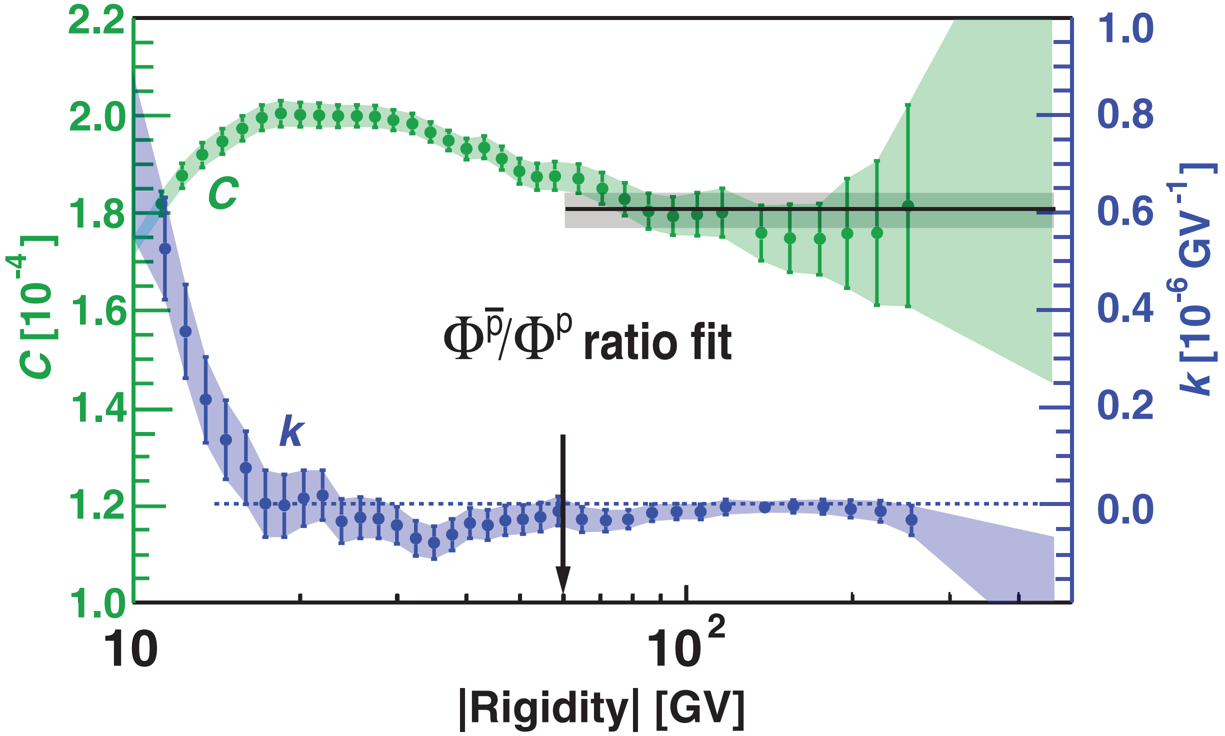
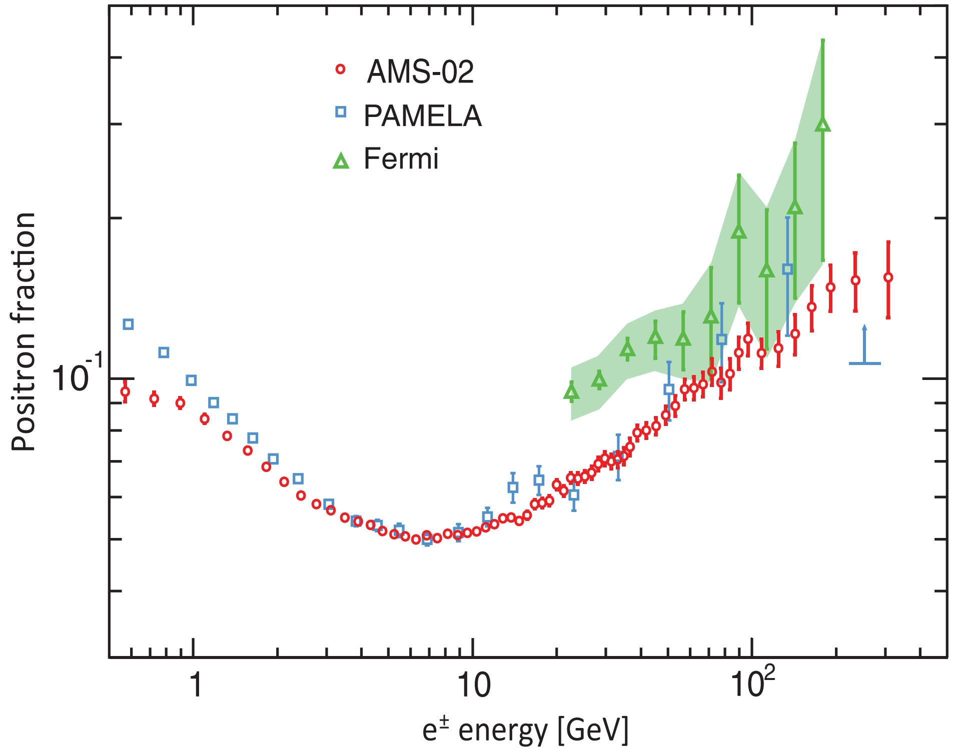
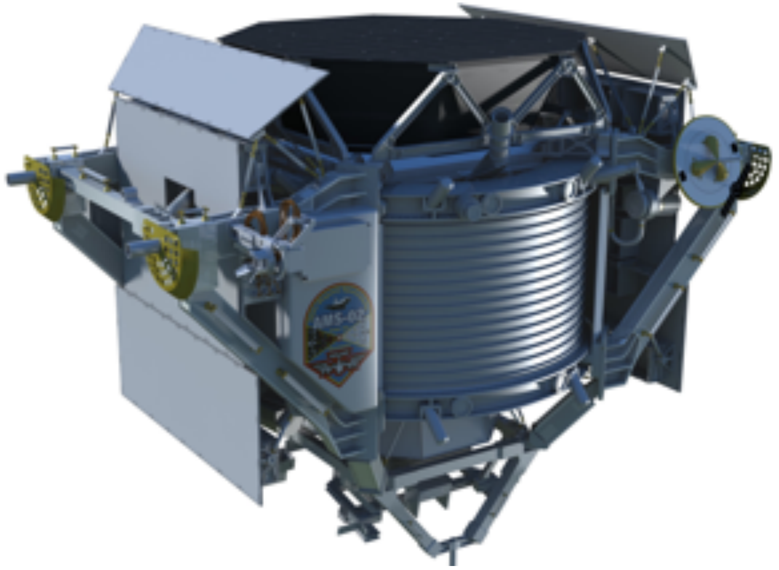
JOHNS HOPKINS
UNIVERSITY

Evidence of Stochastic Acceleration of Secondary Antiprotons by Supernova Remnants





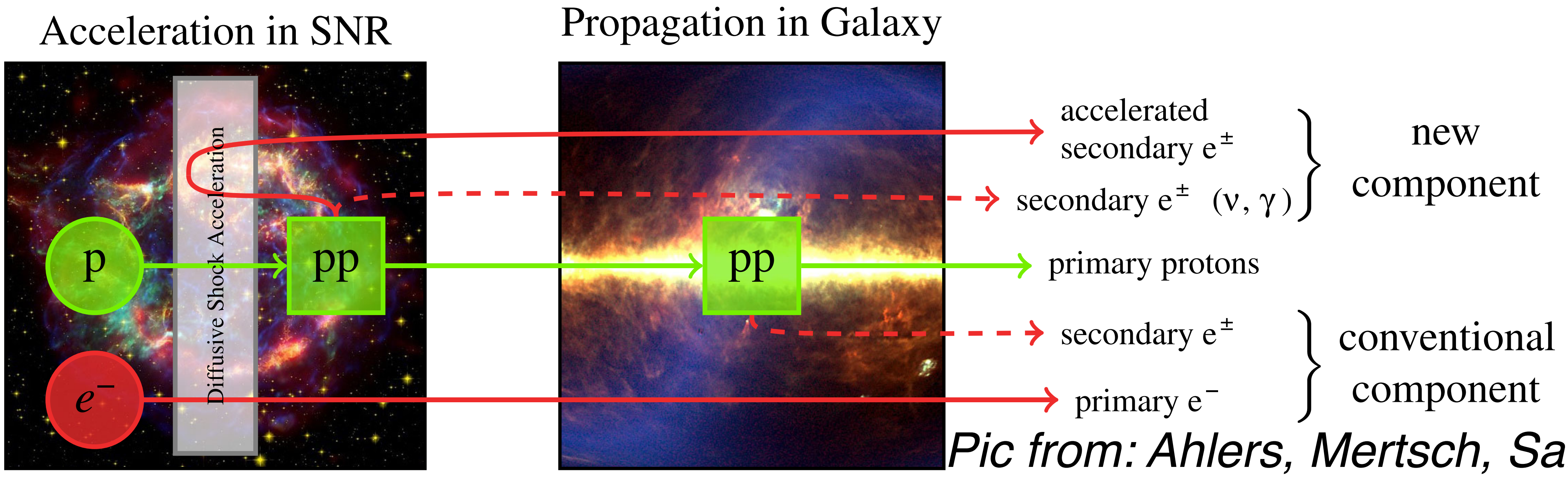
IC, D. Hooper, T. Linden, Phys. Rev. D 95, 123007 (2017)
IC, D. Hooper, T. Linden Phys. Rev. D 93, 043016 (2016)
IC, D. Hooper, Phys. Rev. D 89, 043013 (2014)



Ilias Cholis, 08/09/2017

Producing hard CR Secondary component from Stochastic Acceleration inside SNRs

Blasi, PRL 2009, Mertsch & Sarkar PRL 2009



accelerated secondary e±
secondary e± (ν, γ)
new component

primary protons

secondary e±
primary e^-
conventional component

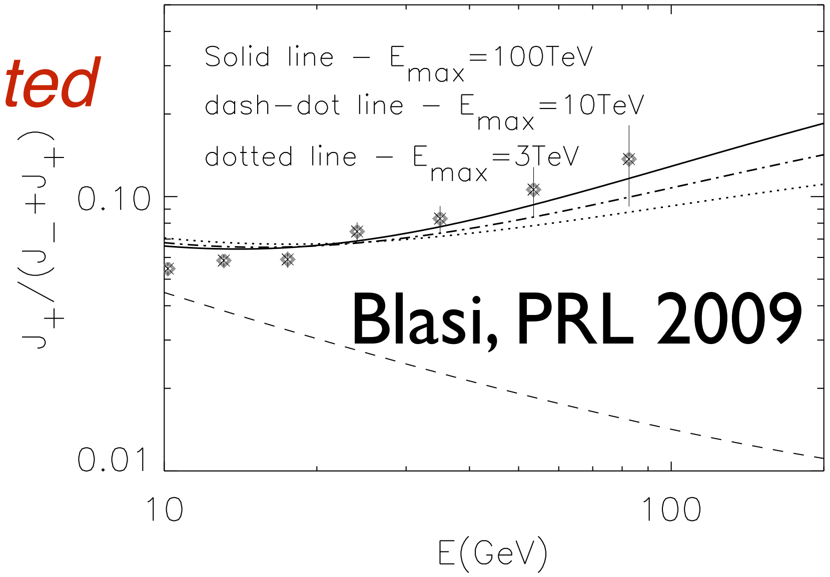
Pic from: Ahlers, Mertsch, Sarkar PRD 2009

Interplay of three typical timescales for CRs: Spallation, Escape and Acceleration inside the Sources.

If: $\tau^{spall}_{A\to B} < \tau^{esc}_{A}$, *then we have secondaries produced inside the acceleration region*

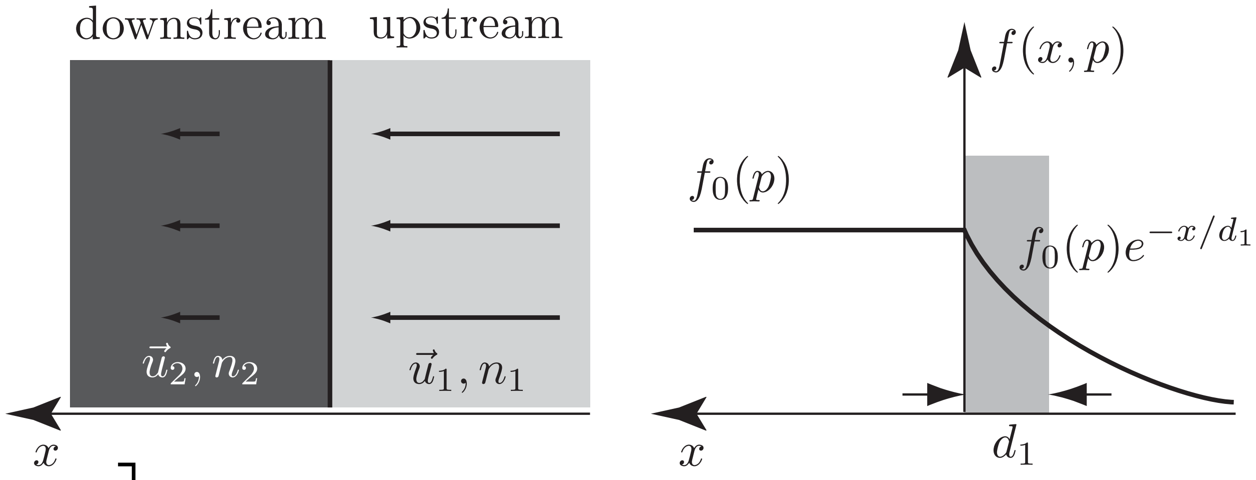
If: $\tau_{acc} < \tau^{spall}$, *then secondaries are efficiently accelerated*

So: $Acc^{A} \to Spall^{A\to B} \to Acc^{B} \to Escape \to Propagation \to Obesrvation$



Blasi, PRL 2009

Some details on the accelerated secondary CRs:



Source term inside the SNR:

$$Q_i(E_{kin}) = \Sigma_j N_j(E_{kin}) \left[\sigma^{sp}_{j\to i}\, \beta\, c\, n_{gas} + \frac{1}{E_{kin}\, \tau^{dec}_{j\to i}} \right]$$

Propagation inside the SNR (diffusion, advection, source, decay/spallation and adiabatic E losses):

$$v\frac{\partial f_i}{\partial x} = D_i \frac{\partial^2 f_i}{\partial x^2} + \frac{1}{3}\frac{dv}{dx} p \frac{\partial f_i}{\partial p} - \Gamma_i f_i + q_i$$

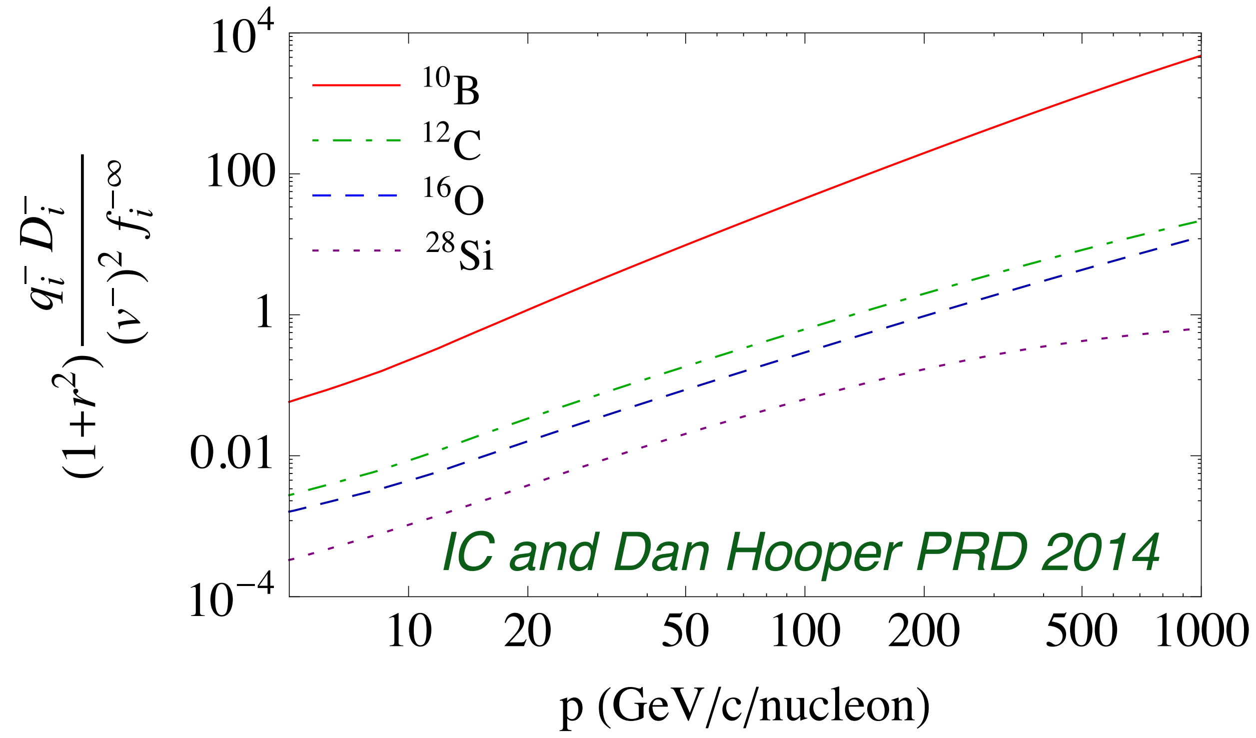
Bohm diffusion: $D_i^{\pm}(E) = \dfrac{K_B\, r_L(E)\, c}{3} = 3.3\times 10^{22} K_B B^{-1}\, E\, Z_i^{-1} \mathrm{cm}^2\, \mathrm{s}^{-1}$

Here the factor that defines the amplitude of the enhancement is: $K_B \simeq (B/\delta B)^2$ *allowing for faster diffusion around the shock front .*

Thus the source term of SNR CR changes: $f_i^{+}(x,p) = f_i(0,p) + \dfrac{q_i^{+}(0,p) - \Gamma_i^{+}(p) f_i(0,p)}{v^{+}} x$

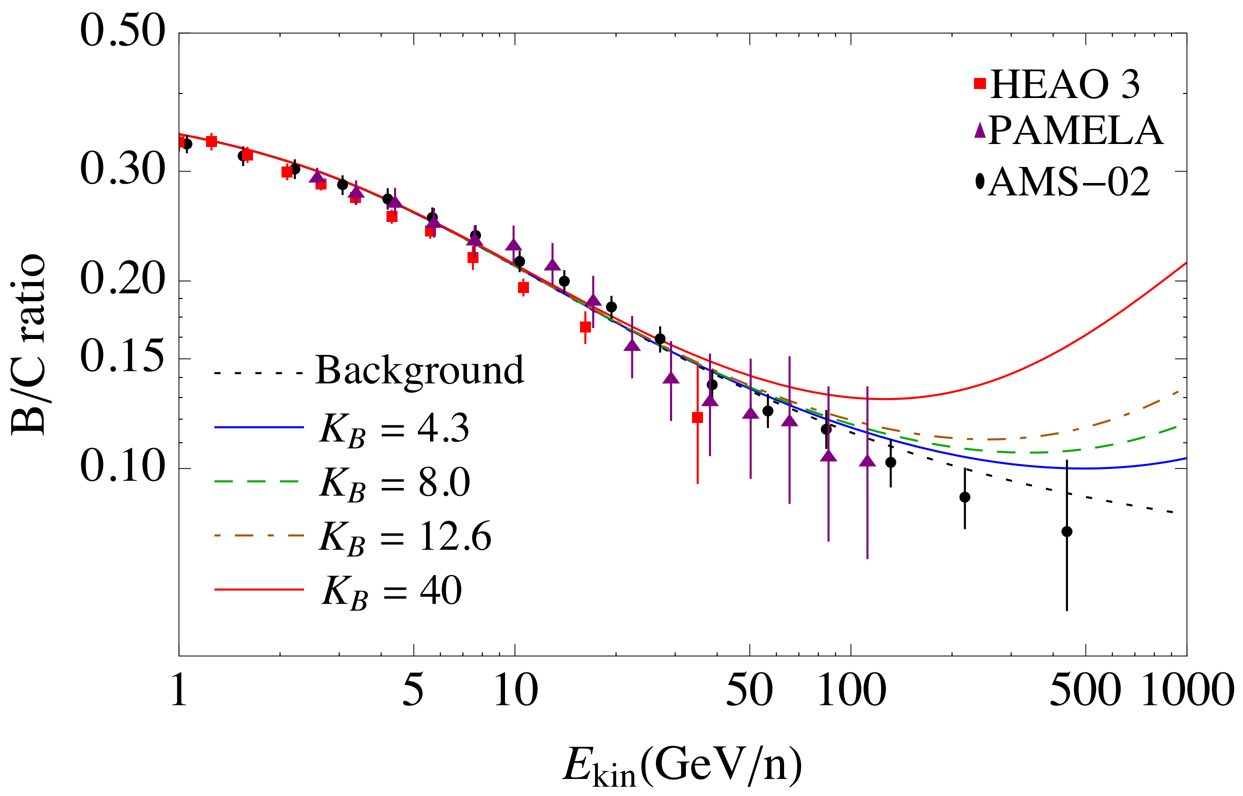
Accounting for all galactic SNRs and including propagation effects, one can expect a rise in other secondary/primary CR ratios should be observed with AMS-02.

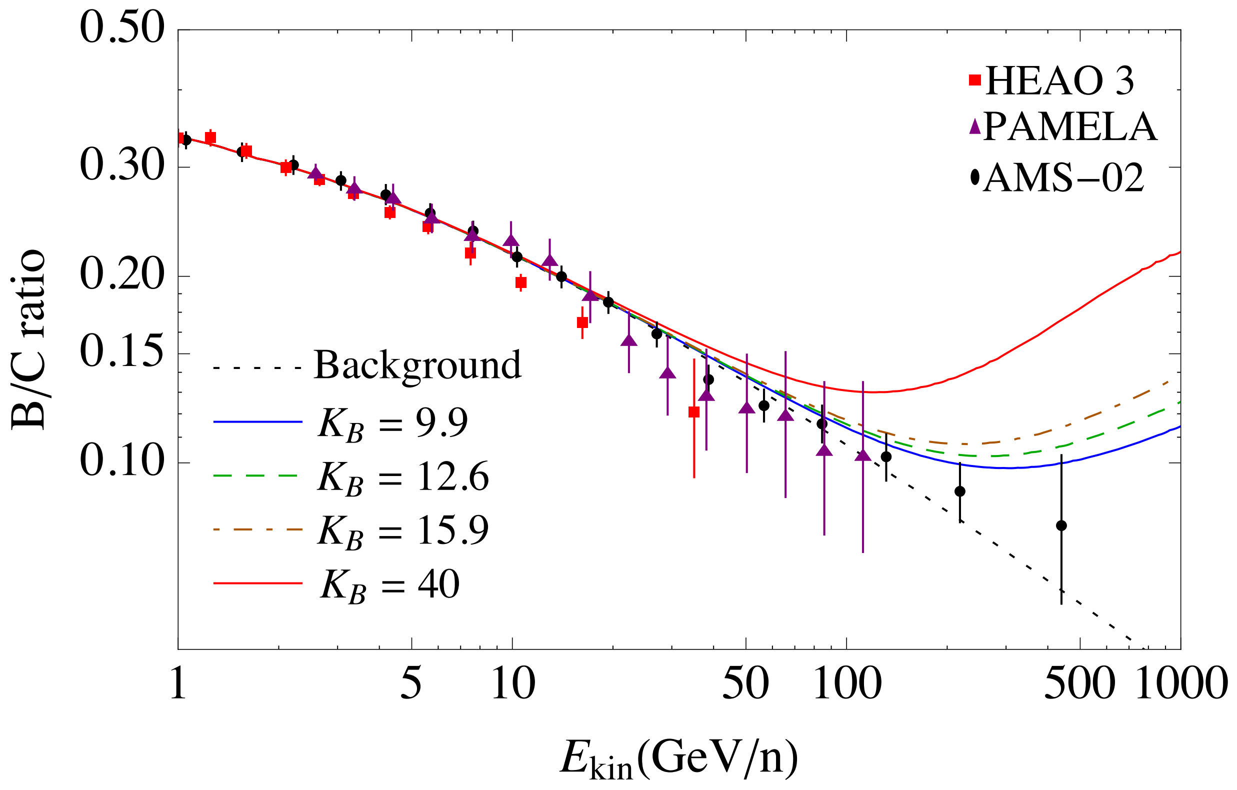
The impact of this additional secondary component is more evident for high E, light nuclei:



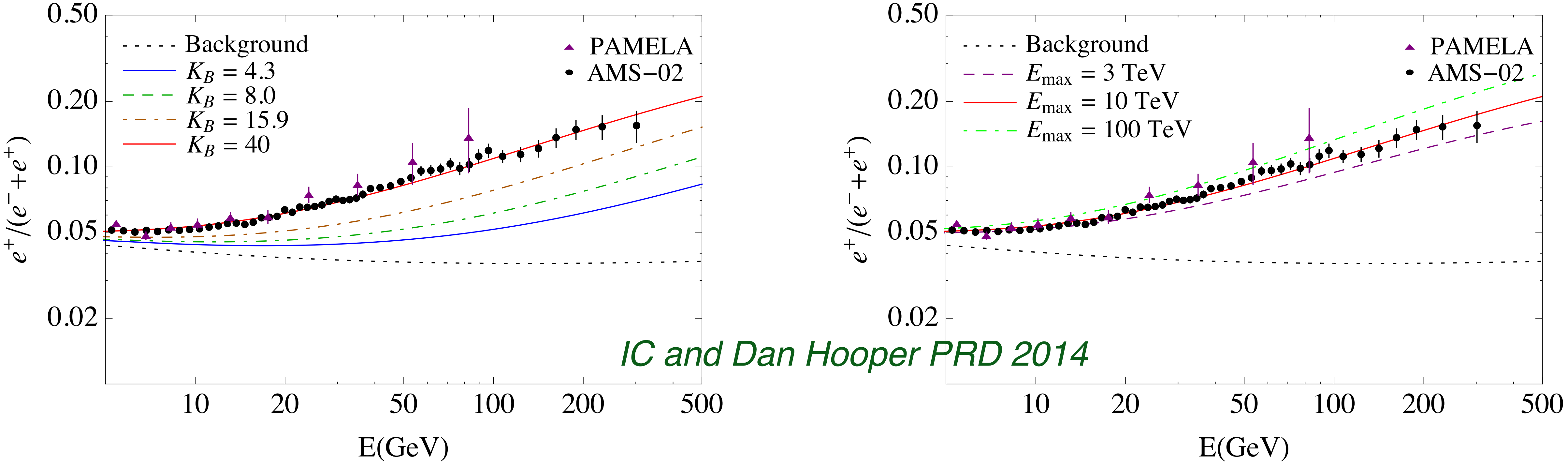
IC and Dan Hooper PRD 2014

This results in ***Limits from B/C*** *(including background uncertainties), on the acceleration of secondary CRs in supernova remnants:*





Implications on the Positron fraction



IC and Dan Hooper PRD 2014

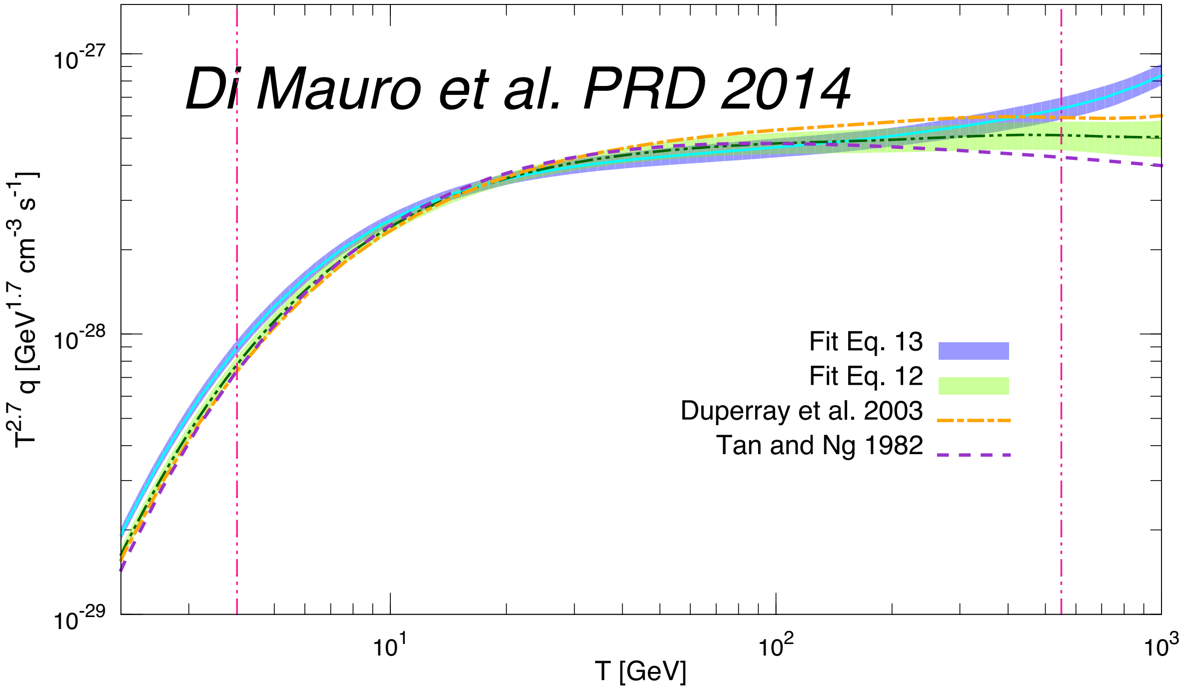
Secondary CRs produced in SNRs can NOT explain the full positron fraction excess even for optimistic cases of energy losses inside the SNRs.

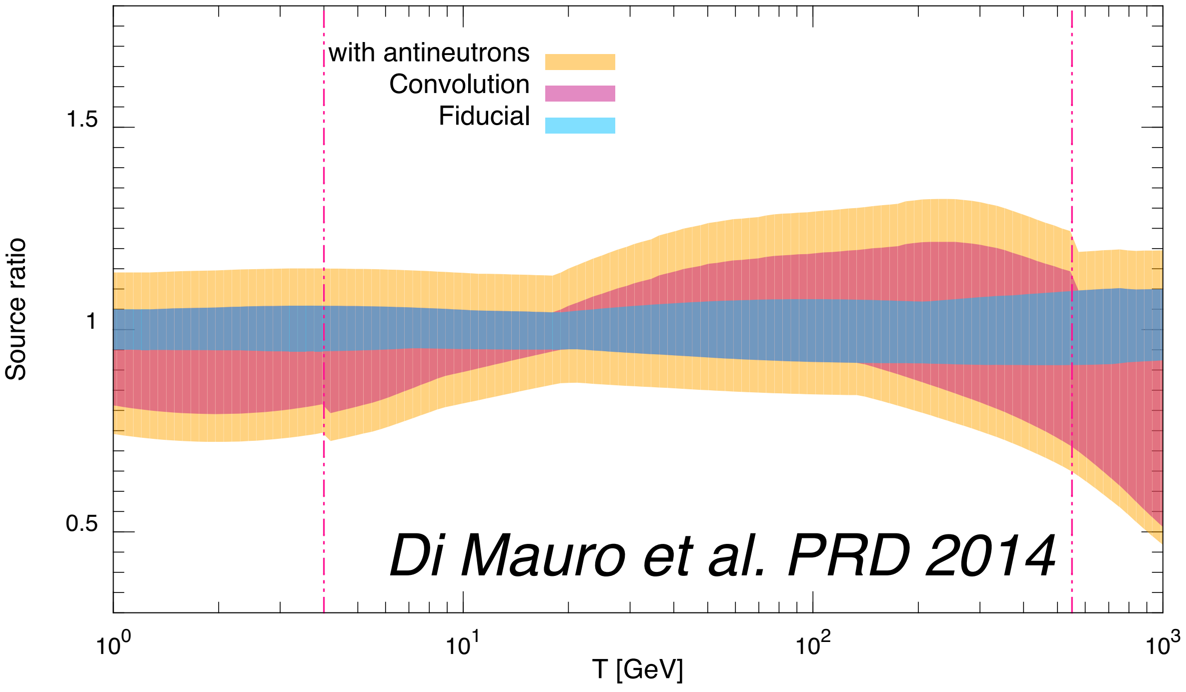
What about the Antiproton to Proton Ratio?

Antiprotons background uncertainties are very large. They are associated with:
i) the antiproton production cross-section from CR protons and heavier nuclei collisions with the ISM gas
ii) the propagation of CRs through the ISM
iii) Solar Modulation

I) Antiproton production cross-section uncertainties

The are significant uncertainties on the antiproton production cross-section directly from p-p collisions. Most parametrizations have only used data from the 70s.





Also one has to include the production of antiprotons from collisions with heavier nuclei (mainly He), which can contribute ~40% more antiprotons than the p-p collisions alone. Also contribution from antineutrons produced first at p-p.

FIG. 8. Estimate of the uncertainties in the antiproton source term from inelastic *pp* scattering. The blue band indicates the 3σ uncertainty band due to the global fit with Eq.(13), while the red band corresponds to the convolution of the uncertainties brought by fits to the data with Eq.(13), Eq.(12) and with the spline interpolation (see Fig.6.). The orange band takes into account the contribution from decays of antineutrons produced in the same reactions. Vertical bands as in Fig.6. See text for details.

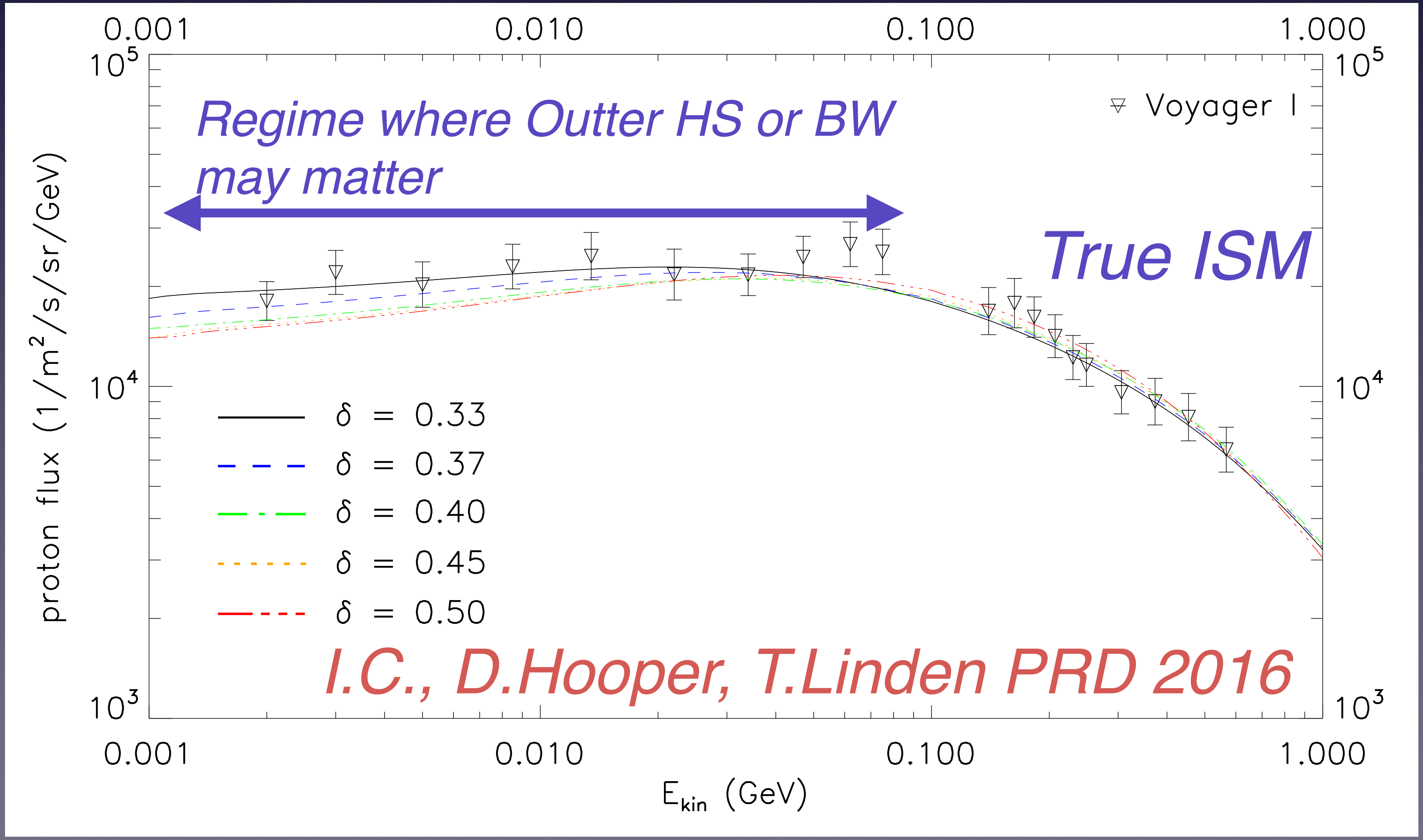
See also results from Kappl & Winkler JCAP 2014

II) Accounting for ISM galactic propagation uncertainties for Cosmic Rays

$$\frac{\partial\psi(r,p,t)}{\partial t} = \overset{\text{sources}}{q(r,p,t)} + \overset{\text{diffusion}}{\vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi)} + \underset{\text{re-acceleration}}{\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{\psi}{p^2}\right)\right]} + \underset{\text{convection}}{\frac{\partial}{\partial p}\left[\frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right]}$$

Voyager 1

Voyager 1 (ISM) proton flux:



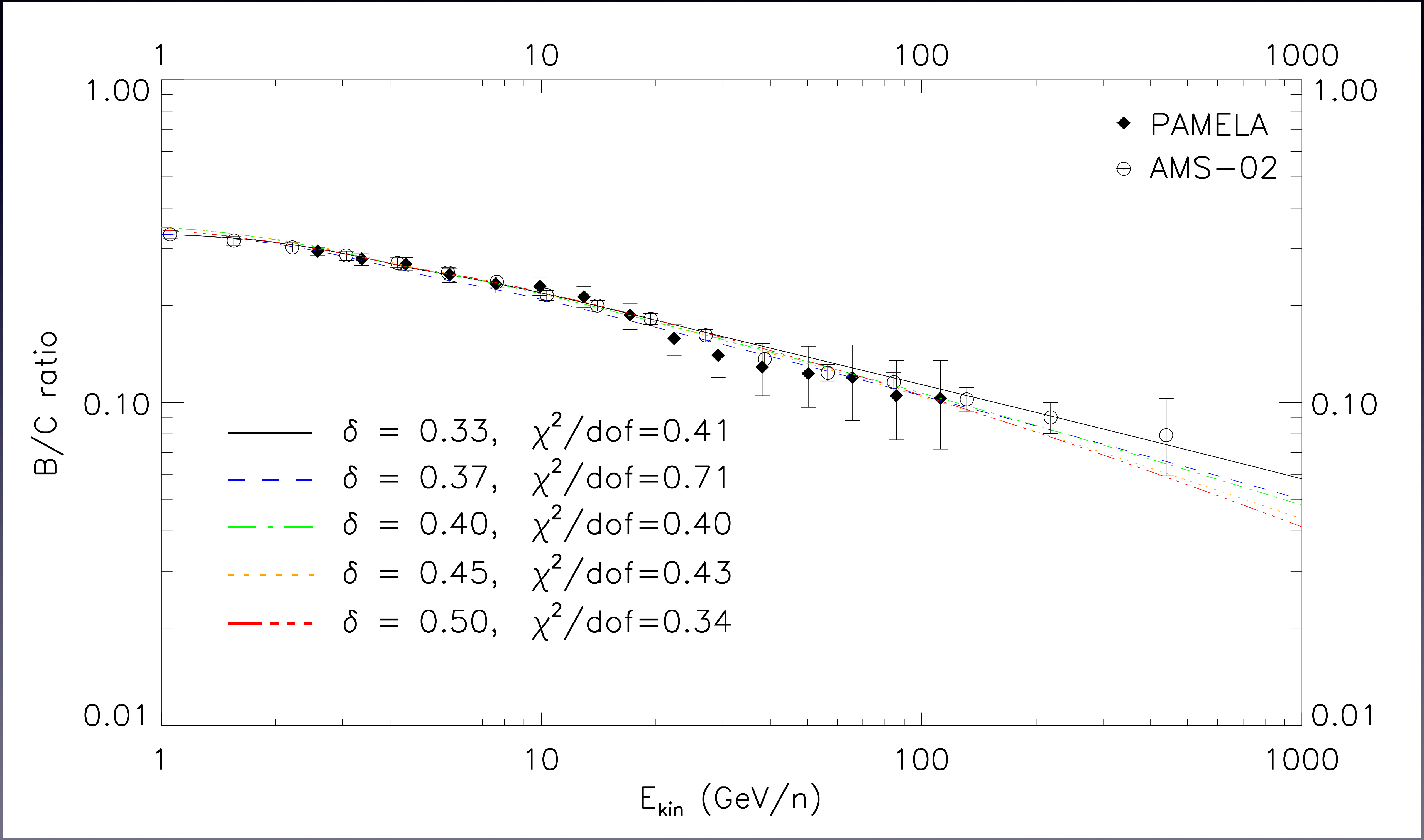
Regime where Outter HS or BW may matter

True ISM

I.C., D.Hooper, T.Linden PRD 2016

We use a numerical solver, GALPROP, and build several models that are in agreements with CR measurements

B/C from PAMELA and AMS-02; Sets the time scale for CRs to diffuse away from the galactic disk. Also sets constraints on the combination of convection and re-acceleration.



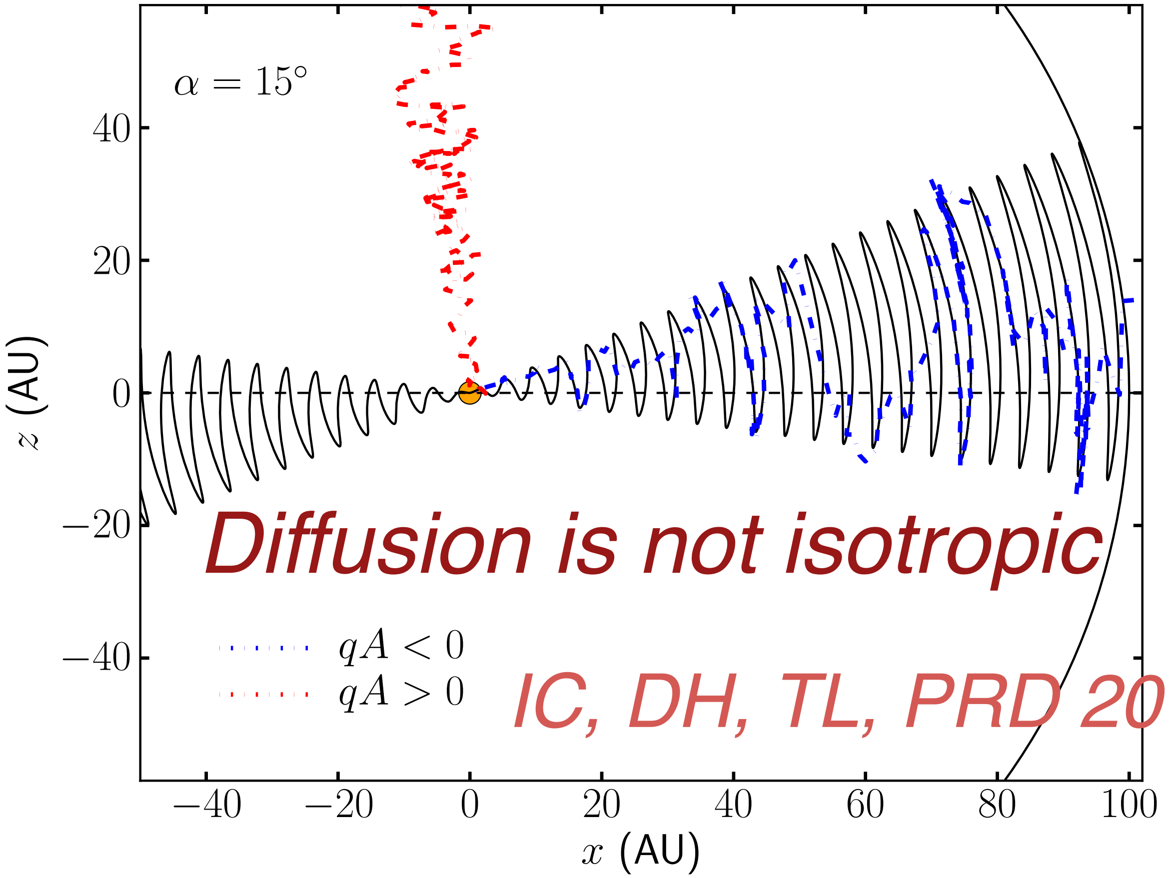
III) Dealing with Solar Modulation Uncertainties

Strauss et. al ApJ 2011

There is Charge Dependence

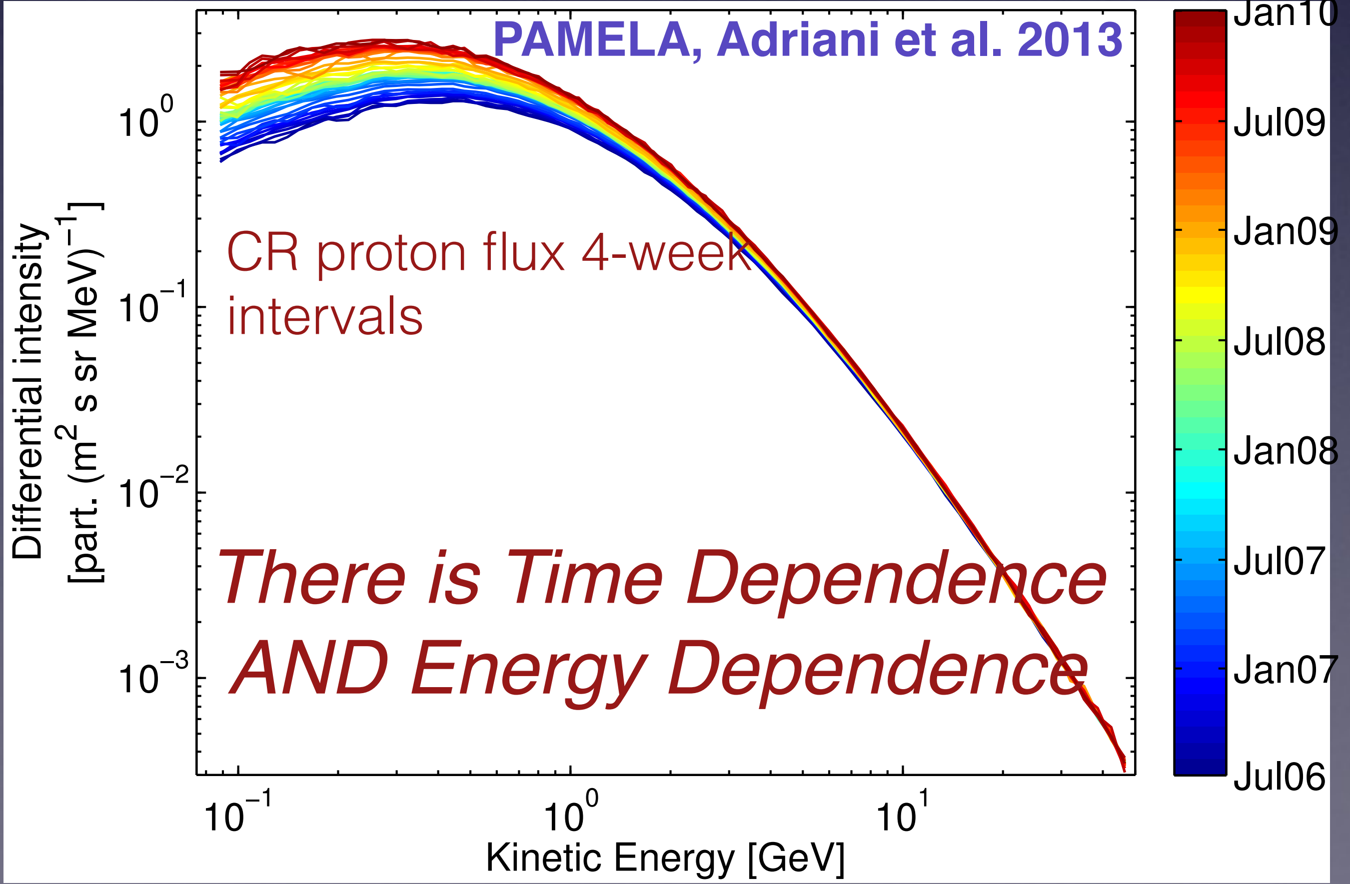
Figure 7. Three-dimensional spatial representation of the particle trajectories shown in Figure 1. Two representative particle trajectories (black and gray lines) are shown for the $A > 0$ (left panel) and $A < 0$ (right panel) HMF polarity cycles. In the $A < 0$ cycle, the pseudo-particles (galactic electrons) are transported mainly toward higher latitudes, while in the $A > 0$ cycle, the particles remain confined to low latitudes and drift outward mainly along the HCS. This illustration is consistent with the results of galactic electrons shown in the previous figure.

Drifts Can NOT be ignored



Diffusion is not isotropic

IC, DH, TL, PRD 2016



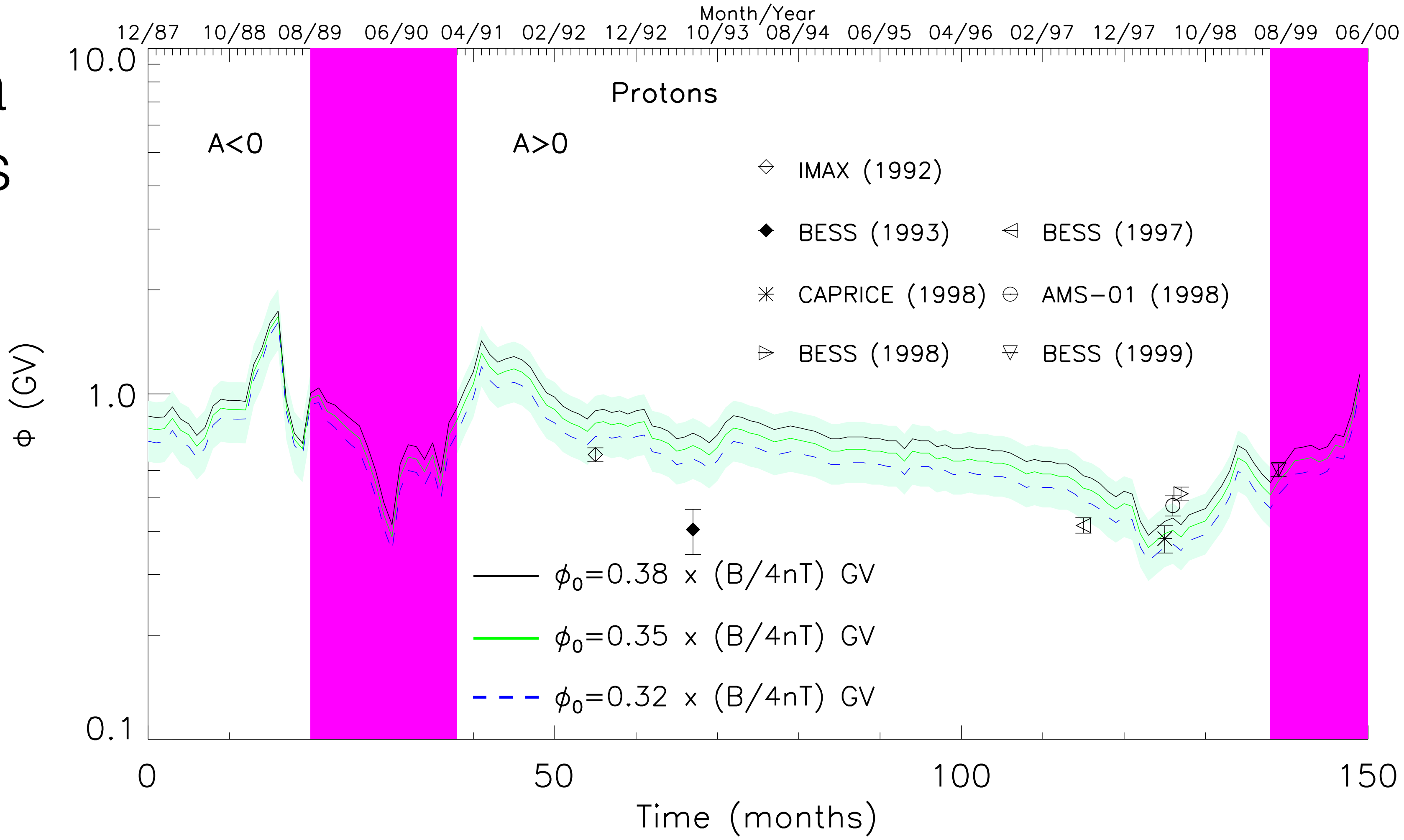
PAMELA, Adriani et al. 2013

CR proton flux 4-week intervals

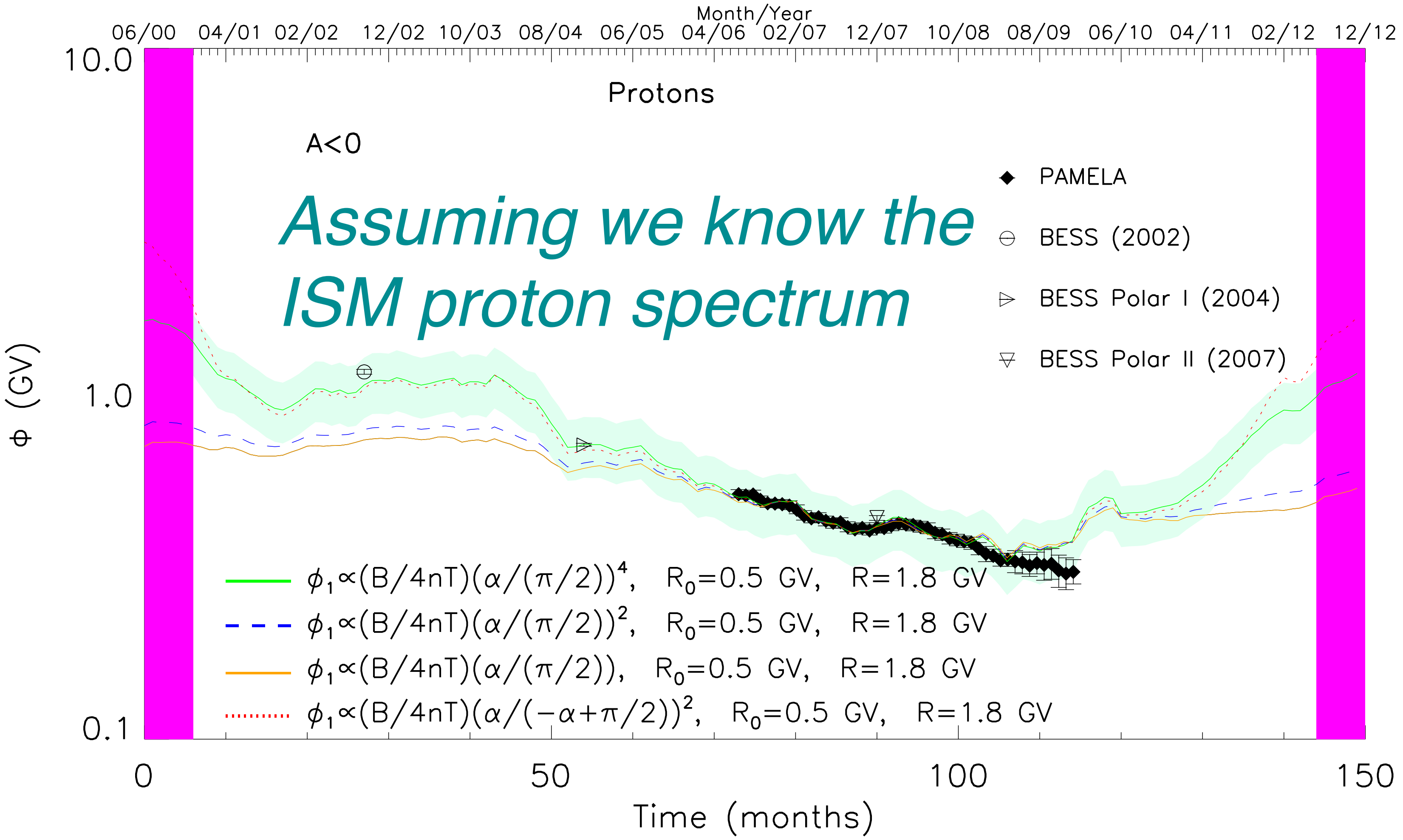
There is Time Dependence AND Energy Dependence

Let the CR archival Data tell us how the CR fluxes have been modulated:

Constraining the qA>0 era:



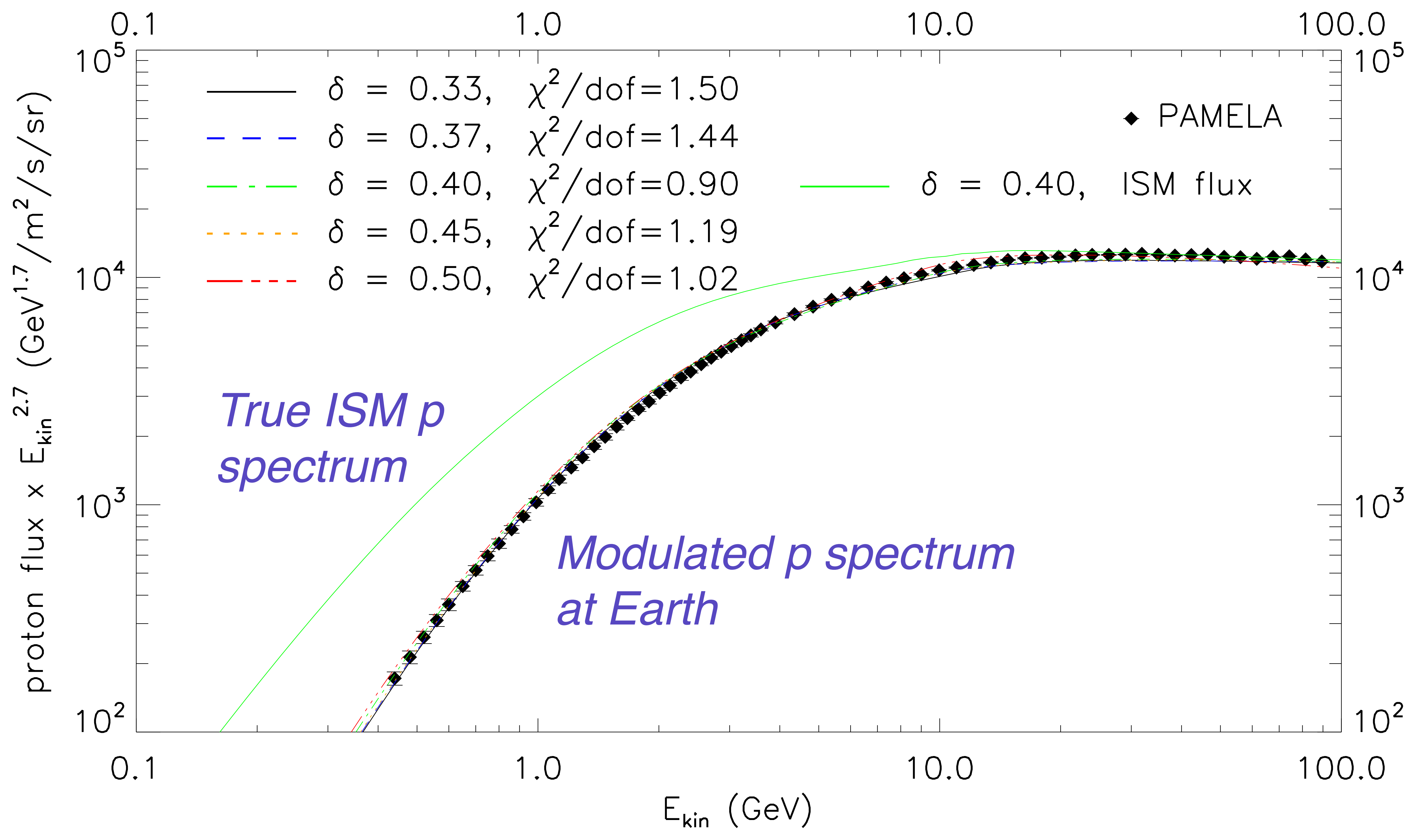
Constraining the qA<0 era:



Assuming we know the ISM proton spectrum

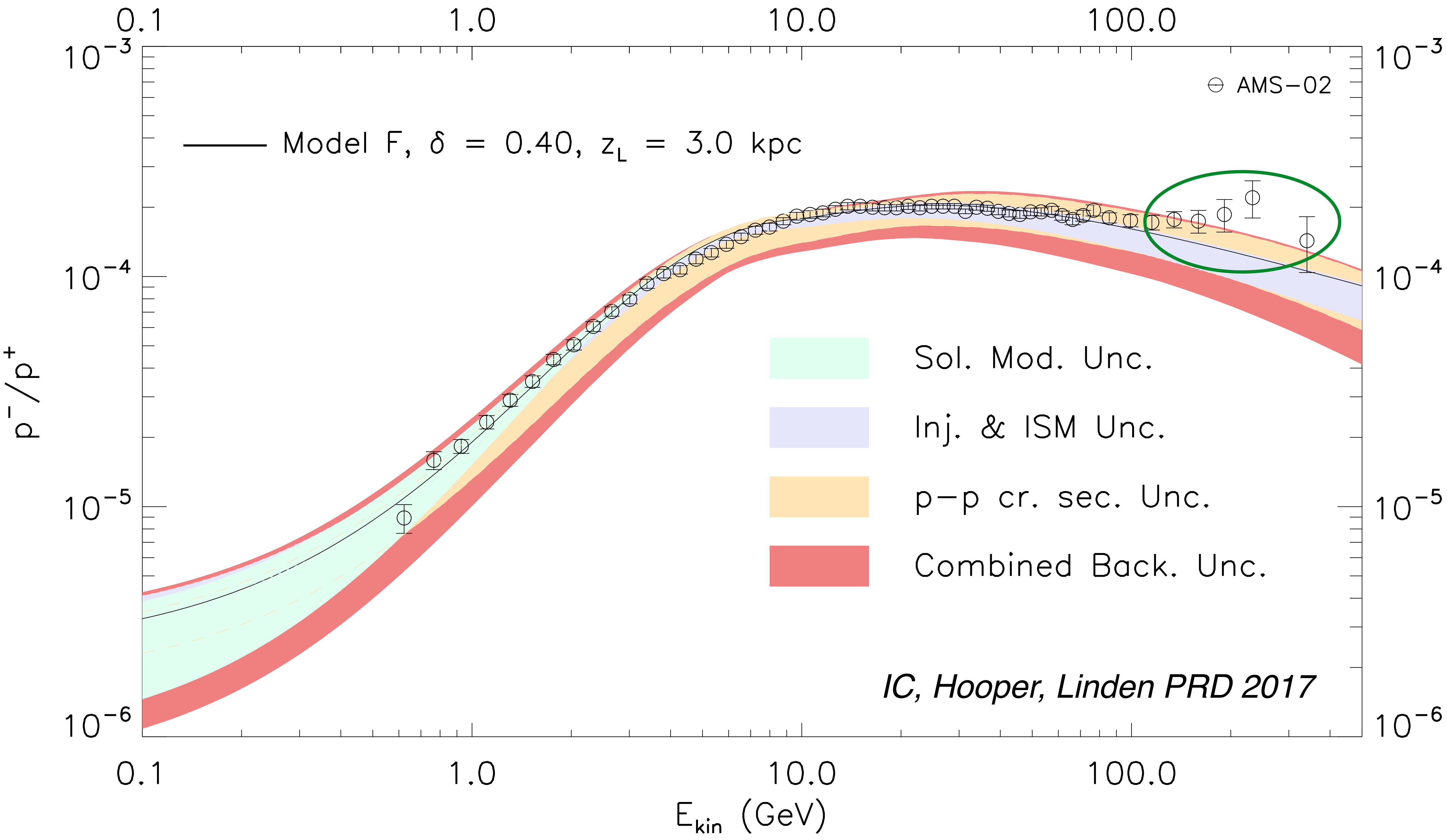
IC, DH, TL, PRD 2016

II) & III) Cross-checking every time with all the PROTON data; monthly AND total (i.e ISM & Solar Modulation):



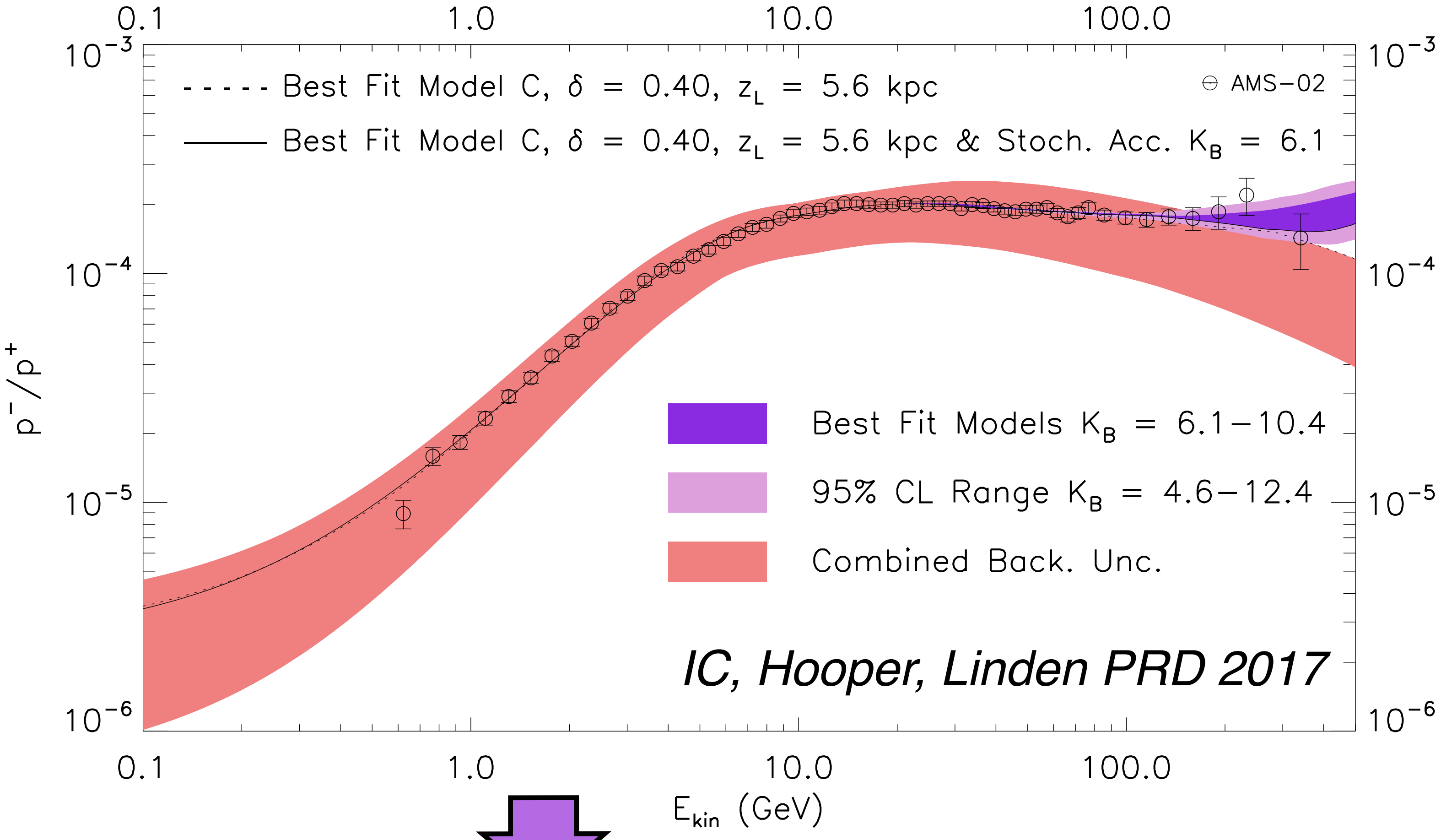
Constraining the form of the Modulation potential and the ISM p spectrum in a recursive manner.

Combining all uncertainties together and marginalizing over them:

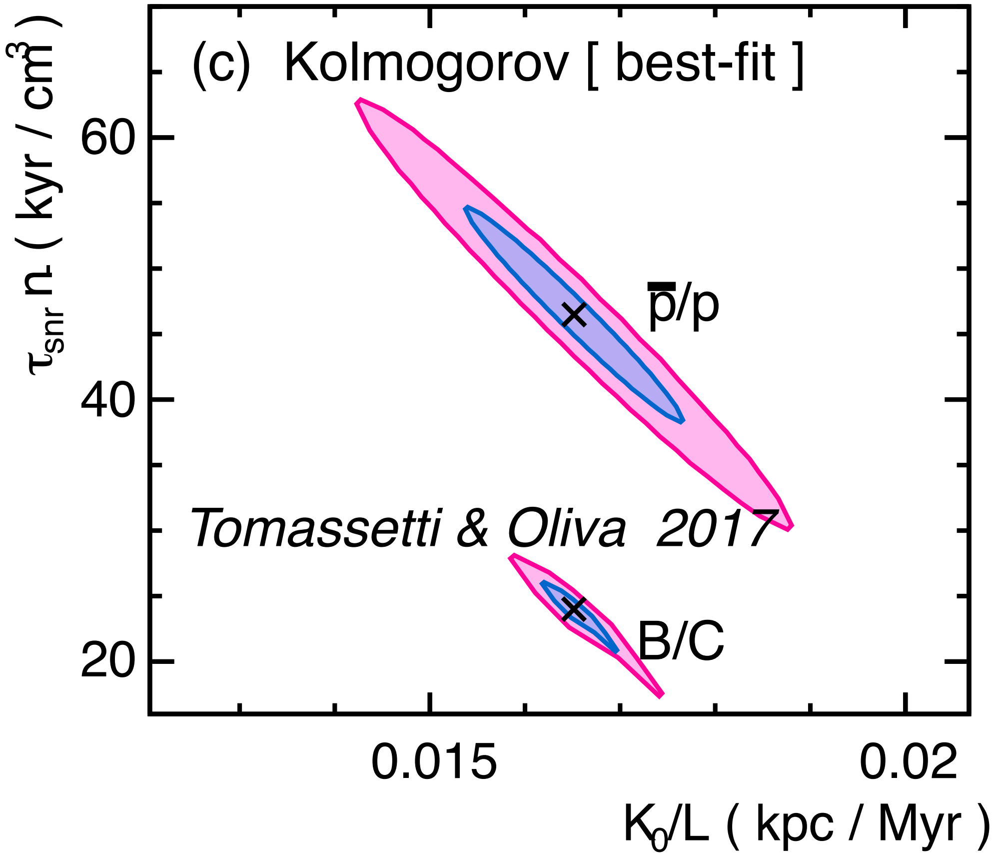


IC, Hooper, Linden PRD 2017

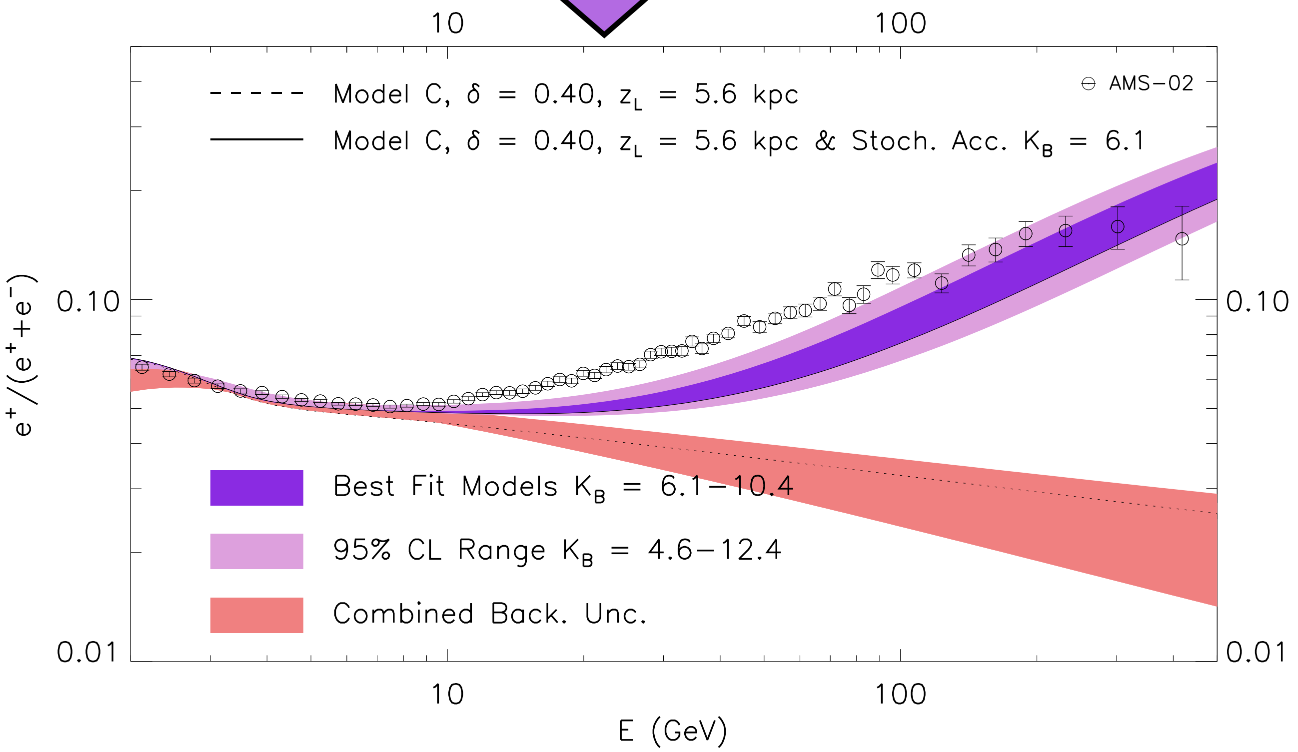
We do get Positive Potential Signal of Stoch. Accel. of Secondaries from antiproton/proton ratio at energies above 100 GeV:



IC, Hooper, Linden PRD 2017



Tomassetti & Oliva 2017



See also Di Mauro et al. JCAP 2014

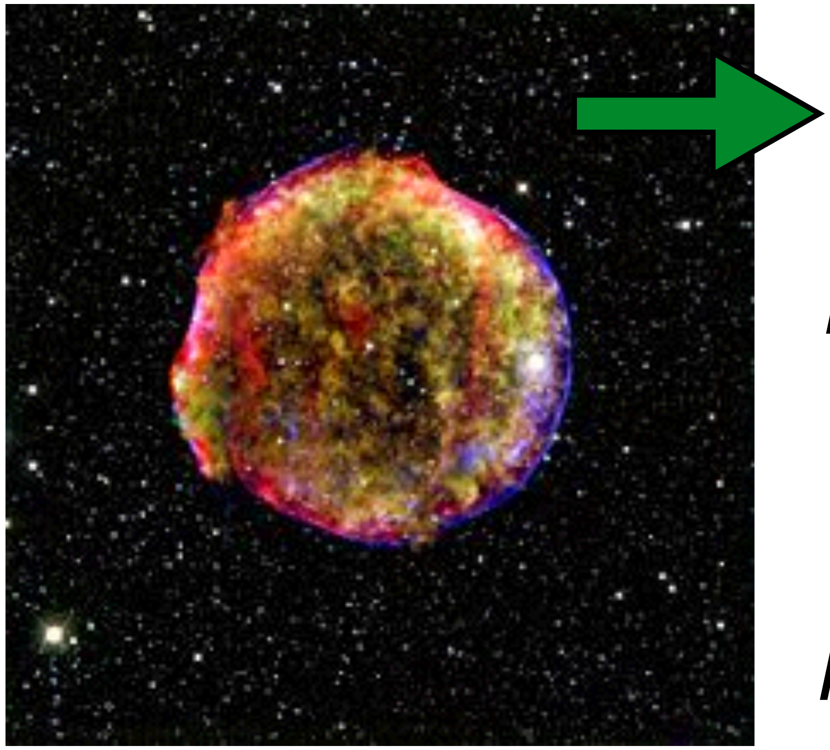
Variations between SNRs. For example if nearby SNRs are efficient accelerators of secondaries, but have low abundances of intermediate mass nuclei, then the connection between the B/C ratio pbar/p could be weakened.

Conclusions

- *Production and stochastic acceleration of secondaries in SNRs is a likely source of high energy hard secondary CR spectra*
- *The amplitude of that "additional" component is not well understood*
- *Using the CR secondary/primary spectra we can probe it*
- *From B/C we have been able to place some upper bound on the contribution of the stoch. accel. secondaries*
- *On the antiproton/proton ratio we find an increase/hardening of the spectrum compared to theoretical expectations above 100 GeV*
- *To study the pbar/p ratio we have taken into account all basic uncertainties (injection and propagation through the ISM, antiprotons production cross-sections).*
- *May possibly be an indication of a lower bound on the contribution of the stoch. accel. secondaries and tell us something about variations between SNRs (in distance from us and/or in their metallicity environments)*

Thank you

Why the *Rise* of the positron fraction is interesting:



For all *primary *CRs:

$q(E)^{inj} \sim E^{-\gamma}$ at injection into the ISM

For CR protons: $n(E)^p = q(E)\tau_{Diff}$

with $\tau_{Diff} \sim E^{-\delta}$ Thus: $n(E)^p \sim E^{-\gamma-\delta}$

For CR electrons: $n(E)^{e^-} \sim \frac{q(E)\tau_{loss}}{\sqrt{D(E)\tau_{loss}}}$

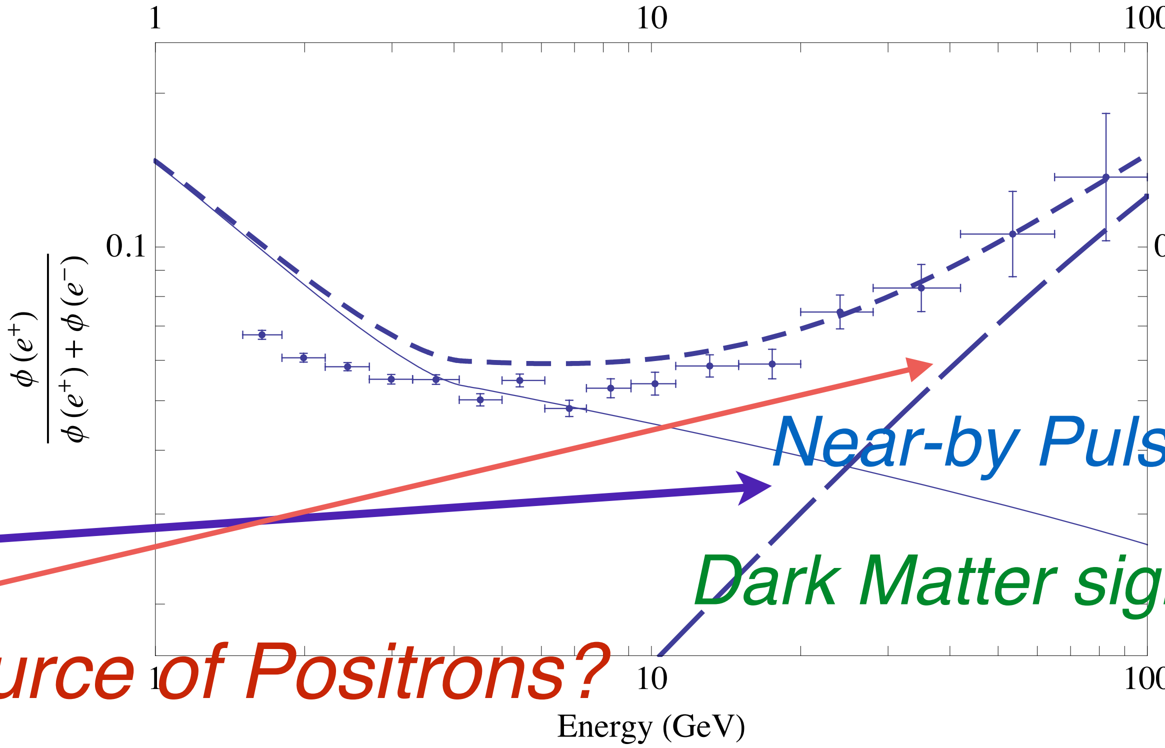
with: $\tau_{loss} \sim E^{-1}$ Thus: $n(E)^{e^-} \sim E^{-\gamma-1+1/2-\delta/2}$

For CR positrons (secondary CRs):

$pp \to K^{\pm}\pi^{\pm} \to e^{\pm}$

Thus: $n(E)^{e^+} \sim E^{-\gamma-\delta-1+1/2-\delta/2}$

Expect: $\frac{n(E)^{e^+}_{sec}}{n(E)^{e^-}_{prim}} \sim E^{-\delta}$



Near-by Pulsars?

Dark Matter signal?!

Additional Source of Positrons?