Antimatter in cosmic rays: Signal of new physics?

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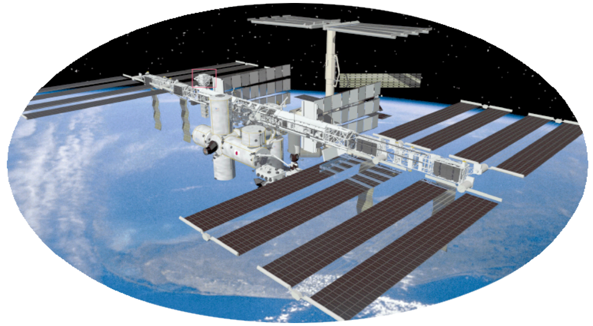
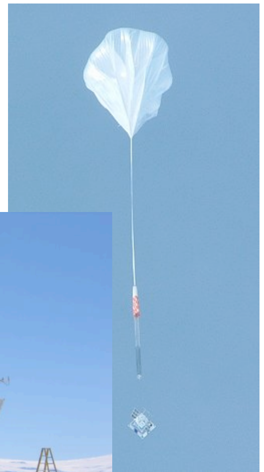
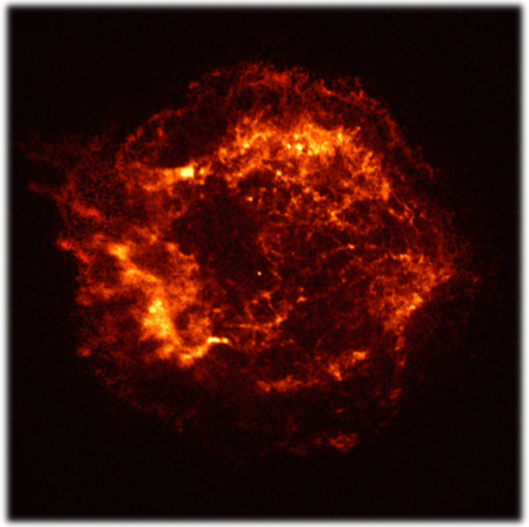






The new, the rare and the beautiful, University of Zurich, 6-8 January 2010

The *PAMELA* anomaly

PAMELA has measured the positron fraction:

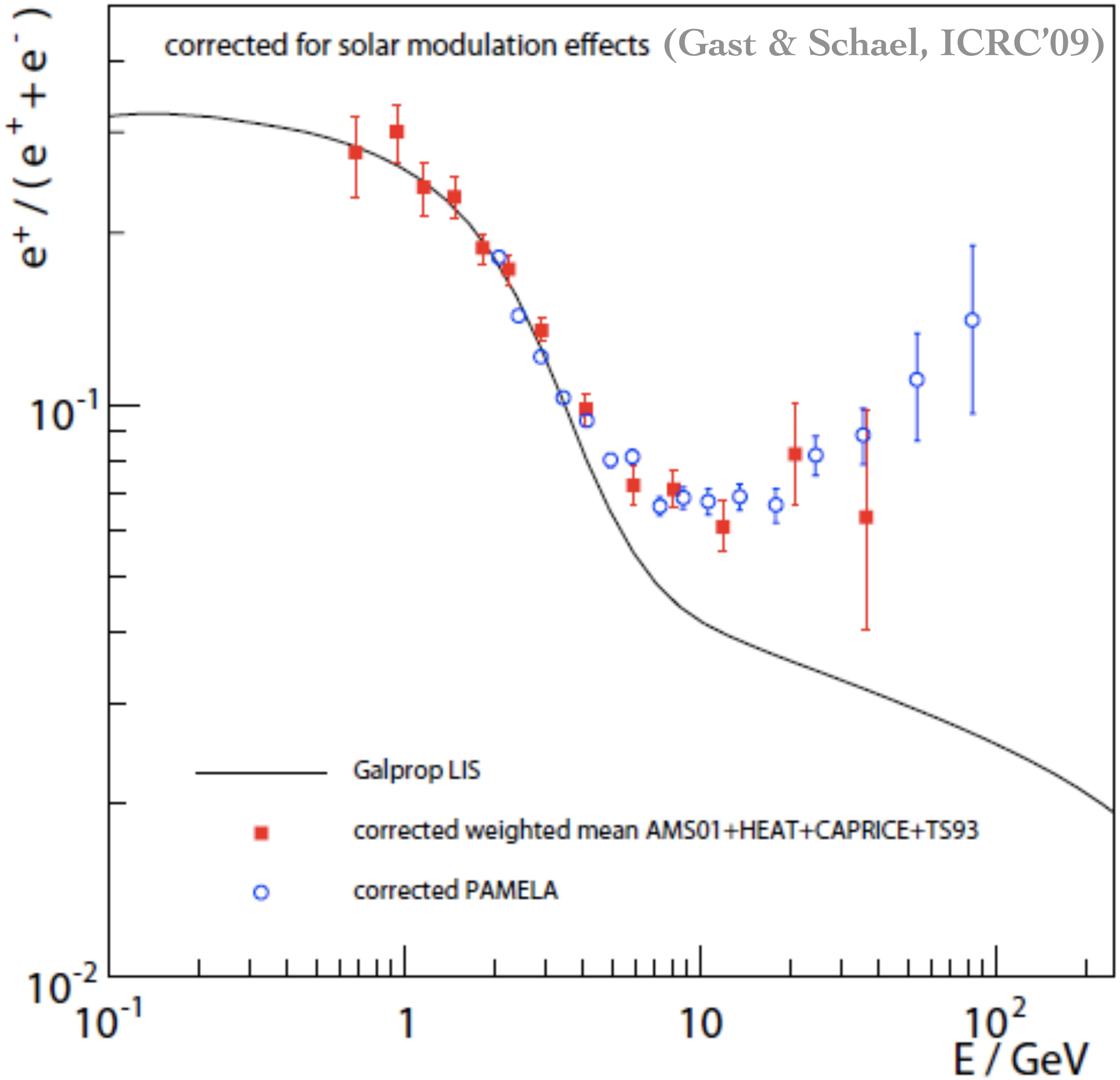
$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$

Anomaly ⇒ excess above 'astrophysical background'

Source of anomaly:

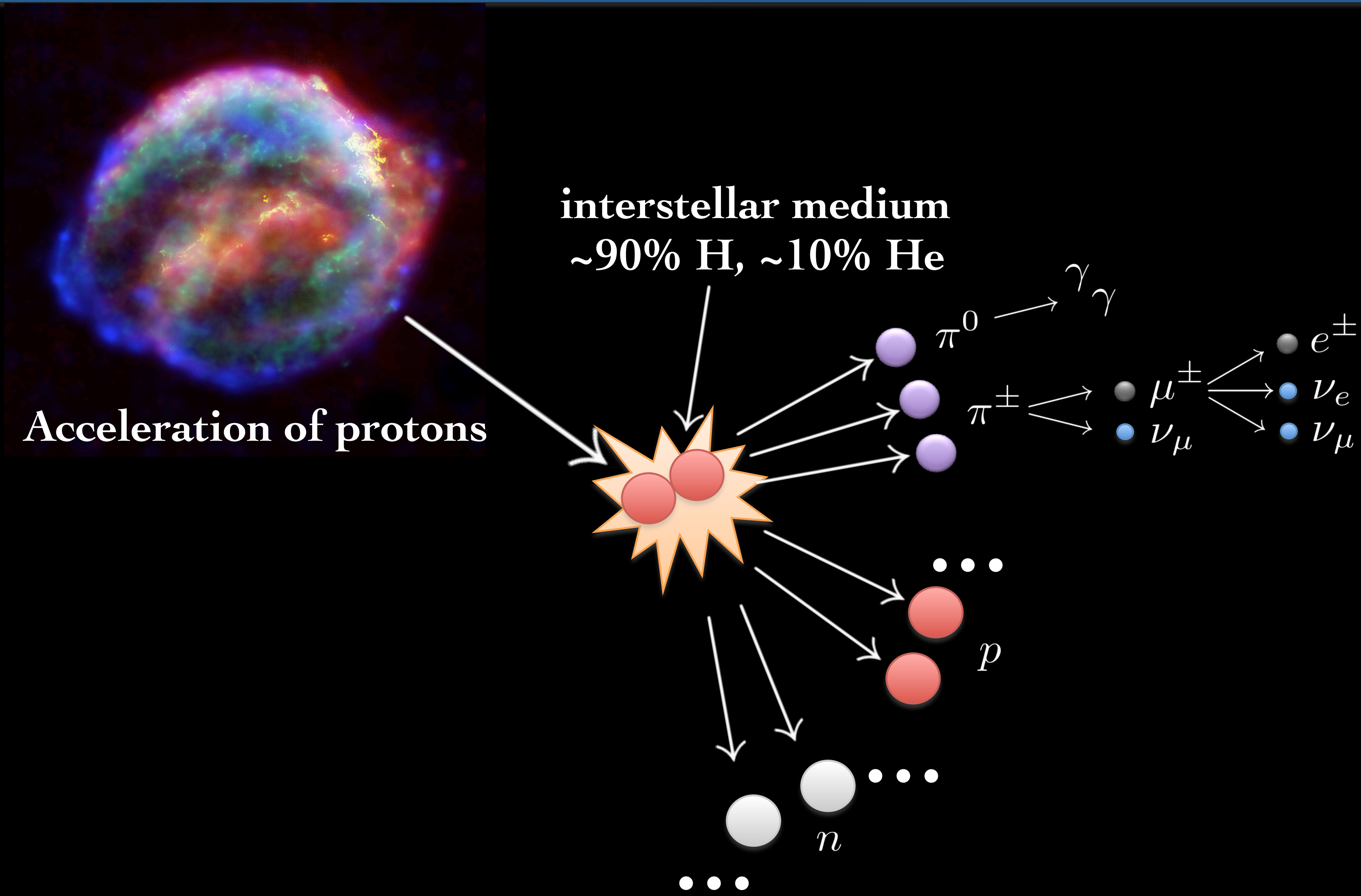
- DM decay/annihilation?
- Pulsars?
- Nearby SNRs?

… over 300 citations already!



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

The 'background' is the production of secondary e^+ during propagation (calculated using GALPROP)

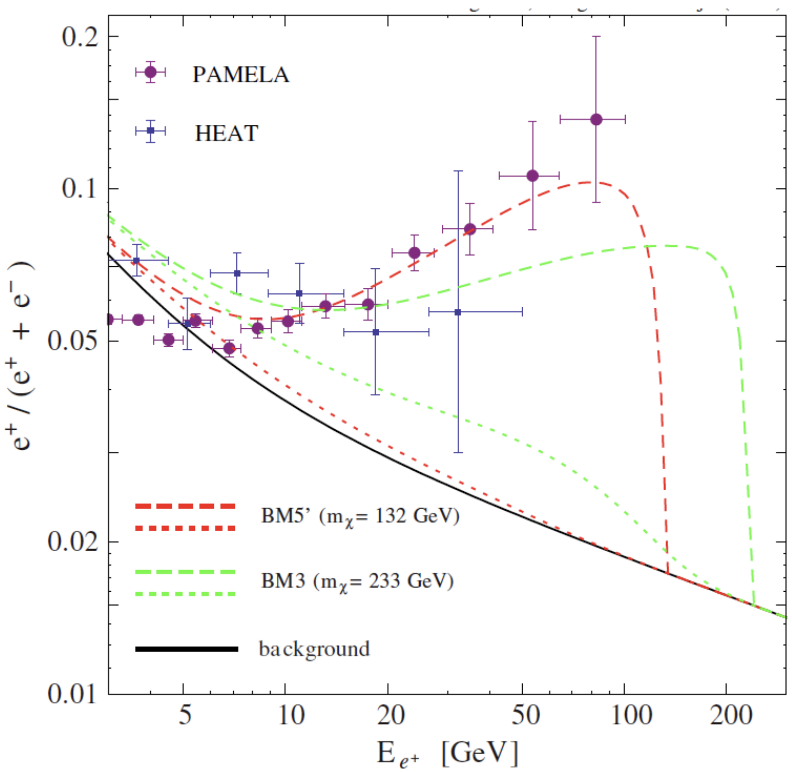


Dark matter has been widely invoked as the source of the excess e^+.

DM annihilation

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

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

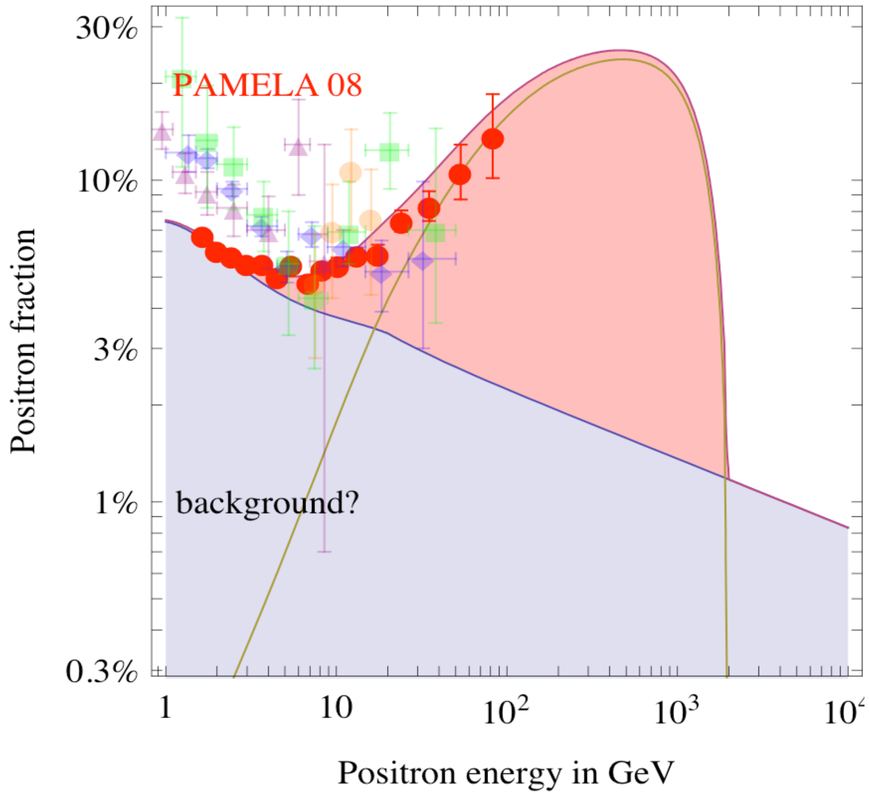


Bergström, Bringmann & Edjsö, PR D78:127850,2008

DM decay

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

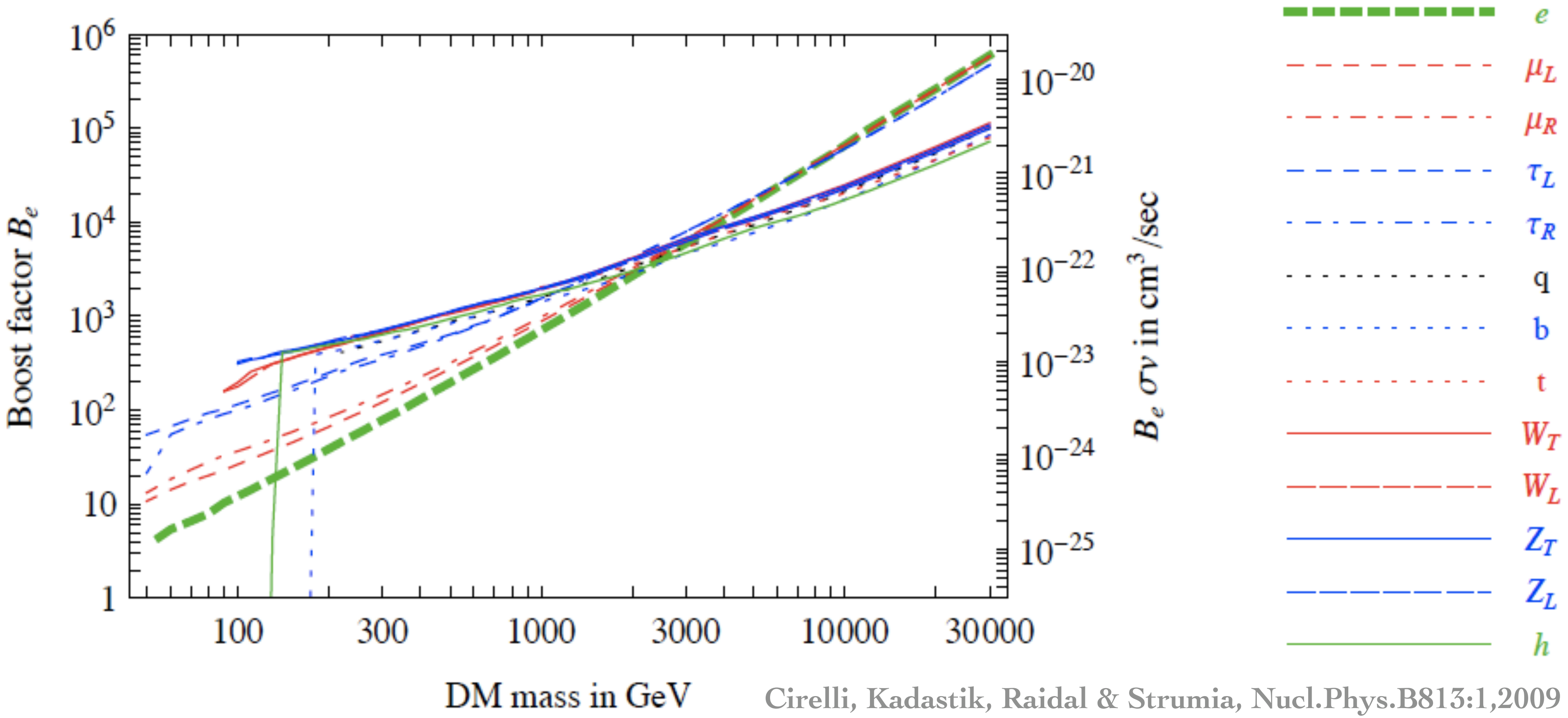
(lifetime ~10^9 x age of universe e.g. dim-6 operator suppressed by M_{GUT} for a TeV mass techni-baryon)



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

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

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



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

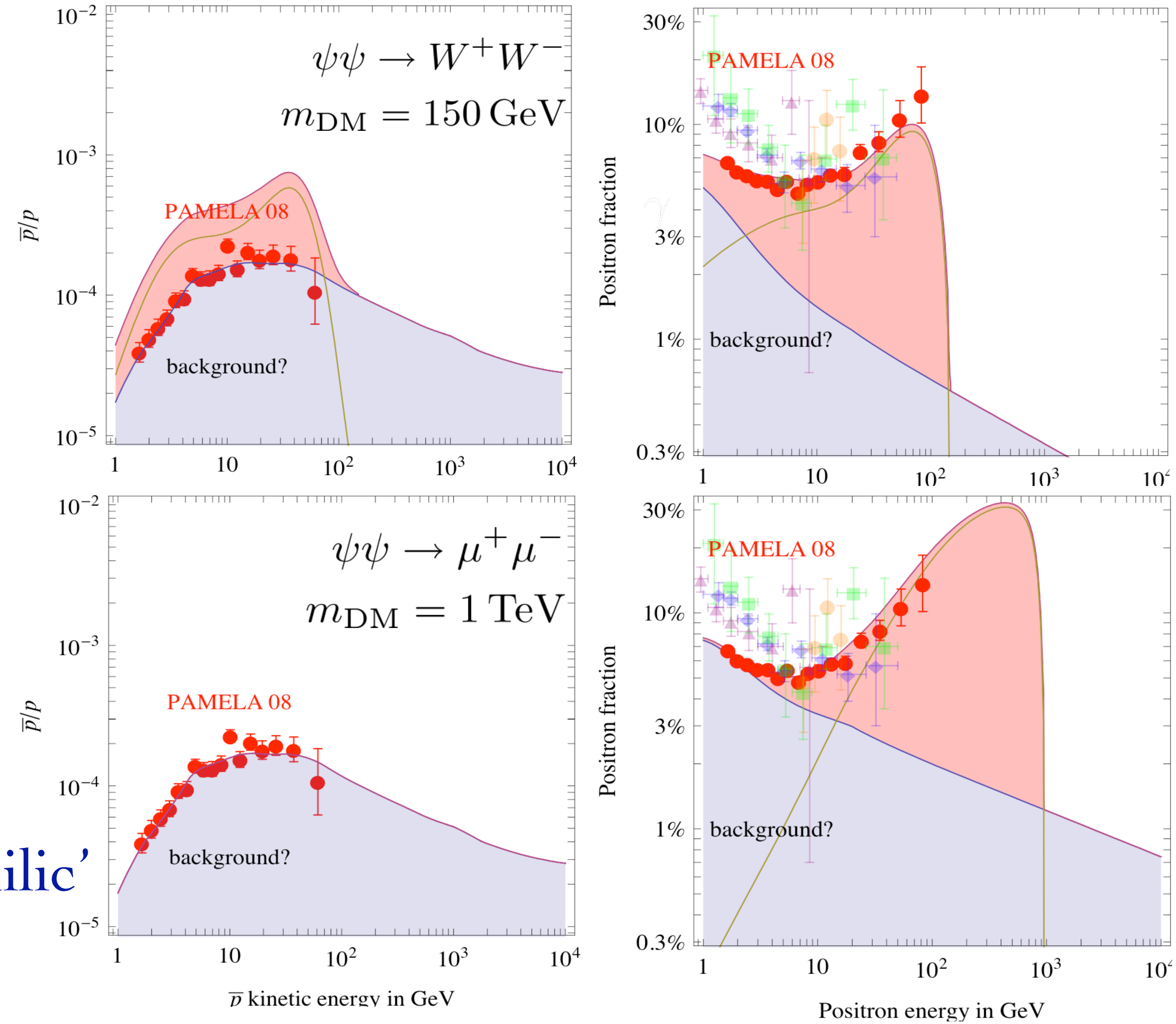
... no such problem for decaying dark matter models (just tune lifetime!)

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

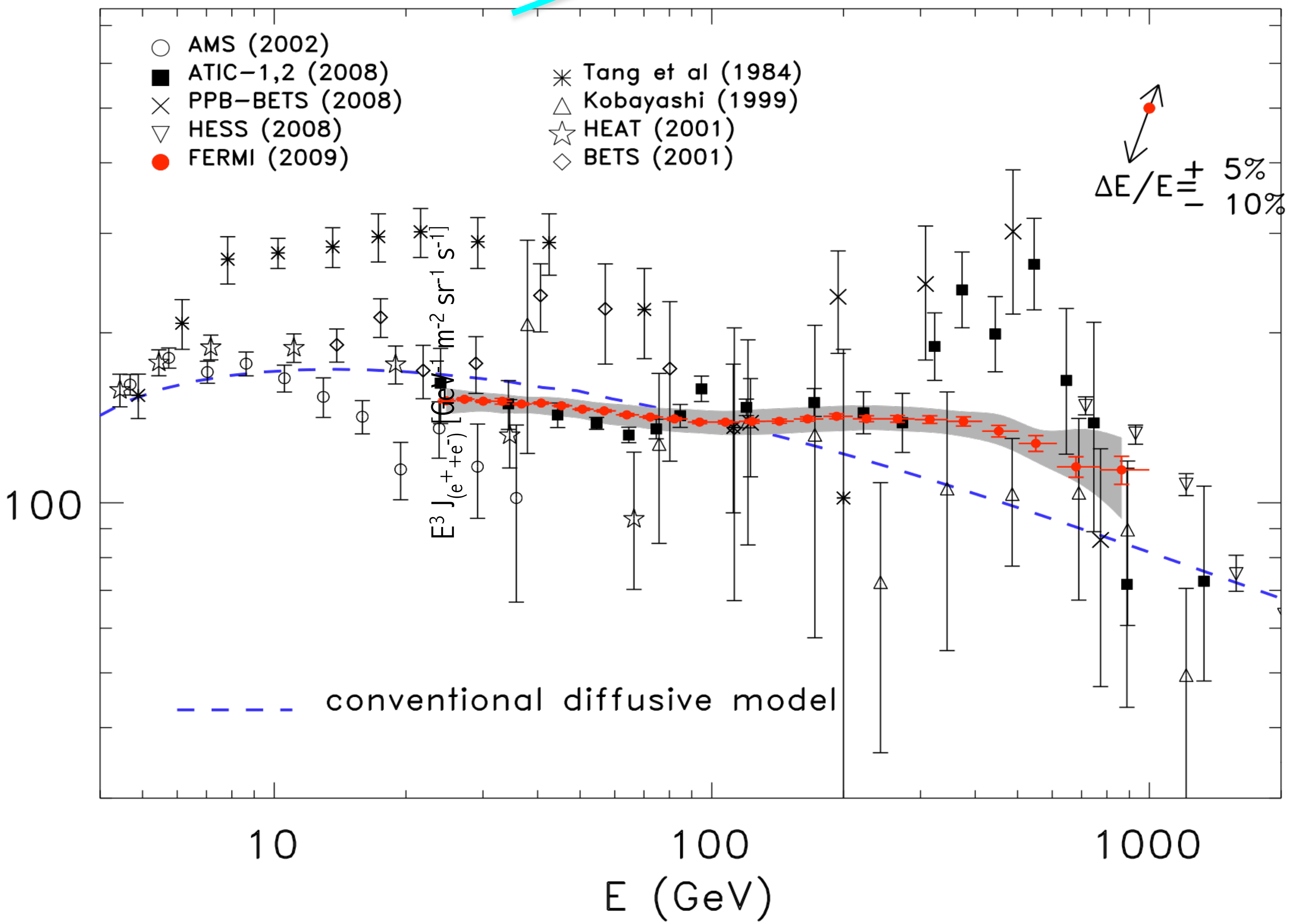
… can fit with DM decay/annihilation model only if DM particles are 'leptophilic'

➔ rather contrived!



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

FERMI
The ~~ATIC~~ excess



Moreover *Fermi* LAT also sees 'excess' $e^{\pm}$ over expectation (although it does *not* confirm the peak seen earlier by *ATIC*-2)

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.

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

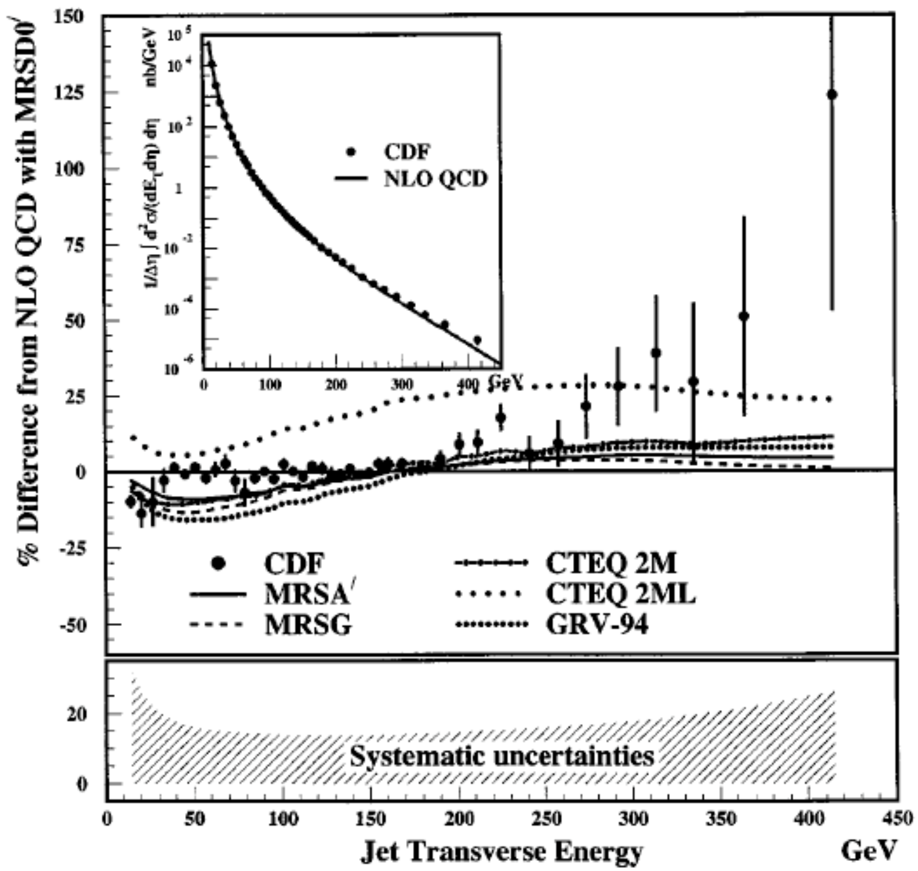


FIG. 1. The percent difference between the CDF inclusive jet cross section (points) and a next-to-leading order (NLO) QCD prediction using MRSD0′ PDFs. The CDF data (points) are compared directly to the NLO QCD prediction (line) in the inset. The normalization shown is absolute. The error bars represent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

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

Yesterday's discovery is today's calibration

Richard Feynman

… and tomorrow's background!

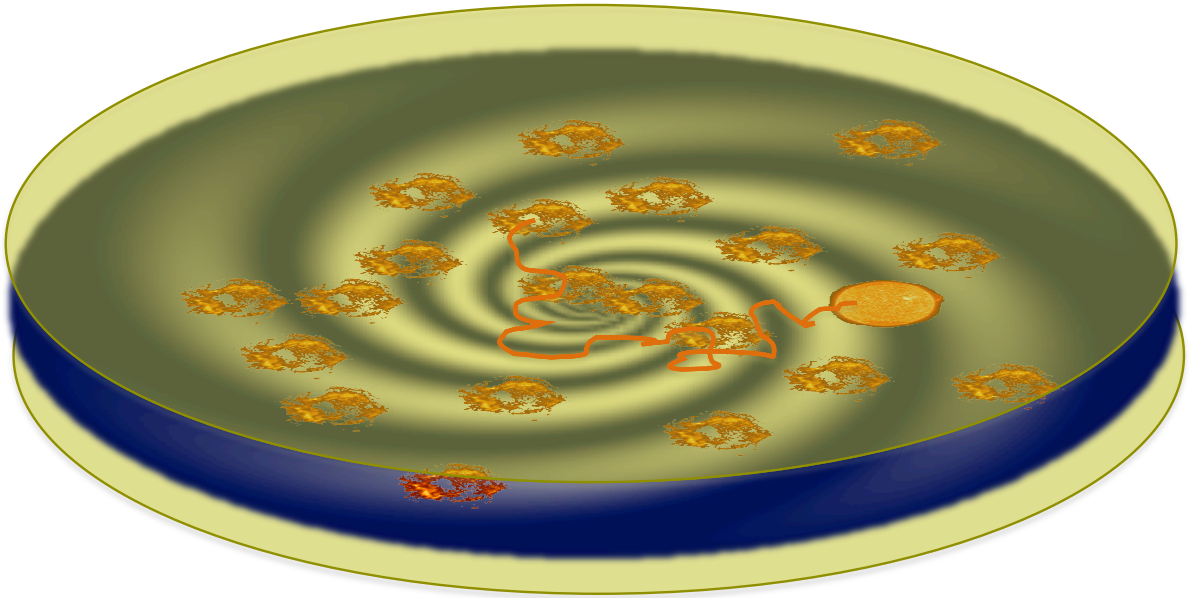
Val Telegdi

… 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 standard model for Galactic cosmic ray origin

. 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)



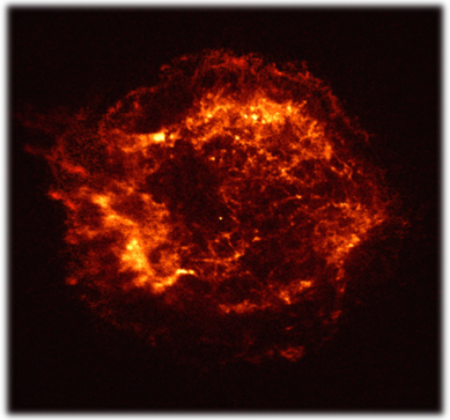
. Secondary production during propagation: $\bar{p}, e^{+}, N'$

. $e^{\pm}$ lose energy through synchrotron and inverse Compton scattering

Measurables: Energy spectra of individual species + diffuse radiation

Why supernova remnants?

… direct evidence for acceleration of electrons to > 40 TeV from observation of synchrotron X-ray emission



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 $1.7 \times 10^{58}\,\mathrm{GeV} \simeq 2.8 \times 10^{55}\,\mathrm{erg}$

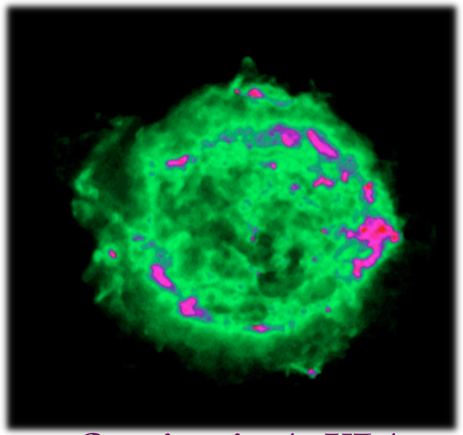
- Residence time of CRs in Galaxy $20\,\mathrm{Myr}$

⇒ 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 a few % of the benchmark kinetic energy of 10^{51} erg produced in a SN explosion



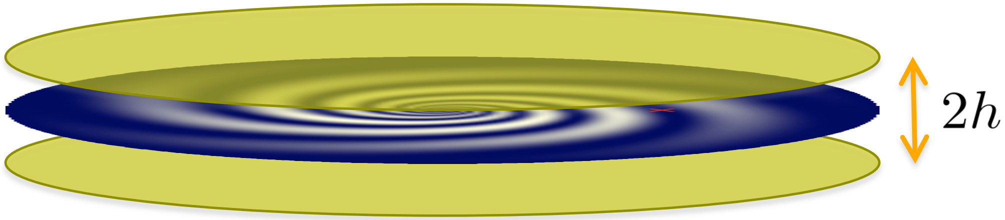
Cassiopeia A: VLA

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 one discrete, burst-like source

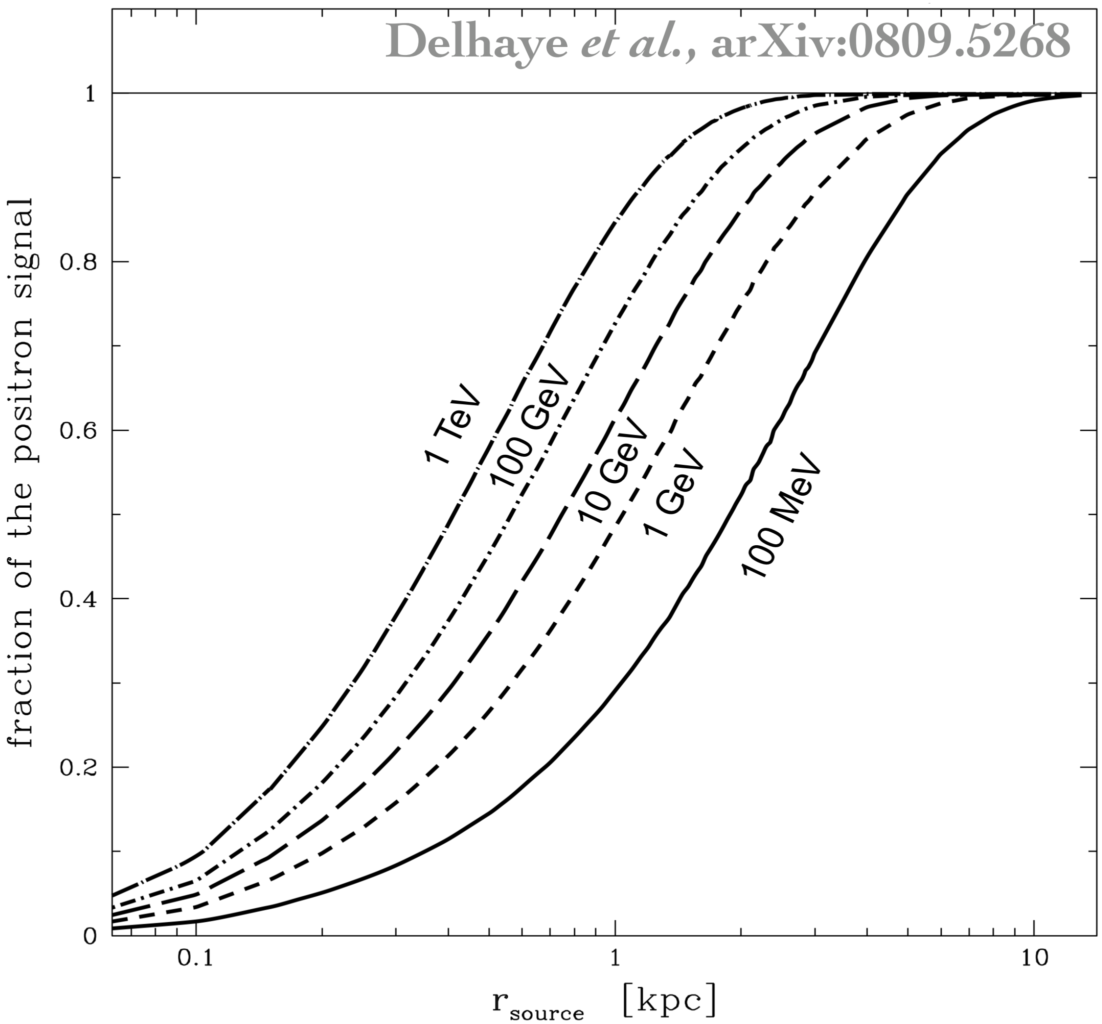
… integrate over spatial distribution and time-variation of injection

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

➔ exponential distribution of path lengths between cosmic ray source and Earth

However $e^{\pm}$ lose energy readily during propagation, so only *nearby* sources dominate at high energies …

the usual background calculation is then *irrelevant*



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

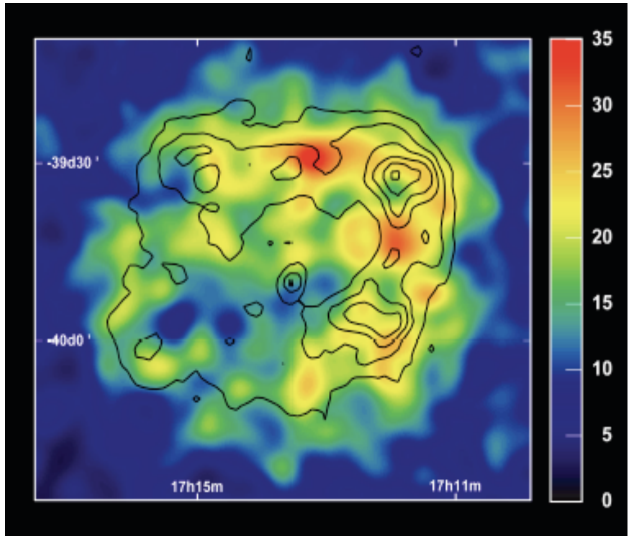
A nearby cosmic ray accelerator?

Rise in e^+ fraction could be due to secondaries being produced *during* acceleration … which are then accelerated along with the primaries

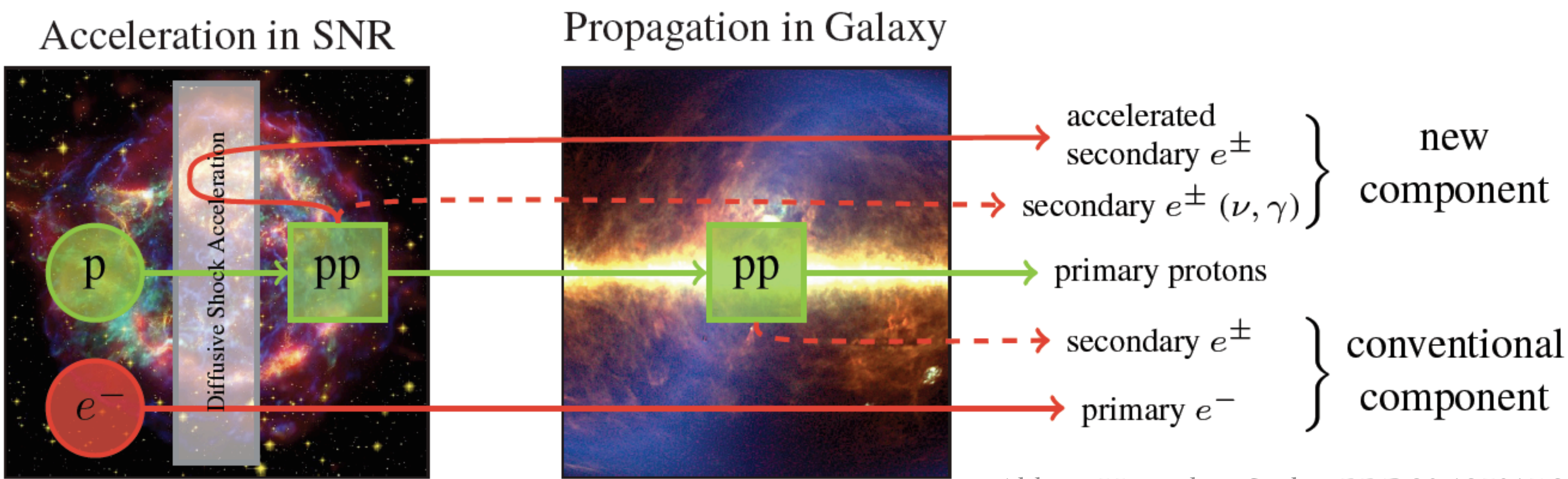
Blasi, PRL 103:051104,2009, Fujita *et al*, PRD80:063003,2009

… generic feature of a *stochastic* acceleration process, if $\tau_{acc} > \tau_{1 \to 2}$ Cowsik 1979, Eichler 1979

This component *naturally* has a hard spectrum and fits *PAMELA* data (with just one free parameter)



RXJ1713.7-3946, HESS

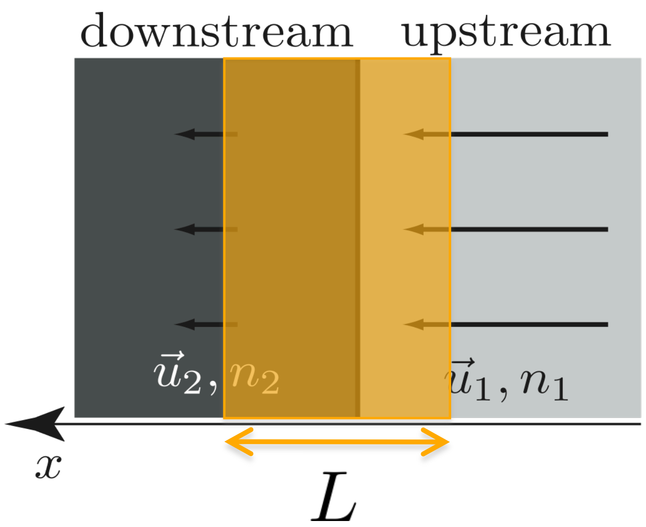


Ahlers, Mertsch & Sarkar,PRD80:123017,2009

Diffusive (1st-order Fermi) shock acceleration

Consider flux:

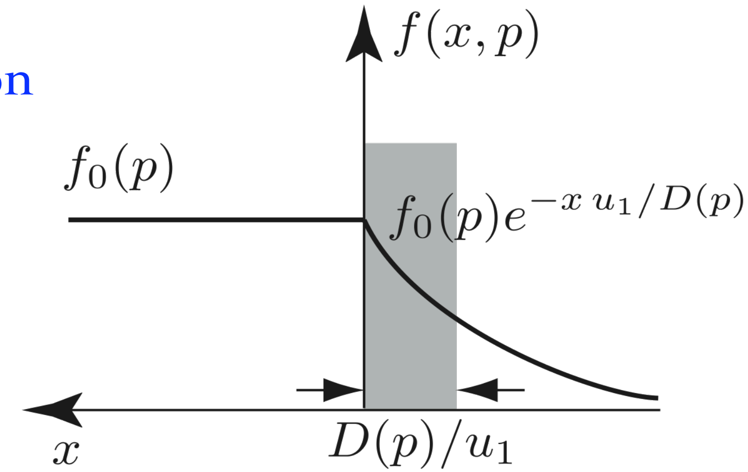
$$\Phi(p) = \int d^3x \, \frac{4\pi p^2}{3} f(p)(-\nabla \cdot \vec{u})$$



Conservation equation:

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

density change acceleration convection injection



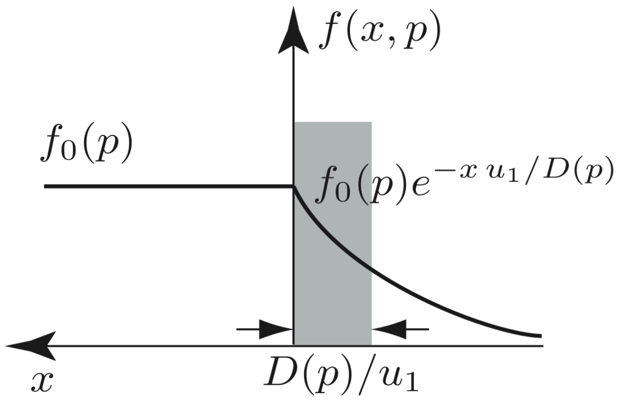
Steady state: $\frac{u_1 - u_2}{3} p \frac{\partial f}{\partial p} + u_1 f = 0$

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

DSA with secondary production

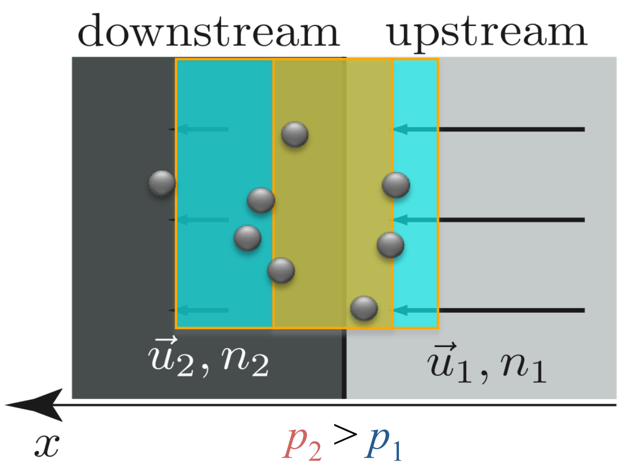
- Secondaries are produced with primary spectrum:

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



- 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 at source!

Diffusion near accelerating shock front

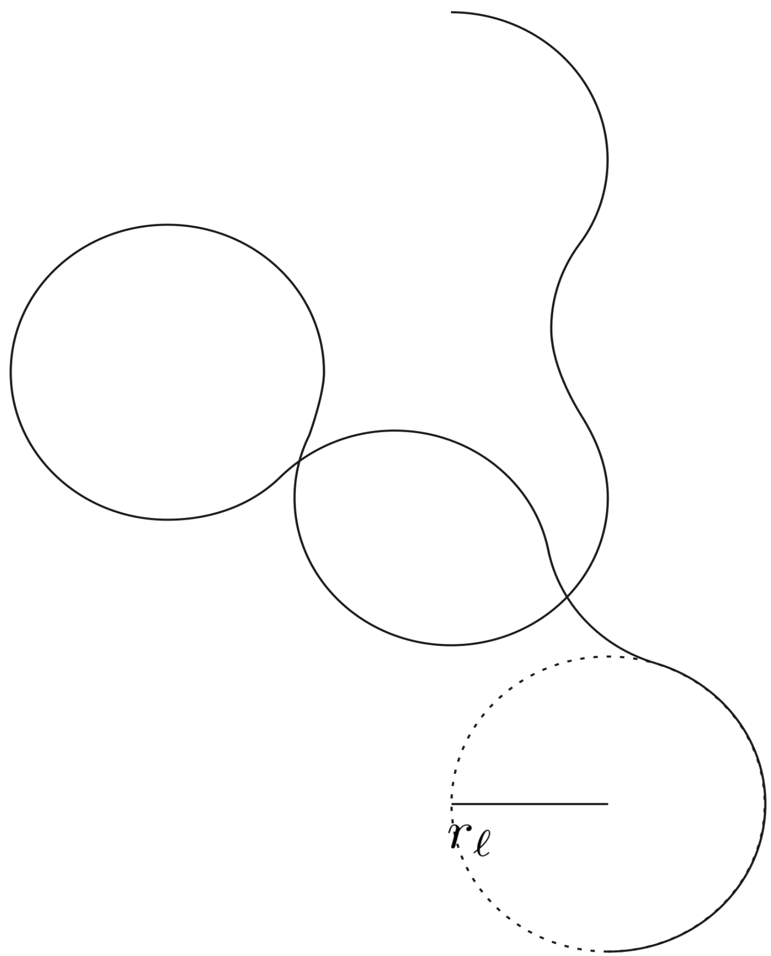
- Diffusion rate near shock front not known *a priori*
- Bohm diffusion sets *lower* limit

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

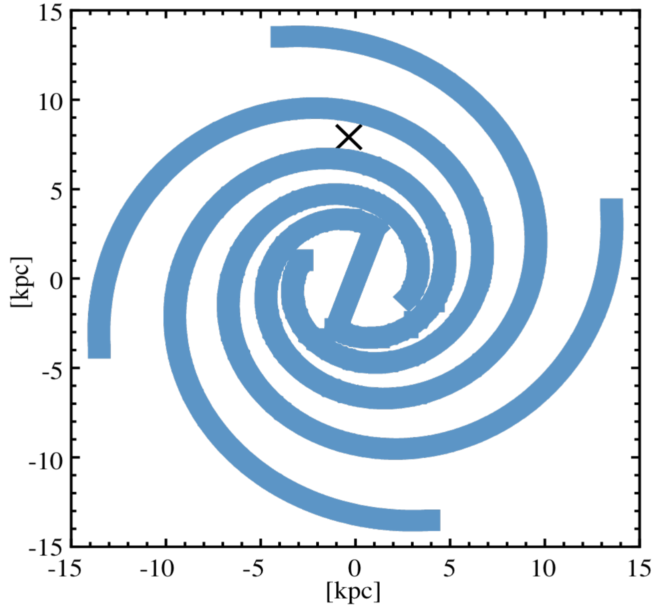
- Parametrise by fudge factor $\mathcal{F}^{-1}$

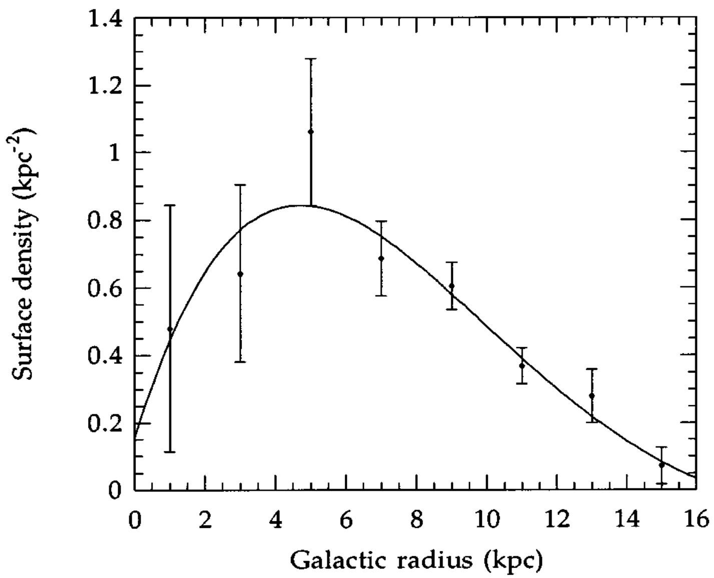
$$D = D^{\text{Bohm}} \mathcal{F}^{-1}$$

- $\mathcal{F}^{-1}$ determined by fitting to one measured secondary/primary ratio … can then *predict* any other ratio
- More sophisticated modelling needs better understanding of shock structure, feedback of cosmic rays …

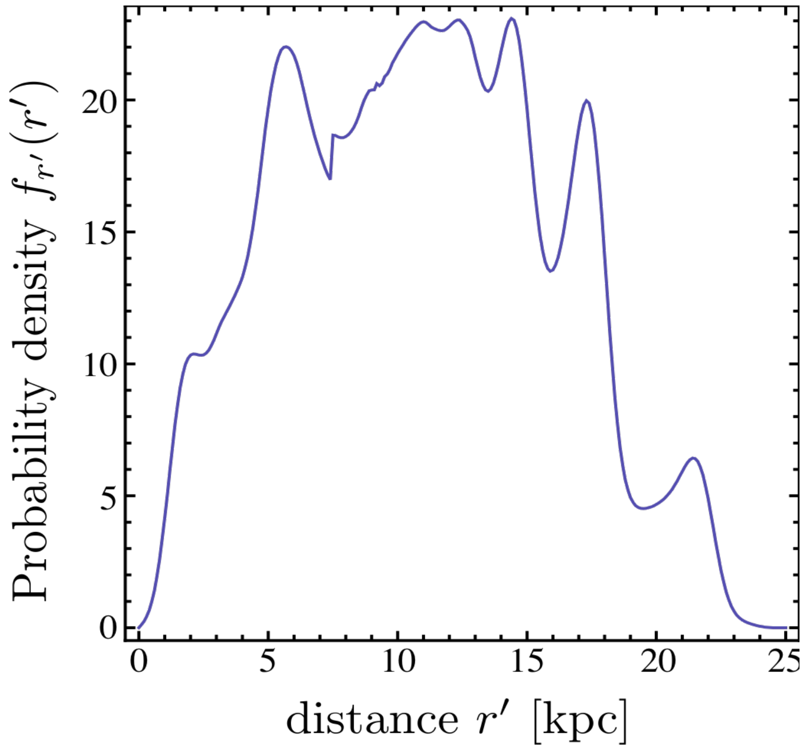


Statistical distribution of sources





Case & Bhattacharya, ApJ 504 (1998) 761

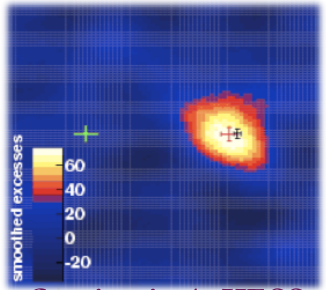


<u>Strategy:</u>

- 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

Normalising the source spectra



Cassiopeia A, HESS

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

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

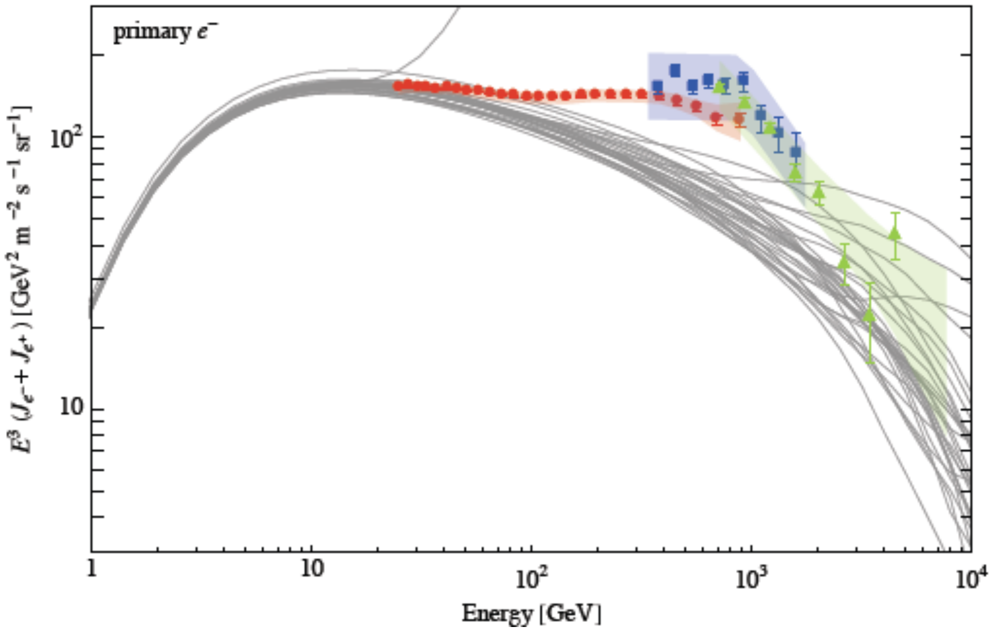
Source	Other name(s)	Γ	$J_\gamma^0 \div 10^{-12}$ $[(\mathrm{cm}^2\,\mathrm{s\,TeV})^{-1}]$	$E_{\max}$ [TeV]	d [kpc]	$Q_\gamma^0 \div 10^{33}$ $[(\mathrm{s\,TeV})^{-1}]$
HESS J0852−463	RX J0852.0-4622 (Vela Junior)	2.1 ± 0.1	21 ± 2	> 10	0.2	0.10
HESS J1442−624	RCW 86, SN 185 (?)	2.54 ± 0.12	3.72 ± 0.50	$\gtrsim 20$	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

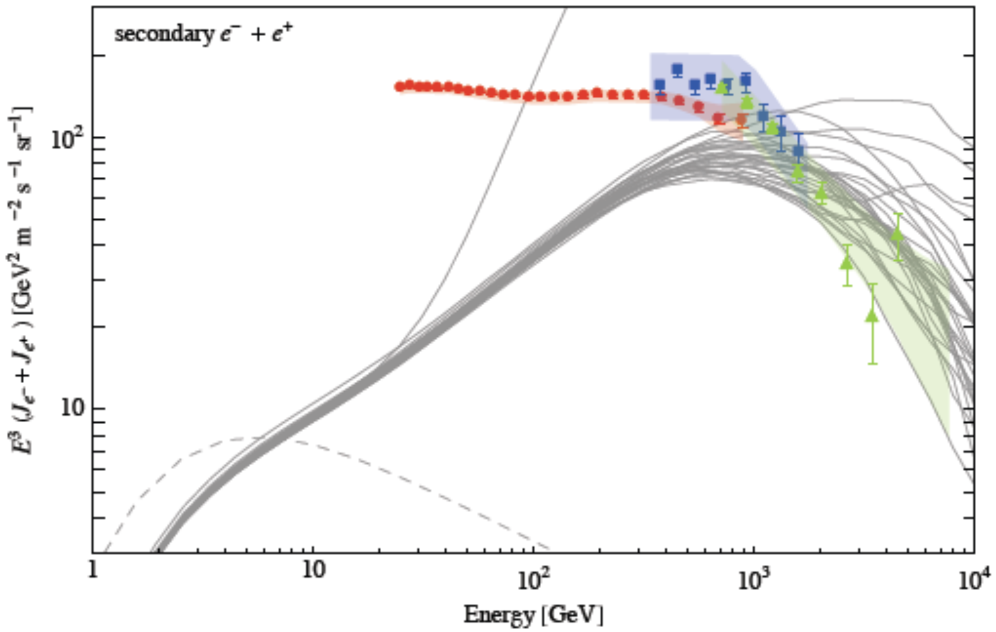
Ahlers, Mertsch & Sarkar, PRD80:123017,2009

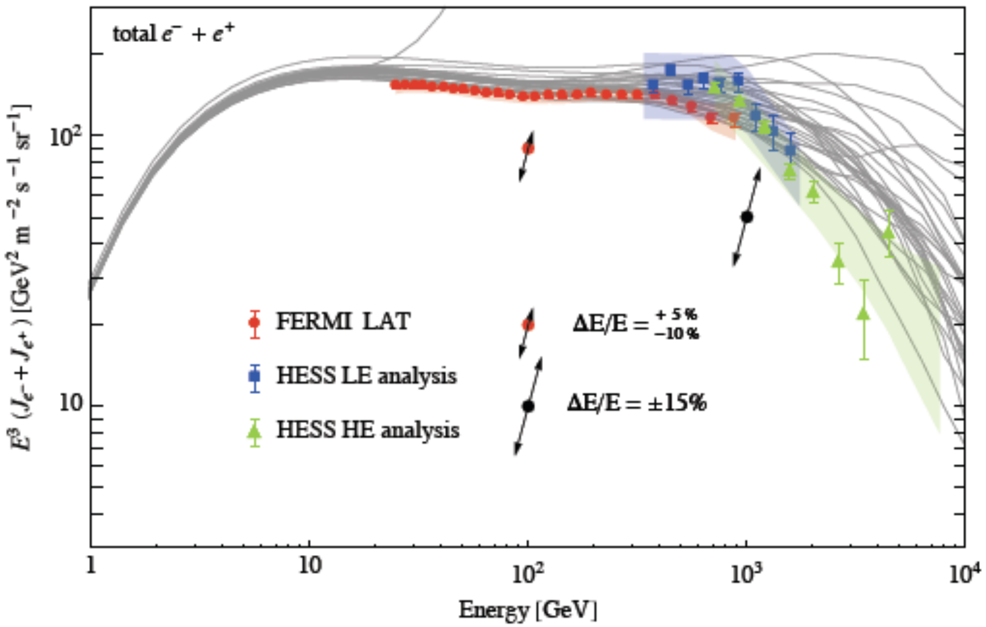
Fitting the $e^+ + e^-$ flux

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'!

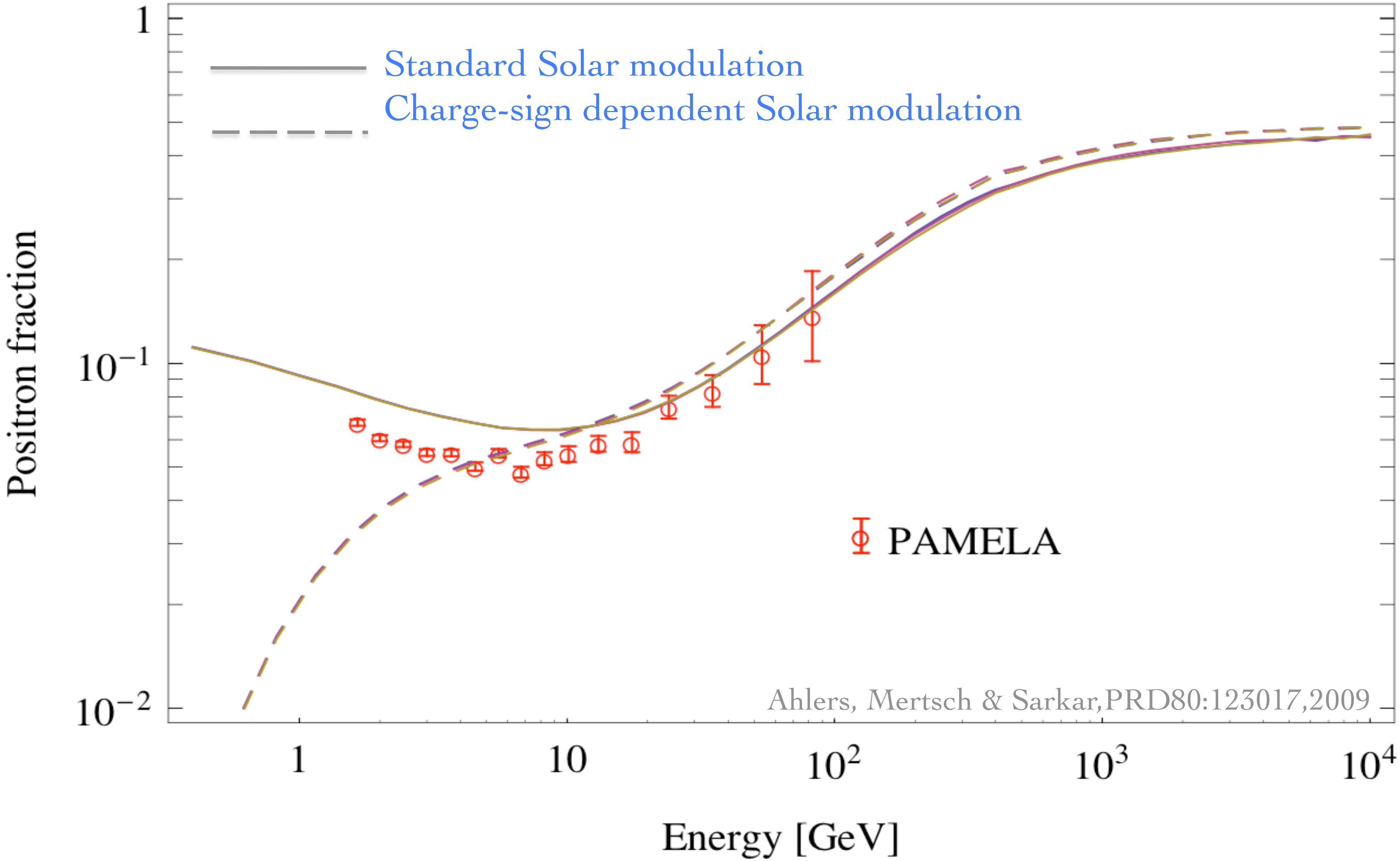
Ahlers, Mertsch & Sarkar, PRD80:123017,2009







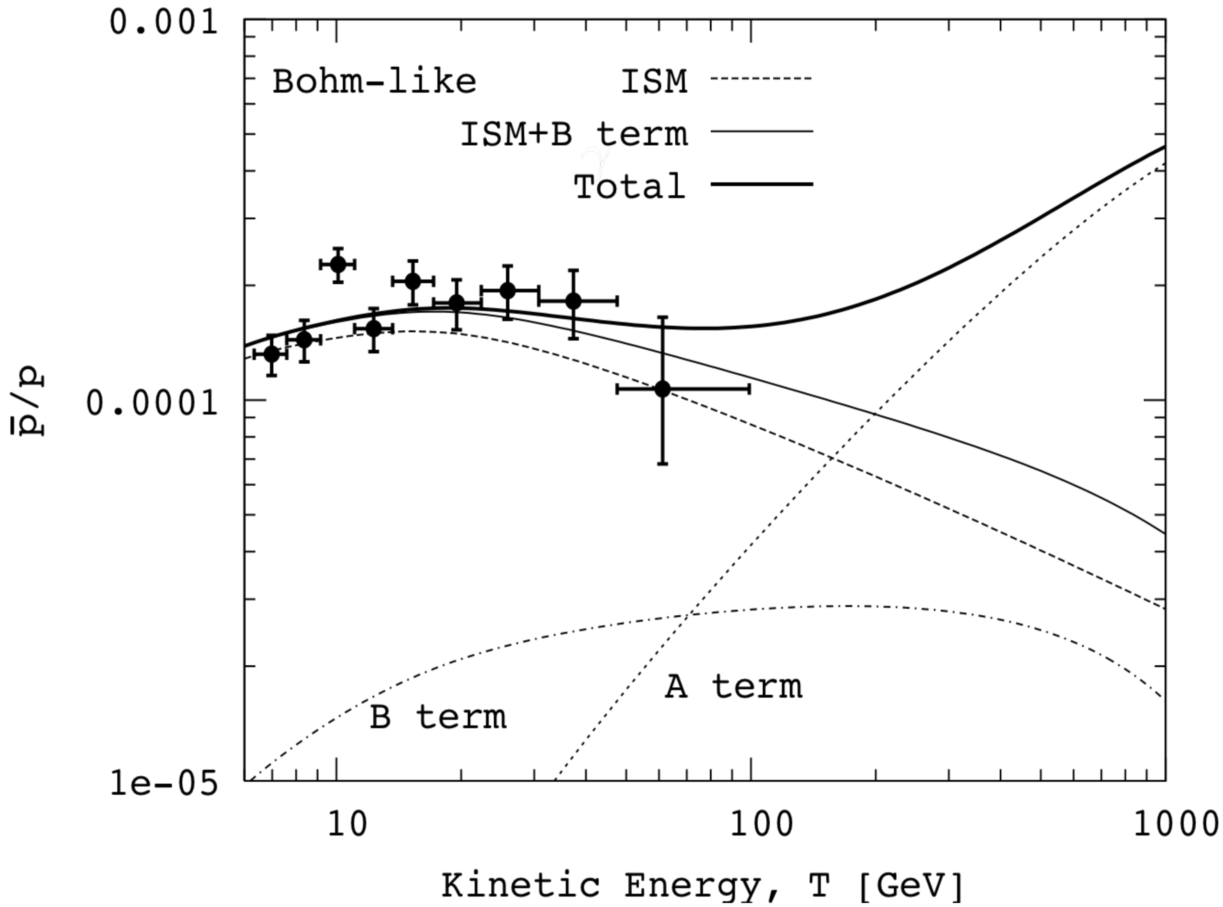
The *predicted* positron fraction



Antiproton-to-proton ratio

Blasi & Serpico, PRL 103:081103,2009

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



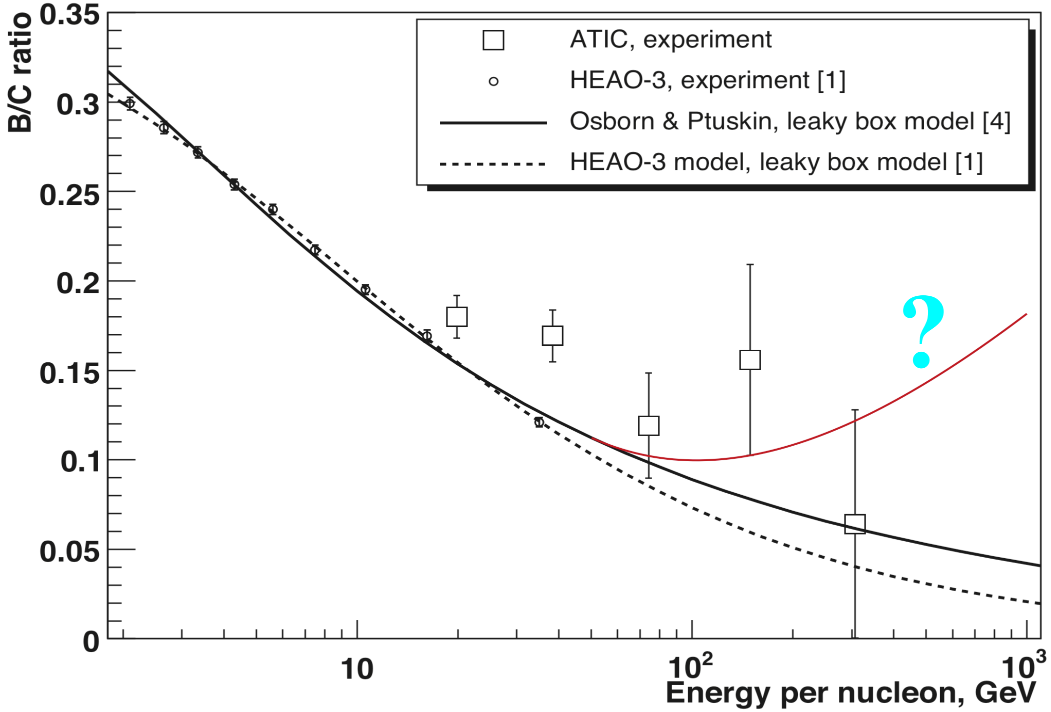
… much more natural in secondary acceleration model, which predicts rise *beyond* 100 GeV (will be tested by **AMS-02**)

Nuclear secondary-to-primary Ratios

	nuclei
Dark matter	✗
Pulsars	✗
Acceleration of secondaries	✓

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

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

Can solve problem *analytically* (no need for numerical code!)

… 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 $f_i(x,p) \xrightarrow{x \to -\infty} Y_i \delta(p - p_0)$

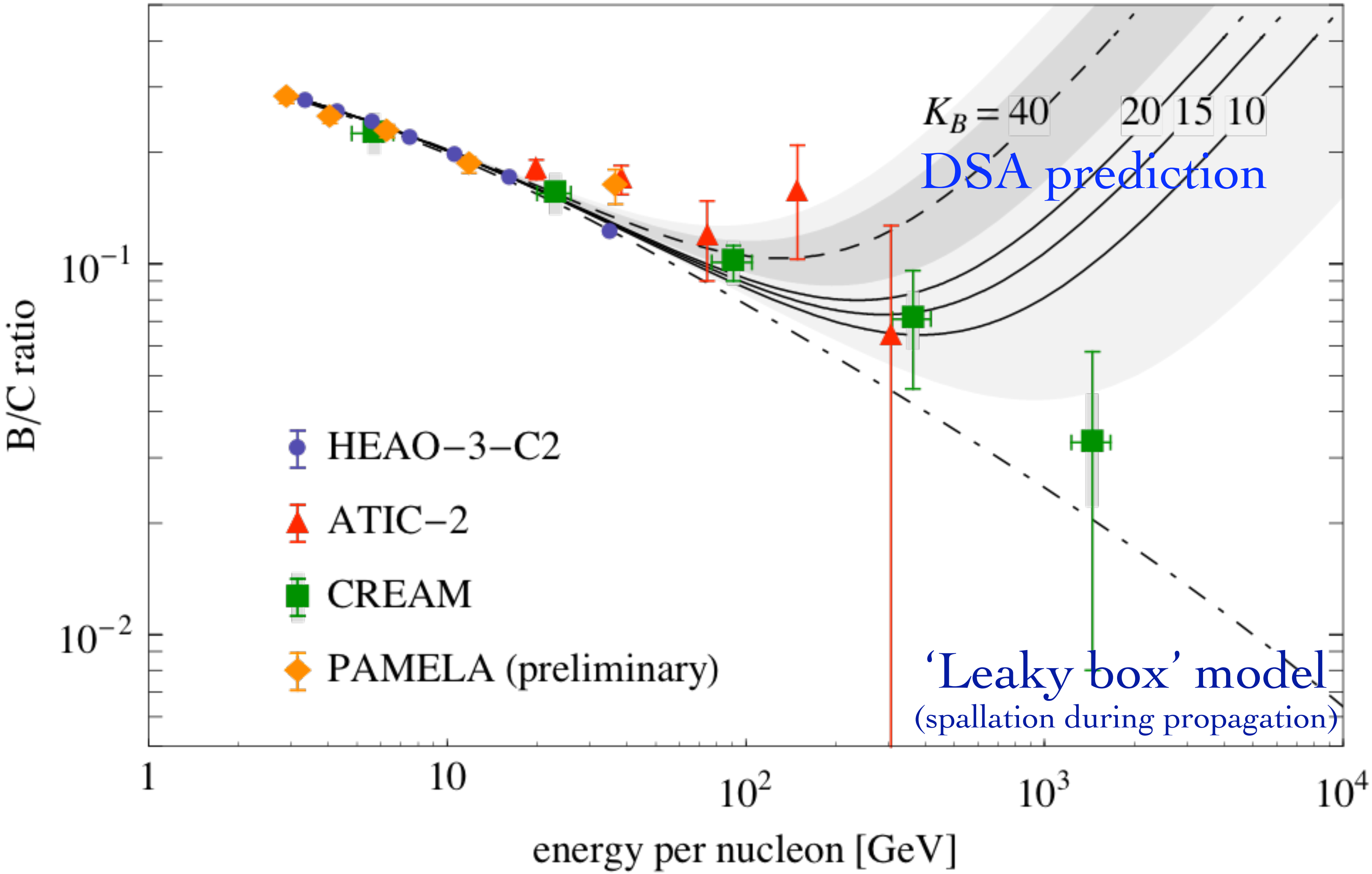
. Solution:

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

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

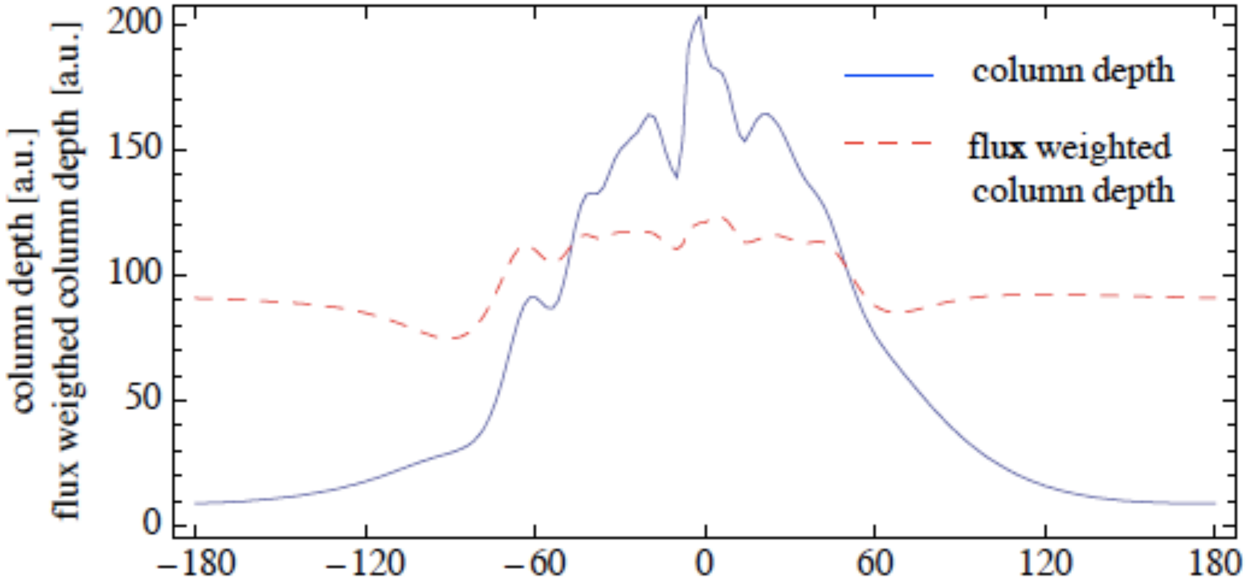
Mertsch & Sarkar, PRL 103:081104,2009

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

A nice test would be to see these old SNRs in neutrinos …

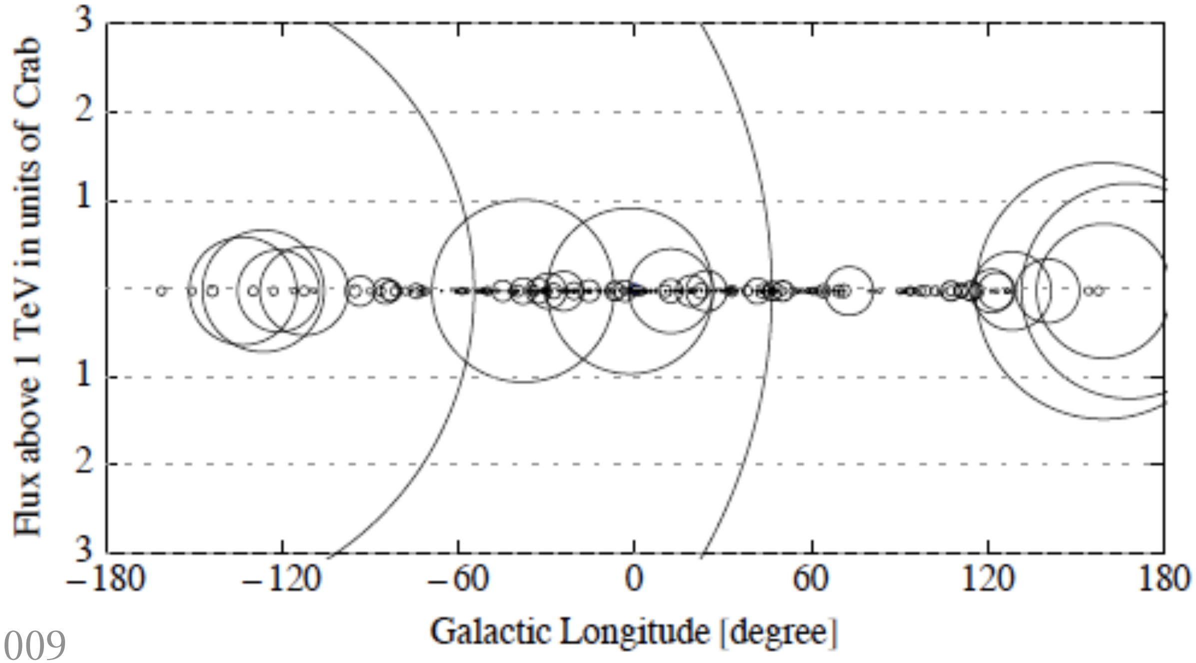


The column depth and flux weighted column depth of the SNR density in the Galactic plane

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

… detectable by IceCube!

Example of a distribution of SNRs in γ-rays/neutrinos from the Monte Carlo simulation. The position of a circle denotes the Galactic longitude of the source and the radius is proportional to the brightness in units of the Crab nebula.



Ahlers, Mertsch & Sarkar,PRD80:123017,2009

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 indicate a nearby hadronic accelerator rather than dark matter - forthcoming data on antiprotons (AMS-02), B/C ratio (CALET) etc will provide a resolution

… the source(s) may also be detected *directly* using γ-rays (e.g. HAWC) and neutrinos (IceCube)