SDO/AIA – 193 2013/07/18 00:28:54

The HelMod model: highlights on recent developments

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AMS Italy meeting

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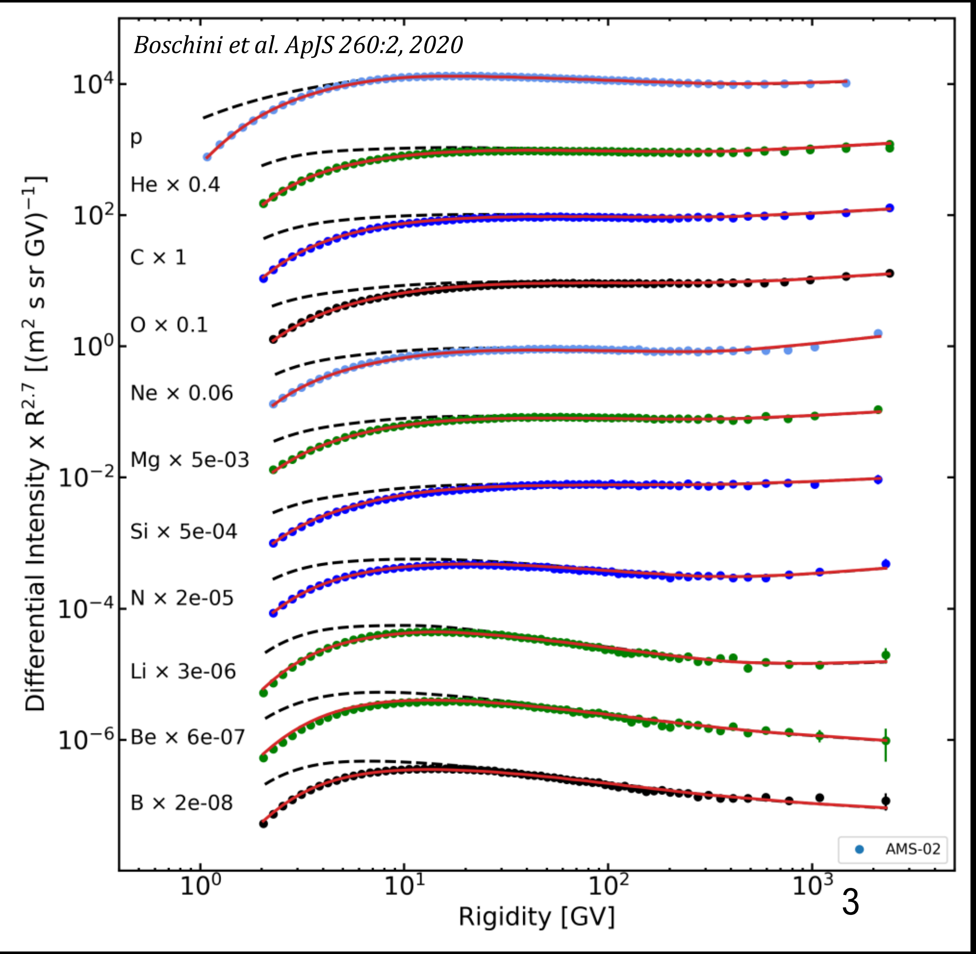
HelMod: The Cosmic ray model for space radiation environment

HelMod: The Cosmic ray model for space radiation environment

www.helmod.org

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

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



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
Boschini et al. ApJ 913:5, 2021
Boschini et al. ApJ 925:108, 2022
Boschini et al. ApJ 933:147 2022

The GalProp-HelMod join effort:

The Local Interstellar Spectrum (LIS) were estimated using an iterative procedure involving GALPROP, HelMod and latest GCR observations.

A summary for Ions with Z<=28
Boschini et al. ApJS 260:2, 2020

HelMod is available as online calculator at www.helmod.org

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Recent milestone publications

Boschini et al. (2022a) Adv. S. Res. 70(9):2636 *The transport of galactic cosmic rays in heliosphere: The HelMod model compared with other commonly employed solar modulation models*

Boschini et al. (2022) Adv. S. Res. 70(9):2649 *Forecasting of cosmic rays intensities with HelMod Model.*

Boschini et al. (2019) Adv. S. Res. 64(12):2459 *The HelMod model in the works for inner and outer heliosphere: From AMS to Voyager probes observations*.

Boschini et al. (2018) Adv. S. Res. 62(10):2859 *Propagation of Cosmic Rays in Heliosphere: the HelMod Model.*

Bobik et al. (2016) JGR. 121(5) *On the forward-backward-in-time approach for Monte Carlo solution of Parker's transport equation: One-dimensional case.*

Bobik et al. (2013) Adv. Ast., ID 793072 *Latitudinal Dependence of Cosmic Rays Modulation at 1 AU and Interplanetary Magnetic Field Polar Correction.*

Bobik et al. (2012) ApJ 745:132 *Systematic Investigation of Solar Modulation of Galactic Protons for Solar Cycle 23 Using a Monte Carlo Approach with Particle Drift Effects and Latitudinal Dependence.*

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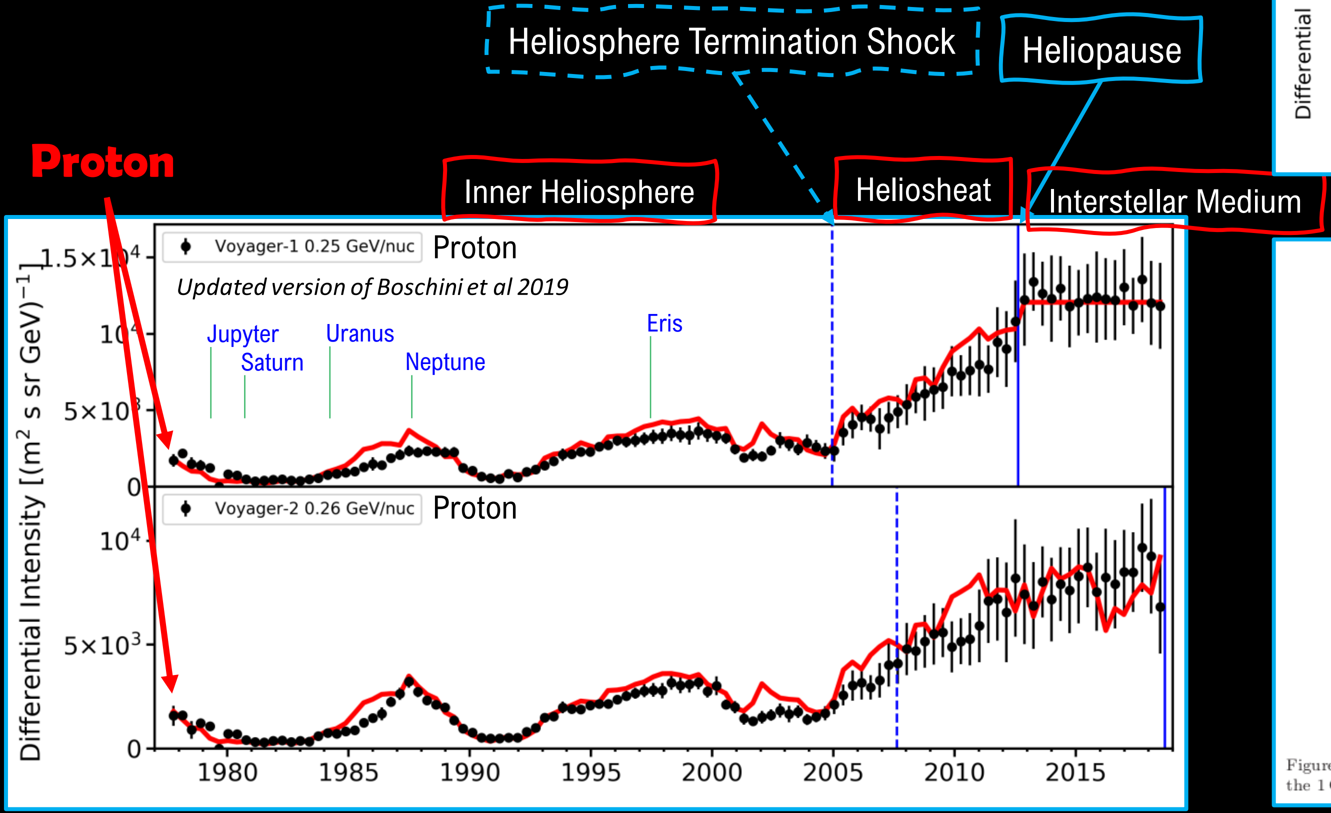
HelMod can reproduce ions:

- along the full 22 years solar cycle
- At several solar distance
- Outside the ecliptic plane



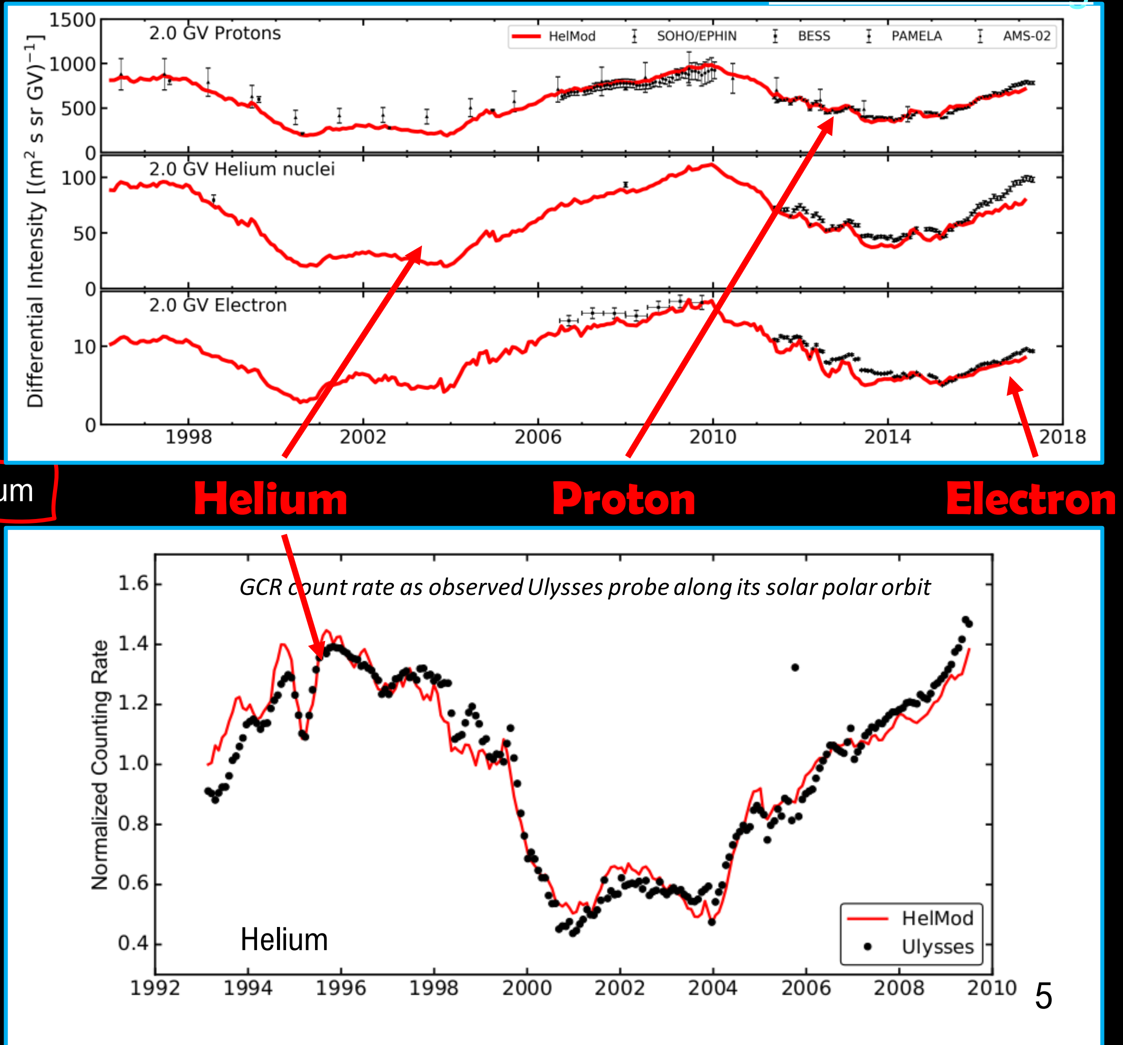


Figure 8: Helium normalized counting rate measured by Ulysses (full black circles) at ±80° of solar latitude and 1 to 5 AU compared with the 1 GeV energy modulated spectrum from HelMod code (red solid line) as function of time.

Comparison with other models

International standards (ECSS-E-ST-10-04C) were defined in order to provide simple and easy-to-use space radiation environment descriptions.

- empirical approaches
- ~20% uncertainty on the effective dose
- Validated at Earth orbit only

Comparison with other models

ISO Model 15390:2004, from ECSS-E-ST-10-04C – Space environment
ISO/TC 20/SC 14 Space systems and operations, June 2004

*ISO-DLR A **simplified version of the ISO-15390 model**, modified in order to **reduce the number of free parameters to one***
Matthia, D., Berger, T., Mrigakshi, A.I., Reitz, G., Adv. Space Res. 51: 329-338, 2013

Cosmic Ray Effects on MicroElectronics Code (CRÈME) GCR model based on Nymmik *et al.* (1992)
CRÈME96 – Tylka et al. 1997 IEEE Transactions on Nuclear Science44(6), 2150–2160.
CRÈME2009 – update of CRÈME96 (https://creme.isde.vanderbilt.edu/)

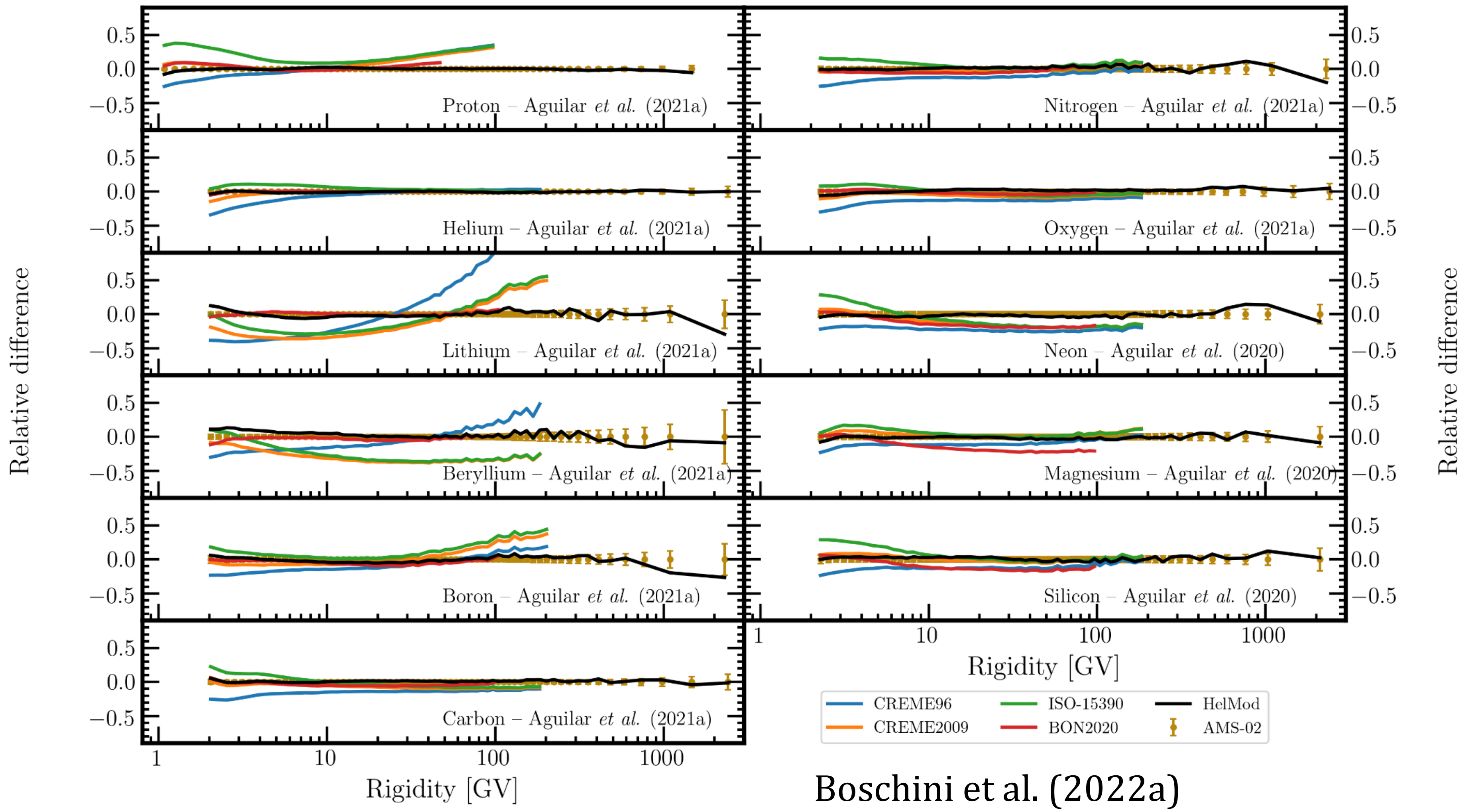
Badhwar-O'Niell (BON) model - *NASA GCR environment tool*
Slaba, T.C., Whitman, K., 2019. The Badhwar-O'Neill 2020 Model, Technical Report NASA/TP-2019-220419 NASA, USA

ECSS-E-ST-10-04C (2020) - Section 9.2.3 - suggested to adopt the approximation for which the GCR differential flux is taken uniform throughout the heliosphere

See also Sect. 9.3 *ECSS-E-ST-10-04C* (2020)

Comparison with other models

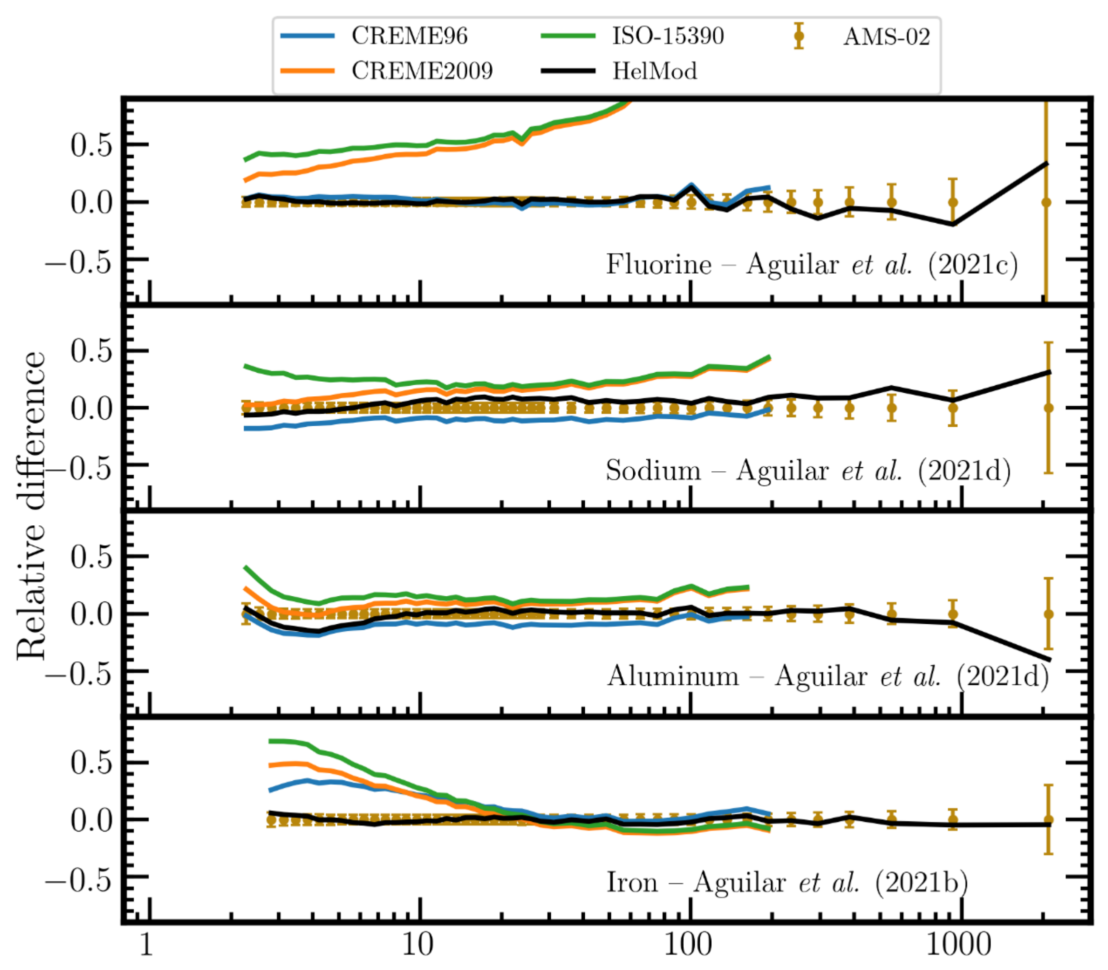
www.helmod.org



Boschini et al. (2022a)

HelMod looks to exhibit an overall better agreement with AMS–02 data concerning the other solar modulation models here discussed

Comparison with other models

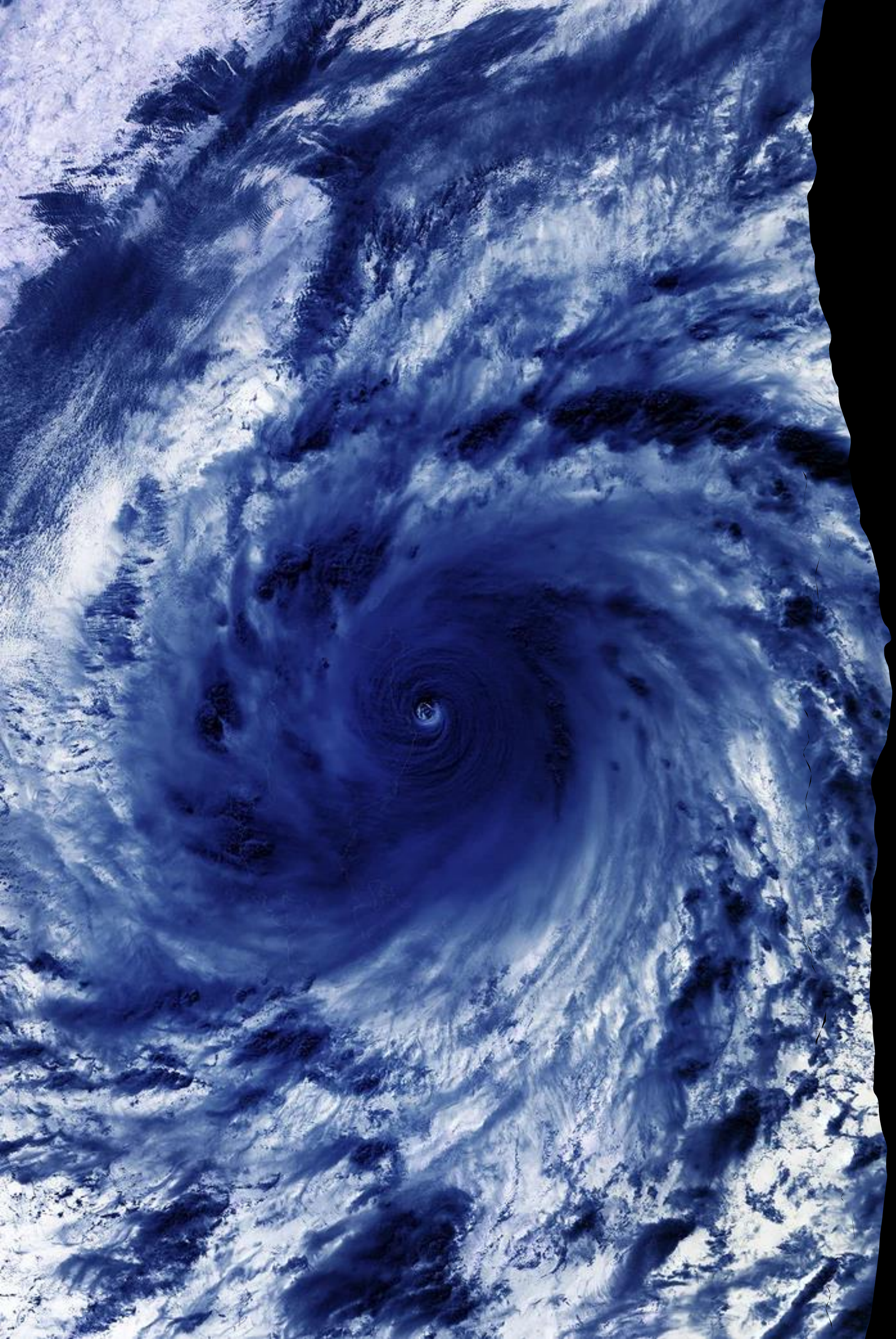


Boschini et al. (2022a)

www.helmod.org

HelMod was found to achieve a good agreement over the full set of experimental data with, typically, **$\Delta\Phi$ within ±2.5% and RMS within 5%.**
Usually larger or, in a few cases, much larger values for $\Delta\Phi$ and ηRMS were found for the other models.

HelMod looks to exhibit an overall better agreement with AMS–02 data concerning the other solar modulation models here discussed



Forecast

The modulated GCR intensity is directly predicted employing the heliospheric parameters such as sunspot numbers, solar wind speed & density,…

The historical value of previous cycle allow to make a prediction for future cycles

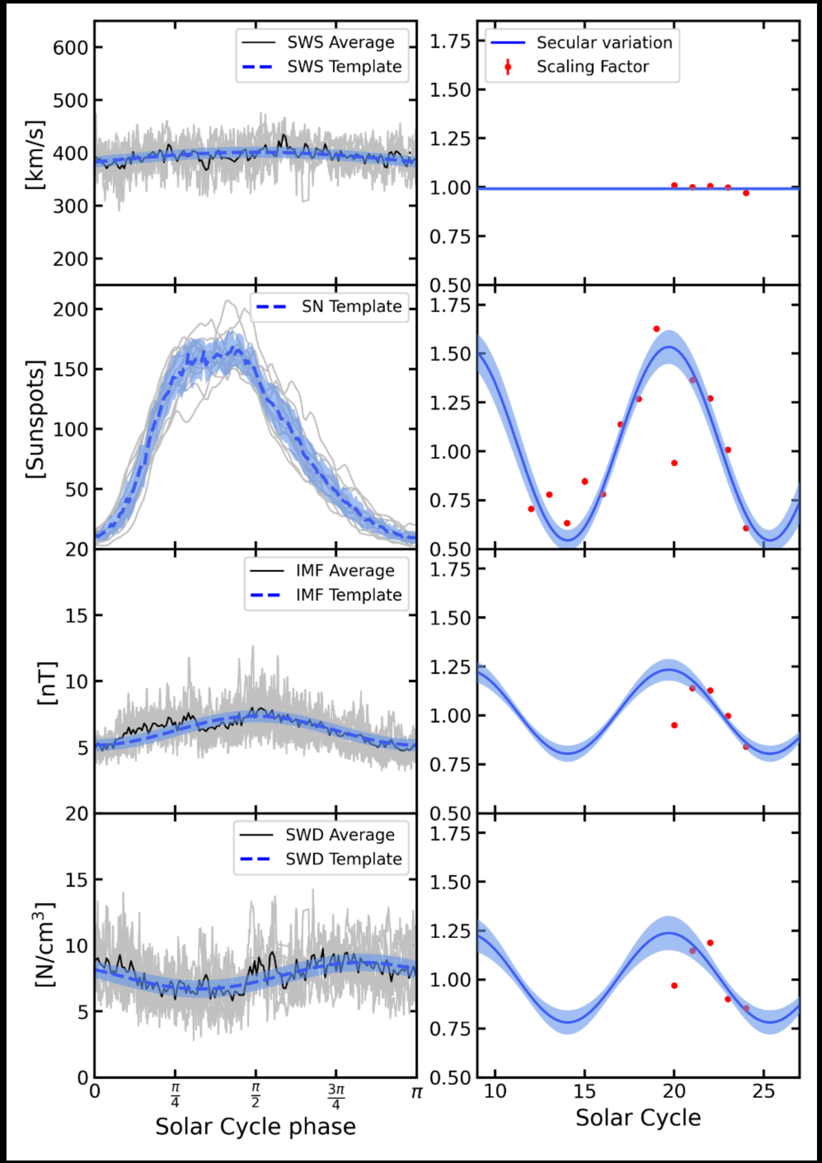
Boschini et al. (2022b) Adv. S. Res. *In press*

Forecast

The procedure is used to forecast:

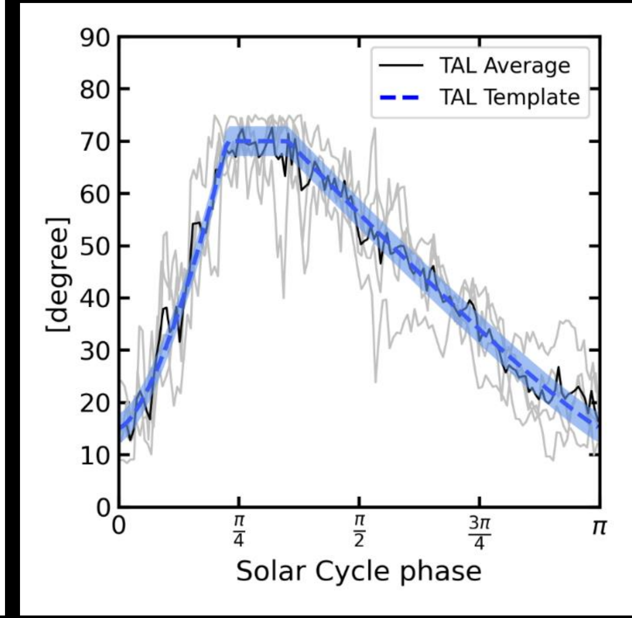
- Sunspot numbers
- Tilt Angle of Neutral Sheet
- IMF
- Solar Wind Speed
- Plasma Density

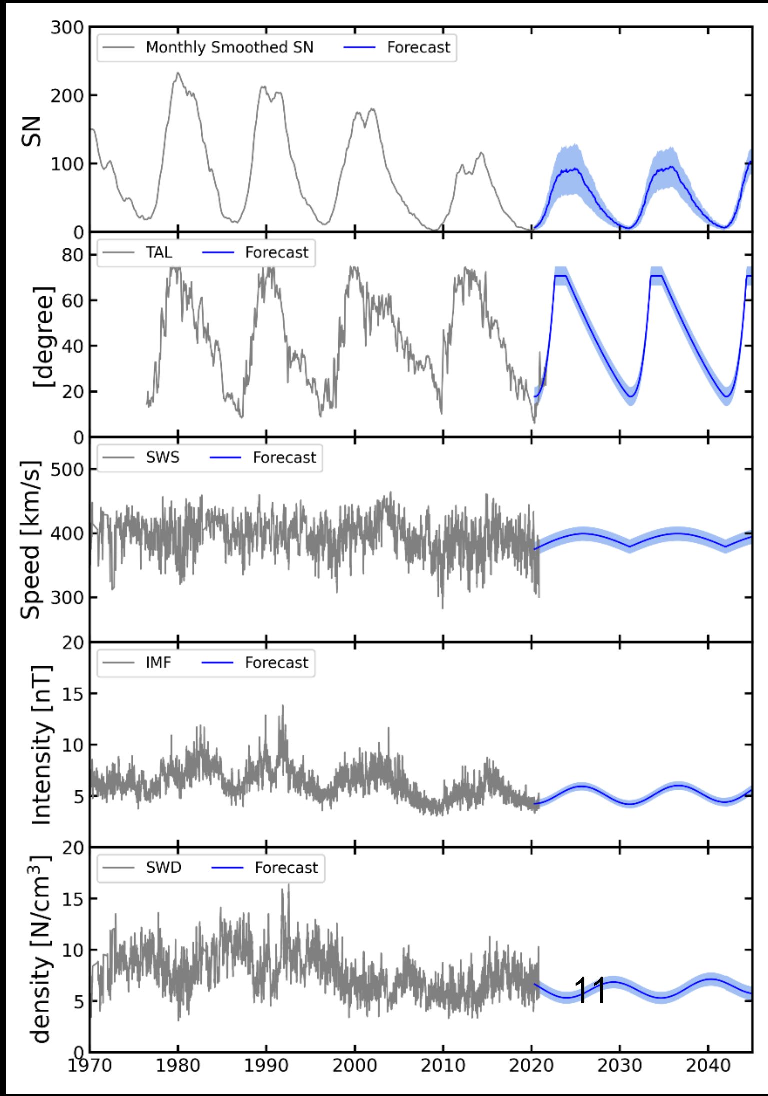
The procedure can optimize the forecast up to 3-5 years using the measured parameters of last 3 years



We interpolate the effect of Gleissberg cycle on each parameter template to highlight the secular variation

For further details, see Boschini et al. (2022b)





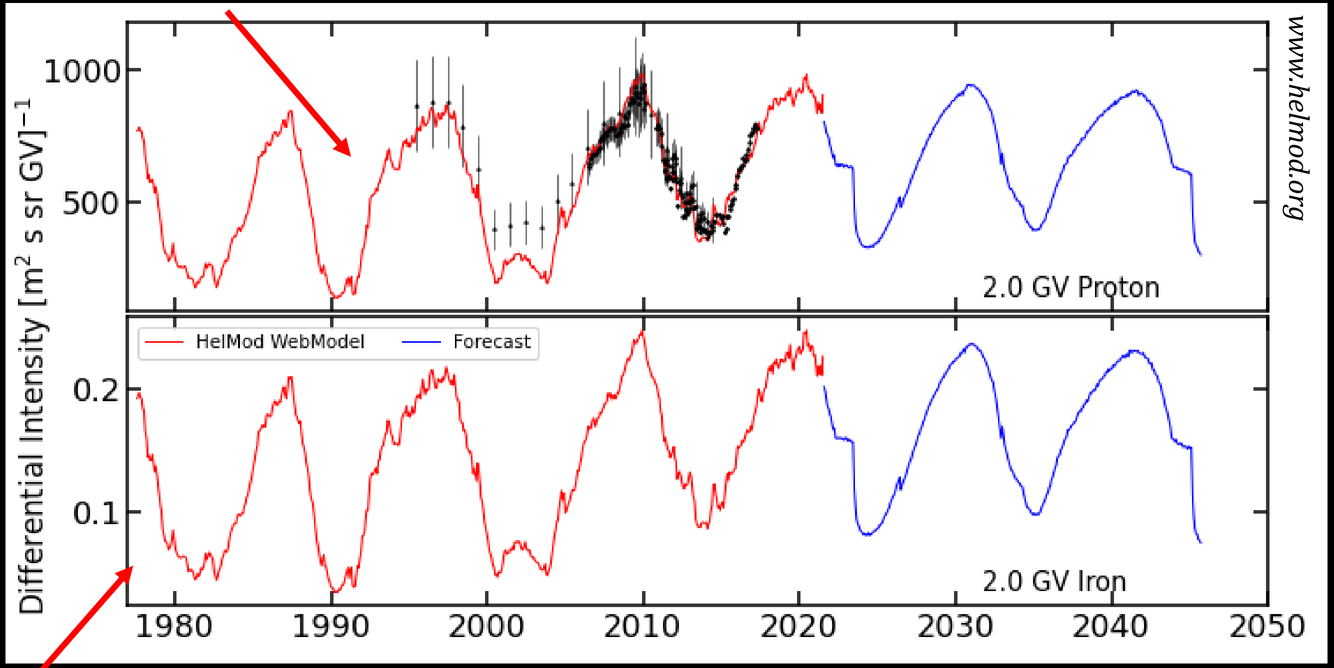
Forecast

The accuracy is estimated applying the procedure in past years in order to compare them with the HelMod simulations reproducing missions' data. In these case any discrepancy between the two are due to the forecasting method itself.

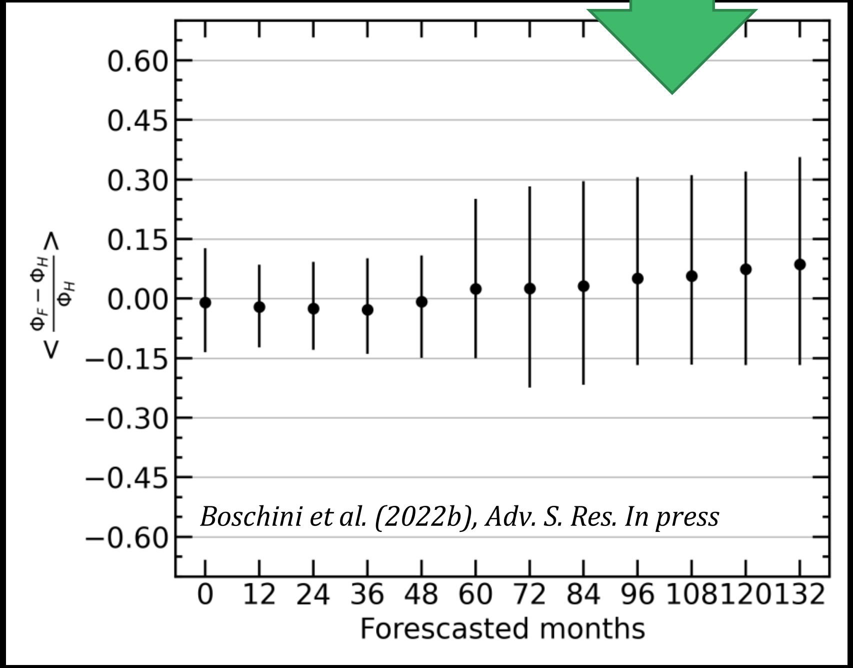
The forecasting procedure can reproduce HelMod fluences with an accuracy:

- **below 5% (±10% at 68% C.L.) for short time predictions (up to 4 years)**
- **below 15% (±(20−25)% at 68% C.L.) for long time predictions (up to 9 years).**

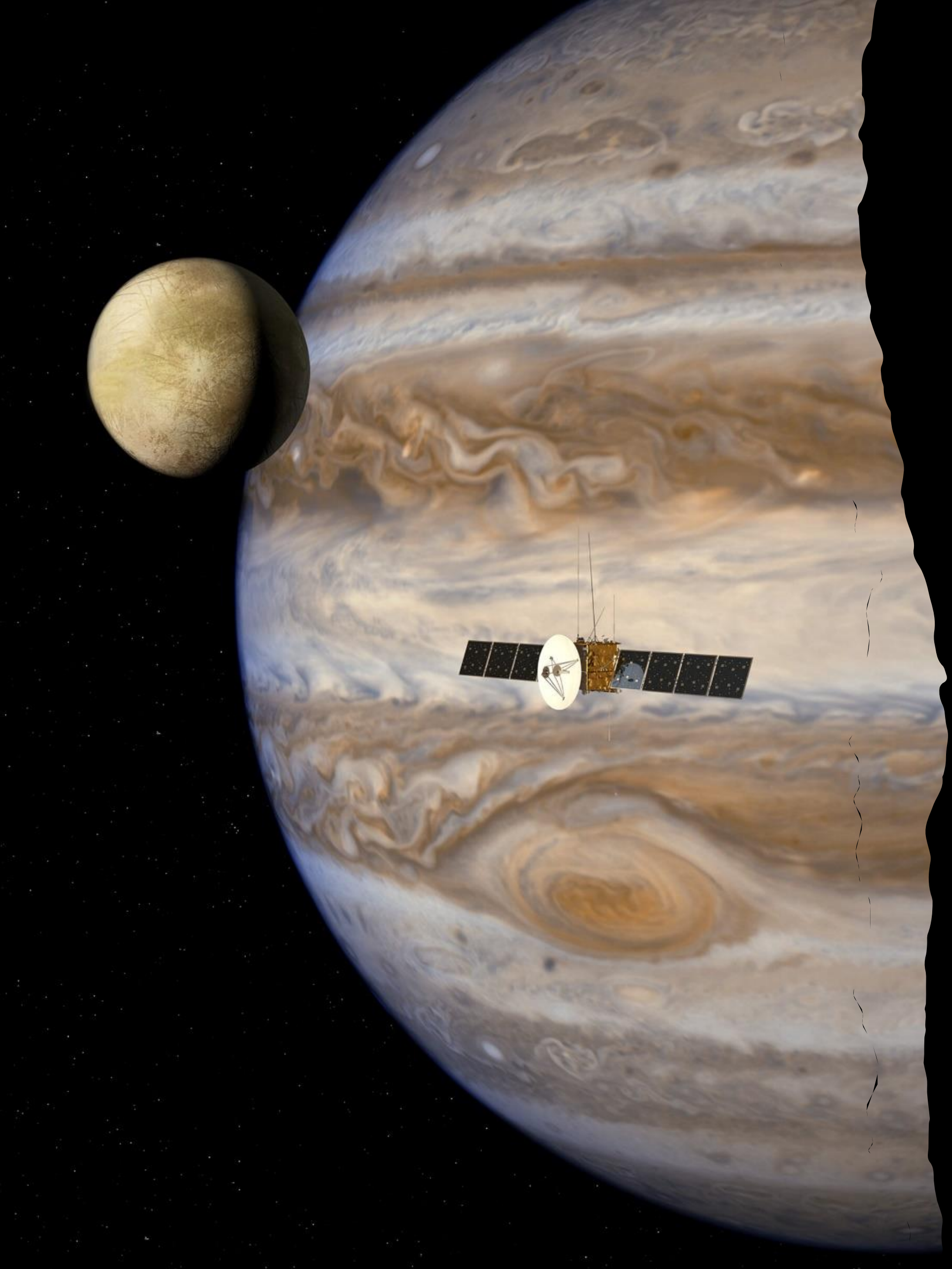
Proton



Iron Differential intensity at 2 GV (red is HelMod, Blue is forecasted HelMod)



Average Relative difference fluence evalauted with Helmod and with forecast procedure



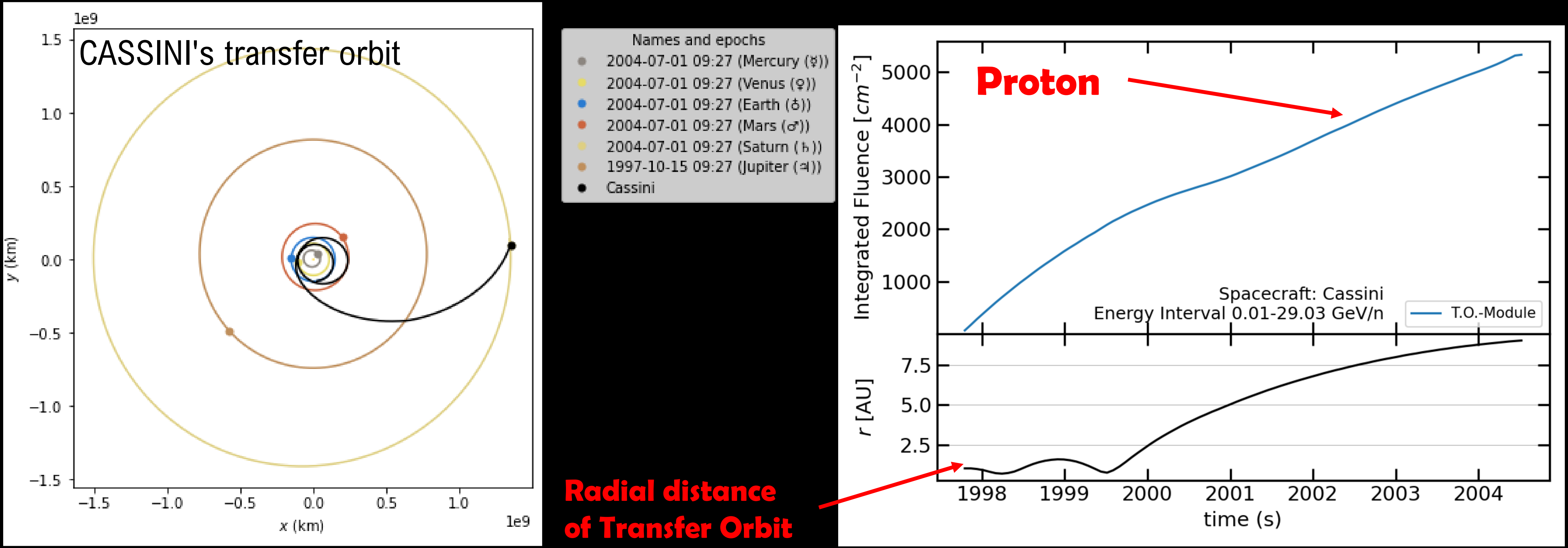
Transfer orbit fluence calculator

GCR spectra increase with increasing the solar distance.

This gradient depends on solar activity and global magnetic field polarity

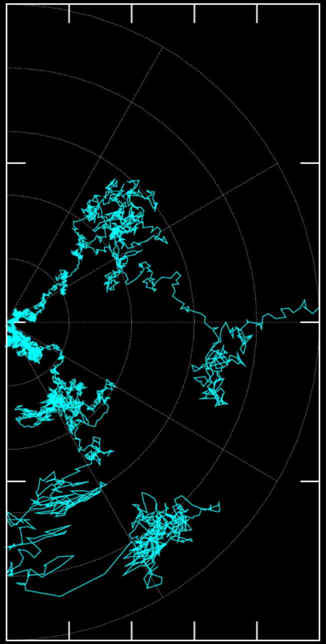
Transfer orbit fluence calculator

HelMod can evaluate the GCR fluence at any orbital position in the inner heliosphere



A proper fast calculator is available on HelMod.org to provide an immediate estimation of GCR fluence on transfer orbits provided by the user

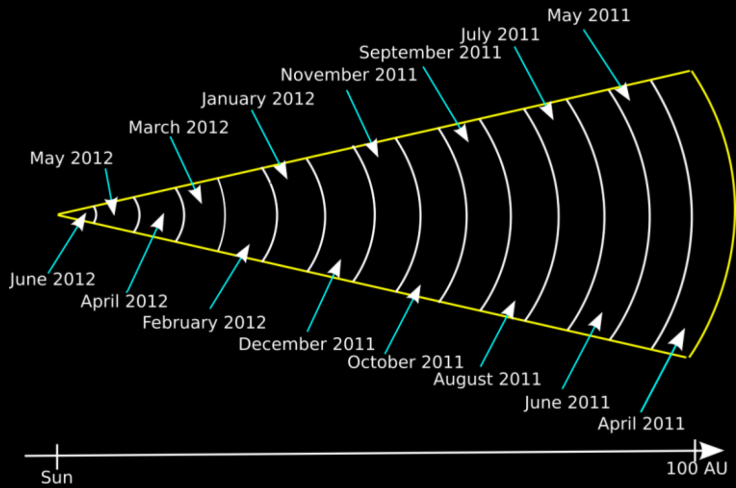
HelMod: The Cosmic ray model for space radiation environment

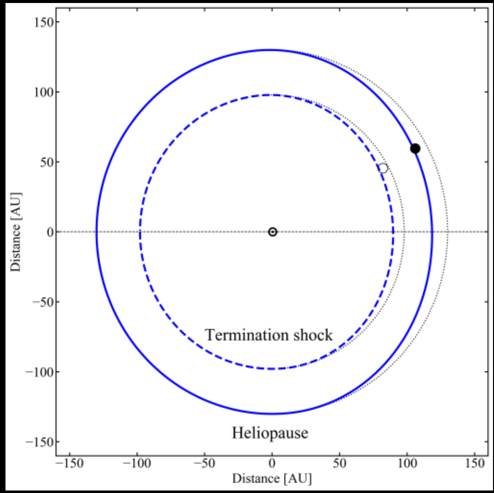


HelMod numerically solves the Cosmic Rays Propagation Equations With a Backward-in-time Monte Carlo Approach

The model describes the interplanetary medium following the solar disturbances propagation time from the Sun.

Model is tuned along a complete 22years solar cycle using CR Proton data with the highest statistics and lowest systematics.
The same parametrization is then applied to all nuclei

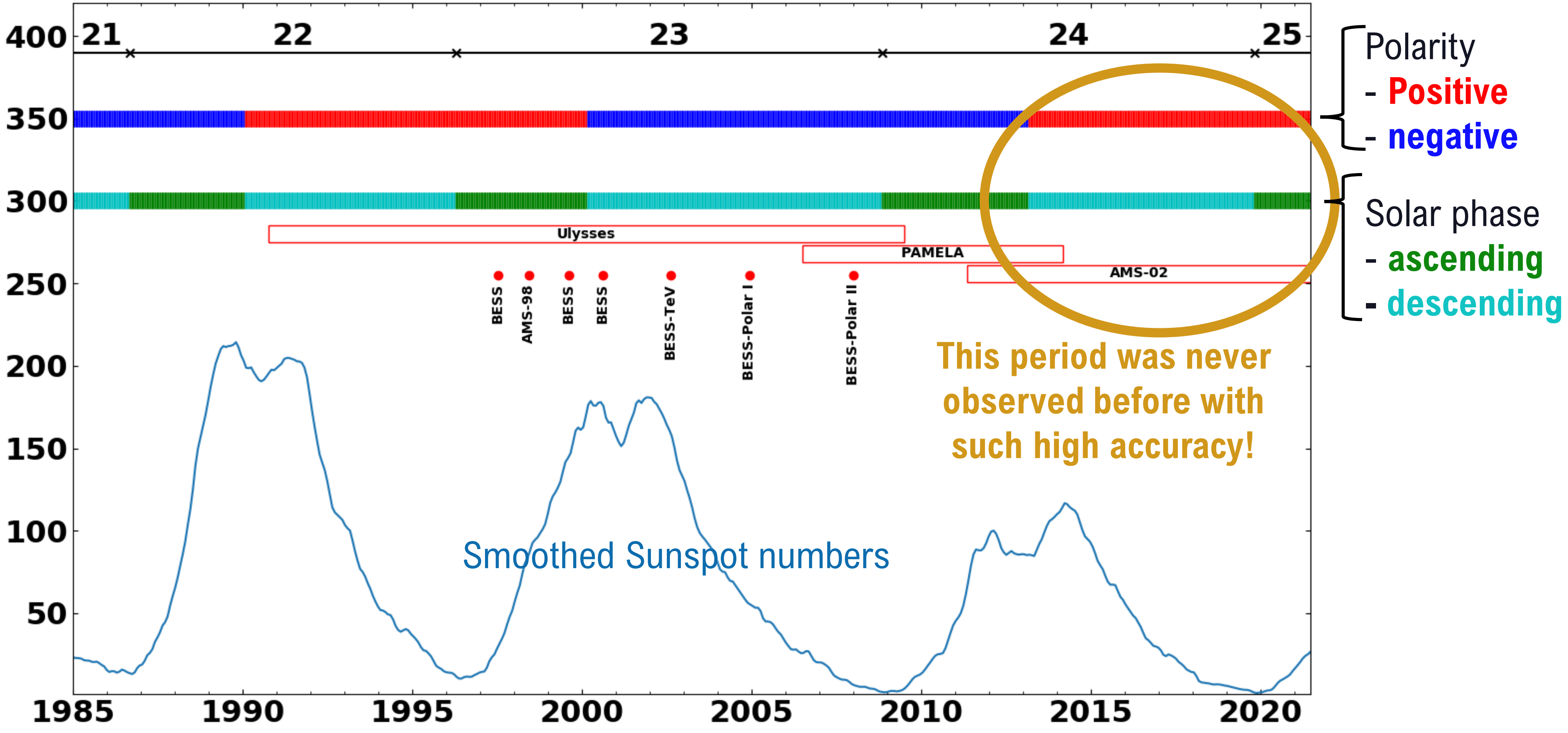




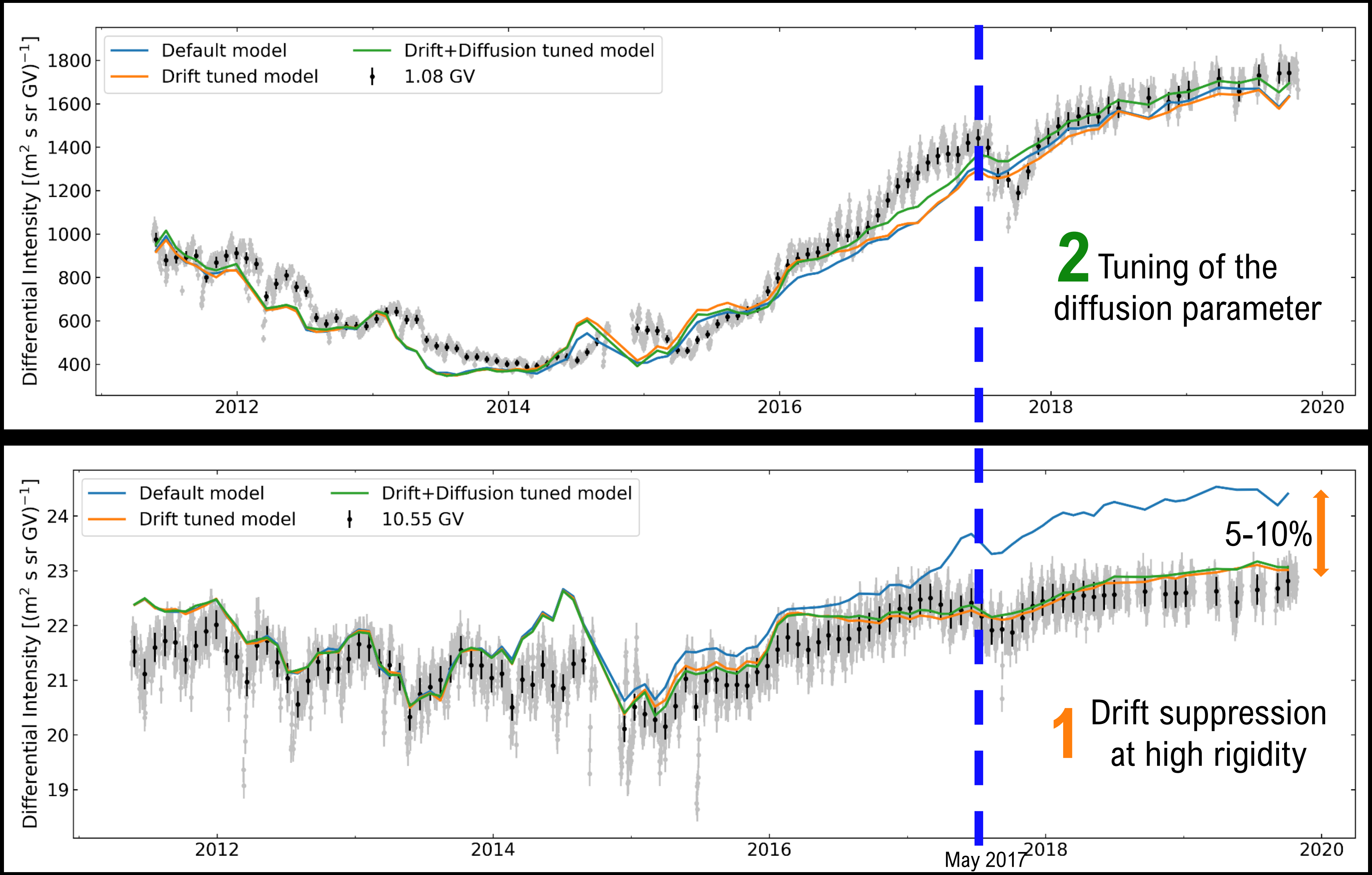
AMS-02 data are the only data available for tuning the model during the present period (positive polarity)

On-going:
Tuning HelMod using
the latest AMS-02 proton (daily) fluxes

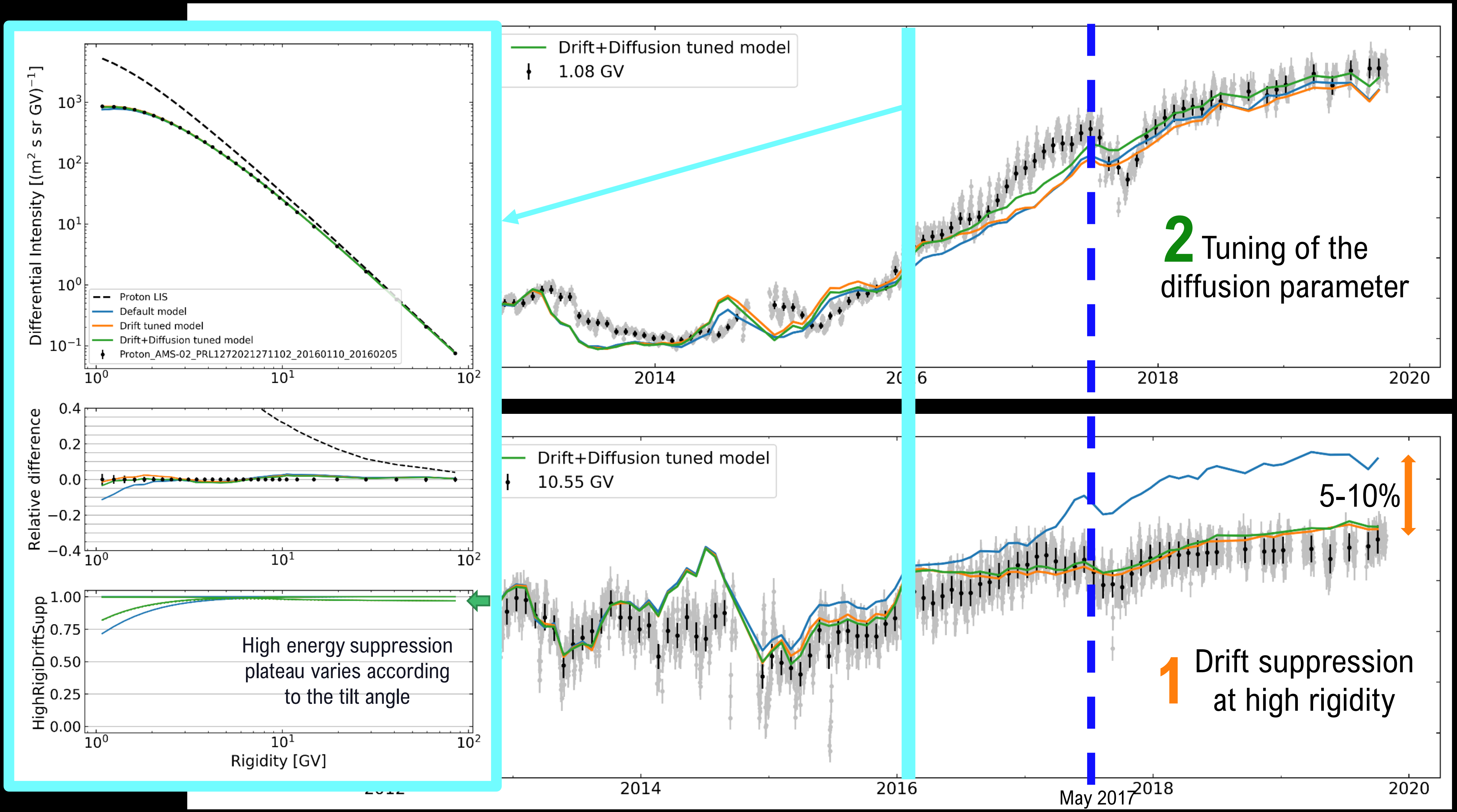
Tuning HelMod on latest AMS-02 proton flux data



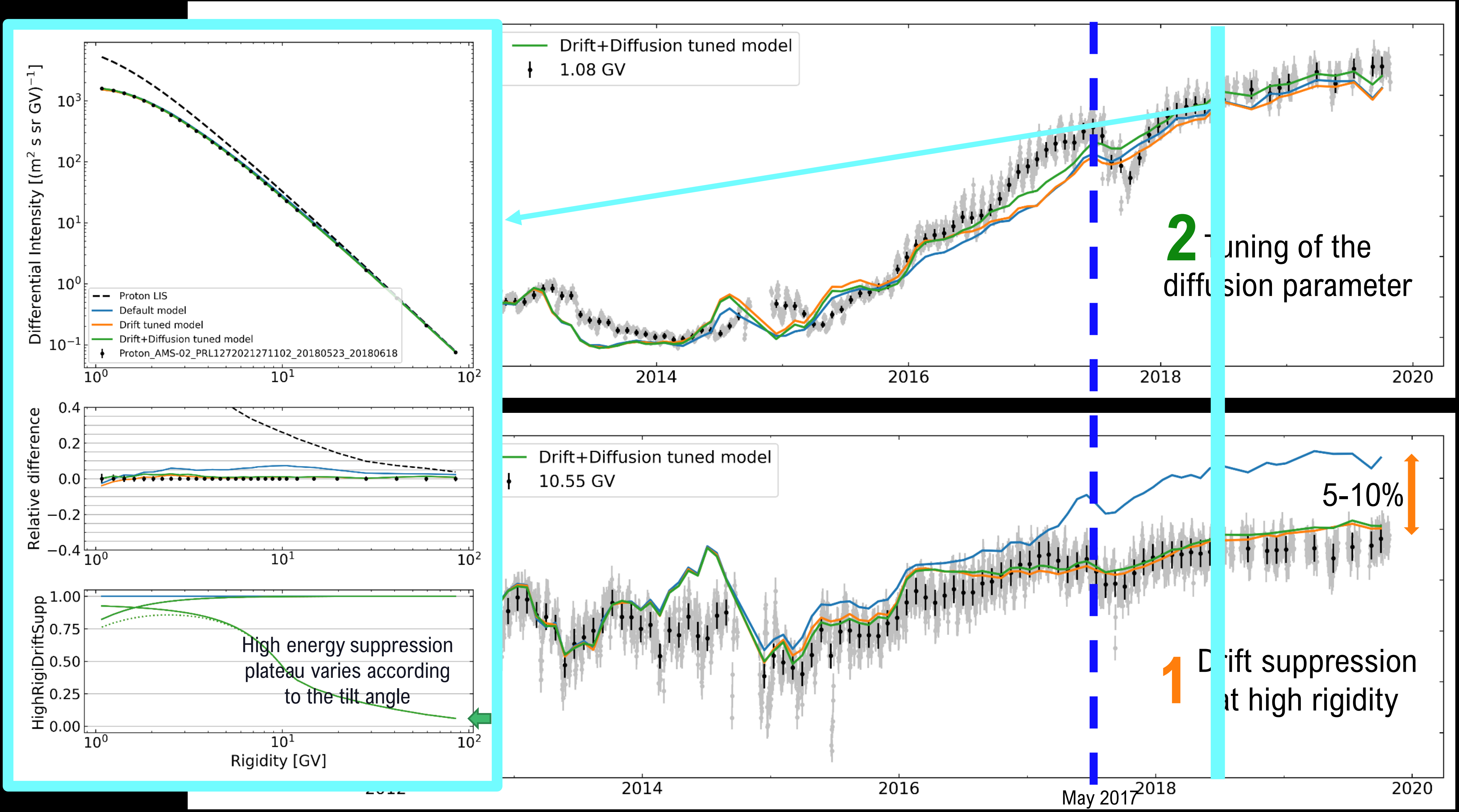
Tuning HelMod on latest AMS-02 proton flux data



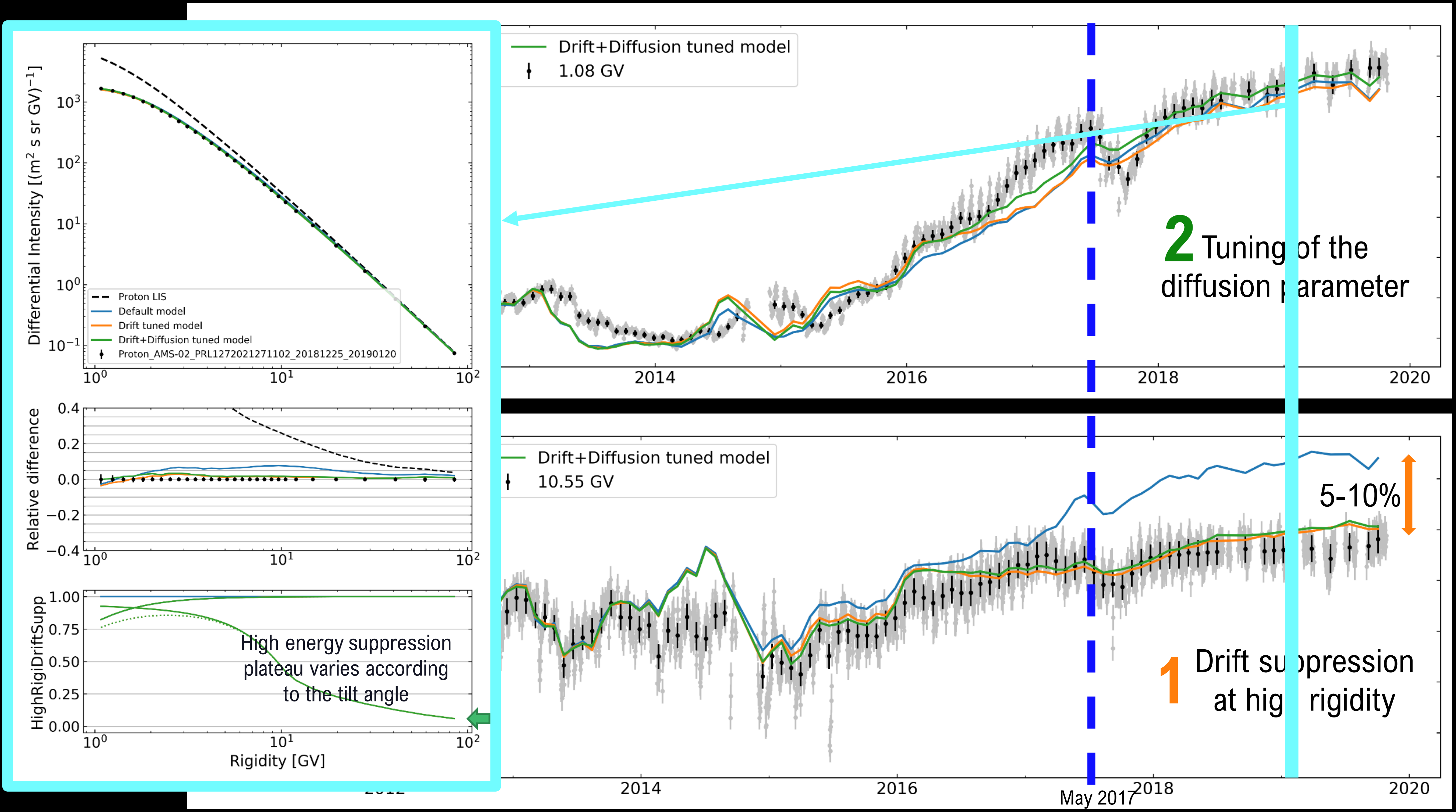
Tuning HelMod on latest AMS-02 proton flux data



Tuning HelMod on latest AMS-02 proton flux data



Tuning HelMod on latest AMS-02 proton flux data



On-going: HelMod-4-CUDA

HelMod-4-CUDA

Particle propagation in a realistic heliosphere, including heliopause, is a cpu-time consuming activity. Moreover, large set of data with ~% accuracy require a larger computation effort to match the same accuracy and time-granularity

The parallel computing on Graphical Processor unit is an established technique used in many field:

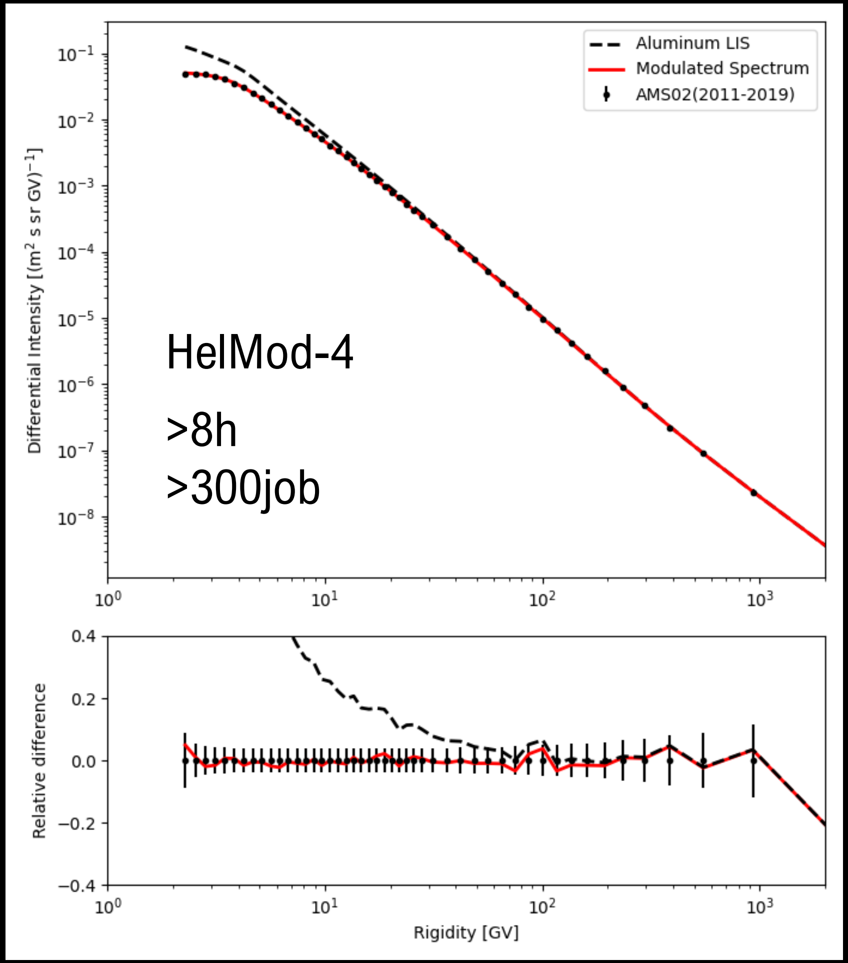
- Gaming
- Graphics/Rendering
- Cripto
- Machine learning

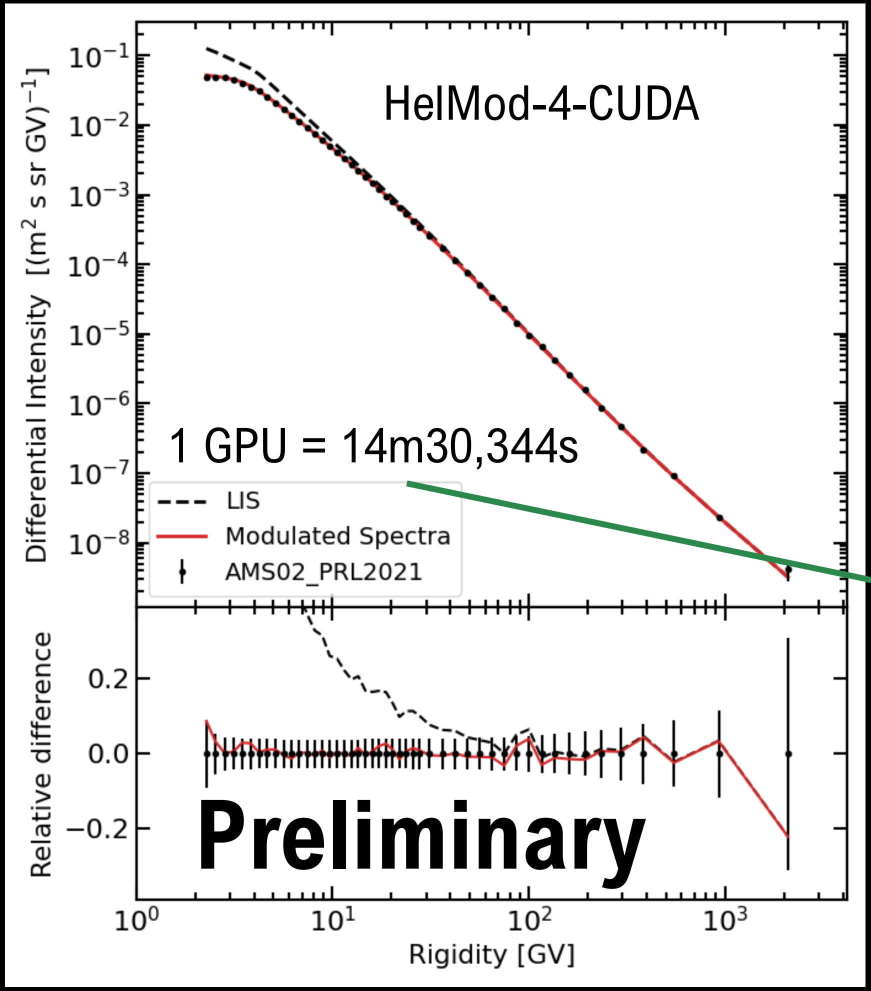
GPU well suit with problem with computational approach *single instruction, multiple data (SIMD) —> All processors in a SIMD-parallel architecture execute the same instruction at the same time;*

HelMod use Monte Carlo SDE integration → same equations are computed recursively from Detector to Source → That’s a GPU Job!

HelMod-4-CUDA

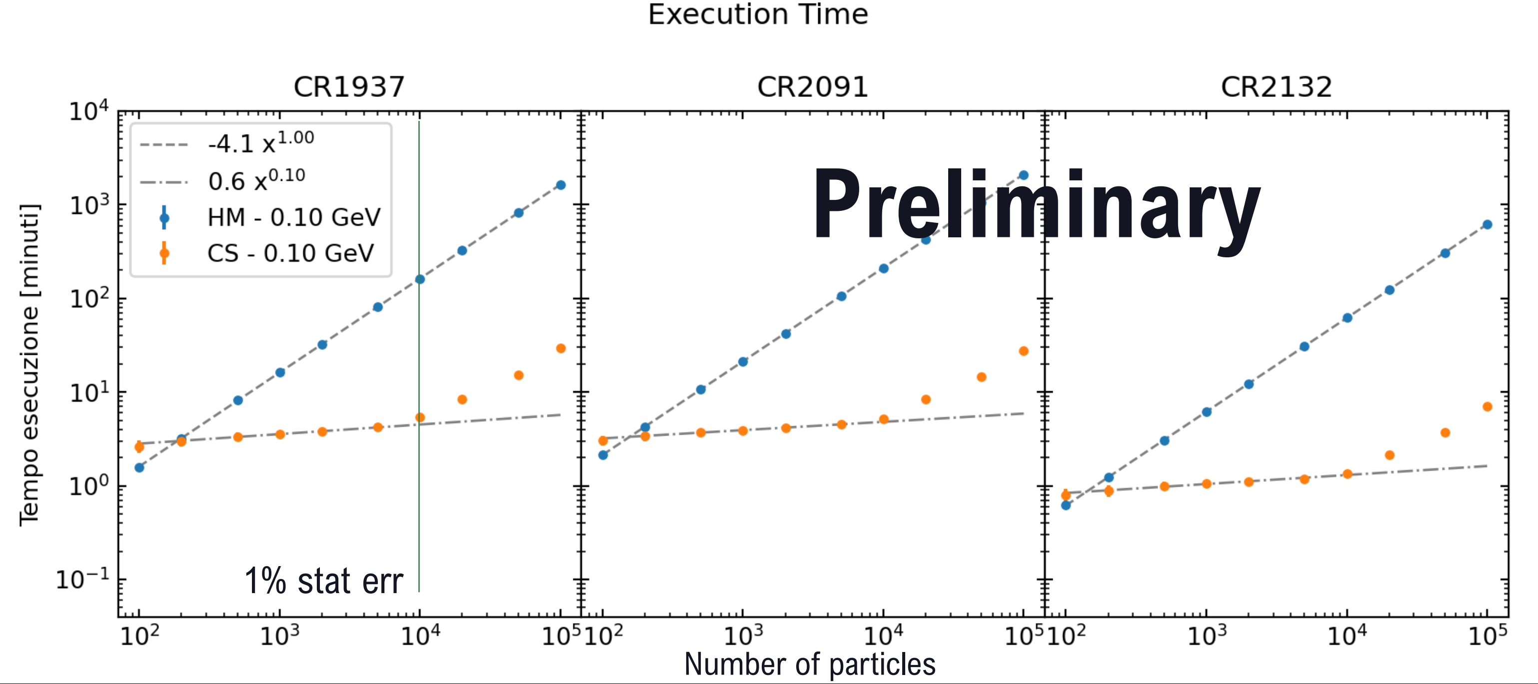
We are re-designing the model in C-CUDA language to profit of all best performance from NVIDIA hardware



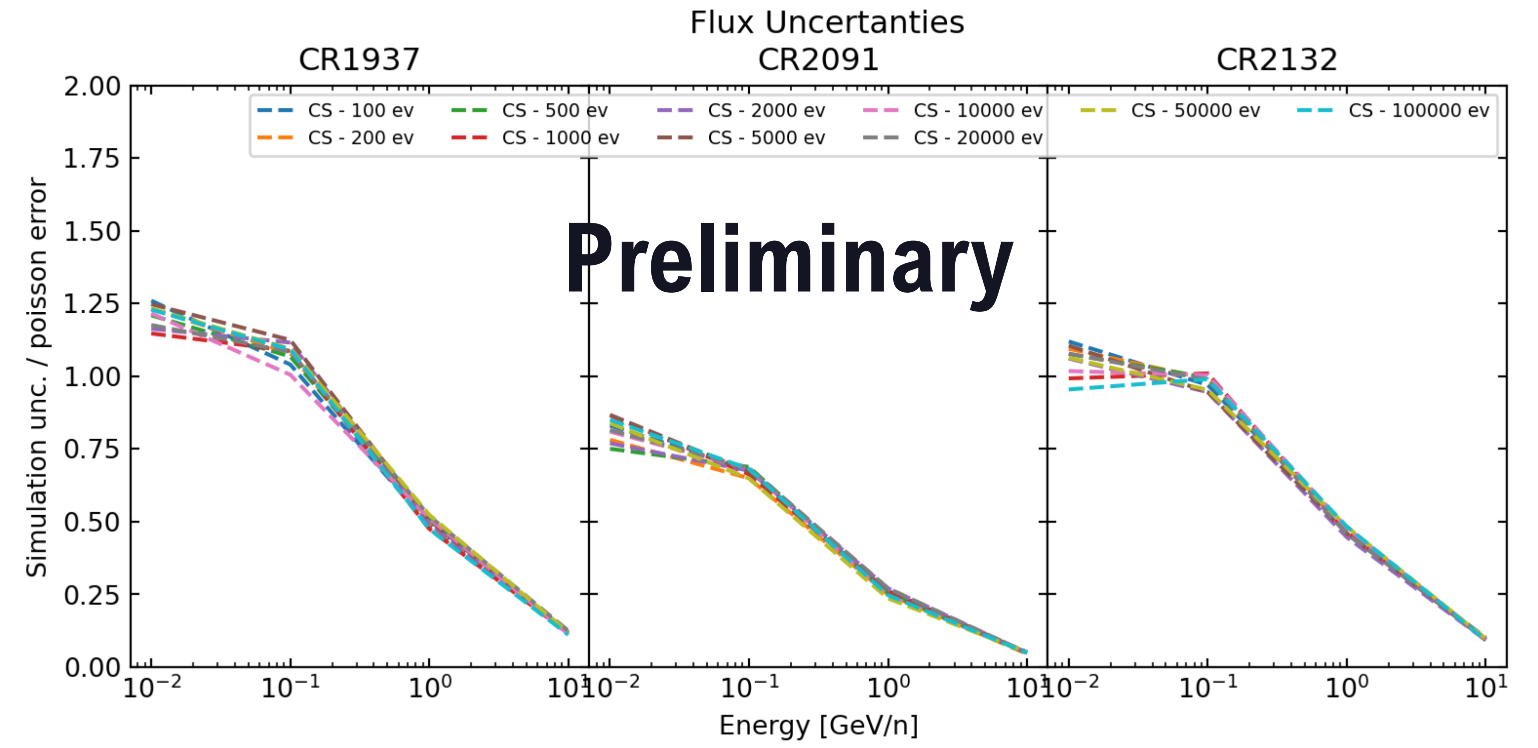


without any Algorithm and compiler optimization

HelMod-4-CUDA



The speed improvement is more than one order of magnitude a 1% stat. accuracy



This speed-up allows to compute the first estimation of the systematic uncertainties due to the method

in plot is reported the ratio of simulated uncertainties (i.e. standard deviation of Monte Carlo results) and the expected Poisson error

Conclusions

We presented highlights on recent developments of the **HelMod Model** for the propagation of cosmic rays through the heliosphere:

- The averaged fluxes of AMS-02 cosmic rays ions seem to be better reproduced by HelMod with respect to CREAM96, CREAM2009, ISO-15390 and ISO-DLR.
- New features are available in the web model at *www.helmod.org*
  - the **forecast** tool allowing to predict the GCR fluence for future deep space missions
  - **the transfer orbit fluence calculator**
- **On going developments:**
  - **Tuning** of the model using the AMS-02 proton daily fluxes
  - **HelMod-4-CUDA**

Backup slides

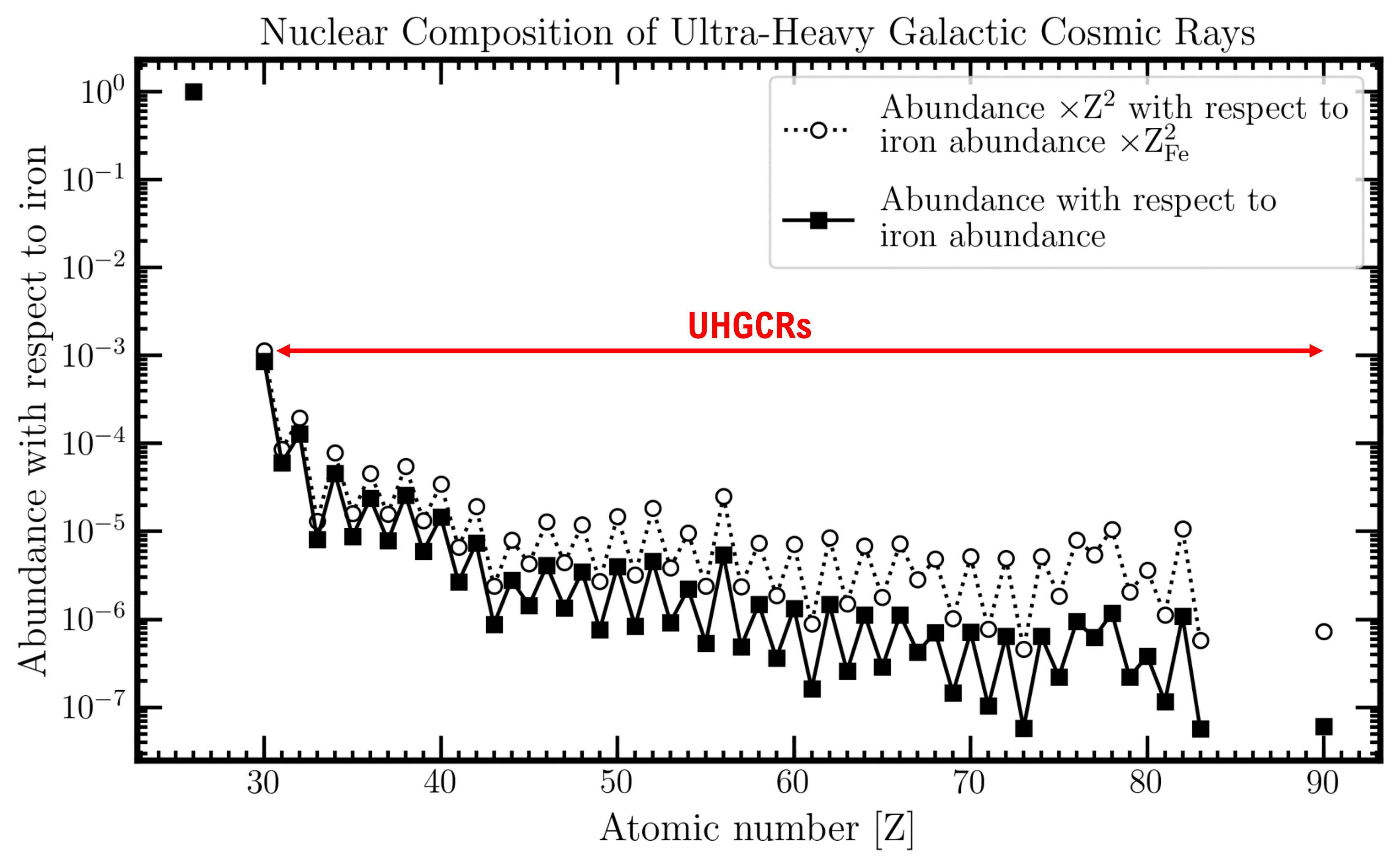
HelMod: The Cosmic ray model for space radiation environment

A Reliable modelling and forecasting of GCR radiation should provide:

- Reproduction of the mean flux
- Reproduction of the flux time dependence
- Reproduction of the flux spatial (radial and latitudinal) dependence

HelMod is available as online calculator at www.helmod.org

Ultra-heavy galactic cosmic rays



Calculated from GCR modulated spectra at **16.2GeV/n** from the **SPENVIS** website (using the **ISO-15390 model**).

This model is suggested by the European Cooperation for Space Standardization (ECSS) for GRC differential flux calculations (Section 9.2.3 of ECSS, 2020)

Ultra-heavy galactic cosmic rays

Z	Symbol	Abundance with respect to iron abundance	Abundance $\times Z^2$ with respect to iron abundance $\times Z^2_{Fe}$	Z	Symbol	Abundance with respect to iron abundance	Abundance $\times Z^2$ with respect to iron abundance $\times Z^2_{Fe}$
29	Cu	6.589E-04	8.197E-04	29	Pm	1.618E-07	8.905E-07
30	Zn	8.586E-04	1.143E-03	30	Sm	1.484E-06	8.441E-06
31	Ga	6.041E-05	8.588E-05	31	Eu	2.578E-07	1.514E-06
32	Ge	1.283E-04	1.943E-04	32	Gd	1.131E-06	6.852E-06
33	As	8.150E-06	1.313E-05	33	Tb	2.868E-07	1.793E-06
34	Se	4.589E-05	7.848E-05	34	Dy	1.128E-06	7.267E-06
35	Br	8.802E-06	1.595E-05	35	Ho	4.272E-07	2.837E-06
36	Kr	2.376E-05	4.555E-05	36	Er	7.097E-07	4.855E-06
37	Rb	7.834E-06	1.587E-05	37	Tu	1.463E-07	1.031E-06
38	Sr	2.591E-05	5.536E-05	38	Yb	7.127E-07	5.166E-06
39	Y	5.912E-06	1.330E-05	39	Lu	1.045E-07	7.795E-07
40	Zr	1.455E-05	3.443E-05	40	Hf	6.454E-07	4.949E-06
41	Nb	2.663E-06	6.621E-06	41	Ta	5.821E-08	4.589E-07
42	Mo	7.348E-06	1.917E-05	42	W	6.430E-07	5.208E-06
43	Tc	8.784E-07	2.403E-06	43	Re	2.226E-07	1.852E-06
44	Ru	2.789E-06	7.987E-06	44	Os	9.420E-07	8.049E-06
45	Rh	1.448E-06	4.338E-06	45	Ir	6.227E-07	5.462E-06
46	Pd	4.089E-06	1.280E-05	46	Pt	1.179E-06	1.061E-05
47	Ag	1.349E-06	4.409E-06	47	Au	2.211E-07	2.041E-06
48	Cd	3.487E-06	1.189E-05	48	Hg	3.835E-07	3.631E-06
49	In	7.666E-07	2.723E-06	49	Tl	1.162E-07	1.128E-06
50	Sn	4.010E-06	1.483E-05	50	Pb	1.083E-06	1.077E-05
51	Sb	8.368E-07	3.220E-06	51	Bi	5.675E-08	5.784E-07
52	Te	4.616E-06	1.846E-05	52	Po	—	—
53	J	9.260E-07	3.848E-06	53	At	—	—
54	Xe	2.218E-06	9.569E-06	54	Rn	—	—
55	Cs	5.393E-07	2.413E-06	55	Fr	—	—
56	Ba	5.433E-06	2.520E-05	56	Ra	—	—
57	La	4.913E-07	2.361E-06	57	Ac	—	—
58	Ce	1.494E-06	7.436E-06	58	Th	6.069E-08	7.272E-07
59	Pr	3.635E-07	1.872E-06	59	Pa	—	—
60	Nd	1.339E-06	7.130E-06	60	U	—	—
				Total		1.907E-03	2.781E-03

UHGCRs total abundance at 16.2GeV/n is $\sim$ **0.19%** of the iron abundance

UHGCRs total energy loss at 16.2GeV/n is $\sim$ **0.28%** of the iron energy loss