The PAMELA anomaly: Evidence for a nearby cosmic ray accelerator?

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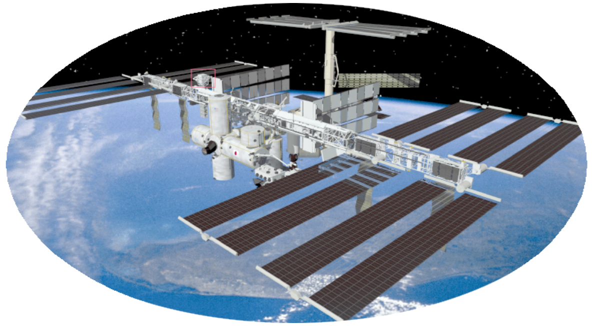
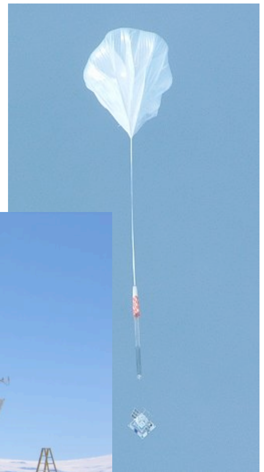
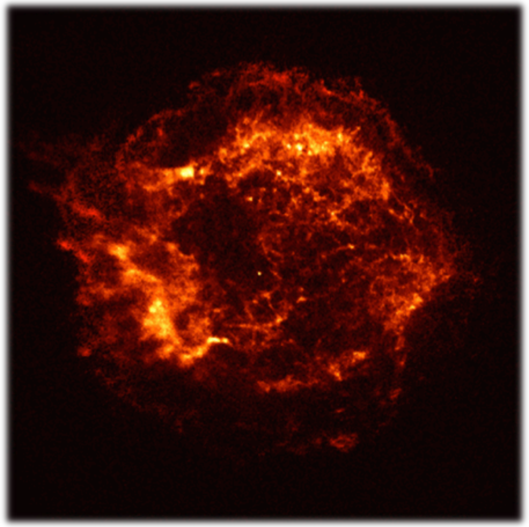






The TeV Universe, UK-CTA Meeting, University of Liverpool, 28 January 2010

The *PAMELA* anomaly

PAMELA has measured the positron fraction:

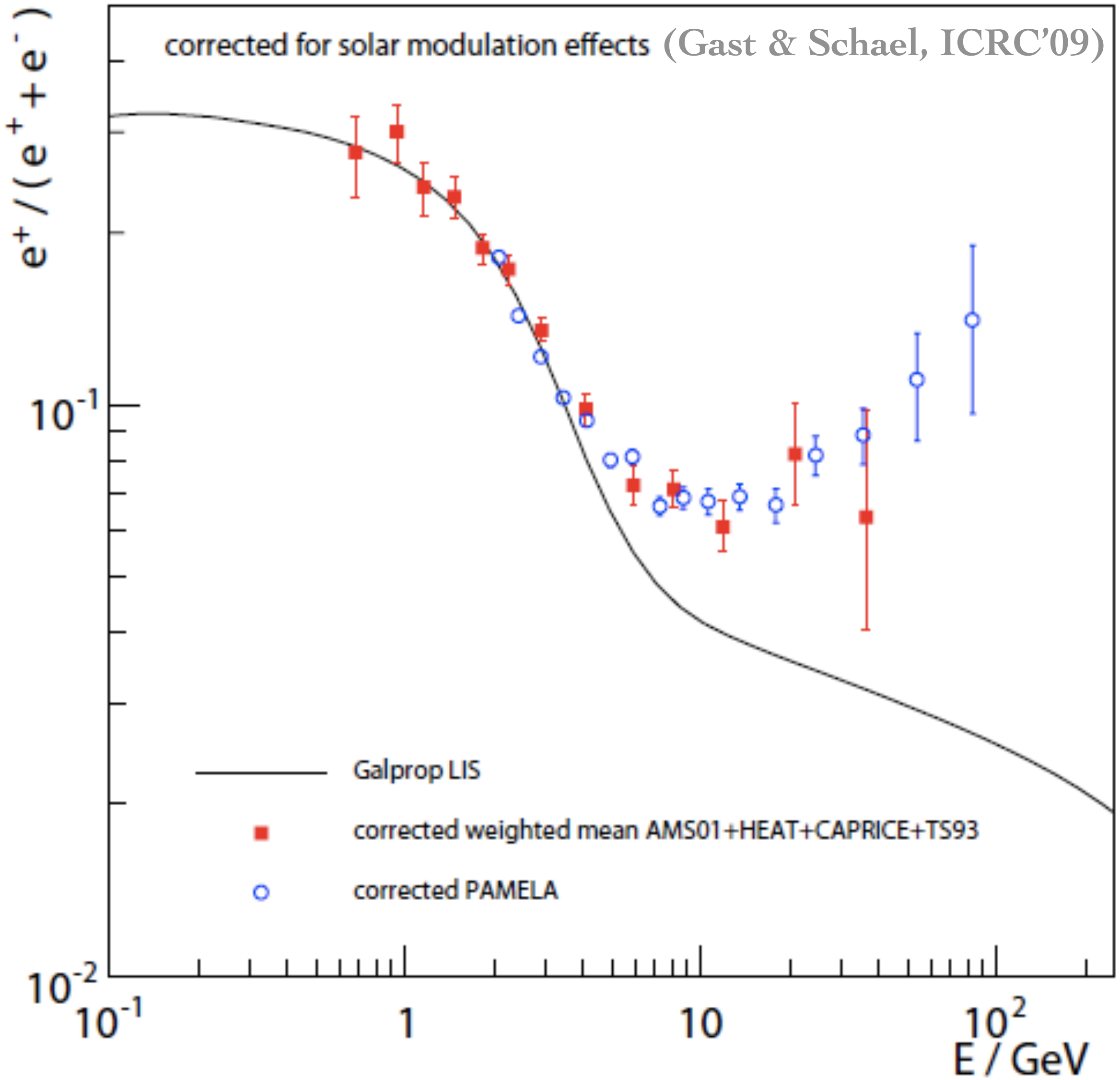
$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$

Anomaly ⇒ excess above 'astrophysical background'

Source of anomaly:

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

… over 300 citations already!



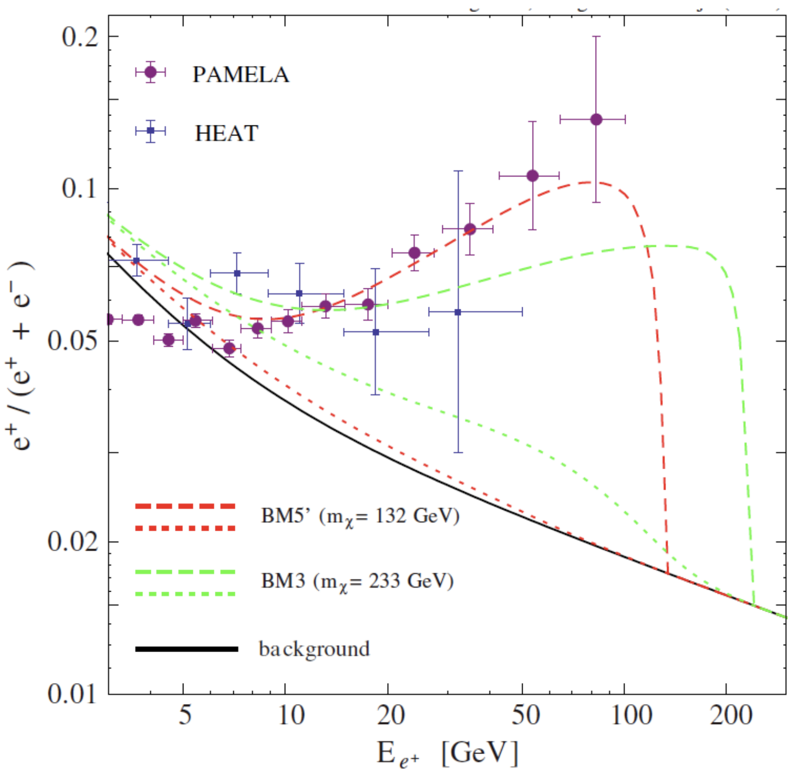
Adriani *et al*, Nature 458:607,2009

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)

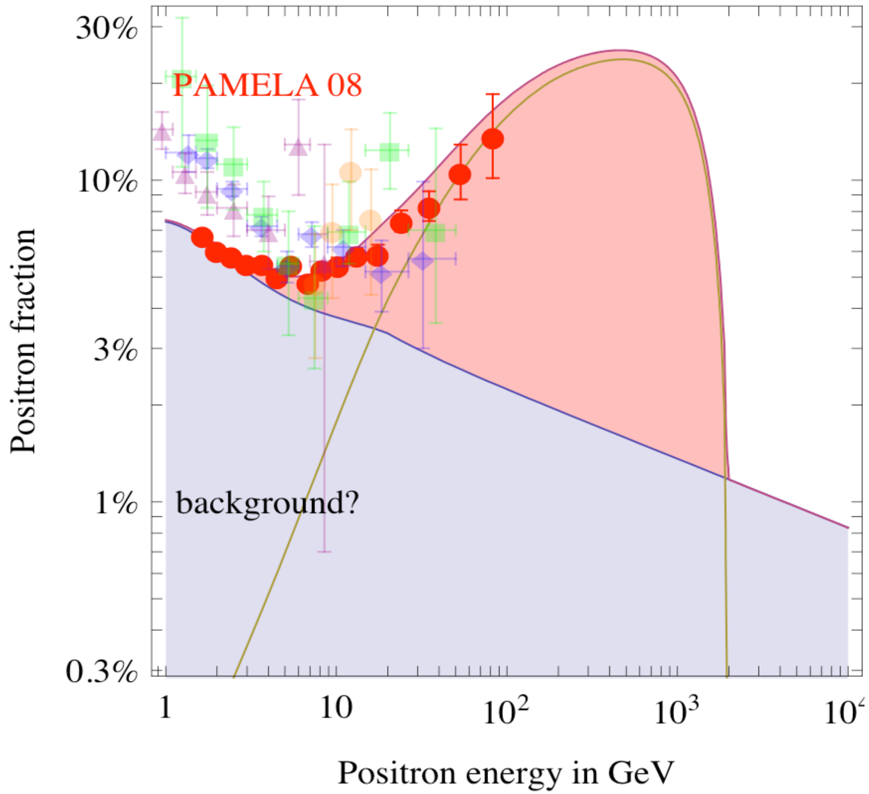


Bergström, Bringmann & Edjsö, PR D78:127850,2008

DM decay

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

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



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

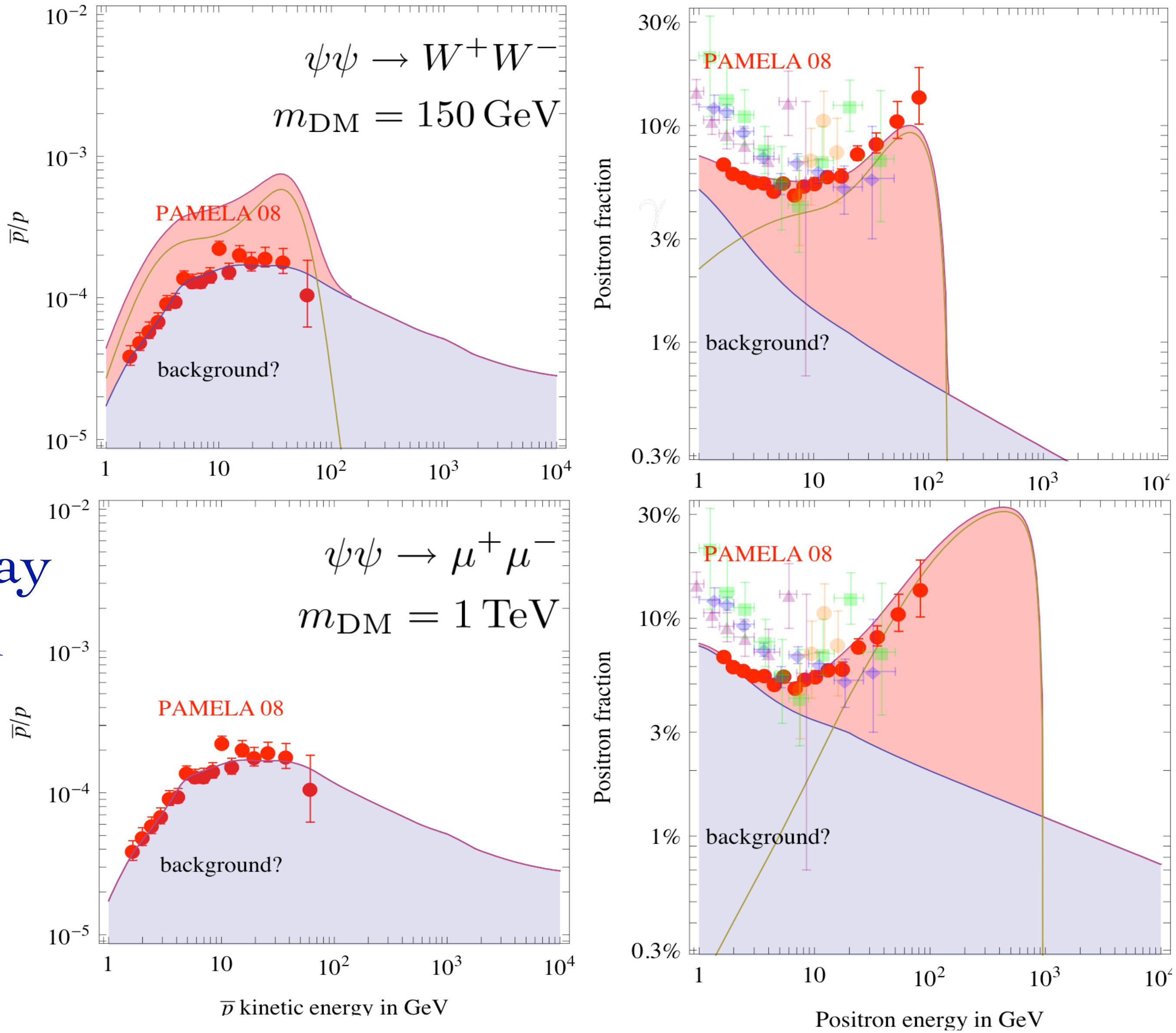
But the observed antiproton flux is *consistent* with the background expectation (from standard cosmic ray propagation in the Galaxy)

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

Can fit with DM decay or annihilation model only if DM particles are 'leptophilic'

... very contrived!

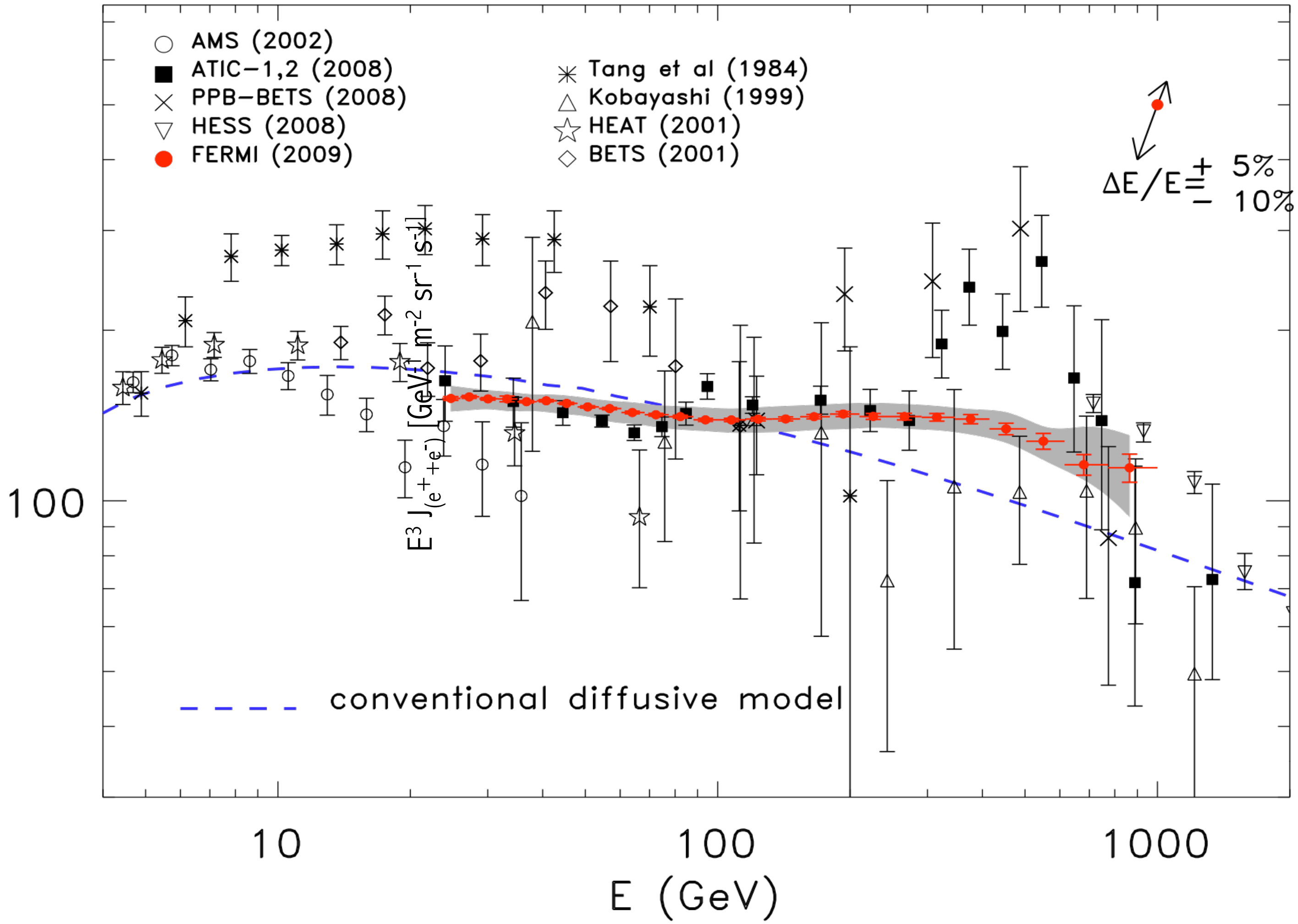
(nevertheless *many* models proposed)



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)

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.

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

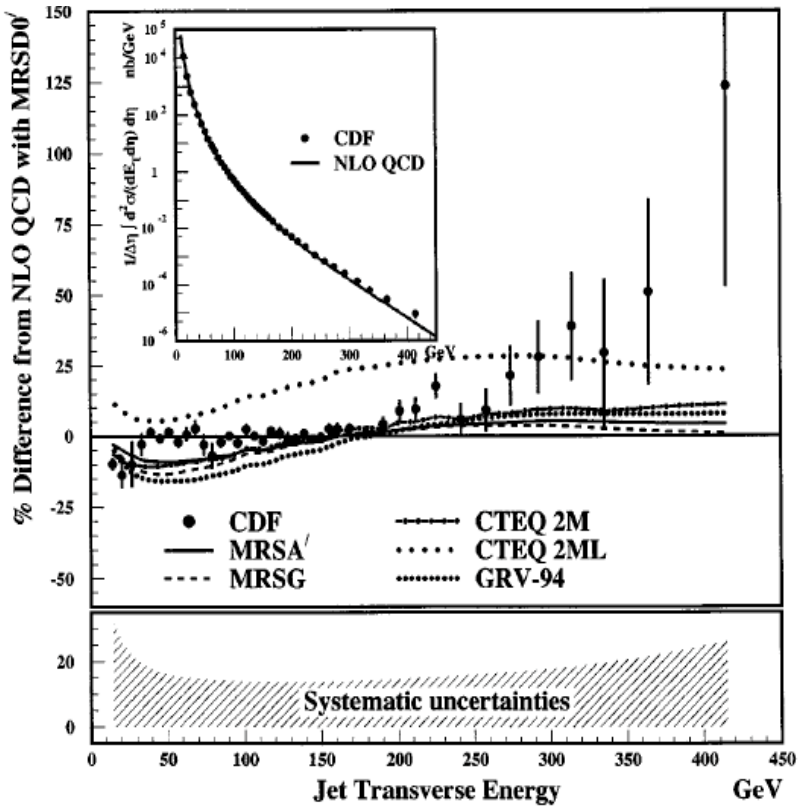
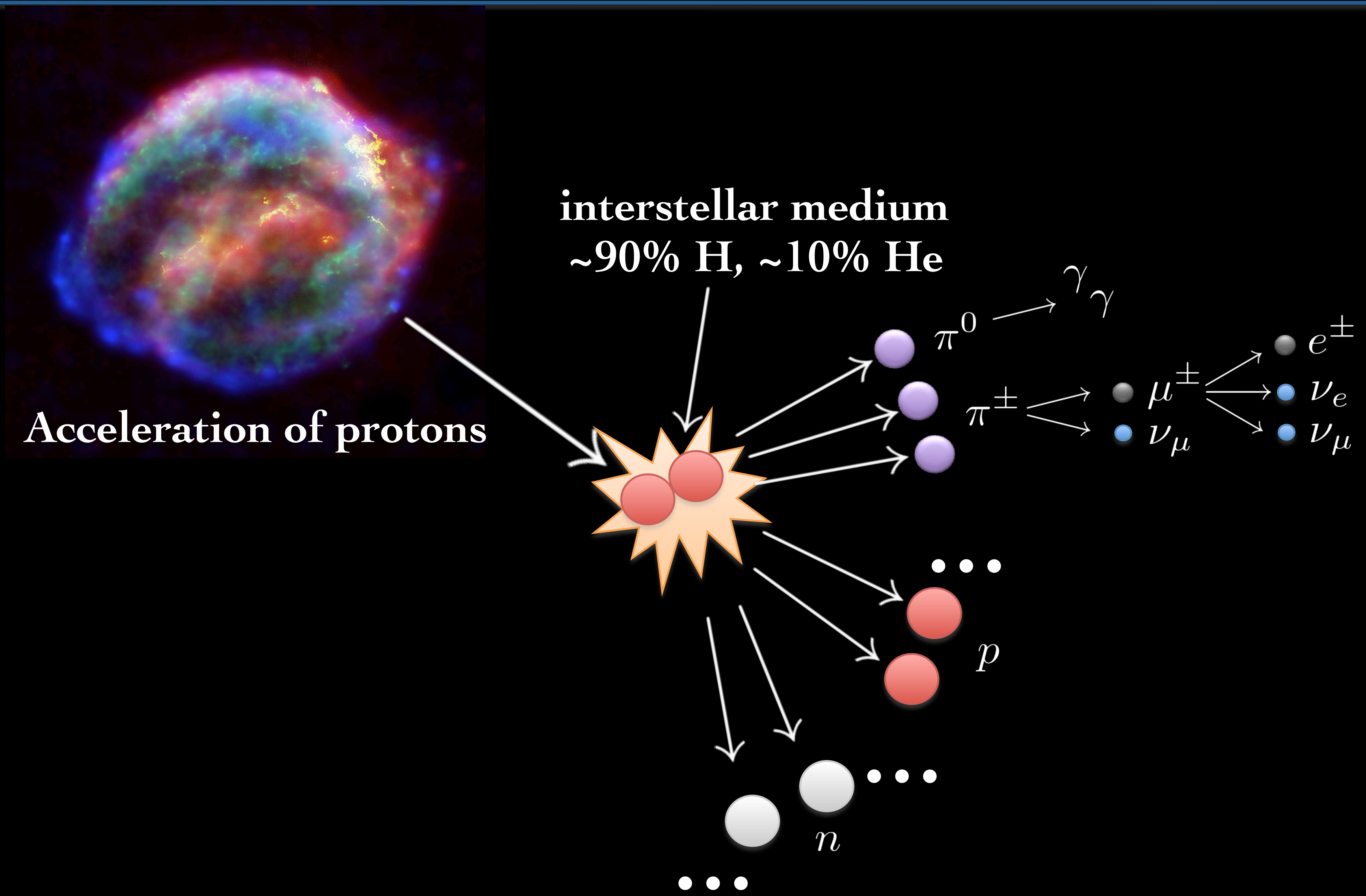


FIG. 1. The percent difference between the CDF inclusive jet cross section (points) and a next-to-leading order (NLO) QCD prediction using MRSD0′ PDFs. The CDF data (points) are compared directly to the NLO QCD prediction (line) in the inset. The normalization shown is absolute. The error bars represent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

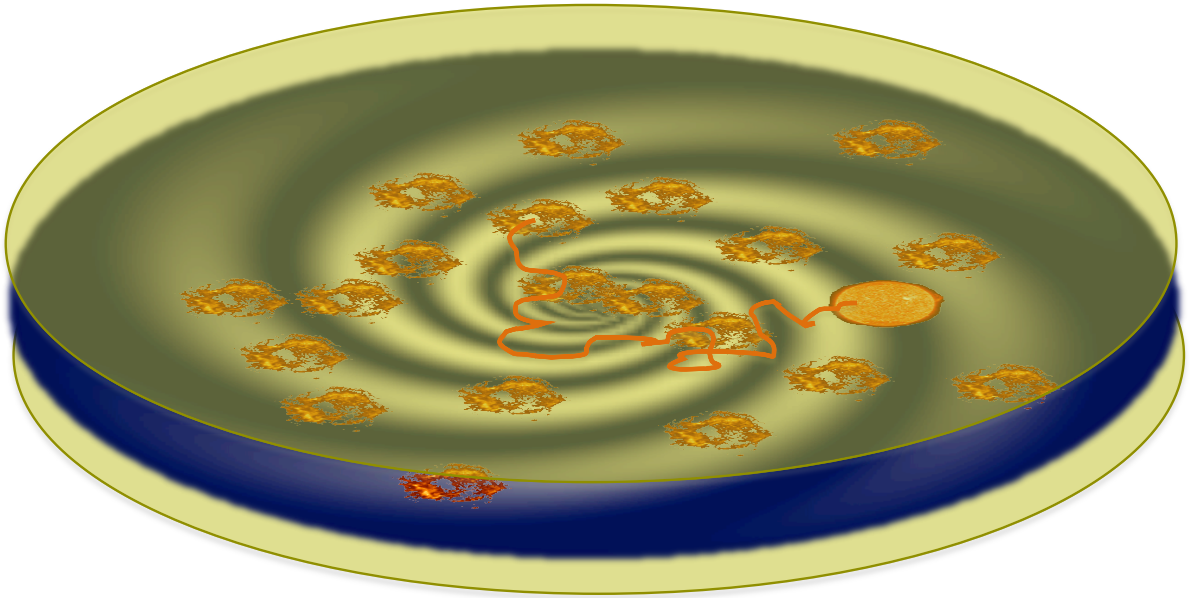
… it turned out to be a mis-estimation of the QCD background – *not* new physics!

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



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)

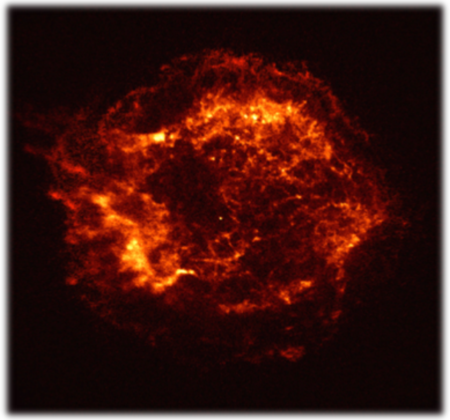


- Secondary production during propagation: $\bar{p}, e^+, N'$
- $e^\pm$ lose energy through synchrotron and inverse Compton scattering

Measurables: Energy spectra of individual species + diffuse radiation

Why supernova remnants?

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

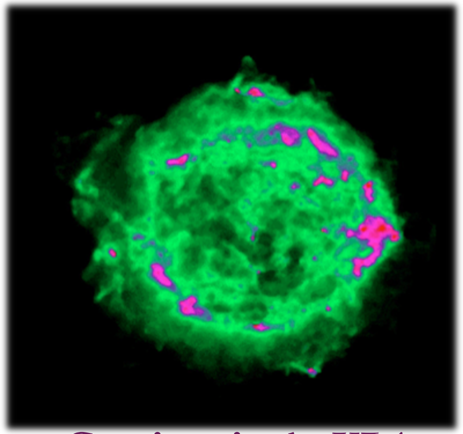


Cassiopeia A: *Chandra*

Energetics

• GCR energy density	$0.3\,\mathrm{eV\,cm^{-3}}$
• Volume of extended halo	$\pi(15\,\mathrm{kpc})^2\,3\,\mathrm{kpc} \simeq 5.7\times10^{67}\,\mathrm{cm^3}$
⇒ Total GCR energy	$1.7\times10^{58}\,\mathrm{GeV} \simeq 2.8\times10^{55}\,\mathrm{erg}$
• Residence time of CRs in Galaxy	20 Myr
⇒ Power needed	$1.4\times10^{48}\,\mathrm{erg\,yr^{-1}}$
• Galactic SN rate	$0.03\,\mathrm{yr^{-1}}$
⇒ Required output/SN (remnant)	$4.6\times10^{49}\,\mathrm{erg}$

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



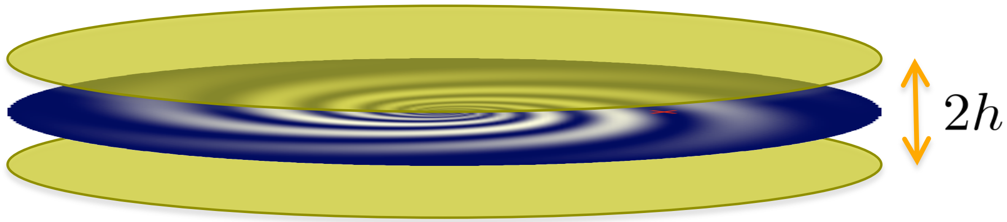
Cassiopeia A: *VLA*

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:



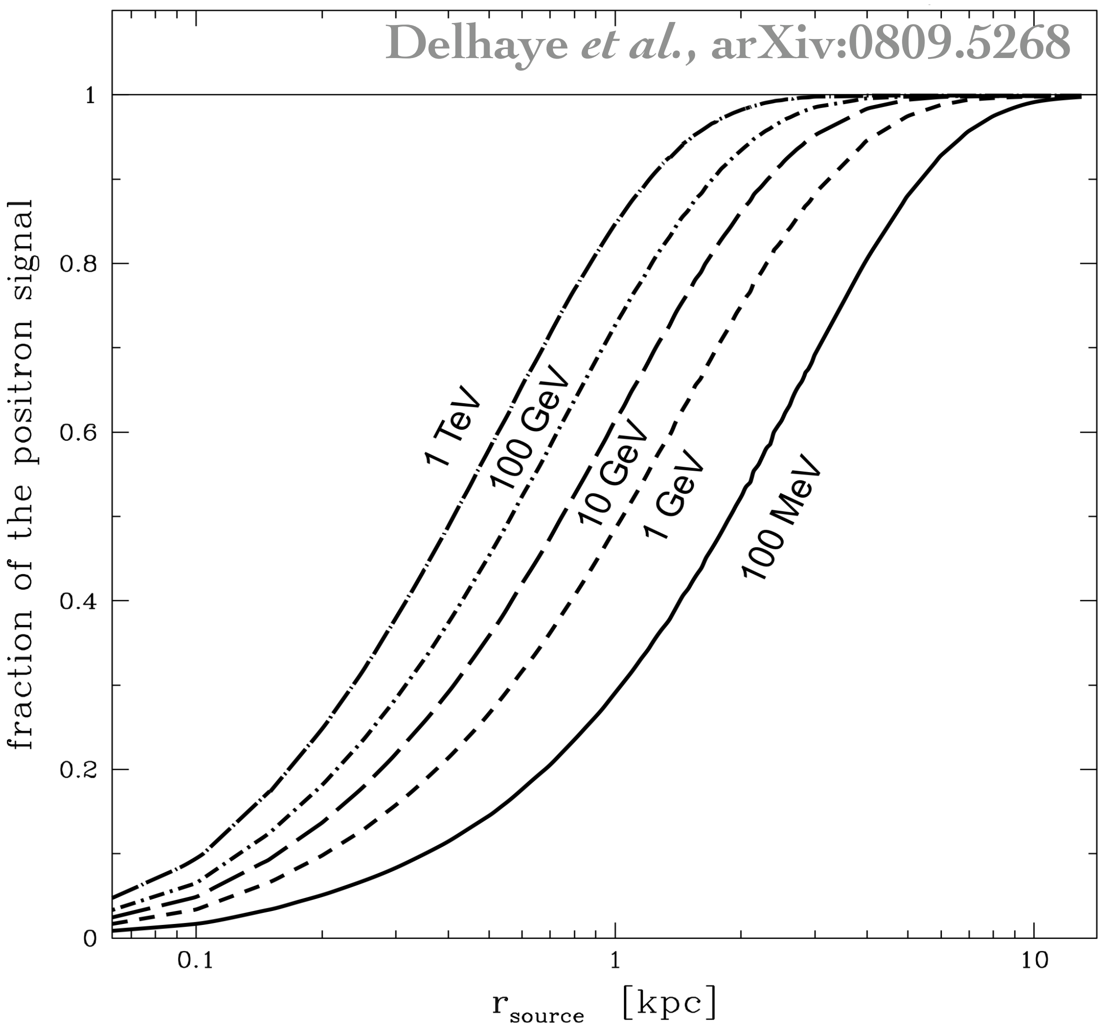
Green's function: describes flux from one discrete, burst-like source
… integrate over spatial distribution and time-variation of injection

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

$\Rightarrow$ 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*



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

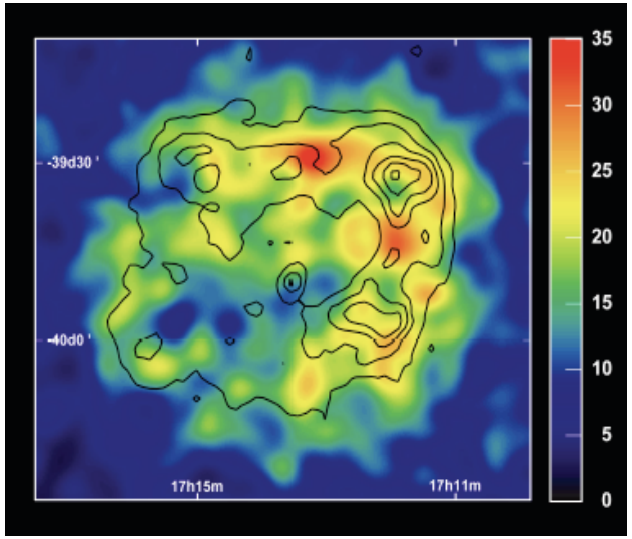
A nearby cosmic ray accelerator?

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

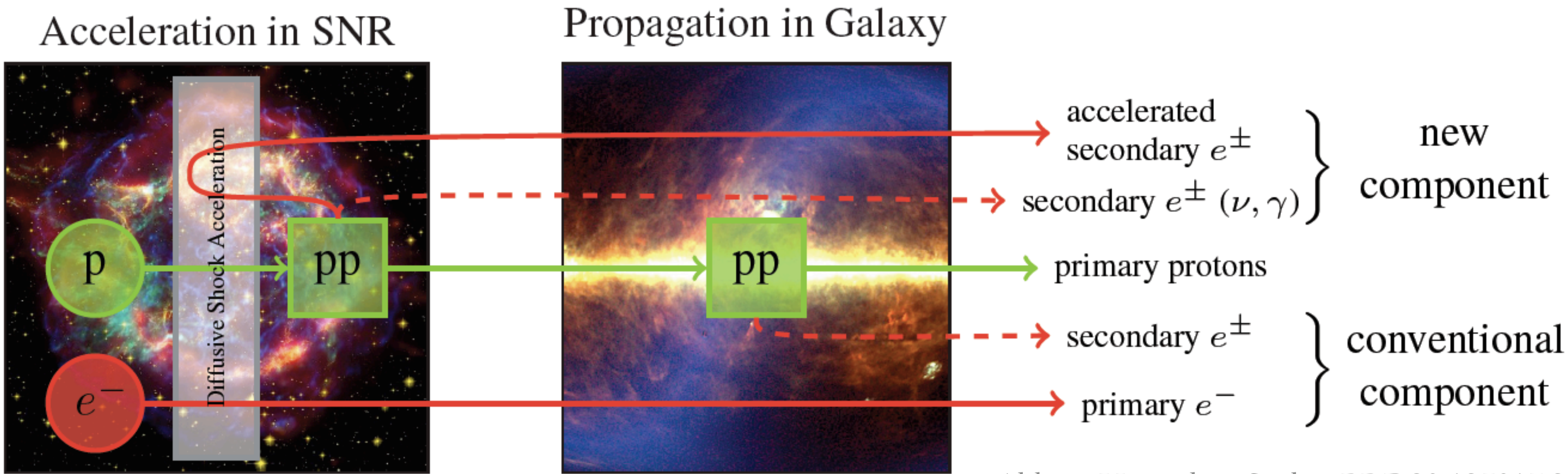
(Blasi, PRL103:051104,2009, Fujita *et al*, PRD80:063003,2009)

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

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



RXJ1713.7-3946, *HESS*

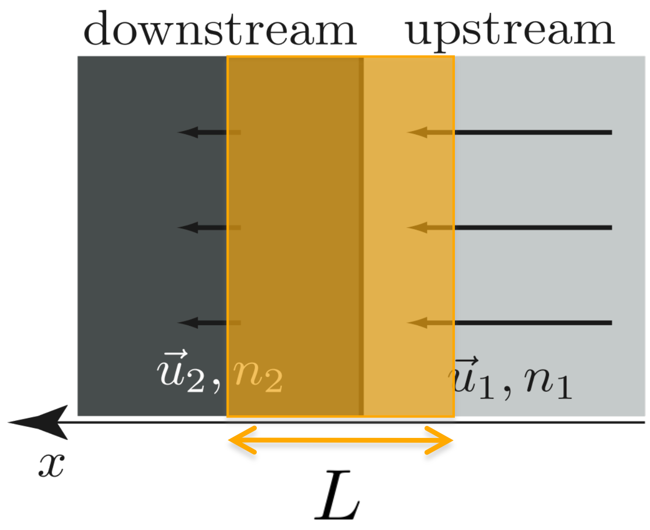


Ahlers, Mertsch & Sarkar,PRD80:123017,2009

Diffusive (1st-order Fermi) shock acceleration

Consider flux:

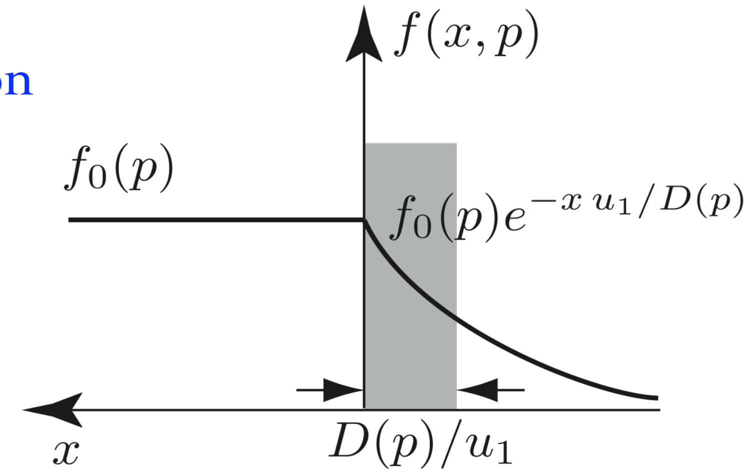
$$\Phi(p) = \int \mathrm{d}^3x \, \frac{4\pi p^2}{3} f(p)(-\nabla \cdot \vec{u})$$



Conservation equation:

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

density change acceleration convection injection



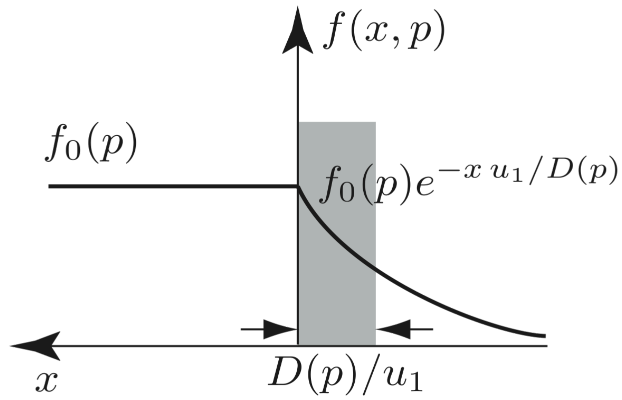
Steady state: $\frac{u_1 - u_2}{3} p \frac{\partial f}{\partial p} + u_1 f = 0$

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

DSA with secondary production

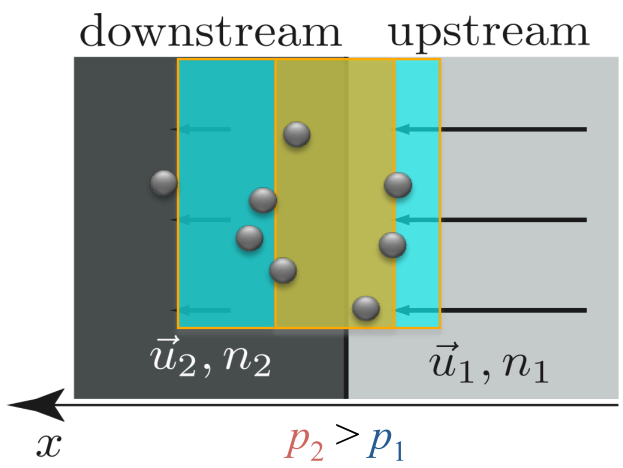
- Secondaries are produced with primary spectrum (Feynman scaling of #-secn):

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



- 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

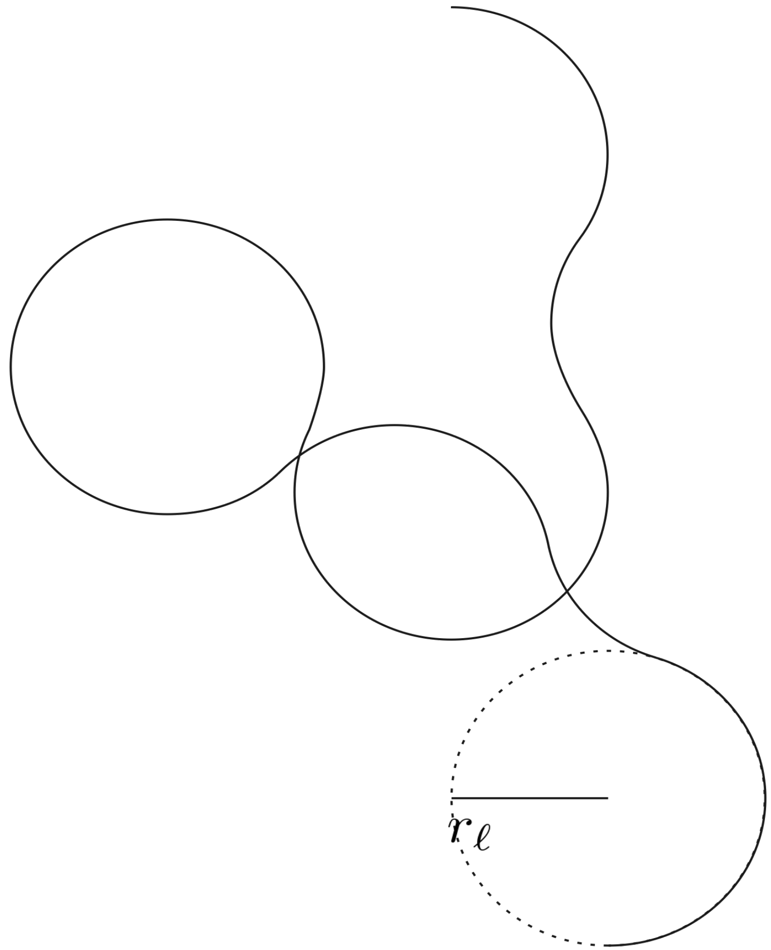
- Diffusion rate near shock front not known *a priori*
- Bohm diffusion sets *lower* limit

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

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

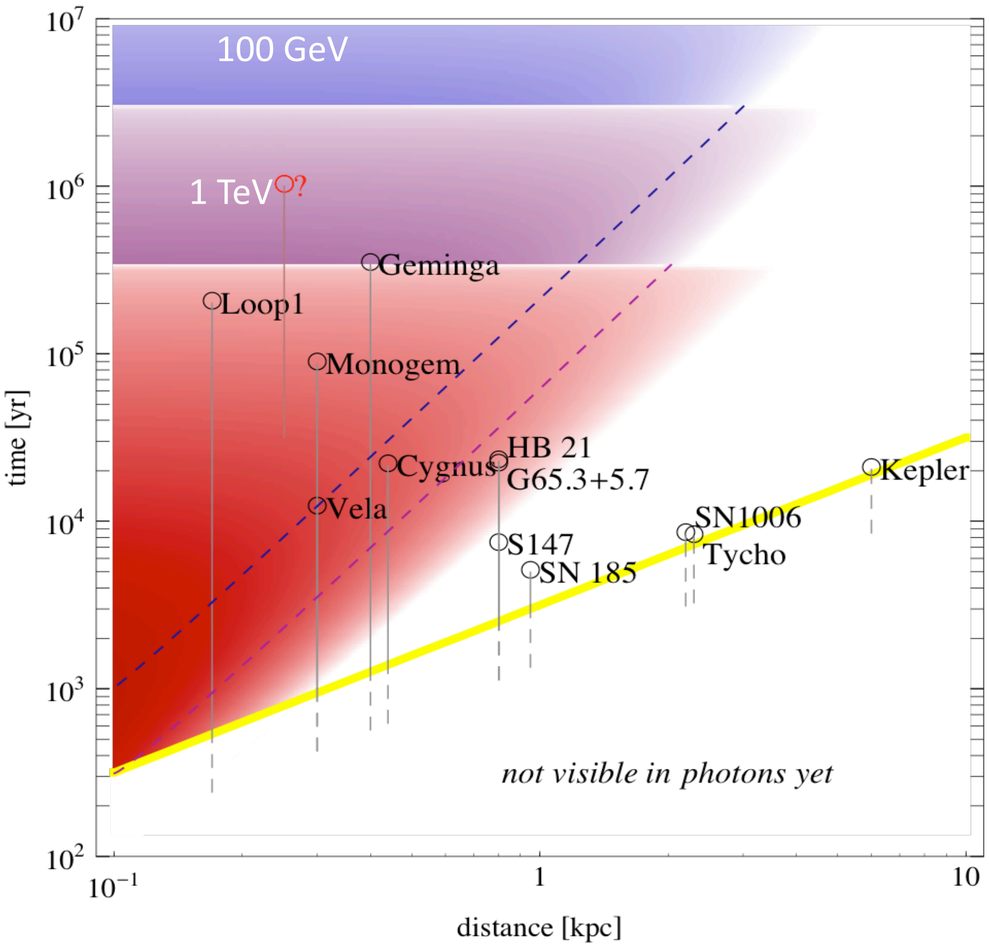
$$D = D^{\mathrm{Bohm}} \mathcal{F}^{-1}$$

- $\mathcal{F}^{-1}$ 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 …

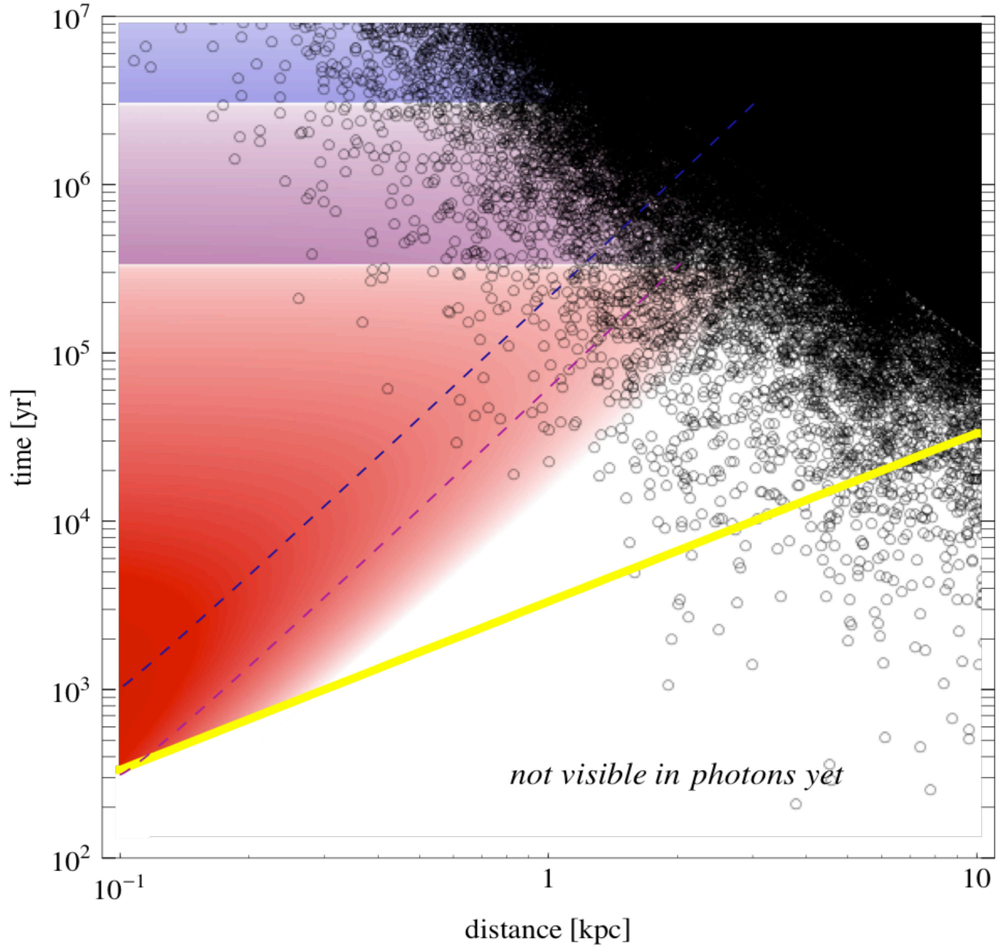


Moreover it is not just the (optically) observed SNRs which contribute … there must be *many* other hidden SNR

known

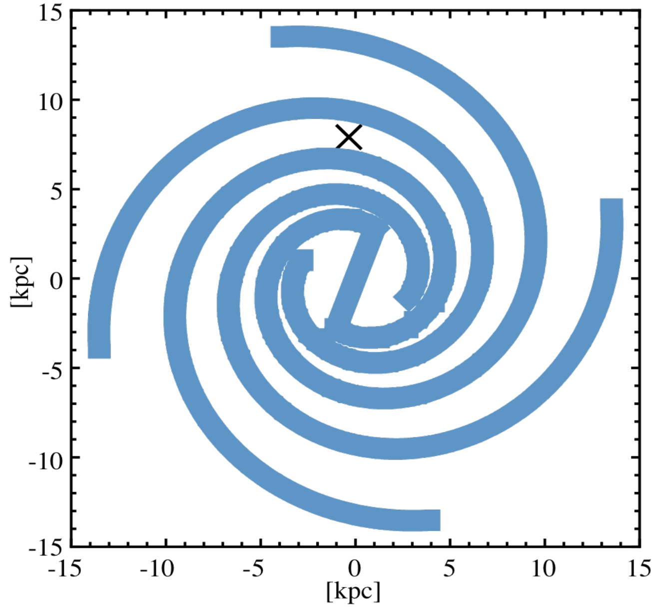


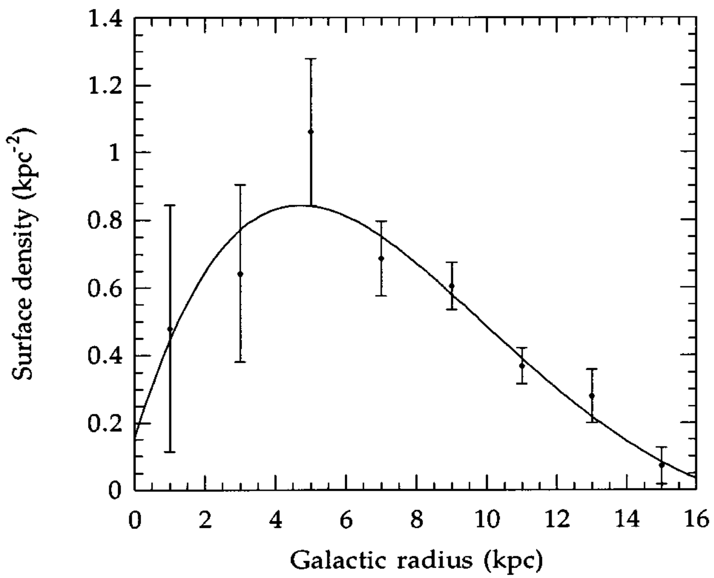
simulated



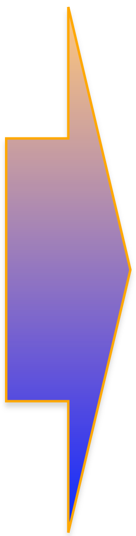
Ahlers, Mertsch & Sarkar, PRD80:123017,2009

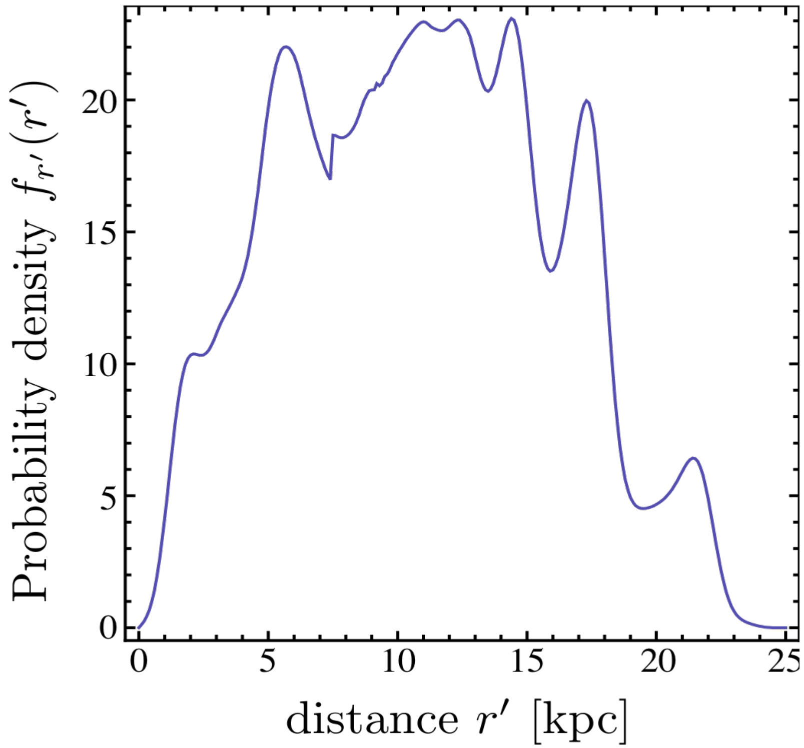
Statistical distribution of sources





Case & Bhattacharya, ApJ504:761,1998





<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

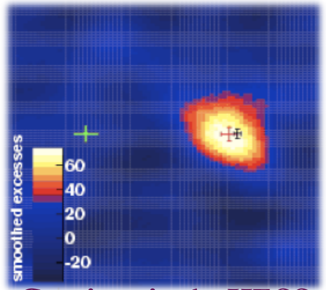
Ahlers, Mertsch & Sarkar,PRD80:123017,2009

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	
L	3 kpc	
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 $e^\pm$: $p + p \rightarrow \begin{cases} \pi^0 + \ldots & \rightarrow \quad 2\gamma + \ldots \\ \pi^\pm + \ldots & \rightarrow \quad e^\pm + \ldots \end{cases}$

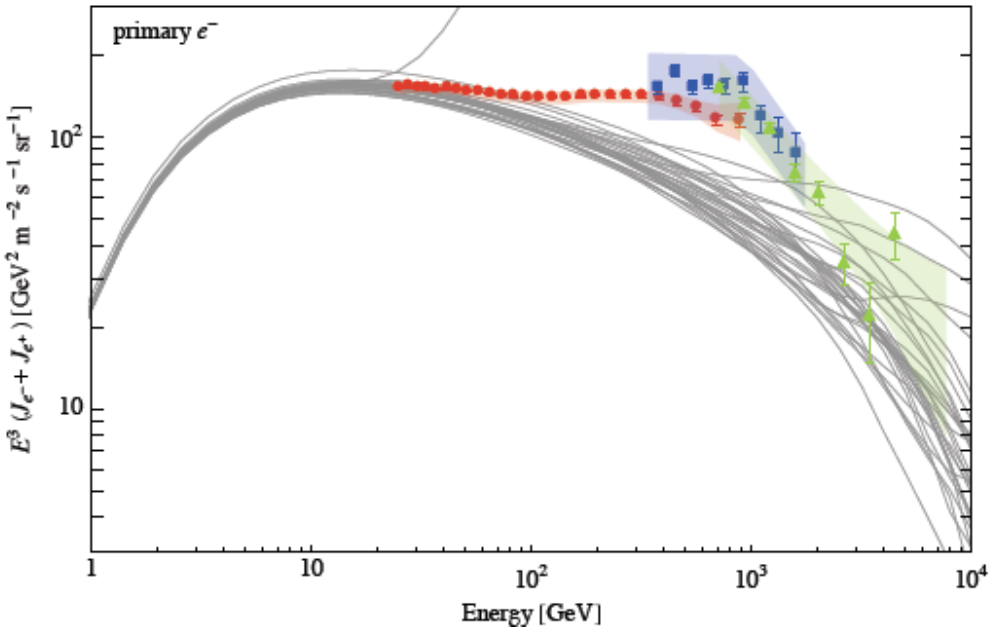
Source	Other name(s)	Γ	$J^0_\gamma \div 10^{-12}$ [$(\mathrm{cm}^2\,\mathrm{s\,TeV})^{-1}$]	$E_{\max}$ [TeV]	d [kpc]	$Q^0_\gamma \div 10^{33}$ [$(\mathrm{s\,TeV})^{-1}$]
HESS J0852−463	RX J0852.0-4622 (Vela Junior)	2.1 ± 0.1	21 ± 2	> 10	0.2	0.10
HESS J1442−624	RCW 86, SN 185 (?)	2.54 ± 0.12	3.72 ± 0.50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

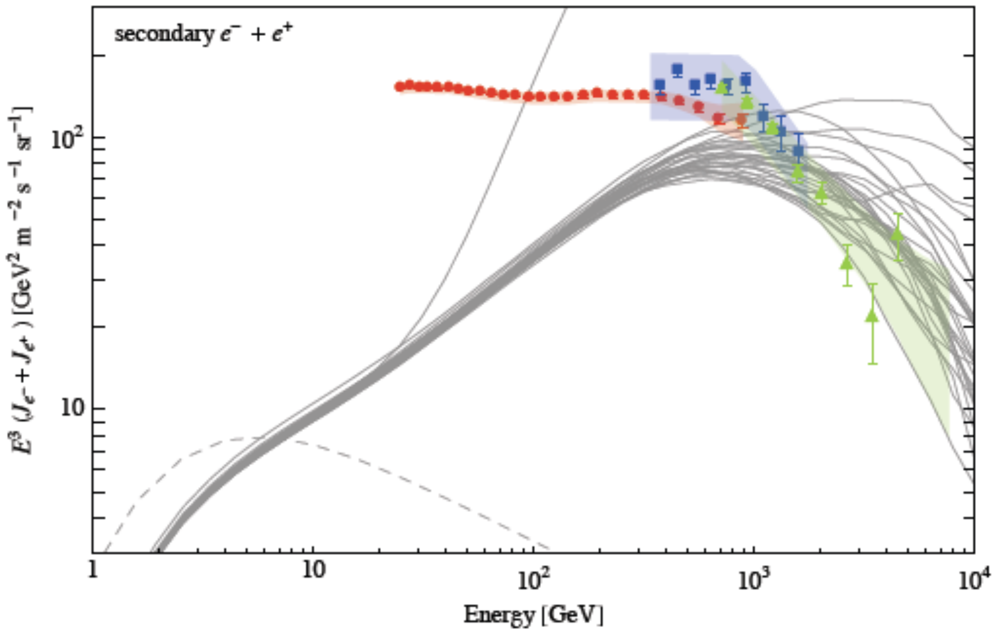
Ahlers, Mertsch & Sarkar, PRD80:123017,2009

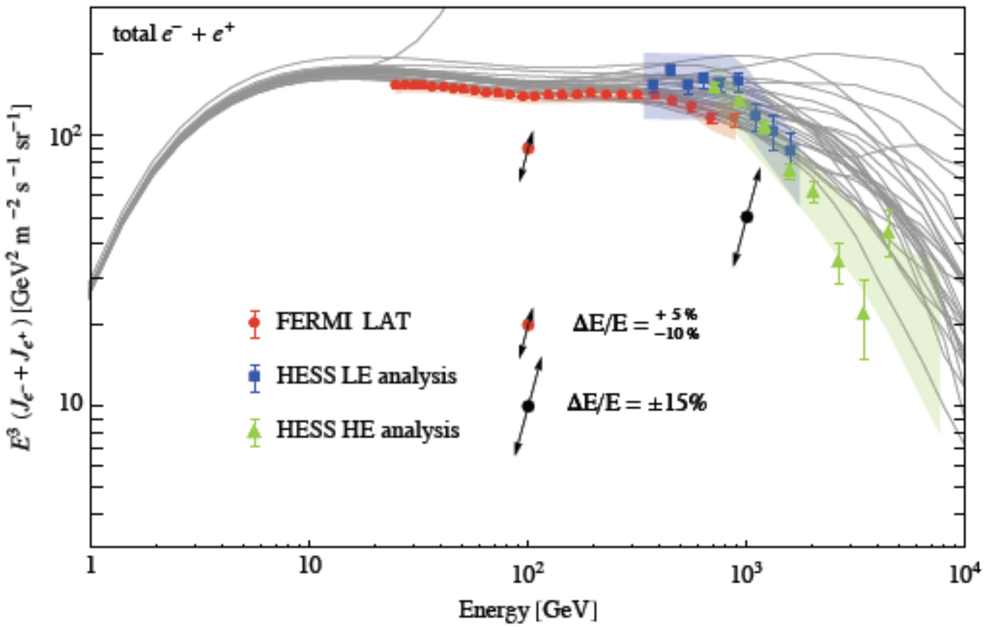
Fitting the $e^+ + e^-$ flux

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'!

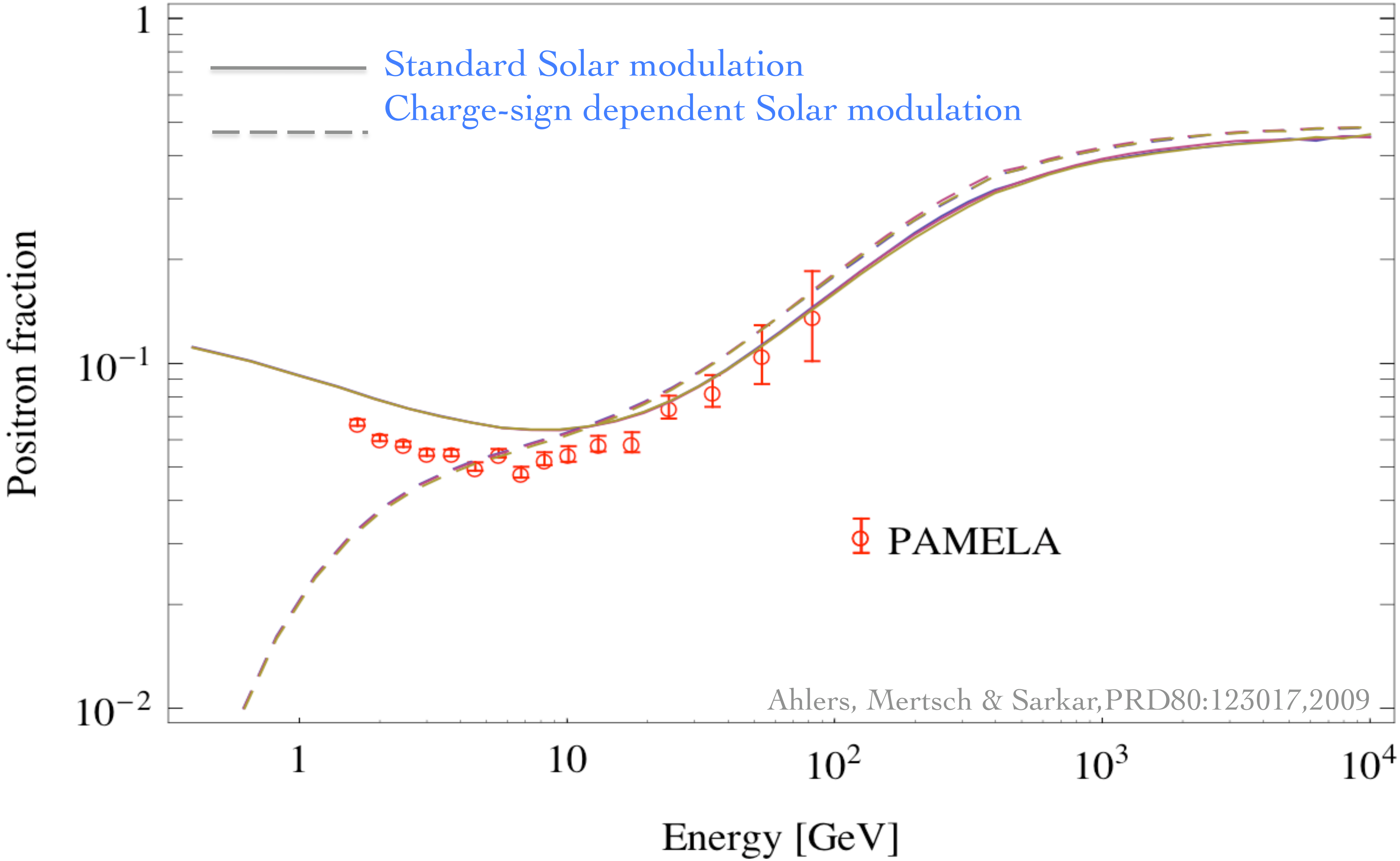
Ahlers, Mertsch & Sarkar, PRD80:123017,2009







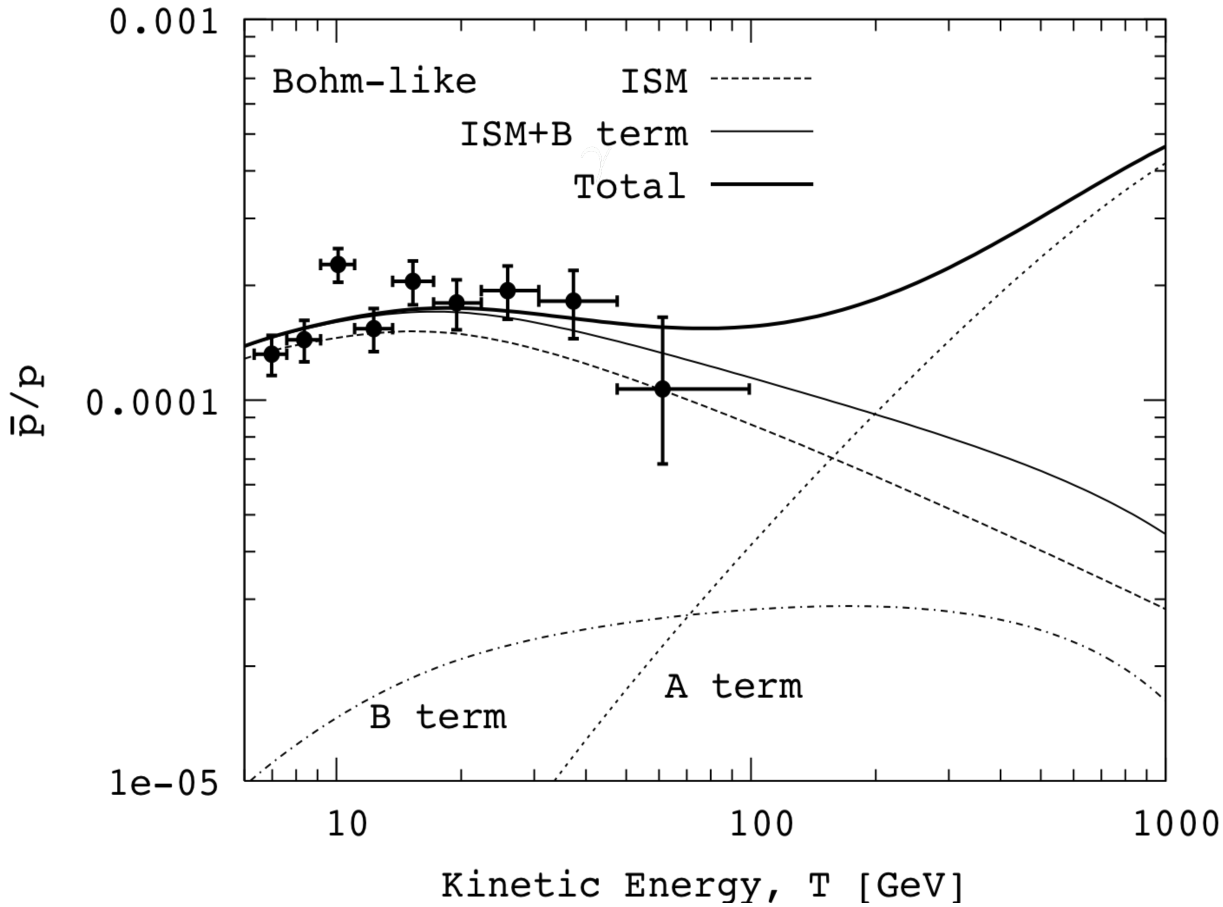
The *predicted* positron fraction



Antiproton-to-proton ratio

Blasi & Serpico, PRL 103:081103,2009

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



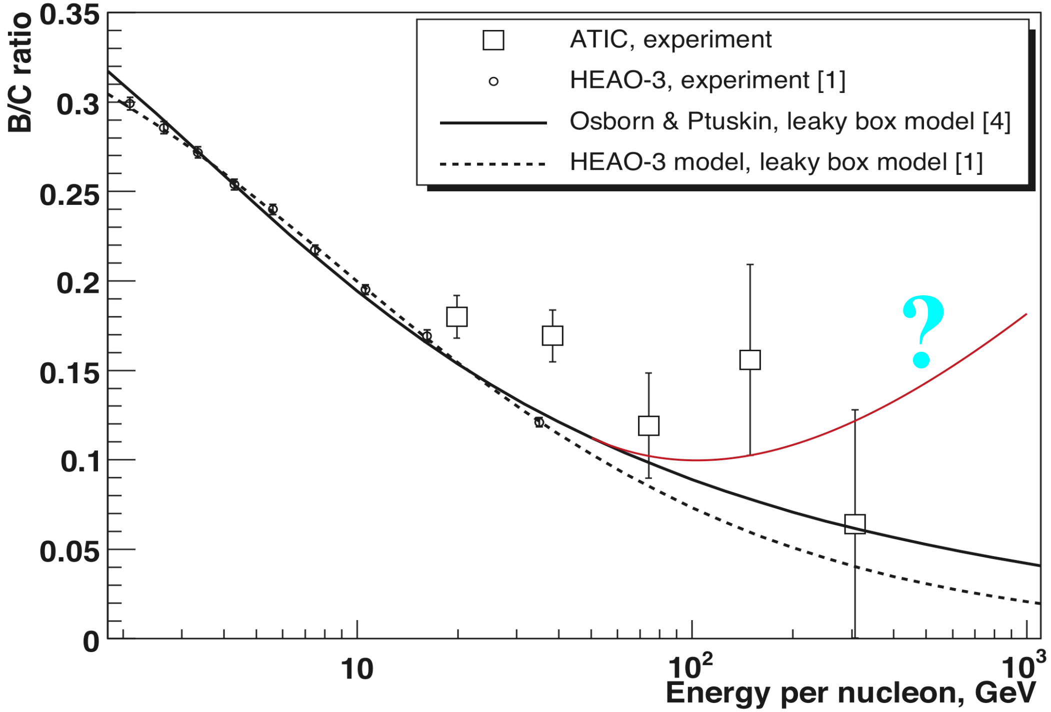
… consistent with secondary acceleration model, which predicts rise *beyond* 100 GeV (will be tested by ***AMS-02***)

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:

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

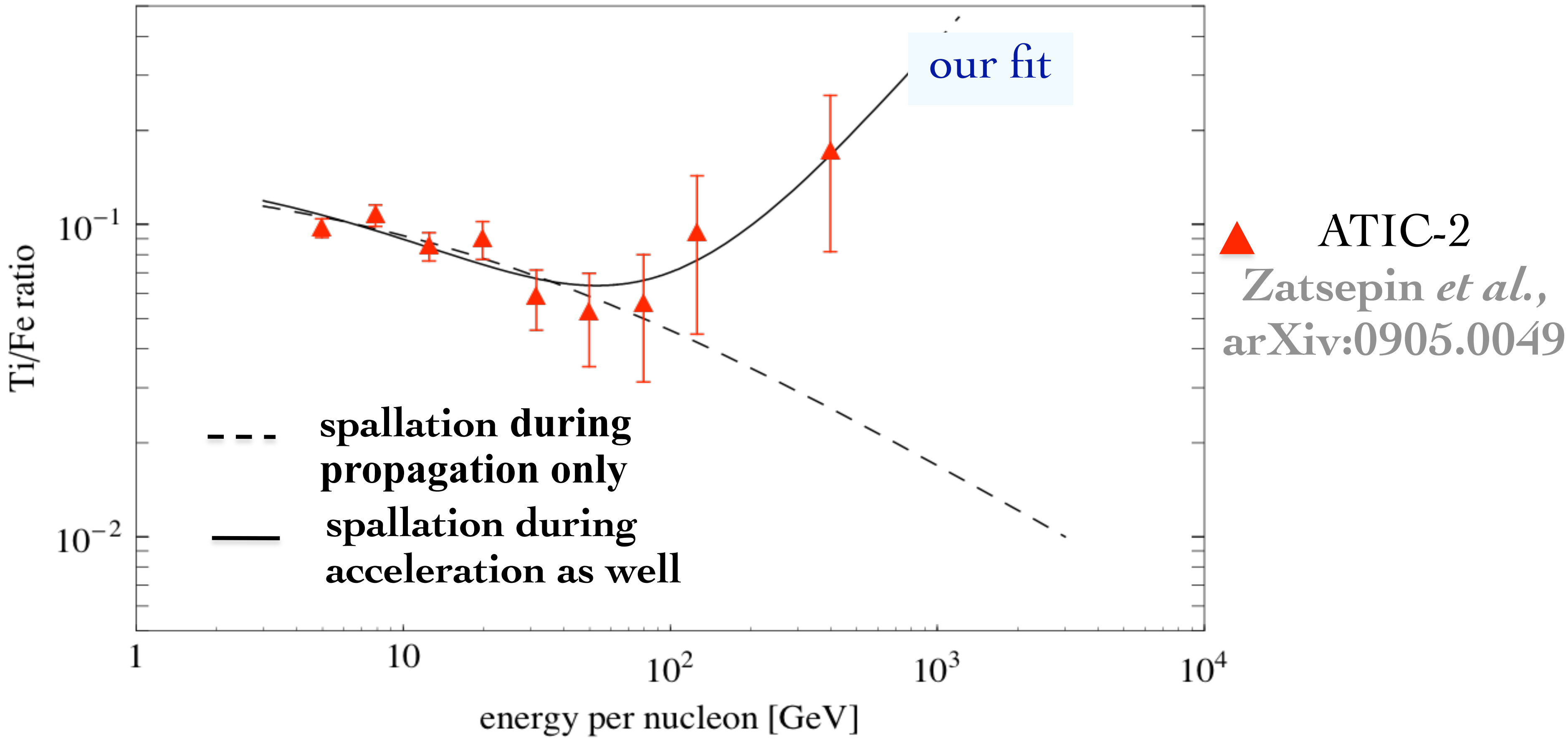
$$f_i^0(p) = \int_0^p \frac{\mathrm{d}p'}{p'} \left(\frac{p'}{p}\right)^\gamma \mathrm{e}^{-\gamma(1+r^2)(D_i^-(p)-D_i^-(p'))\Gamma_i^-/u_-^2}$$

$$\times \gamma \left[(1+r^2)\frac{D_i^-(p')q_i^-(x=0)}{u_-^2} + Y_i \delta(p' - p_0)\right]$$

$$\sim \text{“}q_i^-(p) + D_i^-(p) q_i^-(p)\text{”}$$

Mertsch & Sarkar, PRL 103:081104,2009

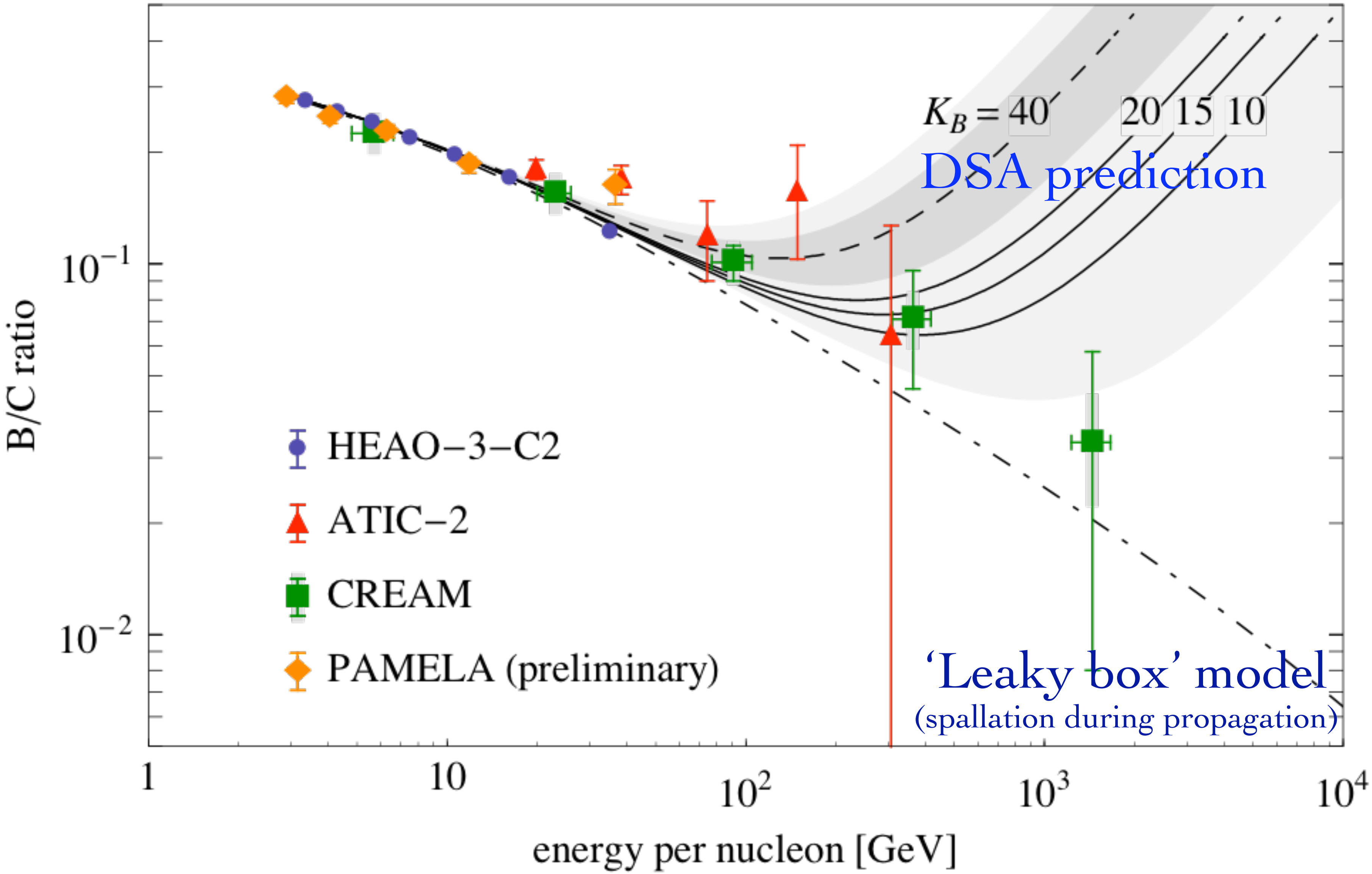
Titanium-to-Iron Ratio



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

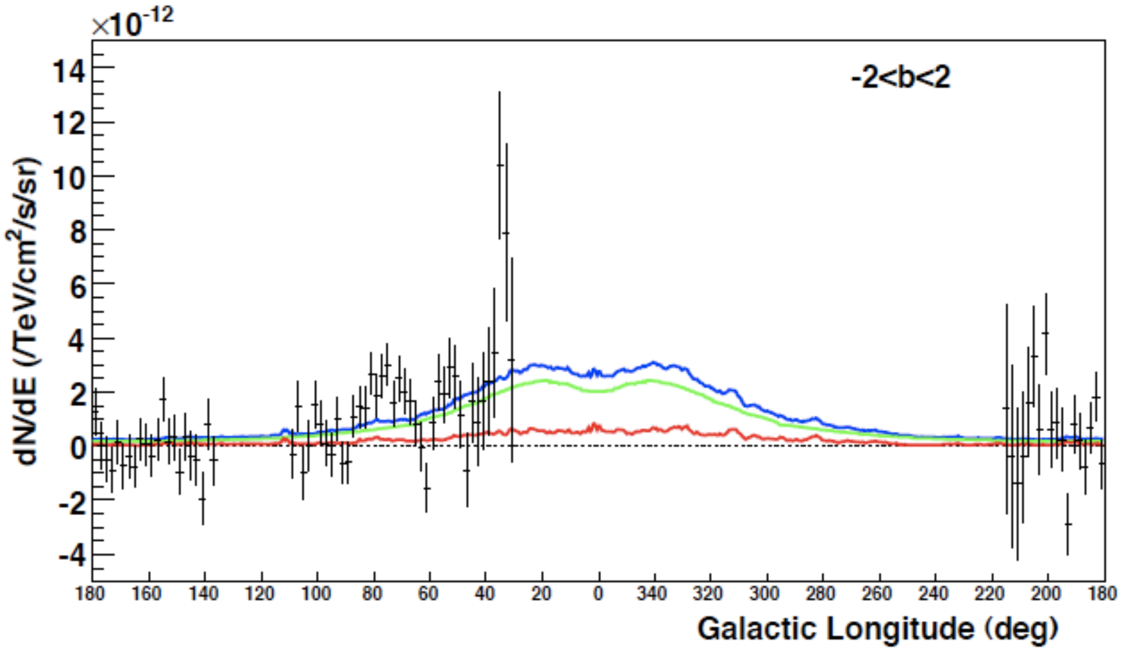
Mertsch & Sarkar, PRL 103:081104,2009

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

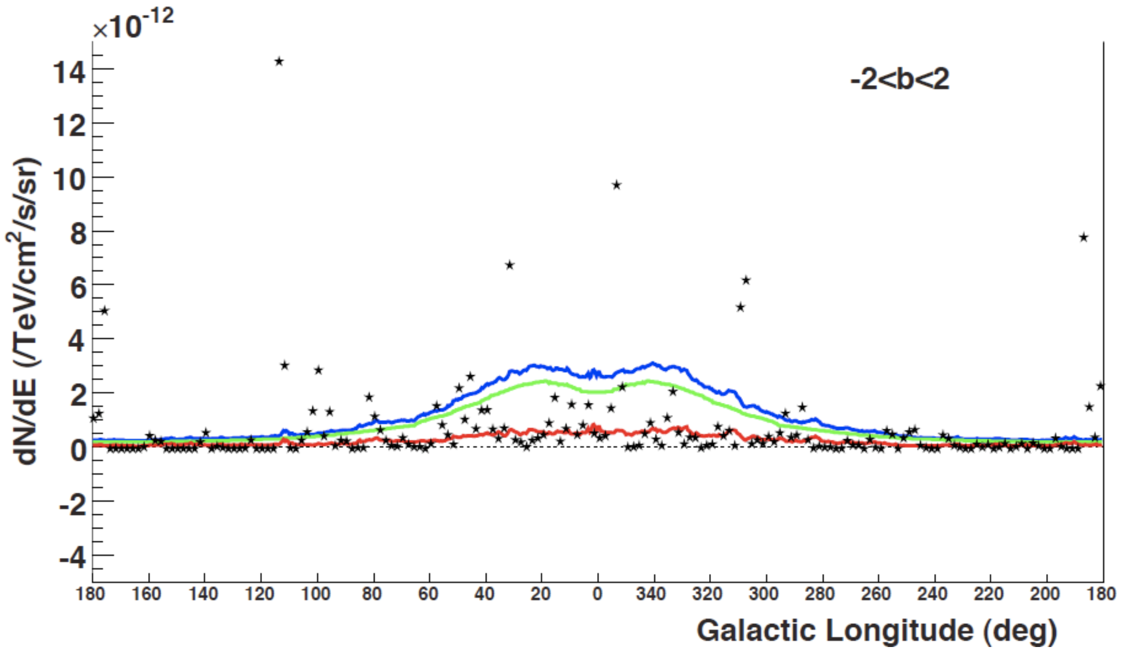
Has *MILAGRO* seen some of these old SNRs already?



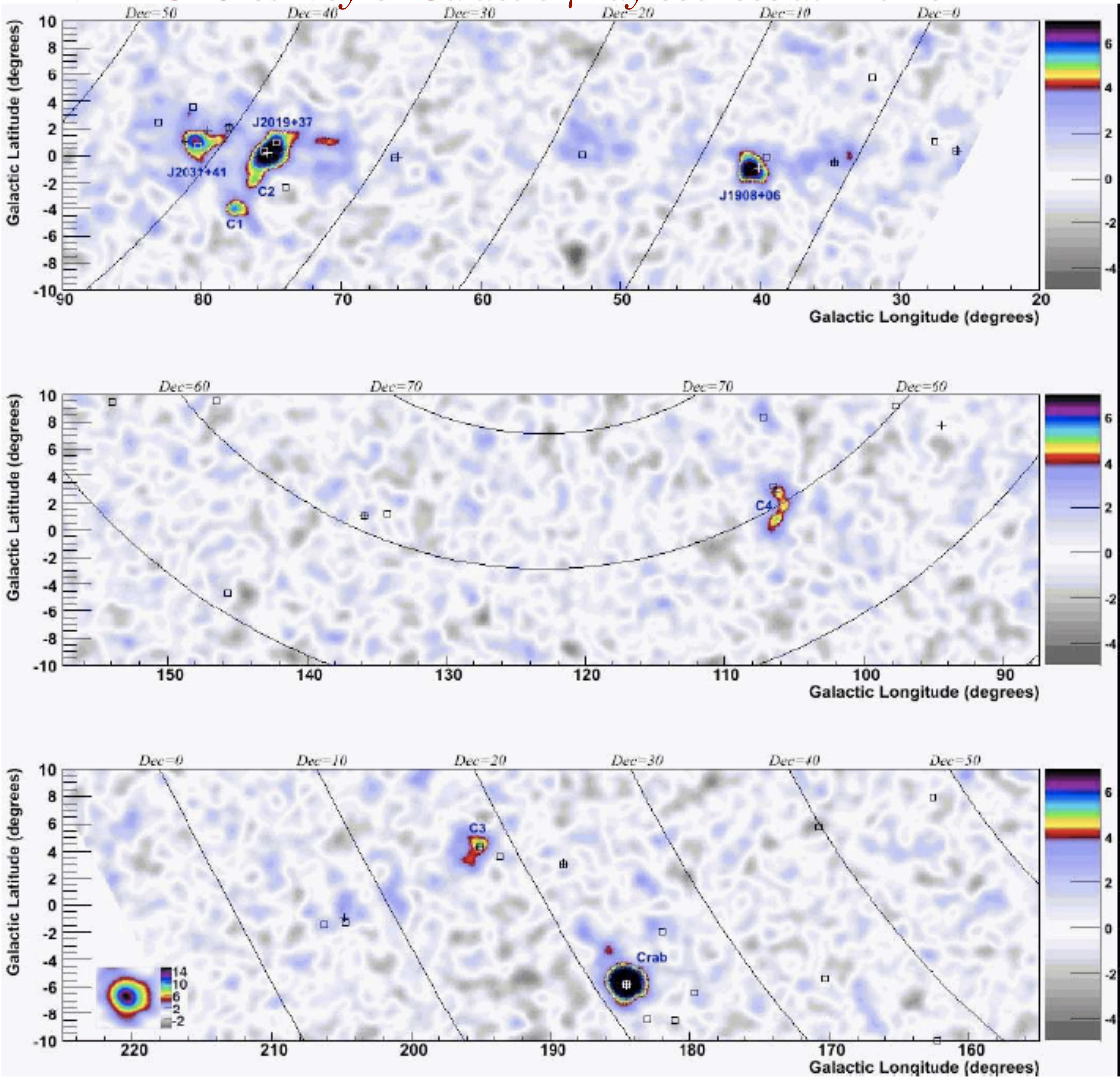
MILAGRO profile of the Milky Way overlaid with GALPROP 'prediction'
(red: π^0 decay, green: IC, blue: total)

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



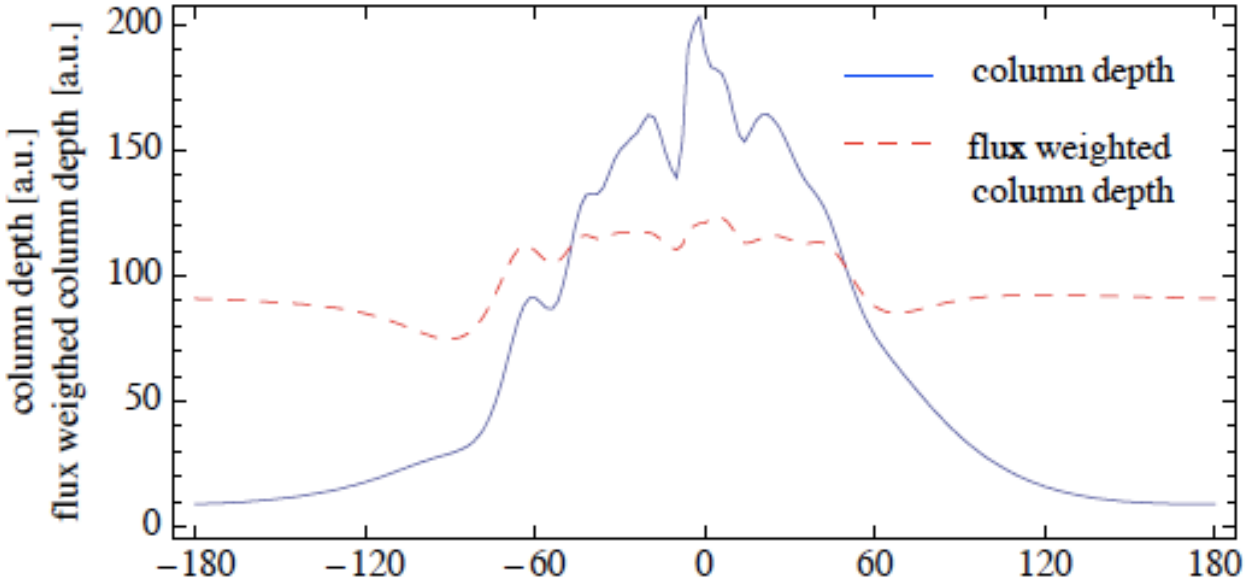
MILAGRO survey of Galactic γ-ray sources at ~20 TeV



Eight candidate sources of TeV emission are detected with pre-trials significance >4.5σ 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 > 4σ 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.

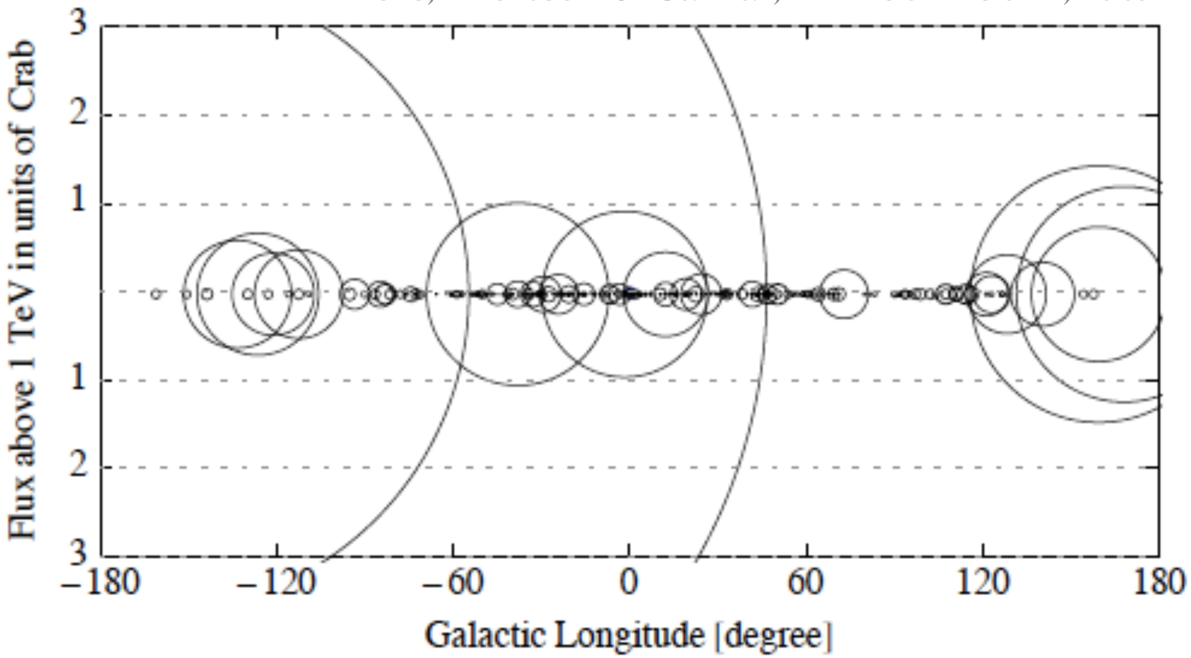
Abdo *et al*, arXiv:0805.0417

A *definitive* cross-check 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 …
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

There has been great progress in TeV particle astrophysics 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 indicates a nearby *hadronic* accelerator rather than dark matter - forthcoming data (*AMS*-02, *CALET* …) on antiprotons, B/C ratio *etc* will provide definitive tests

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