# *Seeing the high energy universe*

## *i) galactic cosmic rays*

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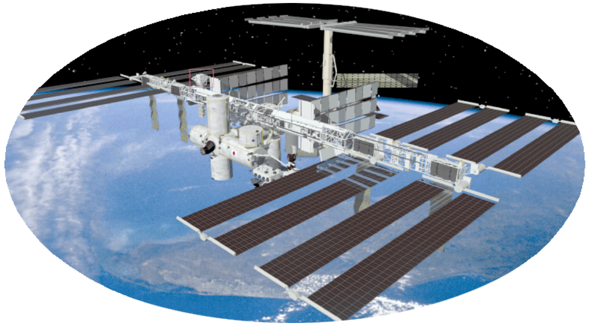
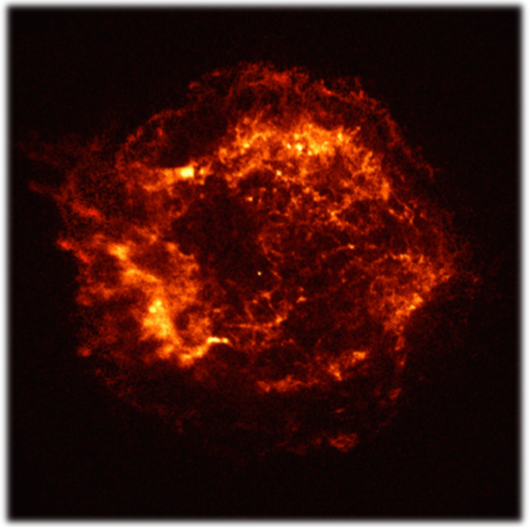
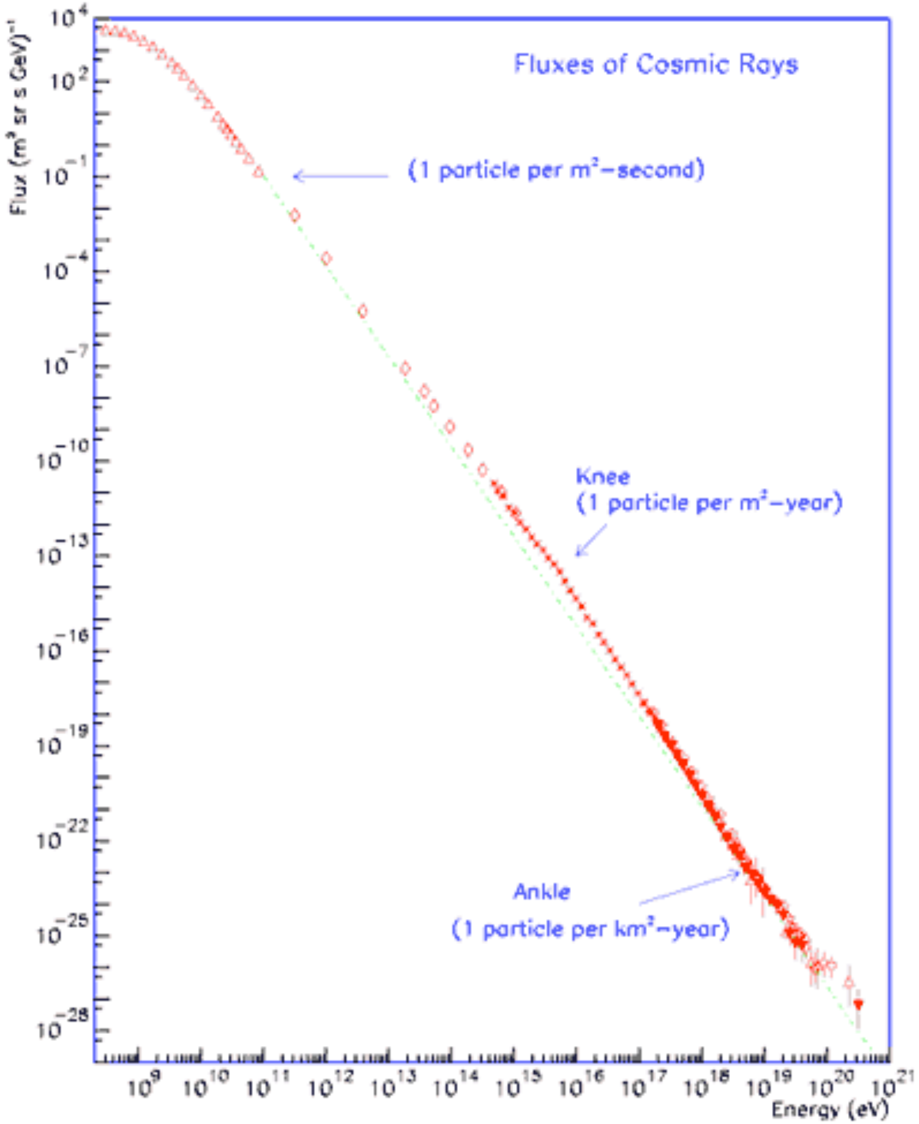
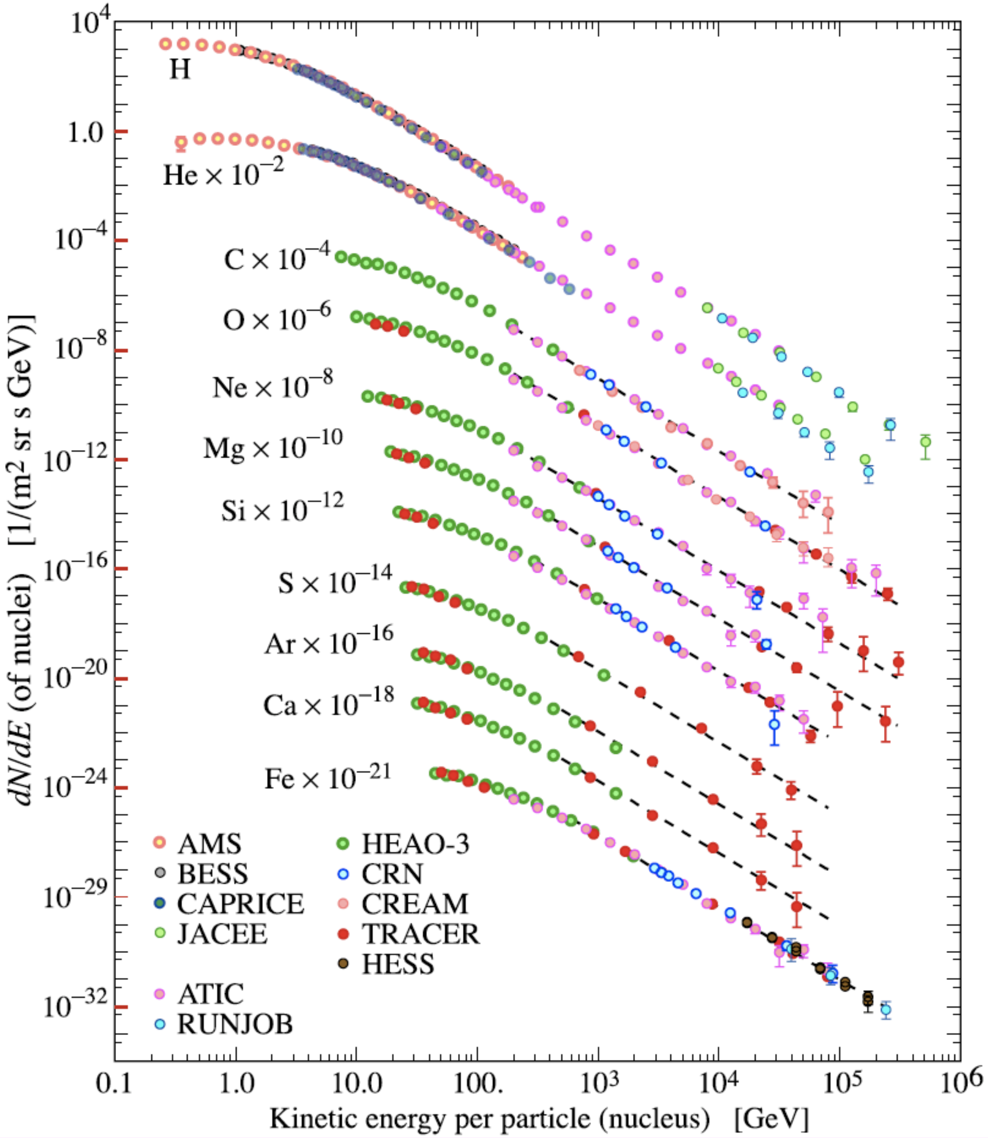




Lectures 1 & 2, *Taller de Altas Energias*, Universitat de Barcelona, 8th September 2010

# We are constantly bombarded by cosmic rays with energies ranging up to ~$10^8$ TeV

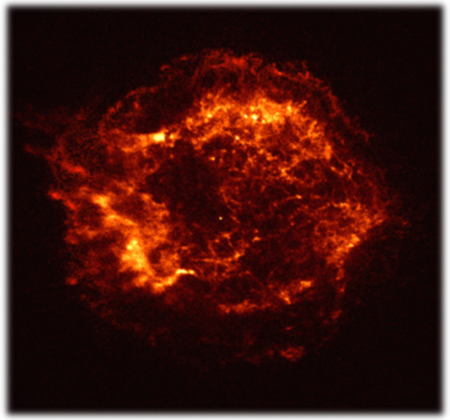




The composition of cosmic rays (up to the 'knee') mirrors that of the interstellar medium … with refractory elements enhanced, suggesting acceleration of circumstellar gas & dust grains by supernova shock waves (Meyer, Drury & Ellison, ApJ 487:182,1997, *ibid* 487,197)

# The sources of galactic cosmic rays have long been presumed to be supernova remnants

Direct evidence for acceleration of electrons (to > 40 TeV) from observation of synchrotron emission: radio ➔ X-rays

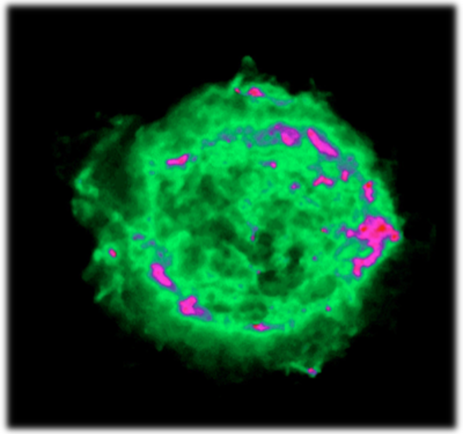


**Cassiopeia A**: *Chandra*

Energetics:

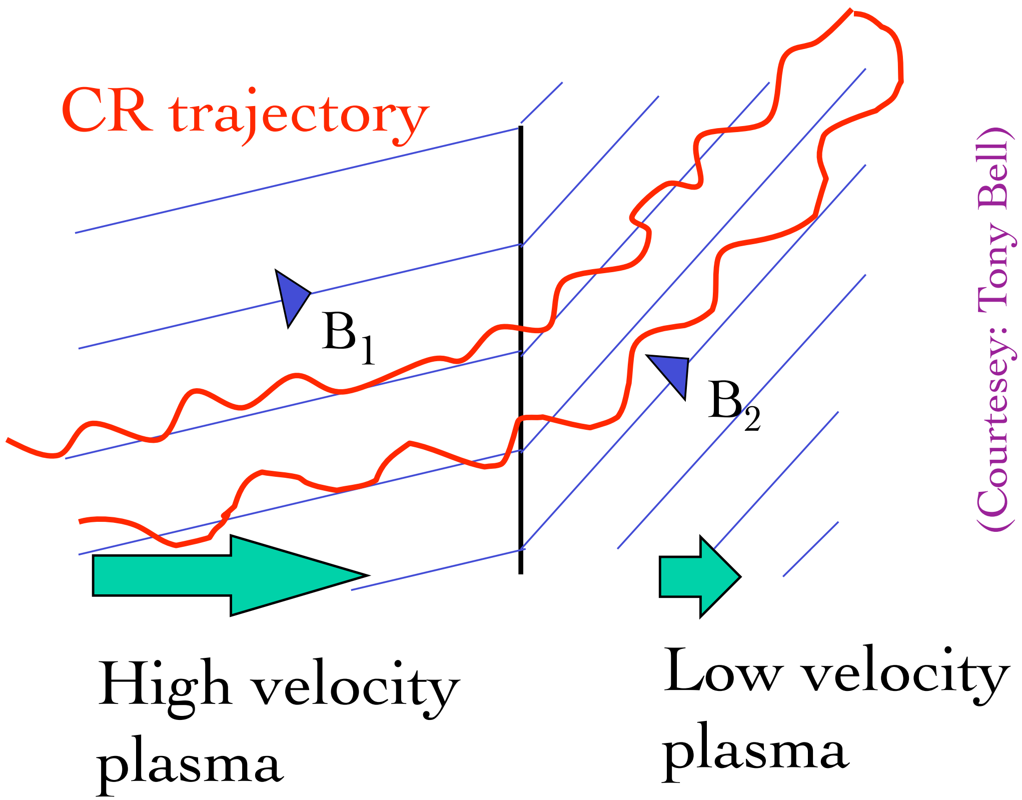
| | | |
|---|---|---|
| • | GCR energy density | $0.3\,\mathrm{eV\,cm^{-3}}$ |
| • | Volume of extended halo | $\pi(15\,\mathrm{kpc})^2\,3\,\mathrm{kpc} \simeq 5.7 \times 10^{67}\,\mathrm{cm}^3$ |
| ⇒ | Total GCR energy | $1.7 \times 10^{58}\,\mathrm{GeV} \simeq 2.8 \times 10^{55}\,\mathrm{erg}$ |
| • | Residence time of CRs in Galaxy | $20\,\mathrm{Myr}$ |
| ⇒ | Power needed | $1.4 \times 10^{48}\,\mathrm{erg\,yr^{-1}}$ |
| • | Galactic SN rate | $0.03\,\mathrm{yr}^{-1}$ |
| ⇒ | Required output/SN (remnant) | $4.6 \times 10^{49}\,\mathrm{erg}$ |

This is only ~5% of the benchmark kinetic energy of $10^{51}$ erg produced in a SN explosion



**Cassiopeia A**: *VLA*

# 1st-order Fermi acceleration by shock waves (DSA)



(Courtesey: Tony Bell)

Shock velocity $v_s$: $\beta = v_s/c$

Simple diffusion theory: prob. of CR crossing shock > $m$ times is $(1-\beta)^m$

Average fractional energy gained at each crossing is: $\Delta\varepsilon/\varepsilon = \beta$

$\Rightarrow$ differential spectrum $\propto \varepsilon^{-2}$

However if ~10% of the shock wave K.E. is converted into relativistic particles, then backreaction of cosmic ray pressure on shock will make spectrum somewhat **harder and slightly concave** (*cf.* radio observations) … but *time-integrated* spectrum will still be close to Fermi form (Caprioli, Amato & Blasi, Astropart.Phys.33:160,2010)

If cosmic rays diffuse out of Galaxy on a time-scale decreasing $\propto 1/\varepsilon^{0.6}$, then the observed spectrum $\propto \varepsilon^{-2.6}$ is matched (but why is no anisotropy $\propto \varepsilon^{0.6}$ observed?)

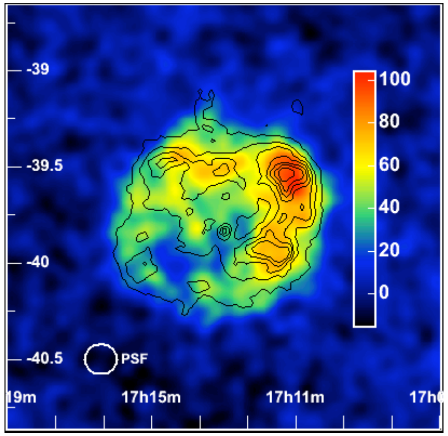
# We are witnessing rapid advances in γ-ray astronomy

→ the sources of low energy cosmic rays may soon be known: **SNRs**?

➢ Do the observed γ-rays arise from hadronic interactions ($\pi^0$ decays) , or from inverse-Compton scattering by (radio synchrotron emitting) electrons ?

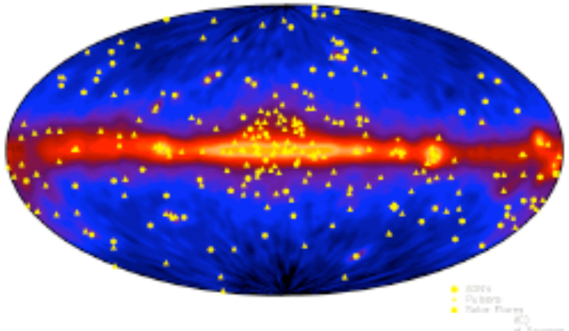
➢ Can 1st-order Fermi acceleration at SNR shocks explain the spectrum (injection, magnetic field amplification, diffusion losses vs anisotropy) ?

➢What are the 'unidentified' γ-ray sources in the Milky Way – are there new source classes (micro-quasars, PWN, binaries …), acceleration mechanisms ?

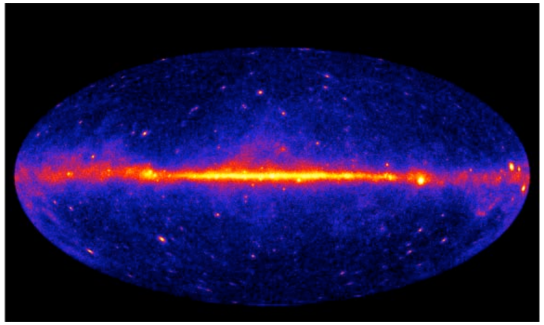


**RXJ1713.7-3946** (*HESS*, 2004)

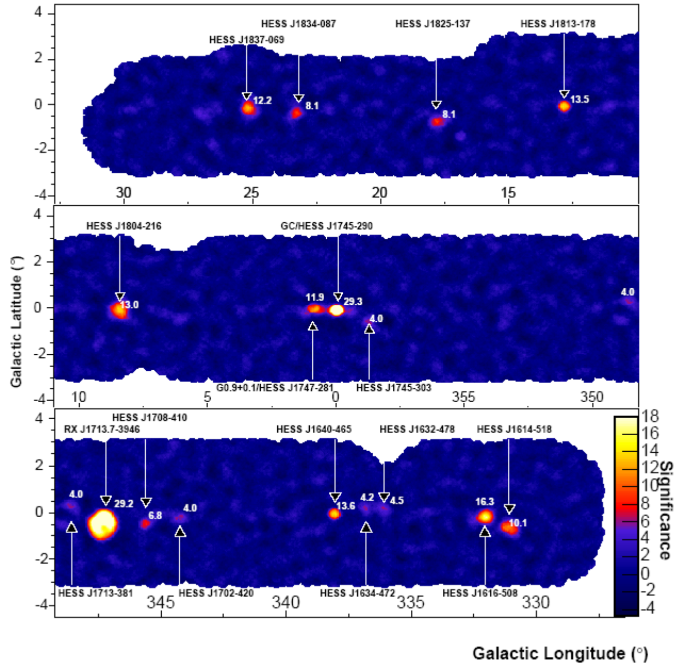
**EGRET 1991 - 2000**



**Fermi 2009 -**



**HESS Southern Plane Survey 2005**

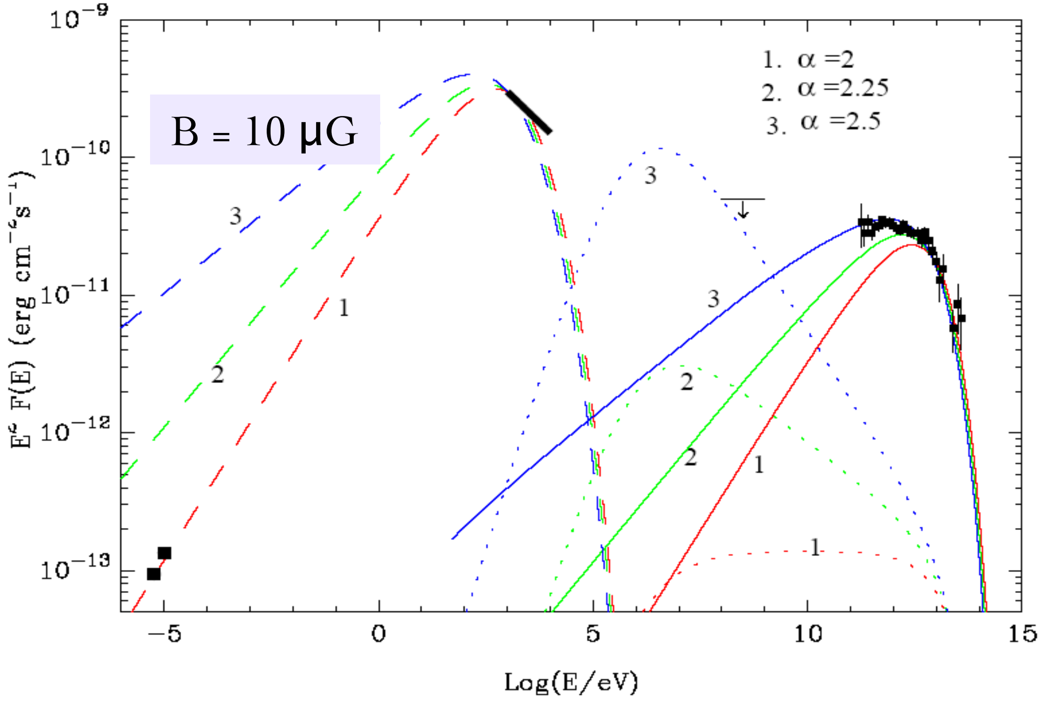


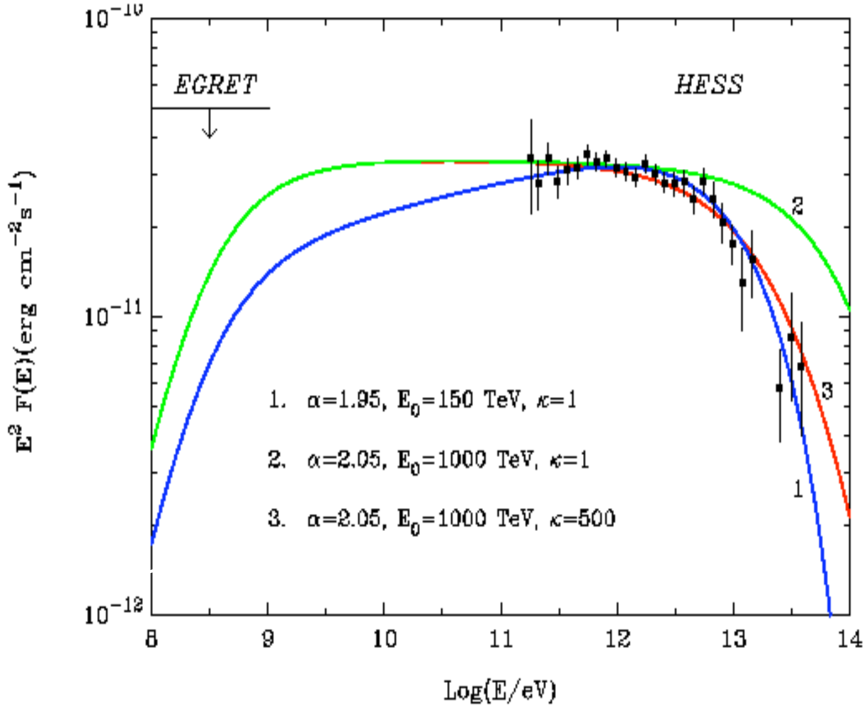
Much progress has been made but these questions are *not* fully answered …

to *unambiguously* identify the cosmic ray sources, we need to detect TeV neutrinos!

… also the *PAMELA* and *Fermi* 'anomalies' have highlighted the limitations of the standard diffusion model

# Cosmic ray acceleration in RXJ1713.7-3946: **electrons** or **protons**?





(HESS collaboration, 2006)

$\gamma$-ray emission well fitted by IC scattering of ~$10^2$ TeV electrons on CMB/starlight
… alternatively $\gamma$-rays may be from decays of $\pi^0$s produced by ~$10^3$ TeV protons

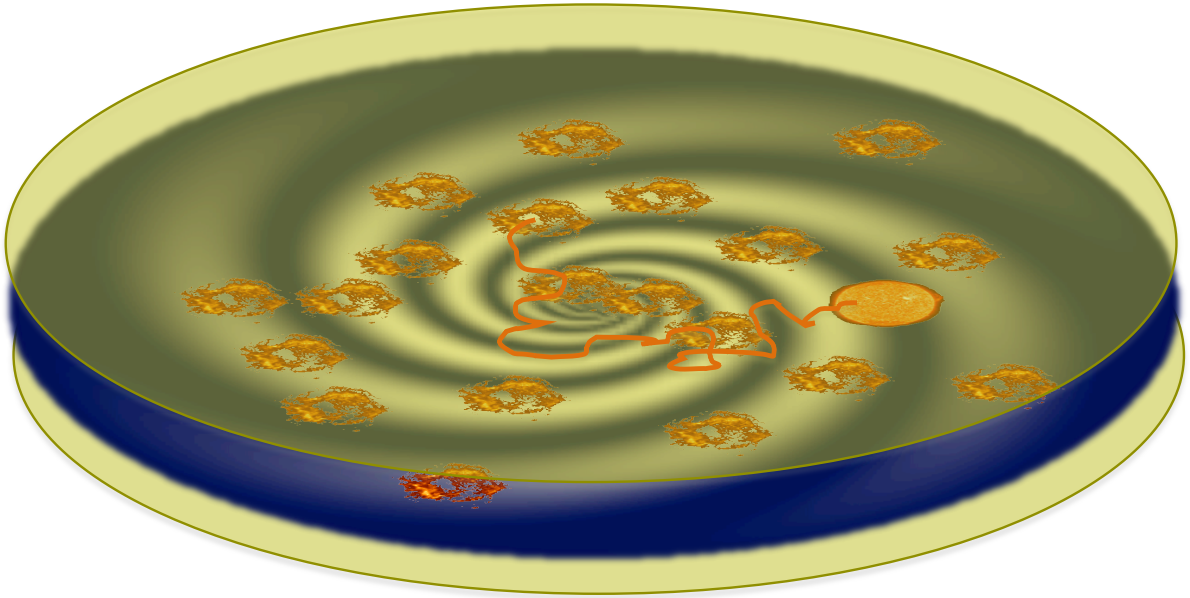
**There is no *definite* evidence yet that SNRs accelerate *protons* to high energies**
… this will be *proved* only when the **neutrinos** from $\pi^0$ decay are detected

# The ‘standard model’ for galactic cosmic rays

❑ SNR shock waves accelerate relativistic particles by Fermi mechanism

➪ power law spectrum (synchrotron radio/X-ray + $\gamma$-ray emission)

❑ Diffusion through magnetic fields in Galaxy (disk + halo)



❑ Secondary production during propagation: $\bar{p}, e^+, N'$

❑ $e^\pm$ lose energy through synchrotron & inverse Compton scattering

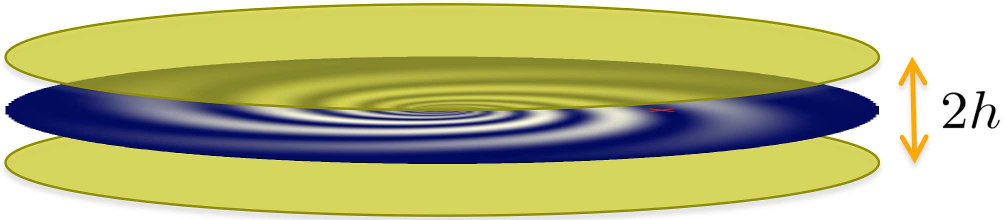
Measurables: Energy spectra of individual species, diffuse radiation

# 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:

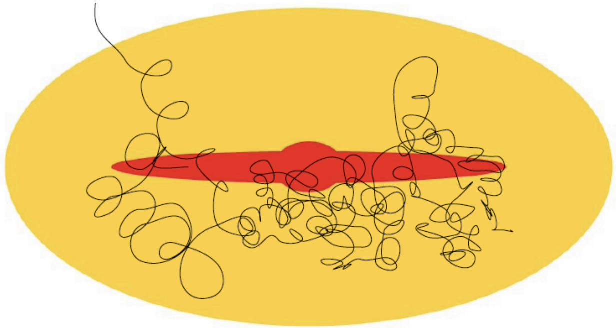


Green's function: describes flux from a discrete, burst-like source

… integrate over spatial distribution and time-variation of injection

**GALPROP** (Moskalenko & Strong ApJ 493:694,1998, *ibid* 509:212,1998) can solve the time-dependent transport equation but yields ~the same answer for the *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

# The ‘leaky box’ model



Transport equation:

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

Averaging over extended cosmic ray halo ⇒ steady state solution

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

Escape through diffusion: $\tau_{esc} \sim E^{-\delta}$, with $\delta \sim 0.6$ (from secondary/primary ratios)

Energy loss through synchrotron radiation/IC scattering: $\tau_{cool} \sim E^{-1}$

# Energy spectra

**Primary $e^-$**

— Production: $q \propto E^{-2.2}$ (from radio spectrum)

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

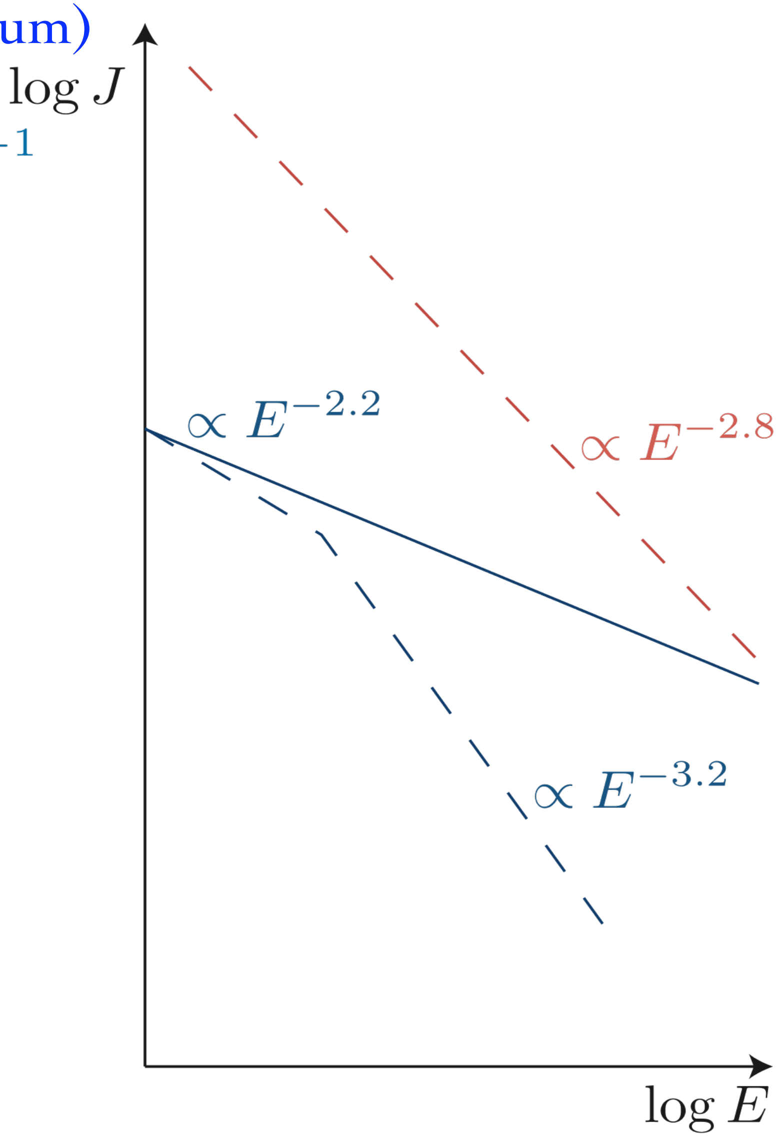
Observed: $n \propto E^{-2.8}, E^{-3.2}$

**Primary protons/nuclei**

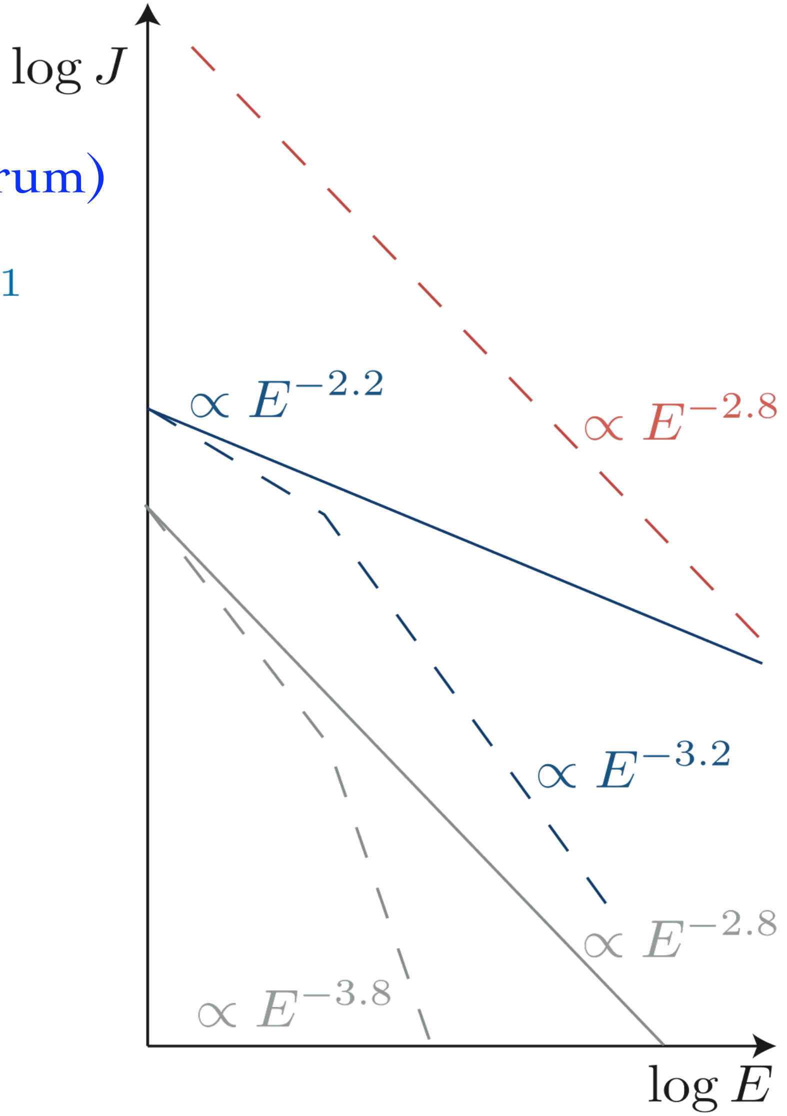
Production: presumably same as $e^-$

- - - Propagation:

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



# Energy spectra



**Primary $e^-$**

— Production: $q \propto E^{-2.2}$ (from radio spectrum)

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

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

**Primary protons/nuclei**

Production: presumably same as $e^-$

- - - Propagation:

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

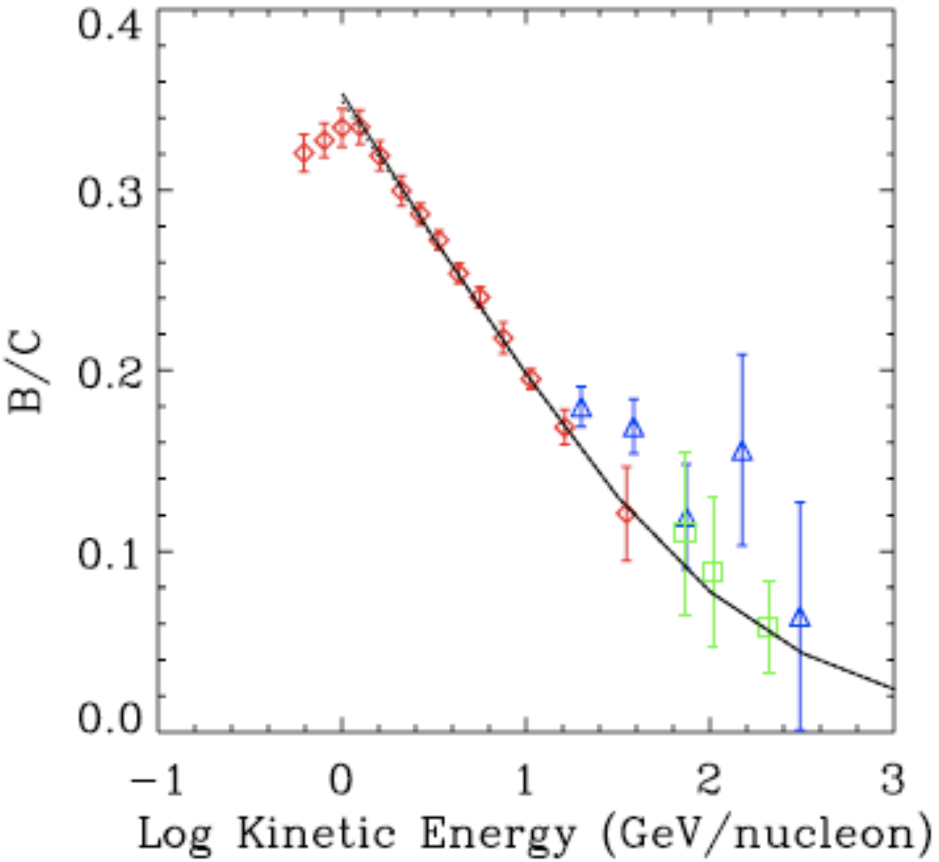
**Secondary**

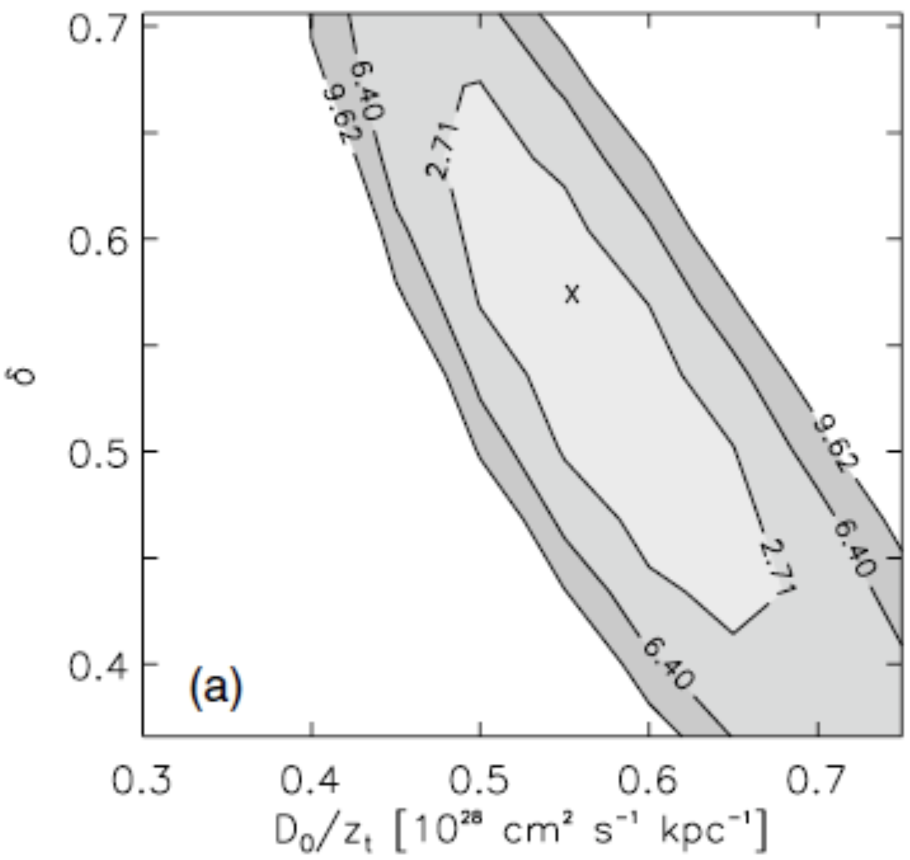
production: $q \propto E^{-2.8}$

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

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

# Secondary-to-primary ratios (using DRAGON code)



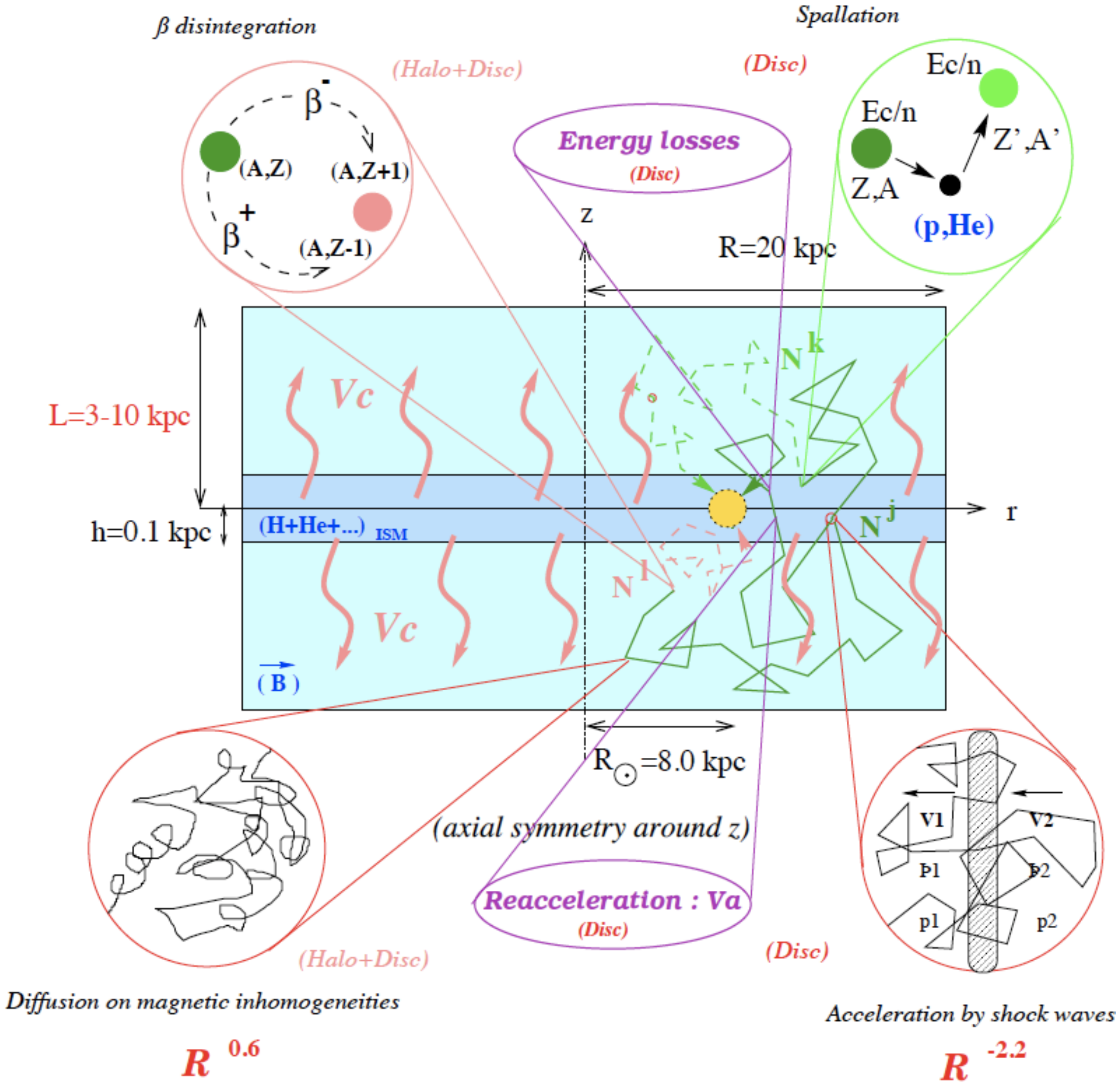


(Evoli, Gaggero, Grasso & Maccione, JCAP 10:018,2008)

All measured ratios consistent with 'leaky box' model with $\tau_{\rm esc} \sim E^{-\delta}$, $\delta \sim$ 0.4-0.6

NB: Kolmogorov spectrum for interstellar magnetic field turbulence implies $\delta = 1/3$, while Kraichnan spectrum implies $\delta = 1/2$

# The ‘two zone’ model



Maurin, Taillet, Donato, Salati, Barrau & Boudoul [astro-ph/0212111]

Semi-analytic formulation provides better insight and estimation of uncertainties

# But none of this would be particularly interesting to high energy physicists if it were not for **the *PAMELA* 'anomaly'** …

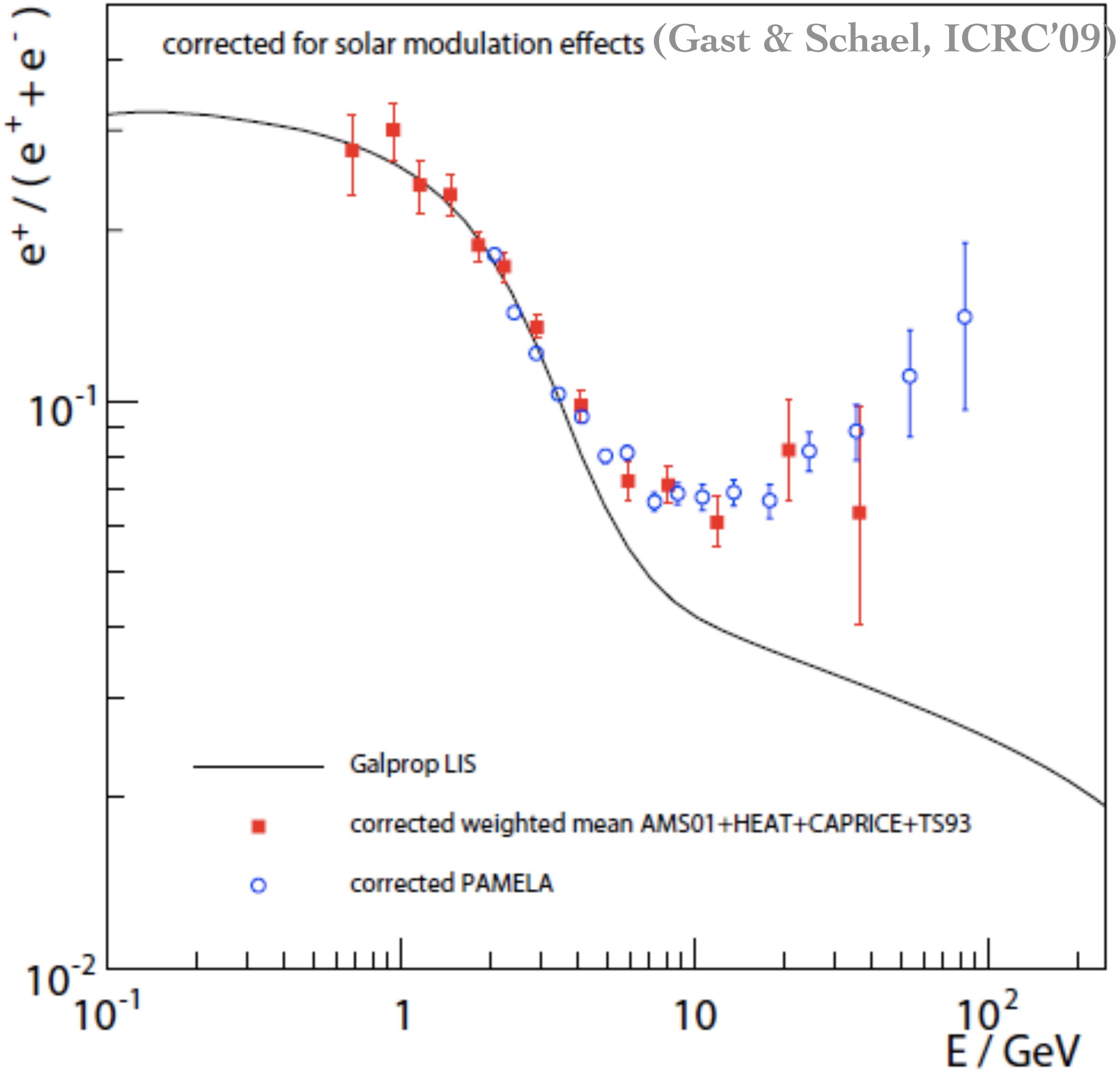
***PAMELA*** has measured the positron fraction:

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

Anomaly ⇒ excess above 'astrophysical background'

Source of anomaly:

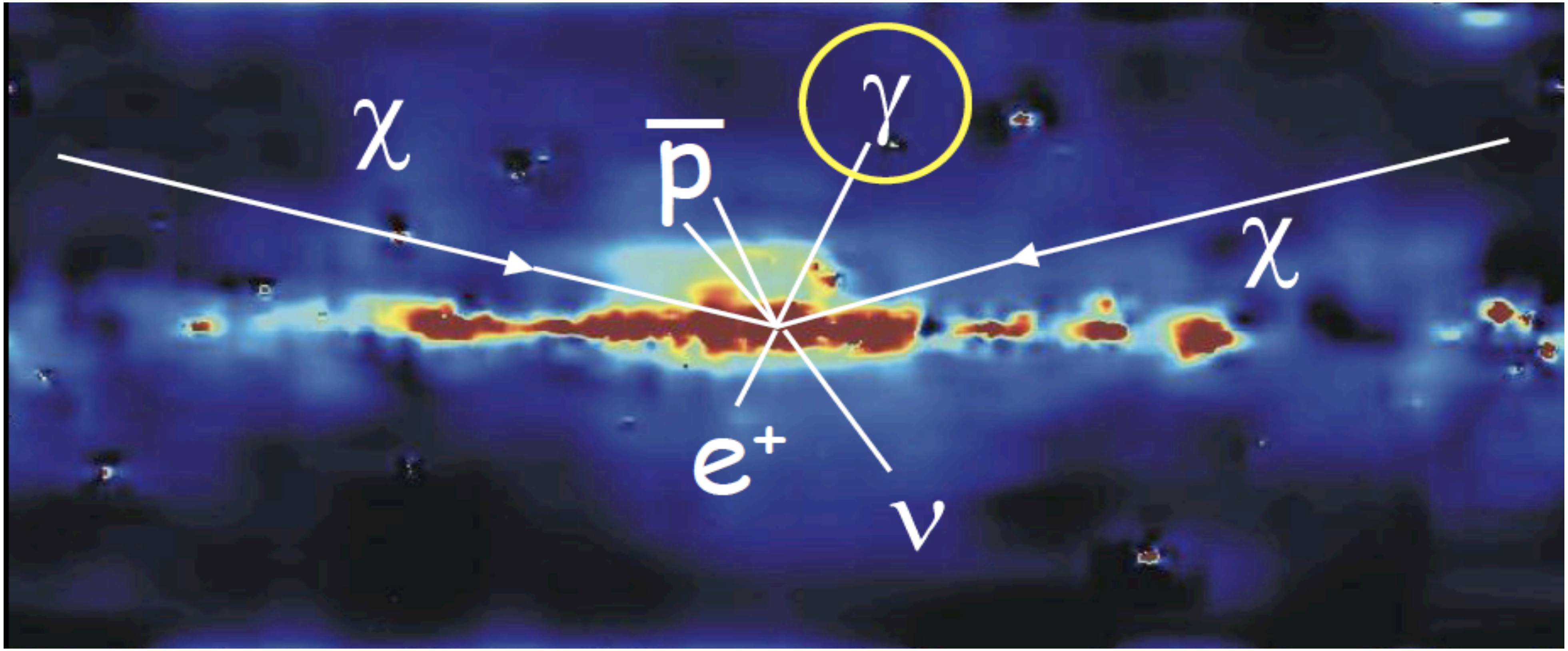
- Dark matter?
- Pulsars?
- Supernova remnants?



(Gast & Schael, ICRC'09)

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

# *PAMELA* was designed to search for cosmic *anti*-matter



(courtesey: Gianfranco Bertone)

… positrons from the annihilations or decays of dark matter in the Galaxy would *naturally* have a hard spectrum corresponding to rising $e^+$ fraction

# Indeed dark matter has been widely invoked as the source of the ‘excess’ $e^+$.

## DM annihilation

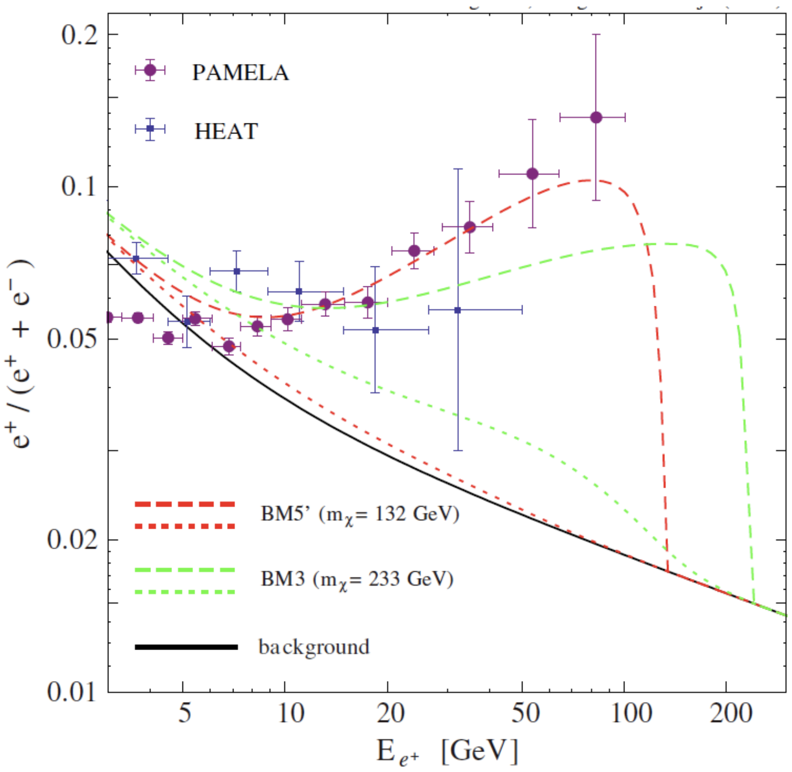
Rate $\propto n_{\mathrm{DM}}^2$

(e.g. few hundred GeV neutralino LSP or Kaluza-Klein state)

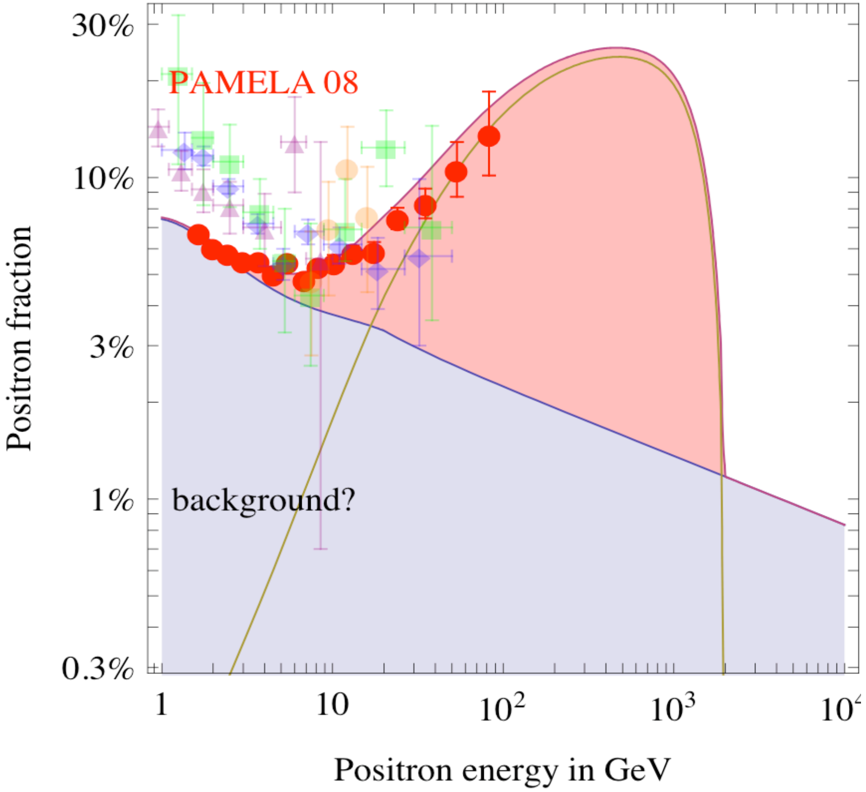
## DM decay

Rate $\propto n_{\mathrm{DM}}/\tau_{\mathrm{DM}}$

(lifetime ~$10^9$ x age of universe e.g. dim-6 operator suppressed by $M_{\mathrm{GUT}}$ for a TeV mass techni-baryon)



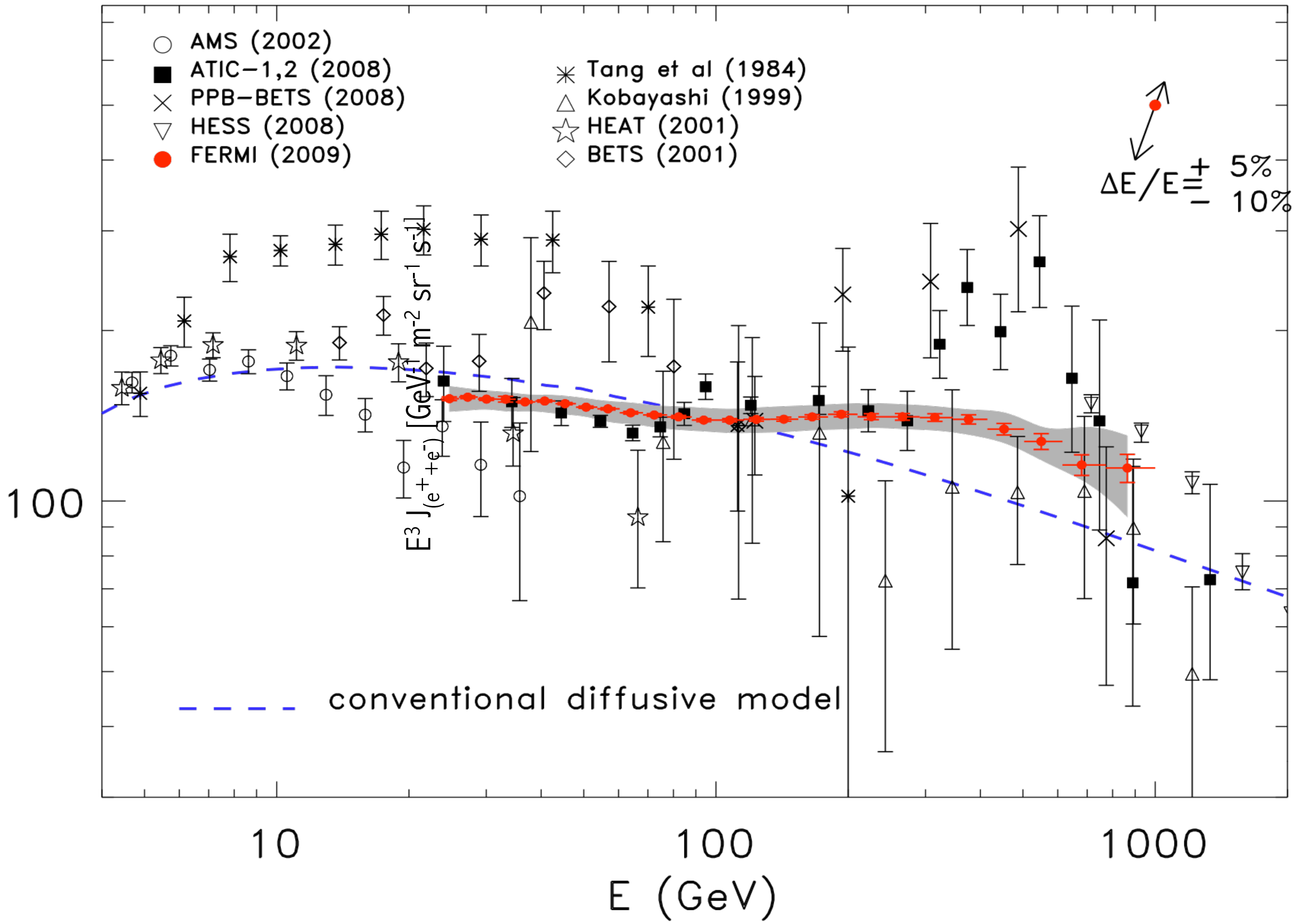
Bergström, Bringmann & Edjsö, PR D78:127850,2008



Nardi, Sannino & Strumia, JCAP 0901:043,2009

FERMI

# The ~~ATIC~~ excess

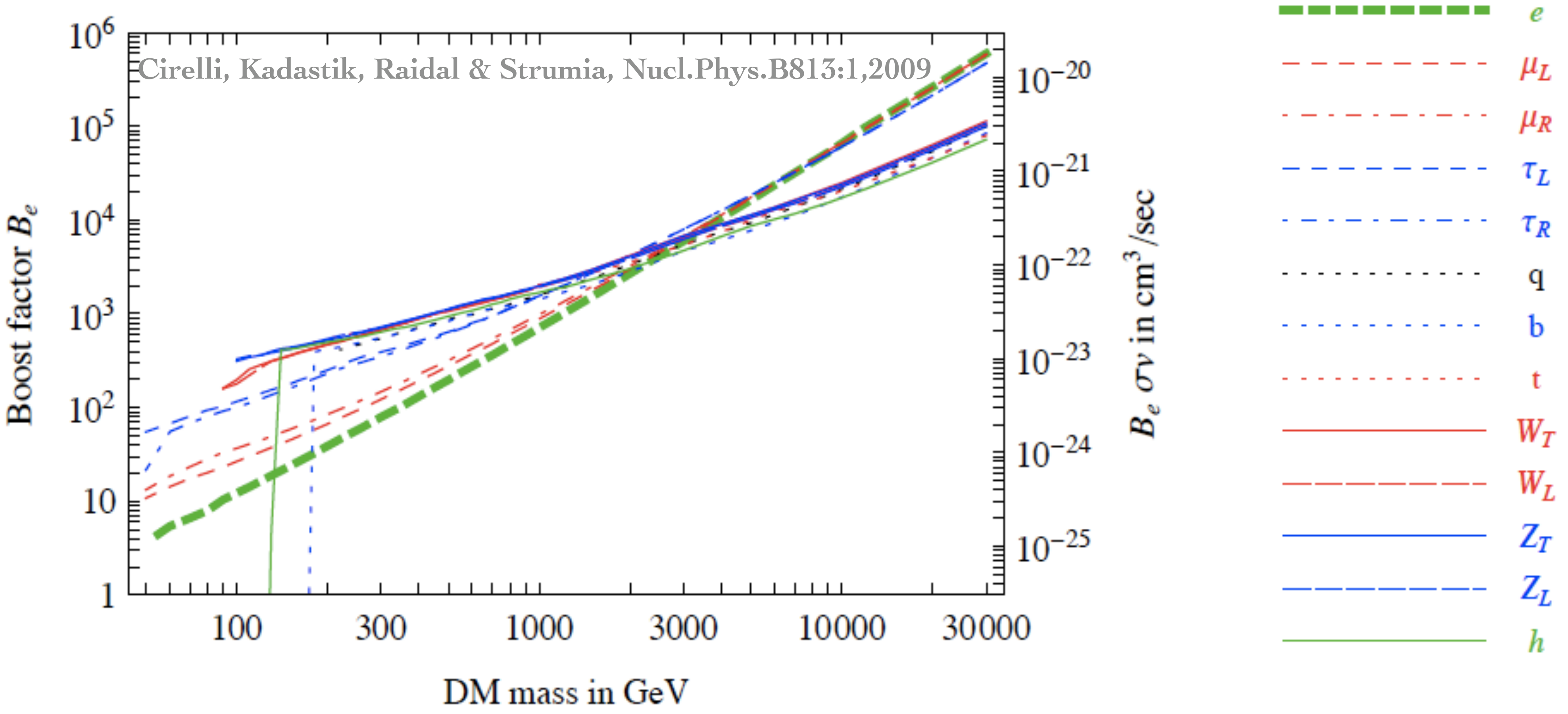


***Fermi* LAT also sees 'excess' $e^\pm$ over expectation** (Abdo *et al*, PRL 102:181101,2009)
(although it does *not* confirm the peak seen earlier by *ATIC*-2)

# But DM annihilation requires huge 'boost factor' to match flux

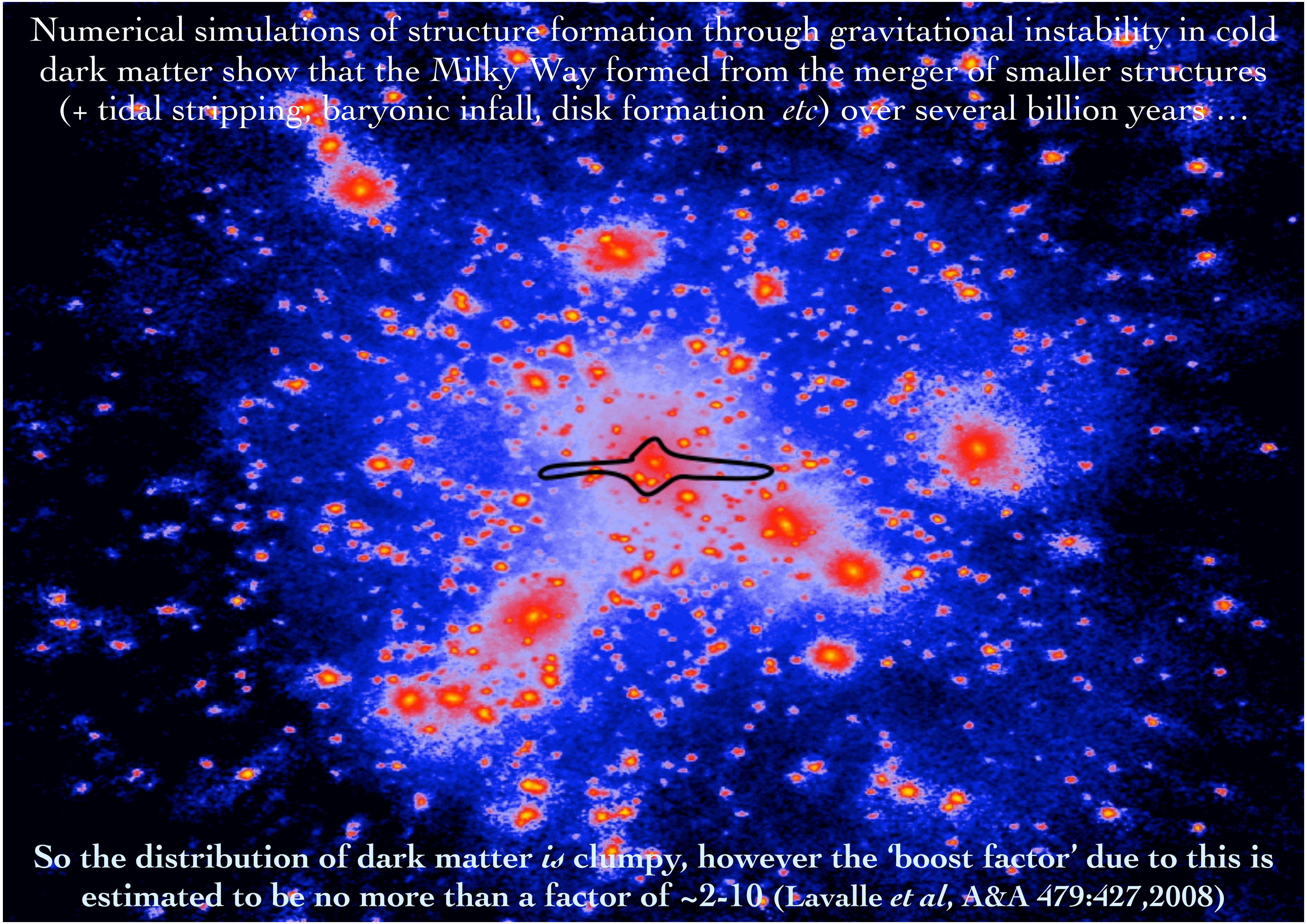
➔ Such a large annihilation #-section would imply *negligible* relic abundance unless an *inverse* velocity dependence is invoked e.g. 'Somerfeld enhancement' (this requires hypothetical light gauge bosons to provide new long range force)

Arkani-Hamed *et al*, PR D79:015014,2009


Cirelli, Kadastik, Raidal & Strumia, Nucl.Phys.B813:1,2009

... no such problem for decaying dark matter (just tune the lifetime!)

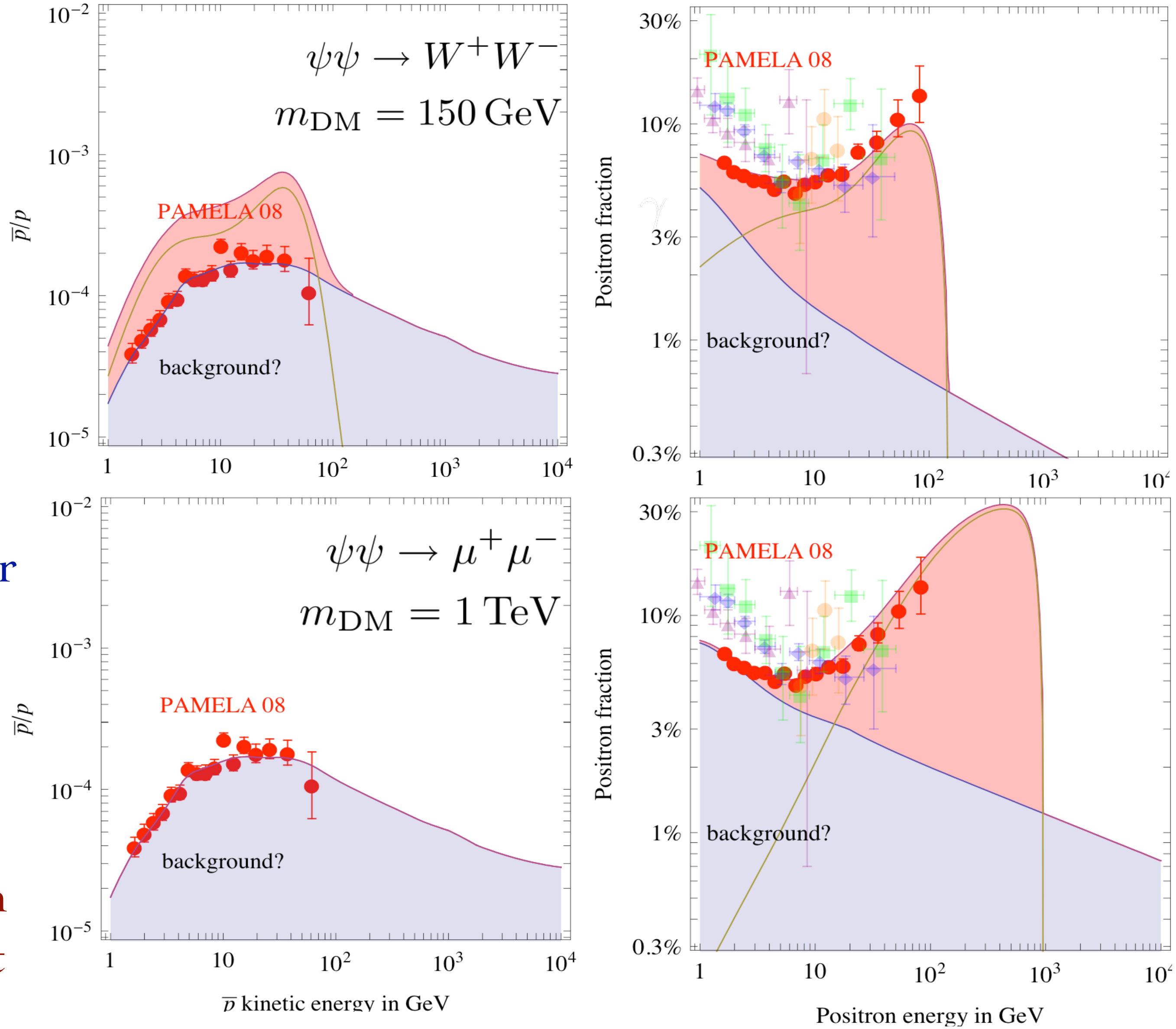
Numerical simulations of structure formation through gravitational instability in cold dark matter show that the Milky Way formed from the merger of smaller structures (+ tidal stripping, baryonic infall, disk formation *etc*) over several billion years …



**So the distribution of dark matter *is* clumpy, however the 'boost factor' due to this is estimated to be no more than a factor of ~2-10 (Lavalle *et al*, A&A 479:427,2008)**

# But the observed antiproton flux is *consistent* with the background expectation (from standard cosmic ray propagation in the Galaxy)

**This is a serious constraint on *all* dark matter models of the *PAMELA* anomaly**



Can fit with DM decay or annihilation only if DM particles are 'leptophilic' which is rather contrived

… In any case, most such models are now ruled out by *Fermi* [arXiv:1002.4415]

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

# This is not the first time an anomalous ‘excess’ over background has been seen …

## Inclusive Jet Cross Section in $\overline{p}p$ 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

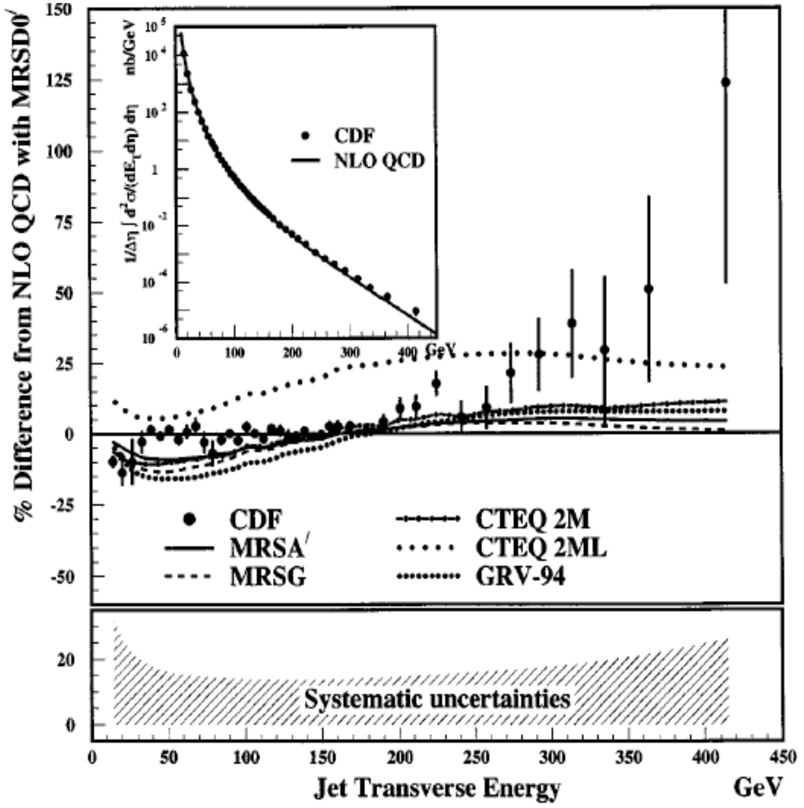
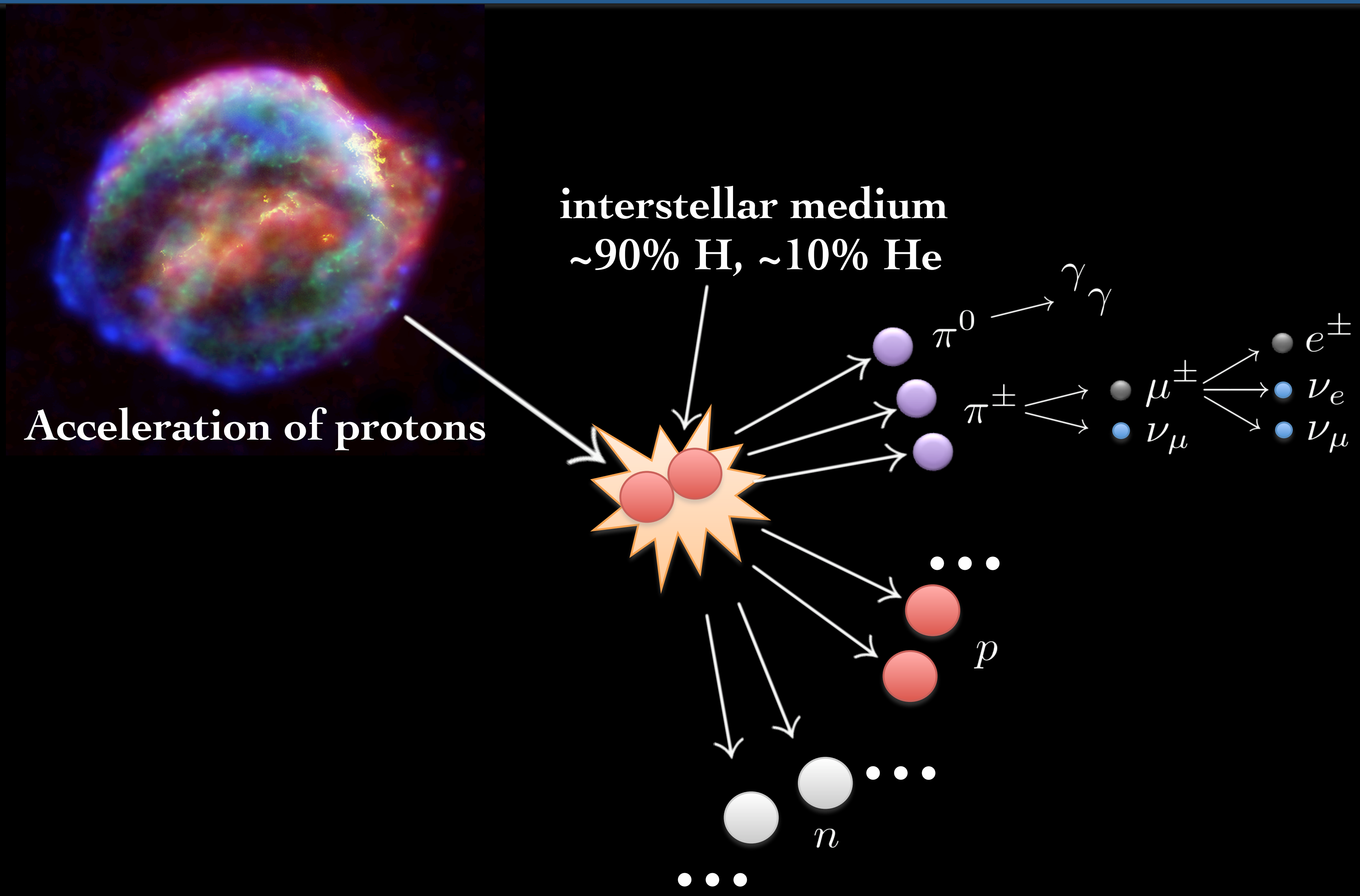


FIG. 1. The percent difference between the CDF inclusive jet cross section (points) and a next-to-leading order (NLO) QCD prediction using MRSD0′ PDFs. The CDF data (points) are compared directly to the NLO QCD prediction (line) in the inset. The normalization shown is absolute. The error bars represent 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!

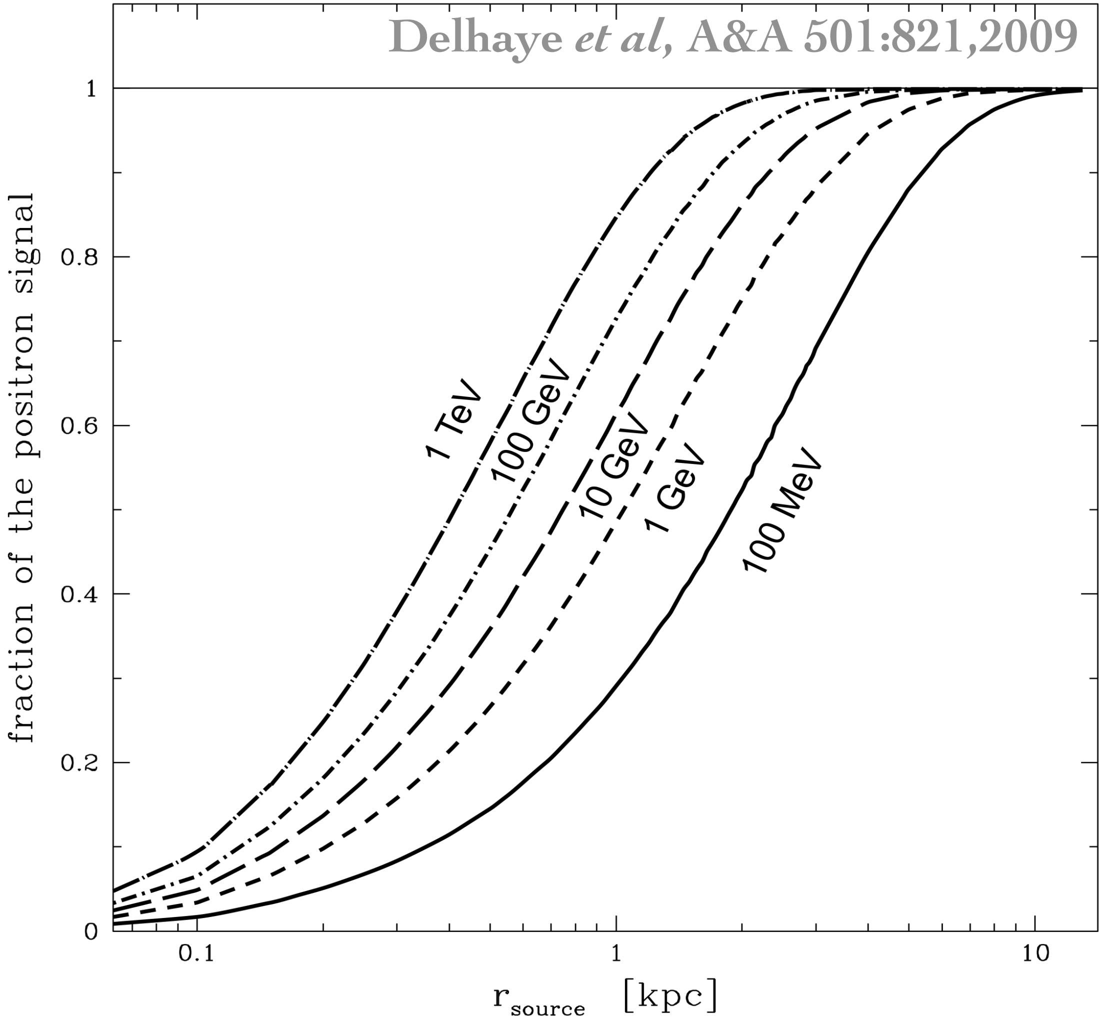
# The ‘background’ here is the production of secondary $e^{\pm}$ during propagation (calculated using GALPROP)



**Acceleration of protons**

**interstellar medium**
**~90% H, ~10% He**

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



Delhaye *et al*, A&A 501:821,2009

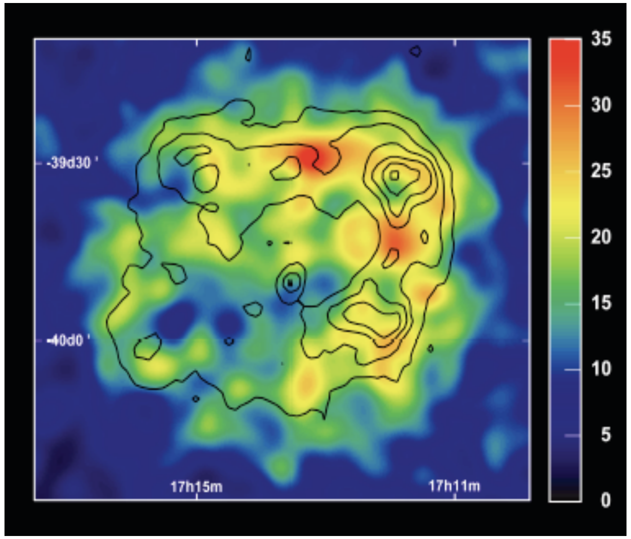
$$\tau \simeq 5 \cdot 10^5 \mathrm{yr} \left(\frac{1\,\mathrm{TeV}}{E}\right)$$

So the real question is:
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 being produced *during* acceleration … which are then accelerated along with the primaries

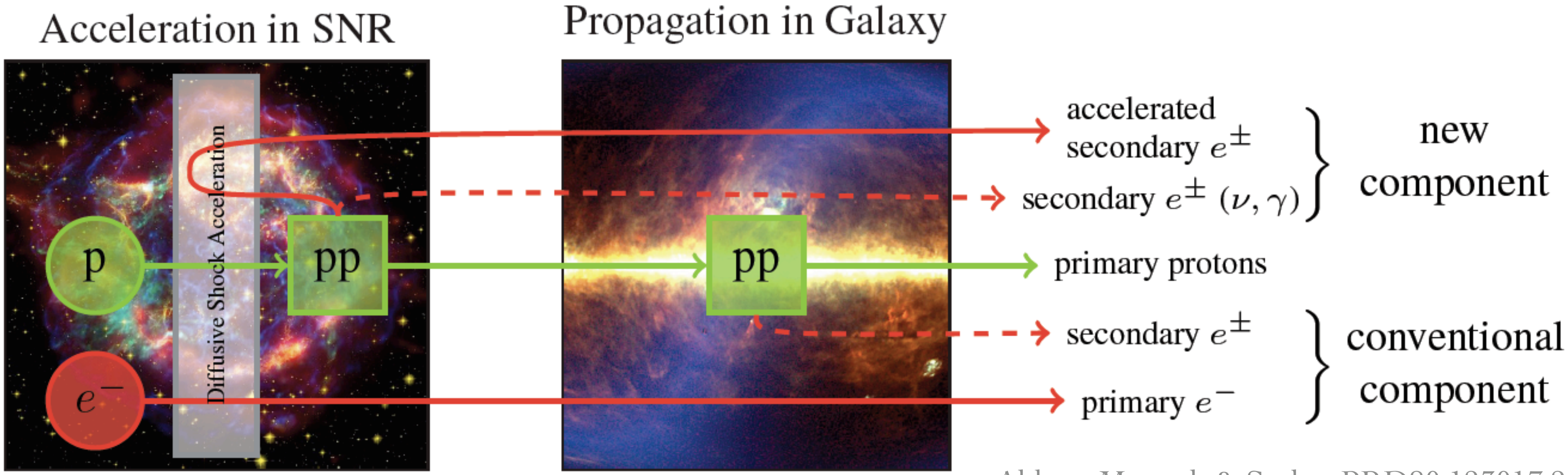
(Blasi, PRL 103:051104,2009)



**RXJ1713.7-3946, *HESS***

… 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 and fits *PAMELA* data (adjusting 1 free parameter)



Acceleration in SNR

Propagation in Galaxy

Diffusive Shock Acceleration

p

$e^-$

pp

pp

accelerated secondary $e^\pm$

secondary $e^\pm$ $(\nu, \gamma)$

new component

primary protons

secondary $e^\pm$

primary $e^-$

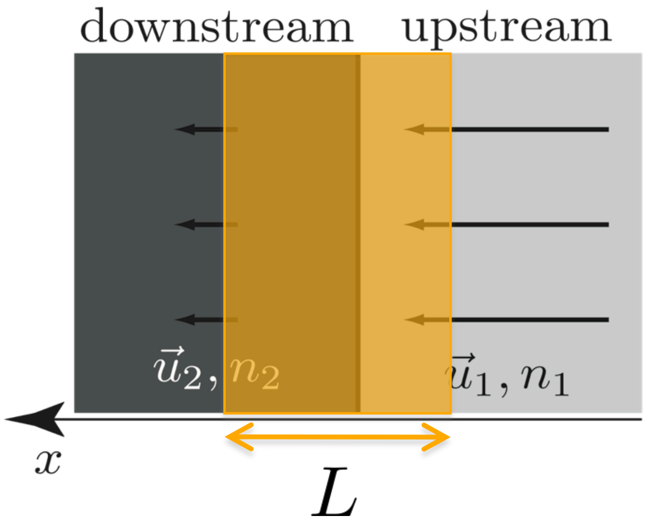
conventional component

Ahlers, Mertsch & Sarkar,PRD80:123017,2009

# Diffusive (1st-order Fermi) shock acceleration

Consider flux:

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

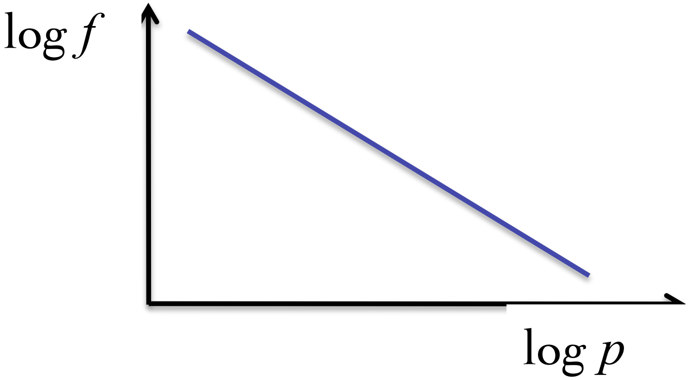


**Conservation equation:**

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

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

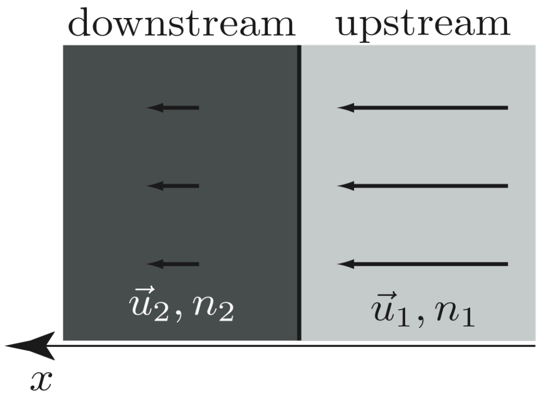
$$\Rightarrow f(p) \propto p^{-3u_1/(u_1 - u_2)} = p^{-\gamma}$$



# Diffusive ($1^{\text{st}}$-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, $u\frac{\partial f}{\partial x} = D\frac{\partial^2 f}{\partial x^2} + \frac{1}{3}\frac{\mathrm{d}u}{\mathrm{d}x}p\frac{\partial f}{\partial p}$

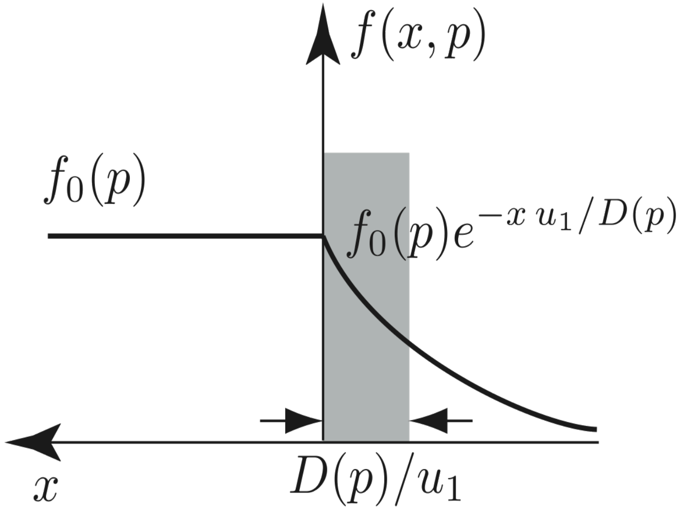
$$f \xrightarrow{x\to-\infty} f_{\mathrm{inj}}(p), \qquad \left|\lim_{x\to\infty} f\right| \ll \infty$$

Solution for $x < 0$:

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

where

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



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

# DSA with secondary production

- Secondaries have same spectrum as primaries:

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

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

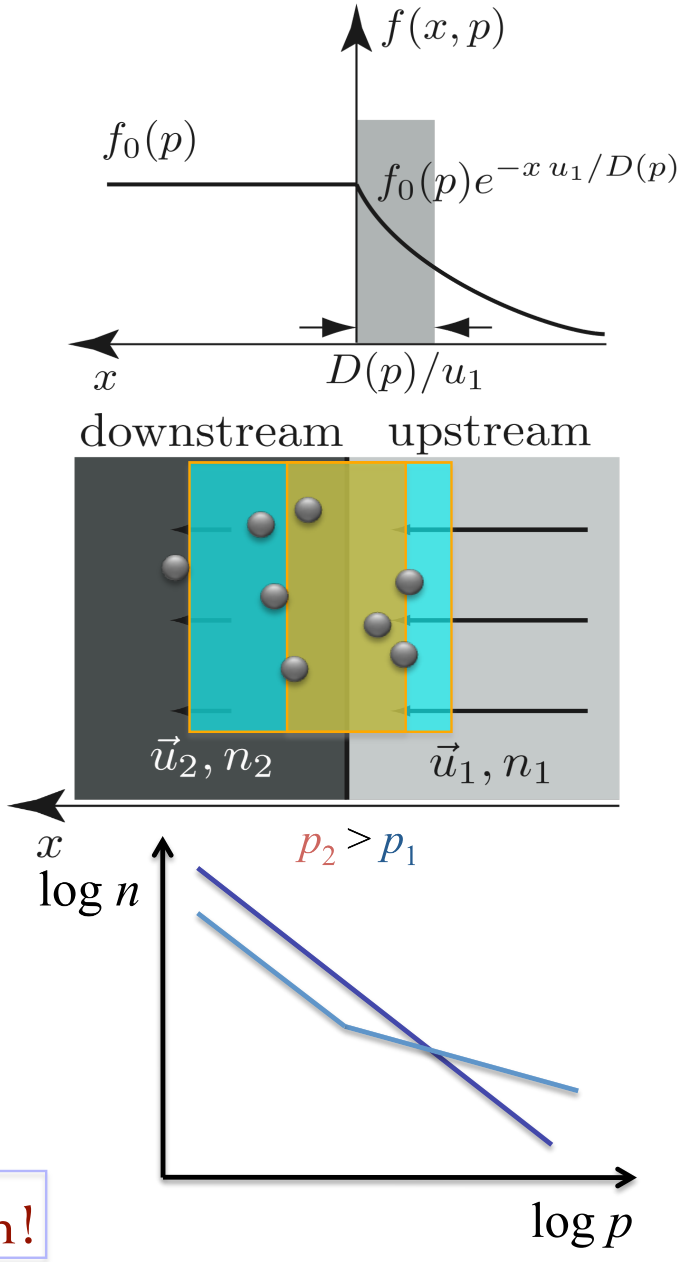
- Bohm diffusion: $D(p) \propto p$

- Fraction of accelerated secondaries is $\propto p$

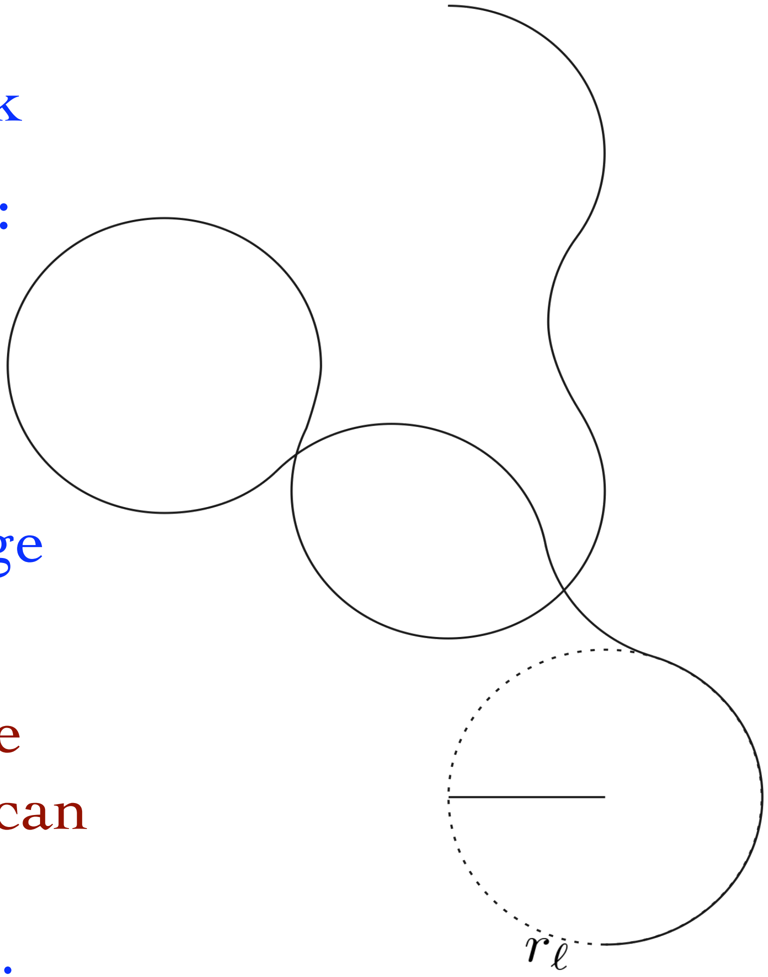
- **Steady state spectrum**

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

➔ *rising* positron fraction!



# Diffusion near shock front



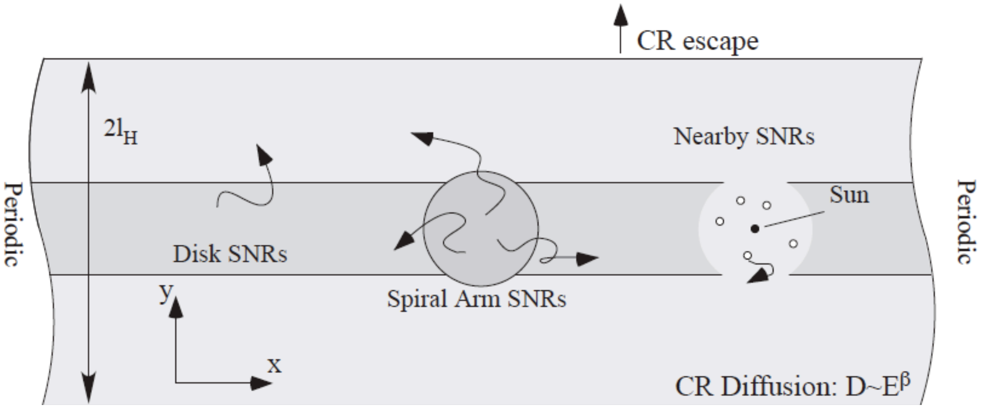
- Diffusion coefficient not known *a priori* in neighbourhood of shock
- 'Bohm diffusion' sets a *lower* limit:

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

- Actual rate parametrised by 'fudge factor': $D = D^{\text{Bohm}} \mathcal{F}^{-1}$
- $\mathcal{F}^{-1}$ determined by fitting to one secondary/primary ratio … then can *predict* other ratios
- Can in principle determine diffusion rate from simulations (difficult!)

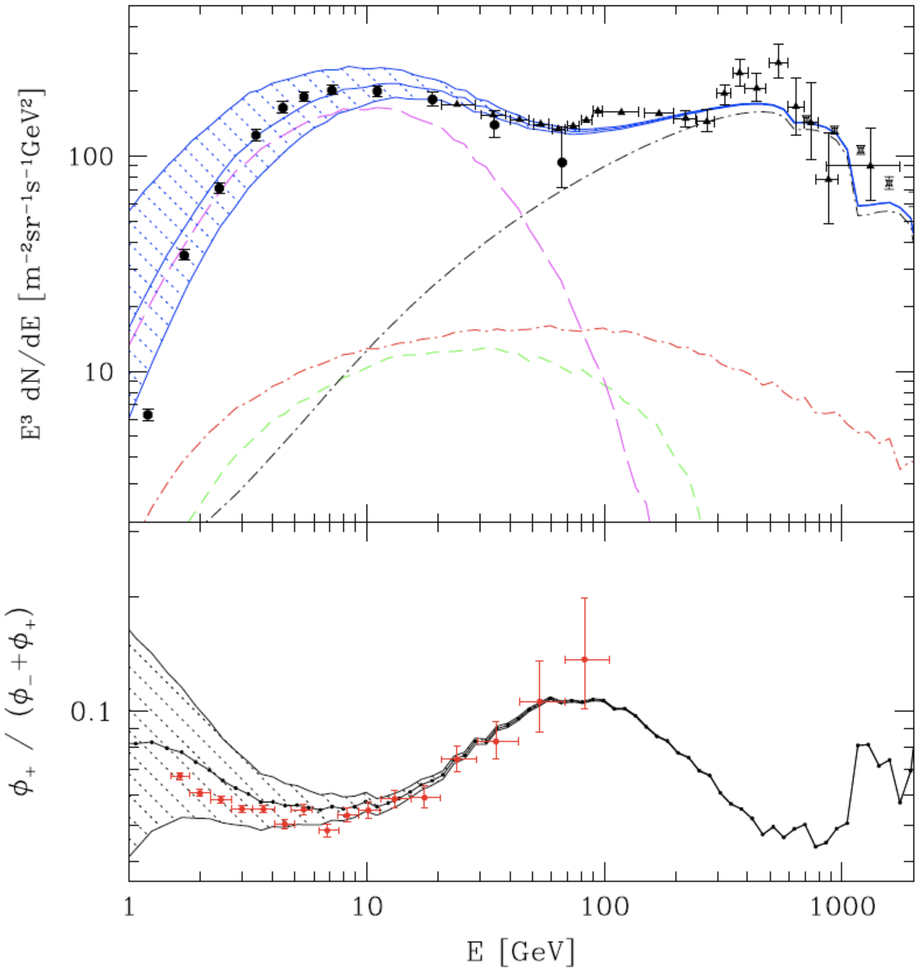
# Inhomogeneity in the SNR distribution as the origin of the PAMELA anomaly

Shaviv, Nakar & Piran, PRL 103:111302,2009



Idea: Electrons from nearby SNRs cool above ~ 20 GeV (through synchrotron and inverse-Compton losses) before reaching us … but protons do *not* cool, so secondary positron production is less affected

⇒ enhancement of $e^+/e^-$

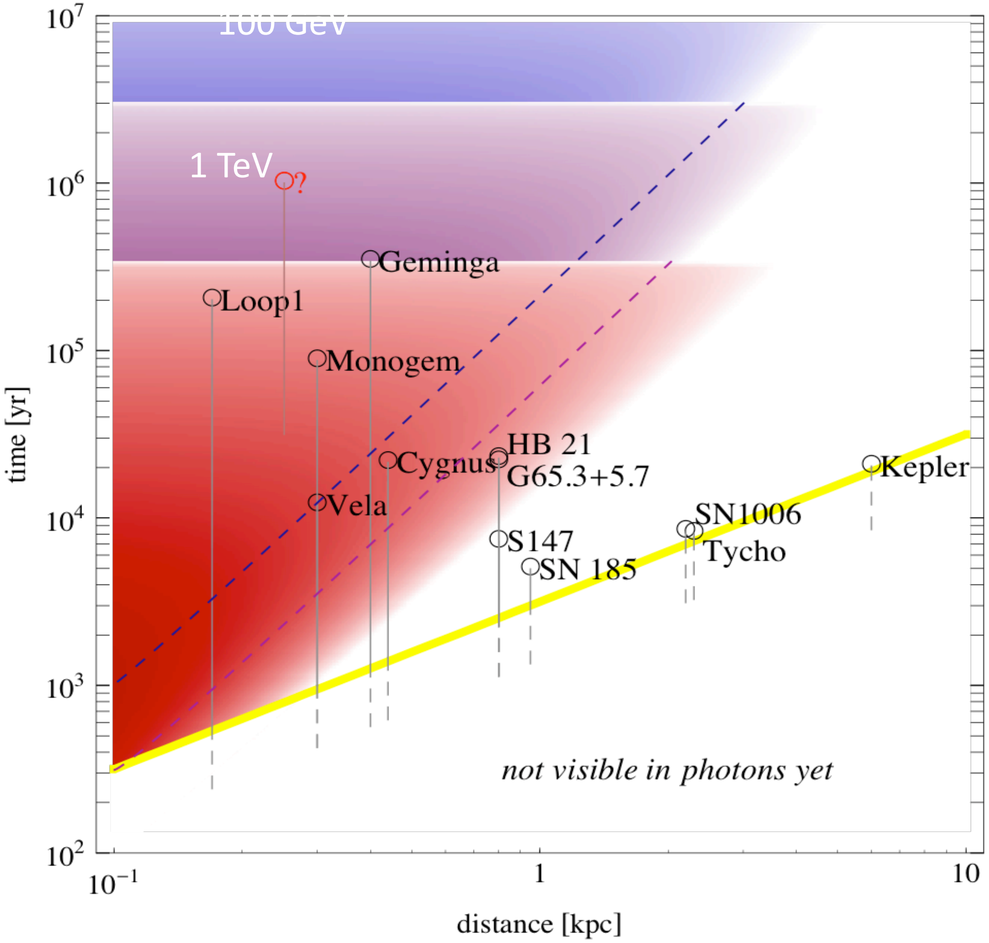


But with usual propagation parameters ($D_0 \sim 10^{28}$ cm$^2$ s$^{-1}$, $\delta \sim 0.6$, $\tau_{esc} \sim 10^{16}$ s) find break energy to be 2 TeV, *not* 20 GeV … also nearby 'invisible' SNRs (e.g. *Geminga*) will fill in dips in the spectrum

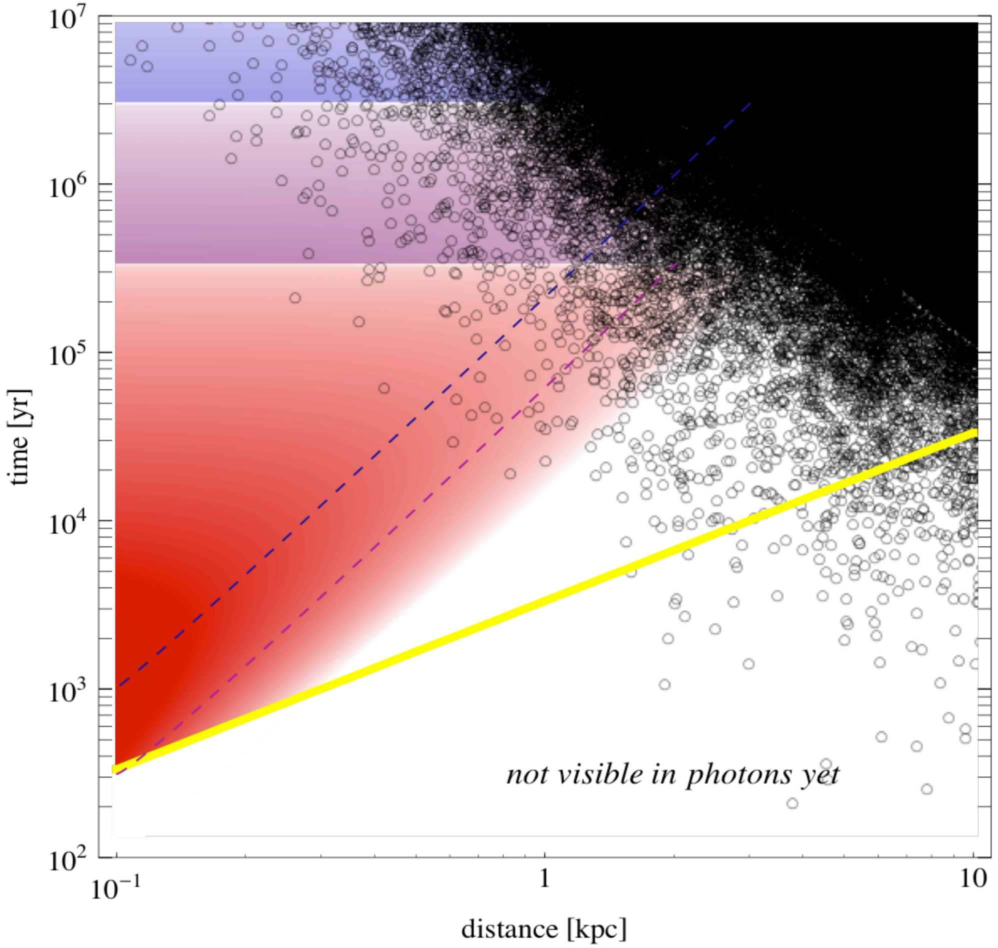
# It is not just the few (optically) observed SNRs which contribute to observed cosmic rays … there must be many other *hidden* SNRs

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

## Known

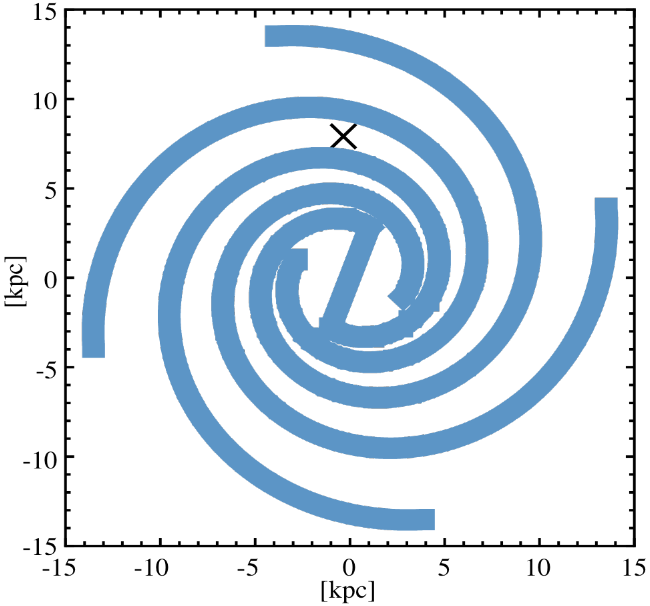


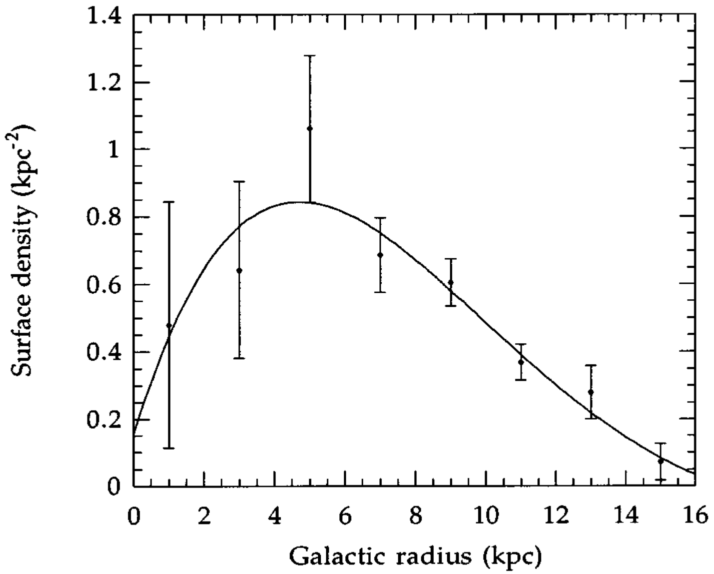
## Simulated



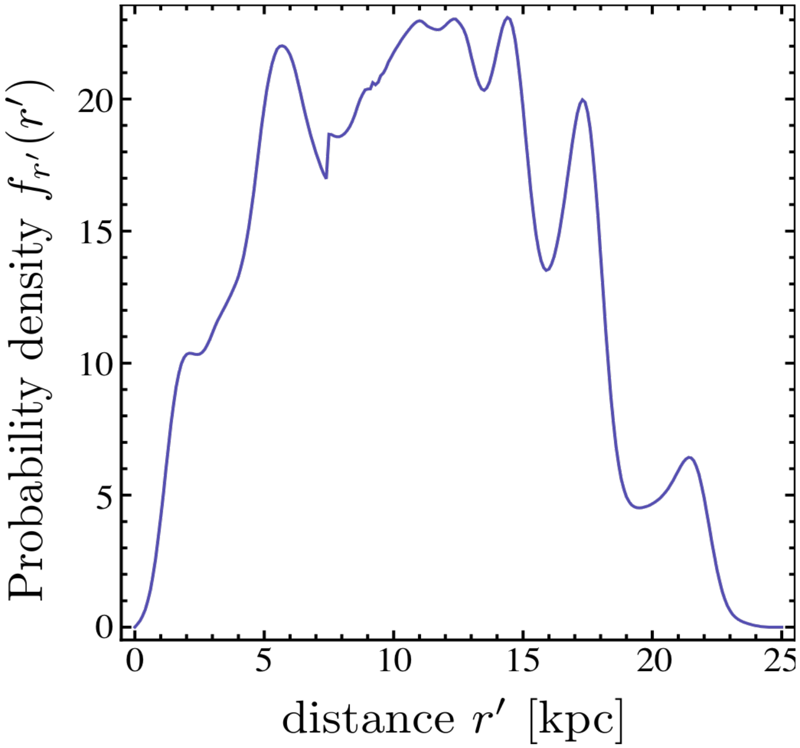
Ahlers, Mertsch & Sarkar,PRD80:123017,2009

# Statistical distribution of SNRs





Case & Bhattacharya, ApJ 504:761,1998



Strategy:

- Draw source positions from this distribution
- Calculate total $(e^+ + e^-)$ flux
- The best fit to data is likely to be *closest* to real distribution

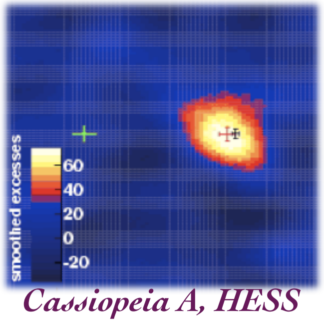
Ahlers, Mertsch & Sarkar,PRD80:123017,2009

# Parameters of the Monte Carlo

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

Ahlers, Mertsch & Sarkar, PRD80:123017, 2009

# Normalising the source spectra



*Cassiopeia A, HESS*

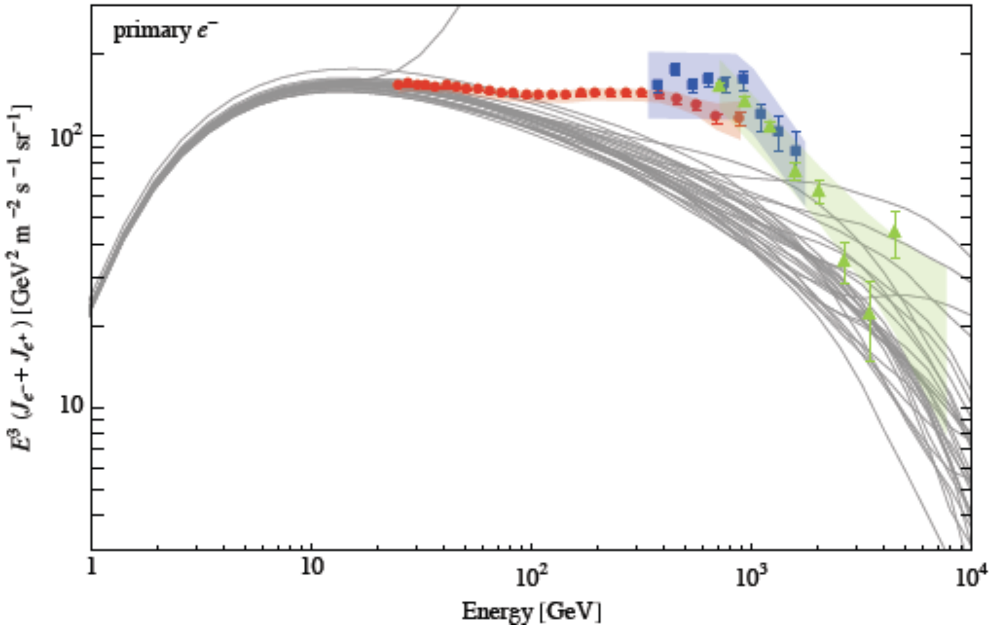
Normalisation of primary $e^-$: fit absolute $e^-$ flux at low energies

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

| Source | Other name(s) | $\Gamma$ | $J_\gamma^0 \div 10^{-12}$ | $E_\text{max}$ | $d$ | $Q_\gamma^0 \div 10^{33}$ |
|---|---|---|---|---|---|---|
| | | | $[(\text{cm}^2\,\text{s}\,\text{TeV})^{-1}]$ | [TeV] | [kpc] | $[(\text{s}\,\text{TeV})^{-1}]$ |
| 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[a] | W 28, GRO J1801-2320 | $2.66 \pm 0.27$ | $0.75 \pm 0.11$ | $\gtrsim 4$ | 2 | 0.359 |
| HESS J1804−216[b] | 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 | $3.1 \pm 0.3$ | 0.58 | $\gtrsim 1$ | 1.5 | 0.156 |
| Cassiopeia A | | $2.4 \pm 0.2$ | $1.0 \pm 0.1$ | $\gtrsim 40$ | 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 $\Gamma > 2.6$ | | $\sim 2.3$ | | $\gtrsim 20$ | | $\sim 4.2$ |

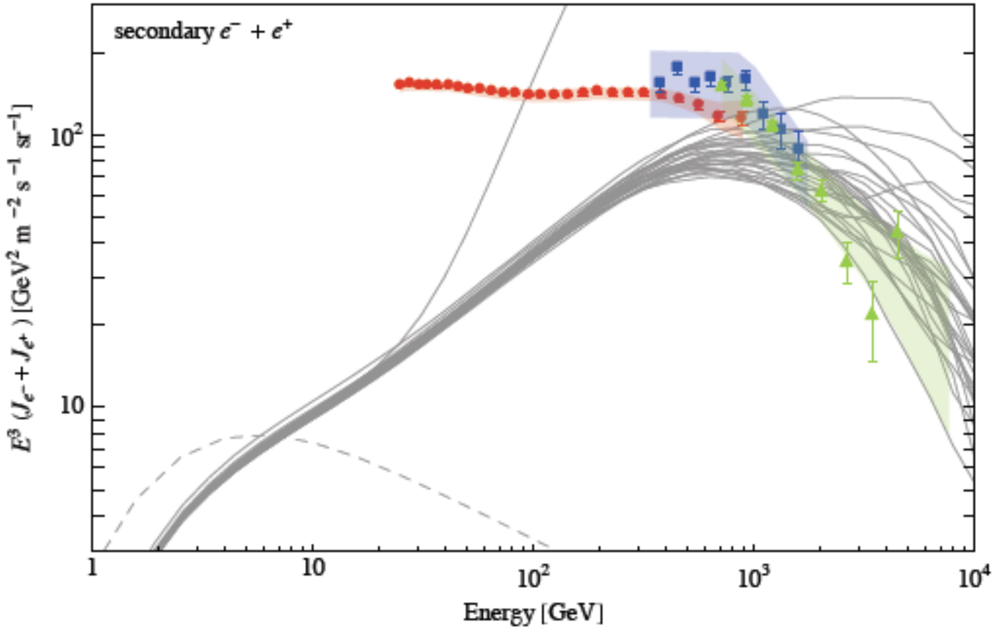
Ahlers, Mertsch & Sarkar,PRD80:123017,2009

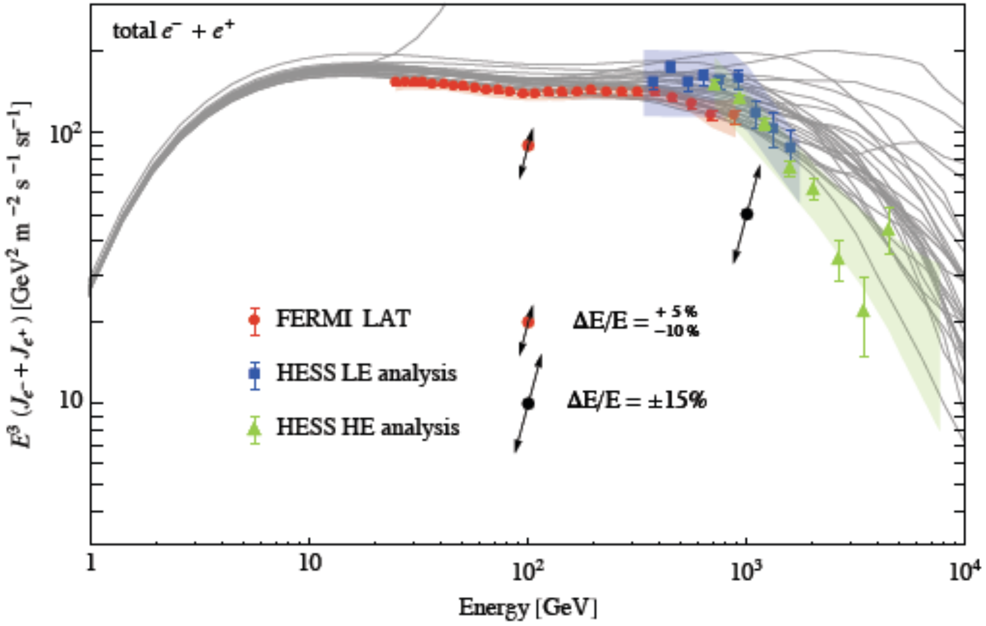
# Fitting the $e^+ + e^-$ flux



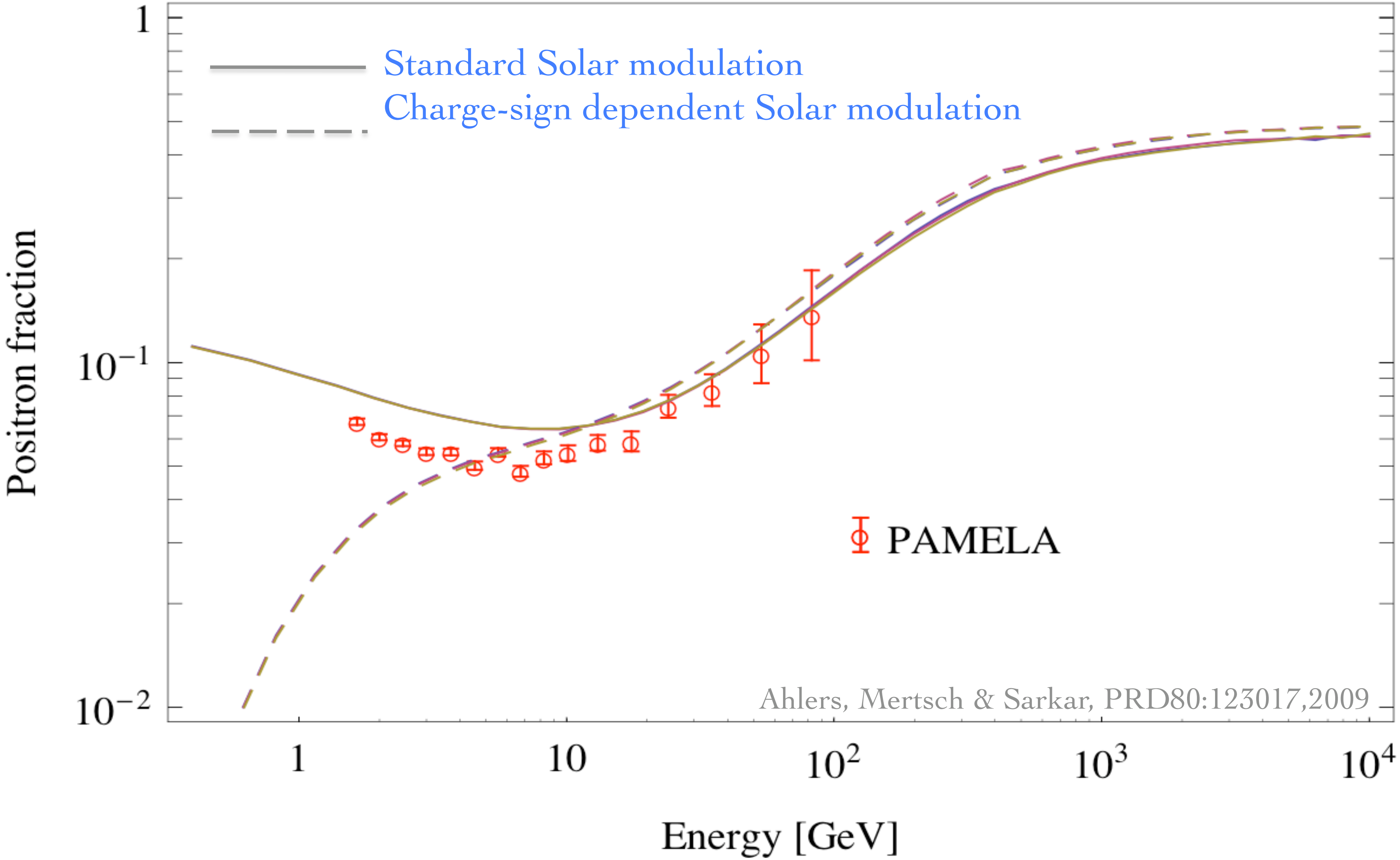
The propagated primary $e^-$ spectrum is much too *steep* to match the Fermi LAT data ... but the *accelerated* secondary $e^+ + e^-$ component has a harder spectrum so fits the 'bump'!

Ahlers, Mertsch & Sarkar, PRD80:123017,2009





# The *predicted* positron fraction

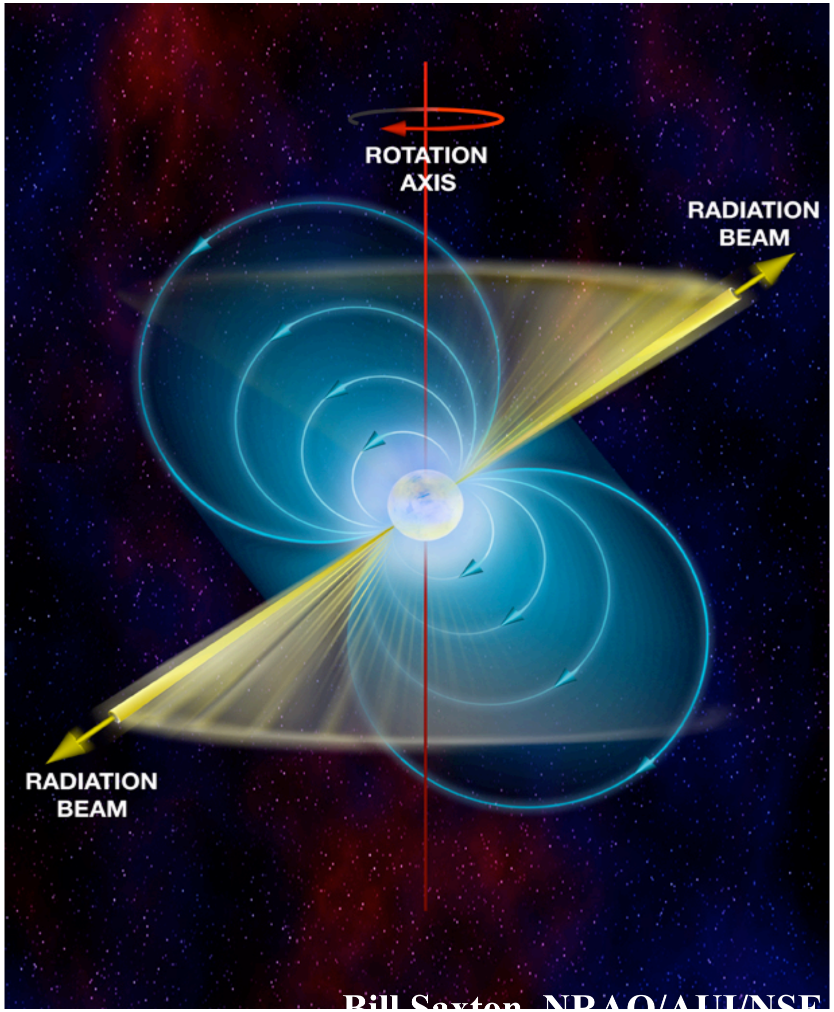


Ahlers, Mertsch & Sarkar, PRD80:123017,2009

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

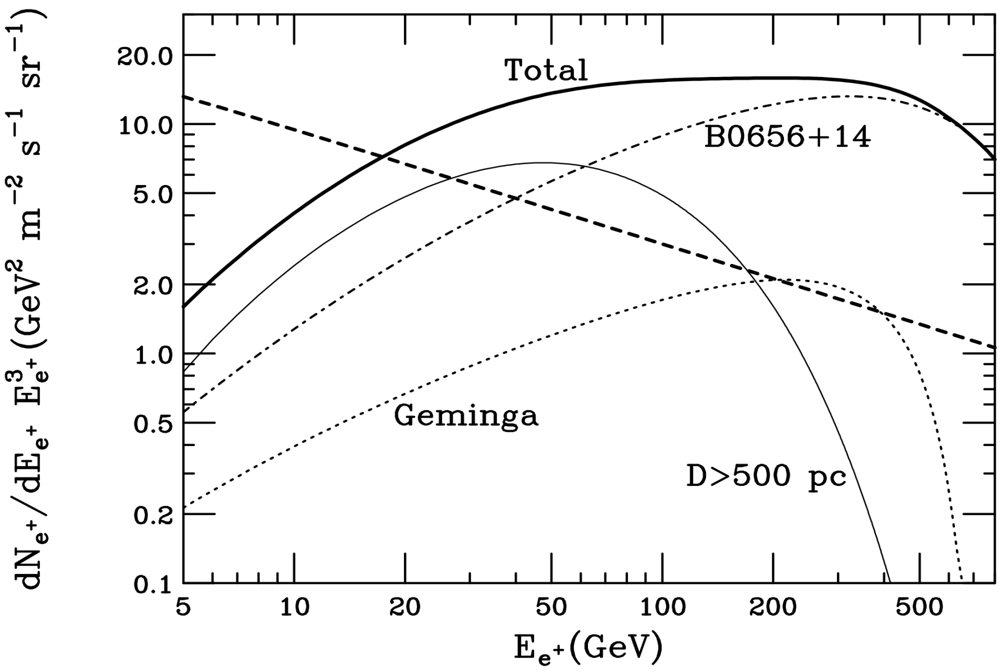
- Highly magnetized, fast spinning neutron stars
- $\gamma$-rays and electron/positron pairs produced along the magnetic axis
- Spectrum *speculated* to be harder than background from propagation:

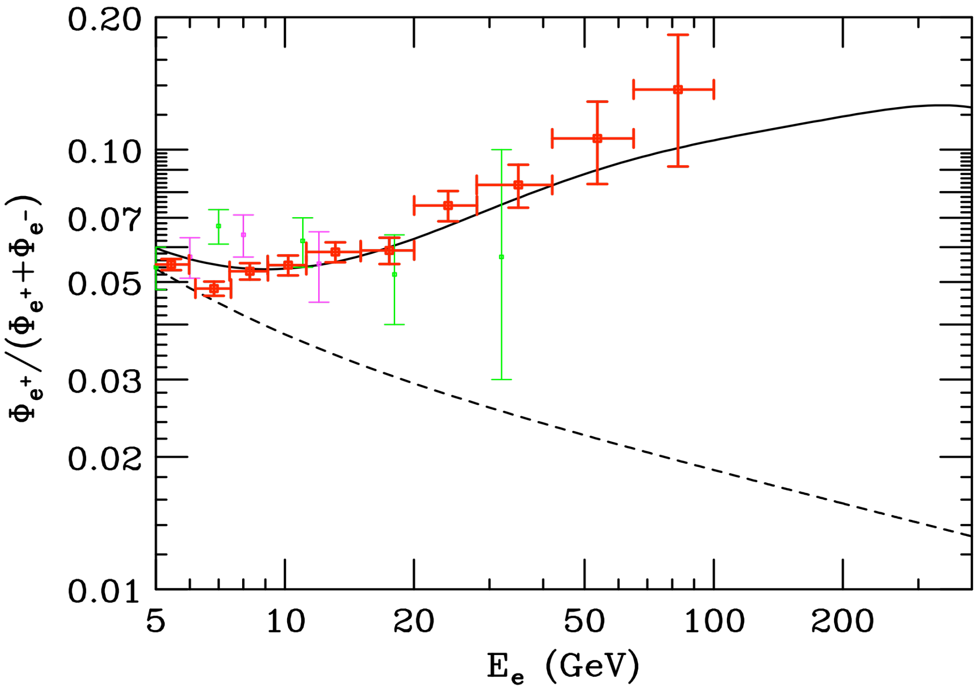
$$N \propto E_e^{\pm\,-1.6} e^{-E_e^{\pm}/100\,\mathrm{GeV}}$$



Bill Saxton, NRAO/AUI/NSF

# 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)





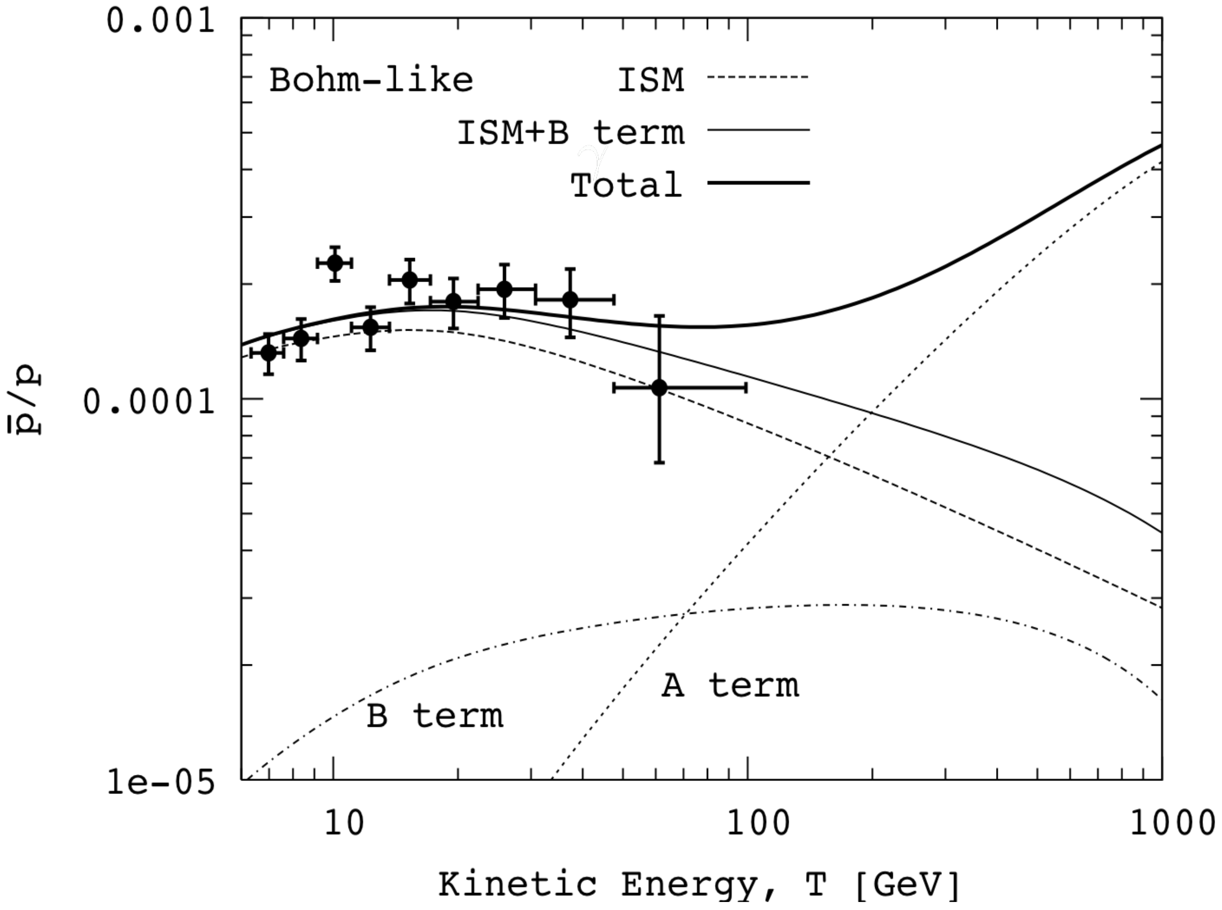
Hooper, Blasi & Serpico, JCAP 0901:025,2009

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

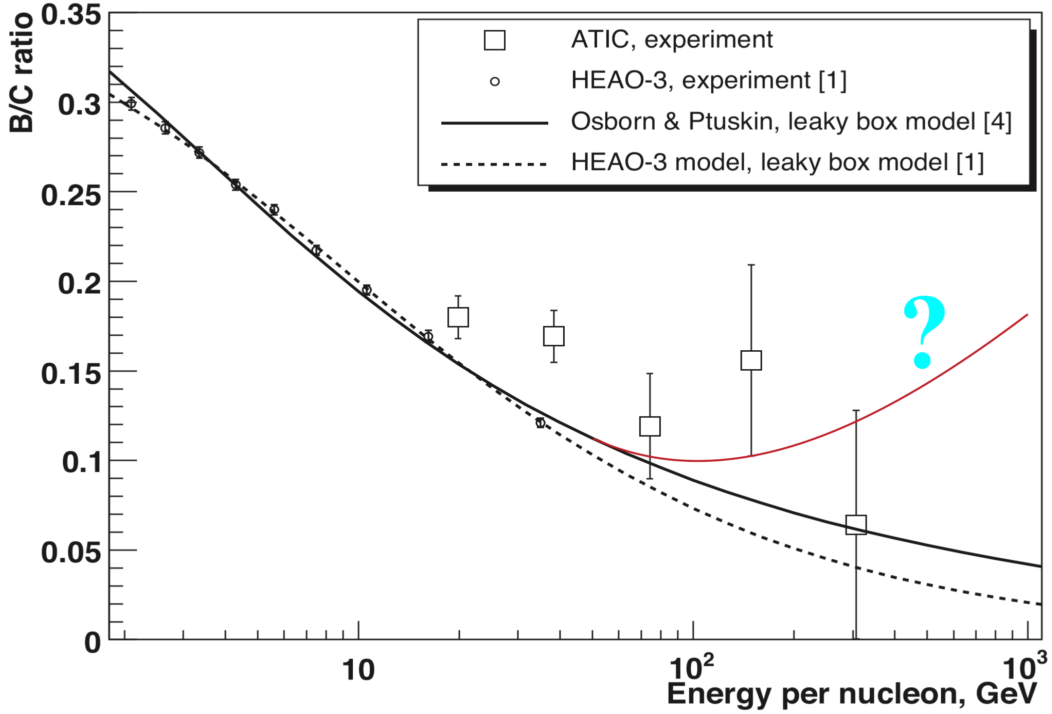
Secondary acceleration model predicts rise *beyond* 100 GeV
… will be tested soon by *AMS*-02

# 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

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



Panov *et al*, ICRC 2007

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

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

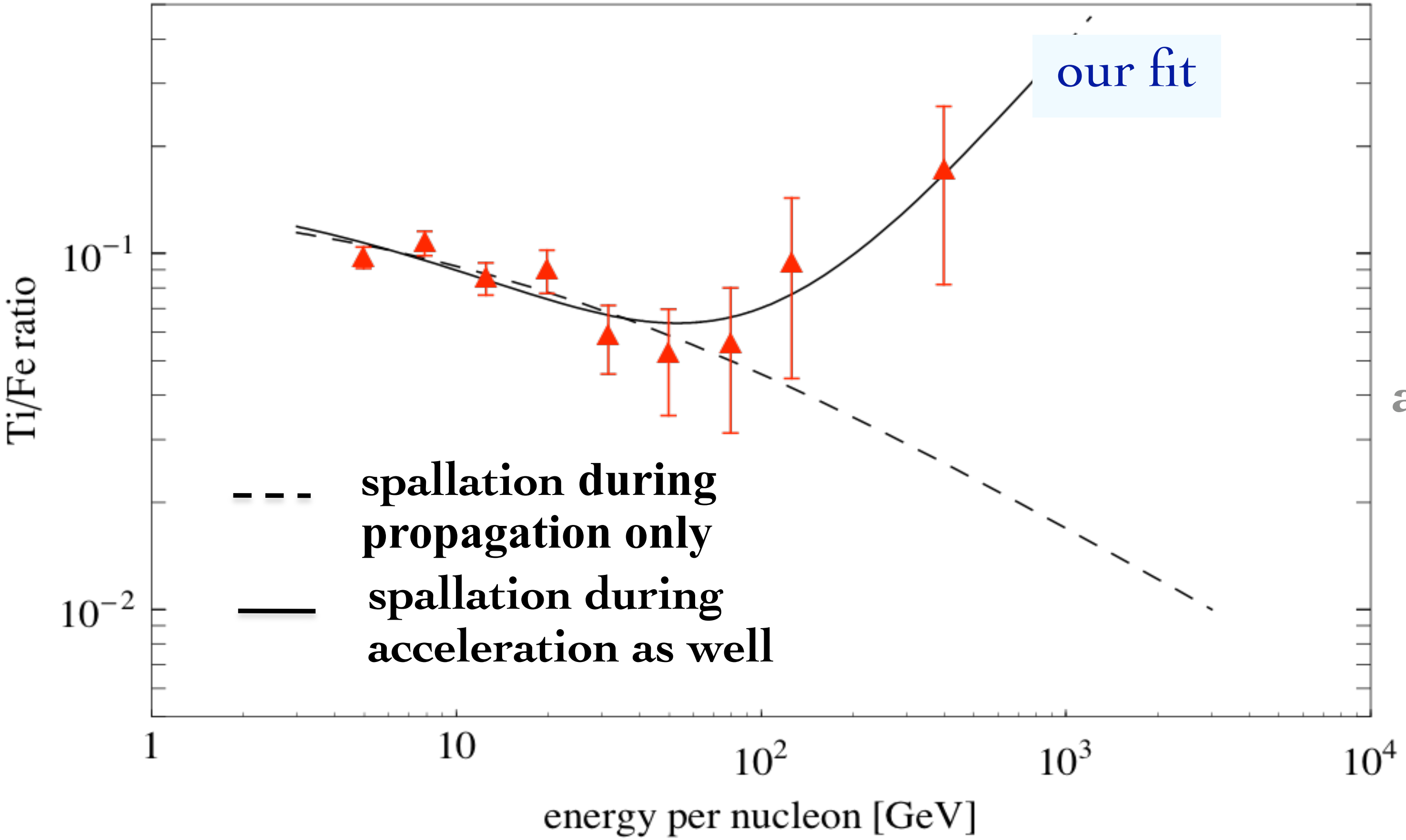
with boundary condition: $f_i(x,p) \xrightarrow{x \to -\infty} Y_i \delta(p - p_0)$

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

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

Mertsch & Sarkar, PRL 103:081104,2009

# Titanium-to-Iron Ratio



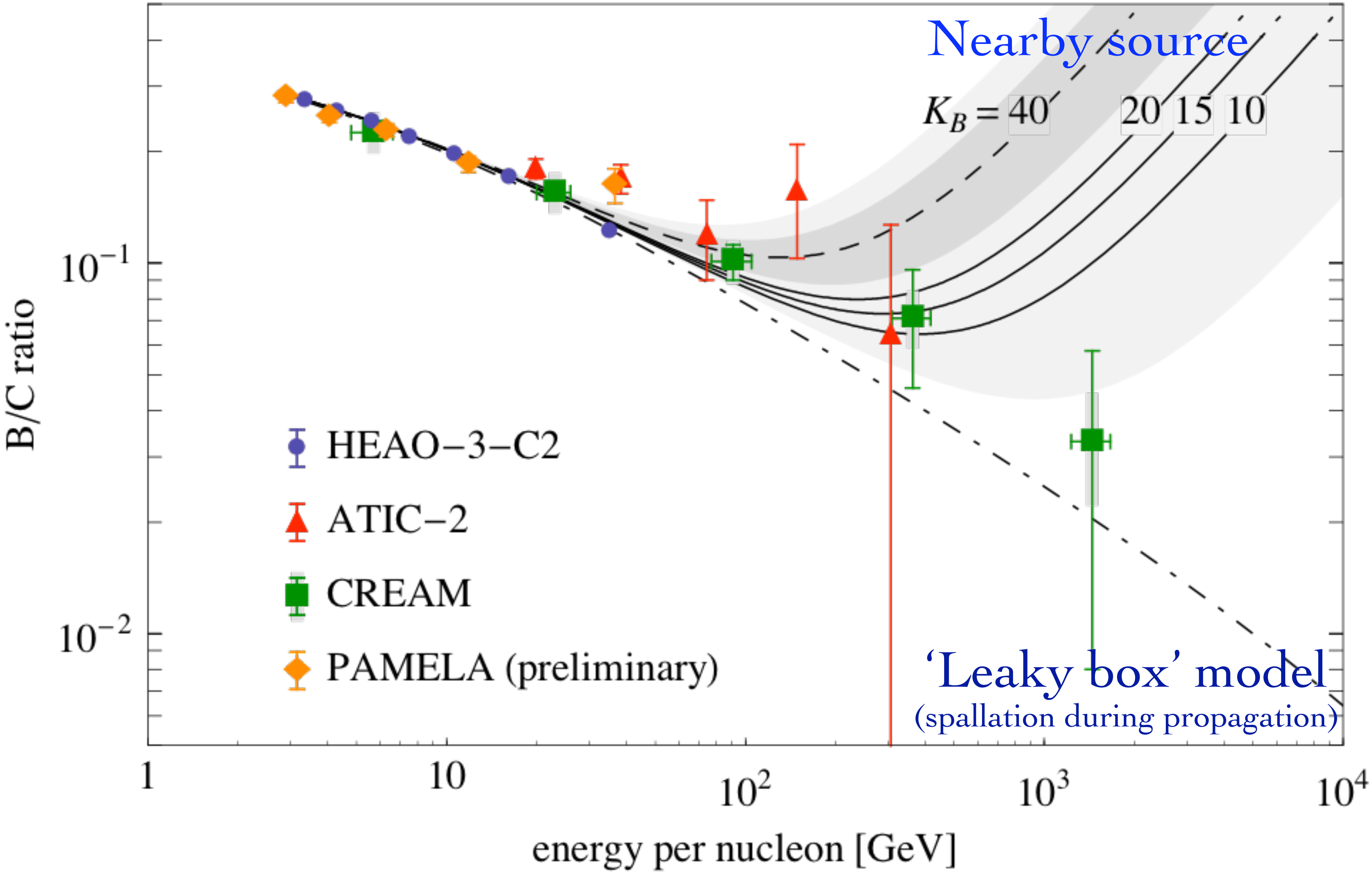
▲ ATIC-2

Zatsepin *et al.*, arXiv:0905.0049

Titanium-to-iron ratio used to fix diffusion coefficient to be $\mathcal{F}^{-1} \simeq 40$ (NB: to fit $e^+$ excess requires ~10-20)

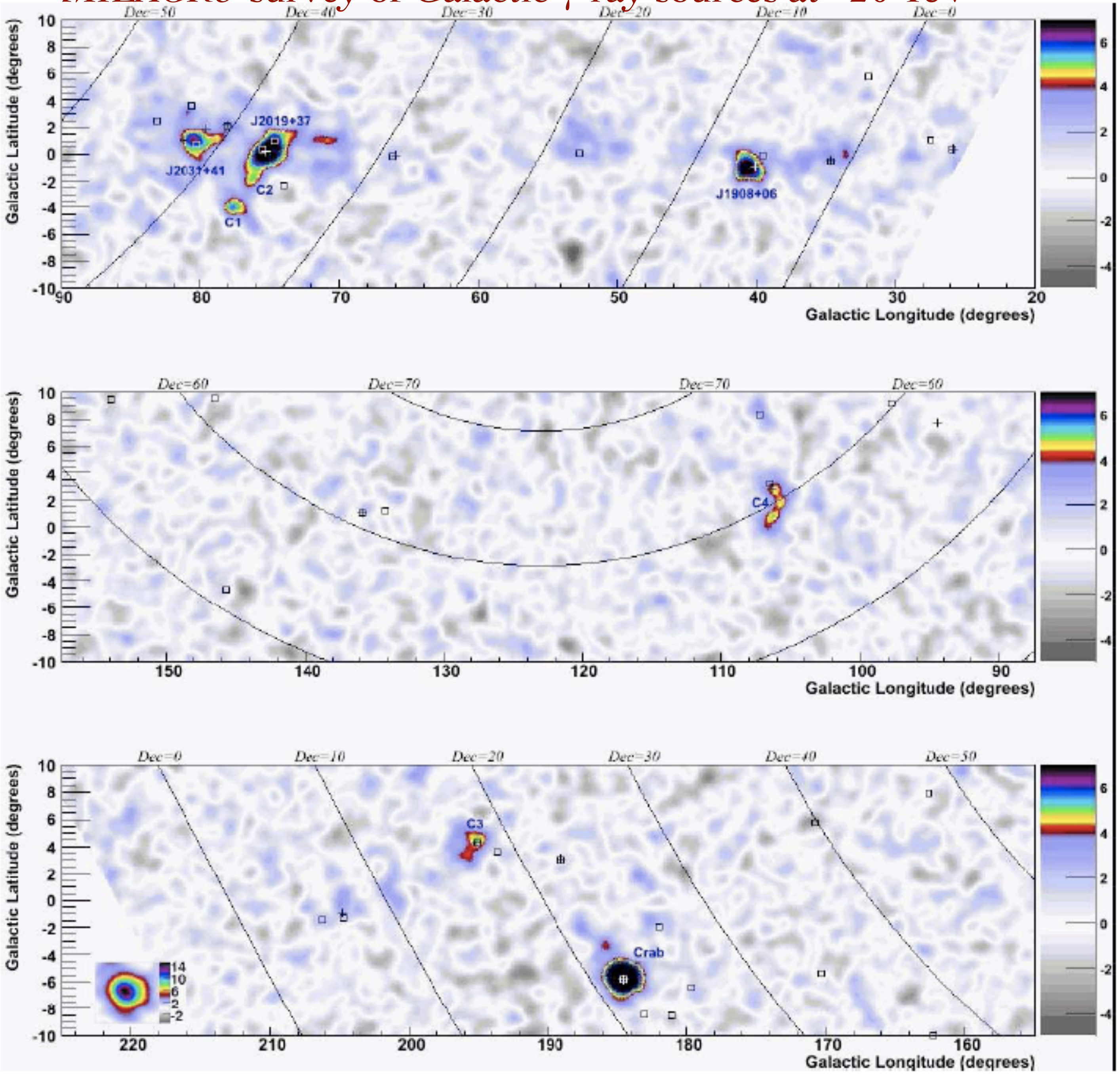
Mertsch & Sarkar, PRL 103:081104,2009

# 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

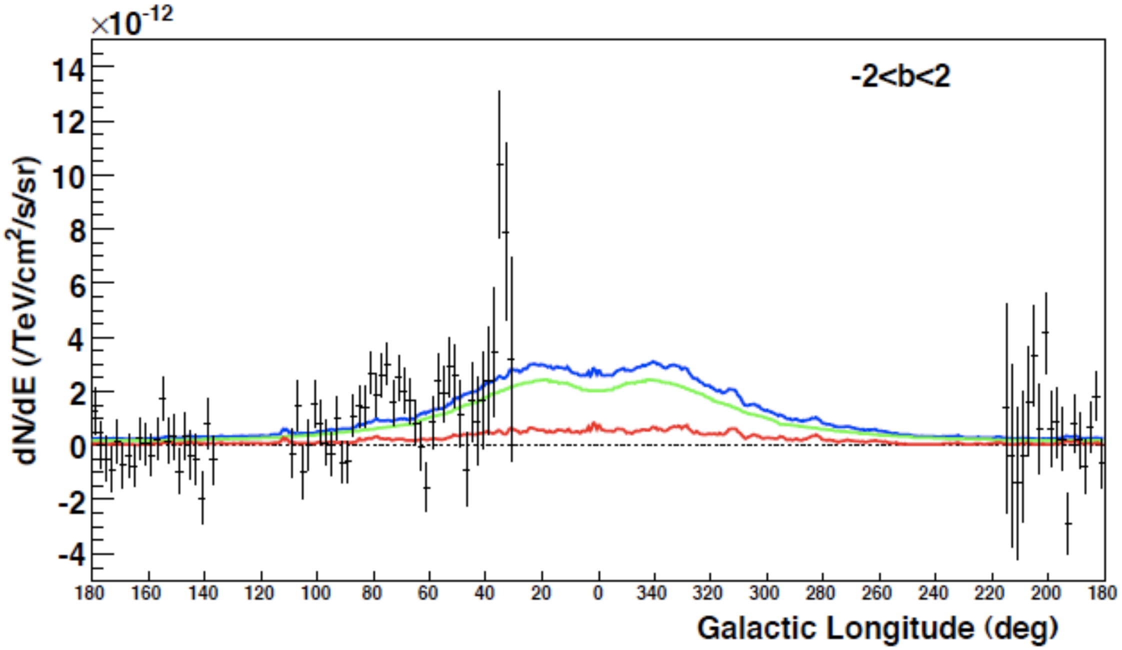
# *MILAGRO* survey of Galactic γ-ray sources at ~20 TeV



Eight candidate sources of TeV emission are detected with pre-trials significance >4.5$\sigma$ in Galactic longitude $[30^0, 220^0]$ 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

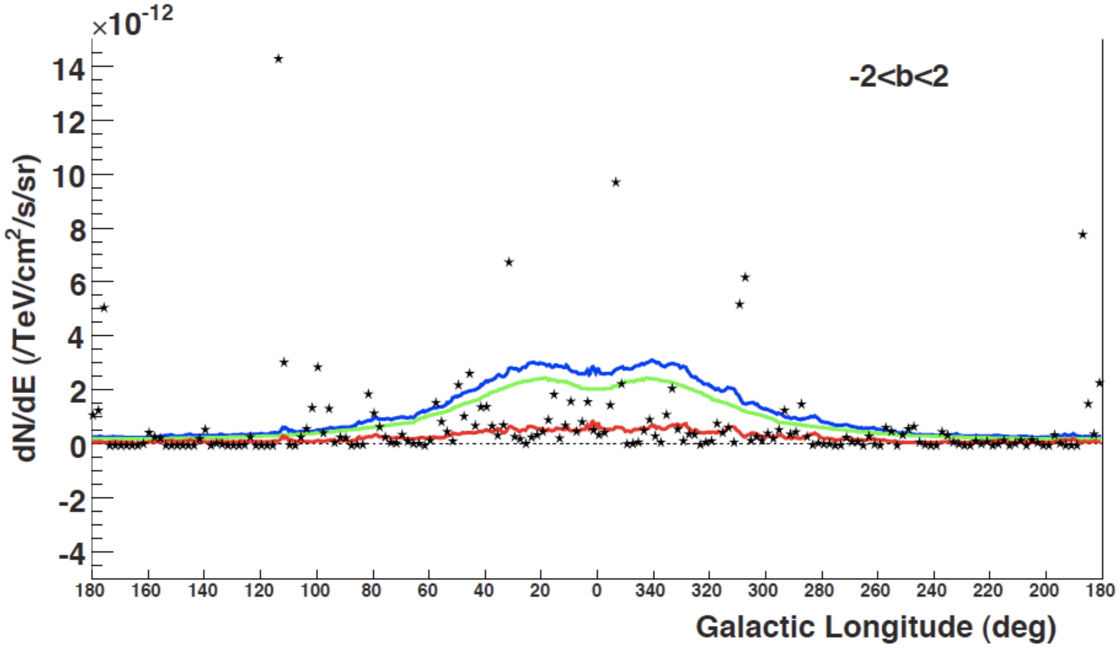
# Have some of these old SNRs been seen already?



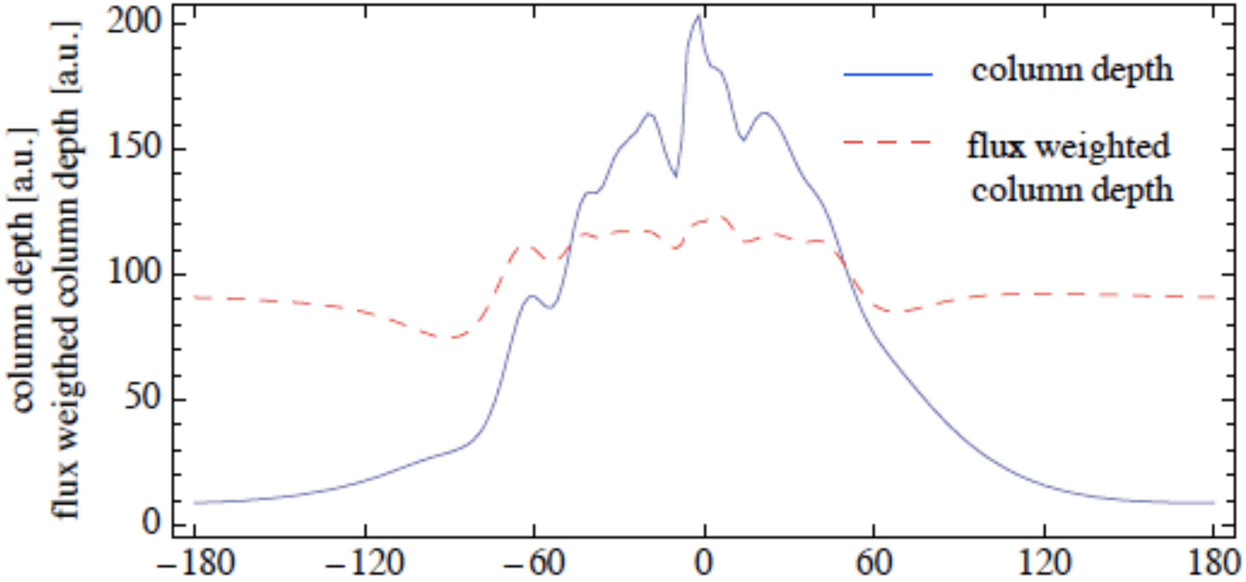
*MILAGRO* profile of the Milky Way overlaid with GALPROP 'prediction'
(red: $\pi^0$ decay, green: IC, blue: total)

Abdo *et al*, arXiv:0805.0417

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 …



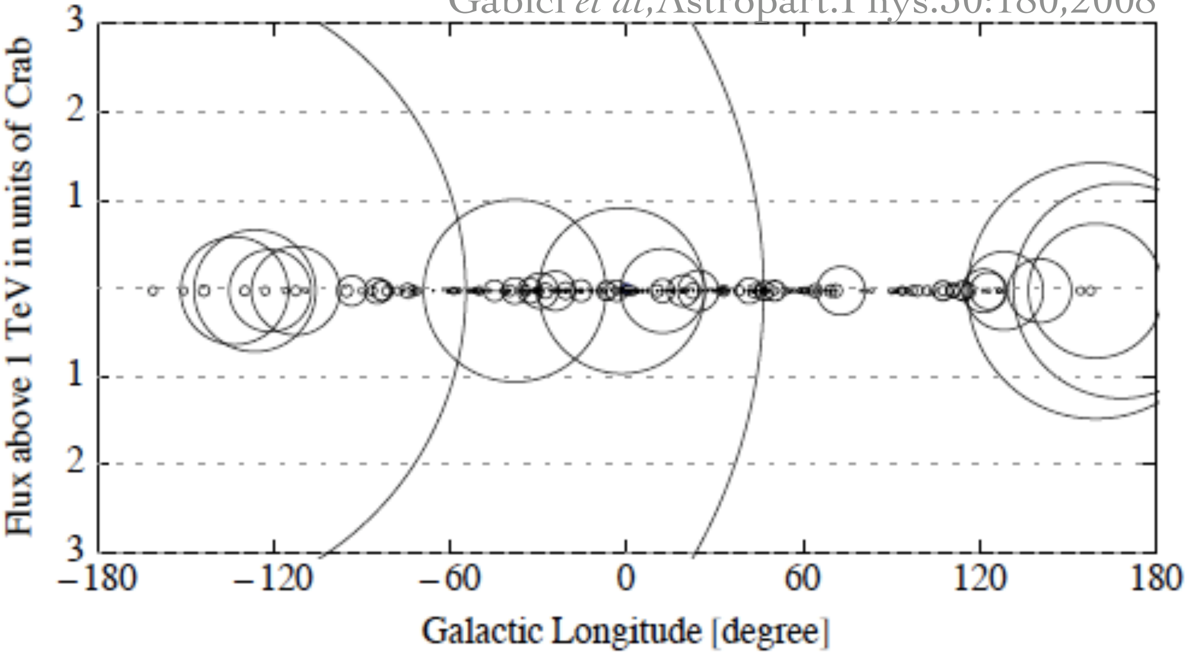
The column depth and *flux weighted* column depth of the SNR density in the Galactic plane …
not very different towards Galactic centre/anti-centre i.e. equally useful to survey Northern/Southern sky

Ahlers, Mertsch & Sarkar,PRD80:123017,2009
Gabici *et al*,Astropart.Phys.30:180,2008

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

Astroparticle physics has made enormous *experimental* progress but to definitively answer old questions e.g. the **origin of cosmic rays** or the **nature of dark matter** will require better *theoretical* modelling of the relevant astrophysical 'backgrounds'

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

… the source(s) should also be detectable directly in **$\gamma$-rays** (*HAWC*, *CTA*) and **neutrinos** (*IceCube*, *KM3NeT*)

This would be the first identification of cosmic 'pevatrons'