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)
Indirect detection – topic of this talk

• confusing situation (did we find it already?)

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

g \rightarrow is it, or is it not, consistent with backgrounds?
g \rightarrow 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 \(\rightarrow\) 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 \(\rightarrow\) test secondary origin
Galactic CR: general picture

- CRs fill our Galaxy. Galactic: up to $\sim$ PeV (at least). Energy density $\sim$ 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 $pp \rightarrow pn\pi^+ \rightarrow pp e^- e^+ \nu_e \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$

- **Open questions:** propagation.
A simple analysis of stable secondaries

- At high energy, flux of stable secondary nuclei follows simple *empirical* relation:
  \[ J_S = \frac{c}{4\pi} X_{\text{esc}} \tilde{Q}_S \quad (S = ^9\text{Be}, \ B, \ \text{Sc}, \ p, \ ...) \]

- \( \tilde{Q}_S \) = **Local** net production density per traversed unit column density of ISM

- \( X_{\text{esc}} \) = **CR grammage.** Crucial point: \( X_{\text{esc}} \) does not carry species label, \( S \)
**CR grammage**

\[ J_S = \frac{c}{4\pi} X_{\text{esc}} \tilde{Q}_S \]

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

- Precise way by which \( X_{\text{esc}} \) 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 \( \Rightarrow \) 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

NIR
Diffusion models fit grammage.

Maurin, Donato, Taillet, Salati

Diffusion models fit grammage.

\[ X_{\text{esc}} = X_{\text{disc}} \frac{Lc}{(2D)g(L/R)} \propto \varepsilon^{-\delta} \]

\[ f(\delta) = \left( \frac{\varepsilon}{\text{GeV}} \right)^{\delta-0.6} \approx 75^{\delta-0.6} \]

\[ g(L/R) = \frac{2R}{L} \sum_{k=1}^{\infty} J_0 \left( \frac{v_k}{R} \right) \frac{\tanh \left( \frac{v_k L}{R} \right)}{v_k^2 J_1 (v_k)} \]
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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 $\rightarrow$ secondary e+ production understood

e+ lose energy radiatively. Measure e+ $\rightarrow$ measure losses
Antiprotons

No free parameters.

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

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

\( pp \rightarrow pn\pi^+ \rightarrow pp e^- e^+ \nu_\mu \bar{\nu}_\mu \)

<table>
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<th>(h)</th>
<th>Exclusive reaction</th>
<th>(\bar{M}_X) (GeV (c^{-2}))</th>
<th>(\sqrt{s_t}) (GeV)</th>
<th>(E_t) (GeV)</th>
<th>(T_t) (GeV)</th>
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<td>(\pi^+)</td>
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<td>1.878</td>
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<td>(pp\pi^0)</td>
<td>1.876</td>
<td>2.011</td>
<td>1.218</td>
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<td>(\kappa^+)</td>
<td>(\Lambda^0\bar{\kappa}^+)</td>
<td>2.053</td>
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<td>(\kappa^-)</td>
<td>(pp\bar{\kappa}^+\kappa^-)</td>
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<td>(\bar{\rho})</td>
<td>(ppp\bar{\rho})</td>
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<td>3.752</td>
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<td>5.628</td>
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<td>(\rho)</td>
<td>(pp)</td>
<td>0.938</td>
<td>1.876</td>
<td>0.938</td>
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Positrons

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

• 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: \( f \sim \sqrt{t_c/t_{esc}} \)

Leaky Box models predict: \( f \sim t_c/t_{esc} \)

• Steep spectrum \( \rightarrow \) loss suppresses flux \( f_{s,e^+} < 1 \)
Study positrons and antiprotons together

Positron flux suppressed by losses.
Positrons: data

\[ f_{s,e^+} < 1 \]
Positrons: data

- $e^+/e^-$
- Kinetic Energy [GeV]
- $e^+/e^-$ FERMI $\Phi=450$ MeV
- $e^+/e^-$ ATIC $\Phi=450$ MeV
- $e^+/e^-$ HEAT $\Phi=712$ MeV
- $e^+/e^-$ AMS01 $\Phi=400$ MeV
- $e^+/e^-$ PAMELA 2010

non secondary
Positrons: data

(very) probably secondary

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

- Suppression factor:

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

- 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: $f_{s,e+} \approx \left( \frac{t_c}{t_{esc}} \right)^\alpha$

  expect $t_c \propto R^{-\delta_c}$. 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 $\approx$ suppression due to radiative loss, if compared at rigidity such that cooling time $\approx$ 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

<table>
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<th>reaction</th>
<th>$t_{1/2}$ [Myr]</th>
<th>$\sigma$ [mb]</th>
</tr>
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<tr>
<td>$^{10}$Be $\rightarrow^{10}$B</td>
<td>1.51 (0.06)</td>
<td>210</td>
</tr>
<tr>
<td>$^{26}$Al $\rightarrow^{26}$Mg</td>
<td>0.91 (0.04)</td>
<td>411</td>
</tr>
<tr>
<td>$^{36}$Cl $\rightarrow^{36}$Ar</td>
<td>0.307 (0.002)</td>
<td>516</td>
</tr>
<tr>
<td>$^{54}$Mn $\rightarrow^{54}$Fe</td>
<td>0.494 (0.006)*</td>
<td>685</td>
</tr>
</tbody>
</table>
Surviving fraction vs. suppression factor

- Convert charge ratios to observable with direct theoretical interpretation
- 1\textsuperscript{st} step: WS98 report surviving fraction
  \[ \tilde{f}_i = \frac{J_i}{J_{i,\infty}} \]
  Well defined quantity, model independently.

- 2\textsuperscript{nd} step: net source includes losses
  \[ \tilde{Q}_S(\mathcal{R}) = \sum_{P} \frac{n_P(\mathcal{R})\sigma_{P\rightarrow S}}{\bar{m}} - \frac{n_S(\mathcal{R})\sigma_{S\rightarrow X}}{\bar{m}} \]
  Surviving fraction over-counts losses \( n_{i,\infty} > n_i \)

Instead, define suppression factor due to decay
Accounts for actual fragmentation loss

\[ f_{s,i} = \frac{J_i}{c \frac{4\pi}{X_{\text{esc}}}} \tilde{Q}_i X_{\text{esc}} \]
Suppression factor

- Different nuclei species on equal footing. Also $e^+$

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

- Expect

Examples:

Leaky Box Model

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

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

Diffusion

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

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

- Magnetic trapping, $t_{esc} = t_{esc}(\mathcal{R})$
Radioactive nuclei: data

Surviving fraction vs. energy (WS98)
Radioactive nuclei: data

Suppression factor vs. energy

Suppression factor $f$ vs. kinetic energy per nucleon $E_{\text{kin/nuc}}$ [GeV] for different elements:
- Be
- Cl
- Al
Radioactive nuclei: data

Consistent with constant residence time

\[ f_{s,i} = \left( \frac{t_i}{t_{esc}} \right)^{0.7}, \quad t_{esc} = 100 \text{ Myr} \]

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

\[ t_{esc} = t_{esc,0} \left( \frac{R}{10 \text{ GV}} \right)^\delta \]
Radioactive nuclei: constraints on $t_{\text{esc}}$

- 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

  $$f_{s,i} \approx \left( \frac{t_i}{t_{esc}} \right)^\alpha \quad f_{s,e^+} \approx \left( \frac{t_c}{t_{esc}} \right)^\alpha$$

  Cooling time

  $$t_c \approx 10 \text{ Myr} \left( \frac{\mathcal{R}}{30 \text{ GV}} \right)^{-1} \left( \frac{\overline{U}_T}{1 \text{ eV cm}^{-3}} \right)^{-1}$$

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

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

→ consistent w/ secondary

More: upper bound from Cl

\[ \bar{U}_T < 5 \left( \frac{R}{20 \, \text{GV}} \right)^{-2} \, \text{eV cm}^{-3} \]

- Test secondary e+:

\[ \bar{U}_T < U_{CMB} \approx 0.25 \, \text{eV/cm}^3 \]
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 \( t_{esc} \propto R^{\delta} \) and cooling time \( t_c \propto R^{-\delta_c} \)
Based on radioactive nuclei. Consistent w/ PAMELA data
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 
  $^{10}\text{Be}$ agrees $\Rightarrow$ e+ secondary

  PAMELA, AMS-02: reach 270-300 GeV

  Fermi 2011: very exciting!

  AMS02 will settle this.

• Compare w/ radioactive nuclei $\Rightarrow$ 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)

\[ \rightarrow \text{ real anomaly} \]

- Lesson:

model independent
no-go conditions
Another clean test:

\[
\frac{e^+}{\bar{p}}
\]
Theoretically clean channel:

\[ \overline{\rho} / \rho \]

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

in general

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

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

if

\[
Q_{\overline{p},\text{sec}}(\epsilon, \vec{r}) = Q_{\overline{p},\text{sec}}(\epsilon, \vec{r}_{\text{sol}}) \times q_{\text{sec}}(\vec{r})
\]

\[
\frac{n_{\overline{p},\text{DM}}(\epsilon, \vec{r}_{\text{sol}})}{n_{\overline{p},\text{sec}}(\epsilon, \vec{r}_{\text{sol}})} = f_V \frac{Q_{\overline{p},\text{DM}}(\epsilon, \vec{r}_{\text{sol}})}{Q_{\overline{p},\text{sec}}(\epsilon, \vec{r}_{\text{sol}})}
\]

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

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

Fixed by B/C, p flux

Local injection: no prop’ effects by def’. (particle physics)
Theoretically clean channel:

$$\overline{\rho} / \rho$$

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

$$f_V = \frac{\int d^3 r q_{DM}(\vec{r}) \overline{G}(\vec{r}_{\text{sol}}, \vec{r})}{\int d^3 r q_{\text{sec}}(\vec{r}) \overline{G}(\vec{r}_{\text{sol}}, \vec{r})} \sim L / h \sim 10 - 100$$
MAGIC e+ 1110.0183, 1110.4008
Stable secondaries, with spallation losses

Equivalently:

\[ dx Q_A = n_{A,\text{out}} + n'_{A,\text{out}} - n_{A,\text{in}} \]

\[ dx Q_{A,\text{eff}} = n''_{A,\text{out}} - n_{A,\text{in}} \]

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

Homogenous composition:

\( Q_{\text{eff}} \) works just the same!
Radioactive nuclei: Charge ratios vs. isotopic ratios

Charge ratios:
- Be/B, Al/Mg, Cl/Ar, Mn/Fe

Isotopic ratios:
- $^{10}\text{Be}/^{9}\text{Be}$, $^{26}\text{Al}/^{27}\text{Al}$, $^{36}\text{Cl}/^{35}\text{Cl}$, $^{54}\text{Mn}/^{54}\text{Mn}$

- 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

\[
\log \left( \frac{f_{S,i}(R')}{f_{S,j}(R')} \right) \approx \alpha \log \left( \frac{A_j Z_i \tau_i}{A_i Z_j \tau_j} \right)
\]

\[
\Delta \alpha \propto \frac{1}{\log (\tau_i/\tau_j)}
\]
Radioactive nuclei: data

Residual rigidity dependence

![Graph showing residual rigidity dependence](image)
Radioactive nuclei

rigidity dependence: hints from current data

beware - systematics!
Radioactive nuclei

\[ t_{esc} \approx (20 \text{ to } 40) \times (R/10 \text{ GV})^{0.2} \text{ Myr, DLBM,} \]
\[ t_{esc} \approx (200 \text{ to } 500) \times (R/10 \text{ GV})^{-0.7} \text{ Myr, diffusion} \]

**Examples**

\[ f_{s,i} = \frac{1}{1 + t_{esc}/t_i}, \text{ DLBM,} \]
\[ f_{s,i} = \sqrt{t_i/t_{esc}} \tanh \left( \sqrt{t_{esc}/t_i} \right), \text{ diffusion.} \]
Interpretation

• Decay suppression factor probes propagation

\[ n \sim \frac{Q V_{\text{source}} t_{\text{eff}}}{V_{\text{eff}}} \]

\[ f \sim \frac{n_{\text{decay}}}{n_{\text{no decay}}} \sim \frac{V_{\text{esc}}}{V_{\text{decay}}} \times \frac{t_{\text{decay}}}{t_{\text{esc}}} \sim \left( \frac{t_{\text{decay}}}{t_{\text{esc}}} \right)^{1-\kappa d} \]

• Scaling of volume depends on type of motion, relevant dimensions

\[ V_{\text{eff}} \sim (t_{\text{eff}})^{\kappa d} \]

→ 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

\[ f_{s,i} \approx \left( \frac{t_i}{t_{\text{esc}}} \right)^\alpha \]

• Lastly, if trapping is magnetic, expect

\[ t_{\text{esc}} = t_{\text{esc}}(R) \]
Comparing with radioactive nuclei

- Suppression factor due to decay $\approx$ suppression due to radiative loss,

  \textit{if compared at rigidity such that cooling time} $\approx$ \textit{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.

\begin{align*}
\text{decay:} \quad \partial_t n_i &= -\frac{n_i}{t_i} \\
\text{loss:} \quad \partial_t n_{e^+} &= \partial_\mathcal{R} \left( \dot{\mathcal{R}} n_{e^+} \right) = -\frac{n_{e^+}}{t_c} \\
\tilde{t}_c &= \frac{t_c}{\gamma - \delta_c - 1}
\end{align*}

But, $\gamma \sim 3 \implies \tilde{t}_c \approx t_c$
Comparing with radioactive nuclei

Time scales:
cooling vs decay
CR grammage

In some more detail
• Net production includes fragmentation losses

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

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

High-energy \( \rightarrow \) 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:

\[ \bar{m}(r', t') = \bar{m}(r, t) , \quad \frac{n_i(r, t, \mathcal{R})}{n_j(r, t, \mathcal{R})} = f_{ij}(\mathcal{R}) \]

• Thus

\[ \tilde{Q}_S(r', t', \mathcal{R}) = \hat{Q}_S(r, t, \mathcal{R}) \frac{n_{P_1}(r', t', \mathcal{R})}{n_{P_1}(r, t, \mathcal{R})} \]

• Obtain:

\[ n_S(r', t', \mathcal{R}) = \hat{Q}_S(r', t', \mathcal{R}) X_{esc}(\mathcal{R}) \]

\[ X_{esc}(\mathcal{R}) = c \int^{t'} dt \int d^3r \rho_{ISM}(r, t) \frac{n_{P_1}(r, t, \mathcal{R})}{n_{P_1}(r', t', \mathcal{R})} G(r, r'; t, t'; \mathcal{R}) \]
old experiments had it wrong

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

M. Schubnell, arXiv:0905.0444

PAMELA re-analysis