CR propagation with DRAGON

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in collaboration with (in alphabetical order)
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Outline

- Some generalities on CR
- Our strategy to determine the most important propagation parameters
- Results from CR nuclei and antiprotons
- News from leptons and gamma-rays

CR propagation

How to cast the problem?

$$n(E,\vec{r}_{\rm obs}) = \int_0^\infty dt \int d^3 r_0 \int dE_0\, q(E_0,\vec{r}_0,t)\, f(E,\vec{r}_{\rm obs};E_0,\vec{r}_0,t)$$

source function

propagation probability function

$$\phi = \frac{c\beta}{4\pi} n$$

Extremely complicated problem: needs simplifications

CR propagation

CRs obey essentially a diffusion equation (**Ginzburg & Syrovatsky, 1964**)

Diffusion tensor
$D(E) = D_0\,(\rho/\rho_0)^\delta$
$\rho = \text{rigidity} \sim p/Z$

Convection term

Energy loss

Reacceleration
$D_{pp} \propto \frac{p^2 v_A^2}{D}$

$$\frac{\partial N^i}{\partial t} - \nabla\cdot\left(D\,\nabla - v_c\right)N^i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\nabla\cdot v_c\right)N^i - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i}{p^2} =$$
$$= Q^i(p,r,z) + \sum_{j>i} c\beta n_{\rm gas}(r,z)\sigma_{ji}N^j - c\beta n_{\rm gas}\sigma_{\rm in}(E_k)N^i$$

SN source term.
We assume everywhere
a power law energy spectrum

Spallation cross section. Appearance of nucleus i due to spallation of nucleus j

Total inelastic cross section.
Disappearance of nucleus i

The height of the propagation/diffusion region is z_t $\quad D_0(z) \propto e^{z/z_t}$

Several approximations: stationary solution, smoothed source distribution... Turn out to be surprisingly good for hadronic cosmic rays.

Equation solvers...

Several ways of solving the diffusion equation:

- **leaky-box models**: $D(E) \leftrightarrow \tau_{\rm esc}(E)$

  Analytic and surprisingly meaningful solutions. Benchmark model!

- **semi-analytic models** assume simplified distributions for sources and gas, and try to solve the diffusion equation analytically (Maurin, Salati, Donato et al)
- **numerical models** (Galprop) try to use more realistic distributions

A new numerical model: DRAGON (Diffusion of cosmic RAys in the Galaxy modelizatiON)

Features (w.r.t. Galprop):
- same fragmentation cross sections
- position dependent, anisotropic diffusion
- boundary conditions in momentum and at R=0
- independent injection spectra for each nuclear species
- same results in same conditions
- faster (improved treatment of decays)
- interfaced with DarkSUSY
- only 2D
- not public (yet)

References:
C. Evoli et al. JCAP 0810 (2008) 018
G. Di Bernardo et al. arXiv:0909.4548
and works in preparation

Plan of work

Most important propagation parameters: D_0, δ

Standard wisdom: high energy spectra are just the result of diffusion and possibly spallation

At low energy other processes (reacceleration, convection, energy losses, change of diffusion regime at low energy) are relevant and may mask the effects of diffusion, see e.g. the recent **Maurin et al, 1001.0553 & 1001.0551**, also **Ptuskin et al, ApJ 642 (2006)**

High energy data now available (**CREAM, PAMELA**)

Perform an energy dependent analysis of data, to see where low energy effects kick in and disentangle their effects from diffusion

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Final results: learning something about D_0, δ, v_A.

Our tools: secondary to primary ratios

$$\frac{N_{\rm sec}}{N_{\rm pri}} \propto \frac{P_{\rm spall}(E)\tau_{\rm esc}(E)}{\tau_{\rm int}(E)} \to E^{-\delta}$$ at high E

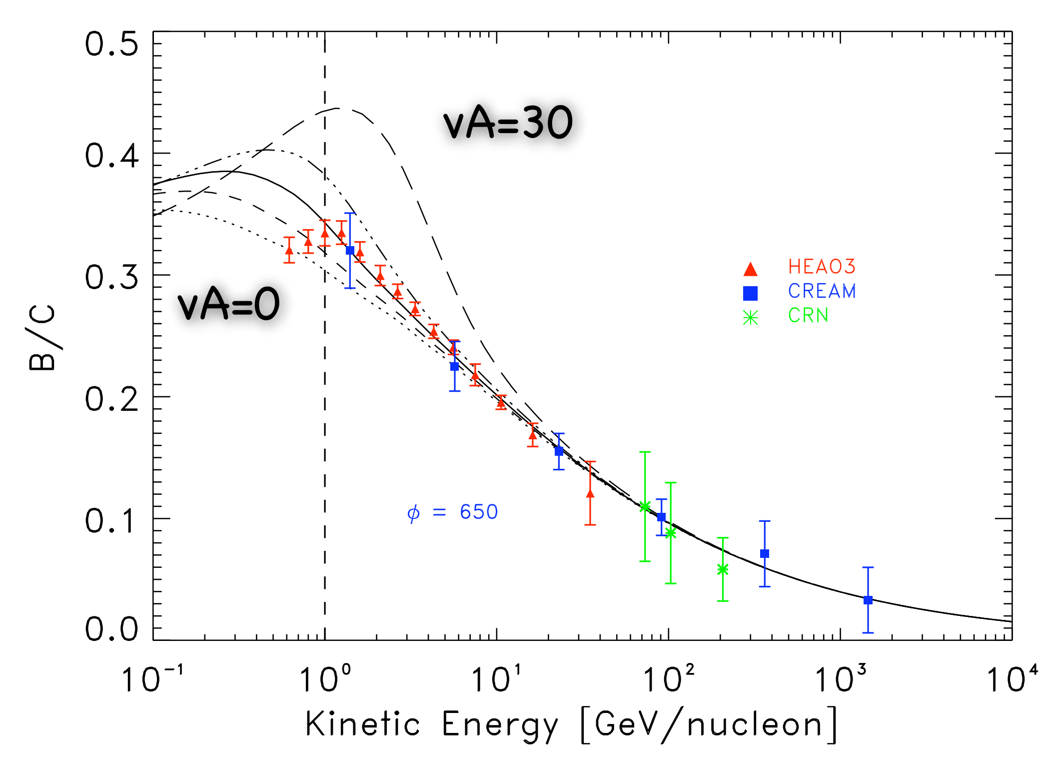
We are interested in mainly in B/C and antiproton/proton ratios

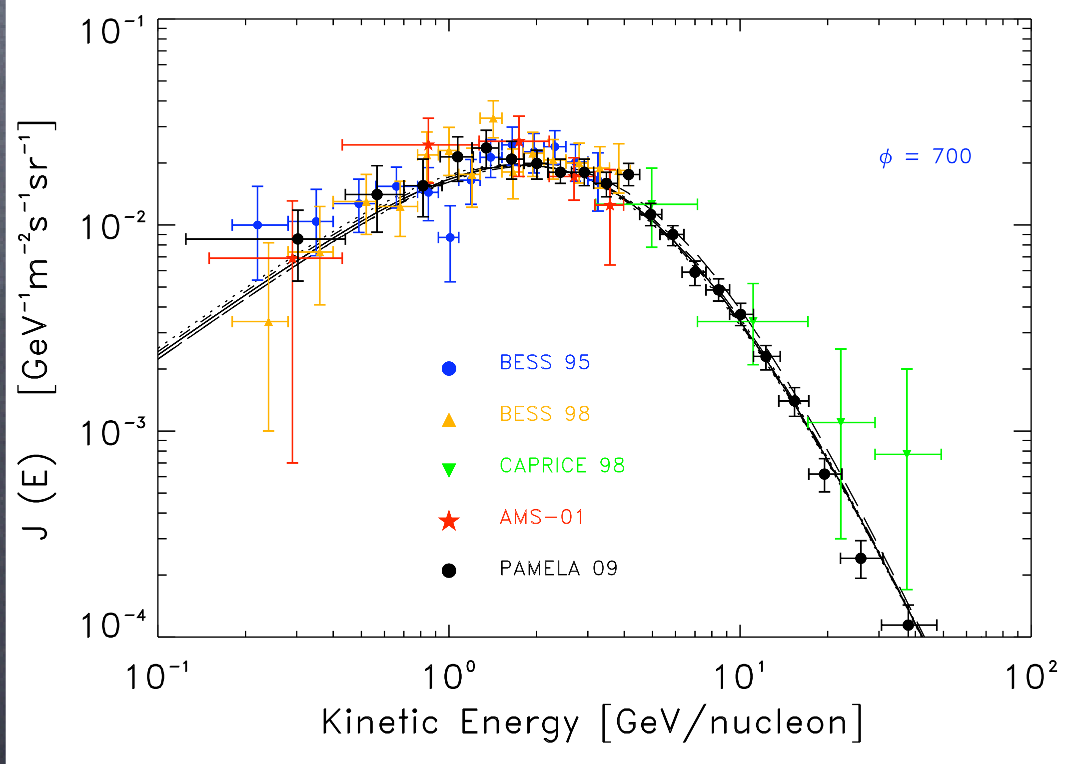
It is very important to consider the high-energy part of these ratios (energy greater than some tens of GeV) because:

- Solar modulation plays a minor role
- Diffusive reacceleration (which introduces a new free parameter, the Alfven velocity) plays a minor role
- Energy losses due to spallation are less important
- Production cross section are known with less uncertainty

Antiprotons have a unique feature: secondary spectrum affected by threshold effects!

threshold energy ~ 7 GeV (in lab)

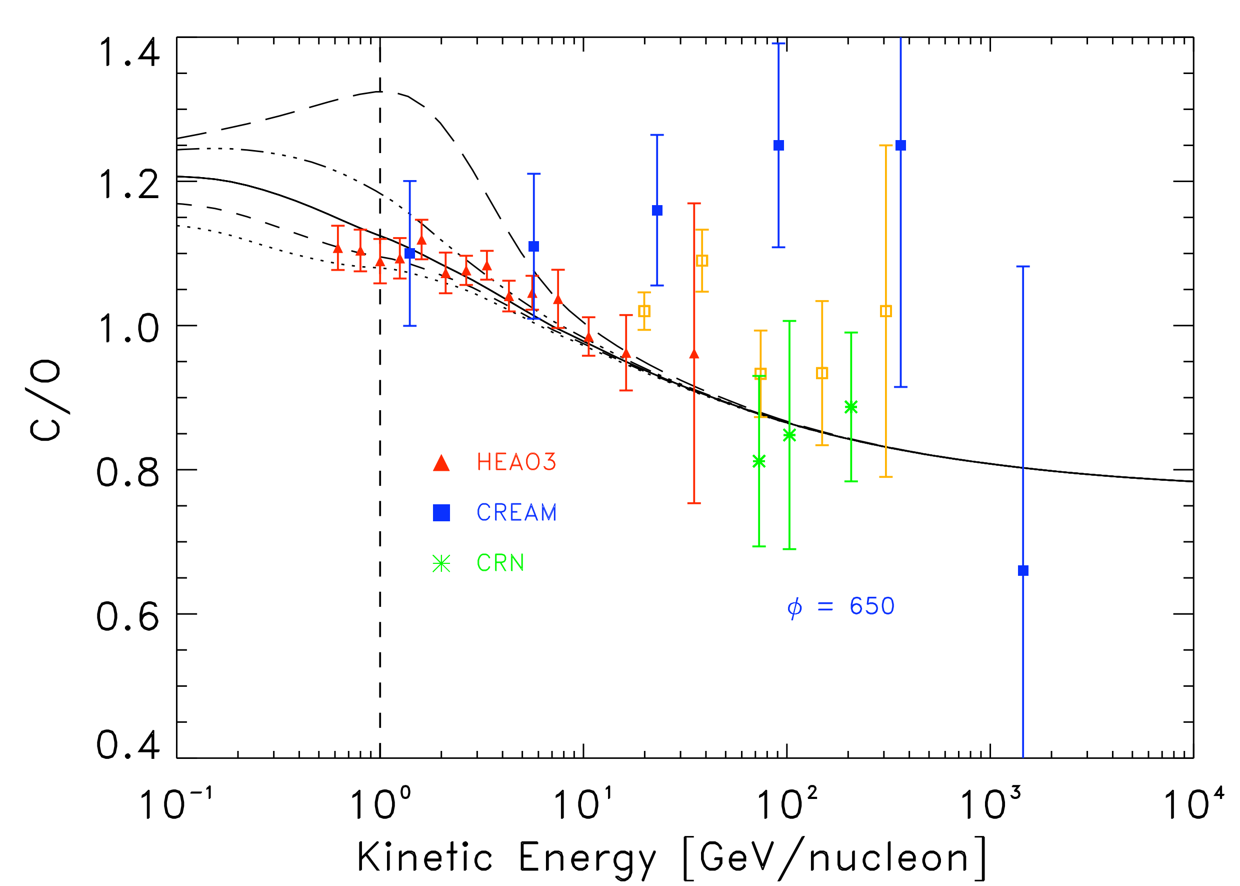


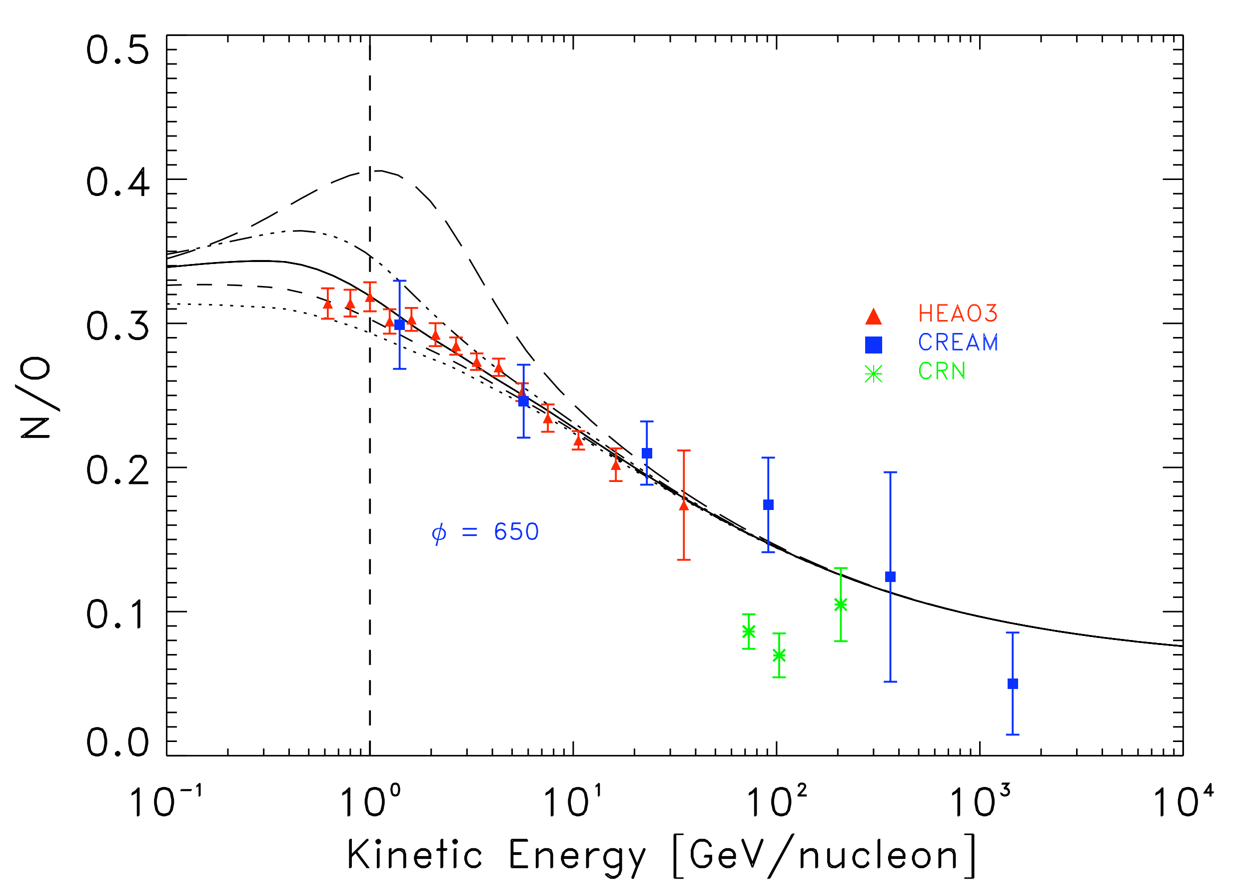


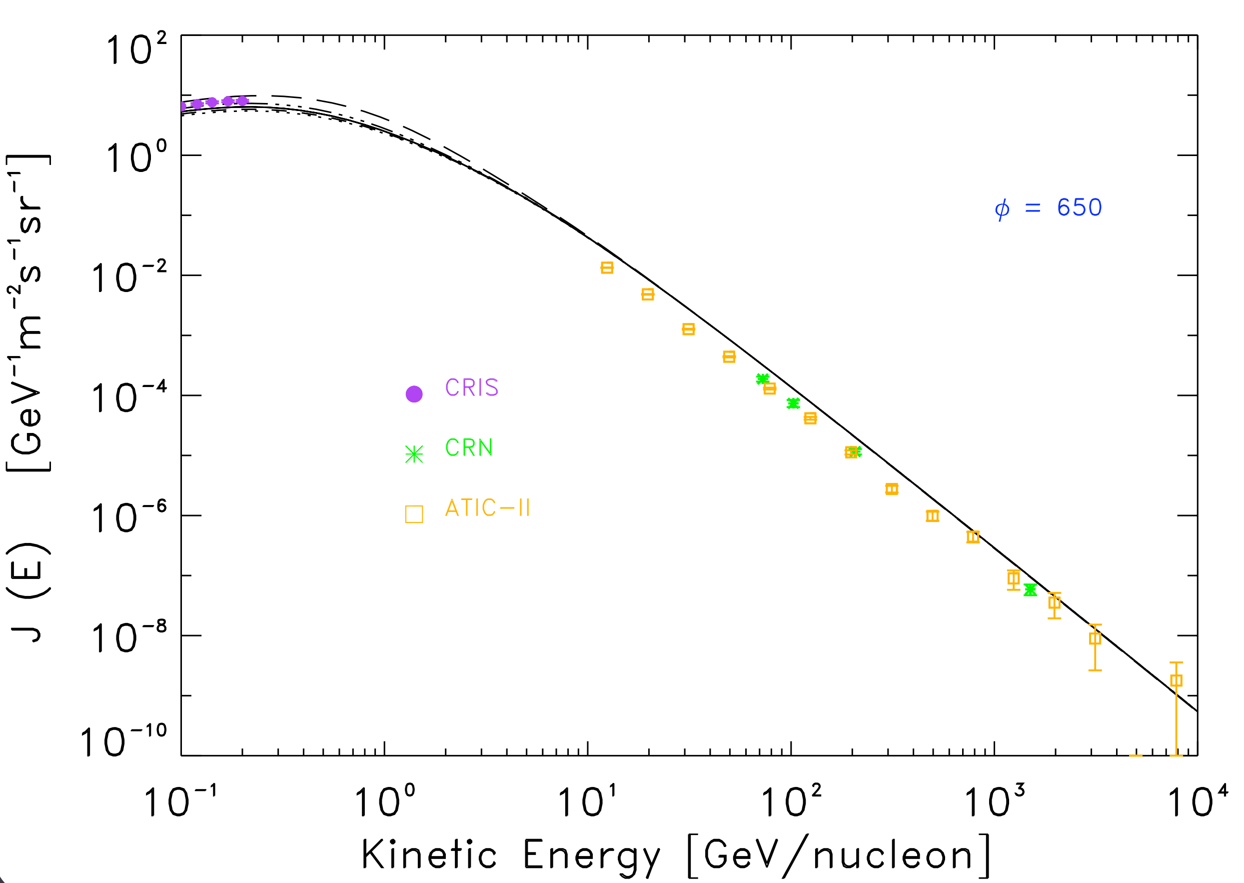
Our tools: secondary to primary ratios

Also data on the main B (and partially C) progenitors are extremely relevant

Also consider N/O and C/O ratios







Secondary/primary in our model

Secondary/primary in our model

Aim:

place limits on δ, v_A, D_0 (actually, D_0/z_t is the right quantity)

Strategy:

✓ for fixed values of the propagation parameters v_A, δ, and D_0/z_t we vary the **C/O and N/O source ratios** to compute the χ^2_{CNO} of the propagated, and modulated, C/O and N/O ratios against experimental data in the energy range 1 GeV < E_k < 1 TeV

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- ✓ for the same fixed value of v_A, we finely sample the parameter space (δ, D_0/z_t) by using, for each couple of these parameters, the C/O and N/O source ratios which minimize χ^2_{CNO}; for each of these realizations we compute the χ^2_{BC} for the B/C modulated ratio against data in several energy ranges

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✓ we repeat the same analysis for several values of v_A to probe the effect of diffusive reacceleration. For each value of v_A we then determine the allowed ranges of δ and D_0/z_t for several Confidence Levels

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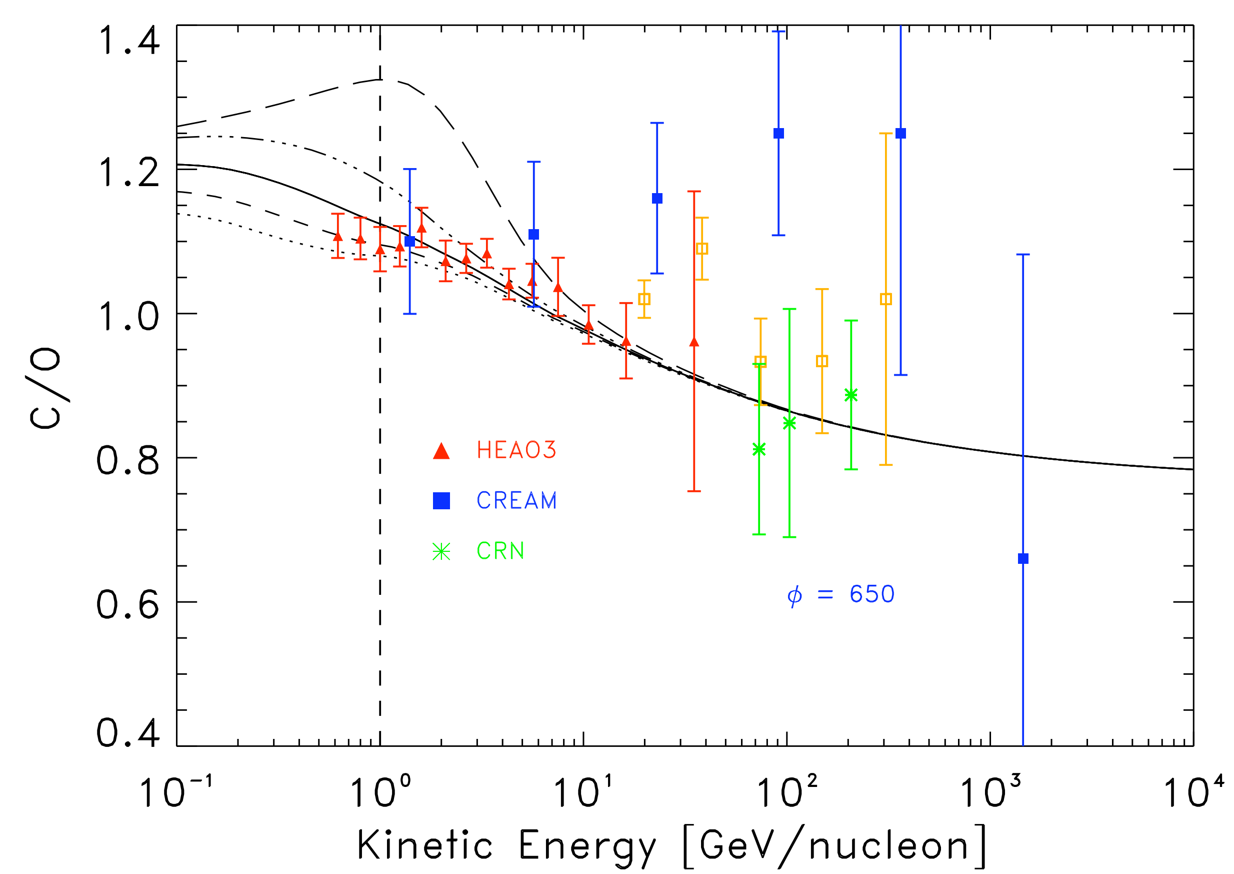
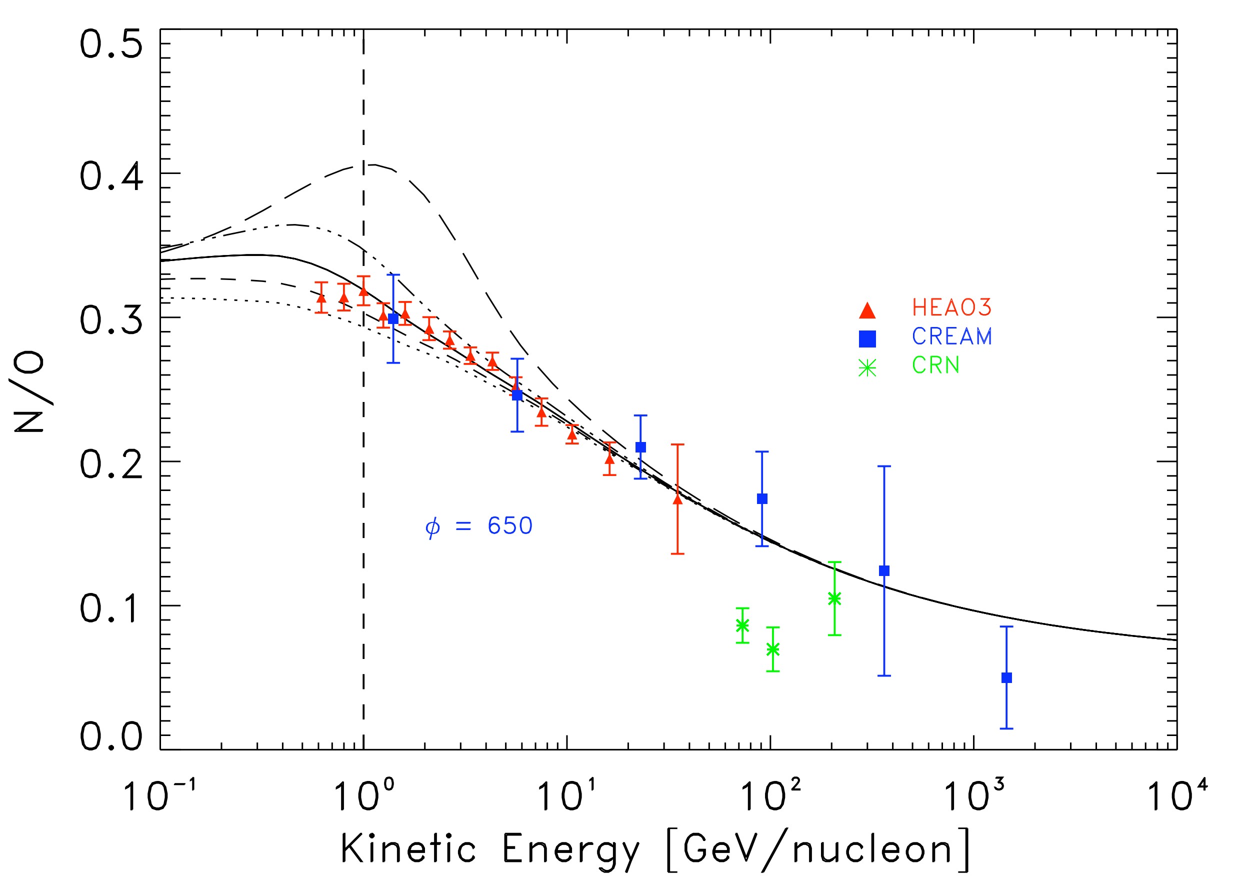
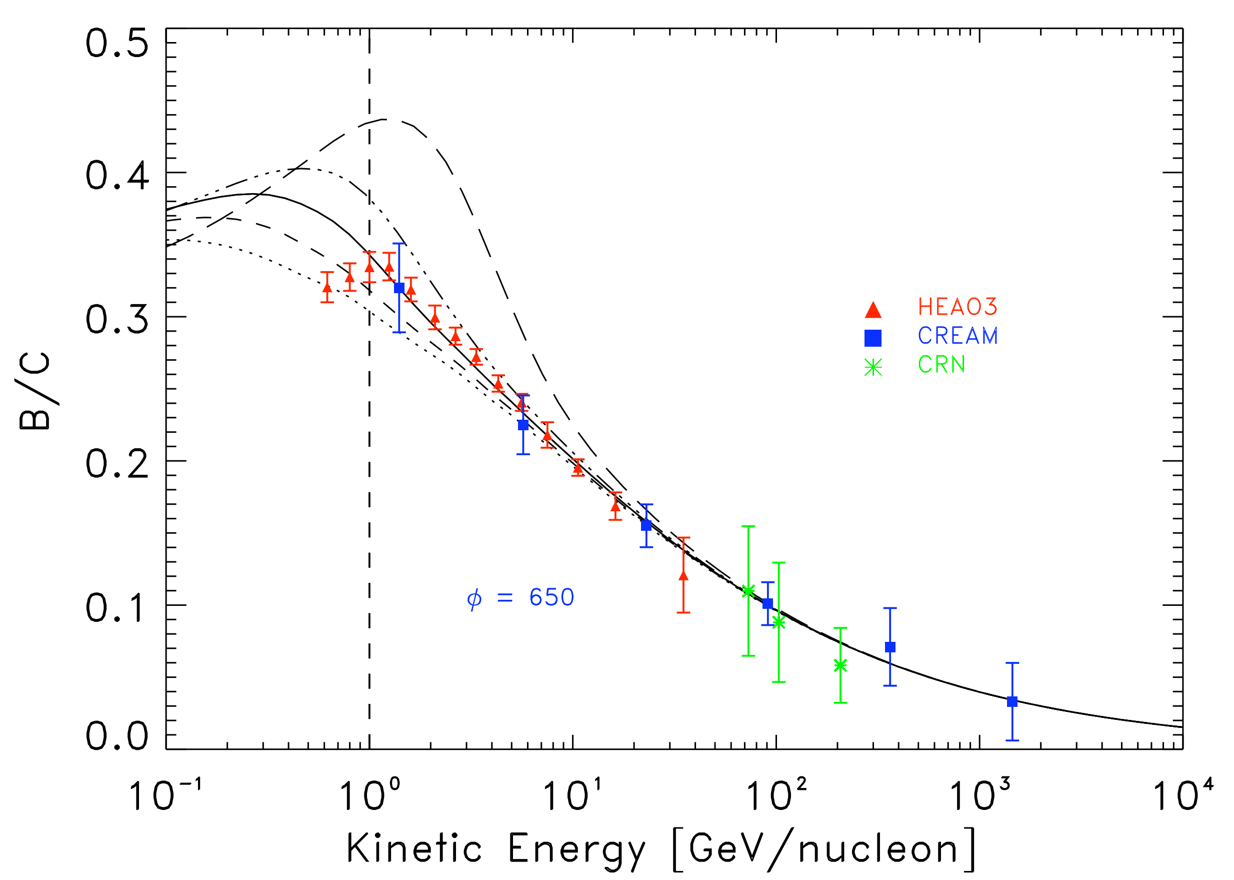
- ✓ we repeat the same analysis for several values of v_A to probe the effect of diffusive reacceleration. For each value of v_A we then determine the allowed ranges of δ and D_0/z_t for several Confidence Levels
- ✓ we repeat steps 2 and 3 for the antiproton/proton ratios

Secondary/primary in our model

Dependence of secondary/primary ratios on the reacceleration level in the "best fit" case.
Modulation potential fixed by requiring to reproduce the proton spectrum



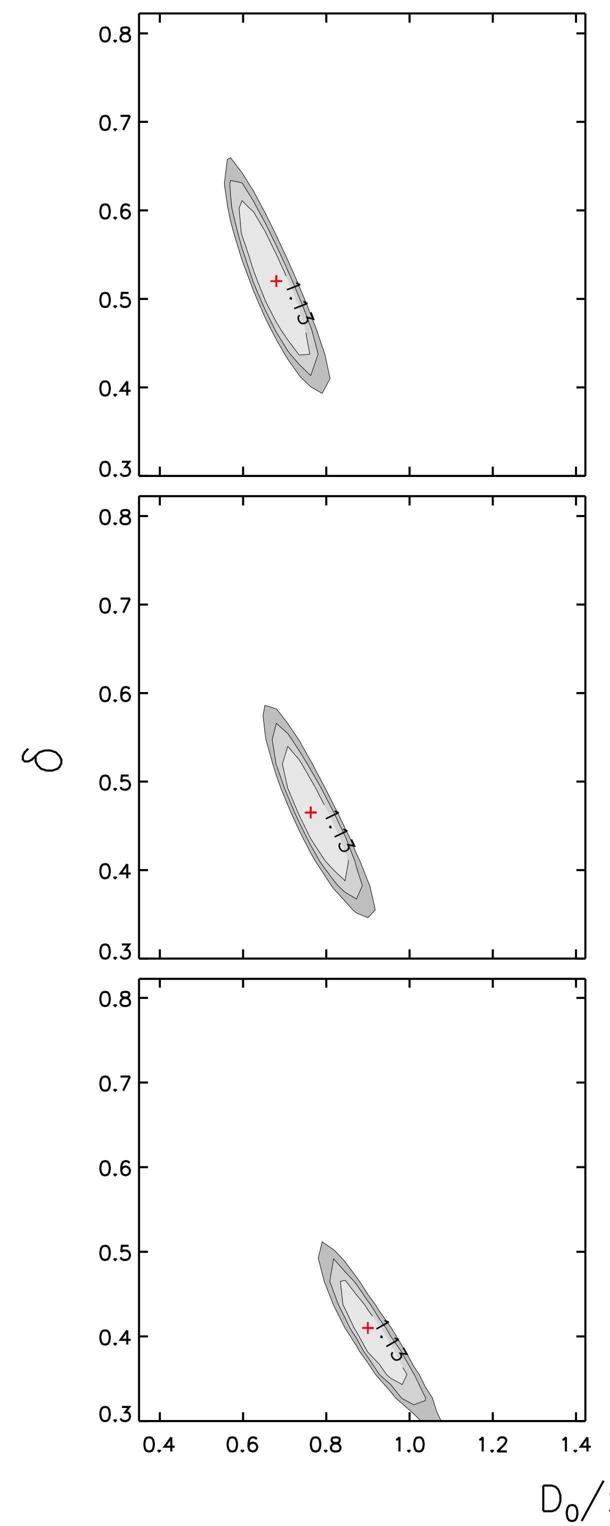




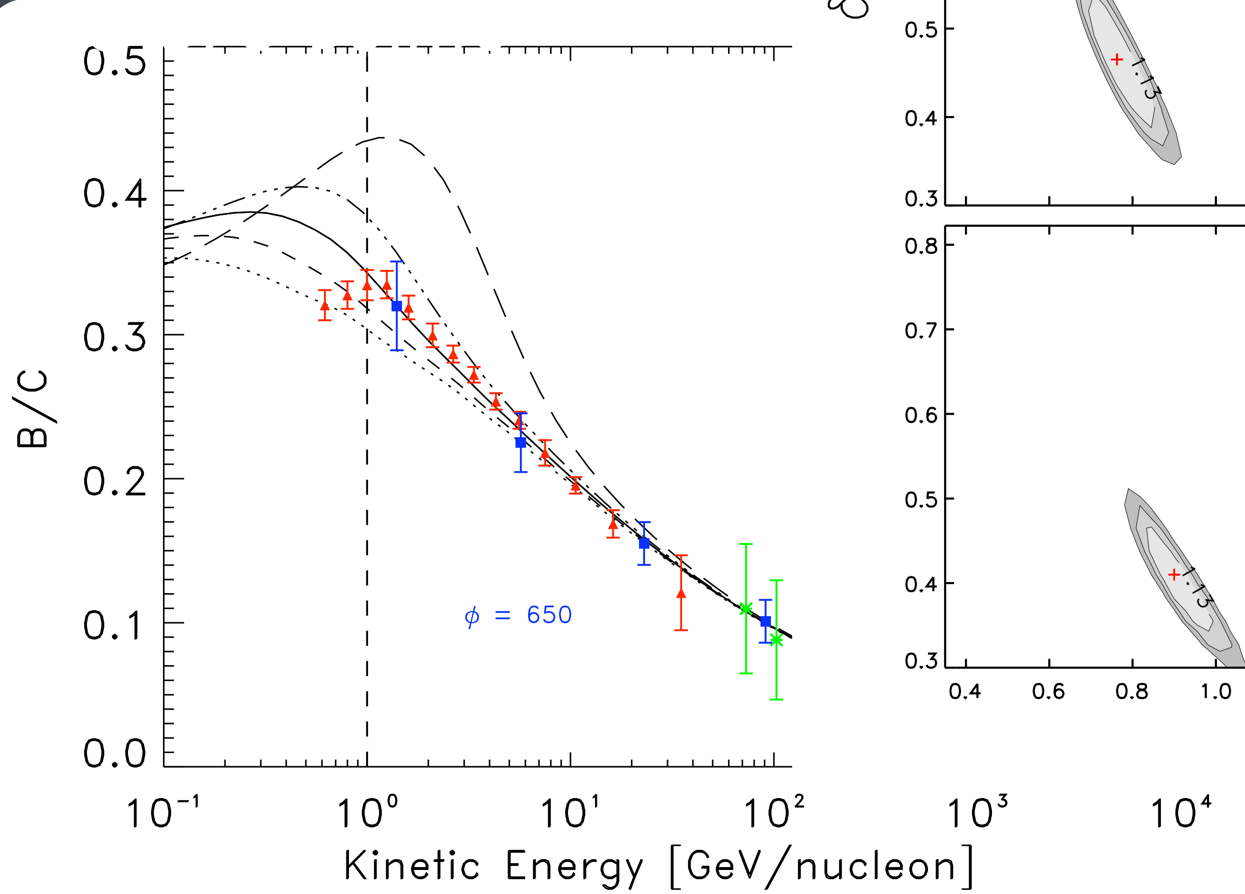
Statistical analysis I

Confidence level contours for various v_A=10,15,20 km/s and E_k^{min} = 1 GeV/n

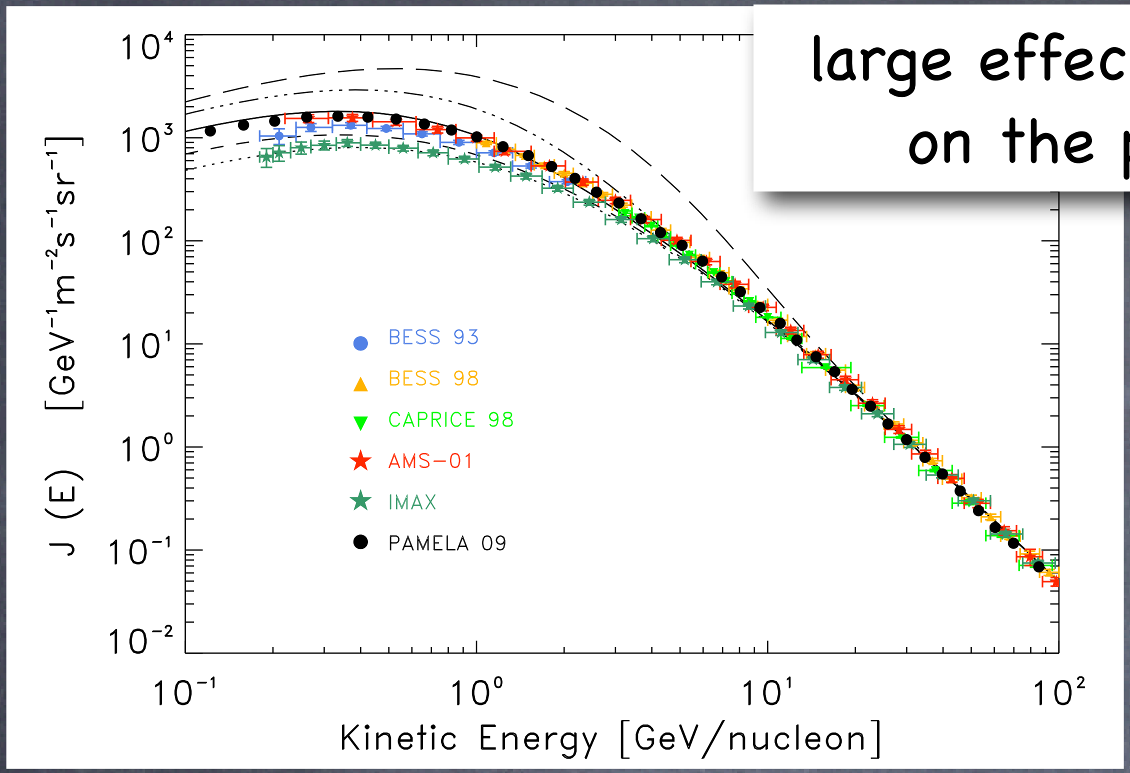
B/C



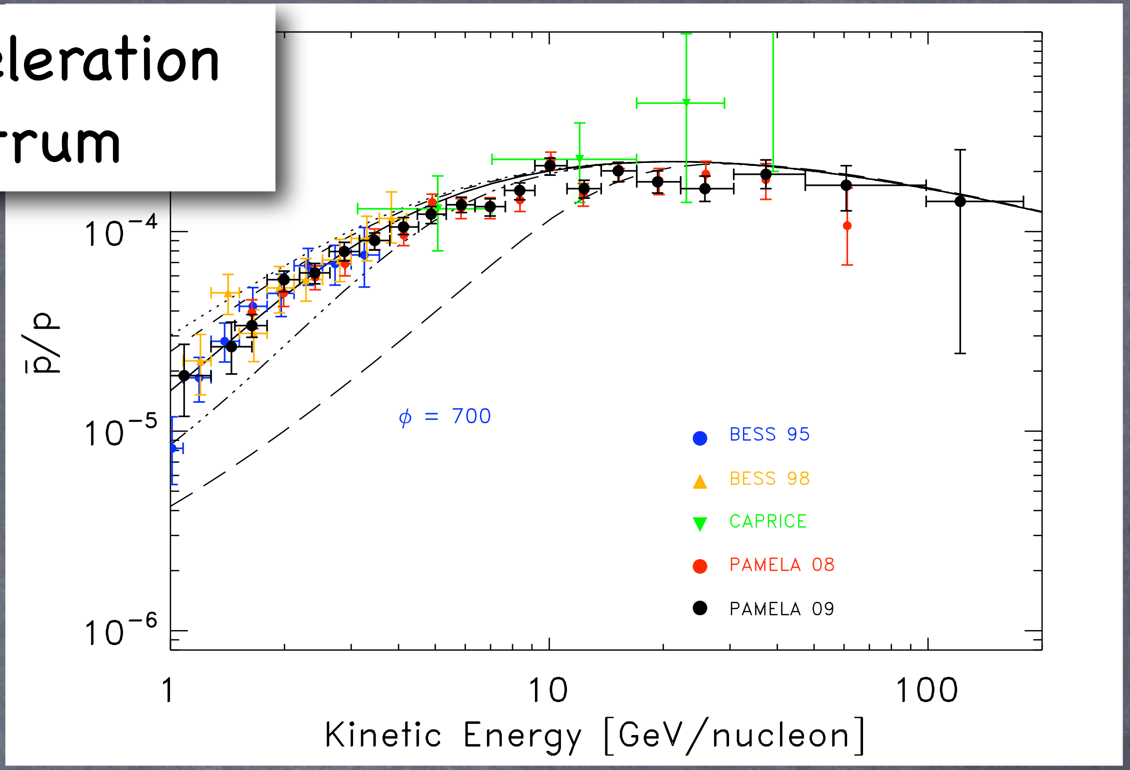
B/C analysis				
v_A [km/s]	$E_{\rm min}$ [GeV/n]	δ	D_0/z_t	χ^2
0	1	0.57	0.60	0.38
	5	0.49	0.68	0.38
	10	0.46	0.73	0.19
10	1	0.52	0.68	0.32
	5	0.46	0.73	0.40
	10	0.44	0.79	0.19
15	1	**0.46**	**0.76**	0.33
	5	0.44	0.79	0.36
	10	0.44	0.82	0.20
20	1	0.41	0.90	0.47
	5	0.46	0.79	0.29
	10	0.41	0.87	0.21
30	1	0.33	1.20	0.40
	5	0.38	1.04	0.19
	10	0.41	0.95	0.16



ap/p in our model



large effects of reacceleration on the proton spectrum



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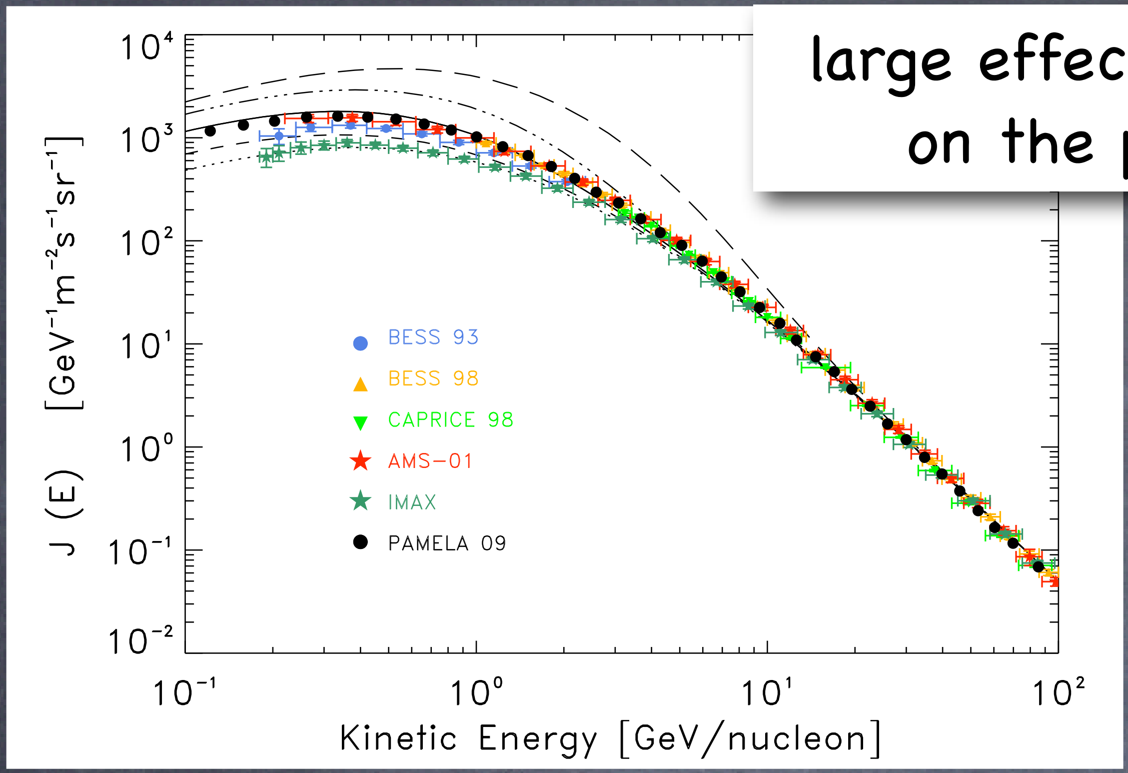

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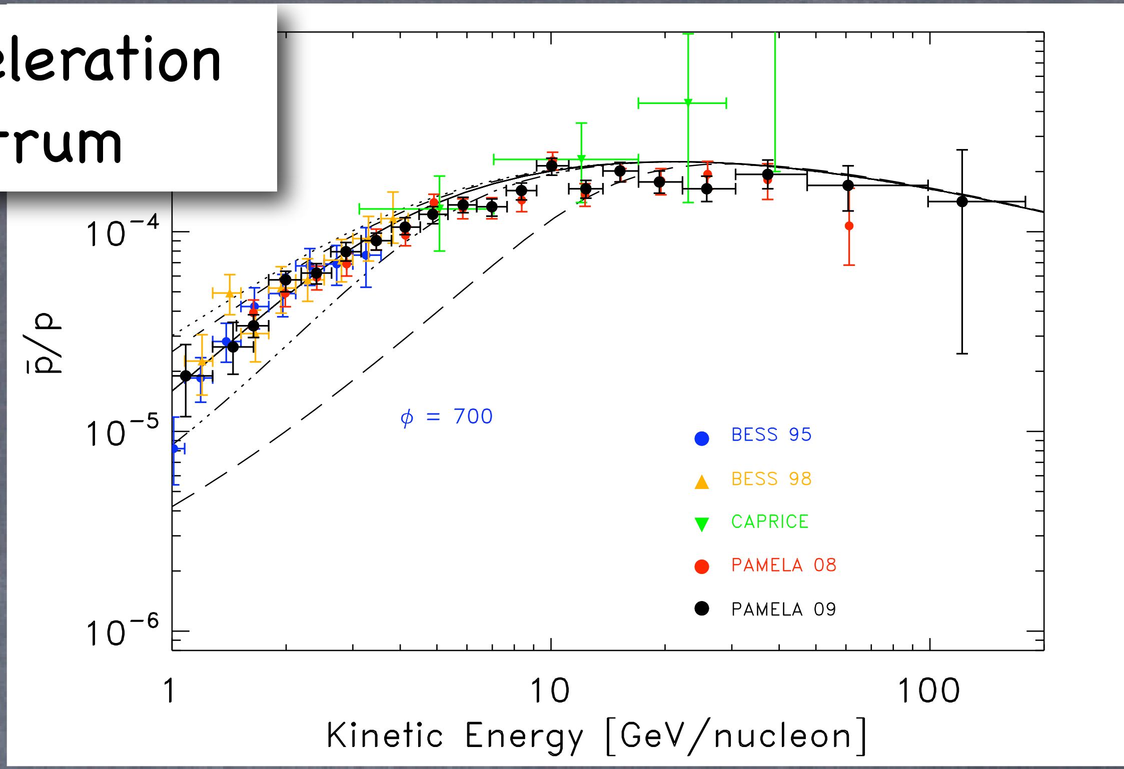
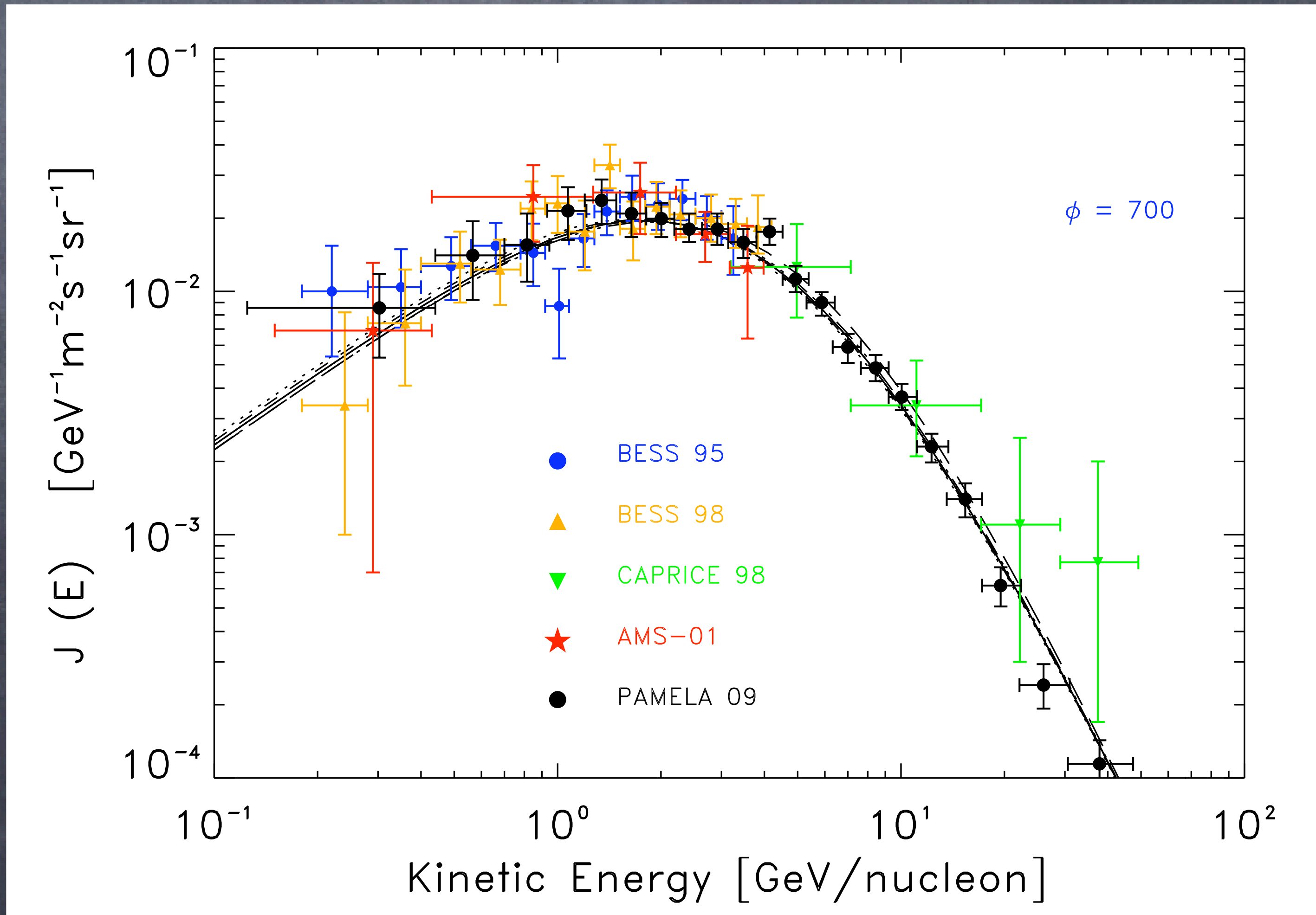


Interesting feature:
the antiproton flux does not depend on v_A
(hence on reacceleration)



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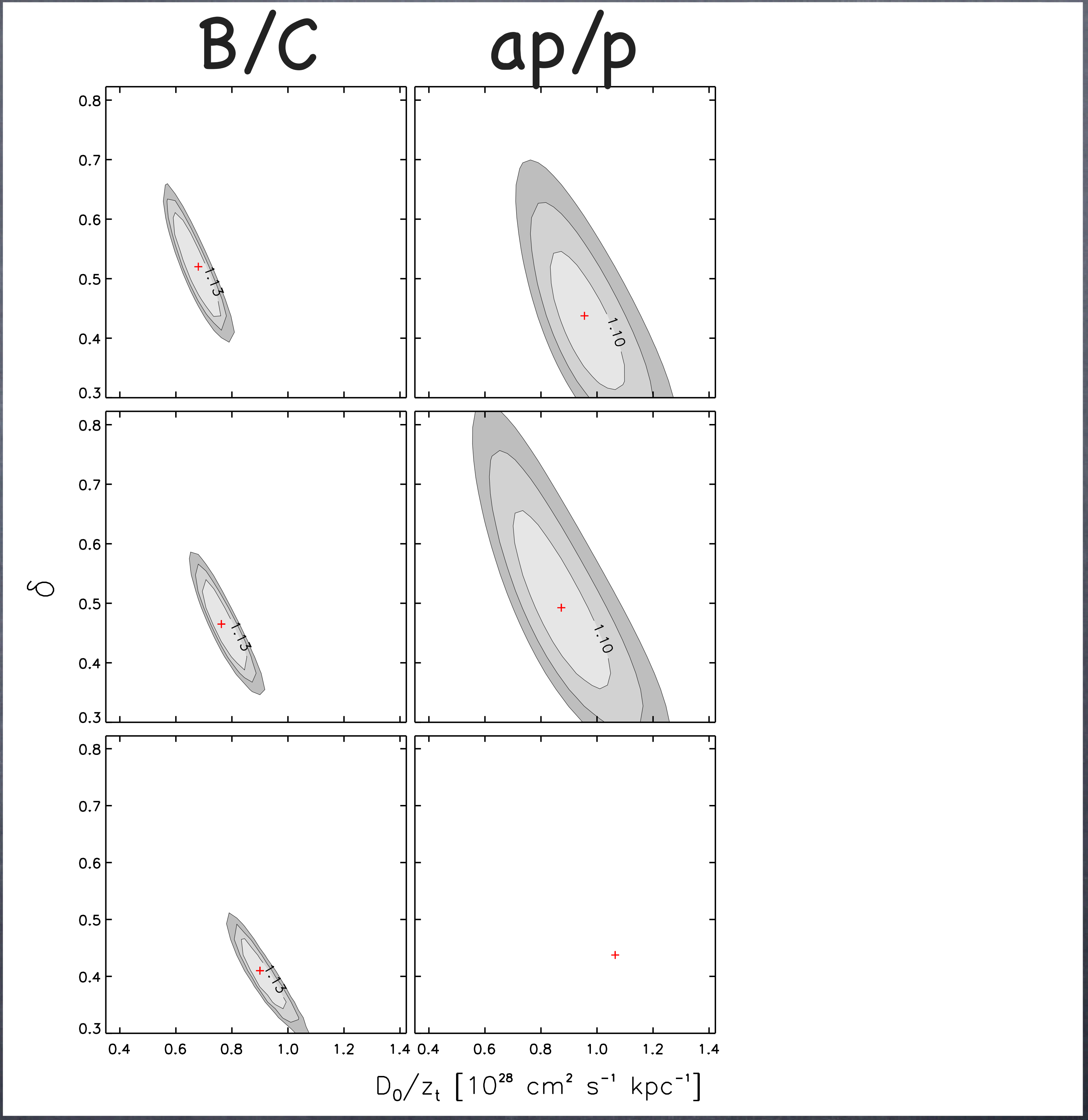
Confidence level contours for various v_A=10,15,20 km/s and E_k^{min} = 1 GeV/n

20 B/C points
38 ap/p points



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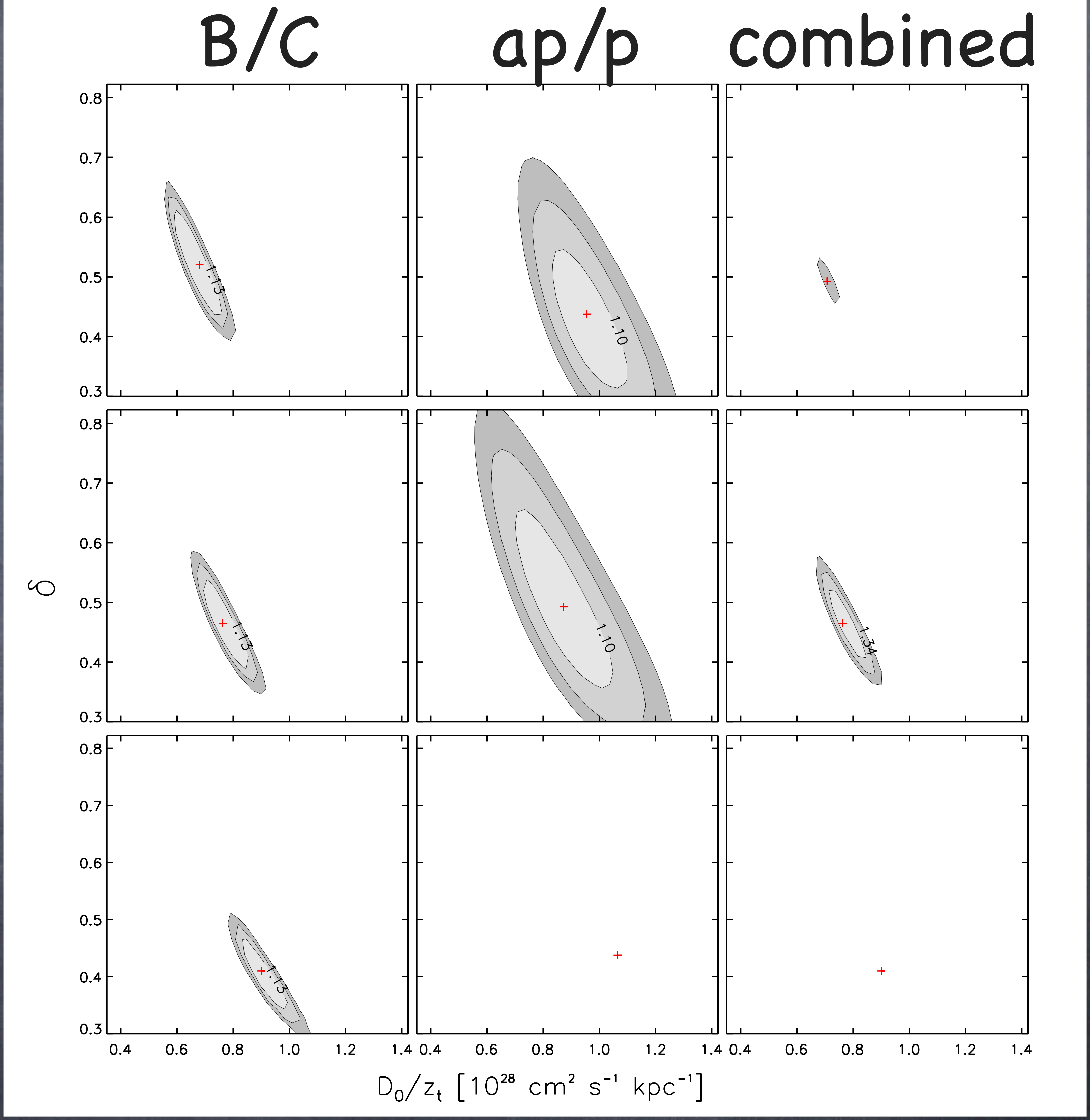

Statistical analysis II

Ideally: in the energy dependent analysis the best model is the one without energy variation of the parameters.

More statistics at high energy is required, with small error bars...

	B/C analysis				joint analysis		
v_A [km/s]	$E_{\min}$ [GeV/n]	δ	D_0/z_t	χ^2	δ	D_0/z_t	χ^2
0	1	0.57	0.60	0.38	0.49	0.79	1.63
	5	0.49	0.68	0.38	0.49	0.96	0.85
	10	0.46	0.73	0.19	0.55	0.90	1.63
10	1	0.52	0.68	0.32	0.49	0.79	0.87
	5	0.46	0.73	0.40	0.52	0.90	1.92
	10	0.44	0.79	0.19	0.60	0.79	3.46
15	1	**0.46**	**0.76**	0.33	0.49	0.79	0.87
	5	0.44	0.79	0.36	0.52	0.90	1.92
	10	0.44	0.82	0.20	0.60	0.79	3.46
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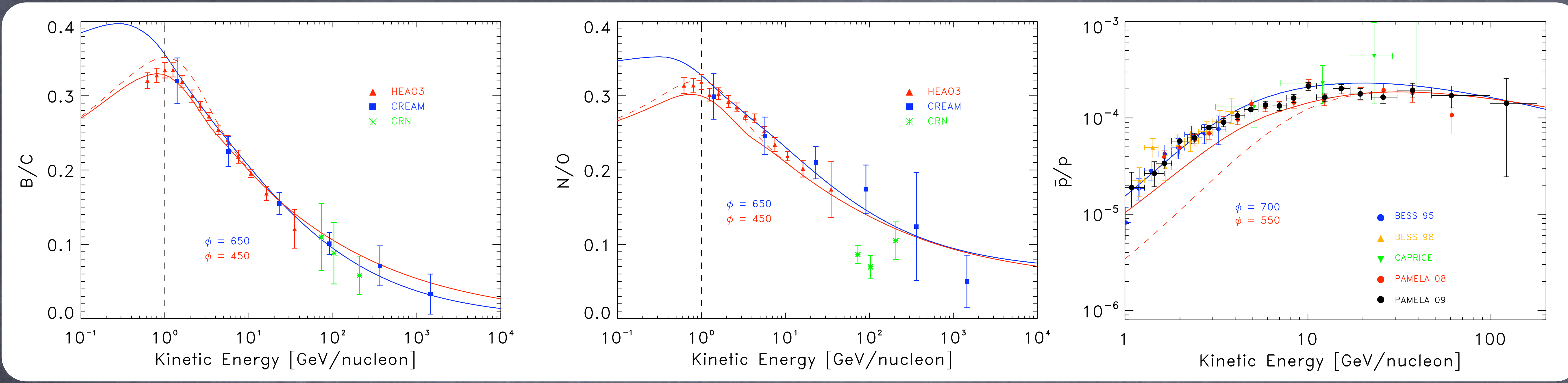
	10	0.41	0.87	0.21	0.52	0.98	1.91
30	1	0.33	1.20	0.40	0.41	1.01	1.92
	5	0.38	1.04	0.19	0.49	0.98	1.09
	10	0.41	0.95	0.16	0.52	0.98	1.91

Comparison with other's results



Galprop models:

δ = 0.33

v_A = 30 km/s

break in CR injection spectrum at 9 GV (required to fit low energy data)

★ fit B/C down to low energy

★ problems with N/O

★ problems with antiprotons (if no break is introduced)

★ no quantitative estimate of quality of fit and more free parameters

DRAGON models:

δ = 0.46

v_A = 15 km/s

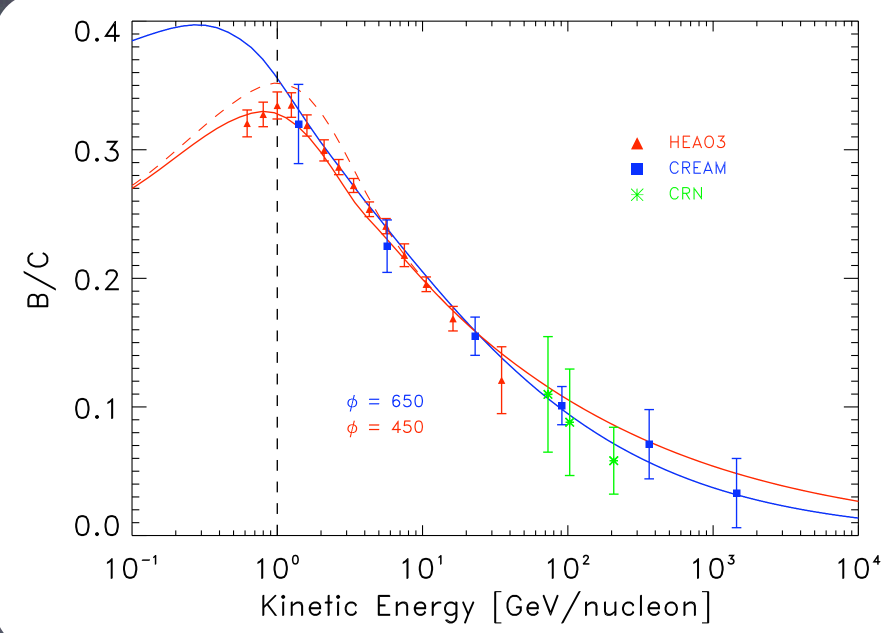
no break in CR injection

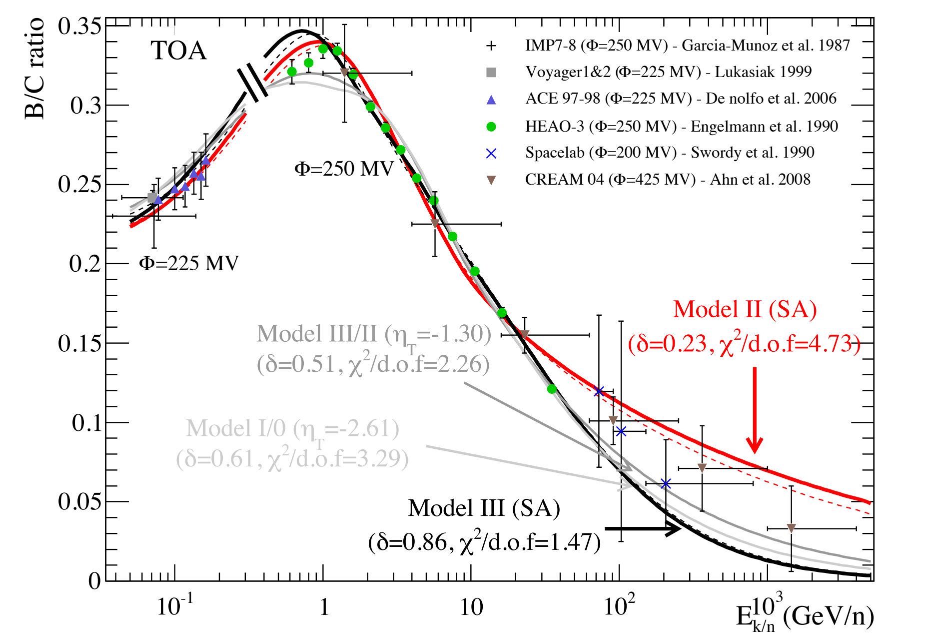
★ work well above 1 GeV/n for both nuclei and ap (no discrepancy between B/C and ap/p measurements)

★ problems at lower energy

★ less free parameters

Comparison with other's results





Semi-analytic models:

more difficult to compare,
due to different assumptions.
Consider Maurin et al, 1001.0553
and a model without convection

$\delta = 0.51$

v_A (rescaled) = 7 km/s

+ low energy effects on diffusion

Overall good agreement.

DRAGON models:

$\delta = 0.46$

v_A = 15 km/s

no break in CR injection

- ★ work well above 1 GeV/n for both nuclei and ap (no discrepancy between B/C and ap/p measurements)
- ★ problems at lower energy
- ★ less free parameters

Systematic uncertainties

see **Maurin et al, 1001.0553**

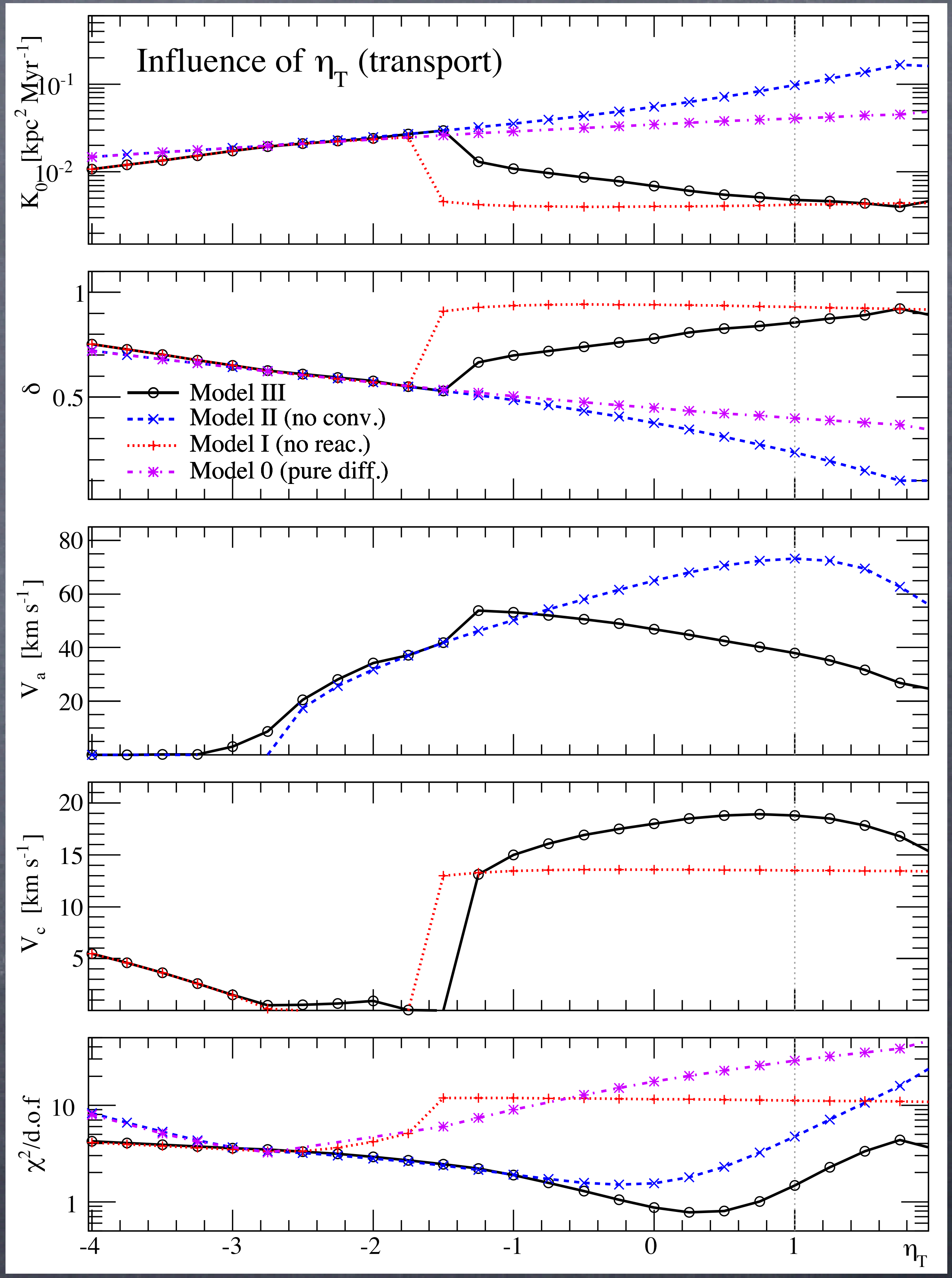
Fragmentation cross section:
- from the cross section itself ~ 20%

Allowing for some systematic energy bias
- factor of 2 on D_0
- 10% on δ
- 50% on v_A

Unknown low energy physics:
parametrized as

$$D \propto \beta^{\eta_T} \left(\rho/\rho_0\right)^{\delta}$$

large effects, especially on v_A

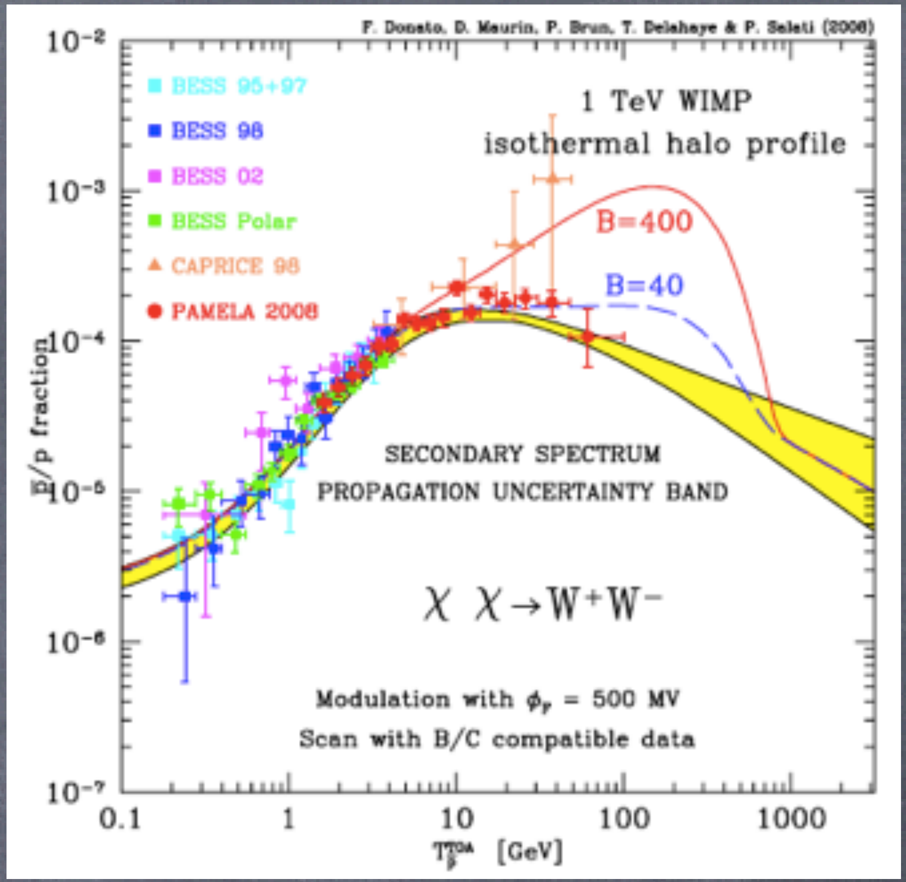


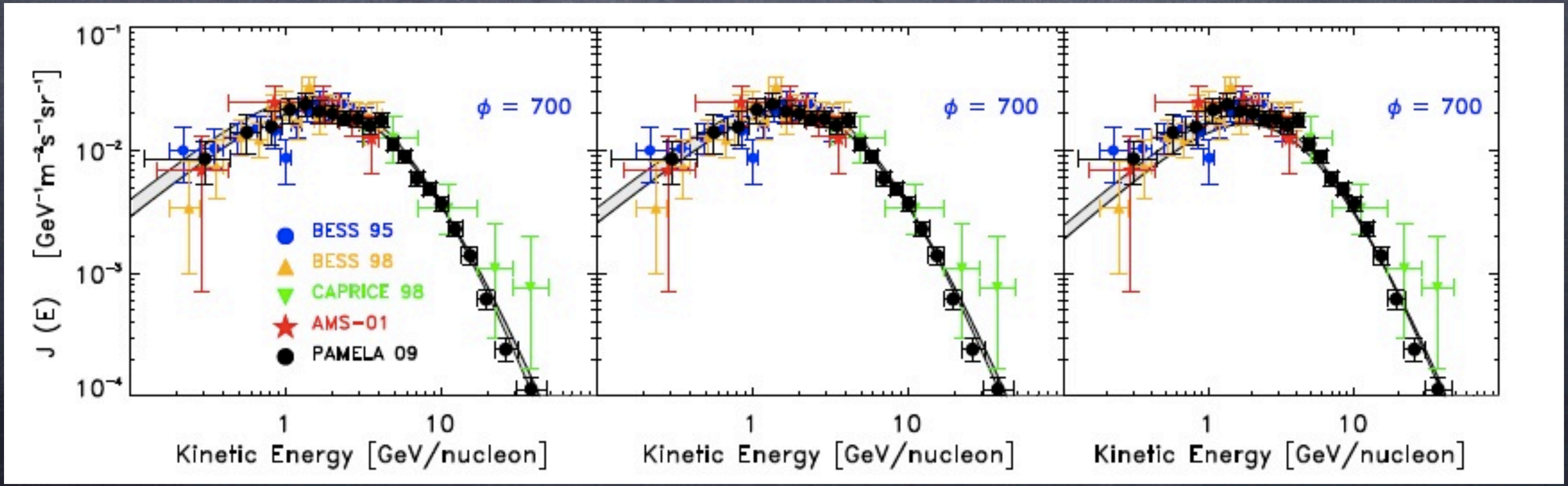
In view of DM studies... study the BG!

Antiprotons can be produced by exotic galactic components, as DM, together with positrons

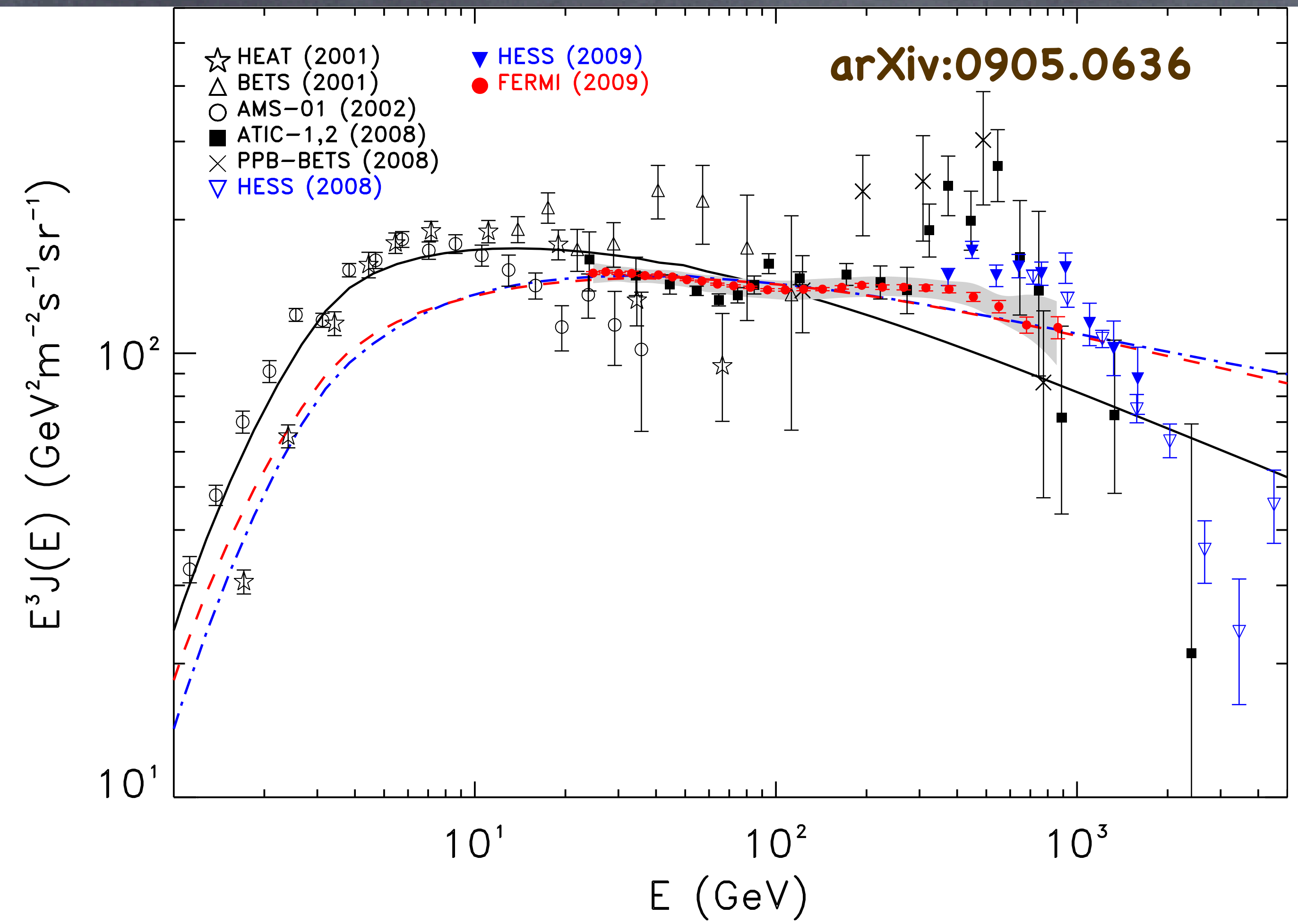
We estimate the max and min flux of CR antiprotons in agreement with B/C data (2σ).

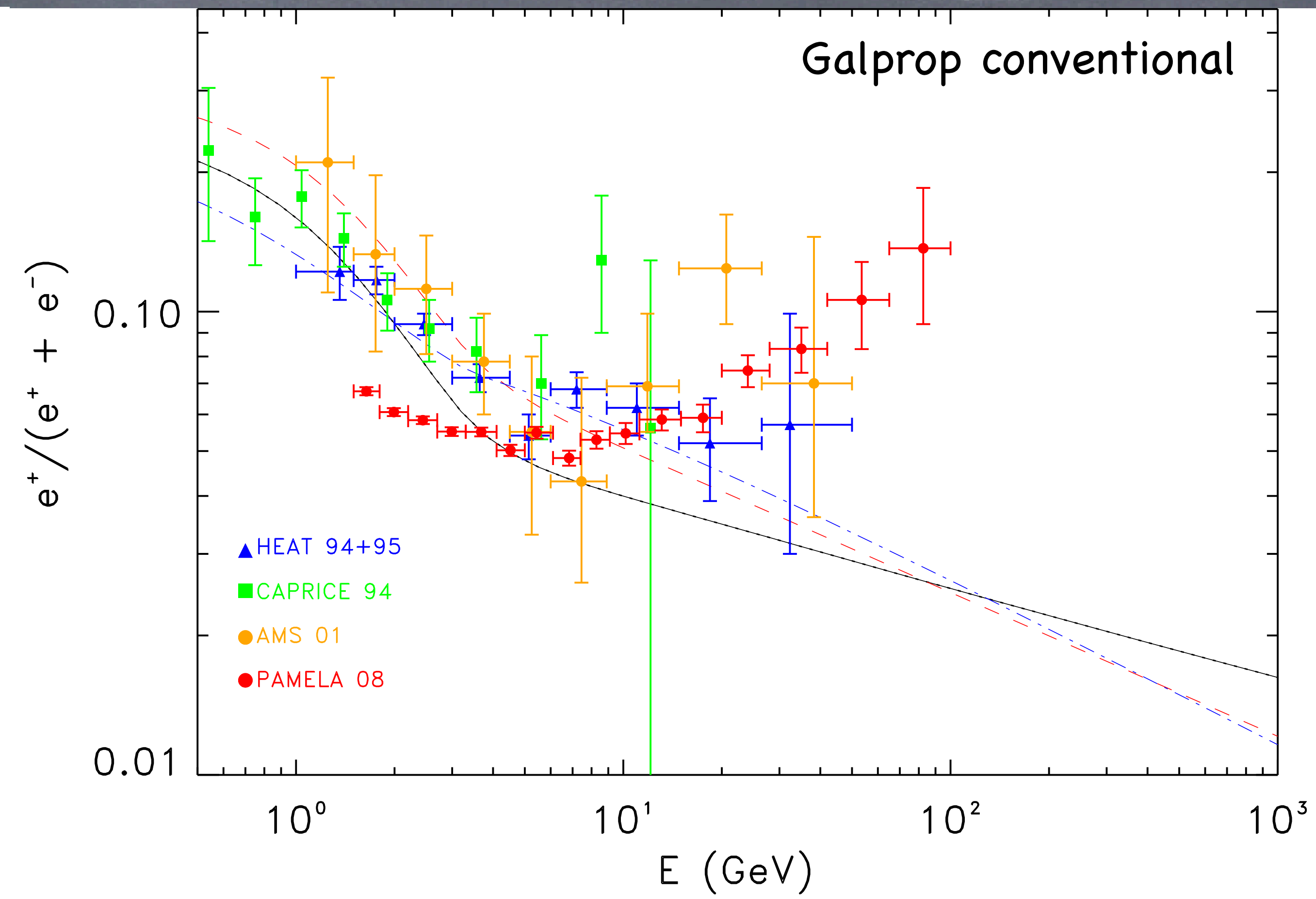
Not too large variation, and overall agreement with data.
Strong constraints are likely.





Electrons/positrons... harder case

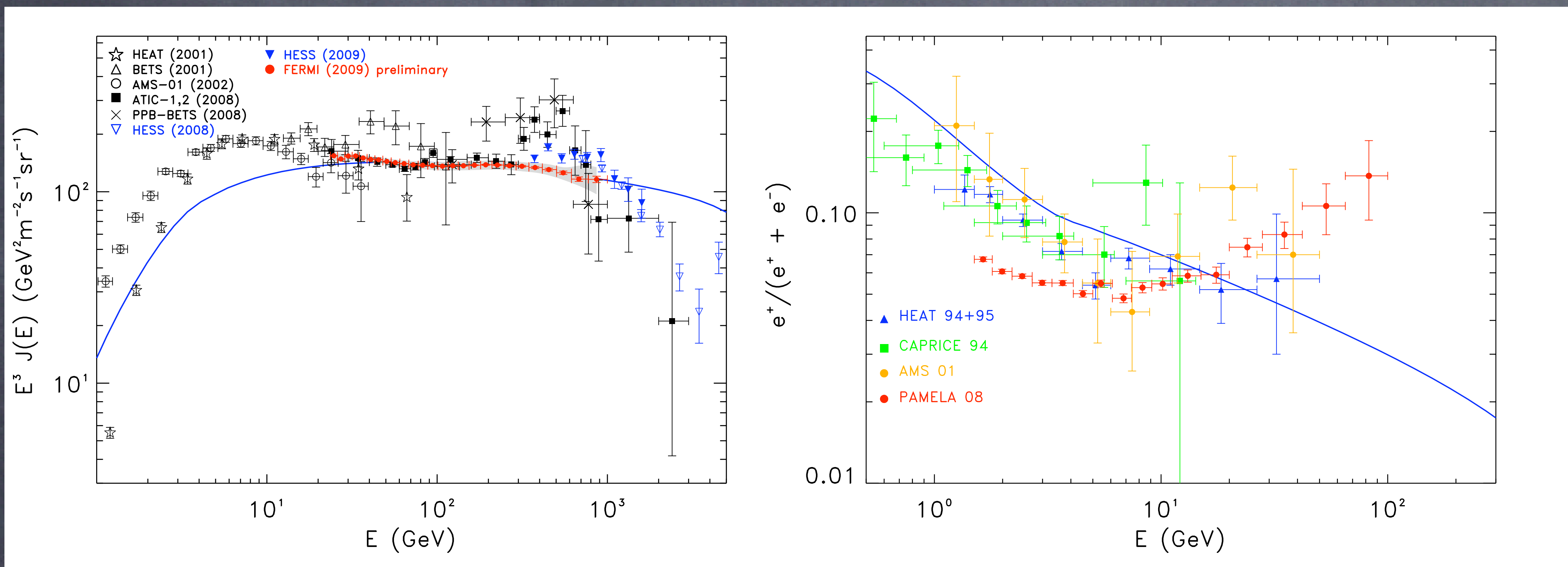




FERMI hard electron+positron spectrum $E^{-3.04}$.
ATIC bump not confirmed (disfavored DM interpretation).
The combination of these data together with antiproton data cannot be explained in a single component diffusion model.
It can be explained via pulsar contribution (Geminga and Monogem).
Also positron production in the source can be viable (**Blasi&Serpico, 2009**)

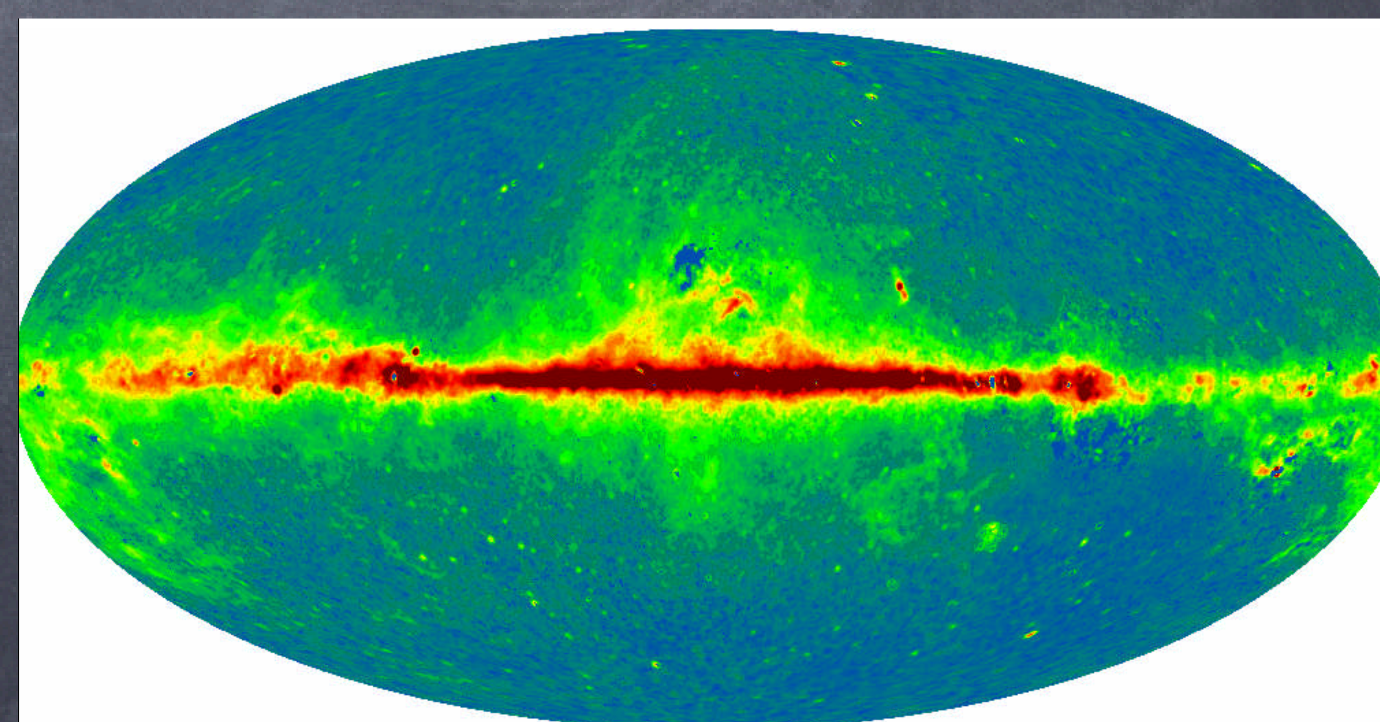
Electrons/positrons with DRAGONe

We are able to reproduce standard data with the best fit model + break in the electron injection spectrum

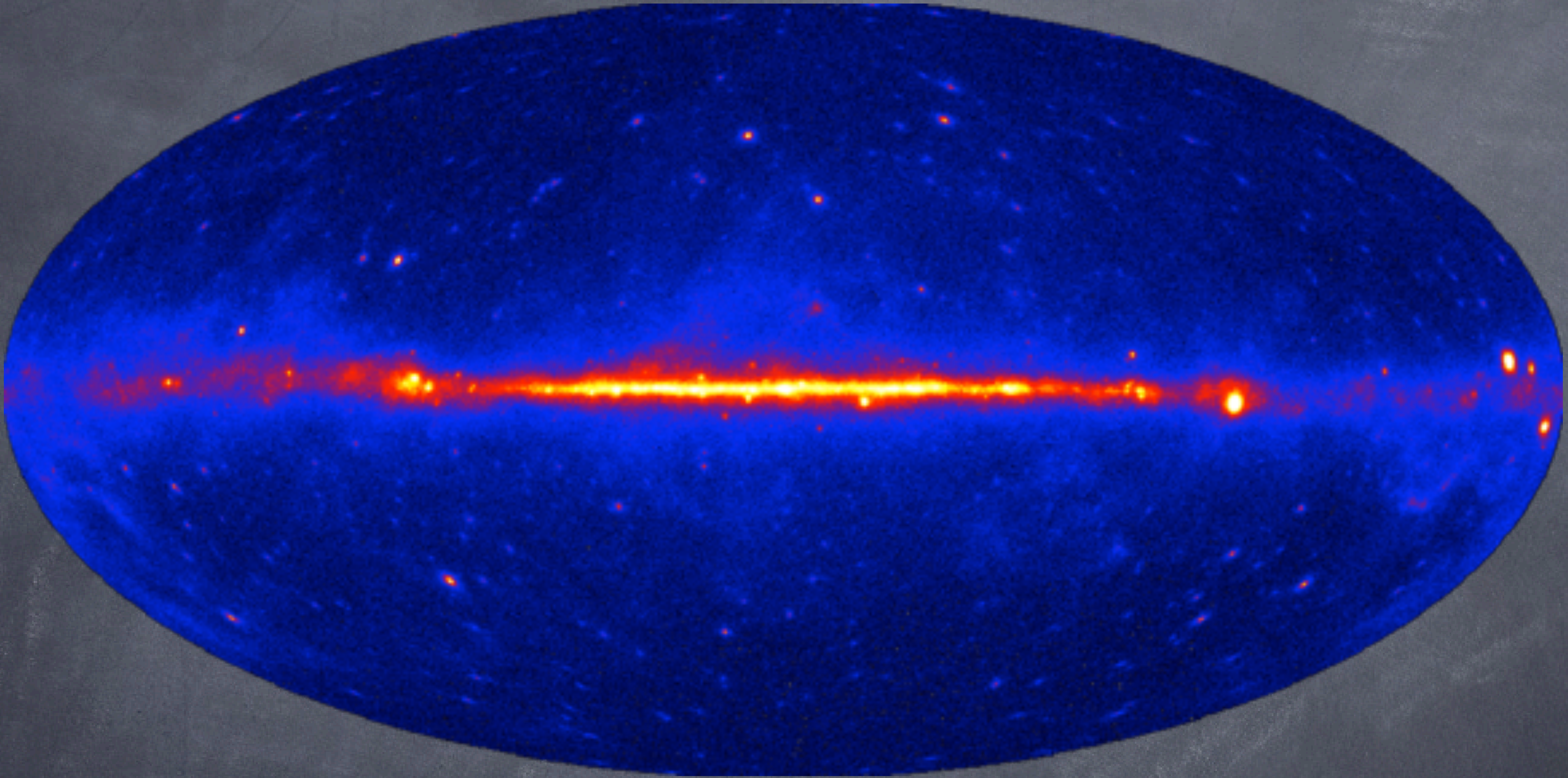


Effects of position dependent and anisotropic diffusion coefficient still to be tested.

Relevant for radio galactic foreground analysis



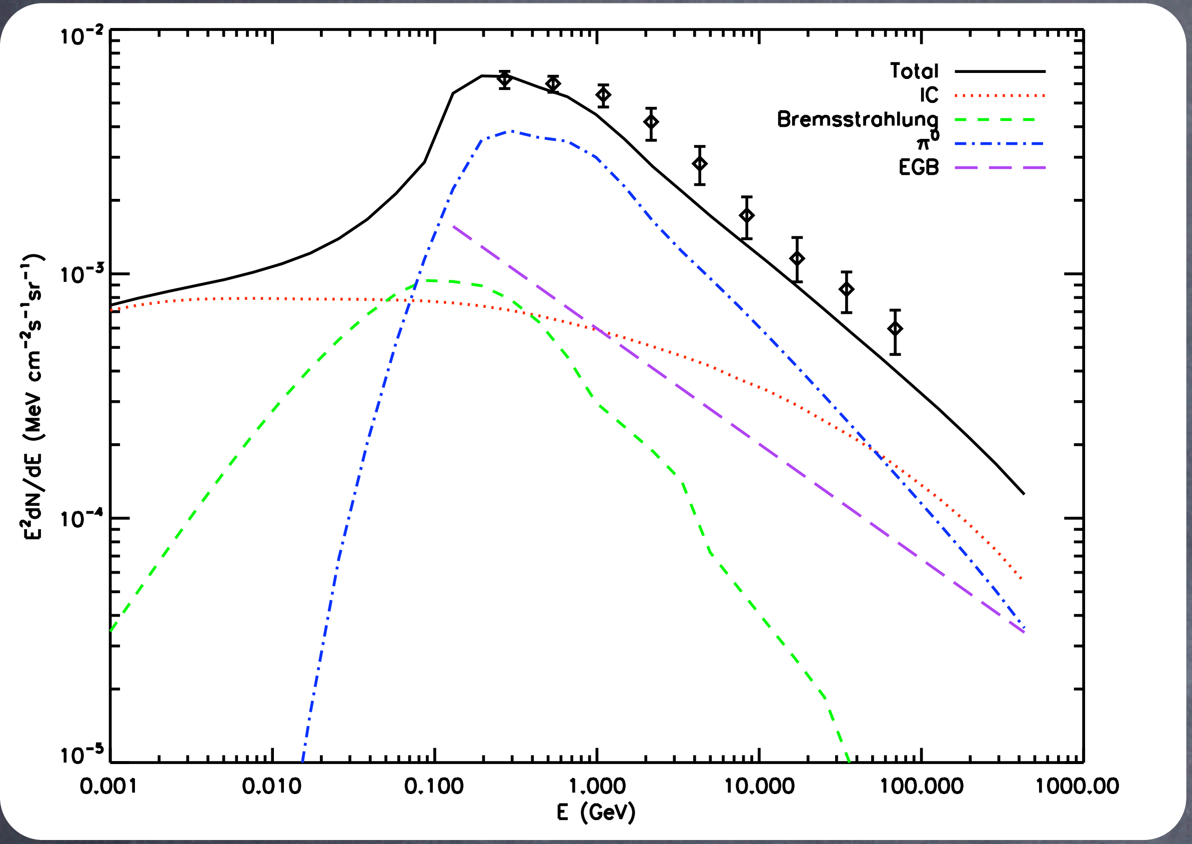
Gamma-rays



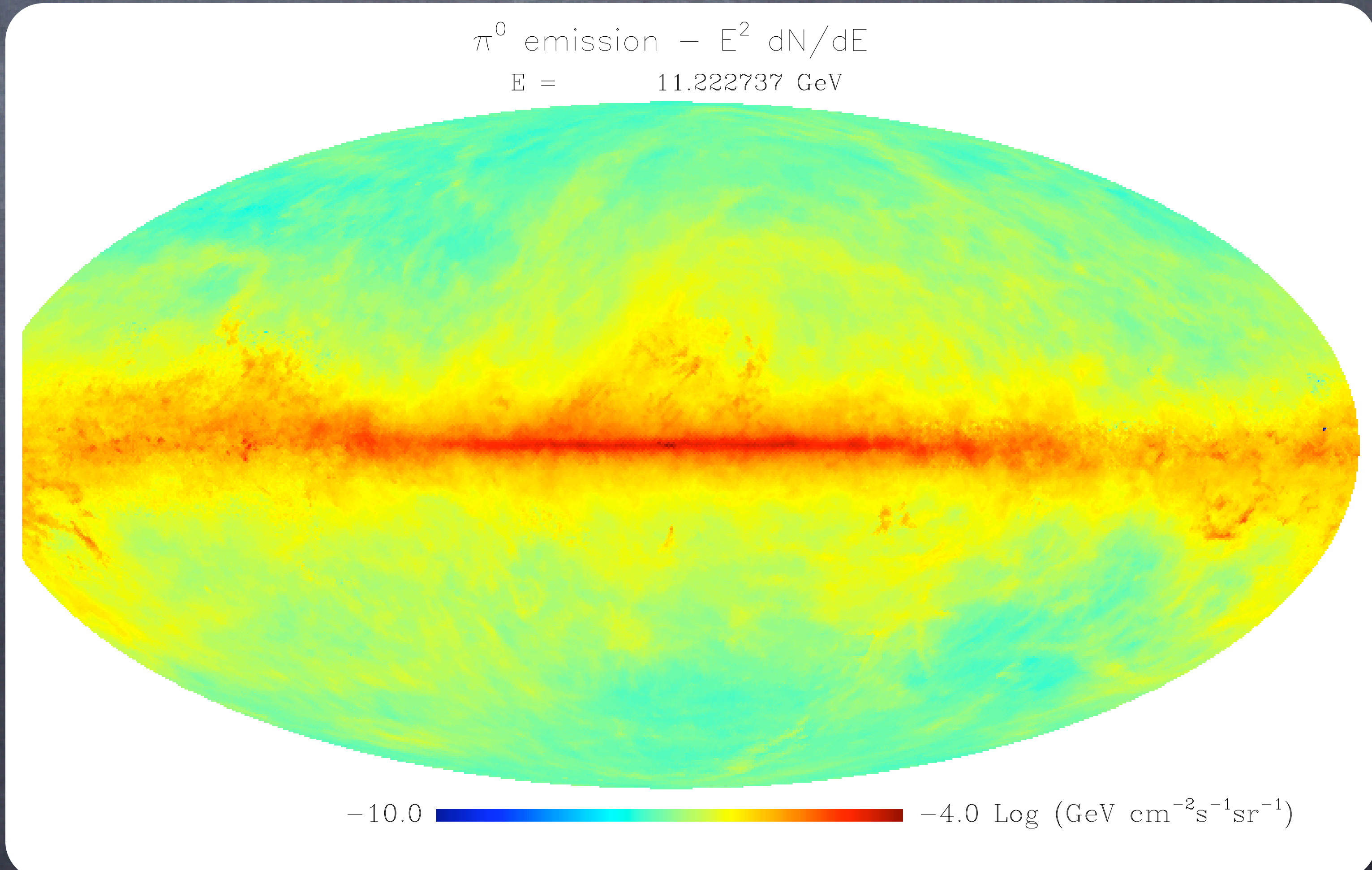
$$pp \rightarrow NN\pi^0 \rightarrow \gamma\text{−rays}$$
$$e\gamma \rightarrow e\gamma \qquad \text{(ICS)}$$
$$e + \text{gas} \rightarrow \gamma \qquad \text{(bremsstrahlung)}$$

Gamma-rays with DRAGONe + gammasky

We developed some tool to compute skymaps from CR interactions. proton-proton, bremsstrahlung and ICS are included (also synchrotron in GMFs...)



γ-ray spectrum in region 10 < |b| < 20, 0 < l < 360. Points from arXiv:0912.0973



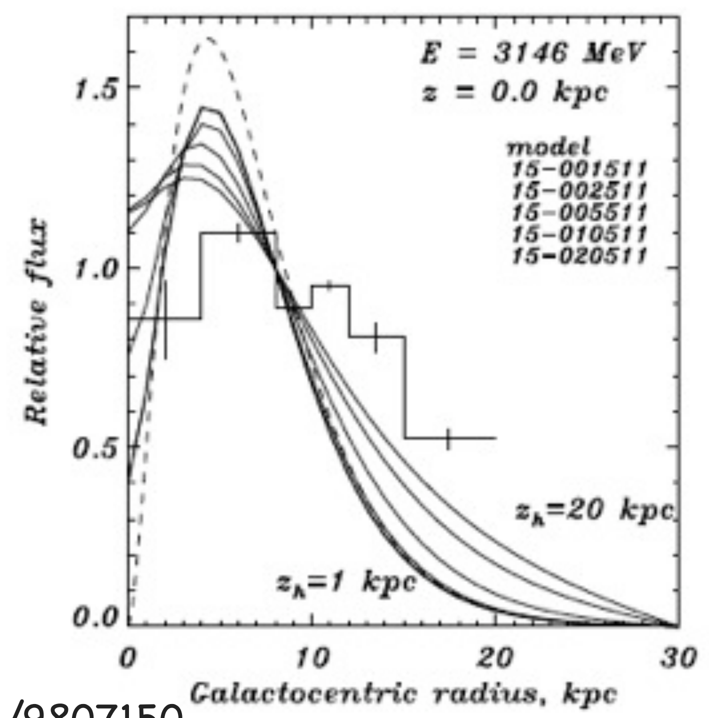
Gamma-rays: the gradient problem

From COS-B and EGRET observations it is possible, assuming to know the distribution of the hydrogen gas, to trace back the radial distribution of CRs.

The so determined "radial gradient" of CRs is much smaller (CRs are more "uniformly distributed") than expected if one assumes SNR to be the acceleration sites.

Proposed solution:
- better tuning of the gas parameters (Strong et al, 2004)
- galactic winds (Breitschwerdt et al., A&A 385, 2002)
- ...

So far: uniform diffusion coefficient over whole Galaxy. Maybe too irrealistic ??



from astro-ph/9807150

FIG. 11.— Radial distribution of 3 GeV protons at $z = 0$, for diffusive reacceleration model with halo sizes $z_h = 1, 3, 5, 10, 15$, and 20 kpc (solid curves). The source distribution is that for SNR given by Case & Bhattacharya (1996), shown as a dashed line. The cosmic-ray distribution deduced from EGRET >100 MeV gamma rays (Strong & Mattox 1996) is shown as the histogram. Parameters as in Table 2.

Reconsider diffusion

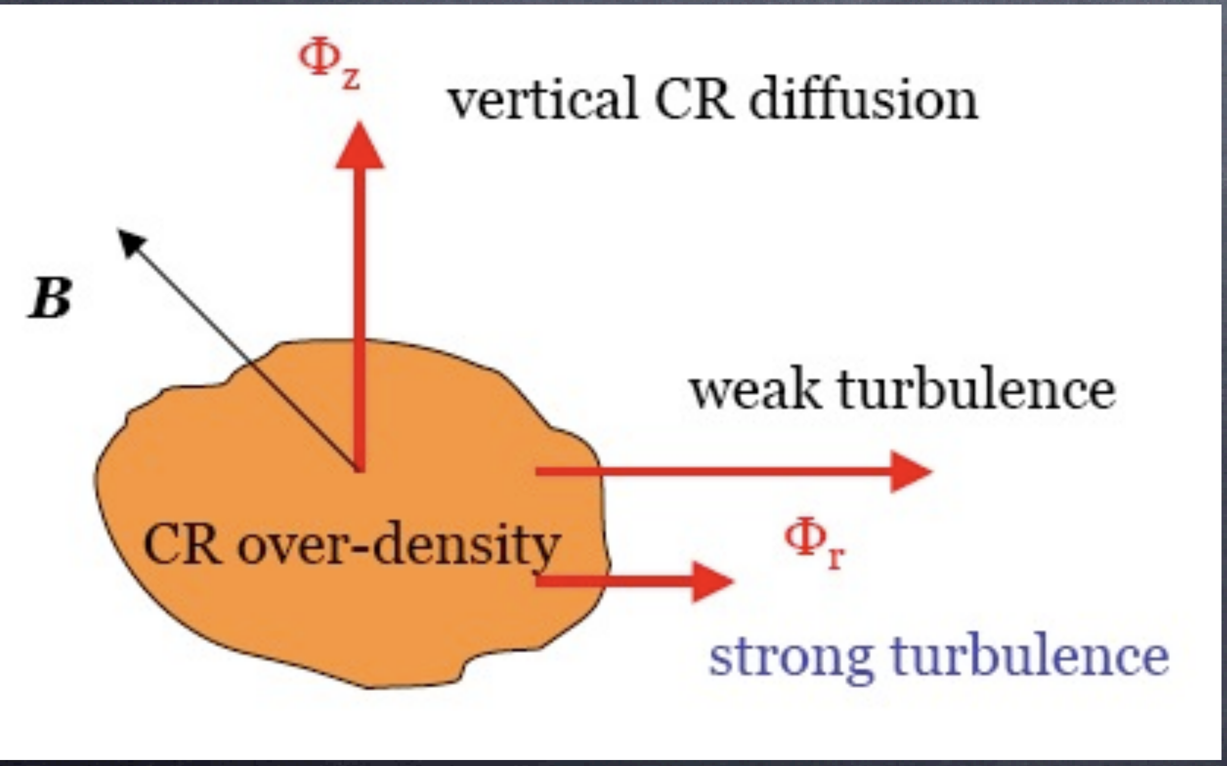
Turbulence mainly driven by CRs

↓

diffusion enhanced in SNR rich regions

↓

position dependent diffusion coefficients
(previous simulations adopted uniform diffusion coefficients and isotropic diffusion)



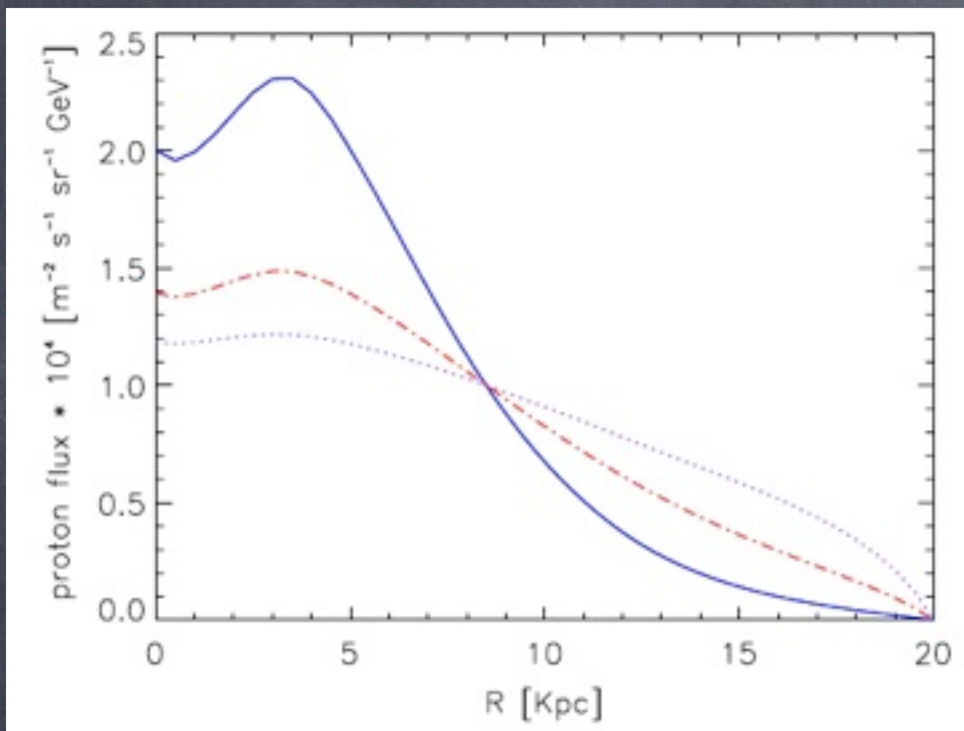
- It may produce a smoothing of the cosmic ray distribution.
- The perpendicular diffusion is enhanced in strong turbulence regime.
- CRs are then likely to diffuse away more easily from the sources filling the voids.

Solving the gradient problem?

Evoli, Gaggero, Grasso, LM, JCAP 0810:018,2008

$$D_\perp(r,z) = f_S(r,0)^\tau e^{z/z_t}$$

Distribution of CR sources in the disk
τ > 0 a free parameter to be determined

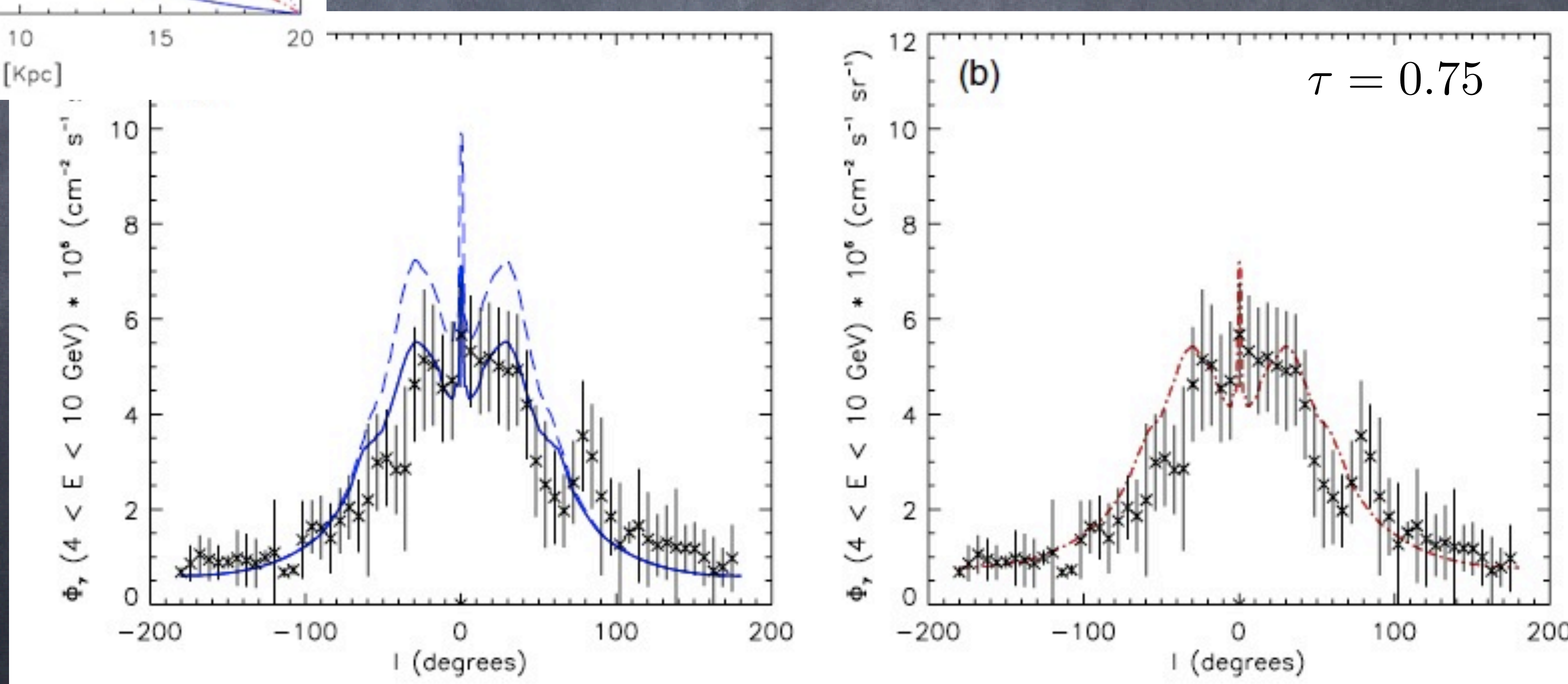


We study the effect of varying τ on the CR radial profile. Increasing τ smooths the CR profile, as expected. Relevant effects also on the gamma-ray longitudinal profile

$\tau = 0$

gas fine tuned

$\tau = 0$



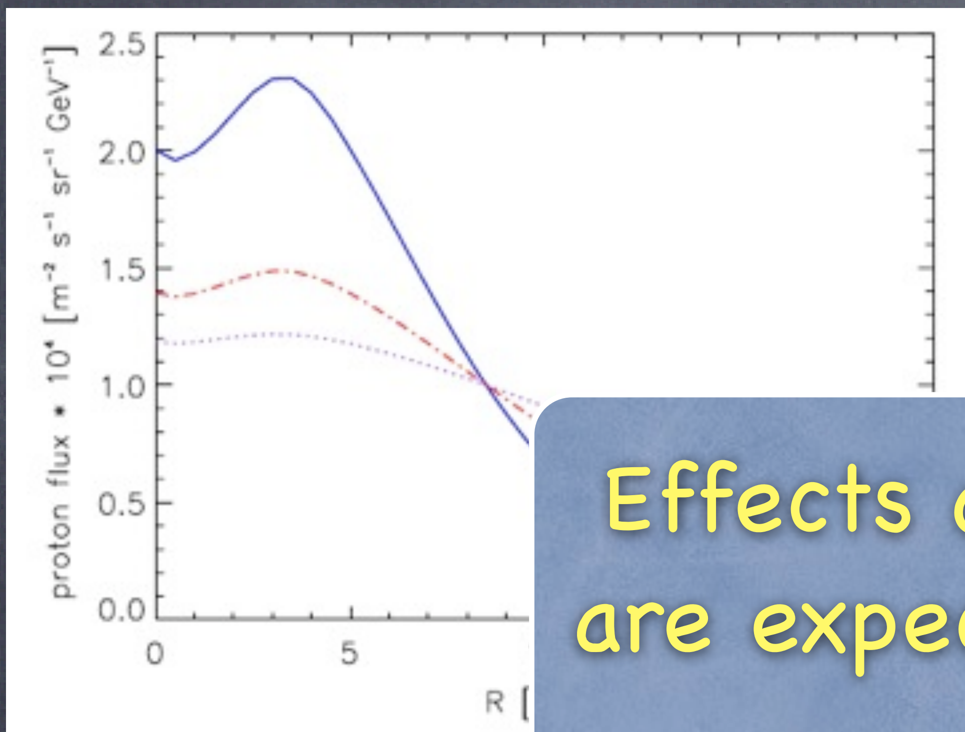
Solving the gradient problem?

Evoli, Gaggero, Grasso, LM, JCAP 0810:018,2008

$$D_\perp(r,z) = f_S(r,0)^\tau e^{z/z_t}$$

Distribution of CR sources in the disk

τ > 0 a free parameter to be determined



We study the effect of varying τ on the CR radial profile. Increasing τ smooths the CR profile,

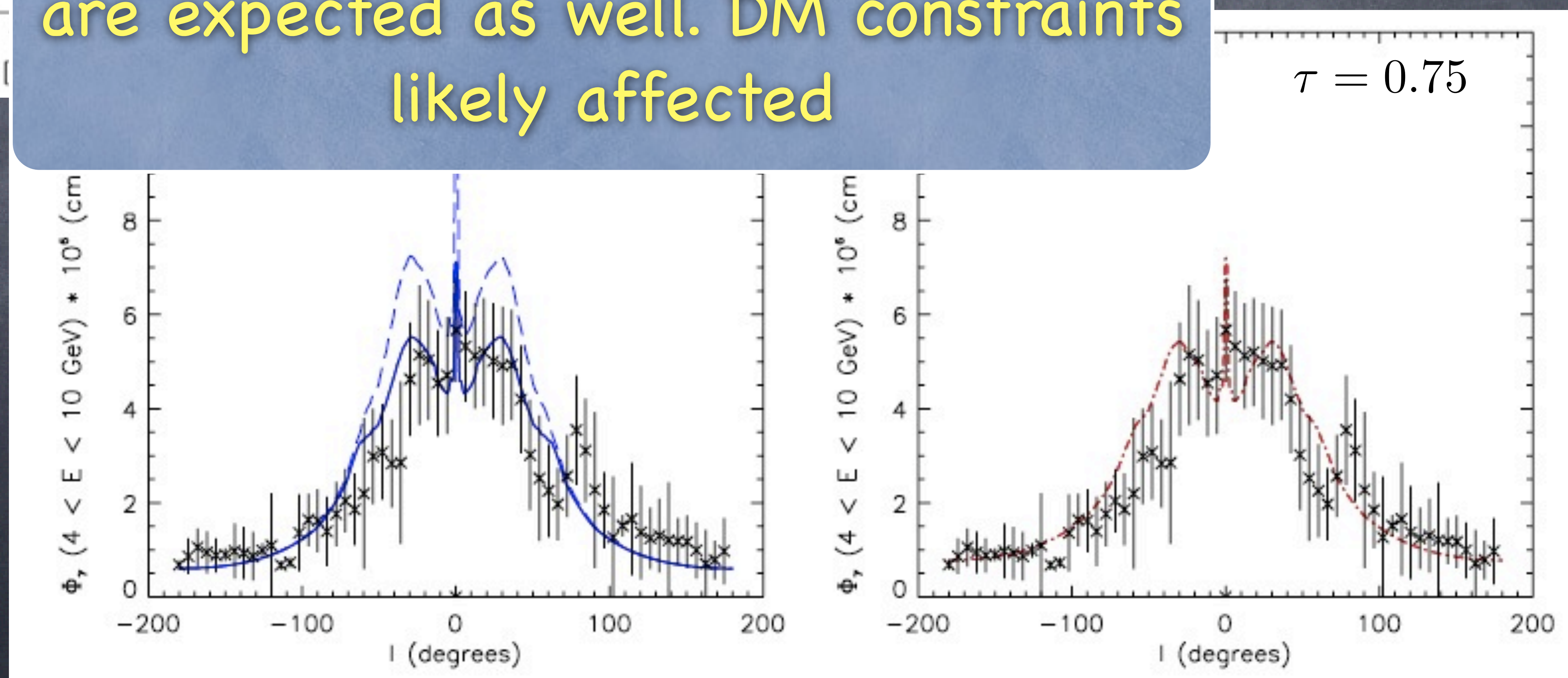
the gamma-

Effects on the electron distribution are expected as well. DM constraints likely affected

$\tau = 0$

gas fine tuned

$\tau = 0$



Conclusions

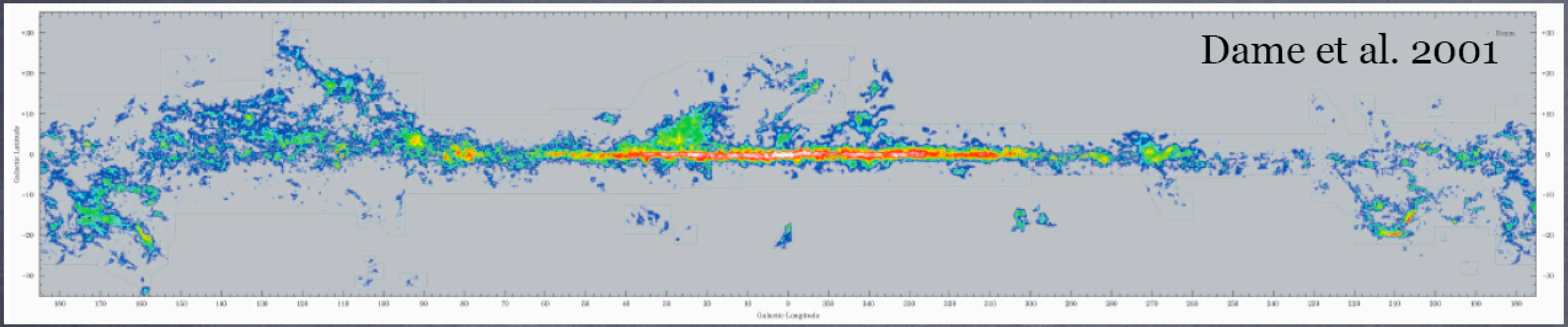
- we exploited for the first time recent CR data (CREAM, PAMELA) to perform a combined statistical analysis of nuclei and antiproton spectra aimed at placing constraints on CR propagation parameters
- the analysis is tailored to understand energy dependent effects
- we placed constraints on D_0, δ, v_A. In particular $0.38 < \delta < 0.57$ at 95% CL and large values of vA are disfavored by antiproton data
- we showed that the nuclear and antiproton data sets above 1 GeV/n are compatible without additional hypotheses on CR sources and propagation
- CR gradient problem: addressed in the context of position dependent diffusion (otherwise uniform diffusion sufficient to reproduce CR data): this might have effects on DM investigations
- we extended DRAGON to propagate electrons and positrons and to compute gamma-ray emission.
- we computed min/max antiproton fluxes, compatible with nuclear data, to help DM studies with CRs. Ongoing analysis of the leptonic and gamma-ray channels

- Backup slides

Gas distribution

H_2 is the main target on the Galactic Plane. Generally traced by ^{12}CO (J=1-0).

Proportionality factor: X_{CO}

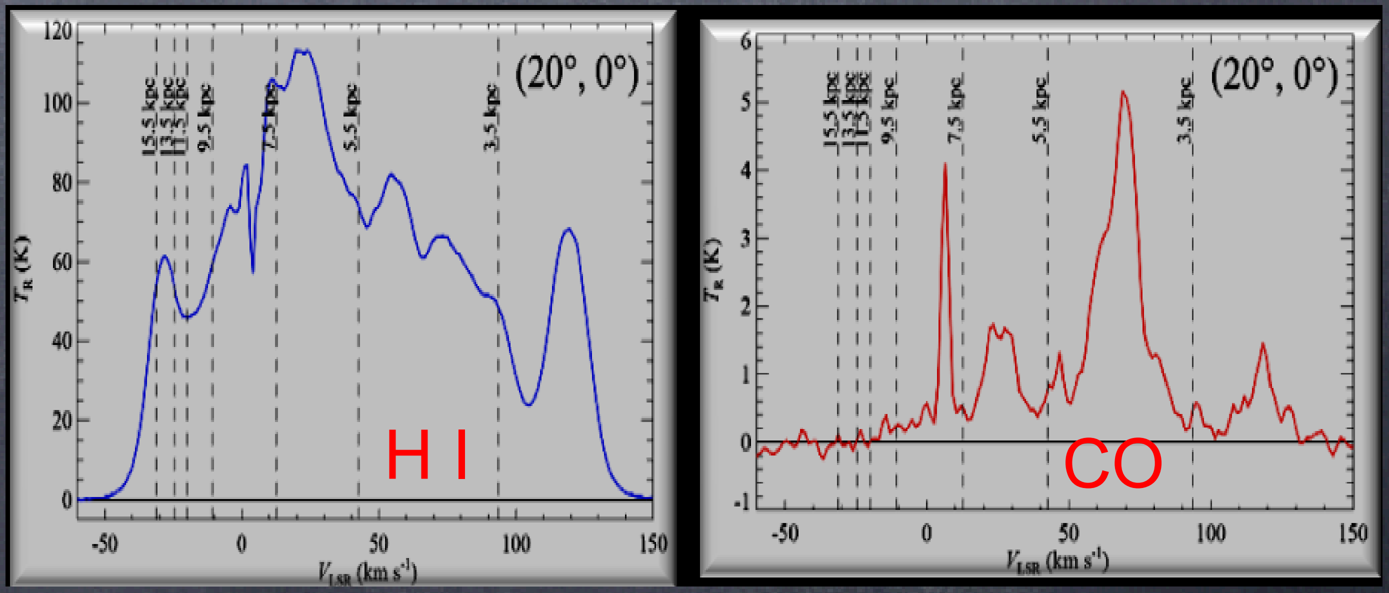


Also HI, traced by 21-cm emission.
HII less relevant in the galactic plane.

3-D structure:

Doppler shift (velocity)

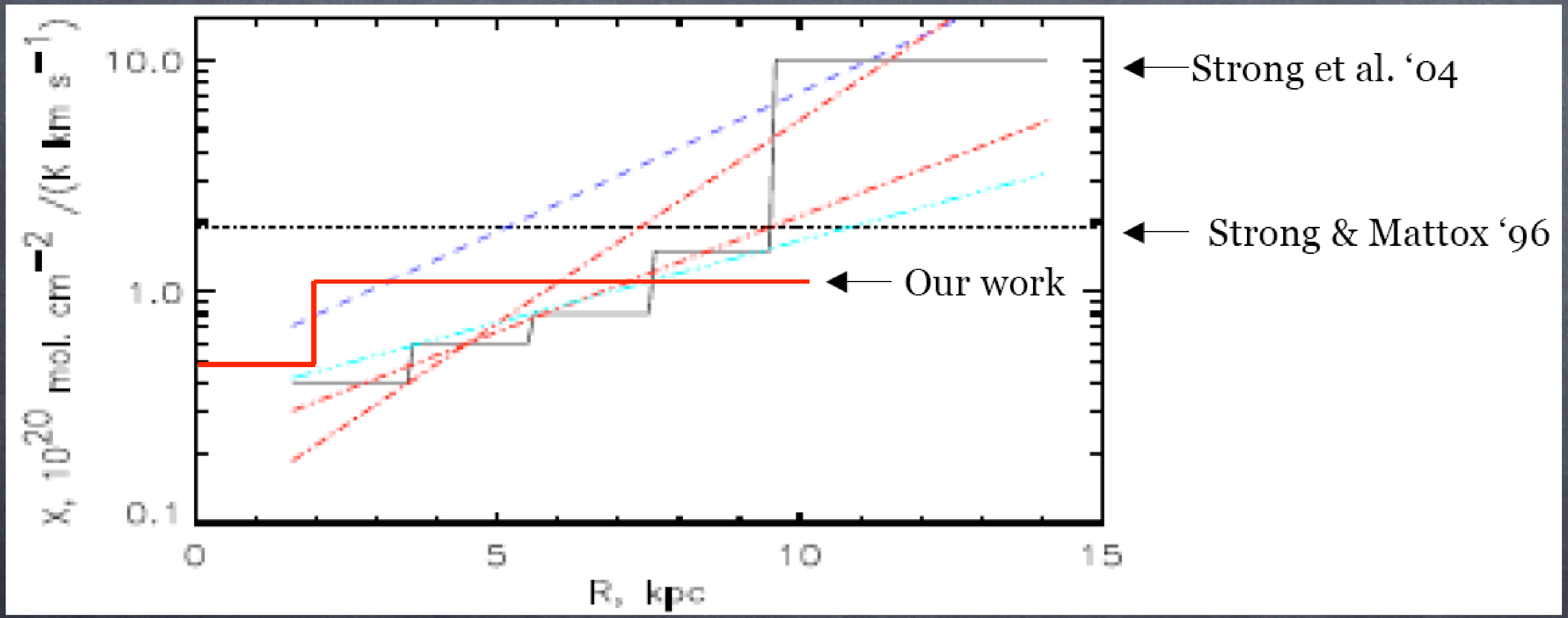
Galactic rotation curve.



T. Porter, Fermi Symposium 2009

Fine tuning the gas distribution: X_{CO}

A scaling factor is needed to convert CO maps into gas column density.
Expected to change with r, dependence on the metallicity.
Fine tuning needed to achieve agreement with EGRET measurements
(**"CR gradient" problem**, see **Strong et al., A&A 422**).



The uncertainty is about a factor of 2.

Useful tools: secondary to primary ratios

Spectral slopes of **Primary CRs** at high energy mainly depend on:
Injection spectrum ($E^{-\alpha}$)
Energy dependence of diffusion coefficient (E^{δ})

$$0 = Q(E) - \frac{N(E)}{\tau_{\rm esc}(E)} \rightarrow N(E) \propto Q(E)\tau_{\rm esc}^{-1}(E) \rightarrow N(E) \propto E^{-\alpha-\delta}$$

The slopes of ratios of **Secondary/Primary CRs** do not show this degeneracy: they only depend on energy dependence of diffusion coefficient.

$$\frac{N_{\rm sec}(E)}{\tau_{\rm esc}(E)} + \frac{N_{\rm sec}(E)}{\tau_{\rm int}(E)} = \frac{N_{\rm pri}(E)P_{\rm spall}(E)}{\tau_{\rm int}(E)} \rightarrow \frac{N_{\rm sec}}{N_{\rm pri}} \propto \frac{P_{\rm spall}(E)\tau_{\rm esc}(E)}{\tau_{\rm int}(E)} \rightarrow E^{-\delta}$$