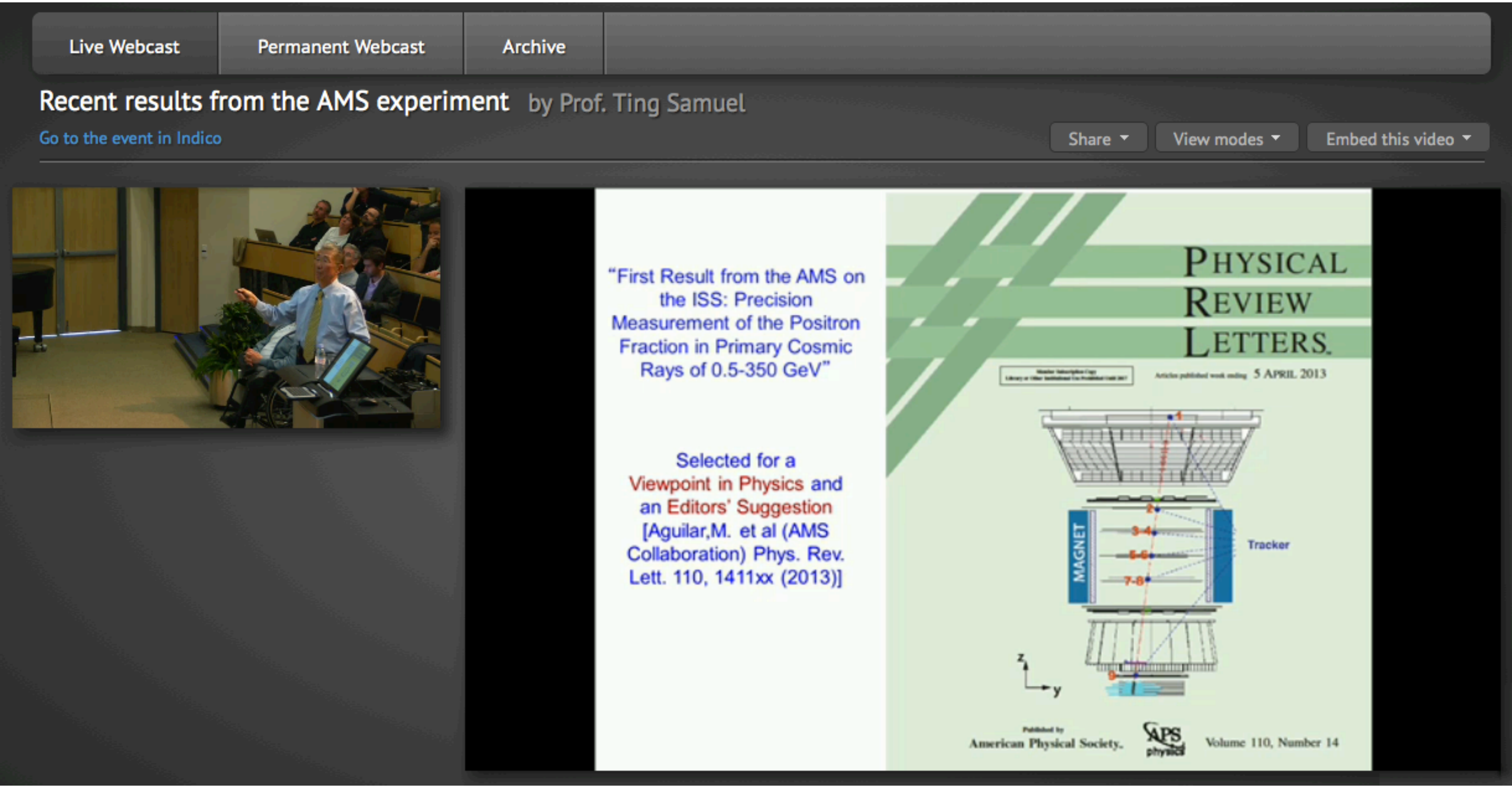
A hadronic explanation of the lepton anomaly

Philipp Mertsch
KIPAC, Stanford

CRA 2013, UW Wisconsin, Madison
27 September 2013

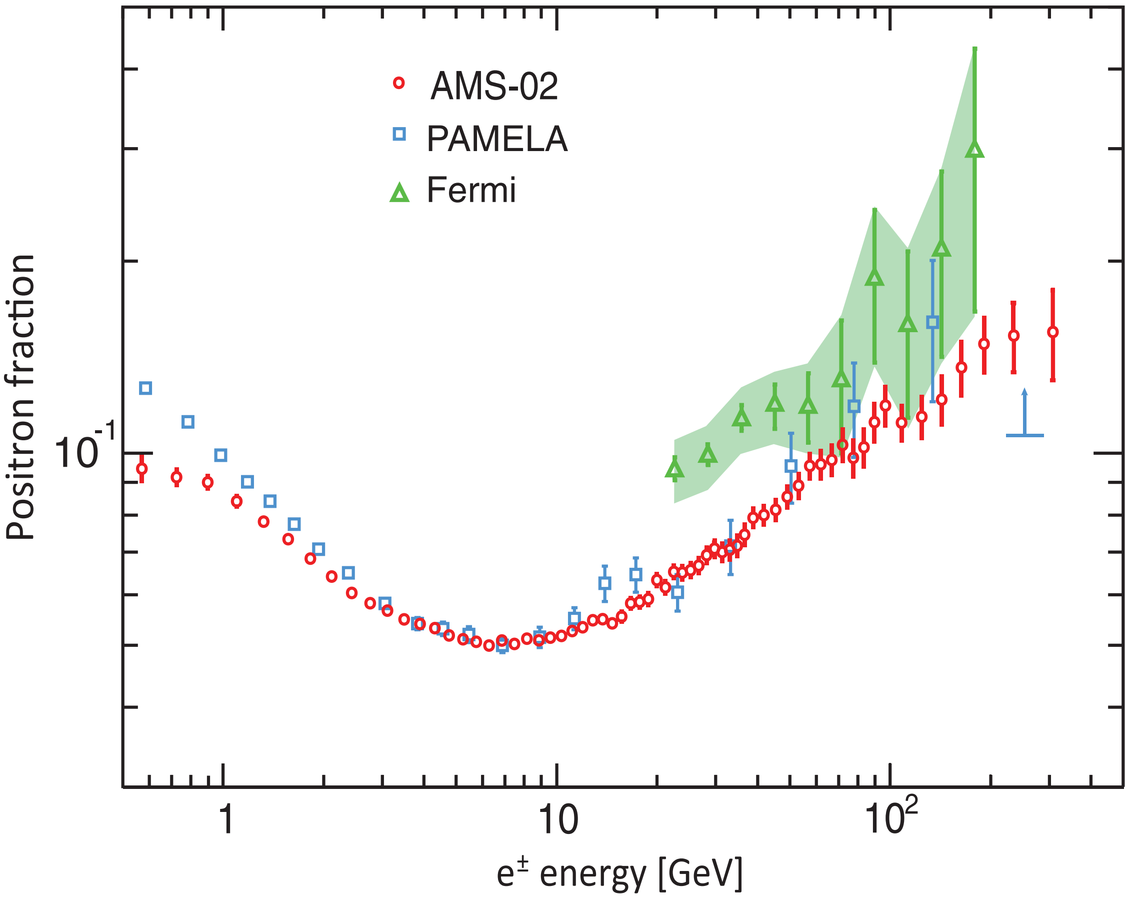
New AMS results



"There's no such thing as disappointing."

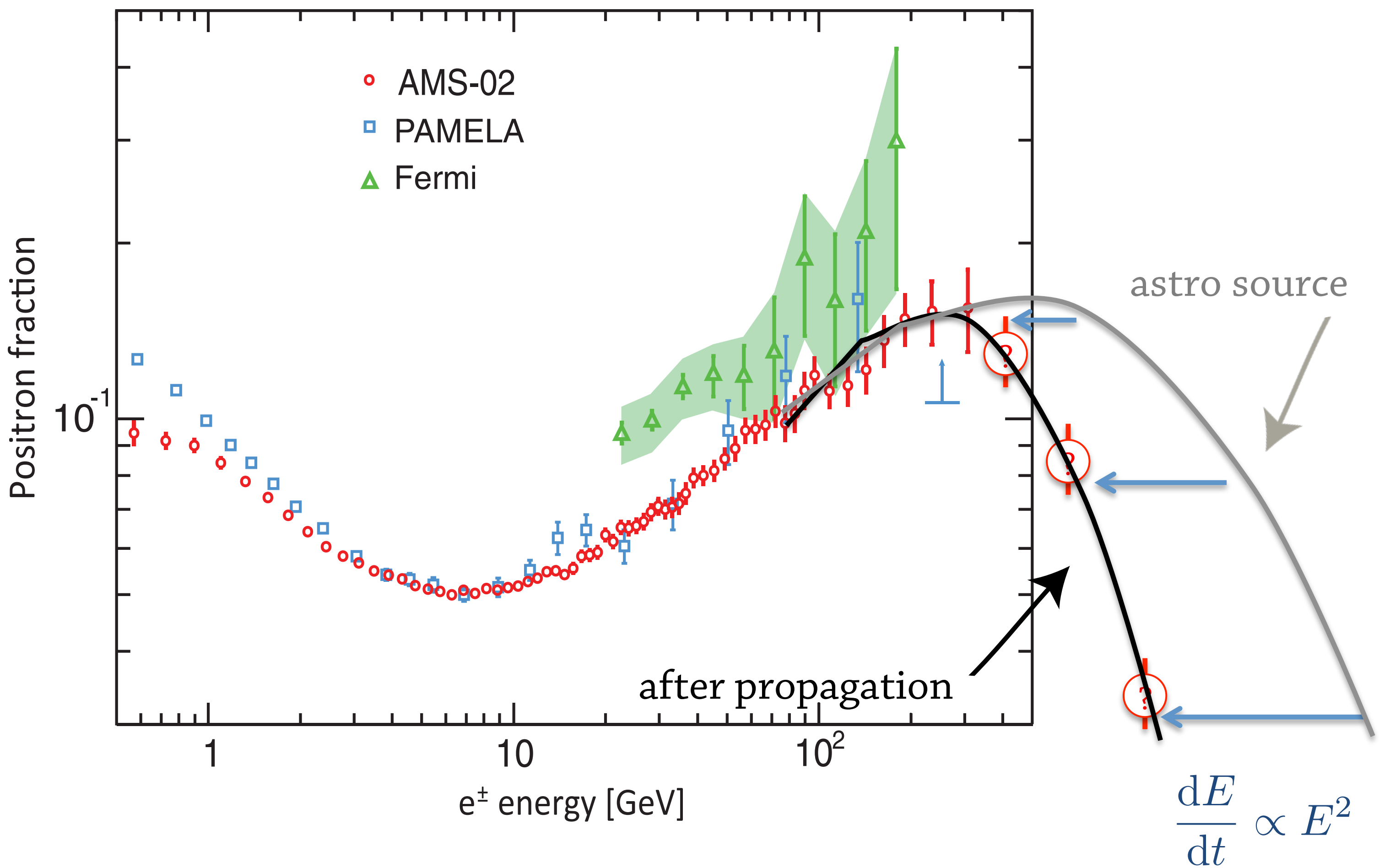
(Sam Ting)

New AMS results



“The positron fraction is turning over, so it must be dark matter.”

“It’s turning over, so it must be DM.”



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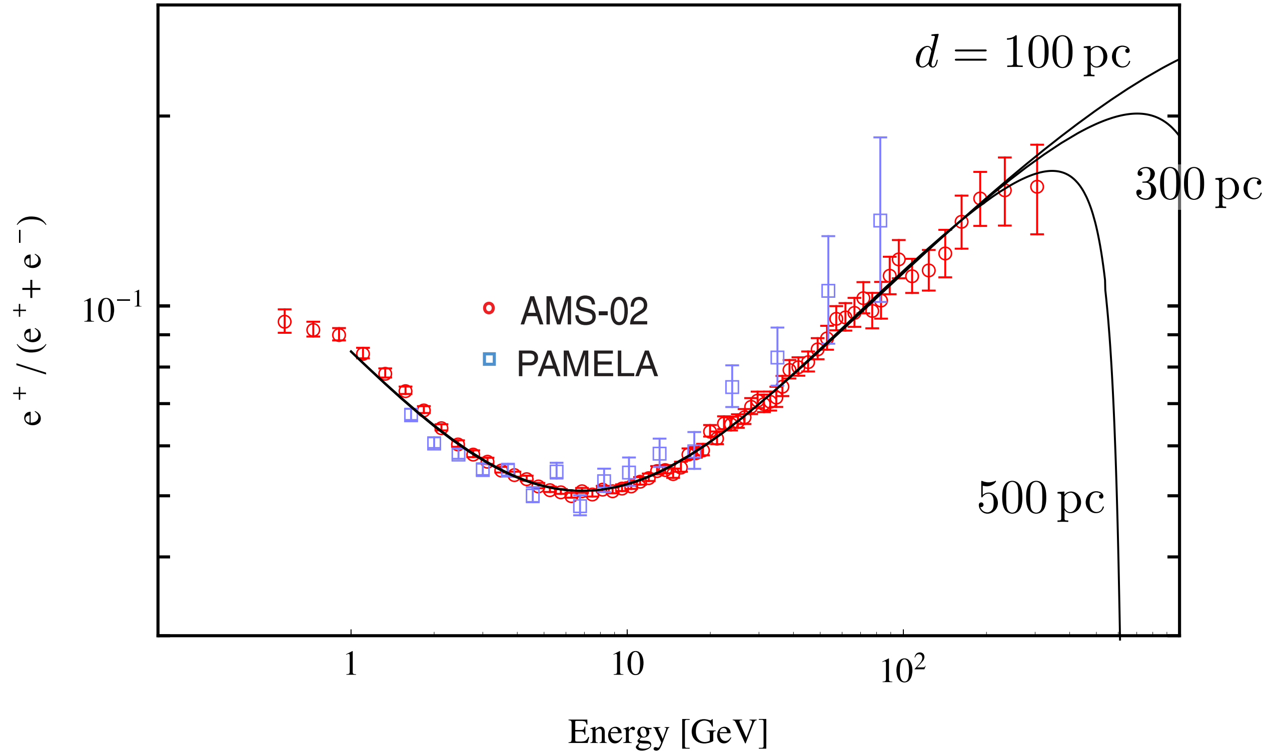
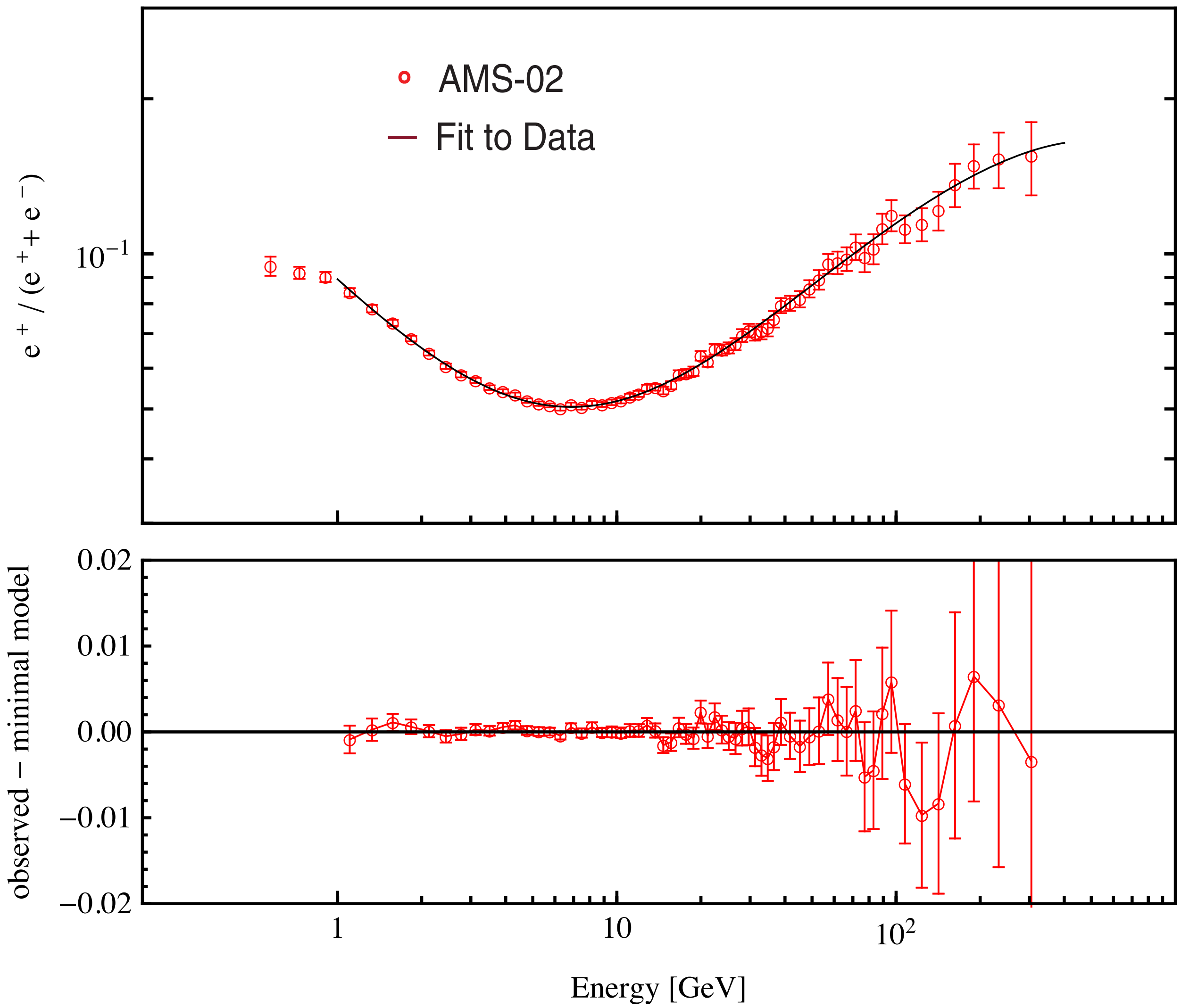


- power law spectrum with spectral index $\Gamma \sim 1.7$
- exponential cut-off at $3\,\mathrm{TeV}$
- impulsive injection $20,000 \ldots 500,000\,\mathrm{yr}$ ago

"The positron fraction has substructure, so it must be dark matter."

“There’s substructure, hence DM.”



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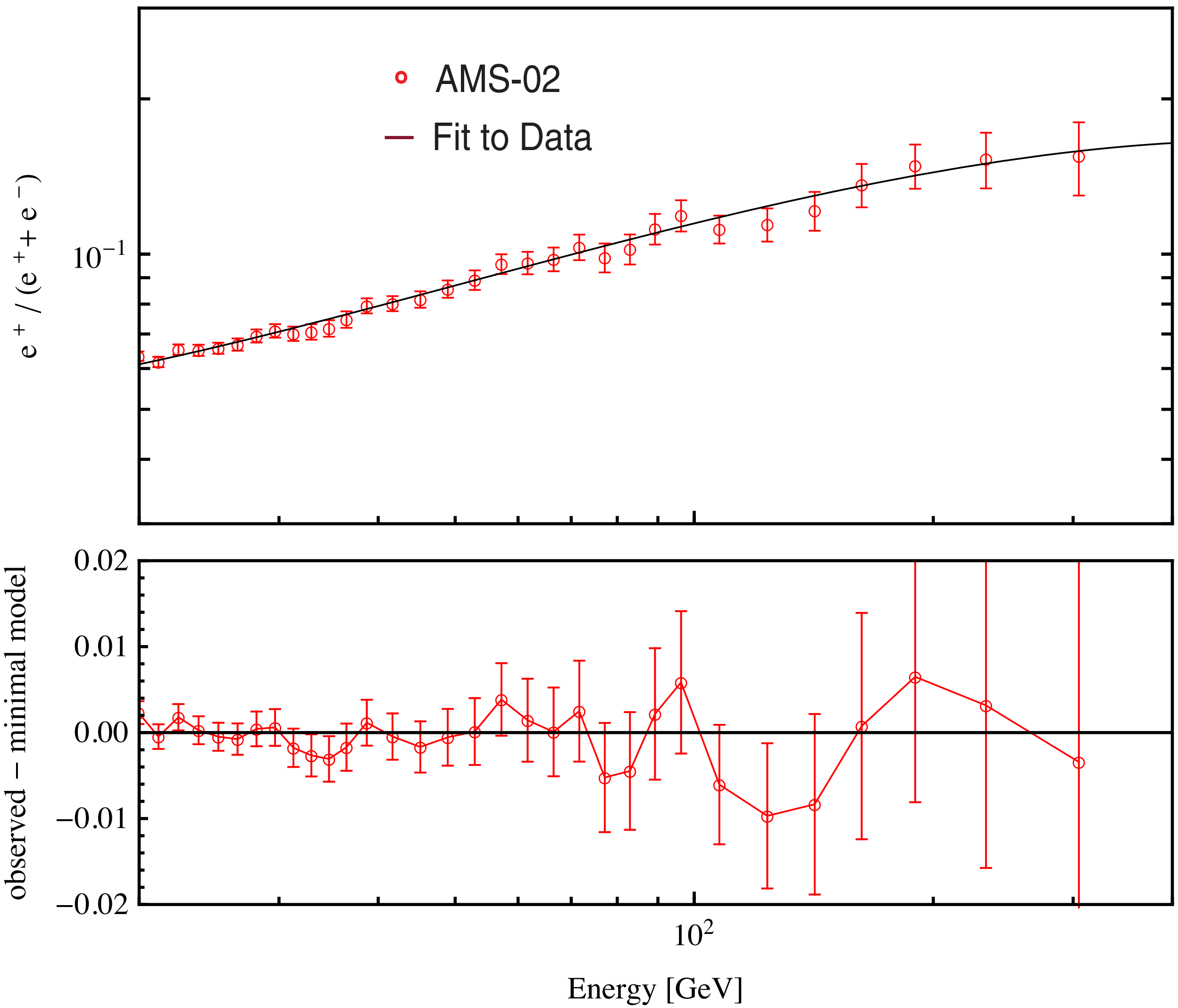

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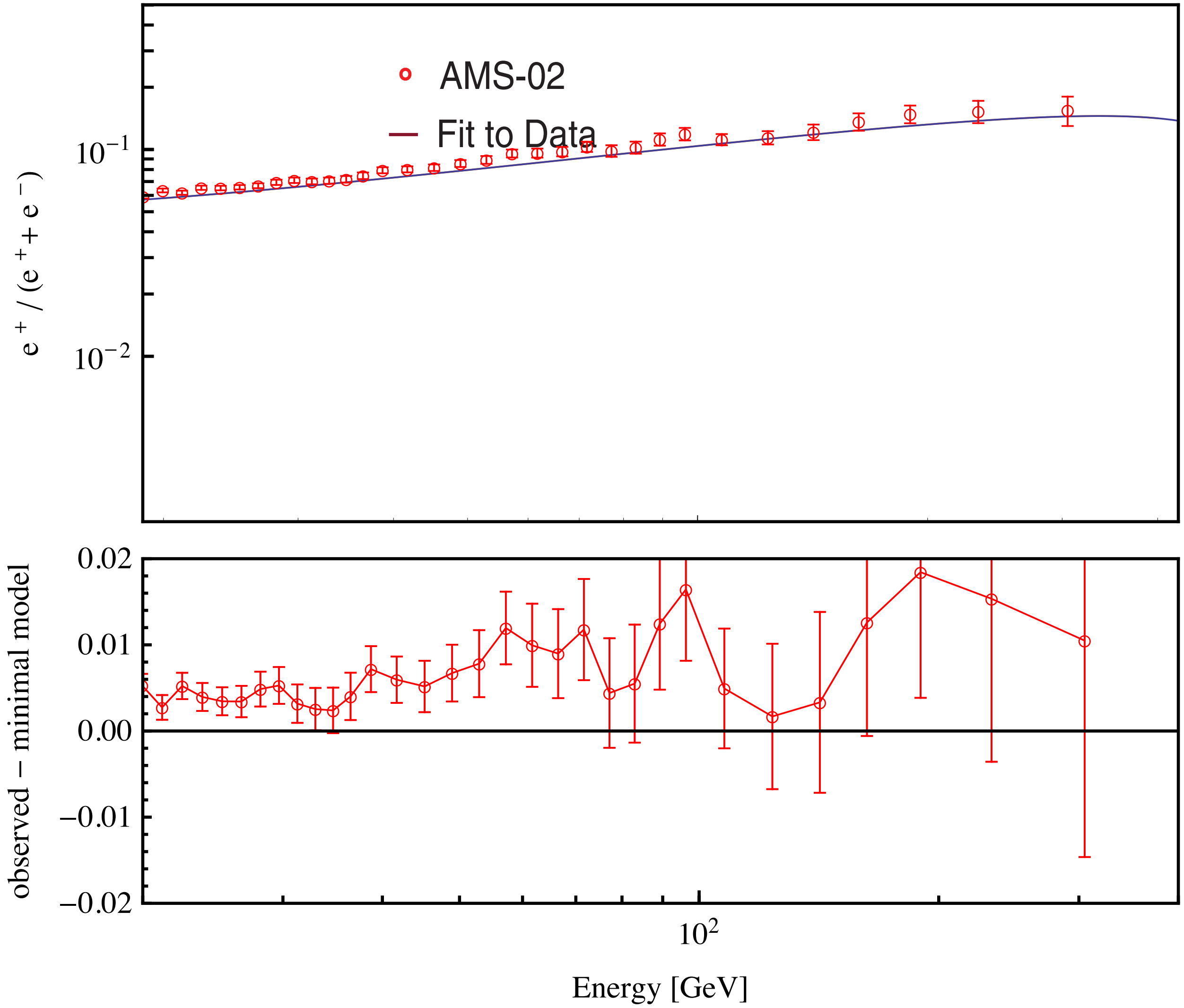

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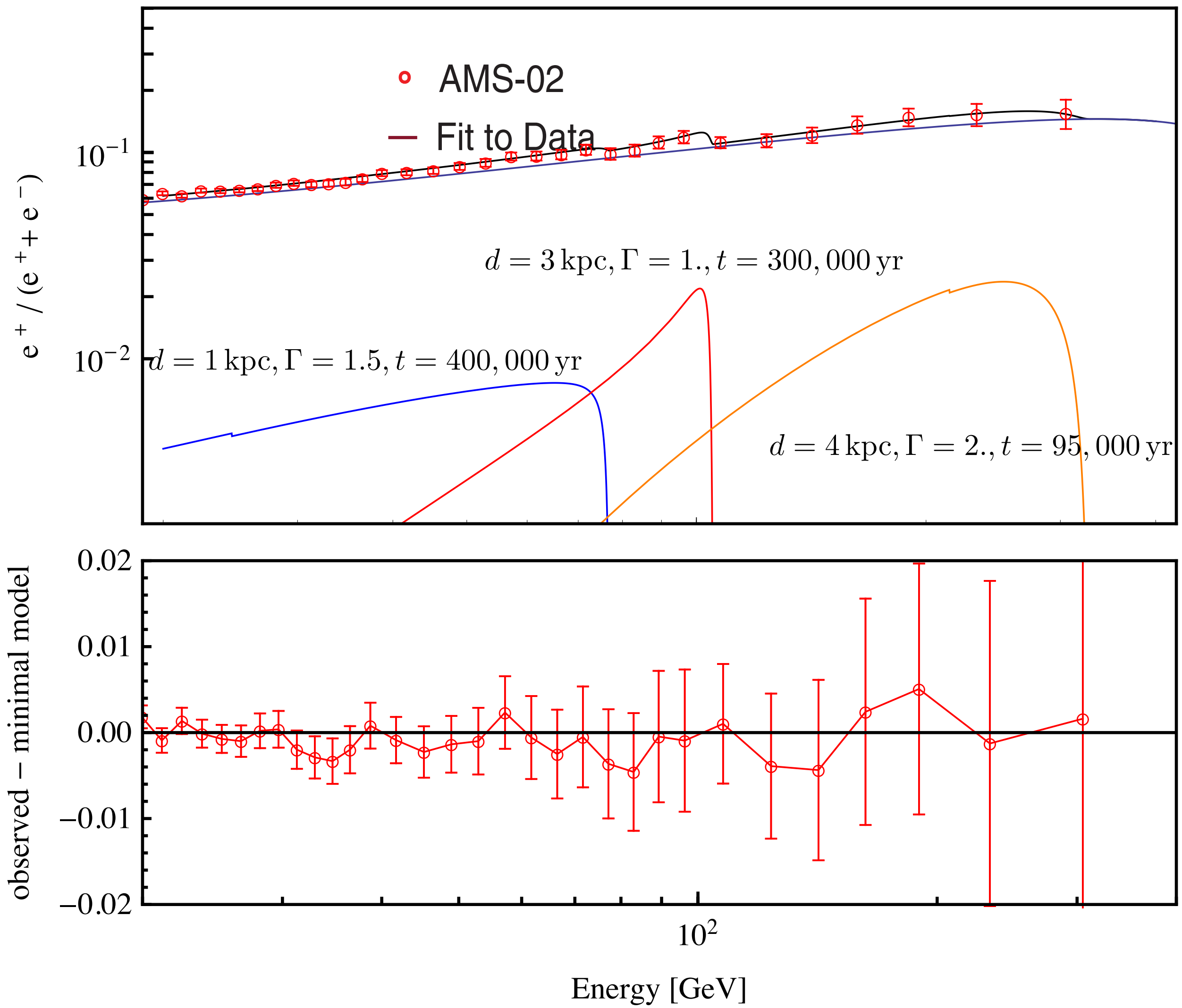
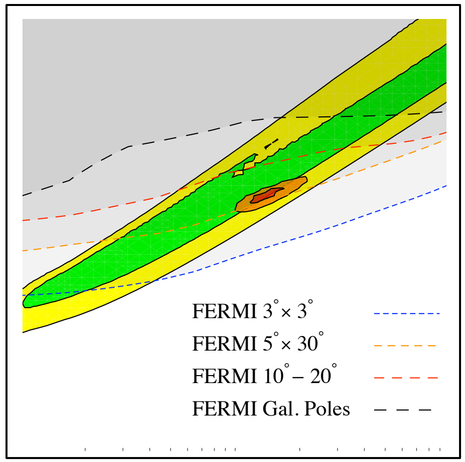
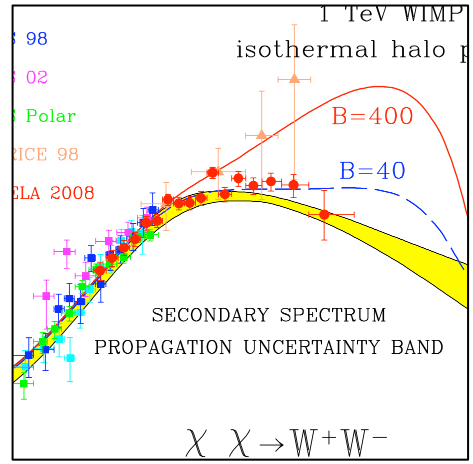


“It’s either dark matter or pulsars.”

Multi-messenger problem

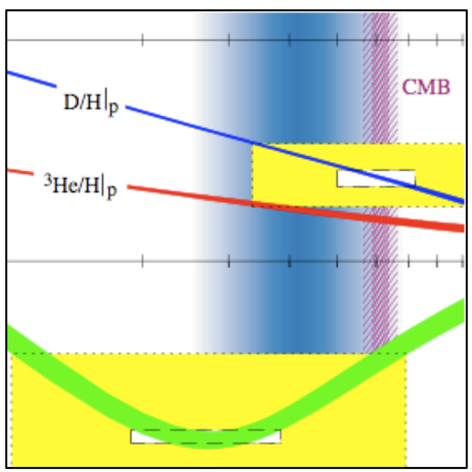
Gamma-ray constraints

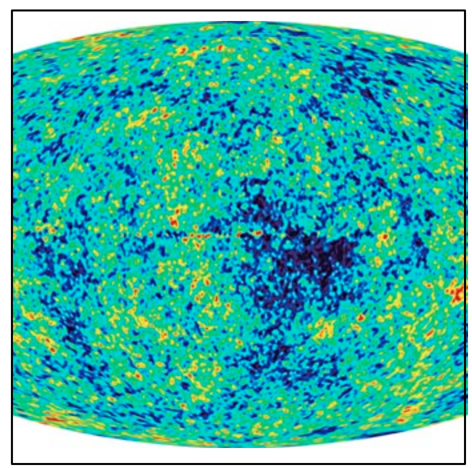




Antiproton constraints

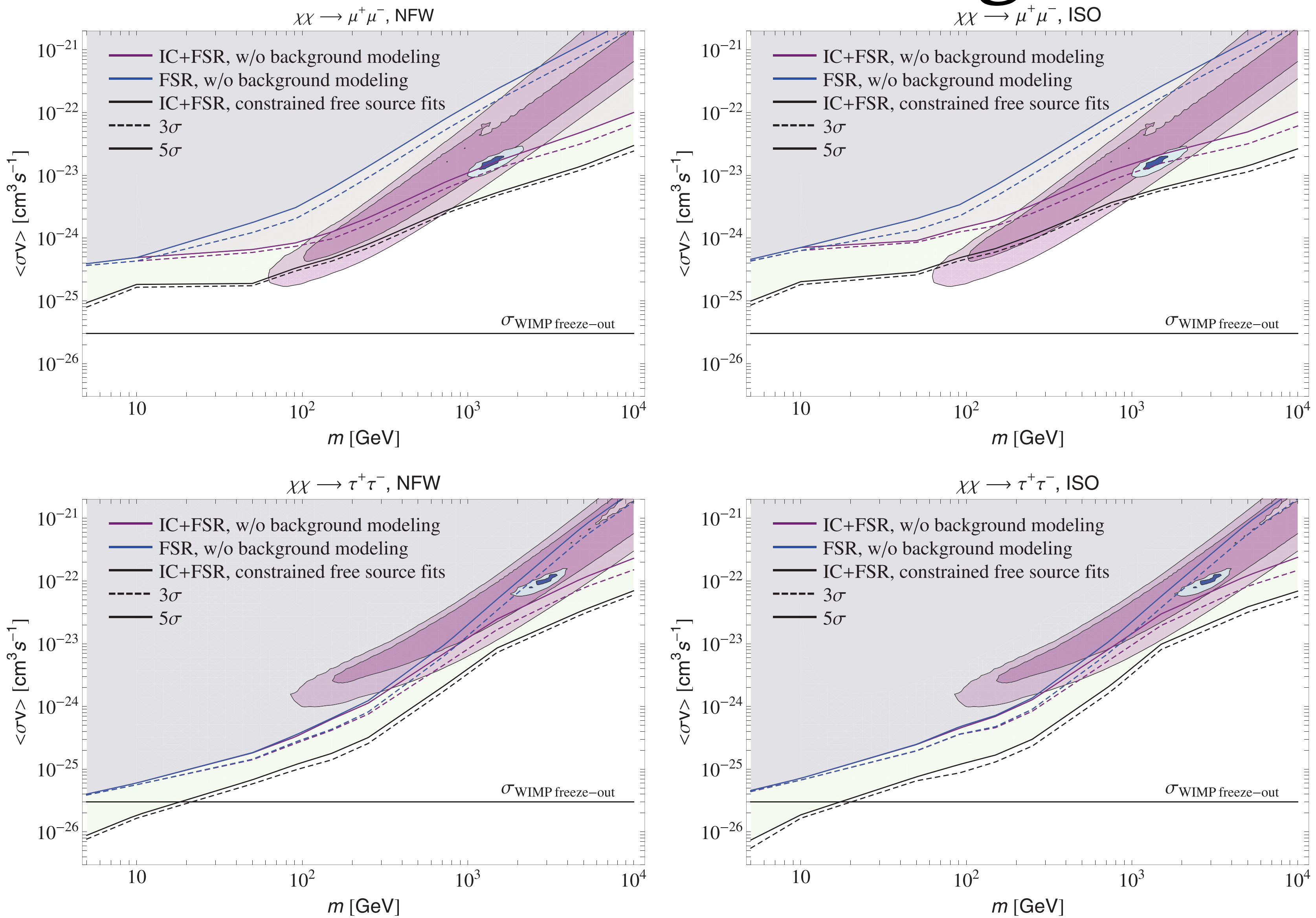
BBN constraints





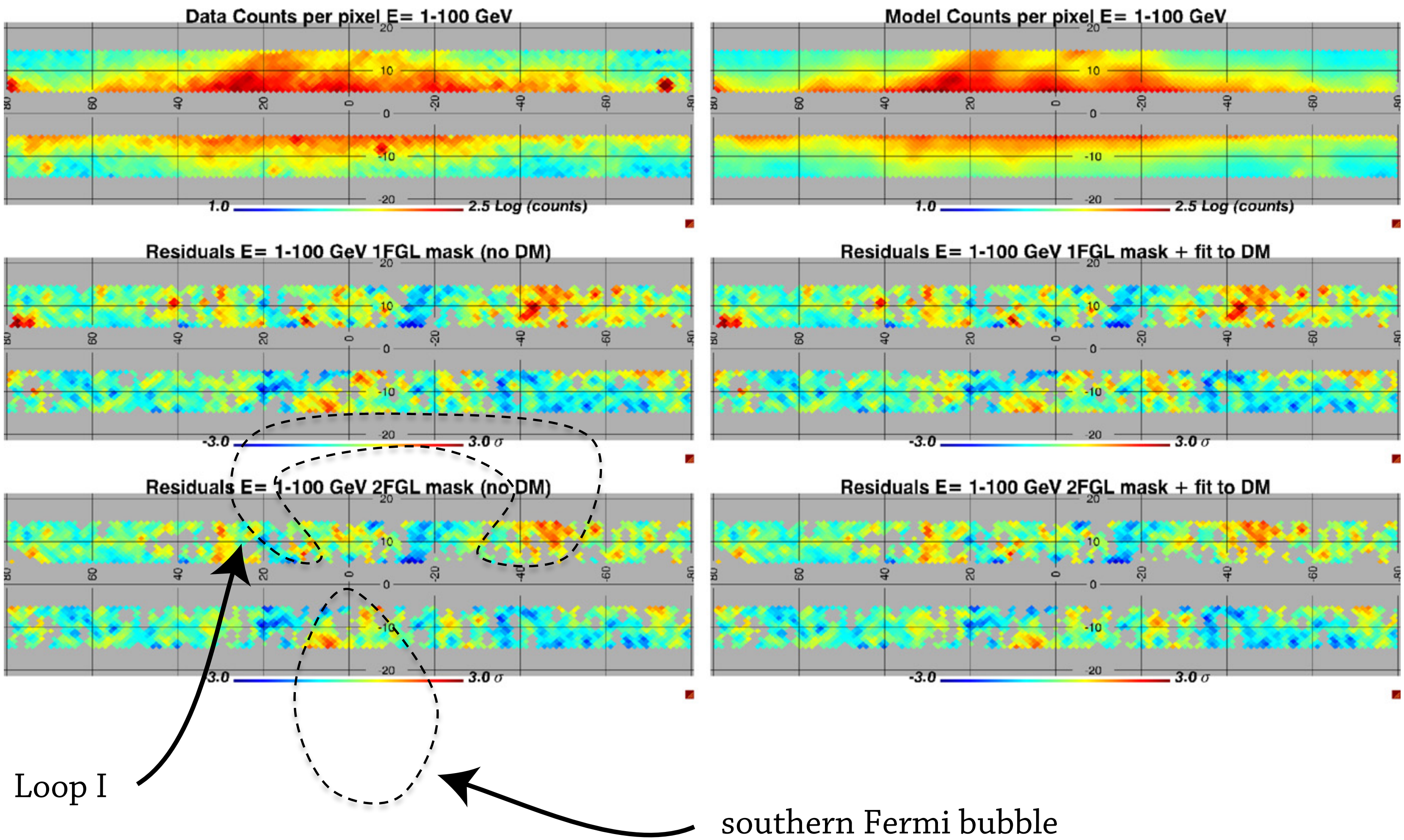
CMB constraints

Bounds on annihilating DM



Ackermann *et al.*, ApJ **761** (2012) 91

Residuals



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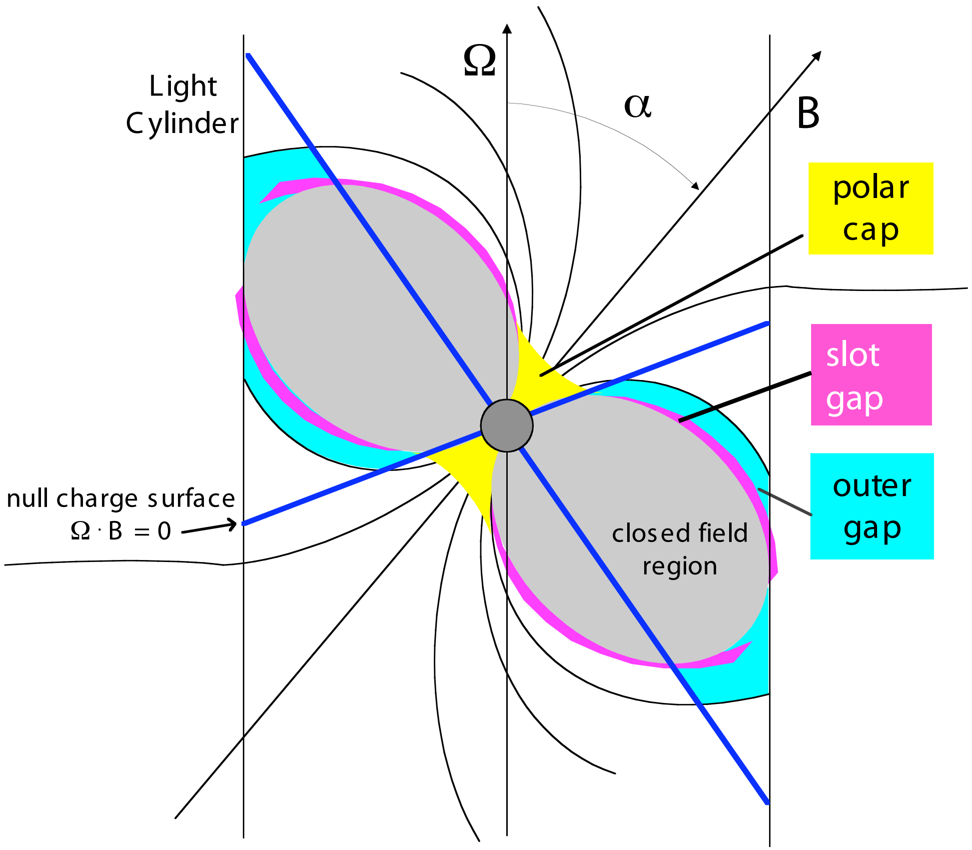
“It’s either dark matter or pulsars.”



acceleration sites:

- polar cap
- outer gap
- slot gap

production of gamma-rays:

- synchrotron radiation
- inverse Compton scattering
- curvature radiation

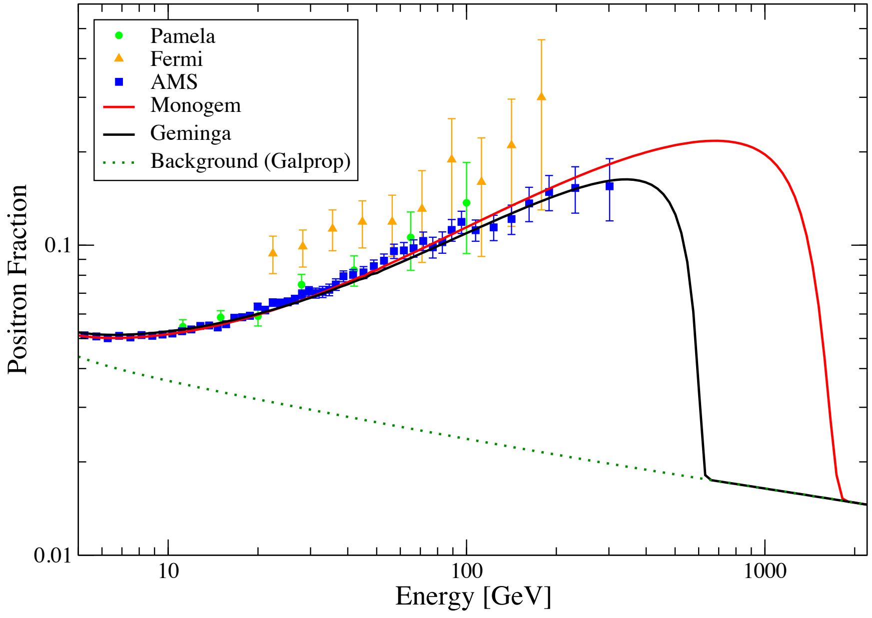
Nearby pulsars

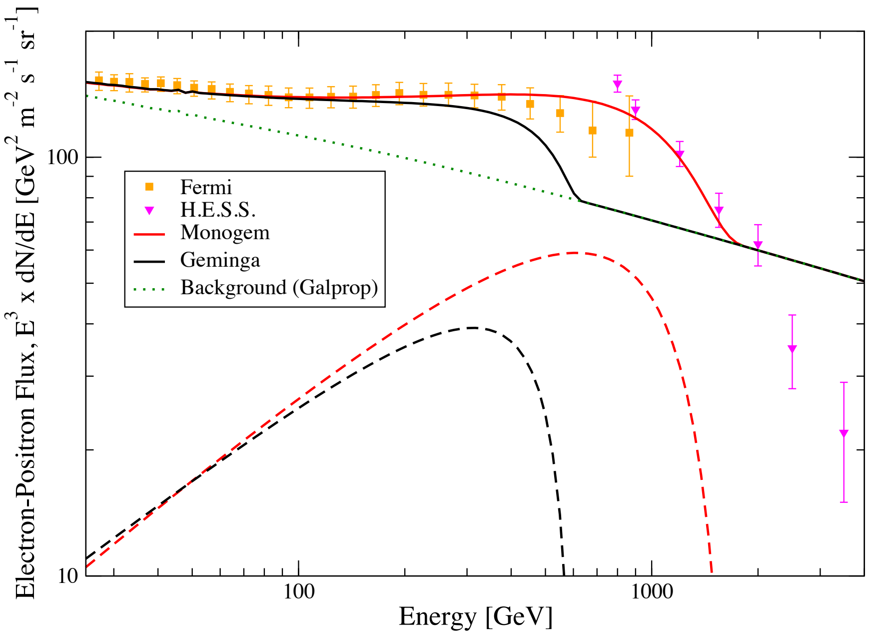
for burst-like injection from point-like source, diffusion equation can be easily solved:

$$J = \frac{e^{-\vec{r}^2/\ell^2(E_0,E)}}{(\pi\ell^2(E_0,E))^{3/2}} Q(E_0) \left(\frac{E}{E_0}\right)^{-2} \quad \text{where} \quad \ell^2(E_0,E) = 4\int_{E_0}^{E} \mathrm{d}E' \frac{D(E')}{b(E')}$$

three-parameter-problem: total energy $\varepsilon_{\mathrm{tot}}$, spectra index Γ, cut-off energy E_{cut}

Linden & Profumo, arXiv:1304.1791





All Galactic pulsars

for burst-like injection from point-like source, diffusion equation can be easily solved:

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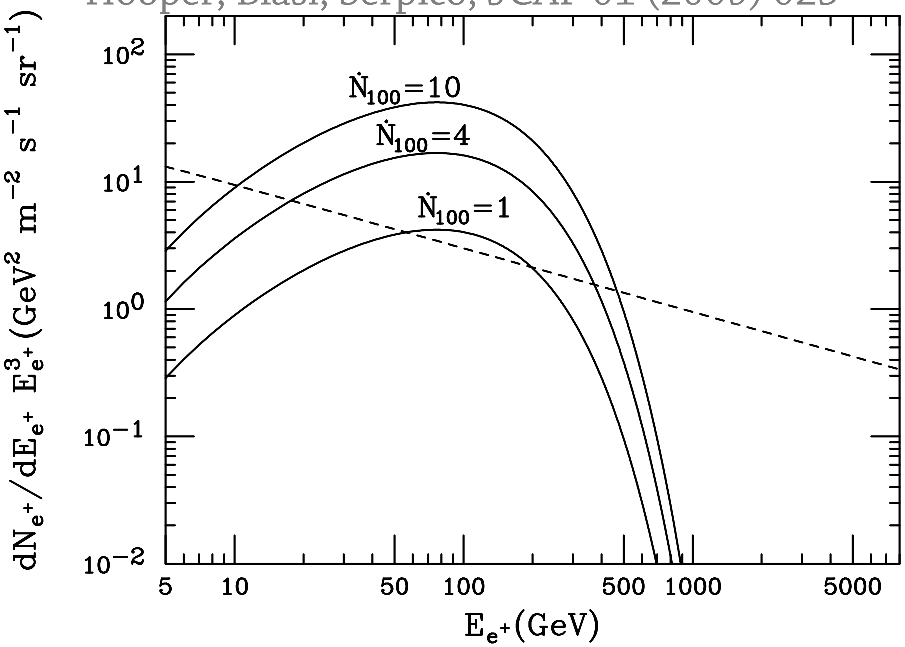
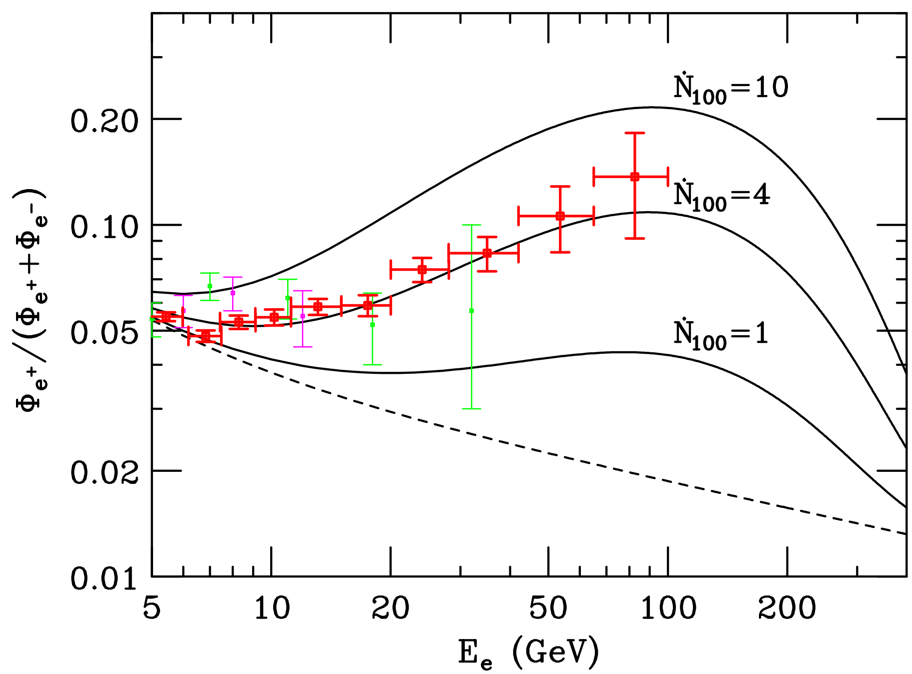
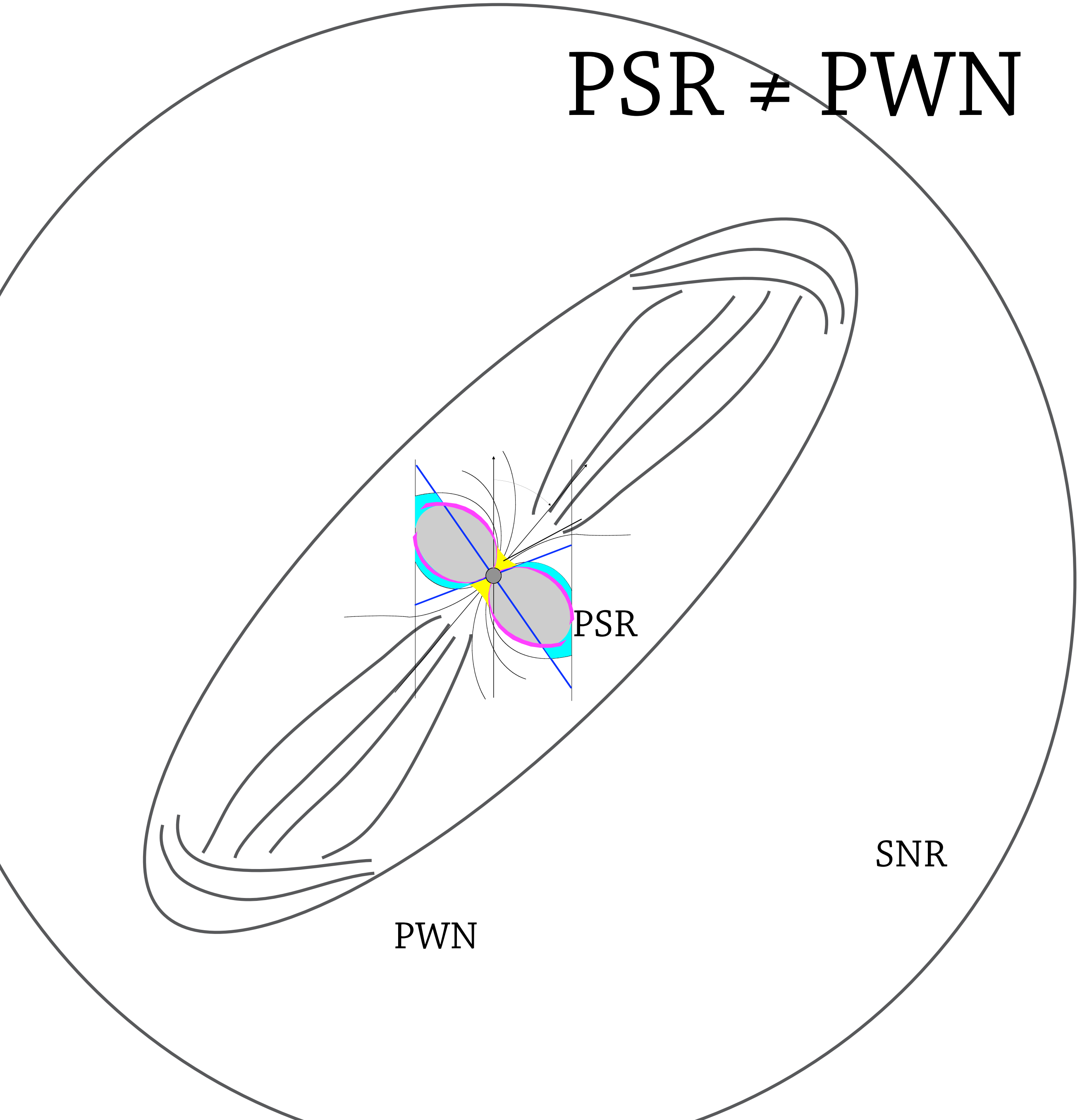
three-parameter-problem: total energy ε_{tot} , spectra index Γ, cut-off energy E_{cut}

Hooper, Blasi, Serpico, JCAP 01 (2009) 025





PSR ≠ PWN



freshly accelerated particles cannot escape the PWN/SNR

the PWN/SNR modifies the spectrum of $e^{\pm}$:

- cooling
- shock acceleration
- turbulent acceleration

all the parameters from pulsar observation, i.e. $\varepsilon_{\rm tot}$, Γ, $E_{\rm cut}$ are modified

➔need statistical model and fit parameters

Malyshev, Cholis, Gelfand PRD 80 (2009) 063005

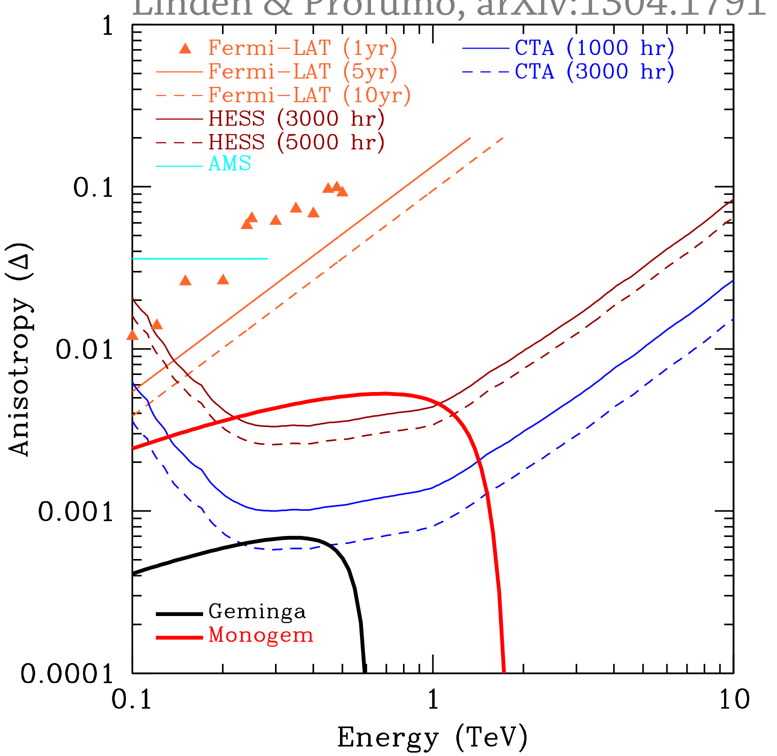
Anisotropies

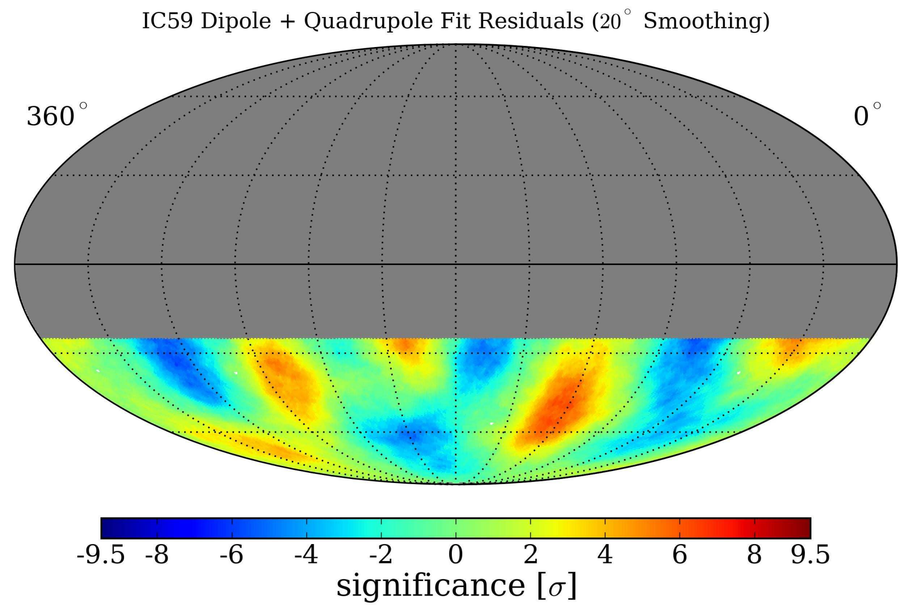
can estimate anisotropy from isotropic flux:

$$\delta = \frac{3D(E)}{c}\frac{|\nabla J(E)|}{J(E)}$$

very sensitive to *local* $D(E)$

Linden & Profumo, arXiv:1304.1791





anisotropies in (hadronic) cosmic rays:

- $\delta \sim 10^{-3}$ on large (dipole) scales
- $\delta \sim 10^{-4}$ down to 10° scales

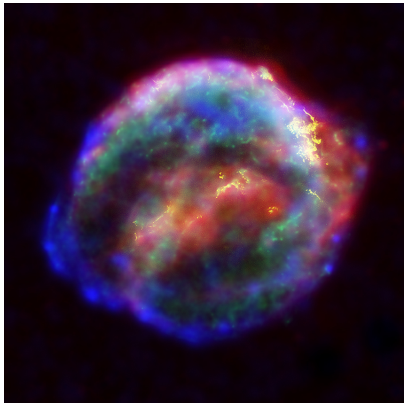
explanations modify local magnetic field

Malkov *et al.*, ApJ 721 (2010) 750

Giacinti & Sigl, PRL 109 (2012) 071101

Secondaries from the Source?

Common belief: secondaries from propagation dominate since the grammage in the ISM is larger than in the source



$$\langle \tau_{\rm src} \rangle \lesssim \tau_{\rm SNR} \approx 10^{4\ldots5}\,{\rm yr}$$

$$n_{\rm src} \lesssim 10\,{\rm cm}^{-3}$$

$$\Rightarrow \lambda_{\rm src} \approx 0.2\,{\rm g\,cm}^{-2}$$

$$\langle \tau_{\rm ISM} \rangle \sim \tau_{\rm esc} \approx 10^{7}\,{\rm yr}$$

$$n_{\rm ISM} \approx 0.1\,{\rm cm}^{-3}$$

$$\Rightarrow \lambda_{\rm ISM} \approx {\rm few\,g\,cm}^{-2}$$

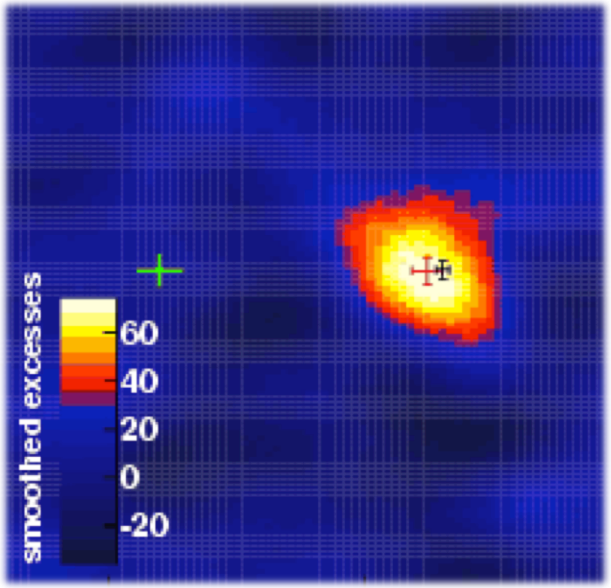
However, the secondaries from the source can have a much harder spectrum!

Secondary Origin of $e^{\pm}$

Rise in positron fraction could be due to secondary positrons produced during acceleration and accelerated along with primary electrons
Blasi, PRL **103** (2009) 051105

Assuming production of galactic CR in SNRs, positron fraction can be fitted

This effect is guaranteed, only its size depends on normalisation and one free parameter that needs to be fitted from observations



Cas A in γ-rays from MAGIC

DSA – Test Particle Approximation

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,

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

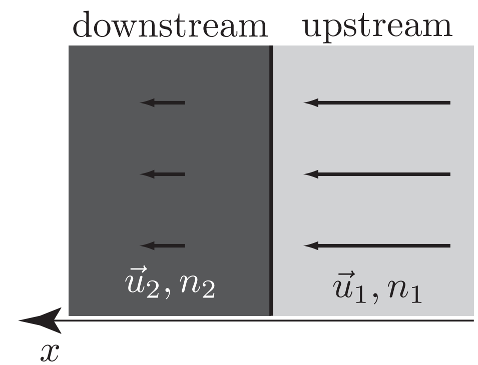
$$f \xrightarrow{x\to-\infty} f_{\rm inj}(p), \qquad \left|\lim_{x\to\infty} f\right| \ll \infty$$

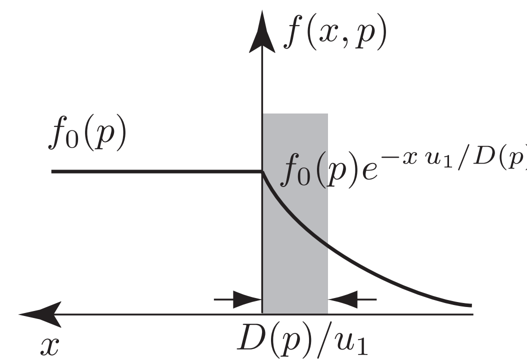
Solution for $x < 0$:

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

where

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





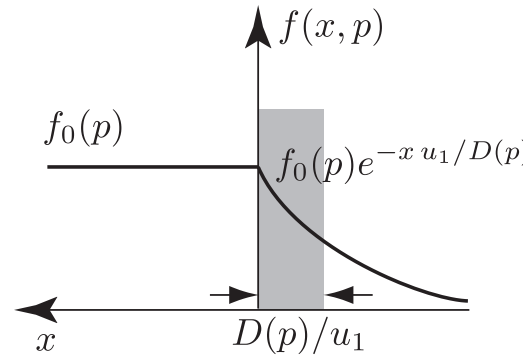
As long as $f_{\rm inj}(p)$ is softer than $p^{-\gamma}$, at high energies:

$$f(x,p) \sim p^{-\gamma}$$

DSA with Secondaries

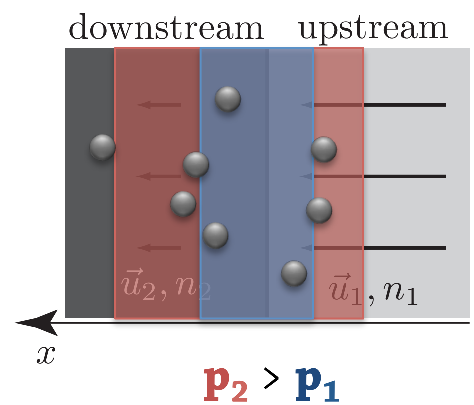
- Secondaries get produced with primary spectrum:

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



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

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



- Fraction of secondaries that go into acceleration $\propto p$

- Equilibrium spectrum

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

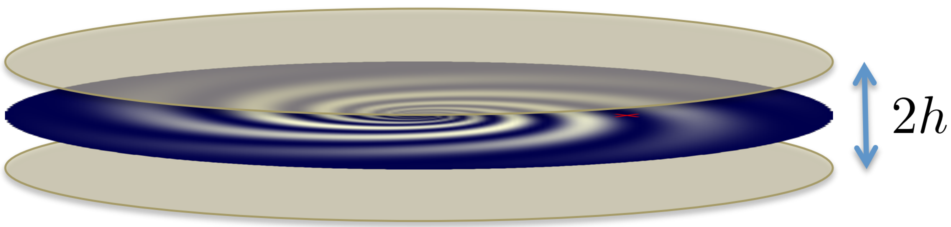
Rising positron fraction at source

Diffusion of GCRs

Transport equation:

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

Boundary conditions:



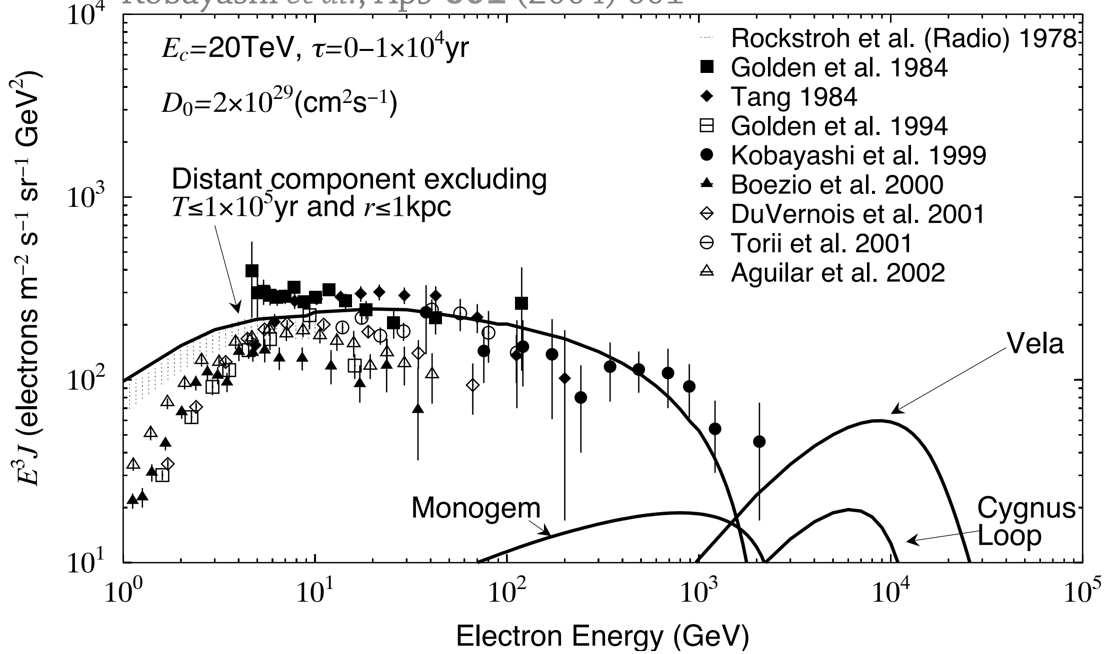
Green’s function:

describes flux from one discrete, burst-like source

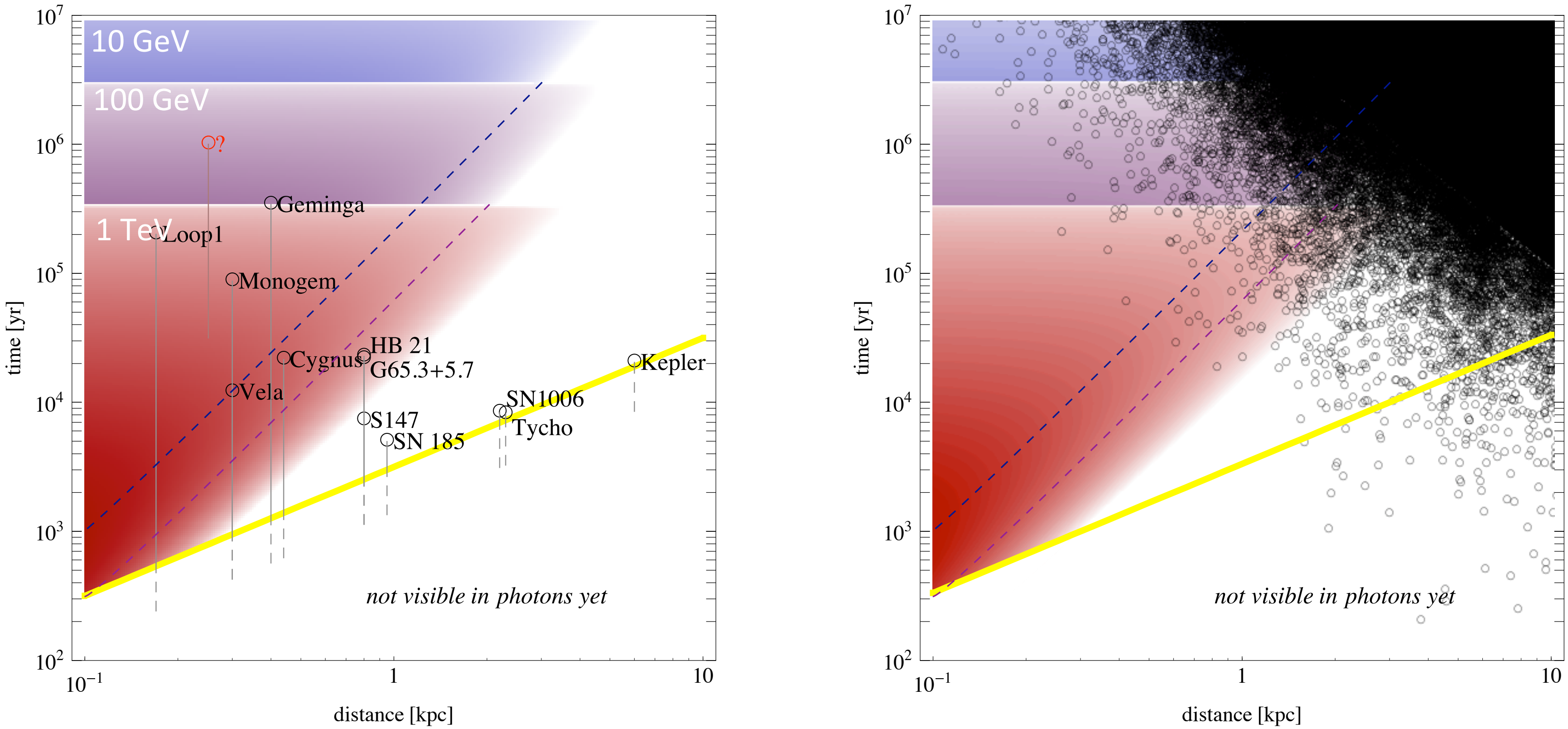
A Hybrid Model

- homogeneous distribution for sources with distances $\gtrsim 1\,\mathrm{kpc}$ or ages $\gtrsim 10^5\,\mathrm{yr}$
- supplement with *known* young and nearby sources

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



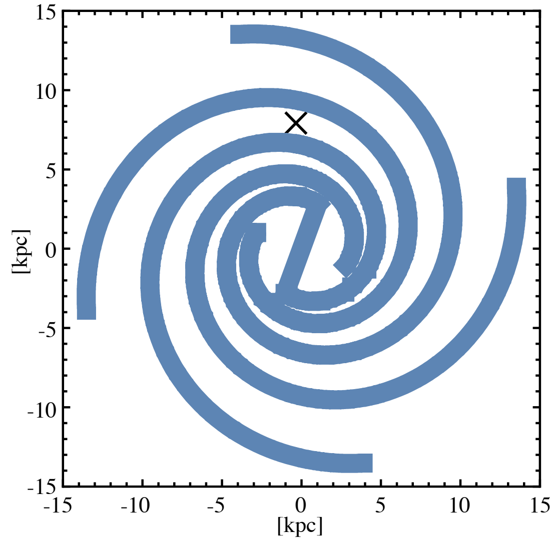
A Caveat



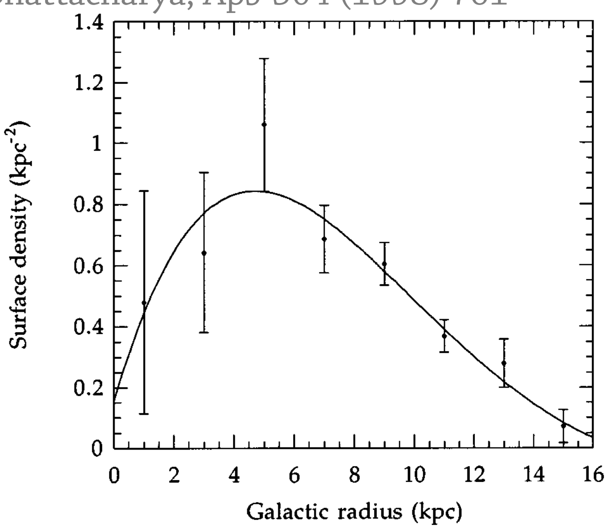
Not only observed sources contribute!

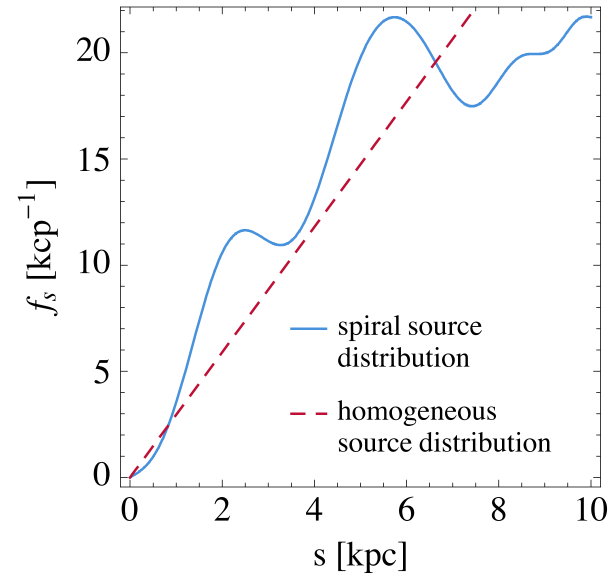
Ahlers, Mertsch, Sarkar, PRD **80** (2009) 123017

Statistical Distribution of Sources



Case, Bhattacharya, ApJ 504 (1998) 761



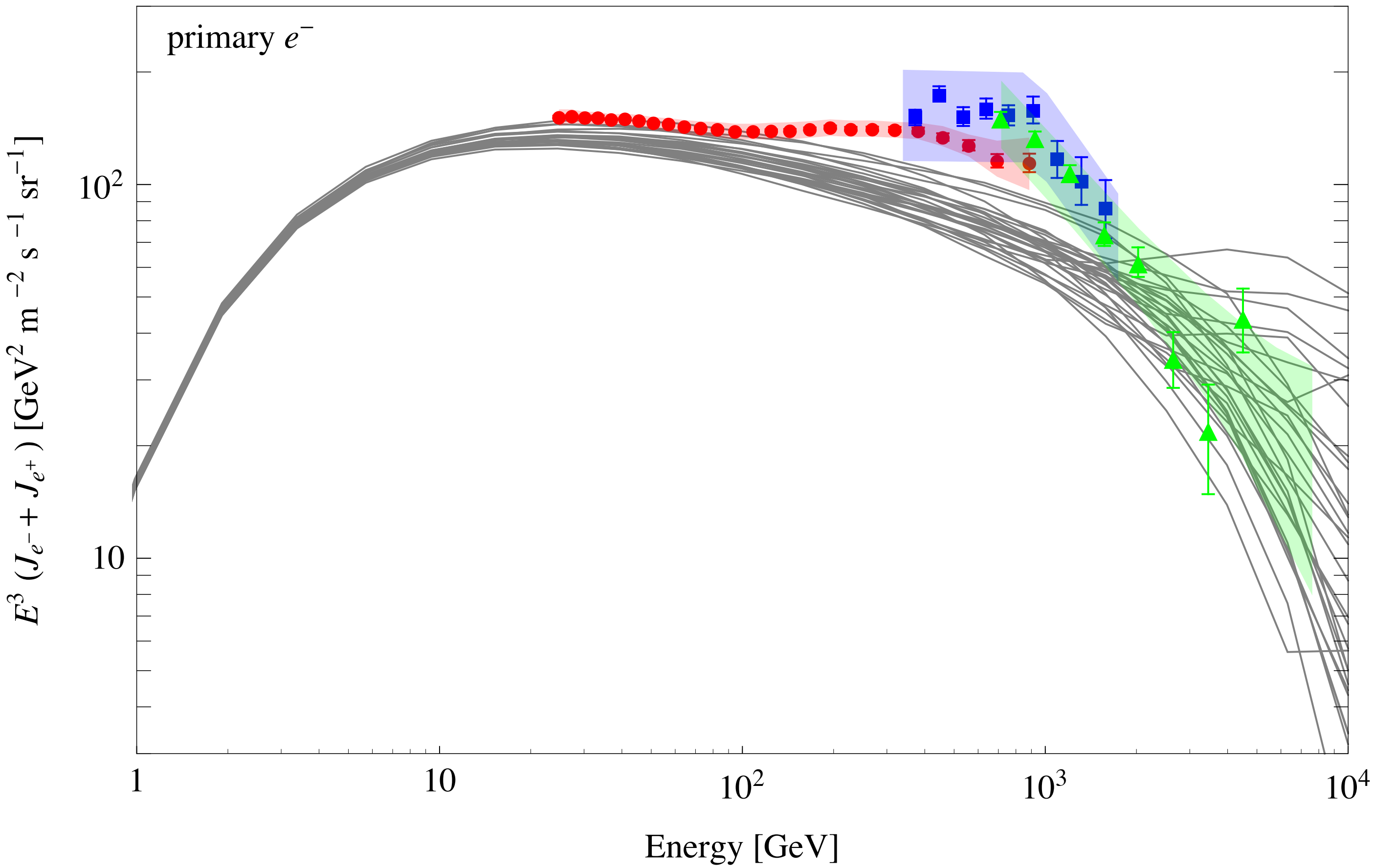


probability density for distances, $f_s(s)$

probability density for ages, $f_t(t) = \text{const.}$

Ahlers, Mertsch, Sarkar, PRD **80** (2009) 123017

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



Ahlers, Mertsch, Sarkar, PRD **80** (2009) 123017
Mertsch & Sarkar, *in preparation*

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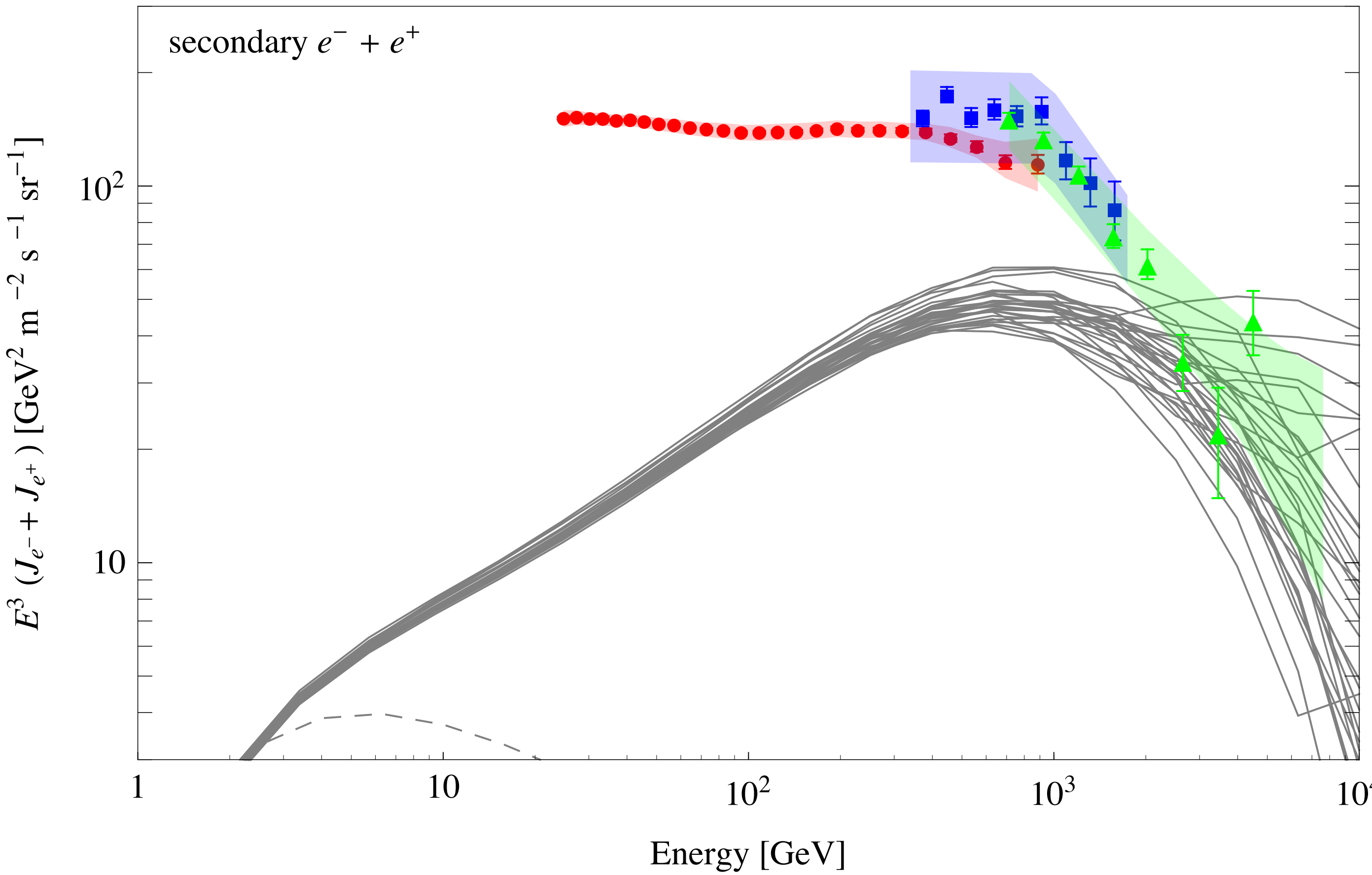

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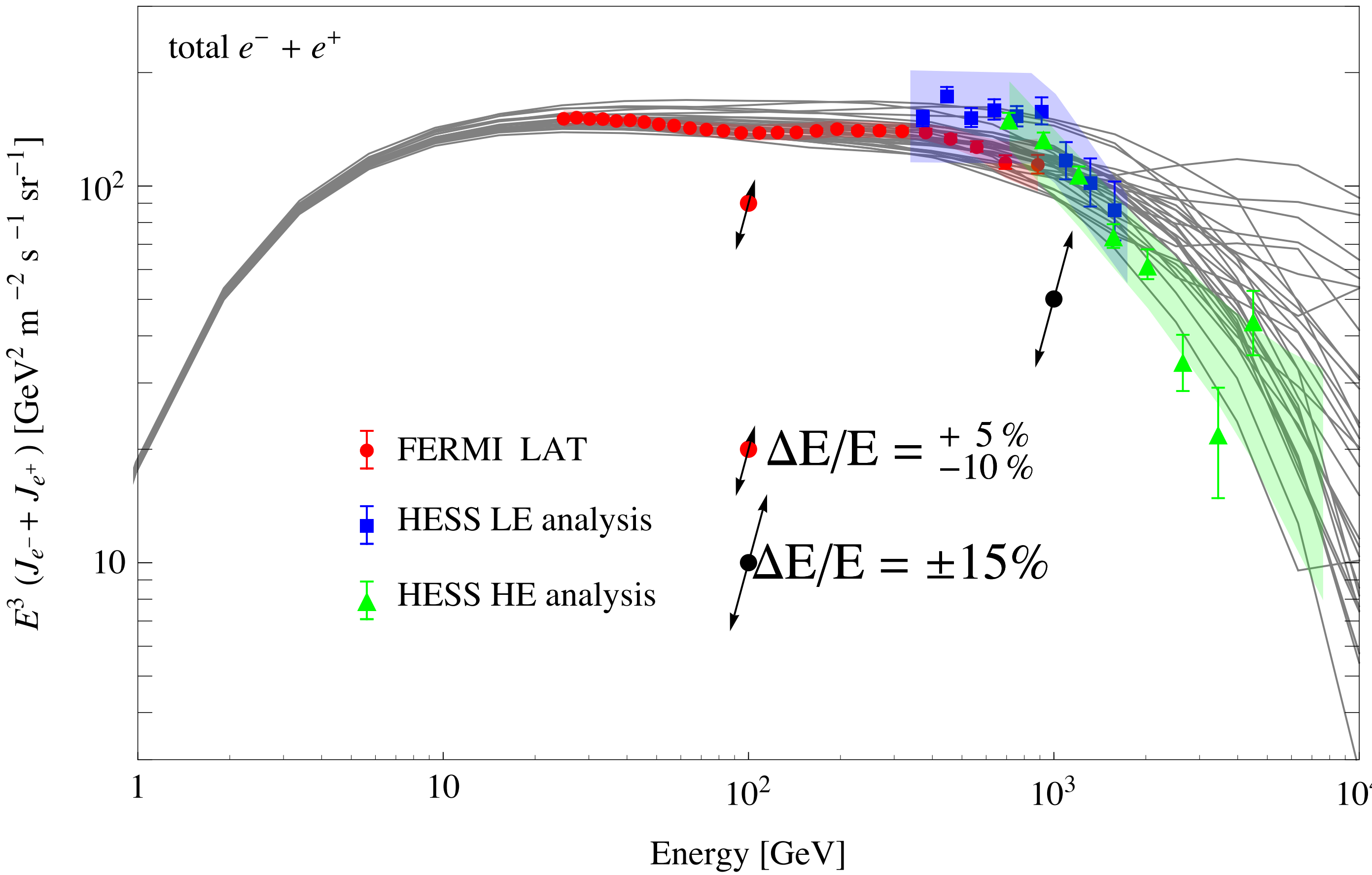

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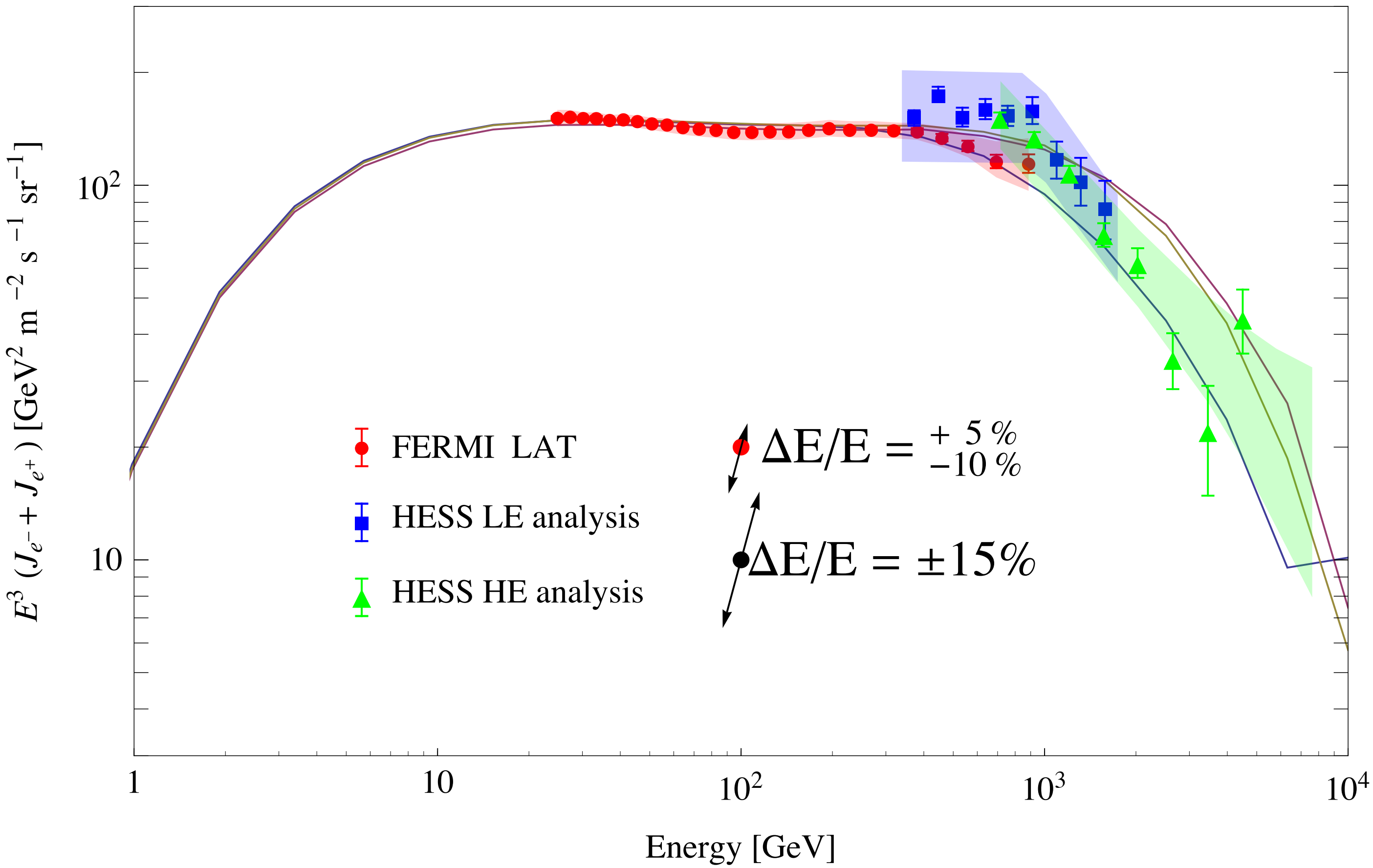
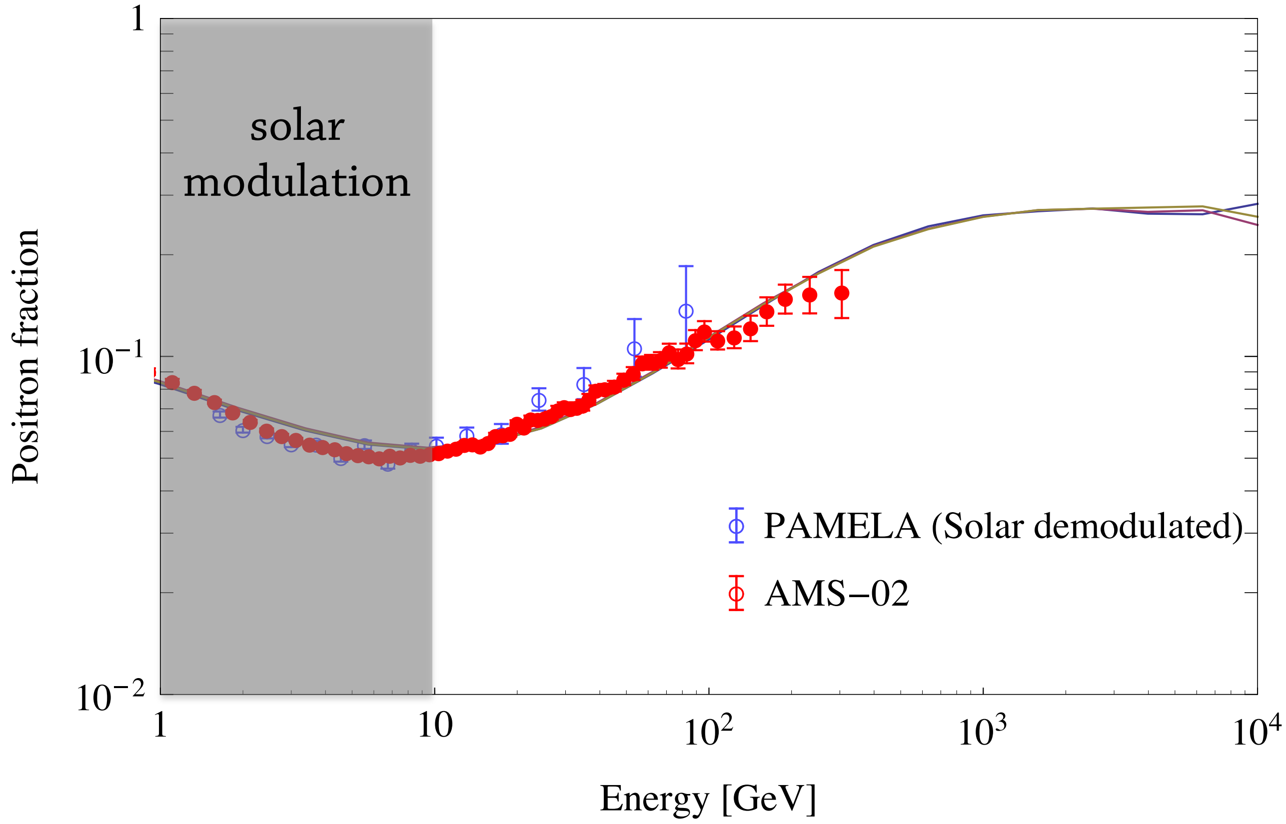


Ahlers, Mertsch, Sarkar, PRD **80** (2009) 123017
Mertsch & Sarkar, *in preparation*

The Positron Fraction



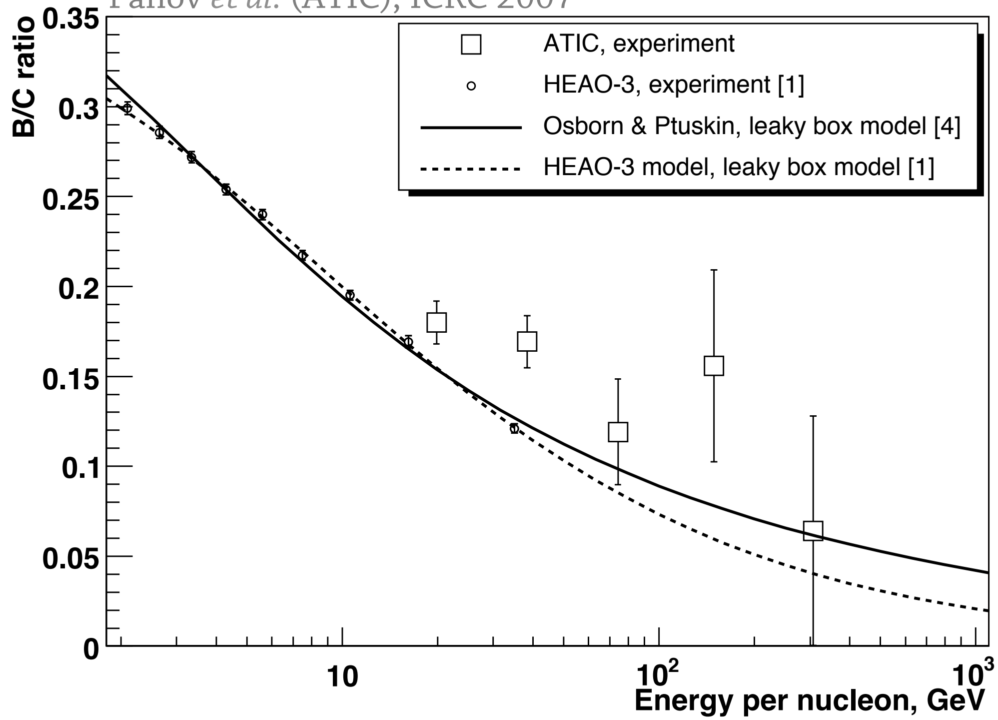
Ahlers, Mertsch, Sarkar, PRD **80** (2009) 123017
Mertsch & Sarkar, *in preparation*

Nuclear Secondary-to-Primary Ratios

rise in...	nuclei
DM	✗
Pulsars	✗

Nuclear secondary-to-primary ratios used for testing and calibrating propagation models

Panov *et al.* (ATIC), ICRC 2007



DM and pulsars do not produce nuclei!

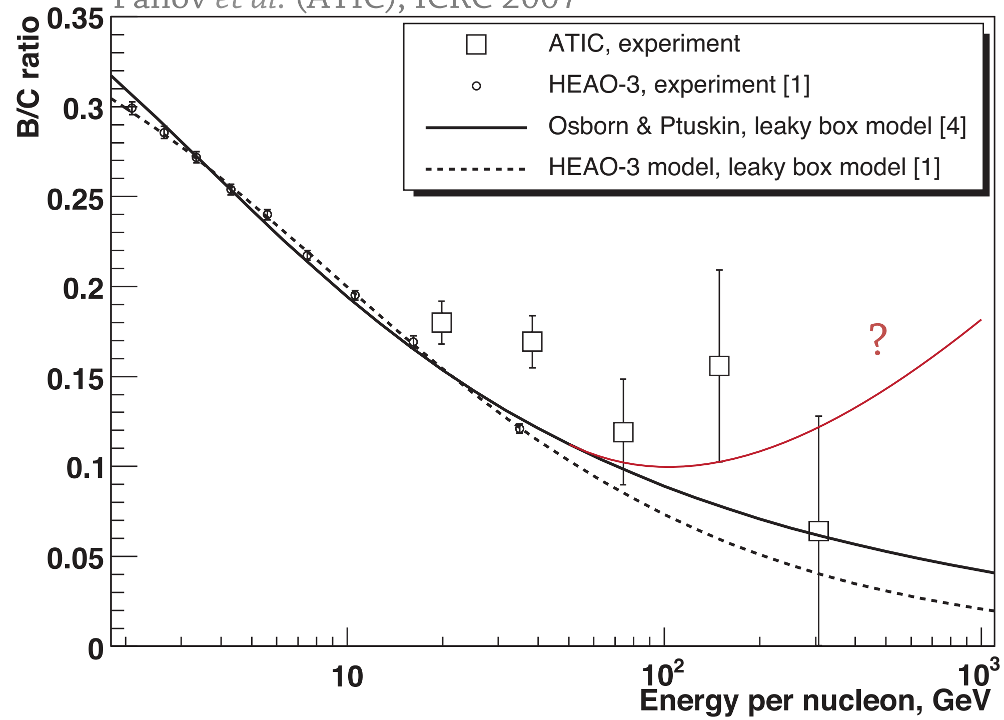
Nuclear Secondary-to-Primary Ratios

rise in...	nuclei
DM	✗
Pulsars	✗
Acceleration of Secondaries	✓

This would be a clear indication for acceleration of secondaries!

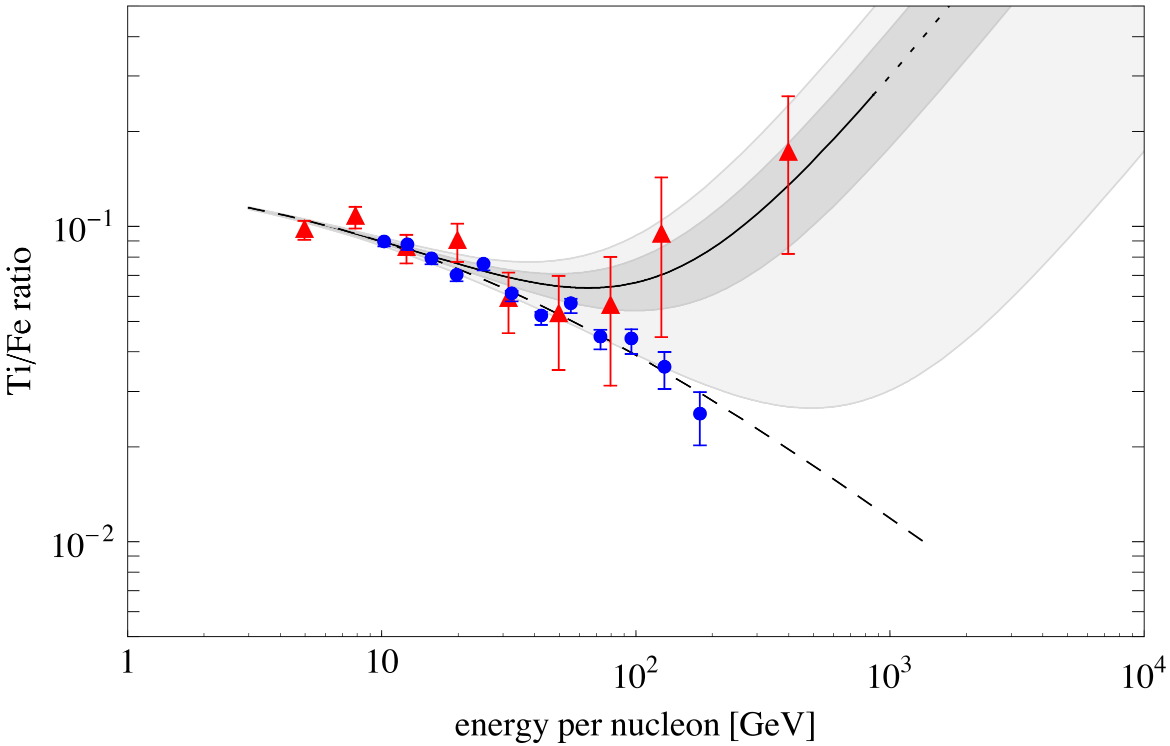
If nuclei are accelerated in the same sources as electrons and positrons, nuclear ratios *must* rise eventually

Panov *et al.* (ATIC), ICRC 2007



Titanium-to-Iron Ratio

PM and Sarkar, PRL **103** (2009) 081104



HEAO-3
Engelmann *et al.*, A&A 233, 96 (1990)

ATIC-2
Zatsepin *et al.*, arXiv:0905.0049

spallation during propagation only

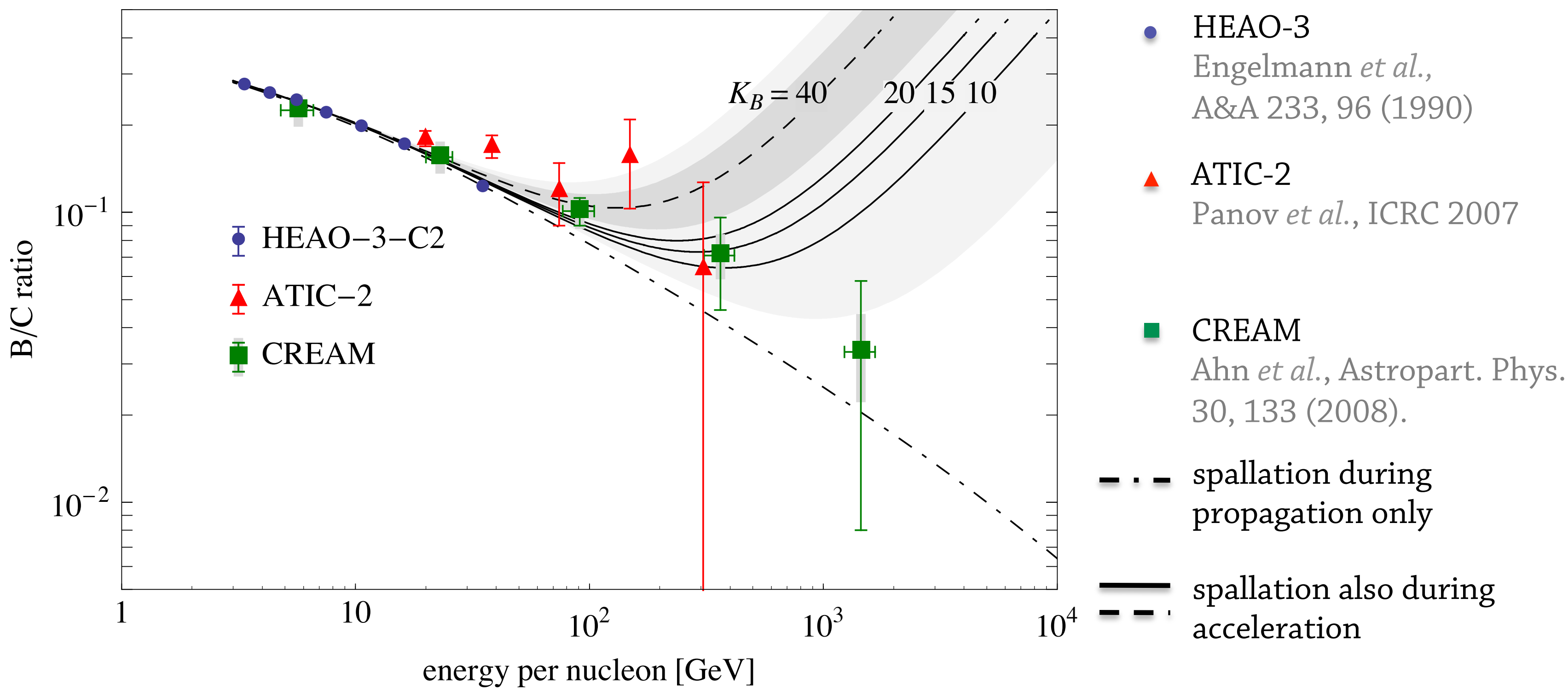
spallation also during acceleration

Titanium-to-iron ratio used as calibration point for diffusion coefficient:

$$K_{\mathrm{B}} \simeq 40$$

Boron-to-Carbon Ratio

PM and Sarkar, PRL **103** (2009) 081104; Ahlers *et al.*, PRD **80** (2009) 123017

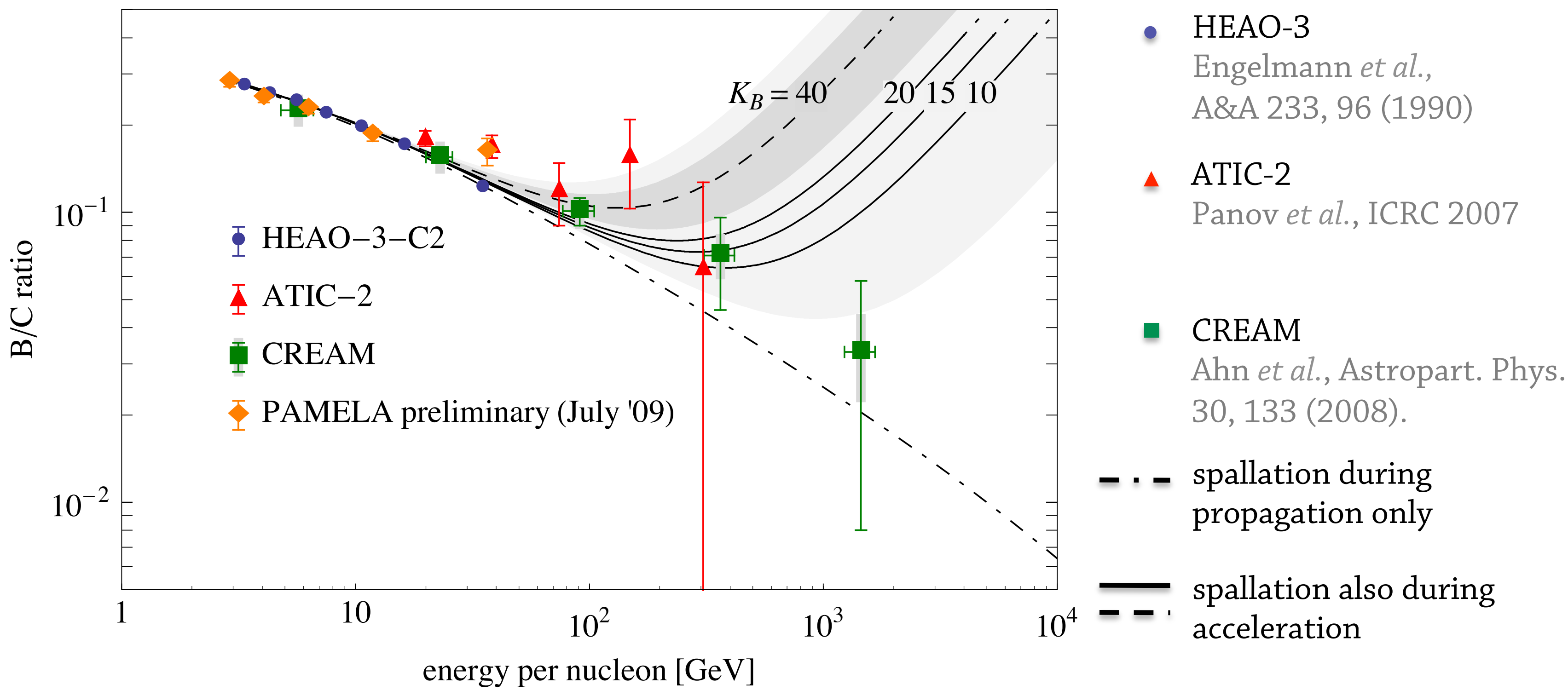


PAMELA is currently measuring B/C with unprecedented accuracy

A rise would rule out the DM and pulsar explanation of the PAMELA e^+/e^- excess.

Boron-to-Carbon Ratio

PM and Sarkar, PRL **103** (2009) 081104; Ahlers *et al.*, PRD **80** (2009) 123017



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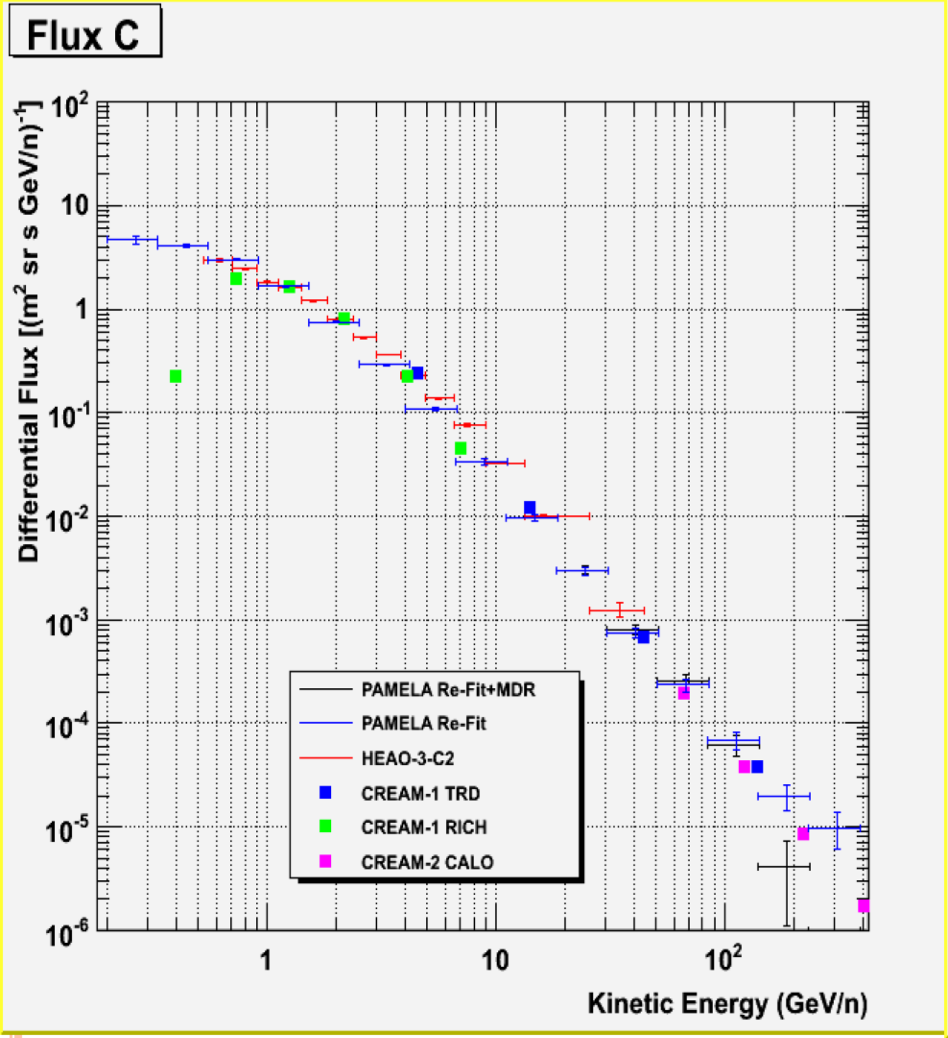
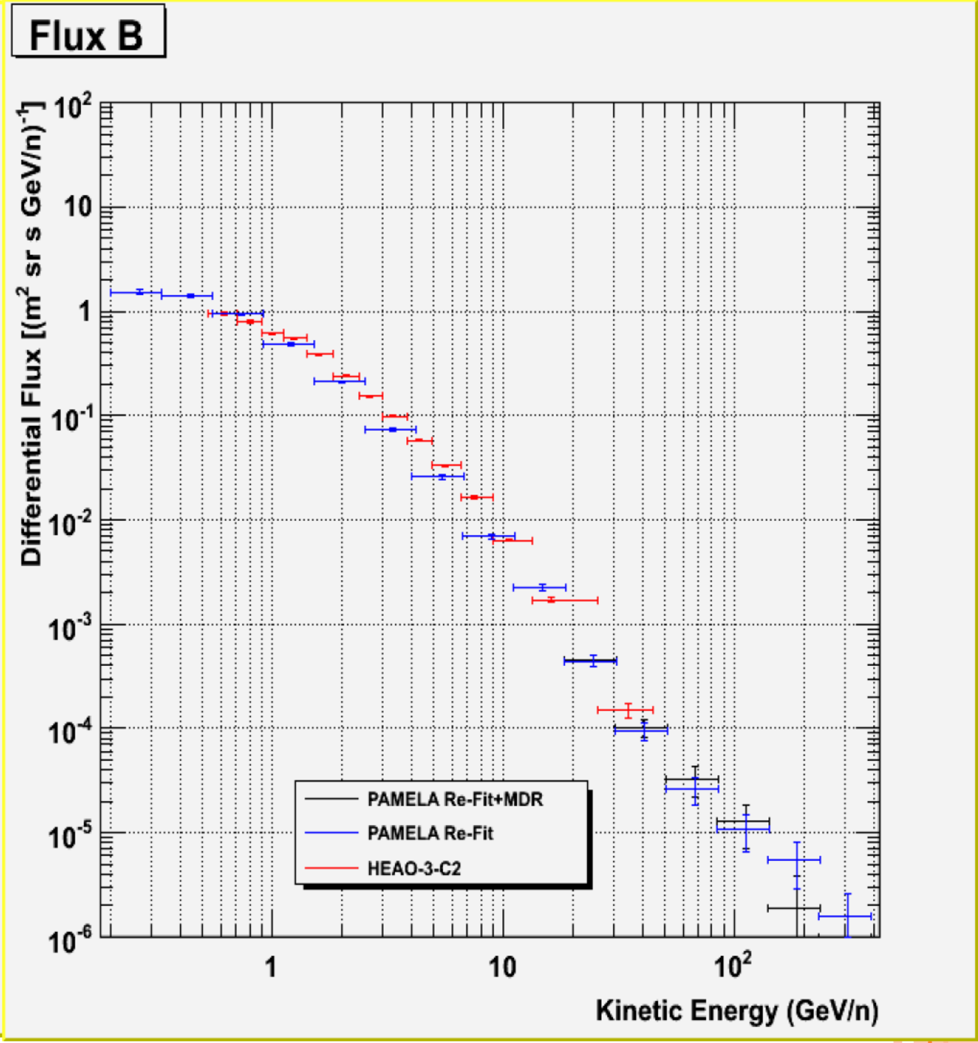
BORON AND CARBON FLUX – IN PROGRESS

R. Sparvoli, 6th Patras Workshop on Axions, WIMPs and WISPs, 5-9 July 2010





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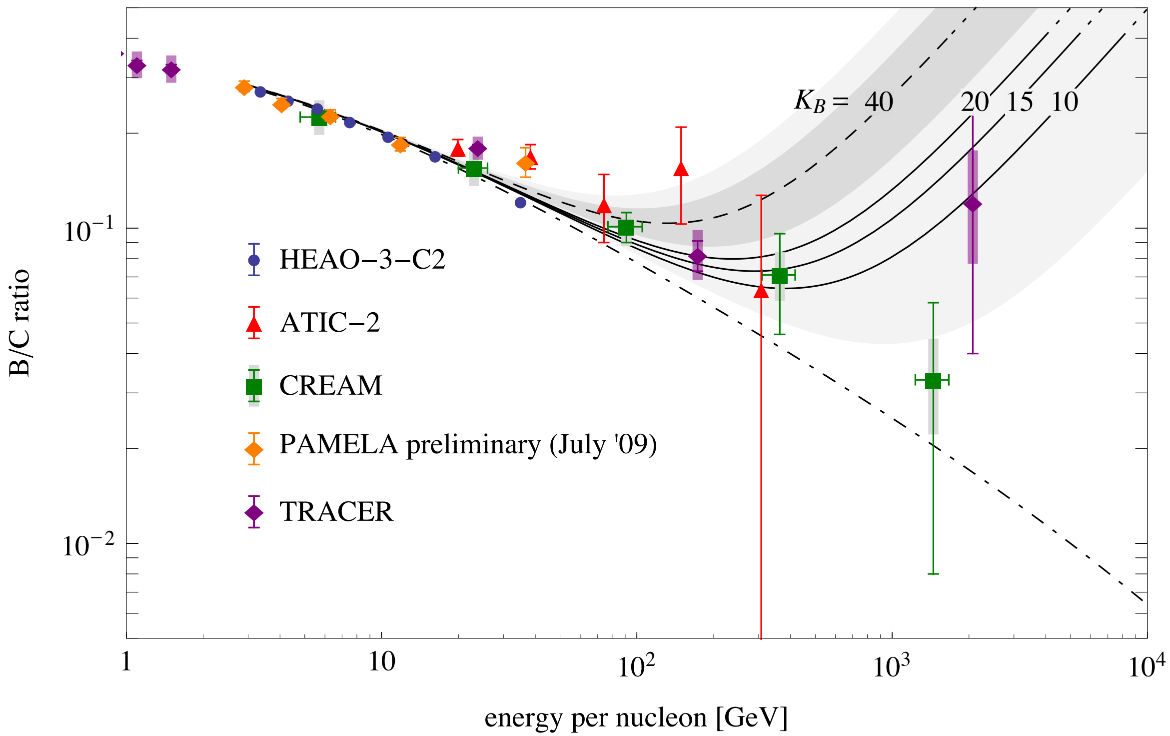

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CREAM
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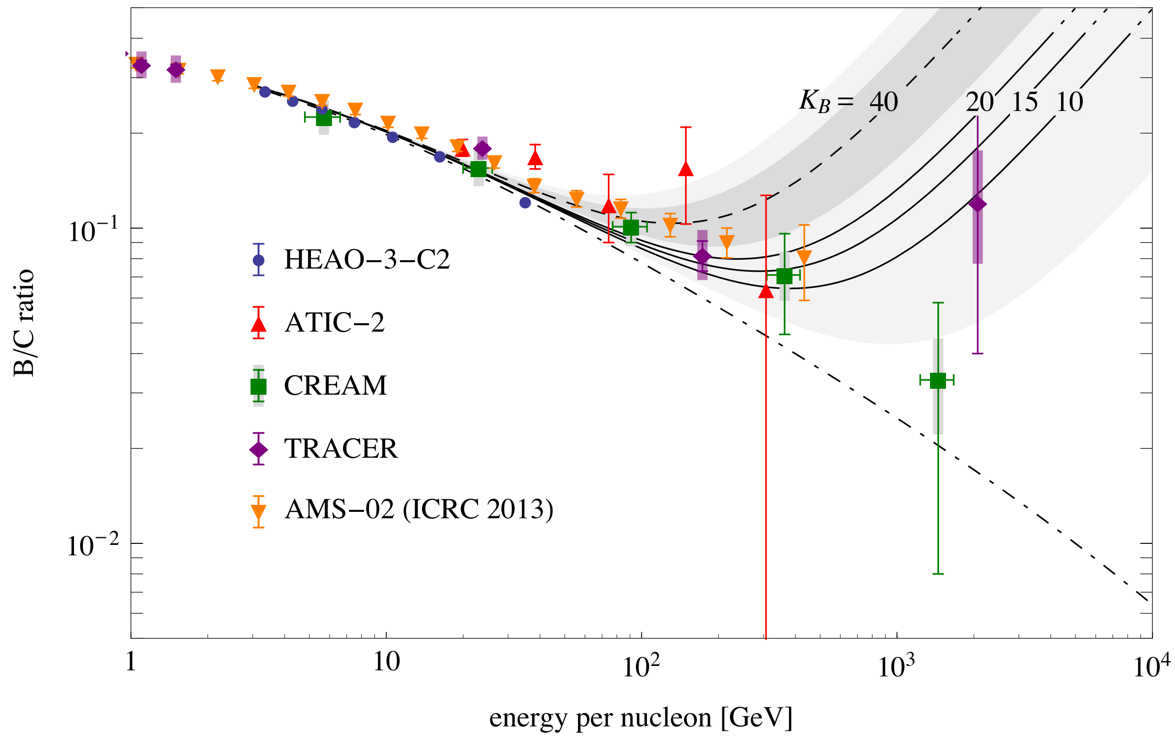

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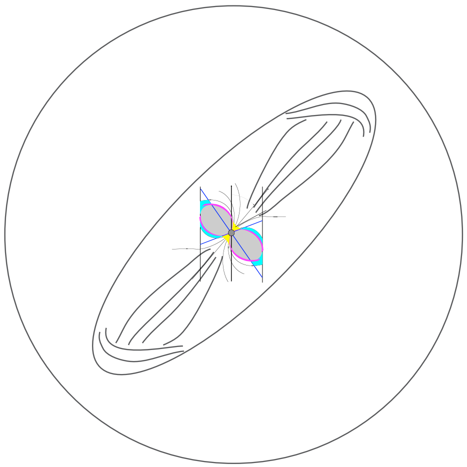
spallation also during acceleration

AMS-02

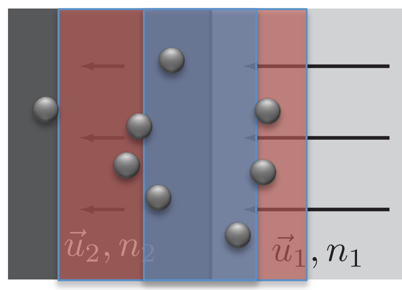
~~PAMELA~~ is currently measuring B/C with unprecedented accuracy

A rise would rule out the DM and pulsar explanation of the PAMELA e^+/e^- excess.

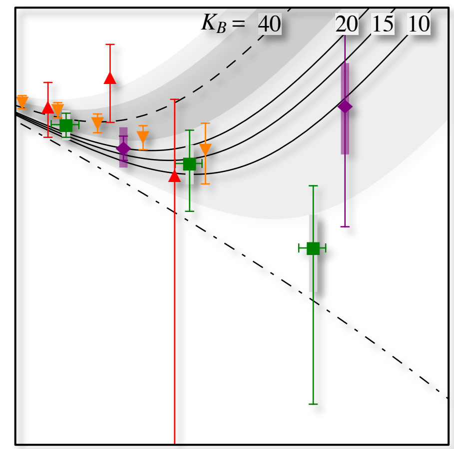
Conclusion



Astrophysical explantions of positron excess: pulsars?



Acceleration of secondary e⁺ in SNRs could explain PAMELA and Fermi-LAT excess



Very predictive model: nuclear secondary-to-primary ratios