# High energy cosmic rays:
# (1) lessons from radioactive nuclei and positrons
# (2) robust tests for exotic sources

**Kfir Blum**

Katz, KB, Morag, Waxman; **MNRAS 405, 1458 (2010)**

KB; **JCAP 1111 (2011) 037**

+work in progress

**Fermilab**

**astro seminar 05/07/2012**

# Motivation: High energy cosmic rays

- Continuing data revolution: HESS, Fermi, ATIC, PAMELA, CREAM, DeepCore,…

  and **AMS02** is running

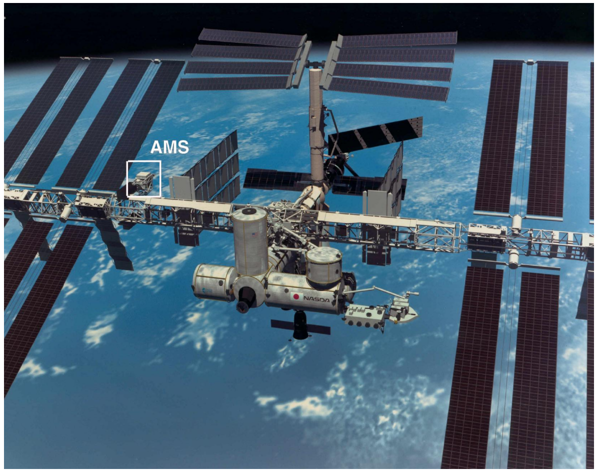
- **Even in *old* data, some rocks left to turn over**

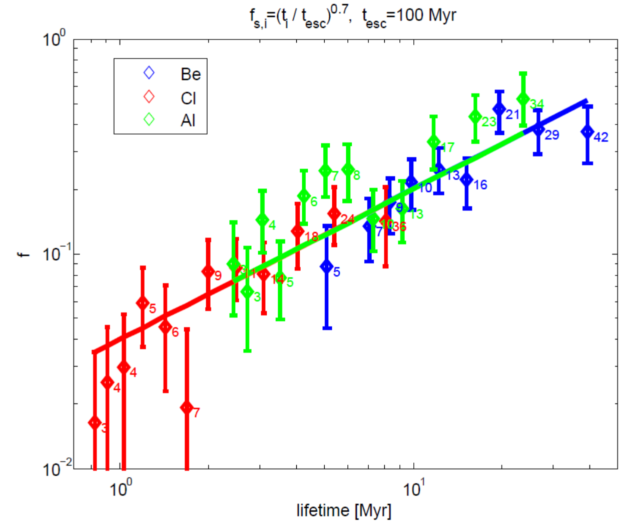
- Primordial **antmatter** extinct

  occurrence in HE CRs relatively well understood

➔ potential window to fundamental physics

**dark matter?** pulsars?



# Plan

- Cosmic rays: simple analysis of stable secondaries

  CR grammage

- Radioactive nuclei: propagation time

  Radioactive nuclei probe escape time up to (surprisingly) high energy

- Positrons, antiprotons;  PAMELA and Fermi

  Know injection → learn propagation

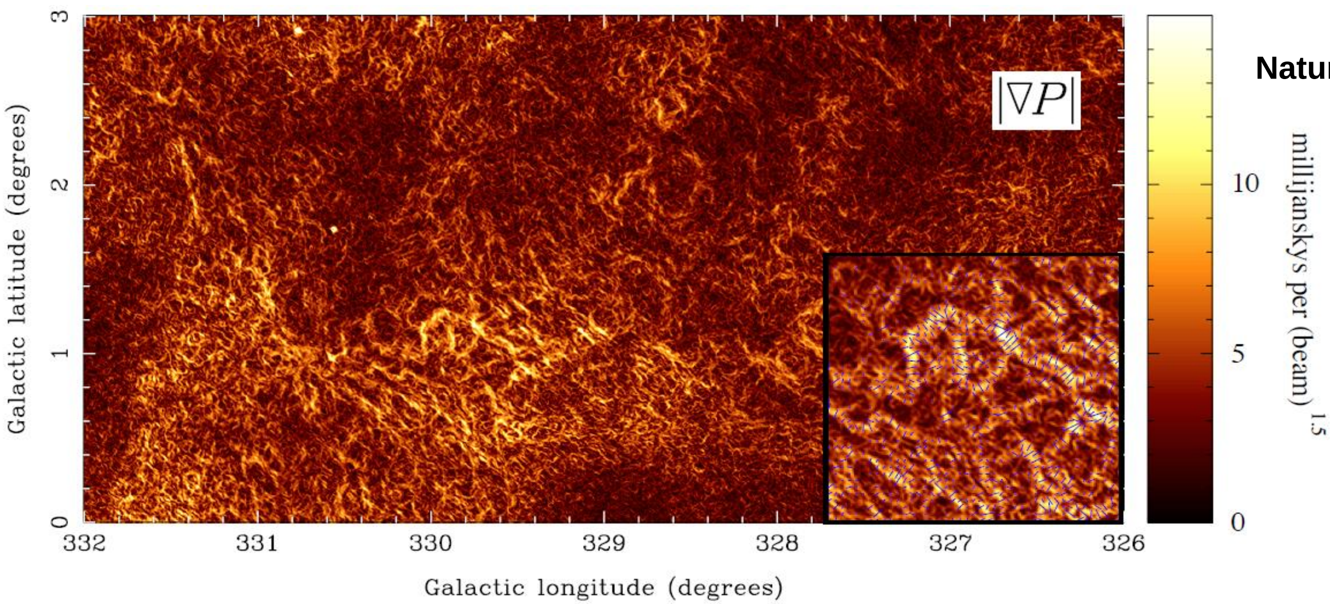
  Robust tests for secondary hypothesis

# Galactic CRs: lightning review

- CRs fill our Galaxy. Galactic: up to ~ PeV (at least). Energy density ~ eV/cm$^3$
- **Primaries**: p, C, Fe, … consistent w/ stellar material, shock-accelerated
- **Secondaries**: B, Be, Sc, Ti, V, … consistent w/ fragmentation of primaries on ISM

**Antimatter occurs as secondary** $pp \rightarrow pn\pi^+ \rightarrow ppe^-e^+\nu_e\bar{\nu}_e\nu_\mu\bar{\nu}_\mu$

- Open questions: propagation, primary source(s)



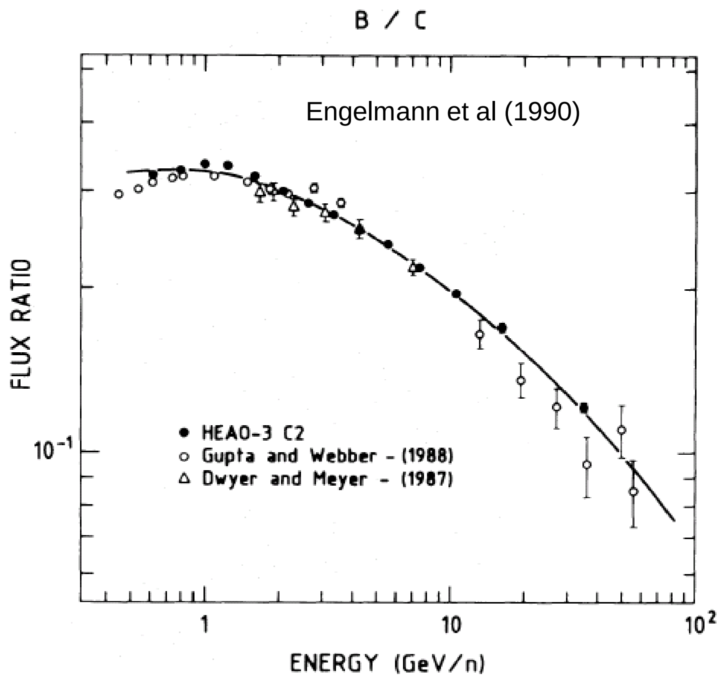

Gaensler et al
Nature 478 (2011) 214-217

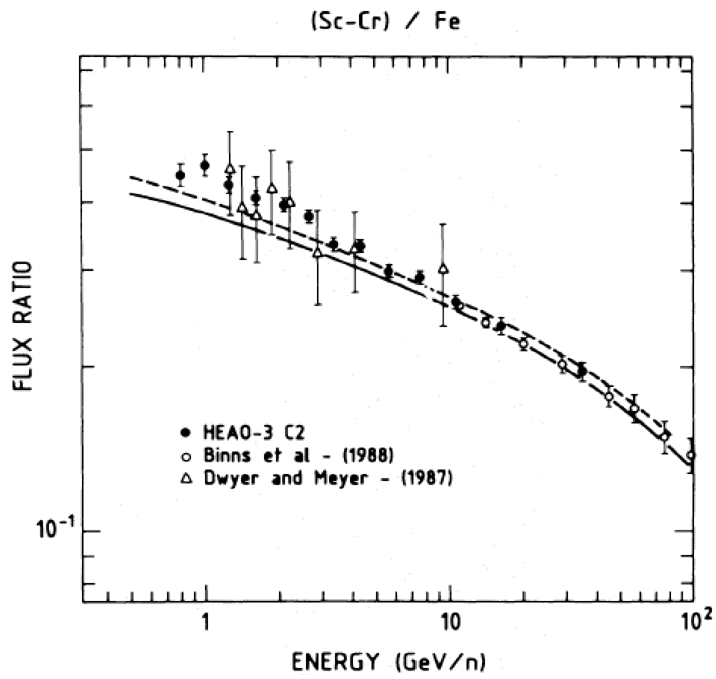
# A simple analysis of stable secondaries

- At high energy, flux of stable secondary nuclei follows *empirical* relation:

$$J_S = \frac{c}{4\pi} X_{\rm esc}\, \tilde{Q}_S \qquad (S = {}^9{\rm Be},\ {\rm B},\ {\rm Sc},\ \bar{p},\ \ldots)$$

- $\tilde{Q}_S$ = Local net production density per traversed unit column density of ISM
- $X_{\rm esc}$ = CR **grammage** = mean column density. $X_{\rm esc}$ : *no* species label, *S*



# CR grammage $J_S = \frac{c}{4\pi} X_{\rm esc} \tilde{Q}_S$

- Measured from B/C, sub-Fe/Fe $X_{\rm esc}(\mathcal{R}) \approx 8.7 \left( \frac{\mathcal{R}}{10\,{\rm GV}} \right)^{-0.5} {\rm g/cm^2}$

- Precise way by which $X_{\rm esc}$ comes about is unknown

- Equivalent to: $\frac{n_A}{n_B} = \frac{\tilde{Q}_A}{\tilde{Q}_B}$ ☆

A,B secondaries, compared at the same rigidity

**Intuition**: ISM bombarded by CRs. Yields $N_{A,B}$ secondary particles per unit time. $N_A/N_B$ depends on CR and ISM *composition*.
If composition uniform everywhere ➔ expect ☆

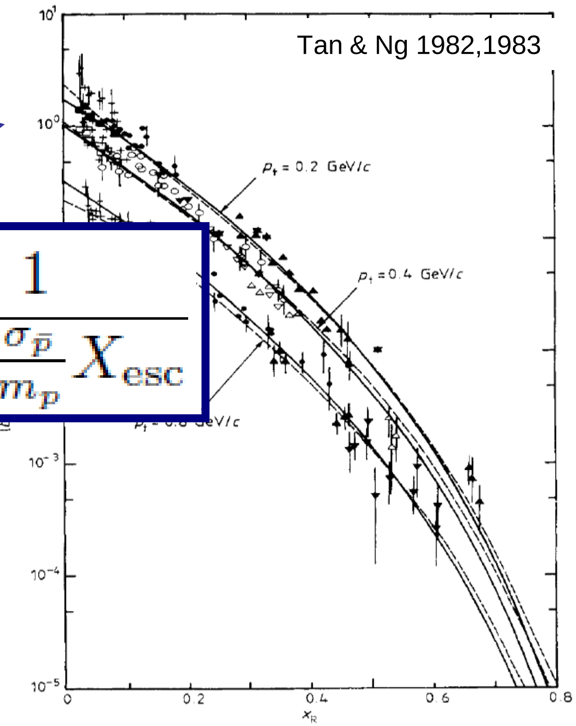
- Sufficient condition:

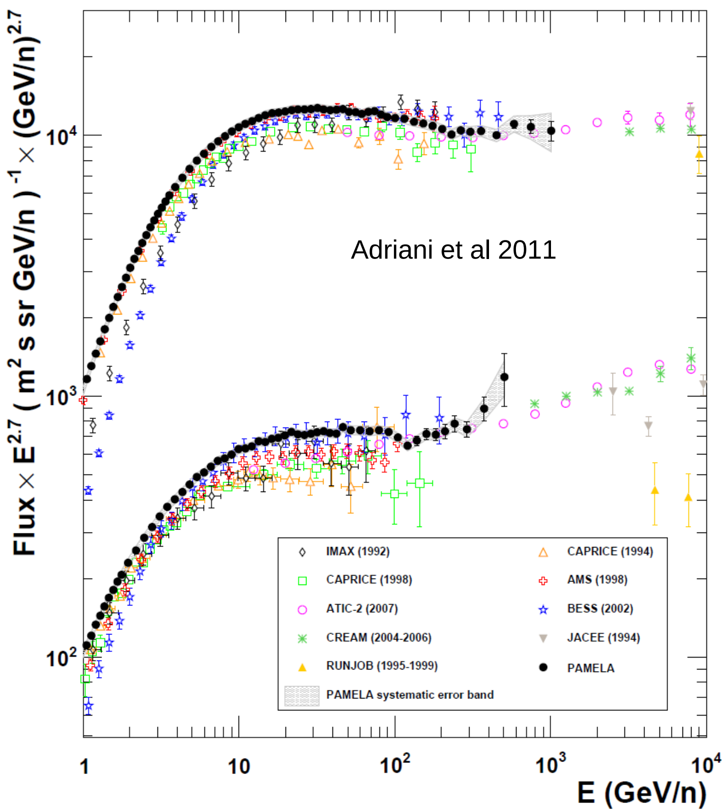
*Composition of CRs and of ISM approximately uniform, in regions where most secondaries observed at earth are produced*

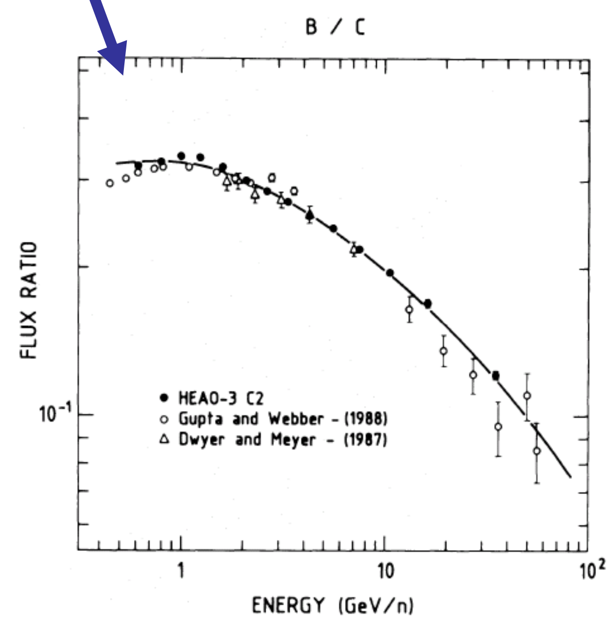
# Example: antiprotons

No free parameters.

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



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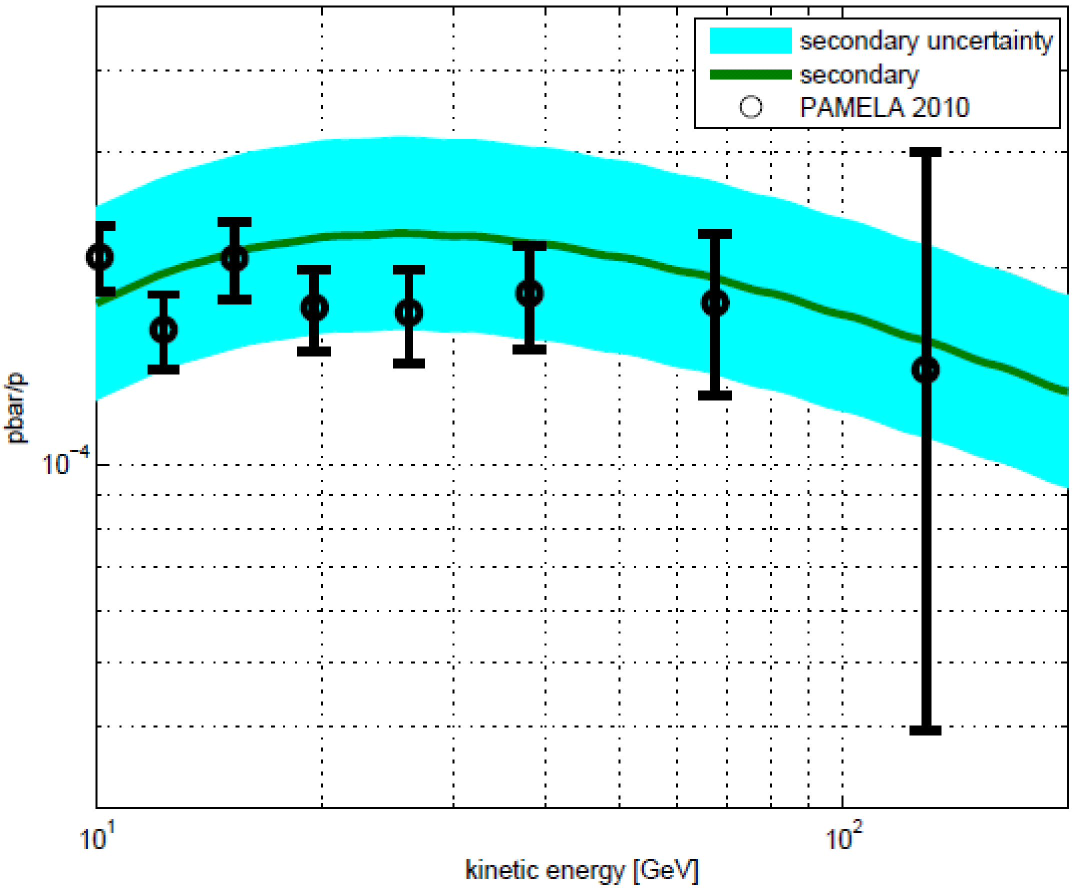
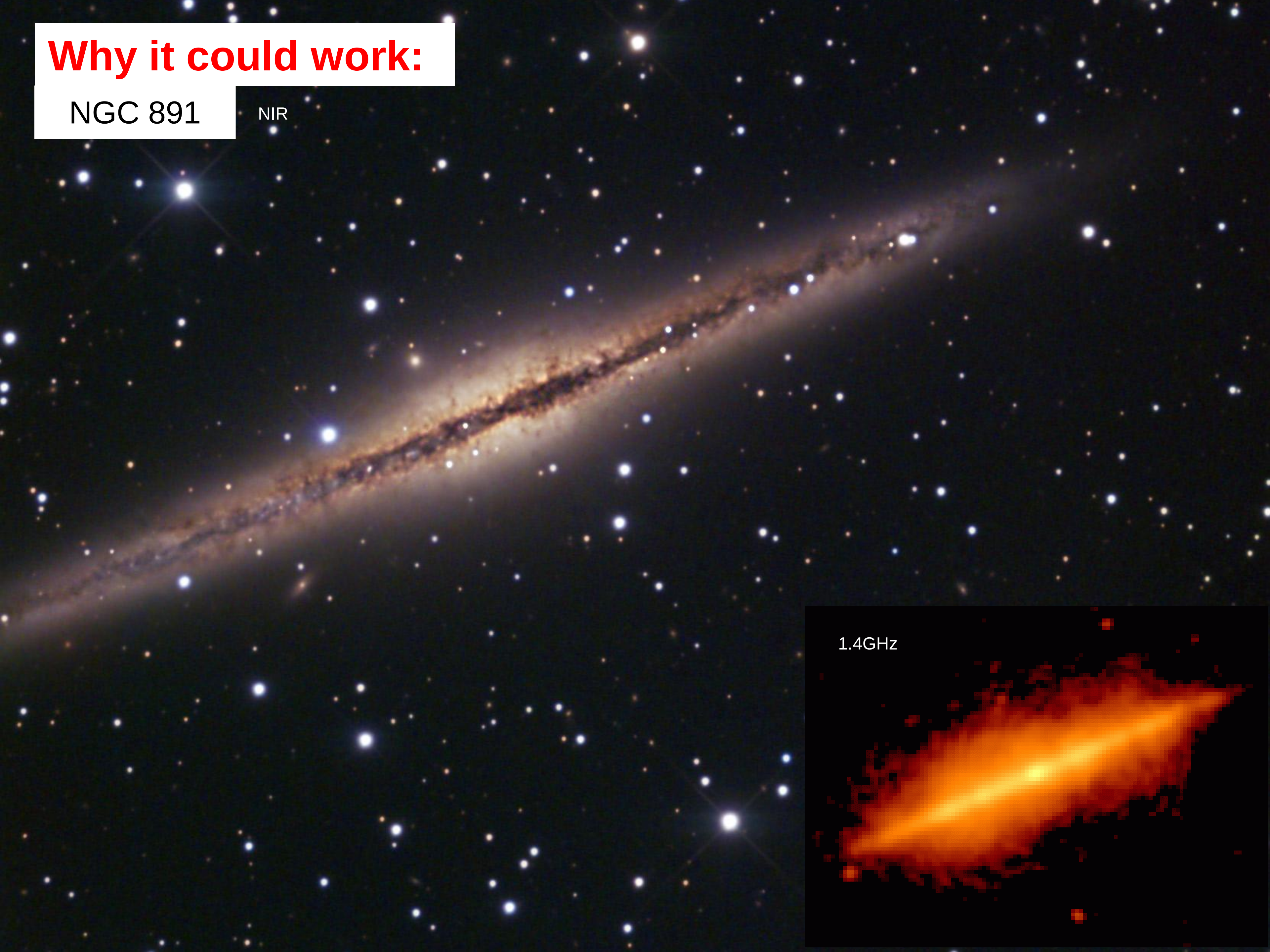


# Why does it work so well?

# Why it could work:

NGC 891

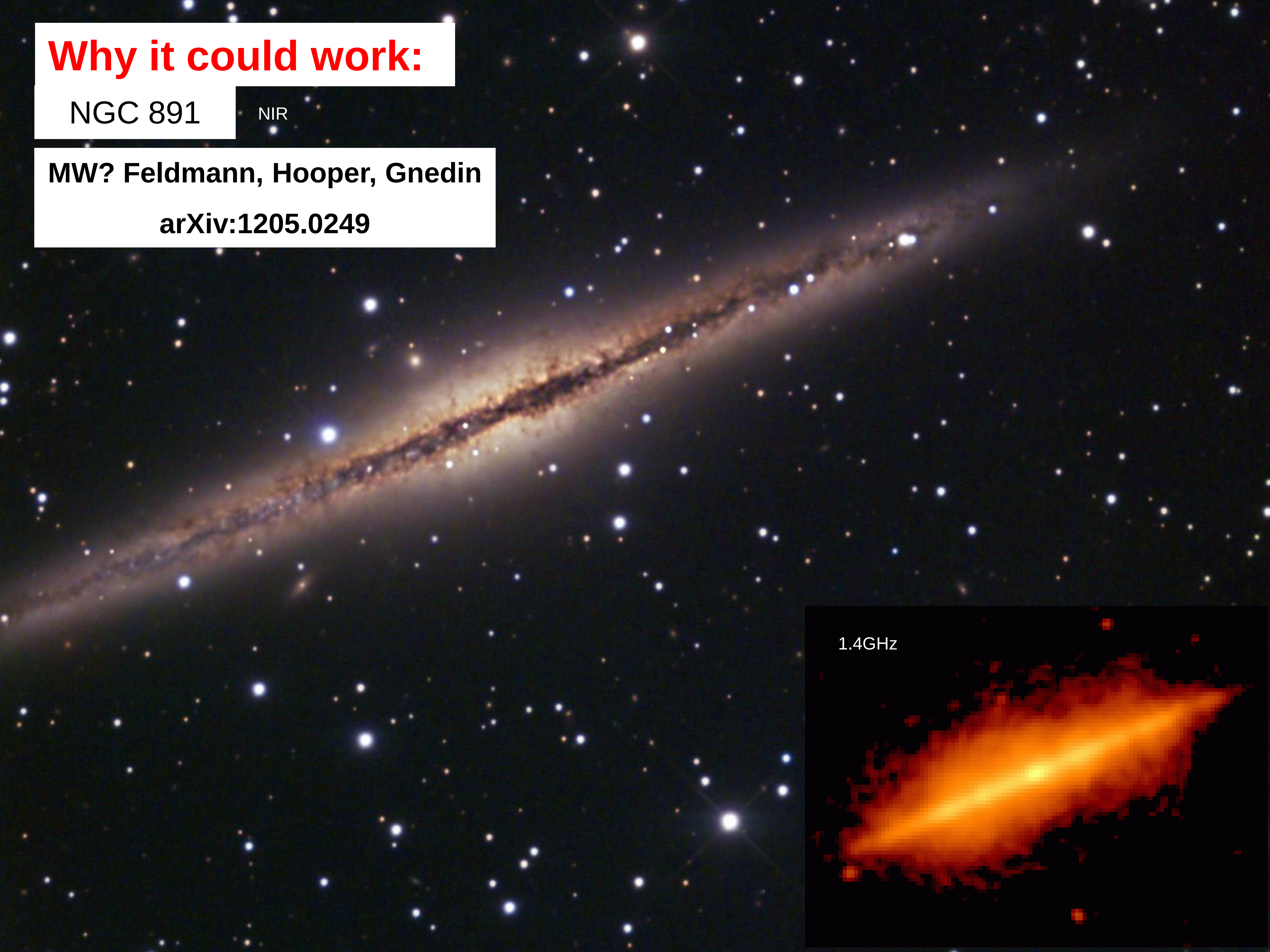


# Why it could work:

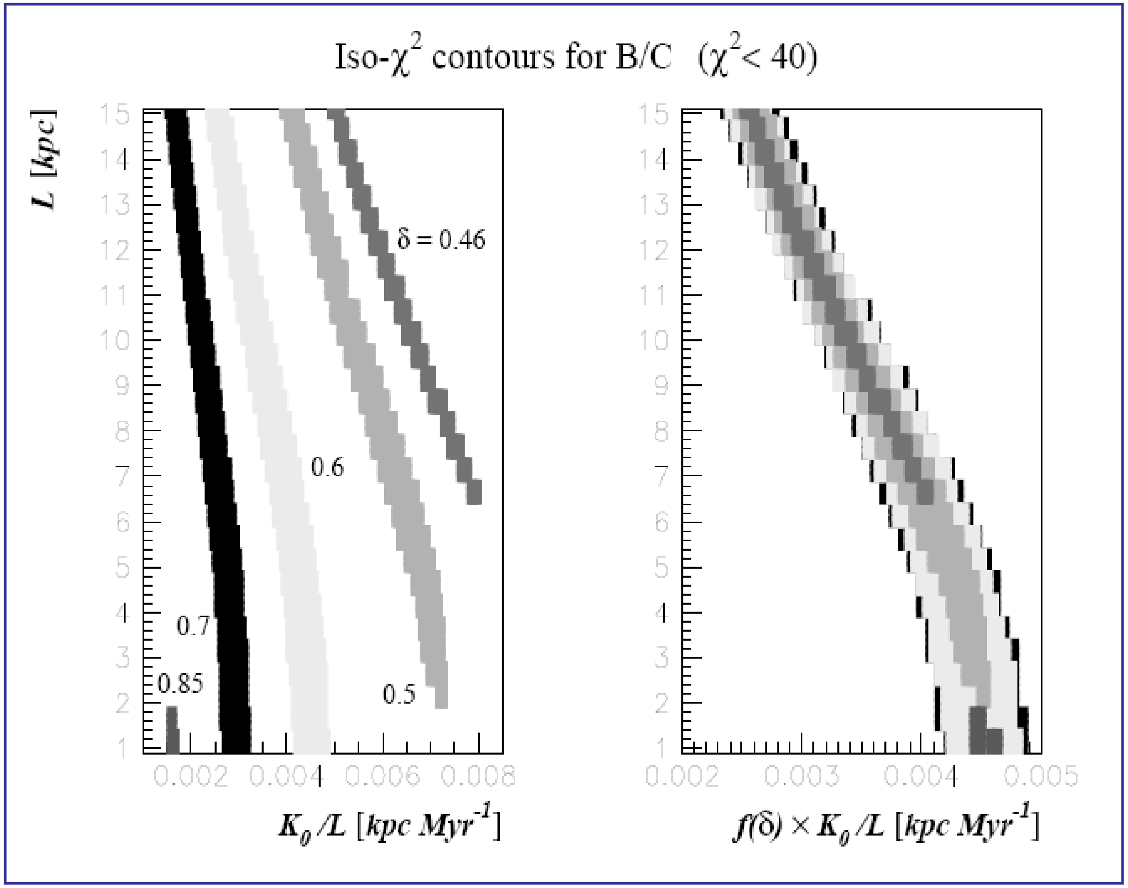
NGC 891

**MW? Feldmann, Hooper, Gnedin**

**arXiv:1205.0249**



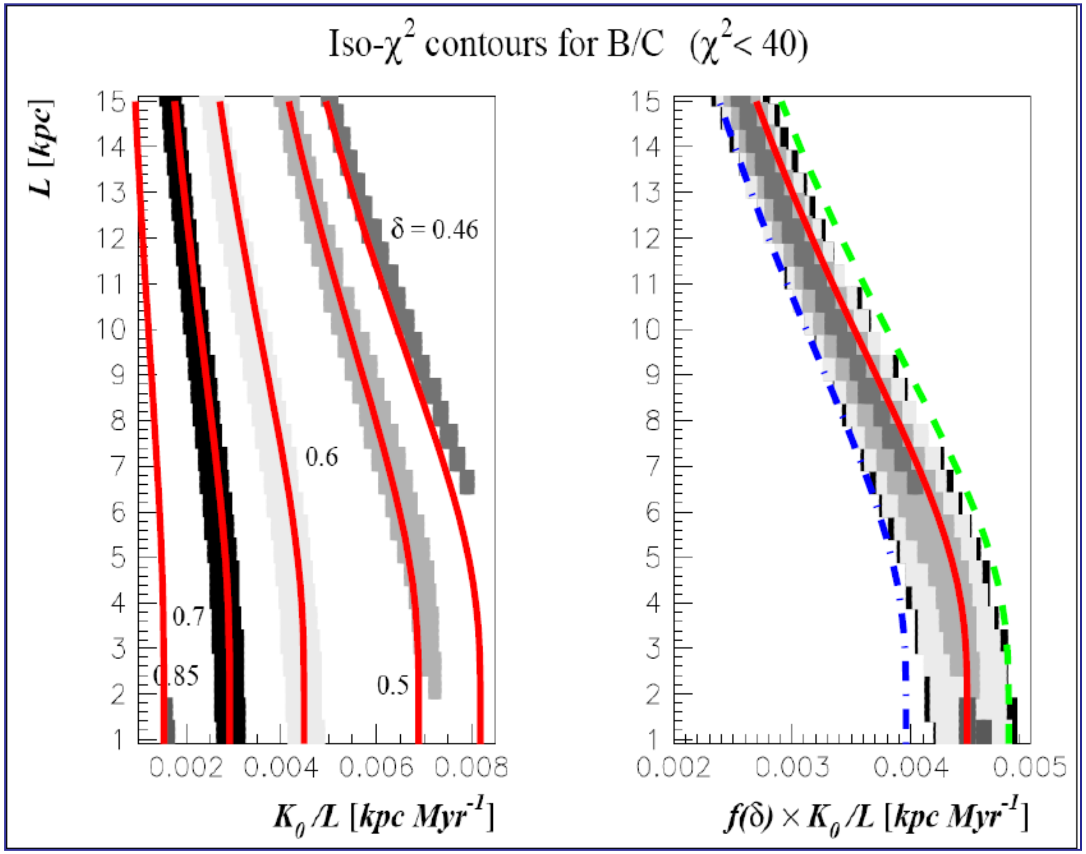
# Diffusion models fit grammage




**Maurin, Donato, Taillet, Salati**

**Astrophys.J.555:585-596,2001**

# Diffusion models fit grammage




$$X_{\rm esc} = X_{\rm disc} Lc/(2D) g(L/R) \propto \varepsilon^{-\delta}$$

$$\Rightarrow \quad f(\delta) = (\varepsilon/\ \mathrm{GeV})^{\delta-0.6} \approx 75^{\delta-0.6}$$

$$g(L/R) = \frac{2R}{L} \sum_{k=1}^{\infty} J_0\left(\nu_k \frac{r_s}{R}\right) \frac{\tanh\left(\nu_k \frac{L}{R}\right)}{\nu_k^2 J_1(\nu_k)}$$

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# Propagation time scales: radioactive nuclei

B/C teach us the mean column density of target material traversed by CRs

But it does not say much about 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 (as do positrons)

# 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 )

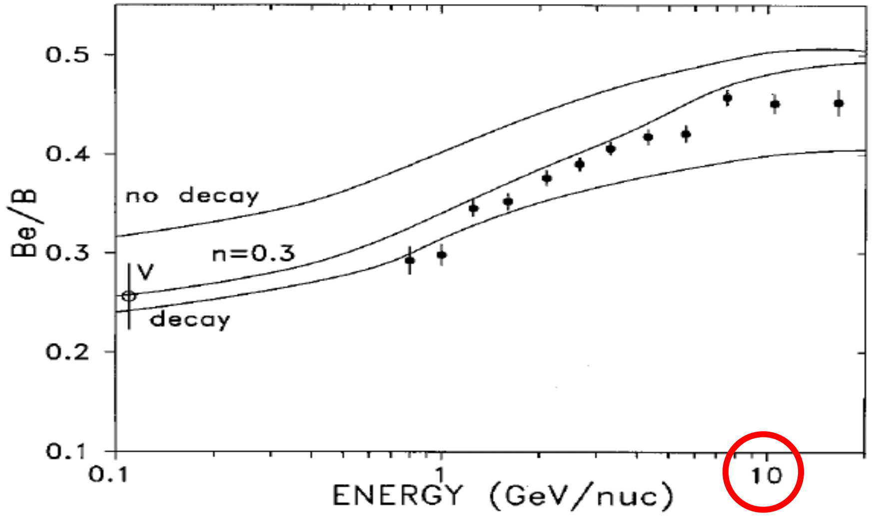
• **Benefit**: avoid low energy complications; significant range in rigidity

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

# Radioactive nuclei: Charge ratios vs. isotopic ratios

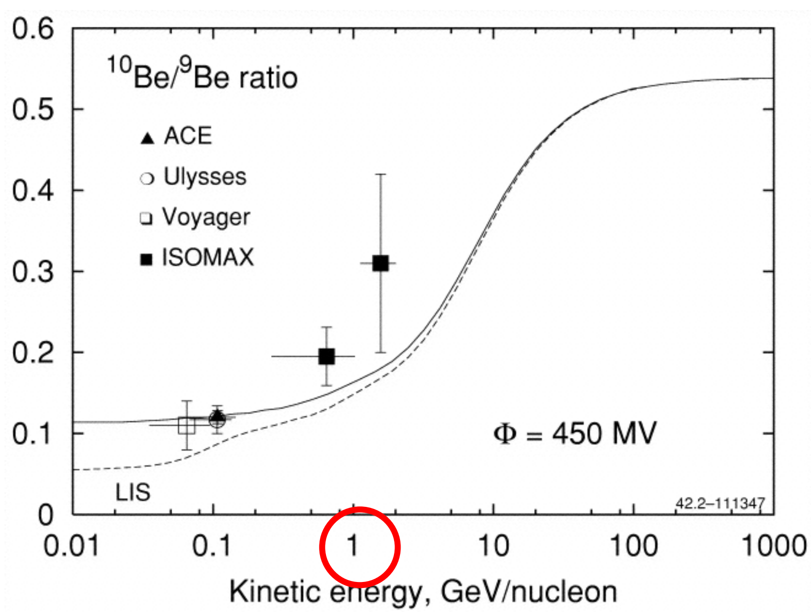
Charge ratios

Be/B, Al/Mg, Cl/Ar




Isotopic ratios

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



# Radioactive nuclei: Charge ratios

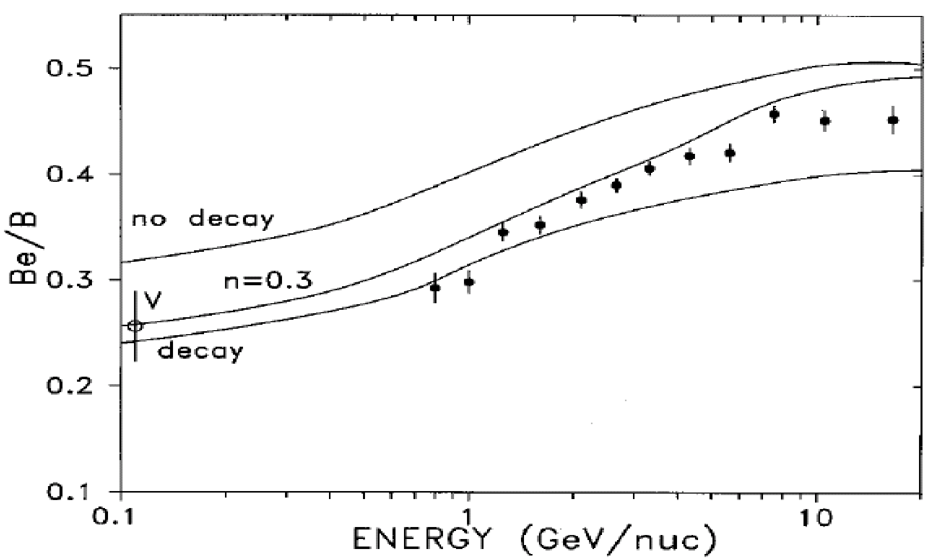
A STUDY OF THE SURVIVING FRACTION OF THE COSMIC-RAY RADIOACTIVE DECAY ISOTOPES $^{10}$Be, $^{26}$Al, $^{36}$Cl, and $^{54}$Mn AS A FUNCTION OF ENERGY USING THE CHARGE RATIOS Be/B, Al/Mg, Cl/Ar, AND Mn/Fe MEASURED ON *HEAO–3*

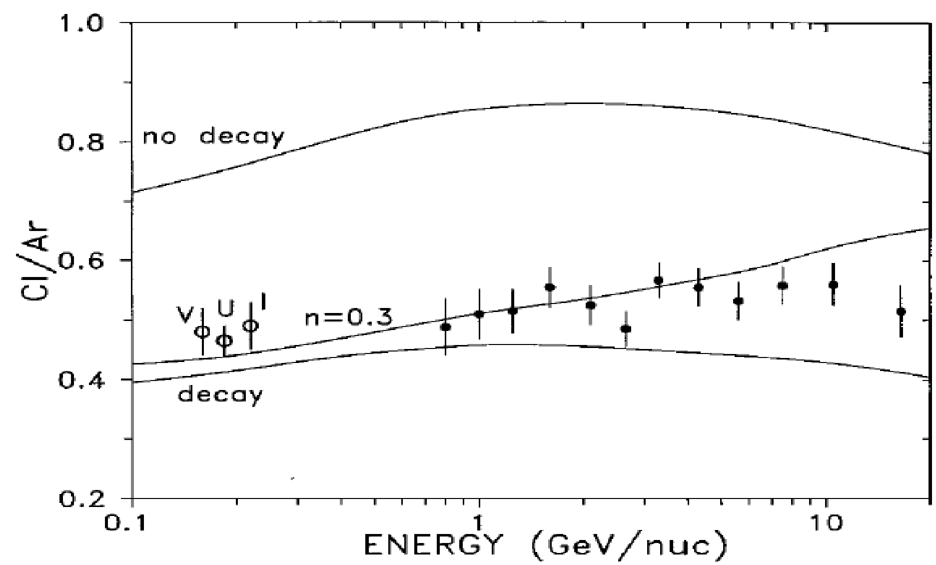
W. R. Webber[1] and A. Soutoul

*Received 1997 November 6; accepted 1998 May 11*

(WS98)

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



# 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

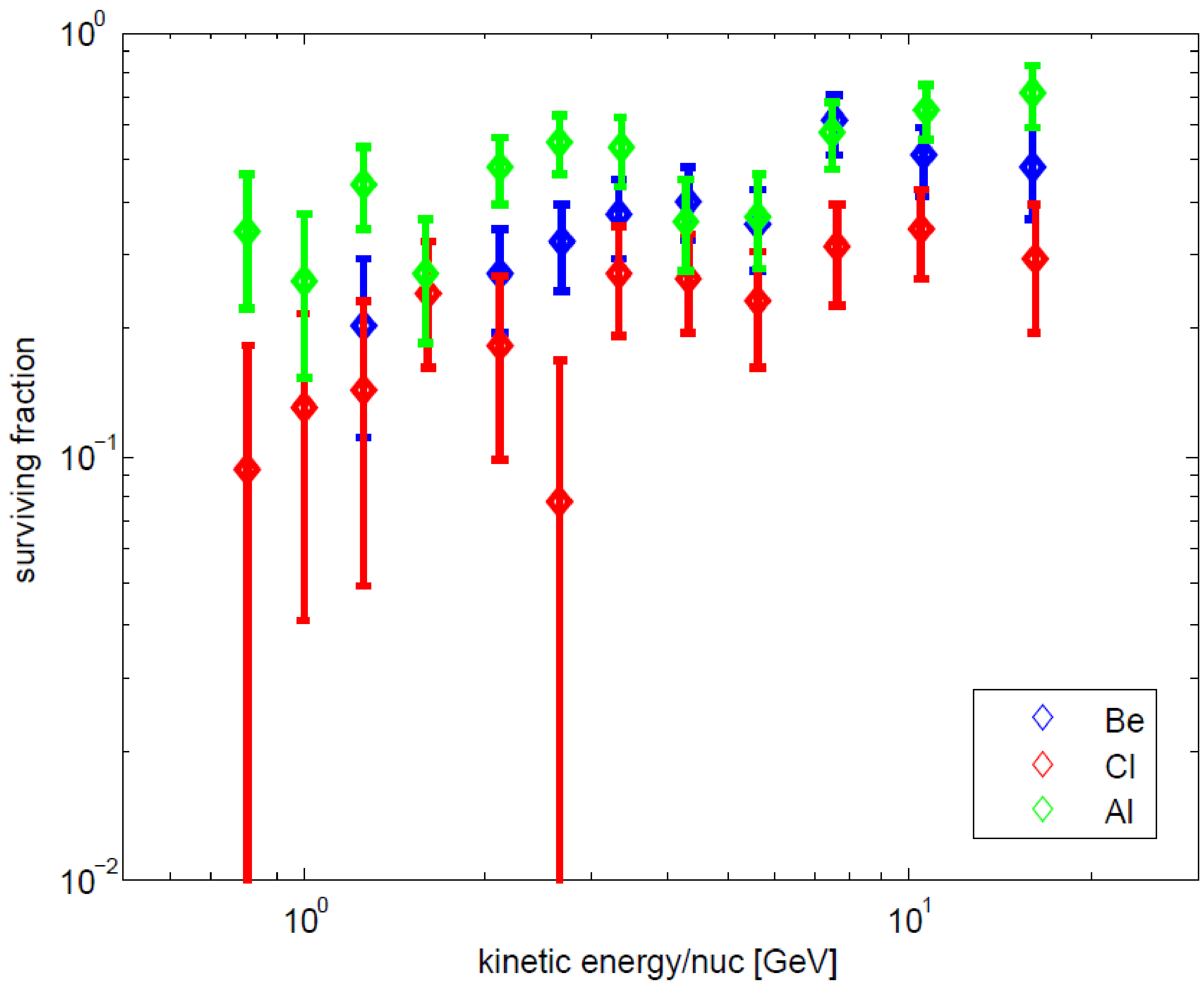
- Expect $t_{\rm esc} = t_{\rm esc}(\mathcal{R})$ , $f_{s,i} \approx \left(\frac{t_i}{t_{\rm esc}}\right)^{\alpha}$

Examples:

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

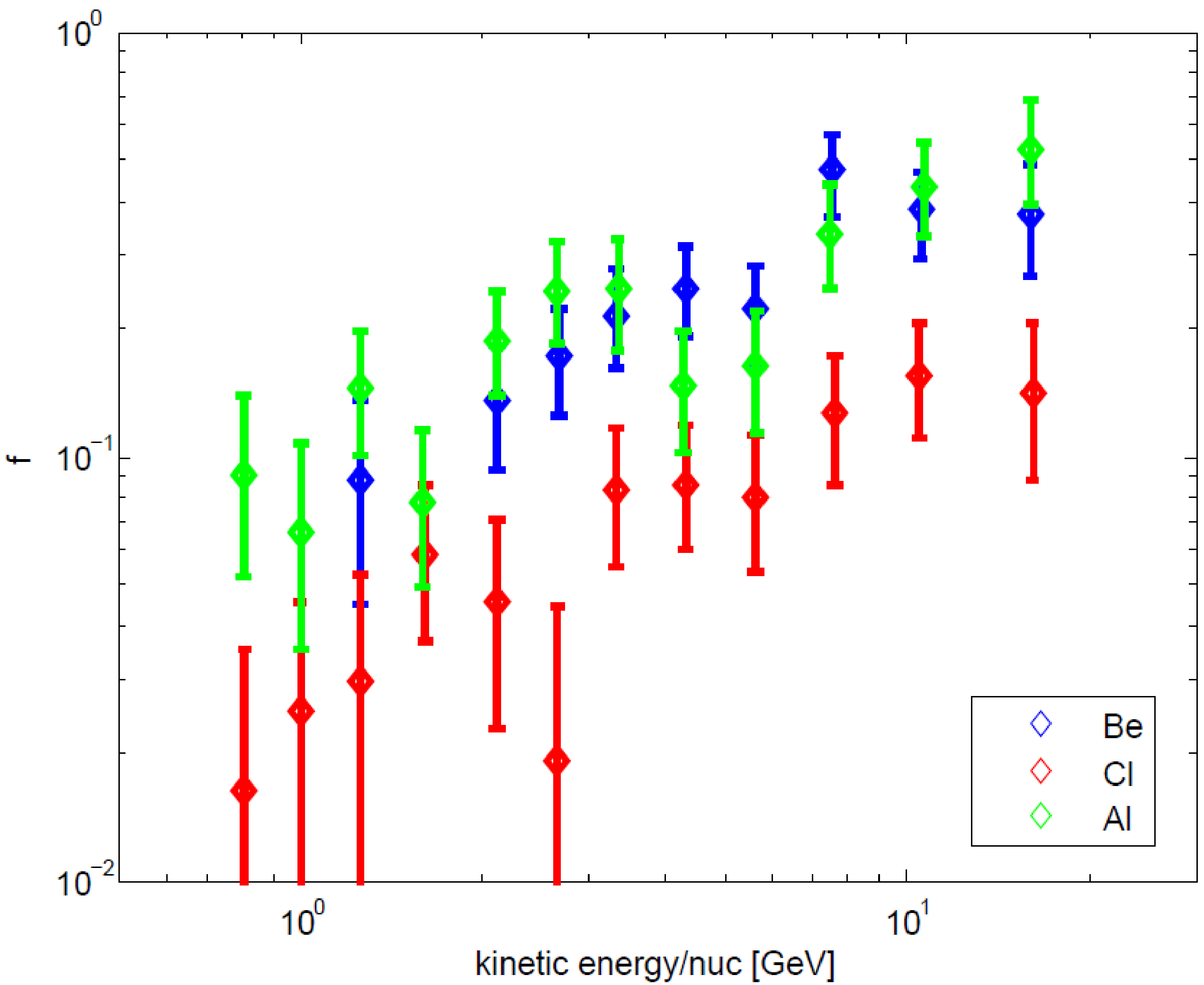
# Radioactive nuclei: data

Surviving fraction vs. energy (WS98)



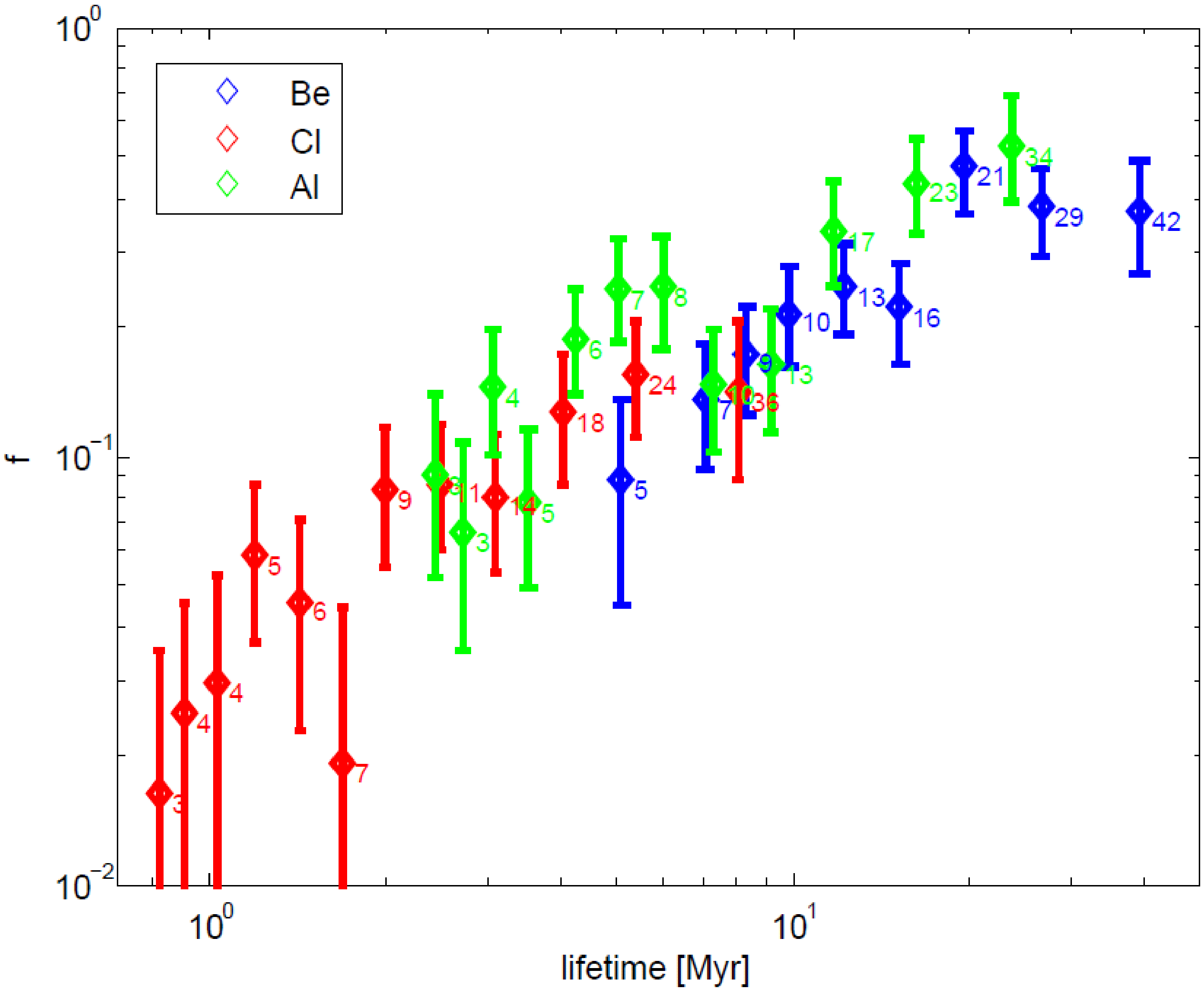
# Radioactive nuclei: data

Suppression factor vs. energy



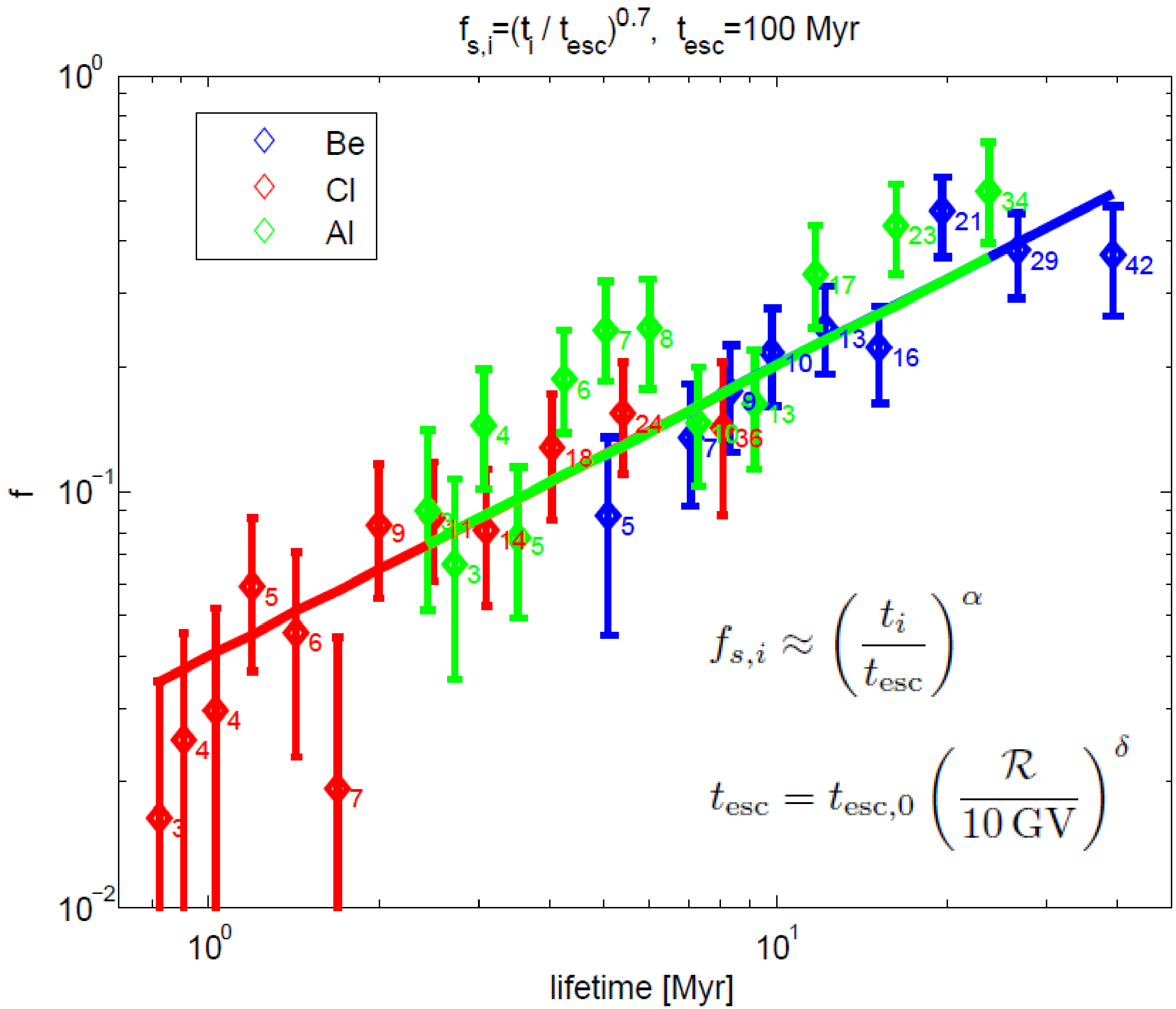
# Radioactive nuclei: data

Suppression factor vs. lifetime



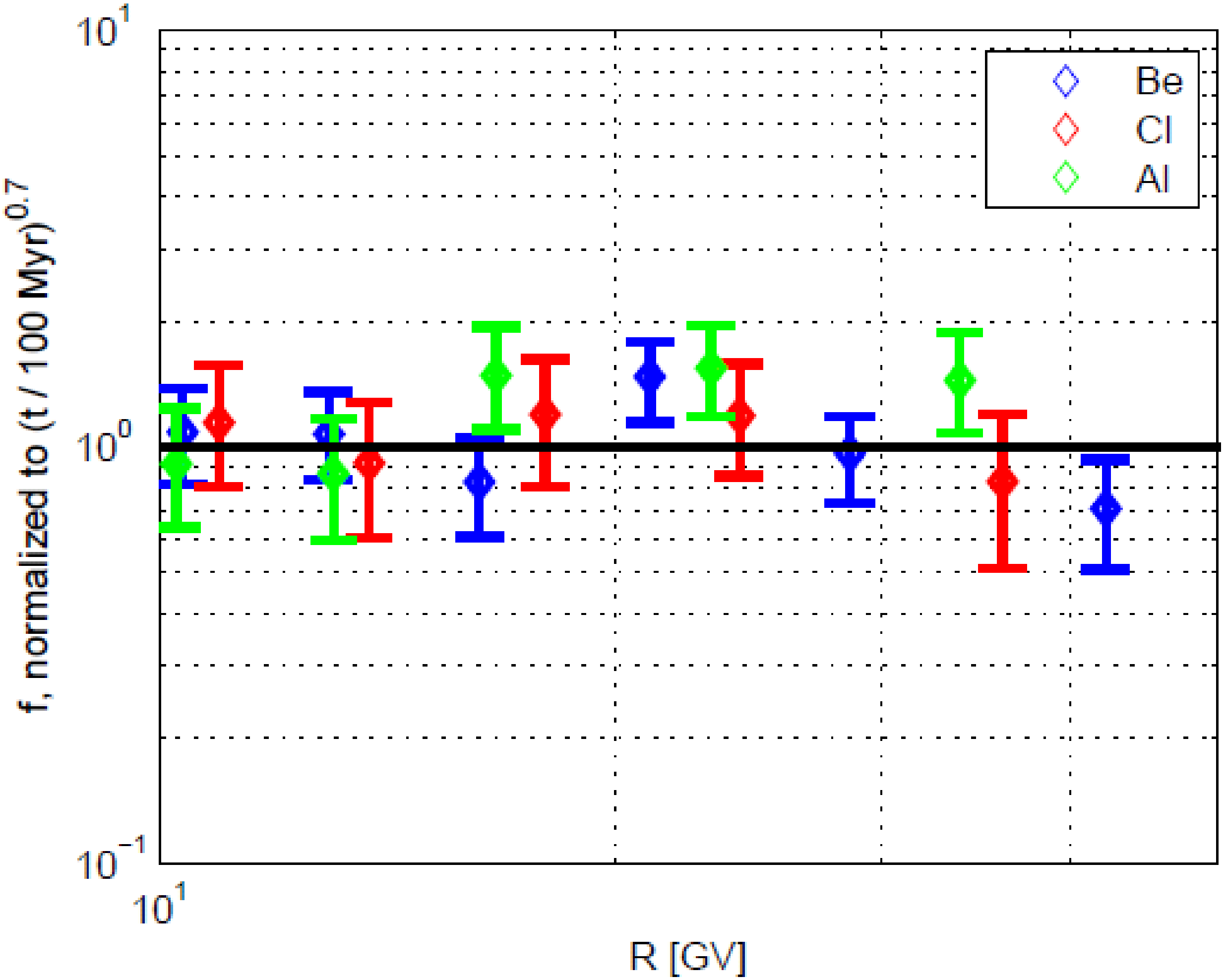
# Radioactive nuclei: data

Consistent with constant residence time



# Radioactive nuclei: data

Residual rigidity dependence



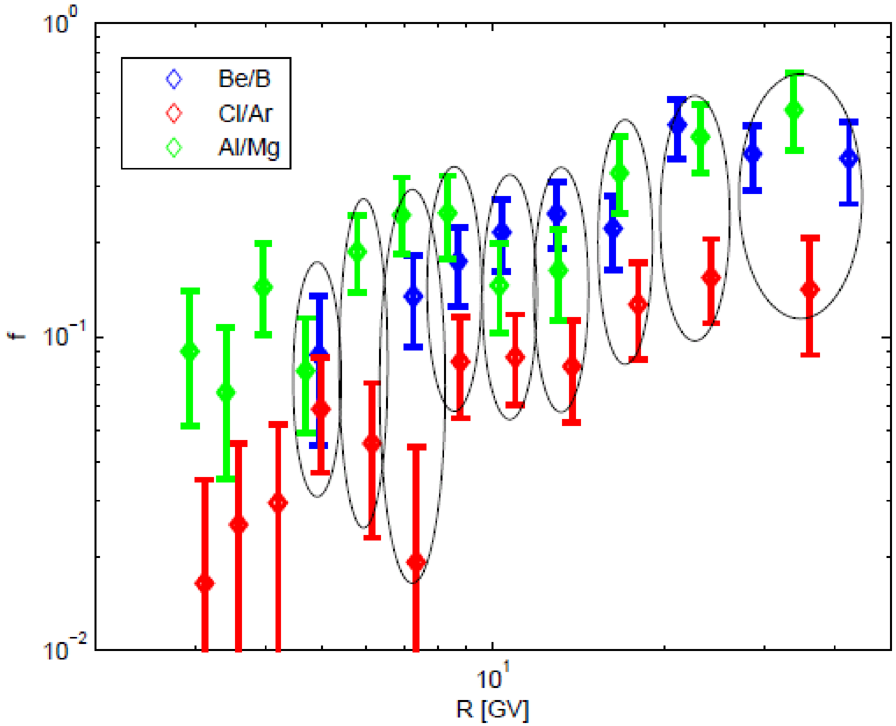
# Radioactive nuclei: data

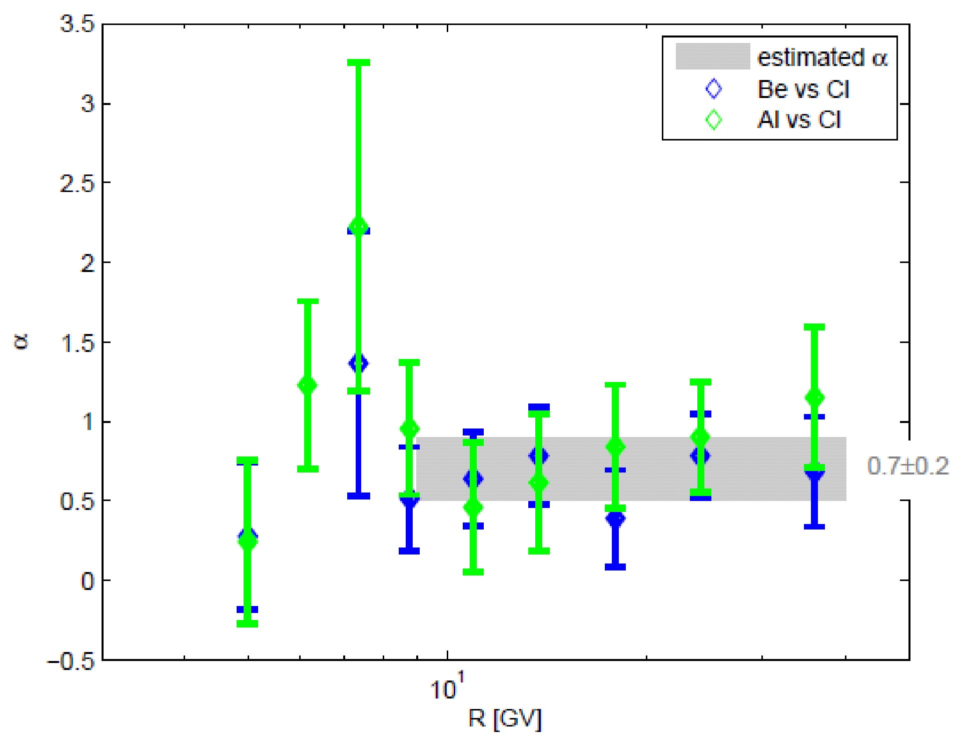
$$f_{s,i} \approx \left( \frac{t_i}{t_{\rm esc}} \right)^{\alpha}$$

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

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

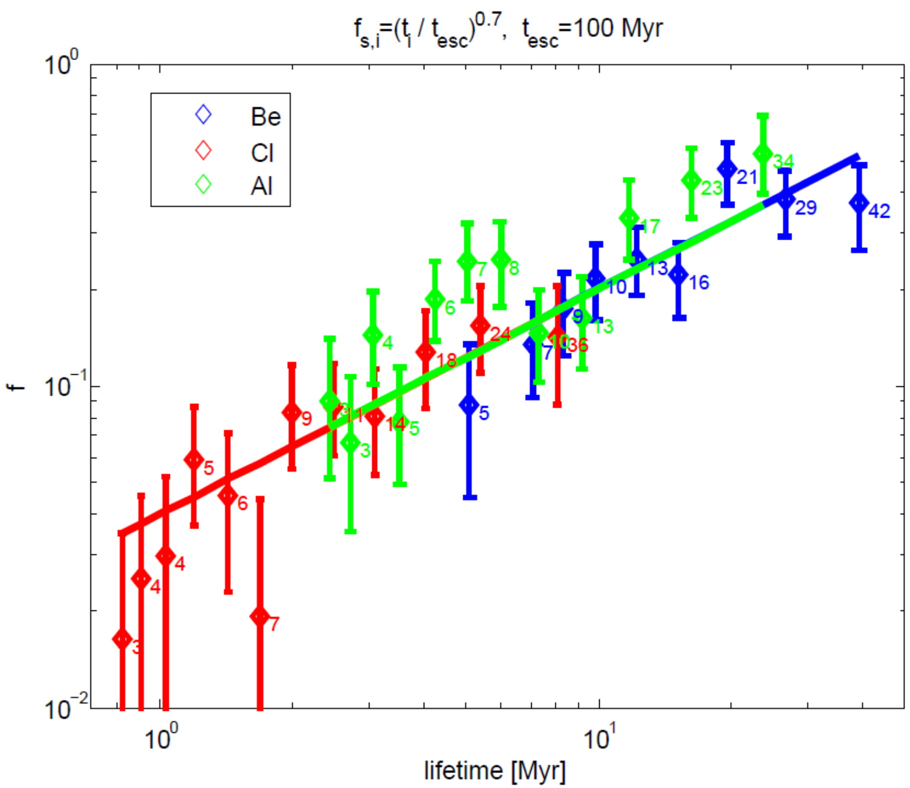
$$\Delta\alpha \propto 1/\log\left(\tau_i/\tau_j\right)$$

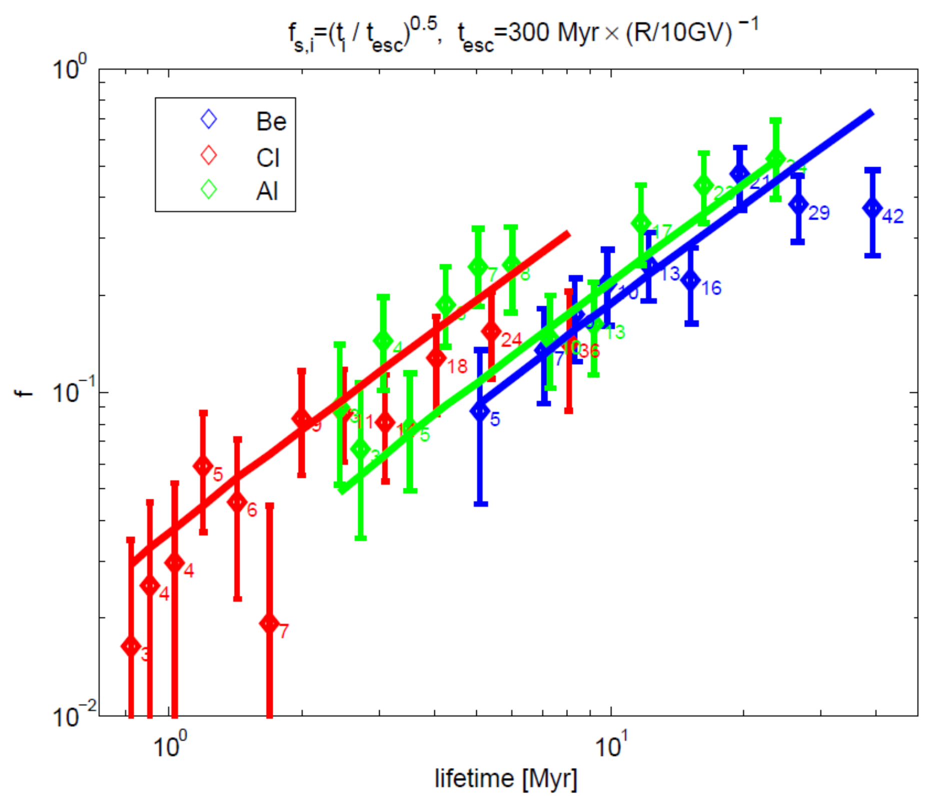


# Radioactive nuclei: constraints on $t_{\mathrm{esc}}$

- Rigidity dependence:  hints from current data
- Cannot (yet) exclude $\delta < -1$ with $\alpha \lesssim 0.5$
- **AMS-02 should do much better!** Looking forward to the verdict: will it stay?



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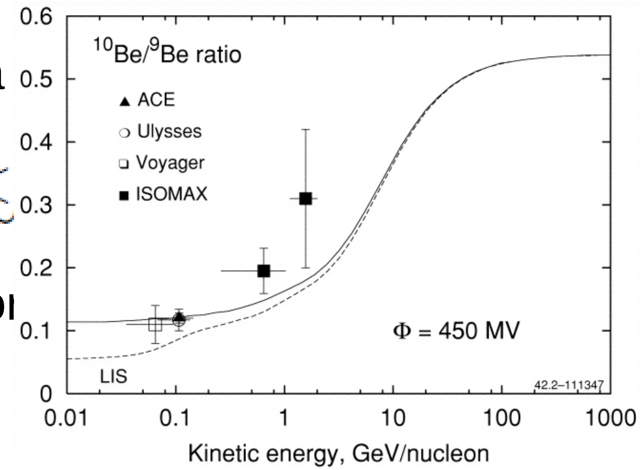


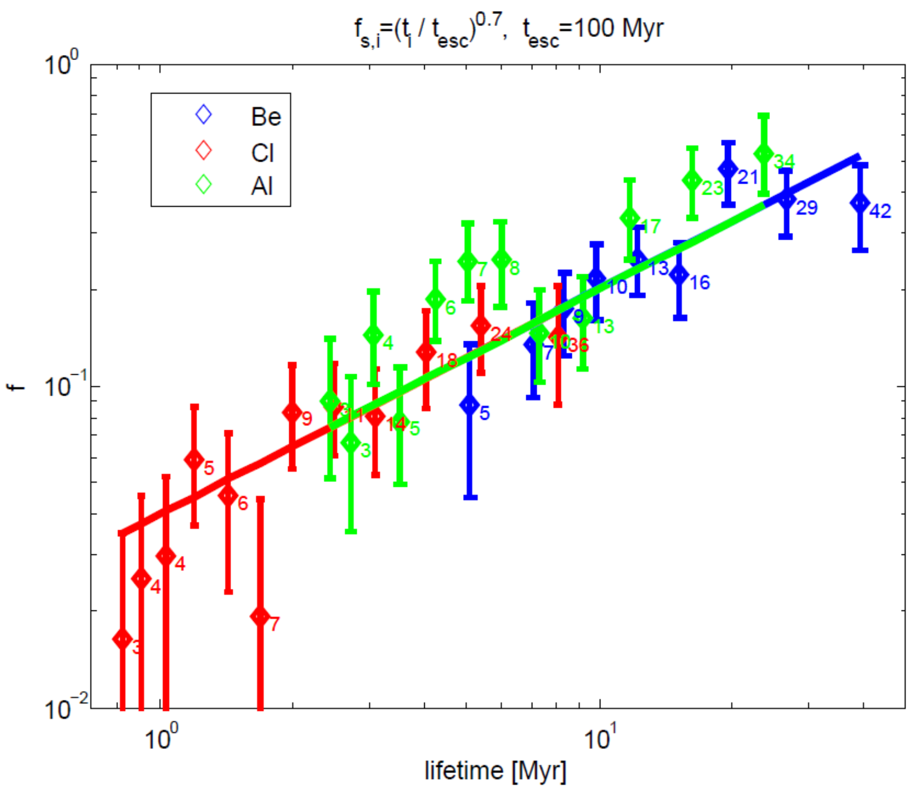


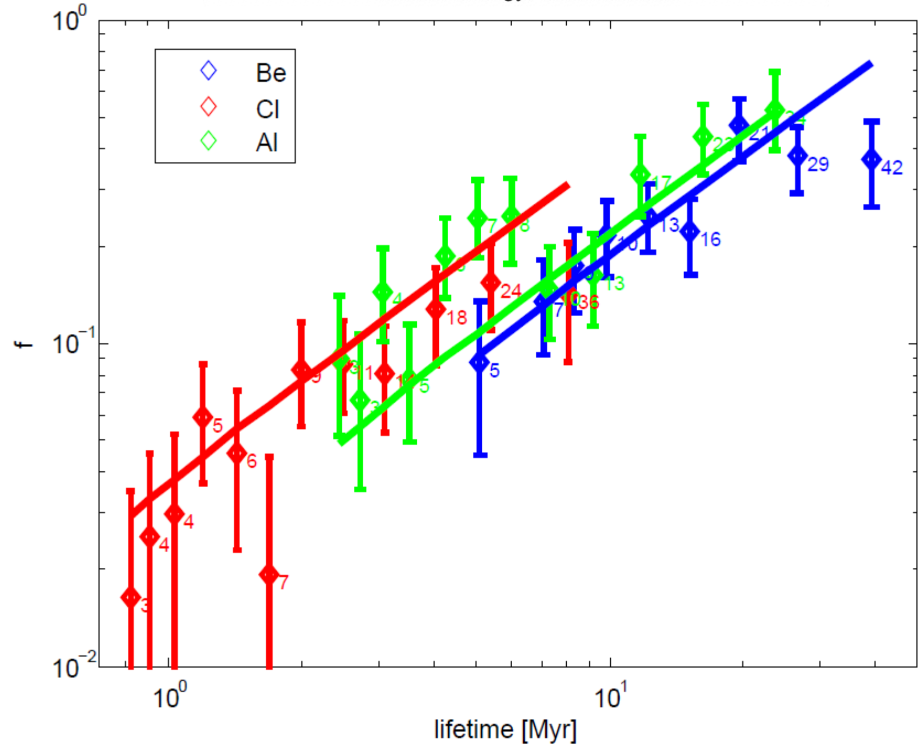

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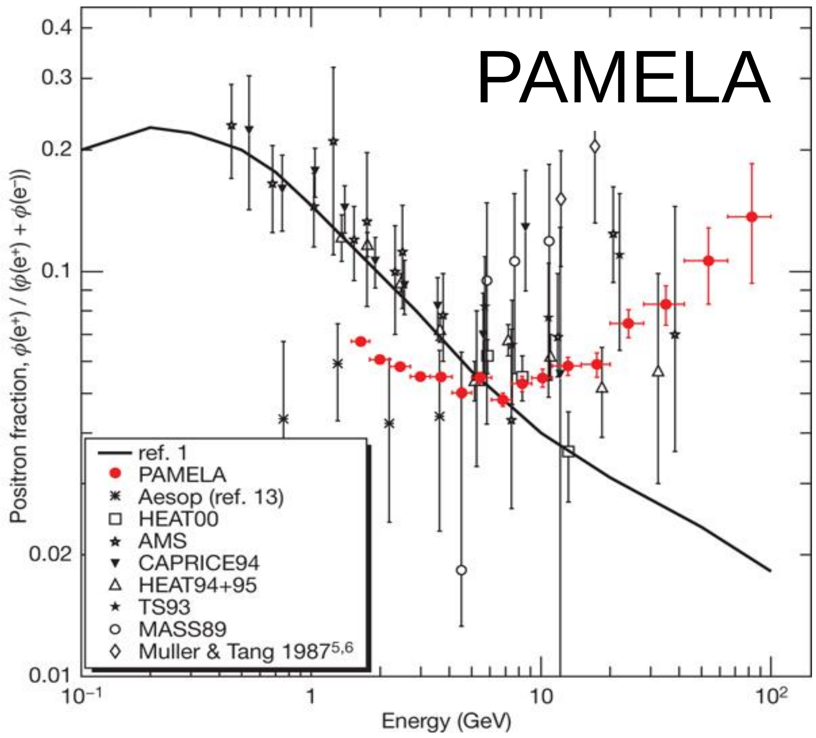
- What to expect from current and upcoming positron measurements?

  Secondary e+ produced in pp interactions, just like e.g. antiprotons

  **Antiprotons understood → *secondary e+ production understood***

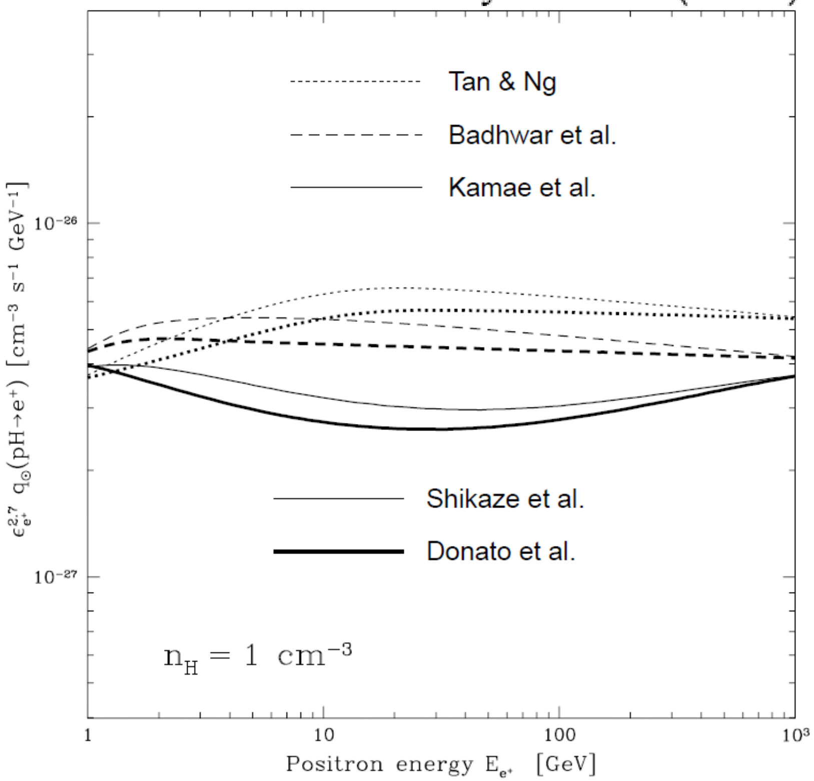
  e+ lose energy radiatively. **Measure e+ → measure losses**



# Positrons

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

T. Delahaye et al. (2008)




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

| h | Exclusive reaction | $\bar{M}_X$ (GeV $c^{-2}$) | $\sqrt{s_t}$ (GeV) | $E_t$ (GeV) | $T_t$ (GeV) |
|---|---|---|---|---|---|
| $\pi^+$ | $pn\pi^+$ | 1.878 | 2.018 | 1.233 | 0.295 |
| $\pi$ | $pp\pi^+\pi^-$ | 2.016 | 2.156 | 1.540 | 0.602 |
| $\pi^0$ | $pp\pi^0$ | 1.876 | 2.011 | 1.218 | 0.280 |
| $\kappa^+$ | $\Lambda^0 p\kappa^+$ | 2.053 | 2.547 | 2.520 | 1.582 |
| $\kappa^-$ | $pp\kappa^+\kappa^-$ | 2.370 | 2.864 | 3.434 | 2.496 |
| $\bar{p}$ | $ppp\bar{p}$ | 2.814 | 3.752 | 6.566 | 5.628 |
| p | pp | 0.938 | 1.876 | 0.938 | 0 |

# Positrons

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

- Cannot apply grammage relation: *energy losses*. Parameterize…

- Cooling suppression depends on time scales for escape and loss.
  Both time scales unknown

- Moreover, precise relation model dependent

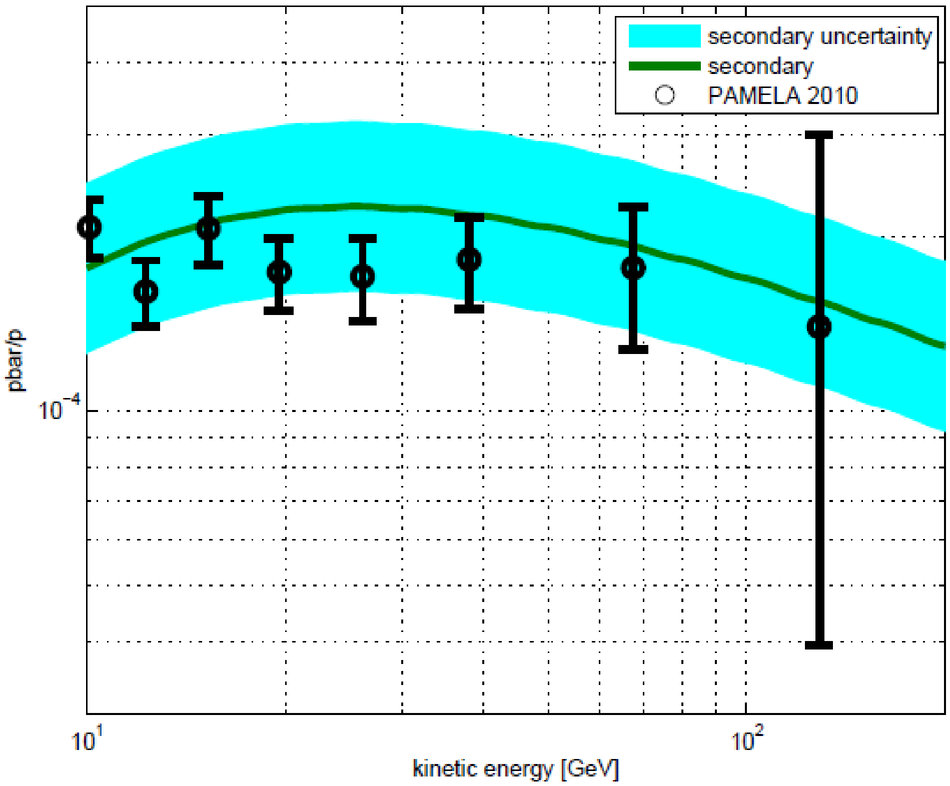
For example, diffusion models predict: $f \sim \sqrt{t_c/t_{\rm esc}}$

Leaky Box models predict: $f \sim t_c/t_{\rm esc}$

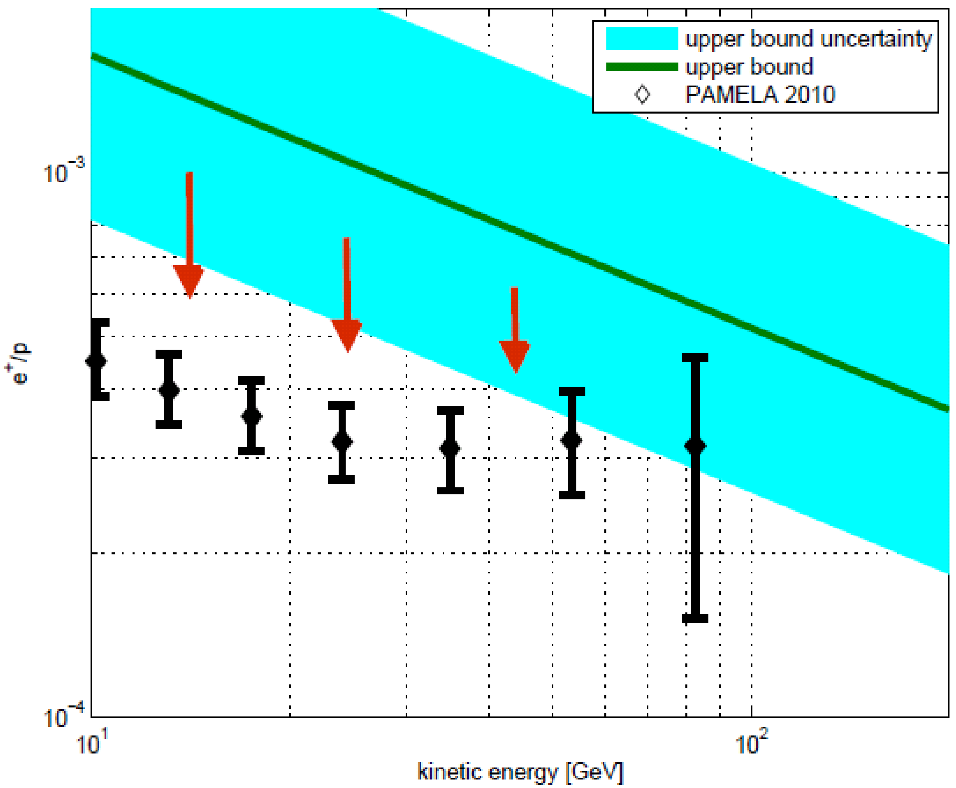
- What we do know: steep spectrum → loss suppresses flux $f_{s,e+} < 1$

# Study positrons and antiprotons together

Antiprotons

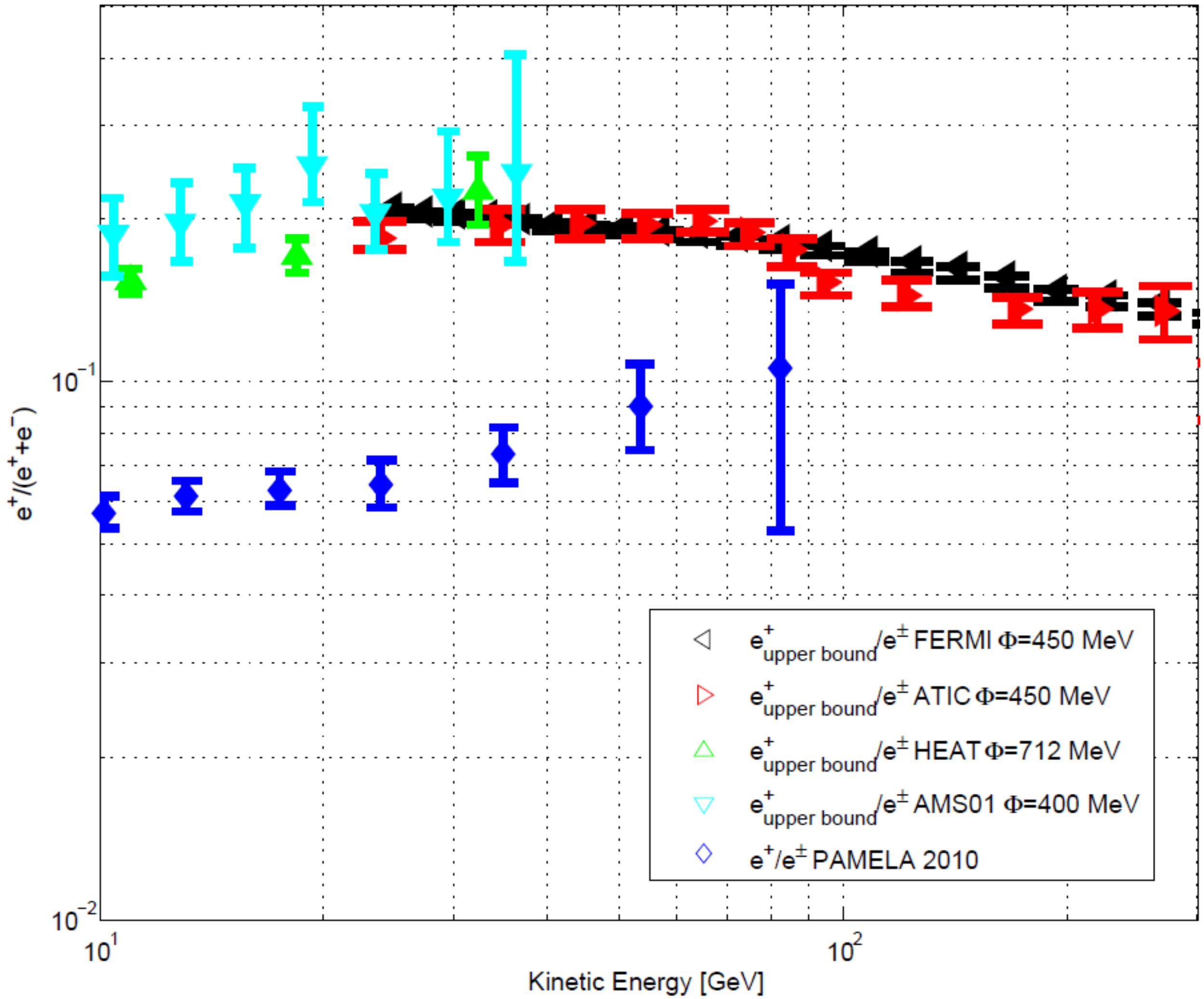



Positrons



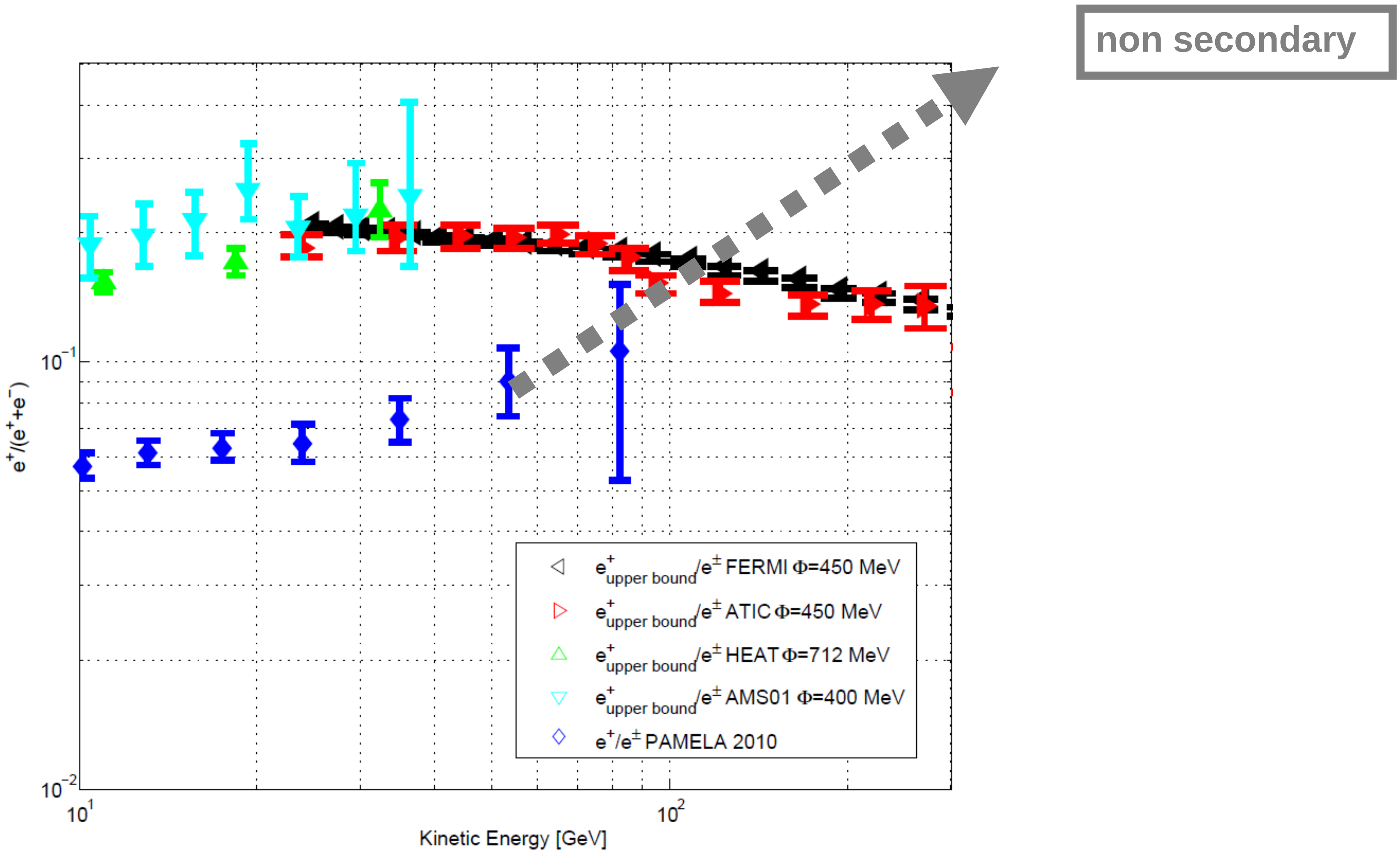

Below ~100 GeV, positron flux consistent w/ secondary + losses.

# Positrons: data




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

# Positrons: data



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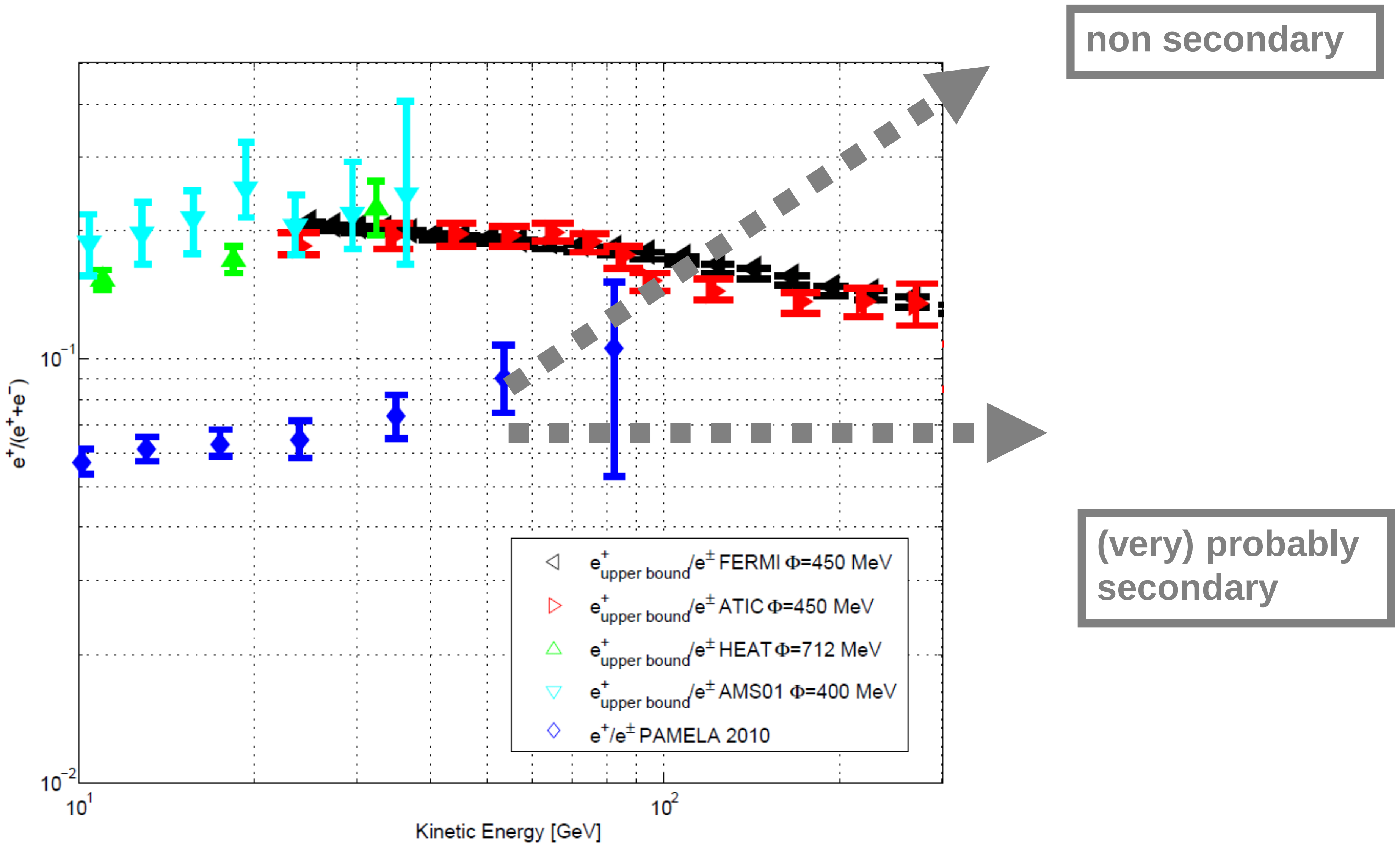
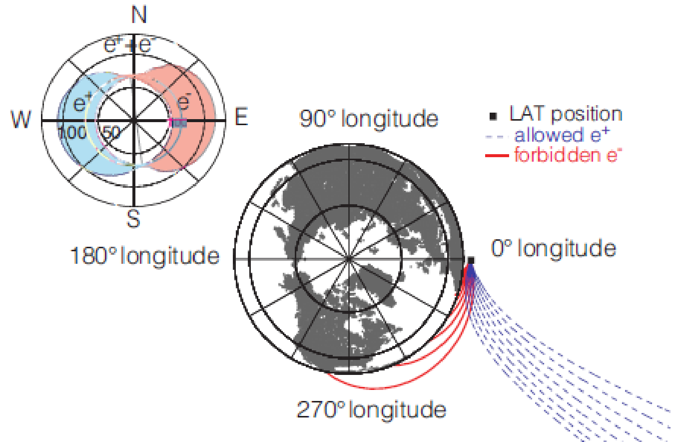
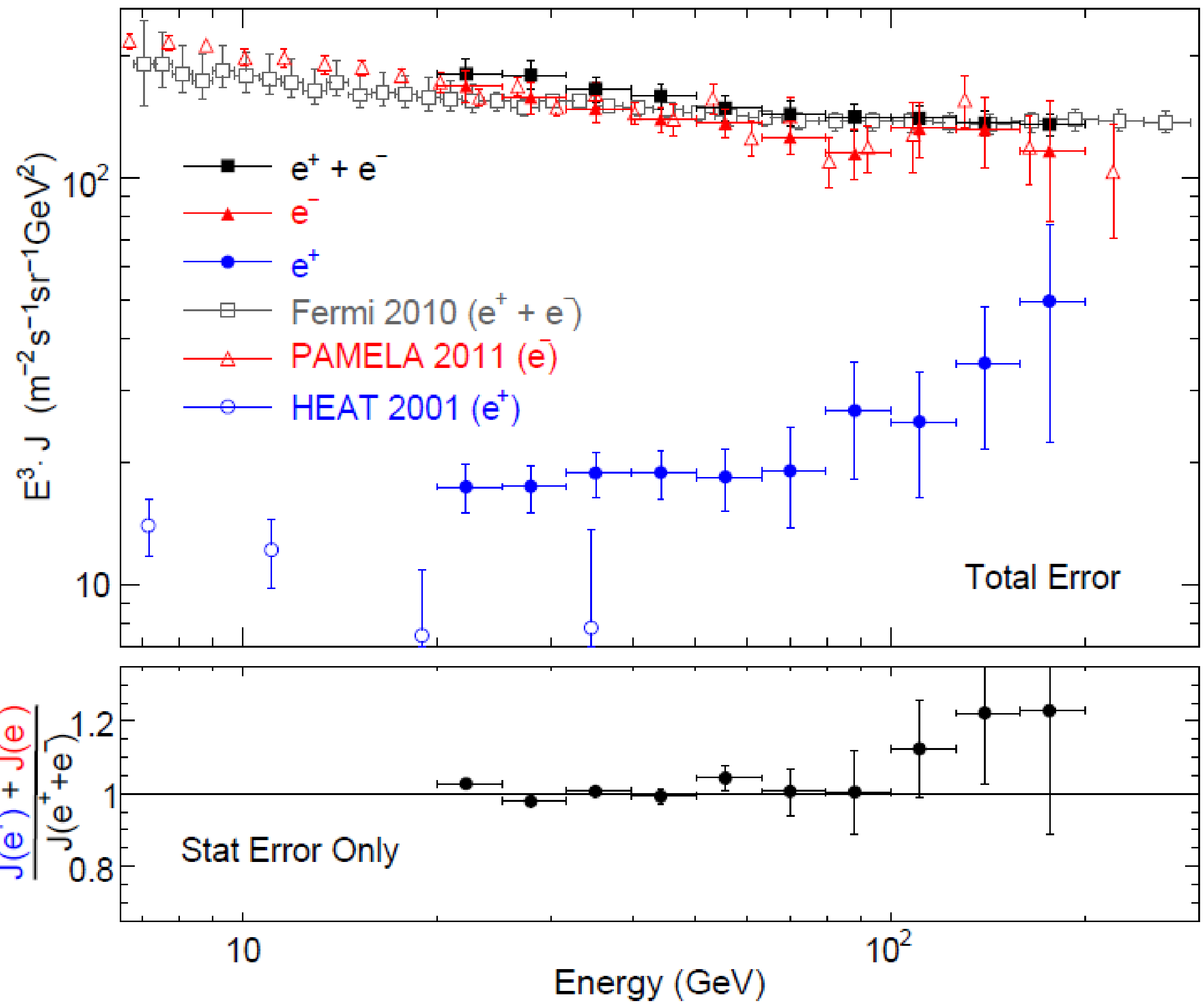


# Fermi e+ 1109.0521



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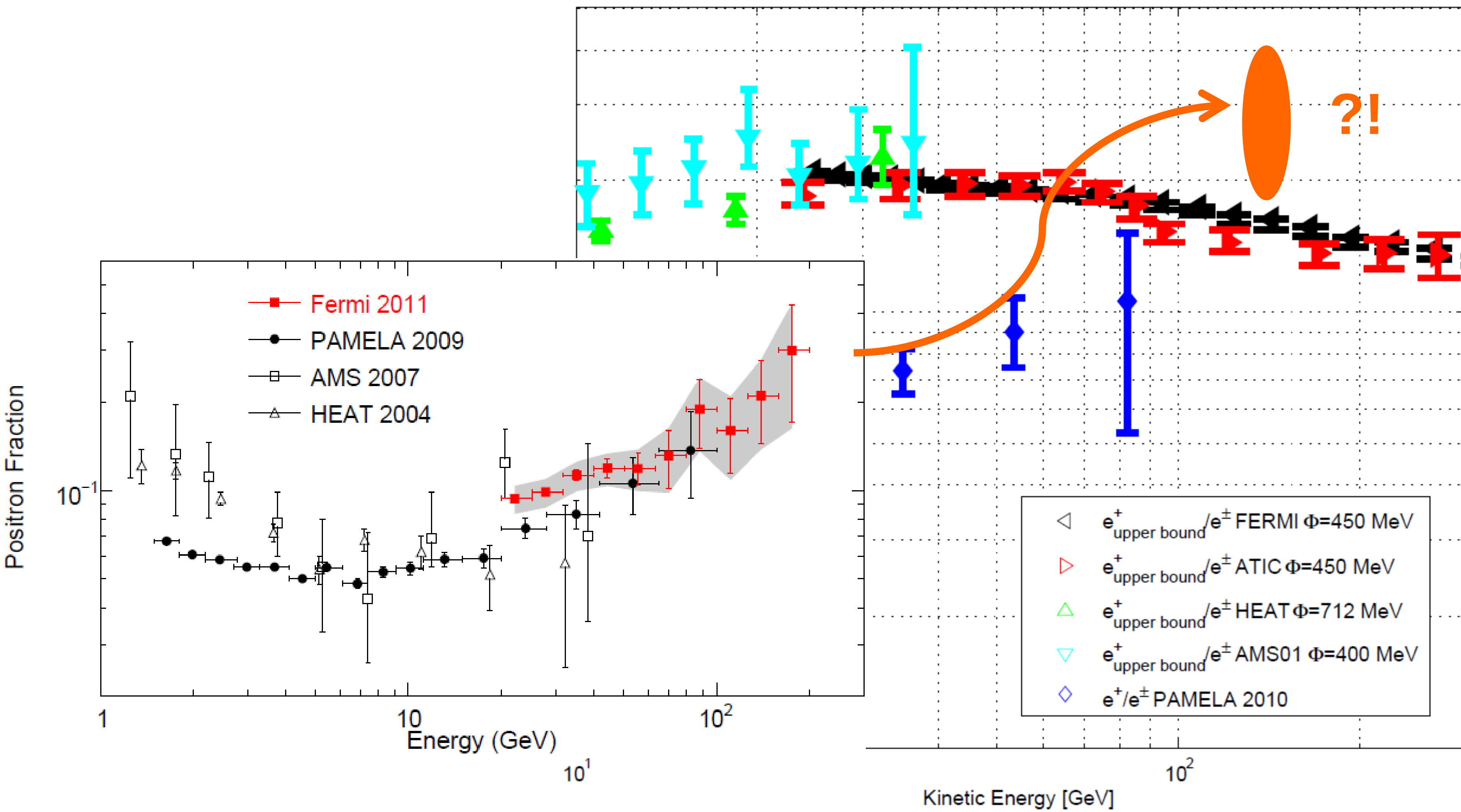

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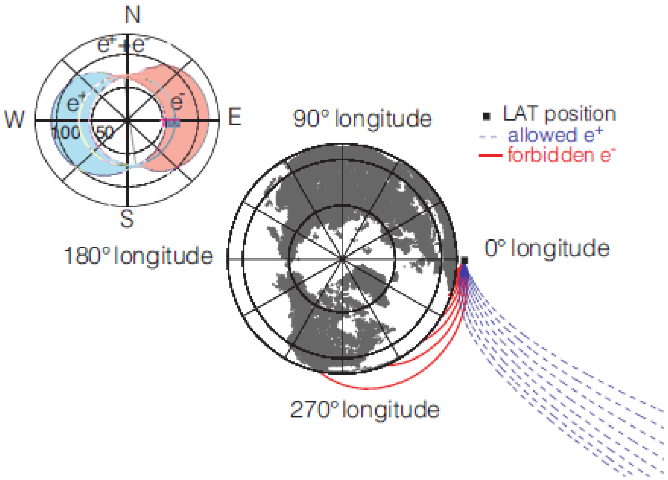
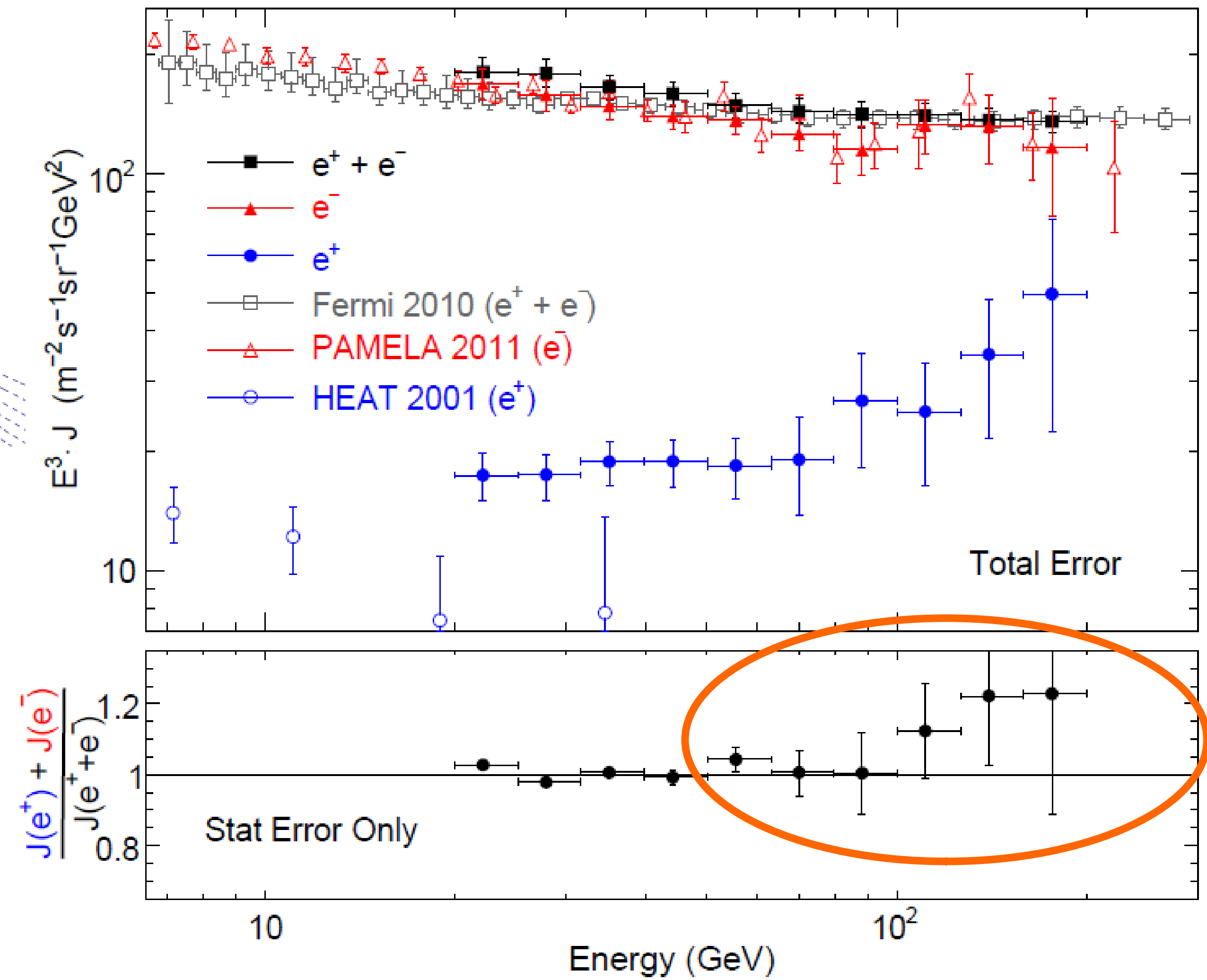
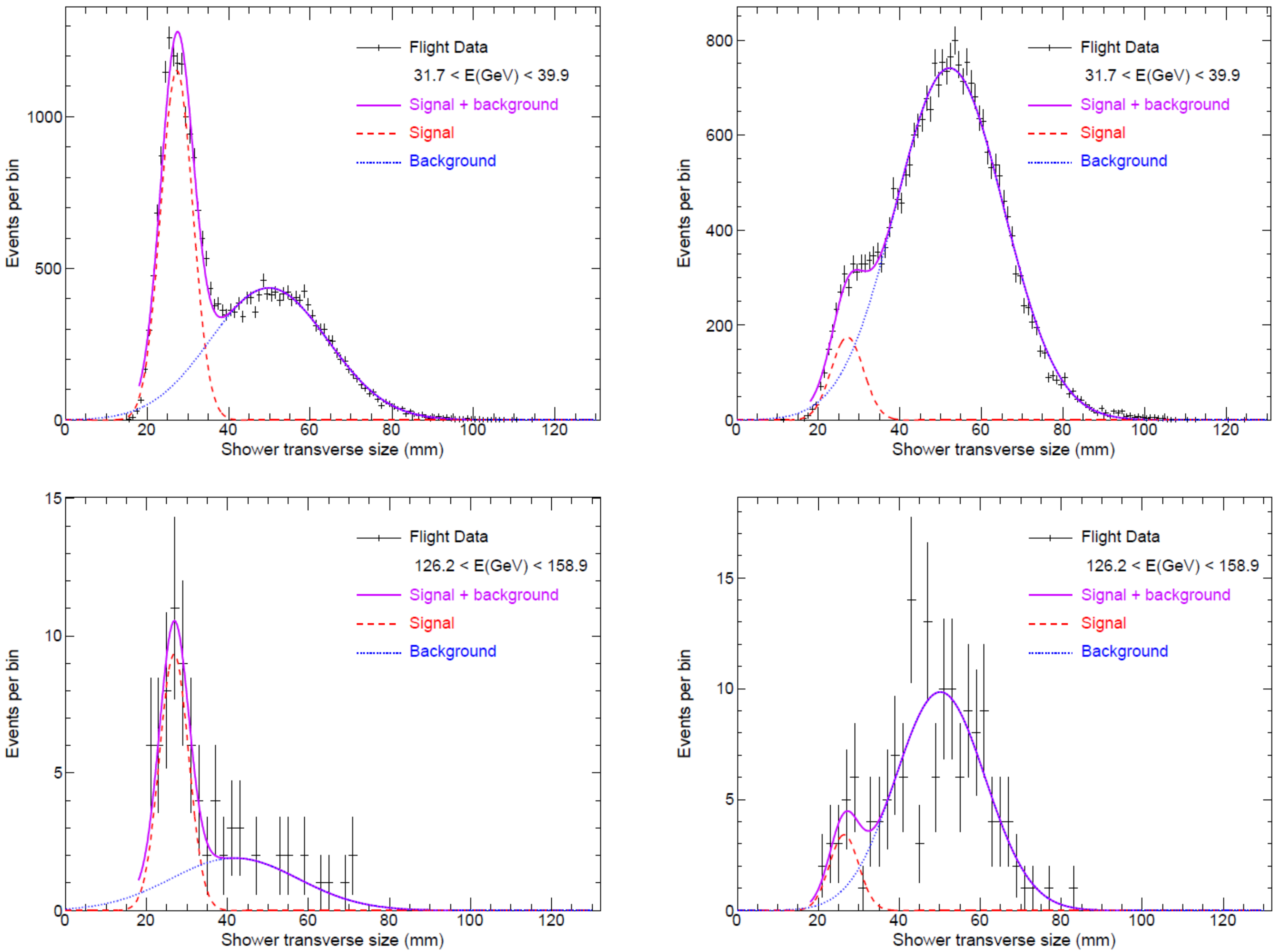


# Fermi e+ 1109.0521



# Constraints on positron energy loss

- Suppression factor: (estimated $f_{e+}$ goes down by~10-20% if adopt new **Adriani et al 1103.4055**)

$$f_{s,e^+} = \frac{J_{e^+}}{\frac{c}{4\pi}\tilde{Q}_{e^+} X_{\rm esc}} \approx 0.6 \times 10^3 \left(\frac{\mathcal{R}}{10\,\rm GV}\right)^{0.5} \times \frac{J_{e^+}(\mathcal{R})}{J_p(\mathcal{R})}$$

- Saw $f_{s,e^+} \sim 0.3 < 1$ @20 GV

  ➔ **Does this result make sense quantitatively?**

- Expect $f_{s,e^+}$ rise if escape time drops faster than cooling time: $f_{s,e^+} \approx \left(\frac{t_c}{t_{\rm esc}}\right)^{\alpha}$

  expect $t_c \propto \mathcal{R}^{-\delta_c}$. If uniform environment, IC/sync', Thomson regime $\delta_c \sim 1$

  ➔ **Does data allow escape time falling faster than $t_c$ ?**

# 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:

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

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

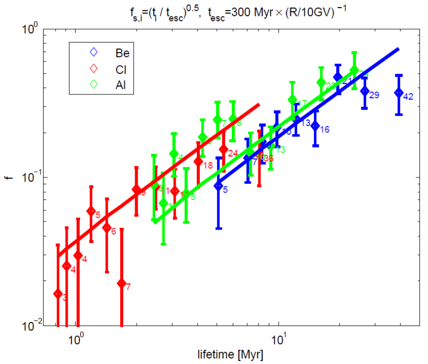
$$\tilde{t}_c = \frac{t_c}{\gamma - \delta_c - 1}$$

But, $\gamma \sim 3$ ➔ $\tilde{t}_c \approx t_c$

# Combined information

- *Is $f_{s,e^+}$ rising with rigidity (=escape time falling faster then cooling time) allowed by data?*

  Currently cannot exclude robustly. Upcoming data should settle this!




Next:

- *Quantitative result for $f_{s,e^+}$*

Cooling ~ decay $$f_{s,i} \approx \left(\frac{t_i}{t_{\rm esc}}\right)^{\alpha} \qquad f_{s,e^+} \approx \left(\frac{t_c}{t_{\rm esc}}\right)^{\alpha}$$

Cooling time $$t_c \approx 10\,{\rm Myr}\left(\frac{\mathcal{R}}{30\,{\rm GV}}\right)^{-1}\left(\frac{\bar{U}_T}{1\,{\rm eV\,cm^{-3}}}\right)^{-1}$$

➔ $$\frac{f_{s,i}(\mathcal{R}')}{f_{s,e^+}(\mathcal{R}')} \approx \left[\left(\frac{\tau_i}{1.5\,{\rm Myr}}\right)\left(\frac{\mathcal{R}'}{20\,{\rm GV}}\right)^2\left(\frac{\bar{U}_T}{1\,{\rm eV\,cm^{-3}}}\right)\right]^{\alpha}$$

# Combined information

- $f_{s,e^+} \sim 0.3 < 1$ @ 20 GV

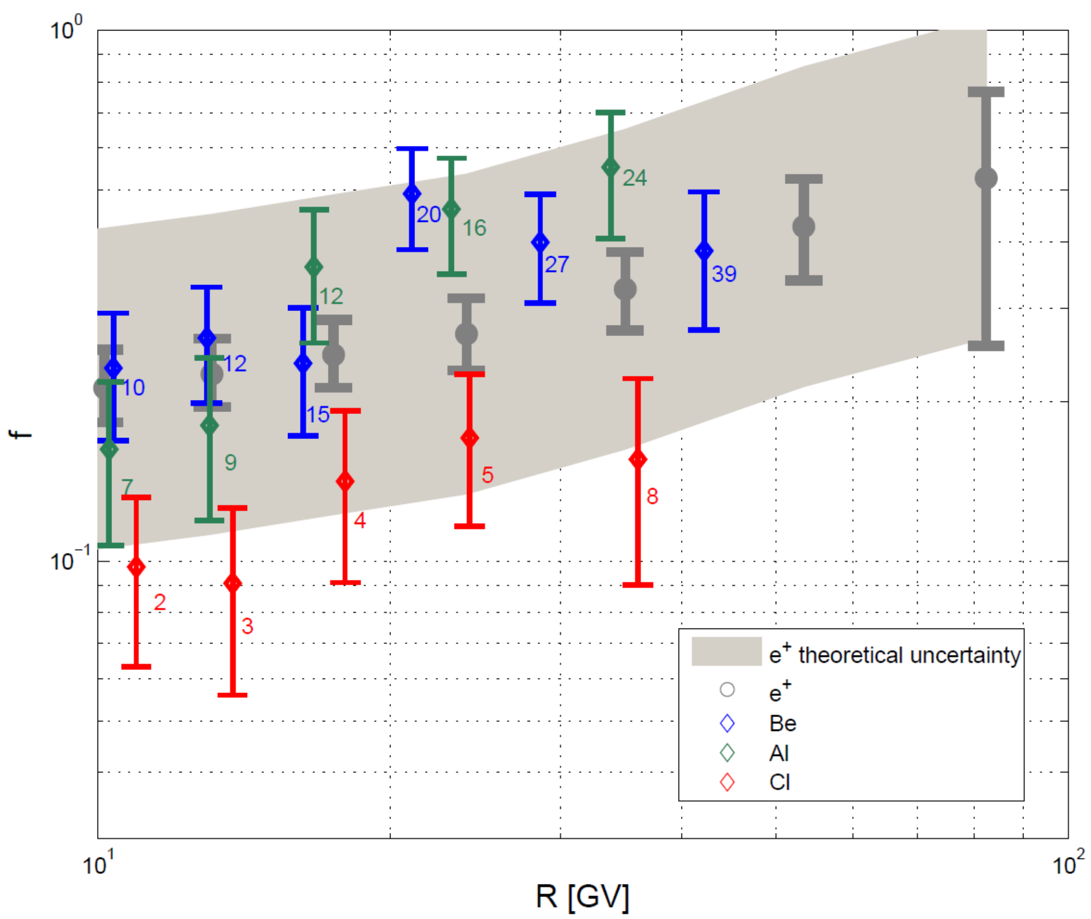
consistent w/ secondary… so far

**Upper bound** from Cl

$$\bar{U}_T < 5 \left(\frac{\mathcal{R}}{20\,\mathrm{GV}}\right)^{-2} \mathrm{eV\,cm^{-3}}$$

- Test secondary e+:

$$\bar{U}_T < U_{CMB} \approx 0.25\ \mathrm{eV/cm^3}$$



# Tests for secondary positrons

**1. Existence of losses:** $f_{s,e^+} < 1$

Independent of radioactive nuclei. Satisfied by PAMELA data

**2. Amount of losses:** $\bar{U}_T > U_{CMB}$

Compare w/ radioactive nuclei. At present, satisfied where Cl and e+ data coexist

*AMS02 can easily expose discrepancy at higher energy, even if* $f_{e+}<1$

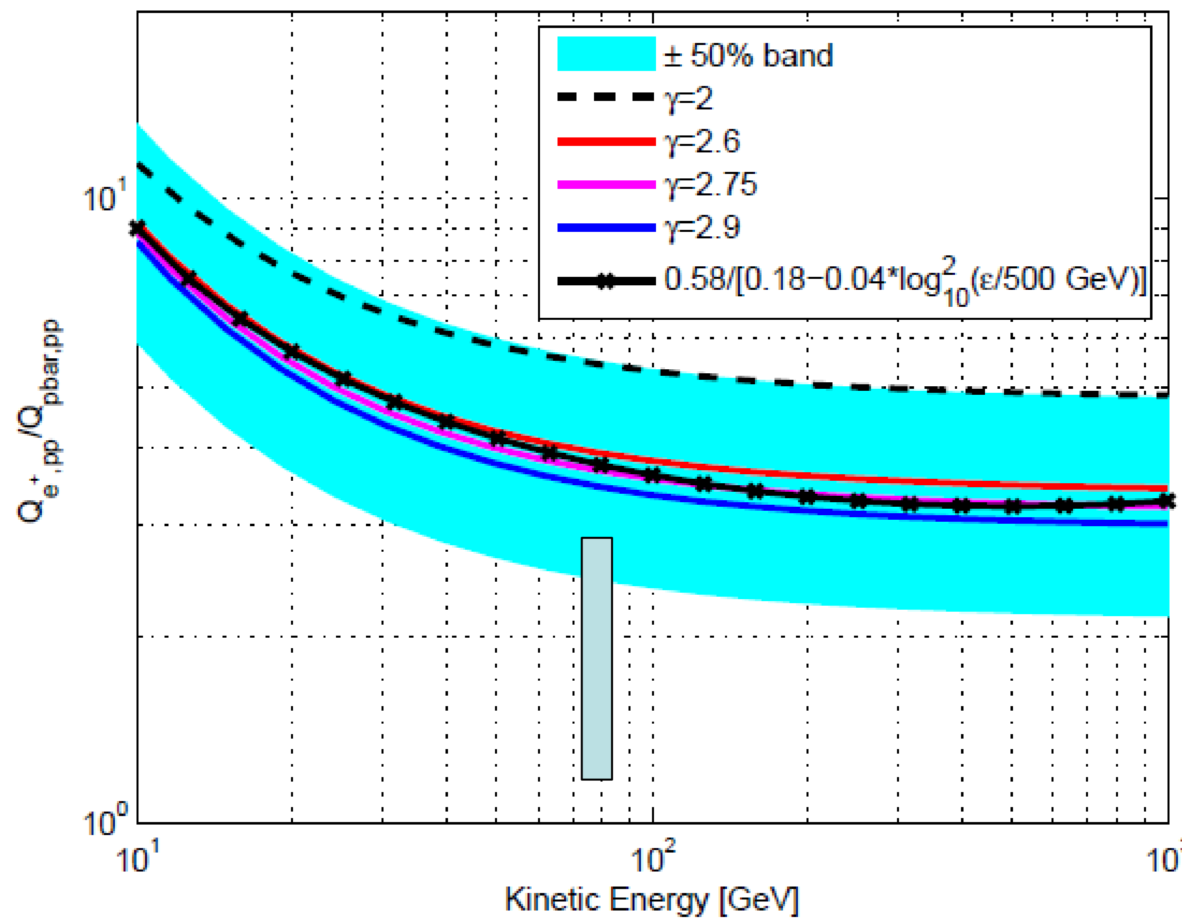
**3. Slope:** $\delta + \delta_c < 0$

Measure escape time $t_{\rm esc} \propto \mathcal{R}^{\delta}$ and cooling time $t_c \propto \mathcal{R}^{-\delta_c}$

Based on radioactive nuclei. Consistent w/ PAMELA data

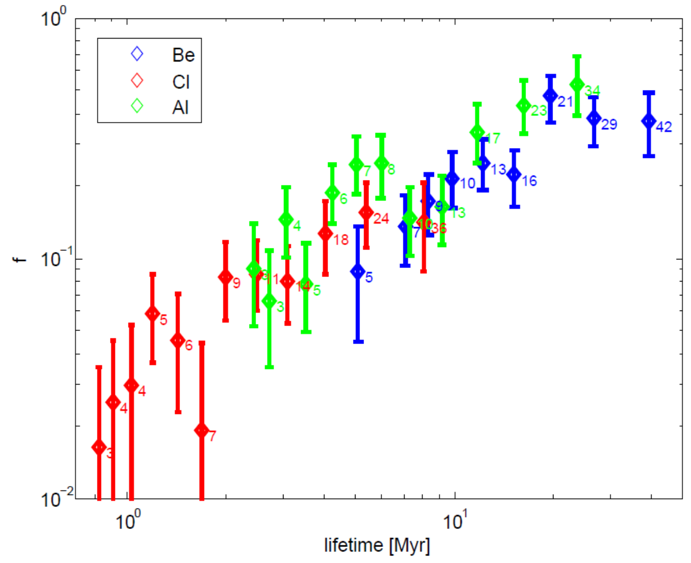
# Another clean test

$$e^+/\overline{p}$$




$$\frac{J_{e^+}}{J_{\bar{p}}} = \left(\frac{\xi_{e^+,A>1}}{\xi_{\bar{p},A>1}}\right)\left(\frac{1}{1+\frac{\sigma_{\bar{p}}}{m_p}X_{\rm esc}}\right) f_{s,e^+}\frac{C_{e^+,pp}(\varepsilon)}{C_{\bar{p},pp}(\varepsilon)} \Rightarrow \frac{J_{e^+}}{J_{\bar{p}}} \lesssim \frac{C_{e^+,pp}(\varepsilon)}{C_{\bar{p},pp}(\varepsilon)} = \frac{Q_{e^+,pp}}{Q_{\bar{p},pp}}$$

# Summary




- Stable secondaries

  propagation models fit grammage

- Radioactive nuclei

  probe propagation time up to surprisingly high E

- Interpreting e+ data

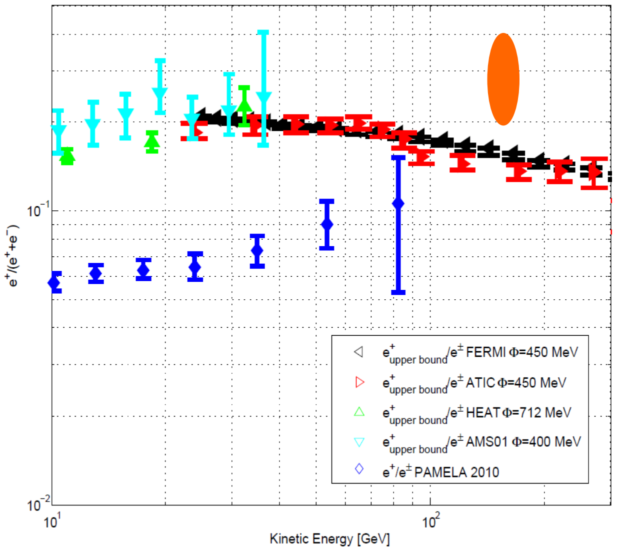
  e+ ~ antiprotons, define robust tests

  secondary $e^+$ consistent up to 100 GeV

  PAMELA , AMS-02 reach ~300 GeV

  Fermi 2011: if correct, rules out secondary model.

  AMS02 should settle this



# Xtras

# Guiding concept: The solar neutrino problem

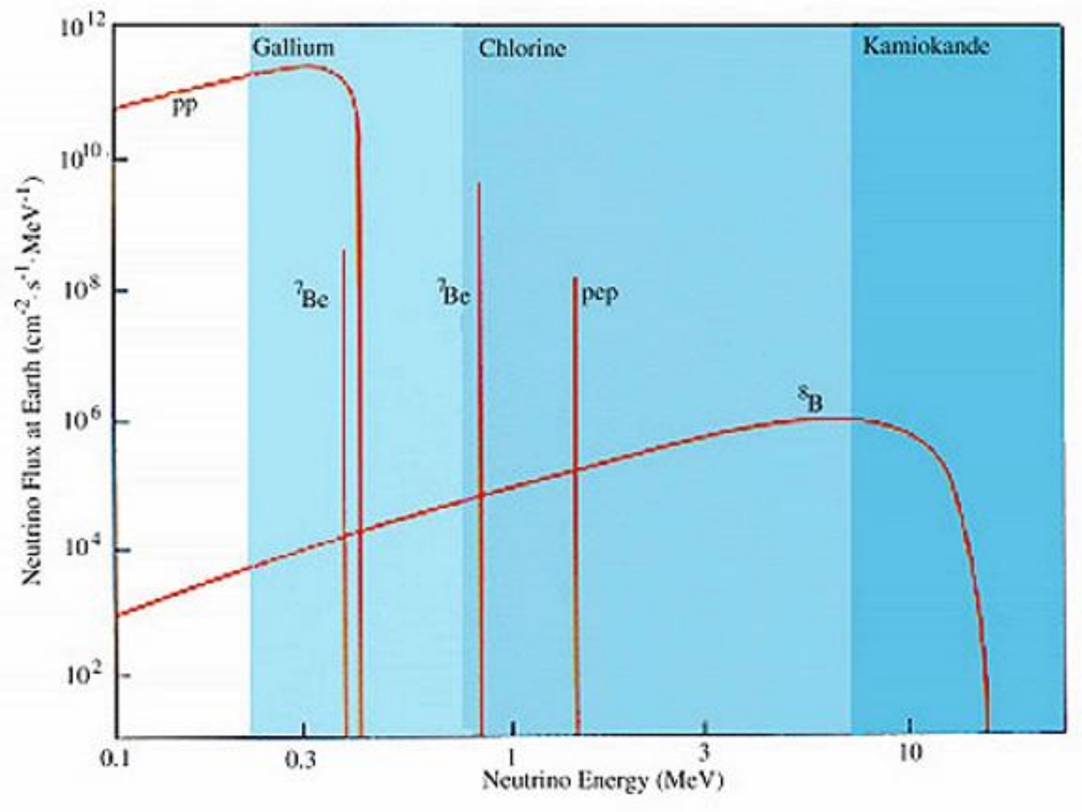
• Major success of particle astrophysics: Solar Neutrinos

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**

# CR grammage

In some more detail

- Net production includes fragmentation losses

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

$\bar{m}$ = mean ISM particle mass (~ 1.3 $m_p$)

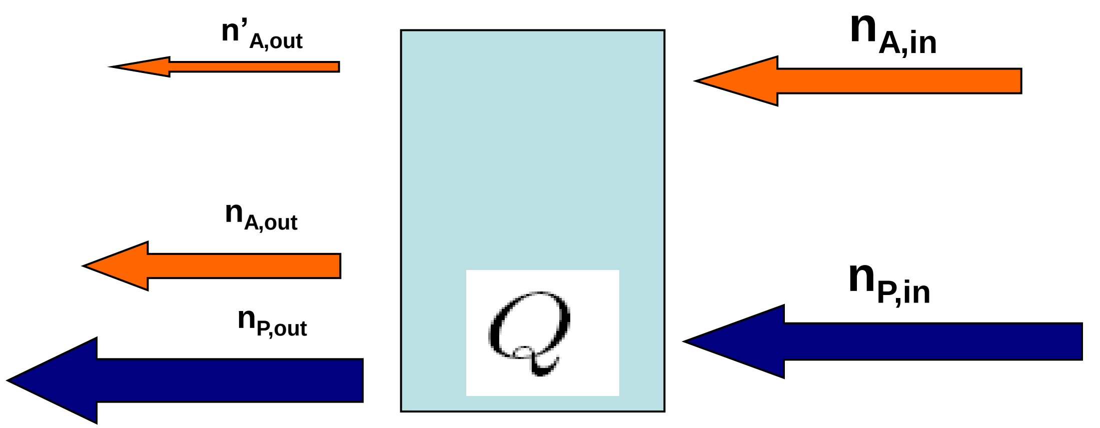
High-energy → energy independent cross sections; negligible energy gain/loss

Approx': secondary inherits rigidity of primary

- In general $$n_S(r',t',\mathcal{R}) = c\int^{t'} dt \int d^3r\, \rho_{ISM}(r,t)\, \tilde{Q}_S(r,t,\mathcal{R})\, G(r,r';t,t';\mathcal{R})$$
- Uniform composition: $$\bar{m}(r',t') = \bar{m}(r,t) \quad , \quad \frac{n_i(r,t,\mathcal{R})}{n_j(r,t,\mathcal{R})} = f_{ij}(\mathcal{R})$$
- Thus $$\tilde{Q}_S(r',t',\mathcal{R}) = \tilde{Q}_S(r,t,\mathcal{R})\,\frac{n_{P_1}(r',t',\mathcal{R})}{n_{P_1}(r,t,\mathcal{R})}$$
- Obtain: $$n_S(r',t',\mathcal{R}) = \tilde{Q}_S(r',t',\mathcal{R})\, X_{\rm esc}(\mathcal{R})$$

$$X_{\rm esc}(\mathcal{R}) = c\int^{t'} dt \int d^3r\, \rho_{ISM}(r,t)\, \frac{n_{P_1}(r,t,\mathcal{R})}{n_{P_1}(r',t',\mathcal{R})}\, G(r,r';t,t';\mathcal{R})$$

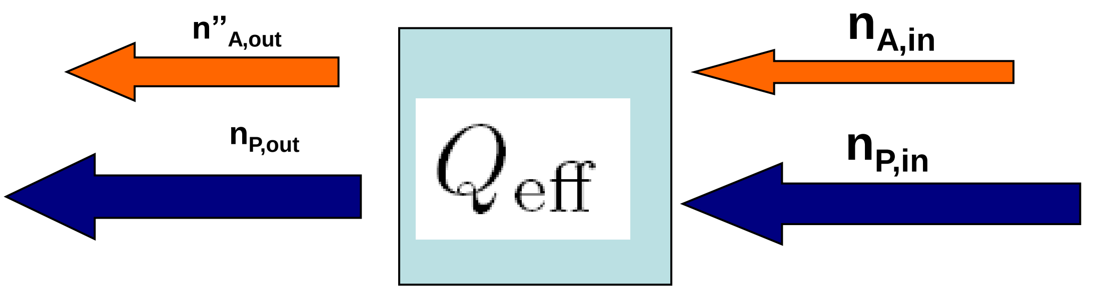
# Stable secondaries, spallation losses




Equivalently:

$$dxQ_A = n_{A,out} + n'_{A,out} - n_{A,in}$$

$$dxQ_{A,\text{eff}} = n''_{A,out} - n_{A,in}$$




$$Q_{A,\text{eff}} = Q_A - n_A \frac{\sigma_{A \rightarrow X}}{m_p} \rho_{ISM} c$$

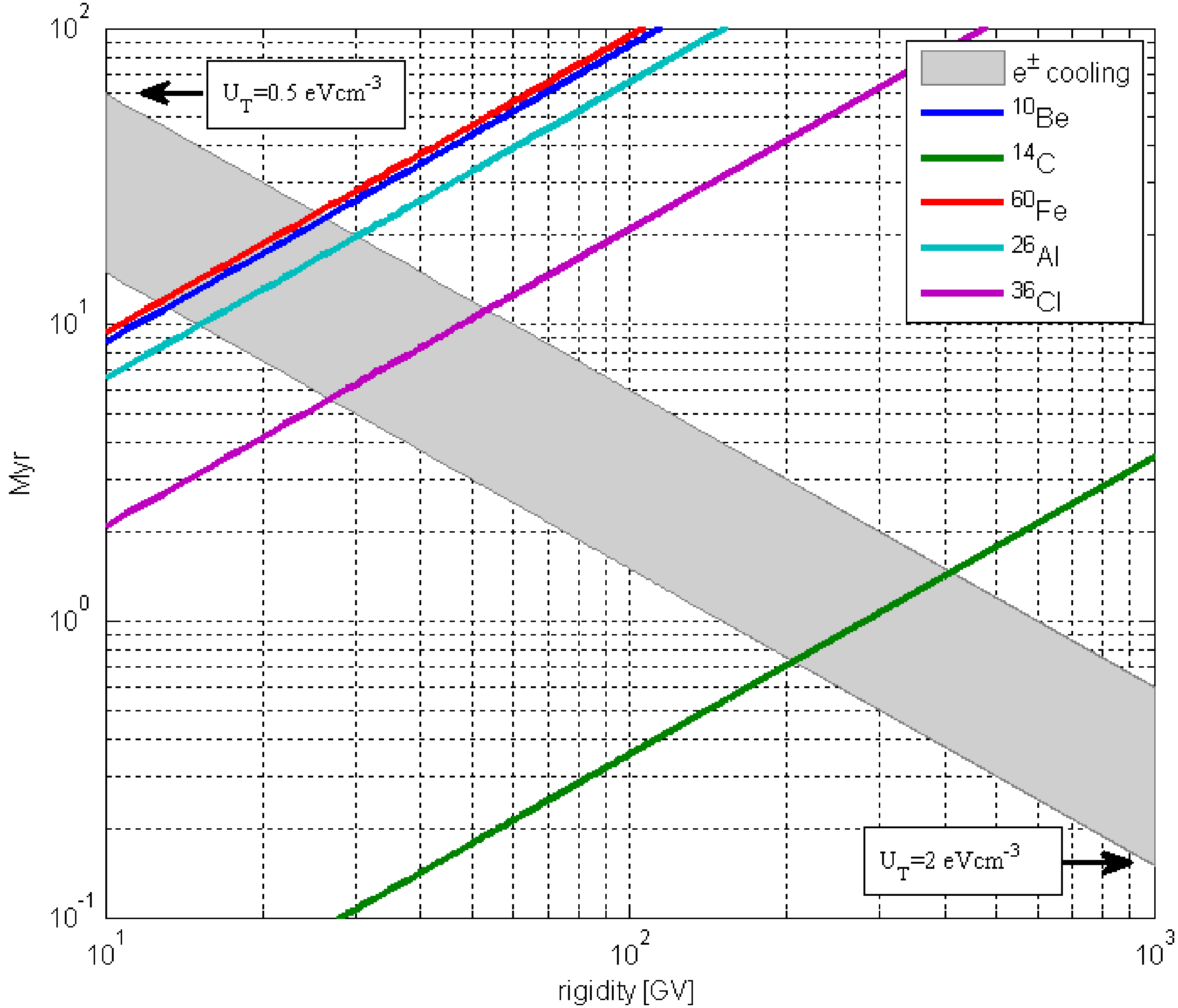
Homogenous composition:

$Q_{\text{eff}}$ works just the same!

# Comparing with radioactive nuclei

Time scales:

cooling vs decay



Agashe, KB, Lee, Perez (2010)

# Theoretically clean channel:

$\bar{p}/p$

- Secondary component robust. Based on observed p flux, B/C
- DM annihilation: volume enhancement

in general

$$n_{\bar{p}}(\epsilon, \vec{r}) = \int d^3 r_S \int d\epsilon_S Q_{\bar{p}}(\epsilon_S, \vec{r}_S) G(\epsilon, \epsilon_S; \vec{r}, \vec{r}_S)$$

*if*

$$G(\epsilon, \epsilon_S; \vec{r}, \vec{r}_S) = \delta(\epsilon - \epsilon_S) g(\epsilon) \bar{G}(\vec{r}, \vec{r}_S)$$

$$Q_{\bar{p},\mathrm{sec}}(\epsilon, \vec{r}) = Q_{\bar{p},\mathrm{sec}}(\epsilon, \vec{r}_{\mathrm{sol}}) \times q_{\mathrm{sec}}(\vec{r})$$

$\Rightarrow$

$$\frac{n_{\bar{p},\mathrm{DM}}(\epsilon, \vec{r}_{\mathrm{sol}})}{n_{\bar{p},\mathrm{sec}}(\epsilon, \vec{r}_{\mathrm{sol}})} = f_V \frac{Q_{\bar{p},\mathrm{DM}}(\epsilon, \vec{r}_{\mathrm{sol}})}{Q_{\bar{p},\mathrm{sec}}(\epsilon, \vec{r}_{\mathrm{sol}})}$$

Volume effect = single fuzz factor.
*Similar to gamma rays.*

$$\frac{J_{\bar{p}}(\epsilon, \vec{r}_{\mathrm{sol}})}{J_p(\epsilon, \vec{r}_{\mathrm{sol}})} = \left(\frac{J_{\bar{p}}(\epsilon, \vec{r}_{\mathrm{sol}})}{J_p(\epsilon, \vec{r}_{\mathrm{sol}})}\right)_{\mathrm{sec}} \times \left[1 + f_V \frac{Q_{\bar{p},\mathrm{DM}}(\epsilon, \vec{r}_{\mathrm{sol}})}{Q_{\bar{p},\mathrm{sec}}(\epsilon, \vec{r}_{\mathrm{sol}})}\right]$$

Fixed by B/C, p flux

Local injection: no prop' effects by def'.
(particle physics)

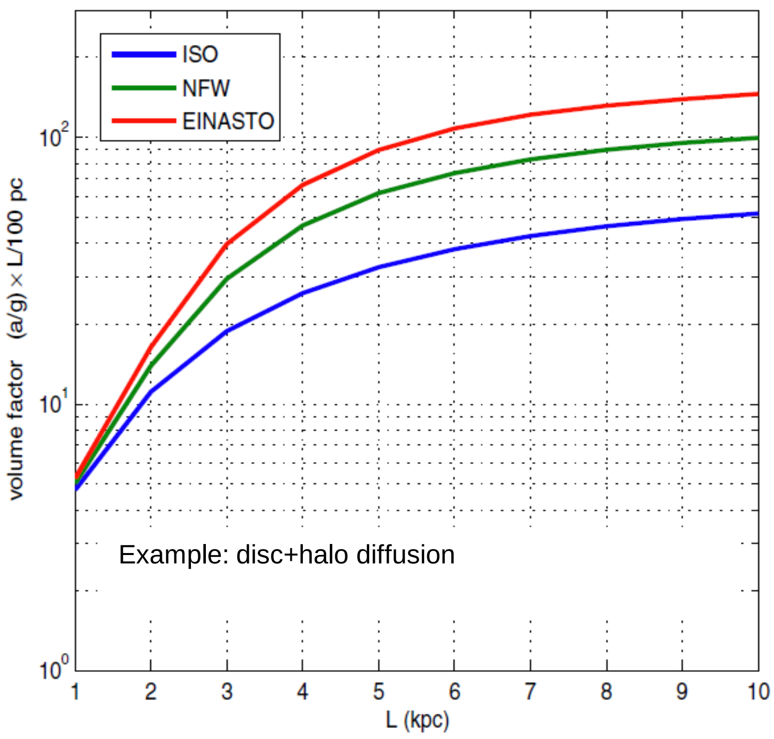
Agashe, KB, Lee, Perez (2010)

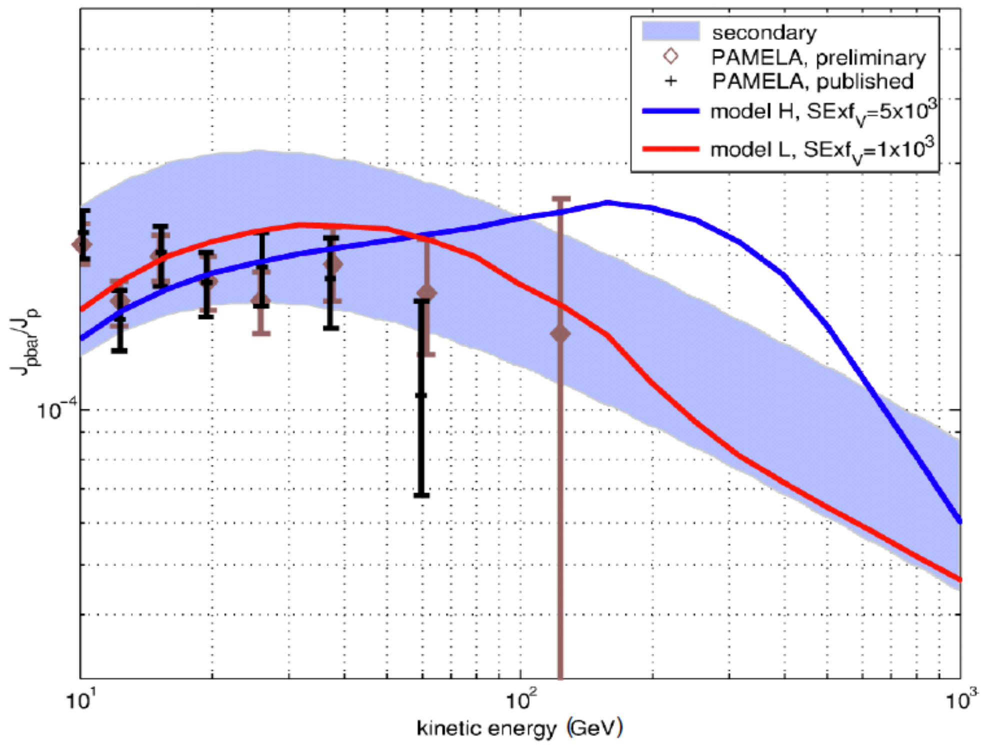
# Theoretically clean channel:

$\overline{p}/p$

Concrete example:
Z3-protected $\nu'$ at the TeV
Annihilation may compete w/ background if light radion ~ 10-100 GeV (Sommerfeld enhanced)

$$f_V = \frac{\int d^3 r q_{DM}(\vec{r}) \bar{G}(\vec{r}_{\rm sol}, \vec{r})}{\int d^3 r q_{\rm sec}(\vec{r}) \bar{G}(\vec{r}_{\rm sol}, \vec{r})} \sim L/h \sim 10 - 100$$



# Positron anomaly?

Claims of a primary source:

- The electrons are assumed to have the same production spectrum as the protons, and to suffer the same energy losses as the positrons $f_{s,e^-} = f_{s,e^+}$.

- The $e^+$ flux, including the energy loss suppression, is calculated within a specific propagation model.

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**?**

**Unknown.** 2

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**?**

**Unknown.**$^{2}$

- The $e^+$ flux, including the energy loss suppression, is calculated within a specific propagation model.

**?**

**Unknown.**$^{n}$

# Interpretation

- Decay suppression factor probes propagation

$$n \sim \frac{Q\, V_{\mathrm{source}}\, t_{\mathrm{eff}}}{V_{\mathrm{eff}}}$$

$$f \sim \frac{n_{\mathrm{decay}}}{n_{\mathrm{no\,decay}}} \sim \frac{V_{\mathrm{esc}}}{V_{\mathrm{decay}}} \times \frac{t_{\mathrm{decay}}}{t_{\mathrm{esc}}} \sim \left(\frac{t_{\mathrm{decay}}}{t_{\mathrm{esc}}}\right)^{1-\kappa\, d}$$

- Scaling of volume depends on type of motion, relevant dimensions $V_{\mathrm{eff}} \sim (t_{\mathrm{eff}})^{\kappa\, d}$

→ In models with thin disc and thick halo, d~1

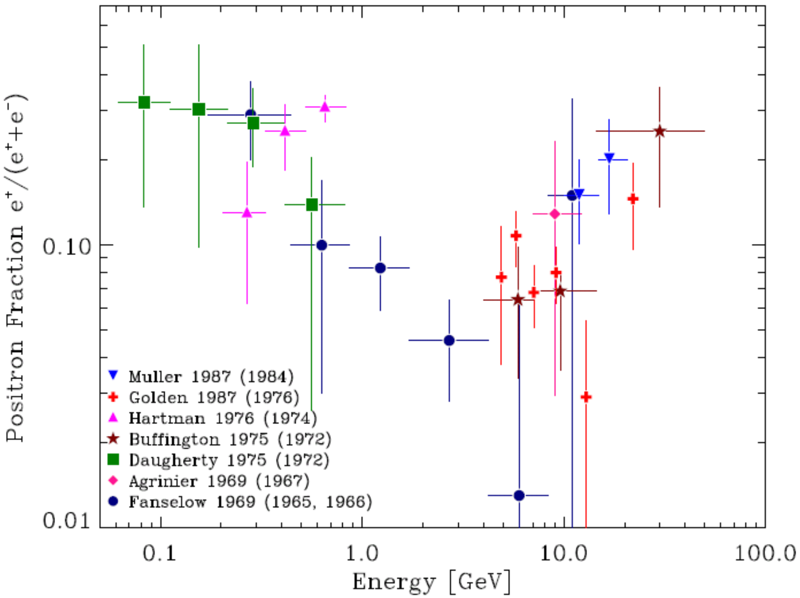
→ Uniform models, diffusion models, compound diffusion, …

$\kappa \sim 0$ $\kappa \sim \frac{1}{2}$ $\kappa \sim \frac{1}{4}$

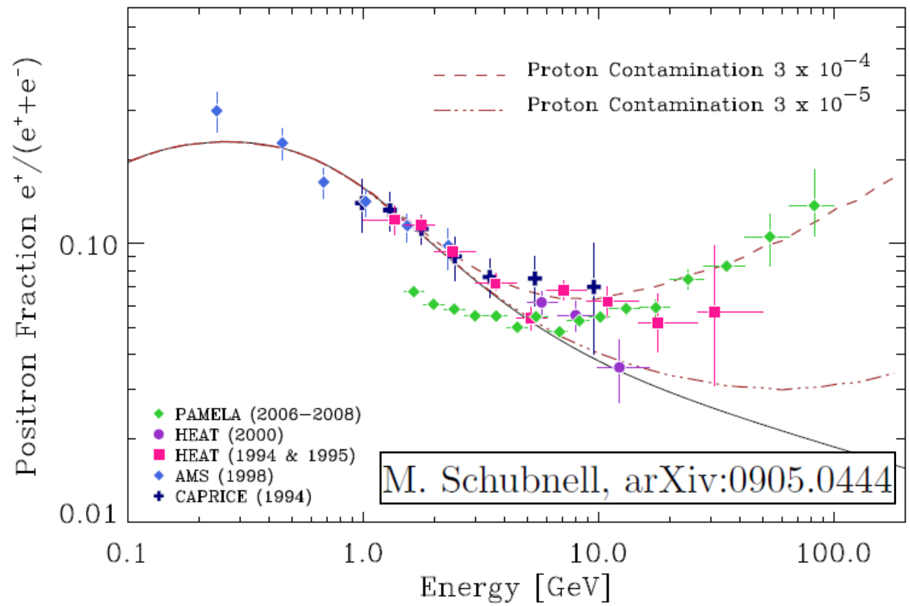
- Expect $f_{s,i} \approx \left(\frac{t_i}{t_{\mathrm{esc}}}\right)^{\alpha}$

- Lastly, if trapping is magnetic, expect $t_{\mathrm{esc}} = t_{\mathrm{esc}}(\mathcal{R})$

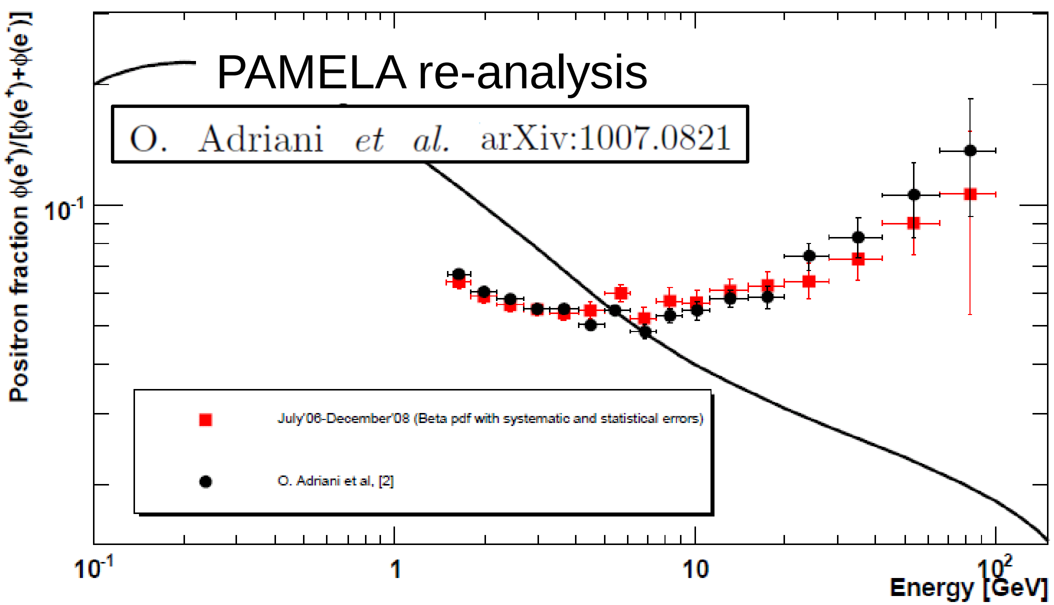
## old experiments had it wrong




## what $10^{-4}$ p contamination can do

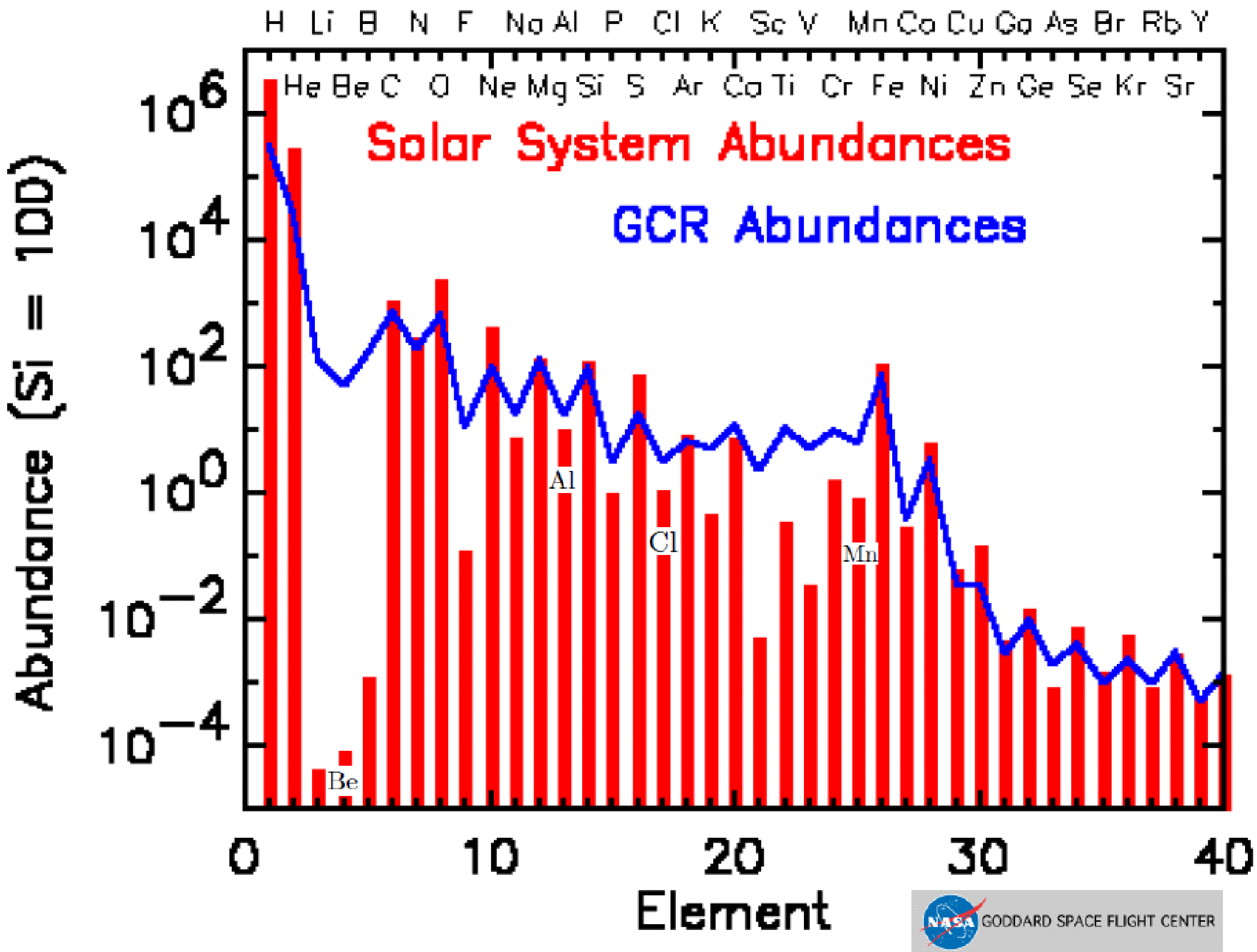



## PAMELA re-analysis




# Galactic CR: general picture

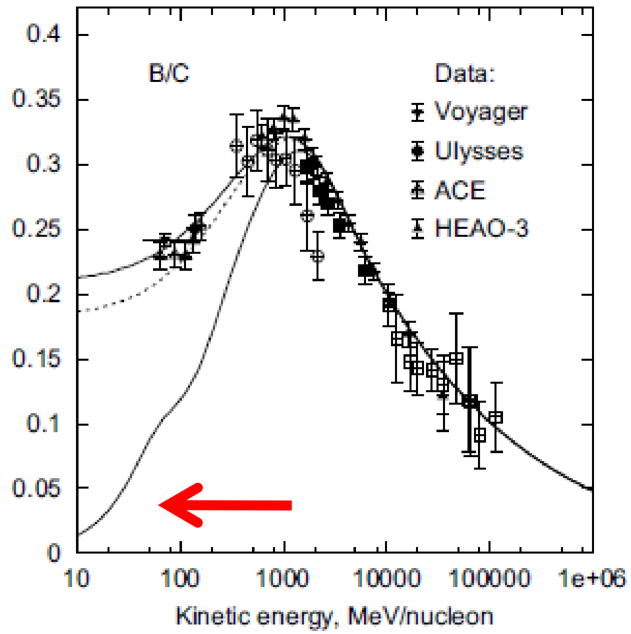
- **Primaries**: p, C, Fe, …  consistent w/ stellar material, shock-accelerated
- **Secondaries**: B, Be, Sc, Ti, V, …   consistent w/ fragmentation of primaries on ISM

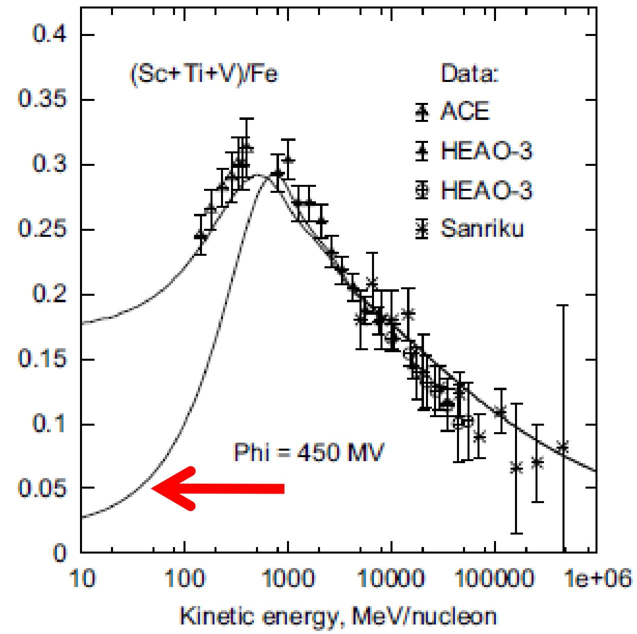


# Low energy complications

- Solar modulation
- Geomagnetic effects
- Reacceleration
- Convection
- Energy dependent fragmentation cross sections
- Ionization losses
- ?

**Limit to R>10 GV**
**→ avoid most effects**



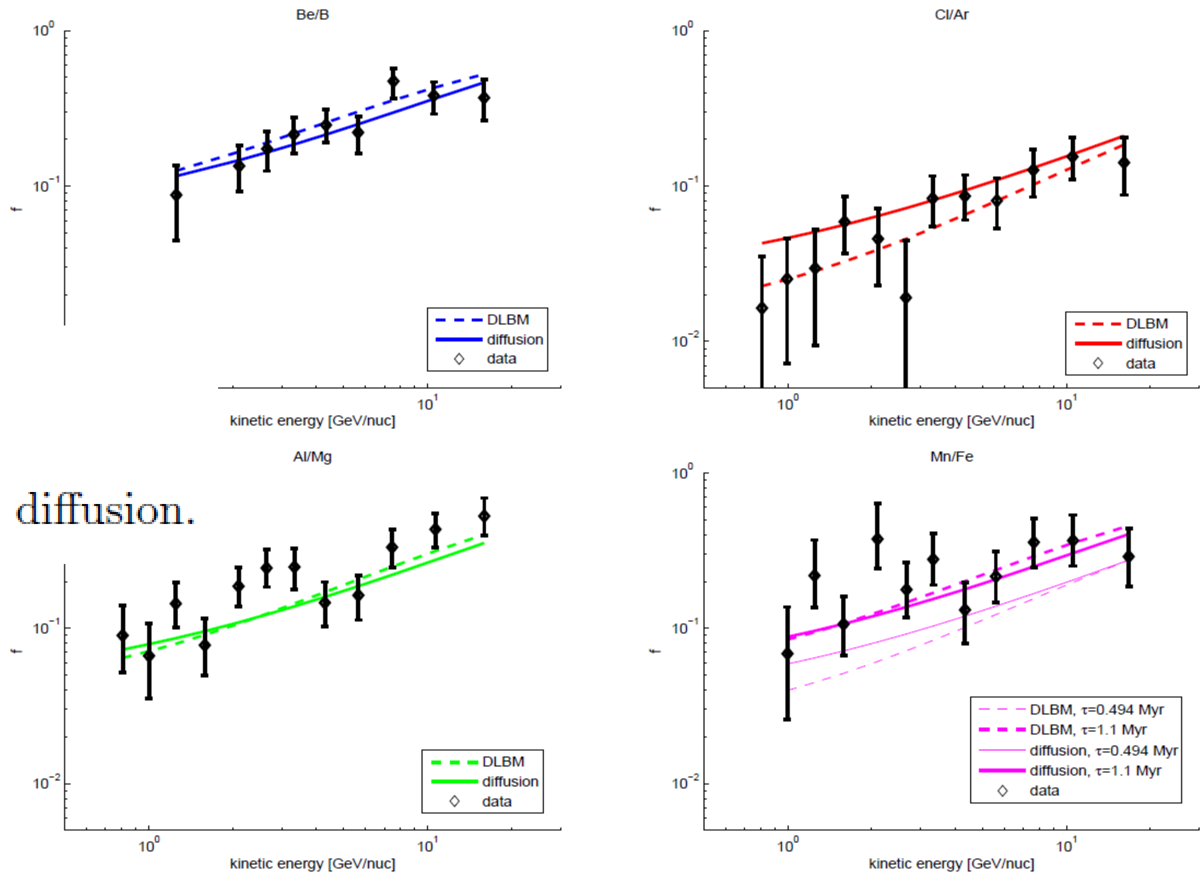



# Radioactive nuclei

$$t_{\rm esc} \approx (20 \,{\rm to}\, 40\,) \times (\mathcal{R}/10\,{\rm GV})^{0\,{\rm to}\,0.2}\ {\rm Myr}, \quad {\rm DLBM},$$
$$t_{\rm esc} \approx (200 \,{\rm to}\, 500\,) \times (\mathcal{R}/10\,{\rm GV})^{-0.7\,{\rm to}\,-0.3}\ {\rm Myr}, \quad {\rm diffusion}$$

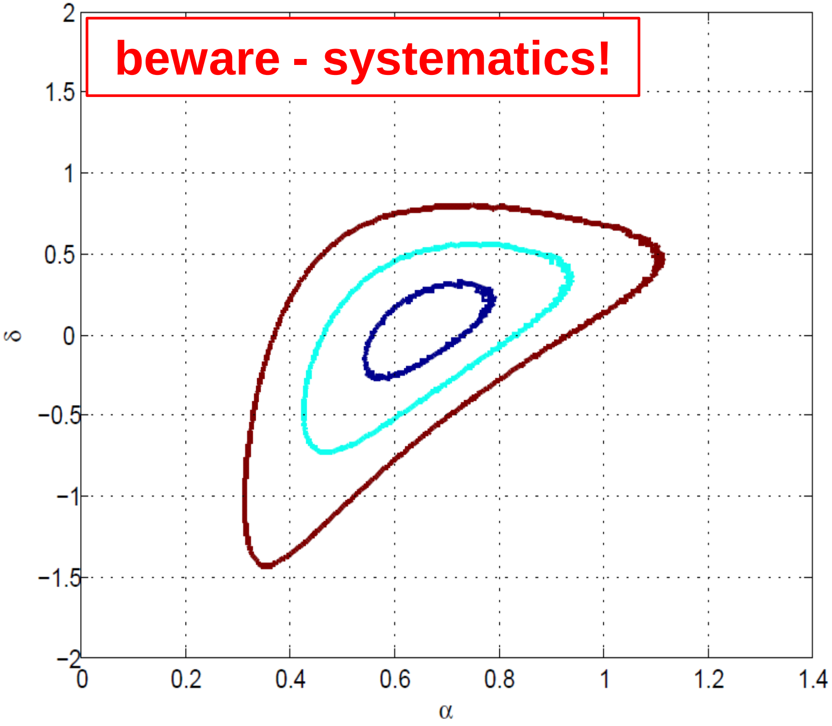
Examples

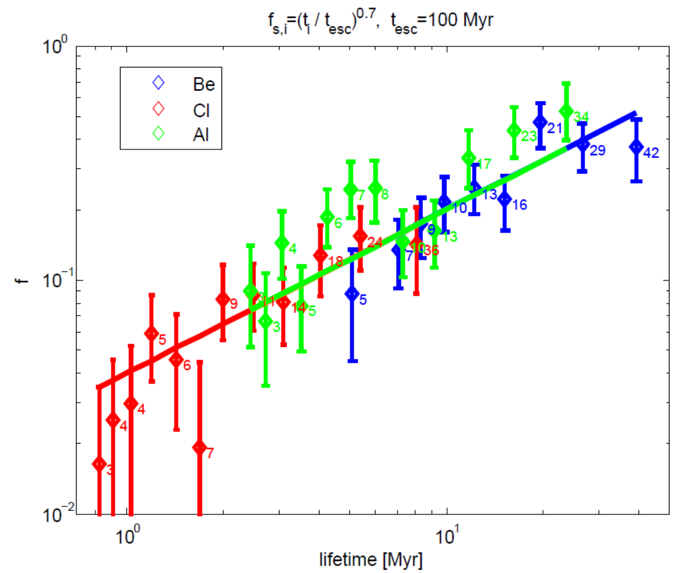
$$f_{s,i} = \frac{1}{1+t_{\rm esc}/t_i}, \quad {\rm DLBM},$$
$$f_{s,i} = \sqrt{t_i/t_{\rm esc}}\,\tanh\left(\sqrt{t_{\rm esc}/t_i}\right), \quad {\rm diffusion}.$$

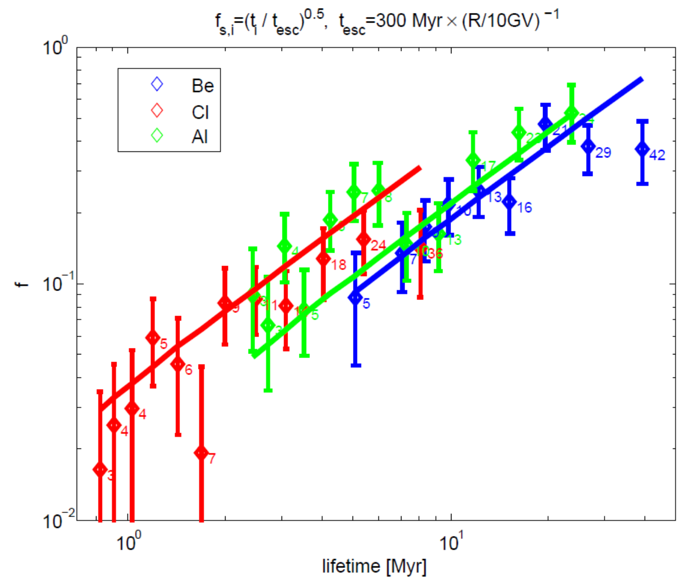


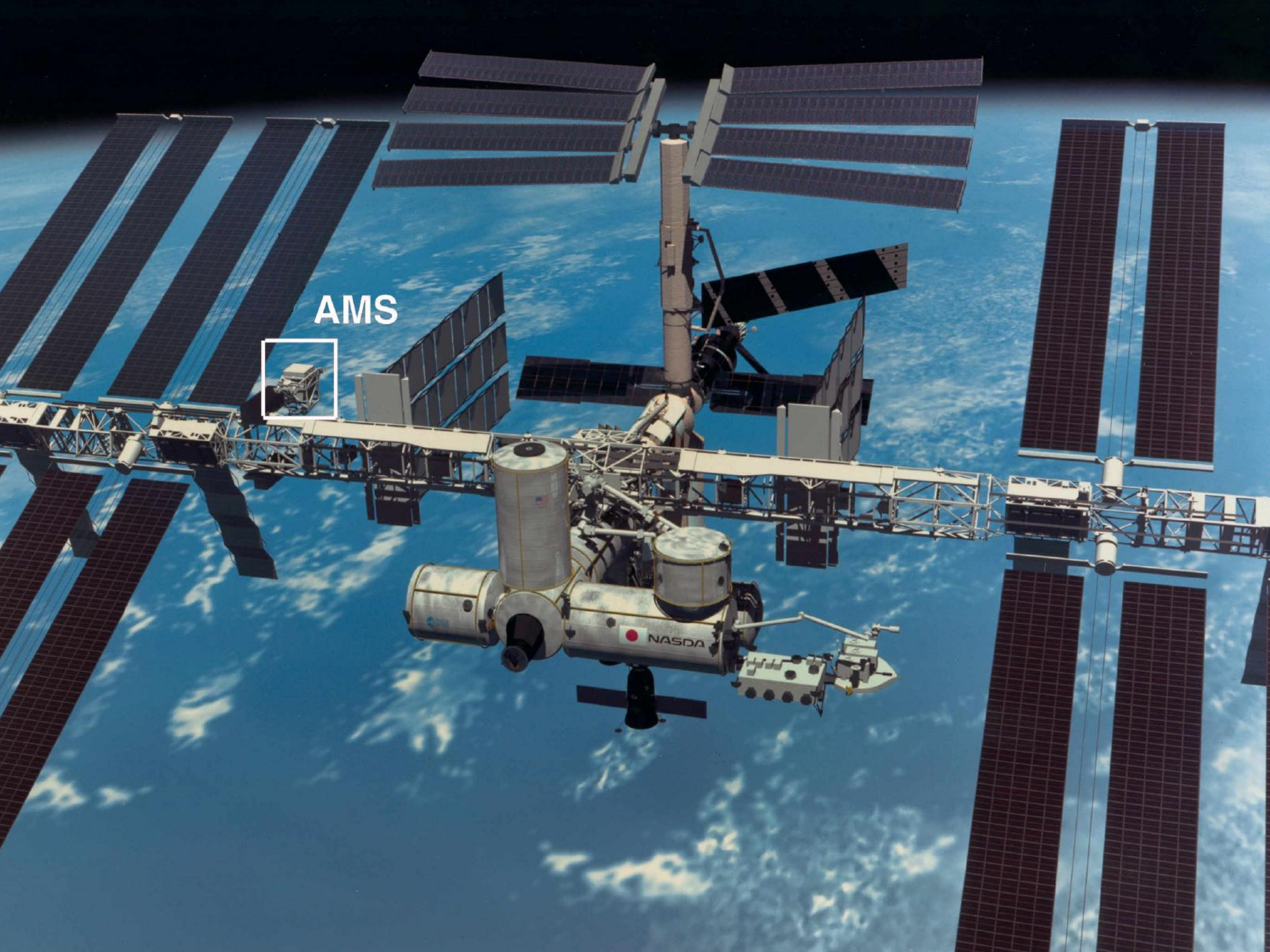
# Radioactive nuclei

rigidity dependence:
hints from current data




AMS
NASDA