It's About Time:
AMS antimatter data and cosmic ray propagation

Kfir Blum, IAS

Katz et al; MNRAS 405 (2010) 1458

KB; JCAP 1111 (2011) 037

KB, Katz, Waxman; PRL 111, 211101 (2013)

AMS Days at CERN 04/15/2015

Open questions:

What is the source of Galactic cosmic rays?
How do cosmic rays escape from the Galaxy?

Do we see exotic sources like dark matter or pulsars?

AMS data = major progress.

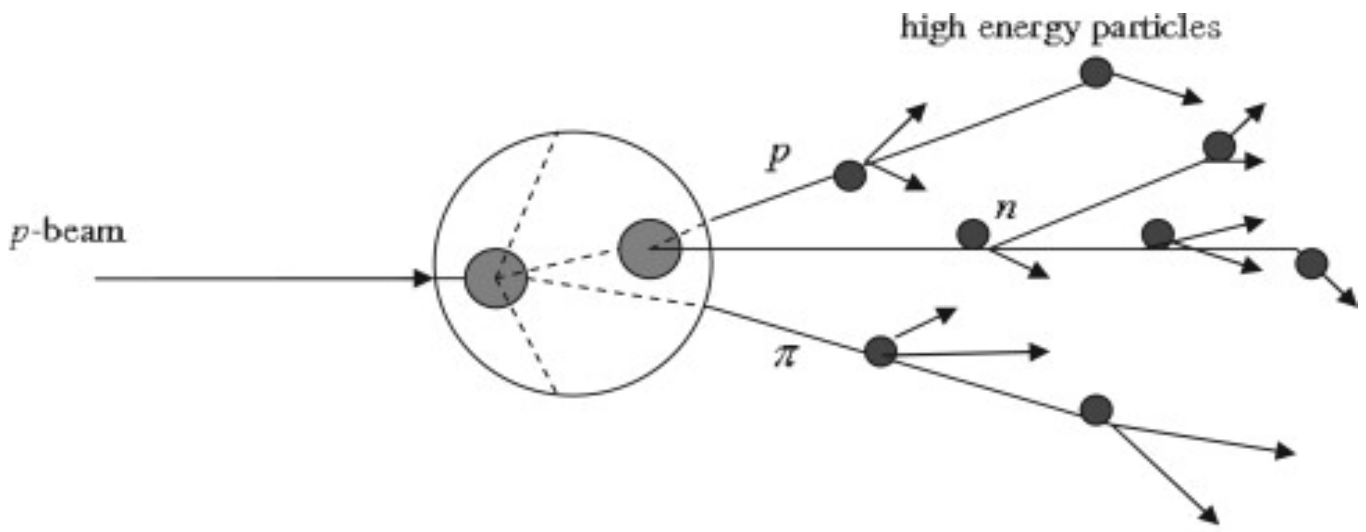
I will give my take on some of the AMS results, focusing on e+ and pbar.

Aim at what we can calculate and what we can learn, without committing to detailed model assumptions.

Secondary CRs

Antimatter occurs as secondary

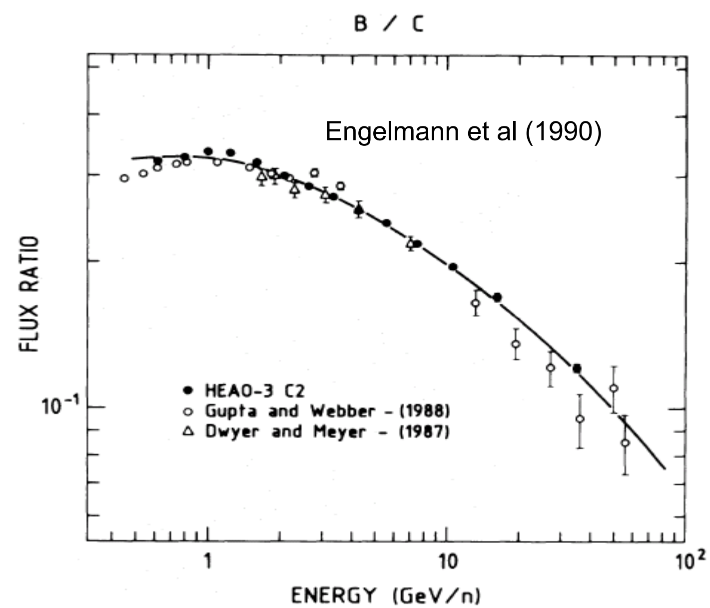
$$pp \longrightarrow pn\pi^+ \longrightarrow ppe^-e^+\nu_e\bar{\nu}_e\nu_\mu\bar{\nu}_\mu$$

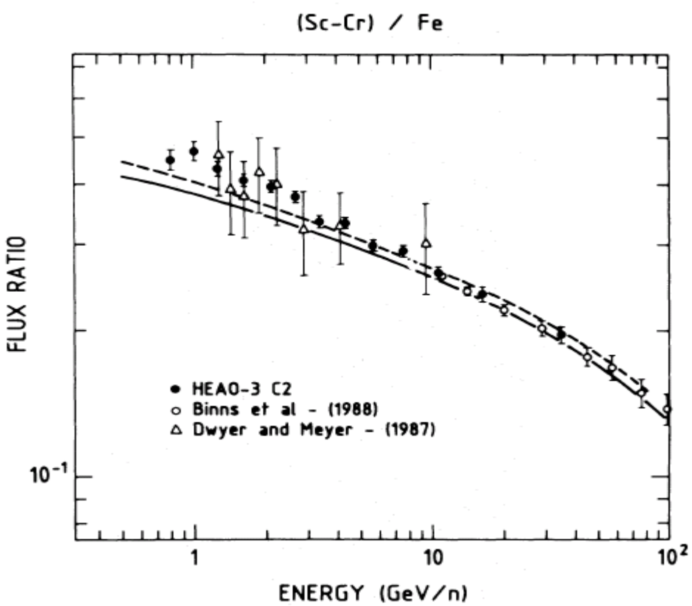


Stable secondaries with no energy loss (boron, pbar, sub-Fe,…)

- **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





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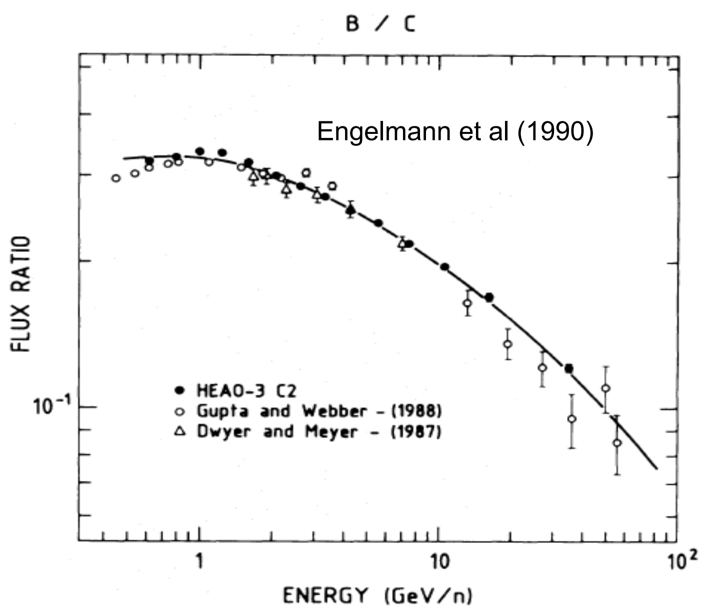
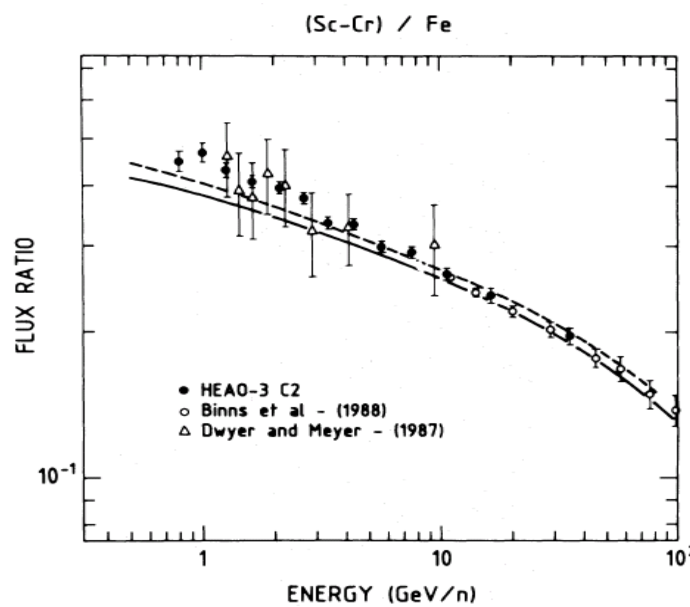
- $Q_A(\mathcal{R})$ = Local net production per unit column density of target, for species A

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





Stable secondaries with no energy loss

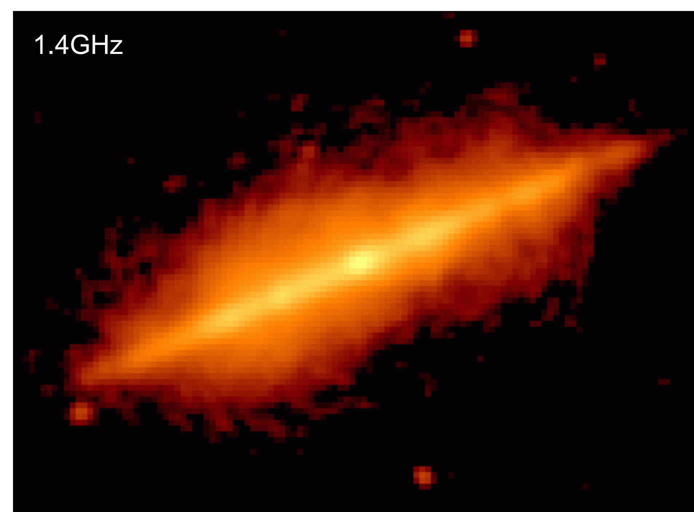
$$\frac{n_A}{n_B} = \frac{Q_A}{Q_B}$$

Theoretically, this is a natural relation.

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

*Check out first 2 extra slides

NGC 891

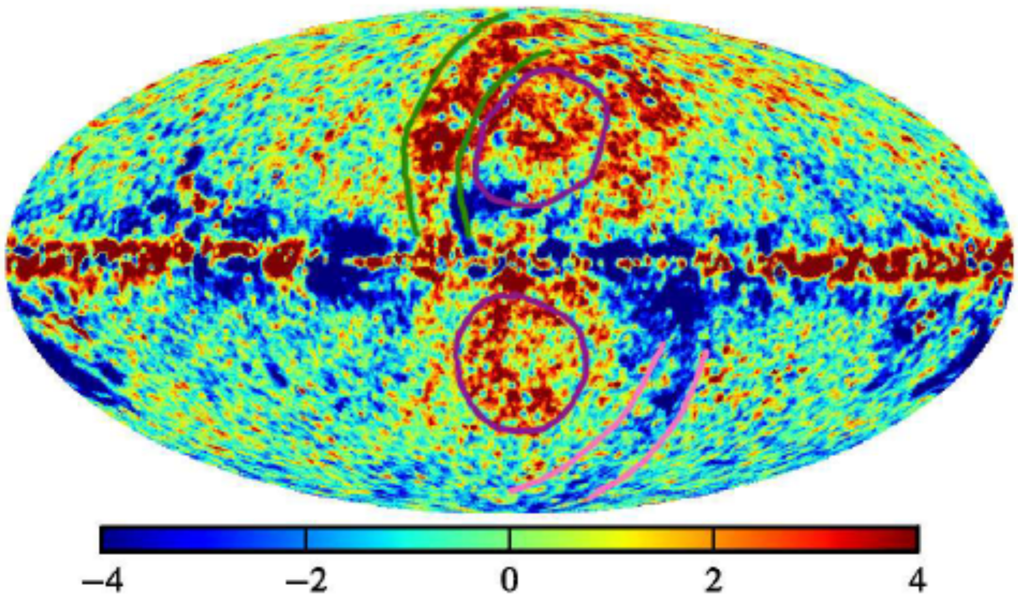


Stable secondaries with no energy loss

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

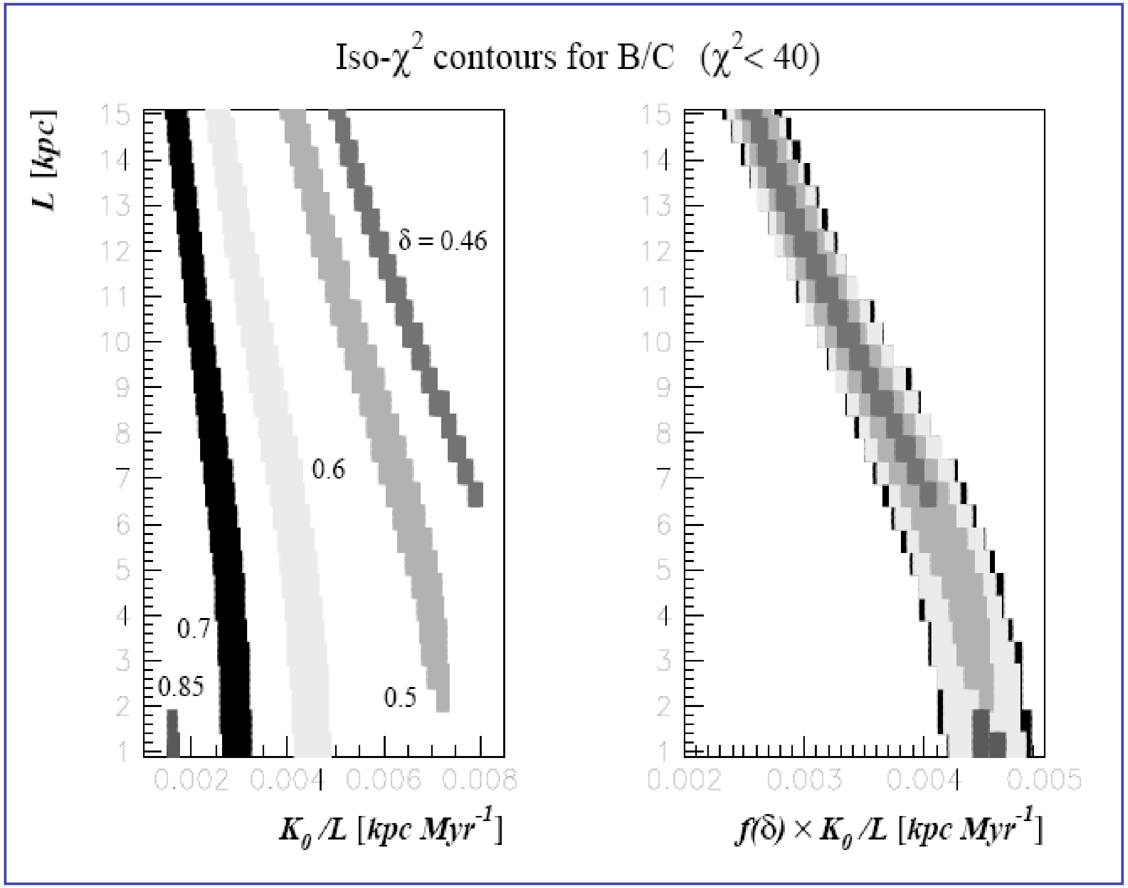
Theoretically, this is a natural relation.

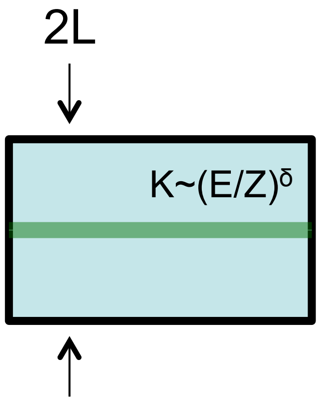
Do not need to assume homogeneous diffusion, boundary conditions, steady state,...



…and verifying this relation does not teach us that any of these assumptions is correct

diffusion models fit the grammage

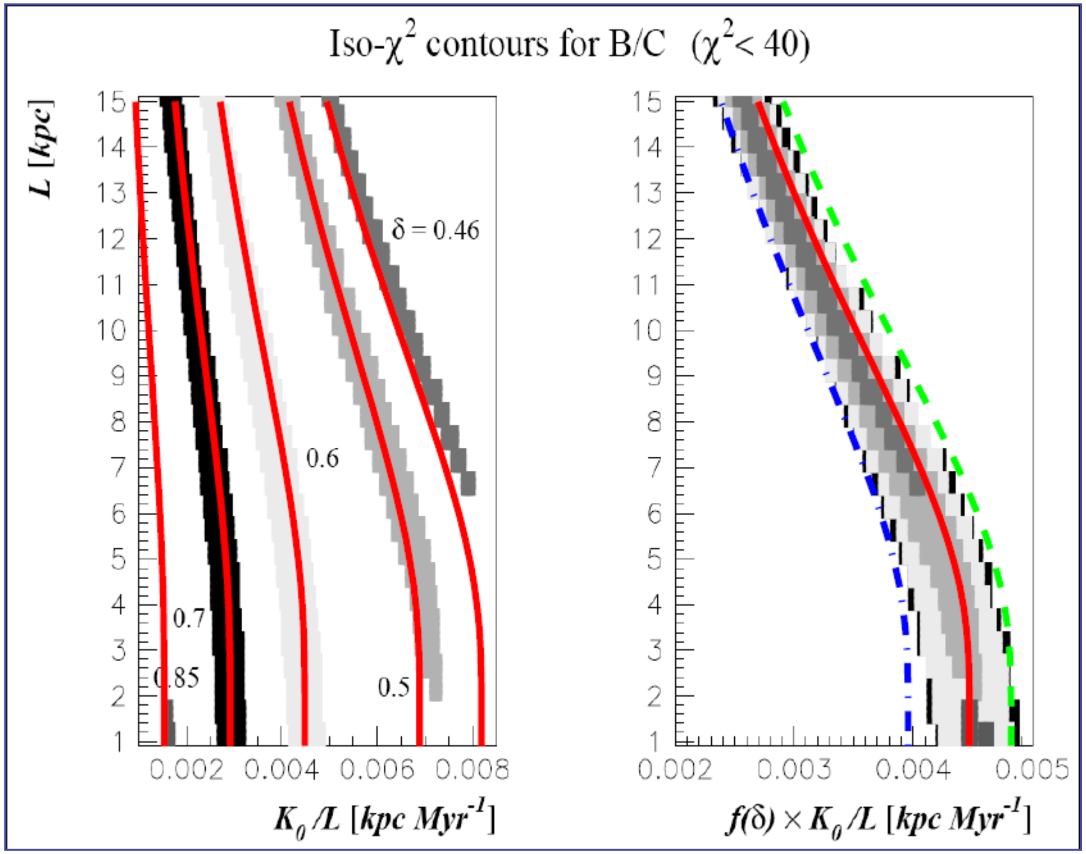


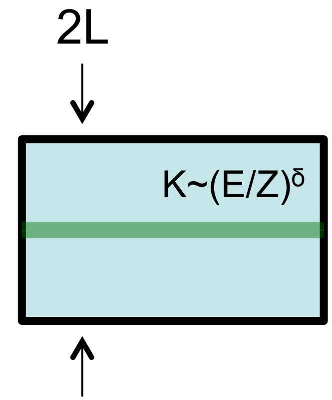


Maurin, Donato, Taillet, Salati

Astrophys.J.555:585-596,2001

diffusion models fit the grammage





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

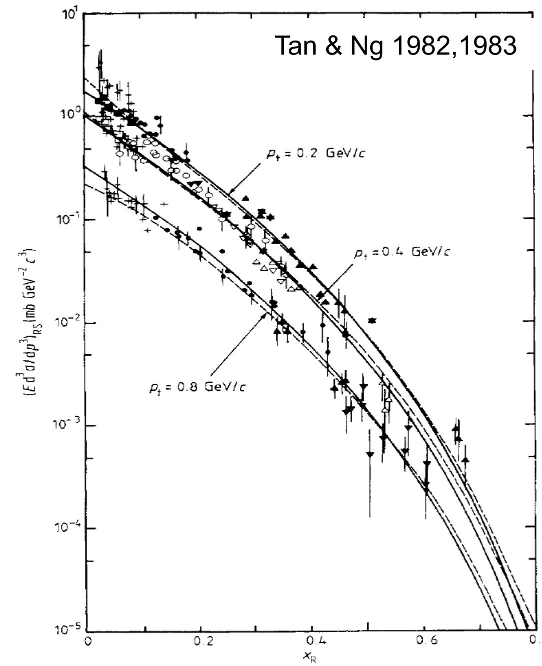
antiprotons

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

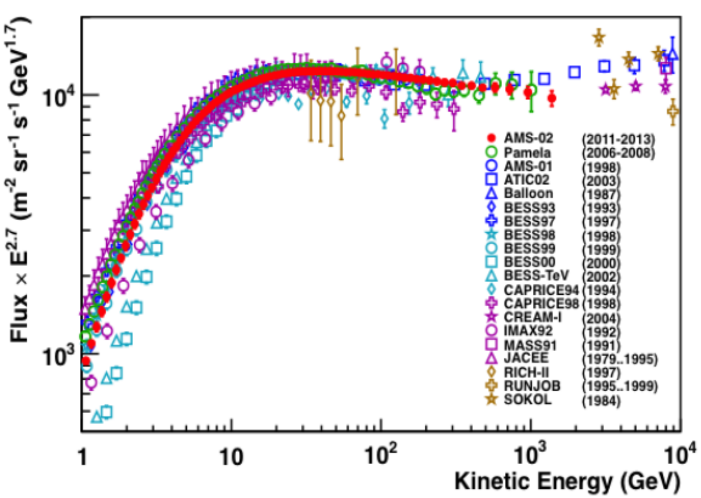
antiprotons

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

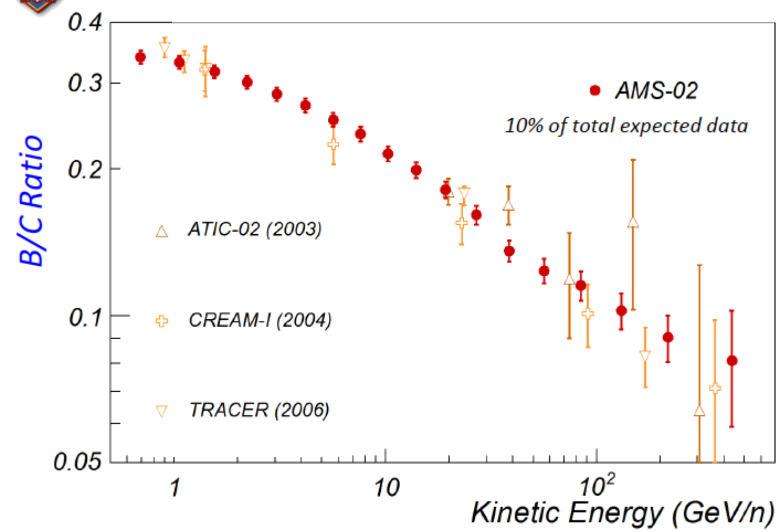
$$\frac{J_{\bar{p}}}{J_p} = 10^{1-\gamma_p}\,\zeta_{\bar{p},A>1}\,C_{\bar{p},pp}\,\frac{\sigma_{pp,{\rm inel}}}{m_p}\,\frac{X_{\rm esc}}{1+\frac{\sigma_{\bar{p}}}{m_p}X_{\rm esc}}$$



Proton flux

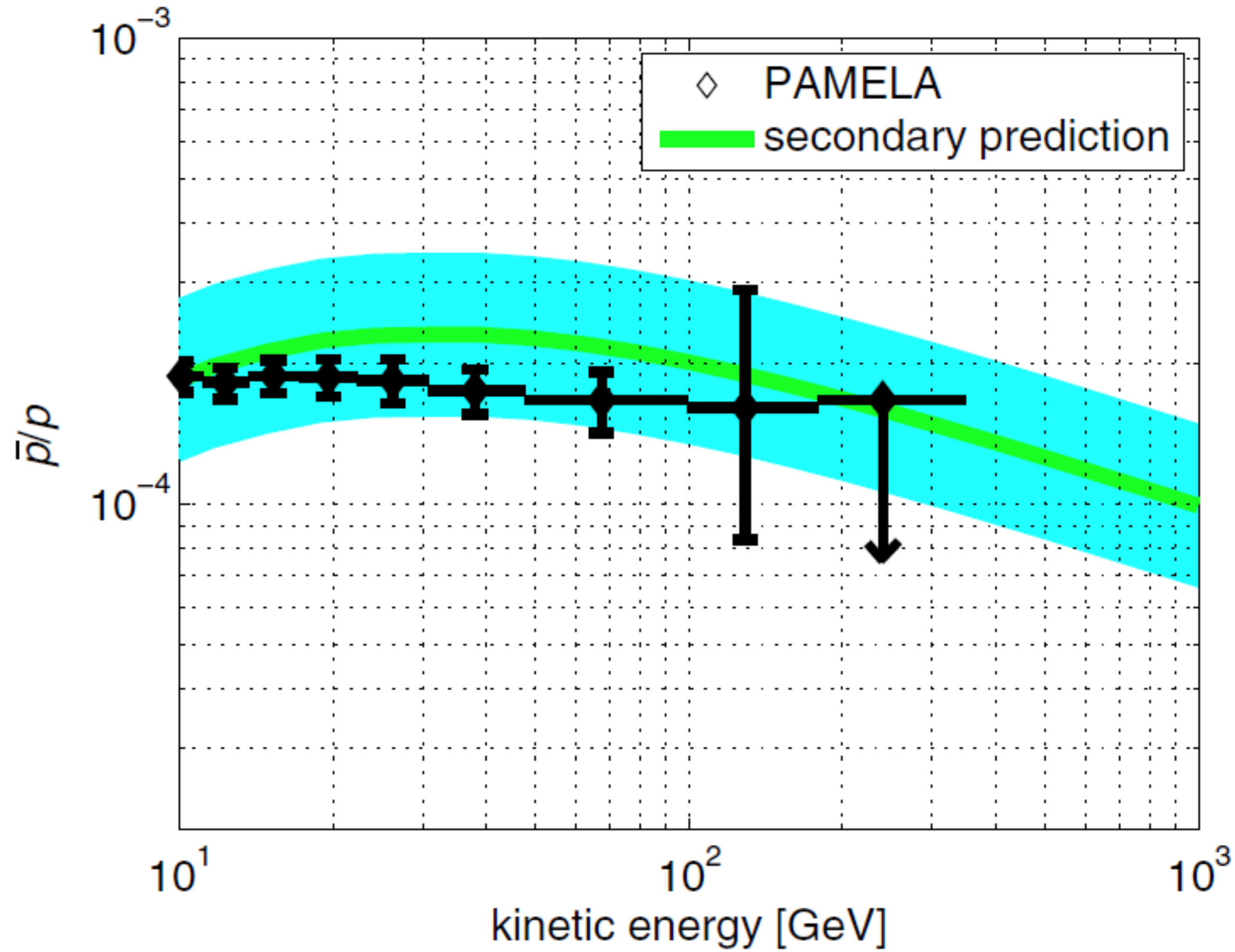


Boron-to-Carbon ratio



antiprotons

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



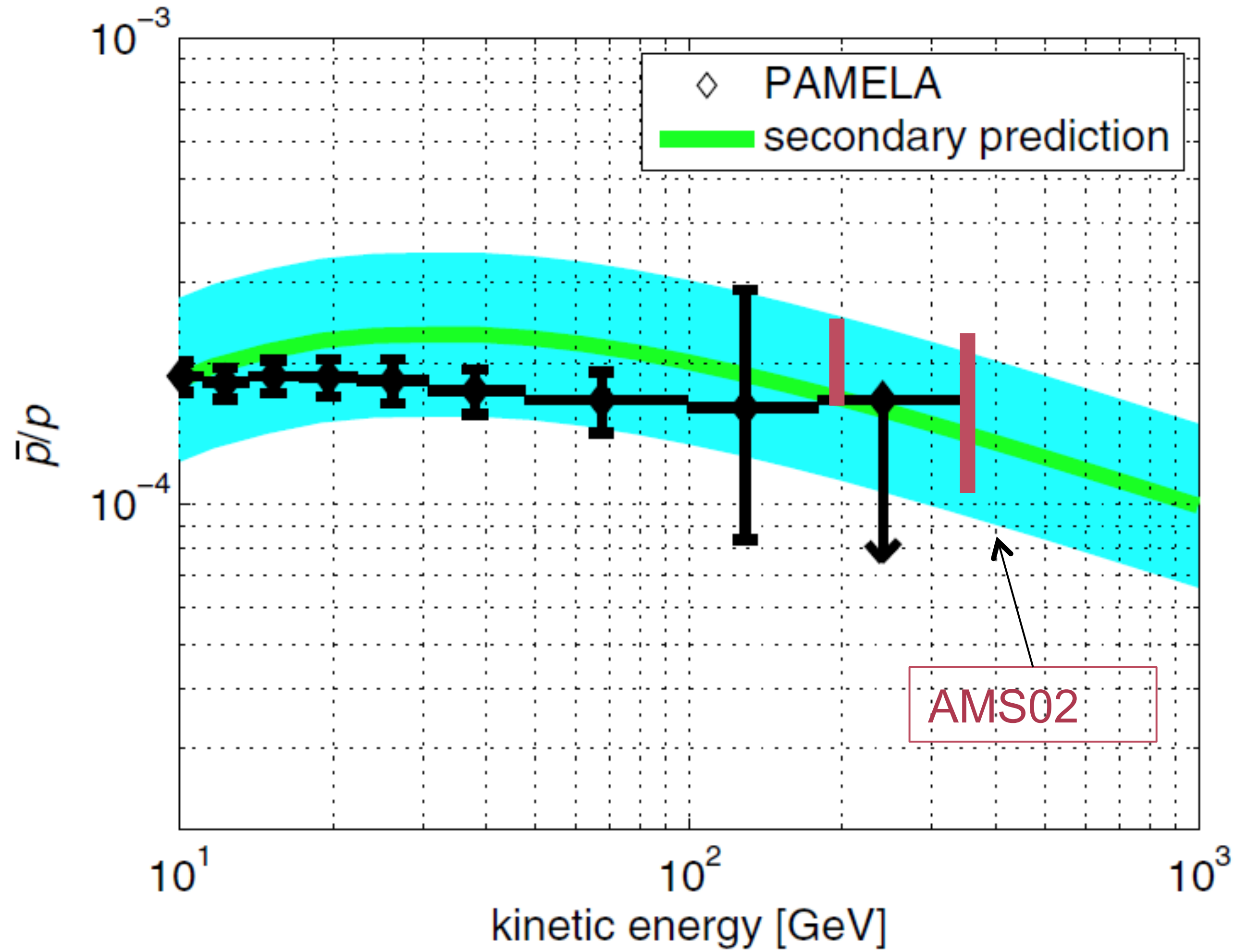
antiprotons

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

Antiprotons look very secondary to me.

1. There should not be a cut-off at higher energy

2. Should be viewed together w/ B/C



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+ loose energy through IC and synchrotron radiation.

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.

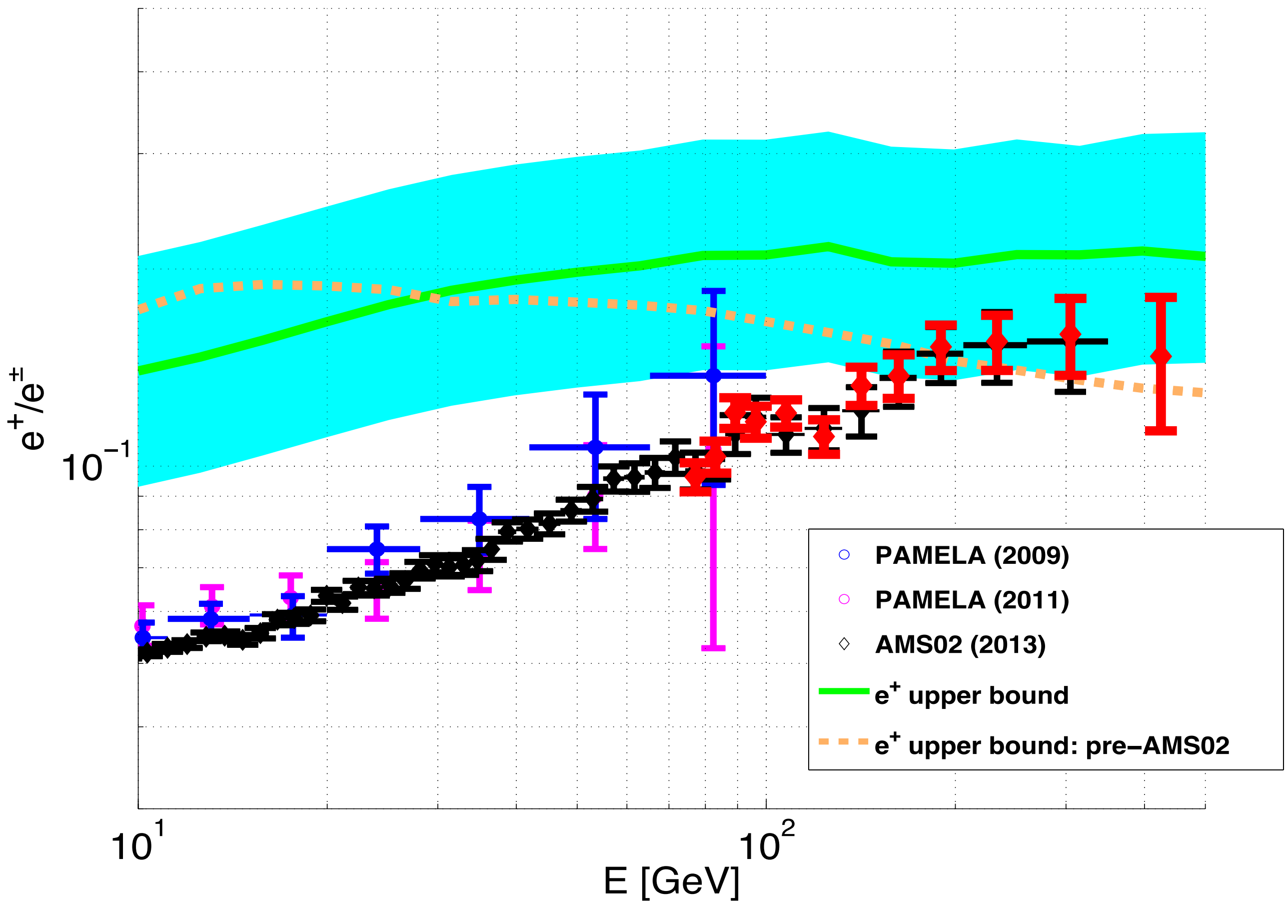
B/C and pbar/p do not measure it.

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

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

positrons

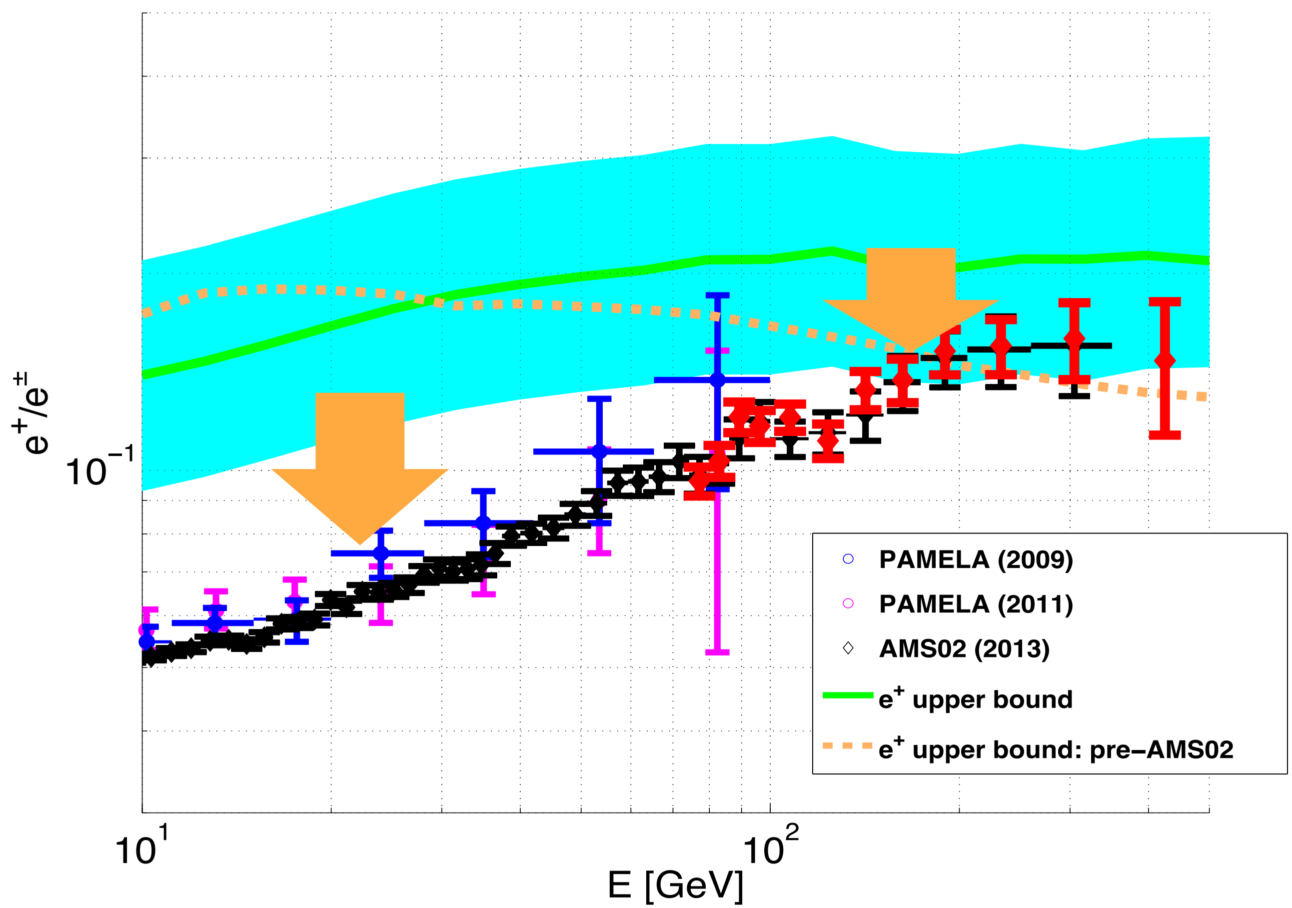
$$\frac{J_{e^+}}{J_p} = f_{e^+} \times 10^{1-\gamma_p}\, \zeta_{e^+,A>1}\, C_{e^+,pp}\, \frac{\sigma_{pp,\mathrm{inel}}}{m_p}\, X_{\mathrm{esc}}$$



positrons

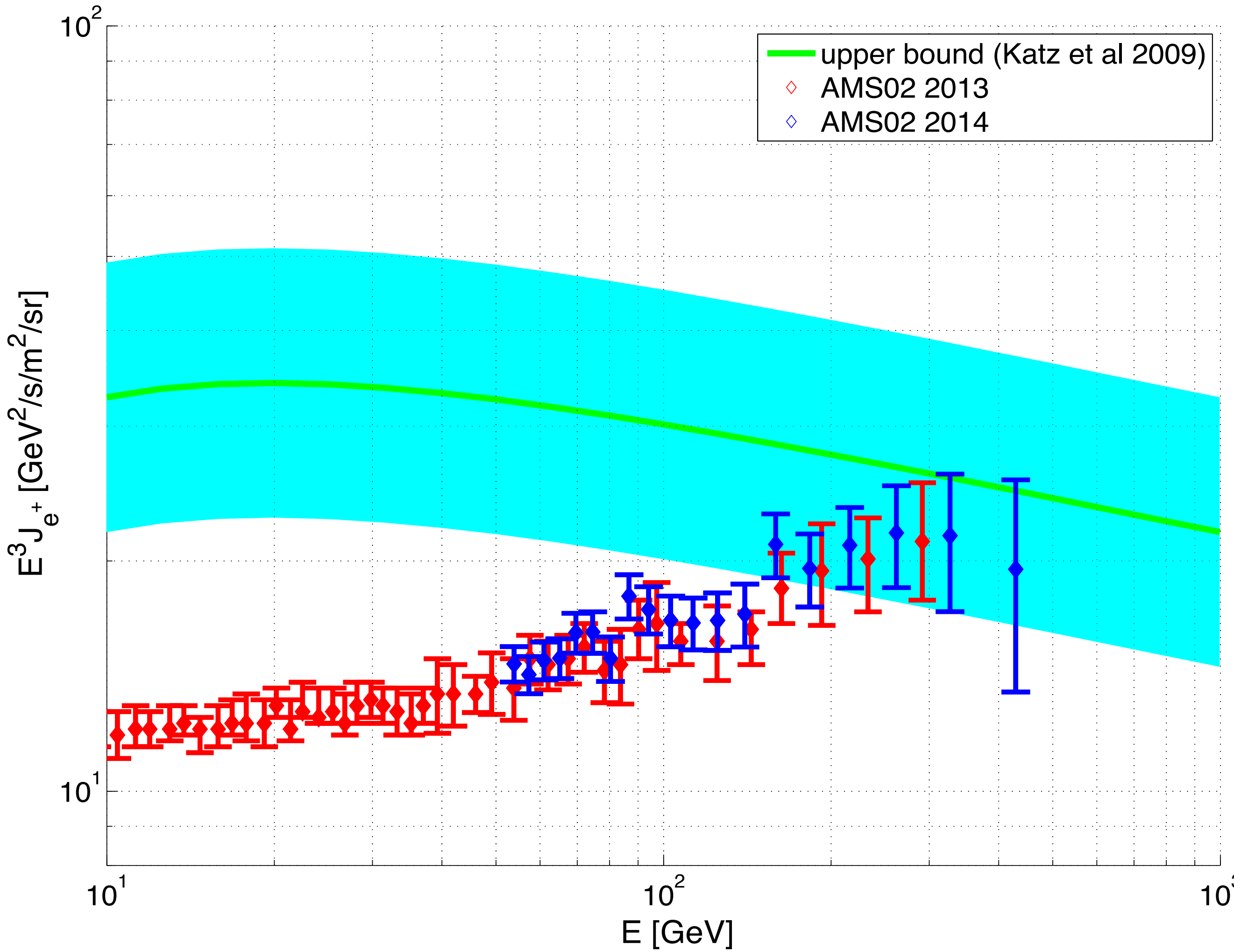
$$\frac{J_{e^+}}{J_p} = f_{e^+} \times 10^{1-\gamma_p} \, \zeta_{e^+,A>1} \, C_{e^+,pp} \, \frac{\sigma_{pp,\mathrm{inel}}}{m_p} \, X_{\mathrm{esc}}$$

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



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

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



- lessons for CR propagation, assuming secondary e+

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:

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

➔ 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>?)

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 $X_{esc}(R)$

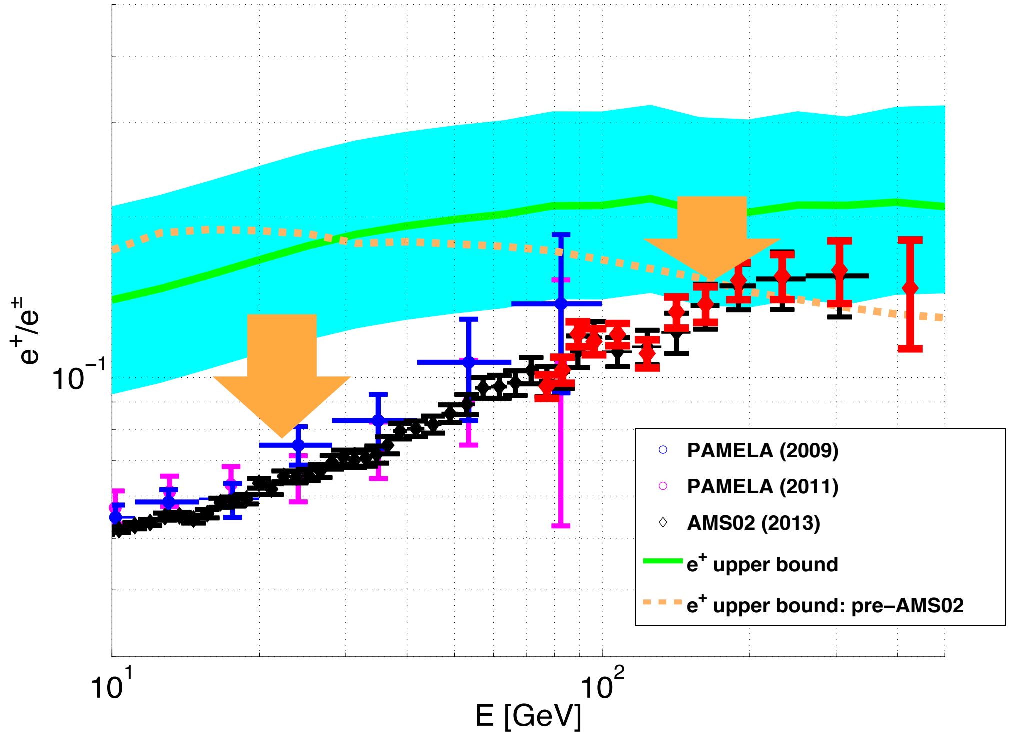
could do with e.g.

R-dependent boundary

need care w/ e+

production cross section,

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



- how do we test the secondary interpretation further?

Propagation time scales: radioactive nuclei

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

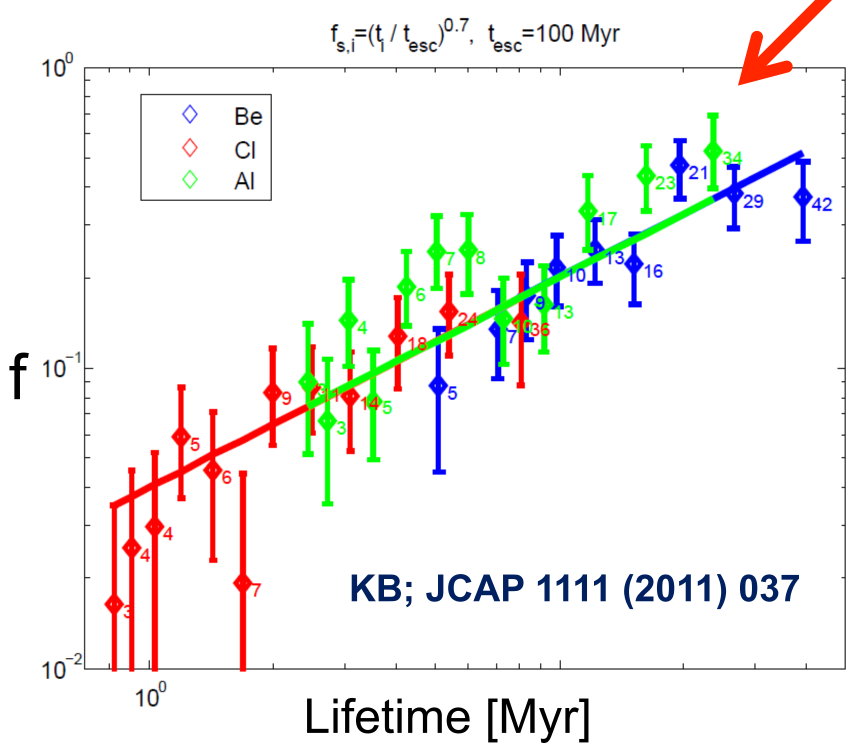
➔ Radioactive nuclei carry time info (like positrons)

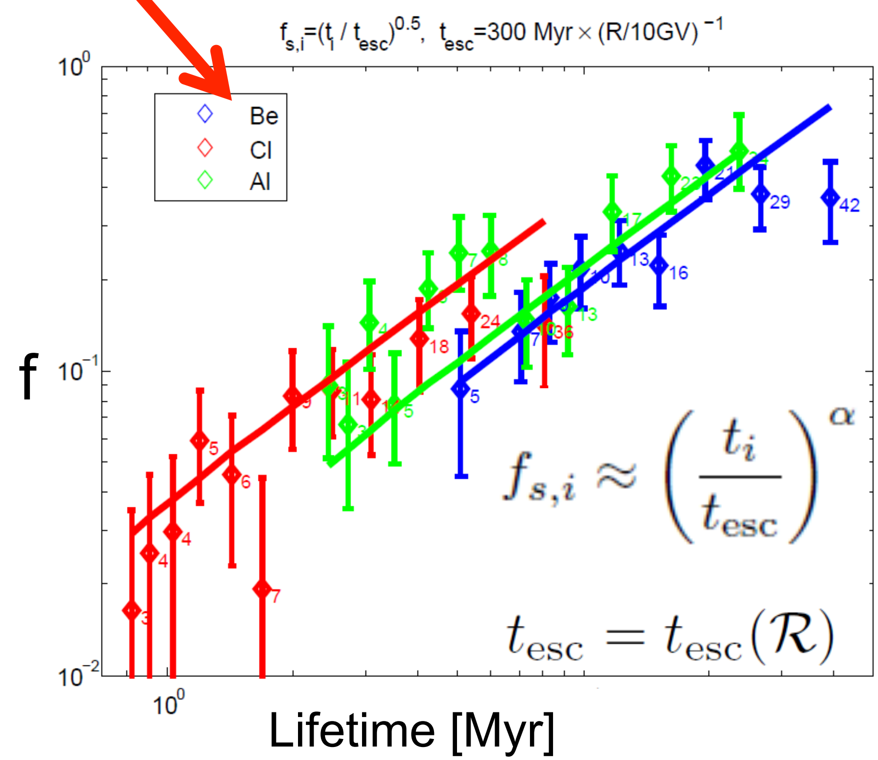
reaction	$t_{1/2}$ [Myr]	σ [mb]
${}^{10}_{4}$Be $\rightarrow$ ${}^{10}_{5}$B	1.51 (0.06)	210
${}^{26}_{13}$Al $\rightarrow$ ${}^{26}_{12}$Mg	0.91 (0.04)	411
${}^{36}_{17}$Cl $\rightarrow$ ${}^{36}_{18}$Ar	0.307 (0.002)	516
${}^{54}_{25}$Mn $\rightarrow$ ${}^{54}_{26}$Fe	0.494 (0.006)*	685

Radioactive nuclei: constraints on t_{esc}

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

Need to tell between these fits





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?

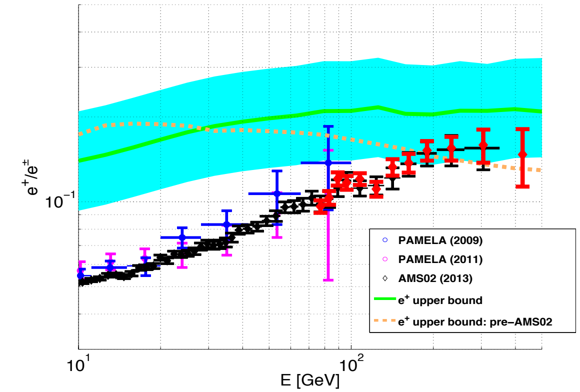
Upcoming tests with AMS

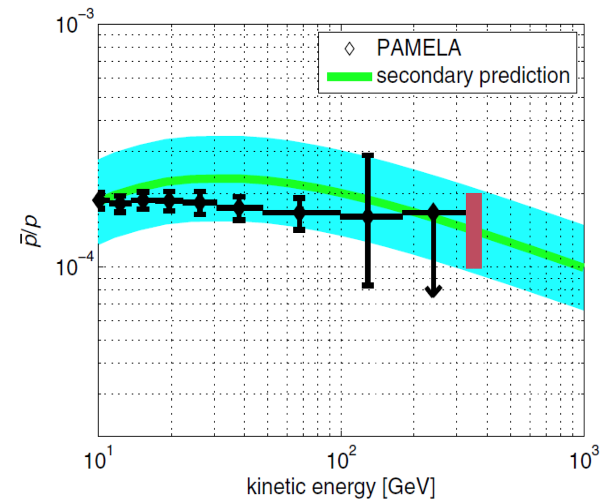
Determination of B/C, pbar at high energy

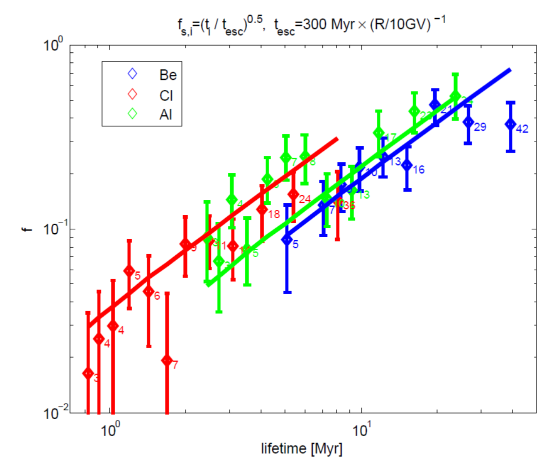
– calibrate out propagation

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

Thank you!







Xtras

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

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

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:

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

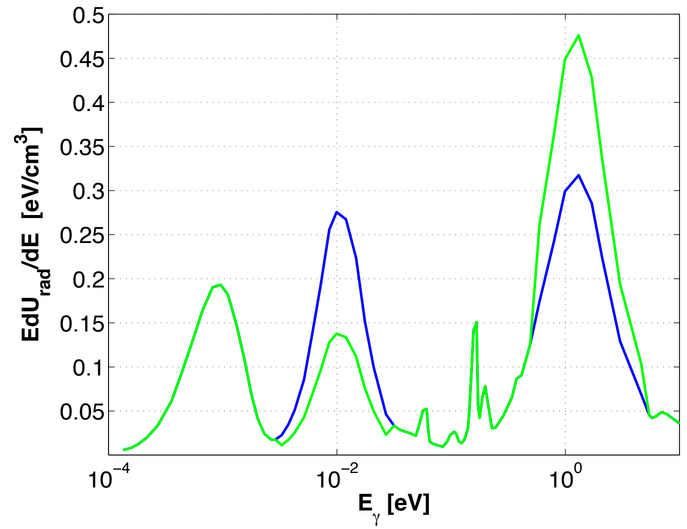
$$= Q_B(\mathcal{R}, \vec{r}_\odot, t_\odot) \int d^3r \int dt\, c\, \rho_{ISM}(\vec{r}, t)\, \frac{n_C(\mathcal{R}, \vec{r}, t)}{n_C(\mathcal{R}, \vec{r}_\odot, t_\odot)}\, P\left(\mathcal{R}; \{\vec{r}, t\}, \{\vec{r}_\odot, t_\odot\}\right) F_B$$

Uniform *composition* ⇒

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

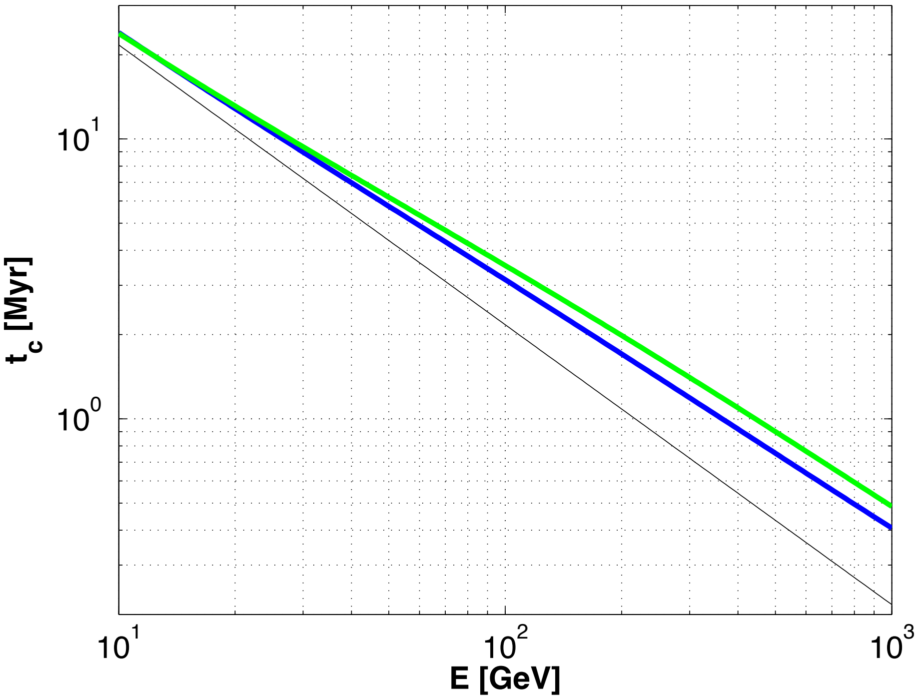
$$X_{\mathrm{esc}} = \int d^3r \int dt\, c\, \rho_{ISM}(\vec{r}, t)\, \frac{n_C(\mathcal{R}, \vec{r}, t)}{n_C(\mathcal{R}, \vec{r}_\odot, t_\odot)}\, P\left(\mathcal{R}; \{\vec{r}, t\}, \{\vec{r}_\odot, t_\odot\}\right)$$

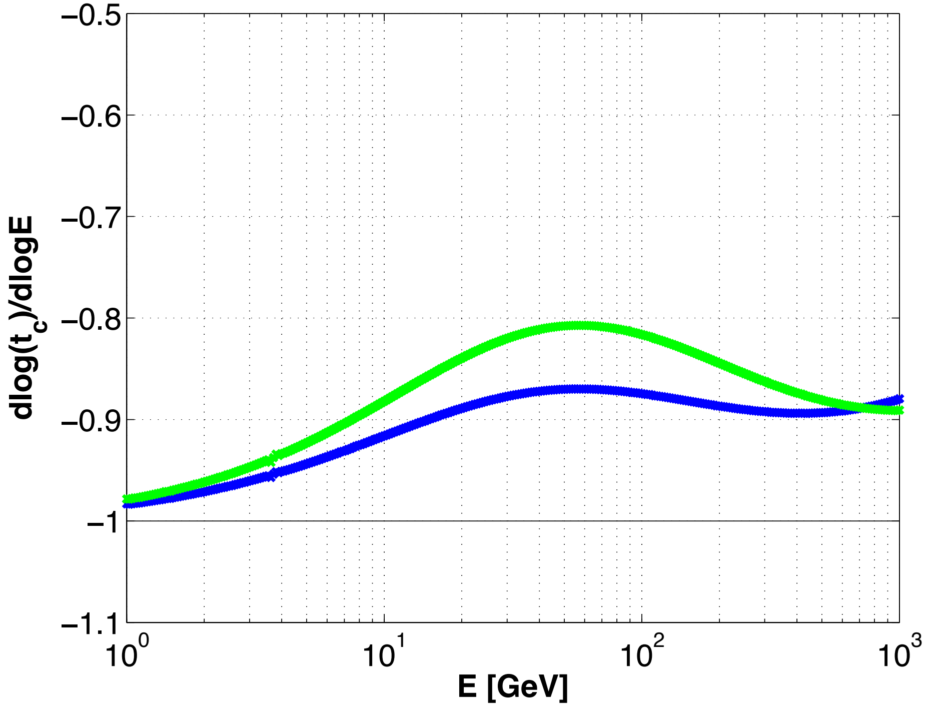
What is the cooling time for CR positrons?
What is it's spectral slope?



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

Index ~ 0.8-0.9
t_{cool} ~ 1 Myr @ 300-500 GeV





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

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

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 $\gamma_0 < 2$?

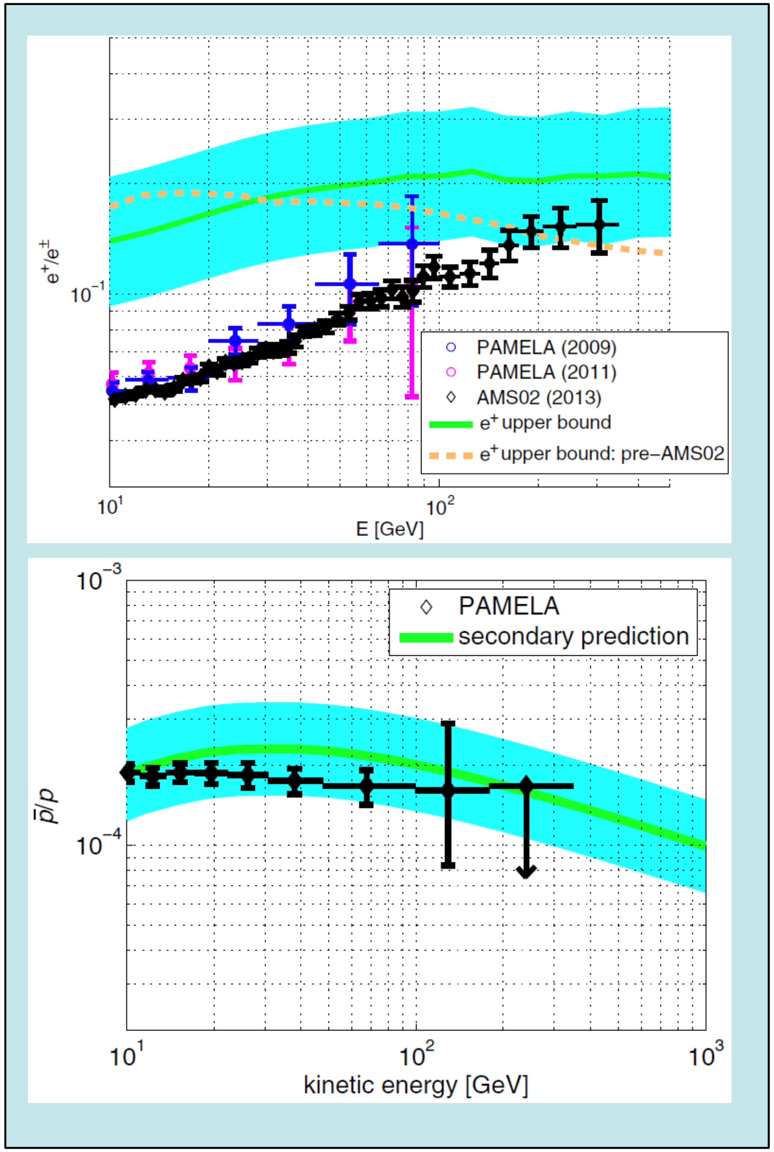
Answer 1: we already saw that $t_{esc} \sim R^{-0.8}$ may be enough.
Answer 2: worry is based on scaling assumption, that may well be incorrect.

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

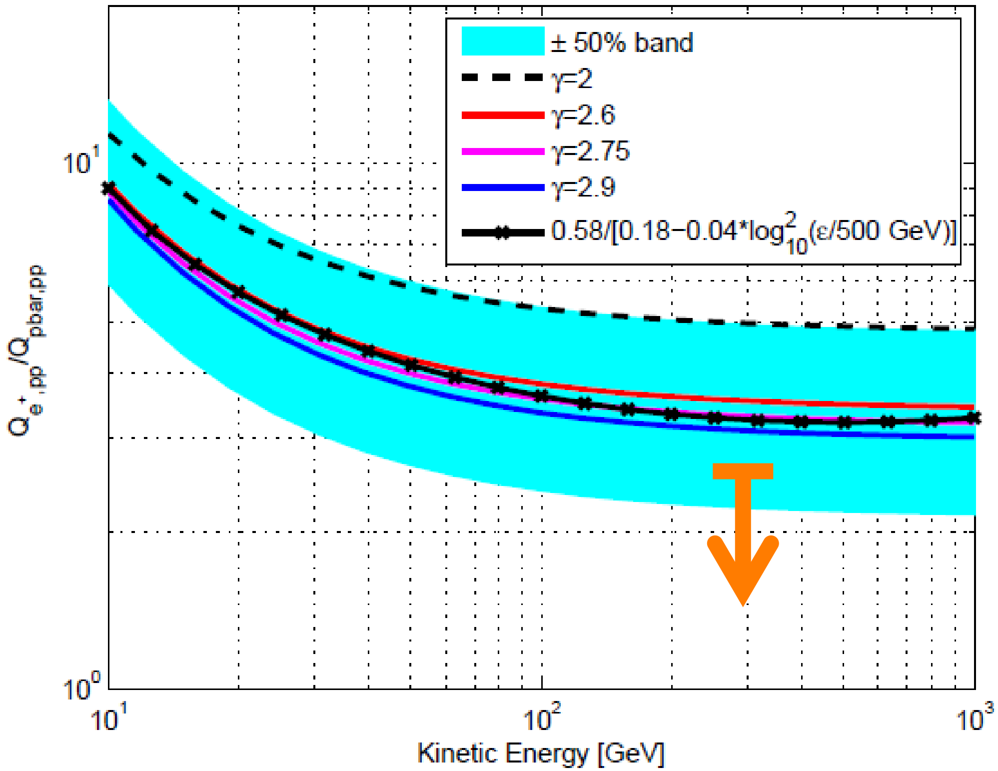
…V can depend on rigidity: V=V(R)
Example: homogeneous thin-disc diffusion with V ~ L = L(R)

$$t_{\mathrm{esc}} \propto \frac{L^2}{D}, \qquad X_{\mathrm{esc}} \propto \frac{L\,c}{D} \times X_{\mathrm{disc}} \quad ➔ \quad J_{p,\mathrm{obs}} \sim X_{\mathrm{esc}} \times J_{p,\mathrm{inject}} \propto \mathcal{R}^{-\gamma_0-0.4}$$

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



branching fraction in pp collision:



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

Radioactive nuclei: Charge ratios

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*

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(WS98)

reaction	$t_{1/2}$ [Myr]	σ [mb]
$^{10}_{4}$Be $\rightarrow$ $^{10}_{5}$B	1.51 (0.06)	210
$^{26}_{13}$Al $\rightarrow$ $^{26}_{12}$Mg	0.91 (0.04)	411
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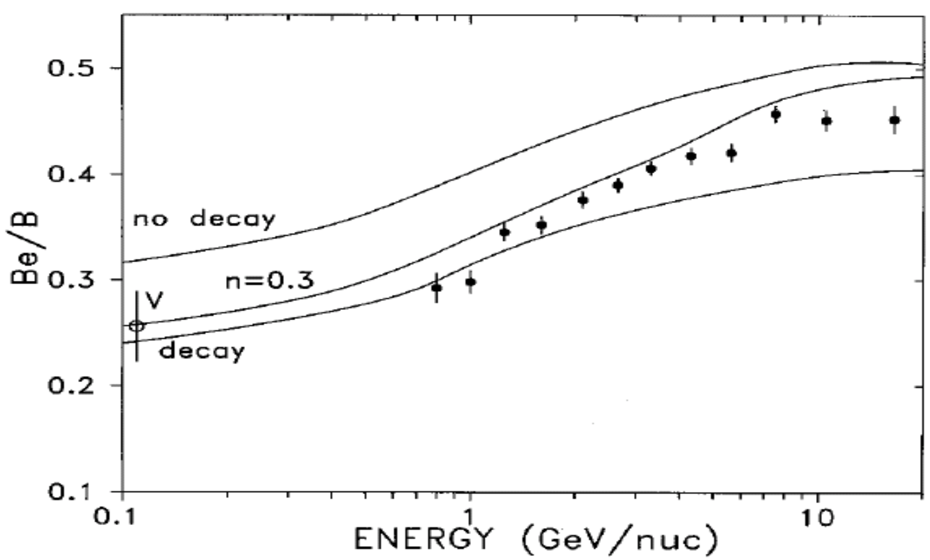
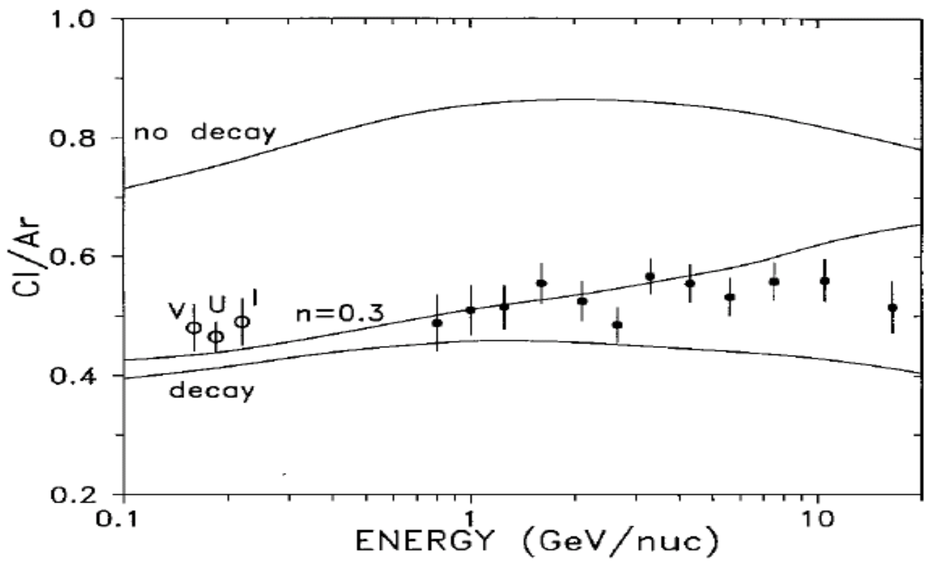




Radioactive nuclei: Charge ratios vs. isotopic ratios

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. Must resolve mass
Isotopic ratios 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)

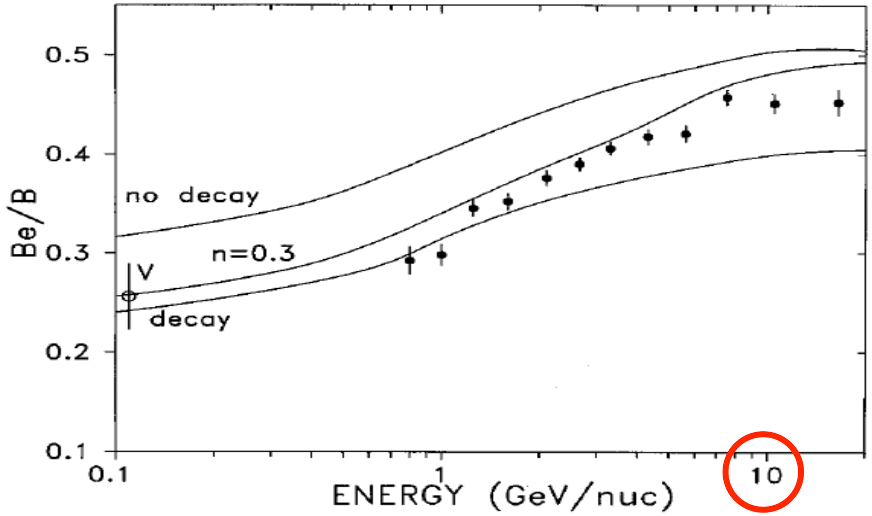
• **Benefit**: avoid low energy complications; significant range in rigidity

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

Radioactive nuclei: Charge ratios vs. isotopic ratios

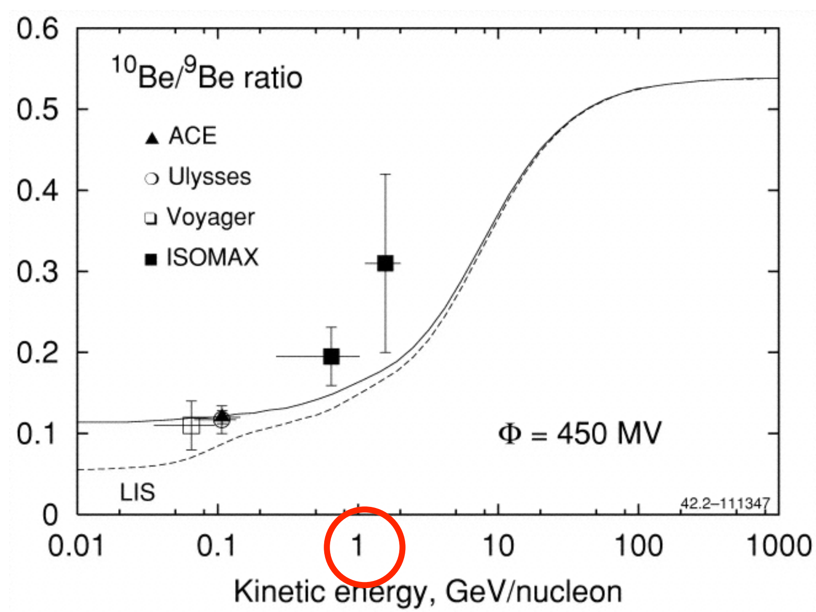
Charge ratios

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



Isotopic ratios

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



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:

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

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

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

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

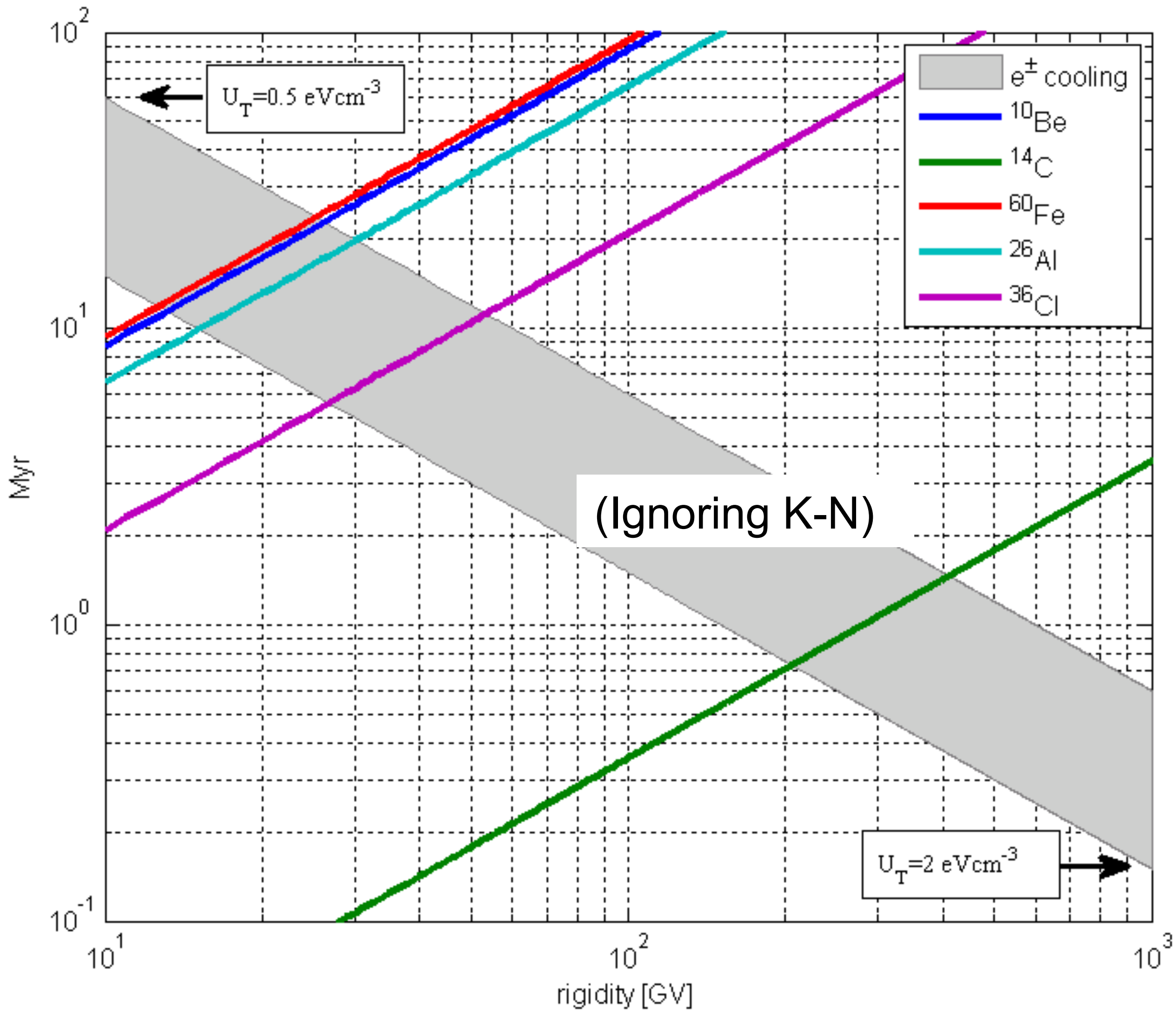
$$\tilde{t}_c = \frac{t_c}{\gamma - \delta_c - 1}$$

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

Comparing with radioactive nuclei

Time scales:

cooling vs decay



Comparing with radioactive nuclei

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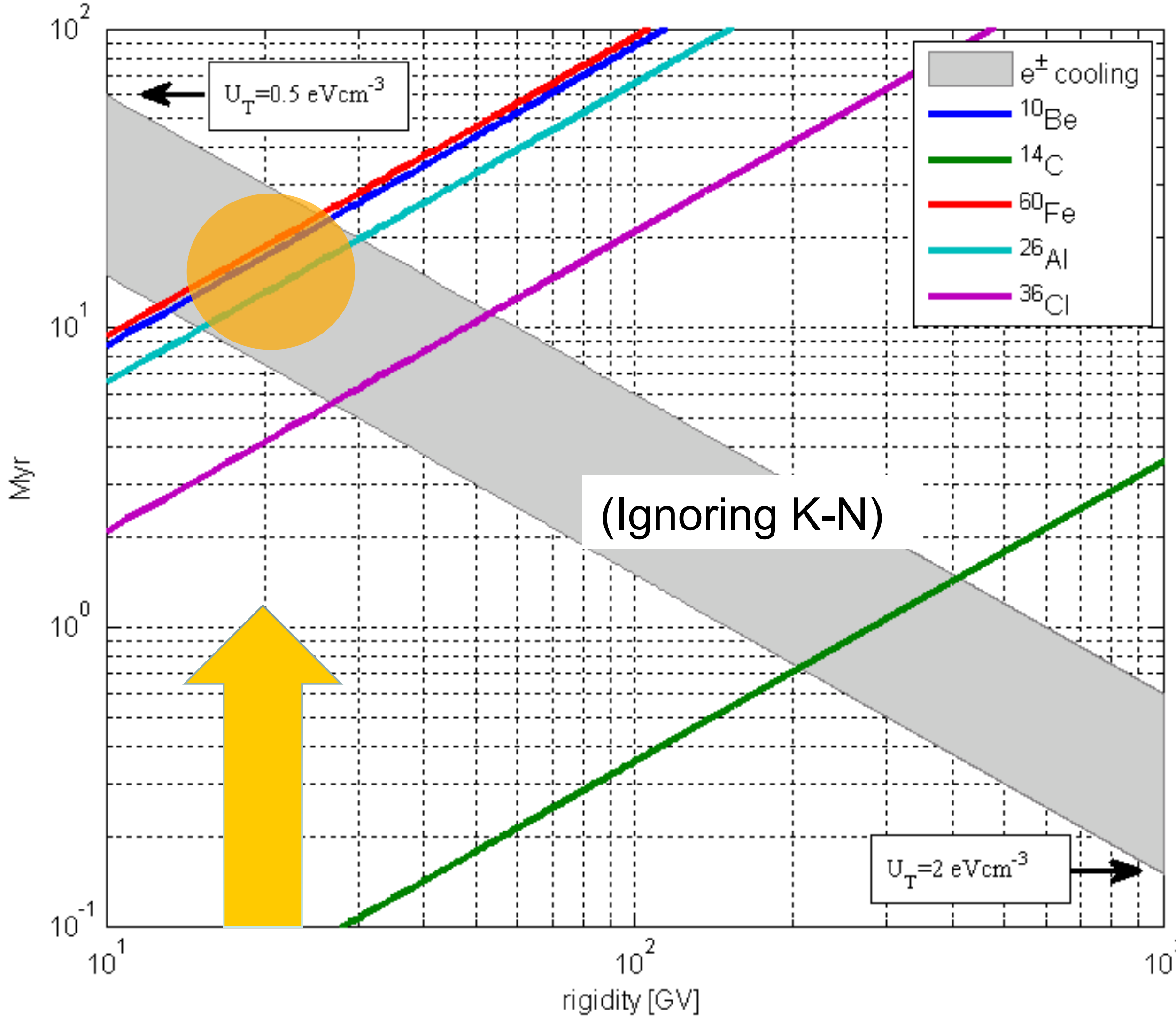
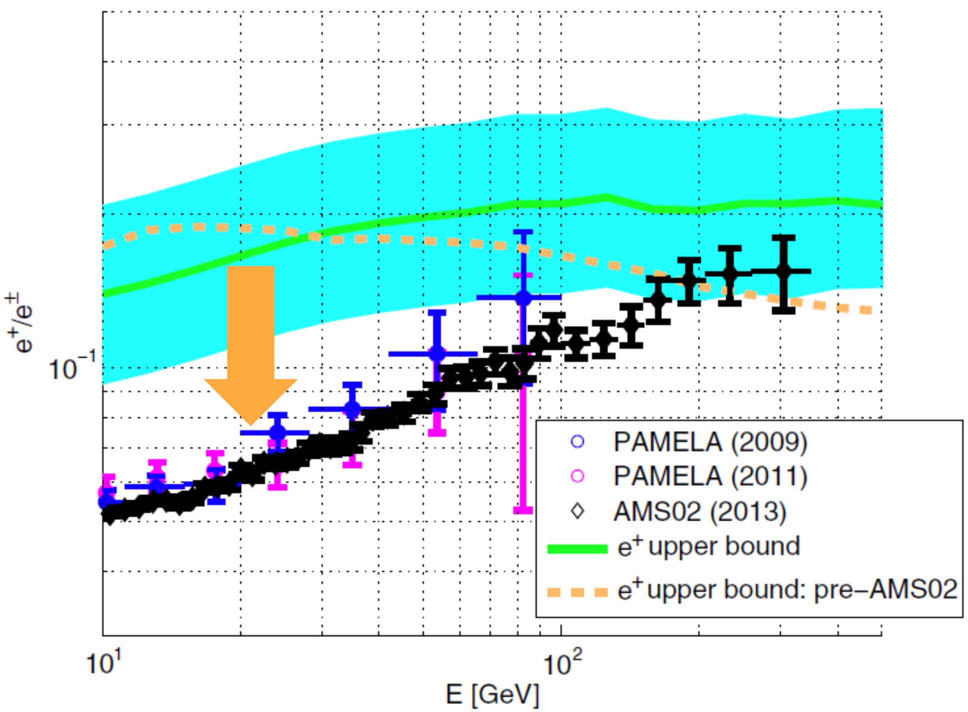
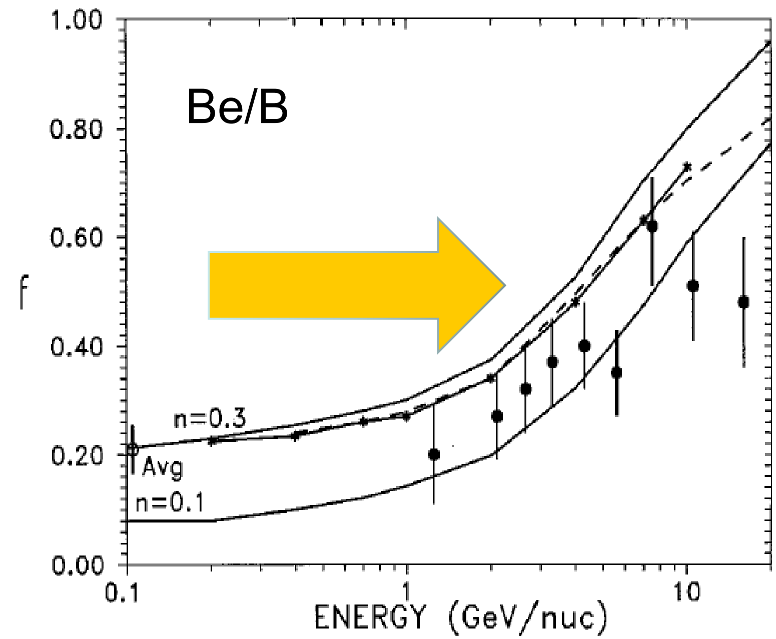
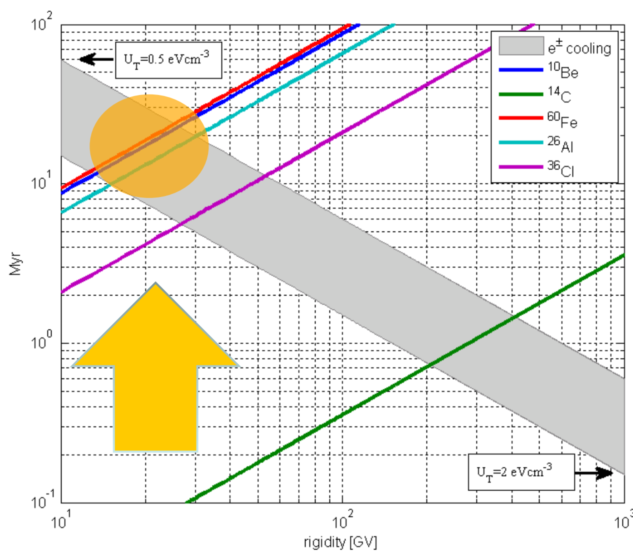


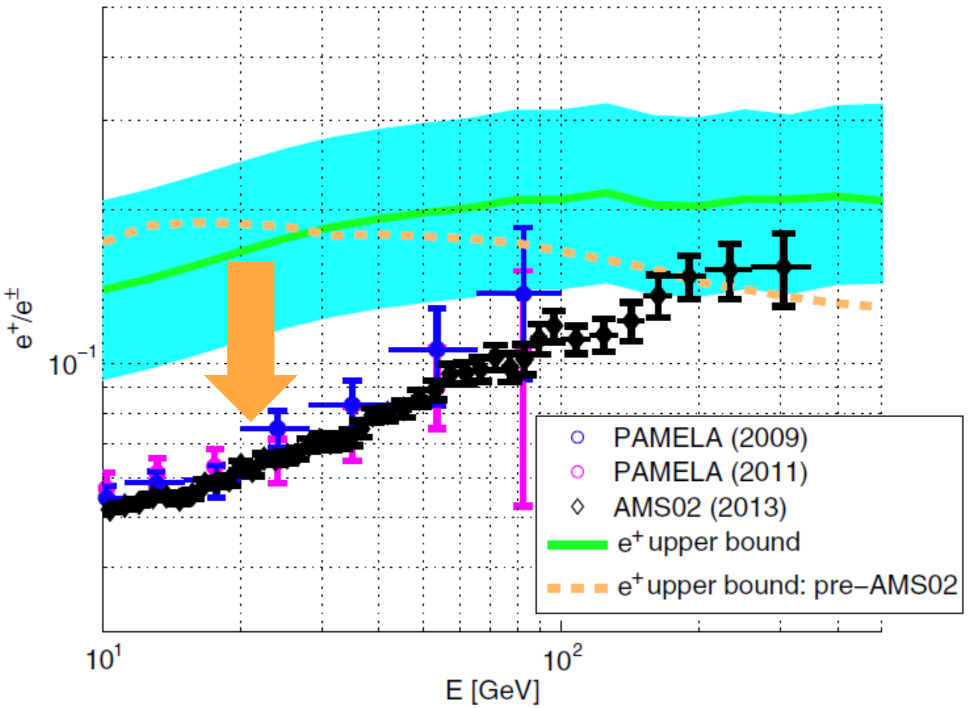
Comparing with radioactive nuclei

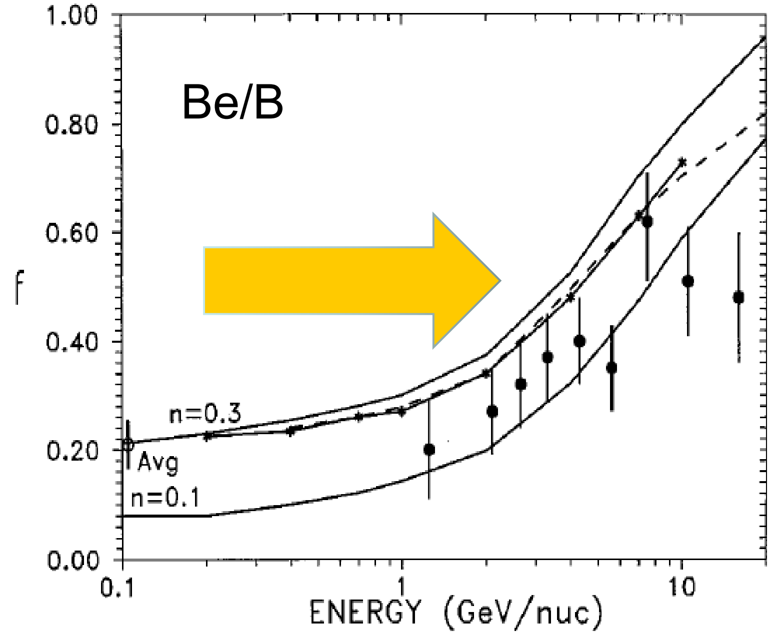


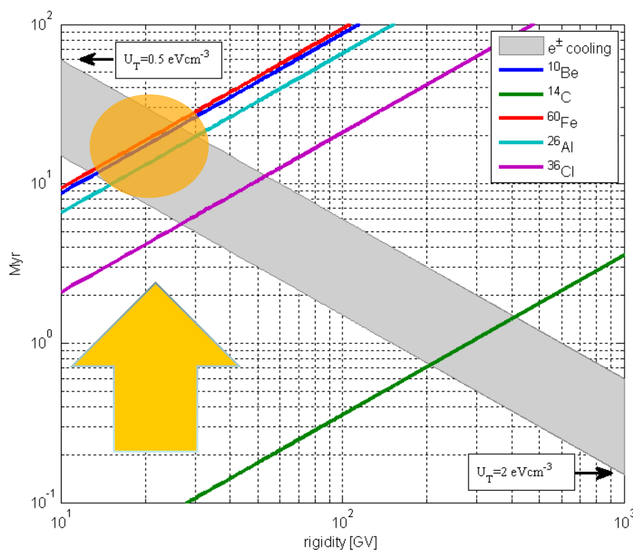




Comparing with radioactive nuclei







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

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

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

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

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

Suppression factor

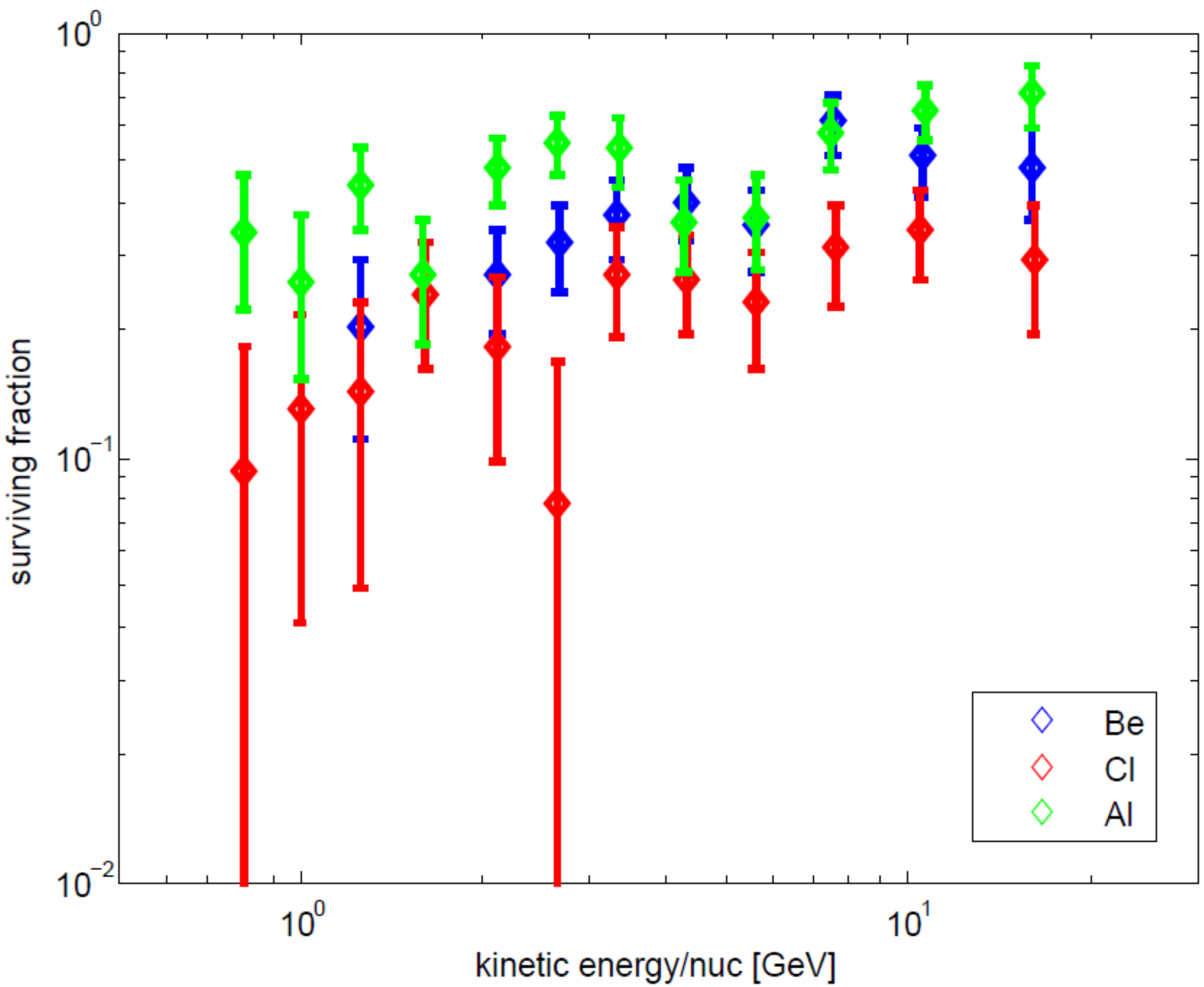
- Different nuclei species on equal footing
- Expect $t_{\rm esc} = t_{\rm esc}(\mathcal{R})$, $f_{s,i} \approx \left(\frac{t_i}{t_{\rm esc}}\right)^{\alpha}$

Examples:

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

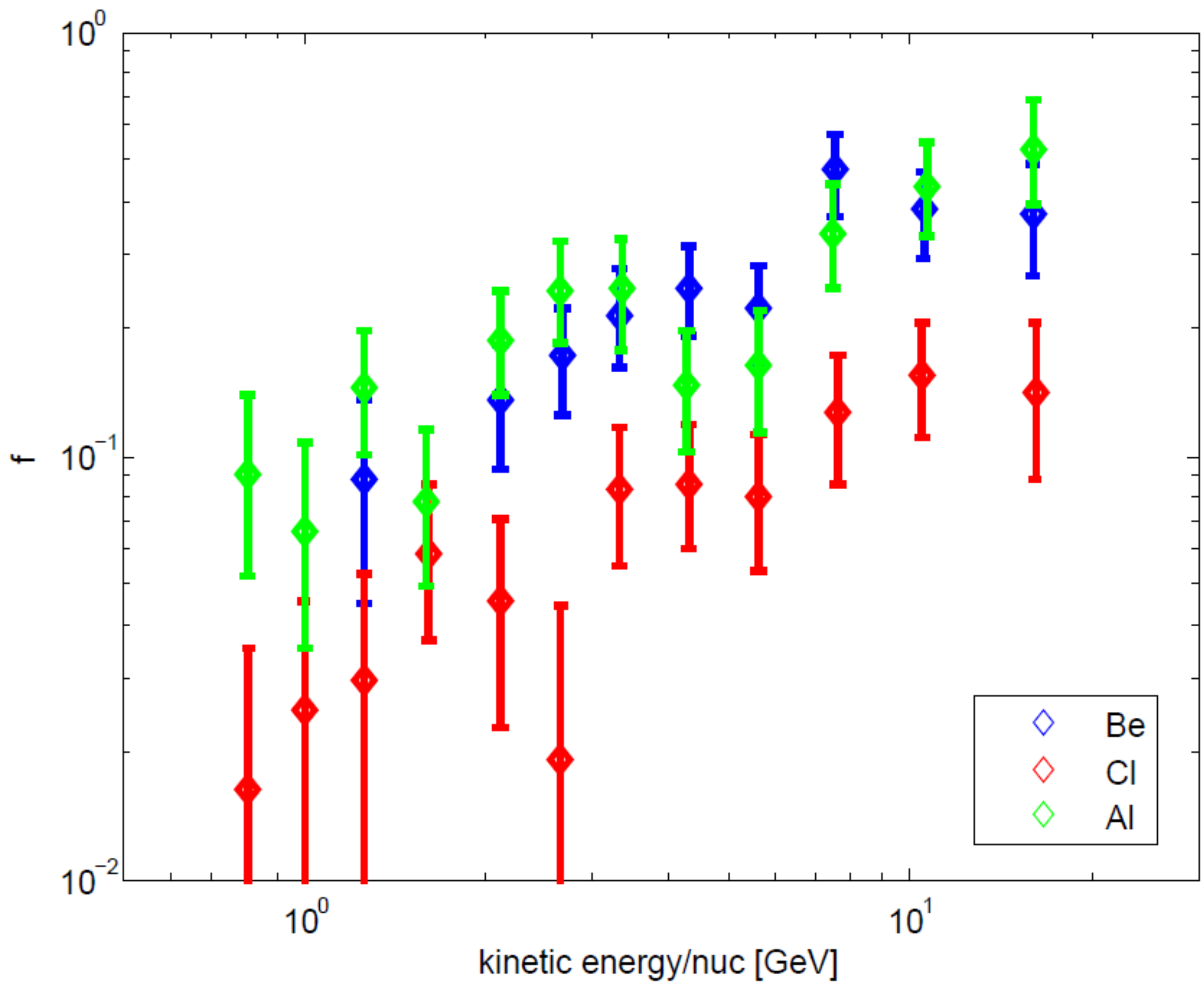
Radioactive nuclei: data

Surviving fraction vs. energy (WS98)



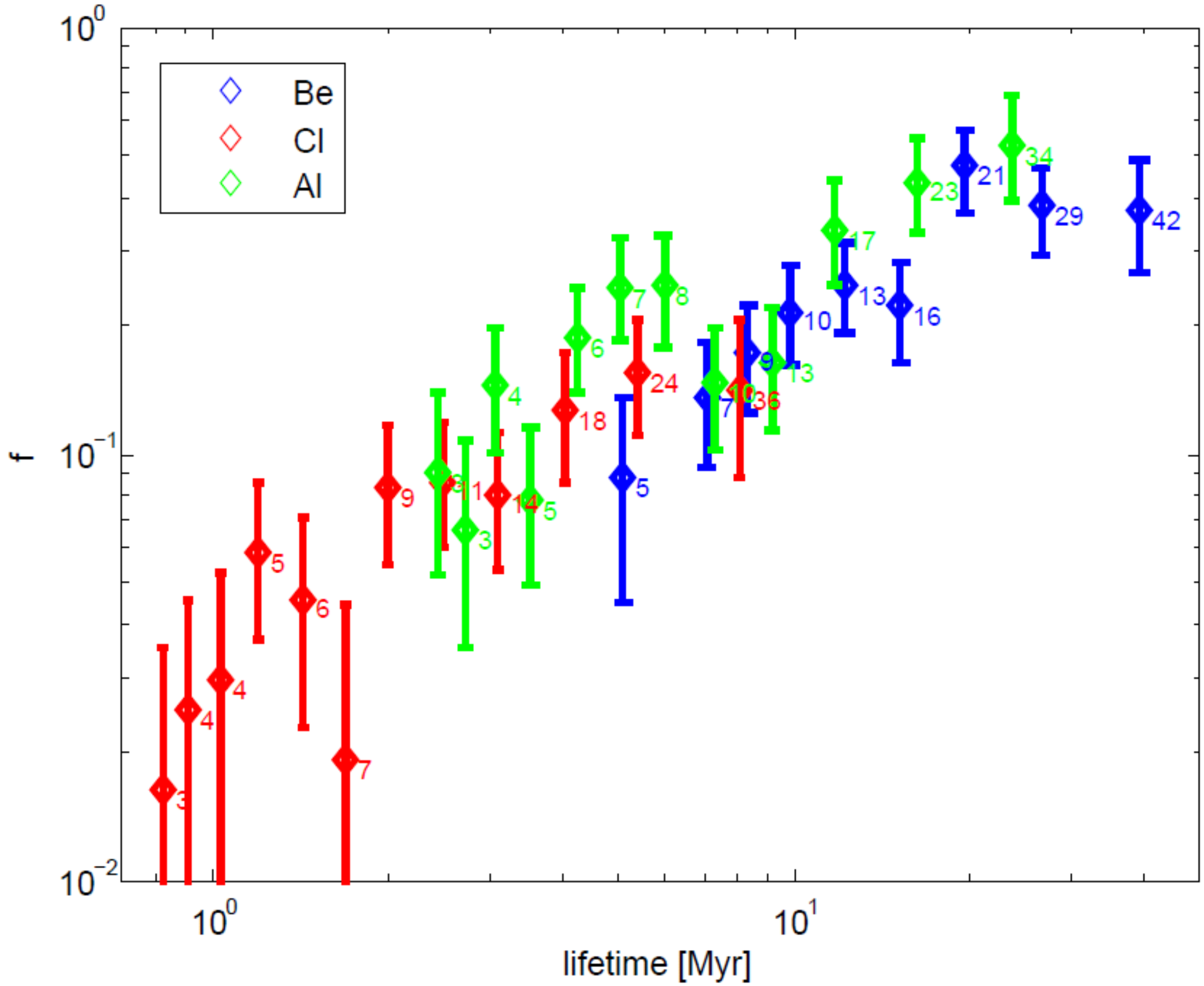
Radioactive nuclei: data

Suppression factor vs. energy



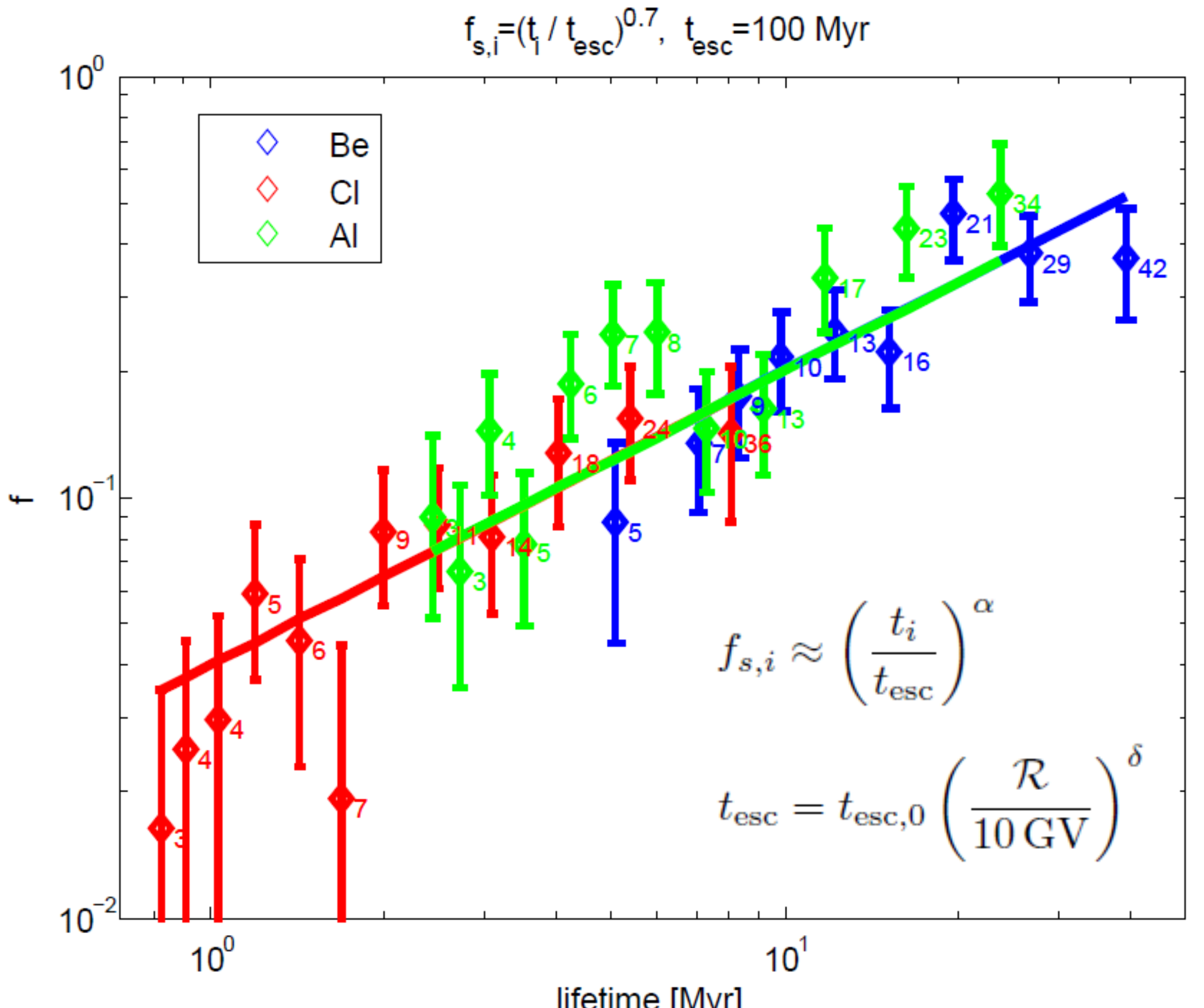
Radioactive nuclei: data

Suppression factor vs. lifetime



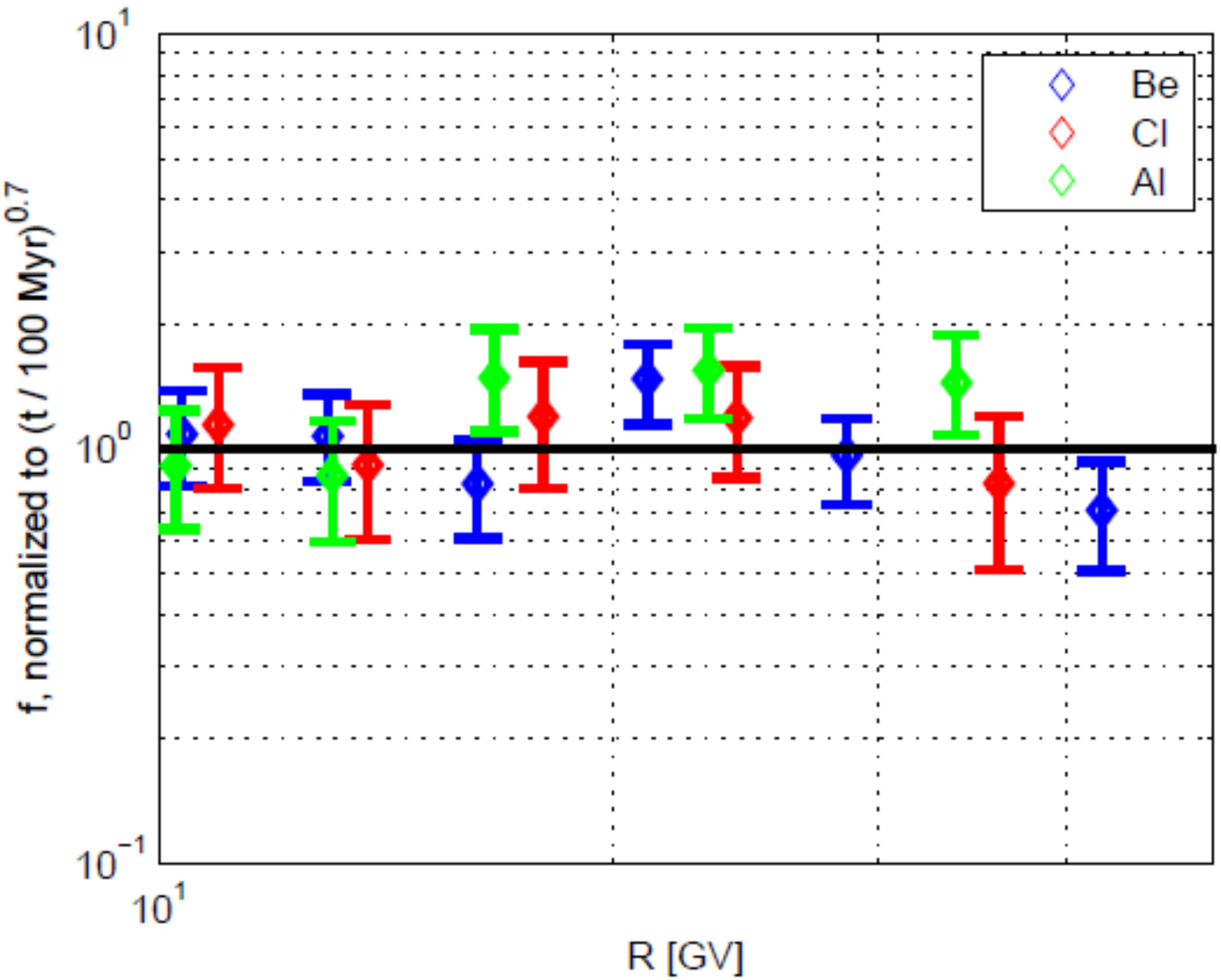
Radioactive nuclei: data

Consistent with constant residence time



Radioactive nuclei: data

Residual rigidity dependence



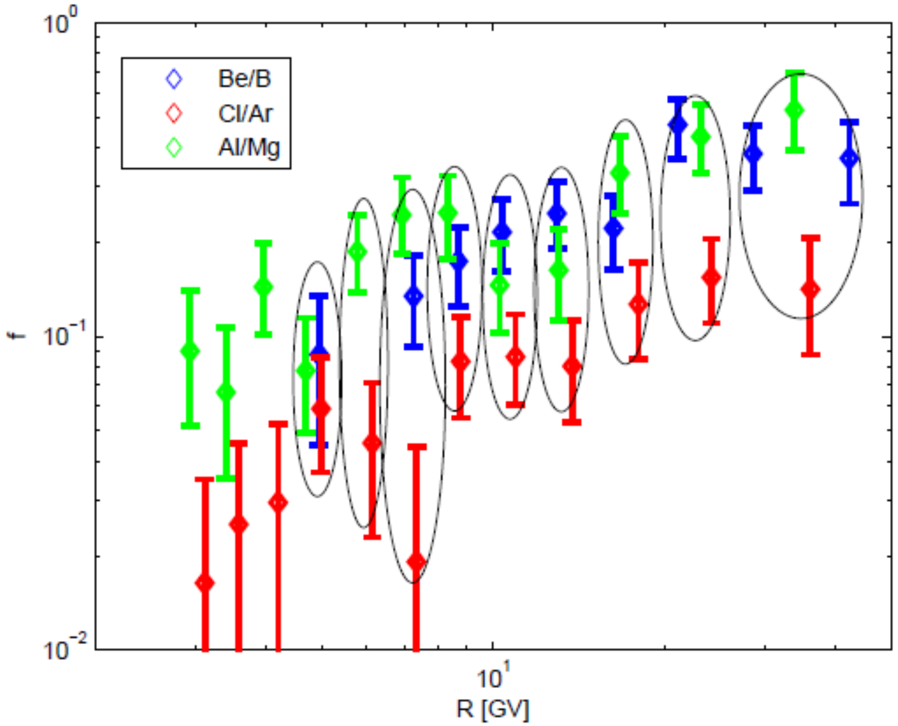
Radioactive nuclei: data

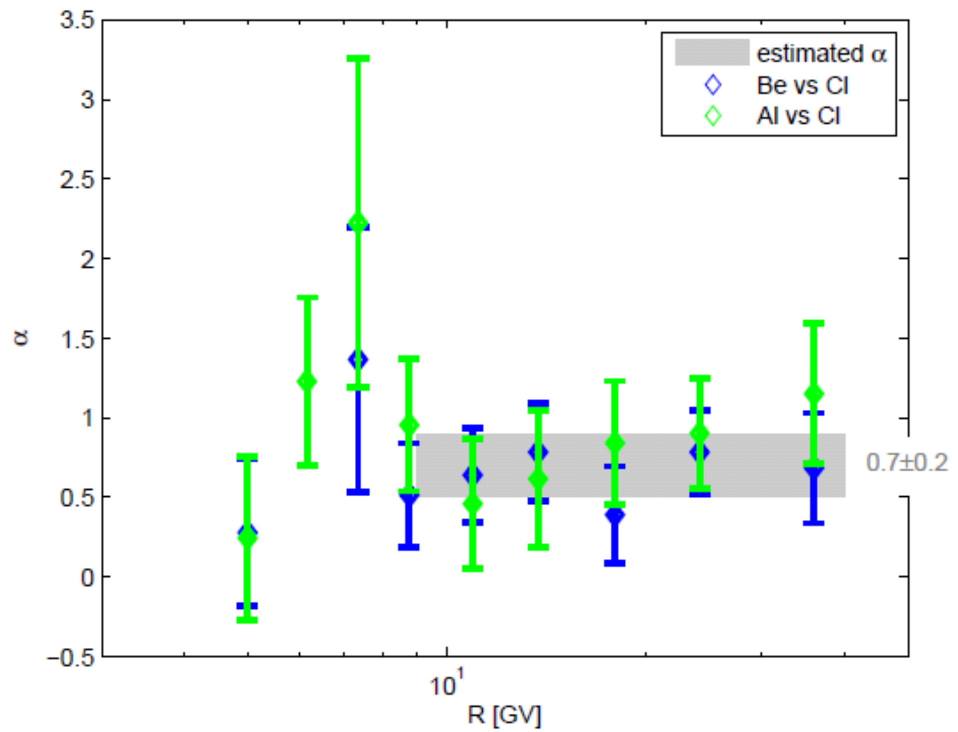
$$f_{s,i} \approx \left(\frac{t_i}{t_{\rm esc}}\right)^{\alpha}$$

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

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

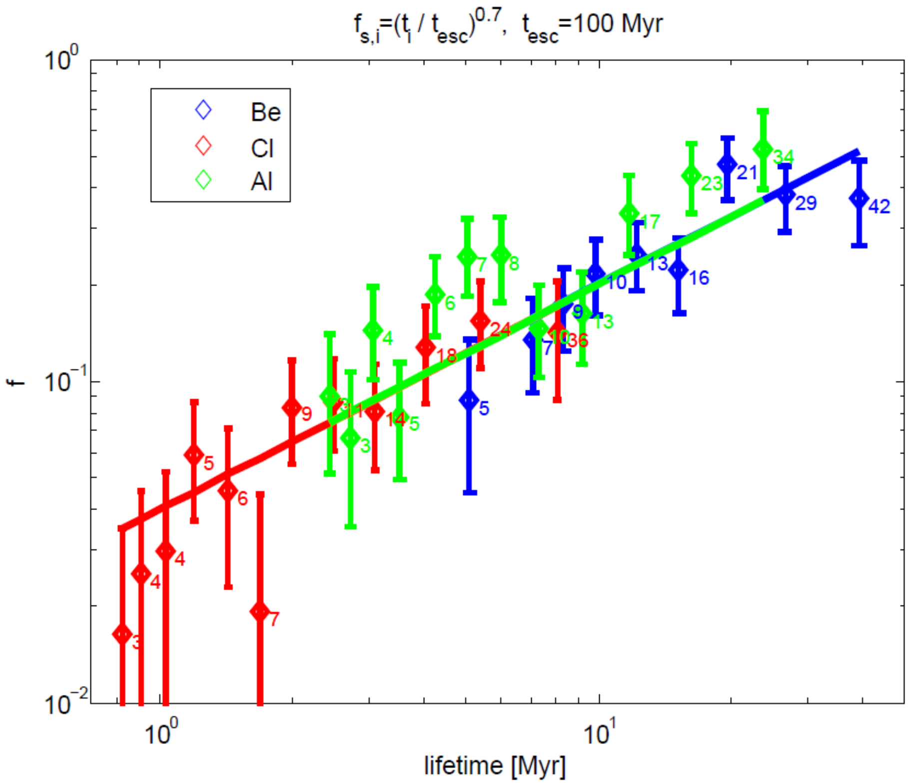
$$\Delta\alpha \propto 1/\log(\tau_i/\tau_j)$$

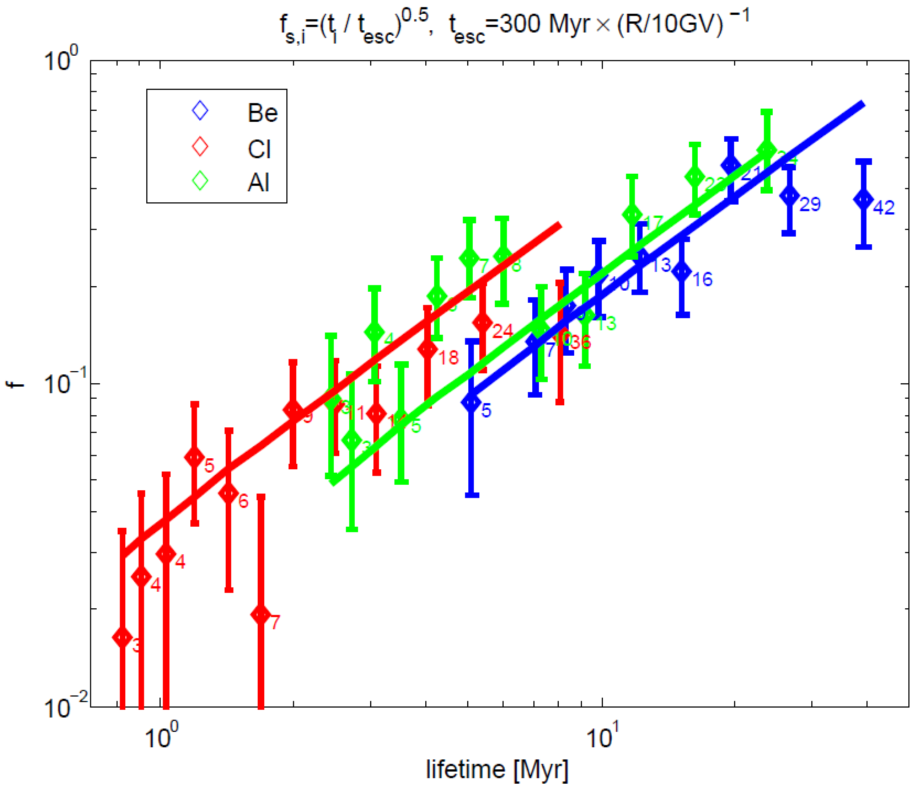




Radioactive nuclei: constraints on t_{esc}

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





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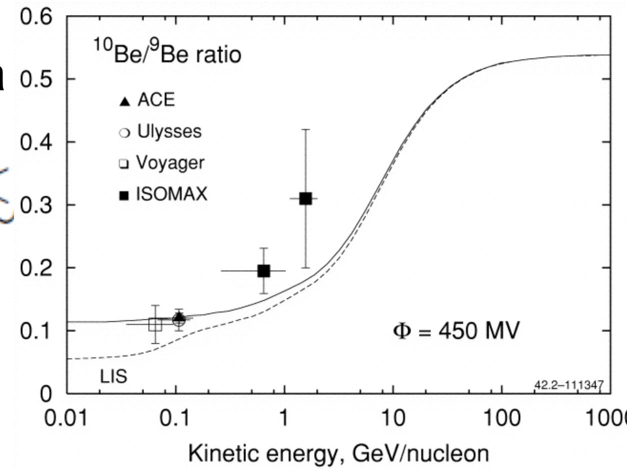
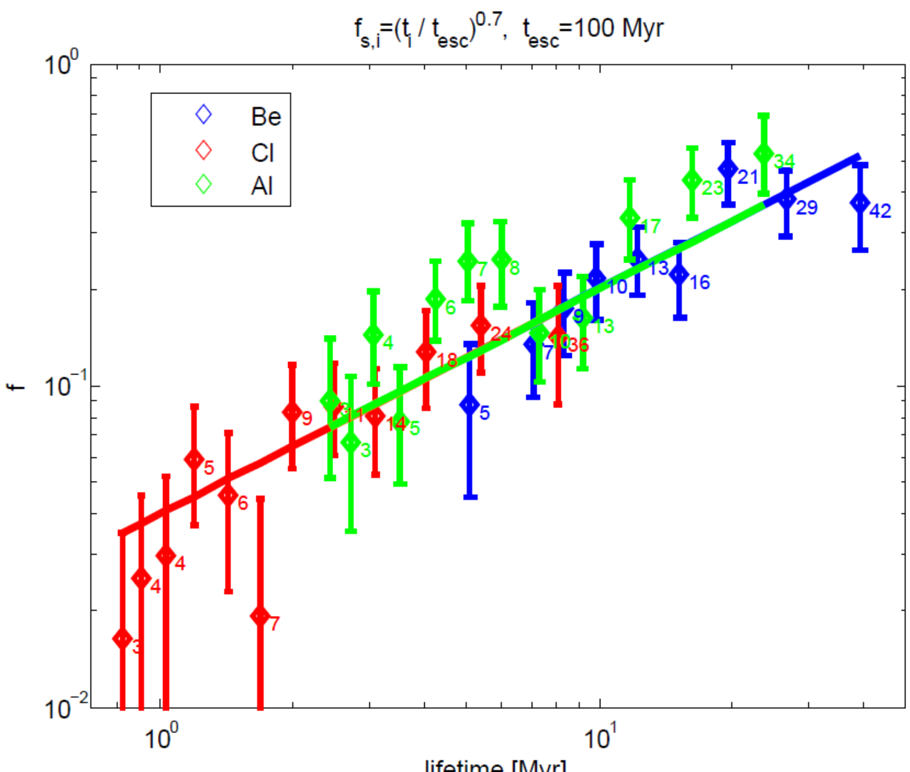
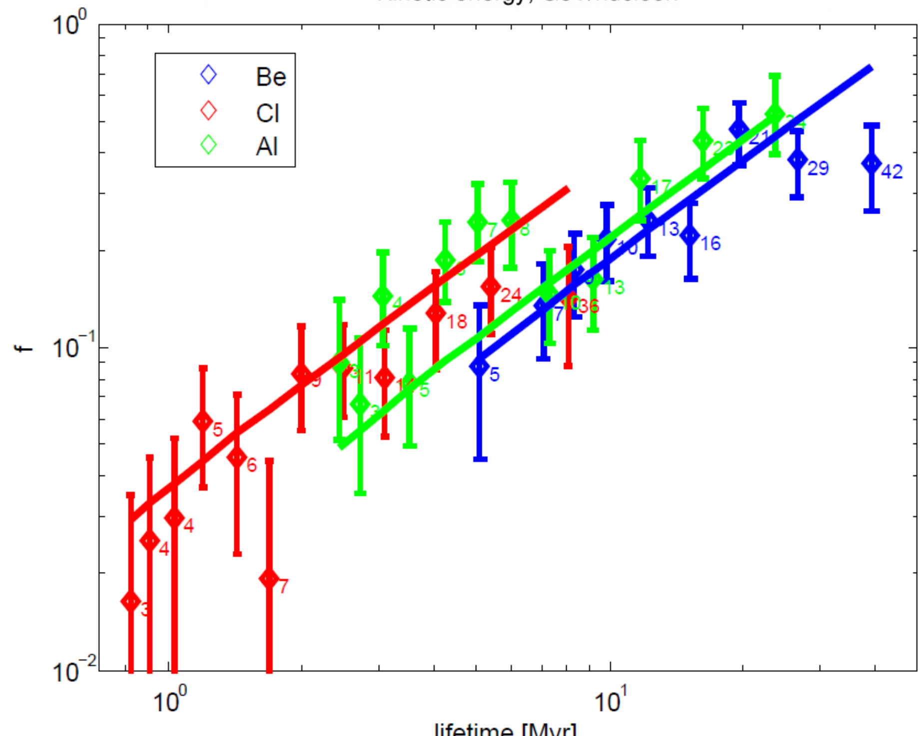
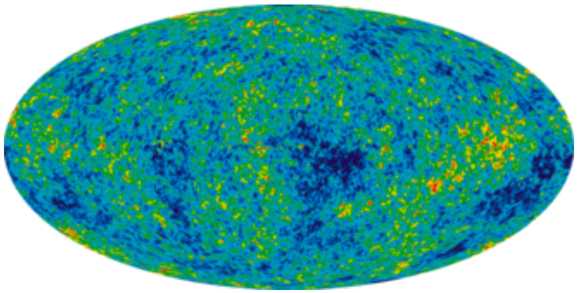


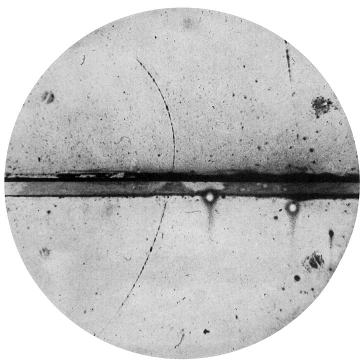


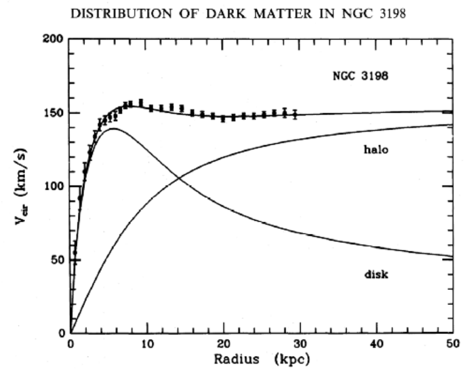


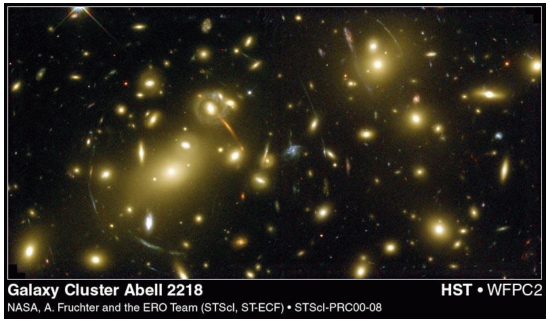
It is possible to learn something fundamental from astrophysical data.

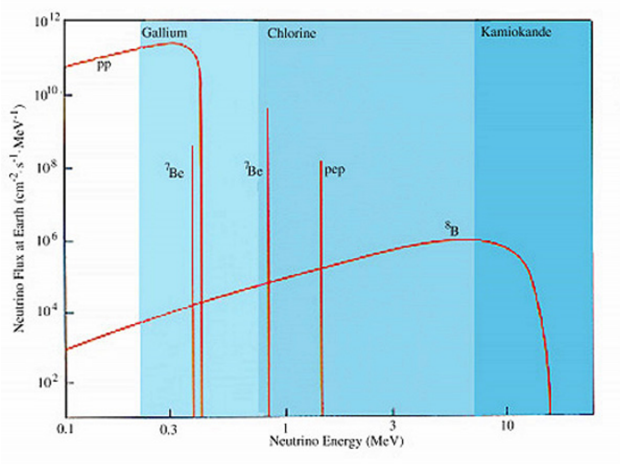
It has happened in the past

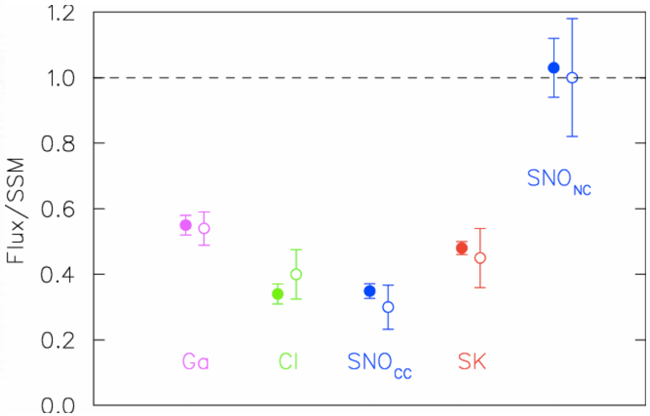


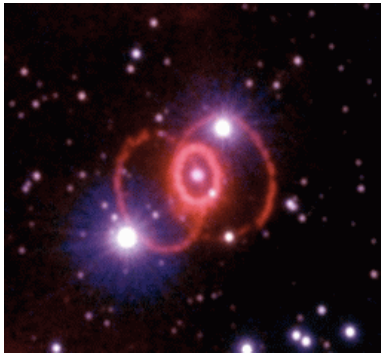












Example: The solar neutrino problem

• Major success of particle astrophysics

Case was only closed when astro uncertainties were removed model independently. Done from basic principles:

- Low energy deficit (Homestake) – T uncertainty?

- Smaller deficit at higher energy (Kamiokande)

  ➔ ***real* anomaly**

• **Lesson**:

model independent

no-go conditions