

# On cosmic ray acceleration in supernova remnants and the FERMI/PAMELA data

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Focus Week on Indirect Dark Matter Searches

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Science & Technology  
Facilities Council

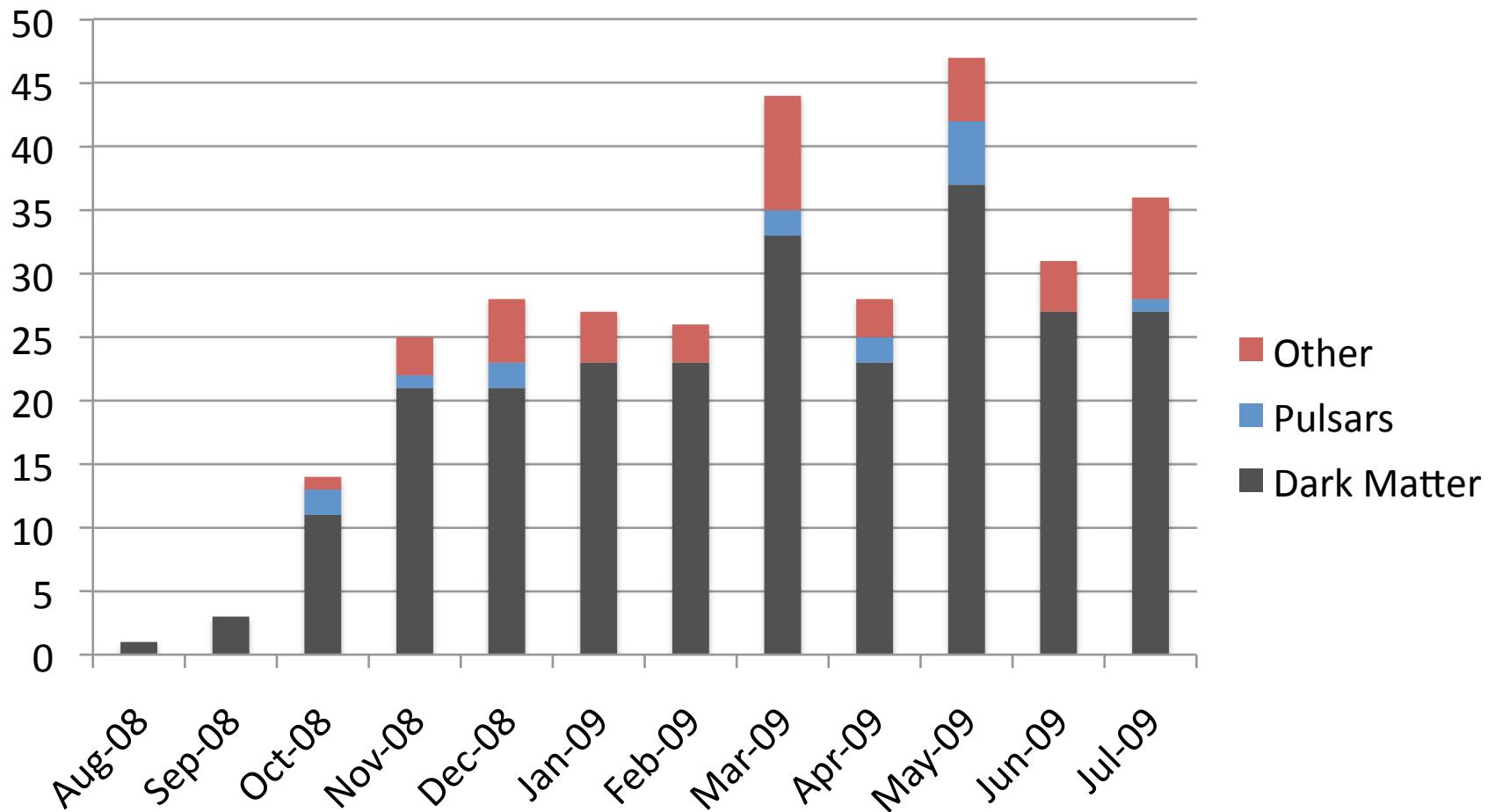


SIXTH FRAMEWORK PROGRAMME

# Huge Interest in CR Physics

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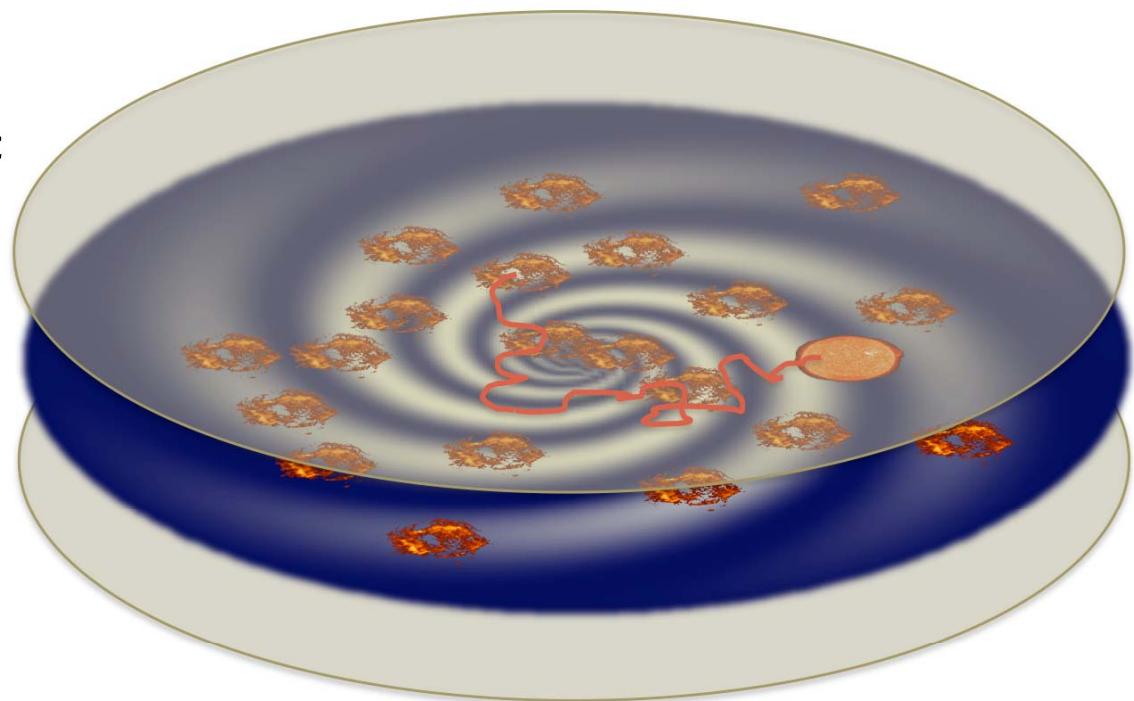
Citations of Adriani *et al. Nature* **458**, 607-609 (2009)



# The Standard Picture of GCRs

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1. Sources of GCRs are localised SNRs
  2. Injection of GCRs with power law spectrum
  3. Diffusion through Galactic halo due to presence of turbulent magnetic field
  4. Secondary production during propagation:  
 $e^\pm, \gamma, \nu, N$  etc.
  5.  $e^\pm$  loose energy through synchrotron and ICS
- ⇒ { primaries:  $p, e^-, N$   
secondaries:  $\bar{p}, e^+, N'$   
 $\gamma$ -rays, synchrotron



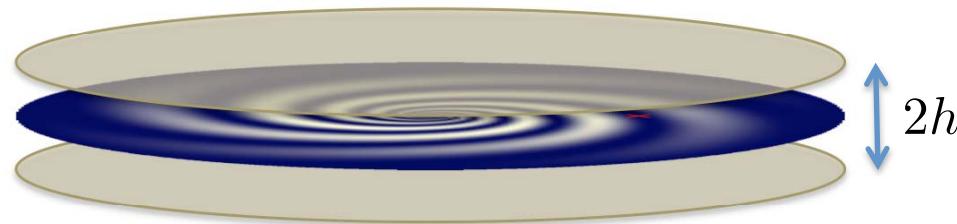
# Diffusion of GCRs

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Transport equation:

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

Boundary conditions:



Green's function:

describes flux from one discrete, burst-like source

# The Leaky Box Model

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Transport equation:

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

Averaging over extended CR halo; steady state solution

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

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

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

# Energy Spectra

**primary  $e^-$**

— production:  $q \propto E^{-2.2}$

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

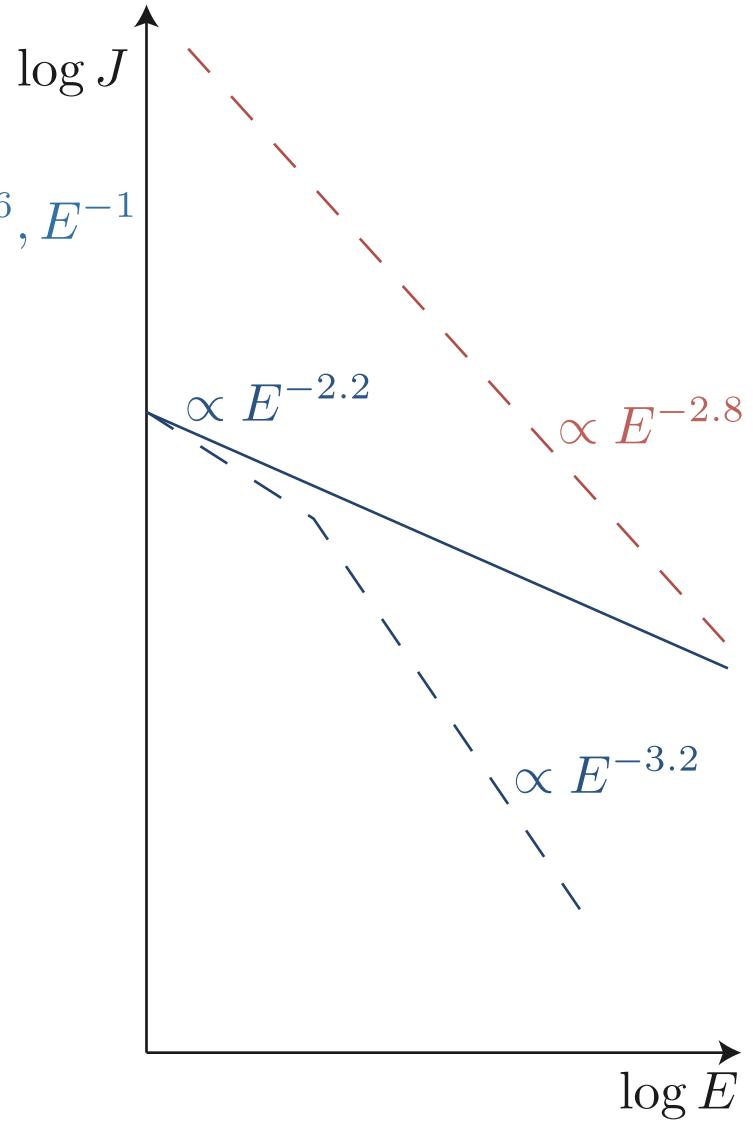
- - - ambient:  $n \propto E^{-2.8}, E^{-3.2}$

**CR protons/nuclei**

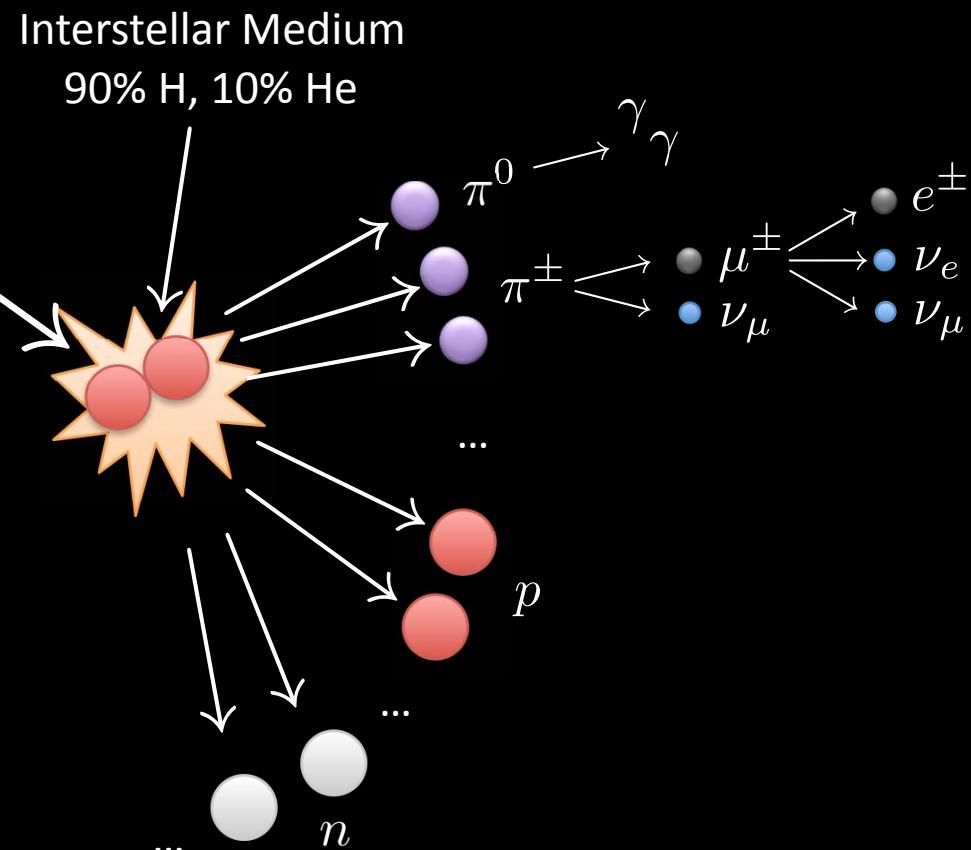
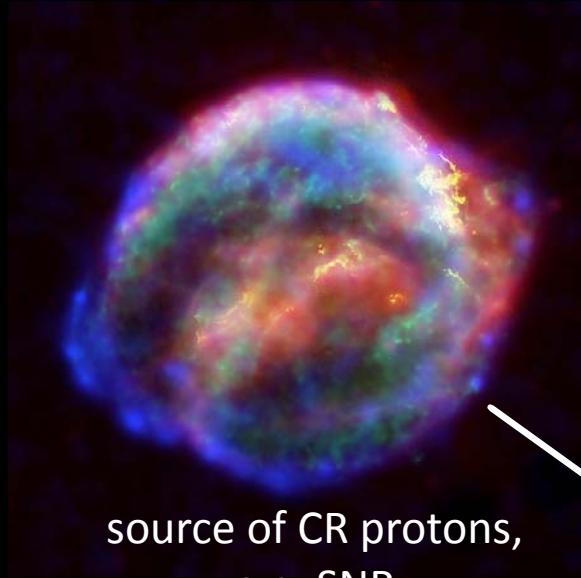
production: ?

propagation: ?

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



# Secondary $e^\pm$ during Propagation



# Energy Spectra

**primary  $e^-$**

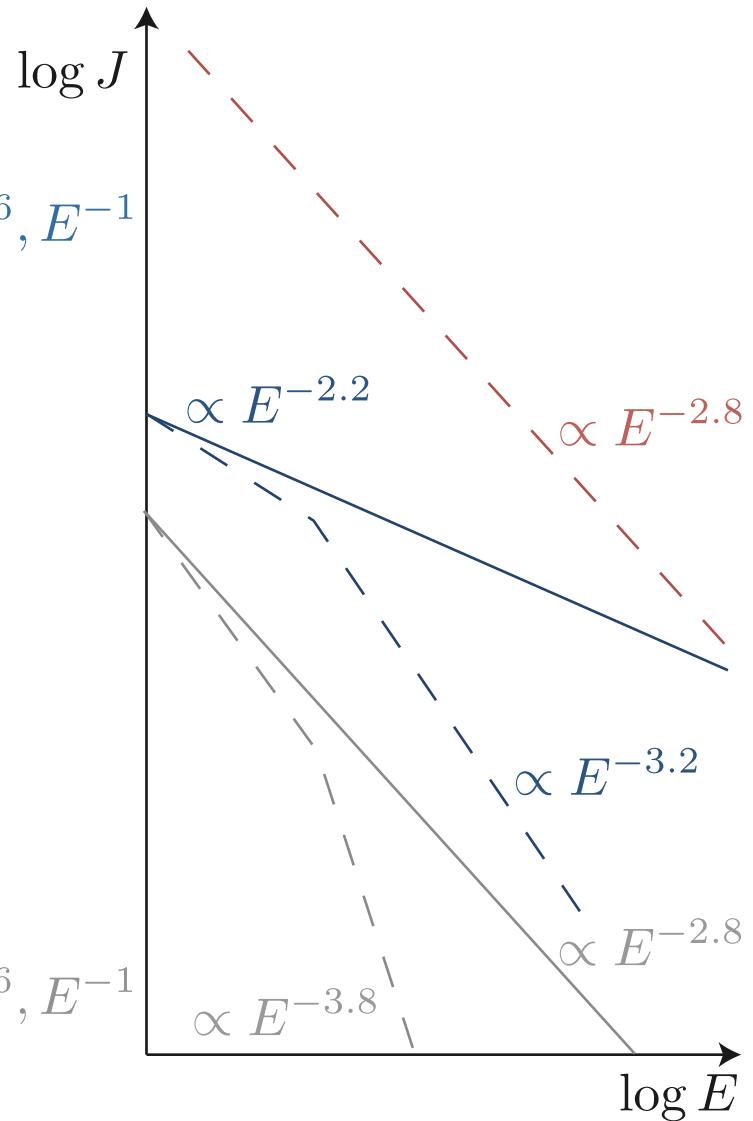
- production:  $q \propto E^{-2.2}$
- propagation:  $\min[\tau_{\text{esc}}, \tau_{\text{cool}}] \propto E^{-0.6}, E^{-1}$
- - - ambient:  $n \propto E^{-2.8}, E^{-3.2}$

**CR protons/nuclei**

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

**secondary  $e^\pm$**

- production:  $q \propto E^{-2.8}$
- propagation:  $\min[\tau_{\text{esc}}, \tau_{\text{cool}}] \propto E^{-0.6}, E^{-1}$
- - - ambient:  $n \propto E^{-3.4}, E^{-3.8}$



# The PAMELA Anomaly

PAMELA has measured positron fraction,

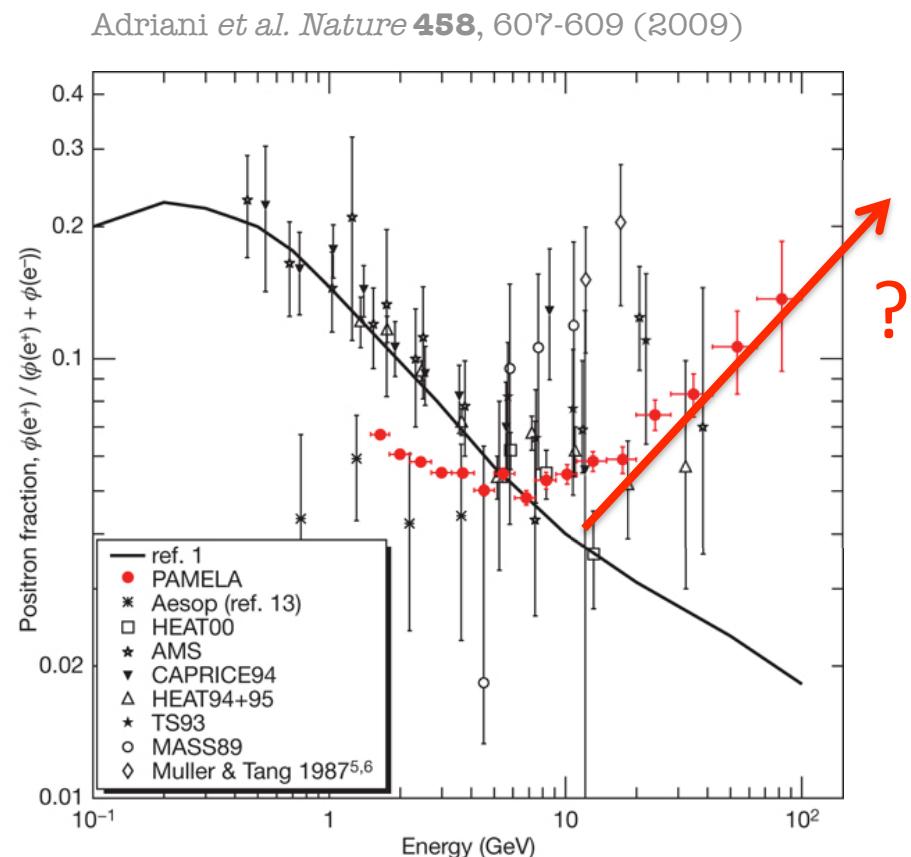
$$\frac{J_{e^+}}{J_{e^-} + J_{e^+}}$$

theoretical prediction:

$$\propto E^{-0.4 \dots 0.8}$$

data:

rise above a few GeV



Anomalous rise

# *FERMI* The ATIC Excess

theoretical prediction:

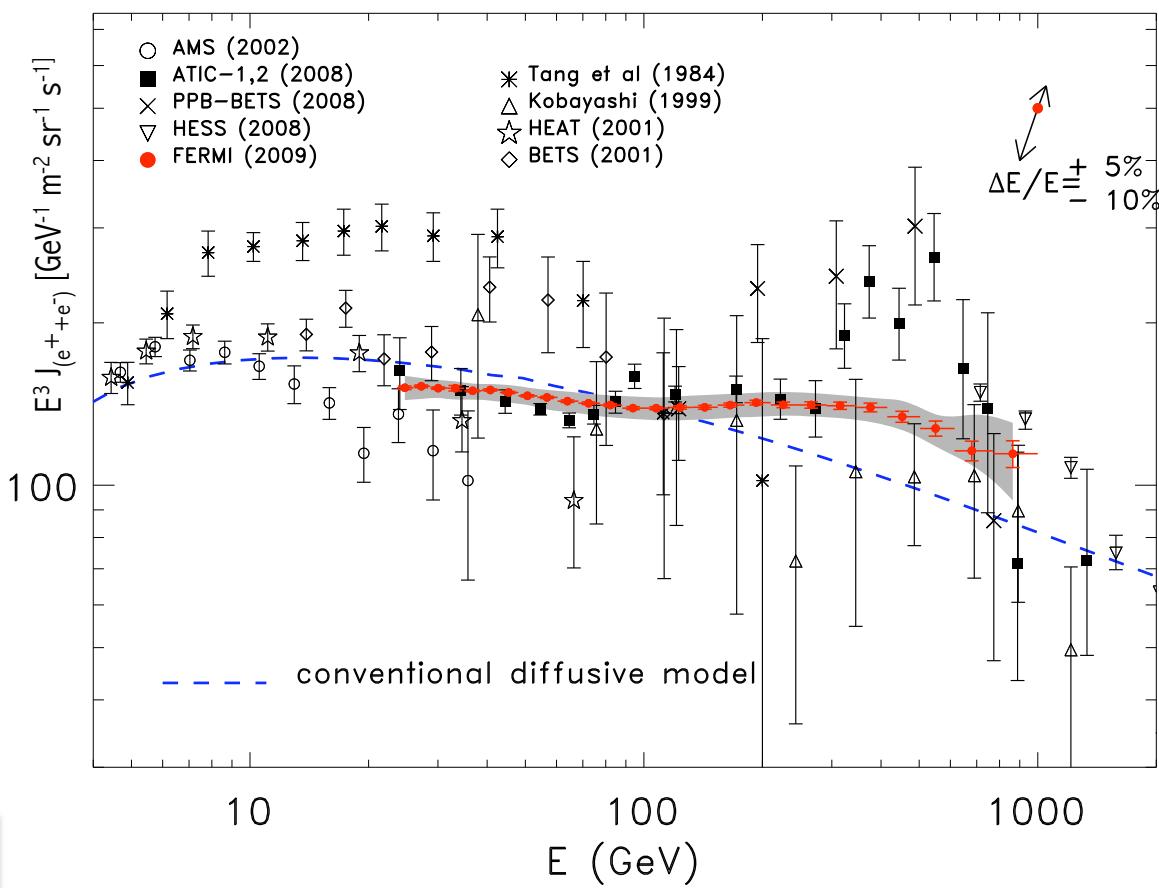
$$\propto E^{-3.2 \dots 3.5}$$

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

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

HESS:

spectral hardening  
at 1 TeV



Excess between  
~100 GeV and ~1 TeV

# Secondary Origin of $e^\pm$

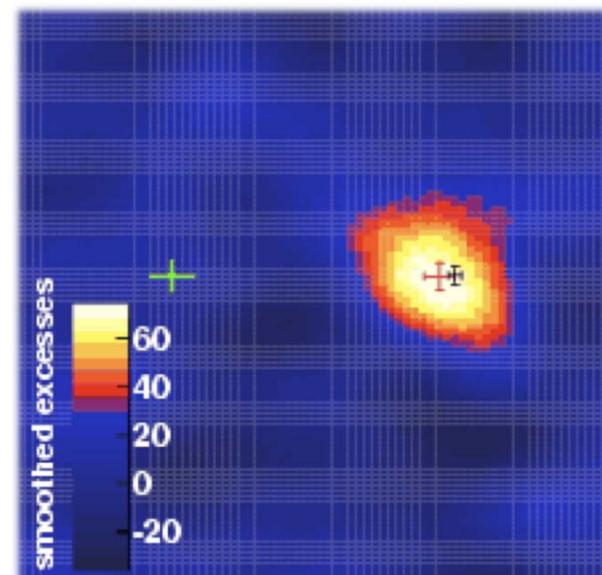
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Rise in positron fraction could be due to secondary positrons produced during acceleration and accelerated along with primary electrons

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  $\gamma$ -rays from MAGIC

# DSA – Test Particle Approximation

Consider flux

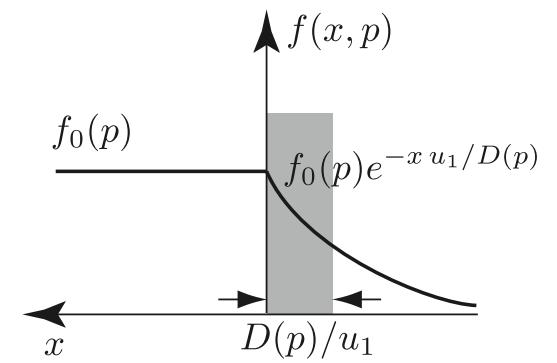
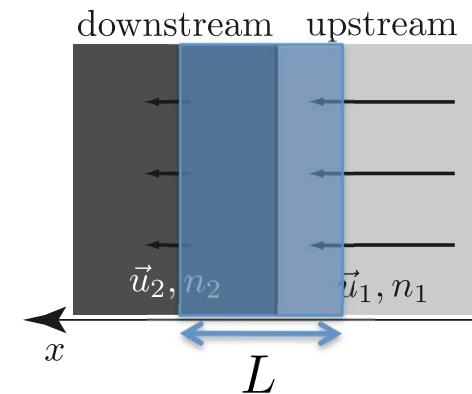
$$\Phi(p) = \int d^3x \frac{4\pi p^2}{3} f(p) (-\nabla \cdot \vec{u})$$

Conservation equation:

$$\underbrace{\frac{\partial}{\partial t} (4\pi p^2 f^0(p)L)}_{\text{change in density}} + \underbrace{\frac{\partial \Phi}{\partial p}}_{\text{acceleration}} = \underbrace{-4\pi p^2 f^0(p) u_2}_{\text{convection}} + Q(p) \underbrace{\downarrow}_{\text{injection}}$$

One finds:

$$\begin{aligned} \frac{u_1 - u_2}{3} p \frac{\partial f}{\partial p} + u_1 f &= 0 \\ \Rightarrow f(p) &\propto p^{-3u_1/(u_1 - u_2)} = p^{-\gamma} \end{aligned}$$



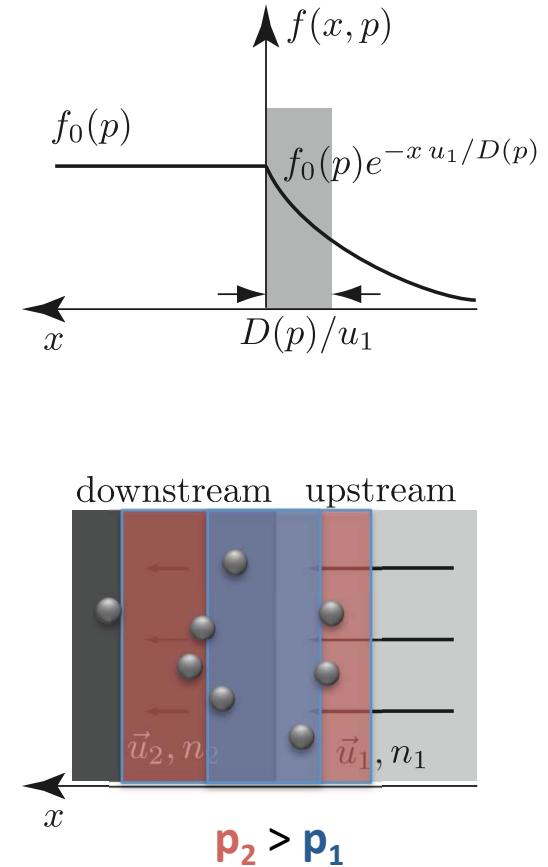
# DSA with Secondaries

- Secondaries get produced with primary spectrum:

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

- Only particles with  $|x| \lesssim D(p)/u$  can be accelerated
- Bohm diffusion:  $D(p) \propto p$
- Fraction of secondaries that go into acceleration  $\propto p$
- Equilibrium spectrum

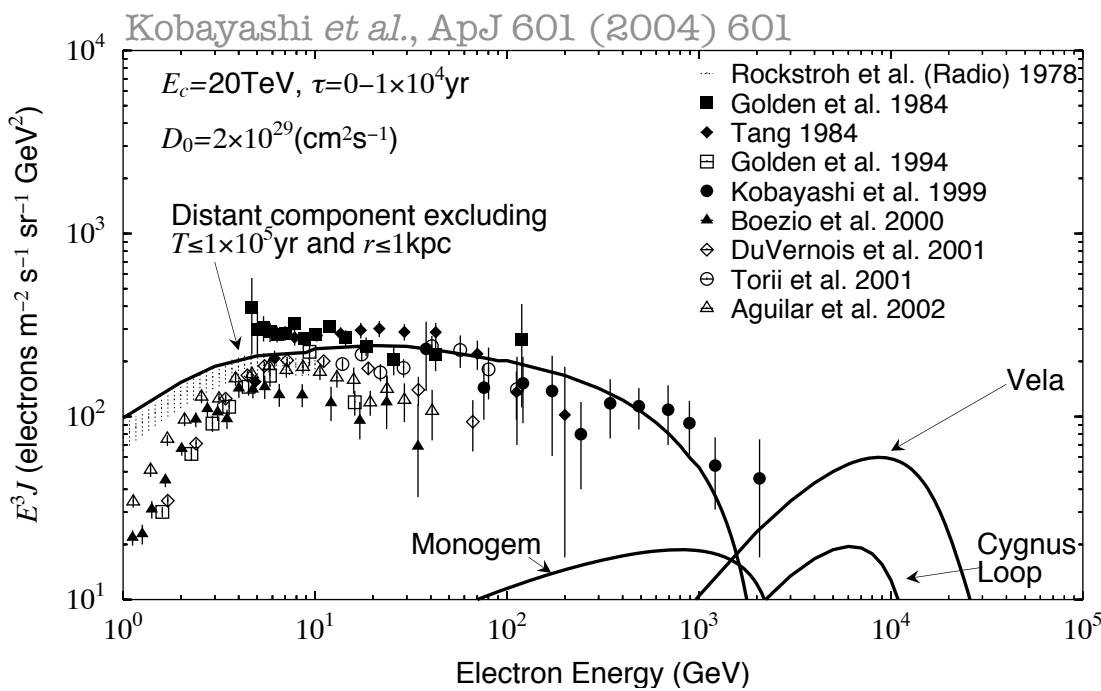
$$n_{e^\pm} \propto q_{e^\pm} \left(1 + \frac{p}{p_0}\right) \propto p^{-\gamma} + p^{-\gamma+1}$$



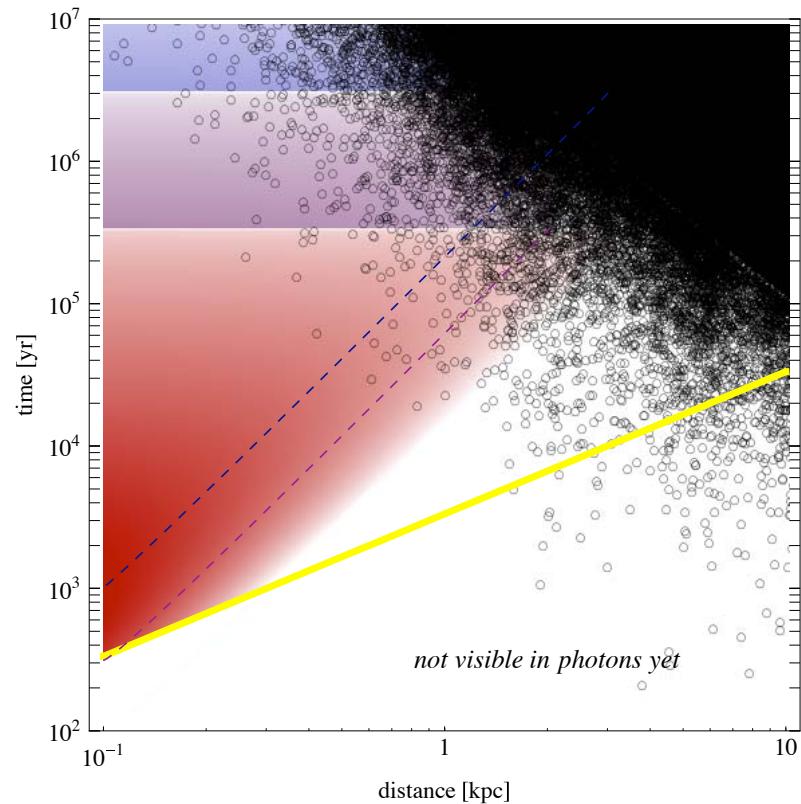
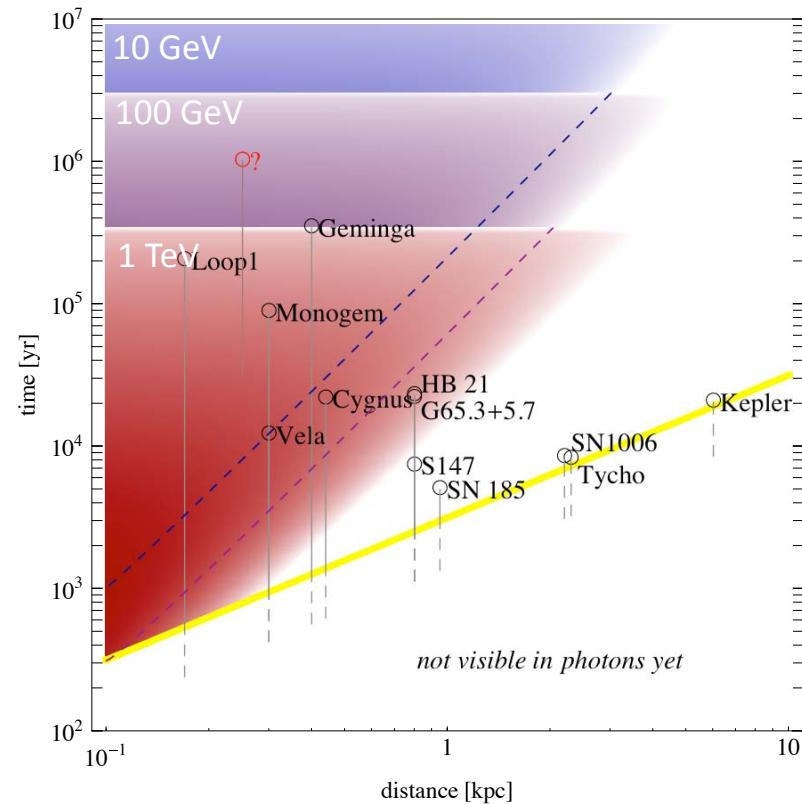
Rising positron fraction  
at source

# The Discreteness of Sources

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

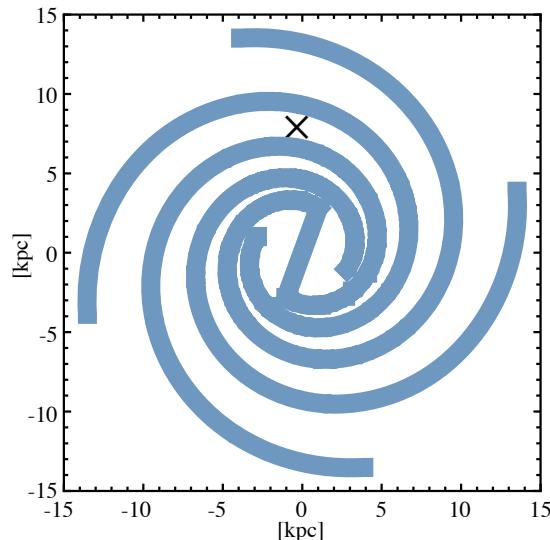


# A Caveat

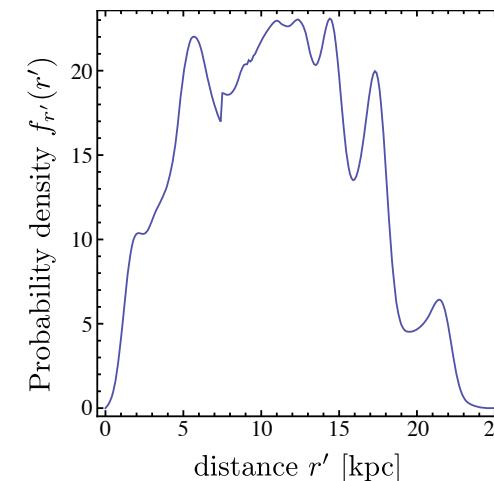
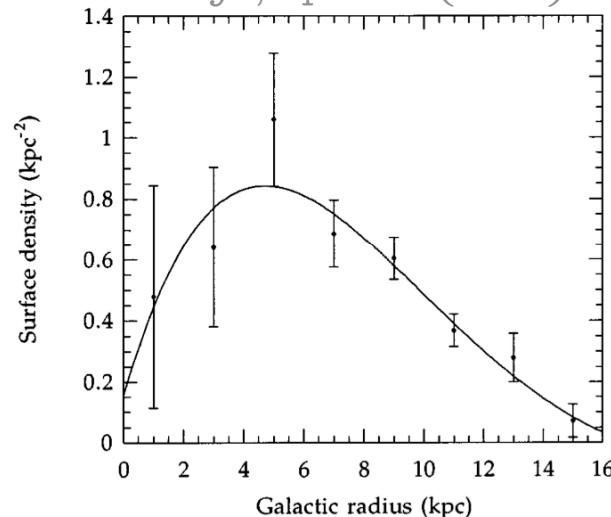


Not only observed  
sources contribute!

# 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, arXiv0909.4060

# Normalising the Source Spectra

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

normalisation of secondary  $e^\pm$ :  $p + p \rightarrow \begin{cases} \pi^0 + \dots & \rightarrow 2\gamma + \dots \\ \pi^\pm + \dots & \rightarrow e^\pm + \dots \end{cases}$

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

# Diffusion Coefficient

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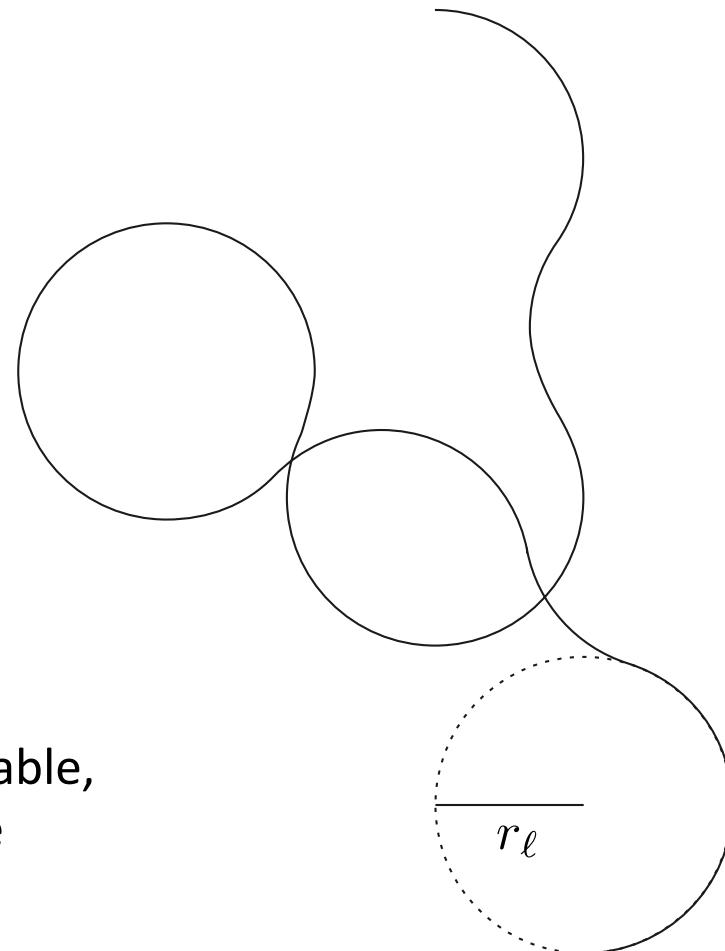
- Diffusion coefficient not known *a priori*
- Bohm diffusion sets lower limit

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

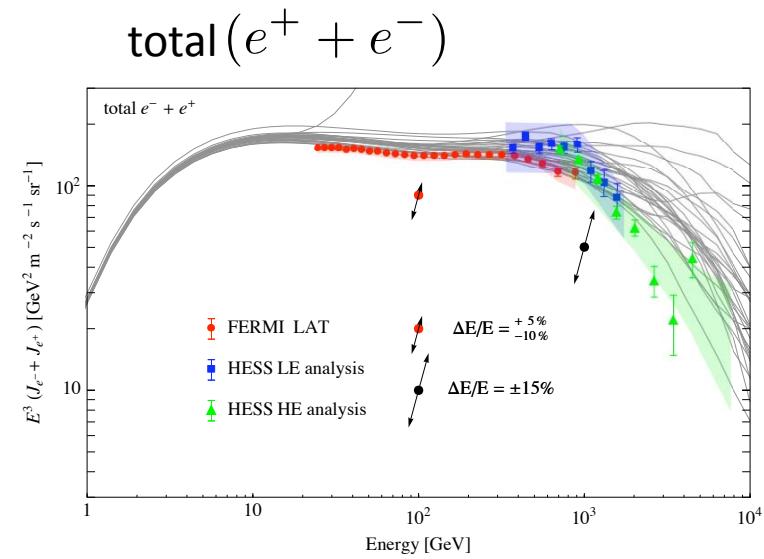
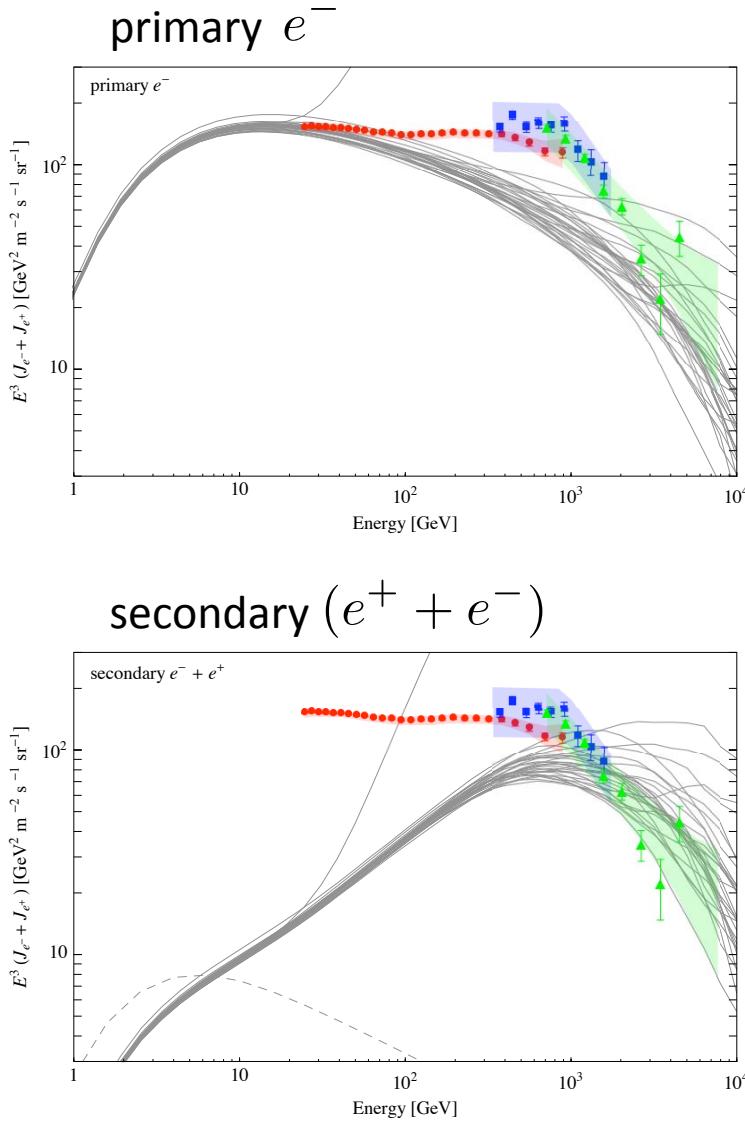
- Difference parametrised by fudge factor  $K_B$

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

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

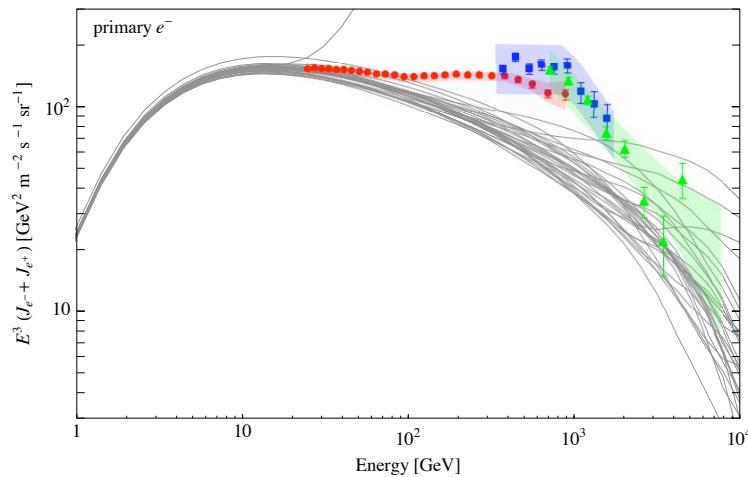


# The Total ( $e^+ + e^-$ ) Flux

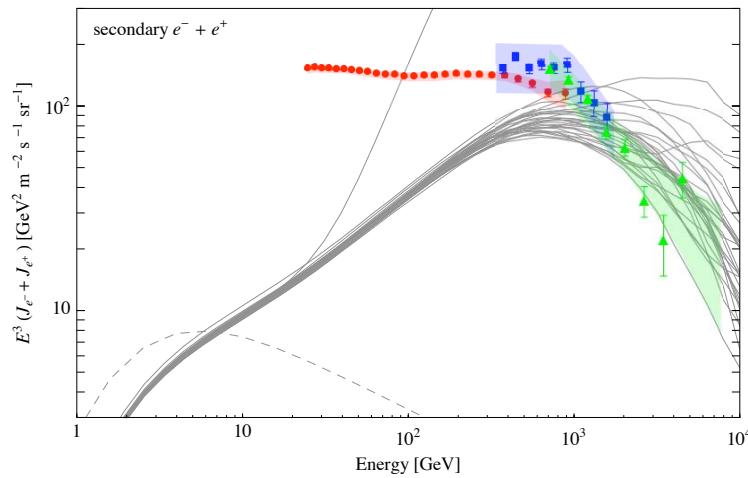


# The Total $(e^+ + e^-)$ Flux

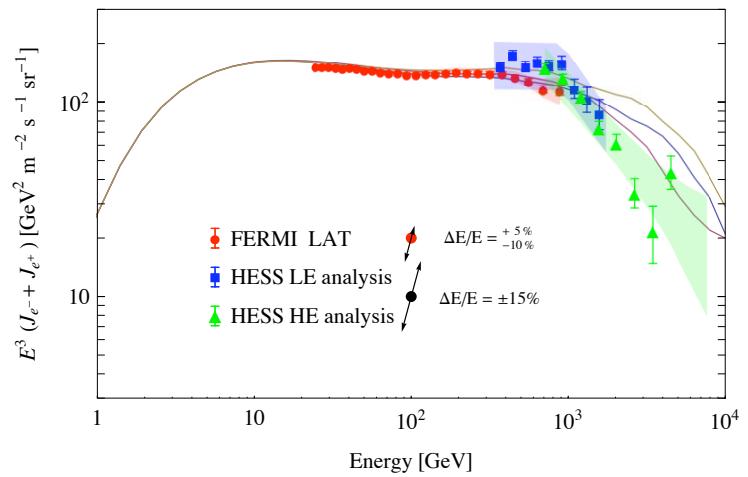
primary  $e^-$



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

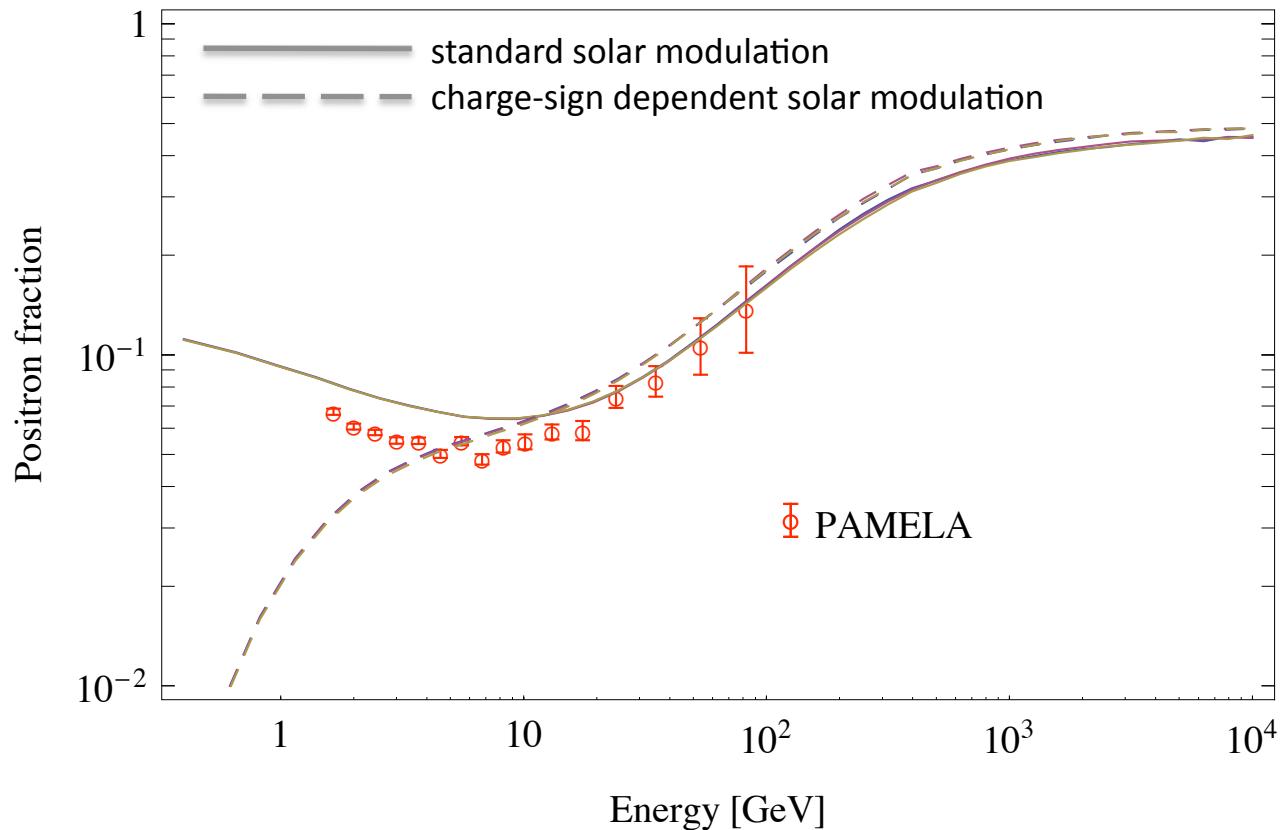


total  $(e^+ + e^-)$



# The Positron Fraction

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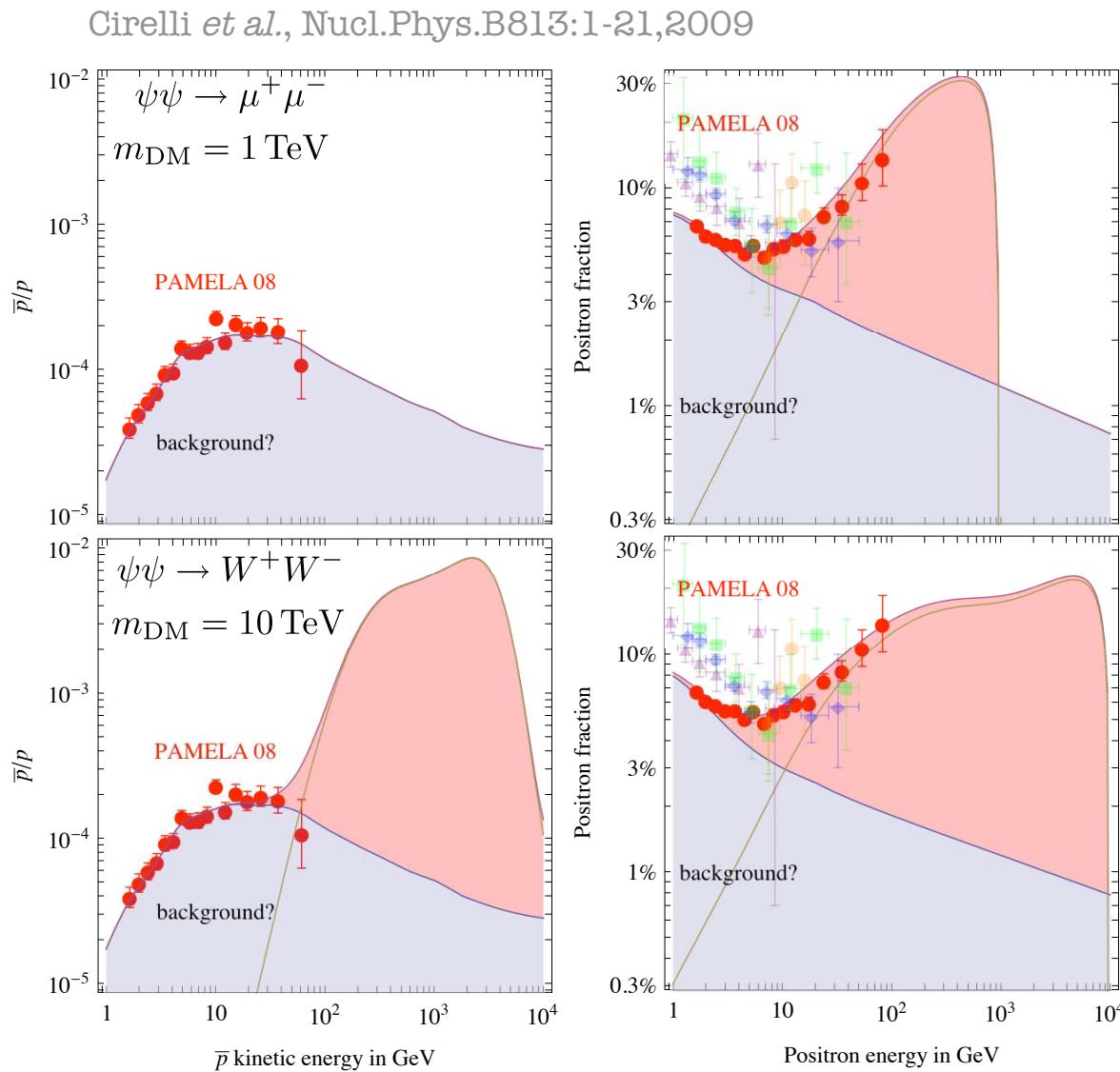
# Explanations for PAMELA Excess

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

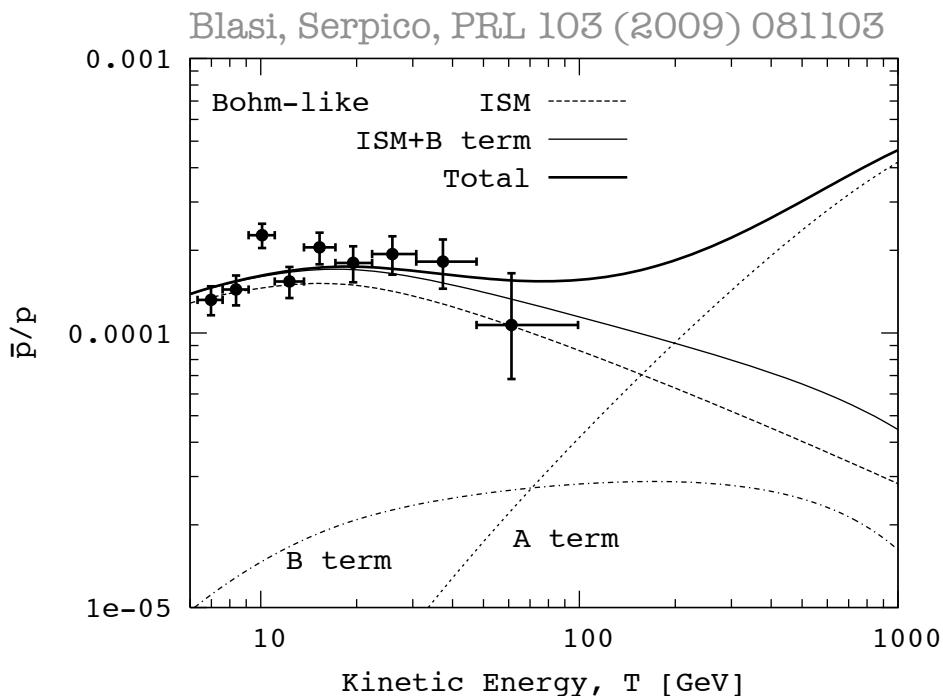
# Antiproton-to-proton Ratio

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



# Antiproton-to-proton Ratio

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

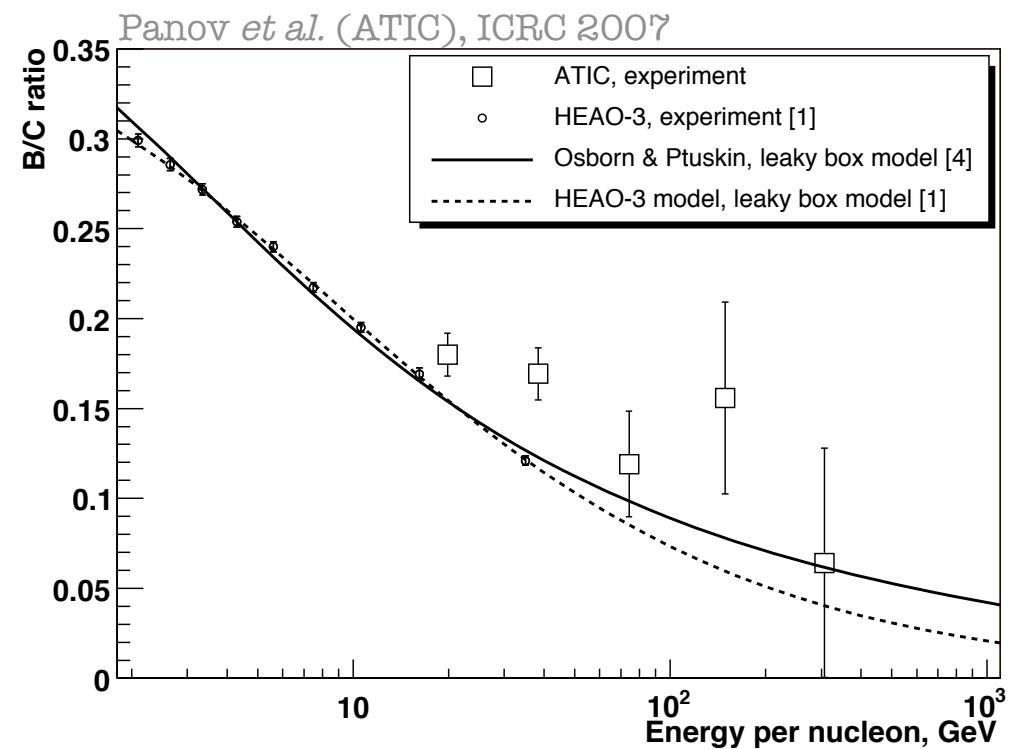


# Nuclear Secondary-to-Primary Ratios

rise in...	nuclei
DM	X
Pulsars	X

DM and pulsars do not produce nuclei!

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

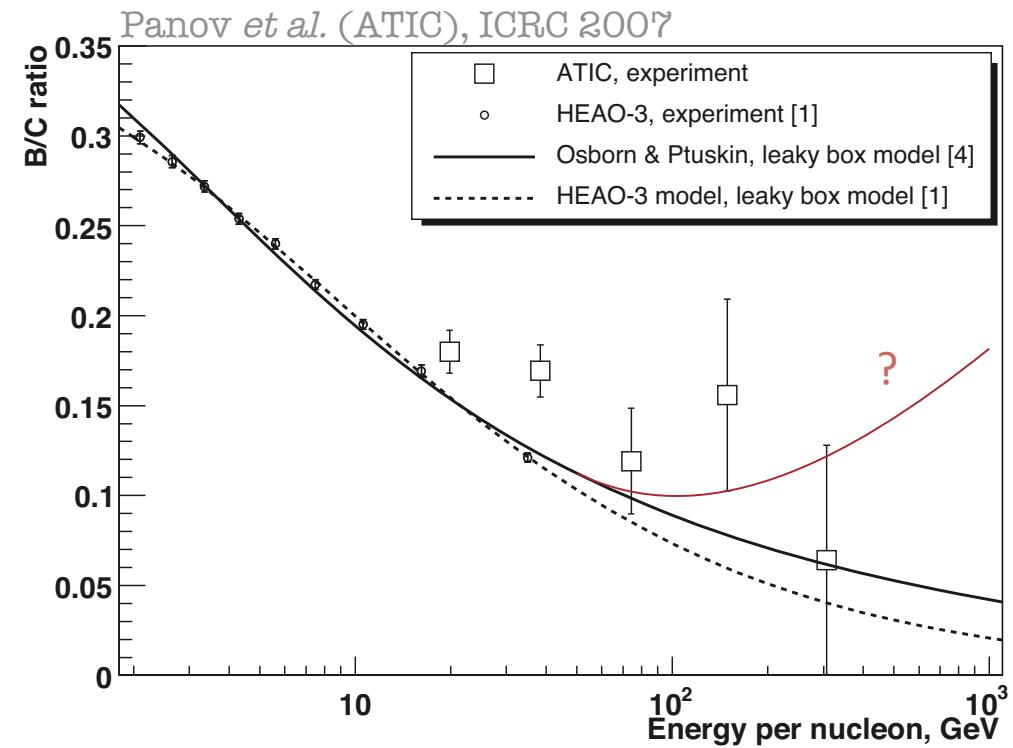


# Nuclear Secondary-to-Primary Ratios

rise in...	nuclei
DM	X
Pulsars	X
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



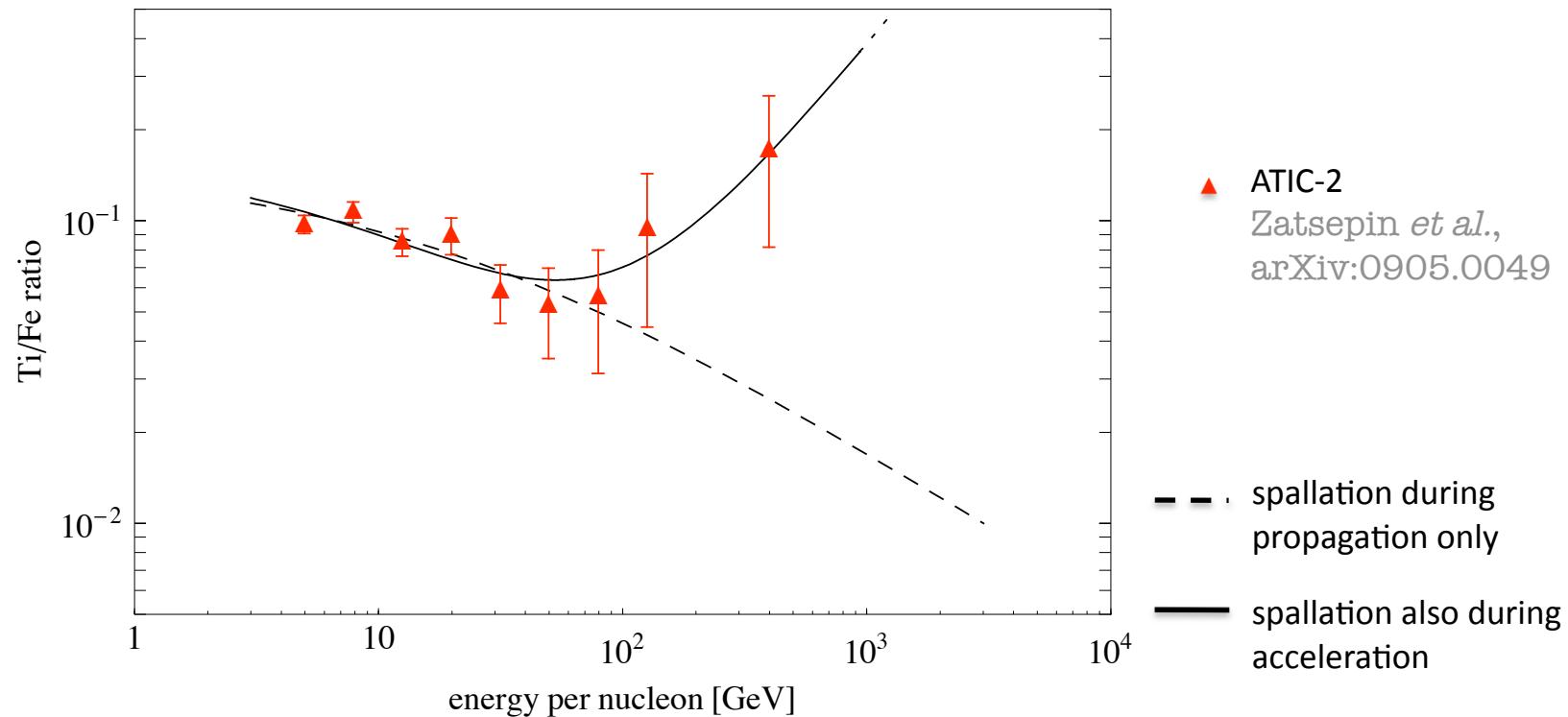
# Explanations for PAMELA Excess

---

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

# Titanium-to-Iron Ratio

PM and Sarkar, PRL 103 (2009) 081104

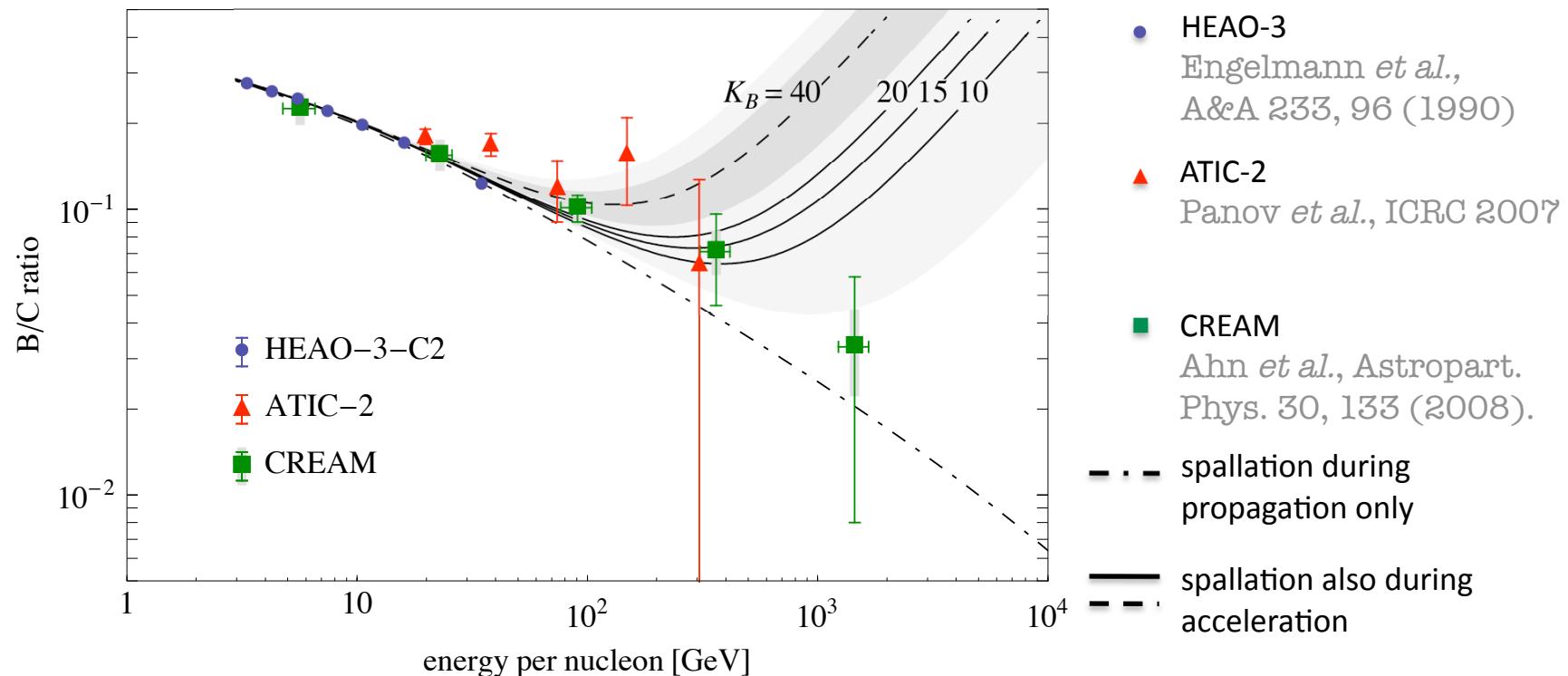


Titanium-to-iron ratio used as calibration point for diffusion coefficient:

$$K_B \simeq 40$$

# Boron-to-Carbon Ratio

PM and Sarkar, PRL 103 (2009) 081104

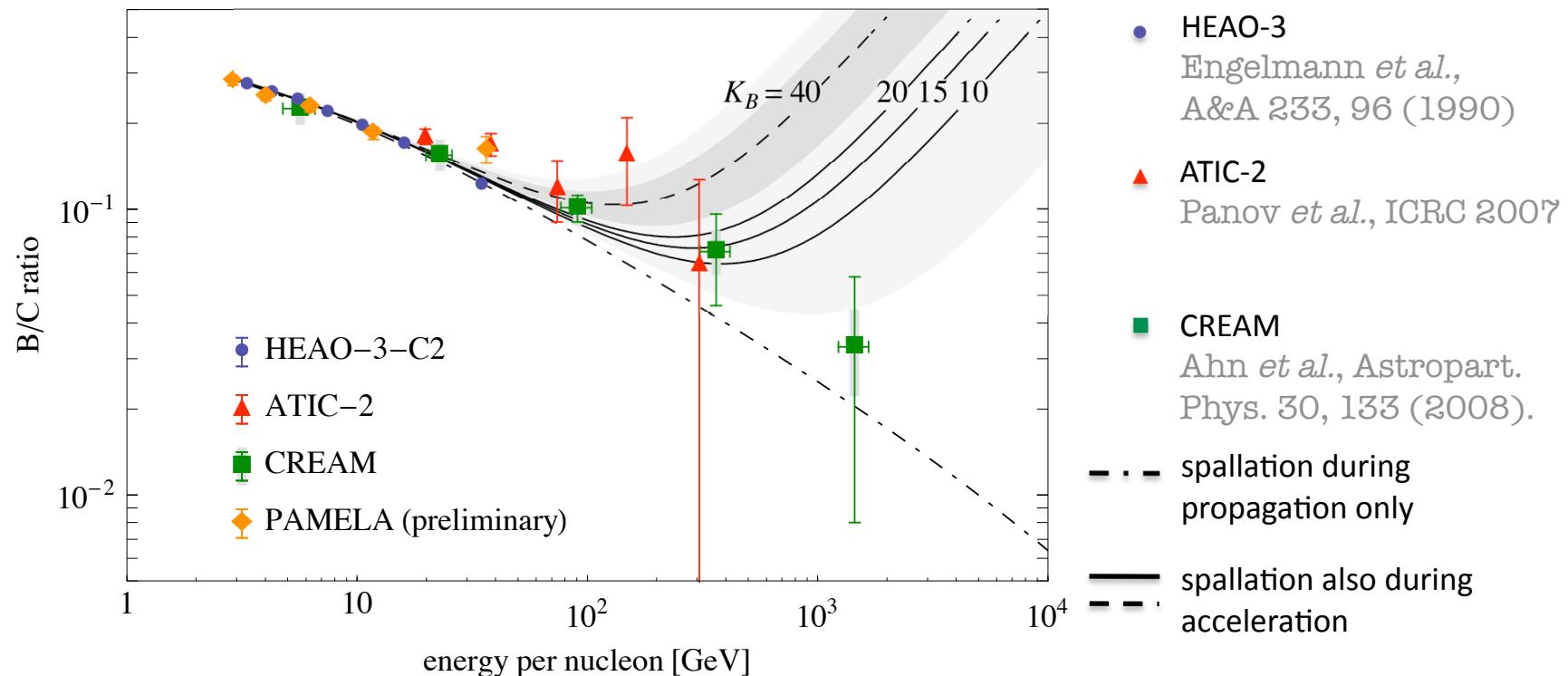


PAMELA is currently measuring B/C with unprecedented accuracy

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

# Boron-to-Carbon Ratio

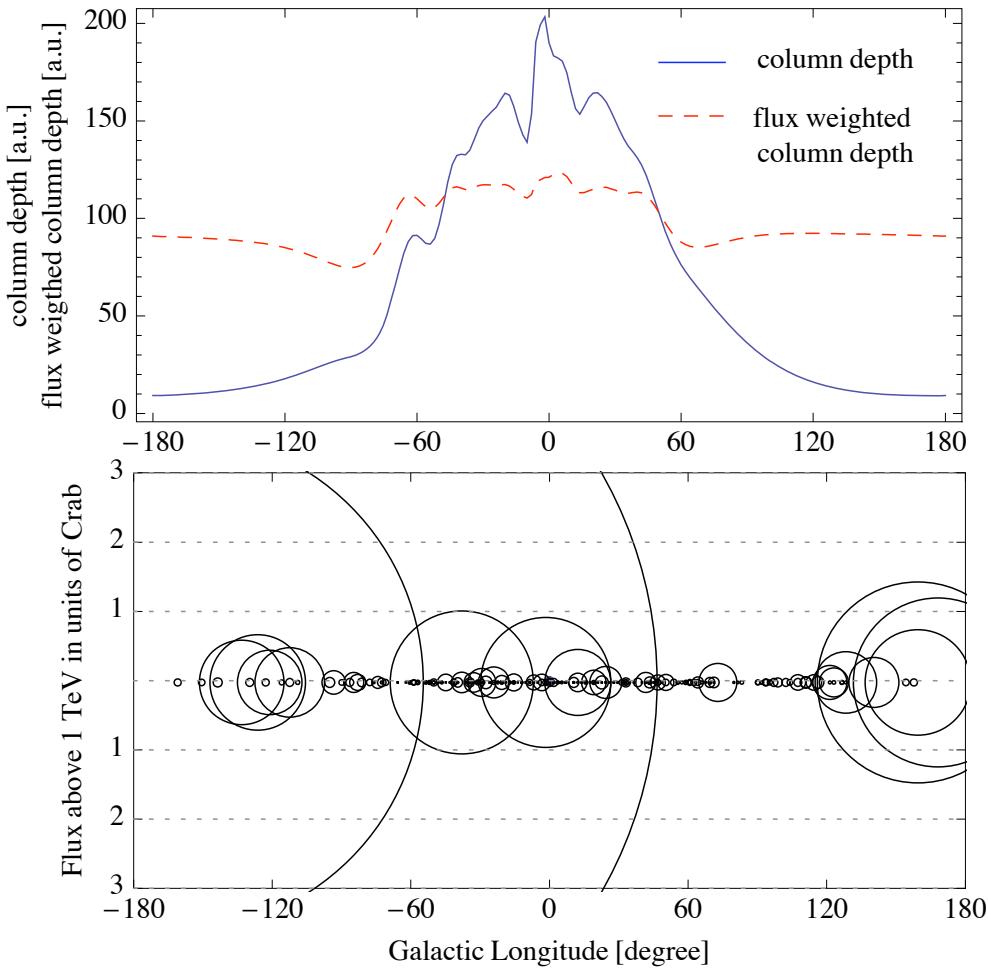
PM and Sarkar, PRL 103 (2009) 081104



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.

# Hint at Hadronic SNRs



Maximum column depth around galactic centre

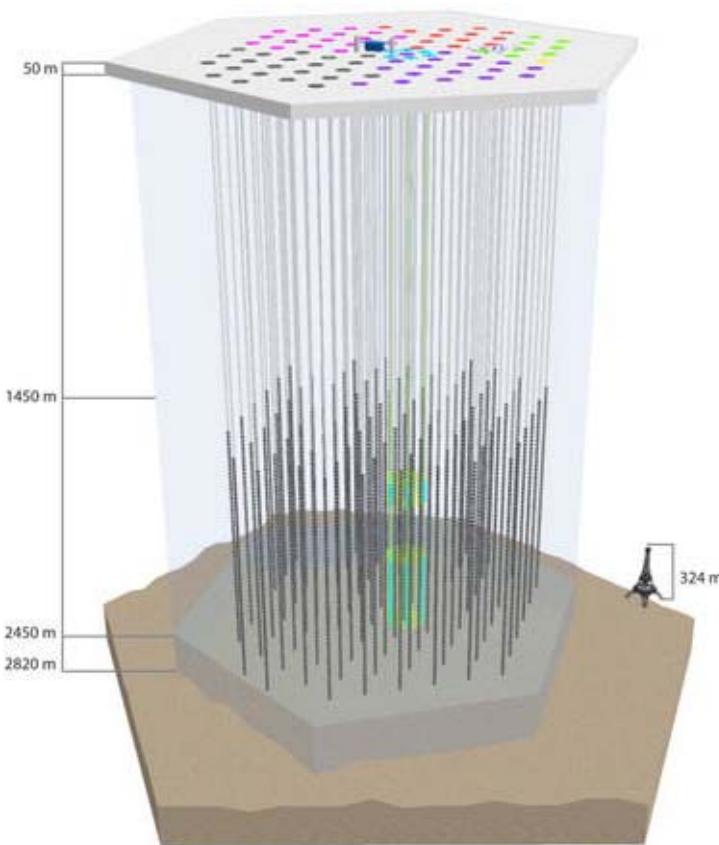
However brightness only smaller by 30% in rest of sky

on average:

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

# Prospects for IceCube

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Flux from SNR at 2 kpc with  $\Gamma=2.4$  and above normalisation:

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

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):

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

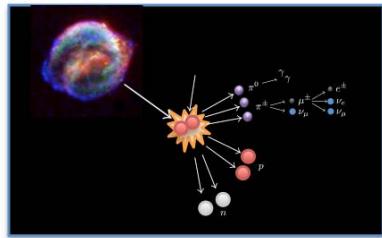
However,  $E^{-2}$  point source with

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

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

# Summary

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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

