they are almost free of normal matter along cosmic history: segregation mechanism?

- 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 anti-star contributes to the AMS-02 observation.

# Back-up

# A common explanation to CR/$\gamma$-rays anomalies?

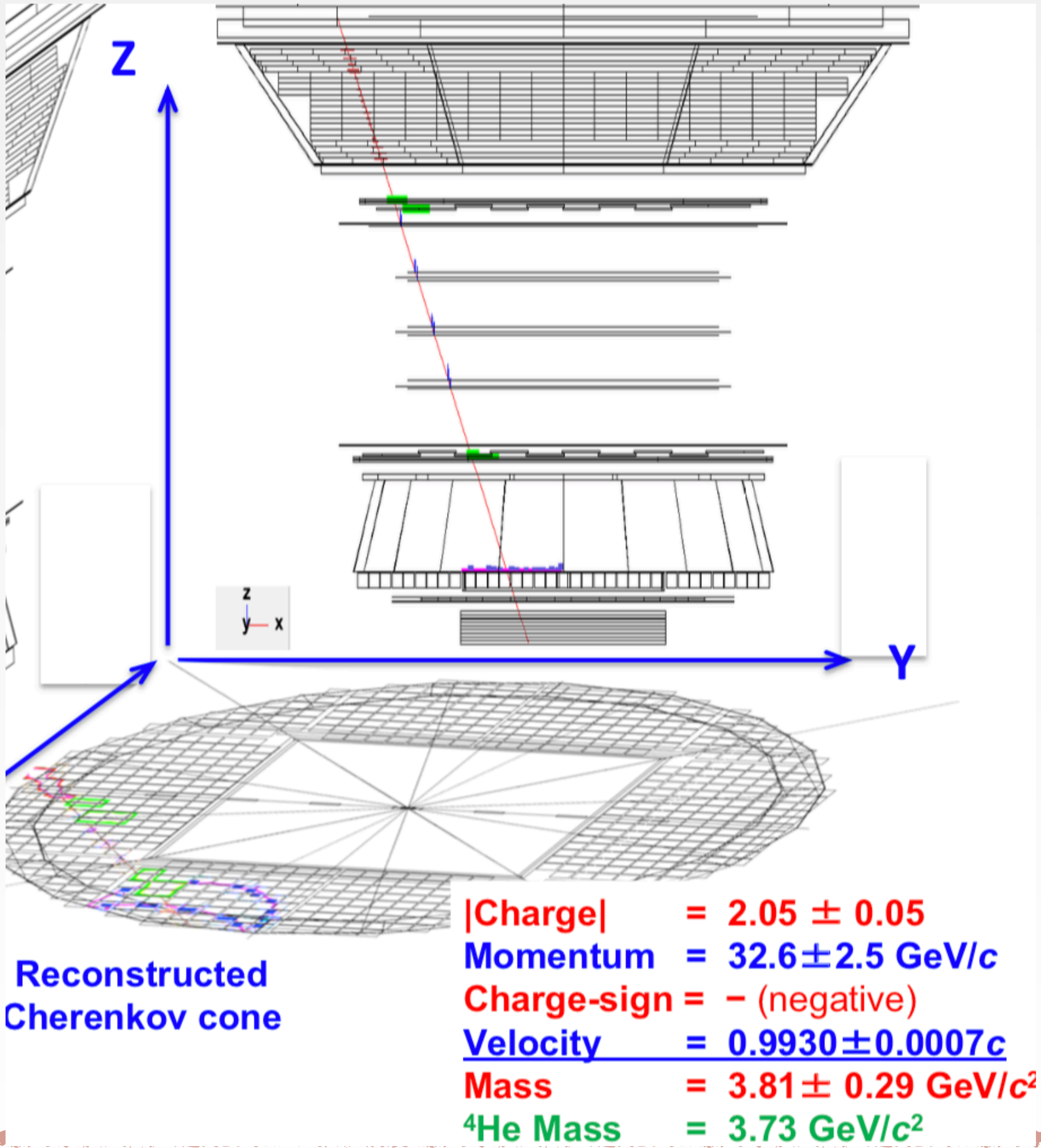


*Cholis, Linden, Hooper 2001.08749*

- Where is the $\bar{d}$??
- How to produce $^4\overline{\mathrm{He}}$??

# What could be wrong?

- 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…



|Charge| = 2.05 ± 0.05
Momentum = 32.6±2.5 GeV/$c$
Charge-sign = − (negative)
Velocity = 0.9930±0.0007$c$
Mass = 3.81± 0.29 GeV/$c^2$
$^4$He Mass = 3.73 GeV/$c^2$

# Constraints from a $\gamma$-ray line

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

- These processes produce line with energy between 0.66 GeV and 0.933 GeV. Decay of mesons will lead to continuum below the proton mass. We ignore this for simplicity.

- Using the FermiLAT data and the largest region "R180", we calculate

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

*Ackermann++ 1506.00013*

- We assume clouds homogeneously distributed in the disk, with a small thickness of 0.1 kpc perpendicular to the disk.

- FermiLAT allows to set (in the case of a cold cloud) $n_p^{\rm local} \lesssim 10^{-10} - \; 2\times 10^{-9}\;{\rm cm}^{-3}.$

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

# 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:

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

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