Searching for New Physics in Galactic Cosmic Rays

Kfir Blum

KB **1010.2836**

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

+work in progress

Cornell

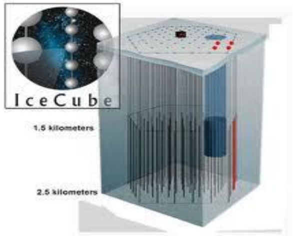
LEPP seminar 10/26/2011

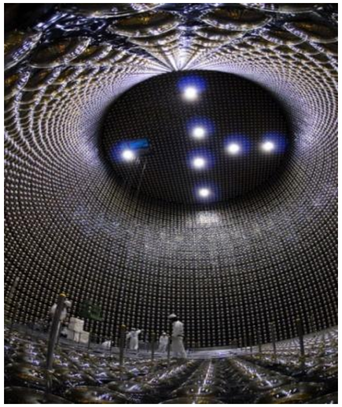
While we’re waiting for new rumors from the LHC…

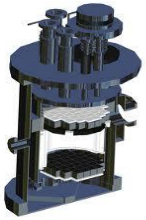
…there’s another front in progress: search for particle dark matter

fundamental to our understanding of the Universe we live in

Many experiments out there for it.







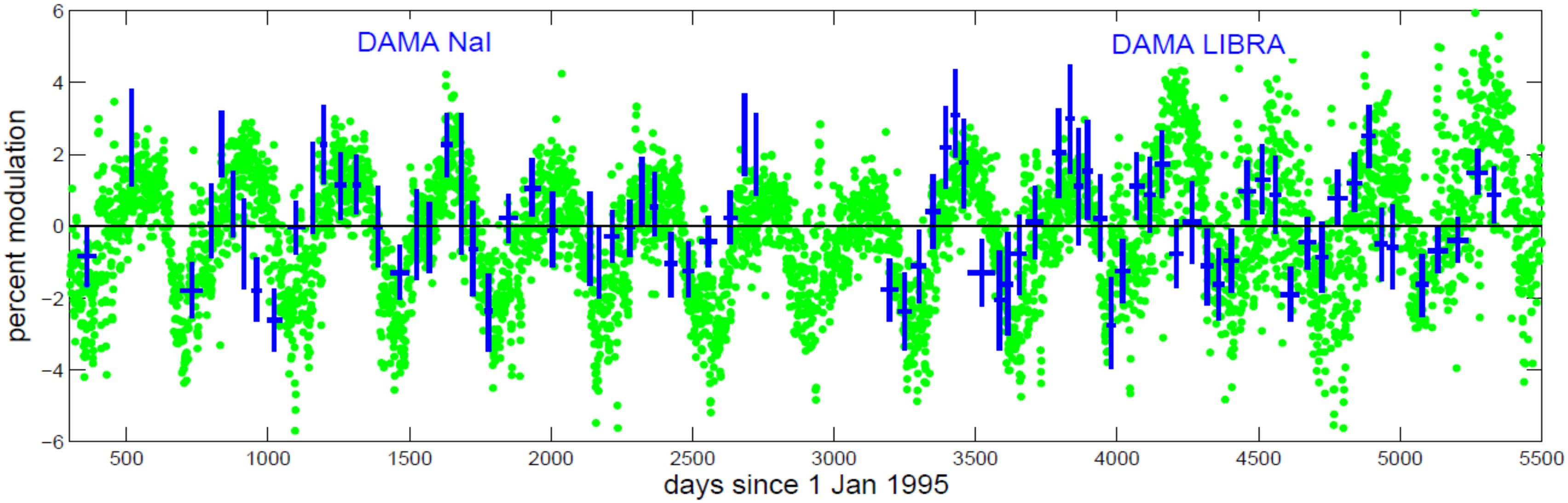
Direct detection

- confusing situation (did we find it already?)

  some experiments put exclusion bounds (Xenon10,100, CDMS, …)

  other experiments detect… something (CRESST, DAMA, CoGeNT)

KB 1110.0857



Indirect detection – topic of this talk

- confusing situation (did we find it already?)

  some experiments detect… something (PAMELA, Fermi, ATIC)

  ➔ is it, or is it not, consistent with backgrounds?

  ➔ what can we do to clarify this issue?

- big question: background predictions.

new data coming up: AMS02

get ready for it!

Plan

- Simple analysis of stable secondaries

  CR grammage

- e+ PAMELA and Fermi

  Know injection → learn propagation

  Robust test for secondary hypothesis

- Radioactive nuclei: lessons for propagation time scales

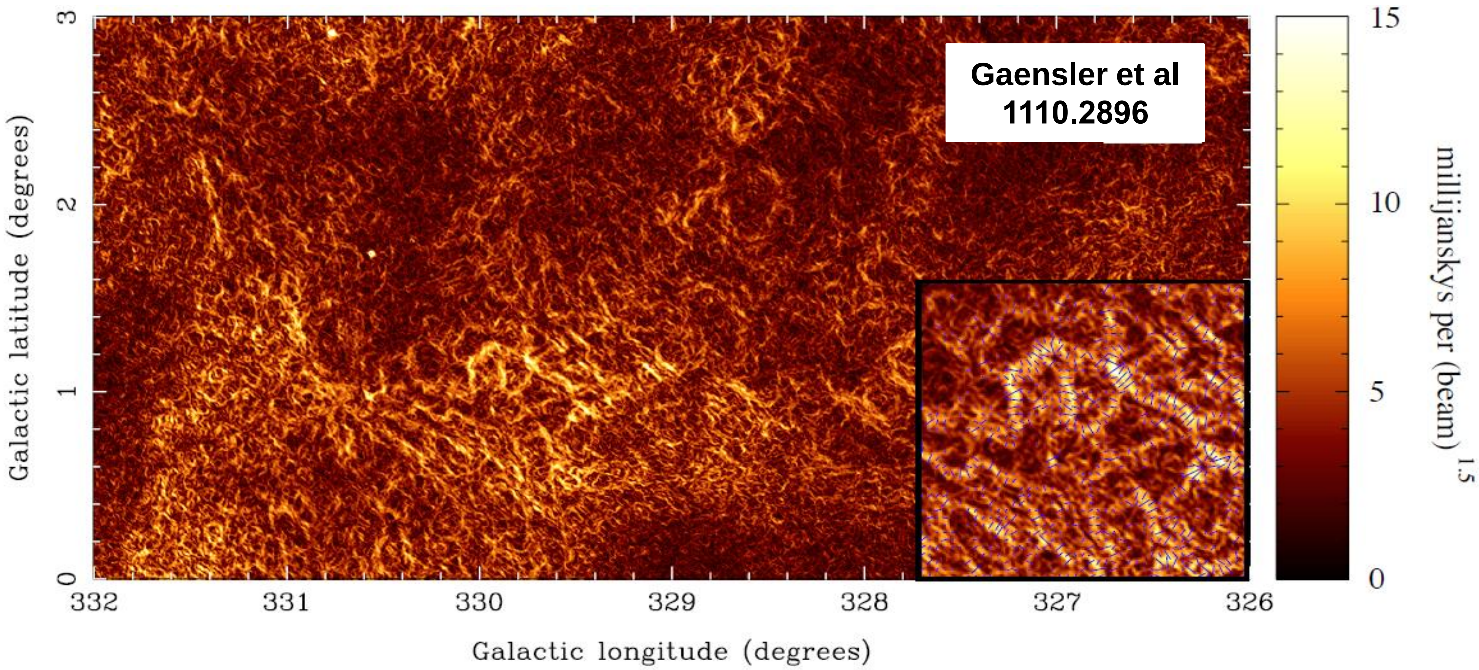
  Radioactive nuclei probe escape time up to (surprisingly) high energy

  Decouples escape from the problem ➔ test secondary origin

Galactic CR: general picture

- 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, … fragmentation of primaries on ISM.

  Antimatter occurs as secondary $pp \to pn\pi^+ \to ppe^-e^+\nu_e\bar{\nu}_e\nu_\mu\bar{\nu}_\mu$
- Open questions: propagation.

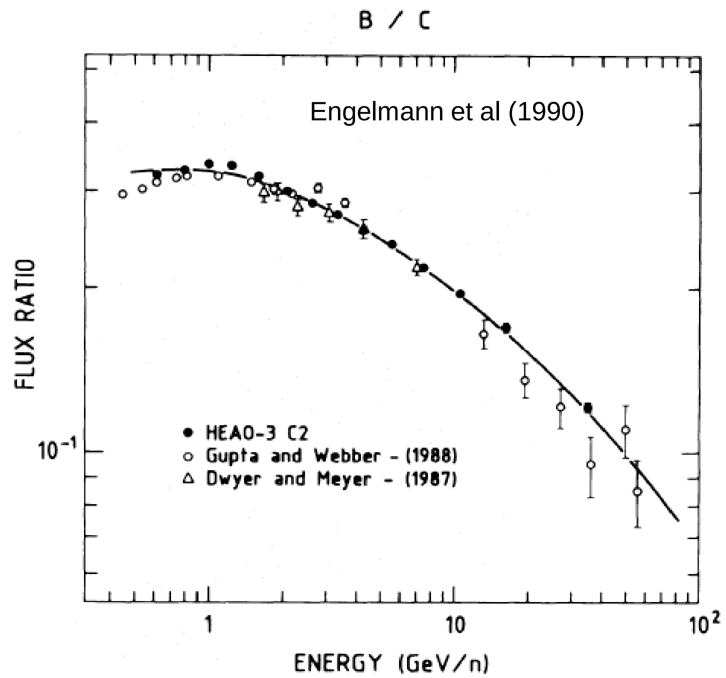


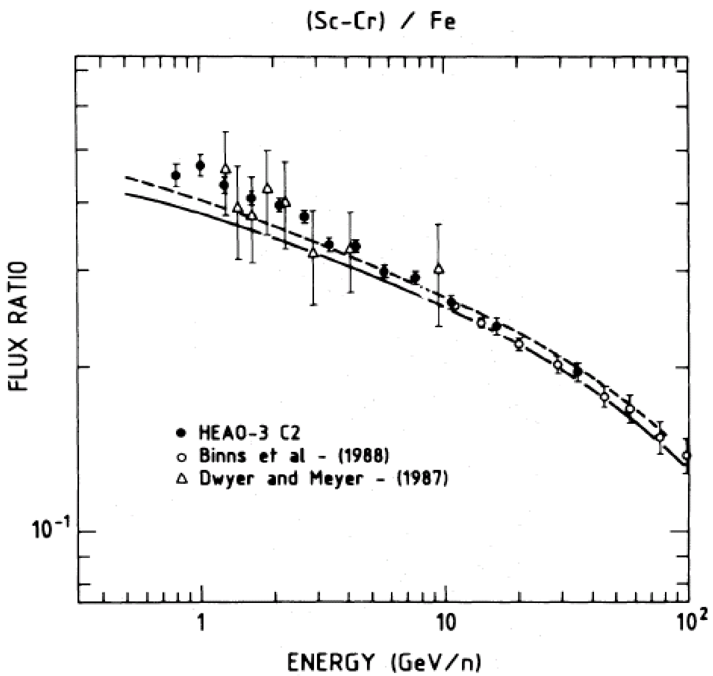
A simple analysis of stable secondaries

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

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

- $\tilde{Q}_S$ = Local net production density per traversed unit column density of ISM
- $X_{\rm esc}$ = CR **grammage**. Crucial point: $X_{\rm esc}$ does not carry 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 ☆

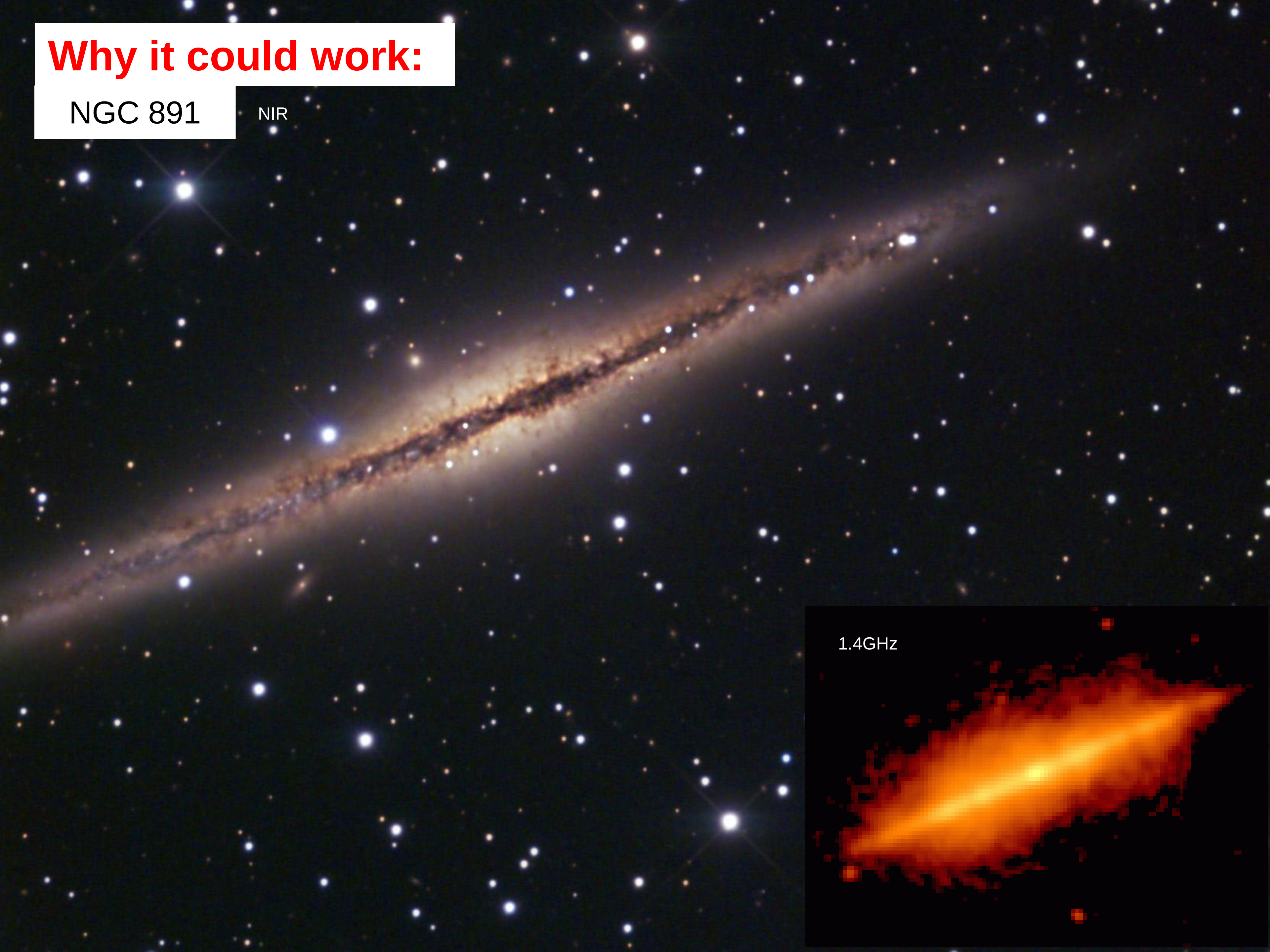
- Sufficient condition:

The composition of CRs and of ISM is approximately uniform, in the regions in which most secondaries observed at earth are produced

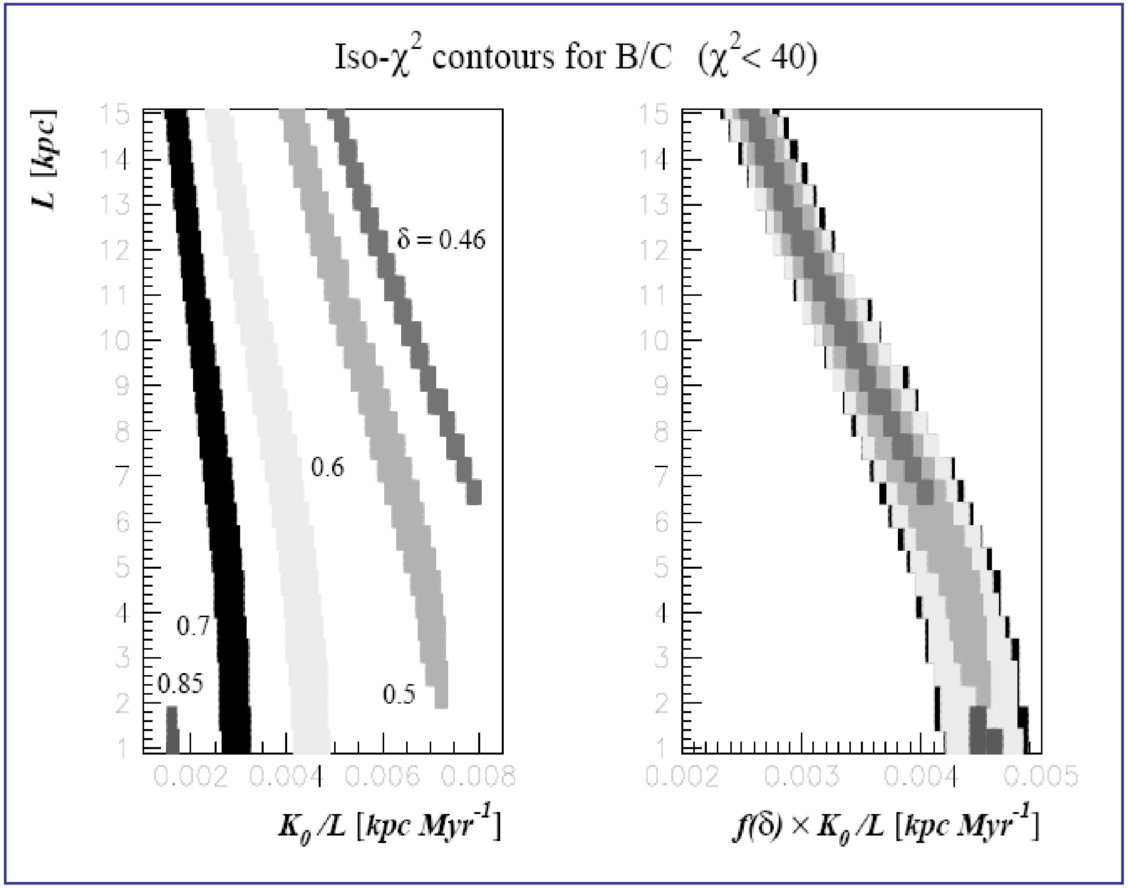
Why does it work so well?

Why it could work:

NGC 891



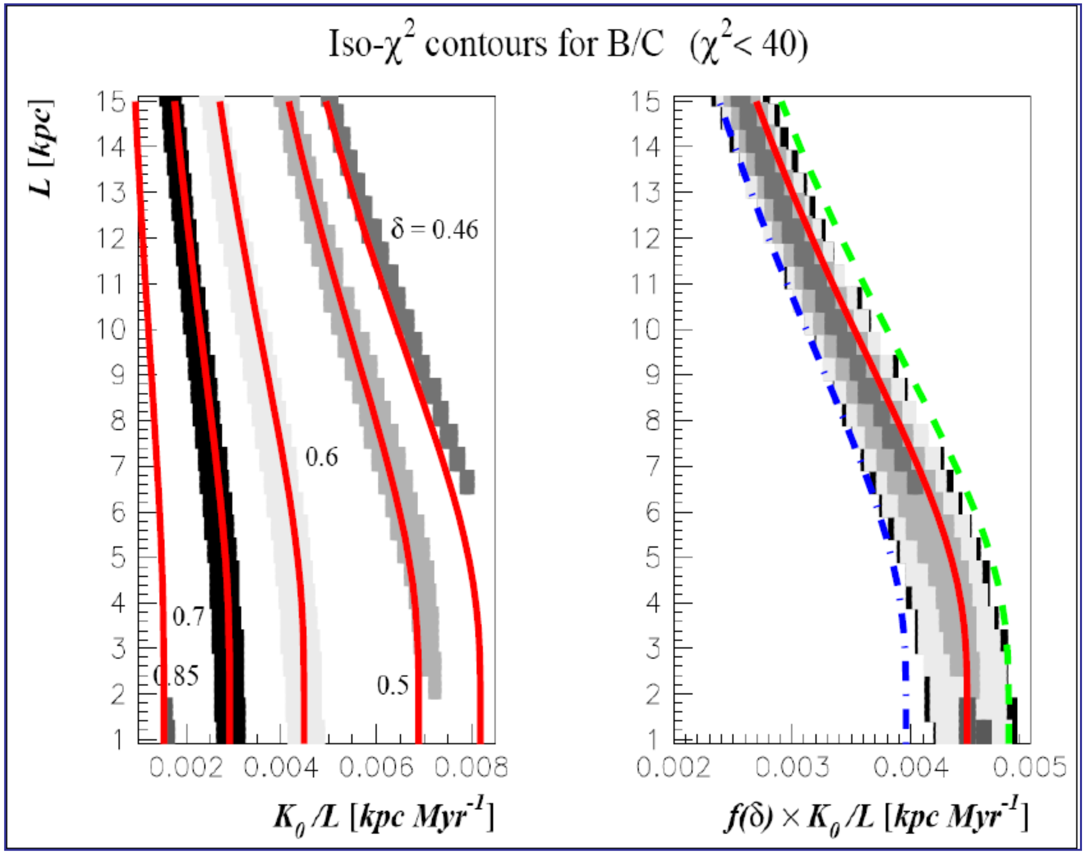
Diffusion models fit grammage.



Maurin, Donato, Taillet, Salati

Astrophys.J.555:585-596,2001

Diffusion models fit grammage.



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

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

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

Plan

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- What do we 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**


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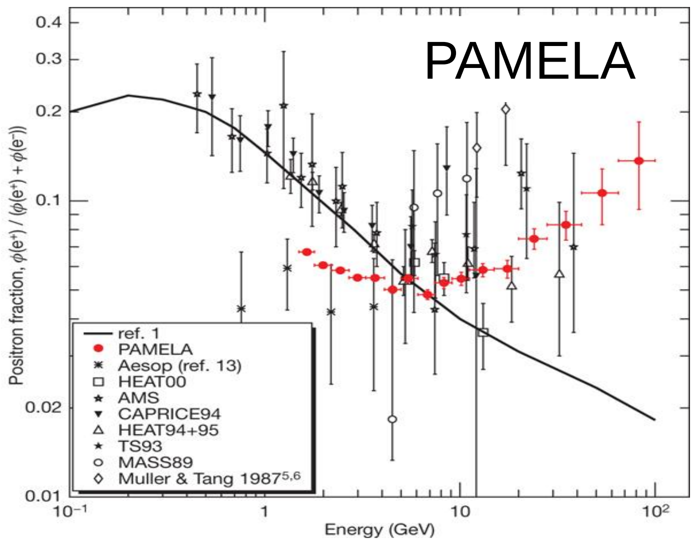
Letter

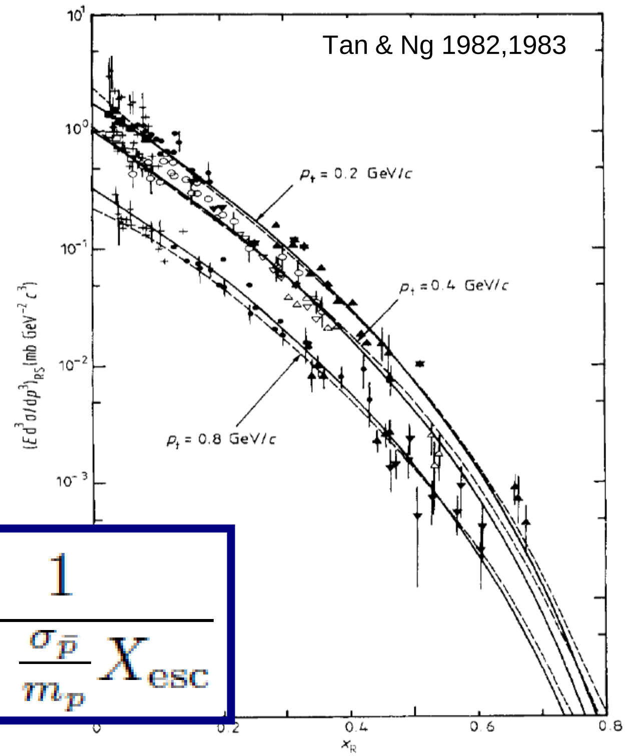
Nature **458**, 607-609 (2 April 2009) | doi:10.1038/nature07942; Received 28 February 2009

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

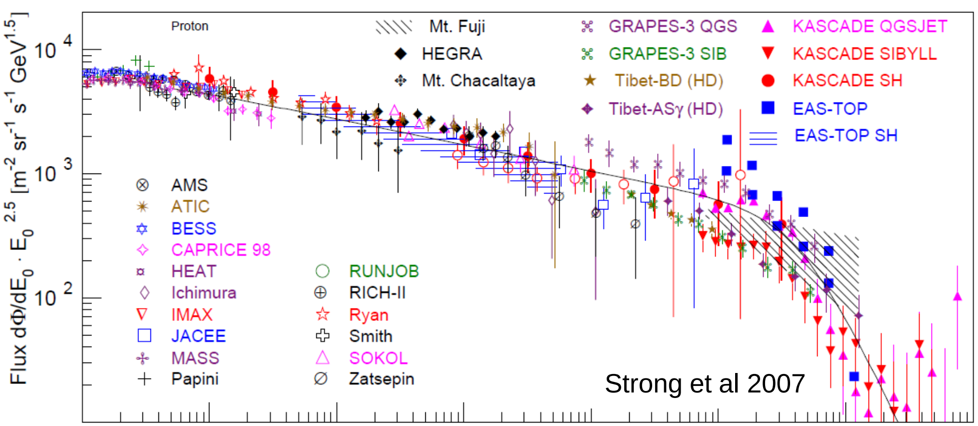


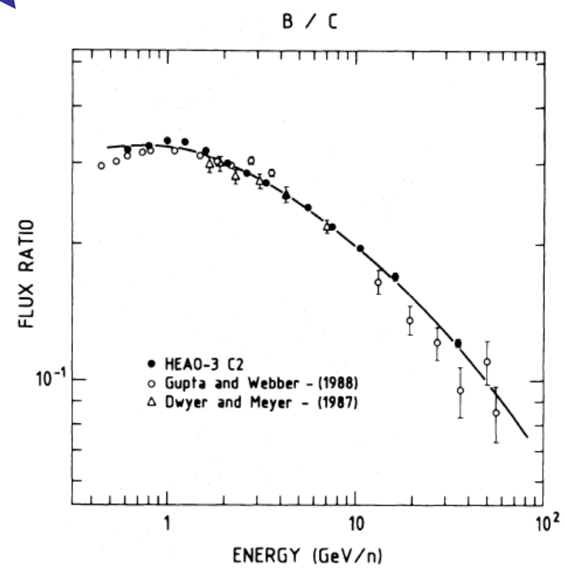
Antiprotons

No free parameters.



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

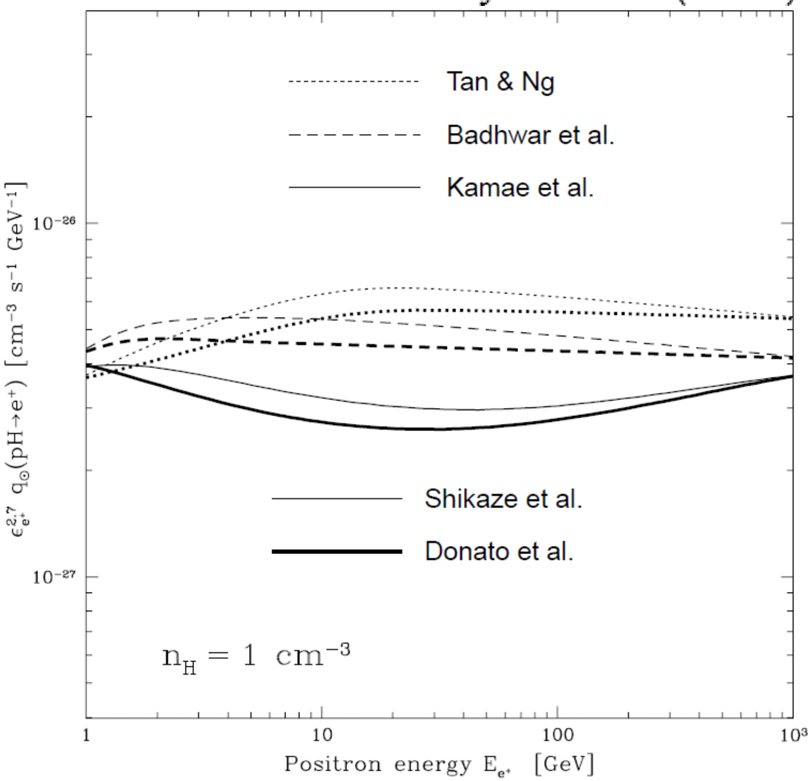




Positrons

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

T. Delahaye et al. (2008)



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

h	Exclusive reaction	$\bar{M}_X$ (GeV c^{-2})	$\sqrt{s_t}$ (GeV)	E_t (GeV)	T_t (GeV)
π^+	$pn\pi^+$	1.878	2.018	1.233	0.295
π	$pp\pi^+\pi^-$	2.016	2.156	1.540	0.602
π^0	$pp\pi^0$	1.876	2.011	1.218	0.280
κ^+	$\Lambda^0 p\kappa^+$	2.053	2.547	2.520	1.582
κ^-	$pp\kappa^+\kappa^-$	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.

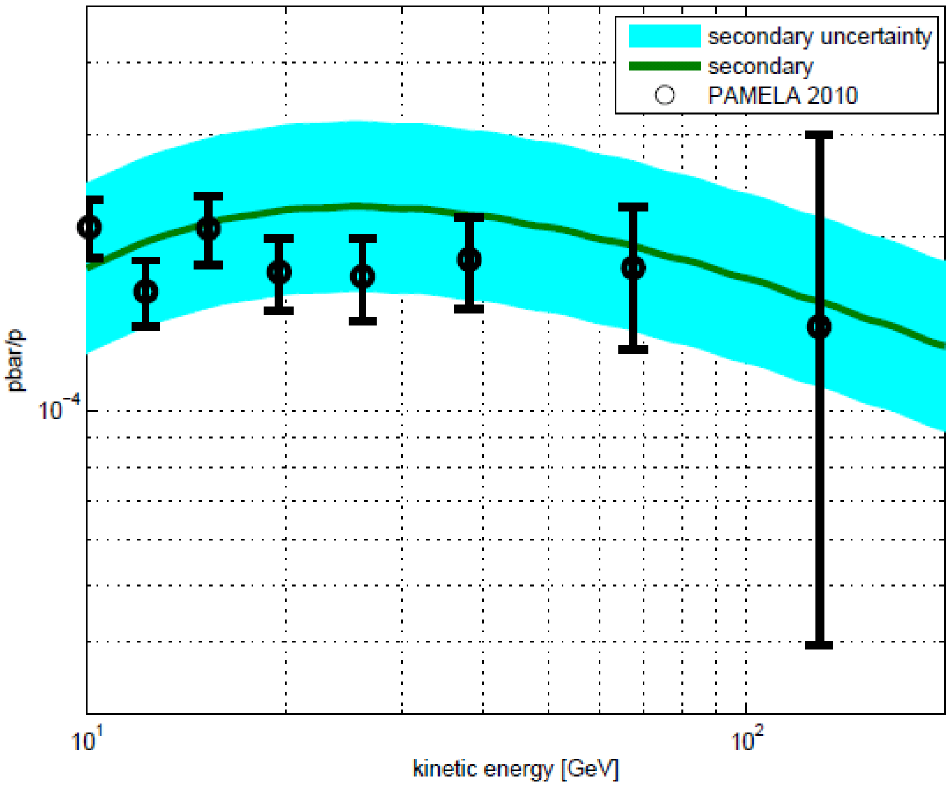
For example, diffusion models predict: $f \sim \sqrt{t_c/t_{\rm esc}}$

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

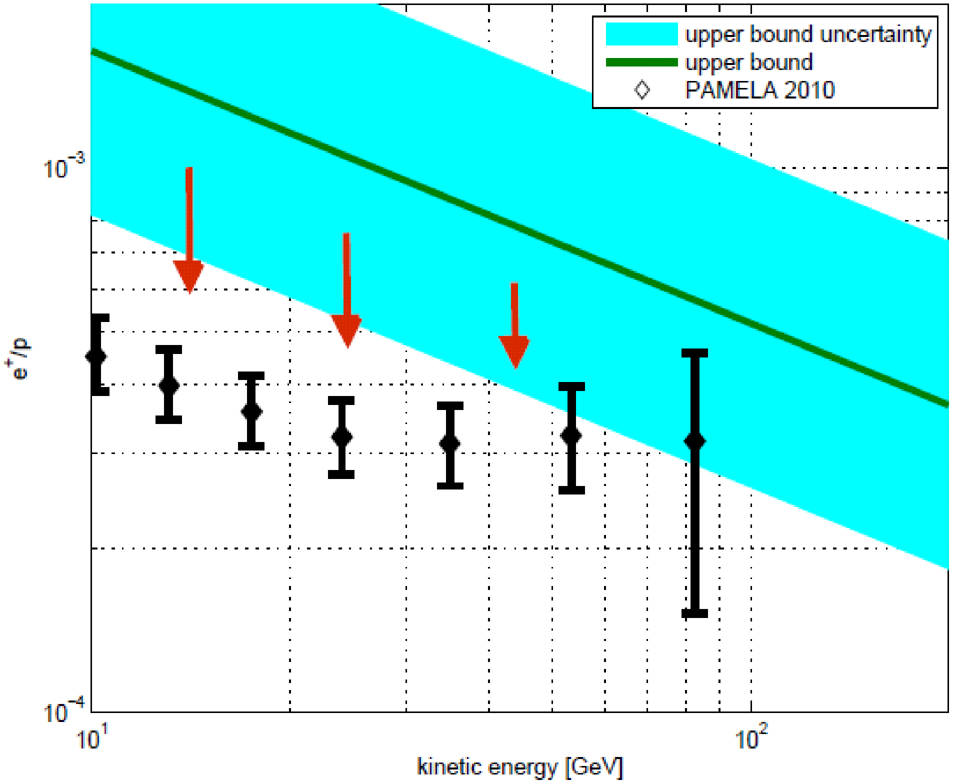
- Steep spectrum → loss suppresses flux $f_{s,e^+} < 1$

Study positrons and antiprotons together

Antiprotons

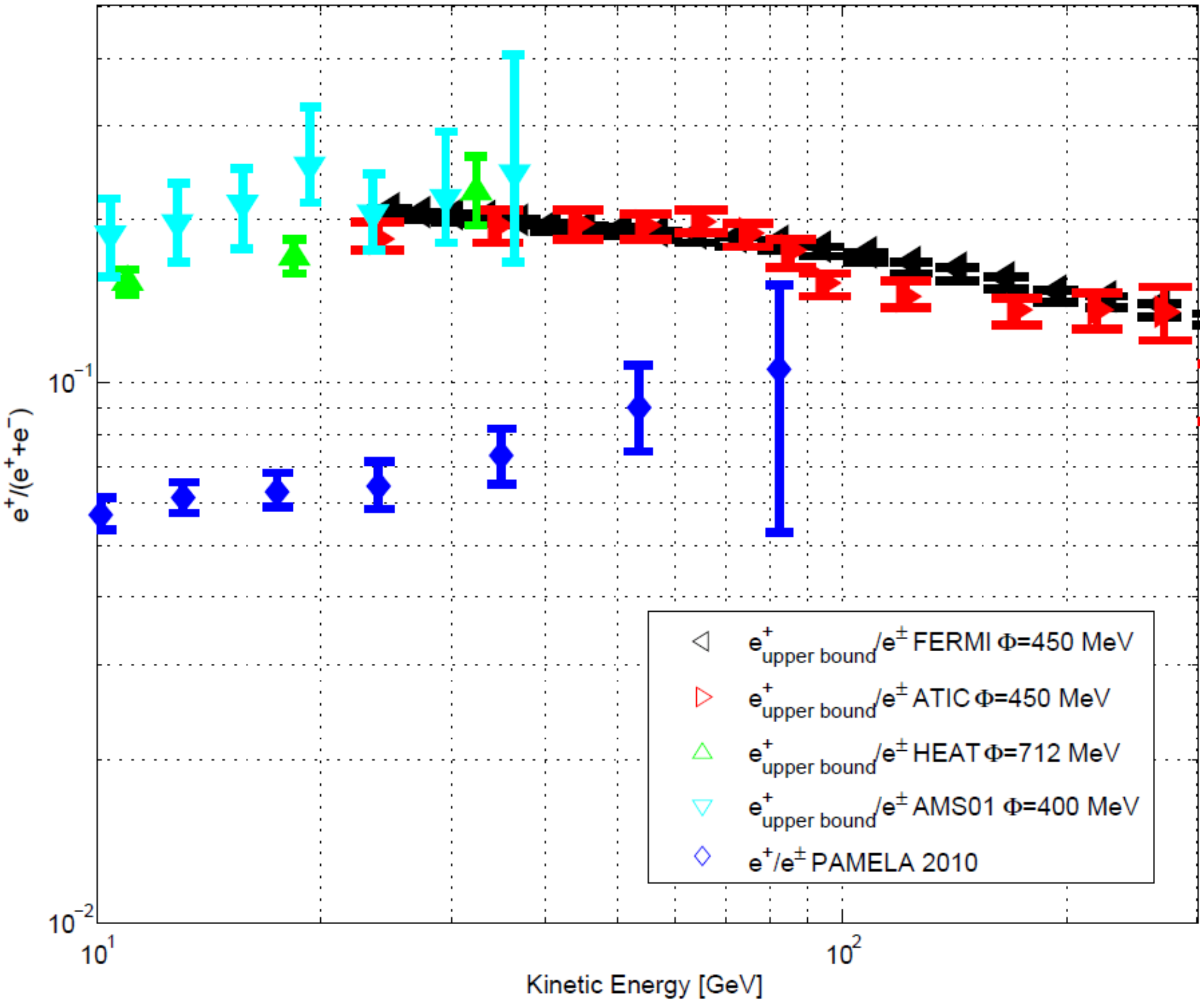


Positrons



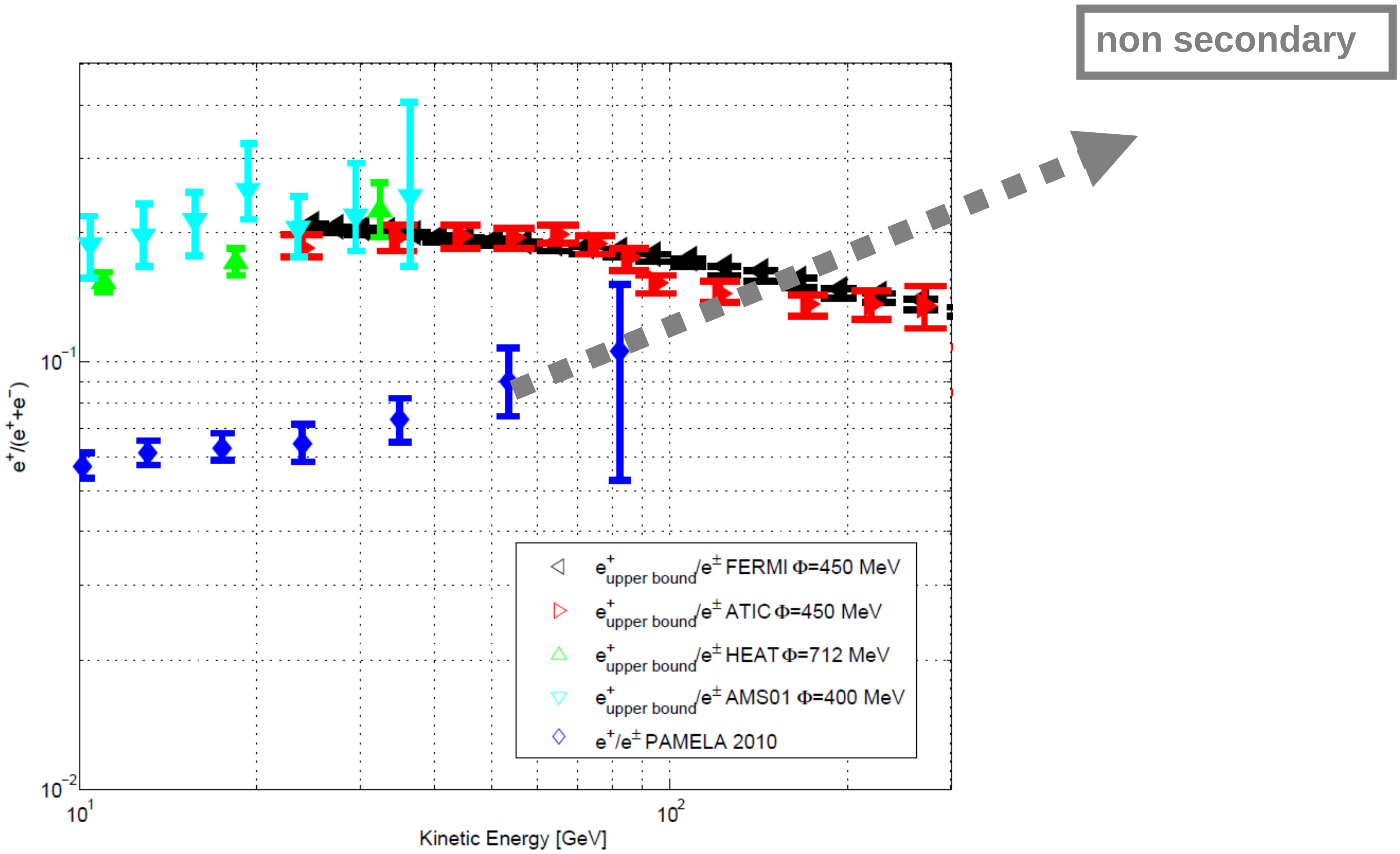
Positron flux suppressed by losses.

Positrons: data

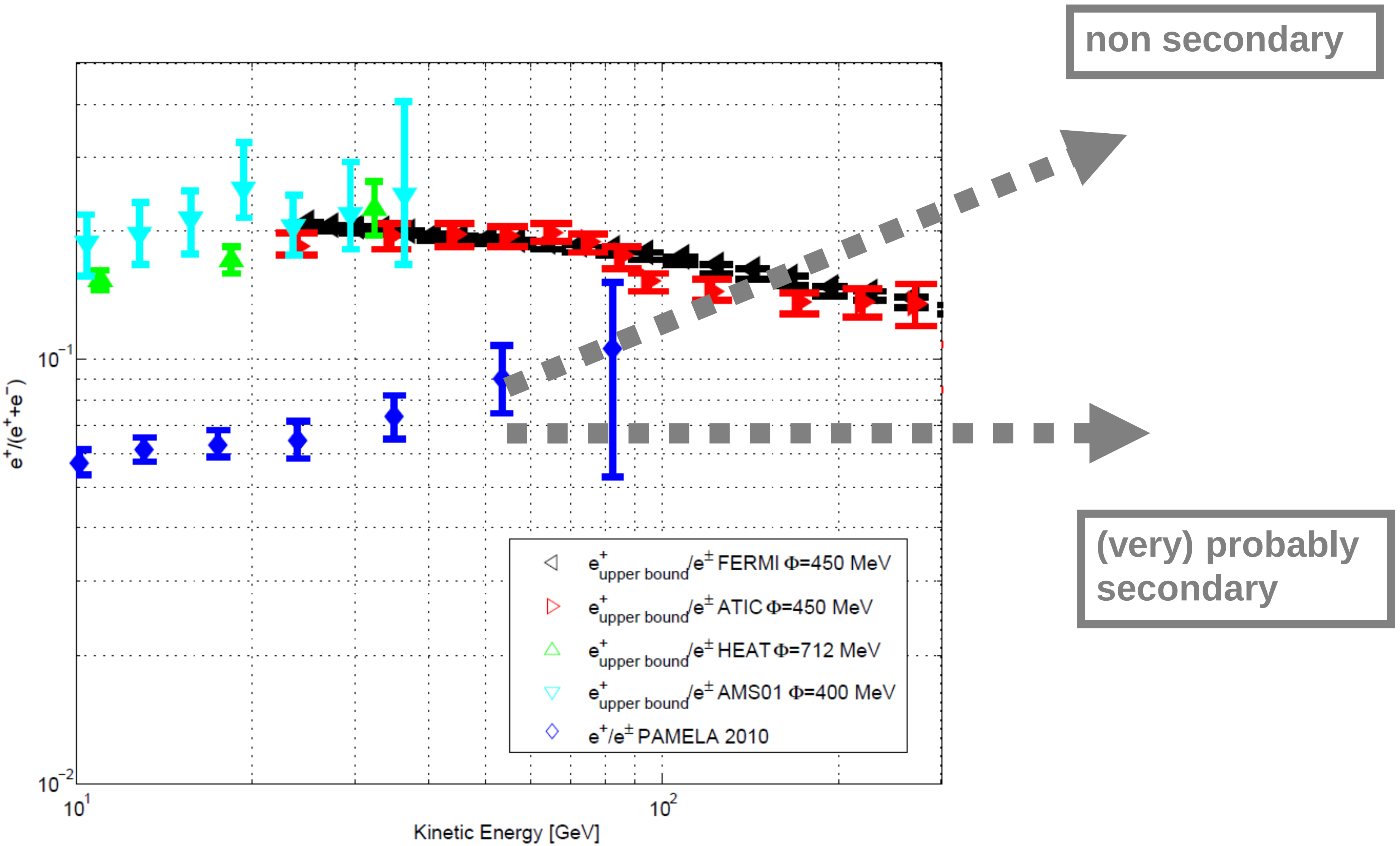


$$f_{s,e^+} < 1$$

Positrons: data



Positrons: data



Quantify losses (go beyond $f_{s,e^+} < 1$)

- Suppression factor:

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

- 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 ?**

- **Answer by studying radioactive nuclei**

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Radioactive nuclei: Charge ratios

Suppression factor due to decay ≈ suppression due to radiative loss,

if compared at rigidity such that cooling time ≈ decay time

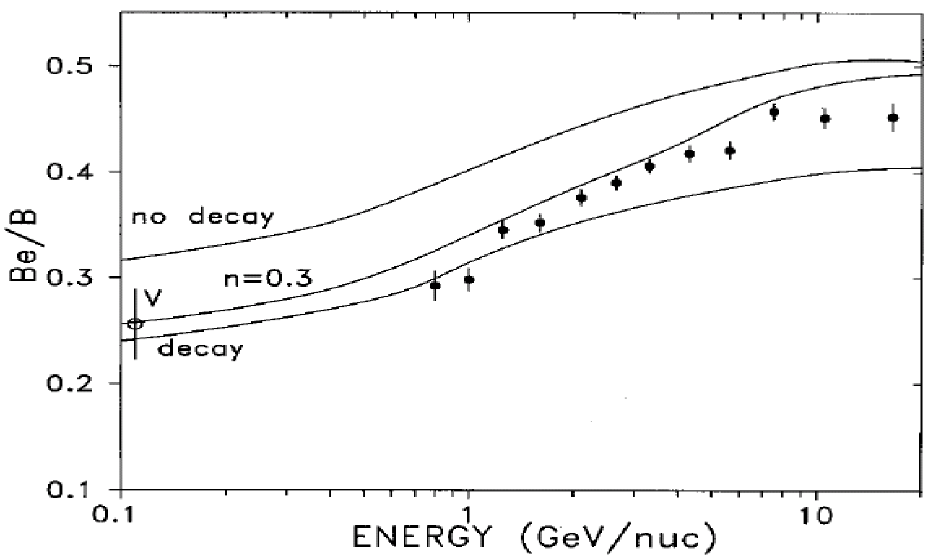
A STUDY OF THE SURVIVING FRACTION OF THE COSMIC-RAY RADIOACTIVE DECAY ISOTOPES ^{10}Be, ^{26}Al, ^{36}Cl, and ^{54}Mn AS A FUNCTION OF ENERGY USING THE CHARGE RATIOS Be/B, Al/Mg, Cl/Ar, AND Mn/Fe MEASURED ON *HEAO*−*3*

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

Received 1997 November 6; accepted 1998 May 11

(WS98)

reaction	$t_{1/2}$ [Myr]	σ [mb]
$^{10}_{4}\mathrm{Be} \to {}^{10}_{5}\mathrm{B}$	1.51 (0.06)	210
$^{26}_{13}\mathrm{Al} \to {}^{26}_{12}\mathrm{Mg}$	0.91 (0.04)	411
$^{36}_{17}\mathrm{Cl} \to {}^{36}_{18}\mathrm{Ar}$	0.307 (0.002)	516
$^{54}_{25}\mathrm{Mn} \to {}^{54}_{26}\mathrm{Fe}$	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. Also e+
- Expect $$f_{s,i} \approx \left(\frac{t_i}{t_{\rm esc}}\right)^{\alpha}$$

  Examples:

  Leaky Box Model

$$f_{s,i} = \frac{1}{1 + t_{\rm esc}/t_i}$$

$$\tilde{f}_i = \frac{1}{1 + \frac{t_{\rm esc}}{t_c}\left(1 + \frac{X_{\rm esc}\,\sigma_{i\to X}}{m_p}\right)^{-1}}$$

  Diffusion

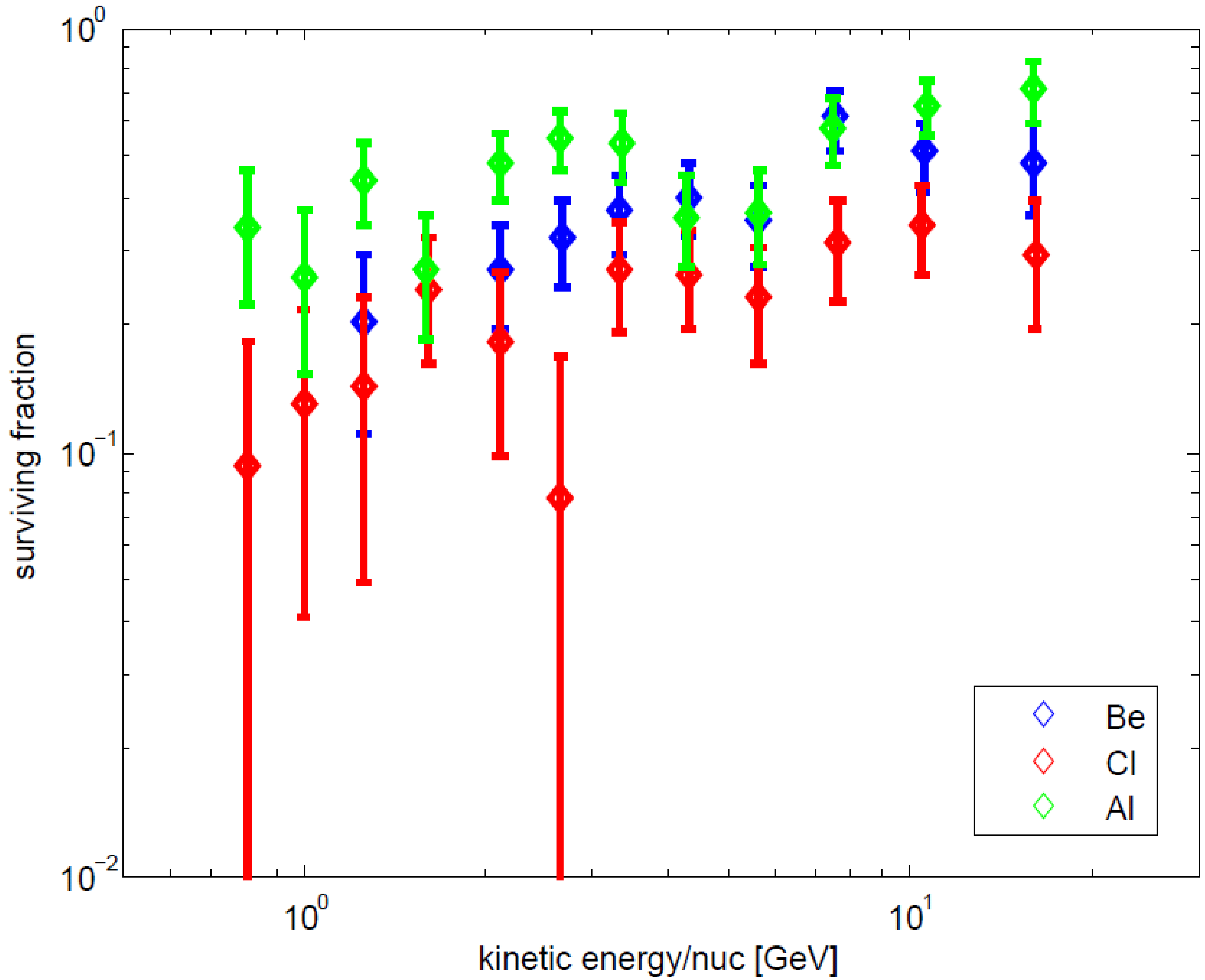
$$f_{s,i} = \sqrt{t_i/t_{\rm esc}}\,\tanh\left(\sqrt{t_{\rm esc}/t_i}\right)$$

$$\tilde{f}_i = \cdots$$

- Magnetic trapping, $$t_{\rm esc} = t_{\rm esc}(\mathcal{R})$$

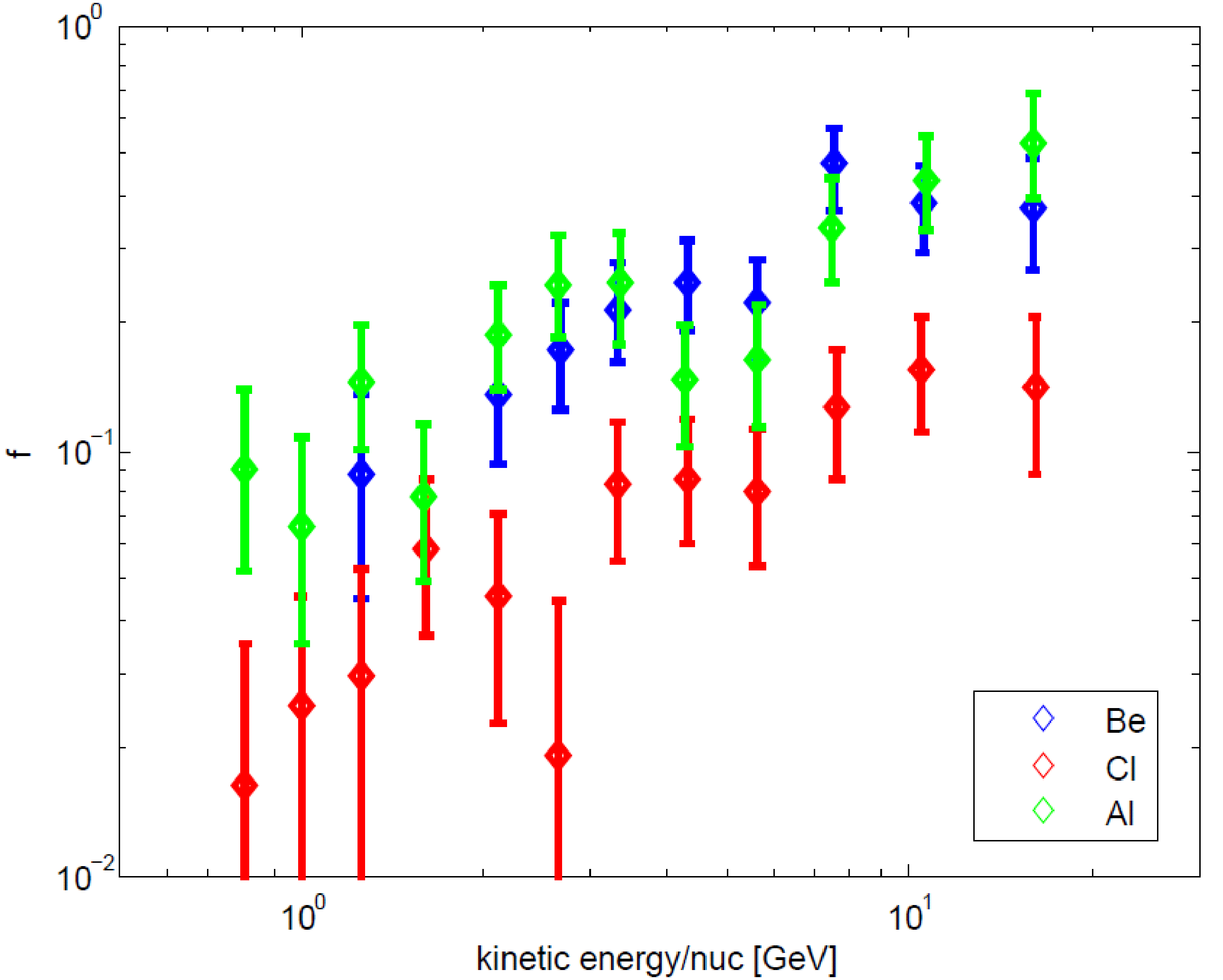
Radioactive nuclei: data

Surviving fraction vs. energy (WS98)



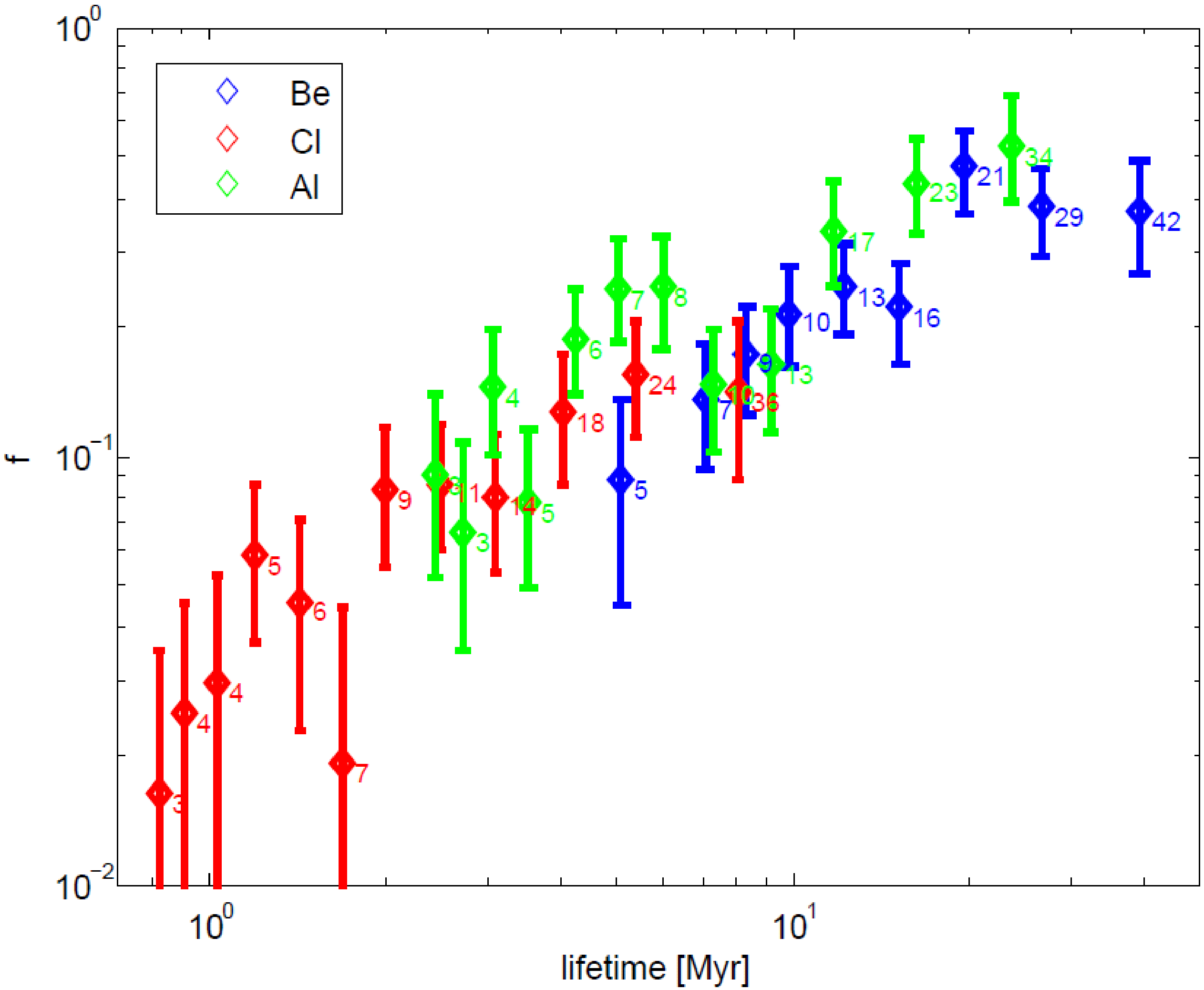
Radioactive nuclei: data

Suppression factor vs. energy



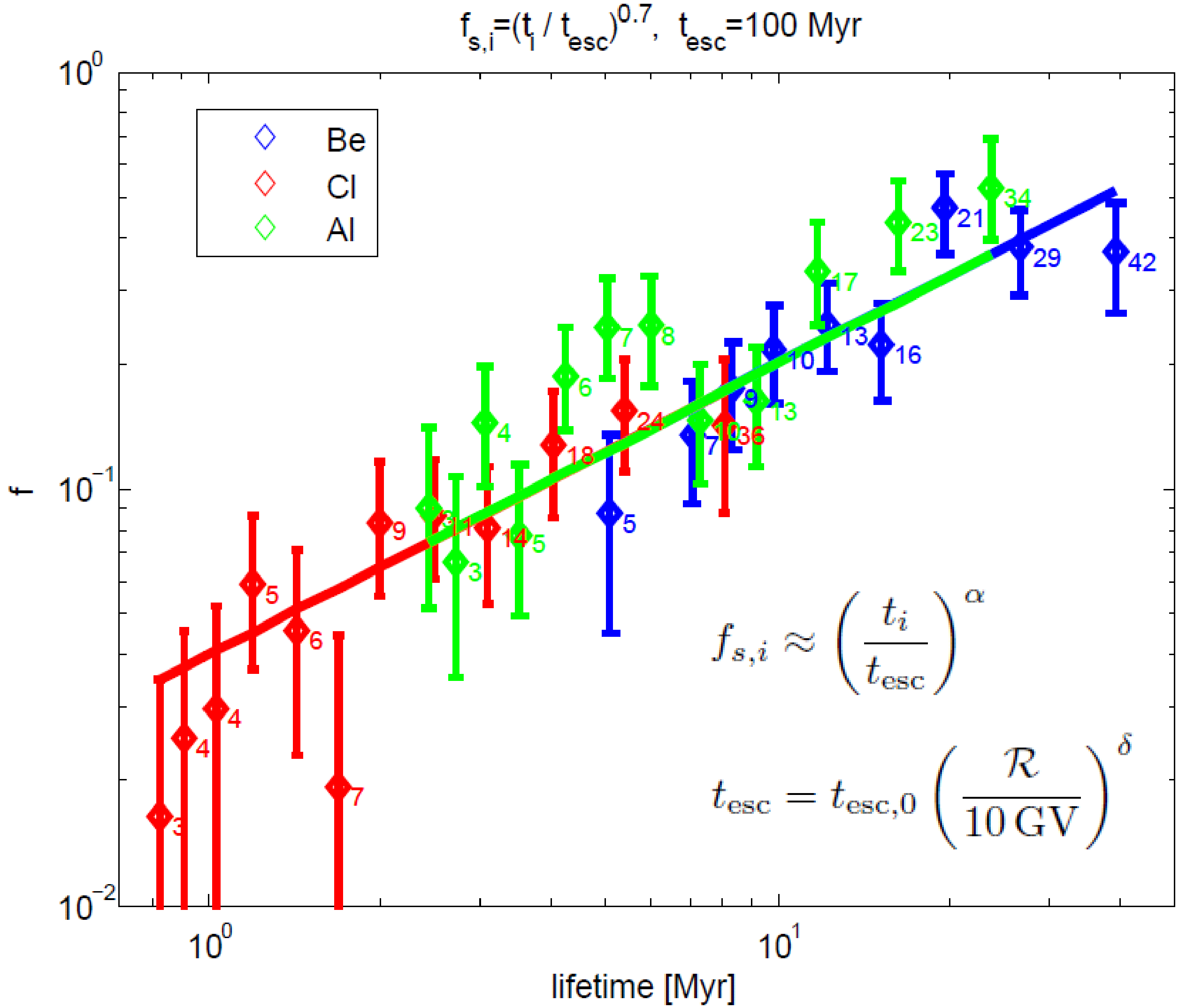
Radioactive nuclei: data

Suppression factor vs. lifetime



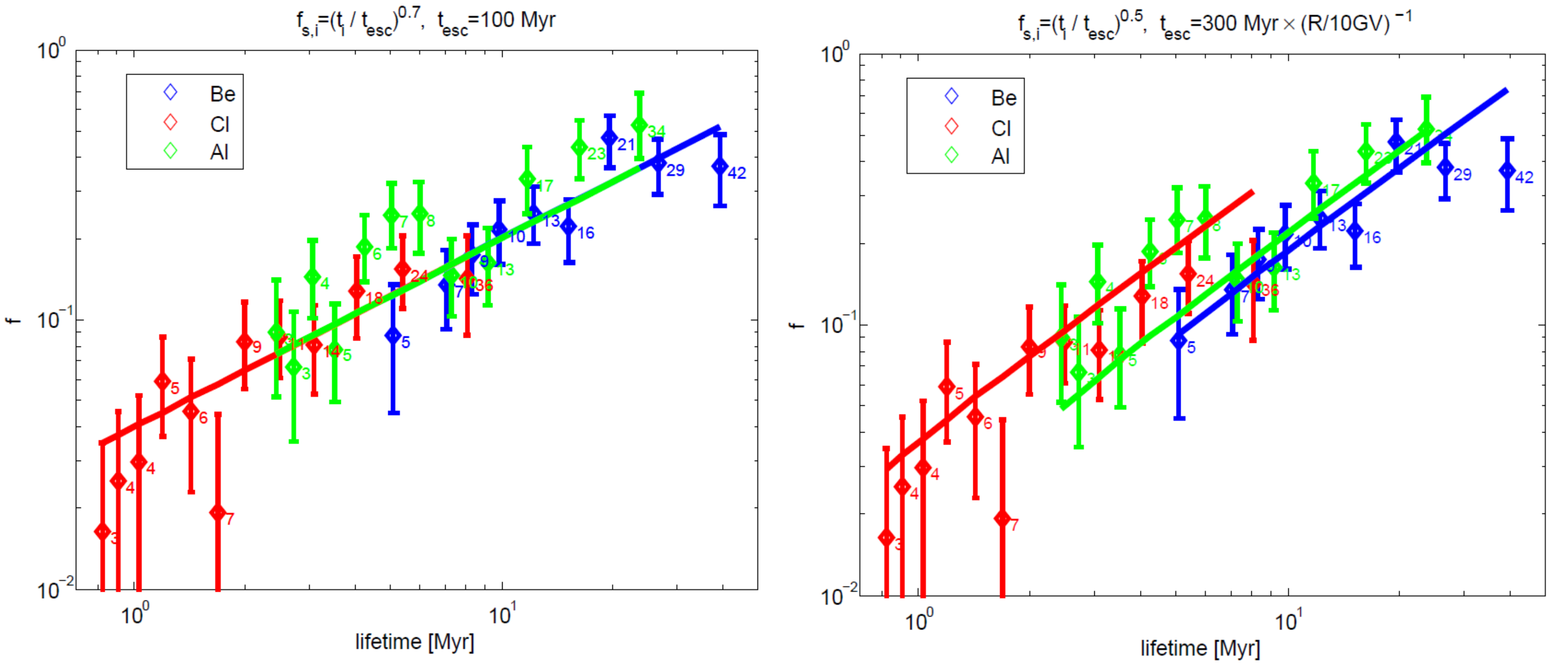
Radioactive nuclei: data

Consistent with constant residence time



Radioactive nuclei: 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!**



Combined information (some answers)

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

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

Combined information (some answers)

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

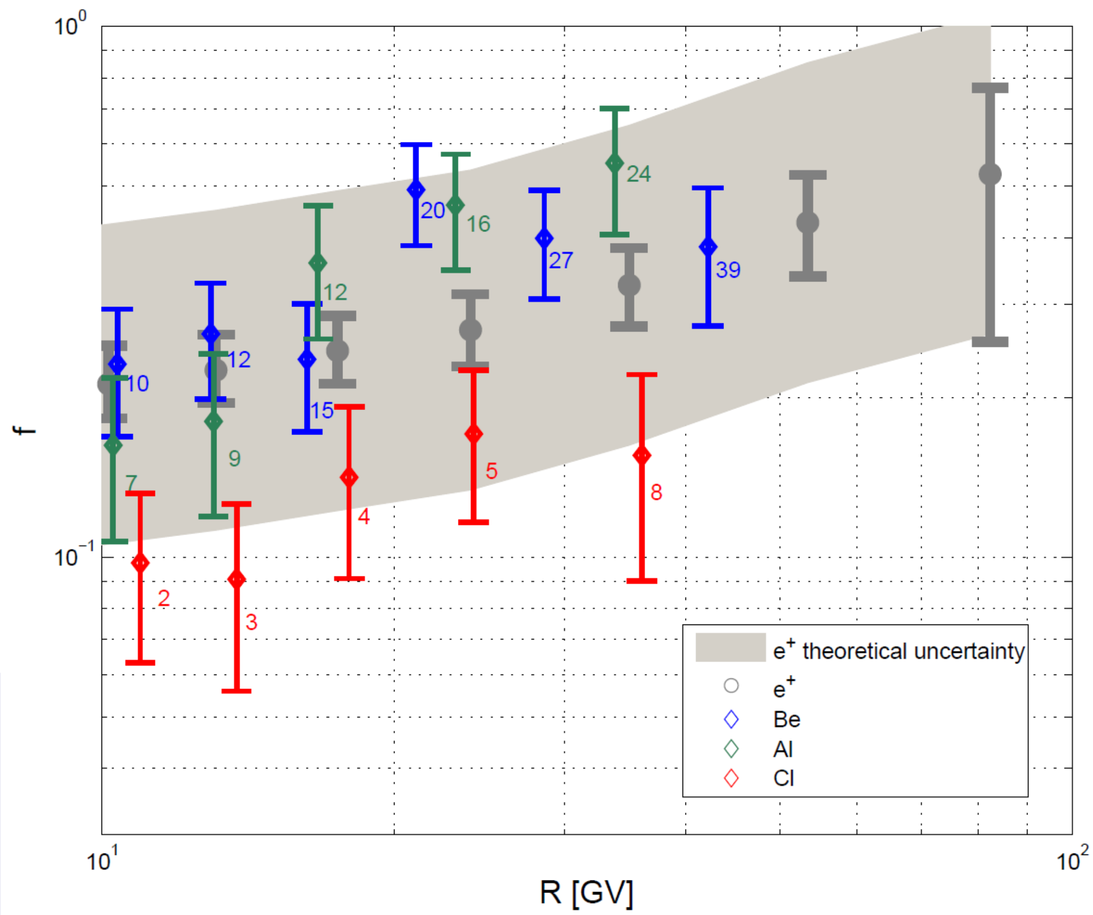
➔ consistent w/ secondary

More: 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. Cooling time – amount of losses: $\bar{U}_T > U_{CMB}$

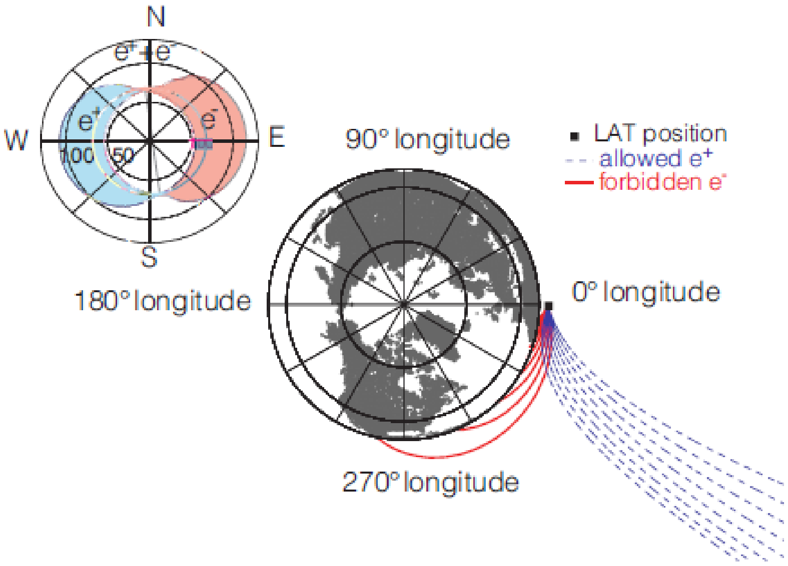
Compare w/ radioactive nuclei. At present, satisfied where Cl and e+ data coexist

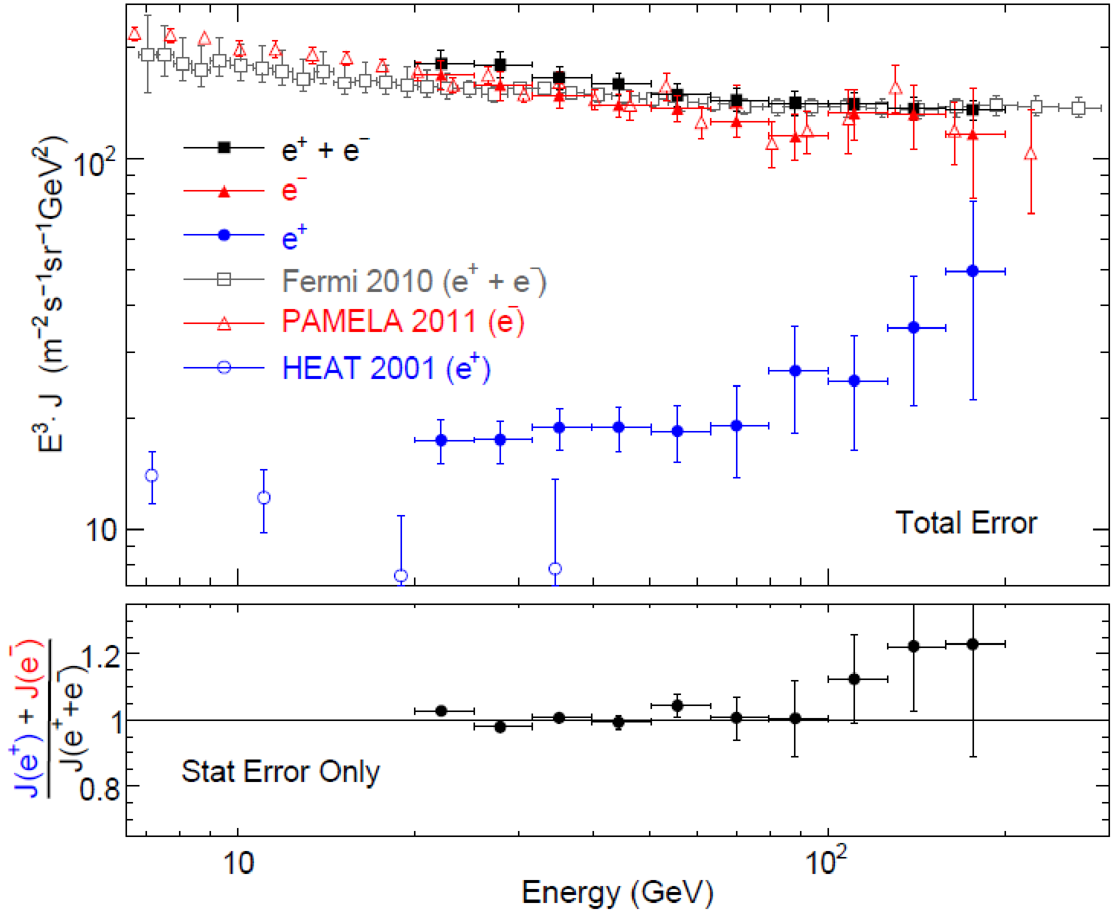
3. Slope: $\delta + \delta_c < 0$

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

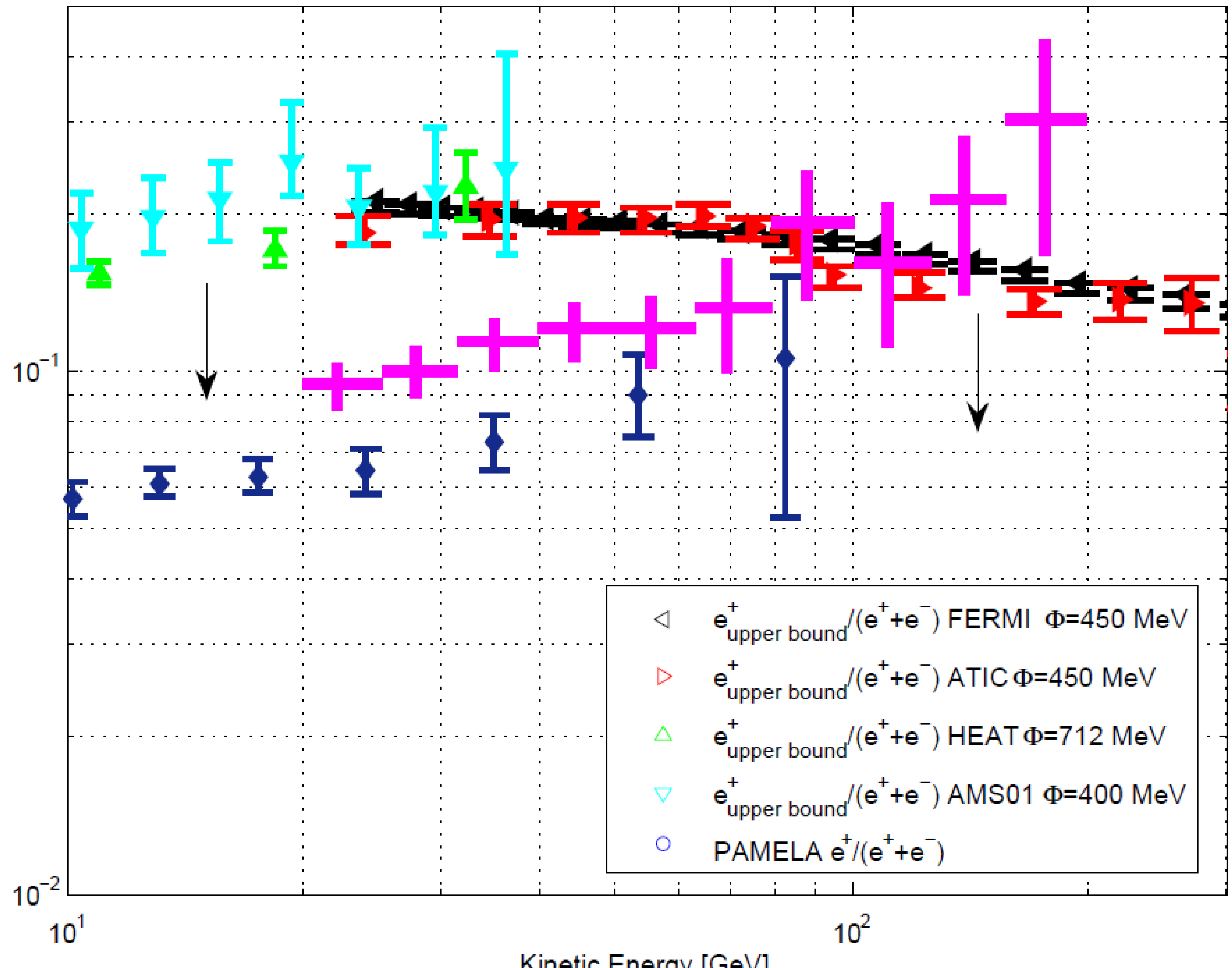
Based on radioactive nuclei. Consistent w/ PAMELA data

Fermi e+ 1109.0521





Fermi e+ 1109.0521 (did we find it already?)



Summary

- Stable secondaries:

  propagation models fit grammage

- Interpreting e+ data:

  e+ ~ antiprotons

- `Anomaly' ? PAMELA data does not show

  ^{10}Be agrees ➔ e+ secondary

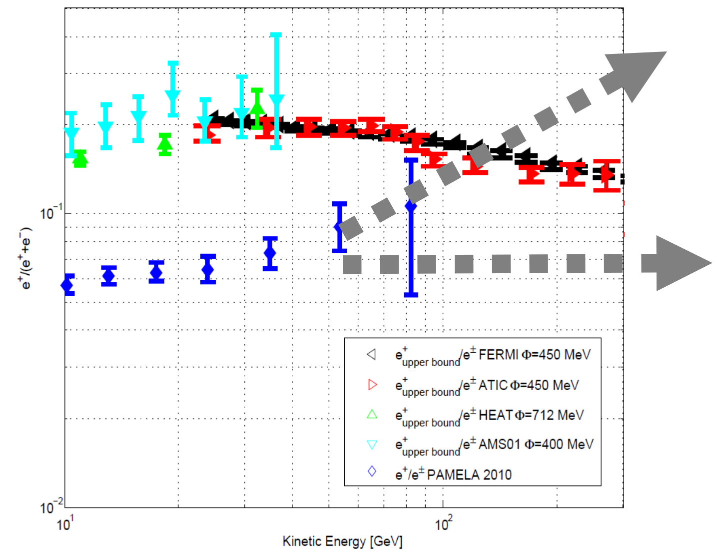
  PAMELA , AMS-02: reach 270-300 GeV

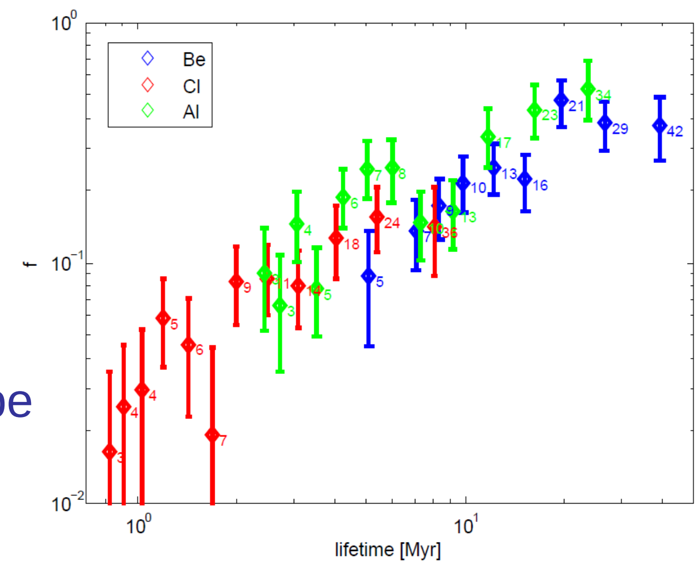
  Fermi 2011: *very exciting*!

  AMS02 will settle this.

- Compare w/ radioactive nuclei ➔ decouple escape

  model independent tests for NP





Xtras

Guiding concept: The solar neutrino problem

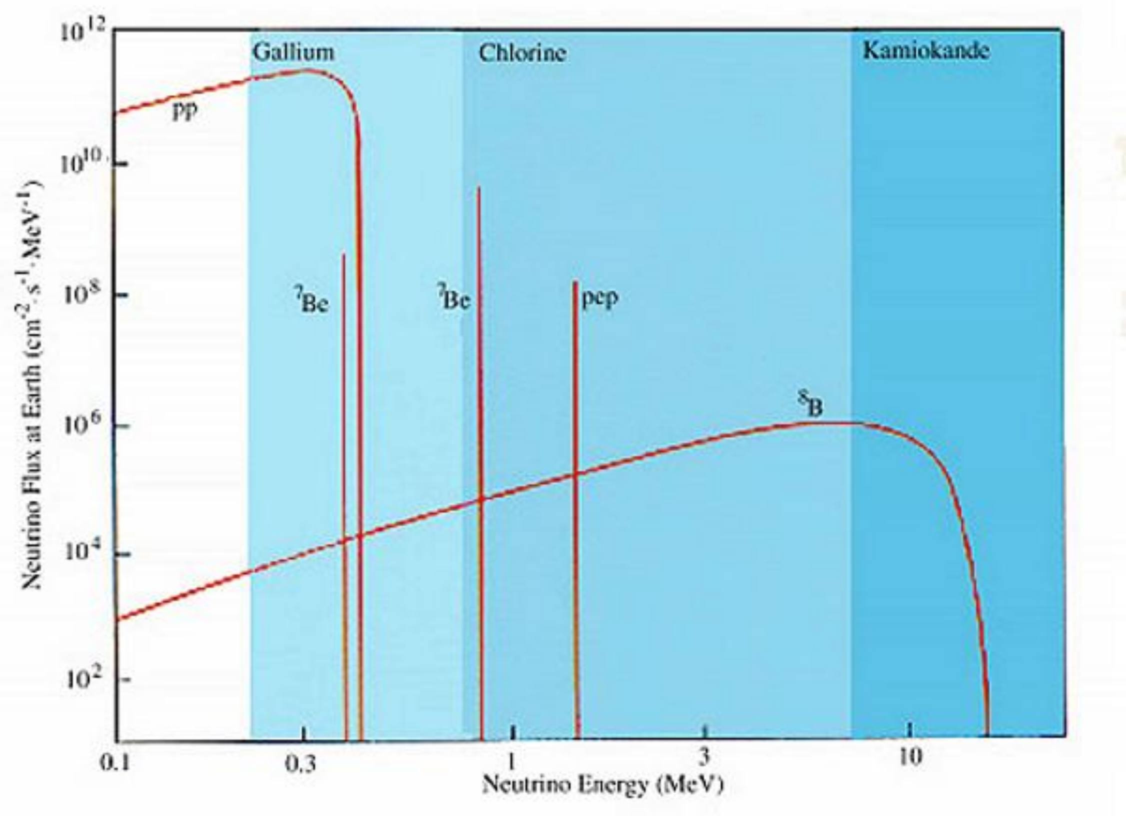
• Major success of particle astrophysics: Solar Neutrinos

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**



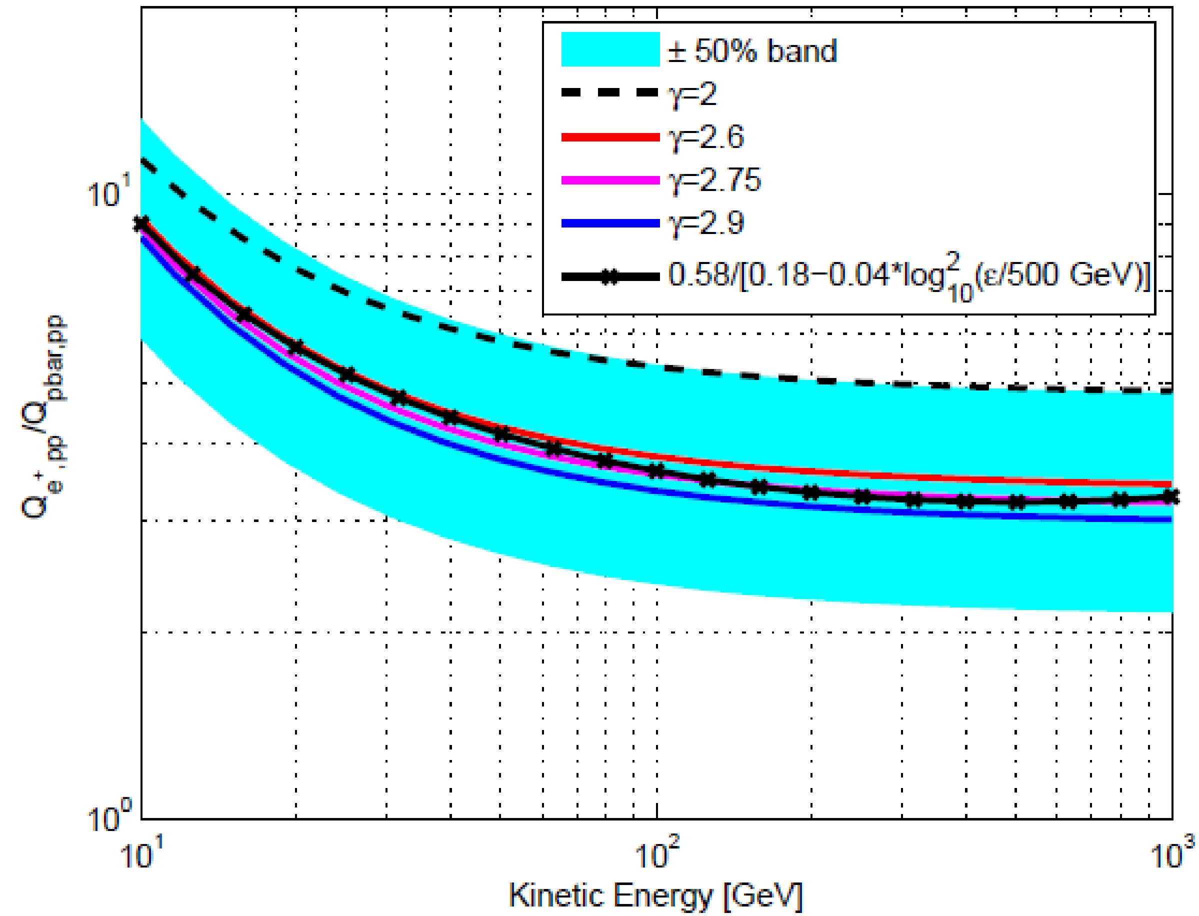
• **Lesson**:

model independent

no-go conditions

Another clean test:

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



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

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

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

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

⇒

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

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)

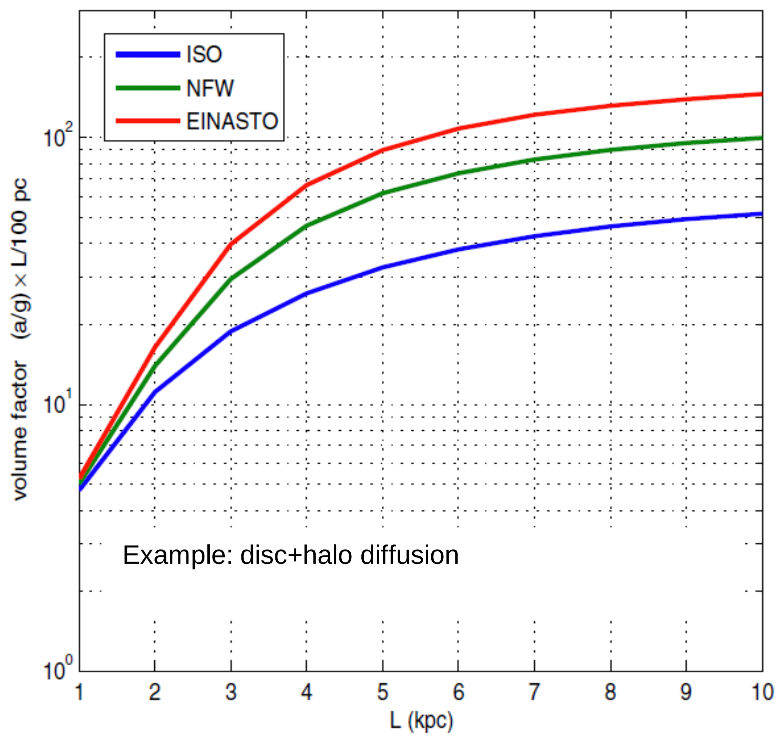
Agashe, KB, Lee, Perez (2010)

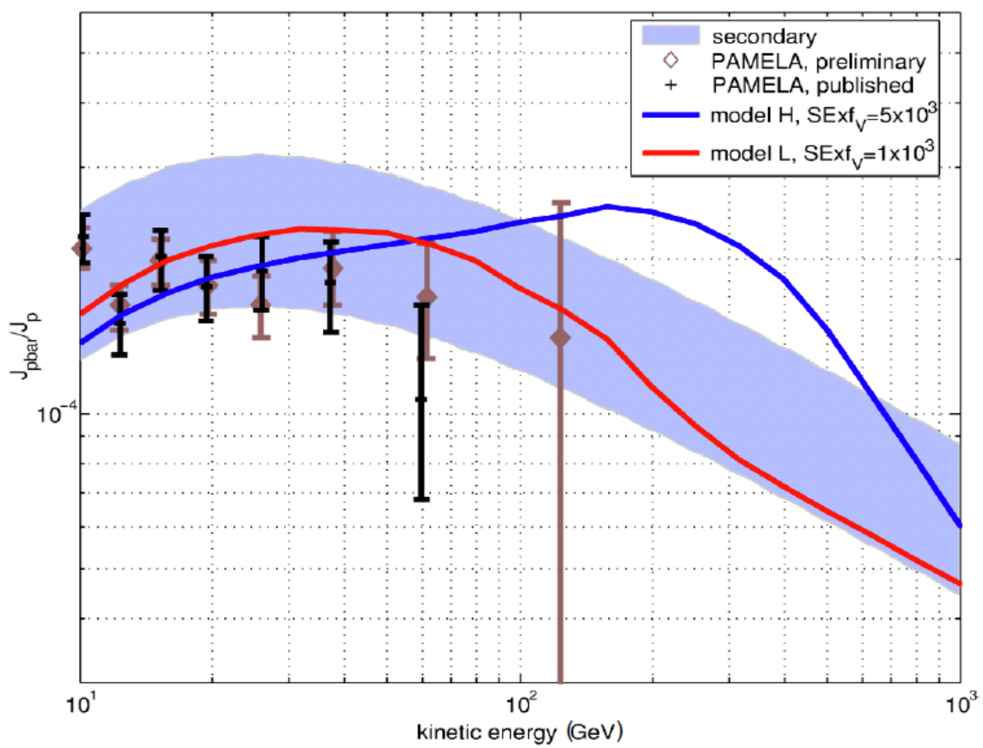
Theoretically clean channel:

$\overline{p}/p$

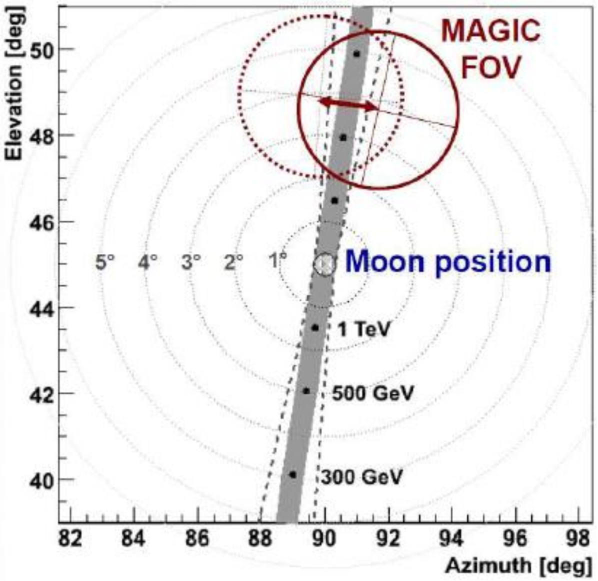
Concrete example:
Z3-protected ν' at the TeV
Annihilation may compete w/ background if light radion ~ 10-100 GeV
(Sommerfeld enhanced)

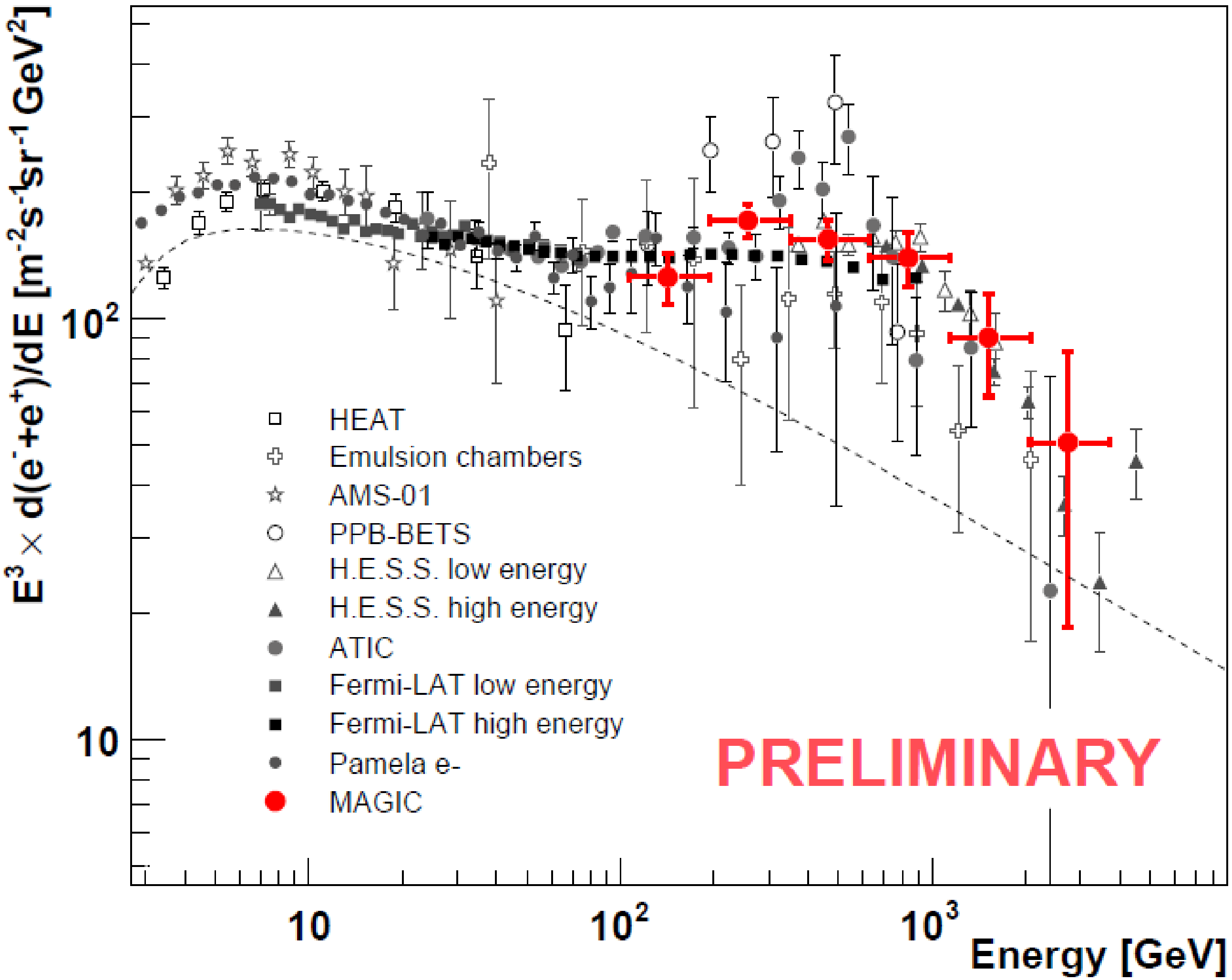
$$f_V = \frac{\int d^3r q_{DM}(\vec{r})\bar{G}(\vec{r}_{\rm sol},\vec{r})}{\int d^3r q_{\rm sec}(\vec{r})\bar{G}(\vec{r}_{\rm sol},\vec{r})} \sim L/h \sim 10 - 100$$



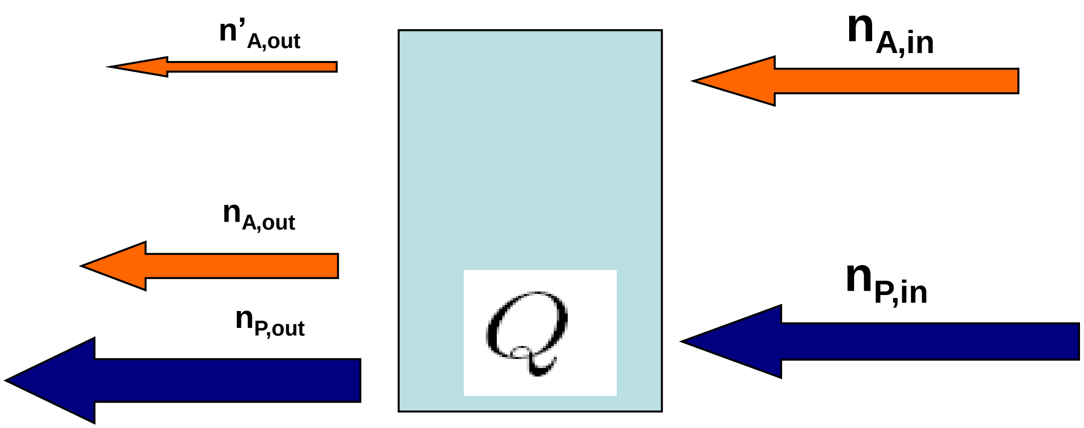


MAGIC e+- 1110.0183 , 1110.4008





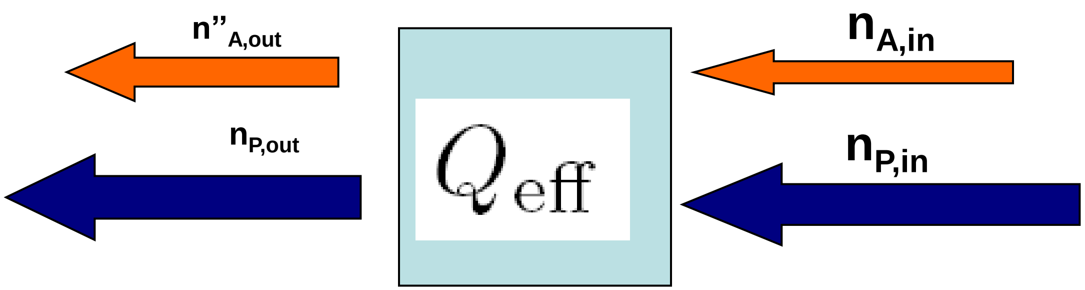
Stable secondaries, with spallation losses



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_{eff} works just the same!

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)

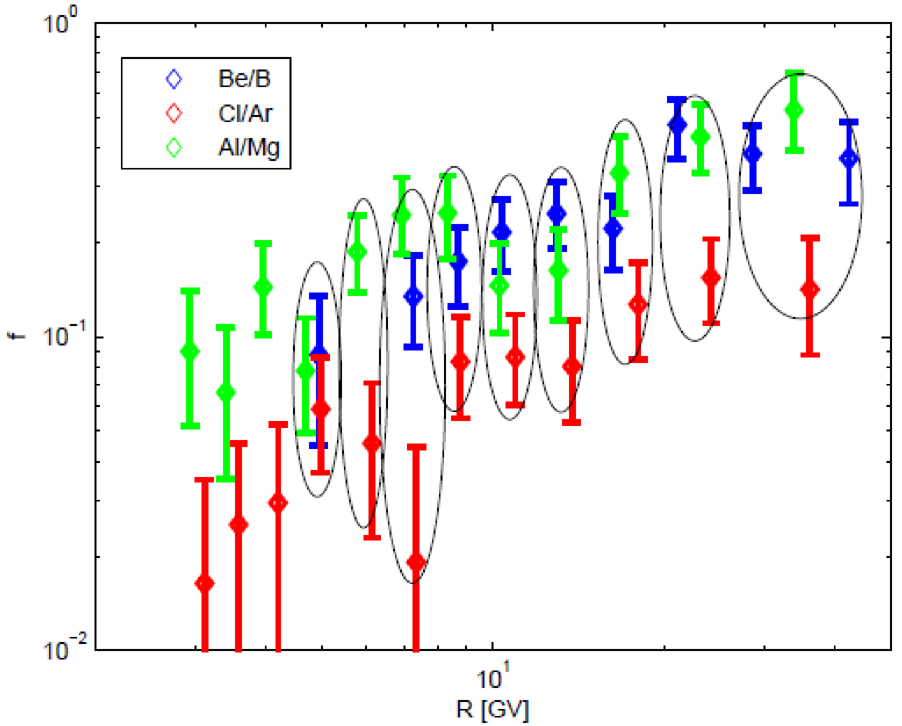
• **Benefit**: avoid low energy complications; significant range in rigidity

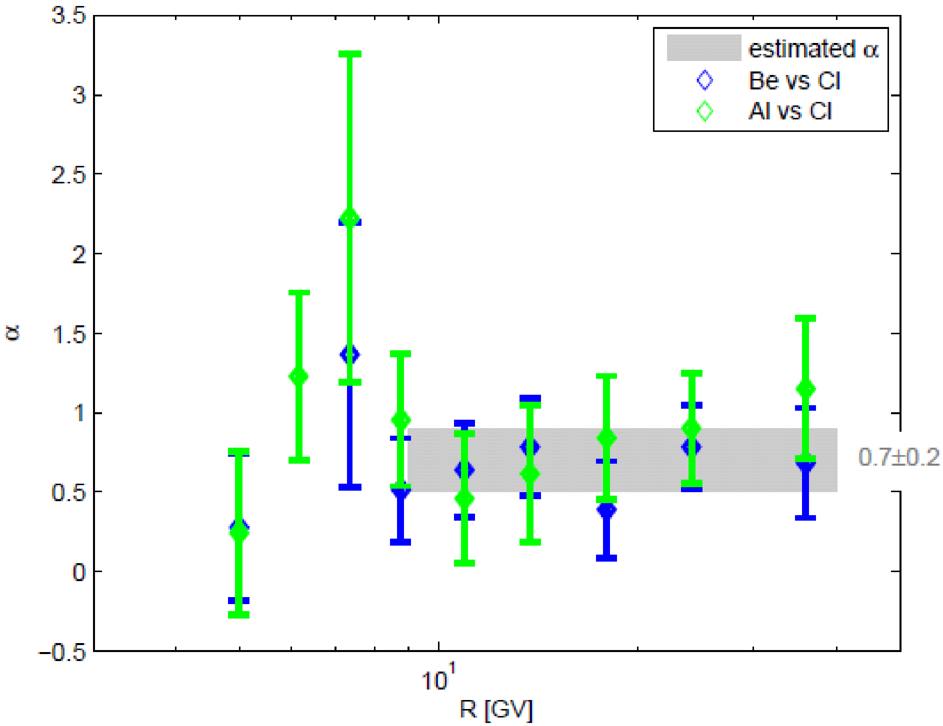
• **Drawback**: systematic uncertainties (cross sections, primary contamination)

Radioactive nuclei

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

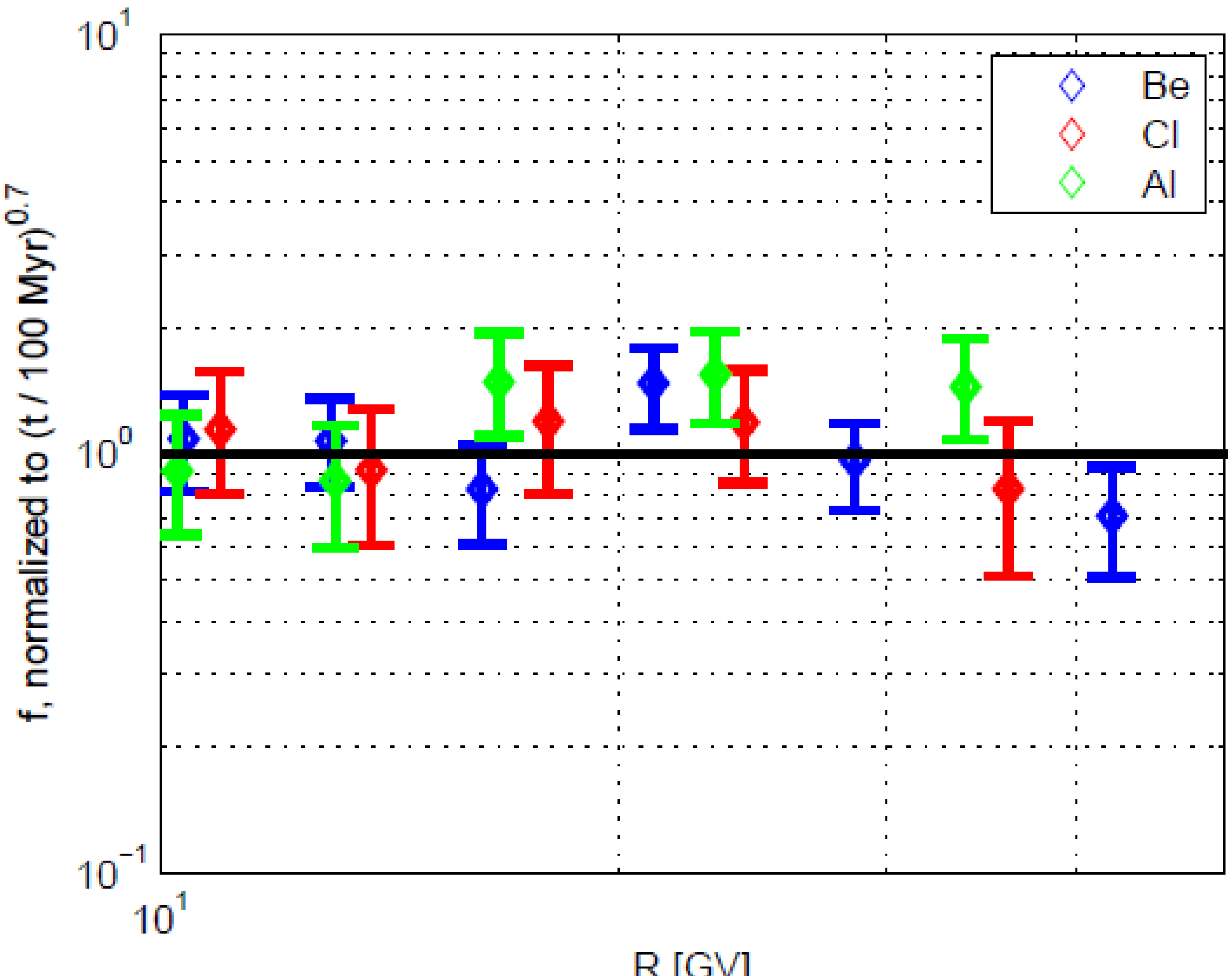
$$\Delta\alpha \propto 1/\log\left(\tau_i/\tau_j\right)$$





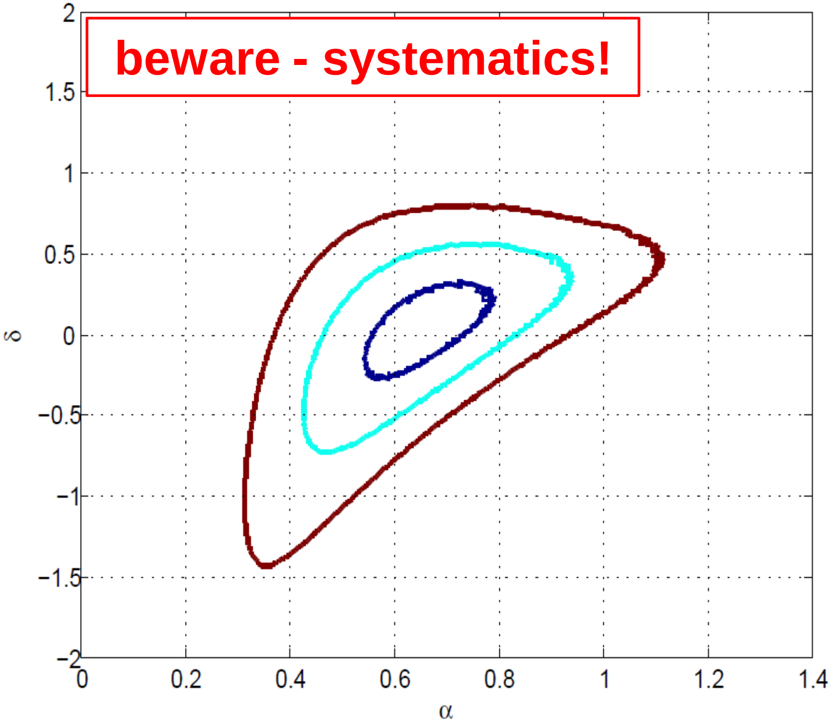
Radioactive nuclei: data

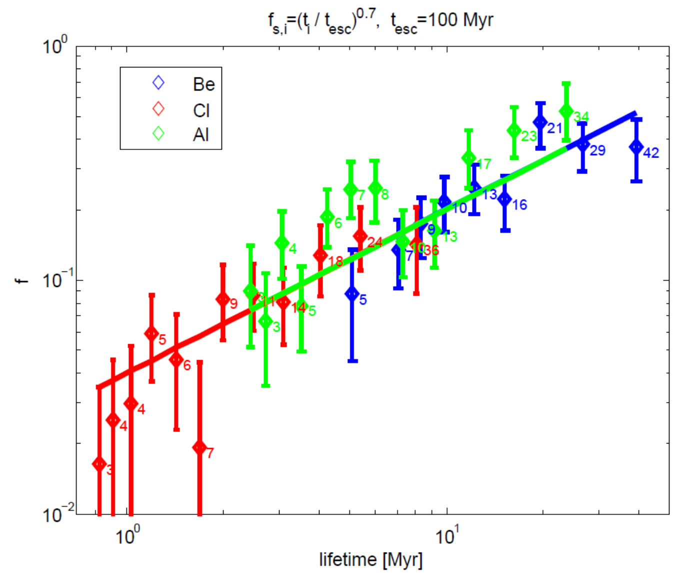
Residual rigidity dependence

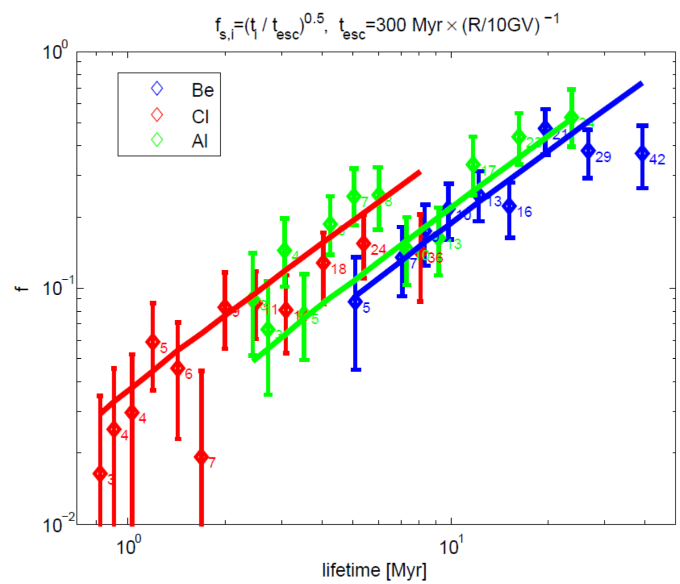


Radioactive nuclei

rigidity dependence:
hints from current data





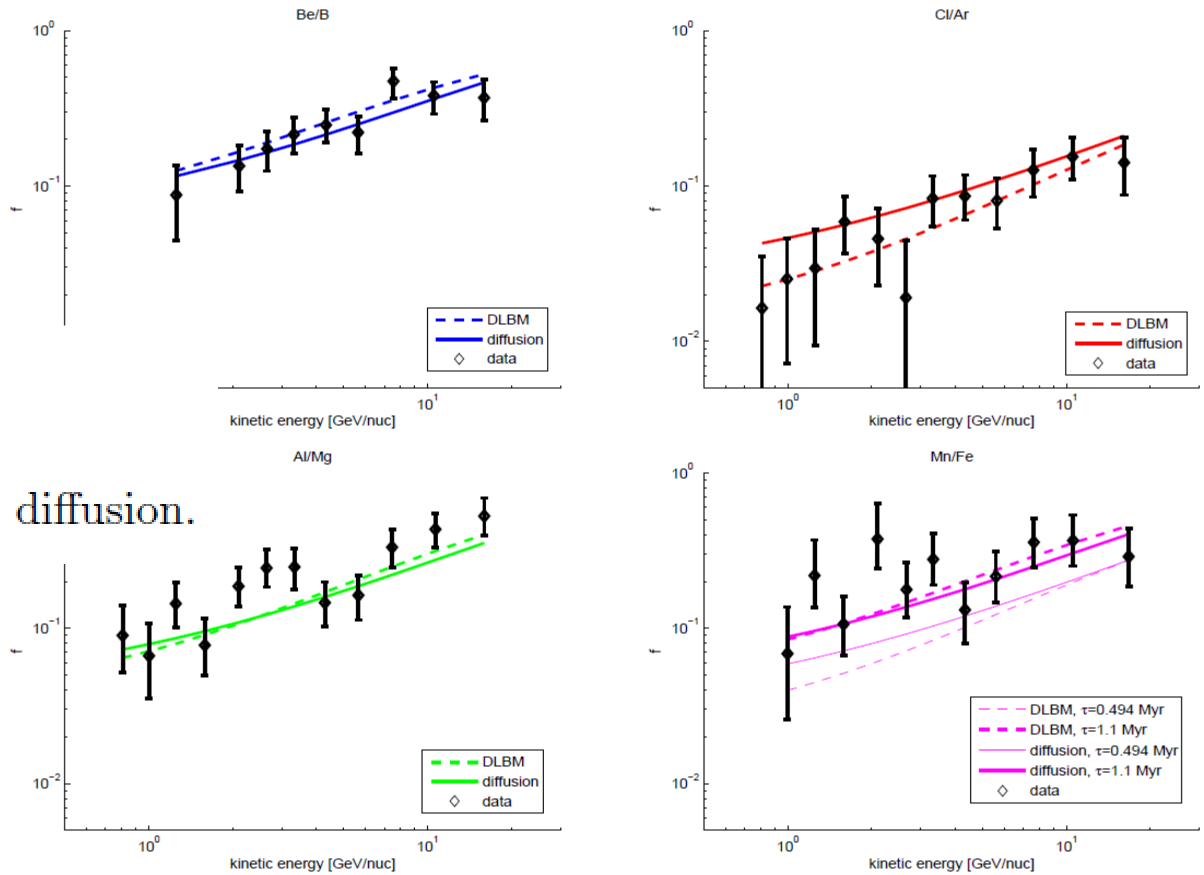


Radioactive nuclei

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

Examples

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



Interpretation

- Decay suppression factor probes propagation

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

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

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

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

→ Uniform models, diffusion models, compound diffusion, …

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

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

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

Comparing with radioactive nuclei

- Suppression factor due to decay ≈ suppression due to radiative loss,

  if compared at rigidity such that cooling time ≈ decay time

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

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

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

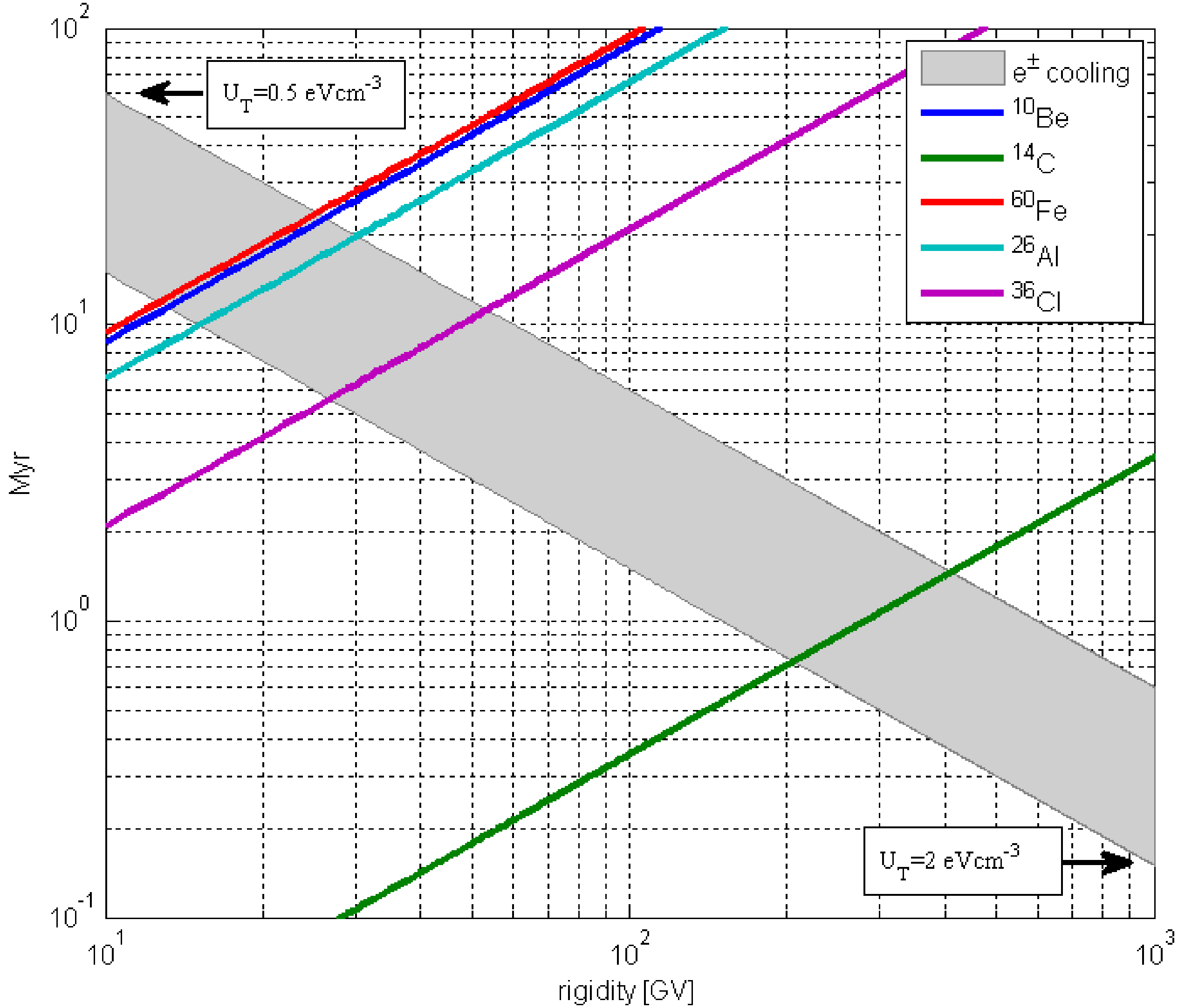
$$\tilde{t}_c = \frac{t_c}{\gamma - \delta_c - 1}$$

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

Comparing with radioactive nuclei

Time scales:

cooling vs decay



CR grammage

In some more detail

- Net production includes fragmentation losses

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

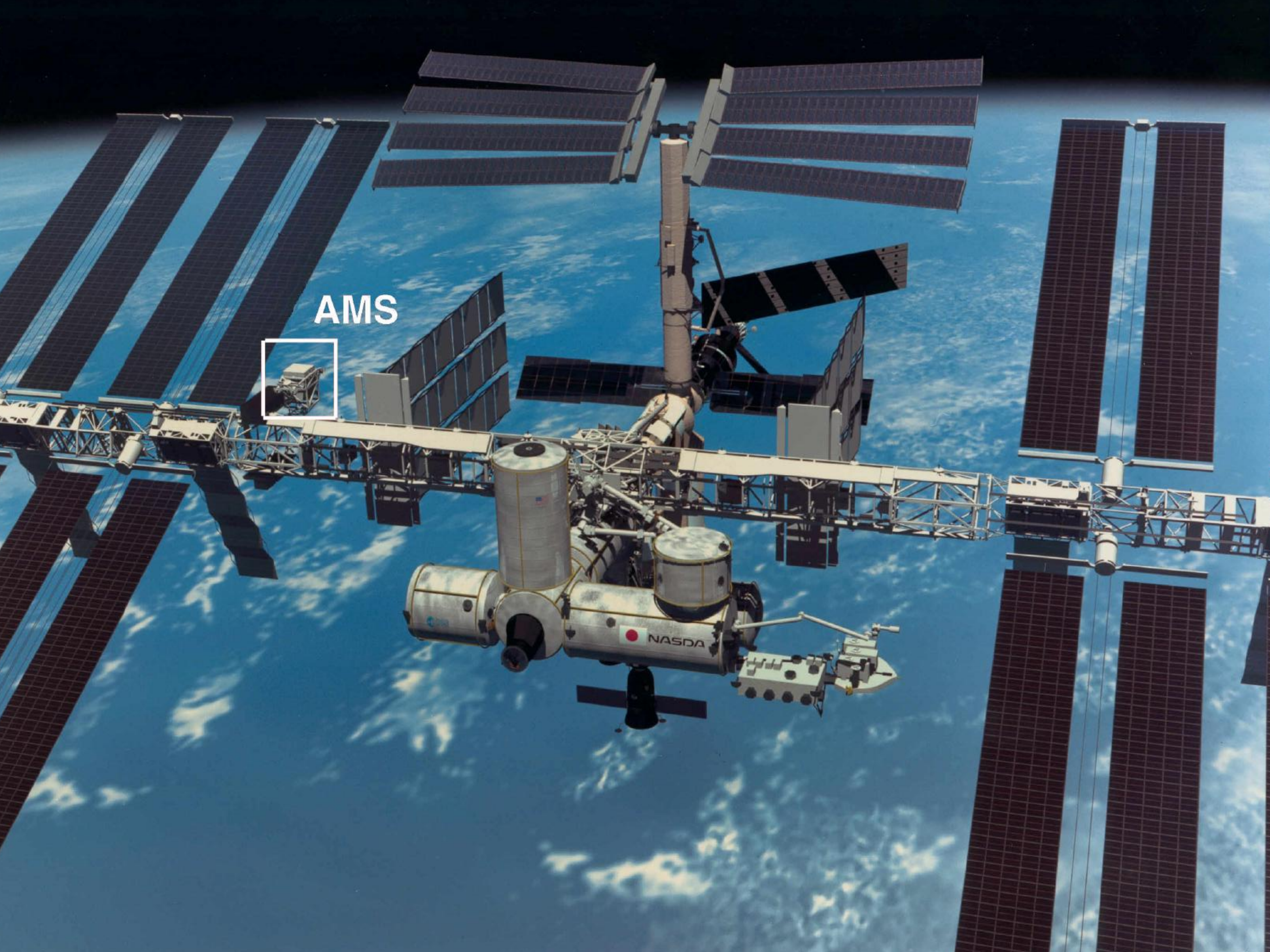
$\bar{m}$ = mean ISM particle mass (~ 1.3 m_p)

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

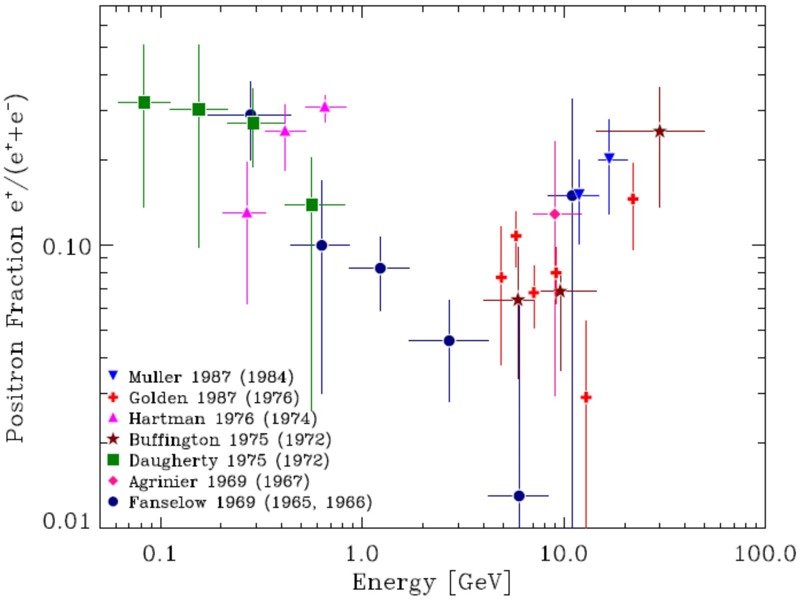
Approx': secondary inherits rigidity of primary

- 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: $\bar{m}(r', t') = \bar{m}(r,t)$, $\dfrac{n_i(r,t,\mathcal{R})}{n_j(r,t,\mathcal{R})} = f_{ij}(\mathcal{R})$
- Thus $\tilde{Q}_S(r', t', \mathcal{R}) = \tilde{Q}_S(r,t,\mathcal{R}) \dfrac{n_{P_1}(r',t',\mathcal{R})}{n_{P_1}(r,t,\mathcal{R})}$
- Obtain: $n_S(r', t', \mathcal{R}) = \tilde{Q}_S(r', t', \mathcal{R}) \, X_{\rm esc}(\mathcal{R})$

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


AMS
NASDA

old experiments had it wrong



what 10^{-4} p contamination can do