What can we learn from cosmic ray antimatter?

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CERN & Weizmann Institute

Work with:
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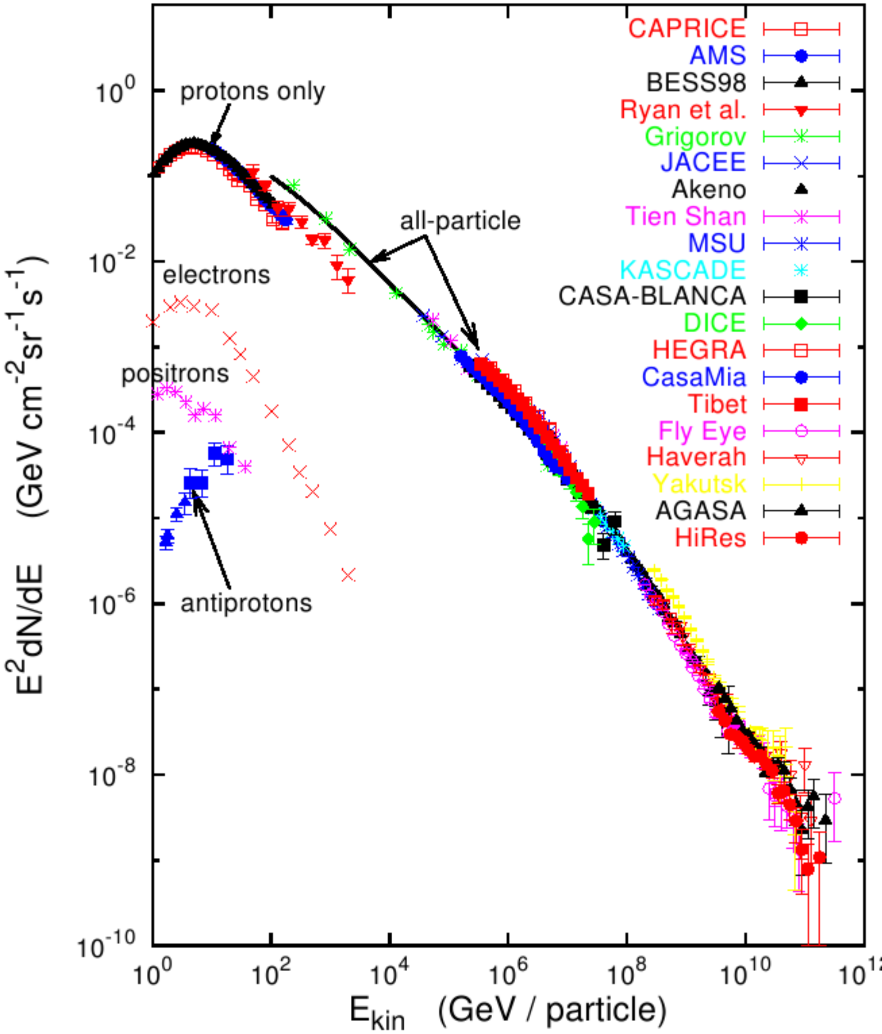
Ryosuke Sato (Weizmann/DESY Hamburg)
Annika Reinert (U. Bonn)

Frankfurt, Feb 2019

Cosmic Rays

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



Hillas, astro-ph/0607109

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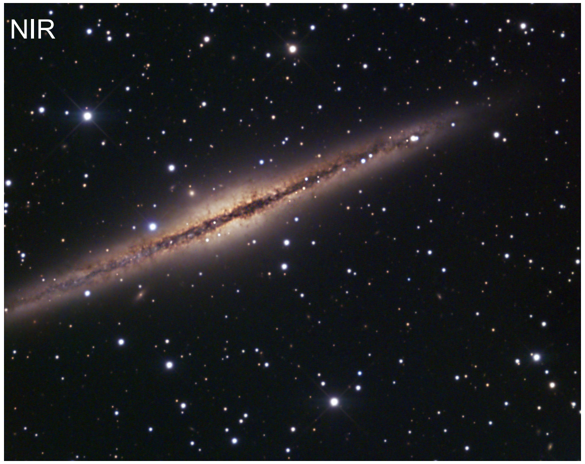

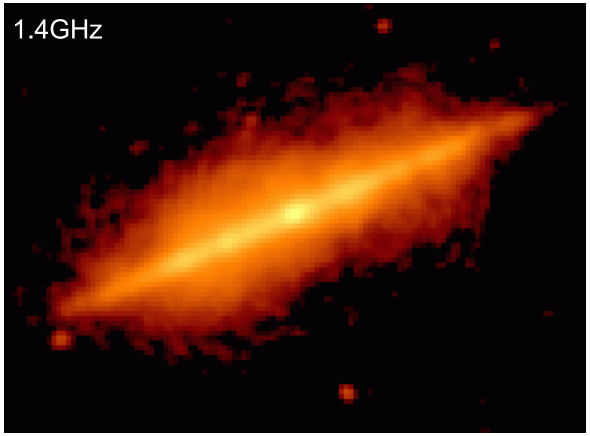

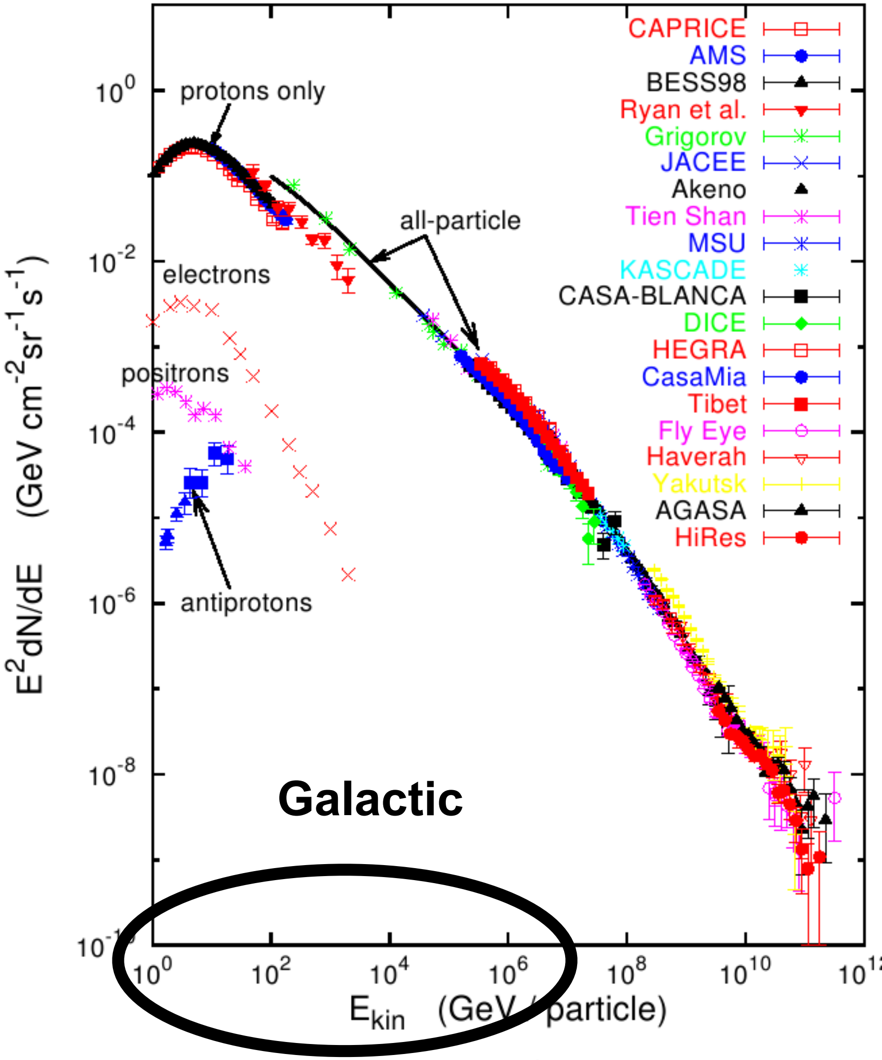

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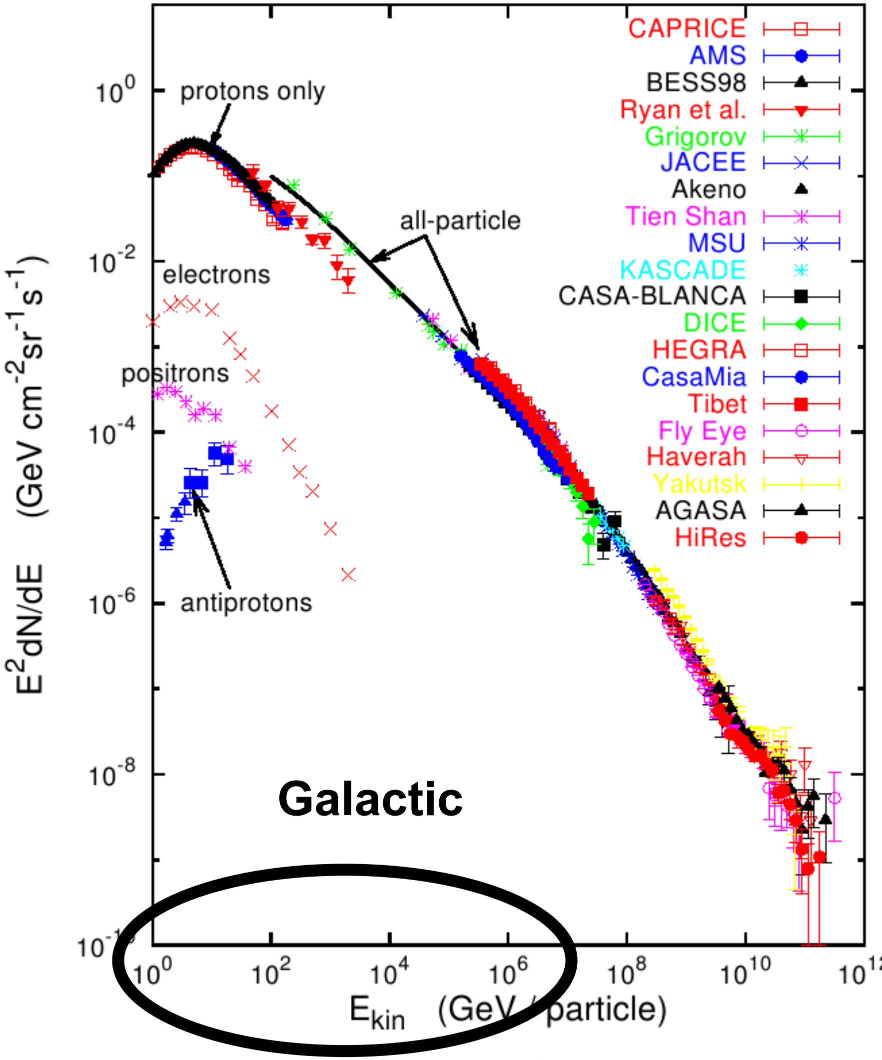
Cosmic Rays

Two basic populations:

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

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



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Two basic populations:

1. **primary** (p, He, C, O, Fe, e-,…), stellar material, accelerated to high energy

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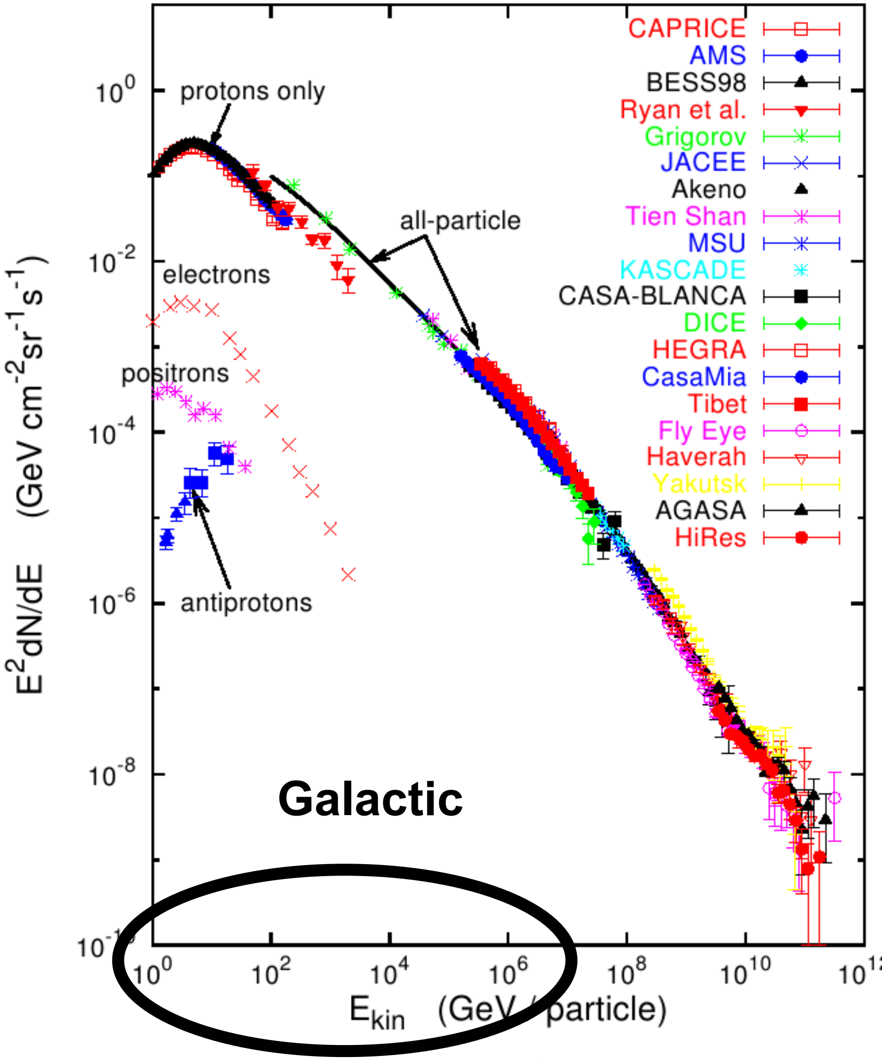

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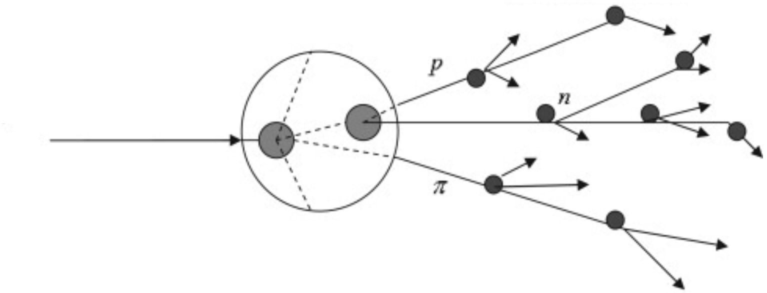

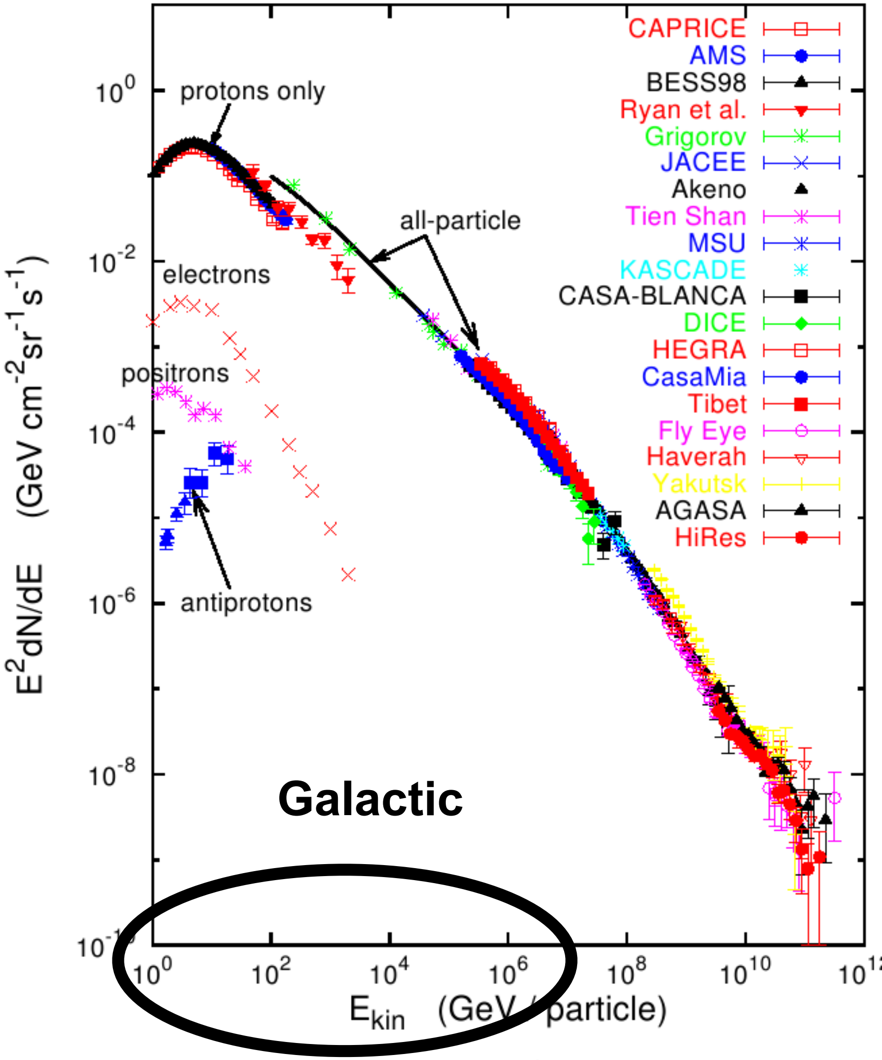

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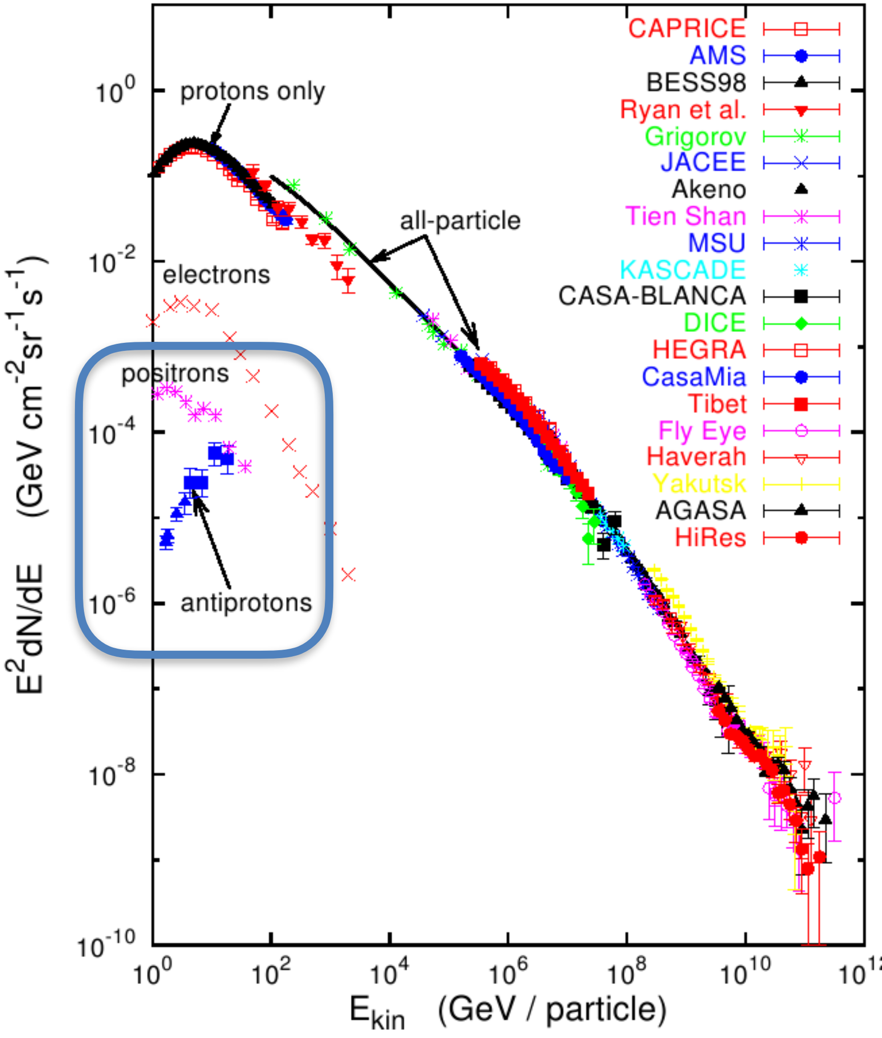
CR antimatter – $\bar{p}$, e^+, $\bar{\mathrm{d}}$, and $\overline{{}^3\mathrm{He}}$ – long thought a smoking gun of exotic high-energy physics like dark matter annihilation



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A host of experiments out there to detect it

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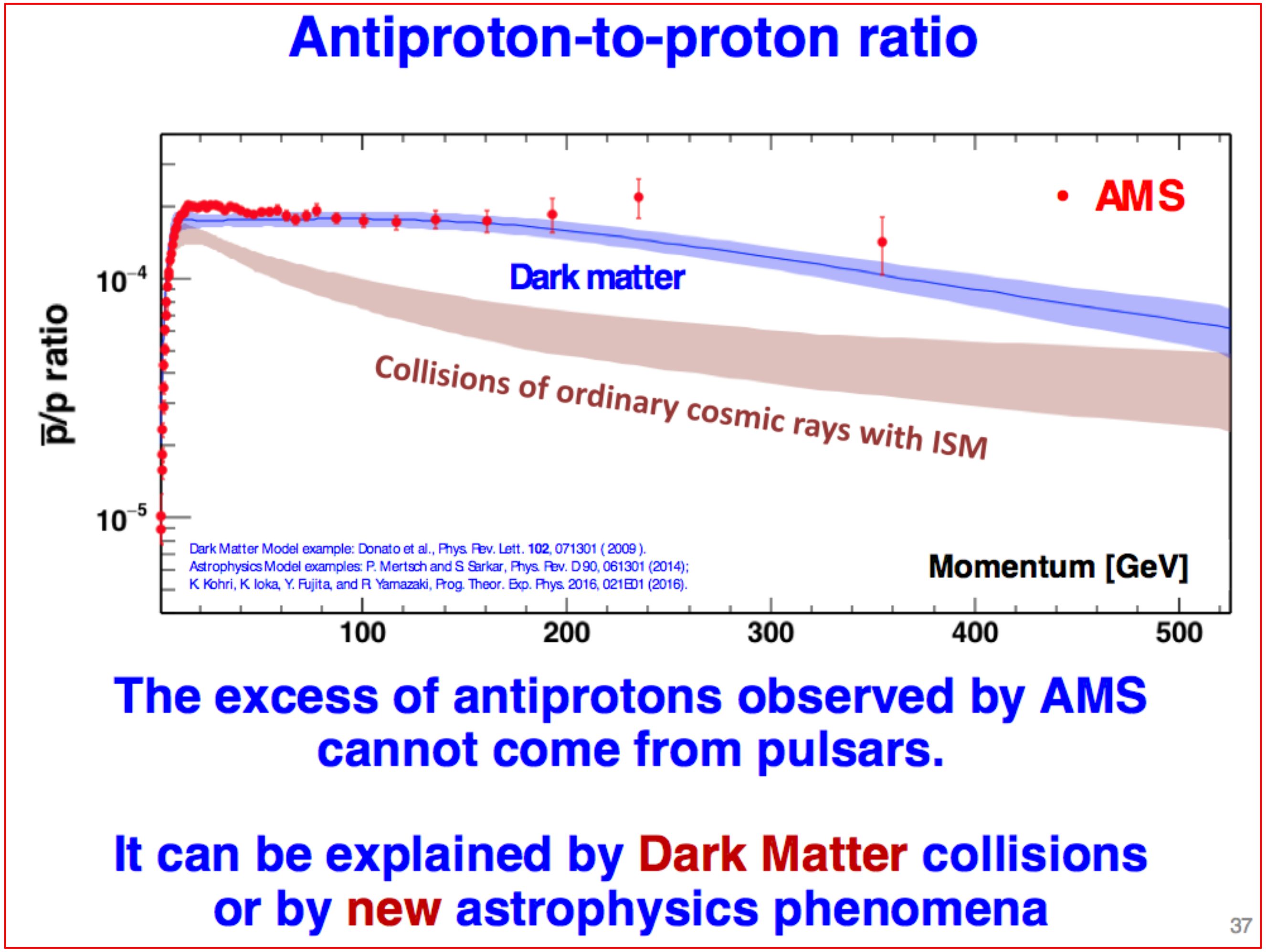
AMS02, Dec 2016



Antiproton-to-proton ratio

Dark Matter Model example: Donato et al., Phys. Rev. Lett. **102**, 071301 (2009).
Astrophysics Model examples: P. Mertsch and S. Sarkar, Phys. Rev. D 90, 061301 (2014);
K. Kohri, K. Ioka, Y. Fujita, and R. Yamazaki, Prog. Theor. Exp. Phys. 2016, 021E01 (2016).

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

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

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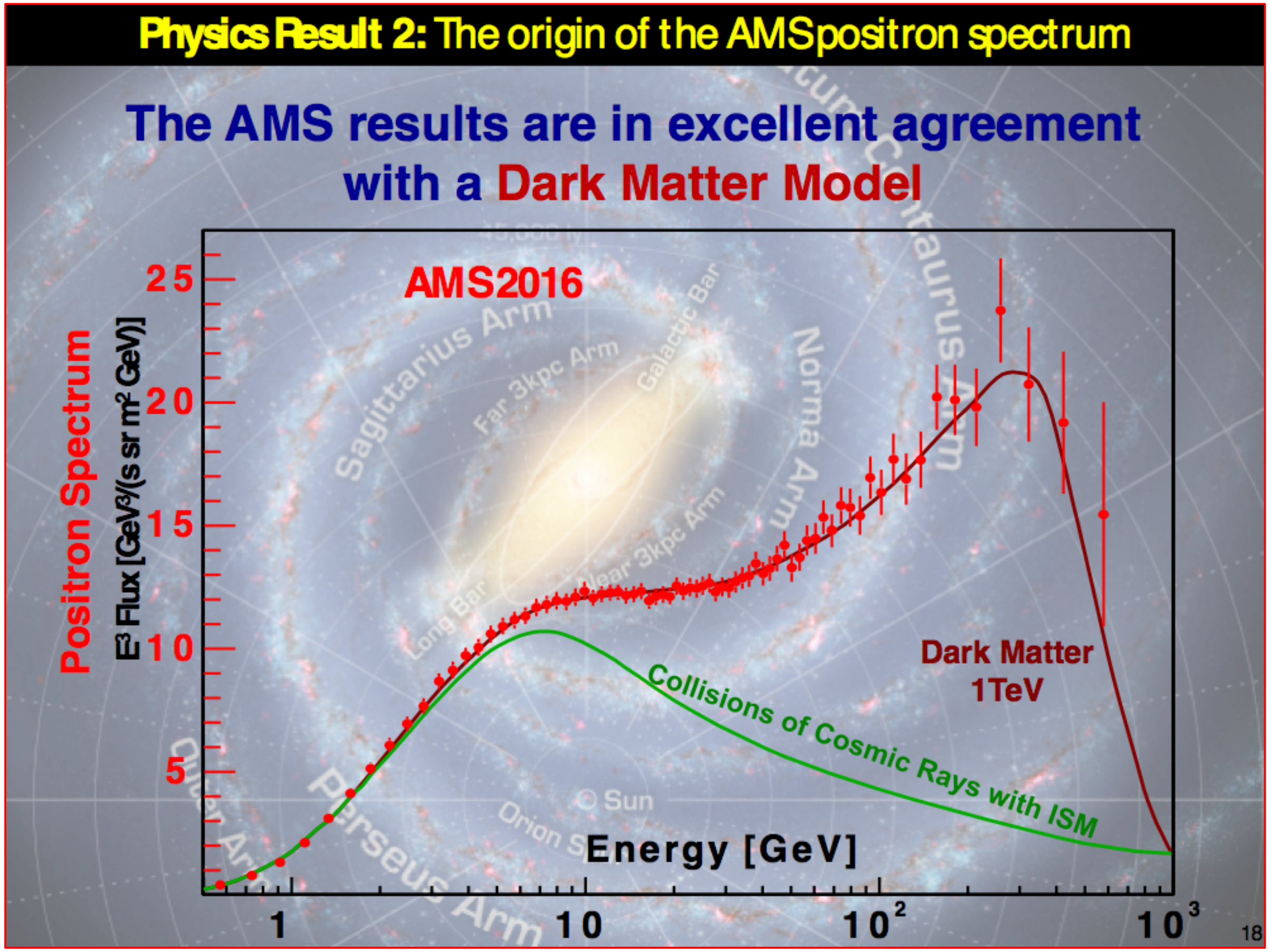


Physics Result 2: The origin of the AMS positron spectrum

The AMS results are in excellent agreement with a Dark Matter Model

Plan

Plan

Antiprotons

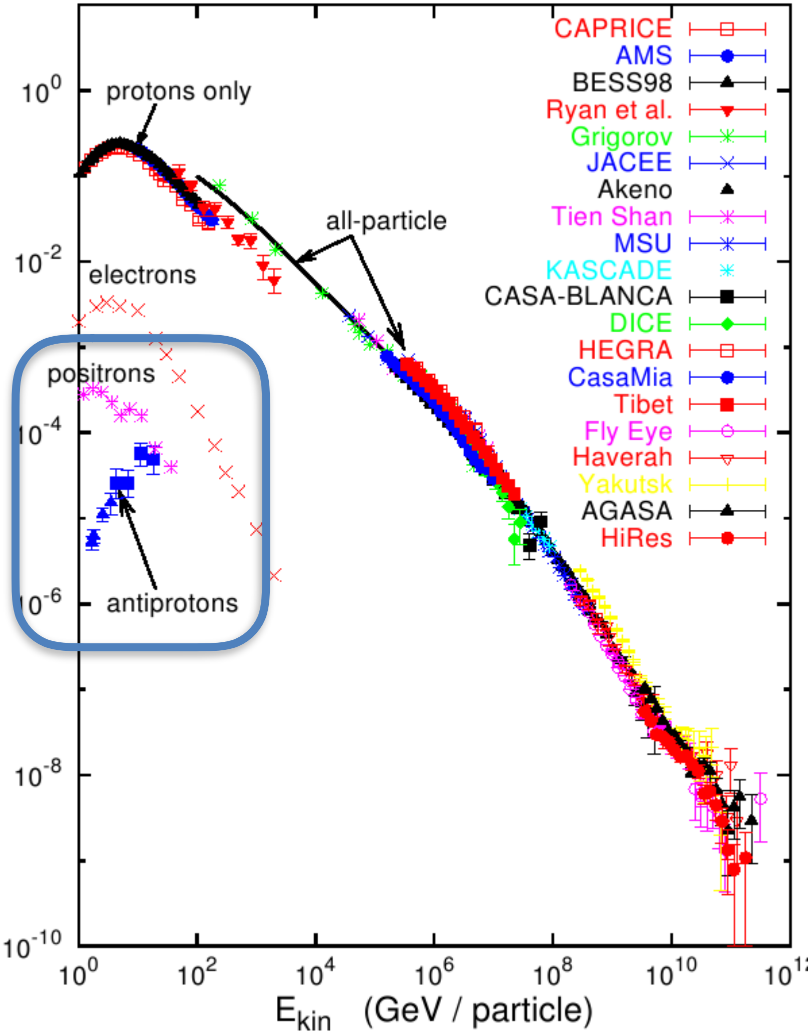
Confusion in the literature,
as to what and how we can calculate.
=> will try to sort this out

Positrons

Common belief: e+ from pulsars or dark matter!
=> *don't think so.* Will try to sort this out, too

Anti-He, anti-D

Thought so scarce that a single event would mark new physics.
=> link to LHC



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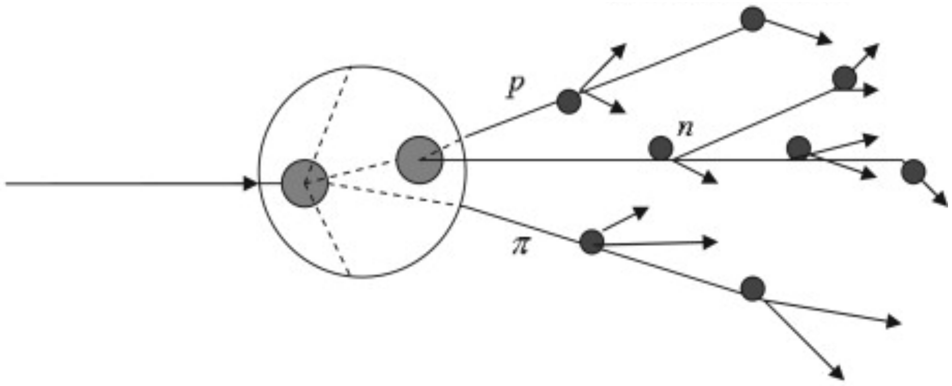
— protons and He – with interstellar gas.

Need to calculate this background to learn about possible exotic sources.



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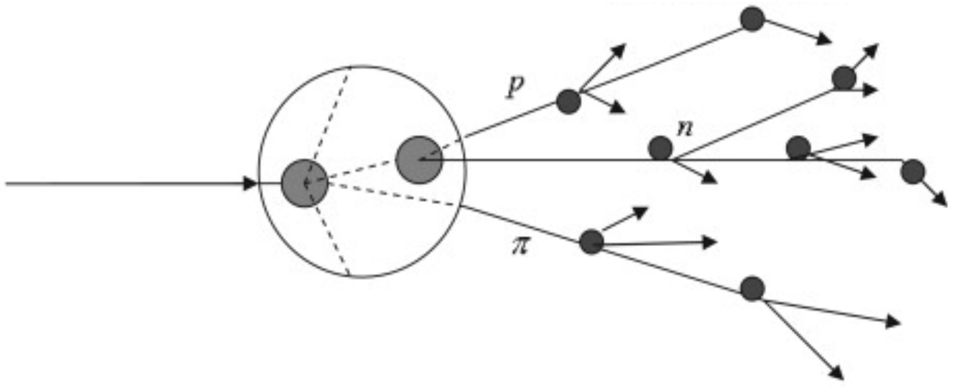
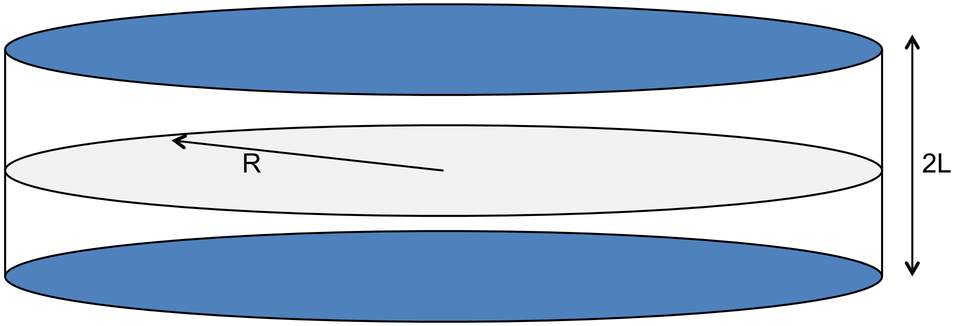
Problem: we don't know where CRs come from, nor how long they are trapped in the Galaxy, nor how they eventually escape.

This problem is often under-stated…

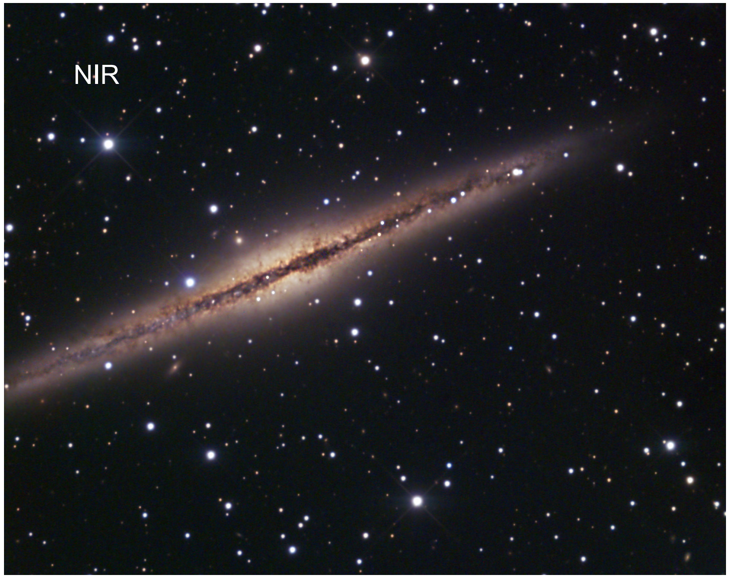


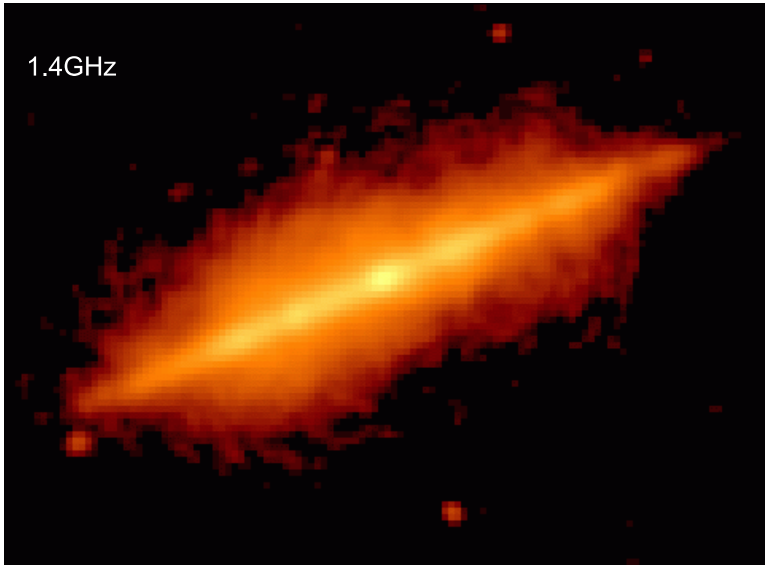
About diffusion models

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



NGC 891

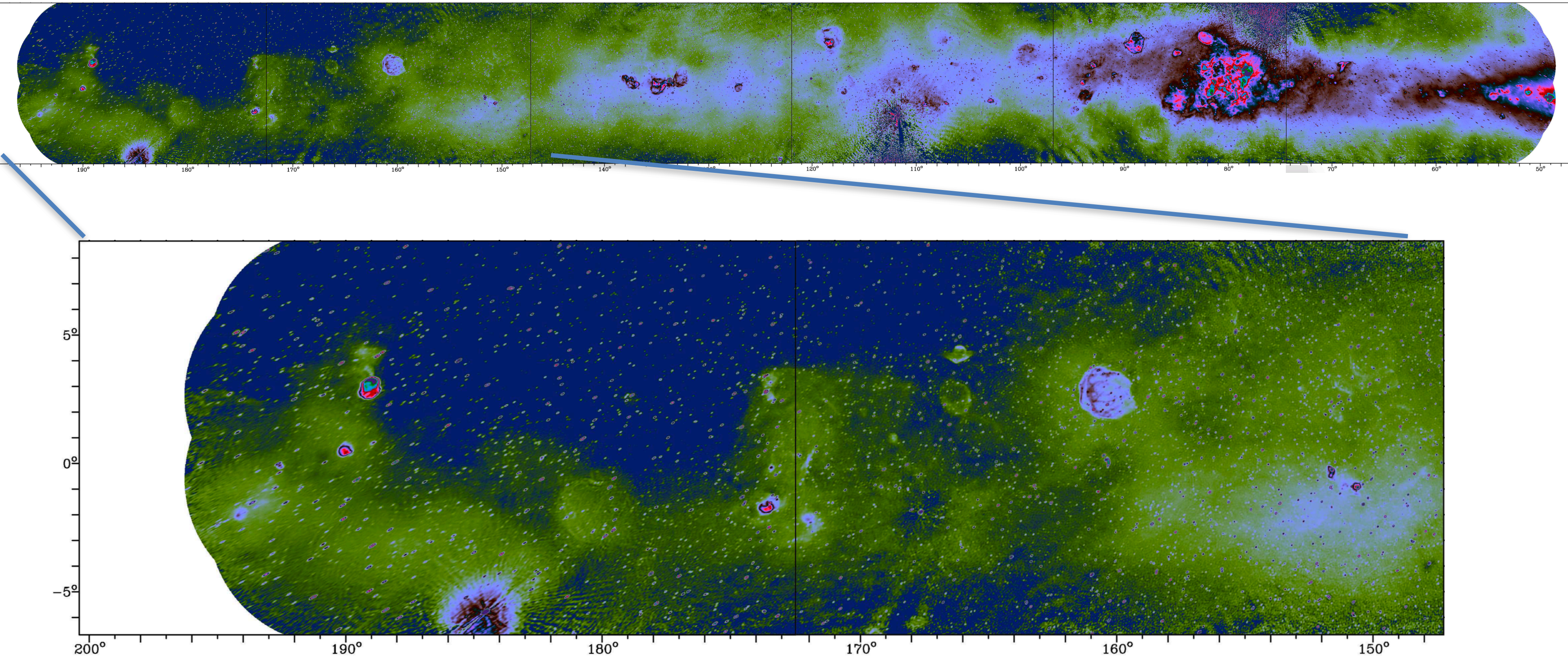




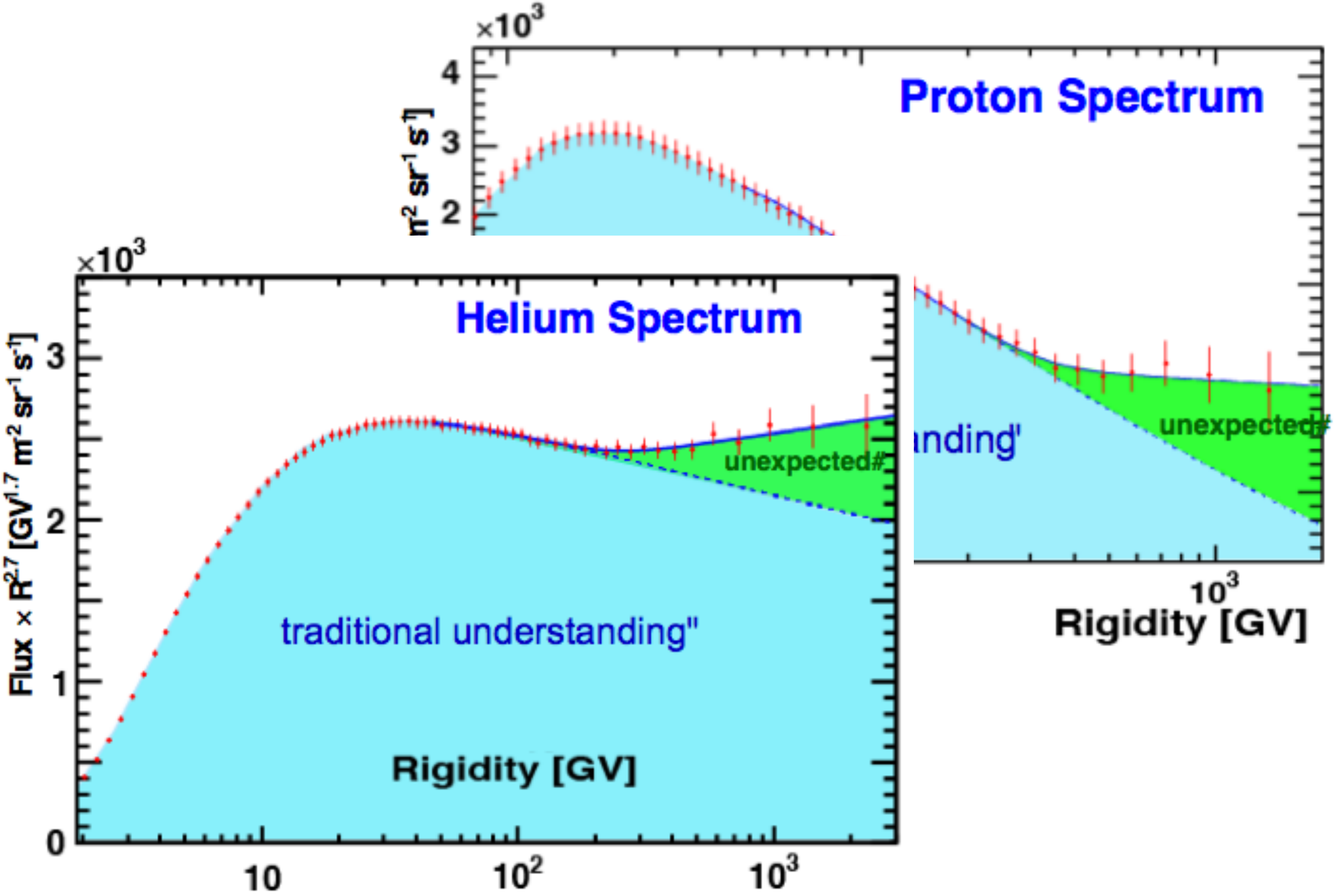
Strong, Moskalenko, Ptuskin, Ann.Rev.Nucl.Part.Sci. 57 (2007) 285-327

Interstellar matter is far from homogeneous.
On ~Myr time scales, it is also far from steady-state

arxiv:1708.04316 (ApJ 1538-3881-154-4-156)
408MHz Canadian Galactic Plane Survey



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



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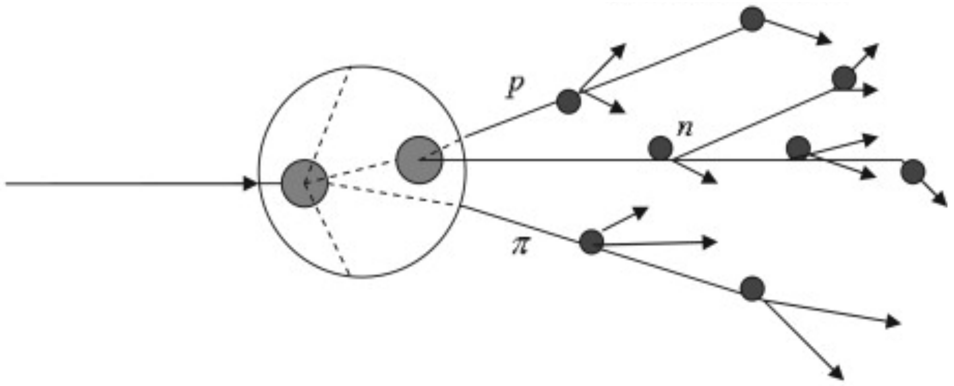

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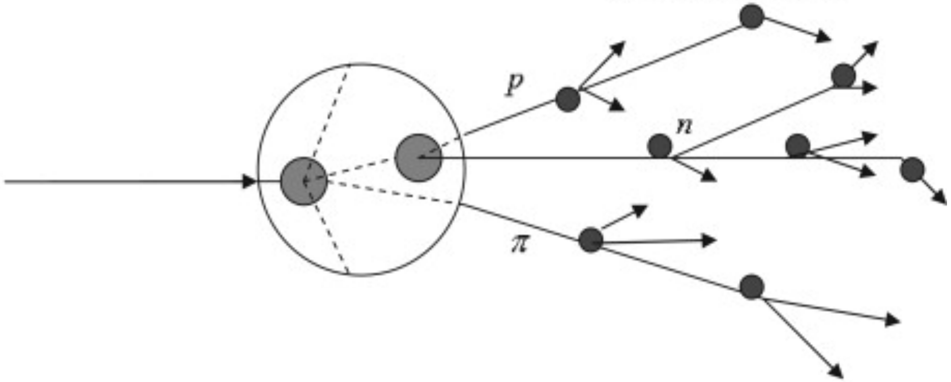
For stable, relativistic secondary CR nuclei, we have a handle: branching fractions

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



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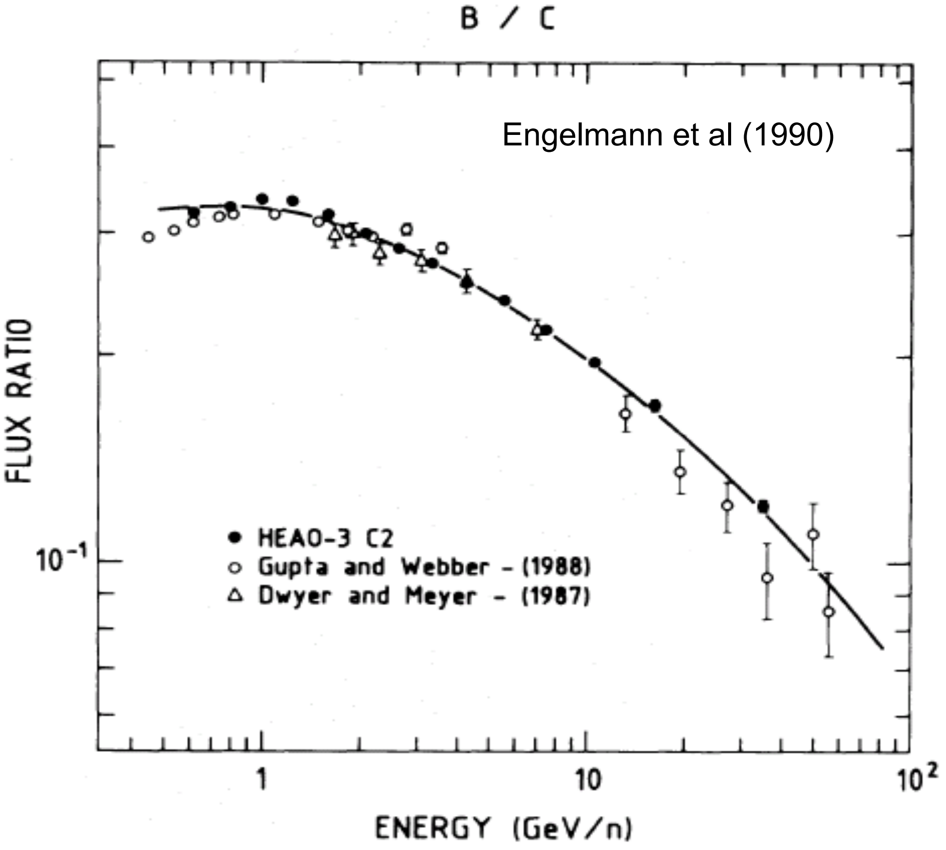
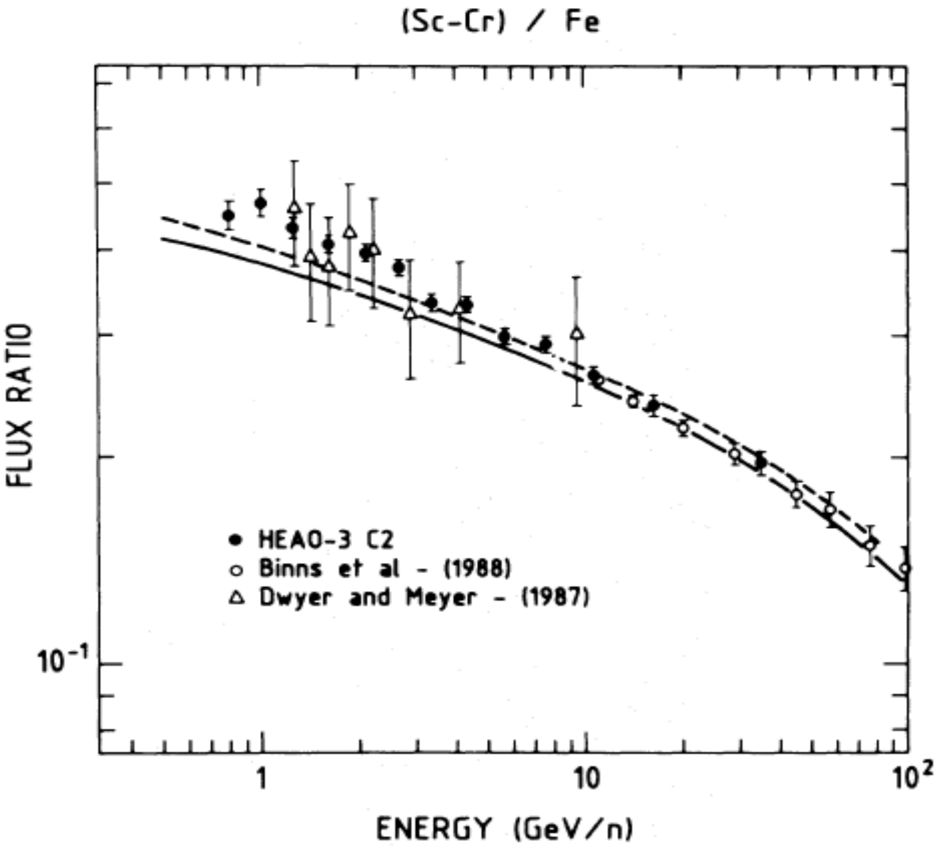

Engelmann et al (1990)



Apply this to antiprotons

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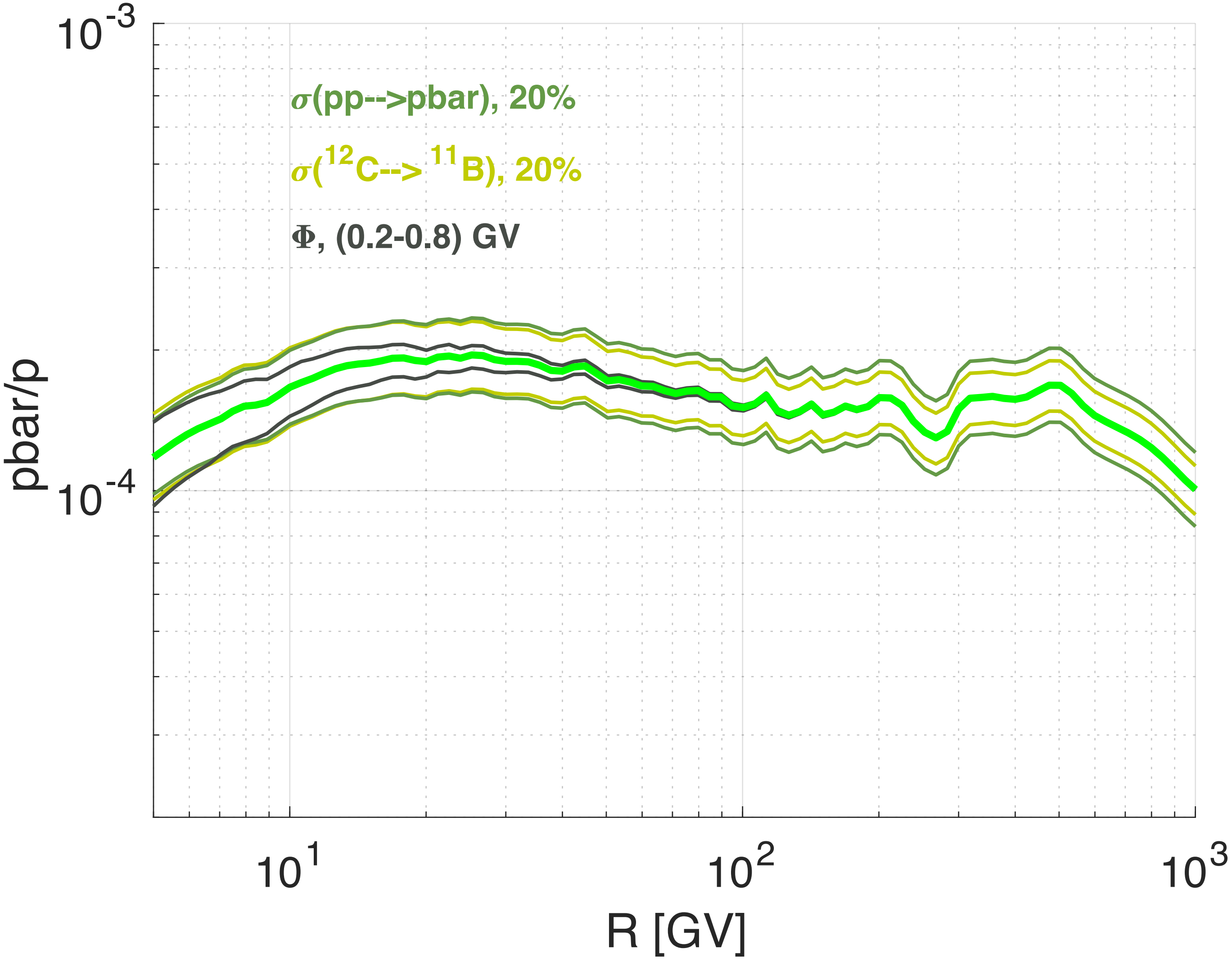

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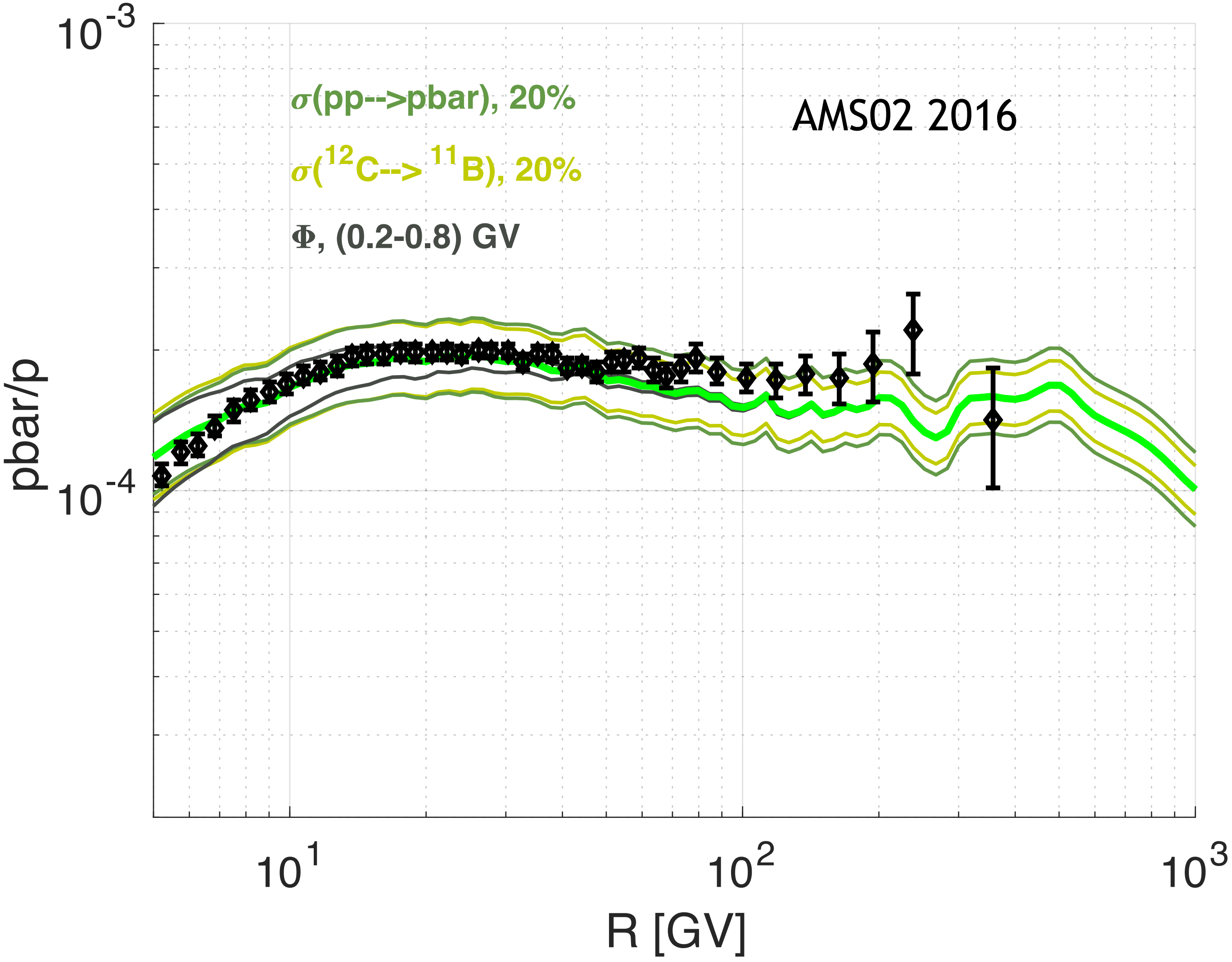

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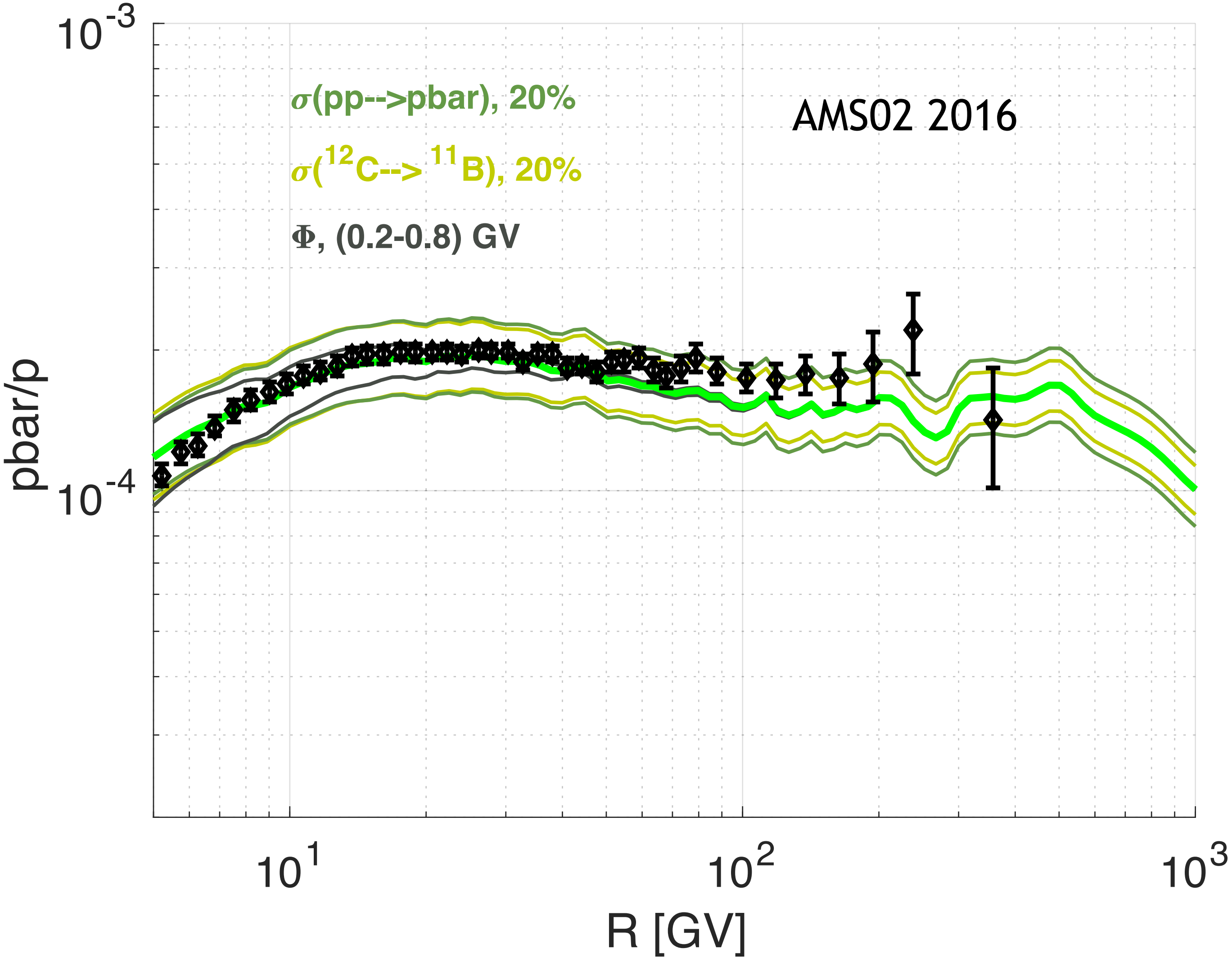
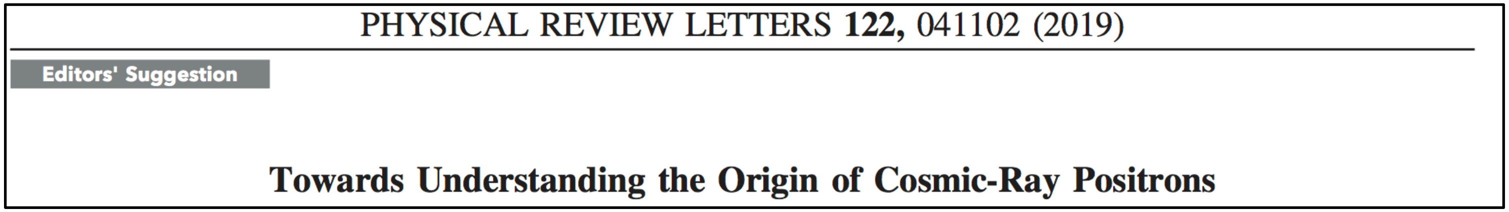


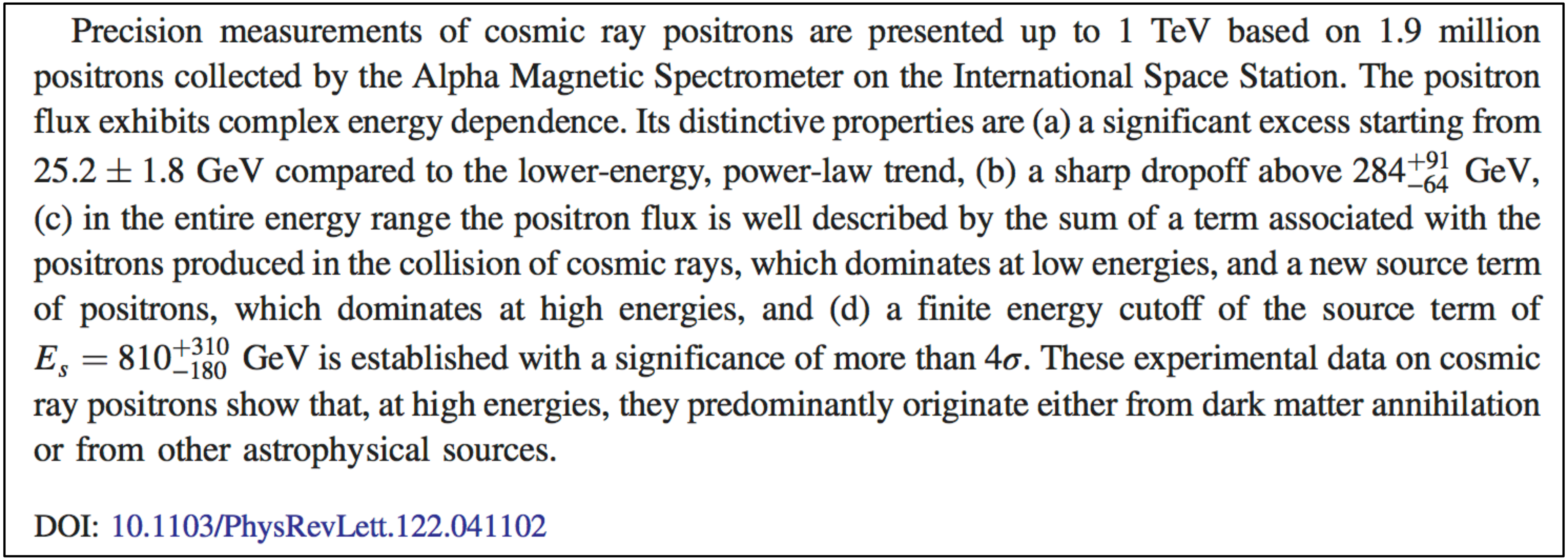
What about e+ ?


PHYSICAL REVIEW LETTERS **122,** 041102 (2019)

Editors' Suggestion

Towards Understanding the Origin of Cosmic-Ray Positrons

(AMS Collaboration)


Precision measurements of cosmic ray positrons are presented up to 1 TeV based on 1.9 million positrons collected by the Alpha Magnetic Spectrometer on the International Space Station. The positron flux exhibits complex energy dependence. Its distinctive properties are (a) a significant excess starting from 25.2 ± 1.8 GeV compared to the lower-energy, power-law trend, (b) a sharp dropoff above 284^{+91}_{-64} GeV, (c) in the entire energy range the positron flux is well described by the sum of a term associated with the positrons produced in the collision of cosmic rays, which dominates at low energies, and a new source term of positrons, which dominates at high energies, and (d) a finite energy cutoff of the source term of $E_s = 810^{+310}_{-180}$ GeV is established with a significance of more than 4σ. These experimental data on cosmic ray positrons show that, at high energies, they predominantly originate either from dark matter annihilation or from other astrophysical sources.

DOI: 10.1103/PhysRevLett.122.041102

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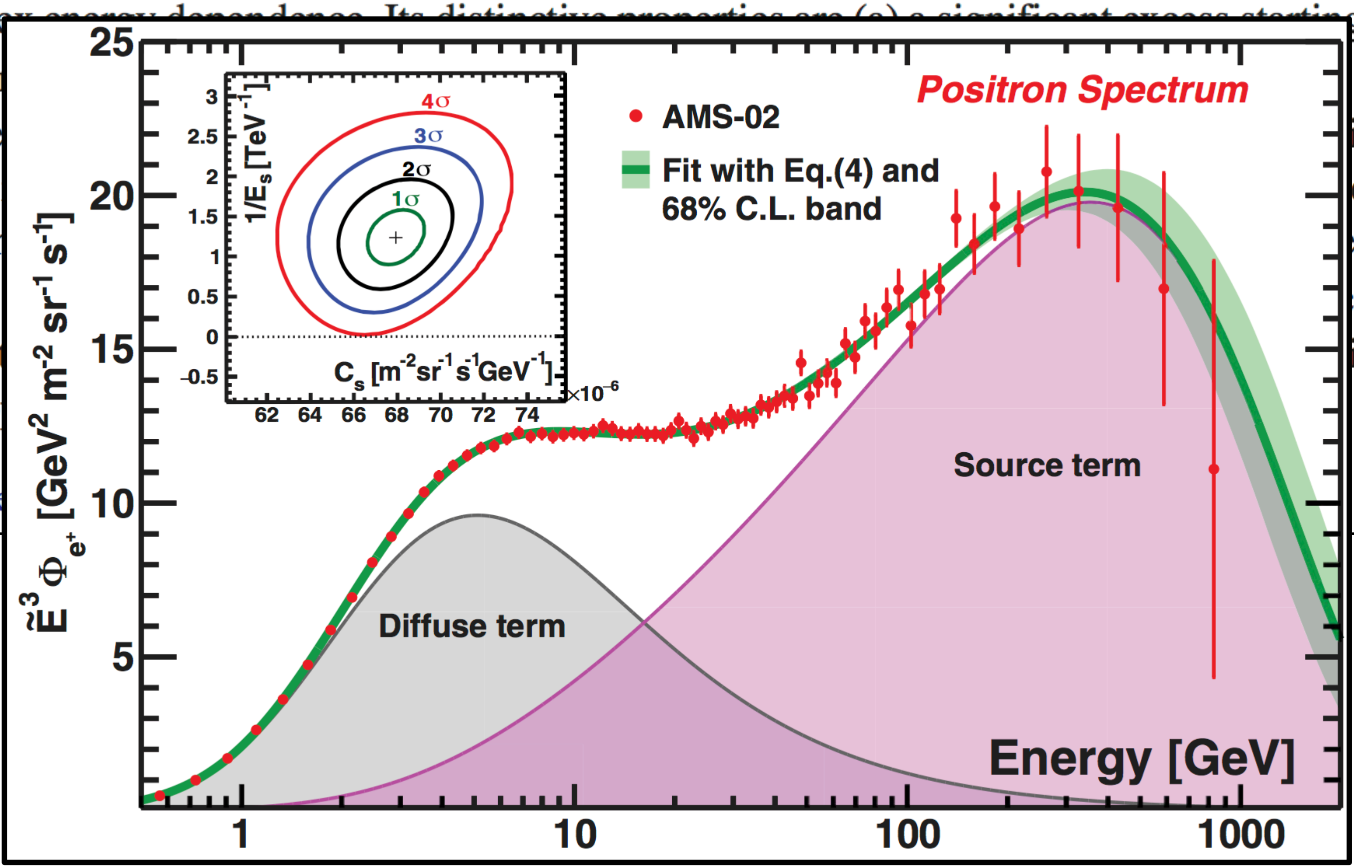

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MNRAS 405 (2010) 1458 Katz, Blum, Morag, Waxman

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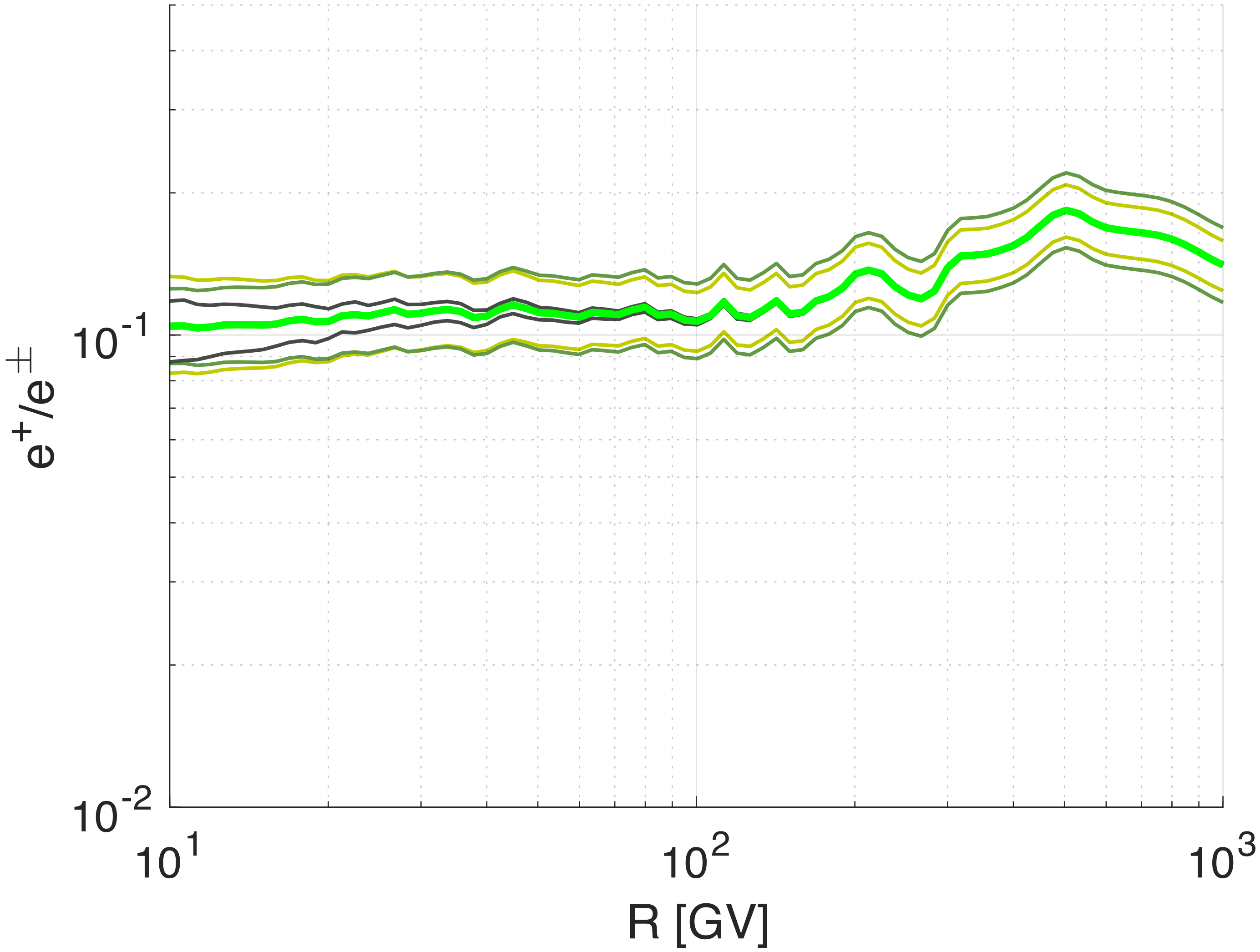

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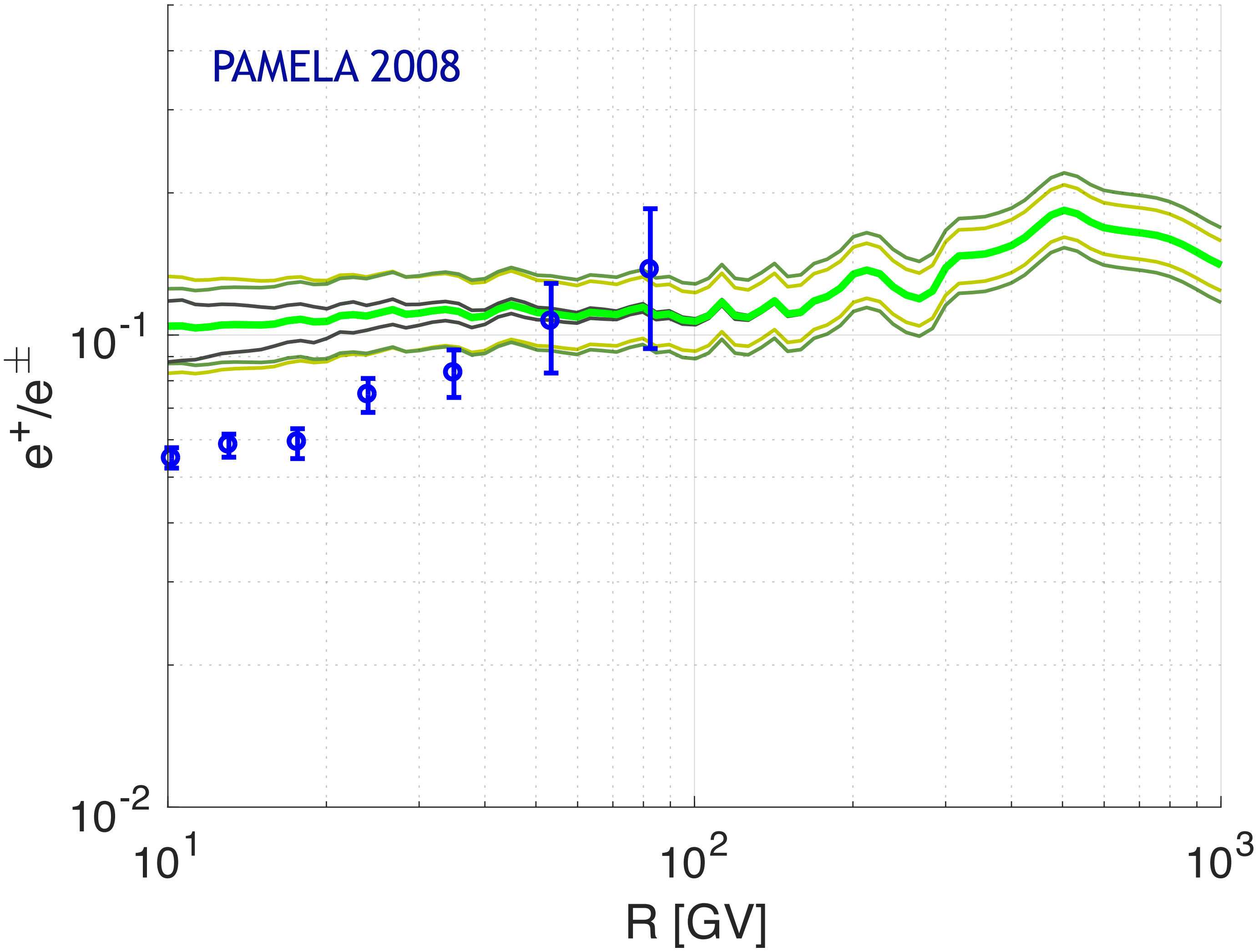

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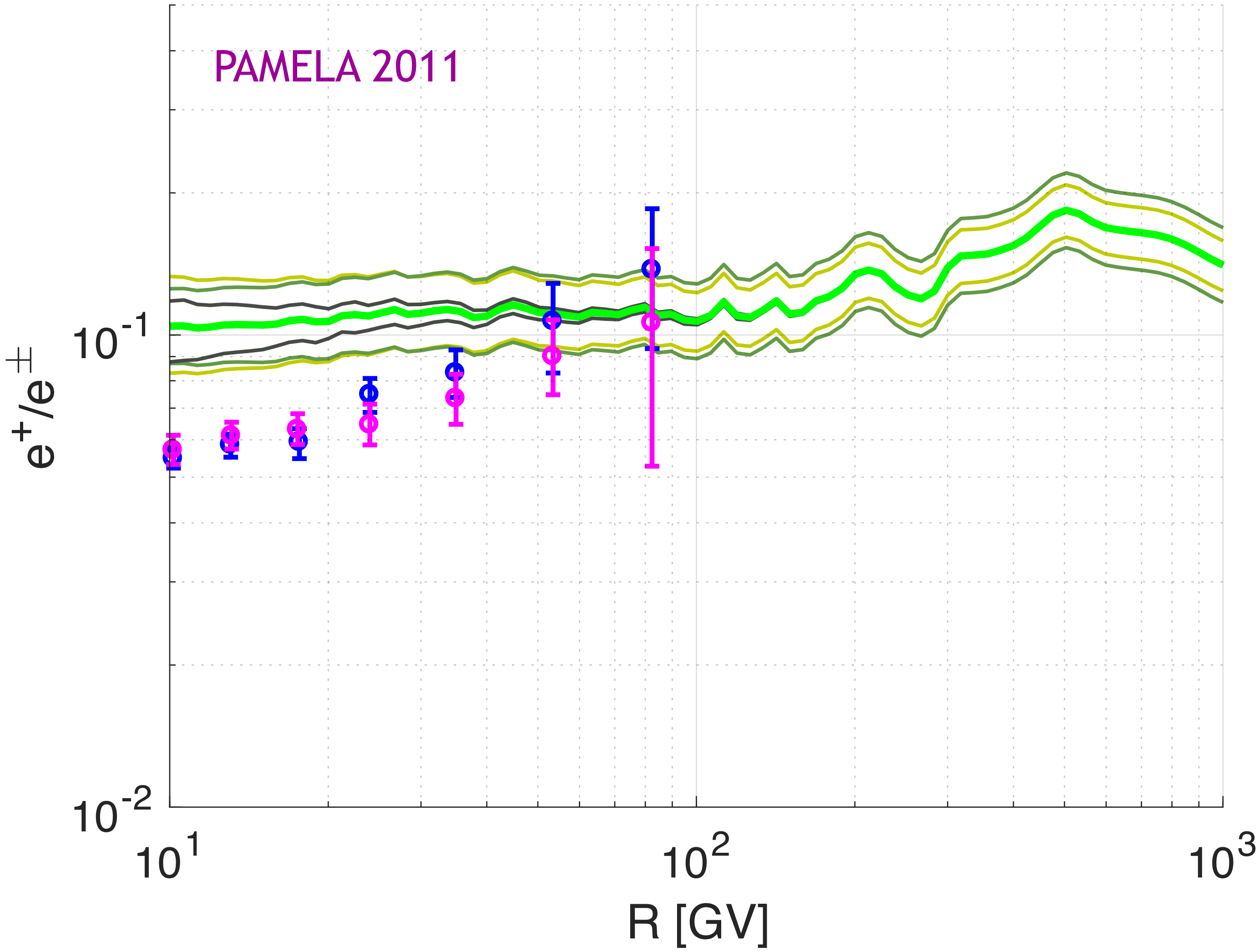

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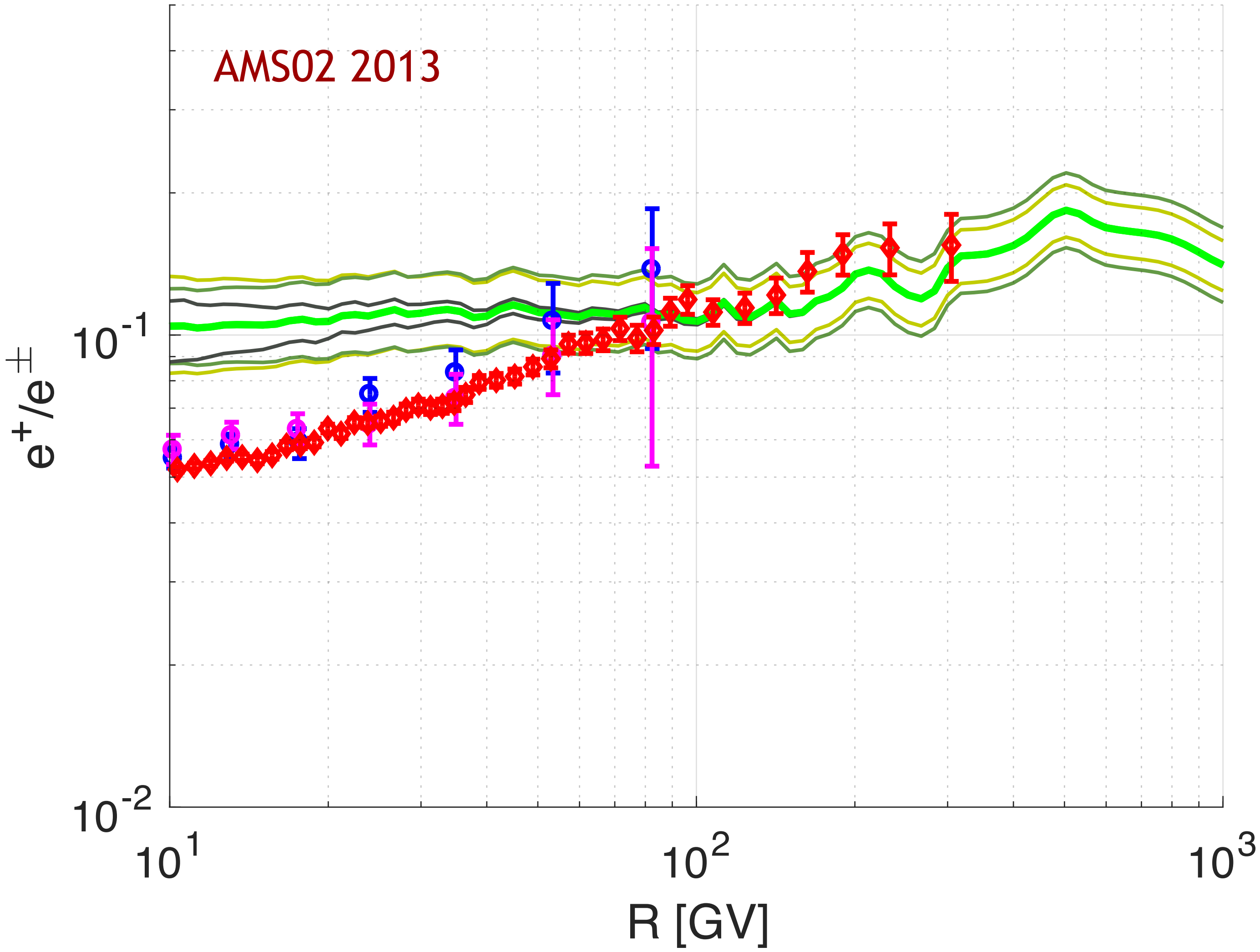

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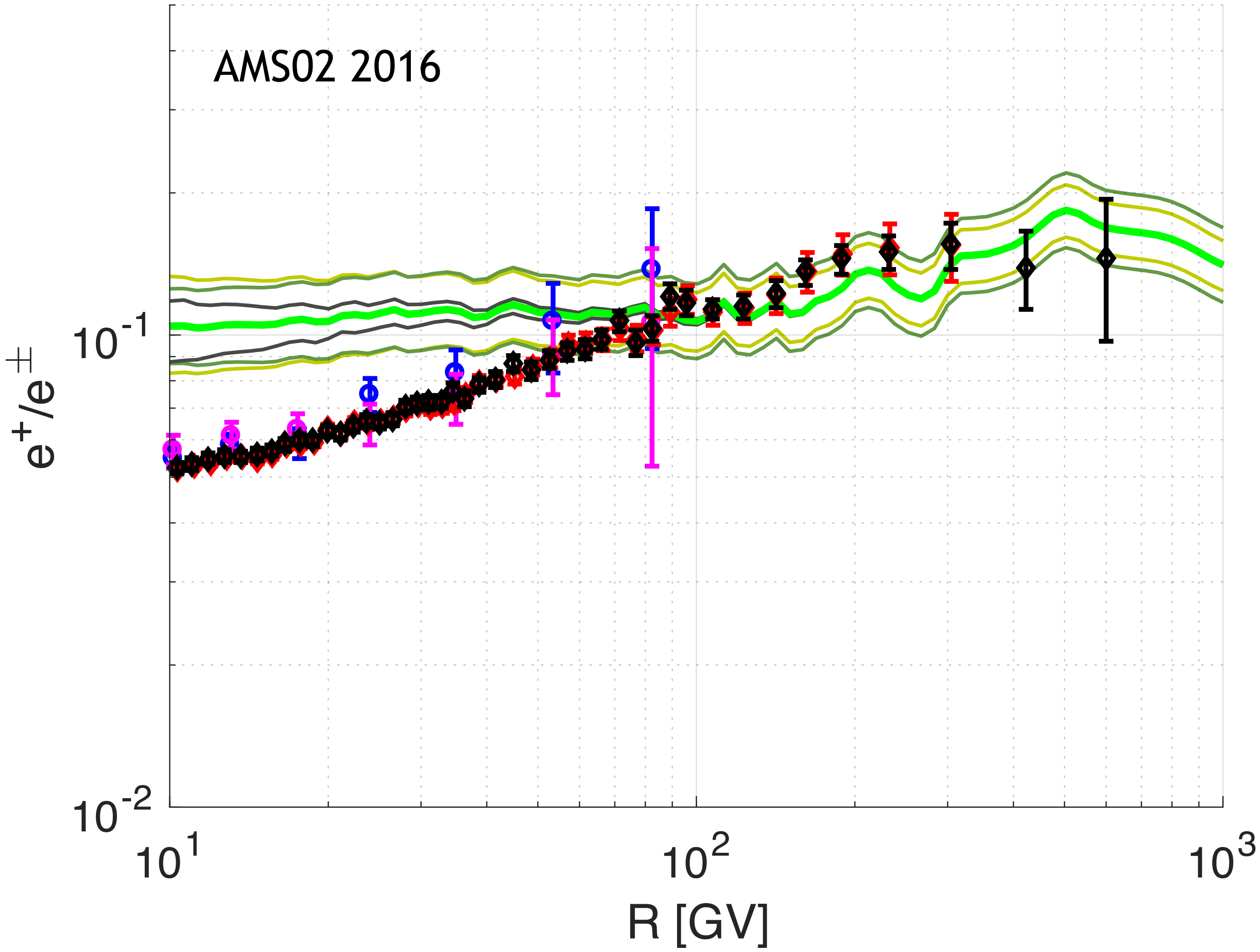

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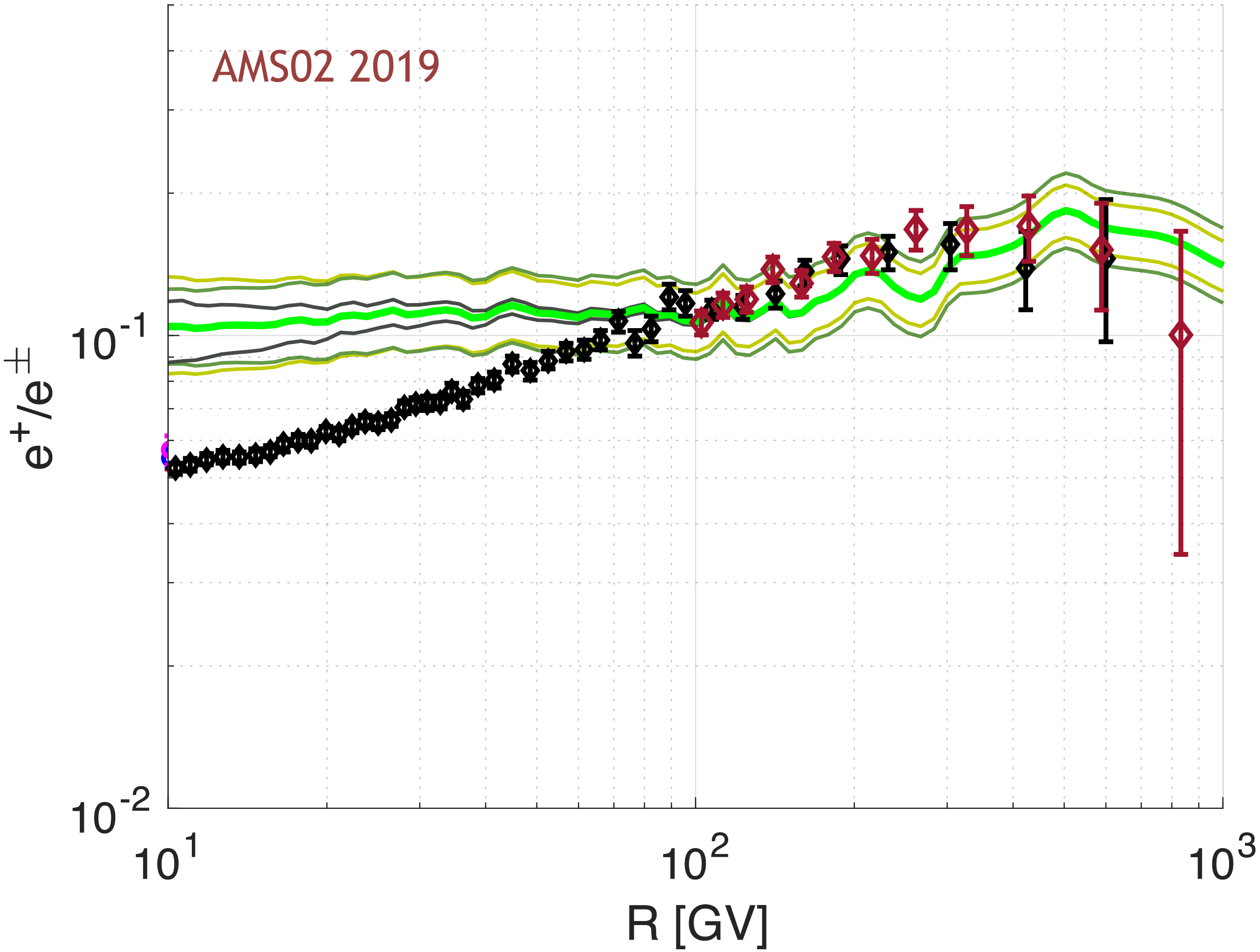

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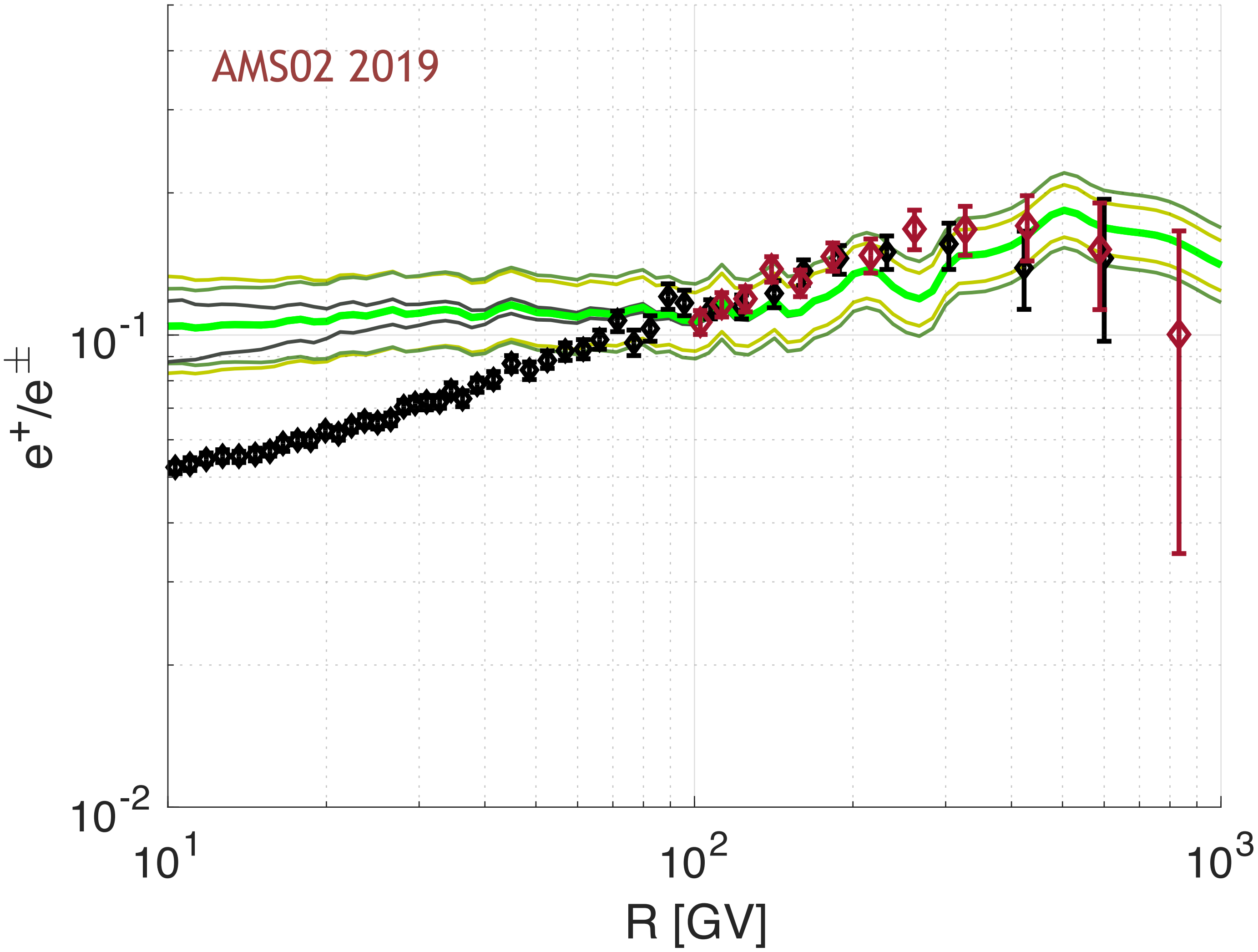

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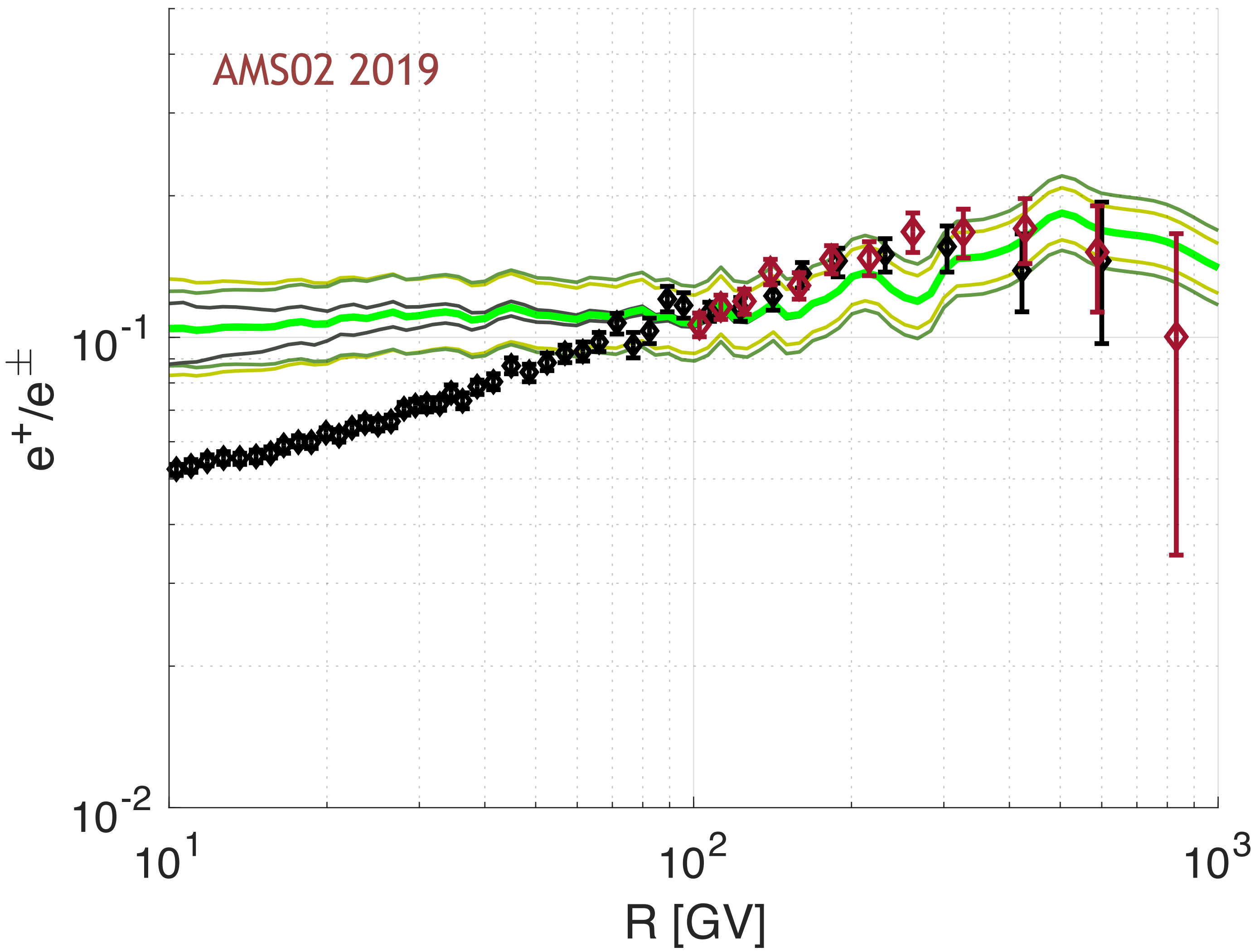
Why would dark matter or pulsars inject ***this*** e+ flux?



Blum, Katz, Waxman, Phys.Rev.Lett. 111 (2013) no.21, 211101

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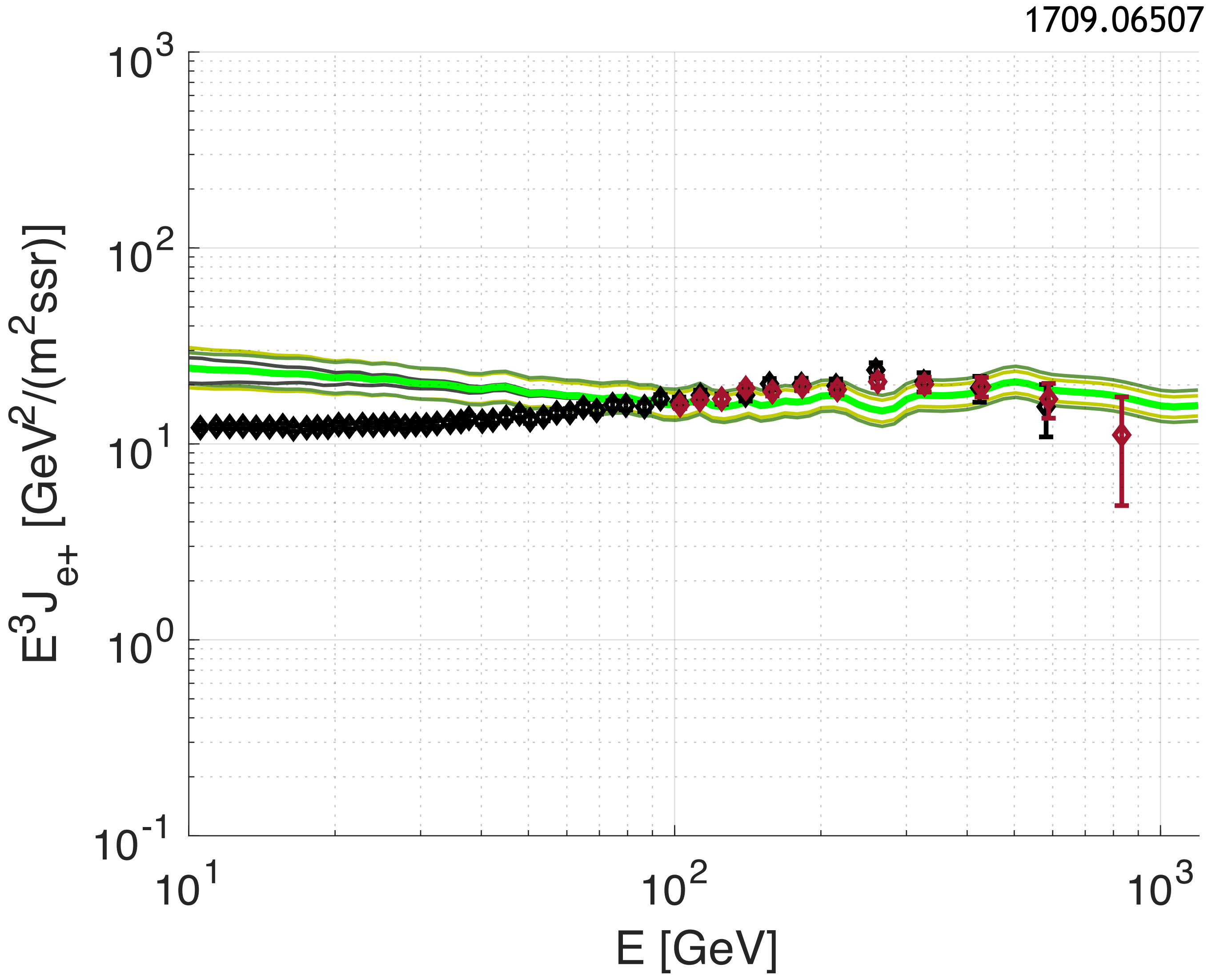

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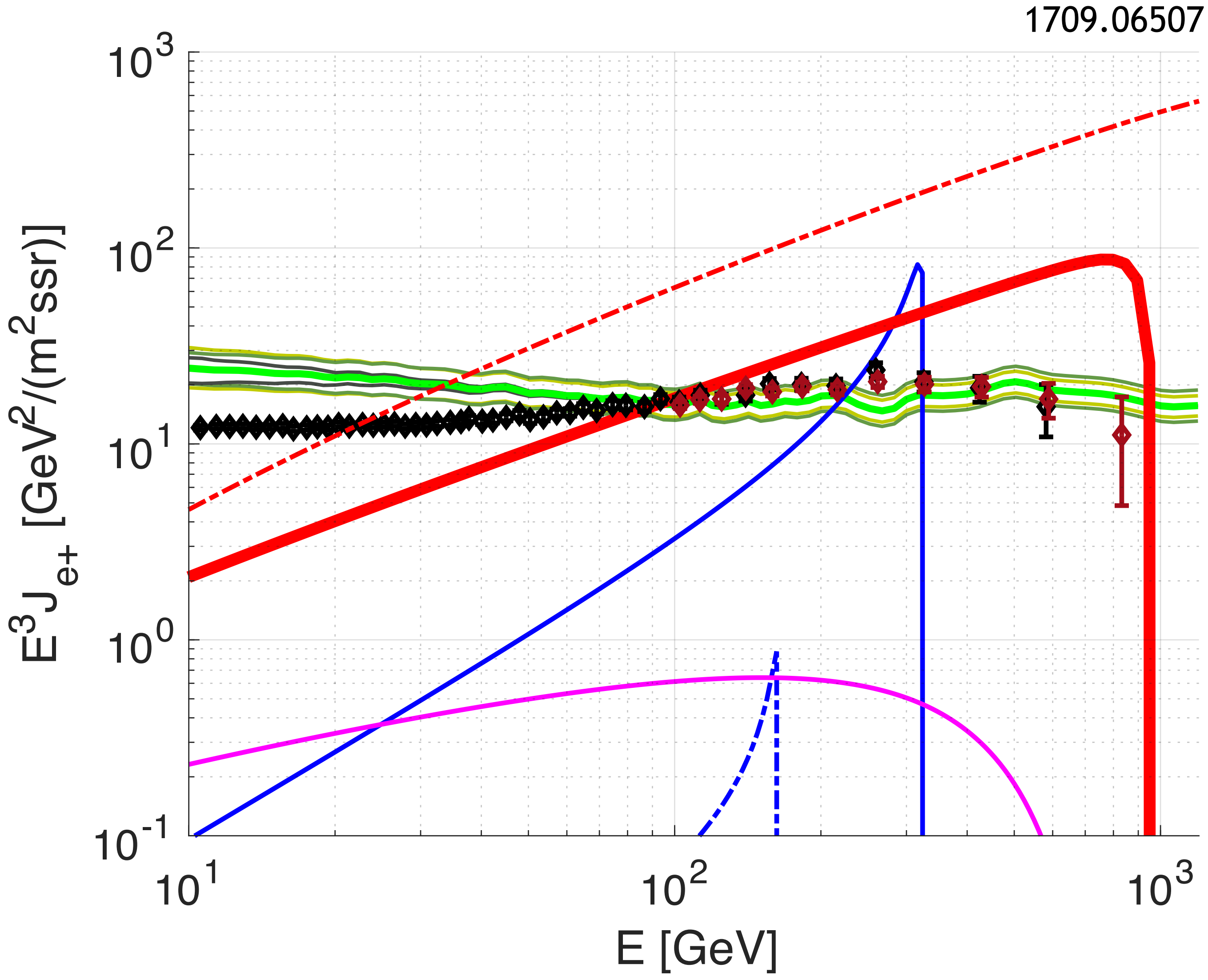
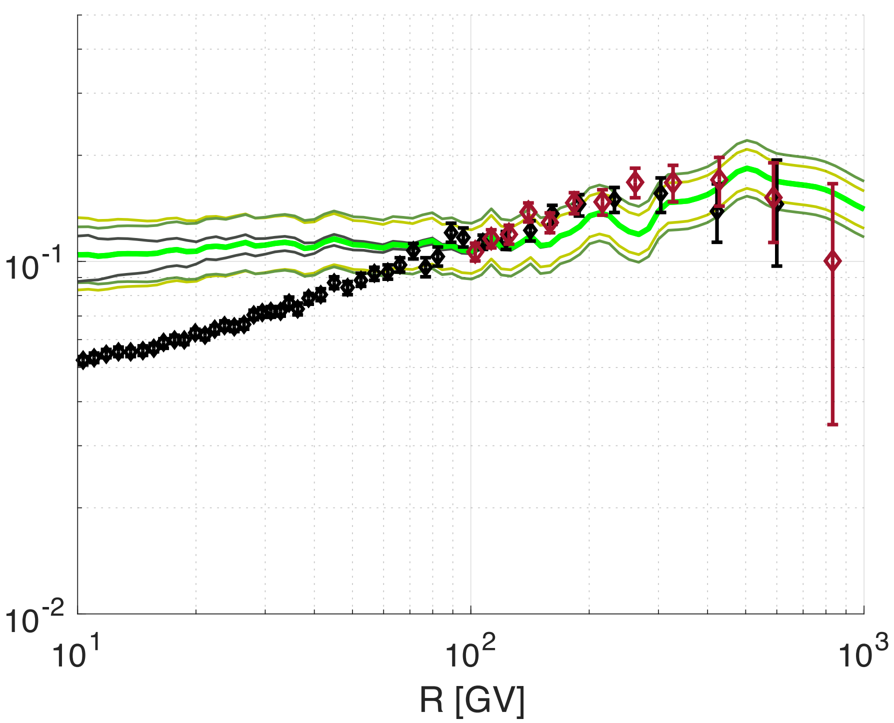
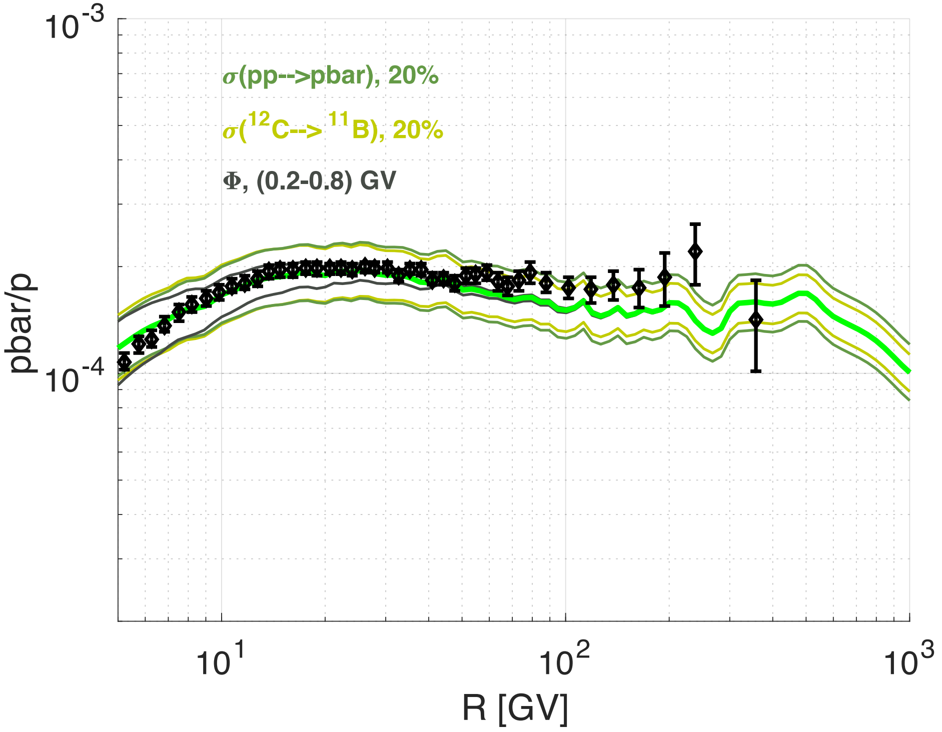


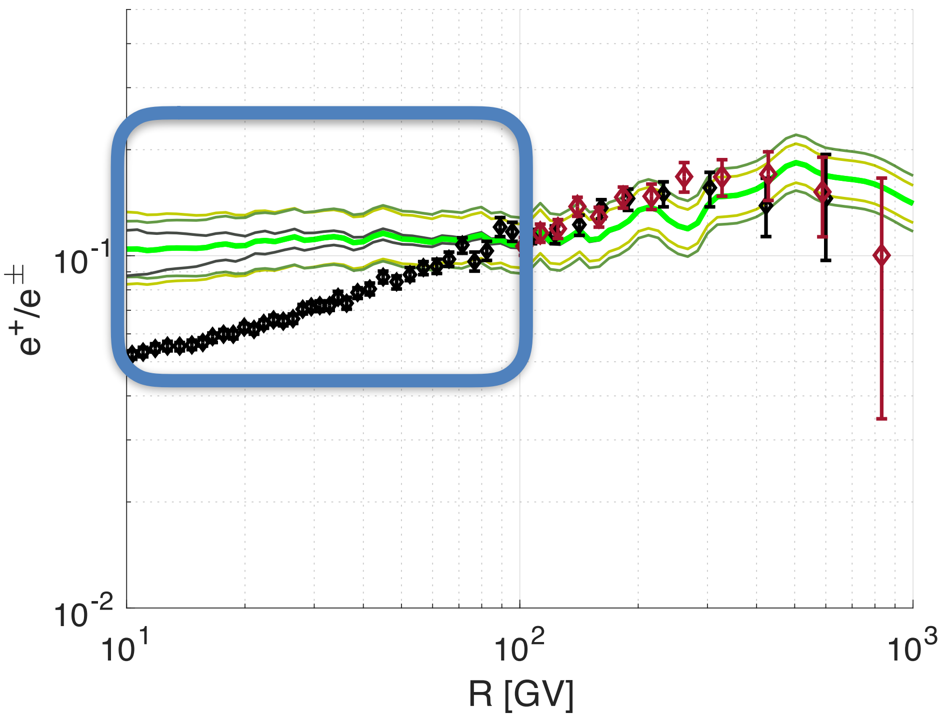
Pulsar model: D. Malyshev, I. Cholis, and J. Gelfand, Phys. Rev. **D80**, 063005 (2009)

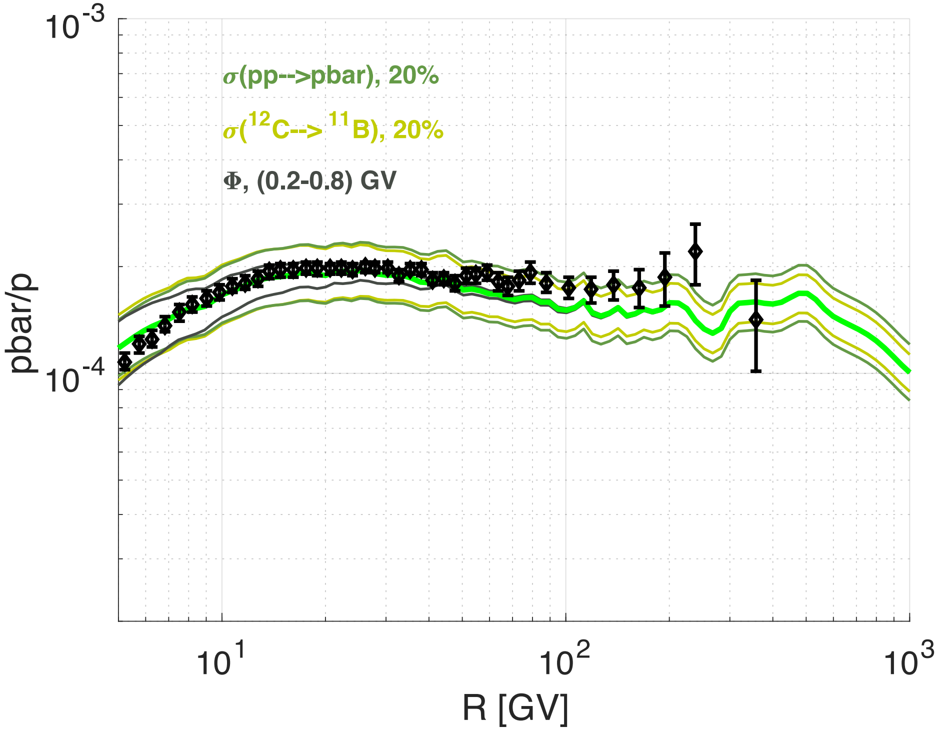
Observational evidence that CR antimatter is secondary, coming from collisions of CRs on ISM.





At R<100 GV, e+ flux lies below the bound, suggesting tesc > tcool





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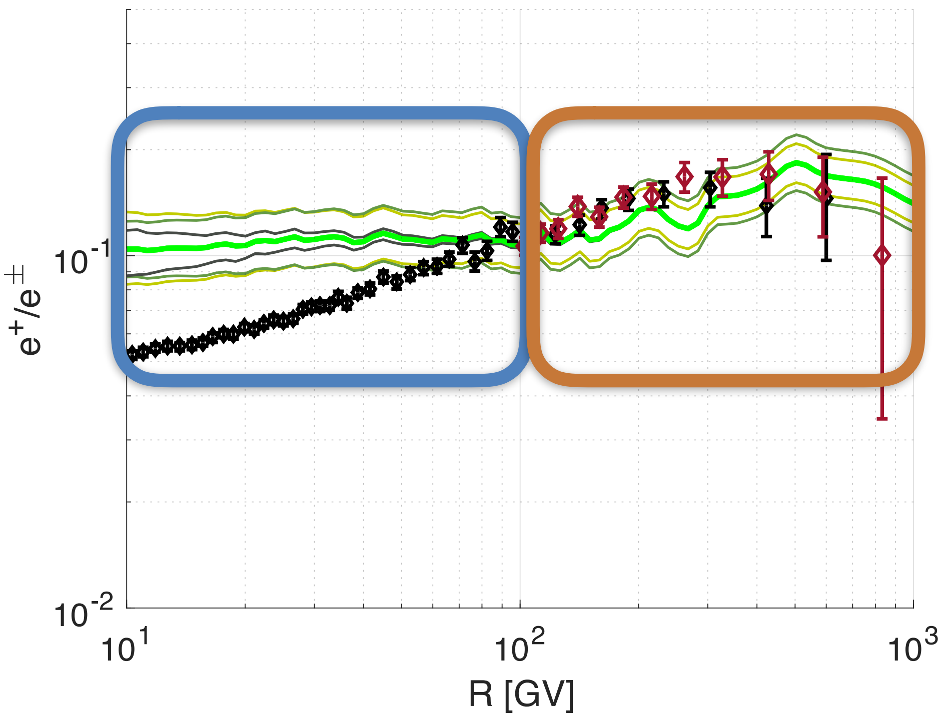
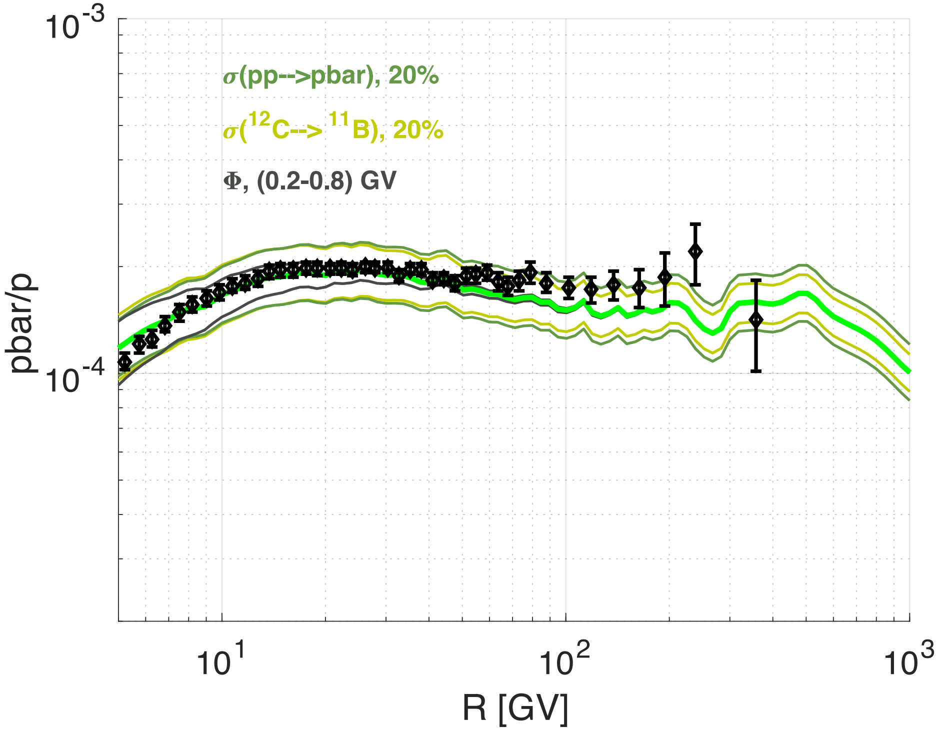
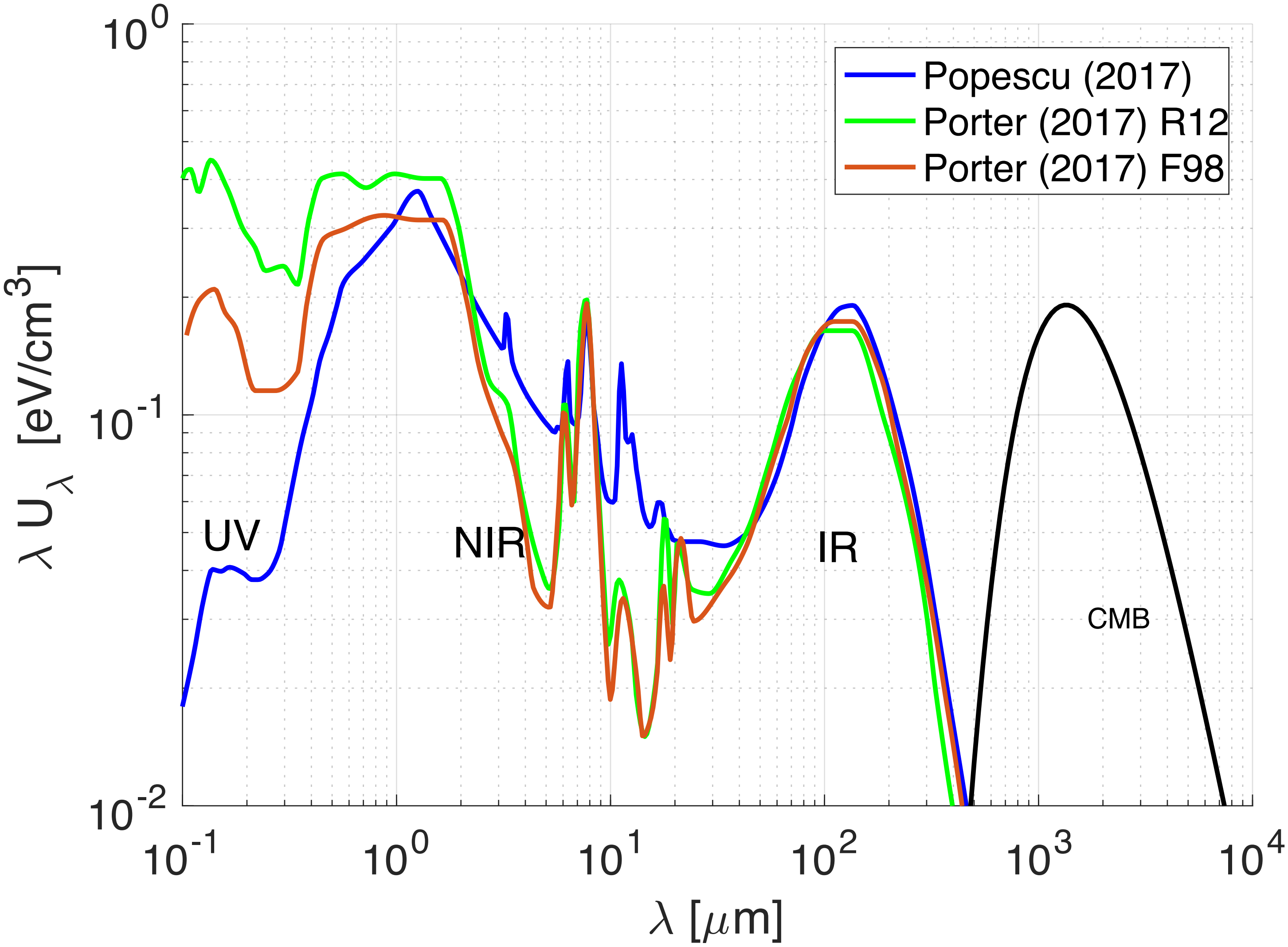




What is the radiative cooling time of CR e+ ?



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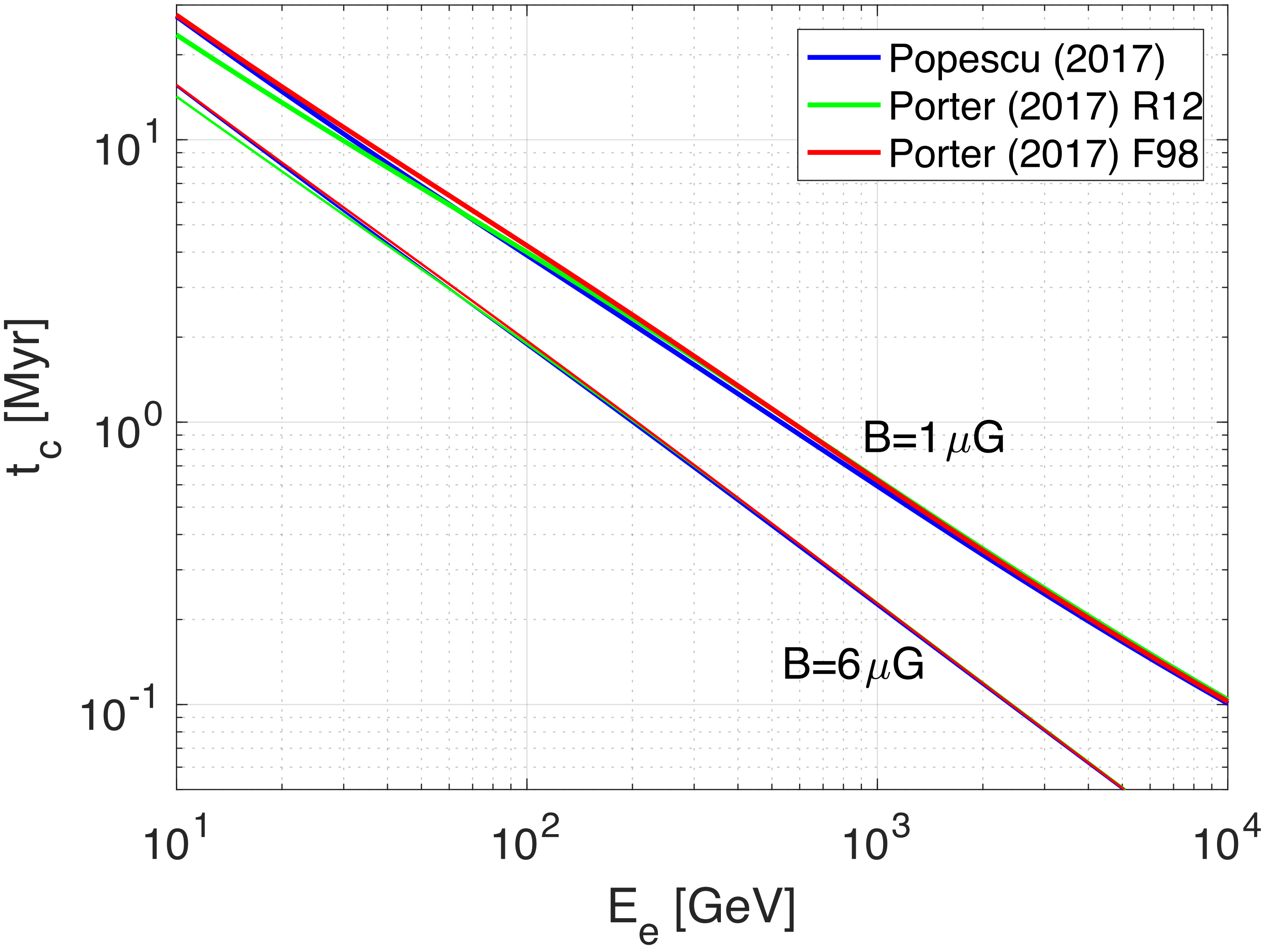

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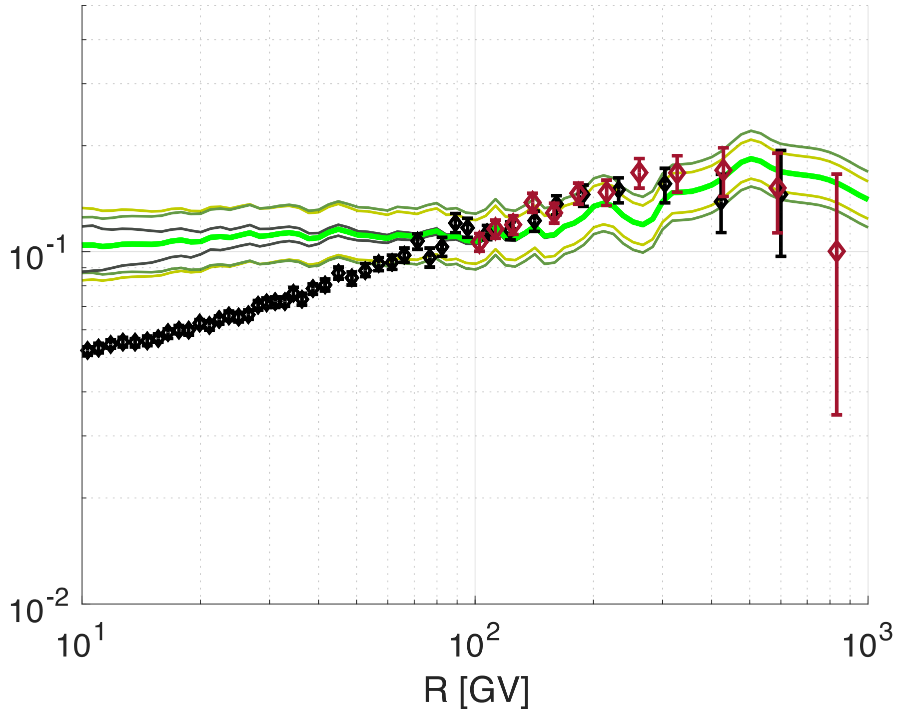

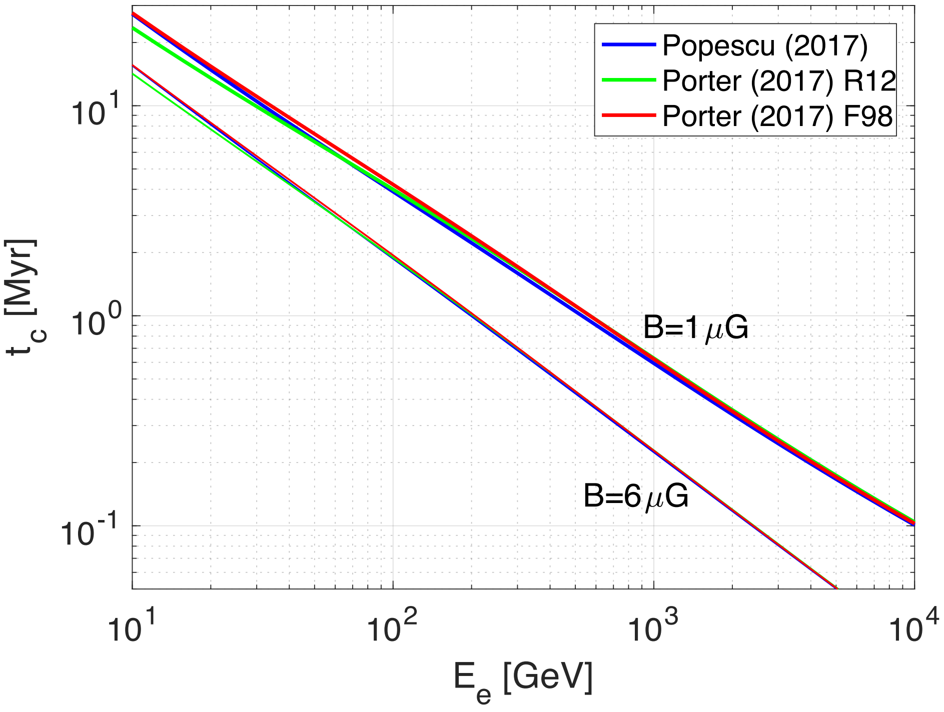

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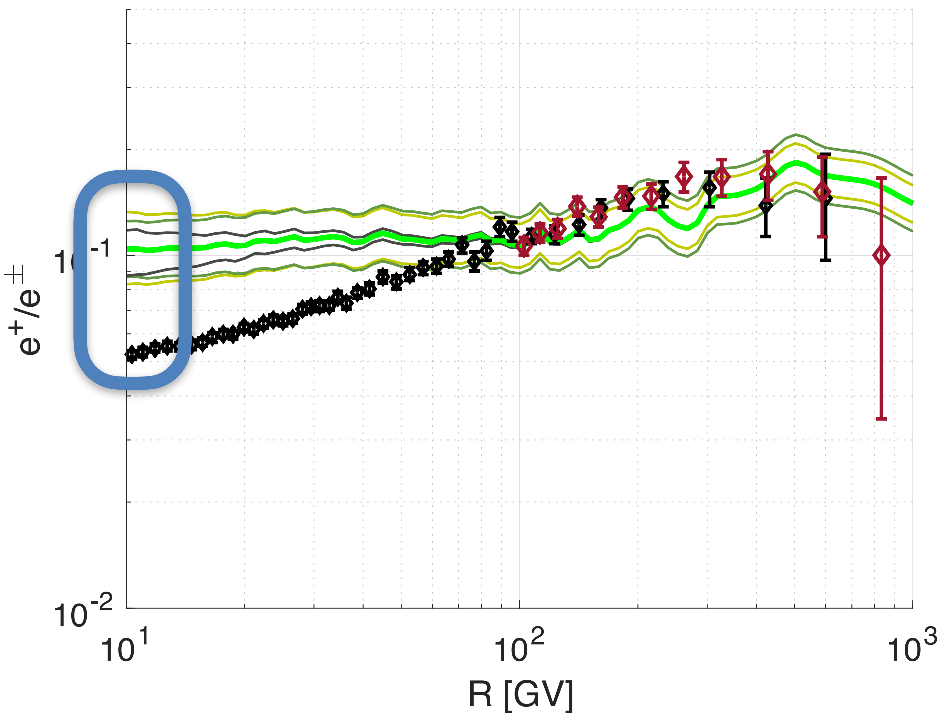
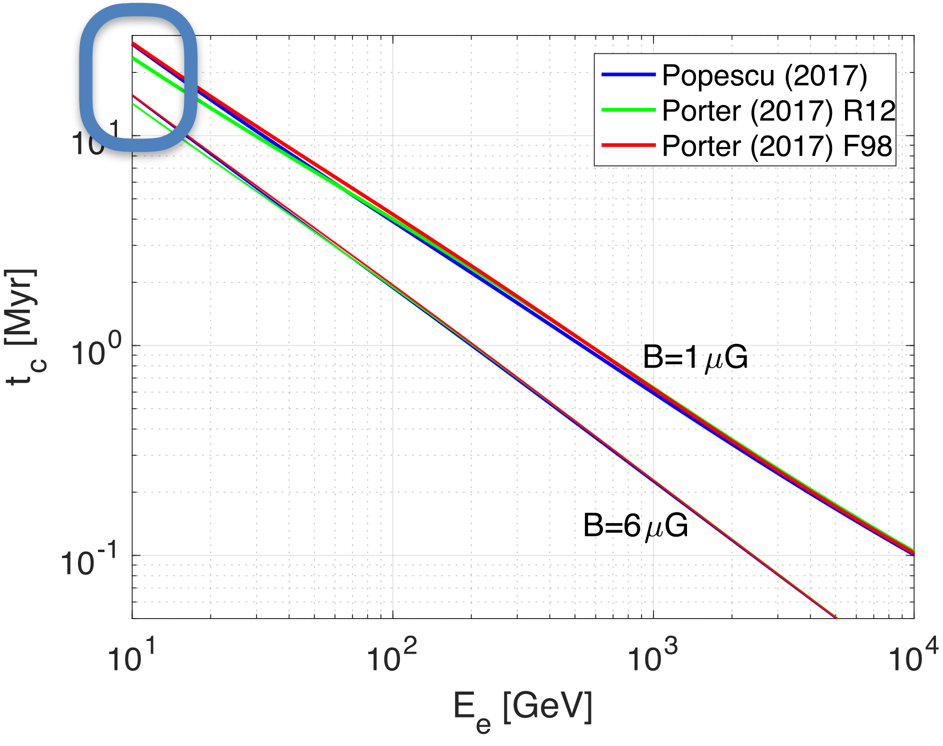
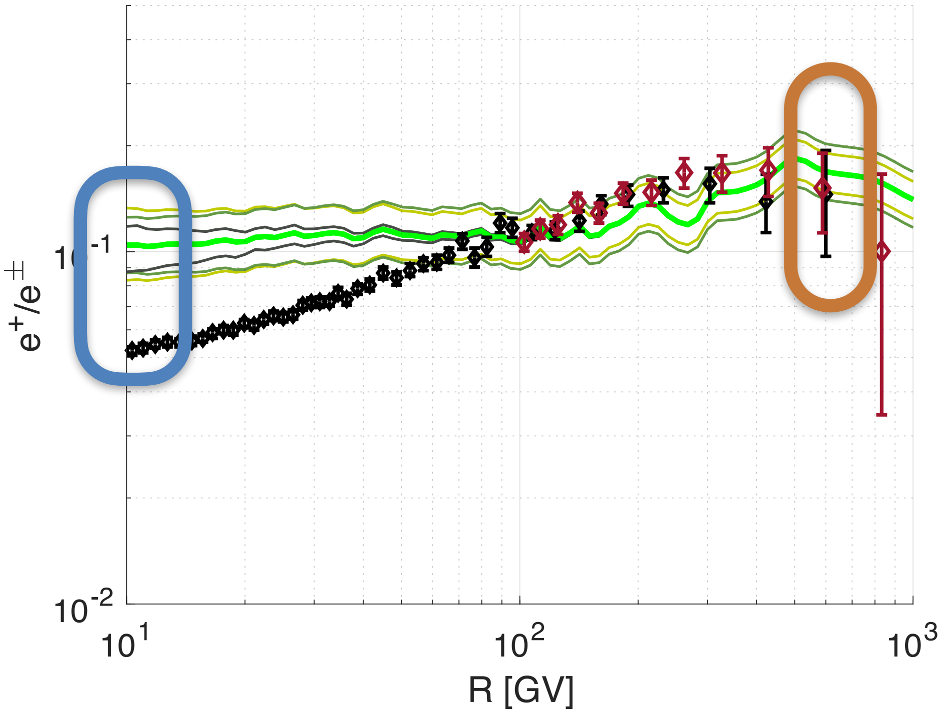
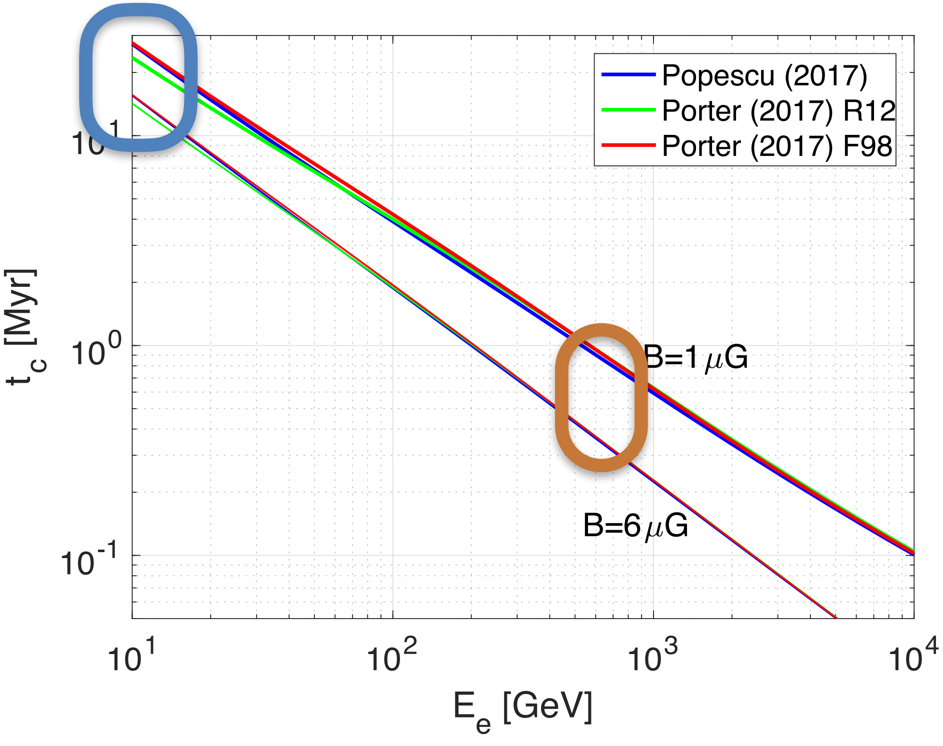




At **R~10 GV**, e+ flux lies below the bound, suggesting **tesc > 10 Myr**

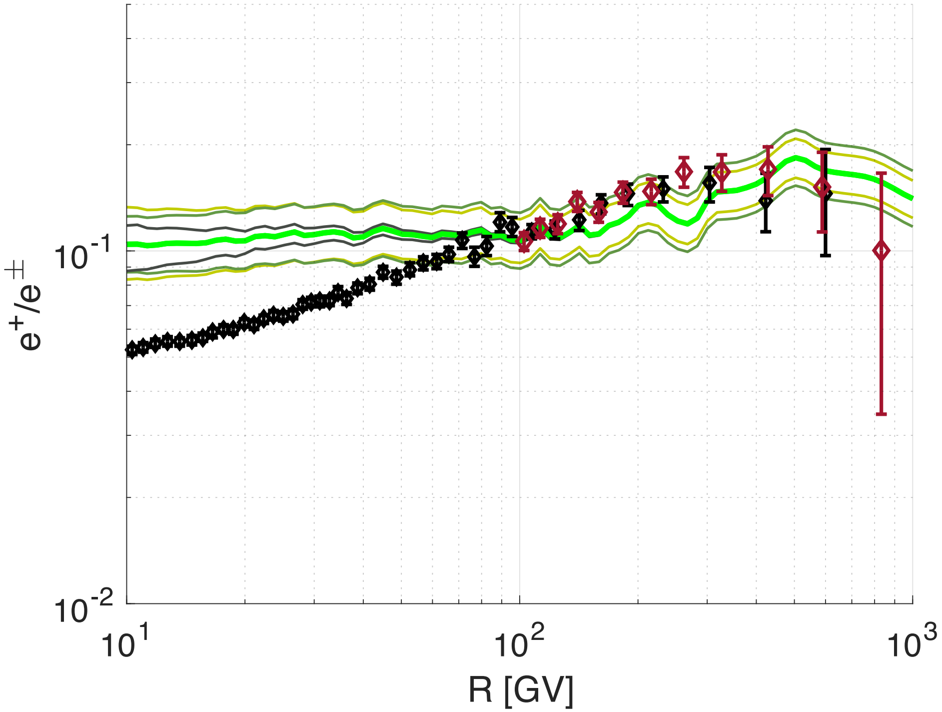
At **R~600 GV**, e+ flux saturates the bound, suggesting **tesc < 0.5 Myr**





It appears likely that some transition in CR propagation takes place around R~100 GV.

e+ are not the only CR species for which something like this may be inferred.



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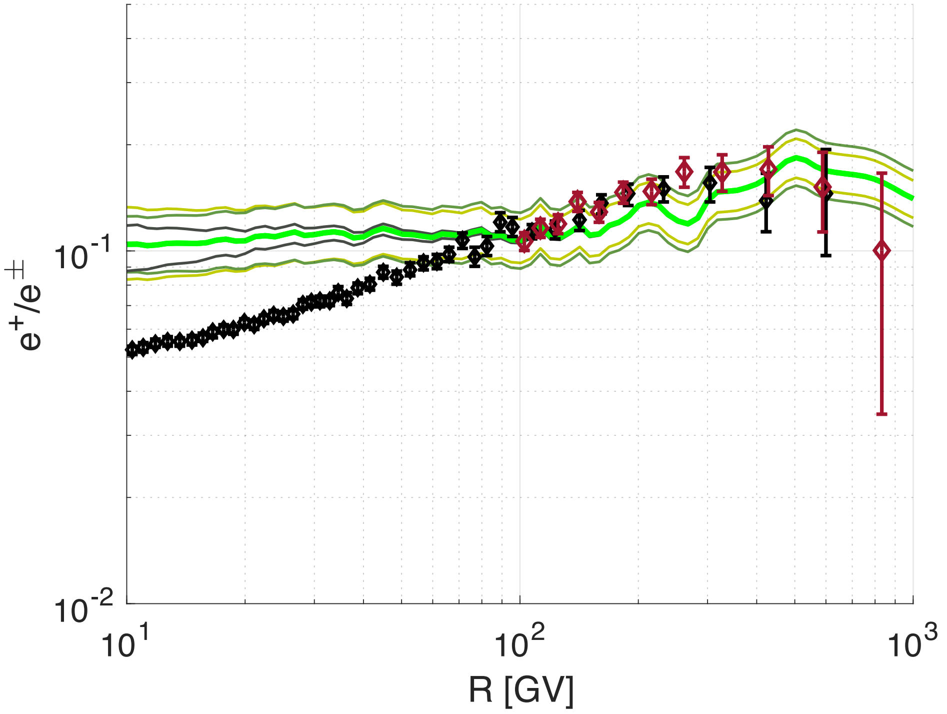
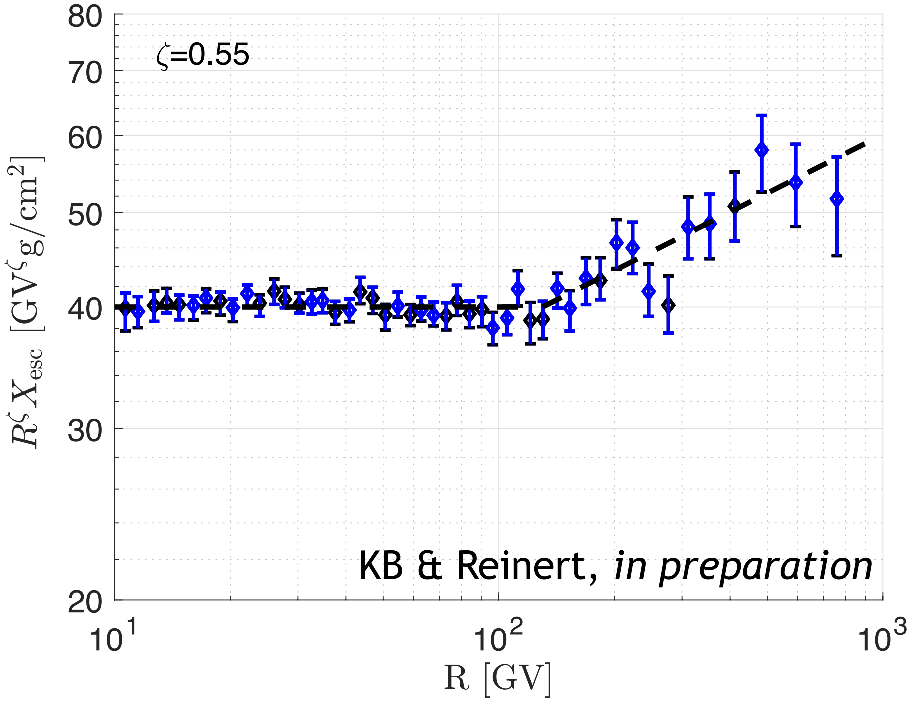


Cosmic ray grammage **Xesc**, derived from **B/CNO**…



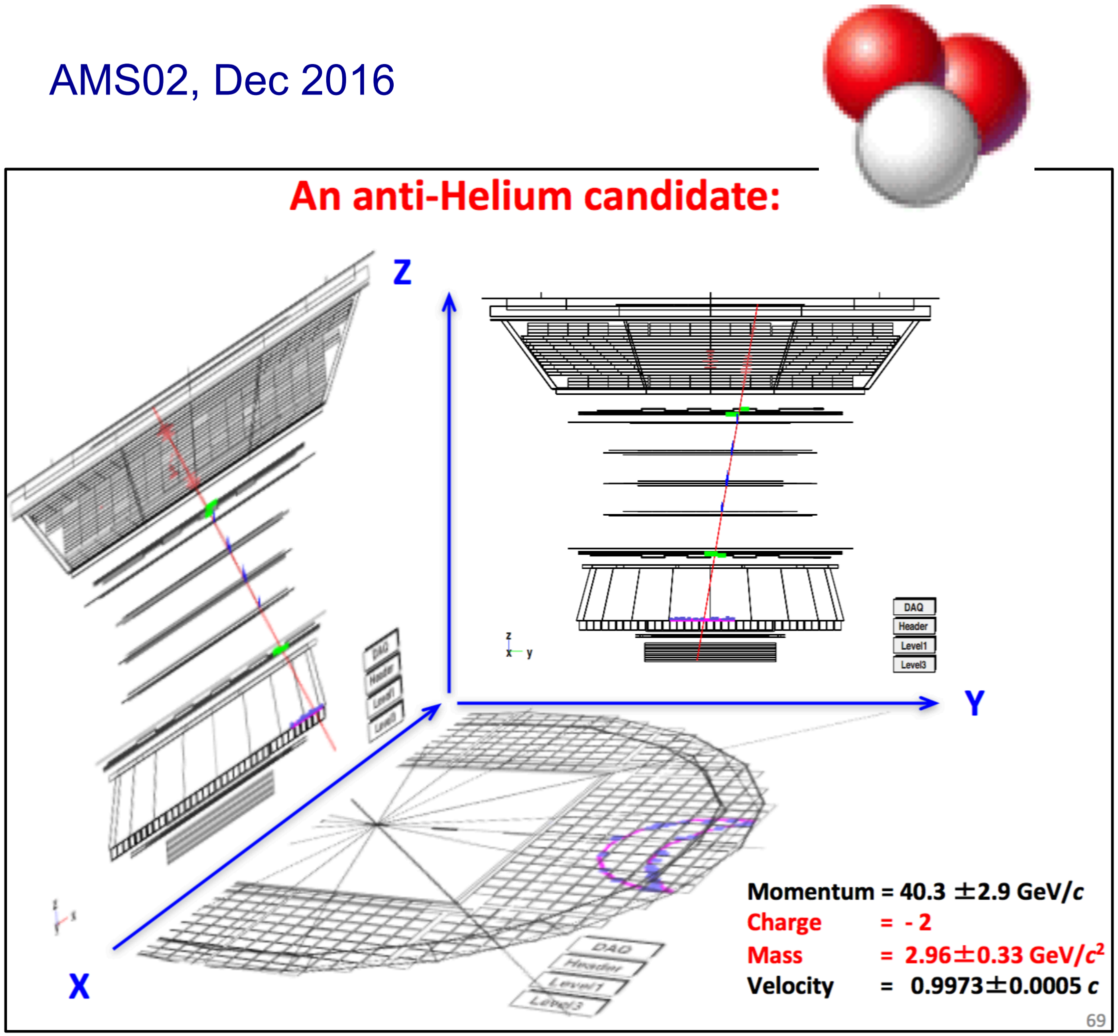
KB & Reinert, *in preparation*

anti He3

anti He3

Handful of events?

AMS02, Dec 2016


An anti-Helium candidate:

Momentum = 40.3 ±2.9 GeV/*c*

Charge = - 2

Mass = 2.96±0.33 GeV/c^2

Velocity = 0.9973±0.0005 *c*

anti He3

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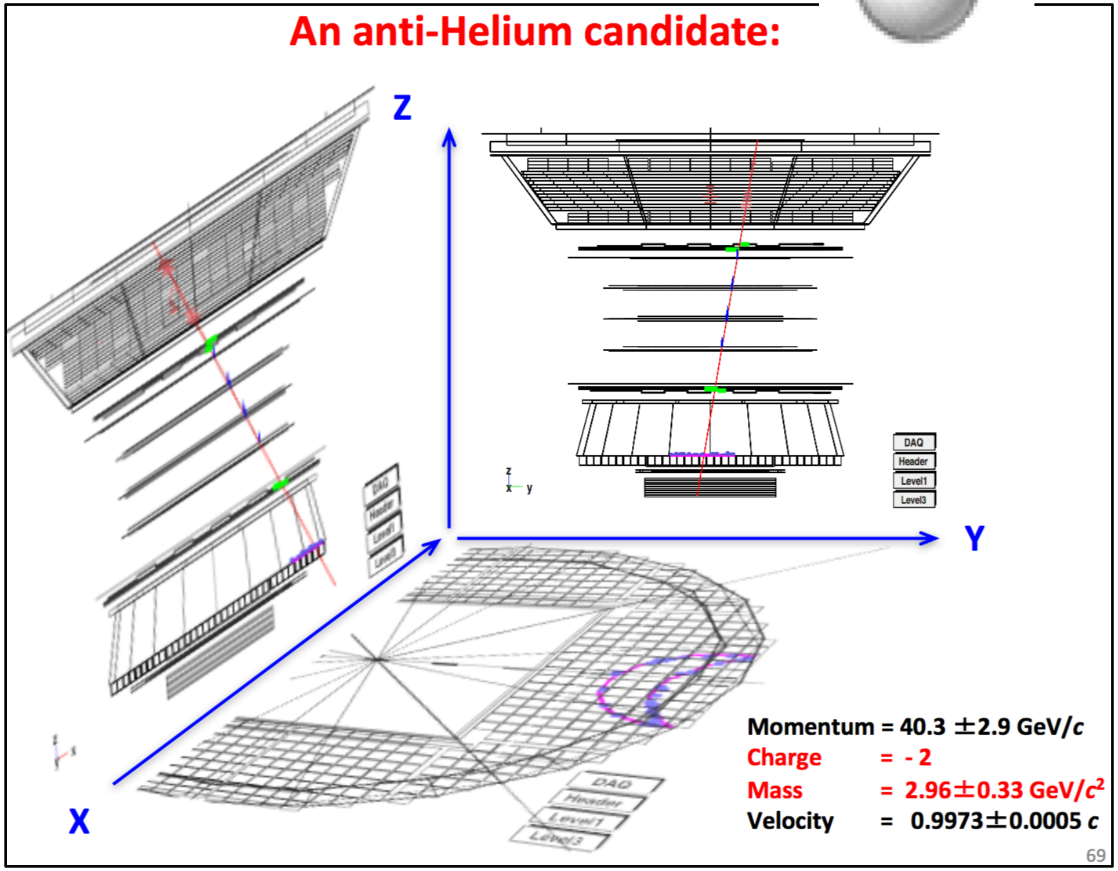
Recently (2018):
AMS report
2 anti-He4 candidates,
And 6 anti-He3 candidates.



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69

anti He3

Handful of events?

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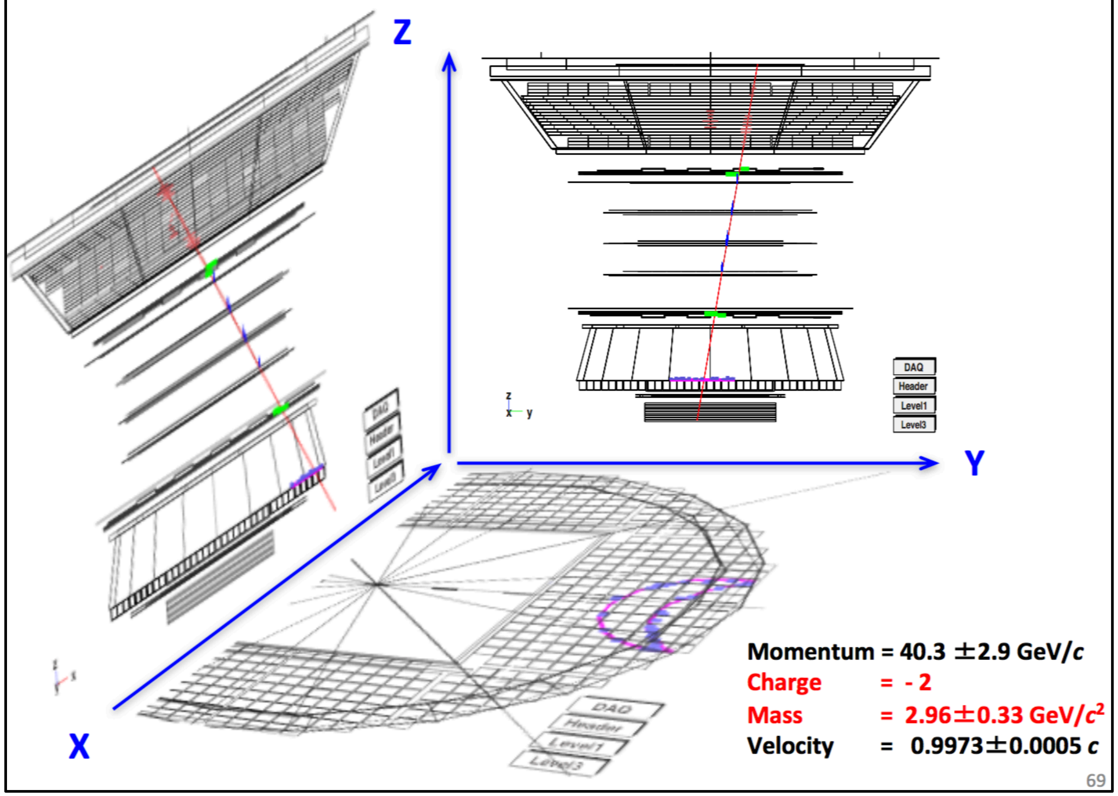
Recently (2018):
AMS report
2 anti-He4 candidates,
And 6 anti-He3 candidates.

Not clear if true CR events,
or rare experimental background.

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

Take it as motivation for theory
examination of astro flux.

An anti-Helium candidate:



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anti He3

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

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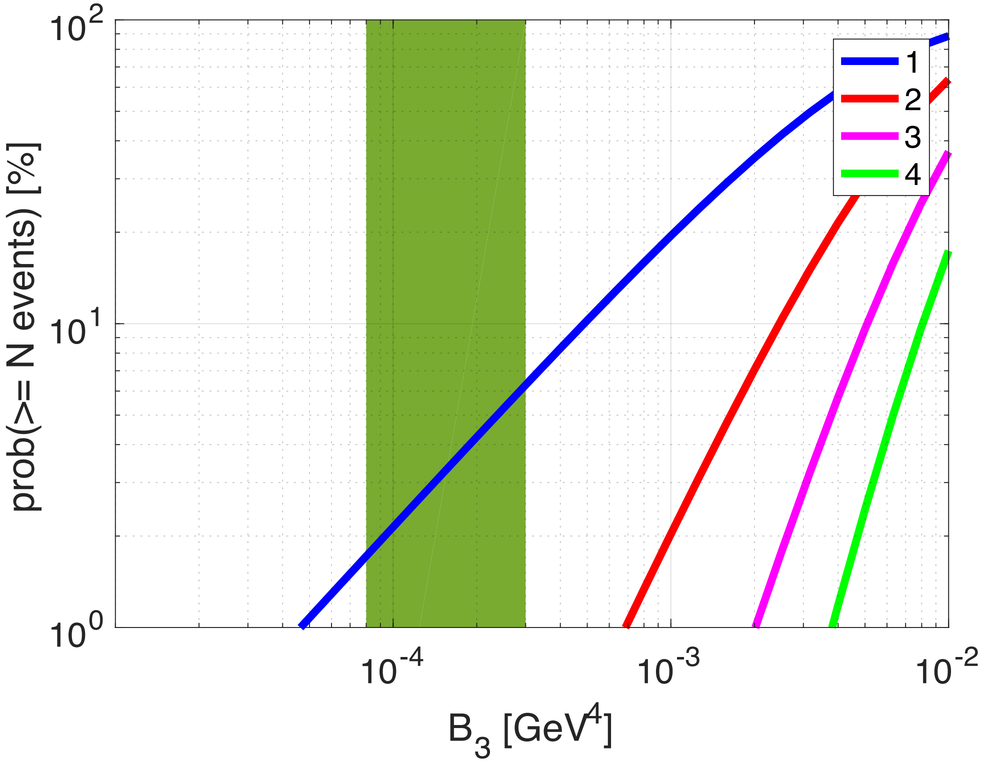

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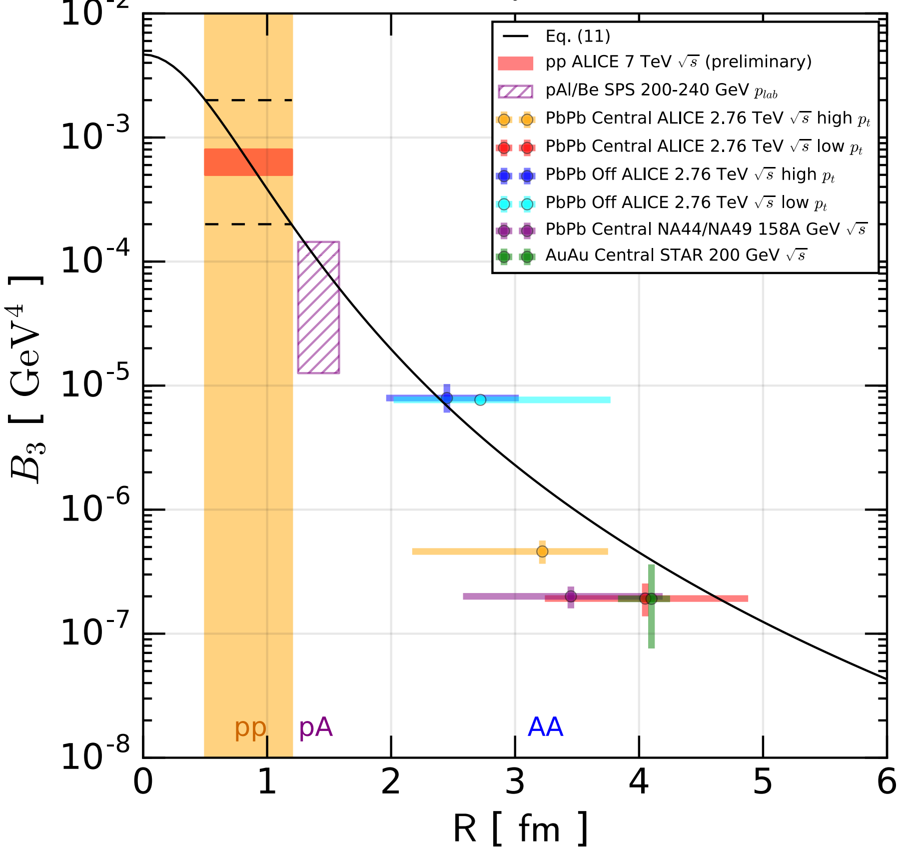
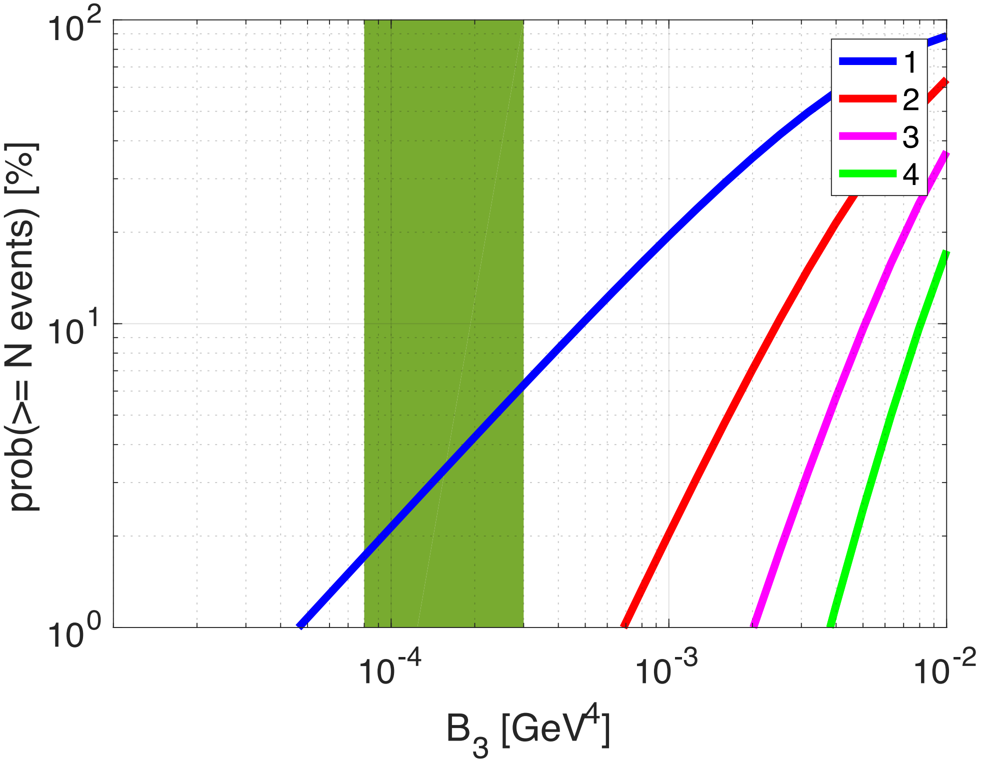
KB et al, Phys.Rev. D96 (2017) no.10, 103021





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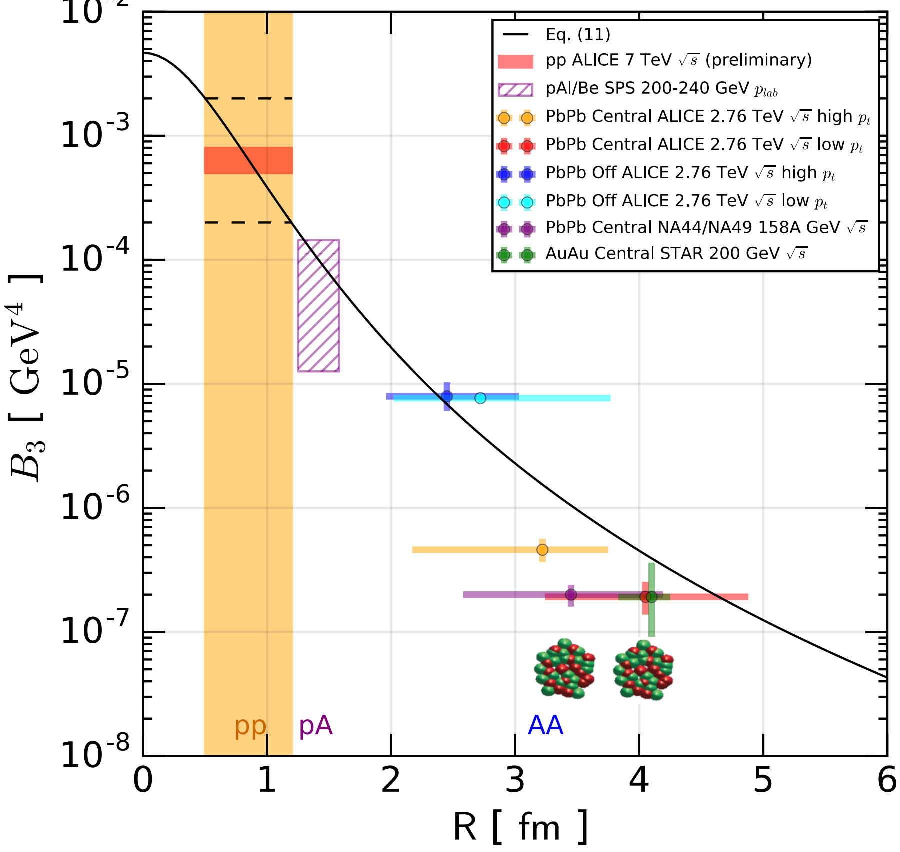

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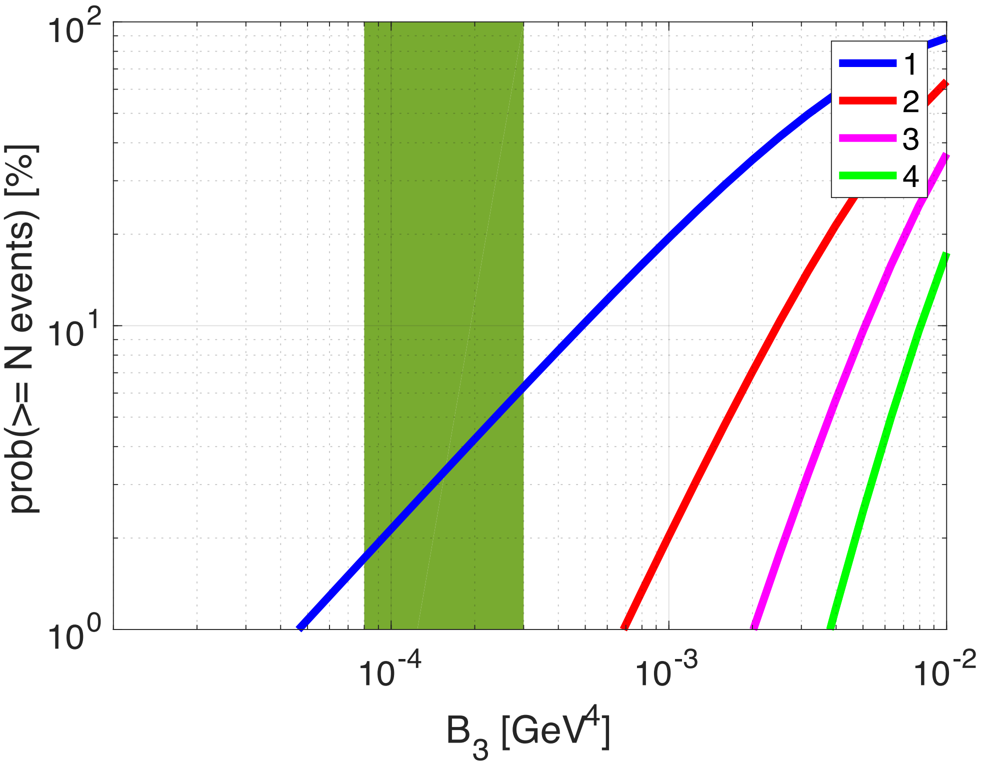

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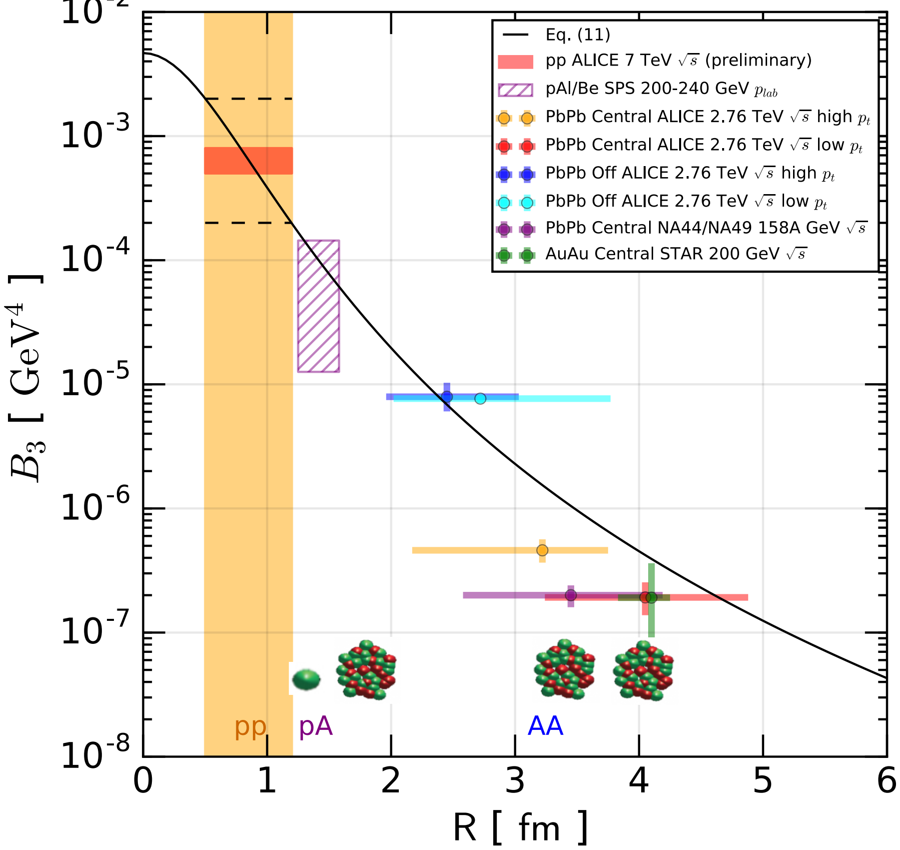

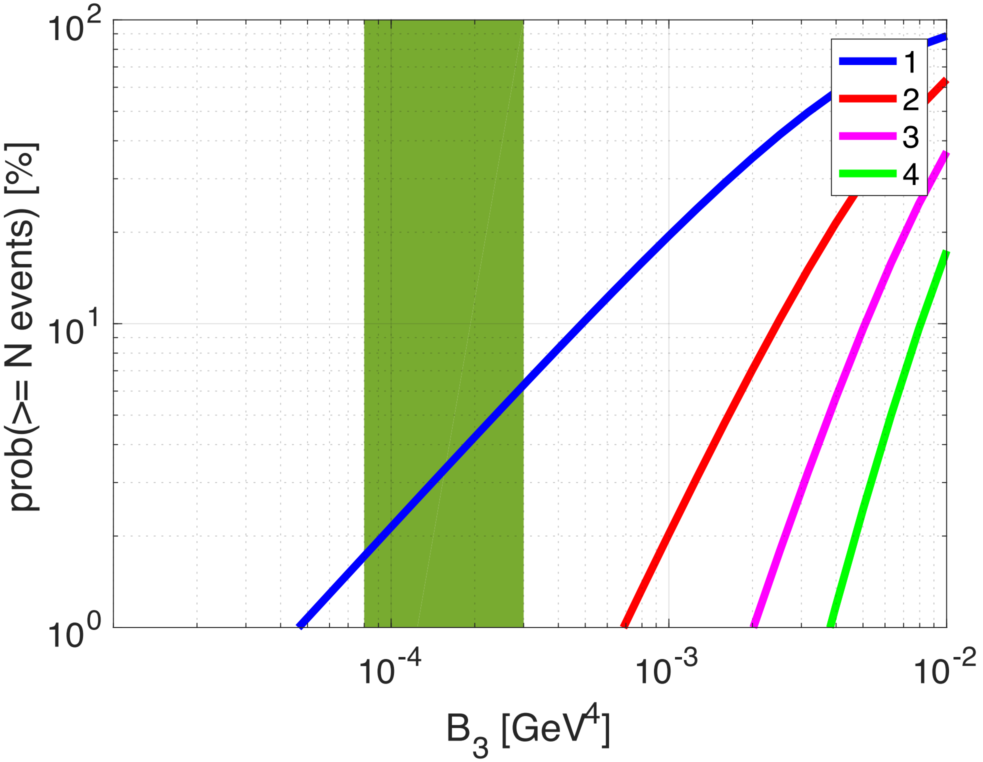

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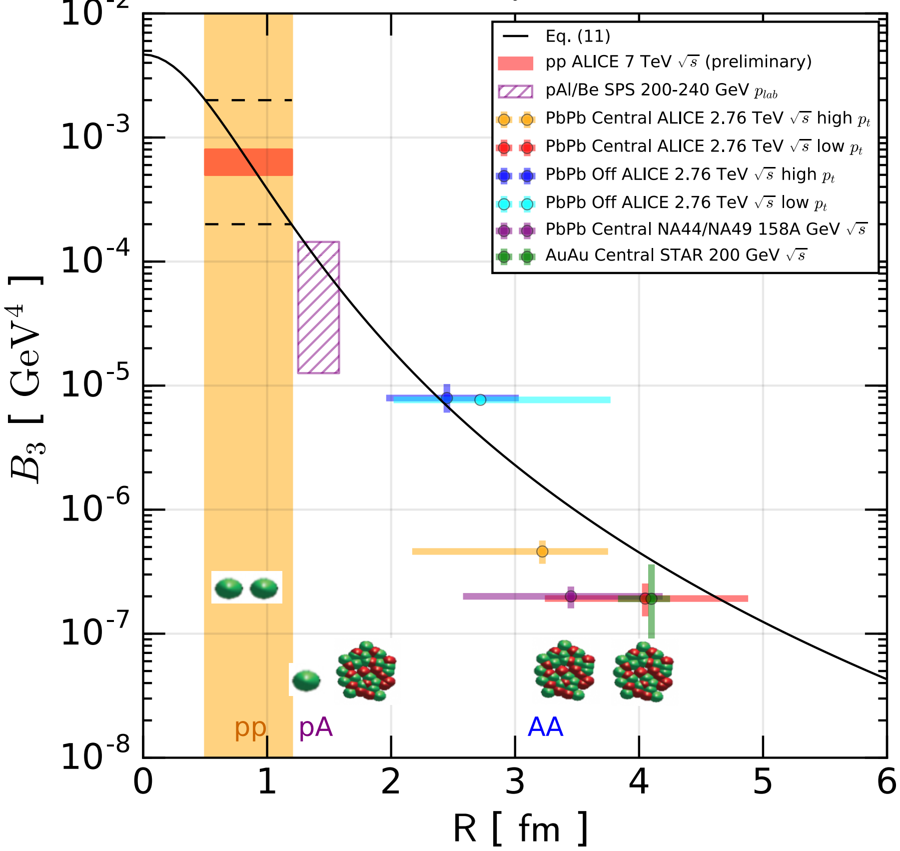
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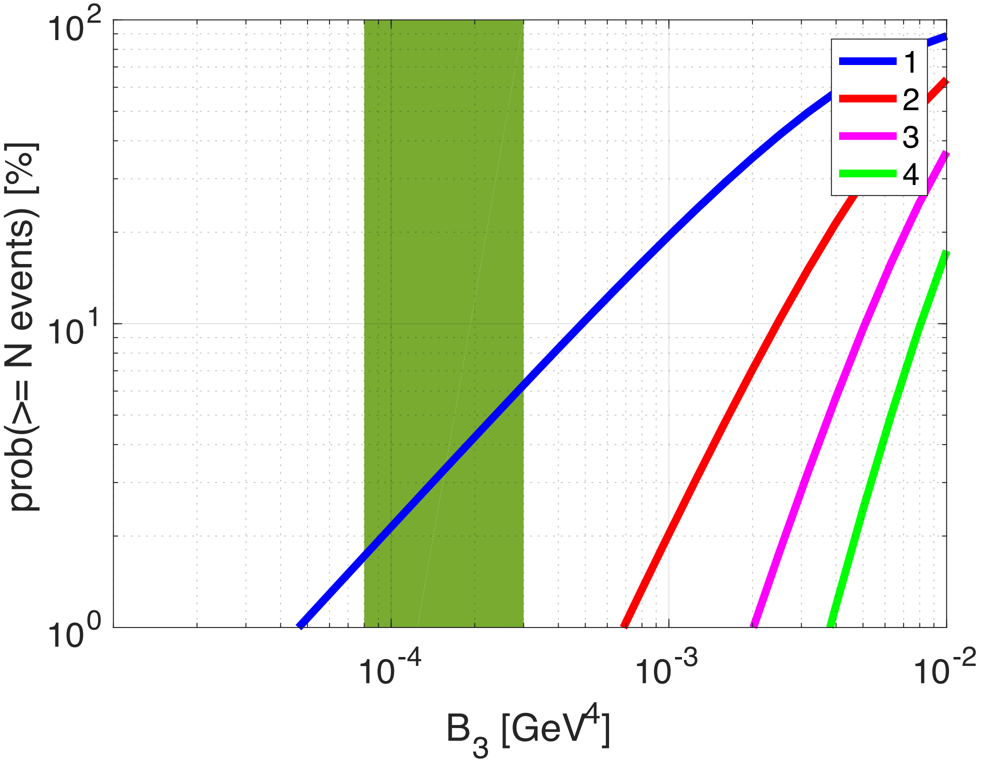

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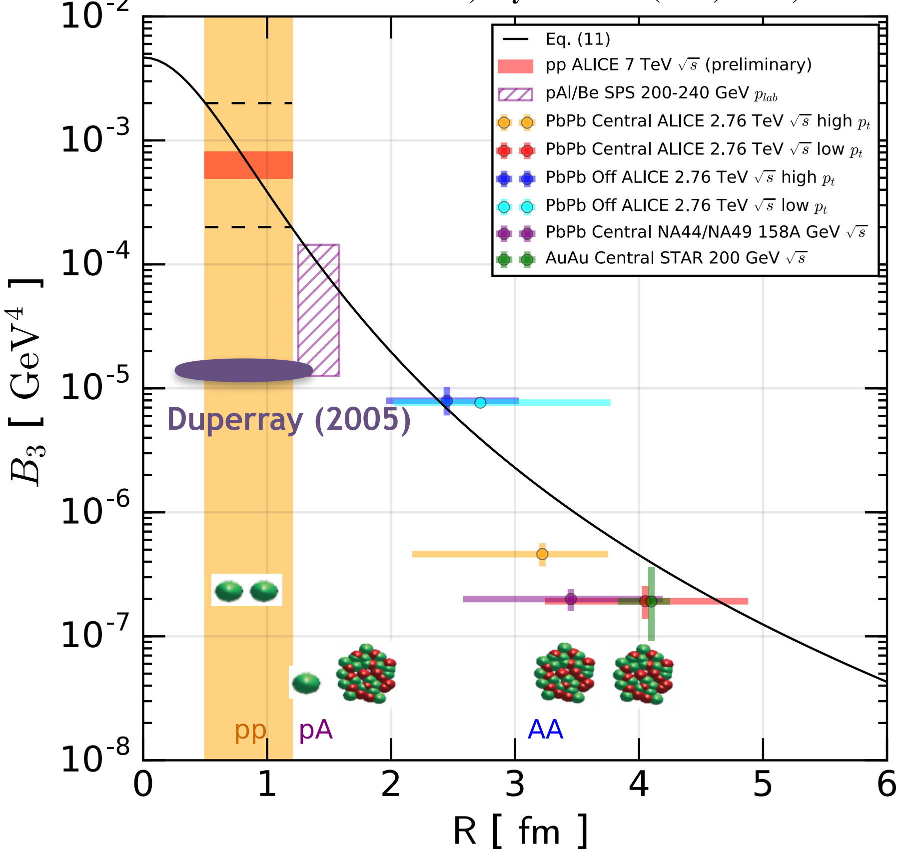
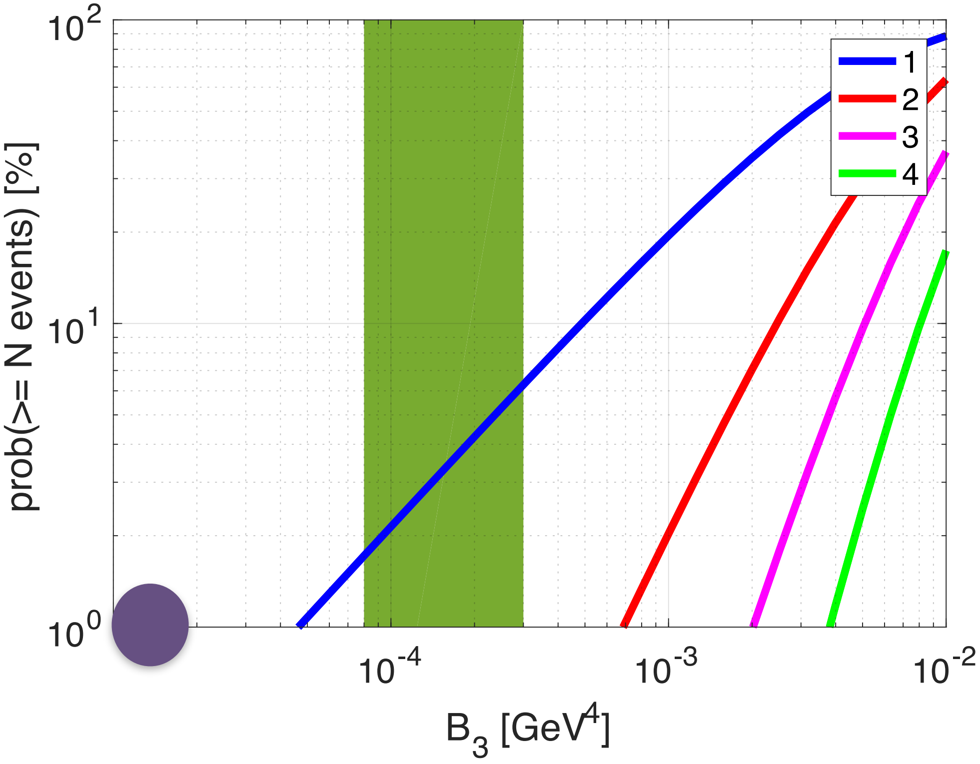




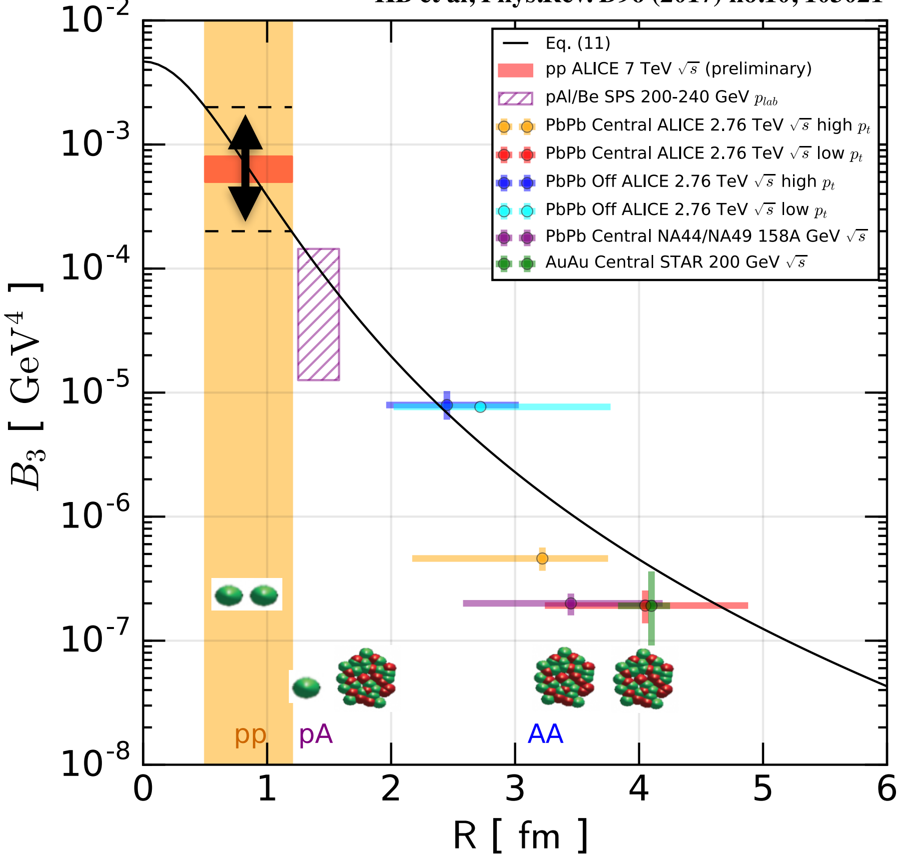
For pp we had no B_3, but we *did have HBT*

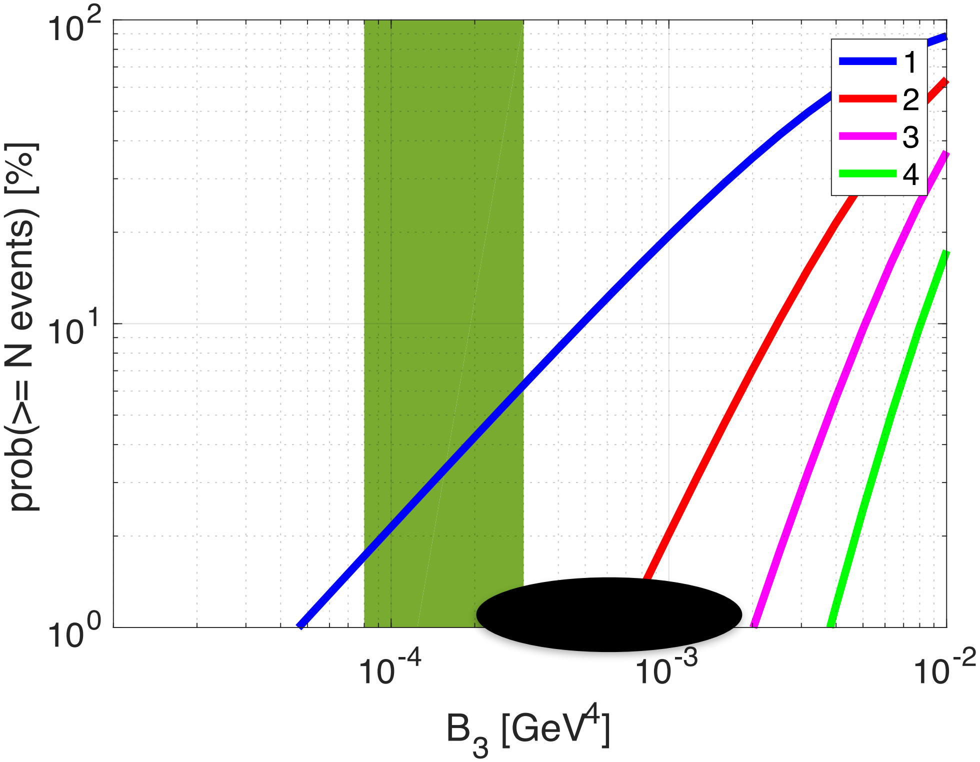
$$\boxed{\frac{\mathcal{B}_A}{m^{2(A-1)}} \approx \frac{2J_A+1}{2^A\sqrt{A}}\left(\frac{m\,R}{\sqrt{2\pi}}\right)^{3(1-A)}}$$

Scheibl & Heinz, PRC59, 1585 (1999)
KB et al, Phys.Rev. D96 (2017) no.10, 103021

KB & Takimoto, 1901.07088

KB et al, Phys.Rev. D96 (2017) no.10, 103021





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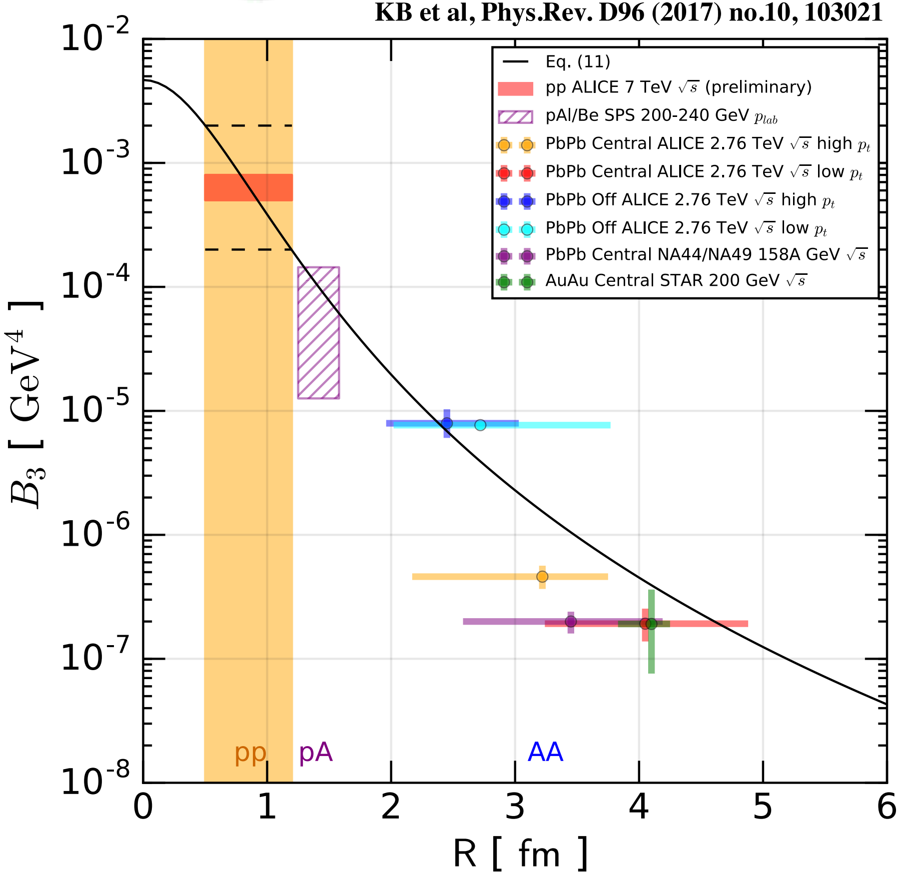
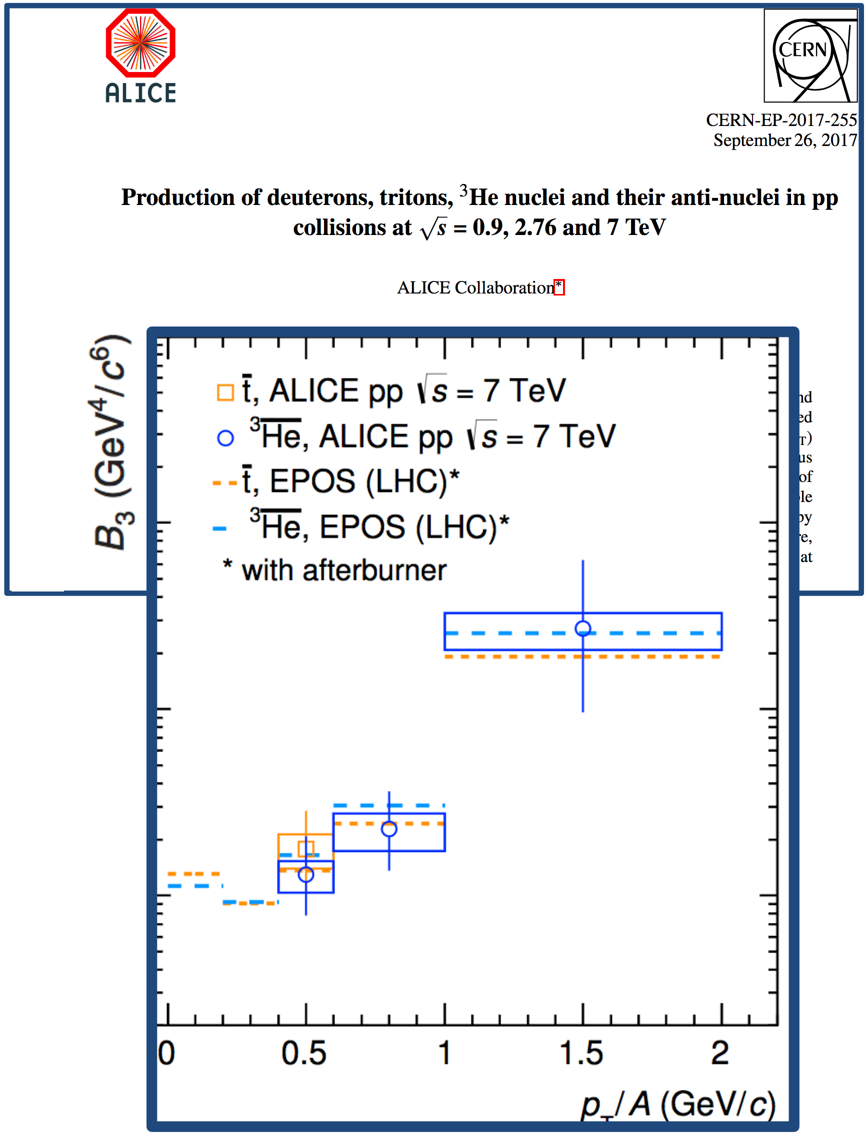


ALICE, PRC97, 024615 (2018)



CERN-EP-2017-255
September 26, 2017

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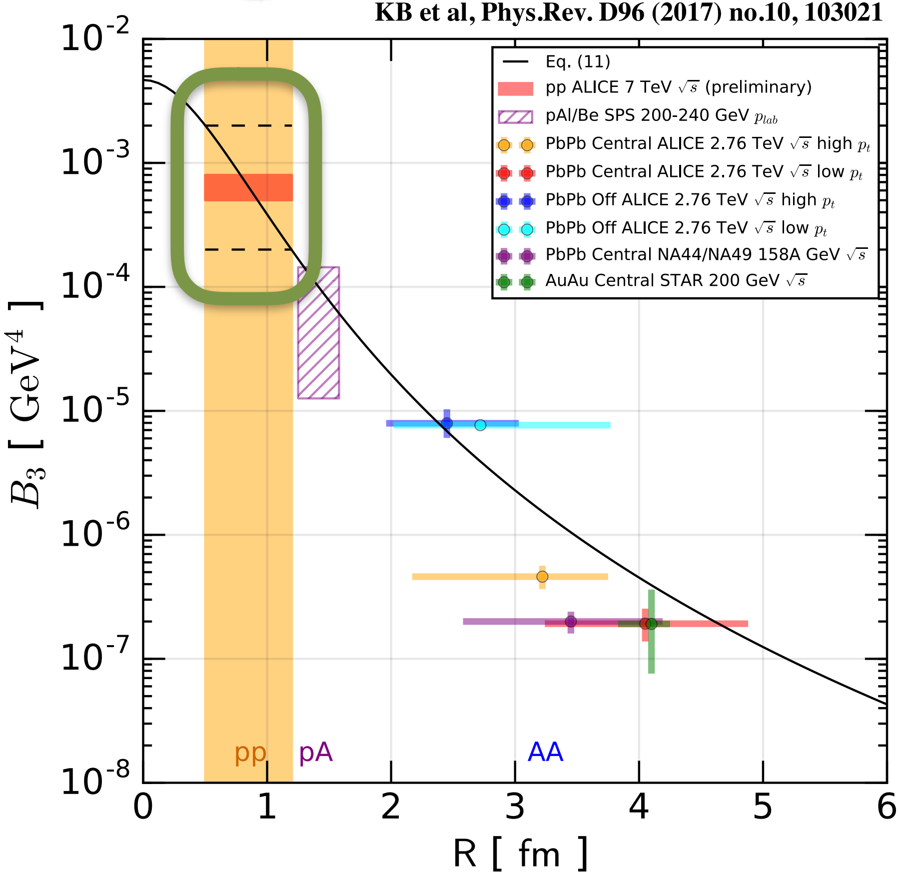

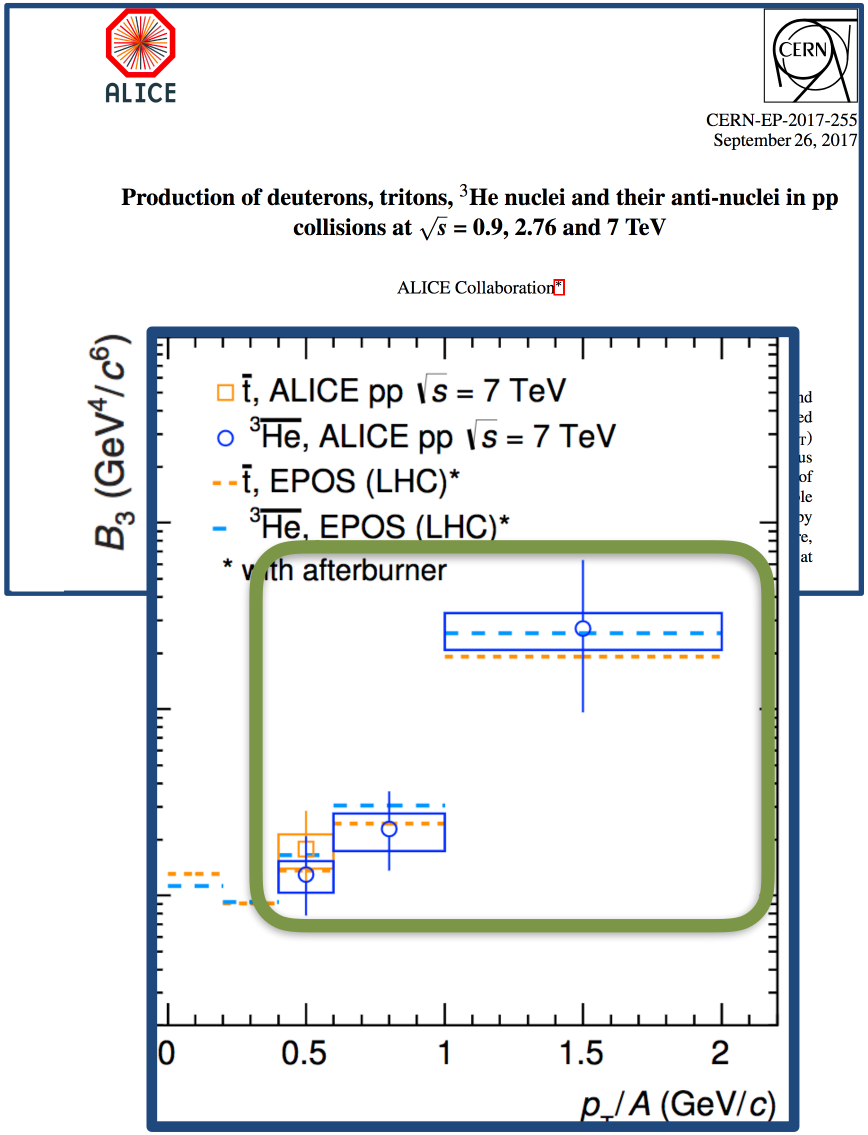

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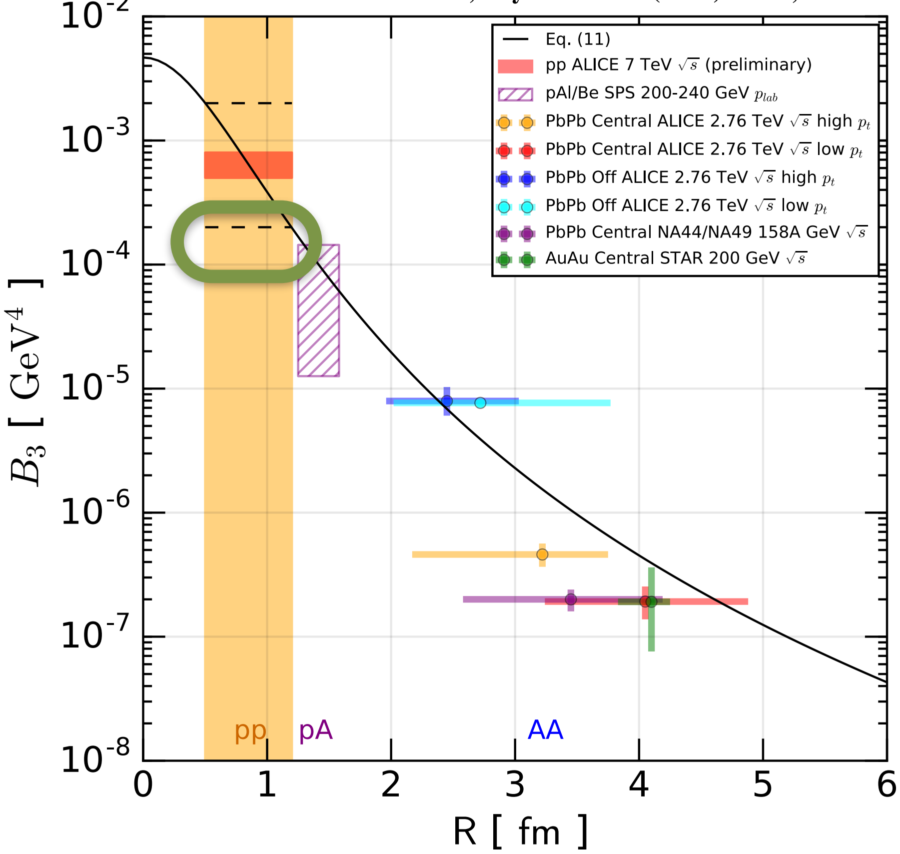

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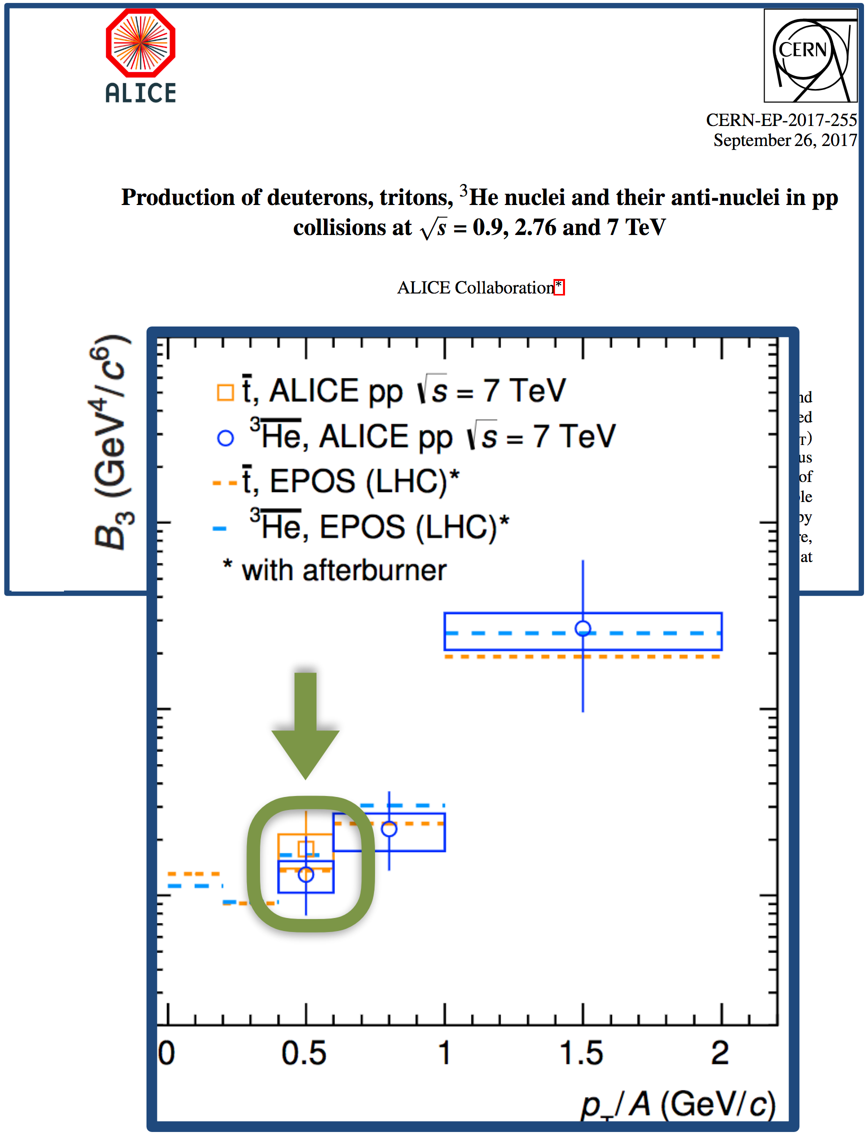

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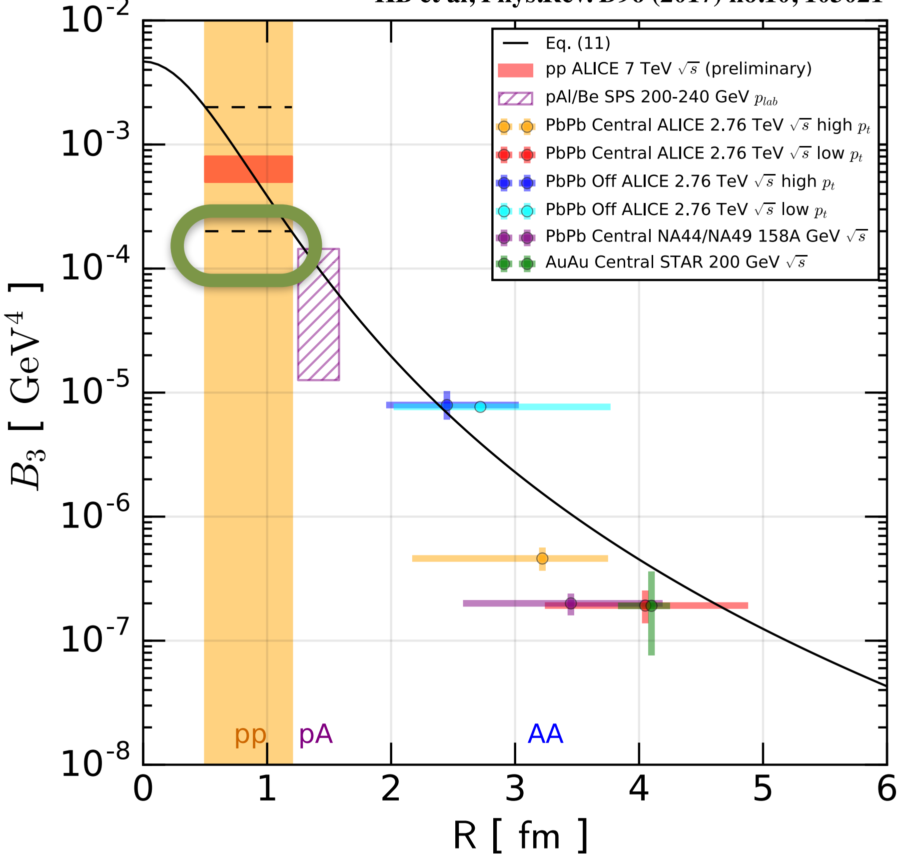

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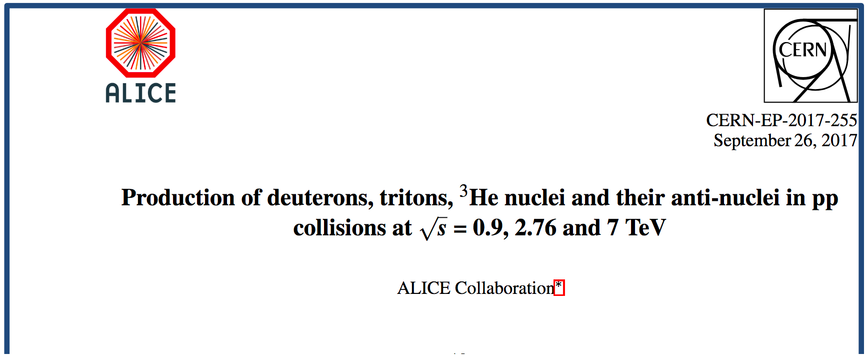

ALICE

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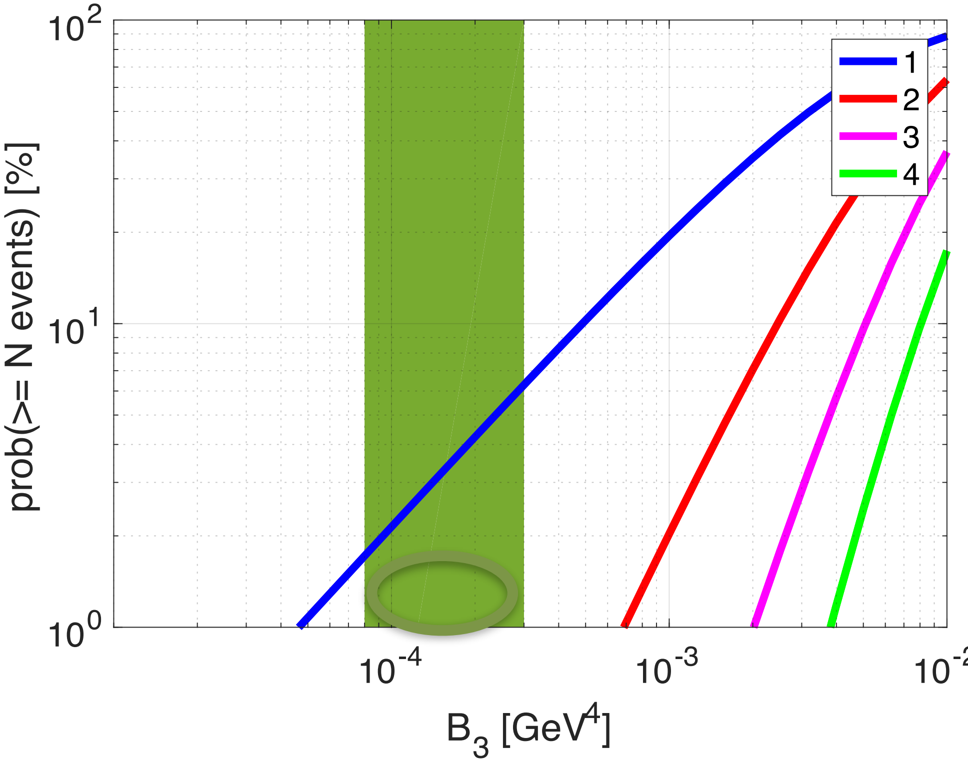

Implications of ALICE results for astrophysics:

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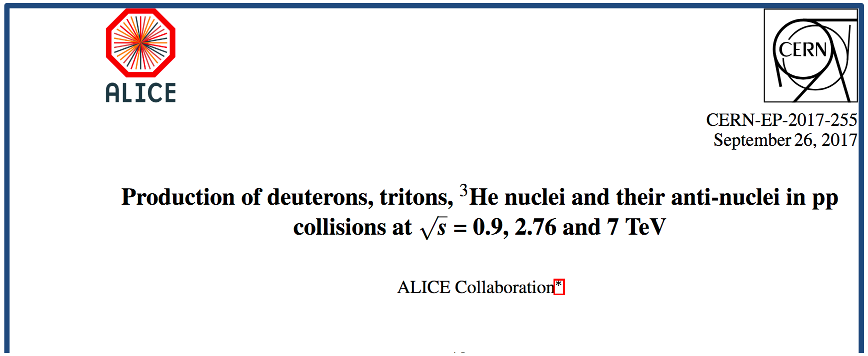

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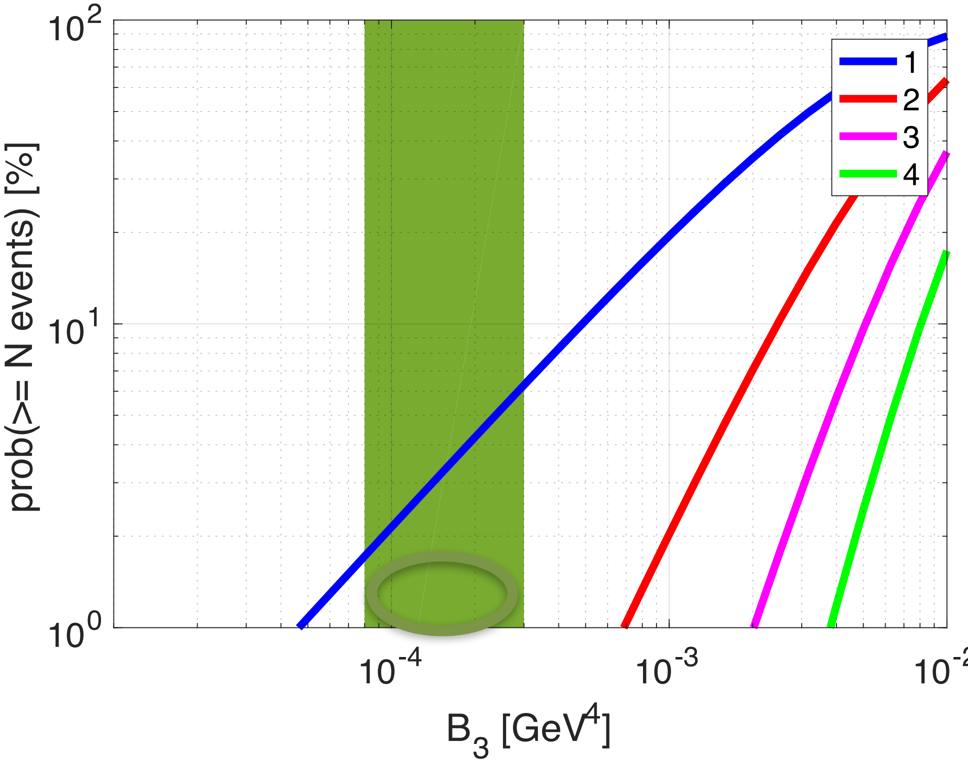

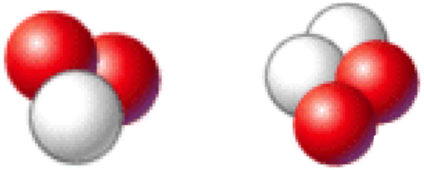

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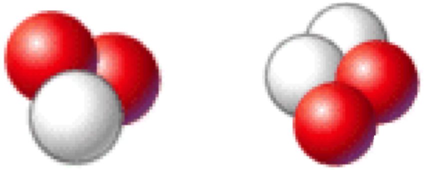

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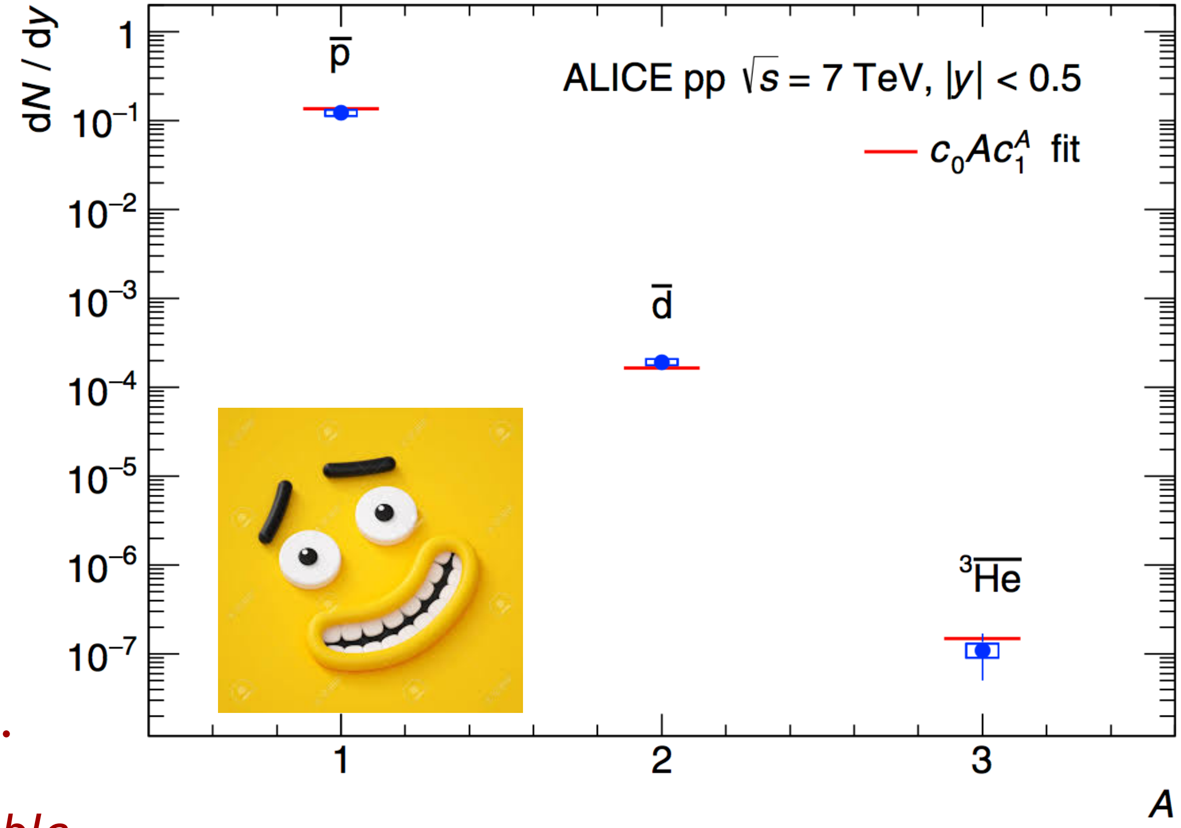

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What can we learn from cosmic ray antimatter?

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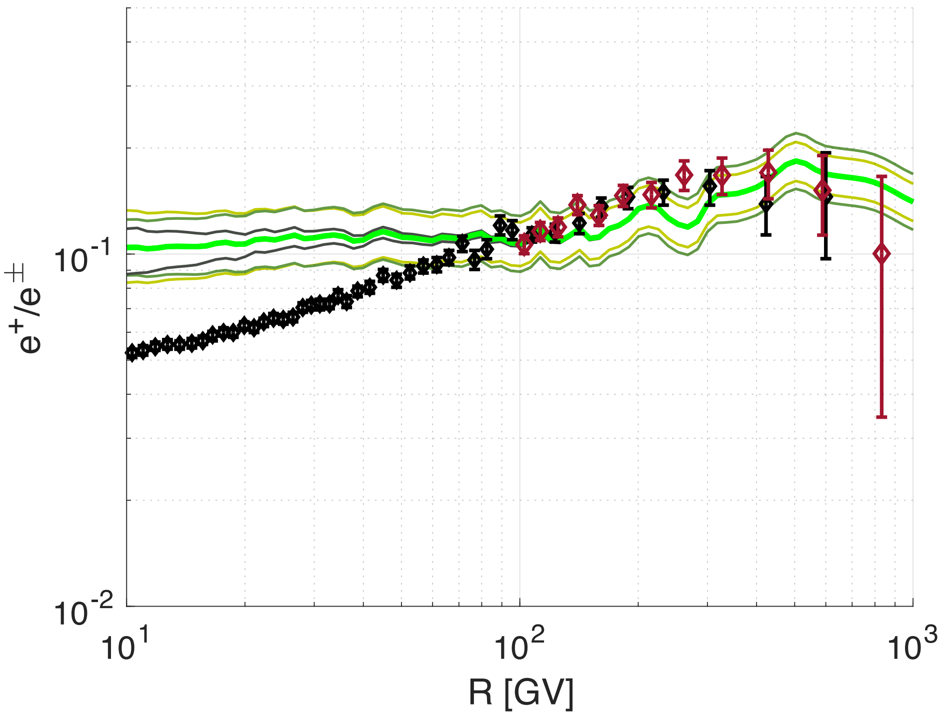
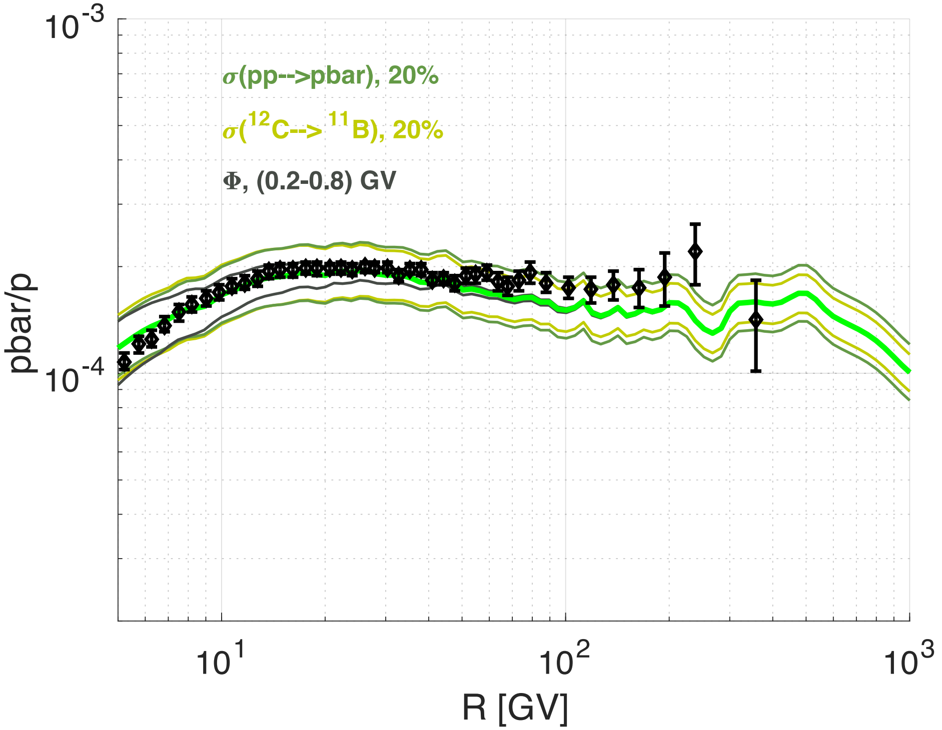
Evidence that CR antimatter is secondary: coming from CR collisions with ISM.
Certainly no clear hint of BSM.





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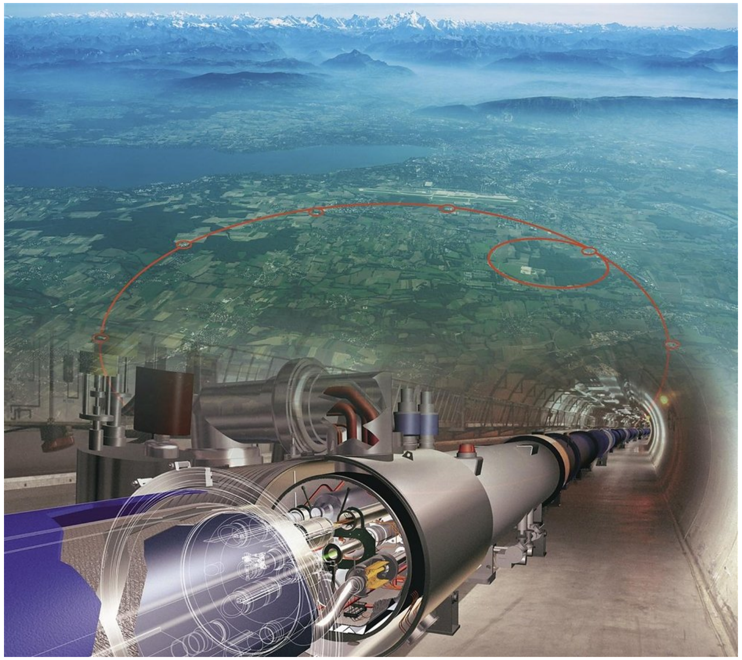
AMS is in really good company in this respect.



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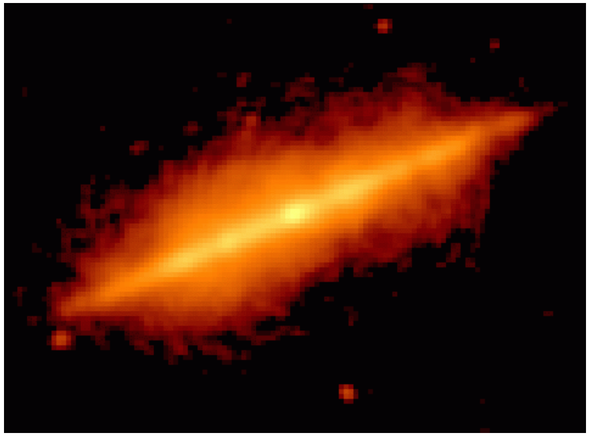


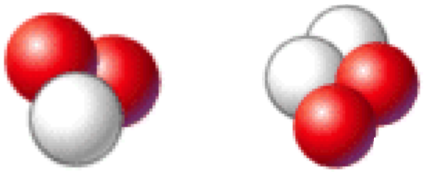
But the CR astrophysics is very interesting:

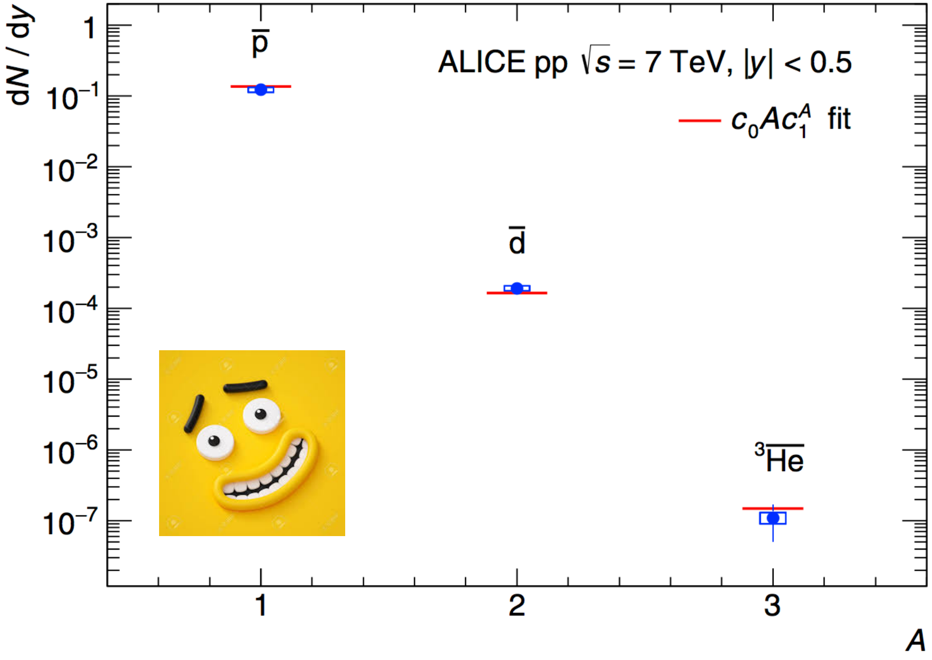
Where do CR come from?
How long are they trapped in the Galaxy?
How do they escape?

When you build a CR experiment, these are the bread-and-butter questions on which you may hope to contribute*.

* Barring, of course, unexpected strokes of luck. These are always possible, but can't be counted on.

What can we learn from cosmic ray antimatter?





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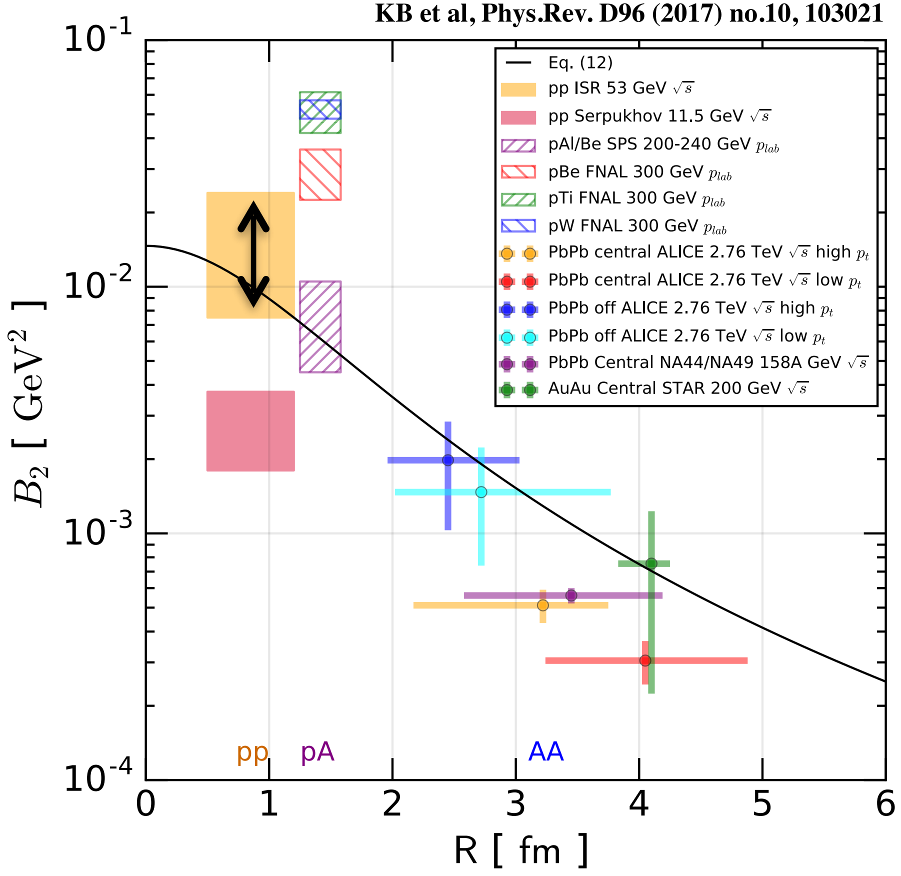
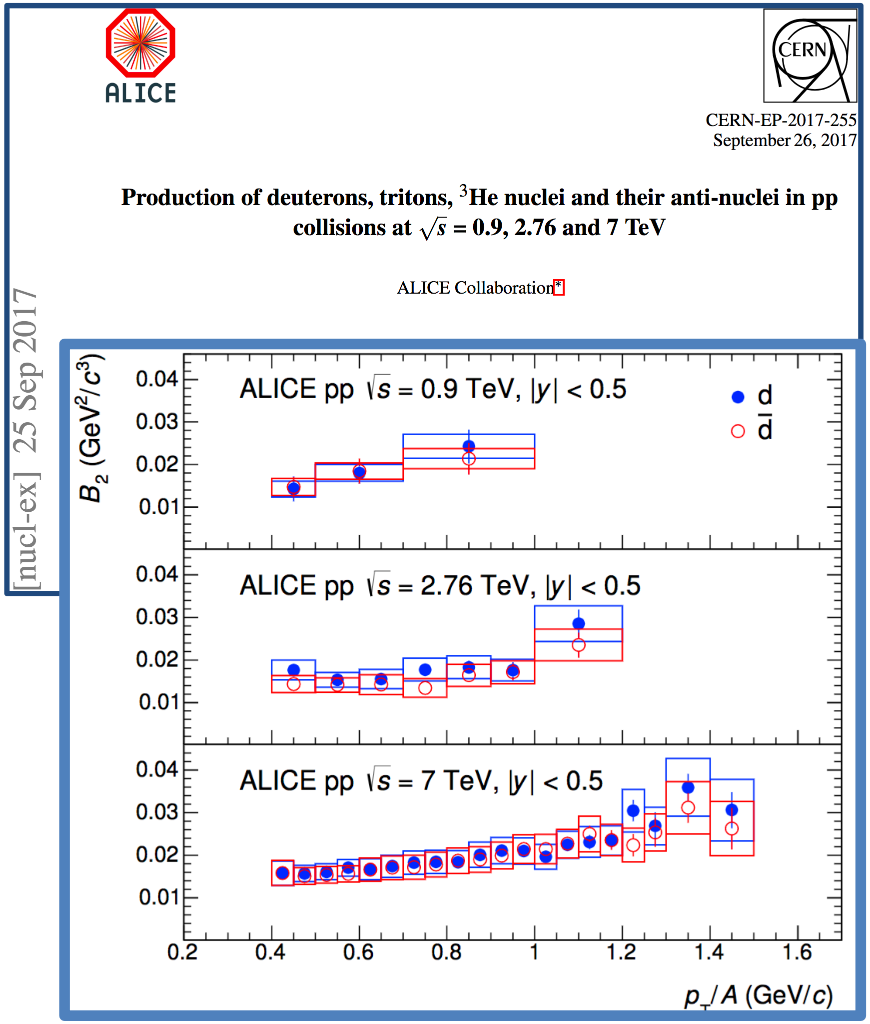
Xtra

KB et al, Phys.Rev. D96 (2017) no.10, 103021





ALICE

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ALICE Collaboration*

[nucl-ex] 25 Sep 2017

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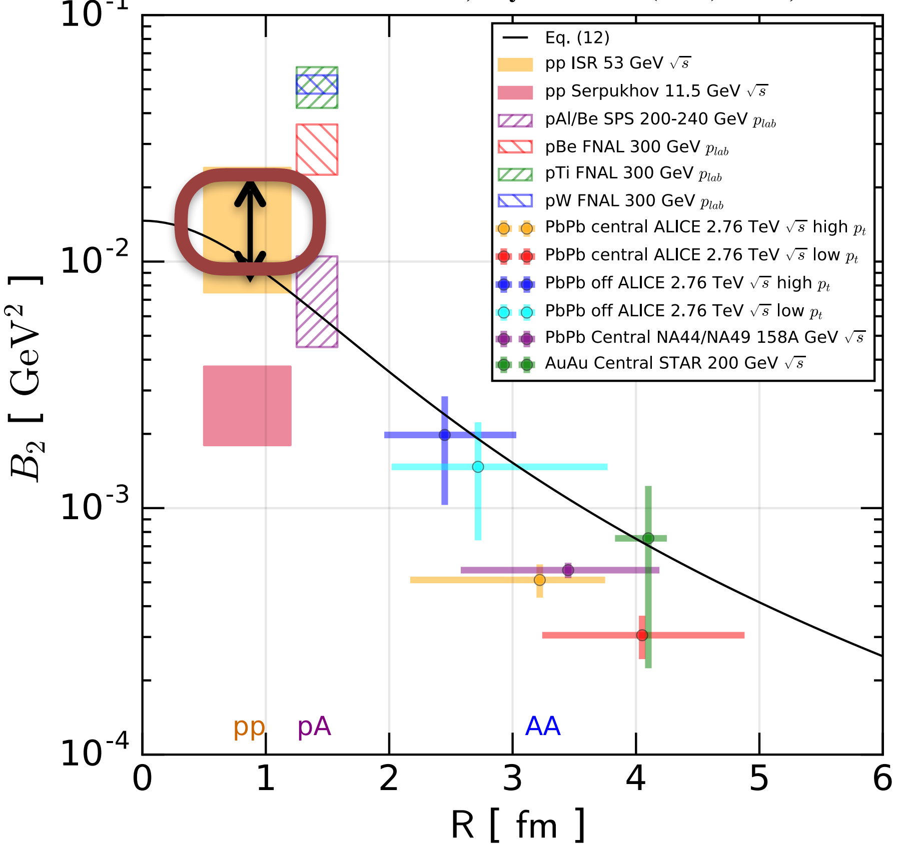

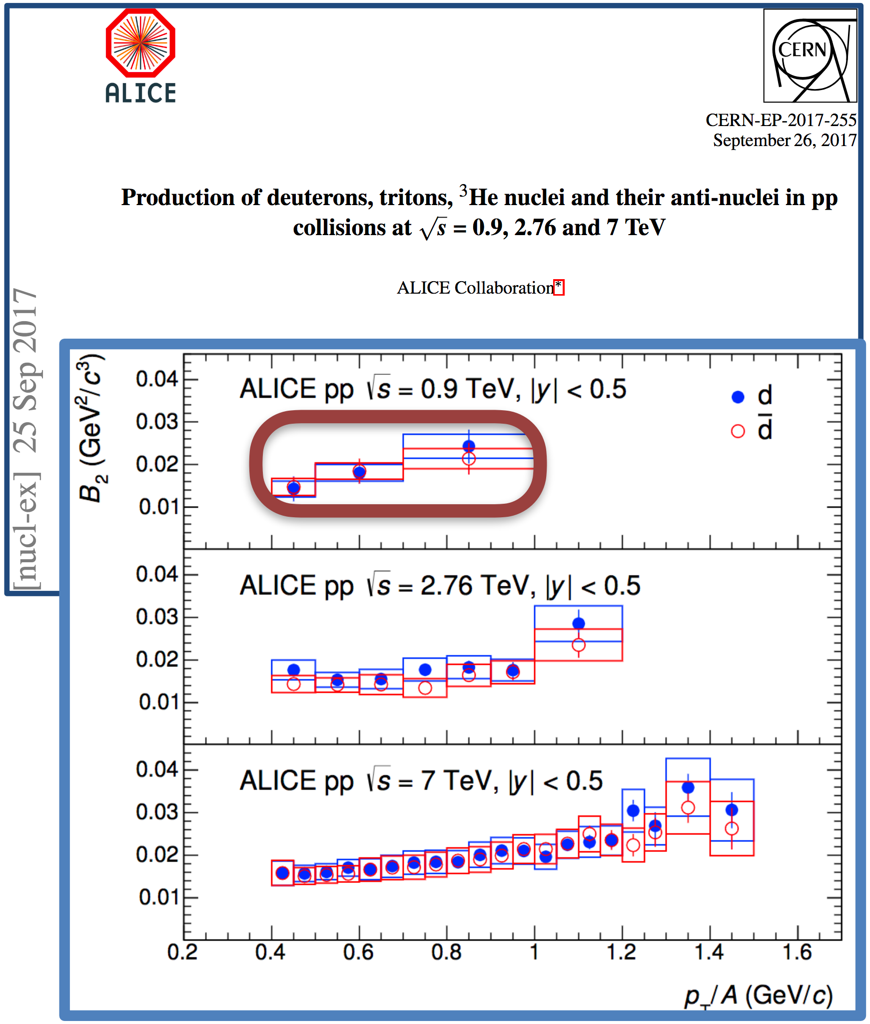

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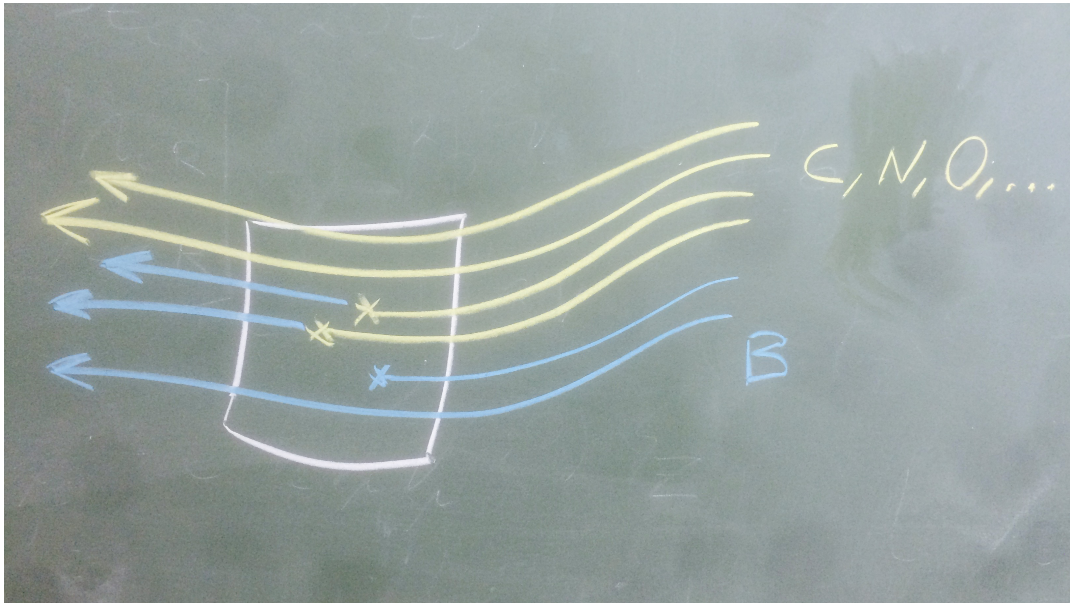
antimatter is produced in collisions of the bulk of the CRs
-- protons and He – with interstellar gas

For secondary CR, we have a handle: particle physics branching fractions

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

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



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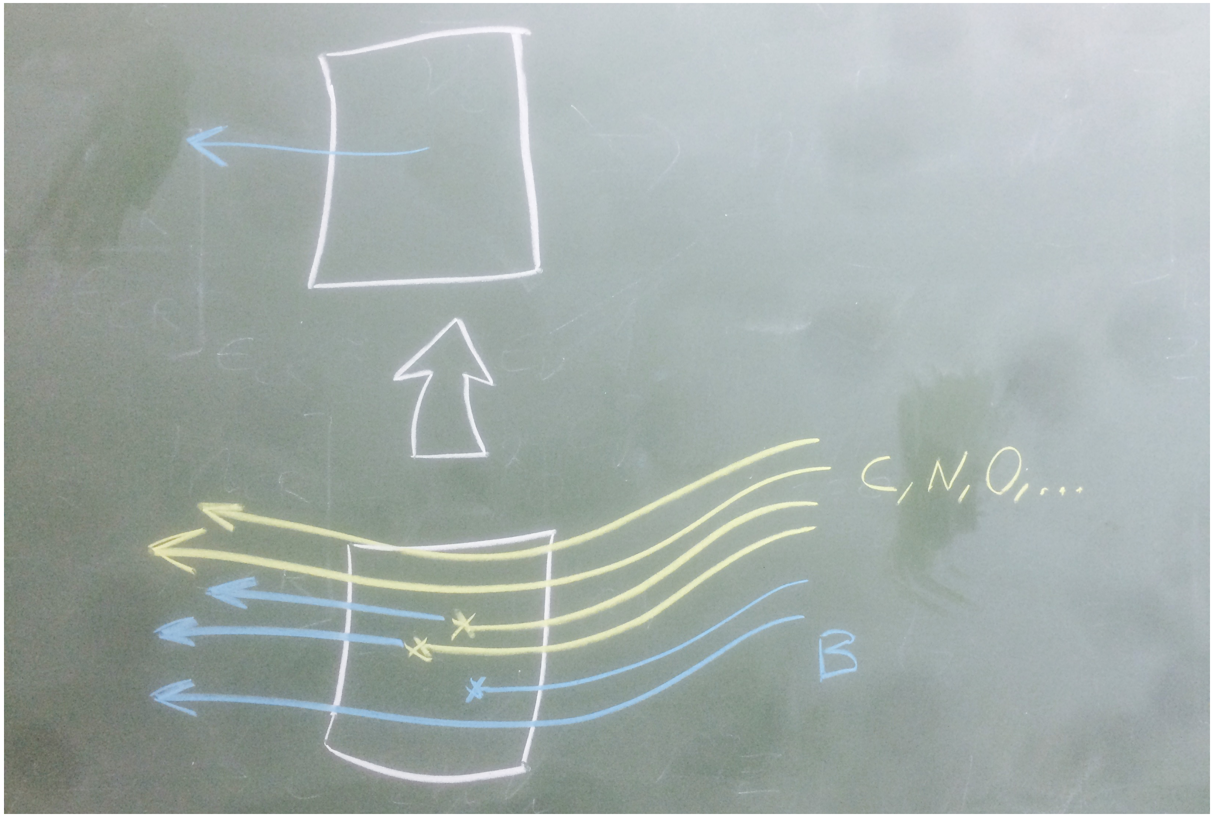

Recipe for antiproton pie:

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


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Recipe for antiproton pie:

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


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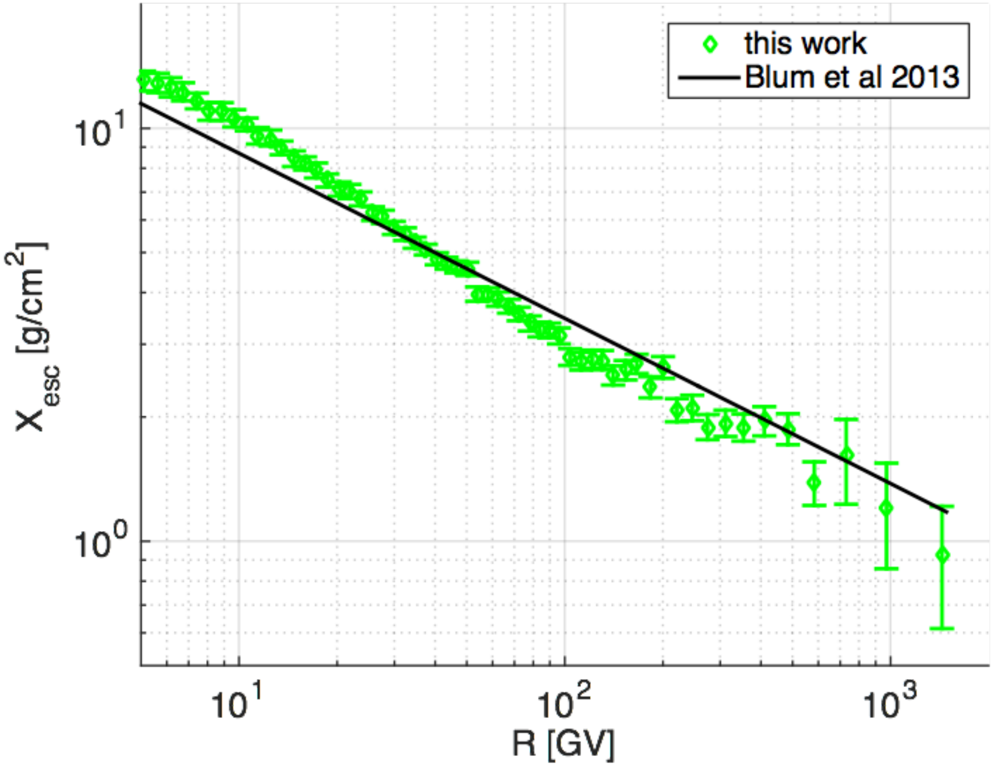
Average column density traversed by CR nuclei during propagation

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



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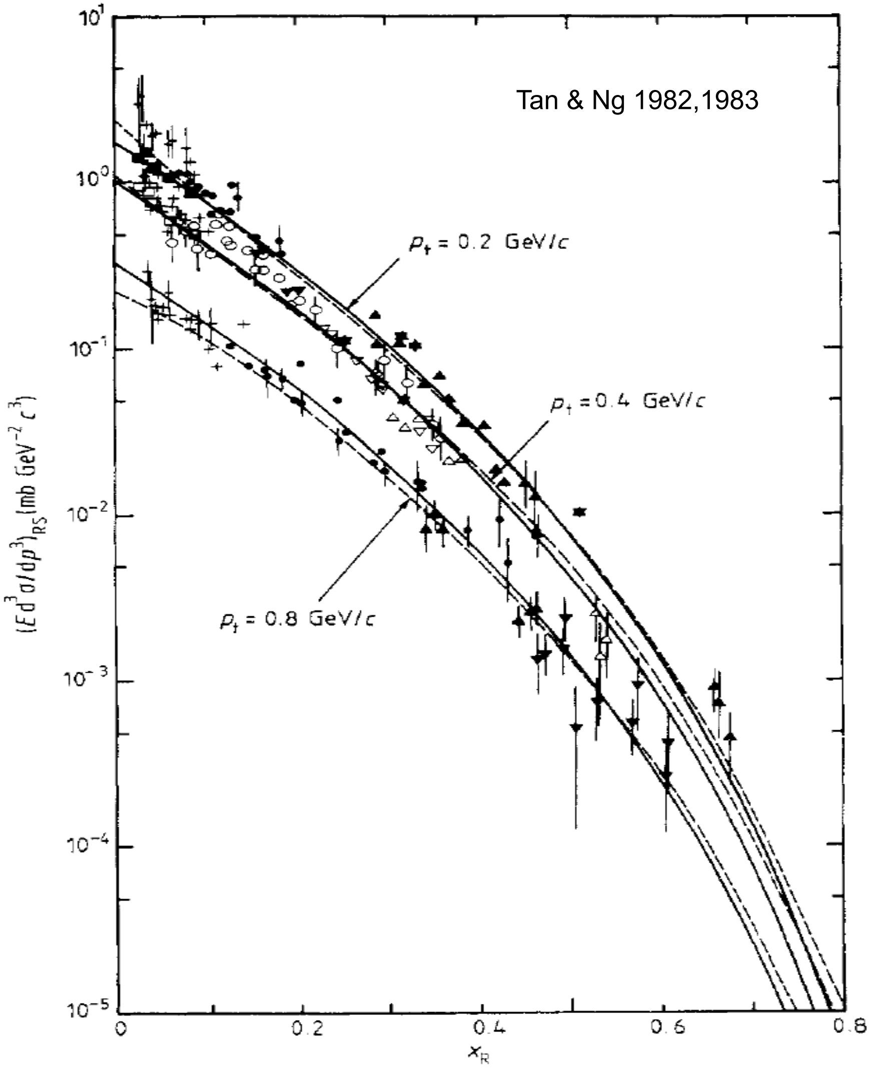
Tan & Ng 1982,1983

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

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

Recipe for antiproton pie:

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

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

KB, Sato, Takimoto, **PRD98 (2018) no.6, 063022**

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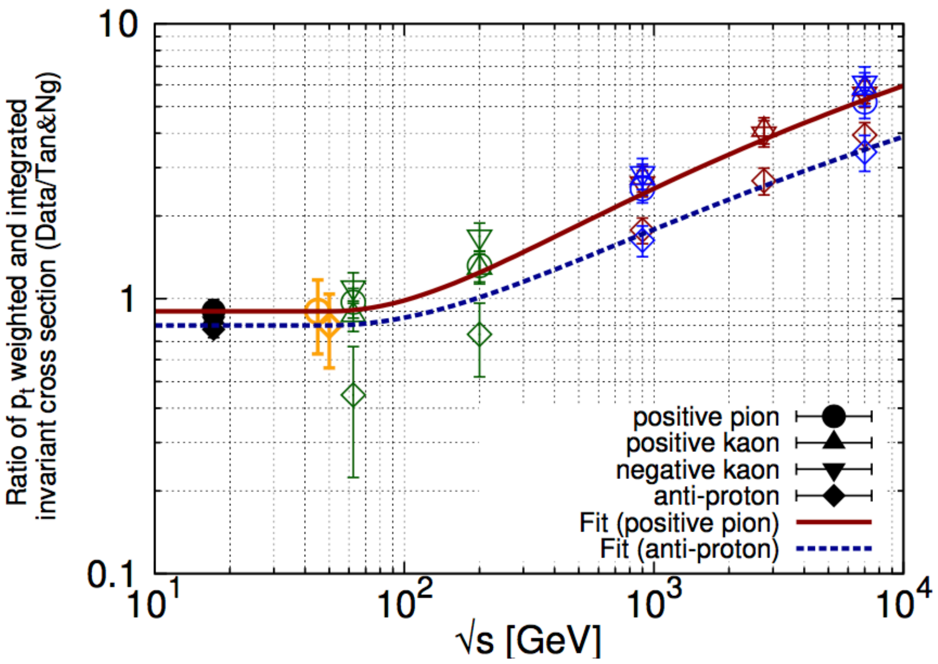

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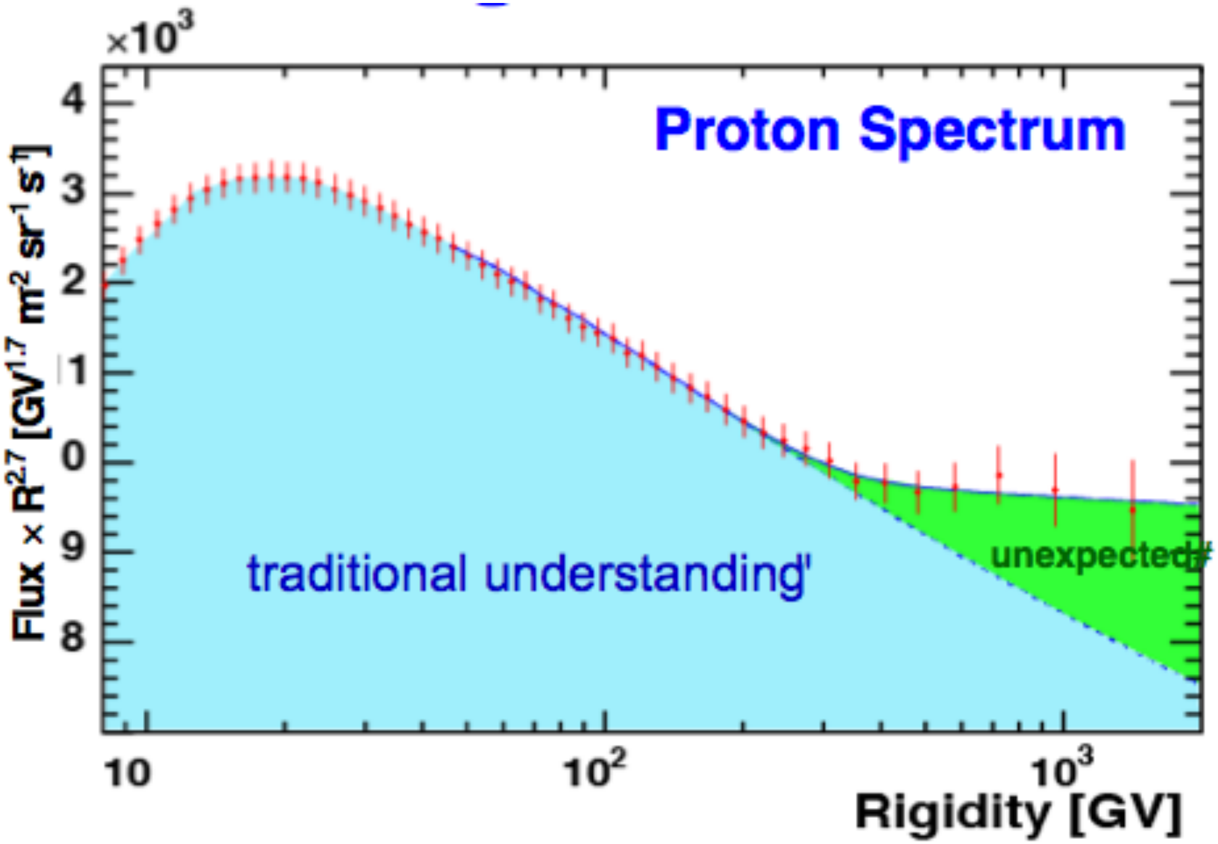
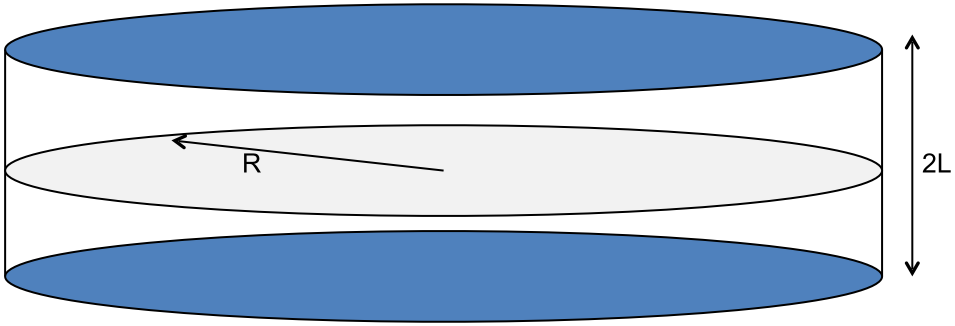
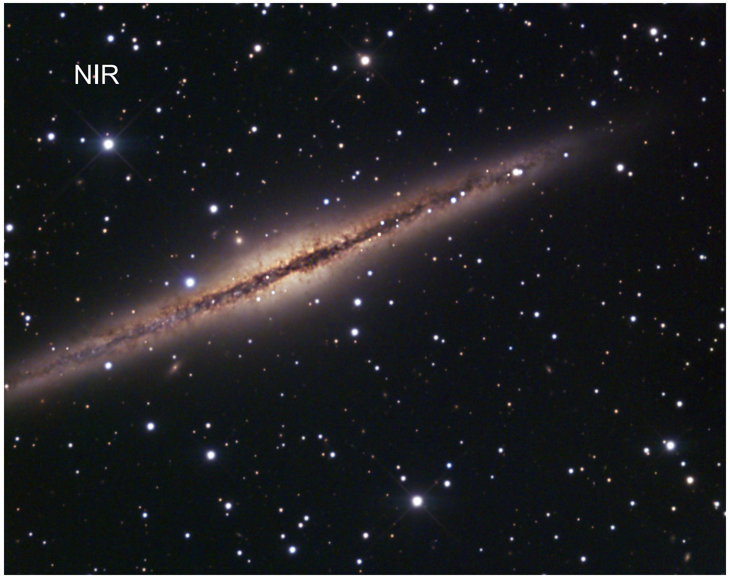


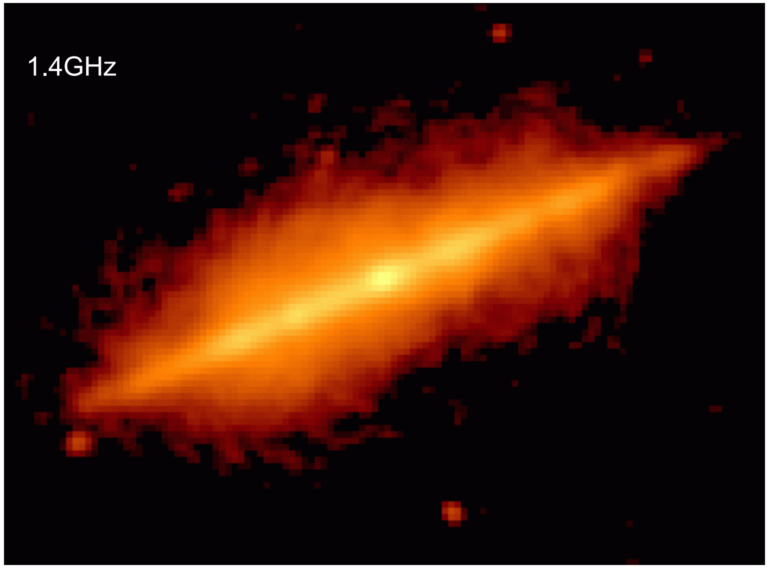
About diffusion models

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



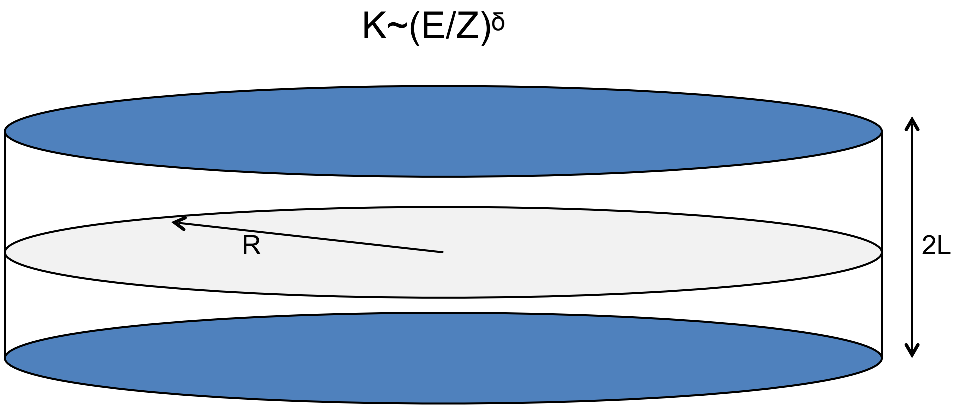
NGC 891





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

About diffusion models

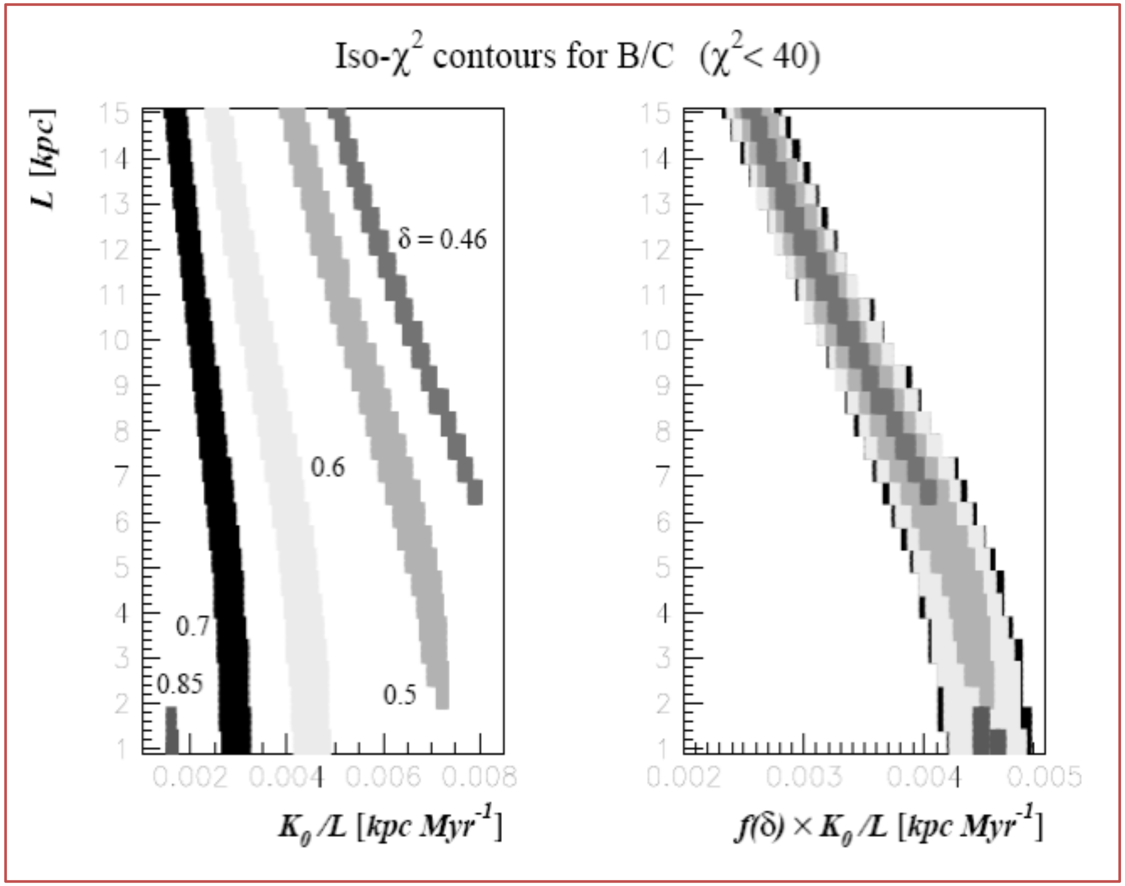


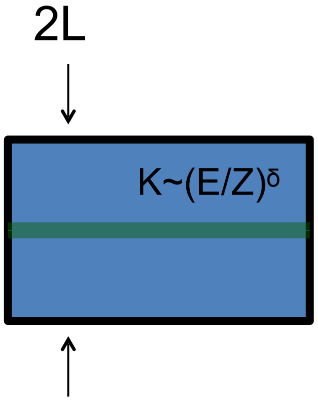
To a good approximation, disc+halo homogeneous diffusion models satisfy the criterion of uniform CR composition *where spallation happens*.

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

diffusion models fit

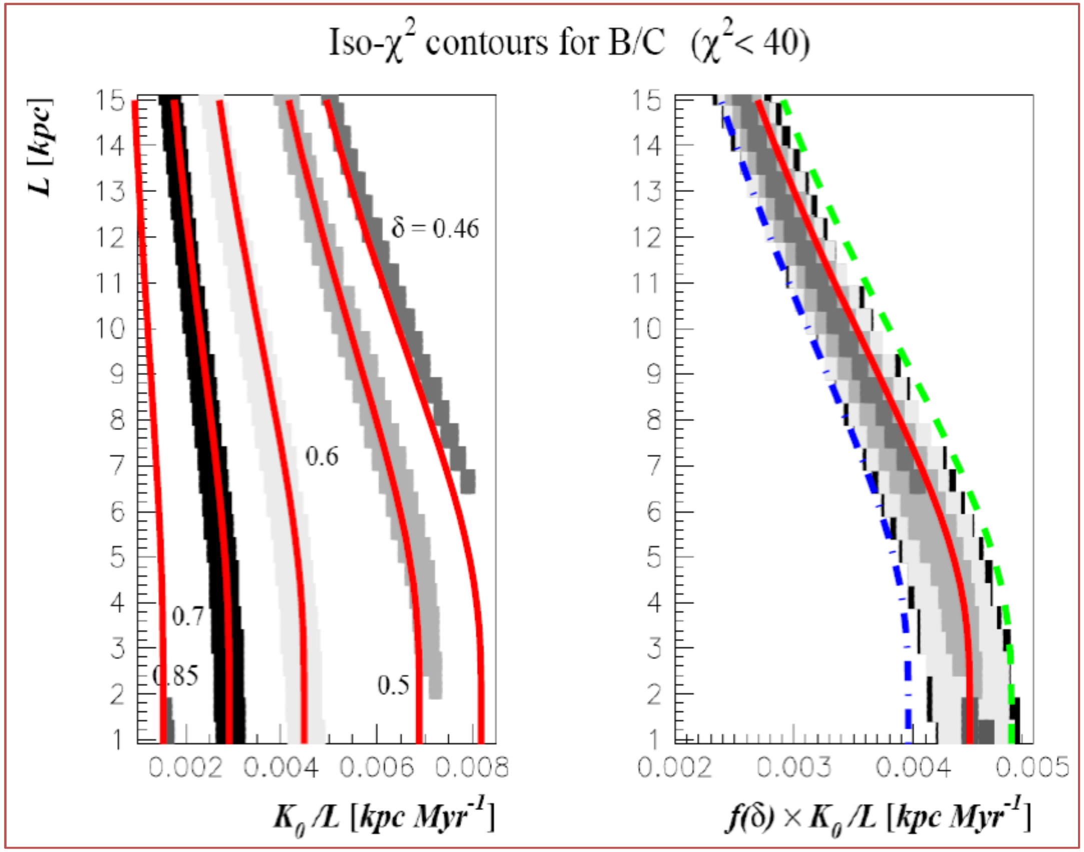
$$X_{\mathrm{esc}}(\mathcal{R}) = \frac{n_{\mathrm{B}}(\mathcal{R})}{Q_{\mathrm{B}}(\mathcal{R})}$$



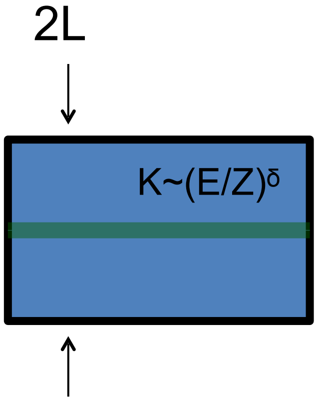


Maurin et al, **Astrophys.J.555:585-596,2001** diffusion models fit

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

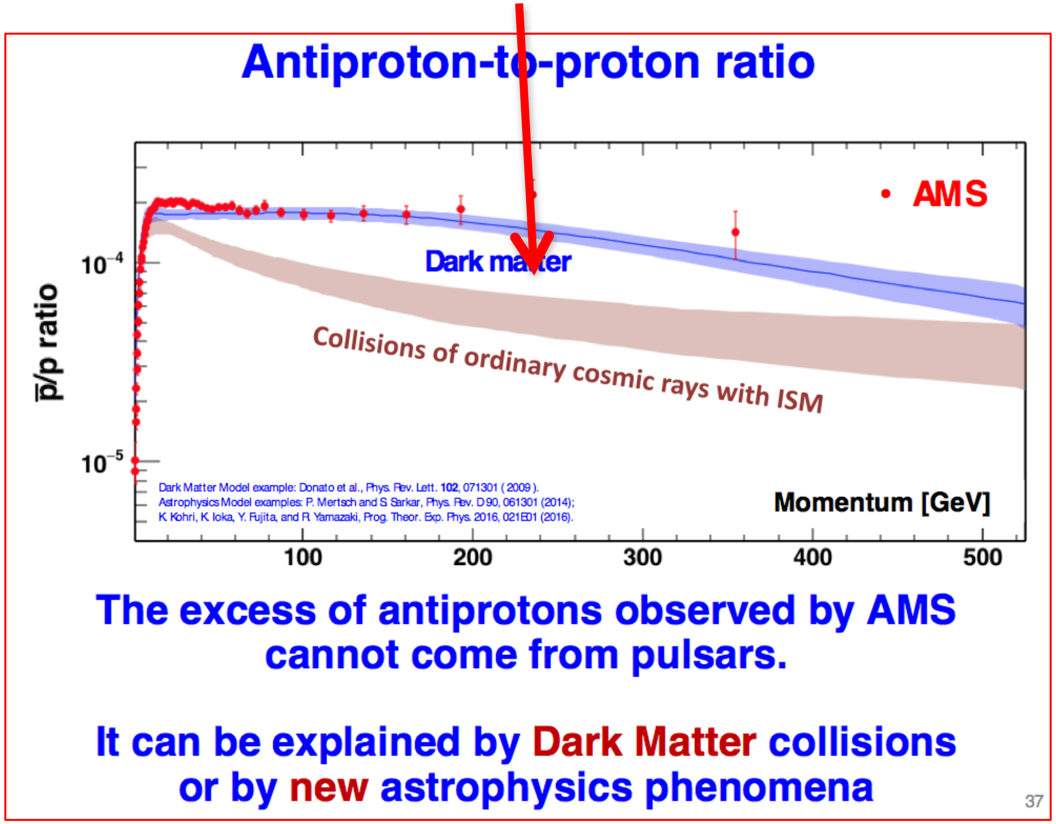


Iso-χ^2 contours for B/C ($\chi^2 < 40$)



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

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



Antiproton-to-proton ratio

Dark Matter Model example: Donato et al., Phys. Rev. Lett. **102**, 071301 (2009).
Astrophysics Model examples: P. Mertsch and S. Sarkar, Phys. Rev. D 90, 061301 (2014);
K Kohri, K Ioka, Y. Fujita, and R Yamazaki, Prog. Theor. Exp. Phys. 2016, 021E01 (2016).

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

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

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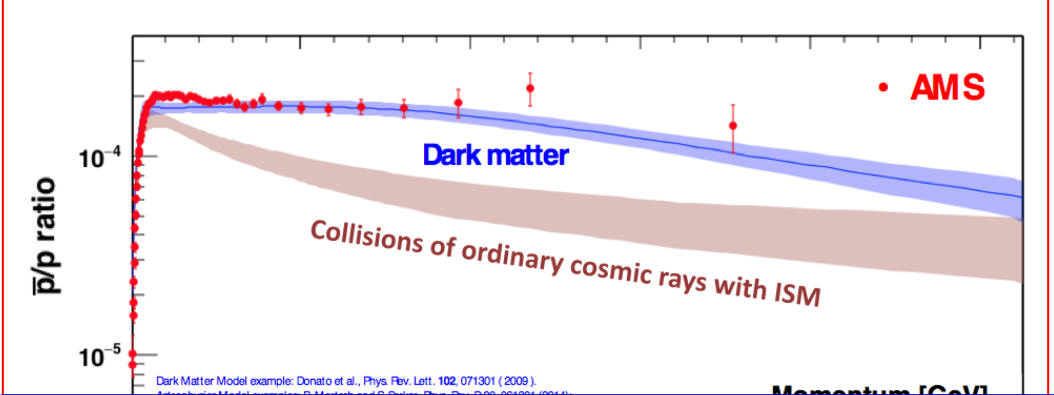
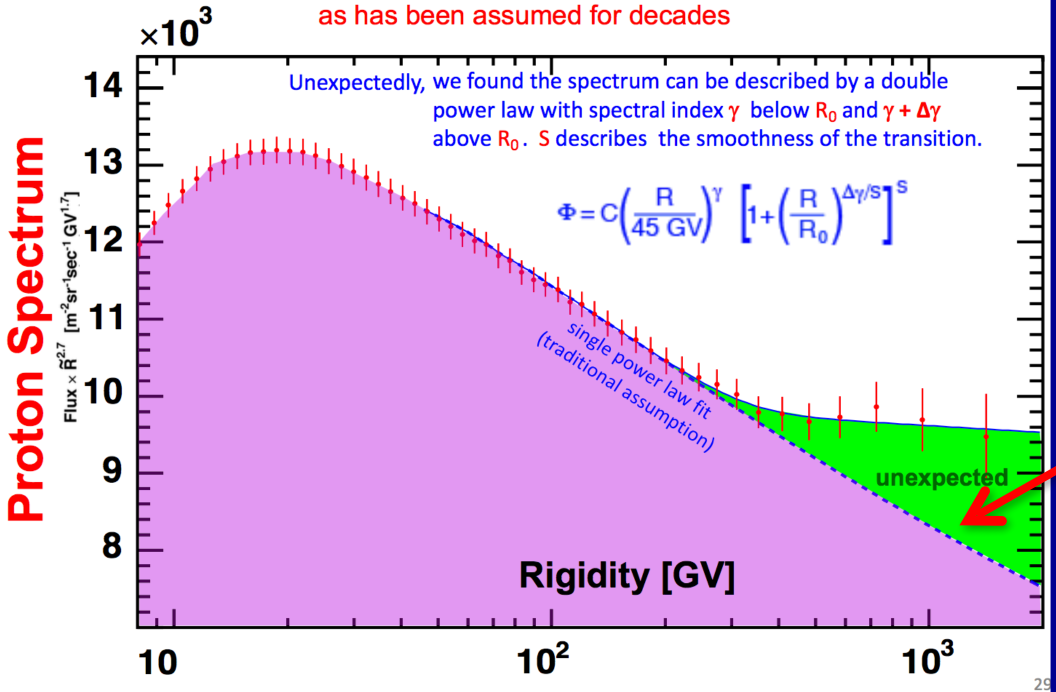


Dark Matter Model example: Donato et al., Phys. Rev. Lett. **102**, 071301 (2009).

AMS proton flux

New information: The proton flux cannot be described by a single power law = CR^{γ}, as has been assumed for decades

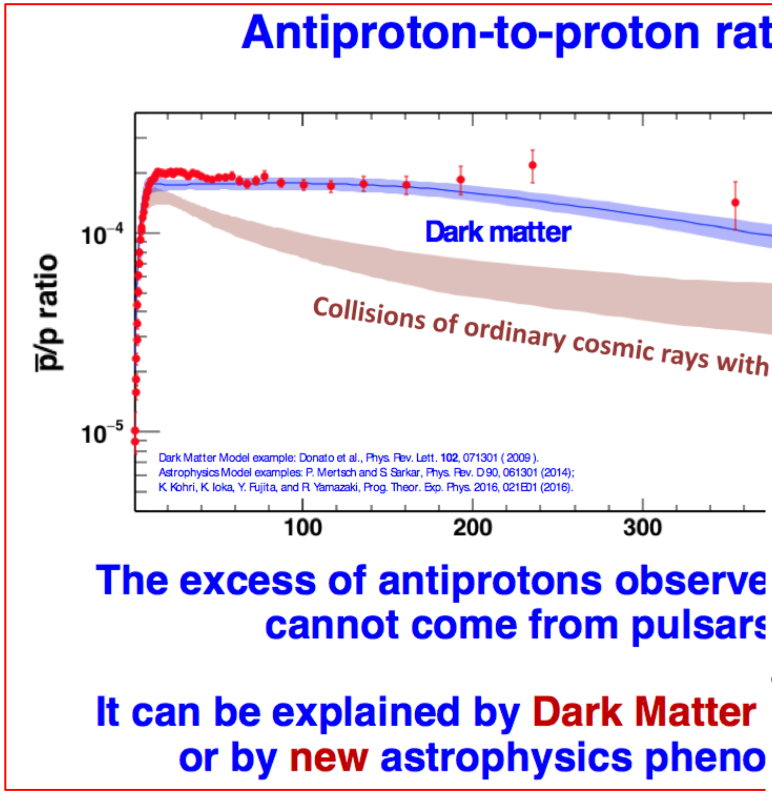


Unexpectedly, we found the spectrum can be described by a double power law with spectral index γ below R_0 and $\gamma + \Delta\gamma$ above R_0. S describes the smoothness of the transition.

$$\Phi = C\left(\frac{R}{45\ \mathrm{GV}}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/S}\right]^{S}$$

proton flux assumed for making the pbar/p grey line

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



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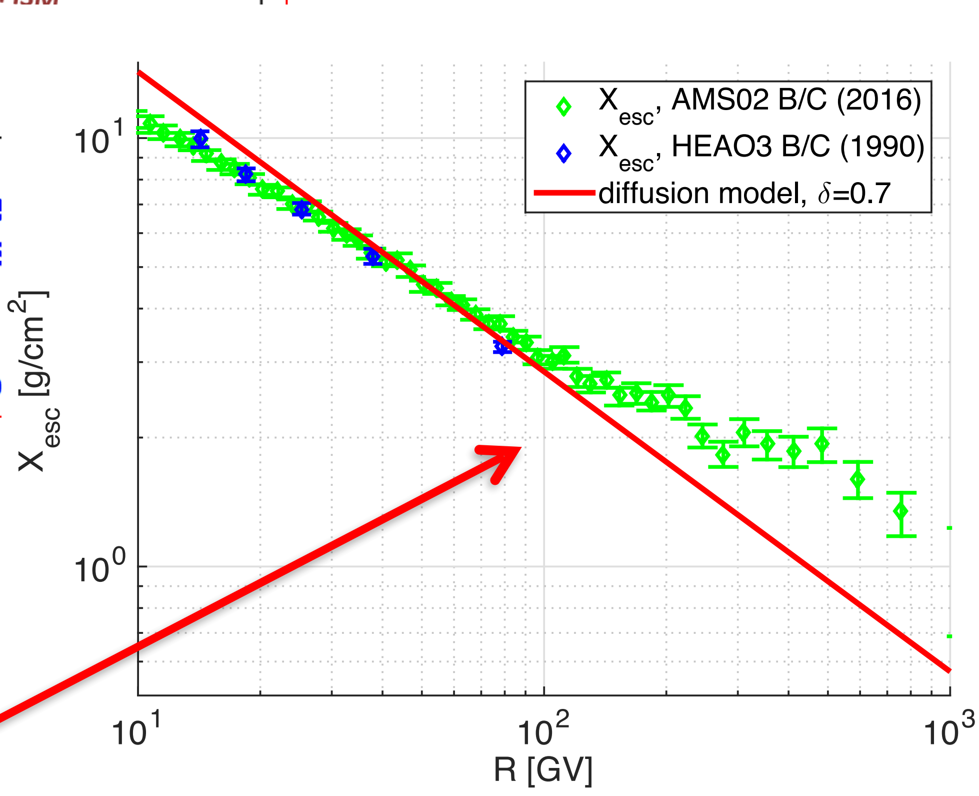
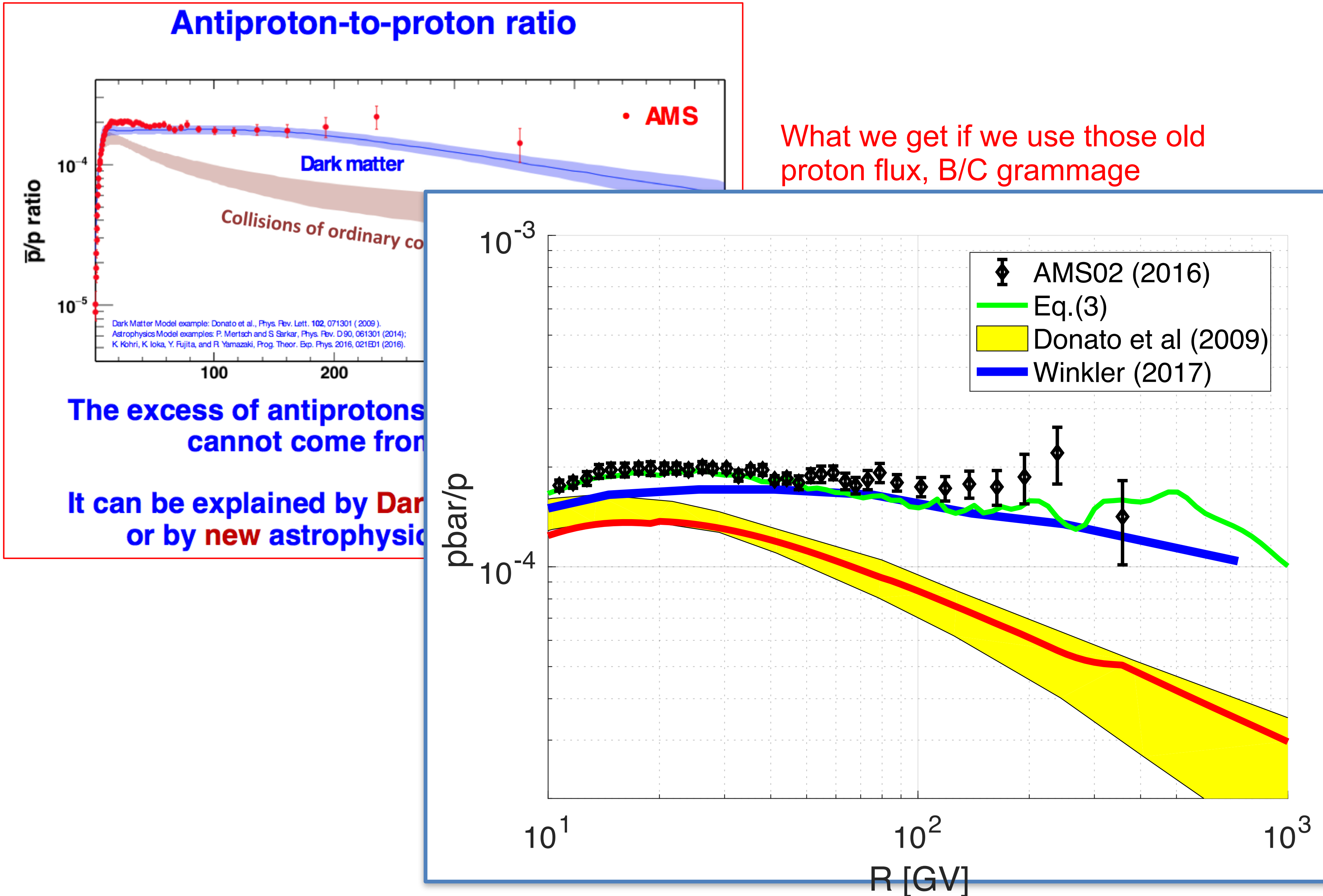


B/C grammage assumed for
making the pbar/p grey line

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



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

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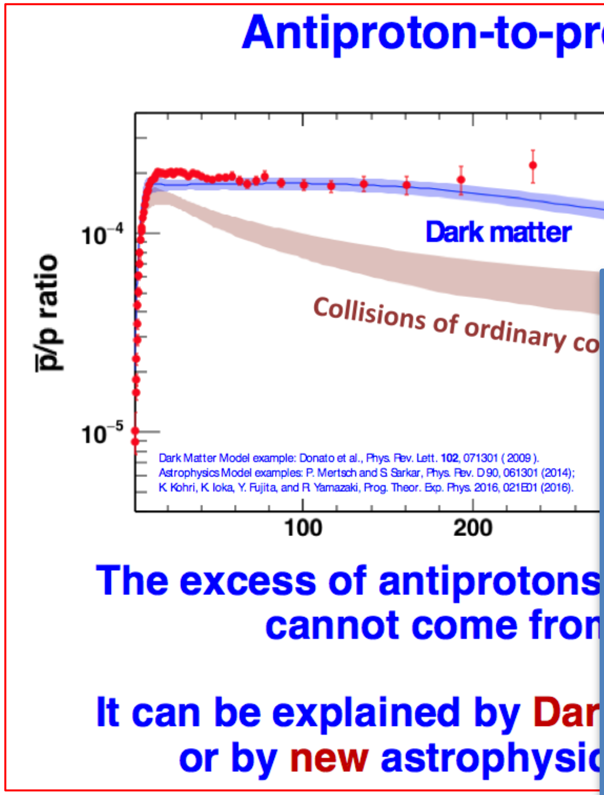

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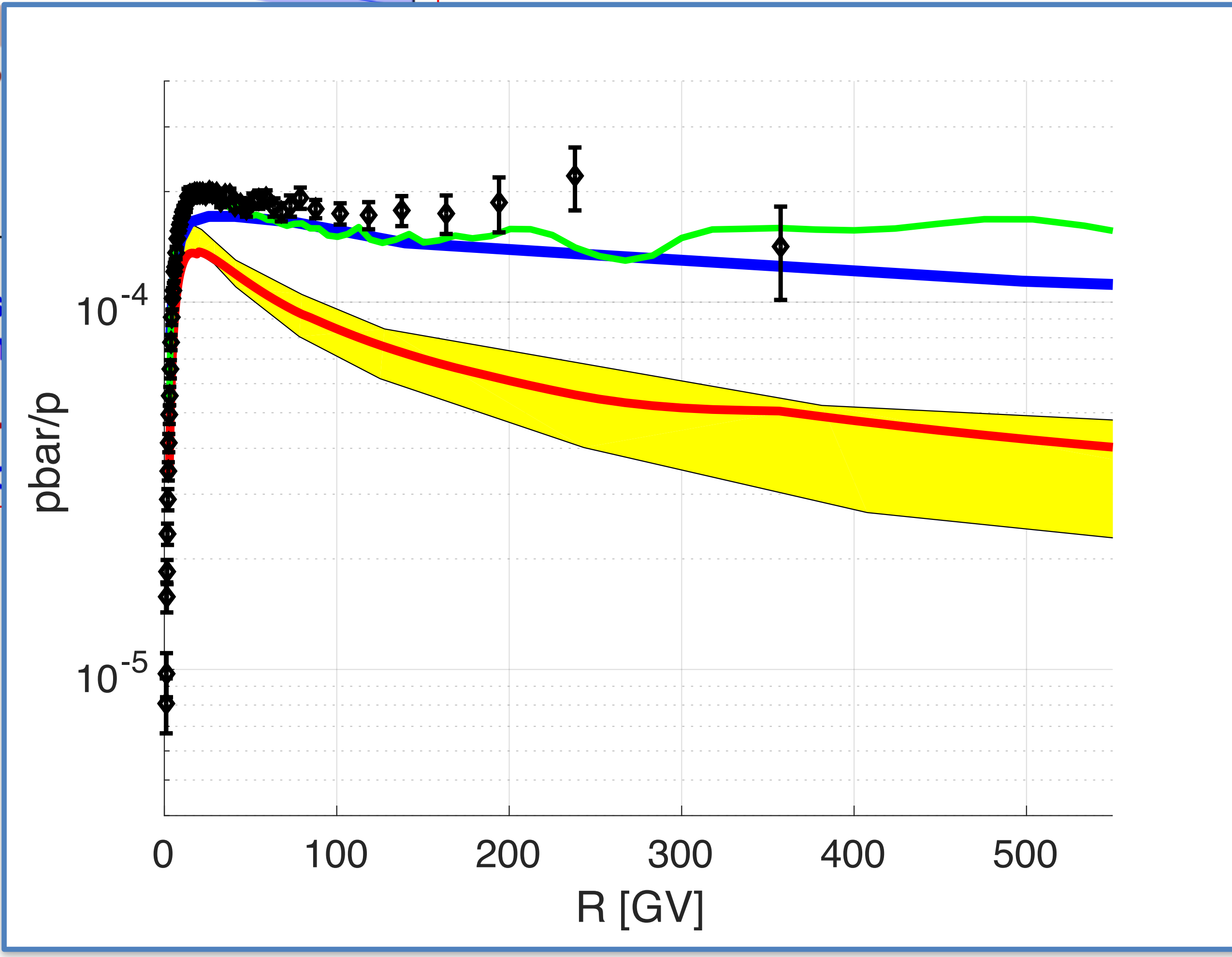
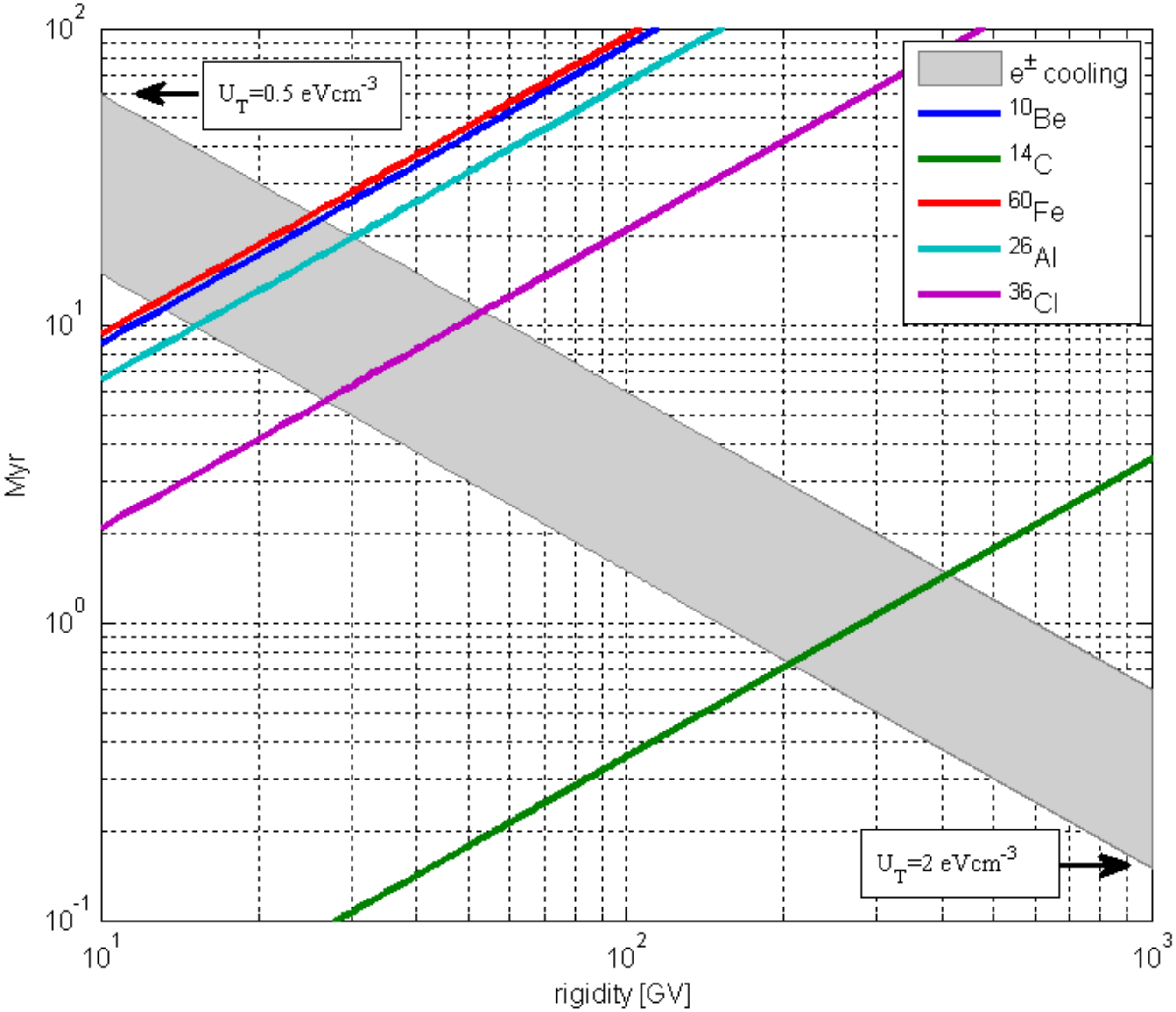


Comparing with radioactive nuclei

Time scales:

cooling vs decay



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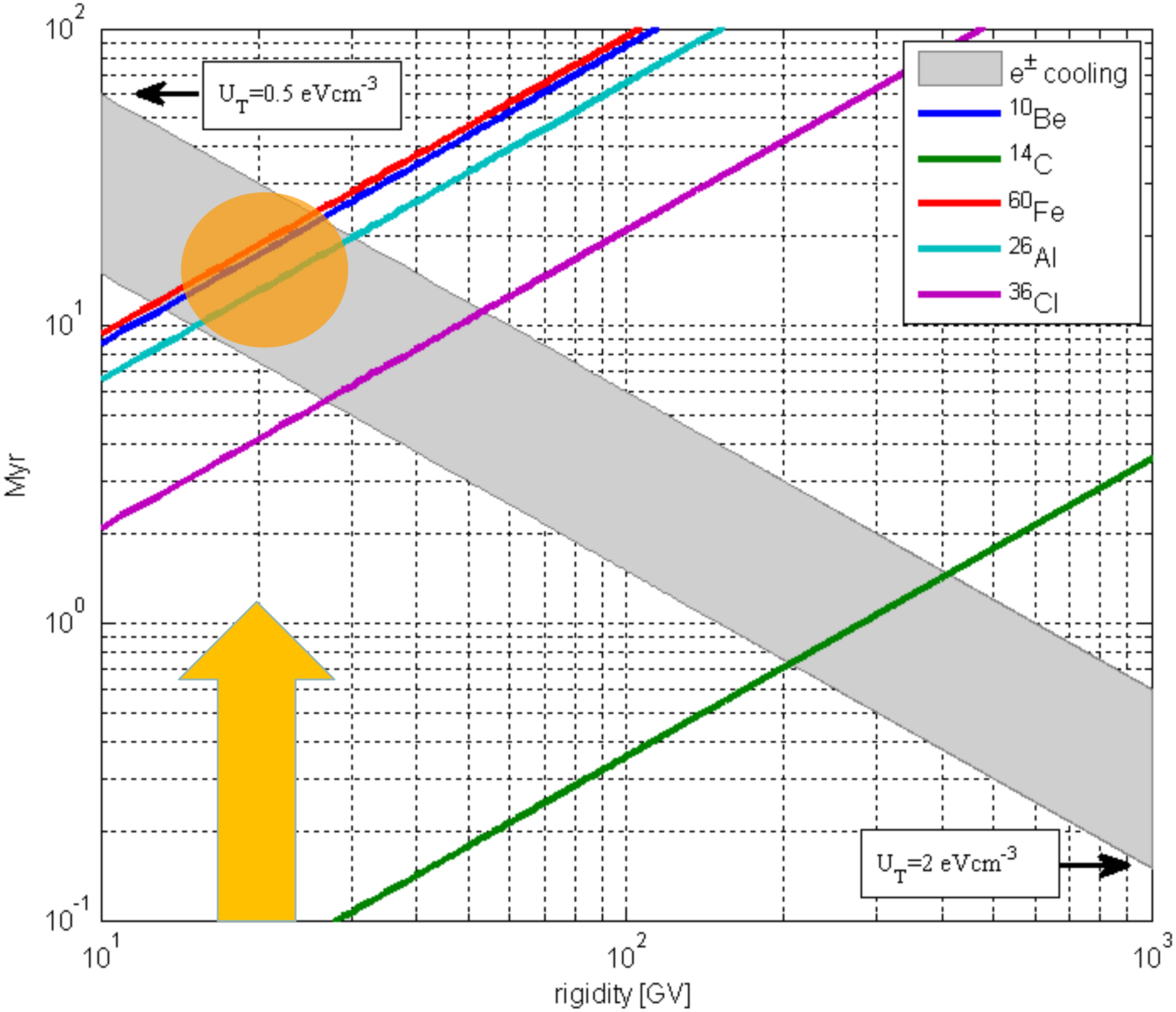

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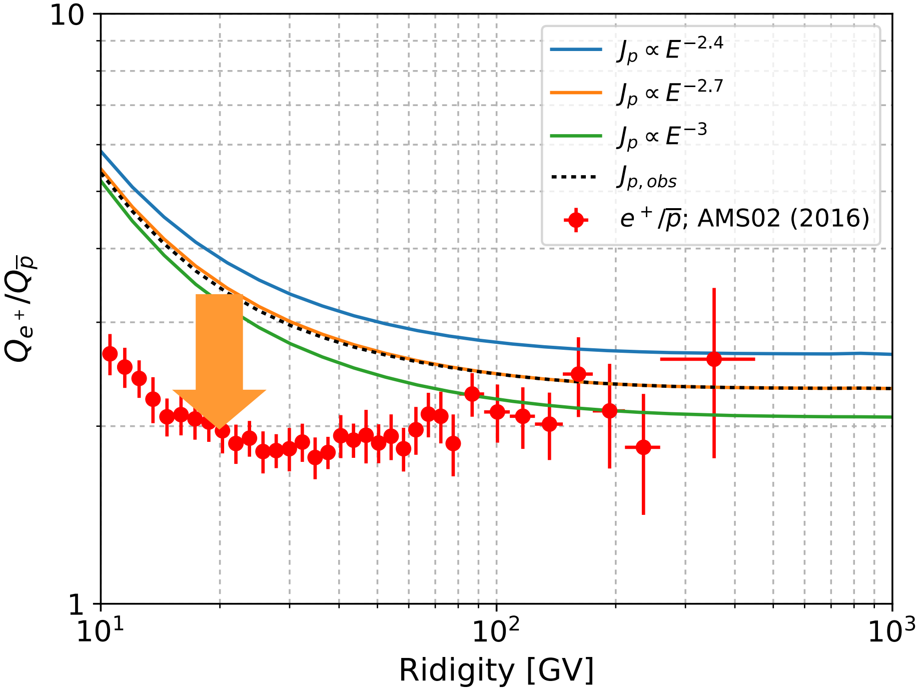

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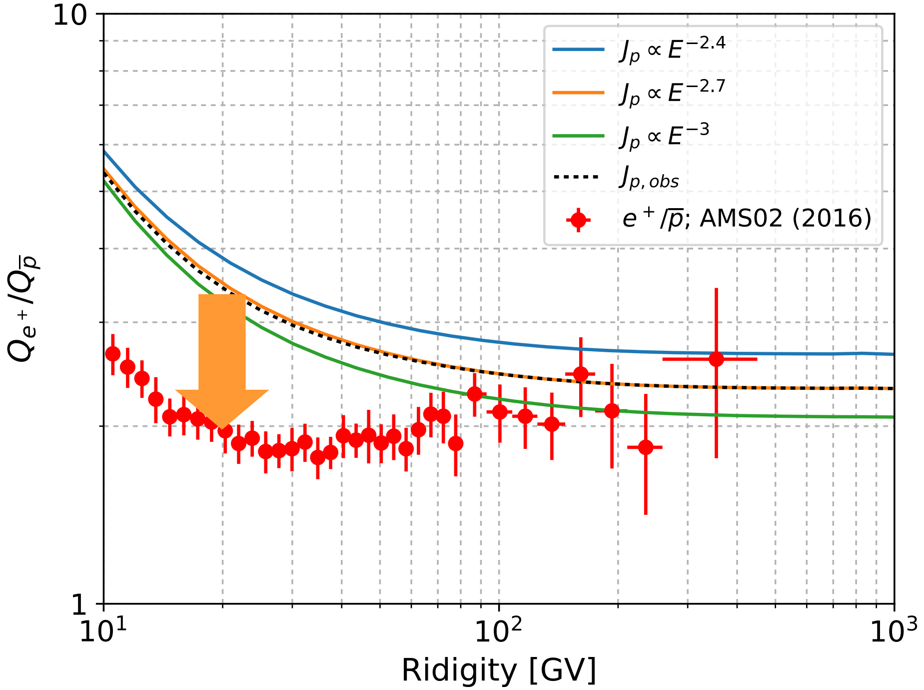

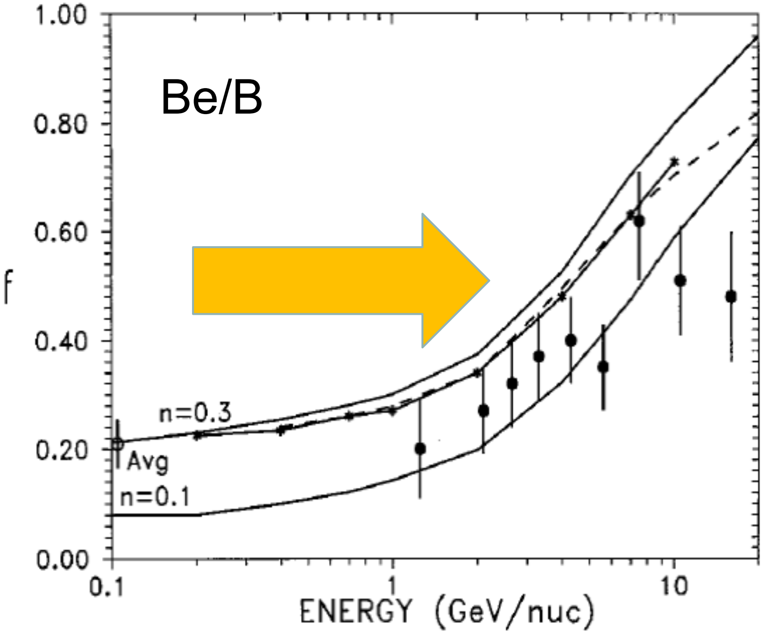

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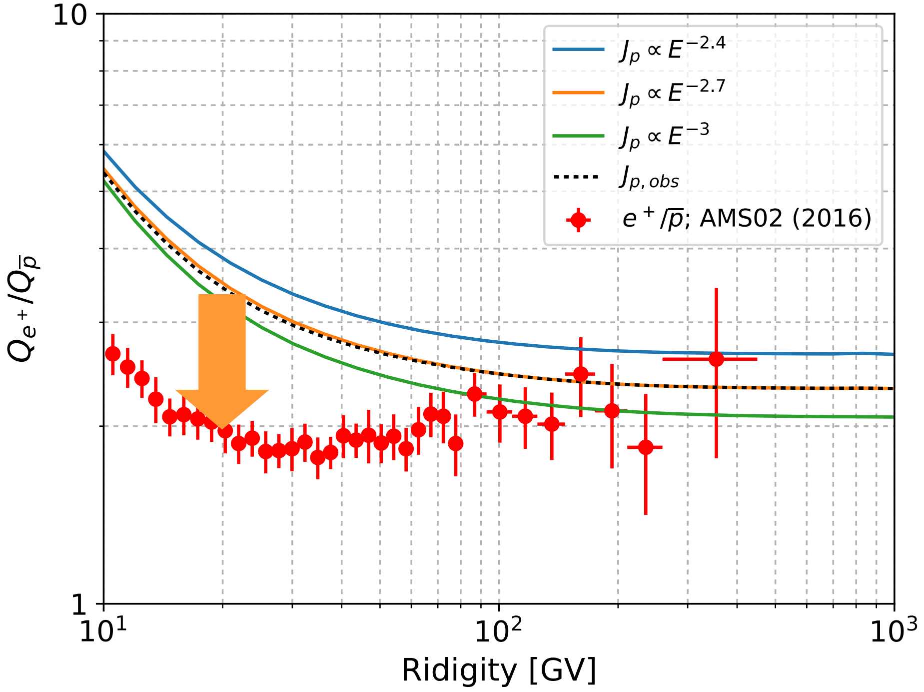
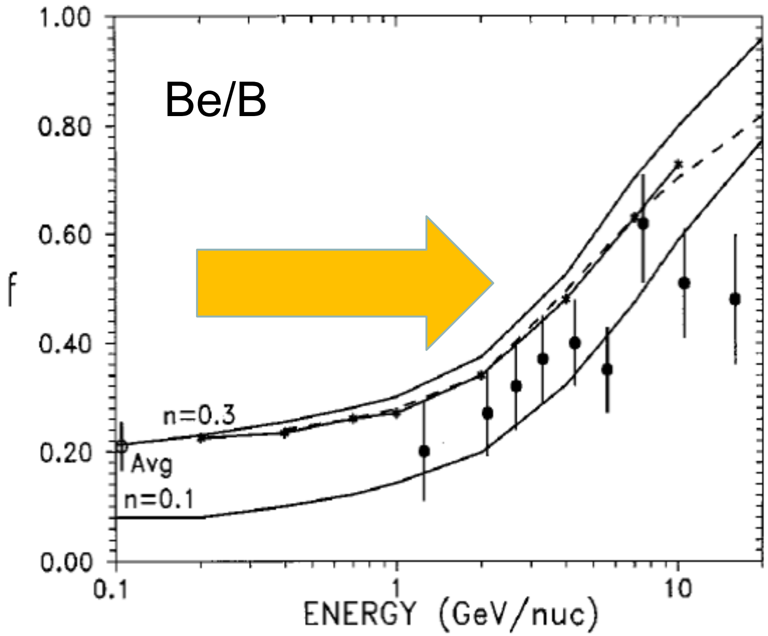
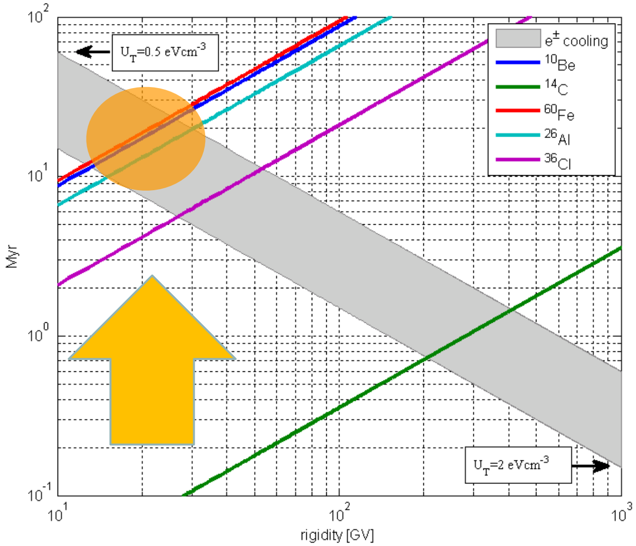






f(Be10) ~ 0.4

f(e+) ~ 0.5

Stable secondaries with no energy loss

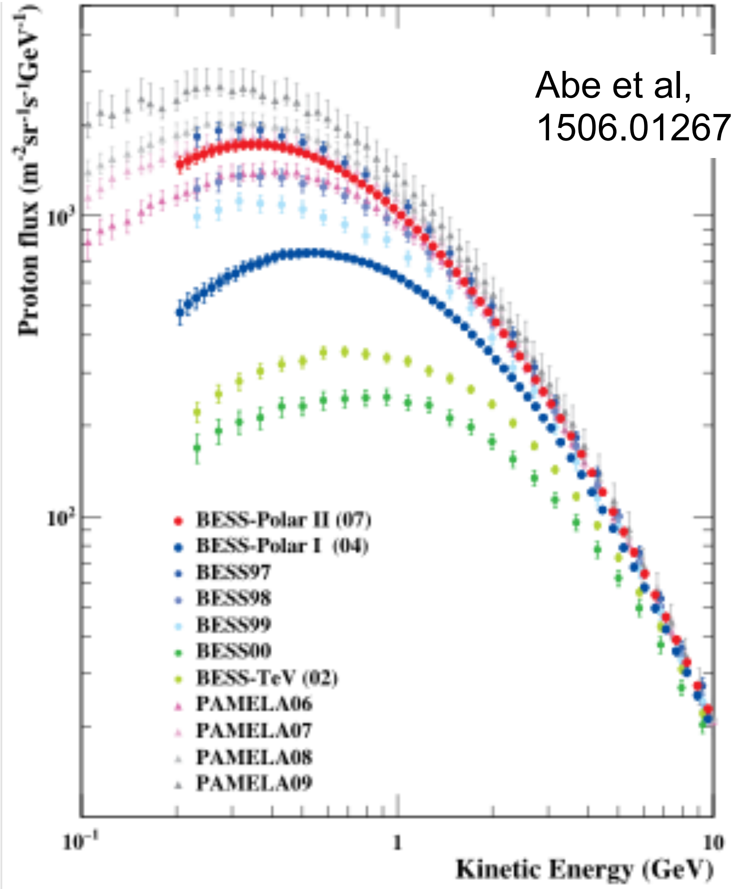
Comment about applicability of the analysis: **high energy (relativistic)**

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

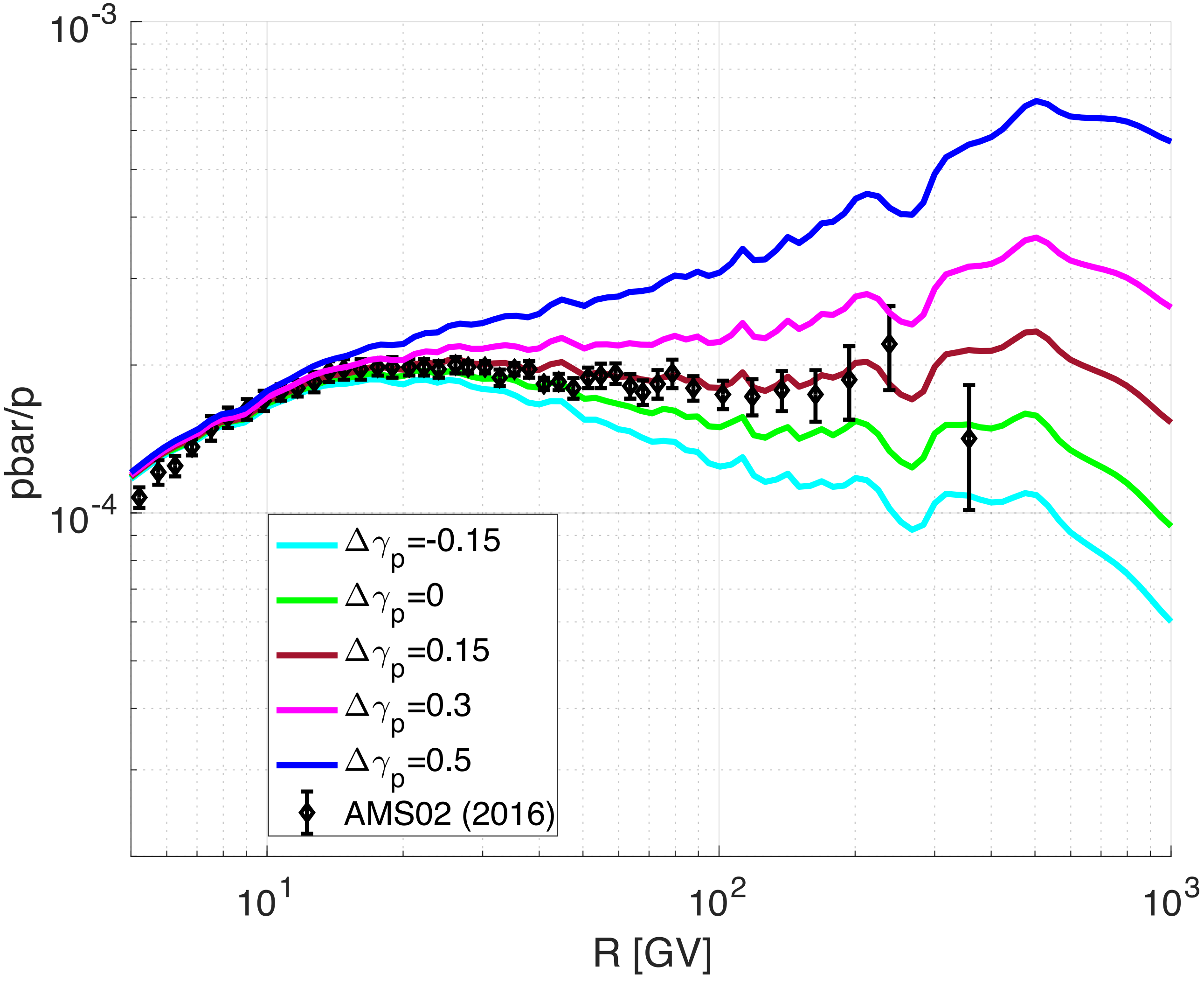
Example: solar modulation

We will keep our

analysis to R > 10GV



Abe et al,
1506.01267



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)

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

A more robust derivation:

Relate e+ to pbar

Rather than directly to B/C

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

Secondary upper bound

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

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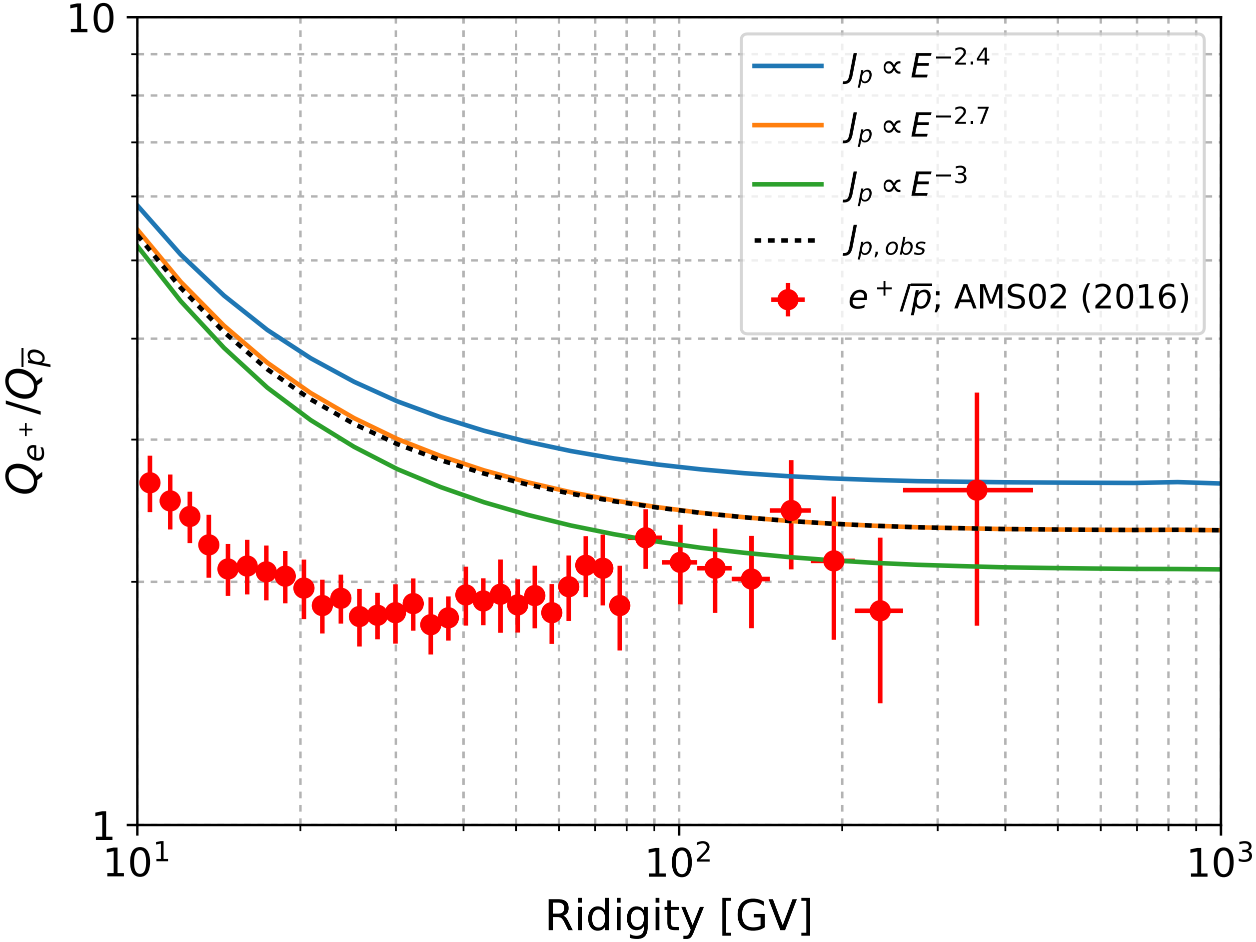

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AMS02 data supports secondary origin for CR e+.