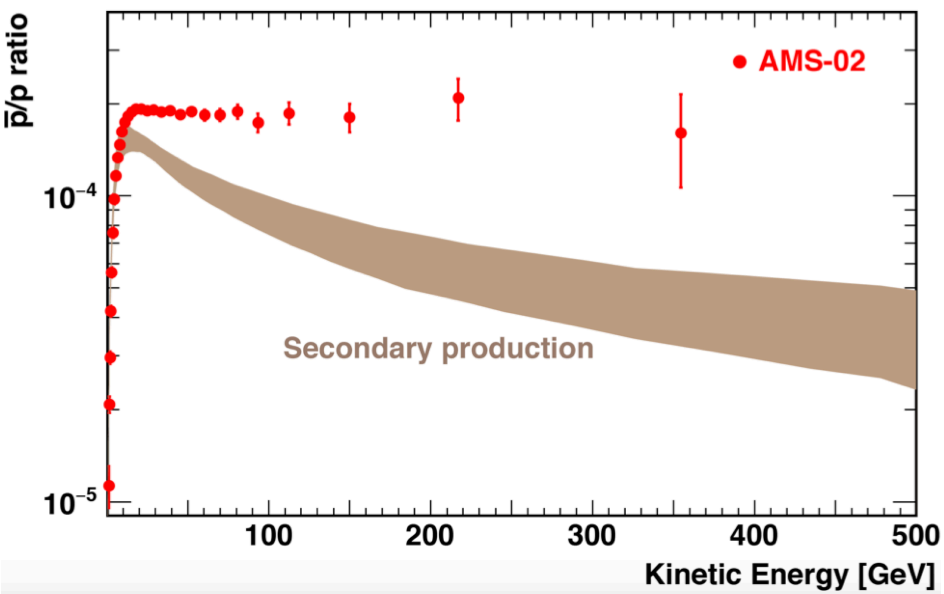
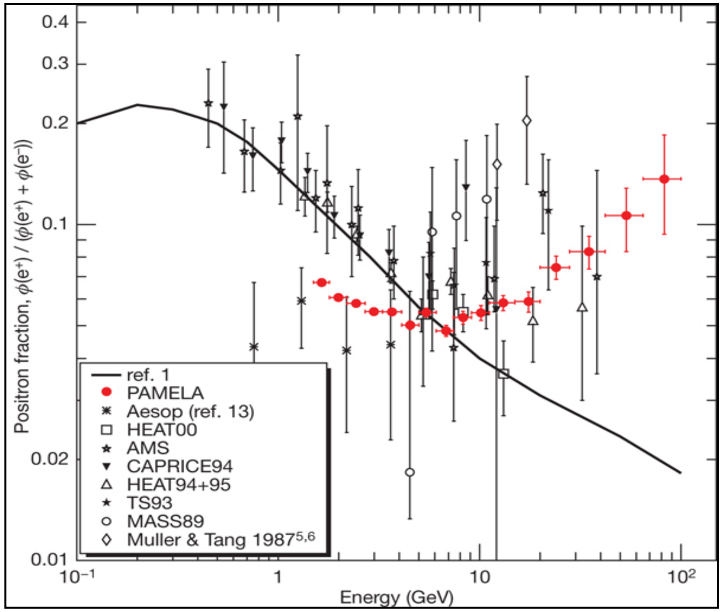
Issues on CR propagation and local sources

Kfir Blum
Weizmann Institute

MACROS 2016 PSU

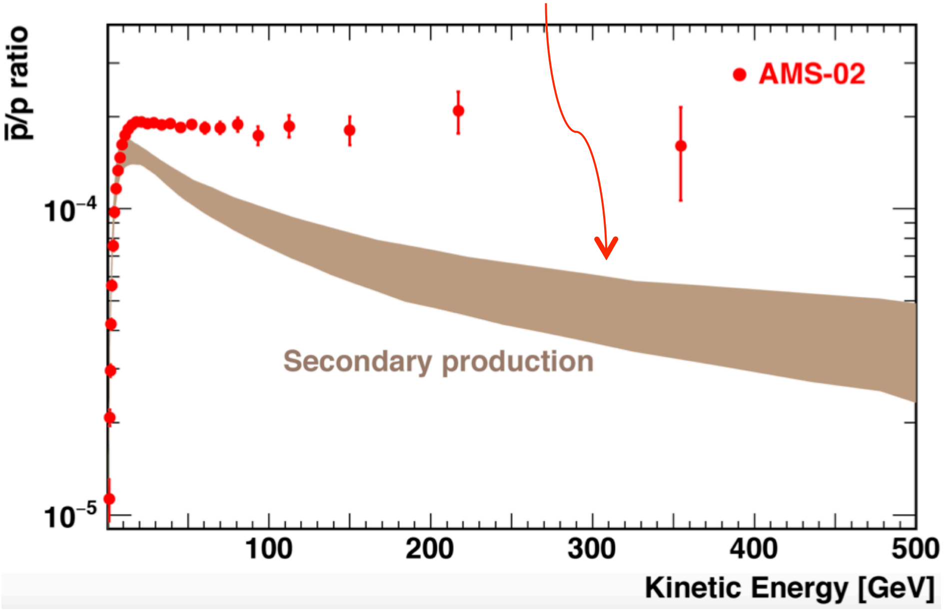
Positrons and antiprotons





Positrons and antiprotons

global,
steady state,
homogeneous diffusion model,
calibrated on old nuclear data



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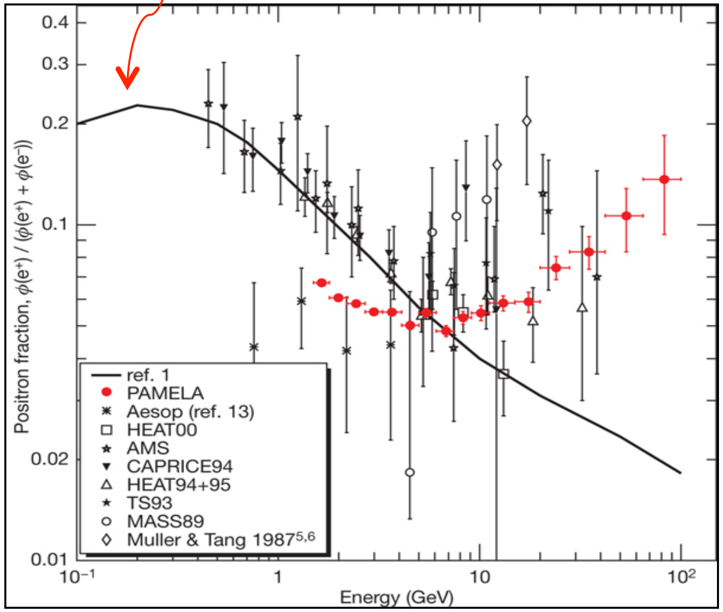
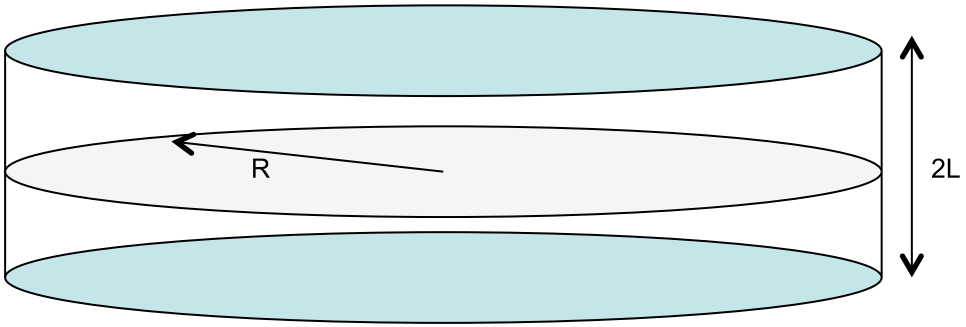
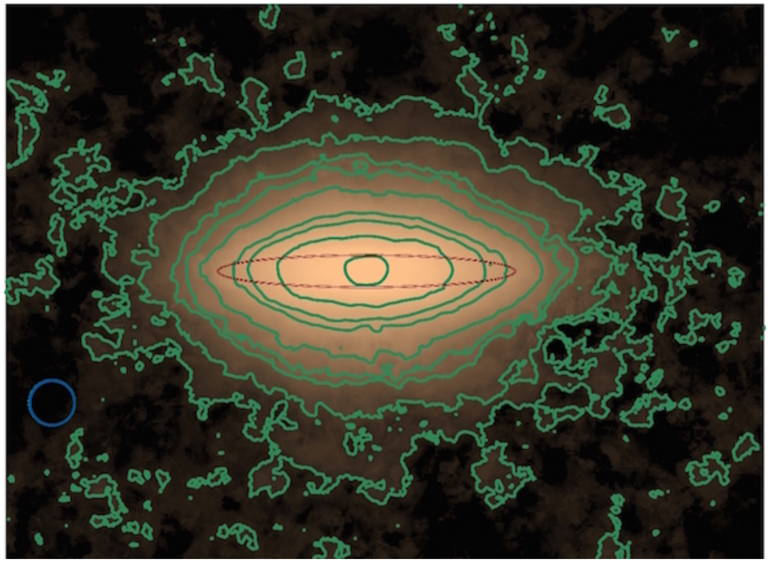


diffusion model constructed to give a large-scale description

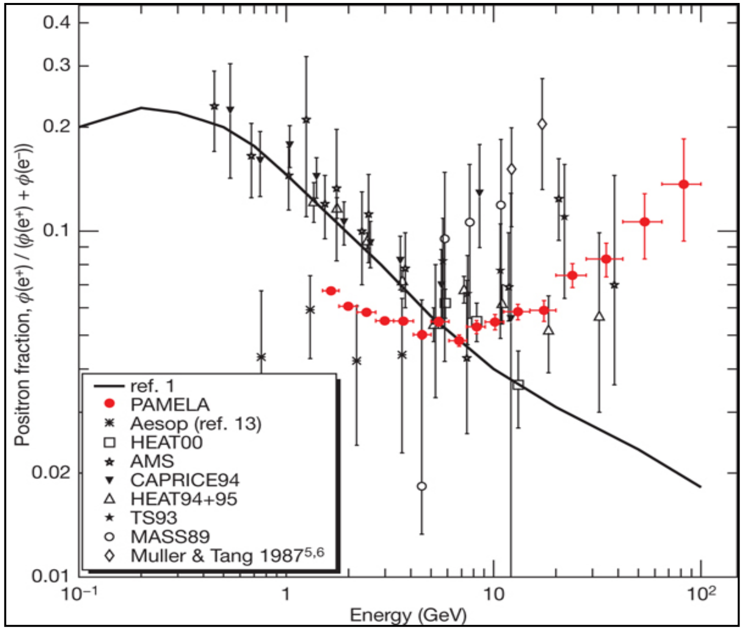
Ginzburg & Ptuskin, Rev.Mod.Phys. 48 (1976) 161-189

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

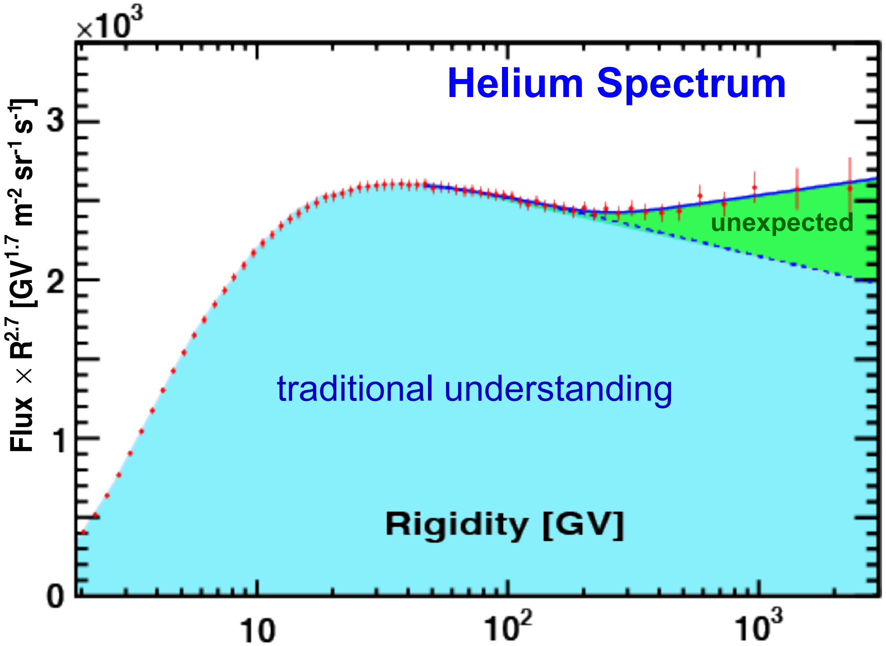


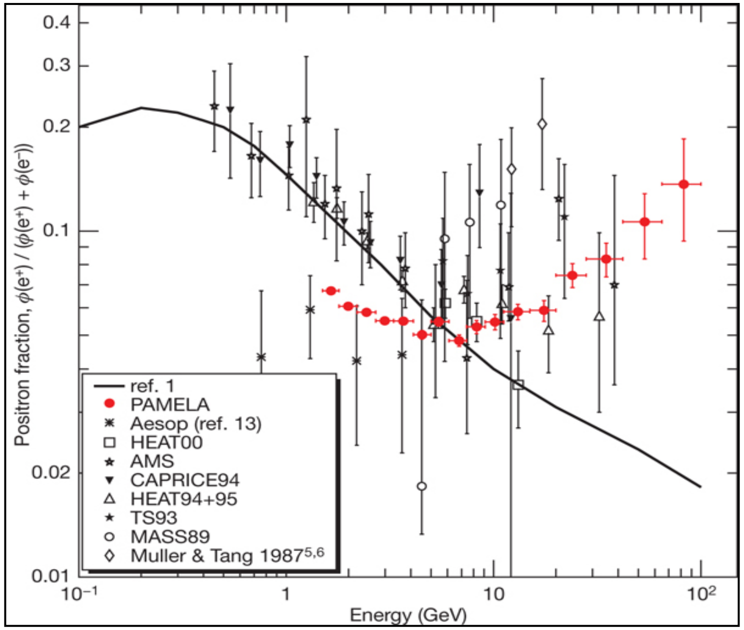


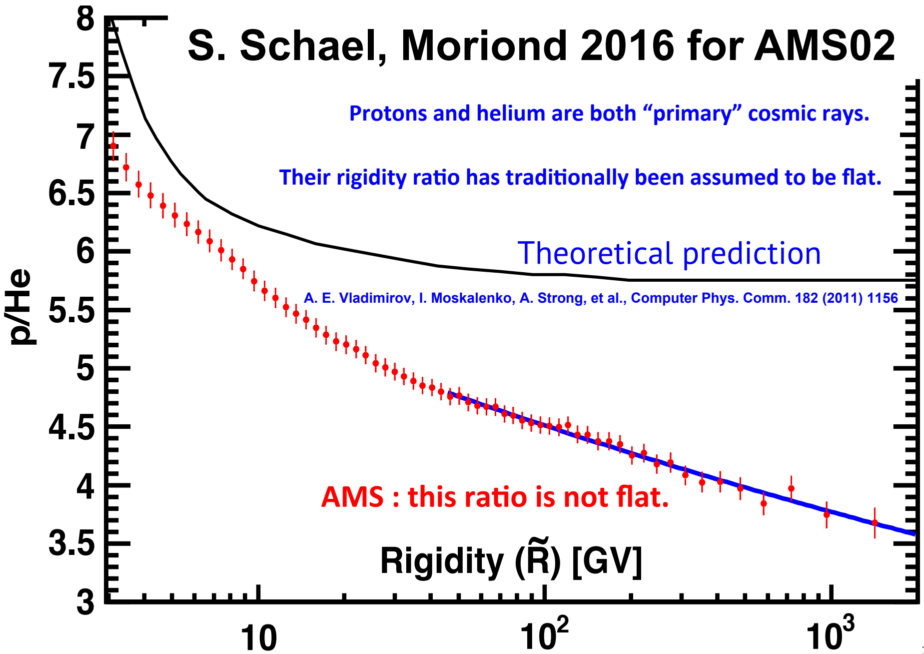
Irwin et al, ApJ 144(2012) [stacking 30 galaxies]

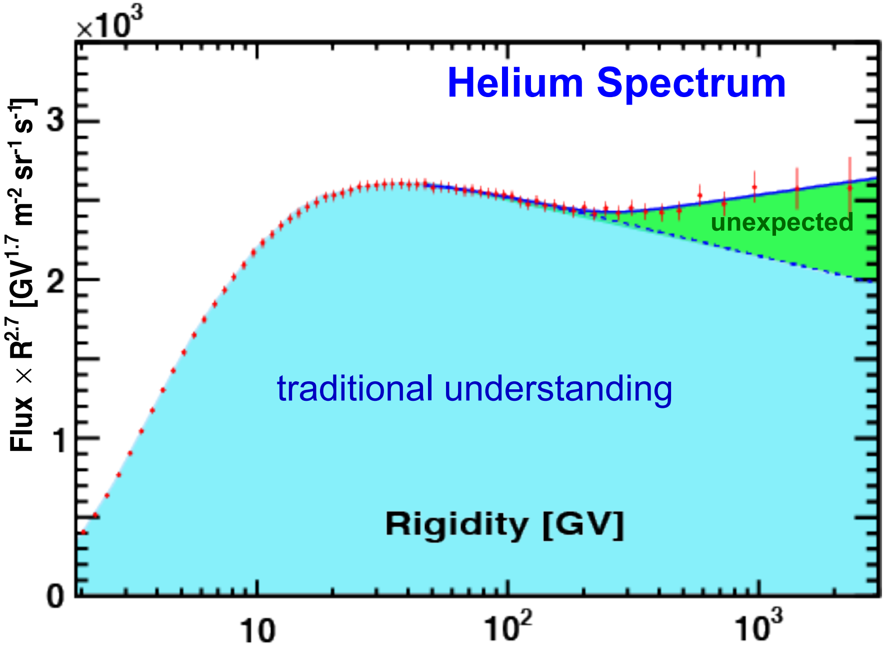


Positron fraction, φ(e⁺) / (φ(e⁺) + φ(e⁻))
Energy (GeV)
0.4
0.3
0.2
0.1
0.02
0.01
10⁻¹
1
10
10²
ref. 1
PAMELA
Aesop (ref. 13)
HEAT00
AMS
CAPRICE94
HEAT94+95
TS93
MASS89
Muller & Tang 1987⁵,⁶


Helium Spectrum
×10^3
Flux × R^2.7 [GV^1.7 m^-2 sr^-1 s^-1]
unexpected
traditional understanding
Rigidity [GV]
0
1
2
3
10
10^2
10^3


Positron fraction, φ(e+) / (φ(e+) + φ(e−))
Energy (GeV)
0.4
0.3
0.2
0.1
0.02
0.01
10^−1
1
10
10^2
ref. 1
PAMELA
Aesop (ref. 13)
HEAT00
AMS
CAPRICE94
HEAT94+95
TS93
MASS89
Muller & Tang 1987^5,6


S. Schael, Moriond 2016 for AMS02
Protons and helium are both "primary" cosmic rays.
Their rigidity ratio has traditionally been assumed to be flat.
Theoretical prediction
A. E. Vladimirov, I. Moskalenko, A. Strong, et al., Computer Phys. Comm. 182 (2011) 1156
AMS : this ratio is not flat.
Rigidity (R̃) [GV]
p/He
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
10
10^2
10^3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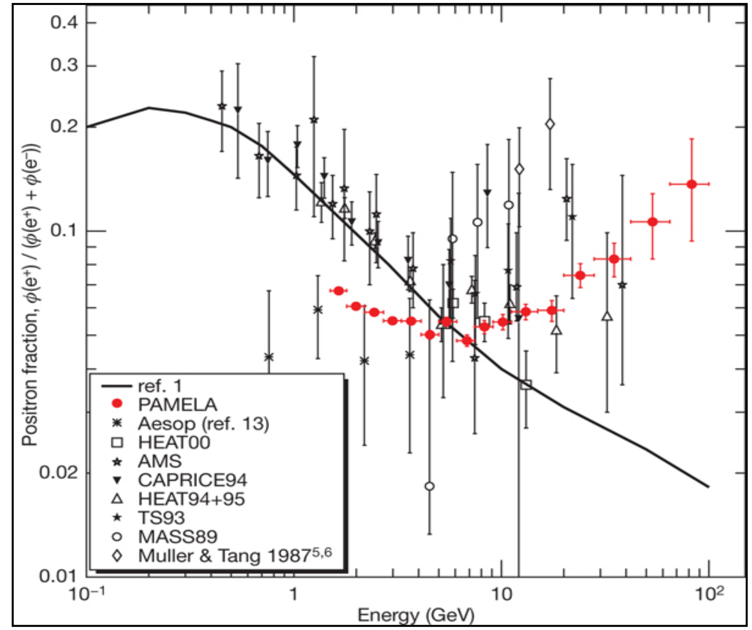
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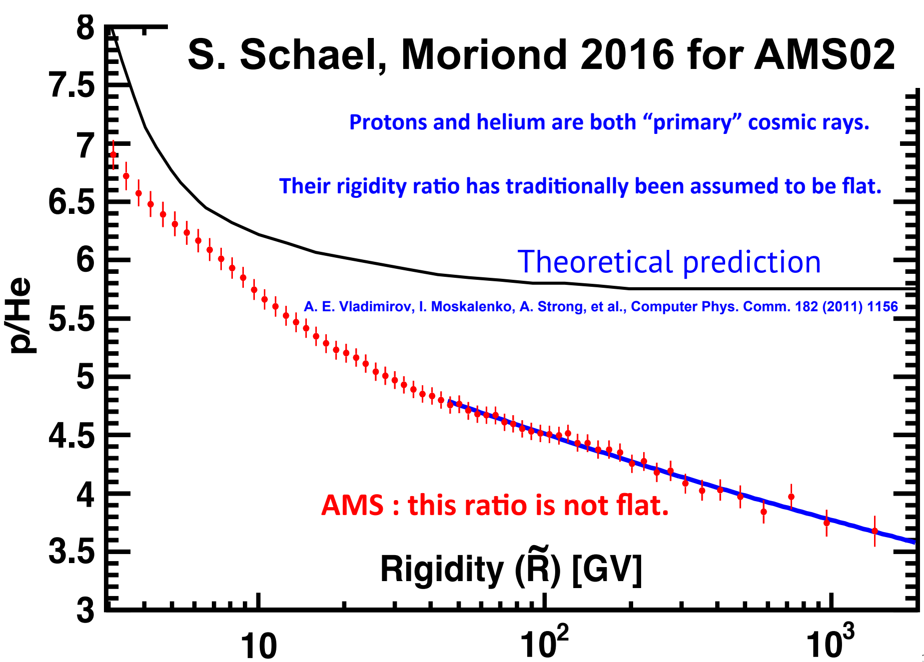
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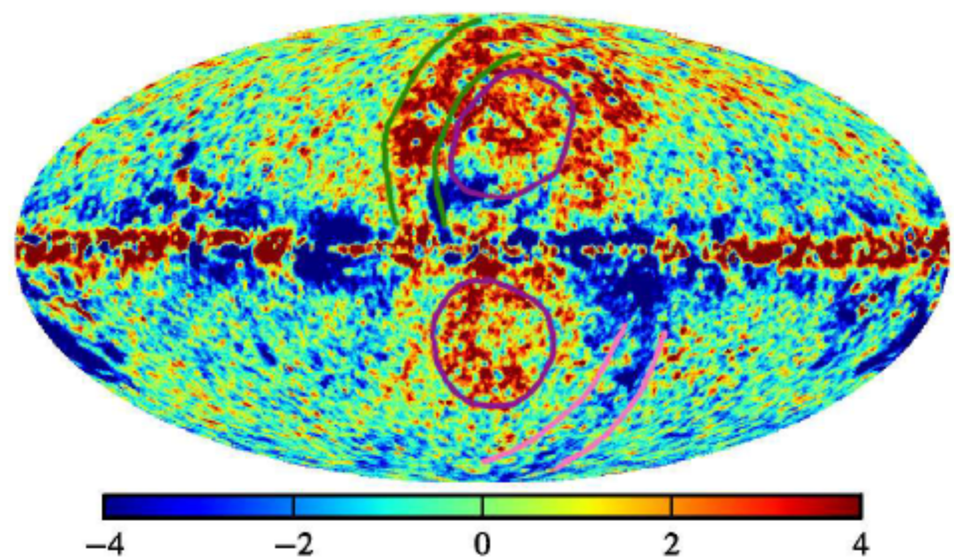

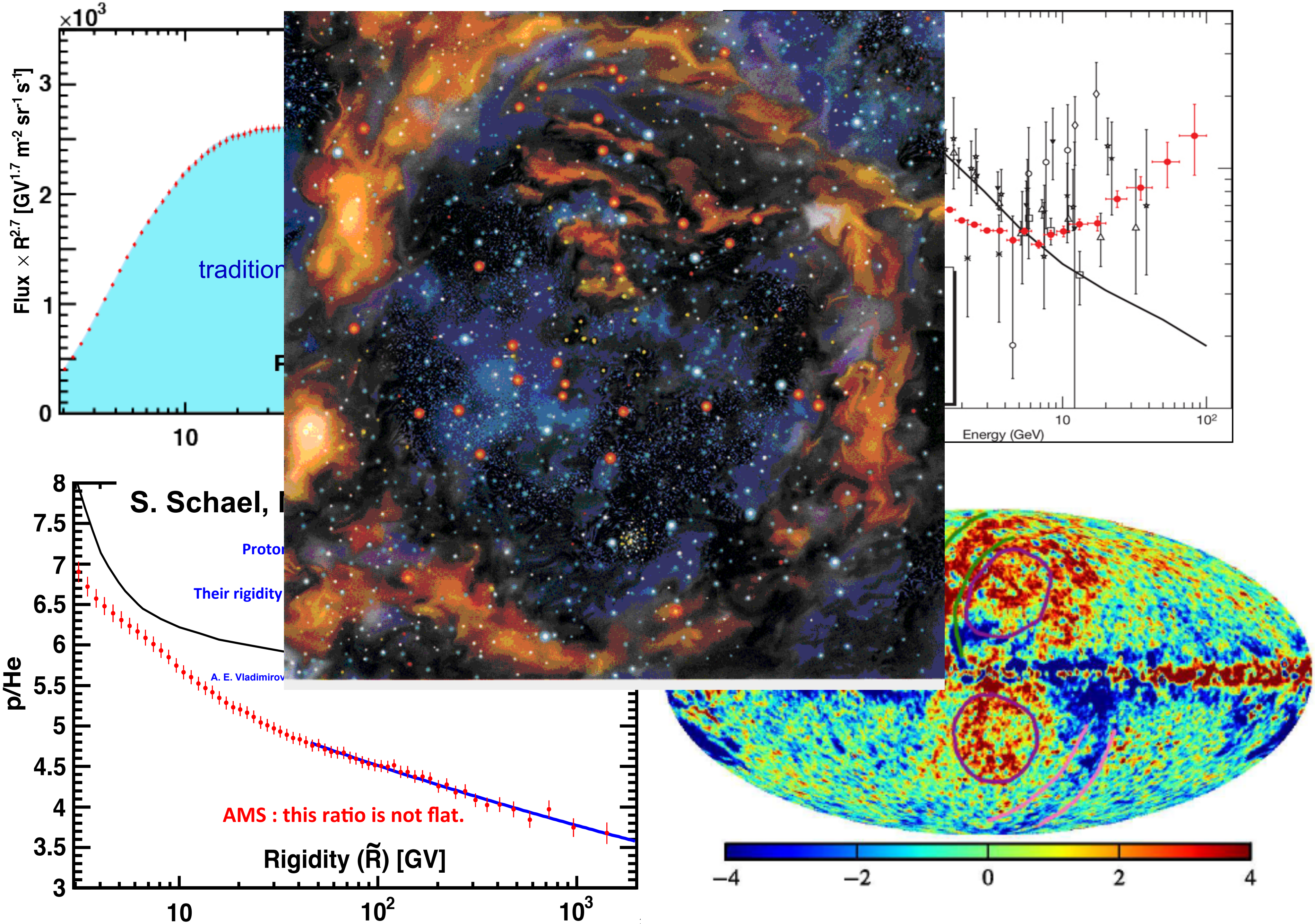

×10^3
Flux × R^2.7 [GV^1.7 m^-2 sr^-1 s^-1]
tradition
P
S. Schael, I
Proton
Their rigidity
A. E. Vladimirov
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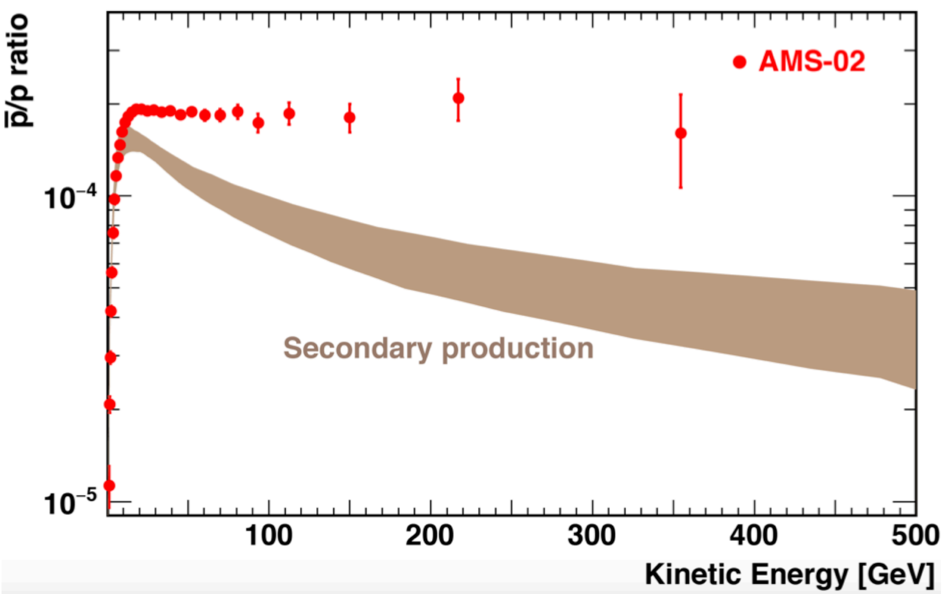
Rigidity (R̃) [GV]
Energy (GeV)
−4
−2
0
2
4

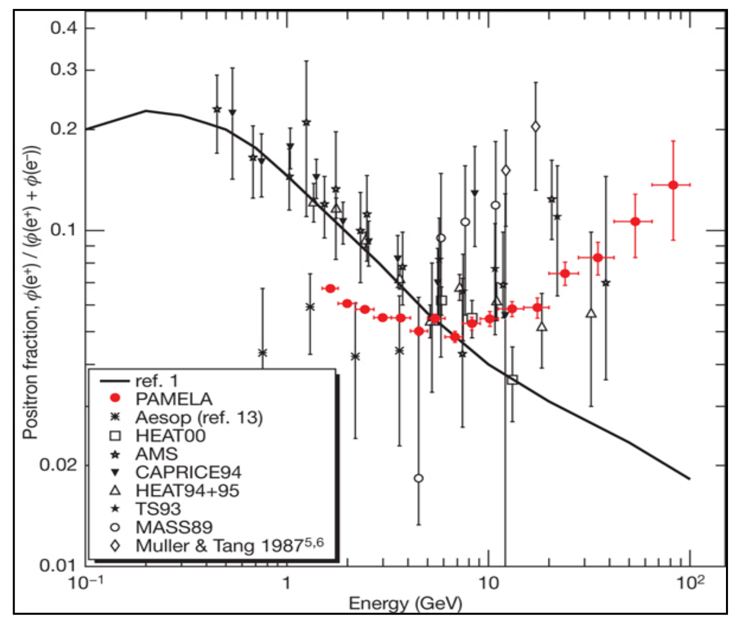
Positrons and antiprotons

What's consistent w/ old global models and what not?

Model building hints in data

- Antiprotons vs. B/C
- e+





antiprotons

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

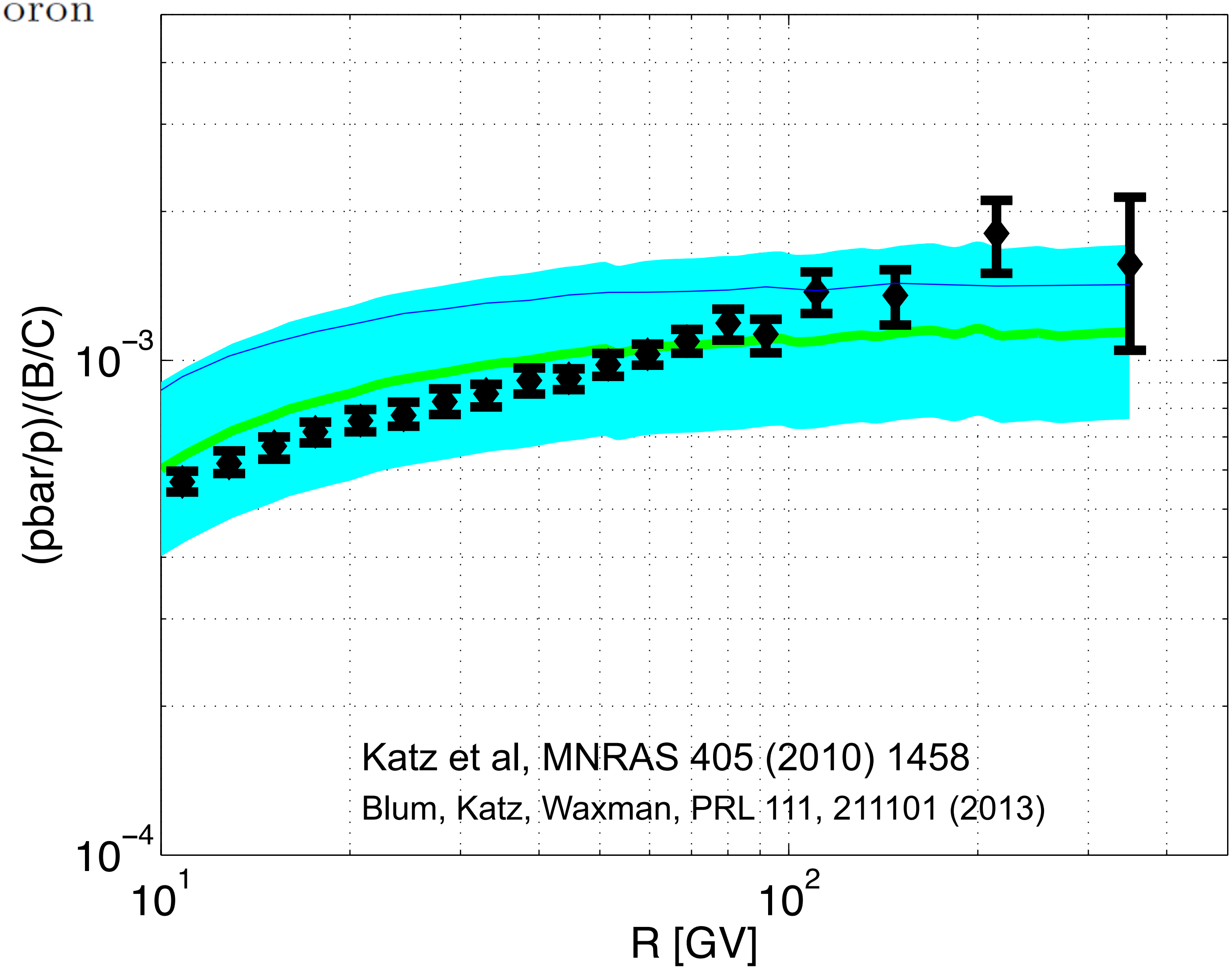
$$\boxed{\frac{J_{\bar{p}}}{J_p} = 10^{1-\gamma_p}\,\zeta_{\bar{p},A>1}\,C_{\bar{p},pp}\,\frac{\sigma_{pp,\mathrm{inel}}}{m_p}\,\frac{X_{\mathrm{esc}}}{1+\frac{\sigma_{\bar{p}}}{m_p}X_{\mathrm{esc}}}}$$

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

antiprotons vs. boron (AMS02 2014): **results**

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

Consistent w/ secondary.



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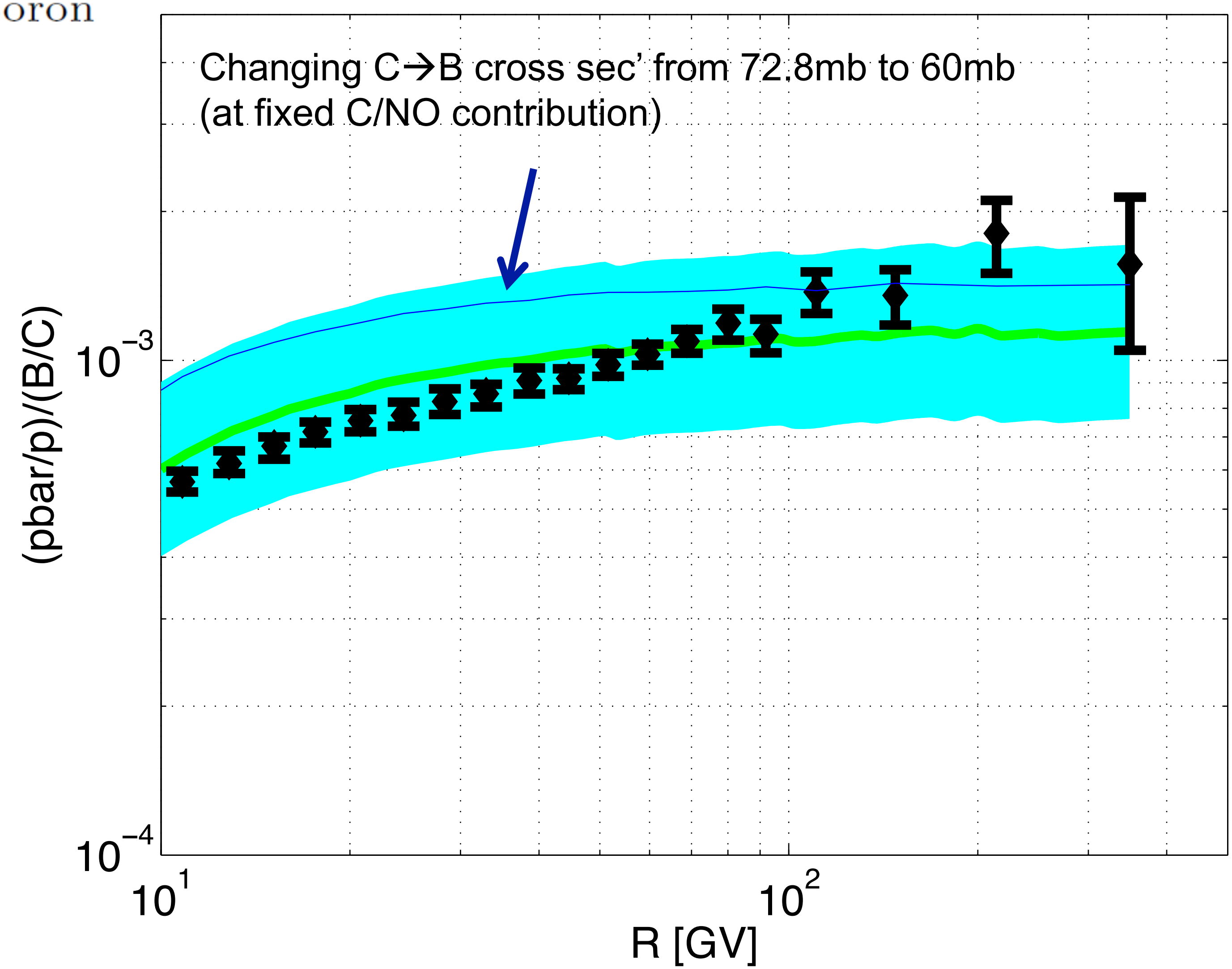

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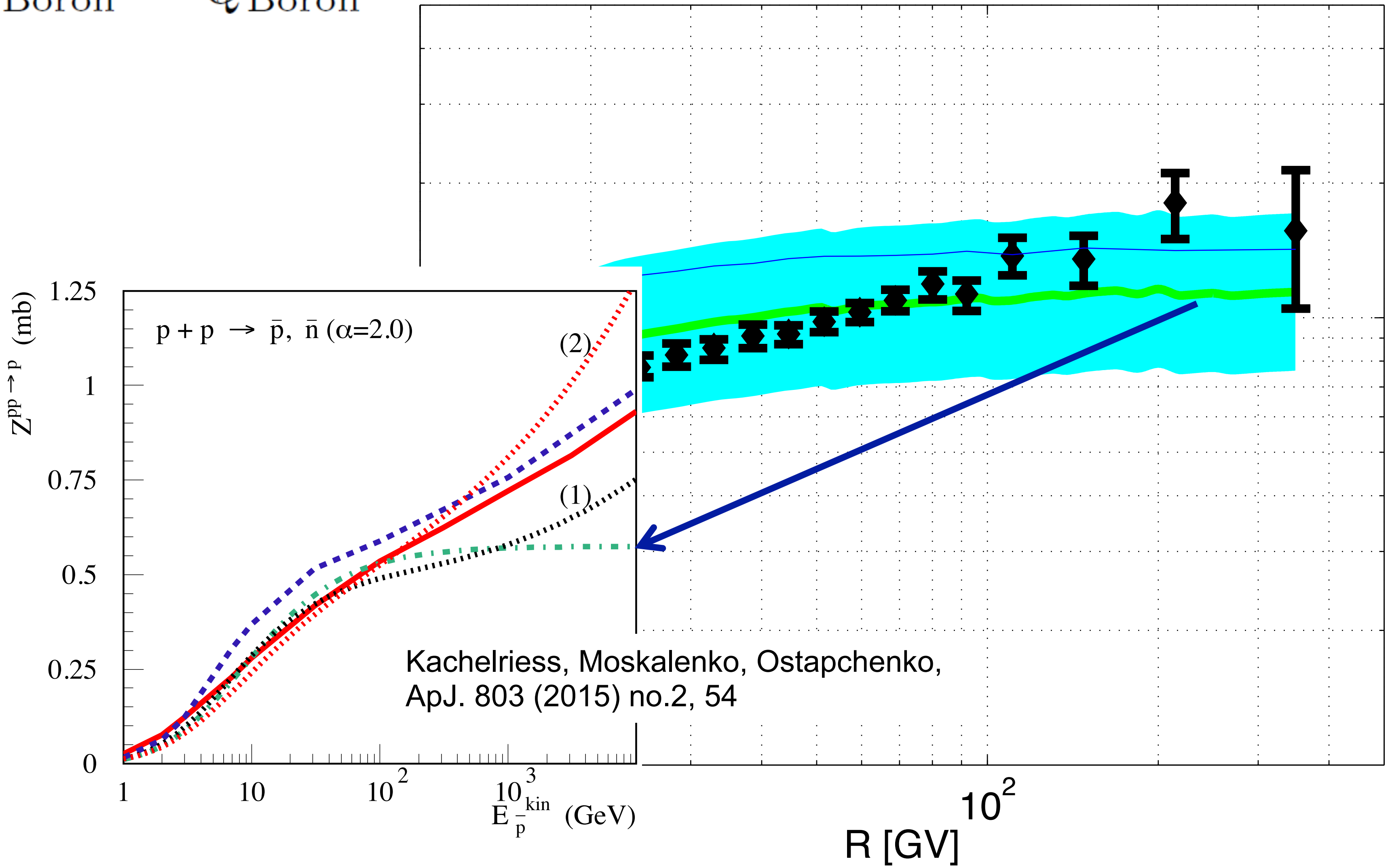


Kachelriess, Moskalenko, Ostapchenko,
ApJ. 803 (2015) no.2, 54

Positrons and antiprotons

What’s consistent w/ old global models and what not?

Model building guidelines in data

- **Antiprotons** vs. B/C **consistent w/ secondary, no problem w/ global models**
- e+

positrons

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

positrons

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

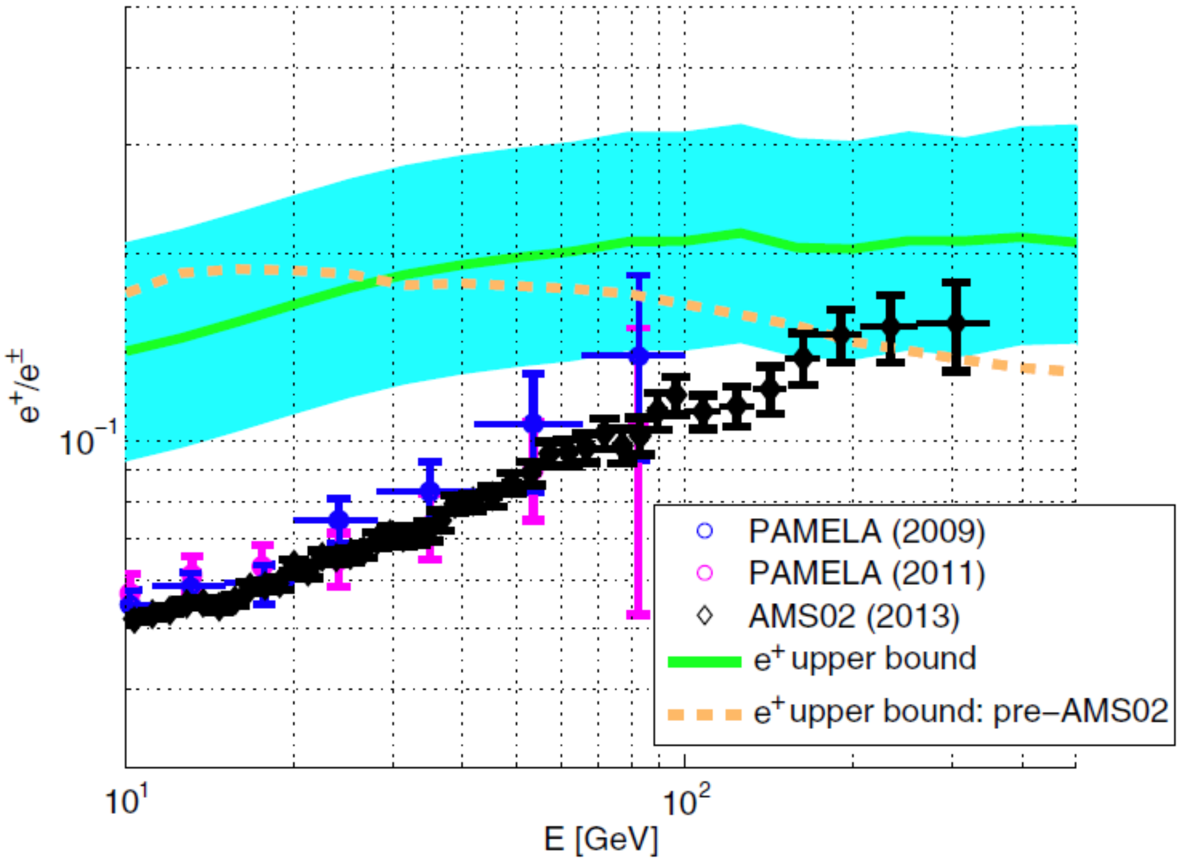
e+ lose energy through IC and synchrotron radiation.

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

e+ data itself is the first (semi-)direct observational probe of t_{esc}.

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

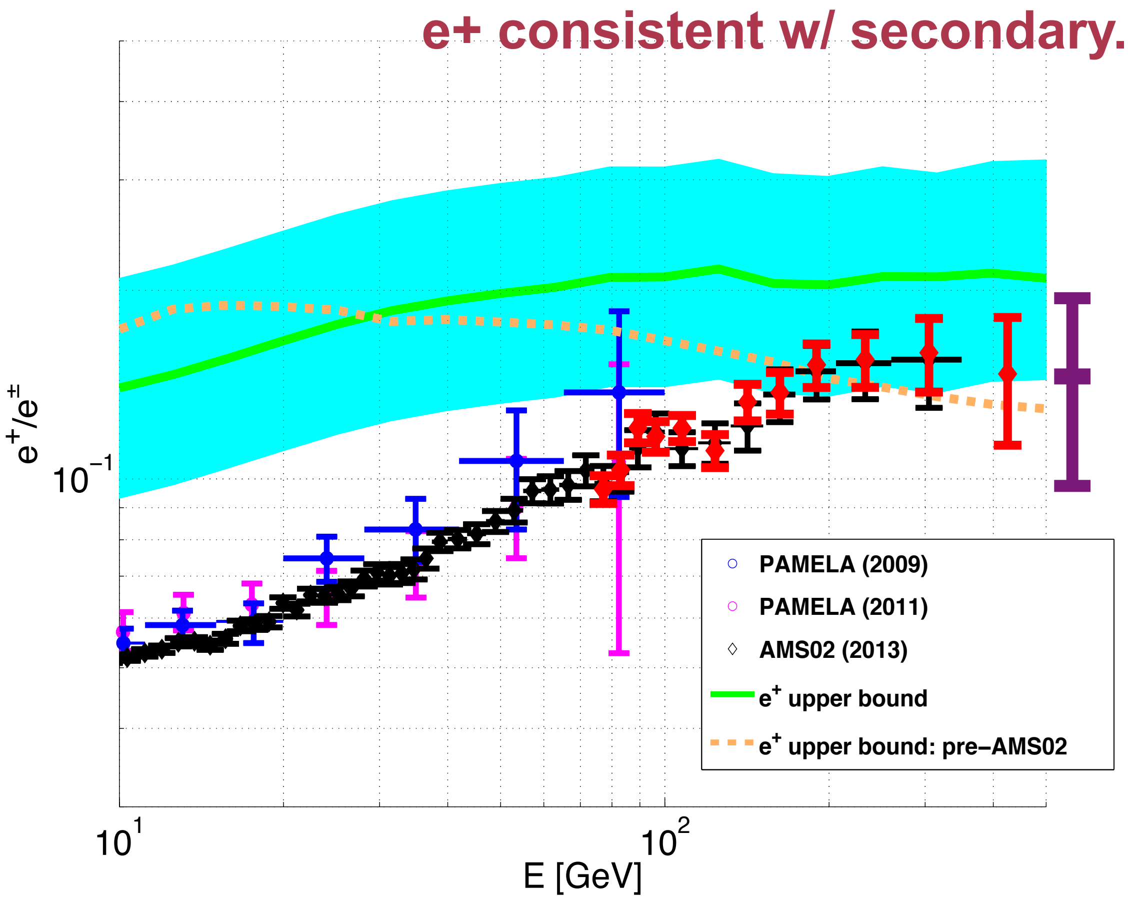
AMS02 (2013): **results**



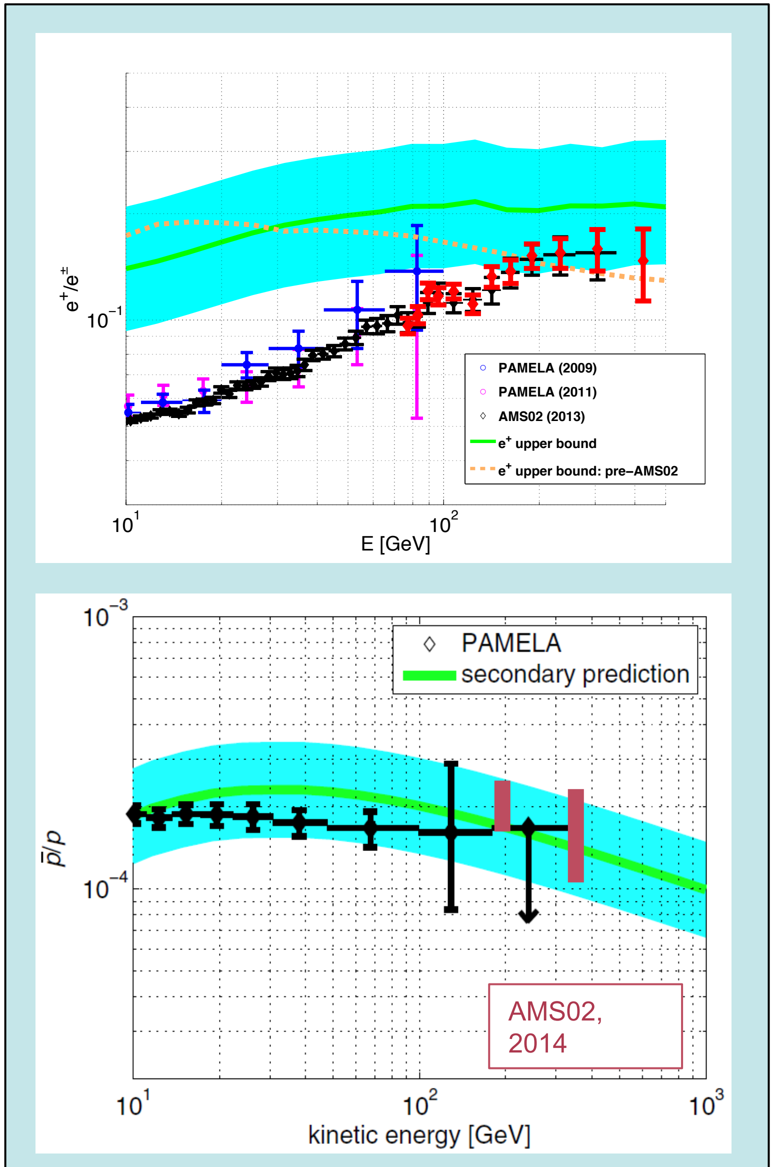
Katz et al, MNRAS 405 (2010) 1458

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

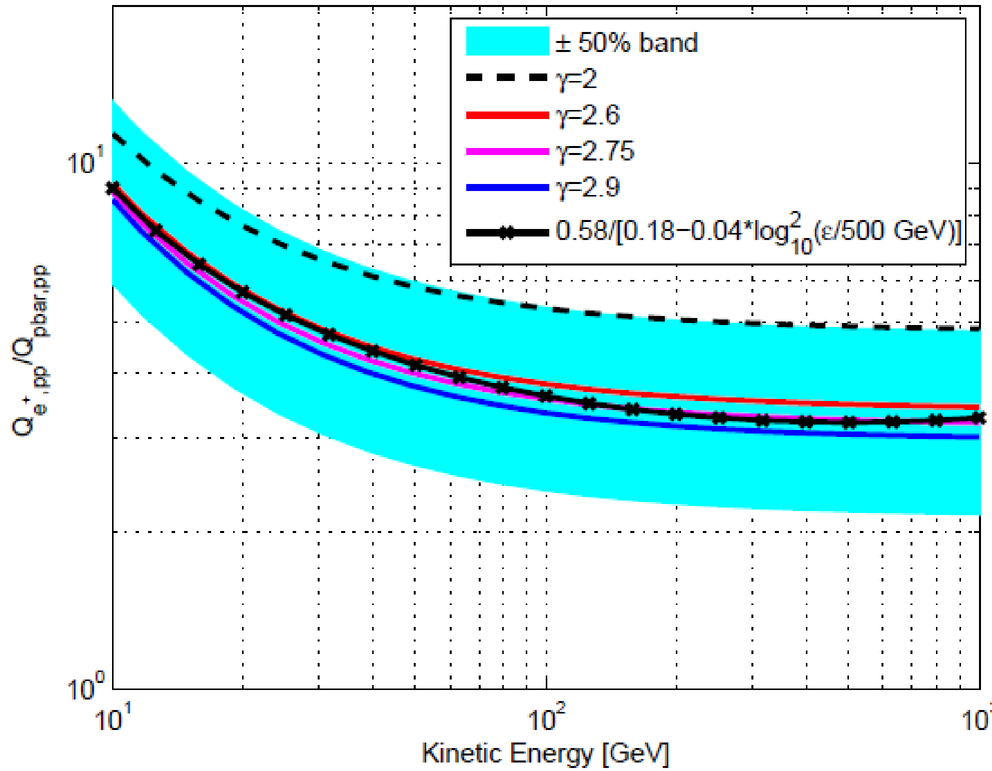
AMS02 (2014 I+II) (last error bar: rough estimate)



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



branching fraction in pp collision:



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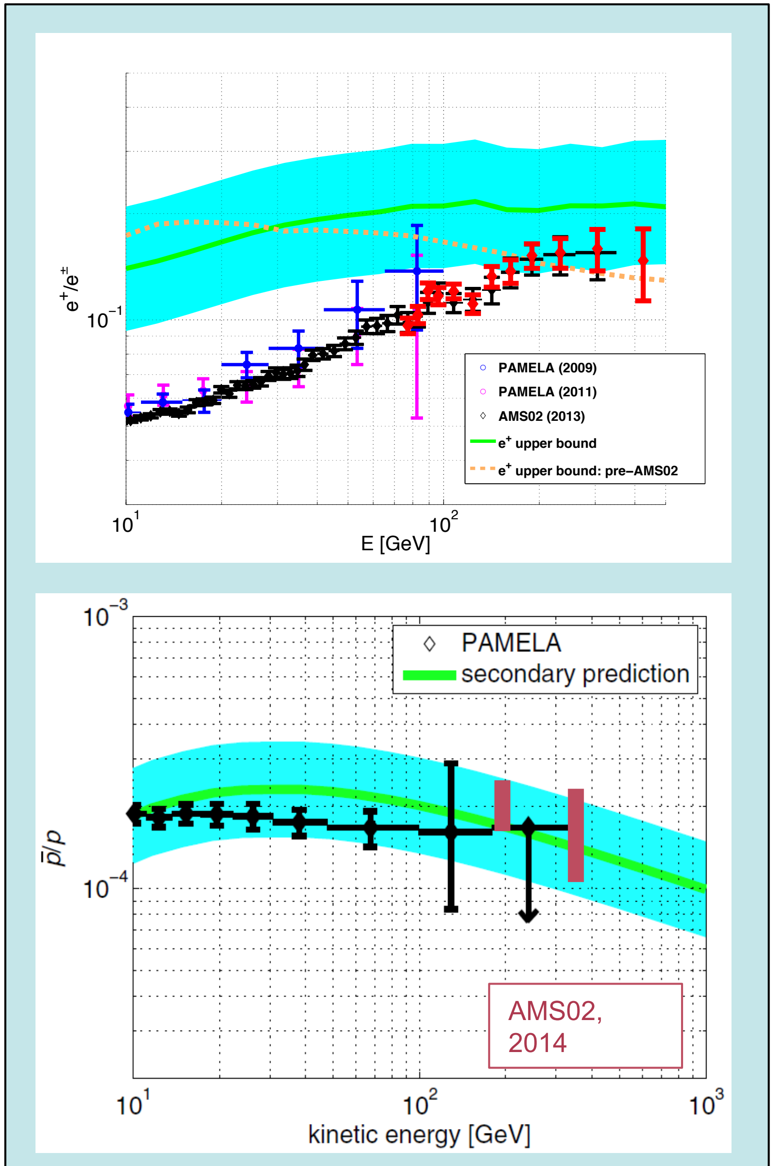

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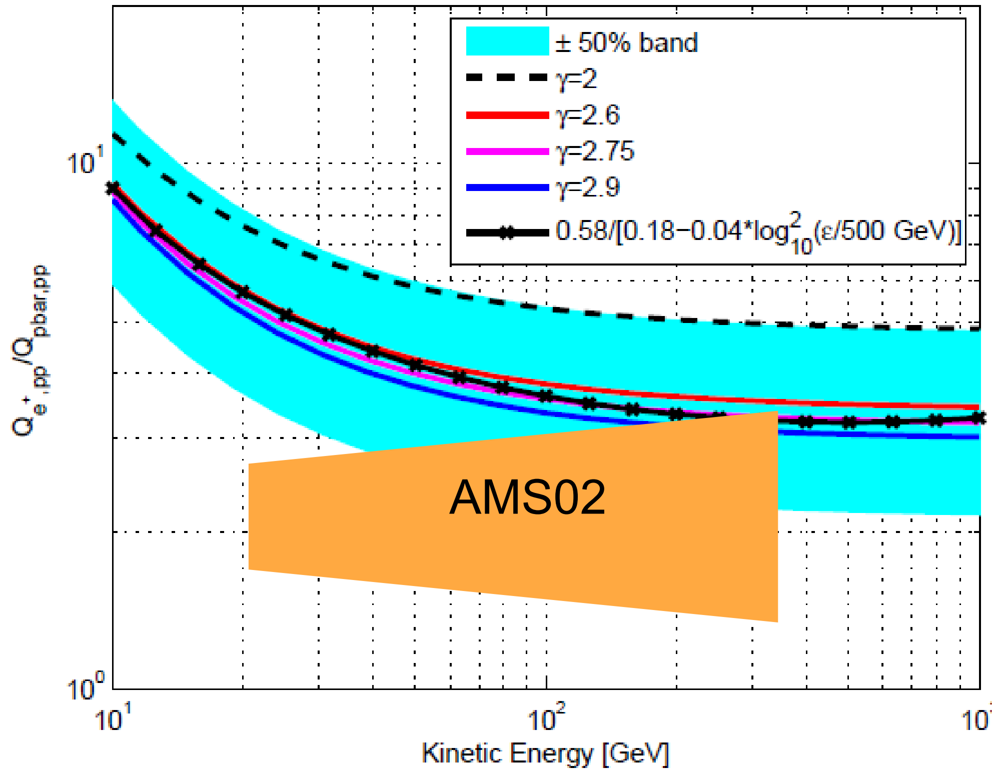

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Positrons and antiprotons

What's consistent w/ old global models and what not?

Model building guidelines in data

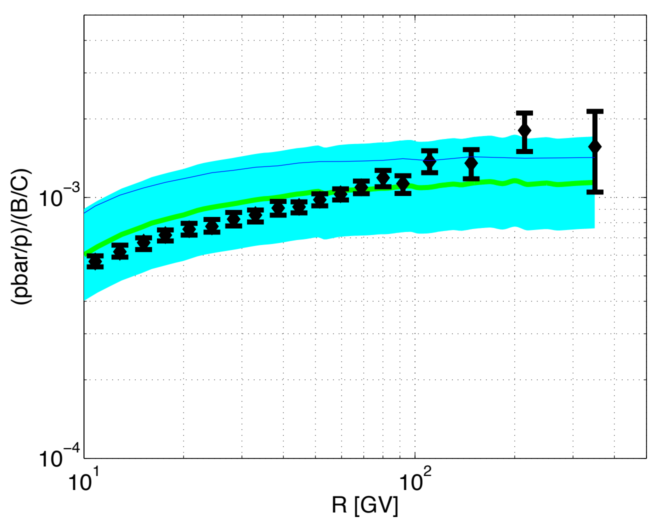
- Antiprotons vs. B/C **consistent w/ secondary, no problem w/ global models**
- e+ **consistent w/ robust calculation for secondary**

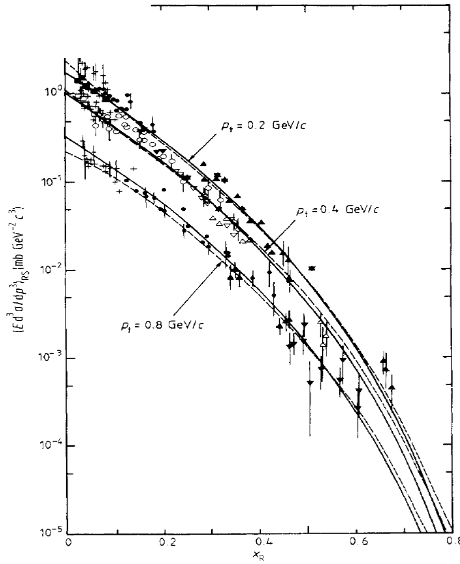
  ***inconsistent* w/ common diffusion model**

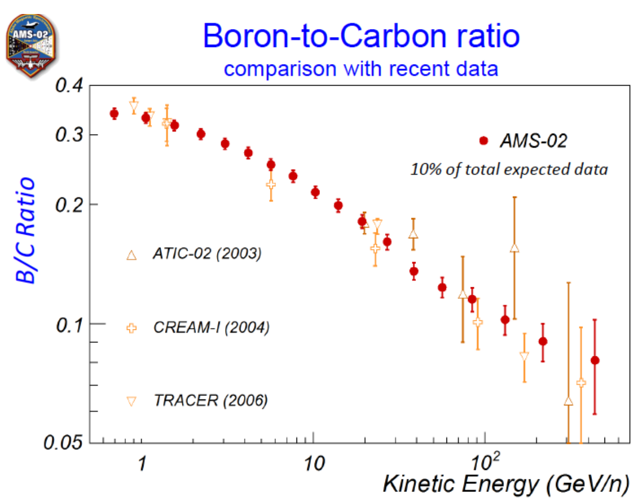
Other ideas:

- Local, non steady state sources
- Pulsars

up to now: dry particle physics perspective







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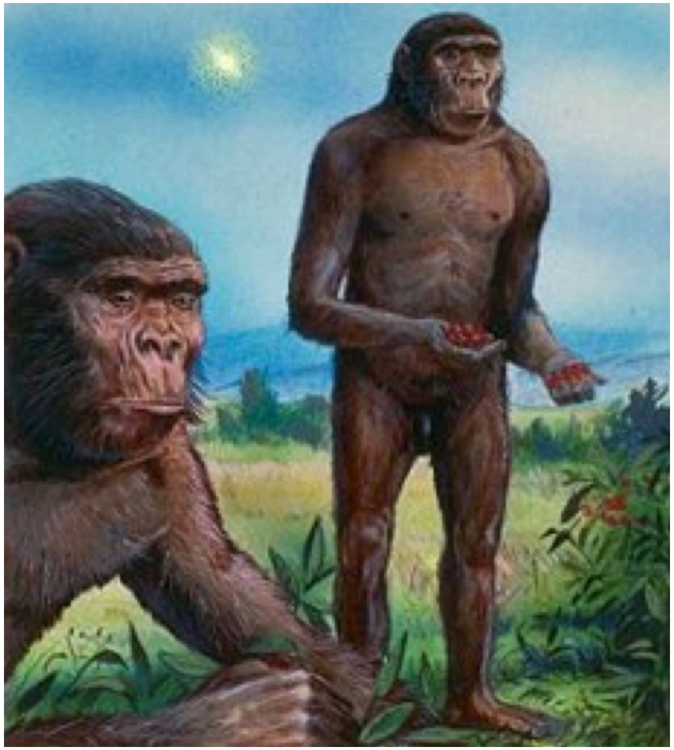
now: astrophysics



Other ideas:

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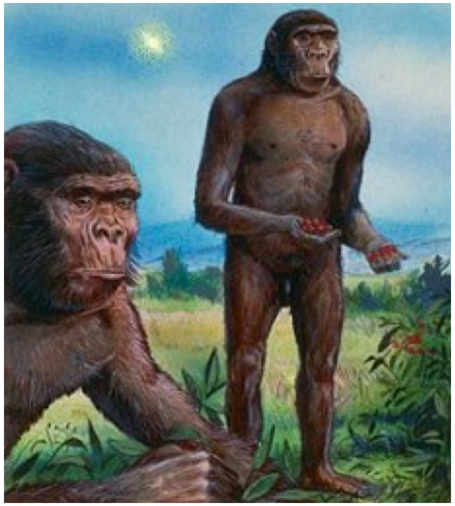

nearby supernova O(100pc) away and 10^6 years ago

Savchenko, Kachelries, Semikoz, ApJ809 (2015)
Kchelries, Neronov, Semikoz, PRL115 (2015)
Giacinti, Kachelries, Semikoz, PRD91 (2015)
Giacinti, Kachelries, Semikoz, PRD88 (2013)

Secondary e+ and pbar from same spectrum p

(should add C, B/C?)

Age of 200GV CR is ~ O(1Myr)

200GV CR live in local ISM density ~ 1mp/cm^3

Calibrating global diffusion model from local nuclei would be wrong

Other ideas:

- **Local, non steady state sources**
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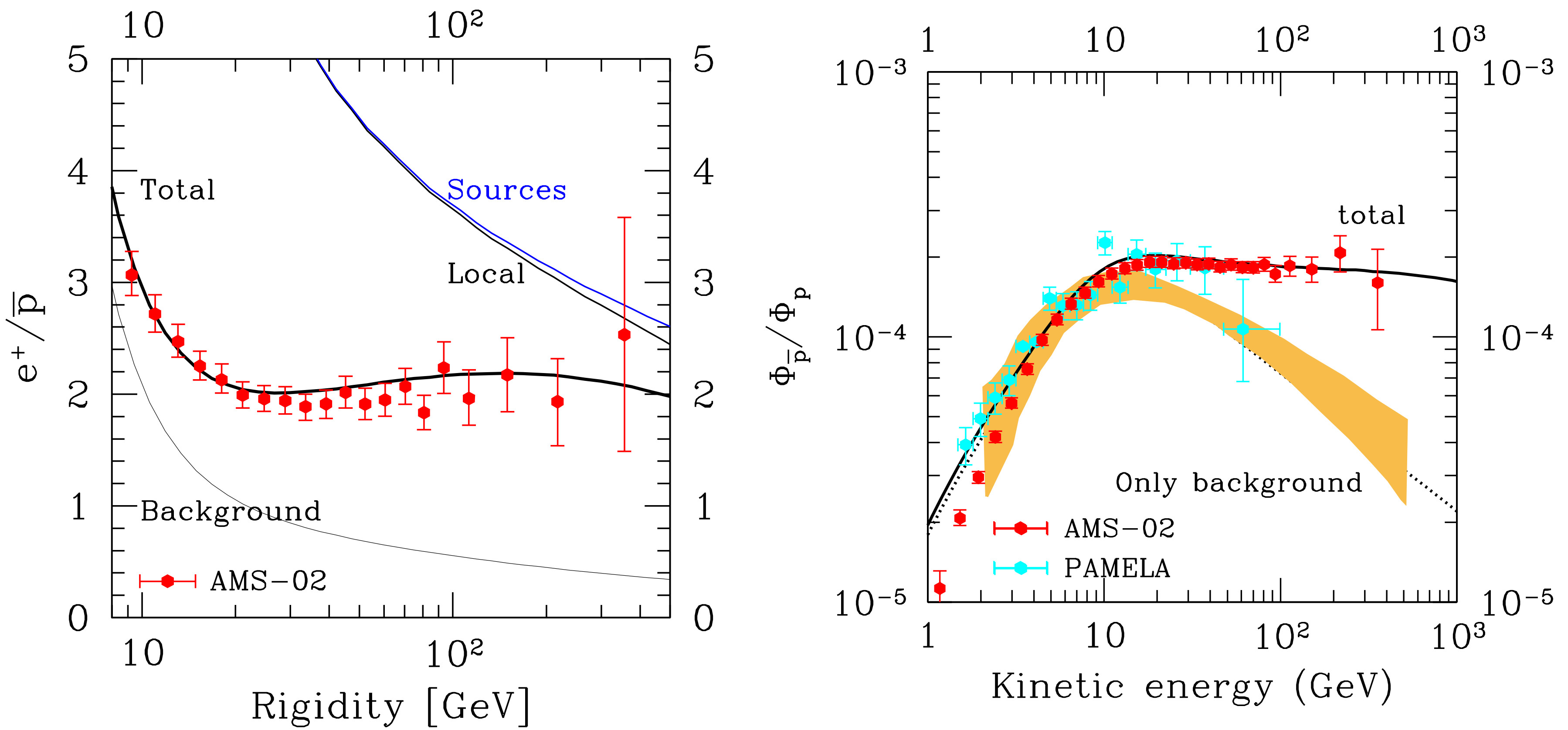
a supernova in a dense gas cloud 200pc away and 10^5 years ago

Kohri, Ioka, Fujita, Yamazaki, 1505.01236

See also e.g. Ohira, Kawanaka, Ioka, PRD93(2016)



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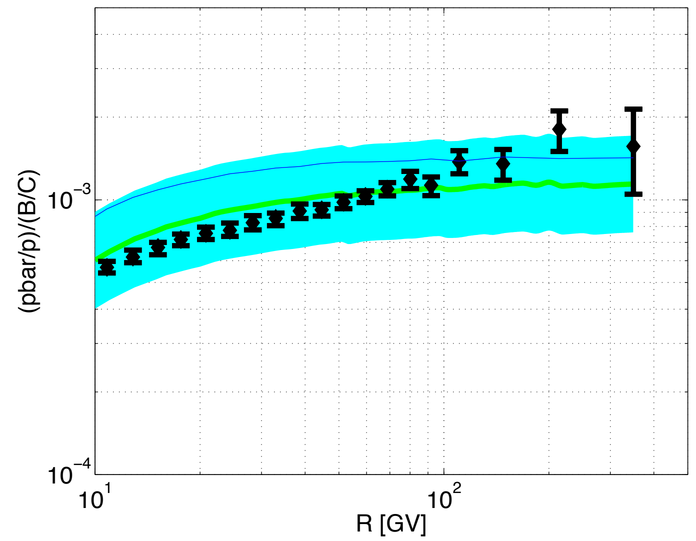

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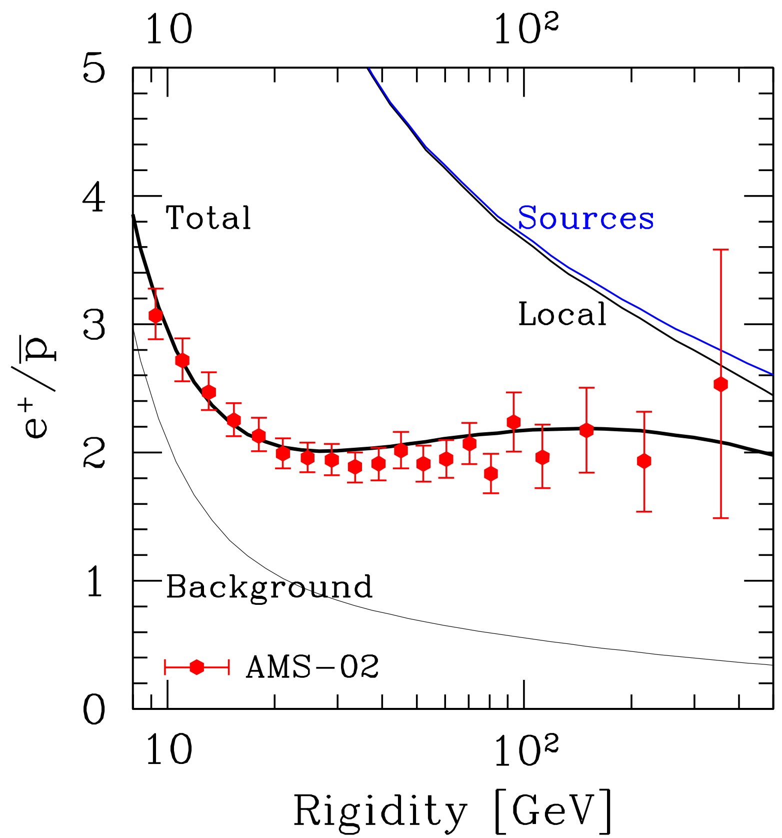

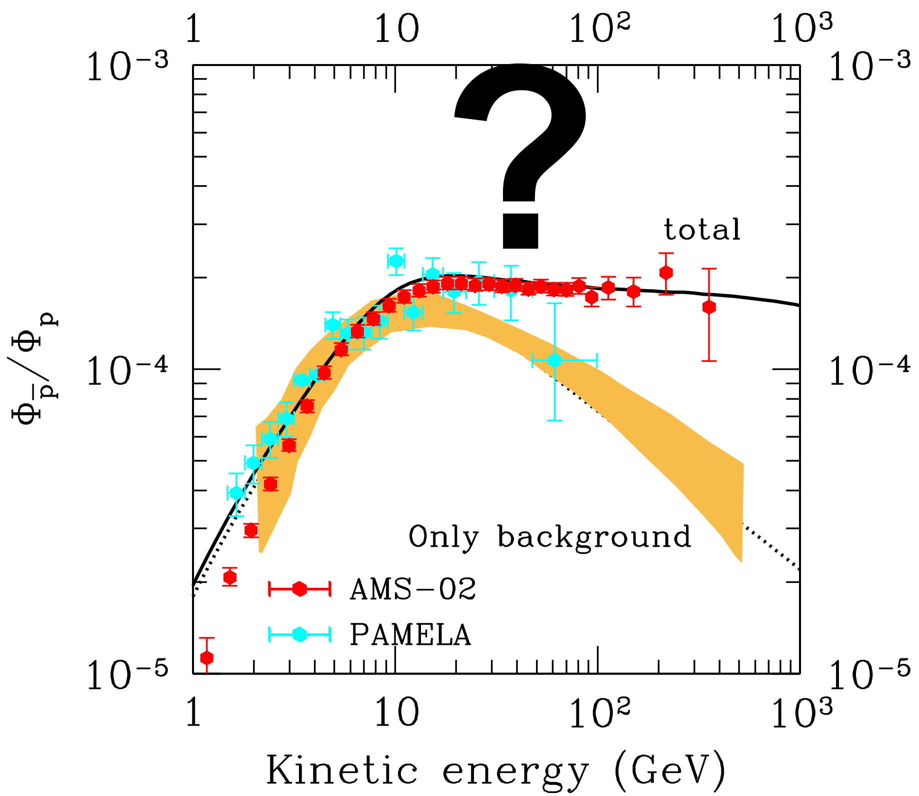

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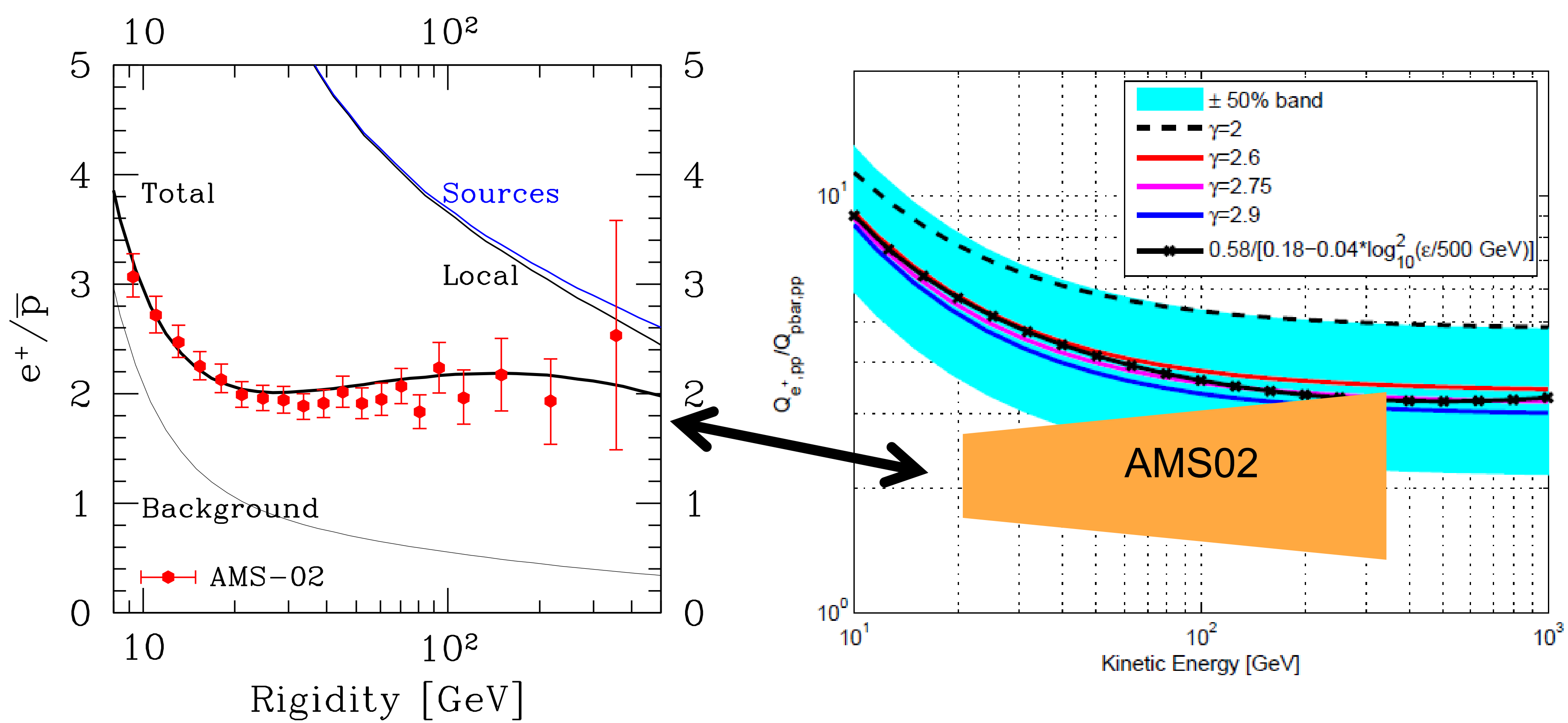

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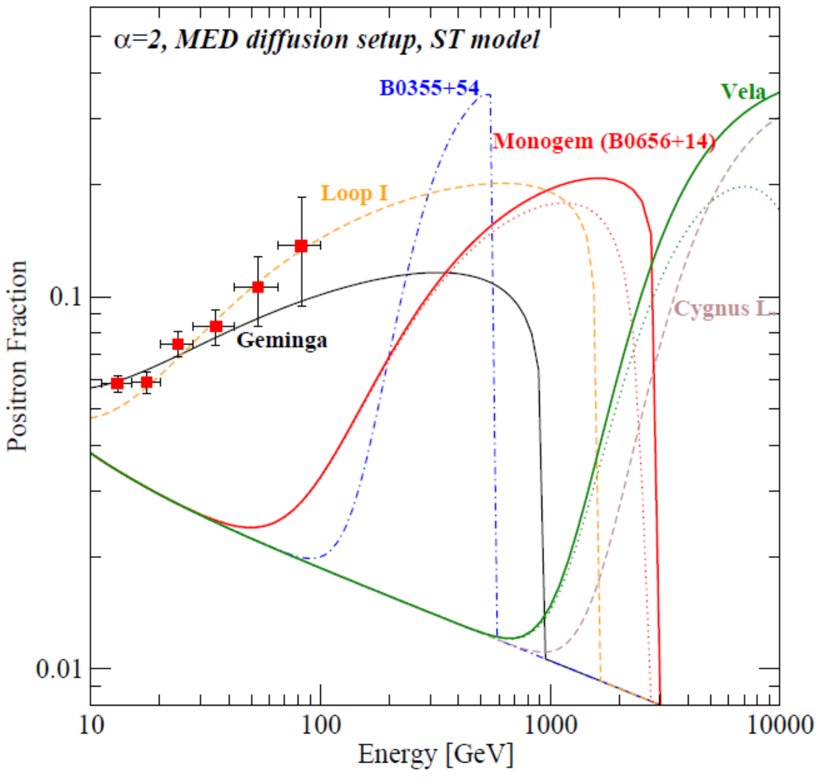
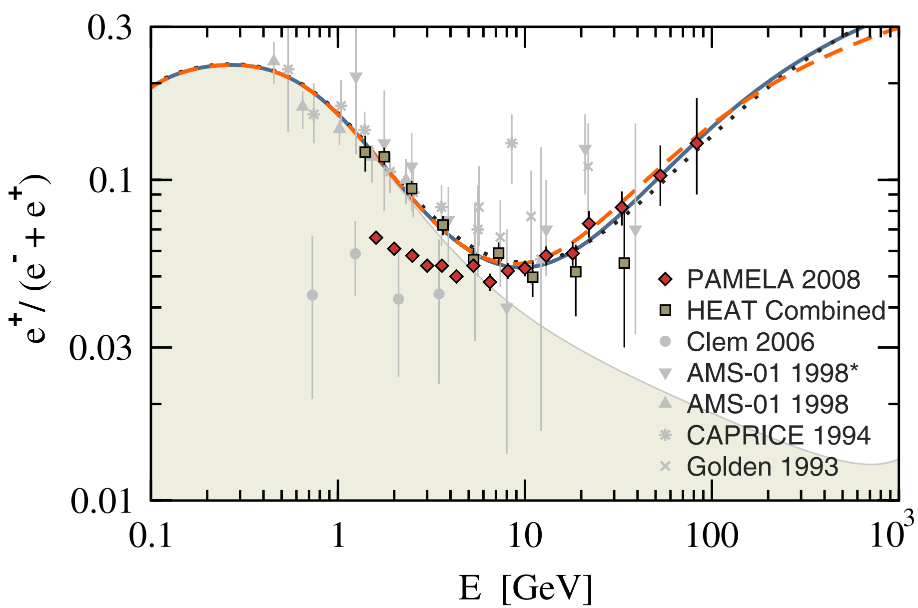


Profumo, Central Eur.J.Phys. 10 (2011) 1-31



Yuksel, Kistler, Stanev, PRL103.051101 (2009)

Other ideas:

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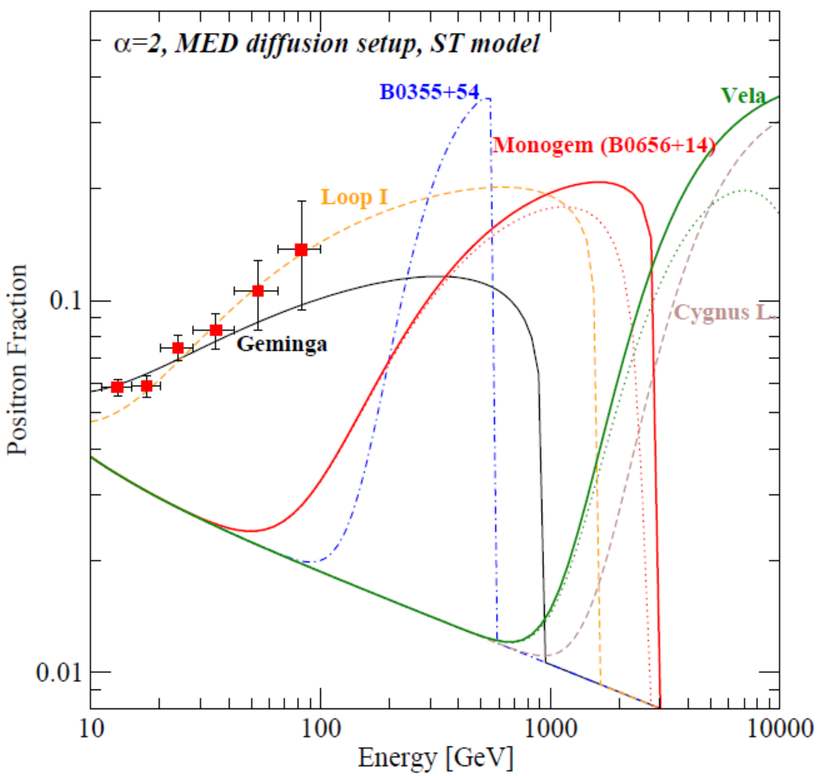
Why would pulsars inject ***this*** e+ flux?



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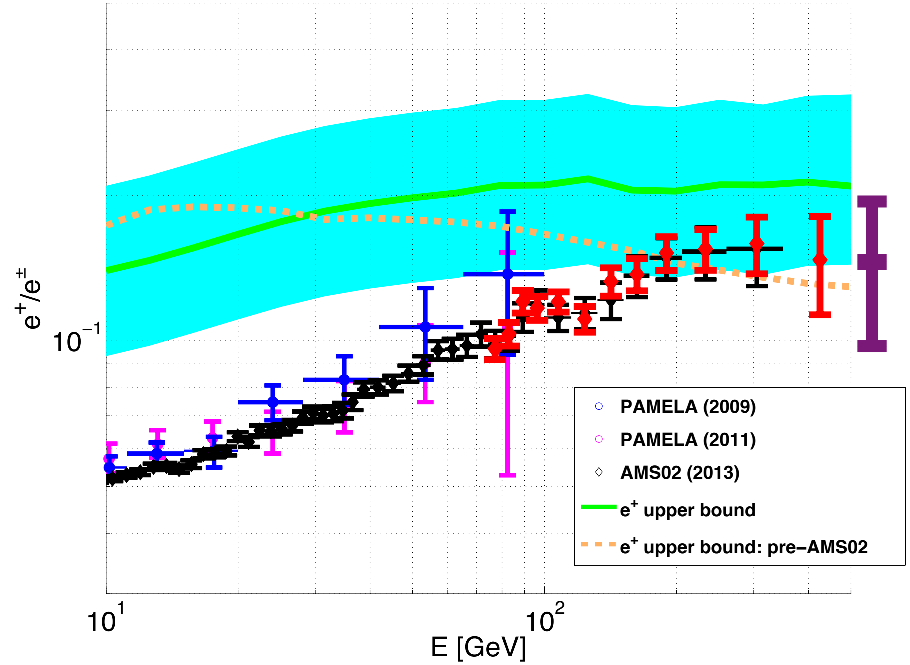

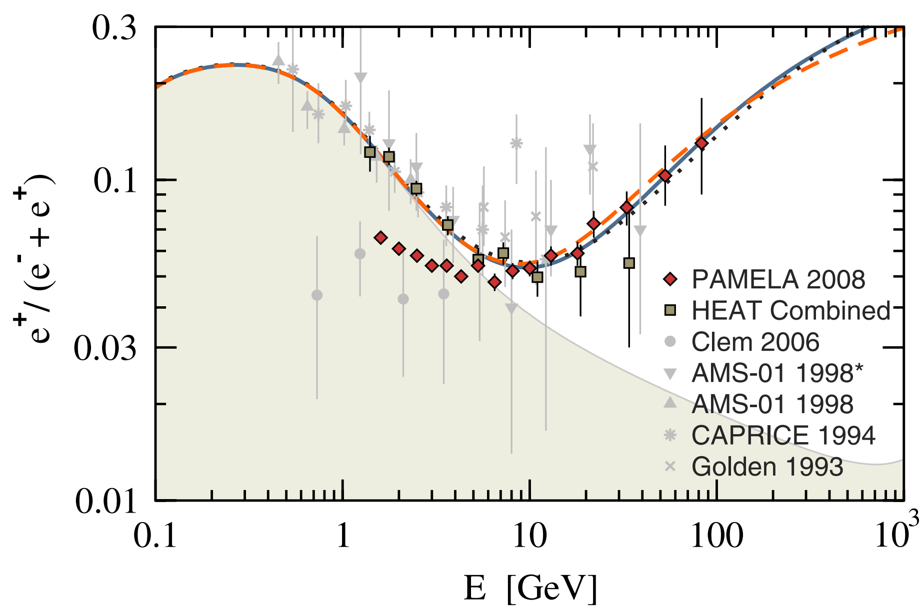

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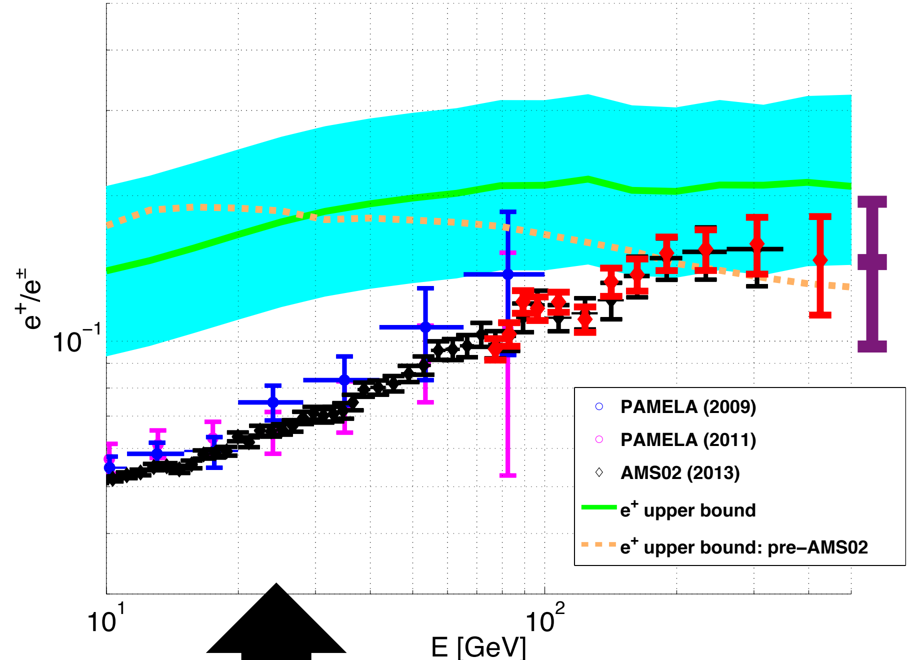
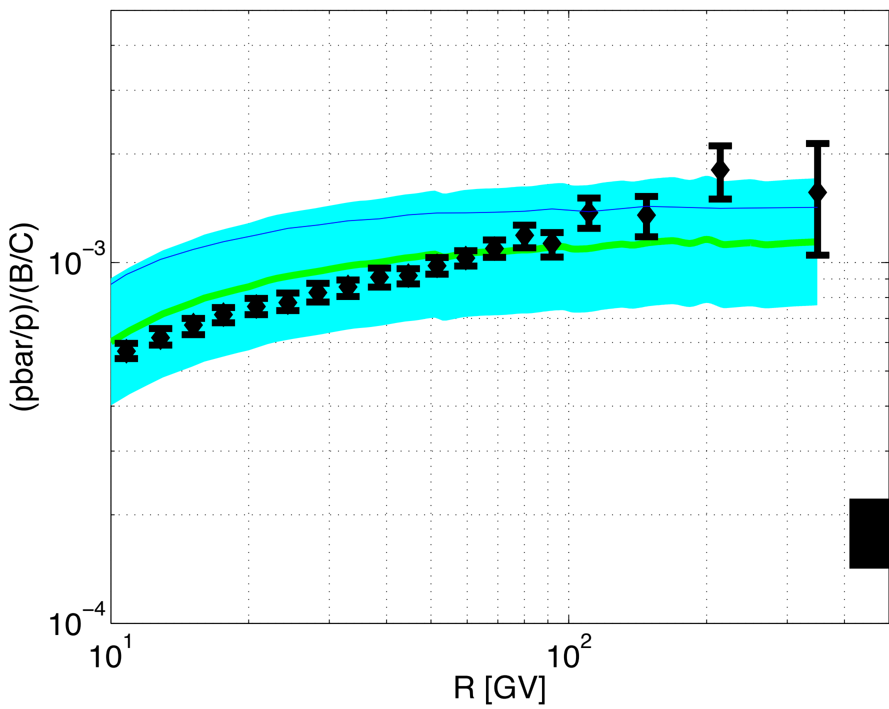
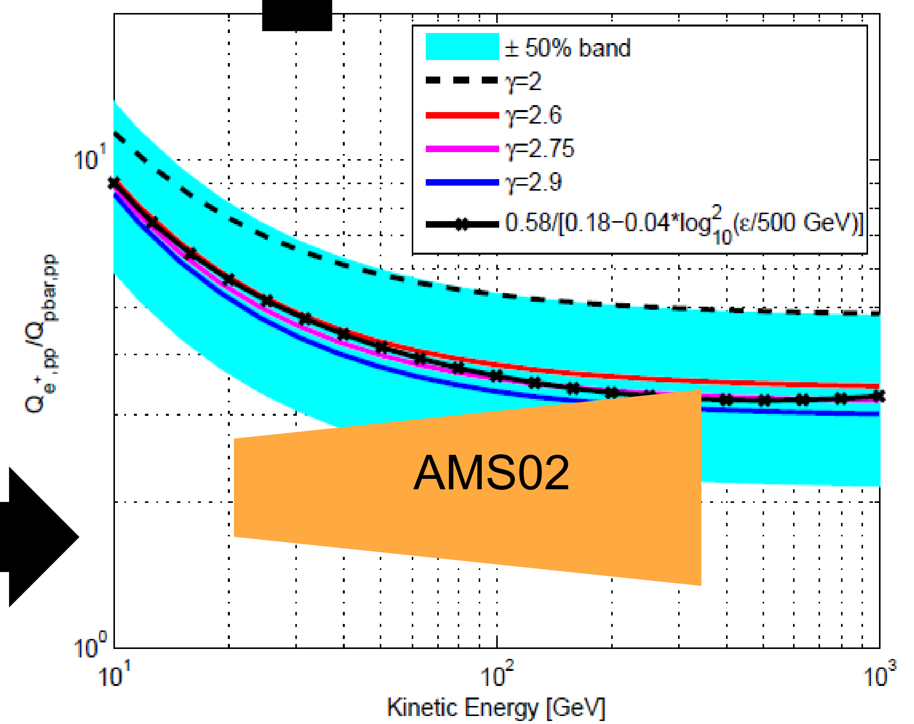






Summary

pbar consistent with secondary **(**pbar/p)/(B/C)
e+ consistent w/ pbar

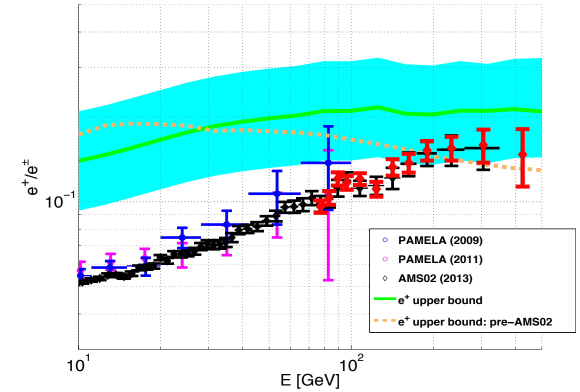
e+ rule out canonical diffusion model
secondary e+ require $t_{esc} \sim t_{cool}$ (*why?*)
➔ R-dependent mean ISM density
CR containment region may vary w/ R (why not?)
inferred density at 300GV ~ density of MW gas disc

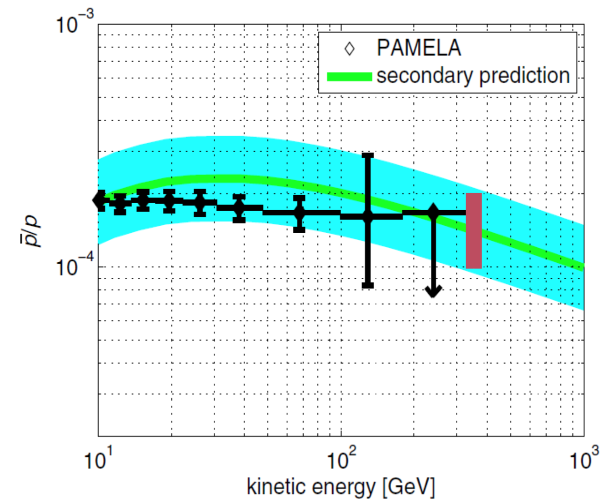
Local secondary source/non steady state:
pbar/p consistent w/ B/C ➔ source better spalate nuclei.
If dominate pbar/p, should also dominate B/C,… p and C…

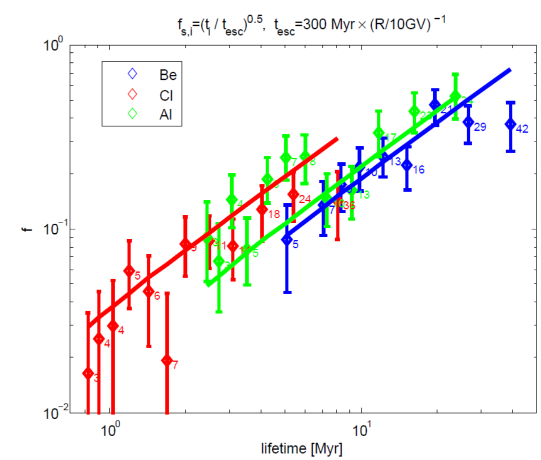
Pulsar/dark matter:
Why would a primary source inject *this* J_{e+}?

Future tests w/ AMS02: radioactive nuclei at 10-100GV

Thank you!

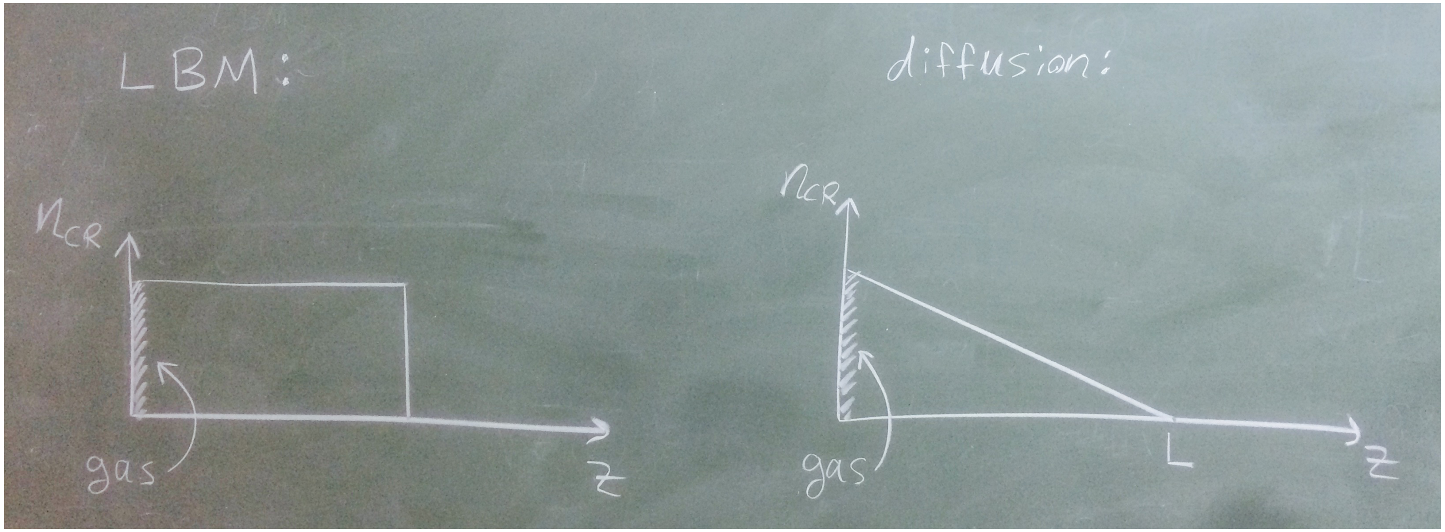




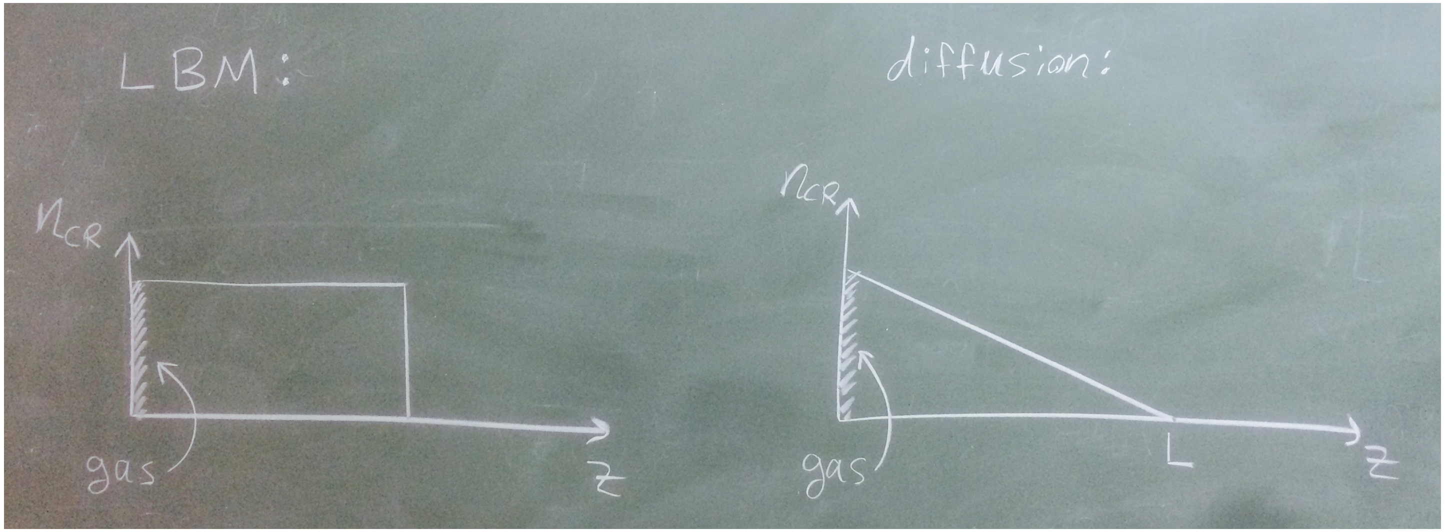


Xtras

Interpretation: model dependence



Interpretation: model dependence

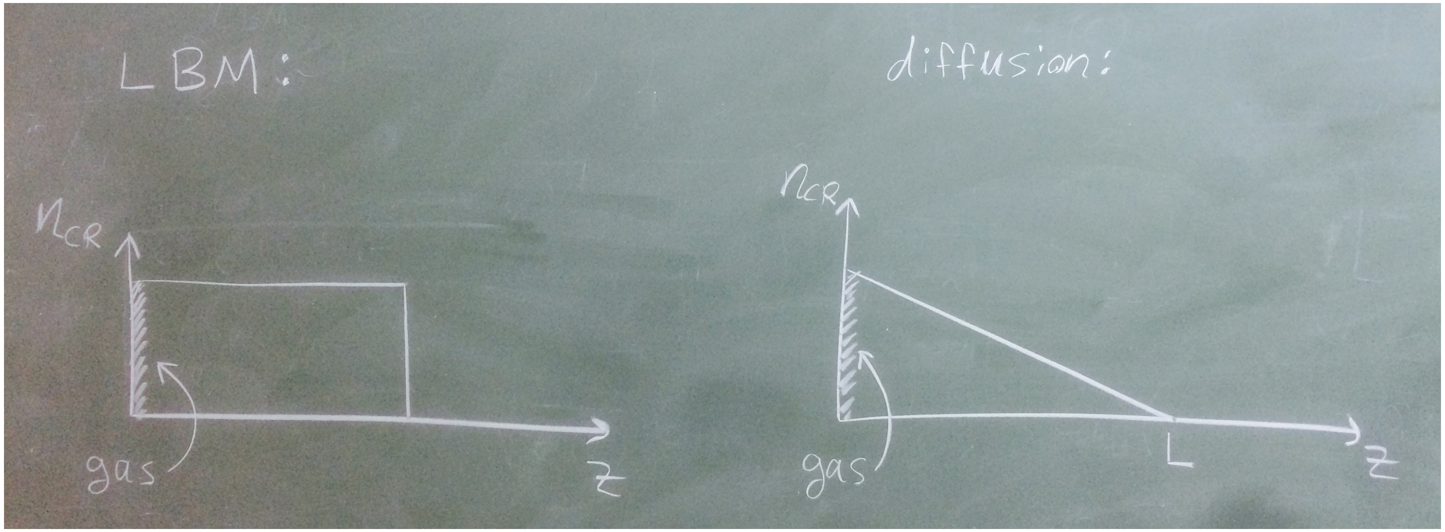


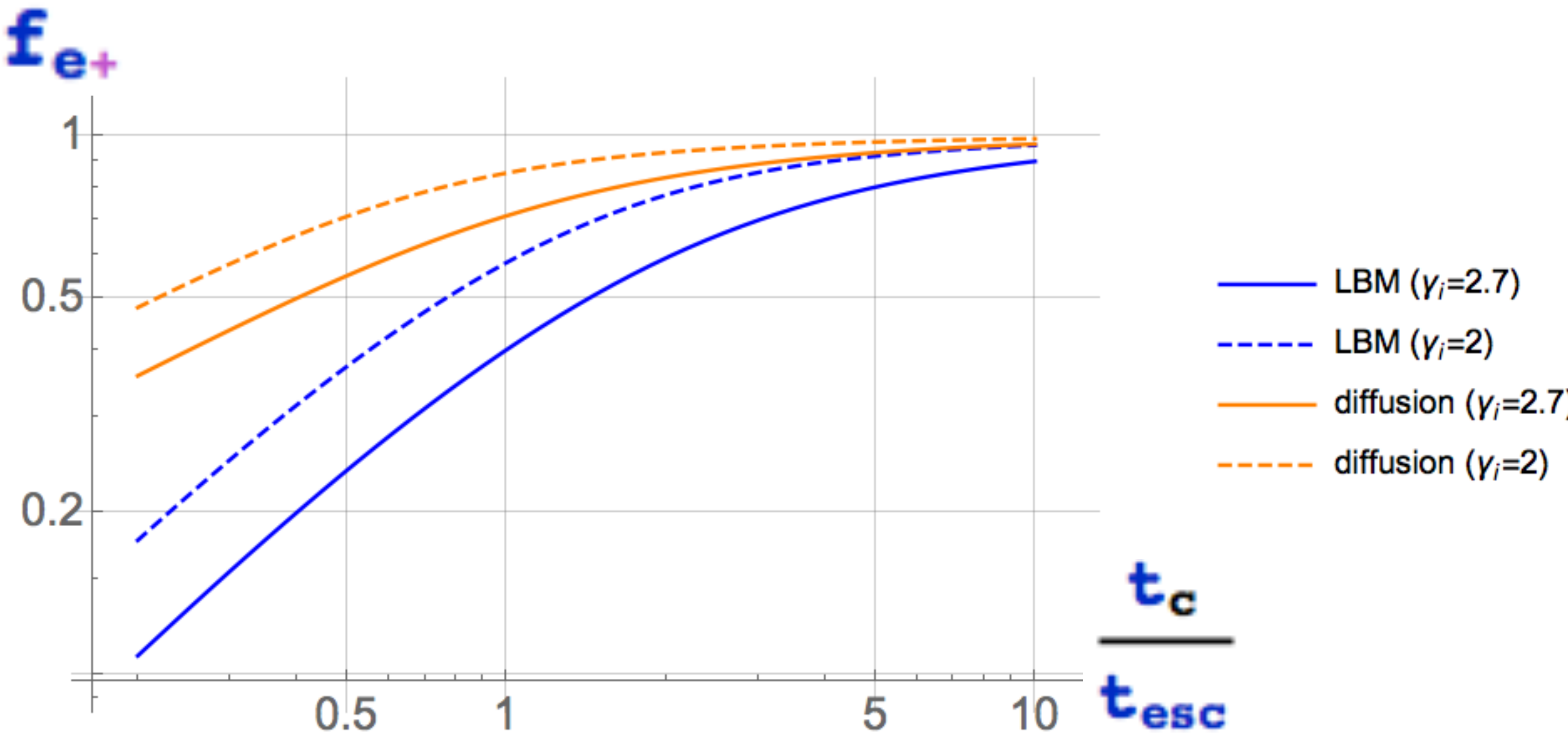
$$f_{e+}^{\rm LBM}(\epsilon) = \frac{t_c(\epsilon)}{t_e(\epsilon)}\int_1^\infty dx x^{-\gamma_i}\exp\left[-\frac{t_c(\epsilon)}{t_e(\epsilon)}\frac{1-x^{\delta-1}}{1-\delta}\right] \longrightarrow \frac{1}{\gamma_i-1}\frac{t_c(\epsilon)}{t_e(\epsilon)}$$

$$f_{e+}^{\rm diff}(\epsilon) = \sqrt{\frac{t_c(\epsilon)}{t_e(\epsilon)}}\sqrt{\frac{1-\delta}{\pi}}\int_1^\infty dx\frac{x^{-\gamma_i}}{\sqrt{1-x^{\delta-1}}}\sum_{n=-\infty}^{\infty}(-1)^n\exp\left[-\frac{1-\delta}{1-x^{\delta-1}}\frac{t_c(\epsilon)}{t_e(\epsilon)}n^2\right]$$

$$\longrightarrow \sqrt{\frac{t_c(\epsilon)}{t_e(\epsilon)}}C_{\rm diff}(\gamma_i,\delta), \quad C_{\rm diff}(2.7,0.4)\approx 0.8$$

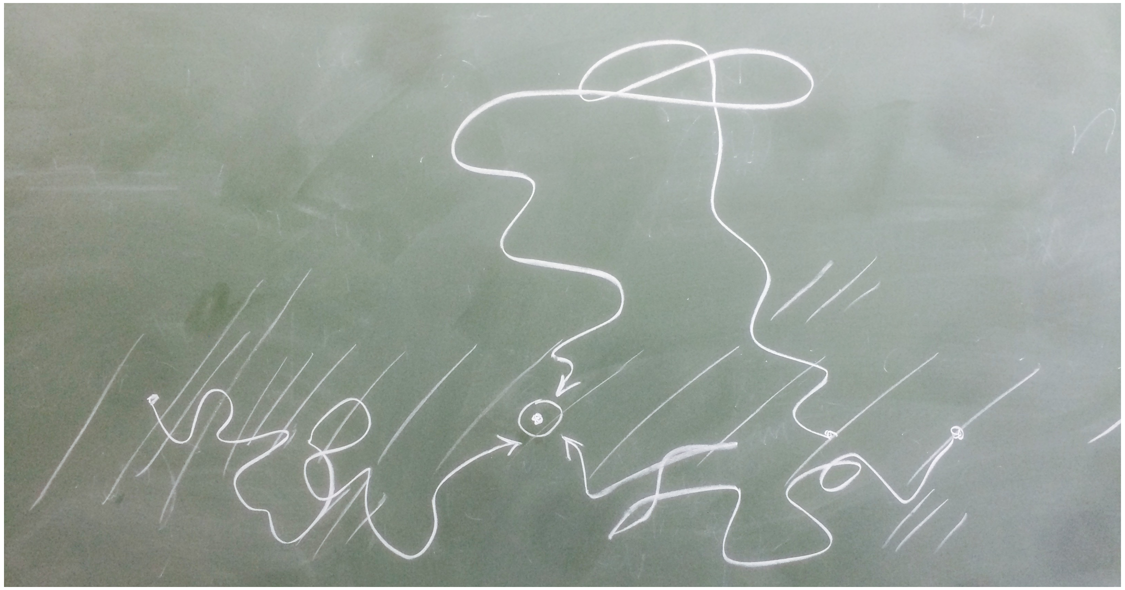
Interpretation: model dependence

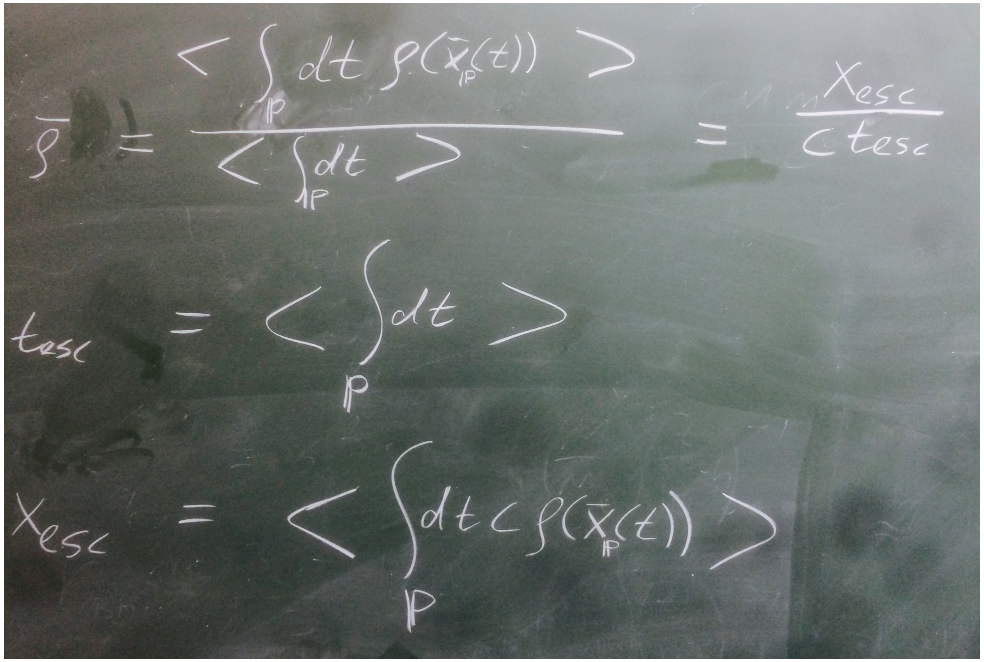




Interpretation:

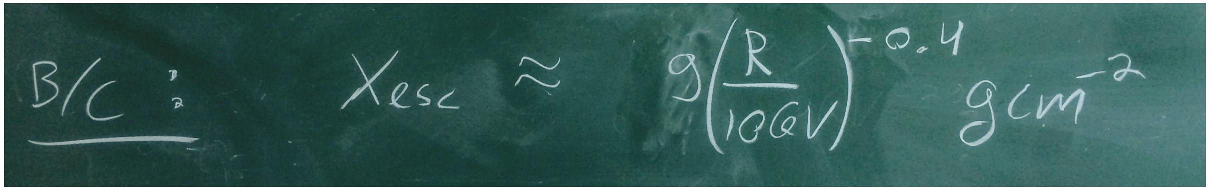
t_{esc}

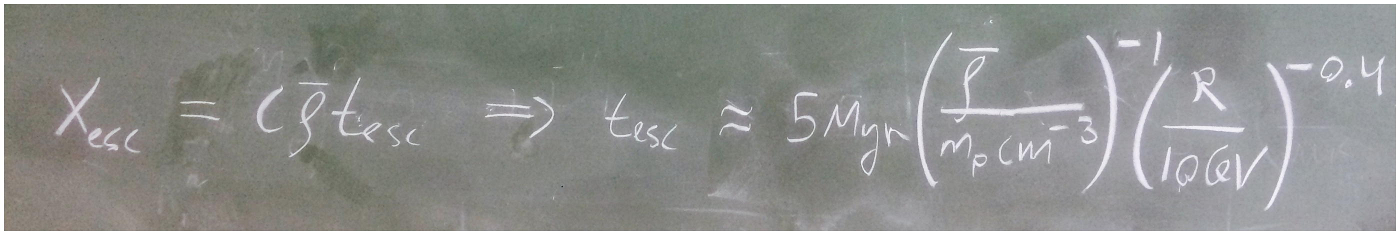




B/C: $X_{esc} \approx 9 \left(\frac{R}{10\,\mathrm{GV}}\right)^{-0.4} \mathrm{g\,cm^{-2}}$

$$X_{esc} = c\bar{\rho}\, t_{esc} \Rightarrow t_{esc} \approx 5\,\mathrm{Myr} \left(\frac{\bar{\rho}}{m_p\,\mathrm{cm^{-3}}}\right)^{-1} \left(\frac{R}{10\,\mathrm{GV}}\right)^{-0.4}$$





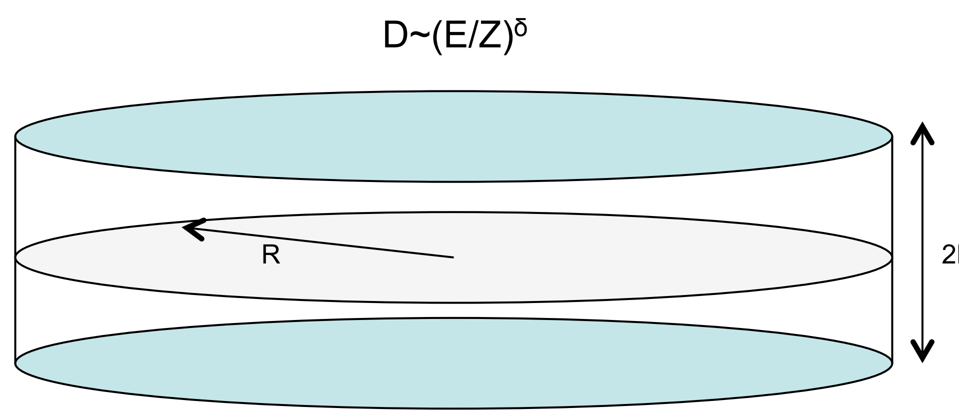
Common diffusion models: $t_{esc} \sim X_{esc}$

$\rho \sim X_{disc}/L$, $X_{esc} \sim (L/D)cX_{disc}$,

$t_{esc} \sim X_{esc}/\rho c \sim L^2/D$,

because L is constant,

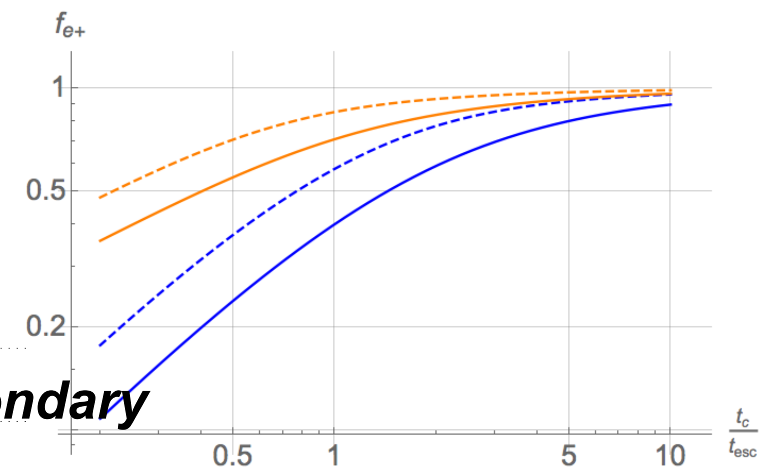
$$\mathbf{t_{esc} \sim X_{esc} \sim R^{-0.4}}$$

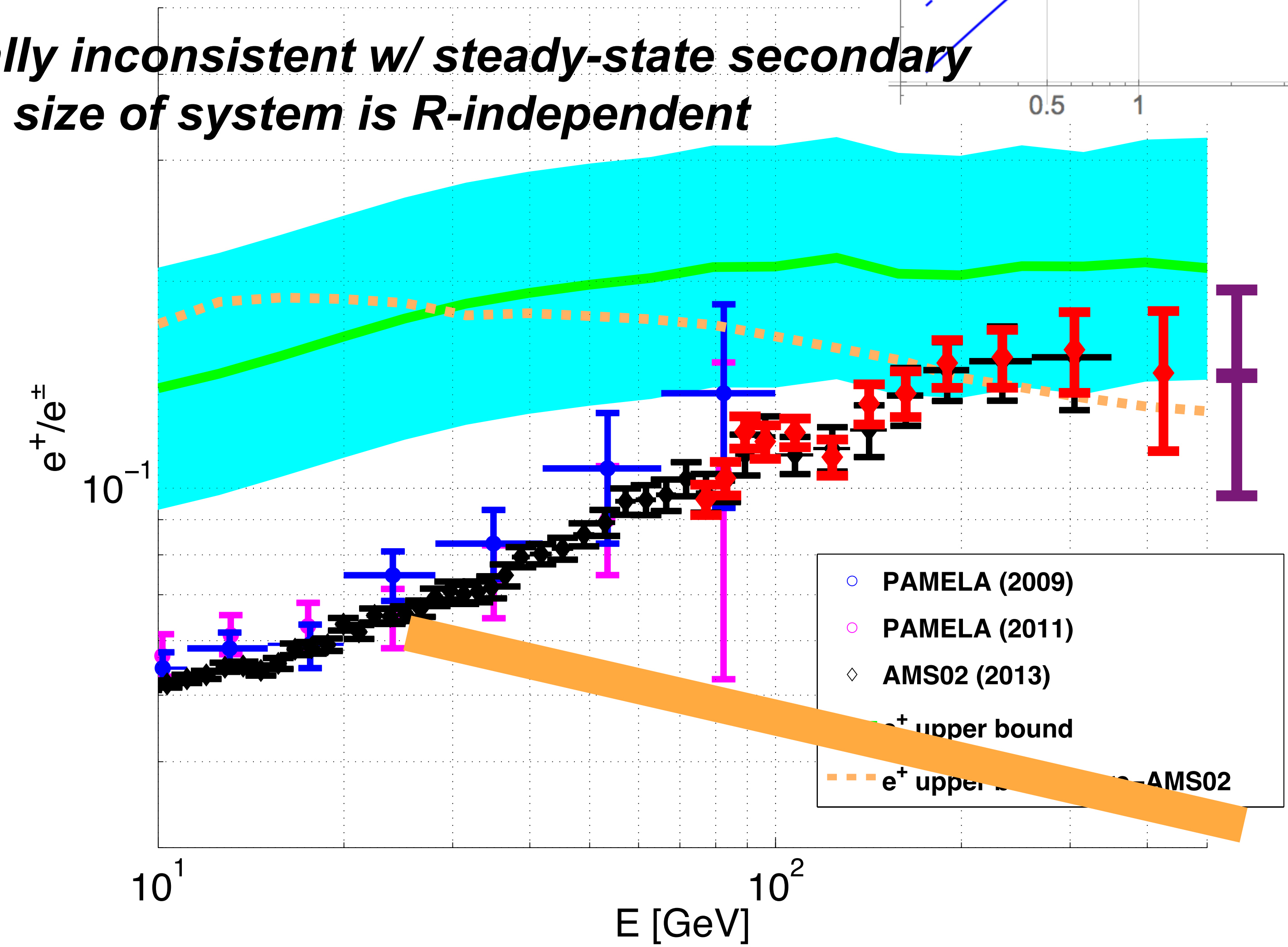


e+ consistent w/ secondary.

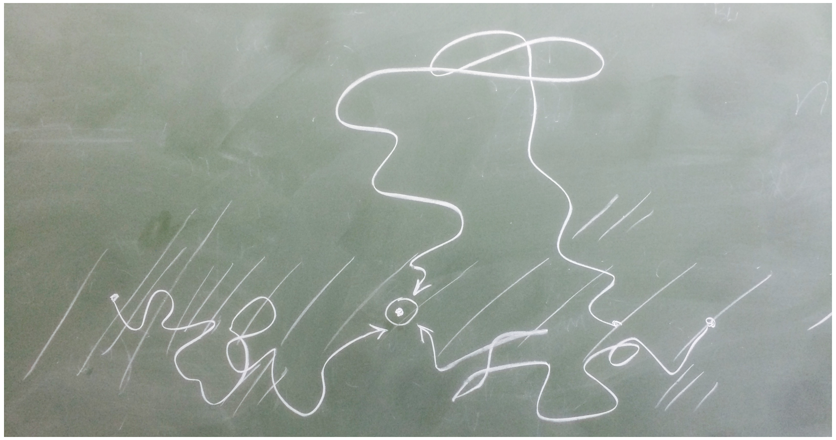
Inconsistent w/ diffusion model

Generally inconsistent w/ steady-state secondary if scale size of system is R-independent





Argument in Katz et al, MNRAS 405 (2010) 1458



R~10GV

R~300GV

More general (still steady state) set-up: ρ depends on CR rigidity

$$X_{\rm esc} = c\,\bar\rho\,t_{\rm esc} \;\; \rightarrow \;\; t_{\rm esc} = 5\ {\rm Myr}\left(\frac{\bar\rho}{m_p\,{\rm cm}^{-3}}\right)^{-1}\left(\frac{\mathcal{R}}{10\ {\rm GV}}\right)^{-0.4}$$

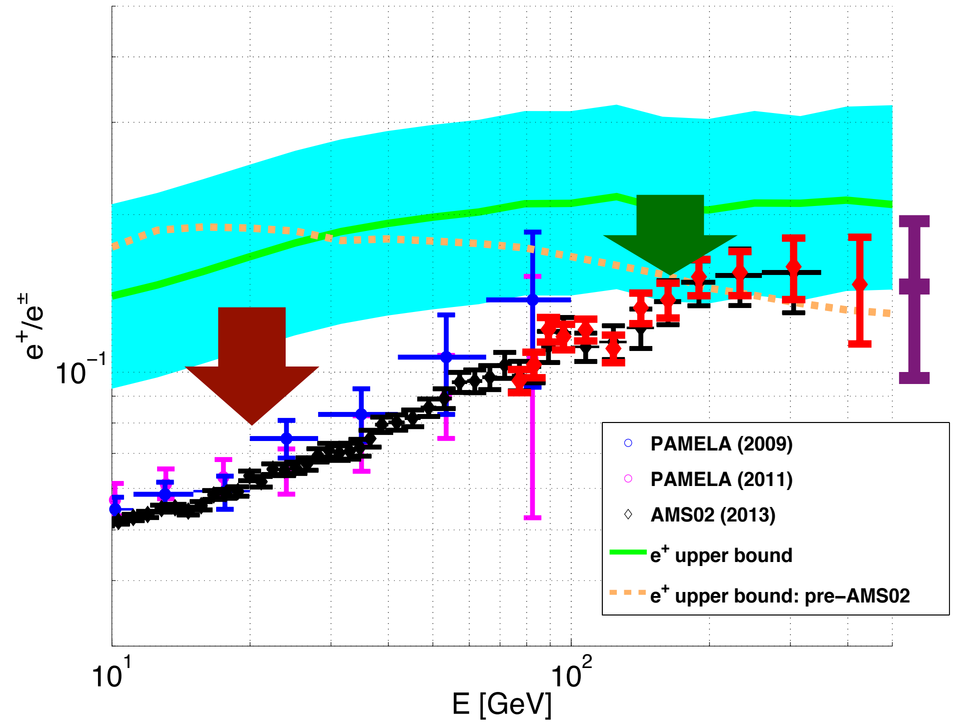
* More energetic CR *fail to return* from far above disc

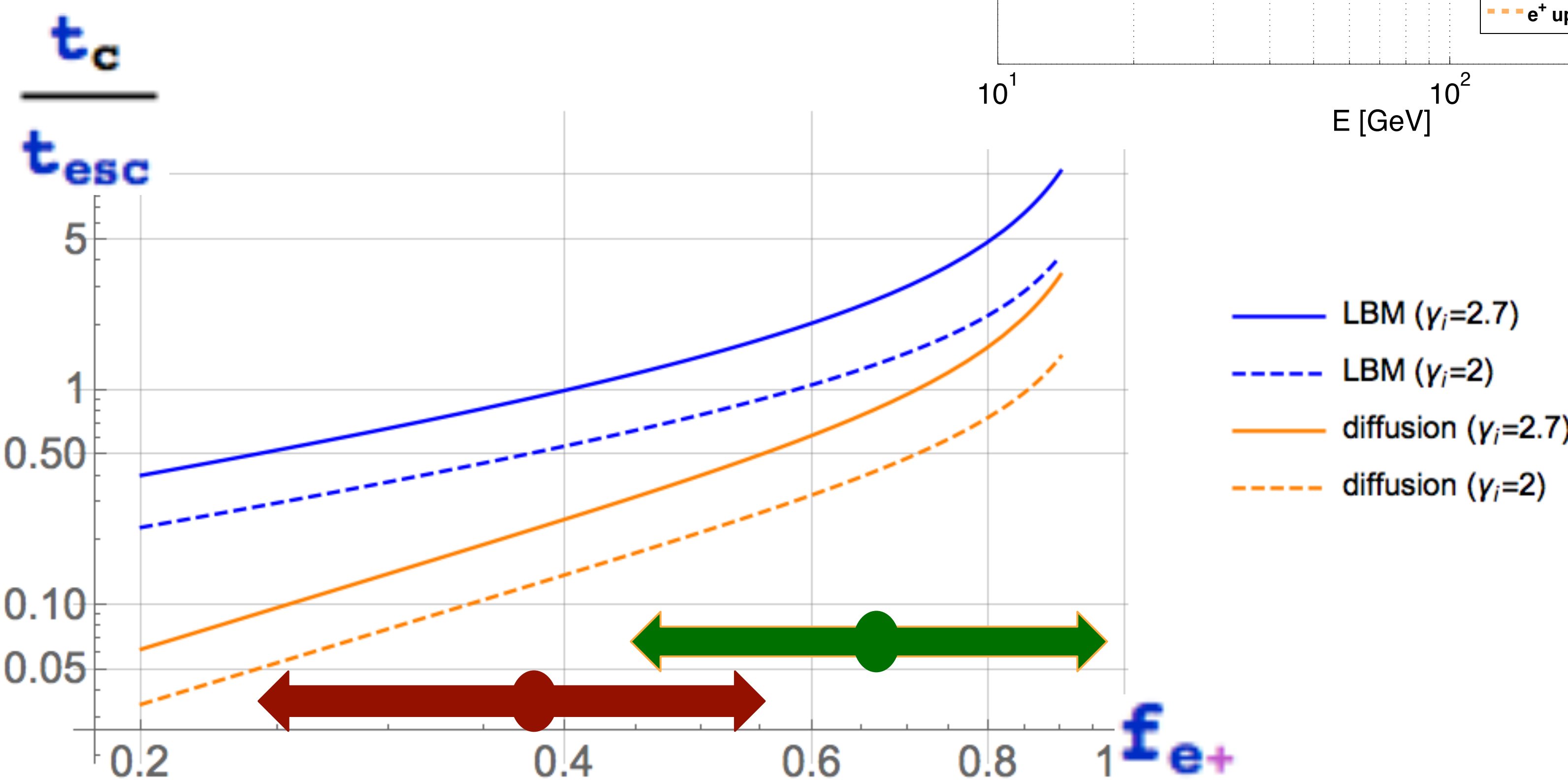
* Leads to ρ rising w/ CR rigidity

~~t_{esc} ~ X_{esc}~~

Interpretation for secondary production

t_c/t_{esc} constant or *growing w/ rigidity?*





Interpretation for secondary production

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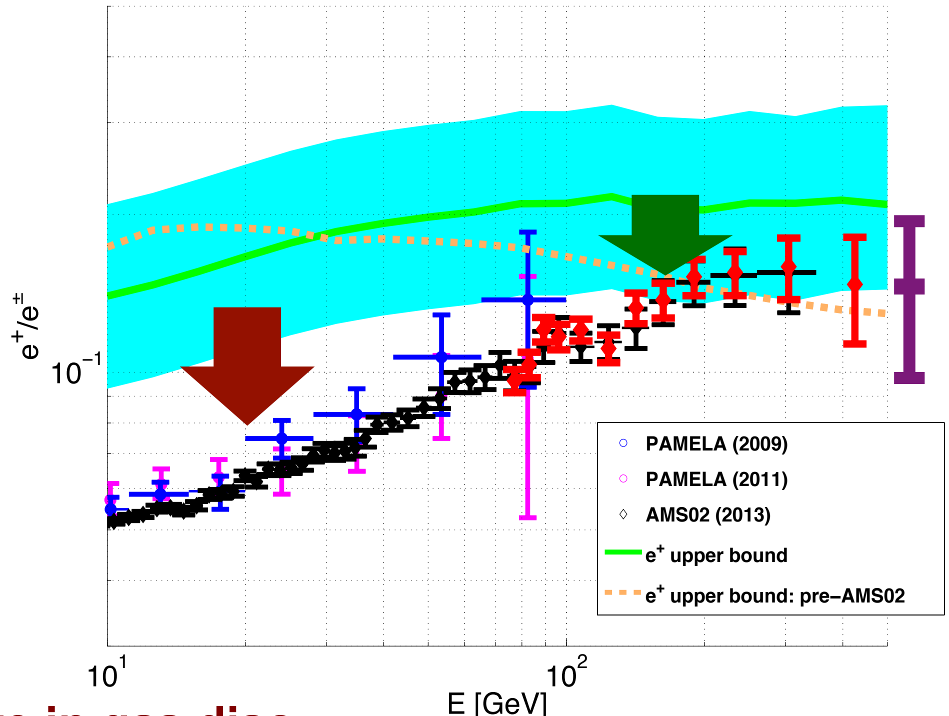
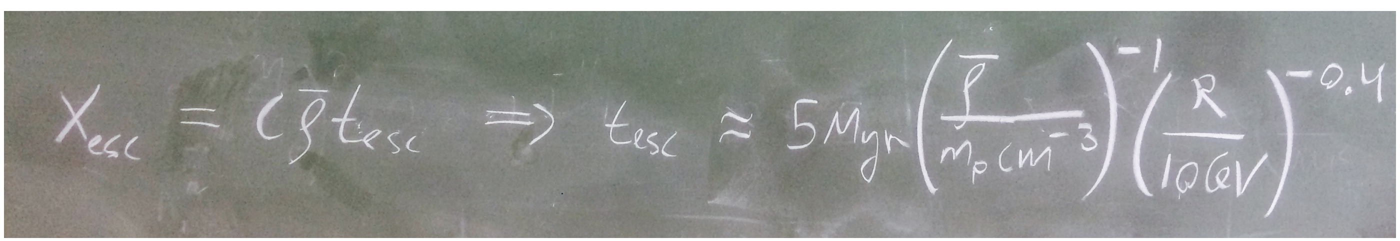


Comments:

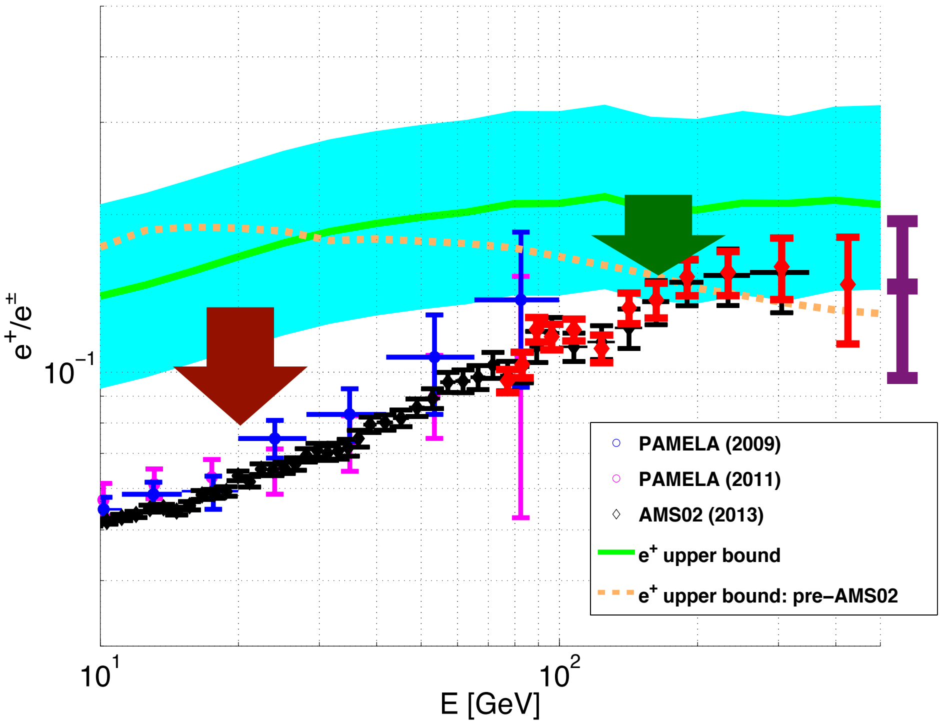
- Cooling time for 300GV e+ is ~1Myr.

  Setting $t_{esc} \sim t_c$, we get $\rho \sim 1\ m_p/cm^3$, **like in gas disc**



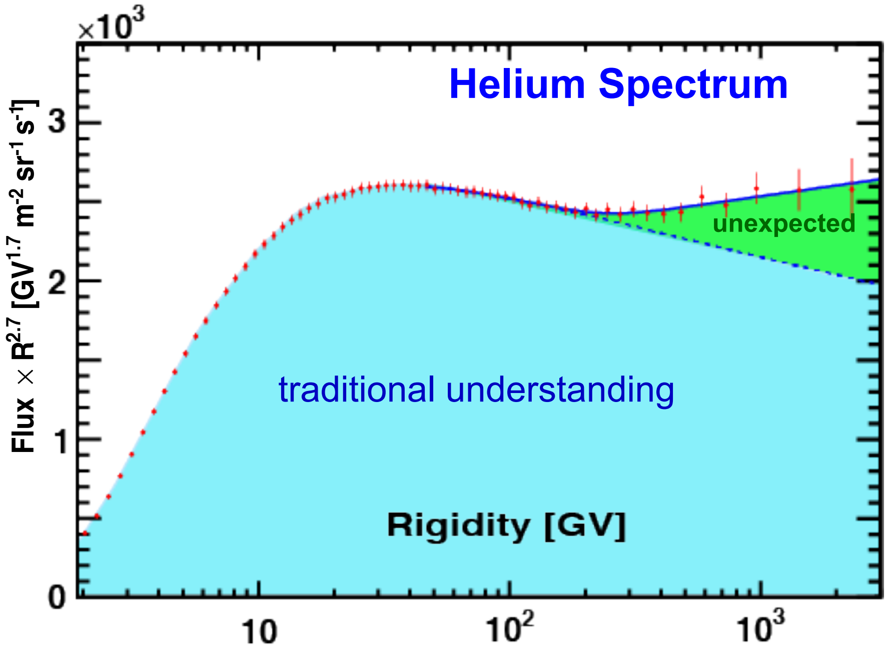
Interpretation for secondary production

t_c/t_{esc} constant or *growing w/ rigidity*?



Comments:

- Other things happen around 200GV?



Escape time falling fast w/ energy: implication for CR injection spectrum

Expect: $$J_{p,\mathrm{inject}} \propto \mathcal{R}^{-\gamma_0}, \qquad \gamma_0 \gtrsim 2$$

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

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

$$\gamma_0 < 2$$

Escape time falling fast w/ energy: implication for CR injection spectrum

Expect: $$J_{p,\mathrm{inject}} \propto \mathcal{R}^{-\gamma_0}, \qquad \gamma_0 \gtrsim 2$$

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

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

$$\gamma_0 < 2$$

Answer: worry is based on constant halo assumption, that may be incorrect.

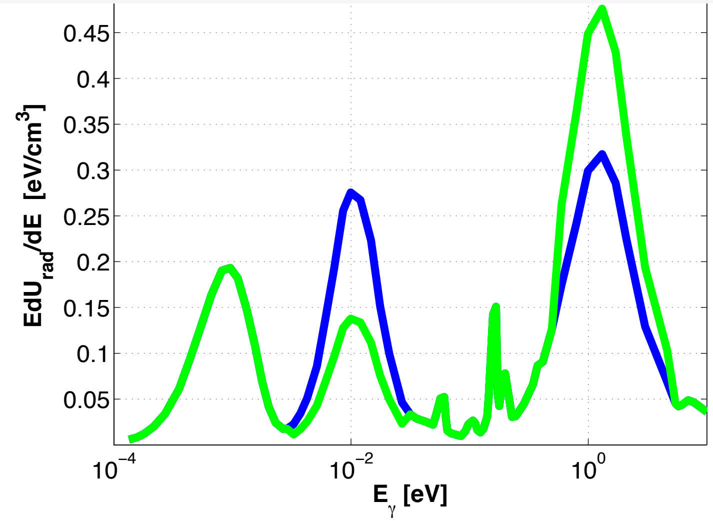
Steady state scaling is $$J_{p,\mathrm{obs}} \sim \frac{Q_p \times t_{\mathrm{esc}}}{V} \propto \frac{J_{p,\mathrm{inject}} \times t_{\mathrm{esc}}}{V}$$

V could depend on rigidity: V=V(R)
Example: homogeneous thin-disc diffusion, V ~ L = L(R)

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

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

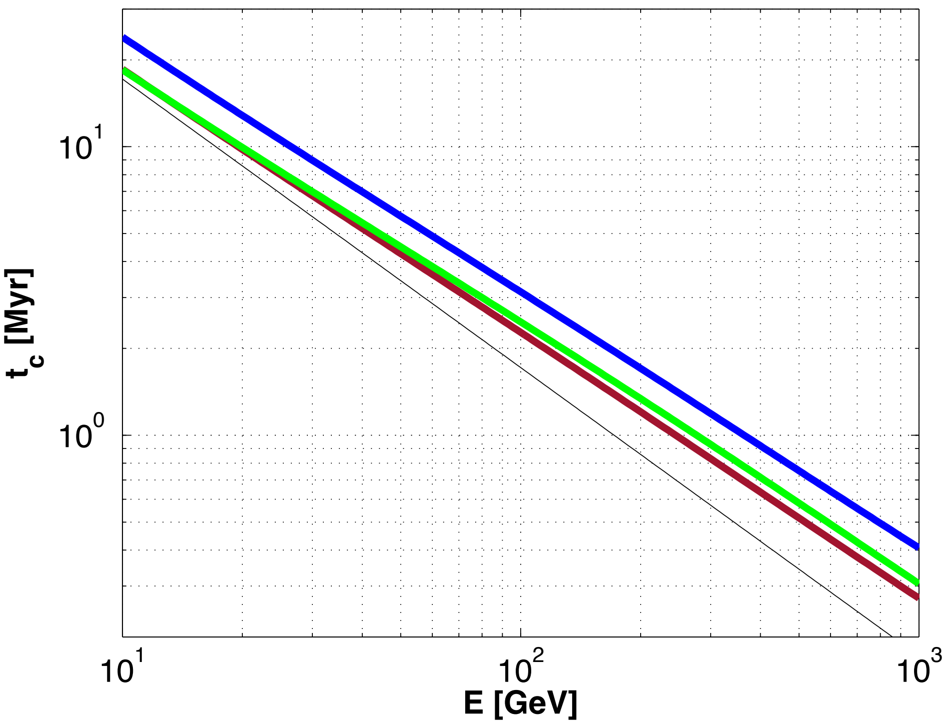
based on: Porter & Strong, astro-ph/0507119

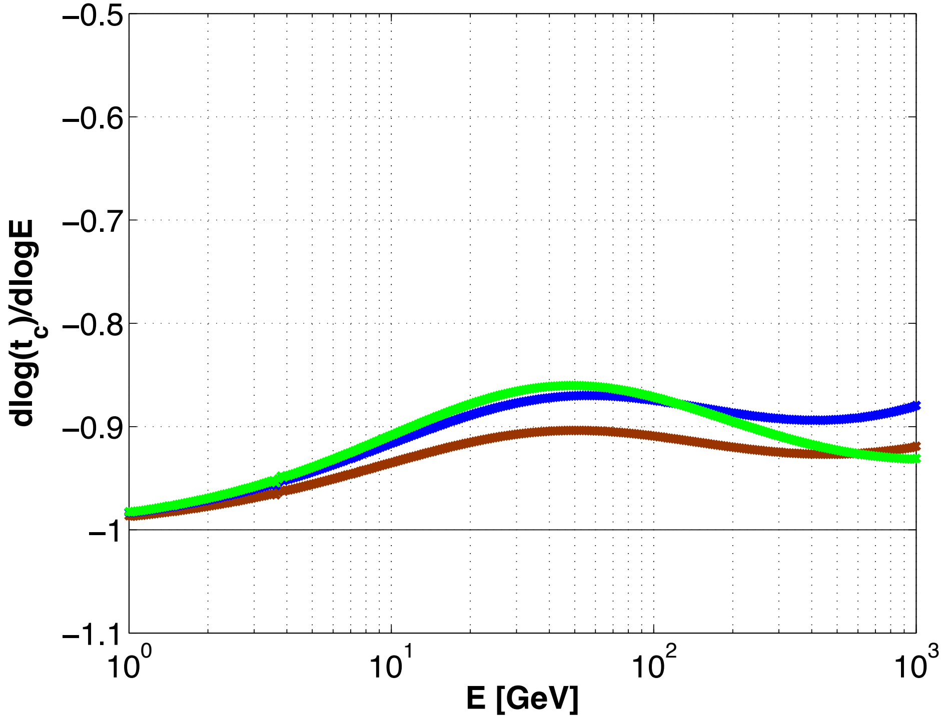


What is the cooling time of CR e±?

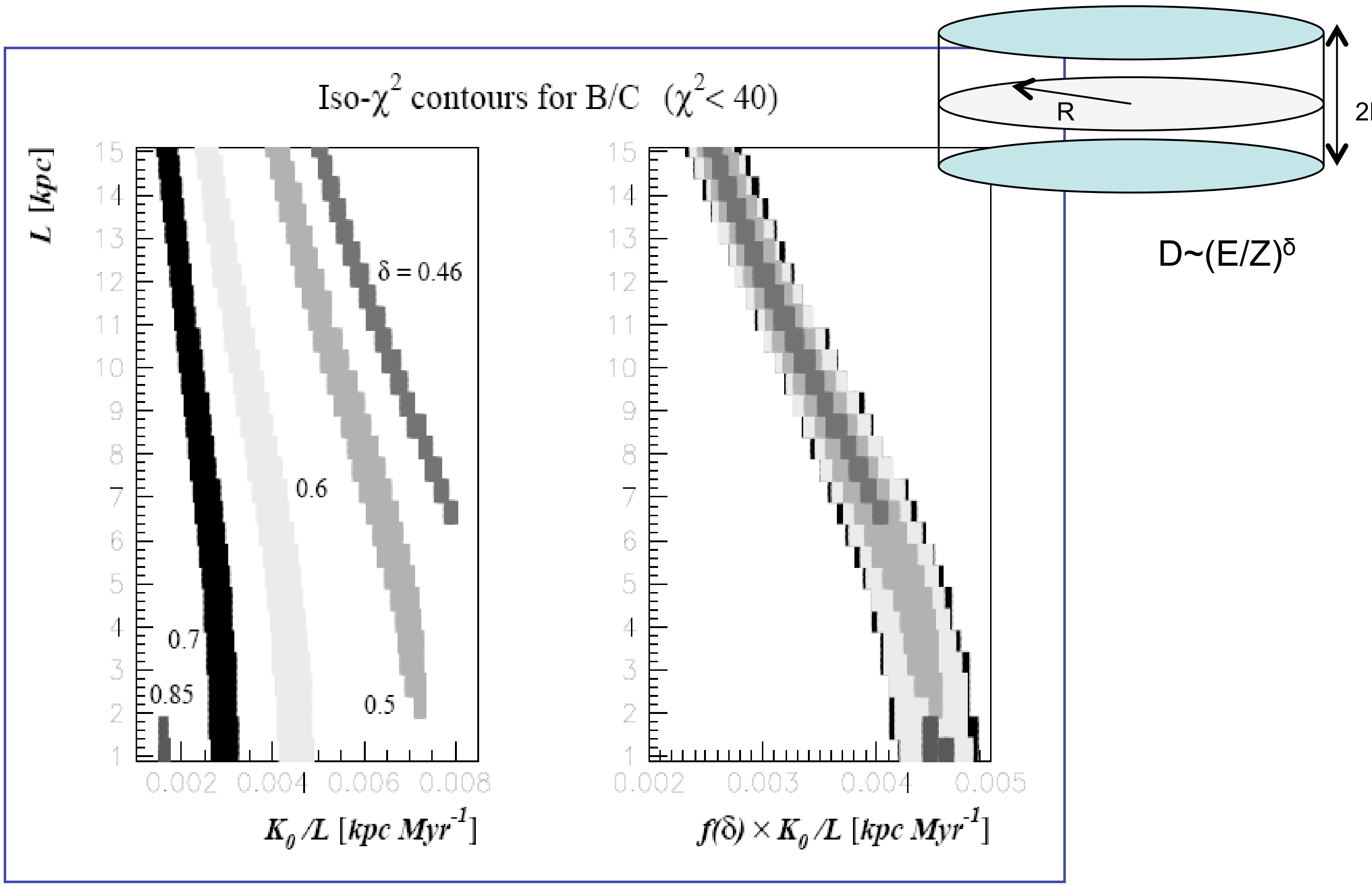
K-N bump @E~10-100 GeV
due to starlight.

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



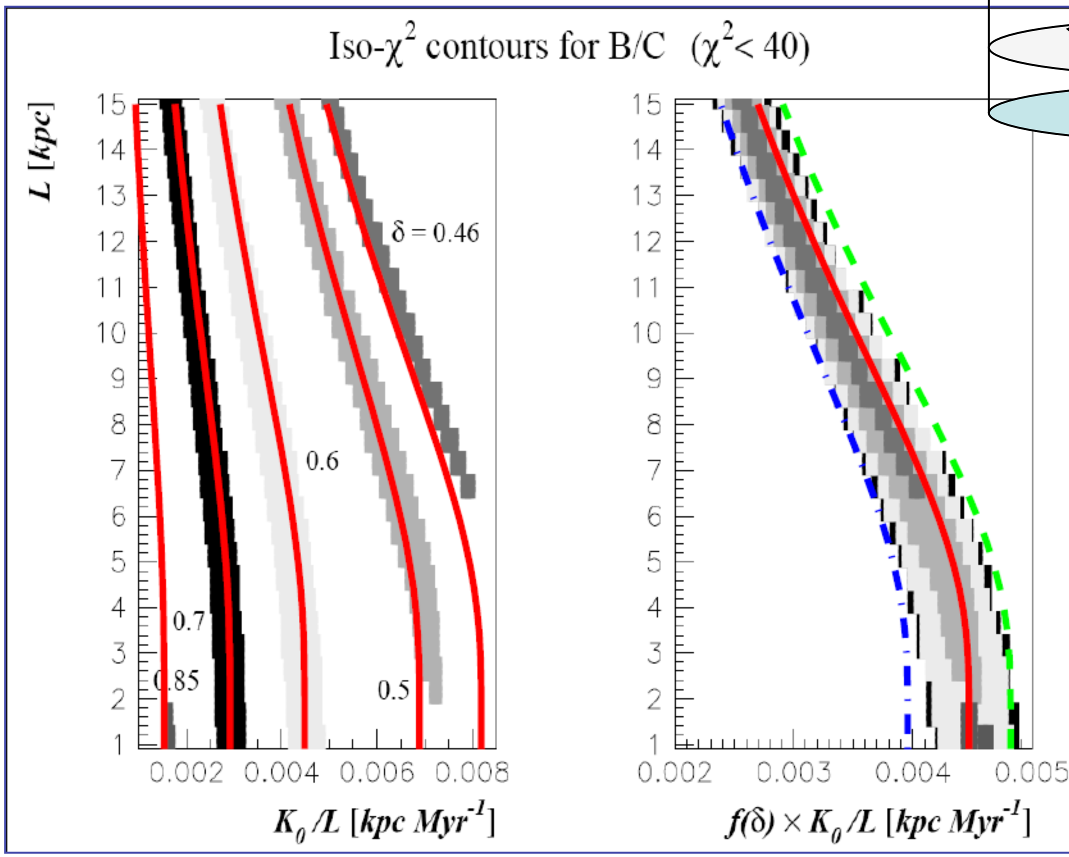


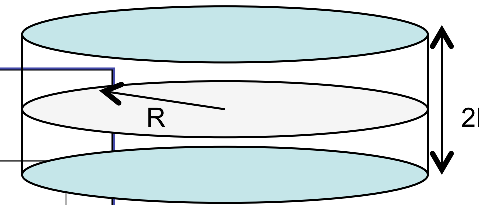
Global diffusion model was tuned to fit local stable nuclei



Maurin et al, Astrophys.J.555:585-596,2001

Global diffusion model was tuned to fit local stable nuclei





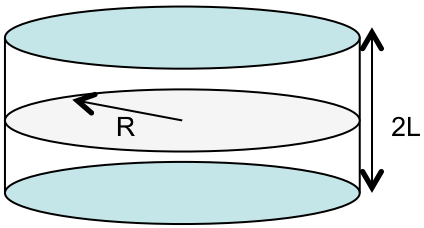
D~(E/Z)$^\delta$

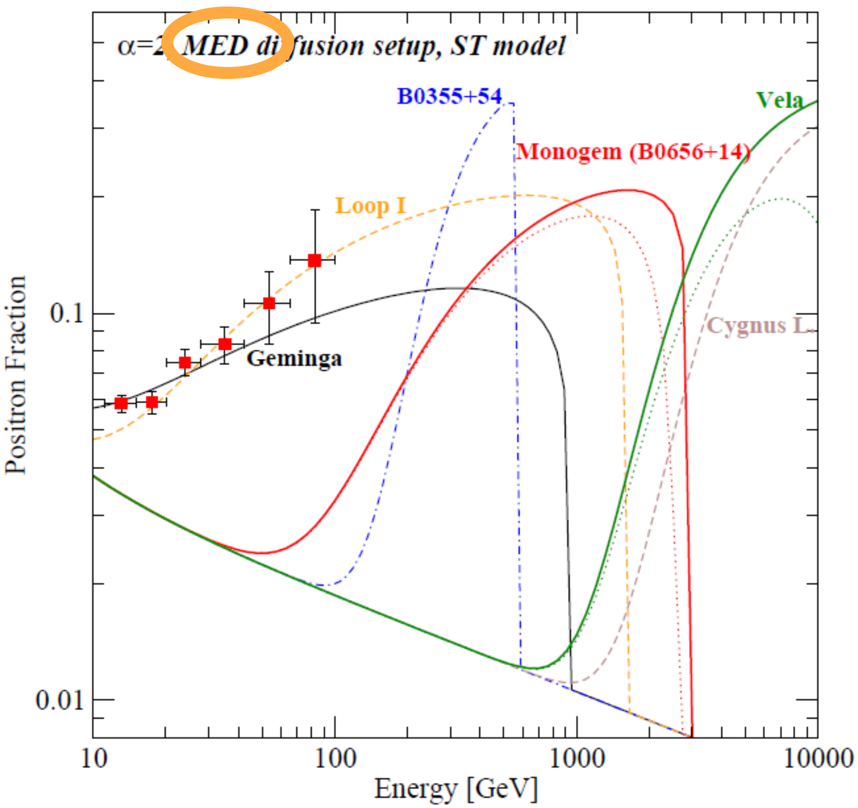
diffusion models fit grammage: $$X_{\rm esc} = X_{\rm disc}\frac{Lc}{2D}\frac{2R}{L}\sum_{k=1}^{\infty} J_0\left[\nu_k(r_{\rm s}/R)\right]\frac{\tanh\left[\nu_k(L/R)\right]}{\nu_k^2 J_1(\nu_k)}$$

Katz et al, MNRAS 405 (2010) 1458

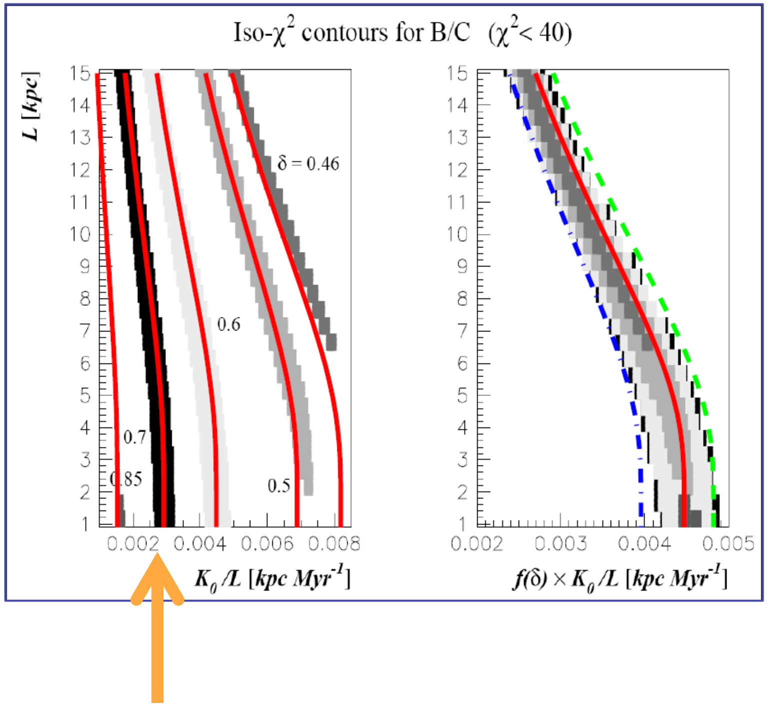
Other ideas:

- Local, non steady state sources
- **Pulsars**





Profumo, Central Eur.J.Phys. 10 (2011) 1-31



remember this?

2. Propagation time scales: radioactive nuclei

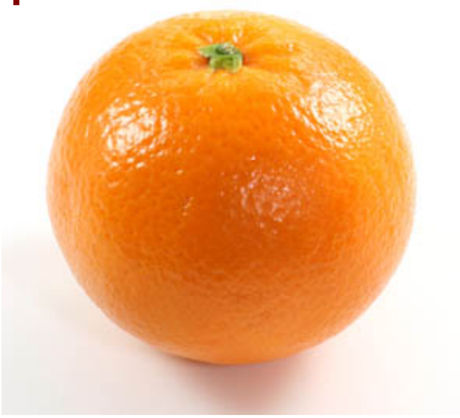
➔ Secondary radioactive nuclei carry time info (like positrons)

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.

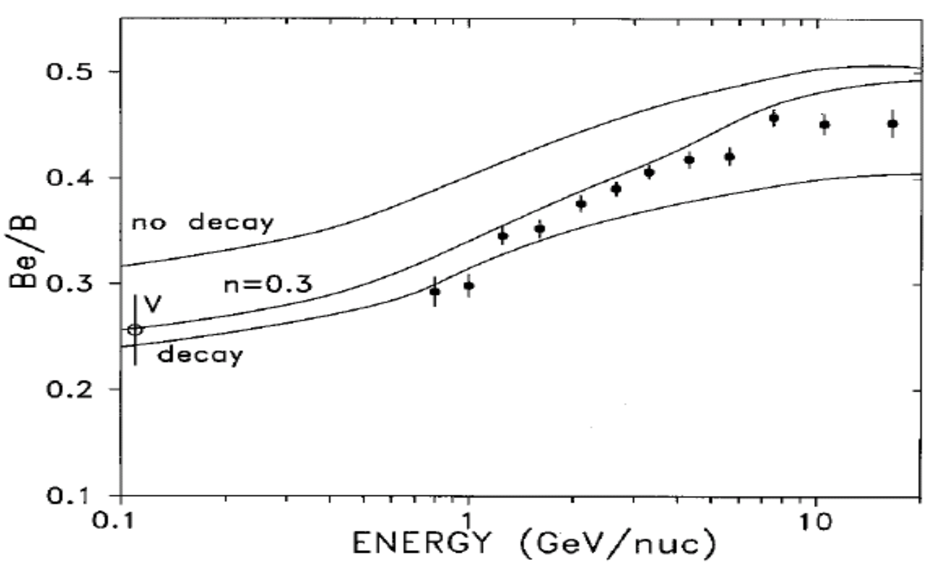
Radioactive nuclei: Charge ratio

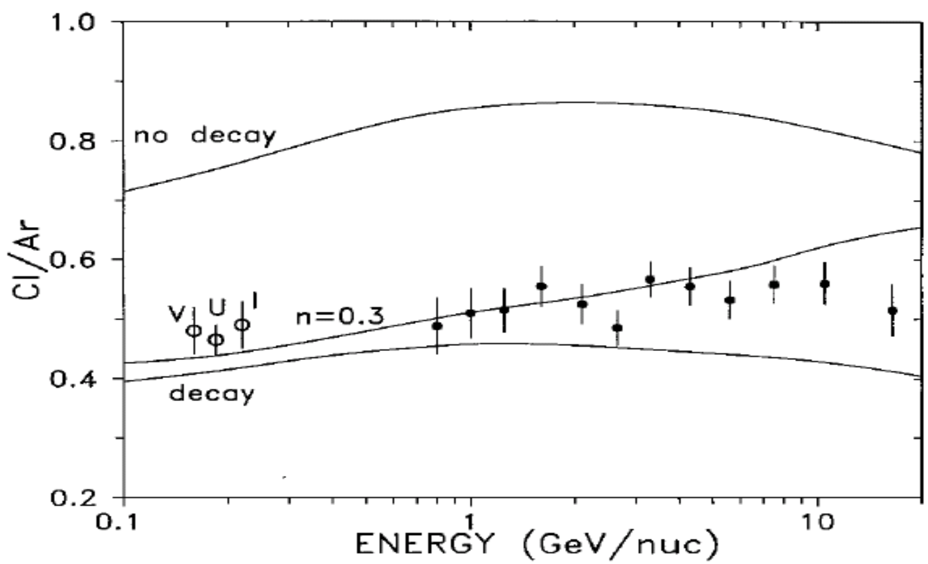
A STUDY OF THE SURVIVING FRACTION OF THE COSMIC-RAY RADIOACTIVE DECAY ISOTOPES ^{10}Be, ^{26}Al, ^{36}Cl, and ^{54}Mn AS A FUNCTION OF ENERGY USING THE CHARGE RATIOS Be/B, Al/Mg, Cl/Ar, AND Mn/Fe MEASURED ON *HEAO–3*

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 $Be/B,\ Al/Mg,\ Cl/Ar,\ Mn/Fe$

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

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)

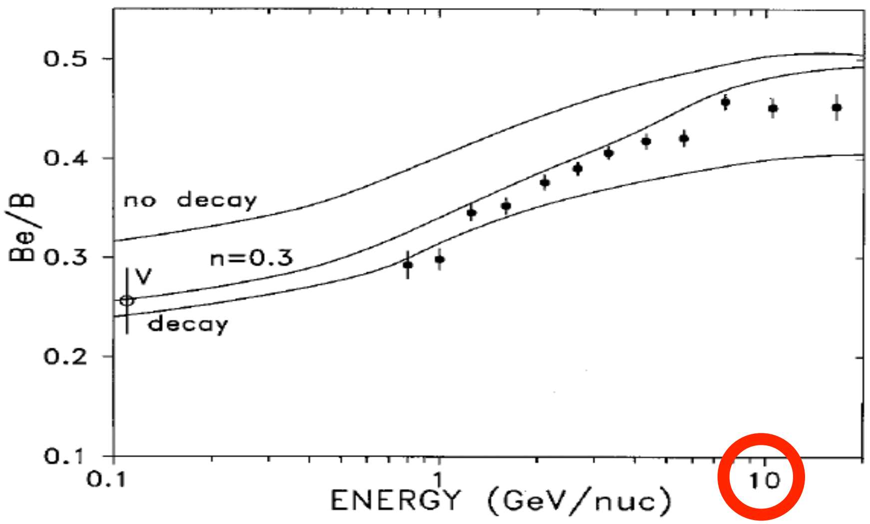
• **Benefit**: avoid low energy complications; significant range in rigidity

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

Radioactive nuclei: Charge ratio vs. isotopic ratio

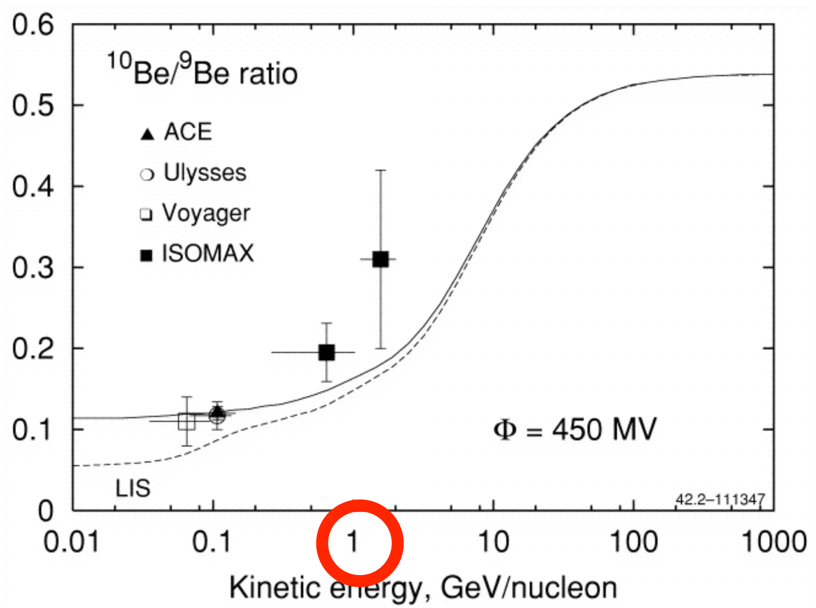
Charge ratios

$$Be/B,\ Al/Mg,\ Cl/Ar$$



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:

$$t_c = \left|\mathcal{R}/\dot{\mathcal{R}}\right| \propto \mathcal{R}^{-\delta_c}$$

$$n_{e^+} \sim \mathcal{R}^{-\gamma}$$

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

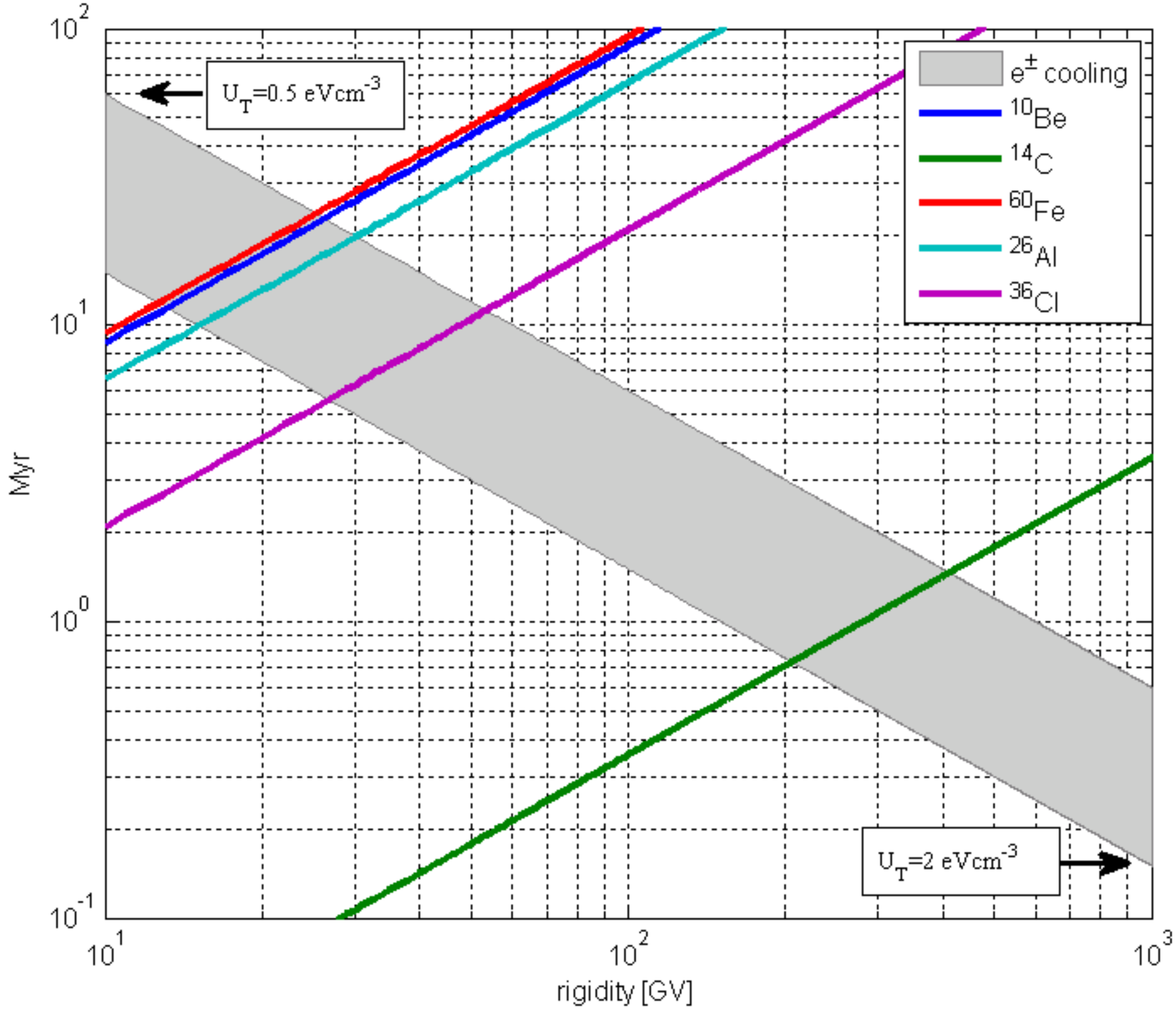
$$\tilde{t}_c = \frac{t_c}{\gamma - \delta_c - 1}$$

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

Comparing with radioactive nuclei

Time scales:

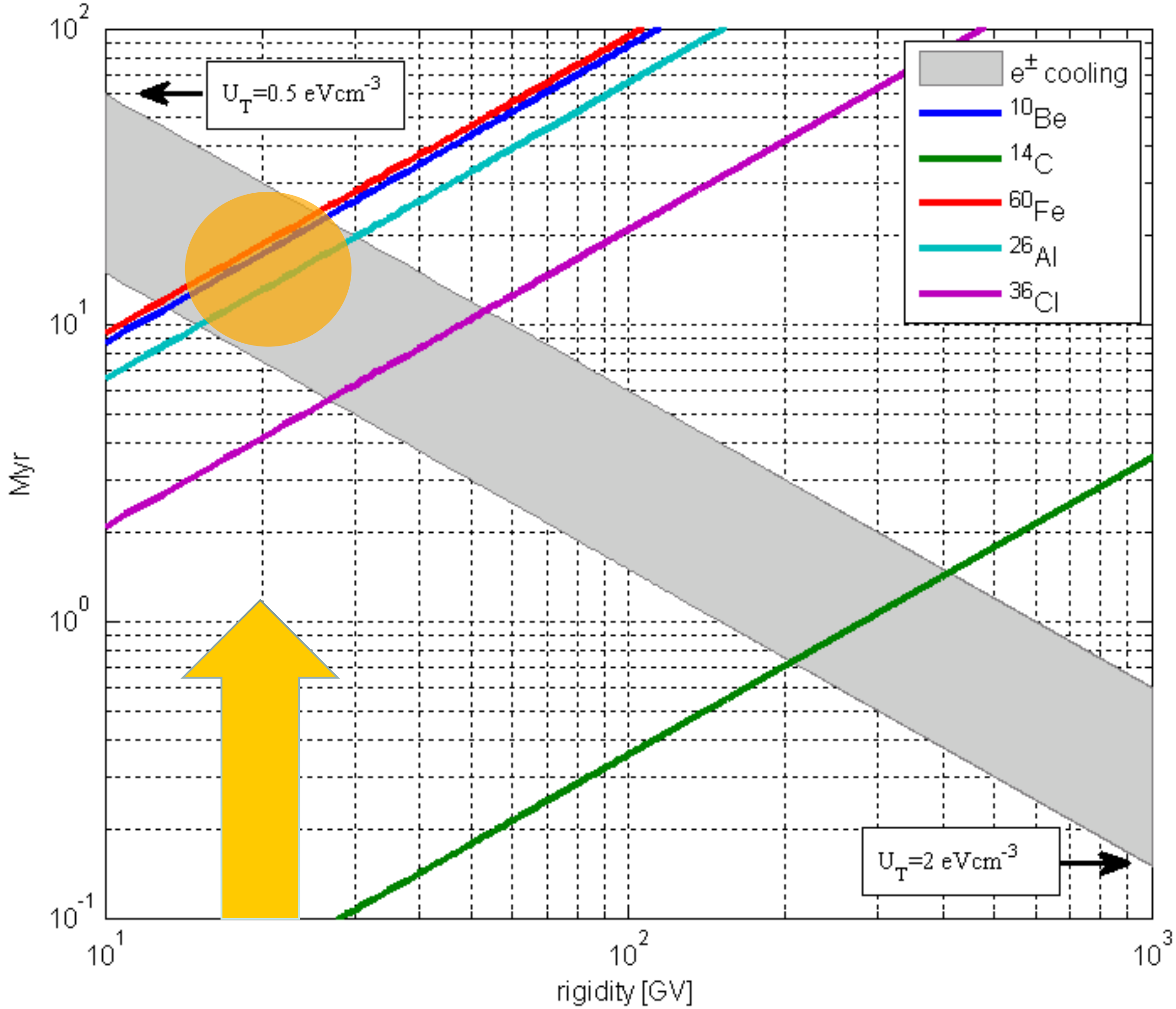
cooling vs decay



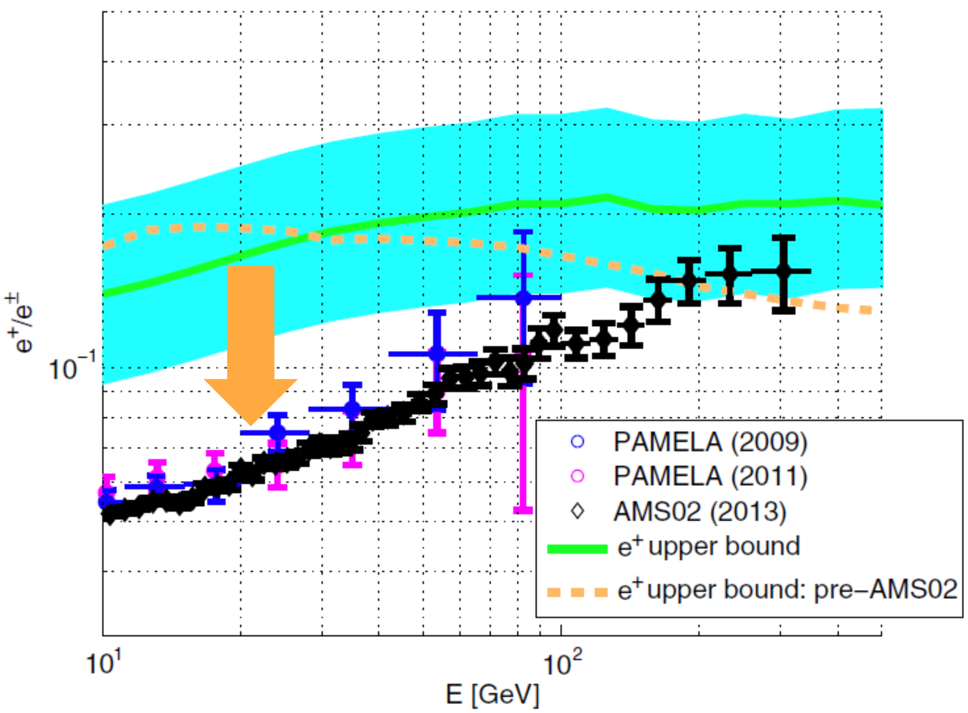
Comparing with radioactive nuclei

Time scales:

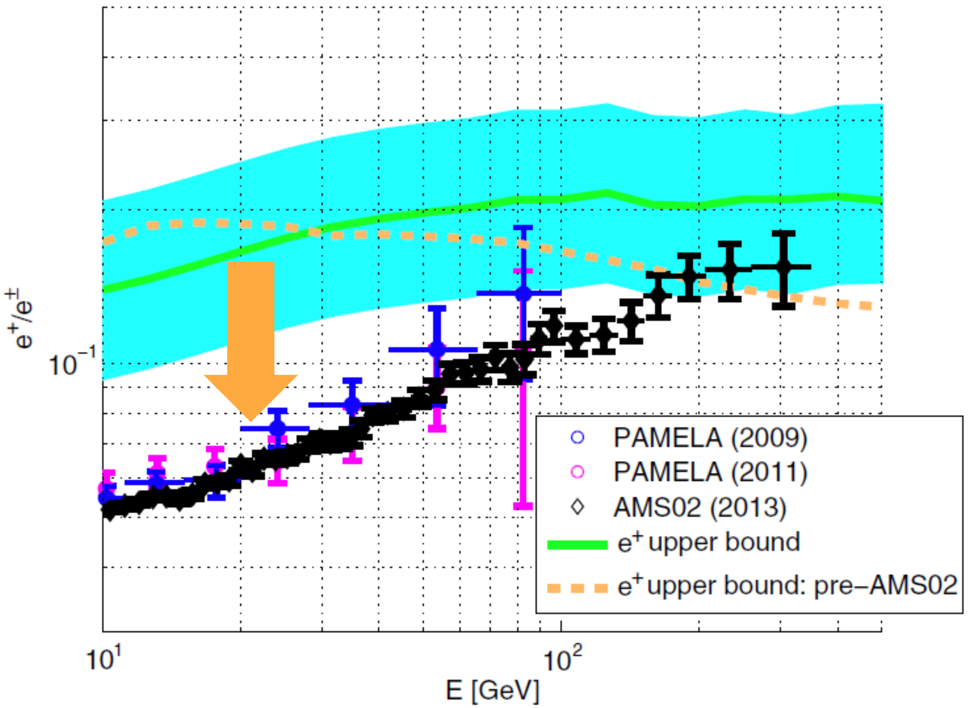
cooling vs decay

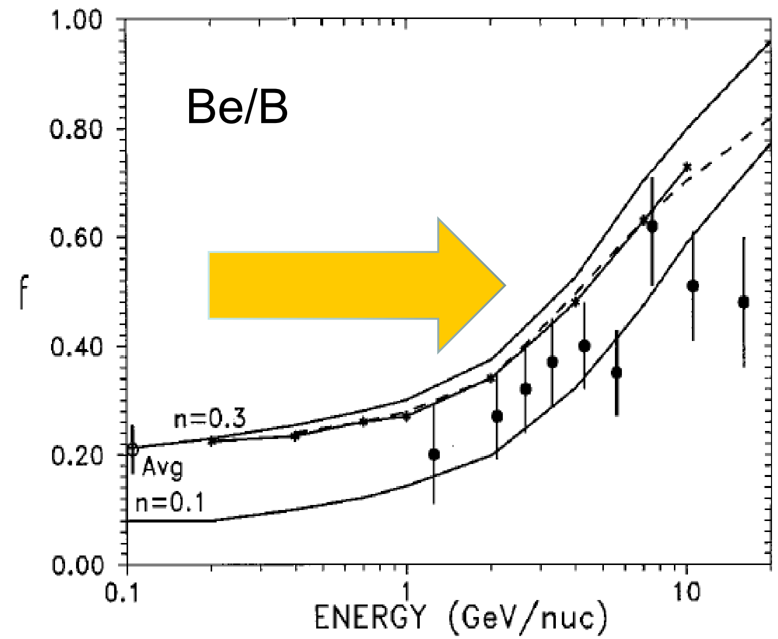


Comparing with radioactive nuclei

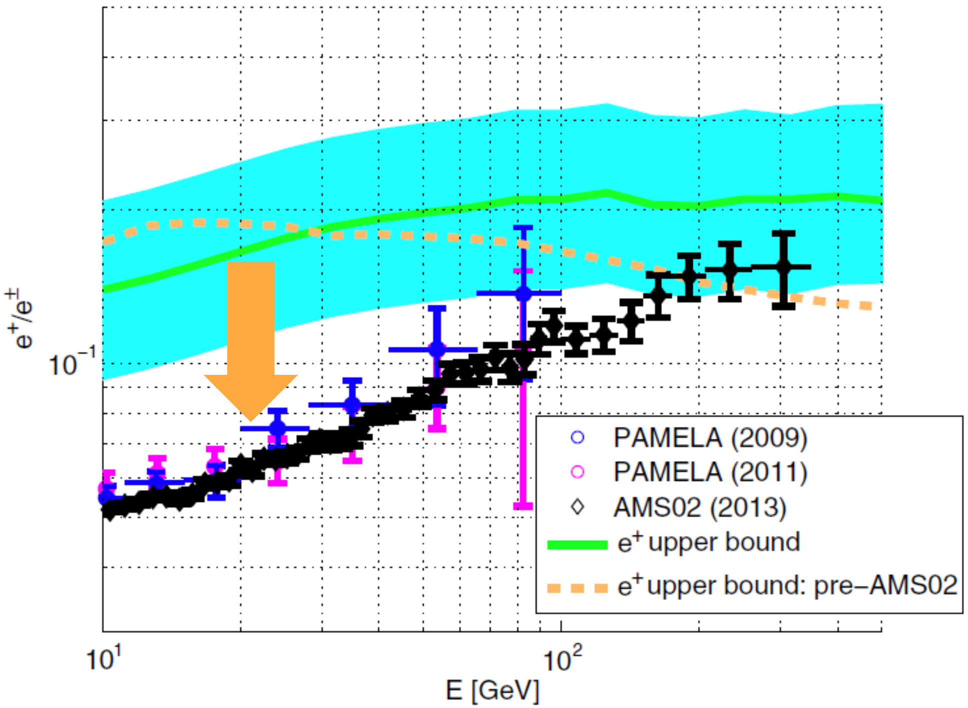


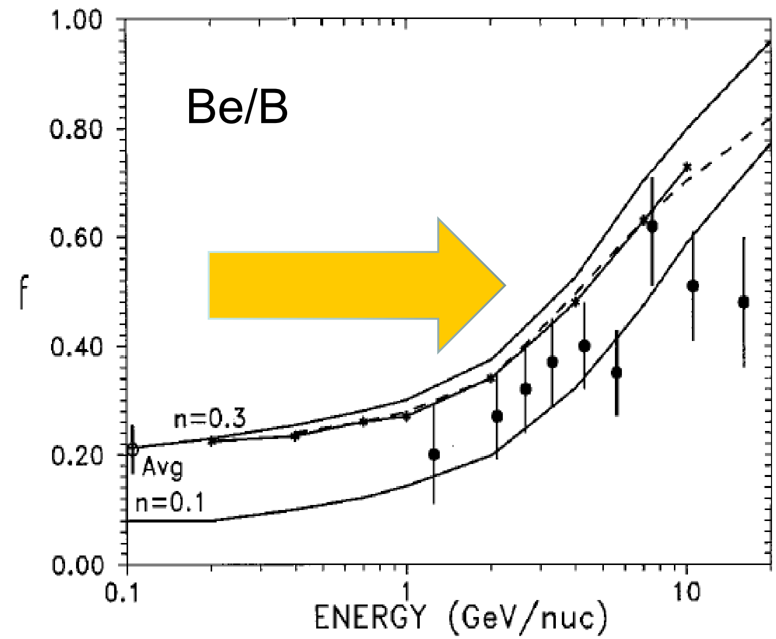
Comparing with radioactive nuclei

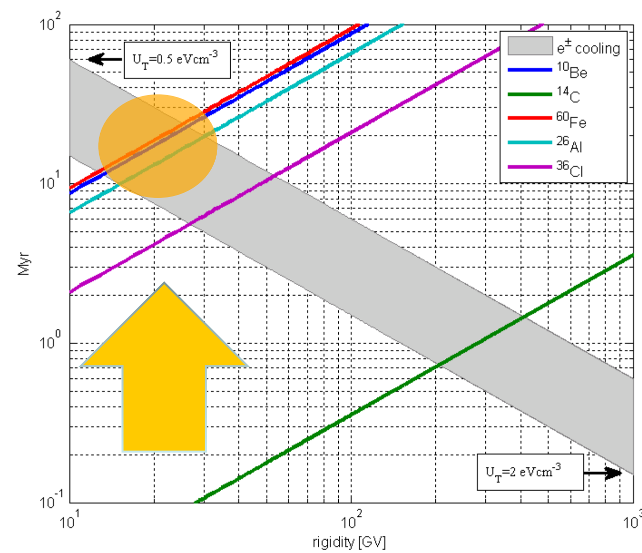




Comparing with radioactive nuclei







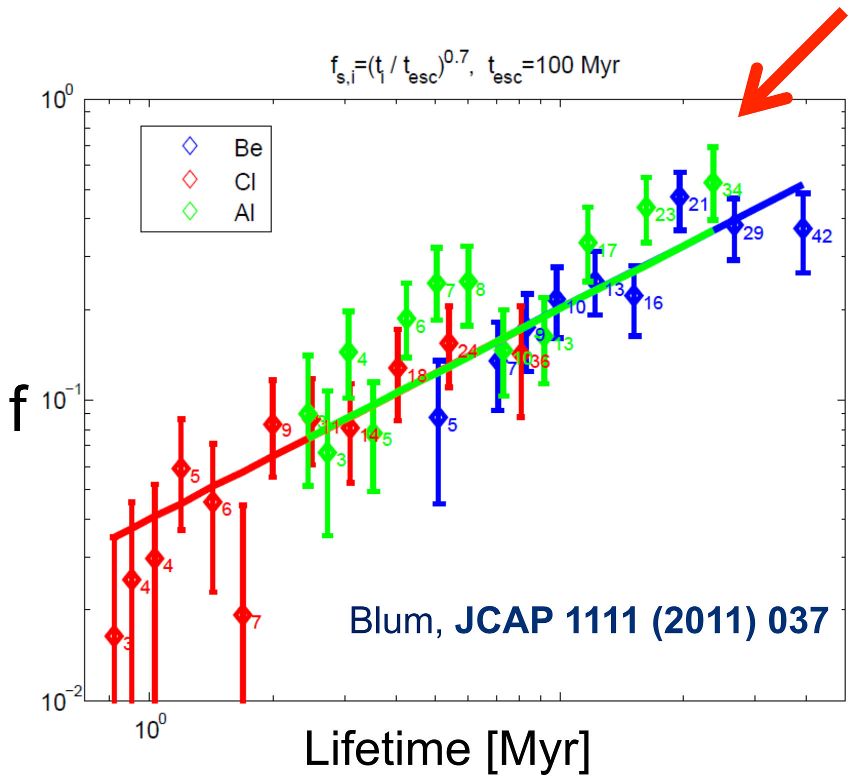
$$f_{s,{}^{10}\mathrm{Be}} \approx 0.4$$

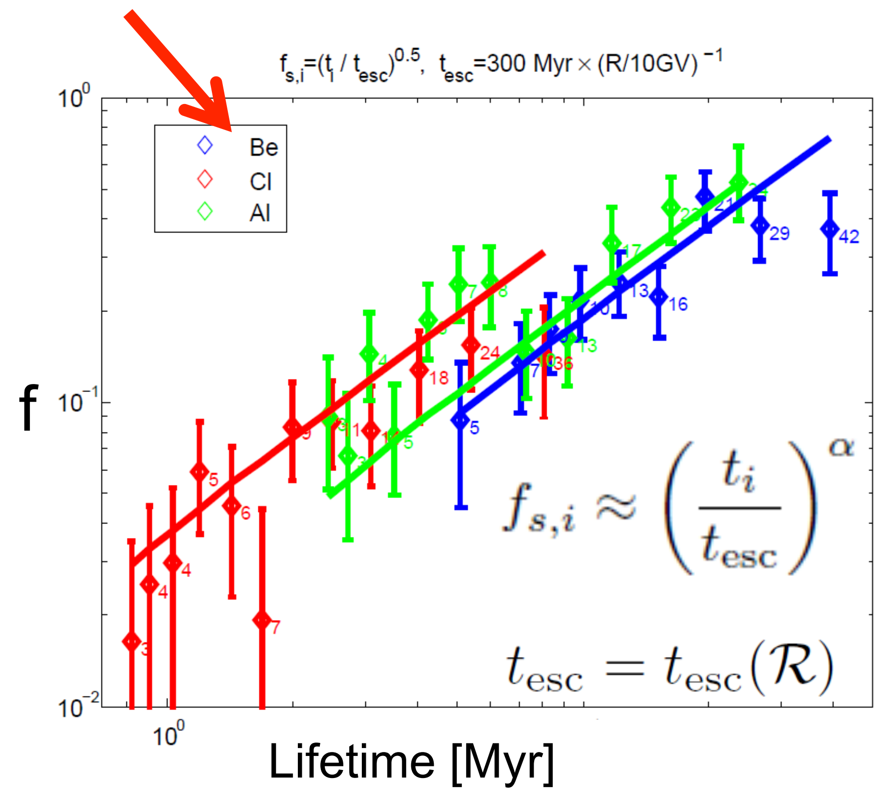
$$f_{s,e^+} \approx 0.3$$

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

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

Need to tell between these fits





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:

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

➔ 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 $X_{esc}(R)$

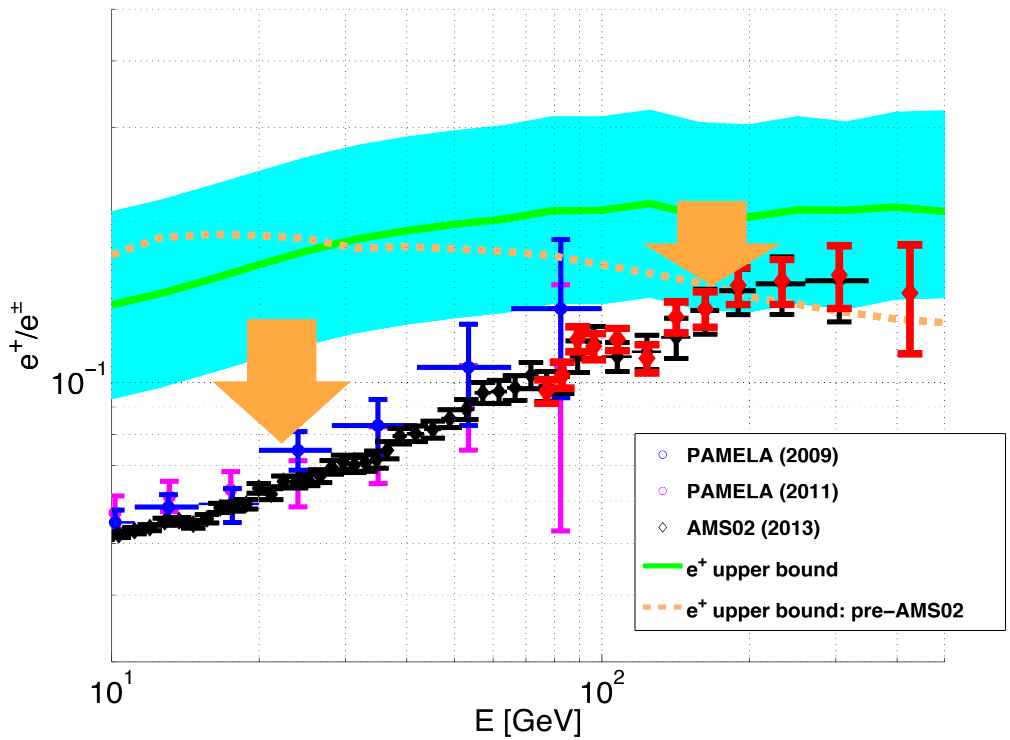
could do with e.g.

R-dependent boundary

need care w/ e+

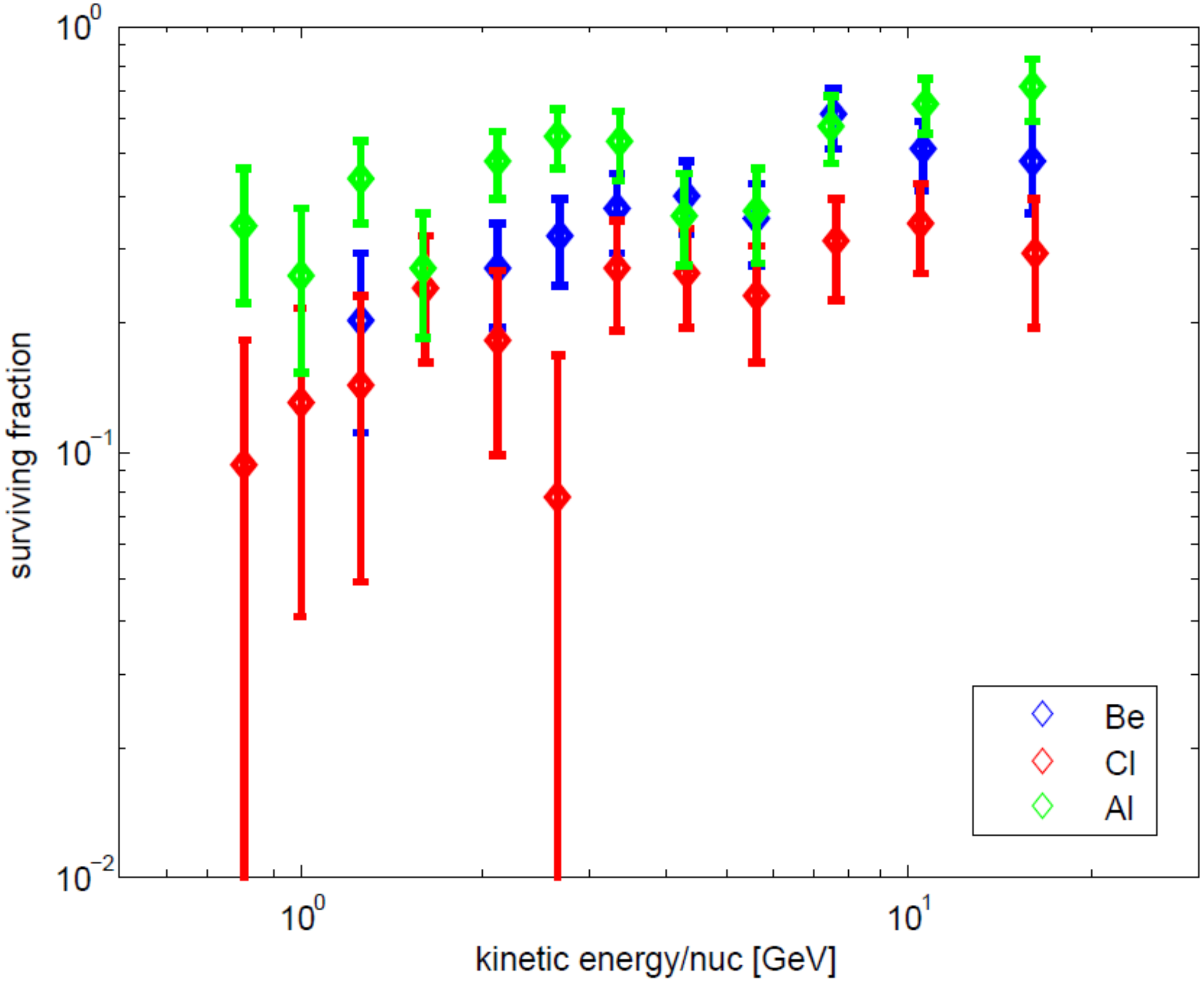
production cross section,

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



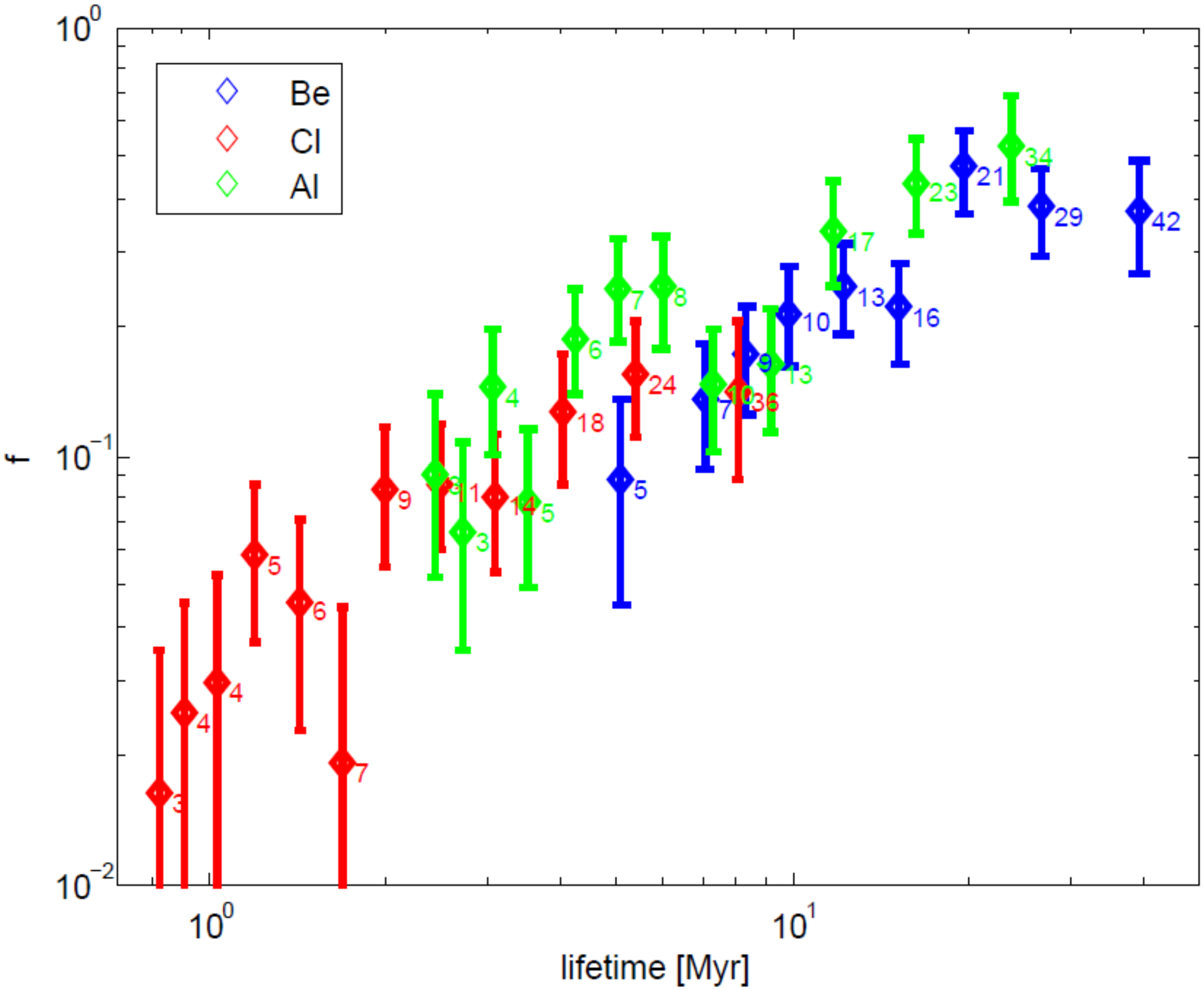
Radioactive nuclei: data

Surviving fraction vs. energy (WS98)



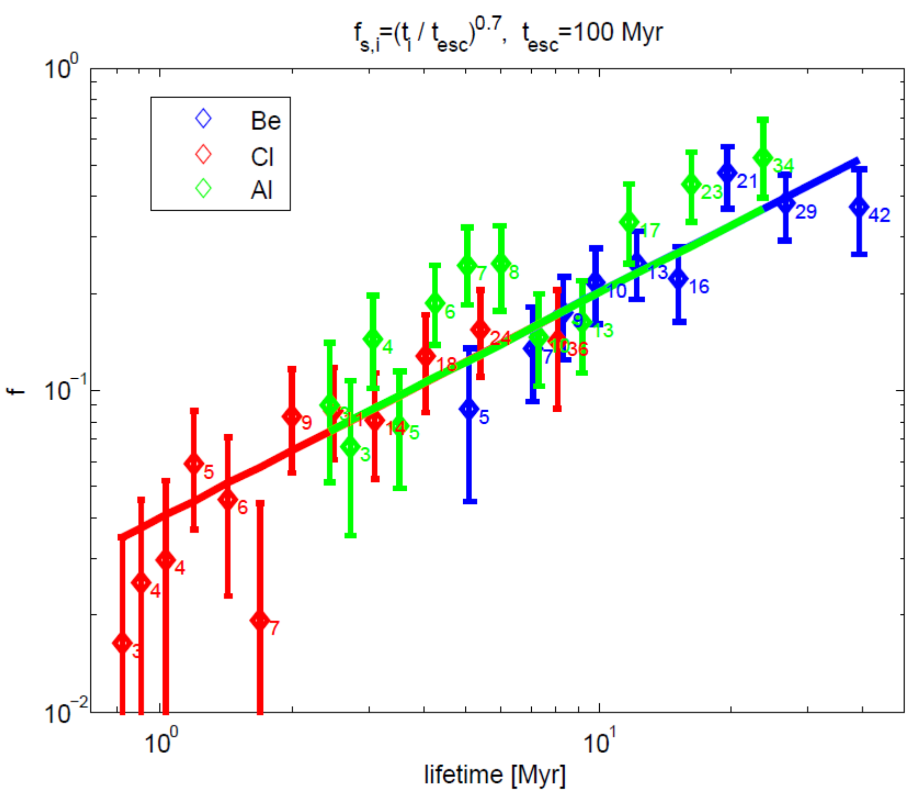
Radioactive nuclei: data

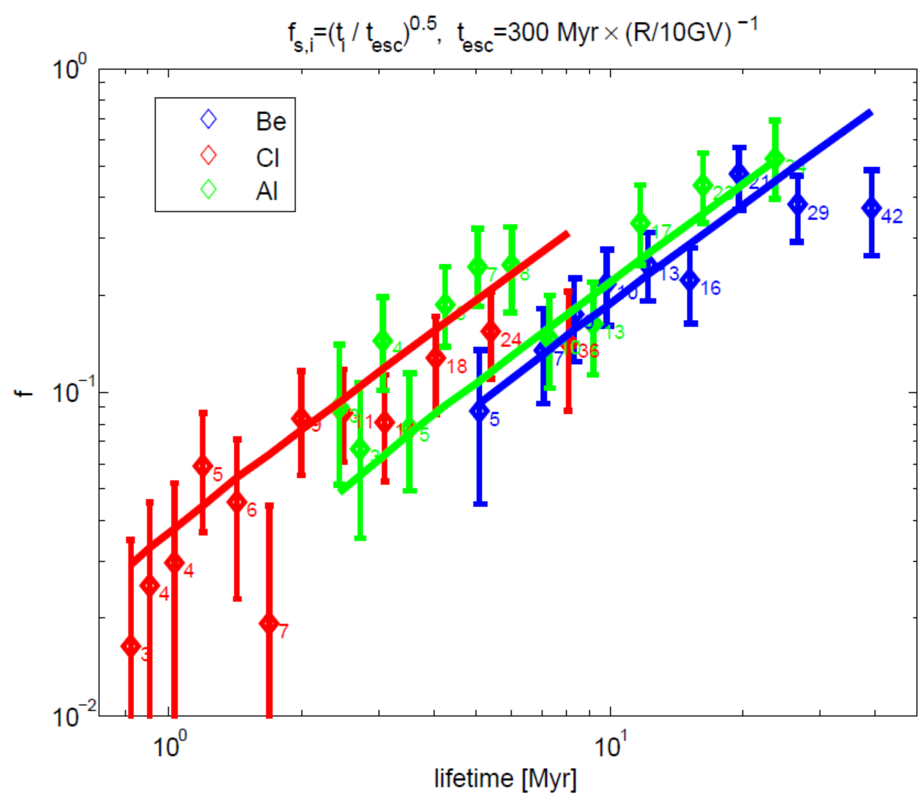
Suppression factor vs. lifetime



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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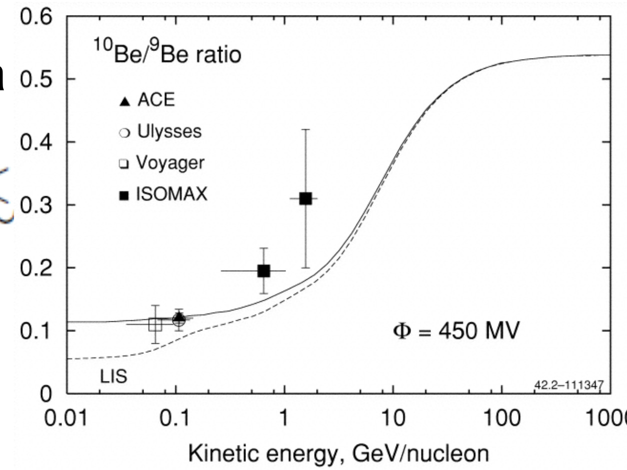
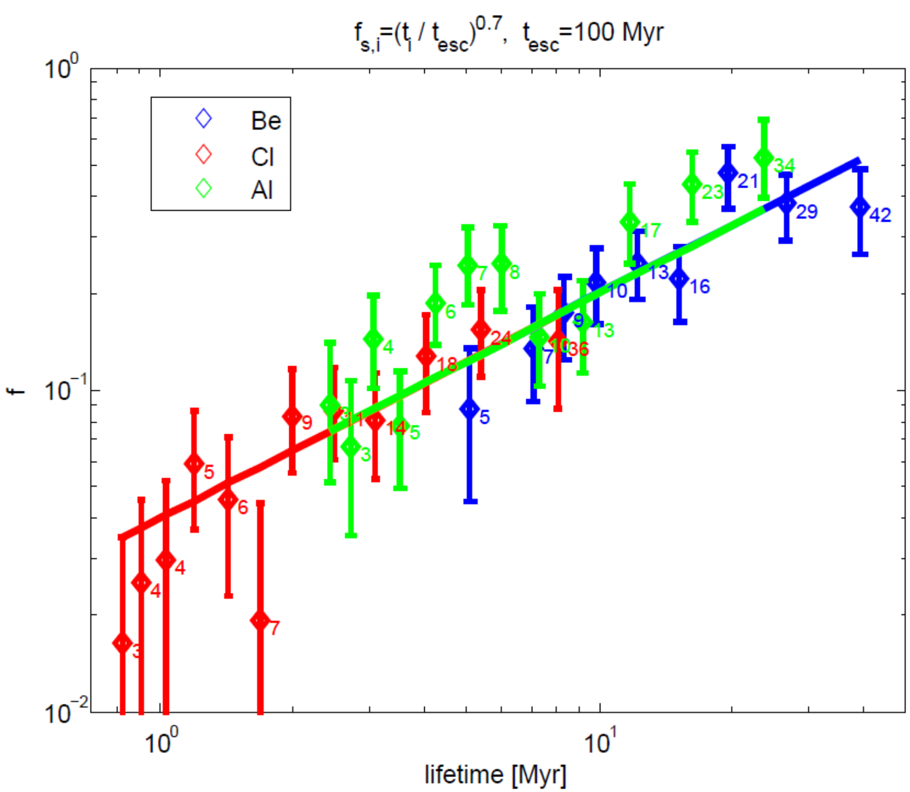
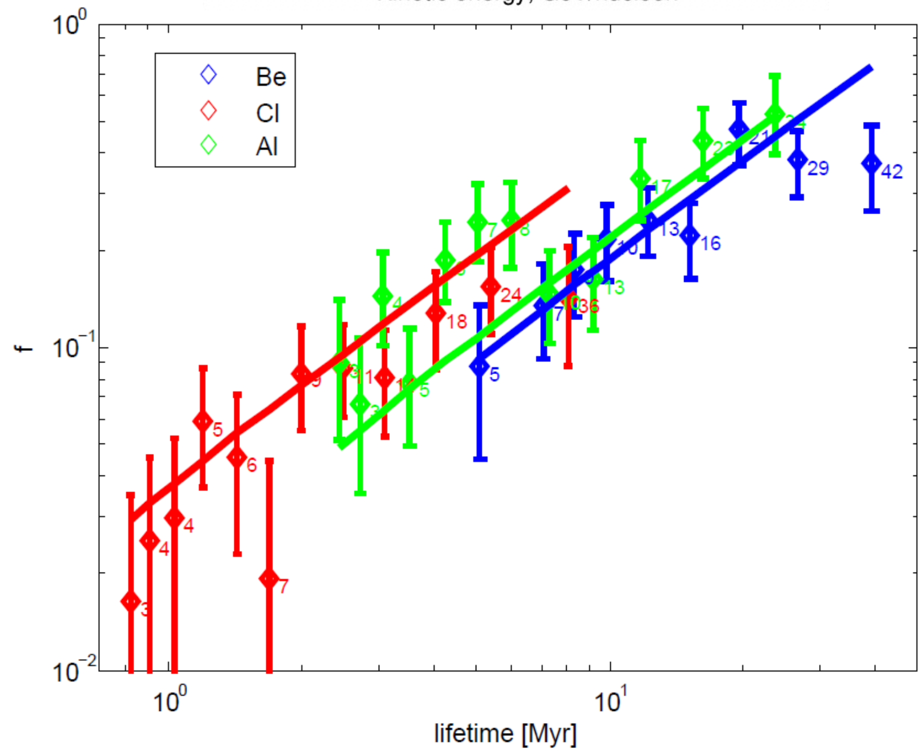
- Cannot (yet) exclude $\delta < -1$ with $\alpha \lesssim$
- **AMS-02 should do much better!**







Stable secondaries with no energy loss (B, pbar, sub-Fe,…)

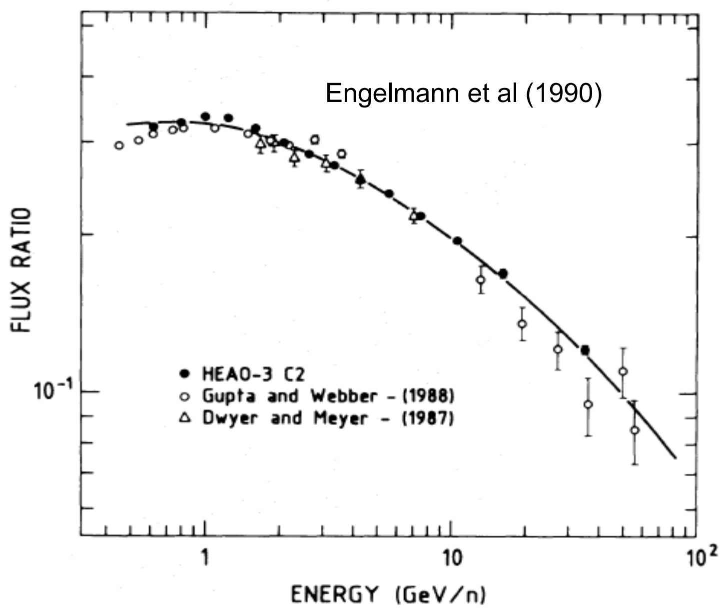
- **Empirical** relation: $$\frac{n_A}{n_B} = \frac{Q_A}{Q_B}$$

- $Q_A(\mathcal{R})$ = Local net production per unit column density of target, for species A

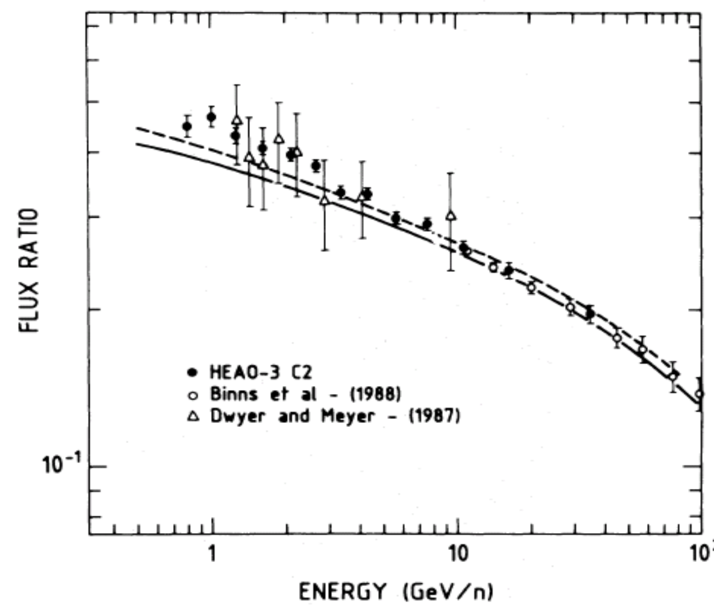
$$\frac{n_A(\mathcal{R})}{n_B(\mathcal{R})} = \frac{Q_A(\mathcal{R})}{Q_B(\mathcal{R})}$$ equivalent to: $$n_A(\mathcal{R}) = Q_A(\mathcal{R}) \times X_{\rm esc}(\mathcal{R})$$

- $X_{\rm esc}$ = "mean column density" ≈ 8.7(R/10GV)$^{-0.4}$ g/cm^2. *No species label*

B / C



(Sc-Cr) / Fe



Stable secondaries with no energy loss (B, pbar, sub-Fe,…)

Theoretically, this is a natural relation.

Guaranteed to apply if the *composition* of CRs and ISM is uniform (well mixed) in the region of the Galaxy where spallation happens

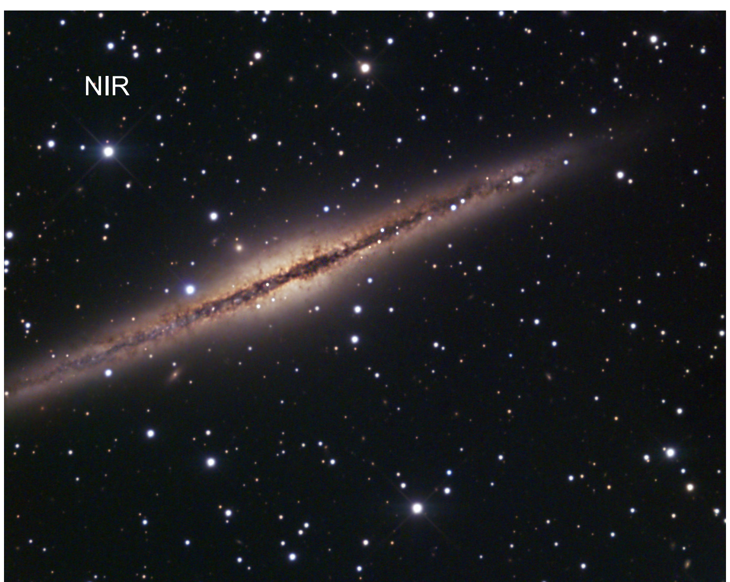
$$\frac{n_A(\mathcal{R})}{n_B(\mathcal{R})} = \frac{Q_A(\mathcal{R})}{Q_B(\mathcal{R})}$$

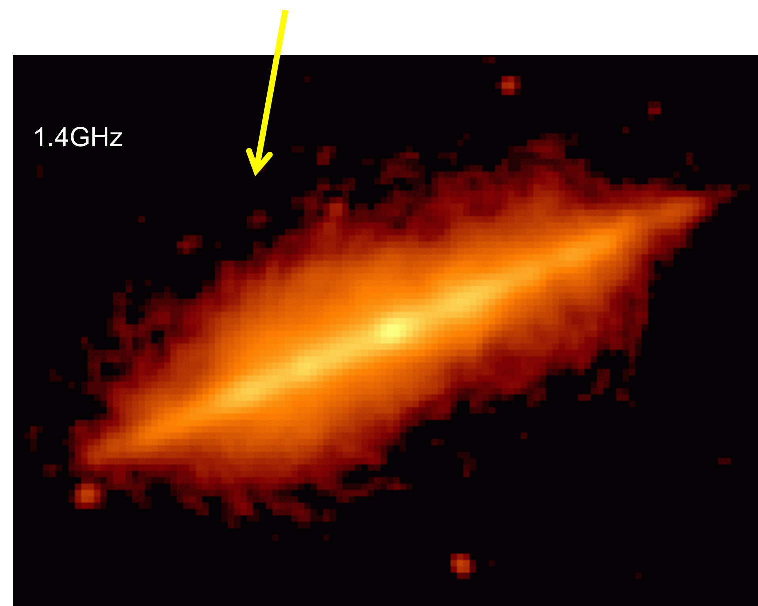
equivalent to:

$$n_A(\mathcal{R}) = Q_A(\mathcal{R}) \times X_{\rm esc}(\mathcal{R})$$

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

NGC 891





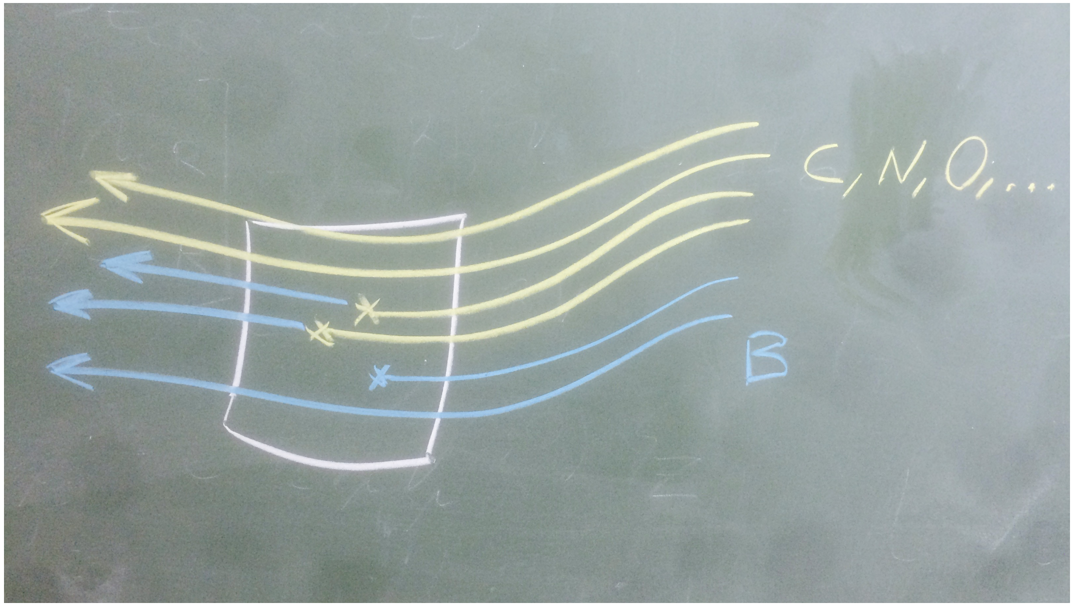
Net source per unit column density traversed: production – loss

$$Q_B(\mathcal{R}, \vec{r}, t) = \sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\to B}}{\bar{m}}\right) n_i(\mathcal{R}, \vec{r}, t) - \left(\frac{\sigma_B}{\bar{m}}\right) n_B(\mathcal{R}, \vec{r}, t)$$

X_{esc}

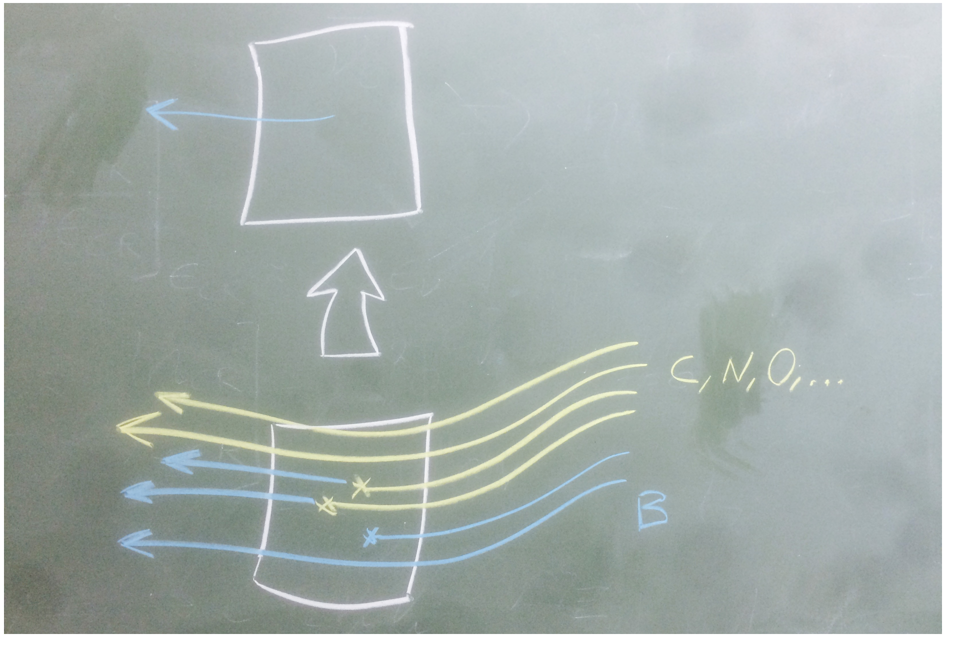
Net source per unit column density traversed: production – loss

$$Q_B(\mathcal{R}, \vec{r}, t) = \sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i \to B}}{\bar{m}}\right) n_i(\mathcal{R}, \vec{r}, t) - \left(\frac{\sigma_B}{\bar{m}}\right) n_B(\mathcal{R}, \vec{r}, t)$$



Net source per unit column density traversed: production – loss

$$Q_B(\mathcal{R},\vec{r},t) = \sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\to B}}{\bar{m}}\right) n_i(\mathcal{R},\vec{r},t) - \left(\frac{\sigma_B}{\bar{m}}\right) n_B(\mathcal{R},\vec{r},t)$$



X_{esc}

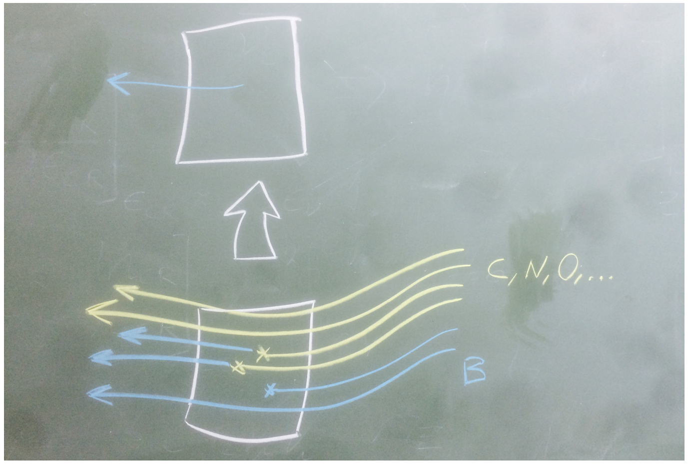
Net source per unit column density traversed: production – loss

$$Q_B(\mathcal{R},\vec{r},t) = \sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\to B}}{\bar{m}}\right) n_i(\mathcal{R},\vec{r},t) - \left(\frac{\sigma_B}{\bar{m}}\right) n_B(\mathcal{R},\vec{r},t)$$

High-energy fragmentation CH → BX: B inherits Lorentz factor Γ of parent C

So B inherits magnetic rigidity, $R_B \approx R_C$

$$R = \frac{p}{Z} = \frac{\Gamma A m_p}{Z} \approx 2\Gamma m_p$$



X_{esc}

Net source per unit column density traversed: production – loss

$$Q_B(\mathcal{R}, \vec{r}, t) = \sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\to B}}{\bar{m}}\right) n_i(\mathcal{R}, \vec{r}, t) - \left(\frac{\sigma_B}{\bar{m}}\right) n_B(\mathcal{R}, \vec{r}, t)$$

High-energy fragmentation CH → BX: B inherits Lorentz factor Γ of parent C

So B inherits magnetic rigidity, $R_B \approx R_C$

$$R = \frac{p}{Z} = \frac{\Gamma A m_p}{Z} \approx 2\Gamma m_p$$

CNO→B: accurate to O(10%)…

A/Z ≈ 2.2 2 2 2

X_{esc}

Net source per unit column density traversed: production – loss

$$Q_B(\mathcal{R}, \vec{r}, t) = \sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\rightarrow B}}{\bar{m}}\right) n_i(\mathcal{R}, \vec{r}, t) - \left(\frac{\sigma_B}{\bar{m}}\right) n_B(\mathcal{R}, \vec{r}, t)$$

In general:

$$n_B(\mathcal{R}, \vec{r}_\odot, t_\odot) = \int d^3r \int dt\, c\, \rho_{ISM}(\vec{r}, t)\, Q_B(\mathcal{R}, \vec{r}, t)\, P\left(\mathcal{R}; \{\vec{r}, t\}, \{\vec{r}_\odot, t_\odot\}\right)$$

X_{esc}

Net source per unit column density traversed: production – loss

$$Q_B(\mathcal{R},\vec{r},t) = \sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\to B}}{\bar{m}}\right) n_i(\mathcal{R},\vec{r},t) - \left(\frac{\sigma_B}{\bar{m}}\right) n_B(\mathcal{R},\vec{r},t)$$

In general:

$$\begin{aligned} n_B(\mathcal{R},\vec{r}_\odot,t_\odot) &= \int d^3r \int dt\, c\, \rho_{ISM}(\vec{r},t)\, Q_B(\mathcal{R},\vec{r},t)\, P\left(\mathcal{R};\{\vec{r},t\},\{\vec{r}_\odot,t_\odot\}\right) \\ &= Q_B(\mathcal{R},\vec{r}_\odot,t_\odot) \int d^3r \int dt\, c\, \rho_{ISM}(\vec{r},t)\, \frac{n_C\left(\mathcal{R},\vec{r},t\right)}{n_C\left(\mathcal{R},\vec{r}_\odot,t_\odot\right)}\, P\left(\mathcal{R};\{\vec{r},t\},\{\vec{r}_\odot,t_\odot\}\right)\, F_B \end{aligned}$$

$$F_B = \frac{\sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\to B}}{\bar{m}}\right) \frac{n_i(\mathcal{R},\vec{r},t)}{n_C(\mathcal{R},\vec{r},t)} - \left(\frac{\sigma_B}{\bar{m}}\right) \frac{n_B(\mathcal{R},\vec{r},t)}{n_C(\mathcal{R},\vec{r},t)}}{\sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\to B}}{\bar{m}}\right) \frac{n_i(\mathcal{R},\vec{r}_\odot,t_\odot)}{n_C(\mathcal{R},\vec{r}_\odot,t_\odot)} - \left(\frac{\sigma_B}{\bar{m}}\right) \frac{n_B(\mathcal{R},\vec{r}_\odot,t_\odot)}{n_C(\mathcal{R},\vec{r}_\odot,t_\odot)}}$$

X_{esc}

Net source per unit column density traversed: production – loss

$$Q_B(\mathcal{R},\vec{r},t) = \sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\to B}}{\bar{m}}\right) n_i(\mathcal{R},\vec{r},t) - \left(\frac{\sigma_B}{\bar{m}}\right) n_B(\mathcal{R},\vec{r},t)$$

In general:

$$n_B(\mathcal{R},\vec{r}_\odot,t_\odot) = \int d^3r \int dt\, c\, \rho_{ISM}(\vec{r},t)\, Q_B(\mathcal{R},\vec{r},t)\, P\left(\mathcal{R};\{\vec{r},t\},\{\vec{r}_\odot,t_\odot\}\right)$$

$$= Q_B(\mathcal{R},\vec{r}_\odot,t_\odot) \int d^3r \int dt\, c\, \rho_{ISM}(\vec{r},t)\, \frac{n_C\left(\mathcal{R},\vec{r},t\right)}{n_C\left(\mathcal{R},\vec{r}_\odot,t_\odot\right)}\, P\left(\mathcal{R};\{\vec{r},t\},\{\vec{r}_\odot,t_\odot\}\right)\, F_B$$

Uniform *composition:* $\frac{n_i(\mathcal{R},\vec{r},t)}{n_j(\mathcal{R},\vec{r},t)} = f_{ij}(\mathcal{R})$ independent of r,t

$$F_B = \frac{\sum_{i=C,N,O,\ldots}\left(\frac{\sigma_{i\to B}}{\bar{m}}\right)\frac{n_i(\mathcal{R},\vec{r},t)}{n_C(\mathcal{R},\vec{r},t)} - \left(\frac{\sigma_B}{\bar{m}}\right)\frac{n_B(\mathcal{R},\vec{r},t)}{n_C(\mathcal{R},\vec{r},t)}}{\sum_{i=C,N,O,\ldots}\left(\frac{\sigma_{i\to B}}{\bar{m}}\right)\frac{n_i(\mathcal{R},\vec{r}_\odot,t_\odot)}{n_C(\mathcal{R},\vec{r}_\odot,t_\odot)} - \left(\frac{\sigma_B}{\bar{m}}\right)\frac{n_B(\mathcal{R},\vec{r}_\odot,t_\odot)}{n_C(\mathcal{R},\vec{r}_\odot,t_\odot)}} \approx 1$$

X_{esc}

Net source per unit column density traversed: production – loss

$$Q_B(\mathcal{R},\vec{r},t) = \sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\to B}}{\bar{m}}\right) n_i(\mathcal{R},\vec{r},t) - \left(\frac{\sigma_B}{\bar{m}}\right) n_B(\mathcal{R},\vec{r},t)$$

In general:

$$\begin{aligned} n_B(\mathcal{R},\vec{r}_\odot,t_\odot) &= \int d^3r \int dt\, c\, \rho_{ISM}(\vec{r},t)\, Q_B(\mathcal{R},\vec{r},t)\, P\left(\mathcal{R};\{\vec{r},t\},\{\vec{r}_\odot,t_\odot\}\right) \\ &= Q_B(\mathcal{R},\vec{r}_\odot,t_\odot) \int d^3r \int dt\, c\, \rho_{ISM}(\vec{r},t)\, \frac{n_C\left(\mathcal{R},\vec{r},t\right)}{n_C\left(\mathcal{R},\vec{r}_\odot,t_\odot\right)}\, P\left(\mathcal{R};\{\vec{r},t\},\{\vec{r}_\odot,t_\odot\}\right)\, F_B \end{aligned}$$

Uniform *composition* →

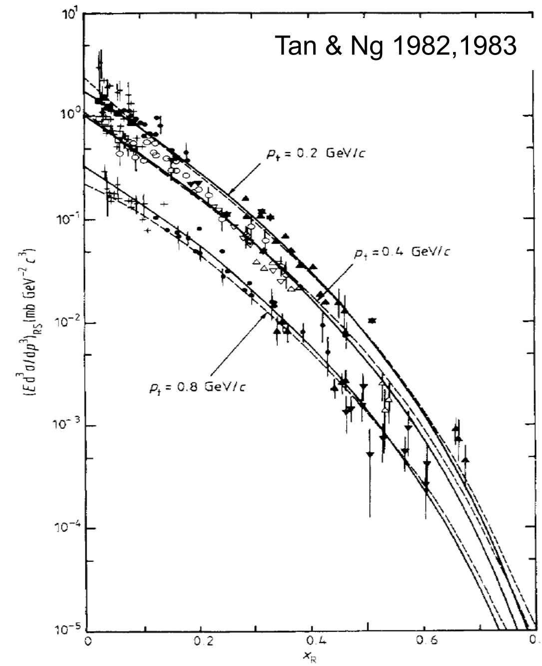
$$n_B(\mathcal{R},\vec{r}_\odot,t_\odot) \approx Q_B(\mathcal{R})\, X_{\rm esc}(\mathcal{R})$$

$$X_{\rm esc} = \int d^3r \int dt\, c\, \rho_{ISM}(\vec{r},t)\, \frac{n_C\left(\mathcal{R},\vec{r},t\right)}{n_C\left(\mathcal{R},\vec{r}_\odot,t_\odot\right)}\, P\left(\mathcal{R};\{\vec{r},t\},\{\vec{r}_\odot,t_\odot\}\right)$$

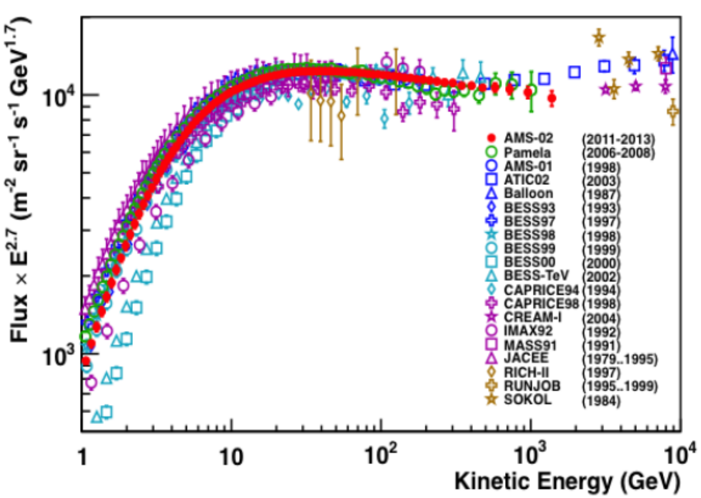
antiprotons

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

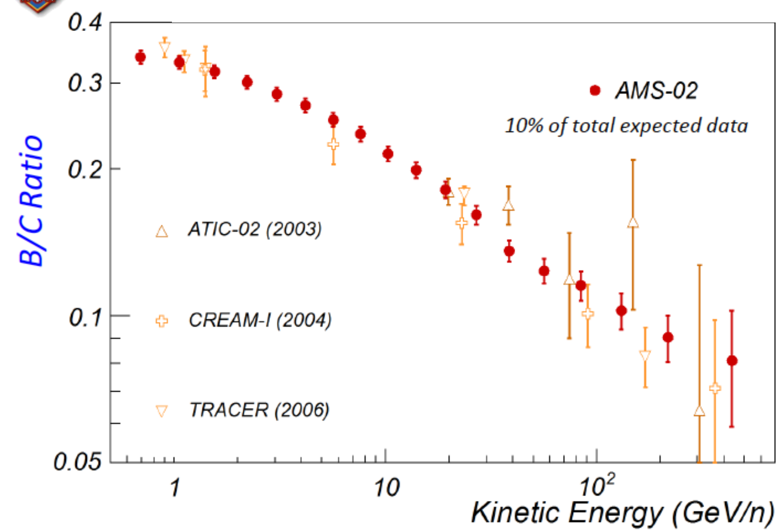
$$\frac{J_{\bar{p}}}{J_p} = 10^{1-\gamma_p}\,\zeta_{\bar{p},A>1}\,C_{\bar{p},pp}\,\frac{\sigma_{pp,\rm inel}}{m_p}\,\frac{X_{\rm esc}}{1+\frac{\sigma_{\bar{p}}}{m_p}X_{\rm esc}}$$



Proton flux



Boron-to-Carbon ratio



Ginzburg & Ptuskin, Rev.Mod.Phys. 48 (**1976**) 161-189

On the origin of cosmic rays: Some problems in high-energy astrophysics*

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This paper reviews the present state of the problem of the origin of cosmic rays . Primary attention is paid to galactic diffusion models with a halo, and questions of cosmic-ray chemical composition, electron component, and synchrotron galactic radioemission. The authors' conclusion is that models with a large halo with a characteristic cosmic-ray age $T_{cr} \sim 10^8$ years are confirmed by radio data, and at least do not contradict the information on cosmic-ray chemical composition. The paper also deals with the problems of anisotropy, plasma phenomena in cosmic rays, and the prospects of gamma-ray astronomy.

Ginzburg & Ptuskin, Rev.Mod.Phys. 48 (1976) 161-189

On the origin of cosmic rays: Some problems in high-energy astrophysics*

We should note here that the applicability of the diffusion approximations (2.8)–(2.9) to cosmic-ray propagation in the magnetic fields is not at all obvious. For this approximation to be valid it is not enough that the field have a strongly pronounced irregular random component since in this case there also exists a strong tendency for particle propagation along the lines of force of the magnetic field, even if they are rather tangled. But in the

Galaxy, for example, differential rotation and the motion of gas clouds and spiral arms cause a constant mixing of the lines of force. At the same time we are usually interested not only in a picture averaged over rather large space regions (say, regions of tens and hundreds of parsecs) but also in a picture which is extended in time. To estimate average cosmic-ray gradients and their lifetime T_{cr} in the Galaxy it is in fact sufficient to know the concentration N_i averaged for the time $t \ll T_{cr} \sim 10^6 - 10^8$ yr, which means that the time of averaging may well be 10^5 yr.