Theoretical interpretation of GeV-TeV cosmic rays

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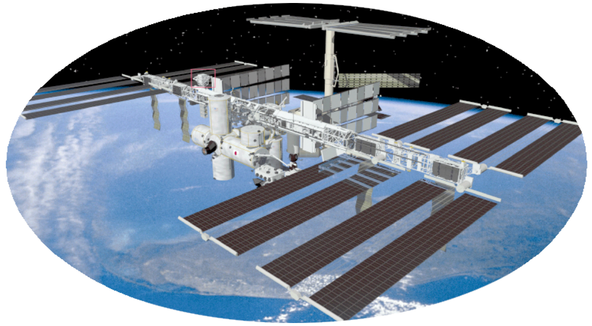
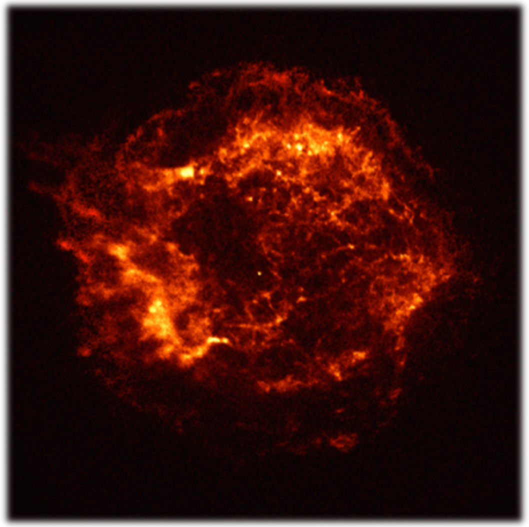
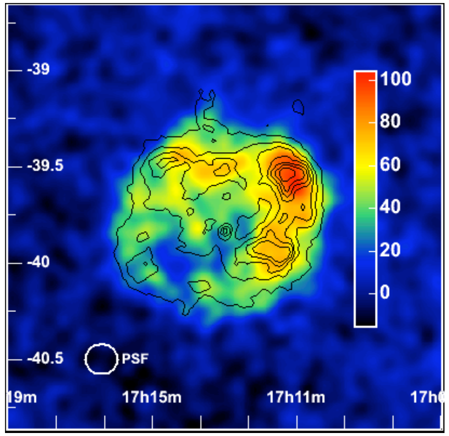
With special thanks to
Philipp Mertch





TeV Particle Astrophysics, Paris, 19-23 July 2010

RXJ1713.7-3946 (HESS, 2004)



We have witnessed a renaissance in γ-ray astronomy

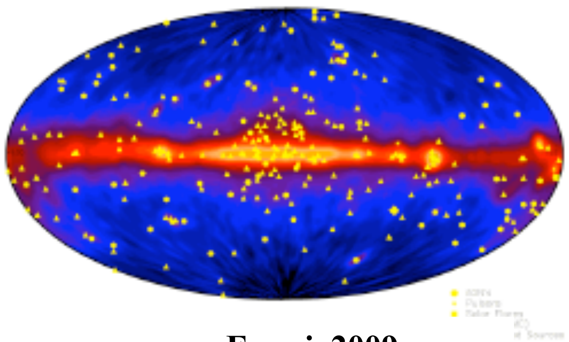
→ the sources of low energy cosmic rays may soon be known: **SNRs**?

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

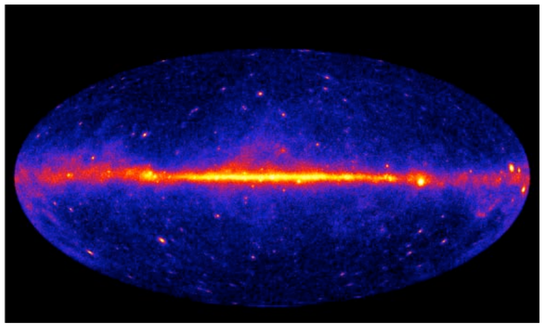
➢ Can 1st-order Fermi acceleration at SNR shocks explain the spectrum (injection, magnetic field amplification, diffusion losses vs anisotropy) ?

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

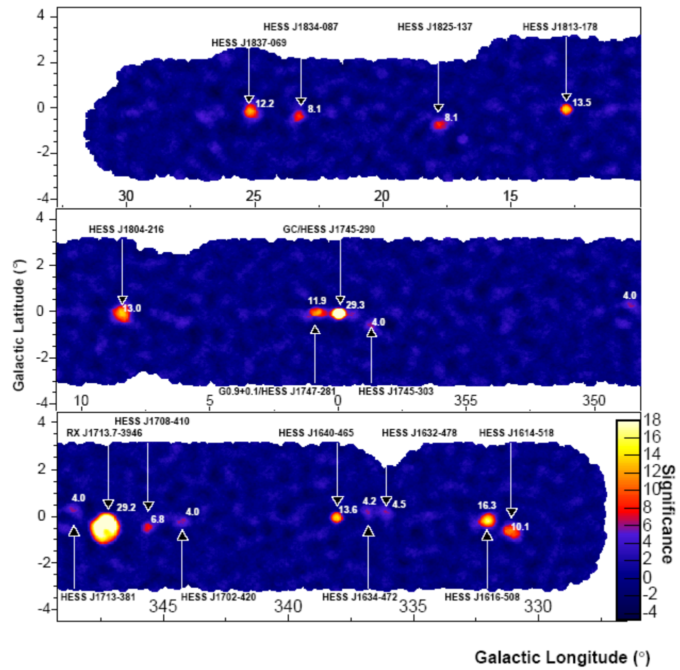
EGRET 1991 - 2000



Fermi 2009 -



HESS Southern Plane Survey 2005

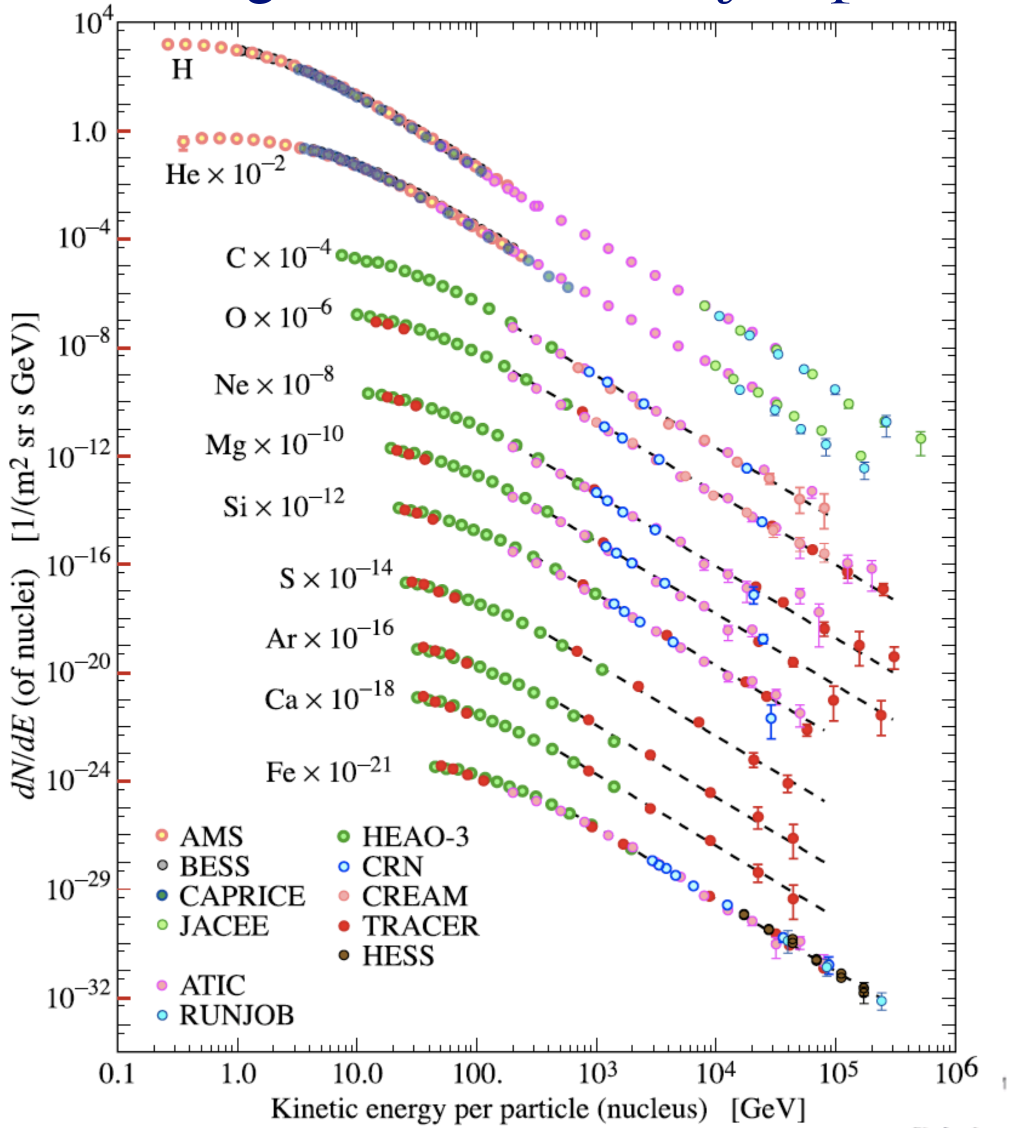


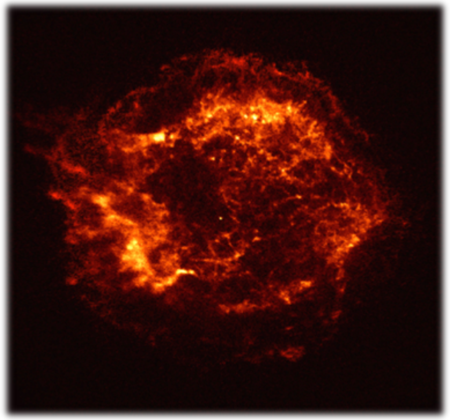
Much progress has been made but these questions are *not* fully answered …

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

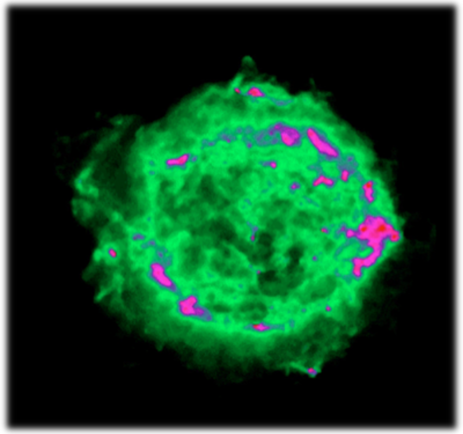
… also the *PAMELA* and *Fermi* 'anomalies' have highlighted the limitations of the standard diffusion model

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





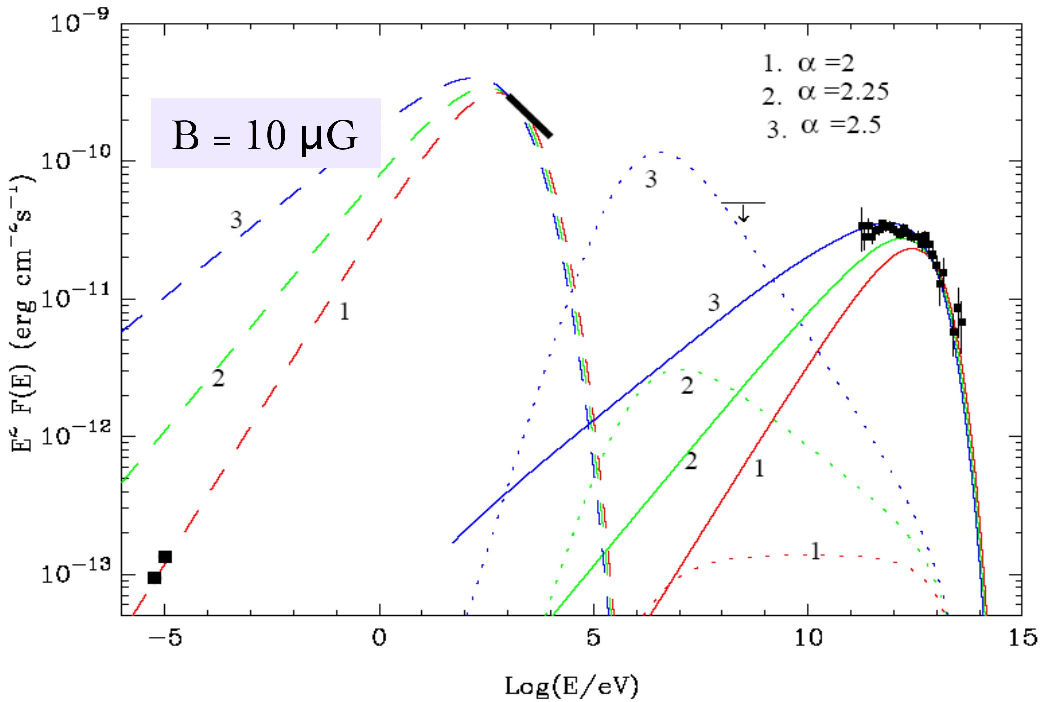
Cassiopeia A: *Chandra*

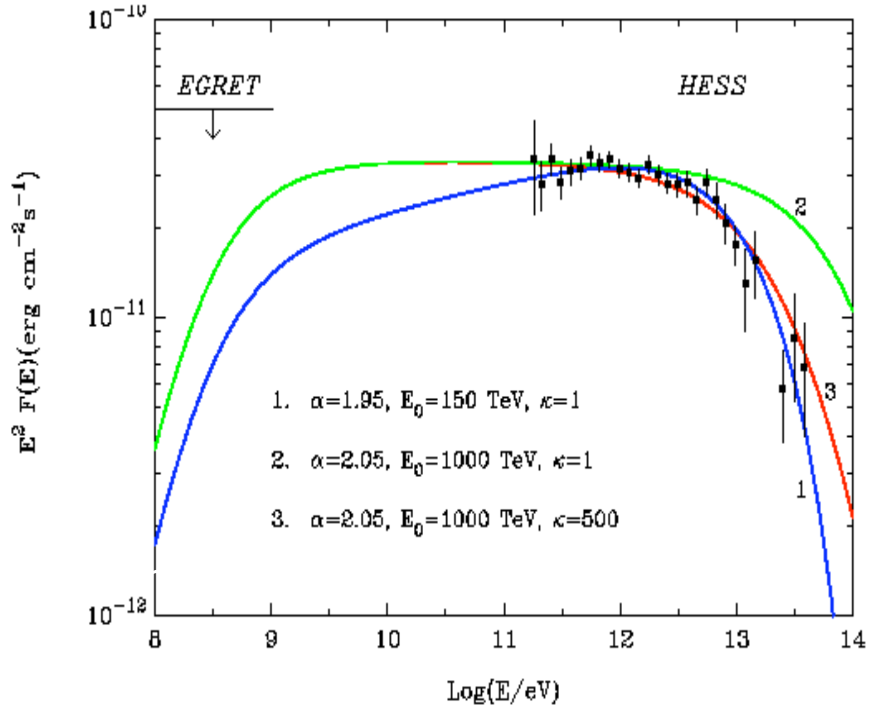


Cassiopeia A: *VLA*

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

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



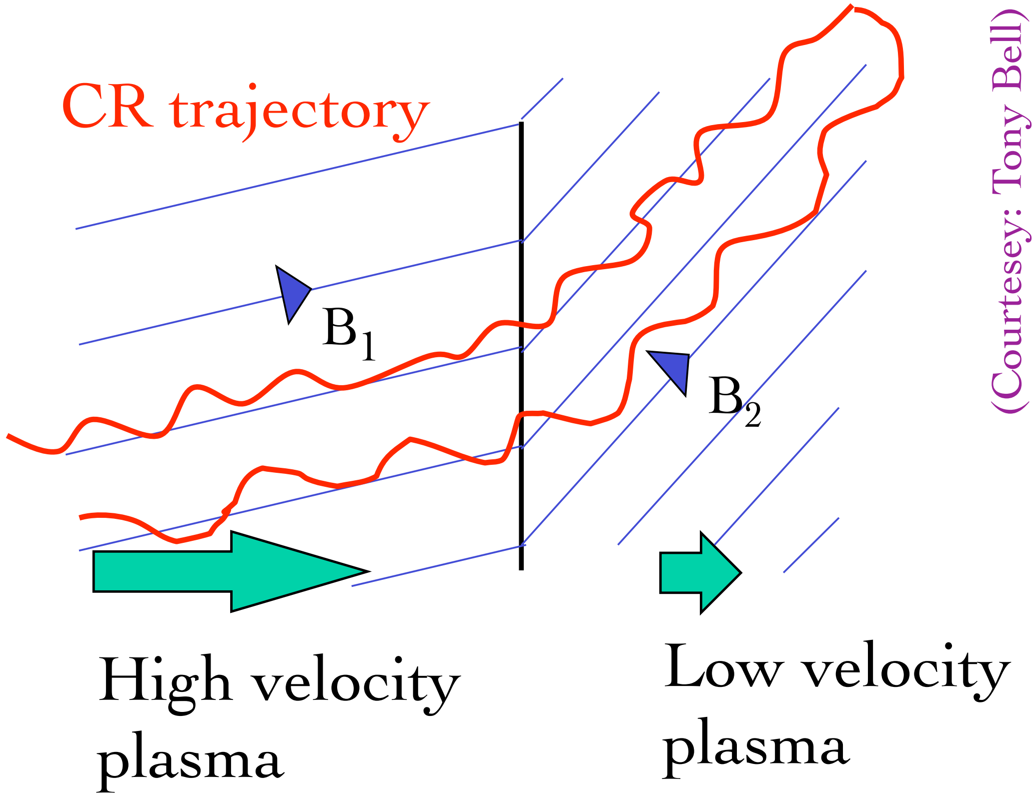


(HESS collaboration, 2006)

γ-ray emission well fitted by IC scattering of ~10^2 TeV electrons on CMB/starlight
… alternatively γ-rays may be from decays of π^0s 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 π^0 decay are detected

1^{st}-order Fermi acceleration by shock waves (DSA)



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: $\Delta\varepsilon/\varepsilon = \beta$

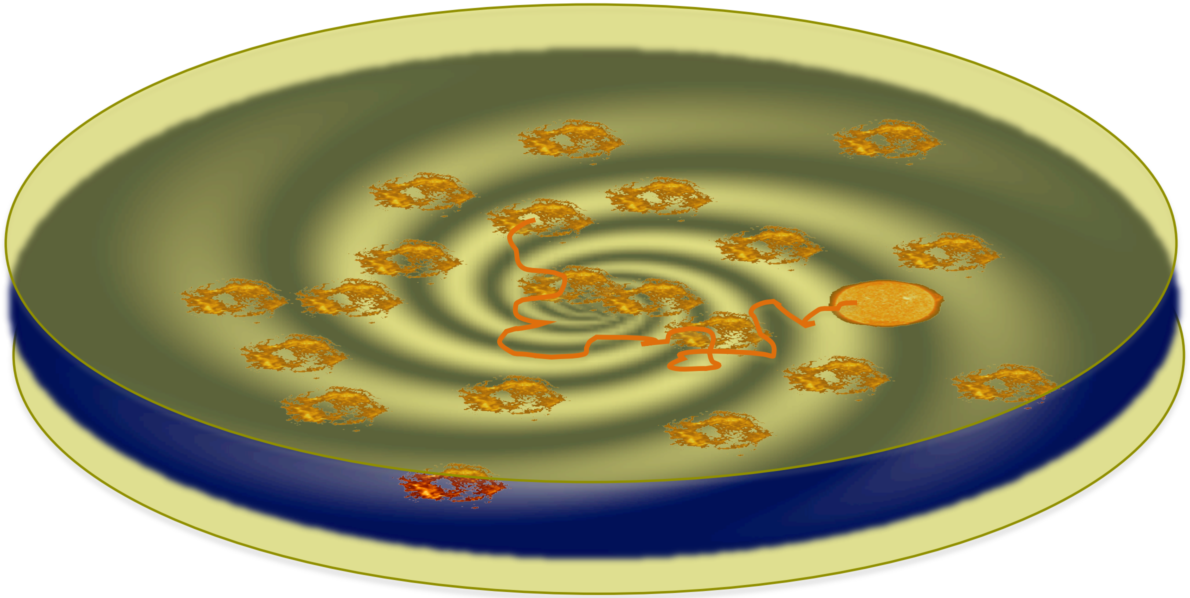
$\Rightarrow$ differential spectrum: $\propto \varepsilon^{-2}$

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 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?)

The 'standard model' for galactic cosmic rays

- ❑ SNR shock waves accelerate relativistic particles by Fermi mechanism
  - ⇨ power law spectrum (synchrotron radio/X-ray + γ-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

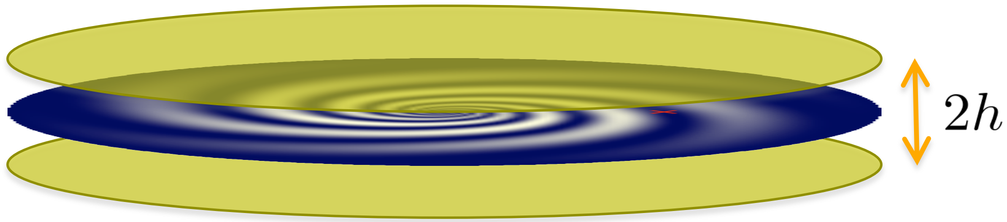
Measurables: Energy spectra of individual species, diffuse radiation

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:

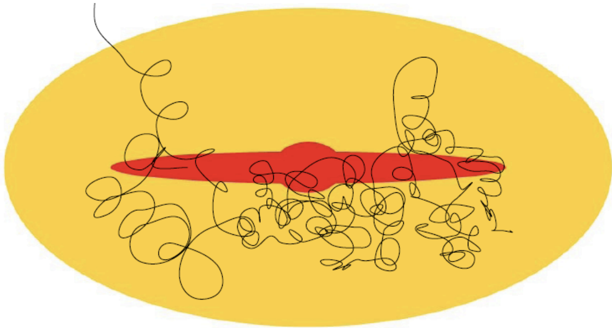


Green's function: describes flux from a discrete, burst-like source
… integrate over spatial distribution and time-variation of injection

GALPROP (Moskalenko & Strong 1998) can solve the 3D time-dependent transport equation but yields ~the same answer for the *equilibrium* fluxes as the **'leaky box' model** in which cosmic rays are assumed to have small energy dependent escape probability

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

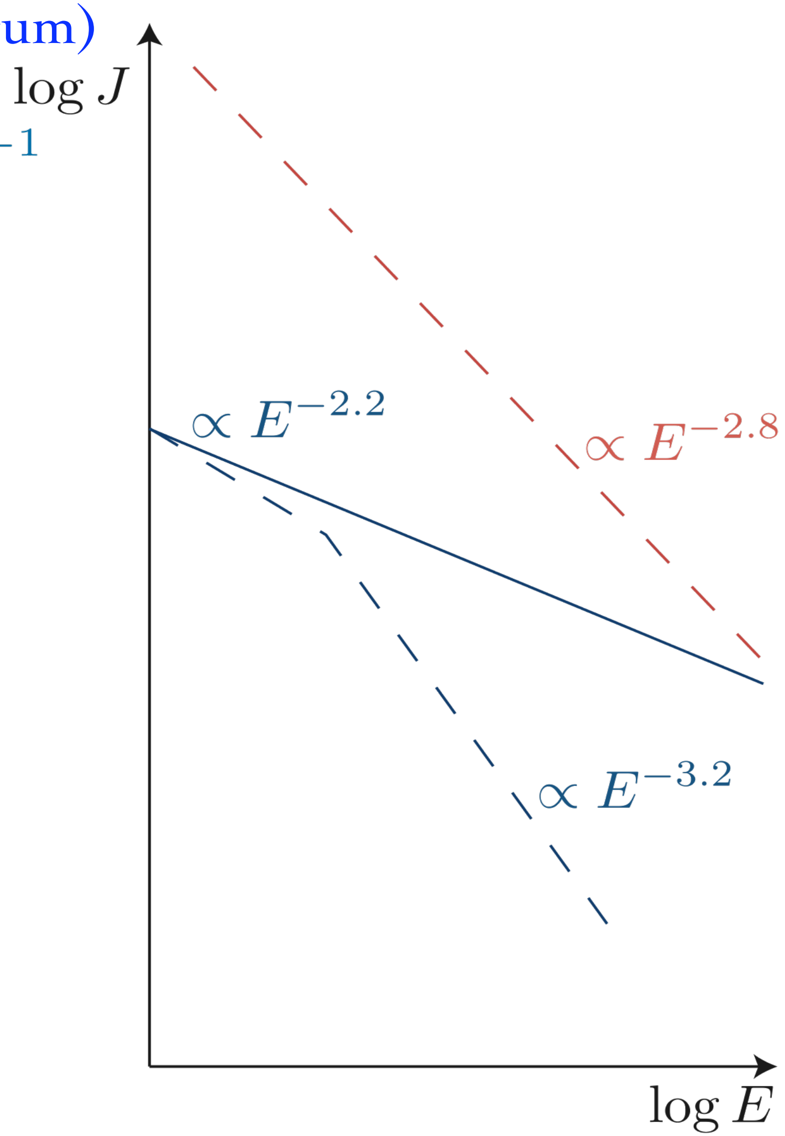
Observed: $n \propto E^{-2.8}, E^{-3.2}$

Primary protons/nuclei

Production: presumably same as e^-

Propagation:

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



Energy spectra

Primary e^-

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

Primary protons/nuclei

Production: presumably same as e^-

Propagation:

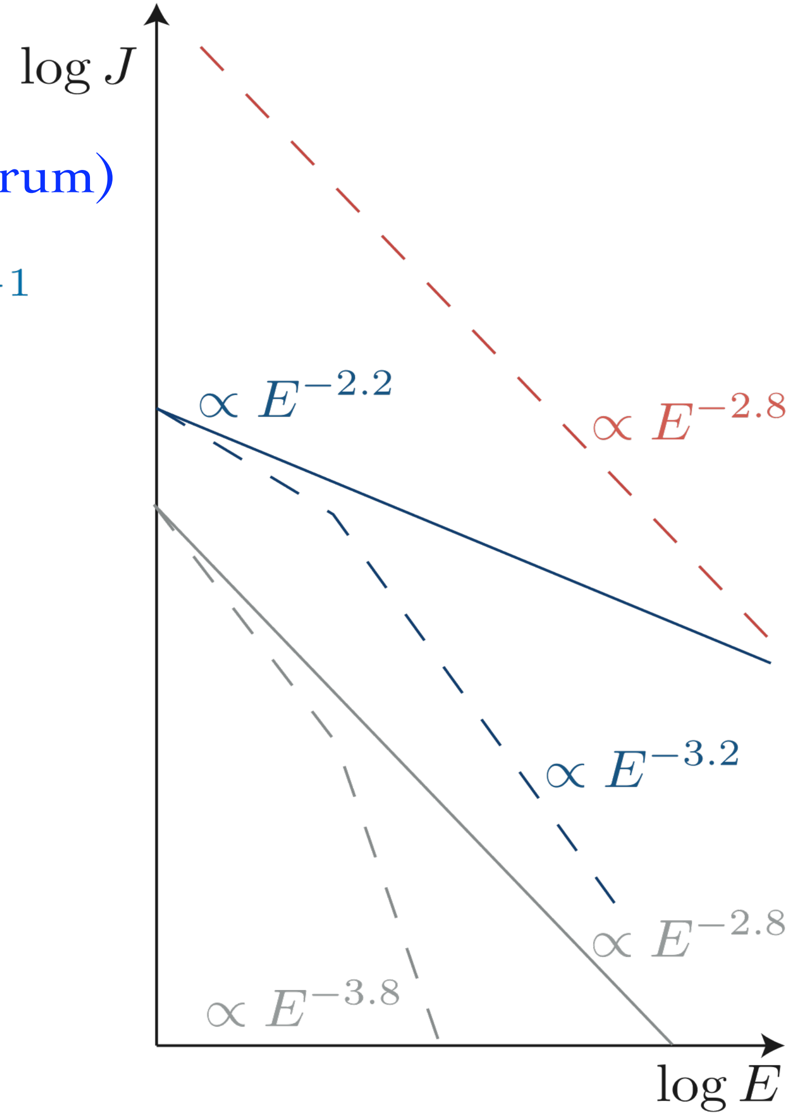
Observed: $n \propto E^{-2.8}$

Secondary

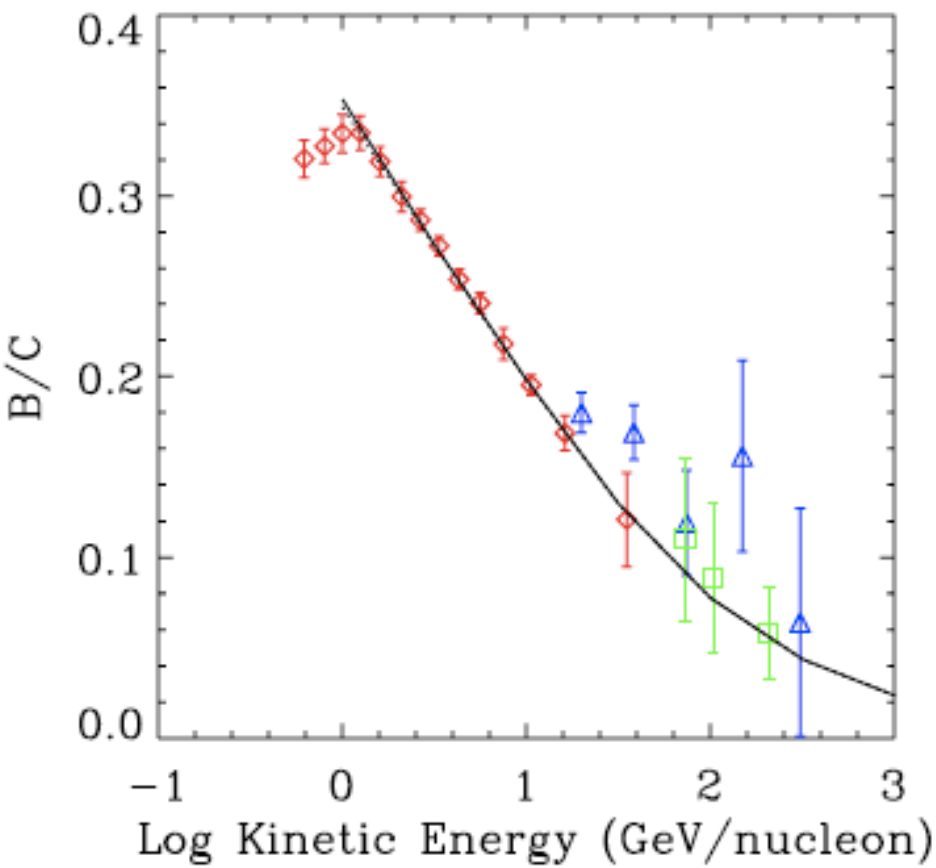
production: $q \propto E^{-2.8}$

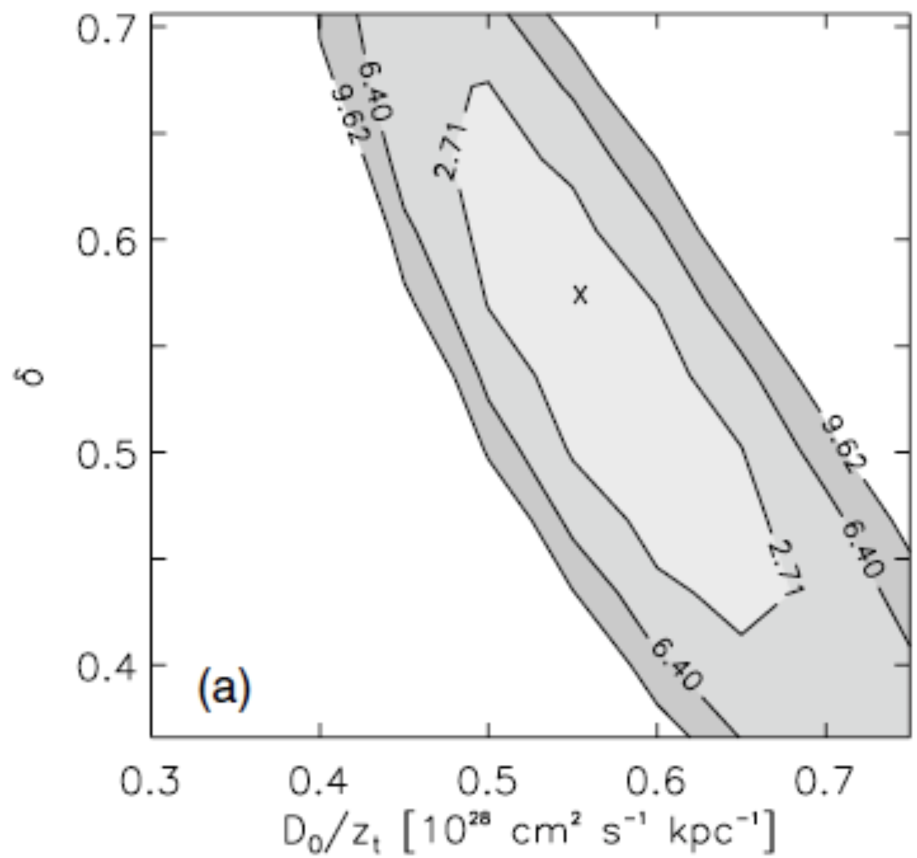
propagation: $\min[\tau_{\rm esc}, \tau_{\rm cool}] \propto E^{-0.6}, E^{-1}$

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



Secondary-to-primary ratios (using DRAGON code)



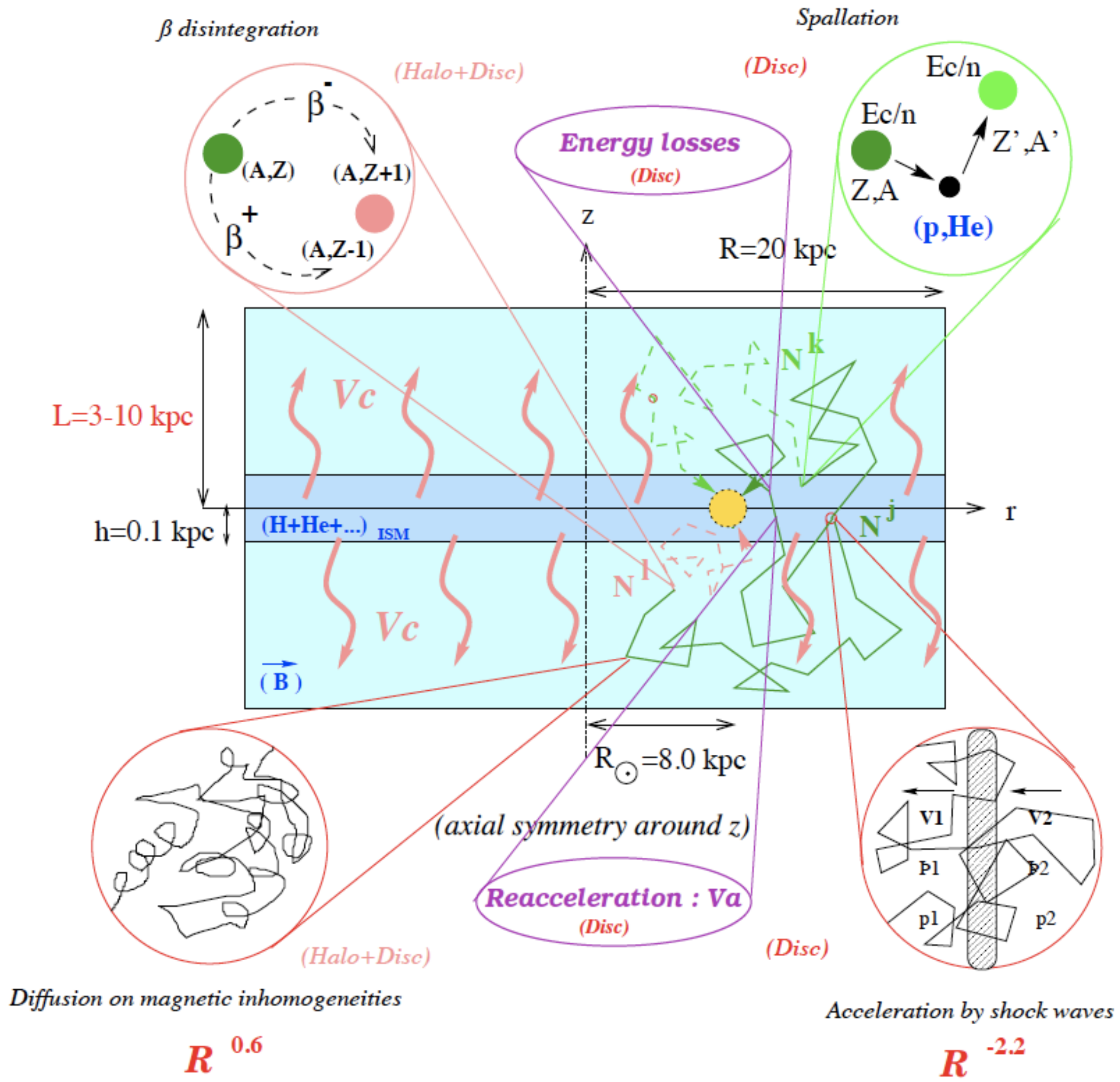


(Evoli, Gaggero, Grasso & Maccione, JCAP 10:018,2008)

All measured ratios consistent with 'leaky box' model with
$\tau_{esc} \sim E^{-\delta}$, $\delta \sim$ 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 particulary interesting if it were not for **the *PAMELA* 'anomaly'** …

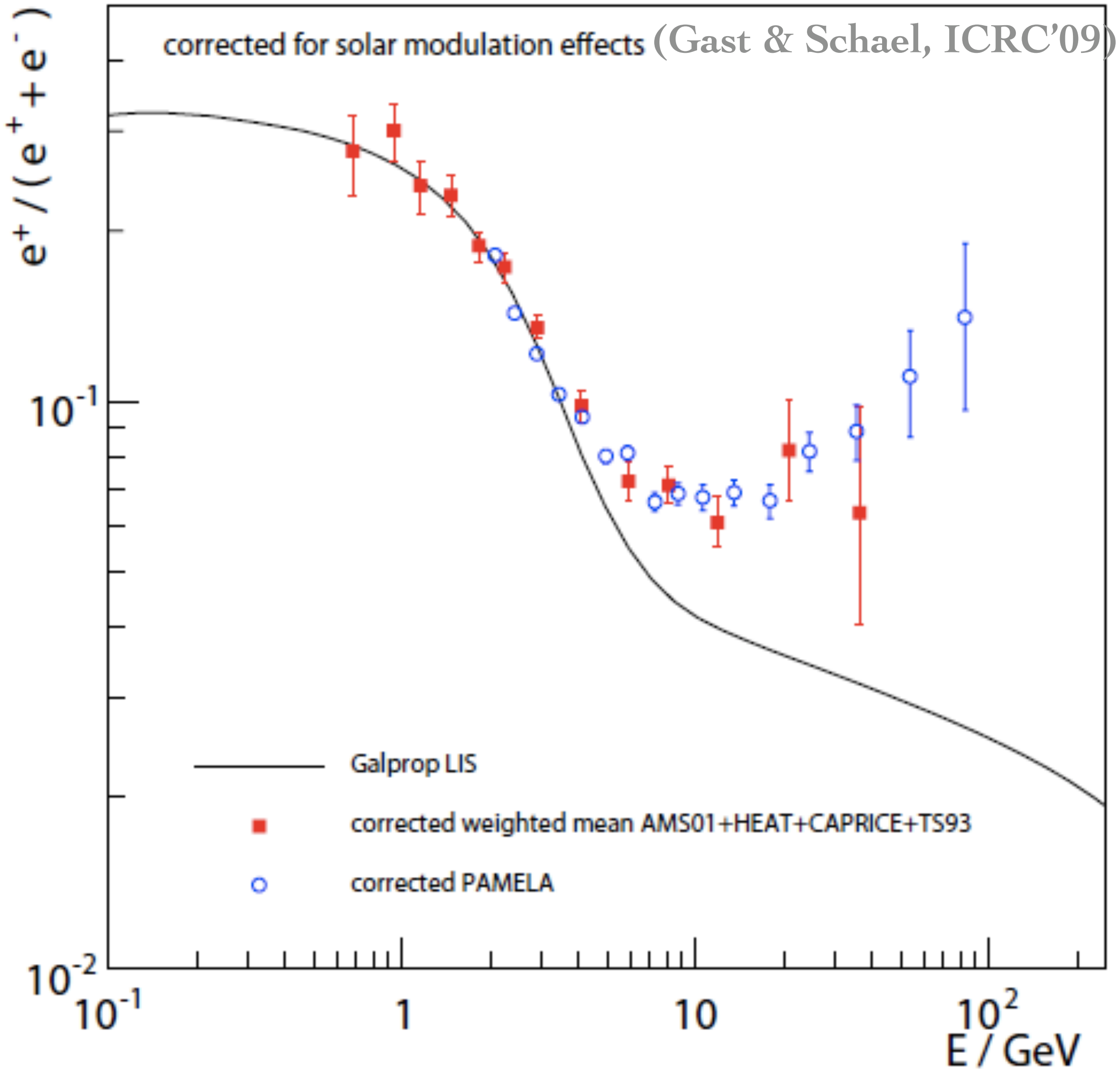
PAMELA has measured the positron fraction:

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

Anomaly ⇒ excess above 'astrophysical background'

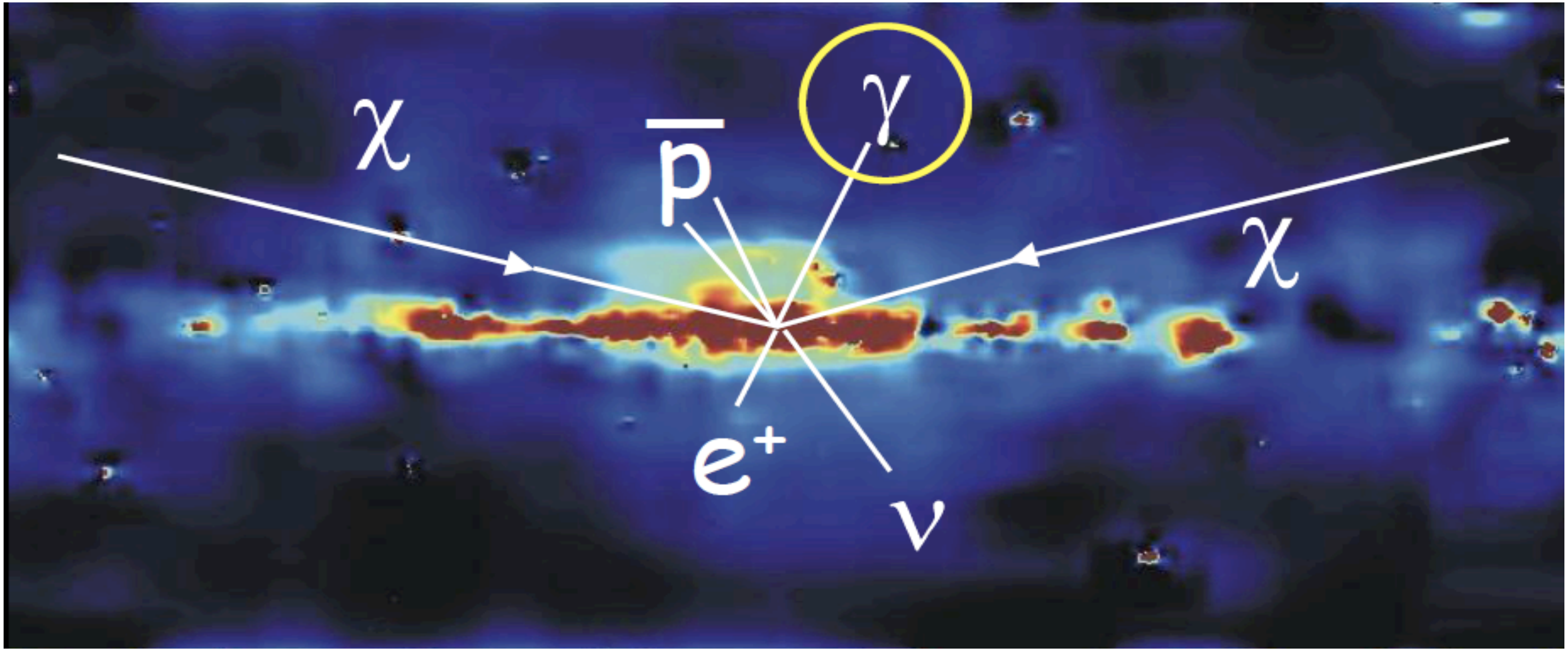
Source of anomaly:

- Dark matter?
- Pulsars?
- Supernova remnants?



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

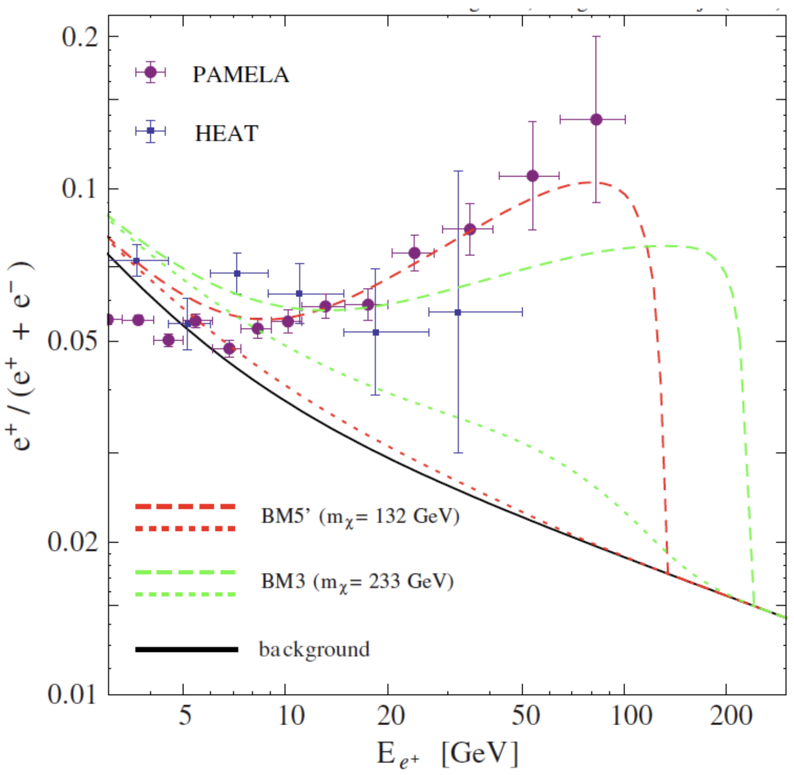
Rate $\propto n_{DM}^2$

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

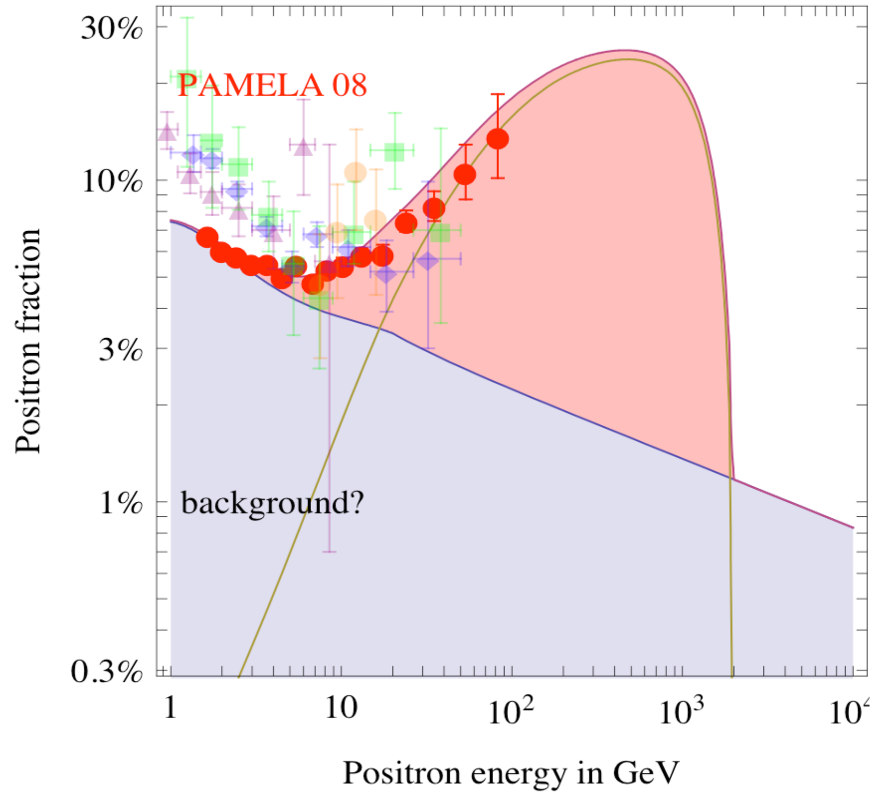
DM decay

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

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

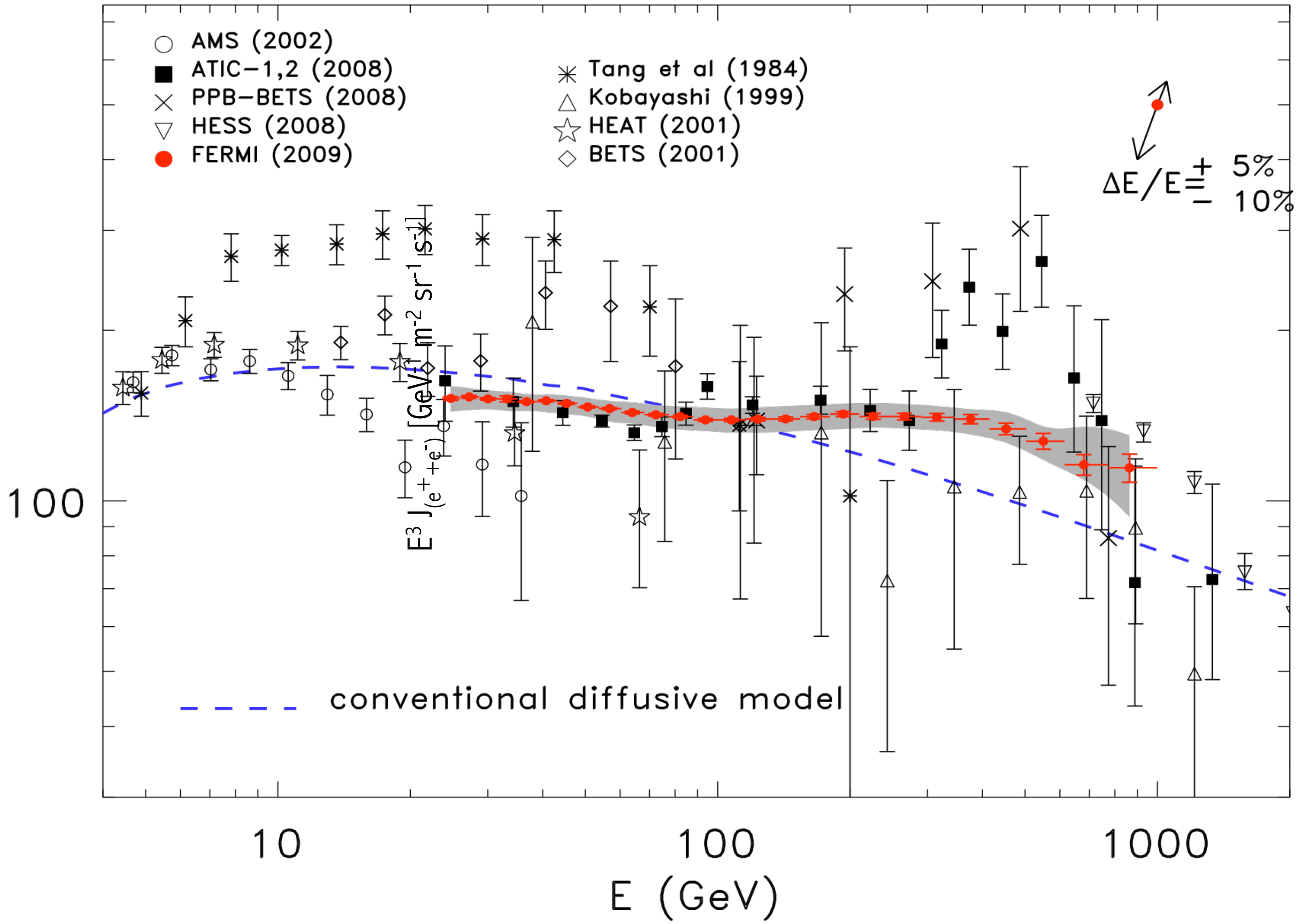


Bergström, Bringmann & Edjsö, PR D78:127850,2008



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

FERMI
The ~~ATIC~~ excess

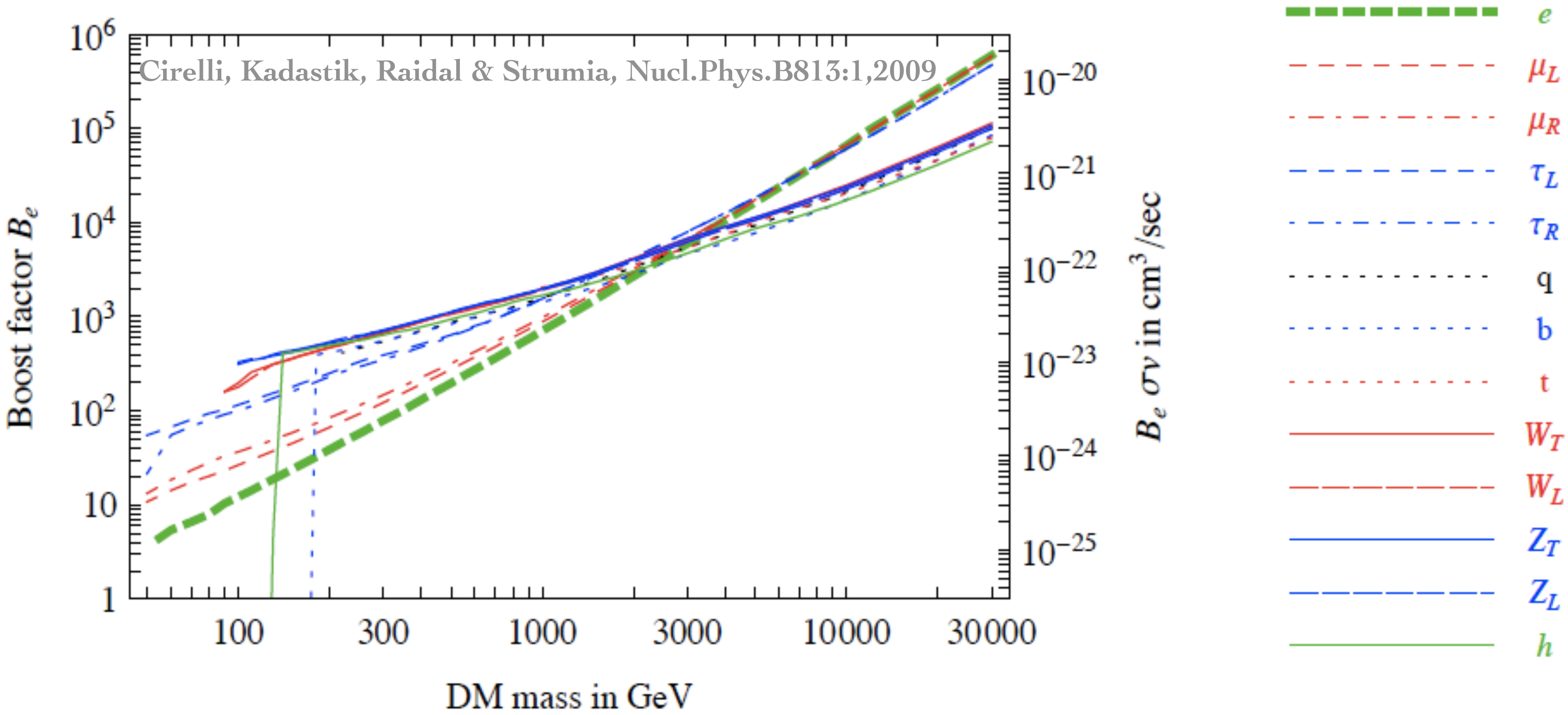


***Fermi* LAT also sees 'excess' $e^{\pm}$ over expectation** (Abdo *et al*, PRL 102:181101,2009)
(although it does *not* confirm the peak seen earlier by *ATIC*-2)

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

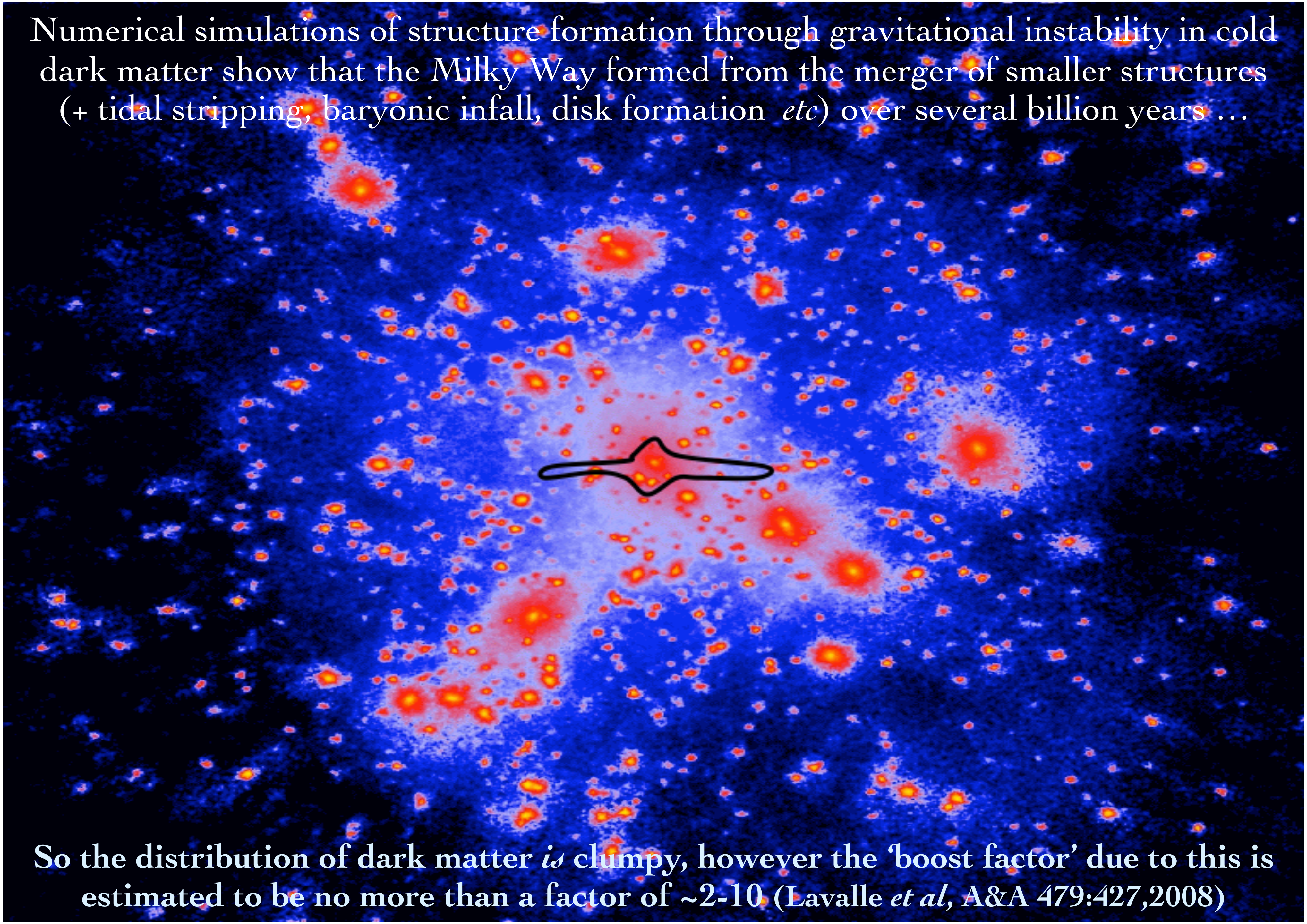
➔ Such a large annihilation #-section would imply *negligible* relic abundance unless an *inverse* velocity dependence is invoked e.g. 'Somerfeld enhancement' (this requires hypothetical light gauge bosons to provide new long range force)

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



... 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 …



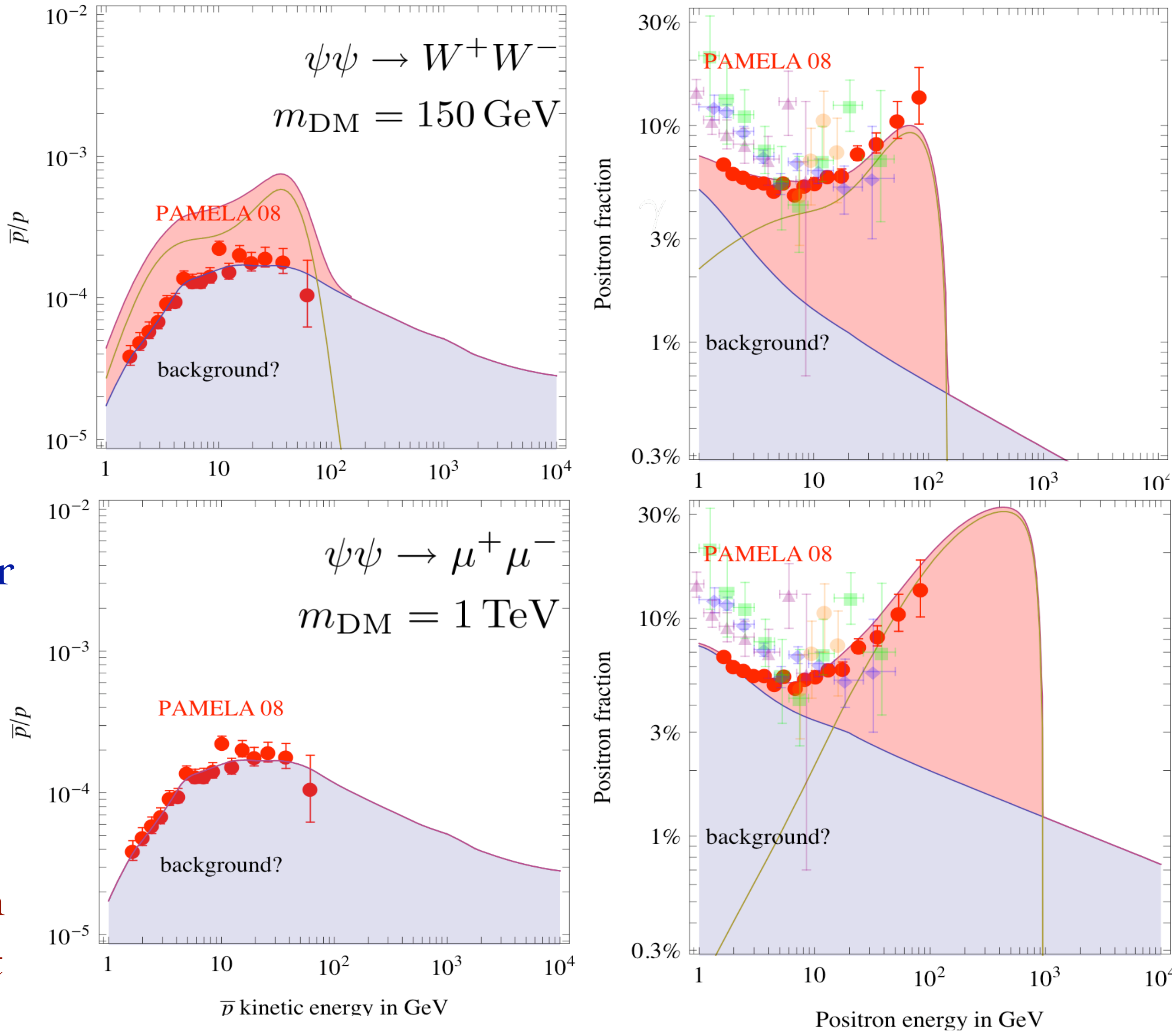
So the distribution of dark matter *is* clumpy, however the 'boost factor' due to this is estimated to be no more than a factor of ~2-10 (Lavalle *et al*, A&A 479:427,2008)

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

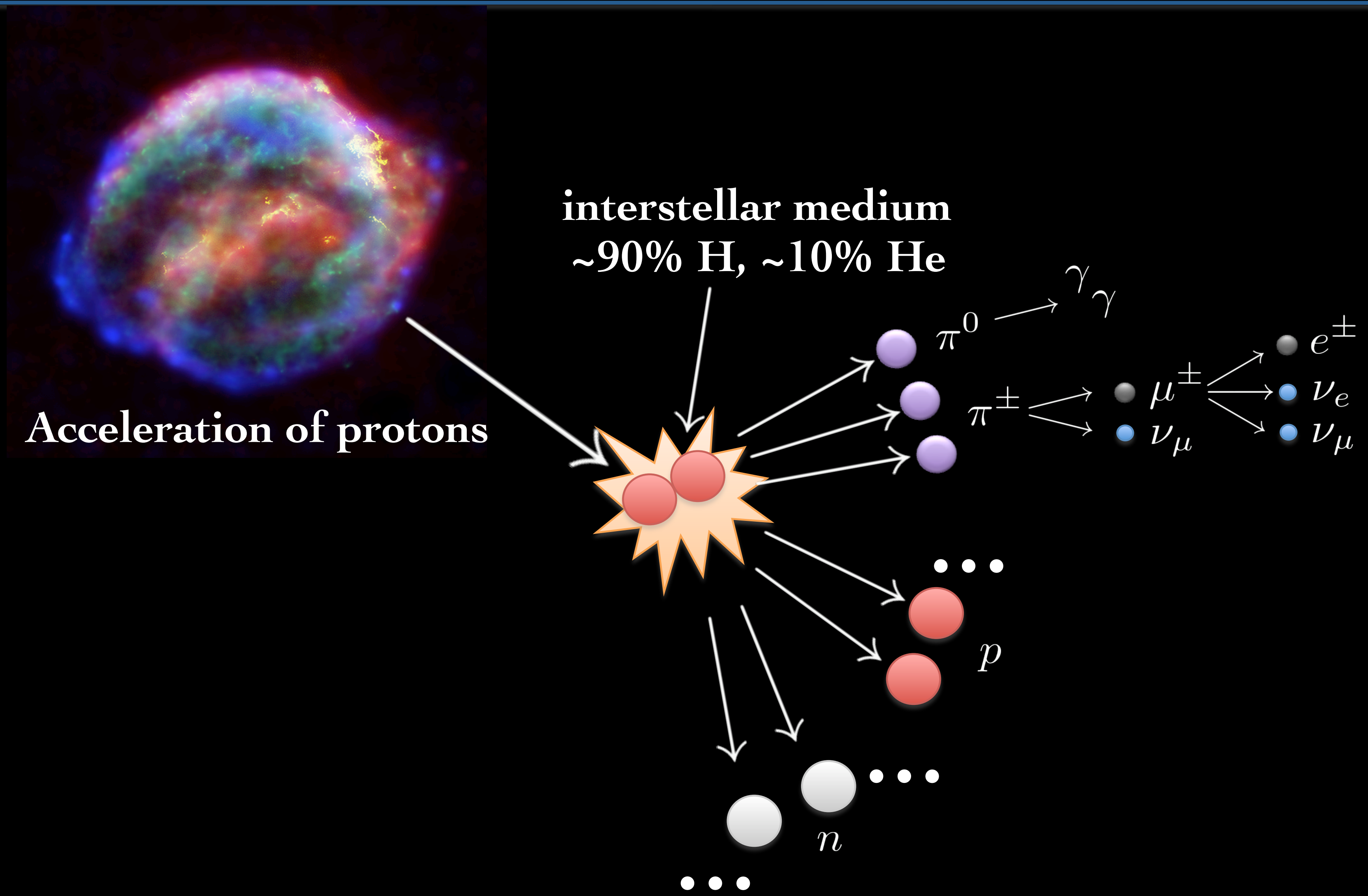
Can fit with DM decay or annihilation only if DM particles are ‘leptophilic’ which is rather contrived

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

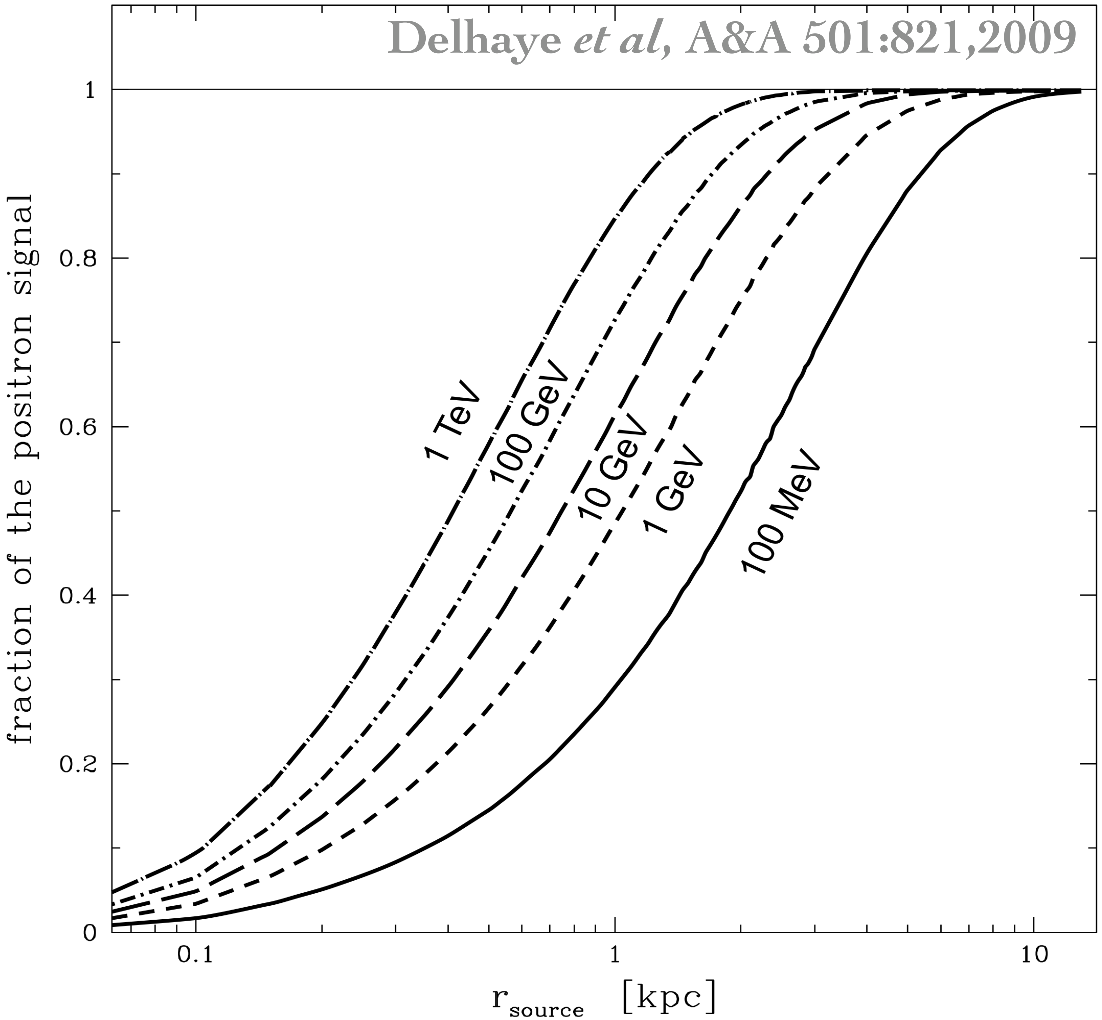


Cirelli *et al*, Nucl.Phys.B813:1,2009

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



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



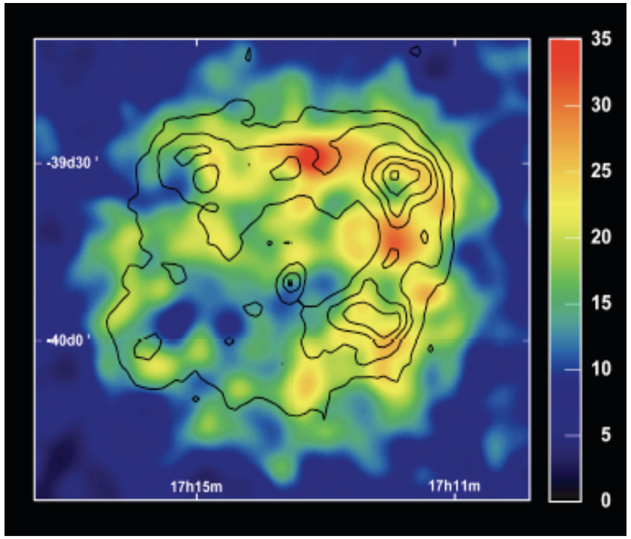
$$\tau \simeq 5 \cdot 10^5 \mathrm{yr} \left(\frac{1\ \mathrm{TeV}}{E} \right)$$

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

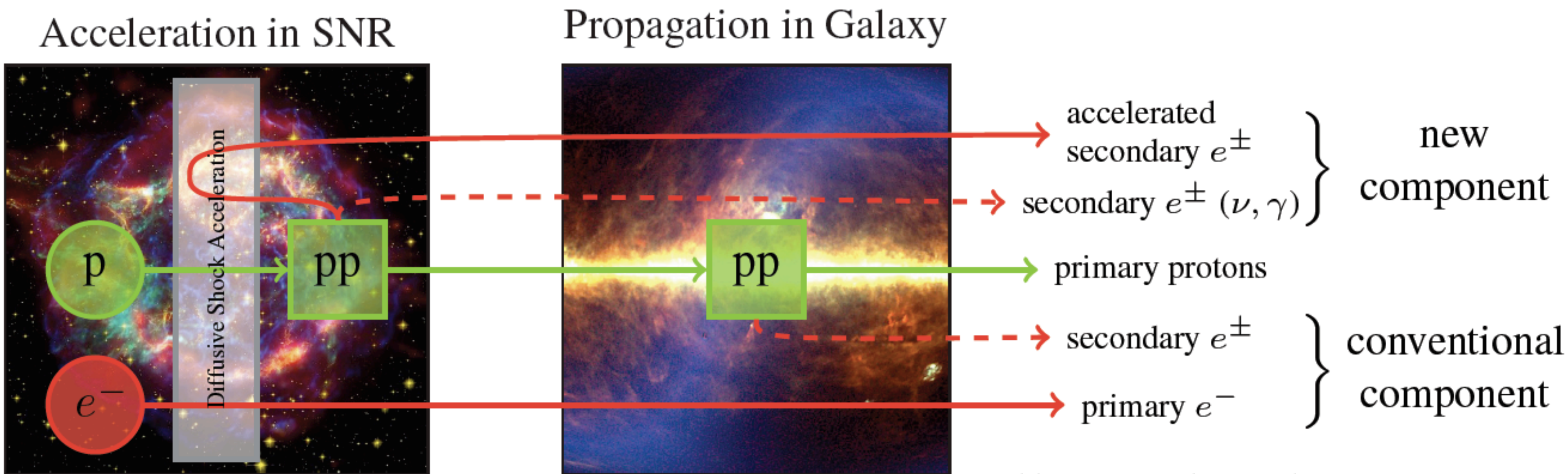
(Blasi, PRL 103:051104,2009)



RXJ1713.7-3946, *HESS*

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

This component *naturally* has a harder spectrum and fits *PAMELA* data (adjusting 1 free parameter)

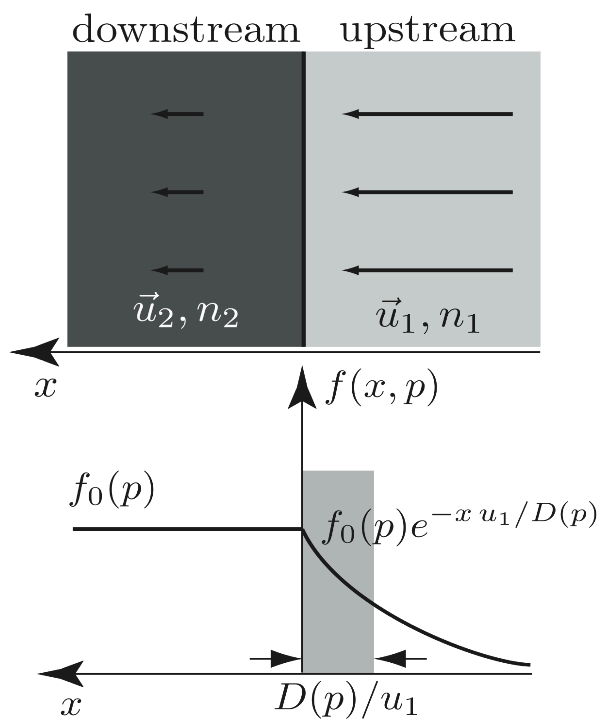


Ahlers, Mertsch & Sarkar,PRD80:123017,2009

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

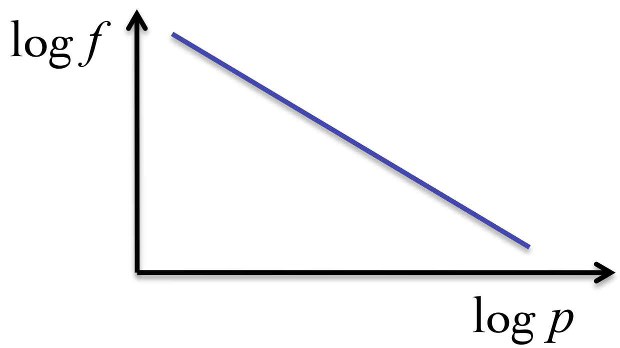
$$f \xrightarrow{x\to -\infty} f_{\mathrm{inj}}(p), \qquad \left|\lim_{x\to\infty} f\right| \ll \infty$$

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

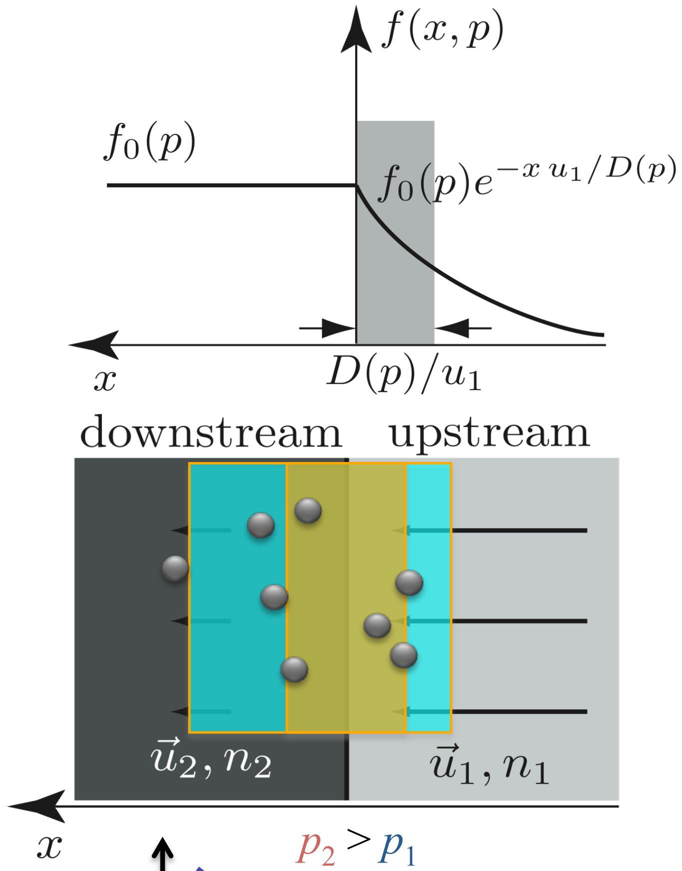
- Bohm diffusion: $D(p) \propto p$

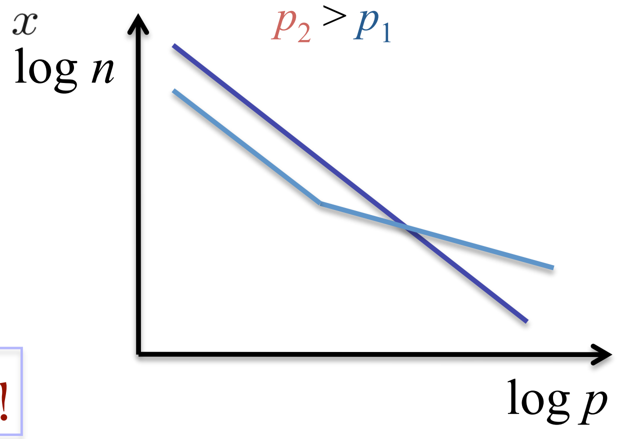
- Fraction of accelerated secondaries is $\propto p$

- **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!



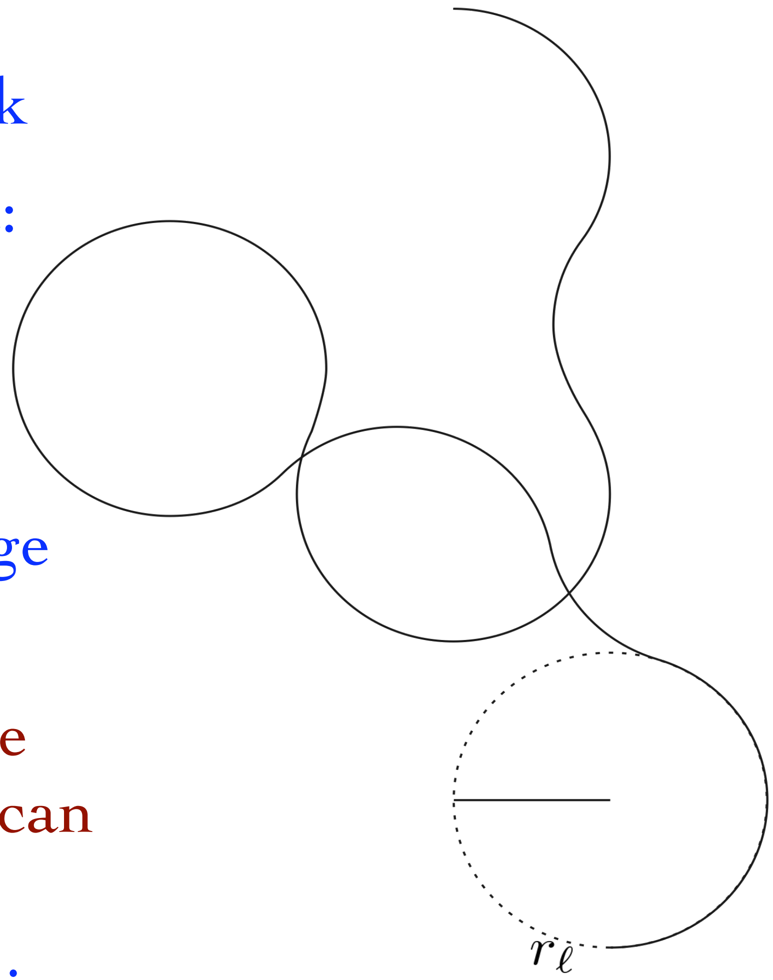


Diffusion near shock front

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

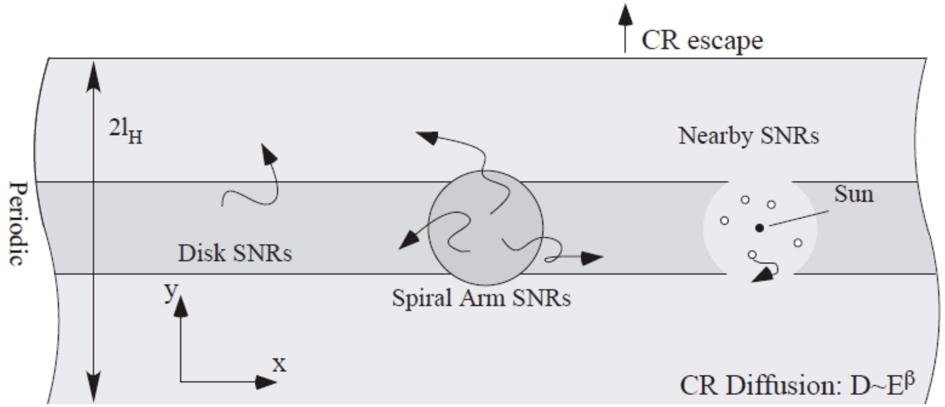
$$D^{\mathrm{Bohm}} = r_\ell \frac{c}{3} \propto \frac{E}{Z}$$

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

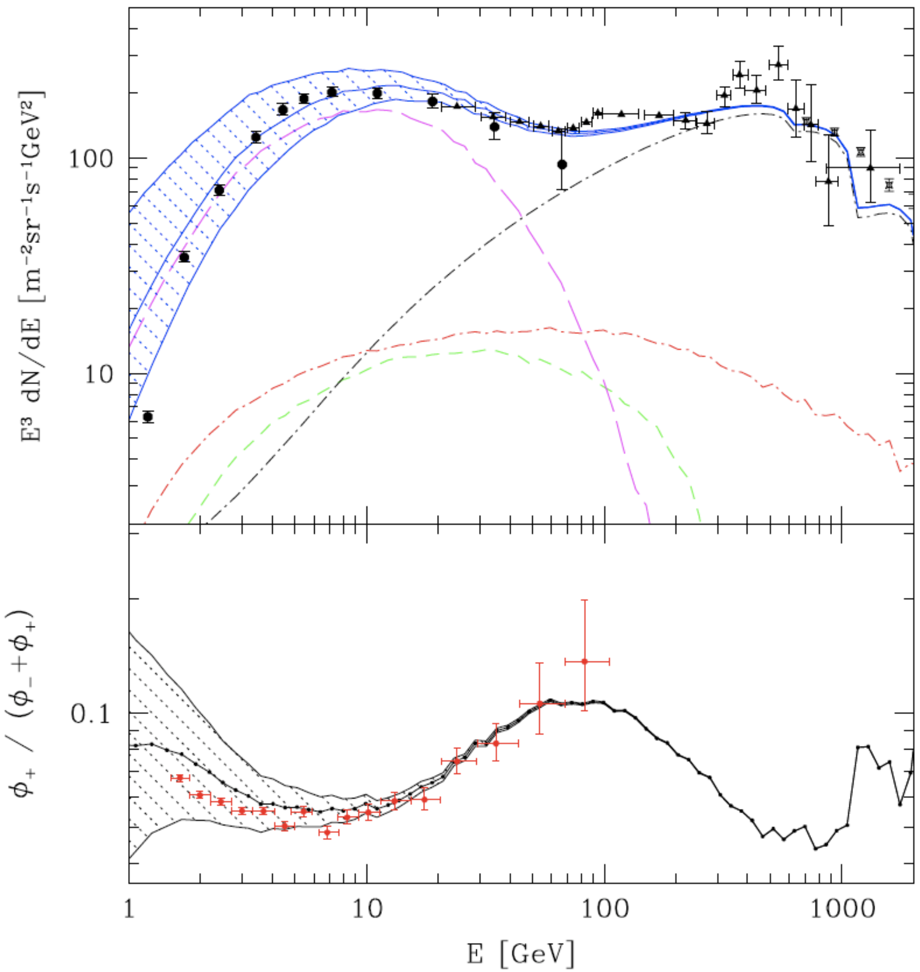


Inhomogeneity in the SNR distribution as the origin of the PAMELA anomaly

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
$\Rightarrow$ enhancement of e^+/e^-

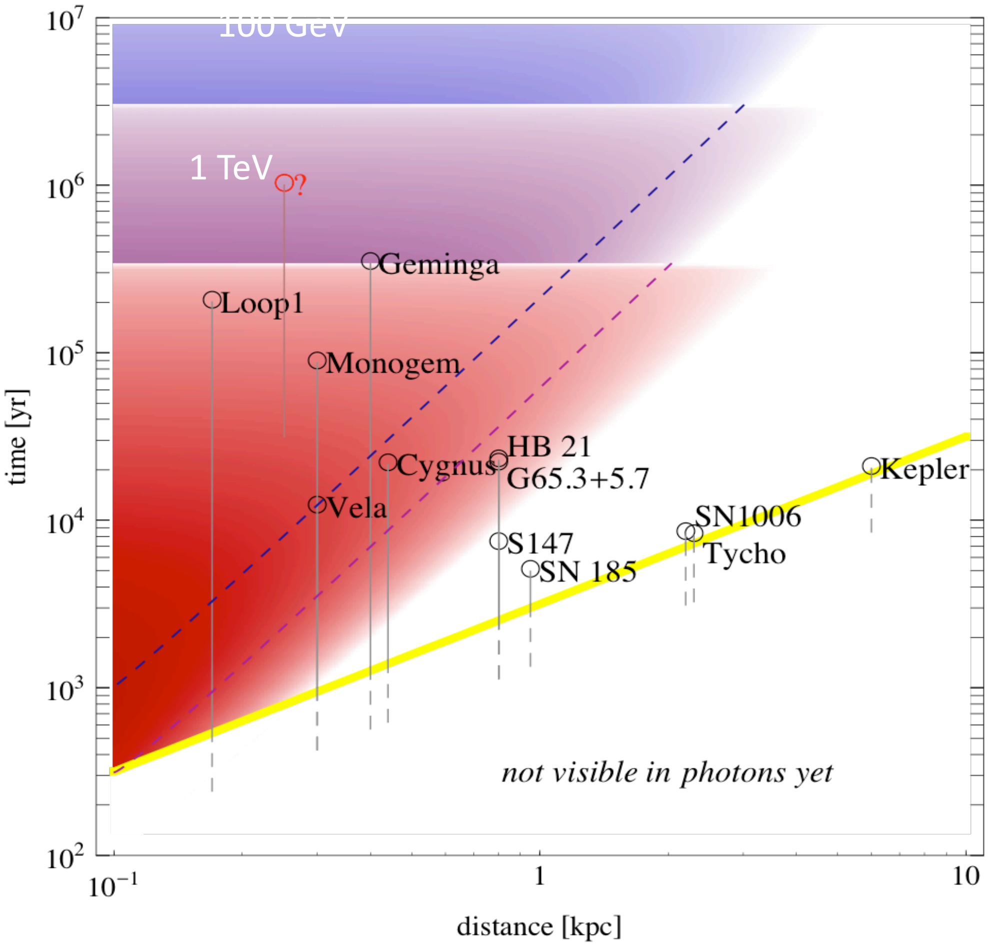


But with usual propagation parameters ($D_0 \sim 10^{28}$ cm^2 s^{-1}, $\delta \sim 0.6$, $\tau_{esc} \sim 10^{16}$ s) find break energy to be 2 TeV, *not* 20 GeV … also nearby 'invisible' SNRs (e.g. *Geminga*) will fill in dips in the spectrum

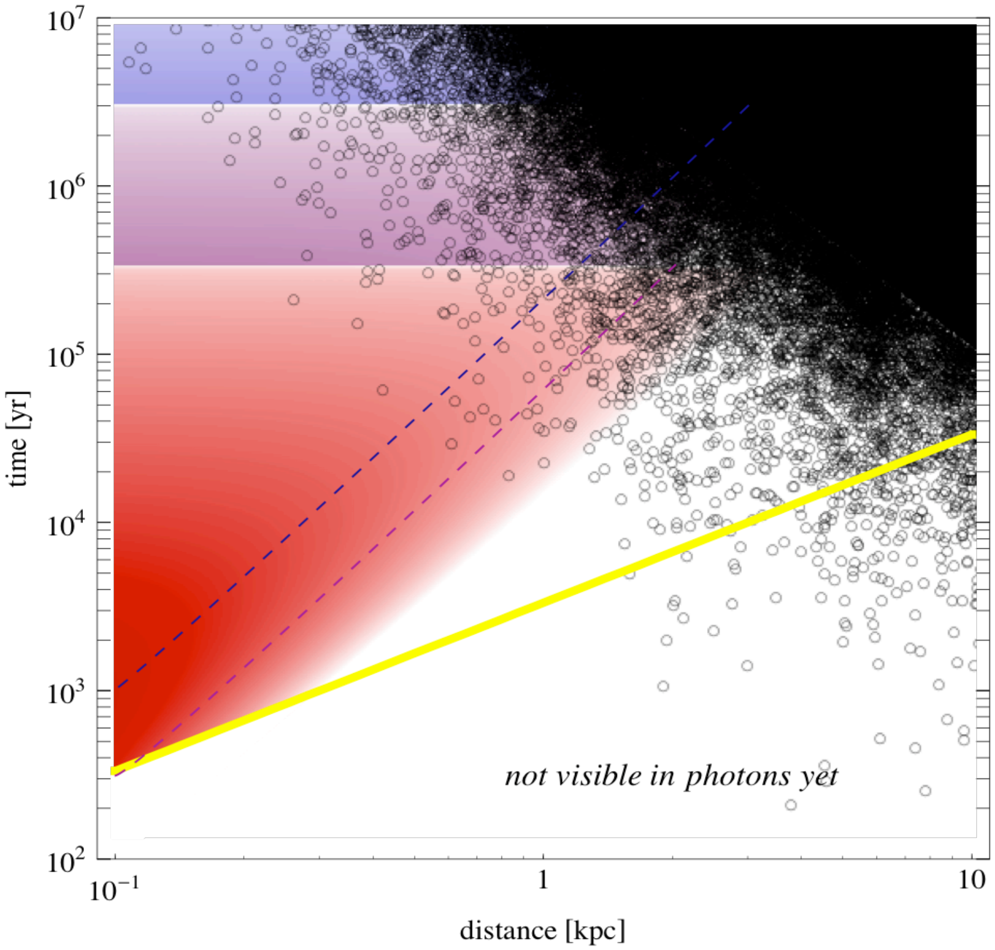
It is not just the few (optically) observed SNRs which contribute to observed cosmic rays … there must be many other *hidden* SNRs

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

Known

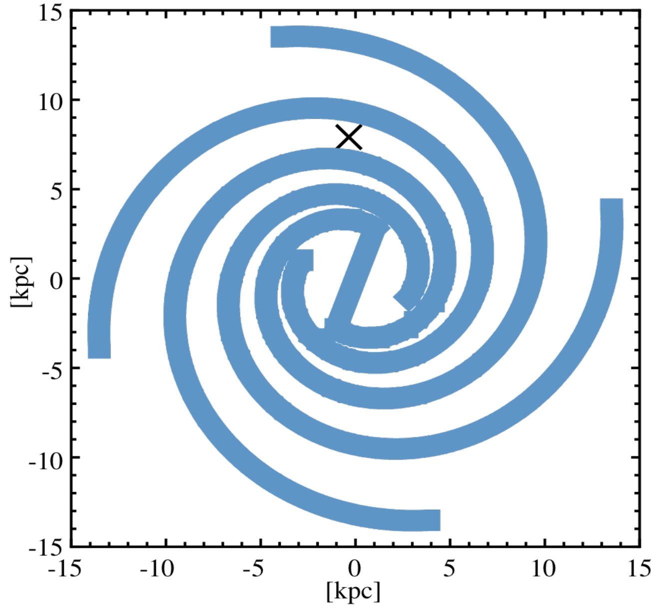


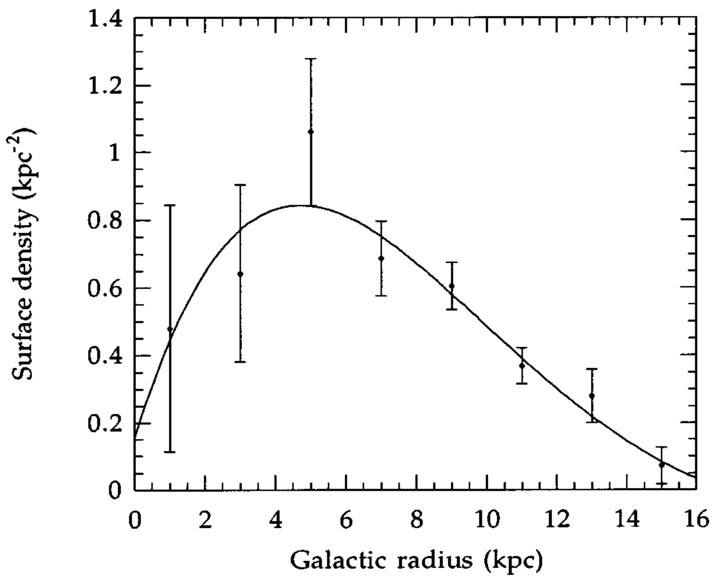
Simulated



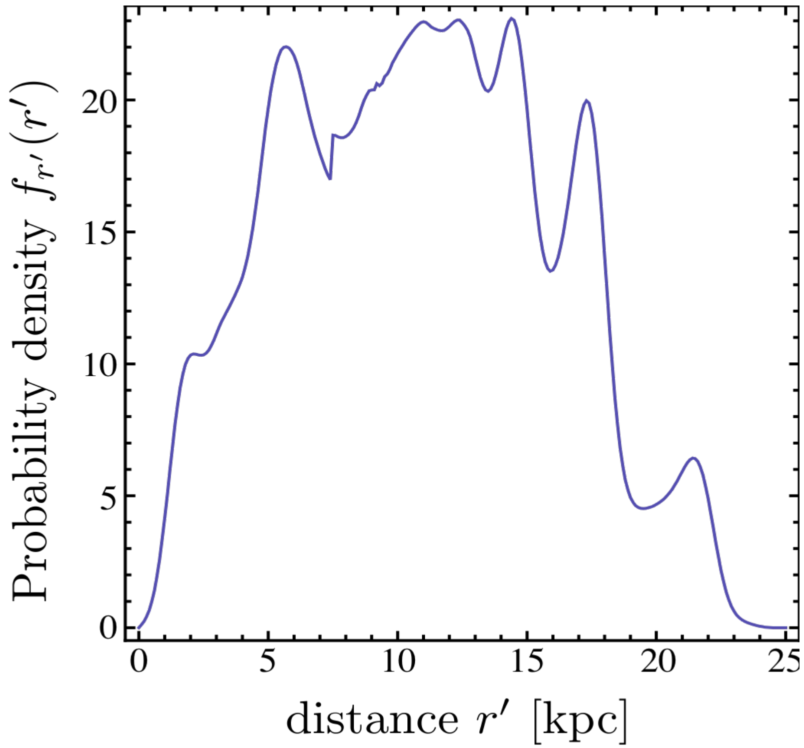
Ahlers, Mertsch & Sarkar, PRD80:123017,2009

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

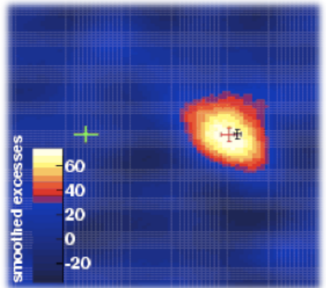
Ahlers, Mertsch & Sarkar,PRD80:123017,2009

Parameters of the Monte Carlo

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 $10\,\mathrm{GeV}$
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

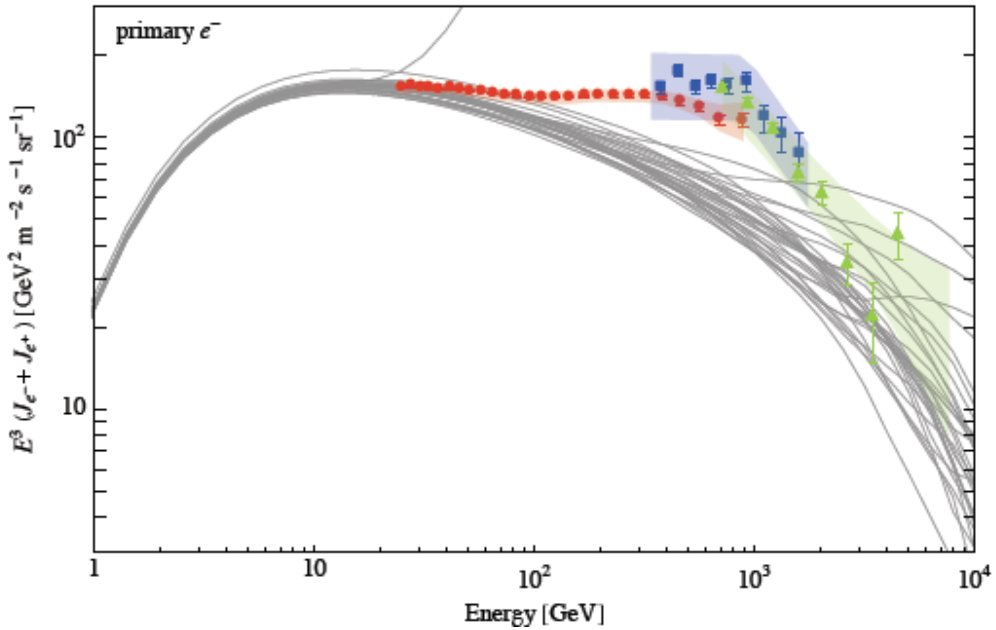
Normalisation of primary e^-: fit absolute e^- flux at low energies

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

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

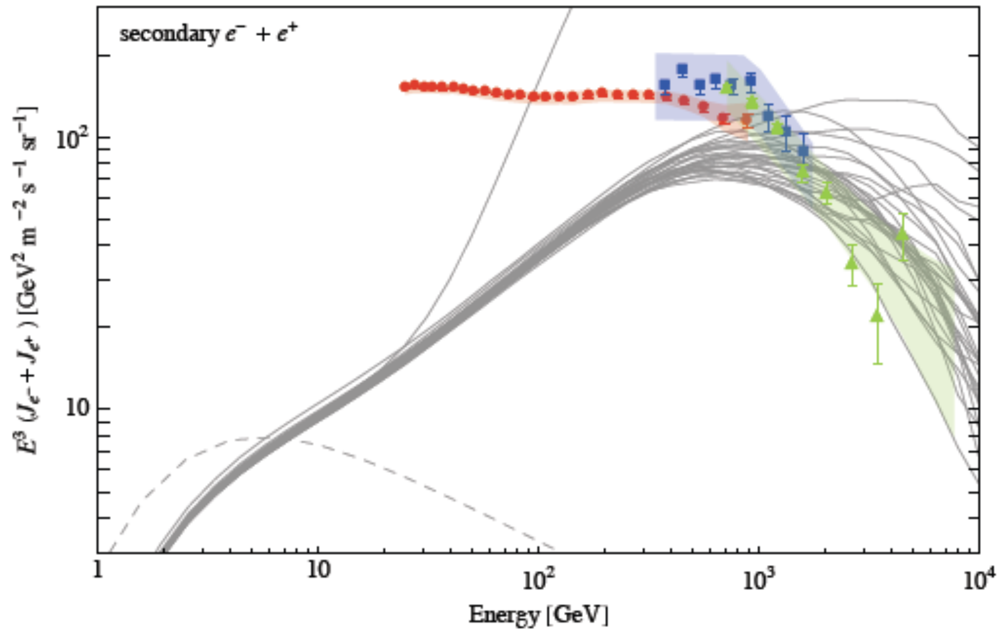
Ahlers, Mertsch & Sarkar, PRD80:123017,2009

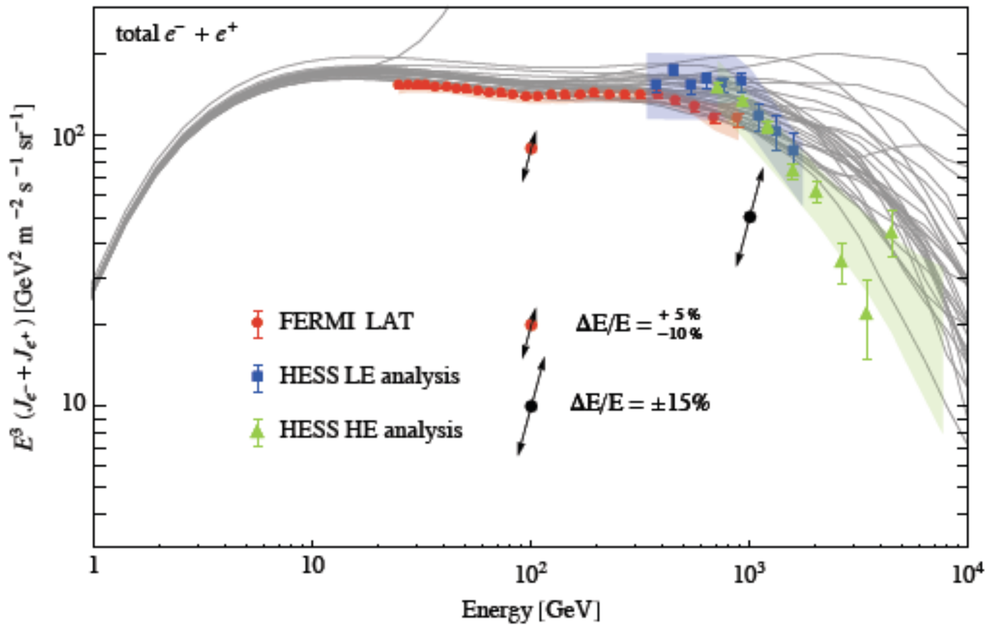
Fitting the $e^+ + e^-$ flux



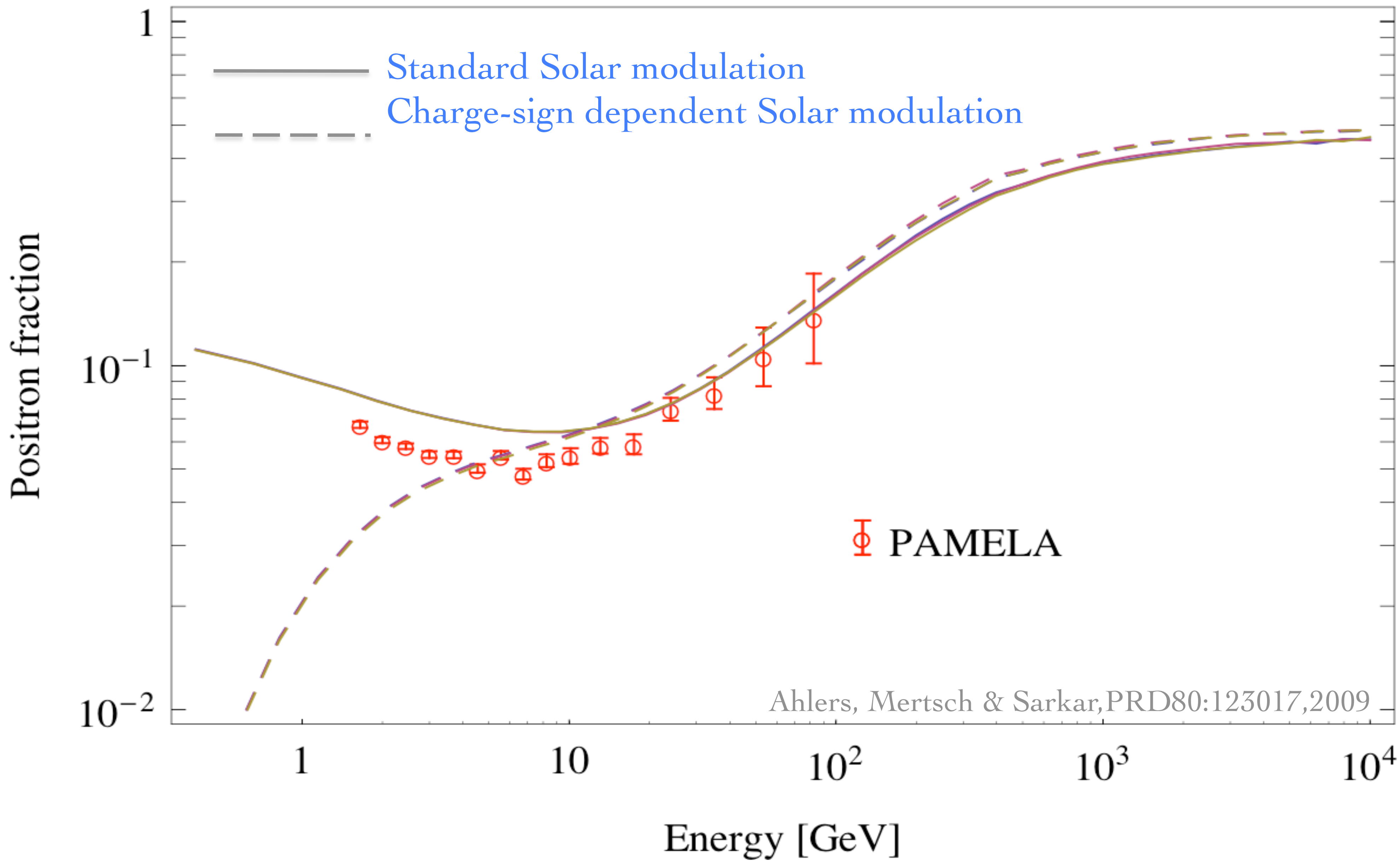
The propagated primary e^- spectrum is much too *steep* to match the Fermi LAT data … but the *accelerated* secondary $e^+ + e^-$ component has a harder spectrum so fits the 'bump'!

Ahlers, Mertsch & Sarkar, PRD80:123017,2009





The *predicted* positron fraction



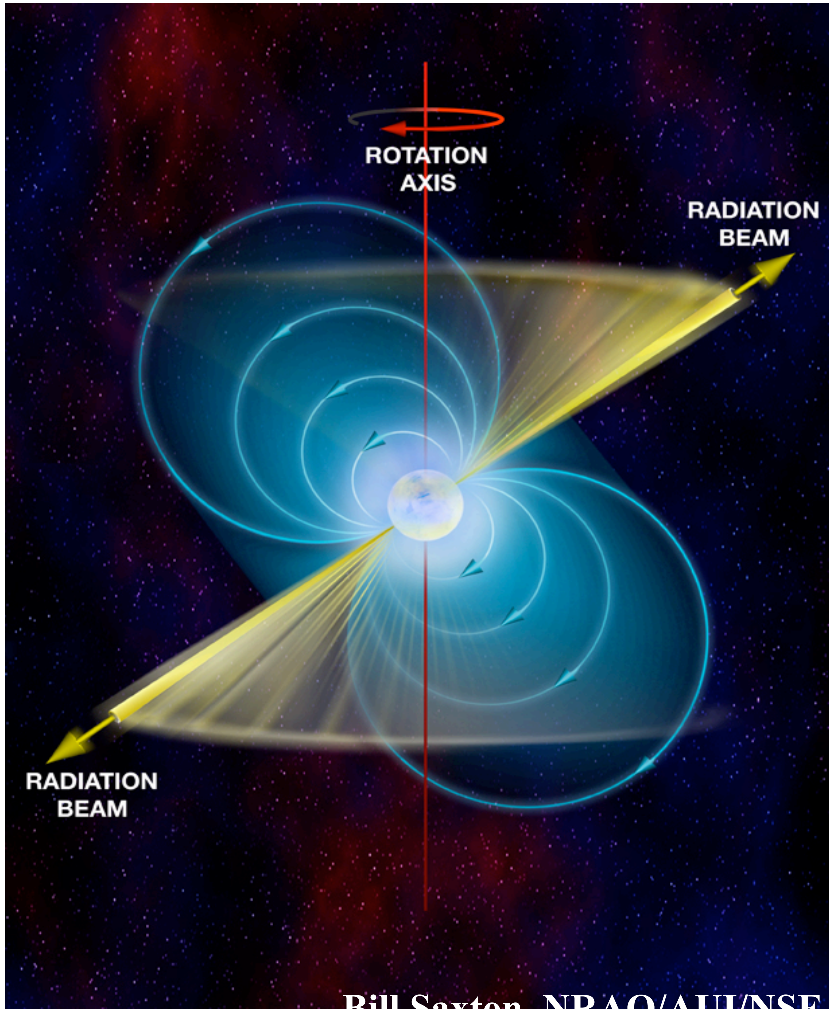
Nearby pulsars as source of $e^{\pm}$

- Highly magnetized, fast spinning neutron stars

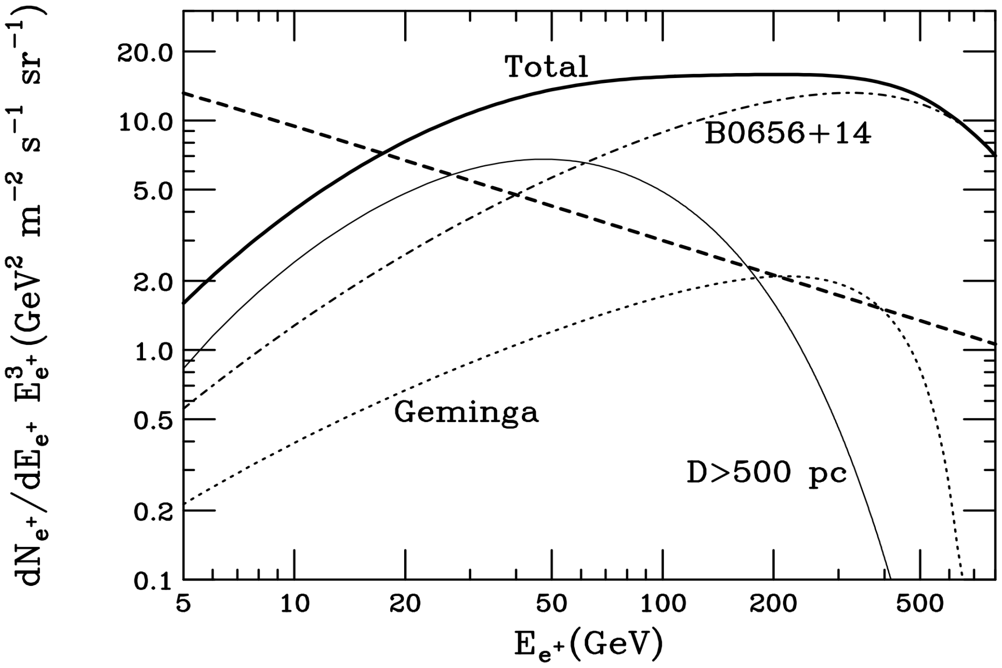
- γ-rays and electron/ positron pairs produced along the magnetic axis

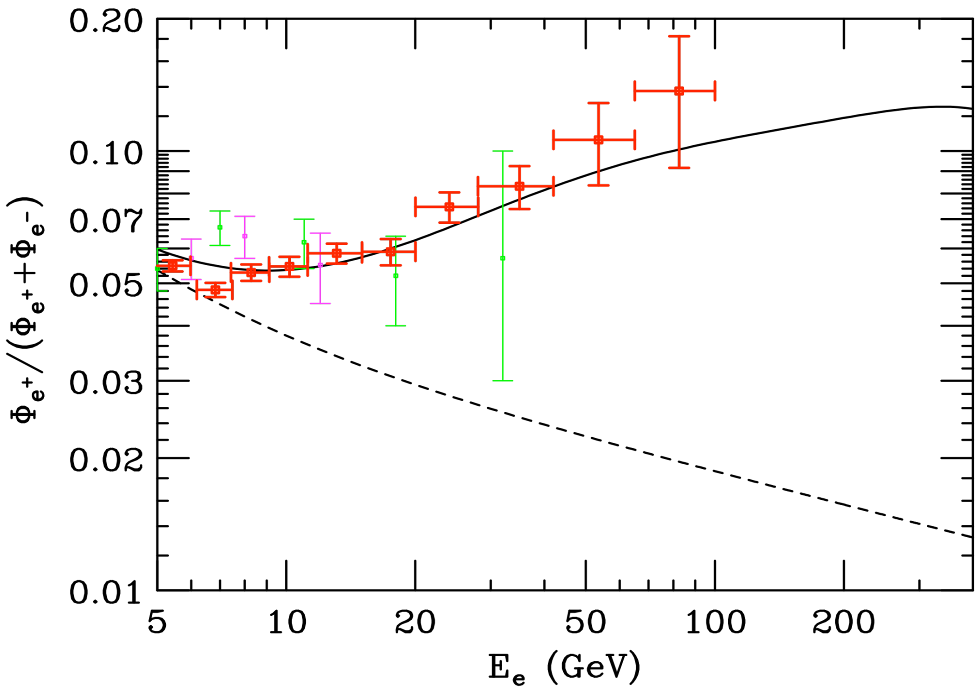
- Spectrum *speculated* to be harder than background from propagation:

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



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

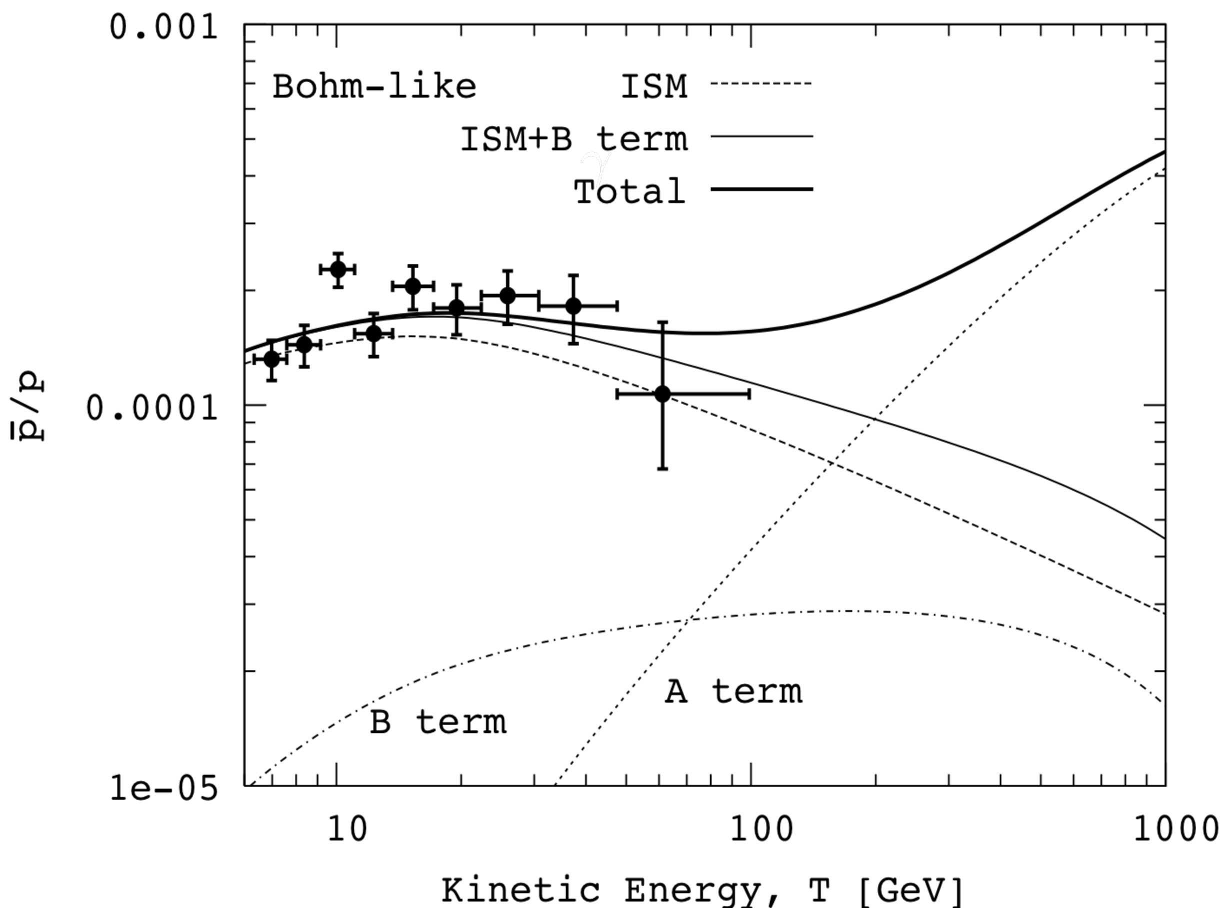
However ~40% of rotational energy must be released as energetic e^+ – plausible?

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

What about the antiproton-to-proton ratio?

Blasi & Serpico, PRL 103:081103,2009

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



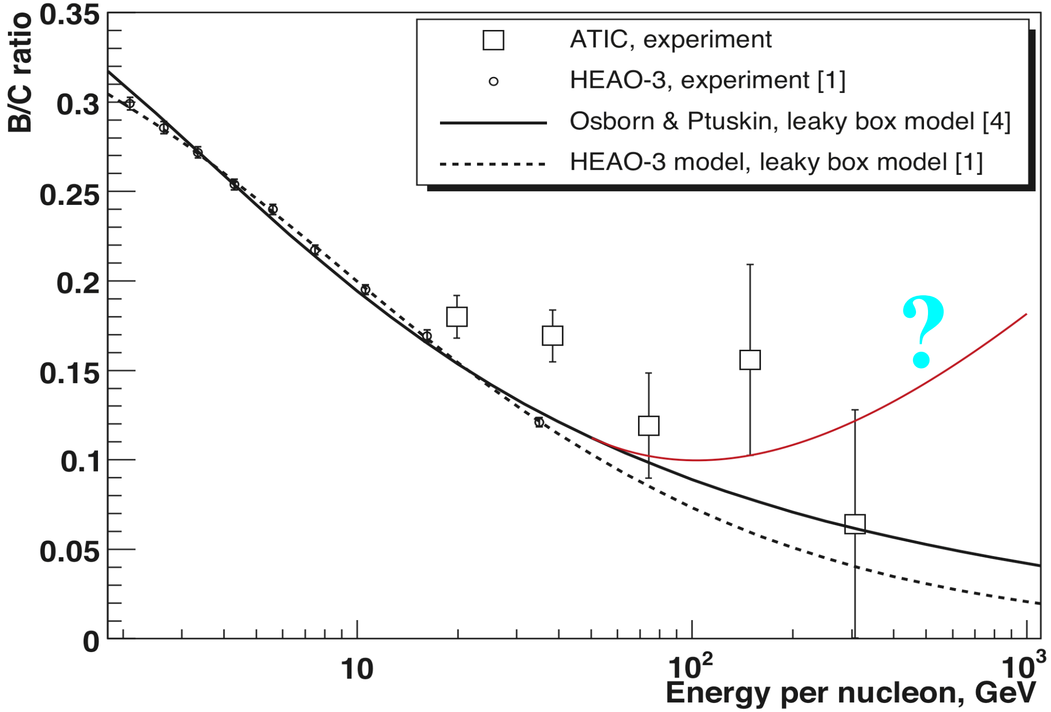
Secondary acceleration model predicts rise *beyond* 100 GeV
… will be tested soon by *AMS*-02

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

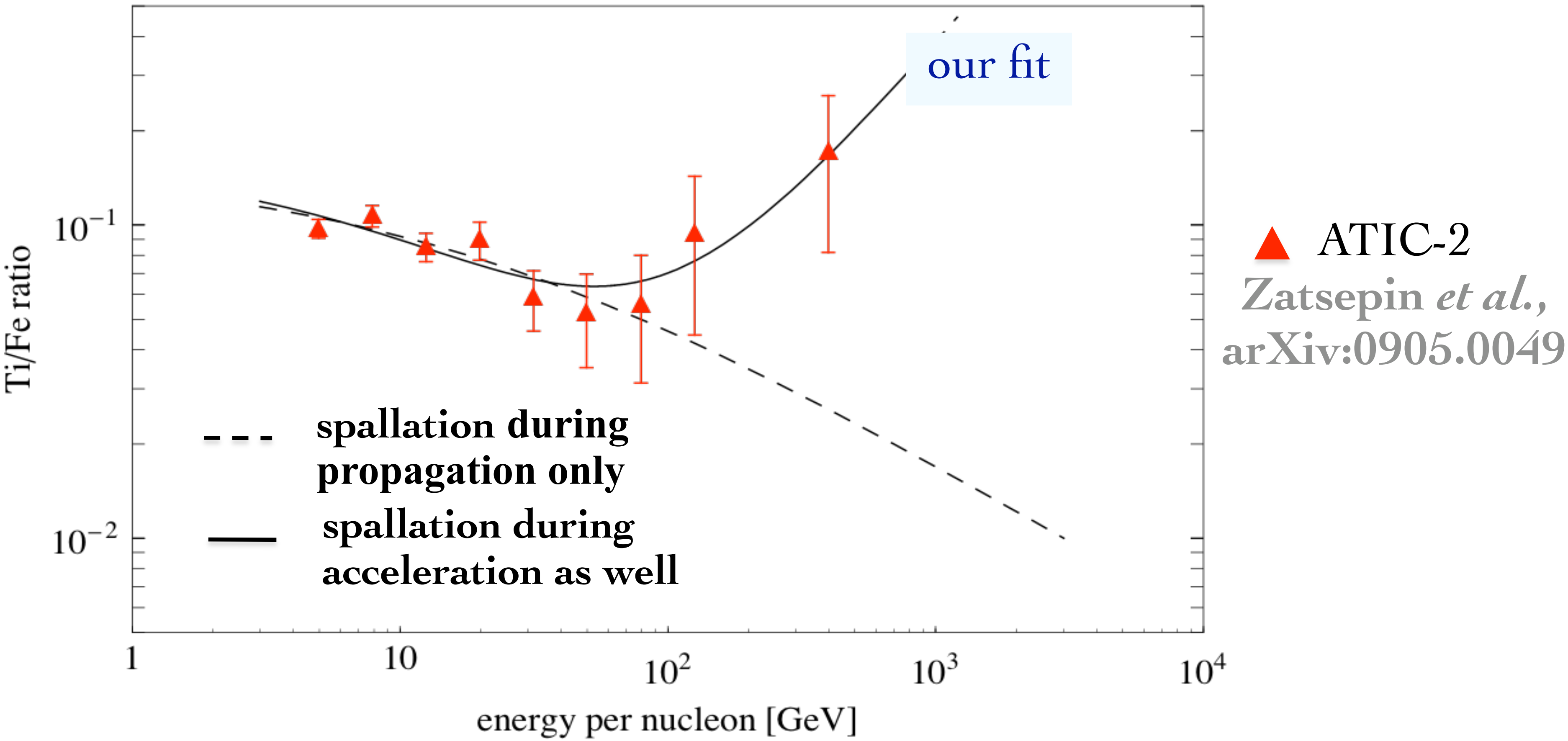
with boundary condition: $f_i(x,p) \xrightarrow{x\to-\infty} Y_i \delta(p - p_0)$

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

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

Mertsch & Sarkar, PRL 103:081104,2009

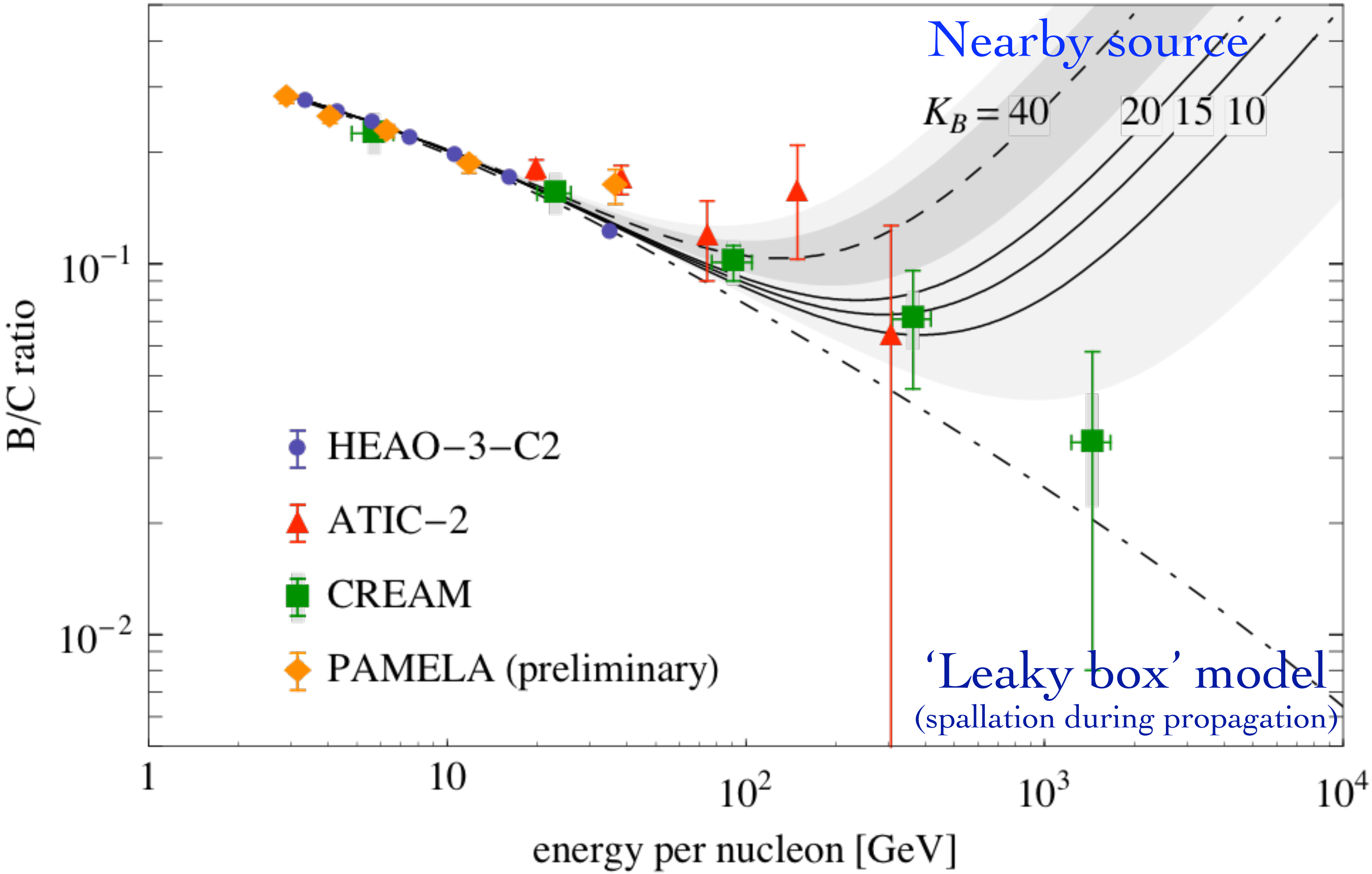
Titanium-to-Iron Ratio



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

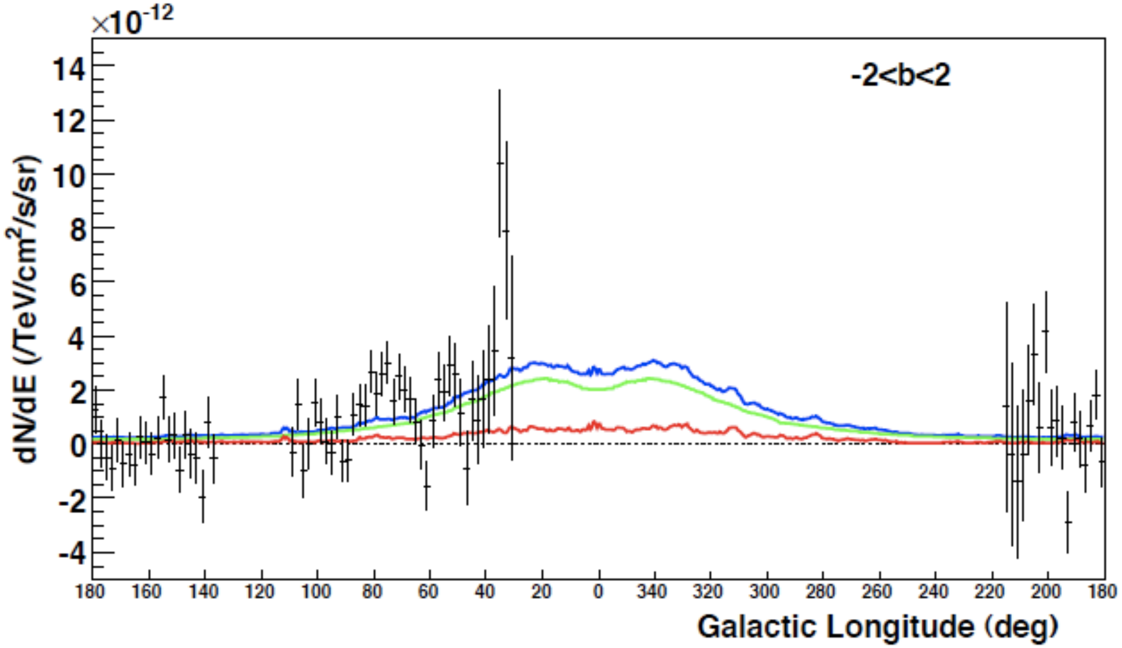
We can then predict another secondary/primary ratio e.g. B/C …



PAMELA is currently measuring B/C with unprecedented accuracy

… a *rise* would establish the nearby hadronic accelerator model

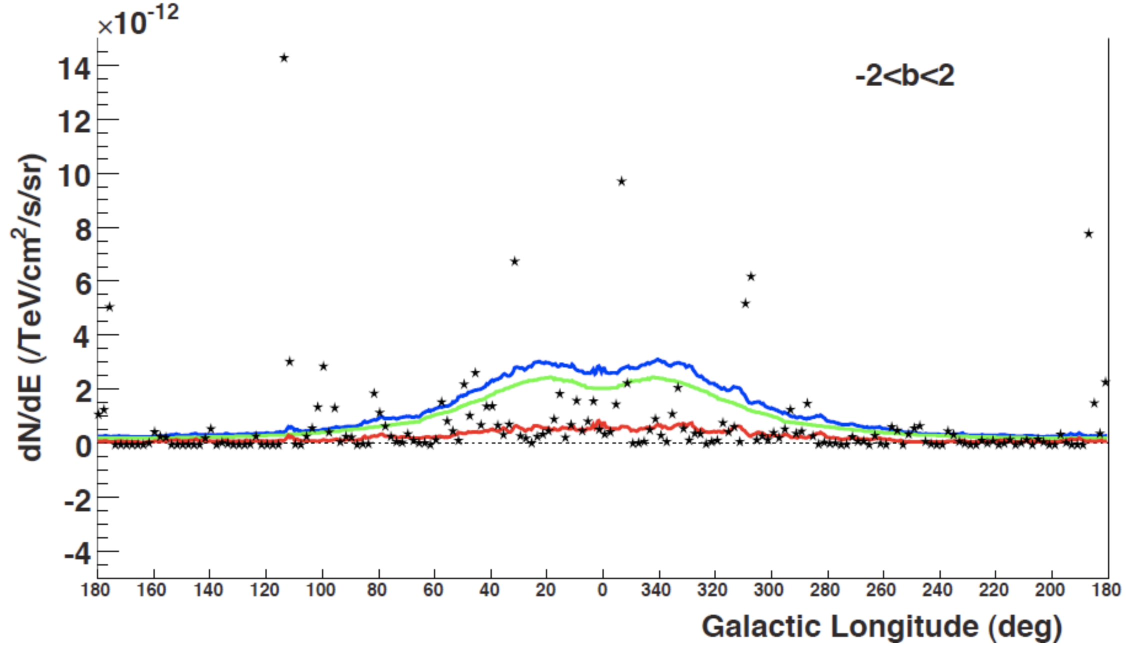
Have some of these old SNRs been seen already?



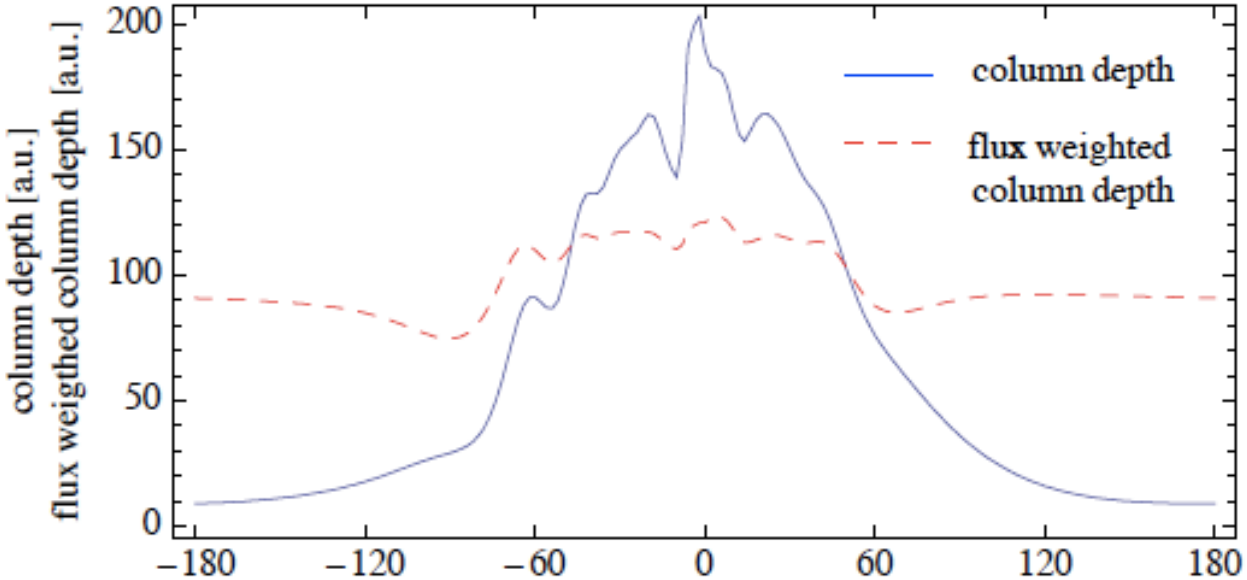
MILAGRO profile of the Milky Way overlaid with GALPROP 'prediction' (red: π^0 decay, green: IC, blue: total)

Abdo *et al*, arXiv:0805.0417

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 2^0x4^0 resolution



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



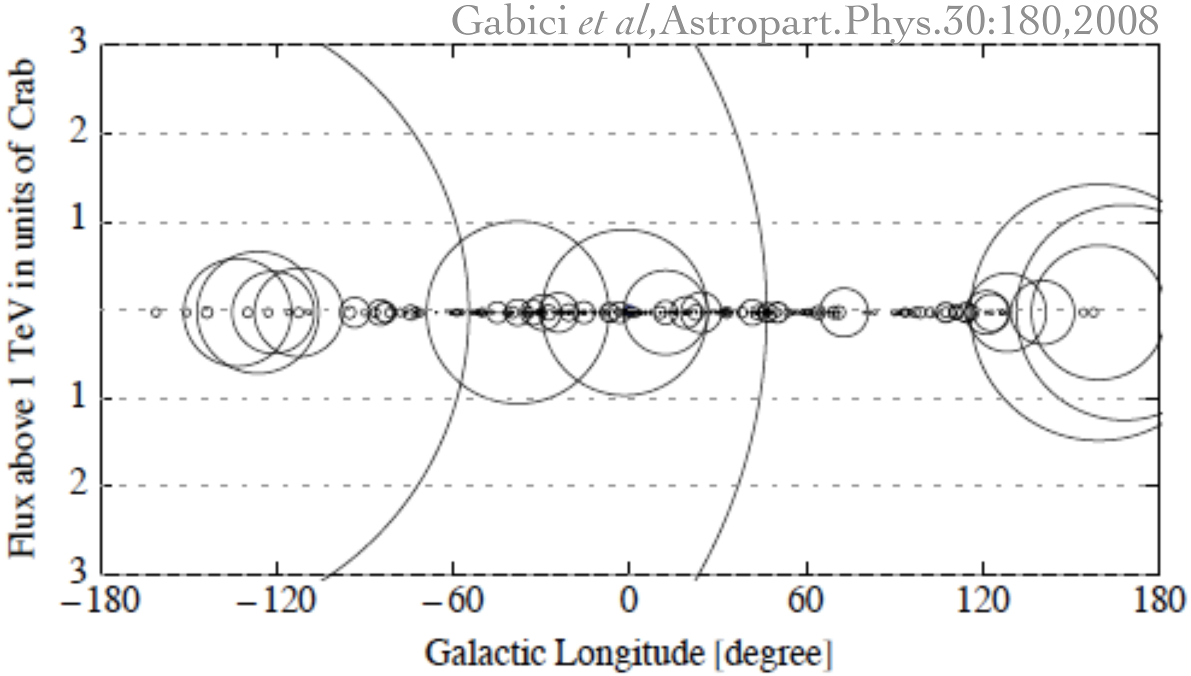
The column depth and *flux weighted* column depth of the SNR density in the Galactic plane …
not very different towards Galactic centre/anti-centre
i.e. equally useful to survey Northern/Southern sky

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 **γ-rays** (*HAWC*, *CTA*) and **neutrinos** (*IceCube*, *KM3NeT*)

This would be the first identification of cosmic 'pevatrons'