# What can we really learn from positron flux 'Anomalies'?

Katz, KB, Morag, Waxman

MNRAS 405, 1458

nature International weekly journal of science

# PAMELA

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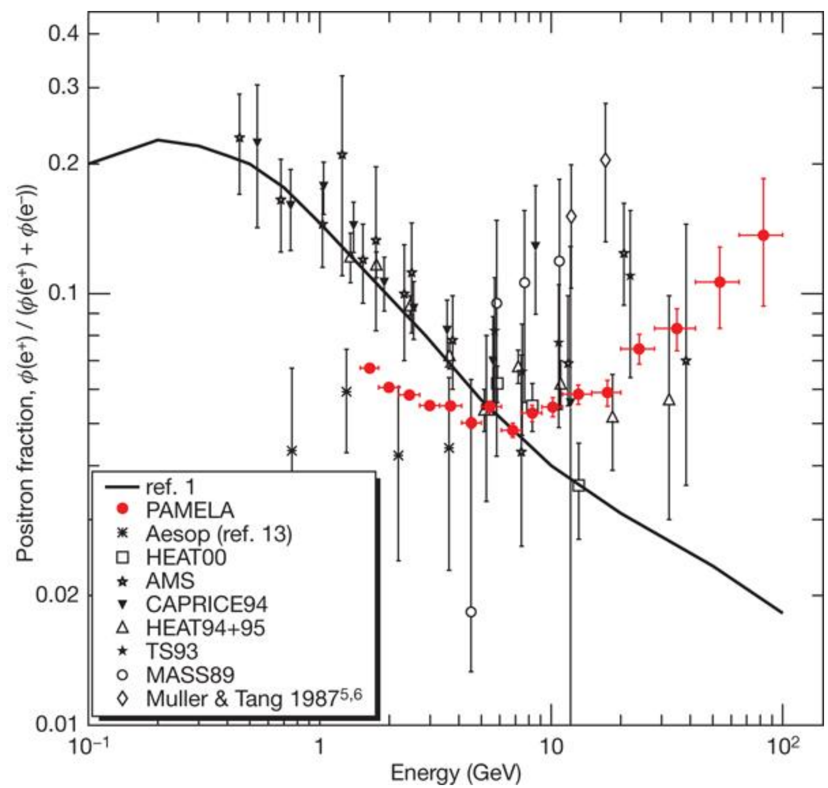
### Letter

*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

…Our results clearly show an increase in the positron abundance at high energy that cannot be understood by standard models describing the secondary production of cosmic-rays.



# Plan:

- e+ ~ antiprotons (up to radiative losses)

  Antiprotons understood

  Measure e+ ➔ measure losses

  Radioactive nuclei data agrees ➔ e+ secondary!

- e+ anomaly?

  Theoretically clean channel: $e^+ / \bar{p}$

# e+ ~ antiprotons (up to radiative losses)

e+ produced in pp and spallation interactions

– similar to $\bar{p}$ , B, Sc, Li,…

e+ lose energy radiatively via IC and sync'

- (ordinarily) steep spectrum, loss suppresses flux.

Ignore energy loss → upper bound on flux.

# Simple analysis of stable secondaries

# Antiprotons understood

## Cosmic Ray Grammage

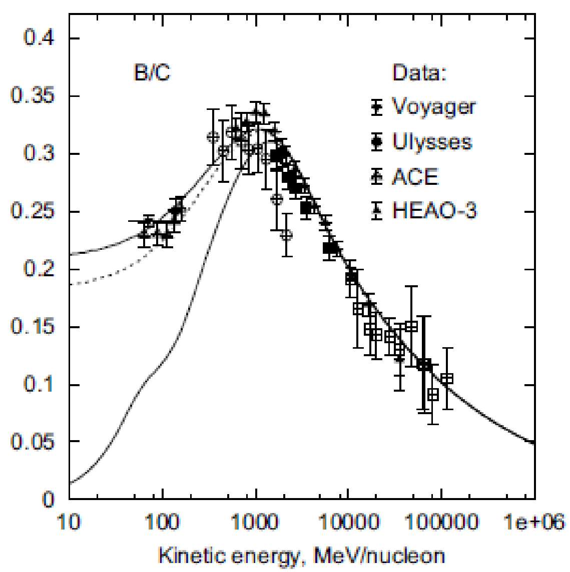
$$\boxed{X_{\rm esc} \approx 8.7 \left(\frac{\varepsilon}{10Z\ {\rm GeV}}\right)^{-0.5} {\rm g\ cm}^{-2}}$$

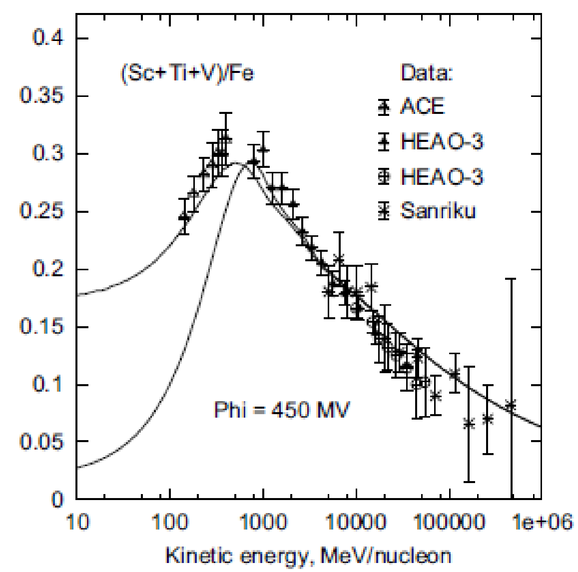
Engelmann et al (1990)
Webber et al (2003)

$$\tilde{Q}_i = \frac{Q_i}{\rho_{\rm ISM} c} - \frac{n_i \sigma_i}{m_p}$$

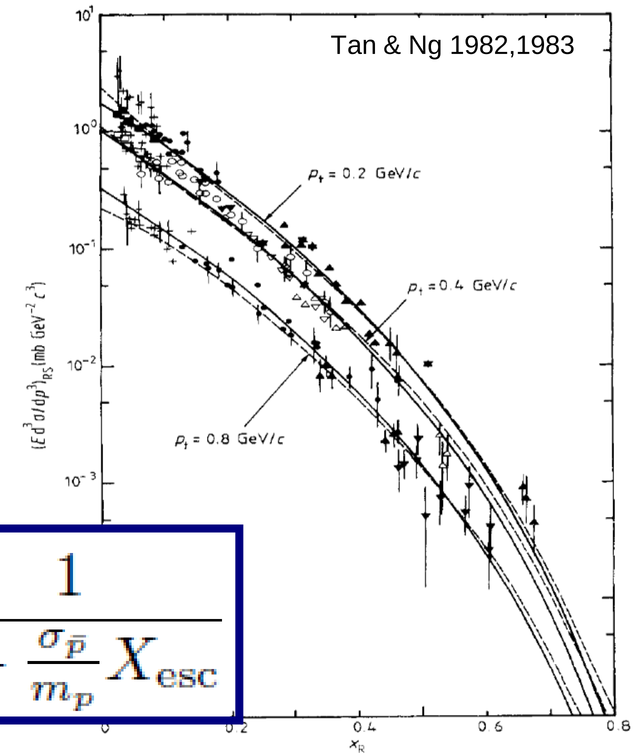
$$\frac{n_A}{n_B} = \frac{\tilde{Q}_A}{\tilde{Q}_B}$$

$$n_i(\varepsilon) = \tilde{Q}_i(\varepsilon) X_{\rm esc}(\varepsilon/Z)$$

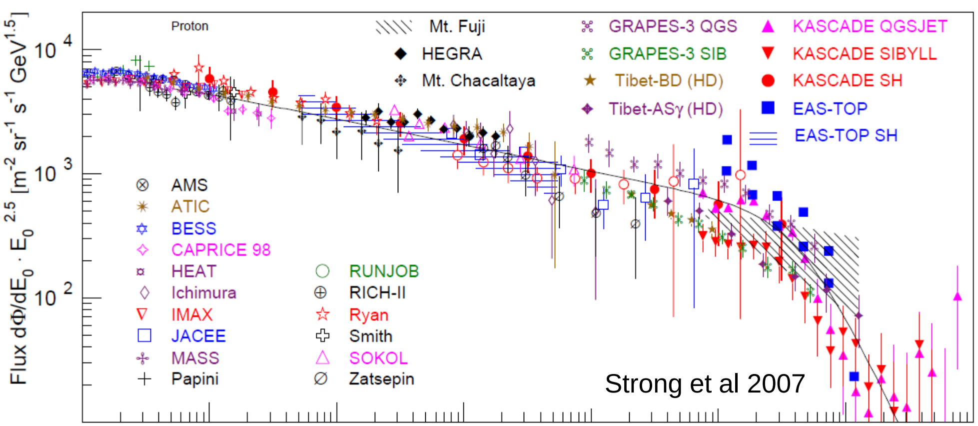


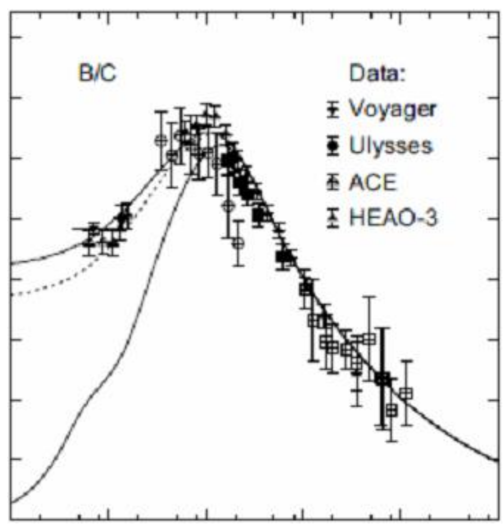



# Antiprotons understood

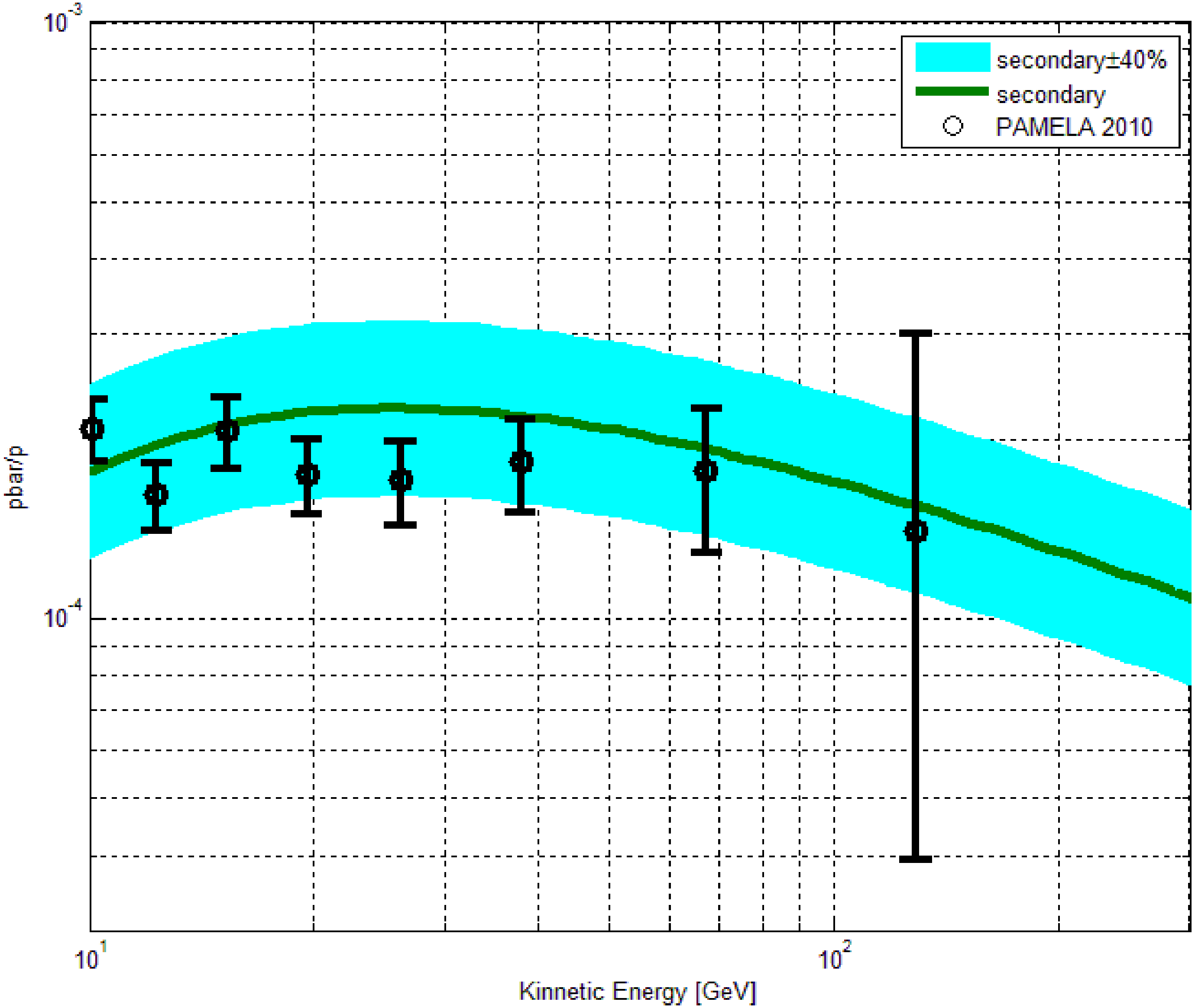



$$\frac{J_{\bar{p}}}{J_p} = 10^{-\gamma+1}\xi_{\bar{p},A>1}C_{\bar{p},pp}(\varepsilon)\frac{\sigma_{pp,inel,0}}{m_p}X_{\rm esc}\frac{1}{1+\frac{\sigma_{\bar{p}}}{m_p}X_{\rm esc}}$$



# Antiprotons: data



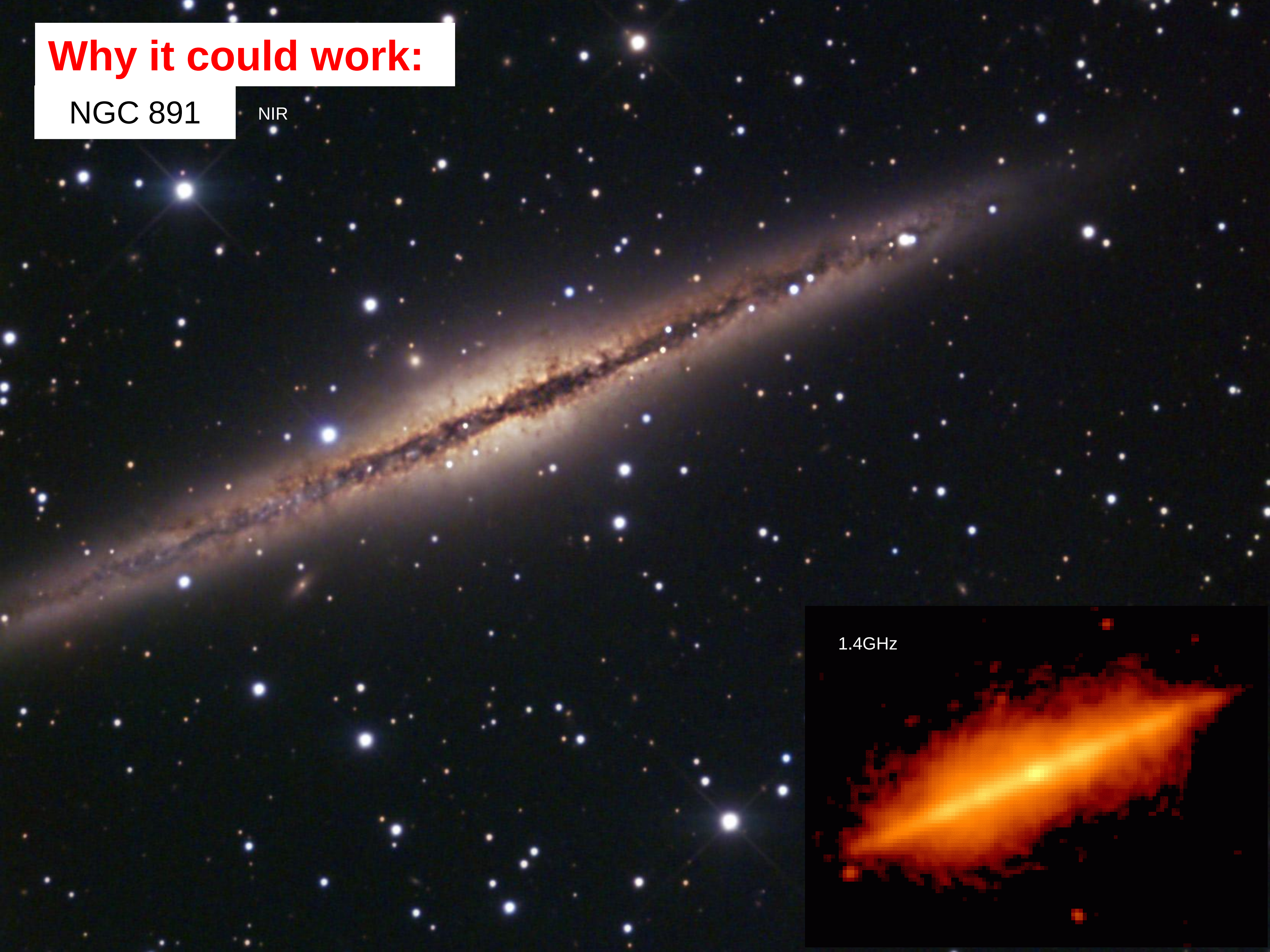

secondary calculation:

*no free parameters.*

# Why does it work so well?

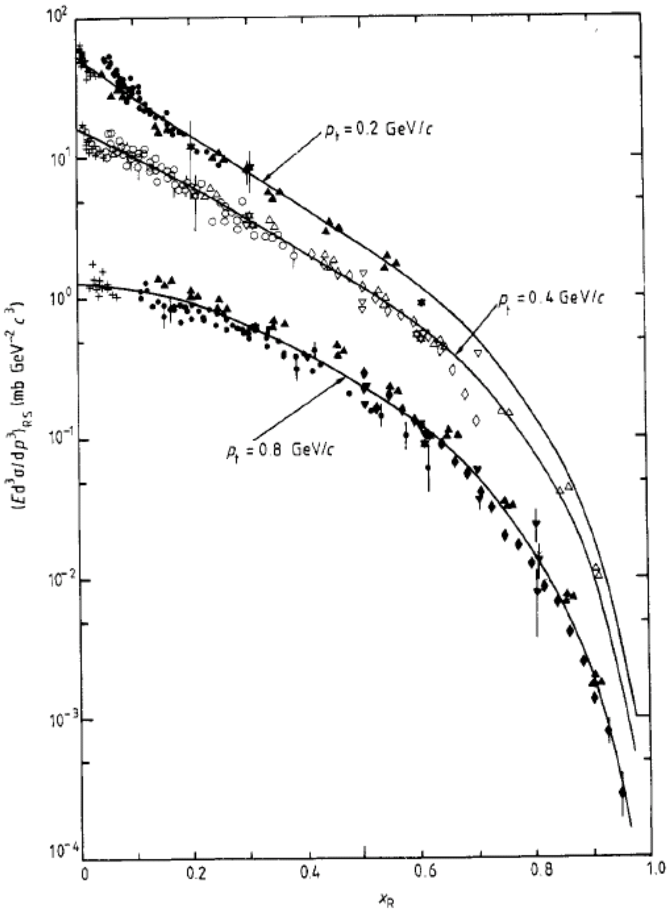
# Why it could work:

NGC 891



# Positrons

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




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

| 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

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

-Cooling suppression depends on time scales for escape and loss

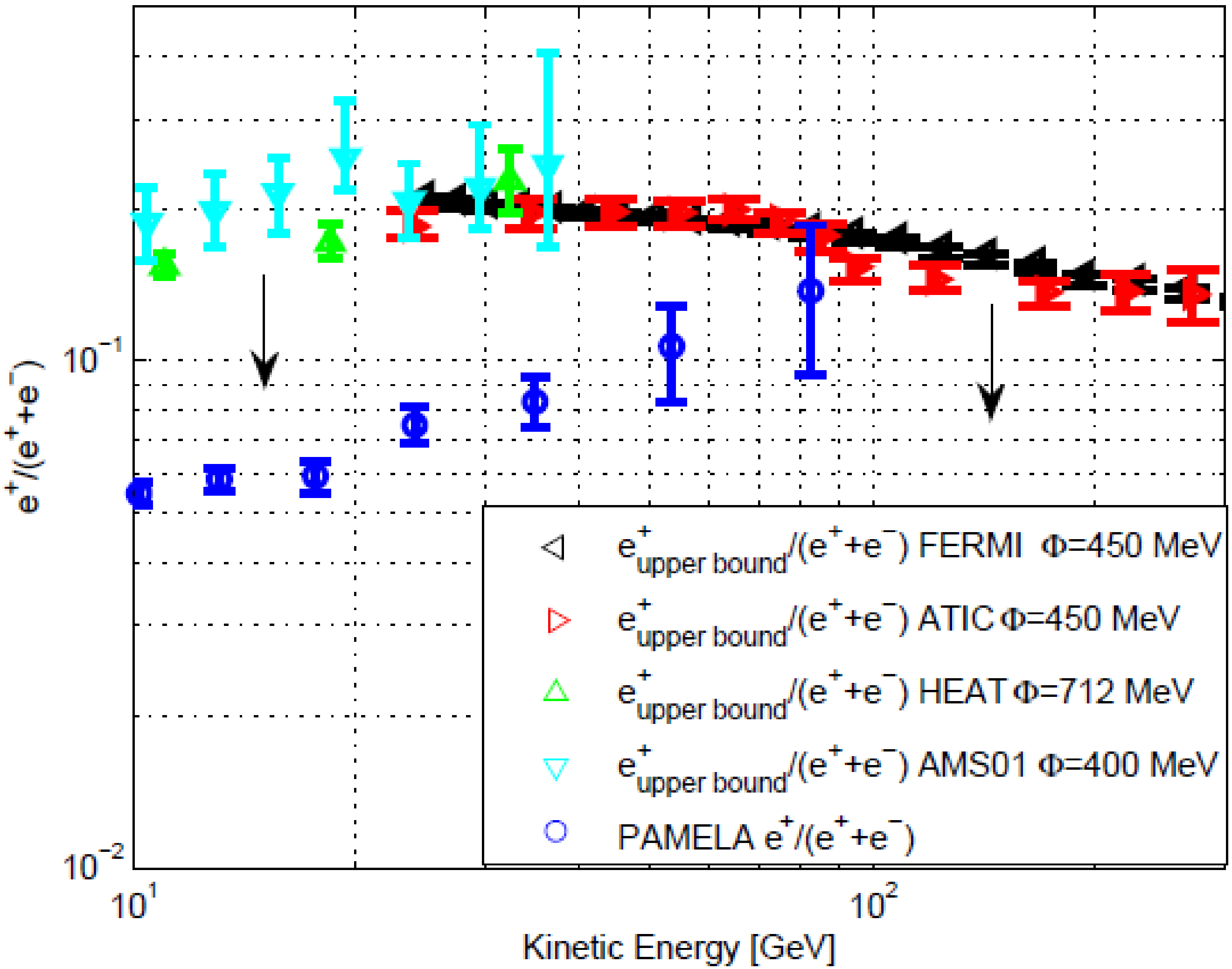
-Precise relation model dependent.
E.g., Leaky Box → $f \sim t_c / t_{esc}$ Diffusion → $f \sim \sqrt{t_c / t_{esc}}$

-At high energy, both time scales *not yet measured*.
Stable nuclei data (B/C) *does not constrain them*

-C*annot predict* precise value of f, beyond $\boxed{f \leq 1}$

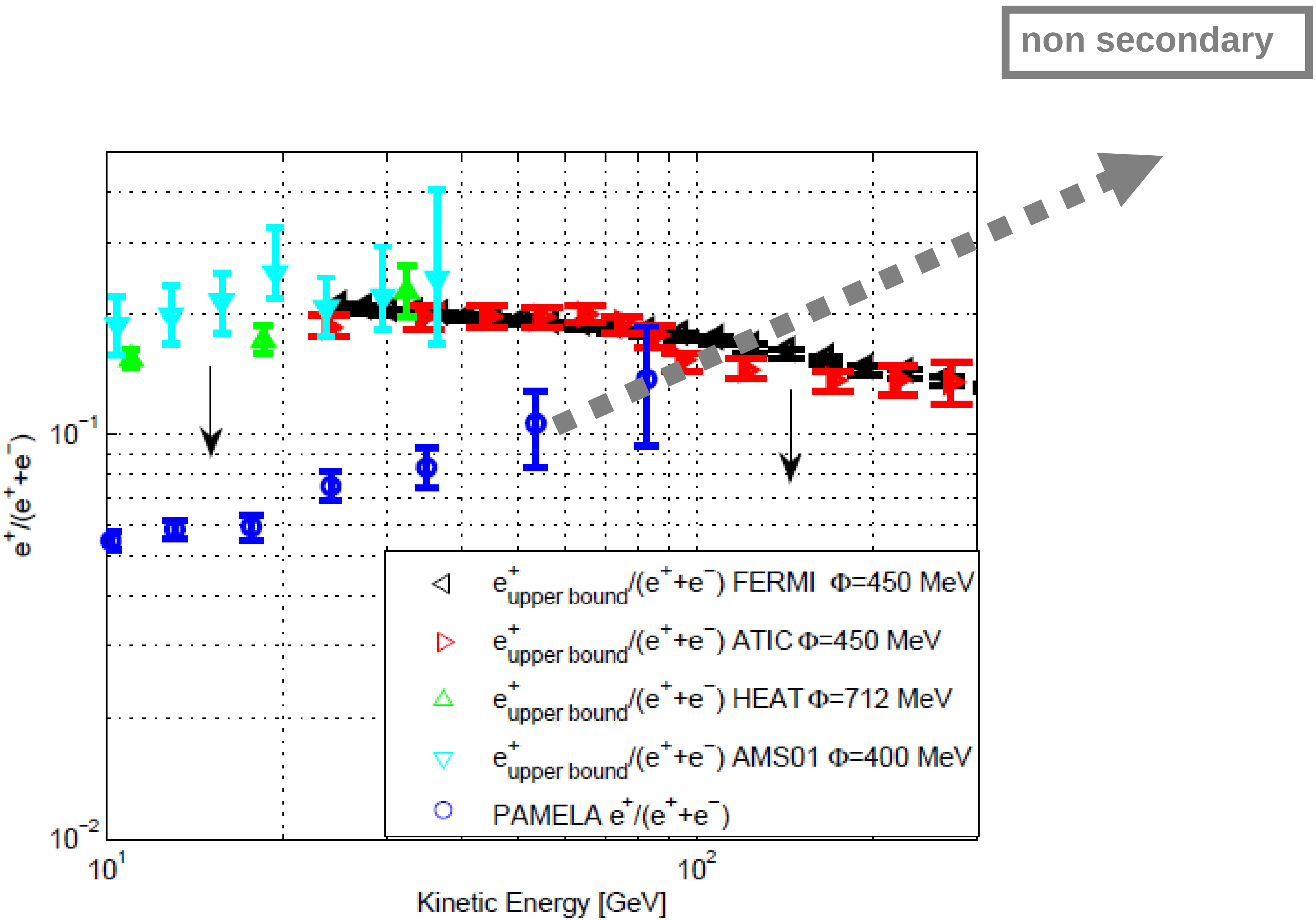
-**PAMELA is the first measurement of f at high energy!**

# Positrons: data

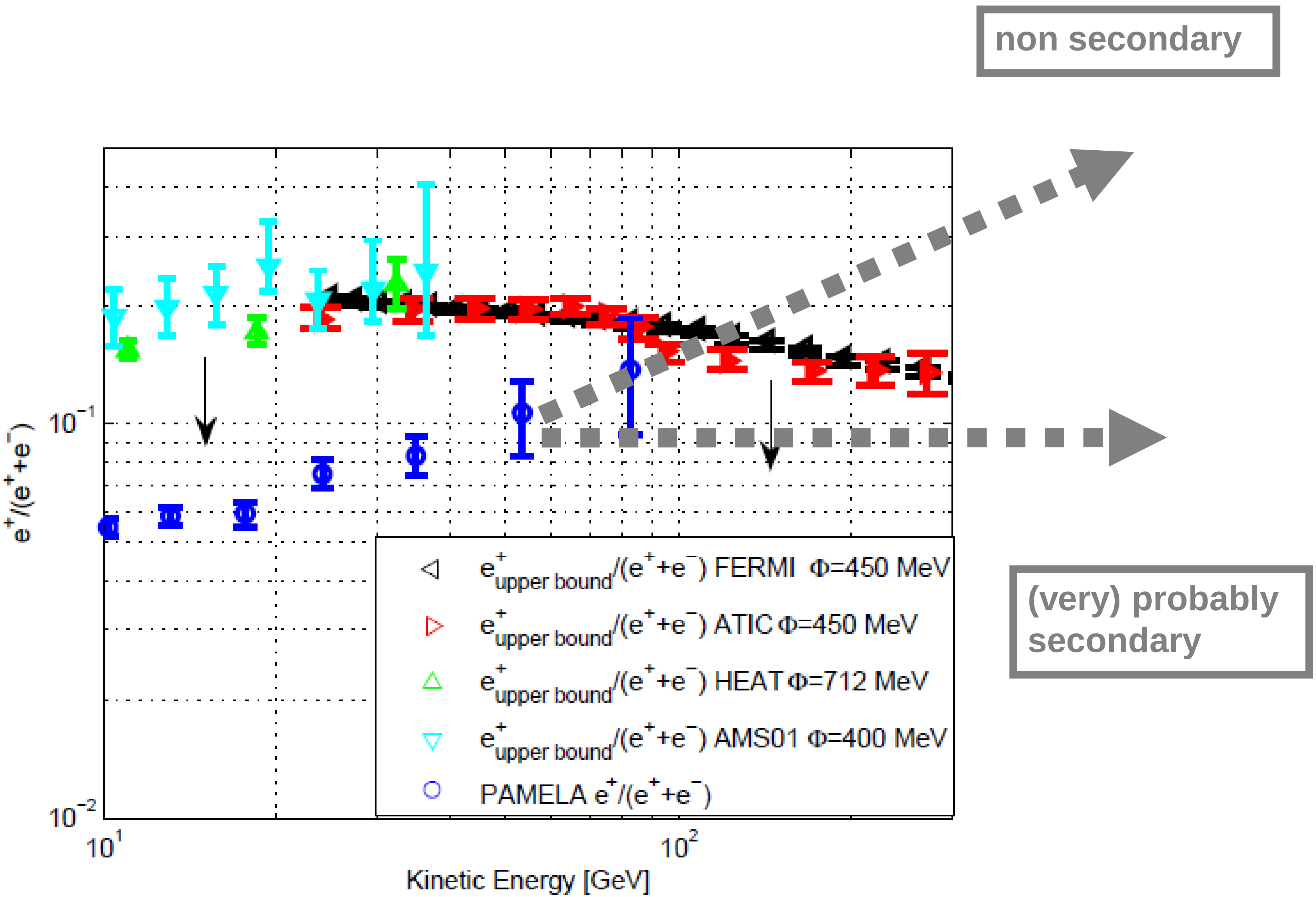



$$f_{s,e^+} < 1$$

# Positrons: data



# Positrons: data



# Comparing with radioactive nuclei

Cooling vs Decay

$$\dot{\varepsilon} \propto \varepsilon^2$$

$$\tau_c = \frac{\varepsilon}{\dot{\varepsilon}} = \frac{m_e^2 c^4}{\frac{4}{3}\varepsilon \sigma_T U_T c} \approx 10^7 \text{ yr}$$

$$\times \left(\frac{\varepsilon}{30 \text{ GeV}}\right)^{-1} \left(\frac{U_T}{1\text{eV cm}^{-3}}\right)^{-1}$$

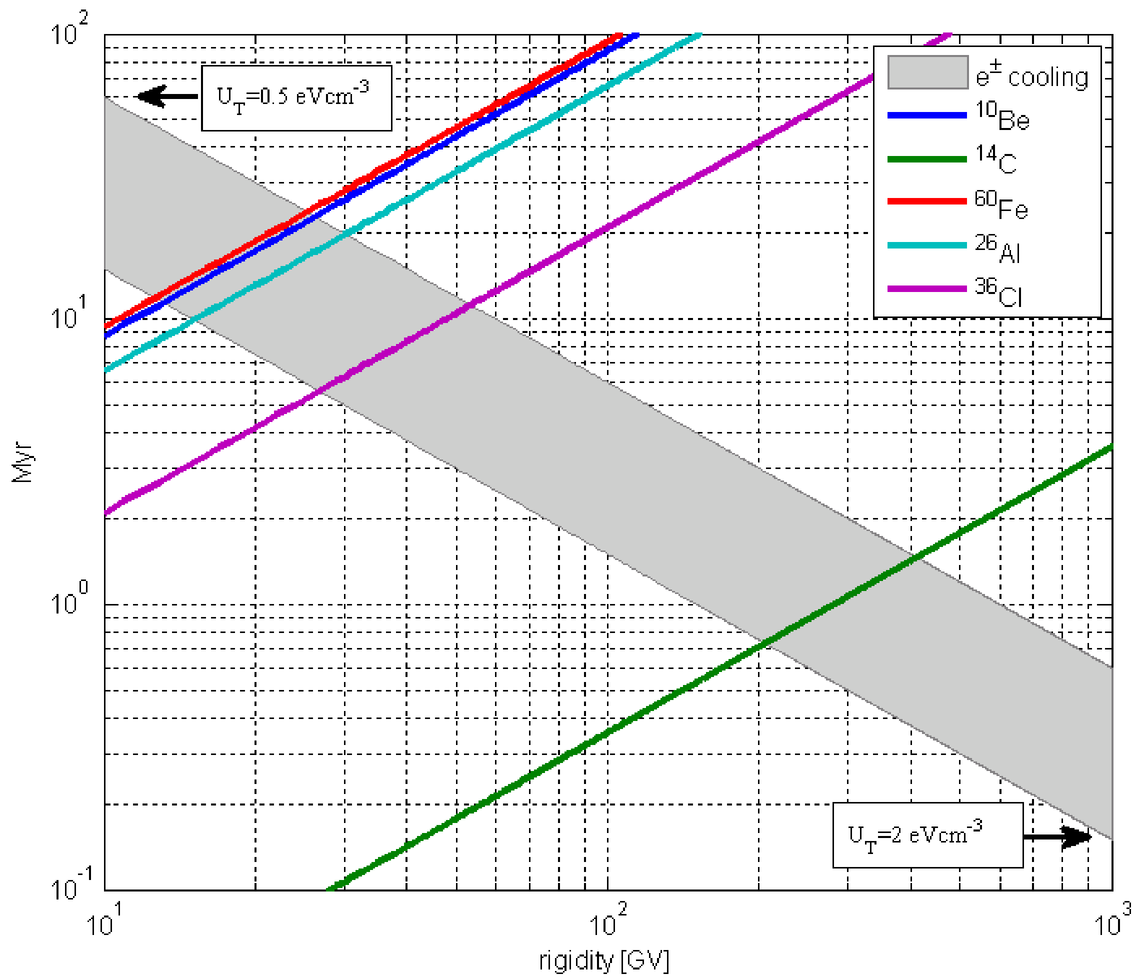
$$\boxed{\begin{gathered}\partial_t n_{i,\text{decay}} = -\frac{n_i}{\tau_d} \\ \partial_t n_{e^+,\text{energy loss}} = \underbrace{\left(\frac{\partial \log(\varepsilon^2 n_{e^+})}{\partial \log(\varepsilon)}\right)}_{\sim -1} \frac{n_{e^+}}{\tau_c}\end{gathered}}$$

# Comparing with radioactive nuclei

Time scales:
cooling vs decay

But…

Data @ 20 GV?




Yes →

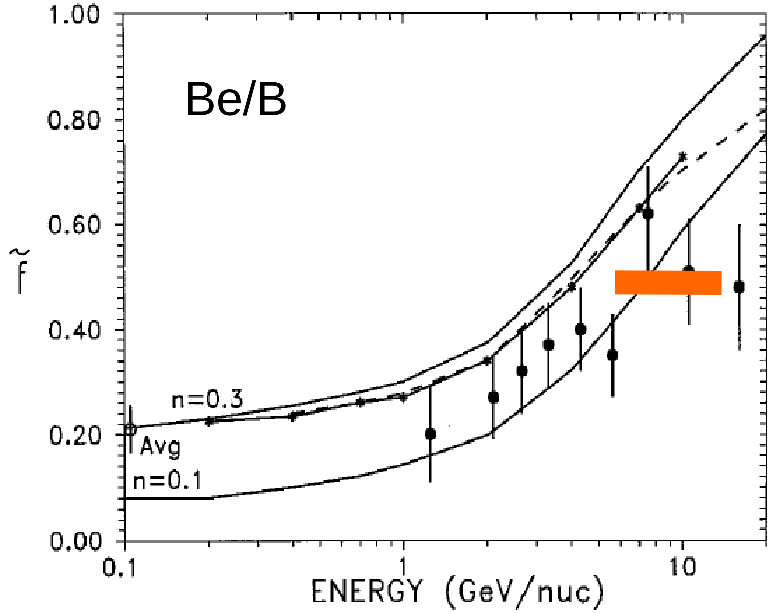
A STUDY OF THE SURVIVING FRACTION OF THE COSMIC-RAY RADIOACTIVE DECAY ISOTOPES $^{10}$Be, $^{26}$Al, $^{36}$Cl, and $^{54}$Mn AS A FUNCTION OF ENERGY USING THE CHARGE RATIOS Be/B, Al/Mg, Cl/Ar, AND Mn/Fe MEASURED ON *HEAO* – 3

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

*Received 1997 November 6; accepted 1998 May 11*

# Comparing with radioactive nuclei

$$n_i = \tilde{f}_{\mathrm{s},i} n_{i,\mathrm{no\ decay}}$$




$$\varepsilon \approx 10\,\mathrm{GeV/nuc}$$

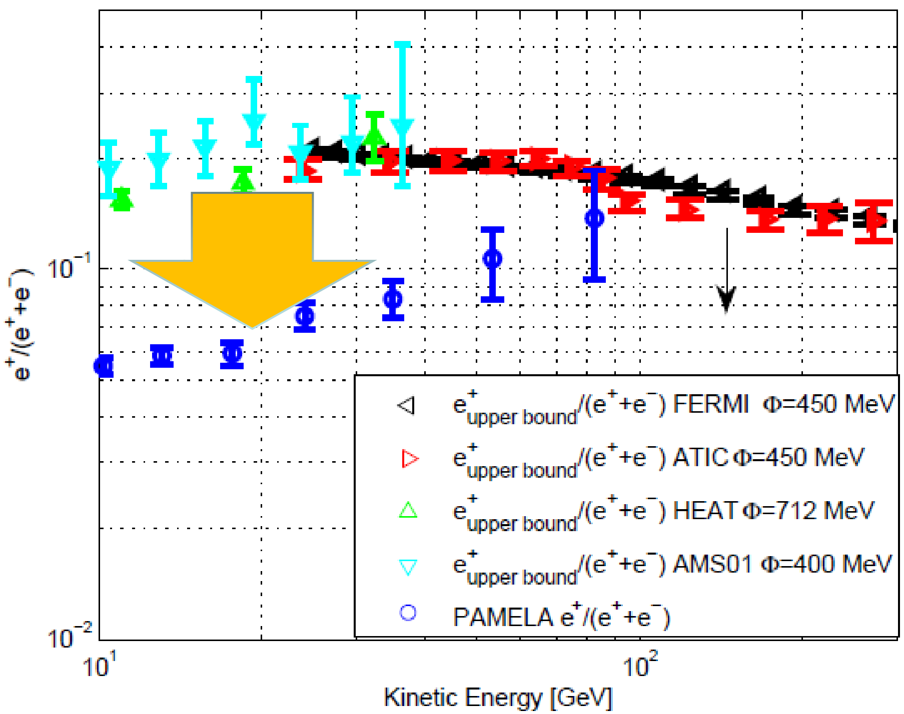
$$\tilde{f}_{s,{}^{10}\mathrm{Be}} \approx 0.5 \pm 0.1$$

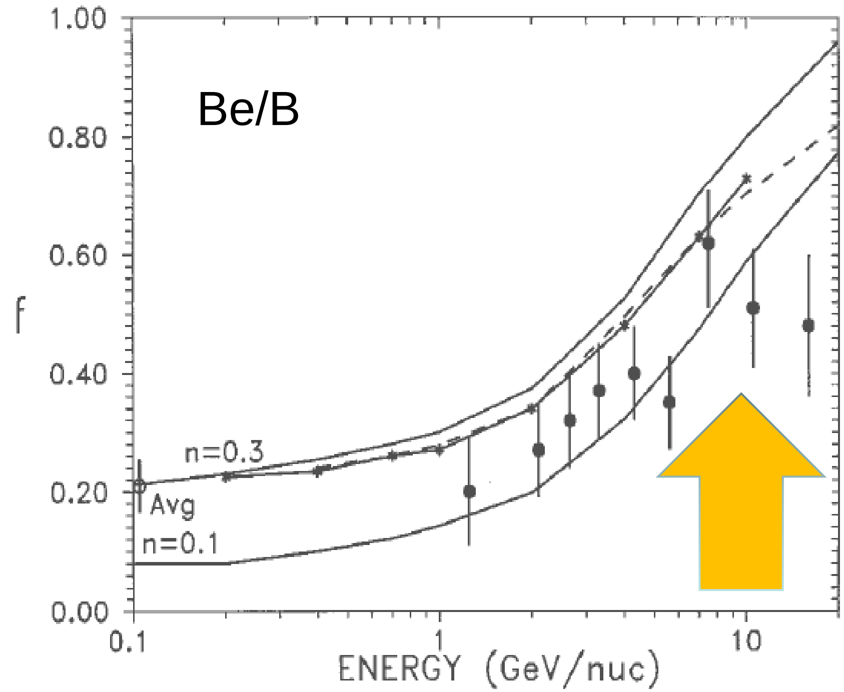
Factor out spallation losses:

$$\frac{f_{s,i}}{\tilde{f}_{s,i}} = \left[1 + \frac{\sigma_i}{m_p} X_{\mathrm{esc}} (1 - \tilde{f}_{s,i})\right]^{-1}$$

$$f_{s,{}^{10}\mathrm{Be}} \approx 0.4$$ → Agree with e+

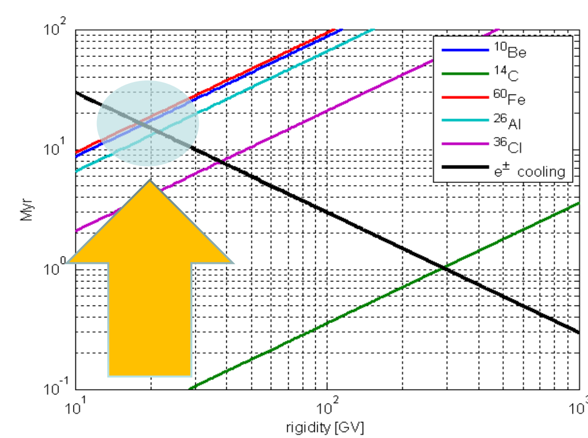
# Let me gather it for you:




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

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



# 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.**$^2$

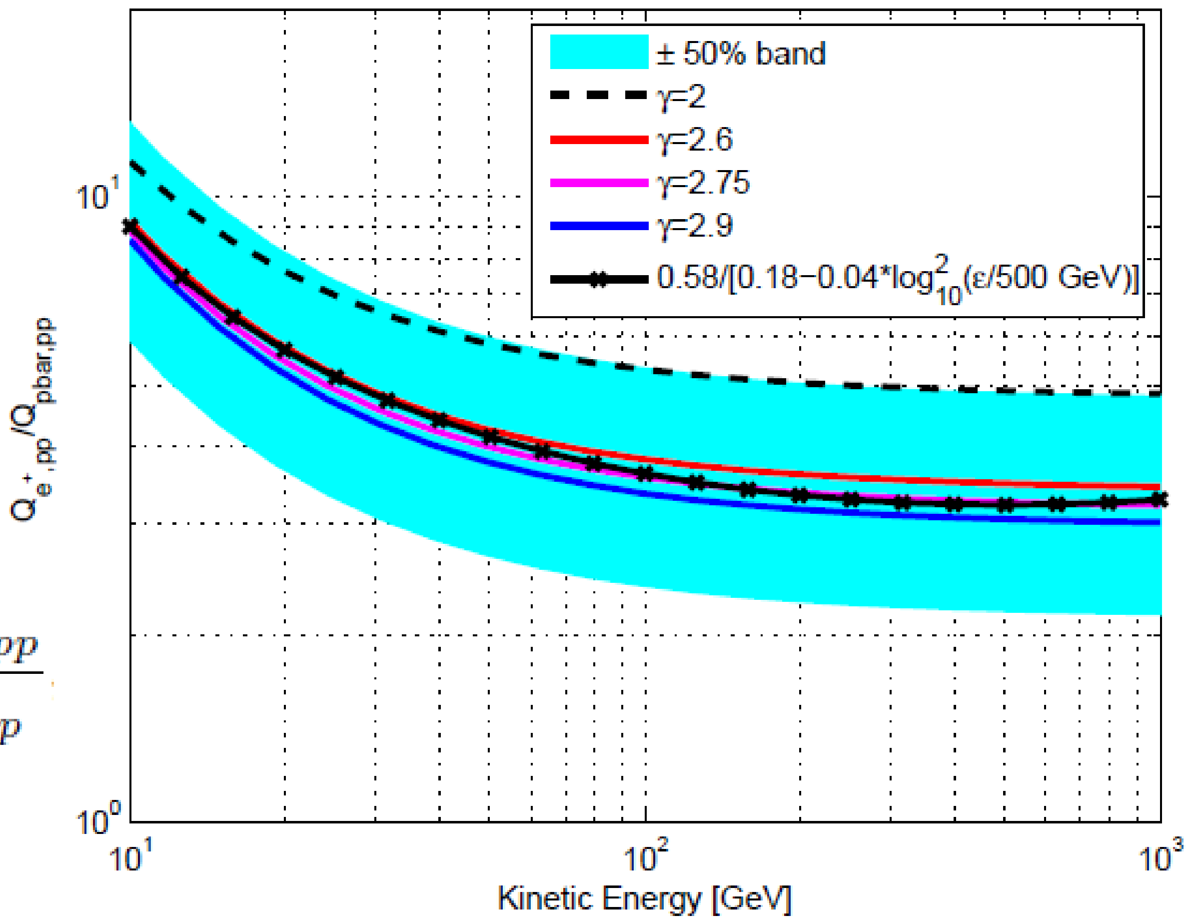
- The $e^+$ flux, including the energy loss suppression, is calculated within a specific propagation model.

**?**

**Unknown.**$^n$

# Theoretically clean channel:

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




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

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

Agashe, KB, Lee, Perez
PRD 81, 075012 (2010)

# Theoretically clean channel:

$$\bar{p}/p$$

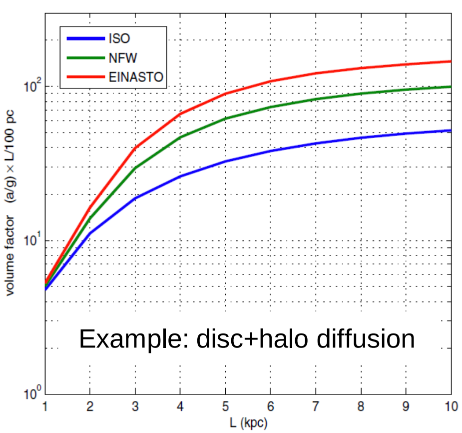
-Secondary component robust. Based on observed p flux, B/C
-DM annihilation: volume enhancement

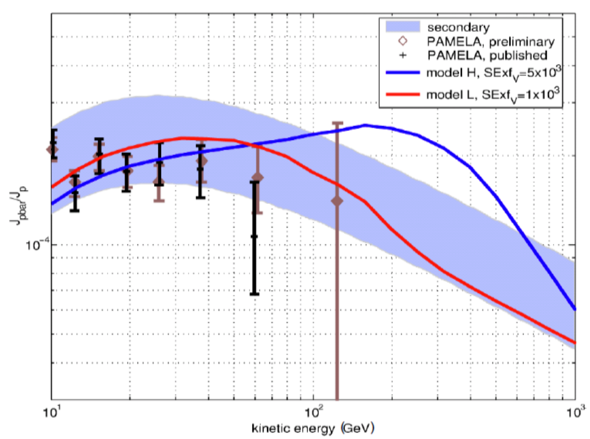
Volume effect = *single fuzz factor.*
*Not worse than gamma rays..*

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

*Fixed* by B/C, p flux

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




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

# Summary & Outlook

- Interpreting e+ data: Measure e+ ➔ measure losses

  e+ ~ antiprotons (up to radiative losses);

  antiprotons understood

- `Anomaly' ? Doesn't seem so right now

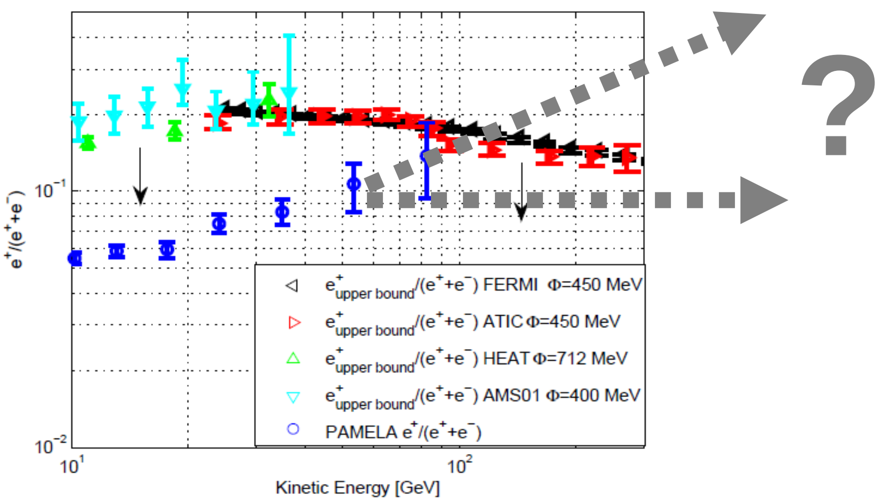
  $^{10}$Be agrees ➔ secondary!

  Wait for further data release;

  PAMELA reach $E_{e+}$< 270 GeV

- $e^+/\overline{p}$ - theoretically clean

  → model independent test for exotics




- Propagation models fit grammage

  what does it mean to be conservative?

# Xtras

# Antiprotons understood

$$\boxed{\begin{gathered}\frac{n_A}{n_B} = \frac{\tilde{Q}_A}{\tilde{Q}_B} \\[2em] n_i(\varepsilon) = \tilde{Q}_i(\varepsilon) X_{\mathrm{esc}}(\varepsilon/Z)\end{gathered}}$$

What is the CR grammage?

Why is the grammage relation natural?

In general
$$n_A(R,\vec{r},t) = \int d^3\vec{r}_S \int dt_S \int dR_S \, Q_A(R_S,\vec{r}_S,t_S)\, G_A(R,R_S;\vec{r},\vec{r}_S;t,t_S)$$

…If:

1. secondary particles with the same rigidity propagate through the ISM in the same way (diffusively or otherwise),
$$G_A = G$$

2. the rigidity of the products equals the rigidity of the primary,
$$Q_S(R,\vec{r},t) = \sum_P \Gamma_{P\to S}(\vec{r},t)\, n_P(R,\vec{r},t) \qquad \Gamma_{P\to S}(\vec{r},t) = \frac{\sigma_{P\to S}}{m_p}\rho_{ISM}(\vec{r},t)c$$

3. the energy of secondary particles does not change during propagation,
$$G(R,R_S;\vec{r},\vec{r}_S;t,t_S) = \delta(R-R_S)\,\tilde{G}(R;\vec{r},\vec{r}_S;t,t_S)$$

4. the composition (but not necessarily flux, spectrum or target density) of CRs is uniform throughout the region in which most of the secondaries observed here are produced and during the time they were produced.
$$\frac{n_i(R,\vec{r}_1,t_1)}{n_j(R,\vec{r}_2,t_2)} = f_{ij}(R)$$
$$\frac{n_A(R,\vec{r},t)}{Q_A(R,\vec{r},t)} = \int d^3\vec{r}_S \int dt_S \frac{\rho_{ISM}(\vec{r}_S,t_S)}{\rho_{ISM}(\vec{r},t)} \frac{n_P(R,\vec{r}_S,t_S)}{n_P(R,\vec{r},t)} \tilde{G}(R;\vec{r},\vec{r}_S;t,t_S)$$

$$\Rightarrow \quad \frac{n_A}{n_B} = \frac{Q_A}{Q_B}; \qquad Q_i = \sum_{j\neq i} n_j \frac{\sigma_{j\to i}}{m_p} c\rho_{\rm ISM}.$$

# Antiprotons understood

…In other words,… if*:

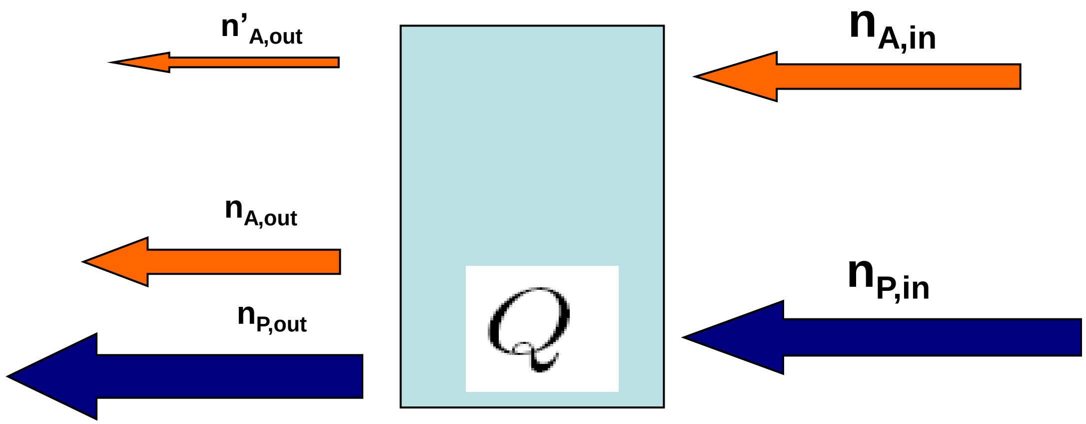
- Propagation only depends on magnetic rigidity
- Rigidity fixed on propagation
- Homogenous composition

*Also use the fact that spallation secondary inherits rigidity of primary

*Without* spallation losses:

$$\boxed{\frac{n_A}{n_B} = \frac{Q_A}{Q_B}; \qquad Q_i = \sum_{j \neq i} n_j \frac{\sigma_{j \to i}}{m_p} c \rho_{\rm ISM};}$$

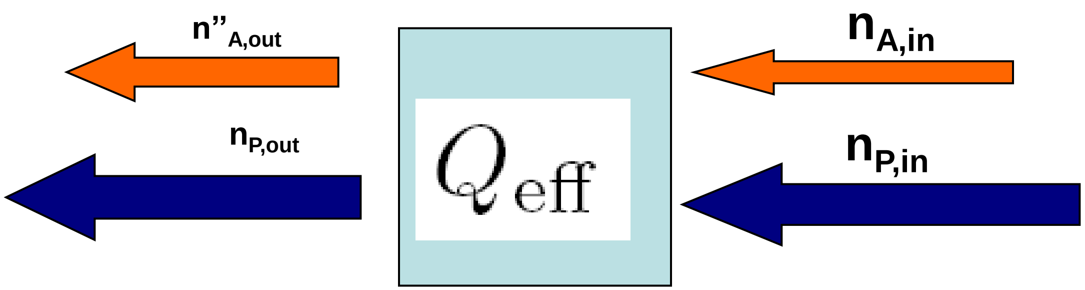
# Stable secondaries, with spallation losses




Equivalently:

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

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




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

Homogenous composition:

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

# Antiprotons understood

...If*:

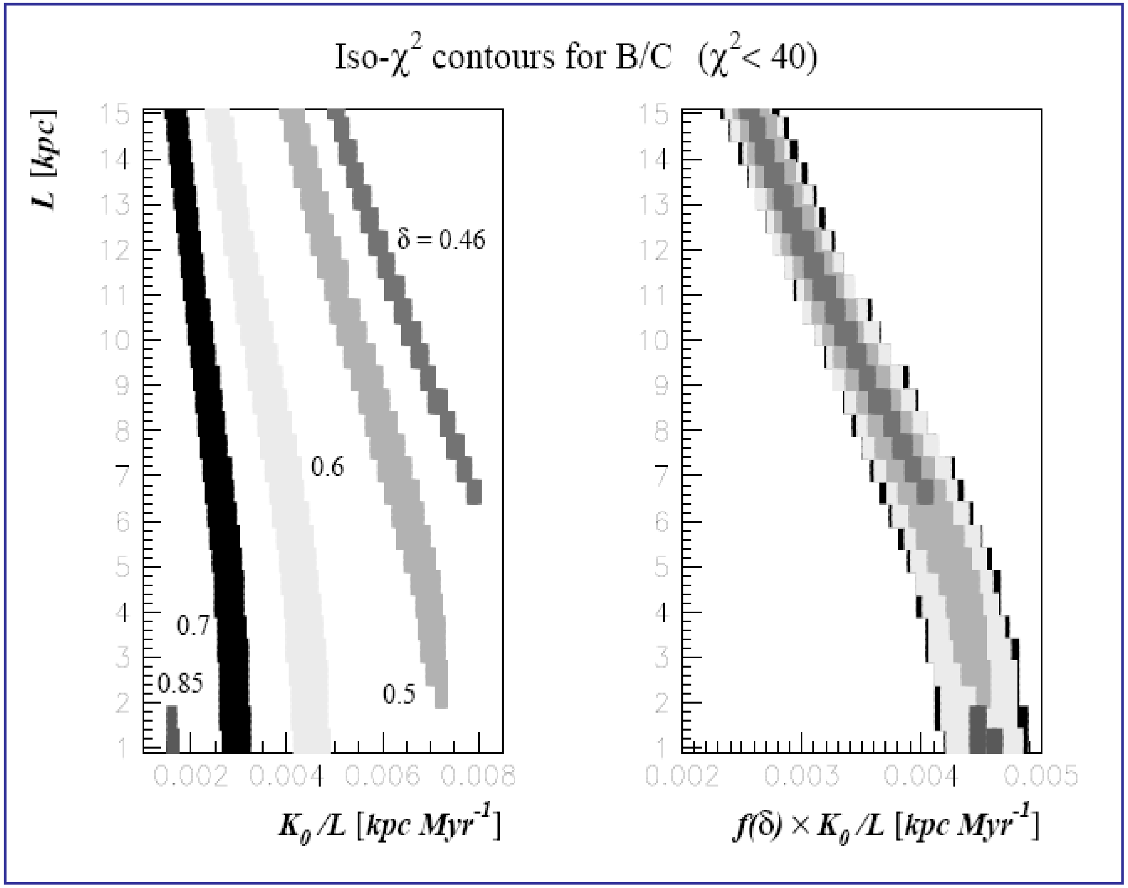
- Propagation only depends on magnetic rigidity
- Rigidity fixed on propagation
- Homogenous composition

*Also use the fact that spallation secondary inherits rigidity of primary

*With* spallation losses:

$$\boxed{\frac{n_A}{n_B} = \frac{\tilde{Q}_A}{\tilde{Q}_B} \qquad \tilde{Q}_i = \frac{Q_i}{\rho_{\rm ISM} c} - \frac{n_i \sigma_i}{m_p}}$$

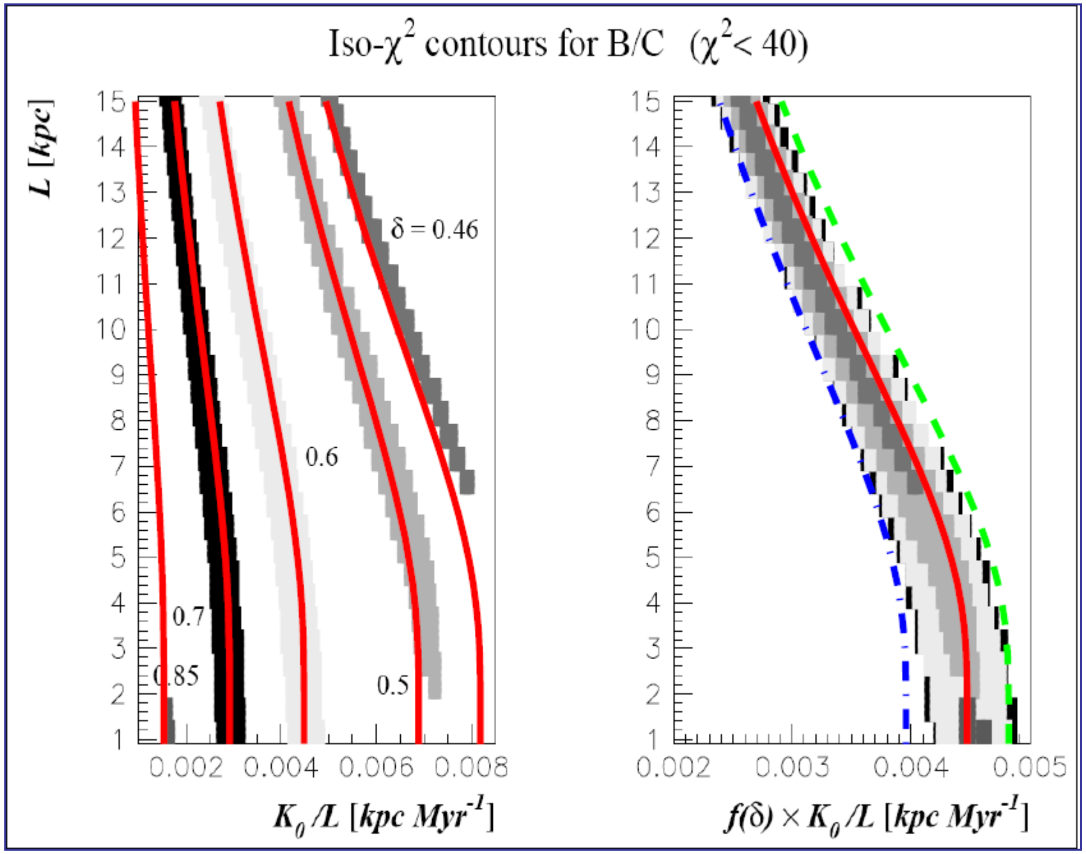
# Diffusion models fit grammage.




**Maurin, Donato, Taillet, Salati**

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

# Diffusion models fit grammage.




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

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

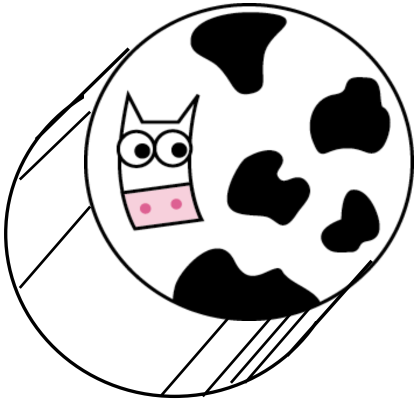
$$\left( g(L/R) = \frac{2R}{L} \sum_{k=1}^{\infty} J_0\left(\nu_k \frac{r_s}{R}\right) \frac{\tanh\left(\nu_k \frac{L}{R}\right)}{\nu_k^2 J_1(\nu_k)} \right)$$

Some things we don’t know.

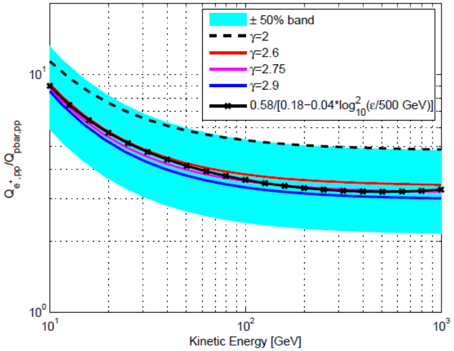
- Basic physics of CR propagation not known. Not even sure were primaries come from.
- Spectrum of MHD turbulence not known. Different analyses give different results. Spatial distribution not known.

  CR back-reaction not known.

  Even mean magnetic fields poorly known.
- Galaxy (probably) not a cylindrical cow.

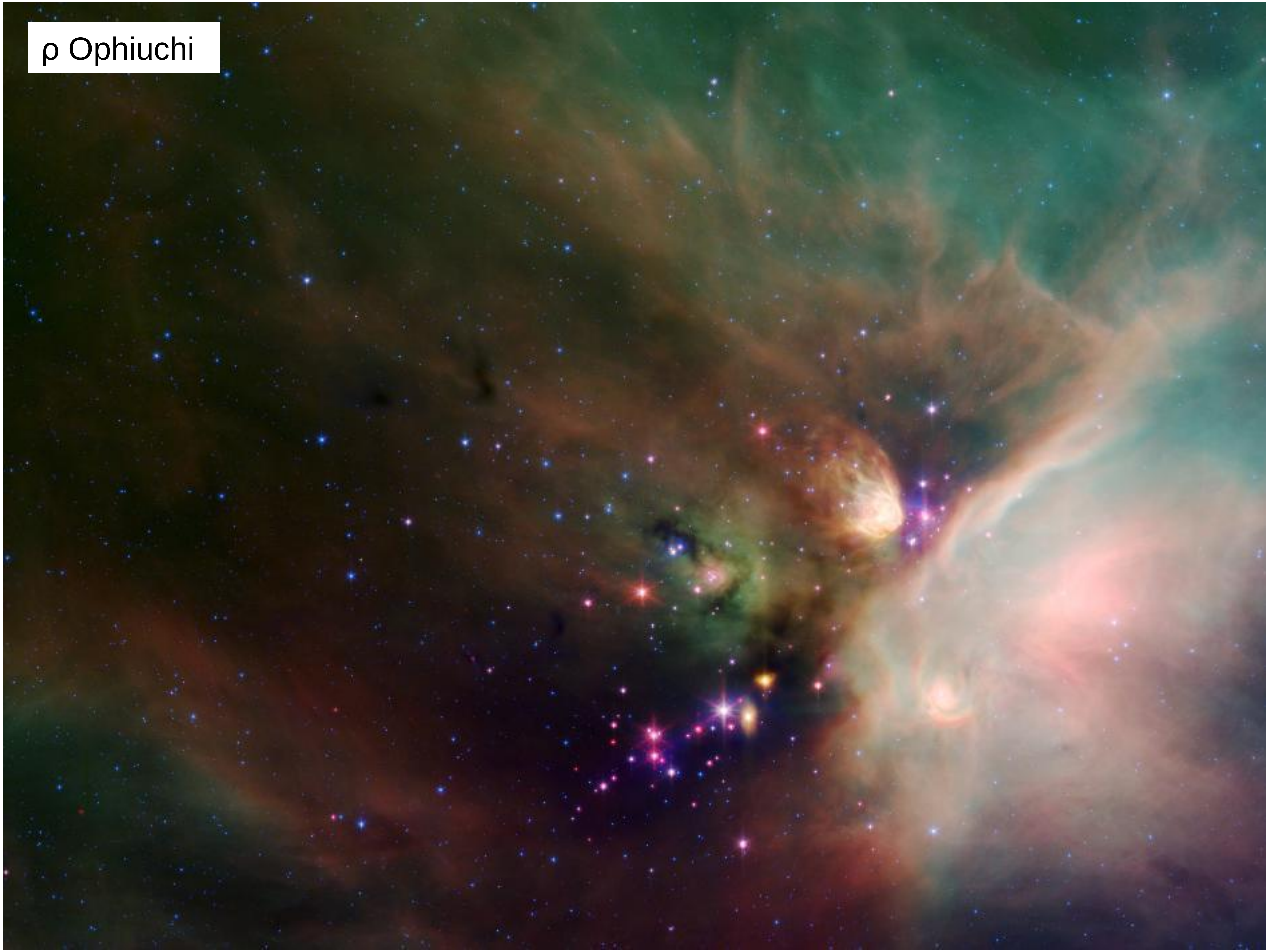


# Search for exotic sources:




Stick to data. Some things we do know.

E.g., secondary $e^+, \bar{p}$ come from pp collisions.


ρ Ophiuchi