Advances in Particle Astrophysics

Session III: Galactic Cosmic Rays

Kfir Blum
Weizmann Institute

CERN academic training 11-15/04/2016

antiprotons

$$\frac{n_{\bar{p}}}{n_{\text{Boron}}} = \frac{Q_{\bar{p}}}{Q_{\text{Boron}}}$$

antiprotons

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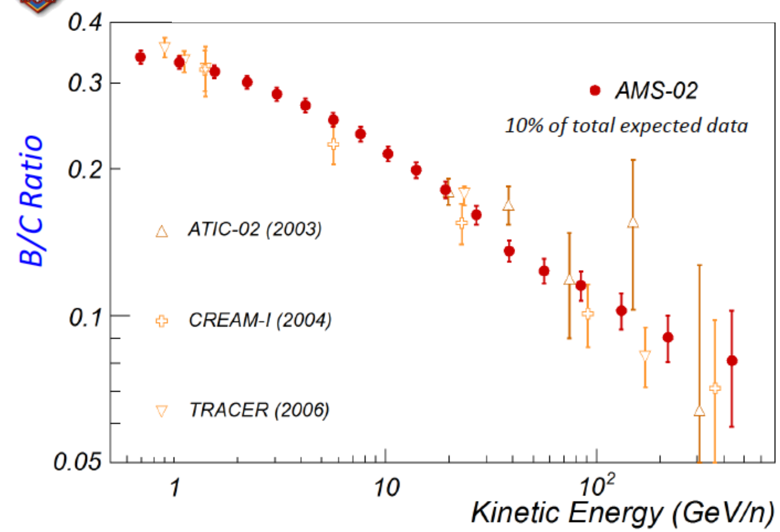
Boron-to-Carbon ratio



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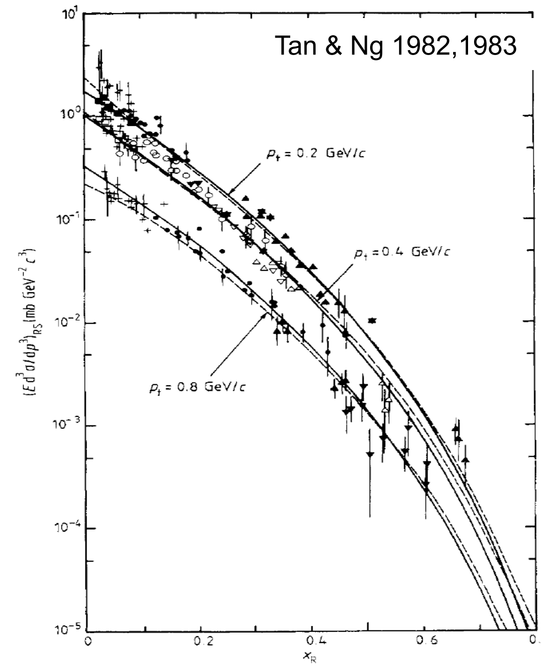

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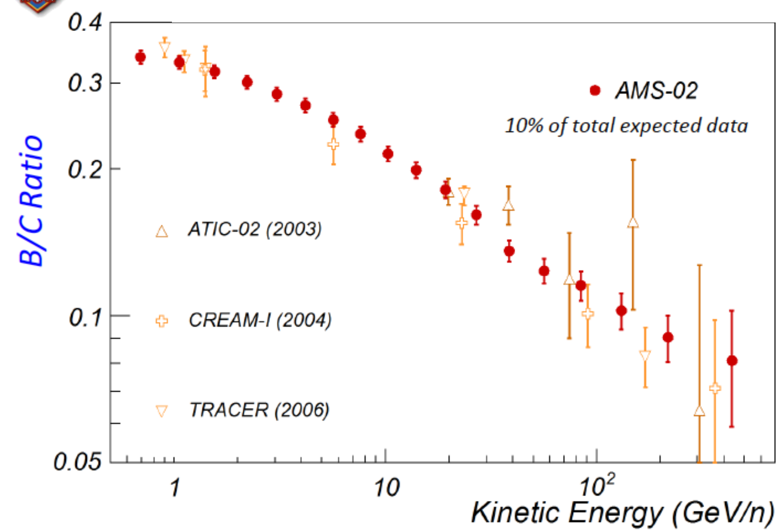

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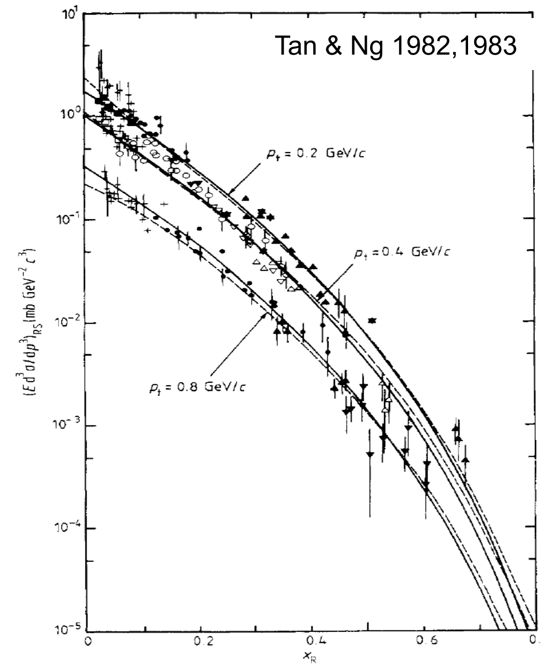
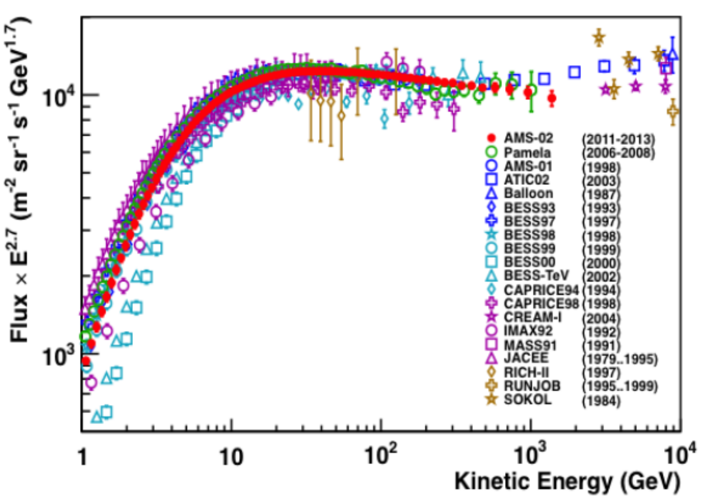


Proton flux



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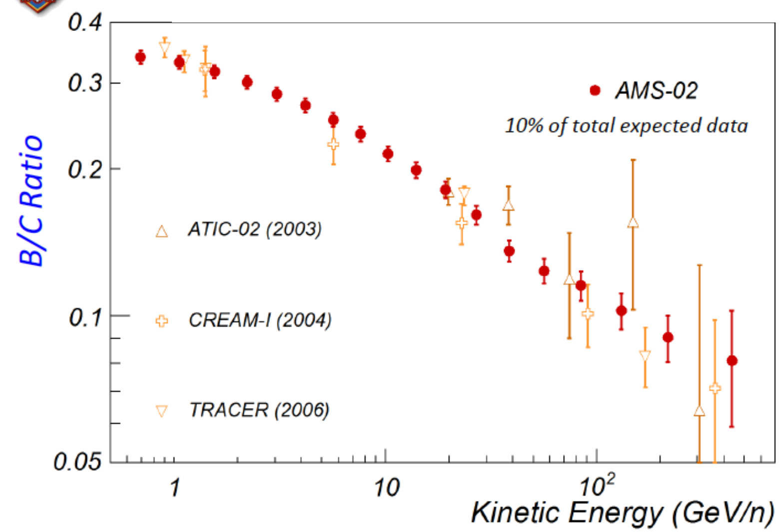
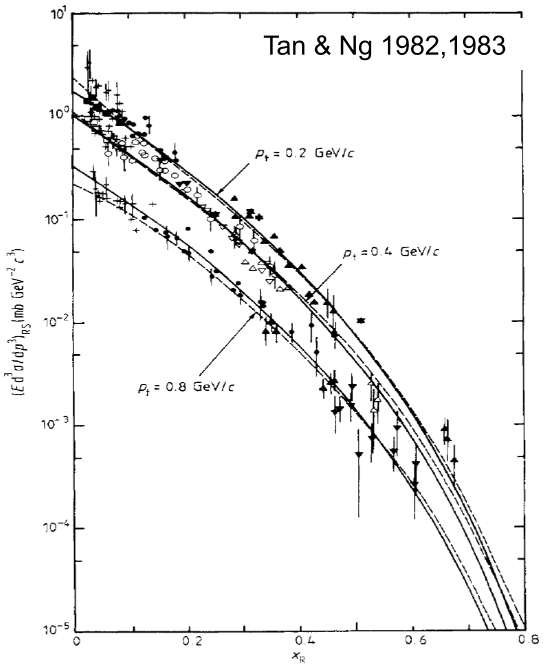


antiprotons

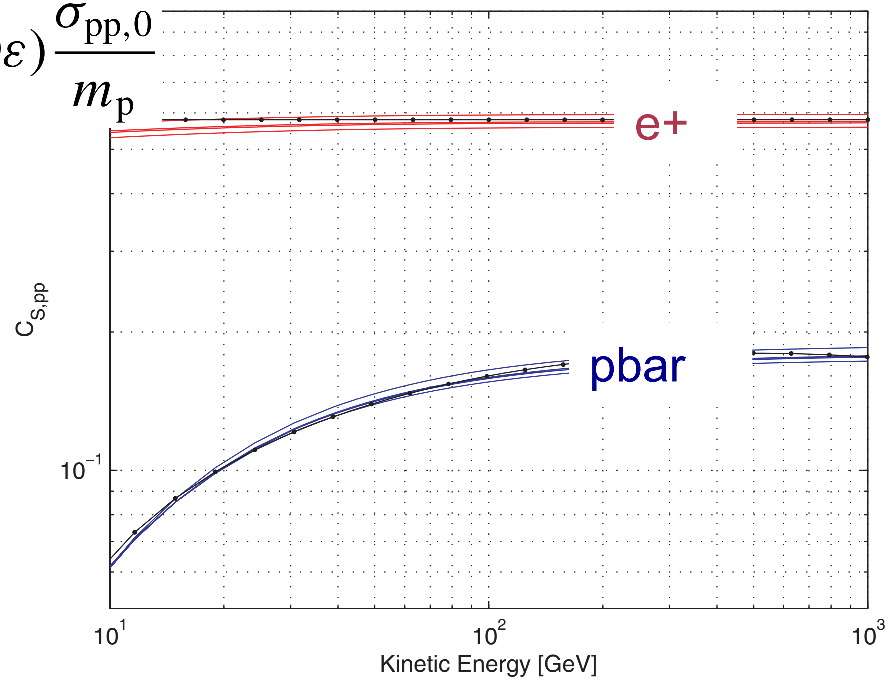


antiprotons form in pp, pHe collisions.

not born with the same rigidity as the primary CR

$$Q_{\bar{p}}(\varepsilon) = 2\xi_{\bar{p},A>1} 4\pi \int_{\varepsilon_{\bar{p}}}^{\infty} d\varepsilon_p J_p(\varepsilon_p) \left(\frac{d\sigma_{\bar{p}}(\varepsilon_p, \varepsilon)}{d\varepsilon_p} \right)$$

$$\varepsilon Q_S(\varepsilon) = \xi_{S,A>1}(\varepsilon) C_{S,pp}(\varepsilon) 4\pi (10\varepsilon) J_p(10\varepsilon) \frac{\sigma_{pp,0}}{m_p}$$



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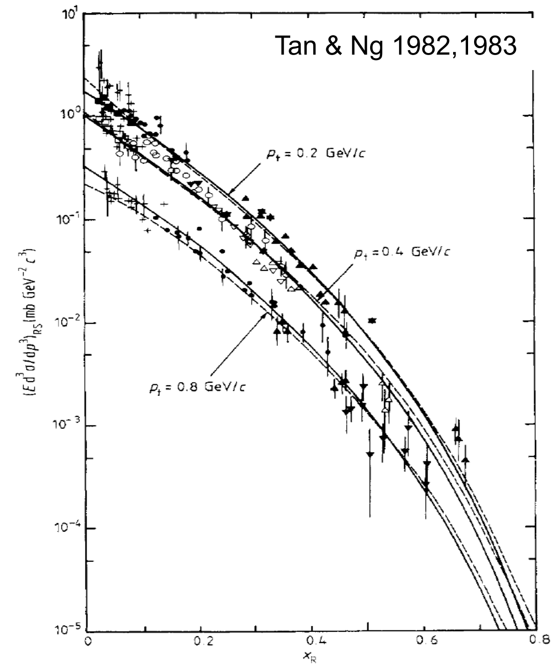
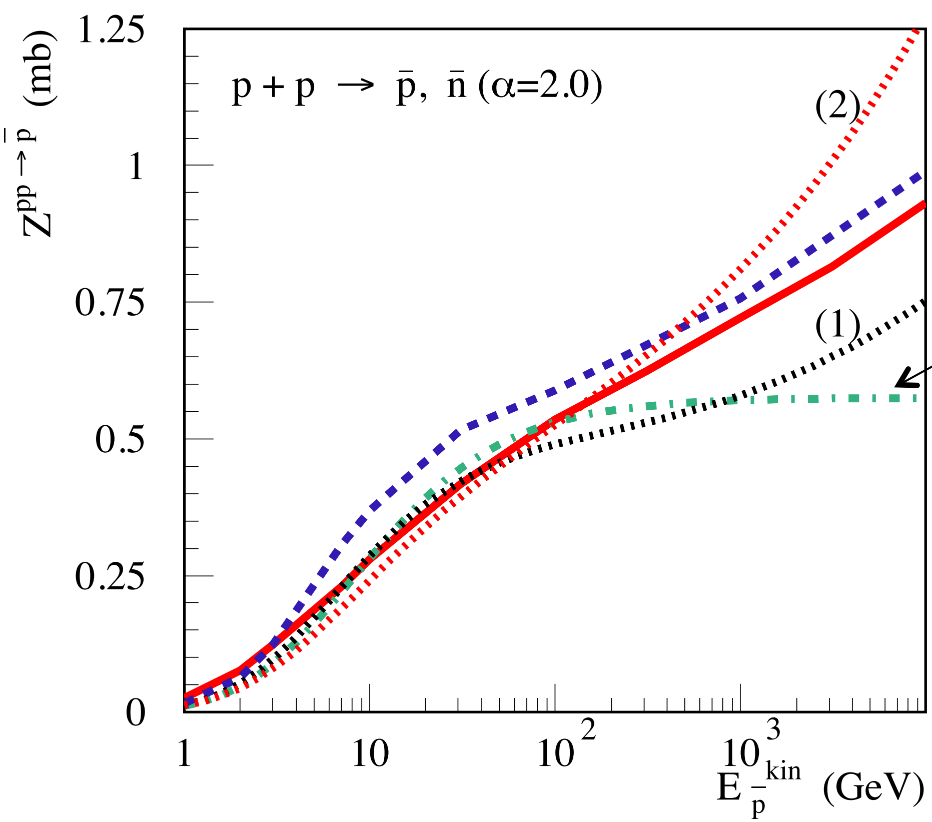


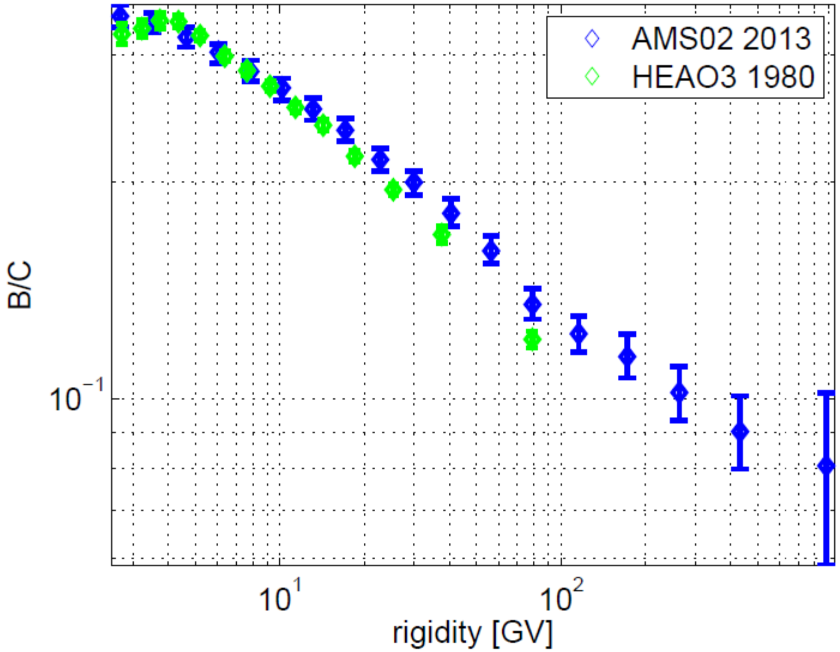
Kachelriess, Moskalenko, Ostapchenko, **ApJ. 803 (2015) no.2, 54**

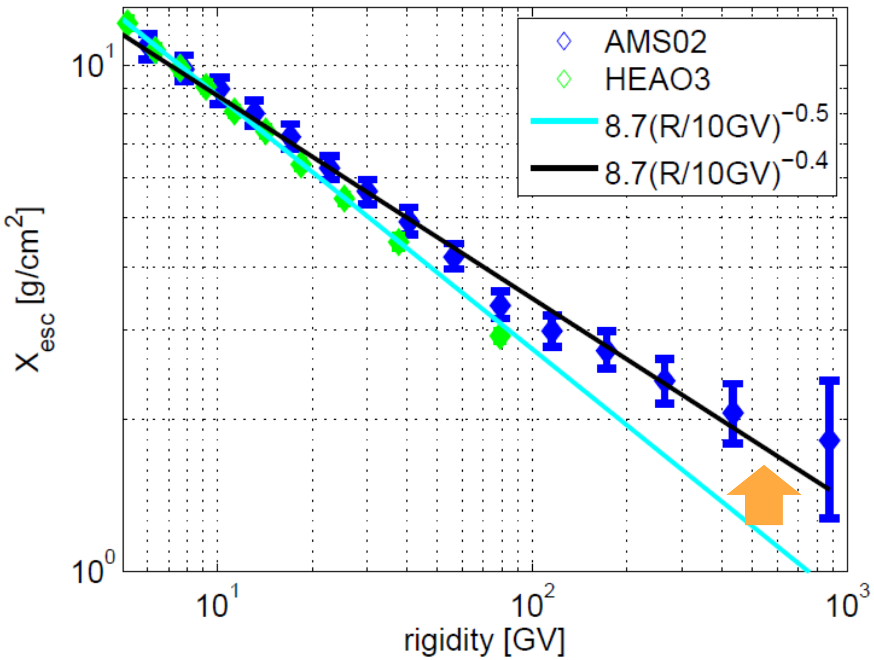


AMS02 update (2013)

$$n_B = Q_B X_{\rm esc} = \left[\sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\to B}}{\bar{m}}\right) n_i - \left(\frac{\sigma_B}{\bar{m}}\right) n_B\right] X_{\rm esc}$$

$$X_{\rm esc} = \frac{\frac{n_B}{n_C}}{\sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\to B}}{\bar{m}}\right)\frac{n_i}{n_C} - \left(\frac{\sigma_B}{\bar{m}}\right)\frac{n_B}{n_C}}$$





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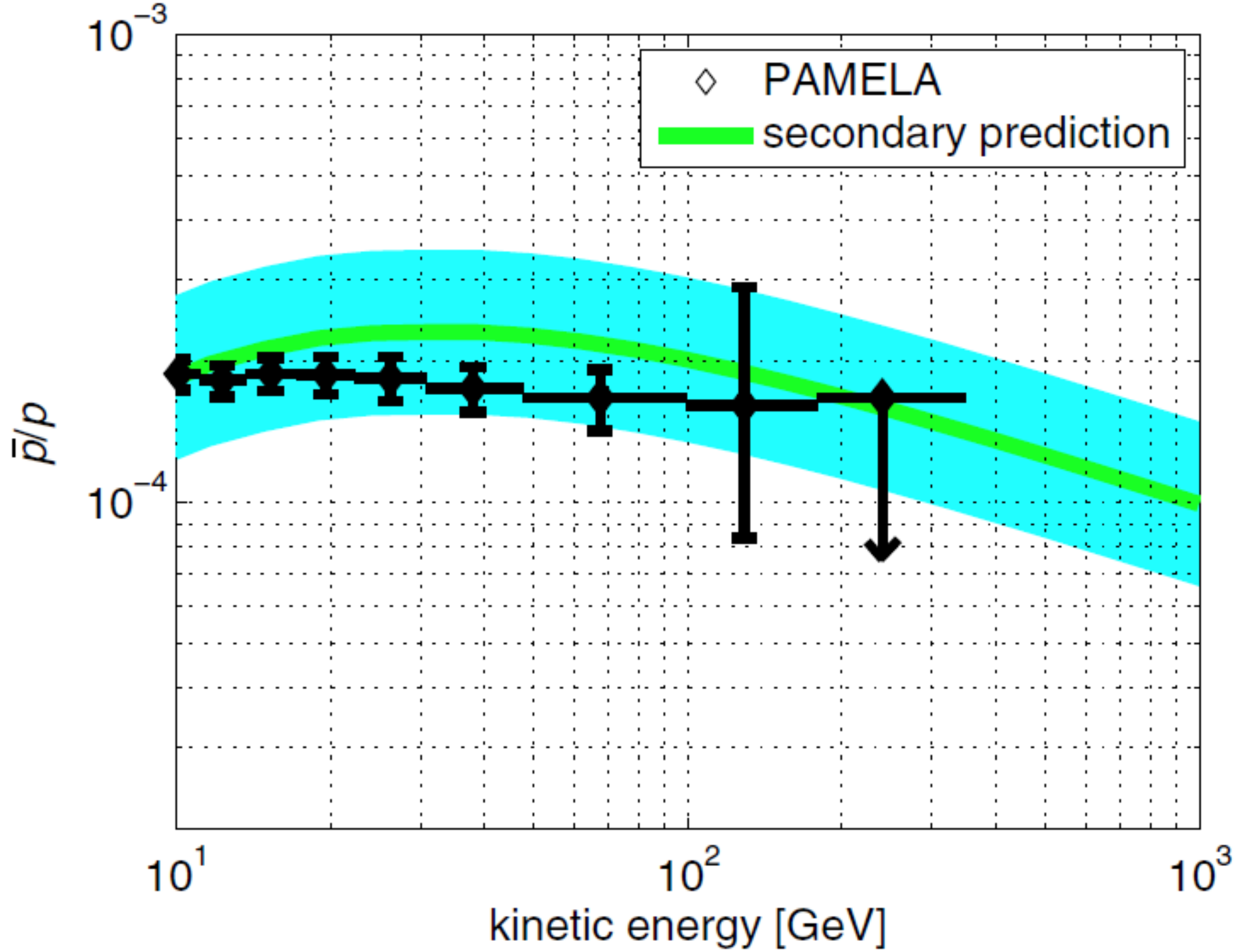

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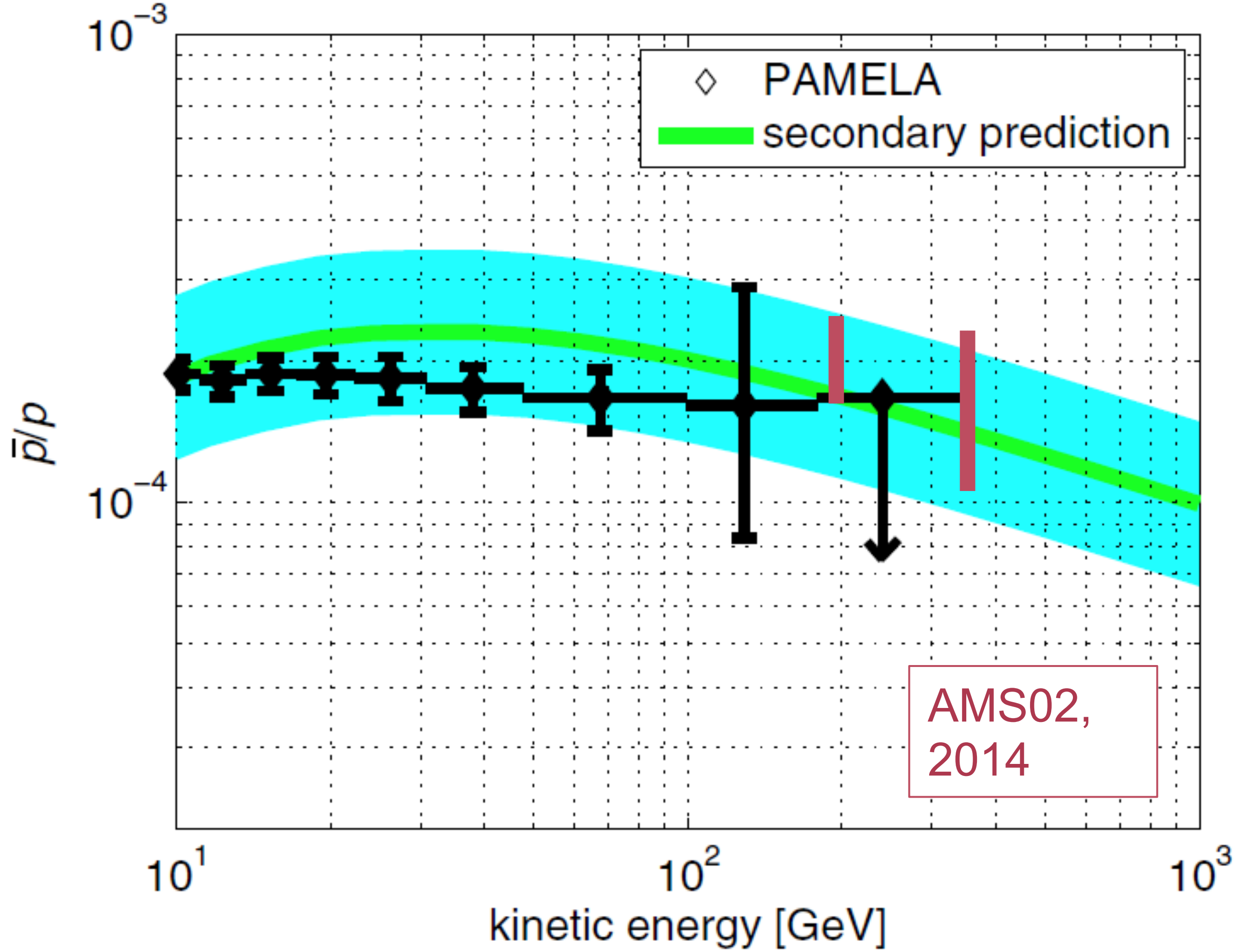


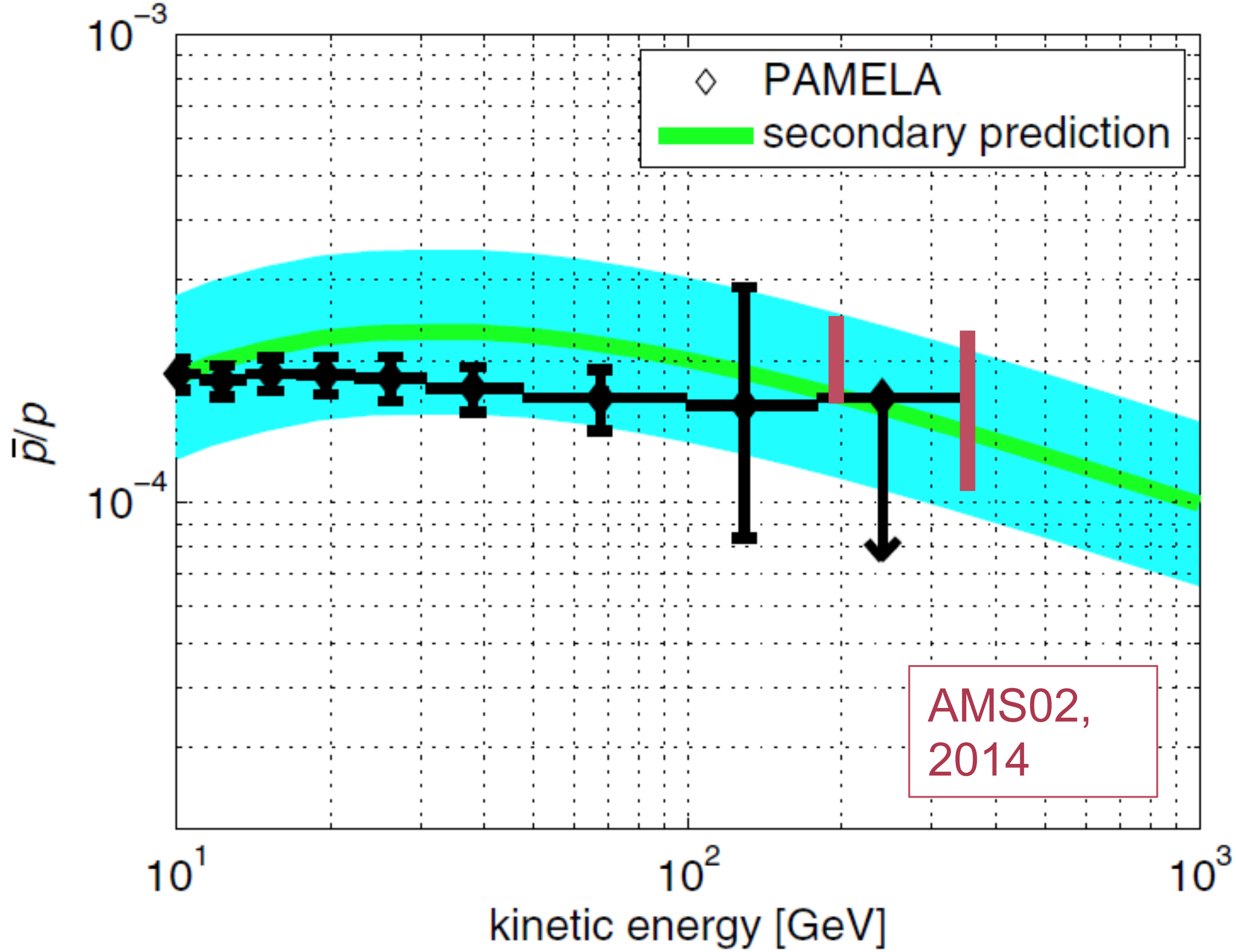
antiprotons

$$\frac{n_{\bar{p}}}{n_{\mathrm{Boron}}} = \frac{Q_{\bar{p}}}{Q_{\mathrm{Boron}}}$$

No free parameters.

This is not a cosmic ray propagation model.

This is particle physics.



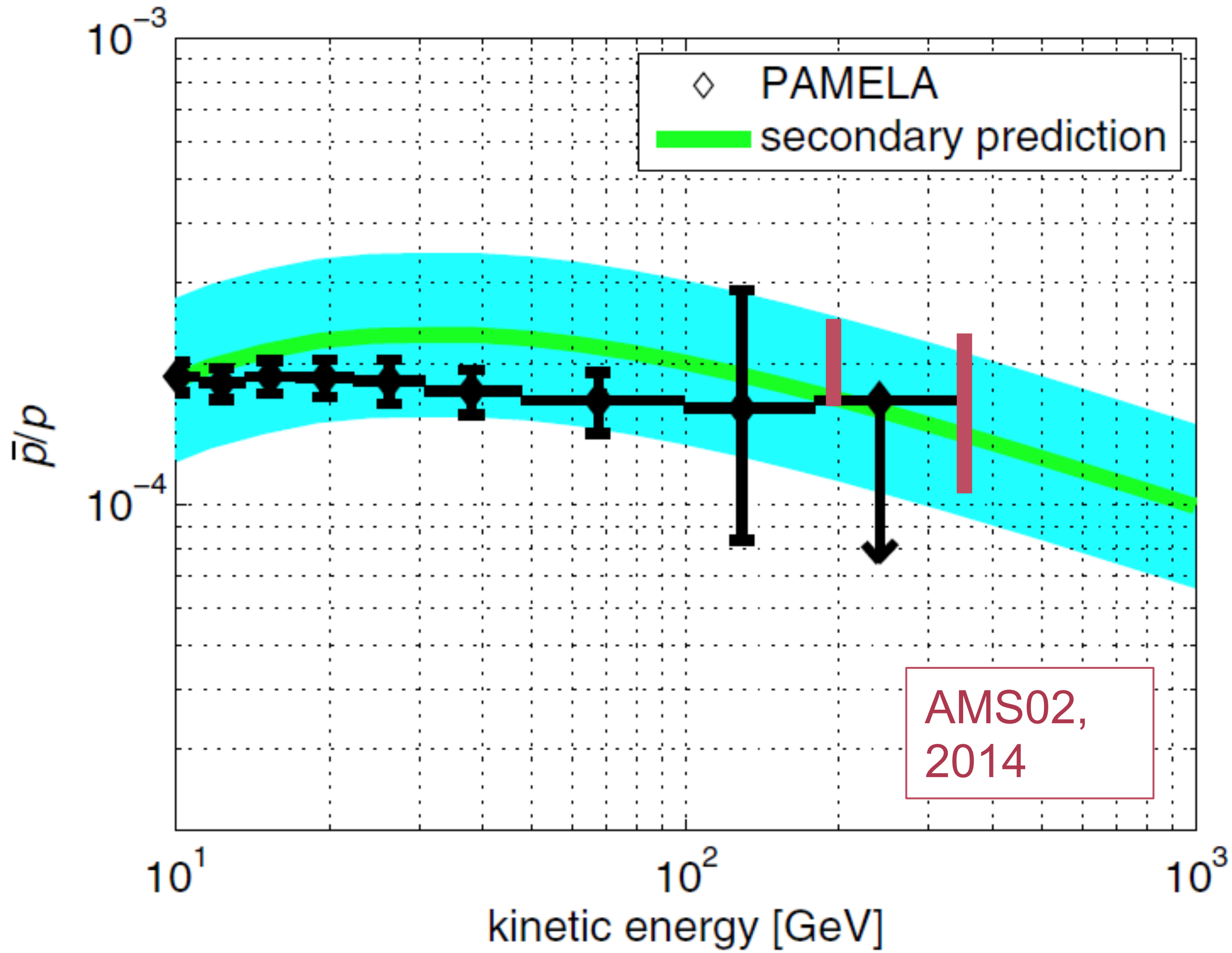
antiprotons

$$\frac{n_{\bar{p}}}{n_{\rm Boron}} = \frac{Q_{\bar{p}}}{Q_{\rm Boron}}$$

Antiprotons look secondary.

1. <u>There should not be a cut-off at higher energy</u>

2. <u>Should be viewed together w/ B/C</u>



positrons

positrons

$$\frac{J_{e^+}}{J_p} = f_{e^+} \times 10^{1-\gamma_p}\,\zeta_{e^+,A>1}\,C_{e^+,pp}\,\frac{\sigma_{pp,\mathrm{inel}}}{m_p}\,X_{\mathrm{esc}}$$

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Wait a minute. Can we use this for positrons?

positrons

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e+ lose energy through IC and synchrotron radiation.

The amount of loss depends on the propagation time t_{esc} vs. energy loss time t_{cool}

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The amount of loss depends on the propagation time t_{esc} vs. energy loss time t_{cool}

we do not know the propagation time of CRs above ~10 GV.

B/C and pbar/p do not measure it.

B/C tells us the mean column density of target material traversed by CRs,
but *not the time* it takes to accumulate this column density

A beam of carbon nuclei traversing 1g/cm^2 of ISM produces the same amount of Boron, whether it spent 1kyr in a dense molecular cloud, or 1Myr in rarified ISM

ISM properties: e.g. Ferriere, Rev.Mod.Phys. 73 (2001) 1031-1066

positrons

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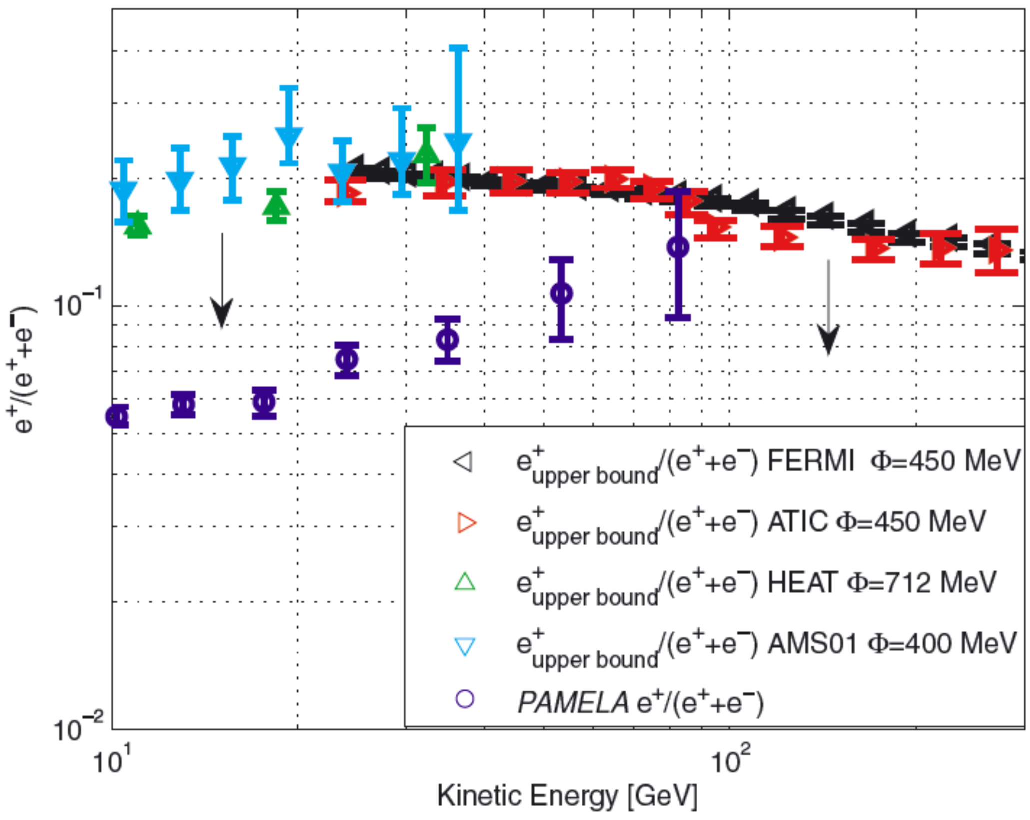
*we do not know the **propagation time of CRs above ~10 GV**.*

B/C and pbar/p do not measure it.

new e+ data itself is the first (semi-)direct observational probe of this quantity.

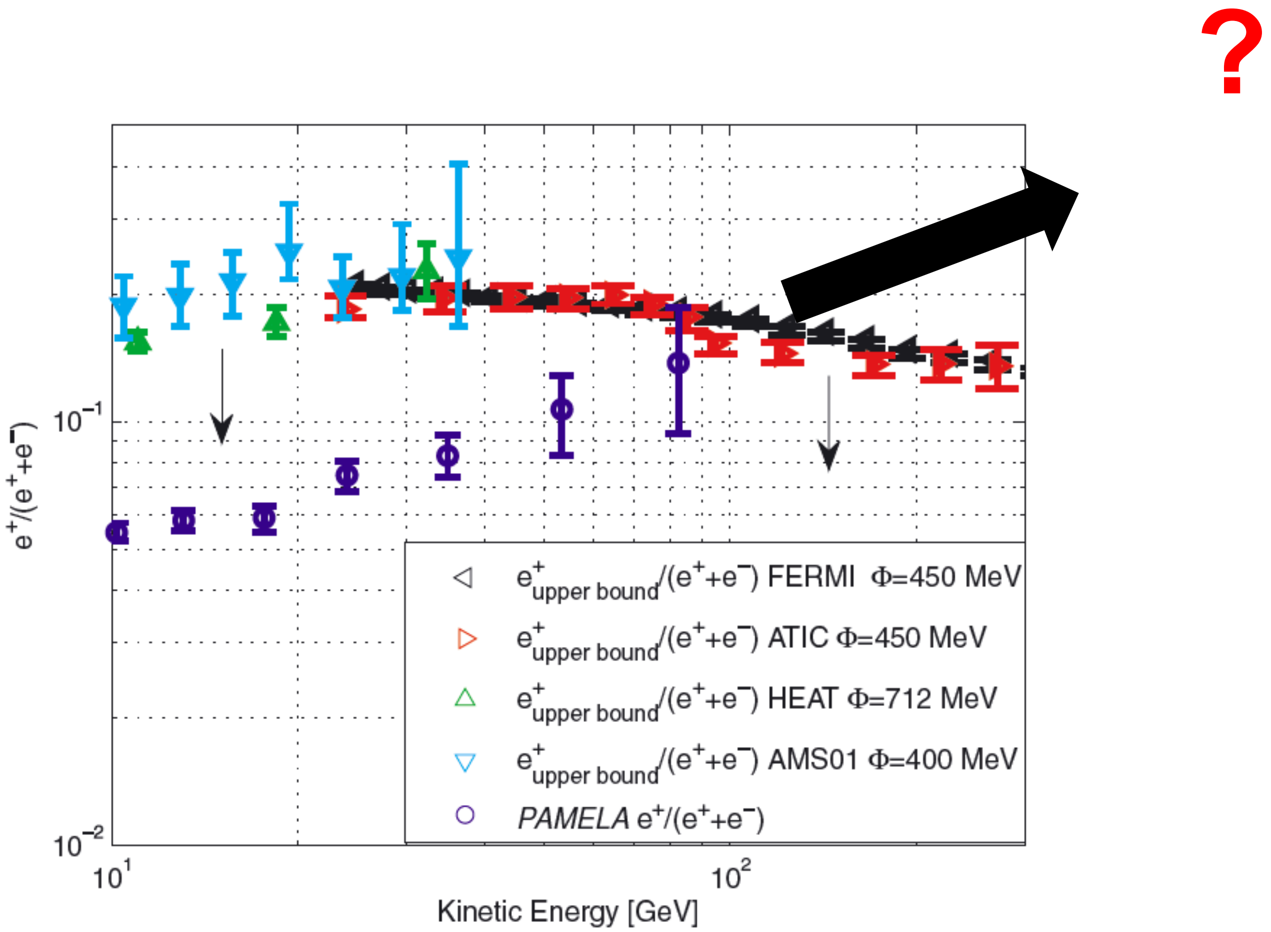
What we can say: $f_{e+} < 1$

PAMELA 2009 vs. positron bound, f<1



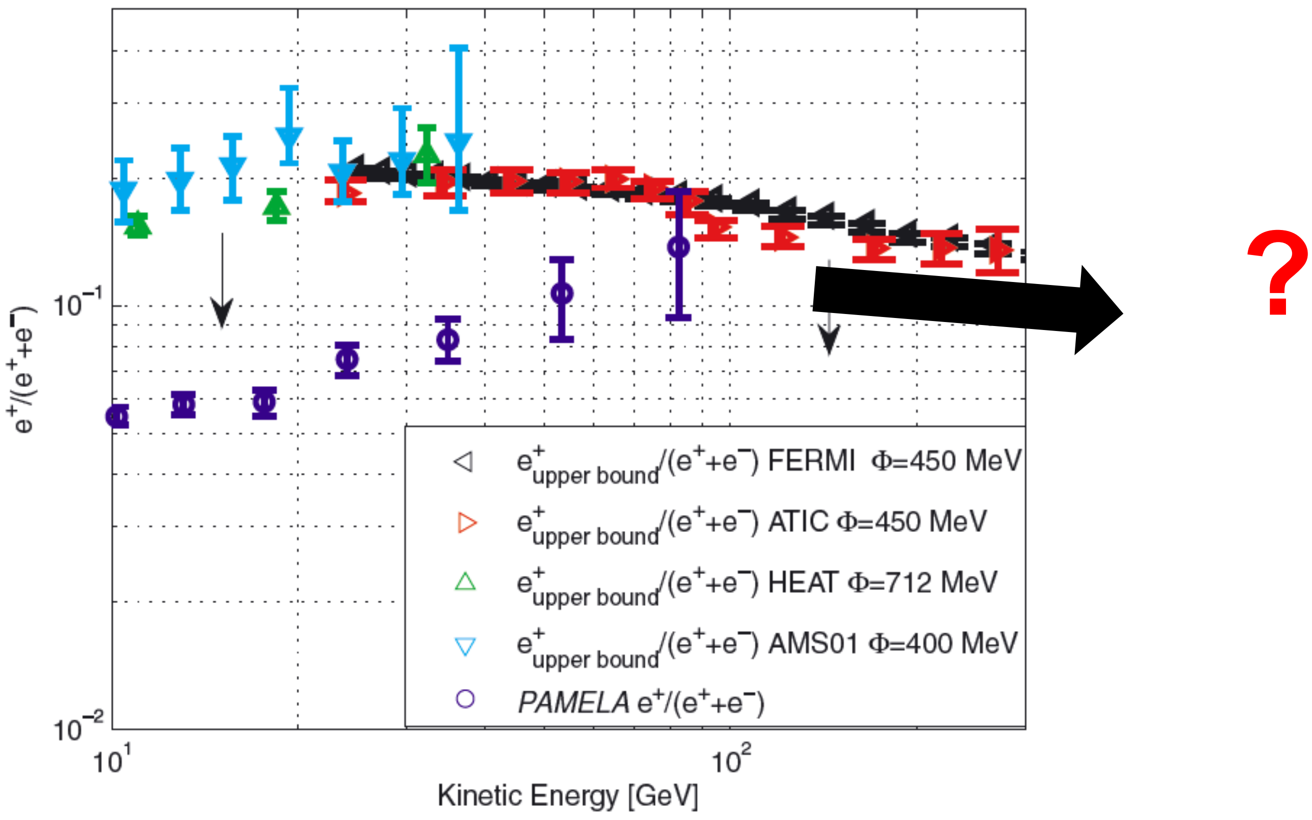
Katz et al, MNRAS 405 (2010) 1458

AMS02



?
e+upper bound/(e+ + e−) FERMI Φ=450 MeV
e+upper bound/(e+ + e−) ATIC Φ=450 MeV
e+upper bound/(e+ + e−) HEAT Φ=712 MeV
e+upper bound/(e+ + e−) AMS01 Φ=400 MeV
PAMELA e+/(e+ + e−)
e+/(e+ + e−)
10−1
10−2
10¹
10²
Kinetic Energy [GeV]

AMS02



e+/(e++e−)
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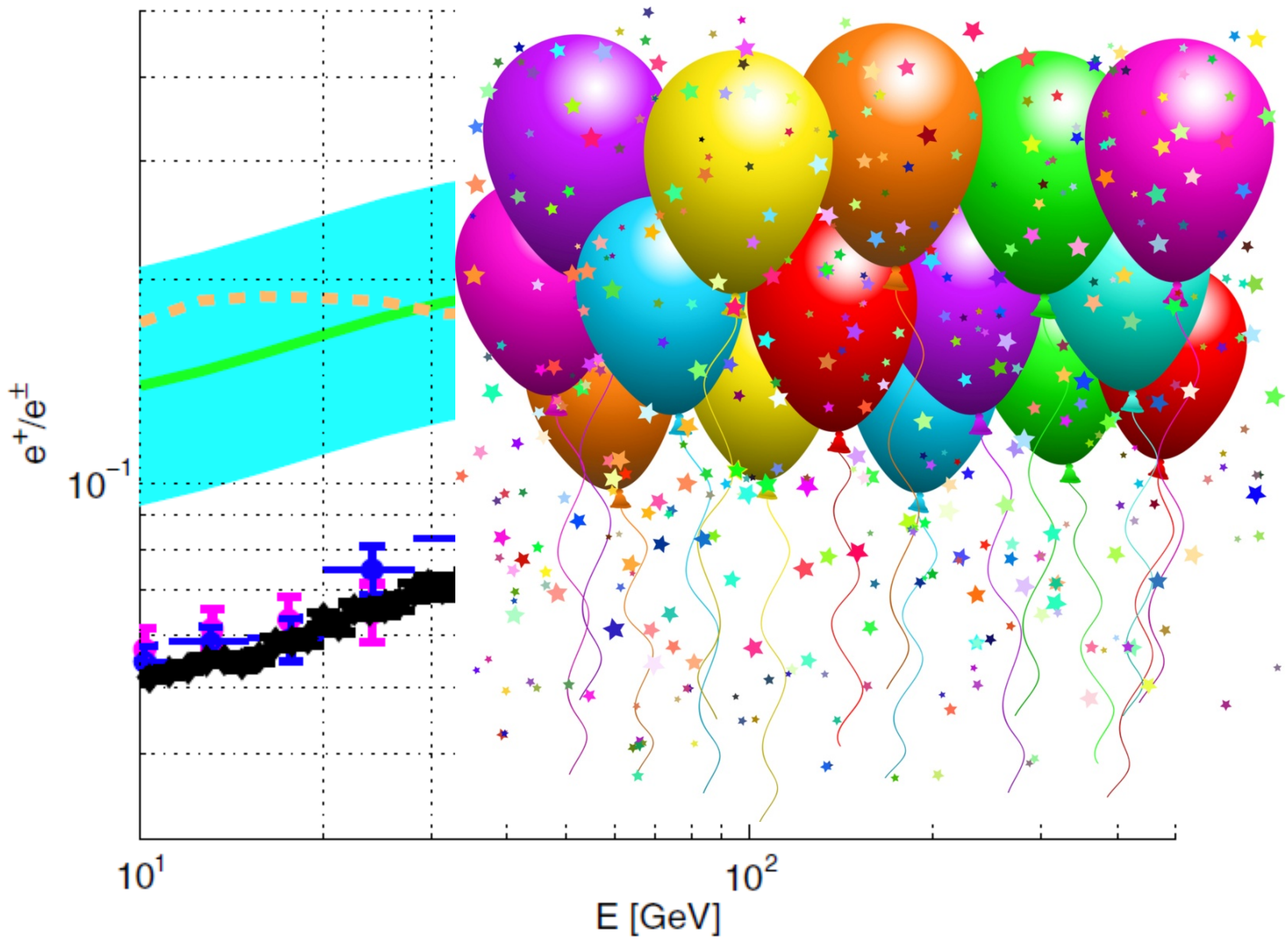
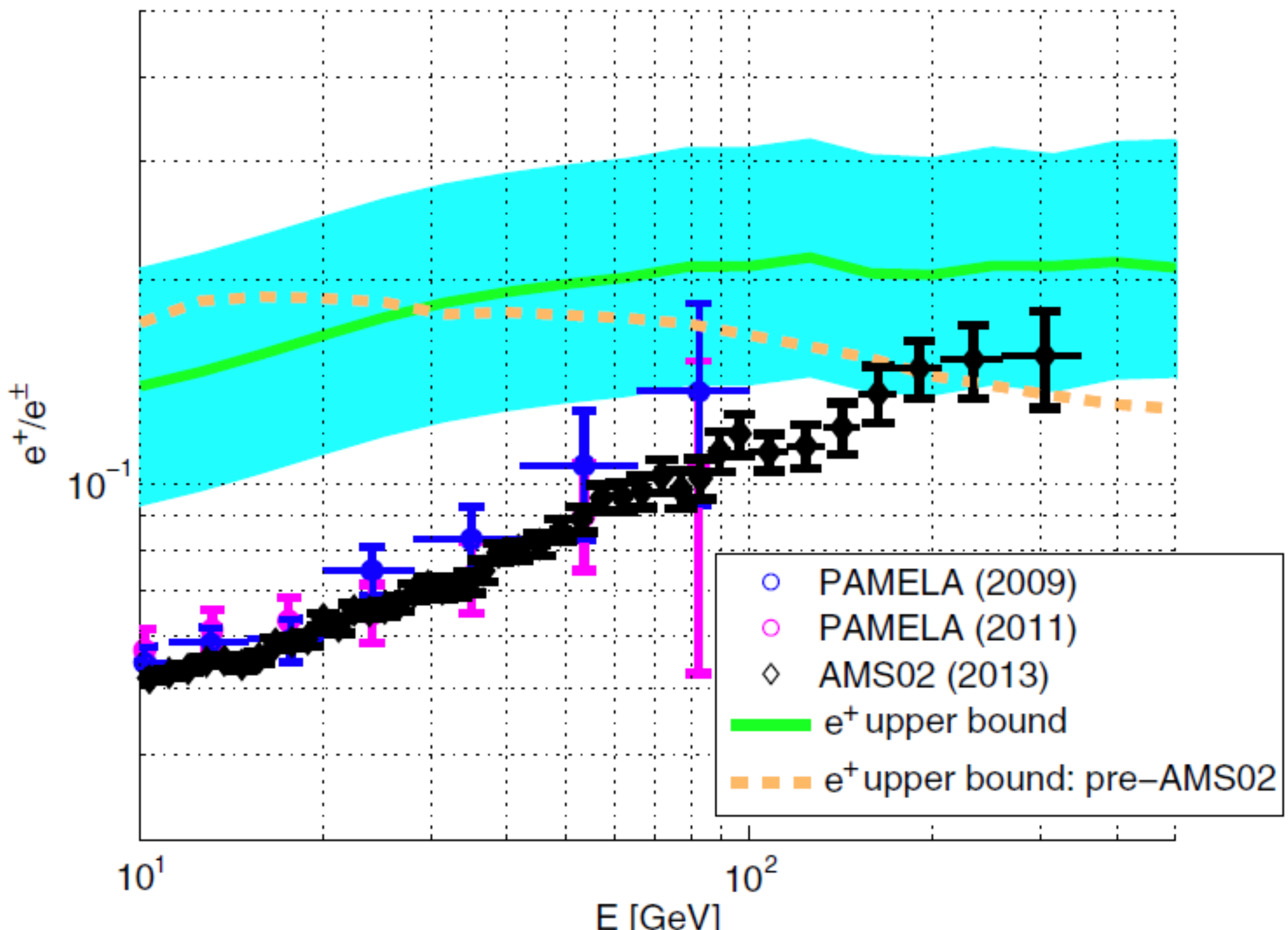
AMS02 (2013)

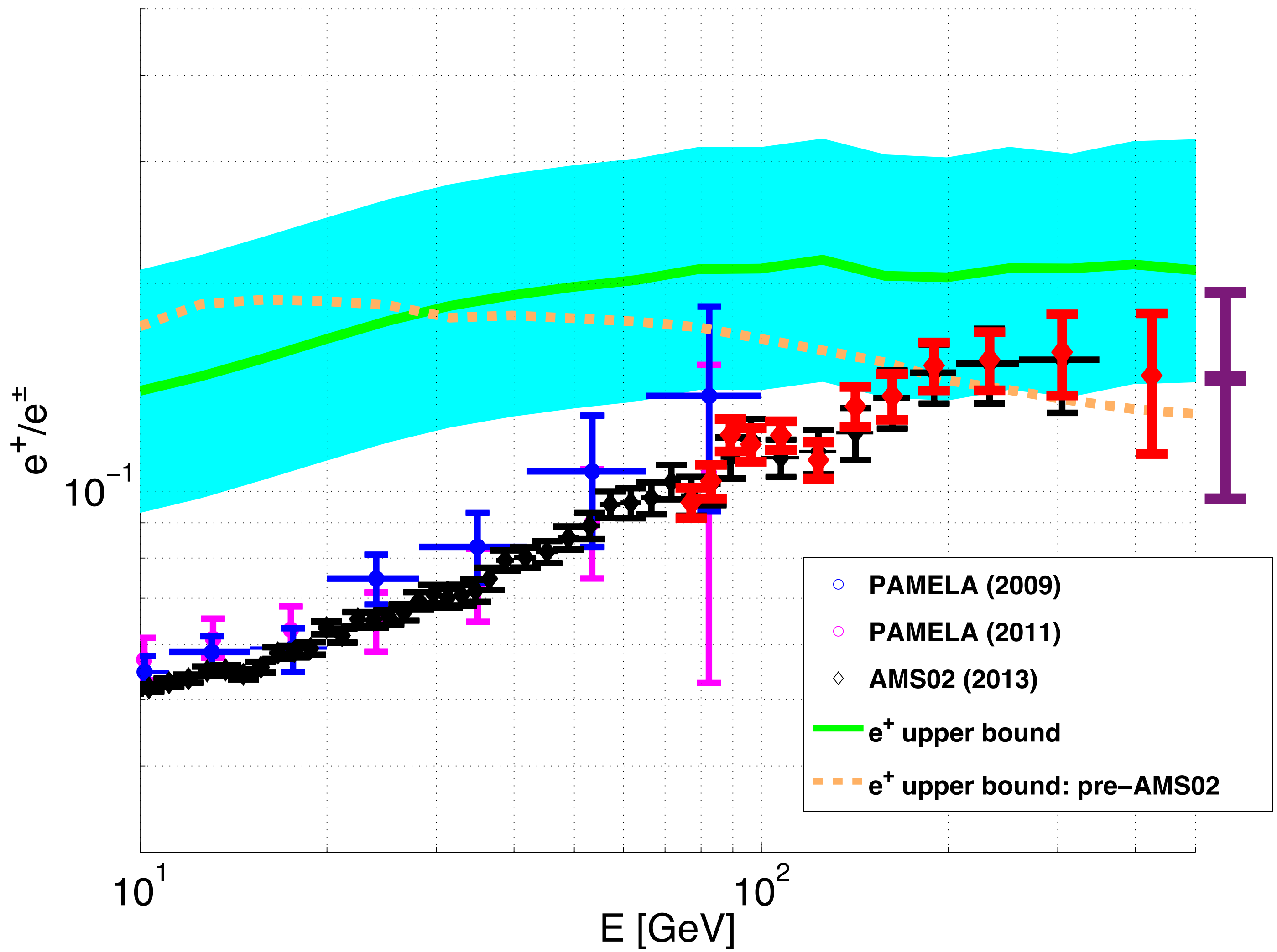


AMS02 (2013)



Blum, Katz, Waxman, **PRL 111, 211101 (2013)**

AMS02 (2014 I+II) (last error bar: my rough estimate)



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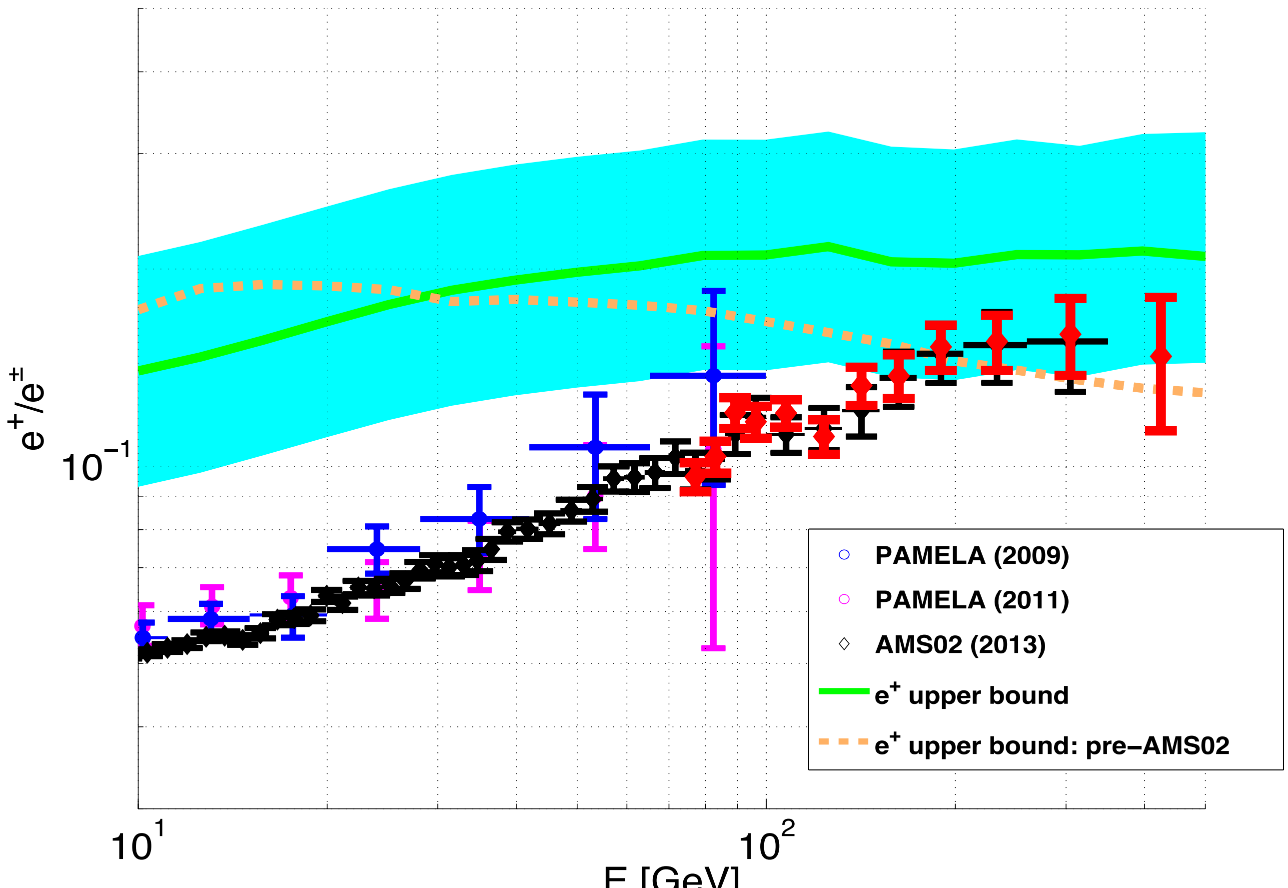

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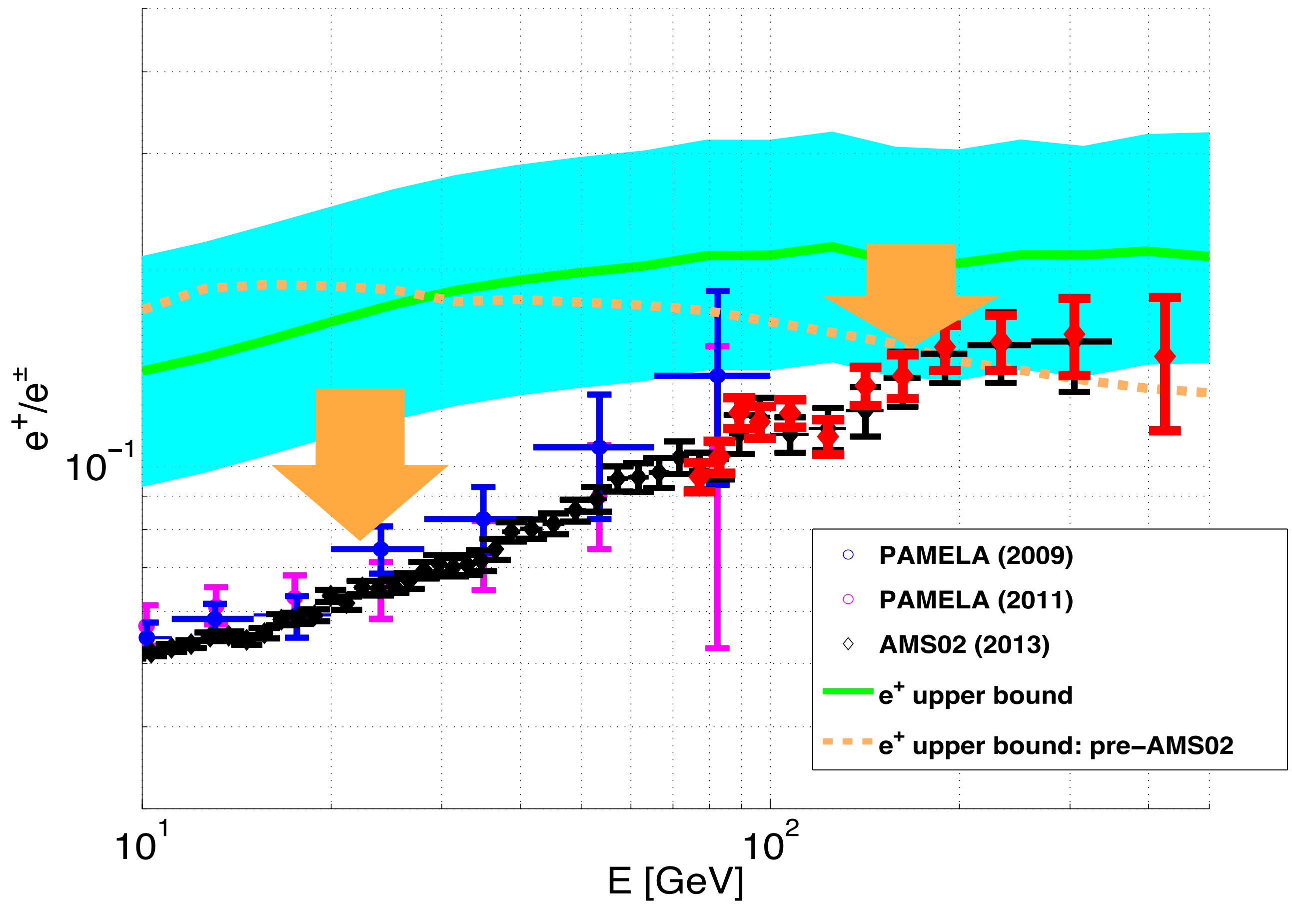
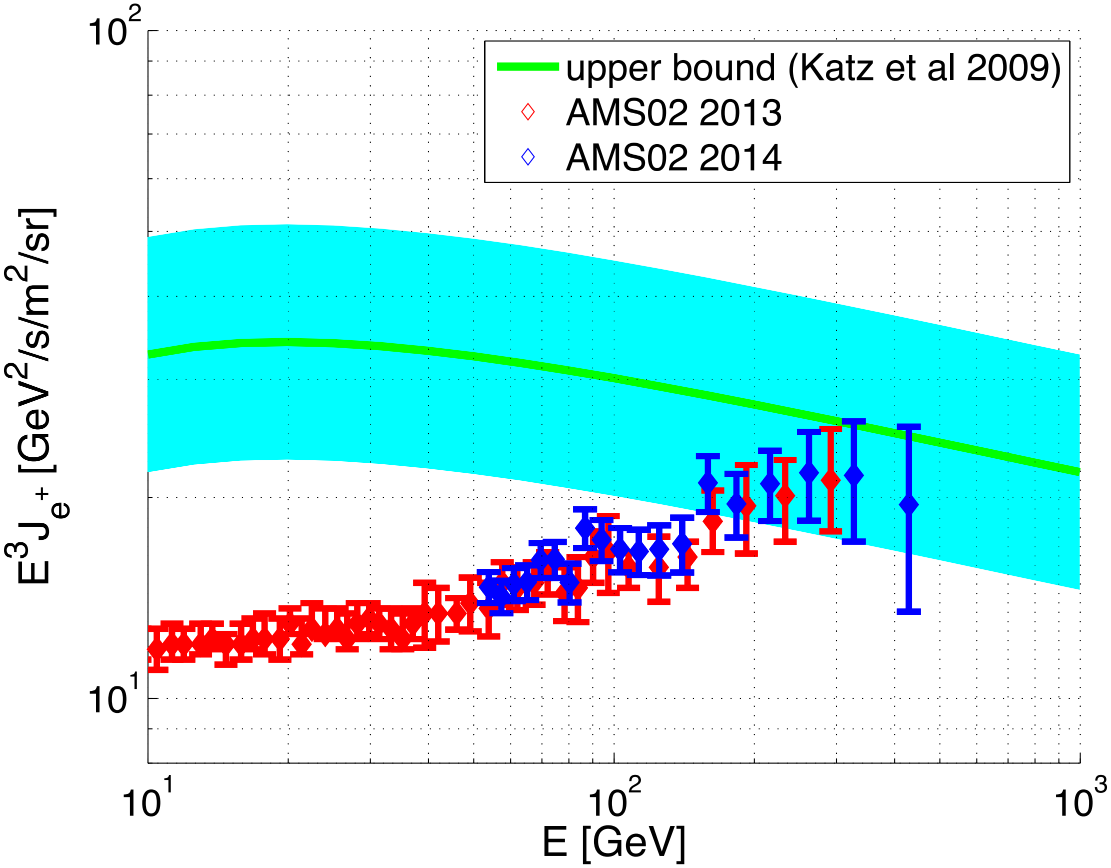
$$f_{e^+} < 1$$



Important point: direct measurement of e+ flux rather than e+/e±

Dynamic range not limited to 0-0.6, in contrast to e+/e±

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



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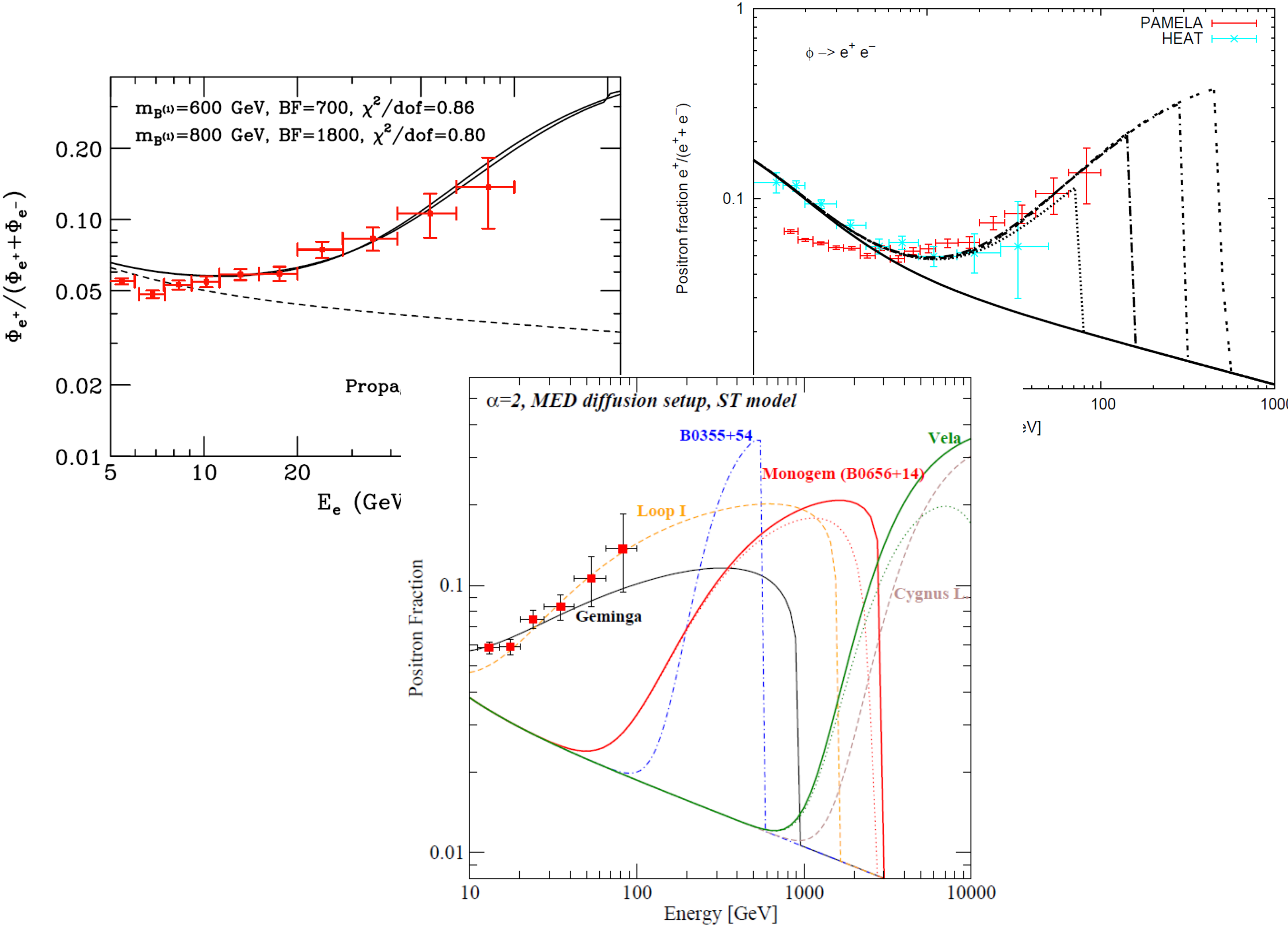
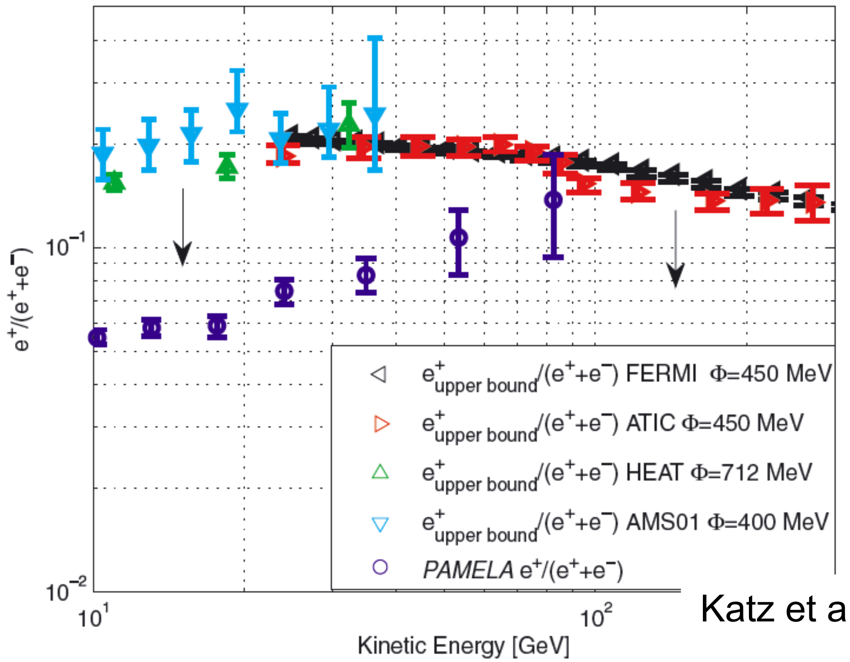
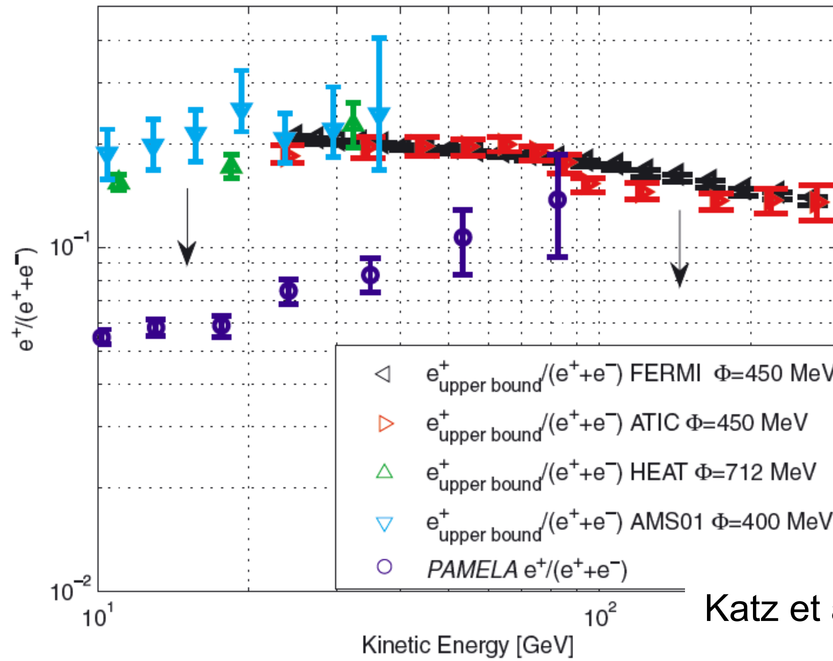




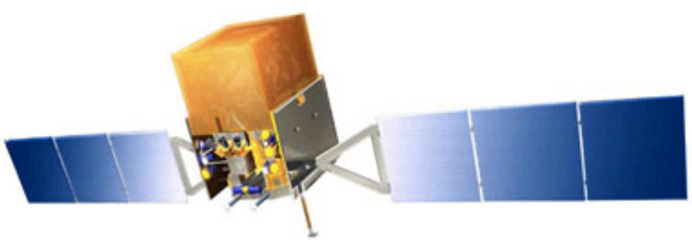
Katz et al, MNRAS 405 (2010) 1458

A comment about progress w/ AMS02



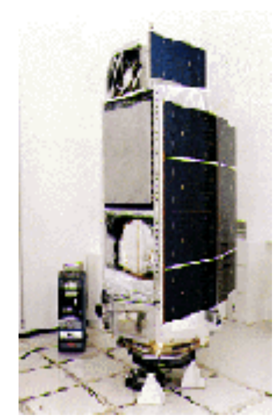
Katz et al, MNRAS 405 (2010) 1458

What we had to do before AMS02:



+

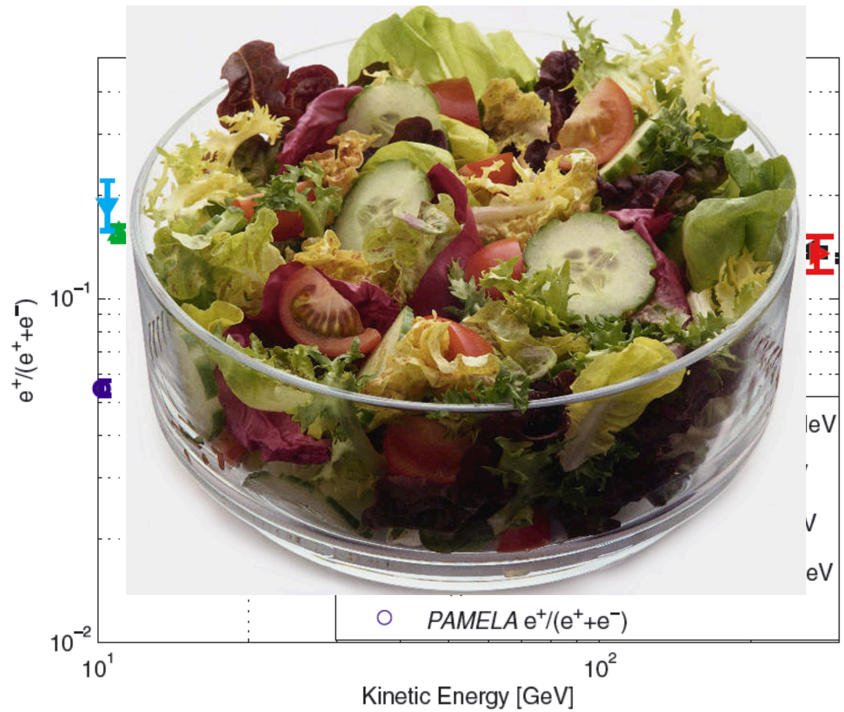
+



total e±

e+/e±, p, He

B/C



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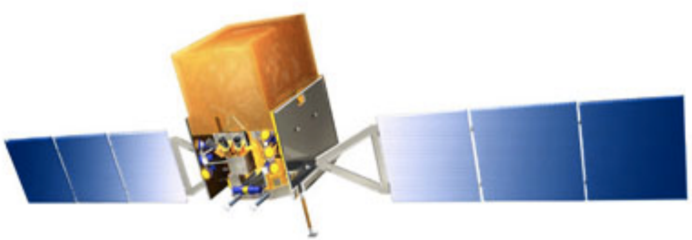
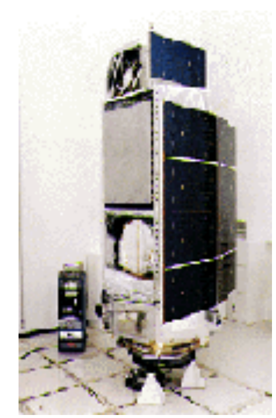


+

+



total e±

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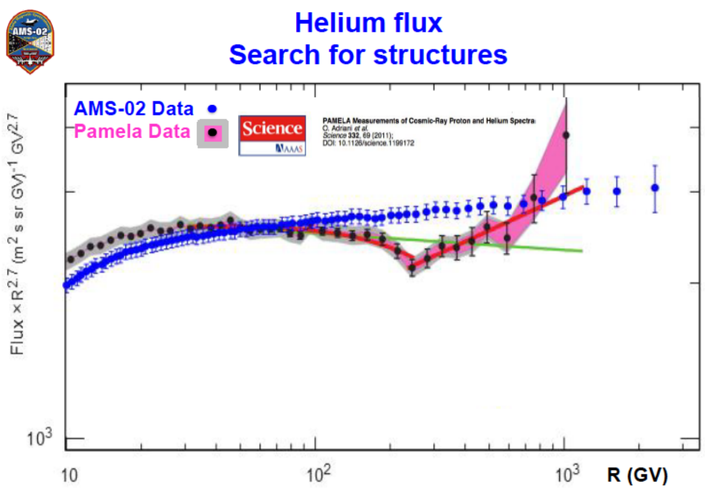
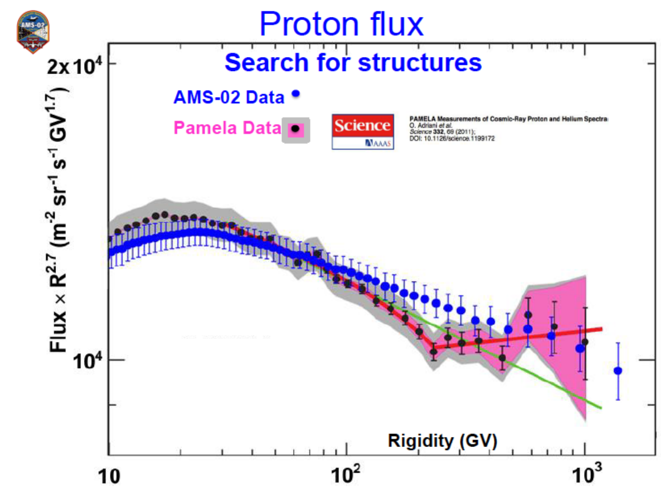
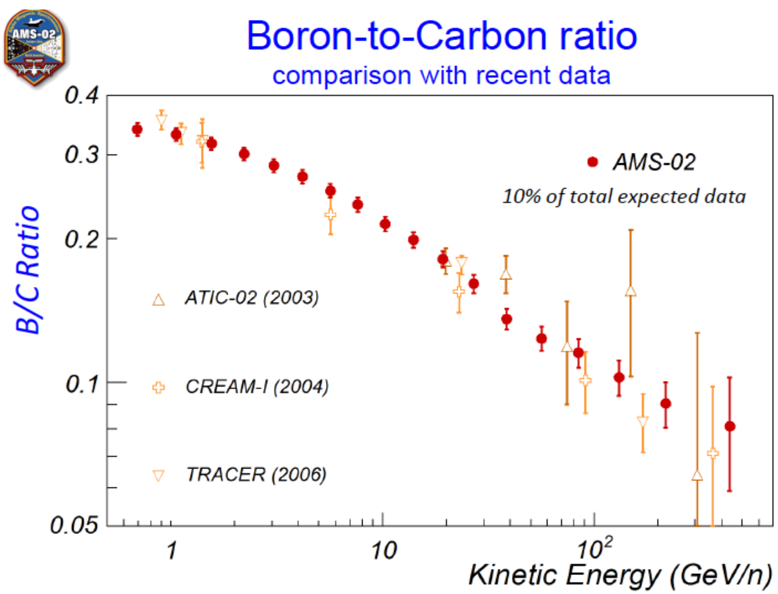
B/C

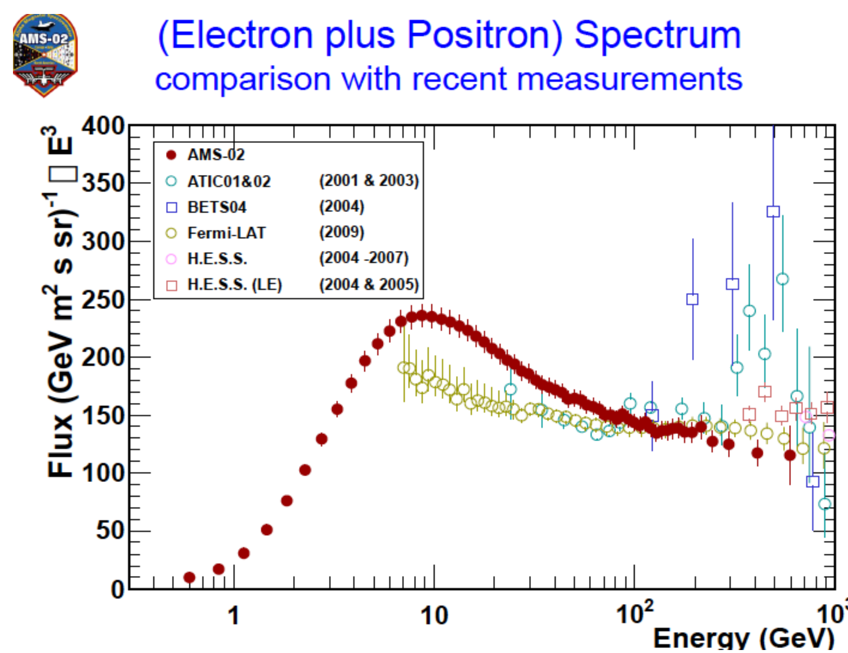
AMS02 update (2013)

For the first time, (almost!) all ingredients from same experiment

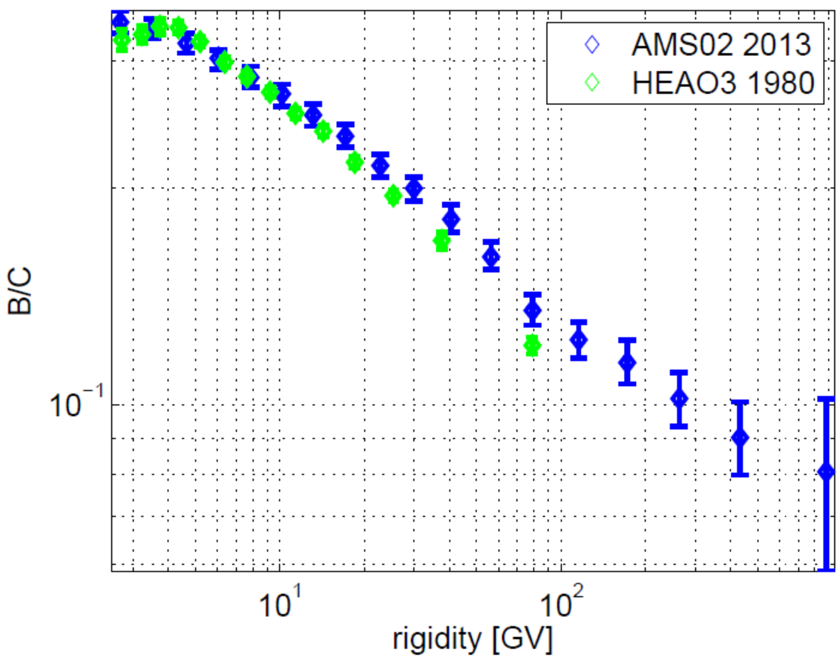


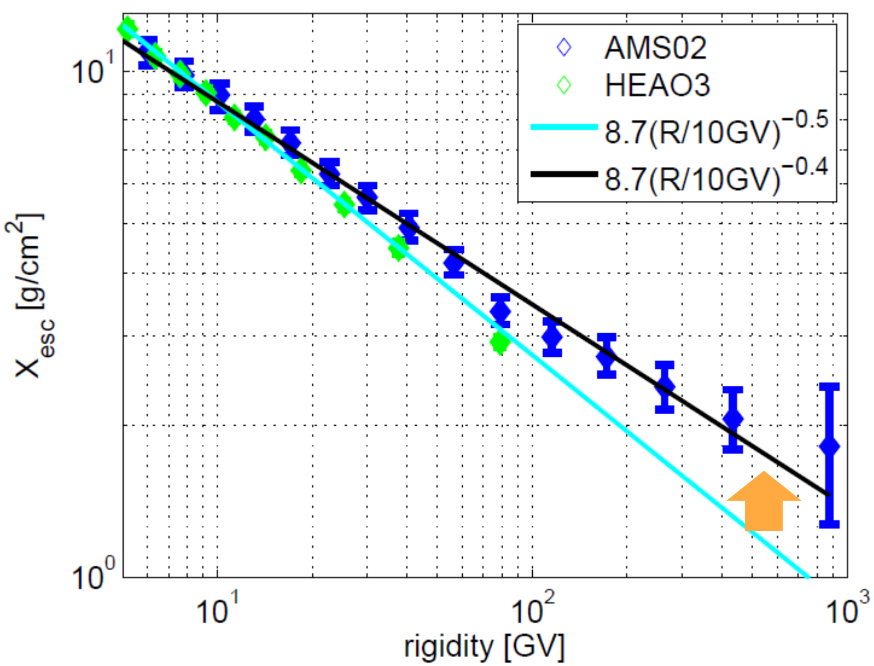


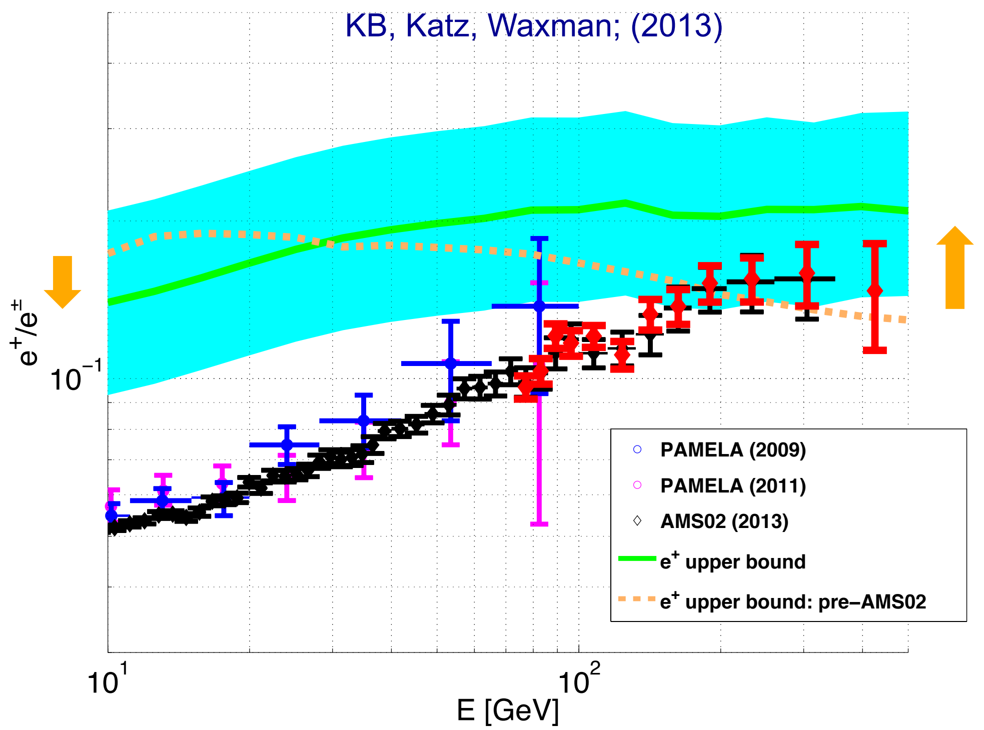




AMS02 update (2013)



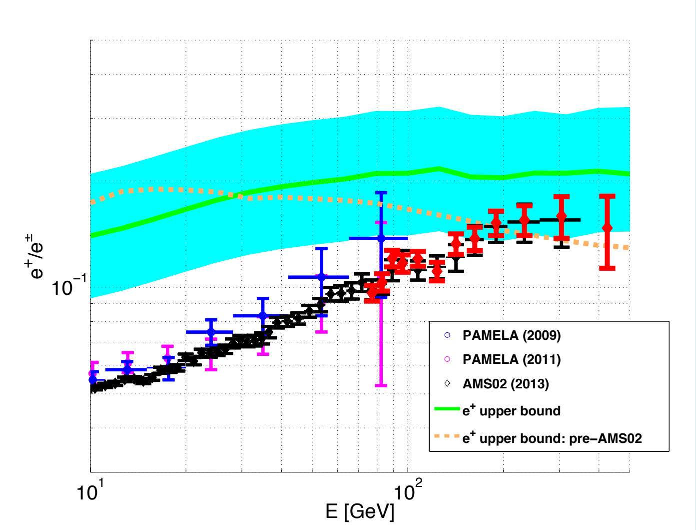


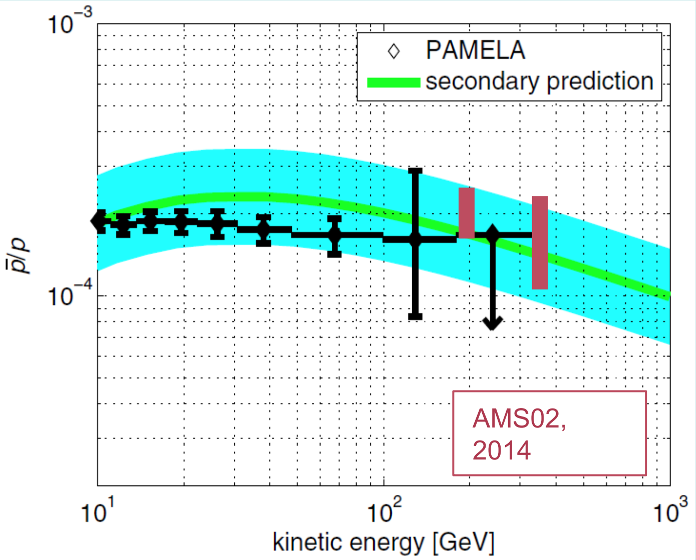


KB, Katz, Waxman; (2013)
$e^+/e^\pm$
10^{-1}
10^1
10^2
E [GeV]
PAMELA (2009)
PAMELA (2011)
AMS02 (2013)
e^+ upper bound
e^+ upper bound: pre-AMS02

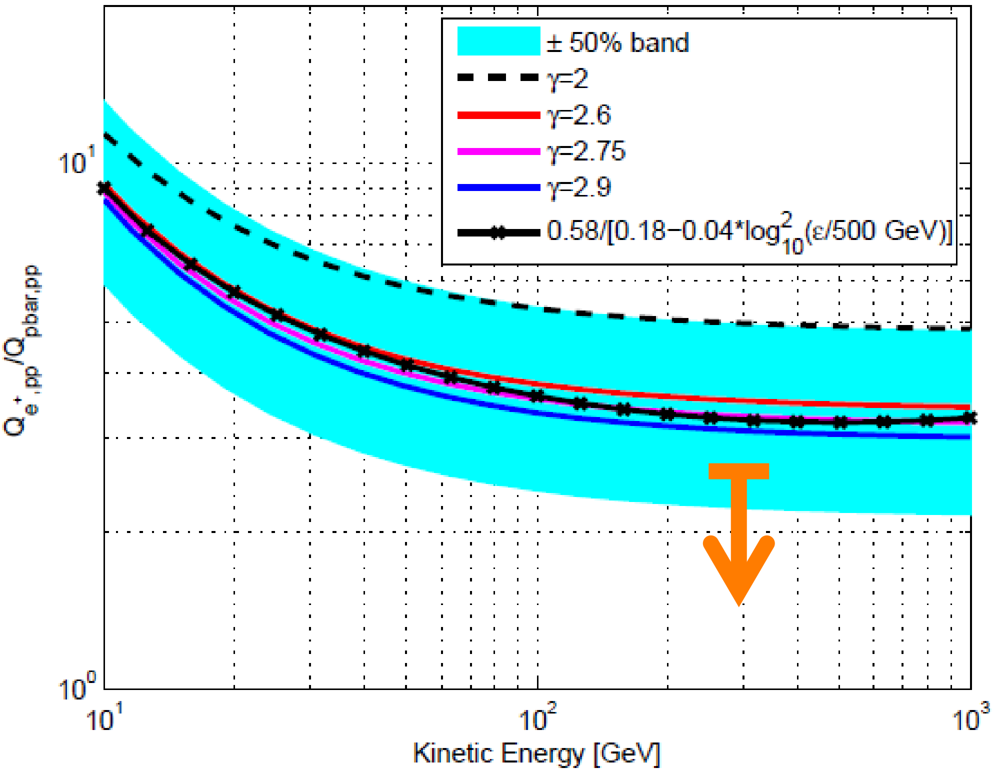
- how do we test the secondary interpretation further?

1. A clean test: $e^+/\bar{p}$





branching fraction in pp collision:



$$\frac{J_{e^+}}{J_{\bar{p}}} \lesssim \frac{C_{e^+,pp}(\varepsilon)}{C_{\bar{p},pp}(\varepsilon)} = \frac{Q_{e^+,pp}}{Q_{\bar{p},pp}}$$

2. Propagation time scales: radioactive nuclei

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➔ 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.

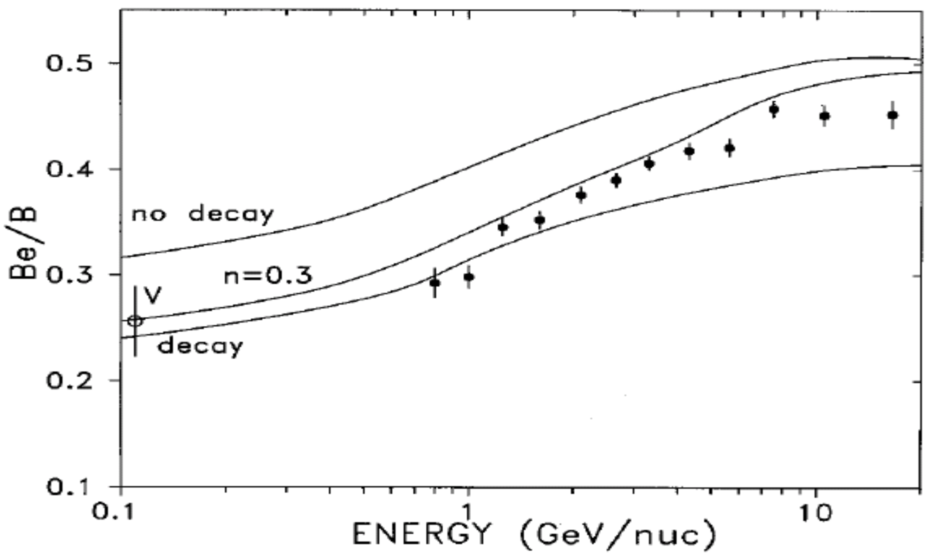
Radioactive nuclei: Charge ratio

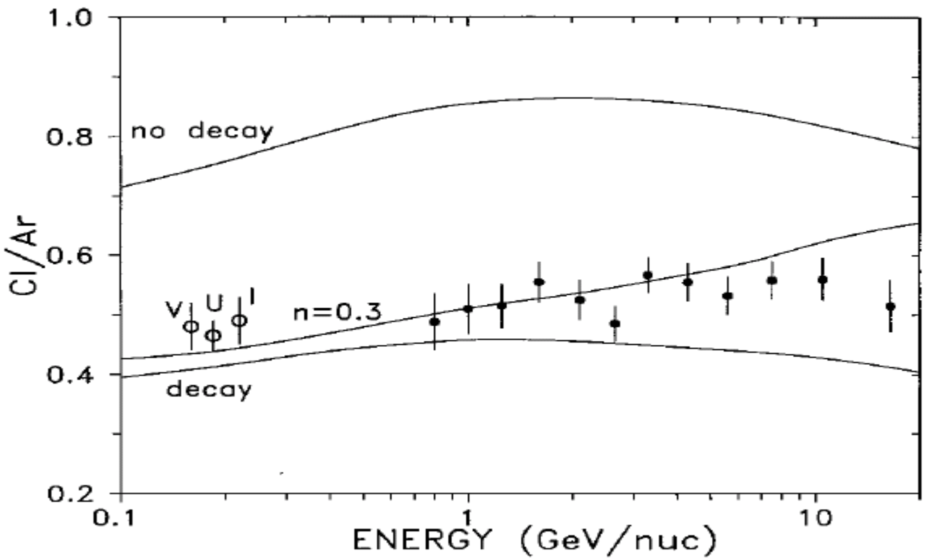
A STUDY OF THE SURVIVING FRACTION OF THE COSMIC-RAY RADIOACTIVE DECAY ISOTOPES ^{10}Be, ^{26}Al, ^{36}Cl, and ^{54}Mn AS A FUNCTION OF ENERGY USING THE CHARGE RATIOS Be/B, Al/Mg, Cl/Ar, AND Mn/Fe MEASURED ON *HEAO – 3*

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

Received 1997 November 6; accepted 1998 May 11

(WS98)





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 <u>difficult</u>. 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)

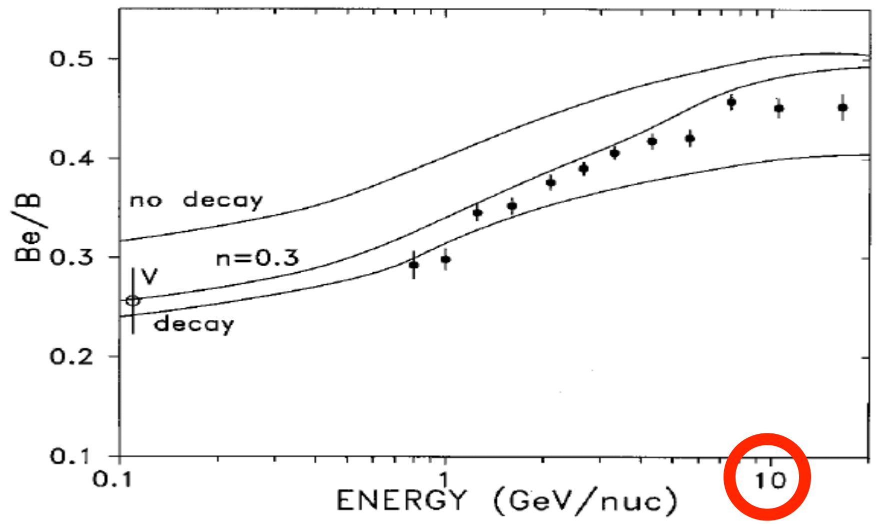
• **Benefit**: avoid low energy complications; significant range in rigidity

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

Radioactive nuclei: Charge ratio vs. isotopic ratio

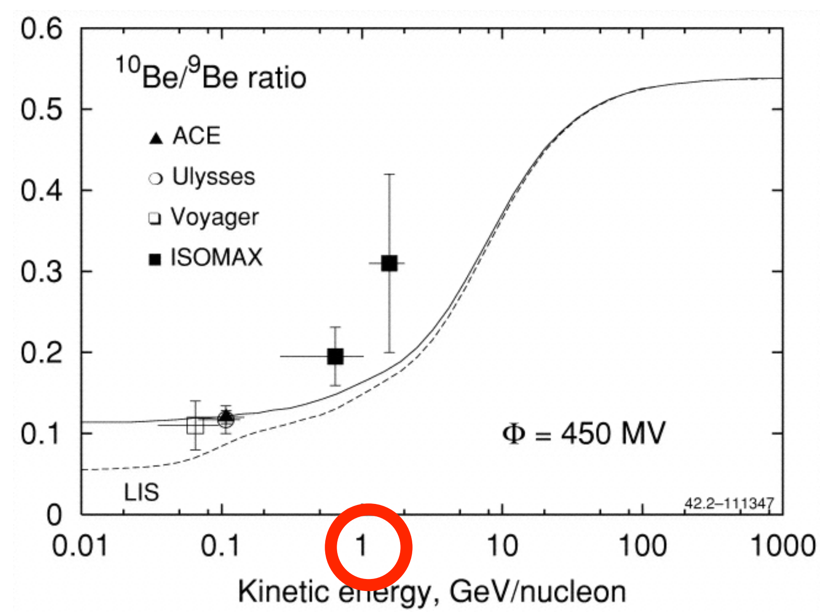
Charge ratios

Be/B, Al/Mg, Cl/Ar



Isotopic ratios

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



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:

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

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

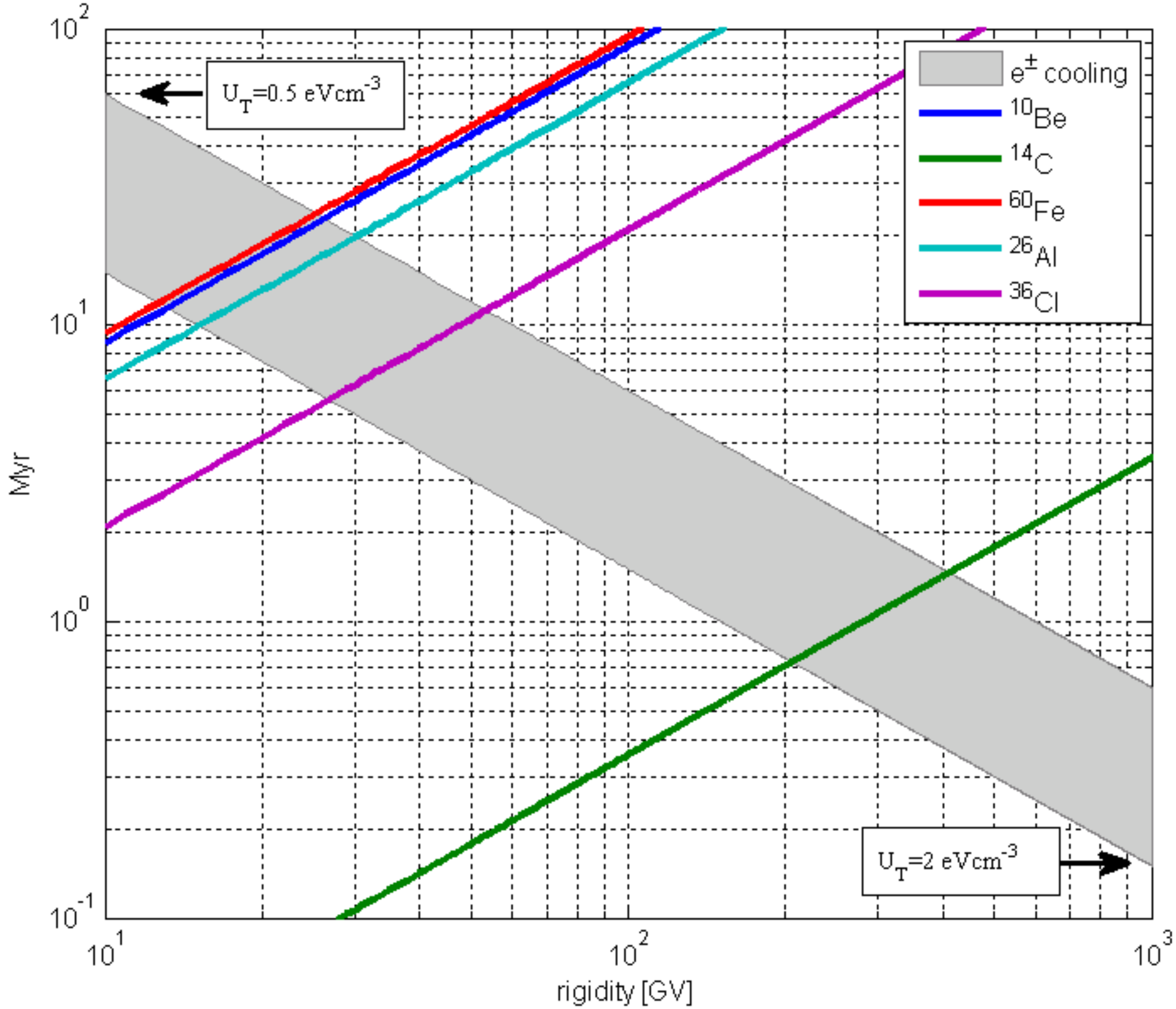
$$\tilde{t}_c = \frac{t_c}{\gamma - \delta_c - 1}$$

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

Comparing with radioactive nuclei

Time scales:

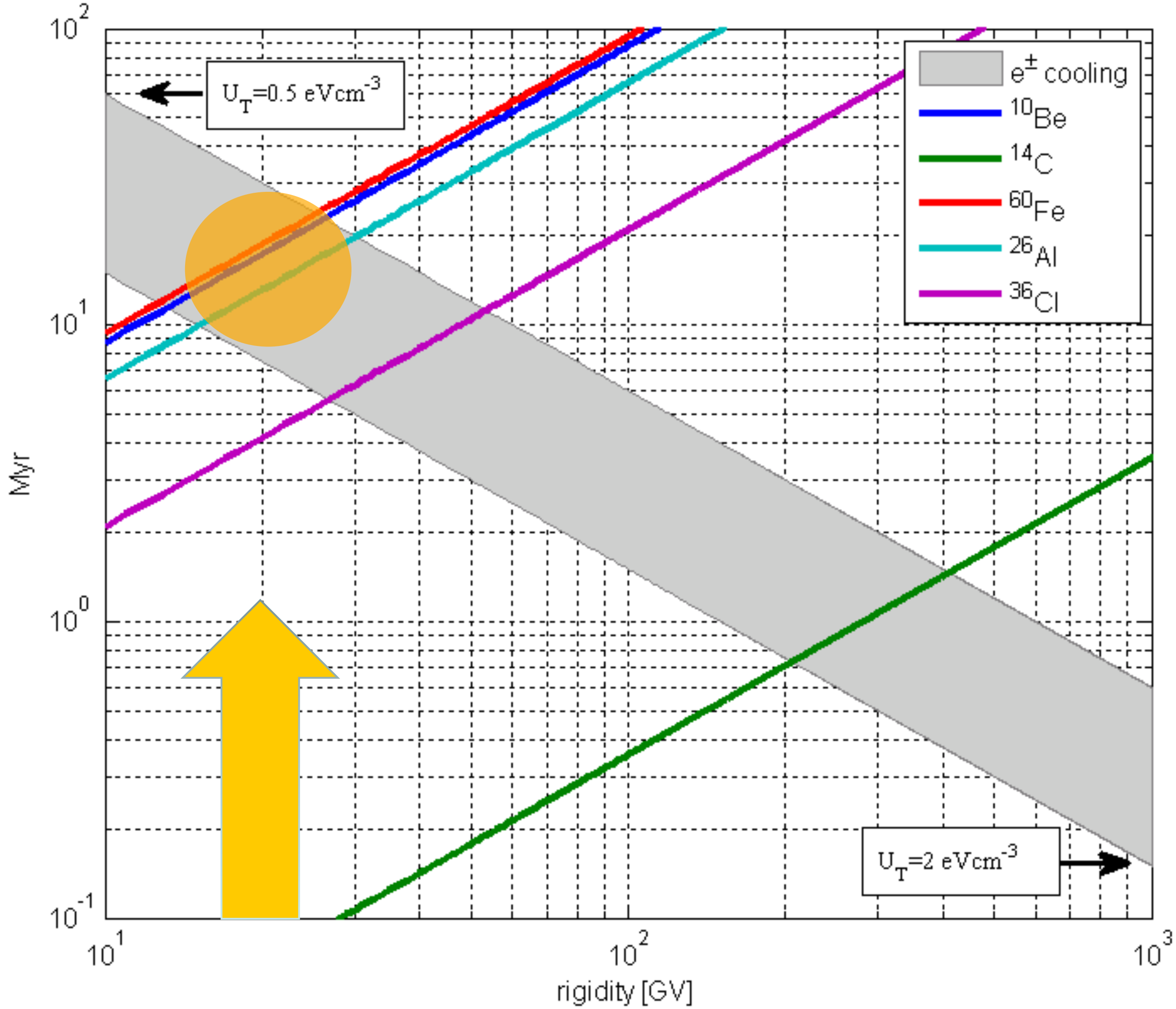
cooling vs decay



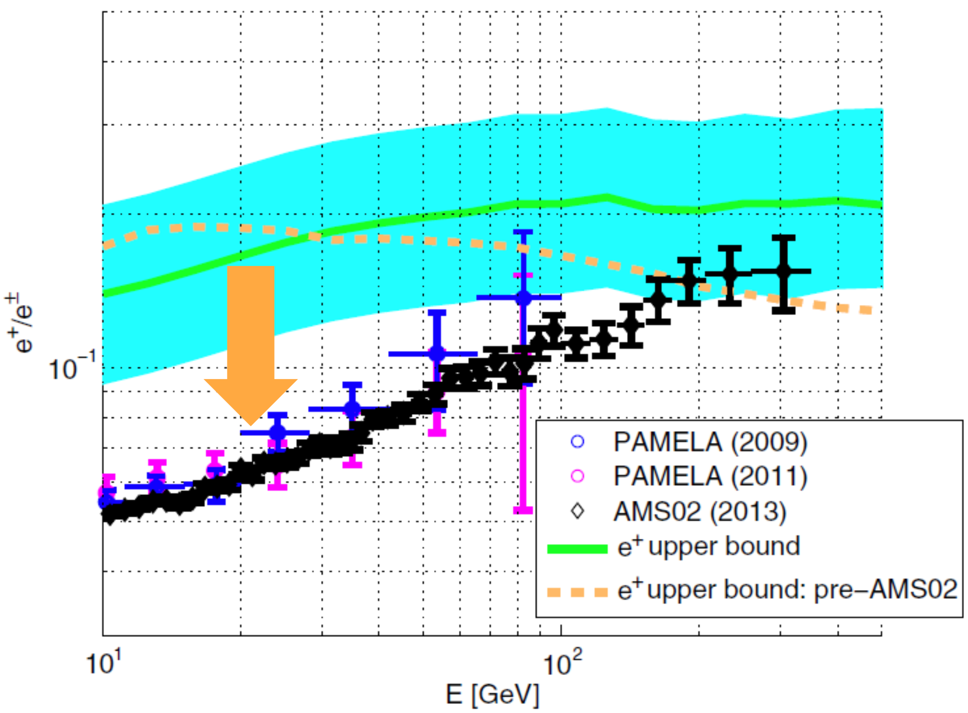
Comparing with radioactive nuclei

Time scales:

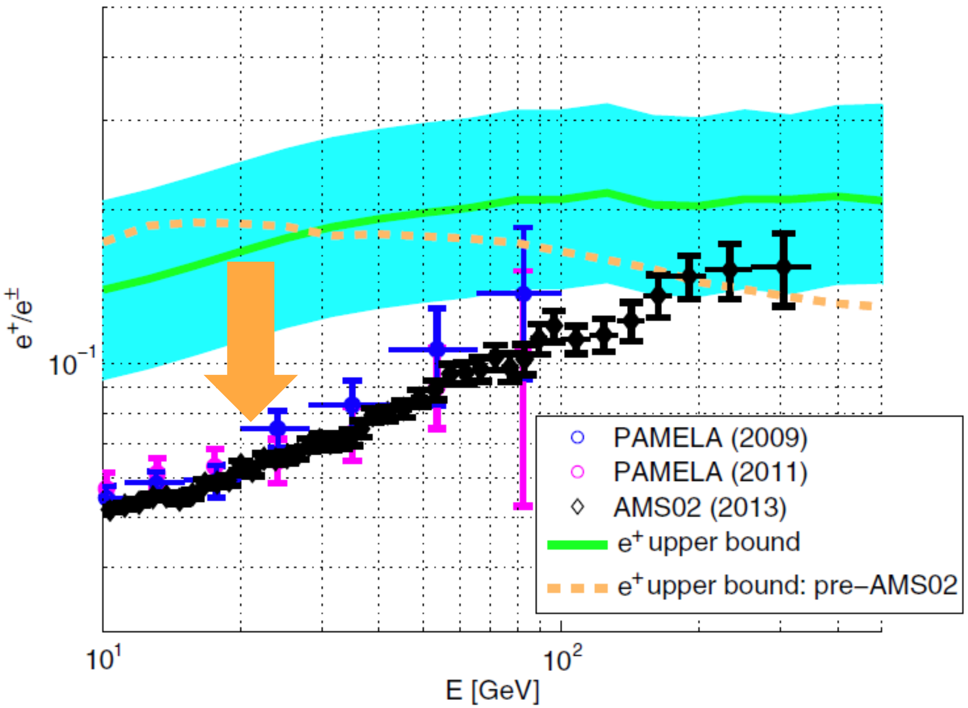
cooling vs decay

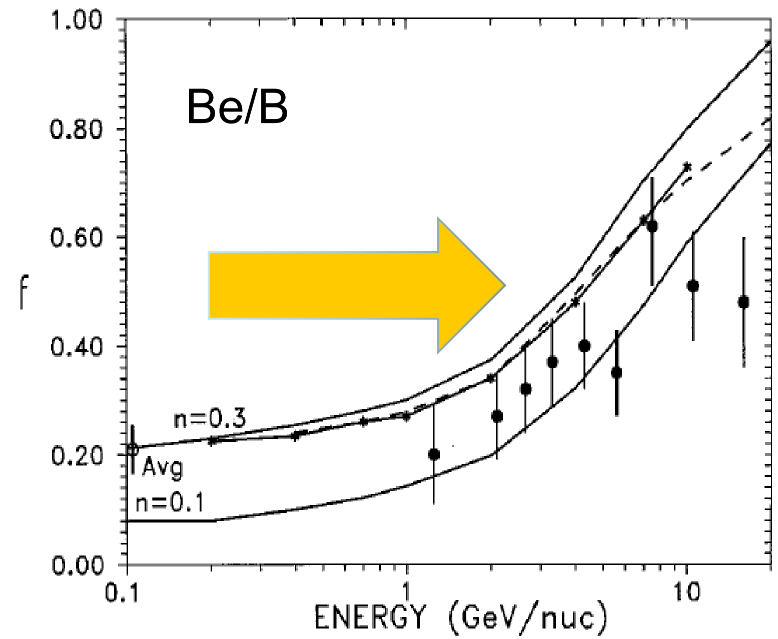


Comparing with radioactive nuclei

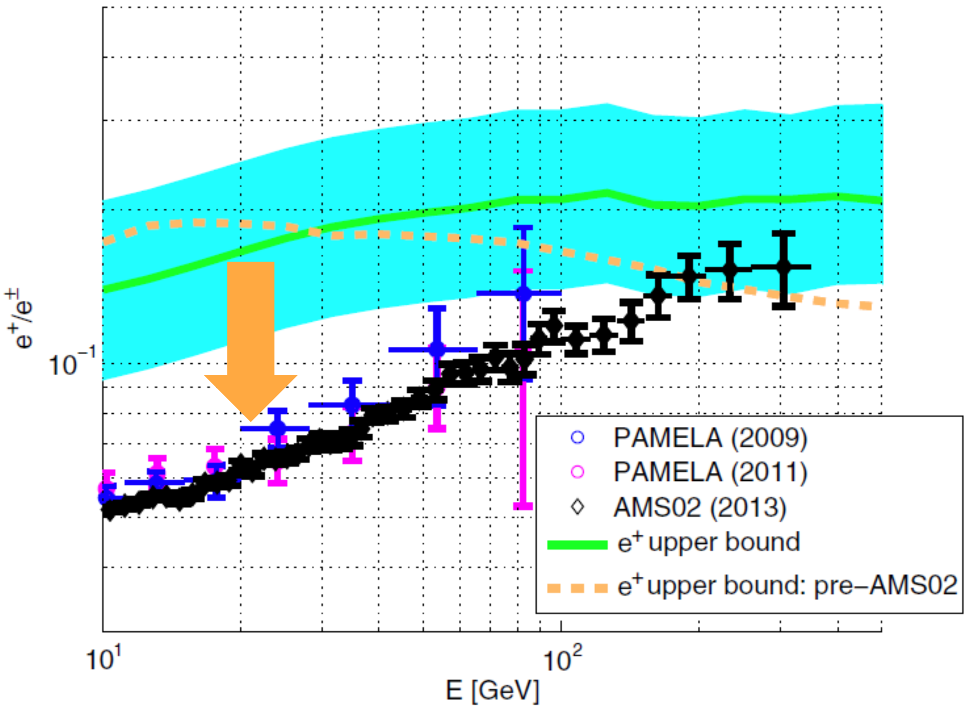


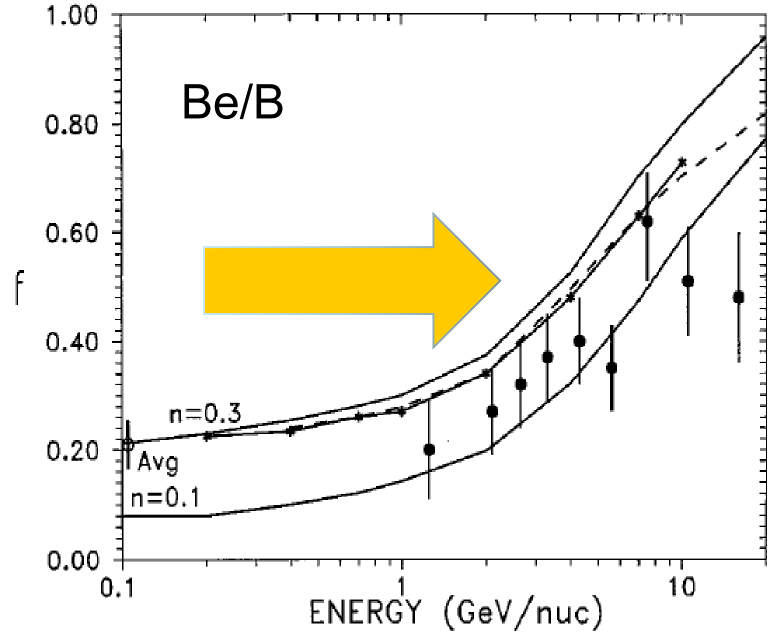
Comparing with radioactive nuclei





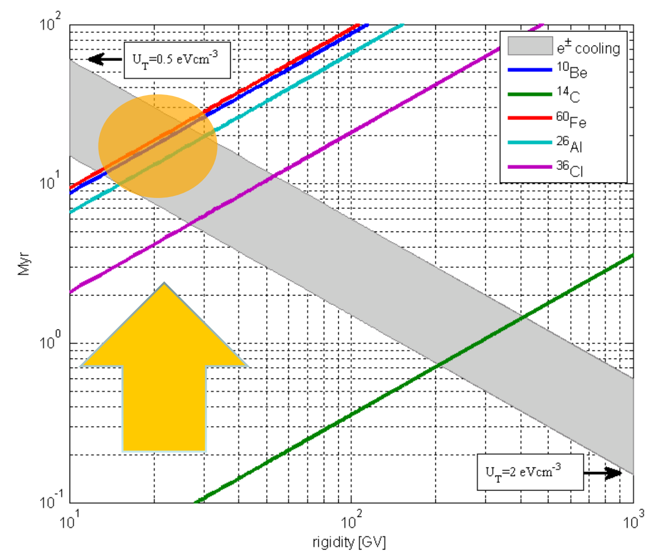
Comparing with radioactive nuclei





$$f_{s,{}^{10}\mathrm{Be}} \approx 0.4$$

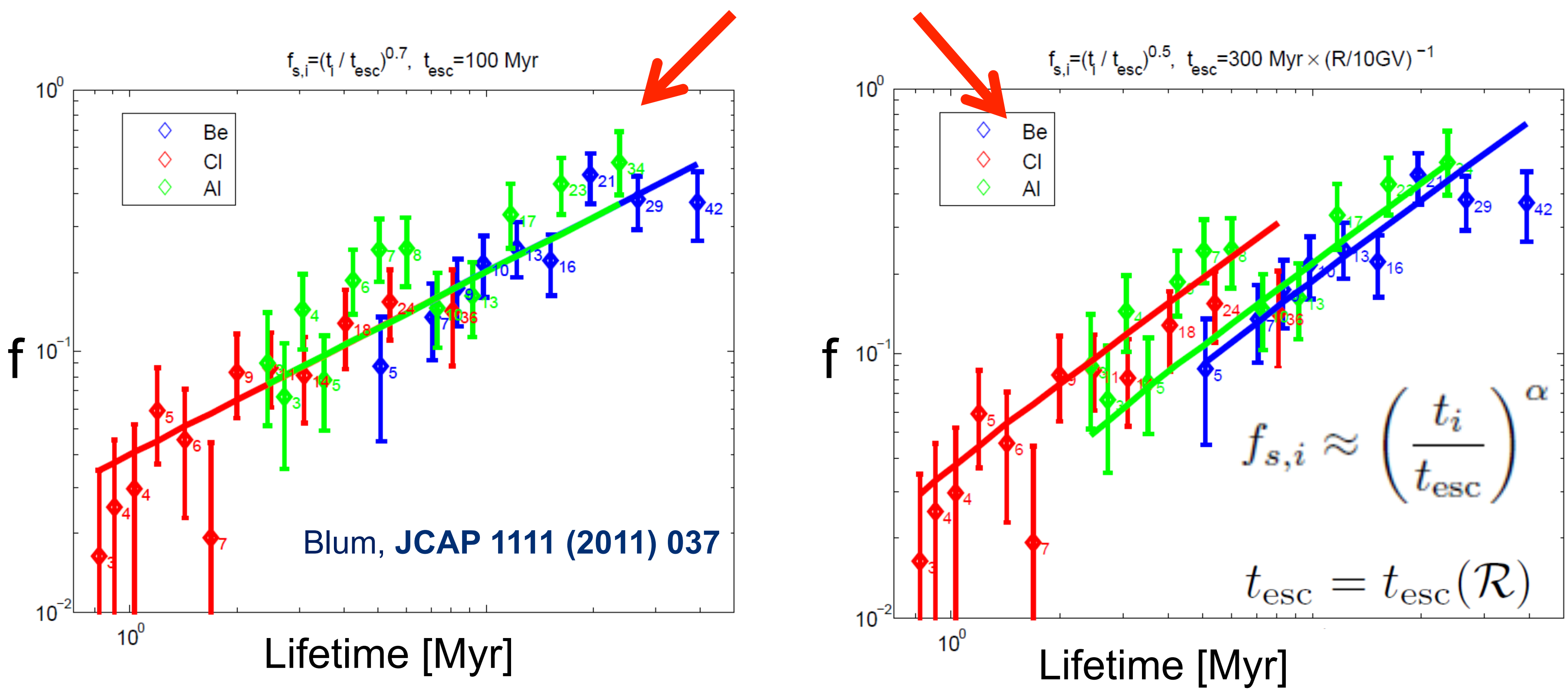
$$f_{s,e^+} \approx 0.3$$



Radioactive nuclei: constraints on t_{esc}

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

Need to tell between these fits



- lessons for CR propagation, assuming secondary e+

What is the cooling time for CR positrons?

What is the cooling time for CR positrons?

As long as CME energy of eγ collision is << m_e

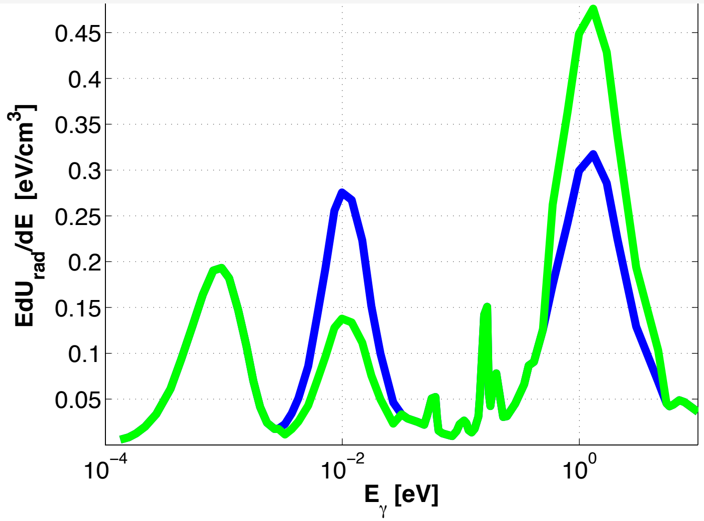
$$\dot{\epsilon} = -\frac{4\sigma_T u \epsilon^2}{3 m_e^2 c^3}$$

$$t_{cool} = \left|\frac{\epsilon}{\dot{\epsilon}}\right| \approx 10 \left(\frac{\epsilon}{30\ \mathrm{GeV}}\right)^{-1} \left(\frac{u}{1\ \mathrm{eV/cm^3}}\right)^{-1} \mathrm{Myr}$$

Once larger CME ($\epsilon_\gamma \epsilon \sim 0.25 m_e^2$), enter Klein-Nishina regime with suppressed cooling

For e+ (or e-) cooling on 1eV starlight photons, the cross to KN limit happens around 60 GeV.

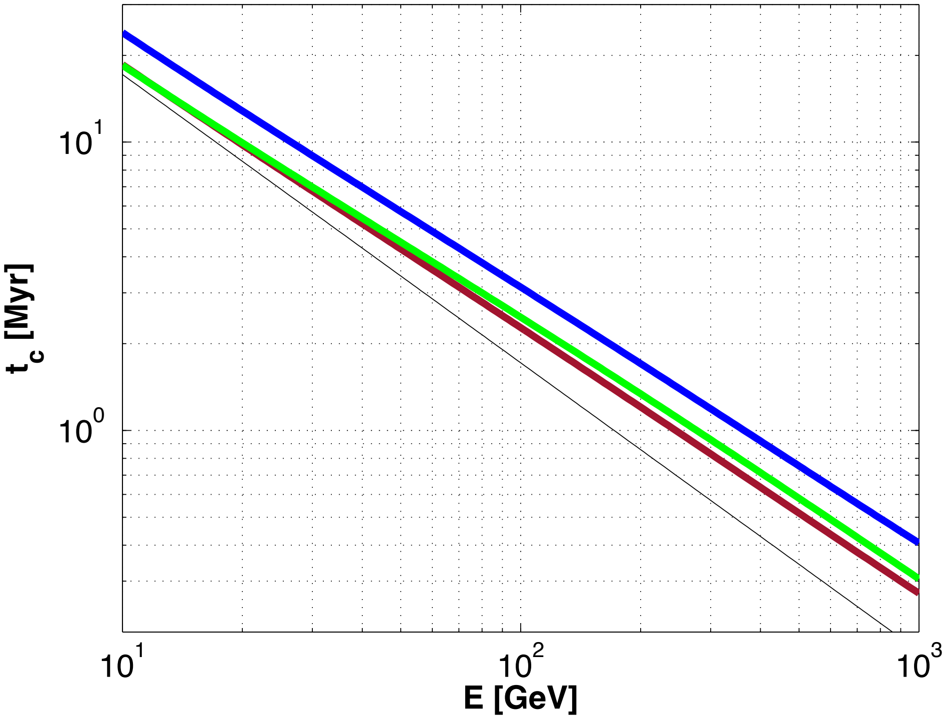
Taken from: Porter & Strong, astro-ph/0507119

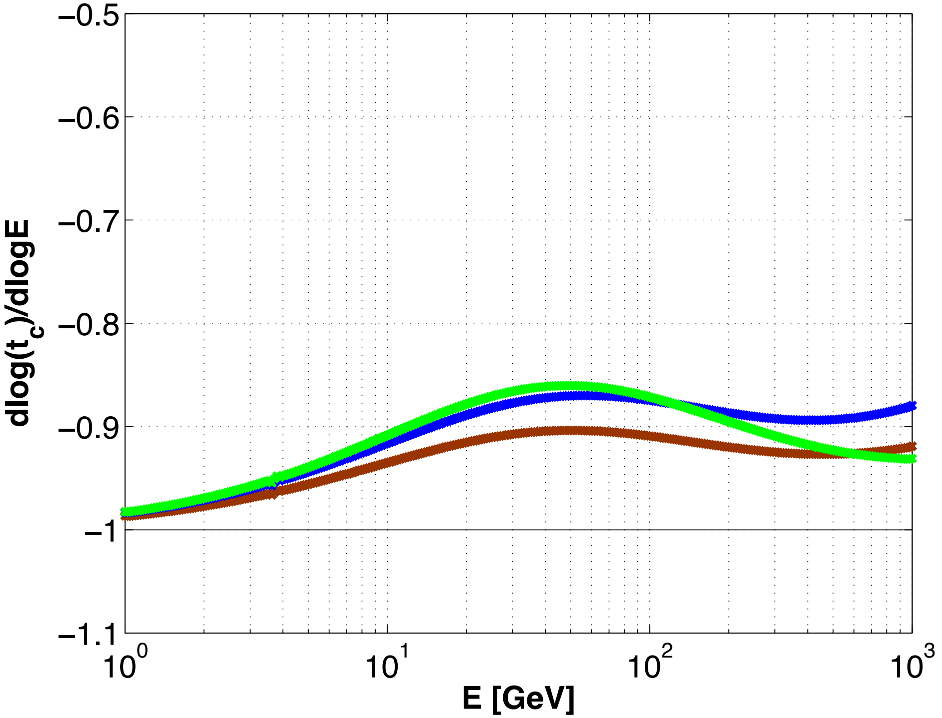


What is the cooling time for CR positrons?

K-N bump @E~10-100 GeV
due to starlight.

Index ~ 0.8-0.9
t_{cool} ~ 1 Myr @ 300 GeV





1. For the first time, limit **cosmic ray propagation time @100's GV**:

$$t_{\rm esc}\,(E/Z = 300\ {\rm GeV})\ \lesssim\ 1\ {\rm Myr}$$

Together with B/C and pbar/p data, this *may* suggest that *high energy CRs do not return from* too far above the Galactic gas disc:

$$\langle n_{\rm ISM}(\mathcal{R})\rangle = \frac{X_{\rm esc}(\mathcal{R})}{c\,m_{\rm ISM}\,t_{\rm esc}(\mathcal{R})}$$ ~ 1/cm^3 @R=300GV

➔ AMS updates on B/C together w/ p, He, and e+ flux

important to check n at yet higher energies.

(will we be led to surprisingly large n>>1?)

2. As rigidity R increases, loss suppression does not decrease (*perhaps even gets closer to unity?*),

imply $t_{esc}(R)/t_{cool}(R)$ ~ constant (*perhaps decreasing?)* with R

➔ $t_{esc}(R)$ decreases faster than $X_{esc}(R)$

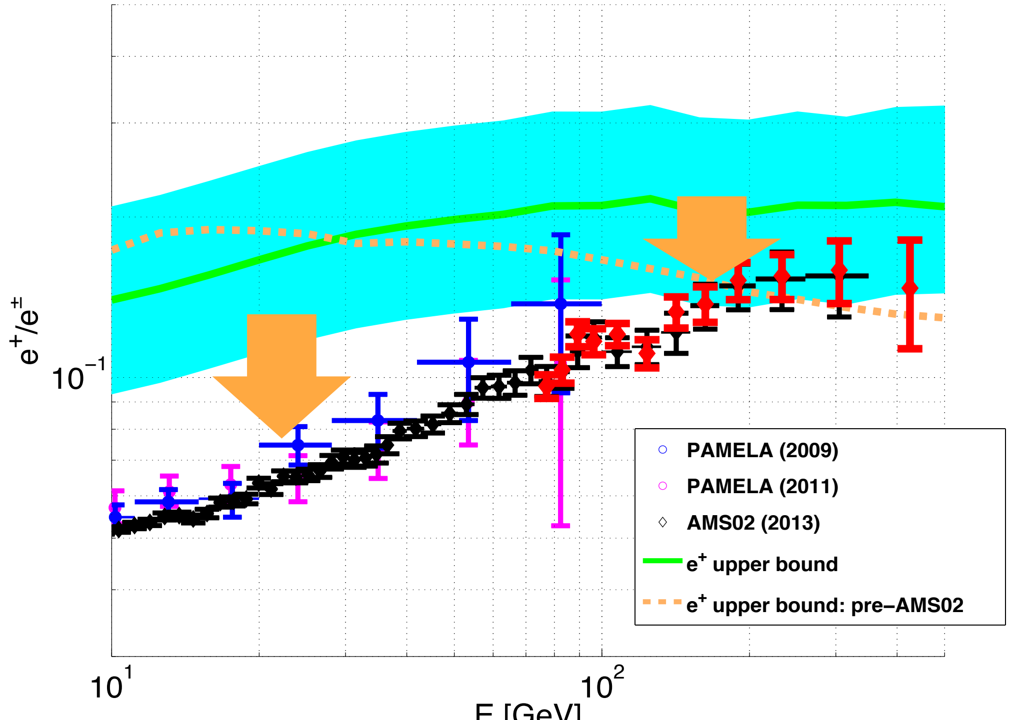
could do with e.g.

R-dependent boundary

need care w/ e+

production cross section,

as well as consistent B/C, p, He data.



Summary

pbar & e+ consistent with simple reliable calculation,

Katz et al, MNRAS 405 (2010) 1458

No need for dark matter annihilation / pulsar contribution

Why would a primary source reproduce secondary J_{e+}?

Very interesting cosmic ray physics

Cosmic ray escape time falling faster than column density?

Escape time < 1 Myr at R~300 GV

CRs at R > 300 GV don't come back from halo?

Upcoming tests with AMS

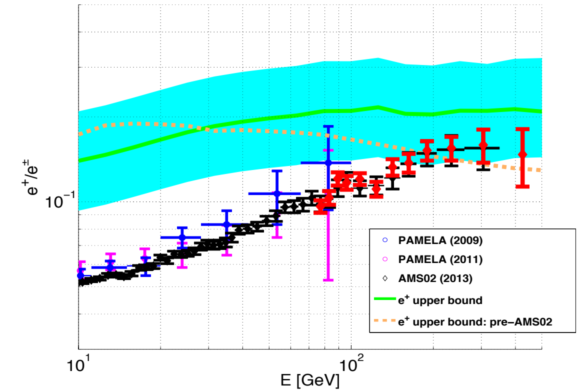
Spectral features?

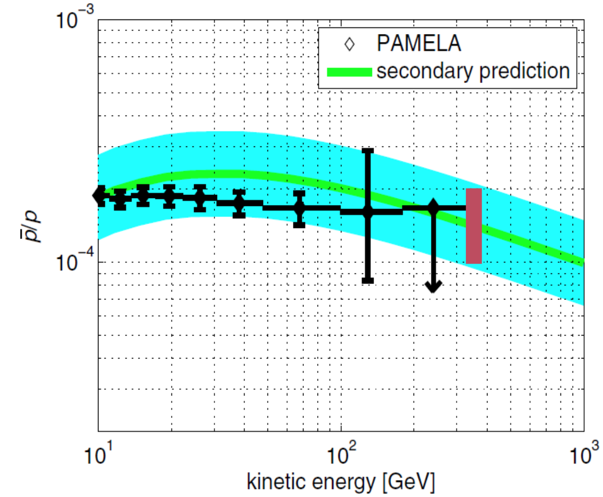
Determination of B/C, pbar at high energy

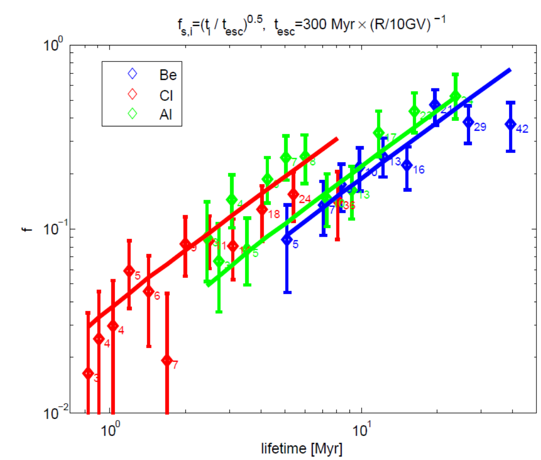
– calibrate out propagation

Relativistic elemental ratios Be/B, Cl/Ar, Al/Mg

Thank you!







Xtras

If escape time falls fast w/ energy, what is the implication for primary injection spectrum?

Fermi acceleration ➔ $$J_{p,\mathrm{inject}} \propto \mathcal{R}^{-\gamma_0}, \qquad \gamma_0 \gtrsim 2$$

Worry in literature: "if $t_{esc} \sim R^{-1}$ then…"

$$J_{p,\mathrm{obs}} \sim t_{\mathrm{esc}} \times J_{p,\mathrm{inject}} \propto \mathcal{R}^{-\gamma_0 - 1} \sim \mathcal{R}^{-2.8}$$

➔ injected $\gamma_0 < 2$?

Answer 1: we already saw that $t_{esc} \sim R^{-0.8}$ may be enough (KN effect in t_{cool}).
Answer 2: worry is based on scaling assumption, that may well be incorrect.

Correct (steady state) scaling is $$J_{p,\mathrm{obs}} \sim \frac{Q_p \times t_{\mathrm{esc}}}{V} \propto \frac{J_{p,\mathrm{inject}} \times t_{\mathrm{esc}}}{V}$$

…V can depend on rigidity: V=V(R)
Example: homogeneous thin-disc diffusion with V ~ L = L(R)

$$t_{\mathrm{esc}} \propto \frac{L^2}{D}, \qquad X_{\mathrm{esc}} \propto \frac{L\,c}{D} \times X_{\mathrm{disc}}$$

➔ $$J_{p,\mathrm{obs}} \sim X_{\mathrm{esc}} \times J_{p,\mathrm{inject}} \propto \mathcal{R}^{-\gamma_0 - 0.4} \sim \mathcal{R}^{-2.8}$$

Surviving fraction vs. suppression factor

- Convert charge ratios to observable with direct theoretical interpretation
- 1st step: WS98 report **surviving fraction**

  Well defined quantity, model independently.

$$\tilde{f}_i = \frac{J_i}{J_{i,\infty}}$$

- 2nd step: net source includes losses

$$\tilde{Q}_S(\mathcal{R}) = \sum_P \frac{n_P(\mathcal{R})\sigma_{P\to S}}{\bar{m}} - \frac{n_S(\mathcal{R})\sigma_{S\to X}}{\bar{m}}$$

  Surviving fraction over-counts losses $n_{i,\infty} > n_i$

  Instead, define **suppression factor** due to decay

  Accounts for actual fragmentation loss

$$f_{s,i} = \frac{J_i}{\frac{c}{4\pi}\tilde{Q}_i X_{\rm esc}}$$

$$\tilde{f}_i = \frac{J_i}{\frac{c}{4\pi} X_{\rm esc}\left(\frac{n_P\sigma_{P\to i}}{m_p} - \frac{n_{i,\infty}\sigma_{i\to X}}{m_p}\right)} \Rightarrow f_{s,i} = \frac{J_i}{\frac{c}{4\pi} X_{\rm esc}\left(\frac{n_P\sigma_{P\to i}}{m_p} - \frac{n_i\sigma_{i\to X}}{m_p}\right)}$$

Suppression factor

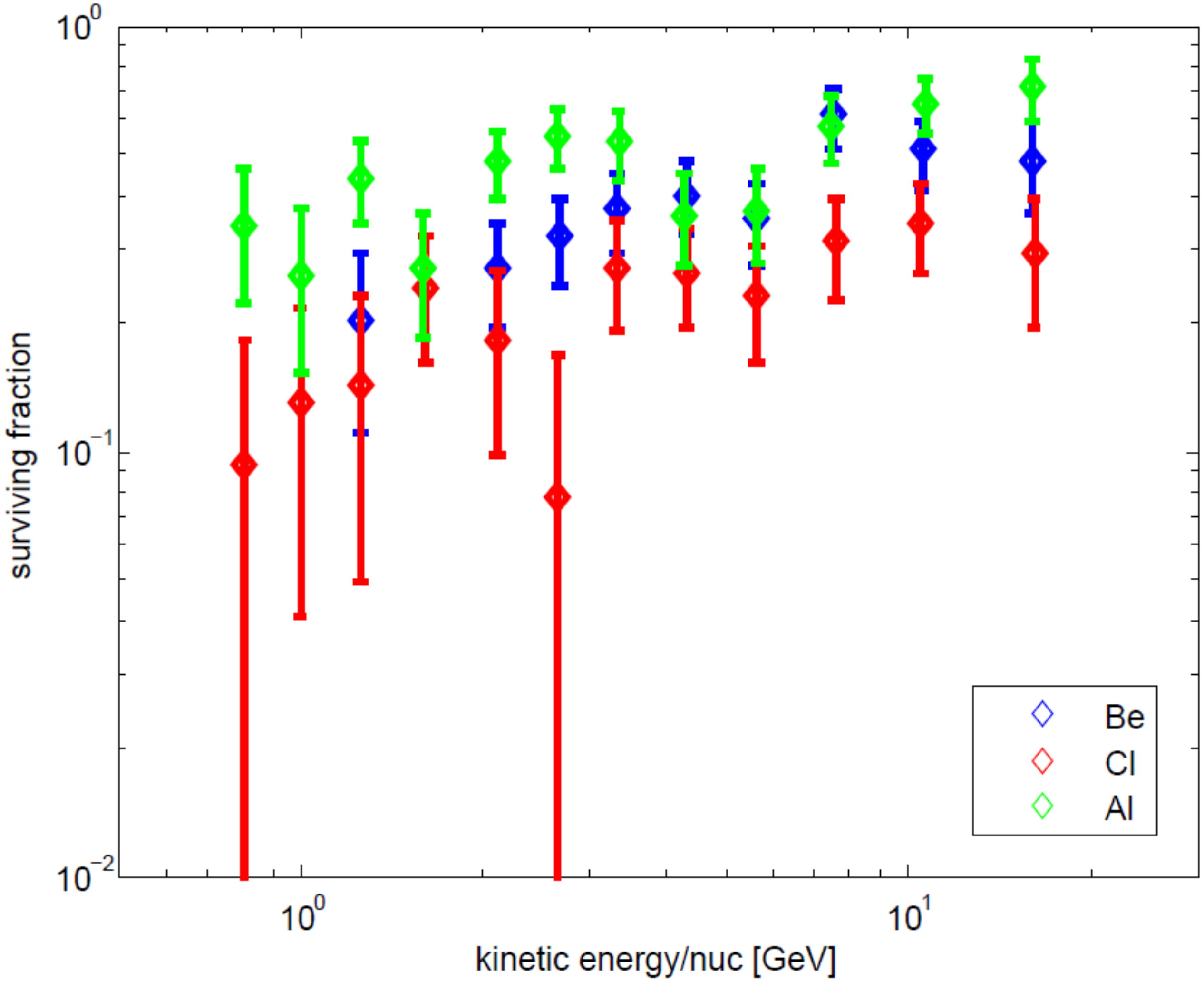
- Different nuclei species on equal footing
- Expect $t_{\text{esc}} = t_{\text{esc}}(\mathcal{R})$, $f_{s,i} \approx \left(\frac{t_i}{t_{\text{esc}}}\right)^{\alpha}$

Examples:

Leaky Box Model	Diffusion
$f_{s,i} = \frac{1}{1 + t_{\text{esc}}/t_i}$	$f_{s,i} = \sqrt{t_i/t_{\text{esc}}} \tanh\left(\sqrt{t_{\text{esc}}/t_i}\right)$
$\tilde{f}_i = \frac{1}{1 + \frac{t_{\text{esc}}}{t_c}\left(1 + \frac{X_{\text{esc}}\,\sigma_{i\to X}}{m_p}\right)^{-1}}$	$\tilde{f}_i = \ldots$

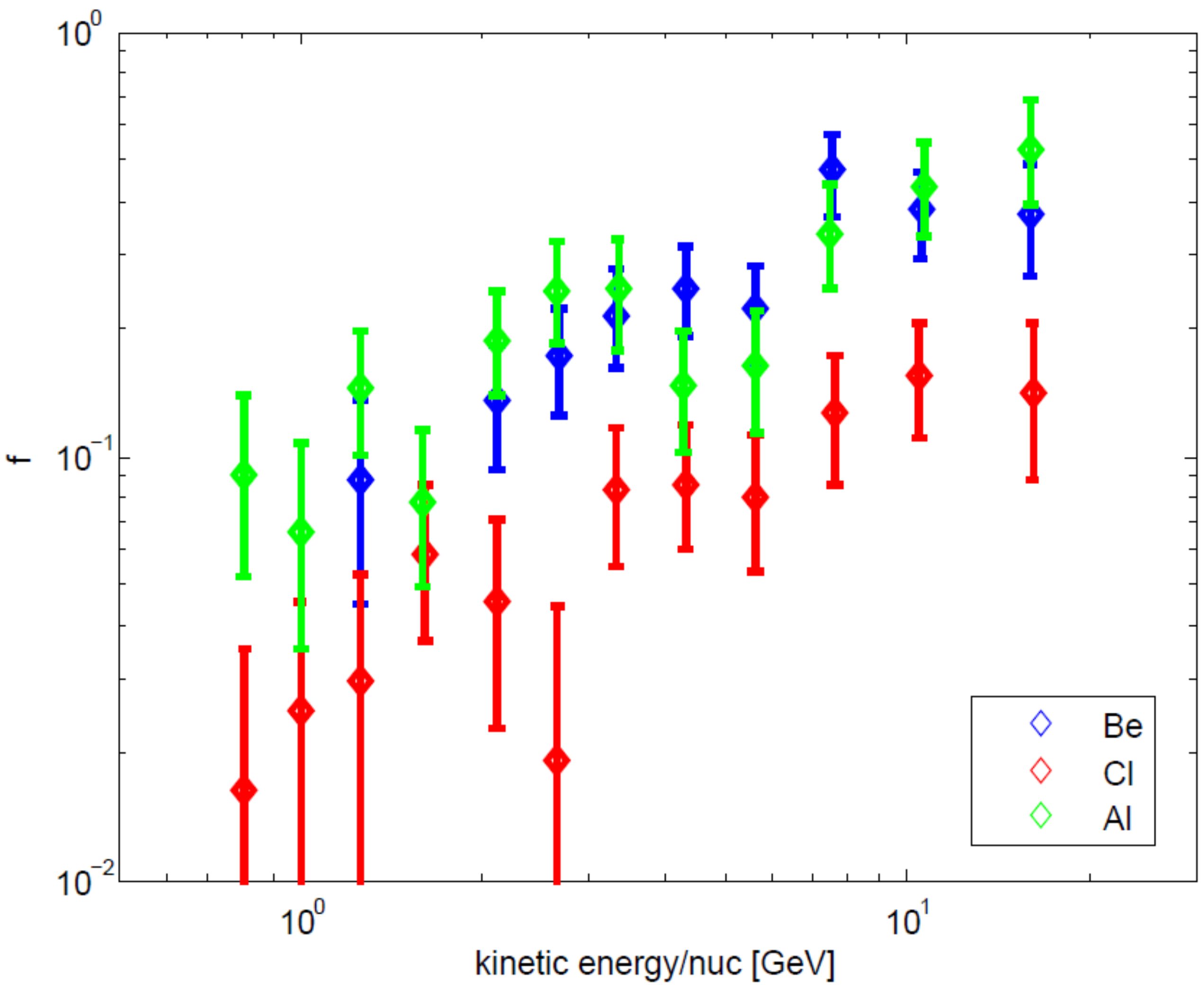
Radioactive nuclei: data

Surviving fraction vs. energy (WS98)



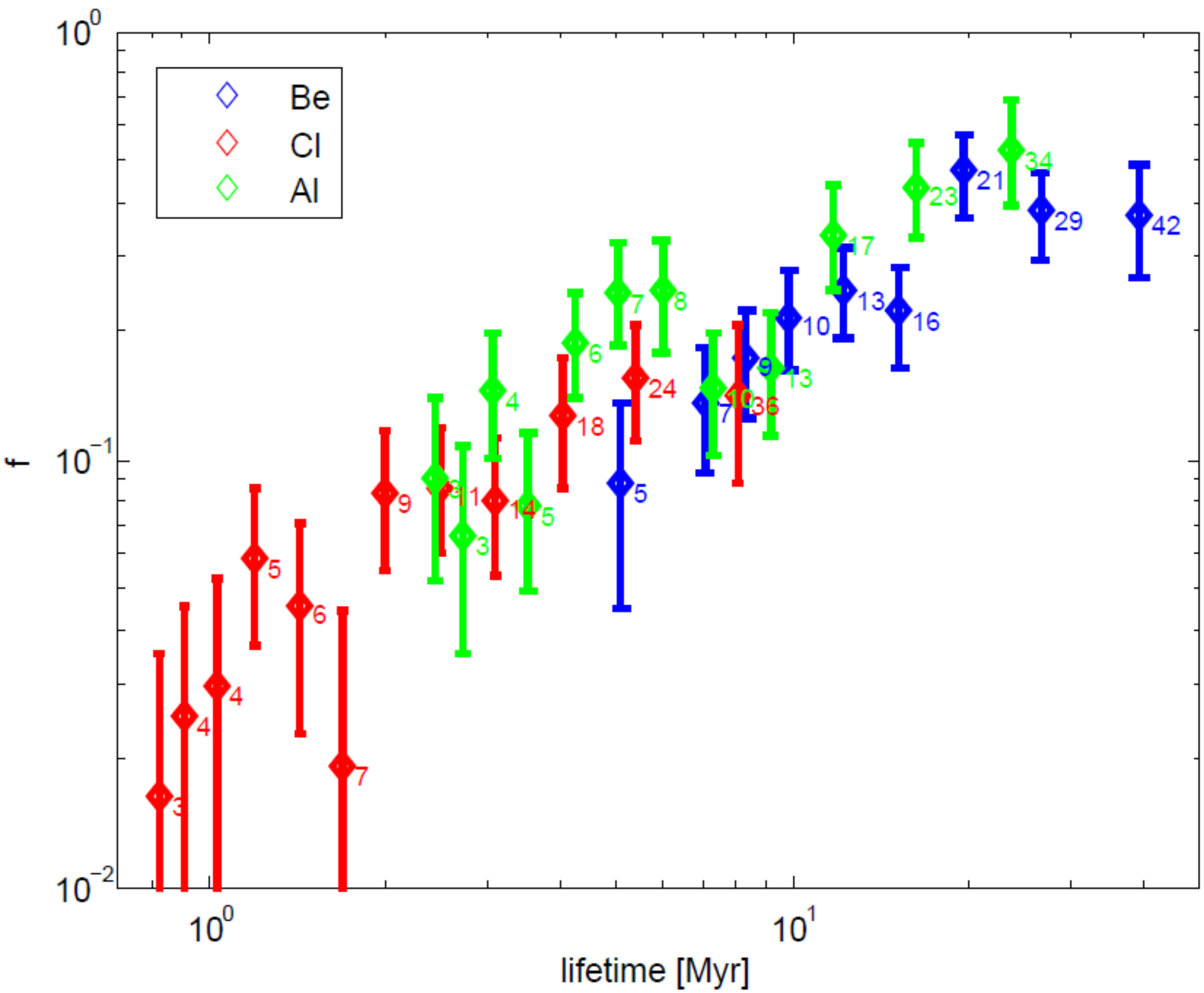
Radioactive nuclei: data

Suppression factor vs. energy



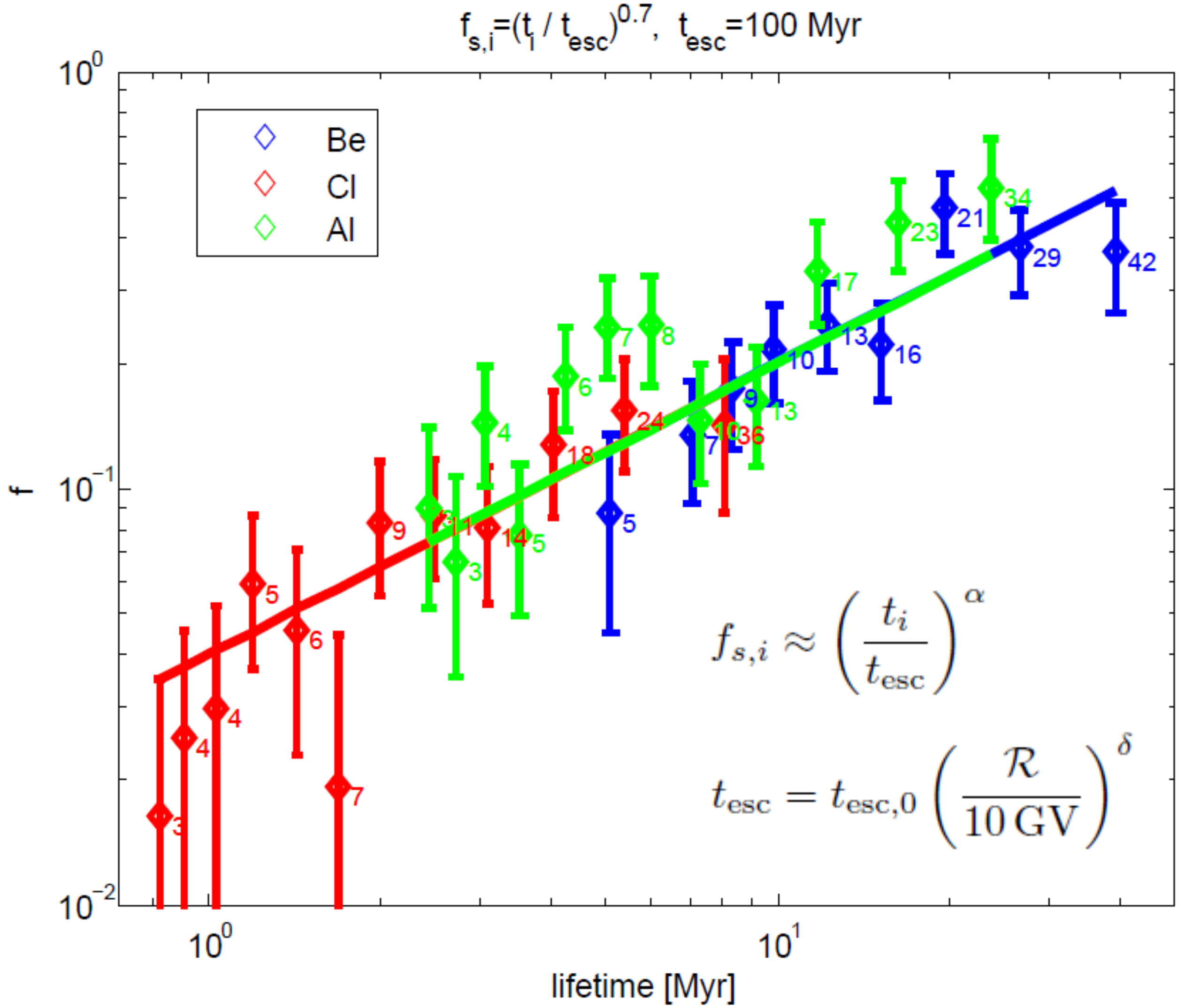
Radioactive nuclei: data

Suppression factor vs. lifetime



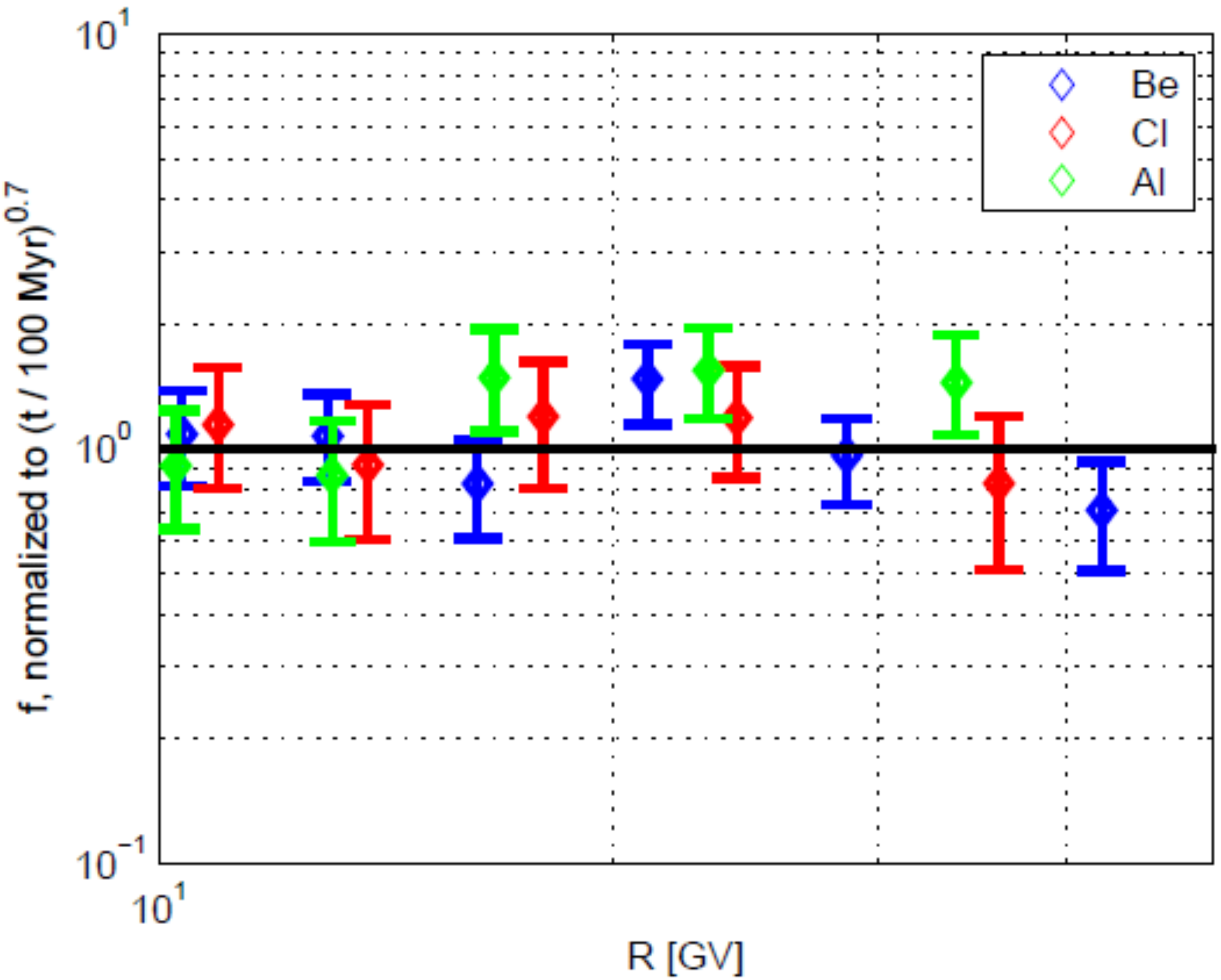
Radioactive nuclei: data

Consistent with constant residence time



Radioactive nuclei: data

Residual rigidity dependence



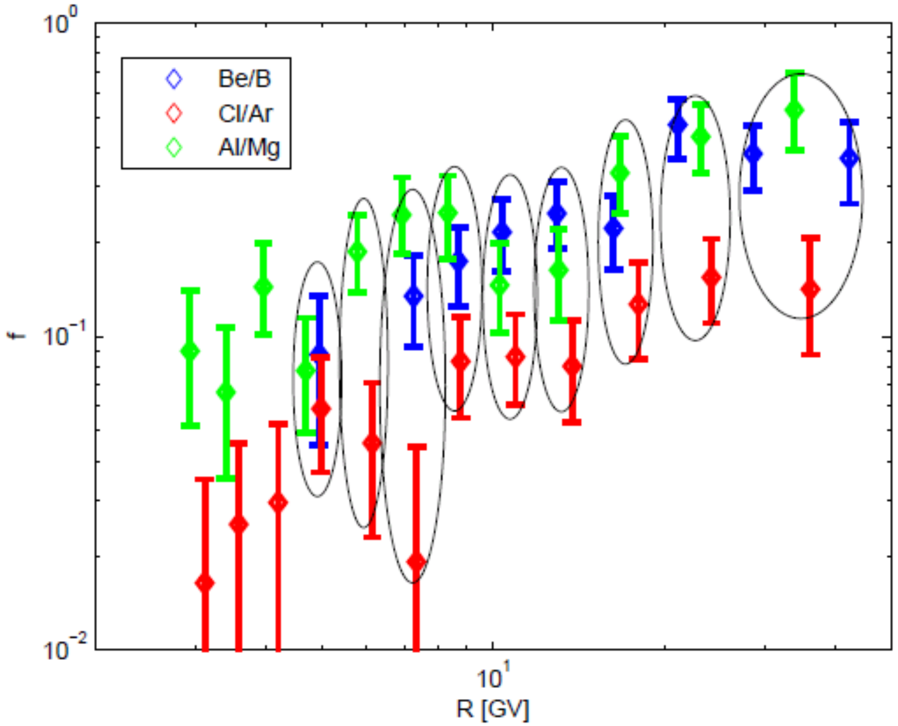
Radioactive nuclei: data

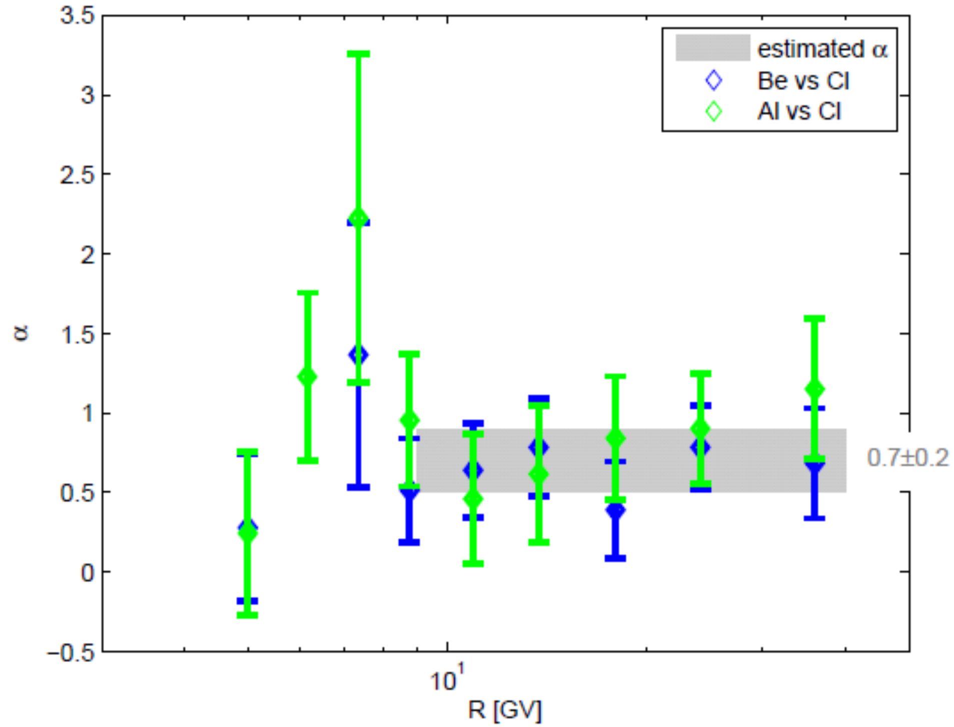
$$f_{s,i} \approx \left(\frac{t_i}{t_{\rm esc}}\right)^{\alpha}$$

$$t_{\rm esc} = t_{\rm esc}(\mathcal{R})$$

$$\log\left(\frac{f_{s,i}(\mathcal{R}')}{f_{s,j}(\mathcal{R}')}\right) \approx \alpha \log\left(\frac{A_j Z_i \tau_i}{A_i Z_j \tau_j}\right)$$

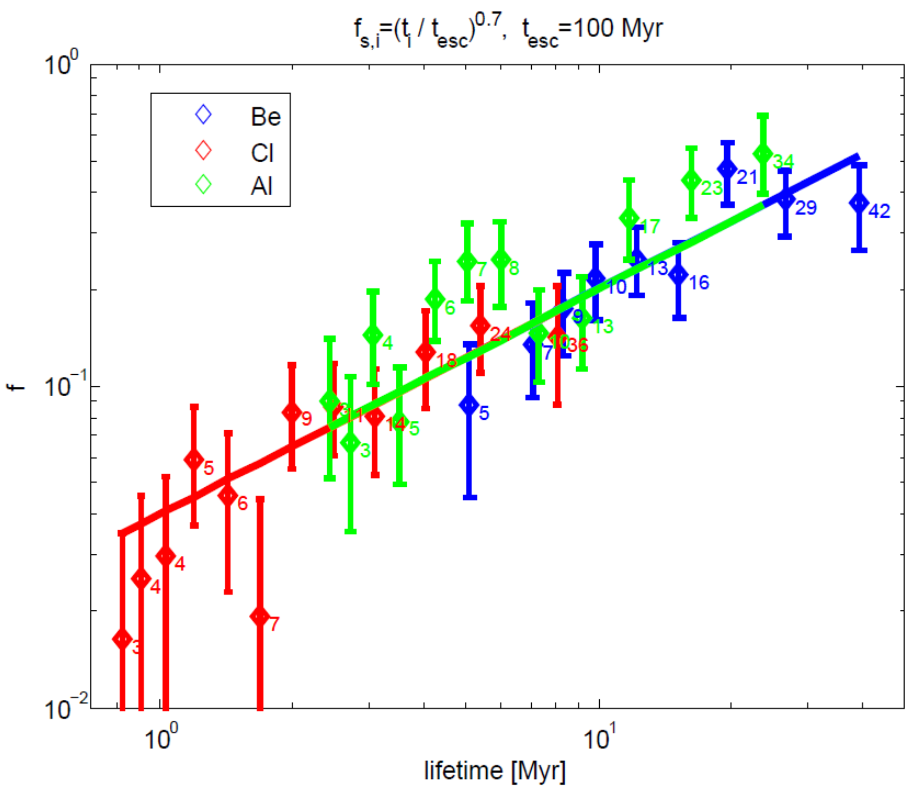
$$\Delta\alpha \propto 1/\log(\tau_i/\tau_j)$$

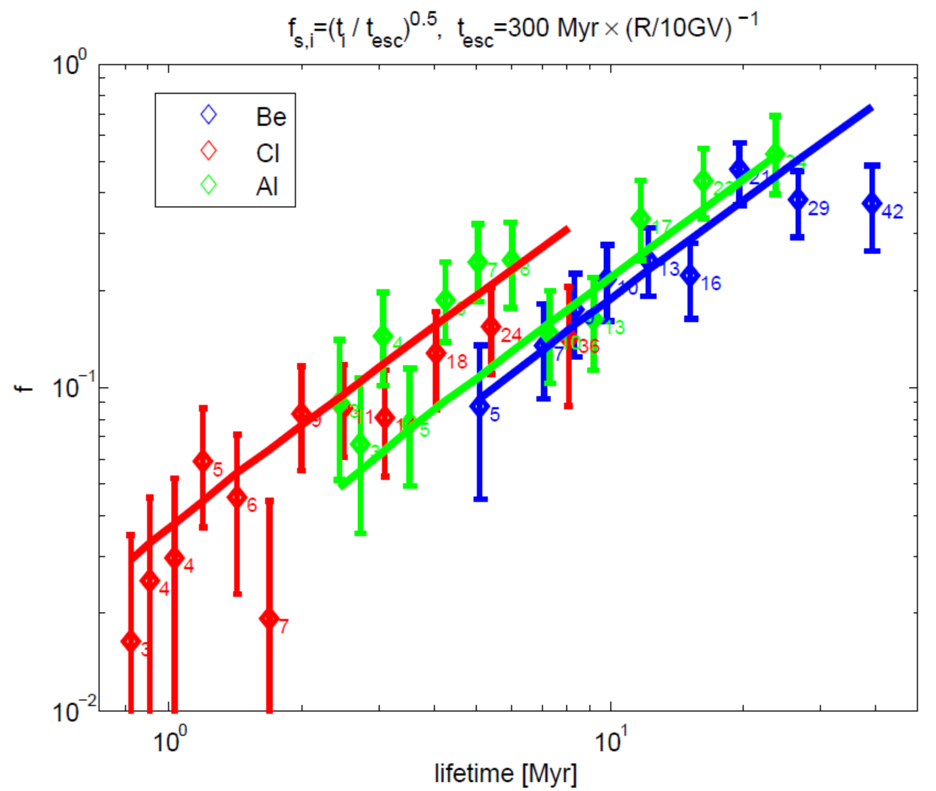




Radioactive nuclei: constraints on $t_{\rm esc}$

- Rigidity dependence: hints from current data
- Cannot (yet) exclude $\delta < -1$ with $\alpha \lesssim 0.5$
- **AMS-02 should do much better!**





Radioactive nuclei: constraints on t_{esc}

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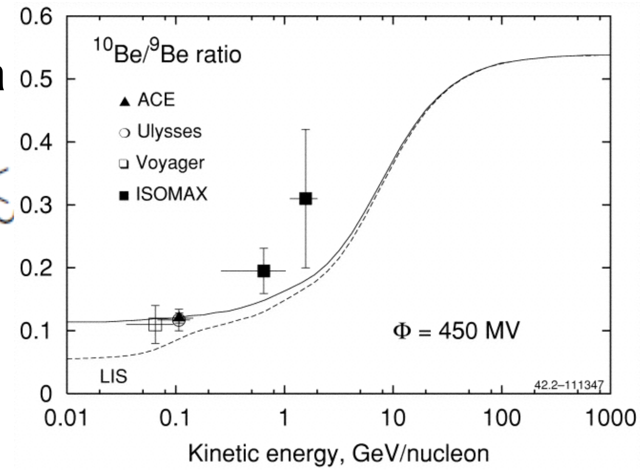
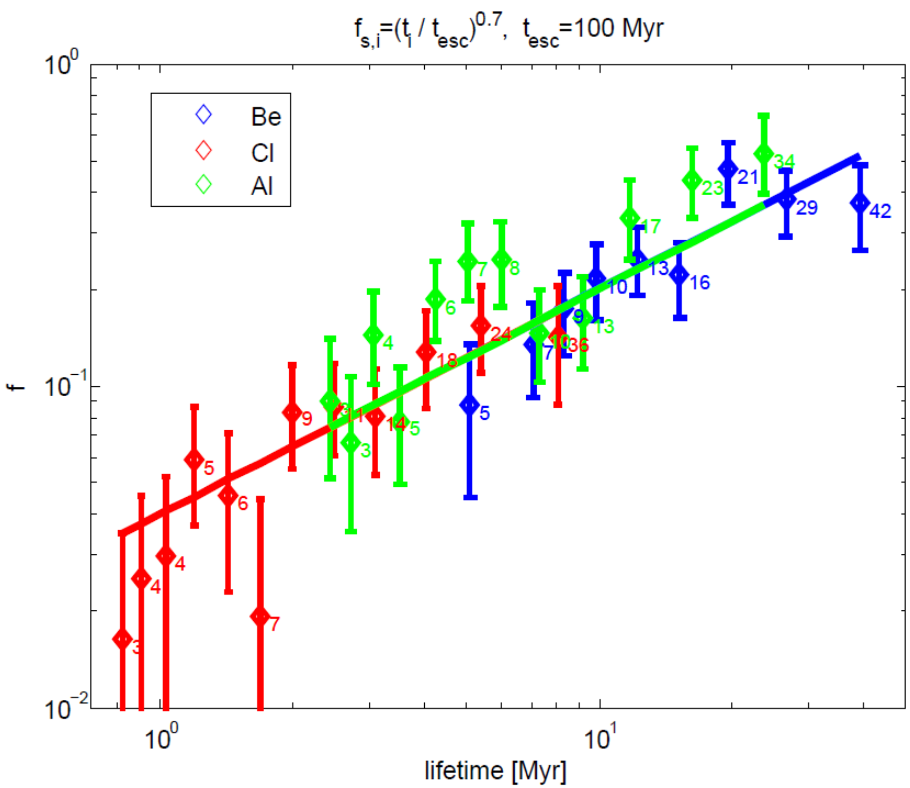
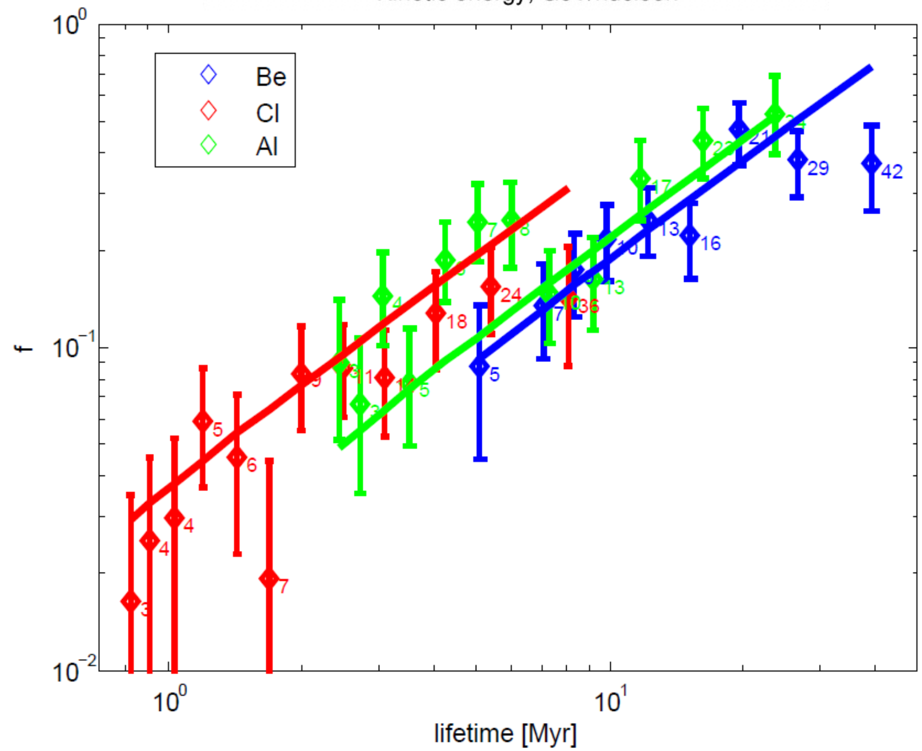
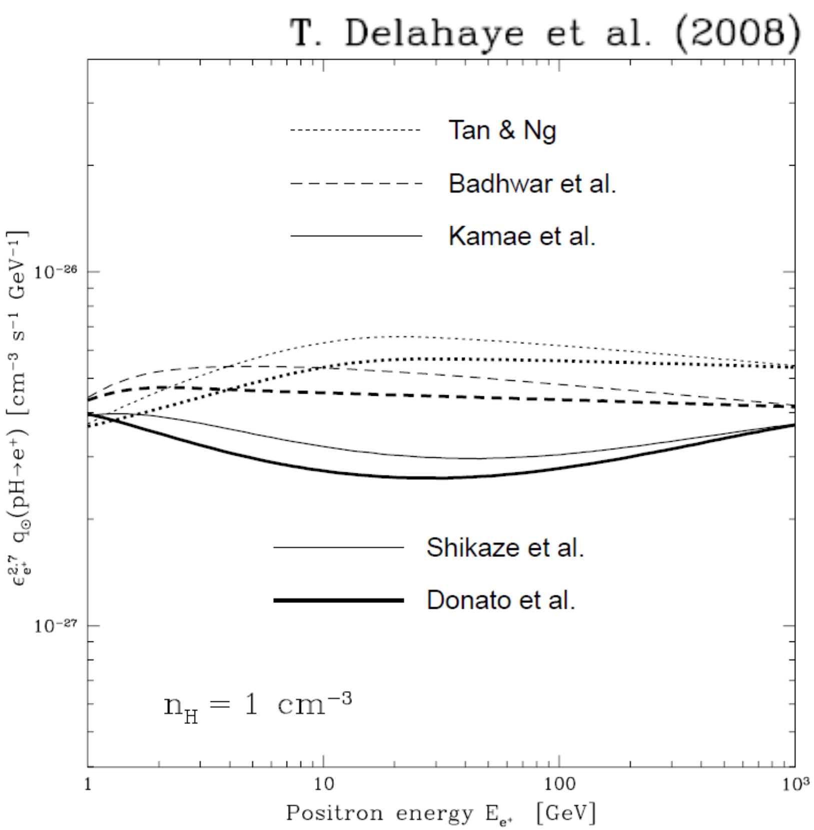


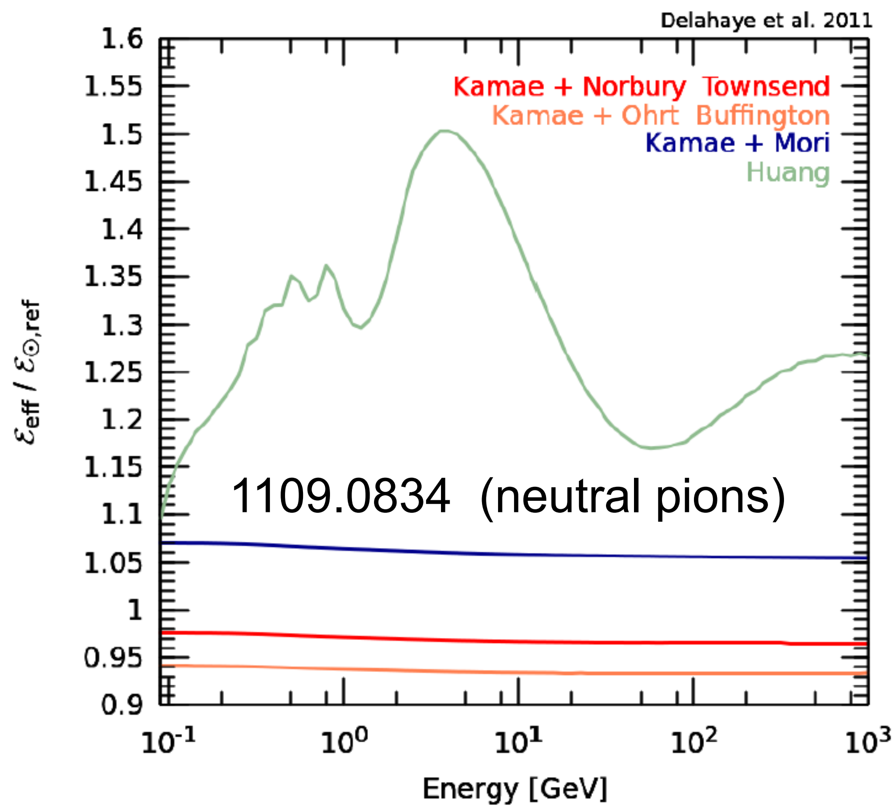




Positrons

$$\frac{J_{e+}}{J_p} = f_{s,e+} 10^{-\gamma+1} \xi_{e+,A>1} C_{e+,pp}(\varepsilon) \frac{\sigma_{pp,inel,0}}{m_p} X_{esc}$$





antiprotons

$$\frac{n_{\bar{p}}}{n_{\text{Boron}}} = \frac{Q_{\bar{p}}}{Q_{\text{Boron}}}$$