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Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

20 - 24 June 2011

The PAMELA/Fermi anomalies and galactic TeV neutrino sources

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The PAMELA & FERMI anomalies and galactic TeV neutrino sources

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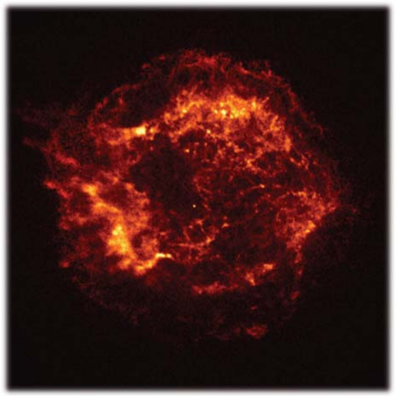
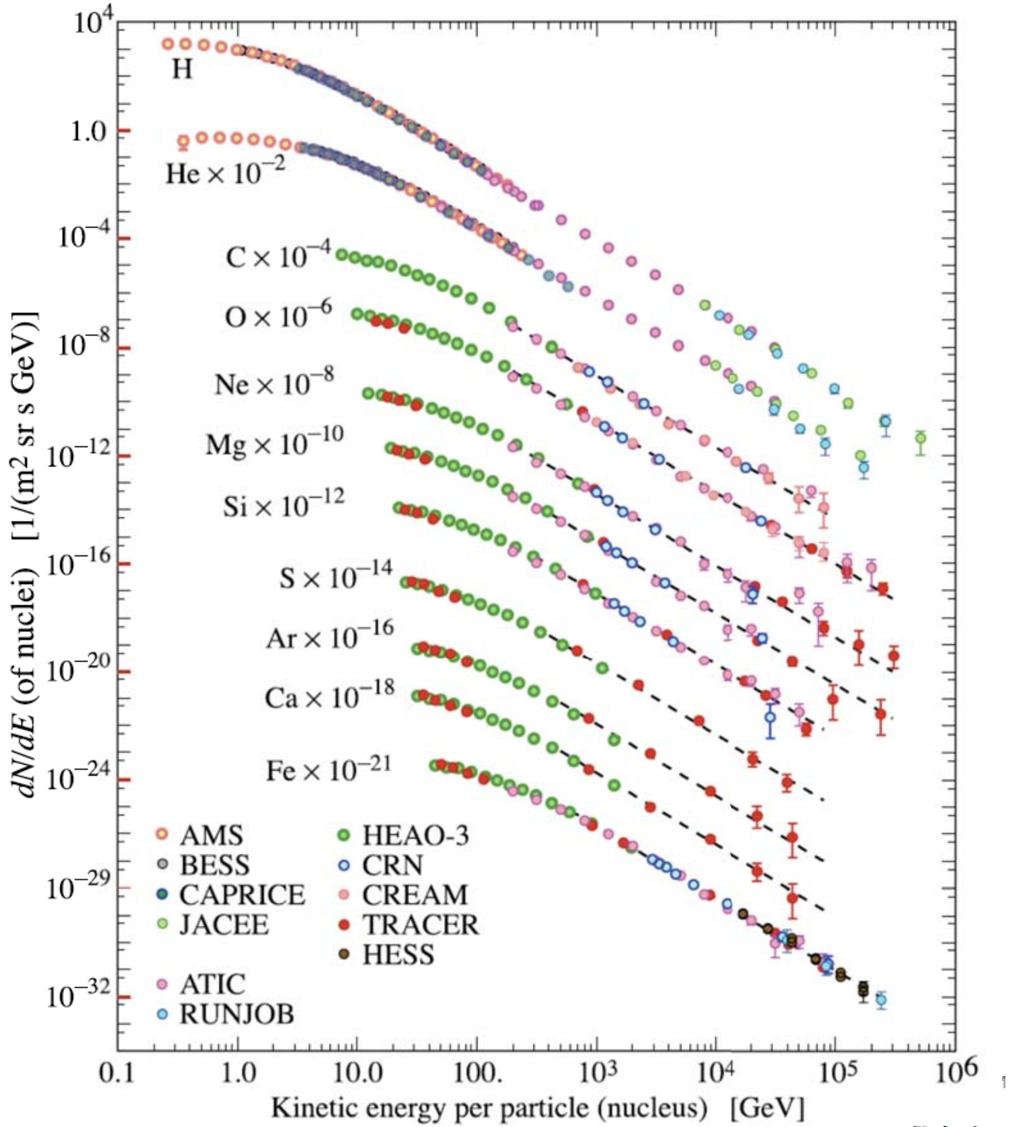
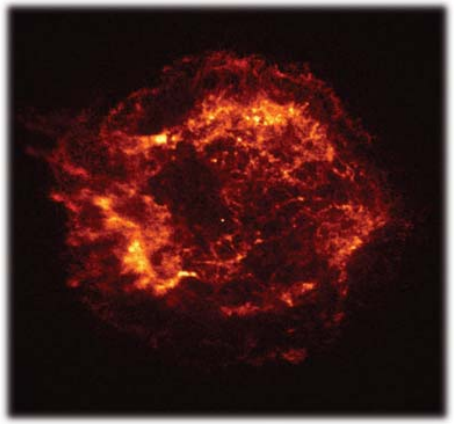
Rudolf Peierls Centre for Theoretical Physics



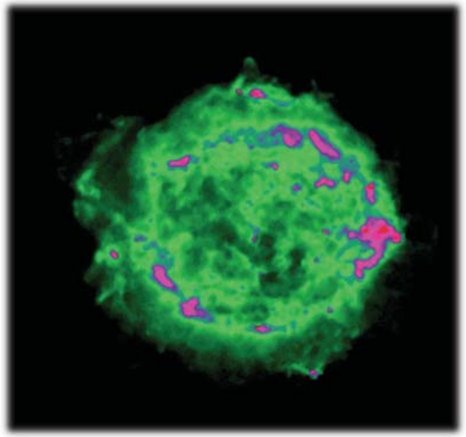
Looking at the neutrino sky, ICTP Trieste, 20-25 June 2011

Supernova remnants are believed to be 'Pevatrons' – responsible for the acceleration of galactic cosmic rays upto the 'knee' at ~few x 10^3 TeV





Cassiopeia A: *Chandra*



Cassiopeia A: *VLA*

If $\mathcal{O}$(10%) of the shock K.E. of ~10^{51} erg can be converted into cosmic rays, then the observed ~3 SN/century can maintain the cosmic ray energy density of ~0.3 eV/cm^3

The *PAMELA* 'anomaly'

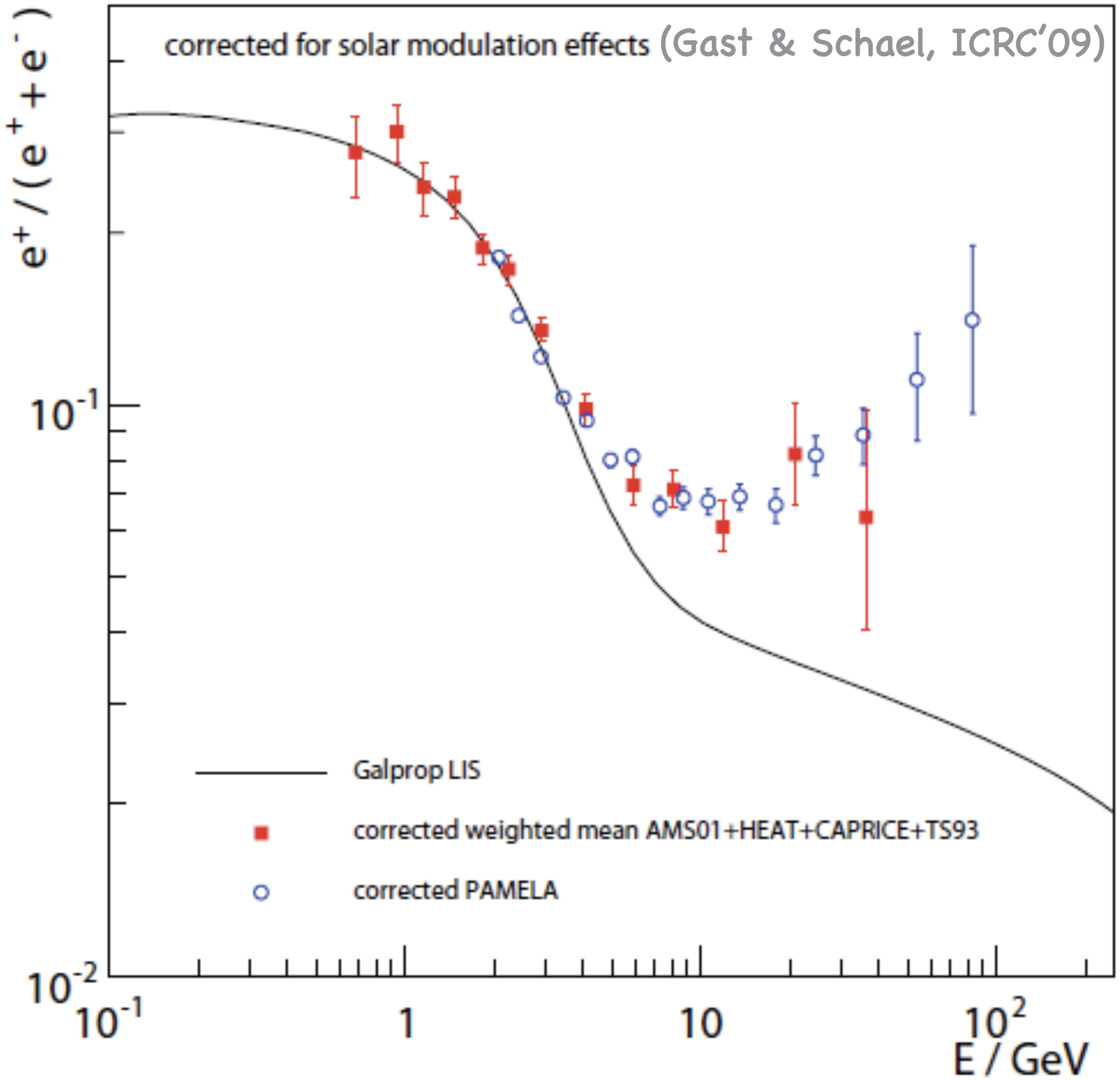
PAMELA has measured the positron fraction:

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

Anomaly $\Rightarrow$ excess above 'astrophysical background'

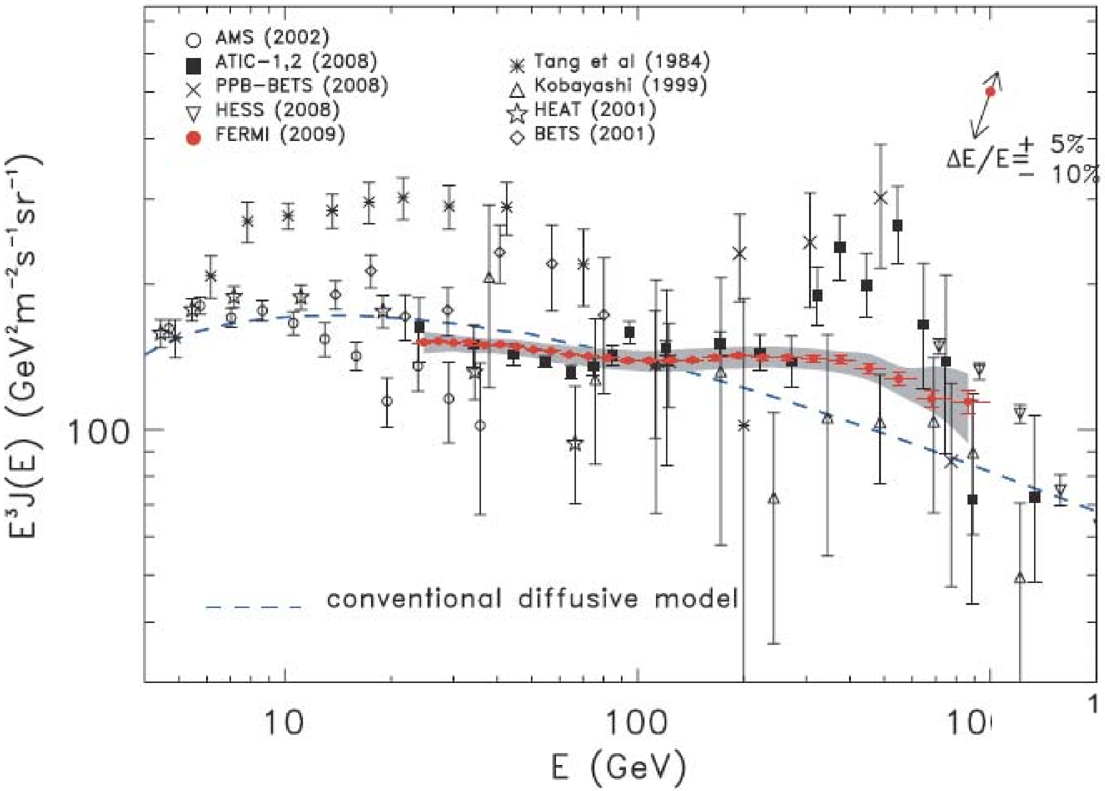
Source of anomaly:

- Dark matter? (500 papers!)
- Nearby pulsars?
- Nearby SNRs?



Adriani *et al*, Nature 458:607,2009

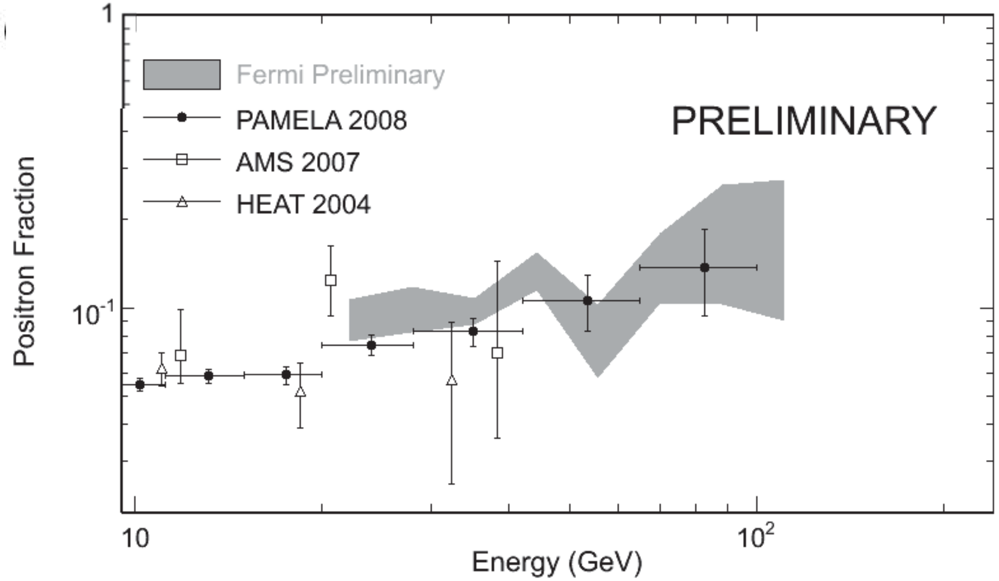
The *Fermi* excess



Fermi-LAT also sees excess $e^{\pm}$ over expectation from propagation model

(Abdo *et al*, PRL 102:181101,2009)

... and has recently also confirmed the rising positron fraction (using Earth's magnetic field to do charge separation)



This is not the first time an anomalous 'excess' over background has been seen …

Inclusive Jet Cross Section in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

The inclusive jet differential cross section has been measured for jet transverse energies, E_T, from 15 to 440 GeV, in the pseudorapidity region $0.1 \leq |\eta| \leq 0.7$. The results are based on 19.5 pb^{-1} of data collected by the CDF Collaboration at the Fermilab Tevatron collider. The data are compared with QCD predictions for various sets of parton distribution functions. The cross section for jets with $E_T > 200$ GeV is significantly higher than current predictions based on $O(\alpha_s^3)$ perturbative QCD calculations. Various possible explanations for the high-E_T excess are discussed.

Abe *et al*, PRL 77:438,1996

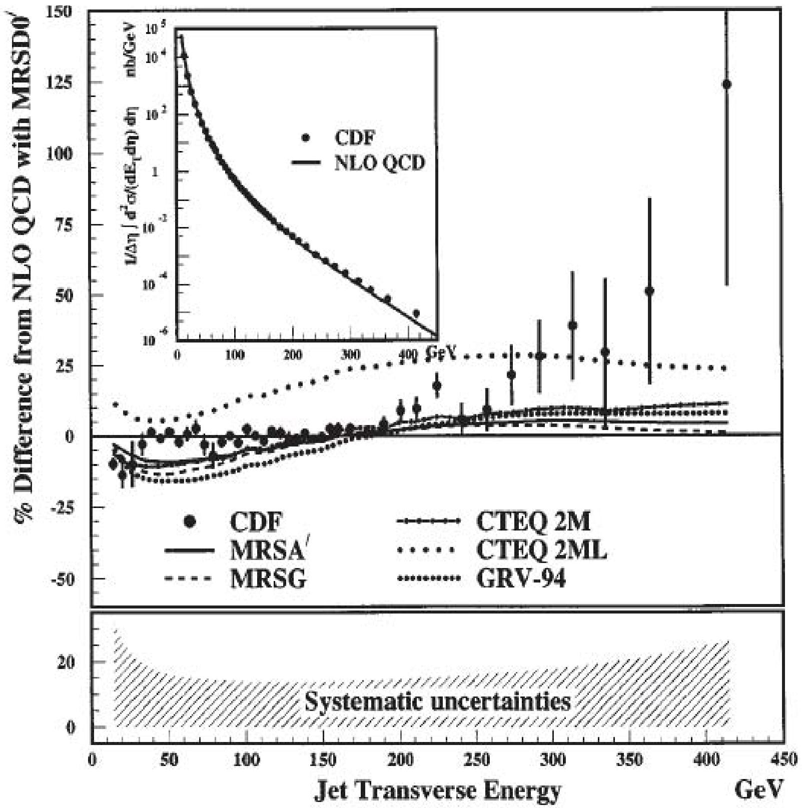


FIG. 1. The percent difference between the CDF inclusive jet cross section (points) and a next-to-leading order (NLO) QCD prediction using MRSD0′ PDFs. The CDF data (points) are compared directly to the NLO QCD prediction (line) in the inset. The normalization shown is absolute. The error bars represent uncertainties uncorrelated from point to point. The hatched region at the bottom shows the quadratic sum of the correlated (E_T dependent) systematic uncertainties which are shown individually in Fig. 2. NLO QCD predictions using different PDFs are also compared with the one using MRSD0′.

… it turned out to be a mis-estimation of the QCD background – *not* new physics!

What particle physicists have learnt through experience (*UA1* monojets, *NuTeV* anomaly, *CDF* high E_T excess, ...)

Yesterday's discovery is today's calibration

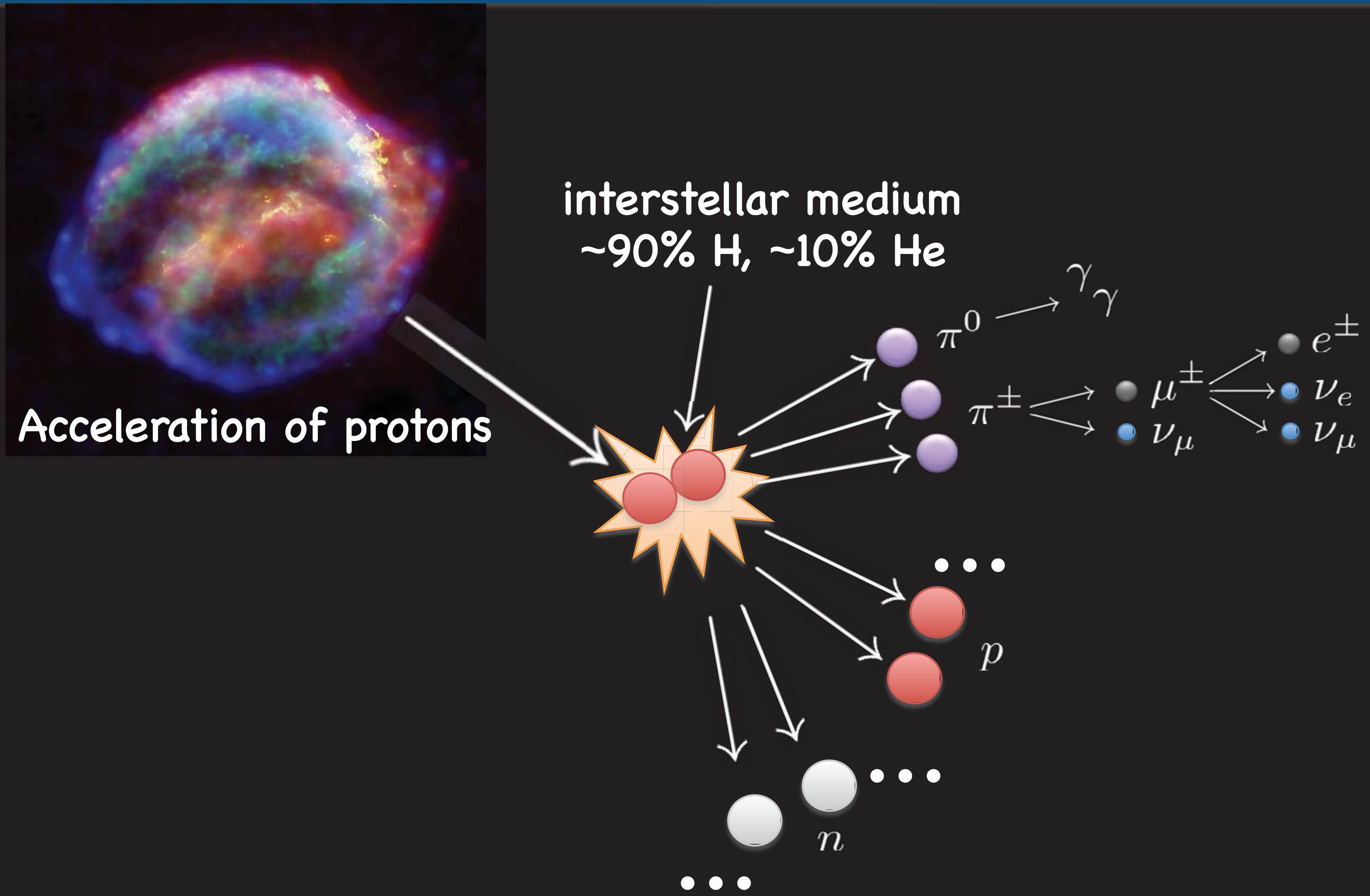
Richard Feynman

... and tomorrow's background!

Val Telegdi

... is also now a major issue for astroparticle physics *viz* **how well do we know the 'astrophysical background' for signals of (apparently) new particle physics?**

The 'background' is the production of secondary $e^{\pm}$ during propagation of nuclear cosmic rays in Galaxy

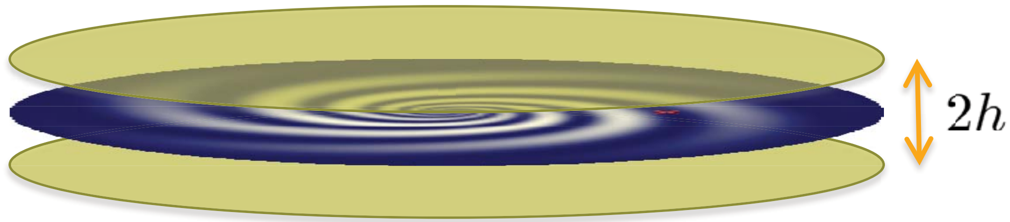


Diffusion of galactic cosmic rays

Transport equation:

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

Boundary conditions:

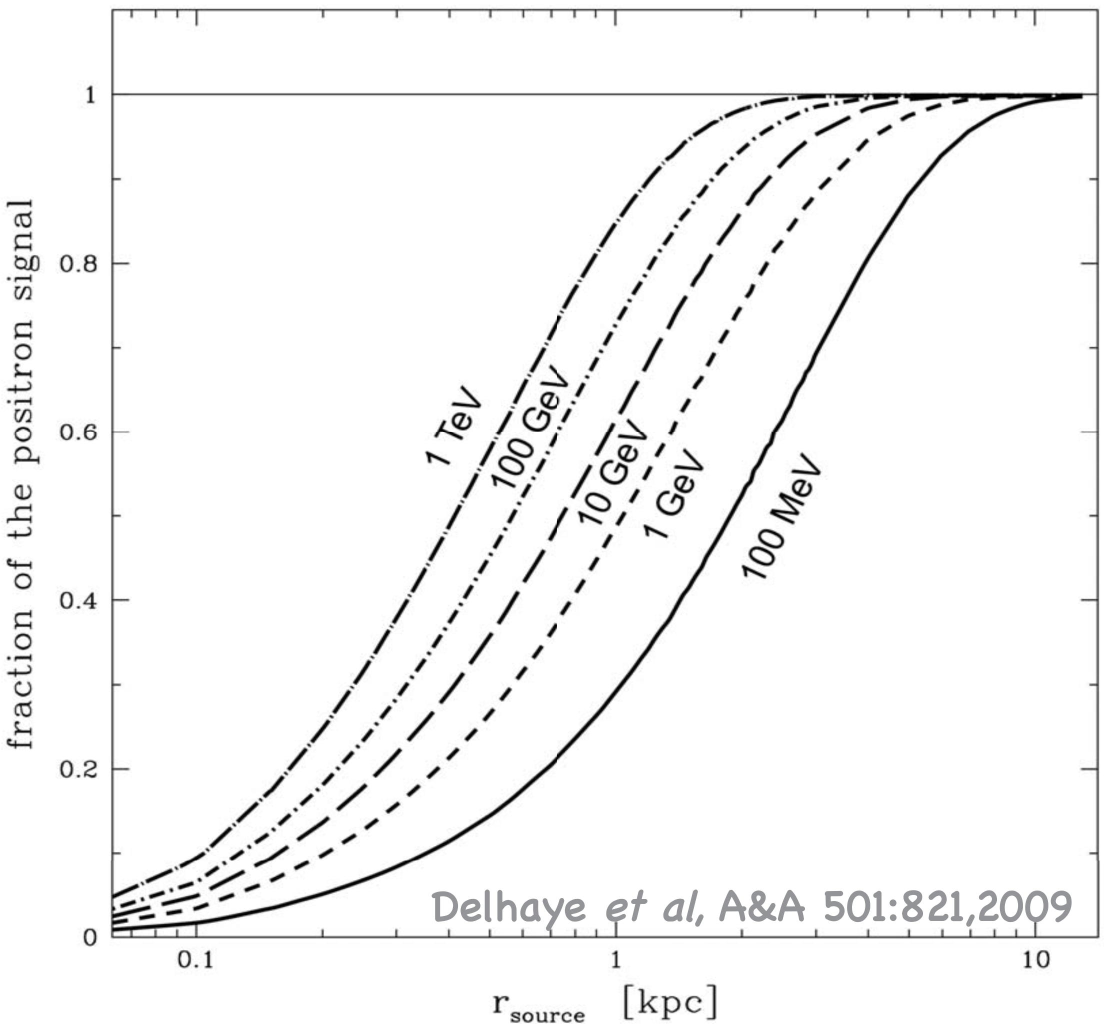


Green's function: describes flux from a discrete, burst-like source …
integrate over spatial distribution and time-variation of injection

GALPROP (Moskalenko & Strong ApJ 493:694,1998, 509:212,1998) solves time-dependent transport equation … yields ~the same answer for *equilibrium* fluxes as the **'leaky box' model** in which cosmic rays have small energy dependent probability of escape from Galaxy
⇒ *exponential* distribution of path lengths between cosmic ray sources and Earth

Expectation: secondary/primary ratio $\propto E^{-\delta}$, where the diffusion co-efficient $D \propto E^{\delta}$
… fit to nuclear ratios (e.g. B/C) gives: $\boldsymbol{\delta \sim 0.3\text{-}0.7}$

However $e^{\pm}$ lose energy readily during propagation, so only *nearby* sources dominate at such high energies … the usual background calculation is then *irrelevant*

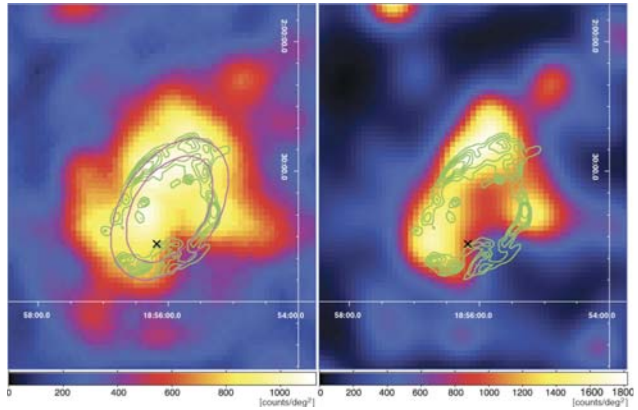


$$\tau \simeq 5 \cdot 10^5 \mathrm{yr} \left(\frac{1\,\mathrm{TeV}}{E} \right)$$

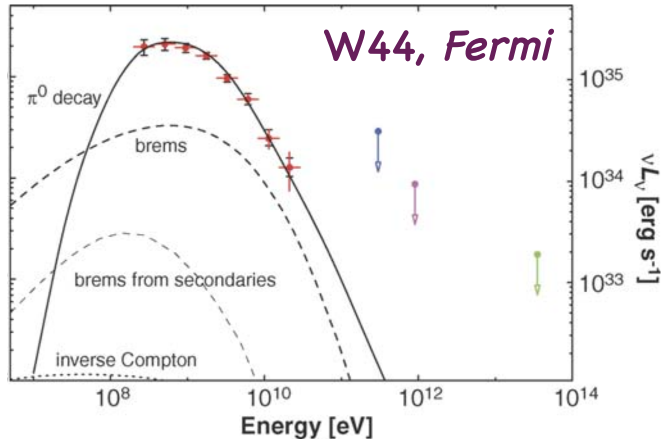
Are there any *primary* sources of positrons (with a hard spectrum) in our Galactic neighbourhood?

A nearby cosmic ray accelerator?

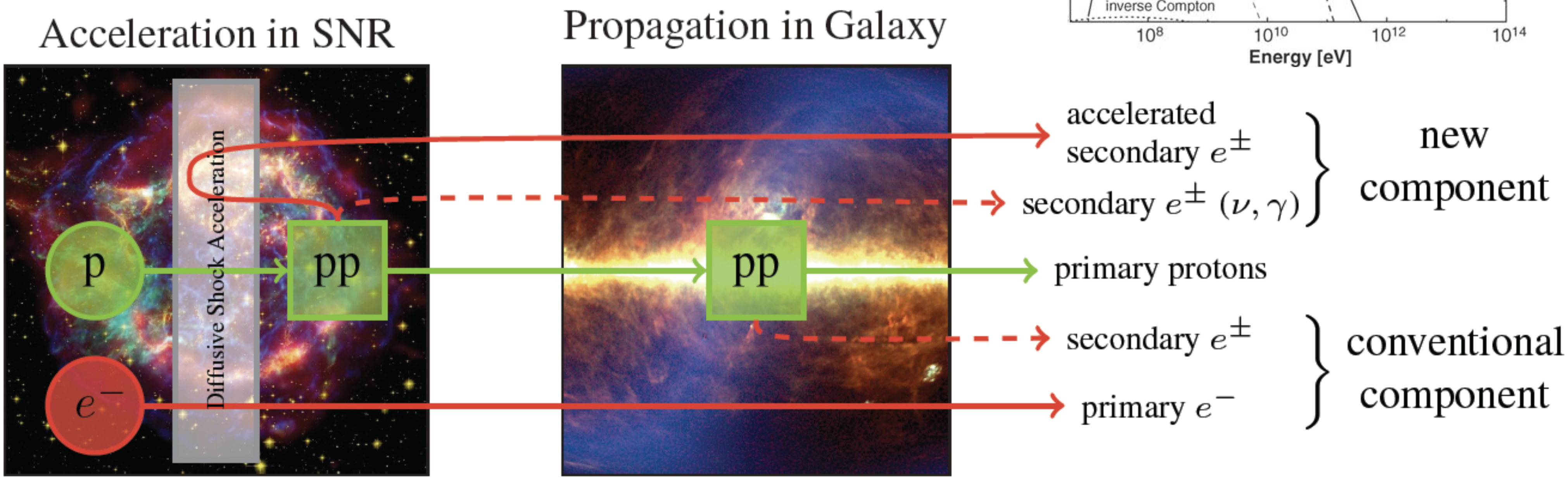
Rise in e^+ fraction could be due to secondaries produced *during* acceleration … which are then accelerated along with the primaries (Blasi, PRL 103:051104,2009)



… generic feature of a *stochastic* acceleration process, if $\tau_{1\rightarrow 2} < \tau_{\rm acc}$ (Cowsik 1979, Eichler 1979)



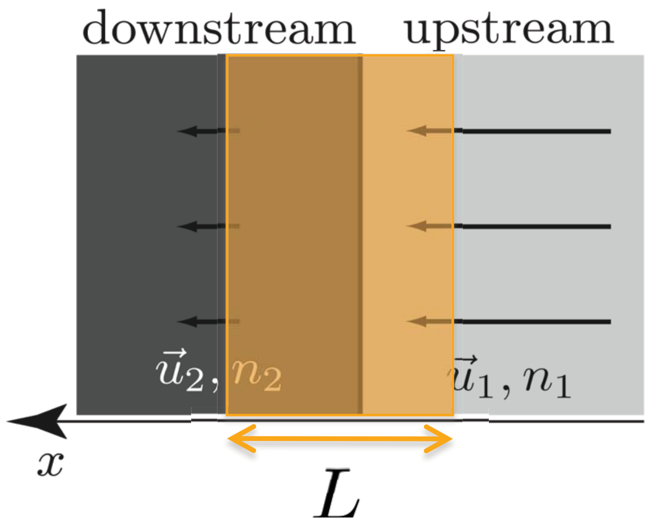
This component *naturally* has a harder spectrum so fits *PAMELA* excess!



Diffusive (1^{st}-order Fermi) shock acceleration

Consider flux:

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



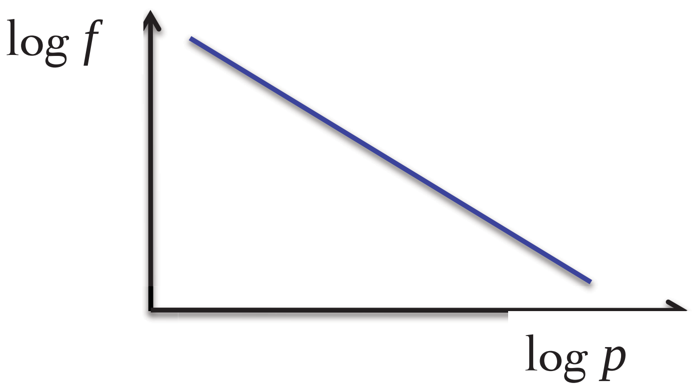
Conservation equation:

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

Steady state: $\dfrac{u_1 - u_2}{3} p \dfrac{\partial f}{\partial p} + u_1 f = 0$

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

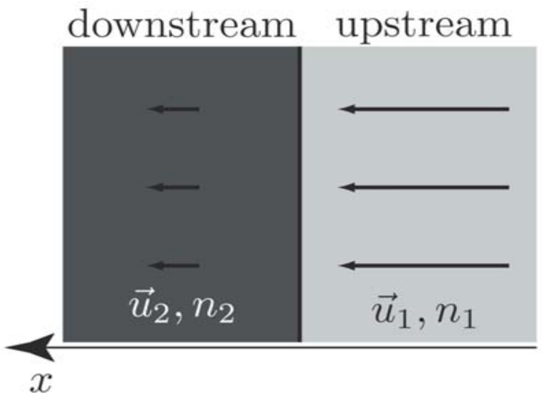
i.e. $\gamma = 4$ for strong shock $(u_1/u_2 = 4)$



Diffusive (1st-order Fermi) shock acceleration

Acceleration determined by compression ratio:

$$r = \frac{u_1}{u_2} = \frac{n_2}{n_1}\,, \qquad \gamma = \frac{3r}{r-1}$$



Solve transport equation, $u\frac{\partial f}{\partial x} = D\frac{\partial^2 f}{\partial x^2} + \frac{1}{3}\frac{\mathrm{d}u}{\mathrm{d}x}p\frac{\partial f}{\partial p}$

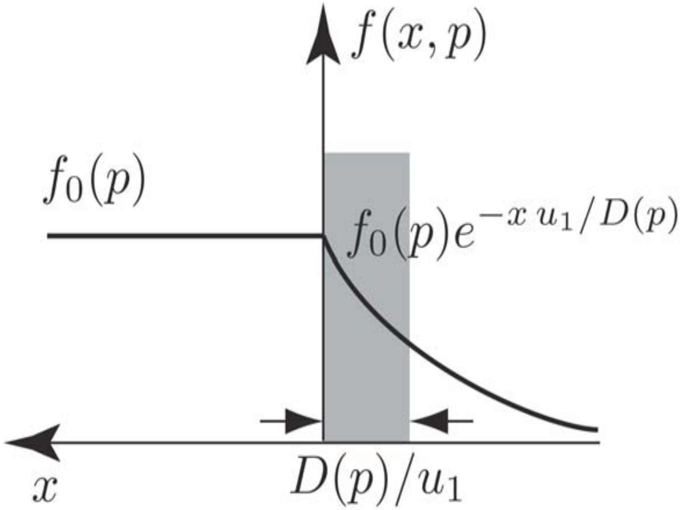
$$f \xrightarrow{x\to-\infty} f_{\rm inj}(p), \qquad \left|\lim_{x\to\infty} f\right| \ll \infty$$

Solution for: $x < 0$

$$f = f_{\rm inj}(p) + (f^0(p) - f_{\rm inj}(p))e^{-x\,u_1/D(p)}$$

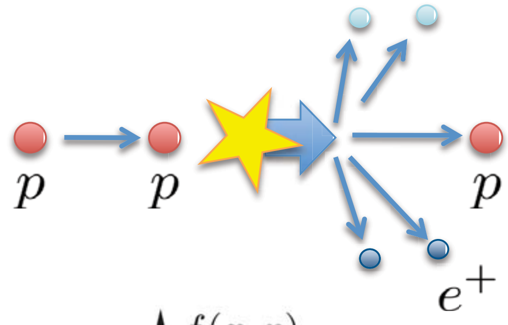
where

$$f^0(p) = \gamma\int_0^p \frac{\mathrm{d}p'}{p'}\left(\frac{p'}{p}\right)^\gamma f_{\rm inj}(p') + Cp^{-\gamma}$$



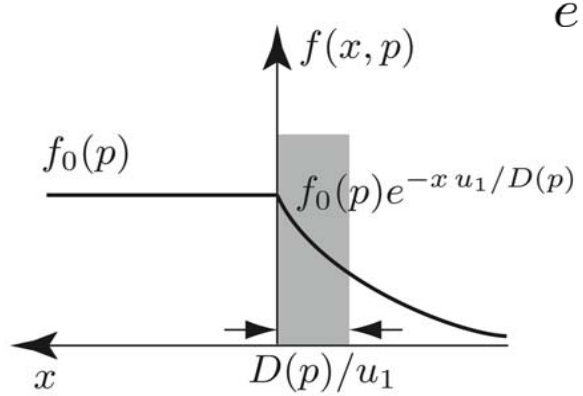
As long as $f_{\rm inj}(p)$ is softer than $p^{-\gamma}$ at high energies: $f(x,p) \sim p^{-\gamma}$

DSA with secondary production

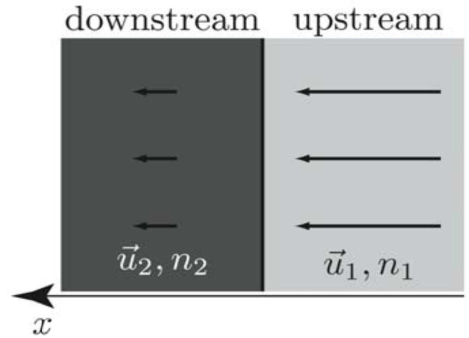


- Secondaries have *same* spectrum as primaries (Feynman):

$$q_{e^\pm} \propto f_{\rm CR} \propto p^{-\gamma}, \quad \gamma = \frac{3r}{r-1} \quad r = \frac{u_1}{u_2} = \frac{n_2}{n_1}$$



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

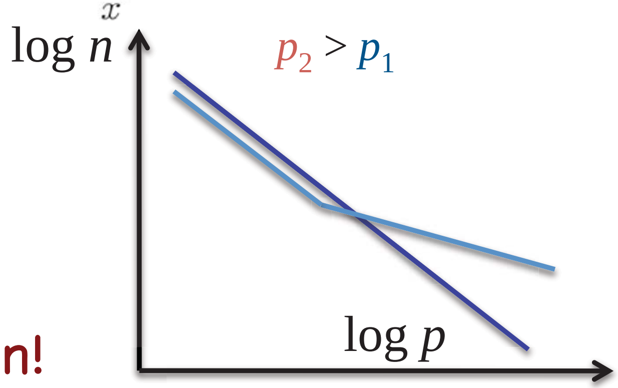


- Bohm diffusion: $D(p) \propto p$

⇒Fraction of accelerated secondaries is $\propto p$

Steady state spectrum:

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



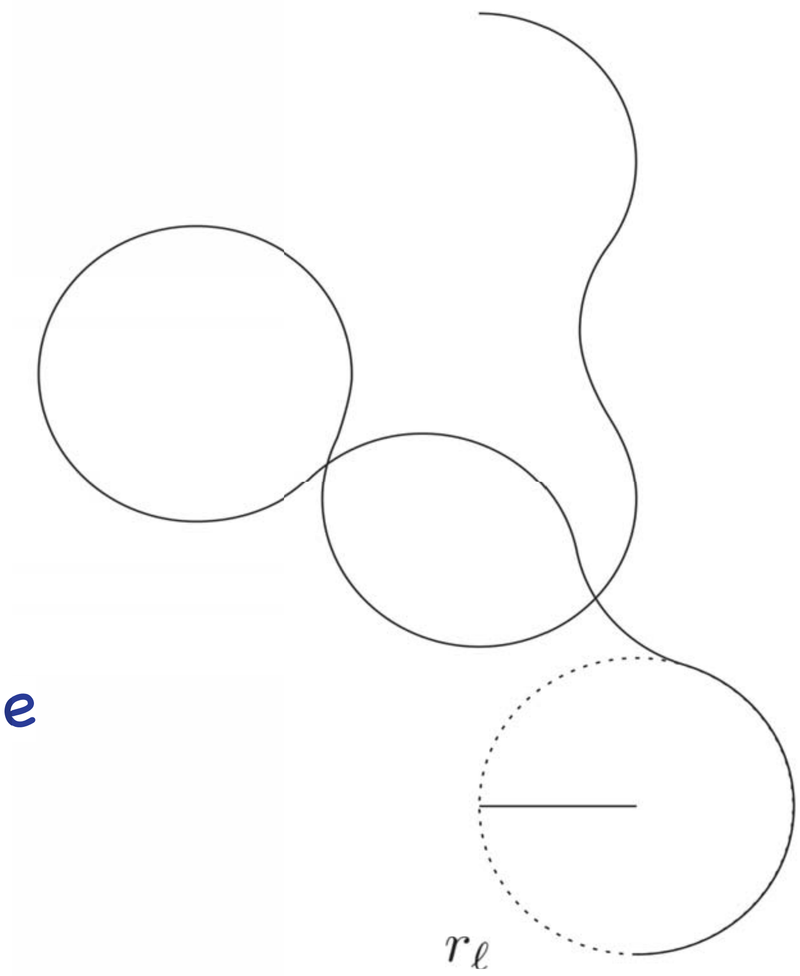
➔ *rising* positron fraction!

Diffusion near shock front

- Diffusion coefficient not known *a priori* in neighbourhood of shock
- 'Bohm diffusion' sets a *lower* limit:

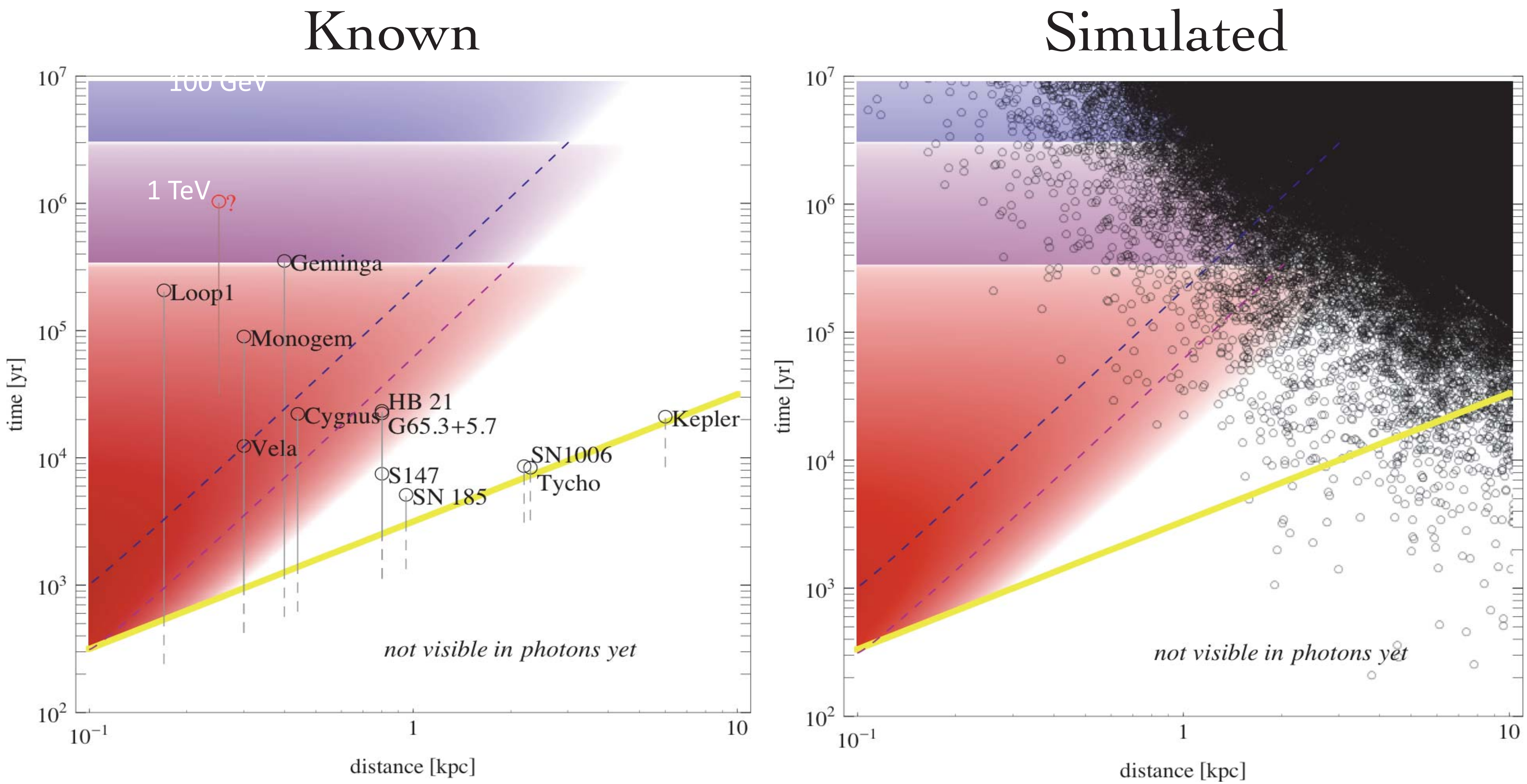
$$D^{\mathrm{Bohm}} = r_\ell \frac{c}{3} \propto \frac{E}{Z}$$

- Actual rate parametrised by 'fudge factor': $D = D^{\mathrm{Bohm}} \mathcal{F}^{-1}$
- Can try and determine diffusion rate from simulations (difficult!)
- So determine $\mathcal{F}^{-1}$ by fitting to *Fermi* $e^{\pm}$ excess … can then *predict* $e^{+}/(e^{+}+e^{-})$ for *PAMELA*, and other secondary/primary ratios (e.g. B/C)



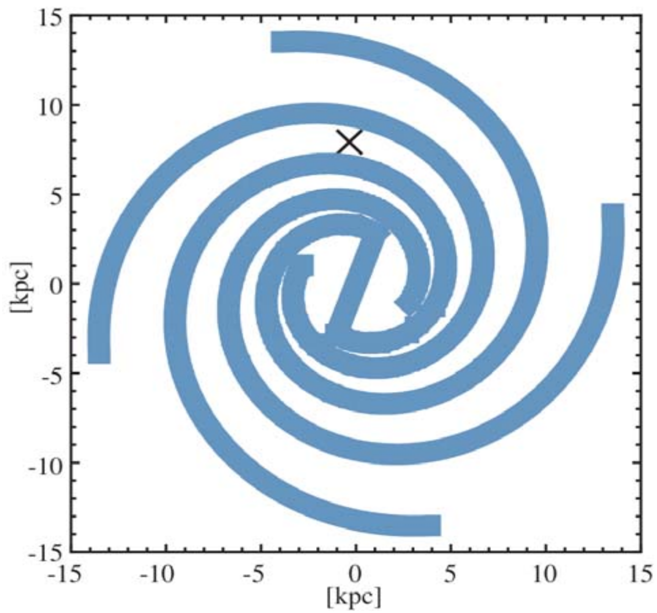
It is not just the few (optically) observed SNRs which contribute to observed cosmic rays … there must be many other *hidden* SNRs

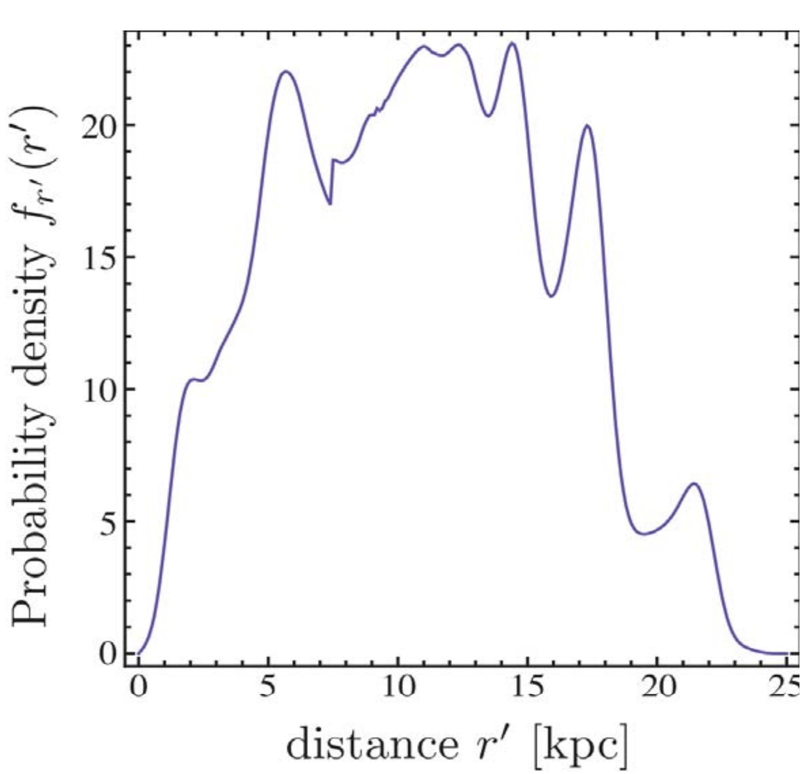
(if there are ~3 SN/century and cosmic rays diffuse in Galaxy for ~10^7 yr)



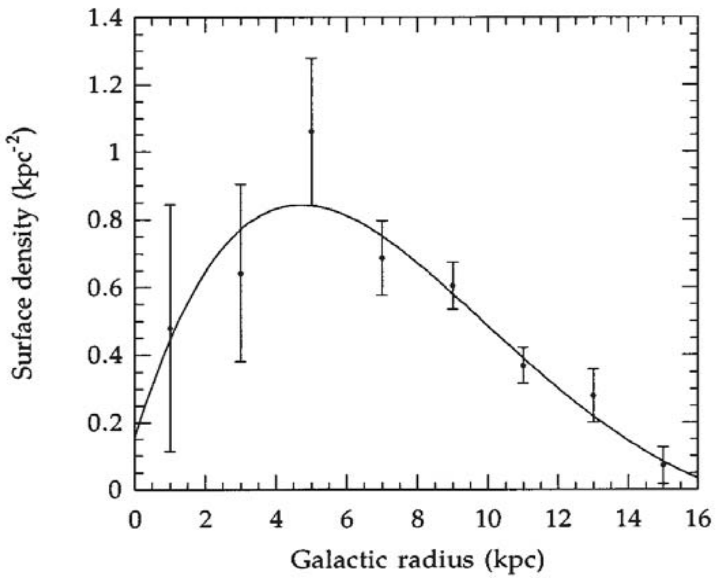
Ahlers, Mertsch & Sarkar,PRD80:123017,2009

Statistical distribution of SNRs in our neighbourhood





Ahlers, Mertsch & Sarkar,PRD80:123017,2009



Case & Bhattacharya, ApJ 504:761,1998

- Draw source positions from this distribution
- Inject e^- & e^+ normalized to observables (*HESS* ...)
- Propagate to Earth accounting for synchrotron and inverse-Compton scattering energy losses
- Confront total e^-+e^+ flux at Earth with *Fermi* data

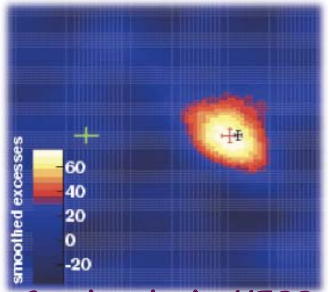
The *best fit* to data is closest to real distribution

Parameters of the Monte Carlo

Diffusion Model		
D_0	$10^{28}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$	from GCR nuclear secondary-to-primary ratios
δ	0.6	from GCR nuclear secondary-to-primary ratios
L	3 kpc	from GCR nuclear secondary-to-primary ratios
b	$10^{-16}\,\mathrm{GeV}^{-1}\,\mathrm{s}^{-1}$	CMB, IBL and $\vec{B}$ energy densities
Source Distribution		
t_{max}	1×10^8 yr	from $E_{\mathrm{min}} \simeq 3.3\,\mathrm{GeV}$
τ_{SNR}	10^4 yr	from observations
N	3×10^6	from number of observed SNRs
Source Model		
$R^0_{e^-}$	$1.8 \times 10^{50}\,\mathrm{GeV}^{-1}$	fit to e^- flux at 10 GeV
Γ	2.4	average γ-ray spectral index
E_{max}	20 TeV	typical γ-ray maximum energy
E_{cut}	20 TeV	DSA theory
R^0_+	$7.4 \times 10^{48}\,\mathrm{GeV}^{-1}$	γ-rays
K_{B}	15	free parameter (for fixed Γ)

Ahlers, Mertsch & Sarkar,PRD80:123017,2009

Normalising the source spectra



Cassiopeia A, *HESS*

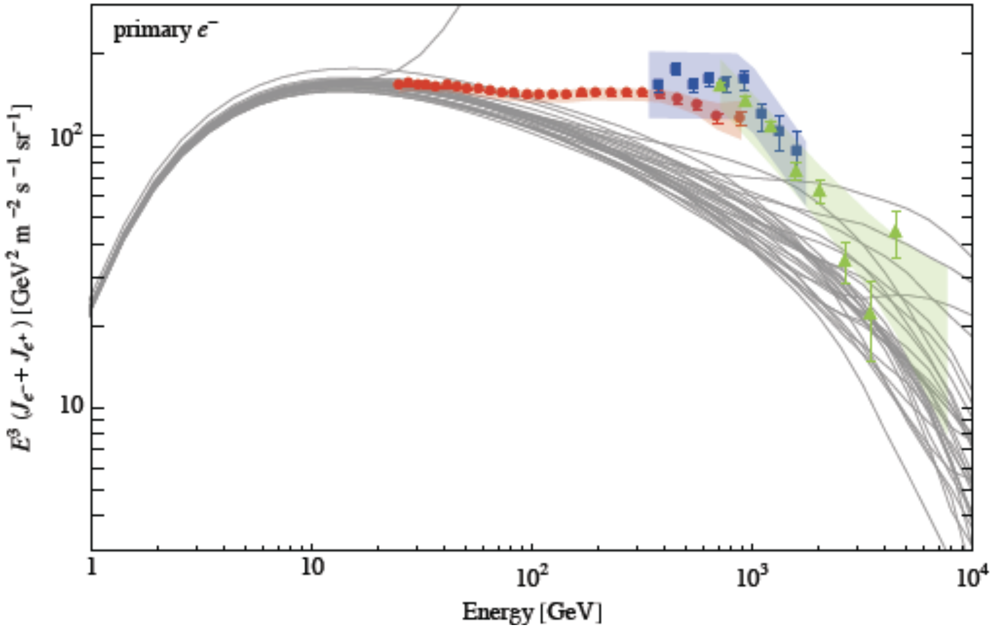
Normalisation of primary e^- : fit absolute e^- flux at low energies

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

Source	Other name(s)	Γ	$J_\gamma^0 \div 10^{-12}$ $[(\mathrm{cm}^2\,\mathrm{s\,TeV})^{-1}]$	$E_{\max}$ [TeV]	d [kpc]	$Q_\gamma^0 \div 10^{33}$ $[(\mathrm{s\,TeV})^{-1}]$
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

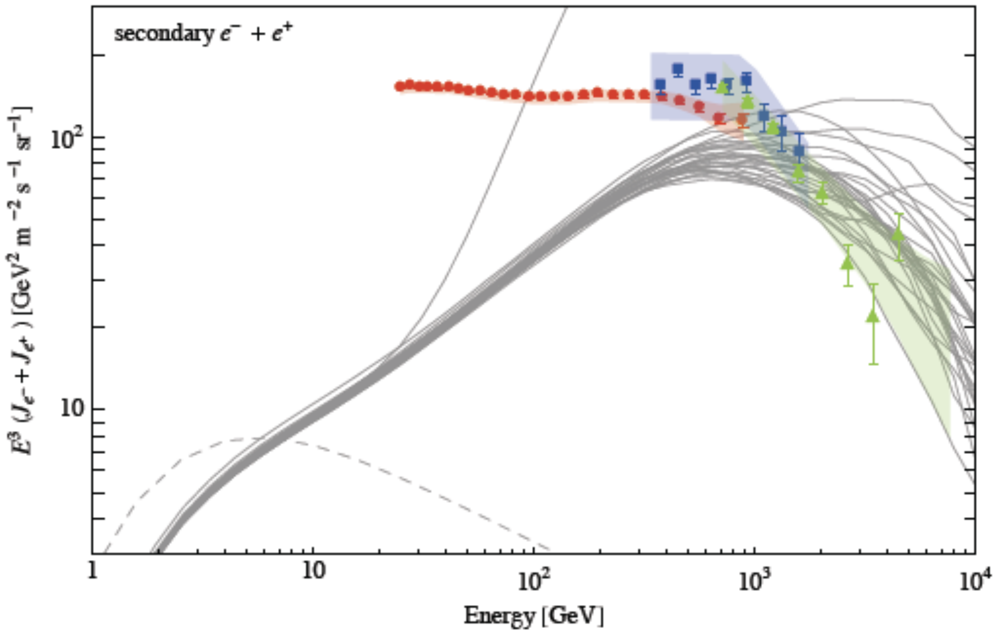
Ahlers, Mertsch & Sarkar,PRD80:123017,2009

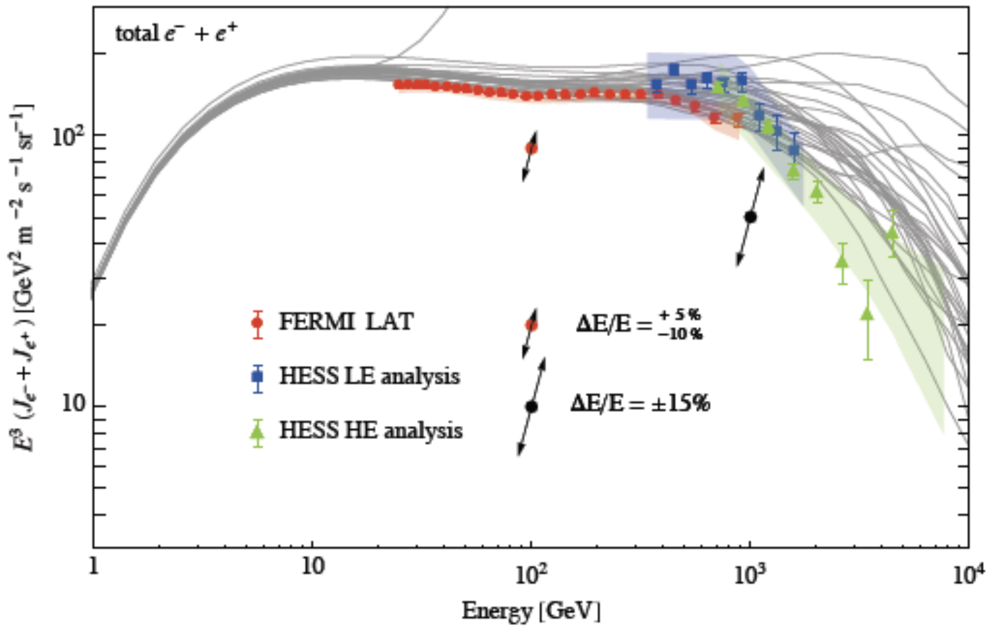
Fitting the $e^+ + e^-$ flux



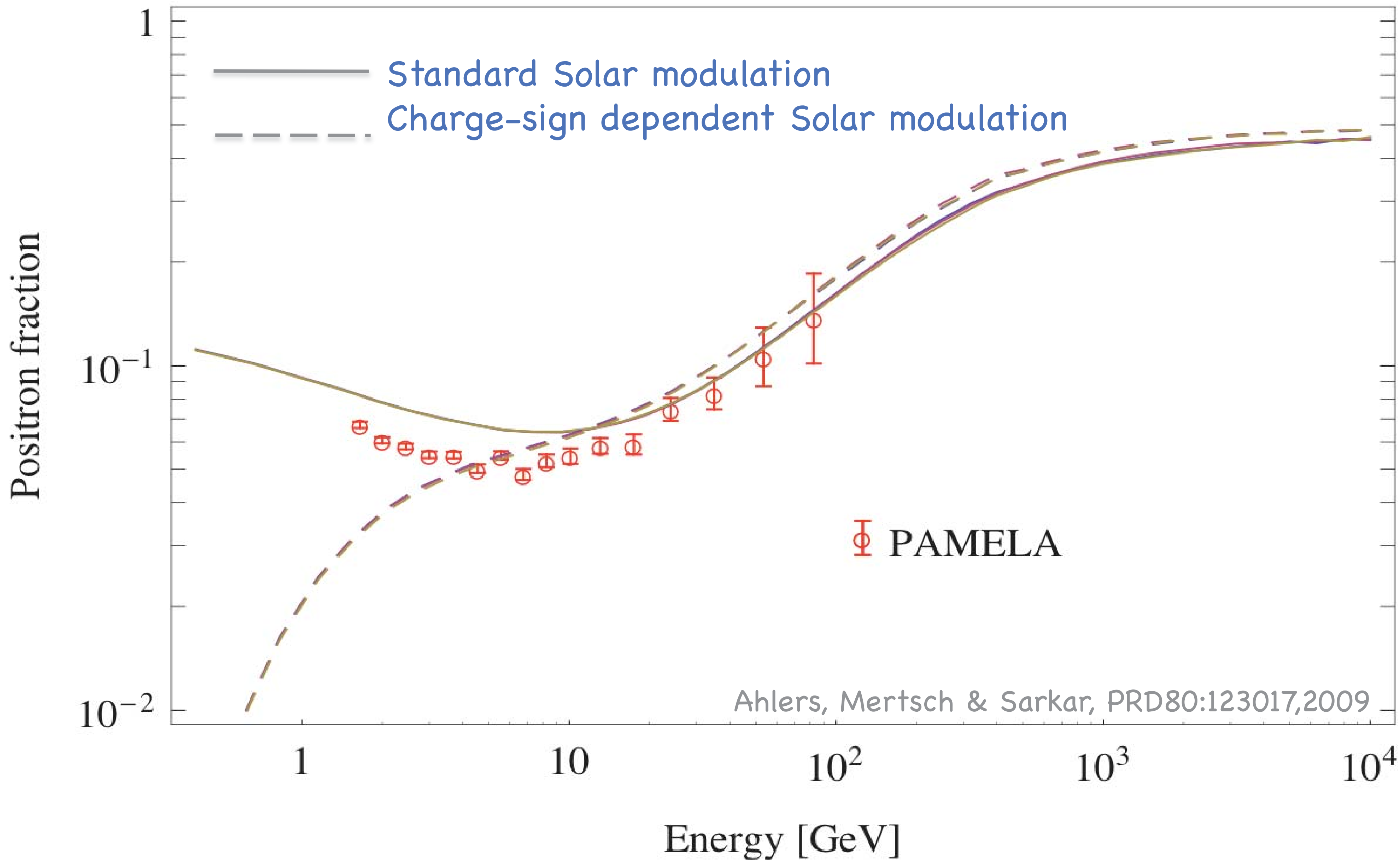
The propagated primary e^- spectrum is much too *steep* to match the Fermi LAT data … but the *accelerated* secondary $e^+ + e^-$ component has a harder spectrum so fits the 'bump'!

Ahlers, Mertsch & Sarkar, PRD80:123017,2009





The *predicted* positron fraction



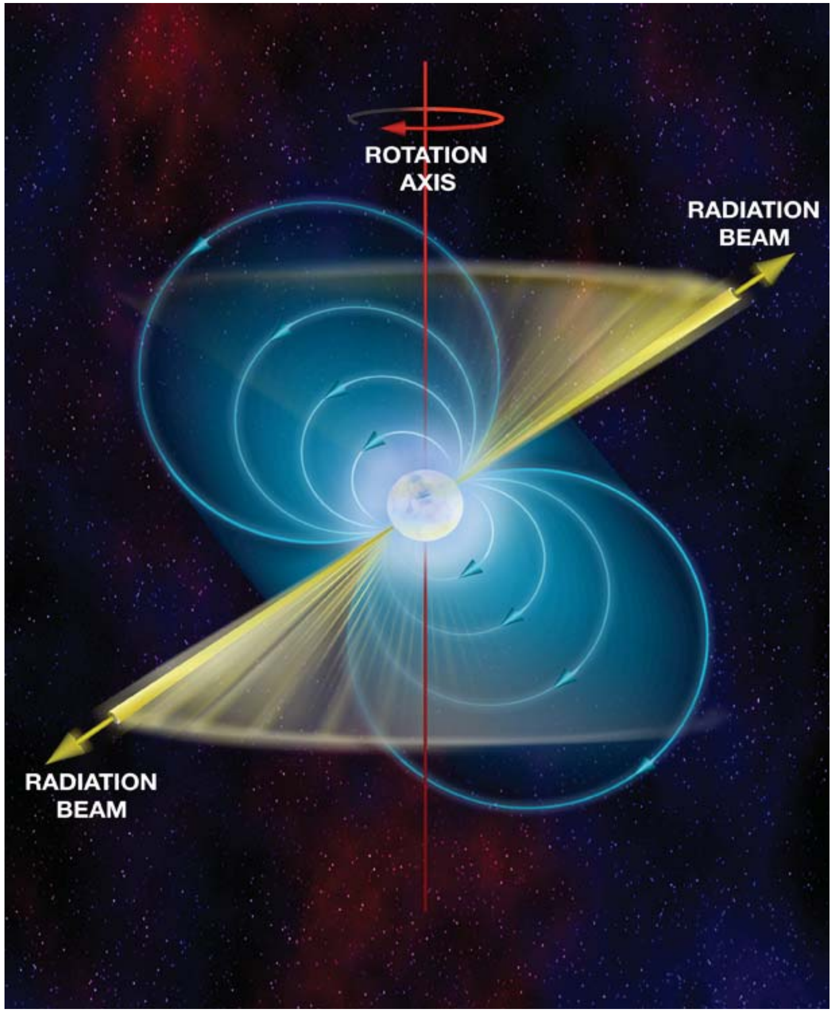
Nearby pulsars as source of $e^{\pm}$

- Highly magnetized, fast spinning neutron stars

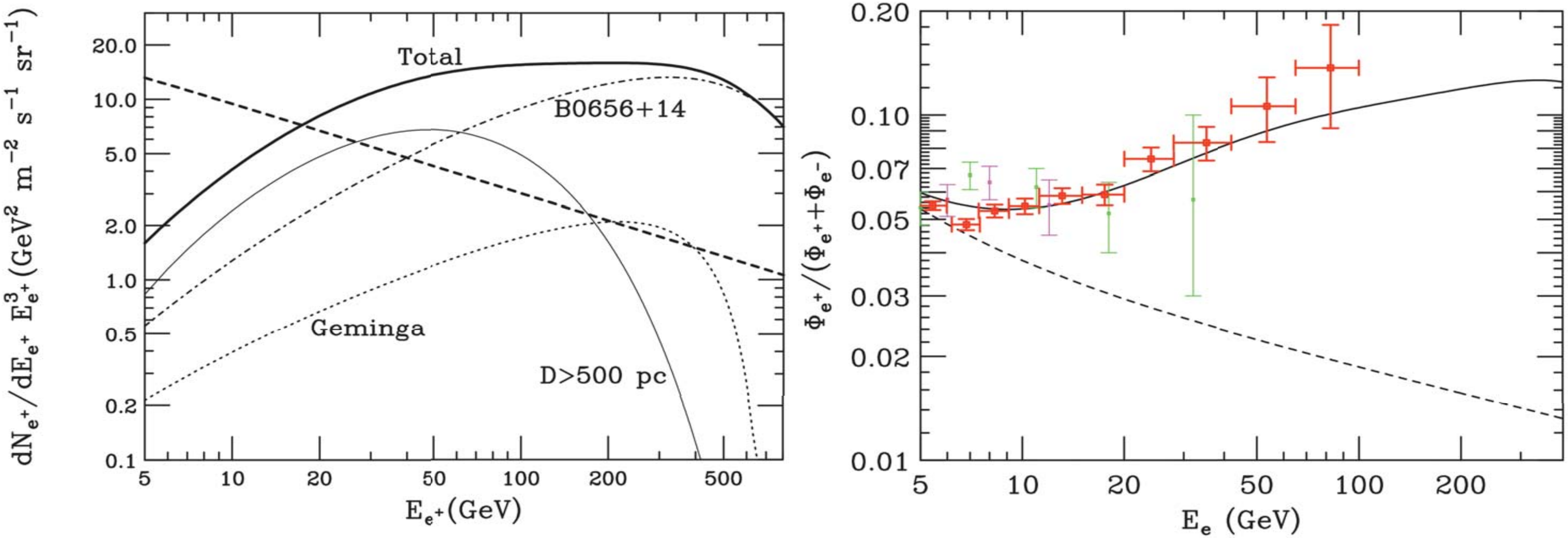
- γ -rays and electron/ positron pairs produced along the magnetic axis

- Spectrum *speculated* to be harder than background from propagation:

$$N \propto E_e^{\pm\,-1.6} e^{-E_e^{\pm}/100\,\mathrm{GeV}}$$



Combination of Galactic contribution and two nearby pulsars, **Geminga** (157 pc) and **B0656+14** (290 pc), *can* fit *PAMELA* excess (and perhaps also *Fermi* bump)



Hooper, Blasi & Serpico, JCAP 0901:025,2009

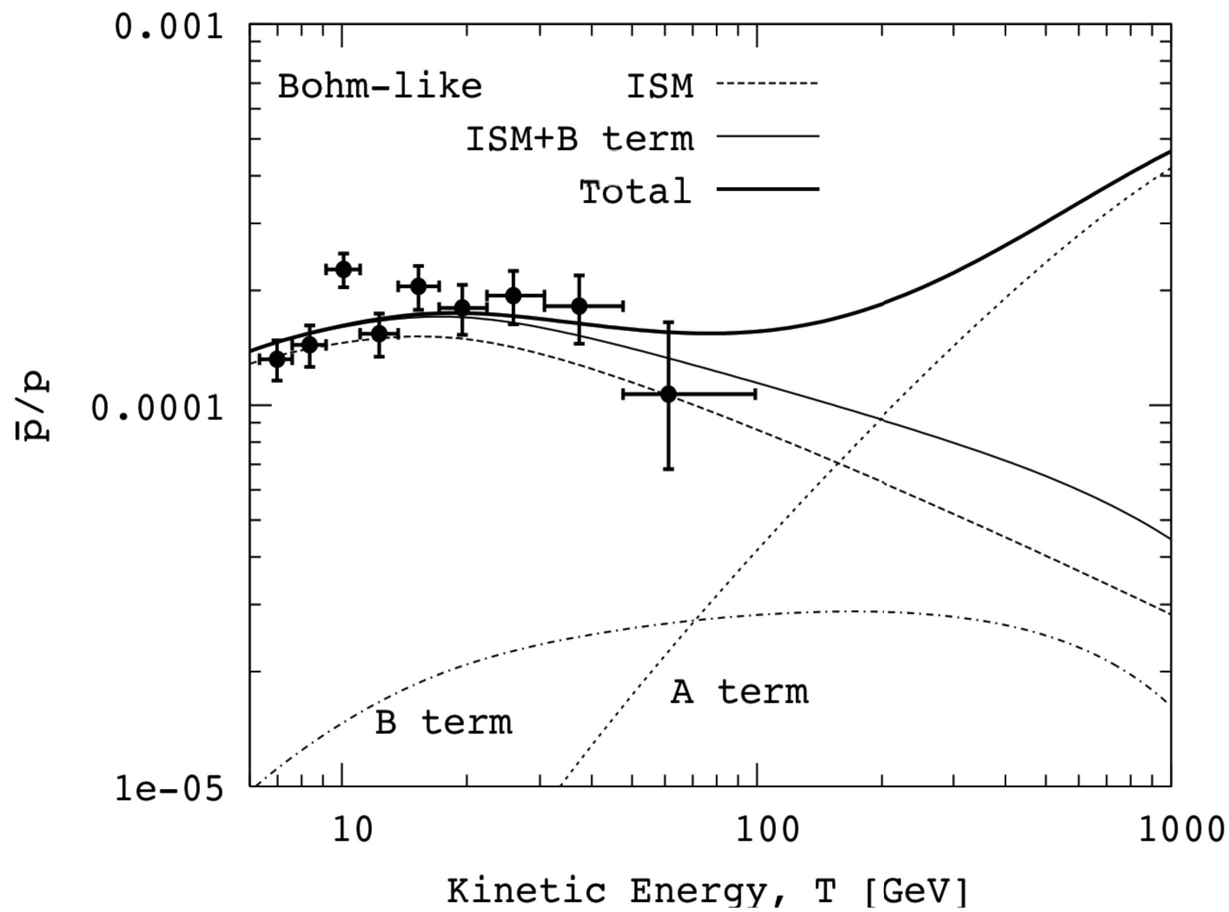
However ~40% of rotational energy must be released as energetic e^+ – plausible?

Fermi can detect expected anisotropy towards B0656+14 in ~5 years

What about the antiproton-to-proton ratio?

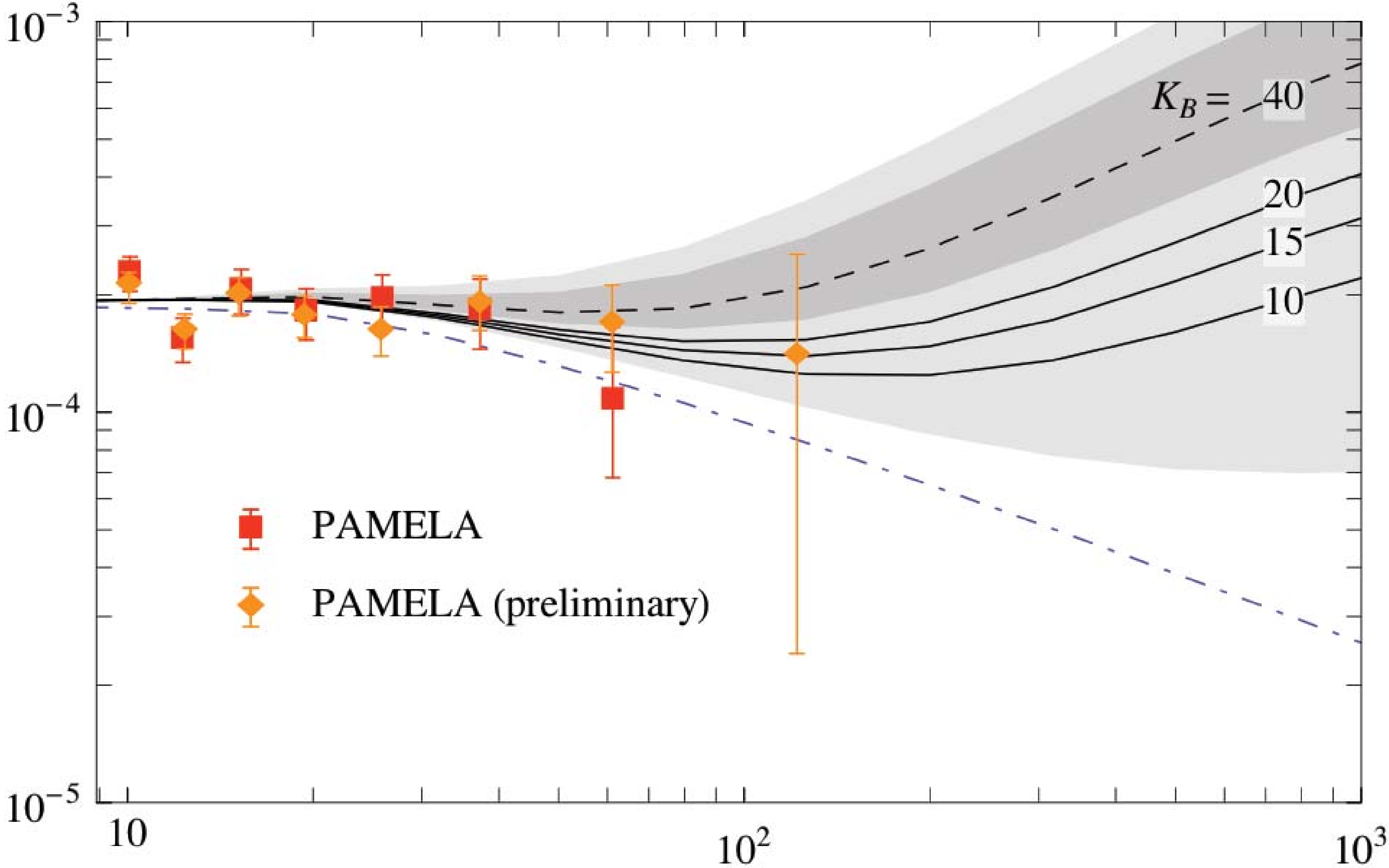
	$\bar{p}/p$
Dark matter	(✓)
Pulsars	✓
Acceleration of secondaries	✓

Blasi & Serpico, PRL 103:081103,2009



Secondary acceleration model predicts rise *beyond* 100 GeV
… will be tested soon by *AMS-02*

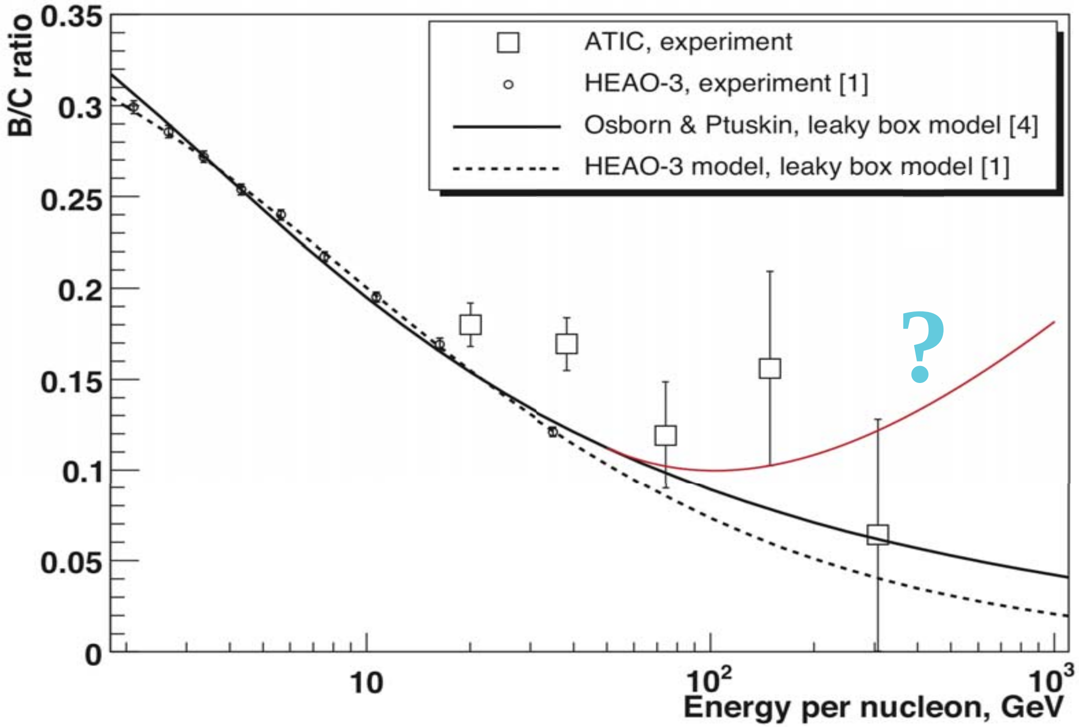
Consistent with recent antiproton flux measurement by PAMELA



Nuclear secondary-to-primary Ratios

Dark matter	✗
Pulsars	✗
Acceleration of secondaries (TBD)	✓

Since nuclei are accelerated in the *same* sources, the ratio of secondaries (e.g. Li, Be, B) to primaries (C, N, O) must also *rise* with energy beyond ~100 GeV



Panov *et al*, ICRC 2007

If we see this, *both* dark matter and pulsar origin models would be ruled out!

Can solve problem analytically … but more complicated than for $\bar{p}/p$ since energy losses must now be included

- Transport equation: $u\frac{\partial f_i}{\partial x} = D_i\frac{\partial^2 f_i}{\partial x^2} + \frac{1}{3}\frac{du}{dx}p\frac{\partial f_i}{\partial p} - \Gamma_i f_i + q_i$

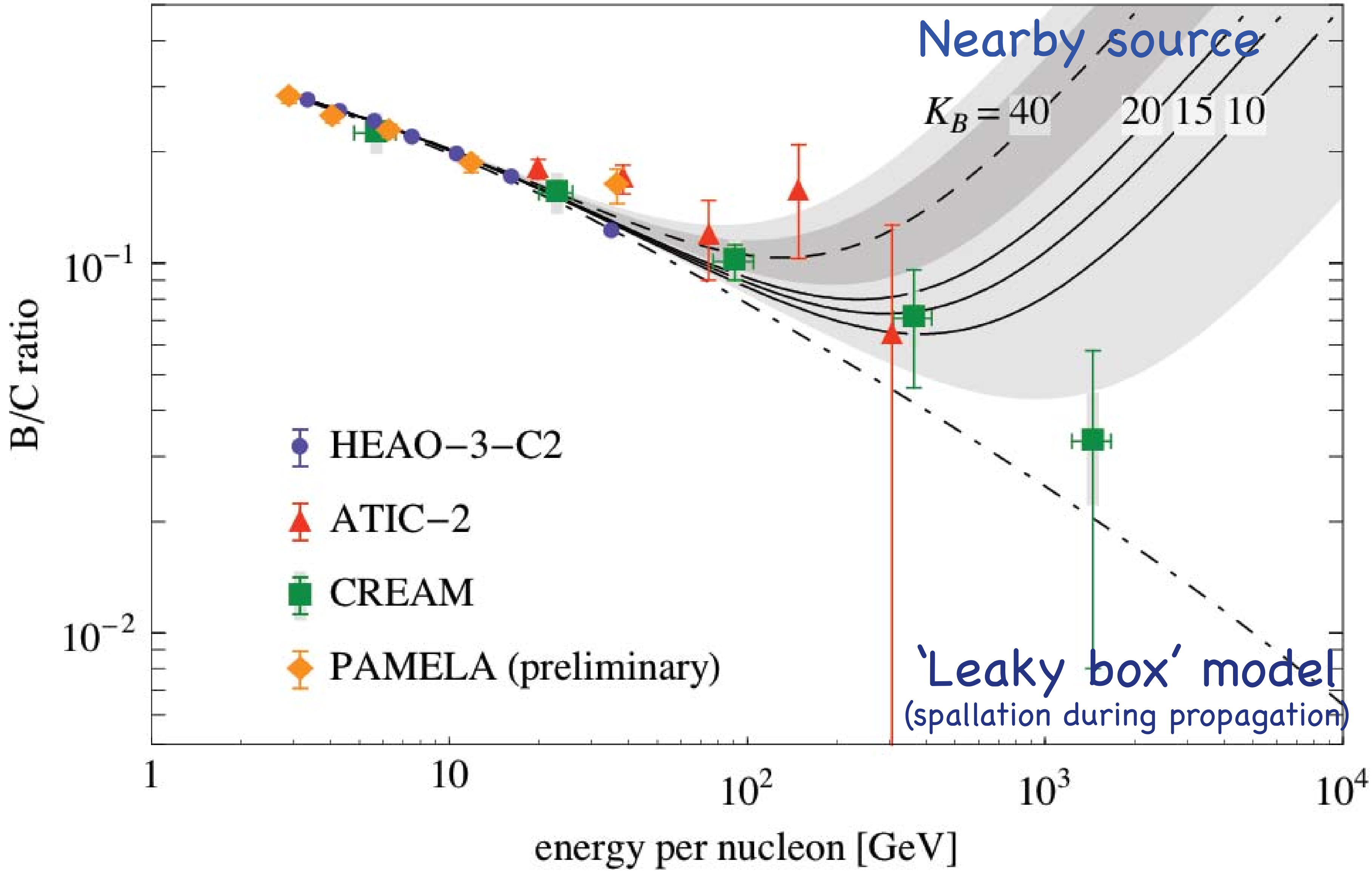
with boundary condition: $f_i(x,p) \xrightarrow{x\to-\infty} Y_i\delta(p-p_0)$

- Solution: $f_i^+ = f_i^0 + \frac{q_i^+(x=0) - \Gamma_i^+ f_i^0}{u_+}x \quad \text{for } x > 0$

$$
\begin{aligned}
f_i^0(p) \quad &= \quad \int_0^p \frac{\mathrm{d}p'}{p'}\left(\frac{p'}{p}\right)^\gamma \mathrm{e}^{-\gamma(1+r^2)(D_i^-(p)-D_i^-(p'))\Gamma_i^-/u_-^2} \\
&\times\gamma\left[(1+r^2)\frac{D_i^-(p')q_i^-(x=0)}{u_-^2} + Y_i\delta(p'-p_0)\right] \\
&\sim \text{“}q_i^-(p) + D_i^-(p)q_i^-(p)\text{”}
\end{aligned}
$$

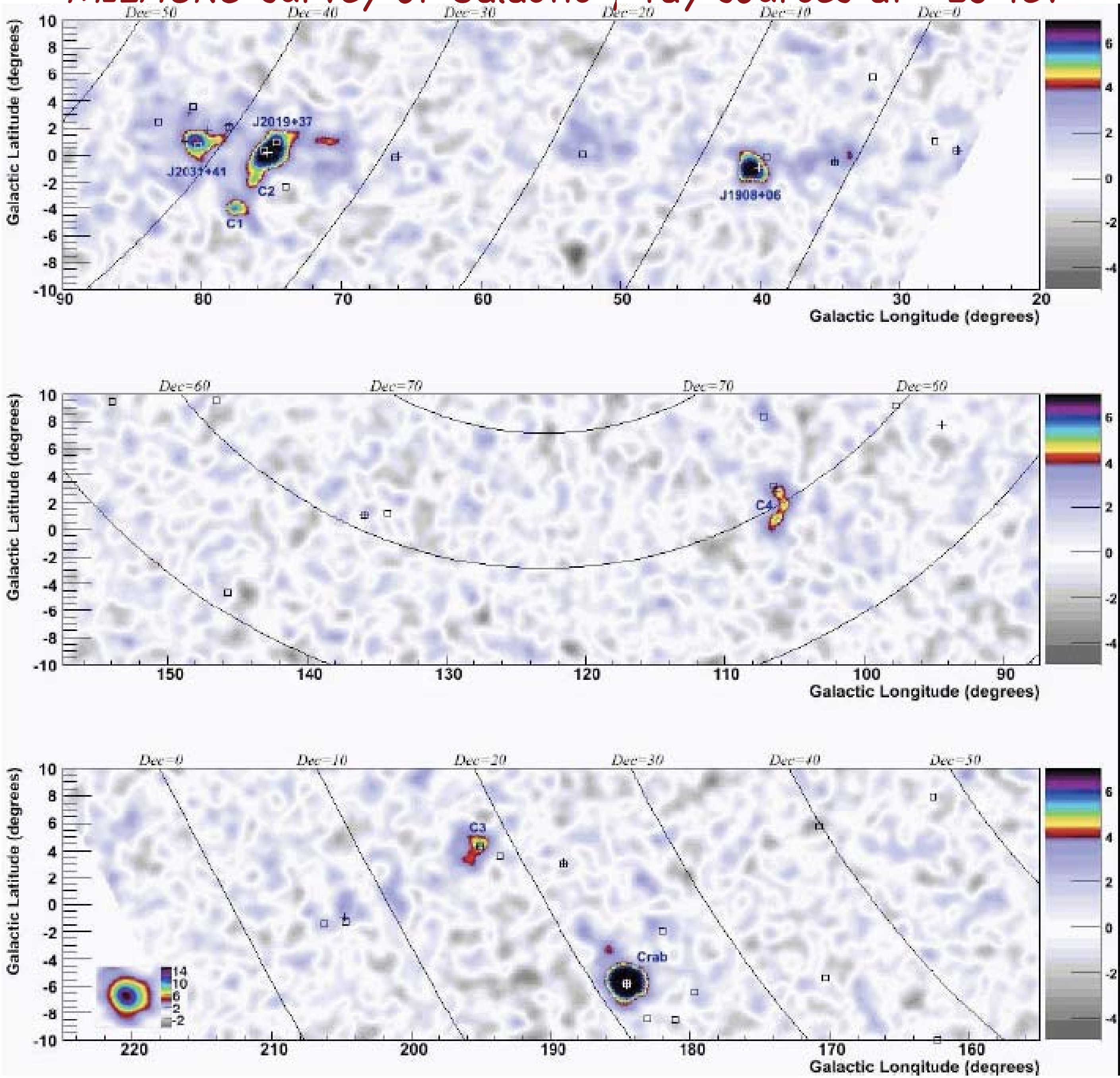
Mertsch & Sarkar, PRL 103:081104,2009

We can then predict another secondary/primary ratio e.g. B/C ...



PAMELA is currently measuring B/C with unprecedented accuracy
... a *rise* would establish the nearby hadronic accelerator model

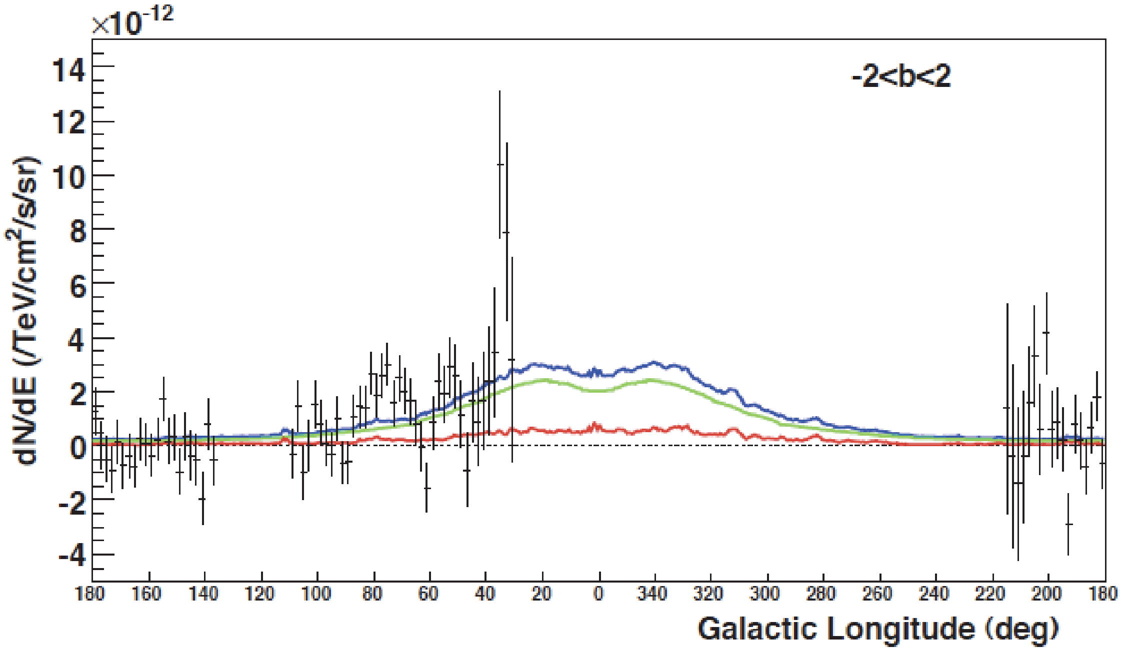
MILAGRO survey of Galactic γ-ray sources at ~20 TeV



Eight candidate sources of TeV emission are detected with pre-trials significance $>4.5\sigma$ in Galactic longitude $[300^0, 220^0]$ and latitude $[-10^0, 10^0]$. Four of these, including the Crab nebula and the recently published MGRO J2019+37, are observed with significances $> 4\sigma$ after accounting for the trials involved in searching the 3800 degree^2 region. All four are also coincident with EGRET sources. Two of the lower significance sources are coincident with EGRET sources and one of these sources is Geminga. The other two candidates are in the Cygnus region of the Galaxy. Several of the sources appear to be spatially extended. The fluxes of the sources at 20 TeV range from 25% of the Crab flux to nearly as bright as the Crab.

Abdo *et al*, arXiv:0805.0417

Have some of these old SNRs been seen already?



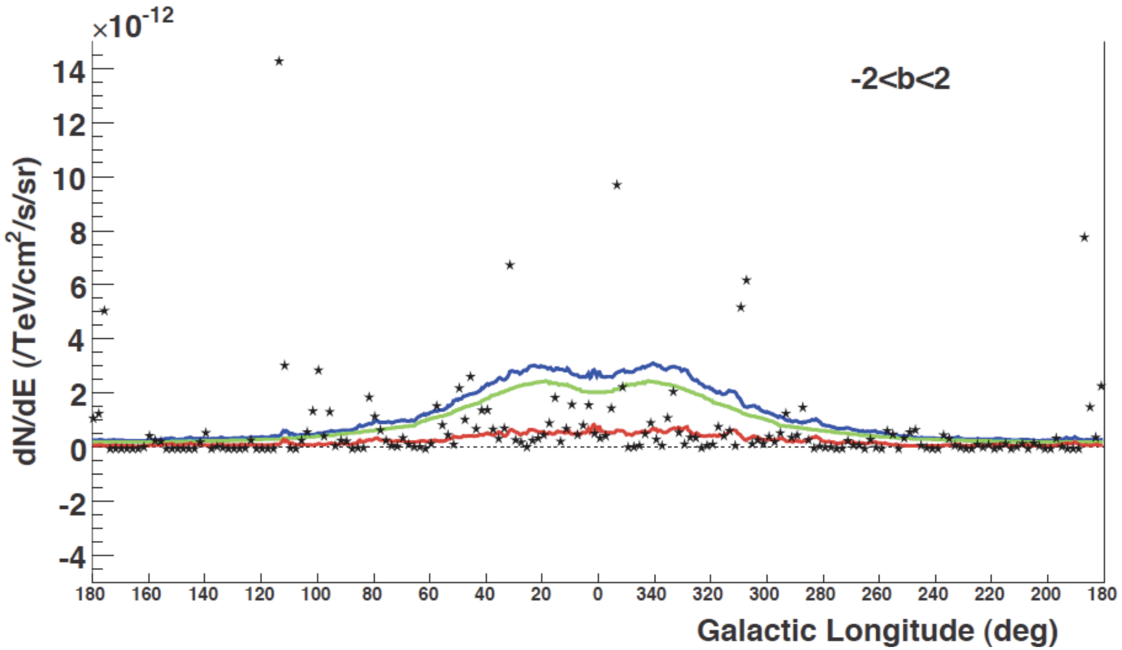
MILAGRO profile of the Milky Way overlaid with GALPROP 'prediction' (red: π^0 decay, green: IC, blue: total)

Abdo *et al*, arXiv:0805.0417

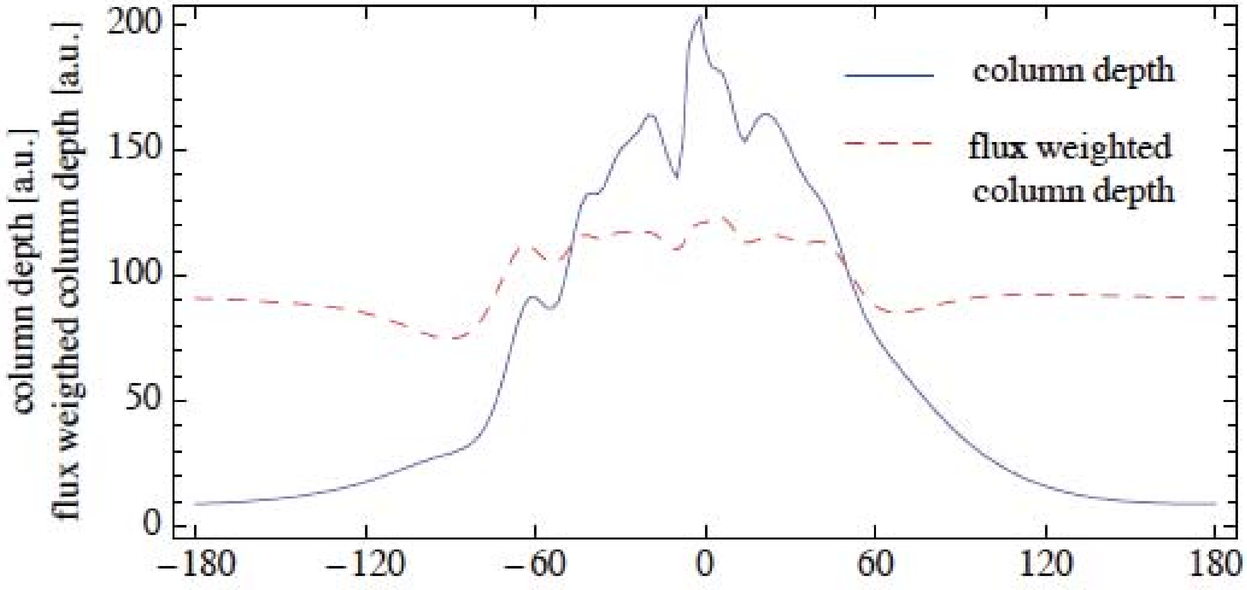
May be detectable with stacking analysis by *IceCube*

Kappes, Halzen & O'Murchadha, NIM A602:117,2008

Simulated SNR distribution which matches the *PAMELA* and *Fermi* data on electrons … with flux @ 15 TeV calculated assuming $E^{-2.75}$ spectrum and binned with $2^0 \times 4^0$ resolution



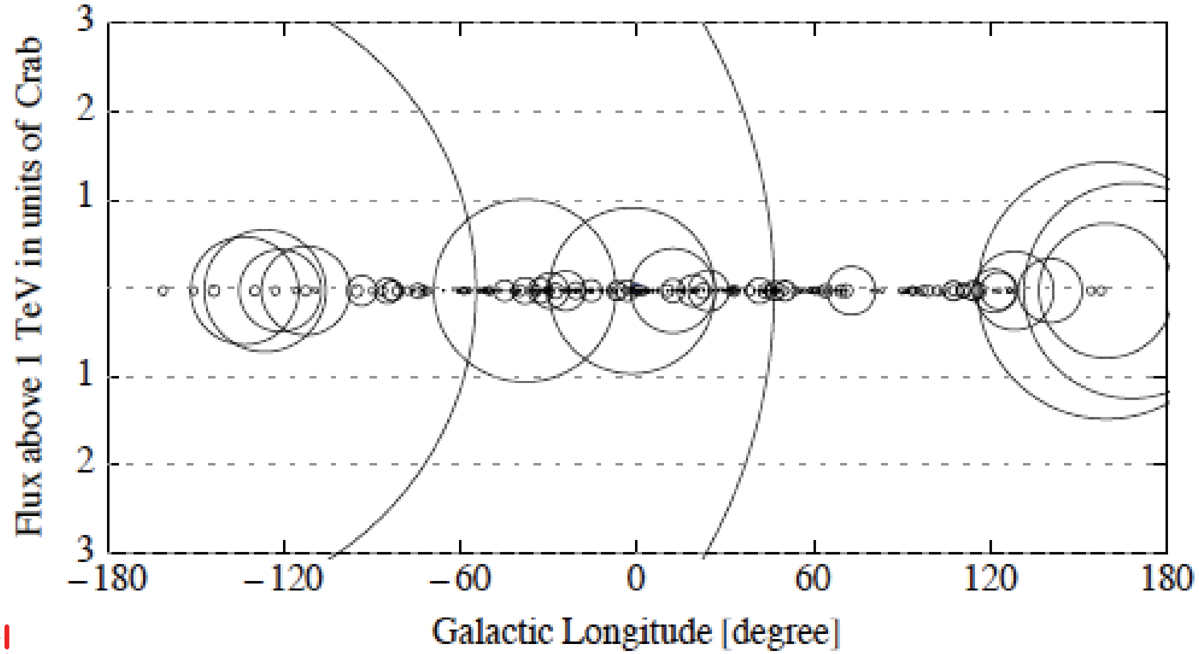
A *definitive* test would be to detect neutrinos from these old SNRs ...



The column depth and *flux weighted* column depth of the SNR density in the Galactic plane ... not very different towards Galactic centre/ anti-centre i.e. equally useful to survey Northern/Southern sky

Ahlers, Mertsch & Sarkar,PRD80:123017,2009

Simulated SNR distribution which matches the *PAMELA* and *Fermi* data on electrons. (the circle radius ⇒ brightness at > 1 TeV in units of the Crab)



$$F_{\nu_\mu}(> 1\ \mathrm{TeV}) \simeq 3.2 \times 10^{-12} \left(\frac{d}{2\ \mathrm{kpc}}\right)^{-2}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

5σ detection by *IceCube* in 3 yr!

Summary

The *PAMELA* anomaly may be the signature of a nearby ***hadronic*** accelerator (rather than of dark matter) – forthcoming data on antiprotons, B/C ratio *etc* (*AMS-02*) will provide a resolution

The source(s) should also be detectable directly in γ-rays (*HAWC, CTA*) and … neutrinos (*IceCube*)

This would be the *first* astronomical identification of cosmic 'pevatrons'