Cosmic Ray Backgrounds for Indirect Detection

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LAPTh, Annecy
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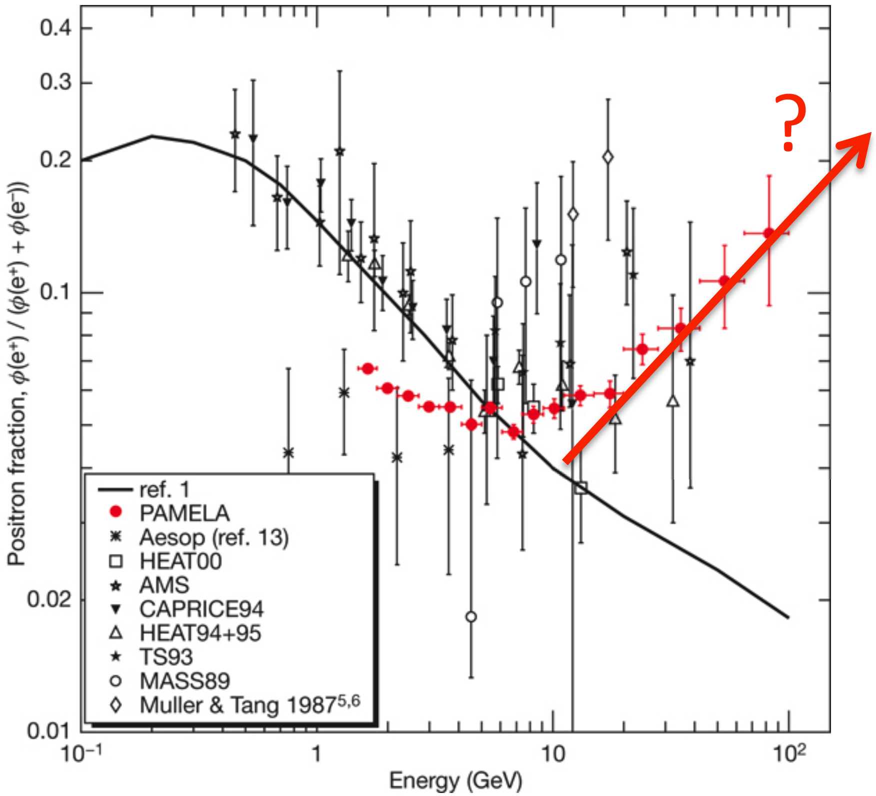
Science & Technology Facilities Council

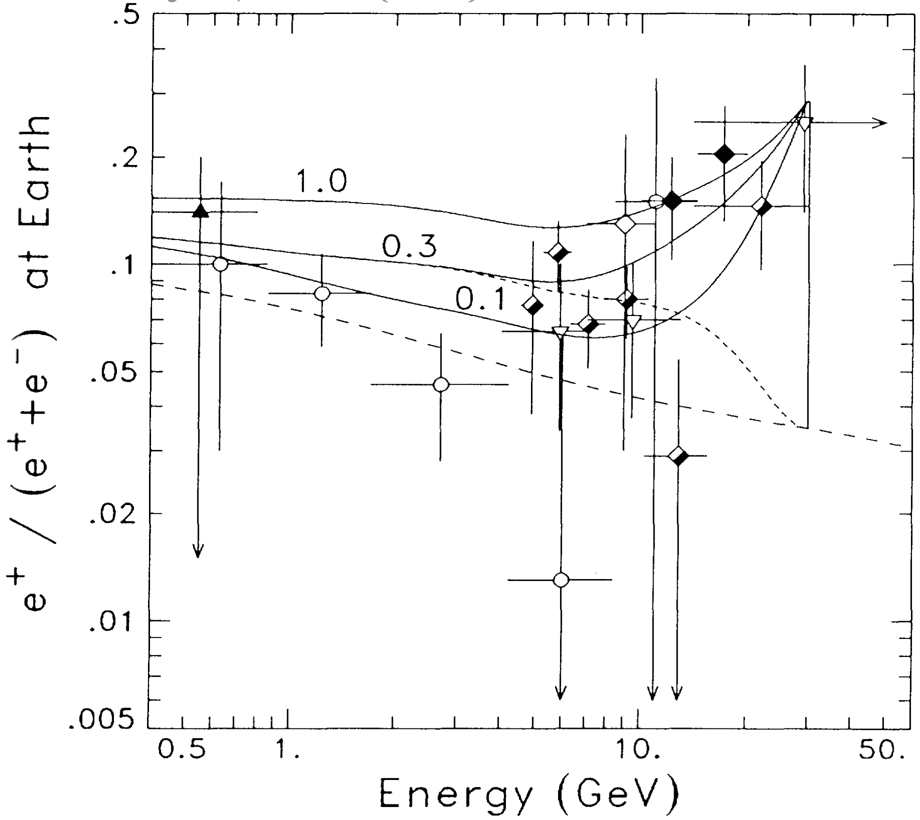
UNIVERSITY OF OXFORD

Autumn 2008

Adriani *et al.* *Nature* **458**, 607-609 (2009)



Tylka, PRL **63** (1989) 840



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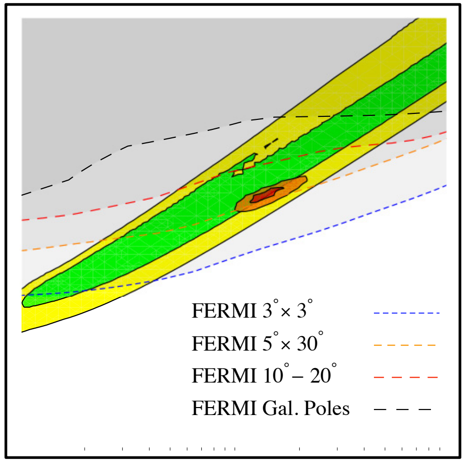
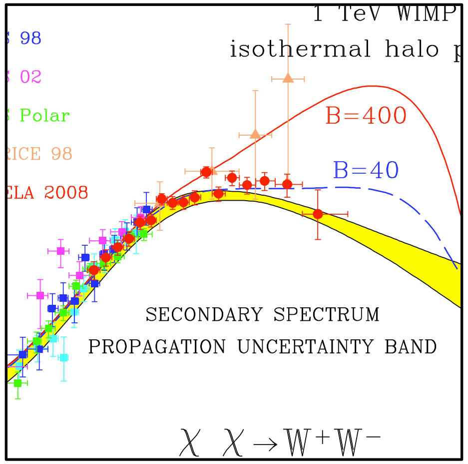
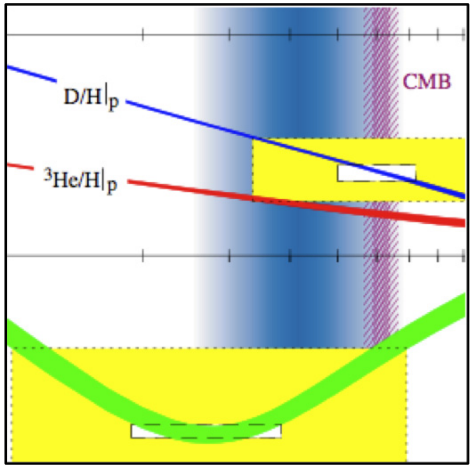
Gamma-ray constraints

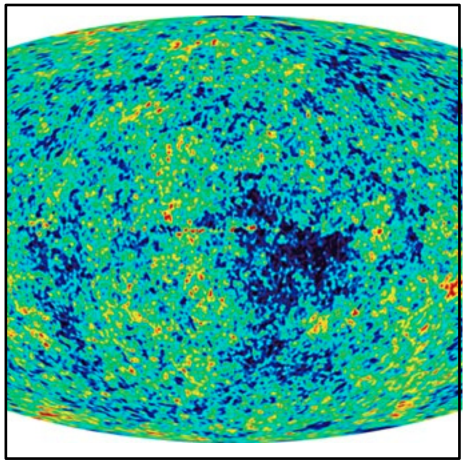




Antiproton constraints

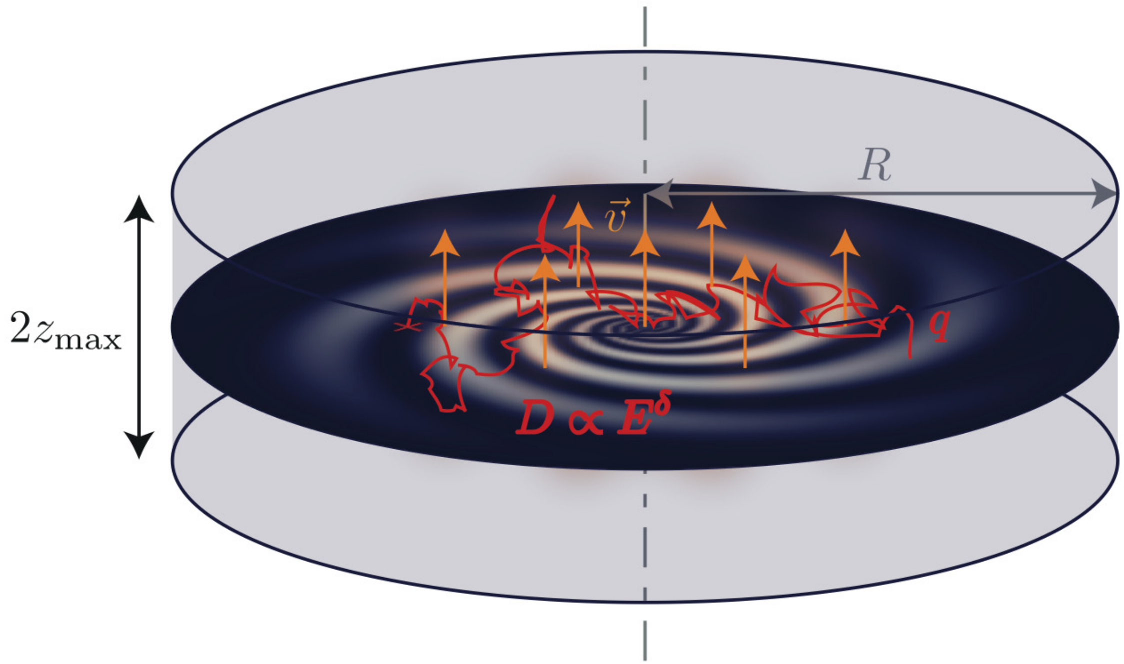
BBN constraints





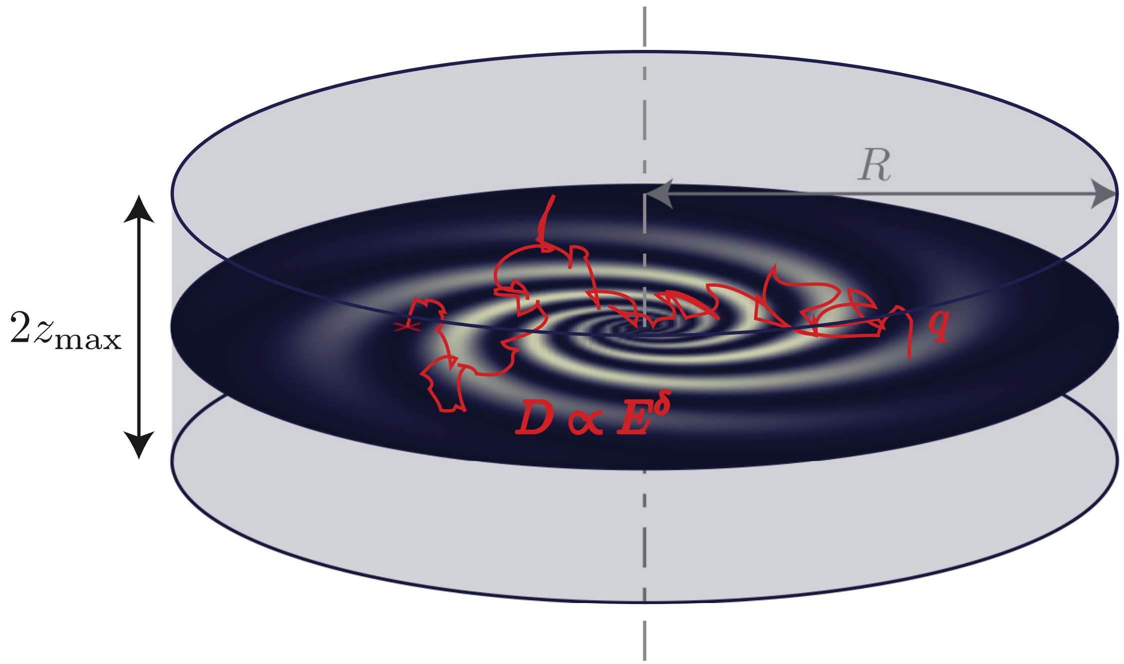
CMB constraints

Propagation of CR e^+ and e^-



Propagation of CR e^+ and e^-

$$\frac{\partial n}{\partial t} - \vec{\nabla} \cdot \left(D \cdot \vec{\nabla}\right) n - \frac{\partial}{\partial E} \left(b(E)n\right) = q$$



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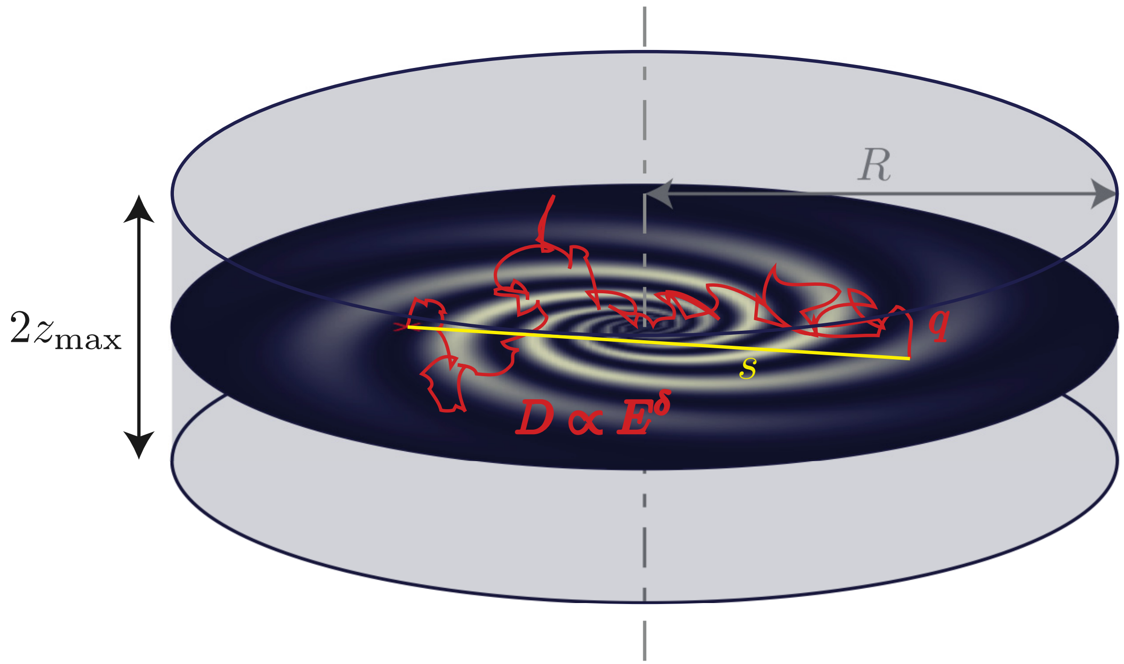
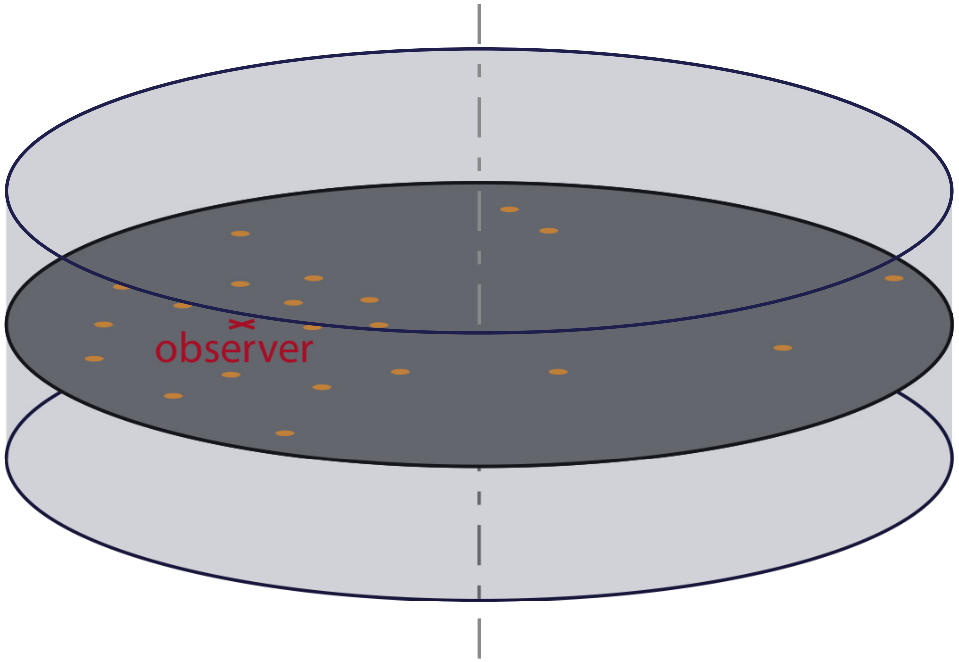


$$G(E, \vec{r}, t) \quad = \left(\pi \ell^2\right)^{-1} e^{-s^2/\ell^2} Q\left(\frac{E}{1 - b_0 E t}\right) \left(1 - b_0 E t\right)^{-2} \frac{1}{z_{\rm cr}} \chi\left(0, \frac{\ell^2}{z_{\rm cr}^2}\right)$$

Knowing Your Sources

e^- and e^+ have diffusion loss length $\ell(E) \sim \mathcal{O}(1)\mathrm{kpc}$ for energies $\gtrsim 100\,\mathrm{GeV}$

➡ discreteness of sources becomes important



Problems: selection effects, distance uncertain, efficiency

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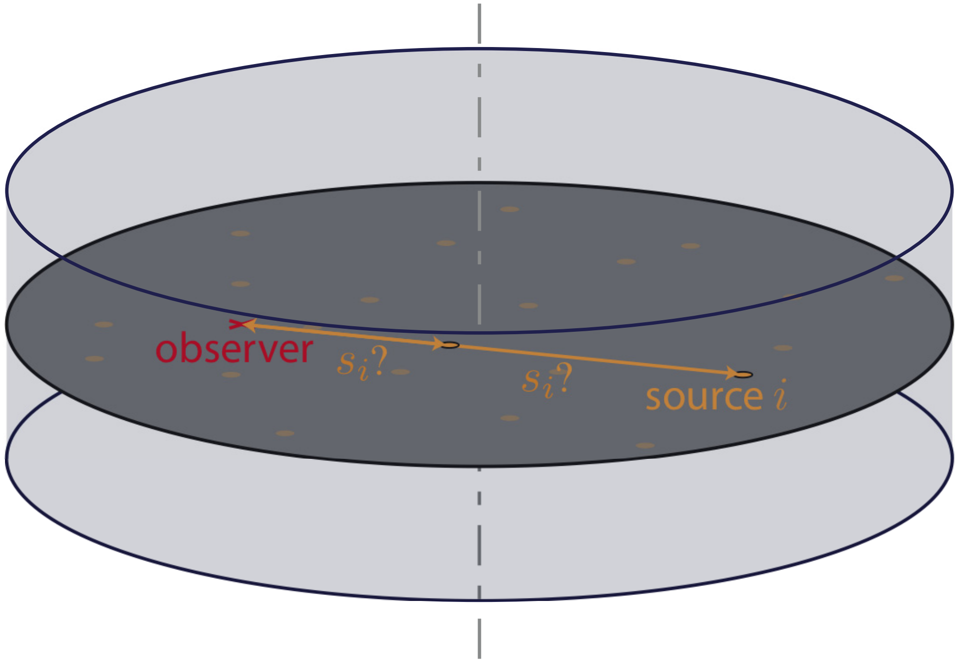

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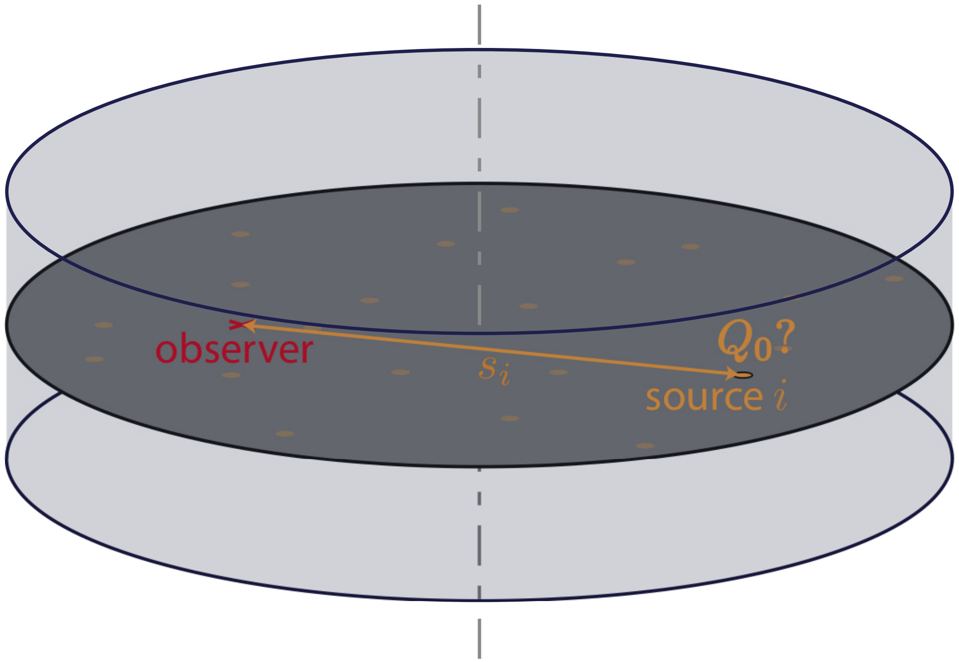
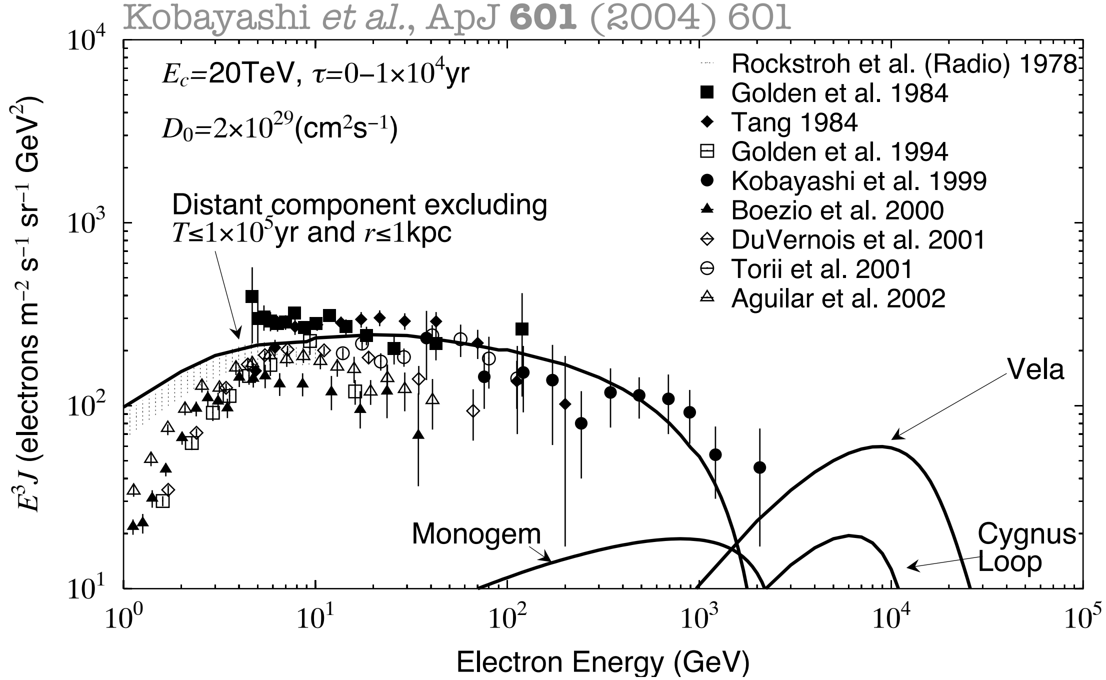


Problems: selection effects, distance uncertain, efficiency

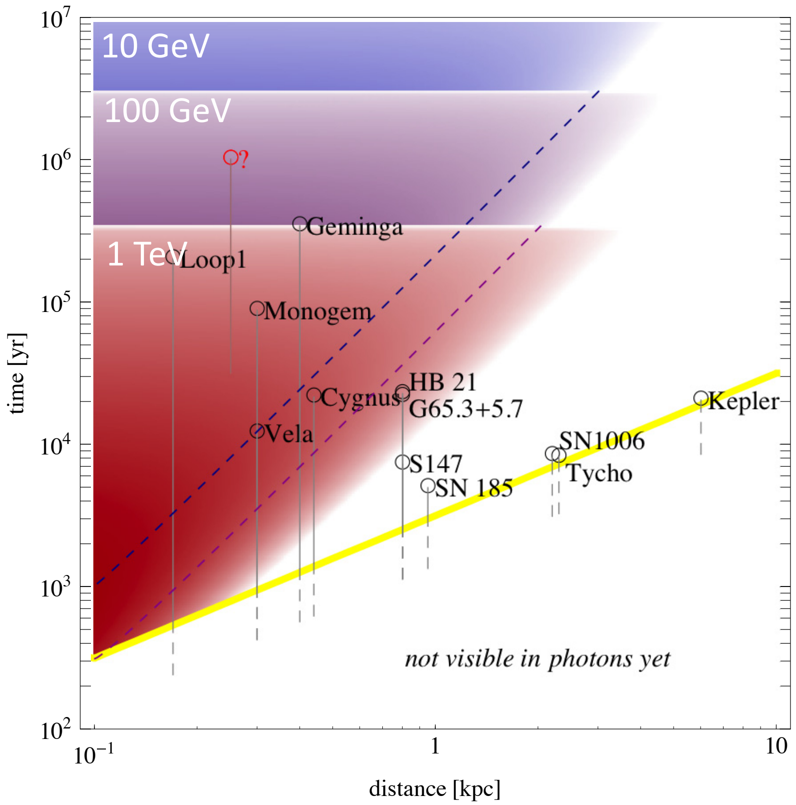
A Hybrid Model

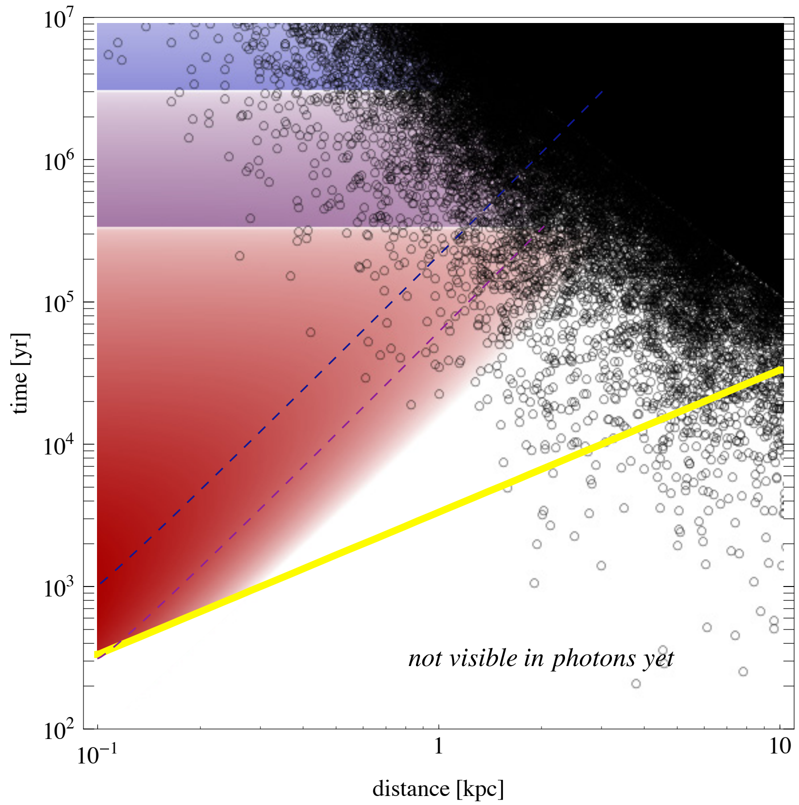
- homogeneous distribution for sources with distances $\gtrsim 1\,\mathrm{kpc}$ or ages $\gtrsim 10^5\,\mathrm{yr}$
- supplement with *known* young and nearby sources

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



A Caveat

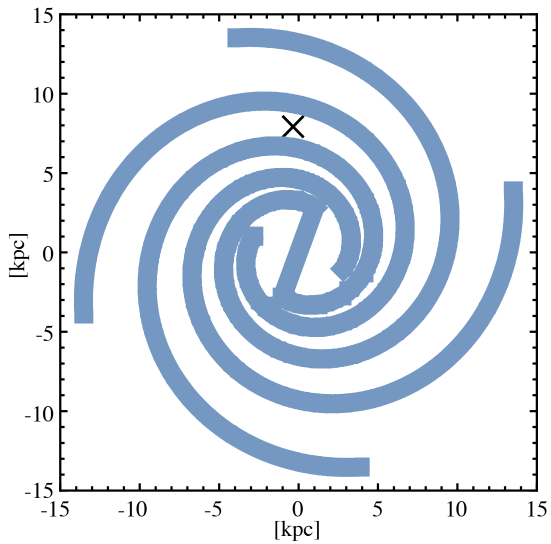




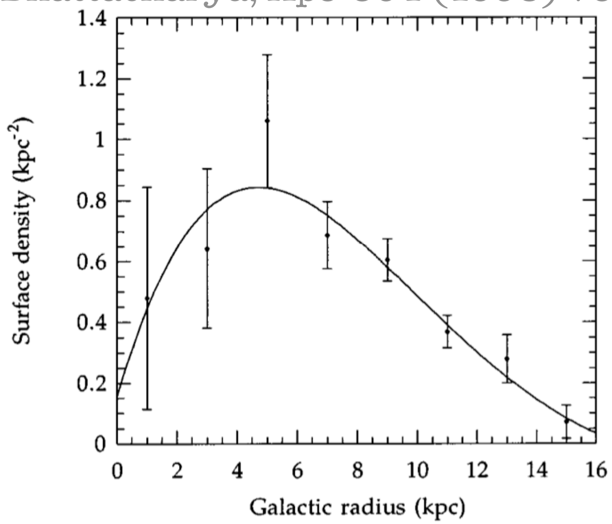
Not only observed sources contribute!

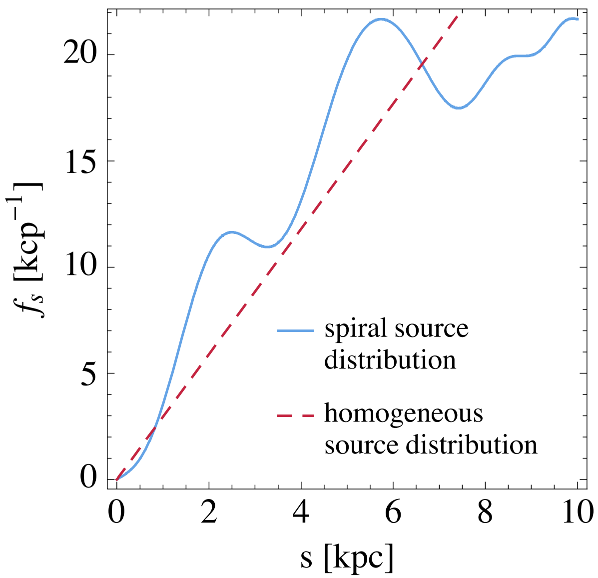
Ahlers, Mertsch, Sarkar, PRD **80** (2009) 123017

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

Central Limit Theorem

moments of the Green's function

$$\langle G^m \rangle = \int \mathrm{d}g\, f_G(g) g^m = \int_0^{t_{\max}} \mathrm{d}t\, f_t(t) \int_0^{s_{\max}} \mathrm{d}s f_s(s)\, G^m(s,t)$$

use central limit theorem for expectation value and standard deviation

$$\mu_J = \frac{c}{4\pi} N \mu_G = \frac{c}{4\pi} N \langle G \rangle \,,$$

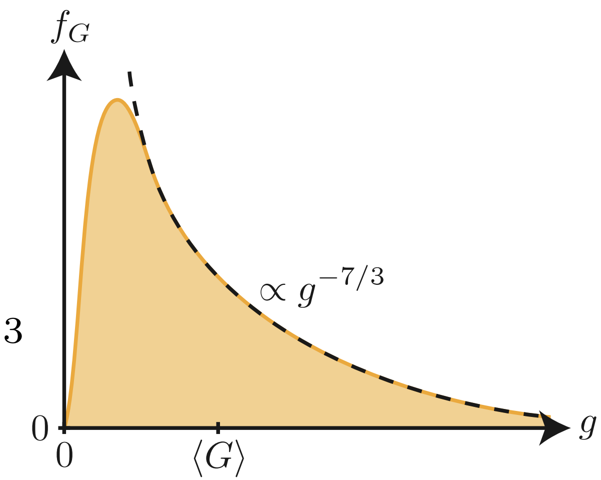
$$\sigma_J = \frac{c}{4\pi} \sqrt{N} \sigma_G = \frac{c}{4\pi} \sqrt{N} \sqrt{\langle G^2 \rangle - \langle G \rangle^2}$$

variance diverges

$$\langle G^2 \rangle \to \infty$$

because of long power law tail

$$f_G \simeq \frac{1}{t_{\max}} \frac{1}{8\pi^2 D_0} \frac{a_0}{2} E^{-\delta - \frac{4}{3}\gamma} Q_0^{4/3} \mathrm{e}^{-\frac{4}{3} E/E_{\mathrm{cut}}} g^{-7/3}$$



Stable Distributions

for $g \to \infty$

$$f_G \simeq \underbrace{\frac{1}{t_{\max}} \frac{1}{8\pi^2 D_0} \frac{a_0}{2} E^{-\delta-\frac{4}{3}\gamma} Q_0^{4/3} \mathrm{e}^{-\frac{4}{3}E/E_{\mathrm{cut}}}}_{w} \, g^{-1-\alpha} \quad \text{with} \quad \alpha = \frac{4}{3}$$

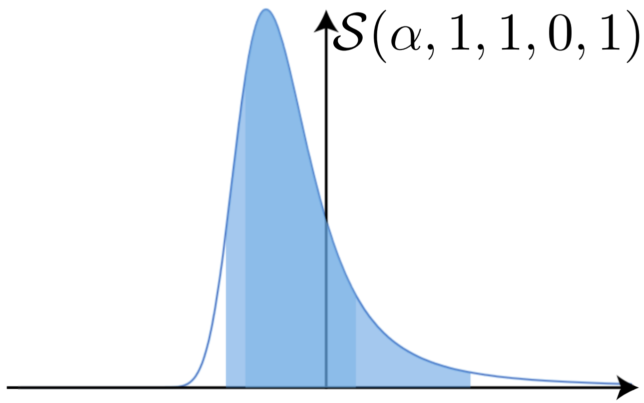
generalised central limit theorem for distributions with power law tail

Gendenko & Kolmogorov

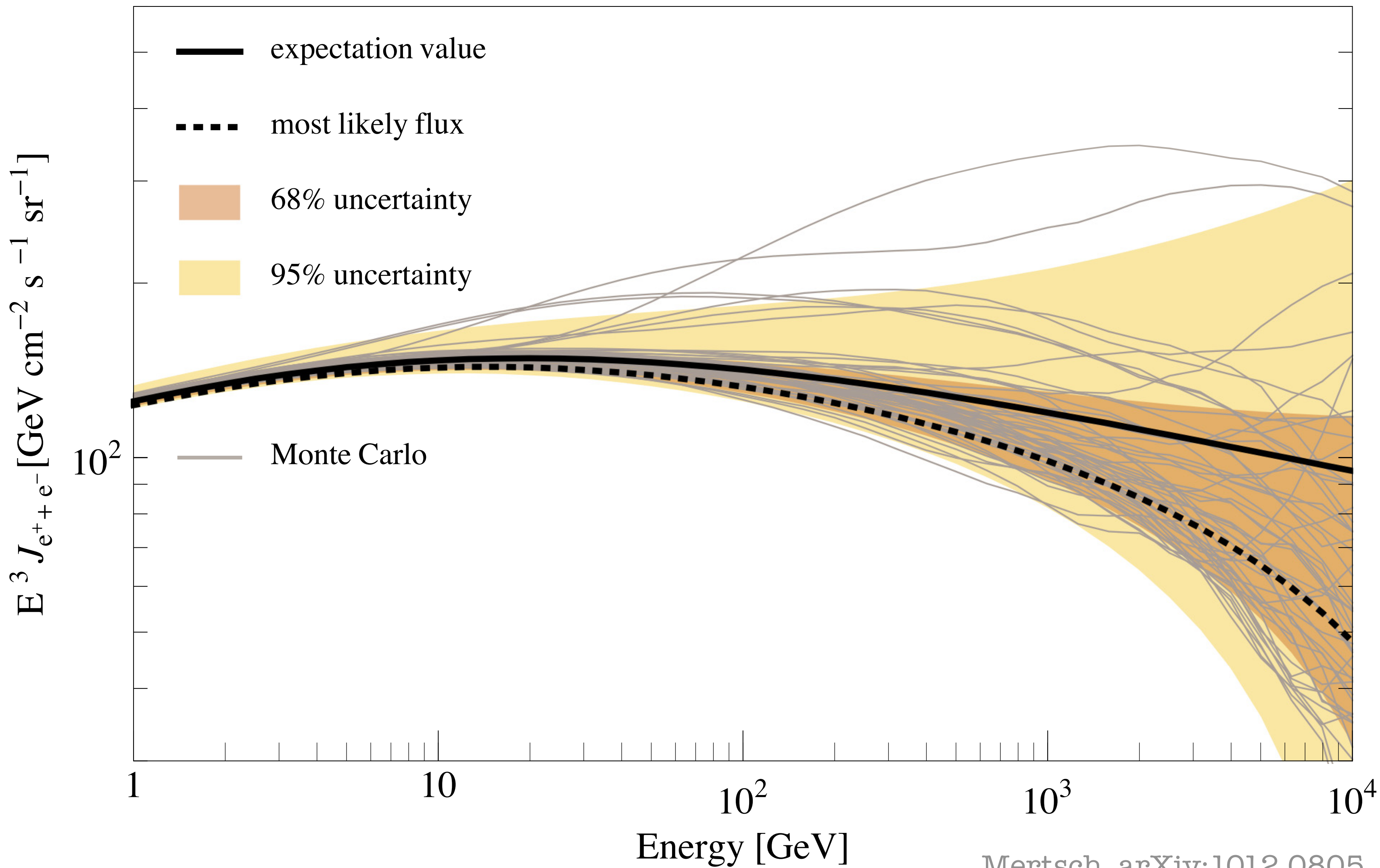
$$\sum_i^N X_i \xrightarrow{N \to \infty} u_N + v_N \mathcal{S}(\alpha, 1, 1, 0, 1)$$

with $u_N = N\mu_G$

$$v_N = \left(\frac{\pi w}{2\Gamma(\alpha) \sin\left(\frac{\pi}{2}\alpha\right)} \right)^{1/\alpha} N^{1/\alpha}$$

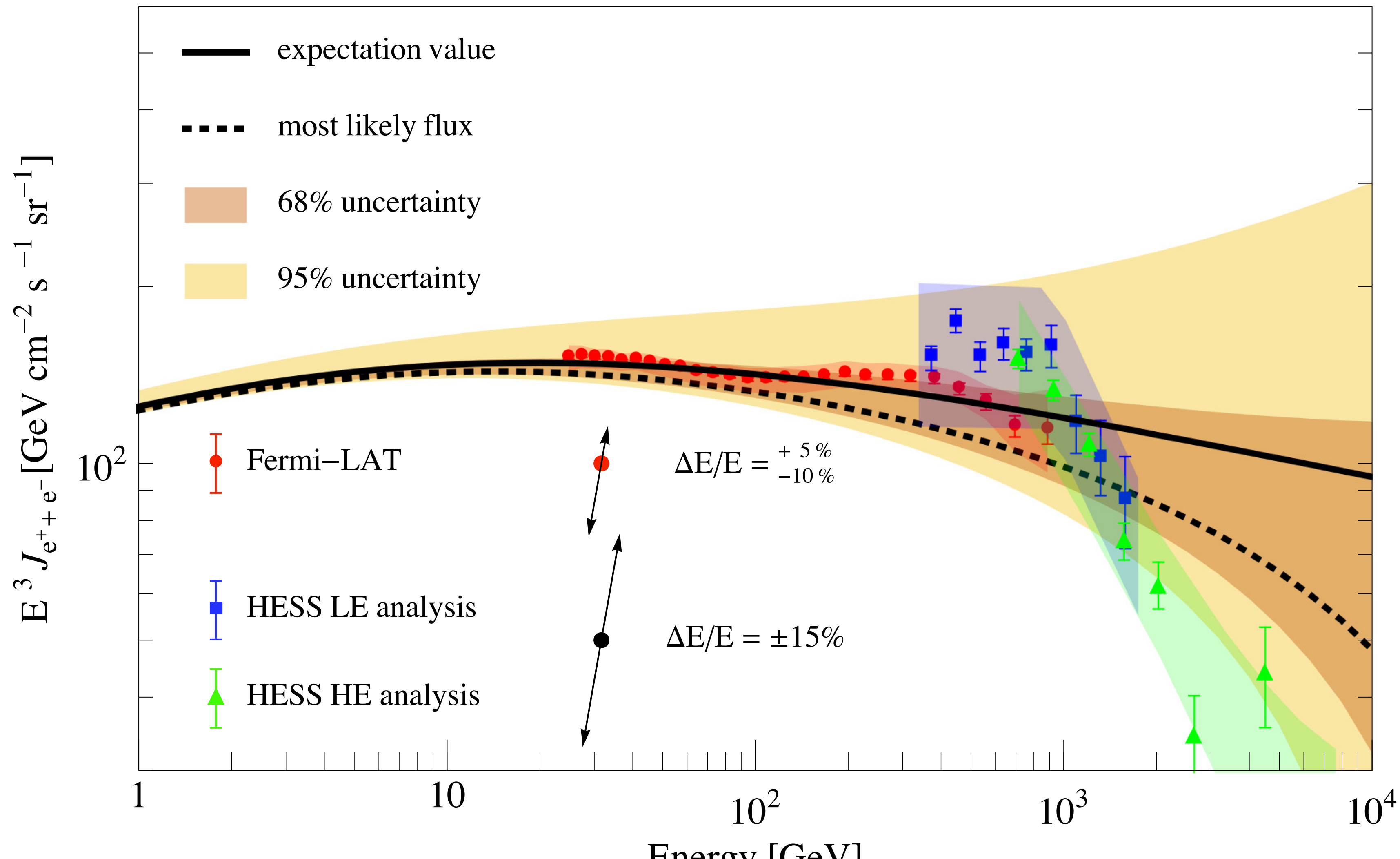


Stochastic Fluctuations



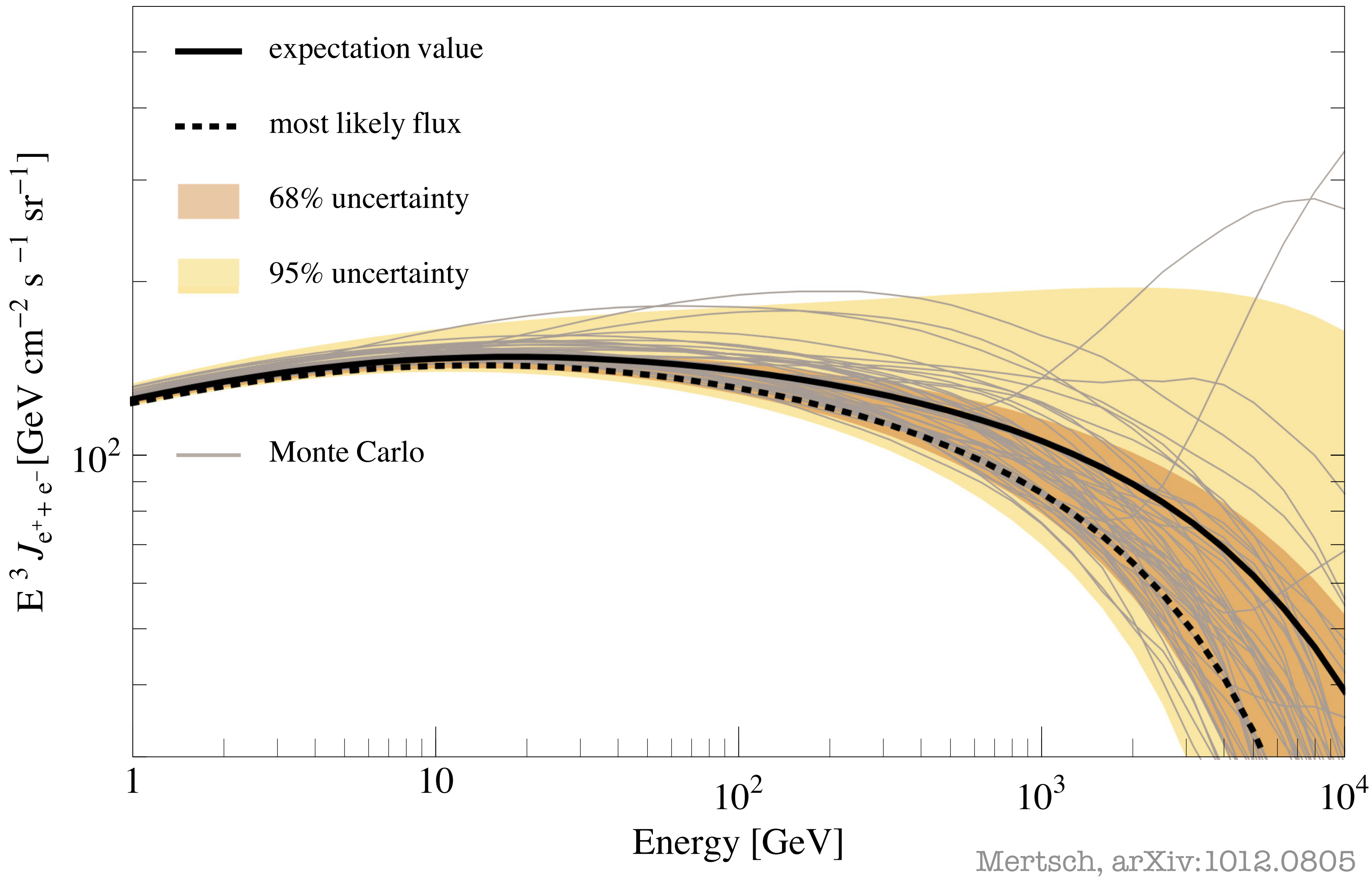
Mertsch, arXiv:1012.0805

Stochastic Fluctuations



Mertsch, arXiv:1012.0805

Stochastic Fluctuations (with cut-off)



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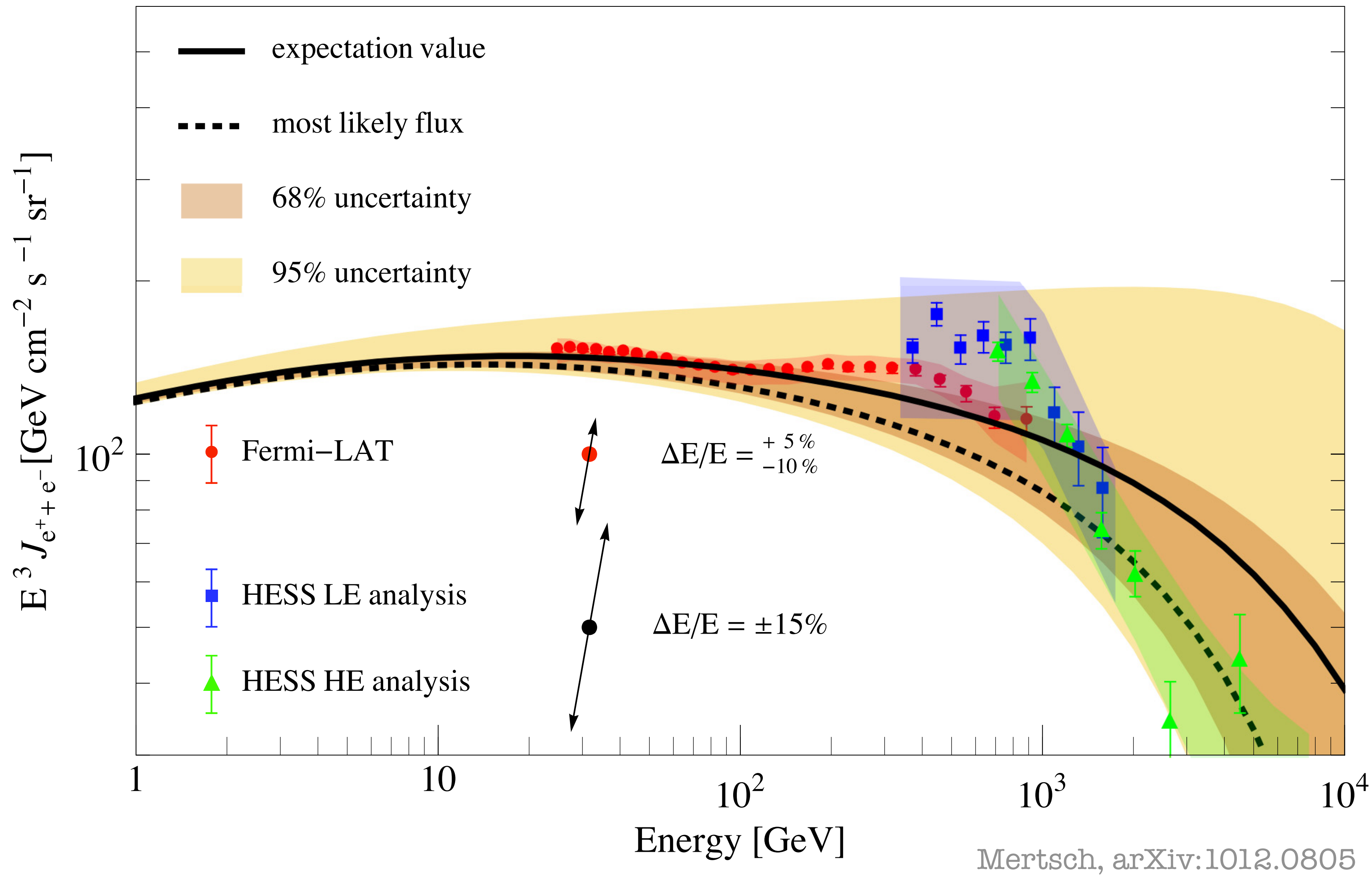


Mertsch, arXiv:1012.0805

Energy Spectra

primary e^-

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

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

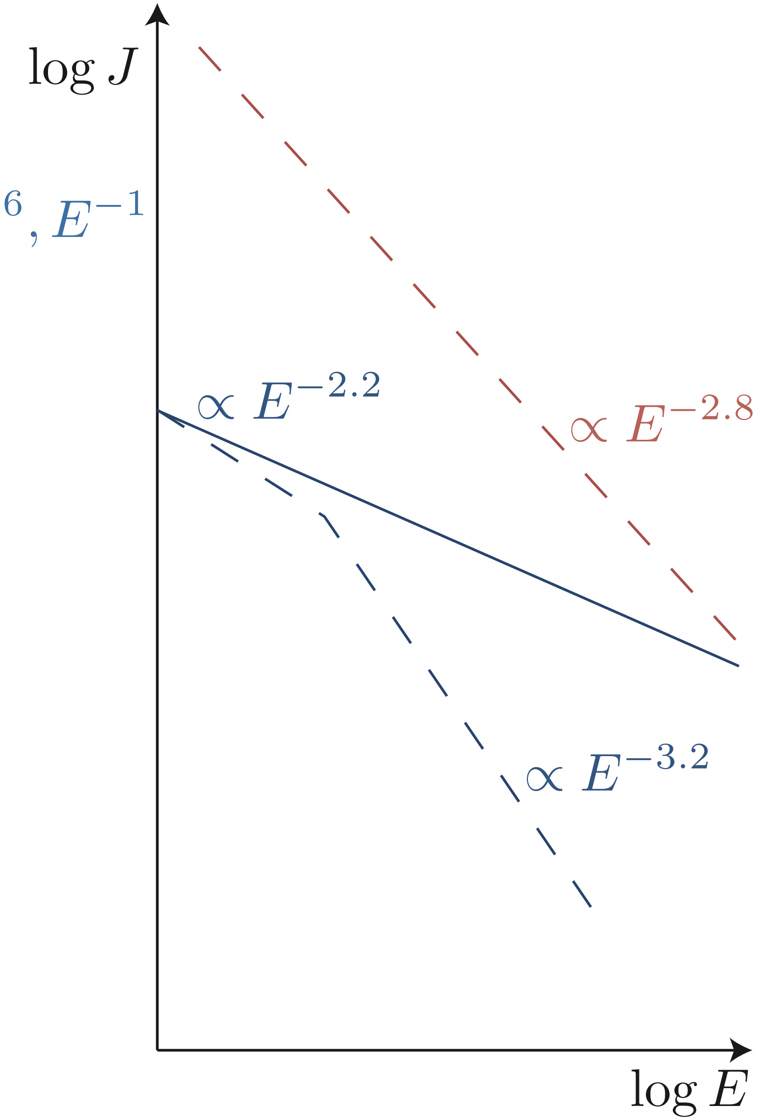
ambient: $n \propto E^{-2.8}, E^{-3.2}$

CR protons/nuclei

production: ?

propagation: ?

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



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CR protons/nuclei

production: ?

propagation: ?

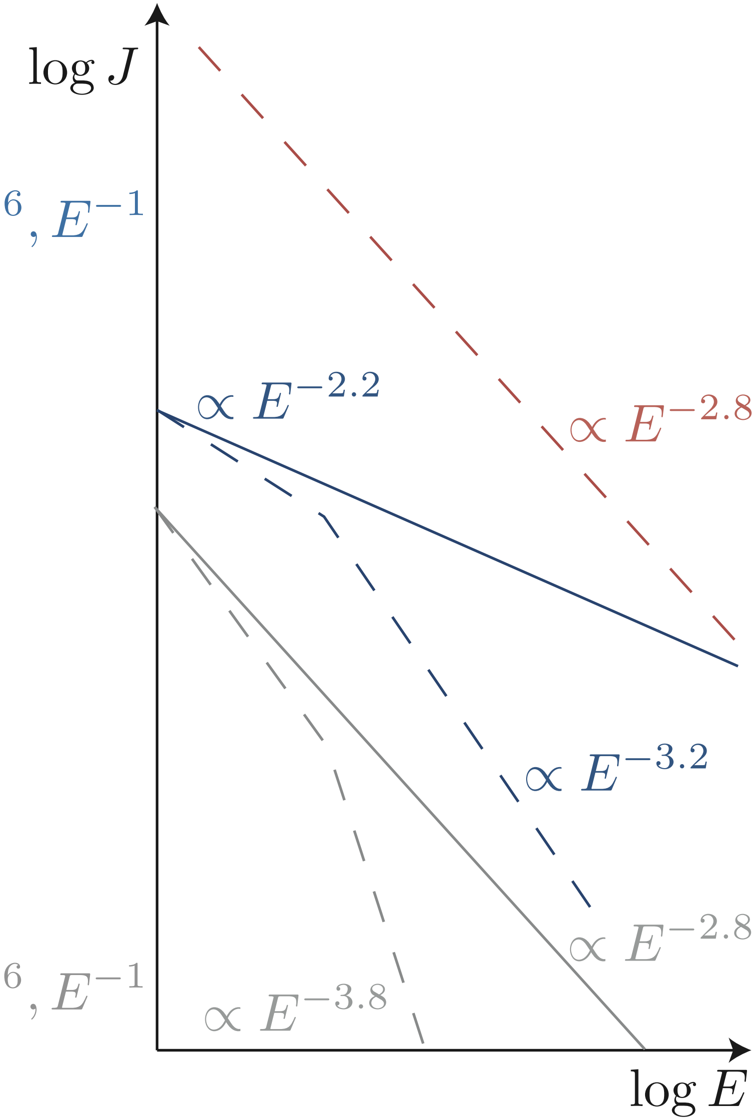
ambient: $n \propto E^{-2.8}$

secondary $e^{\pm}$

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

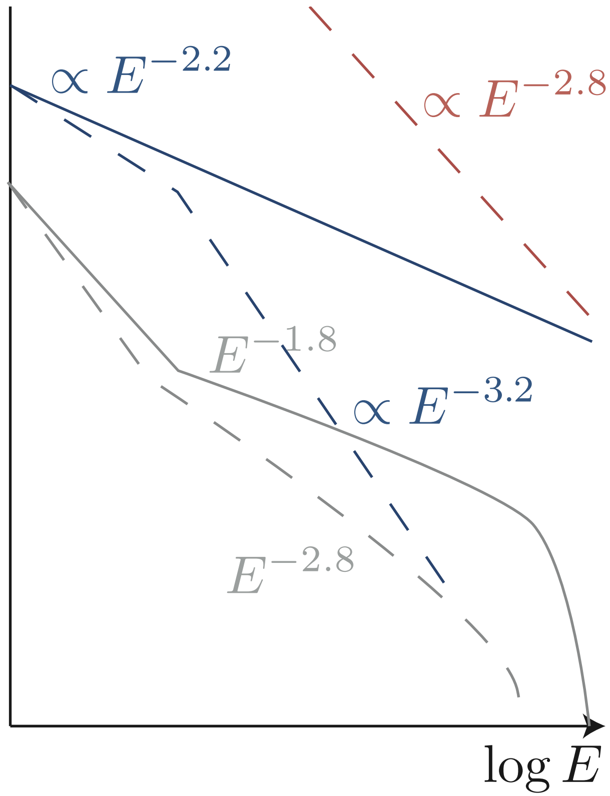
propagation: $\min[\tau_{esc}, \tau_{cool}] \propto E^{-0.6}, E^{-1}$

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



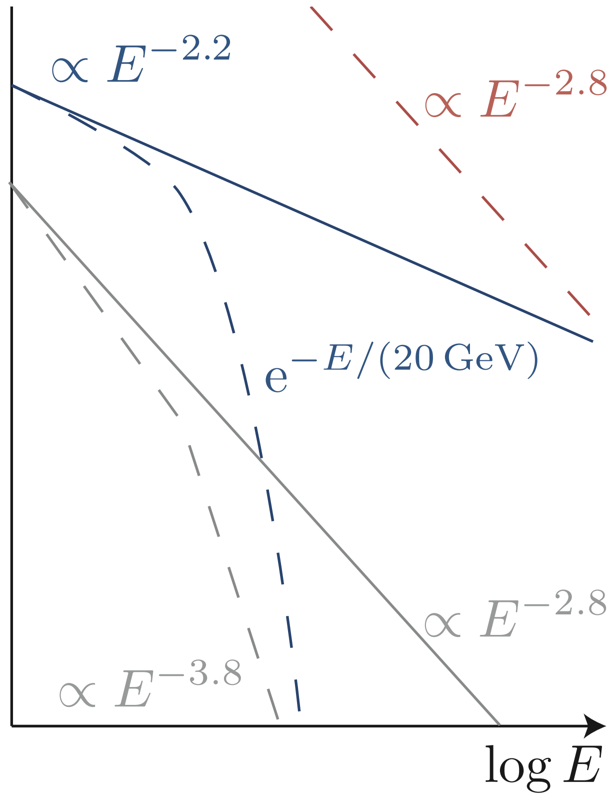
Rising Positron Fraction

harder positron injection



- DM annihilation or decay
- Nearby pulsars
- Acceleration of Secondaries

softer electron spectrum



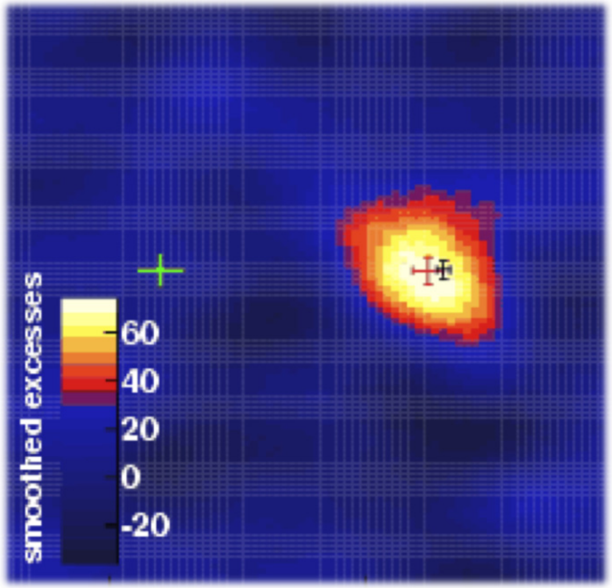
- Propagation cut-off in primary electrons

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, PAMELA 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,

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

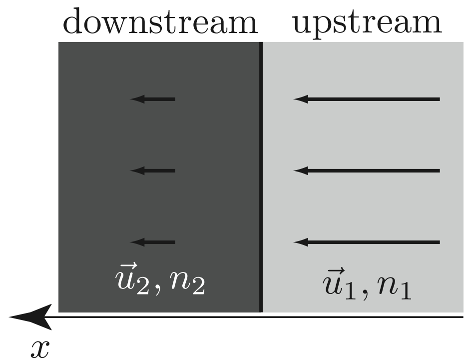
$$f \xrightarrow{x\to-\infty} f_{\rm inj}(p), \qquad \left|\lim_{x\to\infty} f\right| \ll \infty$$

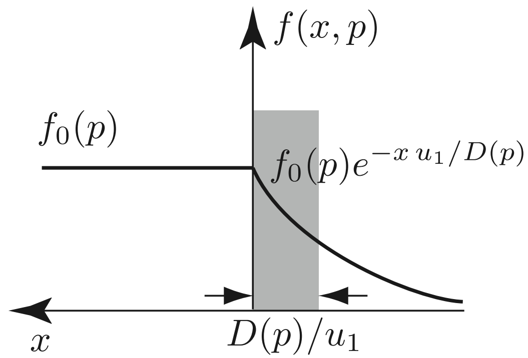
Solution for $x < 0$:

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

where

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





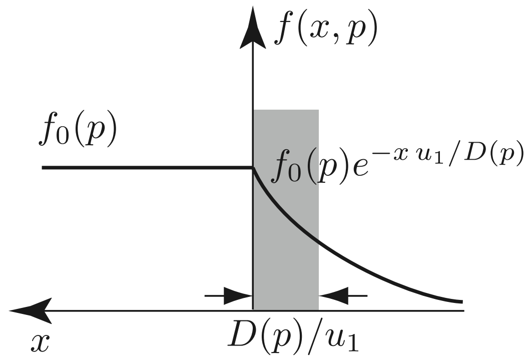
As long as $f_{\rm inj}(p)$ is softer than $p^{-\gamma}$, at high energies:

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

DSA with Secondaries

- Secondaries get produced with primary spectrum:

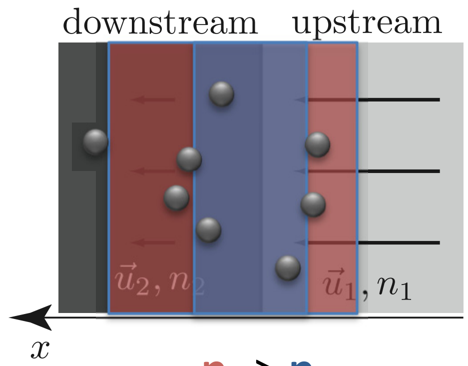
$$q_{e^\pm} \propto f_{\rm CR} \propto p^{-\gamma}$$



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

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

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



$p_2 > p_1$

- 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 Coefficient

- Diffusion coefficient not known *a priori*

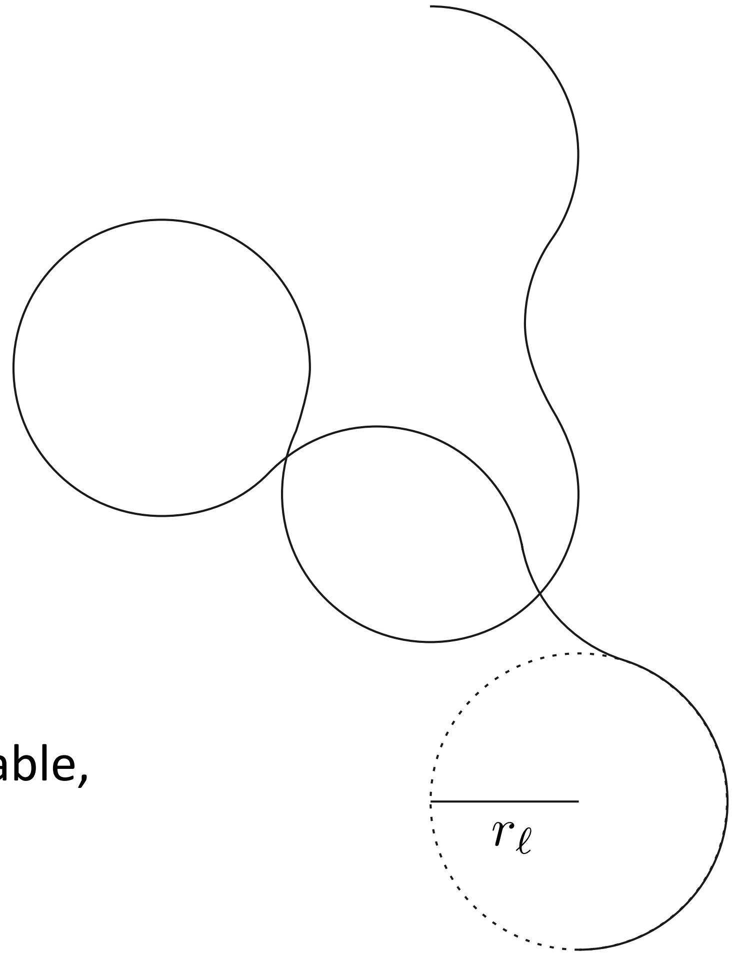
- Bohm diffusion sets lower limit

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

- Difference parametrised by fudge factor K_B

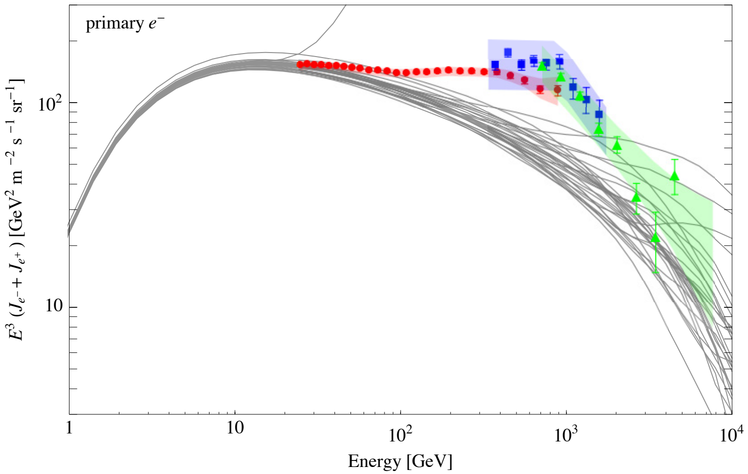
$$D = D_{\text{Bohm}} K_B$$

- K_B determined by fitting to one observable, allows prediction for another observable

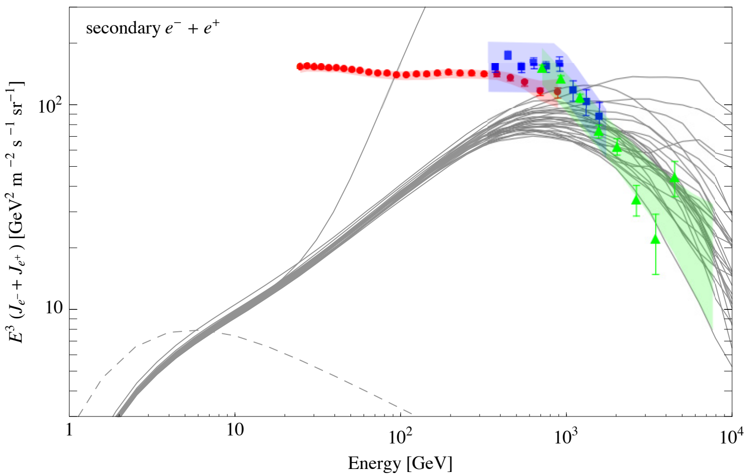


The Total $(e^+ + e^-)$ Flux

primary e^-



secondary $(e^+ + e^-)$



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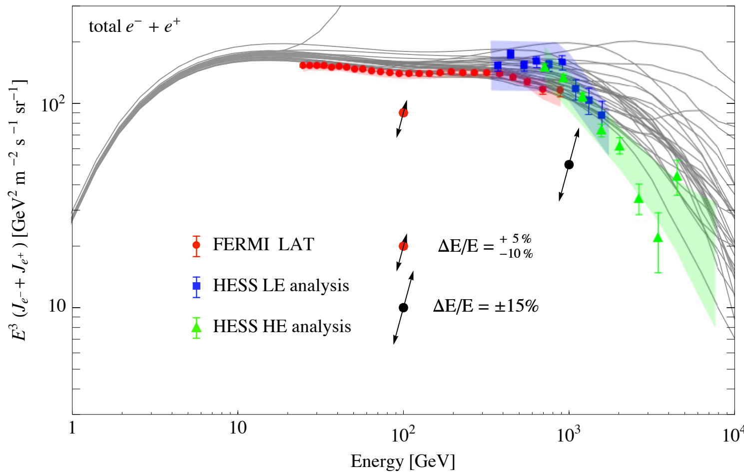

Ahlers, Mertsch, Sarkar, PRD **80** (2009) 123017

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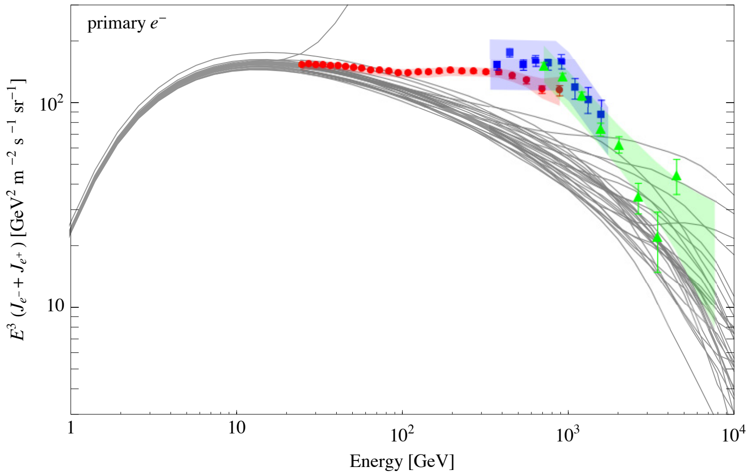

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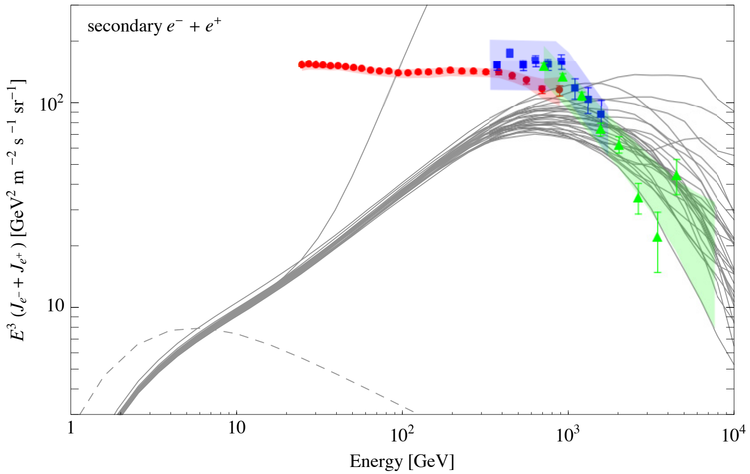

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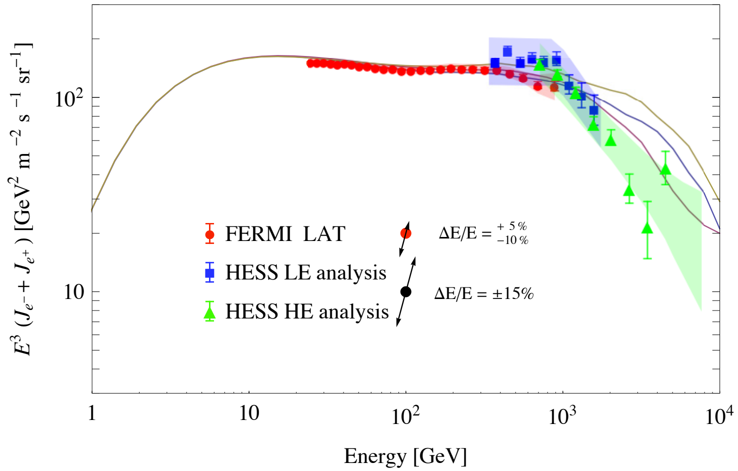
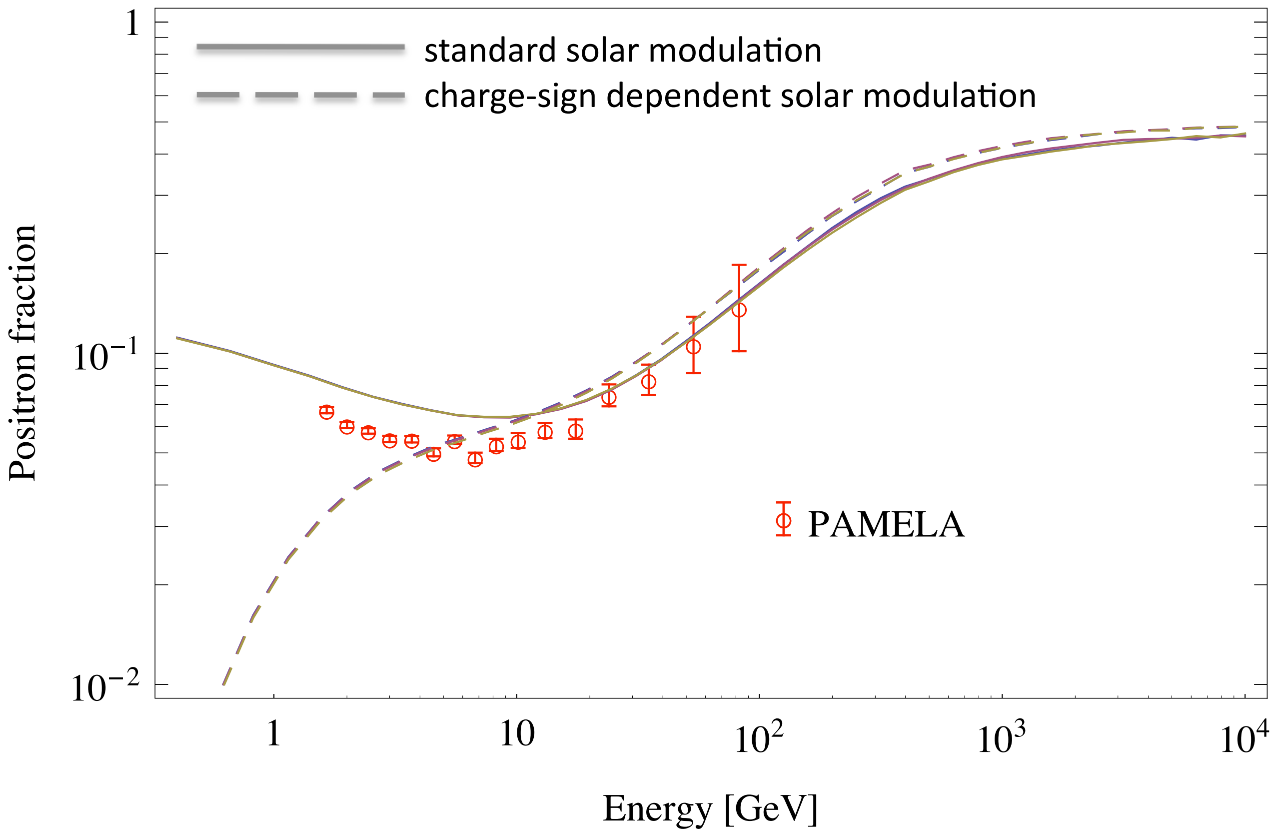


Ahlers, Mertsch, Sarkar, PRD **80** (2009) 123017

The Positron Fraction



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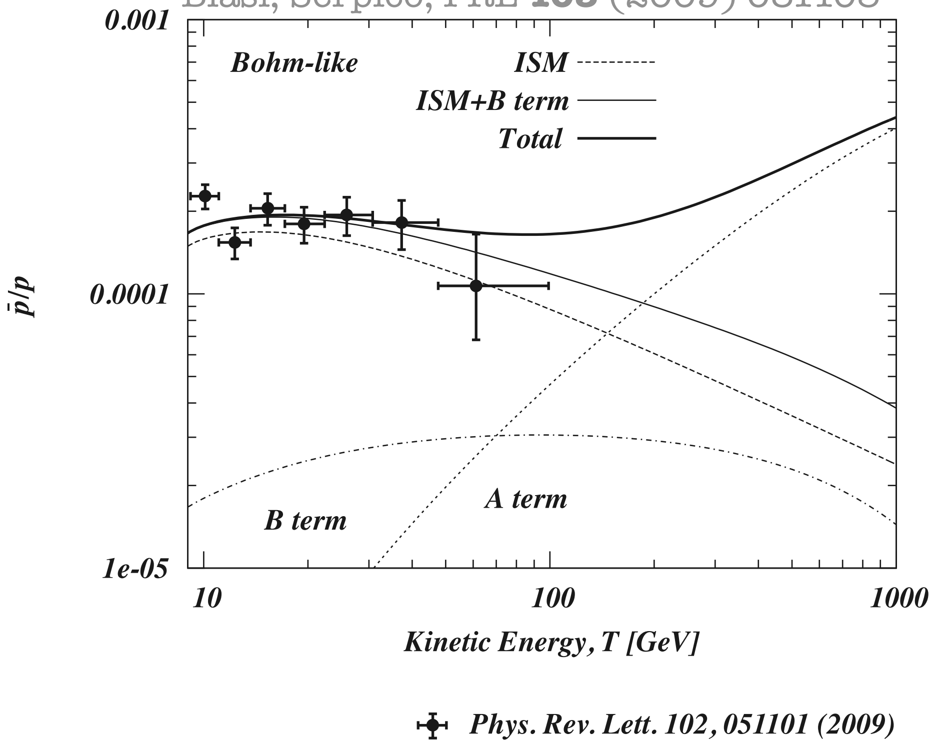
Antiproton-to-proton Ratio

rise in...	$\bar{p}/p$
DM	(✓)
Pulsars	✗
Acceleration of Secondaries	✓

Blasi, Serpico, PRL **103** (2009) 081103



Antiproton-to-proton Ratio

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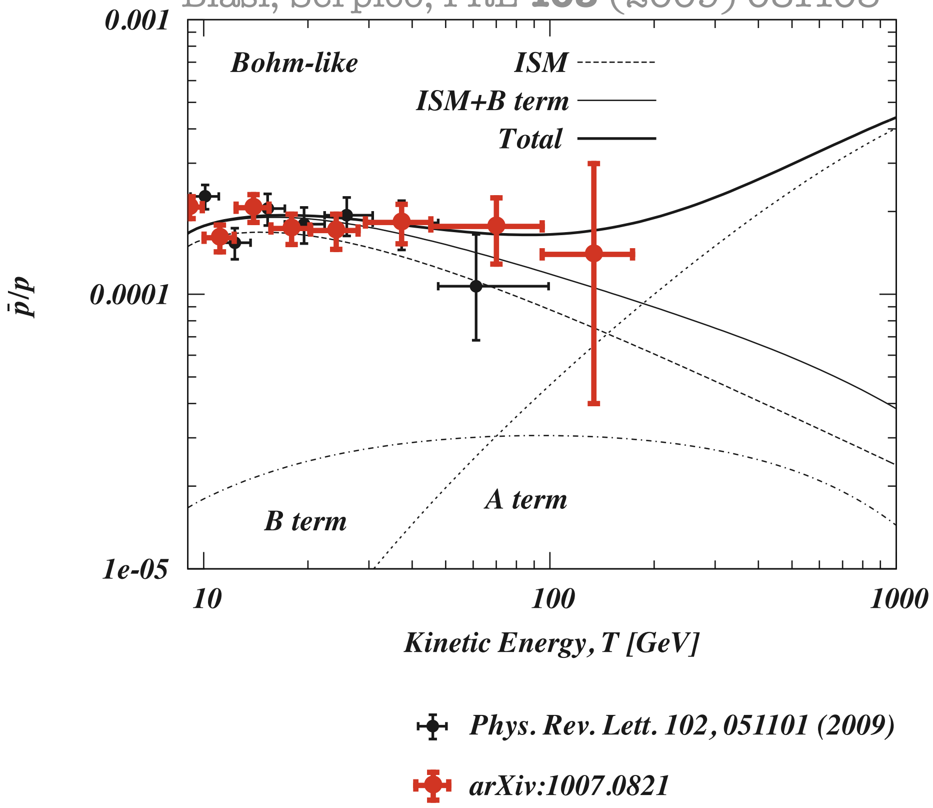
Pulsars	✗
Acceleration of Secondaries	✓

Blasi, Serpico, PRL **103** (2009) 081103

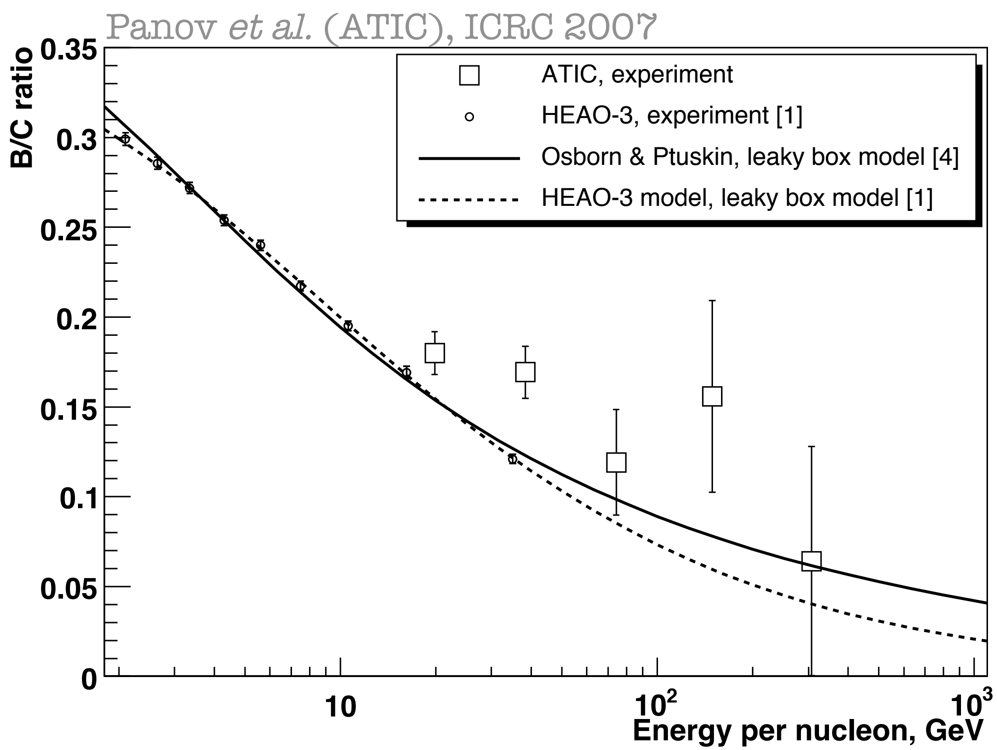


Nuclear Secondary-to-Primary Ratios

rise in...	nuclei
DM	✗
Pulsars	✗

DM and pulsars do not produce nuclei!

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



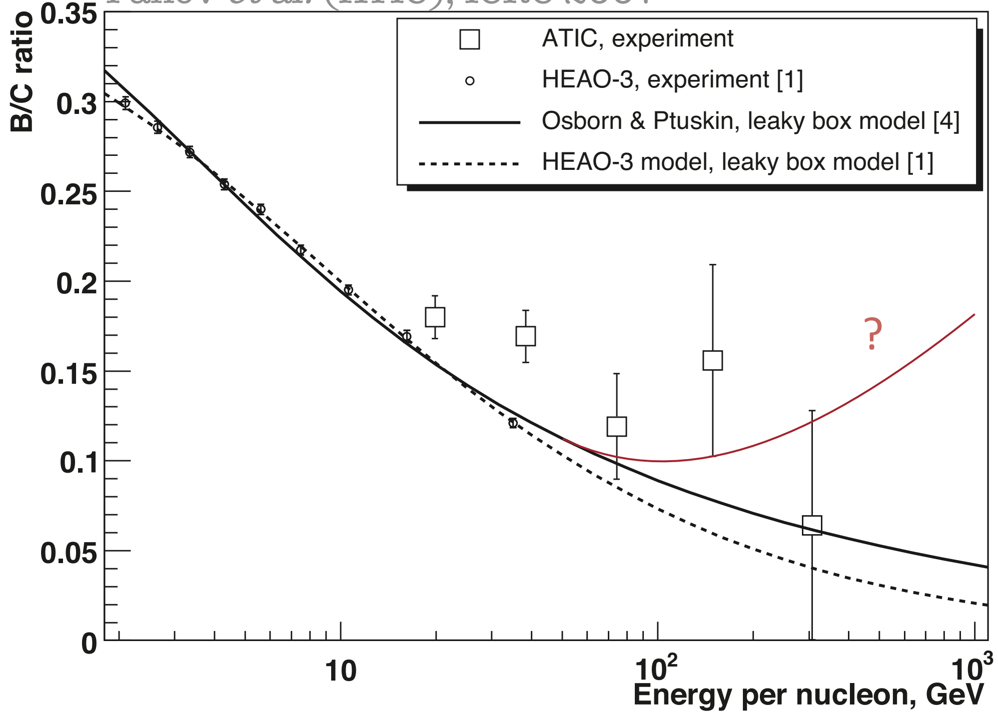
Nuclear Secondary-to-Primary Ratios

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

This would be a clear indication for acceleration of secondaries!

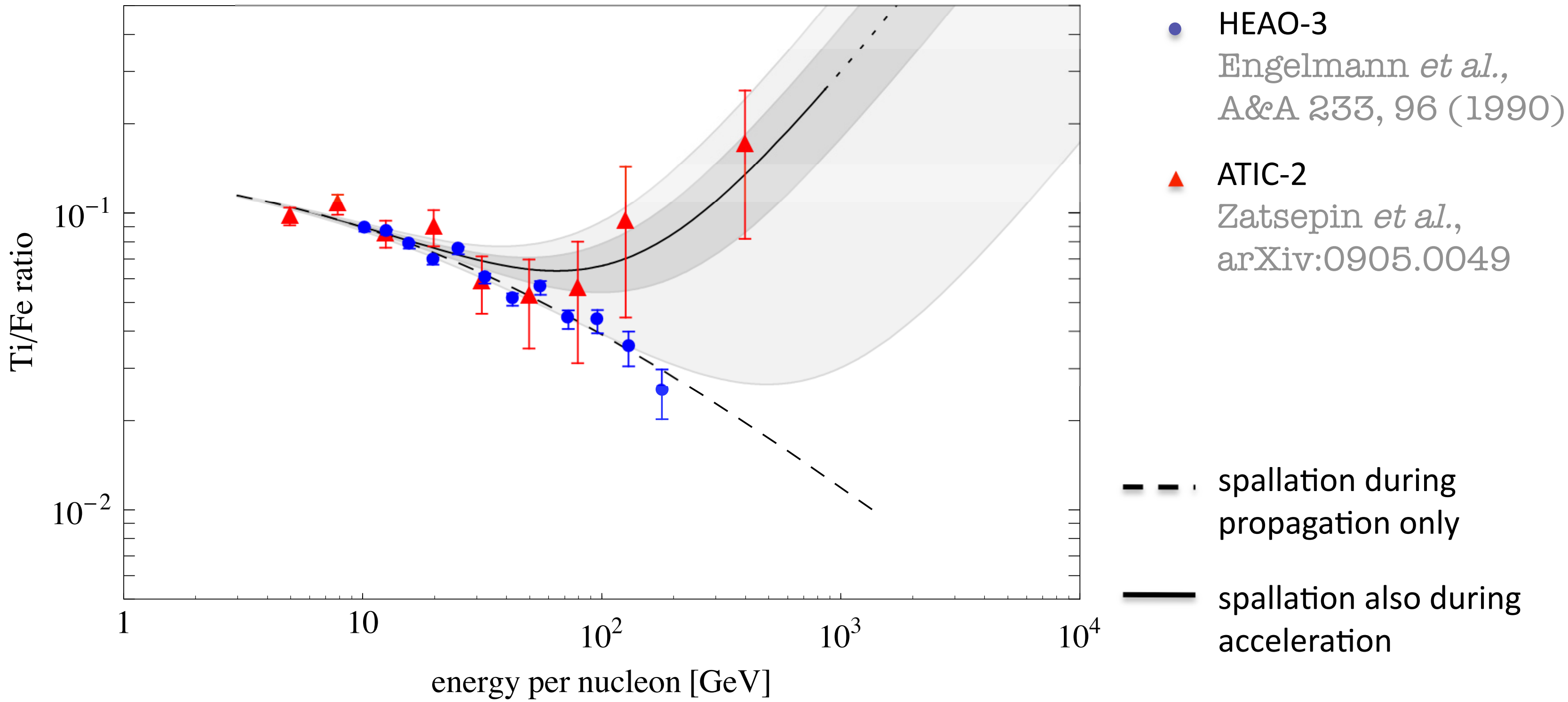
If nuclei are accelerated in the same sources as electrons and positrons, nuclear ratios *must* rise eventually

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



Titanium-to-Iron Ratio

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

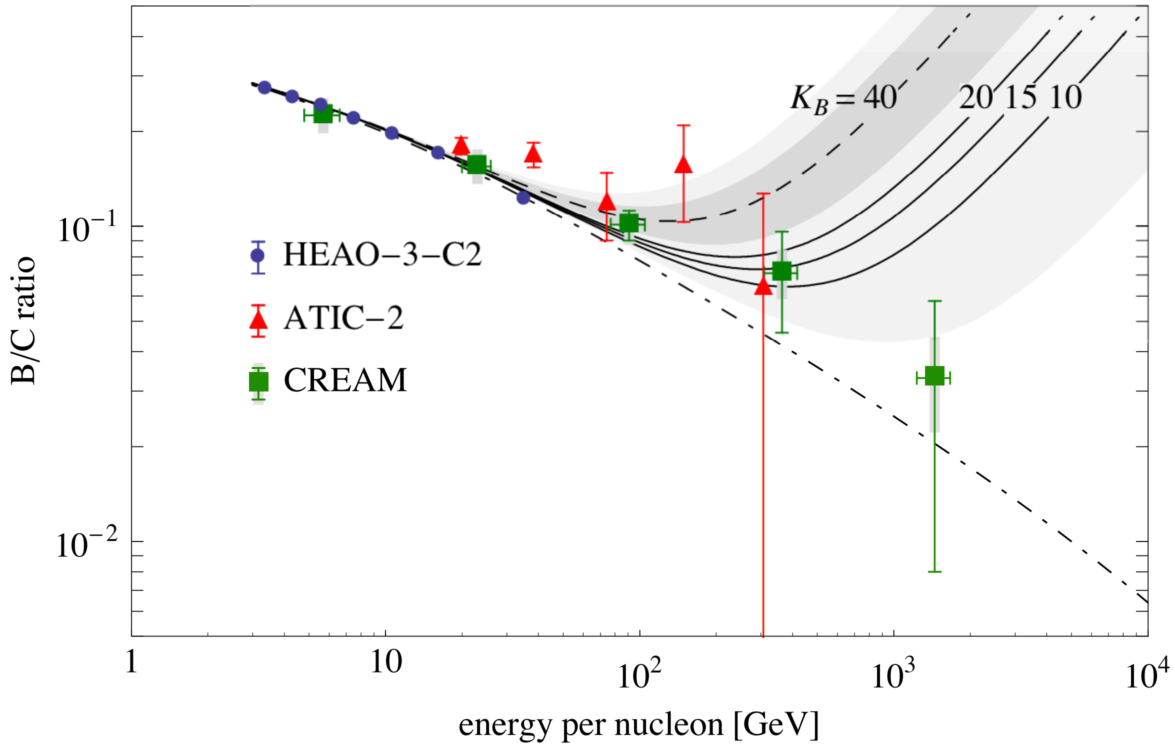


Titanium-to-iron ratio used as calibration point for diffusion coefficient:

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

Boron-to-Carbon Ratio

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



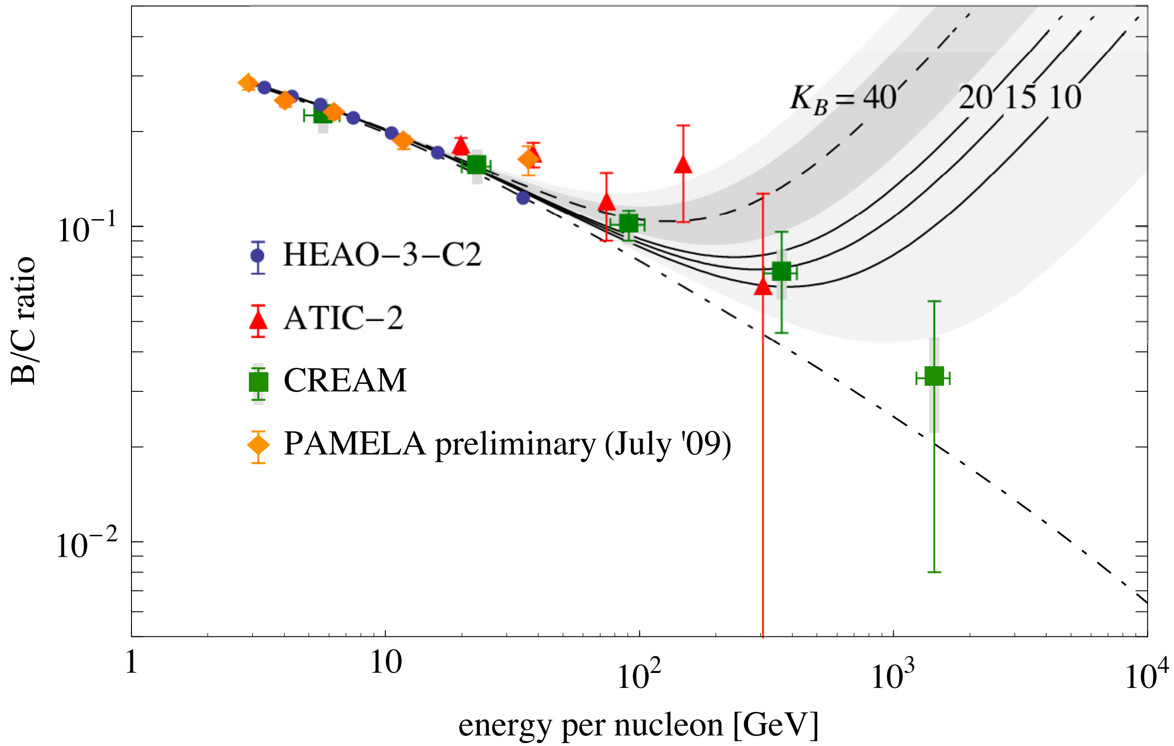
- HEAO-3
  Engelmann *et al.*, A&A 233, 96 (1990)
- ATIC-2
  Panov *et al.*, ICRC 2007
- CREAM
  Ahn *et al.*, Astropart. Phys. 30, 133 (2008).
- spallation during propagation only
- spallation also during acceleration

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



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

ATIC-2
Panov *et al.*, ICRC 2007

CREAM
Ahn *et al.*, Astropart. Phys. 30, 133 (2008).

spallation during propagation only

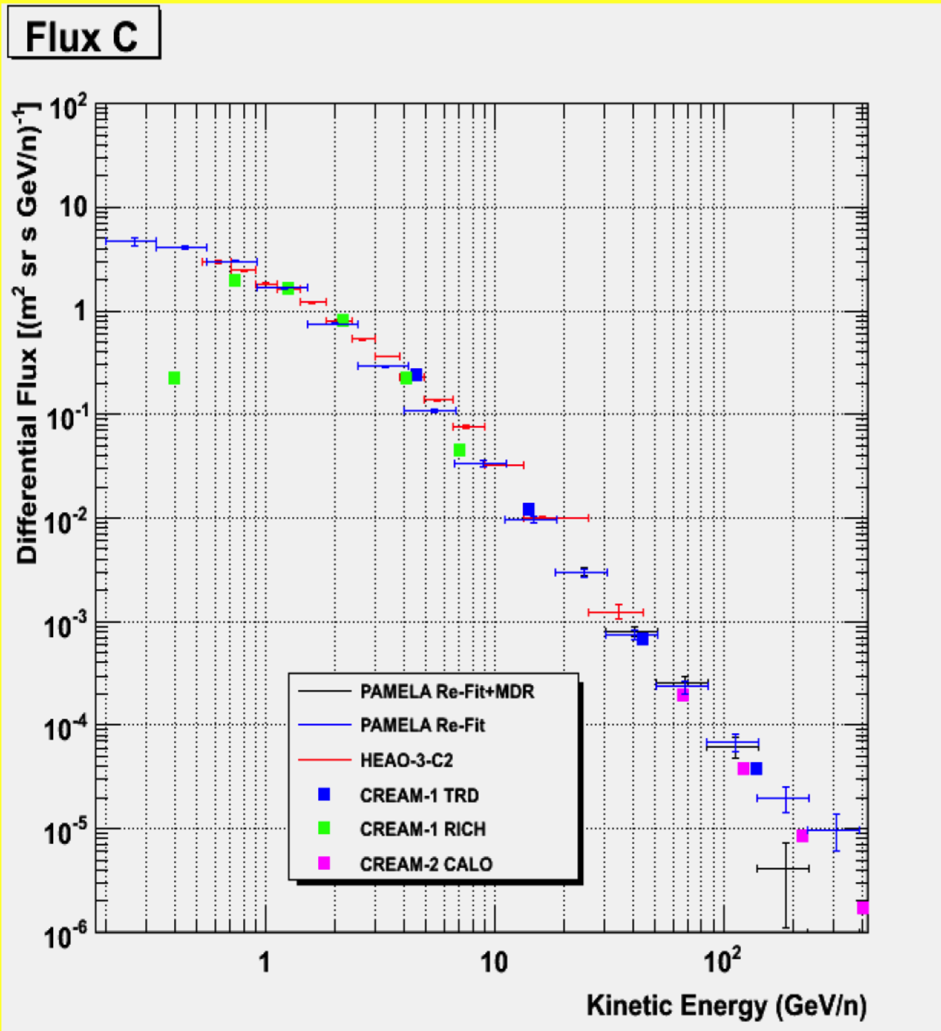
spallation also during acceleration

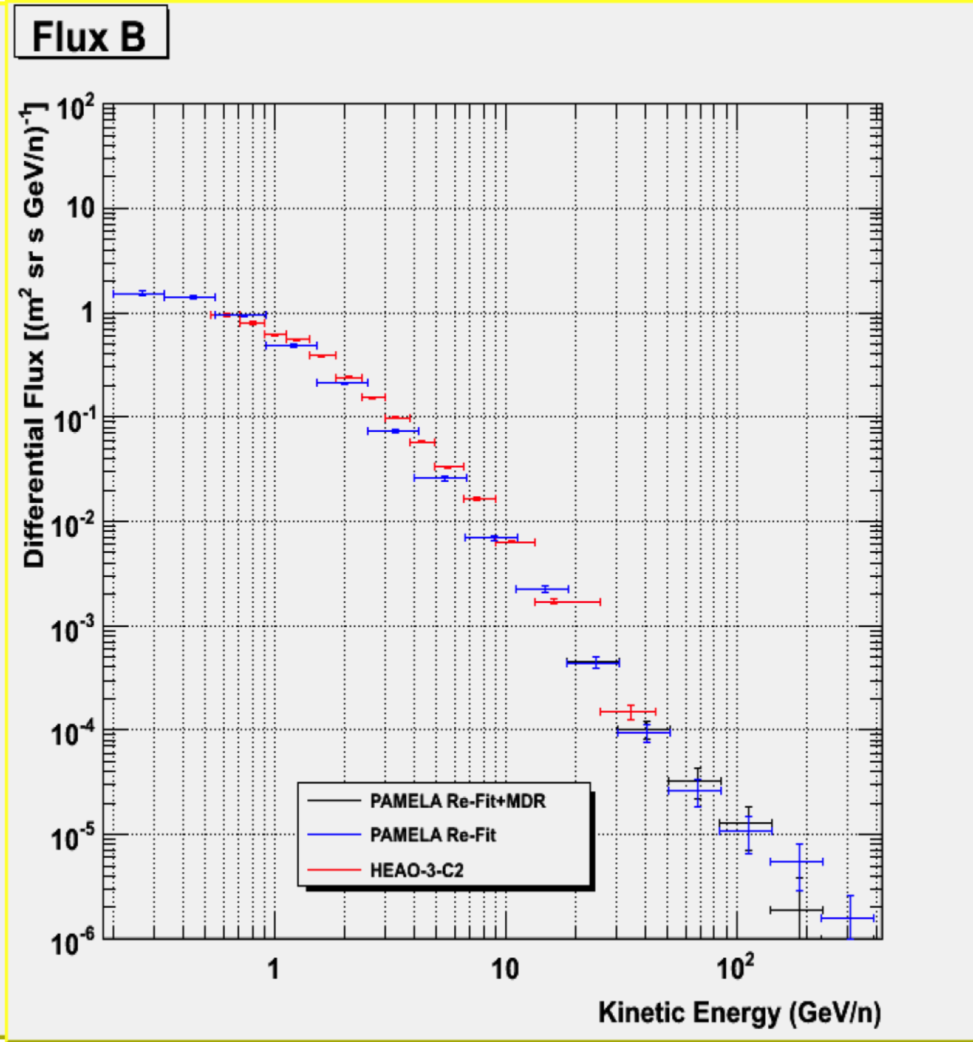
PAMELA is currently measuring B/C with unprecedented accuracy

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

BORON AND CARBON FLUX – IN PROGRESS

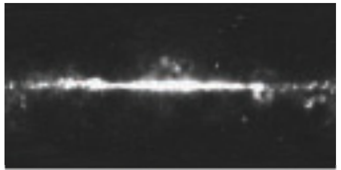
R. Sparvoli, 6th Patras Workshop on Axions, WIMPs and WISPs, 5-9 July 2010



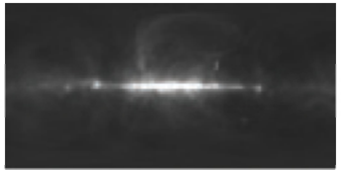


‘WMAP haze’

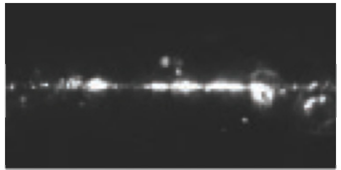
Claim by Finkbeiner (2004)



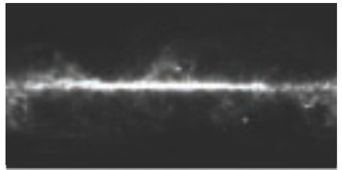
CMB-subtracted WMAP K-band



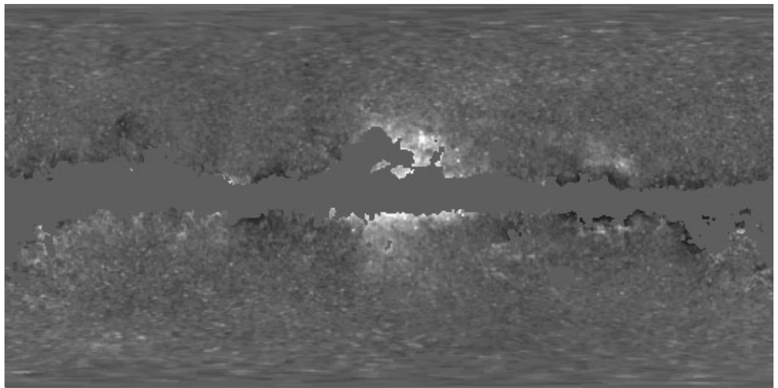
synchrotron



free-free



dust



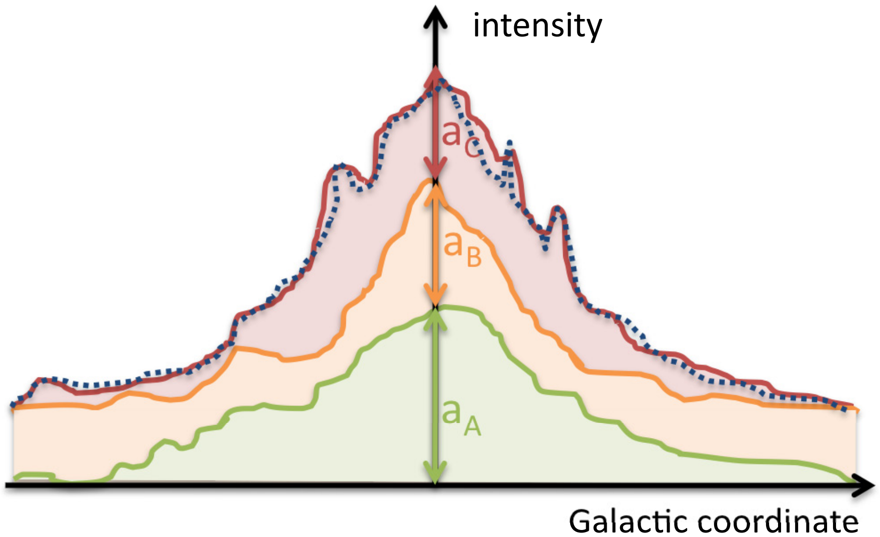
Dobler & Finkbeiner, ApJ **680** (2008) 1222

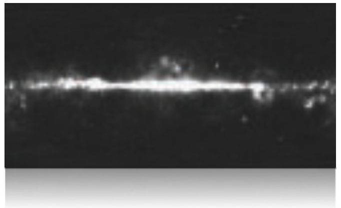
1. morphology: roughly spherical
2. power: few kJy sr^{-1}
3. spectrum: harder than usual synchrotron

Template Subtraction

Based on multi-linear regression for each band

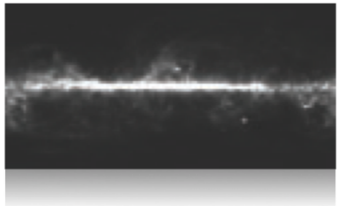
$$\chi^2 \propto \left(\mathrm{data} - \sum_{i=\mathrm{A,B,C}} a_i \ \mathrm{map}_i\right)^2$$



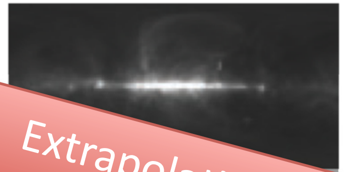


CMB subtracted
WMAP K-band
Hinshaw *et al.*, ApJS **180** (2009) 225

free-free:
Hα map
Finkbeiner, ApJS **146** (2003) 407



dust:
94 GHz map
Finkbeiner *et al.*, ApJ **524** (1999) 867



synchrotron:
408 MHz survey
Haslam *et al.*, A&AS **47** (1982) 1

Extrapolation over 2 orders of magnitude!

Energy-Dependent e± Diffusion

GeV e± produce GHz synchrotron:

$$\nu_{\rm max}(E_{e^\pm}) \simeq 0.29\,\nu_c(E_{e^\pm}) \simeq 23\left(\frac{B}{6\,\mu{\rm G}}\right)\left(\frac{E_{e^\pm}}{30\,{\rm GeV}}\right)^2\ {\rm GHz}$$

diffusive convective transport:

$$\frac{\partial n}{\partial t} = \vec{\nabla}\cdot\left(D_{xx}\vec{\nabla}n - \vec{v}\,n\right) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}n - \frac{\partial}{\partial p}\left(\dot{p}\,n - \frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}\right)n\right) + q$$

(numerically solved with GALPROP code)

$$D_{xx} \propto D_{xx0}\left(\frac{E}{4\,{\rm GeV}}\right)^\delta, \quad \vec{v} = \pm\vec{\rm e}_z\frac{{\rm d}v}{{\rm d}z}z\,, \quad D_{pp} \propto v_{\rm A}^2 D_{xx}^{-1}$$

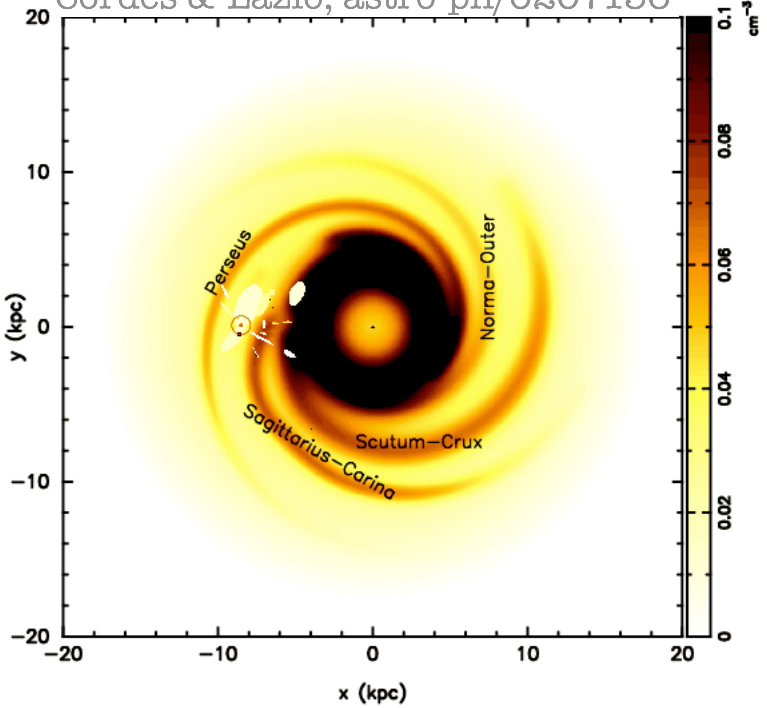
diffusion-loss length:

$$\ell(E) \approx 5\left(\frac{E}{\rm GeV}\right)^{(\delta-1)/2}\ {\rm kpc}$$

Morphology of synchrotron maps at WMAP and at radio frequencies could be quite different!

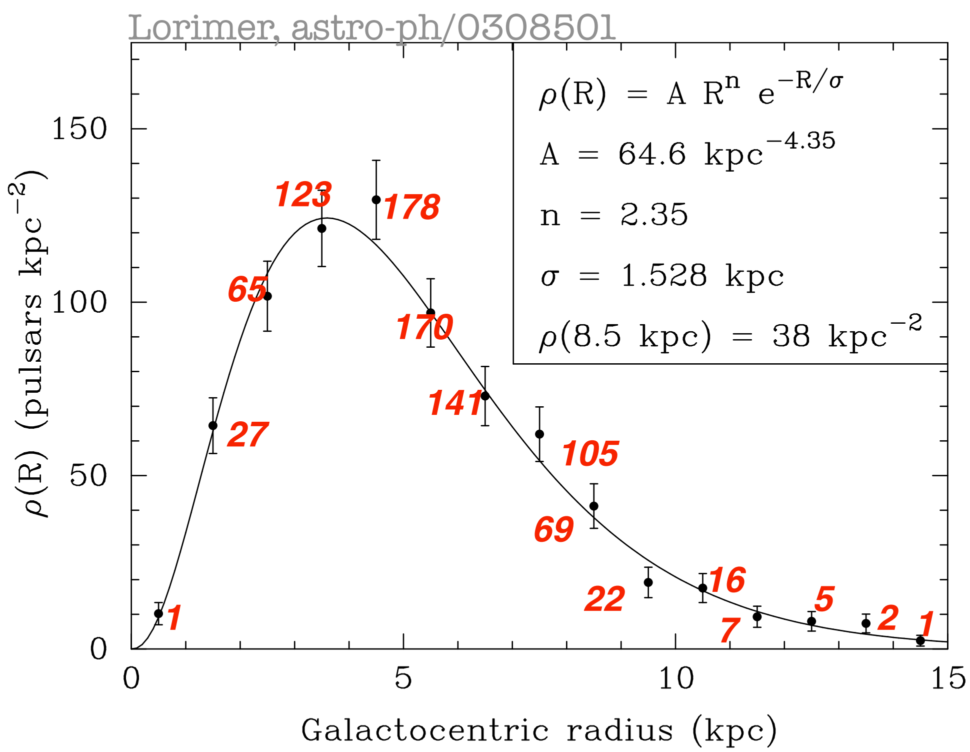
Source Distribution

Cordes & Lazio, astro-ph/0207156



- SNRs traced by pulsars to first approximation
- radial pulsar distribution from rotation and dispersion measure
- depends on thermal electron density

Source Distribution



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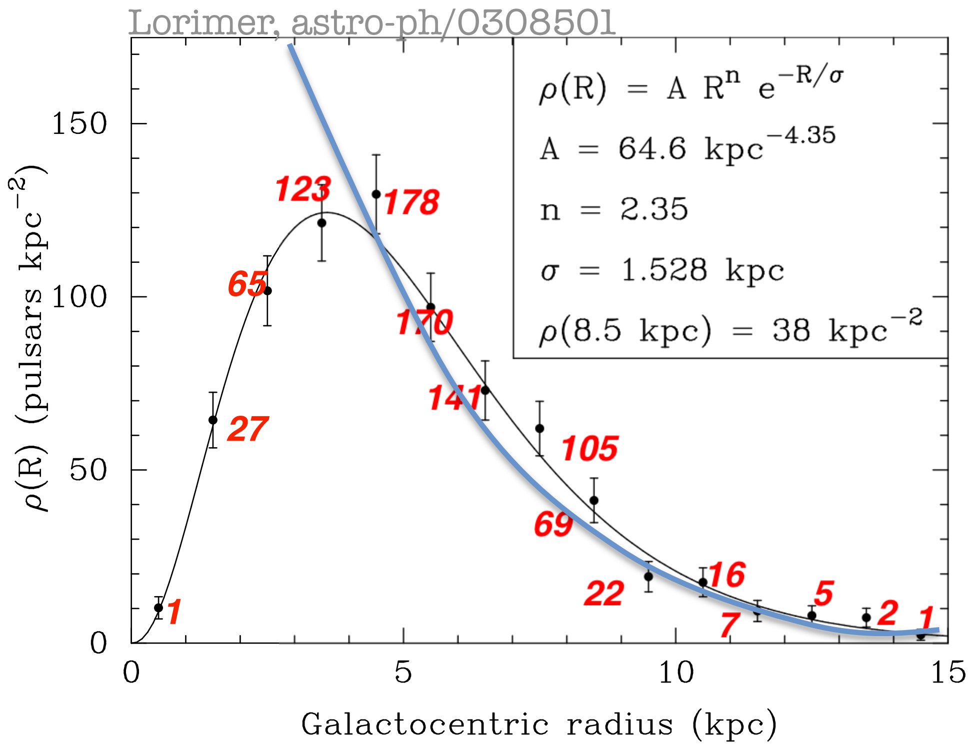
Source Distribution



The distribution of $e^{\pm}$ sources could be *very* different

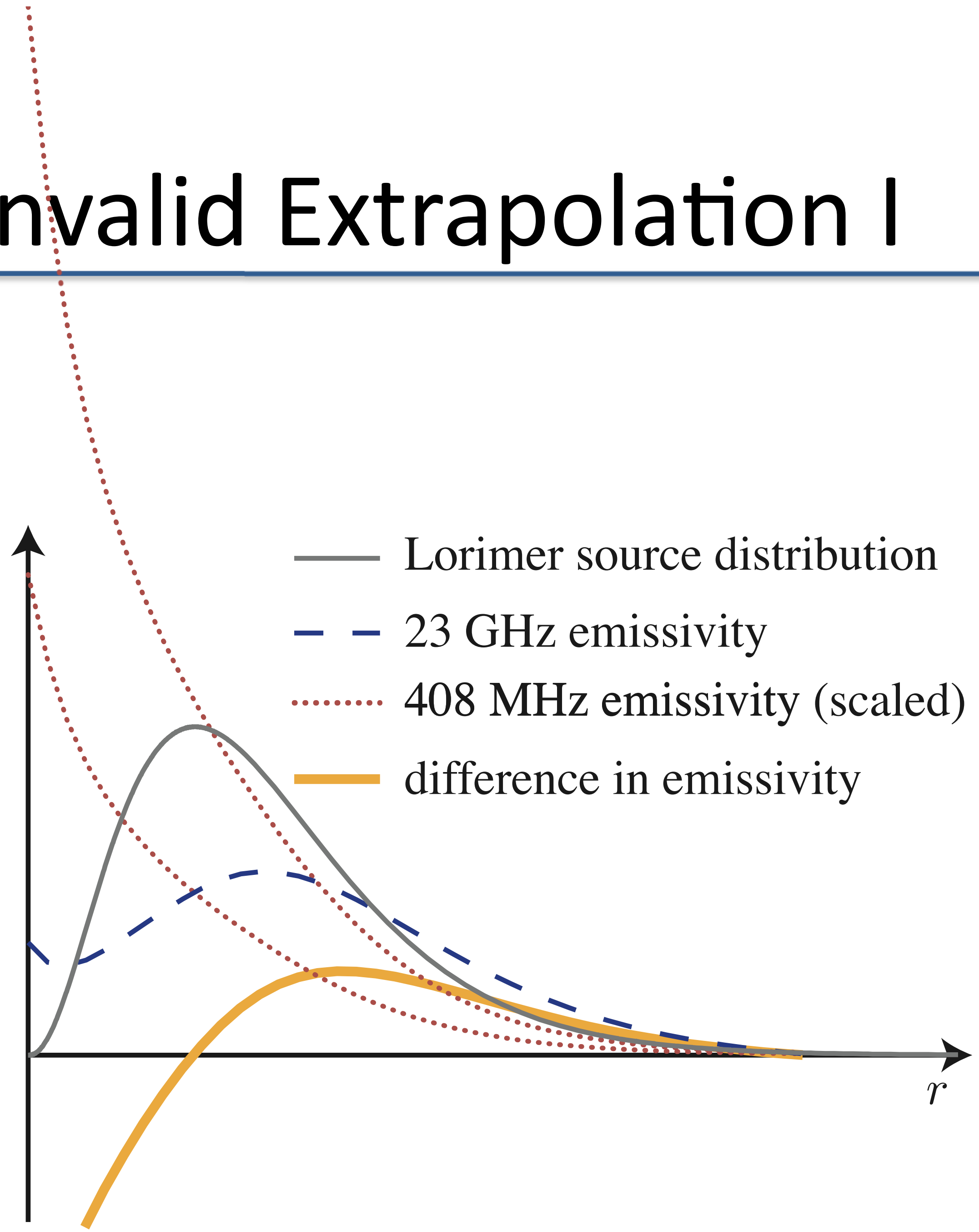
- SNRs traced by pulsars to first approximation
- radial pulsar distribution from rotation and dispersion measure
- depends on thermal electron density
- likely strong selection effects near Galactic Centre

➡ consider alternatively exponential distribution

Effect of Invalid Extrapolation I

- source distribution peaks at intermediate radii
- 23 GHz e$^{\pm}$ do not diffuse much and trace sources
- 408 MHz e$^{\pm}$ diffuse more and wash out source distribution

template subtraction finds ***deficit*** at Galactic centre

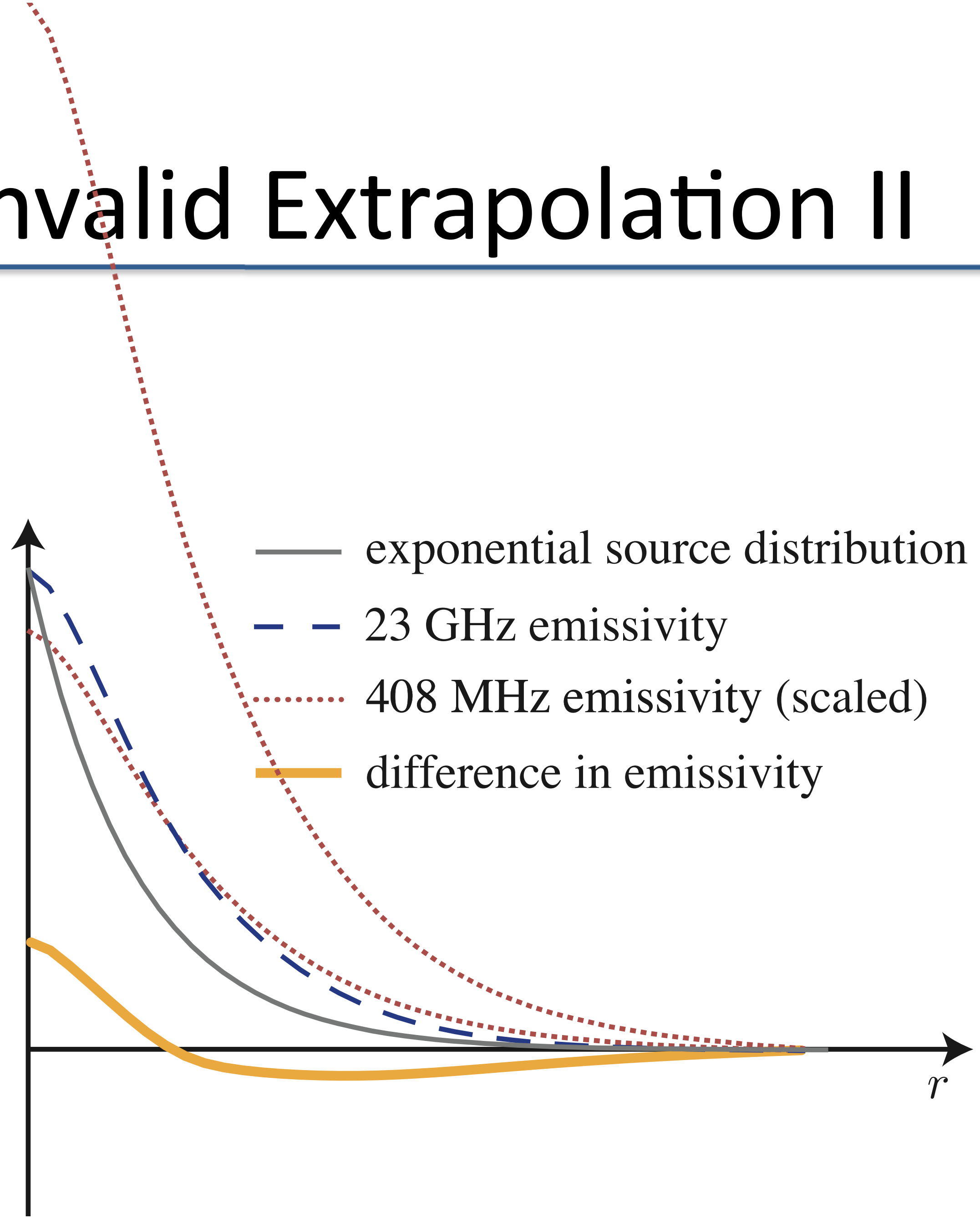


Mertsch & Sarkar, arXiv:1004.3056

Effect of Invalid Extrapolation II

- source distribution peaks at Galactic centre
- 23 GHz e$^{\pm}$ do not diffuse much and trace sources
- 408 MHz e$^{\pm}$ diffuse more and do not trace sources well

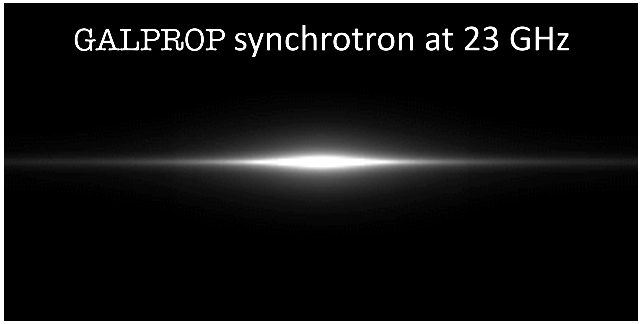
template subtraction finds ***excess*** at Galactic centre



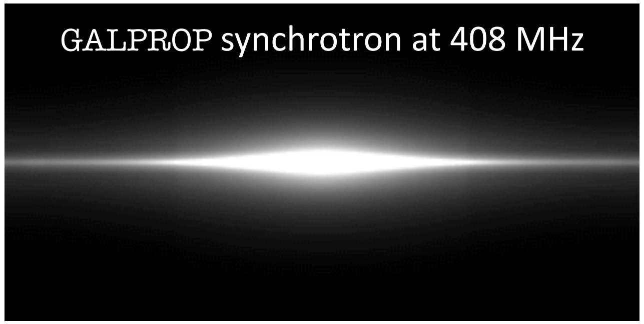
Mertsch & Sarkar, arXiv:1004.3056

Methodology

- Cannot determine synchrotron content in WMAP skymaps independently
- Model synchrotron emission with GALPROP:



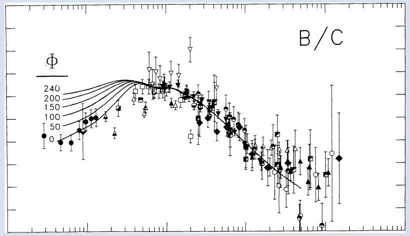
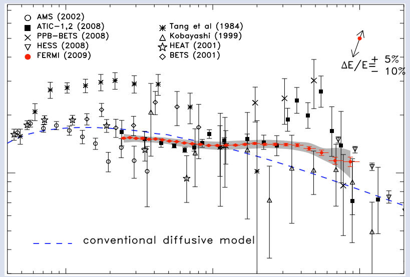
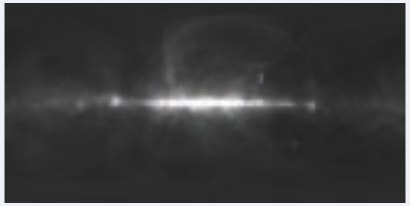
mock WMAP data



mock 408 MHz template

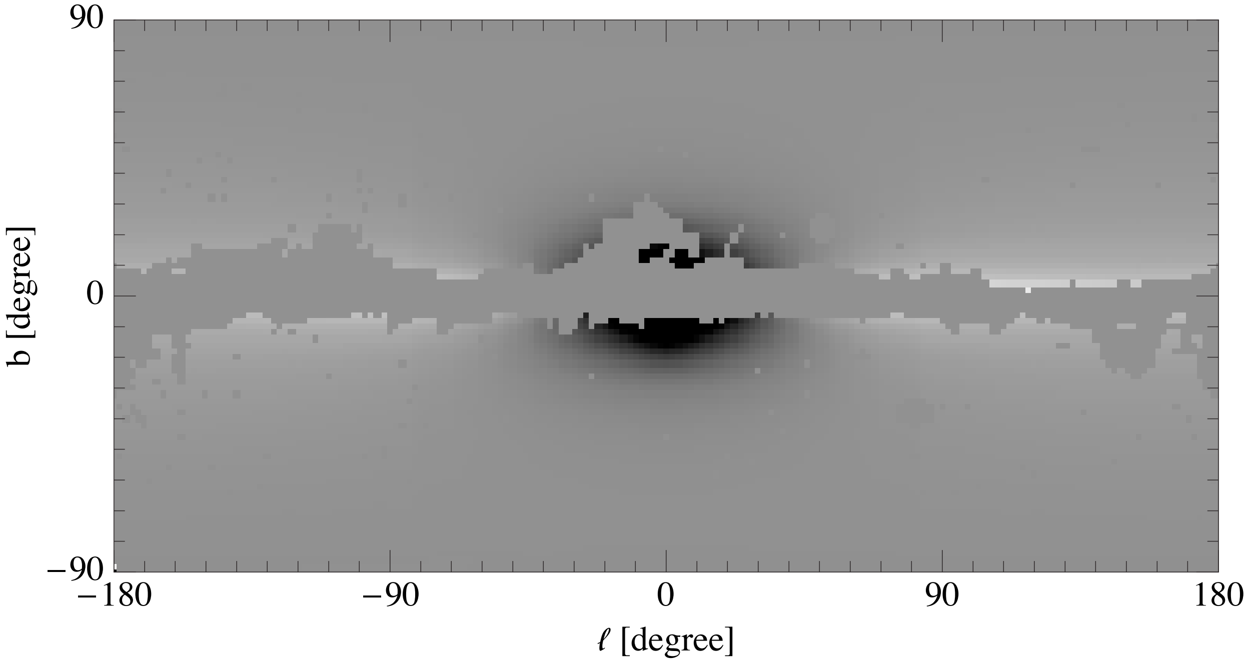
- Perform template subtraction (FS 8) as in
Dobler & Finkbeiner ApJ **680** (2008) 1222
but without free-free and dust

Constraining Input Parameters

Input parameters		observation	
propagation parameters	D_{0xx}, δ v_A, dv_{conv}/dz	local CR nuclei *some freedom*	
source distribution	*Lorimer? exponential?*	*some freedom*	
source spectrum	$N_0\ E^{\alpha 1,2}$	local CR $e^{\pm}$	
Galactic magnetic field	$B_0\ e^{-r/\rho}\ f(z)$	408 MHz survey	

Mertsch & Sarkar, arXiv:1004.3056

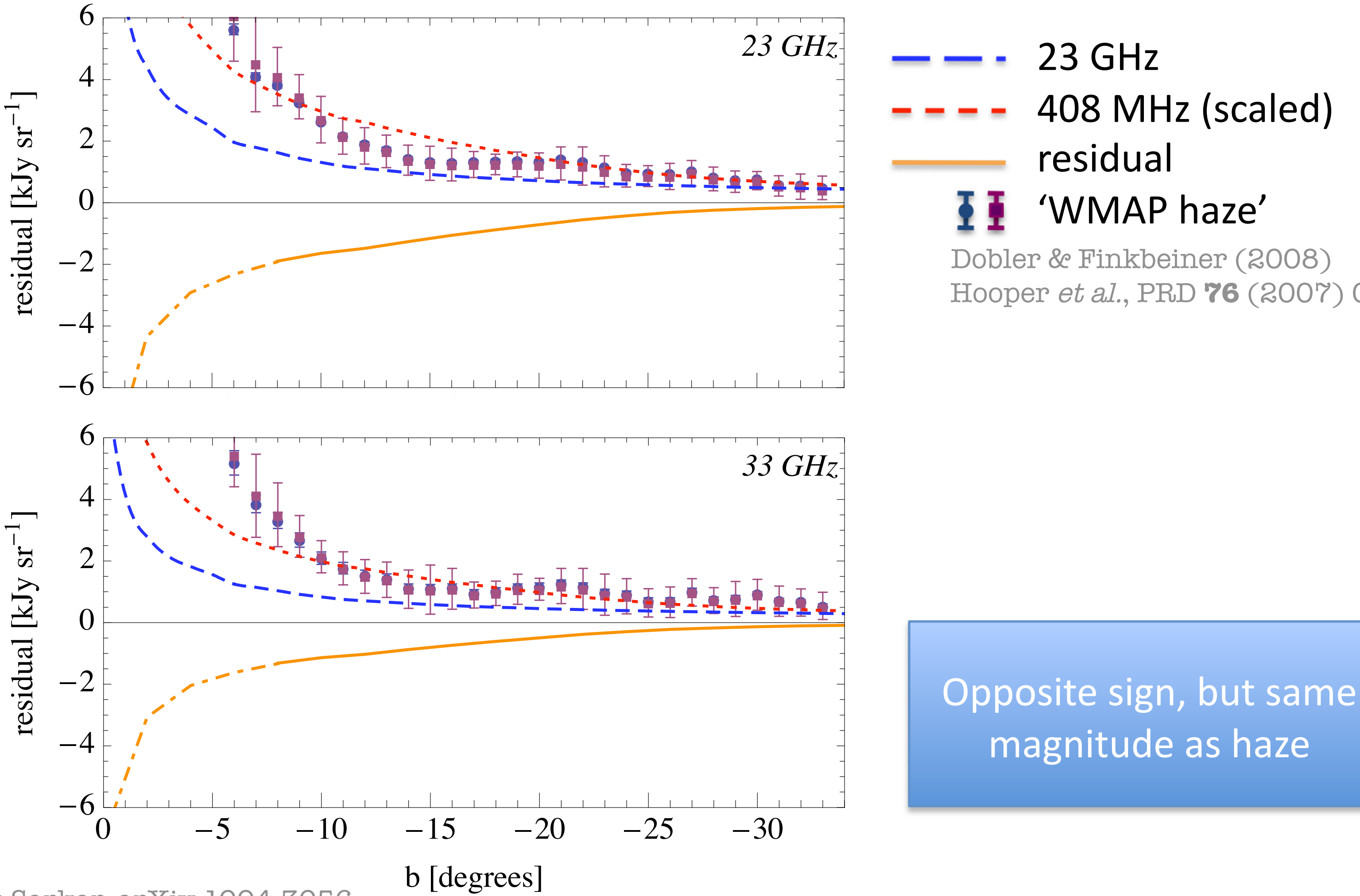
Model 1: Morphology



- deficit around galactic centre
- roughly spherical
- of opposite sign to ‘haze’

Mertsch & Sarkar, arXiv:1004.3056

Model 1: Intensity

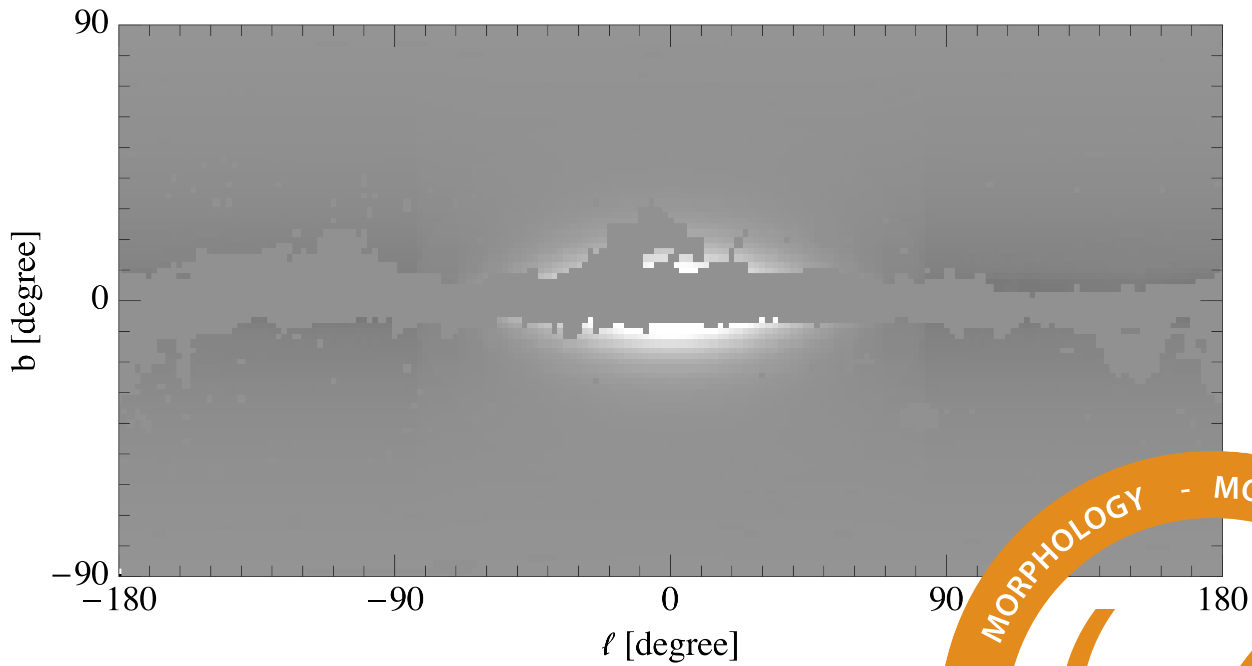


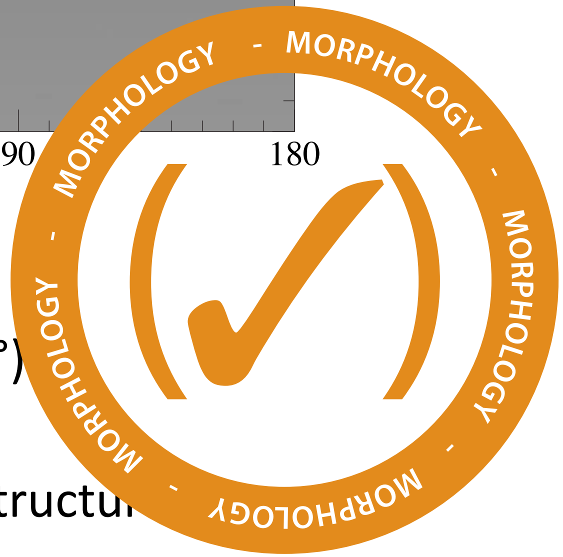
Dobler & Finkbeiner (2008)
Hooper *et al.*, PRD **76** (2007) 083012

Opposite sign, but same magnitude as haze

Mertsch & Sarkar, arXiv:1004.3056

Model 2: Morphology

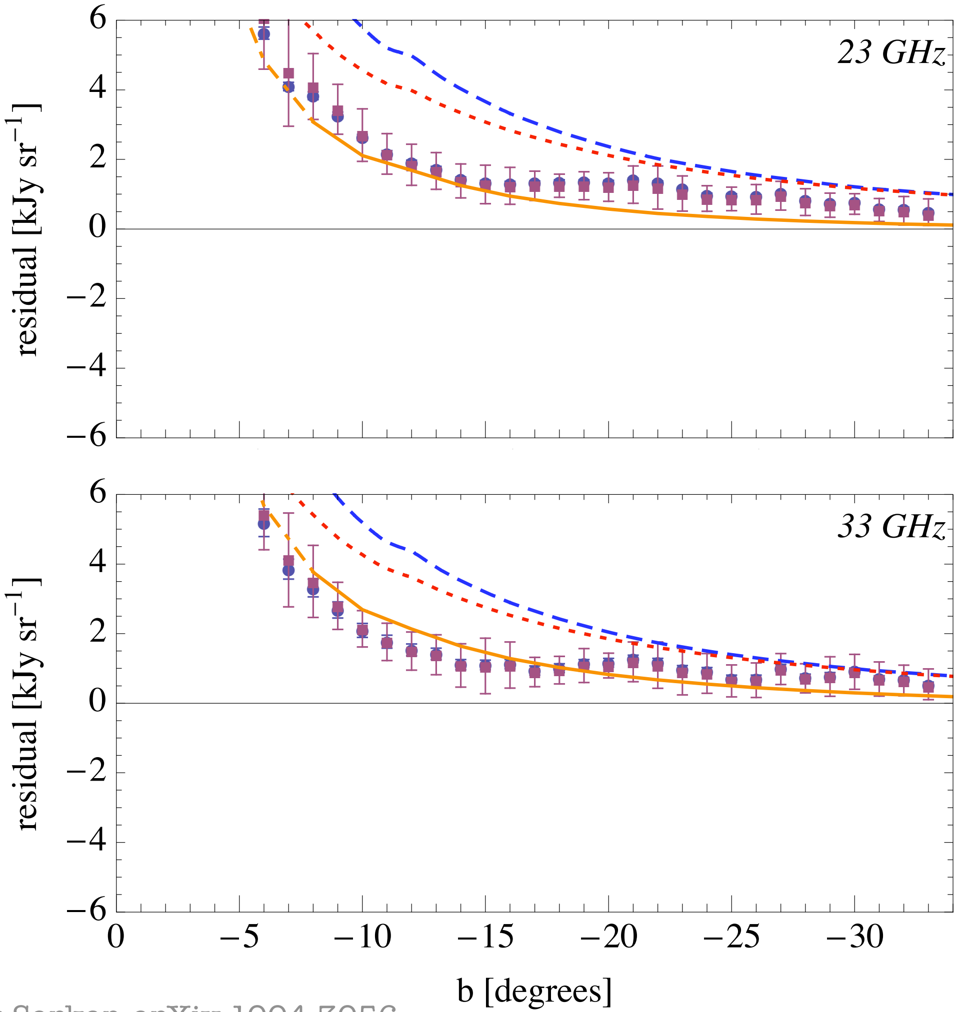




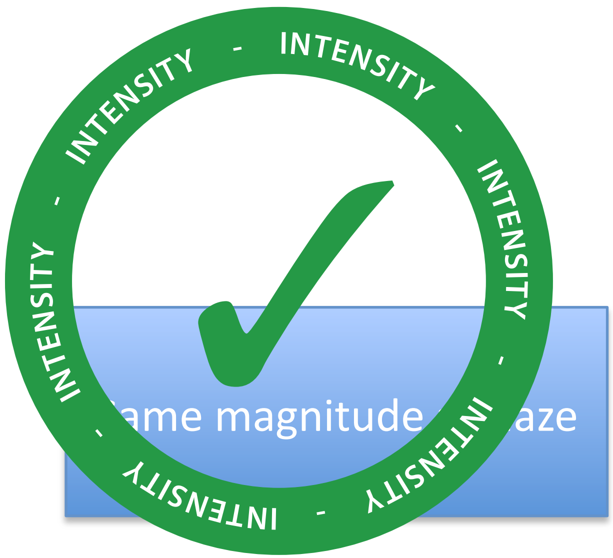
- excess around galactic centre
- more extended in longitude (±60°) than in latitude (±30°)
- major modification due to local structu
expected

Mertsch & Sarkar, arXiv:1004.3056

Model 2: Intensity

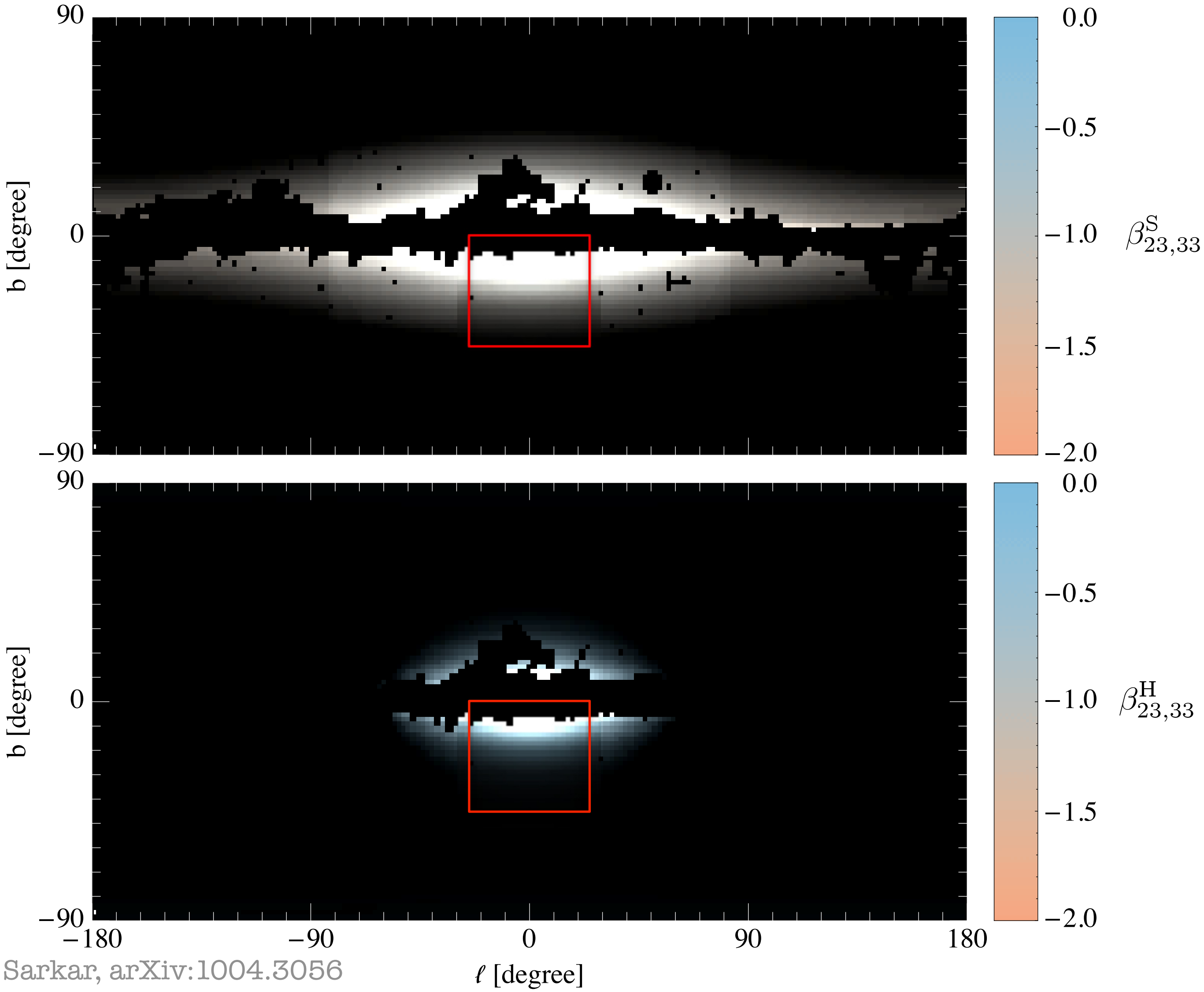


Dobler & Finkbeiner (2008)
Hooper *et al.*, PRD **76** (2007) 083012



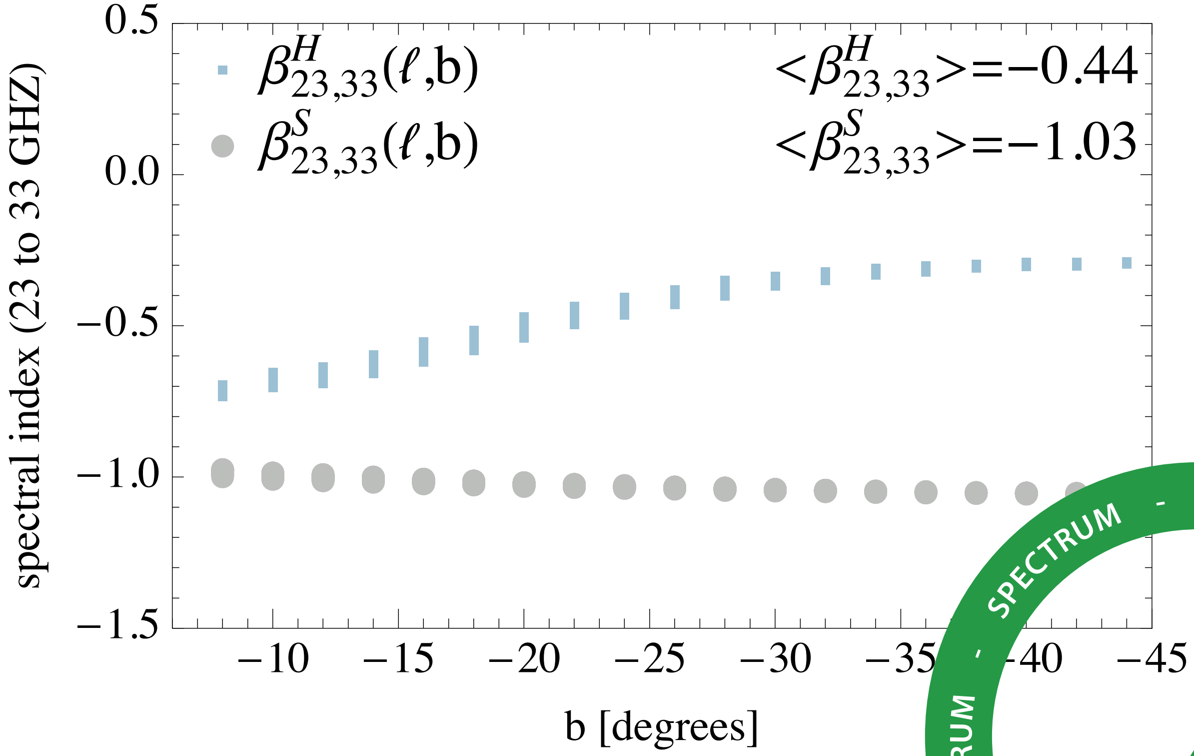
Mertsch & Sarkar, arXiv:1004.3056

Model 2: Spectral Index



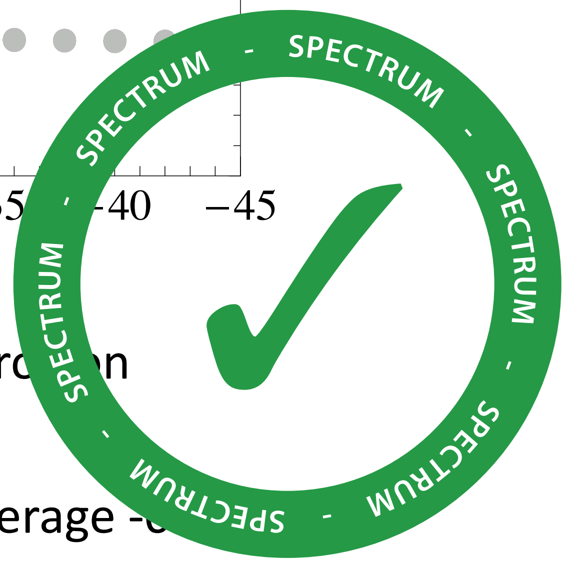
Mertsch & Sarkar, arXiv:1004.3056

Spectral Index

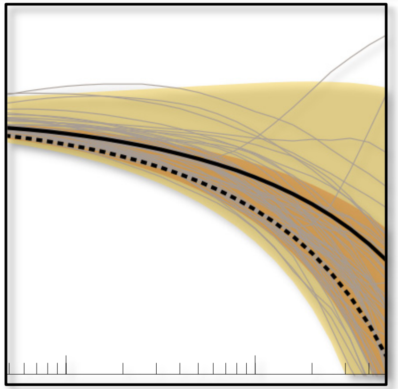


- 'haze' globally harder than synchrotron
- $\beta^H(\ell,b)$ slightly hardening with b
- difference in spectral index on average -0

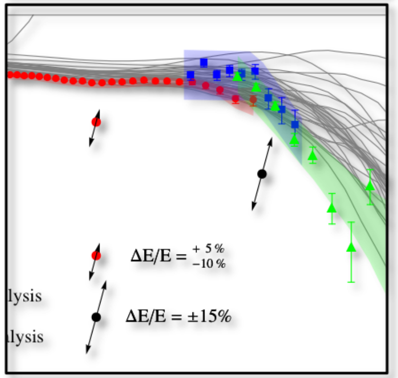
Mertsch & Sarkar, arXiv:1004.3056



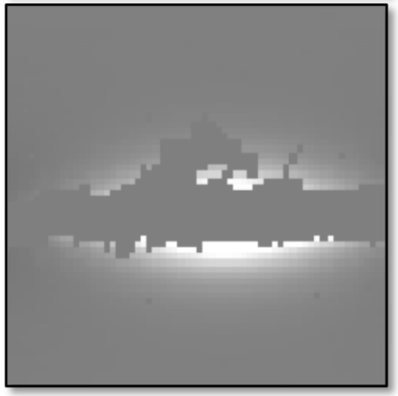
Summary



Discrete stochastic sources imply uncertainty in predicted fluxes



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



Systematic effects in template subtraction - `WMAP haze' could be artefact