Explaining the PAMELA/Fermi data with a nearby cosmic ray accelerator

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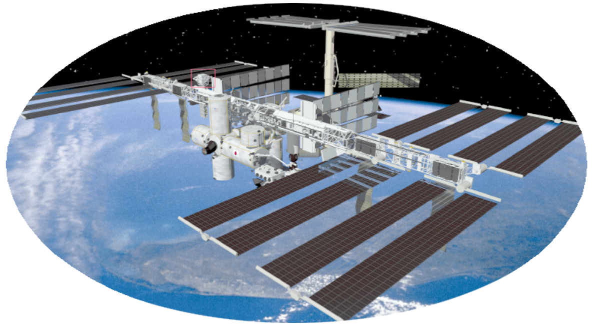
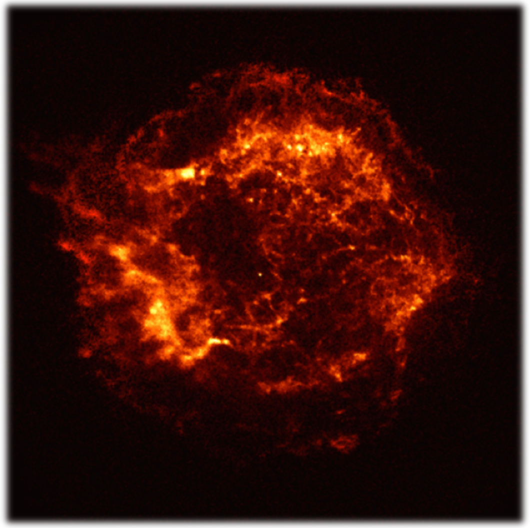




Cosmic Particles, Jets and Accelerator Science, KEK Tsukuba, 10-12 November 2009

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

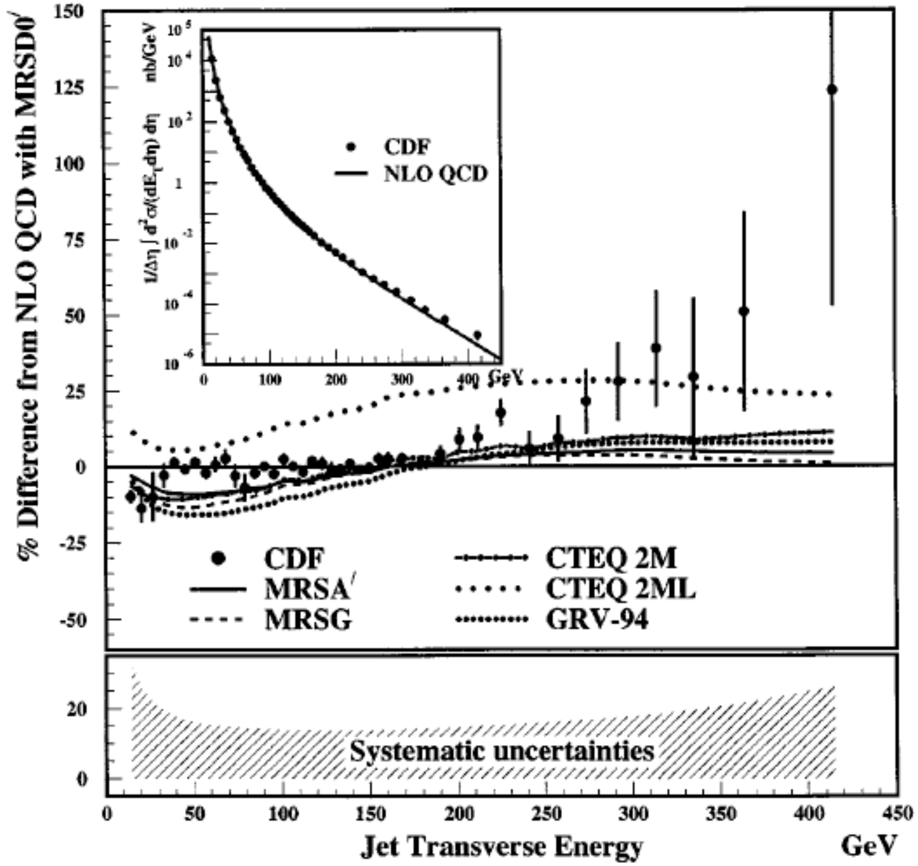


FIG. 1. The percent difference between the CDF inclusive jet cross section (points) and a next-to-leading order (NLO) QCD prediction using MRSD0′ PDFs. The CDF data (points) are compared directly to the NLO QCD prediction (line) in the inset. The normalization shown is absolute. The error bars represent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

PAMELA has measured the positron fraction:

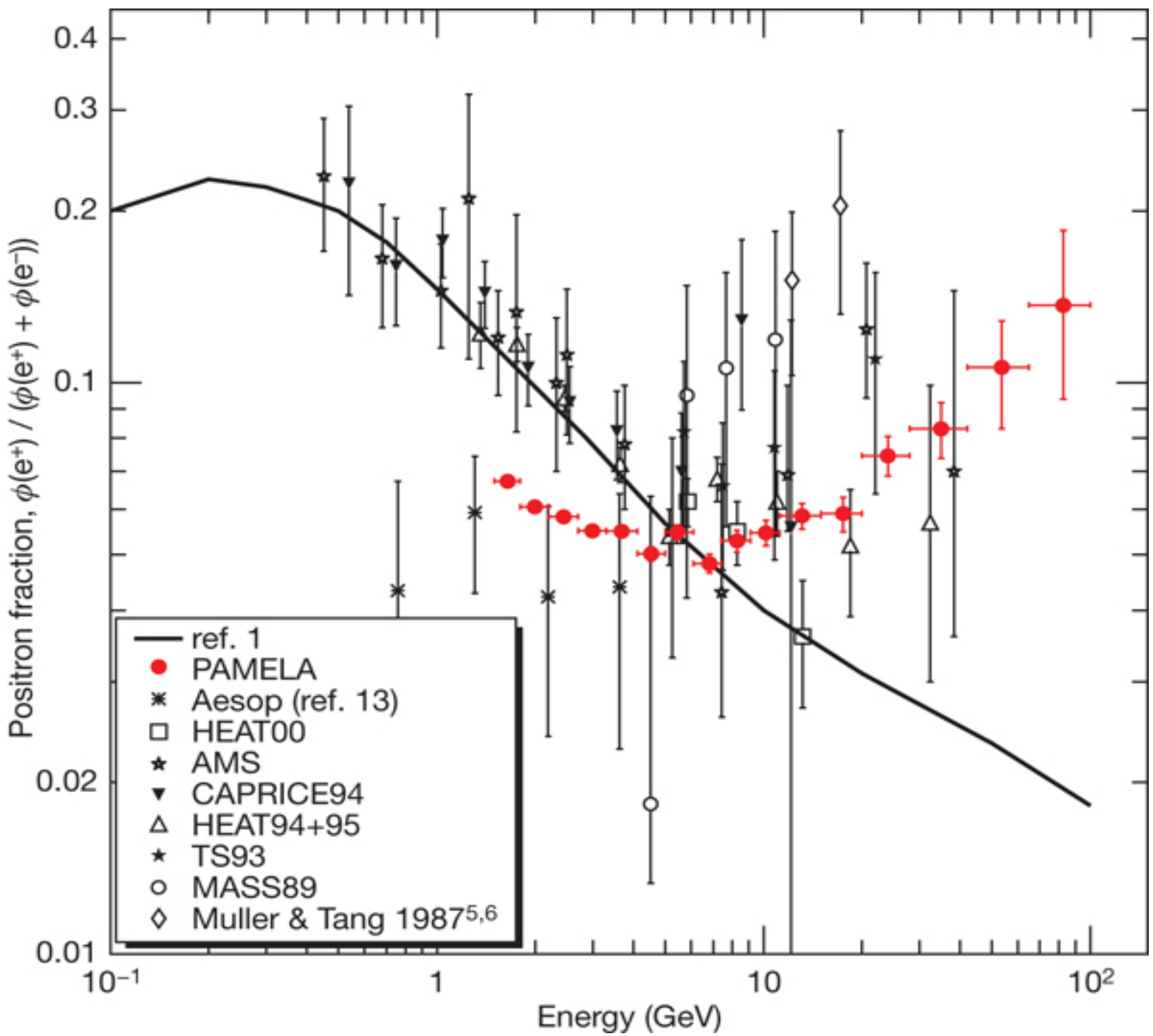
$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$

Anomaly ⇒ excess above 'astrophysical background'

Source of anomaly:

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

… over 200 papers already!



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

Dark matter as source of $e^{\pm}$

Dark matter annihilation

Annihilation rate $\propto n_{\rm DM}^2$

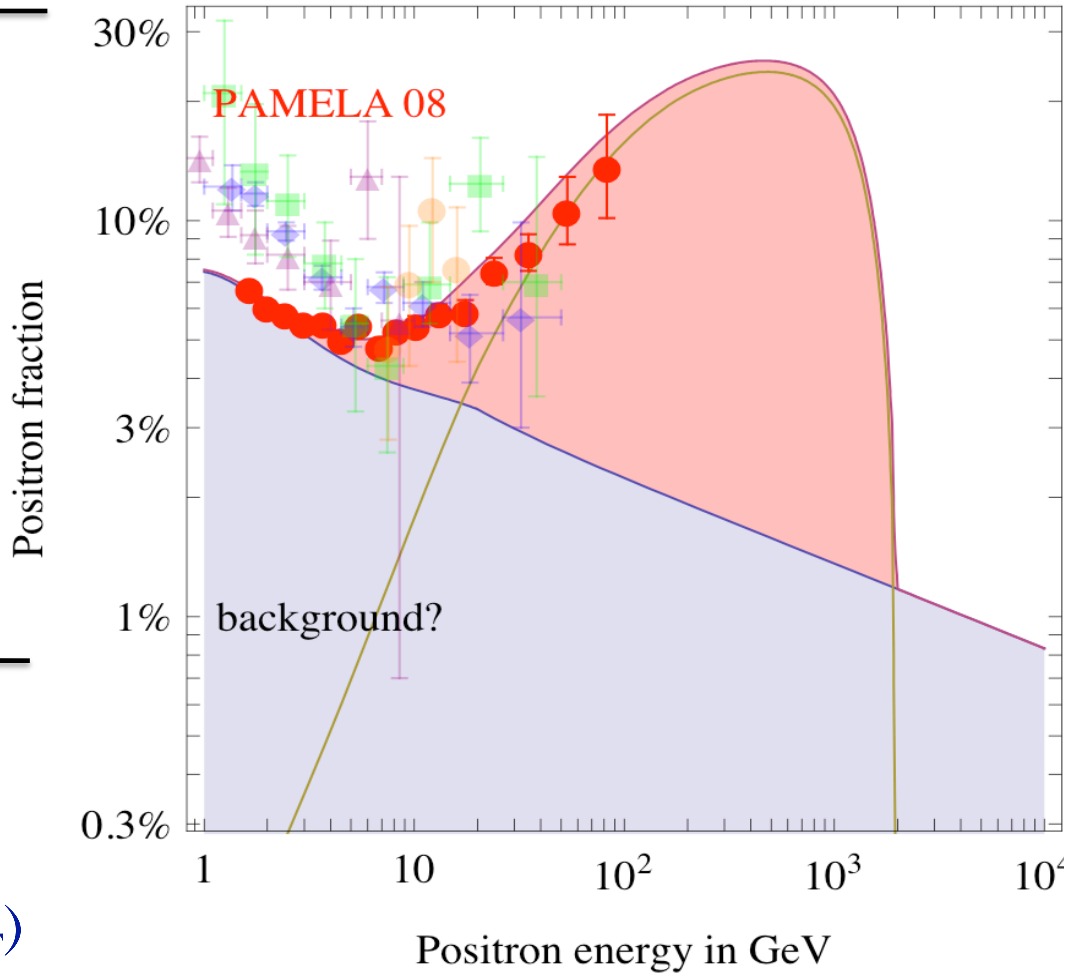
Leads eventually to SM particles

If WIMPs produced thermally, need astrophysical (clumping) or particle physics (Sommerfield) enhancement to yield 'boost factor' of $\mathcal{O}(100)$

Dark matter decay

Similar, but decay rate $\propto n_{\rm DM}$

Lifetime ~ 10^9 x age of universe (dim-6 operator suppressed by $M_{\rm GUT}$)

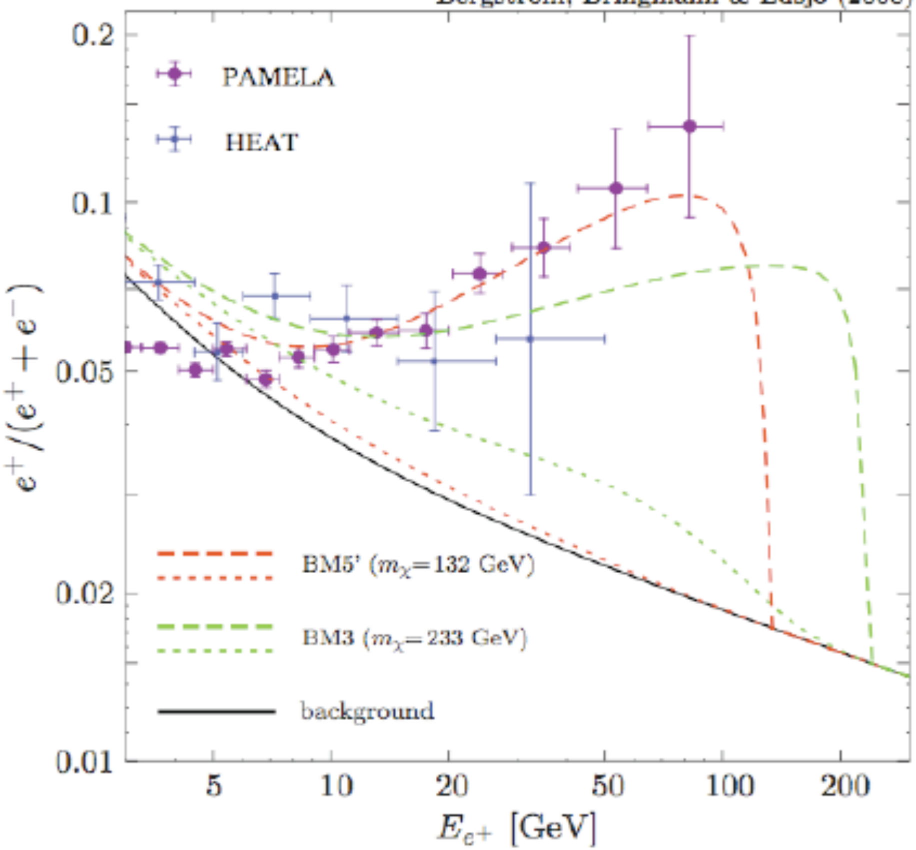


Nardi, Sannino & Strumia, JCAP 0901:043,2009

DM annihilation *can* fit observed e^+ spectrum

arXiv:0808.3725

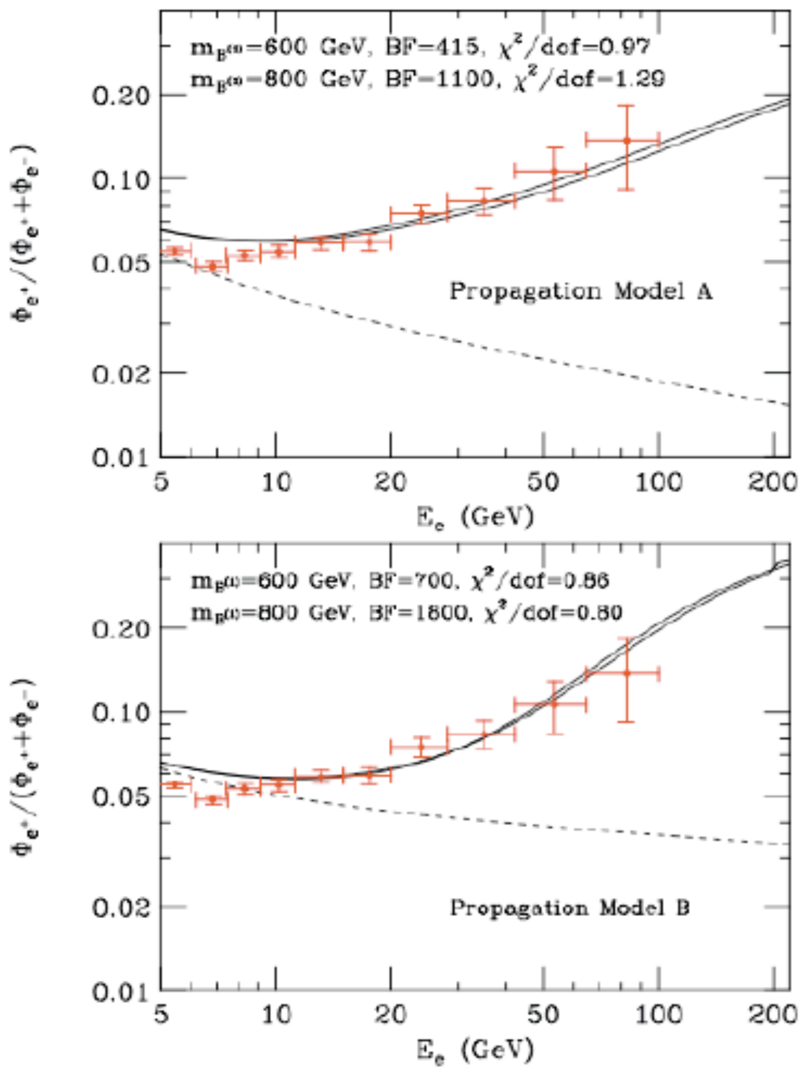
Bergström, Bringmann & Edsjö (2008)



Majorana DM with **new** internal bremsstrahlung correction. NB: requires annihilation cross-section to be 'boosted' by >1000.

Hooper and Zurek

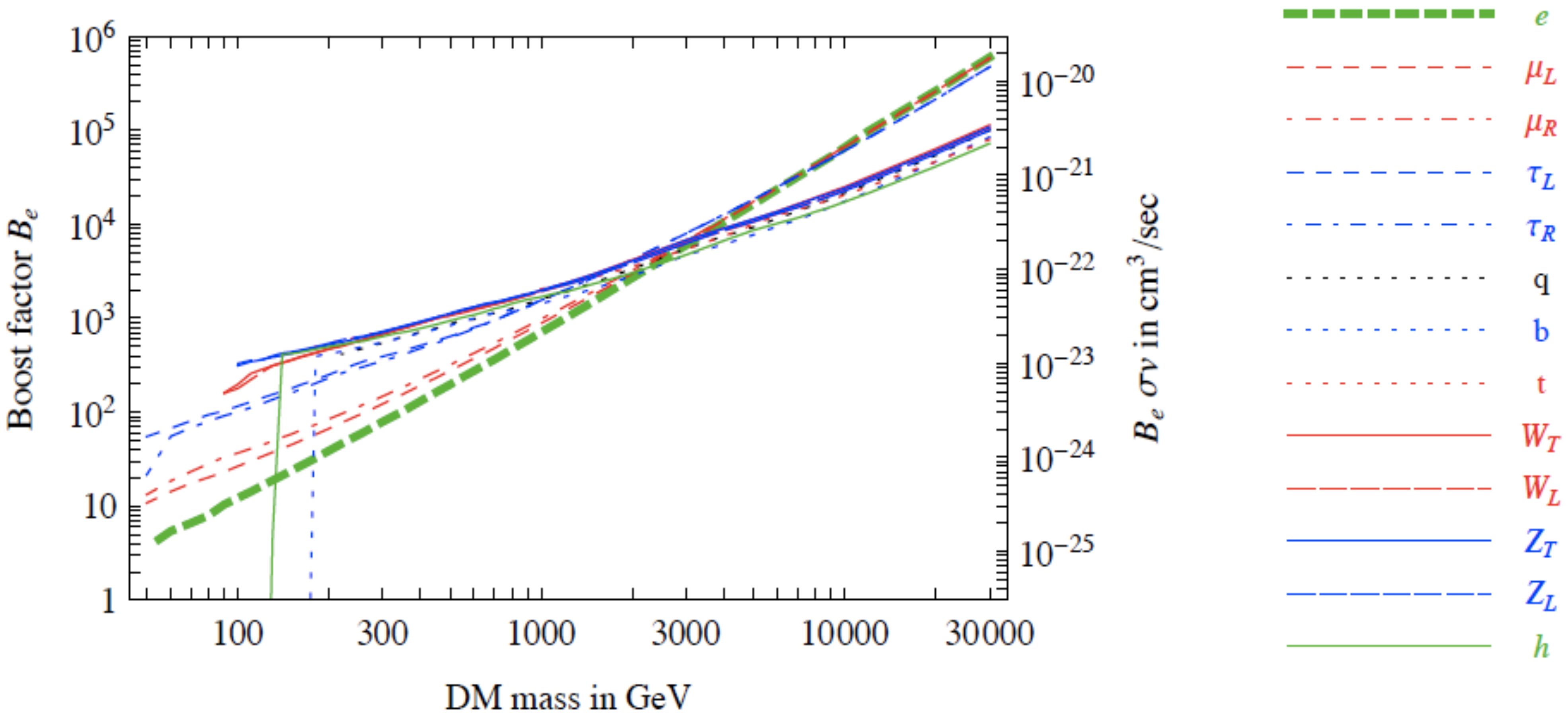
arXiv:0902.0593v1



Kaluza-Klein dark matter

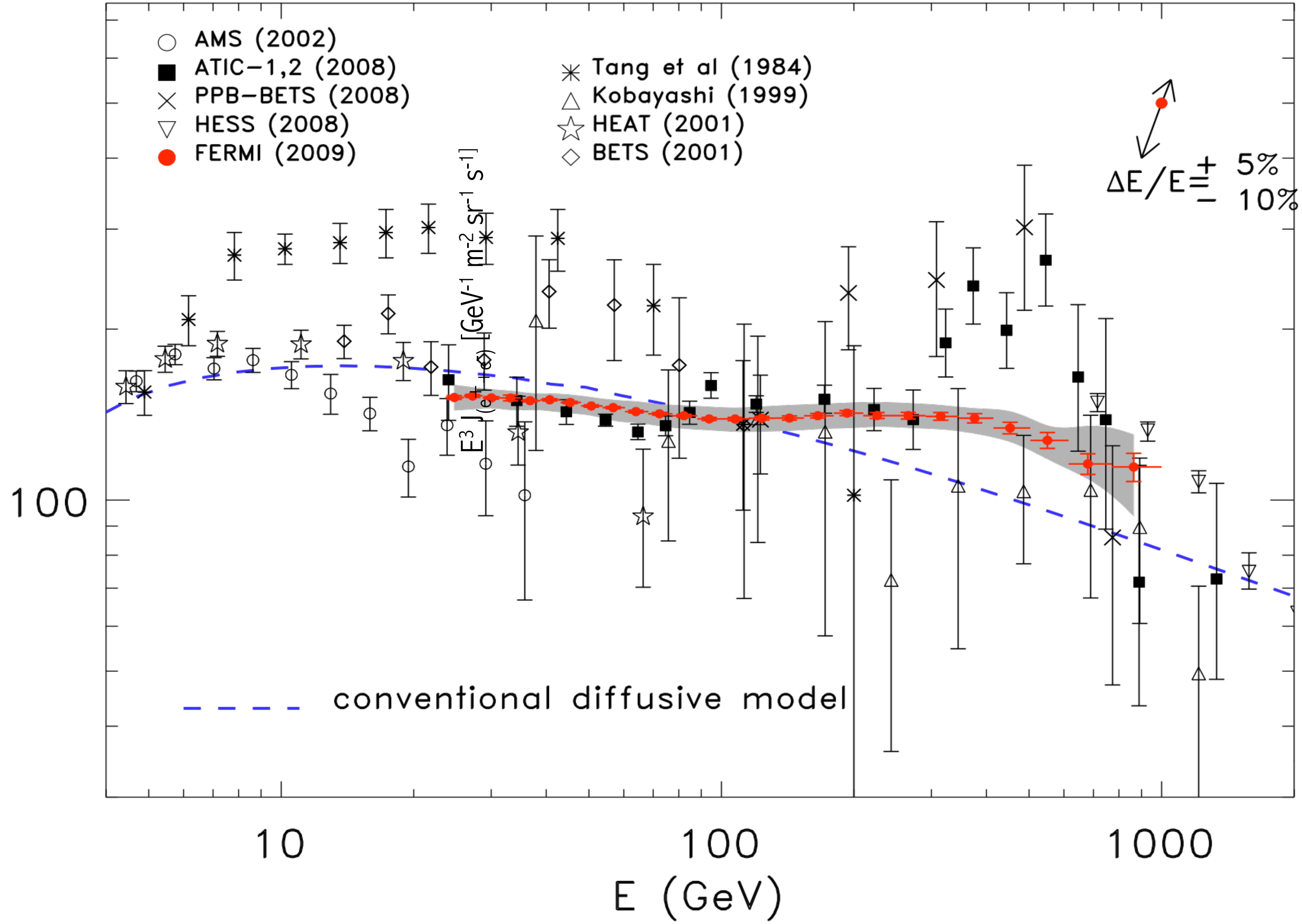
… but requires huge 'boost factor' of annihilation rate to match flux

➔ would imply in general *negligible* relic abundance unless strong velocity dependence (e.g. 'Somerfeld enhancement') of annihilation #-section is invoked



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

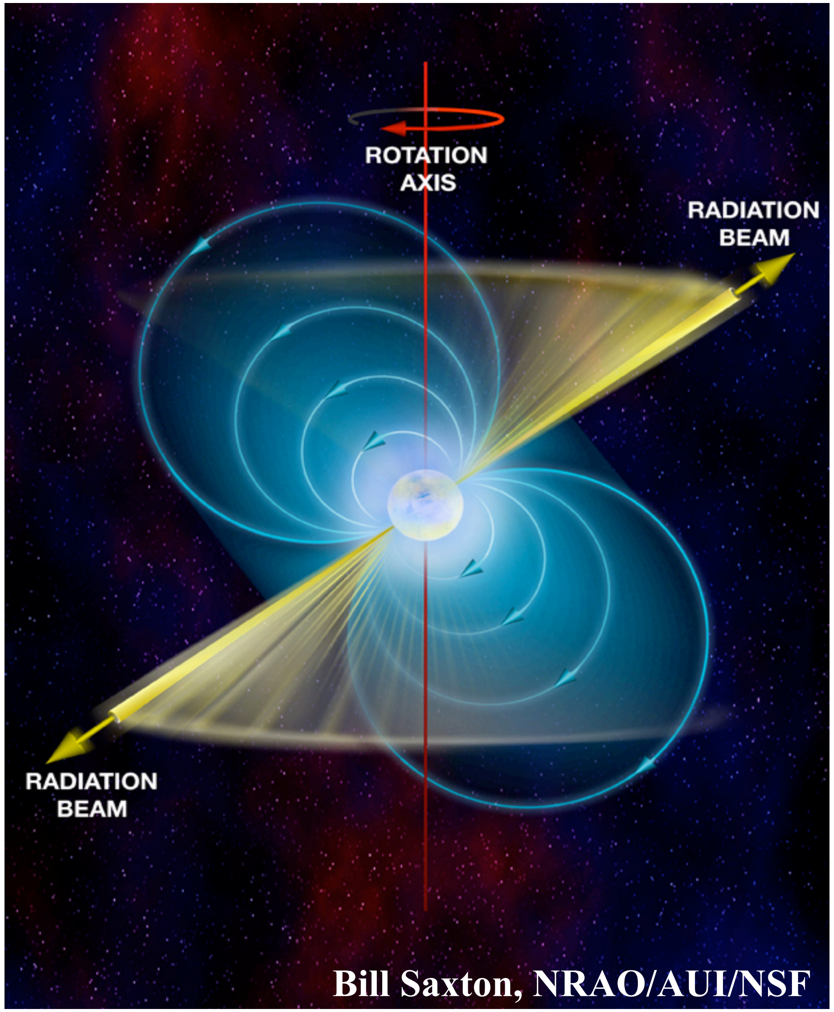
FERMI
The ~~ATIC~~ excess



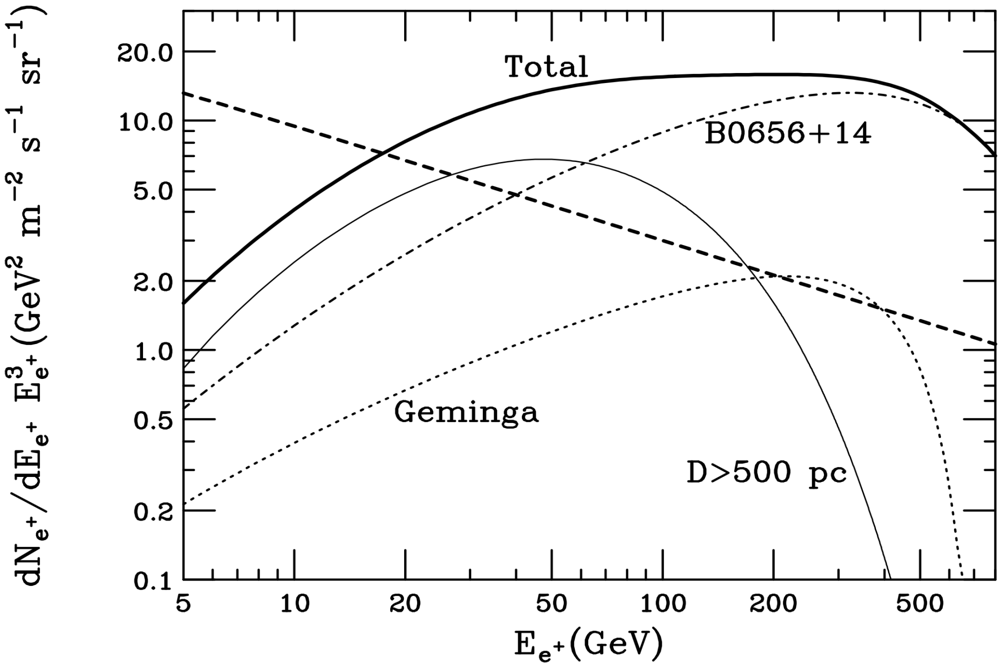
Nearby pulsars as source of $e^{\pm}$

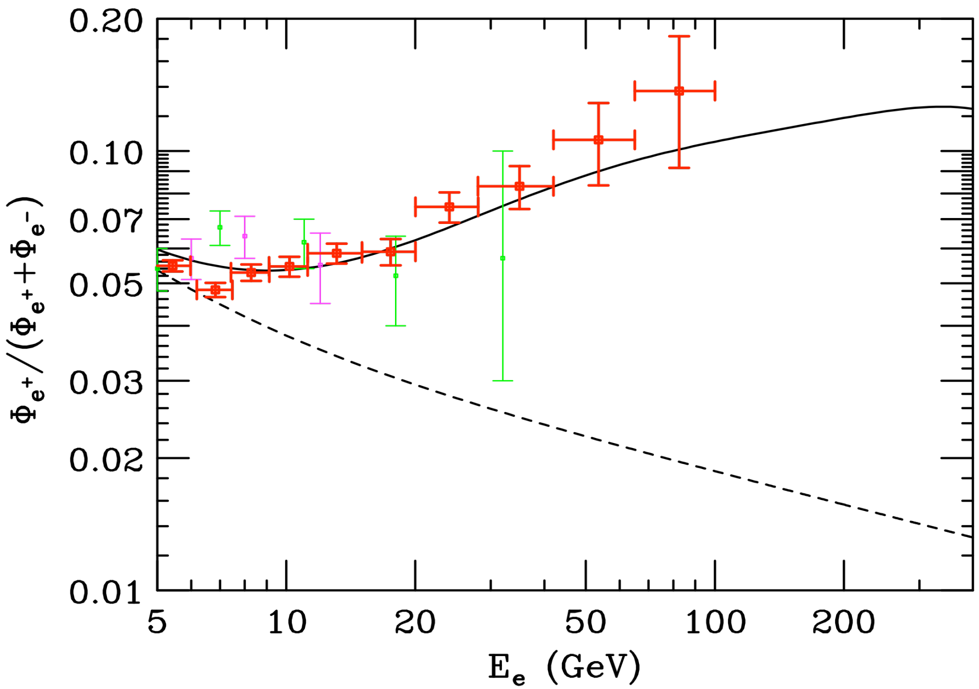
- Highly magnetized, fast spinning neutron stars
- γ-rays and electron/positron pairs produced along the magnetic axis
- Spectrum expected to be harder than background from propagation, *viz.*

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



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





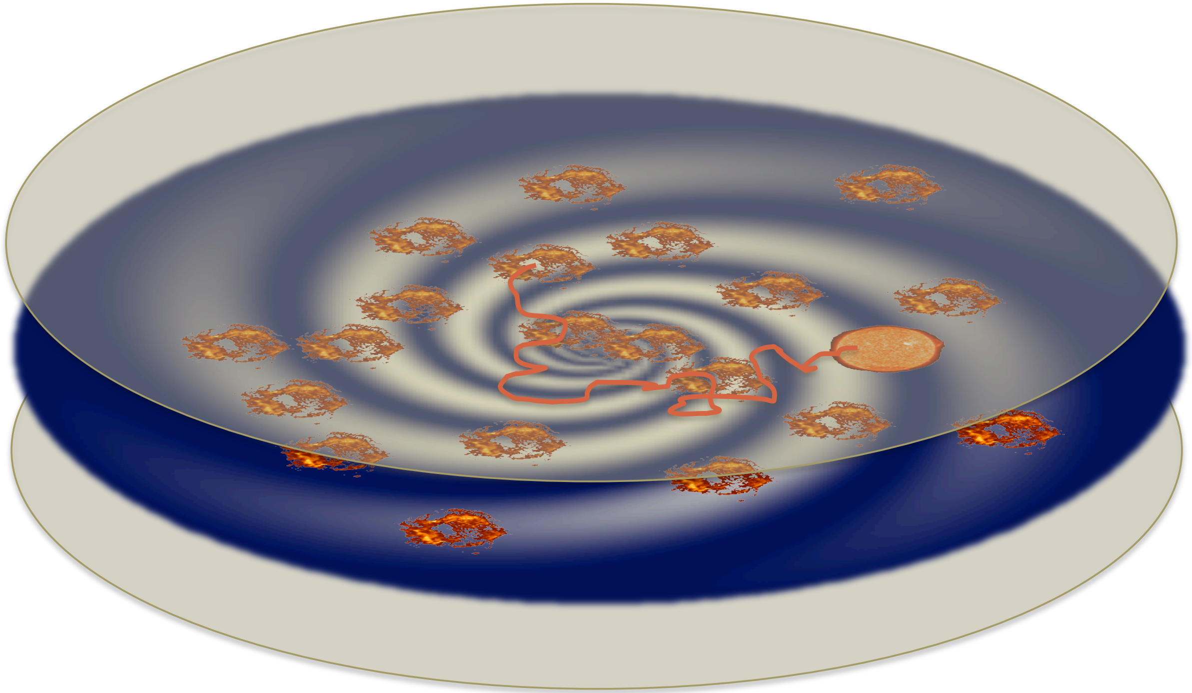
Hooper, Blasi & Serpico, JCAP 0901:025,2009

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

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

The standard model for Galactic cosmic rays

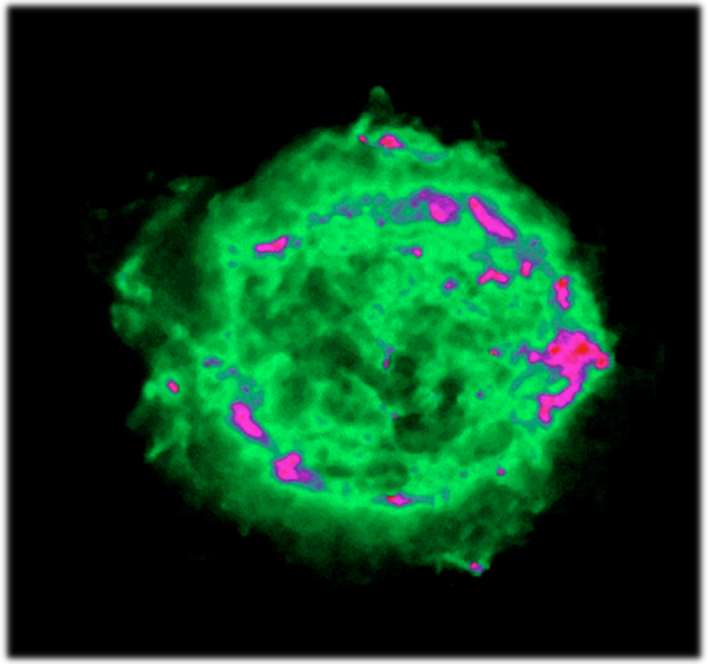
1. SNR shock waves accelerate relativistic particles
2. !st-order Fermi mechanism ➔ power law spectrum
3. Diffusion through magnetic fields in Galaxy
4. Secondary production during propagation: $e^{\pm}, \gamma, \nu, \mathrm{N}$ etc.
5. $e^{\pm}$ lose energy through synchrotron and inverse Compton scattering

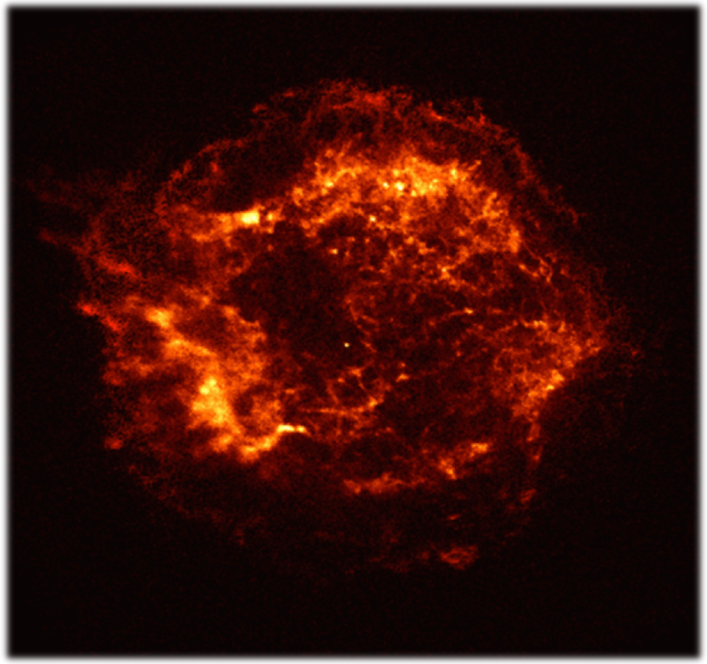


primaries: p, e^{-}, N
secondaries: $\bar{p}, e^{+}, N'$
synchrotron radio/X-ray + γ-ray

Why supernova remnants?

1. Strong shock waves → Diffusive Shock Acceleration
2. Observation of high energy synchrotron radiation





For example radio and X-ray images of *Cassiopeia A* show that electrons are accelerated to energies up to ~50 TeV

Why Supernova Remnants?

3. 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) $4.6 \times 10^{49}\,\mathrm{erg}$

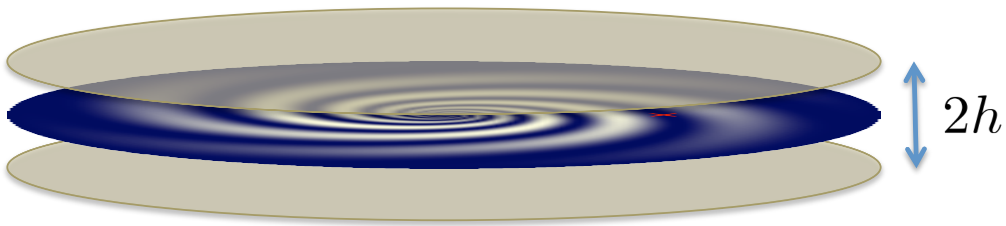
This is only a few % of the benchmark kinetic energy of 10^{51} erg produced in a SN explosion

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

GALPROP (Moskalenko & Strong 1998) solves the 3-D time-dependent transport equation and 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

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 from extended cosmic ray halo: $\tau_{\mathrm{esc}} \propto E^{-0.6}$ (empirical)

Energy loss through synchrotron radiation and
IC scattering on CMB and starlight: $\tau_{\mathrm{cool}} \propto E^{-1}$

Energy spectra

primary e^-

production: $q \propto E^{-2.2}$

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

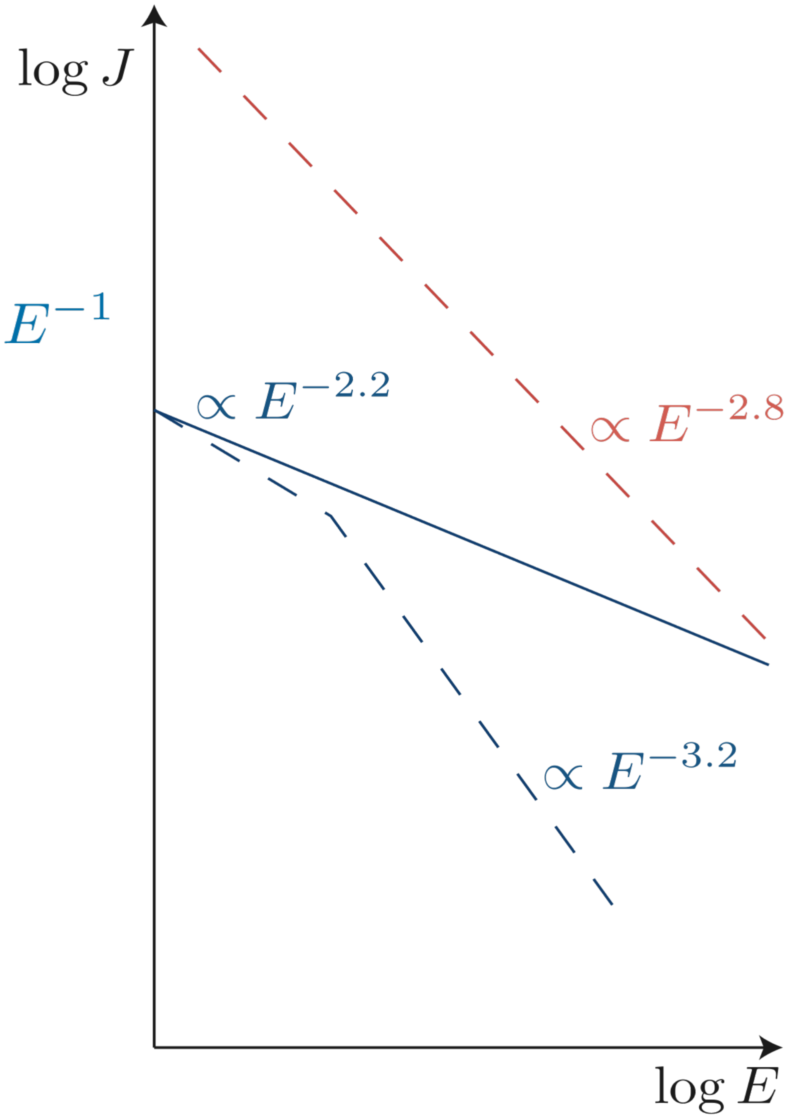
ambient: $n \propto E^{-2.8}, E^{-3.2}$

CR protons/nuclei

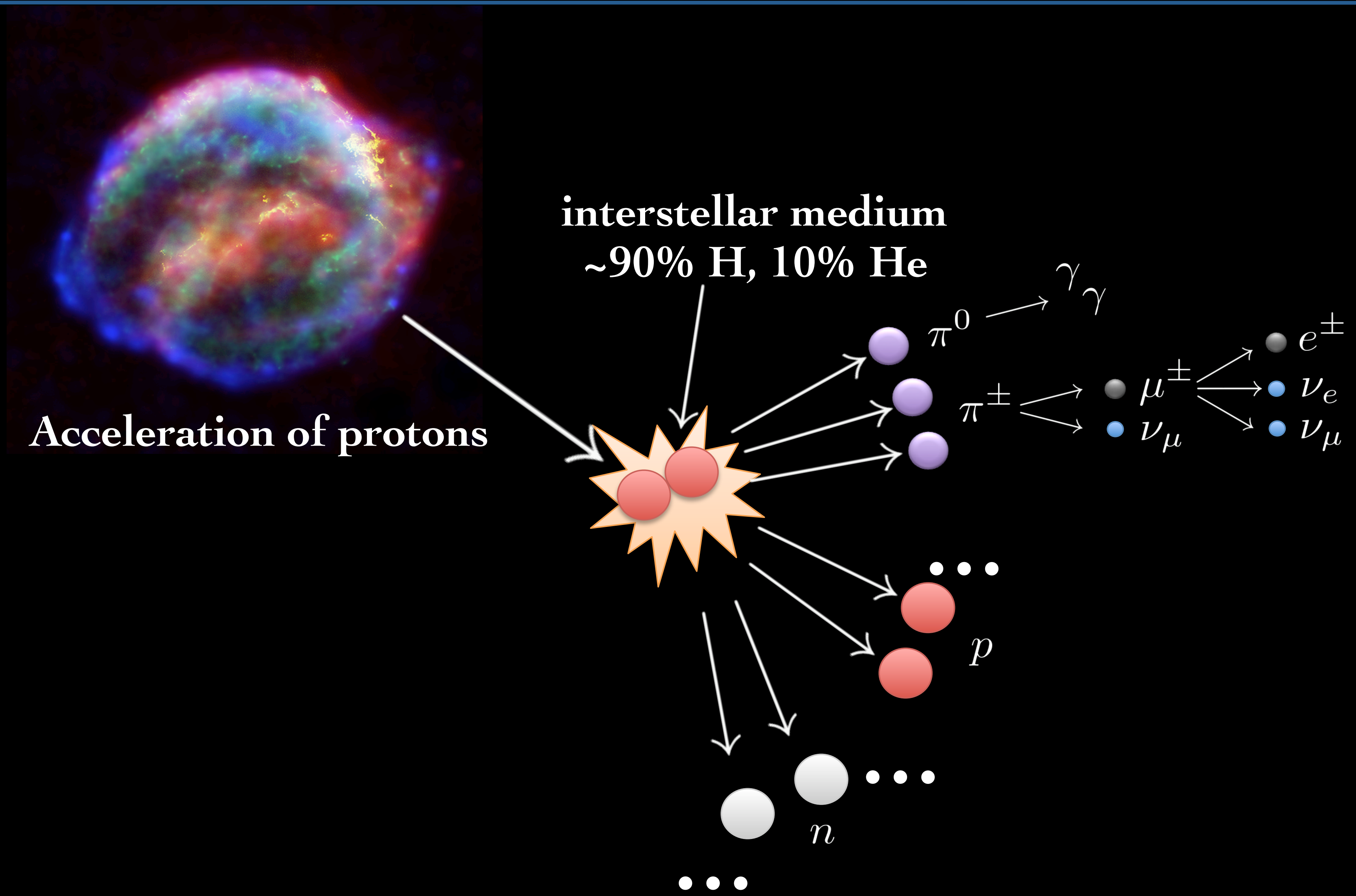
production: ?

propagation: ?

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



Secondary $e^{\pm}$ during propagation



Energy spectra

primary e^-

production: $q \propto E^{-2.2}$

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

CR protons/nuclei

production: ?

propagation: ?

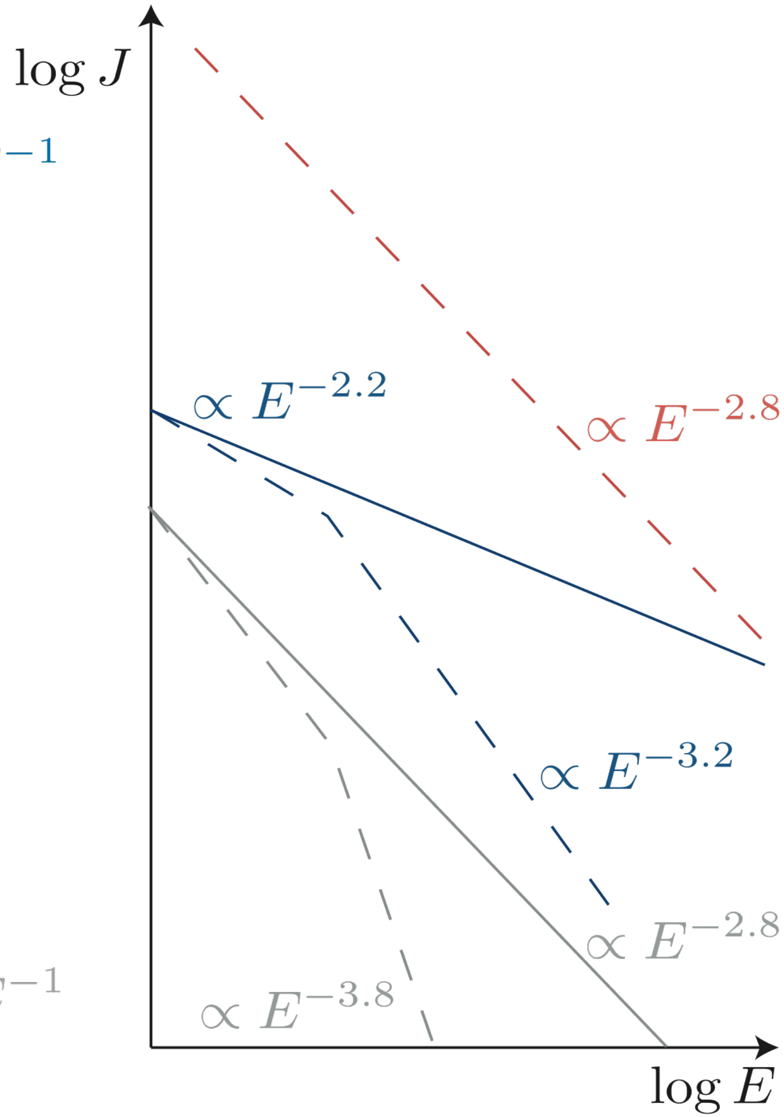
ambient: $n \propto E^{-2.8}$

secondary $e^{\pm}$

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

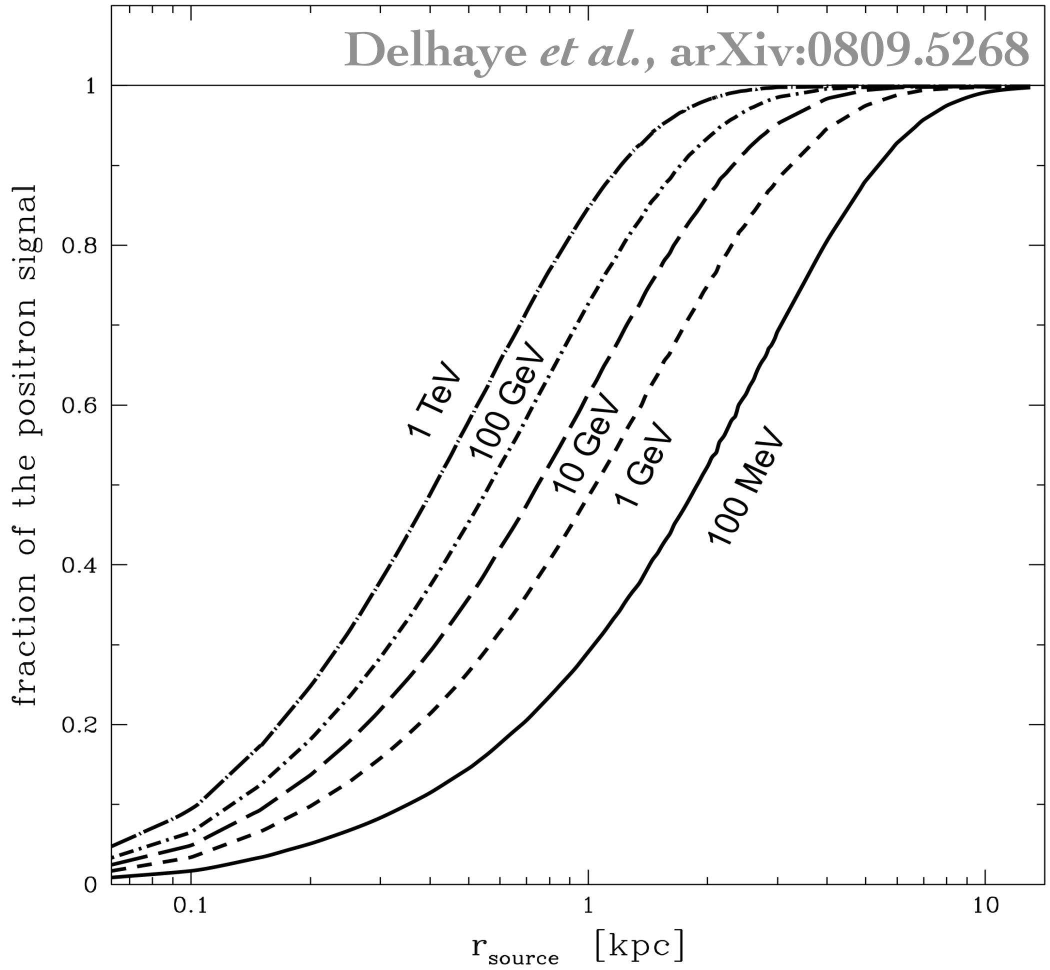
propagation: $\min[\tau_{\rm esc}, \tau_{\rm cool}] \propto E^{-0.6}, E^{-1}$

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



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

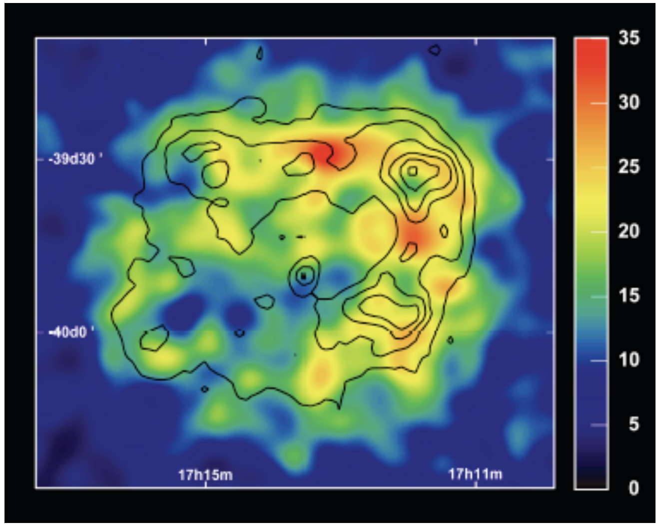
$$\tau \simeq 5 \cdot 10^5 \mathrm{yr} \left(\frac{1\,\mathrm{TeV}}{E} \right)$$



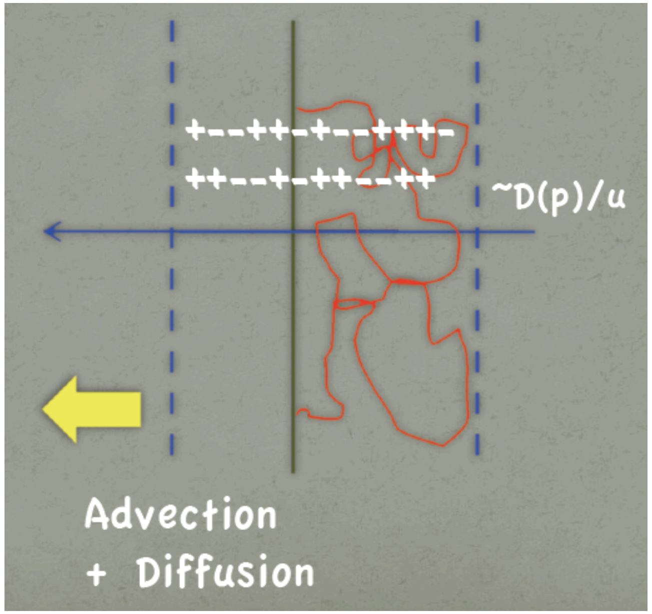
Nearby cosmic ray accelerator?

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 (see also Fujita, Kohri, Yamazaki & Ioka, PRD80:063003,2009)



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

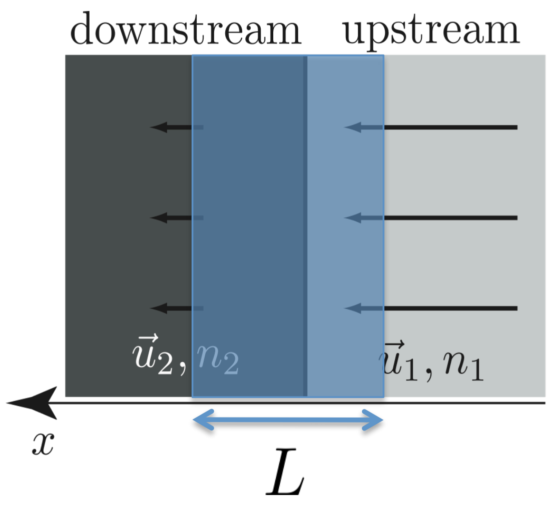


… assuming the sources of galactic cosmic rays are SNR, the **PAMELA** positron fraction can be well fitted (with just one free parameter – the diffusion rate near the shock wave)

Diffusive shock acceleration

Consider flux

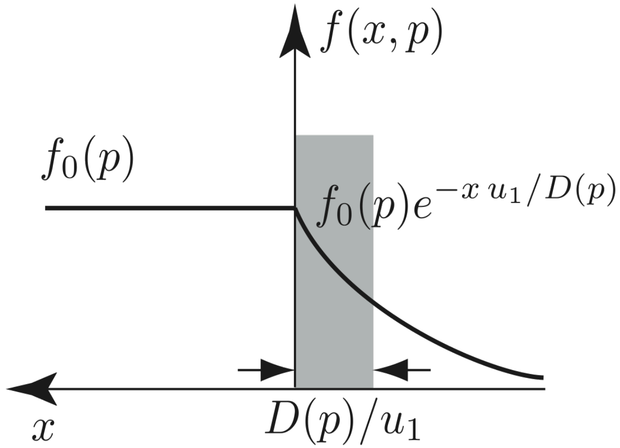
$$\Phi(p) = \int d^3x \, \frac{4\pi p^2}{3} f(p)(-\nabla \cdot \vec{u})$$



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:

$$q_{e^\pm} \propto f_{\mathrm{CR}} \propto p^{-\gamma}$$

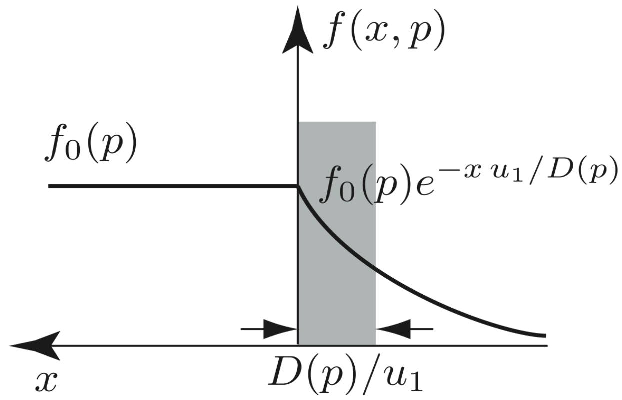
- Only particles with $|x| \lesssim D(p)/u$ can be accelerated

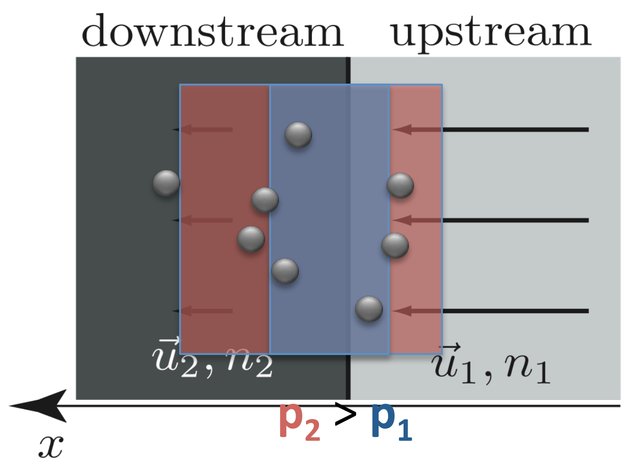
- Bohm diffusion: $D(p) \propto p$

- Fraction of secondaries that are accelerated 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

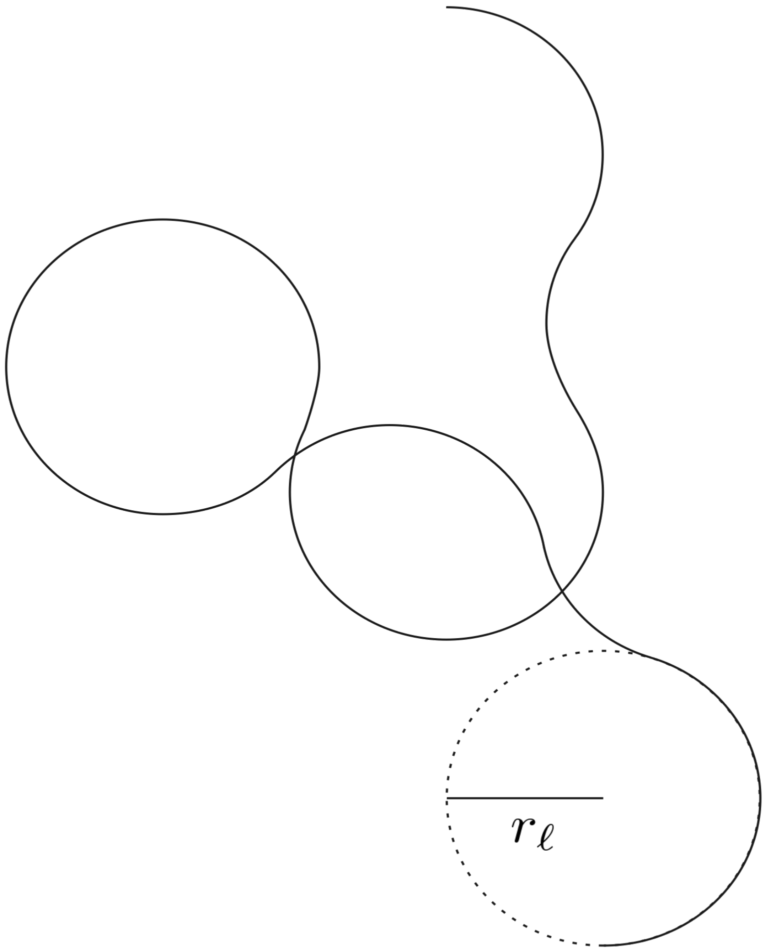
- Diffusion rate due to plasma turbulence not known *a priori*
- Bohm diffusion sets *lower* limit

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

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

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

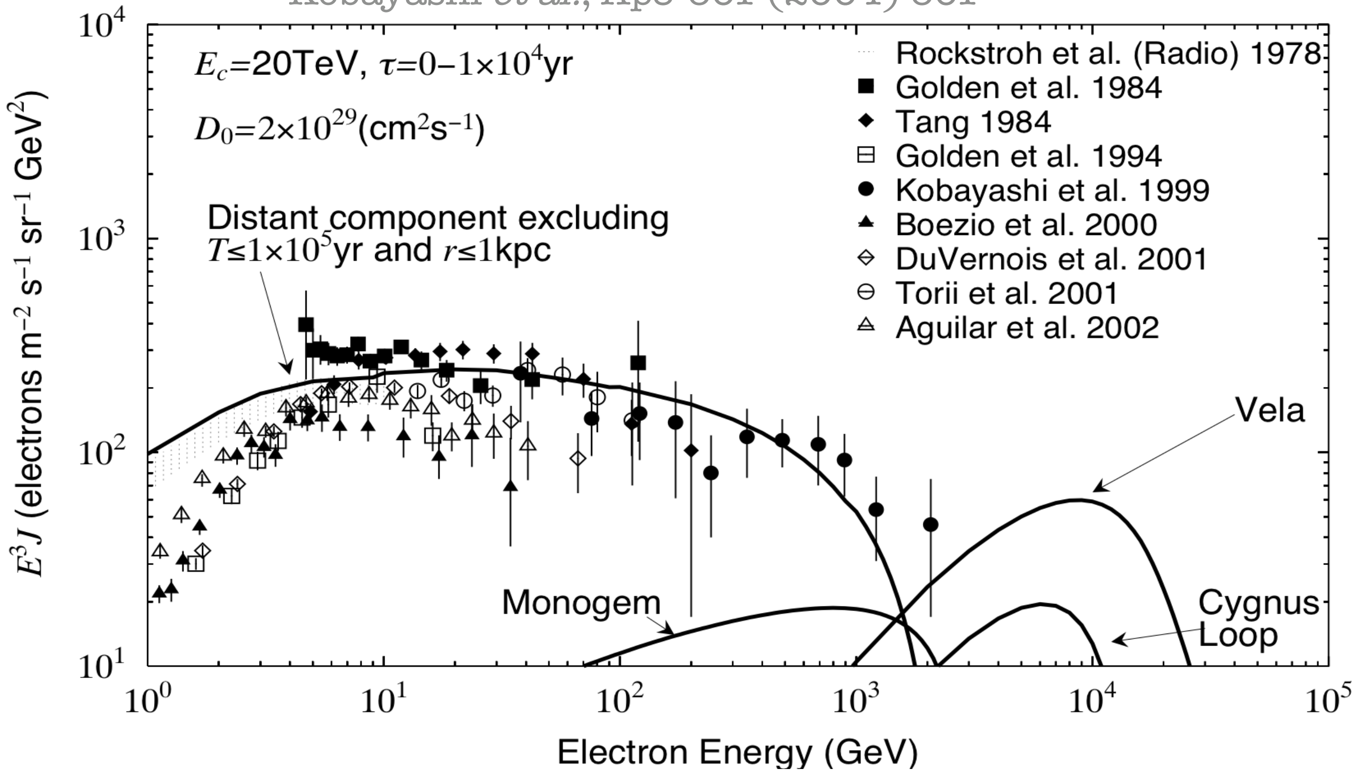
- $\mathcal{F}^{-1}$ determined by fitting to one measured secondary/primary ratio … allows prediction to be made for other ratios



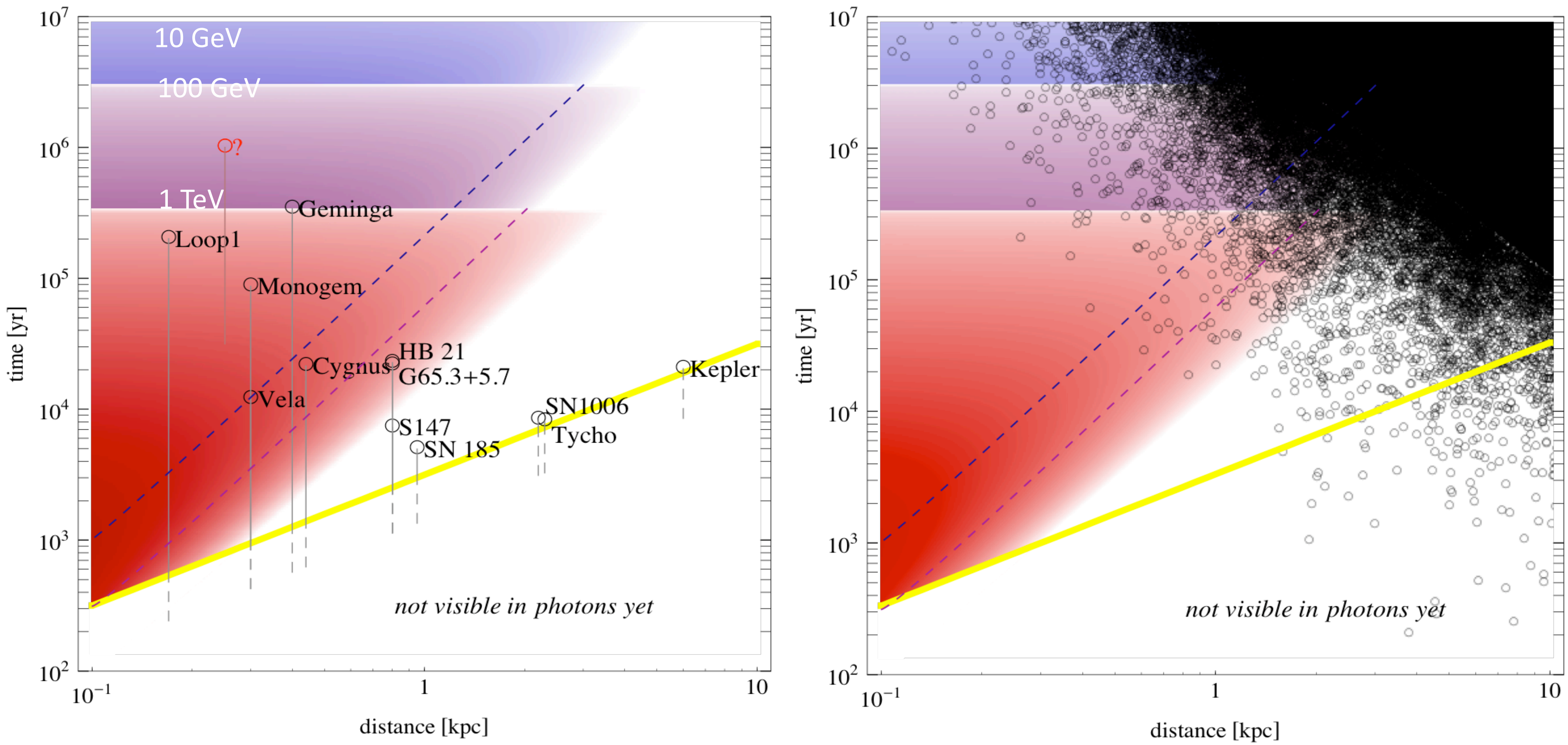
The effect of source discreteness

- Numerical codes like GALPROP are usually used to simulate a *continuous* source distribution
- However once the diffusion length is *shorter* than the average distance between sources, their discrete nature is important

Kobayashi *et al.*, ApJ 601 (2004) 601

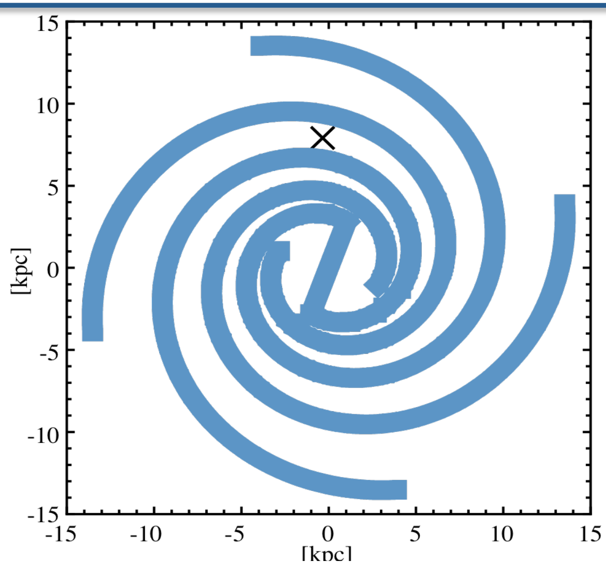


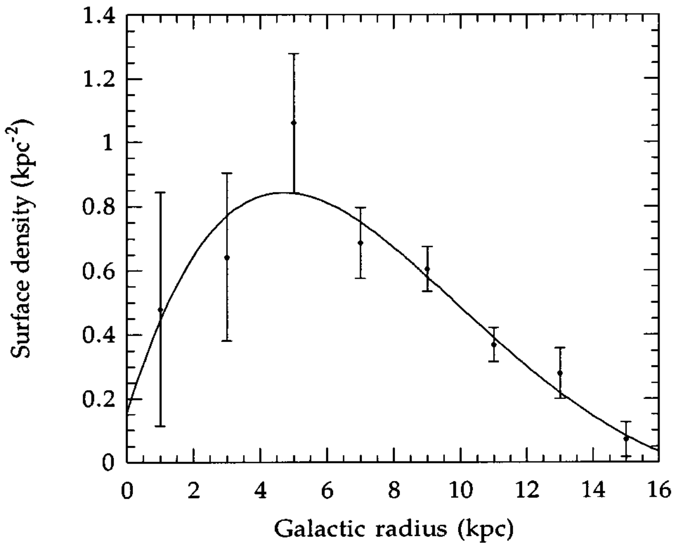
It is not just the (optically) observed SNRs which contribute … there must be many others hidden

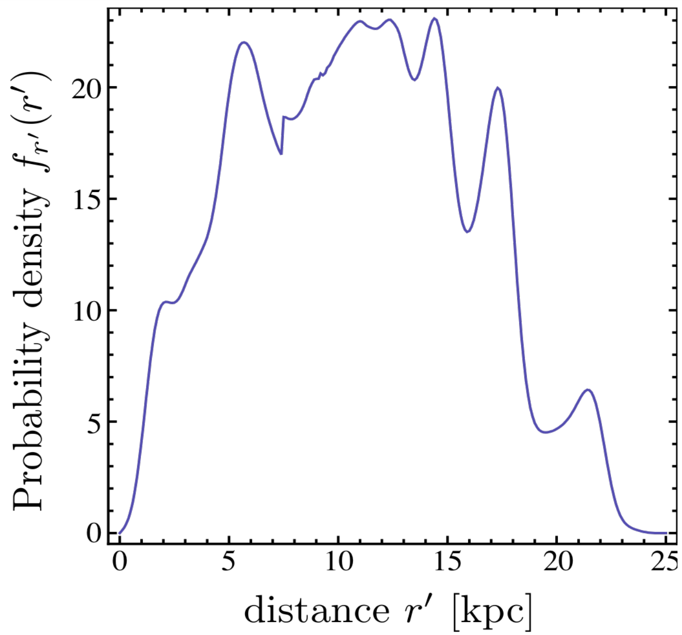


Ahlers, Mertsch & Sarkar, arXiv0909.4060

Statistical distribution of sources







<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

Case, Bhattacharya, ApJ 504 (1998) 761

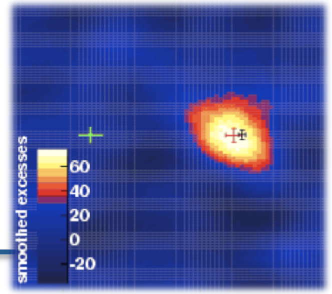
Ahlers, Mertsch & Sarkar, arXiv0909.4060

Parameters of the Monte Carlo

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

Ahlers, Mertsch & Sarkar, arXiv0909.4060

Normalising the source spectra



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

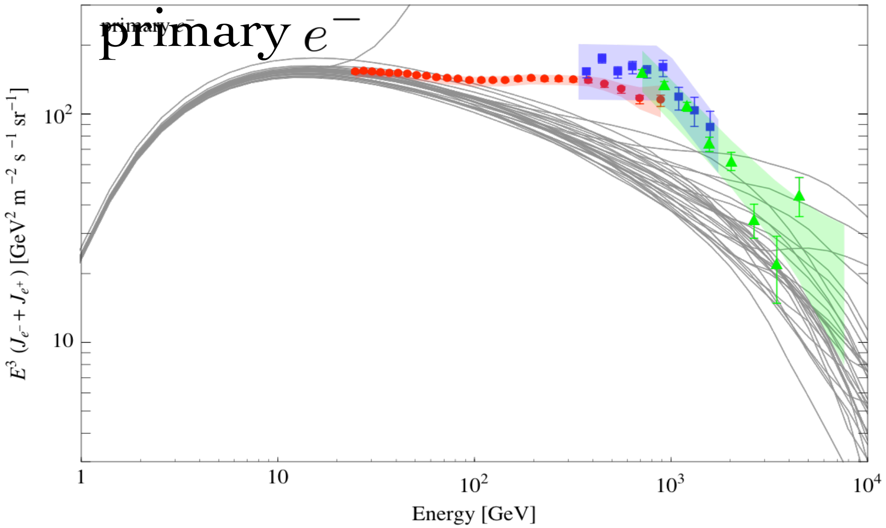
Normalisation of secondary $e^\pm$:

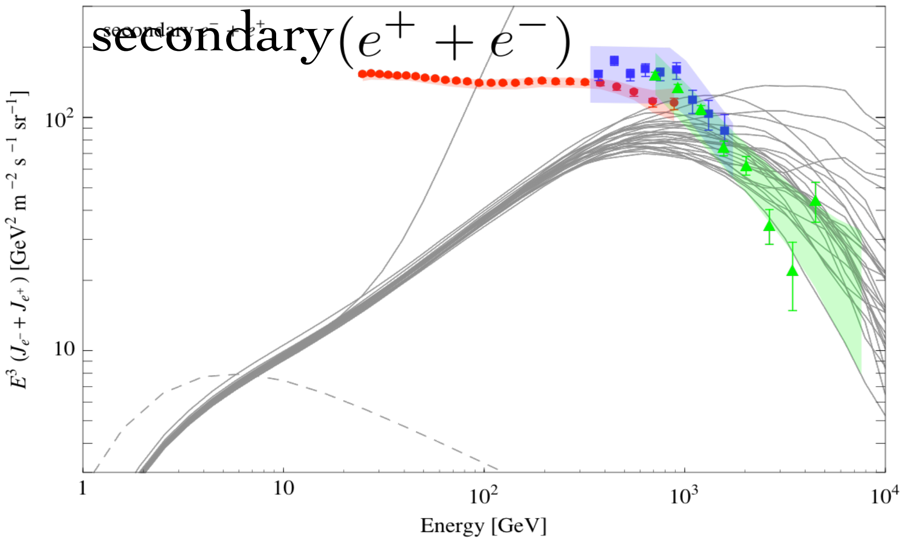
$$p + p \rightarrow \begin{cases} \pi^0 + \ldots & \rightarrow \quad 2\gamma + \ldots \\ \pi^\pm + \ldots & \rightarrow \quad e^\pm + \ldots \end{cases}$$

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

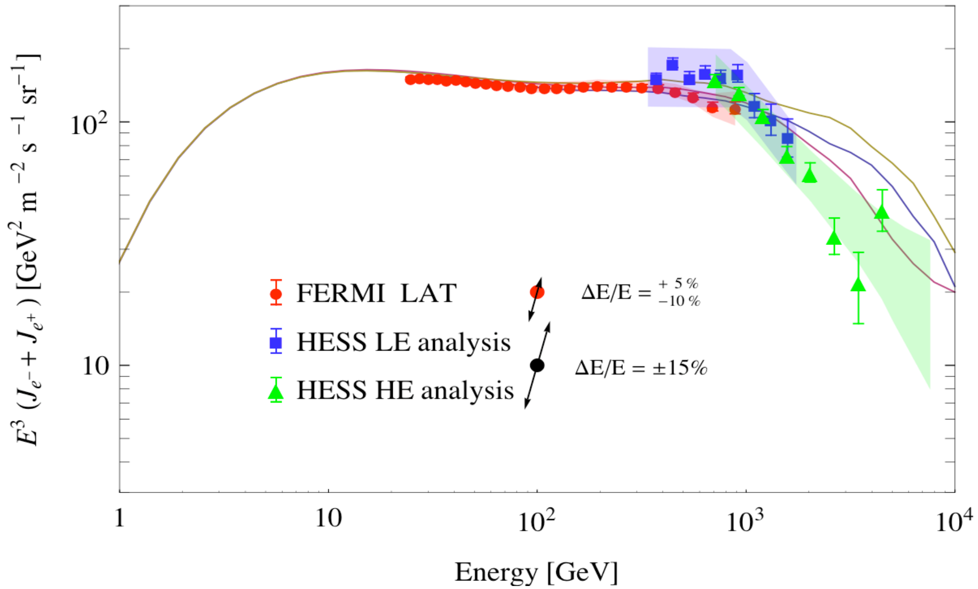
Ahlers, Mertsch & Sarkar, arXiv0909.4060

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



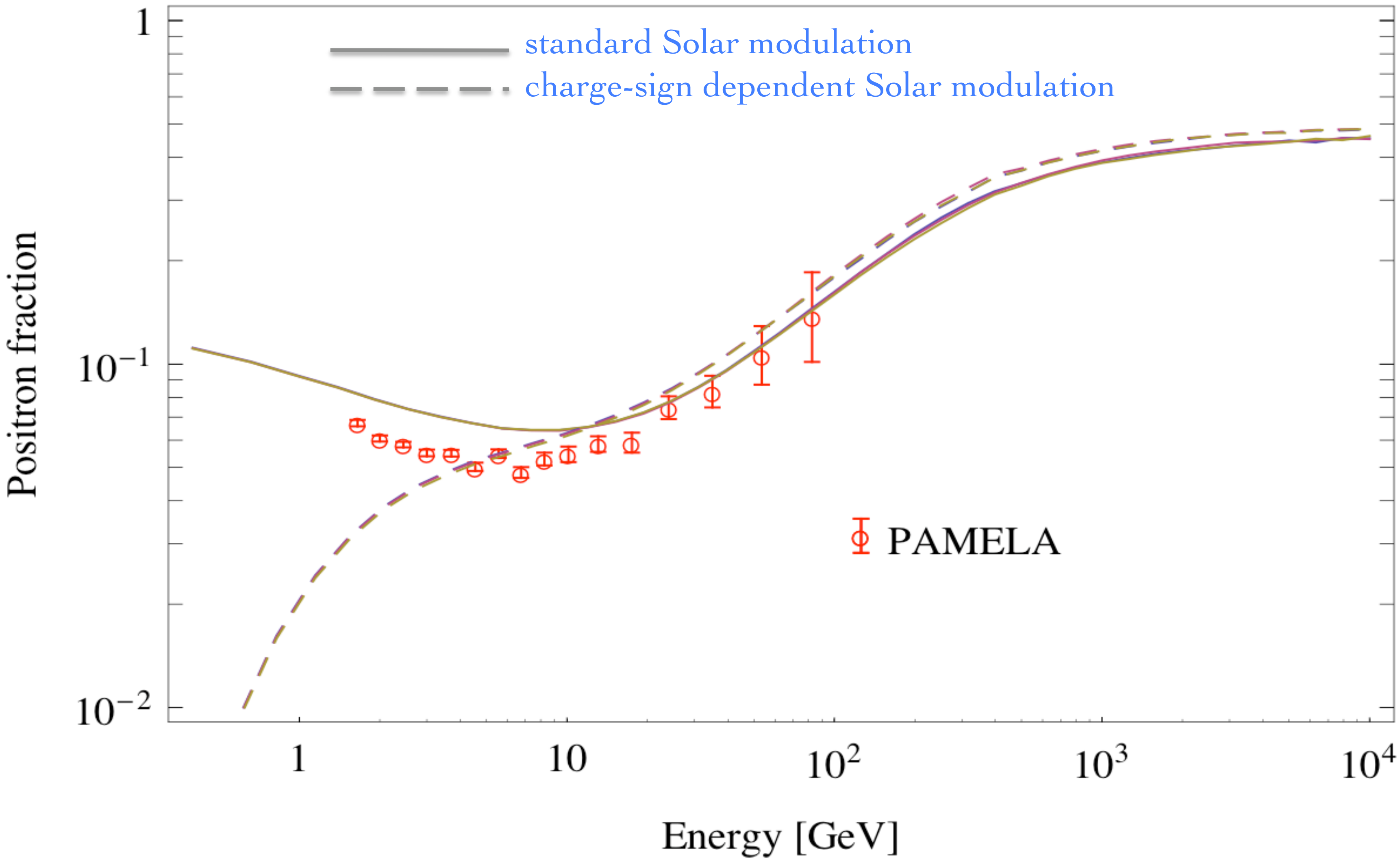


Total $(e^+ + e^-)$



Ahlers, Mertsch & Sarkar, arXiv0909.4060

The *predicted* positron fraction



Ahlers, Mertsch & Sarkar, arXiv0909.4060

Explanations for *PAMELA* excess

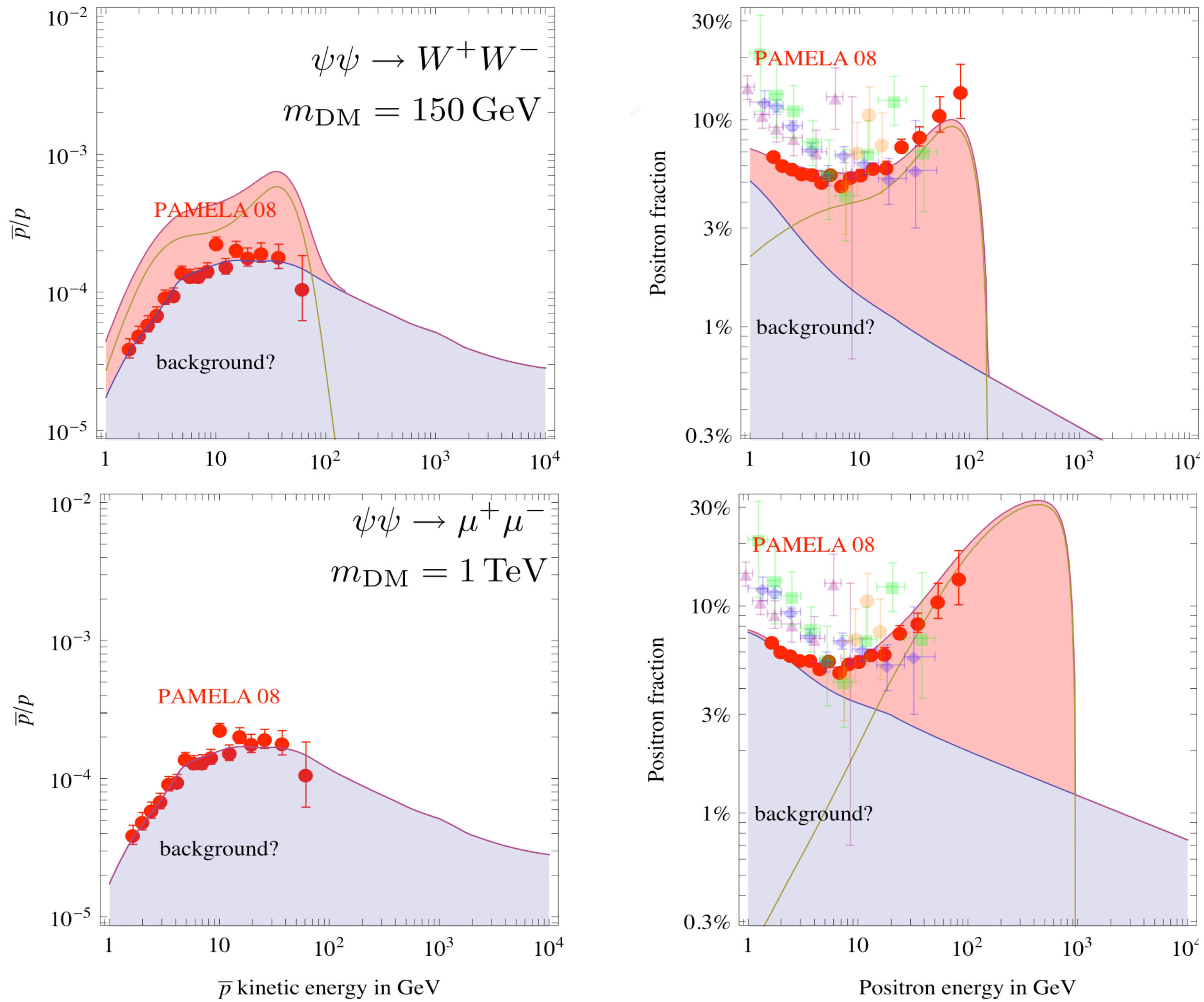
	e^+/e^-		
Dark matter	✓		
Pulsars	✓		
Acceleration of secondaries	✓		

Antiproton-to-proton Ratio

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

	$\bar{p}/p$
DM	(✓)
Pulsars	✗

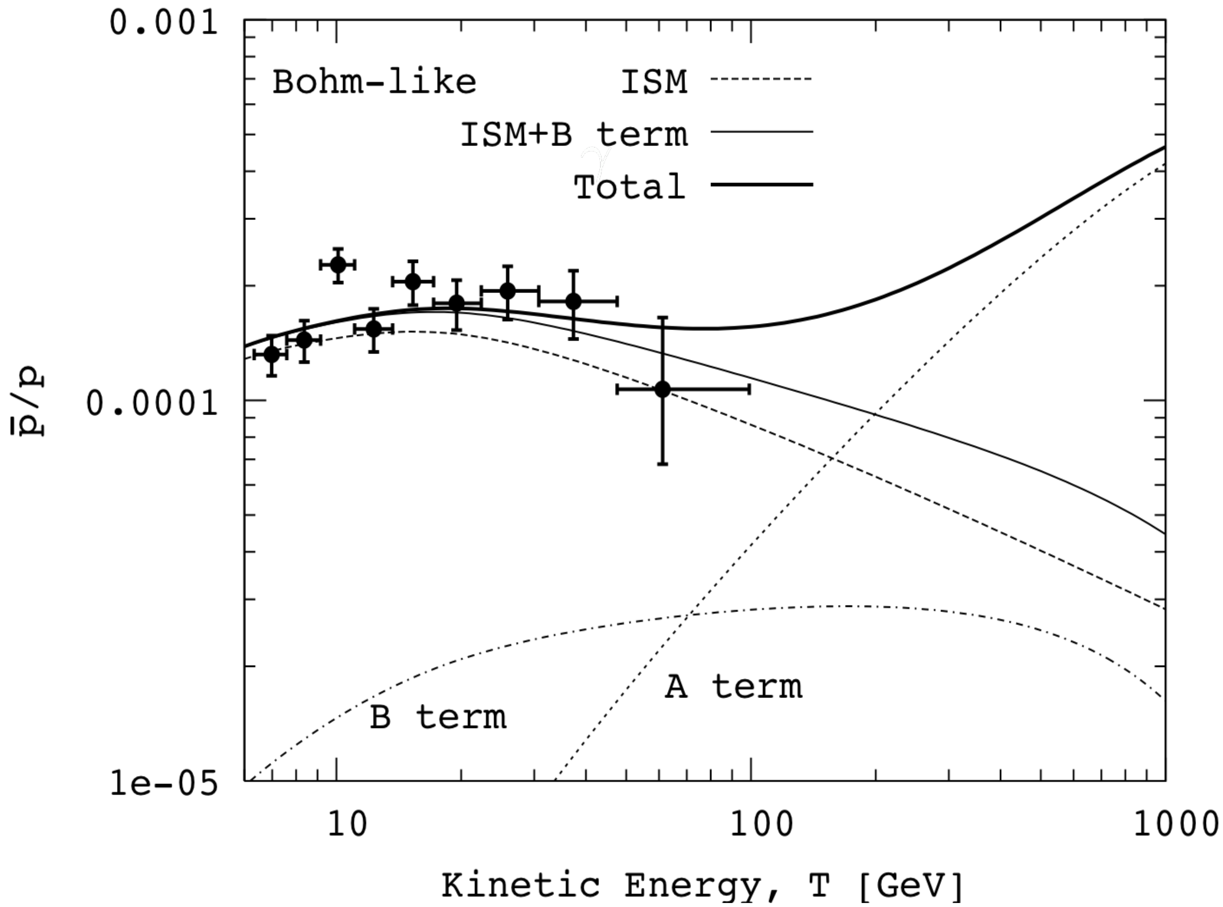
… can fit with annihilation model *only* if parameters are (fine-)tuned ➔ **'leptophilic' DM**



Antiproton-to-proton ratio

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

Blasi & Serpico, PRL 103:081103,2009



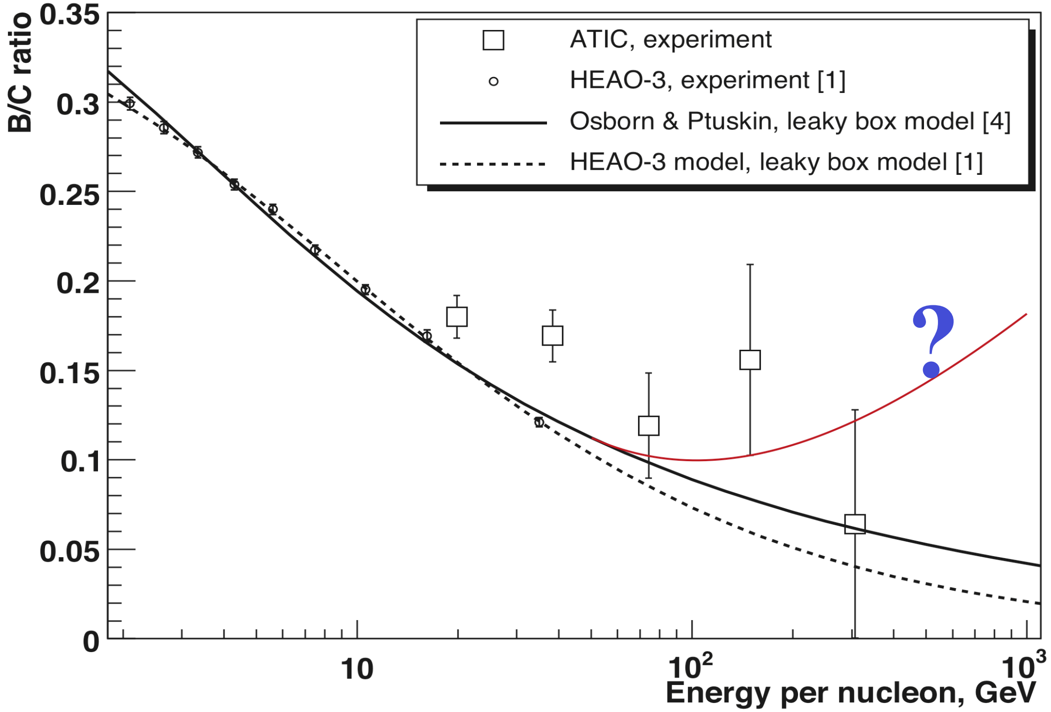
… much more natural in secondary acceleration model, which predicts rise *beyond* 100 GeV (will be tested by **AMS-02**)

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

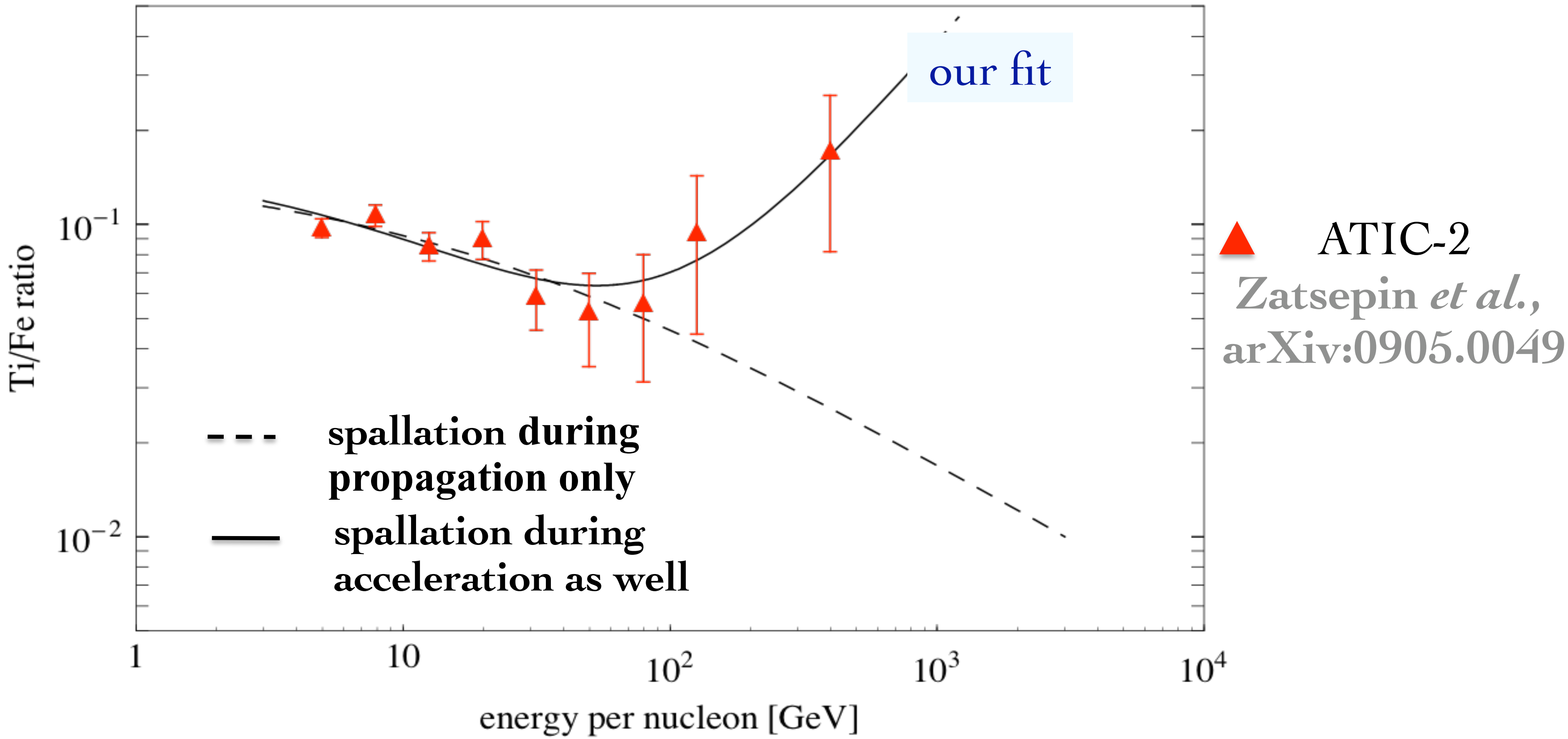
$$f_i^0(p) = \int_0^p \frac{\mathrm{d}p'}{p'}\left(\frac{p'}{p}\right)^\gamma \mathrm{e}^{-\gamma(1+r^2)(D_i^-(p)-D_i^-(p'))\Gamma_i^-/u_-^2}$$

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

$$\sim \text{``}q_i^-(p) + D_i^-(p)q_i^-(p)\text{''}$$

Mertsch & Sarkar, PRL 103:081104,2009

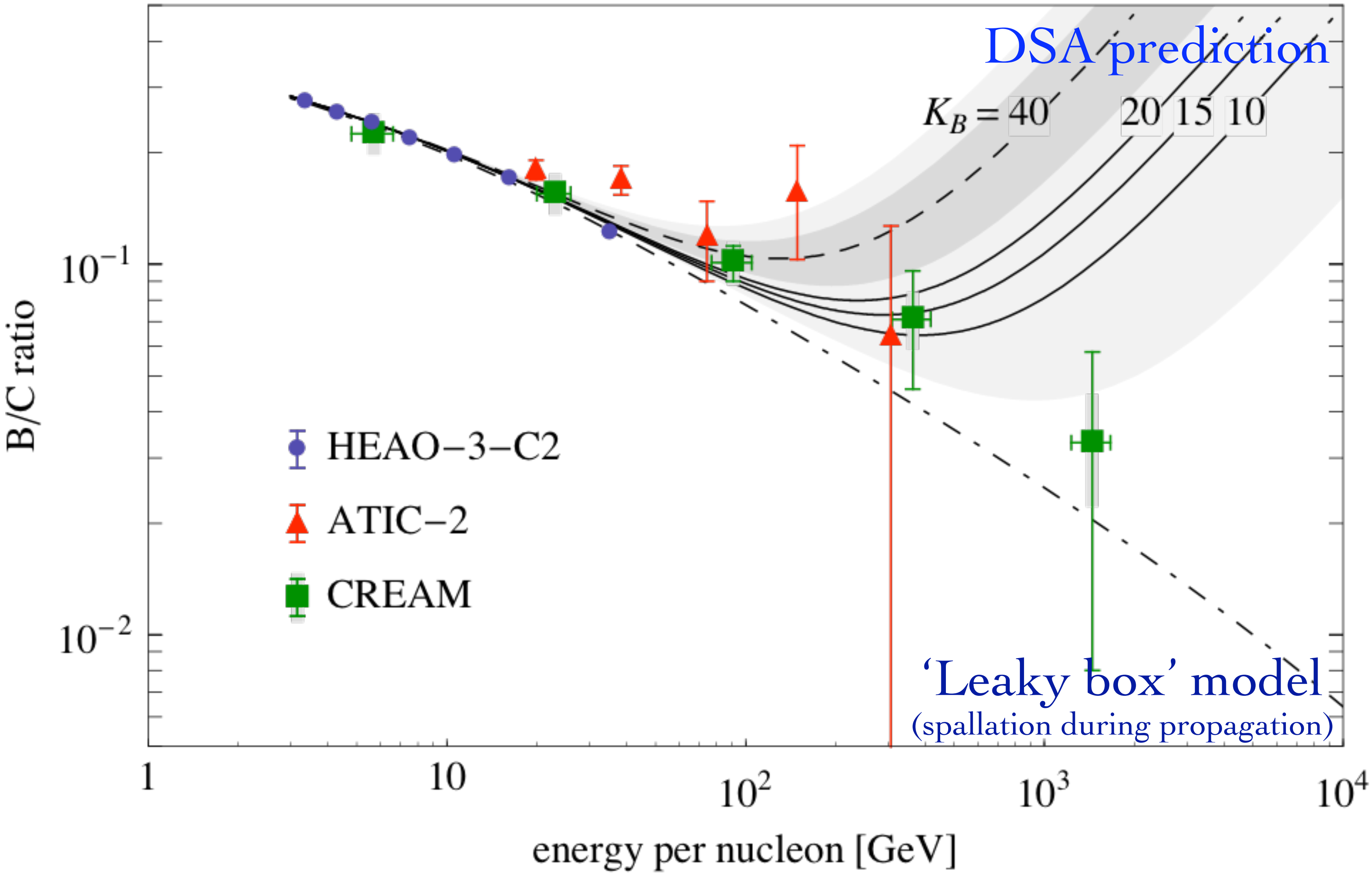
Titanium-to-Iron Ratio



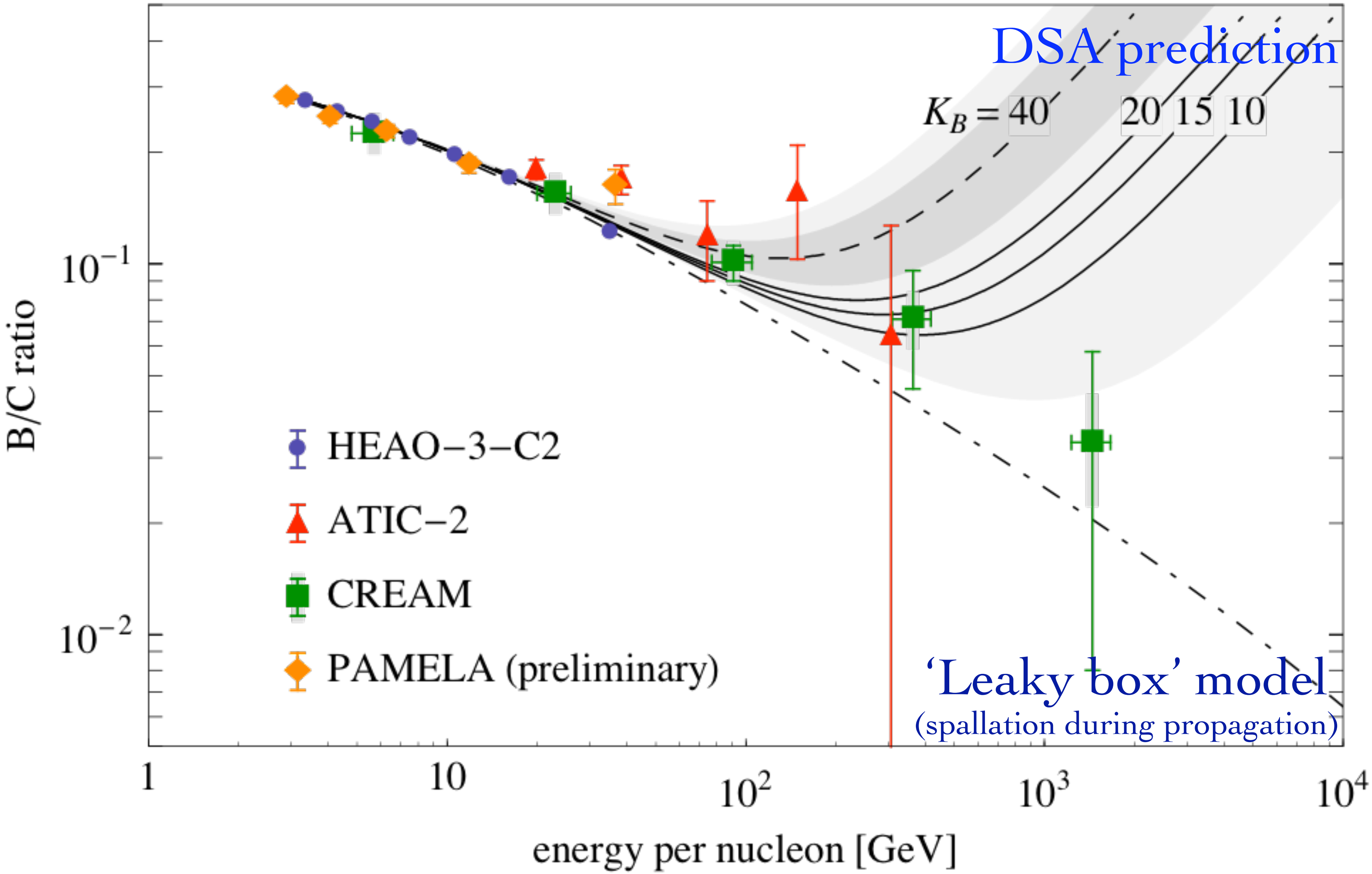
Titanium-to-iron ratio used to fix diffusion coefficient to be $\mathcal{F}^{-1} \simeq 40$ (NB: to fit e^+excess requires ~20)

Mertsch & Sarkar, PRL 103:081104,2009

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



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

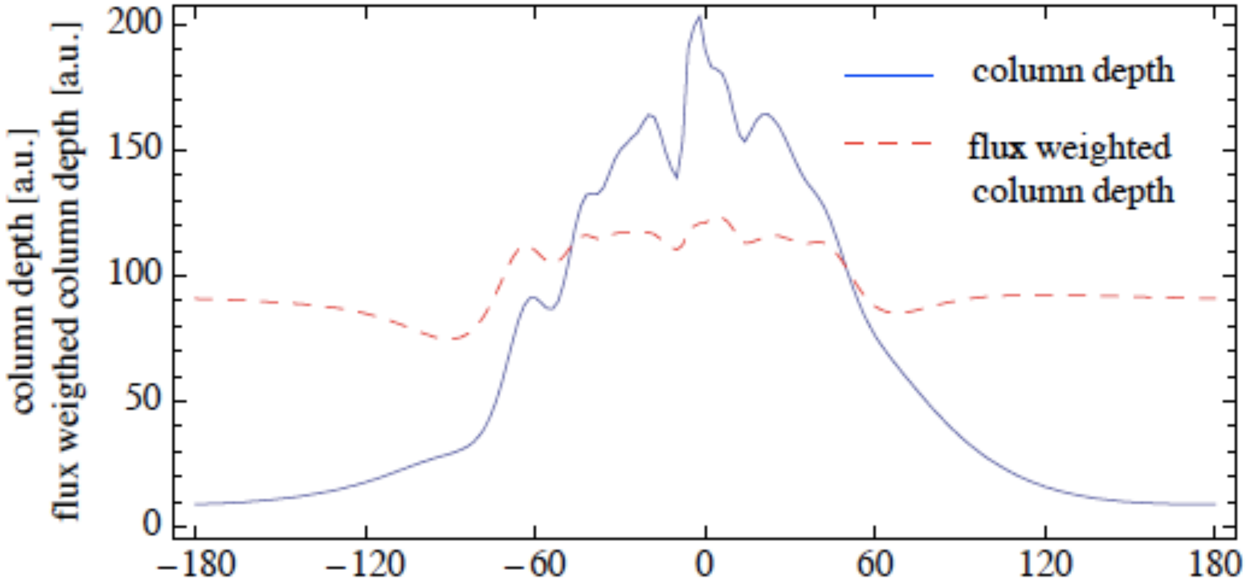


PAMELA is currently measuring B/C with unprecedented accuracy
… a *rise* would establish the nearby hadronic accelerator model

Explanations for **PAMELA** anomaly

	e^+/e^-	$\bar{p}/p$	nuclei
DM	✓	✓	✗
Pulsars	✓	✗	✗
Acceleration of Secondaries	✓	✓	✓

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

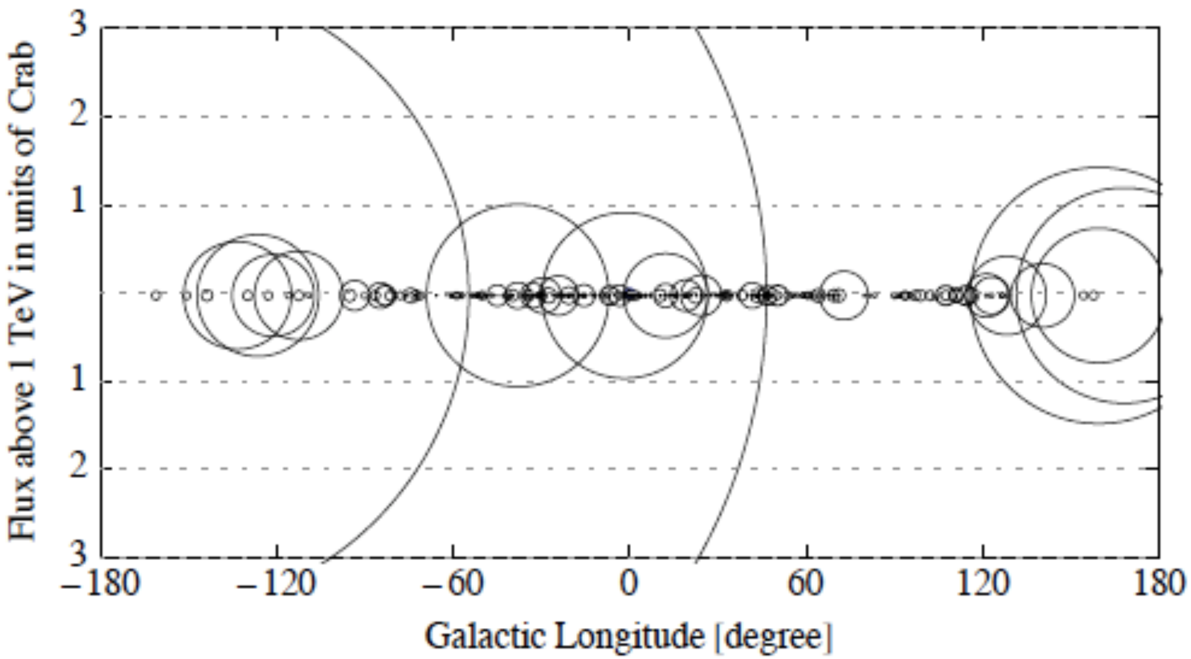


The column depth and flux weighted column depth of the SNR density in the Galactic plane

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

… 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, arXiv0909.4060

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 (PAMELA) etc will provide a resolution

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