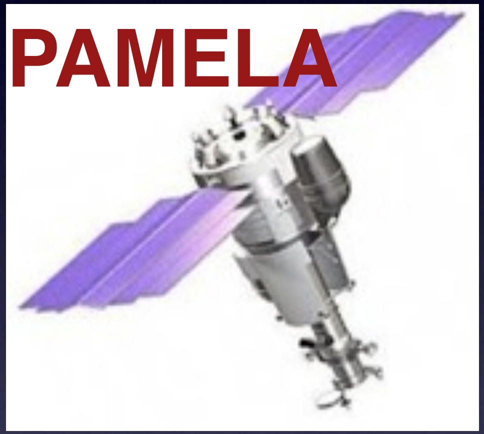
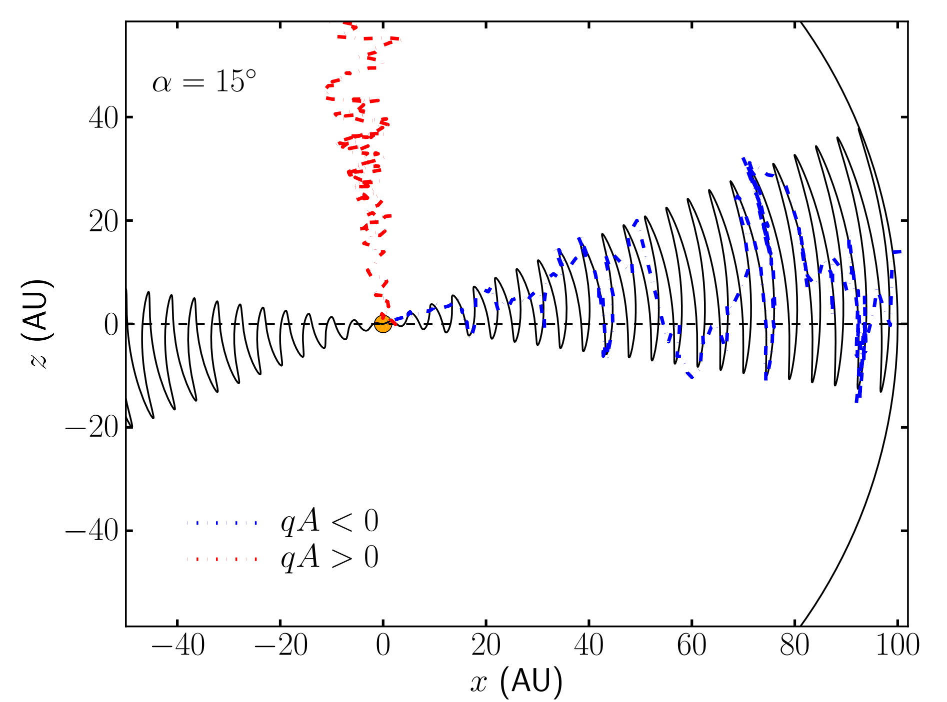
JOHNS HOPKINS UNIVERSITY

# *Towards a predictive analytic model for the solar modulation of cosmic rays*





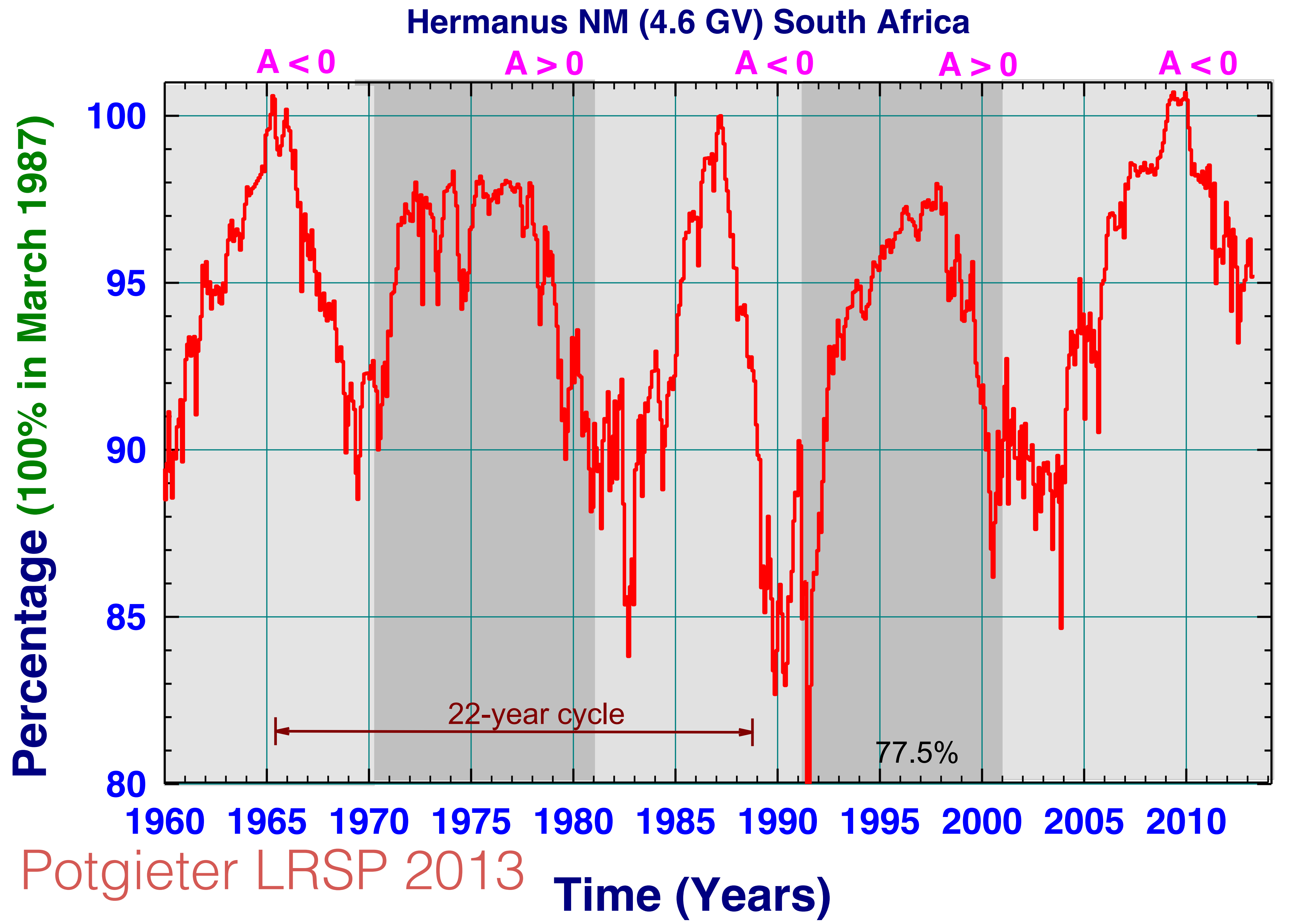
Mainly work with Dan Hooper (Fermilab)
and Tim Linden (Ohio State Univ.)
PRD 2016, arXiv:1511.01507

Wine and Cheese Seminar

Ilias Cholis 02/01/2016

# What is Solar Modulation of CRs?

Galactic cosmic rays encounter a turbulent solar wind with an embedded heliospheric magnetic field (HMF) when entering the heliosphere. This leads to significant variations in their intensity and in their energy as has been observed at Earth.



Potgieter LRSP 2013

CRs with kinetic energies below ~10 GeV, are efficiently deflected and decelerated as they propagate through the heliosphere.

The Solar Modulation of Cosmic Rays has been observed to have a 22-year cycle.

# Importance of understanding  Solar Modulation AND developing analytical models for it

- CR observations have entered a high precision era. Statistical errors are often much smaller than the corresponding systematic uncertainties associated with CR propagation. Among them, those governing diffusive reacceleration and convection, impact primarily the same low-energy CR population that is most affected by solar modulation.

- Improvements in our understanding of solar modulation will allow for more reliable inferences of the parameters describing the injection and transport of CRs throughout the Milky Way.

- Highly sophisticated particle propagation codes have been developed to model the physical processes of three-dimensional diffusion, particle drifts, convection and adiabatic energy losses within the Heliosphere.

- These codes include large numbers of free-parameters which must be scanned over in parallel with parameters associated with CR injection and propagation within the Milky Way. This makes such approaches computationally intensive and non-predictive.

# An analytic formula: The Force Field Approximation

The propagation of CRs through the HMF can be described by:

$$\frac{\partial f}{\partial t} = -(\vec{V} + \langle \vec{v}_D \rangle)\nabla f + \nabla(\hat{D}\nabla f) + \frac{1}{3}(\nabla \vec{V})\frac{\partial f}{\partial \ln p} + J_{\mathrm{source}}$$

average drift velocity

Adiabatic energy losses

solar wind velocity

Diffusion term

CRs produced inside the HS (e.g. Jovian e)

CR phase space density

## Simplifying Assumptions:

Quasi Stationary State: $\frac{\partial f}{\partial t} = 0$

Spherical Symmetry: $f \longrightarrow f(r)$

Radial Solar Wind: $\vec{V} = V\hat{e_r}$

Ignore drifts: $\langle \vec{v}_D \rangle = 0$

Isotropic Diffusion: $\hat{D} \longrightarrow D$

Ignore sources: $J_{\mathrm{source}} = 0$

Then the propagation eq. within the HMF simplifies to:

$$\frac{\partial f}{\partial r} + \frac{V}{3D}\frac{\partial f}{\partial lnp} = 0$$

For highly relativistic Particles: $\beta \simeq 1$

$$E_{kin}^{ISM} \rightarrow E_{kin}^{ISM} - |Z|e\Phi$$

$\Phi$ : Modulation Potential

The observed flux at Earth:

$$\frac{dN^{\oplus}}{dE_{kin}}(E_{kin}) = \frac{(E_{kin}+m)^2 - m^2}{(E_{kin}+m+\mid Z \mid e\Phi)^2 - m^2}\ \frac{dN^{\mathrm{ISM}}}{dE_{kin}}(E_{kin}+\mid Z \mid e\Phi)$$

- Not Predictive in terms of time evolution
- No Charge OR Energy dependence
- It’s regime is surpassed by the quality of data from experiments

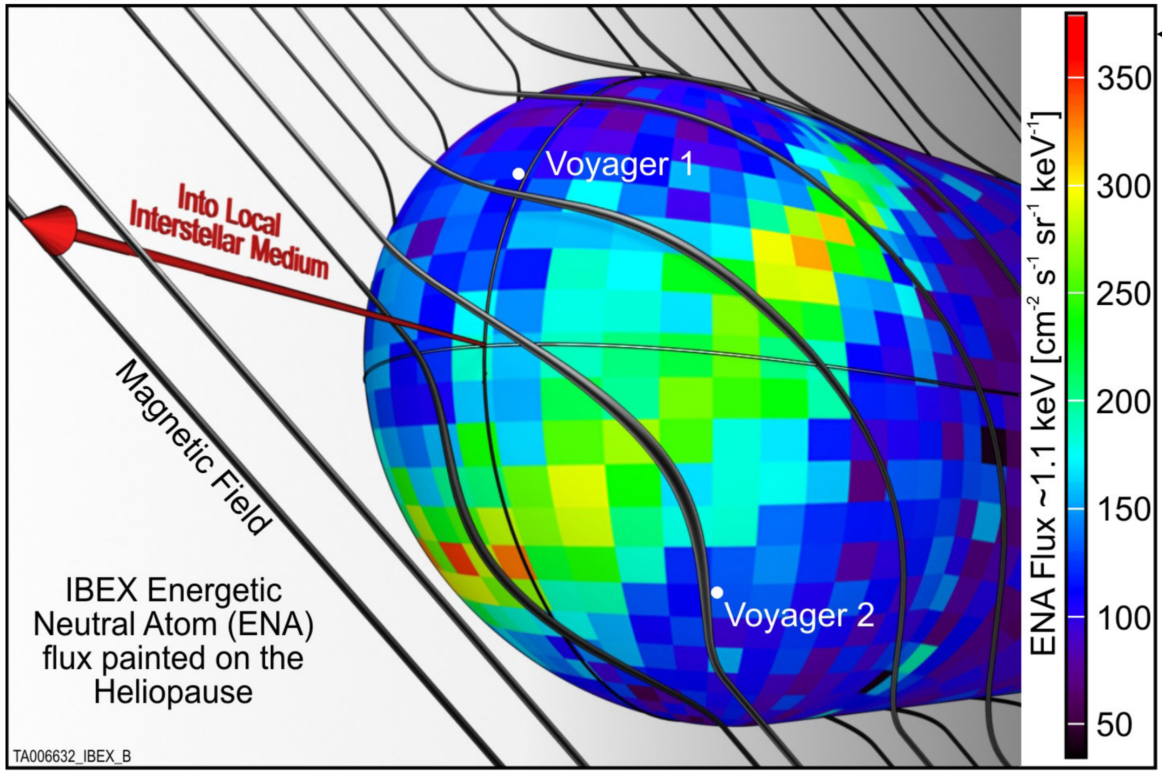
# New advances that allow us to move beyond the Force Field Approximation

- Several well measured solar observables are known to correlate with the solar modulation: the magnitude of the solar magnetic field, the bulk velocity of the solar wind, and the tilt angle of the heliospheric current sheet.

- CR datasets provided by the PAMELA and AMS-02 experiments measure variations in the local CR spectrum over relatively short timescales with high statistical precision.

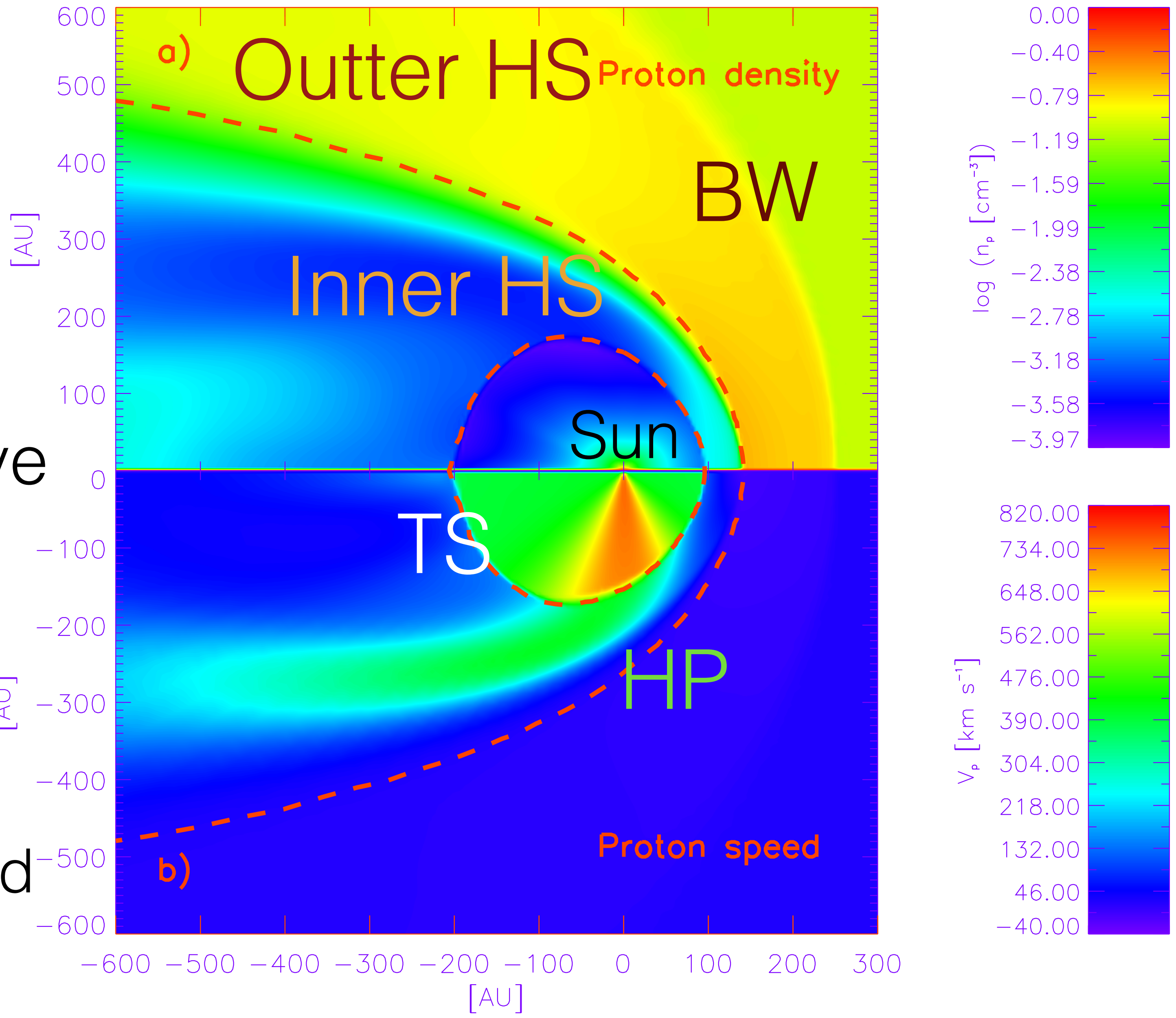
- Voyager 1 spacecraft has passed through the heliopause, (summer 2012) measuring the ISM CR spectrum for the first time

# *Geometry of Heliosphere*



Schematic view of an asymmetric heliosphere together with the directions of the interstellar magnetic field lines.

Potgieter LRSP 2013



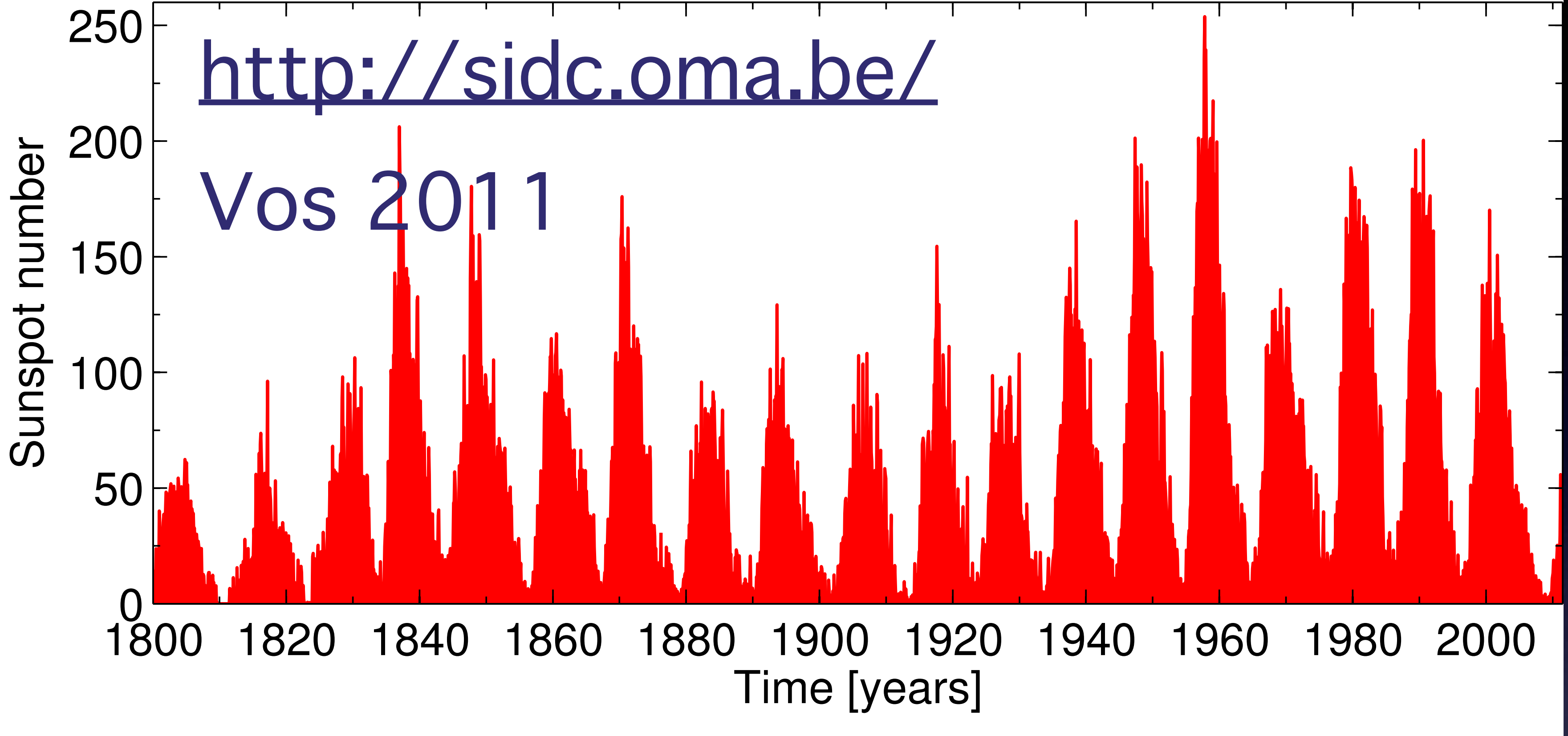
TS: Termination Shock

HP: Heliopause   BW: Bow Wave

HS: Heliosheath

Voyager 1 passed TS on Dec. 2004 (at 94 AU) and HP on Aug. 2012 (at 124 AU). Voyager 2 passed TS on Aug. 2007 (at 84 AU)

# Wealth of Solar Data

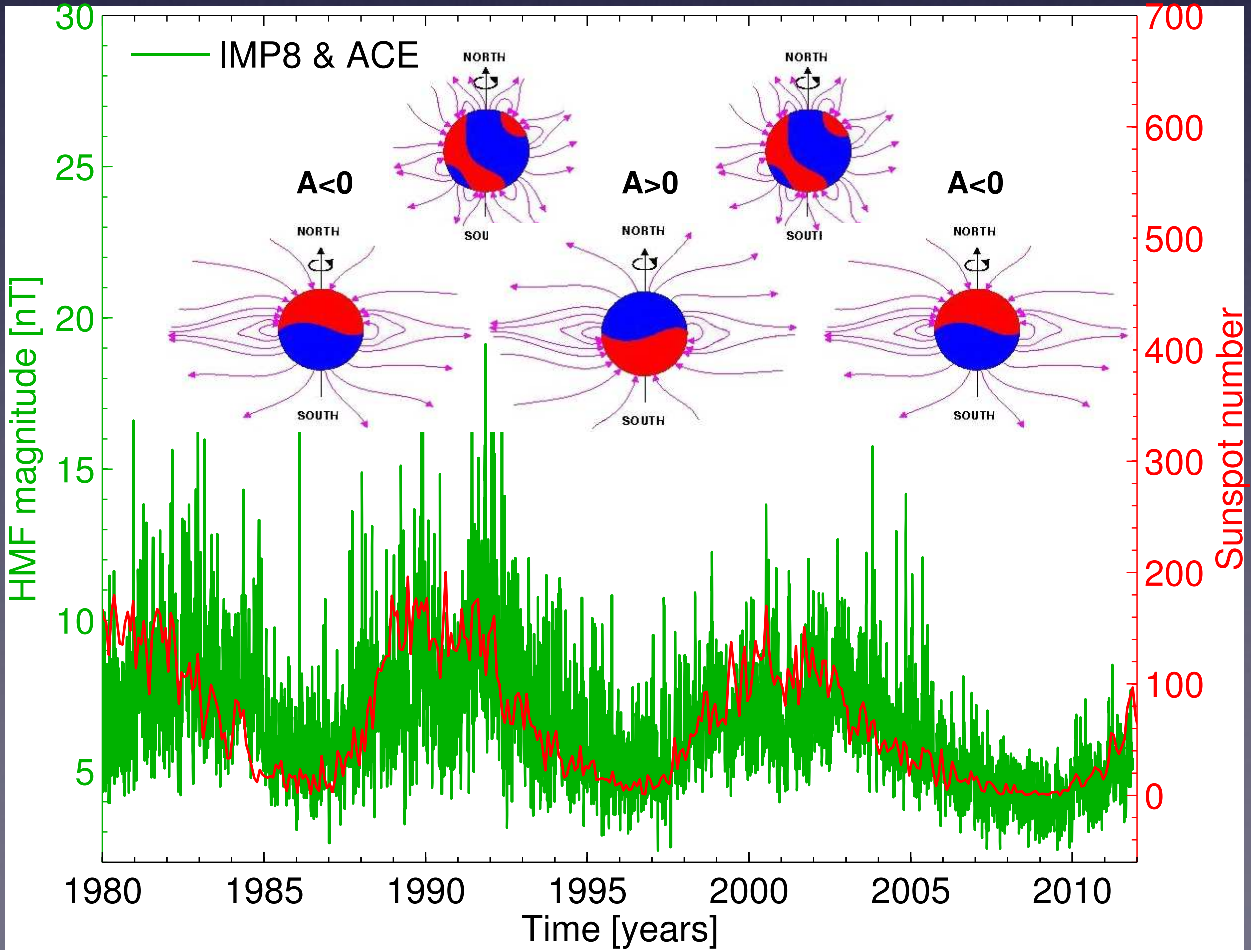


Search for correlations between different measured properties of the Sun:

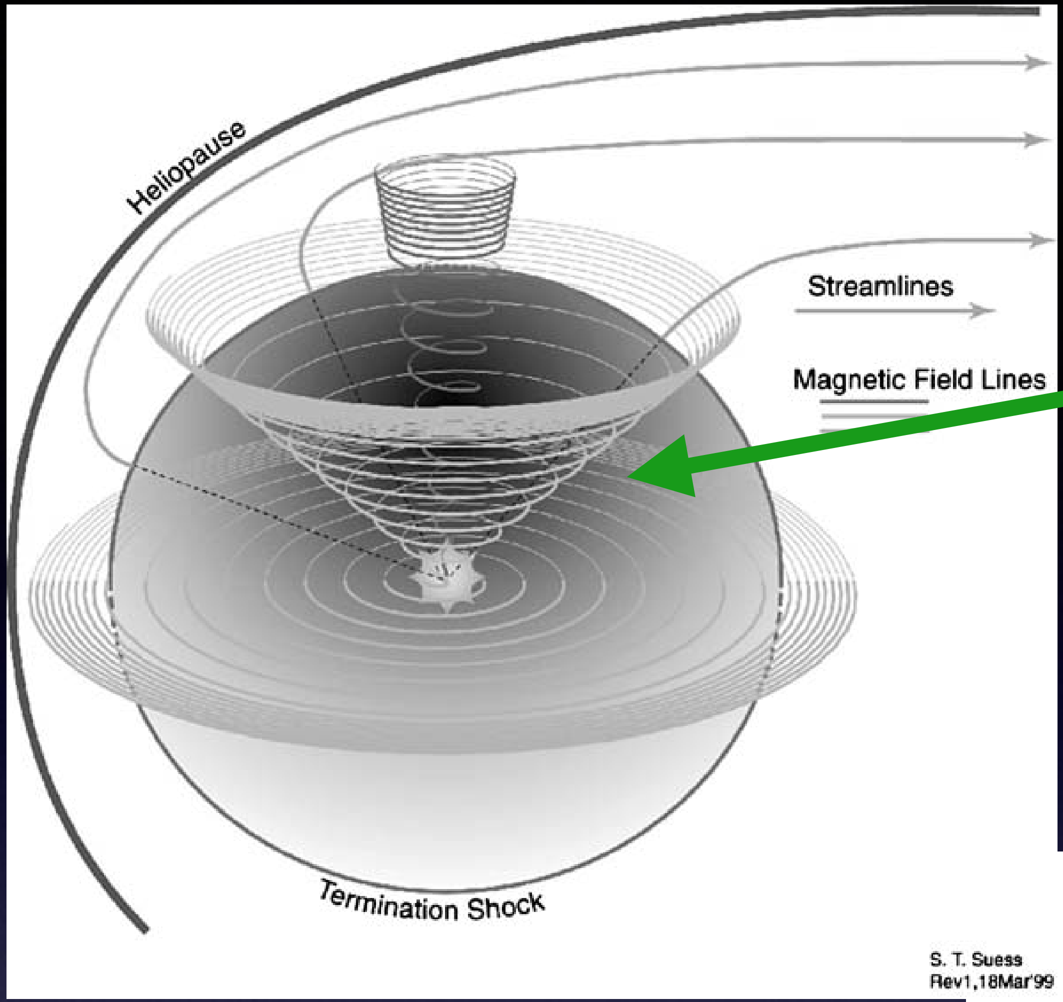
There is Time Dependence

http://nssdc.gsfc.nasa.gov/

Vos 2011



# The structure of the Heliospheric Magnetic field



Spriral structure

There is No Spherical Symmetry

Heber & Potgieter Sp.Sci. Rev. 2006

The Heliospheric Current sheet is a thick titled sheet that through drift effects deflects or constraints CRs to propagate inside or outside of it.

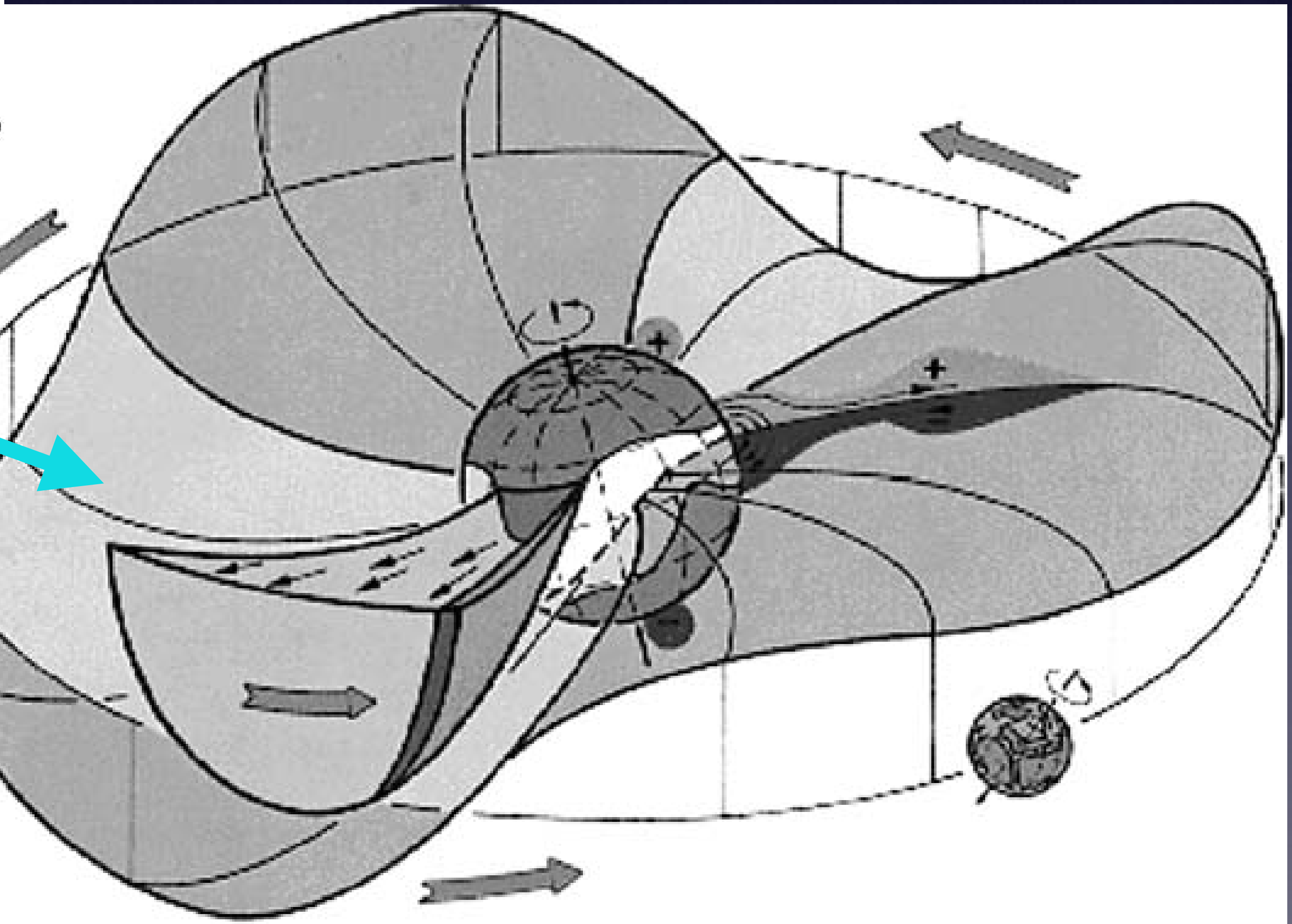


*Figure 4.* Illustration of the sector structure of the heliospheric magnetic field due to the inclination of the wavy heliospheric current sheet (Schwenn, 1990).

# From Simulations that propagate CRs from the Sun outwards:

Strauss et. al ApJ 2011

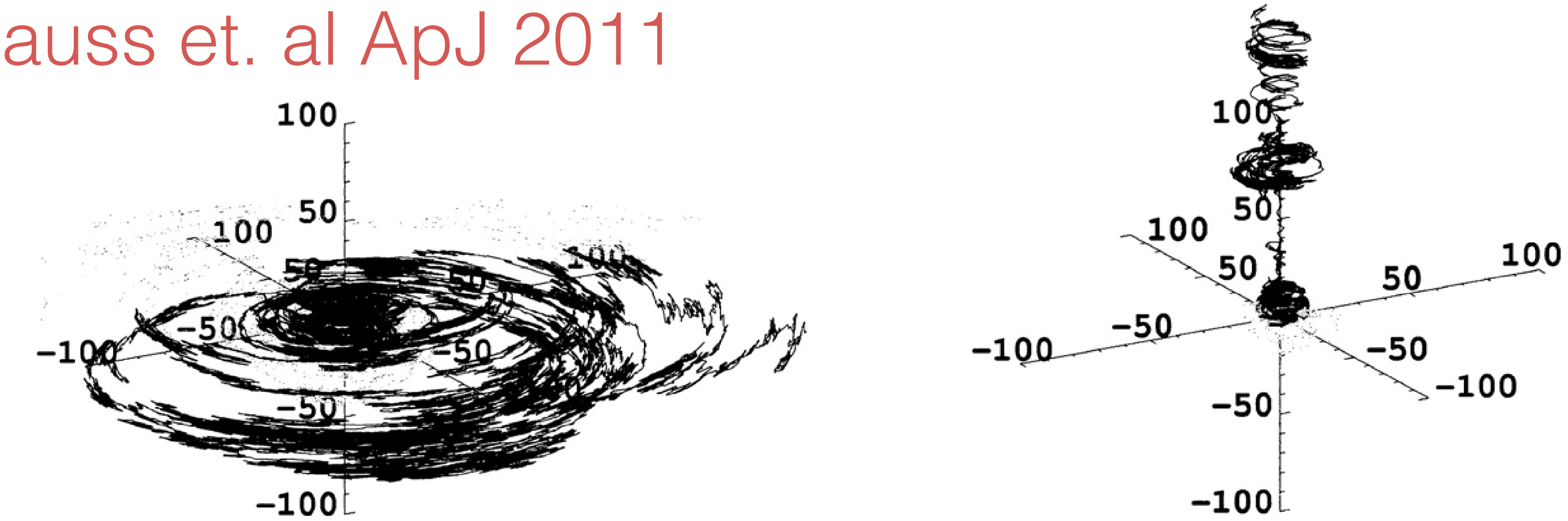
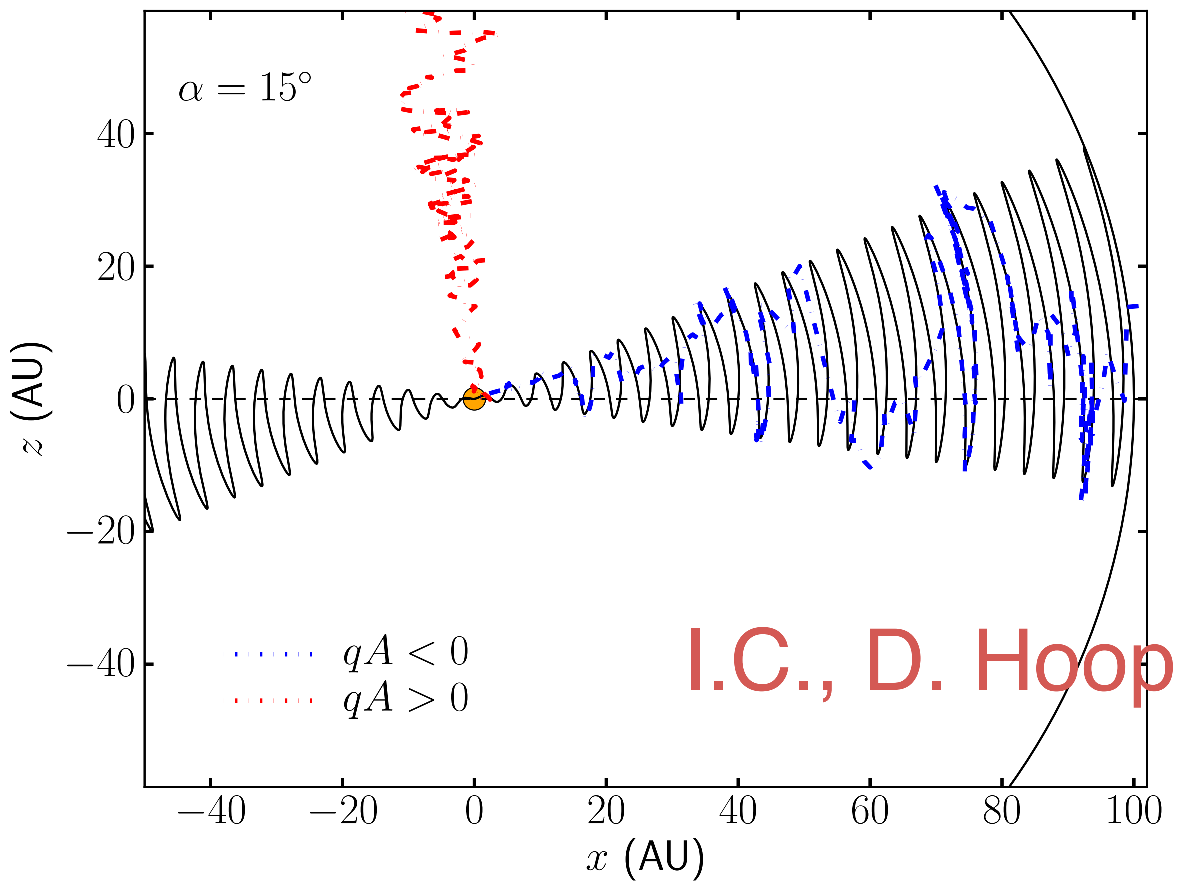


**Figure 7.** Three-dimensional spatial representation of the particle trajectories shown in Figure 1. Two representative particle trajectories (black and gray lines) are shown for the $A > 0$ (left panel) and $A < 0$ (right panel) HMF polarity cycles. In the $A < 0$ cycle, the pseudo-particles (galactic 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.



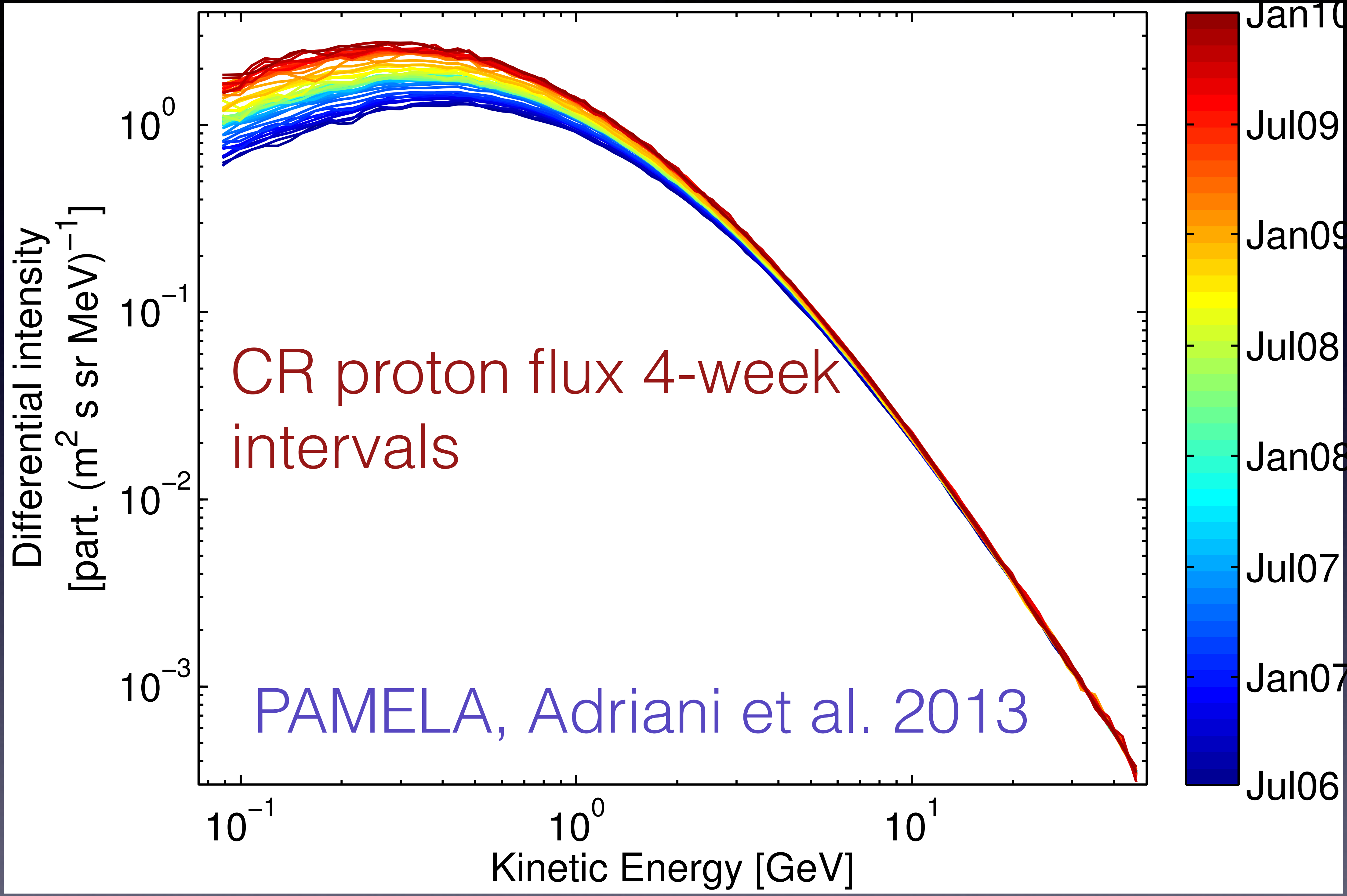
There is Charge Dependence

Drifts Can NOT be ignored

Even diffusion is not isotropic

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

# Wealth of CR Data



CR proton flux 4-week intervals

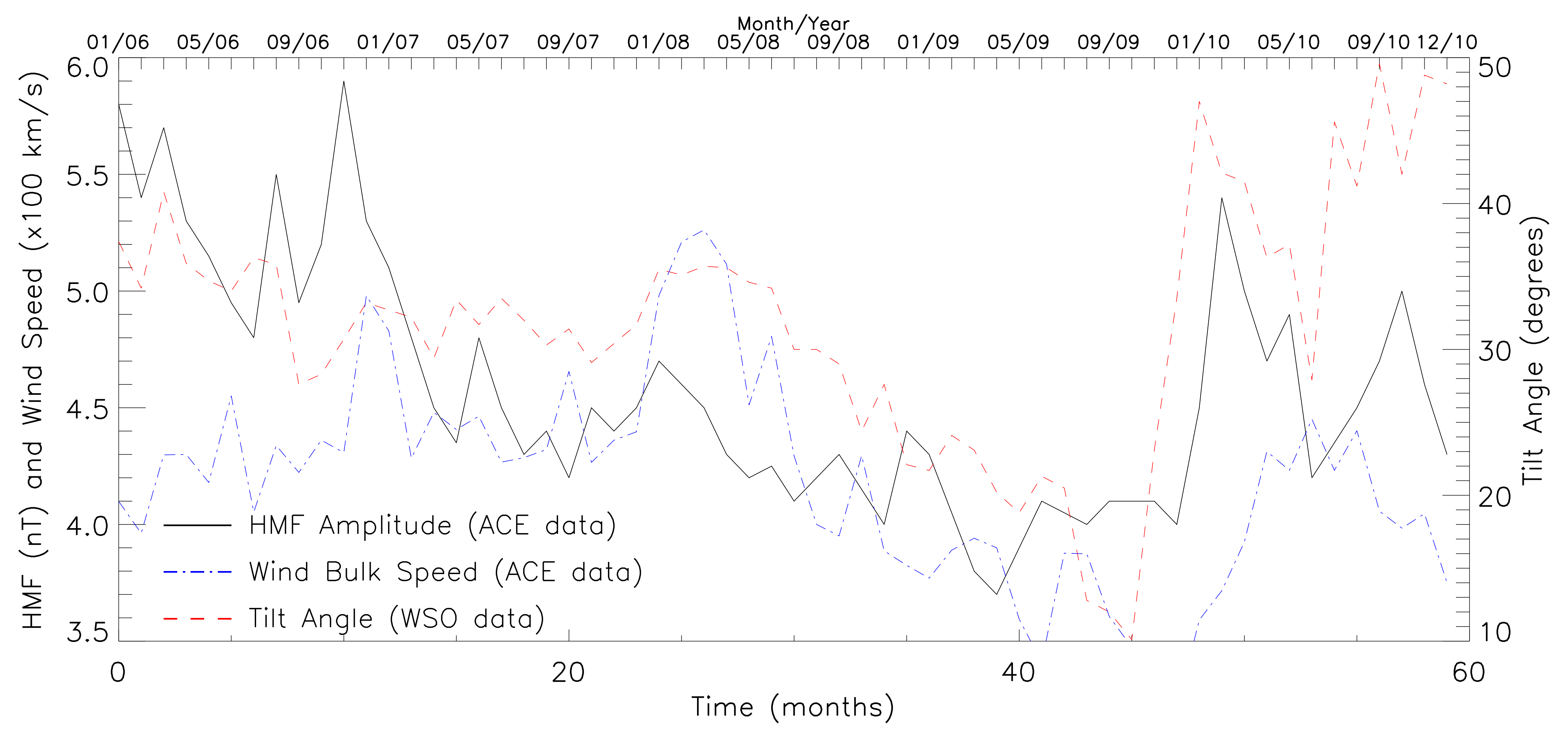
PAMELA, Adriani et al. 2013

CR proton flux at low Energies is smoothly increasing with time

There is Time Dependence AND Energy Dependence

# Combining the CR, the Solar Data and also Simulations

## Zooming in the era of PAMELA data:



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

Strong Correlation between Tilt angle and HMF amplitude, weaker correlation of the Wind Bulk speed. The latter can’t account for the measured variations in the CR flux.

## Necessary changes in the analytical method, i.e. in deriving Phi :

## I) Include drift effects and energy dependence.

The modulation potential Phi depends on the Adiabatic energy losses -> Time of Propagation of CRs from the TS to Earth. Drifts are important only for the CRs traveling through the Heliospheric Current Sheet.

$$\langle \vec{v}_D \rangle = \frac{qv}{3} \nabla \times (\lambda_d \, \hat{e}_B) \quad \text{where} \quad \lambda_d = \underset{\substack{\uparrow \\ p/|q|B}}{r_{\text{Larmor}}} \, \frac{(R/R_0)^2}{1 + \underset{\substack{\uparrow \\ \text{sets the regime}}}{(R/R_0)^2}}$$

At low rigidities: the Larmor Radius of CRs is much smaller than the curvature of the HMF. Particles follow the local magnetic field structure, suppressing the drift velocity.

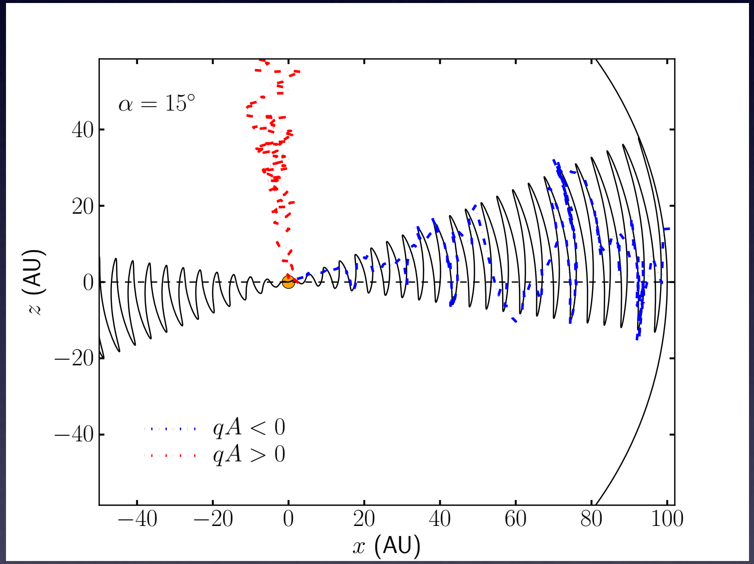
At high rigidities: CRs are not affected by the small-scale structure of the HMF field lines, but instead probe the average HMF structure and intensity, so $\lambda_d = r_{\text{Larmor}}$

Thus the timescale for CR drift is proportional to:

$$\tau_D \propto \frac{1}{|\langle \vec{v}_D \rangle|} \propto B(t)\, \frac{1+(R/R_0)^2}{\beta\,(R/R_0)^3}$$

II) Separate Charges and include Time effects (breaking also spherical symmetry).

qA<0 particles propagate through the Current Sheet, while qA>0 propagate through the poles.



The MOST agnostic form for $\Phi$ is:

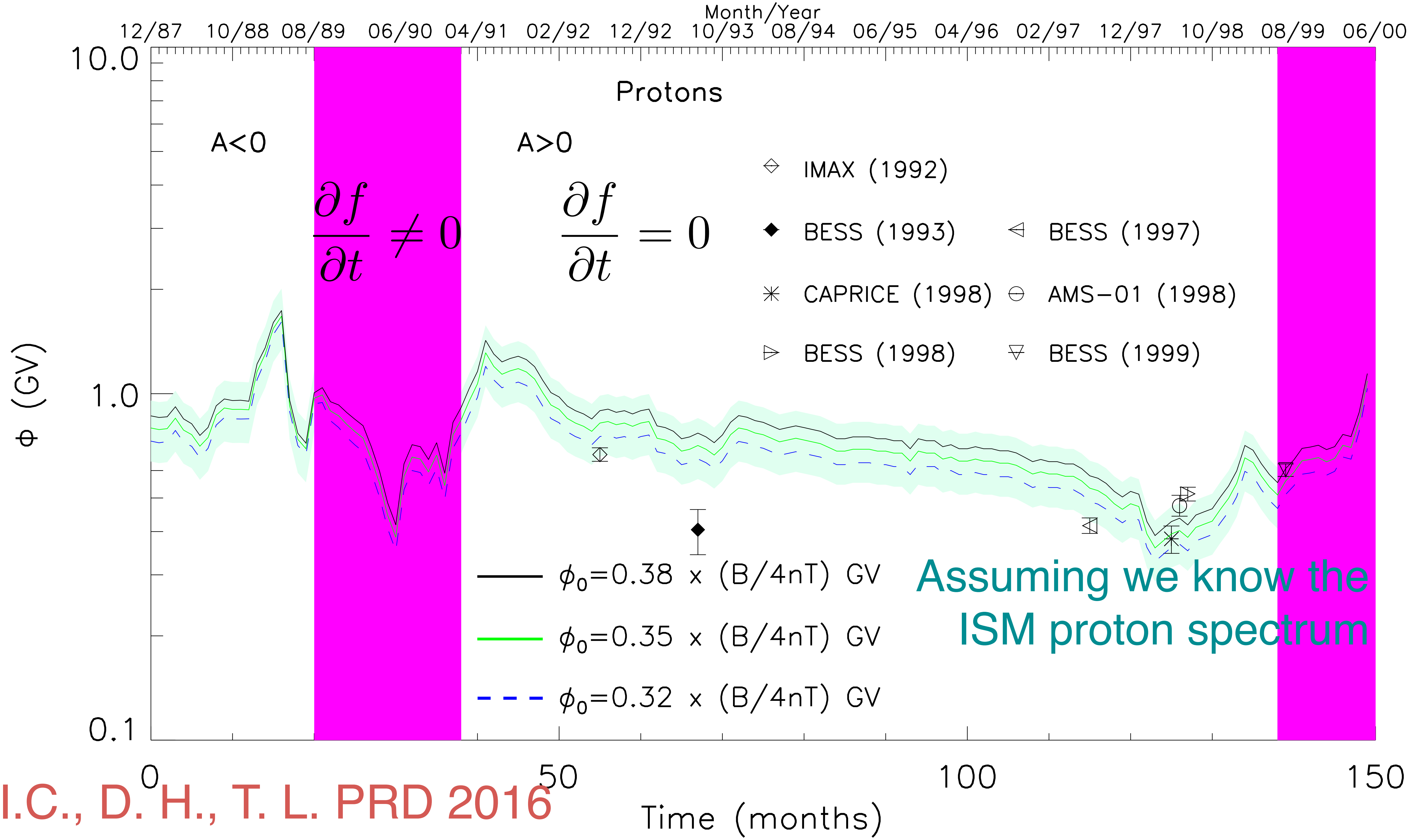
$$\Phi(R,t) = \phi_0\, g(|B_{\rm tot}(t)|)$$

$$+\phi_1\, H(-qA)\, g(|B_{\rm tot}(t)|)\, f(\alpha(t)) \left( \frac{1+(R/R_0)^2}{\beta(R/R_0)^3} \right)$$

# Let the Data tell us what are, $\phi_0, \phi_1, f(\alpha(t))$ and $g(|B_{\rm tot}(t)|)$

From previous slide: $g(|B_{\rm tot}|) \propto |B_{\rm tot}|$

Constraining the first qA>0 term

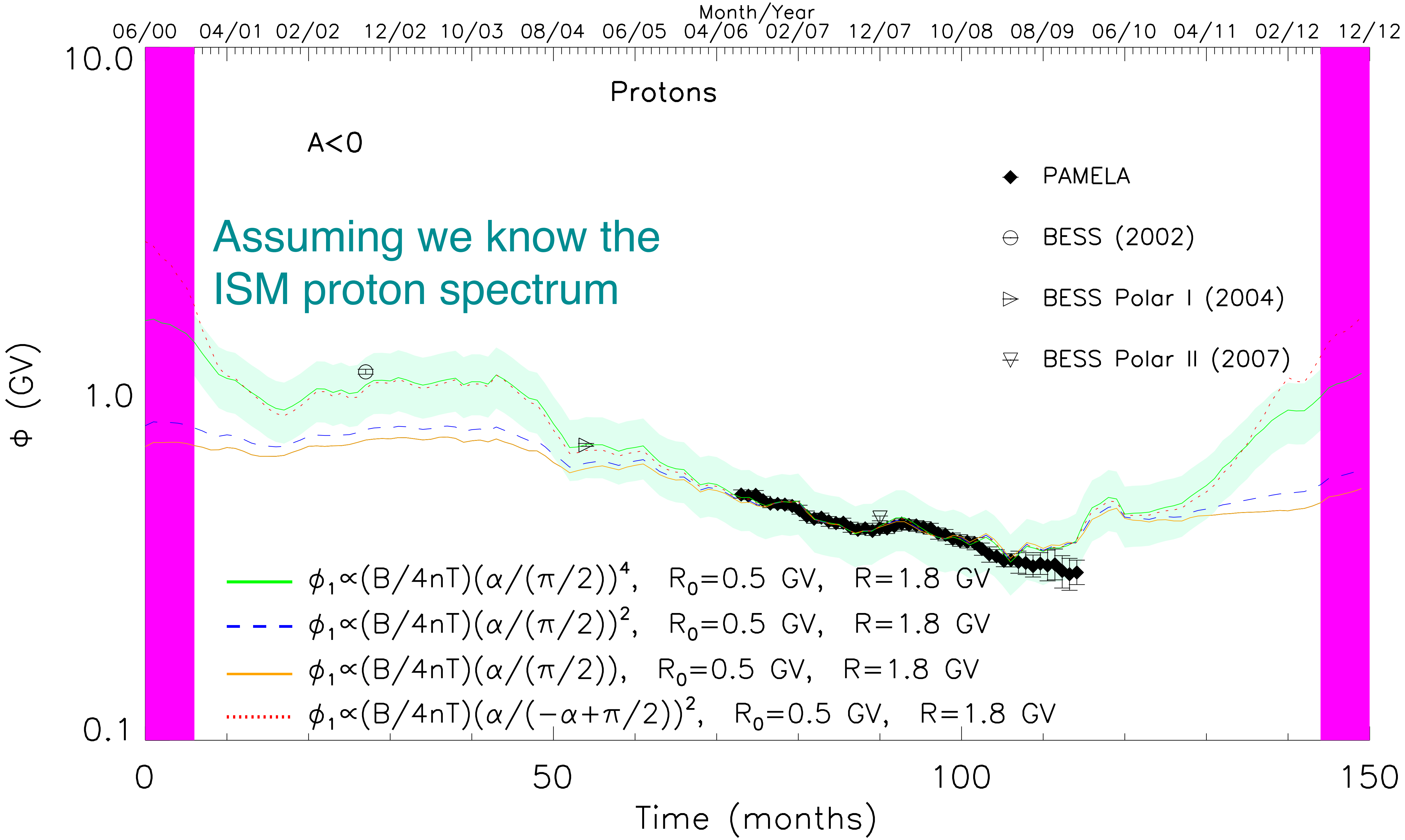


Assuming we know the ISM proton spectrum

I.C., D. H., T. L. PRD 2016

# Constraining the second qA<0 term

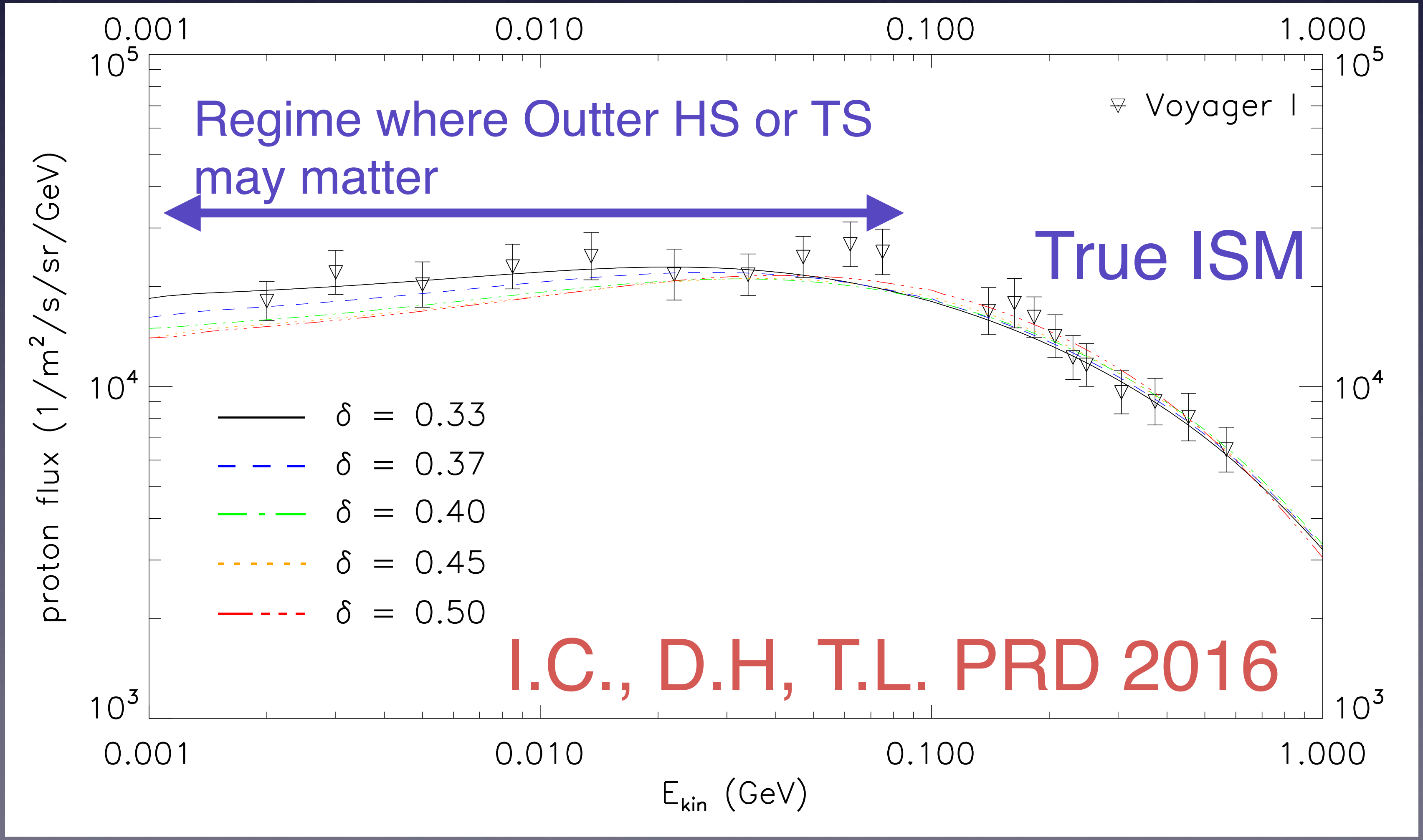
Assuming we know the ISM proton spectrum



# Accounting for ISM galactic propagation uncertainties for protons:

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

Voyager 1 (~ISM) proton flux:



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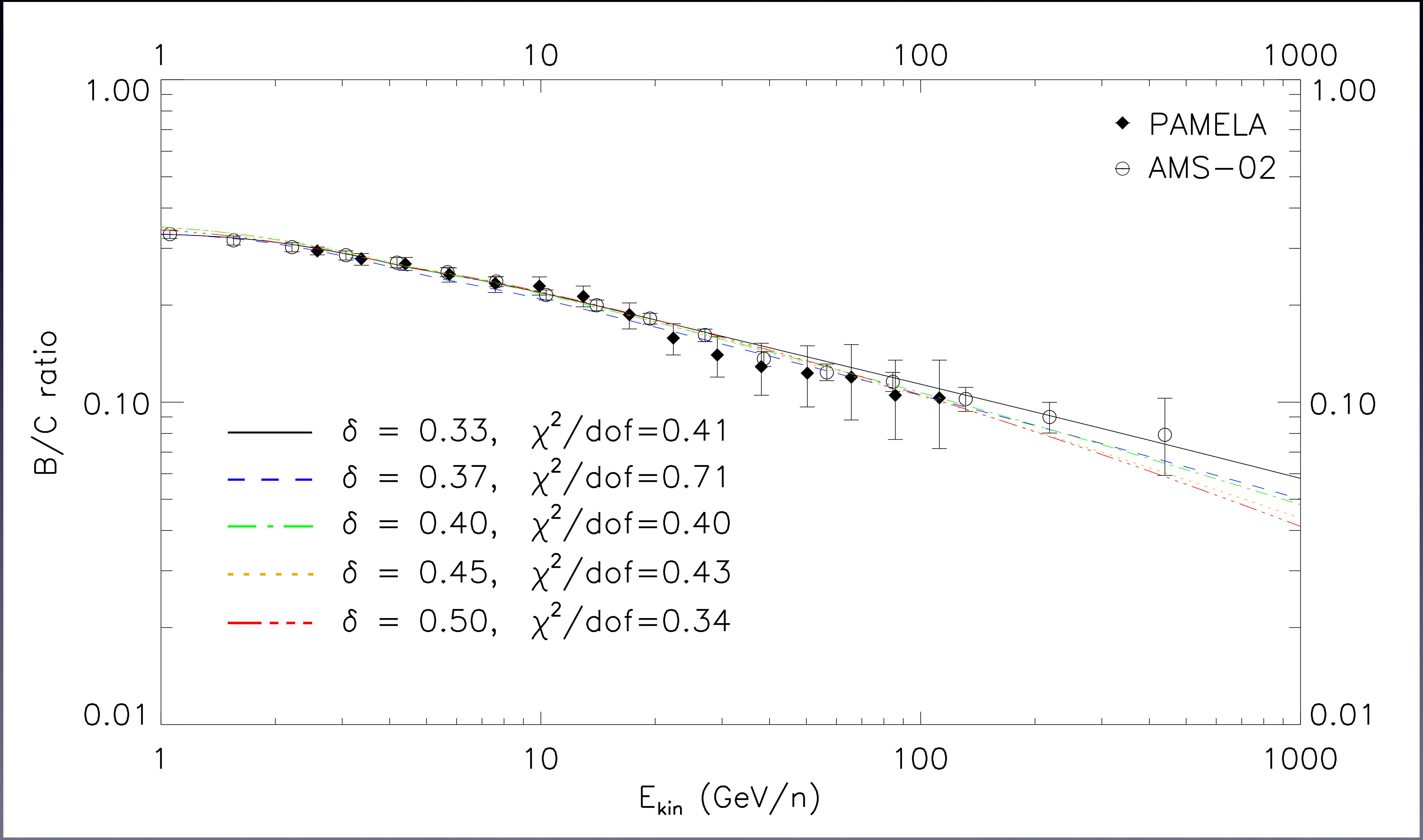
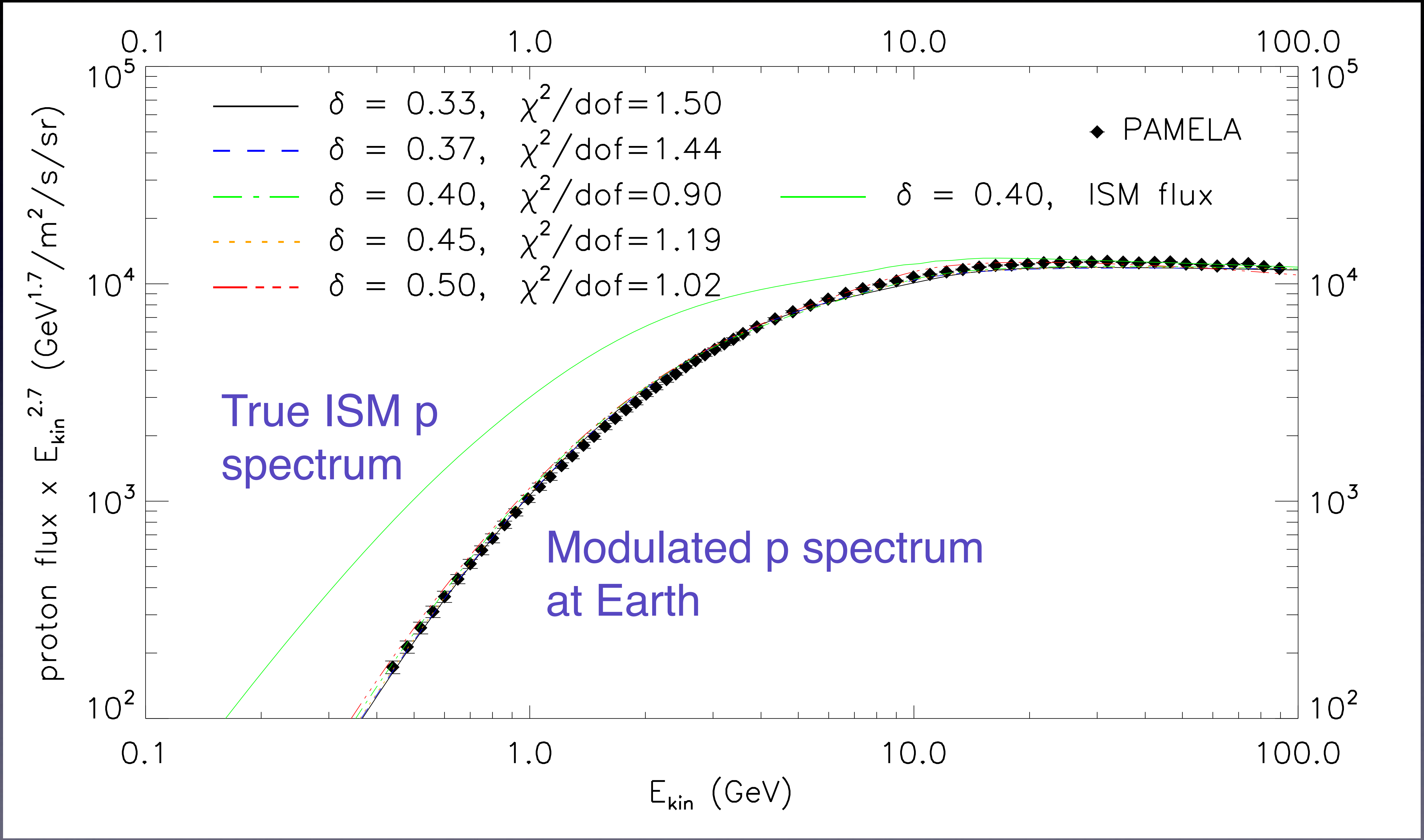
We use a numerical solver, GALPROP, and build several models that are in agreements with CR measurements

# 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.



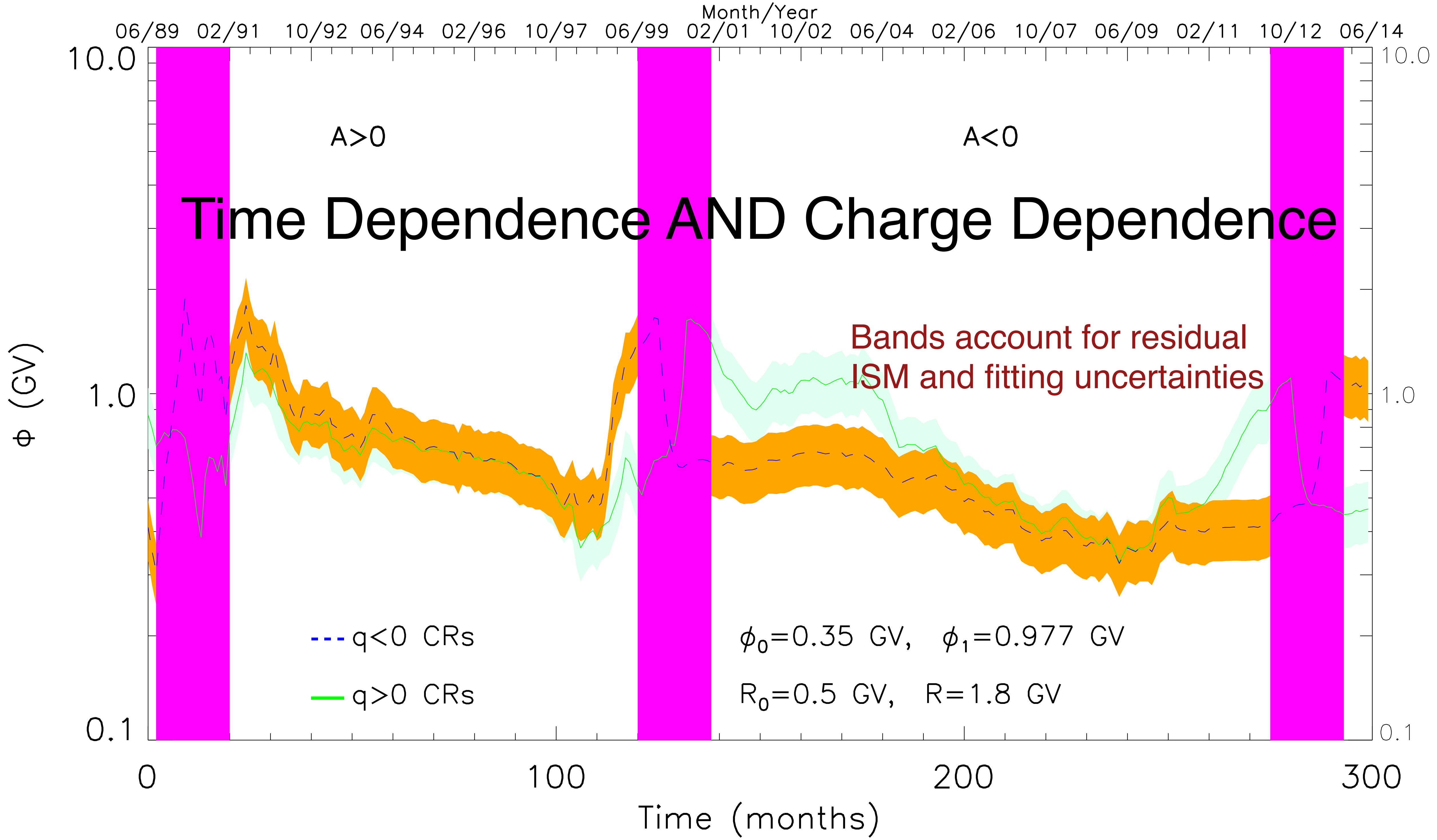
# Cross-cheching every time with all the PROTON data; monthly AND total:



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

After all is set and done:

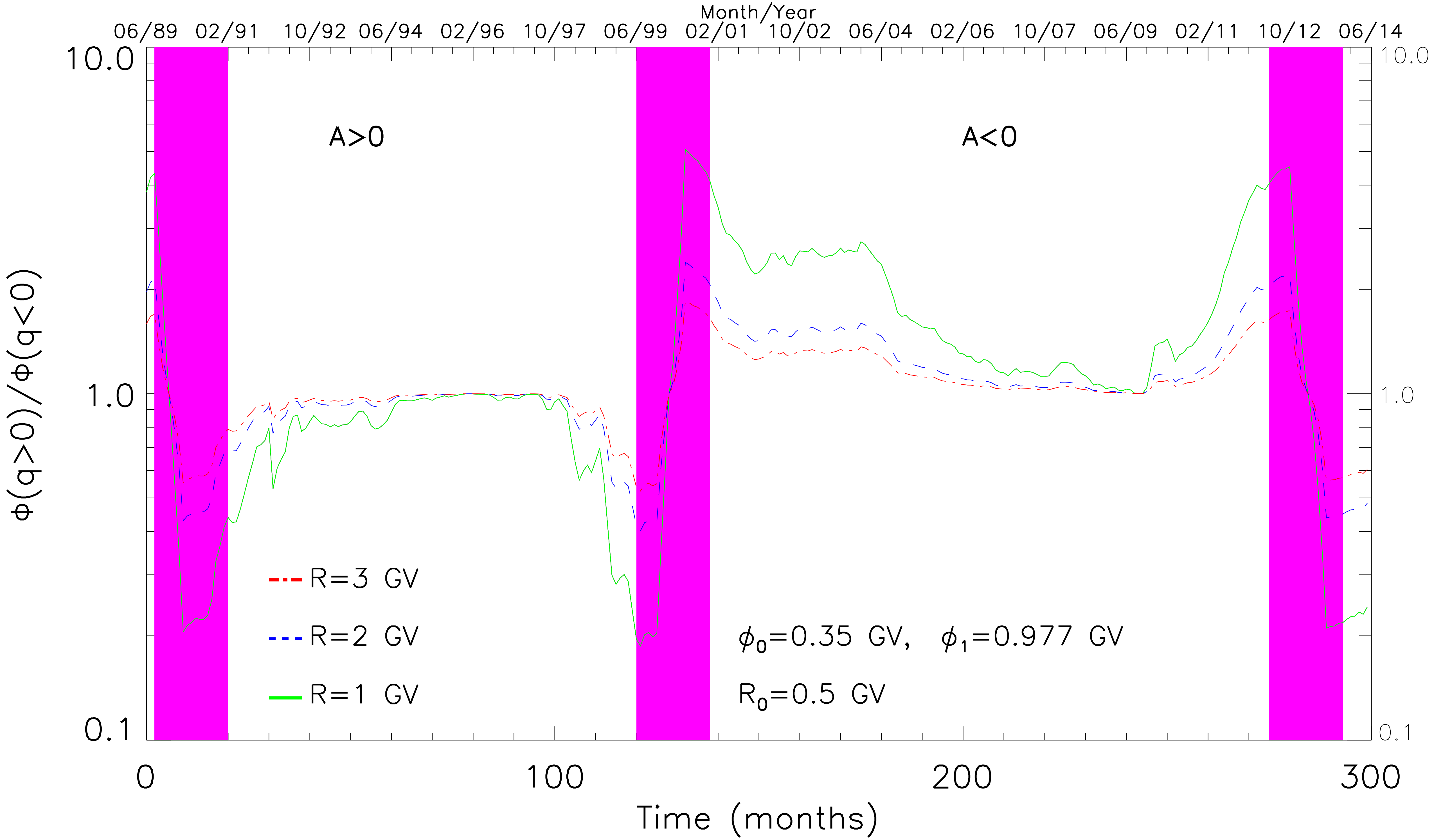
$$\Phi(R,t) = \phi_0 \left(\frac{|B_{\rm tot}(t)|}{4\,{\rm nT}}\right) + \phi_1\, H(-qA(t)) \left(\frac{|B_{\rm tot}(t)|}{4\,{\rm nT}}\right) \left(\frac{1+(R/R_0)^2}{\beta(R/R_0)^3}\right) \left(\frac{\alpha(t)}{\pi/2}\right)^4$$



Time Dependence AND Charge Dependence

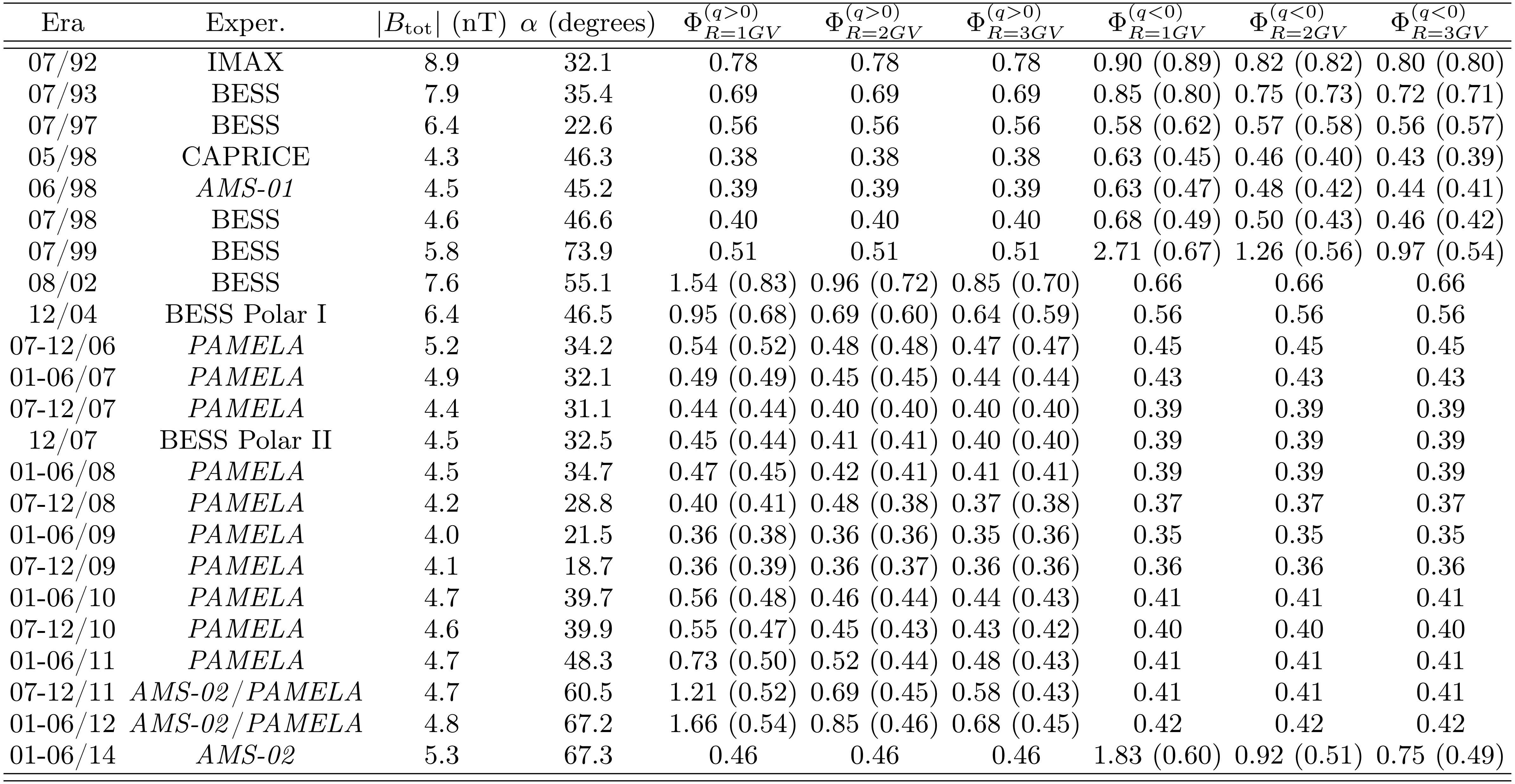
Bands account for residual ISM and fitting uncertainties

# Rigidity AND Charge Dependence



# Conclusions:

Using Solar and CR data: Accounted for Time, Rigidity and Charge dependence which are related to observable HMF properties. Thus Modulation effects can now predicted/probed. Remaining uncertainties will be further constrained by AMS-02 in the next years.

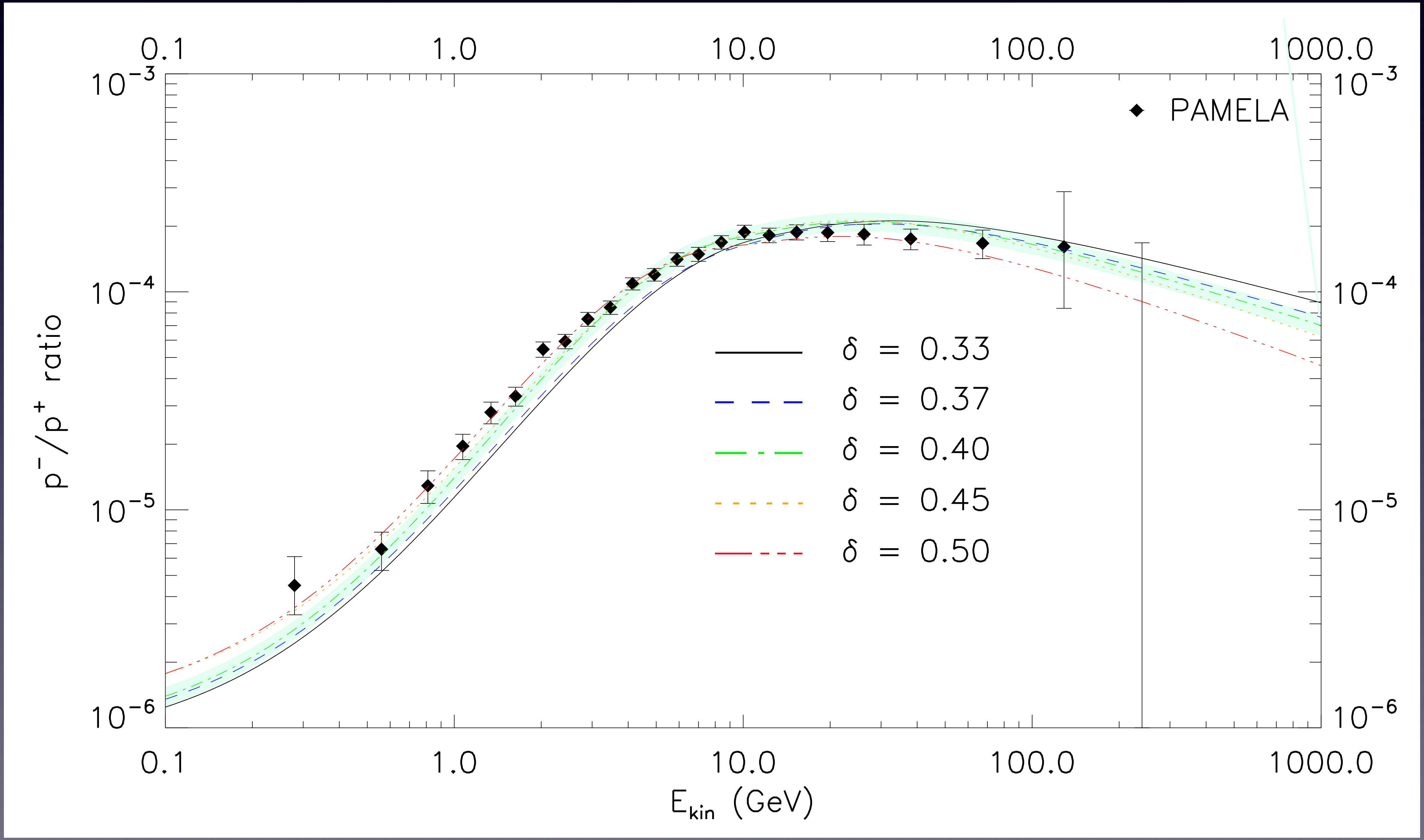


| Era | Exper. | $\lvert B_{\rm tot}\rvert$ (nT) | $\alpha$ (degrees) | $\Phi^{(q>0)}_{R=1GV}$ | $\Phi^{(q>0)}_{R=2GV}$ | $\Phi^{(q>0)}_{R=3GV}$ | $\Phi^{(q<0)}_{R=1GV}$ | $\Phi^{(q<0)}_{R=2GV}$ | $\Phi^{(q<0)}_{R=3GV}$ |
|---|---|---|---|---|---|---|---|---|---|
| 07/92 | IMAX | 8.9 | 32.1 | 0.78 | 0.78 | 0.78 | 0.90 (0.89) | 0.82 (0.82) | 0.80 (0.80) |
| 07/93 | BESS | 7.9 | 35.4 | 0.69 | 0.69 | 0.69 | 0.85 (0.80) | 0.75 (0.73) | 0.72 (0.71) |
| 07/97 | BESS | 6.4 | 22.6 | 0.56 | 0.56 | 0.56 | 0.58 (0.62) | 0.57 (0.58) | 0.56 (0.57) |
| 05/98 | CAPRICE | 4.3 | 46.3 | 0.38 | 0.38 | 0.38 | 0.63 (0.45) | 0.46 (0.40) | 0.43 (0.39) |
| 06/98 | *AMS-01* | 4.5 | 45.2 | 0.39 | 0.39 | 0.39 | 0.63 (0.47) | 0.48 (0.42) | 0.44 (0.41) |
| 07/98 | BESS | 4.6 | 46.6 | 0.40 | 0.40 | 0.40 | 0.68 (0.49) | 0.50 (0.43) | 0.46 (0.42) |
| 07/99 | BESS | 5.8 | 73.9 | 0.51 | 0.51 | 0.51 | 2.71 (0.67) | 1.26 (0.56) | 0.97 (0.54) |
| 08/02 | BESS | 7.6 | 55.1 | 1.54 (0.83) | 0.96 (0.72) | 0.85 (0.70) | 0.66 | 0.66 | 0.66 |
| 12/04 | BESS Polar I | 6.4 | 46.5 | 0.95 (0.68) | 0.69 (0.60) | 0.64 (0.59) | 0.56 | 0.56 | 0.56 |
| 07-12/06 | *PAMELA* | 5.2 | 34.2 | 0.54 (0.52) | 0.48 (0.48) | 0.47 (0.47) | 0.45 | 0.45 | 0.45 |
| 01-06/07 | *PAMELA* | 4.9 | 32.1 | 0.49 (0.49) | 0.45 (0.45) | 0.44 (0.44) | 0.43 | 0.43 | 0.43 |
| 07-12/07 | *PAMELA* | 4.4 | 31.1 | 0.44 (0.44) | 0.40 (0.40) | 0.40 (0.40) | 0.39 | 0.39 | 0.39 |
| 12/07 | BESS Polar II | 4.5 | 32.5 | 0.45 (0.44) | 0.41 (0.41) | 0.40 (0.40) | 0.39 | 0.39 | 0.39 |
| 01-06/08 | *PAMELA* | 4.5 | 34.7 | 0.47 (0.45) | 0.42 (0.41) | 0.41 (0.41) | 0.39 | 0.39 | 0.39 |
| 07-12/08 | *PAMELA* | 4.2 | 28.8 | 0.40 (0.41) | 0.48 (0.38) | 0.37 (0.38) | 0.37 | 0.37 | 0.37 |
| 01-06/09 | *PAMELA* | 4.0 | 21.5 | 0.36 (0.38) | 0.36 (0.36) | 0.35 (0.36) | 0.35 | 0.35 | 0.35 |
| 07-12/09 | *PAMELA* | 4.1 | 18.7 | 0.36 (0.39) | 0.36 (0.37) | 0.36 (0.36) | 0.36 | 0.36 | 0.36 |
| 01-06/10 | *PAMELA* | 4.7 | 39.7 | 0.56 (0.48) | 0.46 (0.44) | 0.44 (0.43) | 0.41 | 0.41 | 0.41 |
| 07-12/10 | *PAMELA* | 4.6 | 39.9 | 0.55 (0.47) | 0.45 (0.43) | 0.43 (0.42) | 0.40 | 0.40 | 0.40 |
| 01-06/11 | *PAMELA* | 4.7 | 48.3 | 0.73 (0.50) | 0.52 (0.44) | 0.48 (0.43) | 0.41 | 0.41 | 0.41 |
| 07-12/11 | *AMS-02/PAMELA* | 4.7 | 60.5 | 1.21 (0.52) | 0.69 (0.45) | 0.58 (0.43) | 0.41 | 0.41 | 0.41 |
| 01-06/12 | *AMS-02/PAMELA* | 4.8 | 67.2 | 1.66 (0.54) | 0.85 (0.46) | 0.68 (0.45) | 0.42 | 0.42 | 0.42 |
| 01-06/14 | *AMS-02* | 5.3 | 67.3 | 0.46 | 0.46 | 0.46 | 1.83 (0.60) | 0.92 (0.51) | 0.75 (0.49) |

I.C., D.H, T.L. PRD 2016

# *Also:*

We will be able to further understand the CR antiprotons which may be a probe of Dark Matter annihilations in the Milky Way (work in progress with D.H and T.L.). Finally, connections with diffuse gamma-ray  and microwave emission.



Thank you!