2.2 Cosmic ray propagation And Secondaries

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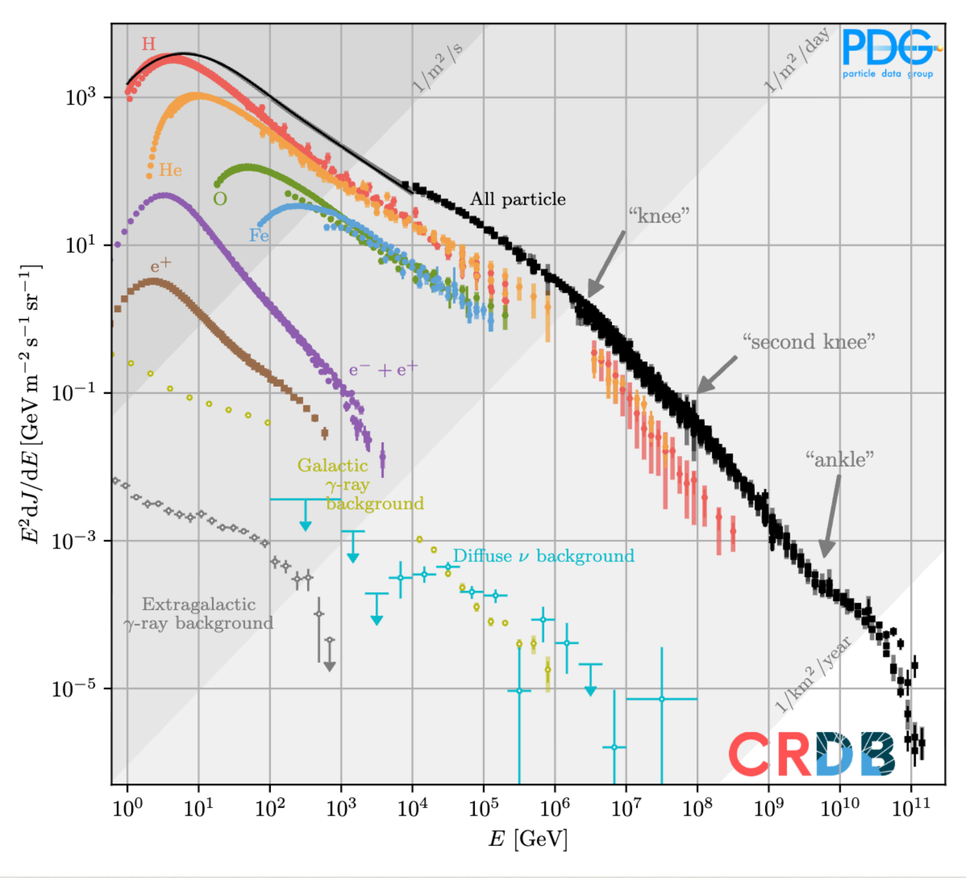
- Course webpage: https://blackboard.cuhk.edu.hk

- Cosmic ray primaries
  - Particles that accelerated directly by a source

Cosmic-ray secondaries

- Particles that are created by primaries during propagation
  - Things that can be produced: photons, electrons/positrons.
  - Radioactive isotopes.
- What is the CR propagation equation for them?



Cosmic-ray secondaries

- The "full" propagation equation (current standard)

Diffusion convection

$$\frac{\partial \psi(\vec{r}, p, t)}{\partial t} = q(\vec{r}, p, t) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi)$$

Energy loss due to convection

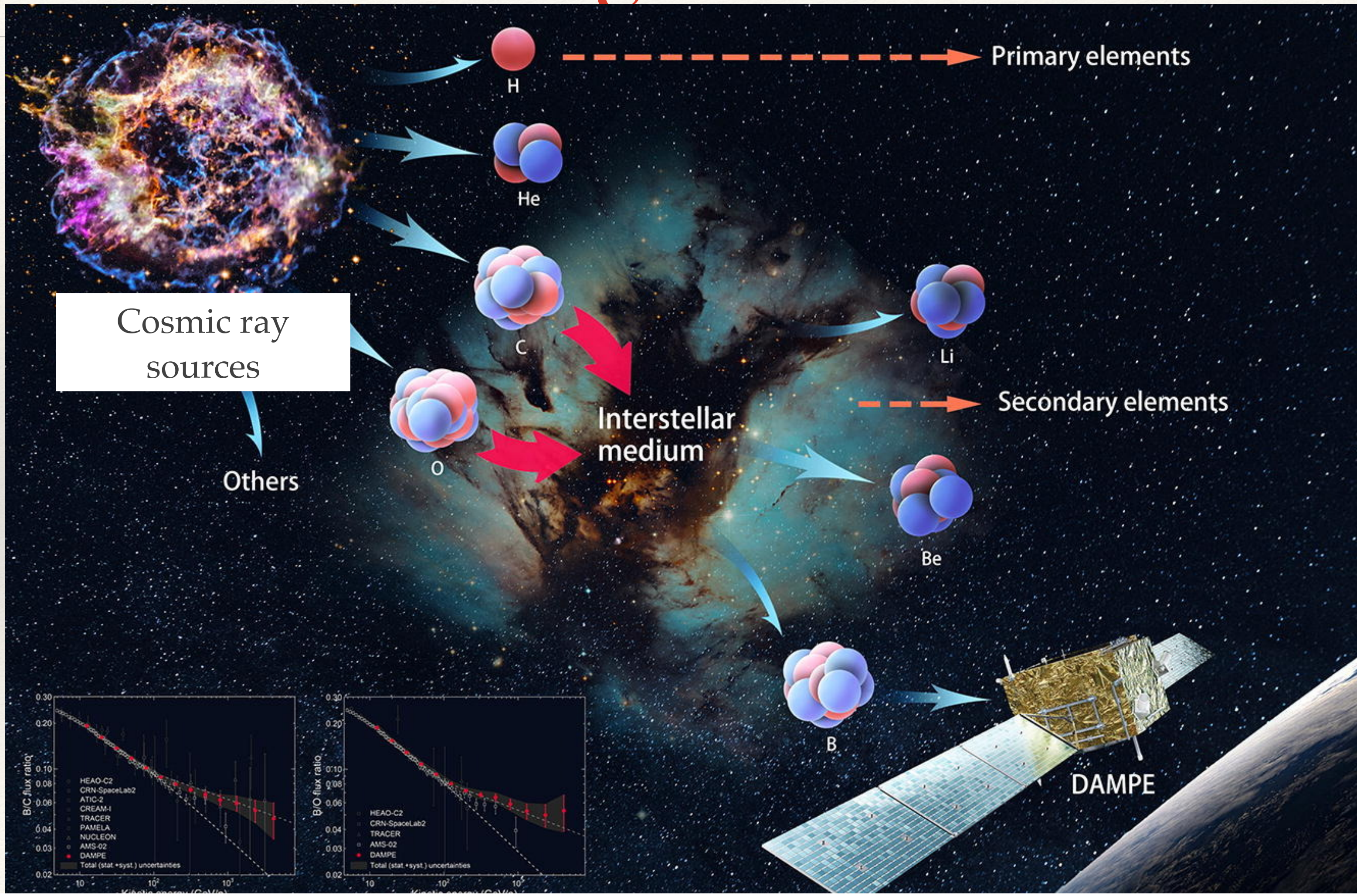
$$+ \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi,$$

Re-acceleration Continuous energy loss Fragmentation loss, Radioactive decay loss

- Fragmentation loss, for the i-th species, it's loss by converting into the j-th species
- $\frac{\partial n_i}{\partial t} = - n_i (\frac{\rho}{m})_{ism} \sigma_{i \to j} v$
- Radioactive decay loss
- $\frac{\partial n_i}{\partial t} = - n_i \frac{1}{\tau_i}$, τ_i is the lifetime.

CR-ISM interaction => Fragmentation loss

- Cosmic-ray source accelerates some primary cosmic rays (we will talk about acceleration later)
- They propagate in the interstellar space, which is not entirely "empty"
  - Averaged density about 1 atom/cm^3
- Primaries like carbon, can interact and produces smaller nucleus like Boron/Be/Li
- This is called "Fragmentation"



Fragmentation loss

- LHS = $\dot{n}$, recall this is $\partial_t \frac{dN}{d^3 x dE}$
- RHS = rate of particle loss per volume per energyA due to interaction during propagation

- Probability of interaction for One particle propagating is
  - dP = $(\rho/m)_{ism}\sigma dx$
  - Rate of interaction: $\frac{dP}{dt} = (\rho/m)_{ism}\sigma v$
  - Rate of interaction per volume per energy = $n_{cr}(E)\frac{dP}{dt} = n_{CR}(E)(\rho/m)_{ism}\sigma v$

Radioactive decay loss

- LHS = $\dot{n}$, recall this is $\partial_t \frac{dN}{d^3x dE}$
- RHS = rate of particle loss per volume per energy due to radioactive decay during propagation

- This is more straightforward
- $\dot{n}_i = \frac{n_i(E)}{\tau_i(E)}$
- Where $\tau(E) = \gamma\tau_0$ is the decay rate of the particle, which is dilated by the relativistic factor γ
  - I explicitly added the energy dependence to remind you.

Cosmic-ray secondaries production terms

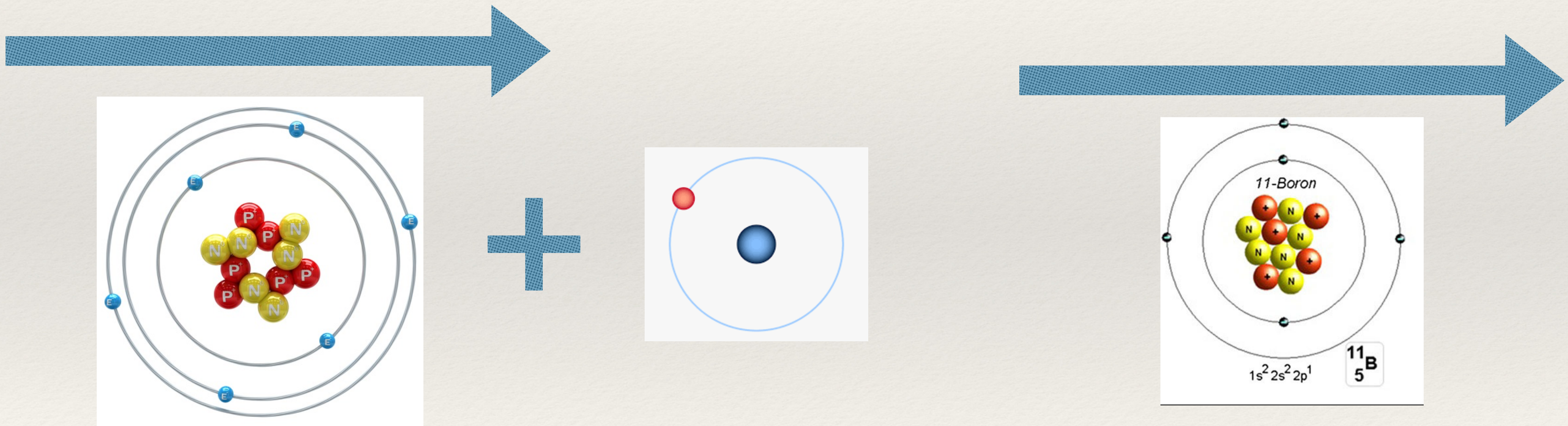
Secondary Source Term

- The full propagation equation
- $$\frac{\partial}{\partial t}n_i = D\nabla^2 n_i - \frac{\partial}{\partial E}\left(n_i\dot{E}\right) + Q_i^{pri} - n_i(\frac{\rho}{m})_{ism}\sigma_{i\to\neq i}v - n_i\frac{1}{\tau_i} + \sum_j\left(n_j(\frac{\rho}{m})_{ism}\sigma_{j\to i}v + n_j\frac{1}{\tau_j}Br_{j\to i}\right)$$
- There are fragmentation and decay loss terms.
- But there is also a gain term from other species.
- We have one equation for each species, so a set of coupled equations to be solved
- Note that in the $\sum_j\left(n_j(\frac{\rho}{m})_{ism}\sigma_{j\to i}v + n_j\frac{1}{\tau_j}Br_{j\to i}\right)$ term, the energy in LHS is differential in E_i, but the gain terms are differential in E_j, which are often different.
- To make our life simpler, we can use “kinetic energy per nucleon” as the energy variable.
  - Then both sides would be the same

I will try to remind you what variable we are working on

KE per nucleon

- Assume that the rest of the nucleus are not affected by the target interaction
- The nuclei retains the **same kinetic energy per nucleon**



Cosmic-ray secondaries

- Leaky box approx
- + assume one species dominates the production
- For **purely secondary species,** Q = 0
- $$\frac{\partial}{\partial t} n_i = D \nabla^2 n_i - \frac{\partial}{\partial E}\left(n_i \dot{E}\right) + Q_i^{pri} - n_i (\frac{\rho}{m})_{ism} \sigma_{i \to \neq i} v - n_i \frac{1}{\tau_i} + \sum_j \left(n_j (\frac{\rho}{m})_{ism} \sigma_{j \to i} v + n_j \frac{1}{\tau_j} Br_{j \to i} \right)$$
- $$\frac{n_i}{T_e} = -\frac{n_i}{T_f} - \frac{n_i}{T_{dec}} + C_i$$
- C_i is the production of "i" due to other species, it does not depends on n_i !!
- $$n_i = \frac{C_i}{1/T_e + 1/T_f + 1/T_{dec}}$$

Cosmic-ray secondaries

- $$n_i = \frac{C_i}{1/T_e + 1/T_f + 1/T_{dec}}$$
- Def $$\frac{1}{T_{e+f}} = \frac{1}{T_e} + \frac{1}{T_f}$$
- Let consider Be10/Be9
- $$\frac{n_{Be10}}{n_{Be9}} = \frac{1/T_{e+f}}{1/T_{e+f} + 1/T_{dec}} \frac{C_{Be10}}{C_{Be9}}$$
- Recall $$C_i = \sum_j \left(n_j (\frac{\rho}{m})_{ism} \sigma_{j\to i} v + n_j \frac{1}{\tau_j} Br_{j\to i} \right) \simeq n_j (\frac{\rho}{m})_{ism} \sigma_{j\to i} v$$
- To zeroth order, is just the ratio of the production cross section.

Main isotopes[6]			Decay	
	abundance	half-life ($t_{1/2}$)	mode	product
^{7}Be	trace	53.22 d	ε	^{7}Li
^{8}Be	0% (extinct)	81.9 as	α	^{4}He
^{9}Be	100%	stable		
^{10}Be	trace	1.387×10^6 y	β^-	^{10}B

Category: Beryllium
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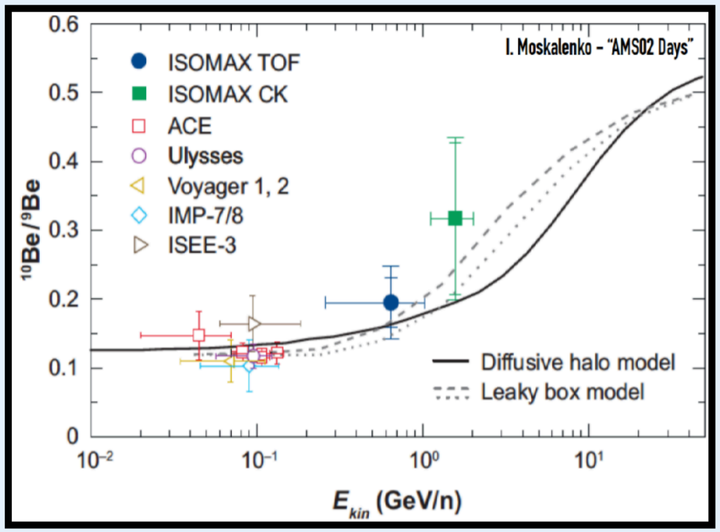
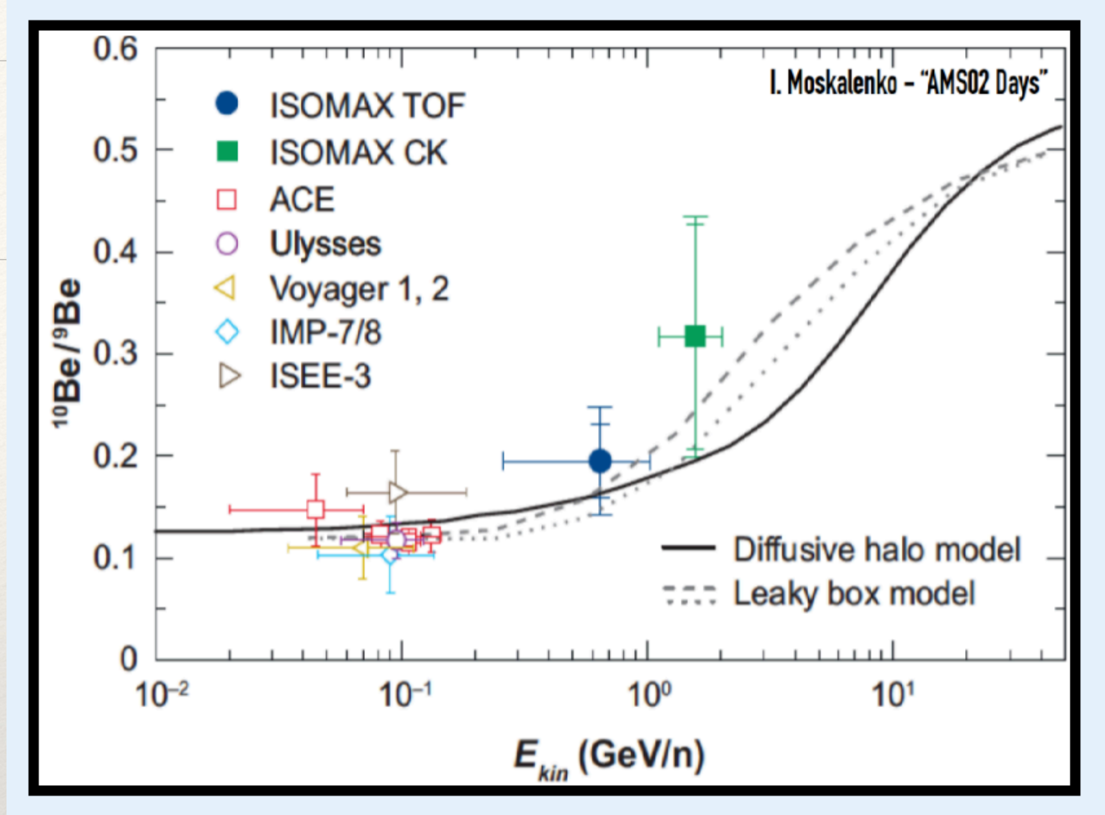
Channel	σ_0 [mb]
$^{12}C \to$ ^{6}Li	20.4
^{7}Li	
^{7}Be	66.5
^{9}Be	
^{10}Be	
^{10}B	35.8
^{11}B	
^{11}C	44.7



Cosmic-ray secondaries
"Cosmic ray clocks"

- $$\frac{n_{Be10}}{n_{Be9}} = \frac{1/T_{e+f}}{1/T_{e+f} + 1/T_{dec}} \frac{C_{Be10}}{C_{Be9}}$$
- $T_{dec} = \gamma \tau_0$
- The actual lifetime is Lorentz boosted
- In high-energy limit, $1/T_{dec} \to 0$
- $$\frac{n_{Be10}}{n_{Be9}} = \frac{C_{Be10}}{C_{Be9}} \sim 1$$
- In the low-energy limit, (assuming $1/\tau_0 > 1/T_{e+f}$ for this isotope)
- $$\frac{n_{Be10}}{n_{Be9}} = \frac{C_{Be10}}{C_{Be9}} \frac{T_{dec}}{T_{e+f}} \quad => \quad T_{e+f} \simeq T_{dec}/0.1 \quad \text{(read this off from the plot)}$$
- Cosmic rays have a lifetime of 10^7 years (at around 1 GeV)



Secondary to Primary ratio

- Stable Secondary Boron, produced mostly from Carbon spallation (C-> B)
- $n_B = \dfrac{C_{C->B}}{1/T_{e+f}} = \dfrac{n_C n_{ism}\sigma c}{1/T_{e+f}}$
- Recall $C = n_j n_{ism}\sigma_{j\to i} v \;= n_C n_{ism}\sigma c$

$n_{ism} = \rho/m$
Note that this
is not differential

- $\dfrac{n_B}{n_C} = \dfrac{n_{ism}\sigma_{C->B}c}{1/T_e + 1/T_f}$
- If $1/T_f = n_{ism}\sigma_{B->X}c$ dominates, [B/C] is just the ratio of the cross section ~ relatively energy independent here
- So, we know $1/T_e$ cannot be too small
- $\dfrac{n_B}{n_C} = n_{ism}\sigma_{C->B}cT_e(E)$

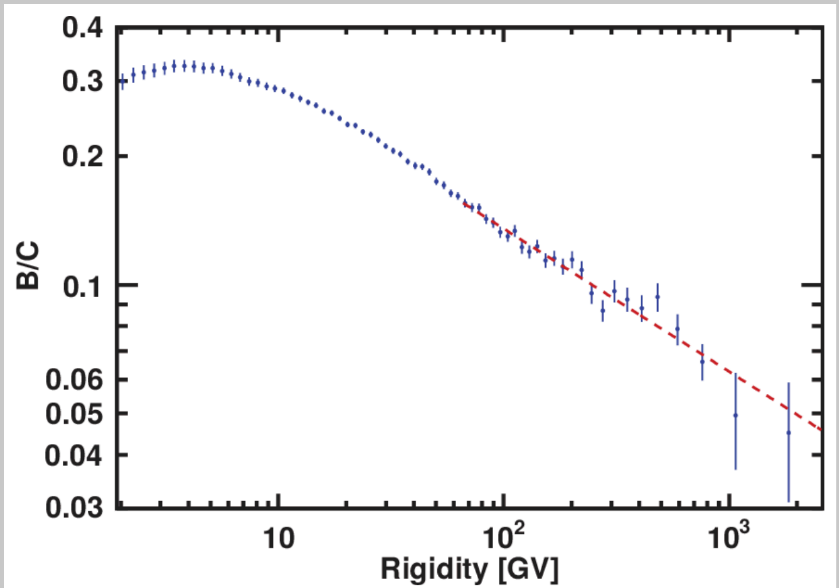


Figure 1. The AMS boron to carbon ratio (B/C) as a function of rigidity in the interval from 1.9 GV to 2.6 TV based on 2.3 million boron and 8.3 million carbon nuclei. The dashed line shows the single power law fit starting from 65 GV with index $\Delta = -0.333 \pm 0.014(\text{fit}) \pm 0.005(\text{syst})$.

Rigidity

$$R = \frac{pc}{q} \simeq E/q$$

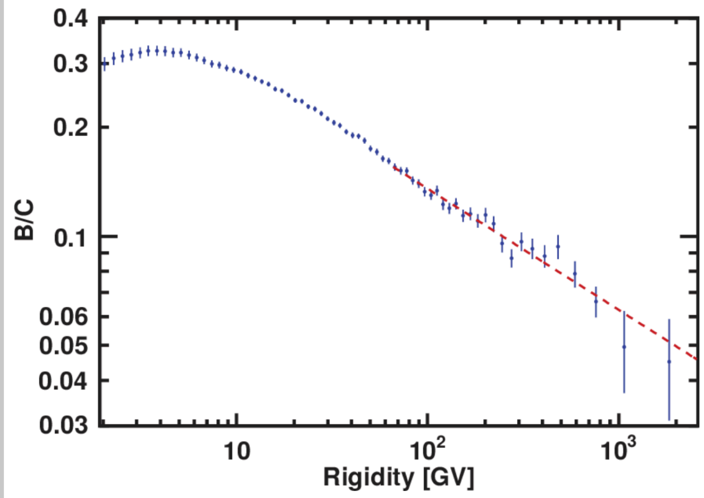
Cosmic-ray grammage

Rigidity

$$R = \frac{pc}{q} \simeq E/q$$

- $\frac{n_B}{n_C} = n_{ism}\sigma_{C->B}cT_e(E)$
- $\frac{n_B}{n_C} < 1$ "Optically thin regime"
- The"Grammage, X" measures the "amount of stuff" cosmic rays pass through
- $n_{ism}cT_e(E) = \frac{1}{\sigma_{C->B}}\frac{n_B}{n_C} \sim \frac{0.3}{30\times10^{-3}10^{-24}\,cm^2}$
- $n_{ism}cT_e(E) \sim 10^{25}\mathrm{cm}^{-2}$
- Convention is
- $\mathrm{X(E)} = \rho_{ism}cT(E) \sim \frac{10^{25}}{6\times10^{23}}\mathrm{gcm}^{-2} \sim 10\mathrm{gcm}^{-2}$ at 10GV

Density of water is about 1g/cc



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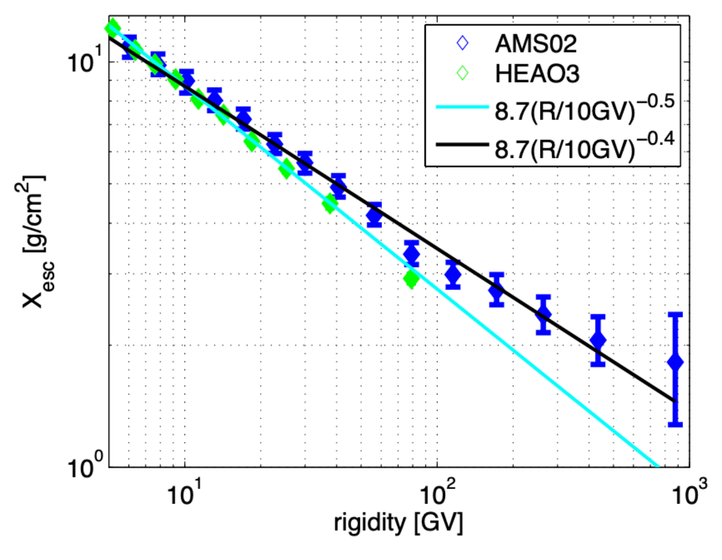


B/C ratio

- $T(E) \propto E^{-\delta}$
  - $\delta \sim [0.3,\ 0.4]$
- Recall that CR spectrum $E^{-2.7}$
- That means $Q(E) \sim E^{-2.3}$ or $E^{-2.4}$

- **B/C ratio is therefore very important**
  - **Help us disentangle the degeneracy between propagation and source power-law index**

Rigidity

$$R = \frac{pc}{q} \simeq E/q$$

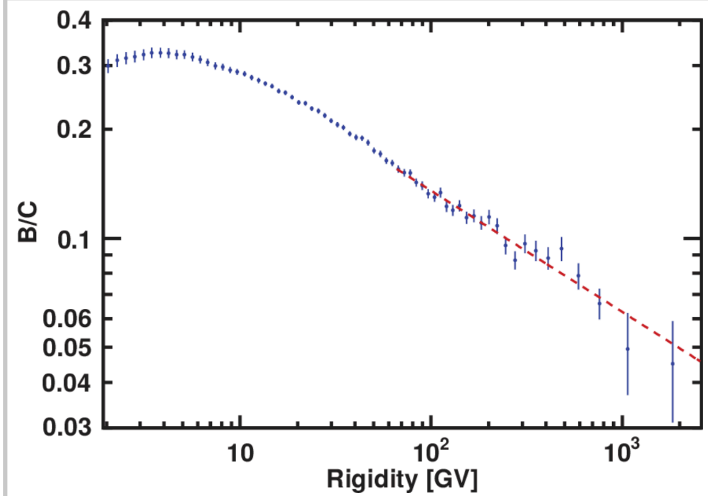
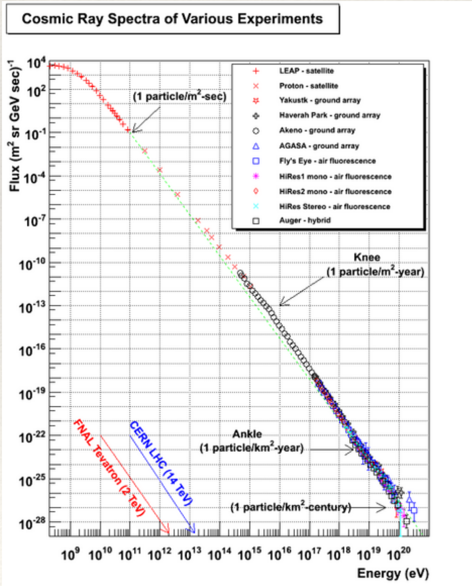
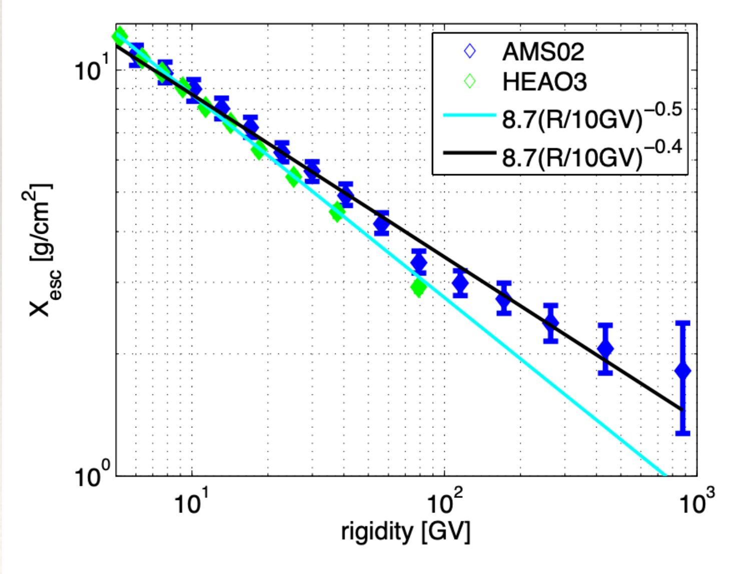


Figure 1. The AMS boron to carbon ratio (B/C) as a function of rigidity in the interval from 1.9 GV to 2.6 TV based on 2.3 million boron and 8.3 million carbon nuclei. The dashed line shows the single power law fit starting from 65 GV with index $\Delta = -0.333 \pm 0.014(\text{fit}) \pm 0.005(\text{syst})$.

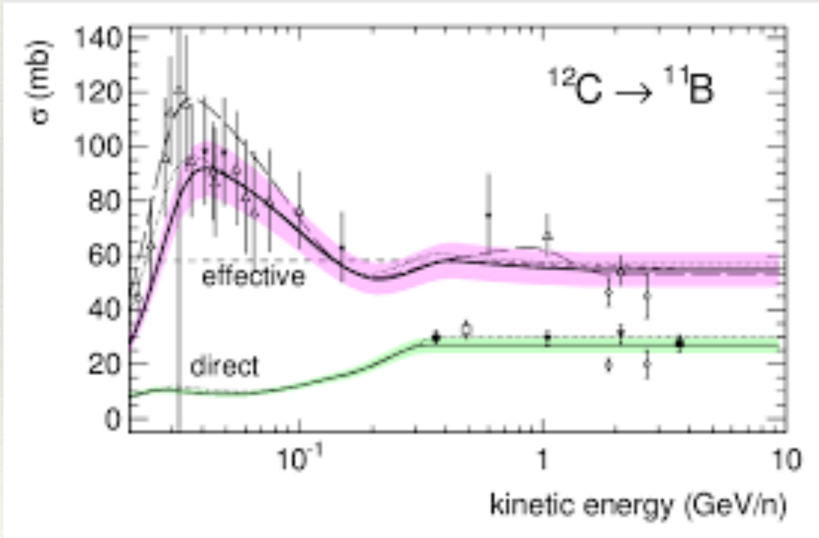




E.g., Fragmentation cross sections

TABLE III. Production cross sections at $E = 10$ GeV/n from the existing formulas and results from the refitting procedure.

Proj → Frag	GALPROP	WNEW	YIELDX	$\sigma^{\mathrm{H}}_{\mathrm{P}\to\mathrm{F}} \pm \delta\sigma^{\mathrm{H}}_{\mathrm{P}\to\mathrm{F}}$	Data sets	$F_{\alpha/p}$	$\sigma^{\mathrm{He}}_{\mathrm{P}\to\mathrm{F}} \pm \delta\sigma^{\mathrm{He}}_{\mathrm{P}\to\mathrm{F}}$	$\xi_{\mathrm{P}\to\mathrm{F}}$	$\eta_{\mathrm{P}\to\mathrm{F}}$
^{16}O → ^{11}B	27.34 mb	14.57 mb	14.41 mb	(25.66 ± 1.06) mb	△●□∗▼	1.34	(34.37 ± 1.43) mb	0.94 ± 0.04	1.01 ± 0.02
^{16}O → ^{10}B	11.00 mb	9.52 mb	8.81 mb	(11.92 ± 0.52) mb	△●□∗▼	1.34	(15.97 ± 0.70) mb	1.08 ± 0.04	0.98 ± 0.03
^{15}N → ^{11}B	26.12 mb	26.12 mb	21.71 mb	(30.63 ± 2.48) mb	●○	1.31	(40.04 ± 3.24) mb	1.17 ± 0.08	0.67 ± 0.51
^{15}N → ^{10}B	9.56 mb	8.81 mb	7.63 mb	(9.69 ± 0.77) mb	●○	1.31	(12.66 ± 1.01) mb	1.01 ± 0.07	1.54 ± 0.05
^{14}N → ^{11}B	29.22 mb	29.98 mb	26.66 mb	(29.80 ± 1.08) mb	●□∗★	1.21	(35.94 ± 1.30) mb	1.02 ± 0.03	0.95 ± 0.02
^{14}N → ^{10}B	10.44 mb	10.64 mb	9.18 mb	(10.15 ± 0.84) mb	●□∗★	1.21	(12.24 ± 1.01) mb	0.97 ± 0.07	0.99 ± 0.05
^{12}C → ^{11}B	56.88 mb	54.86 mb	52.83 mb	(54.73 ± 2.57) mb	●□■∗▼★◇	1.29	(70.50 ± 3.32) mb	0.96 ± 0.04	0.90 ± 0.01
^{12}C → ^{10}B	12.30 mb	16.21 mb	11.59 mb	(12.05 ± 0.58) mb	●□■∗▼★◇	1.29	(15.52 ± 0.74) mb	0.98 ± 0.04	1.00 ± 0.02
^{16}O → ^{10}Be	2.14 mb	1.34 mb	2.07 mb	(1.90 ± 0.13) mb	△▼	1.47	(2.79 ± 0.19) mb	0.88 ± 0.05	0.90 ± 0.01
^{16}O → ^{9}Be	3.48 mb	3.35 mb	3.51 mb	(3.40 ± 0.22) mb	△∗▼	1.47	(4.99 ± 0.32) mb	0.97 ± 0.06	0.98 ± 0.03
^{16}O → ^{7}Be	10.00 mb	8.75 mb	8.92 mb	(8.97 ± 0.29) mb	△▼	1.47	(13.16 ± 0.42) mb	0.89 ± 0.03	0.98 ± 0.02
^{14}N → ^{10}Be	1.75 mb	1.06 mb	1.81 mb	(1.73 ± 0.21) mb	△□	1.43	(2.47 ± 0.30) mb	0.99 ± 0.09	0.95 ± 0.07
^{14}N → ^{7}Be	10.10 mb	7.46 mb	8.47 mb	(7.90 ± 0.47) mb	△▲□	1.43	(11.29 ± 0.67) mb	0.78 ± 0.04	1.05 ± 0.08
^{12}C → ^{10}Be	3.94 mb	2.05 mb	3.41 mb	(3.61 ± 0.27) mb	△□■▼◇	1.41	(5.07 ± 0.38) mb	0.91 ± 0.06	0.92 ± 0.01
^{12}C → ^{9}Be	6.76 mb	5.31 mb	4.98 mb	(6.63 ± 0.29) mb	△□■∗▼◇▲	1.41	(9.32 ± 0.41) mb	0.98 ± 0.04	1.00 ± 0.02
^{12}C → ^{7}Be	9.58 mb	10.32 mb	10.76 mb	(8.88 ± 0.30) mb	△●□■▼★◇	1.41	(12.48 ± 0.42) mb	0.93 ± 0.03	1.09 ± 0.19
^{11}B → ^{10}B	38.91 mb	42.58 mb	38.91 mb	(37.83 ± 9.25) mb	●○	1.29	(48.63 ± 11.89) mb	0.97 ± 0.21	1.10 ± 0.14
^{11}B → ^{10}Be	12.95 mb	5.90 mb	4.56 mb	(7.39 ± 0.90) mb	●□∗×	1.40	(10.36 ± 1.26) mb	0.57 ± 0.06	0.90 ± 0.17
^{11}B → ^{9}Be	10.00 mb	15.27 mb	8.01 mb	(7.22 ± 1.08) mb	△●	1.40	(10.13 ± 1.51) mb	0.72 ± 0.09	0.91 ± 0.12
^{11}B → ^{7}Be	4.48 mb	4.48 mb	3.63 mb	(4.68 ± 0.49) mb	●▲∗	1.40	(6.57 ± 0.69) mb	1.05 ± 0.10	0.90 ± 0.11



For stable secondaries (e.g. Boron)

- $\frac{n_i}{T_e} = -\frac{n_i}{T_f} - \cancel{\frac{n_i}{T_{dec}}} + C_i$
- The ISM is optically thin to cosmic rays, grammage
- $\mathrm{X(E)} = \rho_{ism} c T_e(E) \sim \frac{10^{25}}{6 \times 10^{23}} \mathrm{gcm}^{-2} \sim 10\mathrm{gcm}^{-2}$ at 10GV

- $\frac{n_i}{T_e} = -\frac{n_i}{T_f} + C_i$
- $n_B = C_B T_e - n_B \frac{T_e}{T_f}$
- $n_B = n_C n_{ism} \sigma_{C->B} c T_e - n_B T_e n_{ism} \sigma_{B->X} c$
- $n_B = n_C \sigma_{C->B} \frac{X}{m} - n_B \sigma_{B->X} \frac{X}{m}$

For stable secondaries (e.g. Boron)

- **Approximation relation for Stable pure secondaries**
- $n_B = n_C \sigma_{C->B} \frac{X}{m} - n_B \sigma_{B->X} \frac{X}{m}$
    - The grammage takes cares of the propagation effect ($X(E)$)
- $\frac{n_a}{n_b} \simeq \frac{\sum_j n_j \sigma_{j->a} - n_a \sigma_{a->X}}{\sum_j n_j \sigma_{j->b} - n_b \sigma_{b->X}}$
- This has become largely independent of the propagation! (The most difficult to handle part)
    - (If they have the same propagation properties, like, from the same source)
    - Mostly depends on the cross section

We report the observation of new properties of primary iron (Fe) cosmic rays in the rigidity range 2.65 GV to 3.0 TV with 0.62×10^6 iron nuclei collected by the Alpha Magnetic Spectrometer experiment on the International Space Station. Above 80.5 GV the rigidity dependence of the cosmic ray Fe flux is identical to the rigidity dependence of the primary cosmic ray He, C, and O fluxes, with the Fe/O flux ratio being constant at 0.155 ± 0.006. This shows that unexpectedly Fe and He, C, and O belong to the same class of primary cosmic rays which is different from the primary cosmic rays Ne, Mg, and Si class.

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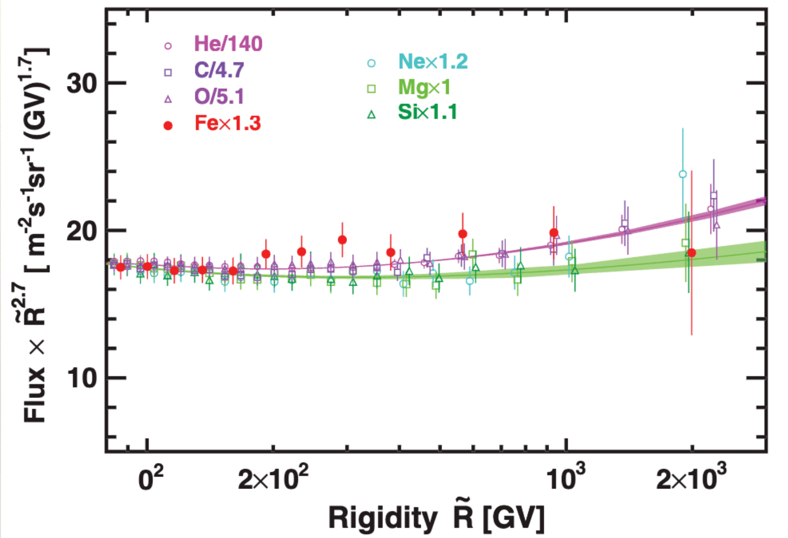

FIG. 4. The rigidity dependence of the Fe flux compared with the rigidity dependence of the He, C, and O fluxes and the Ne, Mg, and Si fluxes above 80.5 GV. For clarity, the He, O, Ne, and Si data points above 400 GV are displaced horizontally. For display purposes only, the He, C, O, Ne, Si, and Fe fluxes were rescaled as indicated. The shaded areas show the fit result of Eq. (5) of Ref. [3] to He, C, and O fluxes (magenta) and Ne, Mg, and Si fluxes (green).

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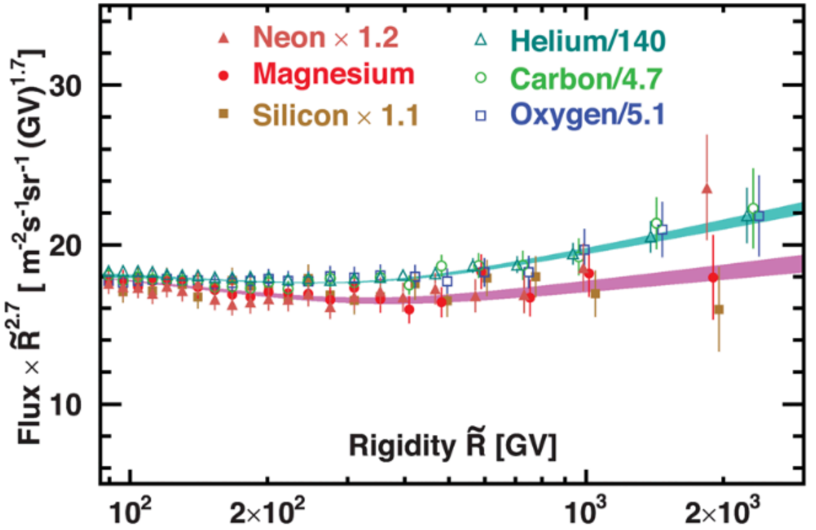
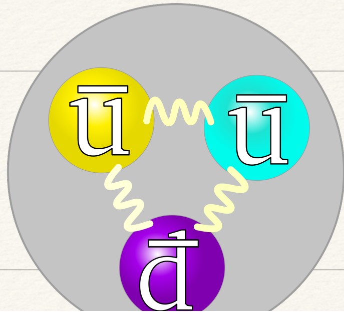
Properties of Iron Primary Cosmic Rays: Results from the Alpha Magnetic Spectrometer

M. Aguilar,[30] L. Ali Cavasonza,[1] M. S. Allen,[10] B. Alpat,[37] G. Ambrosi,[37] L. Arruda,[28] N. Attig,[24] F. Barao,[28] L. Barrin,[15] A. Bartoloni,[43] S. Başeğmez-du Pree,[18,*] R. Battiston,[40,41] M. Behlmann,[10] B. Beischer,[1] J. Berdugo,[30] B. Bertucci,[37,38] M. Bourquin,[16] E. F. Bueno,[18] J. Burger,[10] Castellini,[14] F. Cervelli,[39] Y. H. Chang,[48,49] Y. Chou,[49] S. Chouridou,[1] V. Choutko,[10] orti,[20] Z. Cui,[22,23] K. Dadzie,[10] C. Delgado,[30] i Felice,[45,†] C. Díaz,[30] F. Dimiccoli,[40] A. Eline,[10] J. Feng,[10] E. Fiandrini,[37,38] J. García-López,[27] C. Gargiulo,[15] H. Gast,[1] V. Grabski,[31] D. Grandi,[32,33] M. Graziani,[37,38] ieh,[10] J. Y. Hu,[6,7] M. Incagli,[39] W. Y. Jang,[13] Konyushikhin,[10] O. Kounina,[10] A. Kounine,[10] G. Laurenti,[8] I. Lazzizzera,[40,41] A. Lebedev,[10] I. Li,[6,7] J. Liang,[22] C. Light,[20] C. H. Lin,[48] Z. Luo,[35] Xi Luo,[23] S. S. Lyu,[19] F. Machate,[1] Iasi,[8,9] D. Maurin,[17] A. Menchaca-Rocha,[31] Mussolin,[37,38] J. Negrete,[20] N. Nikonov,[1] Paniccia,[16] A. Pashnin,[10] M. Pauluzzi,[37,38] A. Rozhkov,[10] D. Rozza,[32,33] R. Sagdeev,[11] B. S. Shan,[4] T. Siedenburg,[1] C. Solano,[10] Z. T. Sun,[6,7] M. Tacconi,[32,33] X. W. Tang,[6] Z. C. Tang,[6] J. Tian,[37,38] Samuel C. C. Ting,[10,15] S. M. Ting,[10] N. Tomassetti,[37,38] J. Torsti,[50] C. Tüysüz,[2] T. Urban,[10,21] I. Usoskin,[36] V. Vagelli,[42,37] R. Vainio,[50] M. Valencia-Otero,[49] E. Valente,[43,44] E. Valtonen,[50] M. Vázquez Acosta,[27] M. Vecchi,[18] M. Velasco,[30] J. P. Vialle,[3] C. X. Wang,[22] L. Wang,[5] L. Q. Wang,[22] N. H. Wang,[22] Q. L. Wang,[5] S. Wang,[20] X. Wang,[10] Yu Wang,[22] Z. M. Wang,[23] J. Wei,[16] Z. L. Weng,[10] H. Wu,[35] R. Q. Xiong,[35] W. Xu,[22,23] Q. Yan,[10] Y. Yang,[46] I. I. Yashin,[34] H. Yi,[35] Y. M. Yu,[19] Z. Q. Yu,[6] M. Zannoni,[32,33] C. Zhang,[6] F. Zhang,[6] F. Z. Zhang,[6,7] J. H. Zhang,[35] Z. Zhang,[10] F. Zhao,[6,7] C. Zheng,[23] Z. M. Zheng,[4] H. L. Zhuang,[6] V. Zhukov,[1] A. Zichichi,[8,9] N. Zimmermann,[1] and P. Zuccon[40,41]

(AMS Collaboration)



Cosmic ray anti-protons



- There are no anti-protons in our neighbourhood
- All known physical laws are symmetric between matter and anti-matter*.
- That means if we rewind in time, matter-antimatter asymmetry (baryon asymmetry) exists at least up to where our physics knowledge works
  - ~ TeV

Article | Open access | Published: 27 September 2023

Observation of the effect of gravity on the motion of antimatter

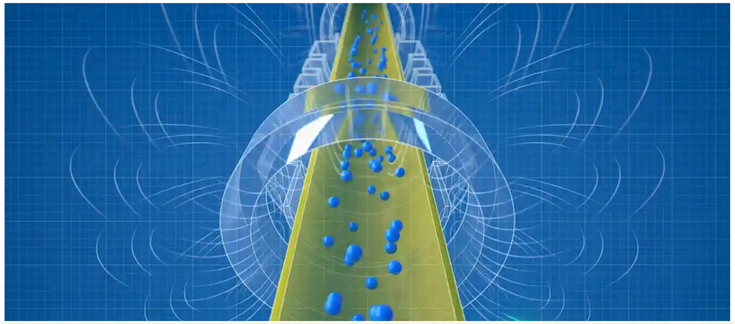
E. K. Anderson, C. J. Baker, W. Bertsche, N. M. Bhatt, G. Bonomi, A. Capra, I. Carli, C. L. Cesar, M. Charlton, A. Christensen, R. Collister, A. Cridland Mathad, D. Duque Quiceno, S. Eriksson, A. Evans, N. Evetts, S. Fabbri, J. Fajans, A. Ferwerda, T. Friesen, M. C. Fujiwara, D. R. Gill, L. M. Golino, M. B. Gomes Gonçalves, ... J. S. Wurtele + Show authors

Nature **621**, 716–722 (2023) | Cite this article

68k Accesses | **1612** Altmetric | Metrics

Scientists find antimatter is subject to gravity

Tests at Cern refute suggestion that antigravity might apply to antimatter, showing instead it also falls downwards



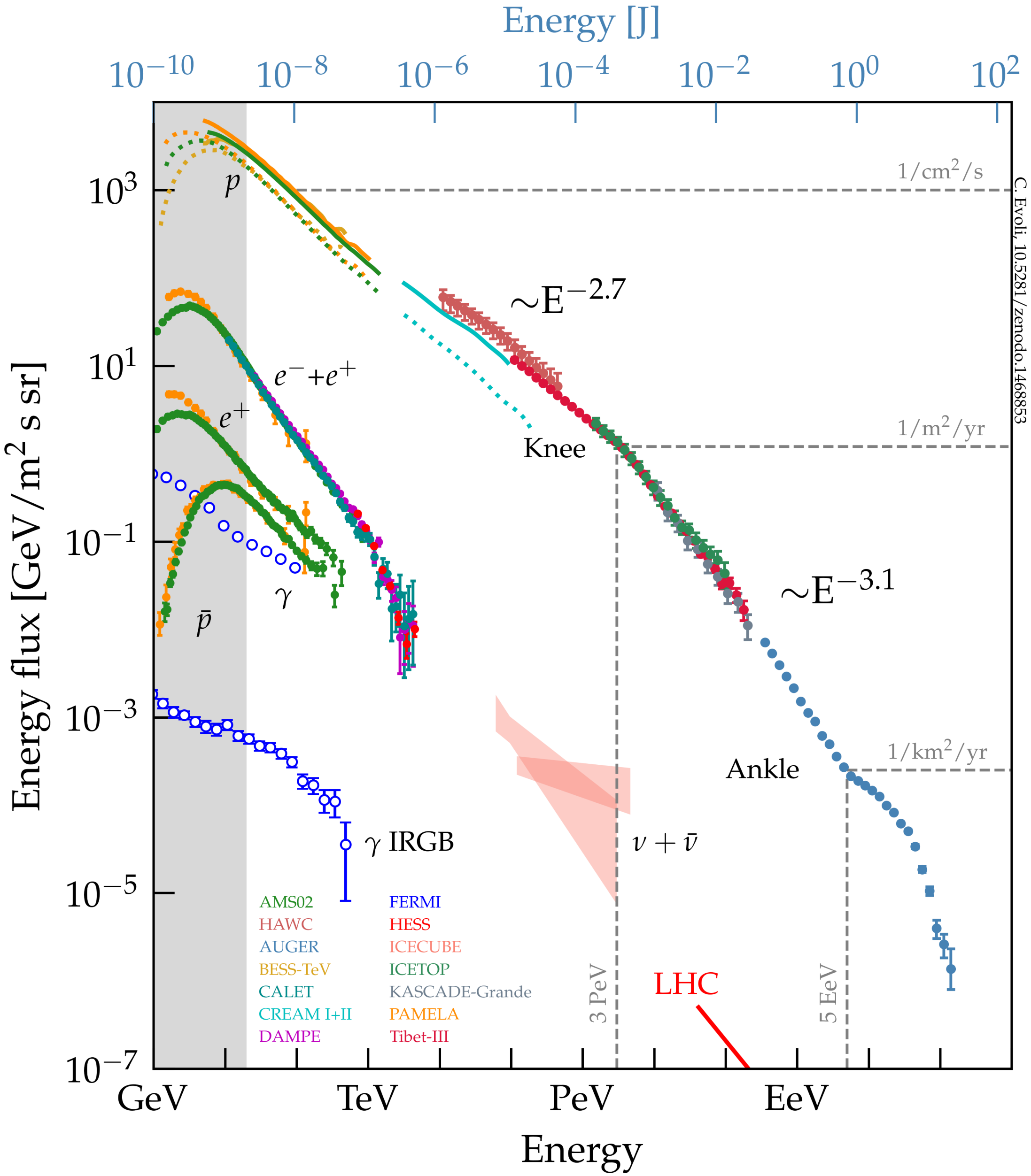
Antiprotons

Side-track on Baryon asymmetry

- Some contexts.

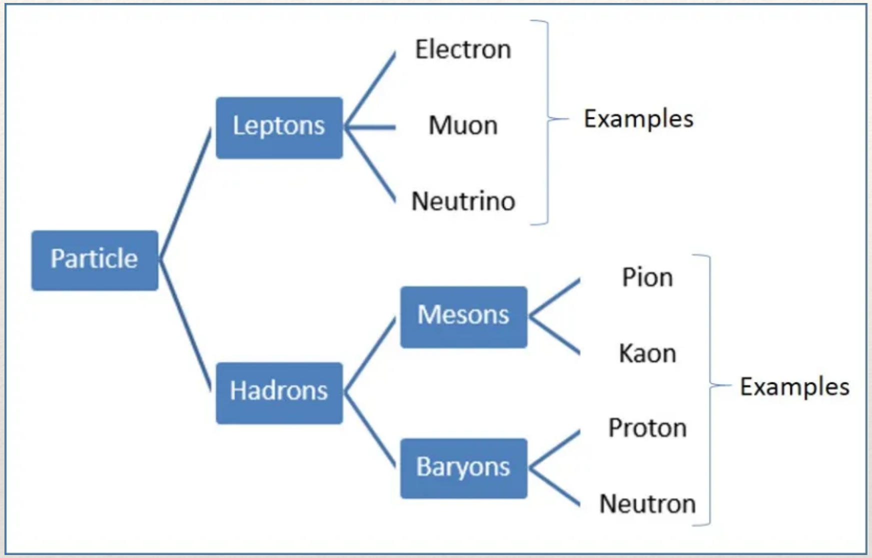
- We will return to this problem when talking about neutrinos
- The problem of Baryogenesis

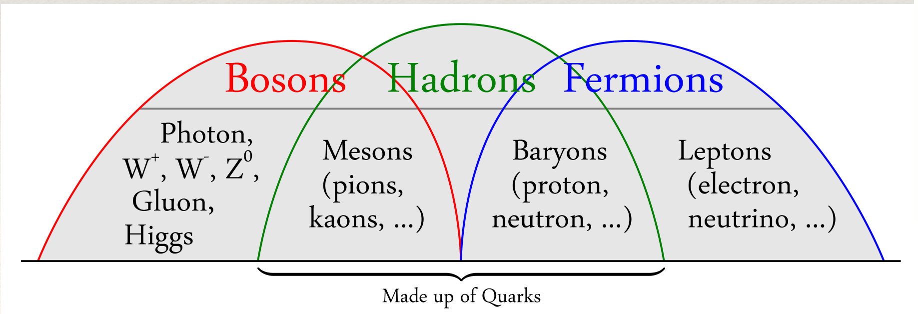
- Also all known physics are symmetric between matter and antimatter
- If the early universe is symmetric, how could we evolve to an asymmetric state?
  - The cosmic baryon to photon ratio is about 10^{-9}
  - In the early universe, when Temperature is above proton mass, free protons/antiprotons are everywhere in the universe.
  - They then annihilated with each other away, only a small fraction is left.
    - This "small fraction" is too big to be "Natural"!

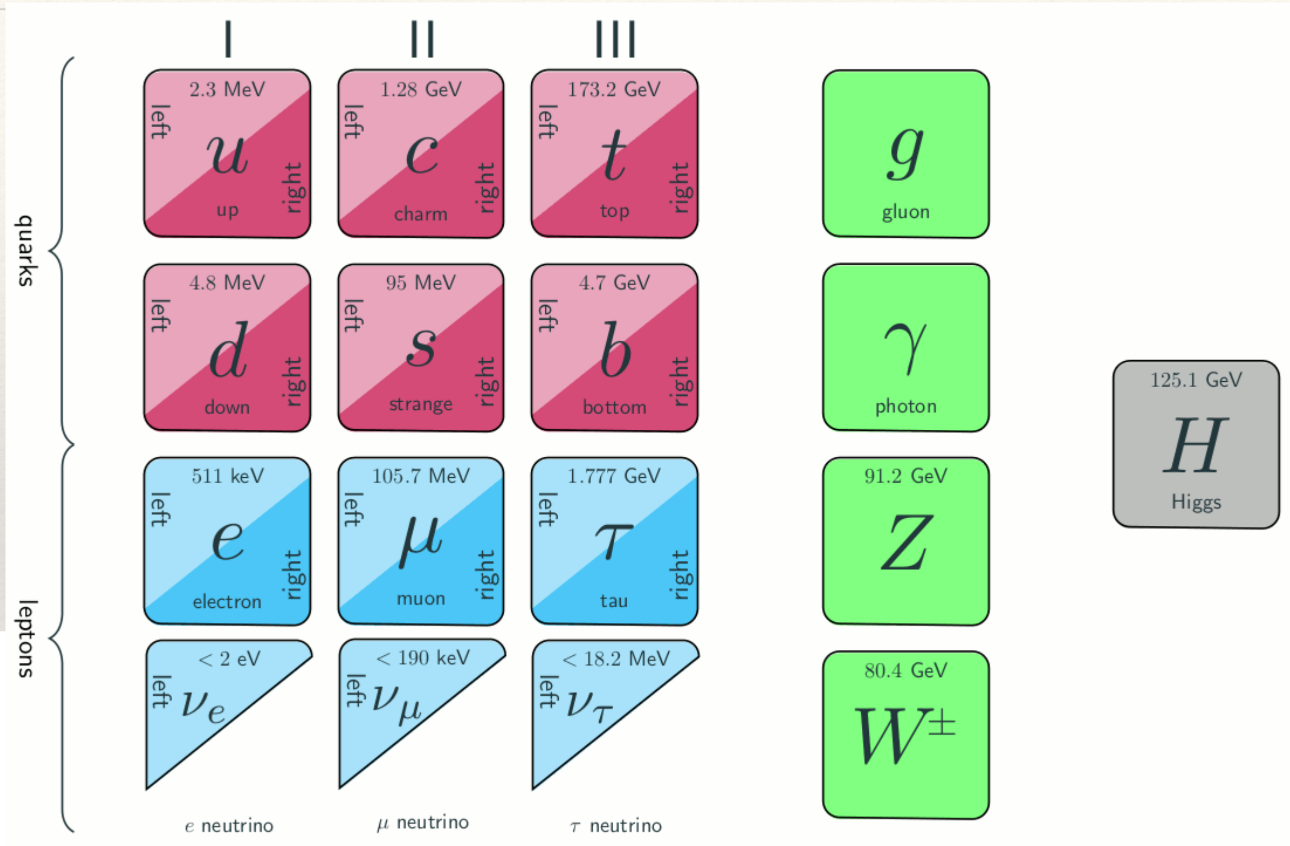


Energy [J]
10^−10
10^−8
10^−6
10^−4
10^−2
10^0
10^2
1/cm²/s
1/m²/yr
1/km²/yr
p
~E^−2.7
e^−+e^+
e^+
Knee
γ
p̄
~E^−3.1
Ankle
γ IRGB
ν + ν̄
AMS02
HAWC
AUGER
BESS-TeV
CALET
CREAM I+II
DAMPE
FERMI
HESS
ICECUBE
ICETOP
KASCADE-Grande
PAMELA
Tibet-III
3 PeV
5 EeV
LHC
10^3
10^1
10^−1
10^−3
10^−5
10^−7
Energy flux [GeV/m² s sr]
GeV
TeV
PeV
EeV
Energy
C. Evoli, 10.5281/zenodo.1468853

Particle physicist



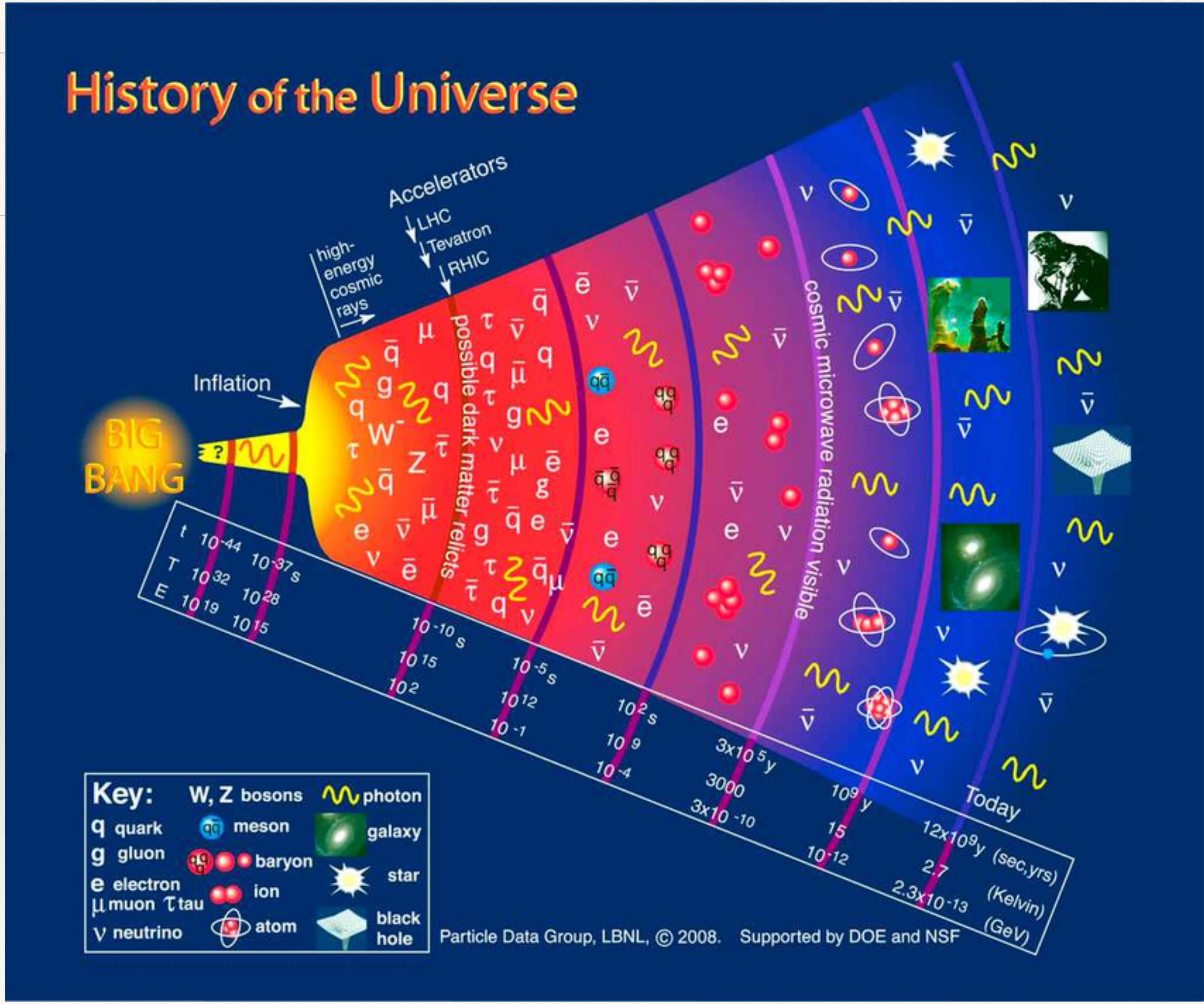




Cosmologists

Baryon = Normal Matter

Matter = non-relativistic stuff

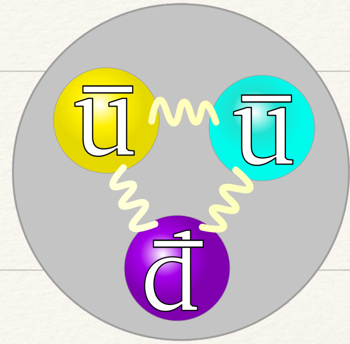

History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s 10-10 s 10-5 s 10² s 3x10⁵ y 10⁹ y 12x10⁹ y (sec,yrs)
T 10³² 10²⁸ 10¹⁵ 10¹² 10⁹ 3000 15 2.7 (Kelvin)
E 10¹⁹ 10¹⁵ 10² 10-1 10-4 3x10-10 10-12 2.3x10-13 (GeV)
Today
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
black hole
ν neutrino
atom
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Sakharnov Conditions for baryogenesis

- **Baryon Number violation**
    - $n + \nu_e \rightarrow p^+ + e^-$ [x]
    - $N \rightarrow B$ (creation of net baryon number)
- **CP and C violation (**$N \rightarrow B$**)**
    - Asymmetric Universe is odd under C and CP
    - $\Gamma_N \neq \Gamma_{\bar{N}}$ ($N \rightarrow B \neq \bar{N} \rightarrow \bar{B}$)
    - $\Gamma_{N_L} \neq \Gamma_{\bar{N}_R}$ (otherwise, $\Gamma_{N_L} + \Gamma_{N_R} = \Gamma_{\bar{N}_L} + \Gamma_{\bar{N}_R}$)
- **Out of thermal equilibrium**
    - Thermal equilibrium drives $B \rightarrow N$ reactions

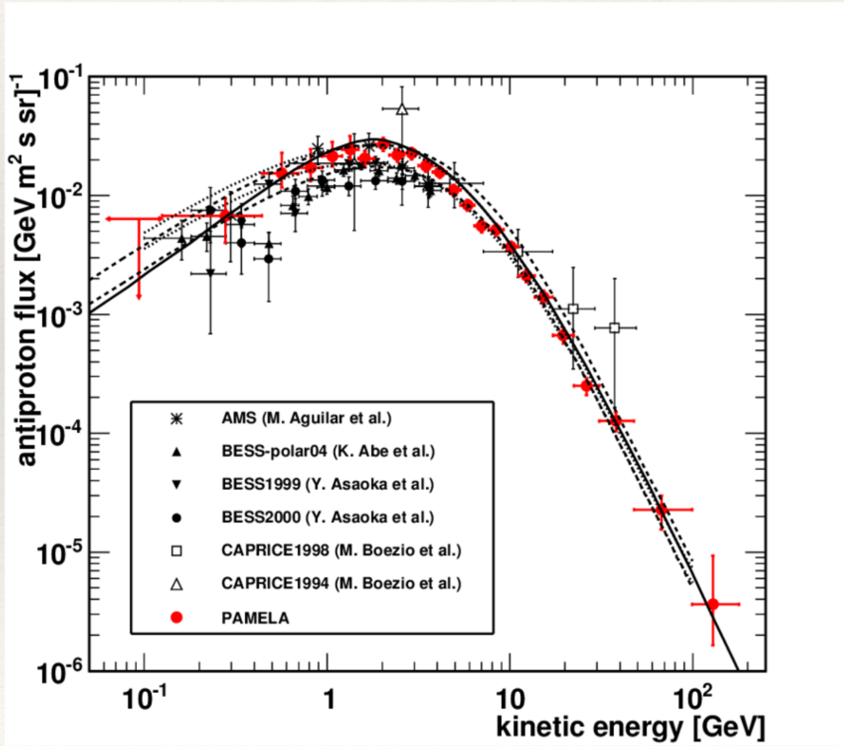
- Peace Price 1975

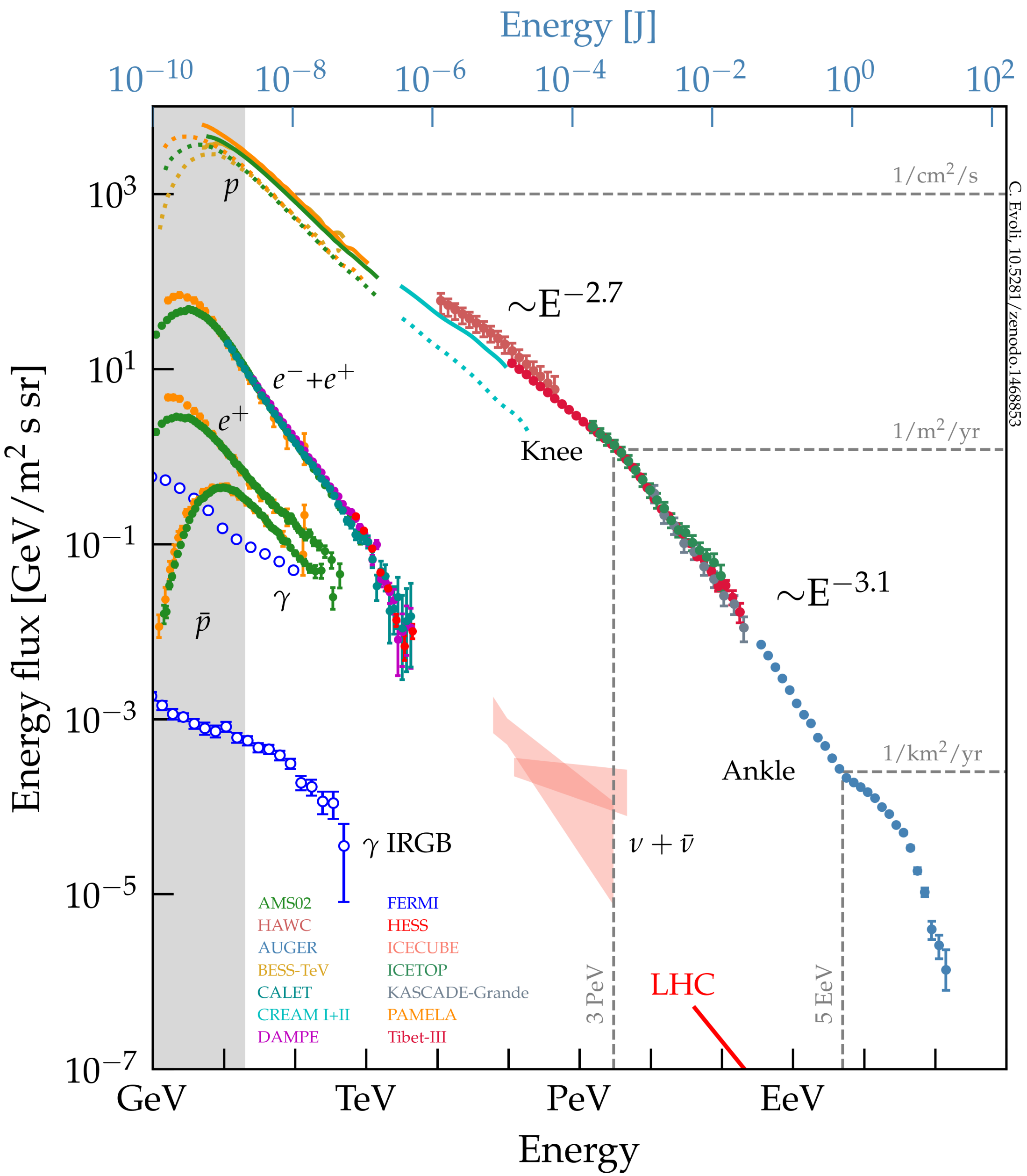
Cosmic ray anti-protons



- Where does anti-proton come from?
  - Anti-proton source
  - Secondary production

- Anti-proton source can be inferred if there are excess above known secondary production





Energy [J]
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
Energy flux [GeV/m² s sr]
10^{3}
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
$1/cm^2/s$
$1/m^2/yr$
$1/km^2/yr$
C. Evoli, 10.5281/zenodo.1468853
p
$\sim E^{-2.7}$
e^-+e^+
e^+
Knee
γ
$\bar{p}$
$\sim E^{-3.1}$
Ankle
γ IRGB
$\nu + \bar{\nu}$
AMS02
HAWC
AUGER
BESS-TeV
CALET
CREAM I+II
DAMPE
FERMI
HESS
ICECUBE
ICETOP
KASCADE-Grande
PAMELA
Tibet-III
3 PeV
LHC
5 EeV
GeV
TeV
PeV
EeV
Energy

CR pbar production

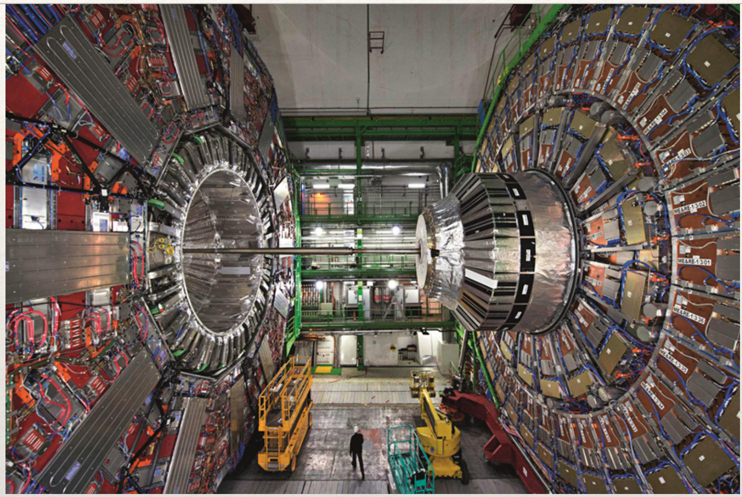
- $n_B = n_C \sigma_{C->B} \frac{X}{m} - n_B \sigma_{B->X} \frac{X}{m}$
- Need anti-proton production cross section
- $n_{\bar{p}} = \left(n_p \sigma_{pp->\bar{p}X} - n_{\bar{p}} \sigma_{\bar{p}->X} \right) \frac{X}{m}$
-

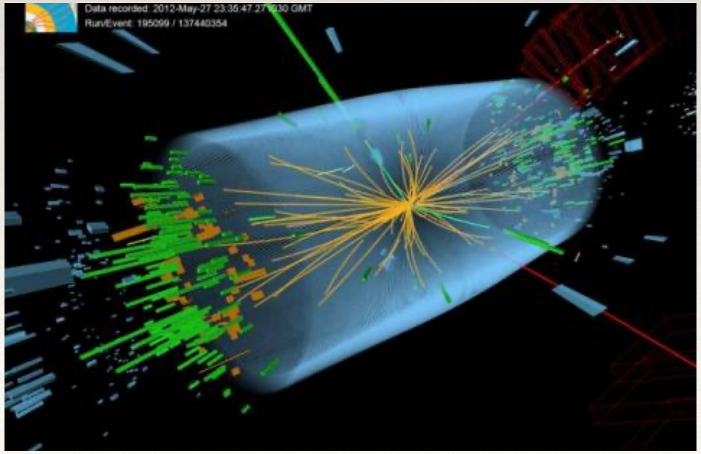
CR pbar production

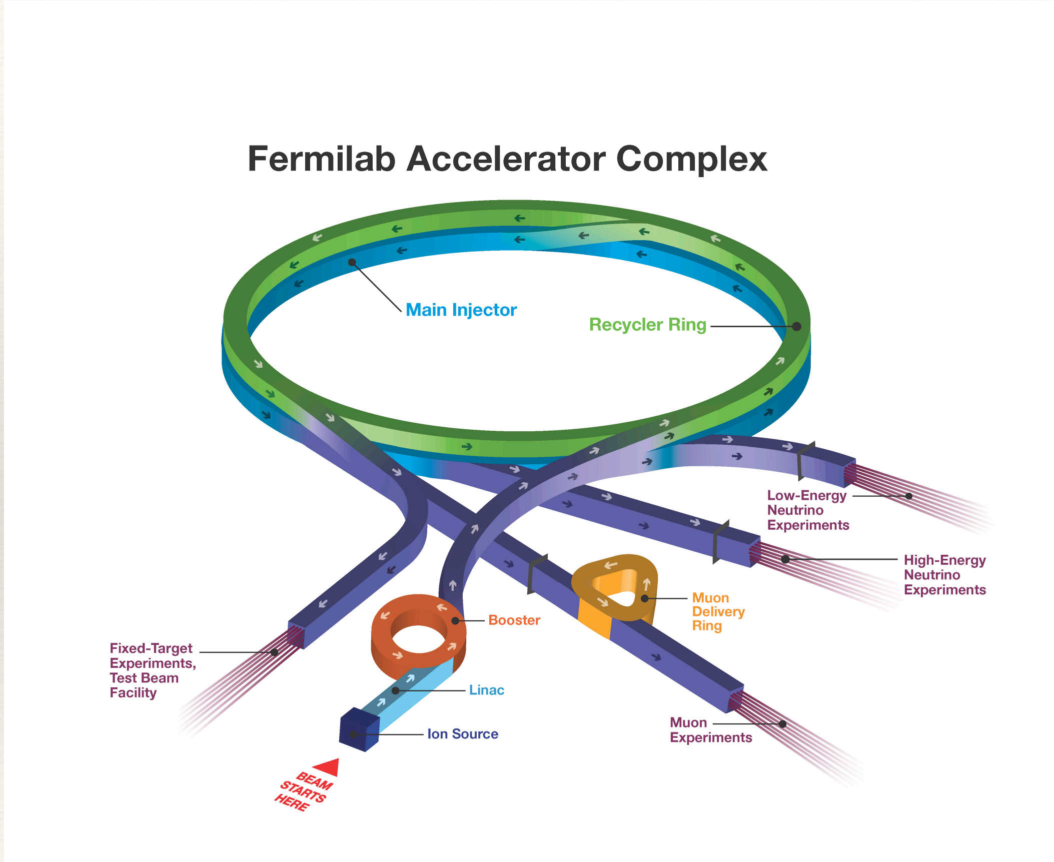
- Need anti-proton production cross section
- Interstellar medium, mostly hydrogen, some Helium (p, He)
- We want $p + p \to X + \bar{p}$ (the dominant one) and $p + He \to X + \bar{p}$
  - things people measure in collider
  - These are called "inclusive" reactions
    - Vs "exclusive" $(p + p \to p + p + p + \bar{p})$

Rule of thumbs for particle interactions
Quantum number conservation
- Baryon number
- Lepton number
- Charge

Collider vs Cosmic rays







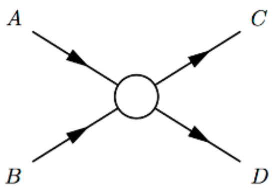
Collider vs Cosmic rays

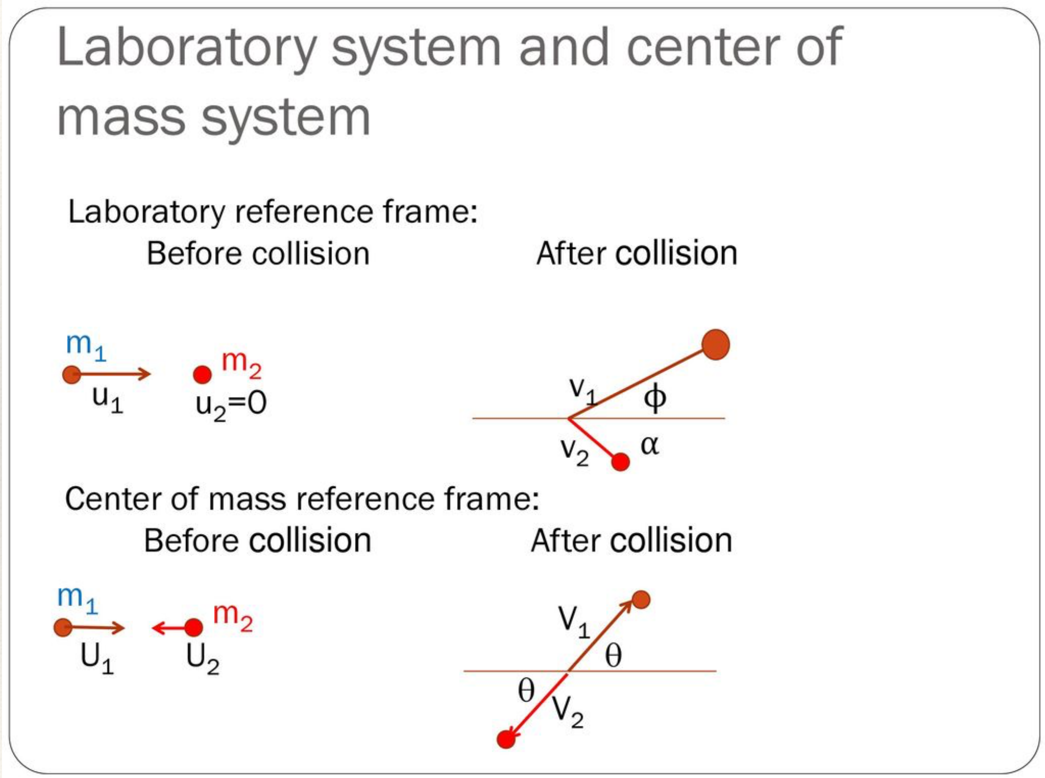
- LHC 14 TeV center of mass energy

- Mandelstam variables
  - Scalars that are Lorentz Invariant

Mandelstam variables: For the scattering process AB to CD, the Mandelstam variables s,t and u can be defined as

$$s \equiv (p_A + p_B)^2, \qquad t \equiv (p_A - p_C)^2, \qquad u \equiv (p_A - p_D)^2$$





- Center of mass energy "s"

Collider vs Cosmic rays

- $s = (p^\mu + p^\nu)^2$
- For LHC, headon beams with 7 TeV each
- $\sqrt{s} = 14$ **TeV**

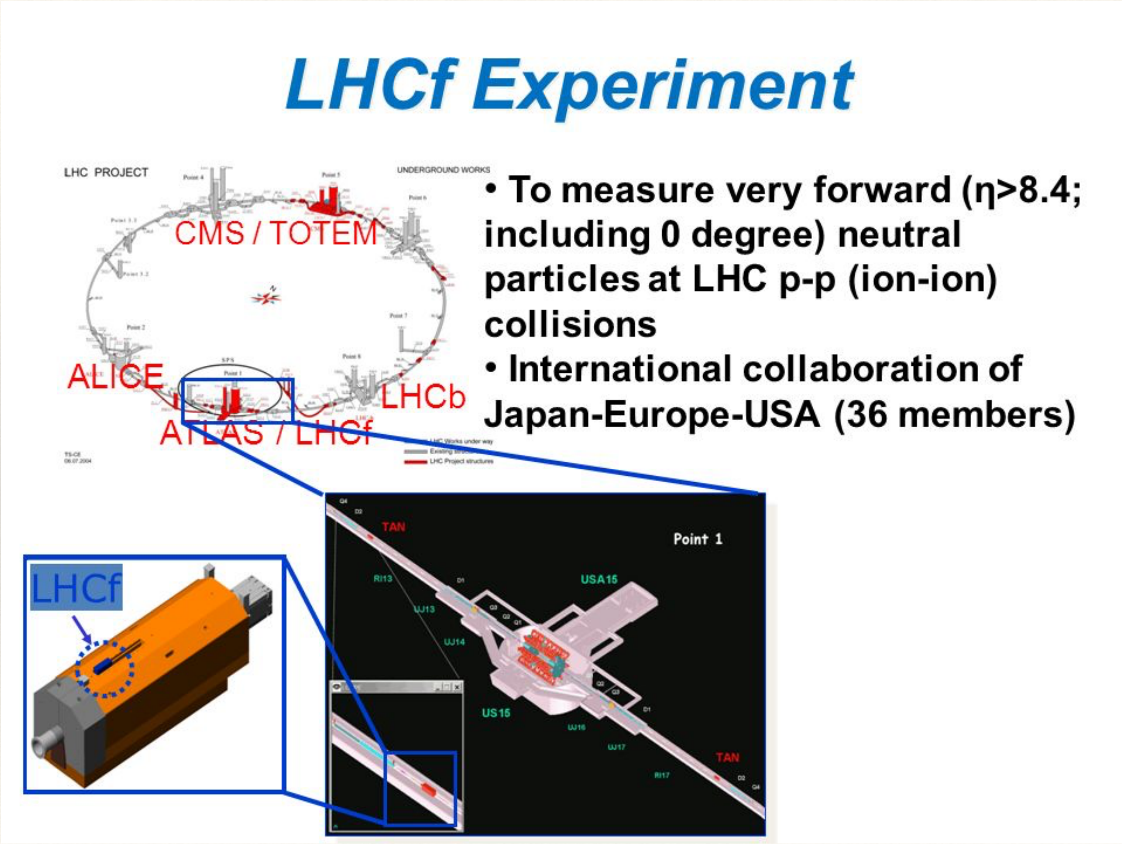
$$p_\mu = \left(\frac{E}{c}, p_x, p_y, p_z\right)$$

- In the CR frame, the target is at rest.

- $s = (p^\mu + p^\nu)^2$
- $p_\mu = (?, ?)$
- $p_\nu = (?, ?)$

LHCf, a collider CR experiment

- Collider data is important for understanding cosmic ray data
- Energy is the not the challenging part
- Rather, it is the kinematic coverage
  - Colliders are inherently most sensitive to transverse events
    - Perpendicular to beam
- For CRs, forward events are most important
  - Why?



pbar production

- There is an energy threshold for production
- $p + p \rightarrow \bar{p} + X$
- Exercise!
- Given a center of mass energy, there is also maximum energy for the antiproton
- Exercise!
-

Imagine what configurations can yield the extremes

pbar production

- There is an energy threshold for production
- $p + p \to \bar{p} + X$

- Want energy of the anti-proton $T_{\bar{p}}$, the rest we dont care
- We need the probability for the production of $\bar{p}$ at specific energies $T_{\bar{p}}$
- Differential cross section $\dfrac{d\sigma_{pp->\bar{p}X}}{dT_{\bar{p}}}(E_p, T_{\bar{p}})$

Differential Cross section

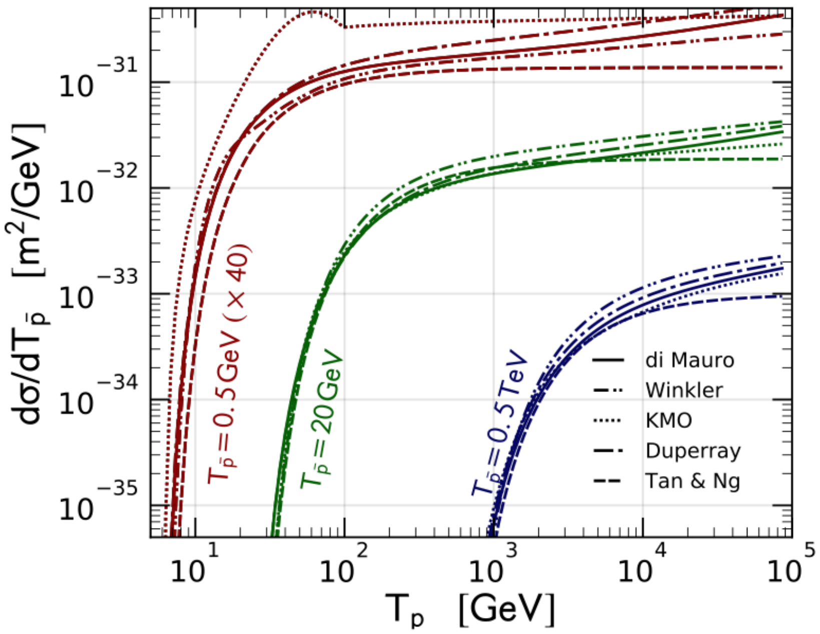
- We need more information than whether an interaction happened or not
  - (Total cross section)
  - $$\frac{dP}{dt} = n\sigma$$
- We need the differential probability that an antiproton with energy T is produced
- $$\frac{dP}{dtdT} = n\frac{d\sigma}{dT}$$
  - The information is contained in the differential cross section.

- The old formalism doesnt tell us what is the outgoing antiproton energy T!!
  - (Not kinetic energy per nucleon to use here)
- $n_{\bar{p}}(T_{\bar{p}}) = \left(n_p(E_p)\sigma_{pp->\bar{p}X} - n_{\bar{p}}\sigma_{\bar{p}->X} \right) \frac{X}{m}$

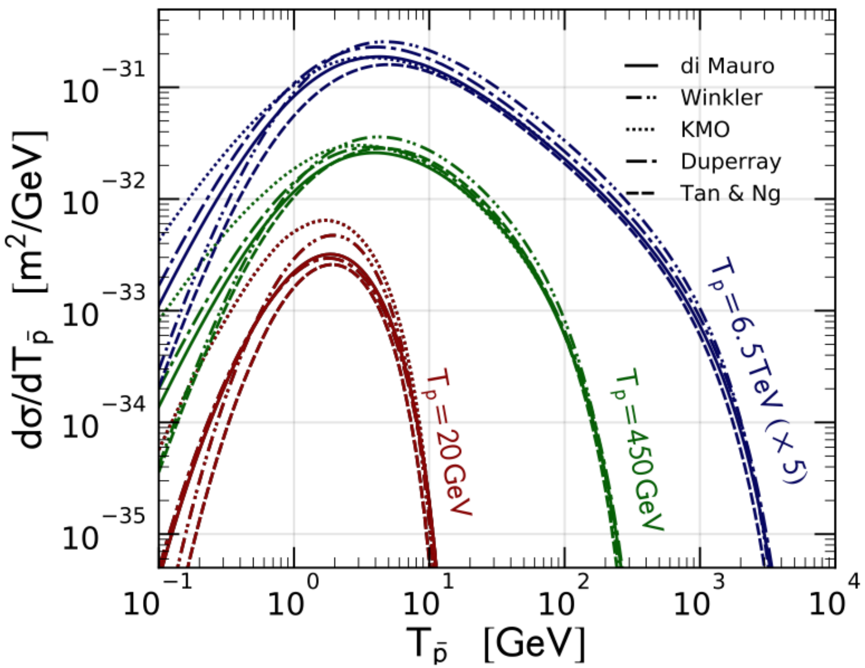
- Need to use the differential cross section.
- $n_{\bar{p}}(T_{\bar{p}}) = \left(\int_{E_{th}} n_p(E_p) \frac{d\sigma_{pp->\bar{p}X}}{dT_{\bar{p}}}(E_p, T_{\bar{p}}) dE_p - n_{\bar{p}}\sigma_{\bar{p}->X} \right) \frac{X}{m}$

pbar production

$$\frac{d\sigma_{ij}}{dT_{\bar{p}}}(T_i, T_{\bar{p}}),$$



(a)

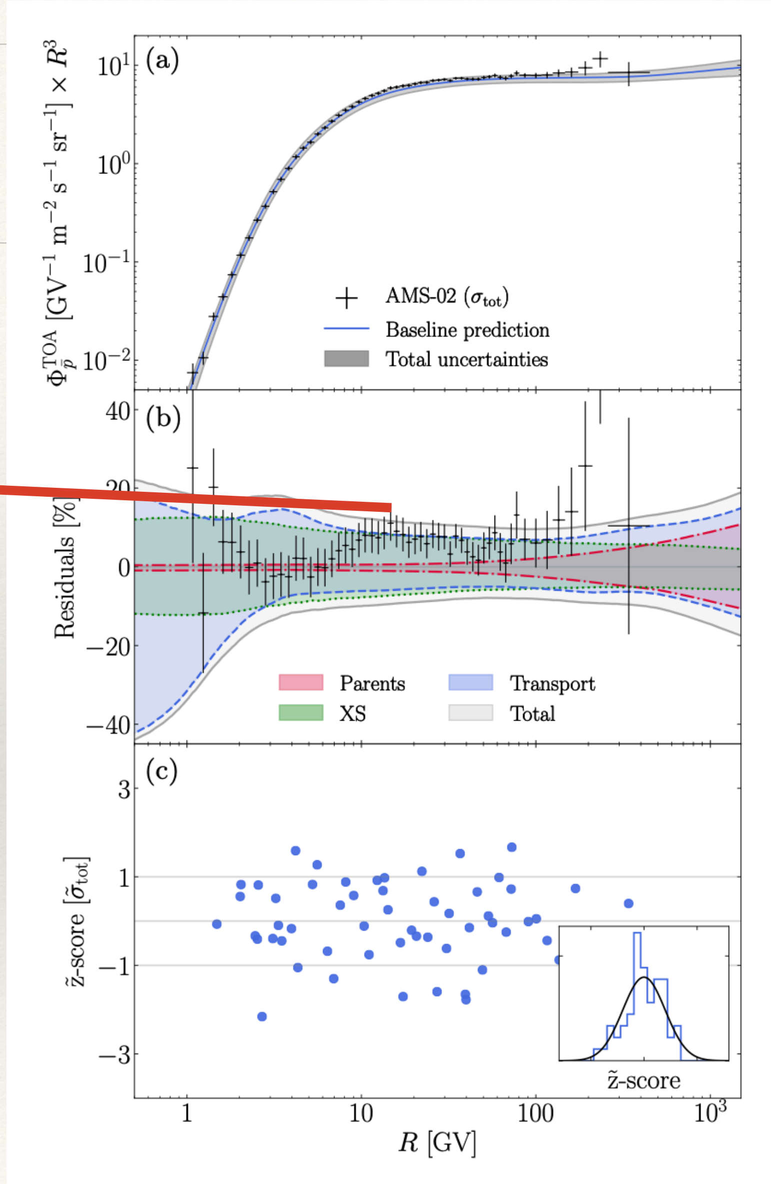


(b)

State of the art for pbar

- Uncertainties wrt
  - Parent proton flux
  - Cross sections
  - Propagation (within some models)
- Maybe more?

Excess?



AMS-02 antiprotons' consistency with a secondary astrophysical origin

Mathieu Boudaud,[1,*] Yoann Génolini,[2,†]
Laurent Derome,[3] Julien Lavalle,[4] David Maurin,[3] Pierre Salati,[5] and Pasquale D. Serpico[5]

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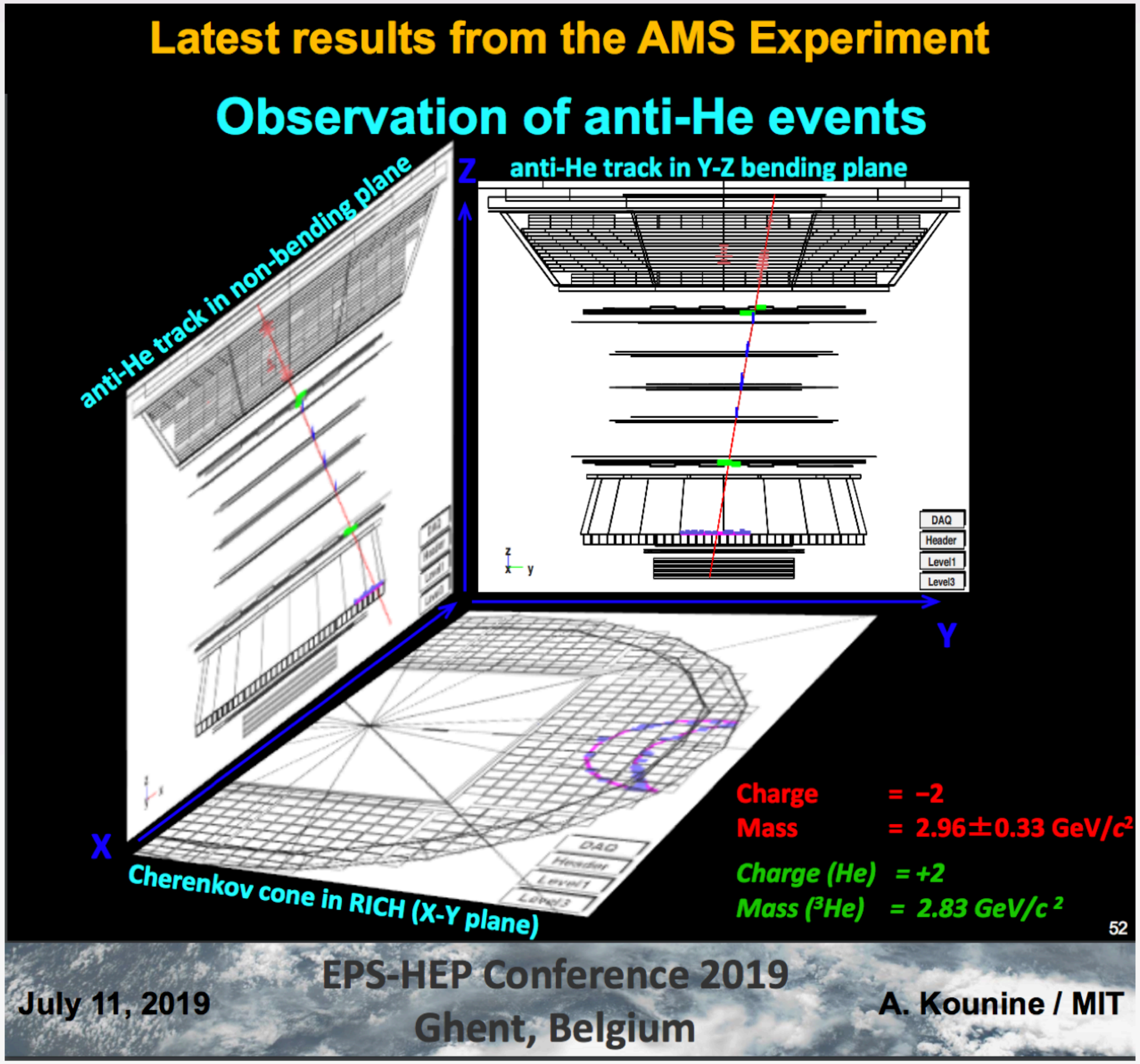
In memory of Mathieu, our dear friend and colleague, who passed away while this work was under review.

Cosmic ray anti-nuclei

- Where do they come from?



Cosmic ray anti-nuclei production

- The coalescence picture

- What we want, is the production cross section for e.g., anti-deuteron
- $\frac{d\sigma}{dT_{\bar{d}}}$
- This is usually expressed in Lorentz invariant form

$$\gamma_{\bar{d}} \frac{\mathrm{d}^3 N_{\bar{d}}}{\mathrm{d}p_{\bar{d}}^3} = \frac{4\pi}{3} p_0^3 \left(\gamma_{\bar{p}} \frac{\mathrm{d}^3 N_{\bar{p}}}{\mathrm{d}p_{\bar{p}}^3} \right) \left(\gamma_{\bar{n}} \frac{\mathrm{d}^3 N_{\bar{n}}}{\mathrm{d}p_{\bar{n}}^3} \right)$$

- Production yield of pbar and nbar
- Fitting parameter, so called "coalescence momentum "
- Where $d\sigma = \sigma_{tot} dN$

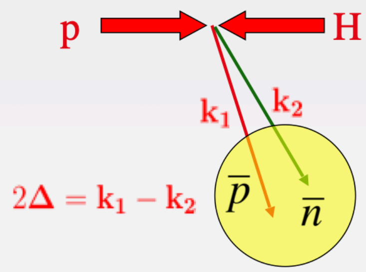
- The coalescence picture

- To form a nucleus from particle interaction, the outgoing particles need have a small relative momentum, so that they can stick together

- So production cross section for d-bar is proportional to (antiparticle production)^2 x Coalescence factor

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

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

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

Coalescence factor B_2

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

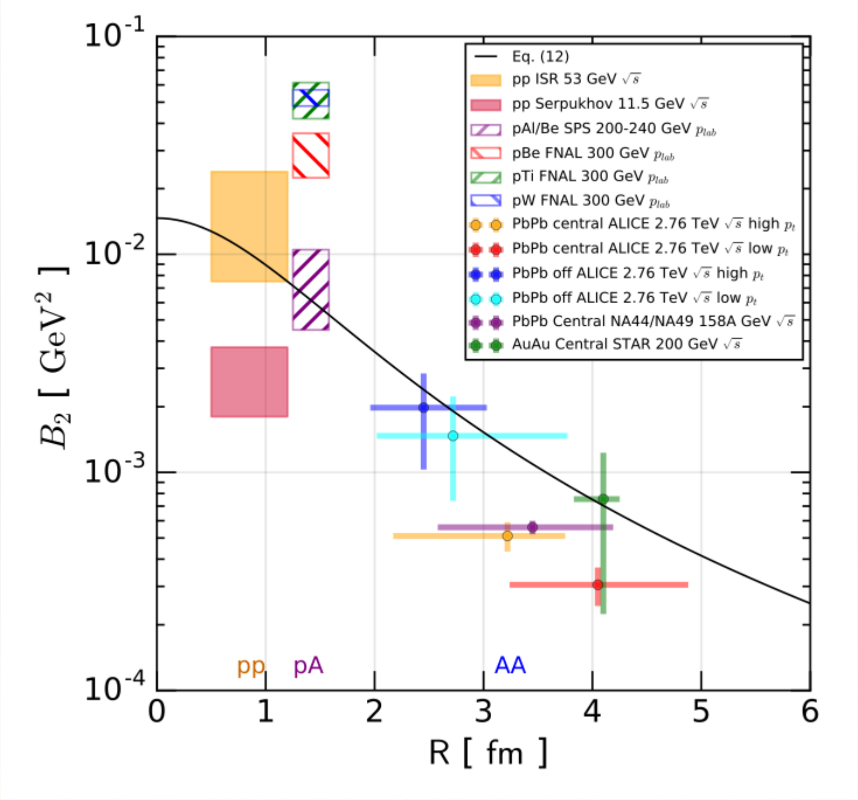
Courtesy Pierre Salati

Cosmic ray anti-nuclei production

- No one knows how to calculate the "coalescence momentum" factor
- Experiments

$$\gamma_{\bar{d}} \frac{\mathrm{d}^3 N_{\bar{d}}}{\mathrm{d}p_{\bar{d}}^3} = \frac{4\pi}{3} p_0^3 \left(\gamma_{\bar{p}} \frac{\mathrm{d}^3 N_{\bar{p}}}{\mathrm{d}p_{\bar{p}}^3} \right) \left(\gamma_{\bar{n}} \frac{\mathrm{d}^3 N_{\bar{n}}}{\mathrm{d}p_{\bar{n}}^3} \right)$$

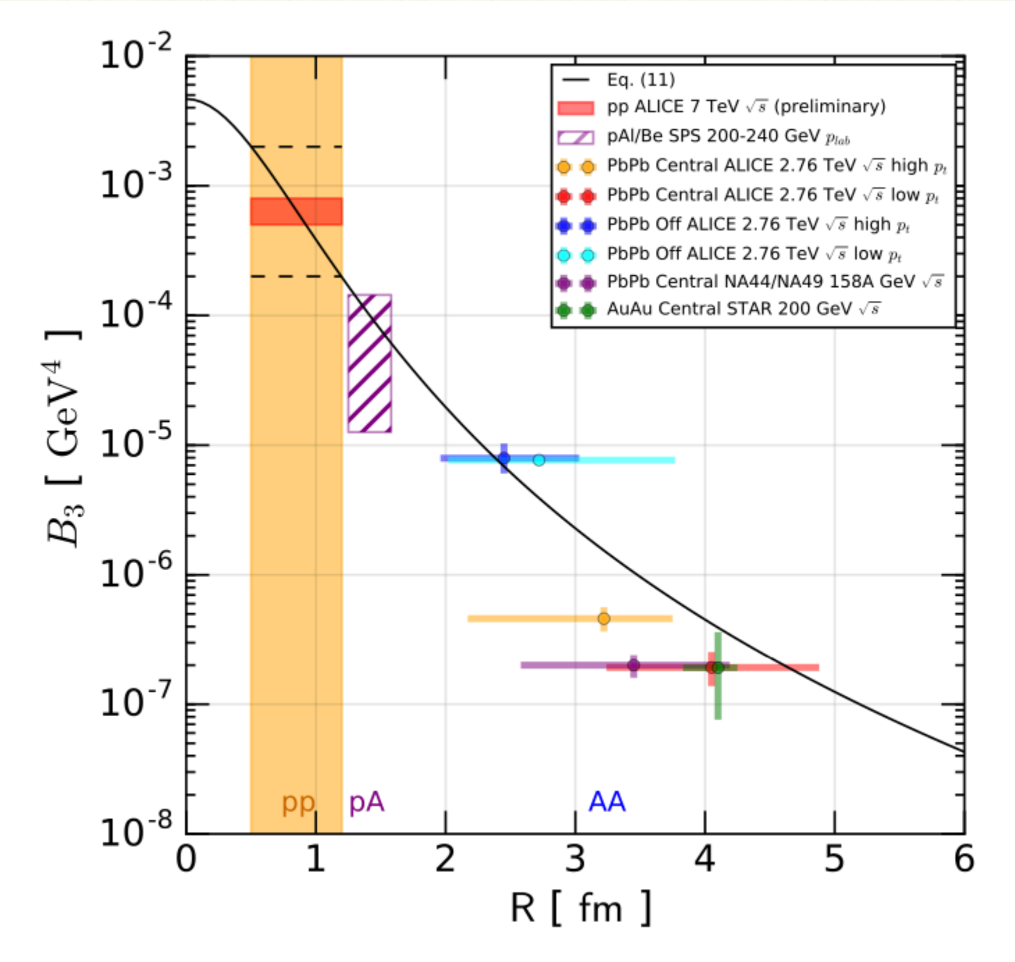
$$B_A = \frac{A}{m_p^{A-1}} \left(\frac{4\pi}{3} p_0^3 \right)^{A-1}$$



Or sometimes, just call it "B" factor

$$E_A \frac{dN_A}{d^3 p_A} = B_A \, R(x) \left(E_p \frac{dN_p}{d^3 p_p} \right)^A$$

Cosmic ray anti-nuclei production



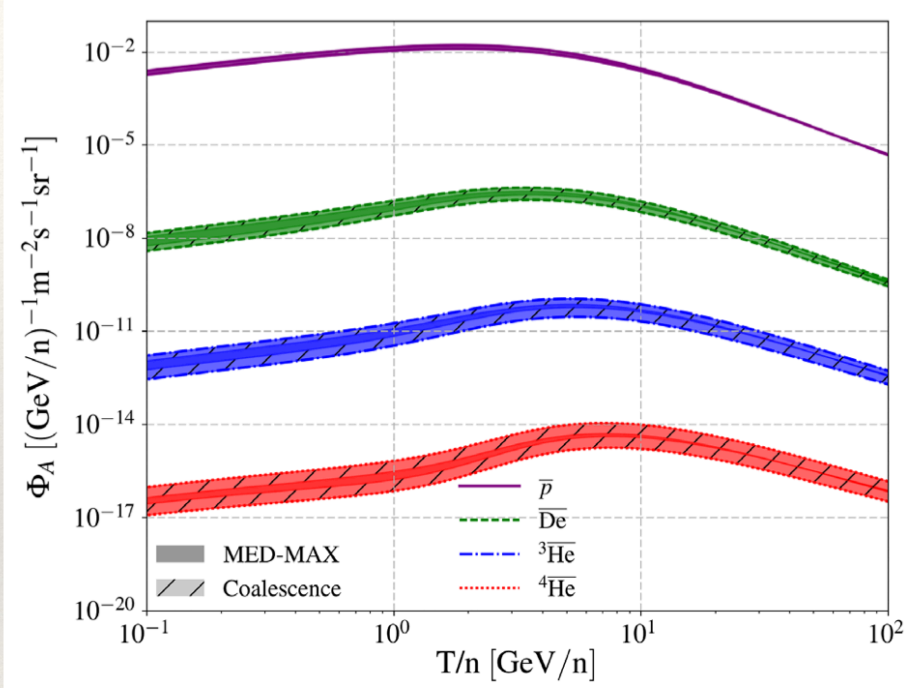


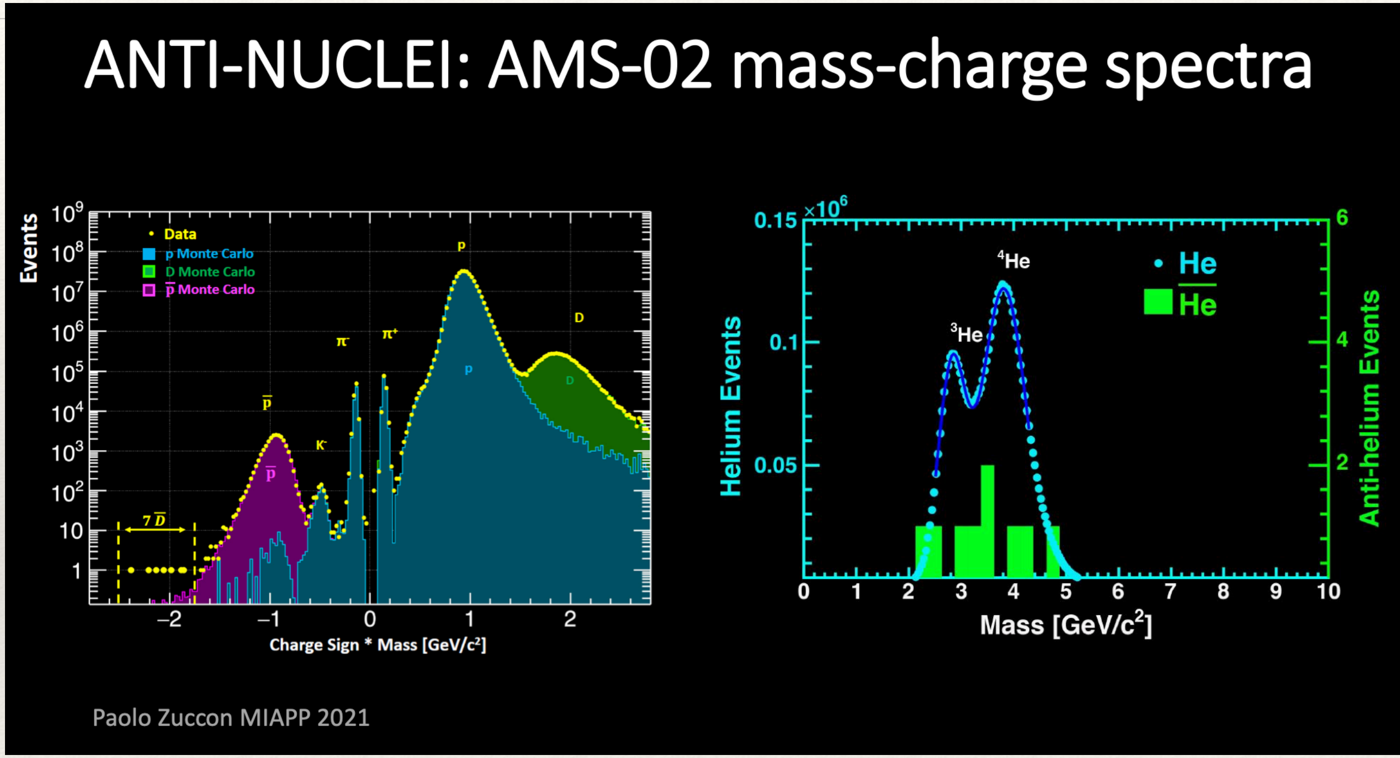
FIG. 2. Predicted secondary flux of $\bar{p}$, $\bar{d}$, $^3\overline{\mathrm{He}}$ and $^4\overline{\mathrm{He}}$ showing the uncertainty associated to the propagation and the coalescence momentum.

Cosmic ray anti-nuclei production

- Ams preliminary data

- 6 anti-helium-3?
- 3 anti-helium-4????

- If true, challenges standard model physics



Cosmic Electrons and Positrons