Cosmic ray acceleration in supernova remnants and the Fermi/PAMELA data

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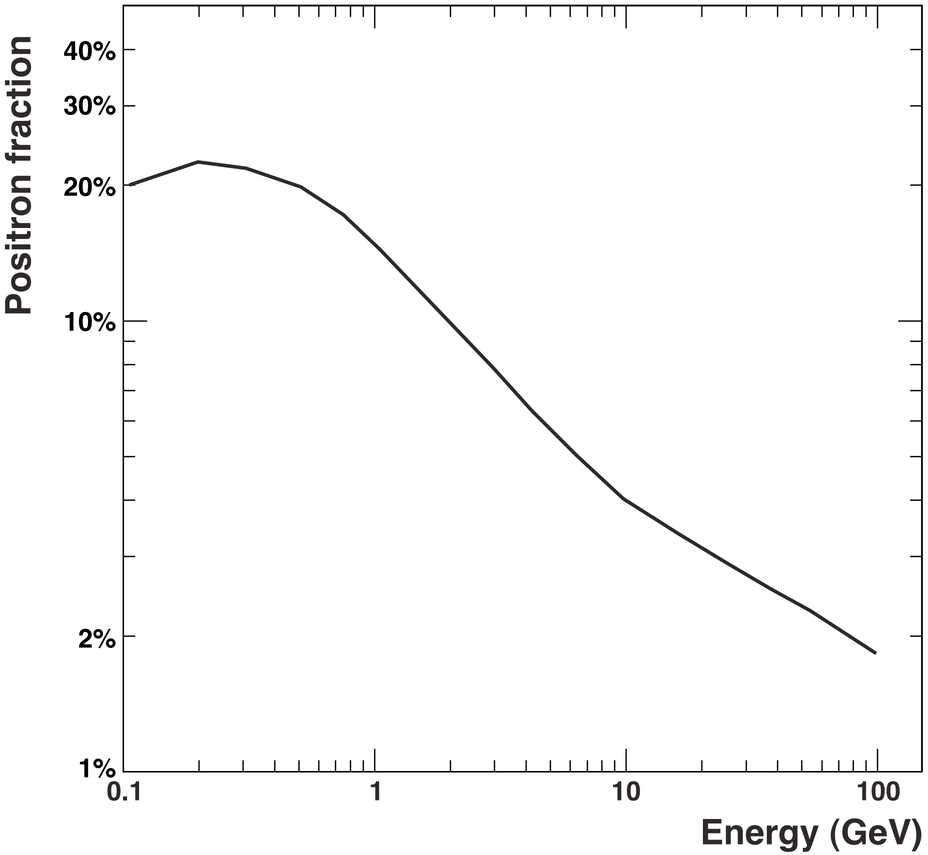
Cosmic ray backgrounds in dark matter searches
Oskar Klein Centre, Stockholm, 25 January 2010

Science & Technology Facilities Council

SIXTH FRAMEWORK PROGRAMME

Positron Fraction

theoretical prediction: $\propto E^{-0.4\ldots0.8}$



Positron Fraction

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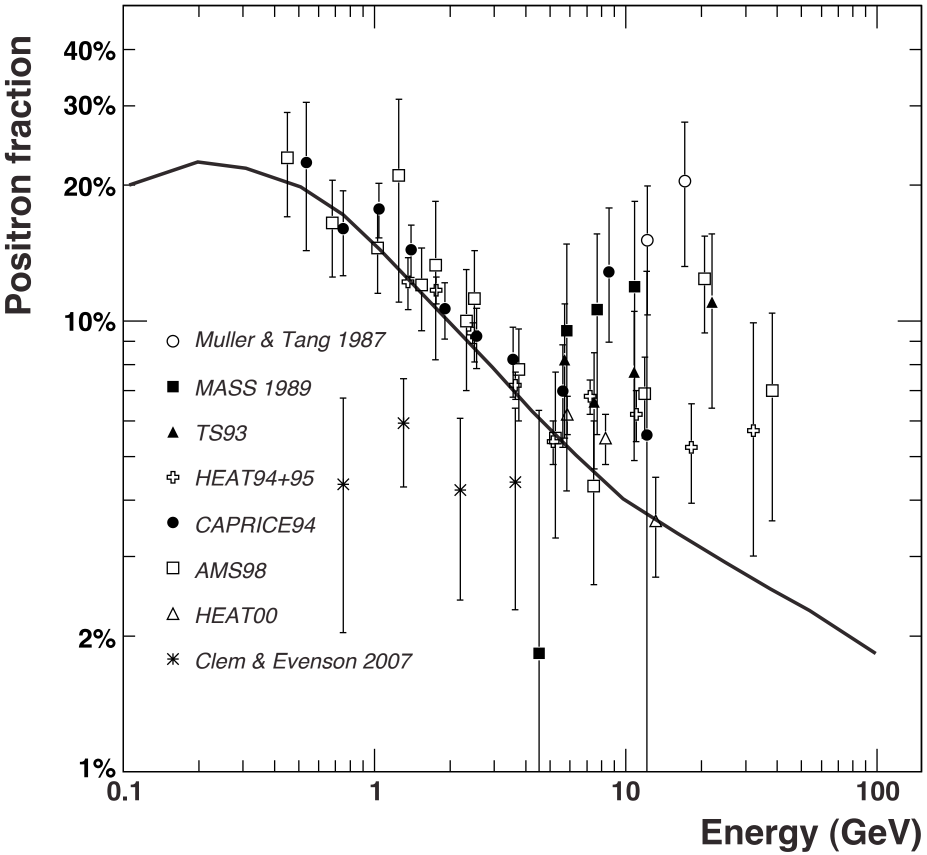

Positron Fraction

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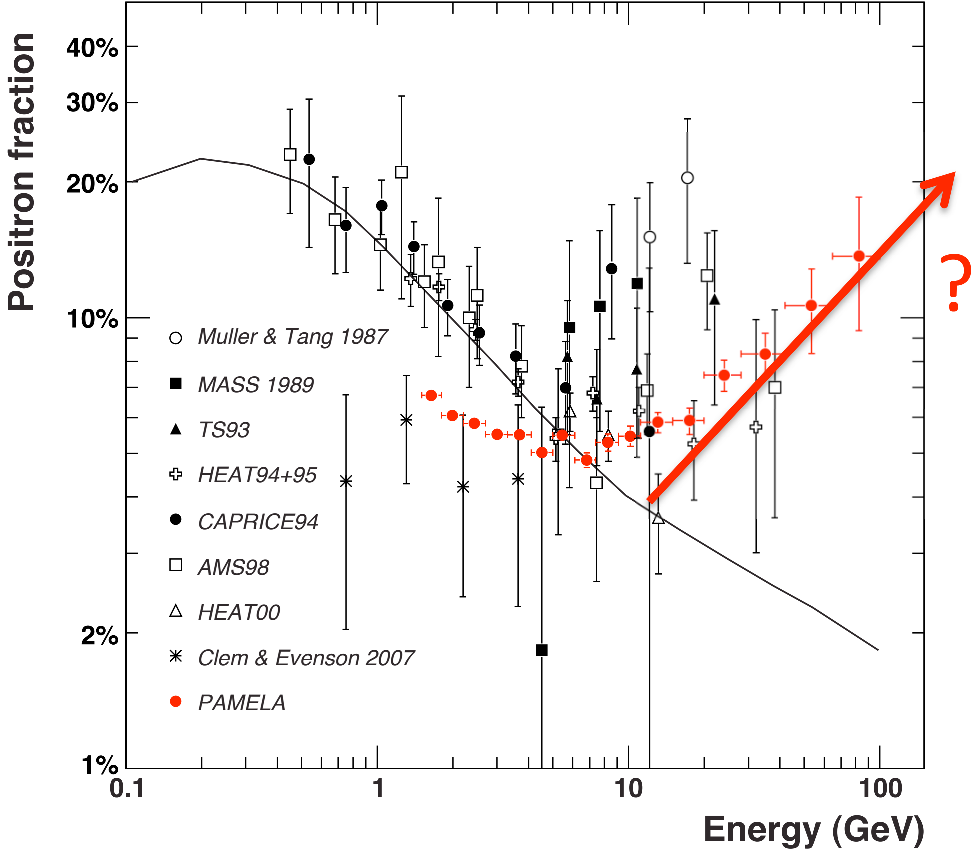


Adriani *et al.* *Nature* **458**, 607-609 (2009)

400

citations of this result

in a year's time!

The Leaky Box Model

Transport equation:

$$\frac{\mathrm{d}n(\vec{r},t)}{\mathrm{d}t} = \underbrace{\nabla(D\nabla n(\vec{r},t))}_{\downarrow\ \text{diffusion}} - \underbrace{\frac{\partial}{\partial E}(b(E)n(r,t))}_{\downarrow\ \text{energy losses}} + \underbrace{q(\vec{r},t)}_{\downarrow\ \text{injection}}$$

Averaging over extended CR halo; steady state solution

$$0 = -\frac{n}{\tau_{\mathrm{esc}}} - \frac{n}{\tau_{\mathrm{cool}}} + q$$

Escape from extended CR halo: $\tau_{\mathrm{esc}} \propto E^{-0.6}$

Energy loss through synchrotron radiation and ICS on CMB and IBL: $\tau_{\mathrm{cool}} \propto E^{-1}$

Energy Spectra

primary e^-

— production: $q \propto E^{-2.2}$

propagation: $\min[\tau_{\rm esc}, \tau_{\rm cool}] \propto E^{-0.6}, E^{-1}$

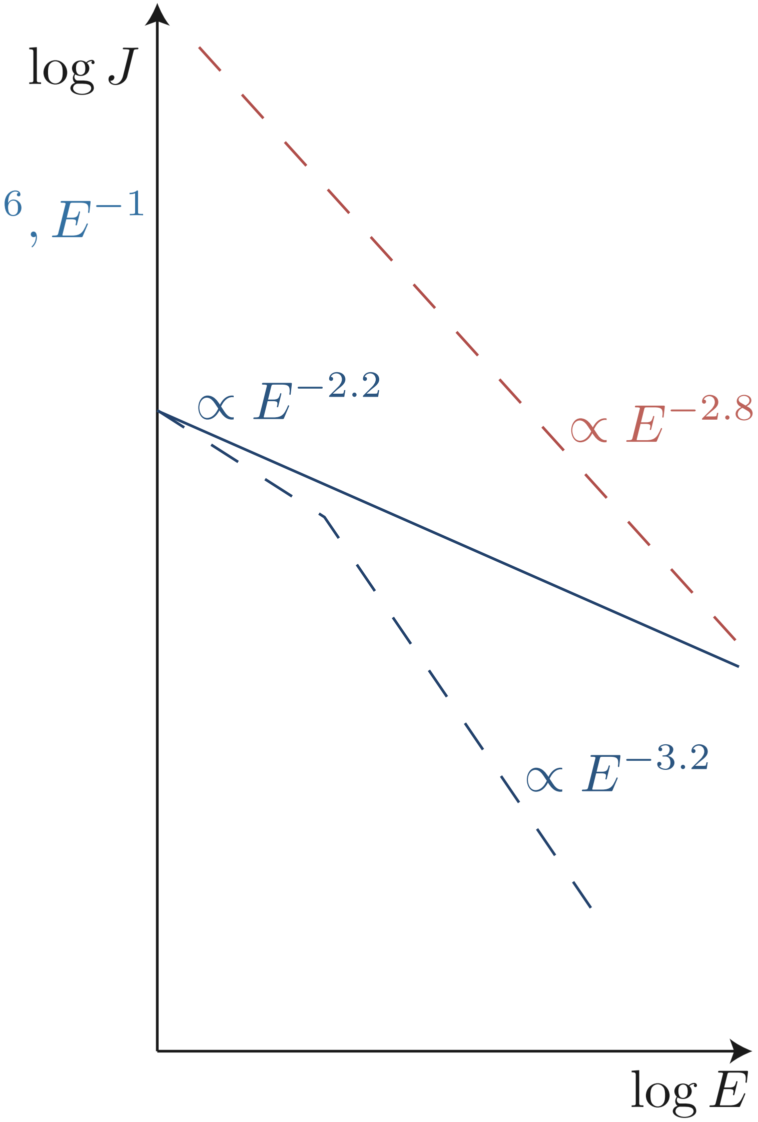
- - - ambient: $n \propto E^{-2.8}, E^{-3.2}$

CR protons/nuclei

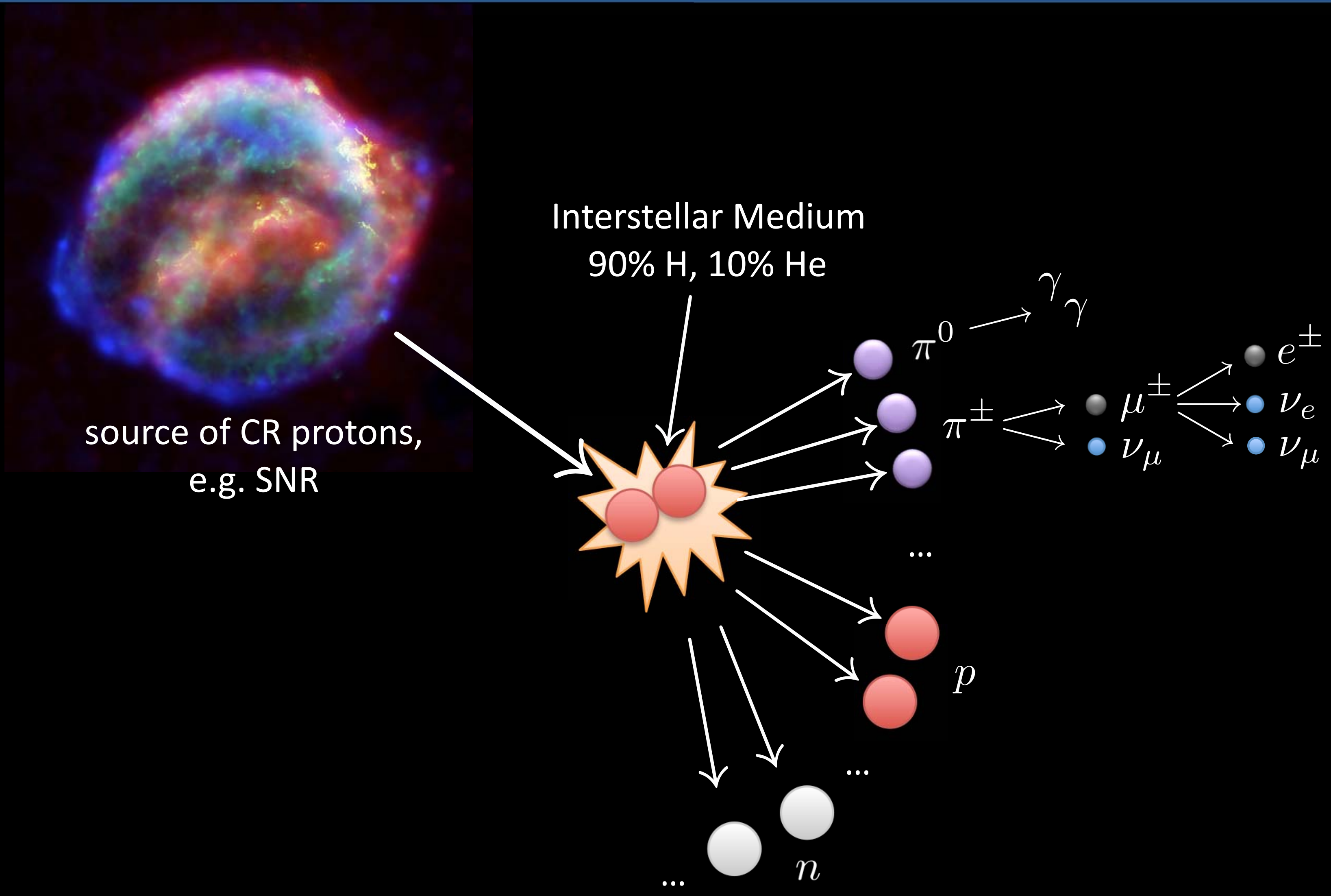
production: ?

propagation: ?

- - - ambient: $n \propto E^{-2.8}$



Secondary $e^{\pm}$ during Propagation



source of CR protons,
e.g. SNR

Interstellar Medium
90% H, 10% He

Energy Spectra

primary e^-

— production: $q \propto E^{-2.2}$

propagation: $\min[\tau_{\rm esc}, \tau_{\rm cool}] \propto E^{-0.6}, E^{-1}$

- - - ambient: $n \propto E^{-2.8}, E^{-3.2}$

CR protons/nuclei

production: ?

propagation: ?

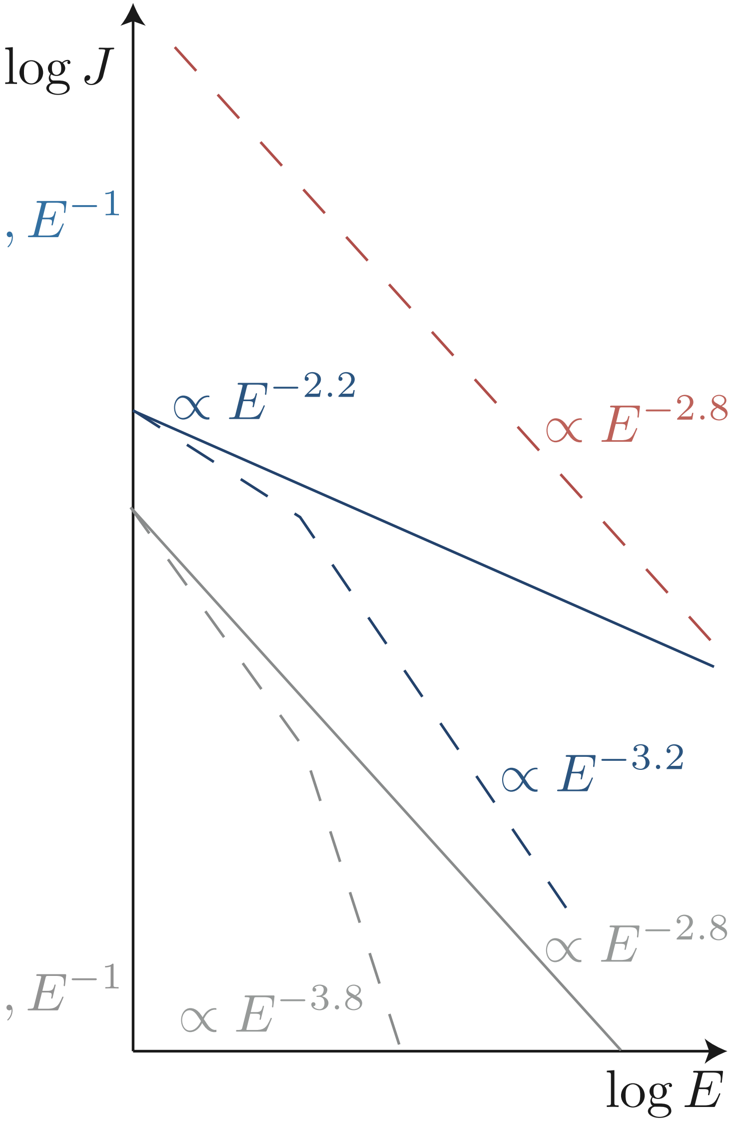
- - - ambient: $n \propto E^{-2.8}$

secondary $e^\pm$

— production: $q \propto E^{-2.8}$

propagation: $\min[\tau_{\rm esc}, \tau_{\rm cool}] \propto E^{-0.6}, E^{-1}$

- - - ambient: $n \propto E^{-3.4}, E^{-3.8}$



FERMI

The ~~ATIC~~ Excess

theoretical prediction:

$$\propto E^{-3.2\ldots3.5}$$

FERMI $(e^+ + e^-)$:

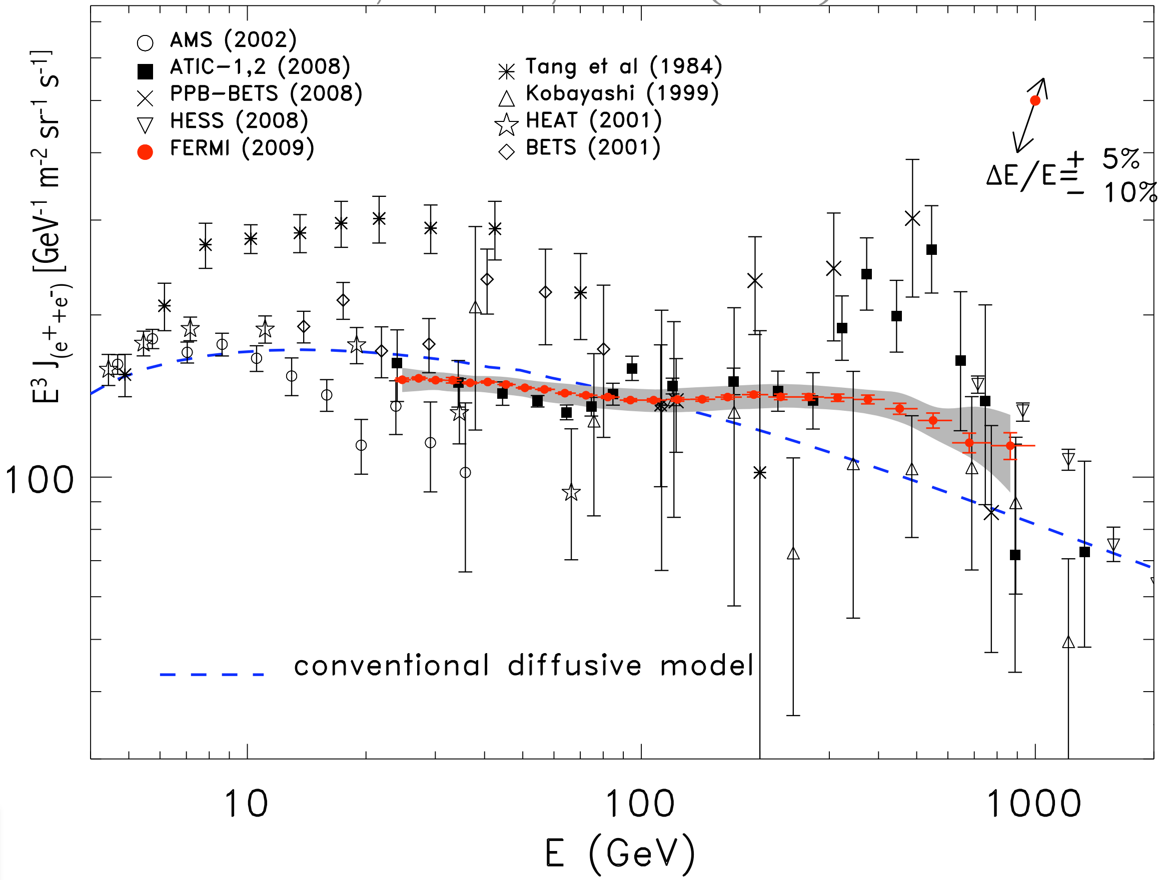
$$\propto E^{-3}$$

HESS:

spectral hardening at 1 TeV

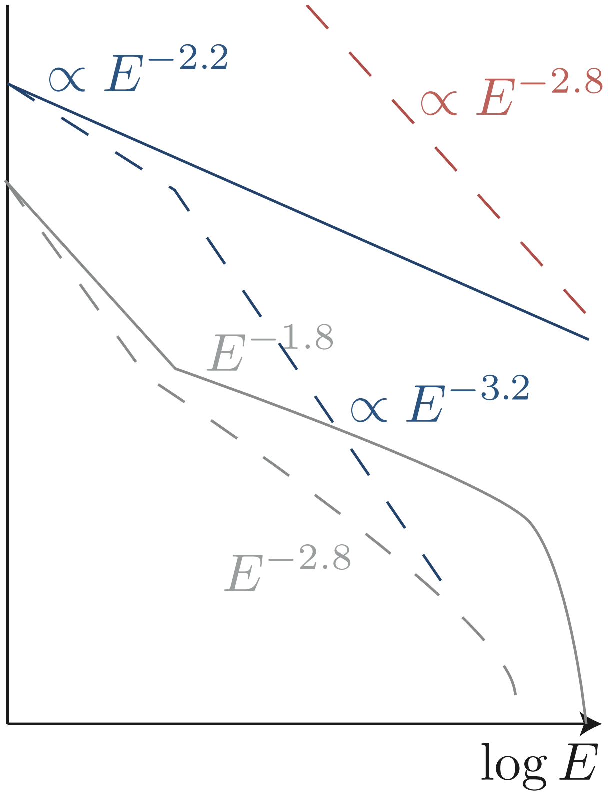
Excess between ~100 GeV and ~1 TeV

A. A. Abdo *et al.*, PRL **102**, 181101 (2009)



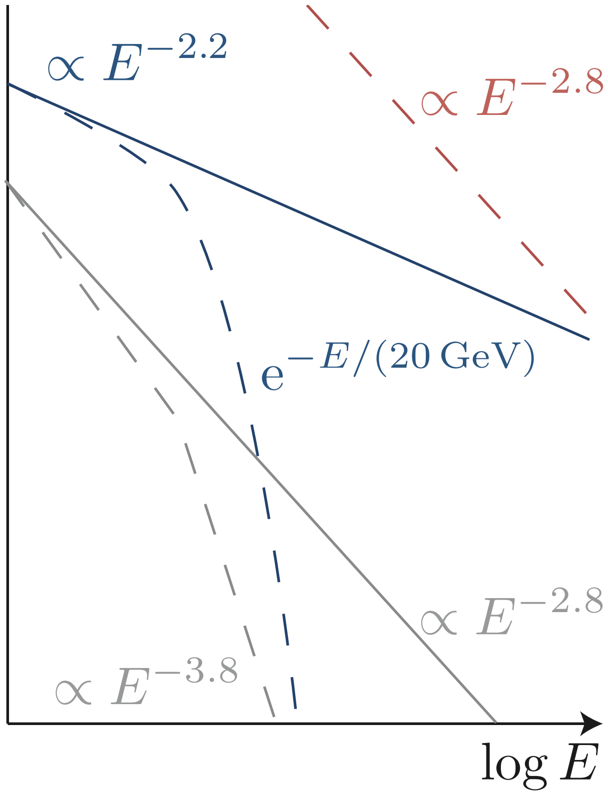
Rising Positron Fraction

harder positron injection



- DM annihilation or decay ➔ P. Ullio
- Nearby pulsars ➔ P. Serpico
- Acceleration of Secondaries ➔ this talk

softer electron spectrum



- Propagation cut-off in primary electrons ➔ T. Piran

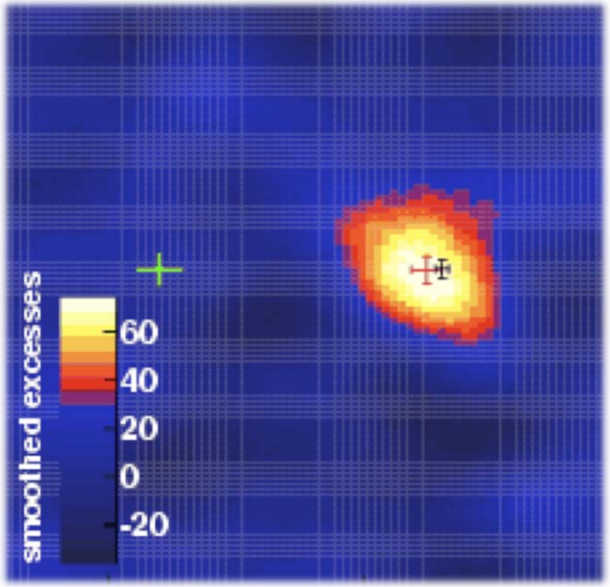
Secondary Origin of $e^{\pm}$

Rise in positron fraction could be due to secondary positrons produced during acceleration and accelerated along with primary electrons

Blasi, PRL **103** (2009) 051105

Assuming production of galactic CR in SNRs, PAMELA positron fraction can be fitted

This effect is guaranteed, only its size depends on normalisation and one free parameter that needs to be fitted from observations



Cas A in γ-rays from MAGIC

DSA – Test Particle Approximation

Consider flux

$$\Phi(p) = \int \mathrm{d}^3x \, \frac{4\pi p^2}{3} f(p)(-\nabla \cdot \vec{u})$$

Conservation equation:

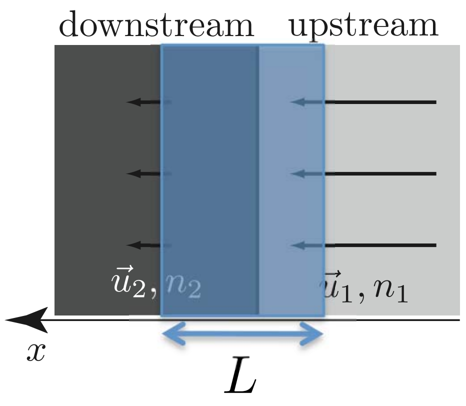
$$\underbrace{\frac{\partial}{\partial t}\left(4\pi p^2 f^0(p) L\right)}_{\downarrow} + \underset{\downarrow}{\frac{\partial \Phi}{\partial p}} = \underbrace{-4\pi p^2 f^0(p) u_2}_{\downarrow} \underset{\downarrow}{+Q(p)}$$

change in density

acceleration

convection

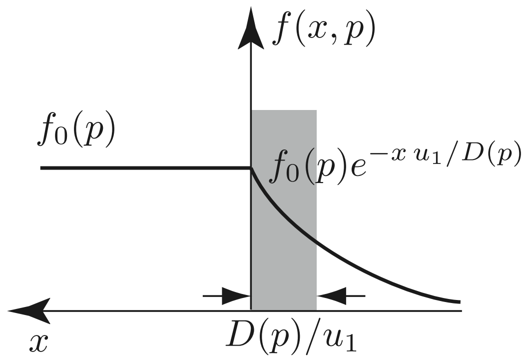
injection



One finds:

$$\frac{u_1 - u_2}{3} p \frac{\partial f^0}{\partial p} + u_1 f^0 = 0$$

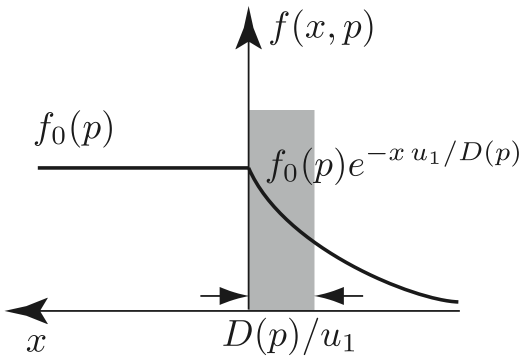
$$\Rightarrow f^0(p) \propto p^{-3u_1/(u_1 - u_2)} = p^{-\gamma}$$



DSA with Secondaries

- Secondaries get produced with primary spectrum:

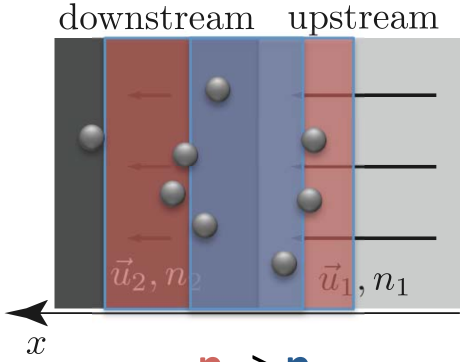
$$q_{e^\pm} \propto f_{\rm CR} \propto p^{-\gamma}$$



- Only particles with $|x| \lesssim D(p)/u$ can be accelerated

- Bohm diffusion: $D(p) \propto p$

- Fraction of secondaries that go into acceleration $\propto p$



$p_2 > p_1$

- Equilibrium spectrum

$$n_{e^\pm} \propto q_{e^\pm}\left(1+\frac{p}{p_0}\right) \propto p^{-\gamma} + p^{-\gamma+1}$$

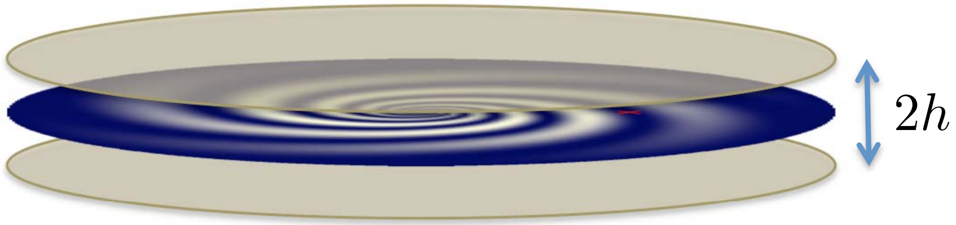
Rising positron fraction at source

Diffusion of GCRs

Transport equation:

$$\frac{\mathrm{d}n(\vec{r},t)}{\mathrm{d}t} = \underbrace{\nabla(D\nabla n(\vec{r},t))}_{\substack{\downarrow \\ \text{diffusion}}} - \underbrace{\frac{\partial}{\partial E}(b(E)n(r,t))}_{\substack{\downarrow \\ \text{energy losses}}} + \underbrace{q(\vec{r},t)}_{\substack{\downarrow \\ \text{injection}}}$$

Boundary conditions:

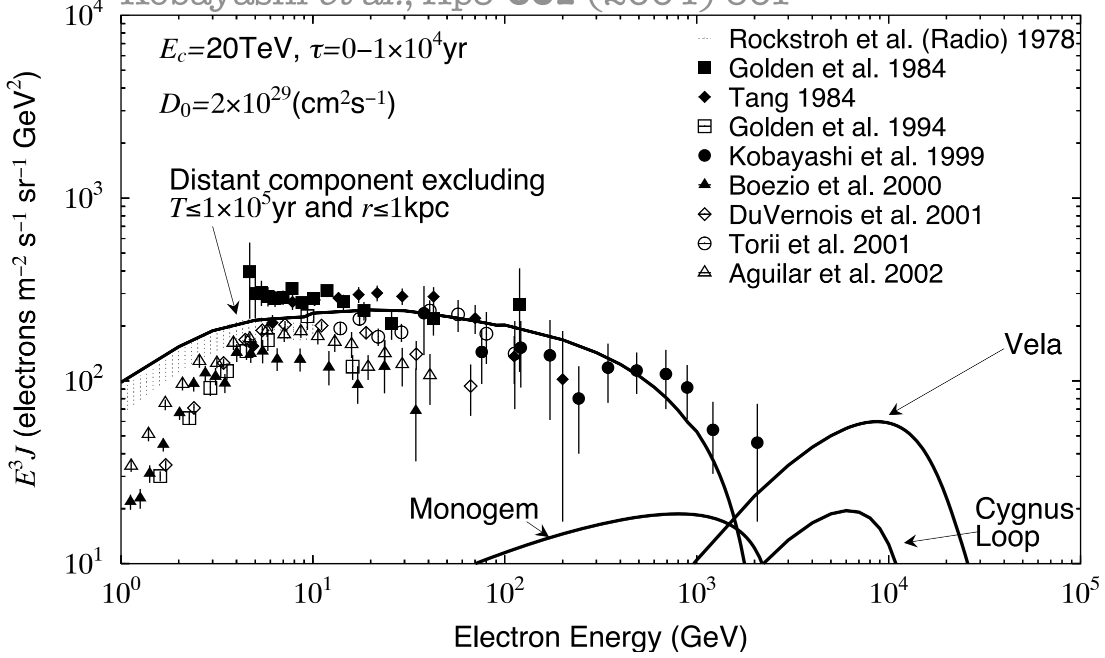


Green's function:

describes flux from one discrete, burst-like source

The Discreteness of Sources

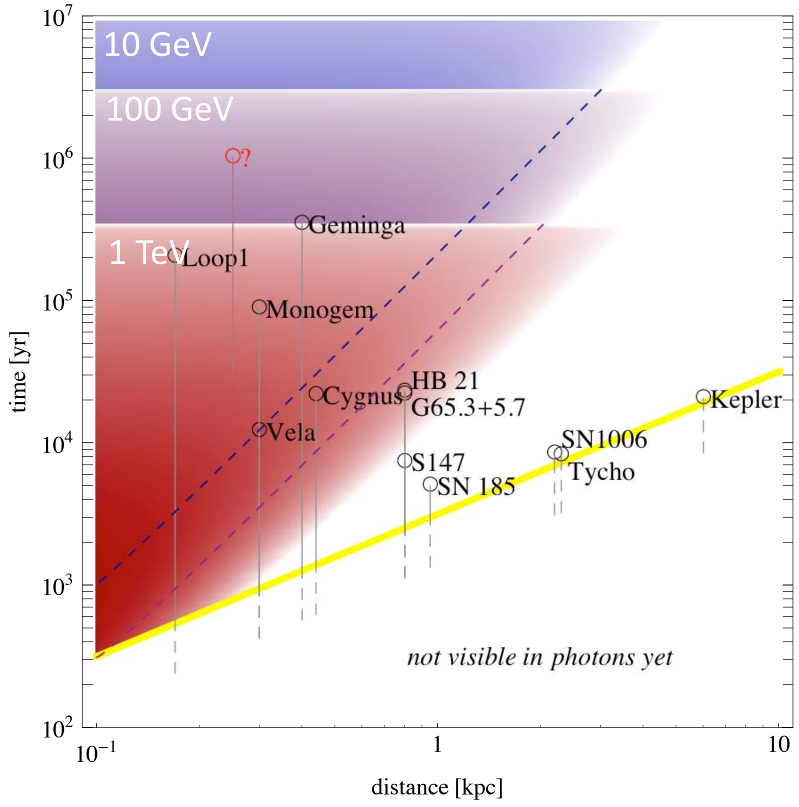
- Numerical codes like GALPROP usually simulate *continuous* source distribution
- However, discreteness of sources important, once the diffusion length shorter than average distance between sources

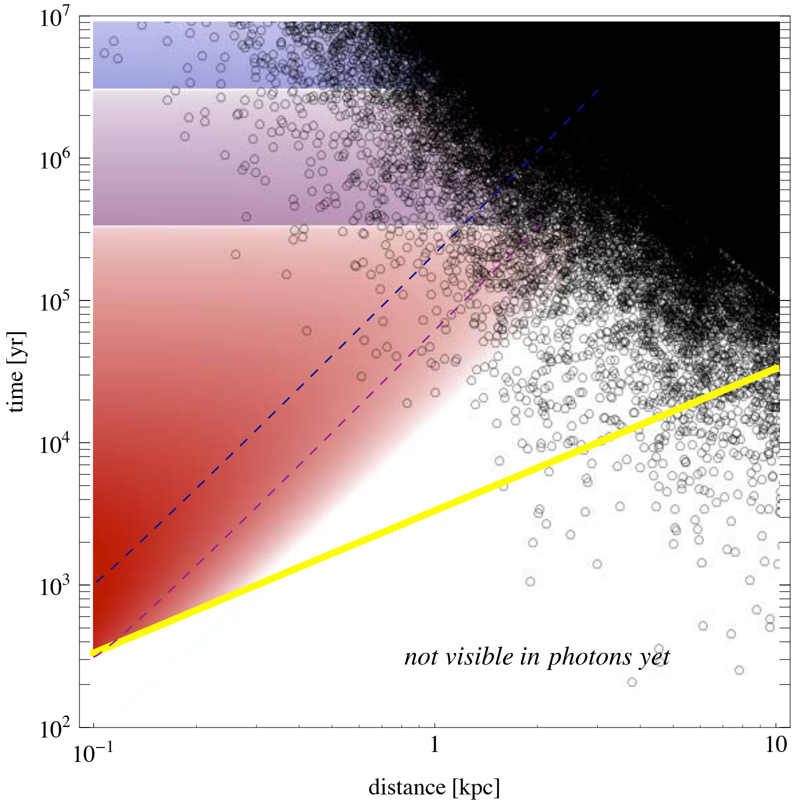


Kobayashi *et al.*, ApJ **601** (2004) 601

Only need to model *known* sources?!

A Caveat

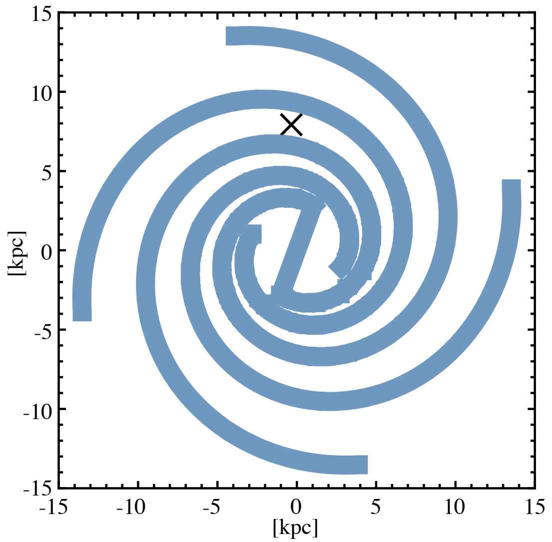




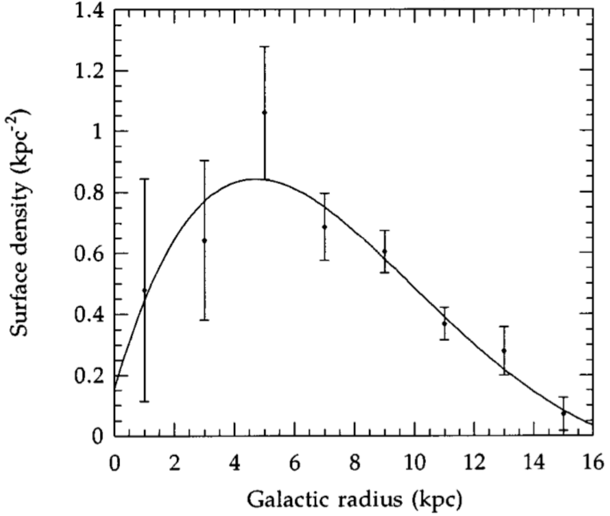
Not only observed sources contribute!

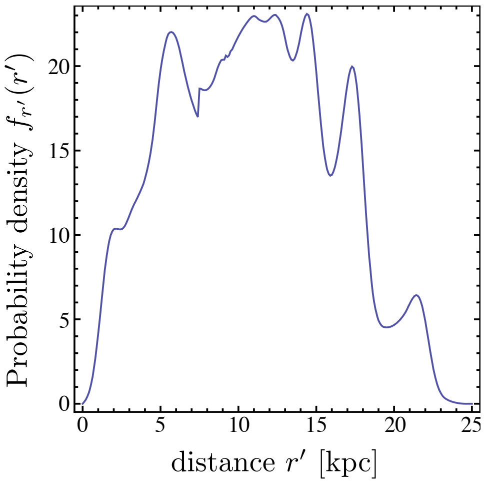
Ahlers, Mertsch, Sarkar, PRD **80** (2009) 123017

Statistical Distribution of Sources



Case, Bhattacharya, ApJ 504 (1998) 761





Idea:

- draw source positions from this distribution
- calculate total $(e^+ + e^-)$ flux
- best fit to data is closest to real distribution

Ahlers, Mertsch, Sarkar, PRD **80** (2009) 123017

Normalising the Source Spectra

normalisation of primary e^- : from fitting absolute e^- flux at low energies

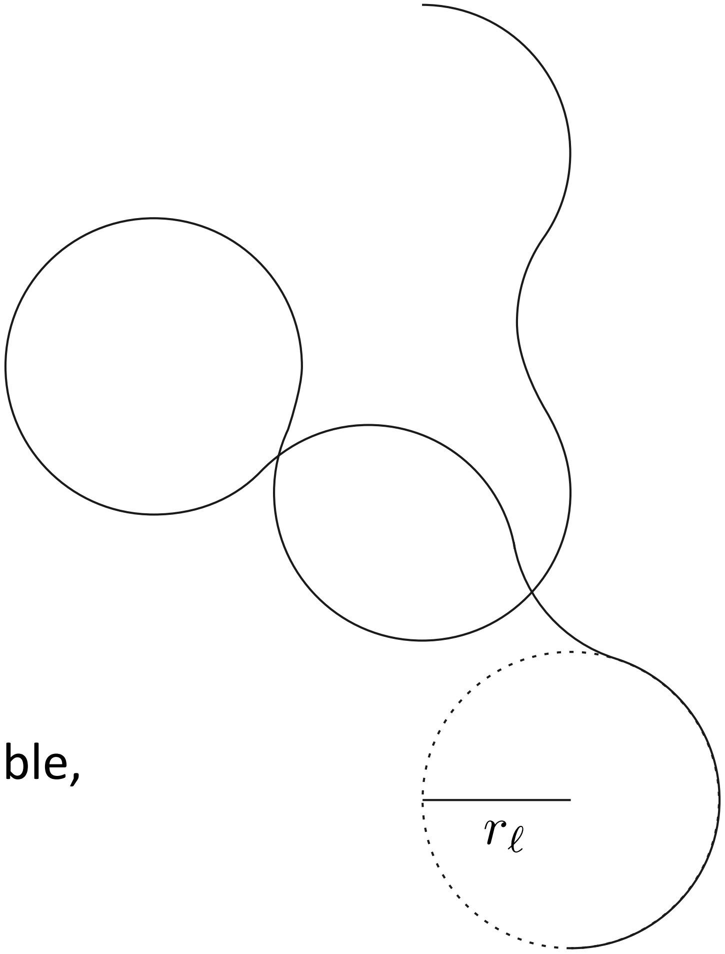
normalisation of secondary $e^\pm$:

$$p + p \rightarrow \left\{ \begin{array}{lcl} \pi^0 + \ldots & \rightarrow & 2\gamma + \ldots \\ \pi^\pm + \ldots & \rightarrow & e^\pm + \ldots \end{array} \right.$$

Source	Other name(s)	Γ	$J^0_\gamma \div 10^{-12}$ $[(\mathrm{cm}^2\,\mathrm{s\,TeV})^{-1}]$	$E_{\max}$ [TeV]	d [kpc]	$Q^0_\gamma \div 10^{33}$ $[(\mathrm{s\,TeV})^{-1}]$
HESS J0852−463	RX J0852.0-4622 (Vela Junior)	2.1 ± 0.1	21 ± 2	> 10	0.2	0.10
HESS J1442−624	RCW 86, SN 185 (?)	2.54 ± 0.12	3.72 ± 0.50	$\gtrsim 20$	1	0.46
HESS J1713−381	CTB 37B, G348.7+0.3	2.65 ± 0.19	0.65 ± 0.11	$\gtrsim 15$	7	3.812
HESS J1713−397	RX J1713.7-3946, G347.3-0.5	2.04 ± 0.04	21.3 ± 0.5	17.9 ± 3.3	1	2.55
HESS J1714−385	CTB 37A	2.30 ± 0.13	0.87 ± 0.1	$\gtrsim 12$	11.3	13.3
HESS J1731−347	G 353.6-07	2.26 ± 0.10	6.1 ± 0.8	$\gtrsim 80$	3.2	7.48
HESS J1801−233[a]	W 28, GRO J1801-2320	2.66 ± 0.27	0.75 ± 0.11	$\gtrsim 4$	2	0.359
HESS J1804−216[b]	W 30, G8.7-0.1	2.72 ± 0.06	5.74	$\gtrsim 10$	6	24.73
HESS J1834−087	W 41, G23.3-0.3	2.45 ± 0.16	2.63	$\gtrsim 3$	5	7.87
MAGIC J0616+225	IC 443	3.1 ± 0.3	0.58	$\gtrsim 1$	1.5	0.156
Cassiopeia A		2.4 ± 0.2	1.0 ± 0.1	$\gtrsim 40$	3.4	1.38
J0632+057	Monoceros	2.53 ± 0.26	0.91 ± 0.17	N/A	1.6	0.279
Mean		~ 2.5		$\gtrsim 20$		~ 5.2
Mean, excluding sources with $\Gamma > 2.8$		~ 2.4		$\gtrsim 20$		~ 5.7
Mean, excluding sources with $\Gamma > 2.6$		~ 2.3		$\gtrsim 20$		~ 4.2

Ahlers, Mertsch, Sarkar, PRD **80** (2009) 123017

Diffusion Coefficient



- Diffusion coefficient not known *a priori*
- Bohm diffusion sets lower limit

$$D_{\text{Bohm}} = r_\ell \frac{c}{3} \propto \frac{E}{Z}$$

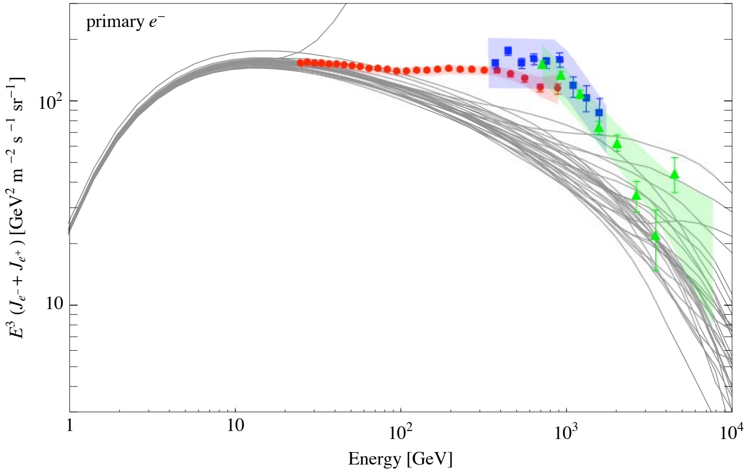
- Difference parametrised by fudge factor K_B

$$D = D_{\text{Bohm}} K_B$$

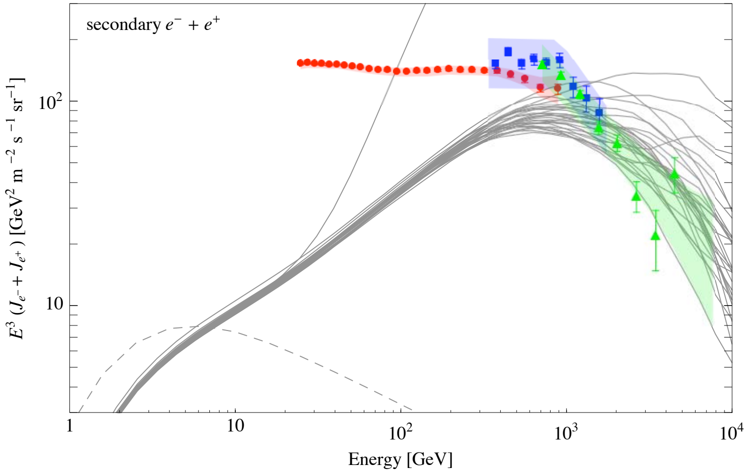
- K_B determined by fitting to one observable, allows prediction for another observable

The Total $(e^+ + e^-)$ Flux

primary e^-



secondary $(e^+ + e^-)$



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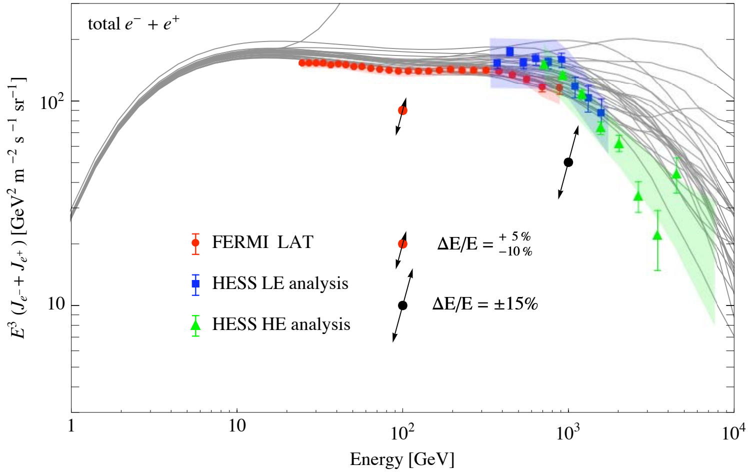

Ahlers, Mertsch, Sarkar, PRD **80** (2009) 123017

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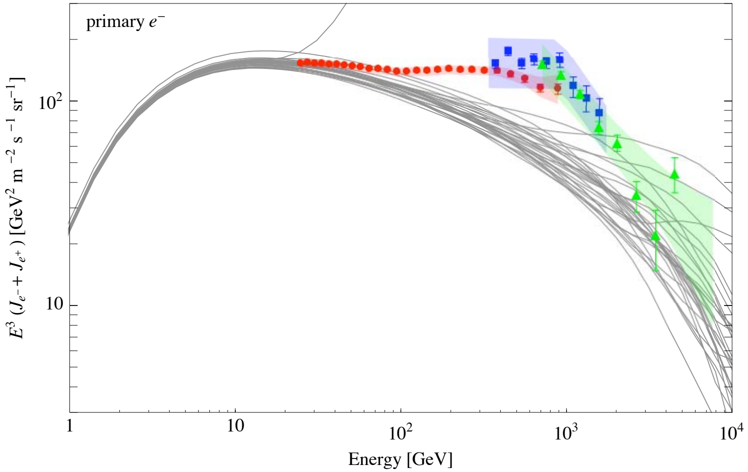

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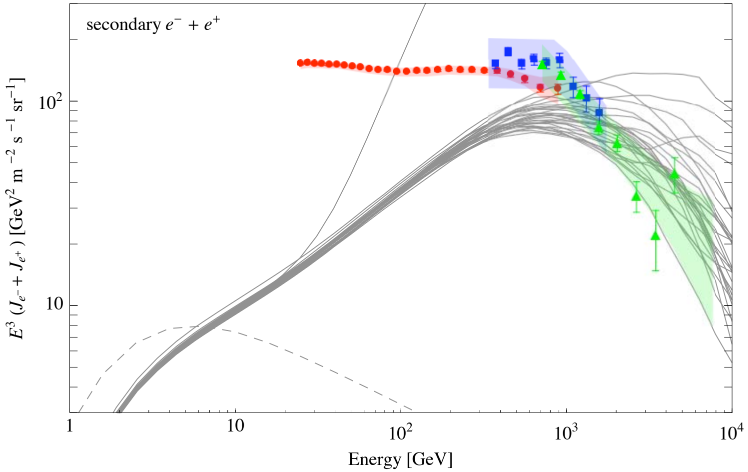

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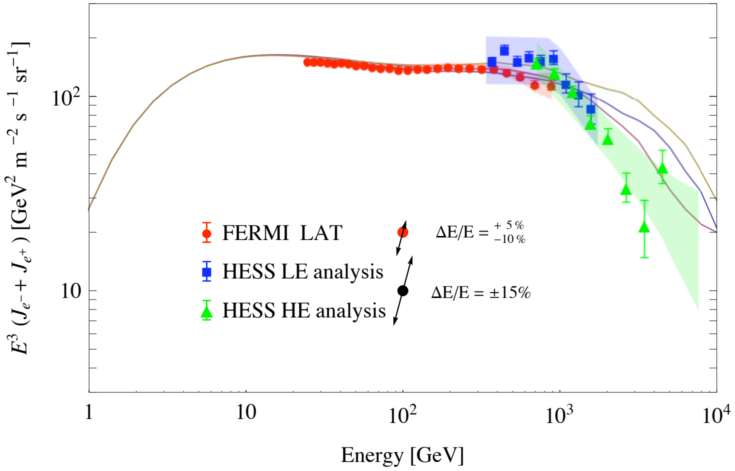
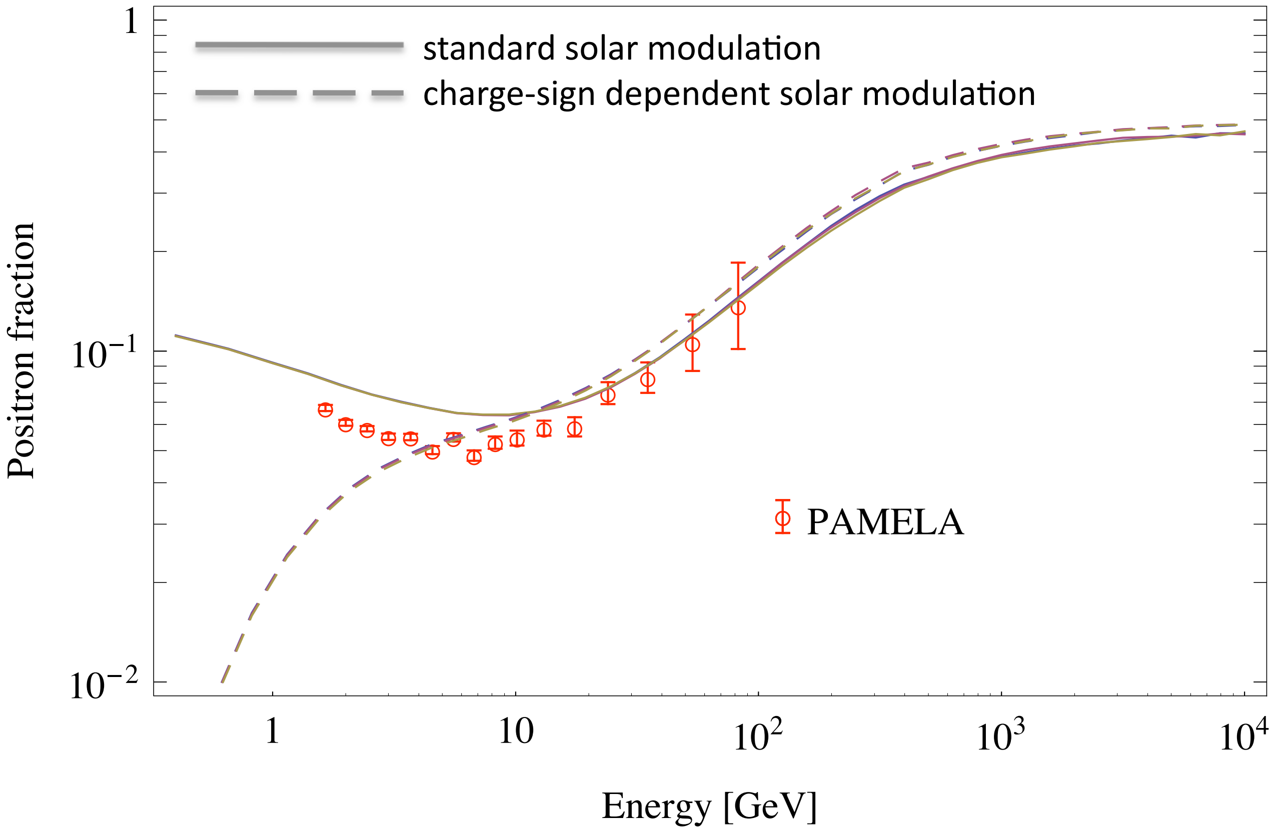


Ahlers, Mertsch, Sarkar, PRD **80** (2009) 123017

The Positron Fraction



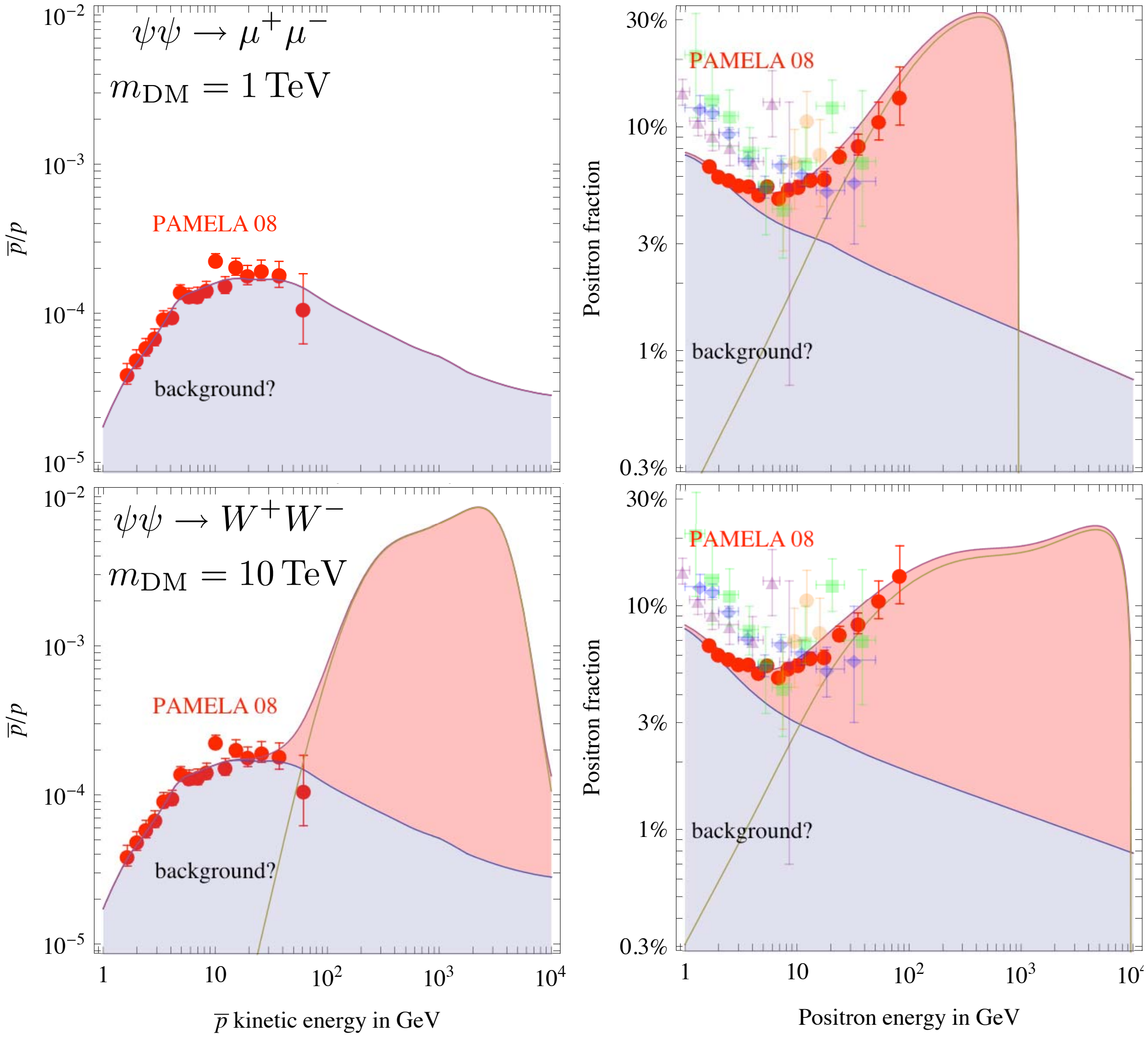
Ahlers, Mertsch, Sarkar, PRD **80** (2009) 123017

Explanations for PAMELA Excess

rise in…	e^+/e^-		
DM	✓		
Pulsars	✓		
Acceleration of Secondaries	✓		

Antiproton-to-proton Ratio

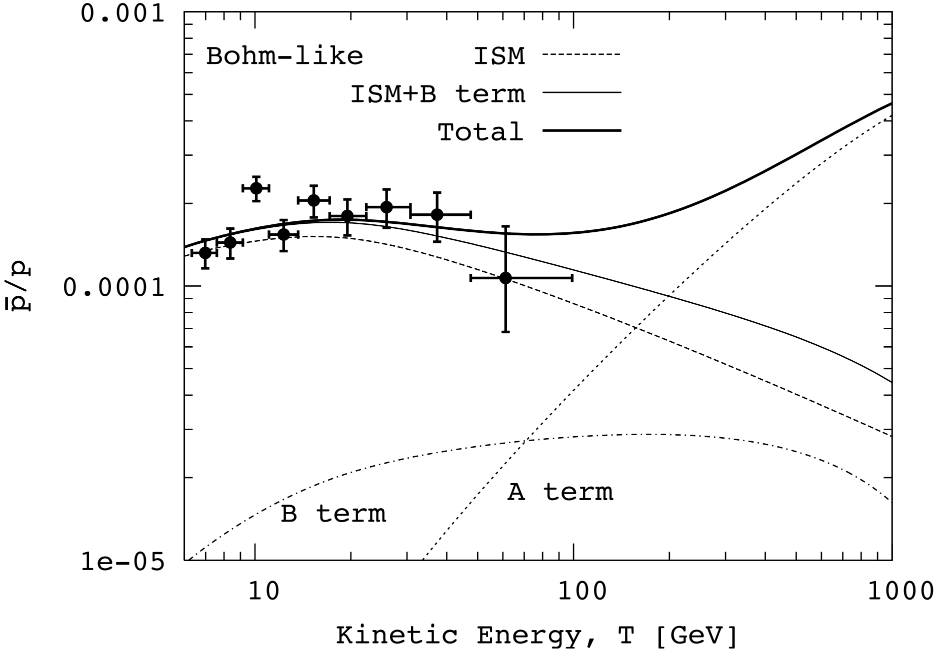
rise in...	$\bar{p}/p$
DM	(✓)
Pulsars	✗



Cirelli *et al.*, Nucl.Phys.B813:1-21,2009

Antiproton-to-proton Ratio

rise in...	$\bar{p}/p$
DM	(✓)
Pulsars	✗
Acceleration of Secondaries	✓



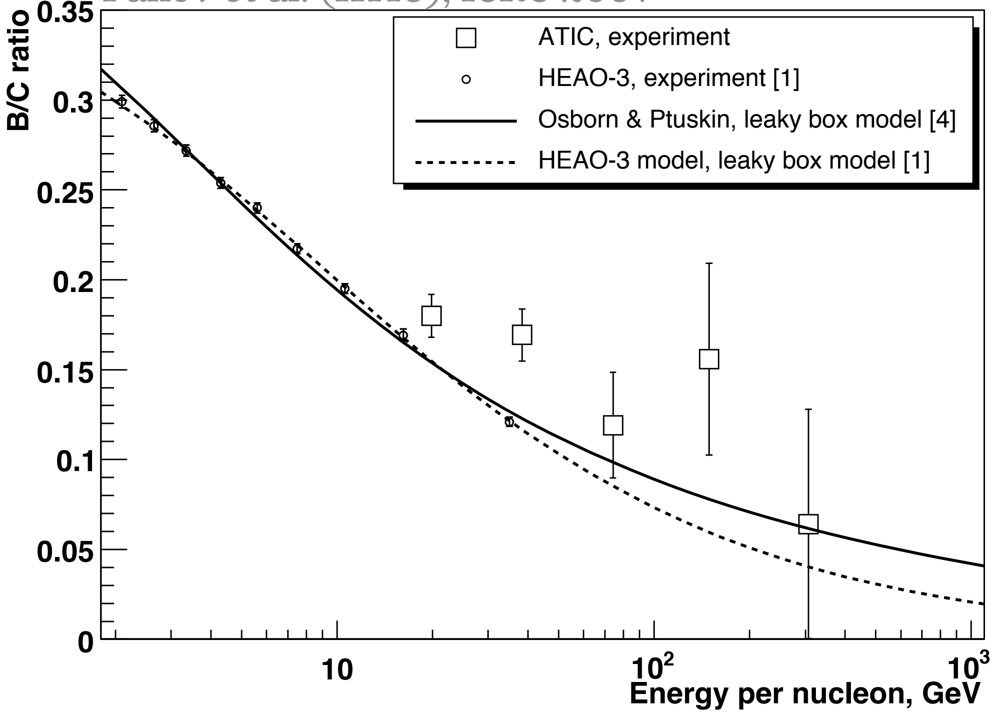
Blasi, Serpico, PRL 103 (2009) 081103

Nuclear Secondary-to-Primary Ratios

rise in…	nuclei
DM	✗
Pulsars	✗

DM and pulsars do not produce nuclei!

Nuclear secondary-to-primary ratios used for testing and calibrating propagation models



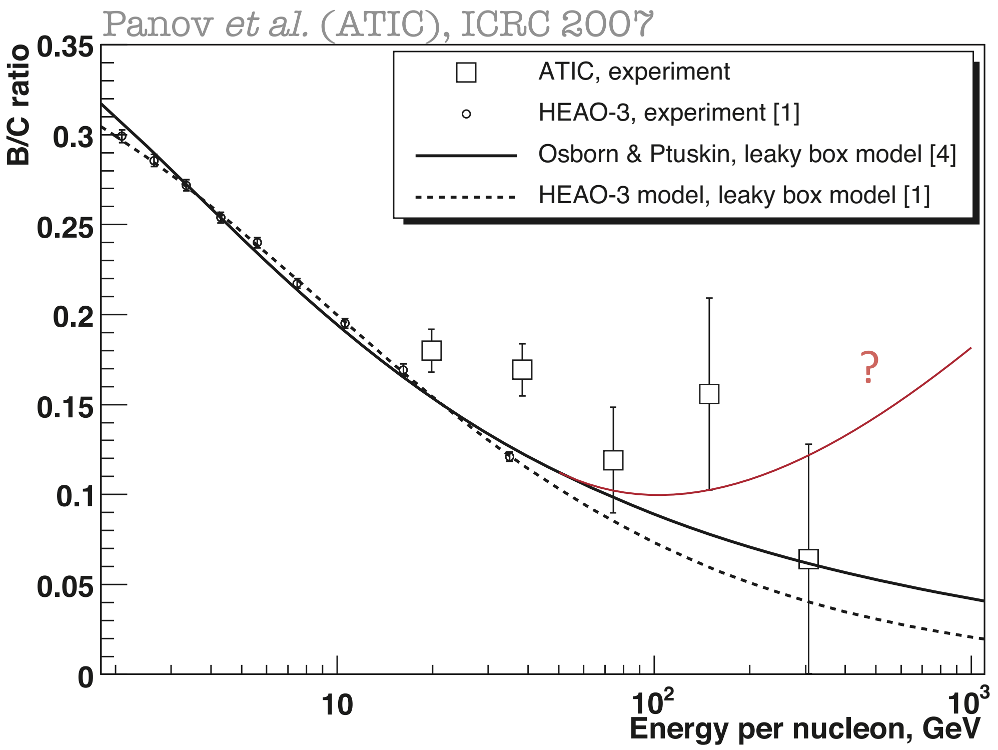
Panov *et al.* (ATIC), ICRC 2007

Nuclear Secondary-to-Primary Ratios

rise in…	nuclei
DM	✗
Pulsars	✗
Acceleration of Secondaries	✓

This would be a clear indication for acceleration of secondaries!

If nuclei are accelerated in the same sources as electrons and positrons, nuclear ratios *must* rise eventually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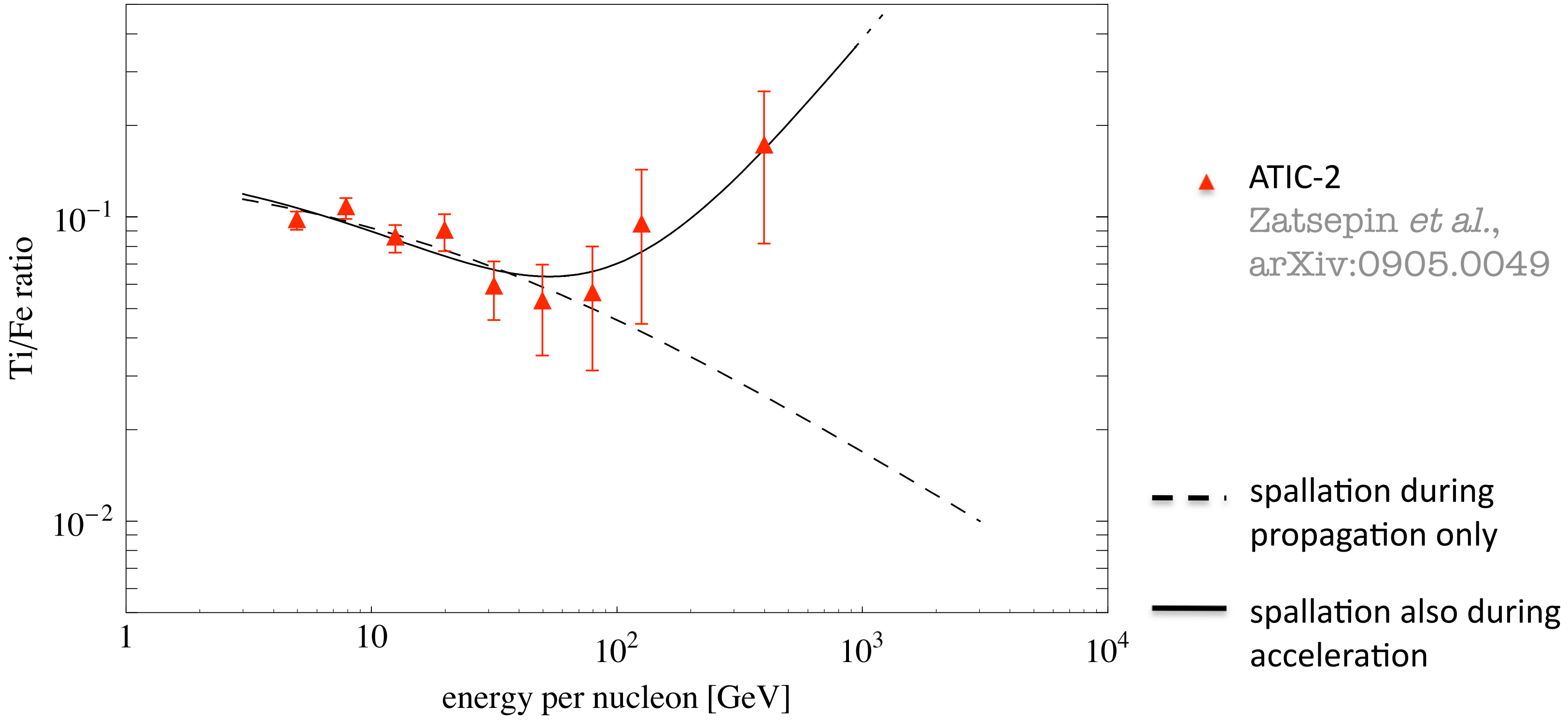
Explanations for PAMELA Excess

rise in…	e^+/e^-	$\bar{p}/p$	nuclei
DM	✓	(✓)	✗
Pulsars	✓	✗	✗
Acceleration of Secondaries	✓	✓	✓

Titanium-to-Iron Ratio

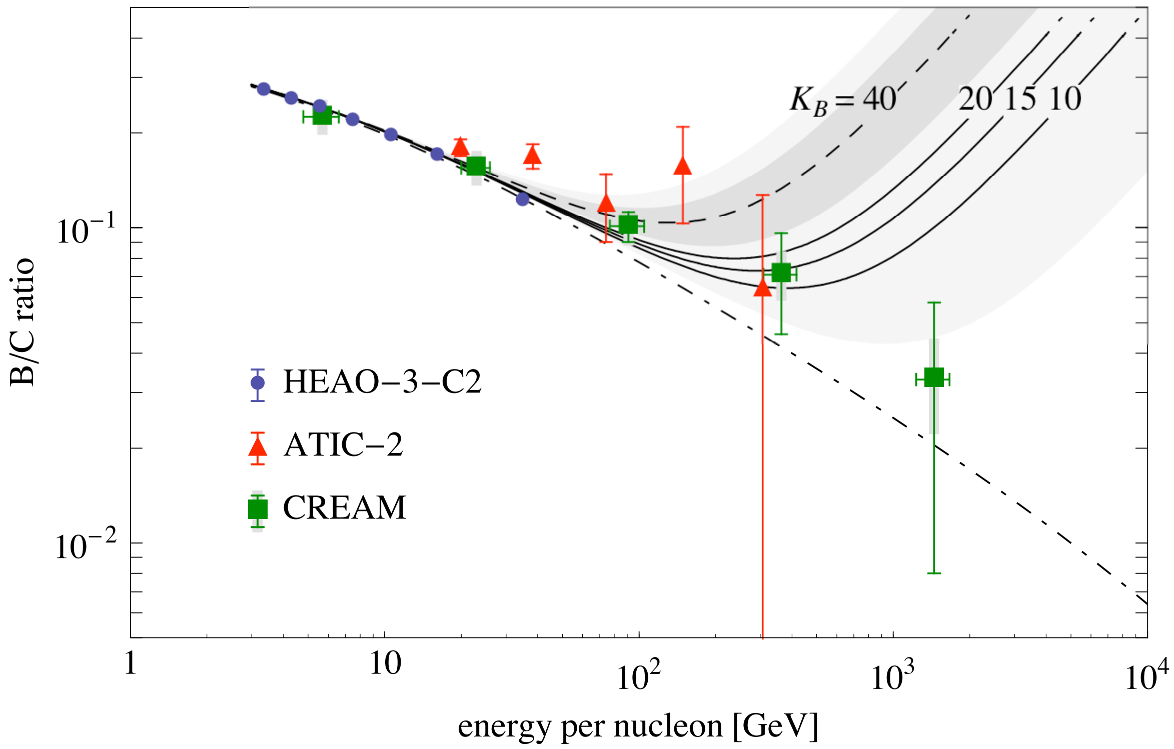

PM and Sarkar, PRL 103 (2009) 081104

Titanium-to-iron ratio used as calibration point for diffusion coefficient:

$$K_{\mathrm{B}} \simeq 40$$

Boron-to-Carbon Ratio

PM and Sarkar, PRL 103 (2009) 081104



● HEAO-3
Engelmann *et al.*,
A&A 233, 96 (1990)

▲ ATIC-2
Panov *et al.*, ICRC 2007

■ CREAM
Ahn *et al.*, Astropart.
Phys. 30, 133 (2008).

– · – spallation during
propagation only

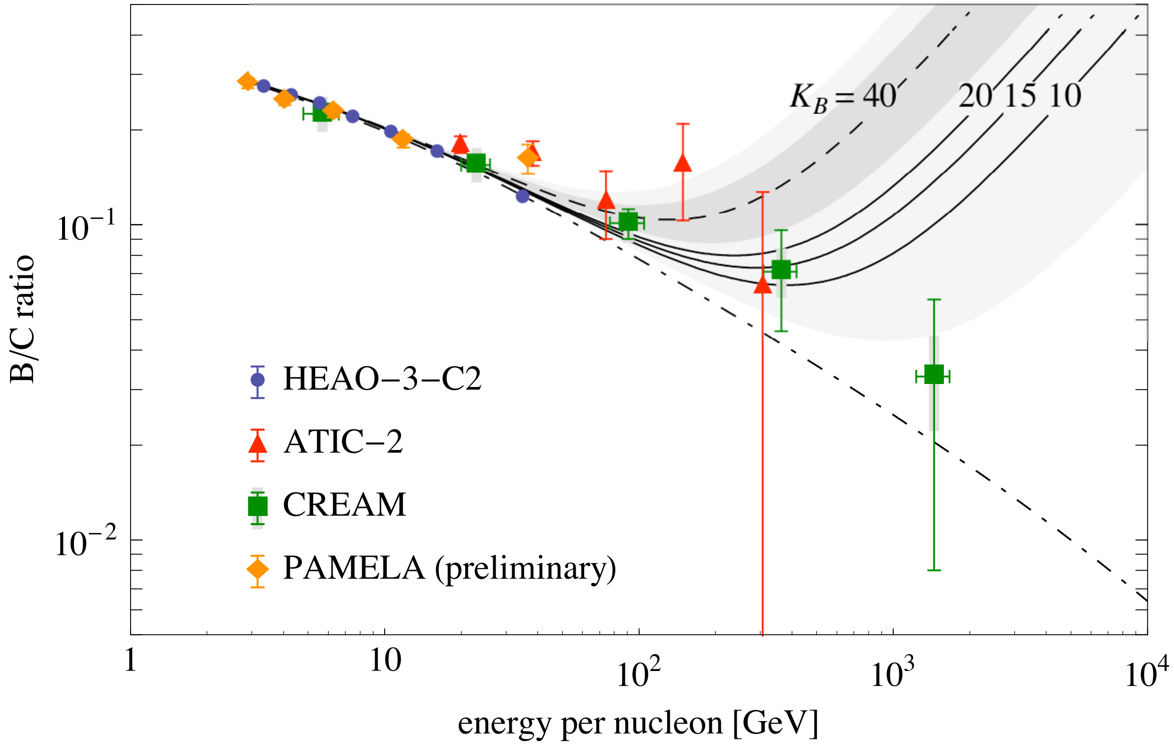
— / – – spallation also during
acceleration

PAMELA is currently measuring B/C with unprecedented accuracy

A rise would rule out the DM and pulsar explanation of the PAMELA e^+/e^- excess.

Boron-to-Carbon Ratio

PM and Sarkar, PRL 103 (2009) 081104



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- · - spallation during
propagation only

— spallation also during
- - acceleration

PAMELA is currently measuring B/C with unprecedented accuracy

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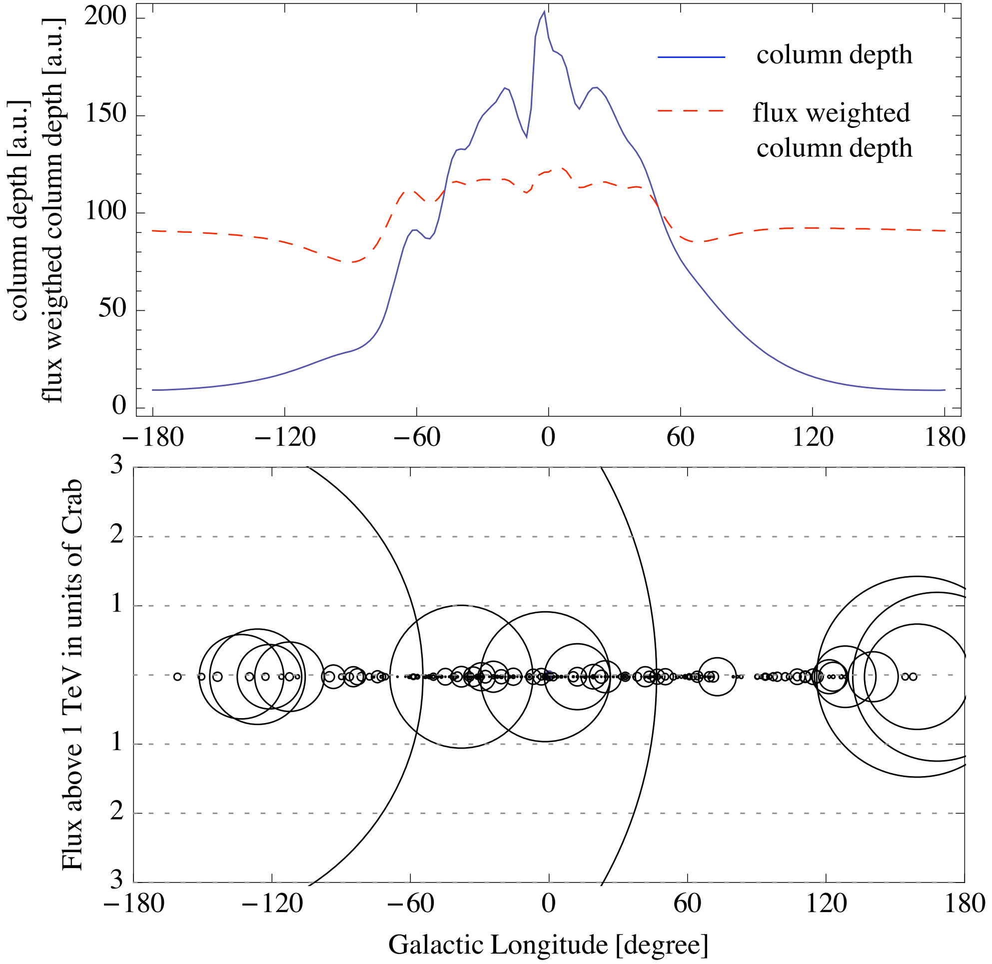
Hint at Hadronic SNRs



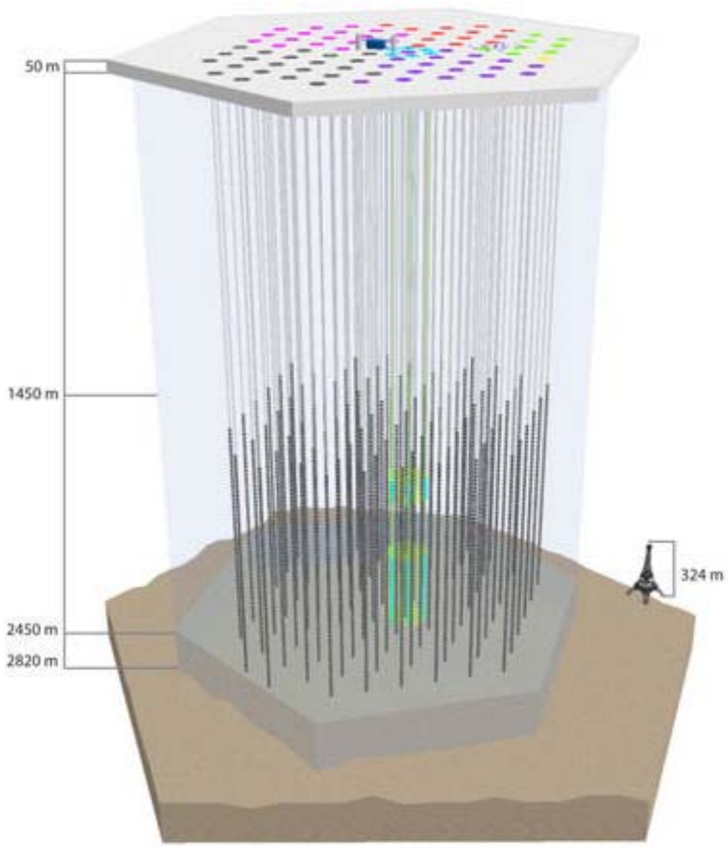
Maximum column depth around galactic centre

However brightness only smaller by 30% in rest of sky

on average:

- 3 sources brighter than Crab
- 7 sources brighter than 50% Crab

Prospects for IceCube



Flux from SNR at 2 kpc with Γ=2.4 and above normalisation:

$$F_{\nu_\mu}(> 3\ \mathrm{TeV}) \simeq 7 \times 10^{-13} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

To be compared with IceCube (22 strings) point source limit (90% CL upper limit on muon neutrino flux for energies between 3 TeV and 3 PeV):

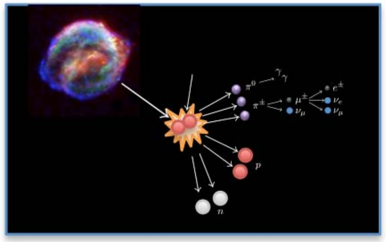
$$F_{\nu_\mu} \leq 4.7 \times 10^{-12} \mathrm{cm}^{-2} \mathrm{s}^{-1}$$

However, E^{-2} point source with

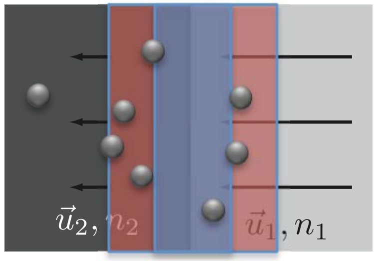
$$F_{\nu_\mu} \simeq 7.2 \times 10^{-12} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

can be detected in full IceCube (80 strings) with 5σ significance in 3 years .

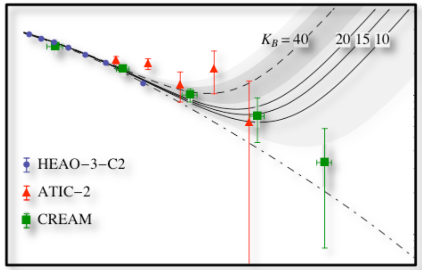
Summary



1. Background for secondary-to-primary ratios in Leaky Box Model



2. Acceleration of secondary positrons and electrons in source explains both PAMELA and Fermi LAT/HESS data



3. Nuclear secondary-to-primary ratios as a unique test of this model