Solar Modulation and Dark Matter Workshop
Nov 14 – 19, 2021
IFPU - Trieste

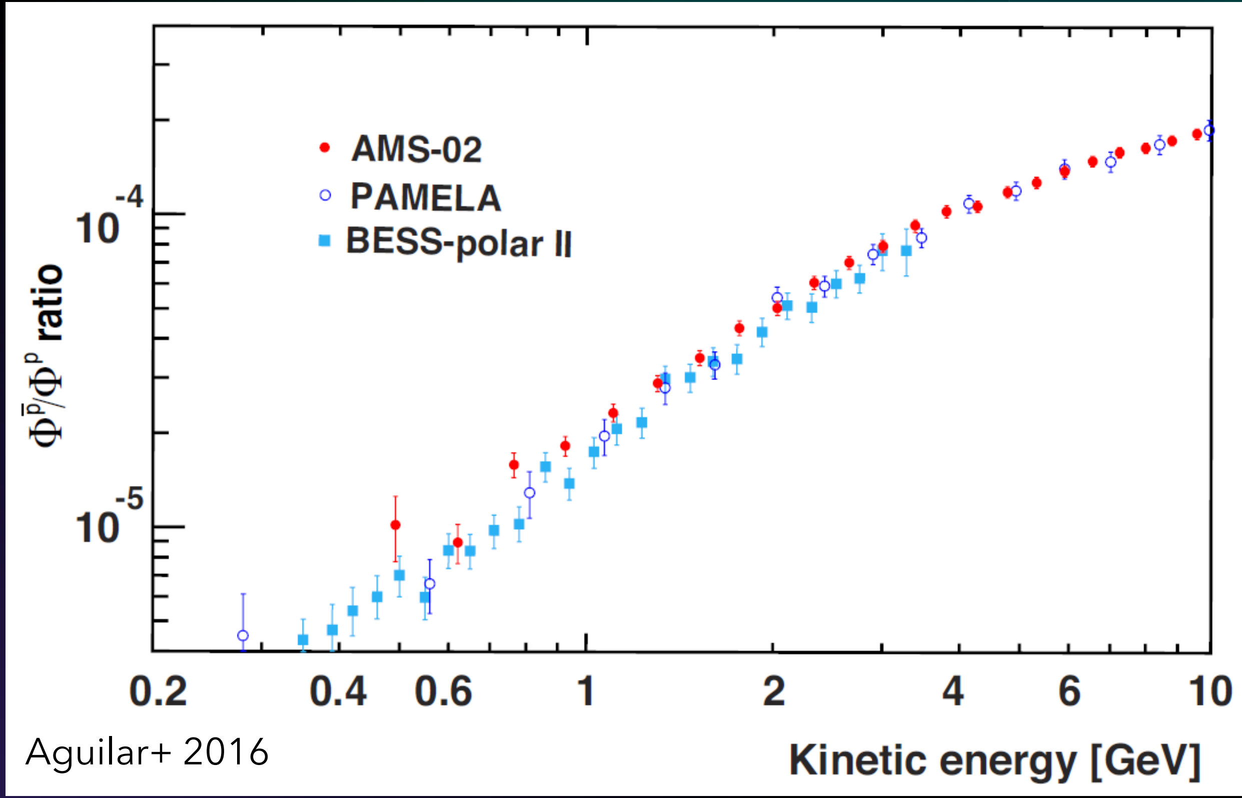
Istituto Nazionale di Fisica Nucleare
Sezione Milano Bicocca

Solar modulation of antiproton GCR for indirect search of dark matter

STEFANO DELLA TORRE

INFN SEZ. MILANO-BICOCCA

Antiproton measurements become extremely precise in the last decade.



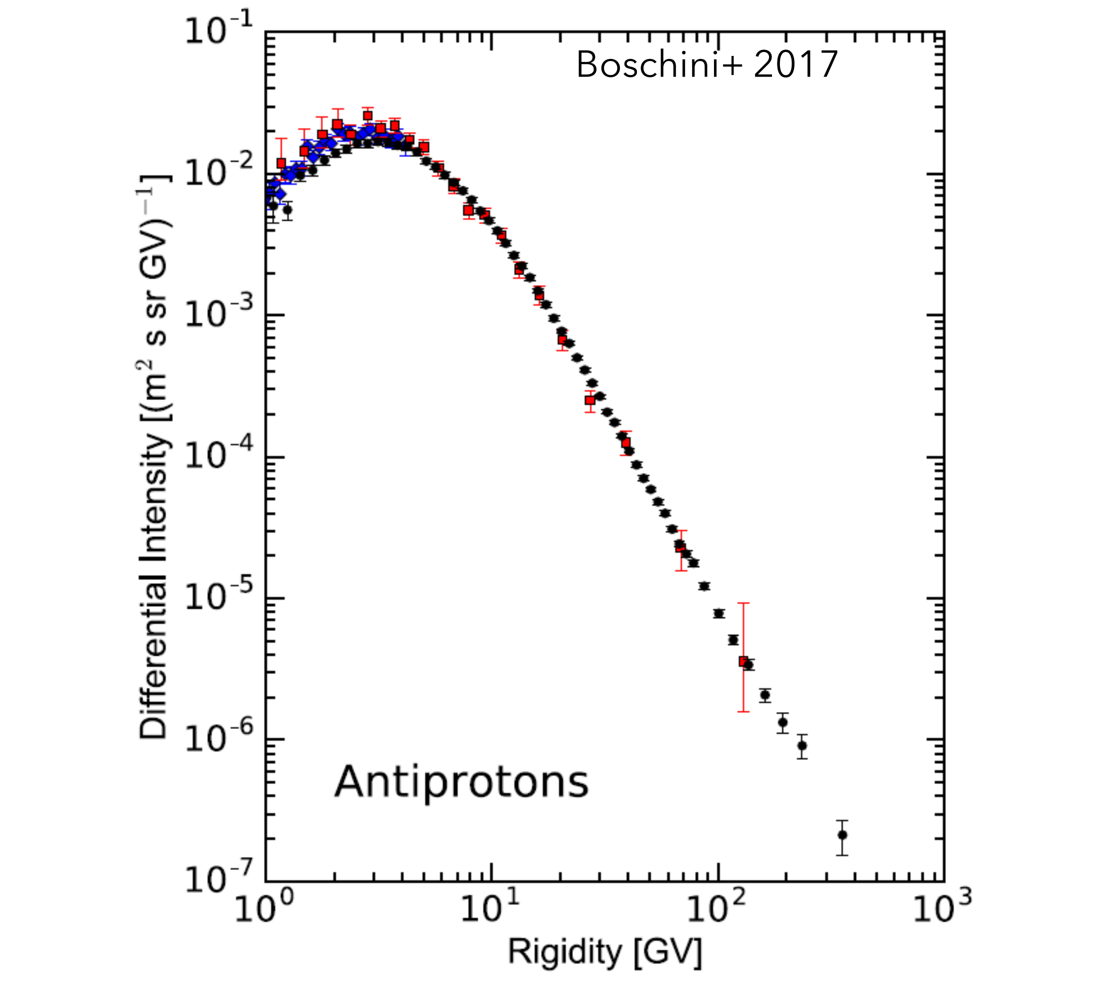
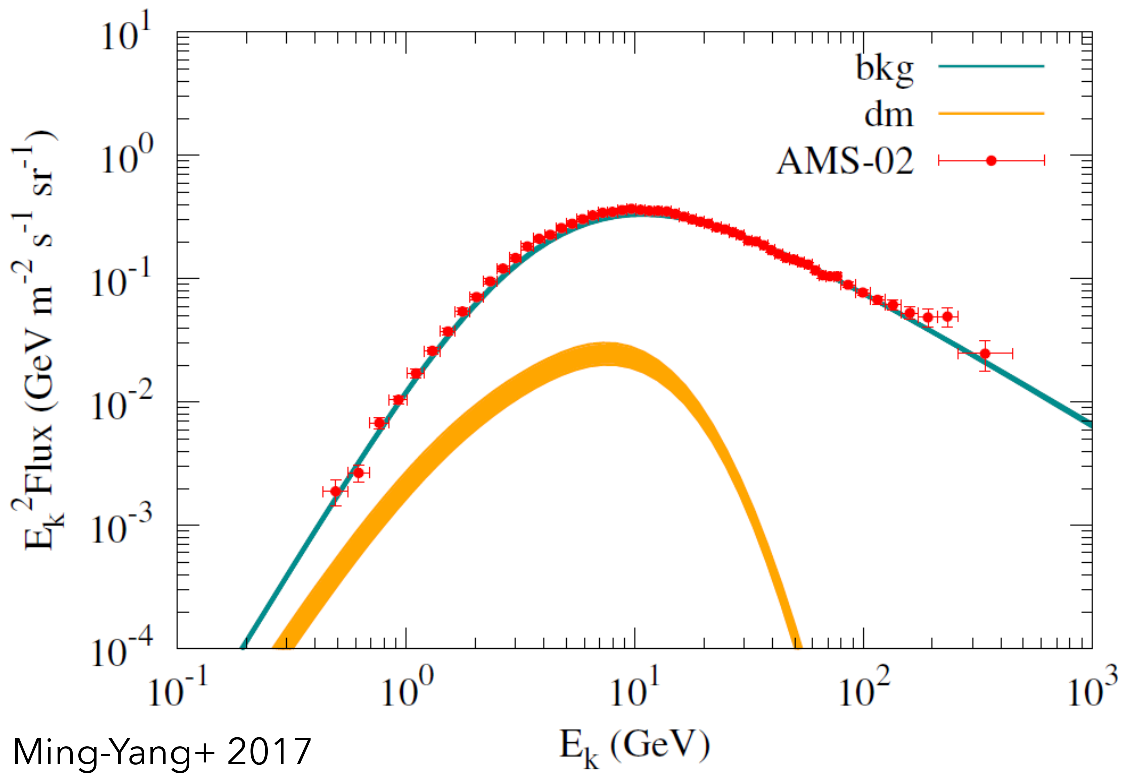


Figure 10. Antiproton differential intensity as measured by AMS-02 (black circles), BESS-Polar II (red squares), and PAMELA (blue diamonds).

Many claims of DM subproducts



Ming-Yang+ 2017

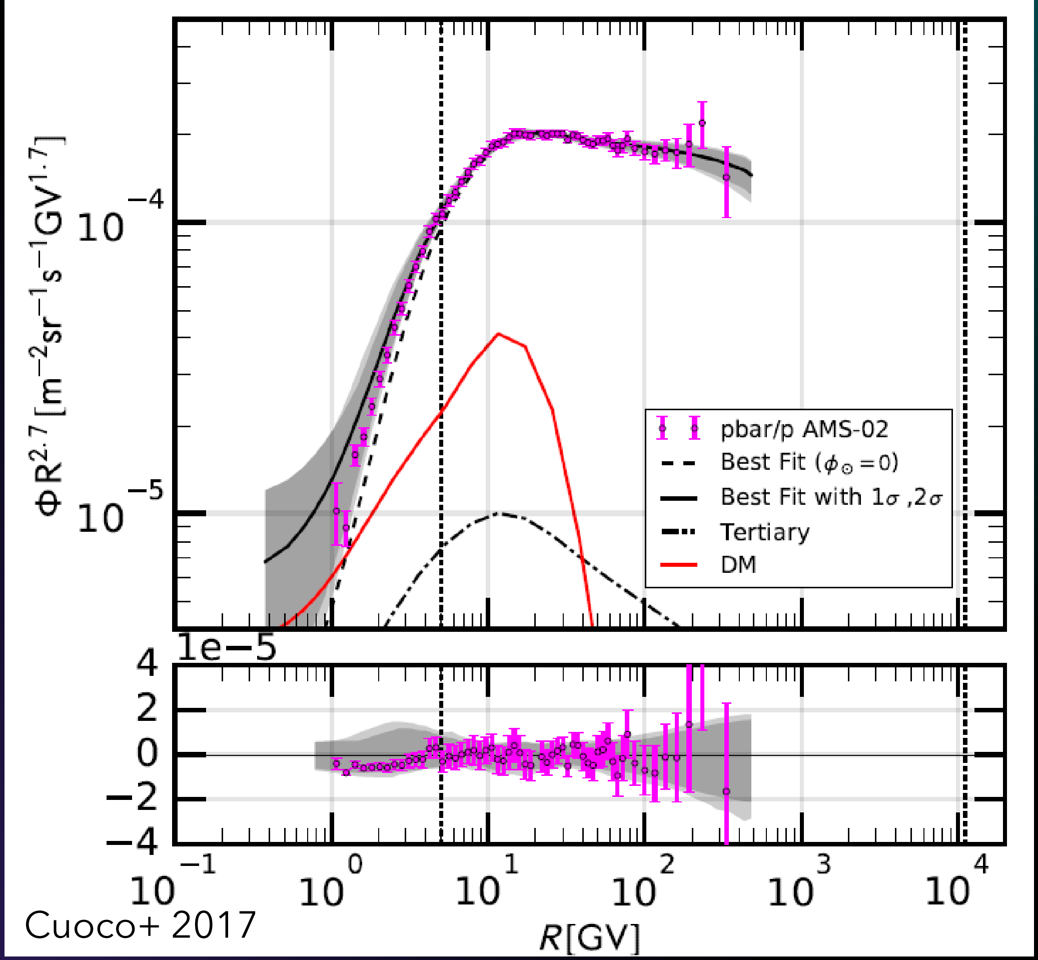
Ming-Yang+ 2017

[…] AMS-02 data favor a DM component with a mass of a few tens GeV and an annihilation cross section of the thermal production level for quark final state […]

[…] The best fit DM mass is about 40 – 60 GeV, and the annihilation cross section is about (1 – 3) × 10^{-26} cm^{3}s^{-1} for $b\bar{b}$ channel. […]

[…] The solar modulation model is adopted to be the force-field approximation […]

Many claims of DM subproducts



Cuoco+ 2017

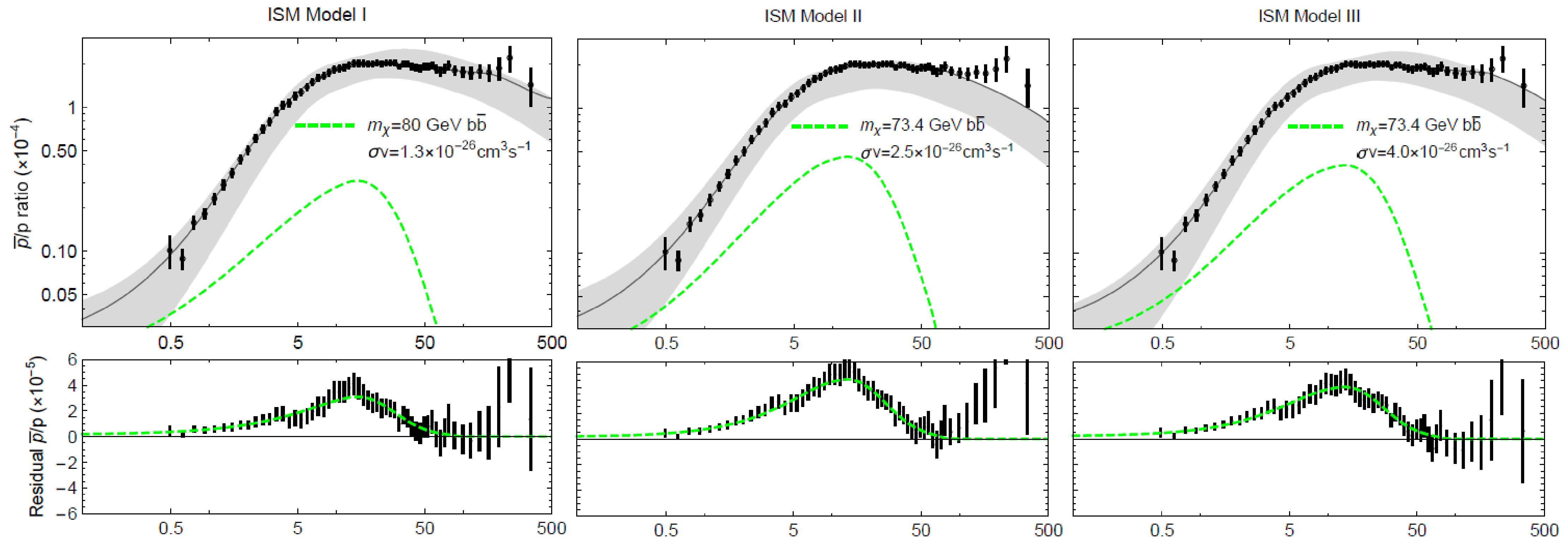
[..] We consider the rigidity range R 5 GV, for <u>which the force-field approximation</u> should describe solar modulation reliably. Adding DM annihilating into $b\bar{b}$, with $m_{DM} \approx 80$ GeV and $\langle\sigma v\rangle \approx 3\times 10^{-26}\ cm^3 s^{-1}$, results in a much better fit and provides an intriguing hint for a DM signal in the antiproton flux. [..]

[..] the DM component corresponds to a significance of $\sim 4.5\sigma$, although this does not take into account possible systematics errors. [..]

Many claims of DM subproducts

Cholis+ 2019

[…] We use the standard formula to model the impact of the modulation potential […]



Cholis+ 2019

Is there a Dark Matter signal in Low Energies $\bar{p}$-GCR?

- What is the impact of using a more complex modulation model?
- How much is reliable an Antiproton LIS?

Outline

- General consideration on antiproton production cross section
- Solar Modulation model
- Antiproton LIS

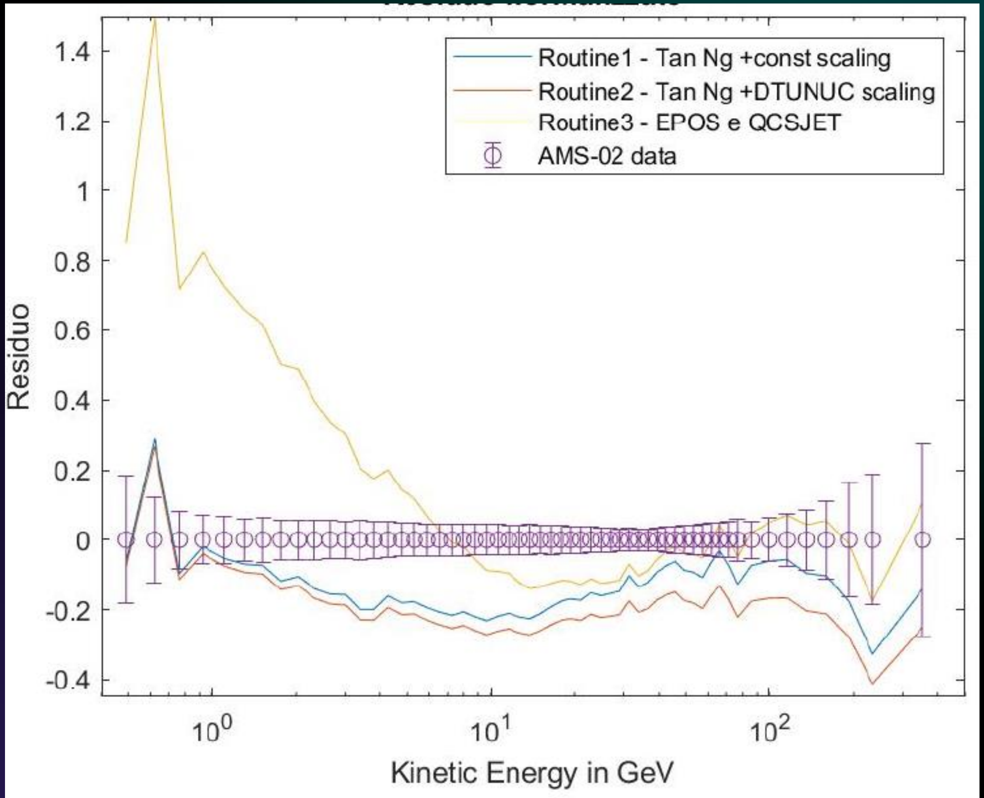
Cross Section

Nuclear uncertanties

$$p + ISM \rightarrow \bar{p} \ldots \quad \begin{cases} p + p_{ISM} \rightarrow \bar{p} \ldots \\ p + He_{ISM} \rightarrow \bar{p} \ldots \end{cases}$$

Fundamental process, poor measurements

No direct measurements

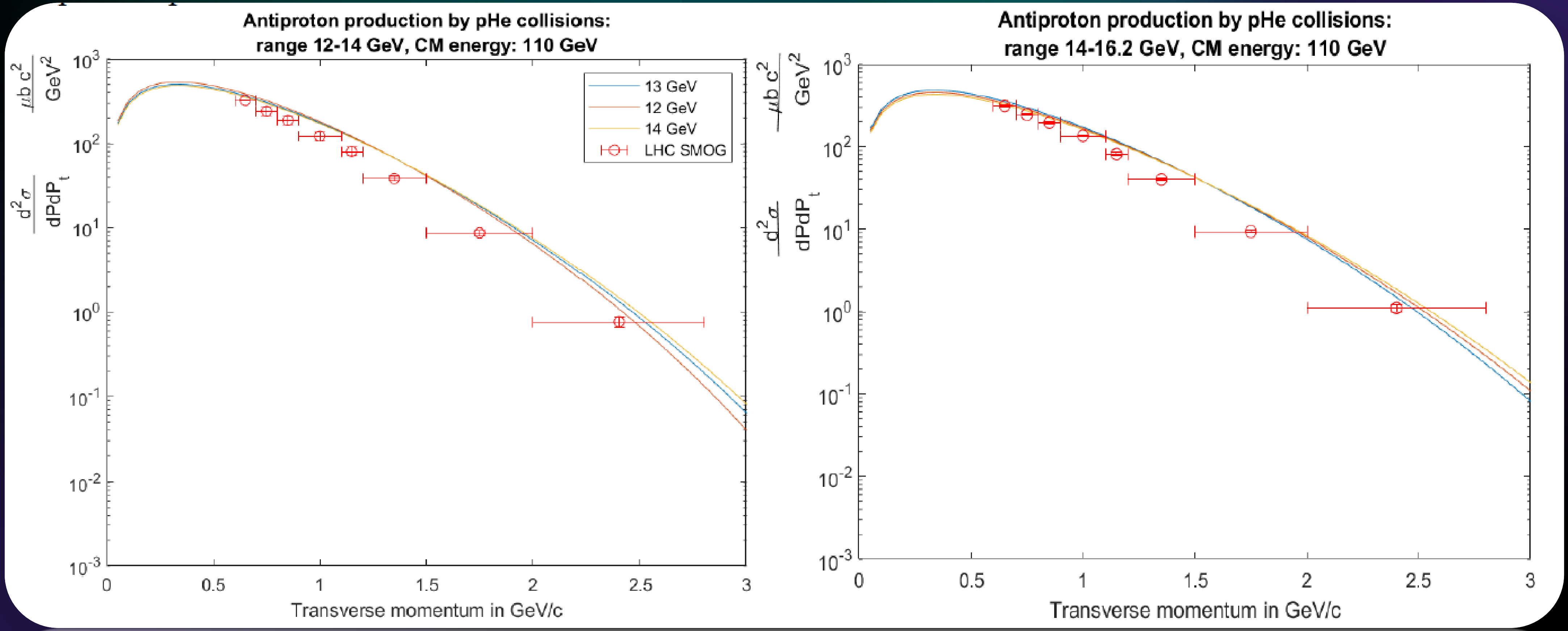


- Uncertainties in the pbar production spectrum are at least 10%.
- Below 100 GeV the uncertainties for $pp \rightarrow \bar{p}$ are about 10-20%
- Above 100 GeV extrapolations lead to errors larger than 30%
- The antineutron decay contribution is usually not included
- A significant contribution to the cosmic antiproton flux is due to reactions involving He: the relevant cross section have never been measured

N. Masi 2017

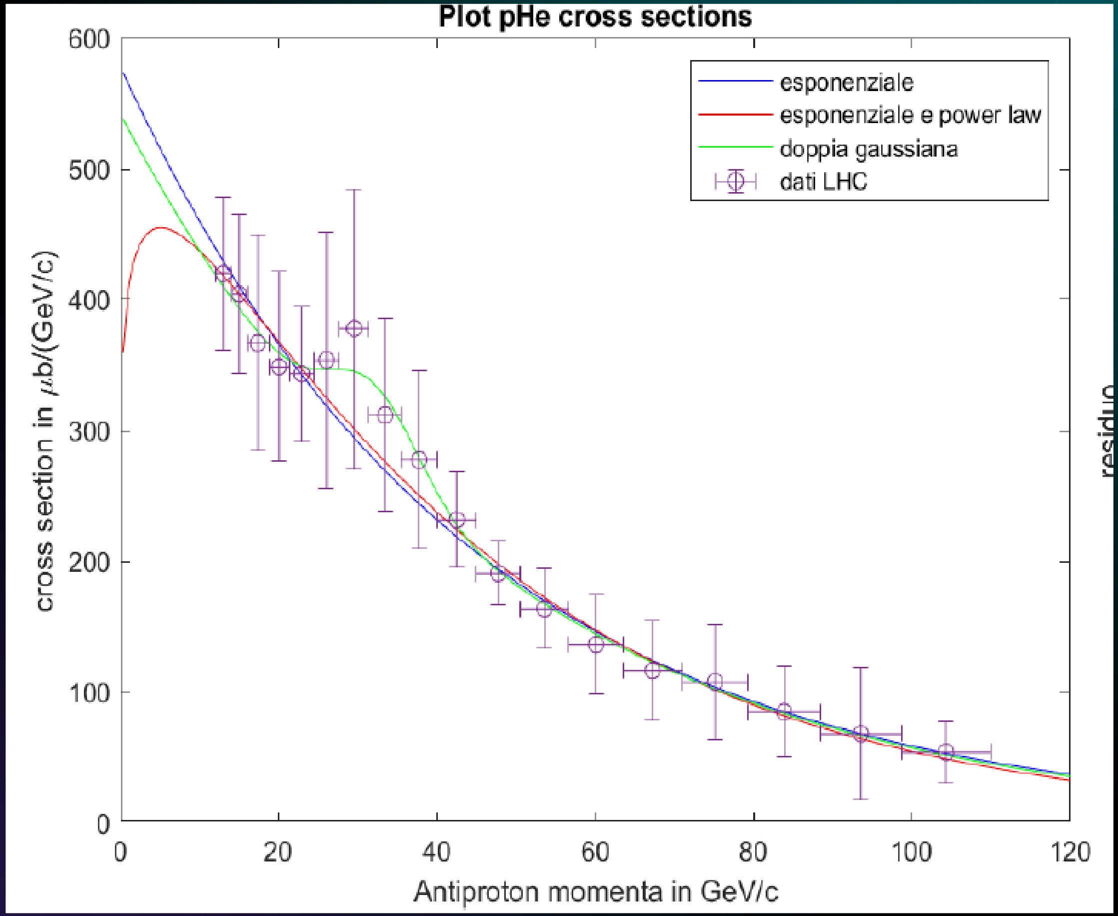
D'Angelo, Thesis 2021

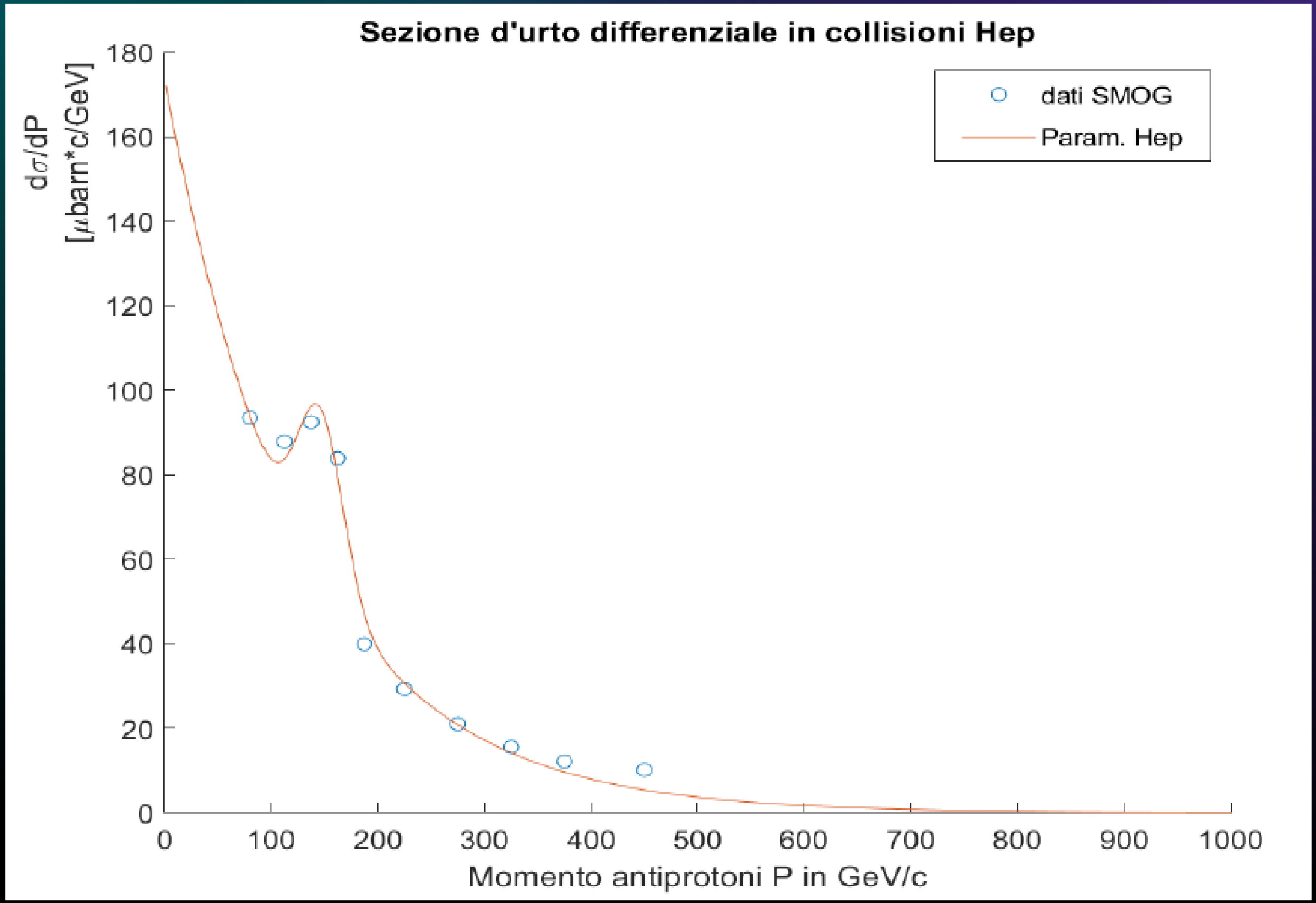
In 2017 LHCb has performed measurement of the antiproton cross section in p He collisions at 6.5 TeV using fixed He target @ SMOG. A precision of around 10% is attained



D'Angelo, Thesis 2021

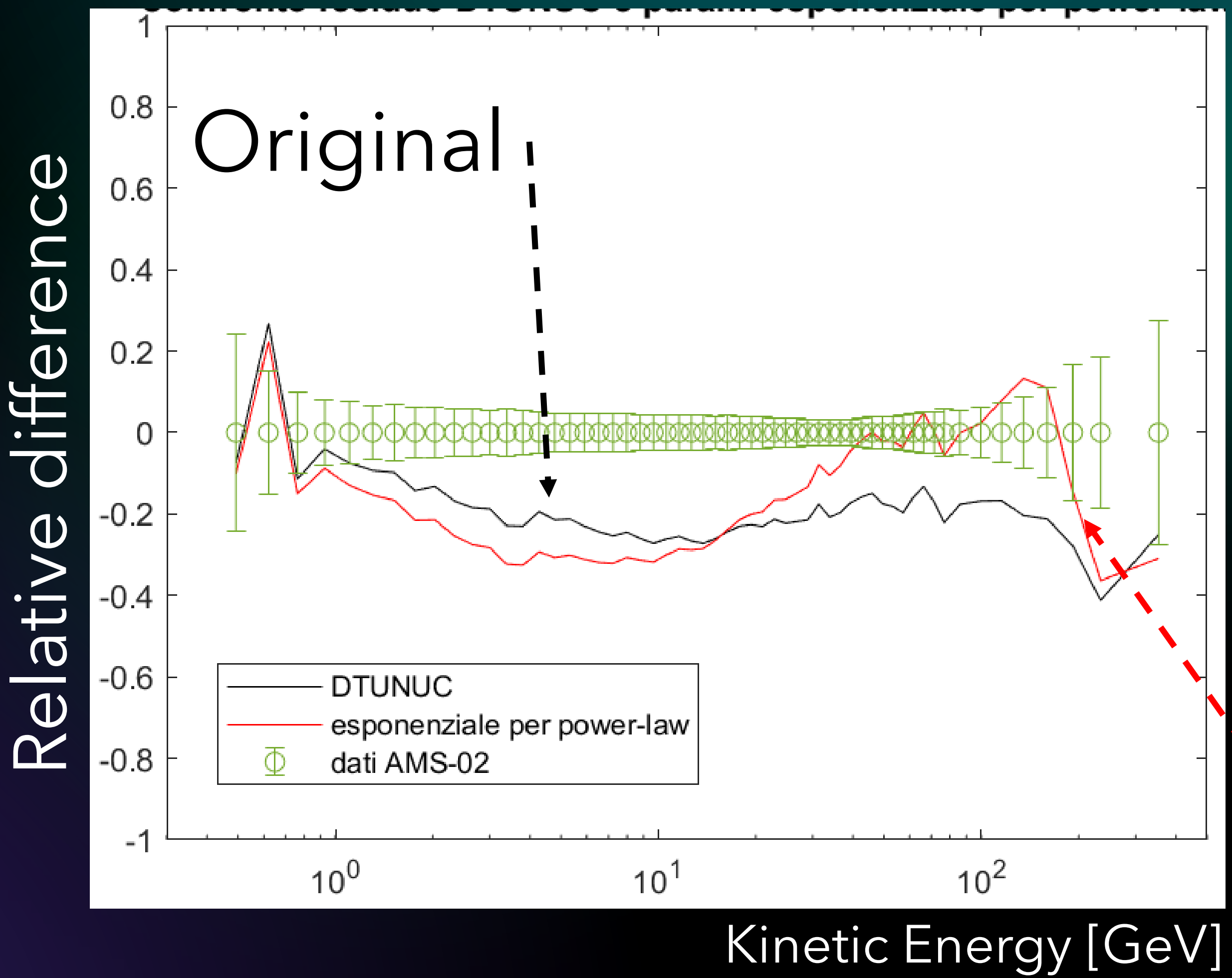
We parametrize p-He, He-p collision cross section from SMOG





D'Angelo, Thesis 2021

Using same propagation parameters in GALPROP but with different cross section



A parallel work on Cross Section is mandatory.

We cannot go much further in reducing astrophysical uncertainties, but we can certainly do it for nuclear ones

Including p-He,He-p collision data

D'Angelo, Thesis 2021

Solar Modulation

THE PASSAGE OF ENERGETIC CHARGED PARTICLES THROUGH INTERPLANETARY SPACE*

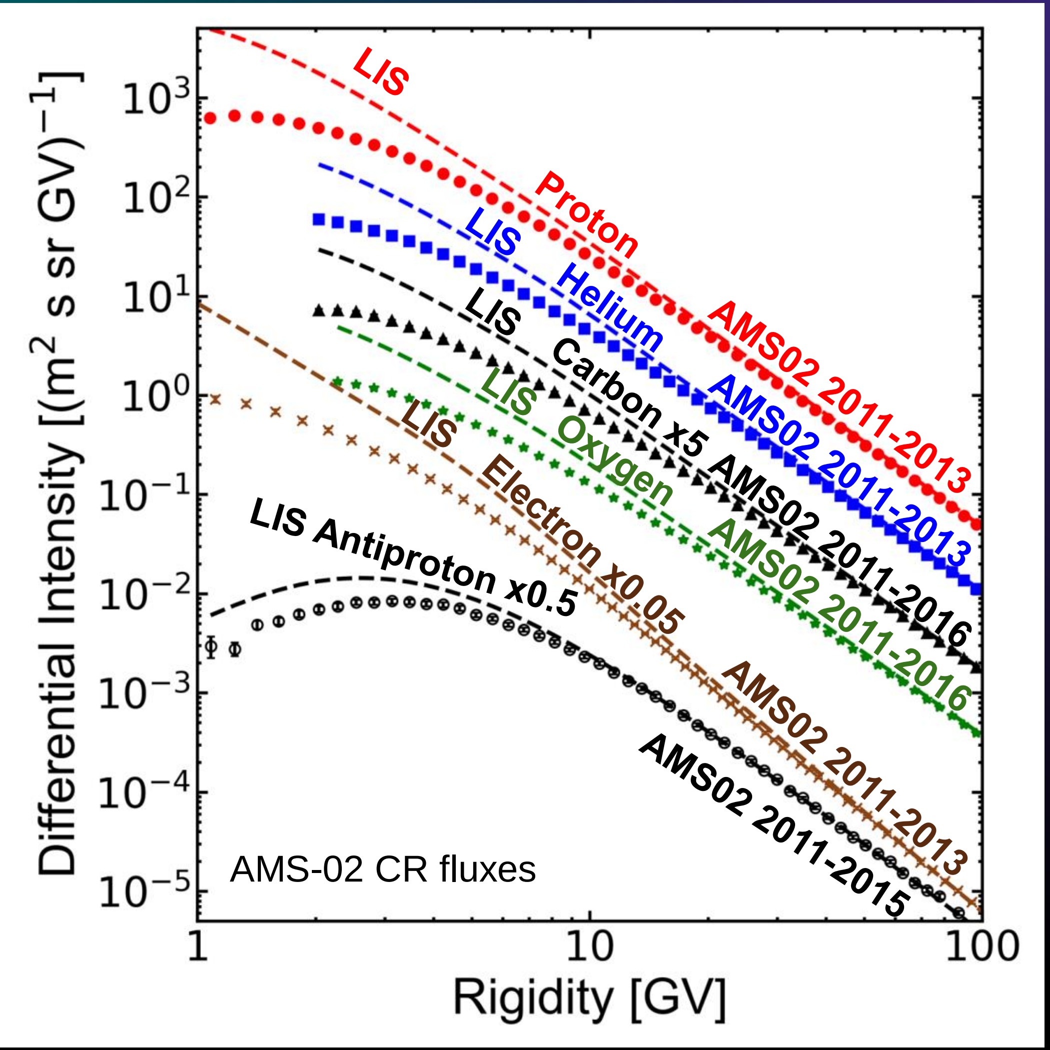
E. N. PARKER

Calculations of the motion of a charged particle in a large-scale field containing smallscale irregularities, shows that a particle is most effectively scattered by irregularities which have a scale comparable to the radius of gyration of the particles

The random walk of the cosmic ray particles is a Markhoff process, describable by a Fokker-Planck equation

*Now while the energetic particle is riding along with the fields in the wind, the magnetic fields in which the particle is moving are expanding because of the radial divergence of the wind. The energetic particle is cooled adiabatically and its kinetic energy **T** decline.*

Parker (1965)



$$\frac{\partial U}{\partial t} = \frac{\partial}{\partial x_i}\left(K^S_{ij}\frac{\partial U}{\partial x_j}\right) + \frac{1}{3}\frac{\partial V_{SW,i}}{\partial x_i}\frac{\partial}{\partial T}(\alpha_{rel} T U) - \frac{\partial}{\partial x_i}[(V_{SW,i} + v_{d,i})U]$$

Solar Modulation

Parker Equation

$$\frac{\partial U}{\partial t} = -\nabla \cdot (U\vec{V}) + \nabla \cdot [\tilde{K} \cdot \nabla U] + \frac{(\nabla \cdot \vec{V})}{3} \frac{\partial}{\partial T} (\alpha_{\rm rel} T U)$$

Use Kinetic Energy

$$\alpha_{\rm rel} = \frac{T + 2m_r c^2}{T + m_r c^2}$$

U → Cosmic Rays number density per unit interval of kinetic energy

$$\frac{\partial f}{\partial t} = -\nabla \cdot (f\vec{V}) + \nabla \cdot [\tilde{K} \cdot \nabla f] + \frac{(\nabla \cdot \vec{V})}{3p^2} \frac{\partial}{\partial p} (p^3 f)$$

Use particle momentum

f → Omnidirectional distribution function

Differential Intensity is measured quantity $J = \frac{vU}{4\pi} = p^2 f$

Diffusion | Convection | Drift | Energetic Loss

Solar Modulation

Computational Complexity →

Analytical

- Gleeson & Axford 1968
- Gieseler et al 2017
- Corti et al 2019
- …

Semi-Analytical

- Kuhlen & Mertsh 2019

Numerical Codes

- Aslam et al 2018
- Engelbrecht and Burger (2013)
- Boschini et al 2019
- Pei et al 2010
- Strauss et al., 2013
- Vos and Potgieter, 2016
- …

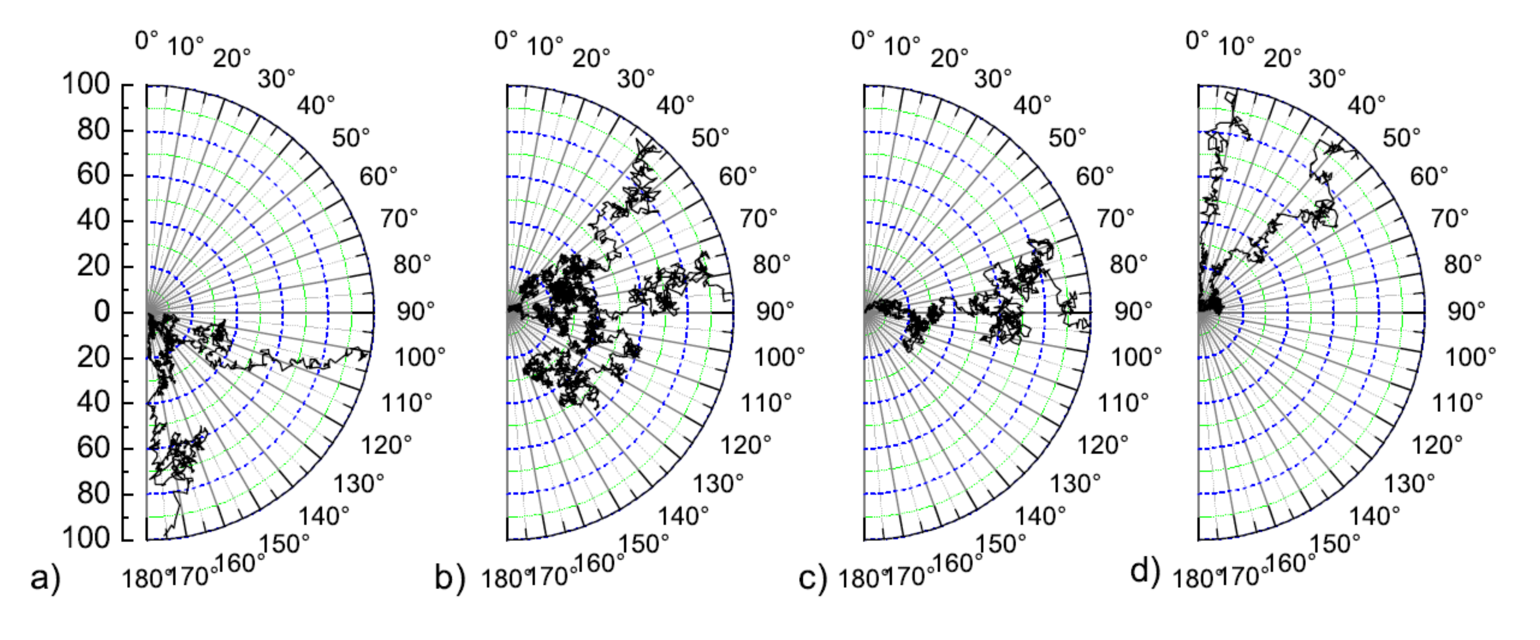
Now GPU technology, in principle, allows to scaledown computational time
Vogt et al 2020; Solanik et al 2021

Monte-Carlo approach

Backward-in-time approach. It evolves a probability density in a phase-space

See:
Bobik et al 2016
Strauss&Effemberger SSR 2017

www.helmod.org



$$\partial_t F = -\sum_i \partial_i [A_i(\mathbf{x}, t) F] + \frac{1}{2} \sum_{i,j} \partial_i \partial_j \{[\tilde{\mathbf{D}}(\mathbf{x}, t)]_{ij} F\}$$

Deterministic **Stochastic**

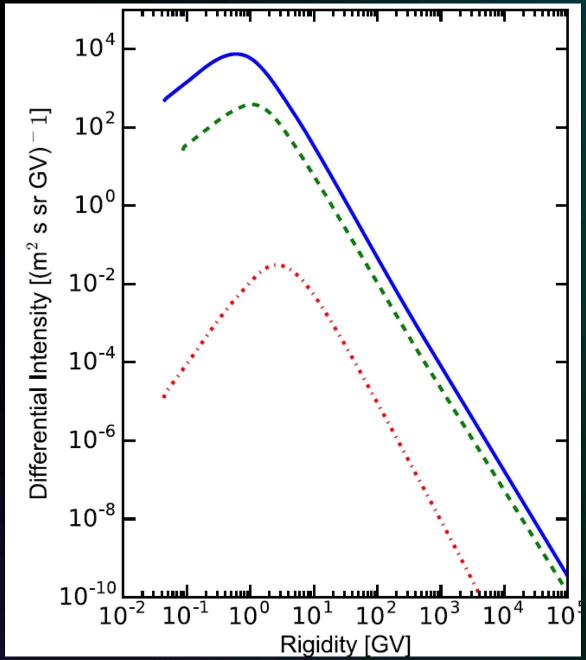
$$dx_i(t) = A_{F,i} dt + B_{F,i,j} dW_j(t)$$

Convection+ Drift

Diffusion

Monte-Carlo approach

Backward-in-time approach. It evolves a probability density in a phase-space



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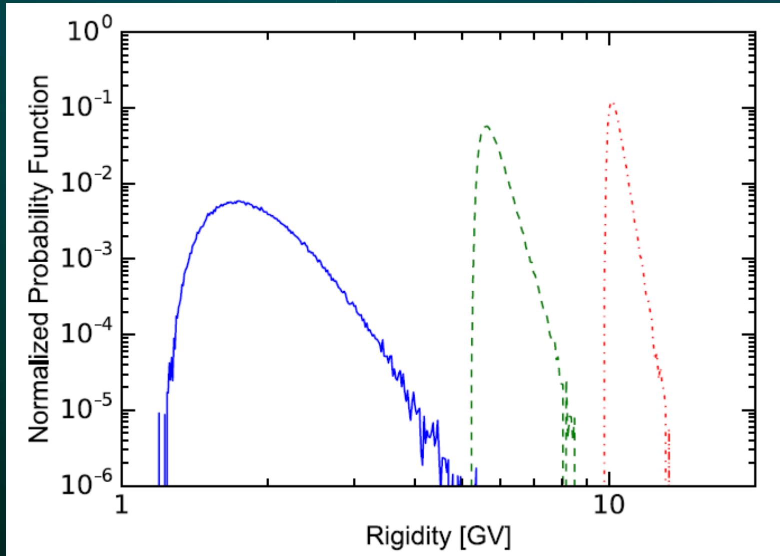

Figure 2. Computed normalized probability function $G(R_0|R)$ for $R_0 = 1.1$, 5.1, and 9.7 GV (left to right) evaluated for AMS-02 proton binning during the period 2011–2014; see the text for details.

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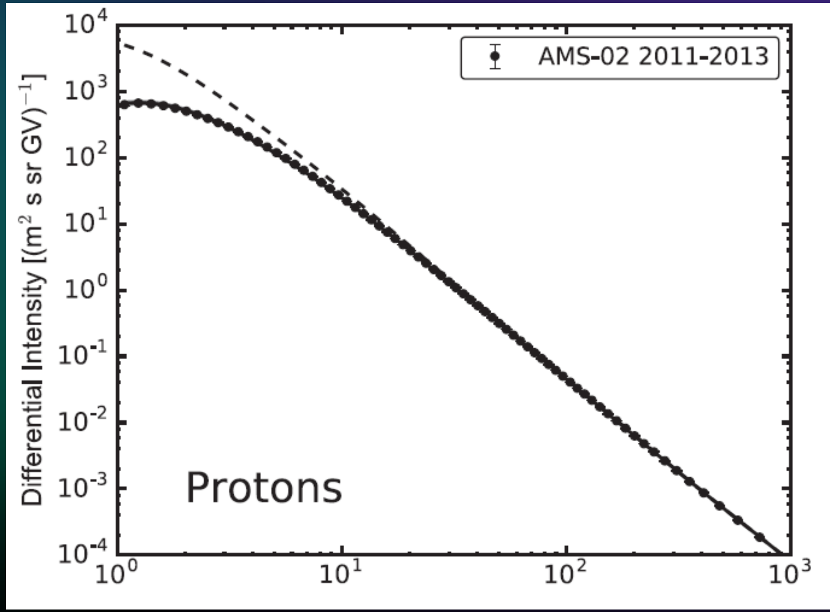


LISs

Monte Carlo Solutions

Modulated Spectra

Testing Multiple LIS do not require Re-Run Simulations

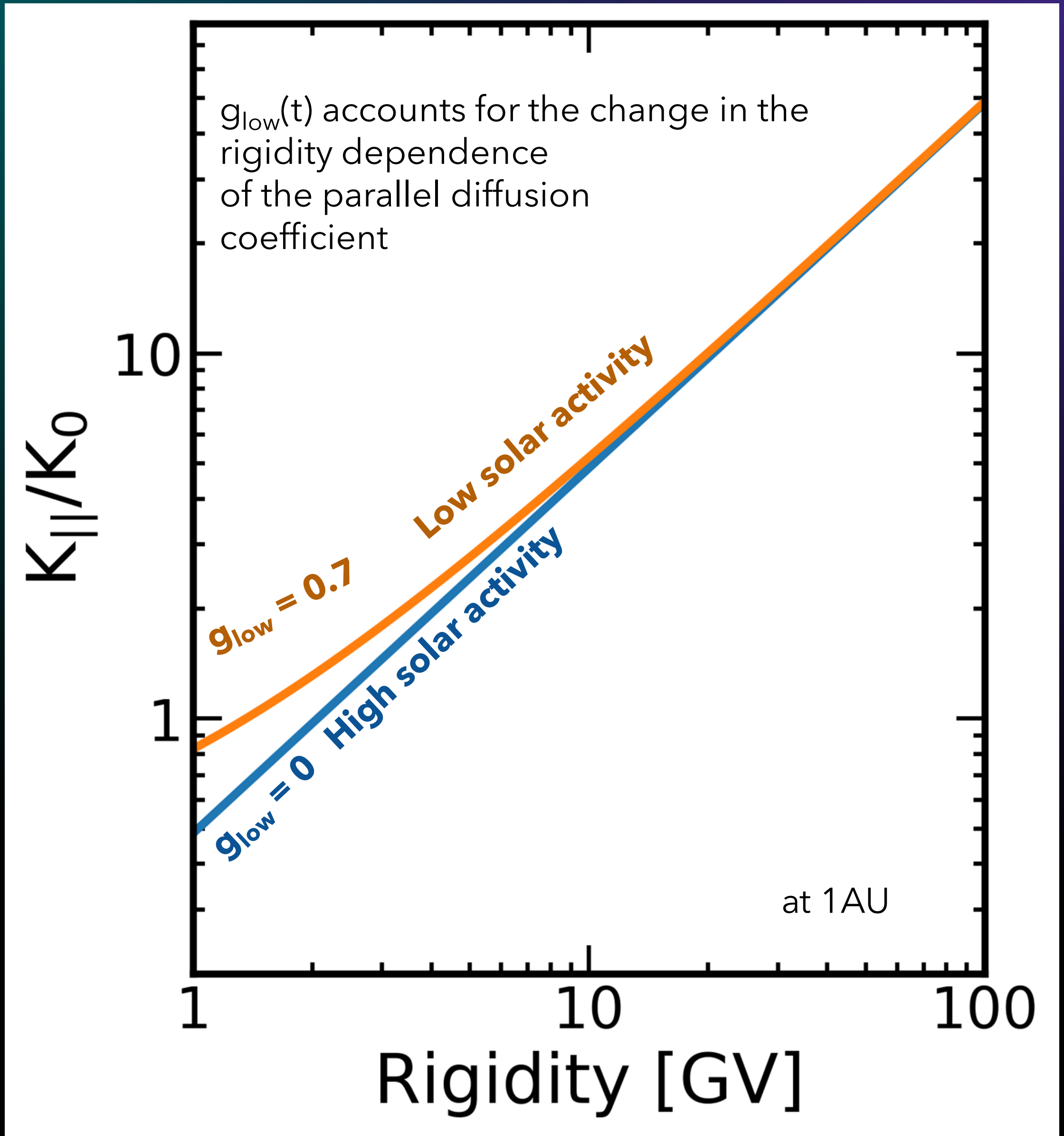
The diffusion tensor

$$K_{ij} = \begin{bmatrix} K_{\|} & 0 & 0 \\ 0 & K_{\perp,2} & K_A \\ 0 & -K_A & K_{\perp,3} \end{bmatrix}$$

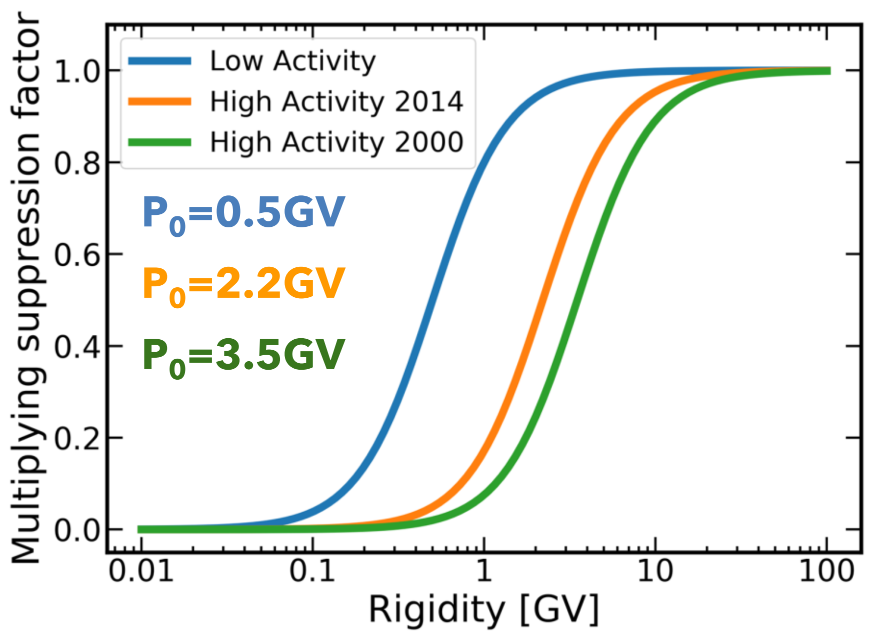
$$\frac{K_{\|}}{K_0} = \frac{\beta}{3}\left[\frac{P}{1\,GV} + g_{low}(t)\right]\left(1 + \frac{r}{1\,AU}\right)$$

$$K_{\perp,i}/K_{\|} = \rho_i$$

see
Bobik et al. ApJ 745:132 (2012)
Bobik et al. AdsAst,ID 793072 (2013)
Boschini et al. Adv. S. Res. (2017)



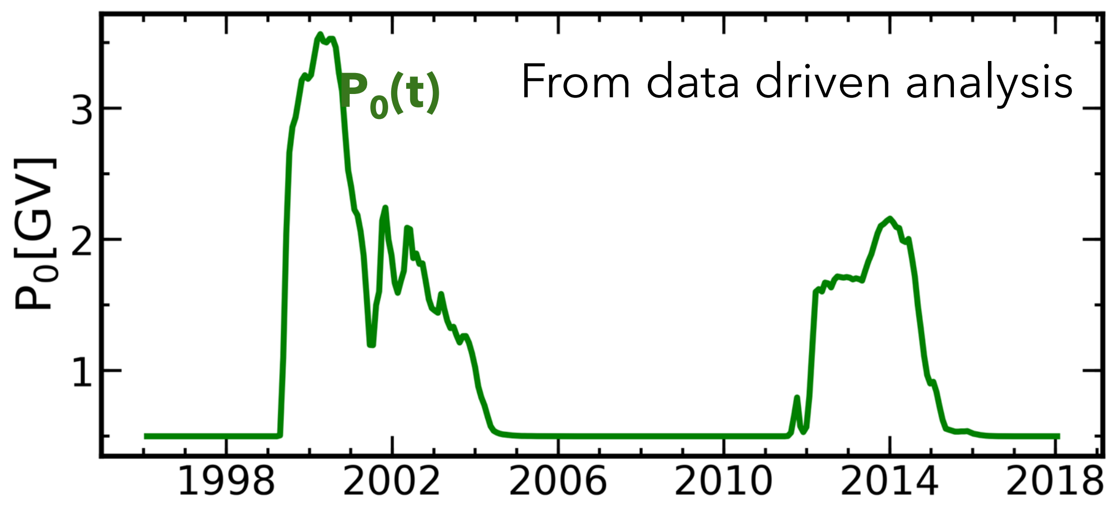
Magnetic Drift



$$K_A = \frac{\beta P}{3 B_0} \frac{P^2}{P_0^2(t) + P^2}$$

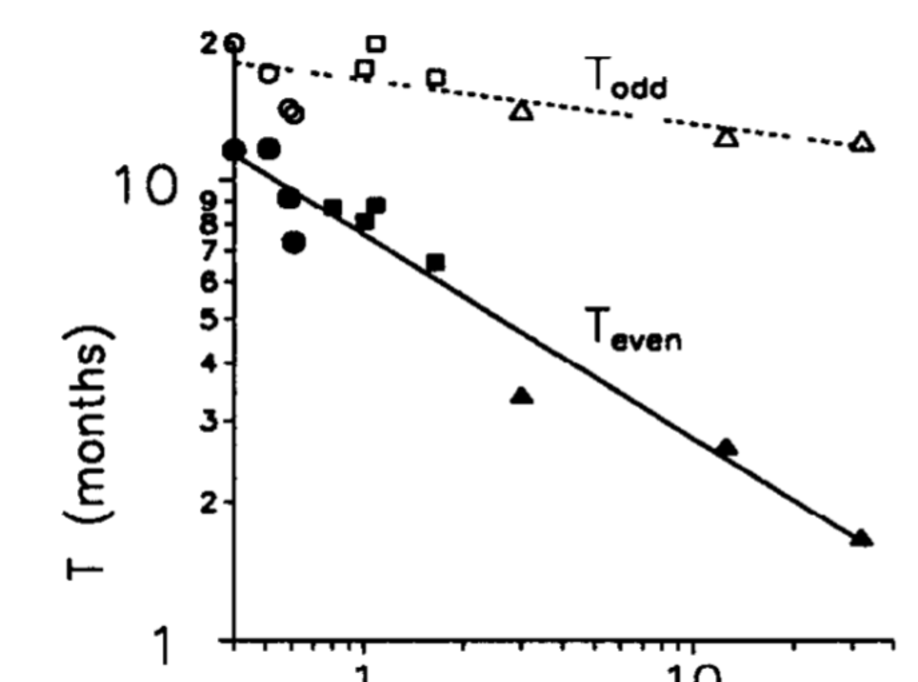
B_0 magnetic field magnitude at Earth

Bieber and Matthaeus (1997)
Burger et al. (2000)
Minnie et al. (2007)
...



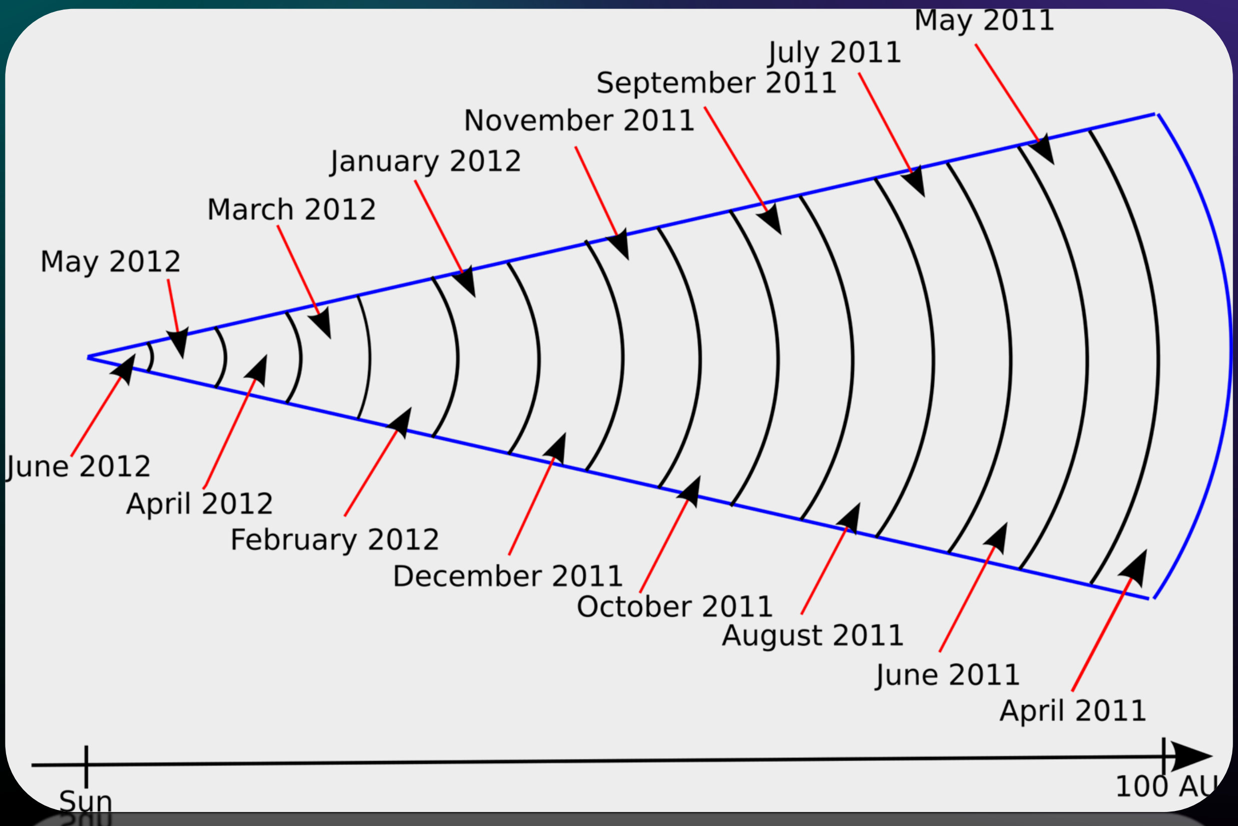
Not same conditions in all Heliosphere

The presence of a time lag between Cosmic Rays intesisty and Solar parameters are known since, e.g.,
Mavromichalaki & Petropoulos 1984
Nymmik 2000



Nymmik 2000

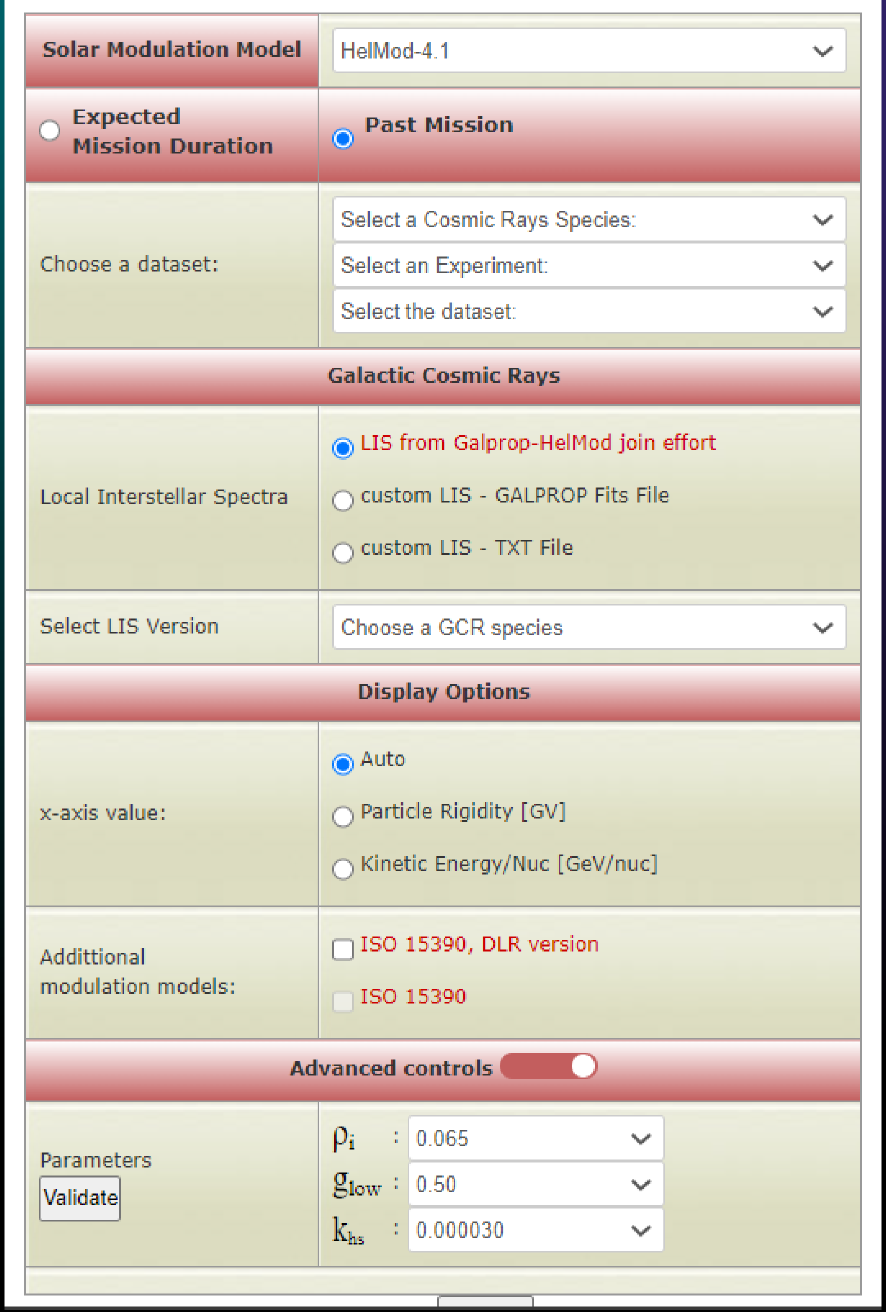
Solar perturbations moves along with Solar wind, thus it took a finite time to pass through the heliosphere



HelMod divide the Heliosphere in 15 regions, each one equivalent to the average of solar activity in the periods before the experiment

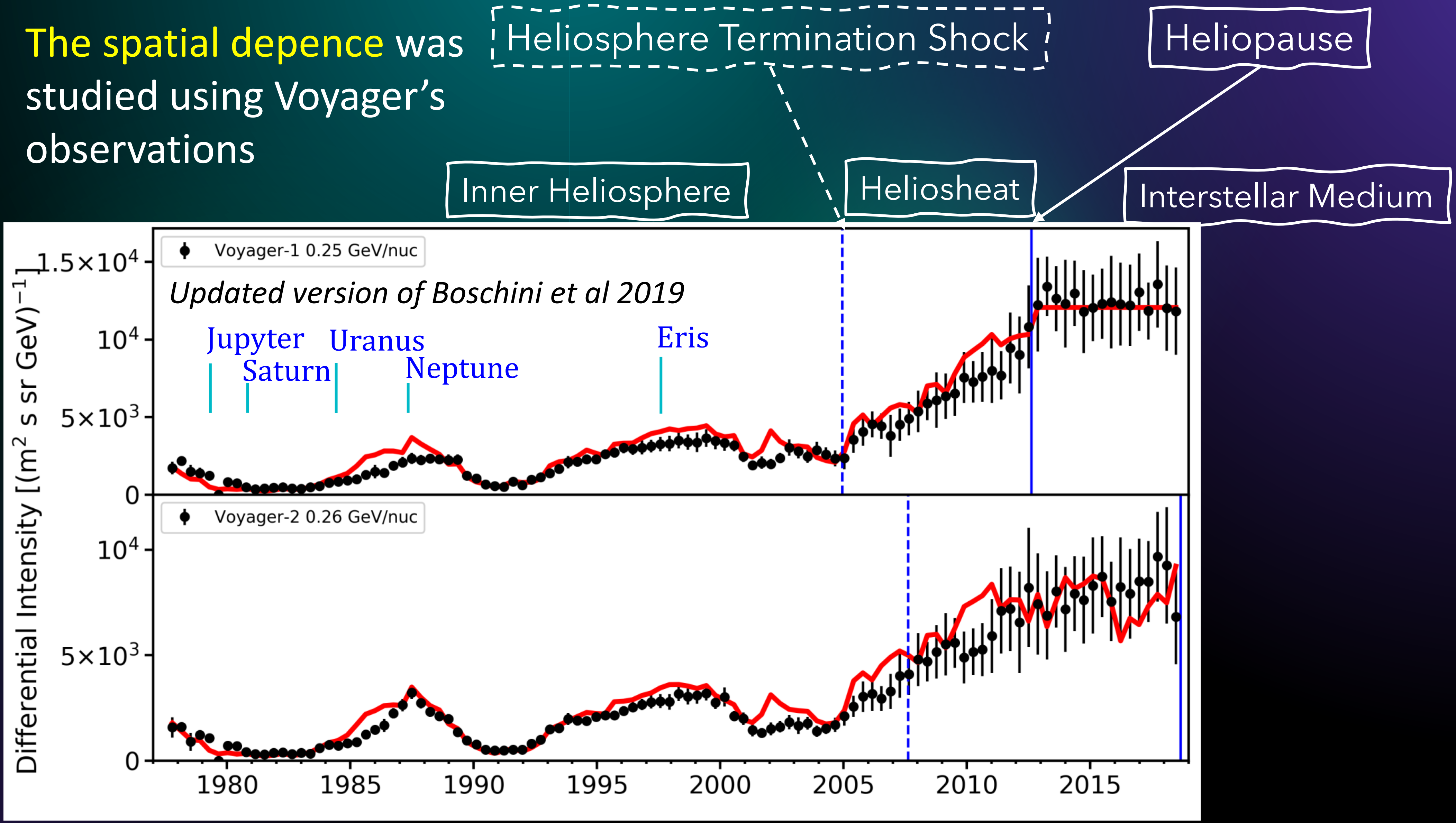
HelMod-4

We provide a web (and offline) calculator that allows a for fast calculation of solar modulation for selected parameters

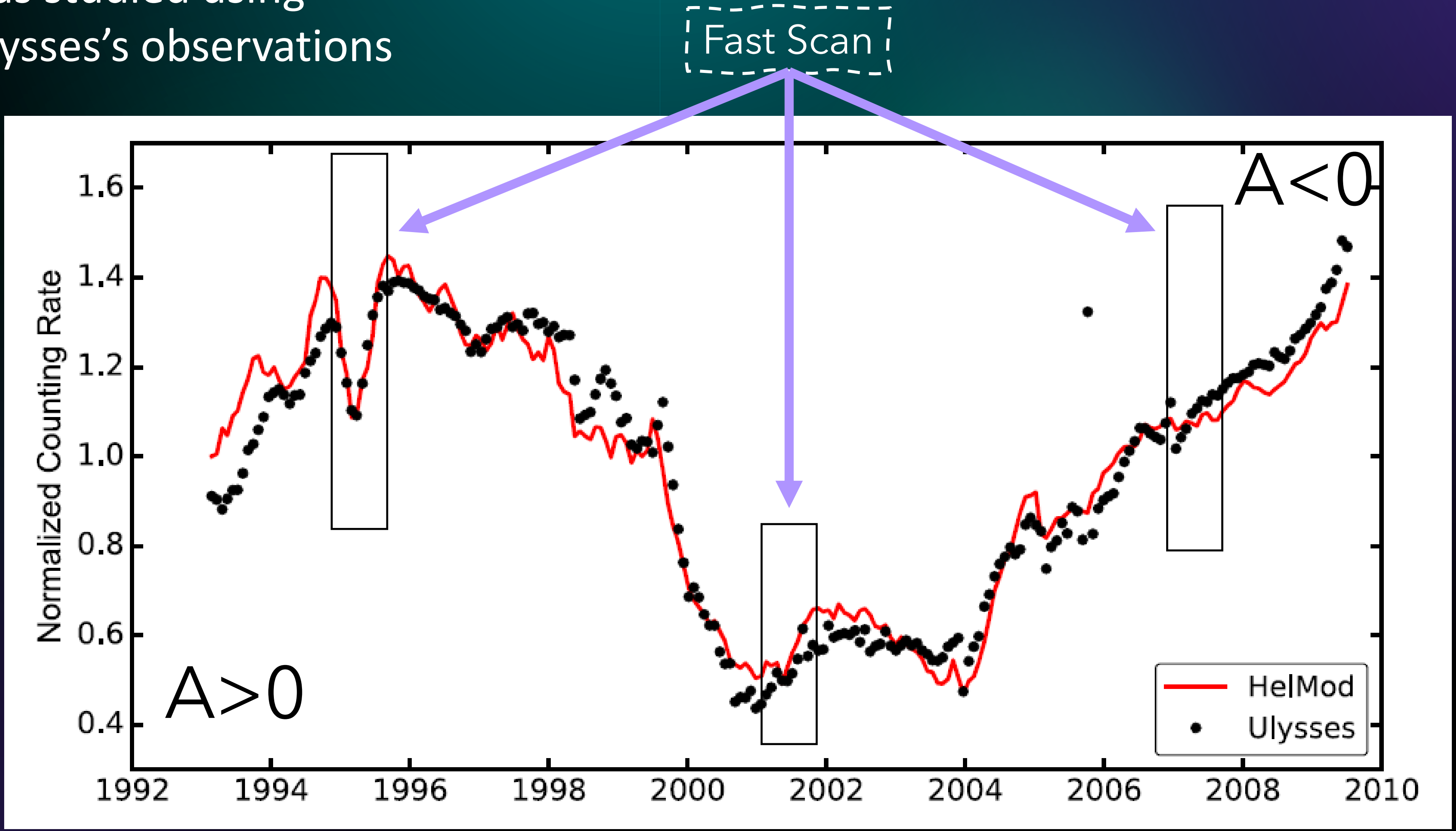


www.helmod.org

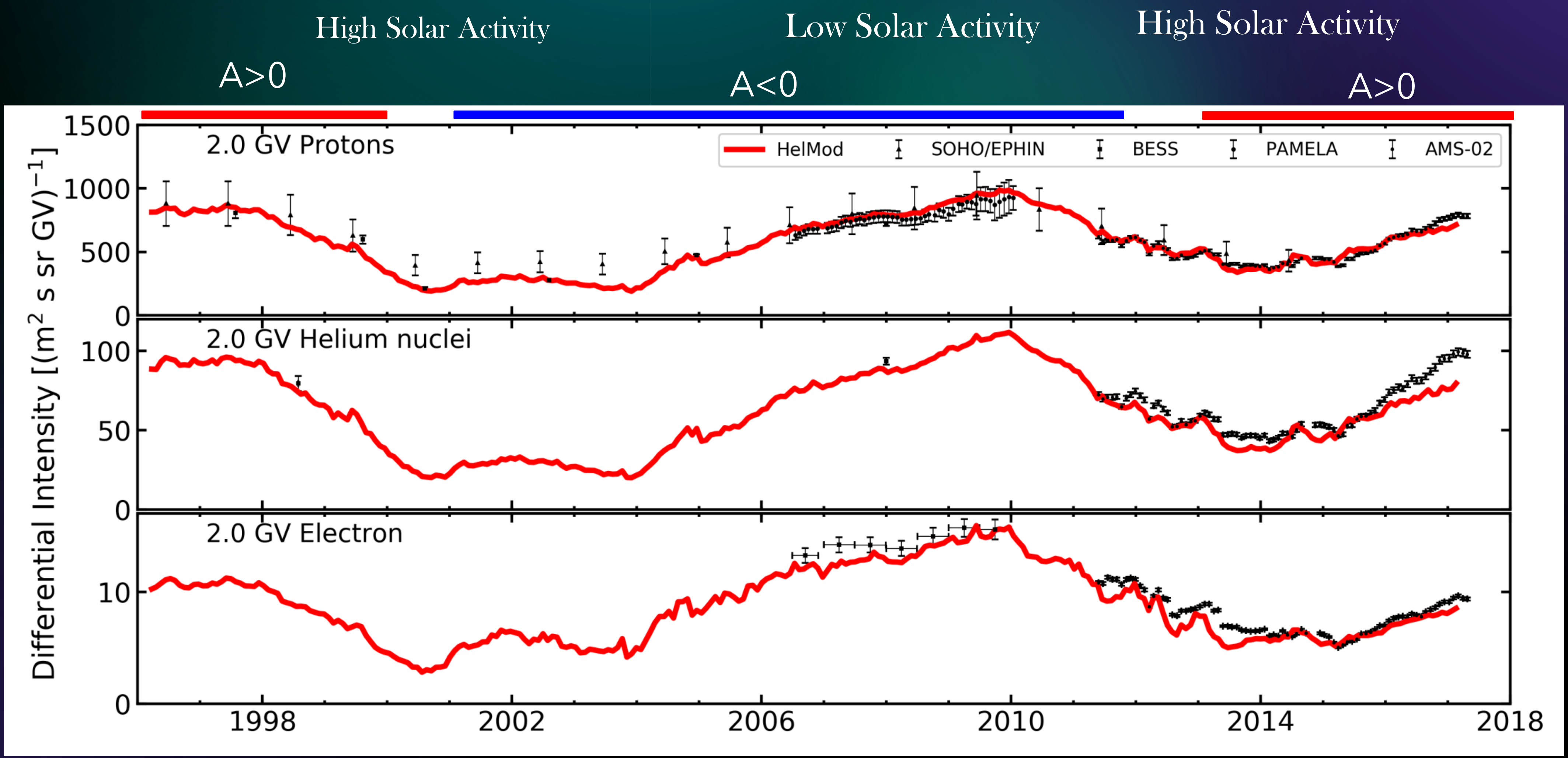
The spatial depence was studied using Voyager's observations



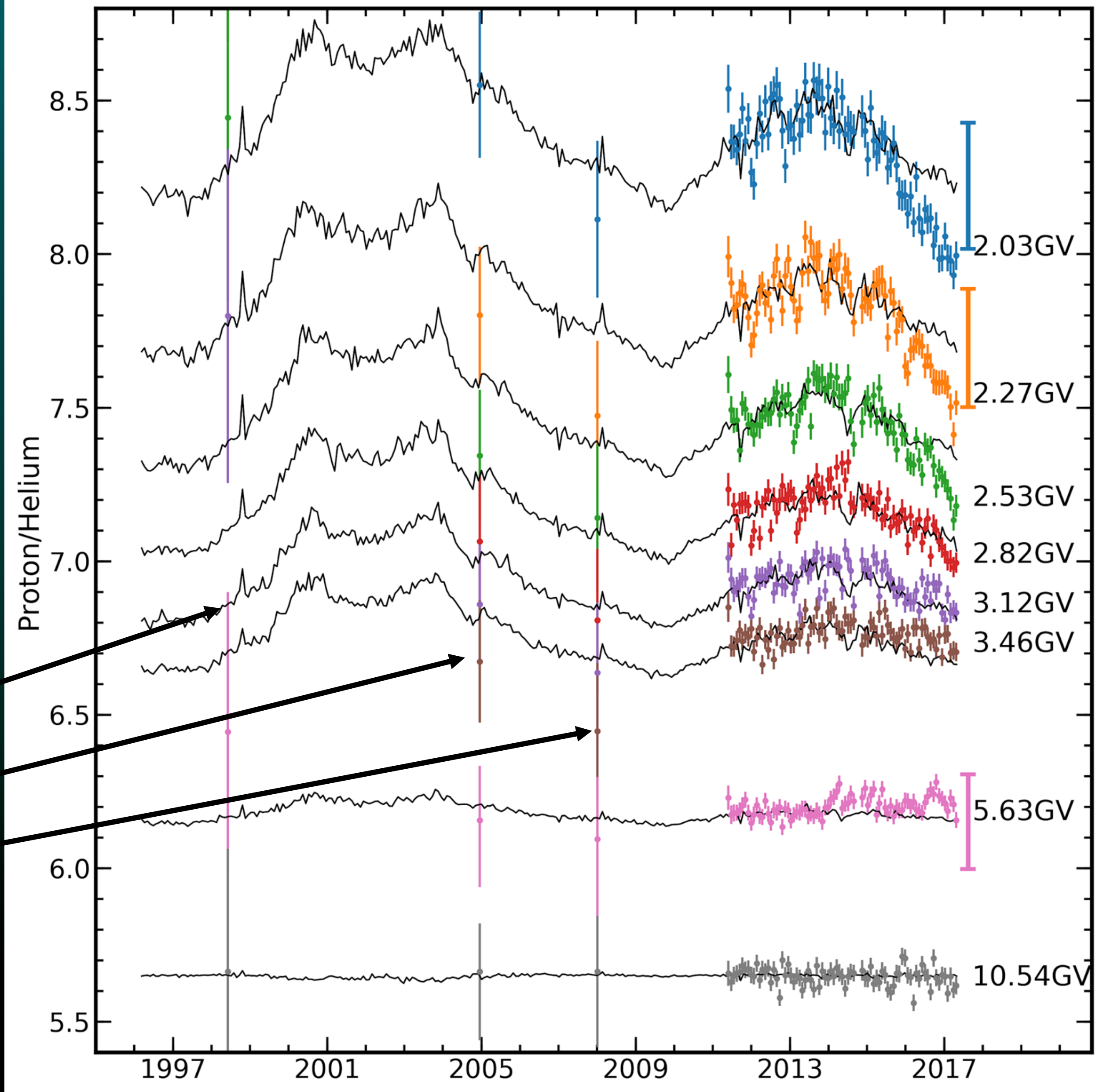
The Latitudinal Depence was studied using Ulysses's observations



The Model can reproduce the long-term variation of cosmic rays along the full 22 years solar cycle.



p/He



AMS-01

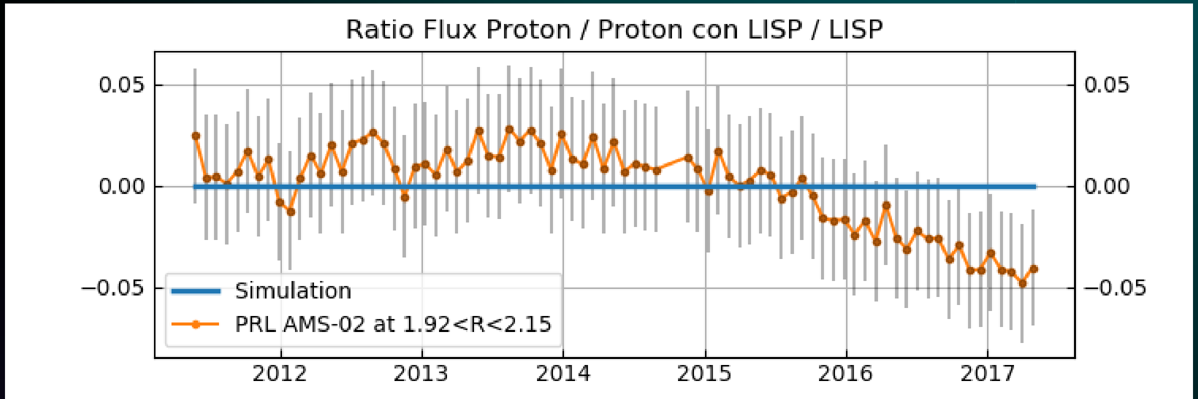
BESS Polar I

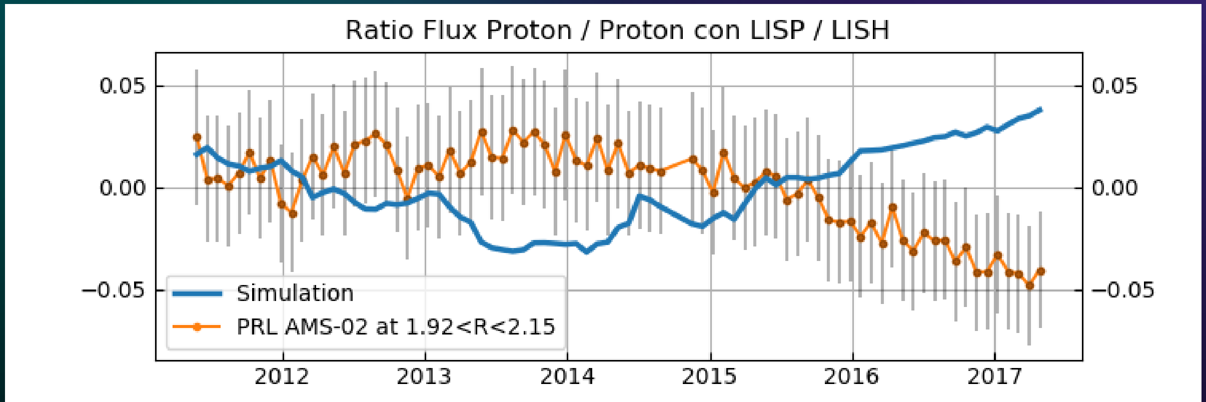
BESS Polar II

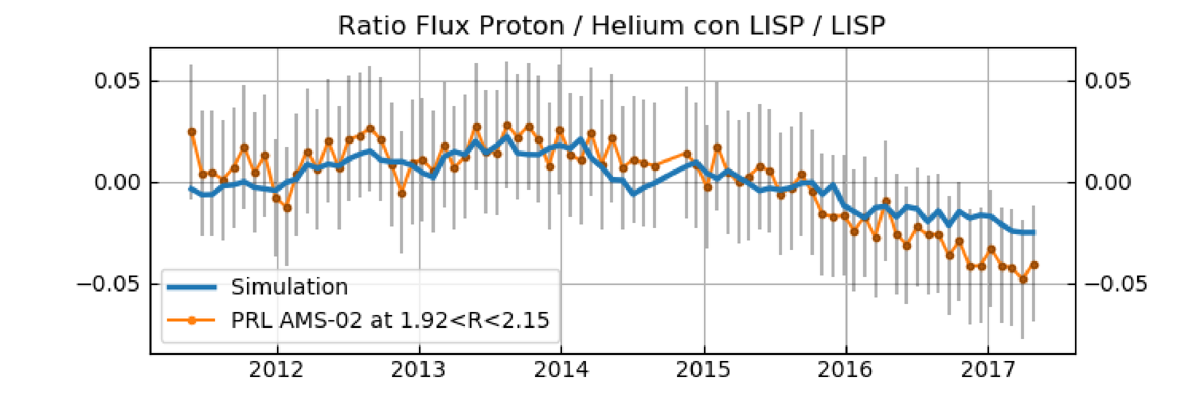
What can cause this time variation?

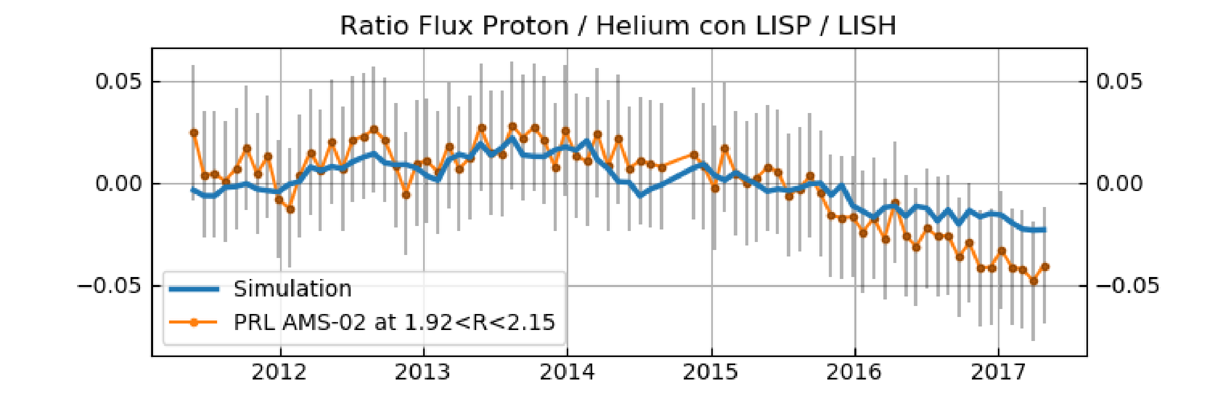
Proton lis → Helium LIS

Proton → Helium





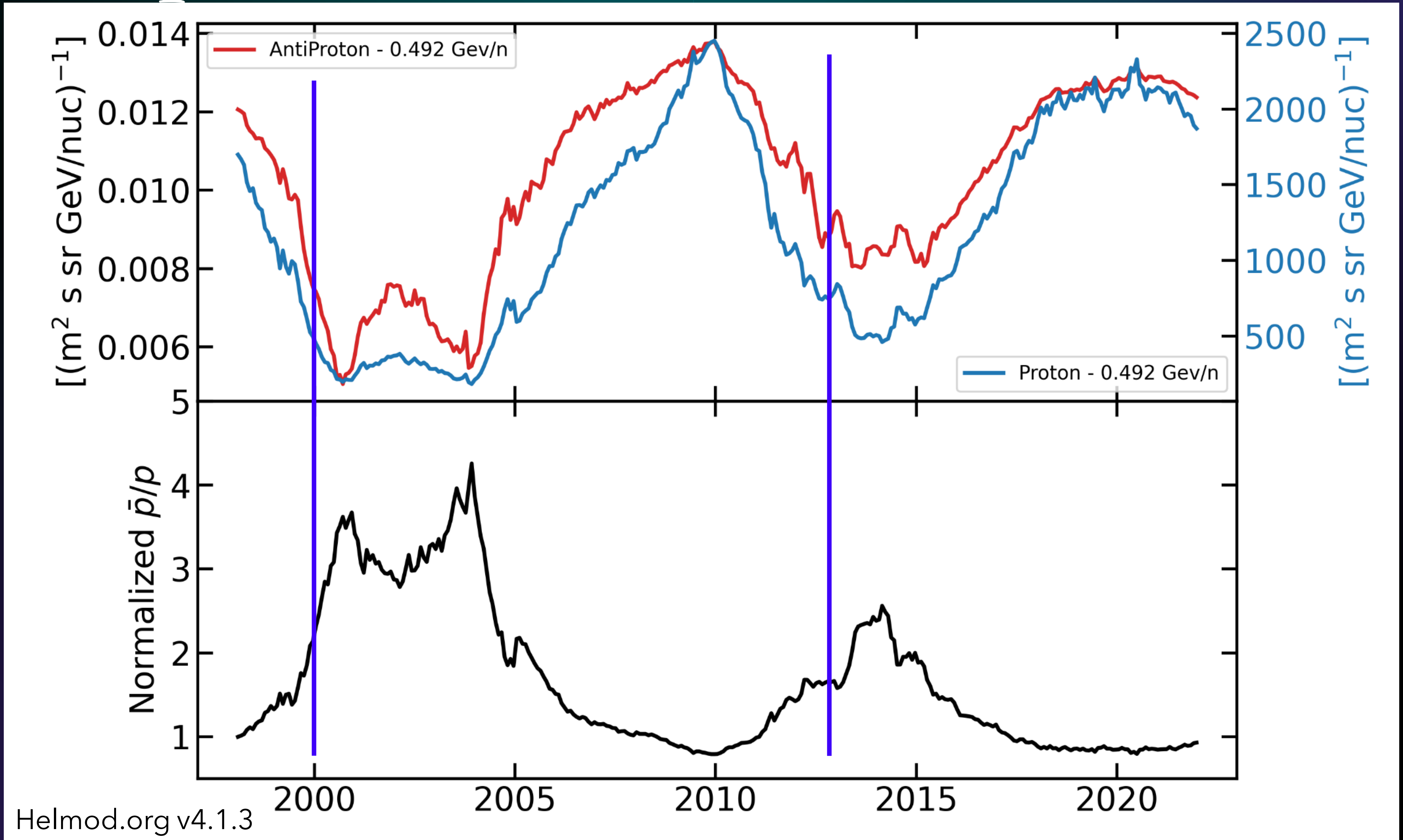




Colella, Thesis 2019

On p/He the main contribution arise from different Z, but a contribution from LIS spectra cannot be negletcted

Antiproton time variation



LIS determination

HelMod Monte Carlo Code and LIS:
GALPROP-HelMod framework

HelMod is a Monte Carlo Code that evaluate modulated spectrum in the heliosphere for:

- *Protons*
- *Helium Nuclei*
- *Ions (Carbon, Oxygen,...,Nickel)*
- *Antiprotons*
- *Electrons*

The Local Interstellar Spectrum (LIS) were estimated using an iterative procedure involving GALPROP and HelMod

Propagation in the Galaxy
galprop.stanford.edu

GALPROP

Describes all relevant process in the galaxy. It use as input:

- Injection spectrum
- Gas distribution
- Particle interaction cross section

As Output:

- LIS for all Ions outside heliosphere

Propagation in the Heliosphere
www.Helmod.org

HelMod

Apply solar modulation to LIS as function of solar activity

Boschini et al. ApJ 840:115, 2017
Boschini et al. ApJ 854:94, 2018
Boschini et al. ApJ 858:61, 2018
Boschini et al. ApJ 889:167, 2020

A summary for Ions with Z<=28
Boschini et al. ApJS 250:2, 2020

Boschini et al. ApJ 913:1, 2021
Boschini et al. accepted on ApJ, 2021

Before AMS-02

	Unit	Error (%)
z	kpc	50%
$D_0/10\^28$	$cm^2 s^{-1}$	100%
δ		60%
V_{Alfven}	$km\ s^{-1}$	90%
V_{0conv}	$km\ s^{-1}$	100%
dV_C/dz	$km\ s^{-1} kpc^{-1}$	100%

After AMS-02

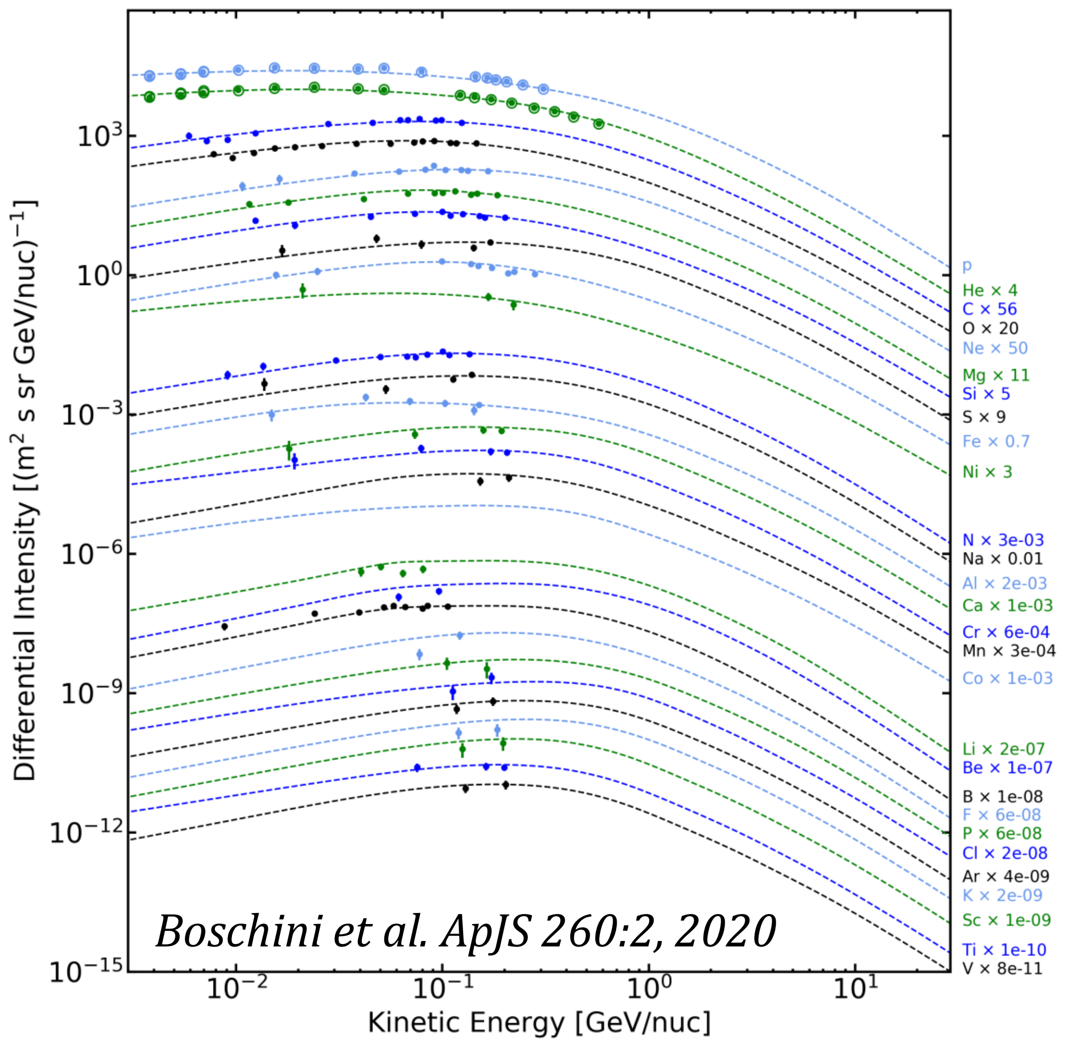
Error (%)	Improvement factor $\varepsilon_{before}/\varepsilon_{after}$
8%	6
7%	14
6%	10
7%	13
6%	16
5%	20

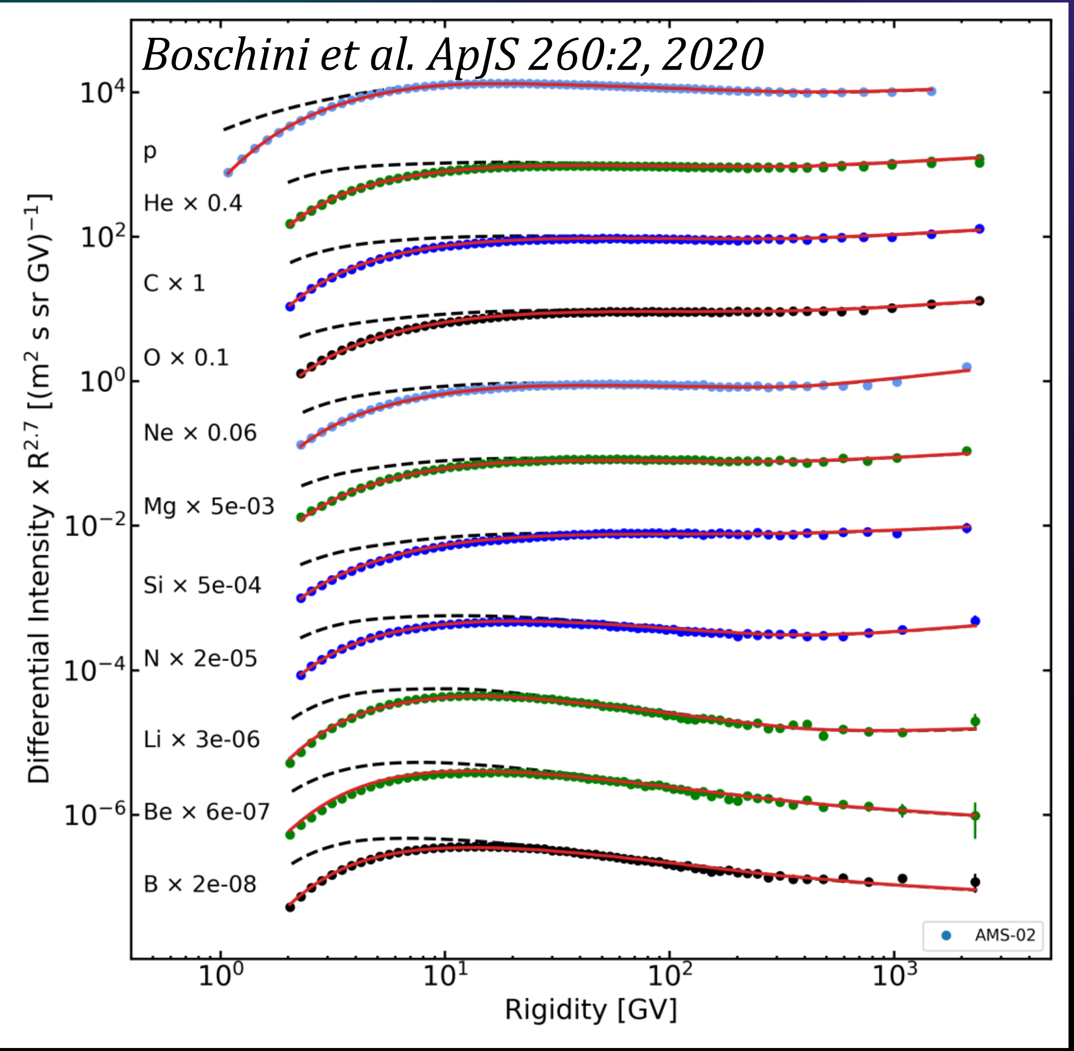
- Before AMS-02 we were not able to fix the CR propagation physics: **the parameters lied in very wide ranges.**
- With AMS-02 data is finally possible to achive a consistent best fit: **the errors associated to the fundamental propagation parameters z, D_{0xx}, $\delta_{1,2}$ are greatly reduced.**
- We still have **some degeneracies/uncertainties which afflict secondaries predictions.**

A factor 10 of improvement for fundamental parameters

N. Masi 2017

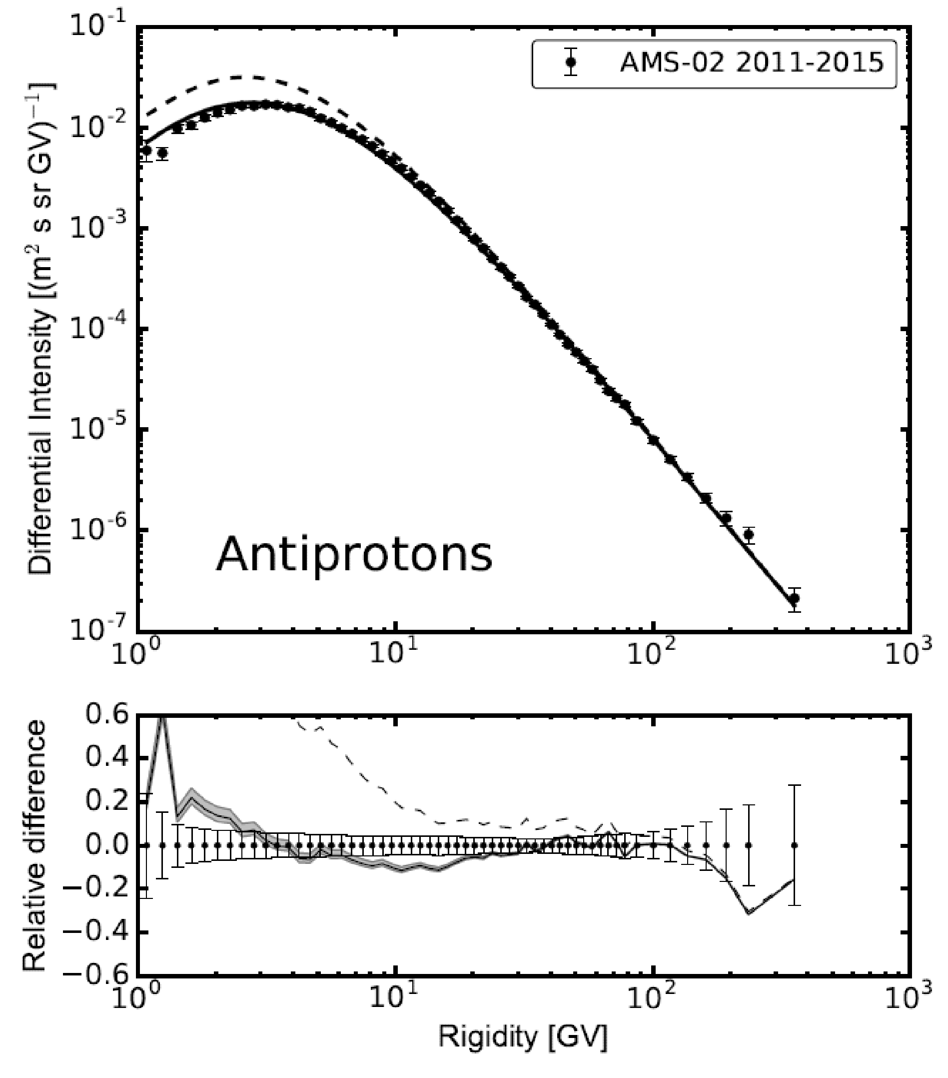
The physically motivated Local Interstellar Spectra were inferred from an iterative procedure was developed to feed the GALPROP output into HelMod to compare with AMS-02 and Voyagers data as observational constraints

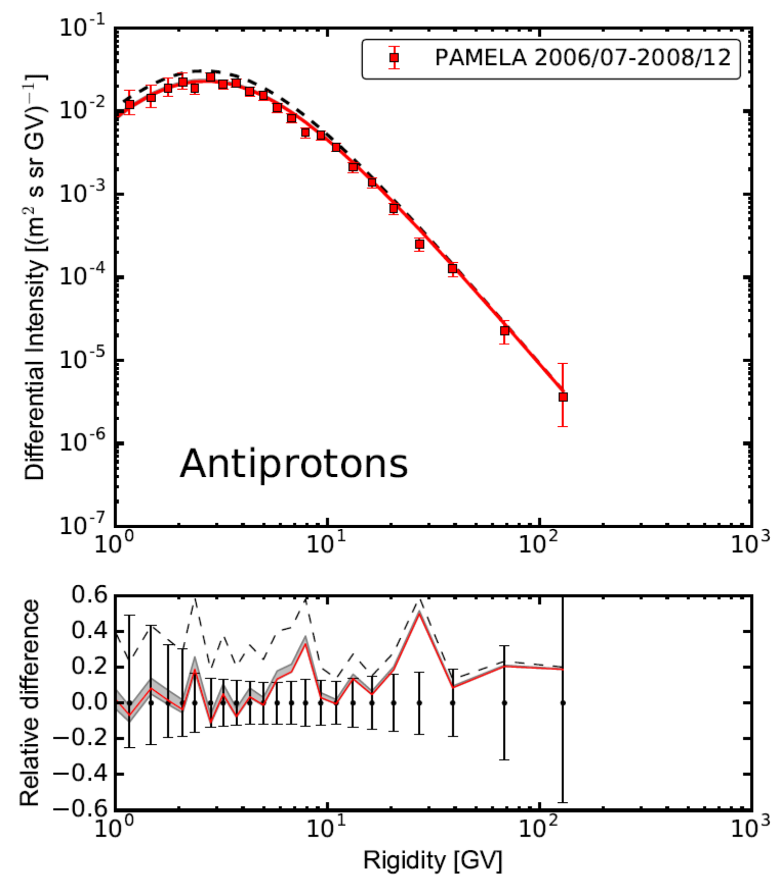




Antiproton

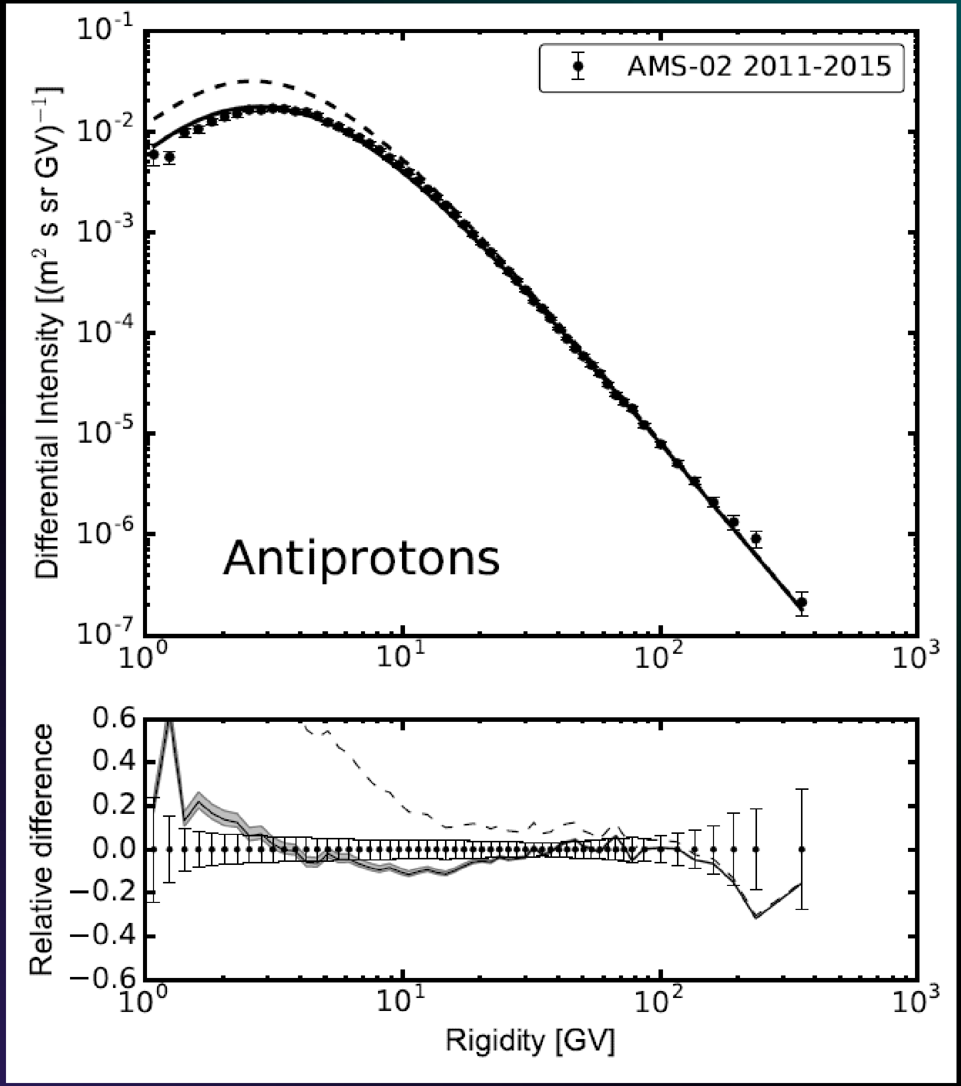
Secondary antiproton production in pp-, pA- and AA-interactions is calculated using the results of QGSJET-IIm (Kachelriess et al. 2015), a dedicated version of the QGSJET-II hadronic interaction model, while inelastically scattered protons and antiprotons are treated as “secondary” protons and “tertiary” antiprotons, respectively.





The obtained Antiproton LIS was NOT constrained with data.

Antiproton

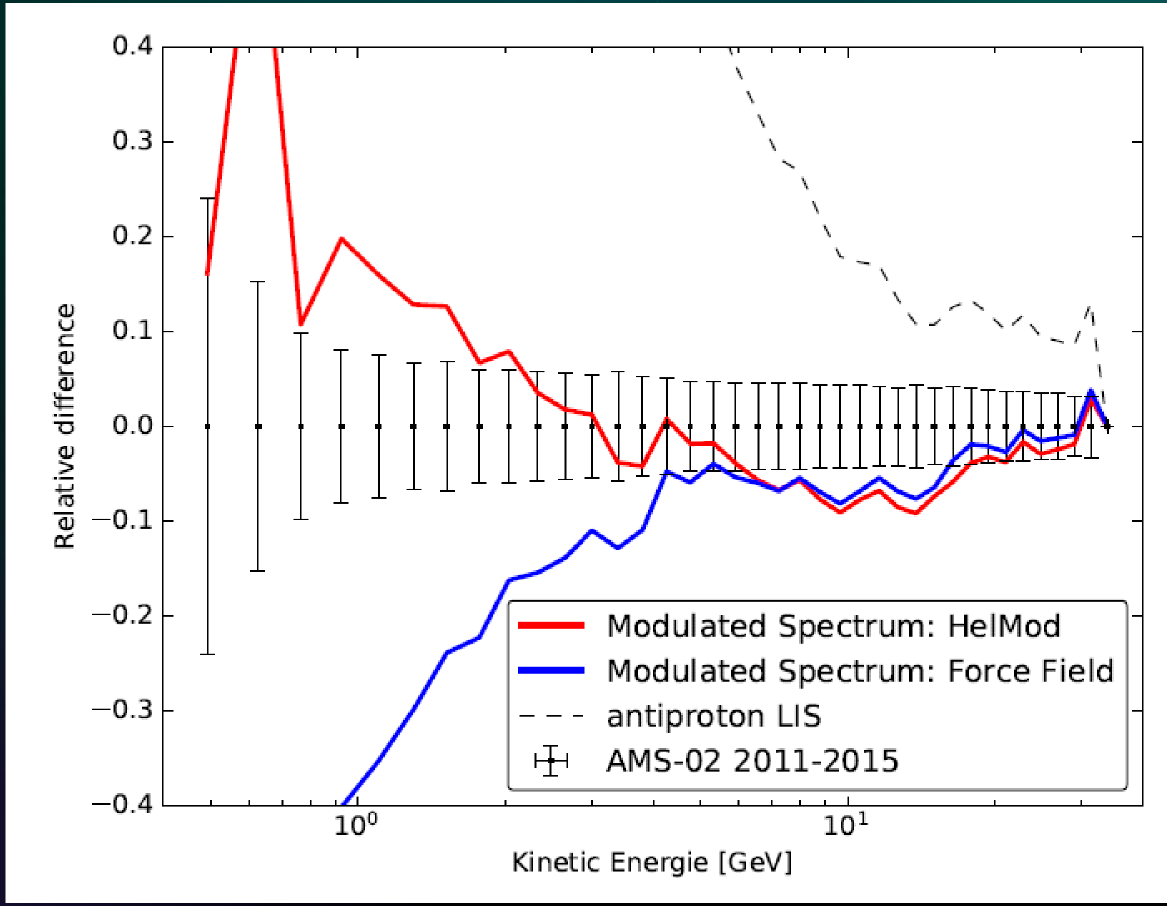


The Antiproton LIS is substantially compatible with AMS-02.

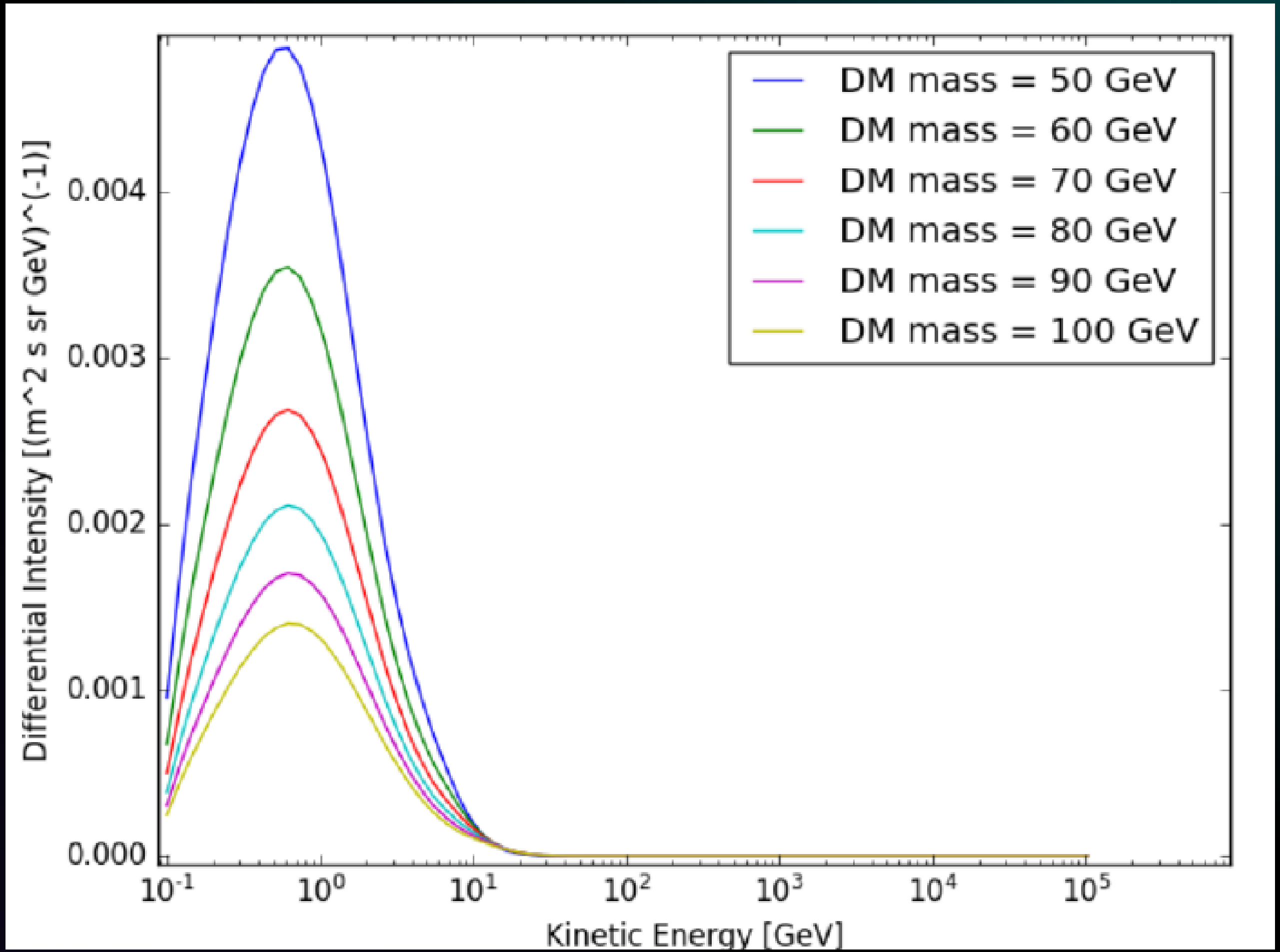
Tiny discrepancies w.r.t. AMS-02 high precision data could be due to:

- Nuclear cross section uncertainties
- Peculiar propagation effects or variation of primary p and He spectra in the Galaxy

Effect on using different Solar modulation model



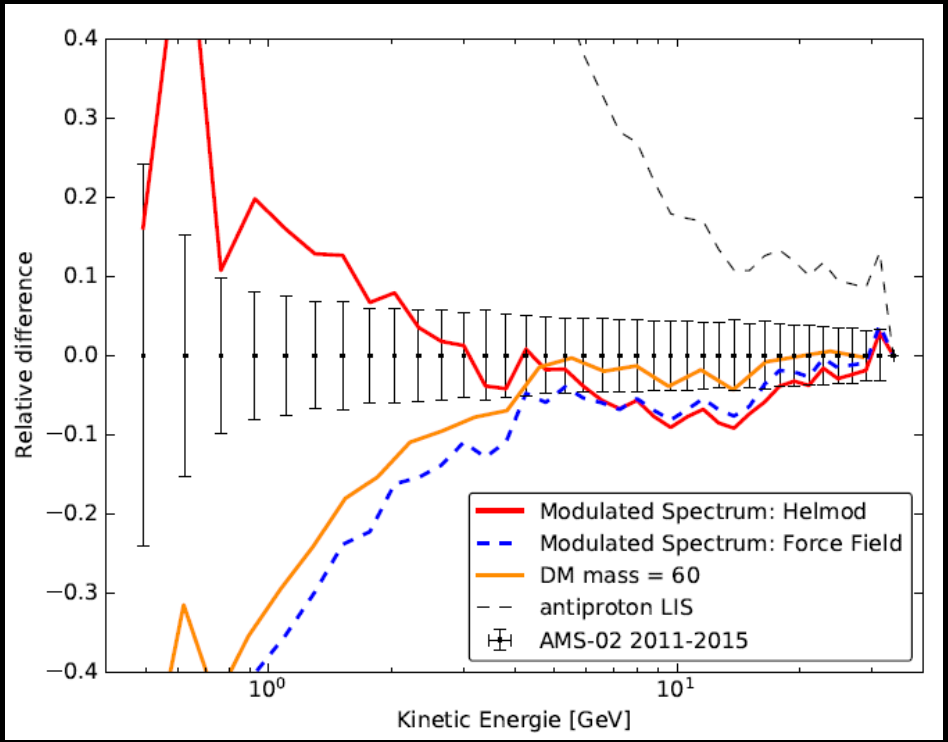
Carella, Thesis 2019

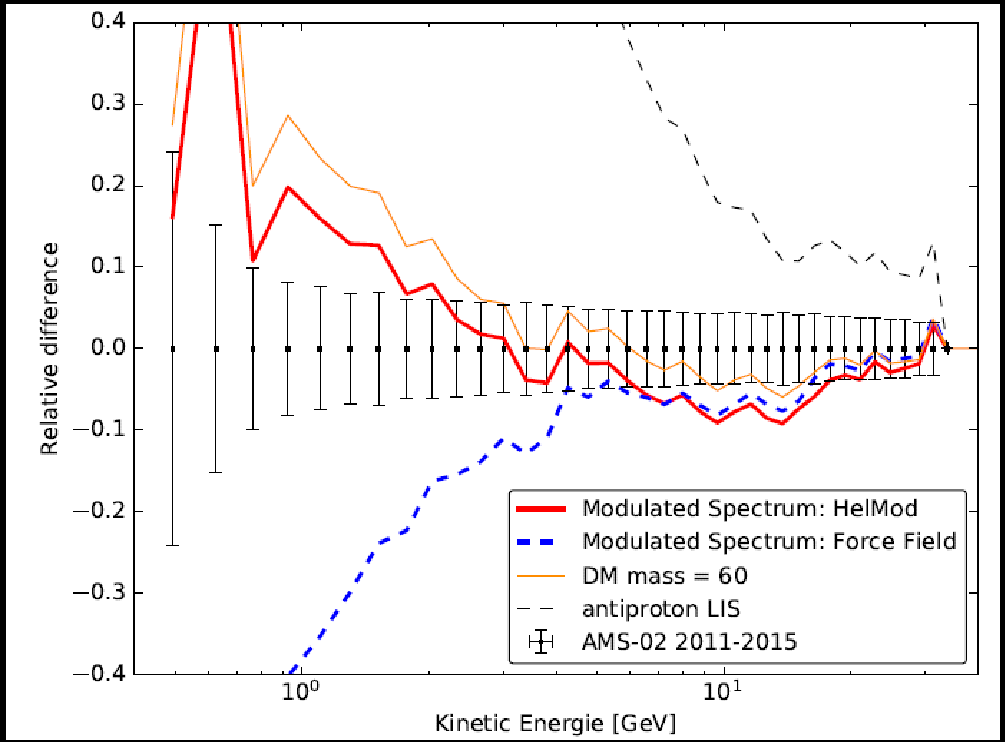


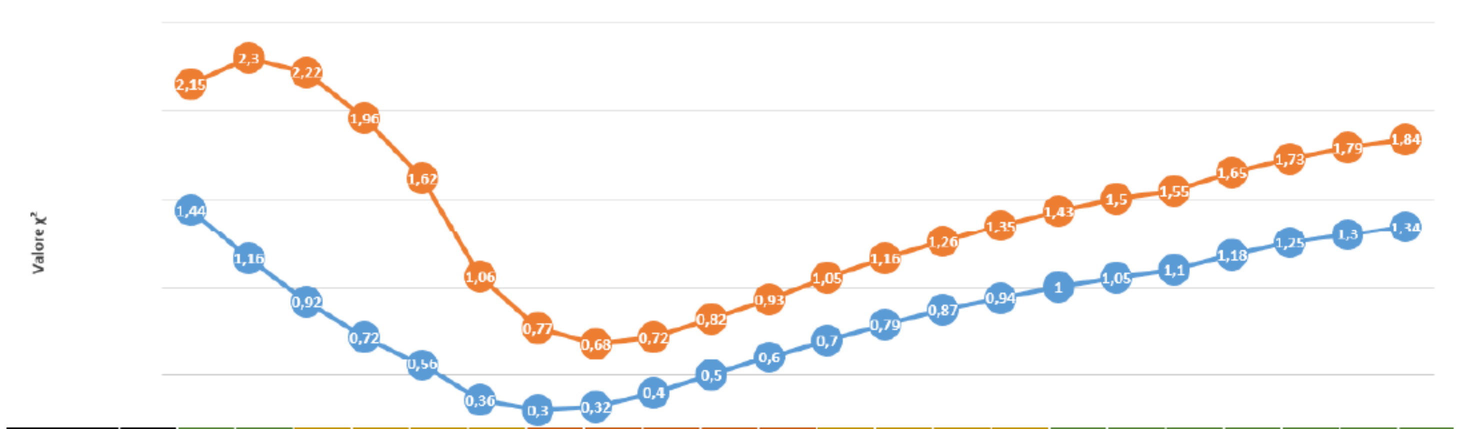
We tested an antiproton produced by $b\bar{b}$ channel similar the one in

- Cuoco et al 2019
- Cholis et al 2019
- …

Carella, Thesis 2019







MASSA DM	Senza	10	15	20	25	30	40	50	60	70	80	90	100	110	120	130	140	150	160	180	200	220	240
Force Field	2,3	1,44	1,16	0,92	0,72	0,56	0,36	0,3	0,32	0,4	0,5	0,6	0,7	0,79	0,87	0,94	1	1,05	1,1	1,18	1,25	1,3	1,34
HelMod	2,27	2,15	2,3	2,22	1,96	1,62	1,06	0,77	0,68	0,72	0,82	0,93	1,05	1,16	1,26	1,35	1,43	1,5	1,55	1,65	1,73	1,79	1,84

The use of HelMod more constrain the mass range for DM candidate

Carella, Thesis 2019

Conclusions

- Dealing with low energy antiproton the major (yet) unsolved issues comes from Nuclear Uncertanties.
- The choice of the solar modulation model is important in the search of exotic signal.
- As far as new data are available, solar modulation model are constrained and becomes more reliable.