Studies of comic ray propagation with PAMELA

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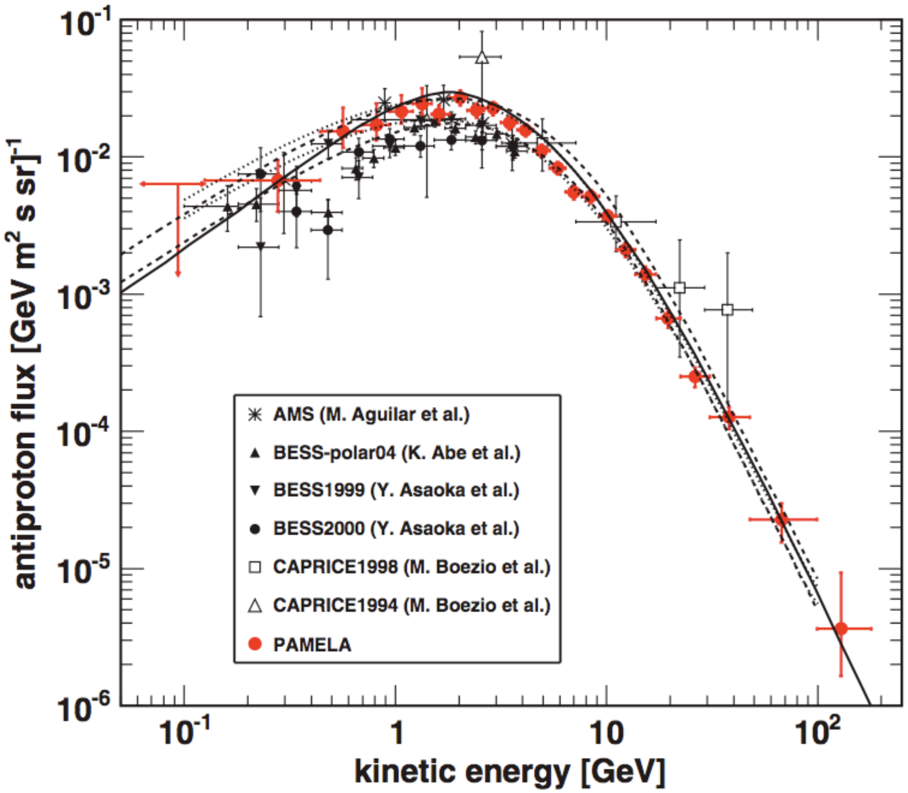
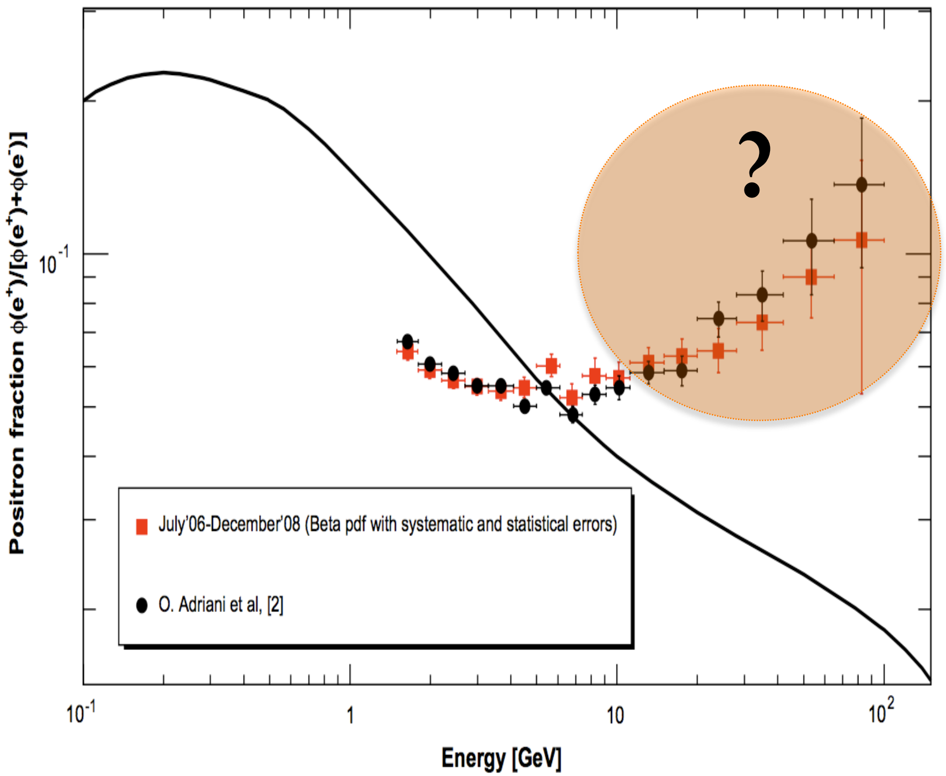
Antimatter measured by PAMELA and dark matter

$$\chi + \chi \rightarrow q\bar{q}, W^+W^-, \ldots \rightarrow \bar{p}, \bar{D}, e^+, \gamma \ \& \ \nu .$$





Accurate and robust determination of cosmic ray propagation allow us to investigate dark matter indirectly.

Cosmic ray propagation equation

Basic mechanism: diffusion, convection, diffusive reacceleration, energy loss

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p)$$ sources: SNRs, spallation…

$$+\vec{\nabla}\cdot[D_{xx}\vec{\nabla}\psi - \vec{V}\psi]$$ diffusion

$$+\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2}\right]$$ diffusive reacceleration

$$-\frac{\partial}{\partial p}\left[\frac{dp}{dt}\psi - \frac{1}{3}p\vec{\nabla}\cdot\vec{V}\psi\right]$$ energy losses: ionization, bremstrahlung; adiabatic loss

$$-\frac{\psi}{\tau_f} - \frac{\psi}{\tau_d}$$ fragmentation; radioactive decay

For primary nucleons

$q_A(p) = N_A (p/p_n)^{-\nu}$

For spallation

$q(r, p) = \beta\, c t\, \Psi_p(r, p)[\sigma_H(p) n_H(r) + \sigma_{He}(p) n_{He}(r)]$

diffusion: $D_{xx} = D_0\, \beta\, (p/p_0)^{\delta}$

diffusive reacceleration: $D_{pp} D_{xx} \sim p^2 v_{Alf}^2$

convection: $V(z) = V(0) + z^* dV/dz$

Cosmic ray S/P ratios are important to study cosmic ray propagation +
Primary fluxes are important to study the injection spectrum

Methods to solve the propagation equation

- **Semi-analytical**: eg. USINE (Maurin et al. 2002, A&A, 394:1039

-- 1D and 2D

-- mean gas density

-- reacceleration is only considered in the Galactic disk

-- isotropic diffusion coefficient

-- difficult to treat electrons and photons well since only mean values of ISRF and B can be imported

-- faster computation than numerical methods.

- **Numerical integration**: eg. GALPROP (Strong & Moskalenko 1998, ApJ, 509:212)

-- 2D and 3D

-- spatial distributed gas density for HI (atomic hydrogen), HII (ionized hydrogen) and H_2 (molecular hydrogen)

-- reacceleration is considered in the Galactic disk+halo

-- allow anisotropic diffusion coefficient

-- can treat electrons and photons more realistic

-- public

Current status of propagation study

Different models were studied in literature use both methods: PD, DR, DC and DRC, but

(1) so far no specific model has been found as the best one to explain all the observations.

(2) for a specific model, the propagation parameters constrained are not consistent in different studies, eg. for DR model, δ differ from ~0.2 to ~0.5

Difficulties:

- **data sets inconsistent** (errors might be underestimated → systematic bias in the reconstructed value of the parameters)

-- study the systematics:

eg Putze et al. A&A 2010: include different data sets → different best-fit parameters

Maurin et al. A&A 2010: a small bias in HEAO3 B/C data → $\Delta\delta$ ~0.2 for pure diffusion model.

-- enlarge errors:

eg Trotta et al. ApJ 2010: introduce a set of nuisance rescaling parameters to decrease the systematic discrepancies between data sets but increase the computational time.

- **data sets from various experiments implemented during different solar period.** (Relatively poorly understood solar physics complicate the CR transport studies.)

⇨ **Only use data from a single experiment to avoid these problems**

PAMELA data are chosen in our work

- PAMELA was installed on Russian satellite Resurs-DK1

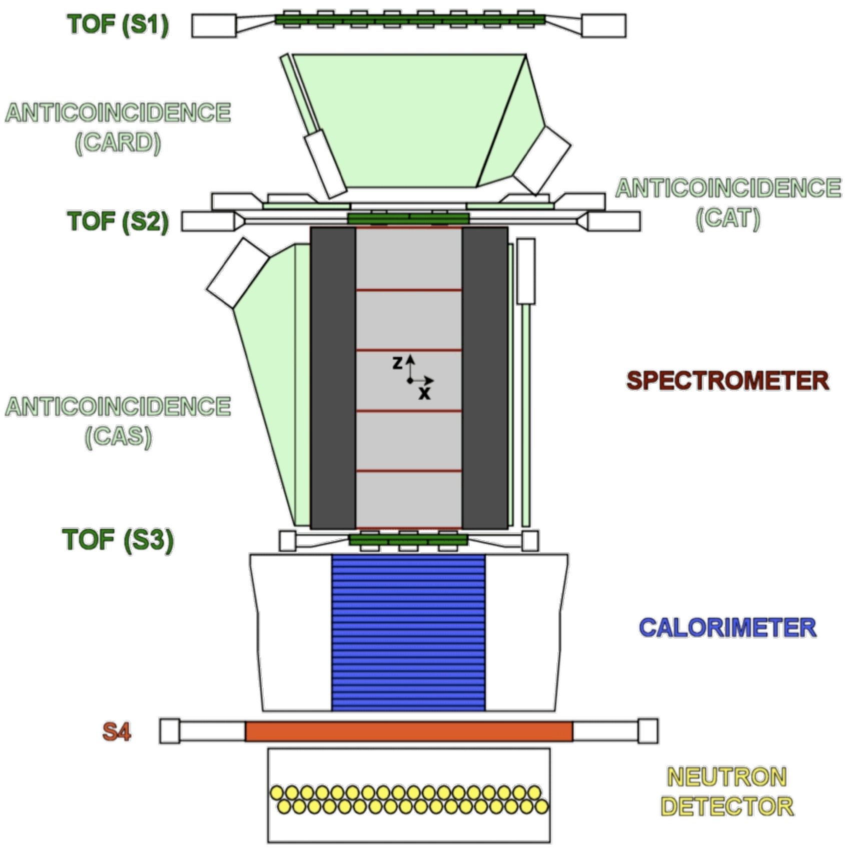
→ suffers no residual overburden from Earth's atmosphere

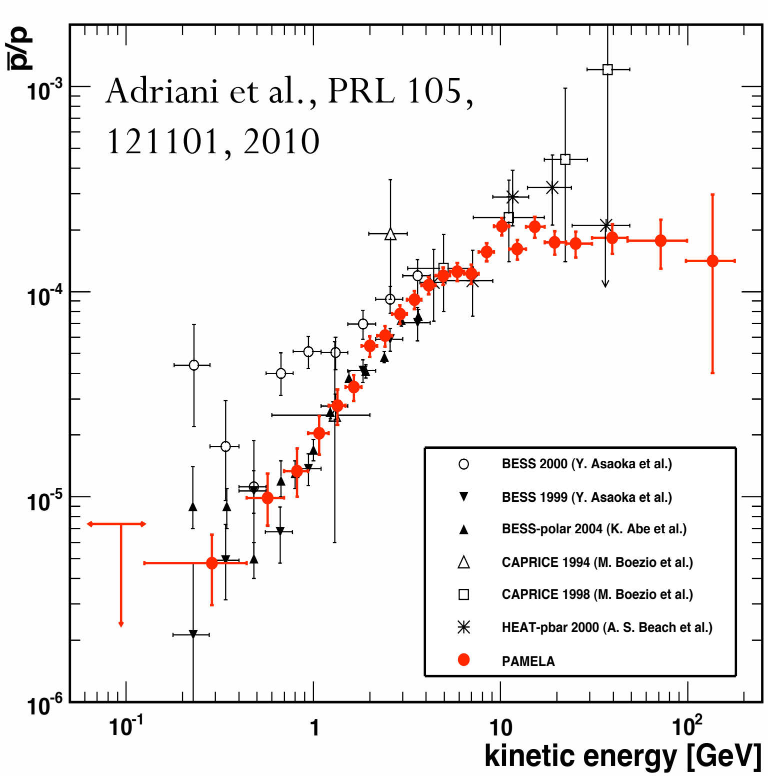
- Operating since June 2006 (almost 6 years exposure time)

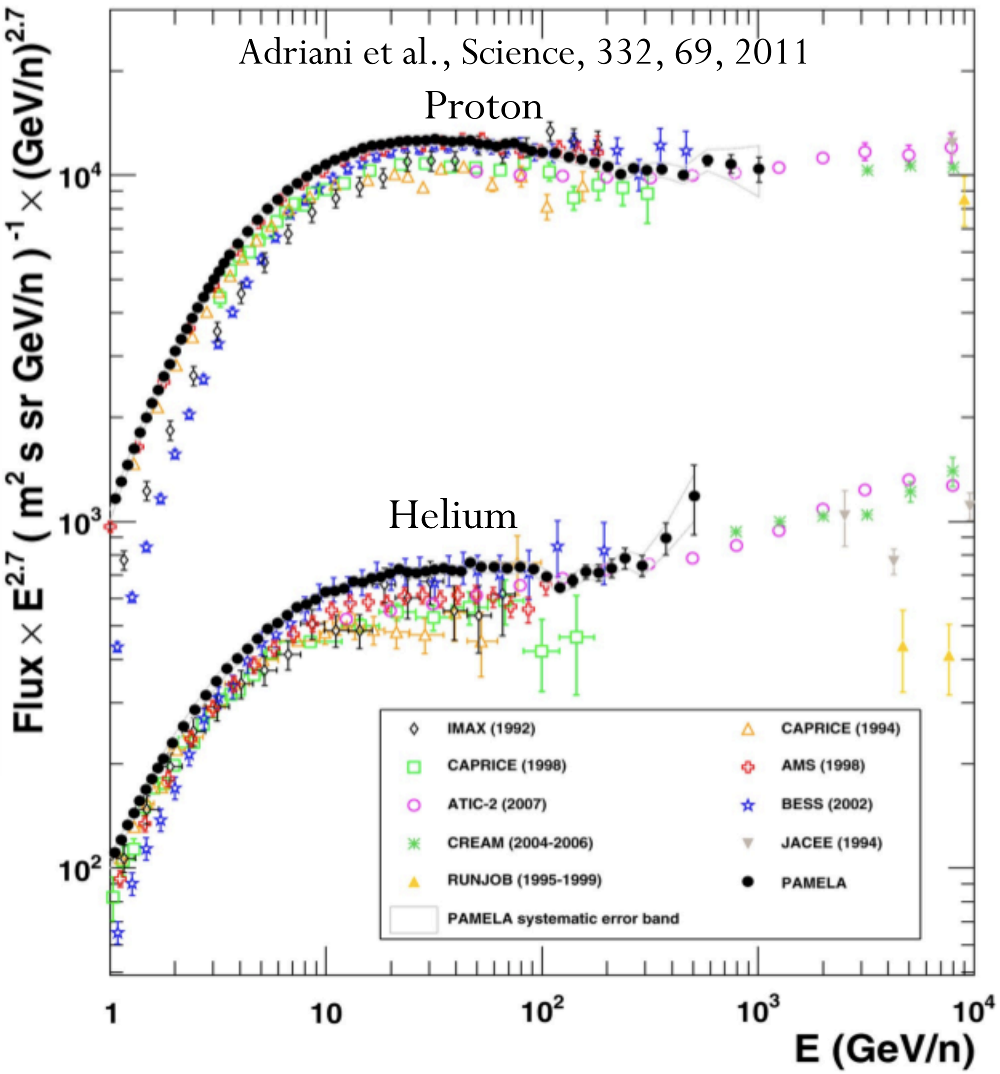
→ high precision

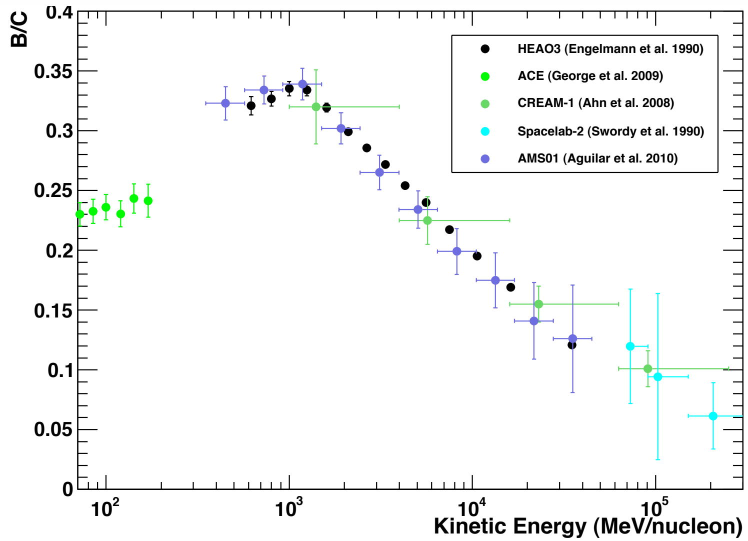
PAMELA measures light nuclei CR fluxes and secondary/primary ratios for a wide energy range with a high precision

GF: 21.6 cm^2 sr
Mass: 470 kg
Size: 130 · 70 · 70 cm^3
Power Budget: 360 W







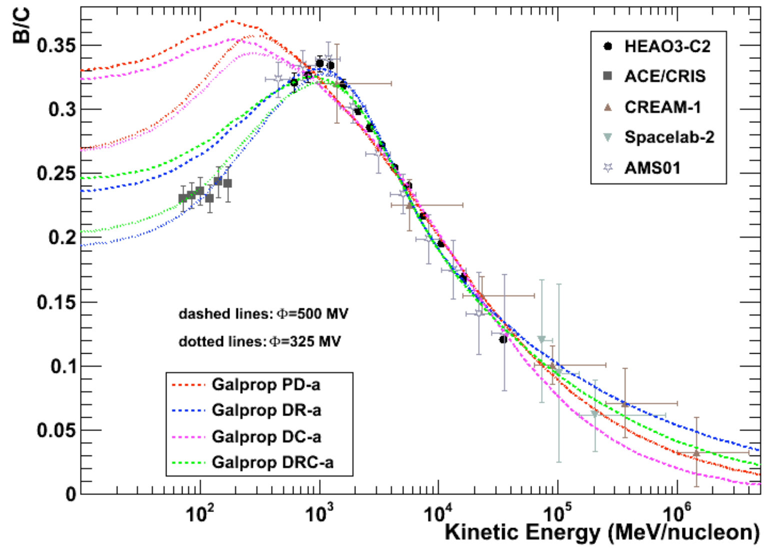


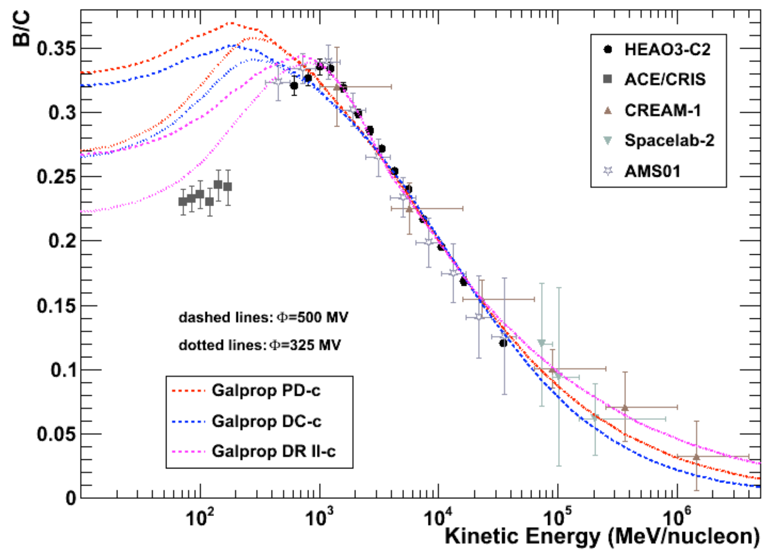
B/C ratio is expected to be provided from 100 MeV/n to 200 GeV/n by PAMELA in near future. Using the data here covering a comparable energy range as PAMELA.

χ^2 minimization $D_{xx}= D_0\beta^\eta (\rho/\rho_0)^\delta$

- Standard case: $\eta=1$
- Studied models: PD, DR, DC &DRC
- Different combinations of data sets are used to constrain models:
  - (a) only the B/C ratio
  - (b) pbar/p ratio+p flux
  - (c) B/C ratio+pbar/p ratio+p flux

- DR and DRC models can explain the B/C ratio, but when data sets (b) or (c) are used, $v_A \rightarrow 0$
- PD and DC can not fit the B/C ratio.
- A break in the injection spectrum can fit the B/C ratio better but still higher B/C ratio than the data at energies <1 GeV.

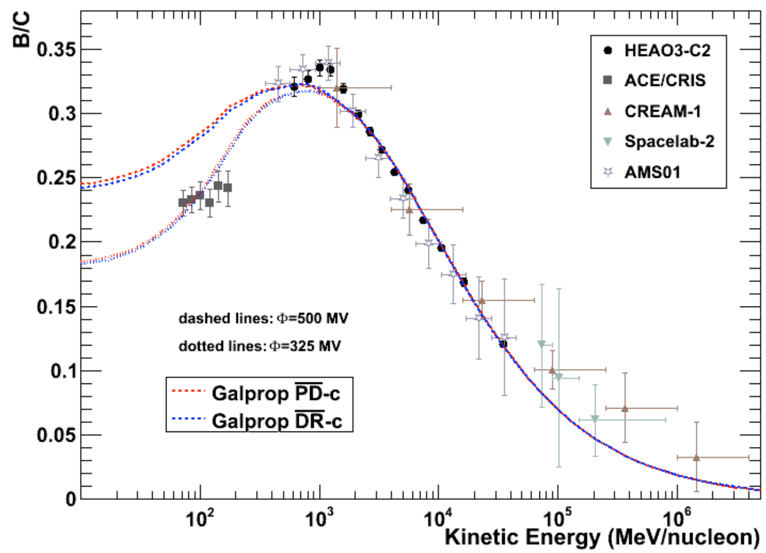


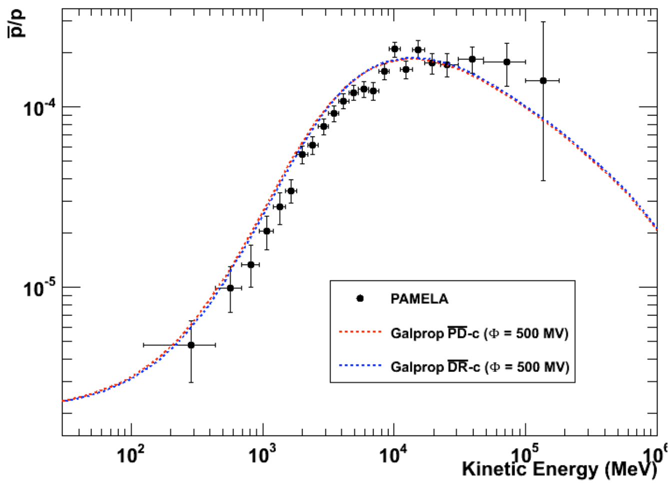


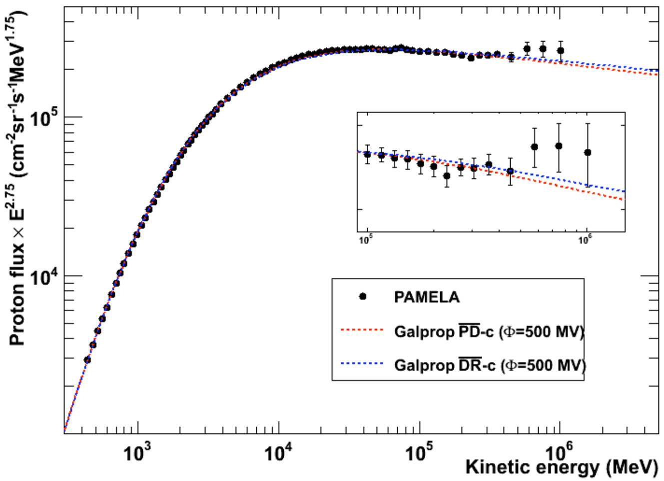
χ^2 minimization $D_{xx} = D_0 \beta^{\eta} (\rho/\rho_0)^{\delta}$

- Modified case: $\eta \neq 1$
- Motivated by nonlinear magnetohydrodynamic wave effects
- Can generally explain all the data, while only slightly overpredict the pbar/p ratio.

- η is dominate over other competing processes ($dV/dz \rightarrow 0$ & v_A is weak and seems not necessary) and result in too many degenerated parameters being constrained.







Bayesian inference

$$P(\boldsymbol{\theta}|\text{data}) = \frac{P(\text{data}|\boldsymbol{\theta}) \cdot P(\boldsymbol{\theta})}{P(\text{data})}$$

Motivation:

(1) Results might be biased due to the very precise PAMELA proton data and specifying priors on the source parameters can reduce the bias.

(2) Systematic uncertainties due to solar modulation can be reduced by specifying priors on modulation parameters.

(3) Correlations between parameters can be studied

(4) Credible intervals on parameters and on fluxes can be produced efficiently.

(5) Models under studied can be compared by the Bayesian evidences.

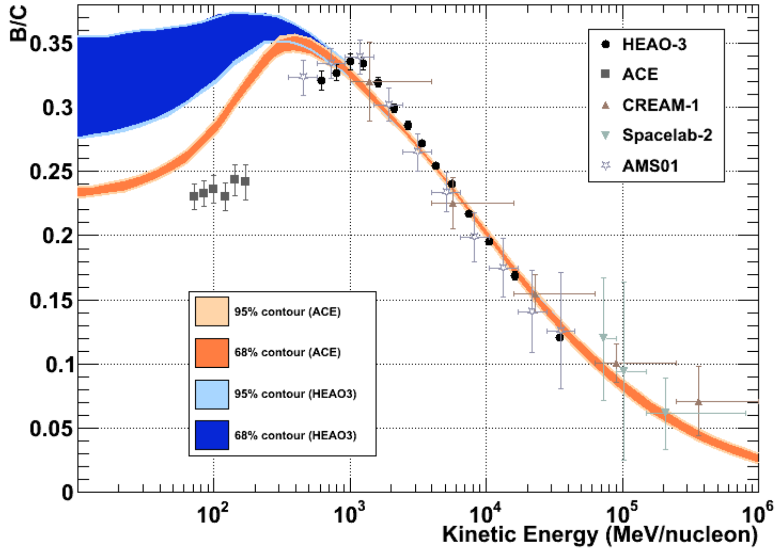
Studied models:

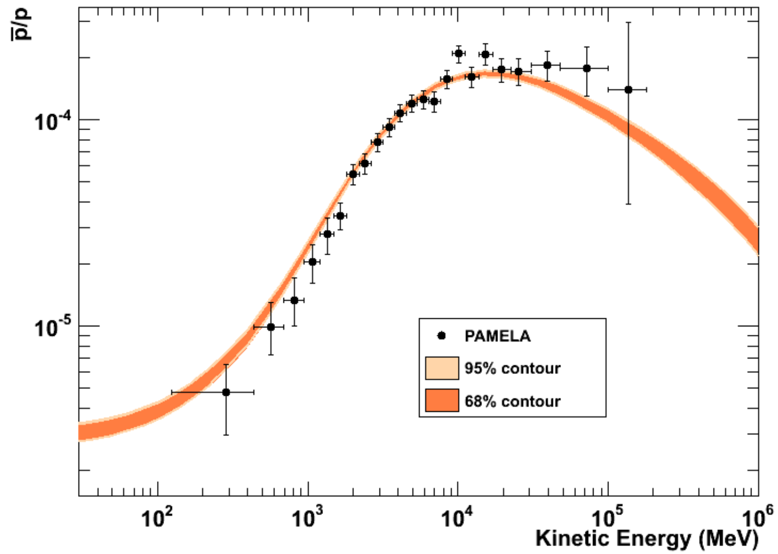
(1) Standard DR and DRC models. They can describe the B/C ratio well as shown in χ^2 study and their disagreement with the proton flux might be reduced by specifying priors on source parameters and modulation parameters.

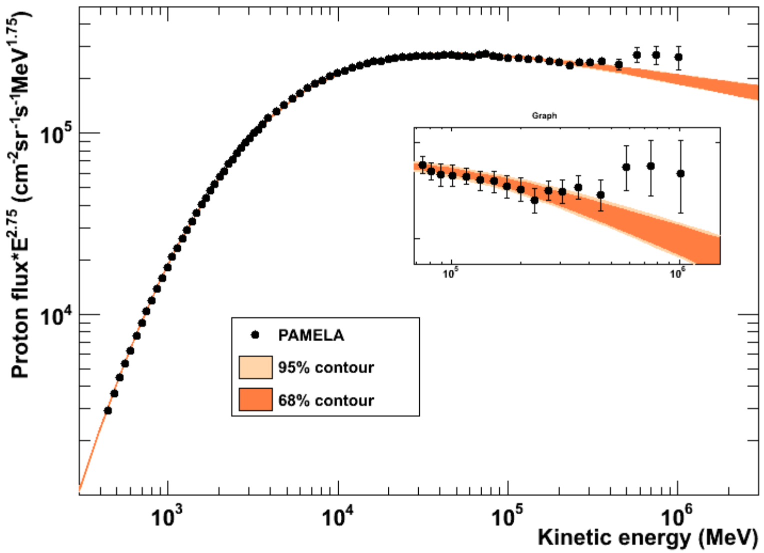
(2) The modified models with $\eta \neq 1$ is not studied by considering that freeing modulation parameters will even increase the degenerated parameters at low energy and no useful information are allowed to be extracted.

$$\frac{P(H_1|\mathbf{D})}{P(H_0|\mathbf{D})} = \frac{P(\mathbf{D}|H_1)\,P(H_1)}{P(\mathbf{D}|H_0)\,P(H_0)}$$

DRC models is better than DR model





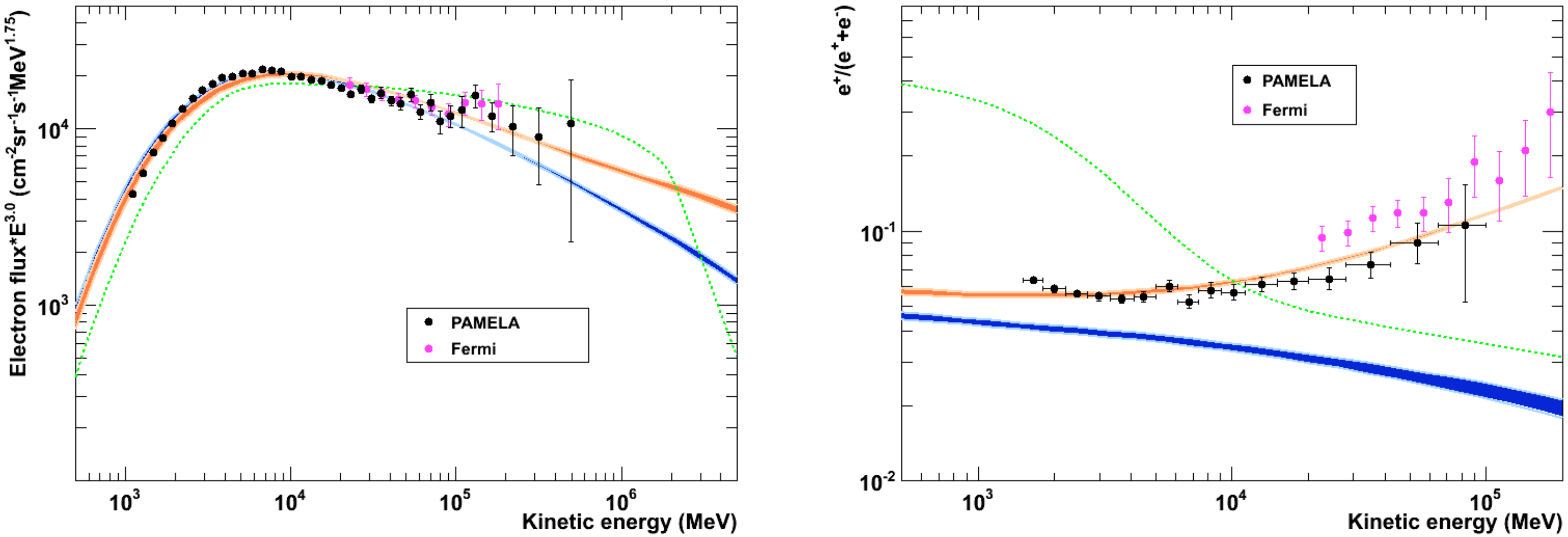


The model prediction is still higher than the B/C data <1 GeV due to the prior limit on Φ_{ACE}

- The B/C ratio is not from PAMELA, inconsistencies between data sets can exist
- A more realistic solar modulation should include a charge-sign dependency
- The very precise of proton spectrum has a dominant weight in the fit. Any systematic bias in the proton data may significantly bias the results

Prediction of electron flux and positron fraction

- blue band: one primary component with e- inj_index= 2.72
- orange band: two primary component with e- inj_index=2.69 and e± inj_index=2.1
- green line: a conventional DR model having a break both in the primary proton injection spectrum and the primary electron injection spectrum (Trotta et al. ApJ 2011)



Two primary components can describe both the electron flux and the positron fraction. The second (extra) component could be dark matter and studies of dark matter need more realistic treatment concerning, for example, the source distribution, the mass of the dark matter particle, etc.

Outlook

- Inconsistencies between data sets and uncertainties due to solar modulation can be reduced with upcoming S/P ratios measured by PAMELA to give better and more robust constraints on propagation models:

(1) B/C 100 MeV/n~200 GeV/n

(2) 2H/4He 100 MeV/n~700 MeV/n

(3) 3He/4He 100 MeV/n~900 MeV/n

- The PAMELA positron fraction used in this work is below 100 GeV. Now the measurements is up to 300 GeV and can improve the constraints on dark matter properties.