From Observations near the Earth to the Local Interstellar Spectra

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Topics

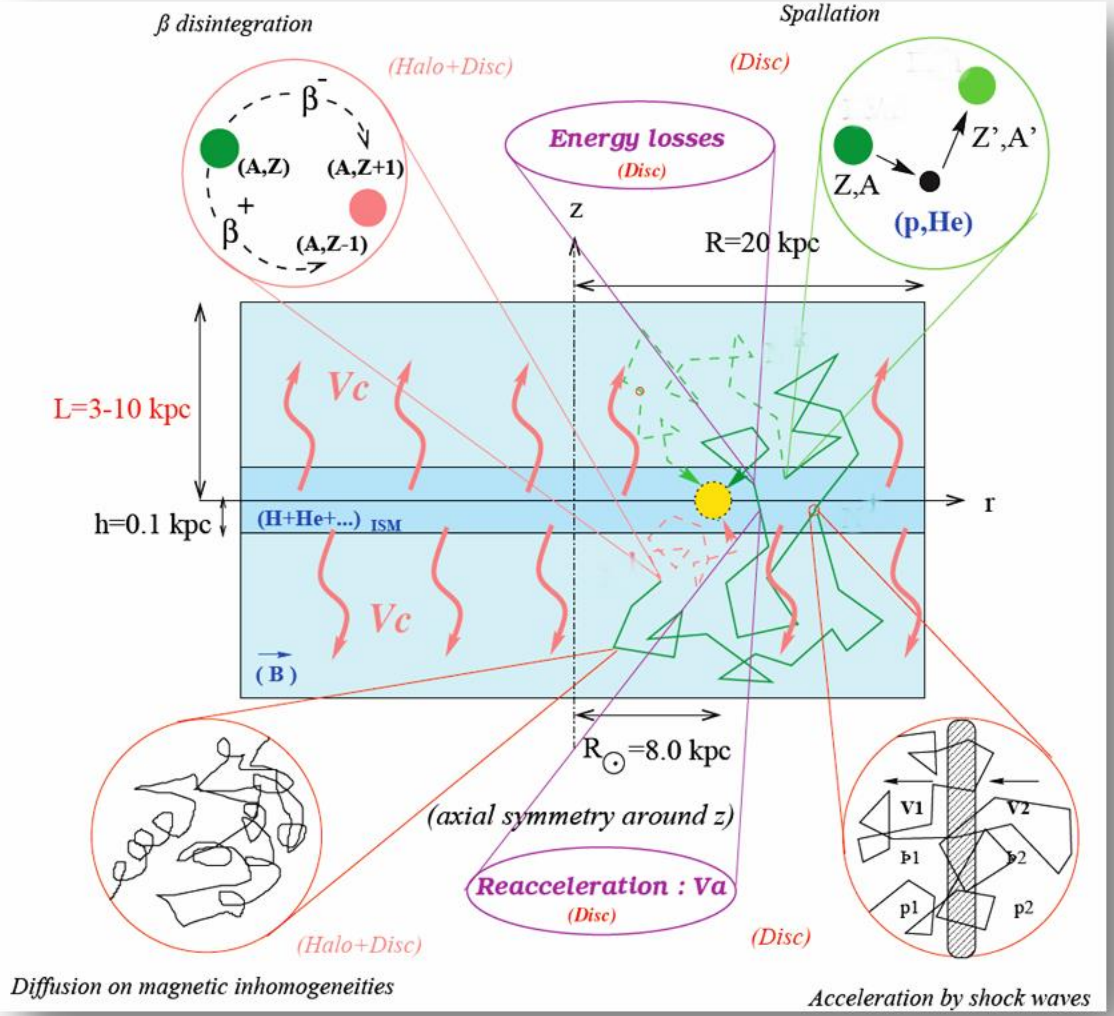
Towards a unified picture of CRs production and propagation by means of GALPROP and HelMod for solar modulation:

- *Astrophysical uncertainties: the MCMC approach to GALPROP v55*
- *Protons, Helium and Antiprotons LIS from GALPROP + HelMod synergy*
- *Interstellar Spectra: AMS-02 vs Voyager-1*

The Propagation Scheme in the Milky Way

$$\frac{\partial \psi}{\partial t} = q(\vec{r},p) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

Source | Diffusion | Convection | Reacceleration | Energy Loss in ISM | Adiabatic Expansion | Fragmentation | Decay



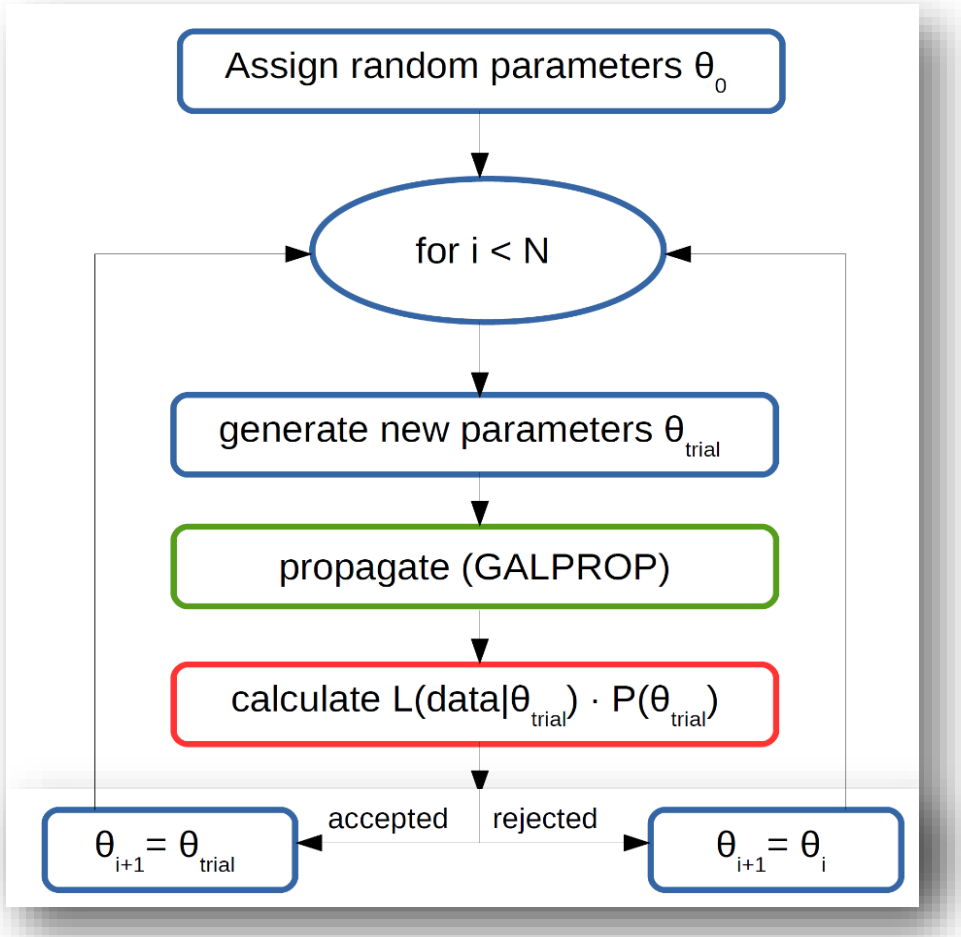
- **Geometry**: halo of thickness z
- **Diffusion**: diffusion in the galactic magnetic field inhomogeneities, propagating through the ISM (D_0, δ, R_0)
- **Convection**: galactic wind with velocity V_c and gradient dV_c/dz
- **Reacceleration**: interstellar turbulence with Alfvén velocity V_A
- **Sources**: SNe shocks produce power law spectra in energy ($\gamma_{1,2}$ indices)

→ 7 fundamental parameters space to fix CR propagation + N specific injection indices

Propagation models uncertainties: almost two orders of magnitude, one above one below the often called in literature MED propagation values set

MCMC + GALPROP Approach

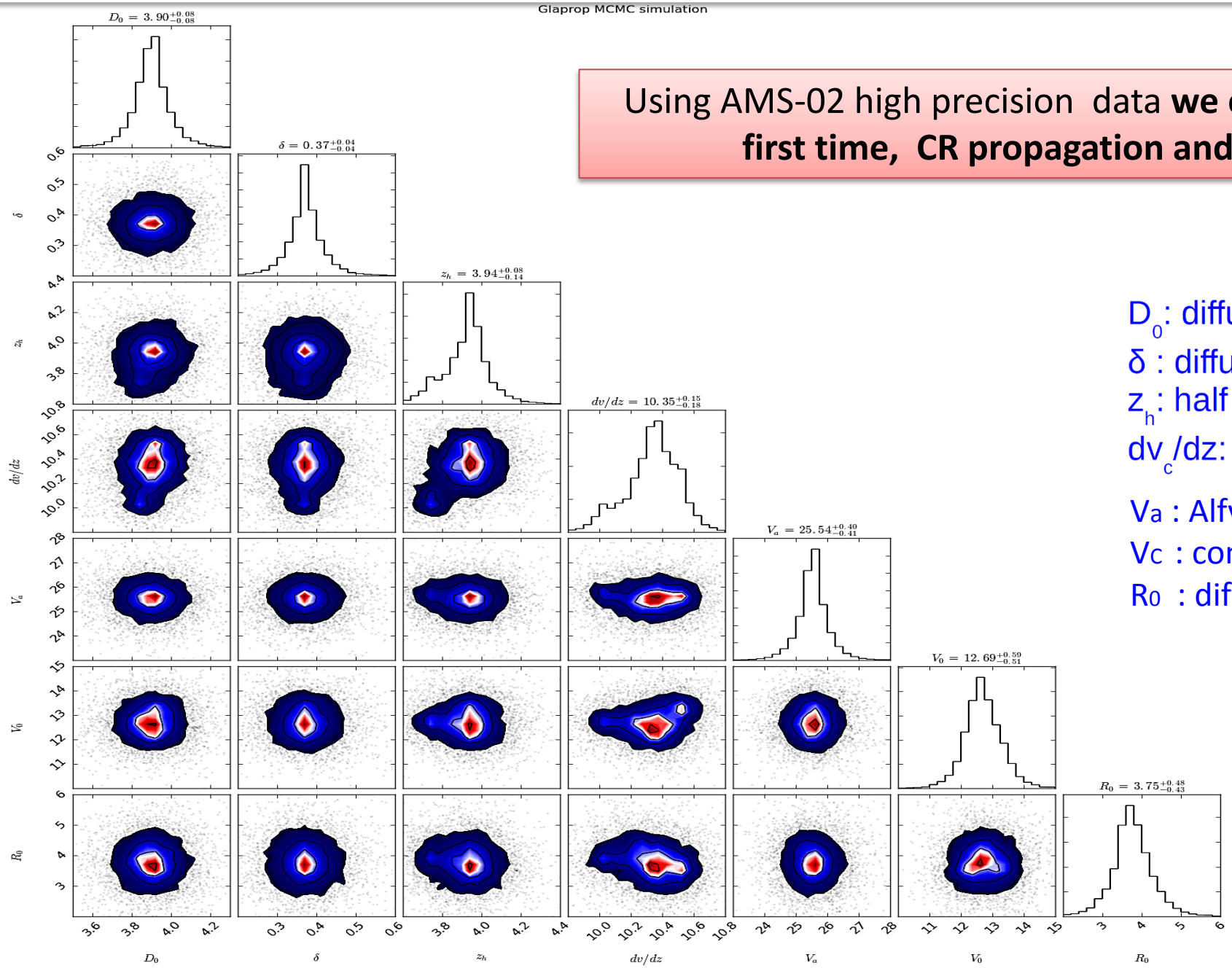
1. The Monte-Carlo-Markov-Chain interface to **GALPROP v55** was developed in Bologna from CosRay-MC and COSMOMC package, embedding GALPROP framework into the MCMC scheme;
2. An iterative procedure is used to sample GALPROP cosmic rays production and propagation parameters using AMS-02 data as observational constraints, exploring a very large parameter space;
3. The solar modulation is made using numerical functions based on HelMod;



4. GALPROP accuracy was tested at the % level, checking solution stability and introducing new “smoothing features”;
5. The experimental observables used in the MCMC scan include all published AMS-02 data on protons, Helium, B/C ratio and electrons, while positrons and antiprotons are excluded.

Precision measurement of Boron-to-Carbon Ratio with AMS-02…, ***Valerio Formato***

MCMC Matrix



Using AMS-02 high precision data **we can easily constrain, for the first time, CR propagation and the galactic physics**

D_0: diffusion coefficient

δ : diffusion coefficient index

z_h: half size of the Halo

dv_c/dz: convection velocity gradient

V_a : Alfvén velocity

V_c : convection velo city

R_0 : diffusion break position

CR Physics Improvements

Before AMS-02

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

After AMS-02

Error (%)	Improvement factor $\varepsilon_{before}/\varepsilon_{after}$
5%	10
5%	20
5%	12
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 10-20 of improvement for fundamental parameters

CR Physics Parameters: a DCR scenario

Simultaneous inclusion of diffusion, convection and reacceleration is required to reproduce AMS-02 measurements

N	Parameters	Best Value	Units	1σ Mean Error	% Error	Scan Range
1	z	4.0	kpc	0.2	5	[1-10]
2	$D_0/10^{28}$	4.3	$cm^2 s^{-1}$	0.2	5	[1-10]
3	δ	0.36	-	0.02	5	[0.3-0.9]
4	R_D	4.2	GV	0.4	10	[1-8]
5	V_{Alfven}	27	$km \cdot s^{-1}$	2	7	[0-40]
6	V_{conv}	12.7	$km \cdot s^{-1}$	0.8	6	[0-20]
7	dV_{conv}/dz	10.0	$km \cdot s^{-1} kpc^{-1}$	0.5	5	[0-20]

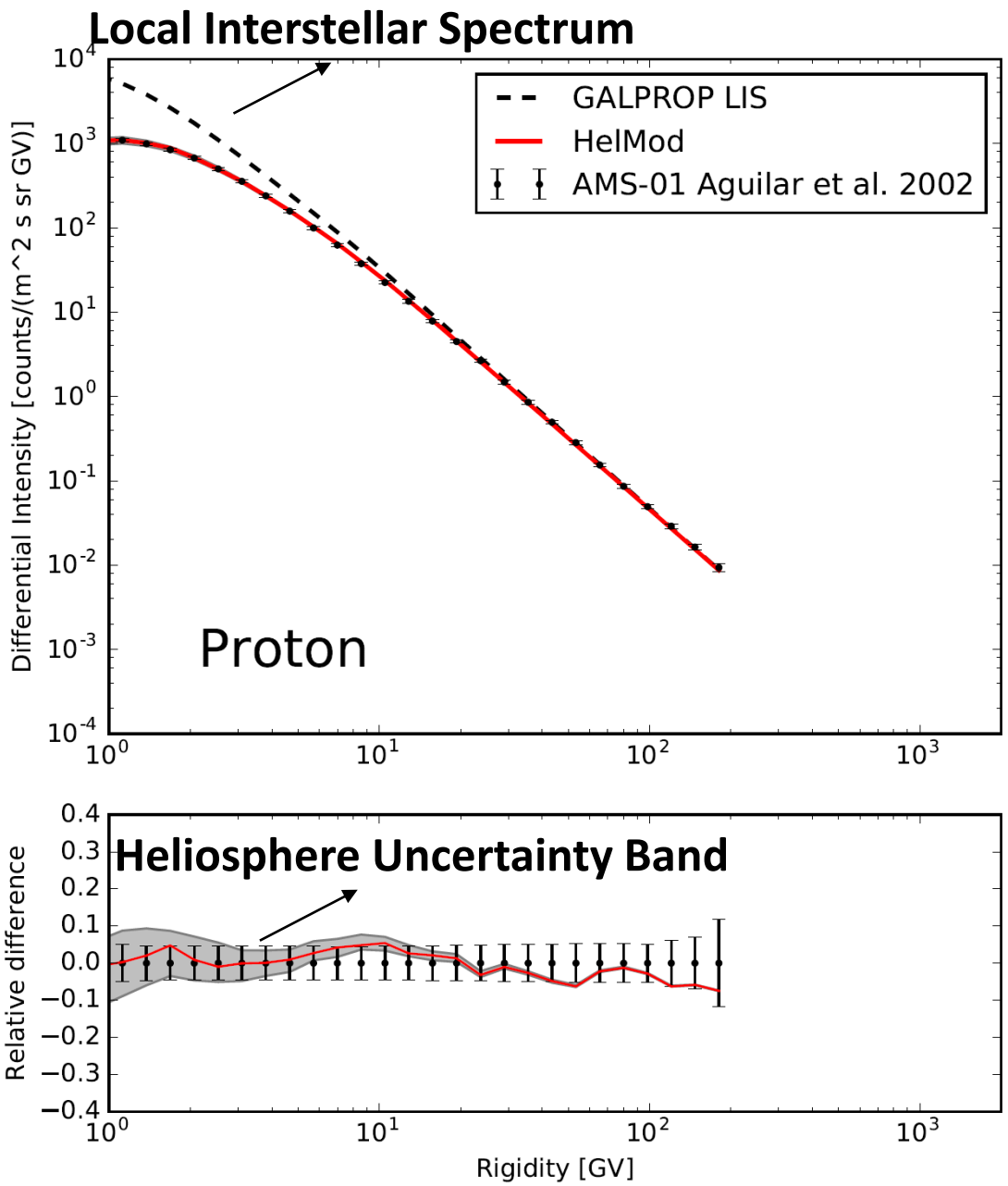
HelMod: a Comprehensive Treatment of the Cosmic Ray transport through the Heliosphere, ***Davide Grandi***

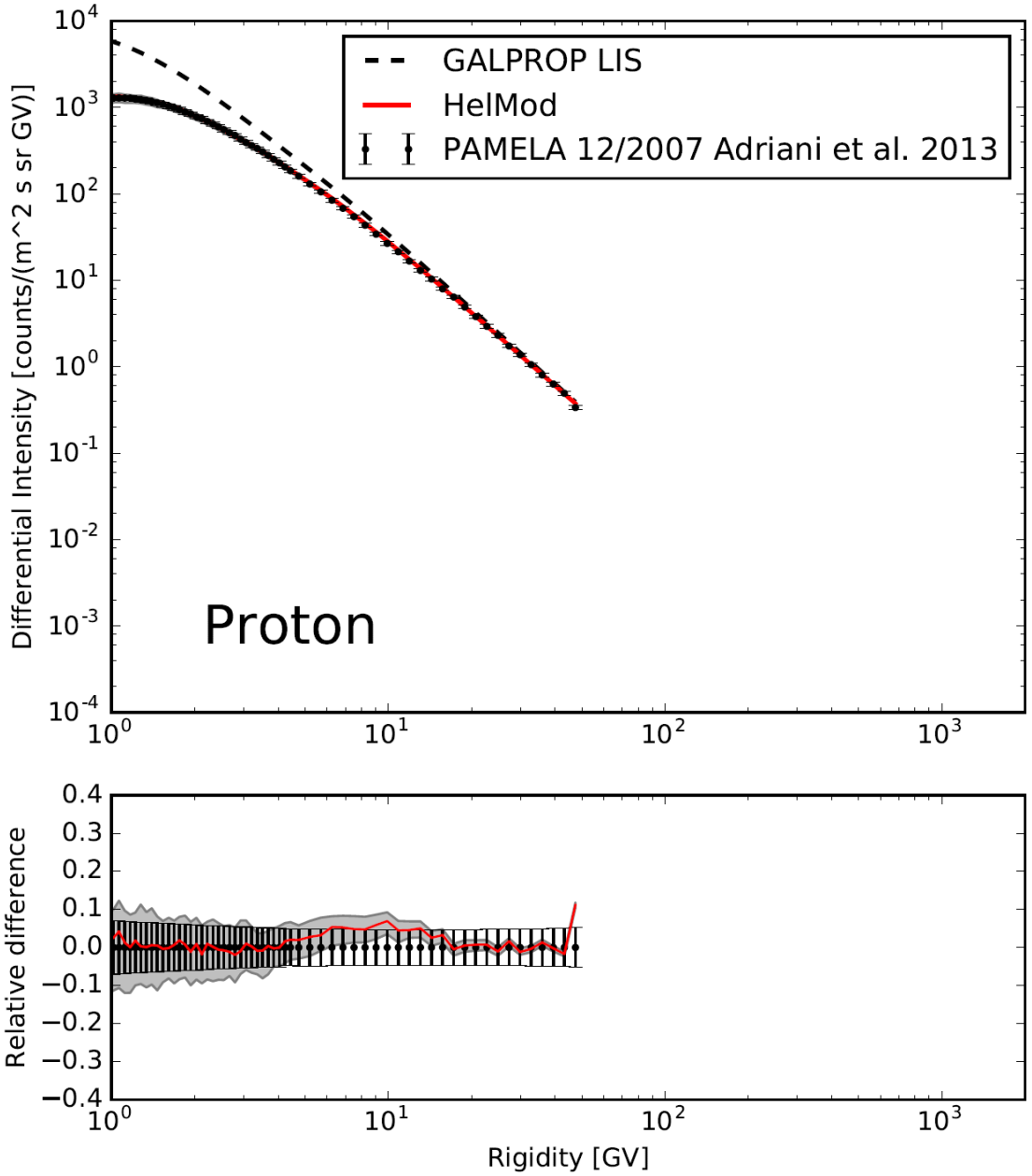
N	Parameters	Protons	Helium	Explored Range
1	R_1	7 GV	9 GV	[4-10]
2	R_2	360 GV	330 GV	[300-400]
3	γ_1	1.74	1.89	[1.5-2.1]
4	γ_2	2.48	2.42	[2.1-2.7]
5	γ_3	2.33	2.25	[2-2.4]

Once defined a consistent parameter space, a methodical calibration employing the **HelMod Model** was performed, involving injection spectra and solar parameters

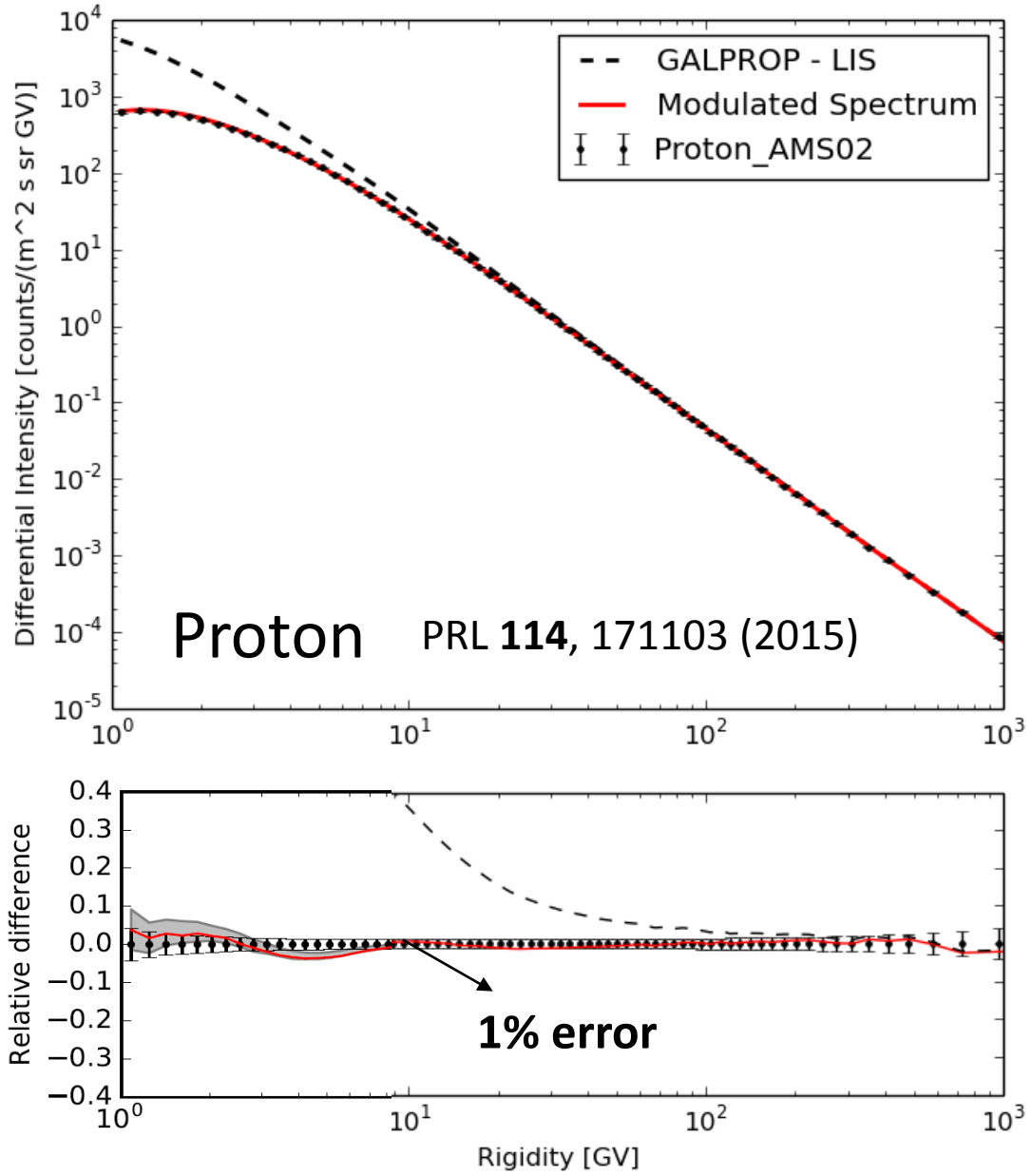
Forthcoming Results:
Protons LIS

Low Solar Activity





High Solar Activity



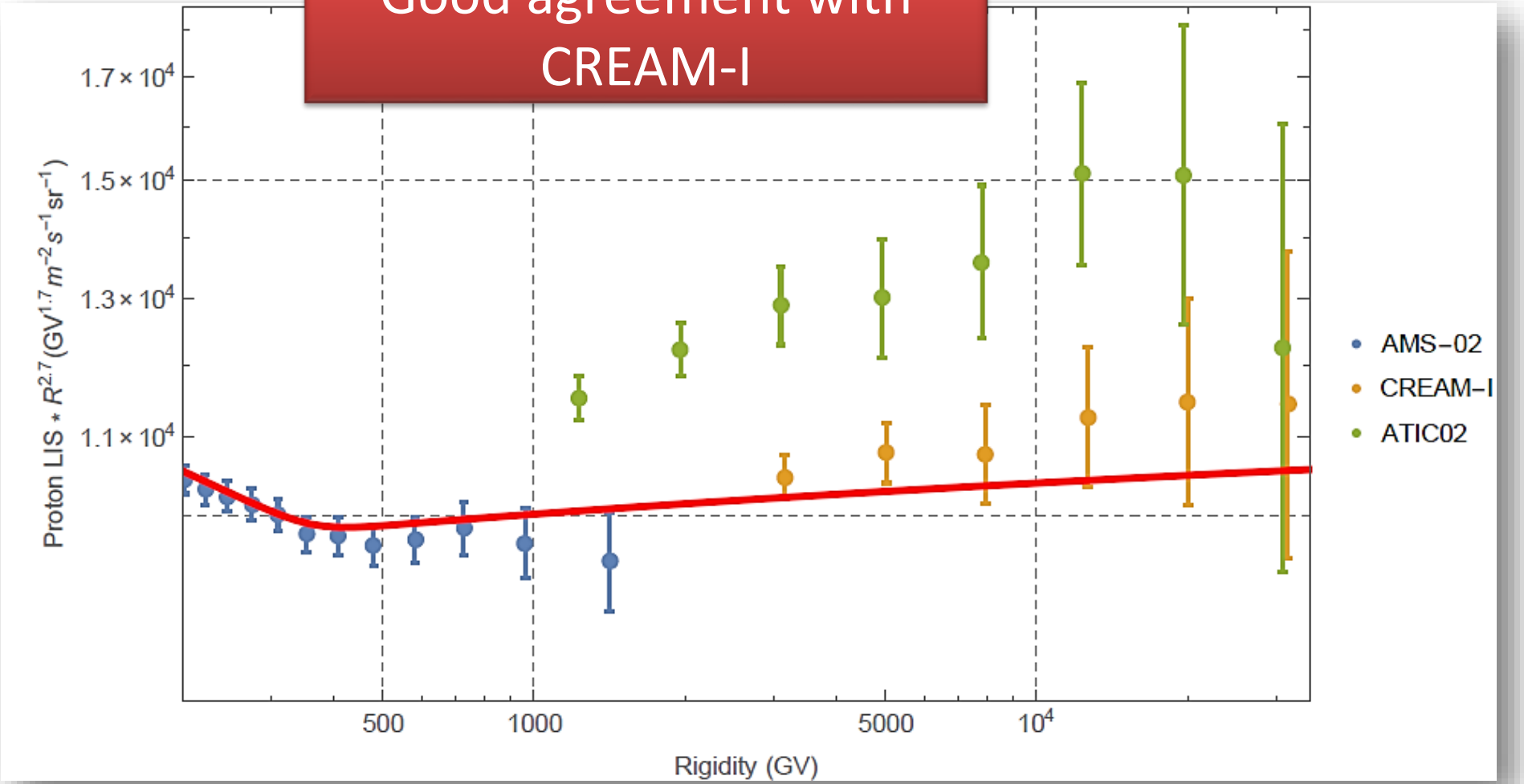
Recent AMS-02 results: impressive agreement between data and HelMod-modulated LIS from GALPROP

Analytic Formula for 0.45 GV < R< 20000 GV:

$$F(R)\cdot R^{2.7} = a + \frac{b}{R} + \frac{c}{d+R} + \frac{e}{f+R} + \frac{g}{h+R}$$

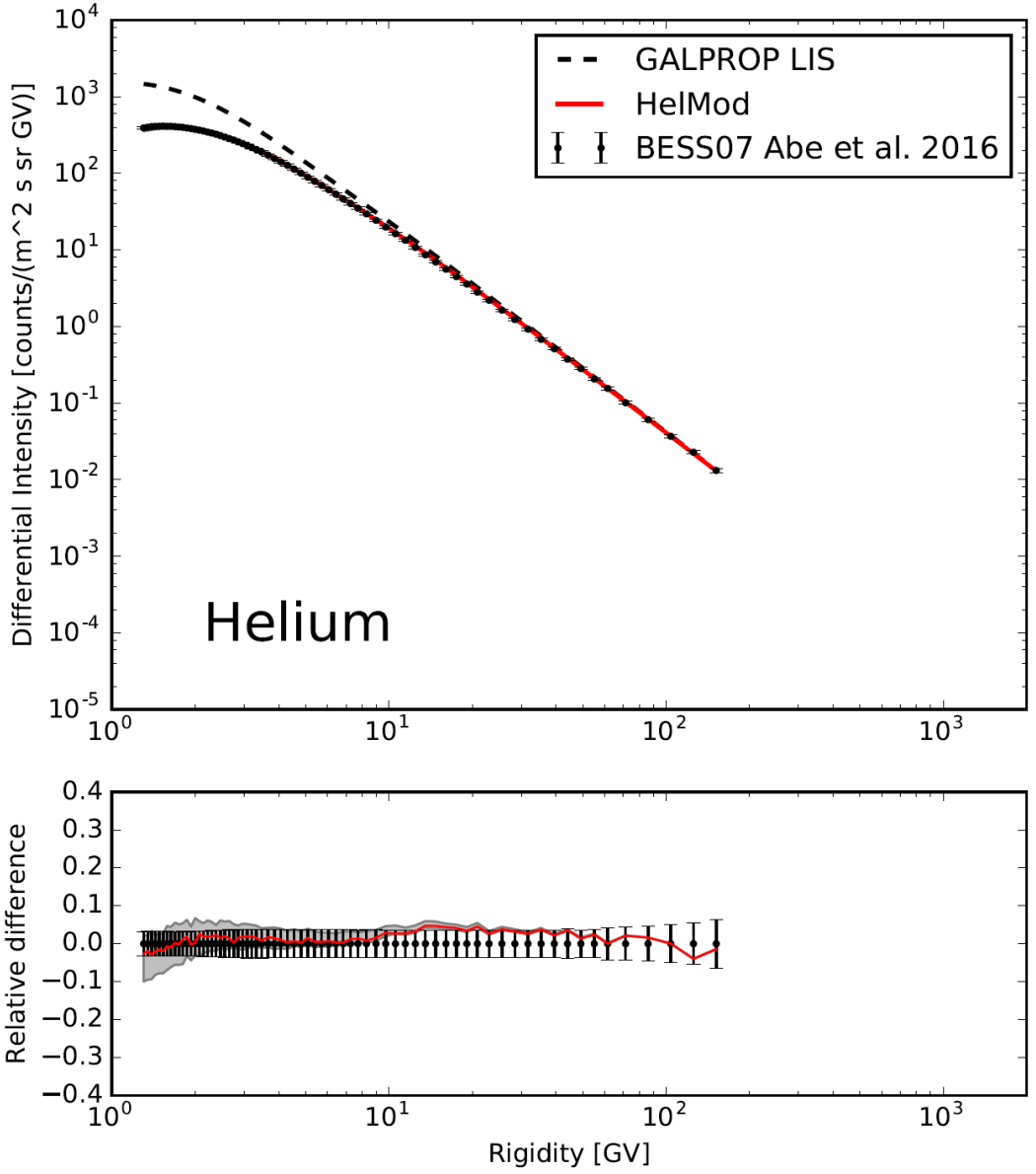
High Energy Comparison

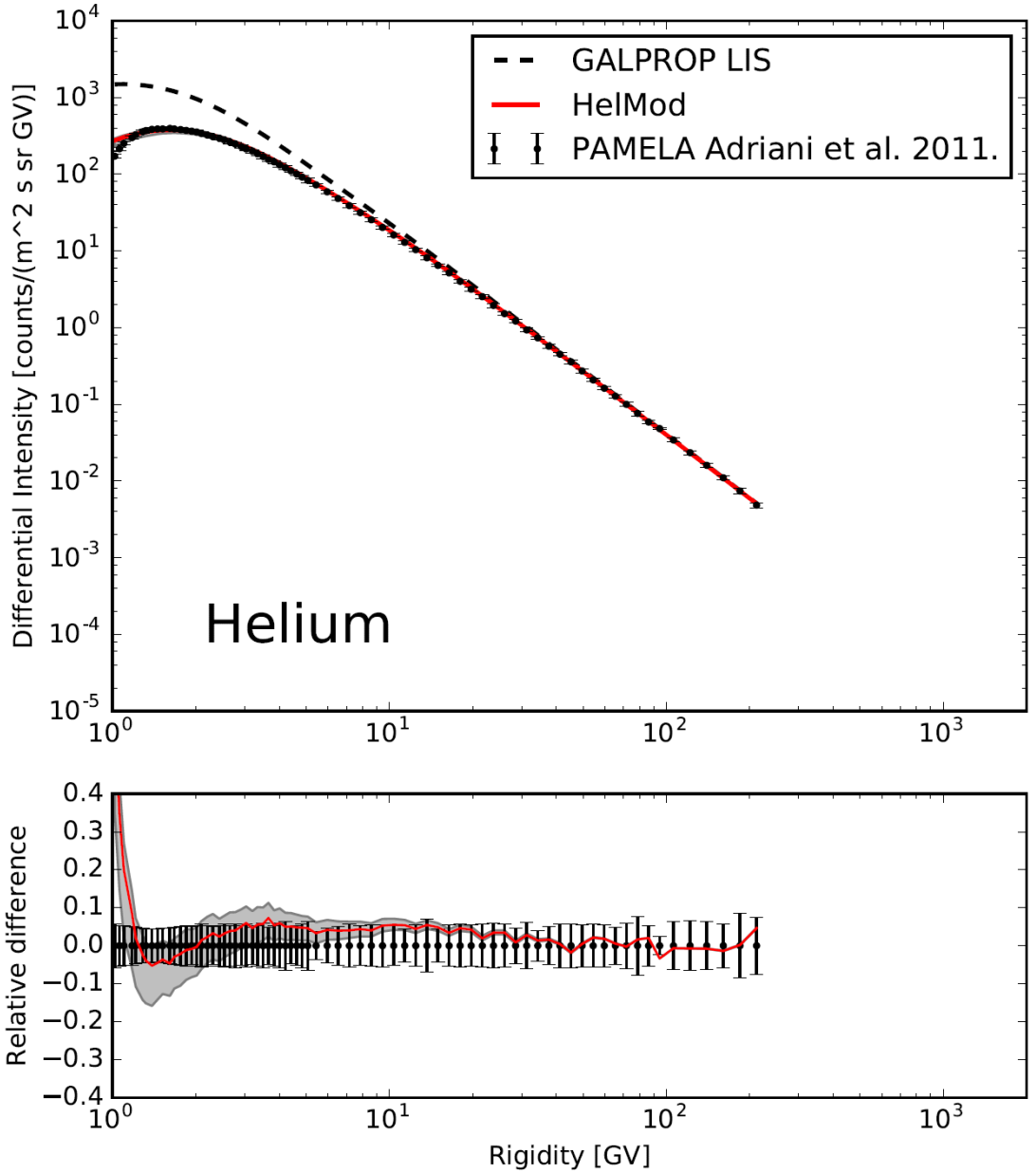
Good agreement with CREAM-I



Helium LIS

Low Solar Activity





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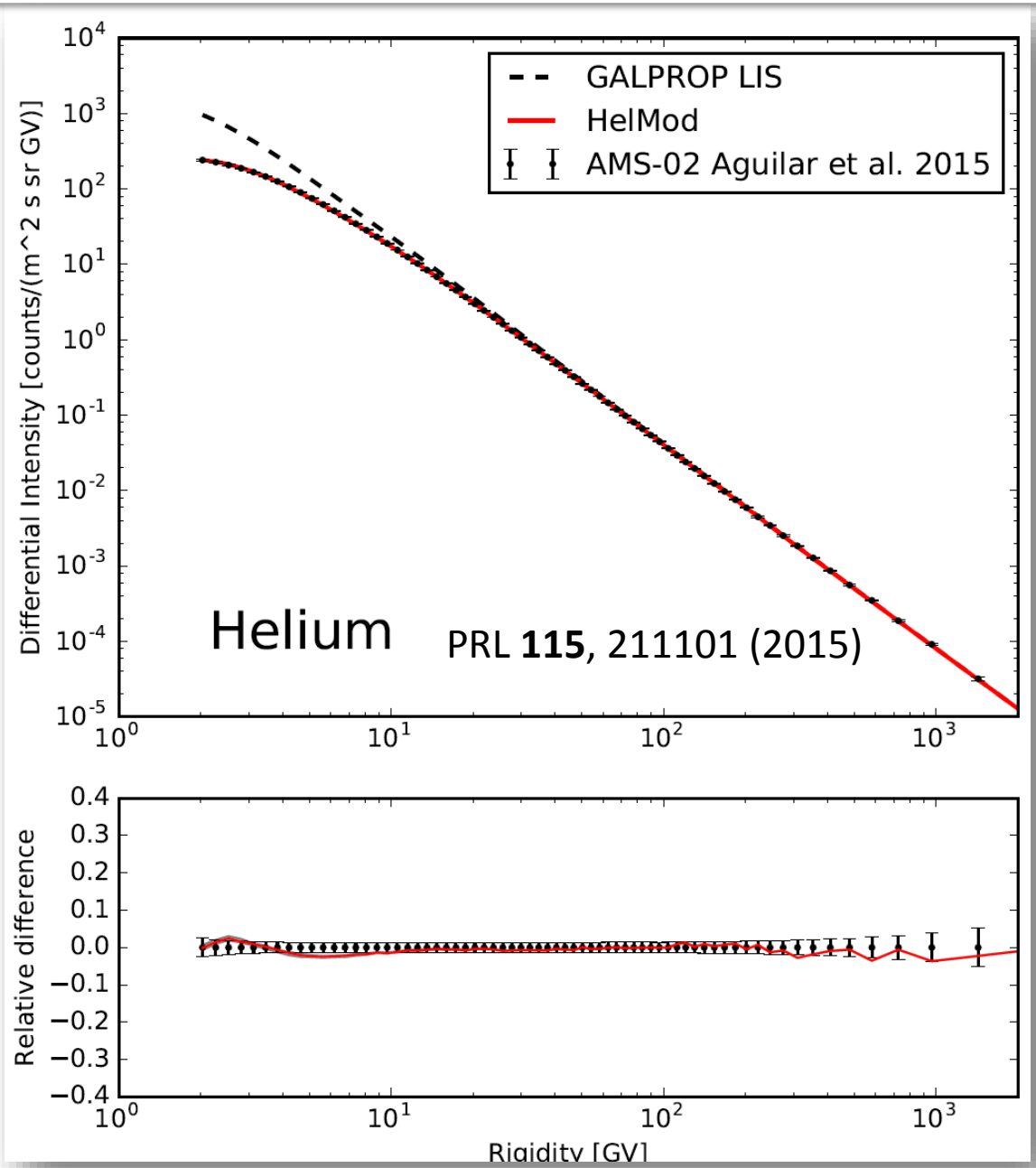
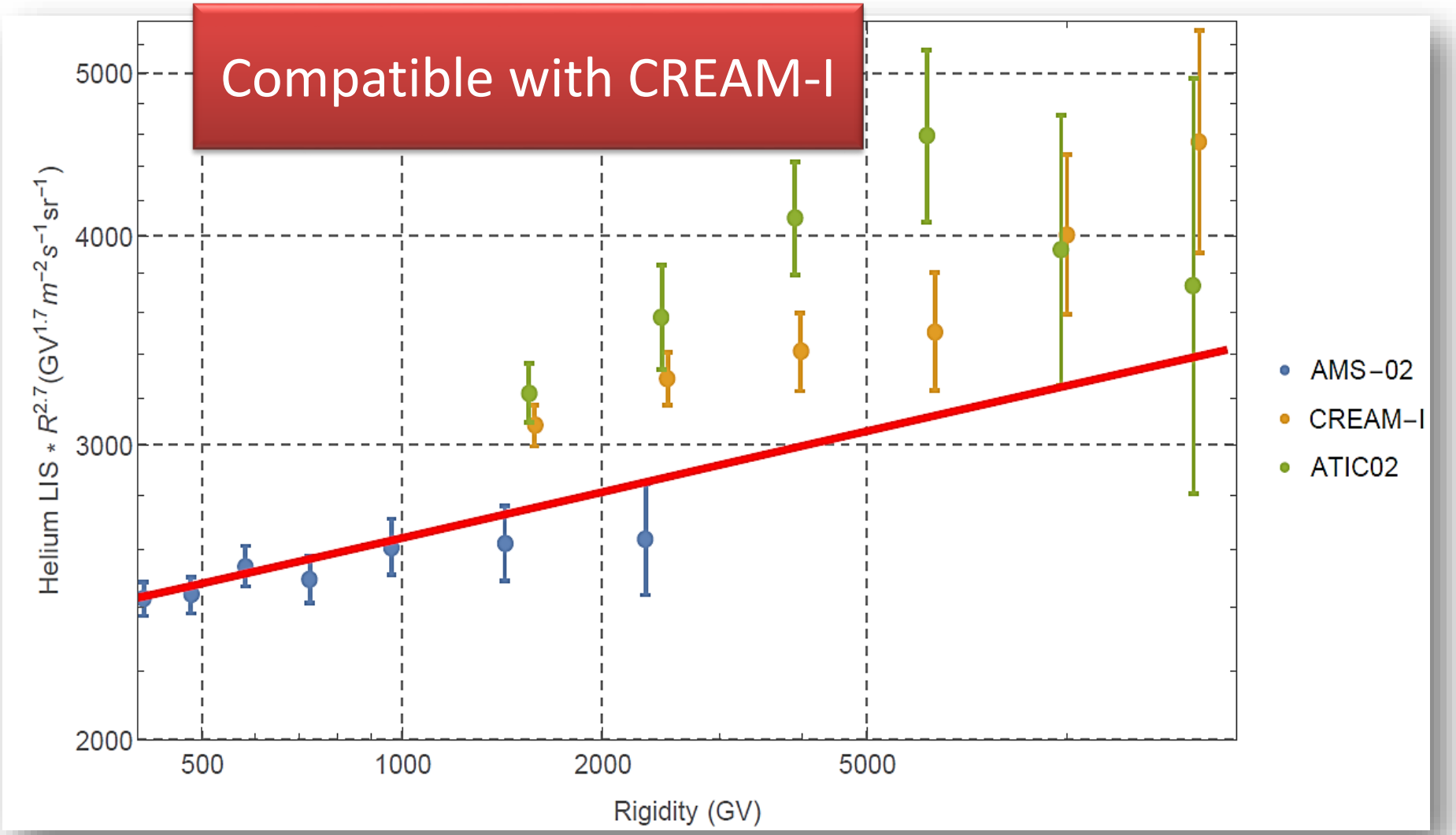


Recent AMS-02 results: impressive agreement between data and HelMod-modulated LIS from GALPROP

Analytic Formula for 1.5 GV < R< 20000 GV:

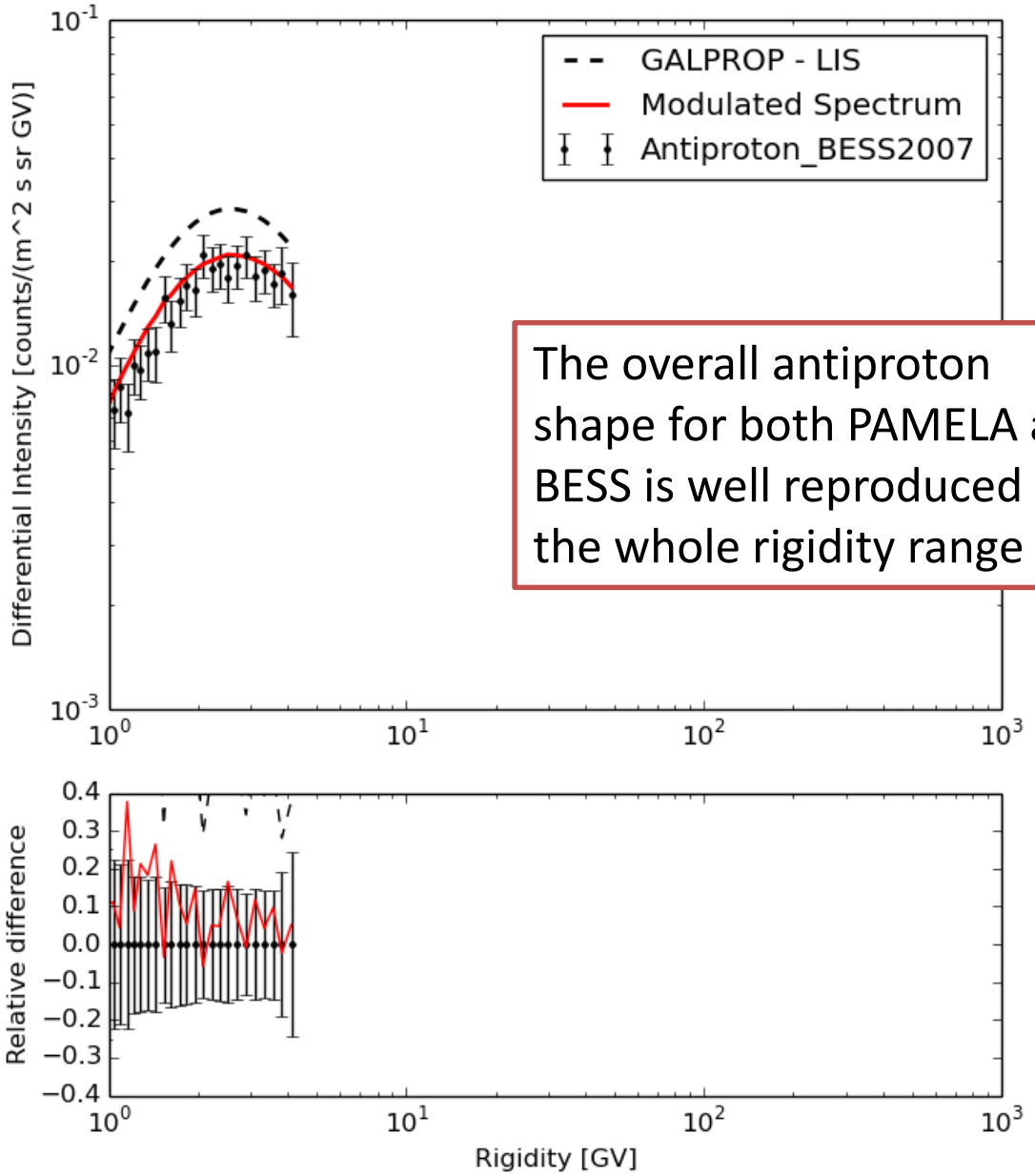
$$F(R)\cdot R^{2.7} = a + b * R + \frac{c}{R} + \frac{d}{e+R} + \frac{f}{g+R} + \frac{h}{\mathrm{k}+R}$$

High Energy Comparison

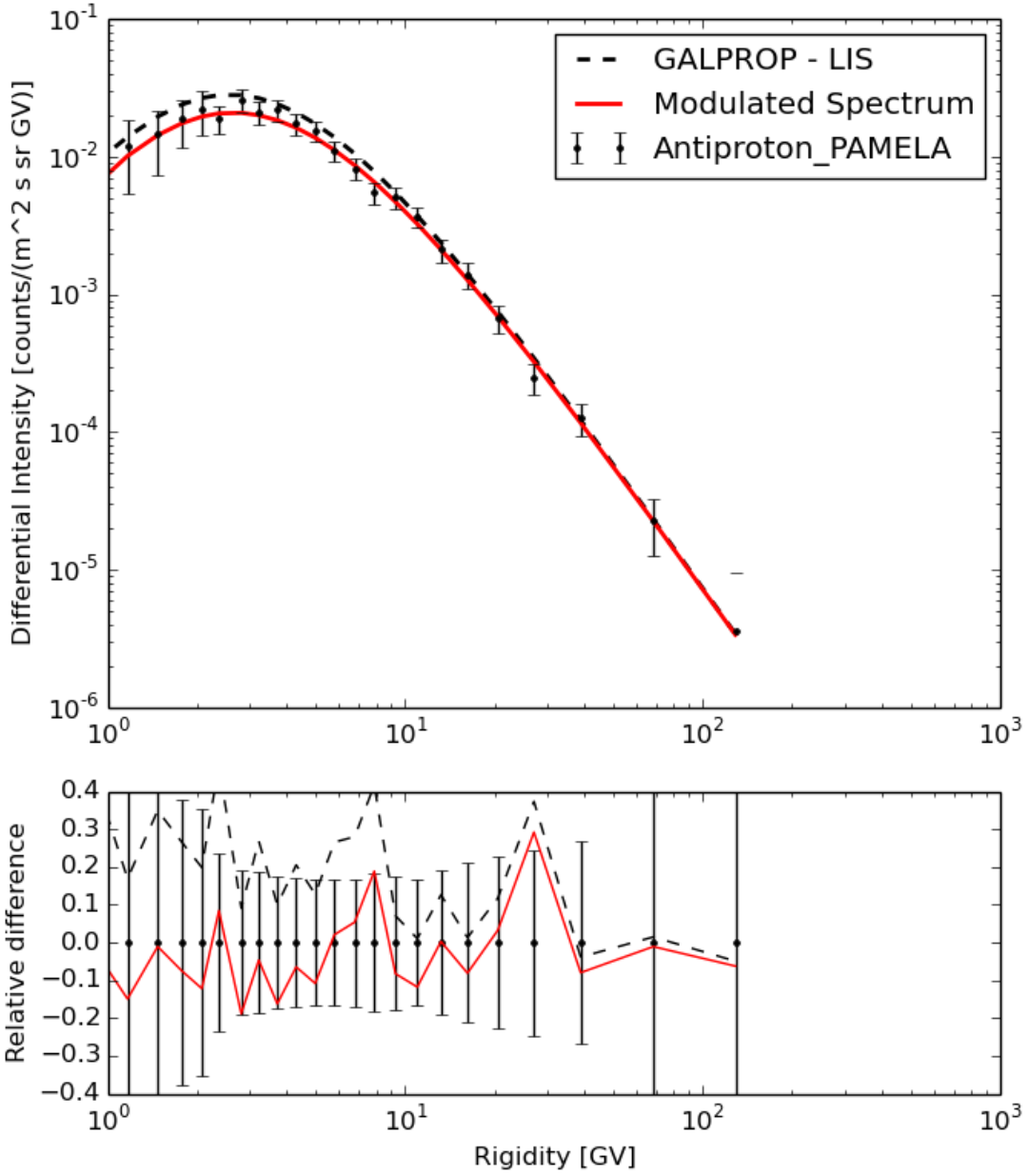


Antiproton LIS

Low Solar Activity



The overall antiproton shape for both PAMELA and BESS is well reproduced over the whole rigidity range



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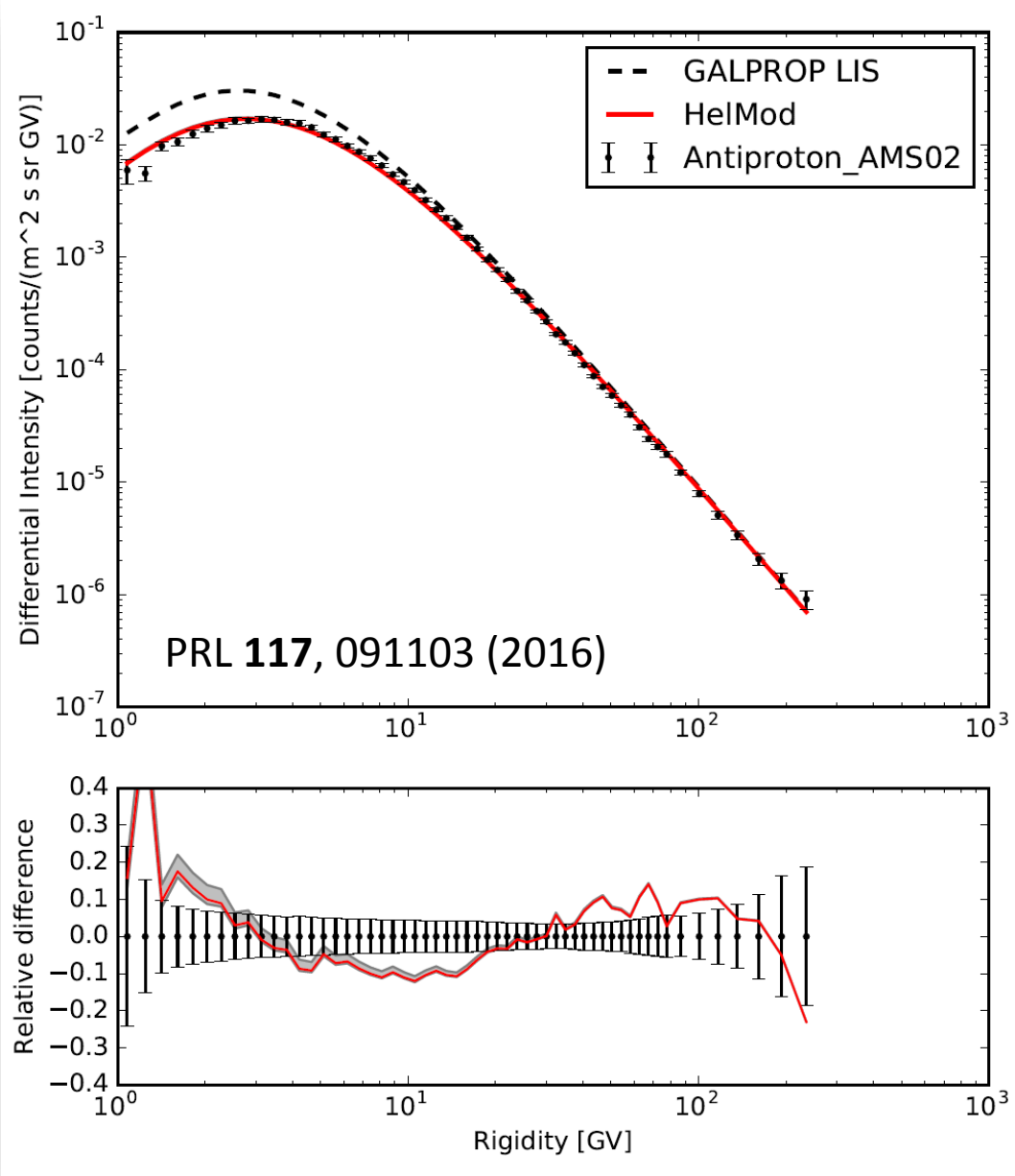


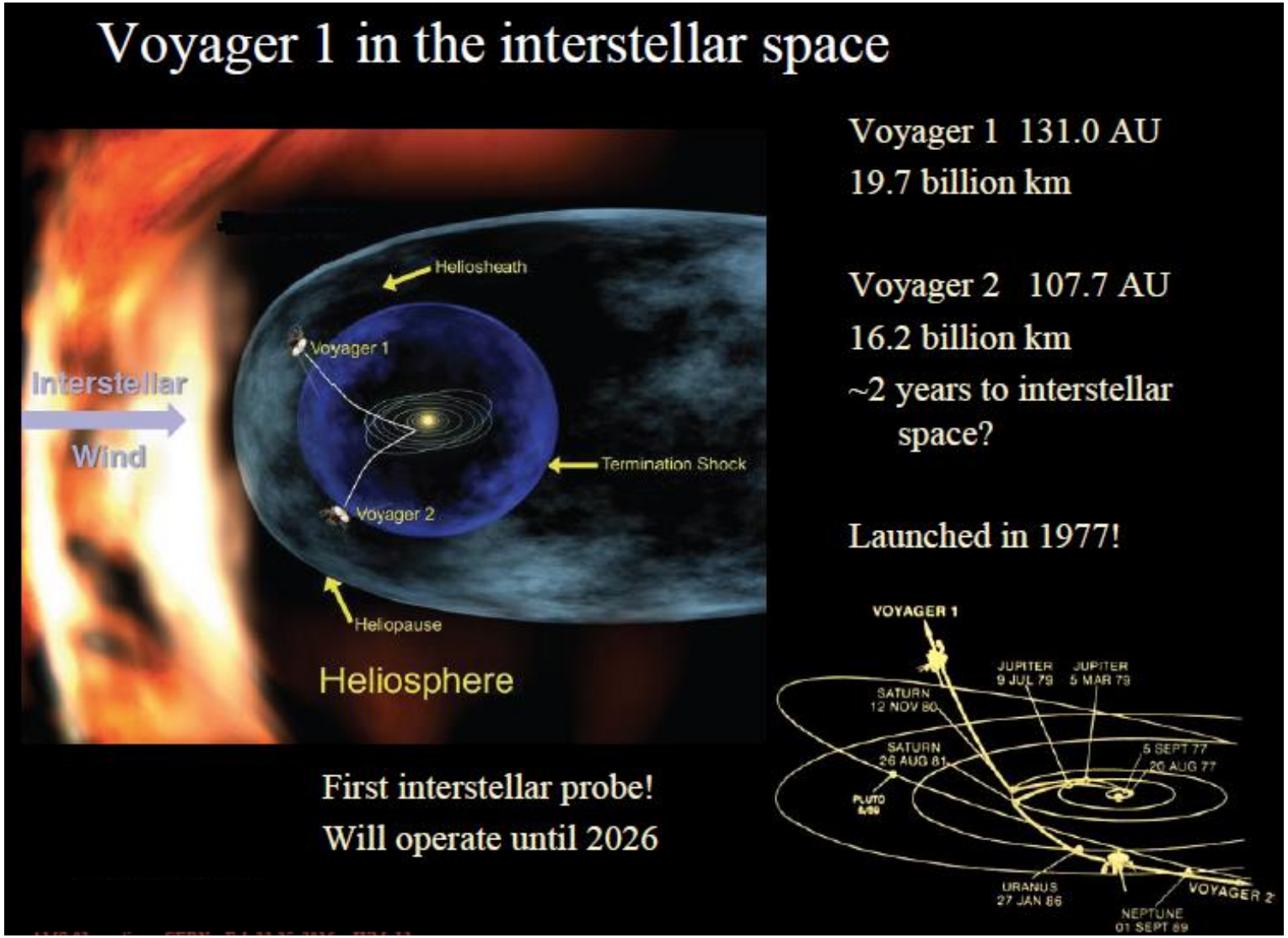
The Antiproton LIS is substantially compatible with AMS-02.

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

- residual astrophysical uncertainties
- nuclear cross section uncertainties
- peculiar propagation effects or variation of primary p and He spectra in the Galaxy

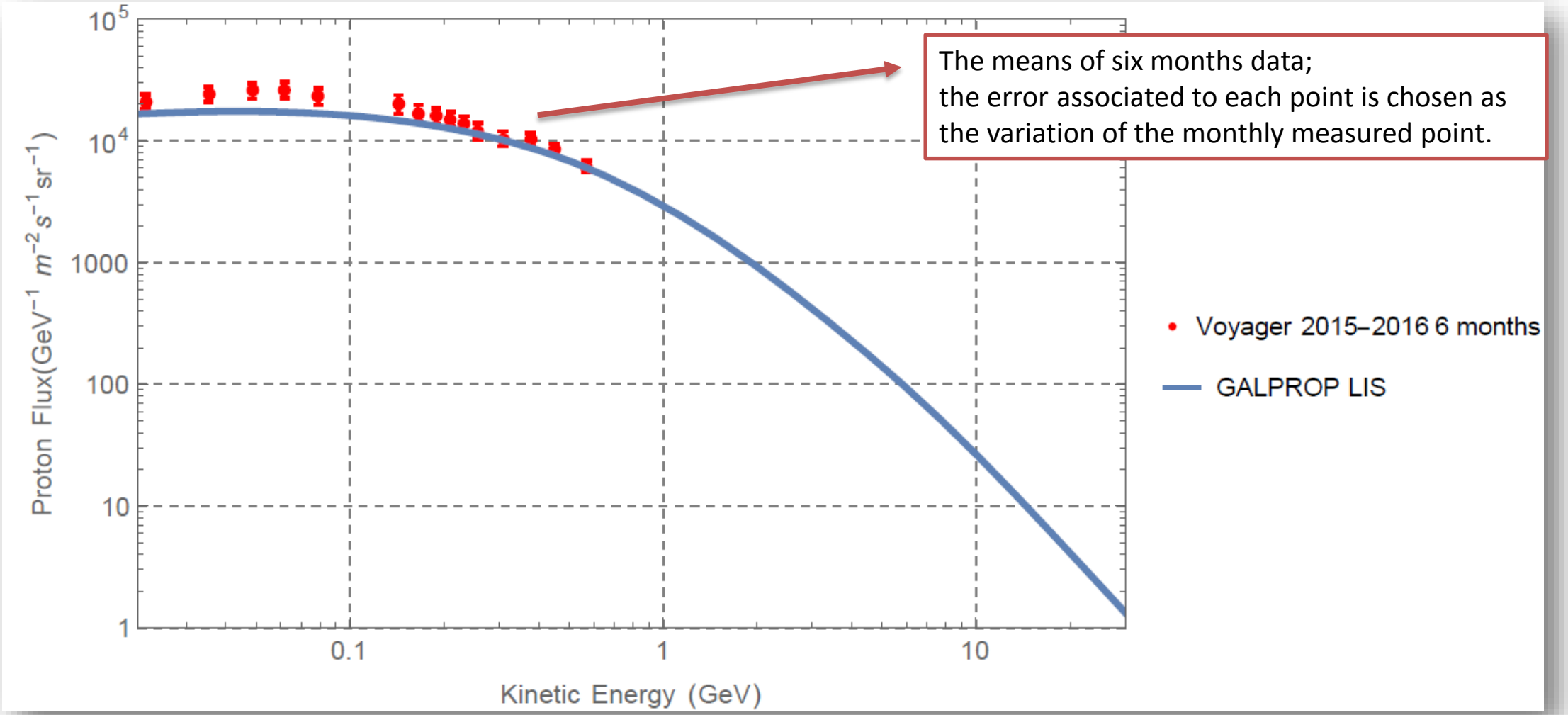
Ultra-low energy physics

AMS – Voyager1 interplay

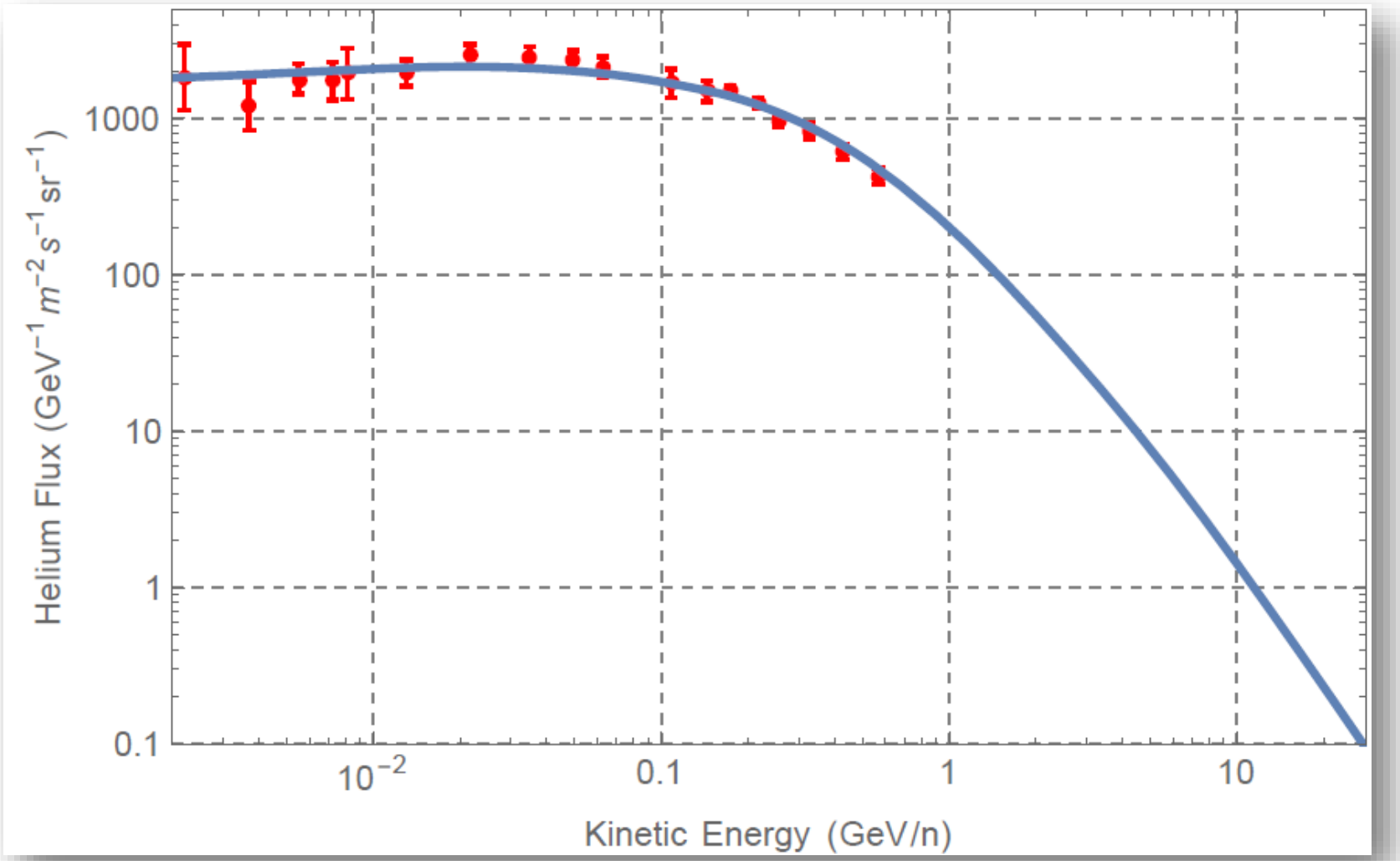


Simulated proton and He LISs have been successfully compared to Voyager1

Proton LIS vs Voyager-1



Helium LIS vs Voyager-1



The LISs show a good agreement with Voyager-1 data:

- Helium perfectly reproduces the shape of the interstellar measurements
- Protons fit Voyager-1 very well, in particular in the region above 100-200 MeV

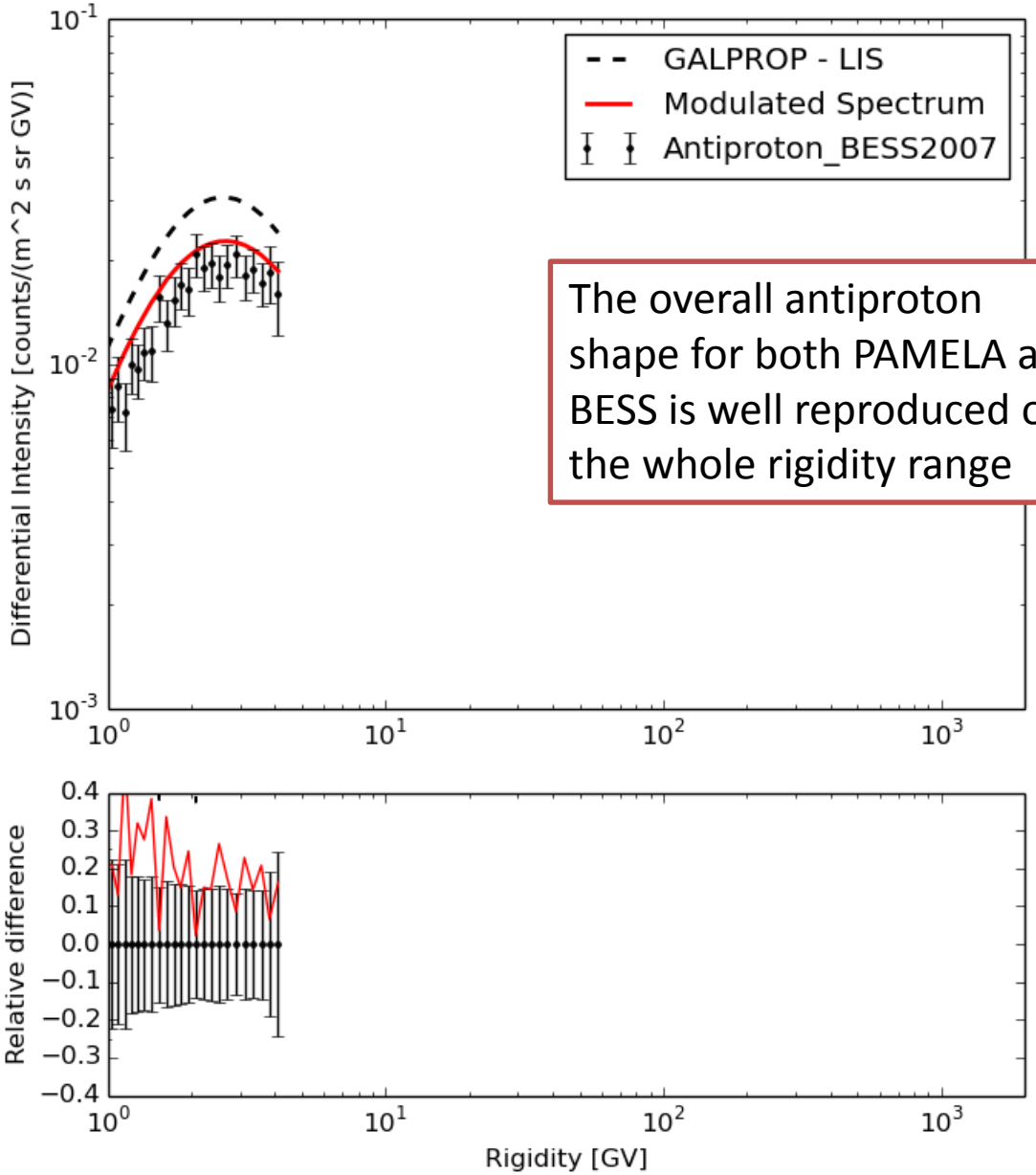
Low energy physics effects at this scale are not included nor calibrated in GALPROP, so this overall agreement is very encouraging and susceptible to future improvements

A new era for astroparticle physics

- AMS-02 data allow a deeper understanding of the «High Energy Universe» and do put the models to the test, highlightning theoretical inaccuracies and driving the models to a precision astroparticle physics;
- Fitting AMS-02 data with the ultimate **GALPROP** framework together with the **HelMod** Model of Heliosphere, a precise and almost univocal propagation scheme was achieved, granting a unitary description of CR physics at the 1-2 % level for protons and Helium;
- Once fixed the CR propagation parameters, the secondary background for DM (and exotic) searches can be removed;
- The proposed LISs accommodate both the very low energy interstellar CR spectra measured by Voyager 1 and the high energy observations at Earth publicly released by BESS, Pamela, AMS-01 and AMS-02;
- Forthcoming papers will be devoted to the description of electrons and positrons LISs, Boron over Carbon ratio and Boron, Carbon and Oxygen spectra, when available from AMS-02.

backup

Low Solar Activity



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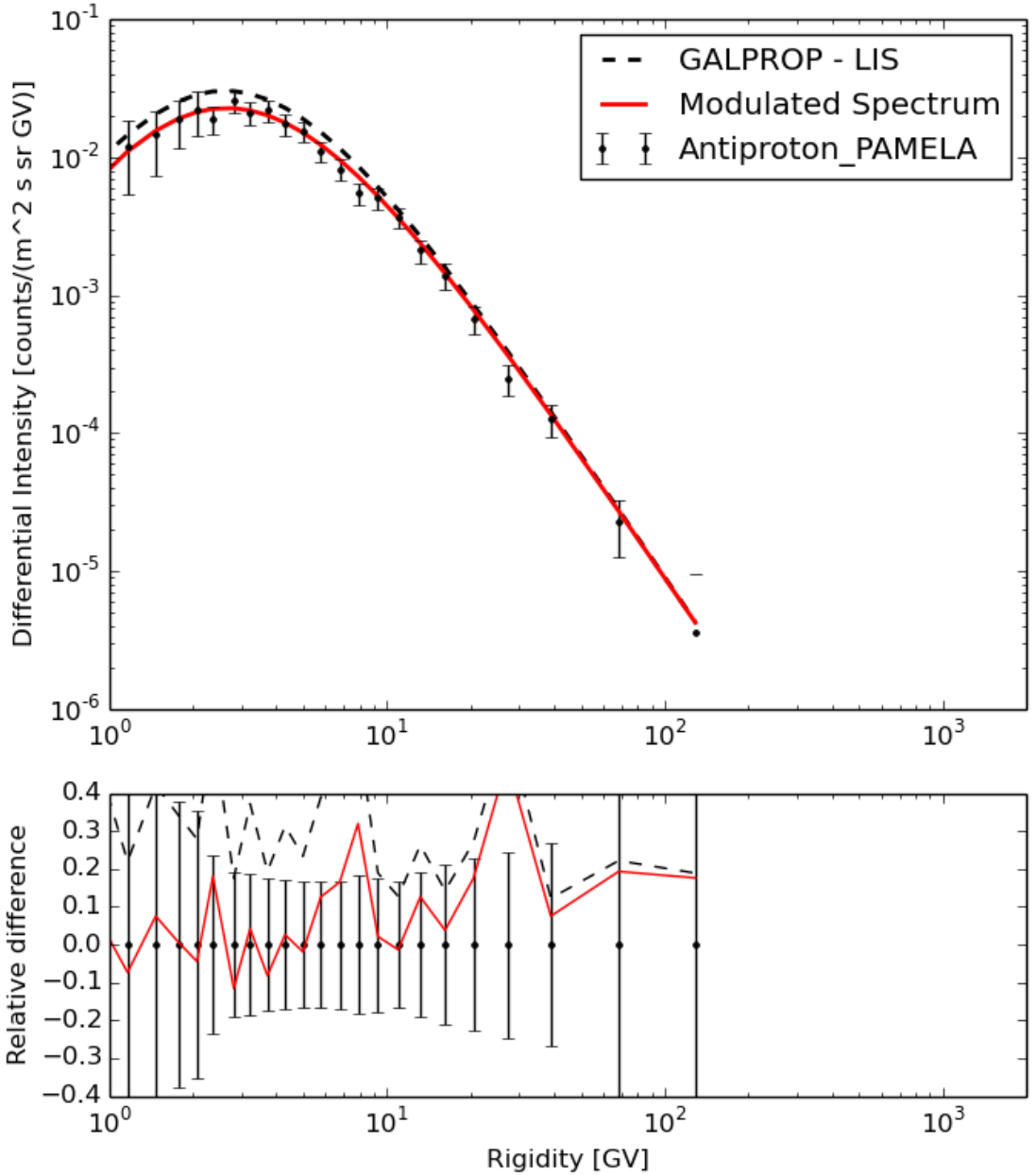
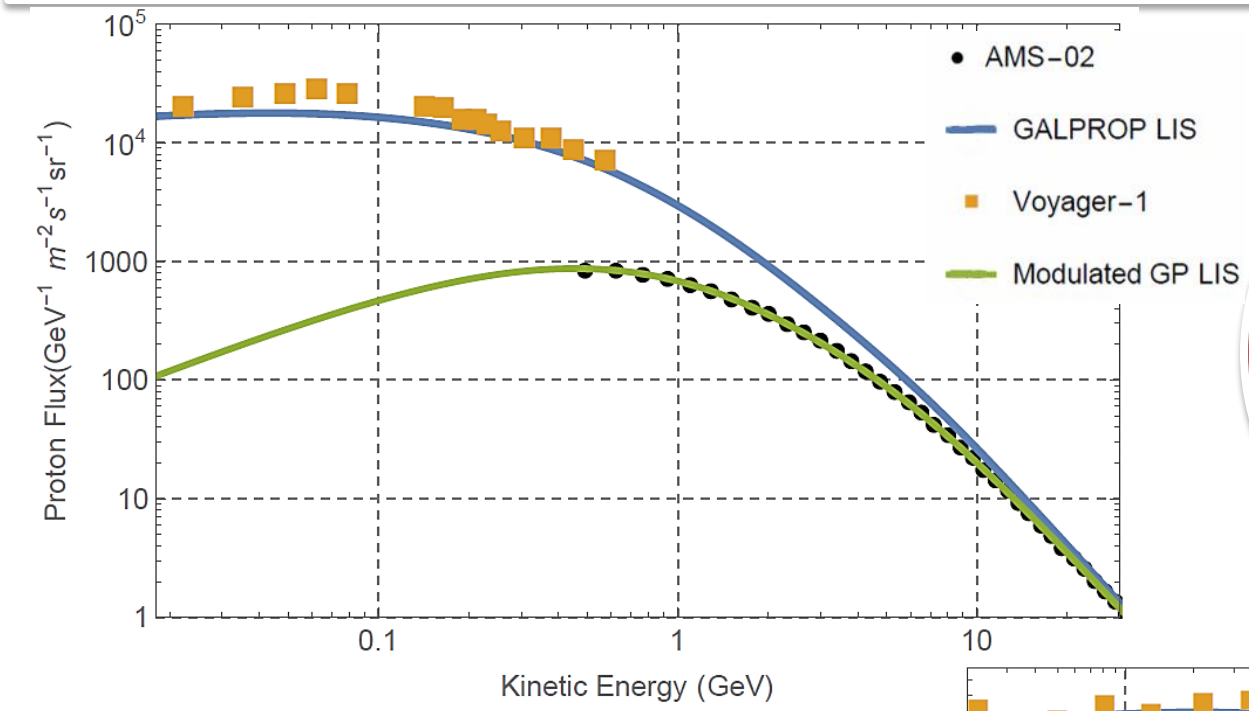
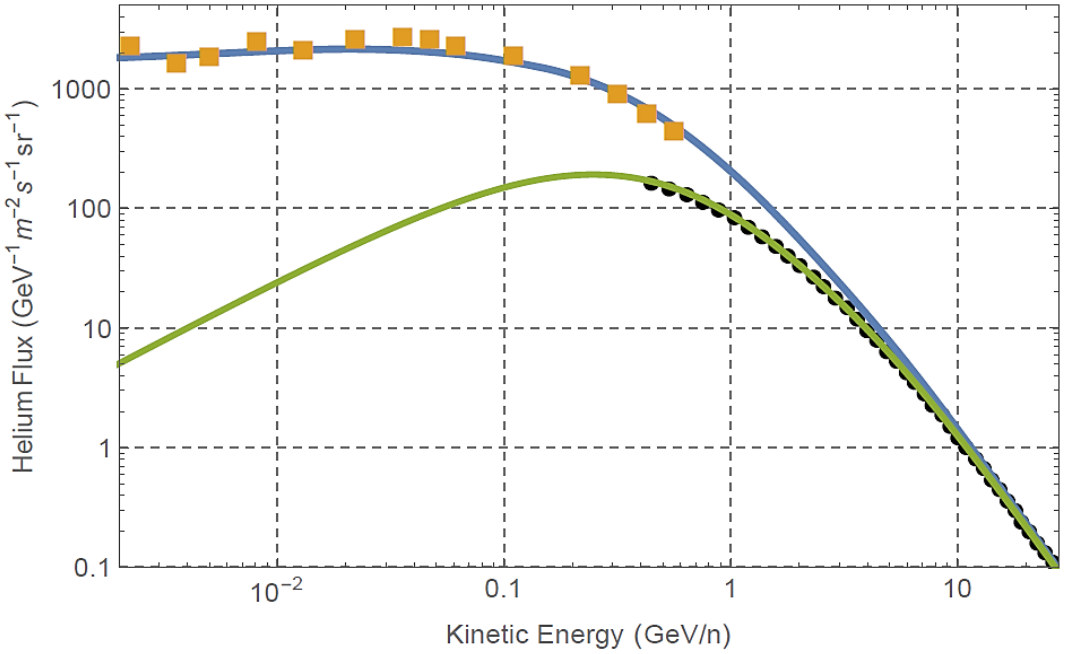


AMS – Voyager1 interplay



Simulated proton and He LISs have been compared to Voyager1

Once modulated, the LISs correctly reproduce AMS-02 (and also PAMELA, BESS, AMS-01…)



Results: Spectra and Ratios Fits @ % level