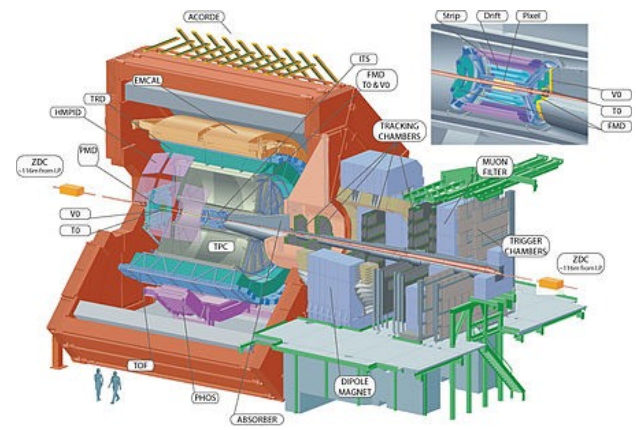
Cosmic rays, anti-helium, and an old navy spotlight

1704.05431, 1709.06507

Kfir Blum
CERN & Weizmann Institute



Geneva U., Sep 27 2017

CR antimatter – $\bar{p}$, e^+, $\bar{\mathrm{d}}$, and $\overline{^3\mathrm{He}}$ – long thought a smoking gun of exotic high-energy physics like dark matter annihilation

…and key diagnostic of CR propagation

CR antimatter – $\bar{p}$, e^+, $\bar{\mathrm{d}}$, and $\overline{^3\mathrm{He}}$ – long thought a smoking gun of exotic high-energy physics like dark matter annihilation

A host of experiments out there to detect it.

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Antiprotons

Some confusion in the literature, as to what and how we can calculate.

=> will try to sort this out

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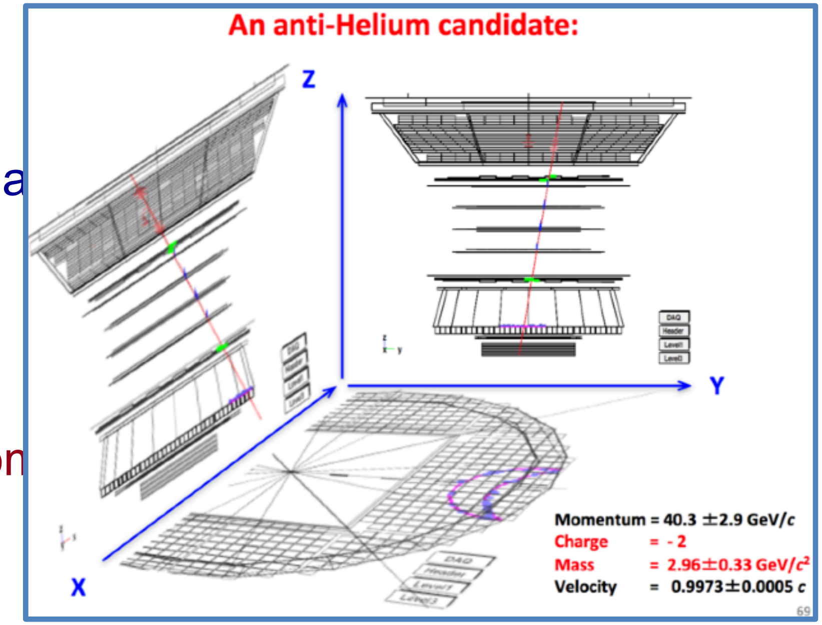

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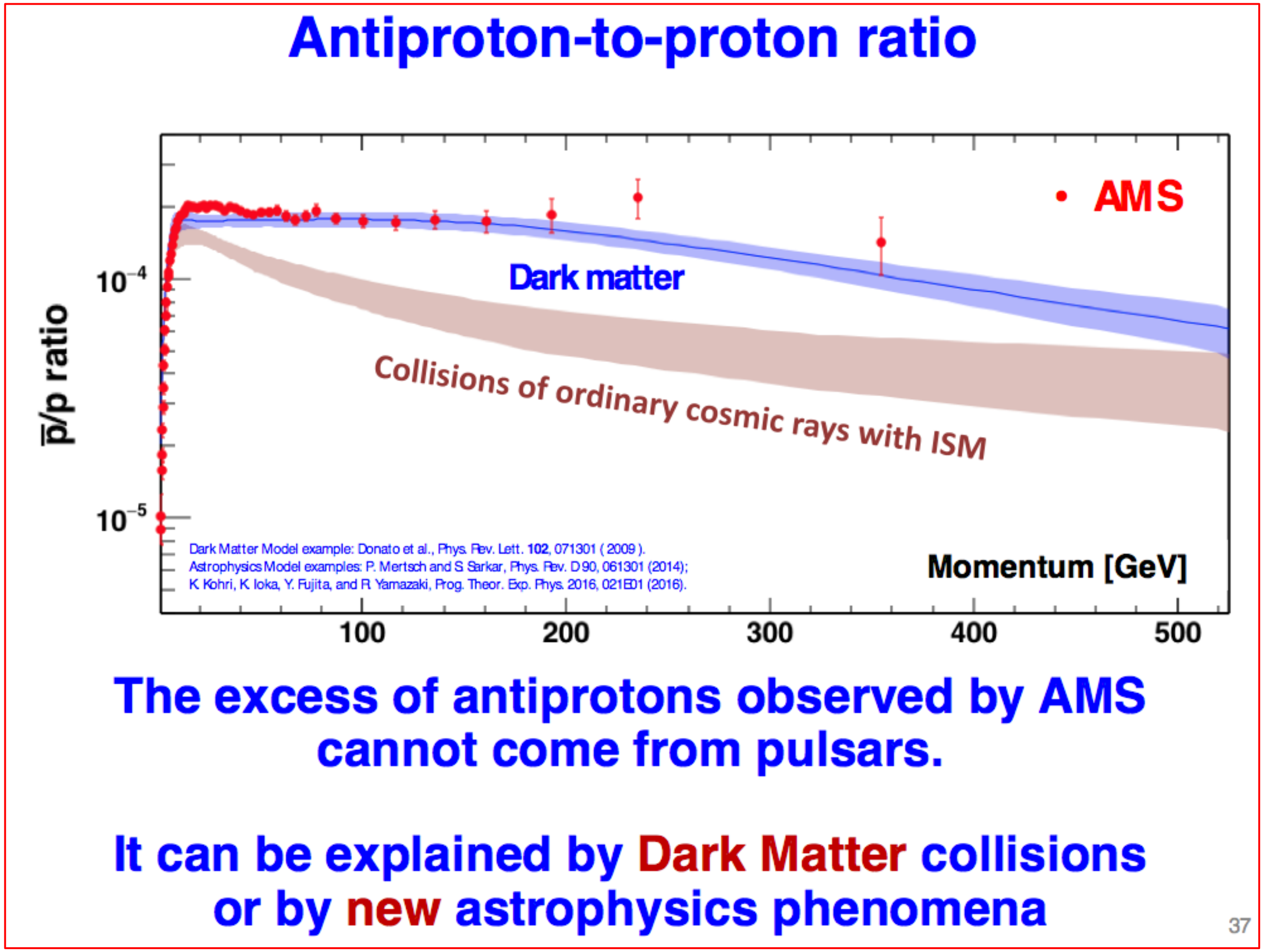
=> but how does one actually calculate the flux?

Could it be that AMS02 **have detected** astrophysical anti-He3?

AMS02, Dec 2016



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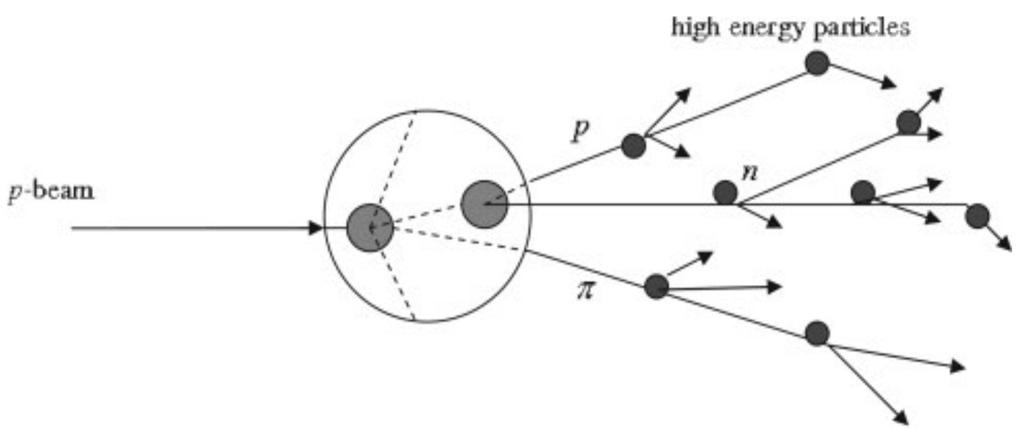
-- protons and He – with interstellar gas

Need to calculate this background to learn about possible exotic sources



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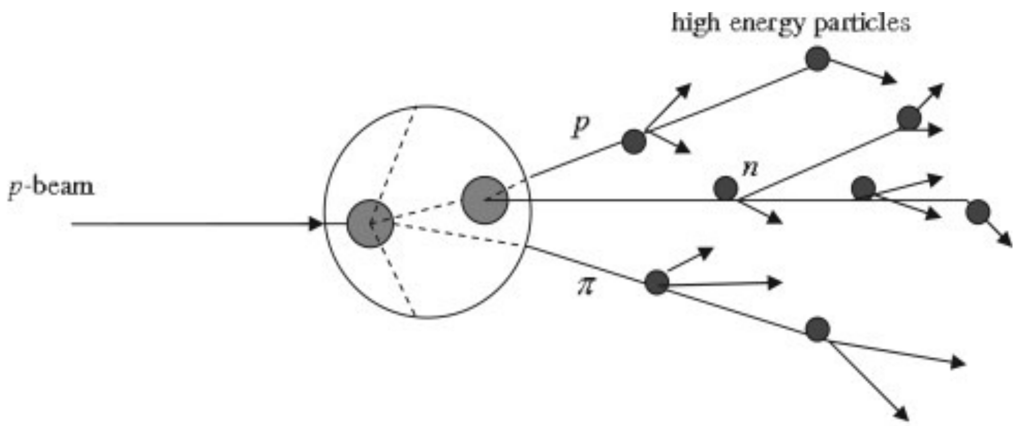
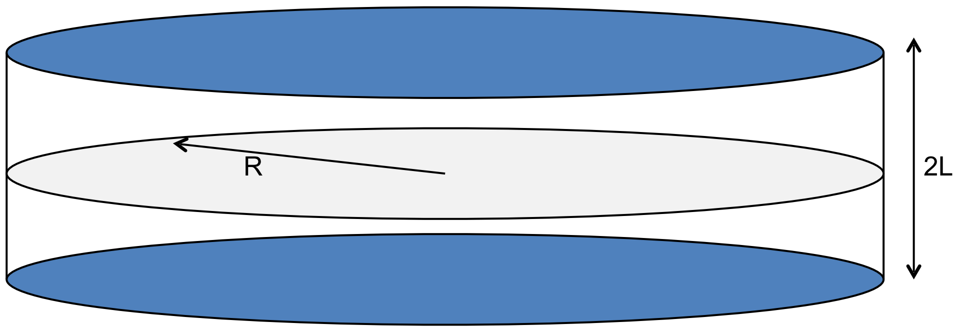
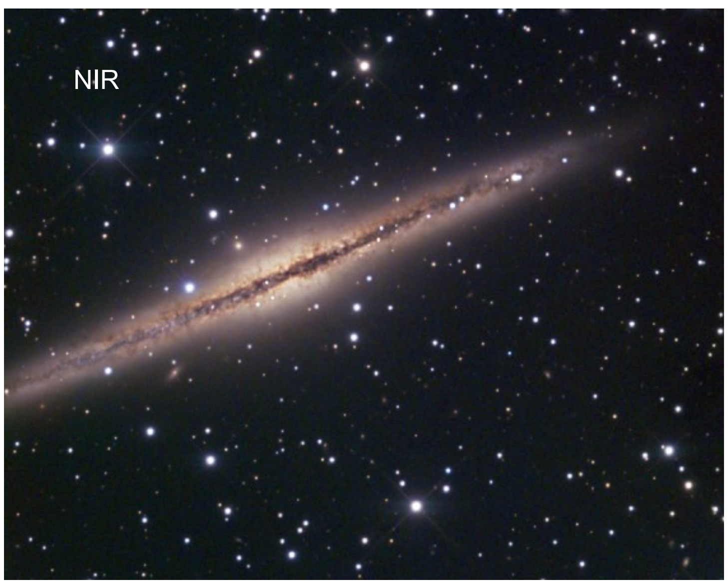


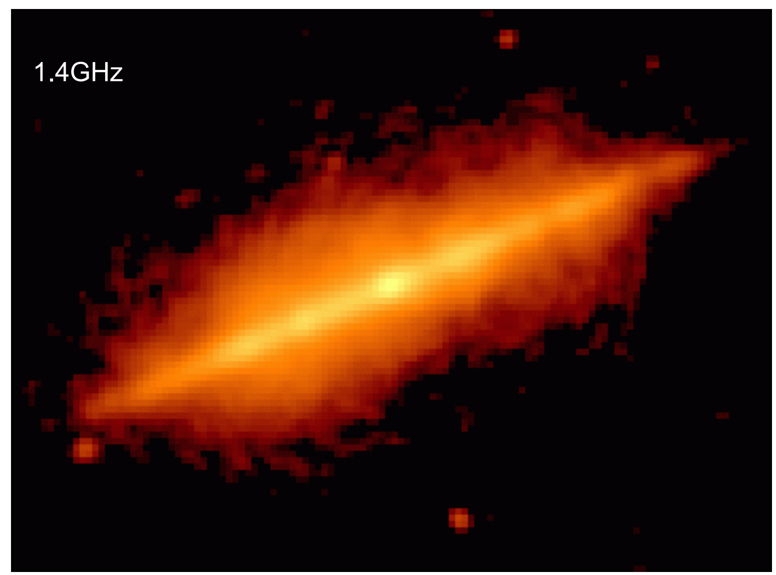
About diffusion models

$K \sim (E/Z)^{\delta}$



NGC 891

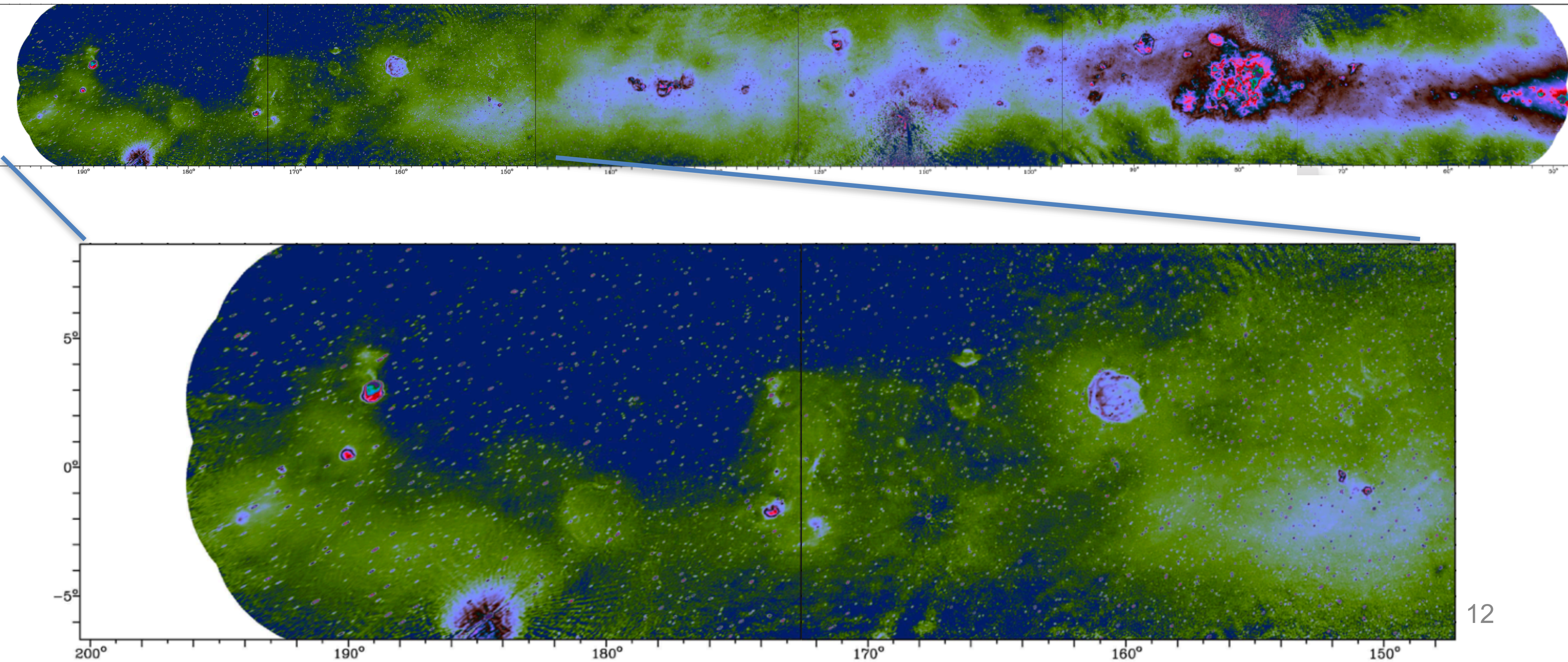




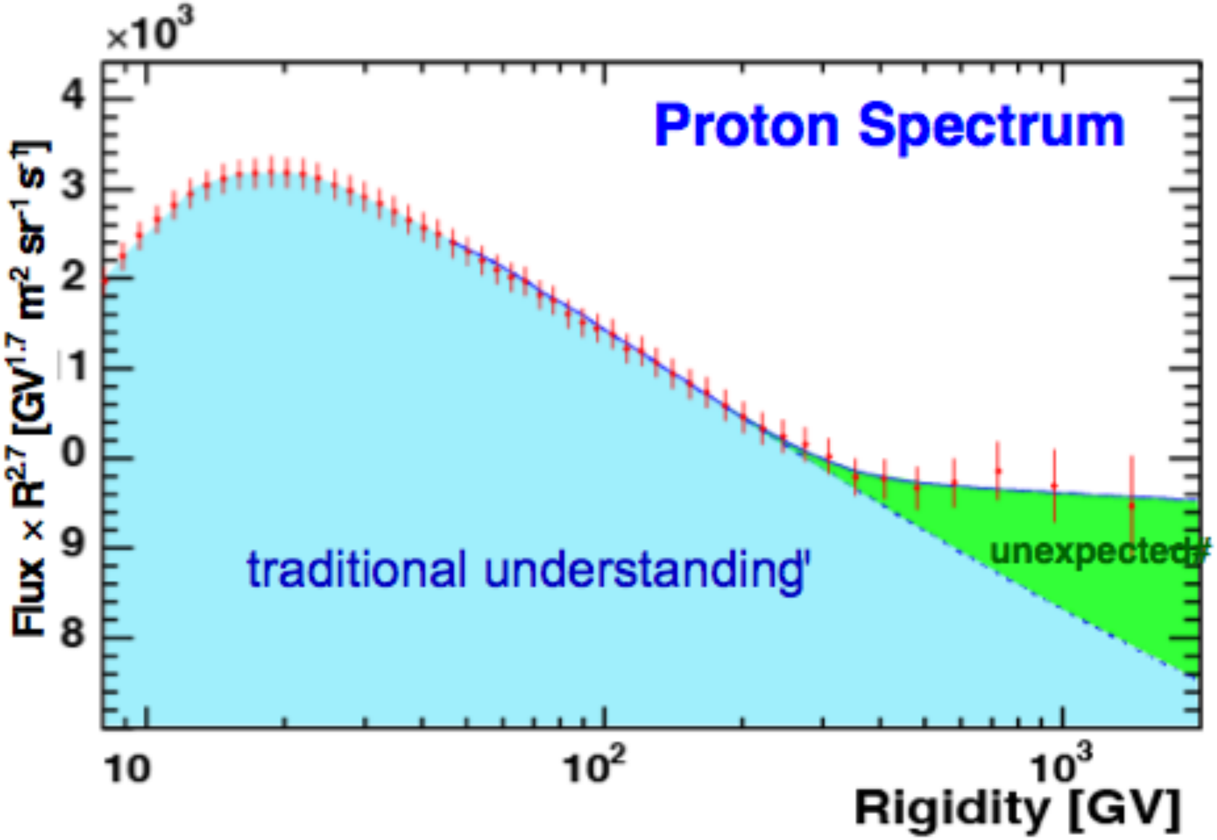
Strong, Moskalenko, Ptuskin, Ann.Rev.Nucl.Part.Sci. 57 (2007) 285-327

arxiv:1708.04316

408MHz (Canadian Galactic Plane Survey)



S. Schael, **Moriond 2016 for AMS02**



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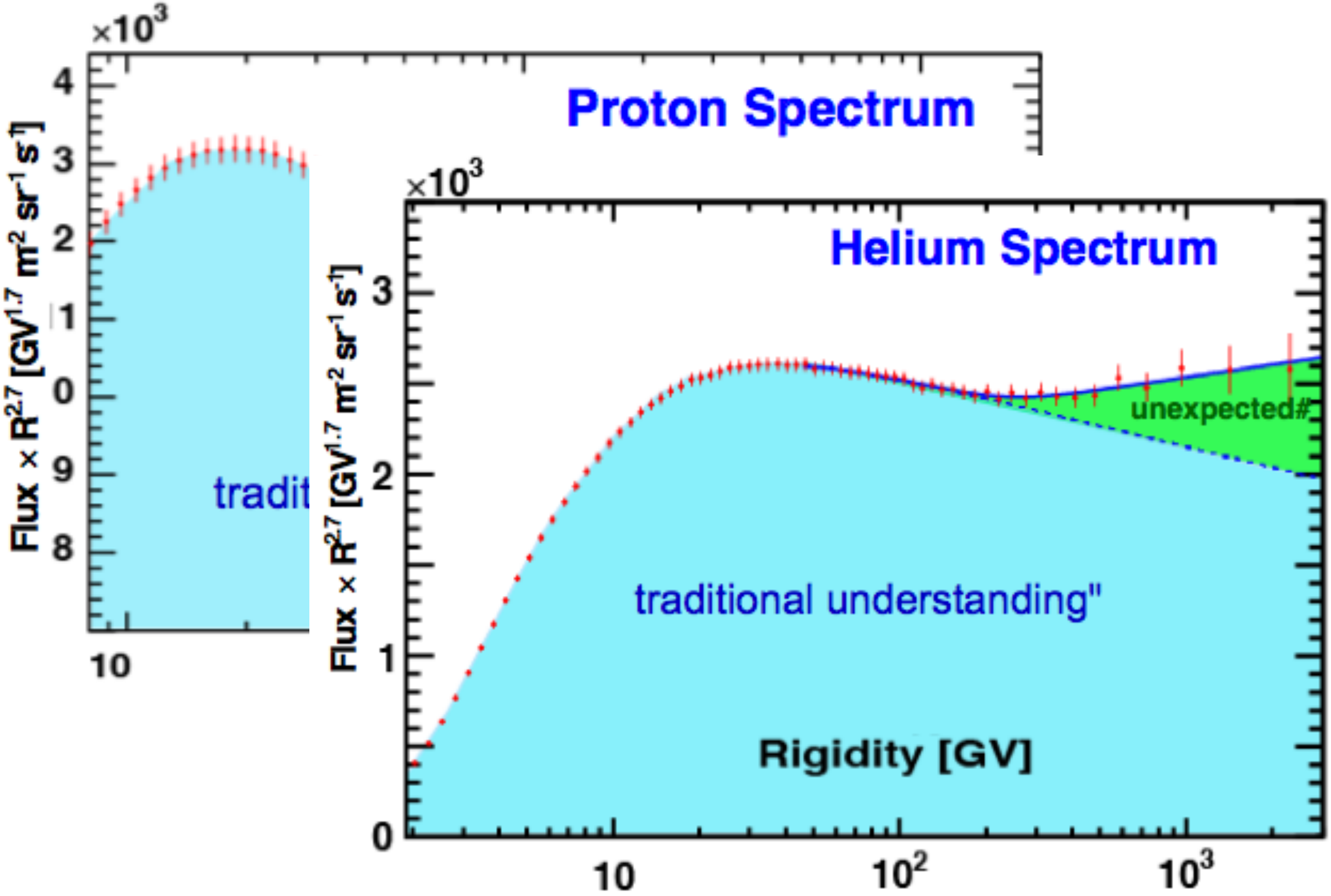

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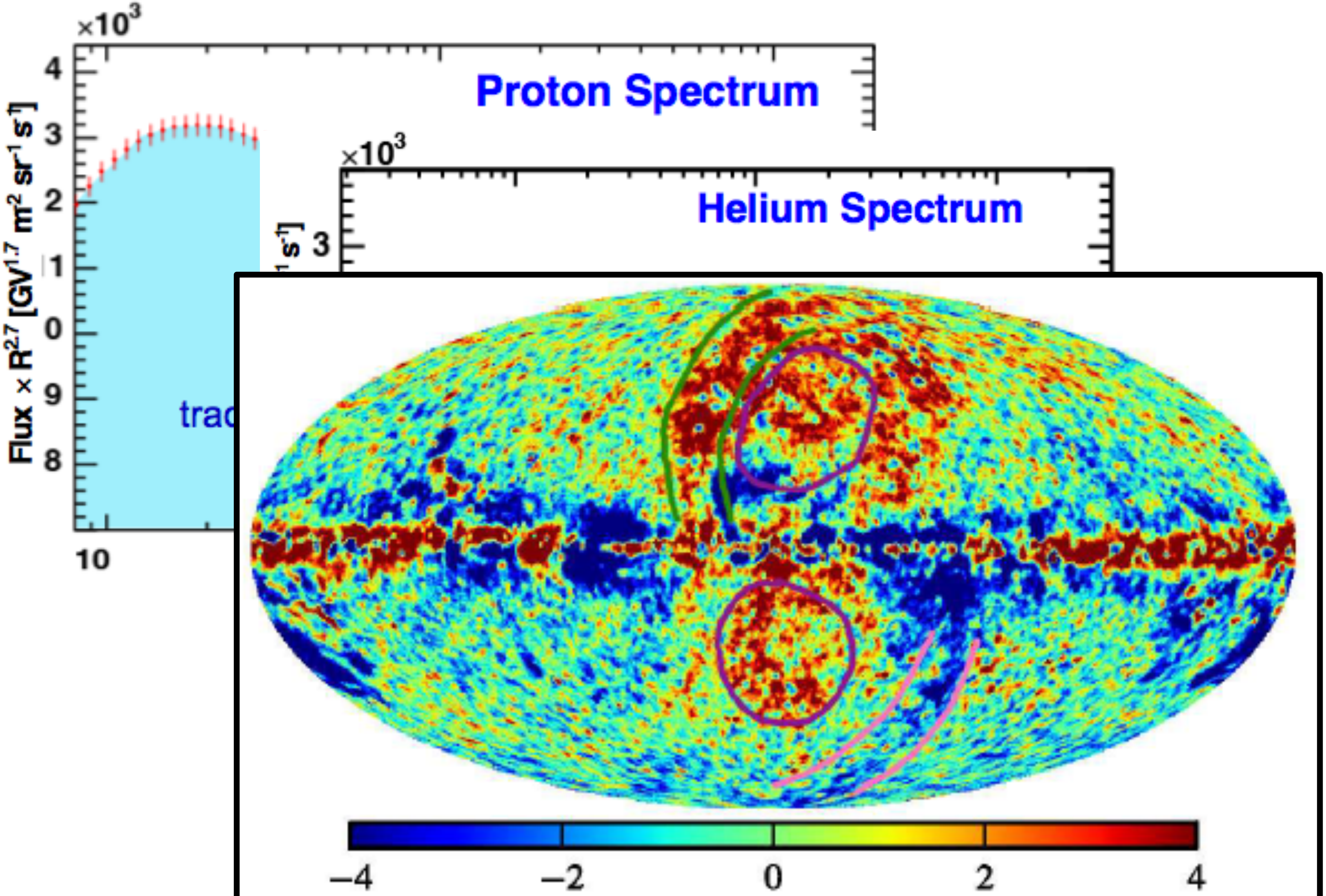

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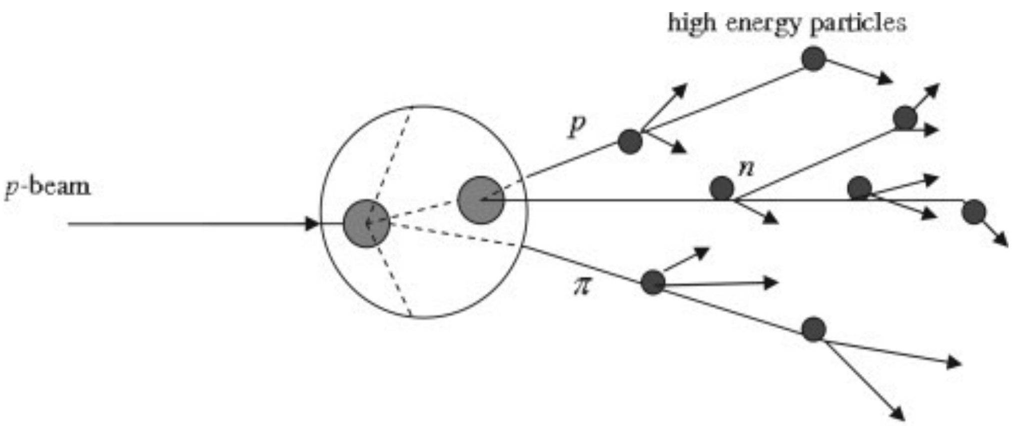

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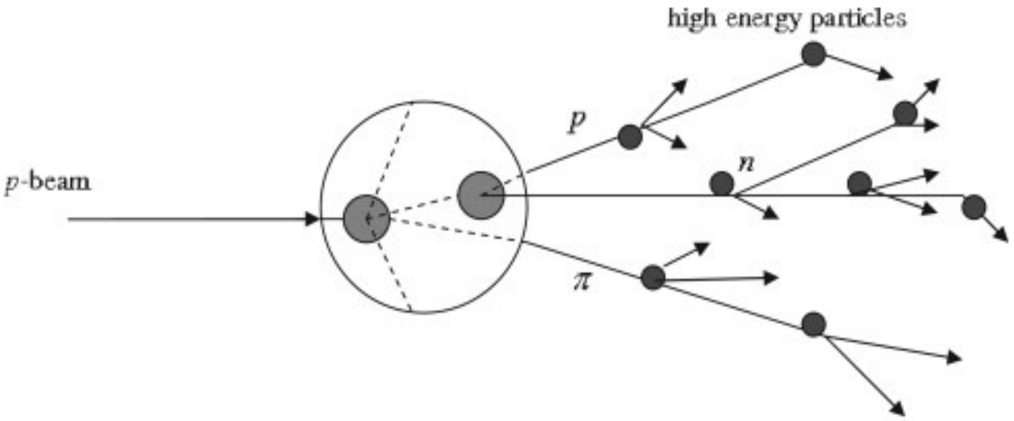
For secondary antimatter we have a handle: particle physics branching fractions

$$\frac{n_a(\mathcal{R})}{n_b(\mathcal{R})} \approx \frac{Q_a(\mathcal{R})}{Q_b(\mathcal{R})}$$



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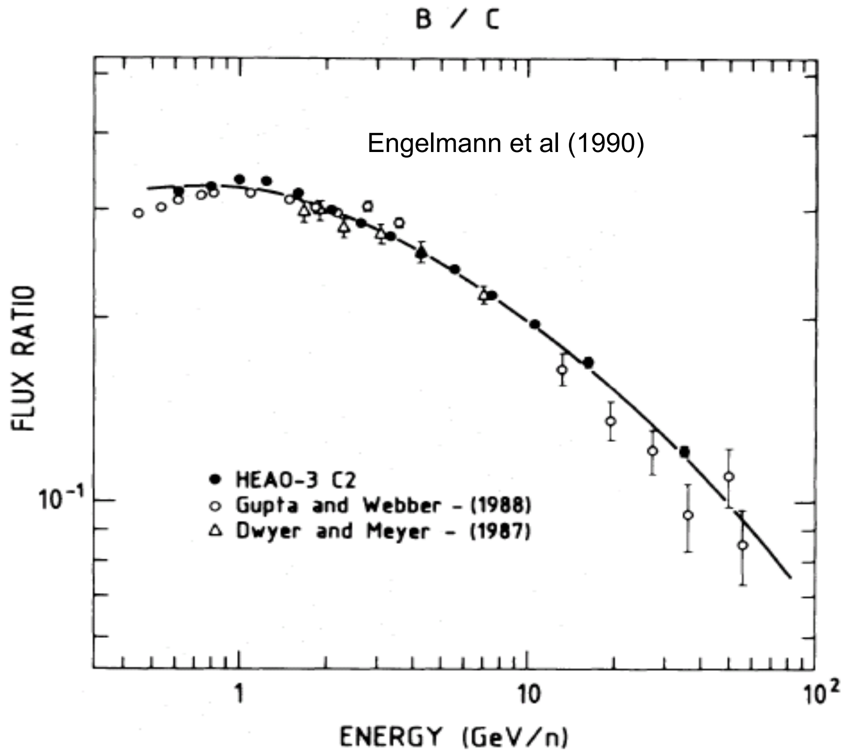
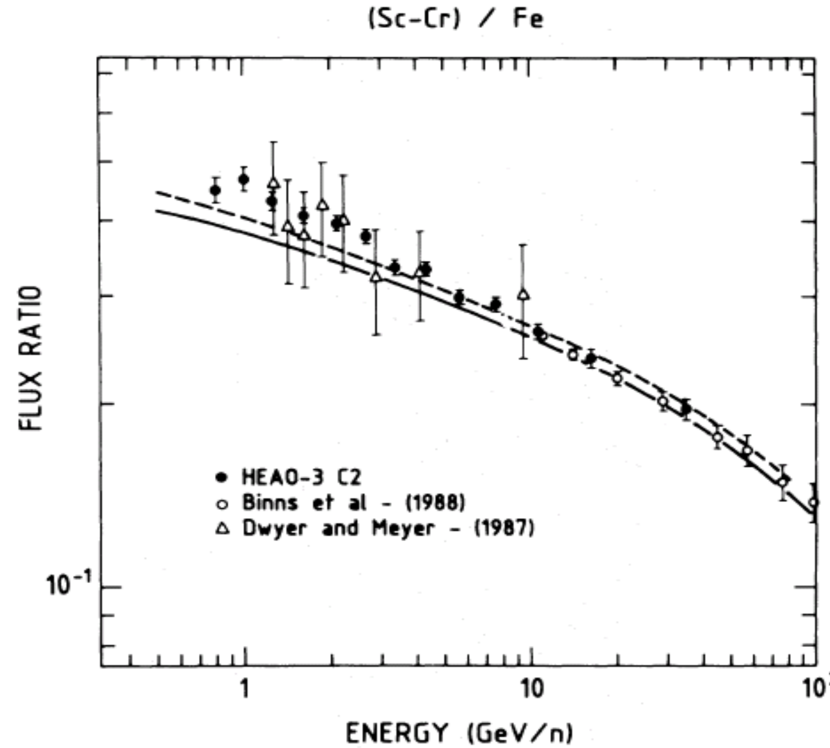
…works for secondary nuclei B, sub-Fe (T-V-Sc-Cr)





Recipe for an antiproton pie:

$$\frac{n_a(\mathcal{R})}{n_b(\mathcal{R})} \approx \frac{Q_a(\mathcal{R})}{Q_b(\mathcal{R})}$$

MNRAS 405 (2010) 1458 Katz, Blum, Morag, Waxman (arXiv:0906.4696)

Recipe for an antiproton pie:

$$\frac{n_a(\mathcal{R})}{n_b(\mathcal{R})} \approx \frac{Q_a(\mathcal{R})}{Q_b(\mathcal{R})} \quad \Rightarrow \quad n_{\bar{p}}(\mathcal{R}) \approx \frac{n_{\mathrm{B}}(\mathcal{R})}{Q_{\mathrm{B}}(\mathcal{R})} Q_{\bar{p}}(\mathcal{R})$$

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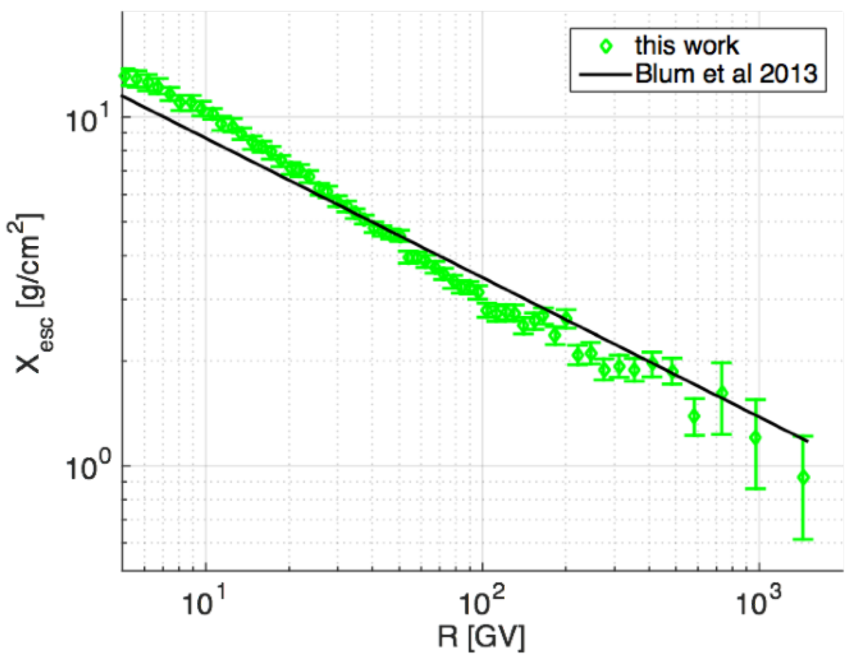
Average column density traversed by CR nuclei during propagation

$$X_{\rm esc}(\mathcal{R}) = \frac{n_{\rm B}(\mathcal{R})}{Q_{\rm B}(\mathcal{R})}$$

$$X_{\rm esc} = \frac{({\rm B/C})}{\sum_{\rm P=C,N,O,...} ({\rm P/C})\frac{\sigma_{\rm P\to B}}{m} - ({\rm B/C})\frac{\sigma_{\rm B}}{m}}$$



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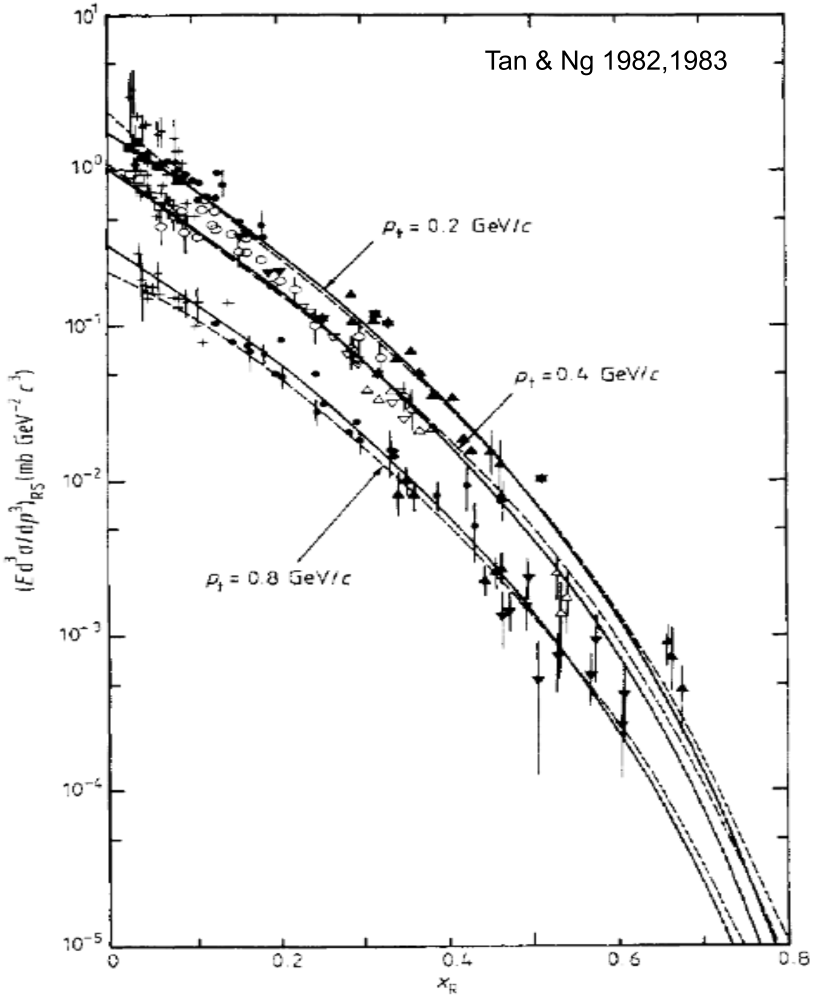

$$n_{\bar{p}}(\mathcal{R}) \approx \frac{n_{\rm B}(\mathcal{R})}{Q_{\rm B}(\mathcal{R})} Q_{\bar{p}}(\mathcal{R})$$

$$\sigma_{p\to\bar{p}}(\mathcal{R}) = \frac{2\int_{\mathcal{R}}^{\infty} d\mathcal{R}_p\, J_p(\mathcal{R}_p)\left(\frac{d\sigma_{pp\to\bar{p}X}(\mathcal{R}_p,\mathcal{R})}{d\mathcal{R}_p}\right)}{J_p(\mathcal{R})}$$

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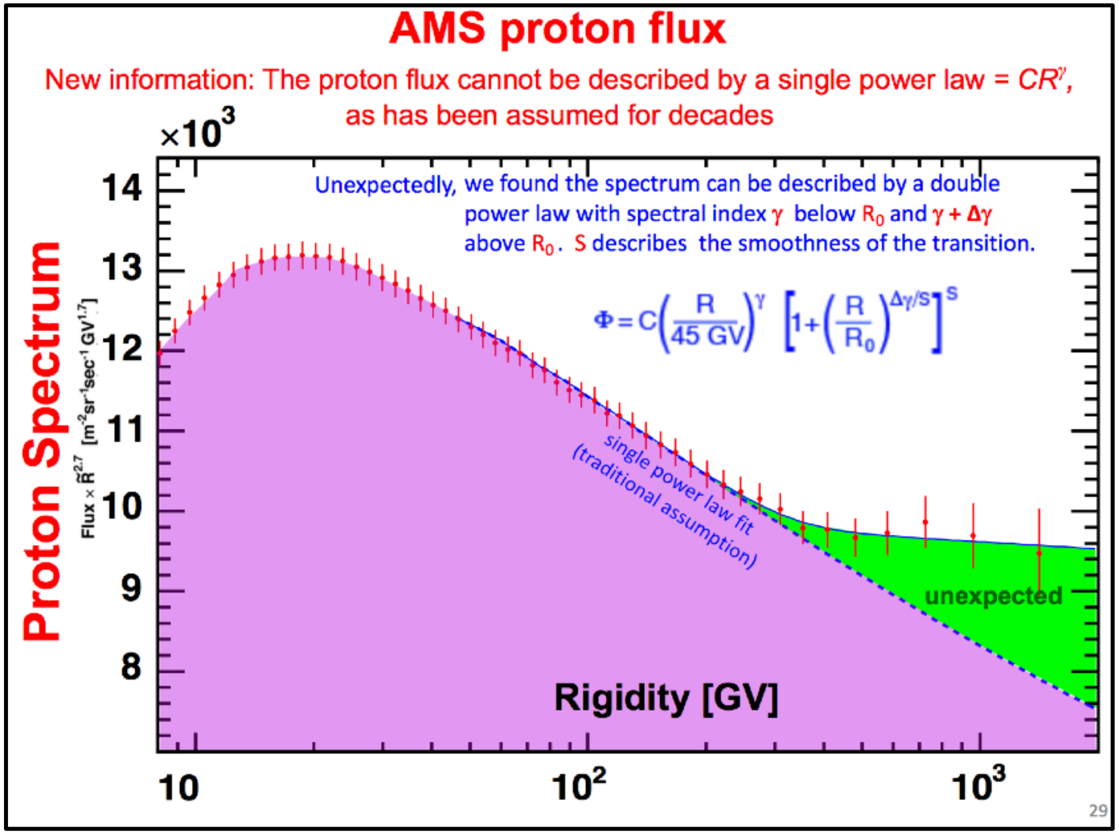

result

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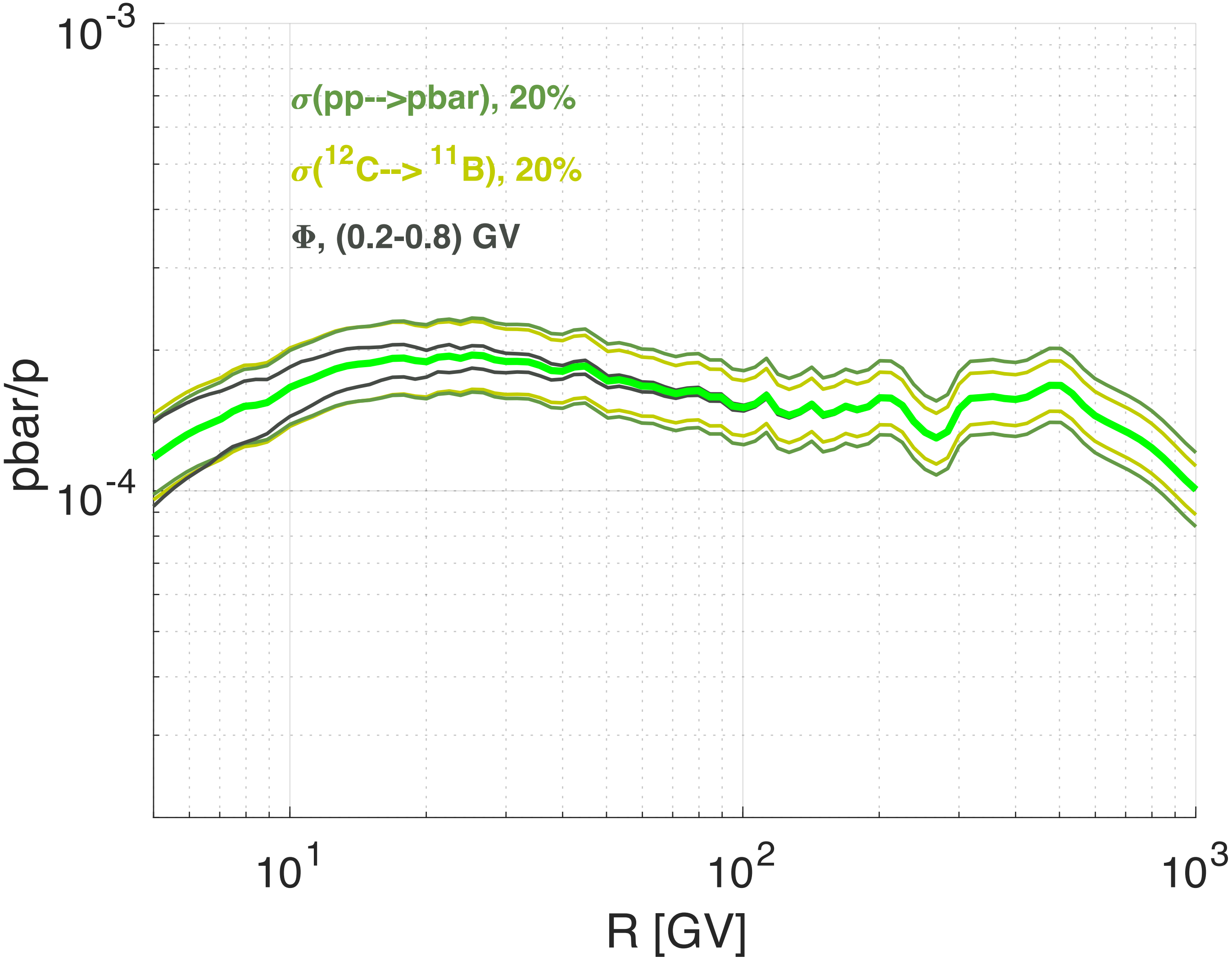

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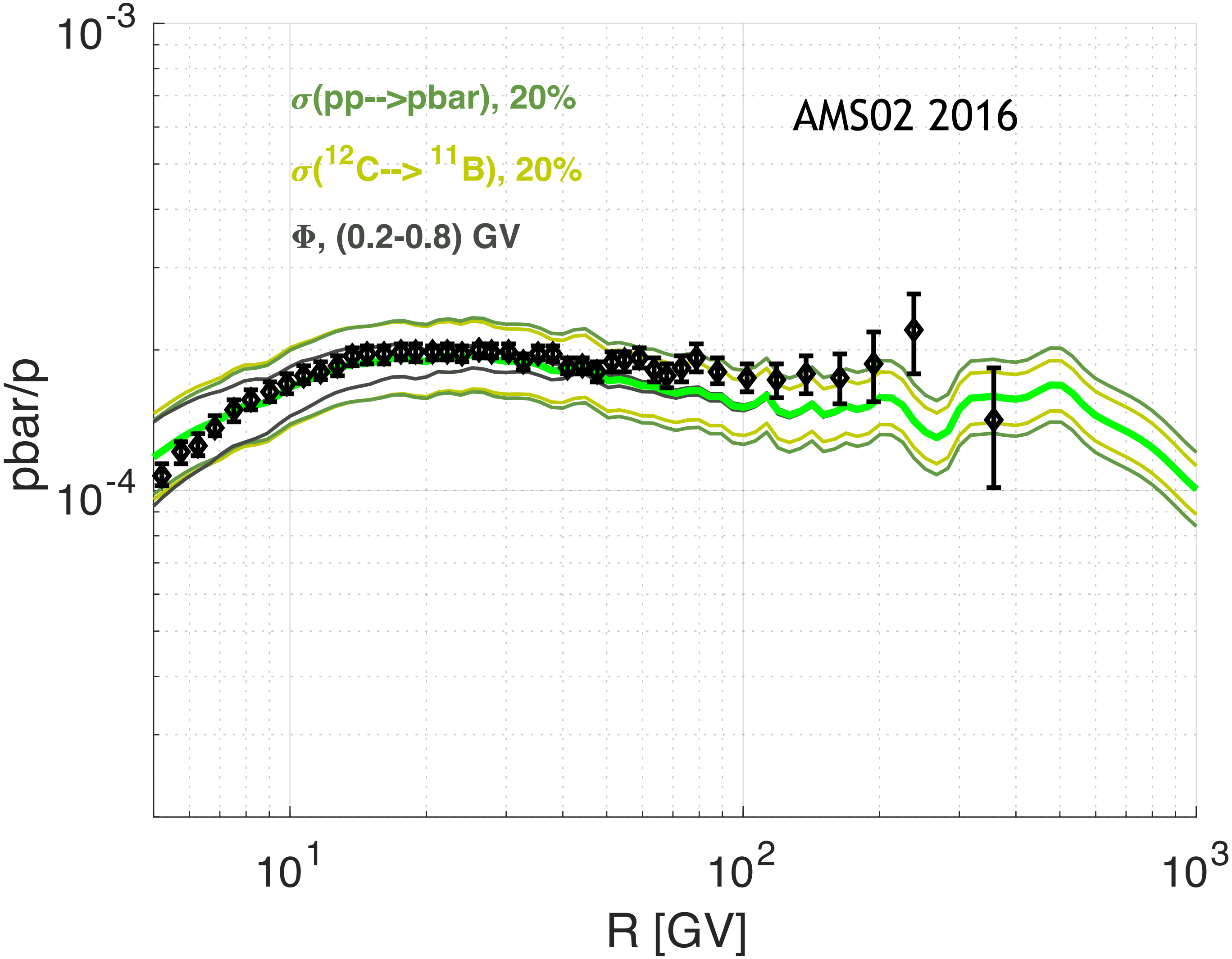
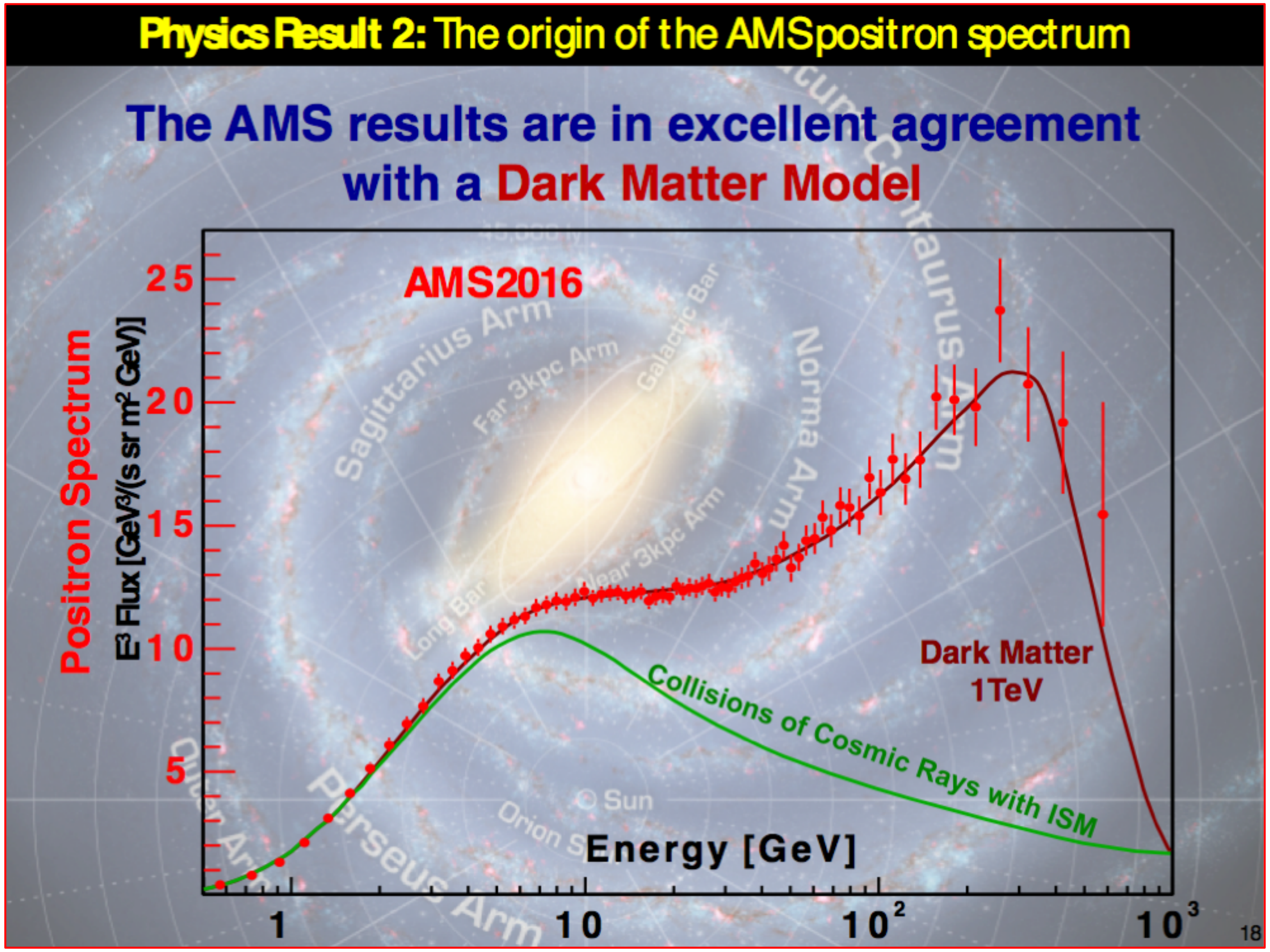


What about e+ ?

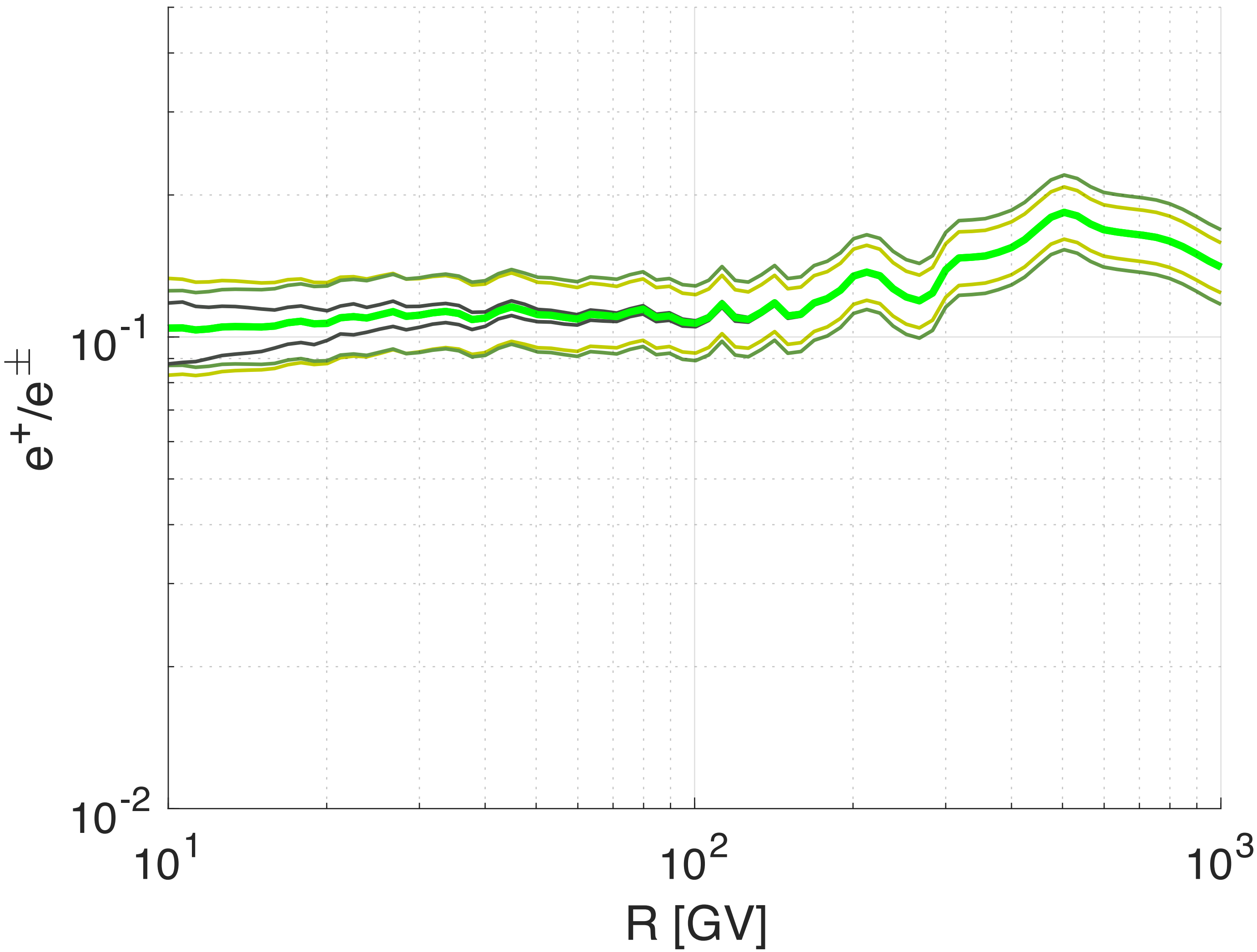
What about e+ ?

AMS02, Dec 2016



Secondary *upper bound*
(Based on B/C)

$$n_{e^+}(\mathcal{R}) \lesssim \frac{n_{\mathrm{B}}(\mathcal{R})}{Q_{\mathrm{B}}(\mathcal{R})} Q_{e^+}(\mathcal{R})$$



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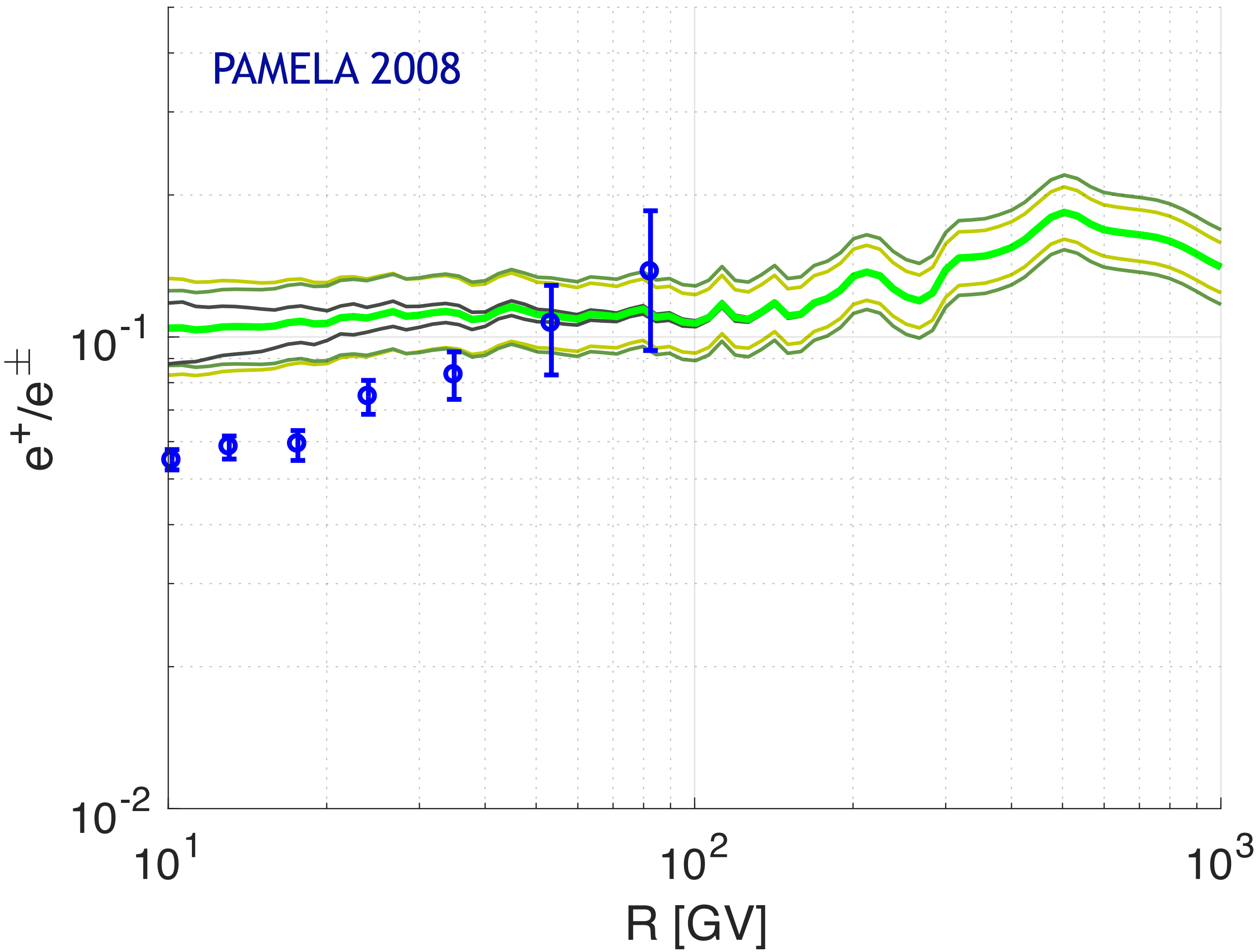

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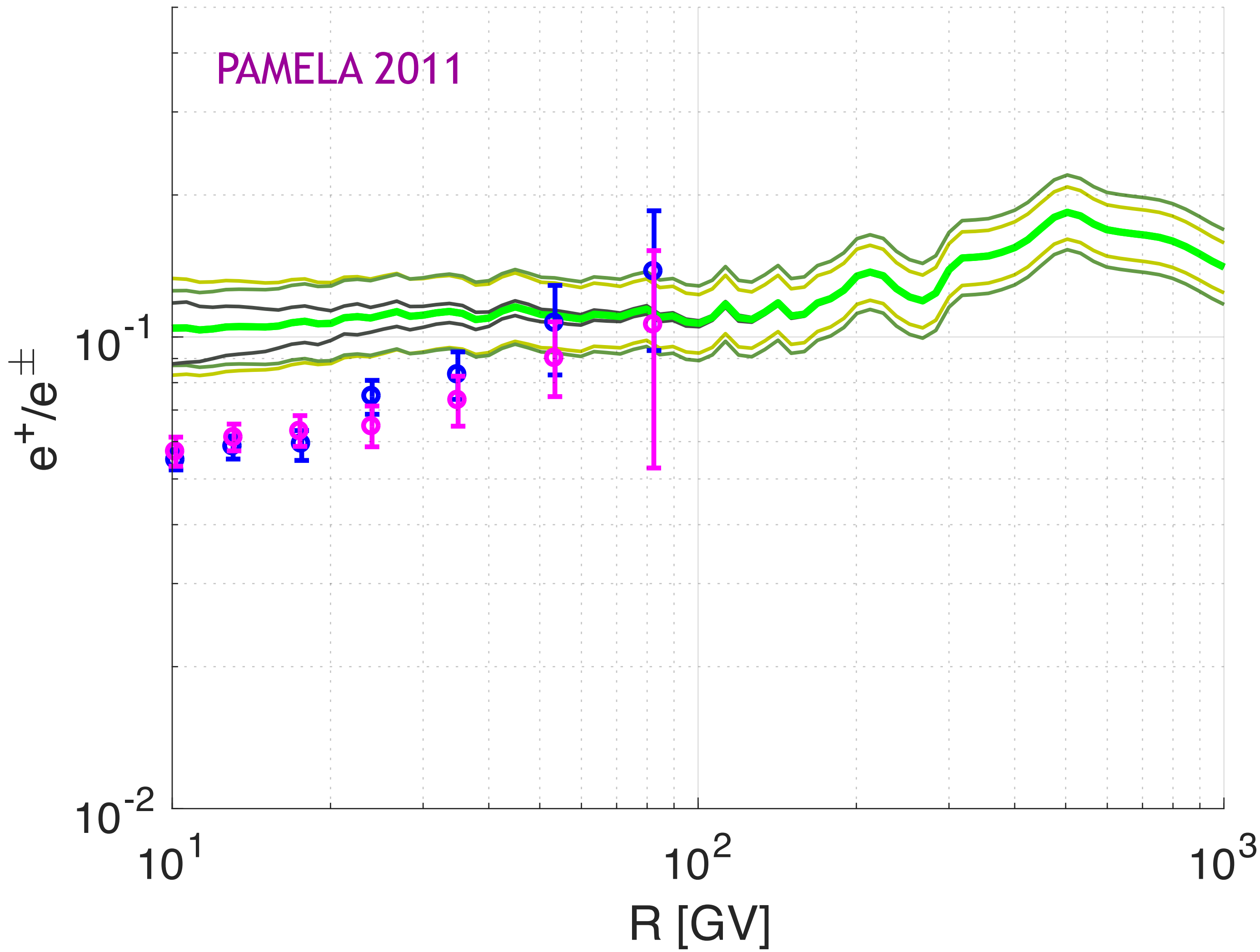

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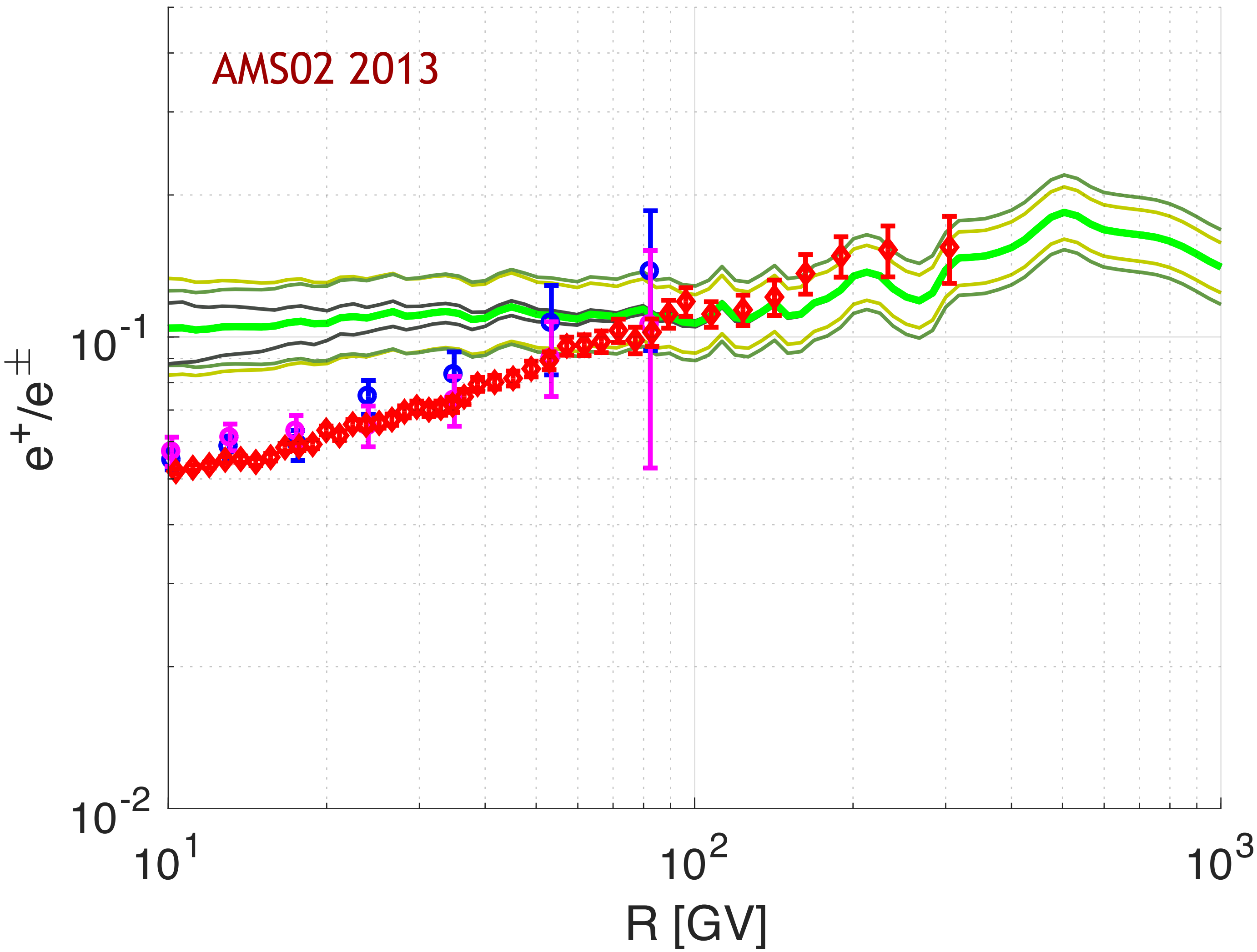

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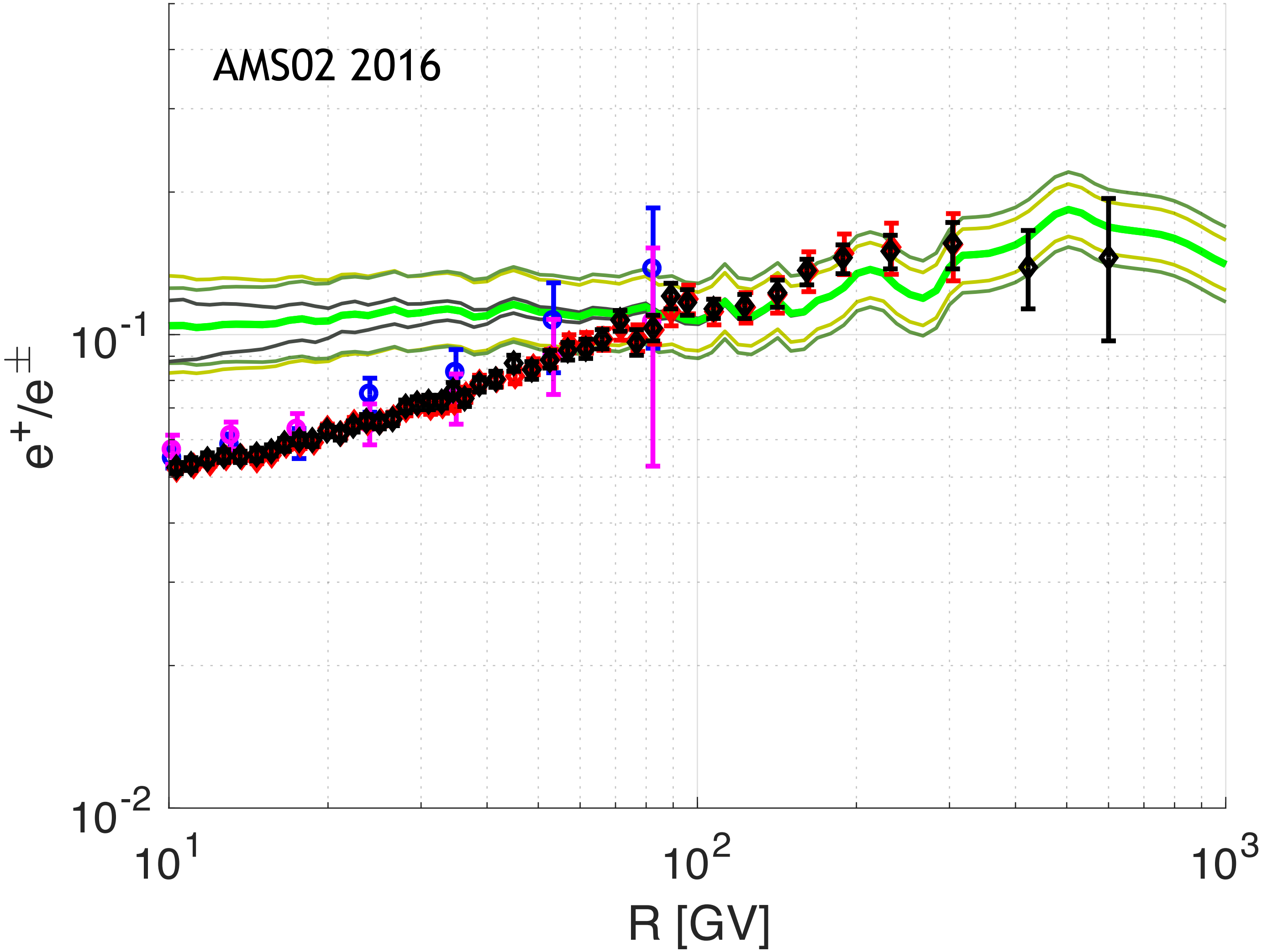

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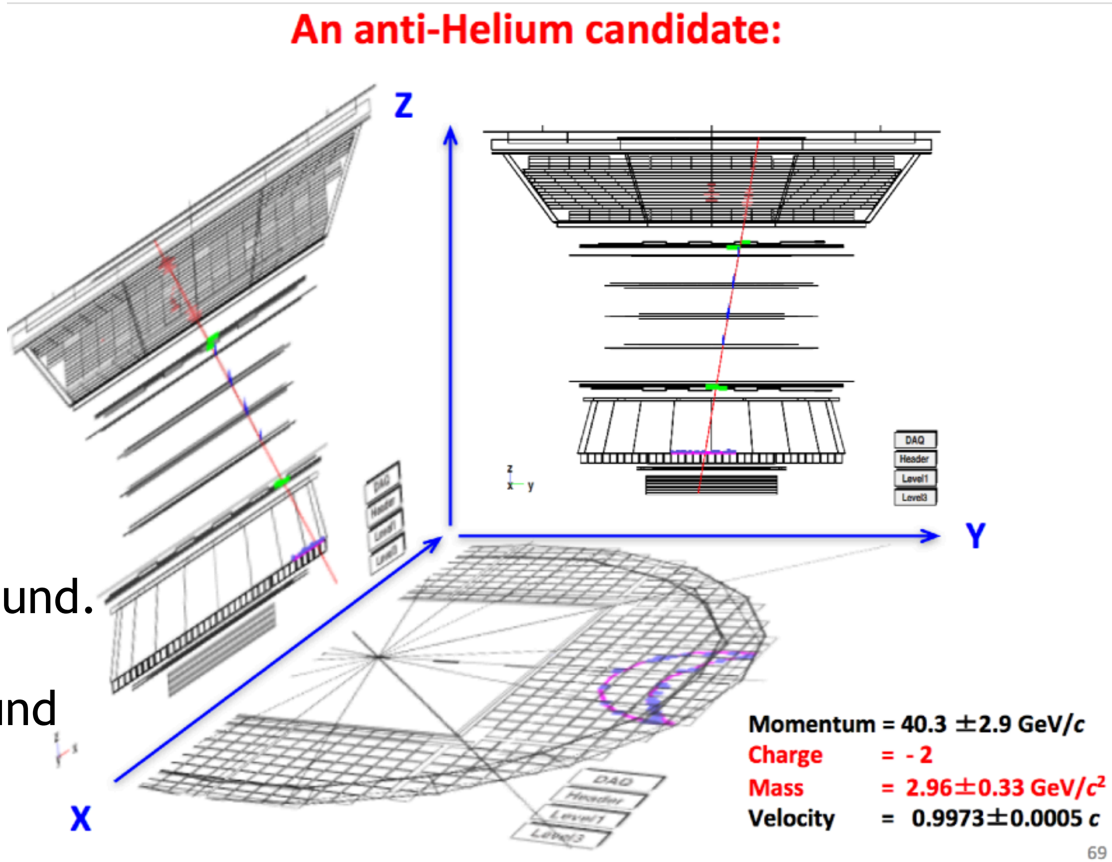
anti He3

anti He3

1. Handful of events

2. Energy of 1 event they show is 40GeV

AMS02, Dec 2016



At this point it is not clear
if AMS02 is seeing true CR events,
or some rare experimental background.

Need to reject such freak background
events at a level of ~ 1:100M…

We take it as motivation for theory examination of what the astro anti-He3 flux is.

anti He3

AMS02, Dec 2016

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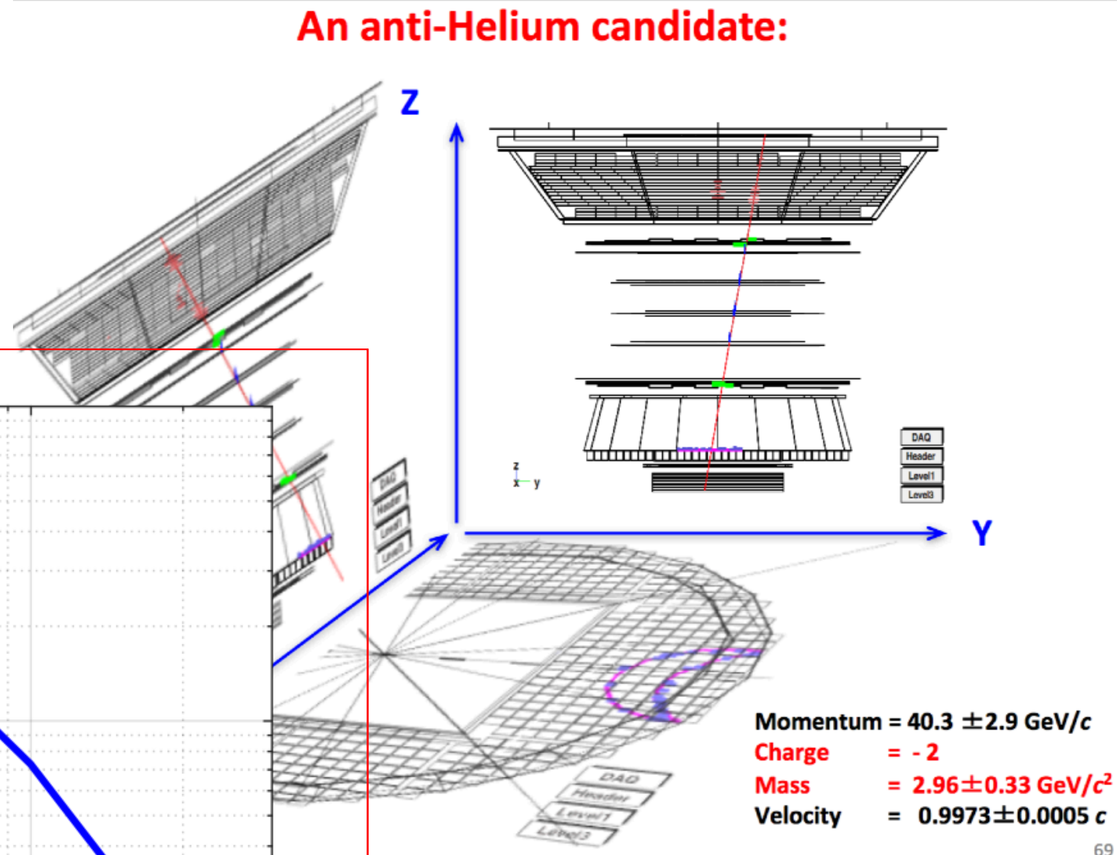

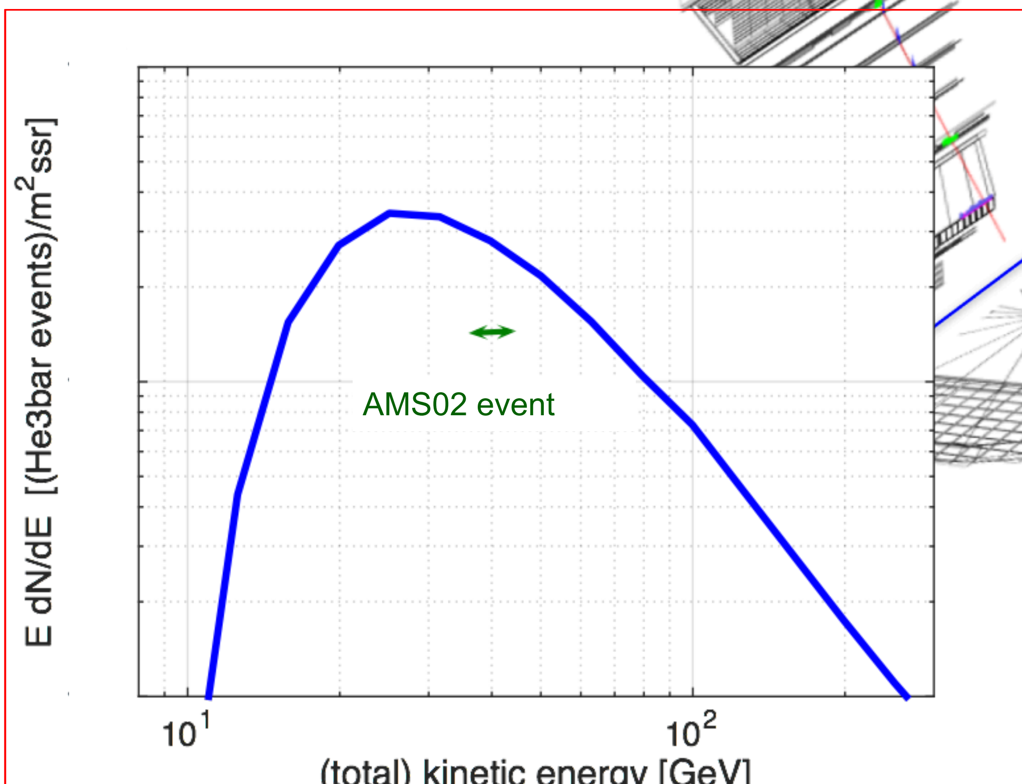

anti He3

1. Handful of events

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

We need B_3.

anti He3

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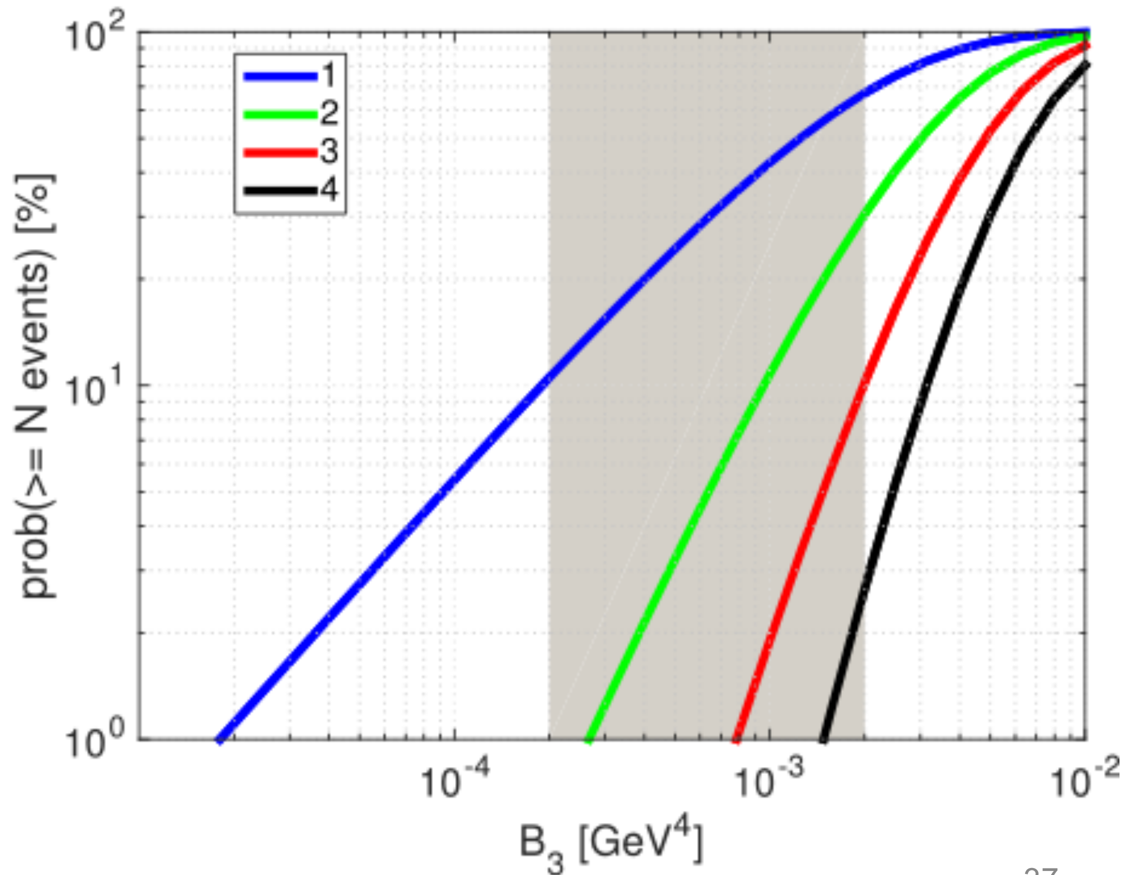
We need B_3.

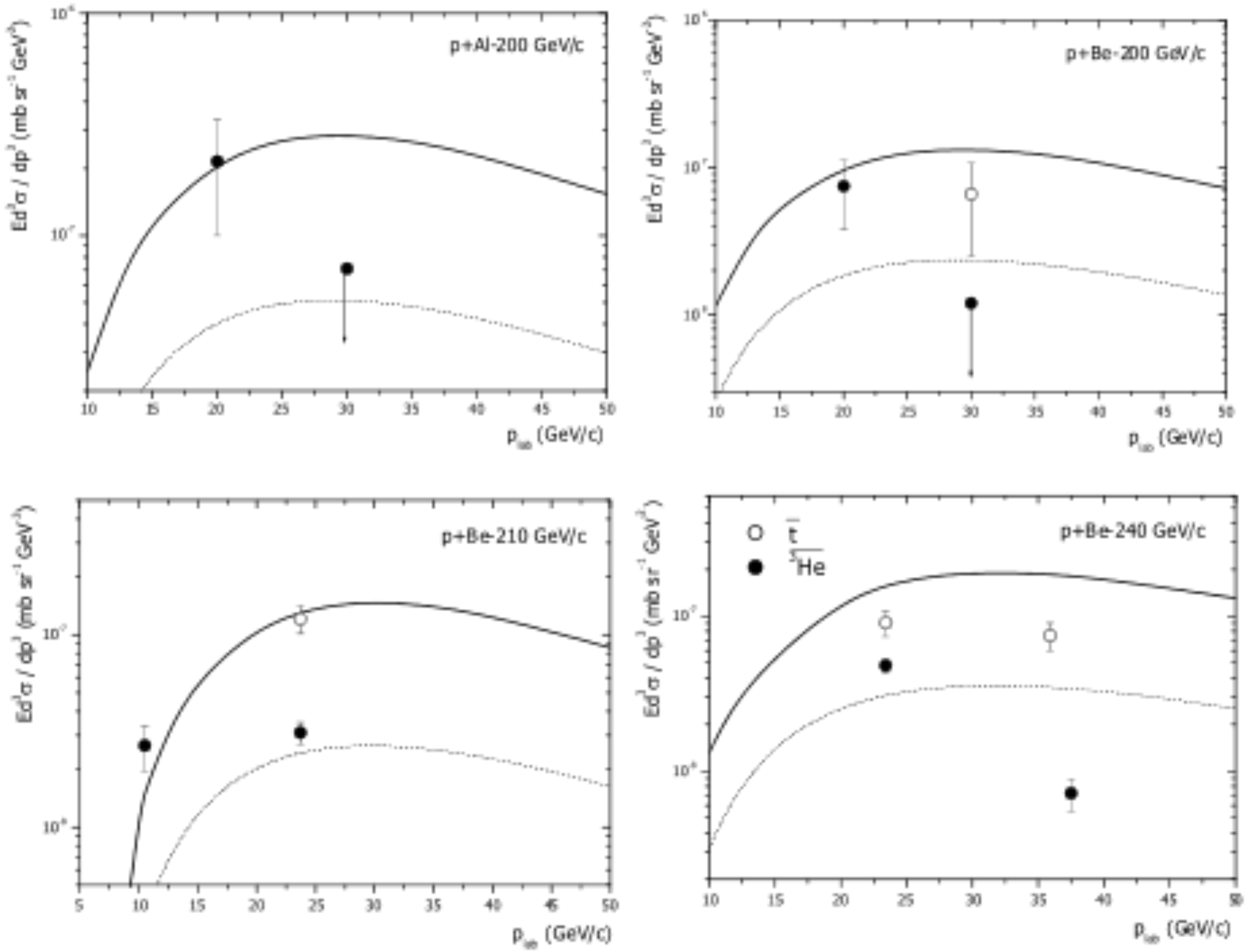
Propagation is not an issue:
Can calibrate it out just like for p-bar.
==> we know what is needed to give observable flux.



Question is:
Does this make sense w.r.t. accelerator data?

Duperray et al, PRD71 083013 (2005), **pA data** from SPS (1980's)

$B_3 = 1.4 \times 10^{-5}$ GeV^4



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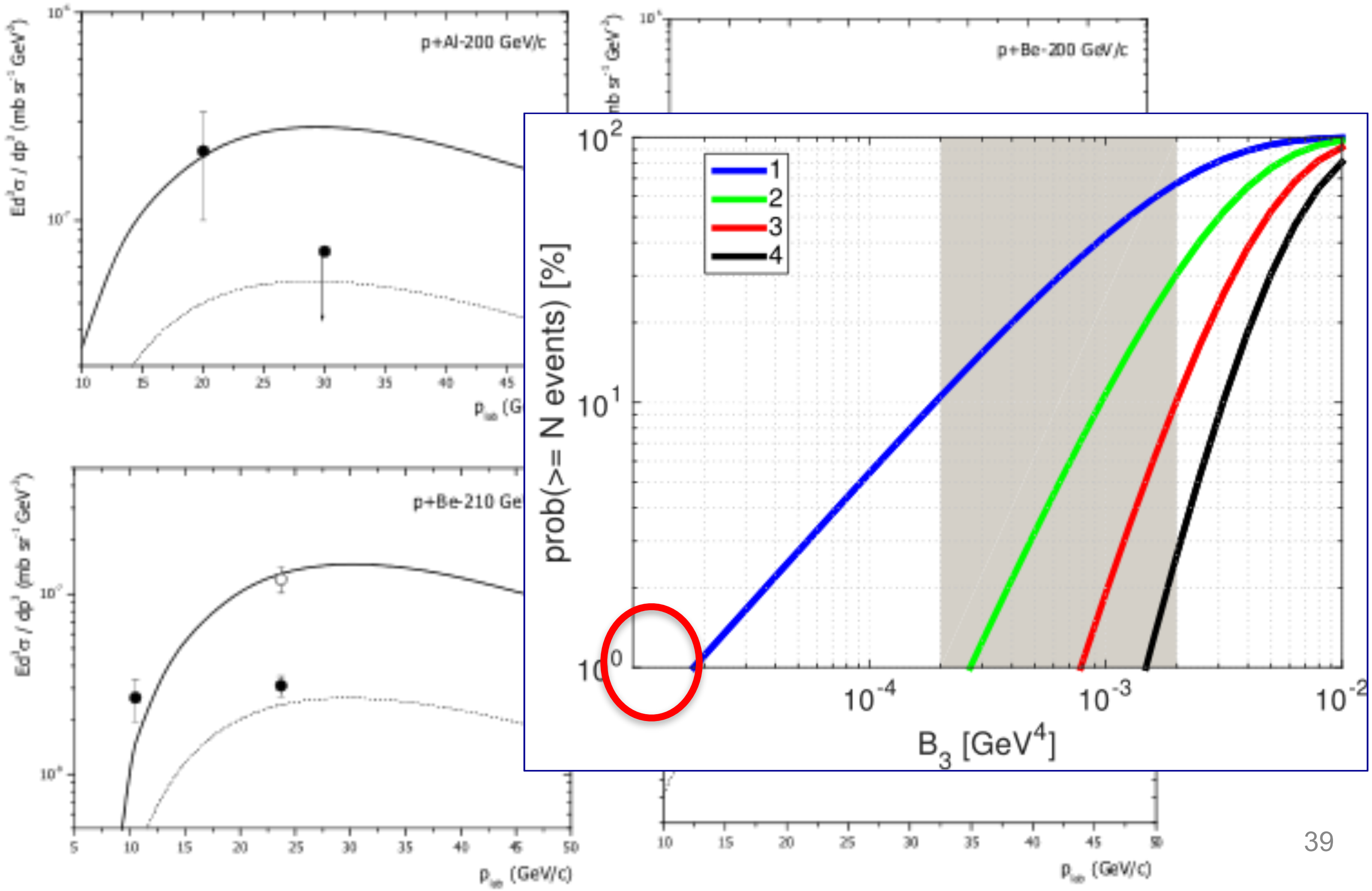

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Complimentary AA, pA, and related pp data exists elsewhere.

Let's take a step back and try to see the bigger picture

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

Hadrons emitted from a finite size emission region.
Typical scales O(fm) ~ 1/(100 MeV)

Natural scaling law: $$\boxed{B_A \propto V^{1-A}}$$

Emission region scale size is probed by two-particle correlations:

Hanbury Brown-Twiss (HBT) data

Scheibl & Heinz, Phys.Rev. C59 (1999) 1585-1602

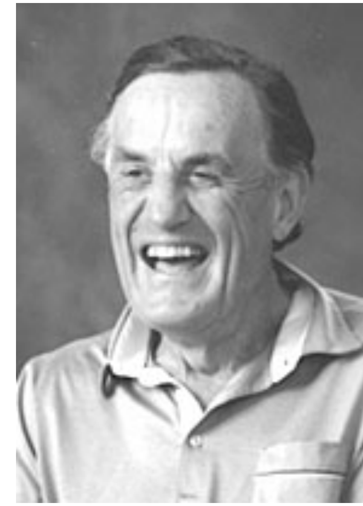
Hanbury Brown-Twiss (HBT)

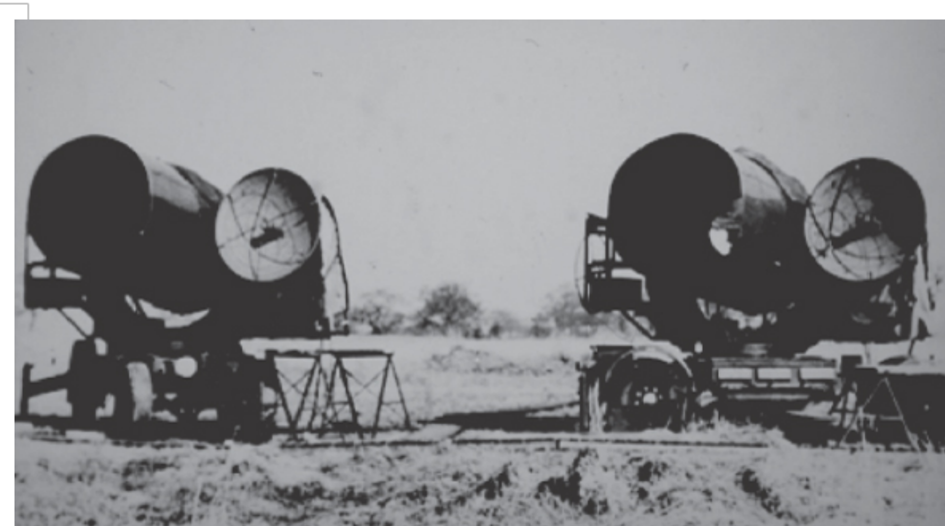
Nature **178**, 1046-1048 (10 November 1956) | doi:10.1038/1781046a0

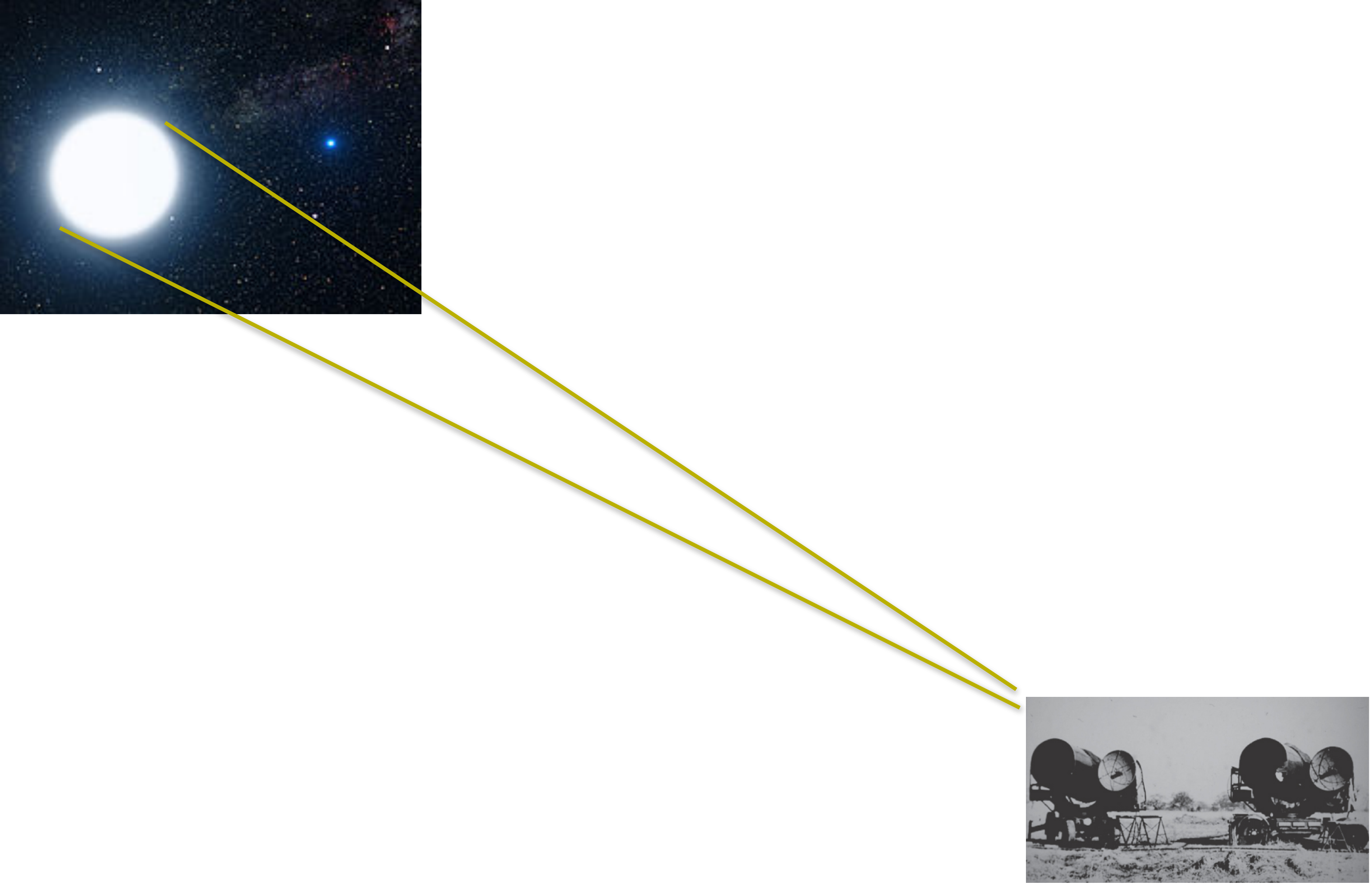
A Test of a New Type of Stellar Interferometer on Sirius

R. HANBURY BROWN & , DR.R. Q. TWISS

1. Jodrell Bank Experimental Station, University of Manchester
2. Services Electronics Research Laboratory, Baldock

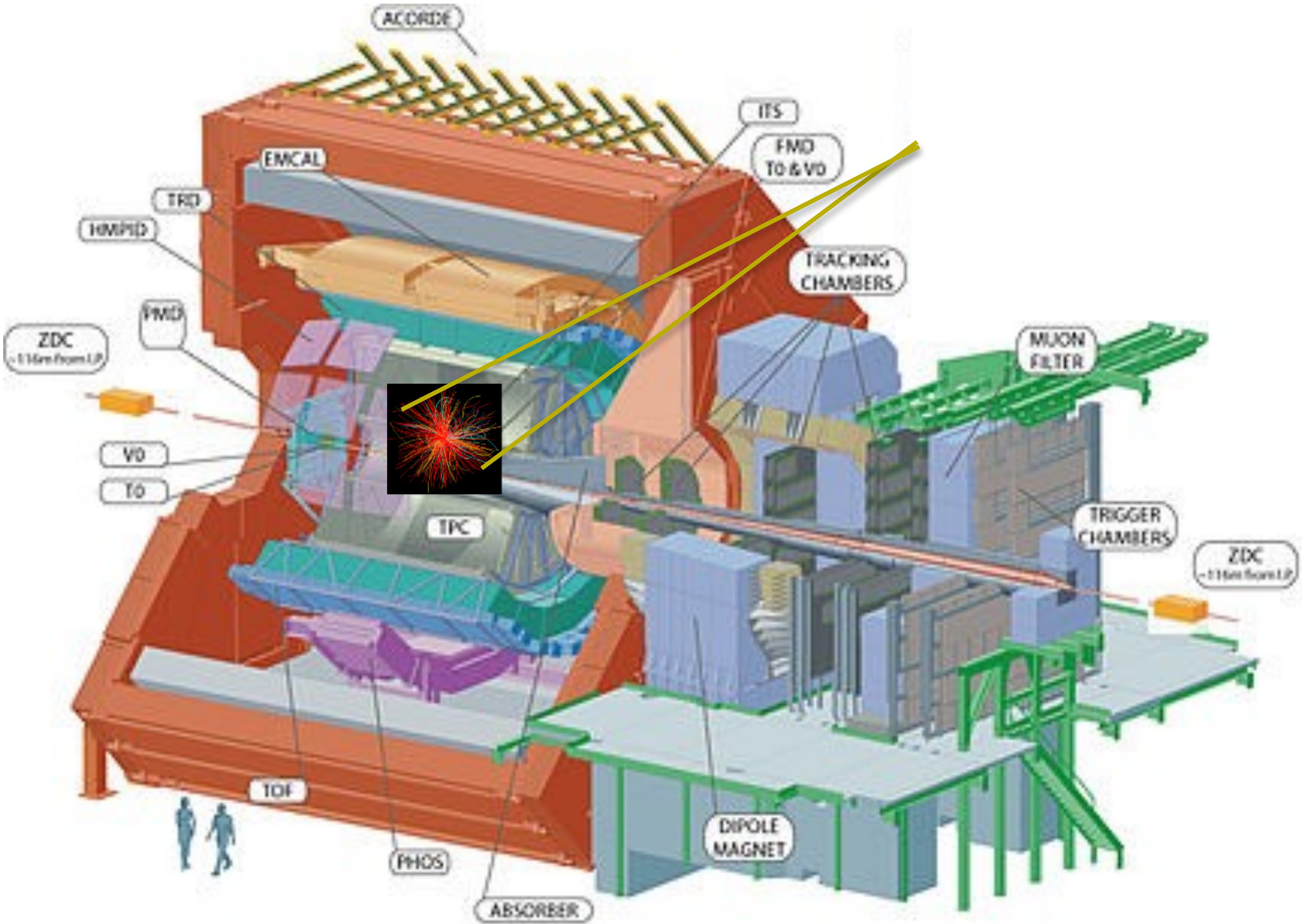






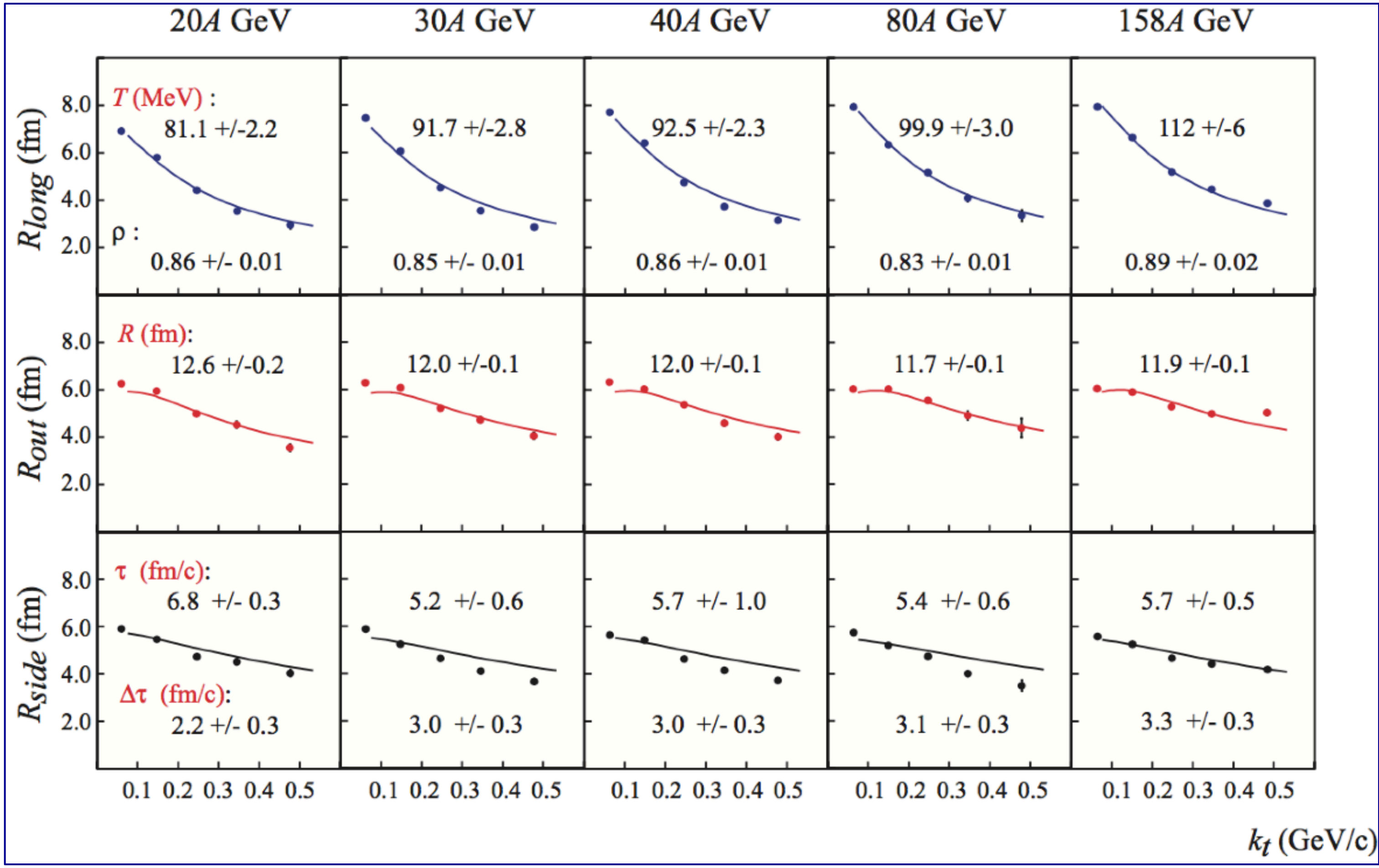
HBT in heavy ion and pp collisions

Lisa et al, Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402
Scheibl & Heinz, Phys.Rev. C59 (1999) 1585-1602
Baym, Acta Phys. Polon. B29 (1998) 1839-1884
…



HBT in heavy ion and pp collisions

Example: CERN SPS, **PbPb** 20, 30, 40, 80, 158A GeV



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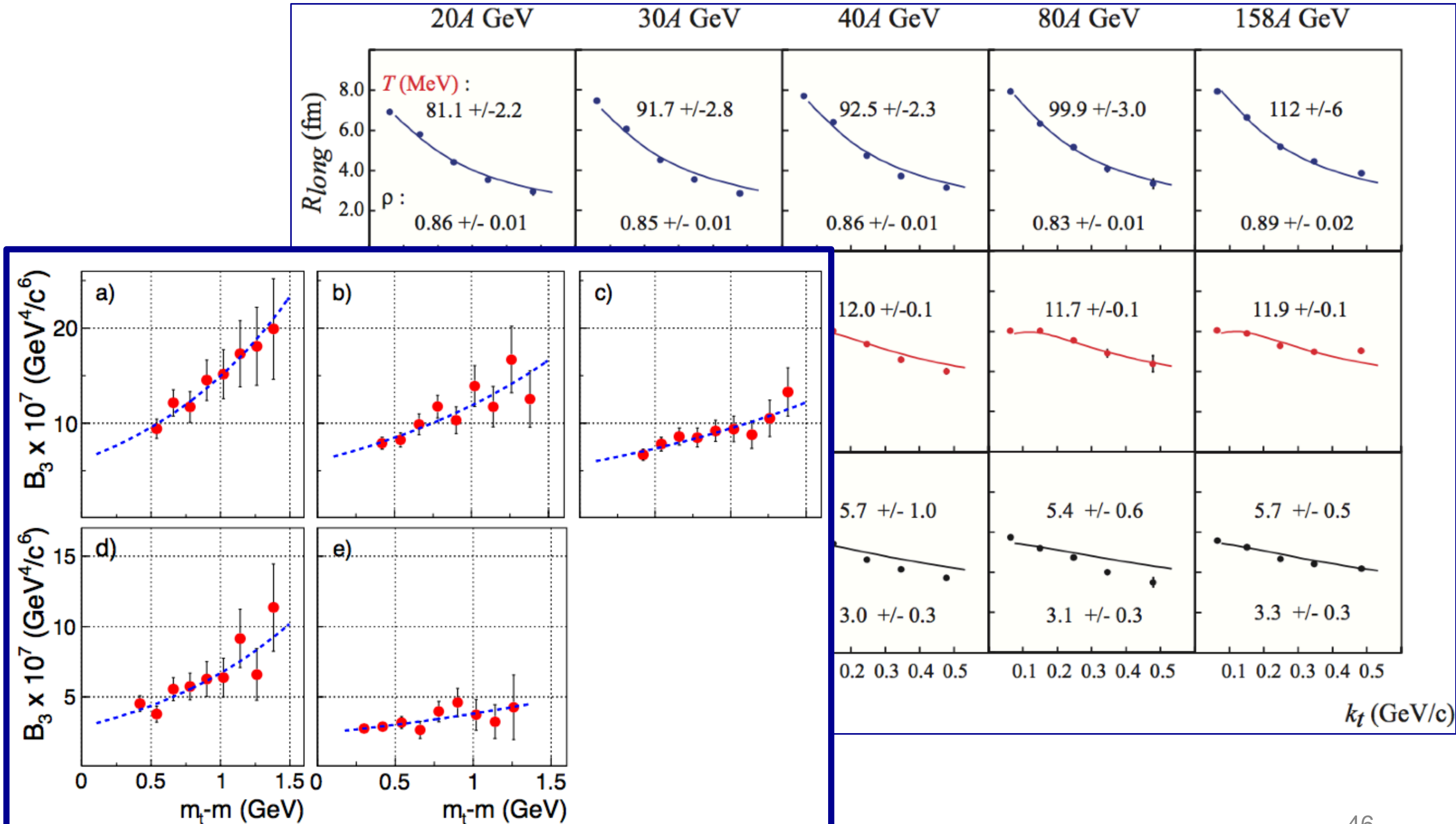
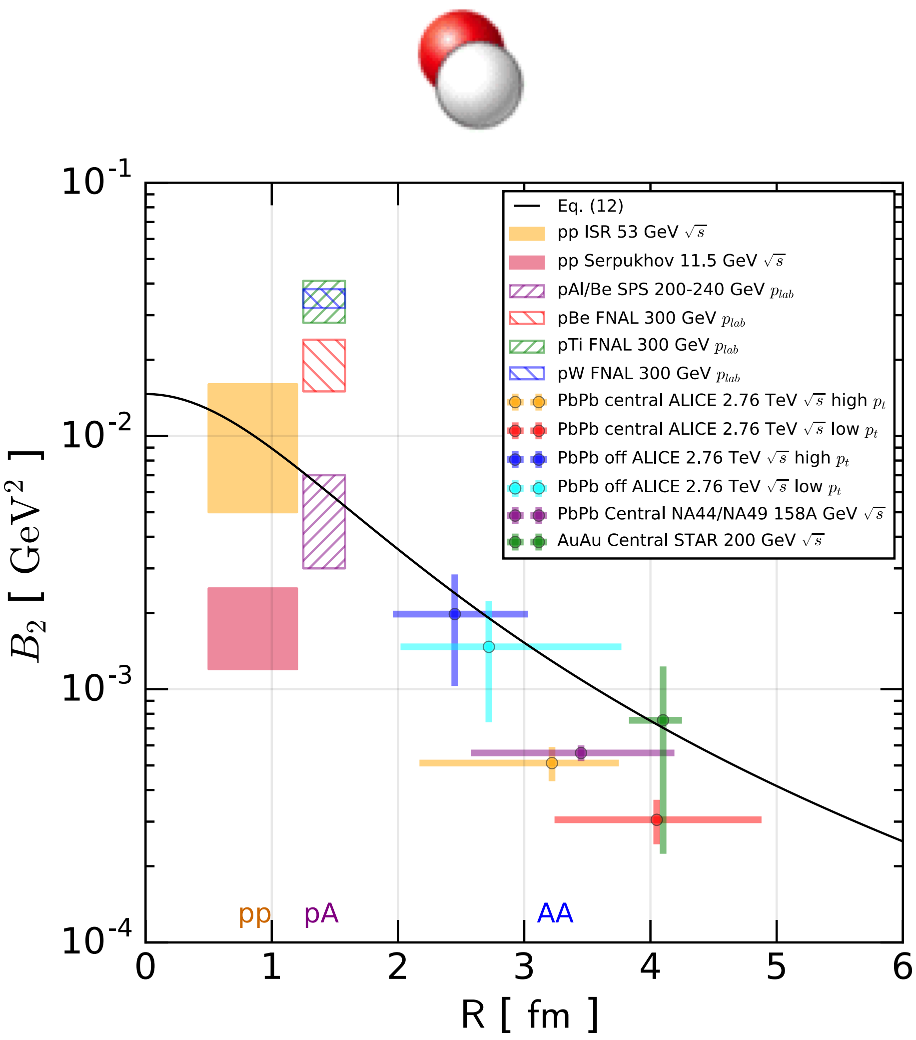
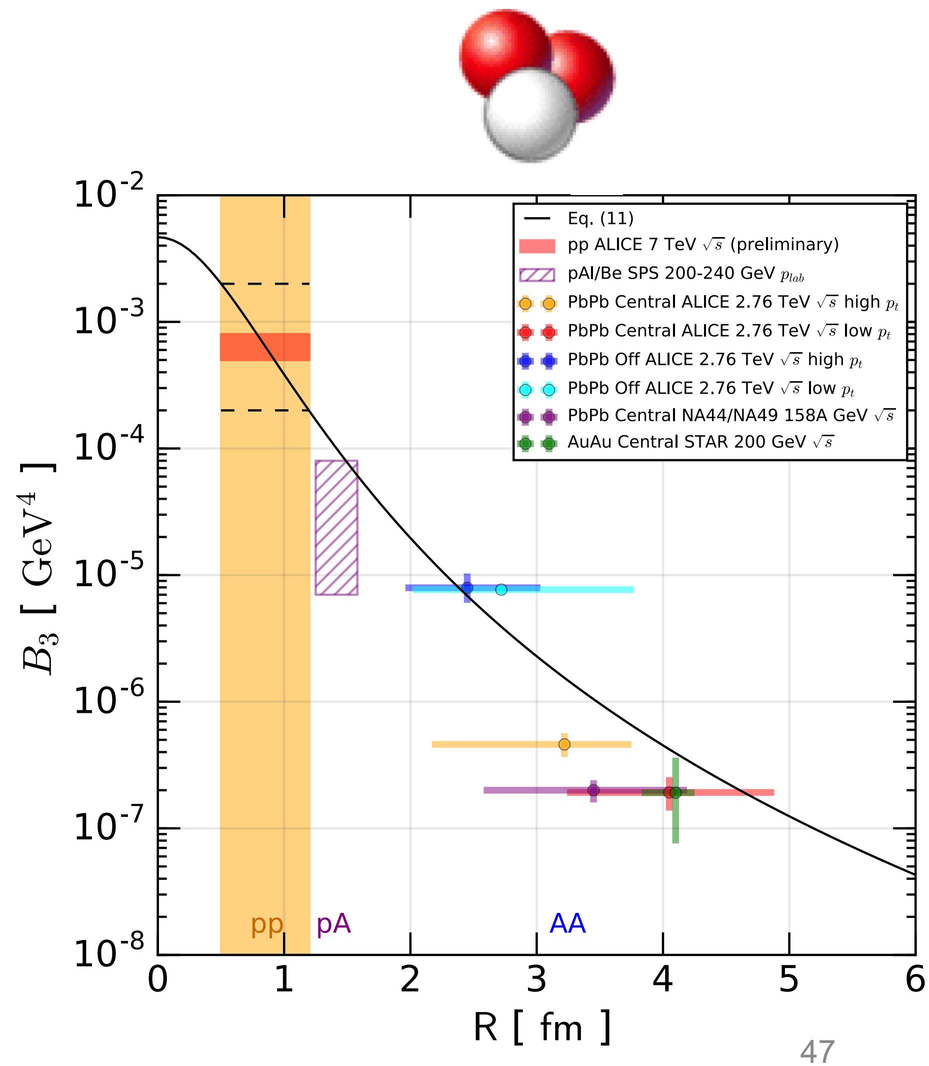


- Collected all systems for which we find nuclear yield & HBT data





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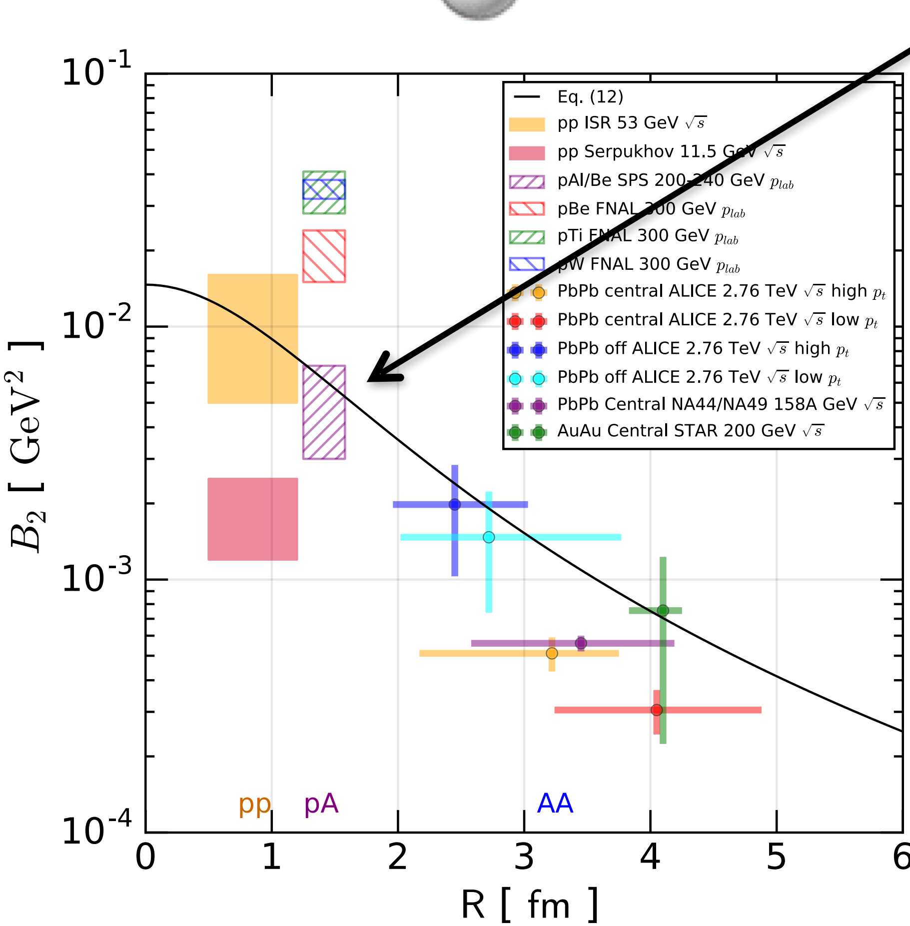
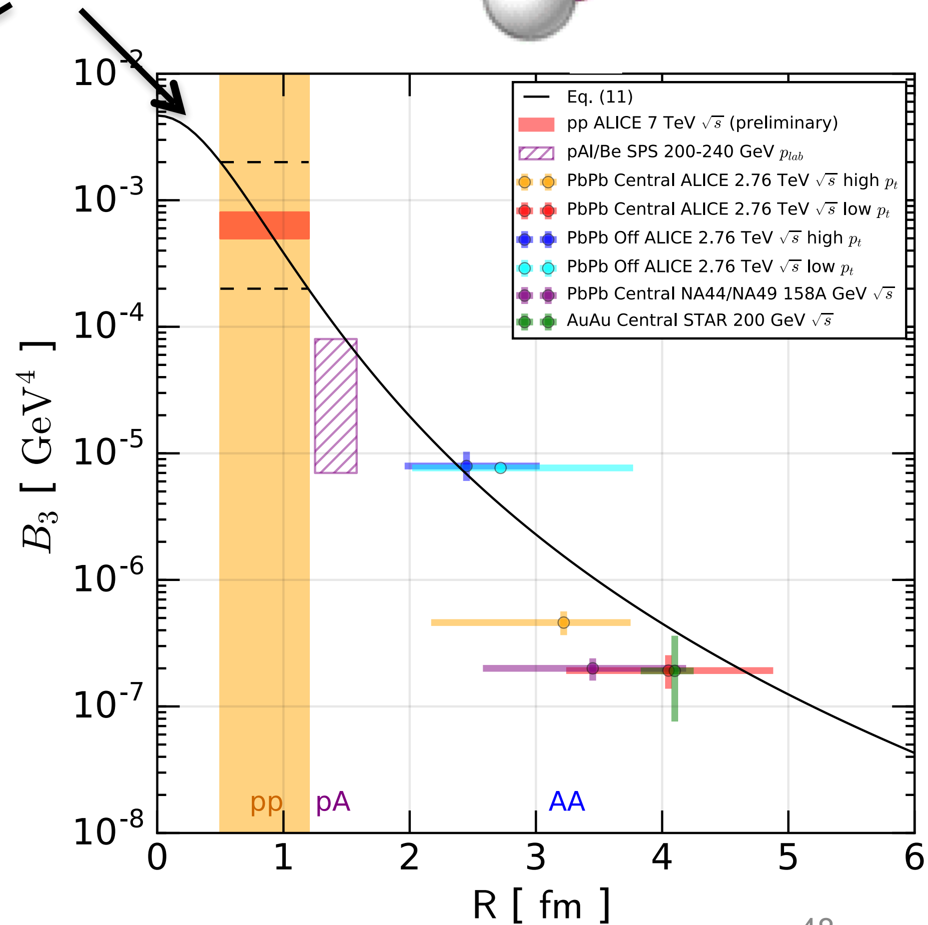
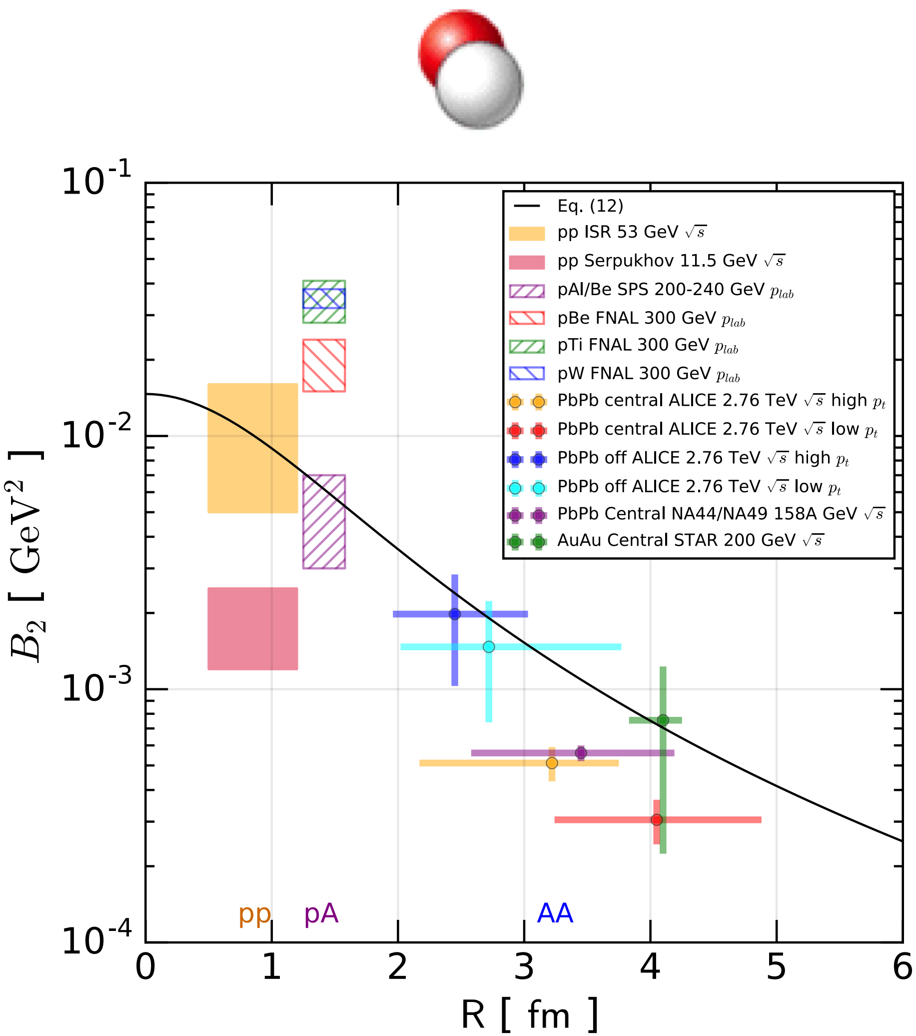
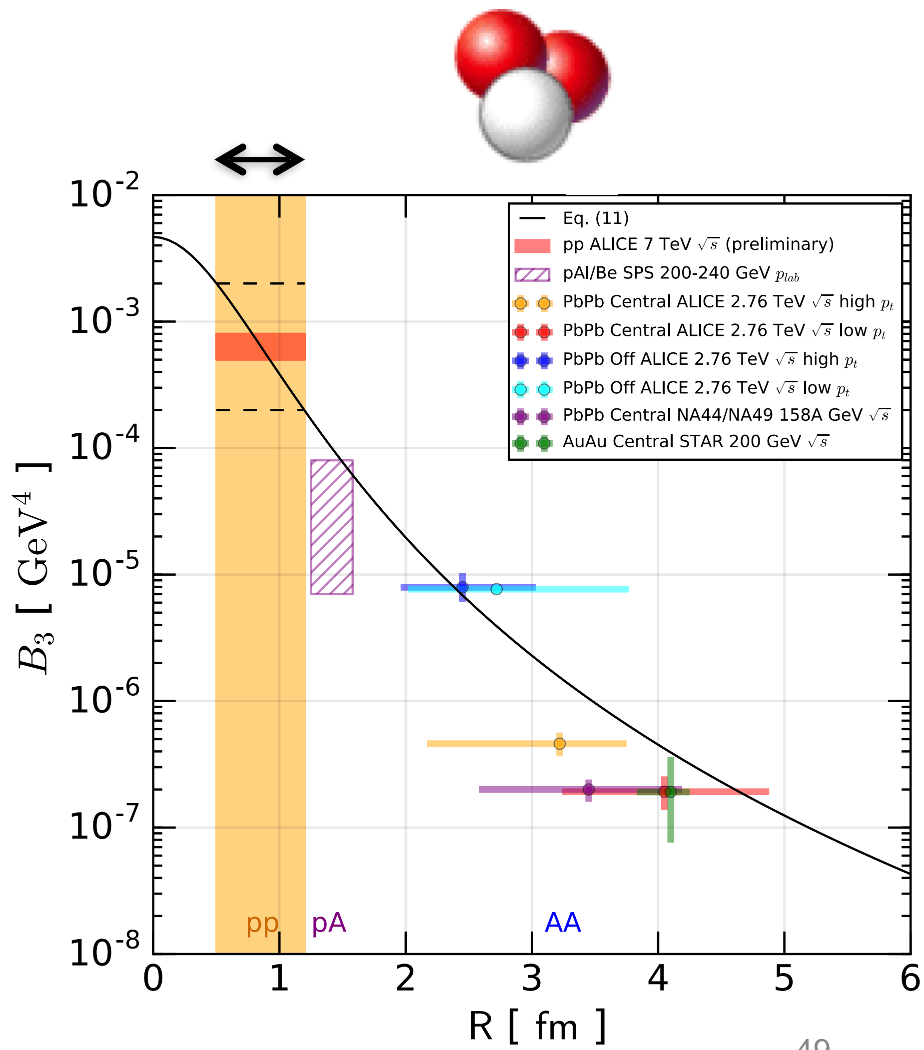


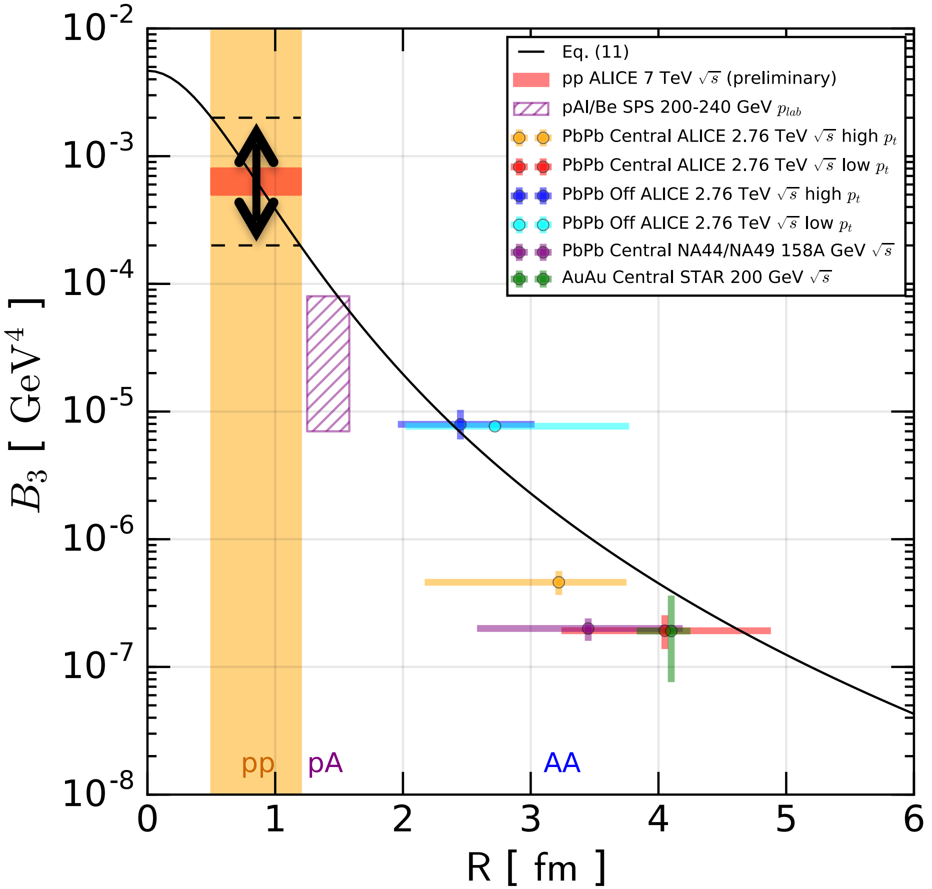


- Collected all systems for which we find nuclear yield & HBT data
- For **pp** we **have no B_3**, but we ***do have HBT***





AMS02, 2017?



Eq. (11)
pp ALICE 7 TeV √s (preliminary)
pAl/Be SPS 200-240 GeV p_{lab}
PbPb Central ALICE 2.76 TeV √s high p_t
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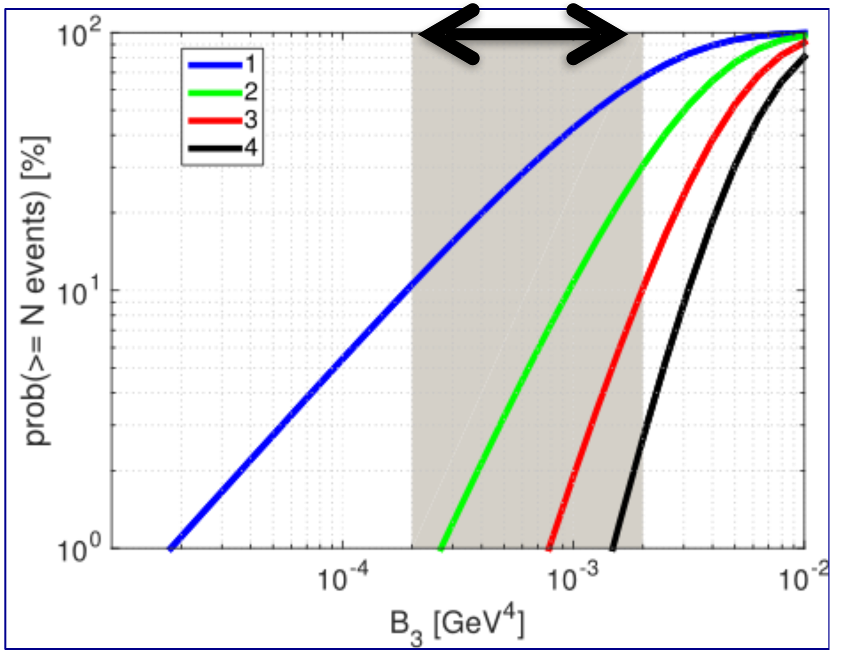
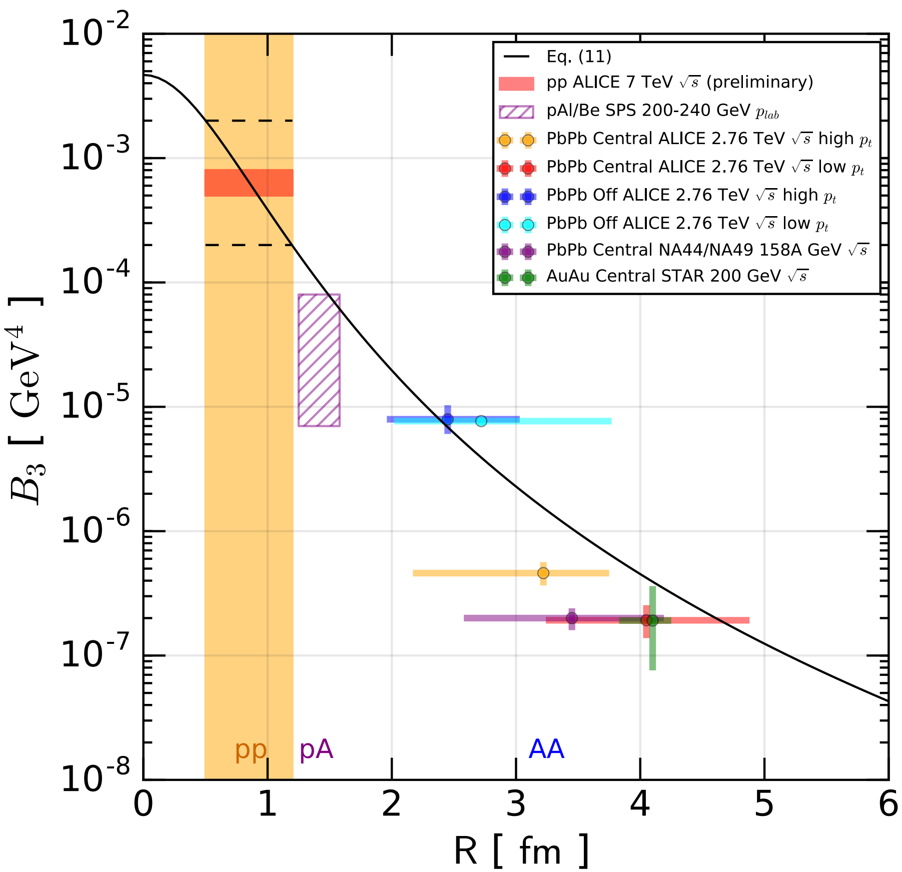
AuAu Central STAR 200 GeV √s
pp
pA
AA
B_3 [GeV^4]
R [fm]

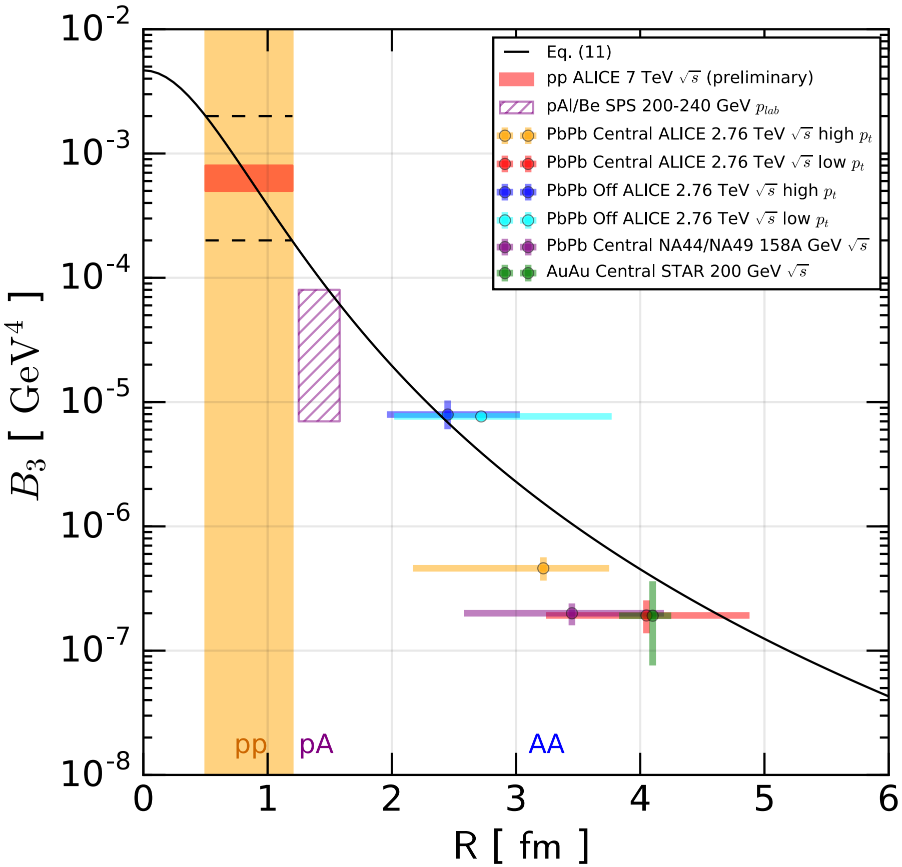


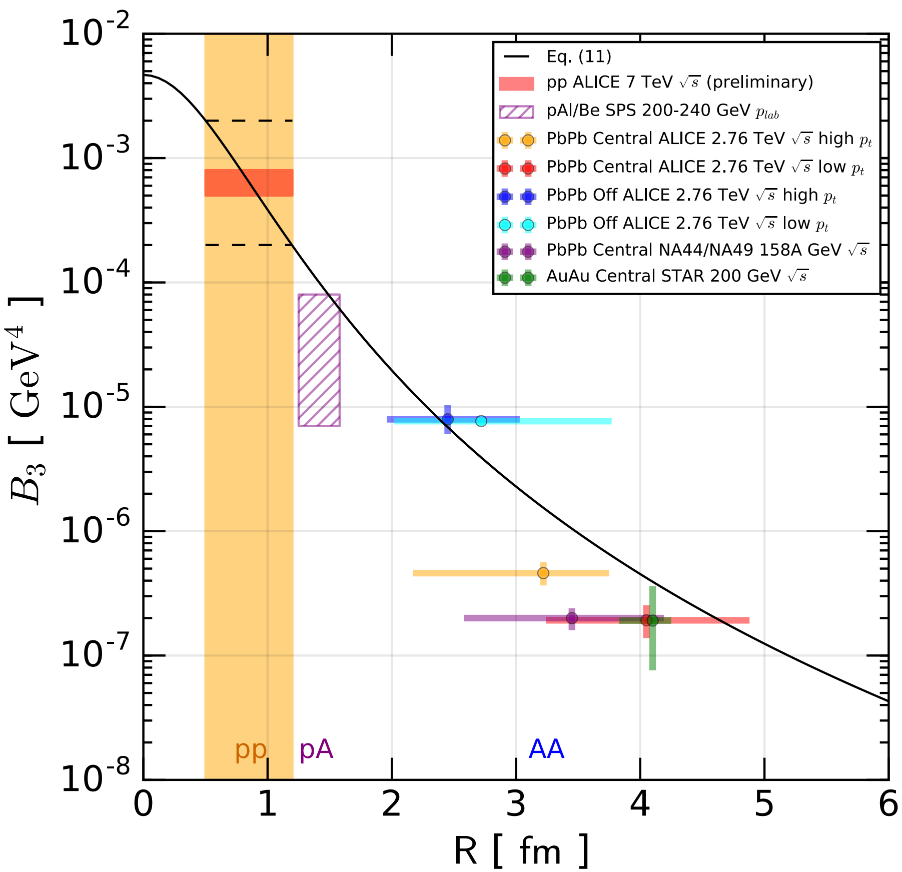
1
2
3
4
prob(>= N events) [%]
B_3 [GeV^4]

- Collected all systems for which we find nuclear yield & HBT data
- For **pp** we **have no B_3**, but we ***do have HBT***



- Collected all systems for which we find nuclear yield & HBT data
- For **pp — until yesterday —** we **had no B_3**… now we do.





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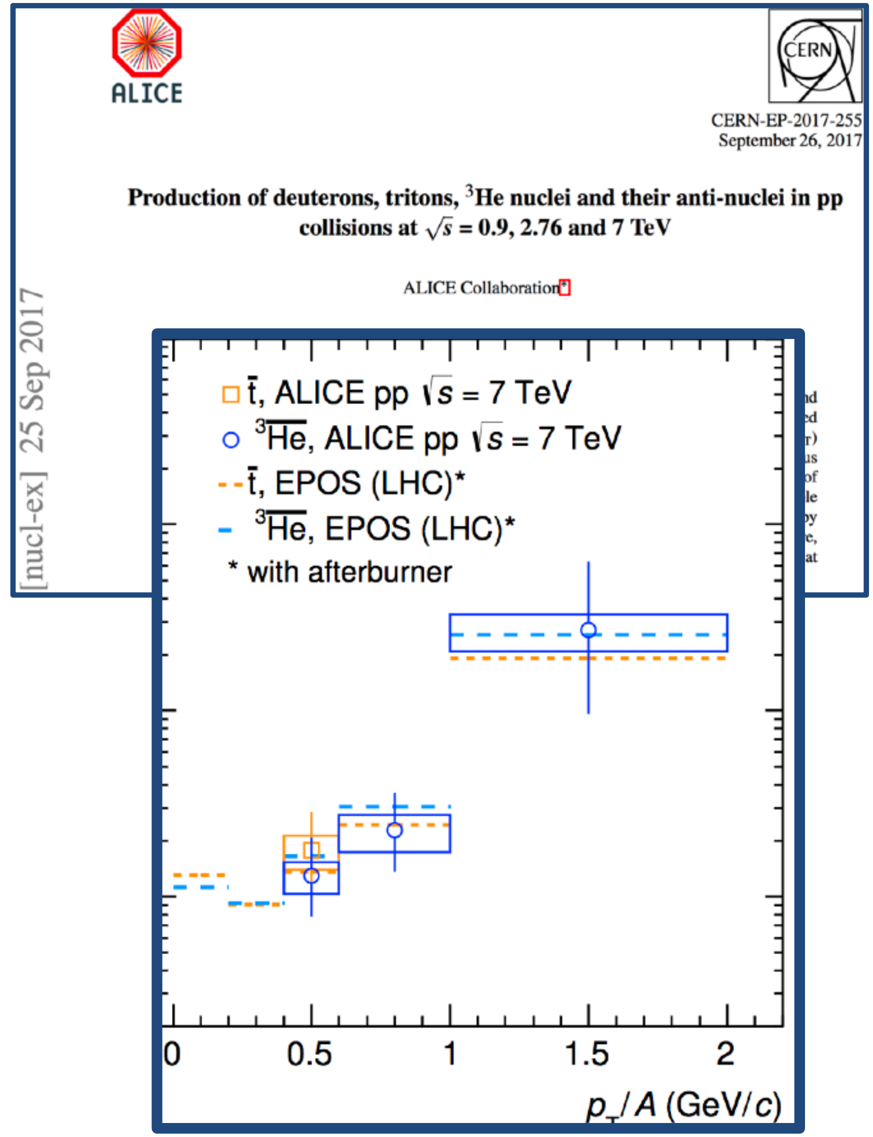

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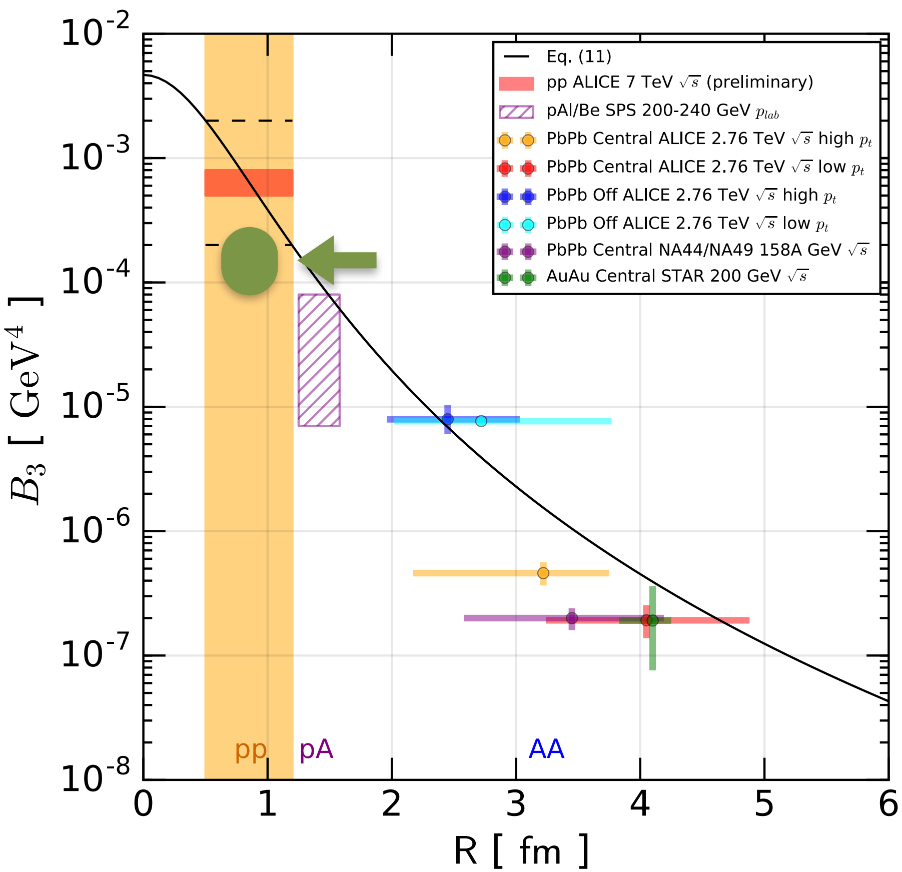

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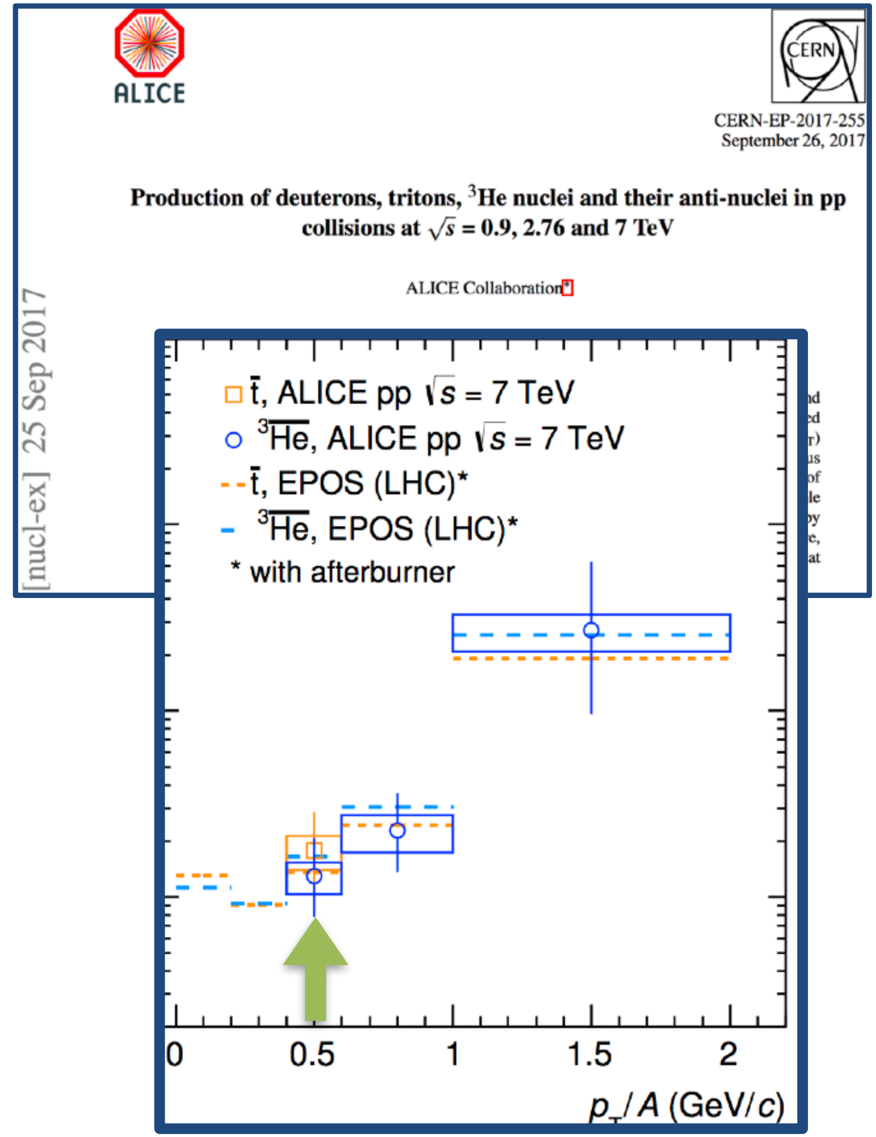

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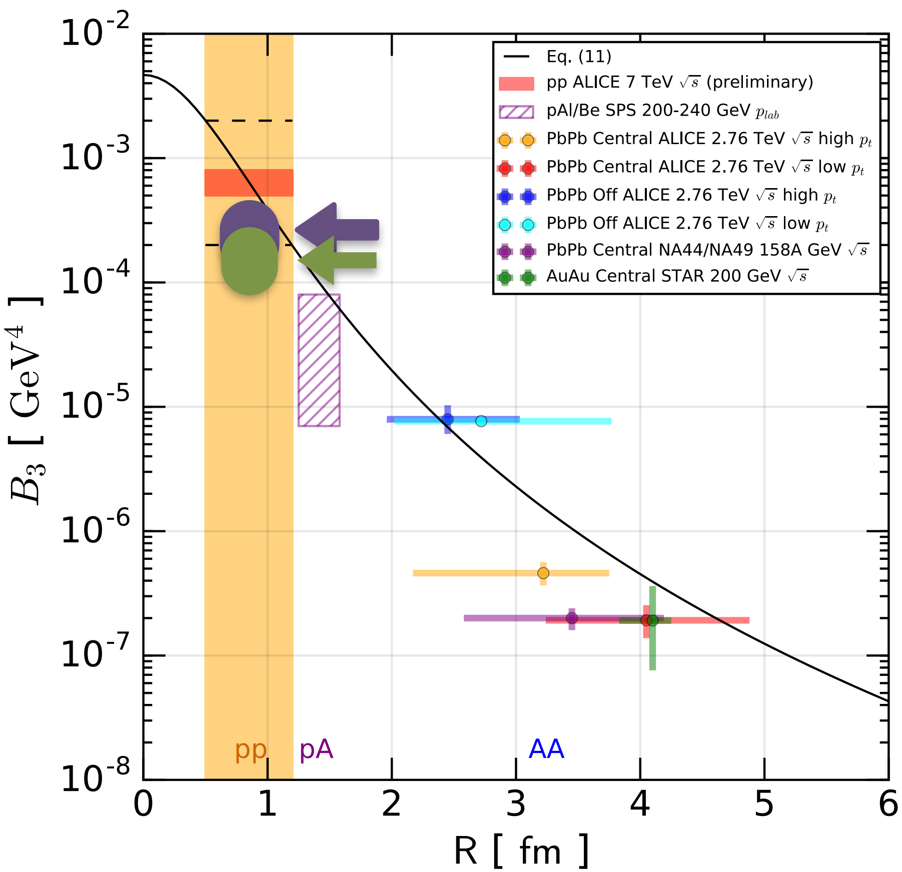
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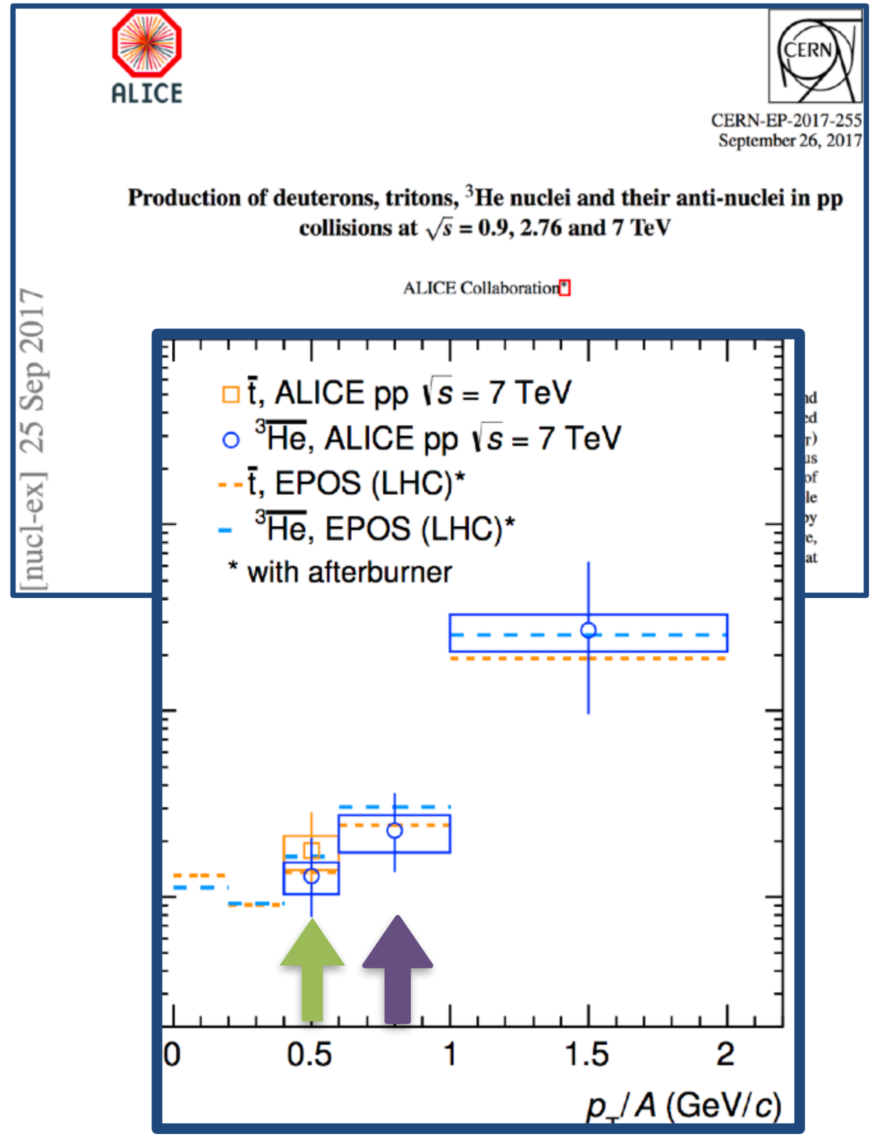
pp
pA
AA
B_3 [GeV^4]
R [fm]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
1
2
3
4
5
6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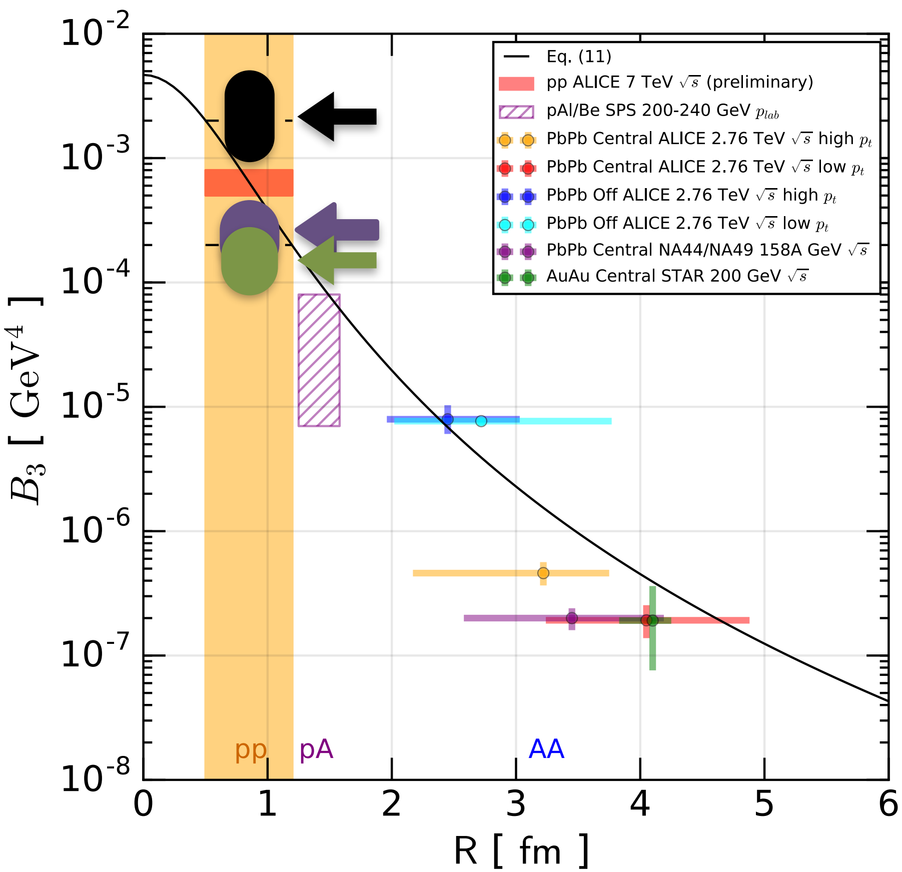
$\bar{t}$, EPOS (LHC)*
$^3\overline{He}$, EPOS (LHC)*
* with afterburner
0
0.5
1
1.5
2
p_T/A (GeV/c)



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pp
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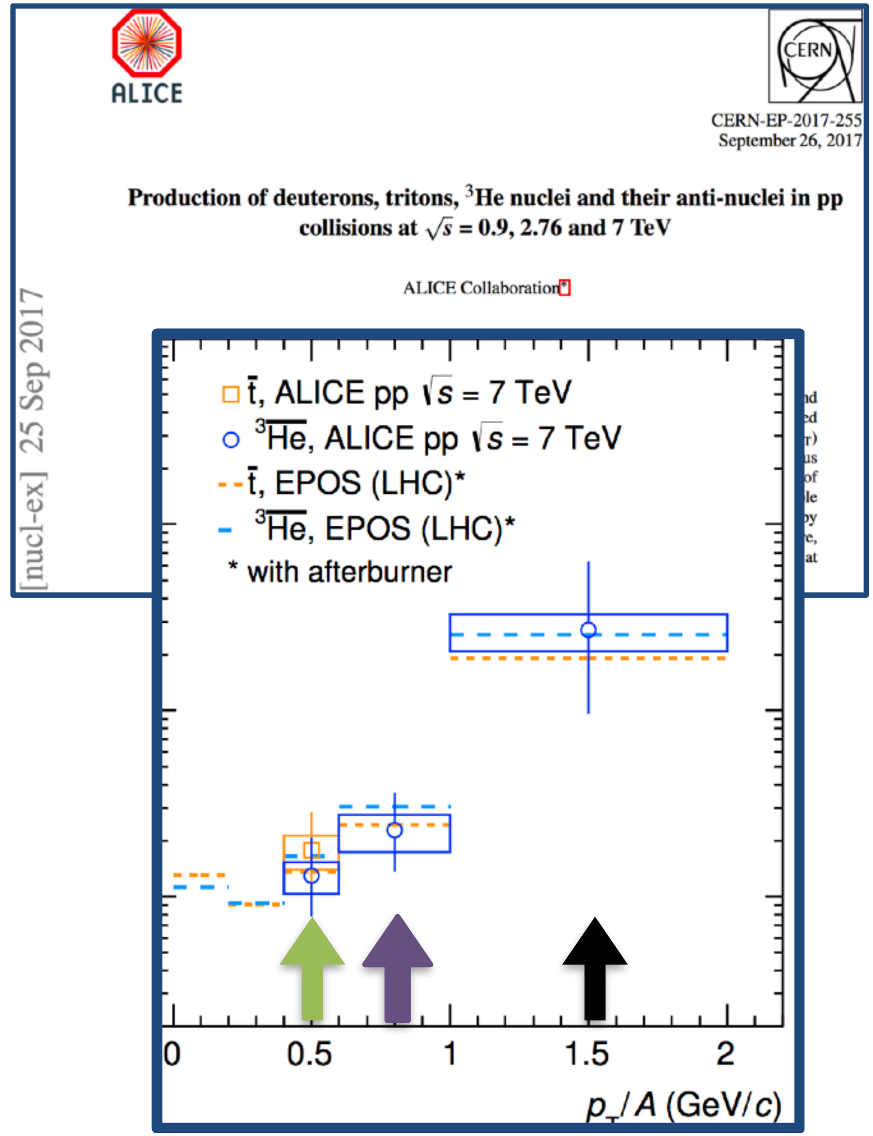

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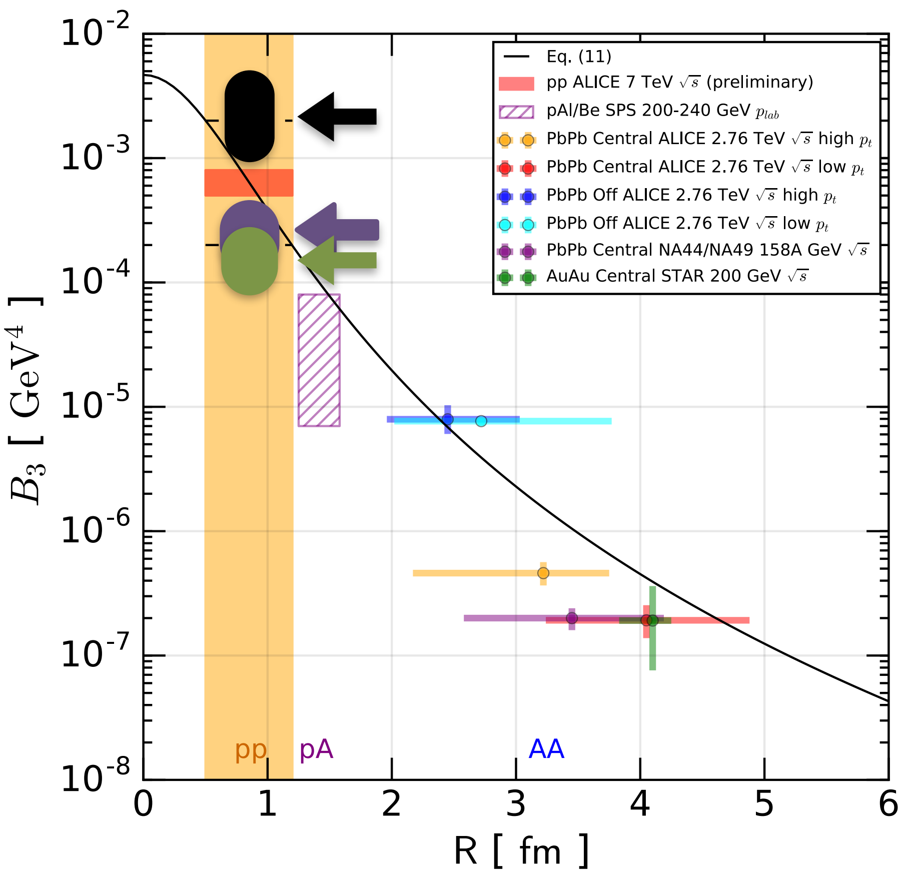
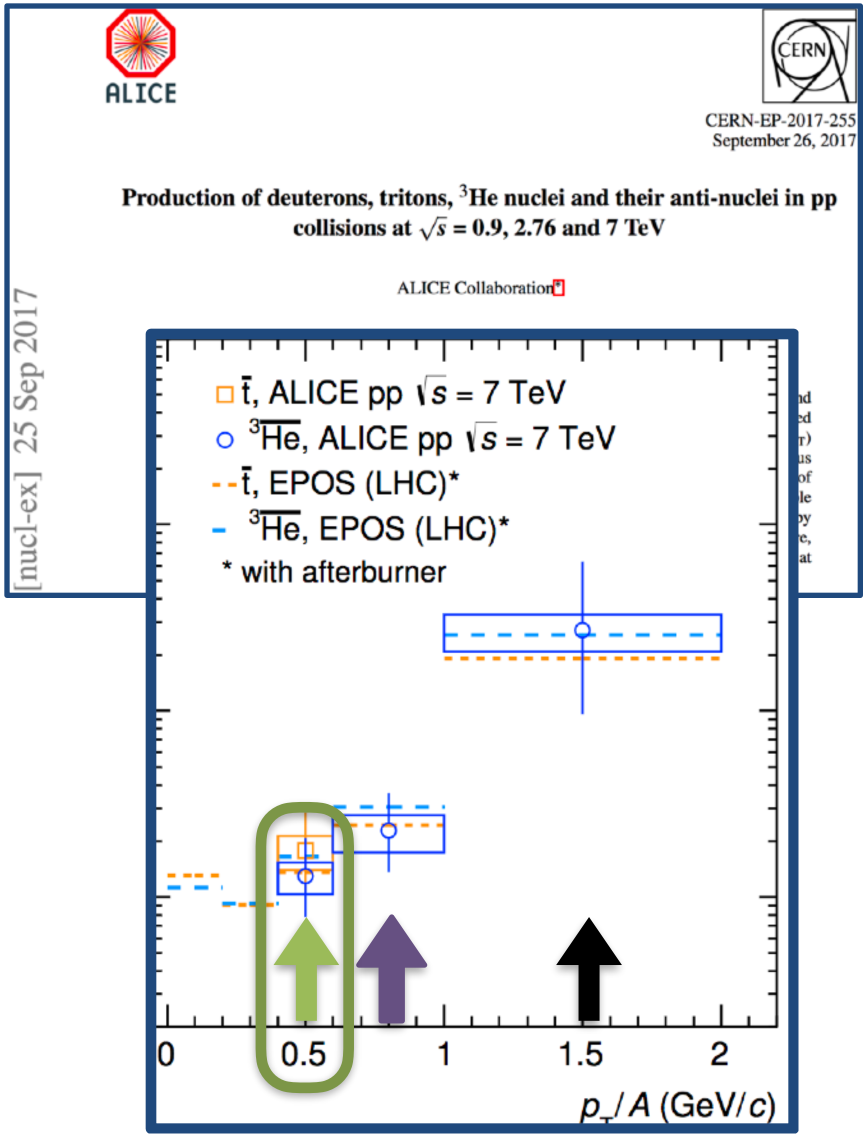
3He̅, EPOS (LHC)*
* with afterburner
p_T/A (GeV/c)

We got the basic picture more or less right.

But we have detailed data now: significant pT dependence in B3.

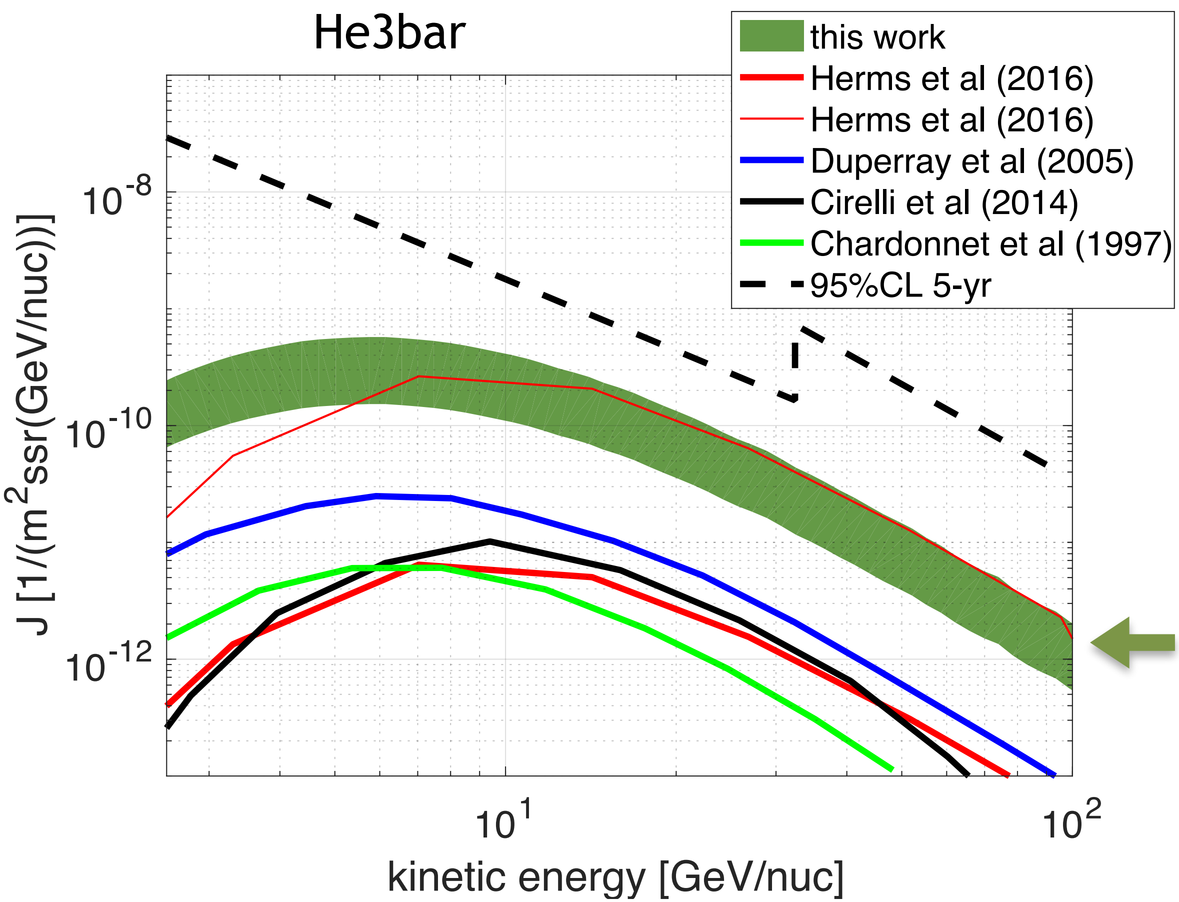
Most relevant for astro is pT/A < 0.3 GeV

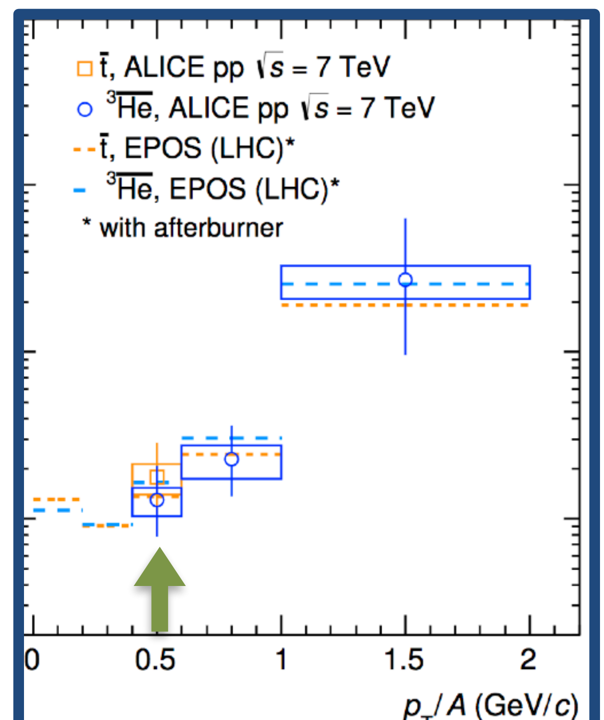




Implication of ALICE results for astrophysics.

He3bar: secondary production by pp collisions
unlikely to explain 1 event/yr at AMS02.



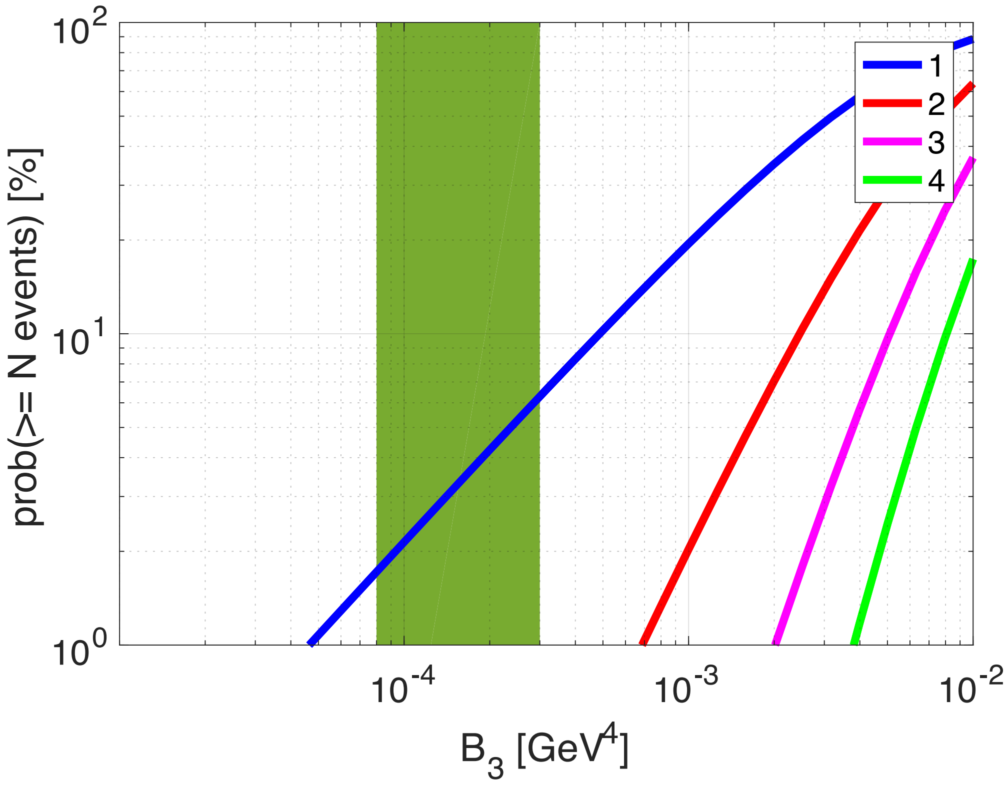


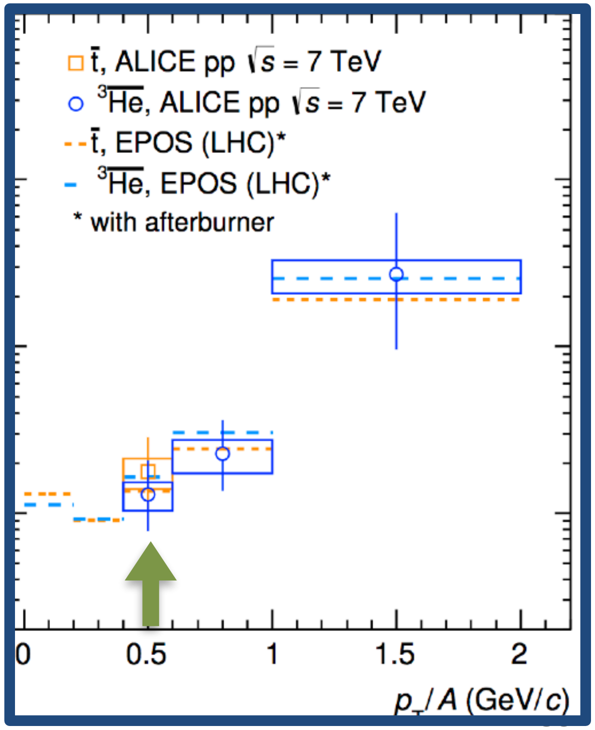
Implication of ALICE results for astrophysics.

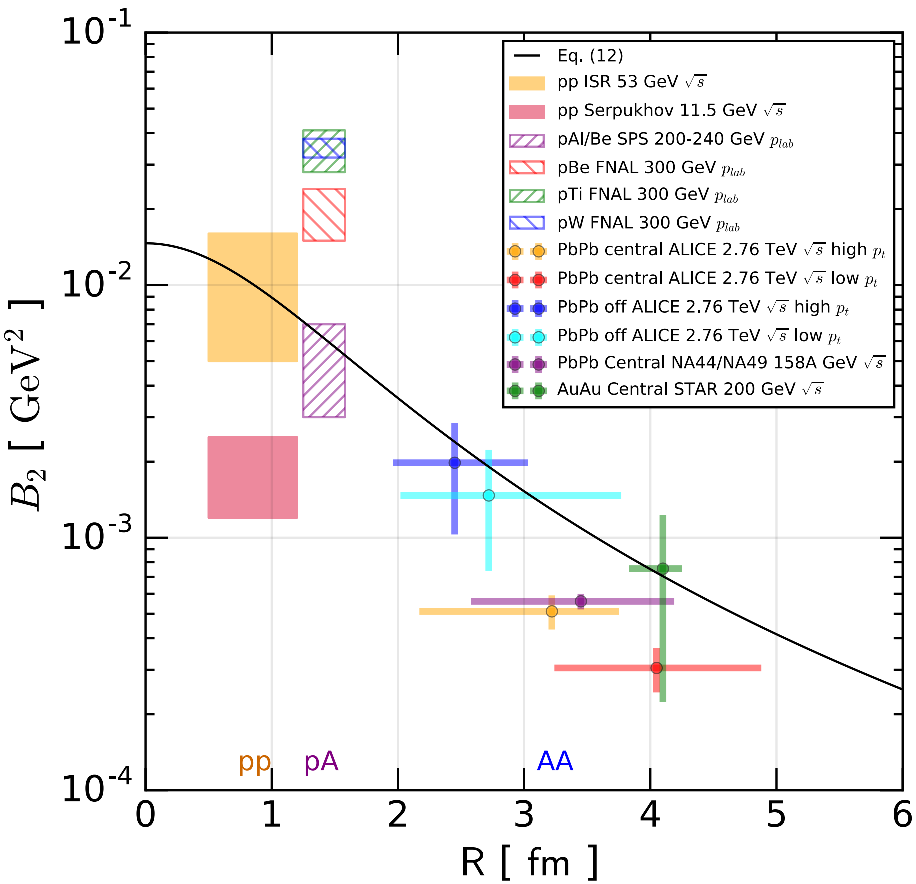
He3bar: secondary production by pp collisions
unlikely to explain 1 event/yr at AMS02.

1 event/5yr we could live with, but 1 event/yr unlikely.

What about p-pbar collisions?



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pp Serpukhov 11.5 GeV $\sqrt{s}$
pAl/Be SPS 200-240 GeV p_{lab}
pBe FNAL 300 GeV p_{lab}
pTi FNAL 300 GeV p_{lab}
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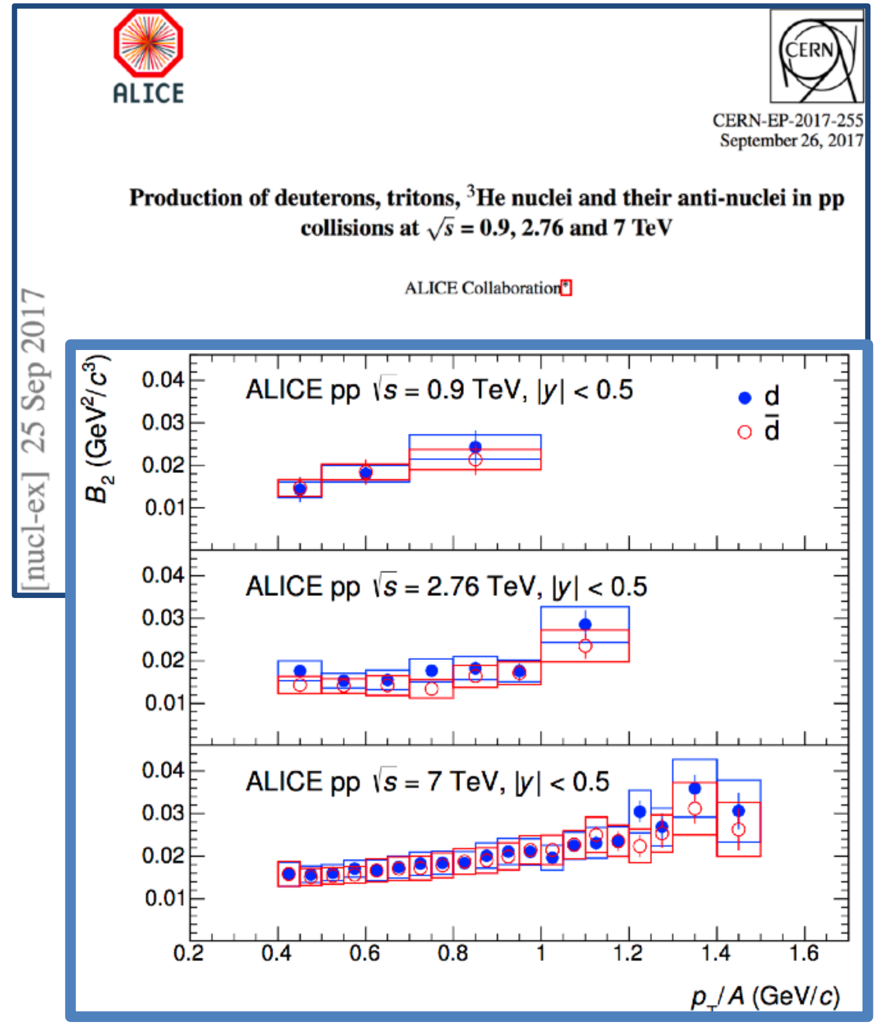
B_2 [GeV^2]
R [fm]
pp
pA
AA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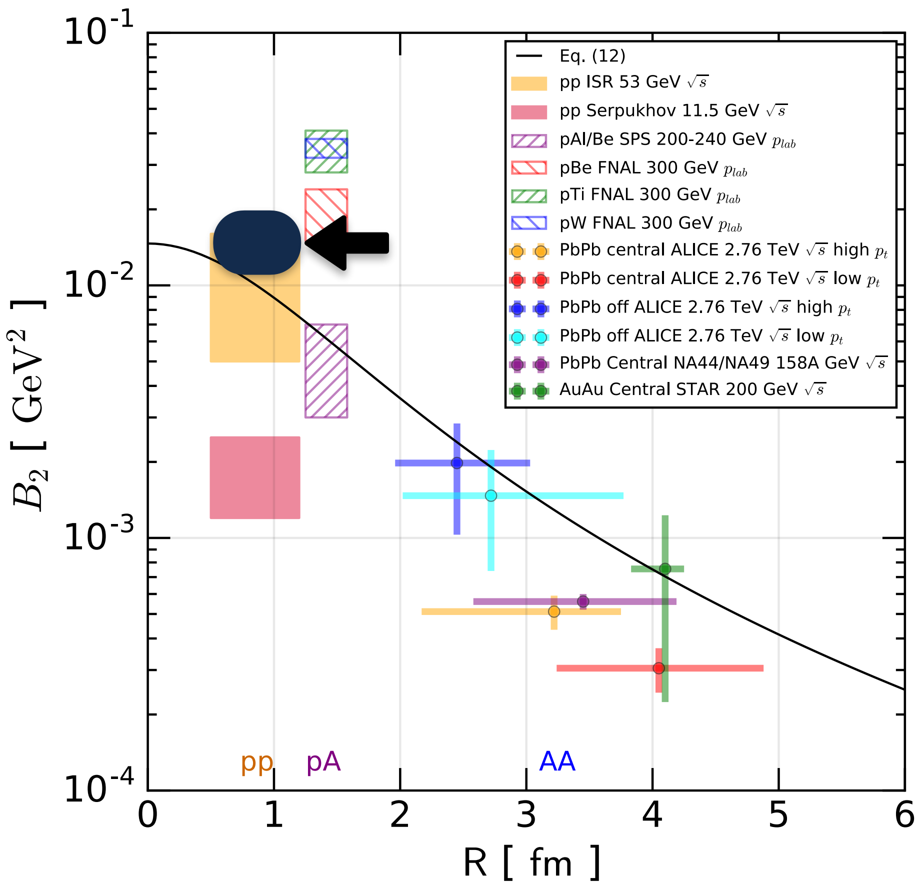
d
$\bar{d}$
B_2 (GeV^2/c^3)
p_T/A (GeV/c)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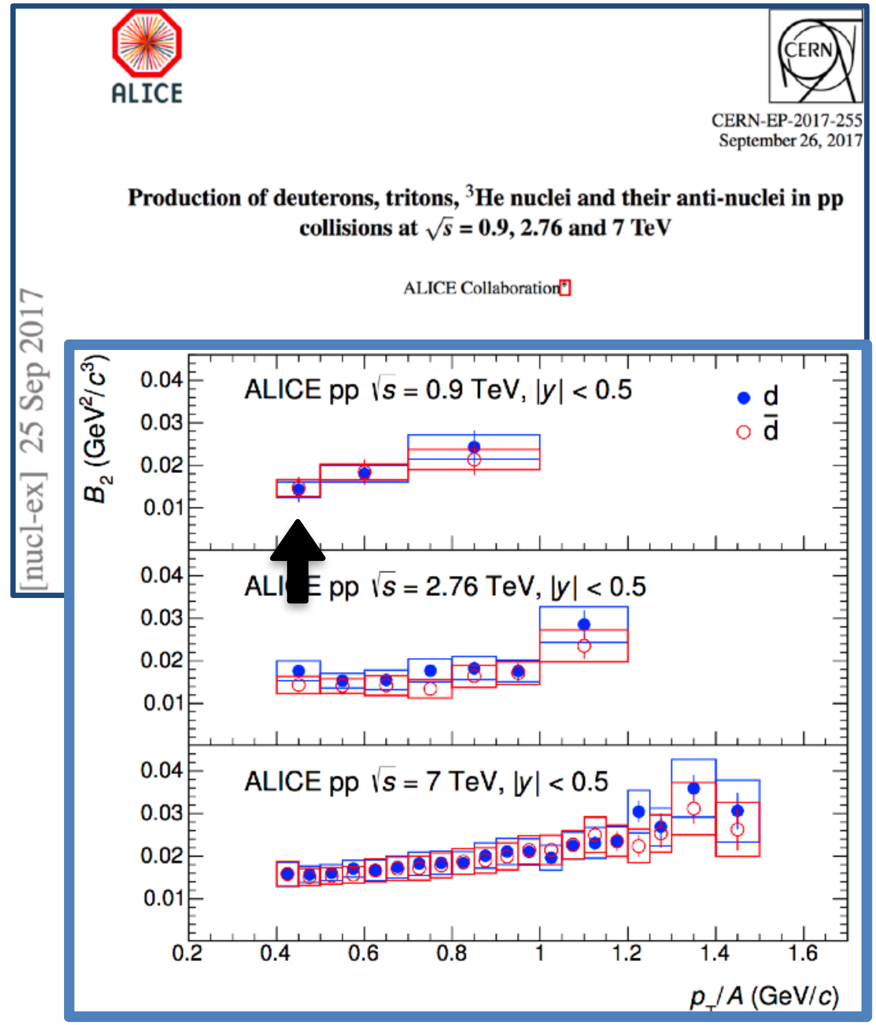
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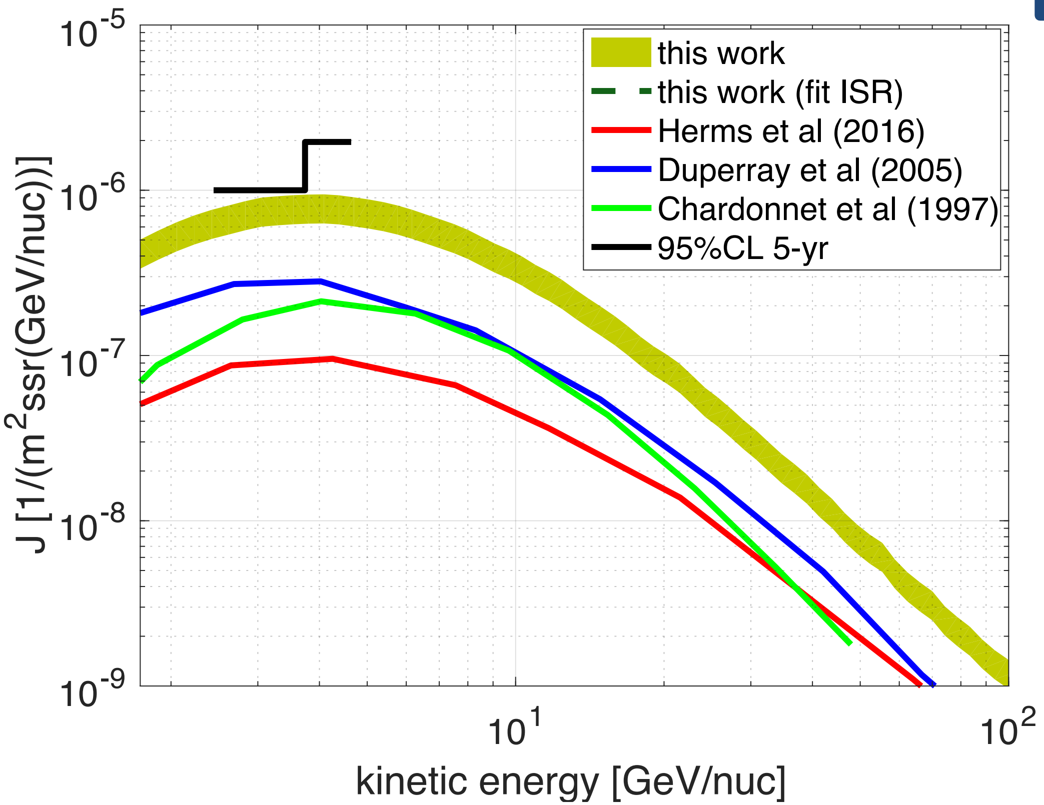
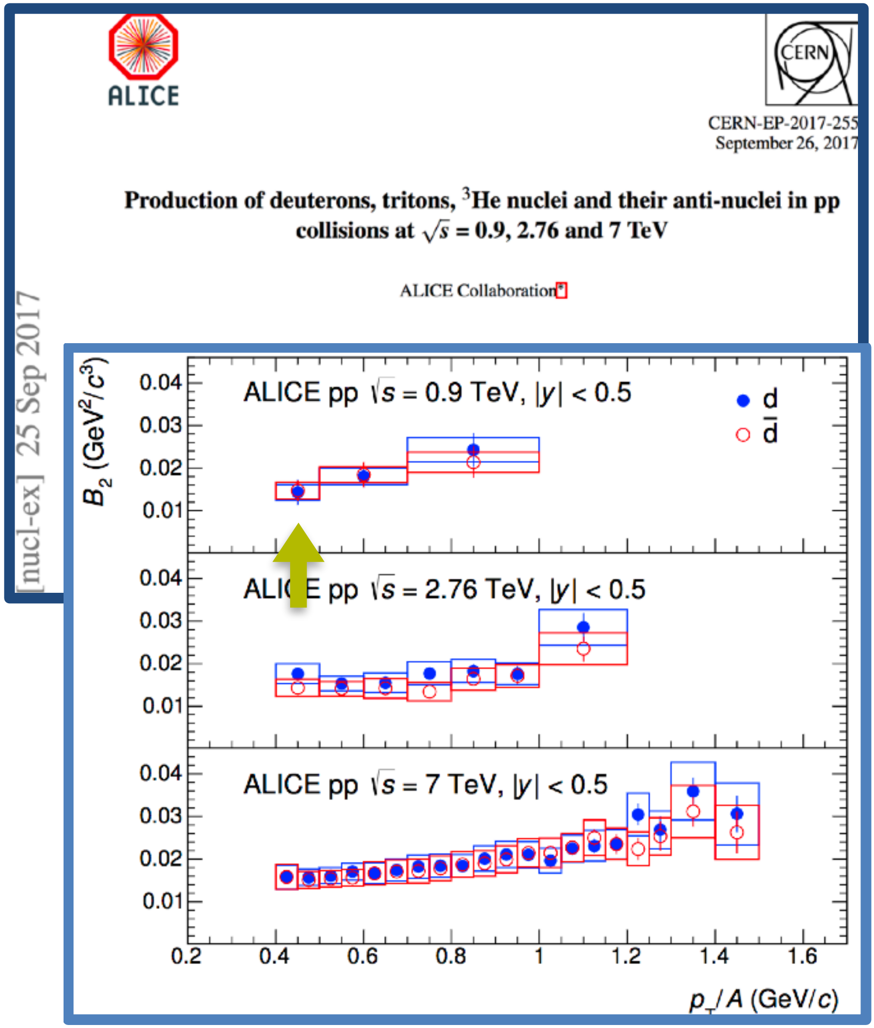
d
d̄
B_2 (GeV²/c³)
p_T/A (GeV/c)

Implication of ALICE results for astrophysics.

dbar: secondary production by pp collisions
may be seen at AMS02 5yr exposure.

dbar





Summary

Summary

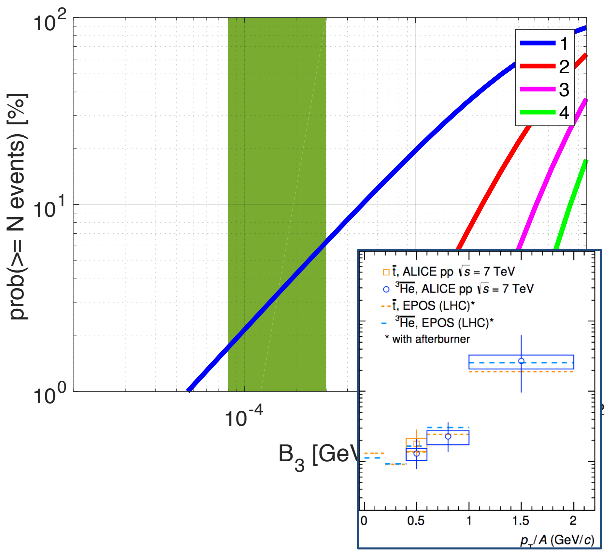
- Antiprotons consistent w/ secondary.

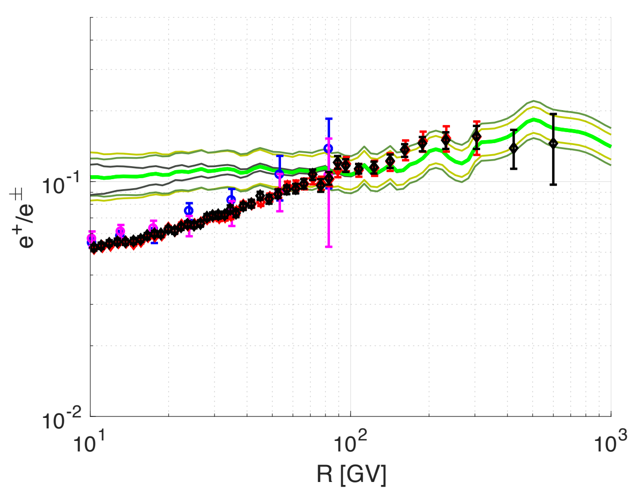
- **Positrons consistent with secondary.**

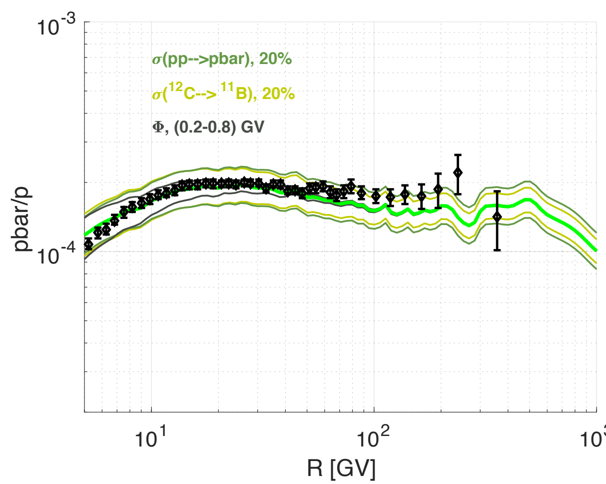
CR propagation more interesting than supposed in simplified diffusion models

- ***Secondary*** anti-He3 events in 5-year of AMS02?

If so, it is unlikely from (the naively dominant) pp collisions

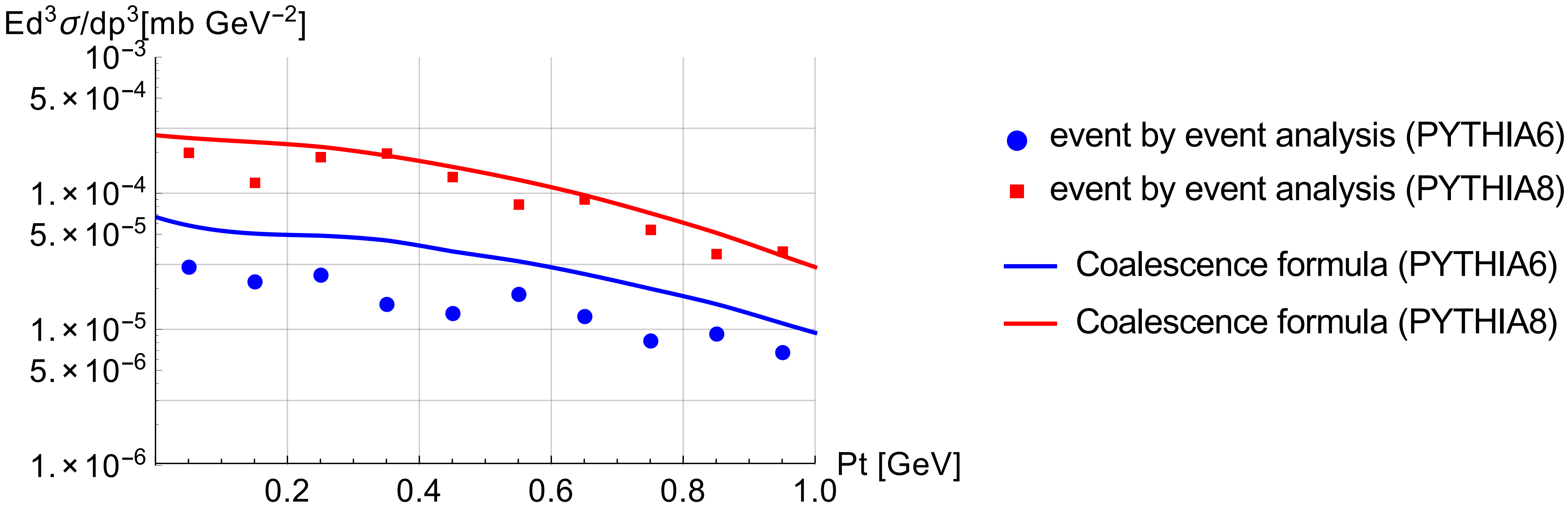




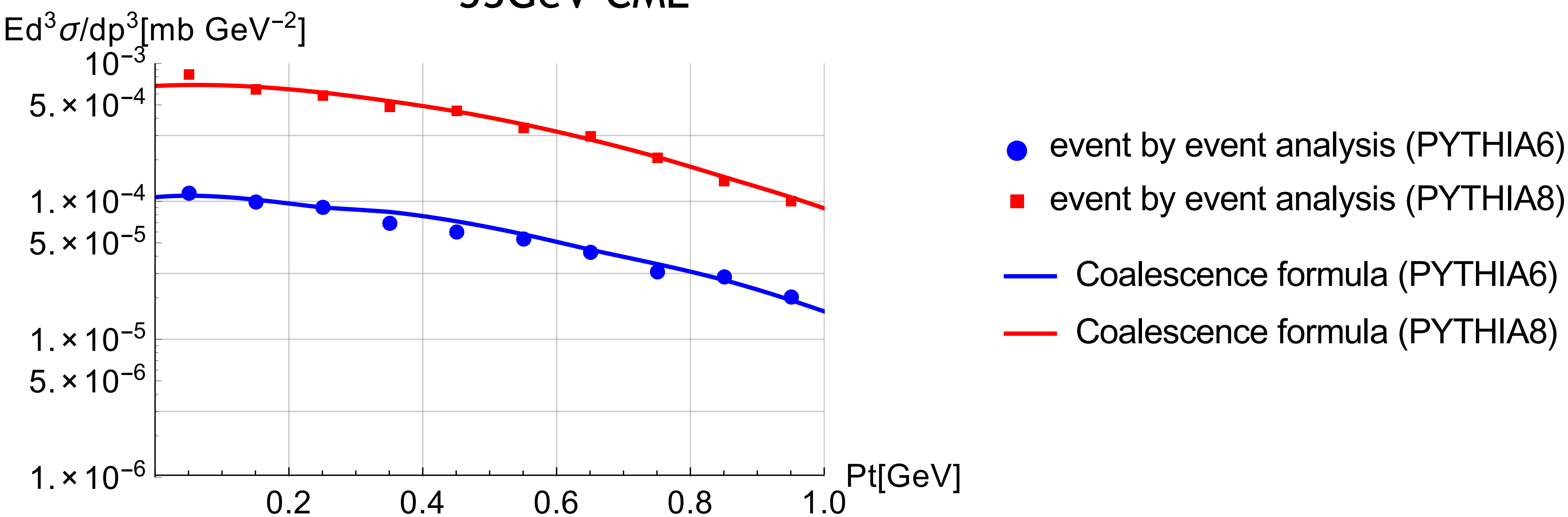


Xtra

20GeV CME



53GeV CME



finally, what about $\bar{p}p \to \overline{{}^3\mathrm{He}}$ **source**

If cross section is ~microbarn, would give a few He3bar events.

finally, what about $\bar{p}p \to \overline{^{3}\mathrm{He}}$ **source**

If cross section is ~microbarn, would give a few He3bar events.

We found one Tevatron ref. (CME 1.8TeV)

Quotes ~microbarn cross section… but need to verify analysis.

PHYSICAL REVIEW D, VOLUME 62, 072004

Cross sections for deuterium, tritium, and helium production in $\bar{p}p$ collisions at $\sqrt{s}=1.8$ TeV

T. Alexopoulos,[7] E. W. Anderson,[3] N. N. Biswas,[4,*] A. Bujak,[5] D. D. Carmony,[5] A. R. Erwin,[7] C. Findeisen,[7] A. T. Goshaw,[1] K. Gulbrandsen,[7] L. J. Gutay,[5] A. S. Hirsch,[5] C. Hojvat,[2] J. R. Jennings,[7] V. P. Kenney,[4] C. S. Lindsey,[6] J. M. LoSecco,[4] N. Morgan,[8] K. Nelson,[9] S. H. Oh,[1] N. Porile,[5] L. Preston,[5] R. Scharenberg,[5] B. Stringfellow,[5] M. Thompson,[7] F. Turkot,[2] W. D. Walker,[1] C. H. Wang,[1] and J. Warchol[4]

finally, what about $\bar{p}p \to \overline{^3\mathrm{He}}$ **source**

If cross section is ~microbarn, would give a few He3bar events.

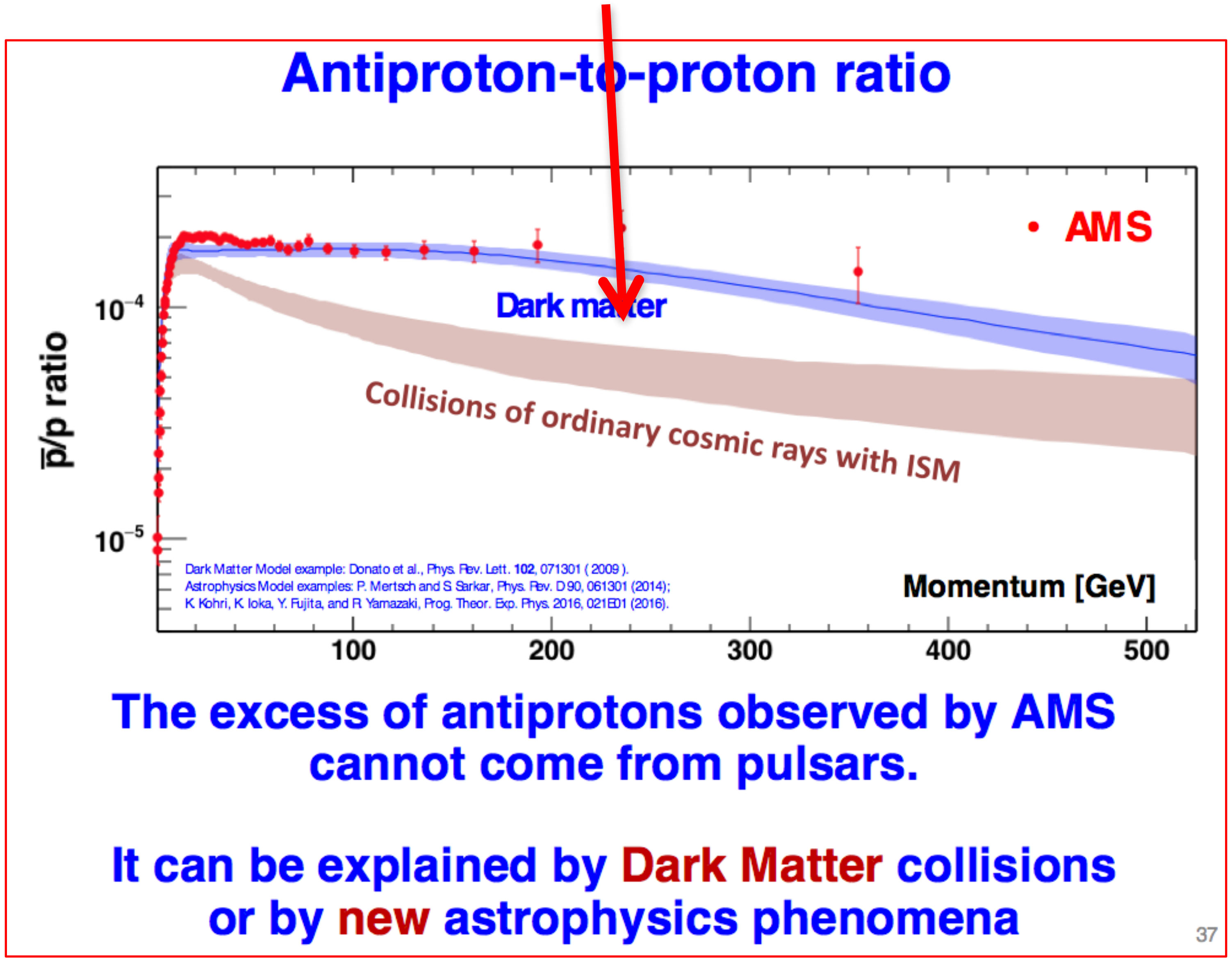
We found one Tevatron ref. (CME 1.8TeV)

Unfortunately, it may be off the truth, because it also seems to be saying

$$\sigma_{\bar{p}p\to d}/\sigma_{\bar{p}p\to t} \sim 3$$

Factor ~few suppression for He3 vs deuterium feels hard to digest: we expect much stronger suppression…

What's going on here? (Donato et al PRL102, 071301 (2009))



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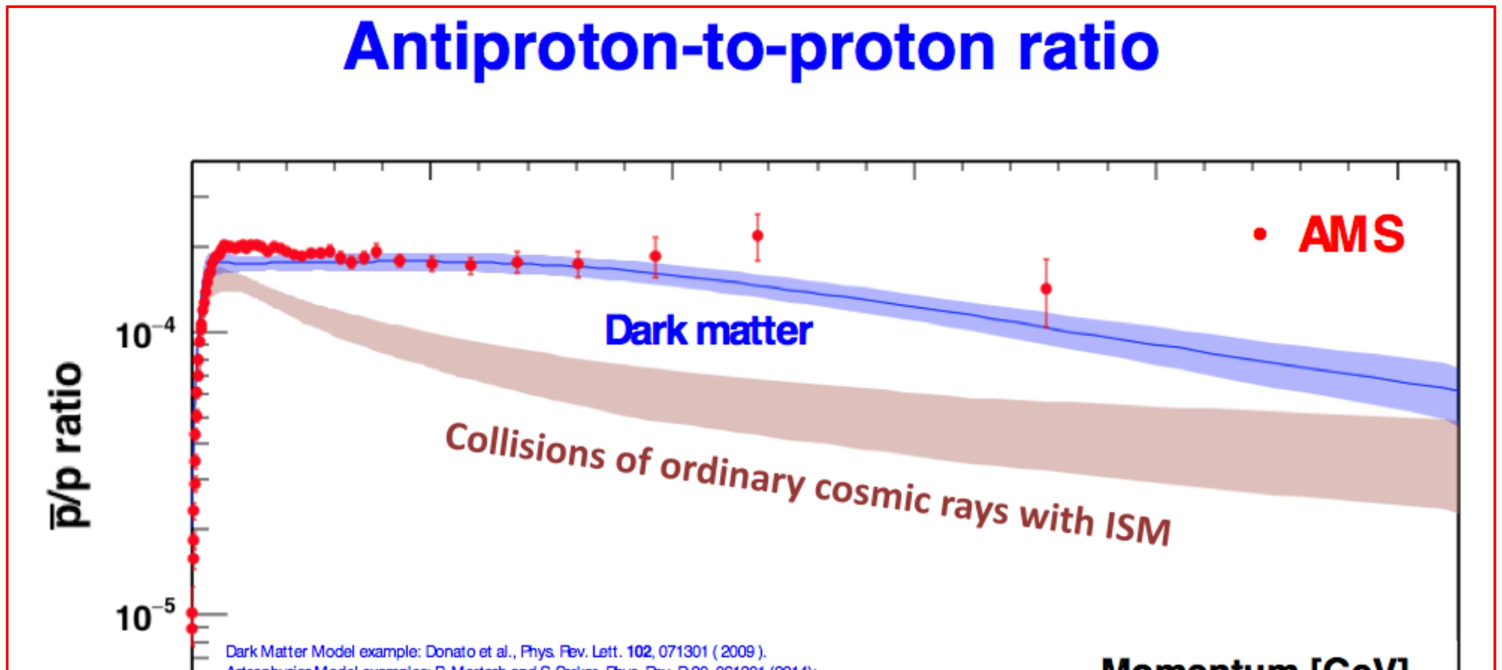
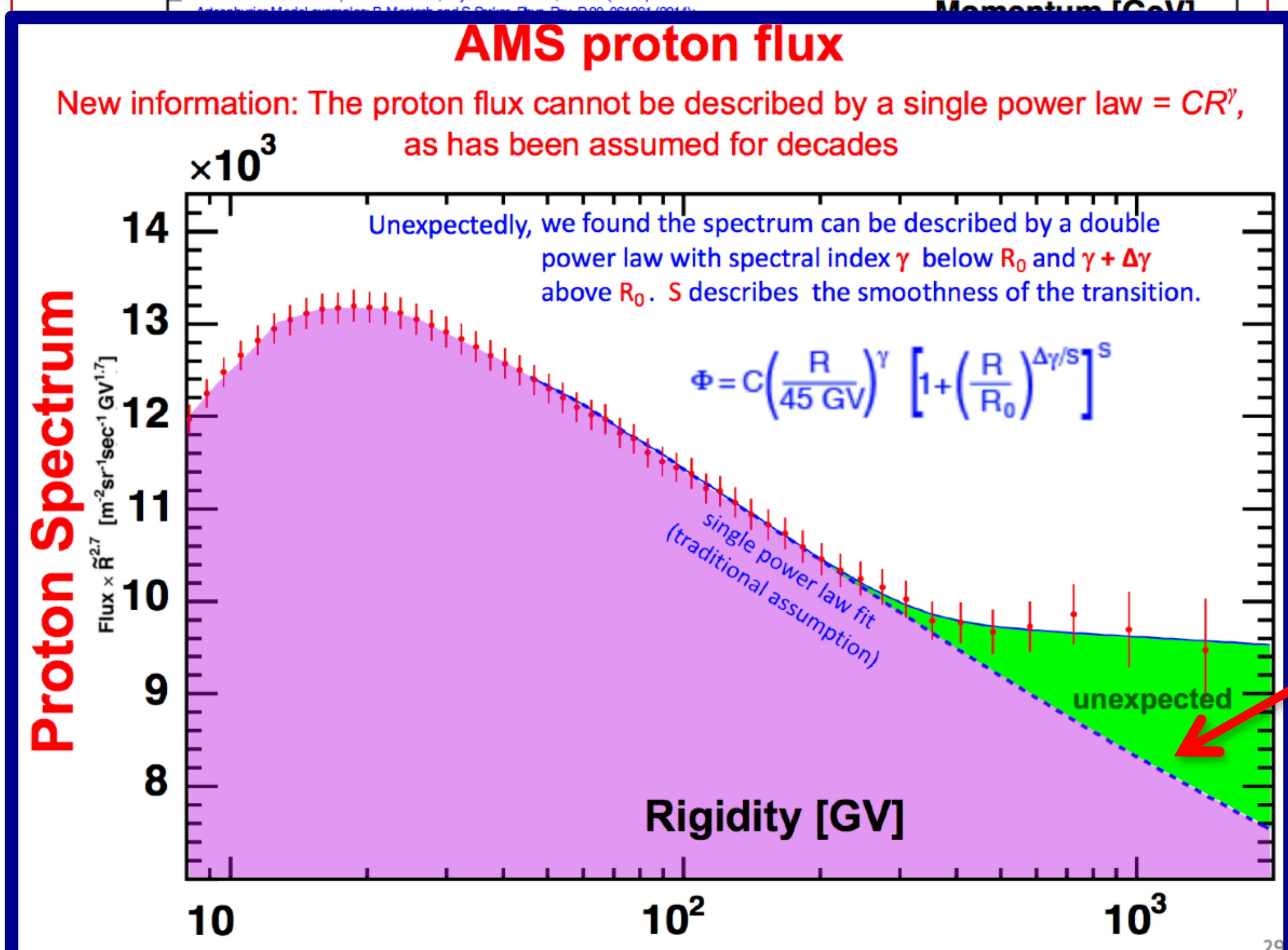
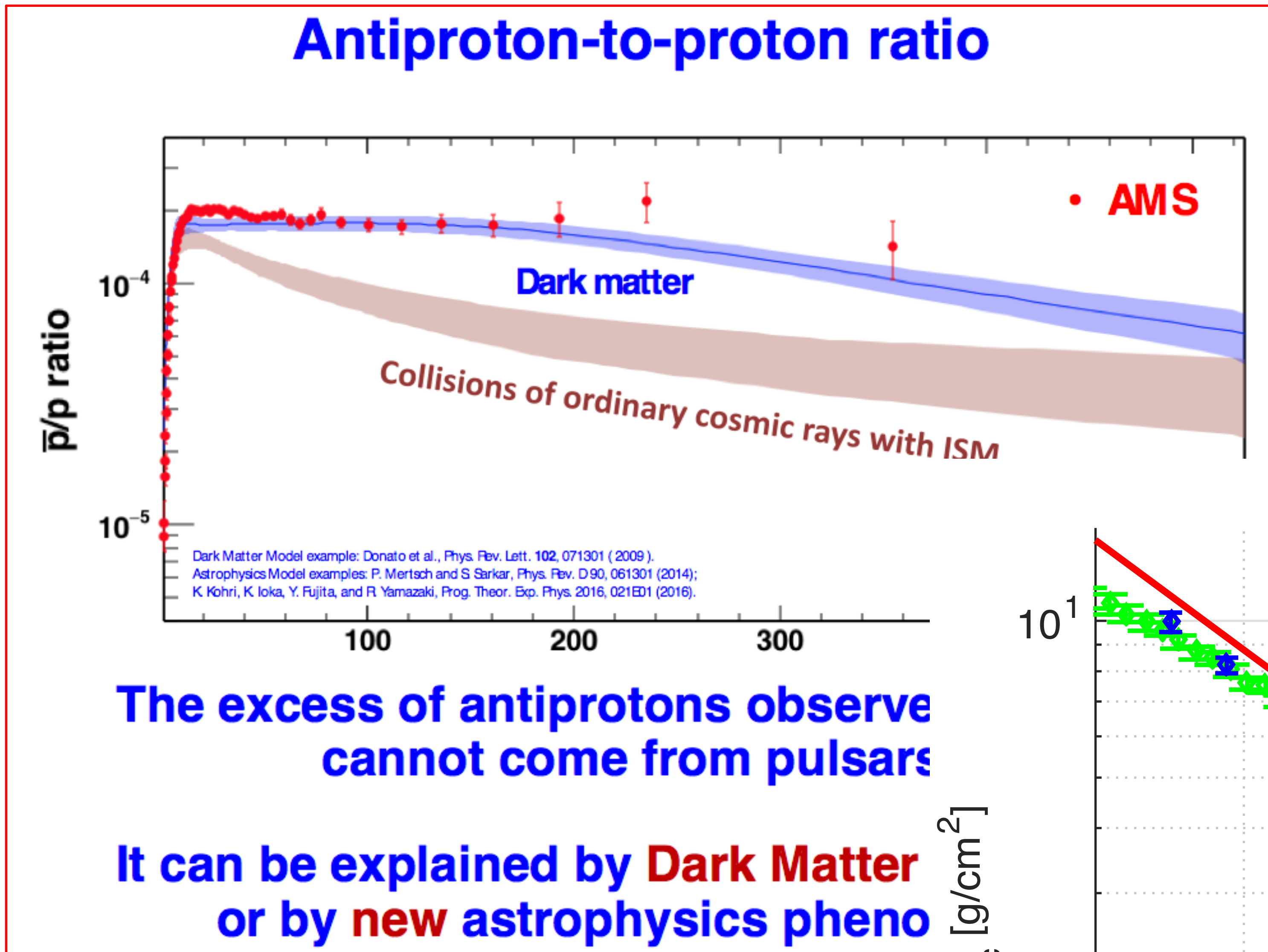
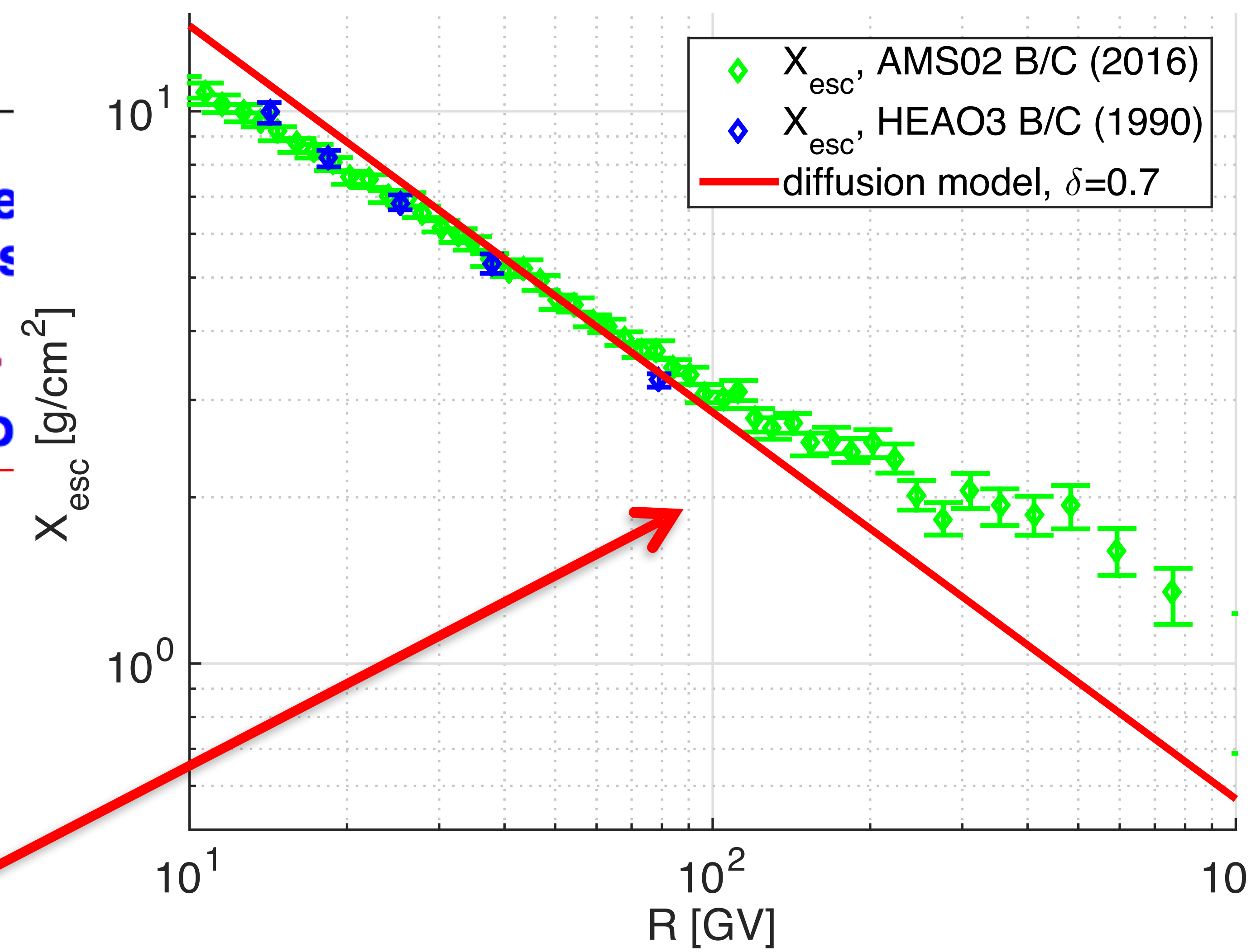




proton flux assumed for making the pbar/p grey line

What's going on here? (Donato et al PRL102, 071301 (2009))





B/C grammage assumed for making the pbar/p grey line

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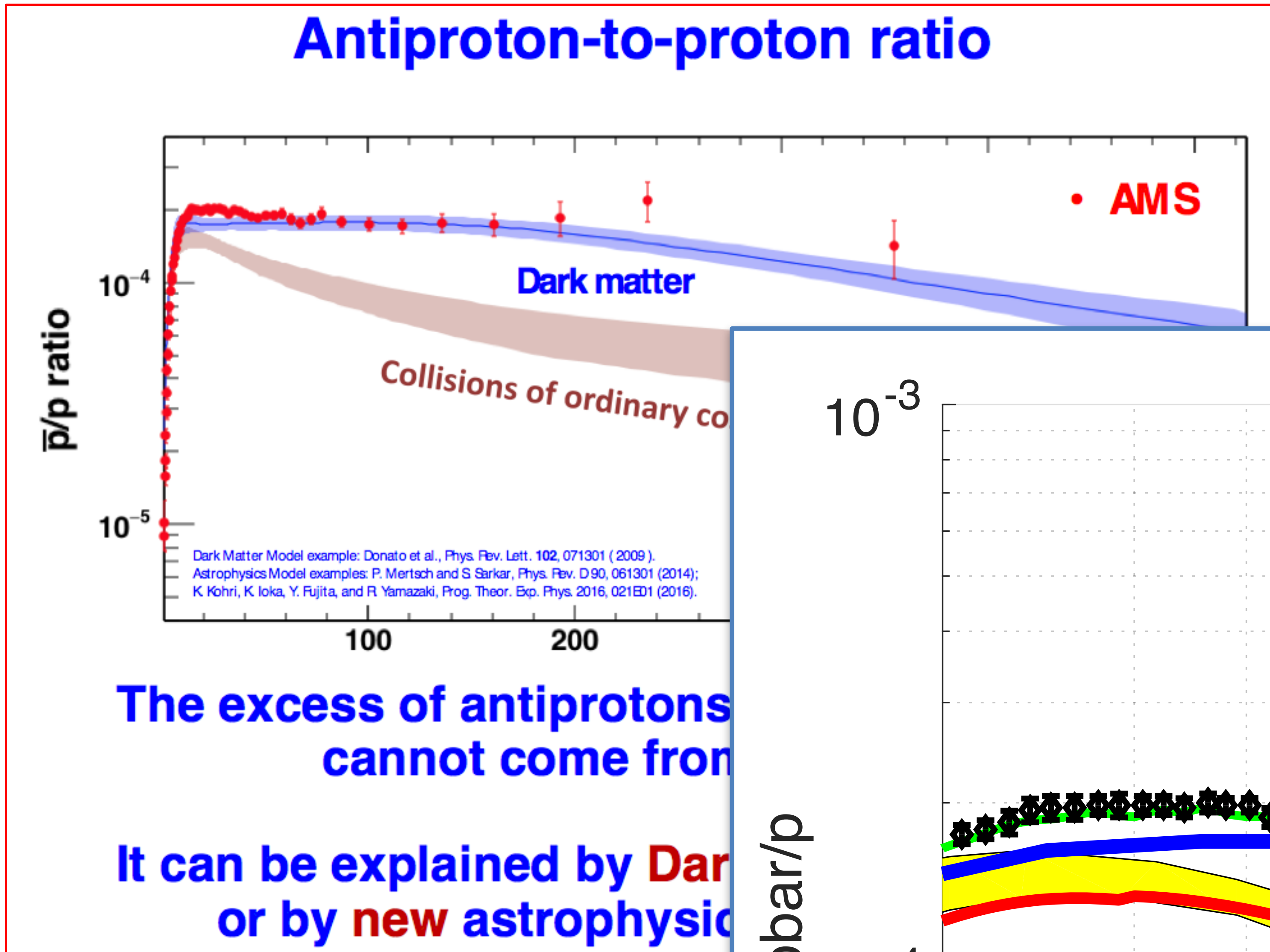
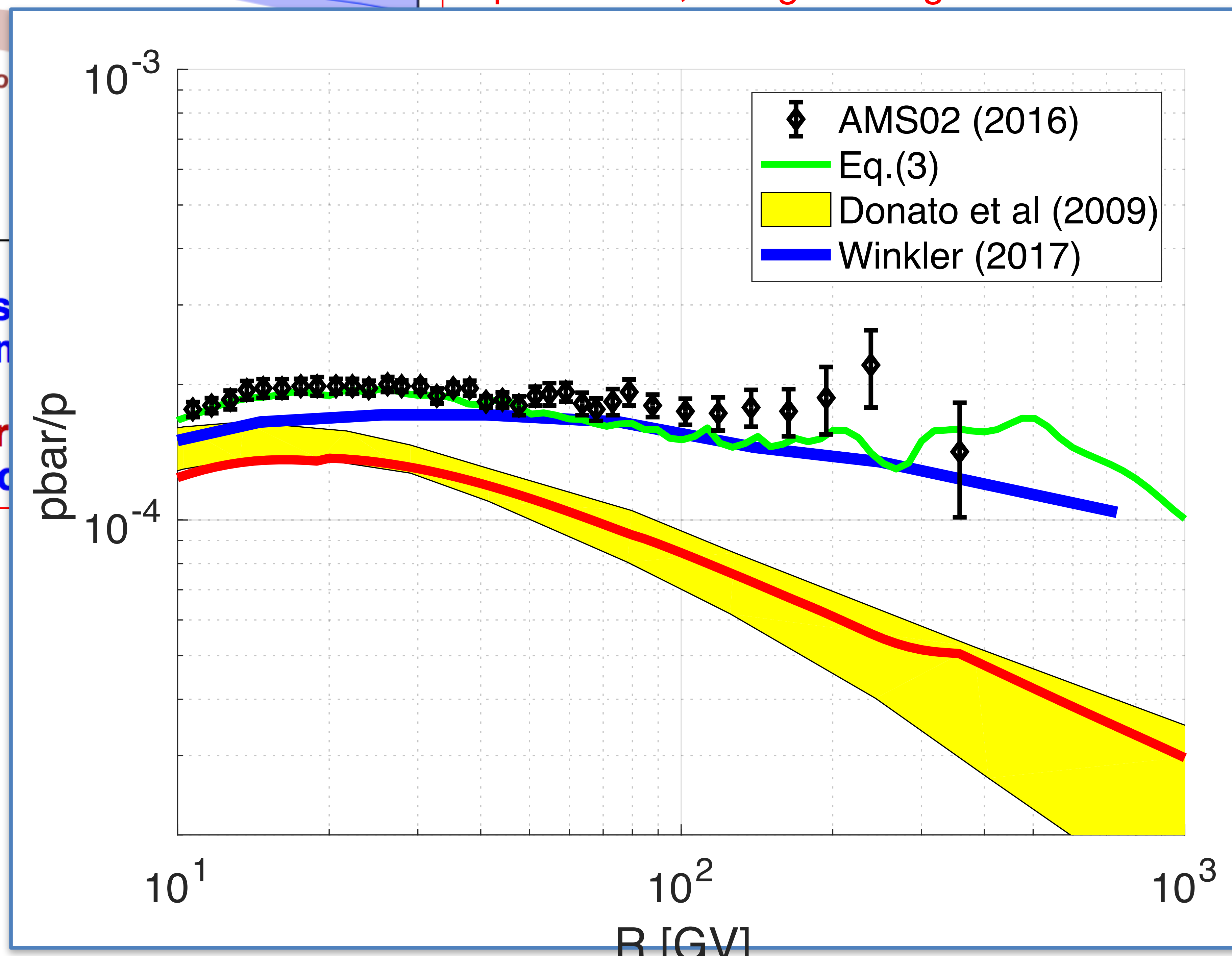


What we get if we use those old proton flux, B/C grammage



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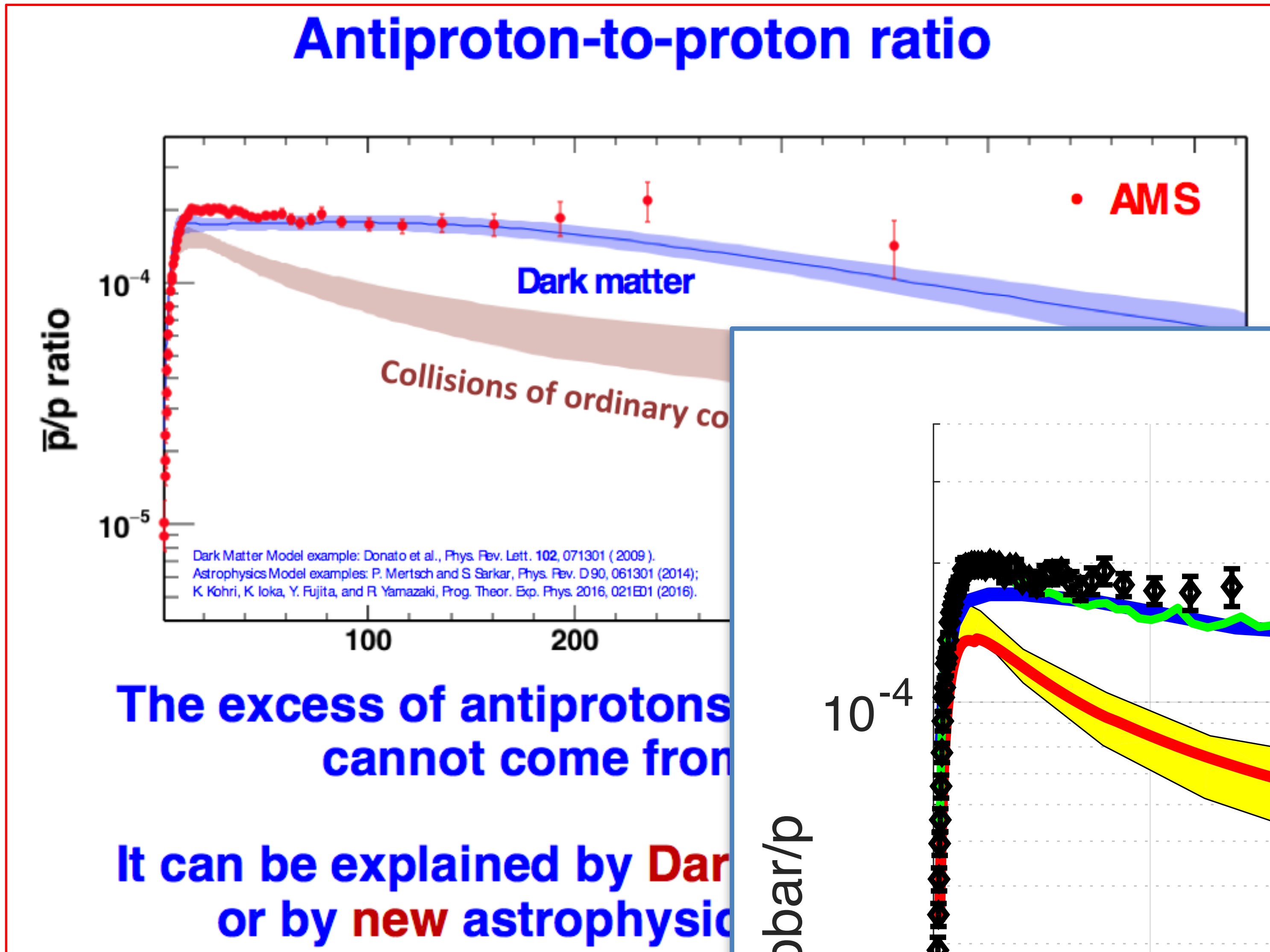

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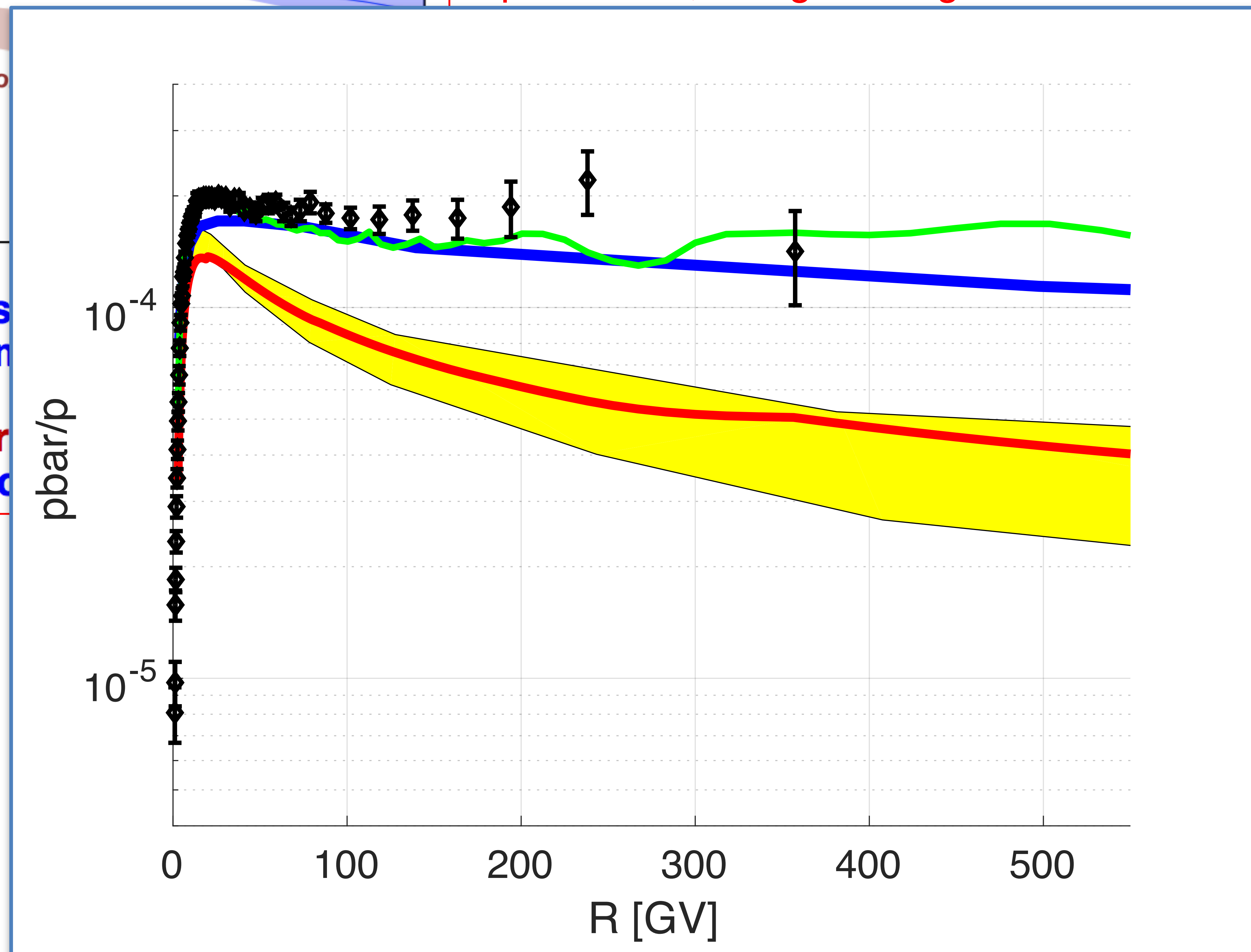


Propagation time scales: radioactive nuclei

Secondary radioactive nuclei carry time info (like positrons)

reaction	$t_{1/2}$ [Myr]	σ [mb]
${}^{10}_{4}\mathrm{Be} \rightarrow {}^{10}_{5}\mathrm{B}$	1.51 (0.06)	210
${}^{26}_{13}\mathrm{Al} \rightarrow {}^{26}_{12}\mathrm{Mg}$	0.91 (0.04)	411
${}^{36}_{17}\mathrm{Cl} \rightarrow {}^{36}_{18}\mathrm{Ar}$	0.307 (0.002)	516
${}^{54}_{25}\mathrm{Mn} \rightarrow {}^{54}_{26}\mathrm{Fe}$	0.494 (0.006)*	685

Positrons vs. radioactive nuclei

How to compare radioactive decay of a nucleus, with energy loss of e+?

e+

^{10}Be

We'll get there in a few slides.

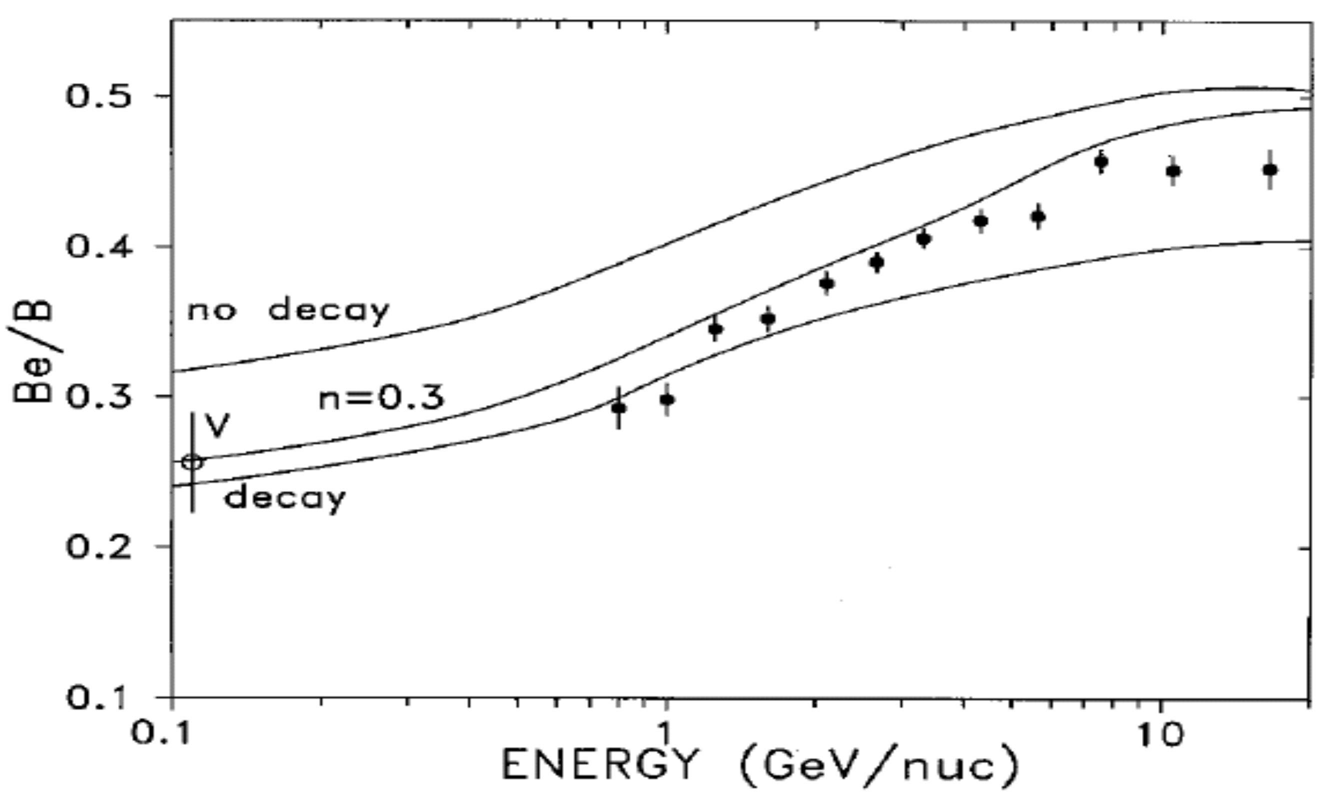
Radioactive nuclei: Charge ratio

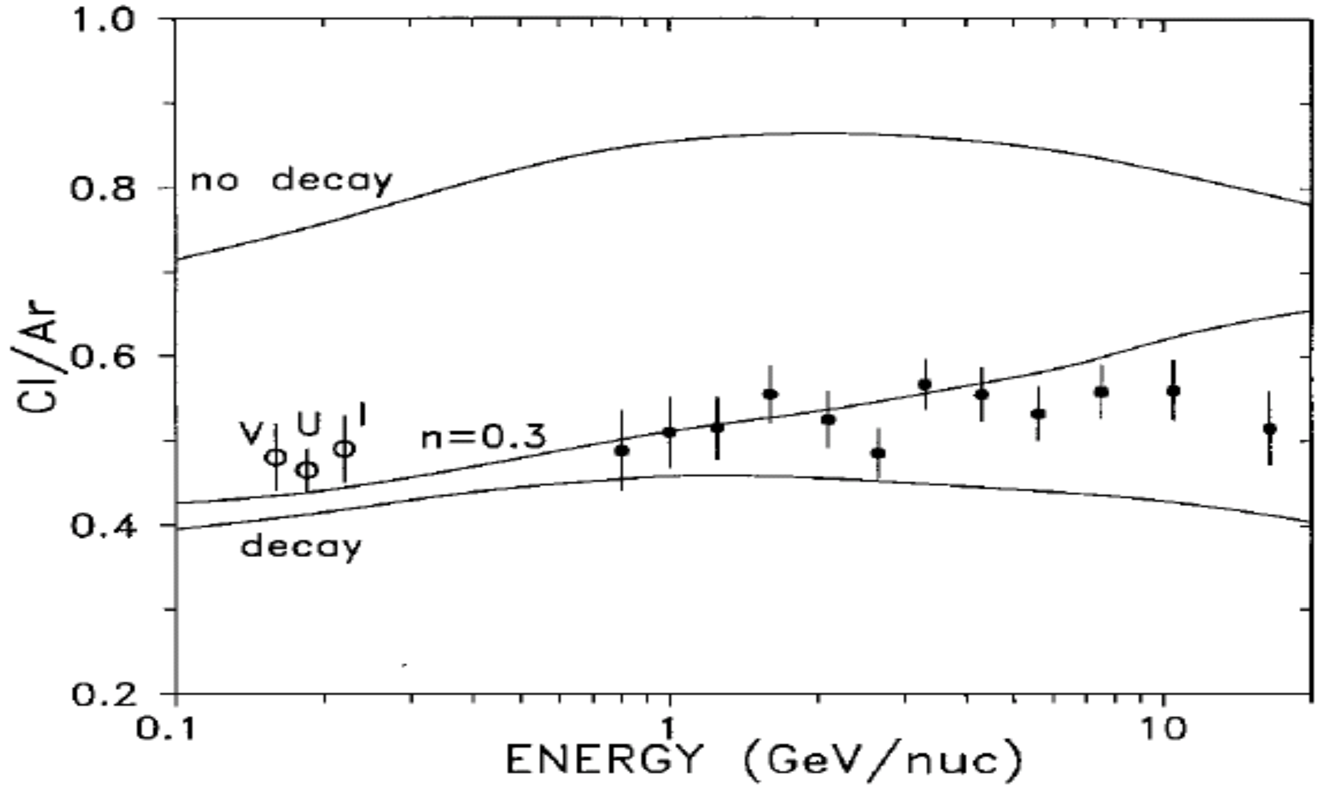
A STUDY OF THE SURVIVING FRACTION OF THE COSMIC-RAY RADIOACTIVE DECAY ISOTOPES ^{10}Be, ^{26}Al, ^{36}Cl, and ^{54}Mn AS A FUNCTION OF ENERGY USING THE CHARGE RATIOS Be/B, Al/Mg, Cl/Ar, AND Mn/Fe MEASURED ON *HEAO-3*

W. R. WEBBER[1] AND A. SOUTOUL

(WS98)

Received 1997 November 6; accepted 1998 May 11





Radioactive nuclei: Charge ratio vs. isotopic ratio

Charge ratios $\mathrm{Be/B,\ Al/Mg,\ Cl/Ar,\ Mn/Fe}$

Isotopic ratios $\mathrm{^{10}Be/^{9}Be,\ ^{26}Al/^{27}Al,\ ^{36}Cl/Cl,\ ^{54}Mn/Mn}$

Radioactive nuclei: Charge ratio vs. isotopic ratio

Charge ratios $\mathrm{Be/B,\ Al/Mg,\ Cl/Ar,\ Mn/Fe}$

Isotopic ratios $\mathrm{^{10}Be/^{9}Be,\ ^{26}Al/^{27}Al,\ ^{36}Cl/Cl,\ ^{54}Mn/Mn}$

• High energy isotopic separation difficult. Need to resolve mass.
Isotopic ratios were measured only up to ~ 2 GeV/nuc (ISOMAX)

• Charge separation easier. Charge ratios up to ~ 16 GeV/nuc (HEAO3-C2)
(AMS-02: Charge ratios to ~ TeV/nuc. Isotopic ratios ~ 10 GeV/nuc)

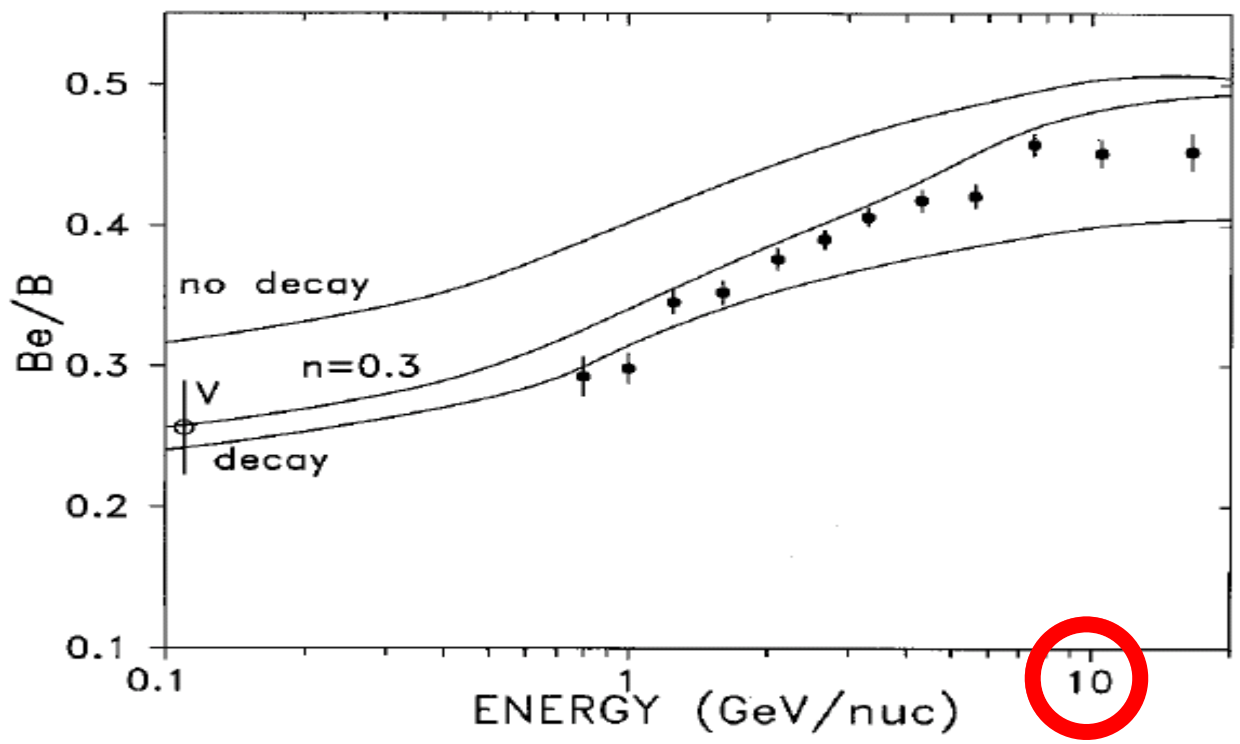
• **Benefit**: avoid low energy complications; significant range in rigidity

• **Drawback**: systematic uncertainties (cross sections, primary contamination)

Radioactive nuclei: Charge ratio vs. isotopic ratio

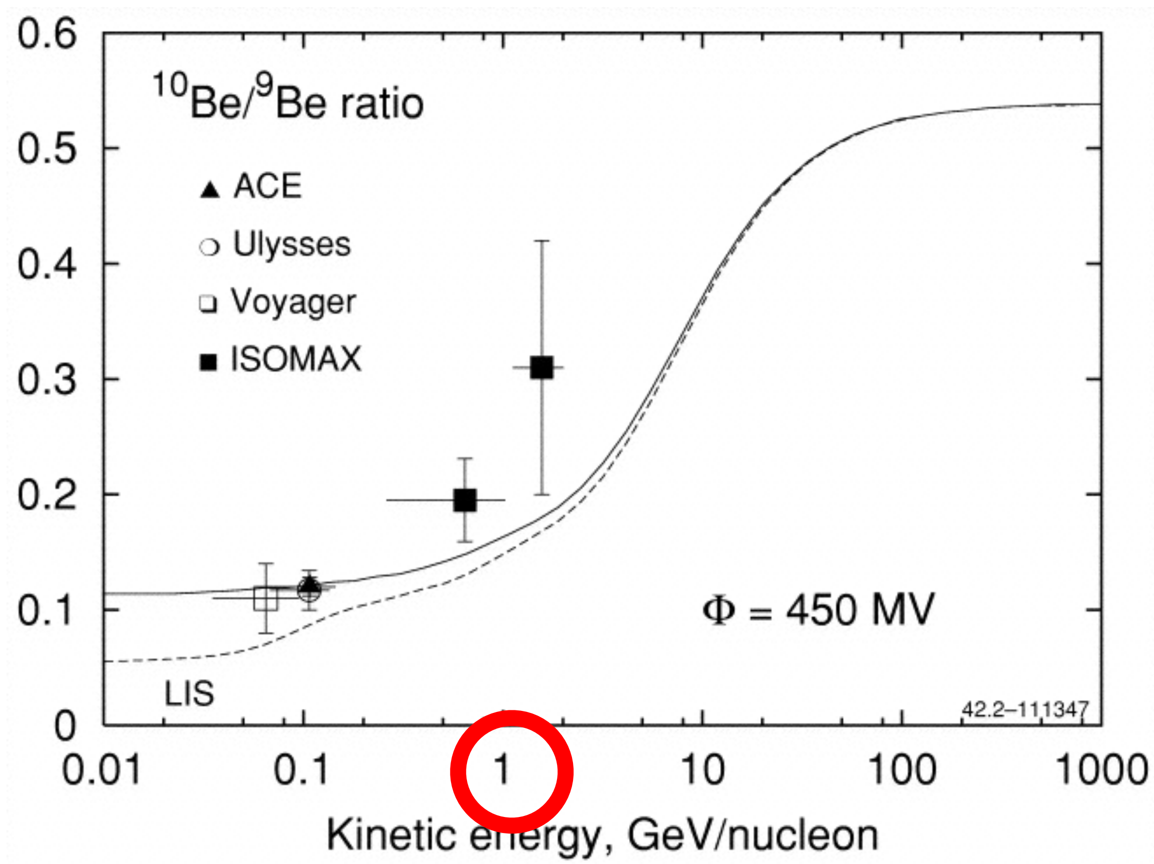
Charge ratios

$$\mathrm{Be/B,\ Al/Mg,\ Cl/Ar}$$



Isotopic ratios

$$^{10}\mathrm{Be}/^{9}\mathrm{Be},\ ^{26}\mathrm{Al}/^{27}\mathrm{Al},\ ^{36}\mathrm{Cl}/\mathrm{Cl}$$



Positrons vs. radioactive nuclei

How to compare radioactive decay of a nucleus, with energy loss of e+?

e+

^{10}Be

Positrons vs. radioactive nuclei

- Suppression factor due to decay ~ suppression factor due to radiative loss,

  if compared at rigidity such that cooling time = decay time

Explain:

$$t_c = \left|\mathcal{R}/\dot{\mathcal{R}}\right| \propto \mathcal{R}^{-\delta_c} \qquad\qquad n_{e^+} \sim \mathcal{R}^{-\gamma}$$

Positrons vs. radioactive nuclei

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Explain:

$$t_c = \left|\mathcal{R}/\dot{\mathcal{R}}\right| \propto \mathcal{R}^{-\delta_c} \qquad n_{e^+} \sim \mathcal{R}^{-\gamma}$$

Consider decay term of nuclei and loss term of e+ in general transport equation.

decay: $$\partial_t n_i = -\frac{n_i}{t_i}$$

loss: $$\partial_t n_{e^+} = \partial_{\mathcal{R}}\left(\dot{\mathcal{R}} n_{e^+}\right) = -\frac{n_{e^+}}{\tilde{t}_c}$$

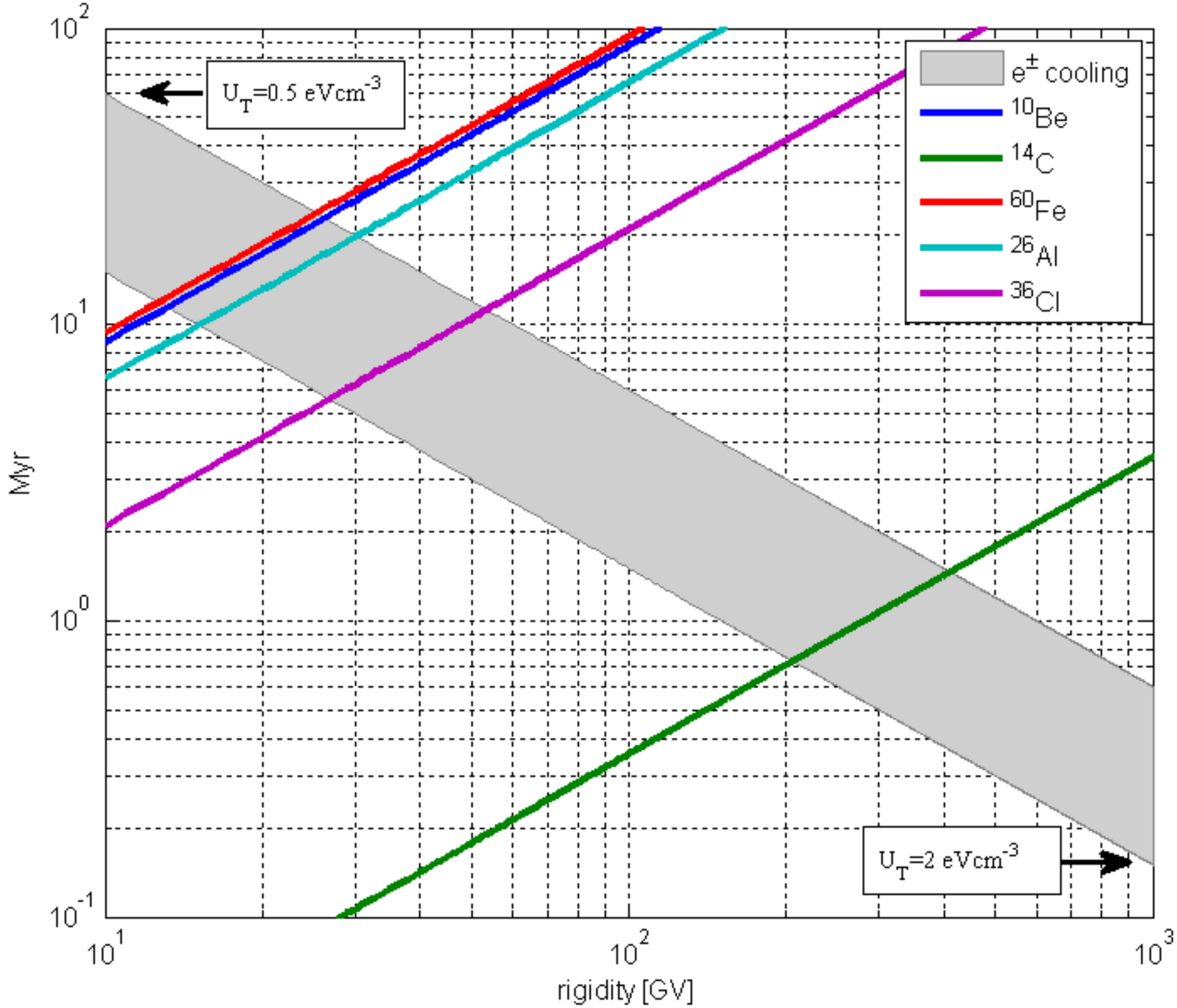
$$\tilde{t}_c = \frac{t_c}{\gamma - \delta_c - 1}$$

$$\gamma \sim 3 \rightarrow \tilde{t}_c \approx t_c$$

Comparing with radioactive nuclei

Time scales:

cooling vs decay



Comparing with radioactive nuclei

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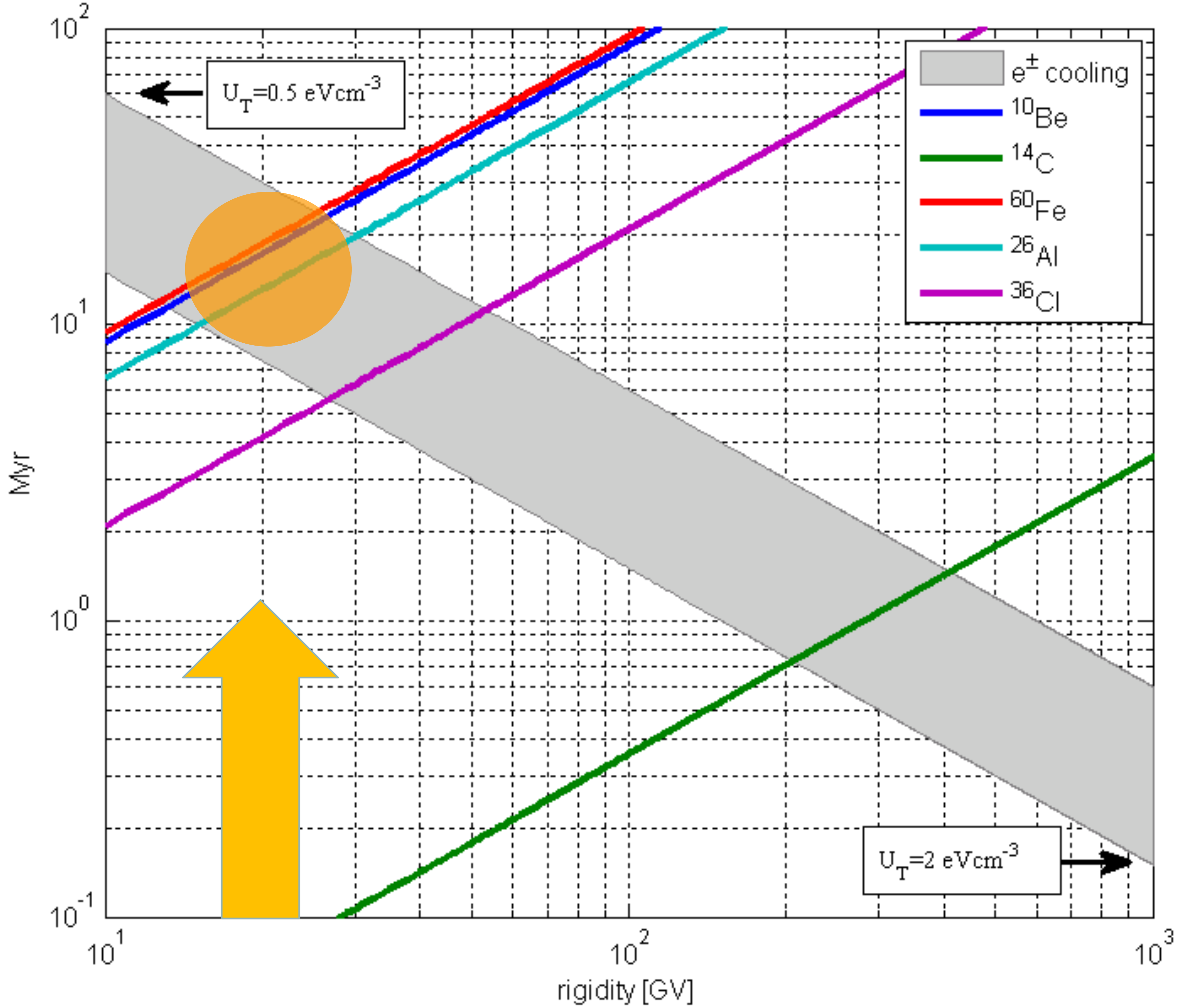
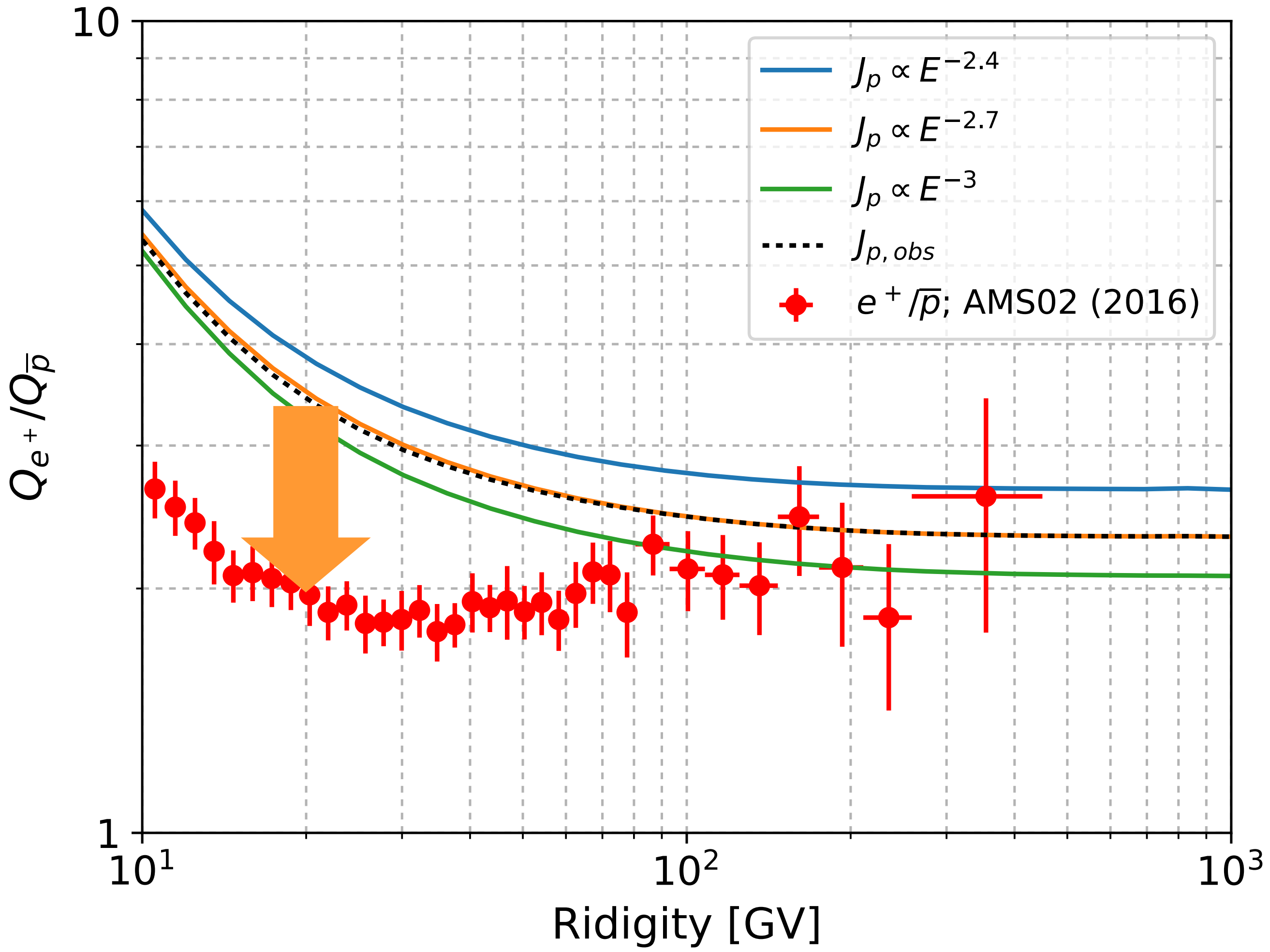
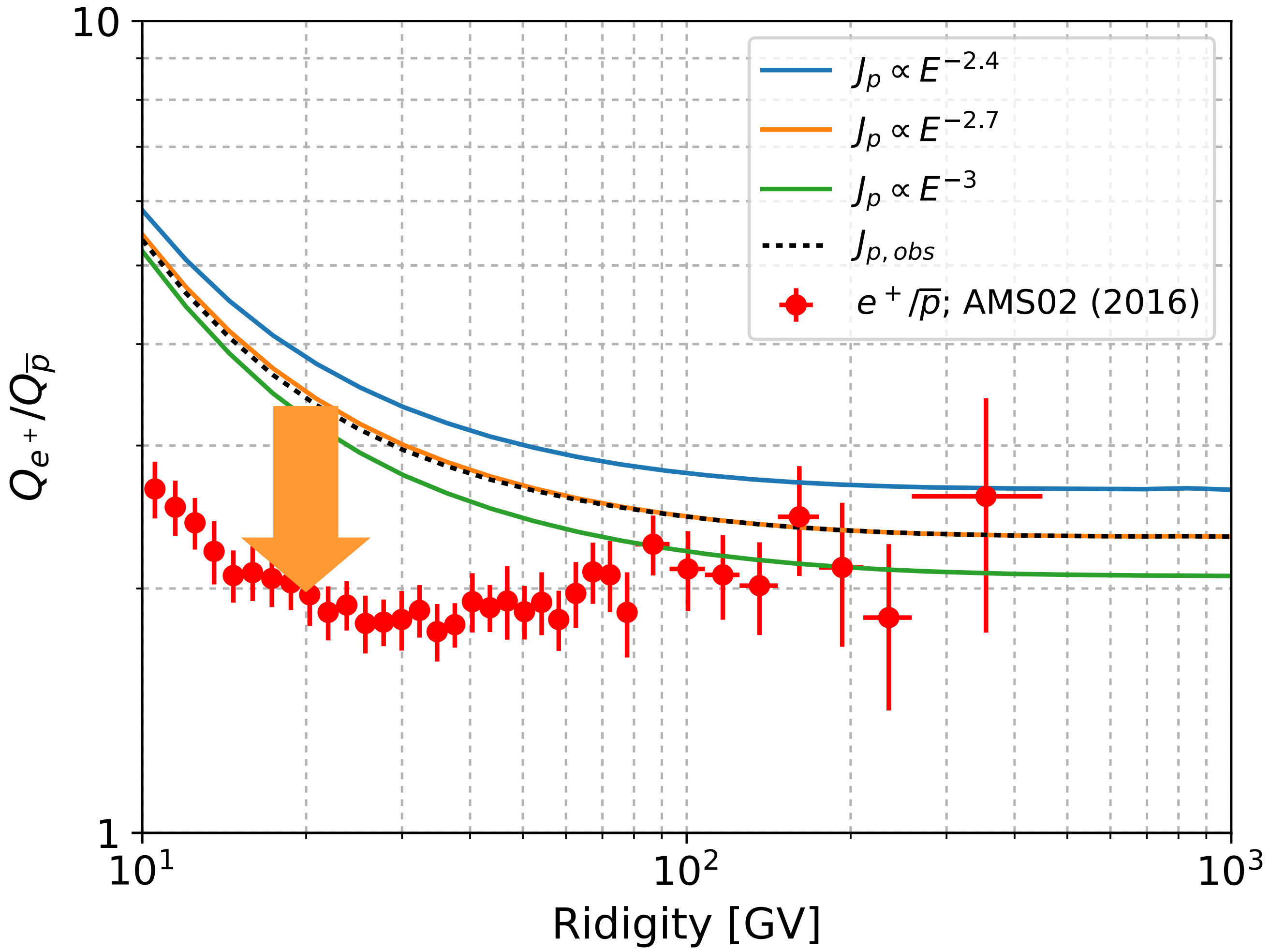
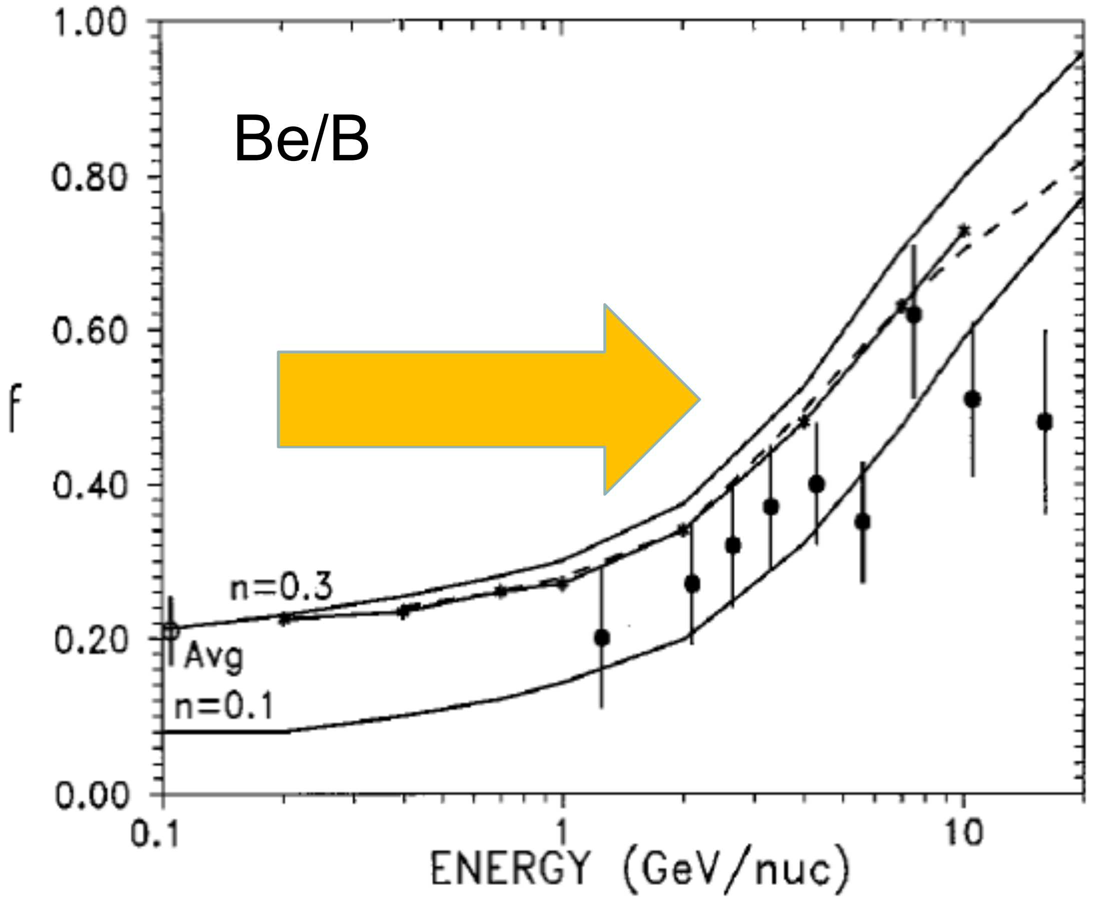


Comparing with radioactive nuclei

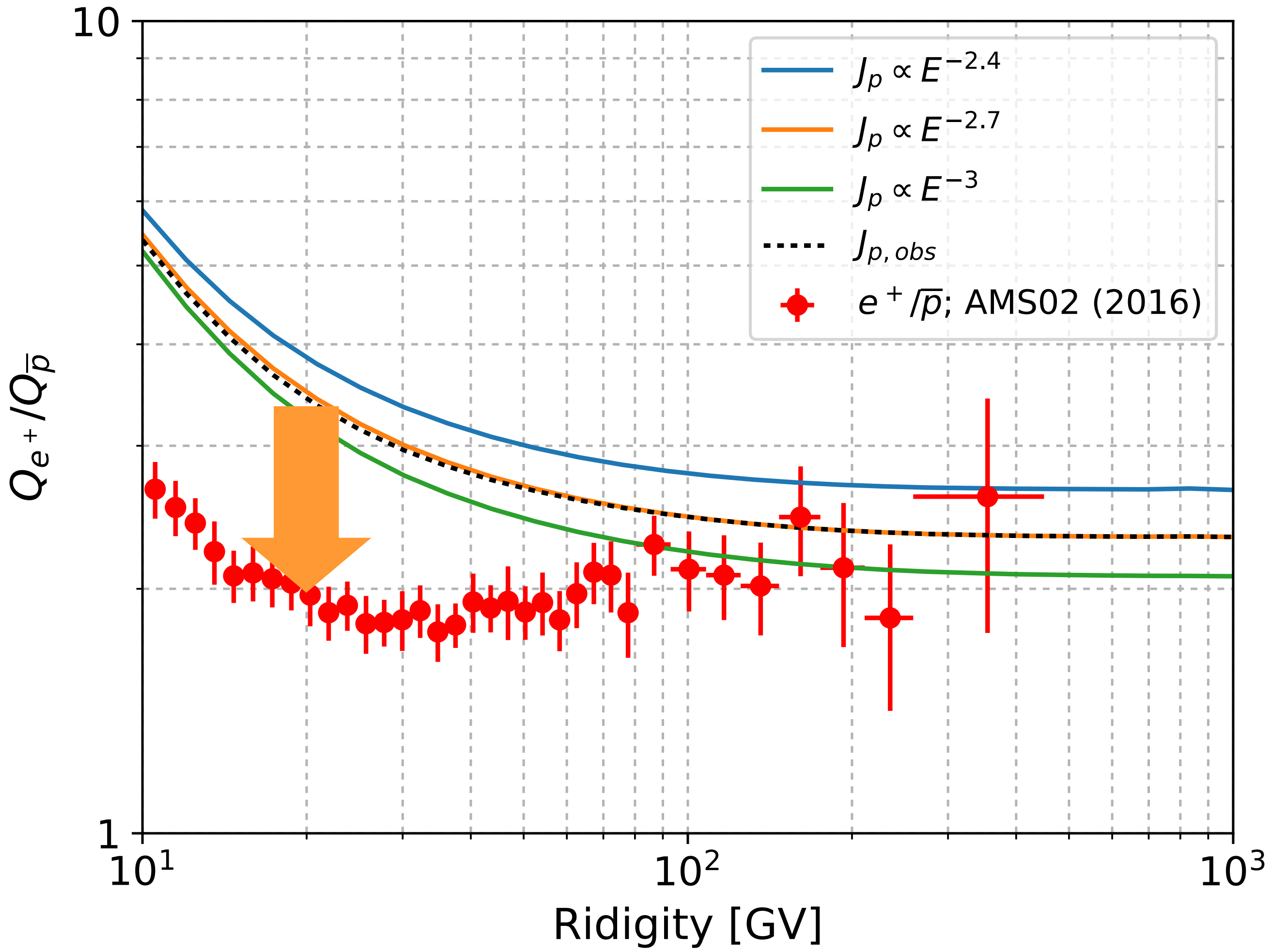


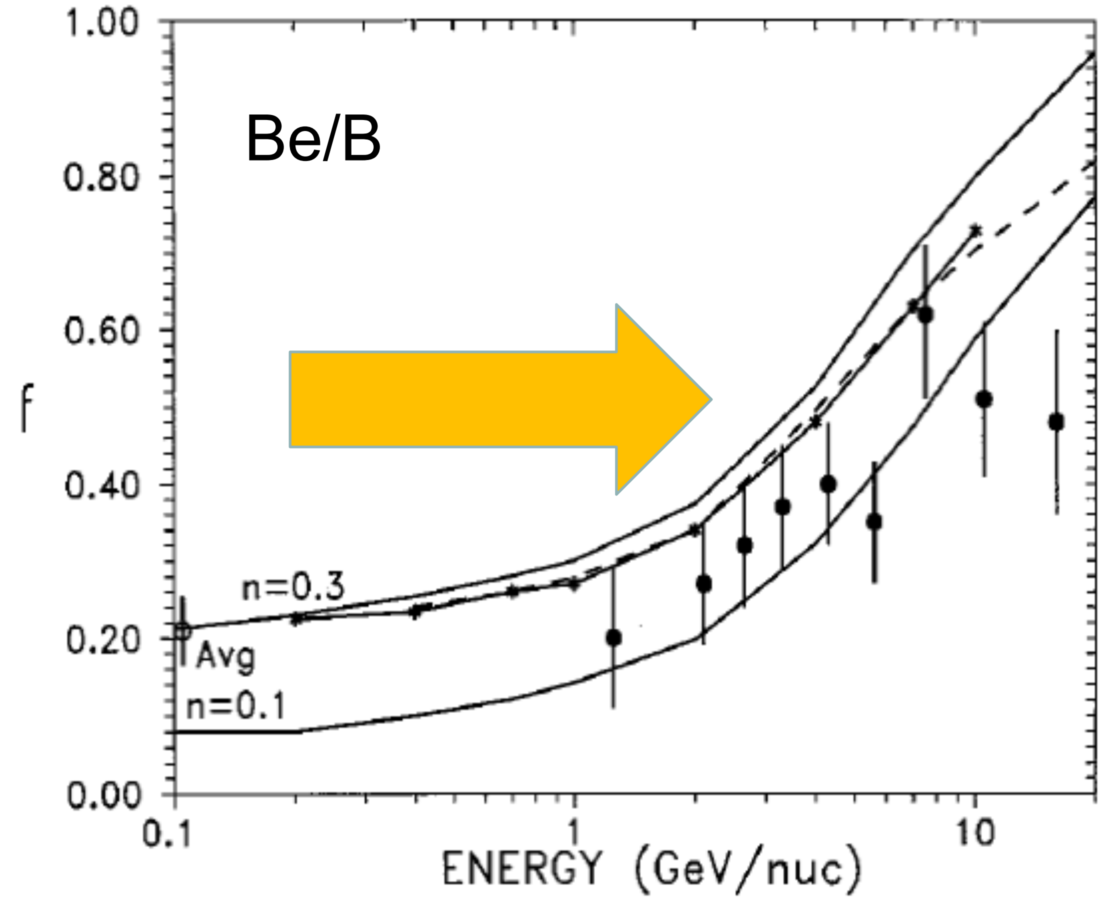
Comparing with radioactive nuclei

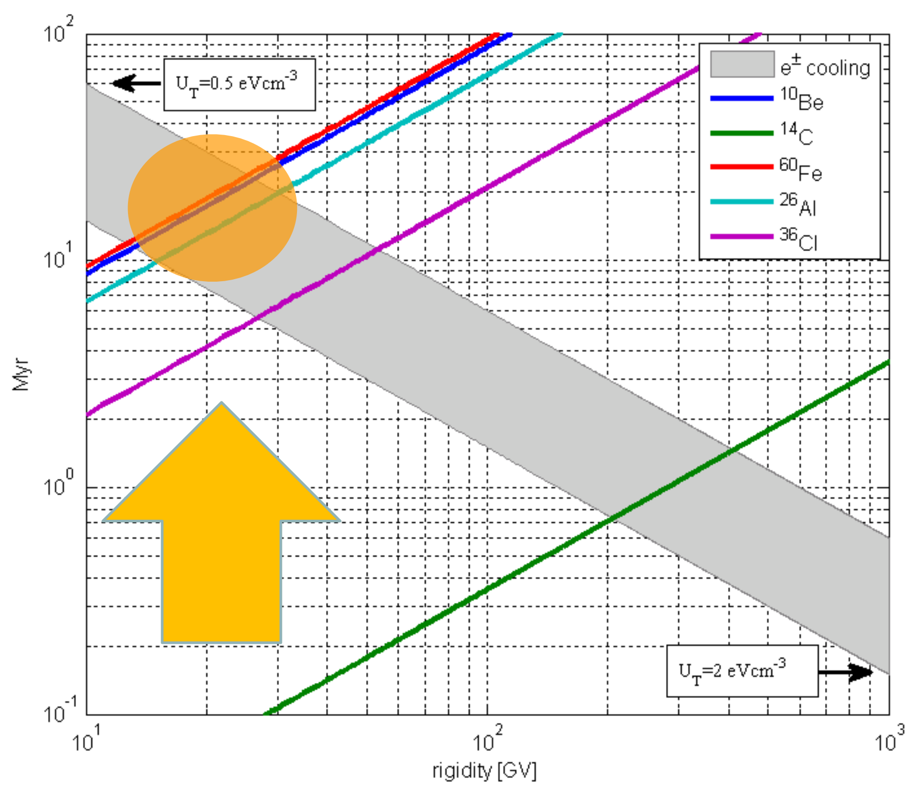




Comparing with radioactive nuclei







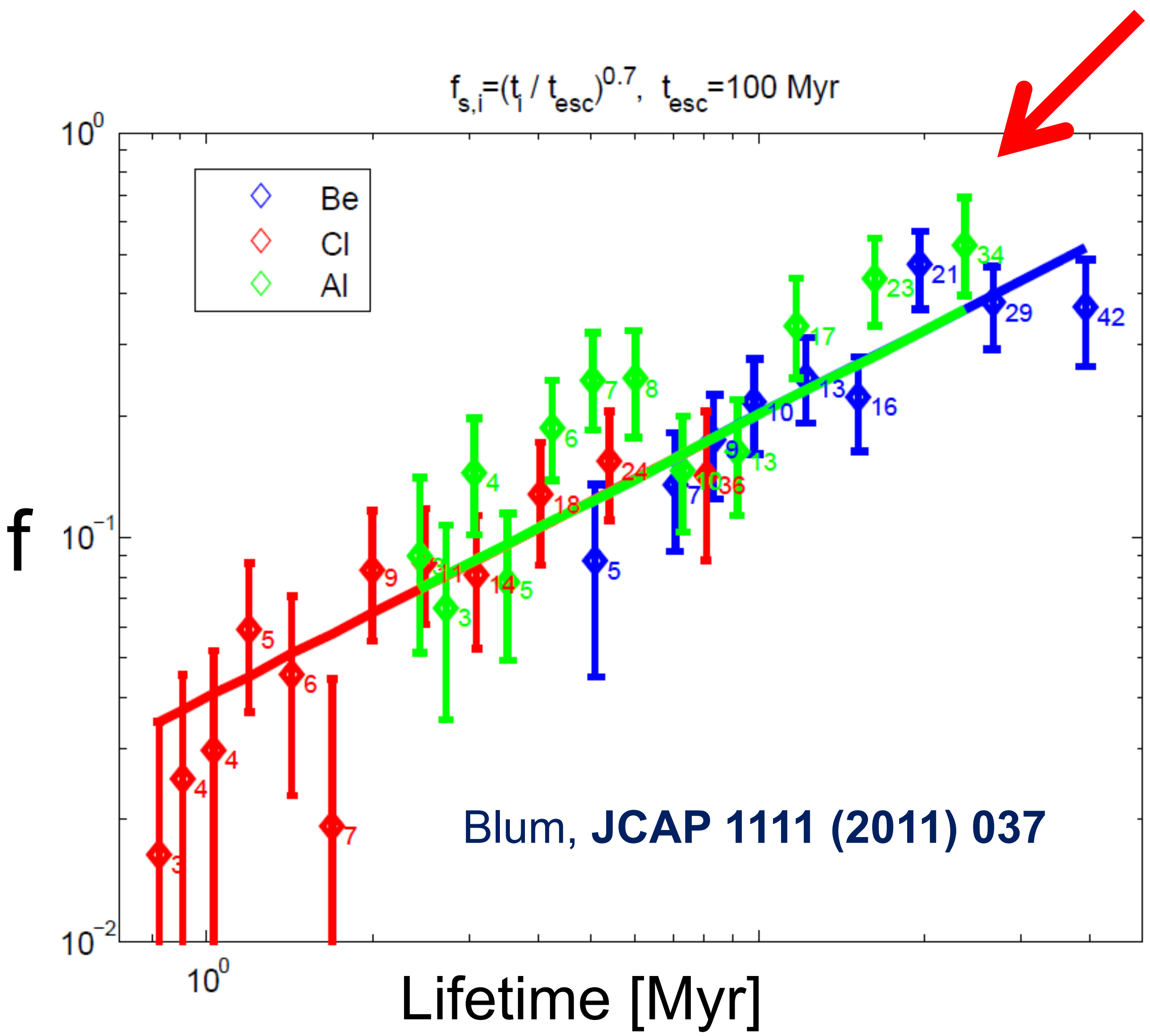
f(Be10) ~ 0.4

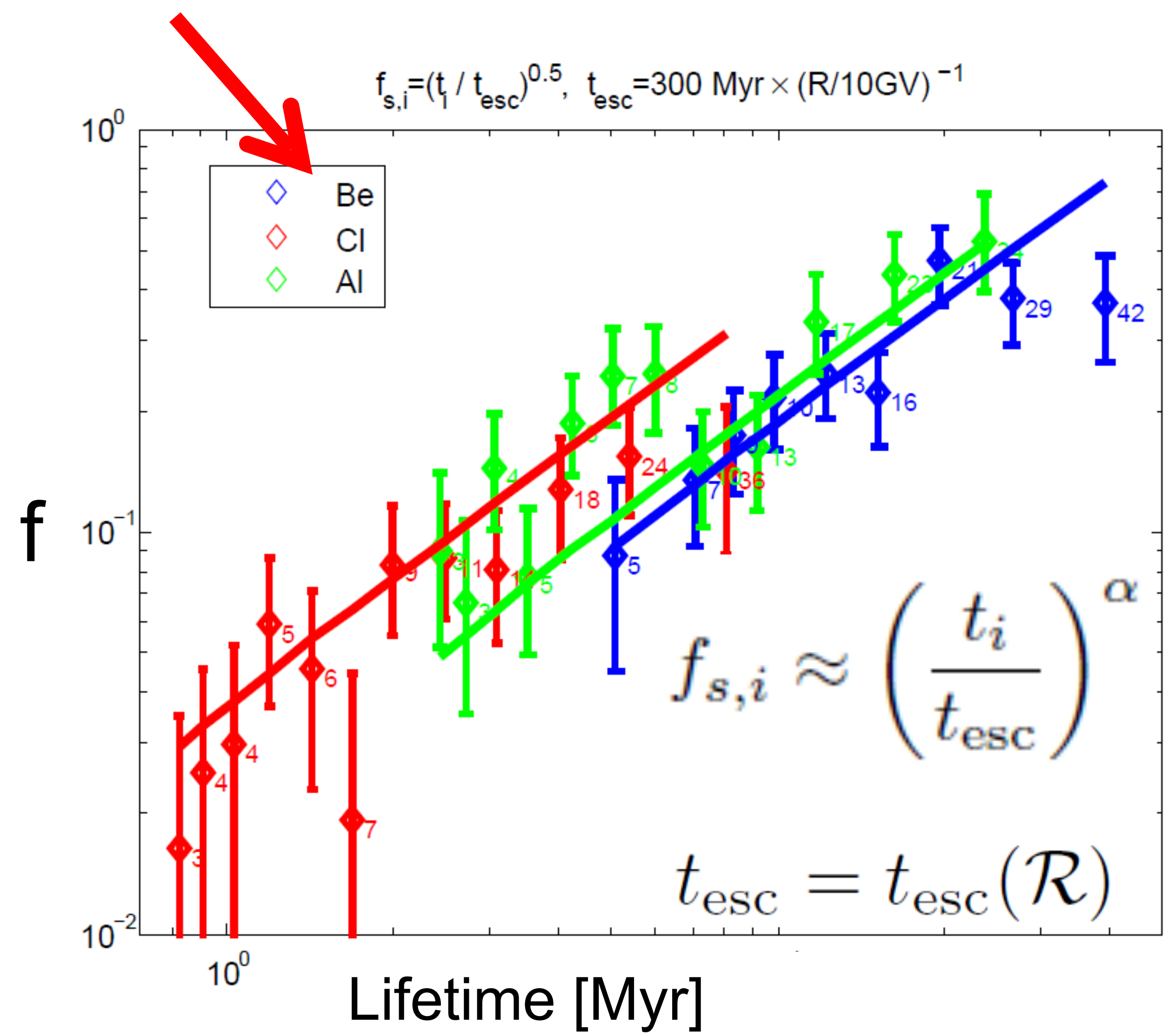
f(e+) ~ 0.5

Radioactive nuclei: constraints on t_{esc}

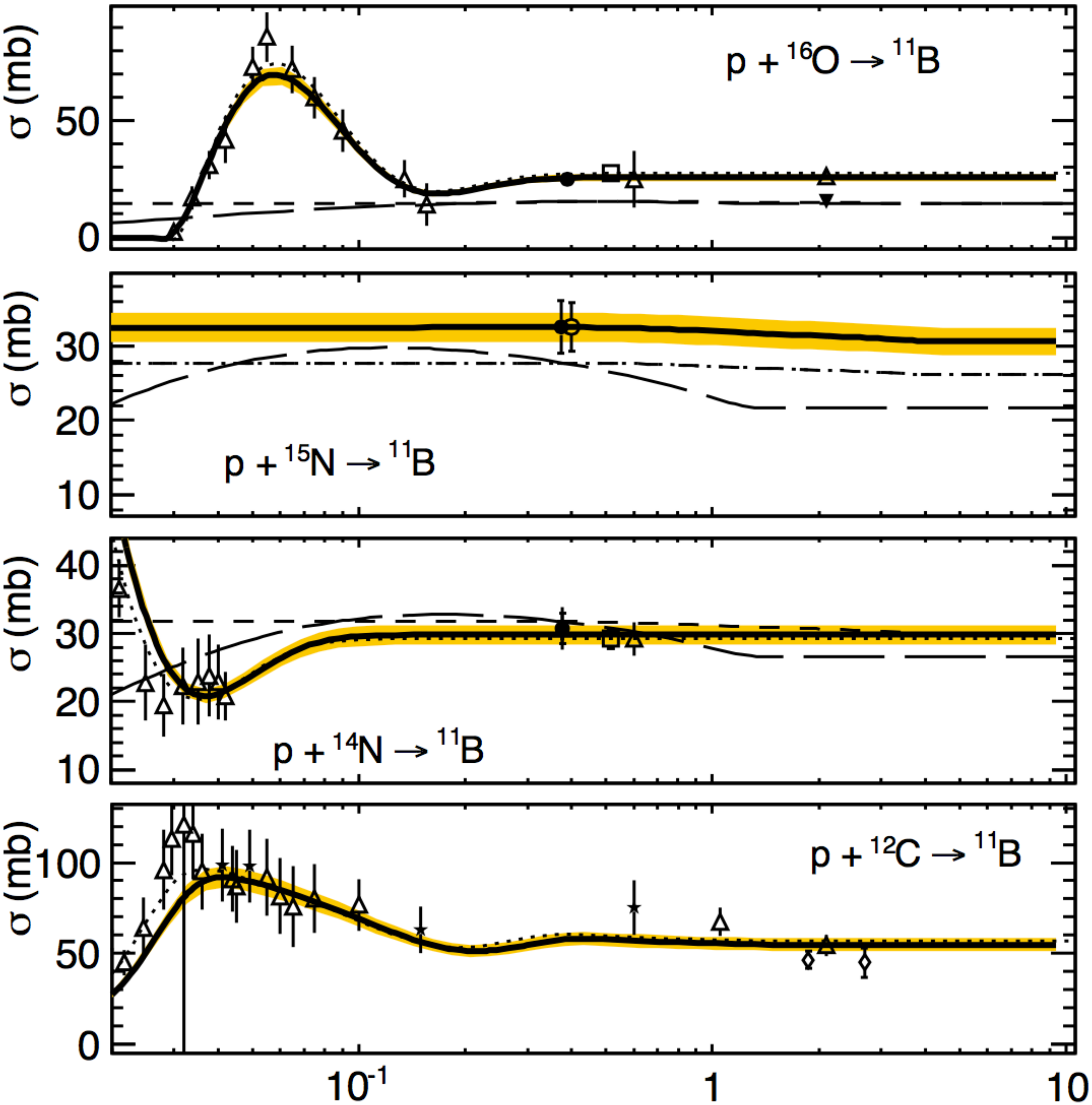
- Cannot (yet) exclude rapidly decreasing escape time
- **AMS-02 should do better!**

Need to tell between these fits





$$X_{\rm esc} = \frac{(B/C)}{\sum_{P=C,N,O,\ldots}(P/C)\frac{\sigma_{P\to B}}{m} - (B/C)\frac{\sigma_B}{m}}$$

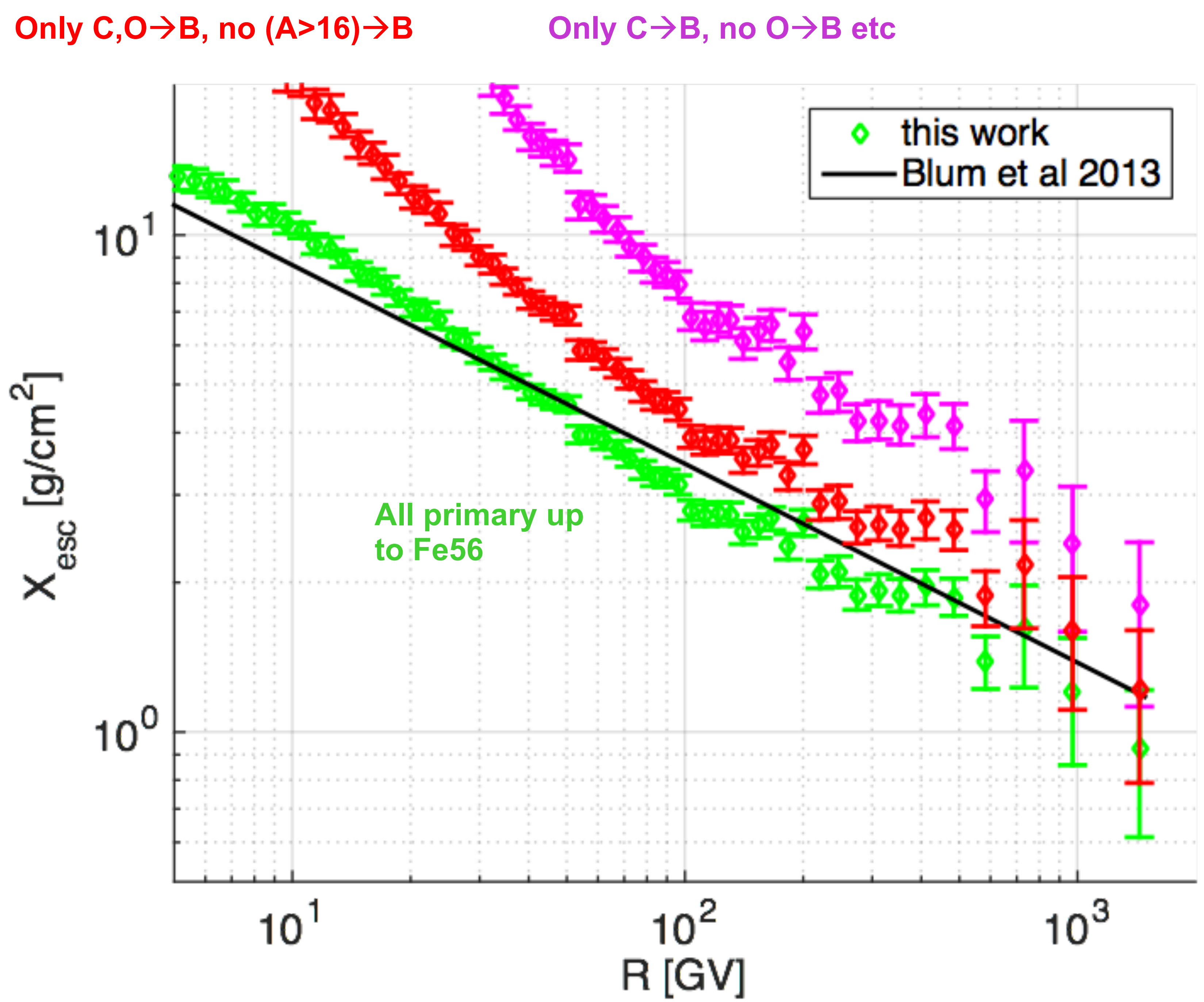


e.g. Tomassetti,
PoS ICRC2015 (2016) 553

GeV/nuc

AMS02 (2013-2016)

$$X_{\rm esc} = \frac{(B/C)}{\sum_{P=C,N,O,\ldots}(P/C)\frac{\sigma_{P\to B}}{m} - (B/C)\frac{\sigma_B}{m}}$$



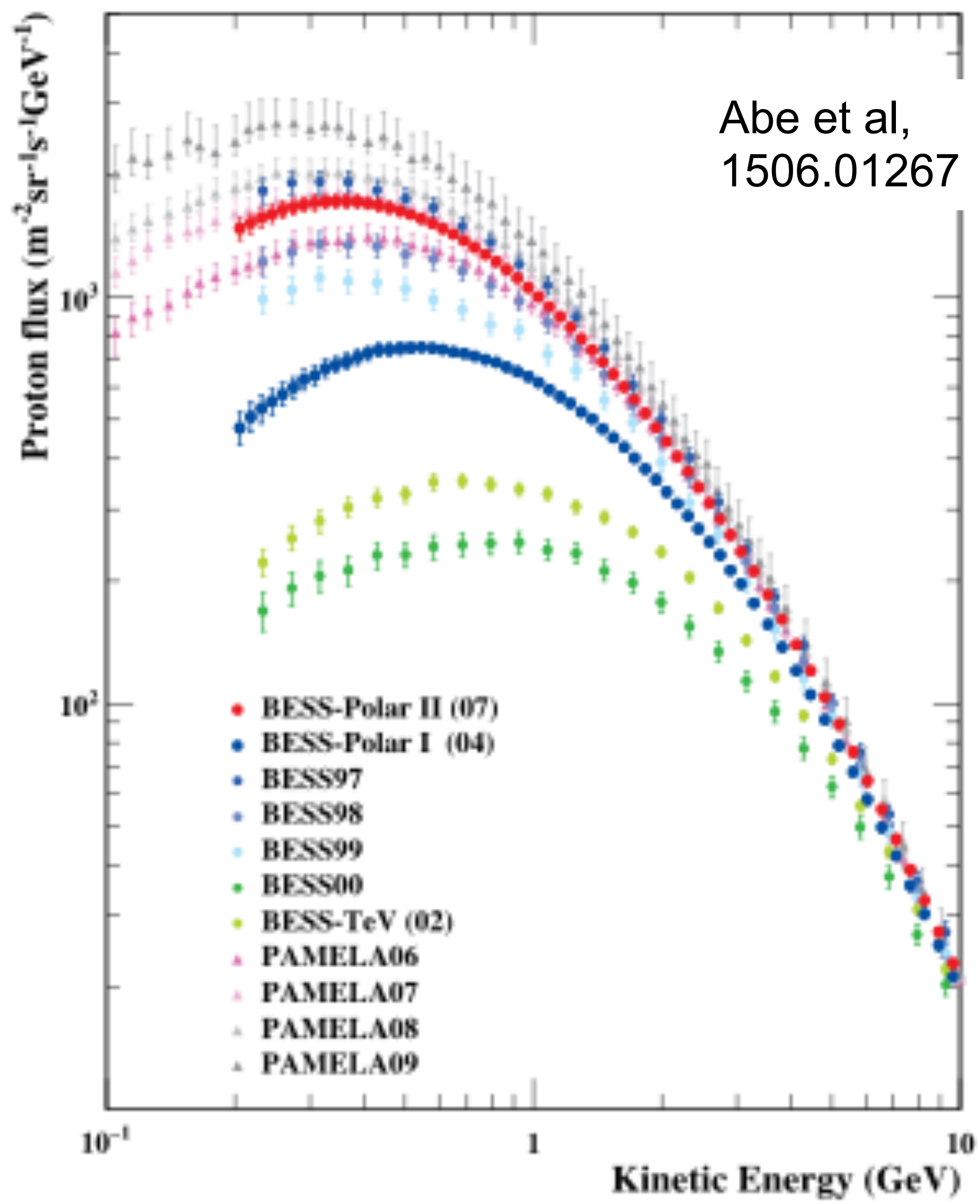
Stable secondaries with no energy loss

Comment about applicability of the analysis: **high energy (relativistic)**

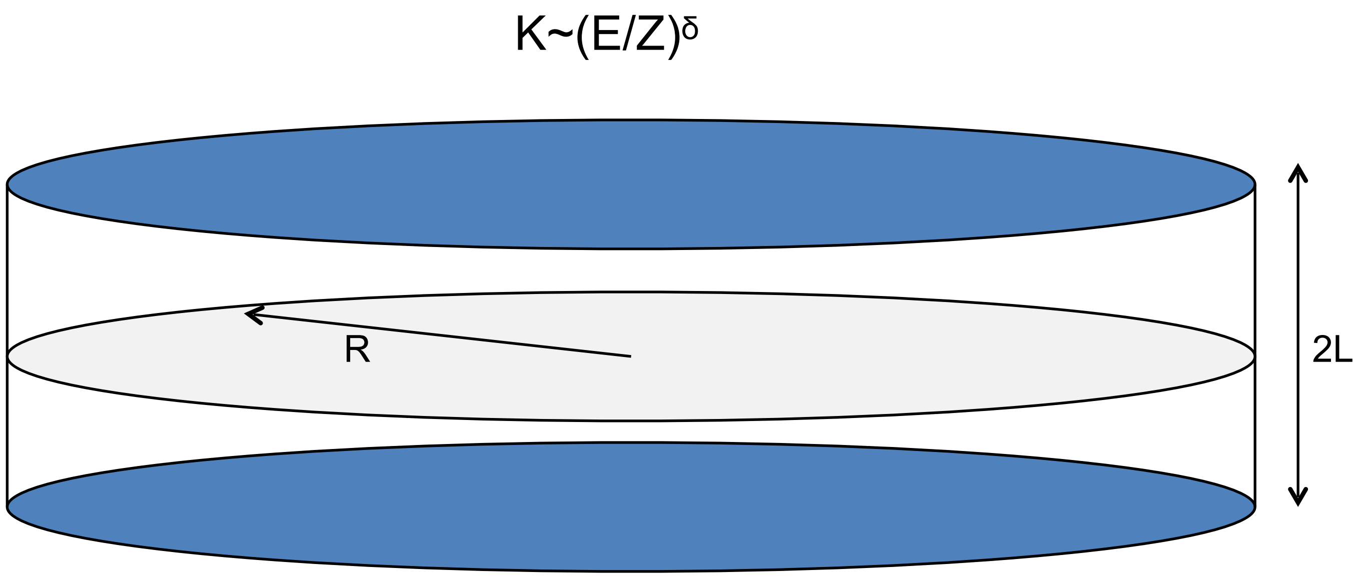
Below R~10GV, various propagation effects can change energy of particle during trajectory; spallation cross sections are energy dependent; rigidity not transferred in fragmentation;…

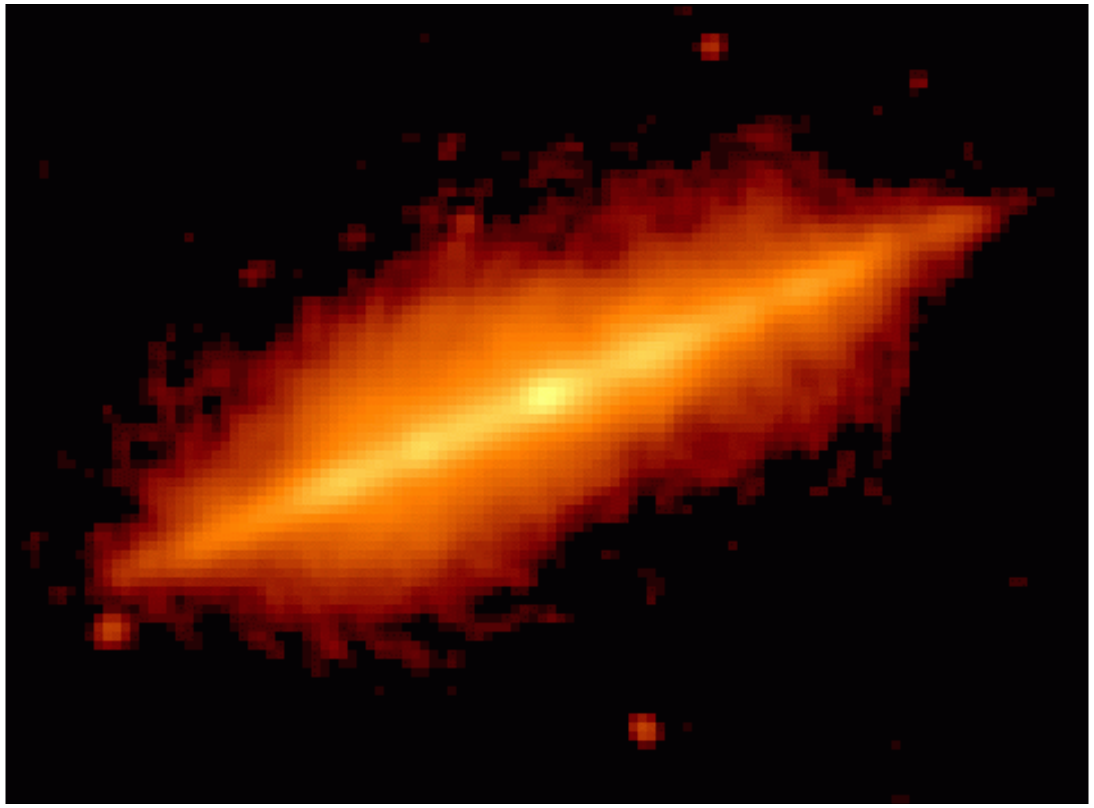
Example: solar modulation

We will keep our analysis to R > 10GV



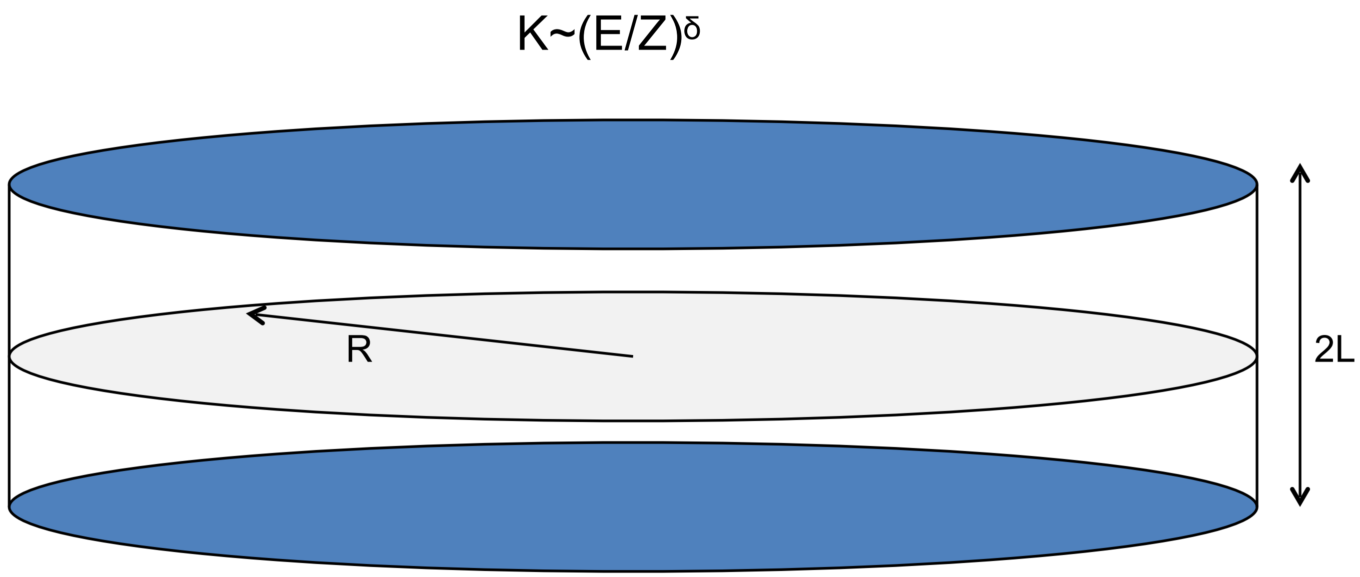
About diffusion models



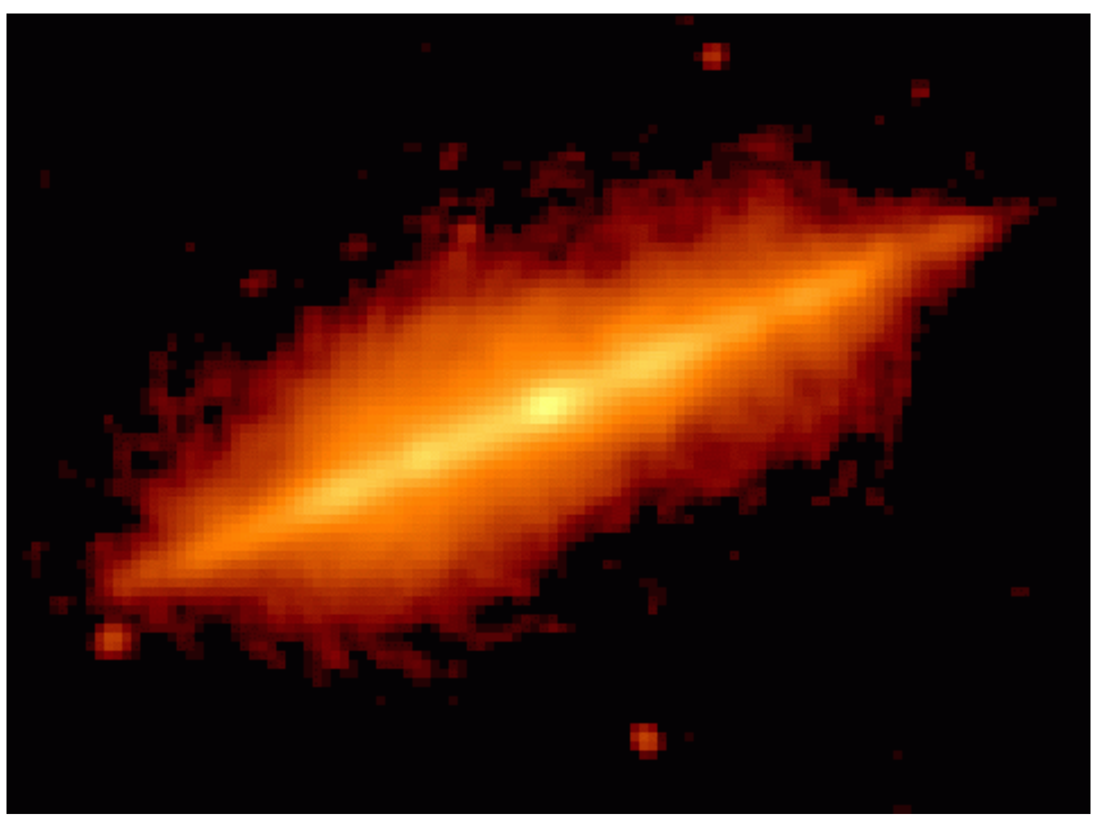


Strong, Moskalenko, Ptuskin, Ann.Rev.Nucl.Part.Sci. 57 (2007) 285-327

About diffusion models



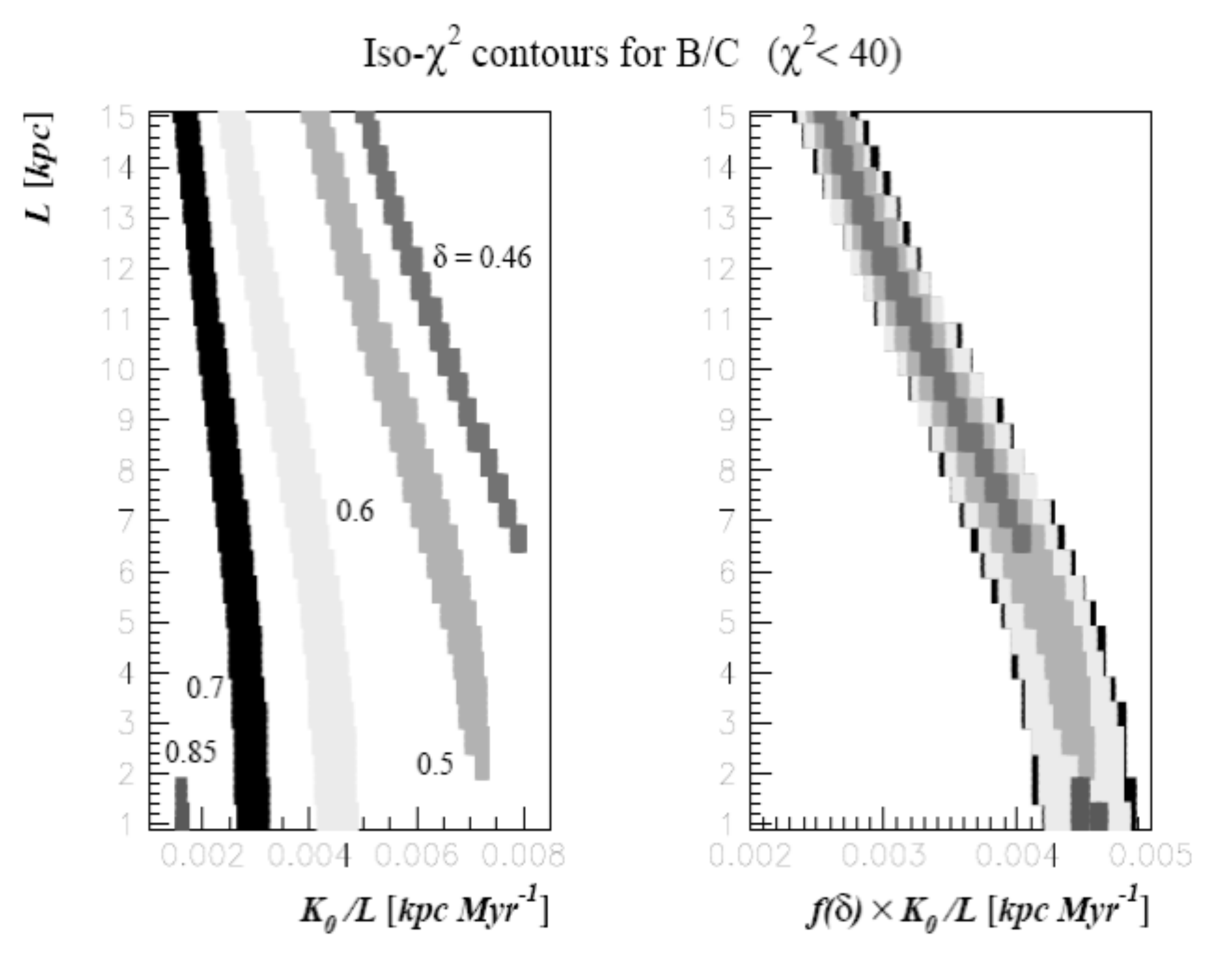
To a good approximation, disc+halo homogeneous diffusion models satisfy the criterion of uniform CR composition *where spallation happens*.

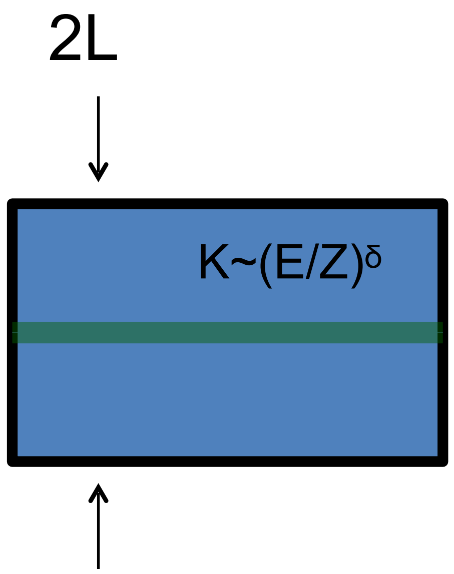


Should satisfy

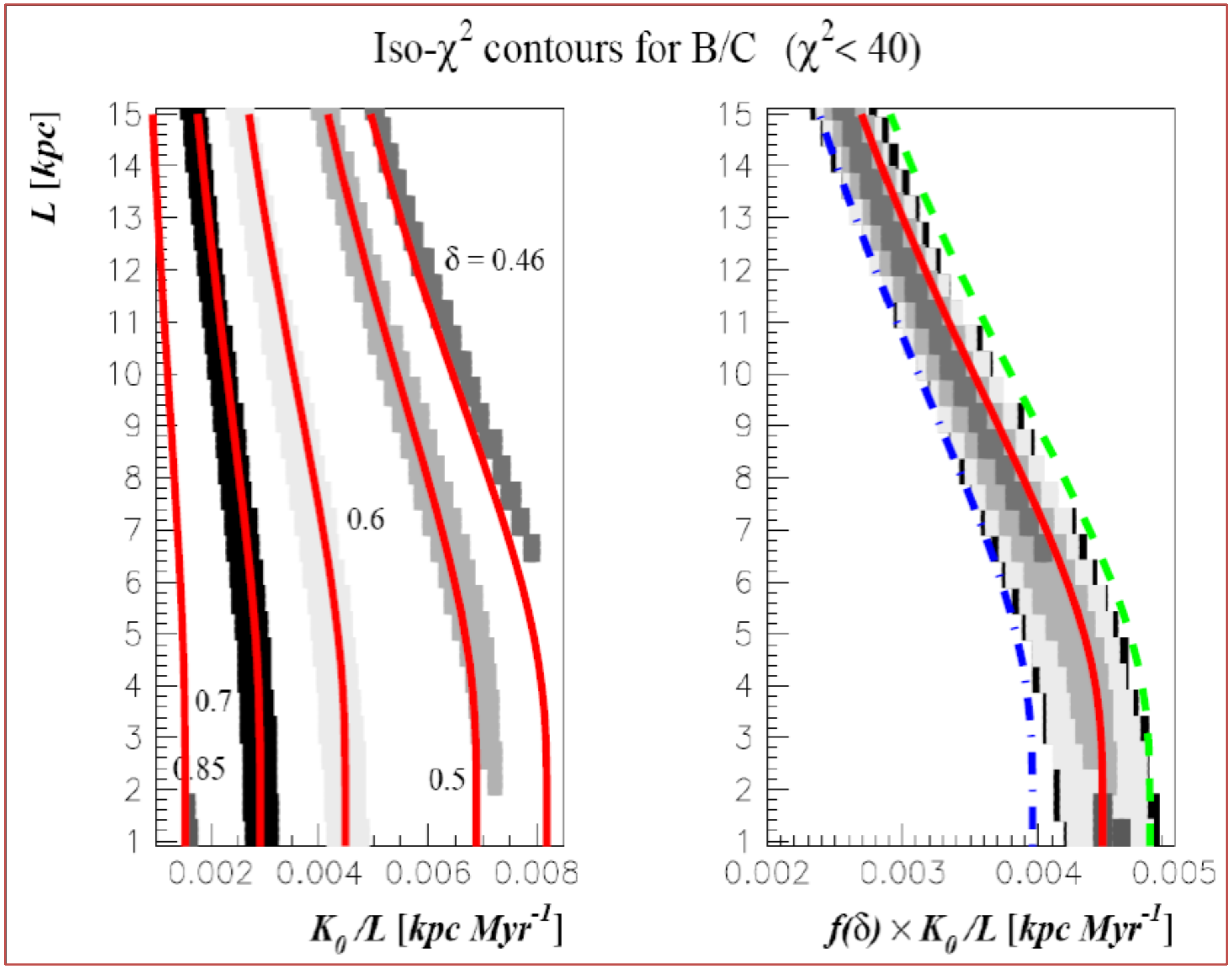
$$\frac{n_A}{n_B} = \frac{Q_A}{Q_B}$$

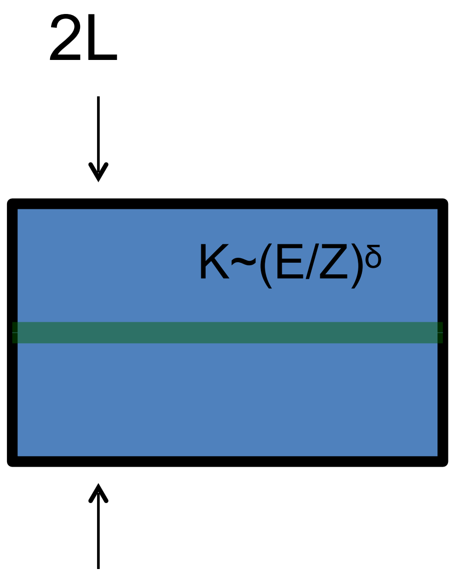
diffusion models fit X_{esc}



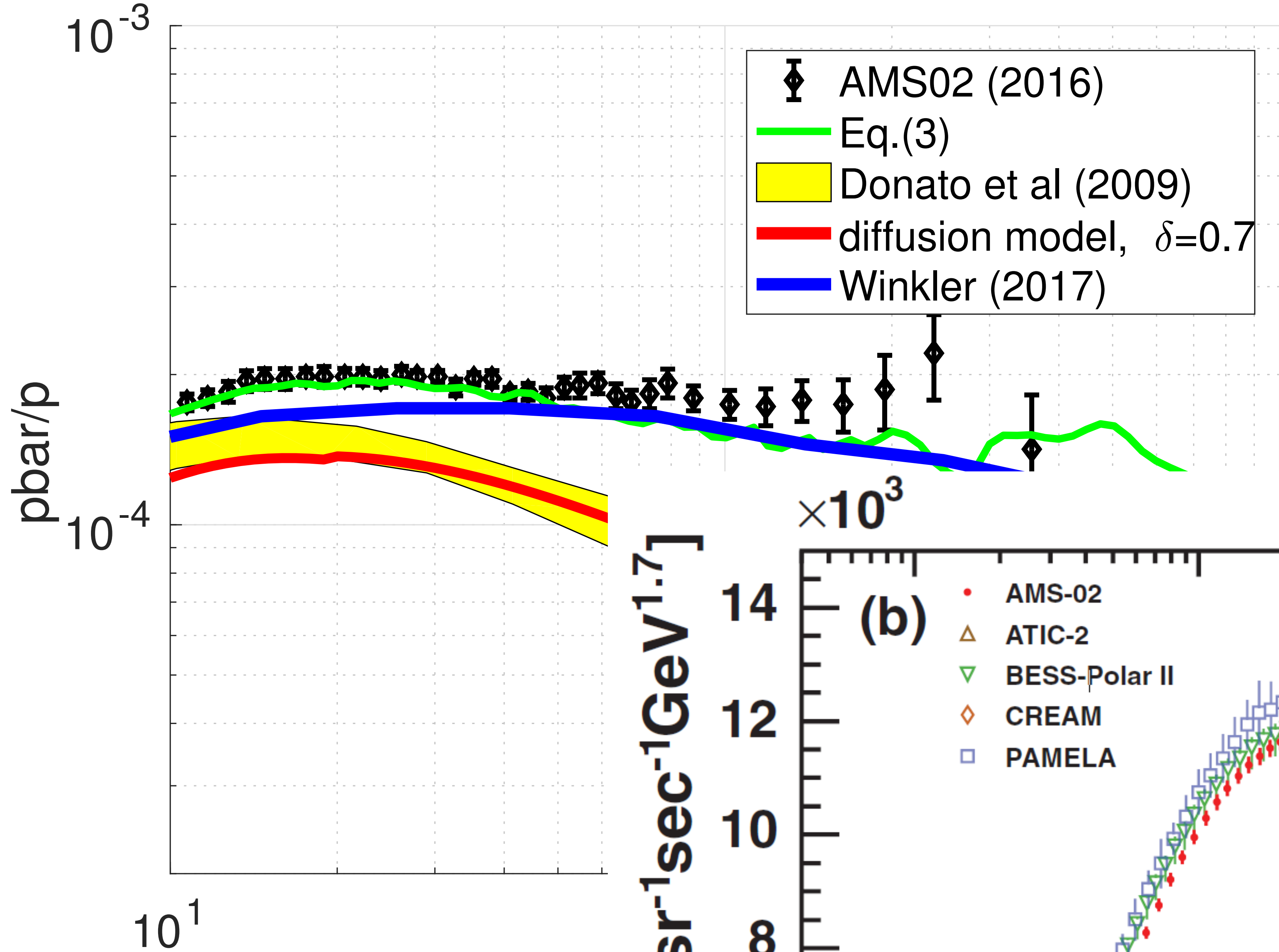


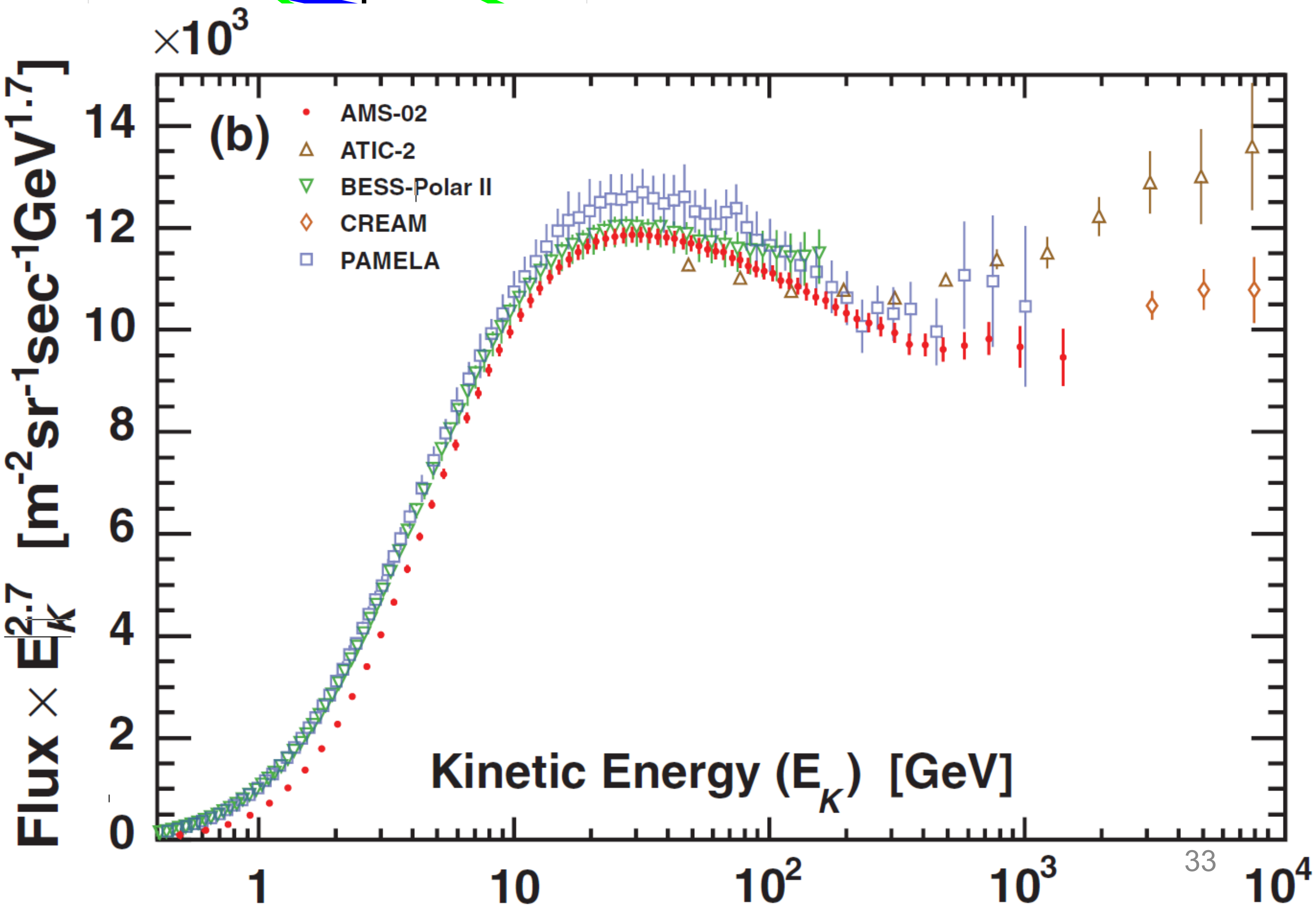
Maurin et al, **Astrophys.J.555:585-596,2001** diffusion models fit $X_{\rm esc}$





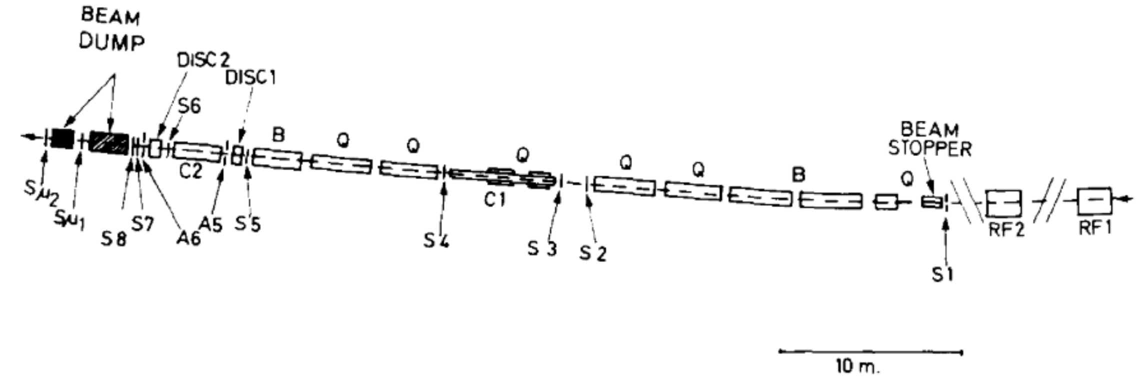
$$X_{\rm esc} = X_{\rm disc} \frac{Lc}{2D} \frac{2R}{L} \sum_{k=1}^{\infty} J_0\left[\nu_k (r_s/R)\right] \frac{\tanh\left[\nu_k (L/R)\right]}{\nu_k^2 J_1(\nu_k)}$$


AMS02 (2016)
Eq.(3)
Donato et al (2009)
diffusion model, δ=0.7
Winkler (2017)
pbar/p
10^{-3}
10^{-4}
10^{1}


(b)
AMS-02
ATIC-2
BESS-Polar II
CREAM
PAMELA
$\times 10^3$
Flux $\times E_K^{2.7}$ [m^{-2}sr^{-1}sec^{-1}GeV$^{1.7}$]
Kinetic Energy (E_K) [GeV]
0
2
4
6
8
10
12
14
1
10
10^2
10^3
10^4

MNRAS 405 (2010) 1458 Katz, Blum, Morag, Waxman (arXiv:0906.4696)
JCAP 1111 (2011) 037 Blum
PRL 111 (2013) no.21, 211101 Blum, Katz, Waxman
1704.05431 Blum, Ng, Sato, Takimoto

Nuclear Physics B174 (1980) 1–15



PARTICLE PRODUCTION AND SEARCH FOR LONG-LIVED PARTICLES IN 200–240 GeV/*c* PROTON–NUCLEON COLLISIONS

A. BUSSIÈRE[3], G. GIACOMELLI[1], E. LESQUOY[2], R. MEUNIER[2], L. MOSCOSO[2], A. MULLER[2], F. RIMONDI[1], S. ZUCCHELLI[1] and S. ZYLBERAJCH[2]

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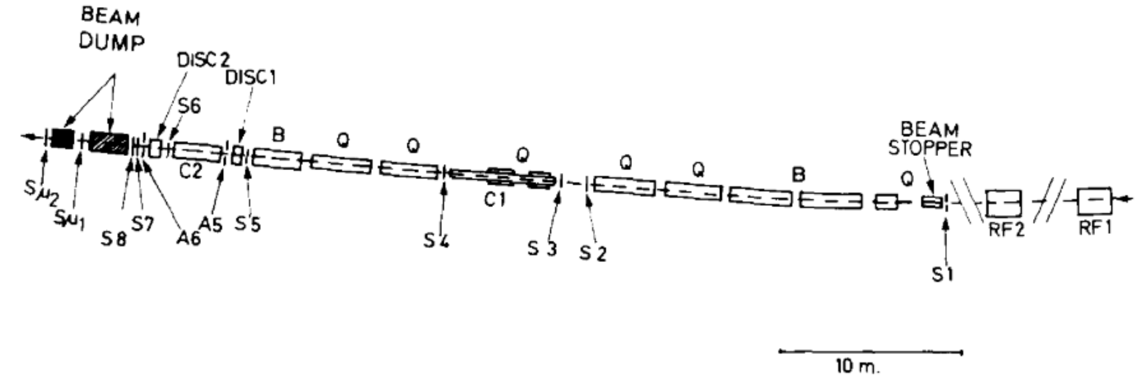

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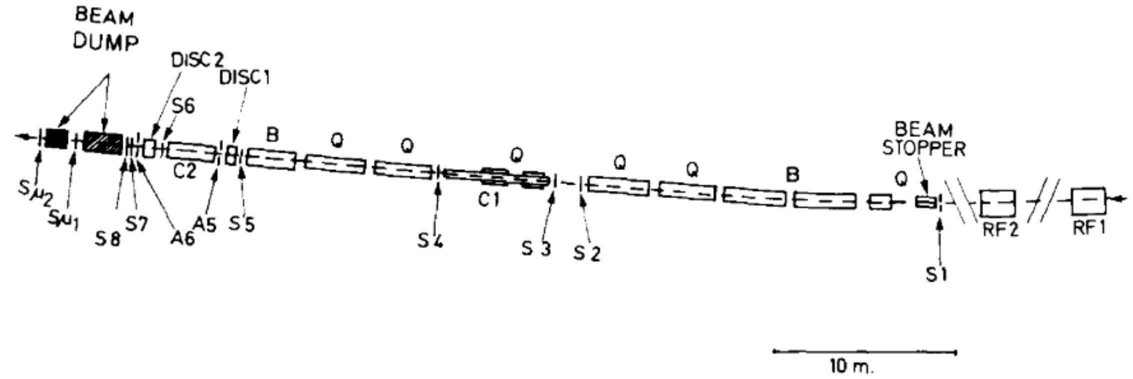
TABLE 2

Rates of production of nuclei and antinuclei relative to pions of the same sign

p_0 (GeV/c)	Target	Lab momentum (GeV/c)	d/π^+ (10^{-4})	t/π^+ (10^{-7})	$^3He/\pi^+$ (10^{-7})	$\bar{d}/\pi^-$ (10^{-6})	$\bar{t}/\pi^-$ (10^{-10})	$^3\overline{He}/\pi^-$ (10^{-10})
200	Al	20	1.33 ± 0.14	1.00 ± 0.21	1.0 ± 0.2	4.85 ± 0.74		10 ± 5
		22	1.41 ± 0.18					
		30	1.72 ± 0.18	0.90 ± 0.20	0.90 ± 0.15	6.36 ± 0.80		≤4
		37	2.55 ± 0.25			4.10 ± 1.20		
	Be	12				3.16 ± 0.63		
		16				4.11 ± 0.78		
		20	0.88 ± 0.09	0.31 ± 0.06	0.80 ± 0.15	4.60 ± 0.92		7.0 ± 3.5
		26				5.52 ± 0.55		
		30	1.54 ± 0.15	0.55 ± 0.10	0.65 ± 0.10	7.06 ± 1.10	8 ± 5	≤1.5
		37	1.92 ± 0.19	0.56 ± 0.12	0.65 ± 0.10			
210		10.5						1.9 ± 0.5
		23.7					12 ± 2	3.1 ± 0.4
		39.5				4.8 ± 0.9		
240		23.4				5.2 ± 1.0	8.0 ± 1.5	4.2 ± 0.4
		35.9					8.7 ± 1.7	
		37.5						0.87 ± 0.20

The data have been corrected to the centre of the production targets.

Nuclear Physics B174 (1980) 1–15



PARTICLE PRODUCTION AND SEARCH FOR LONG-LIVED PARTICLES IN 200–240 GeV/c PROTON–NUCLEON COLLISIONS

sparse data

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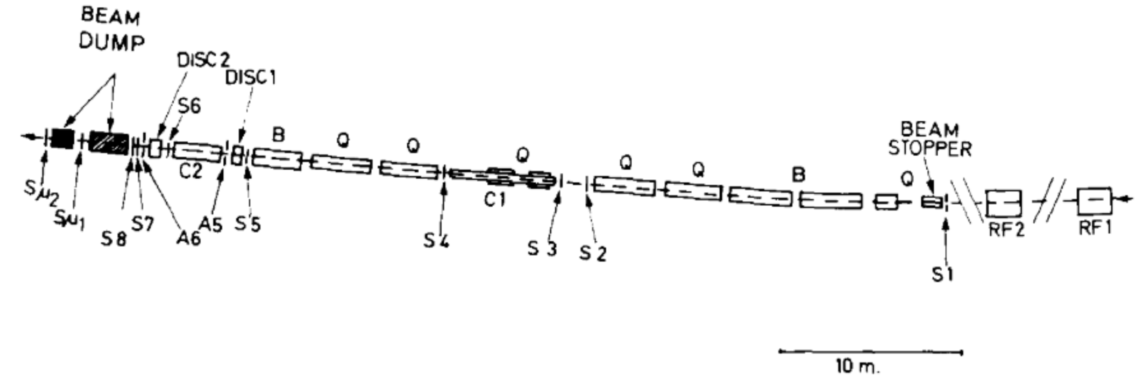
Nuclear Physics B174 (1980) 1–15



PARTICLE PRODUCTION AND SEARCH FOR LONG-LIVED PARTICLES IN 200–240 GeV/c PROTON–NUCLEON COLLISIONS

t/He >> 1 for antimatter,
t/He <= 1 for matter **?**

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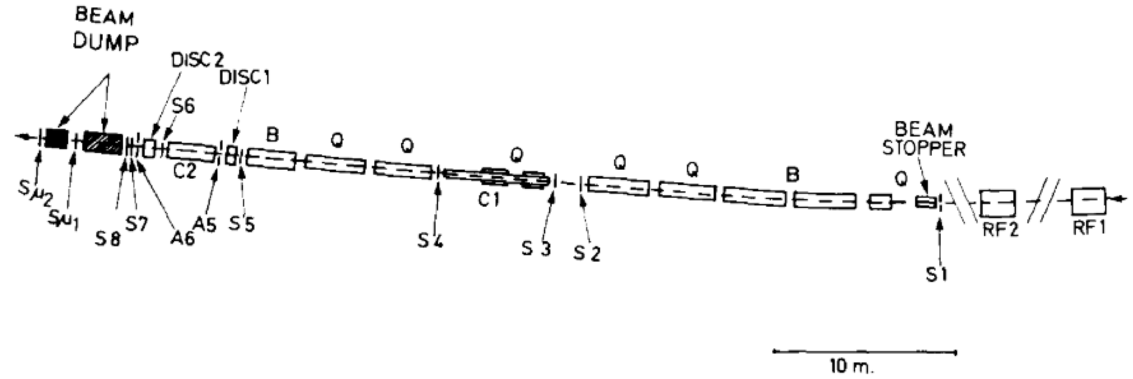

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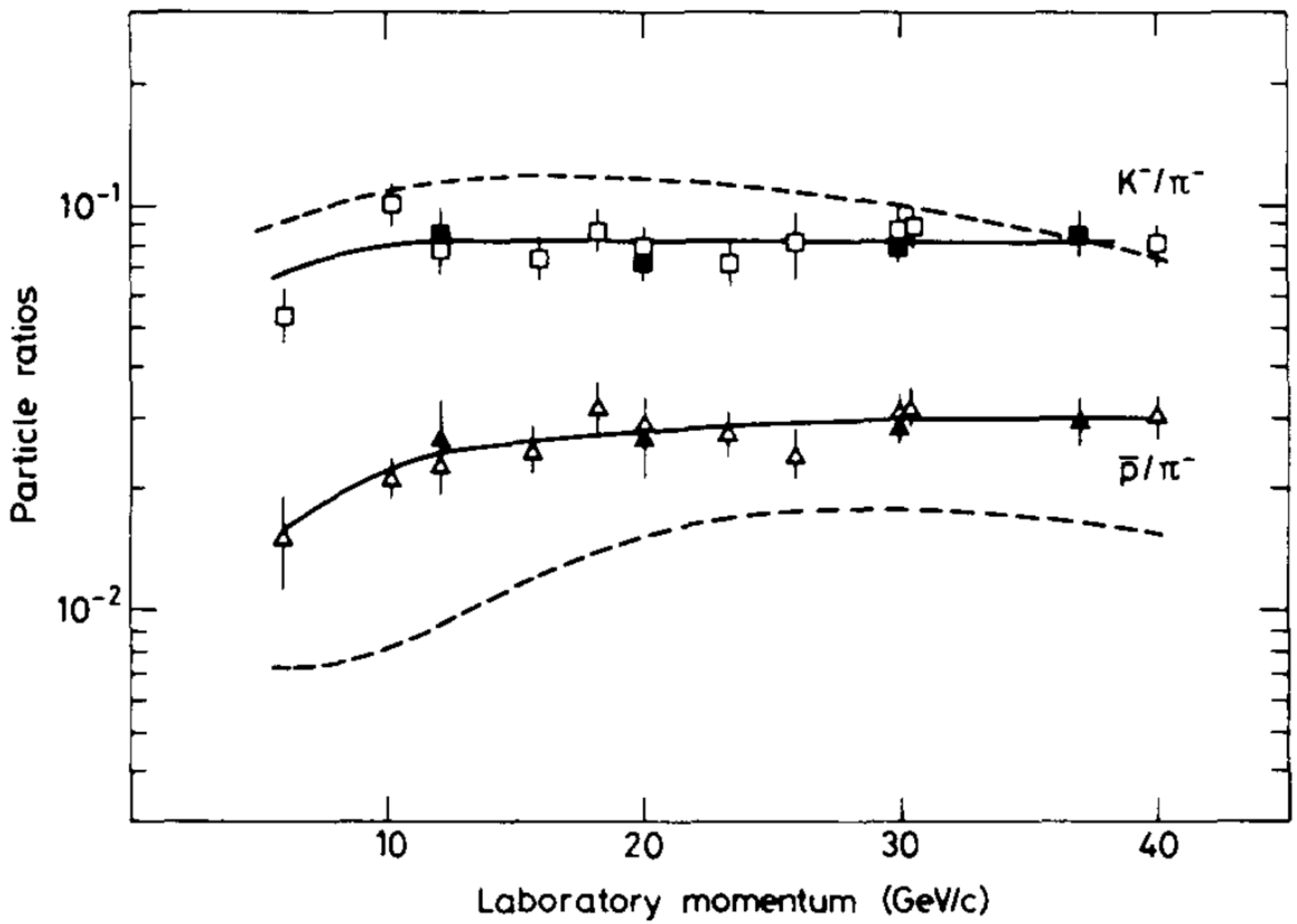


(b)

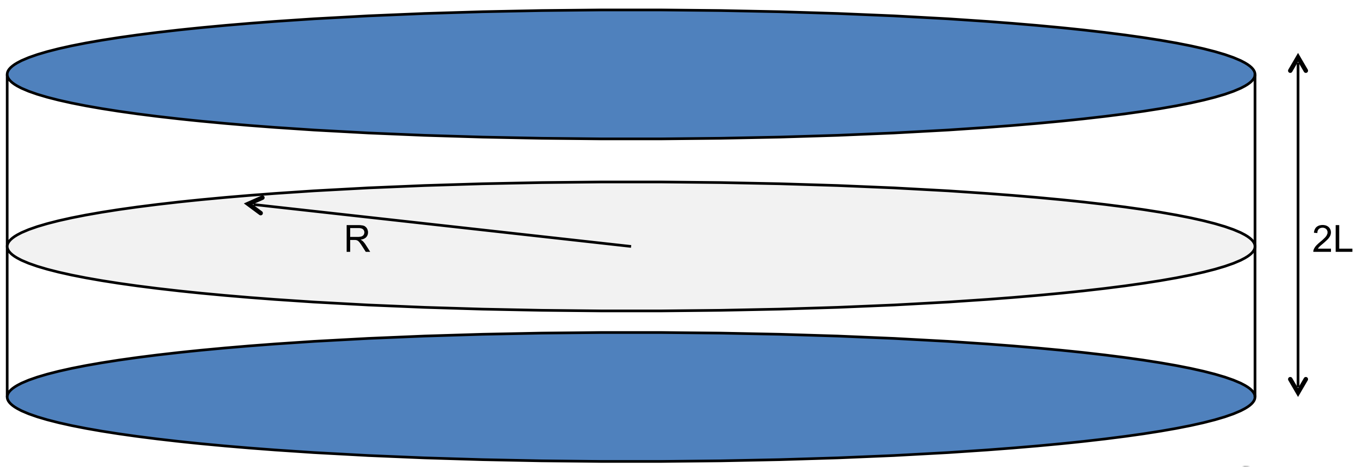
Reported only particle/pion ratios.

Interpreted cross section by scaling w/ model of pion cross section

Prone to large error, especially at < 10 GeV

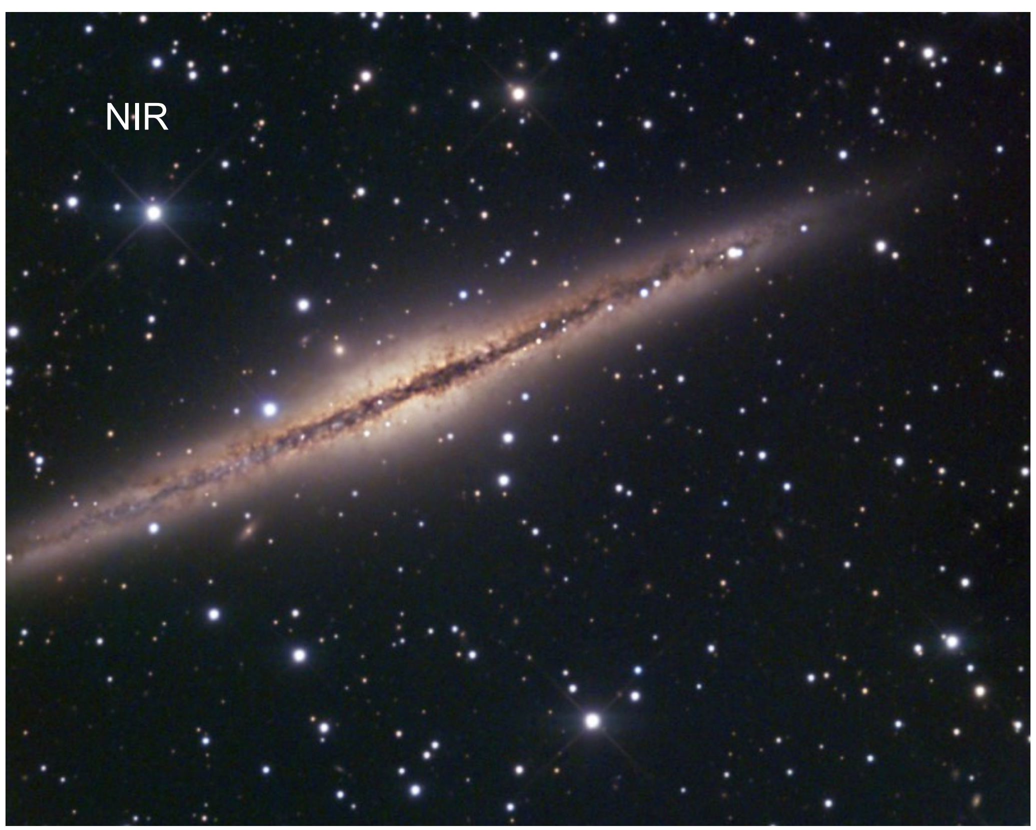
About diffusion models

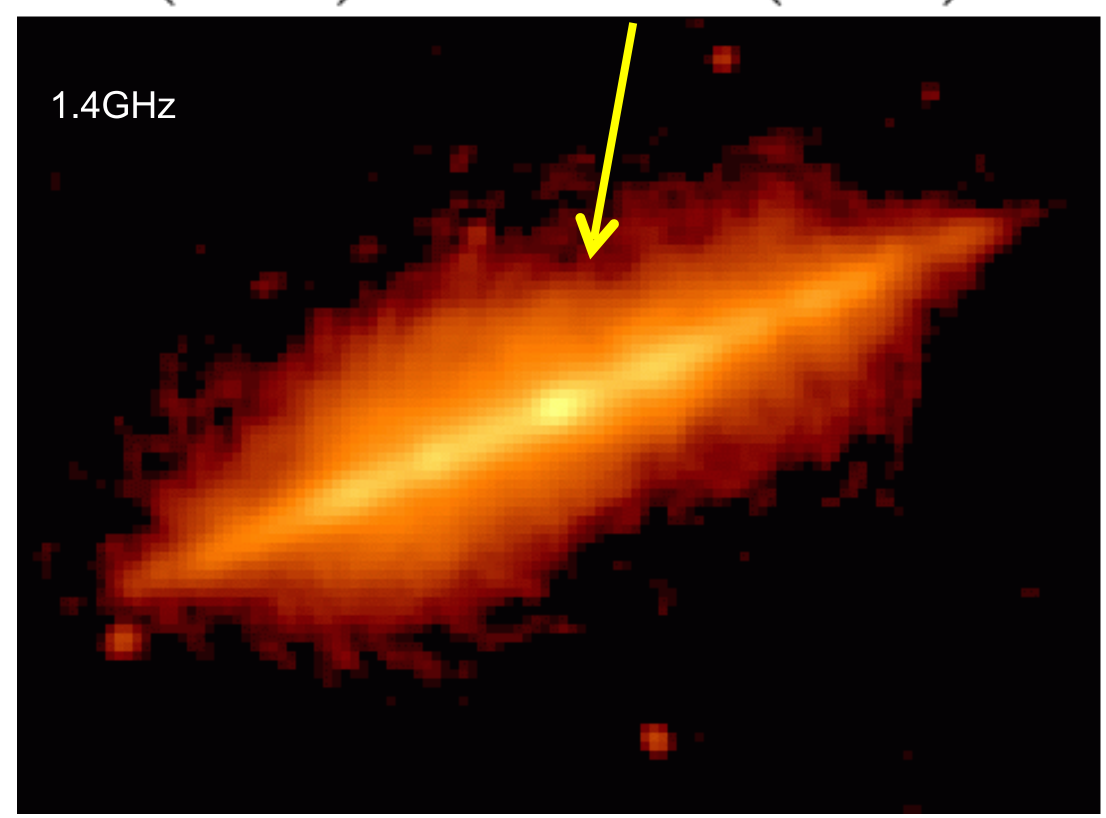
$K \sim (E/Z)^{\delta}$



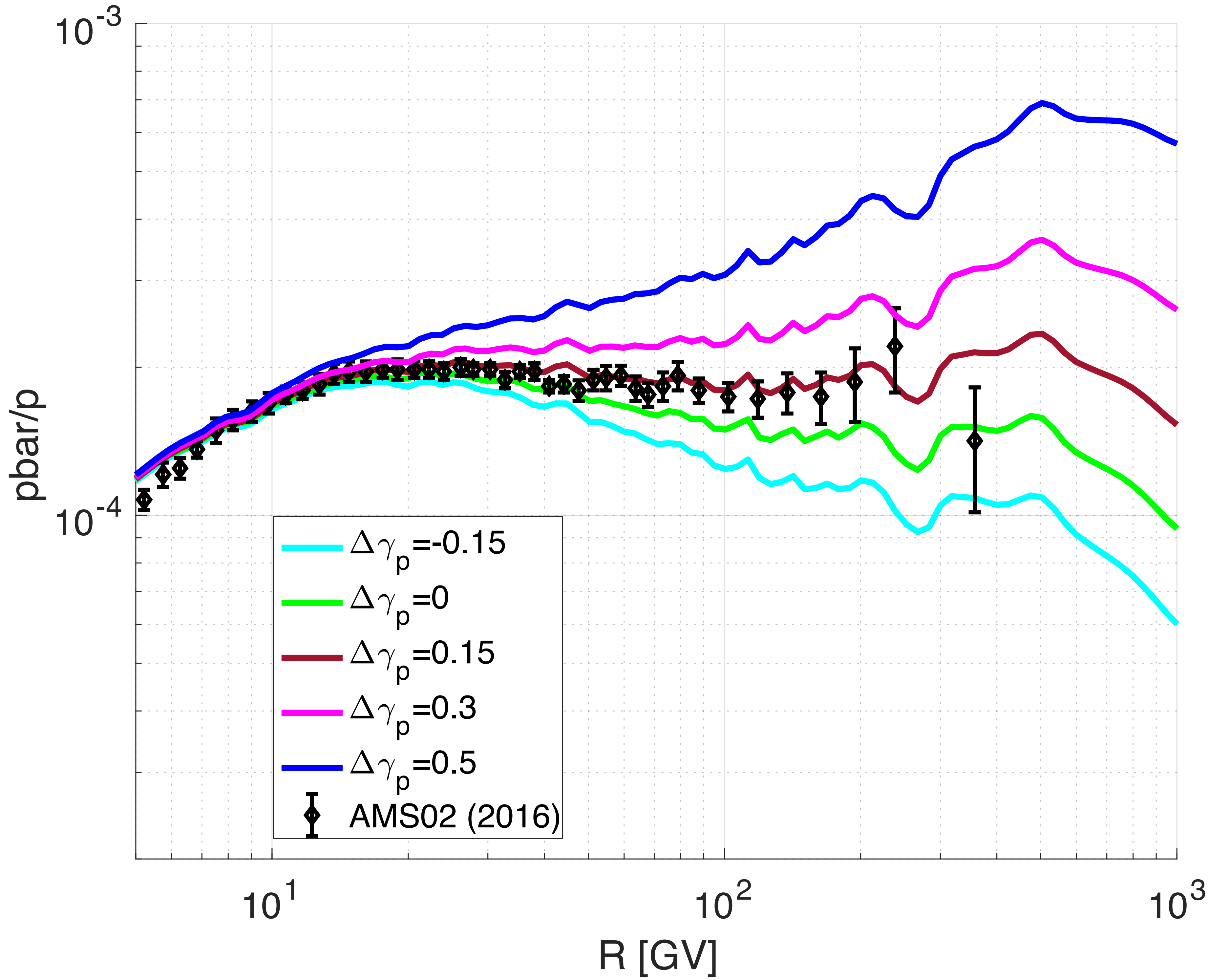
$$\nu \approx 0.29 \times \frac{3eB}{4\pi m_e c}\left(\frac{\epsilon}{m_e c^2}\right)^2 \approx 1\ \mathrm{GHz}\left(\frac{B}{1\ \mu\mathrm{G}}\right)\left(\frac{\epsilon}{15\ \mathrm{GeV}}\right)^2$$

NGC 891





Strong, Moskalenko, Ptuskin, Ann.Rev.Nucl.Part.Sci. 57 (2007) 285-327



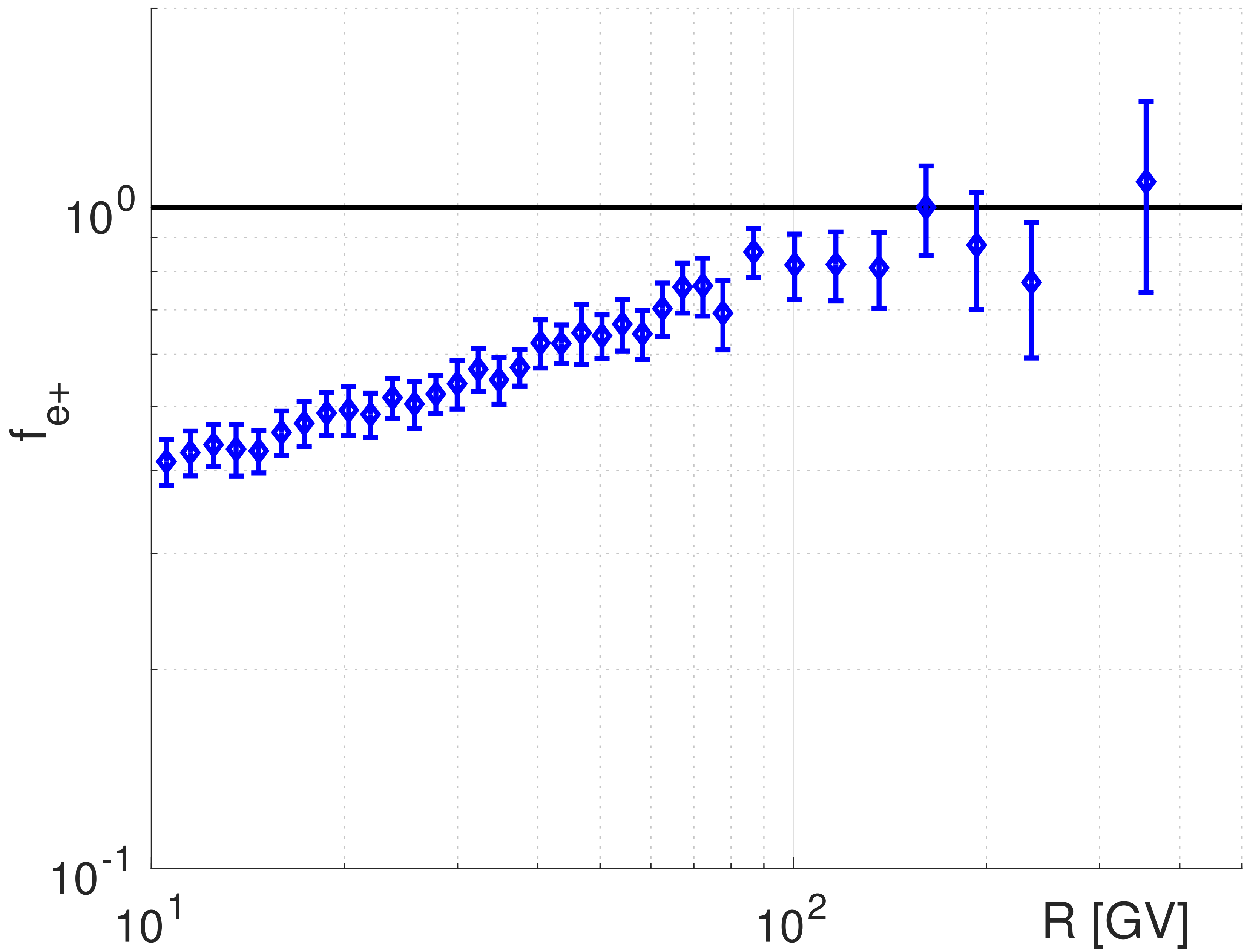
10^{-3}
10^{-4}
pbar/p
10^1
10^2
10^3
R [GV]
$\Delta\gamma_p$=-0.15
$\Delta\gamma_p$=0
$\Delta\gamma_p$=0.15
$\Delta\gamma_p$=0.3
$\Delta\gamma_p$=0.5
AMS02 (2016)

$$\frac{n_{e^+}}{n_{\bar{p}}} = f_{e^+}(\mathcal{R})\frac{Q_{e^+}(\mathcal{R})}{Q_{\bar{p}}(\mathcal{R})}$$

Secondary: upper bound

$$f_{e^+}(\mathcal{R}) \leq 1$$

AMS02 data favours secondary origin for CR e+.



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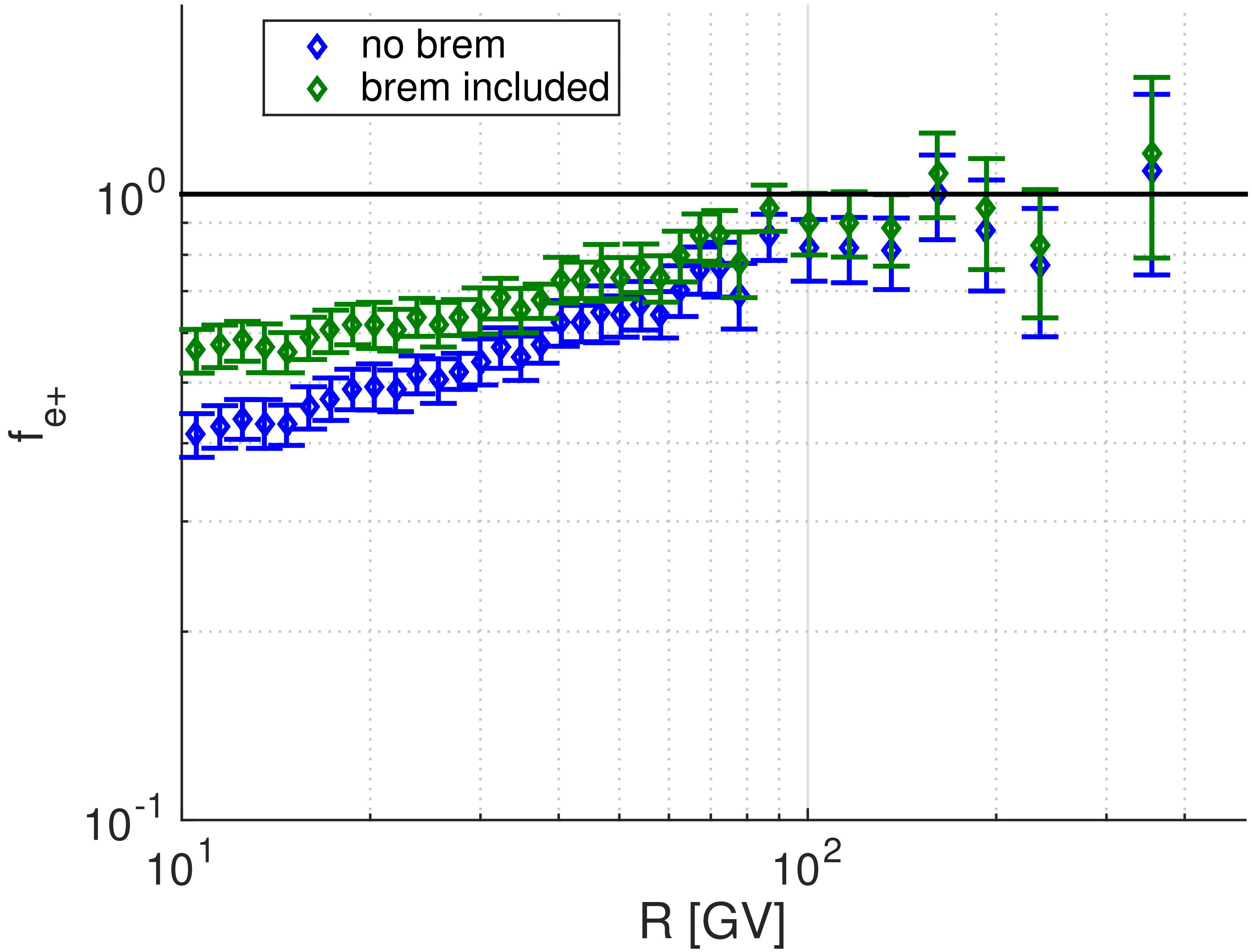


anti He3

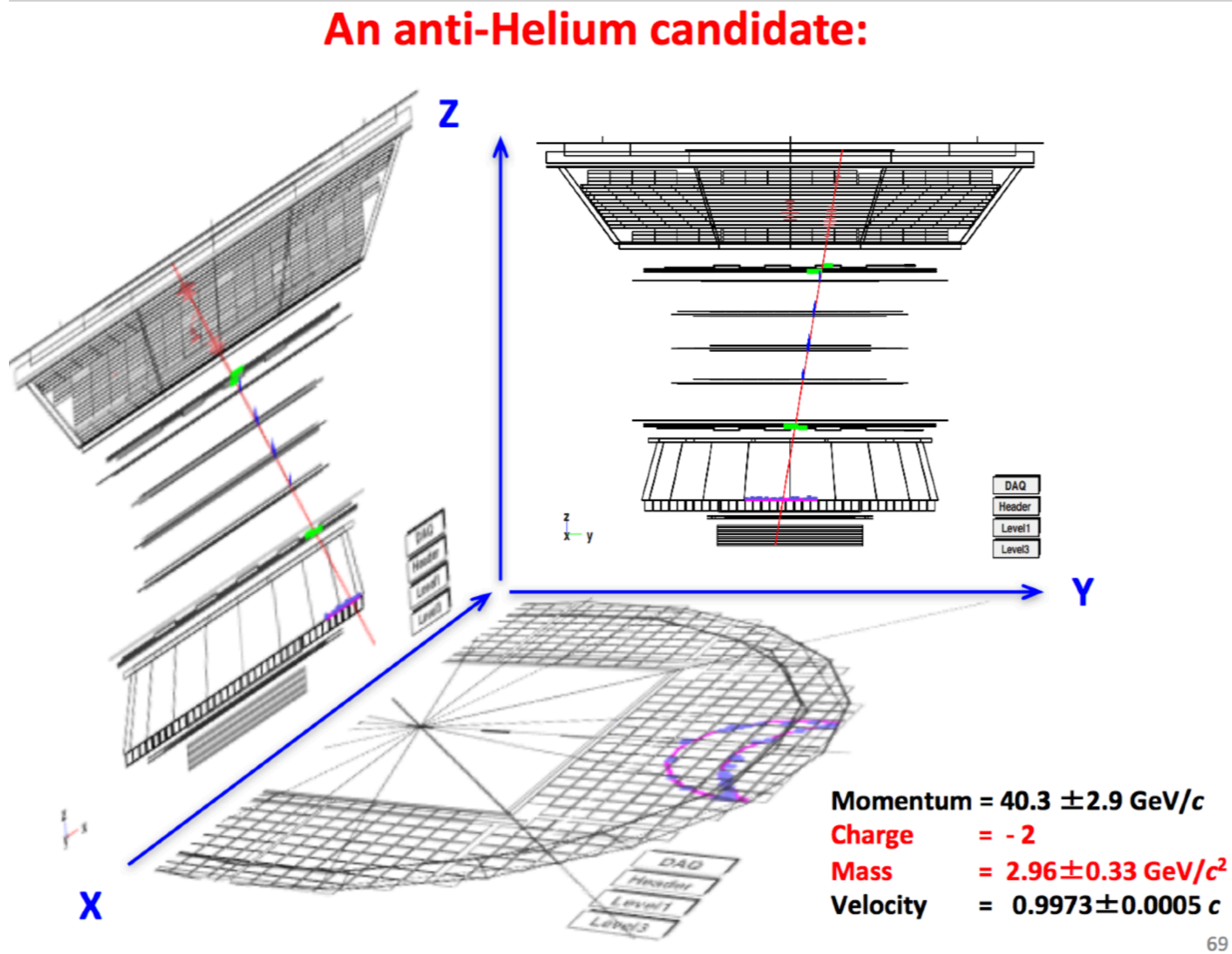
1. Handful of events

2. Energy of 1 event they show is 40GeV (13GeV/nuc)

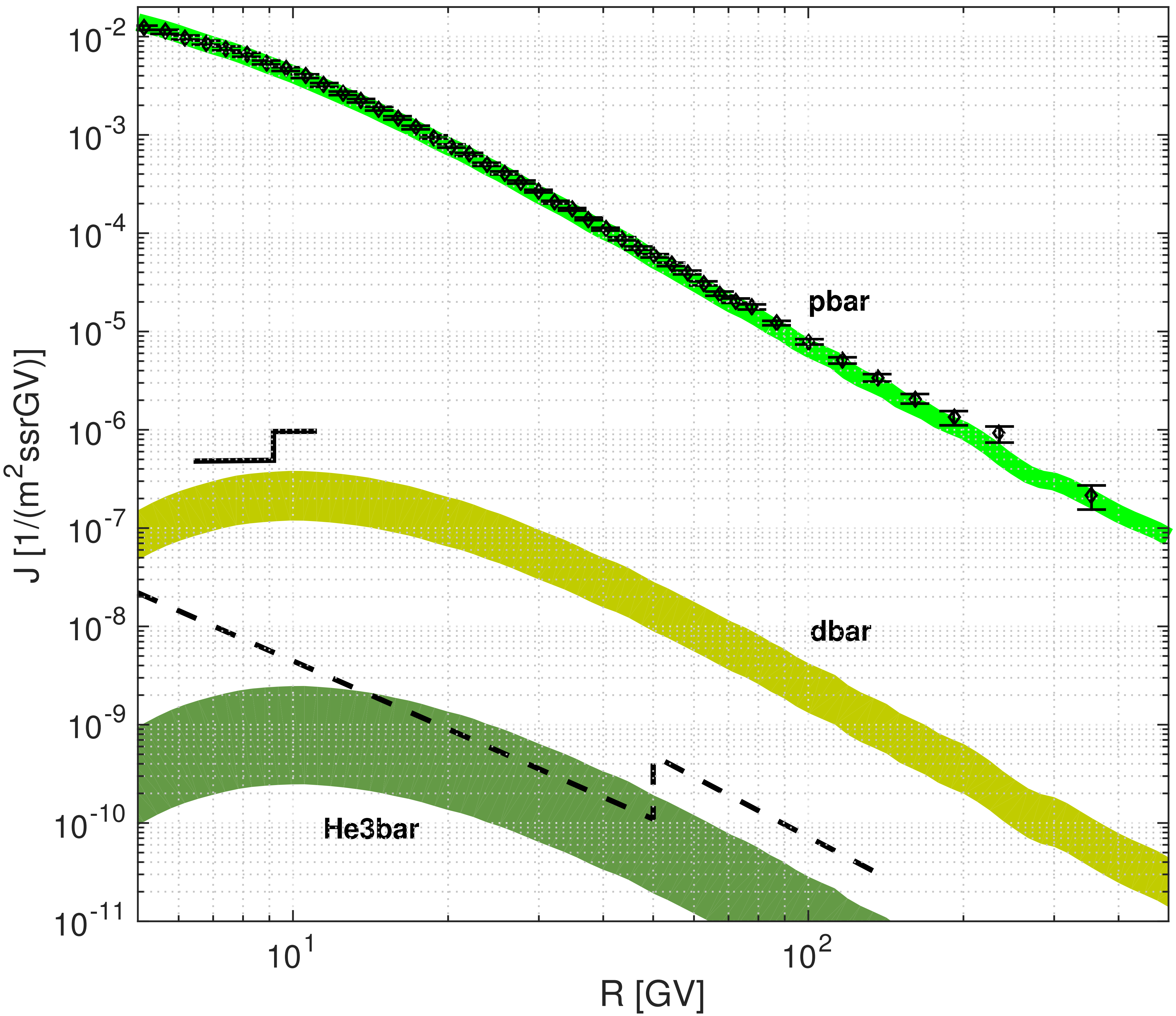
Kinematics:
pp→(He3bar)+X requires minimum 8 baryons

This means threshold in observer frame is 12 GeV

AMS02 press release, Dec 2016



Summary



Cosmic Rays

The Galaxy is filled with a gas of high-energy particles, of several types

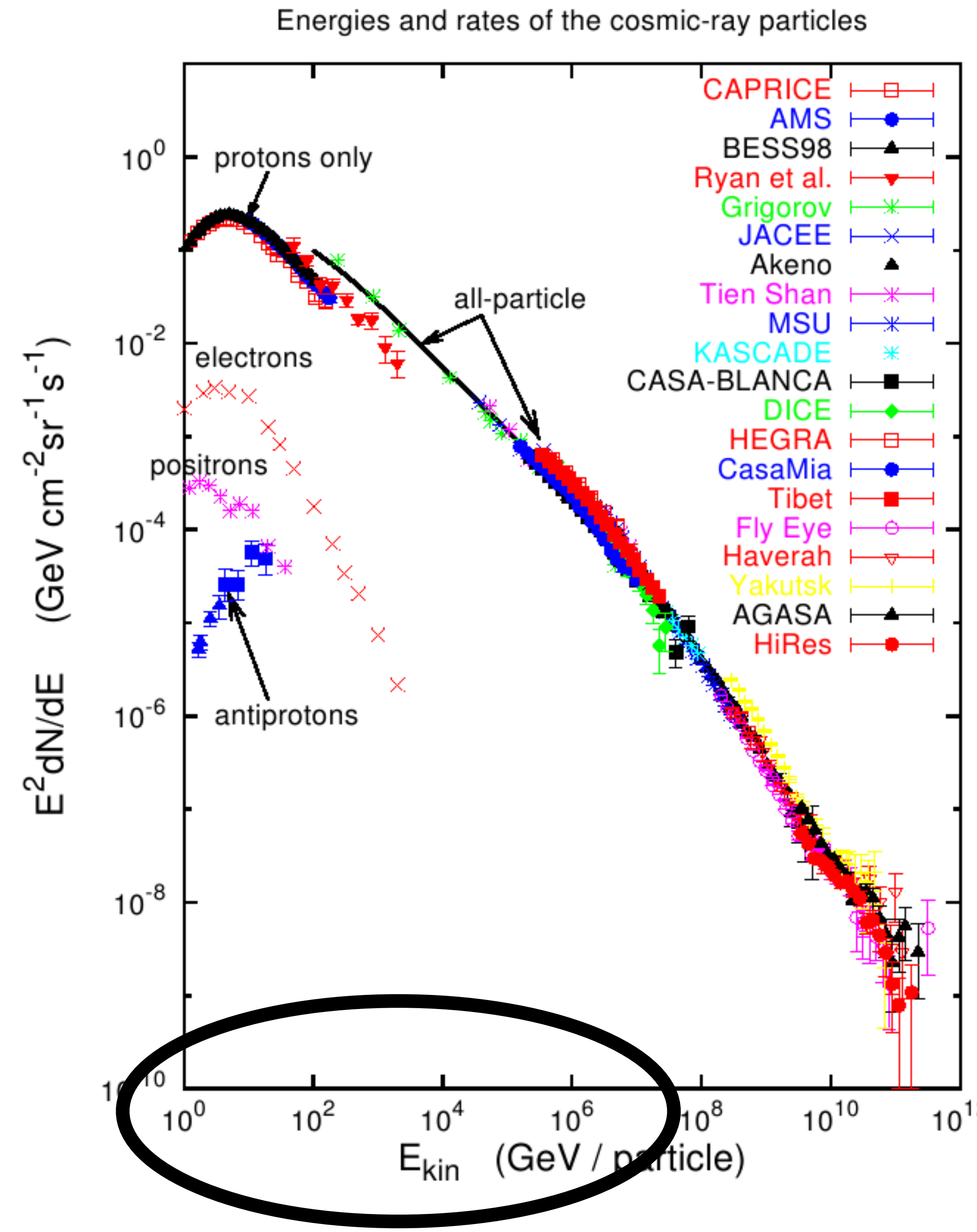
Magnetic rigidity

$$\mathcal{R} = p/Z$$

Larmor radius

$$L = \mathcal{R}/B \approx 3 \times 10^{-4} \left(\frac{\mathcal{R}}{\mathrm{TV}}\right) \left(\frac{\mathrm{B}}{3\ \mu\mathrm{G}}\right)^{-1} \mathrm{pc}$$

Galactic:



Hillas, astro-ph/0607109

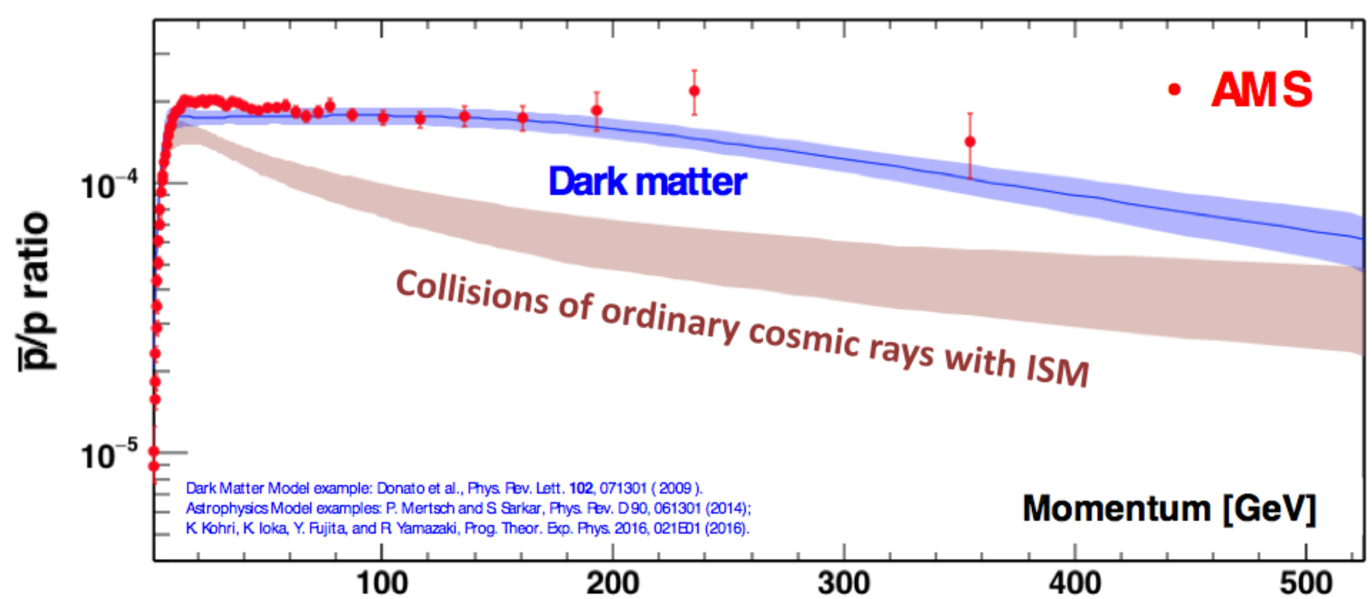
CR antimatter – $\bar{p}$, e^{+}, $\bar{\mathrm{d}}$, and $\overline{^{3}\mathrm{He}}$ long thought a smoking gun of exotic high-energy physics like dark matter annihilation

Antiprotons
Some confusion in the literature, as to what and how we can calculate.

=> will try to sort this out

AMS02, Dec 2016

Antiproton-to-proton ratio



The excess of antiprotons observed by AMS cannot come from pulsars.

It can be explained by Dark Matter collisions or by new astrophysics phenomena

CR antimatter – $\bar{p}$, e^+, $\bar{\mathrm{d}}$, and $\overline{^3\mathrm{He}}$ long thought a smoking gun of exotic high-energy physics like dark matter annihilation

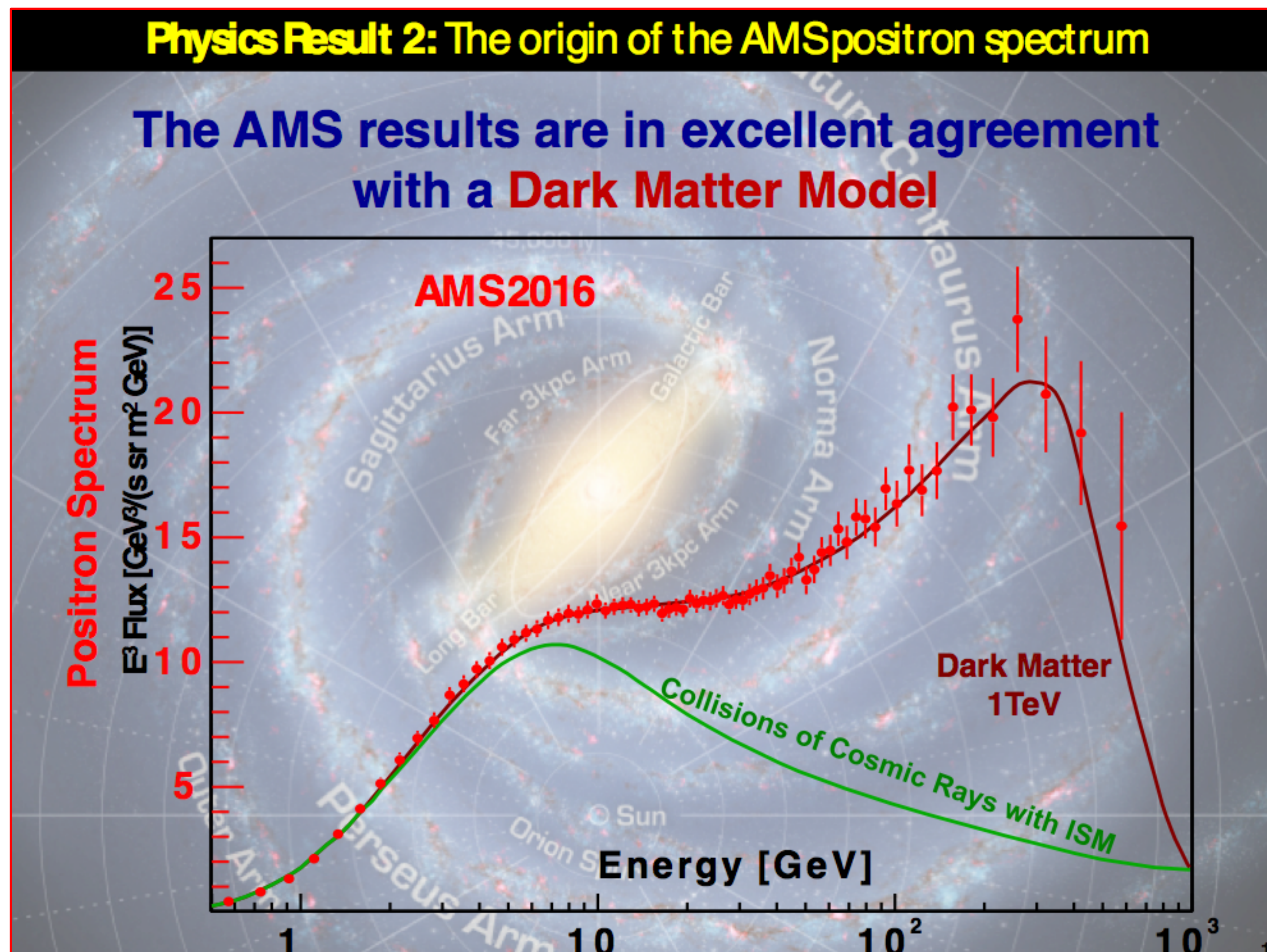
Positrons

Common belief in the literature: e+ come from either pulsars, or dark matter!

=> don't think so.

Will try to sort this out, too

AMS02, Dec 2016



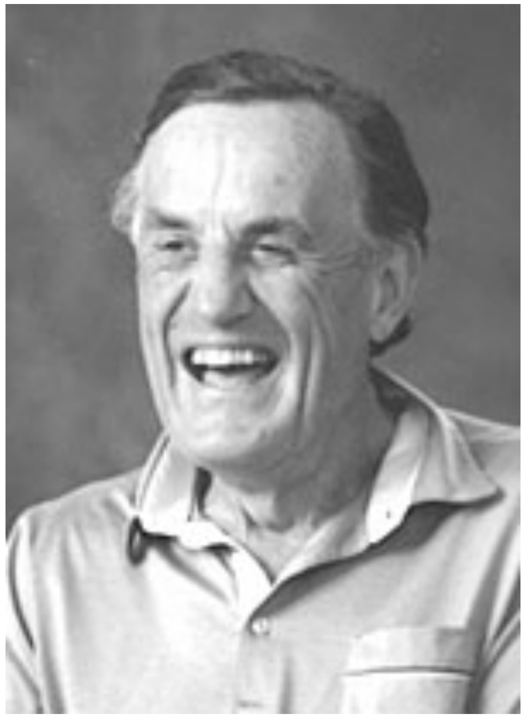
CR antimatter – $\bar{p}$, e^{+}, $\bar{\mathrm{d}}$, and $\overline{^3\mathrm{He}}$ long thought a smoking gun of exotic high-energy physics like dark matter annihilation

Anti-helium

Thought so scarce that a single event would mark new physics.
But how does one actually calculate the flux?

=> will show that previous ideas may have been *off the mark*.

AMS02 may soon detect astrophysical anti-He3



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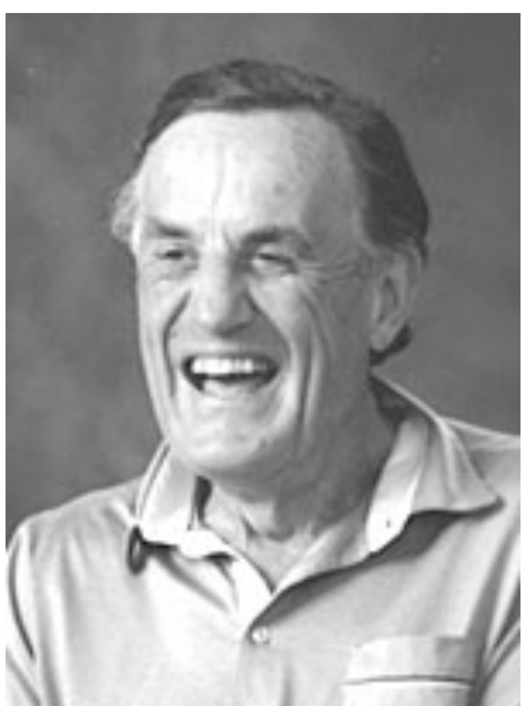
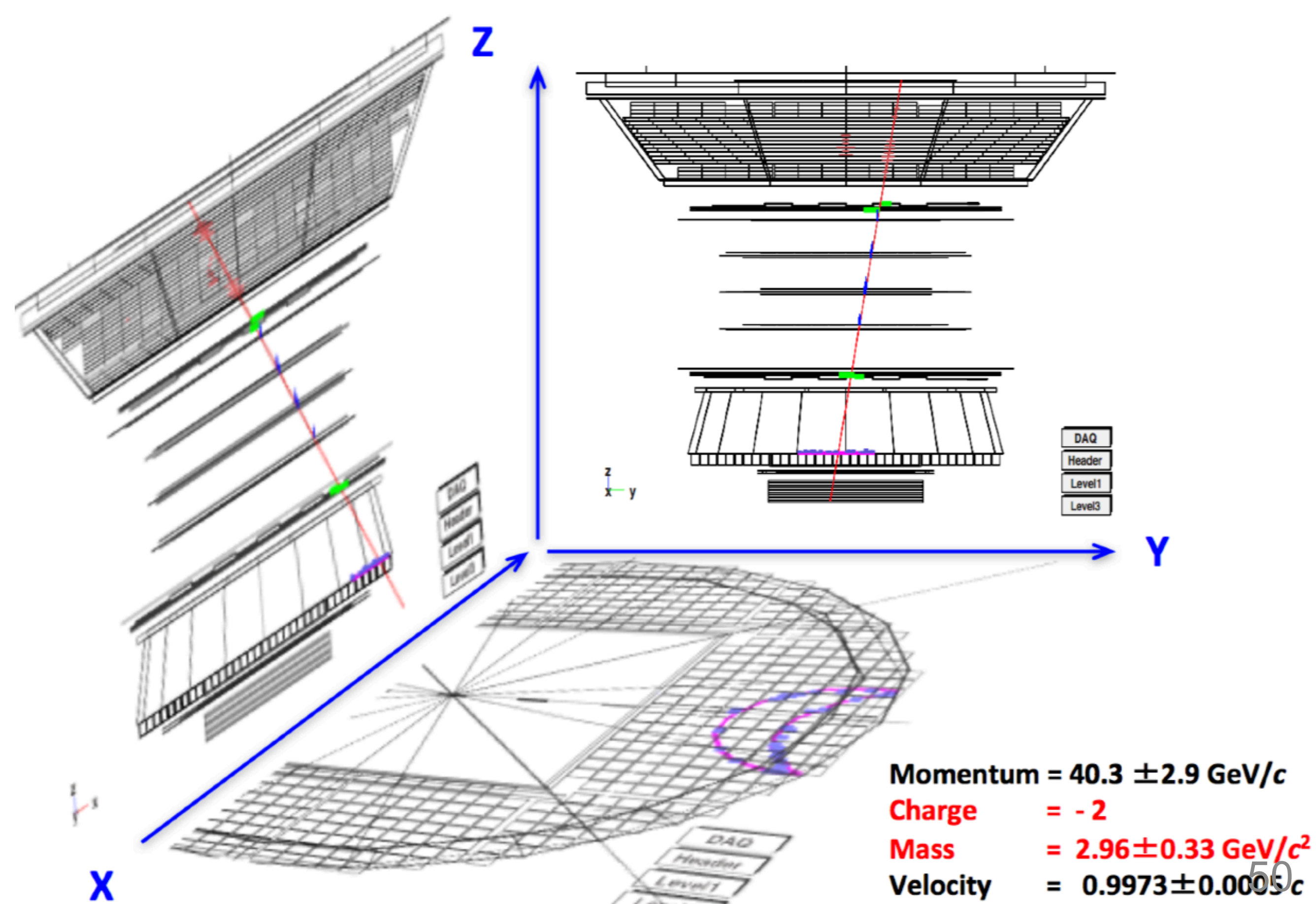
AMS02 may **have detected** astrophysical anti-He3



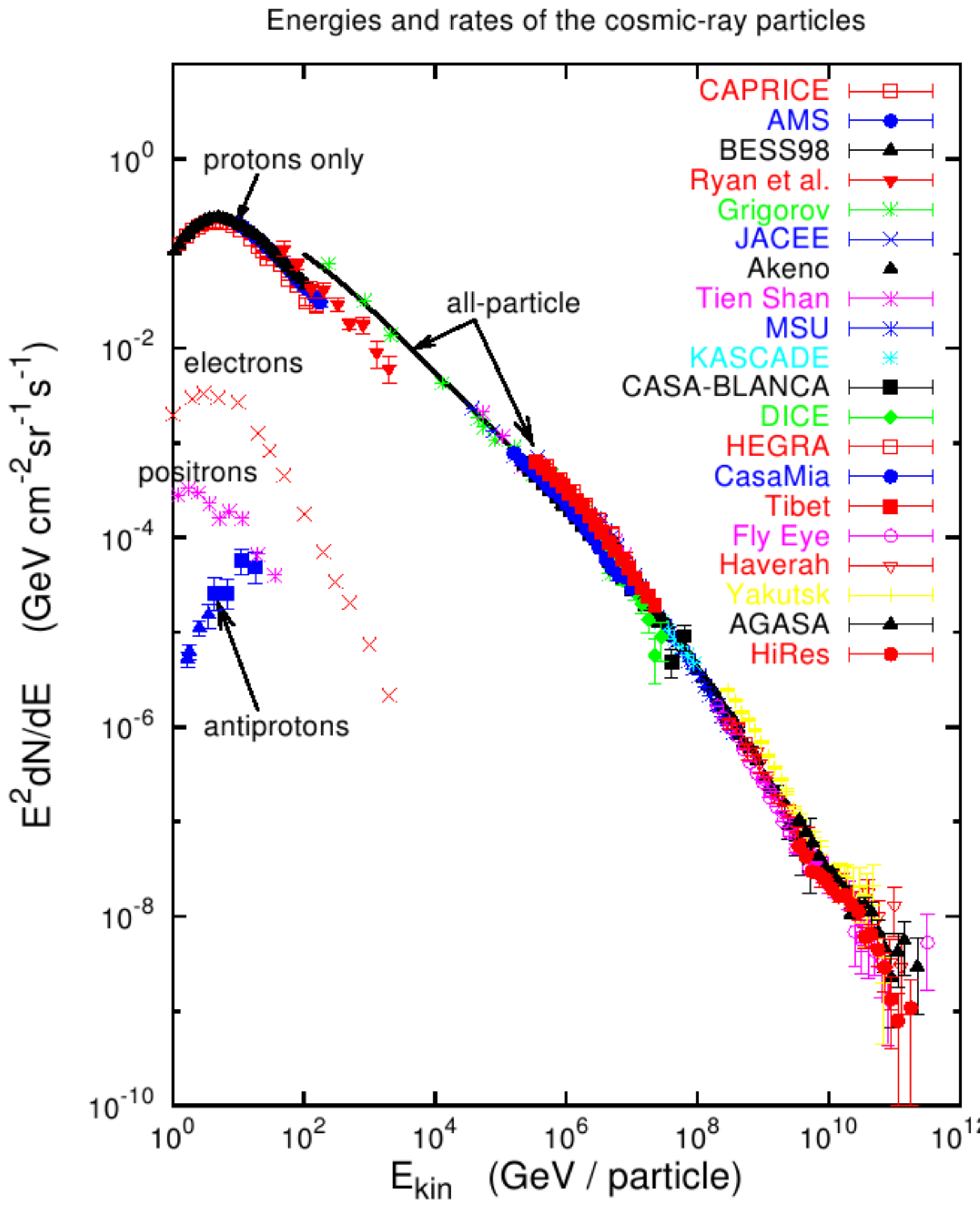
AMS02, Dec 2016

An anti-Helium candidate:



Cosmic Rays

The Universe is filled with a gas of high-energy particles



Hillas, astro-ph/0607109

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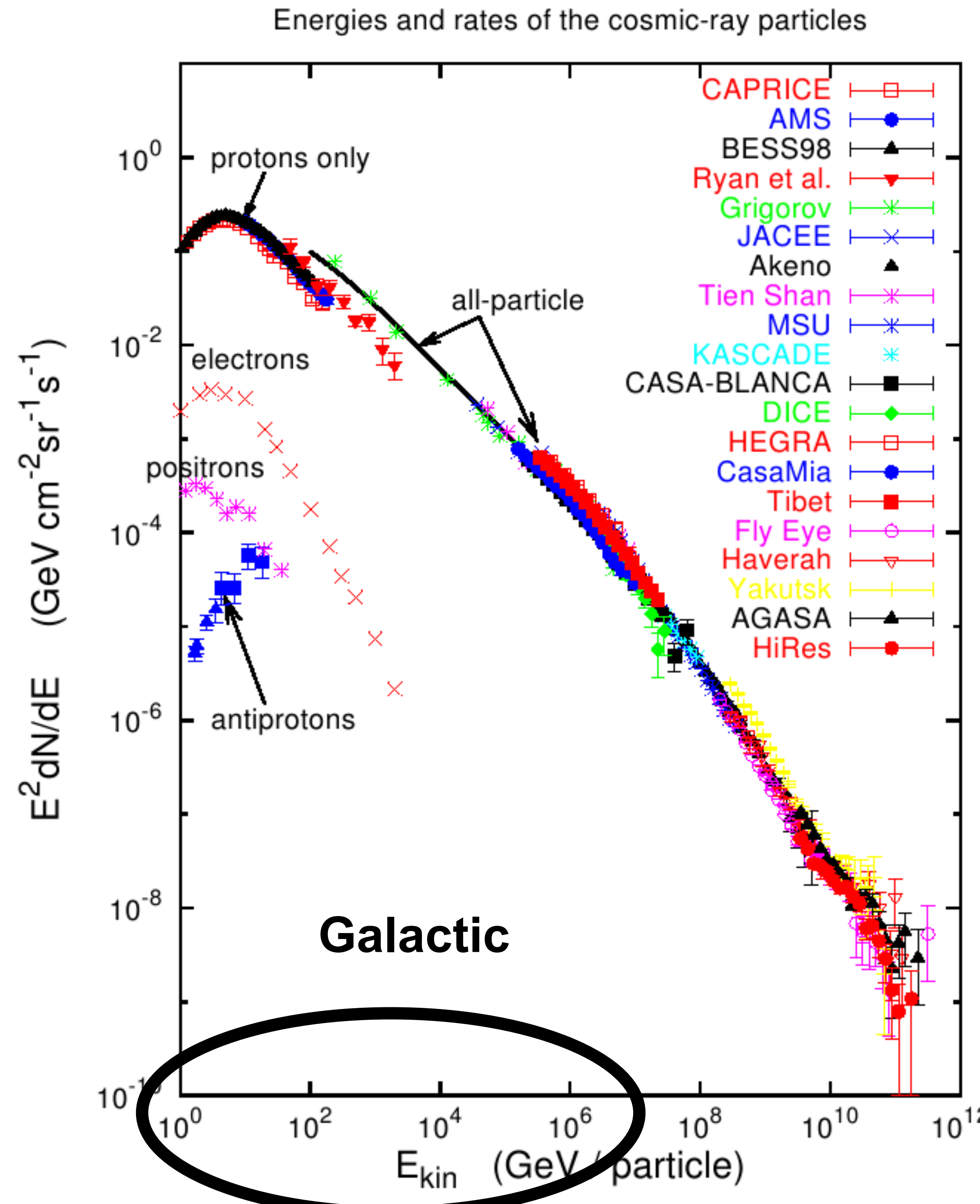


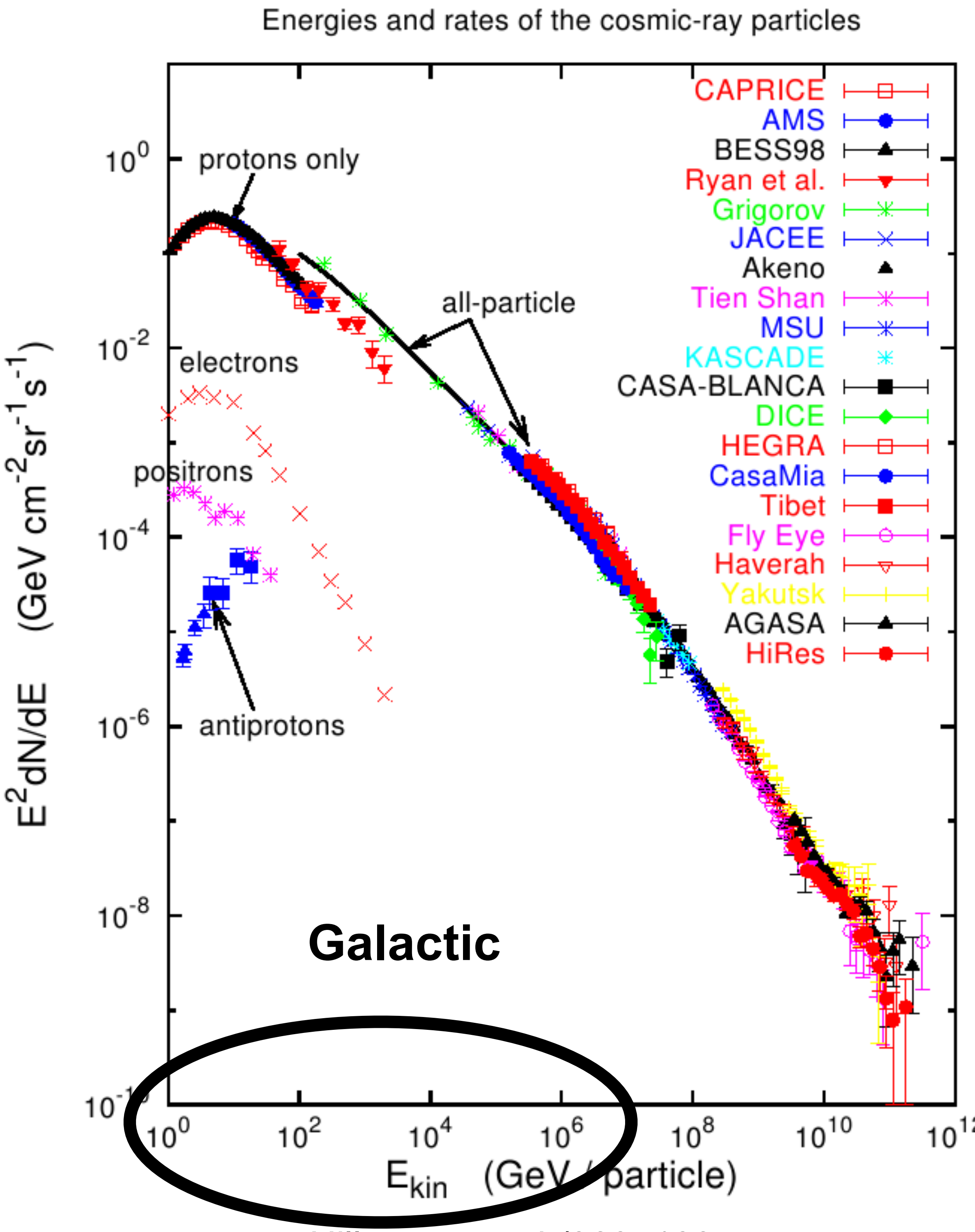
Hillas, astro-ph/0607109

Cosmic Rays

Two basic populations:

1. **primary** (p, He, C, O, Fe, e-,…),

2. **secondary** (B, sub-Fe, pbar, e+,…),



Hillas, astro-ph/0607109

Cosmic Rays

Two basic populations:

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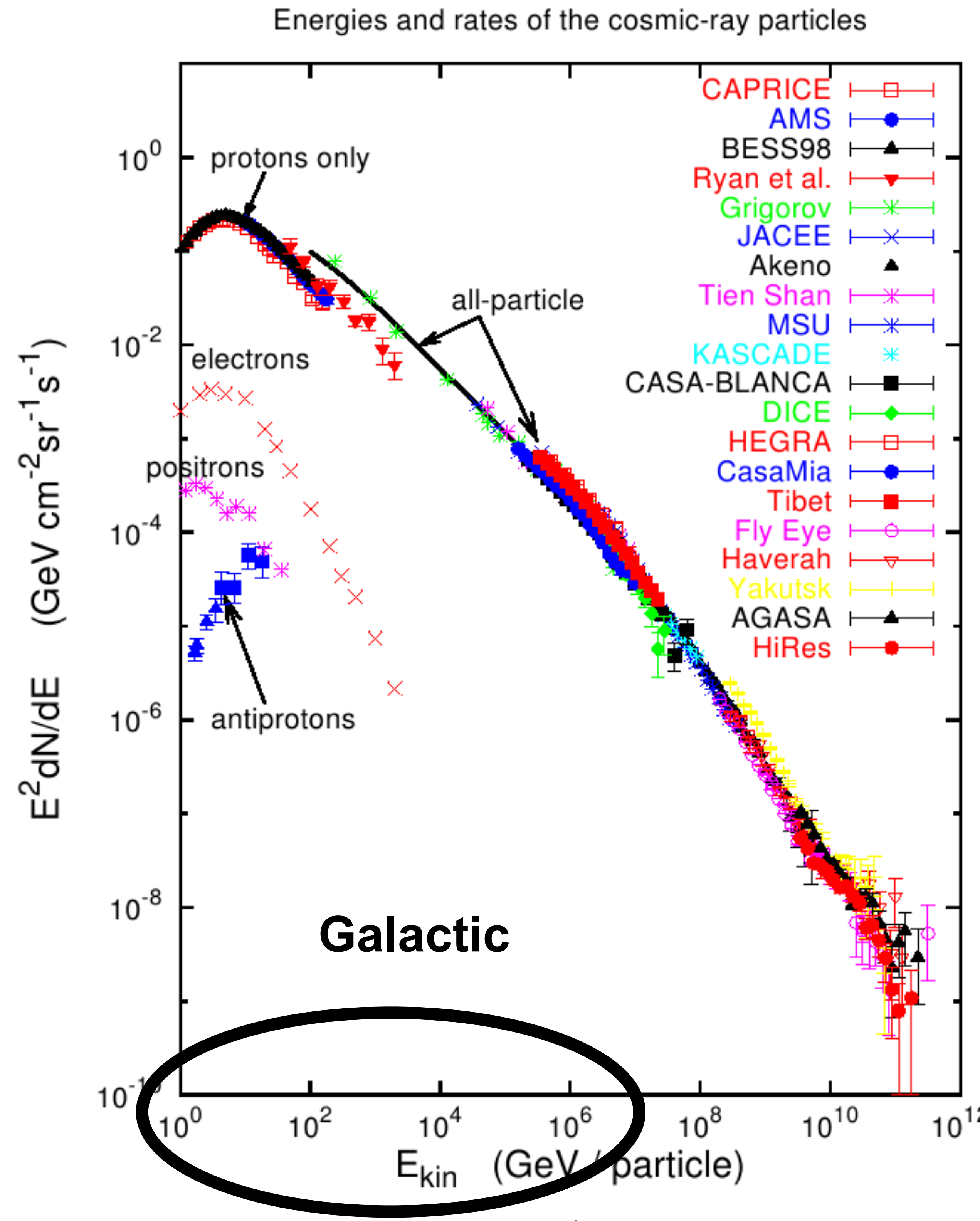

Hillas, astro-ph/0607109

Cosmic Rays

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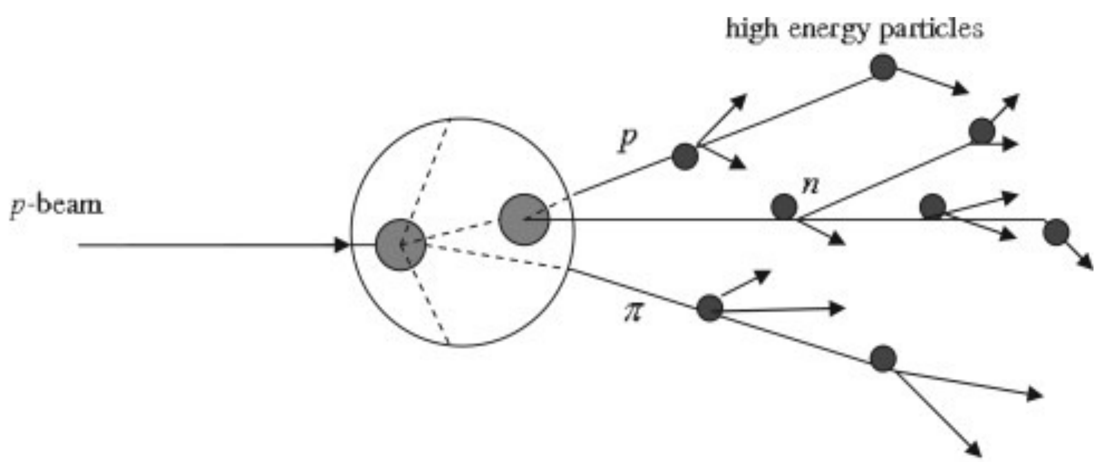

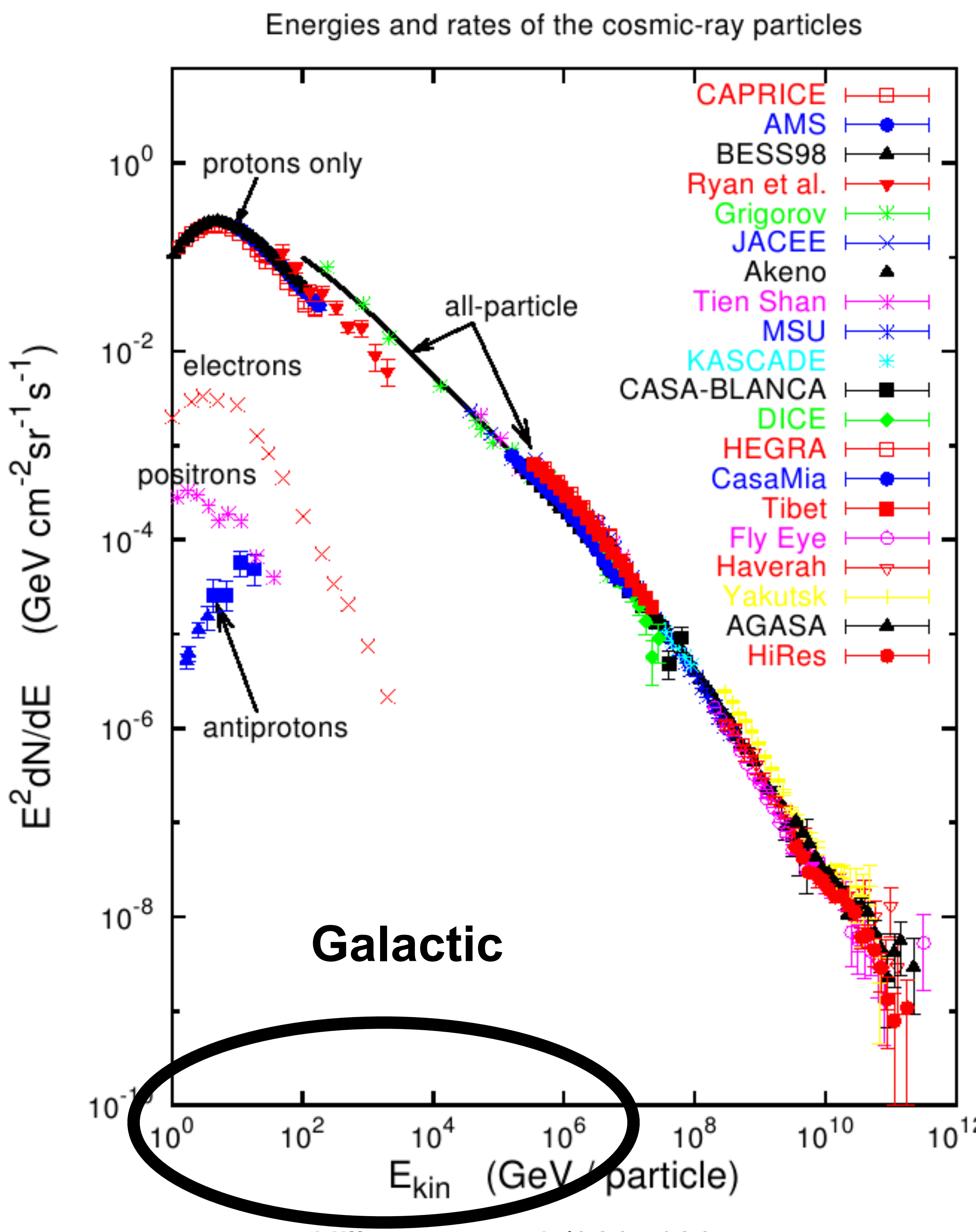

Hillas, astro-ph/0607109

Recipe for an antiproton pie:

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$$\frac{n_a(\mathcal{R})}{n_b(\mathcal{R})} \approx \frac{Q_a(\mathcal{R})}{Q_b(\mathcal{R})} \quad \Rightarrow \quad n_{\bar{p}}(\mathcal{R}) \approx \frac{n_{\mathrm{B}}(\mathcal{R})}{Q_{\mathrm{B}}(\mathcal{R})} Q_{\bar{p}}(\mathcal{R})$$

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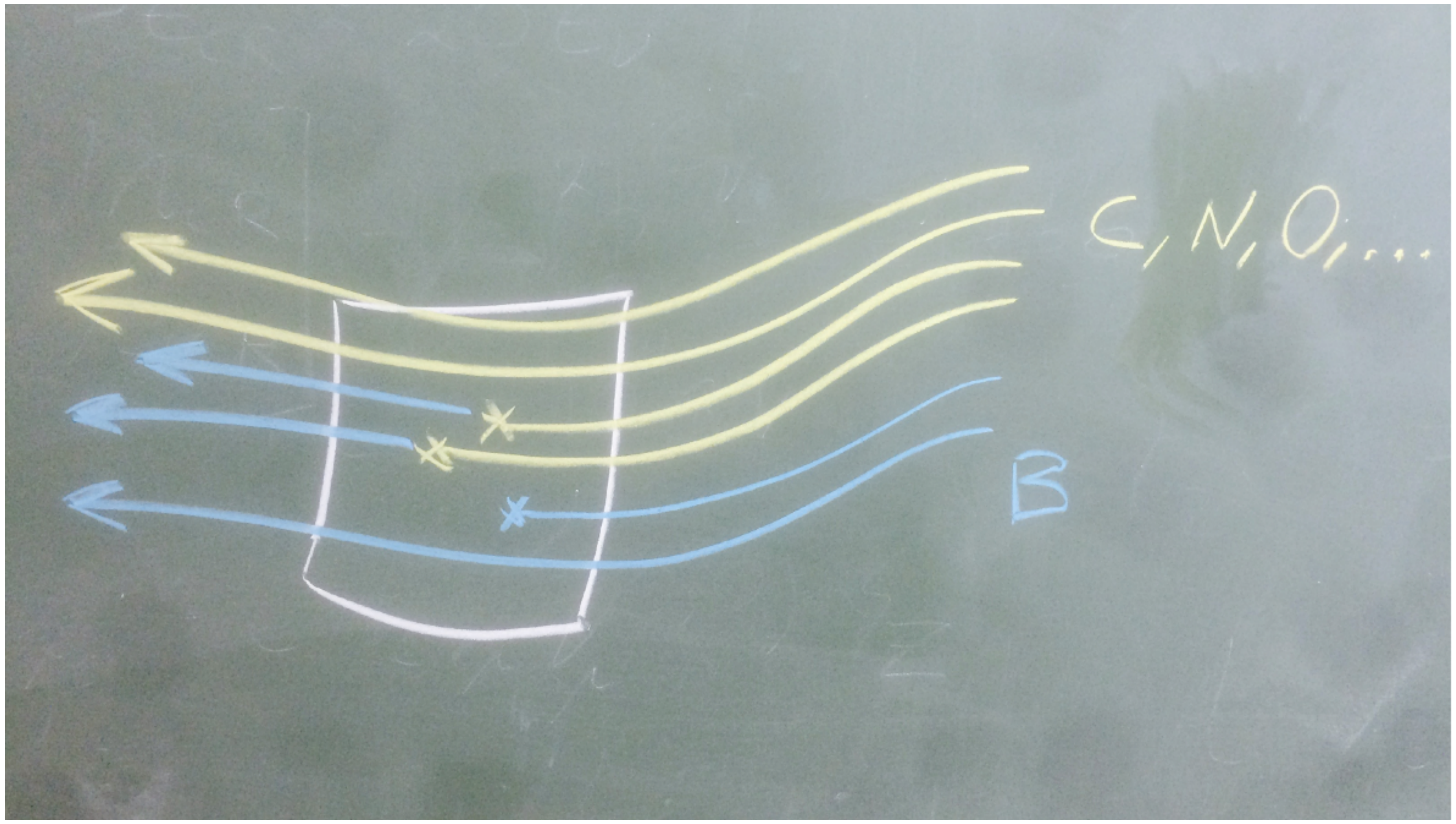
$$Q_a(\mathcal{R}) = \sum_P n_P(\mathcal{R}) \frac{\sigma_{P\to a}(\mathcal{R})}{m} - n_a(\mathcal{R}) \frac{\sigma_a(\mathcal{R})}{m}$$



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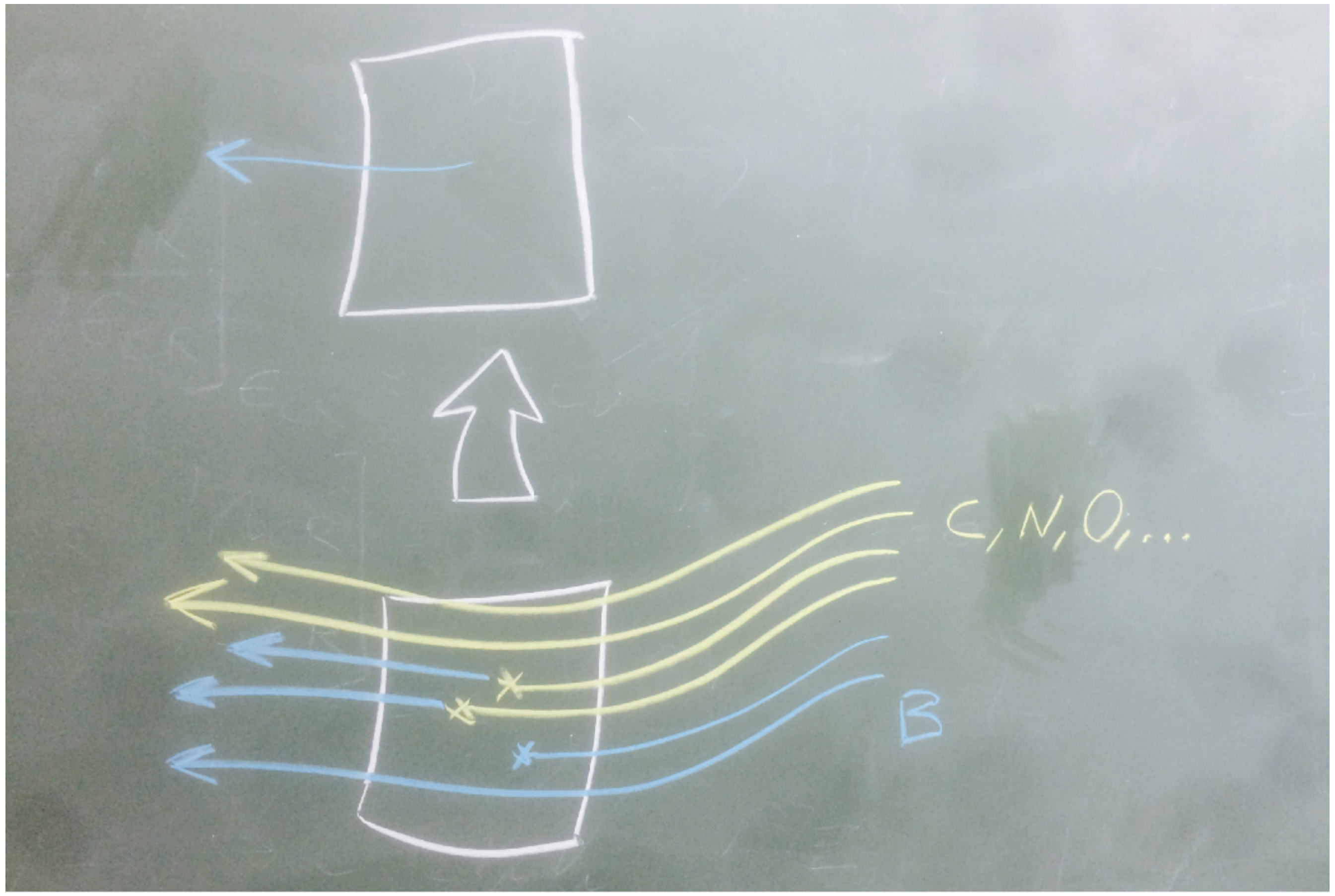

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Average column density traversed by CR nuclei during propagation

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Average column density traversed by CR nuclei during propagation

$$X_{\mathrm{esc}}(\mathcal{R}) = \frac{n_{\mathrm{B}}(\mathcal{R})}{Q_{\mathrm{B}}(\mathcal{R})}$$

$$\boxed{X_{\mathrm{esc}} = \frac{(\mathrm{B}/\mathrm{C})}{\sum_{\mathrm{P}=\mathrm{C,N,O,...}} (\mathrm{P}/\mathrm{C}) \frac{\sigma_{\mathrm{P}\to\mathrm{B}}}{m} - (\mathrm{B}/\mathrm{C}) \frac{\sigma_{\mathrm{B}}}{m}}}$$

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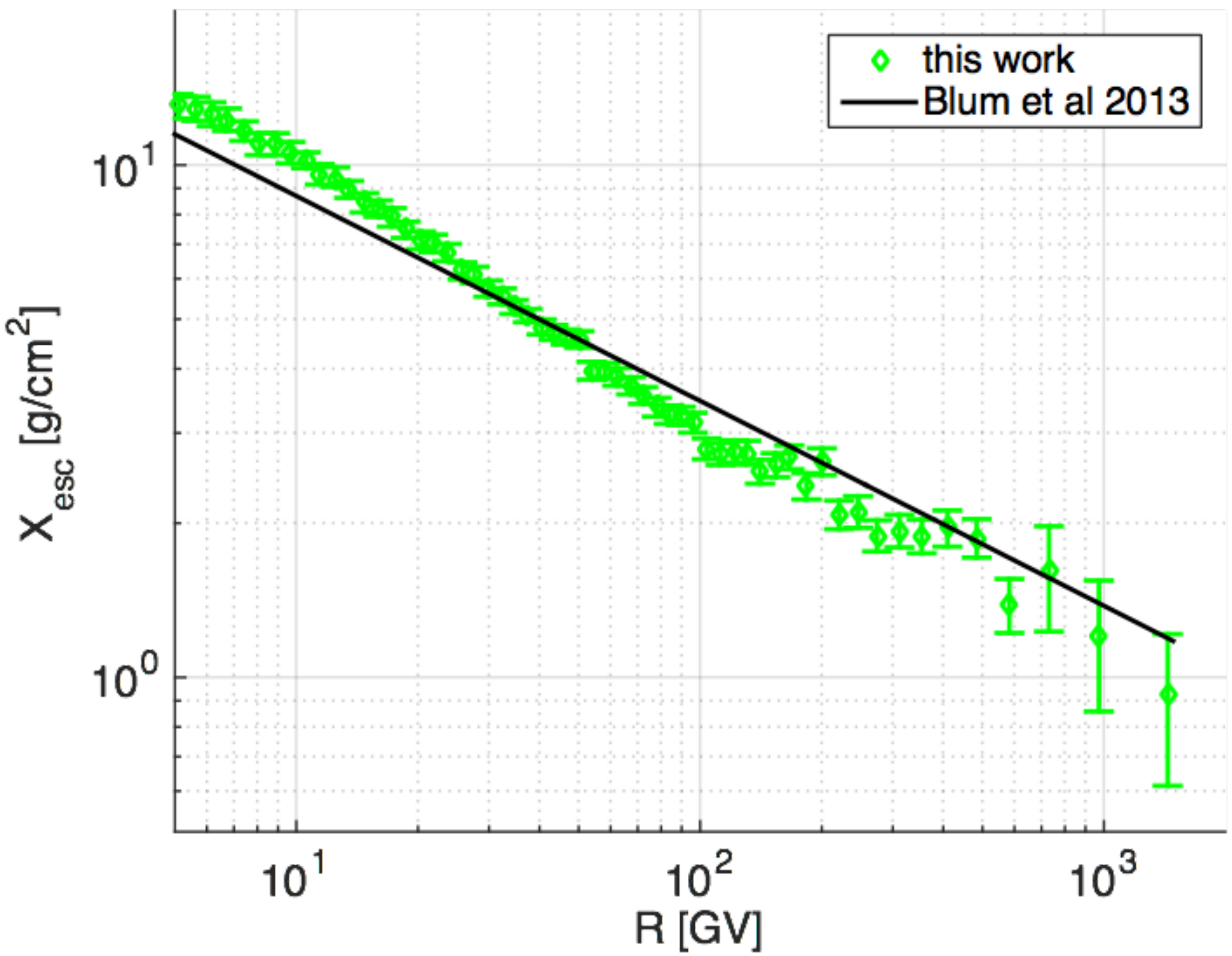

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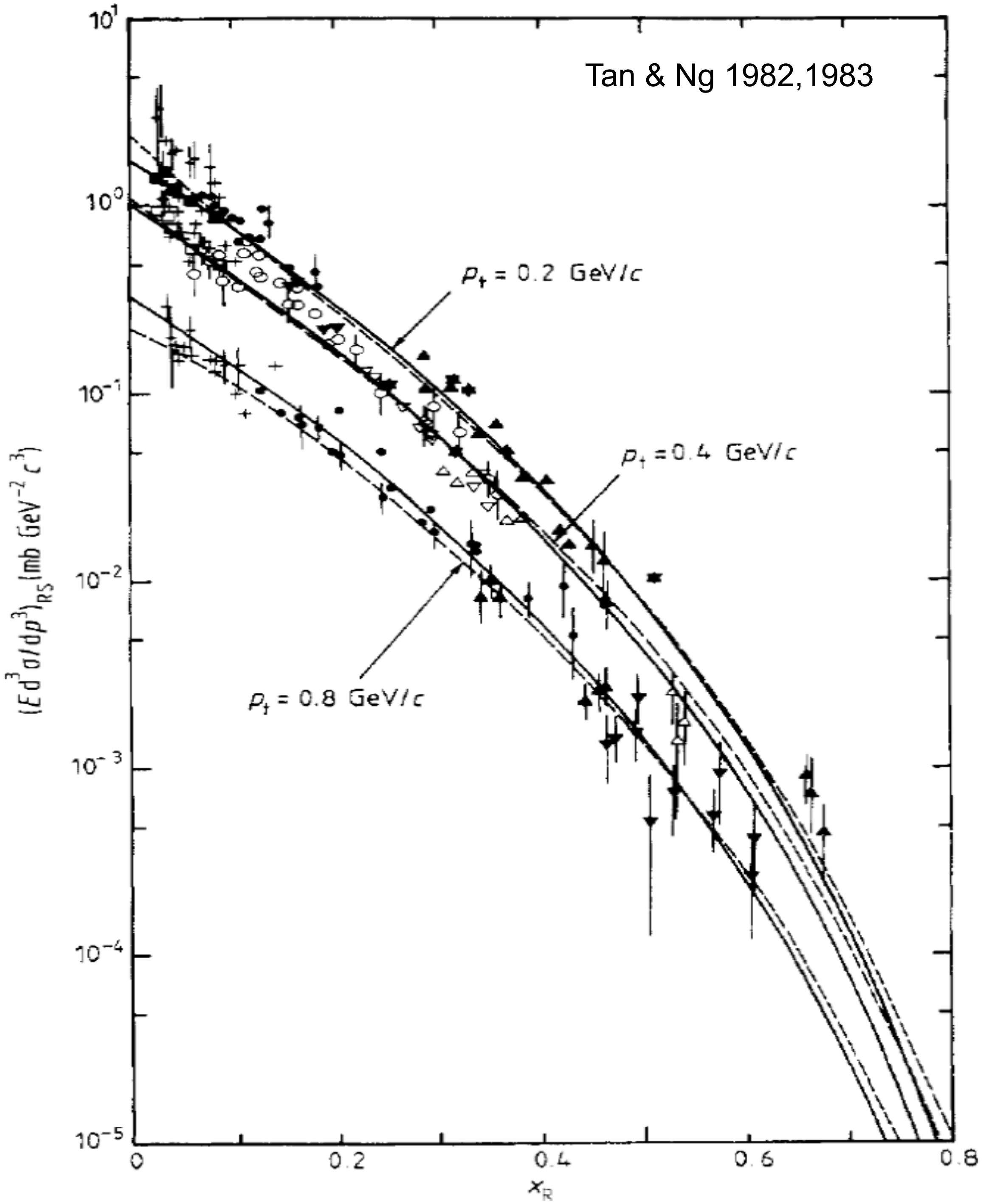

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$$\sigma_{p\to\bar{p}}(\mathcal{R}) = \frac{2\int_{\mathcal{R}}^{\infty} d\mathcal{R}_p\, J_p(\mathcal{R}_p)\left(\frac{d\sigma_{pp\to\bar{p}X}(\mathcal{R}_p,\mathcal{R})}{d\mathcal{R}_p}\right)}{J_p(\mathcal{R})}$$

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Kachelriess et al, **ApJ. 803 (2015) no.2, 54**

Winkler, **JCAP 1702 (2017) no.02, 048**

1709.04953 Blum, Sato, Takimoto

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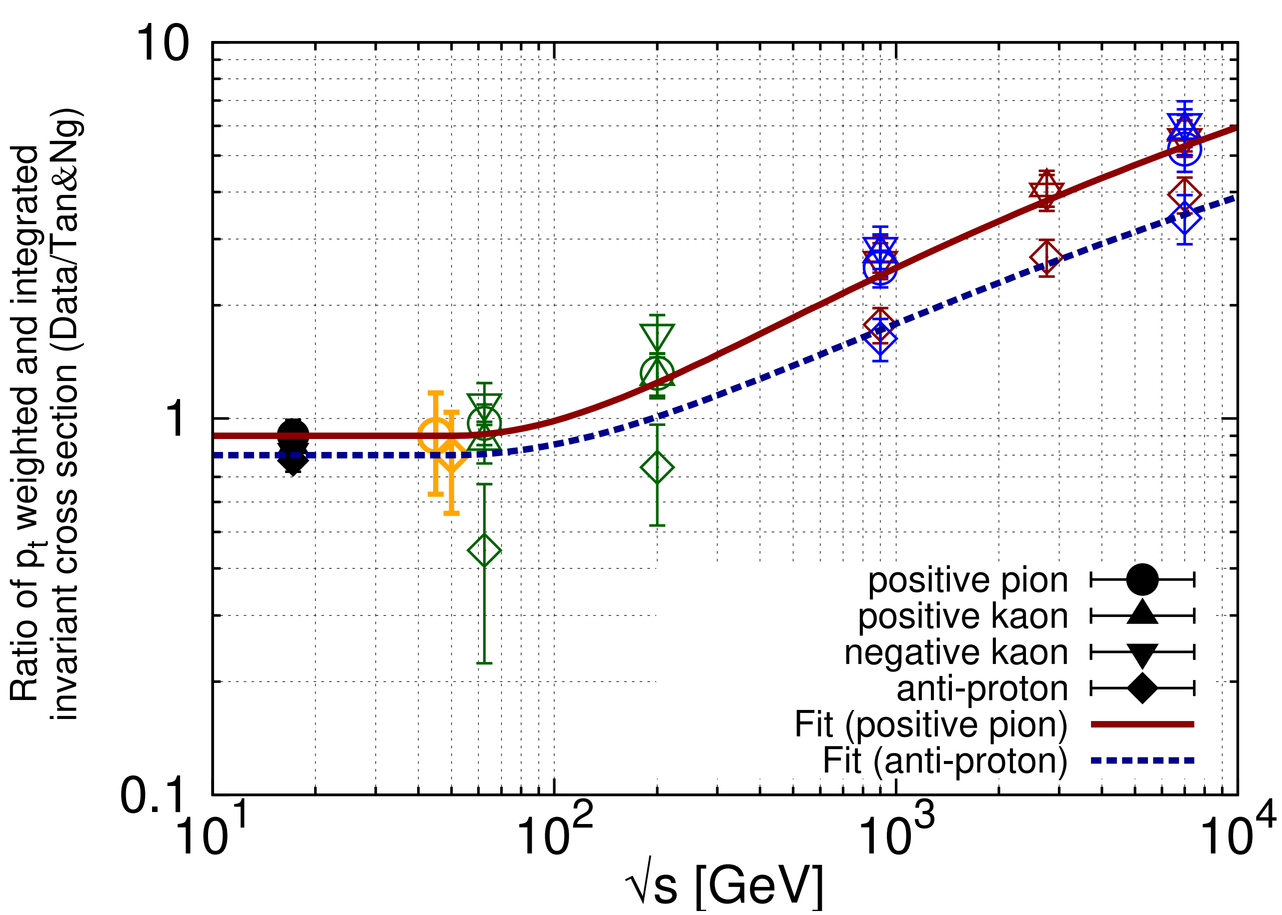

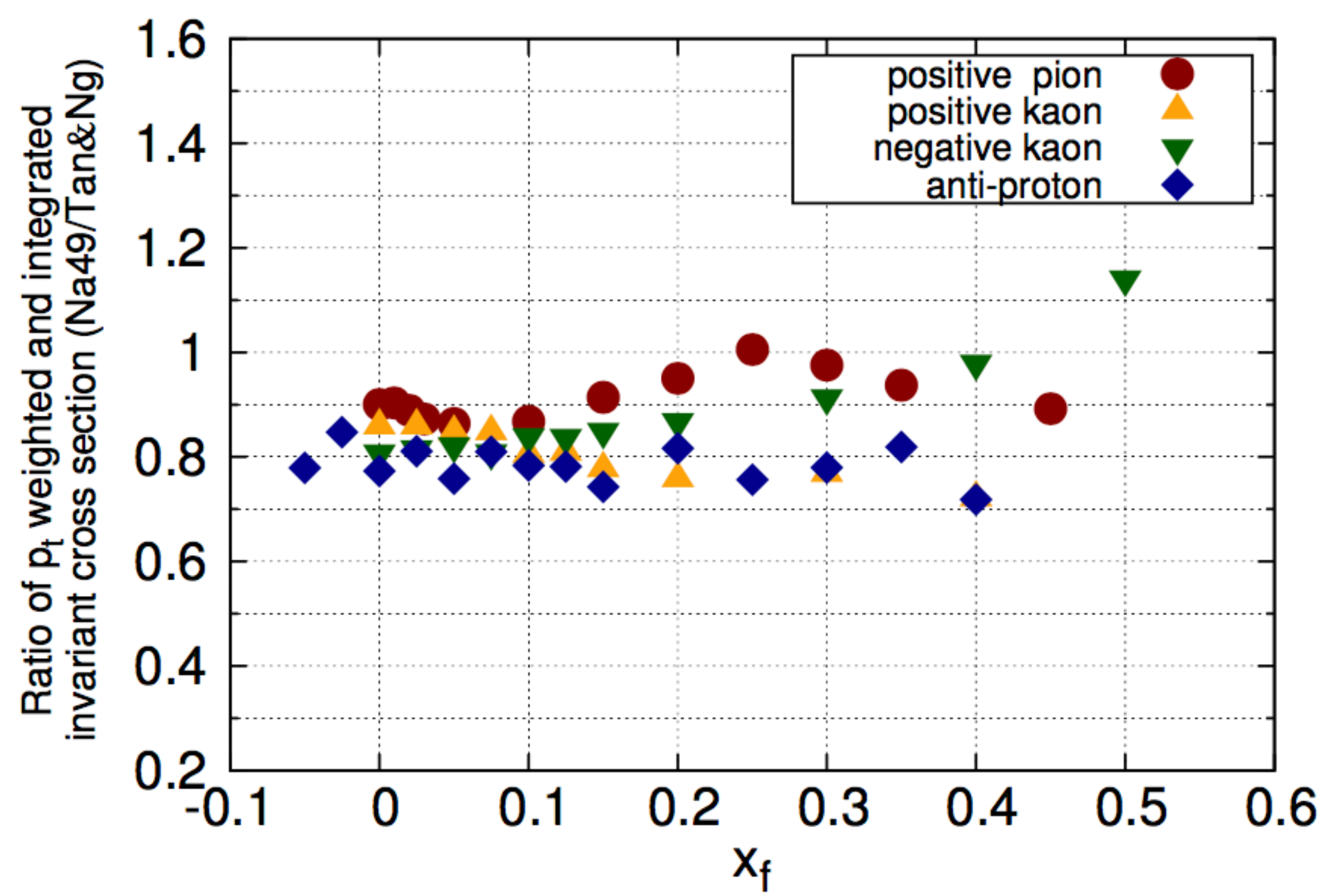

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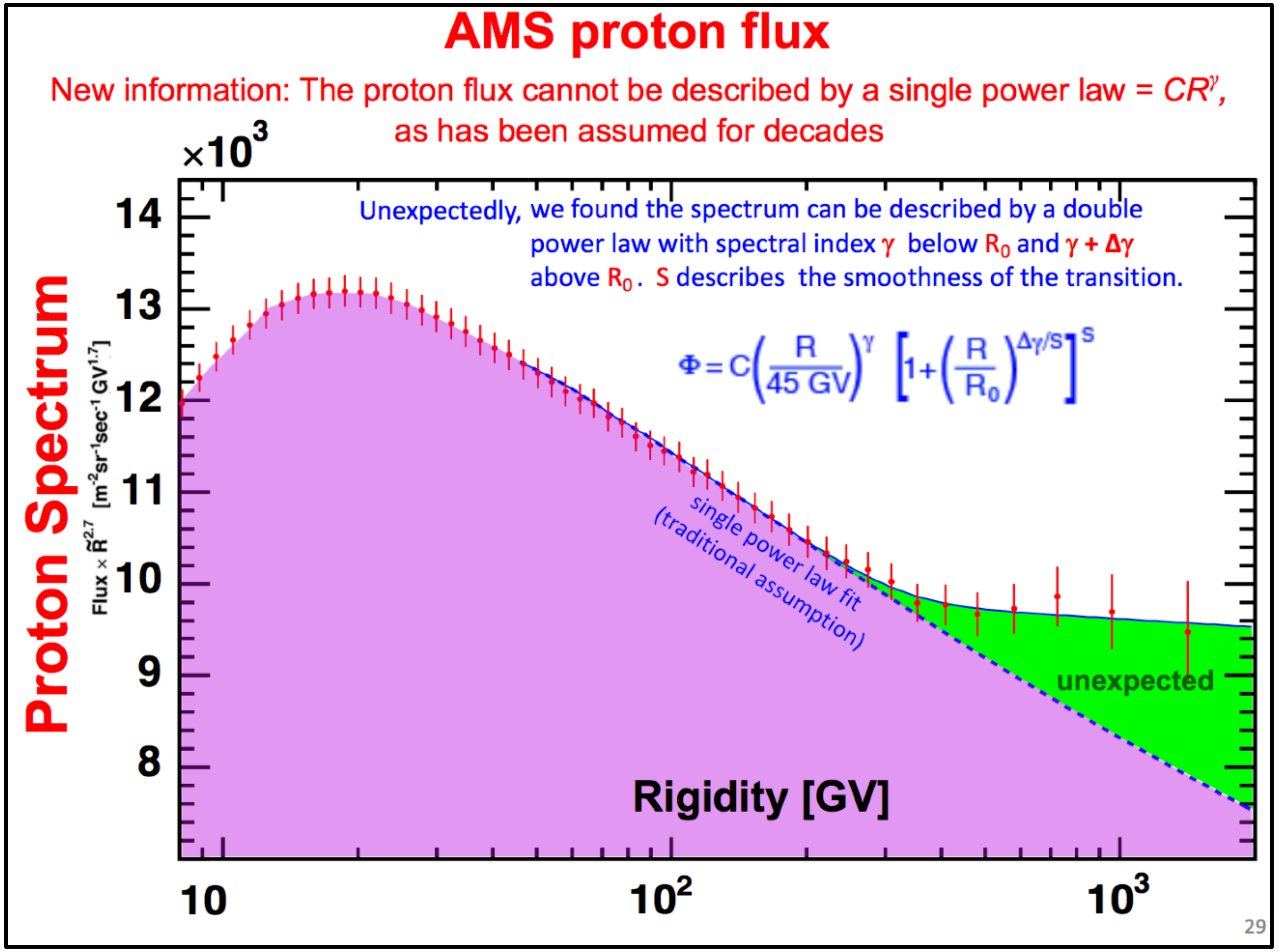

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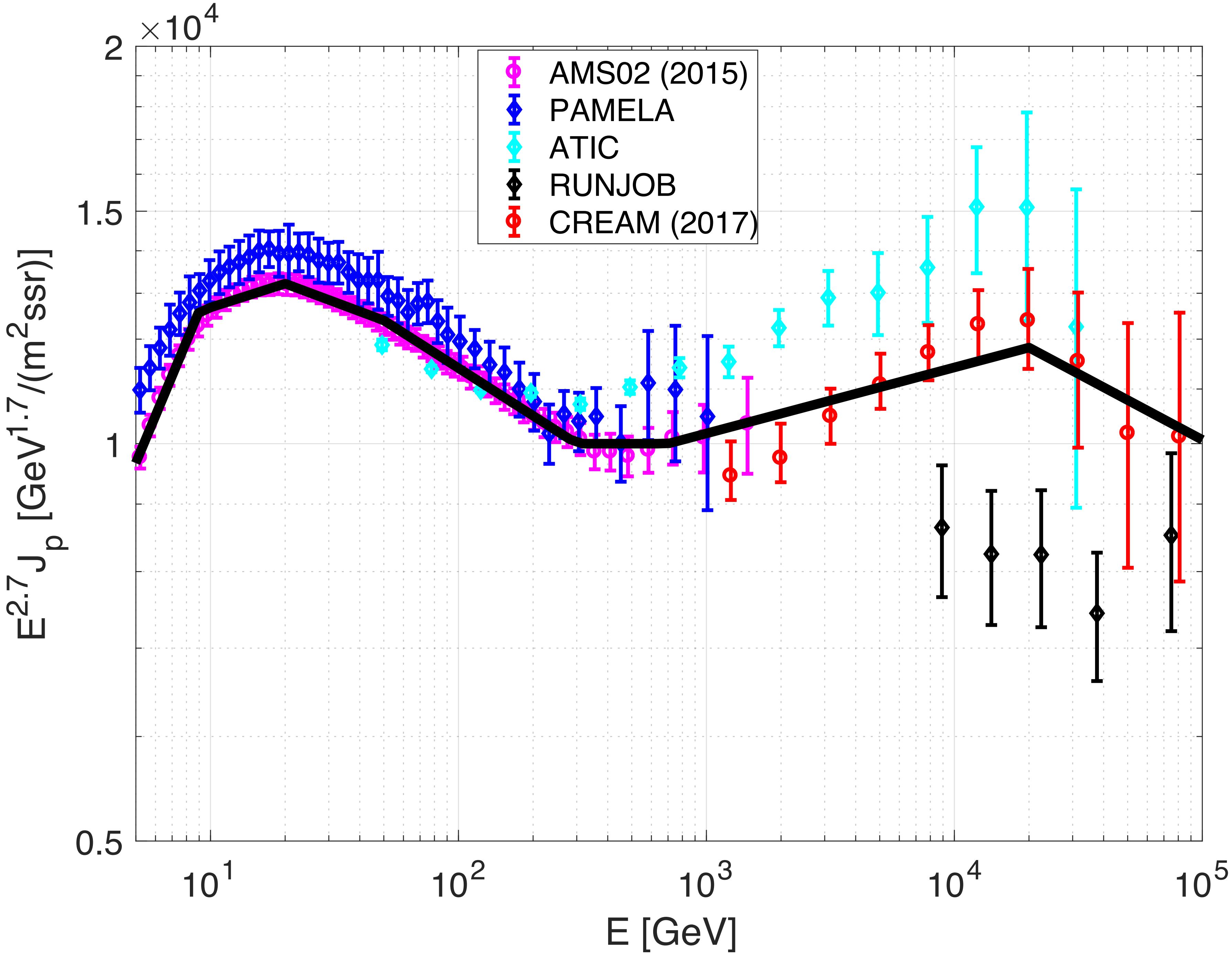
CREAM-III (2017)

ApJ, 839:5 (8pp), 2017 April 10



$$\frac{n_{e^+}}{n_{\bar{p}}} = f_{e^+}(\mathcal{R}) \frac{Q_{e^+}(\mathcal{R})}{Q_{\bar{p}}(\mathcal{R})}$$

A more robust derivation:

Relate e+ to pbar

Rather than directly to B/C

$$\frac{n_{e^+}}{n_{\bar{p}}} = f_{e^+}(\mathcal{R}) \frac{Q_{e^+}(\mathcal{R})}{Q_{\bar{p}}(\mathcal{R})}$$

Secondary upper bound

$$f_{e^+}(\mathcal{R}) \leq 1$$

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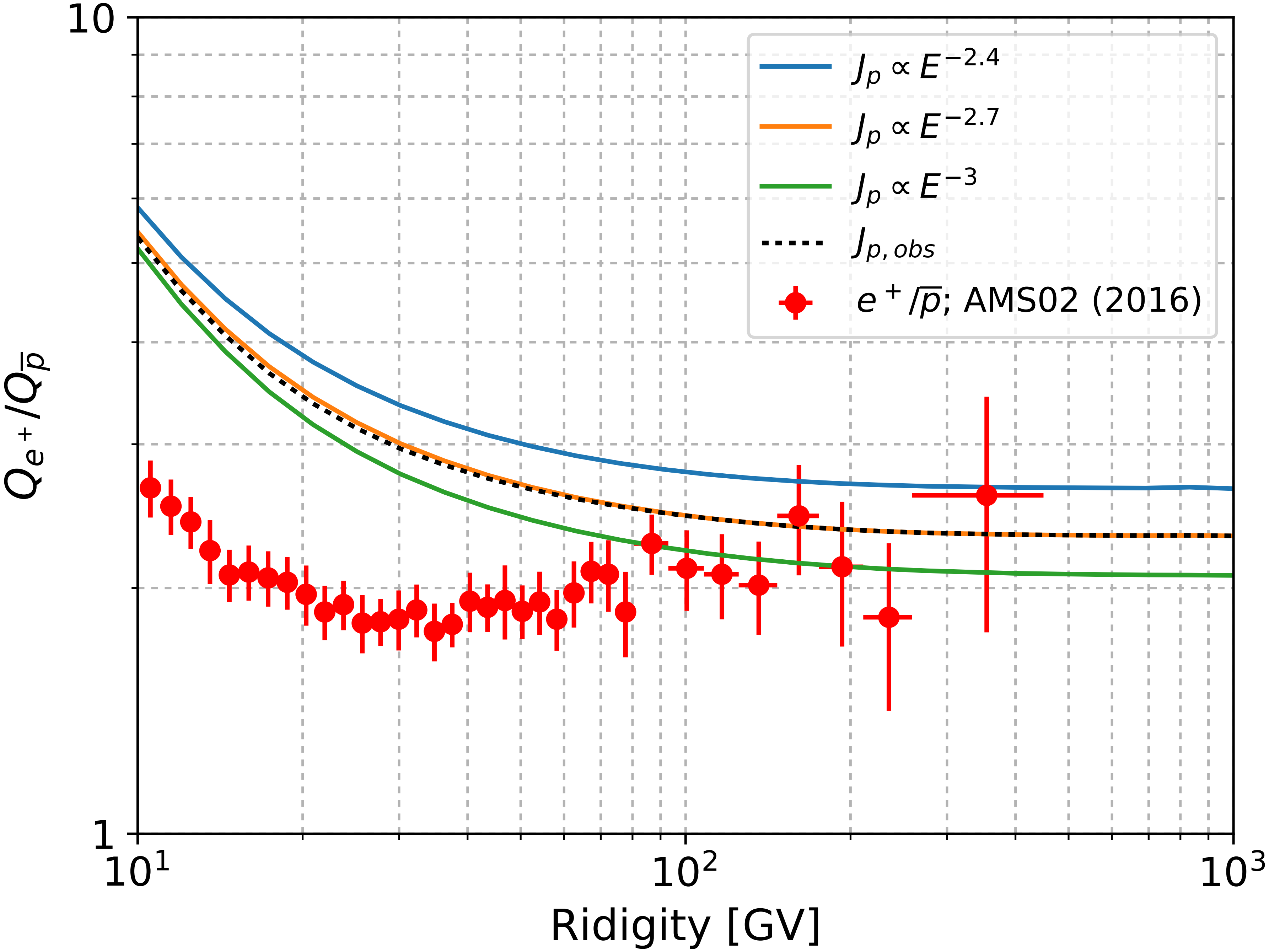
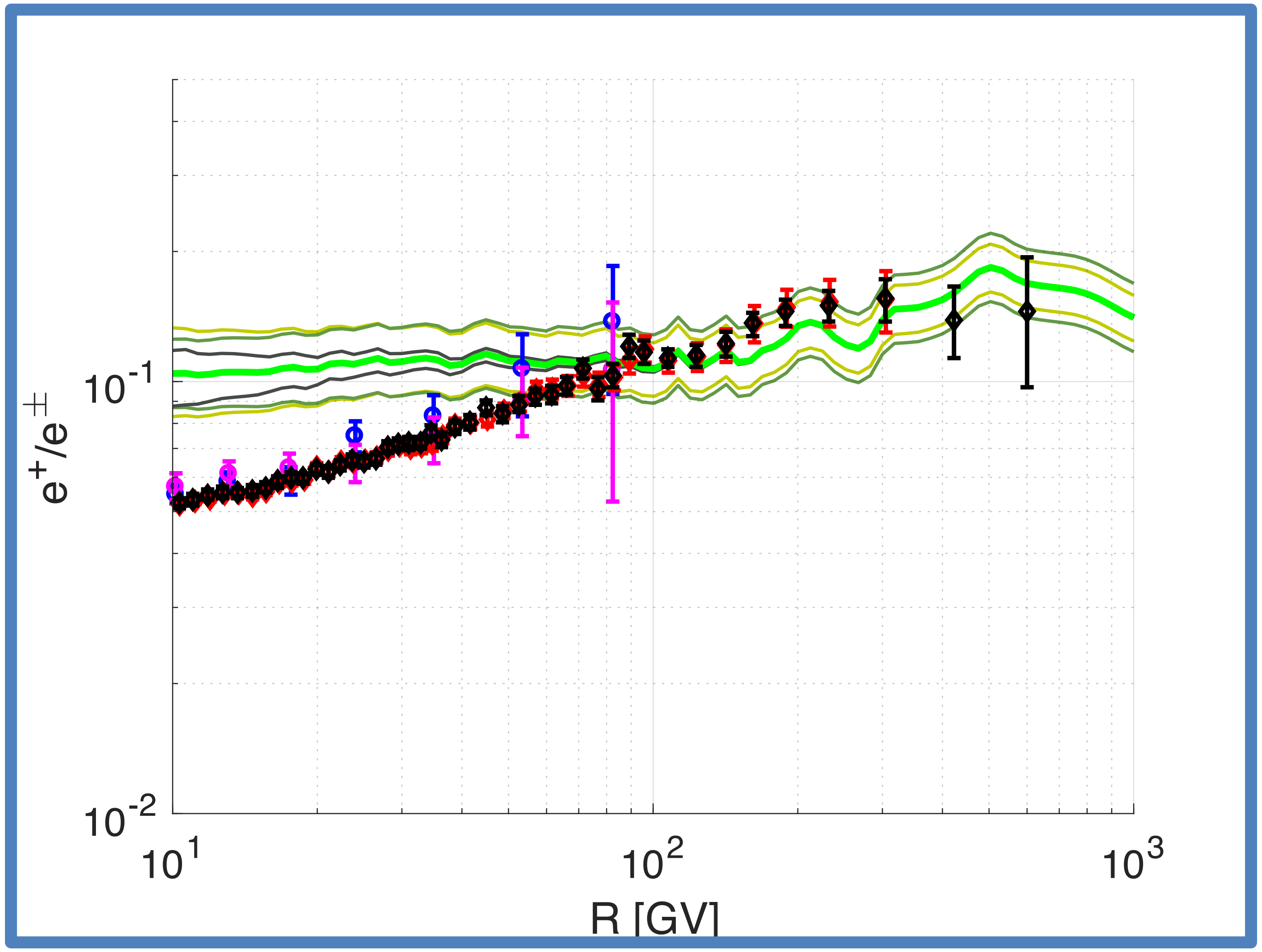


Why would dark matter or pulsars inject ***this*** e+ flux?



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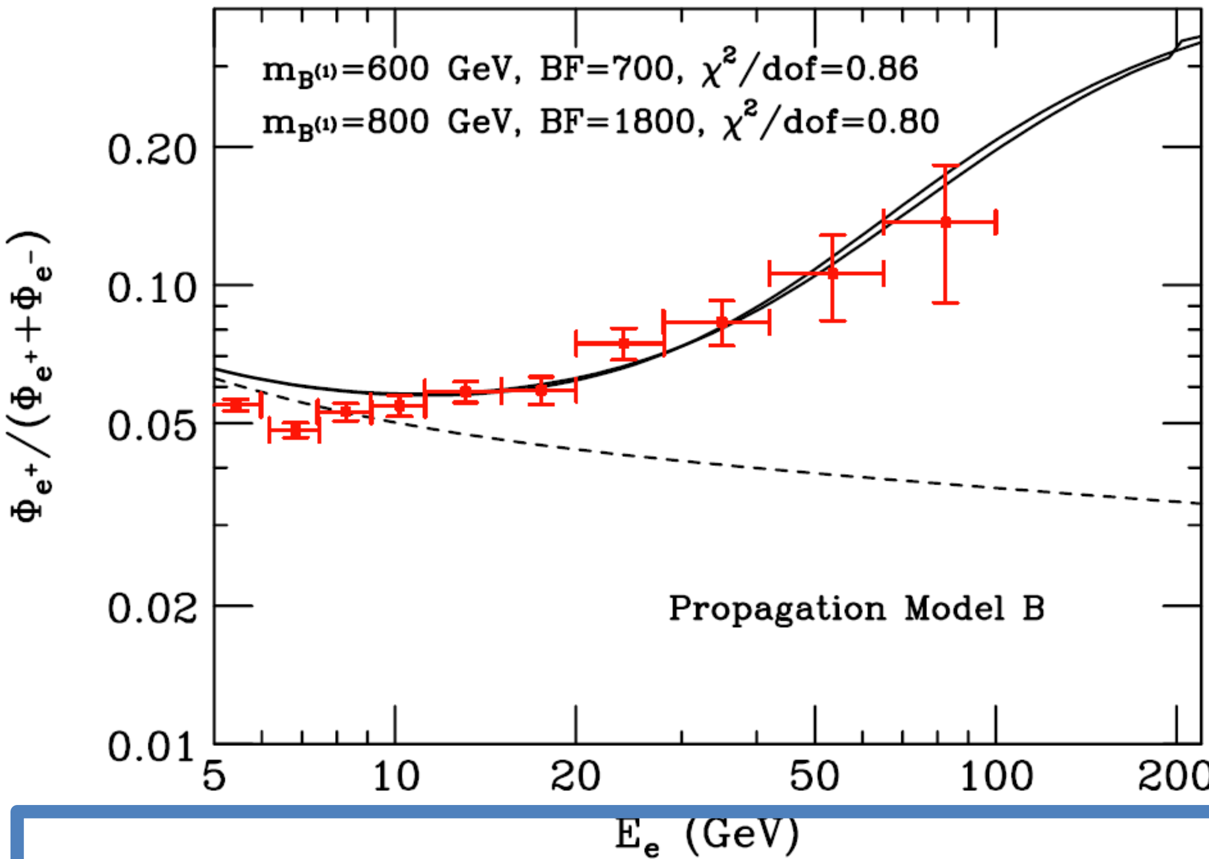

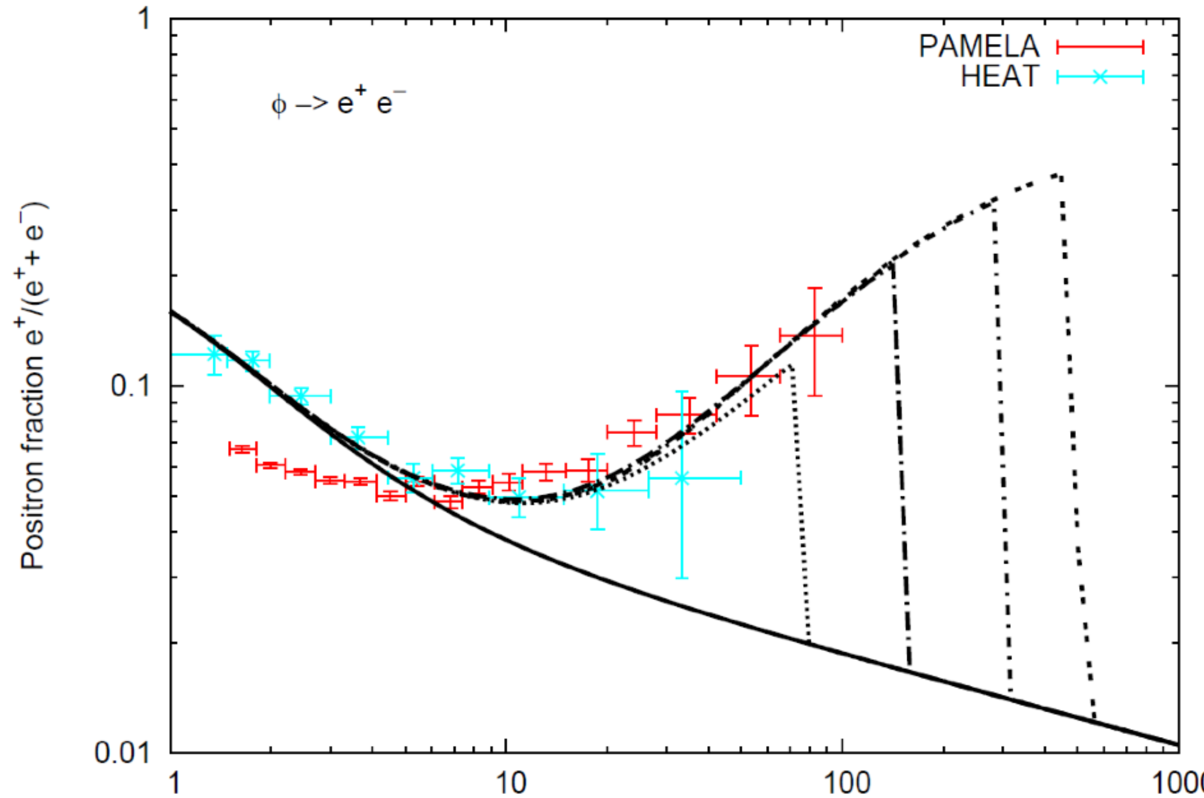

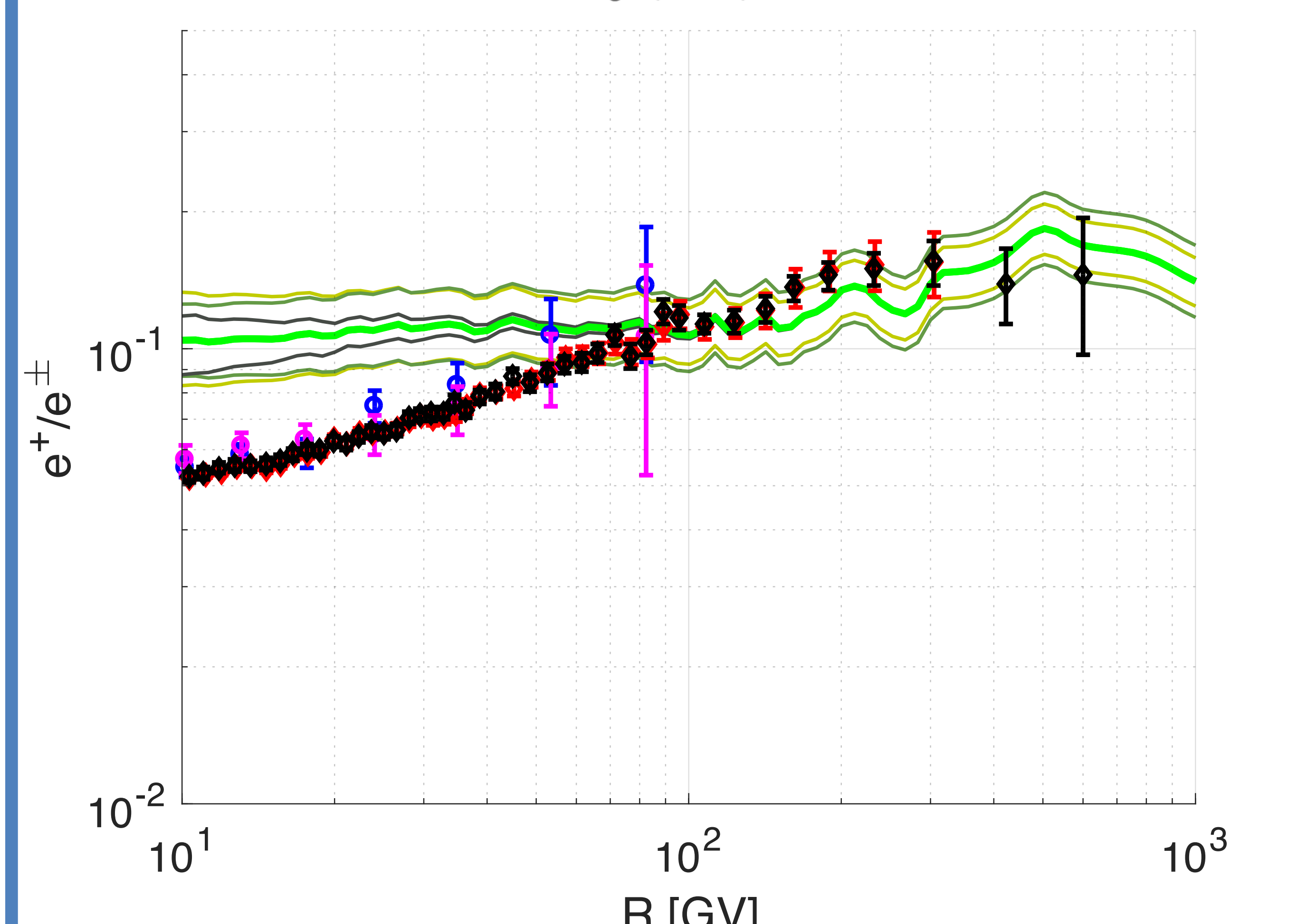

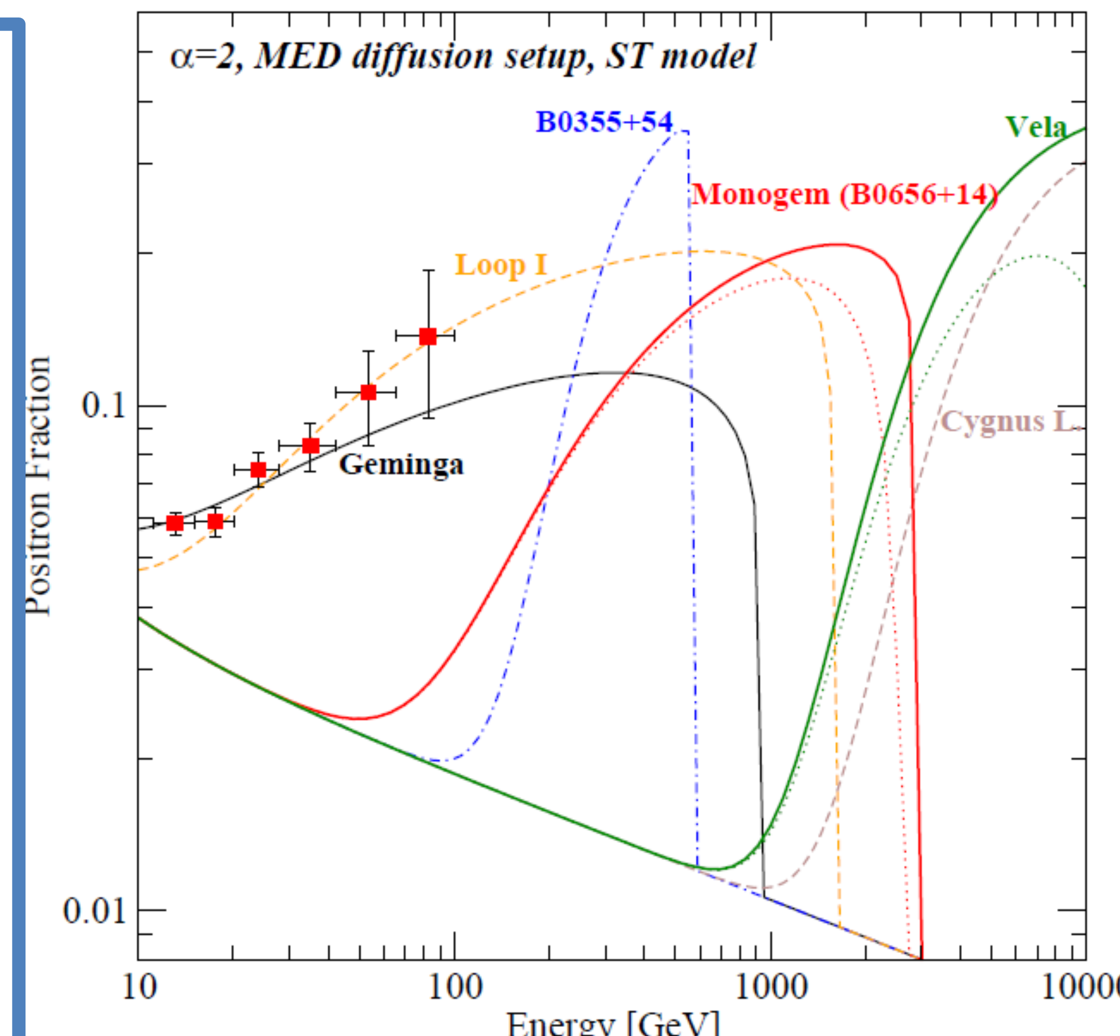

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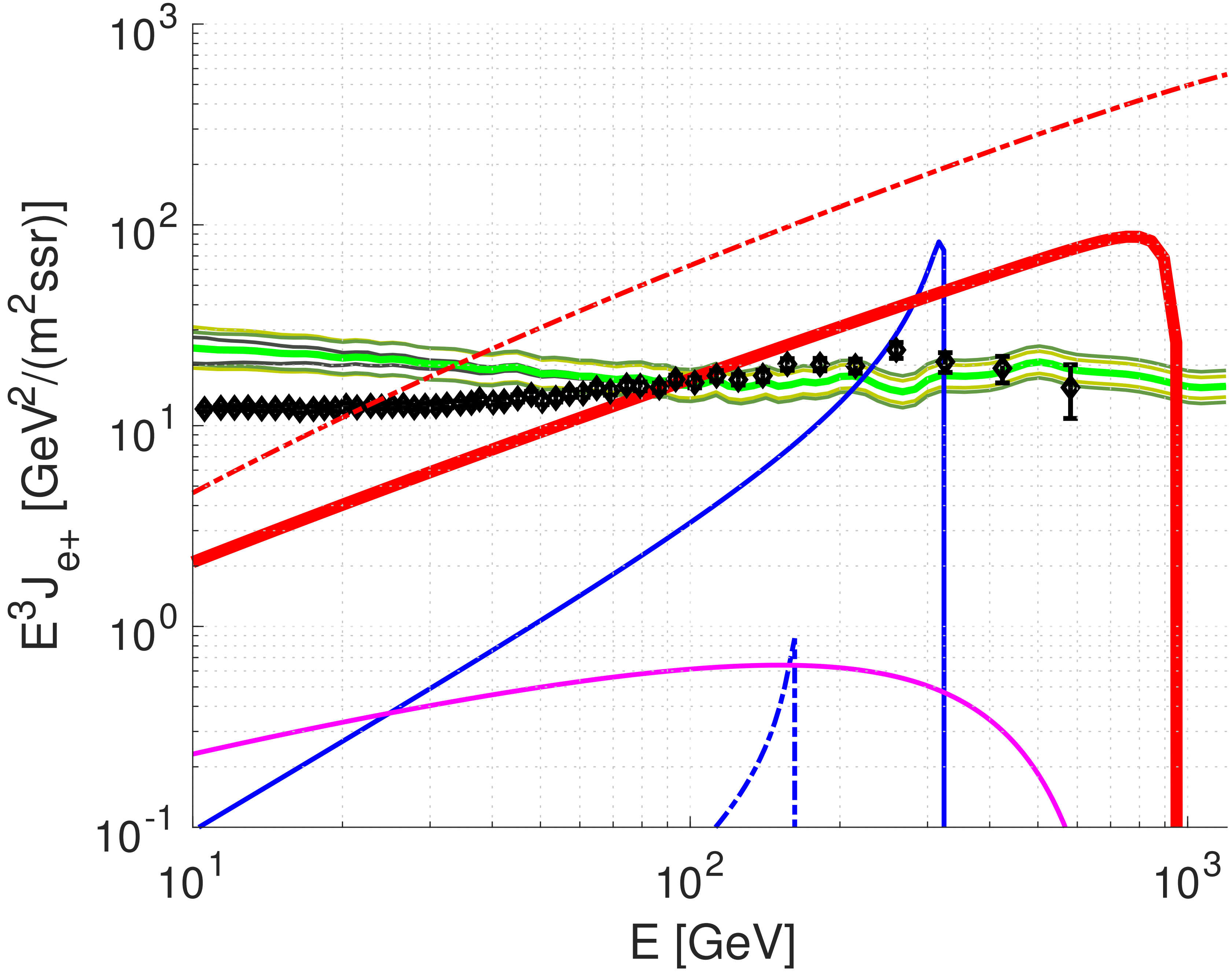

Pulsar model: D. Malyshev, I. Cholis, and J. Gelfand, Phys. Rev. **D80**, 063005 (2009)

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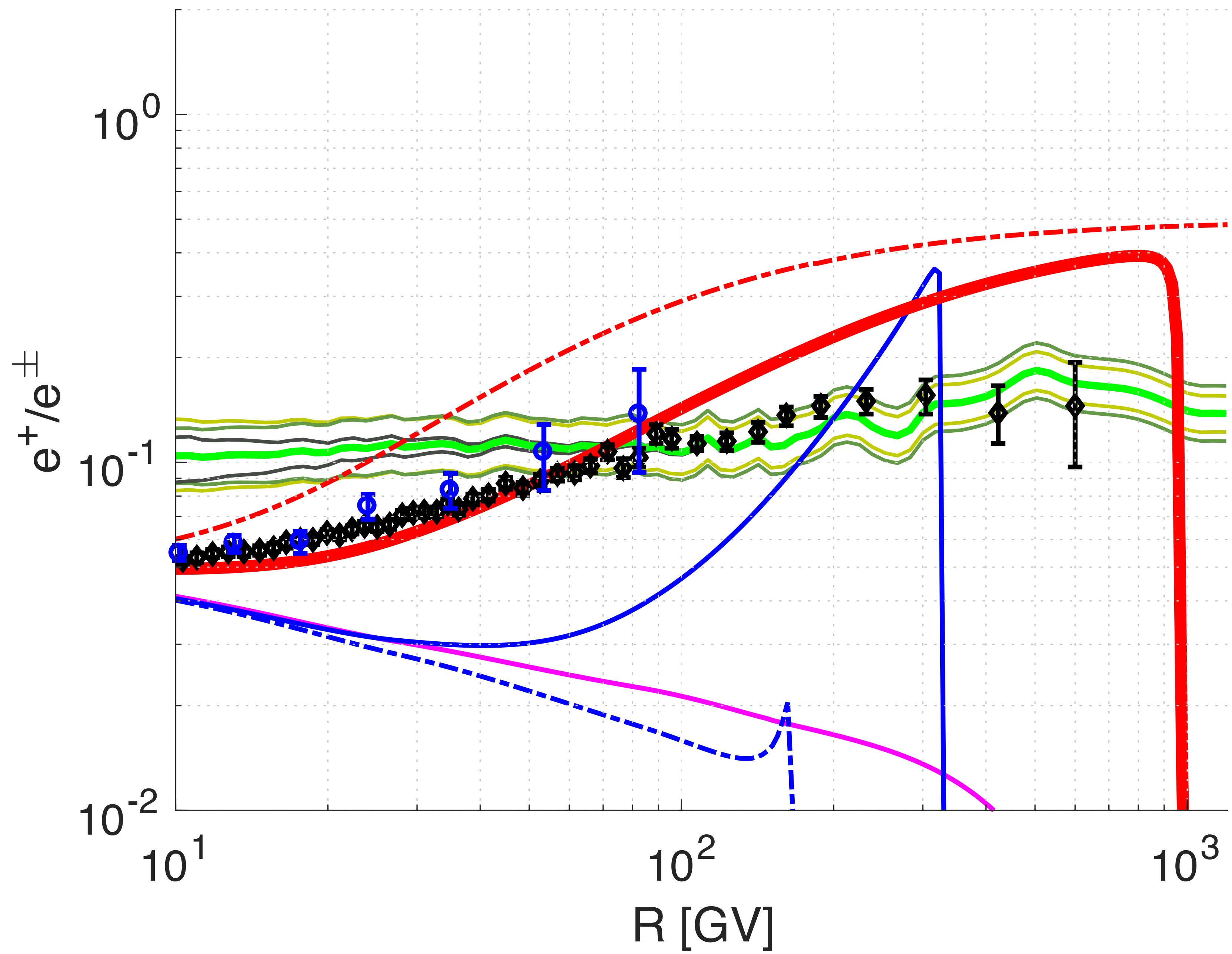

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ALICE 2016, preliminary

Production of light nuclei and anti-nuclei in *pp* and Pb-Pb collisions at energies available at the CERN Large Hadron Collider

J. Adam *et al.* (ALICE Collaboration)
Phys. Rev. C **93**, 024917 – Published 29 February 2016

Production of nuclei and antinuclei in pp and Pb–Pb collisions with ALICE at the LHC

Natasha Sharma (forthe ALICE Collaboration)
Published 10 November 2011 • CERN 2011. Published under licence by IOP Publishing Ltd
Journal of Physics G: Nuclear and Particle Physics, Volume 38, Number 12

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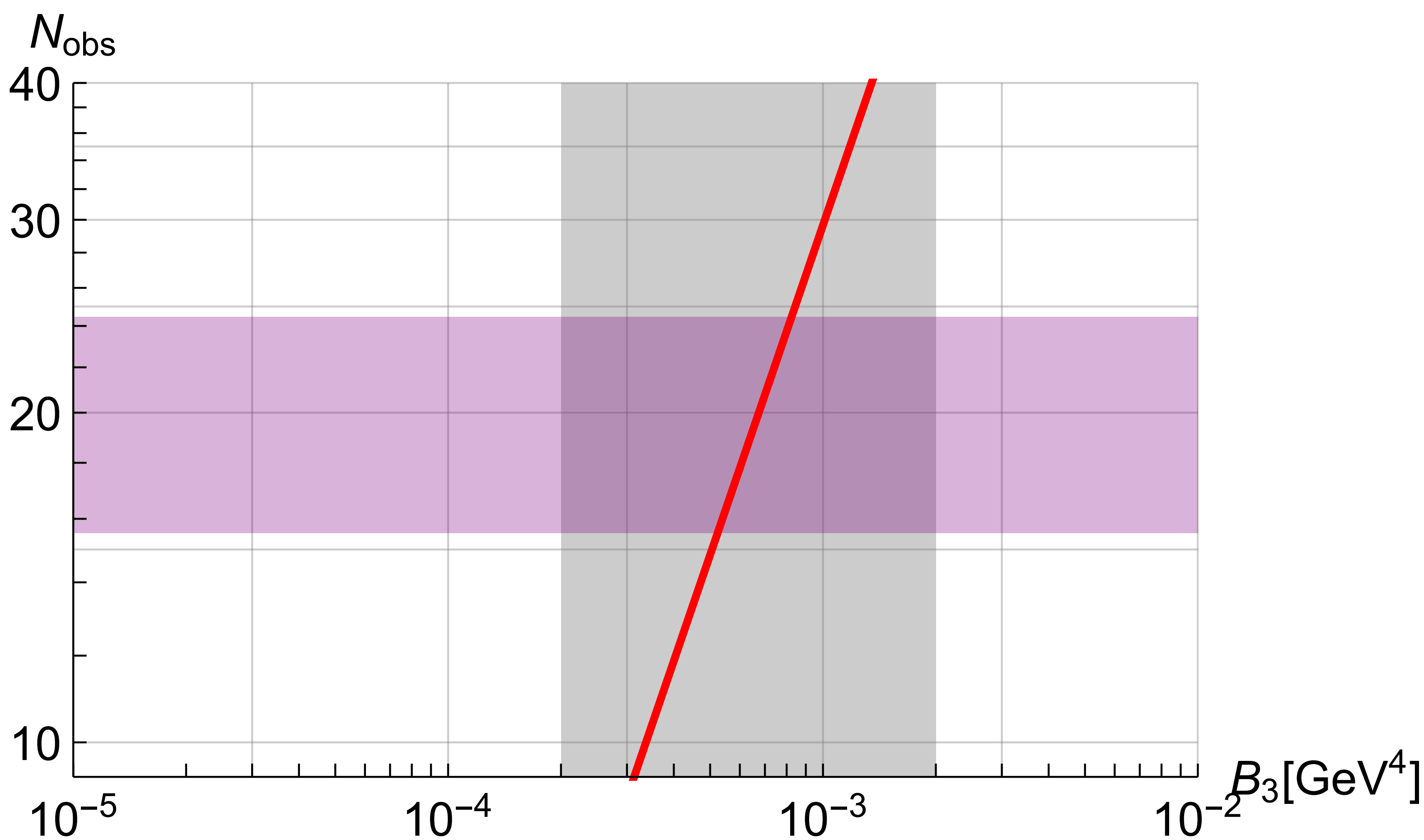

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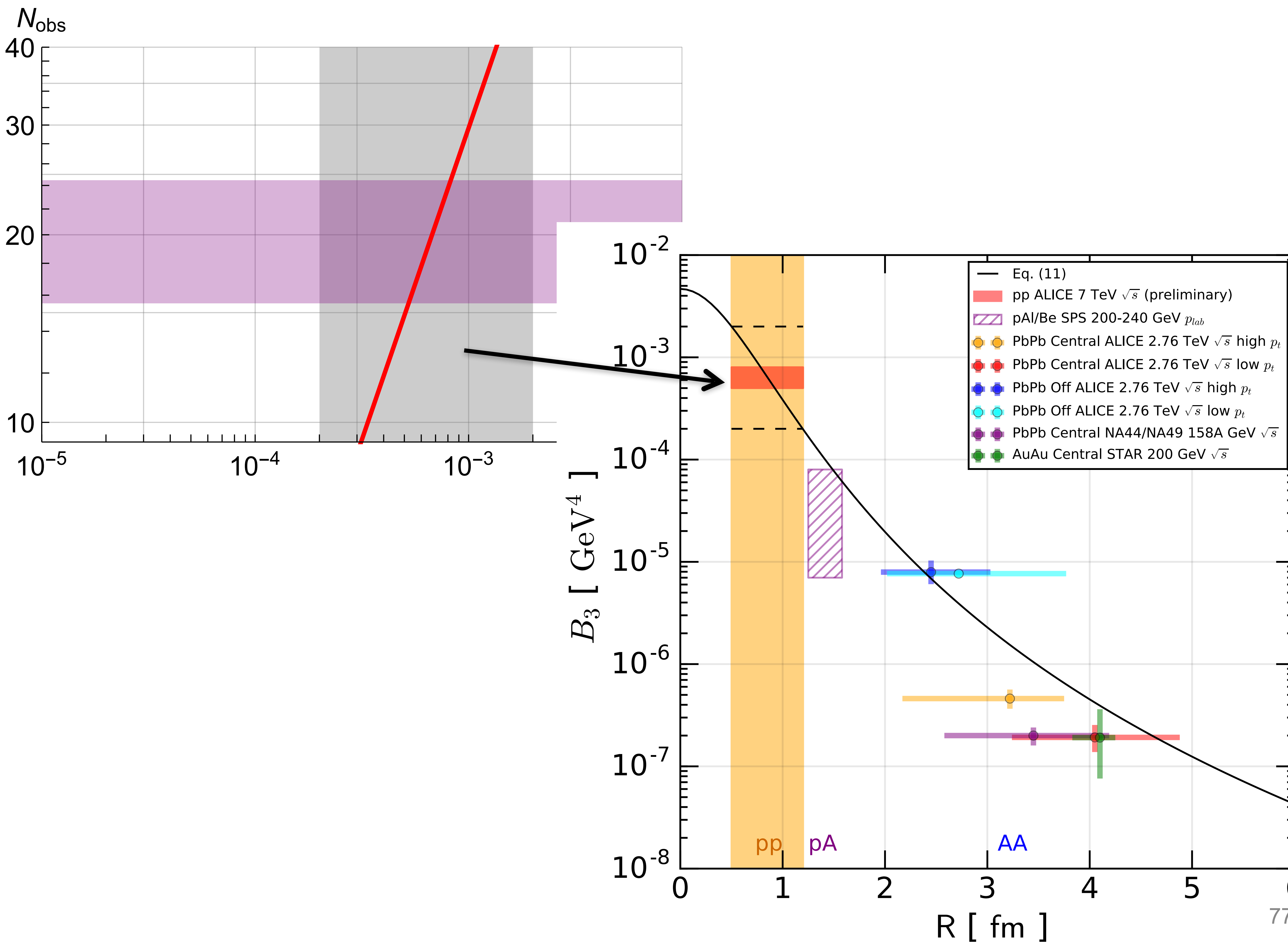
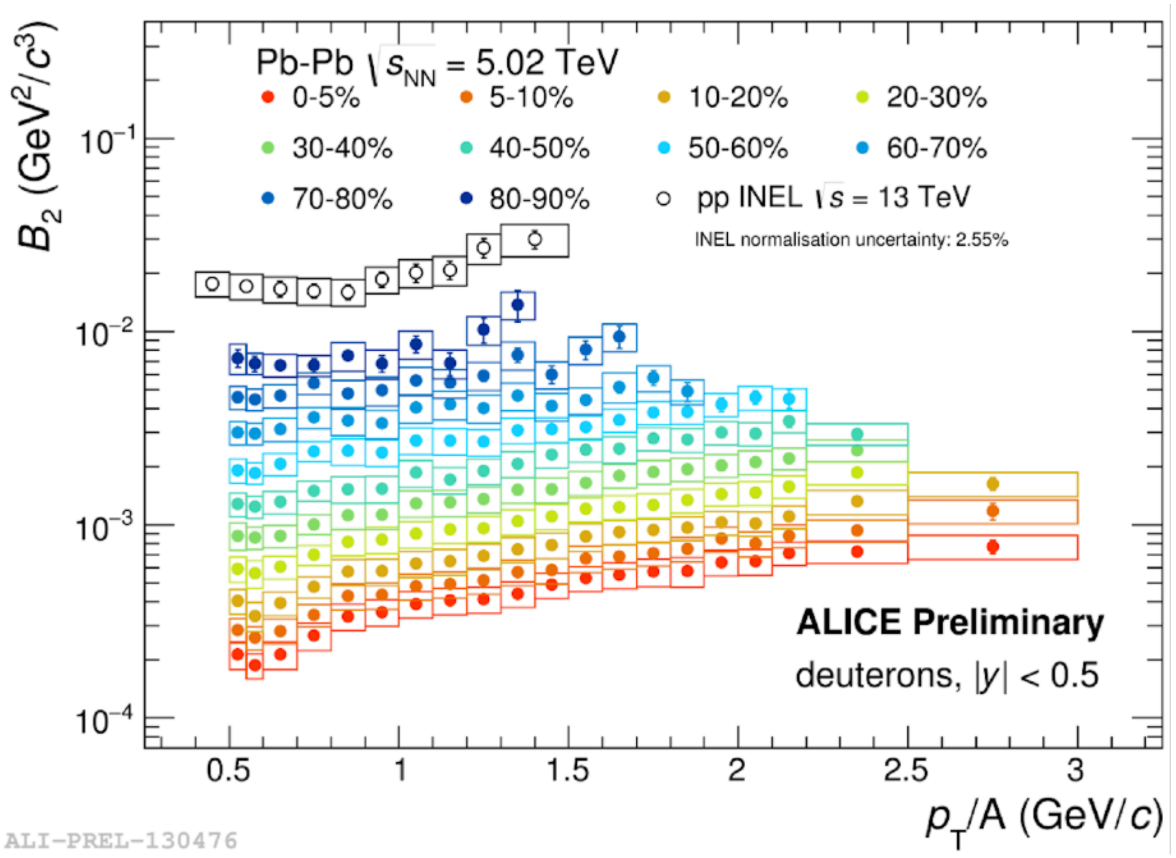


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE-PUBLIC-2017-006

Preliminary Physics Summary:
Deuteron and anti-deuteron production in pp collisions at $\sqrt{s}$ = 13 TeV and in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE 2017



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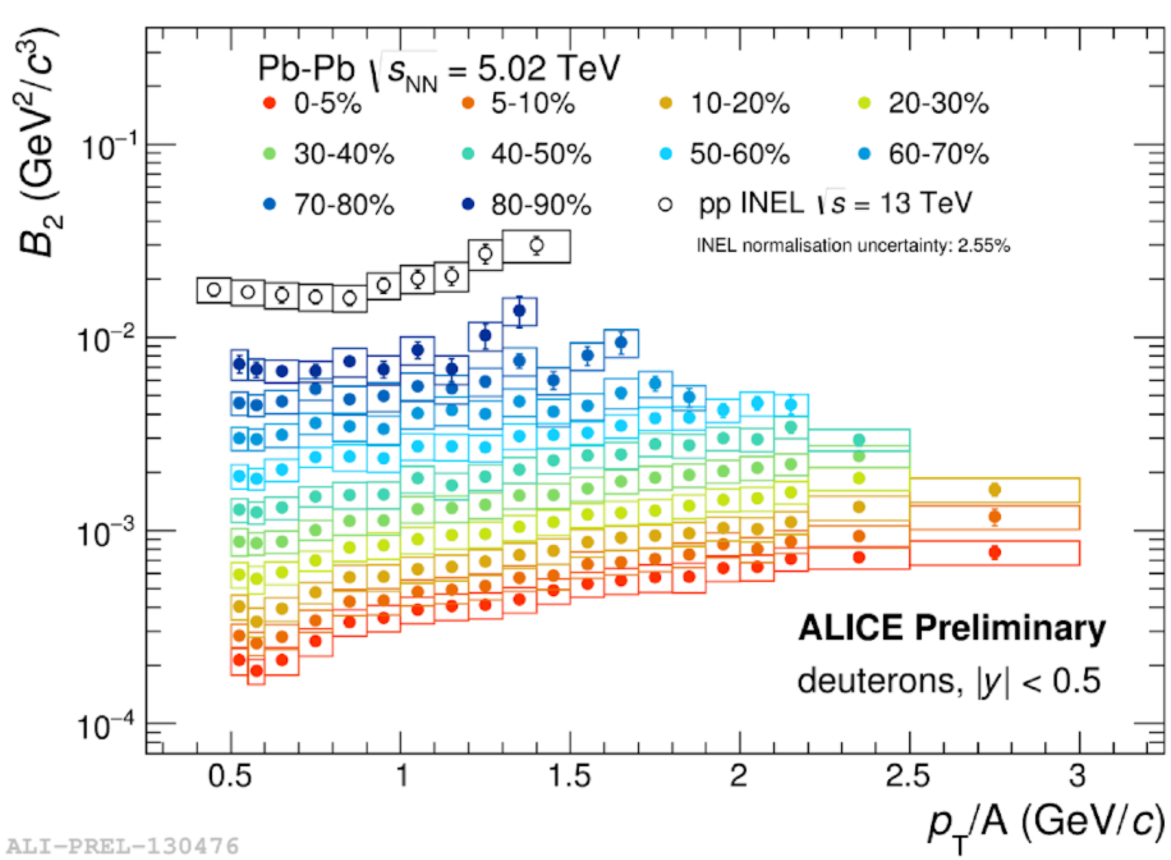
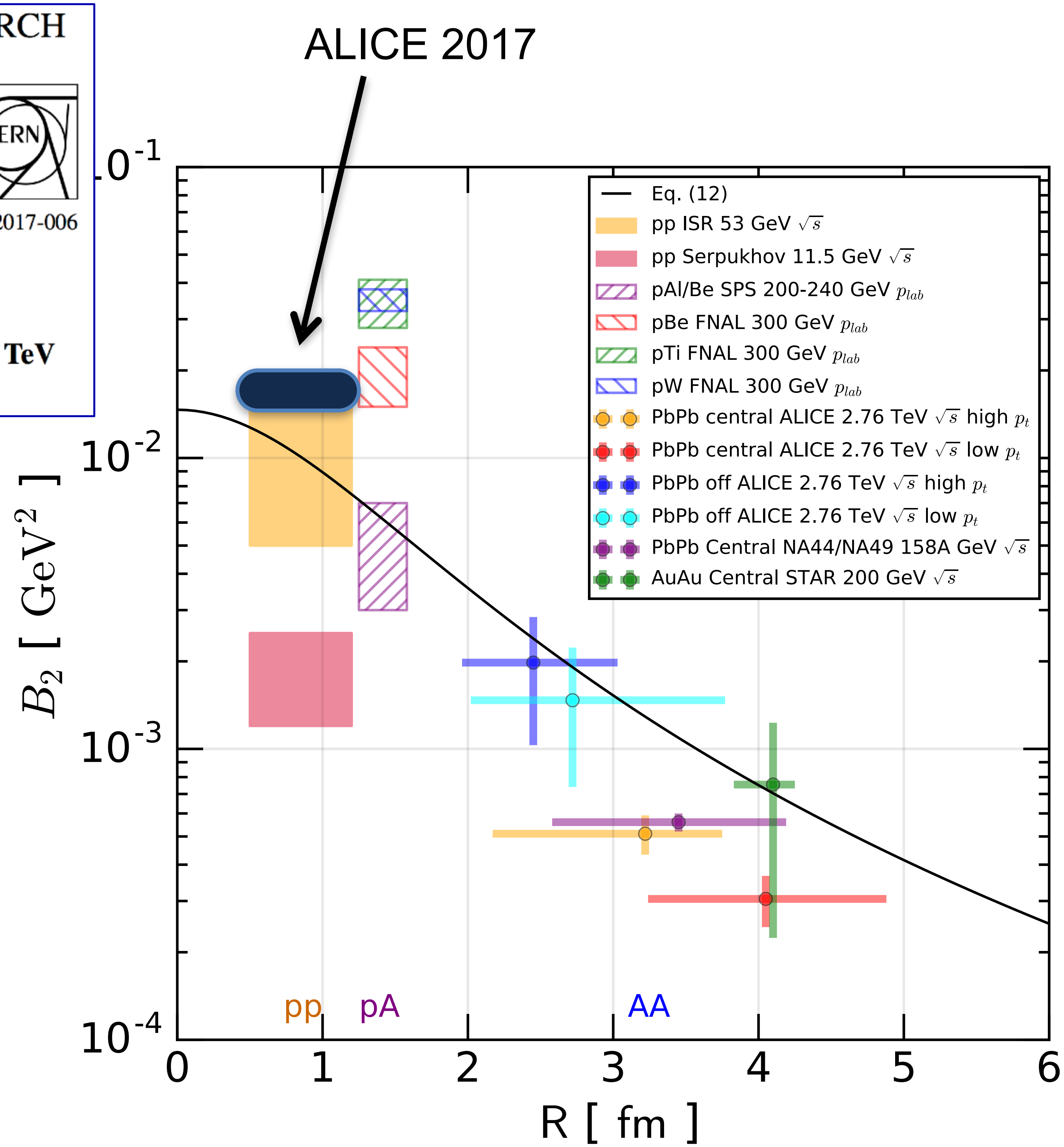
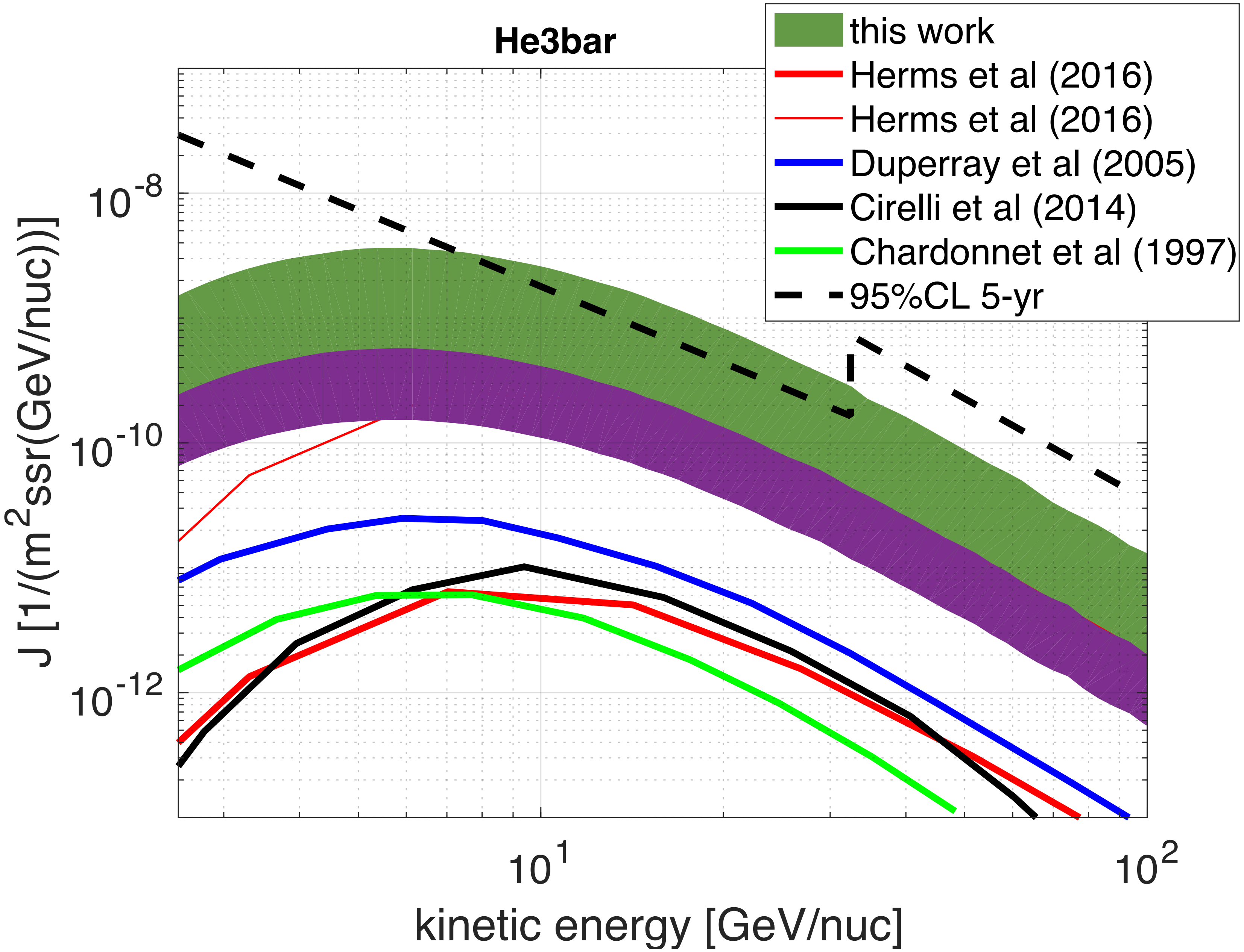
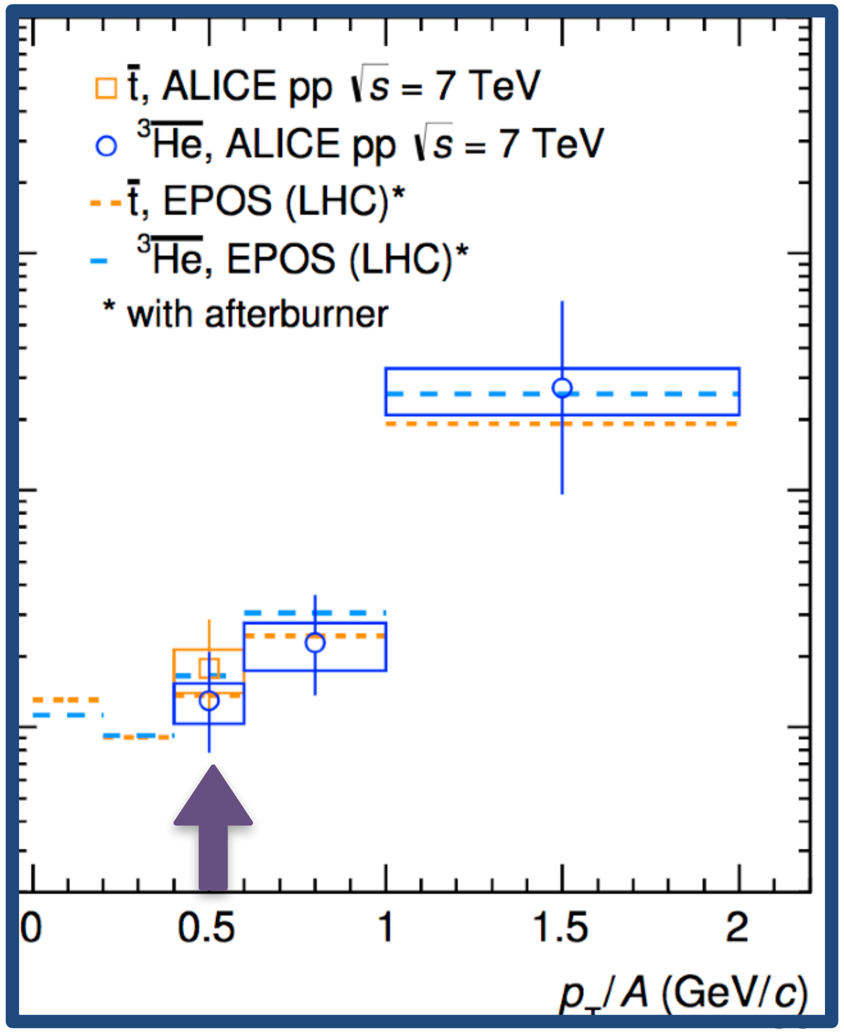




Implication of ALICE results for astrophysics.

He3bar: secondary production by pp collisions
unlikely to explain 1 event/yr at AMS02.





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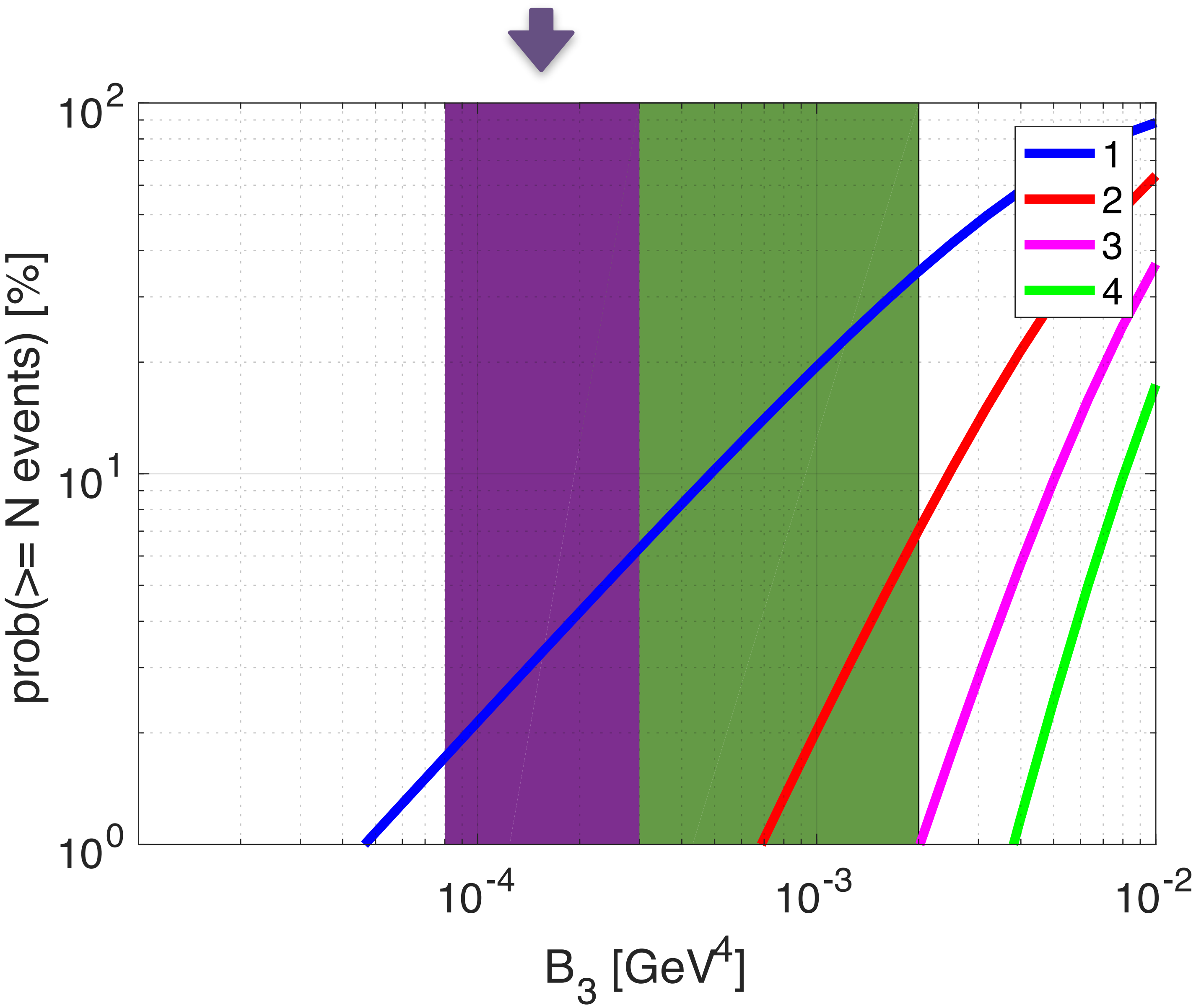
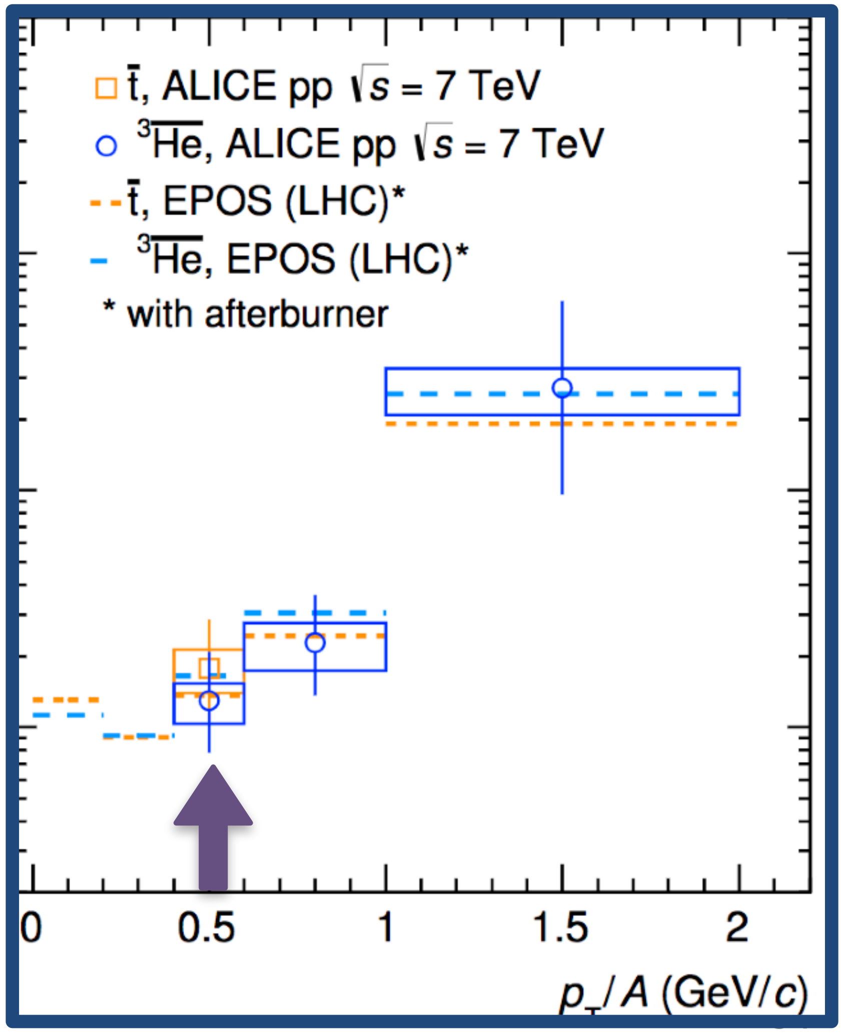
1 event/5yr we could live with, but 1 event/yr seems unlikely.

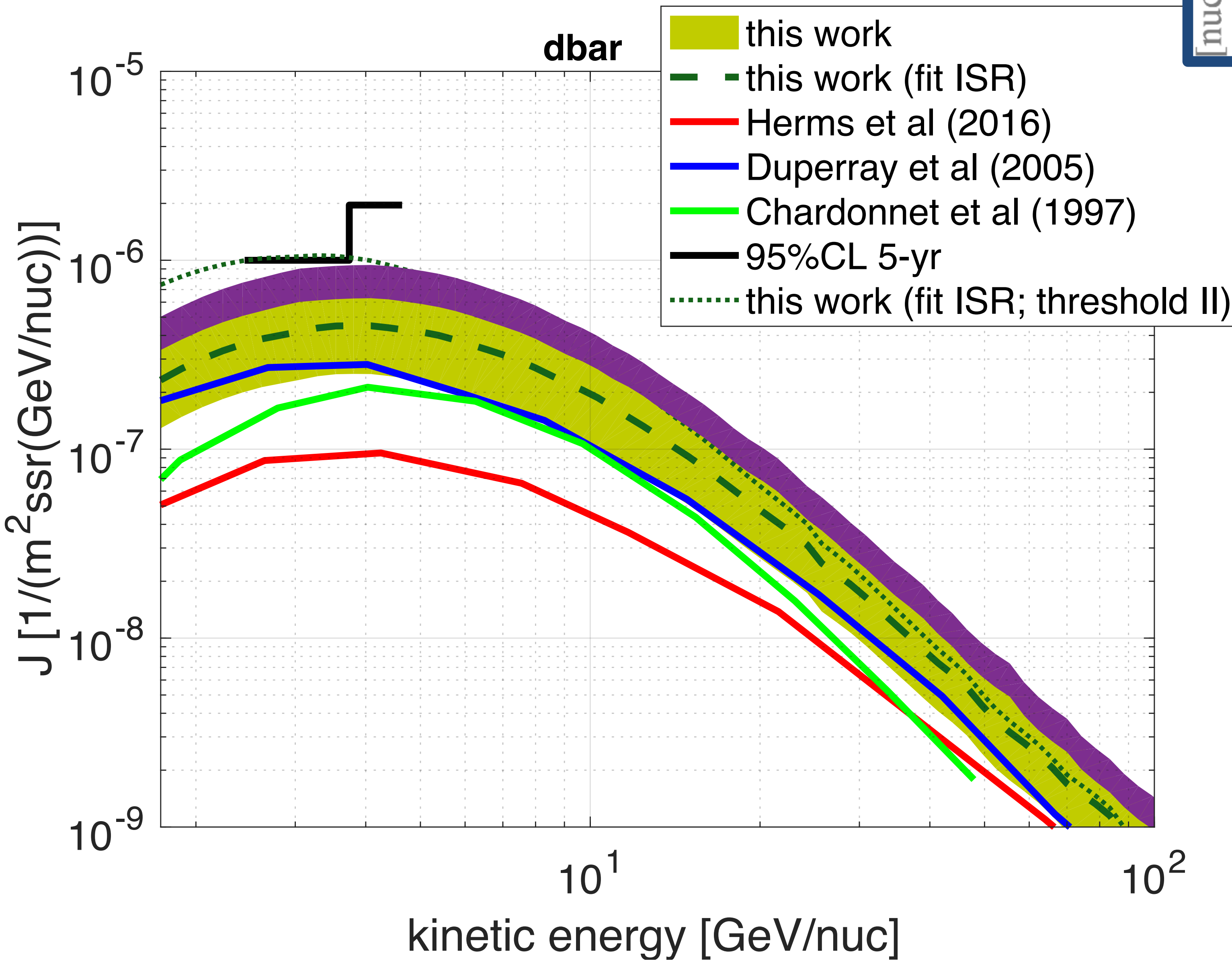
What about p-pbar collisions?

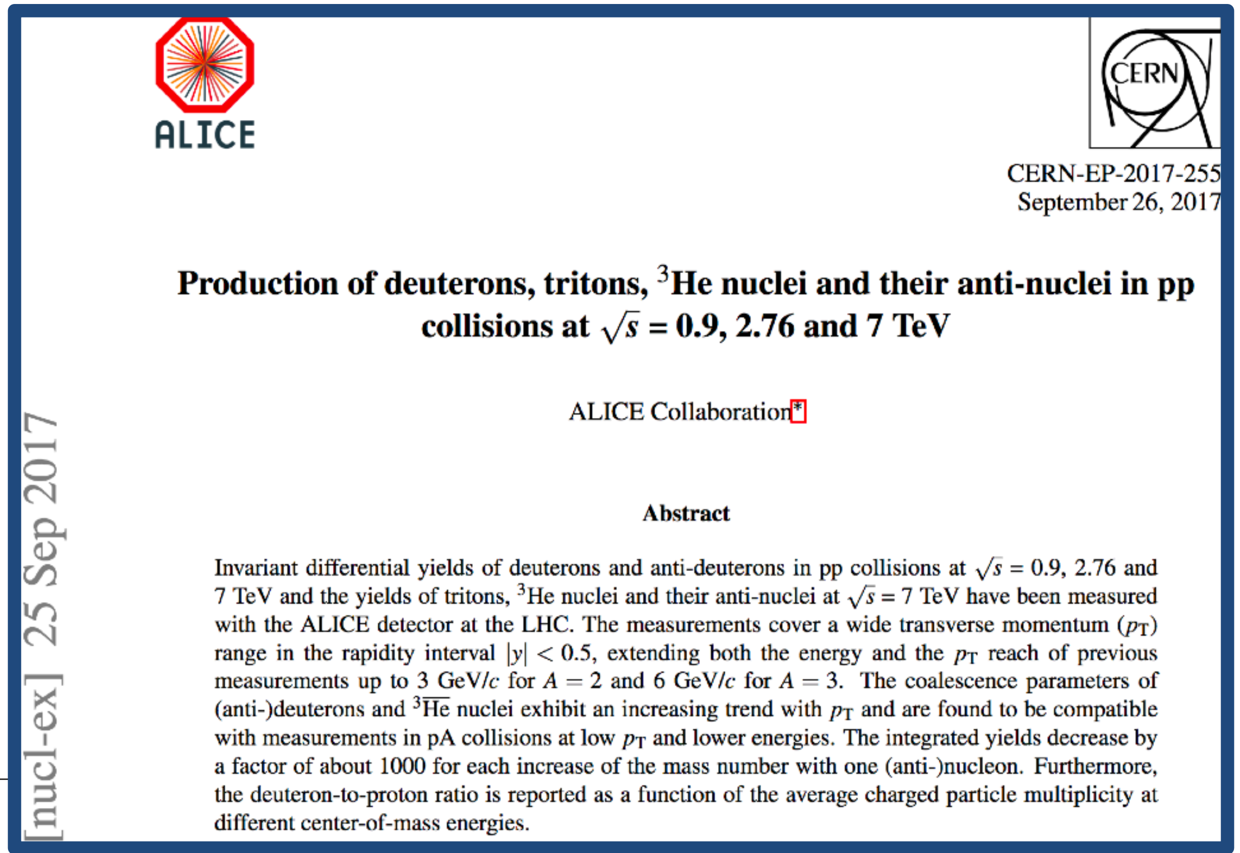




Implication of ALICE results for astrophysics.

Secondary production by pp collisions **may** be seen at AMS02 5yr exposure.





ALICE

CERN

CERN-EP-2017-255
September 26, 2017

[nucl-ex] 25 Sep 2017

Production of deuterons, tritons, ^{3}He nuclei and their anti-nuclei in pp collisions at $\sqrt{s}$ = 0.9, 2.76 and 7 TeV

ALICE Collaboration*

Abstract

Invariant differential yields of deuterons and anti-deuterons in pp collisions at $\sqrt{s}$ = 0.9, 2.76 and 7 TeV and the yields of tritons, ^{3}He nuclei and their anti-nuclei at $\sqrt{s}$ = 7 TeV have been measured with the ALICE detector at the LHC. The measurements cover a wide transverse momentum (p_T) range in the rapidity interval $|y| < 0.5$, extending both the energy and the p_T reach of previous measurements up to 3 GeV/c for $A = 2$ and 6 GeV/c for $A = 3$. The coalescence parameters of (anti-)deuterons and $^3\overline{He}$ nuclei exhibit an increasing trend with p_T and are found to be compatible with measurements in pA collisions at low p_T and lower energies. The integrated yields decrease by a factor of about 1000 for each increase of the mass number with one (anti-)nucleon. Furthermore, the deuteron-to-proton ratio is reported as a function of the average charged particle multiplicity at different center-of-mass energies.