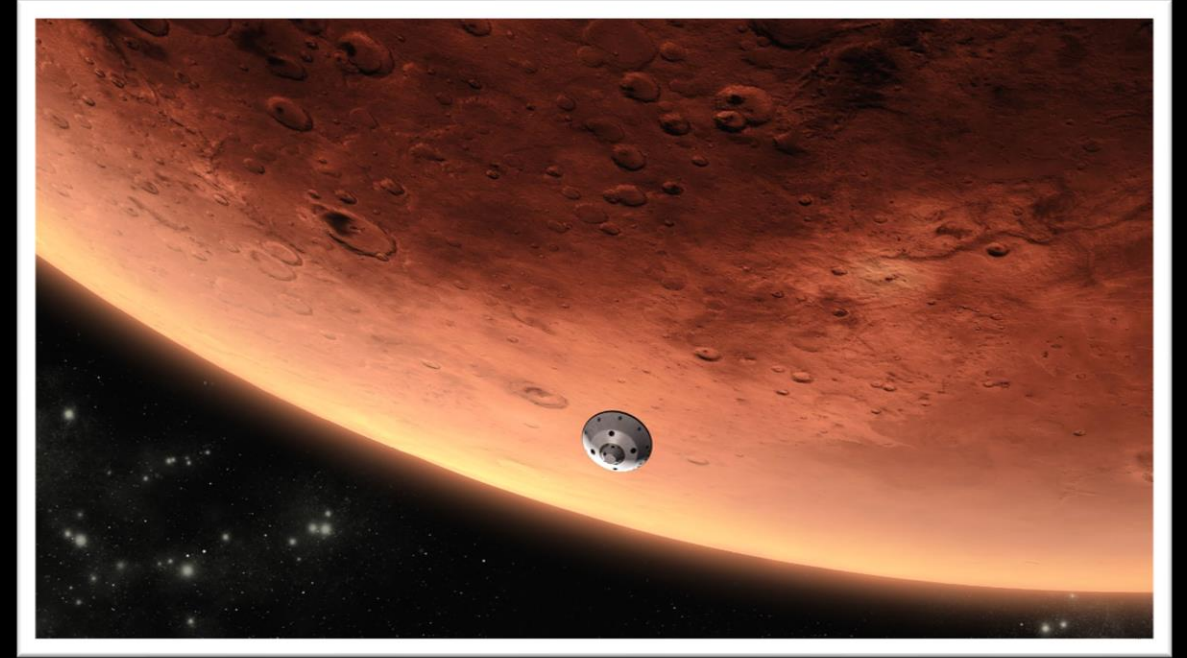# The HelMod model as a tool for the space radiation environment assessment

Giuseppe La Vacca

Università di Milano-Bicocca

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Contribution to the 27th European Cosmic Ray Symposium (ECRS 2022)

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

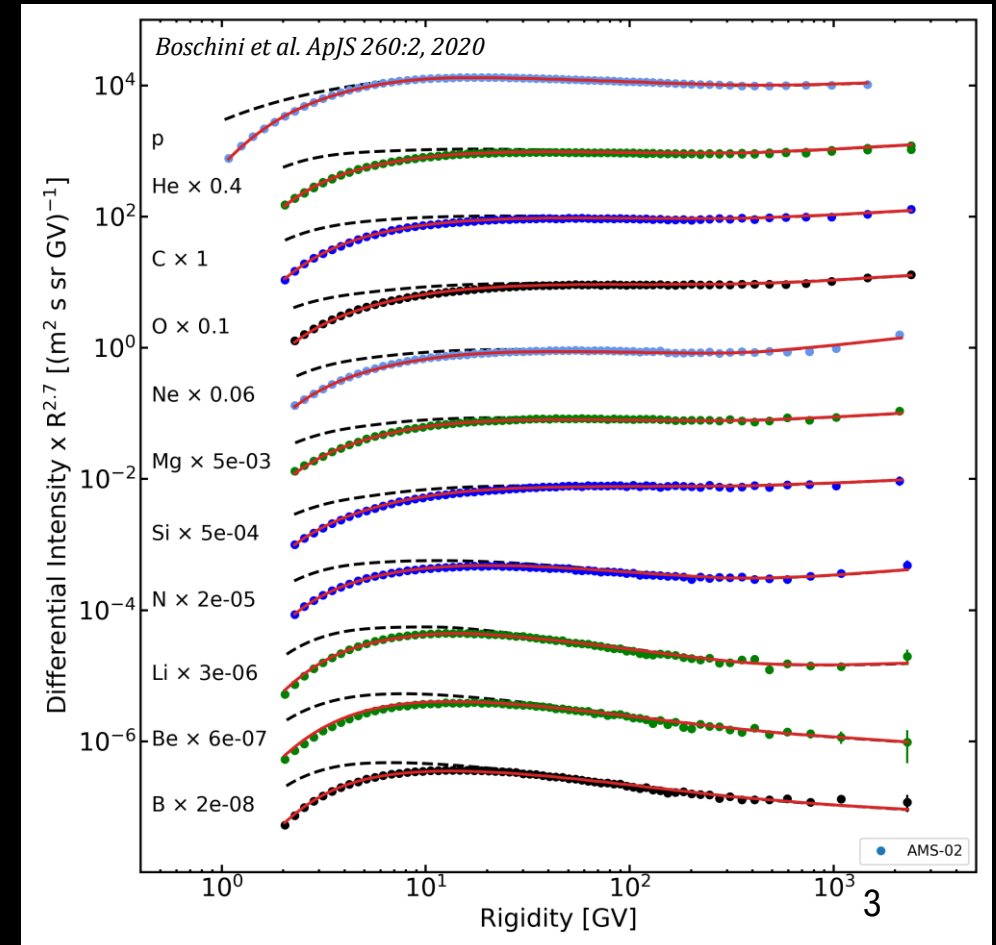# HelMod: The Cosmic ray model for space radiation environment
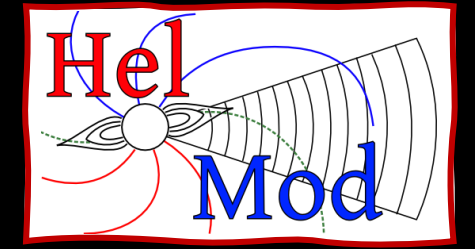
HelMod is a Monte Carlo Code that evaluates modulated spectrum in the heliosphere for:

- *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

Boschini et al. ApJS 260:2, 2020

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HelMod: The Cosmic ray model for space radiation environment

Recent milestone publications

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

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
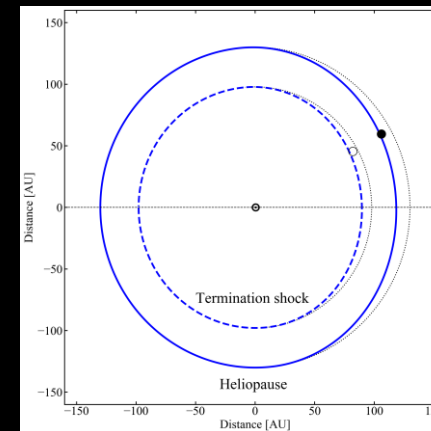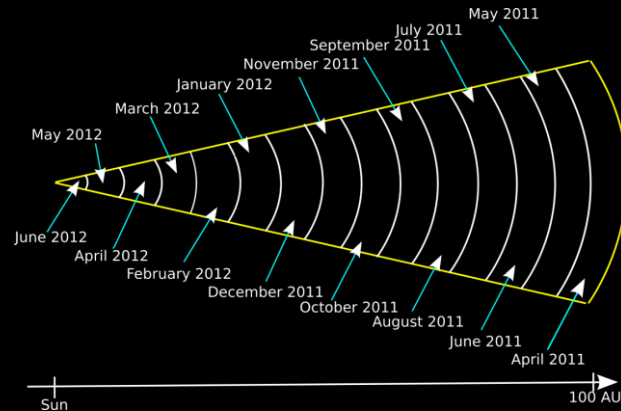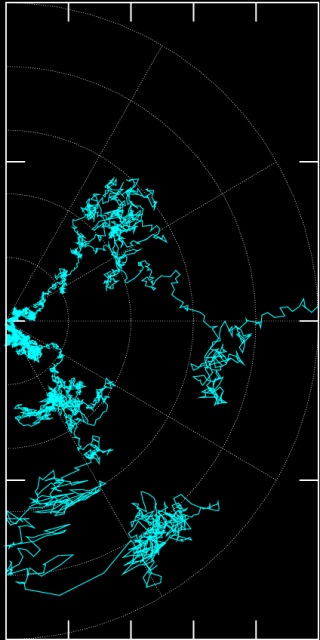
HelMod: The Cosmic ray model for space radiation environment

HelMod can reproduce ions:
- along the full 22 years solar cycle
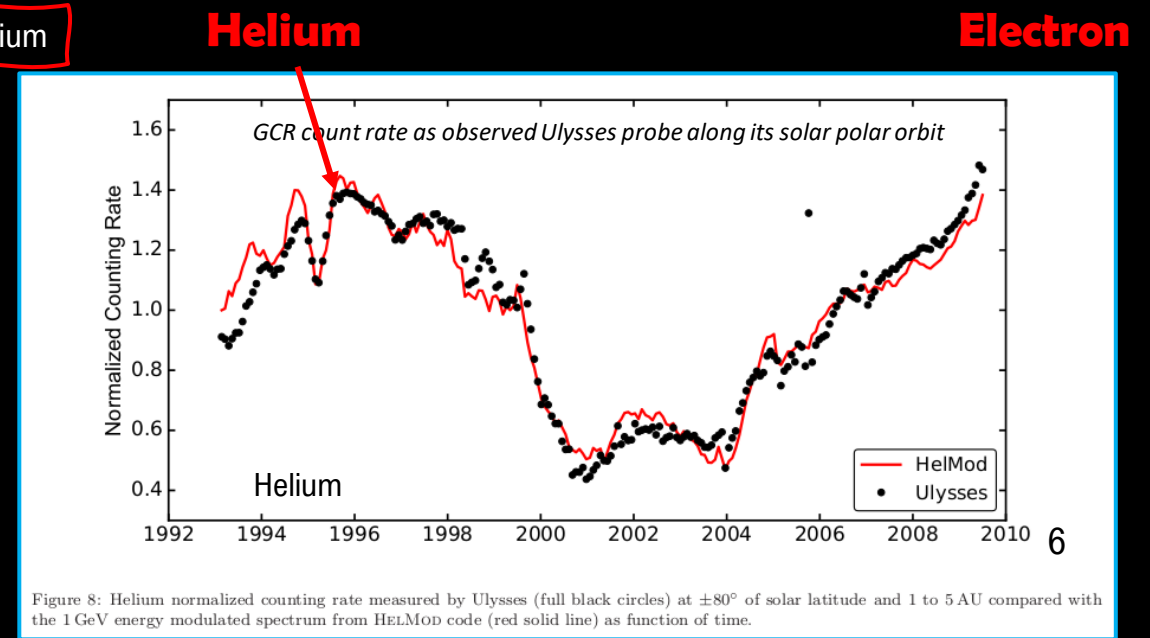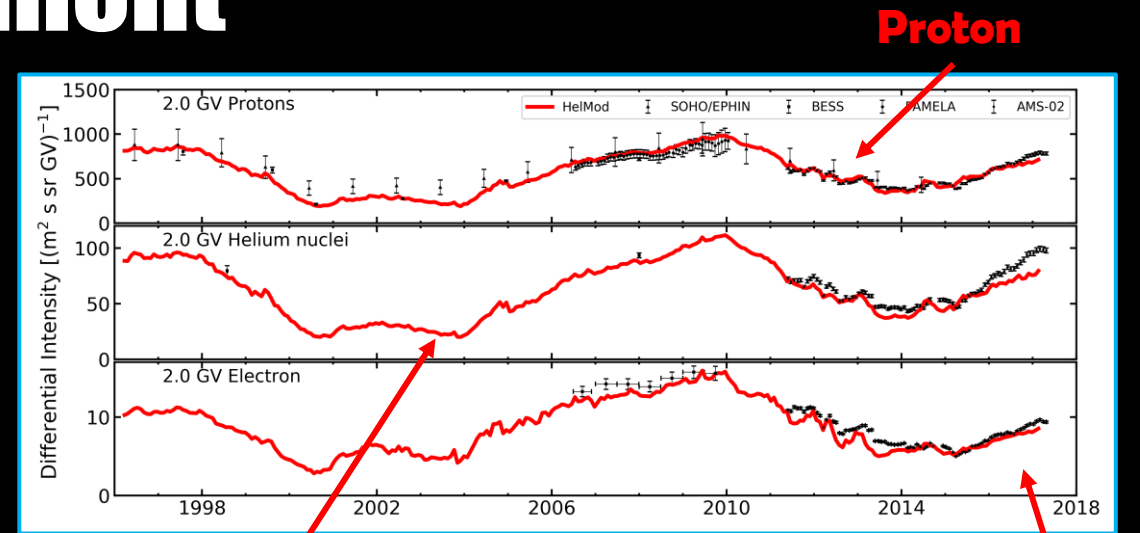- At several solar distance
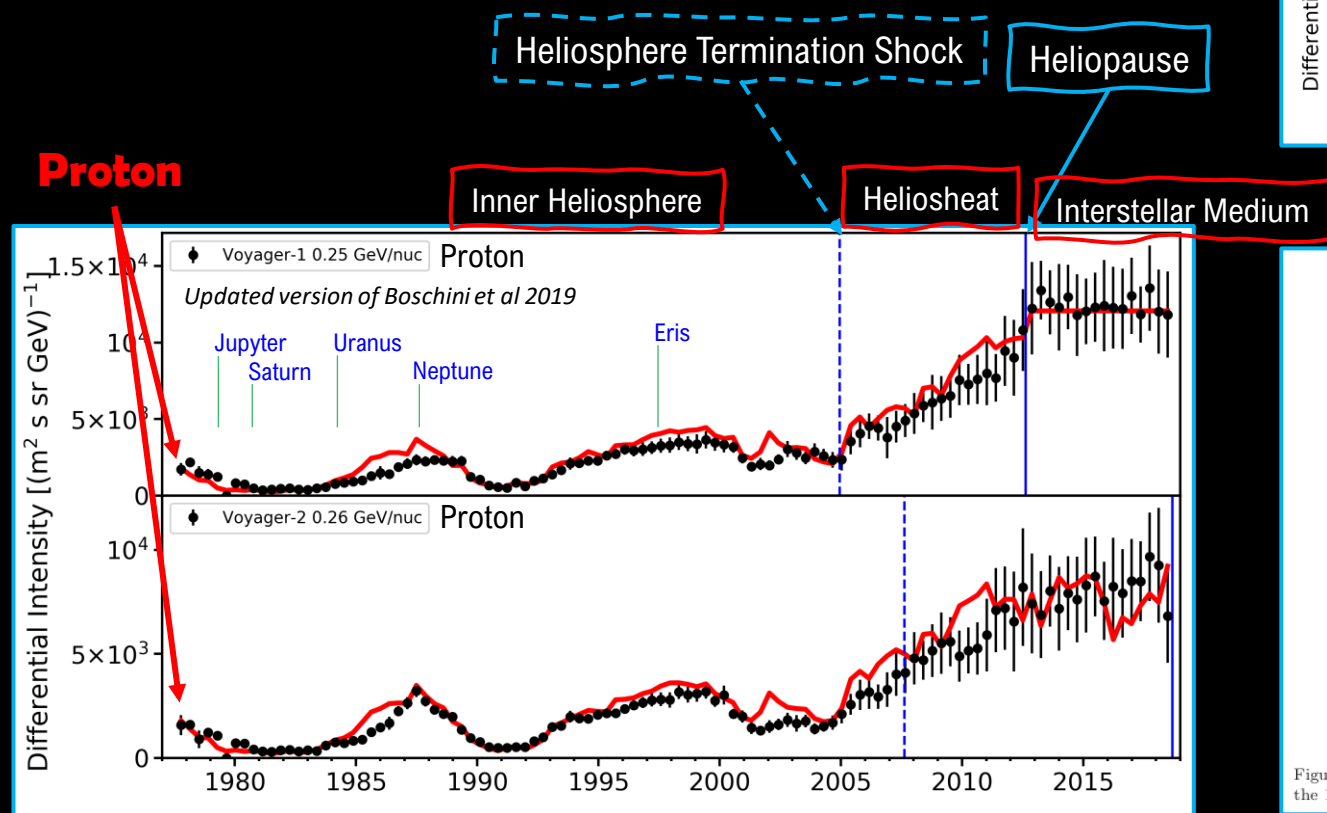- Outside the ecliptic plane

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.

Latest results: Spectra of Cosmic Ray Sodium and Aluminum and Unexpected Aluminum Excess
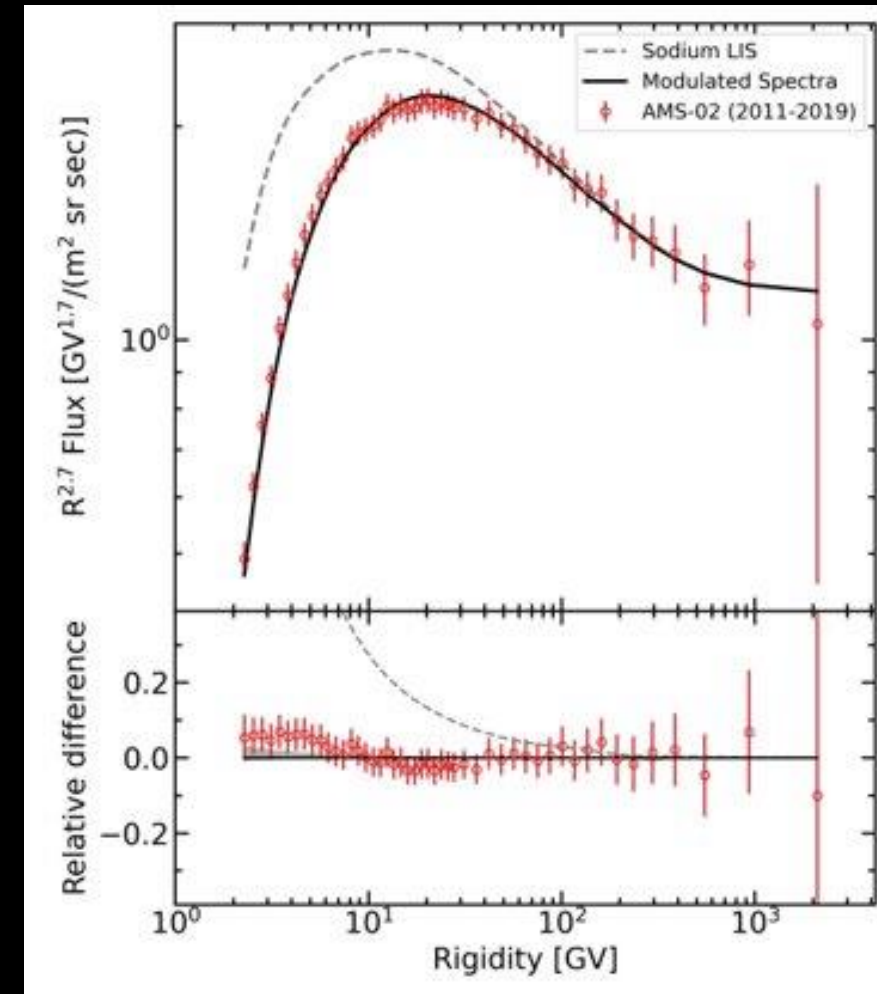
Boschini et al ApJ 933:147 2022
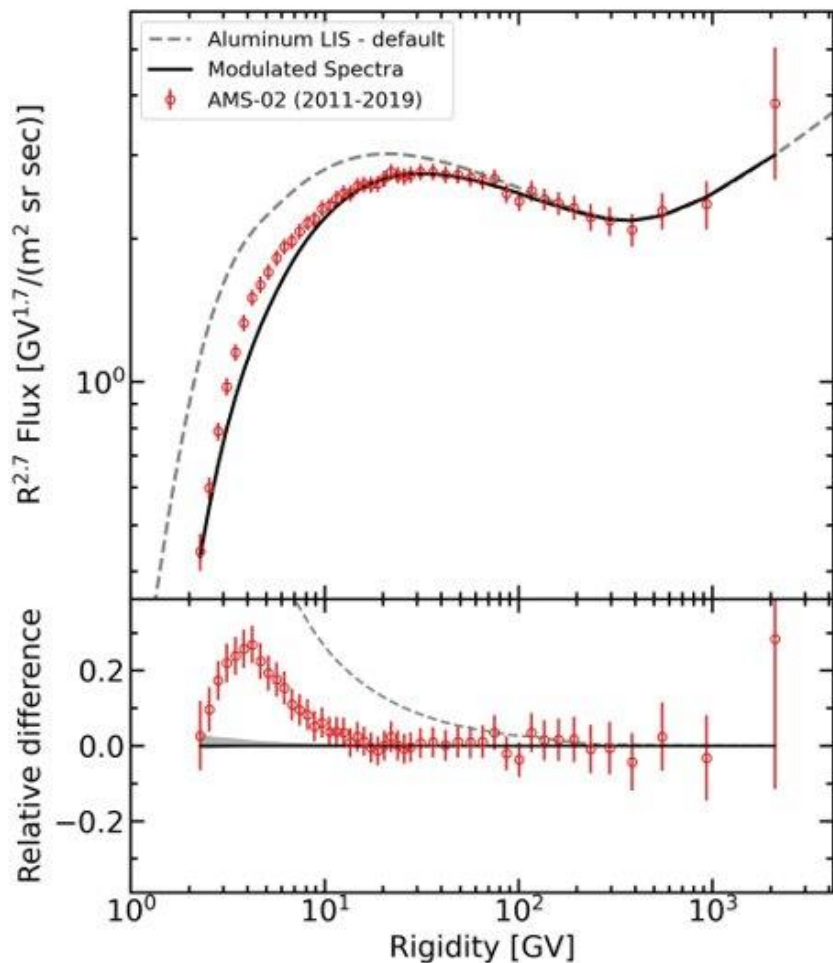
Na spectrum agrees well with the standard scenario

The Al spectrum shows a significant excess.

Other excess were found in F, Li and Fe

Boschini et al (2020) ApJ 889:167
Boschini et al (2021) ApJ 913:5
Boschini et al (2022) ApJ 925:108

Latest results: Spectra of Cosmic Ray Sodium and Aluminum and Unexpected Aluminum Excess

Boschini et al (2022) ApJ 933:147

There are four possible physical reasons of the observed excess in the Al spectrum

(i) an incorrect spectrum of ^{28}Si, the major progenitor of ^{26,27}Al

(ii) errors in the total inelastic cross sections of Al

(iii) errors in the isotopic production cross sections of ^{26,27}Al

} cannot account for such excess

(iv) an additional local component of primary Al
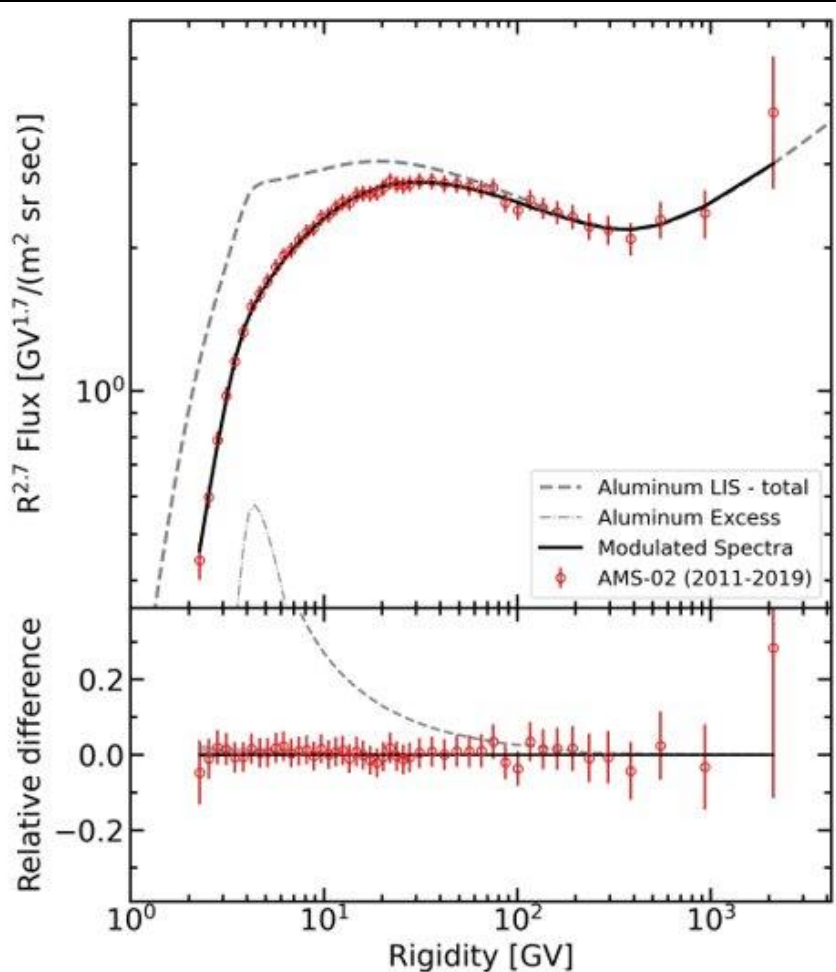
The Absence of a corresponding excess in sodium supports the hypothesis of local primary source due to Wolf-Rayet stars, as the WR winds are not a significant source of sodium.

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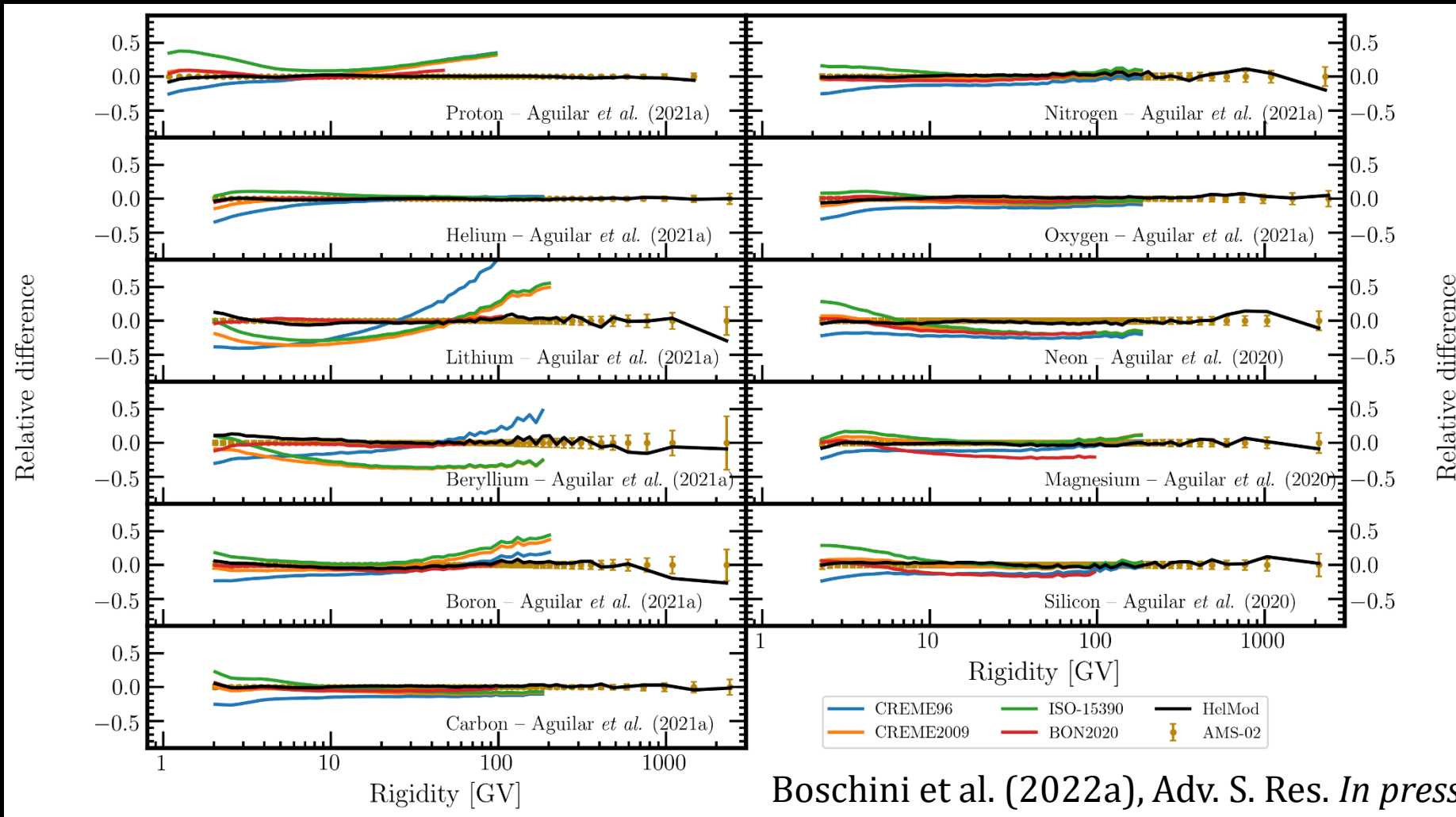
Badhwar-O'Niell (BON) model - *NASA GCR environment tool*
Slaba, T.C., Whitman, K., 2019. The Badhwar-O'Neill 2020 Model, Technical Report NASA/TP-2019-220419 NASA, USA

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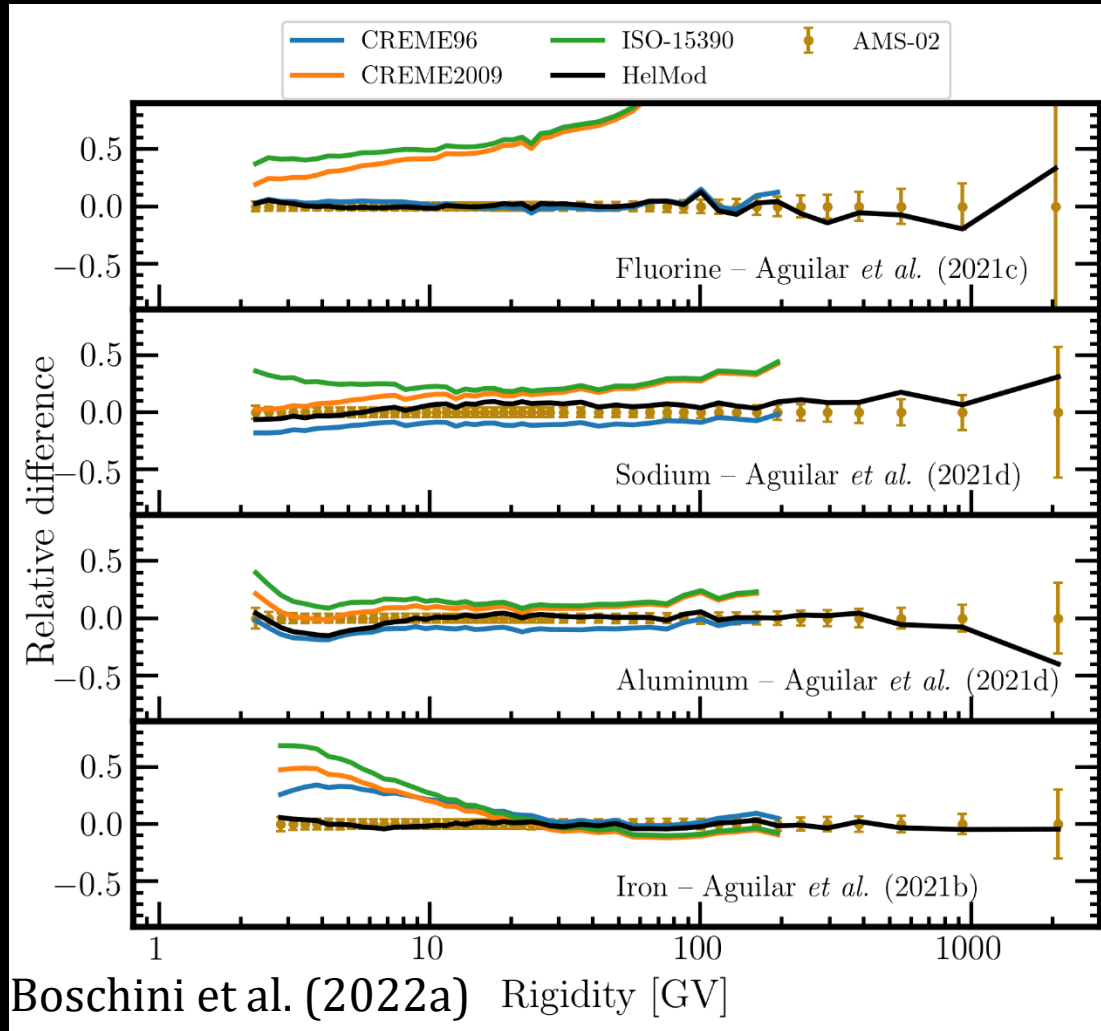
Boschini et al. (2022a), Adv. S. Res. *In press*

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)

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.

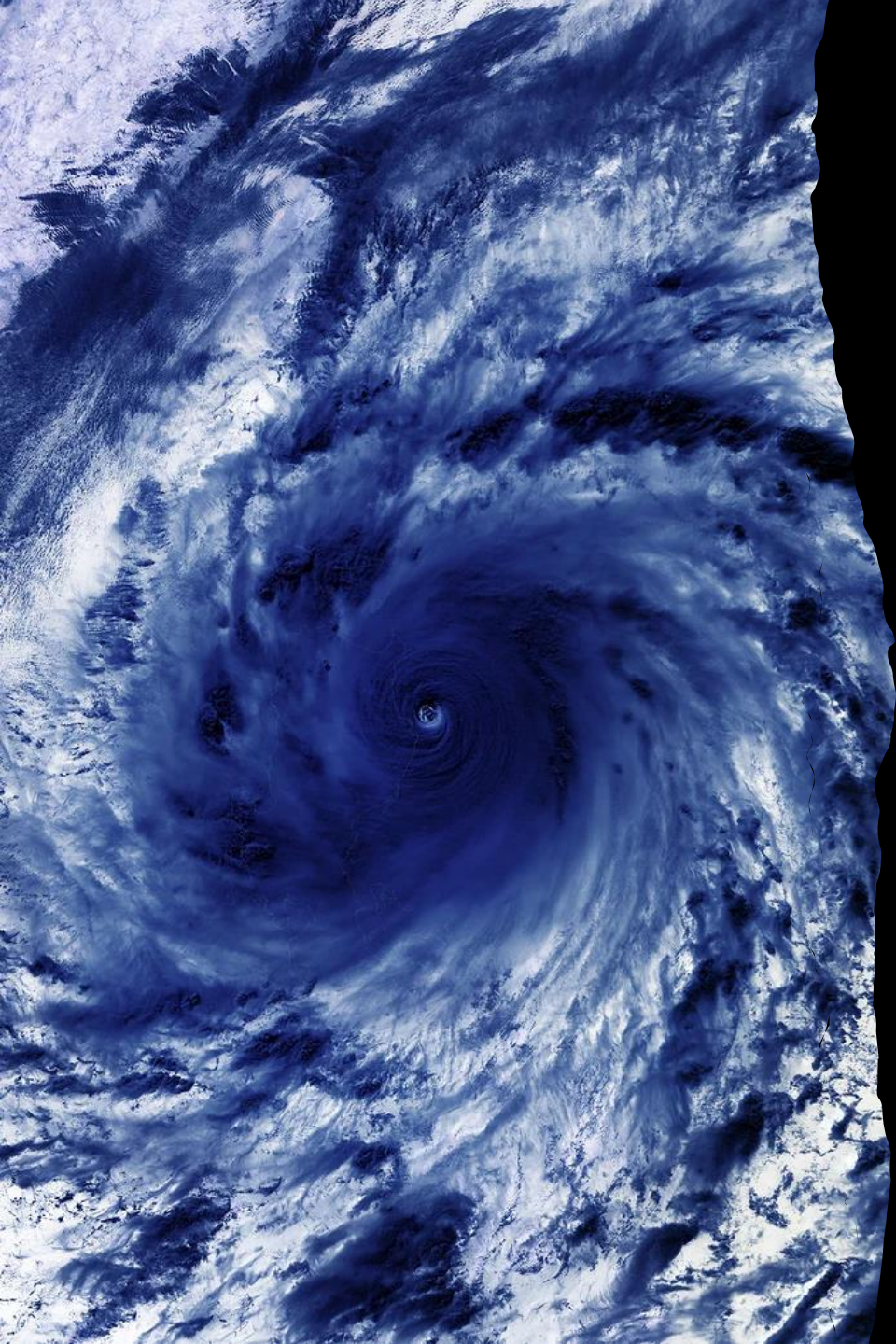HelMod looks to exhibit an overall better agreement with AMS–02 data concerning the other solar modulation models here discussed

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

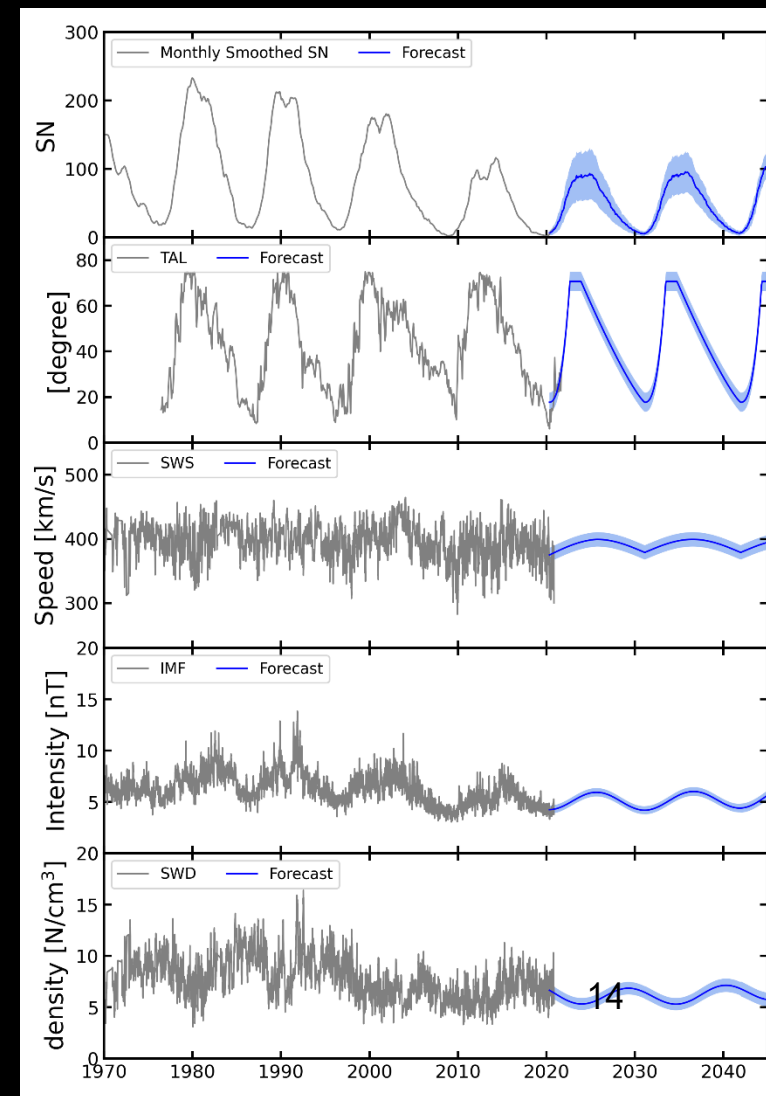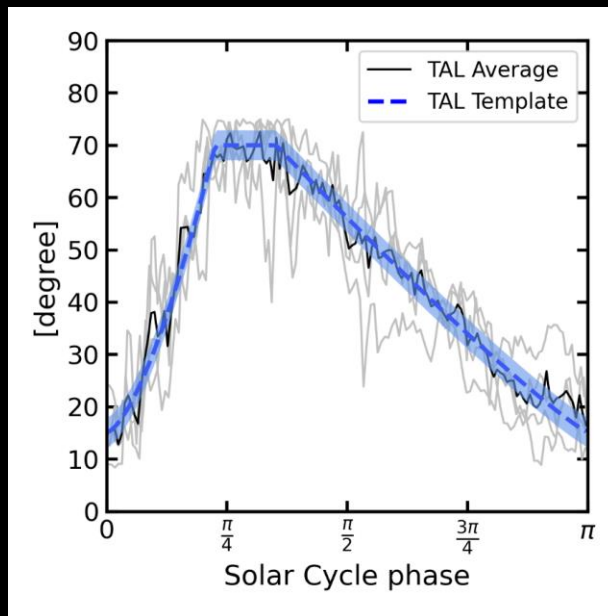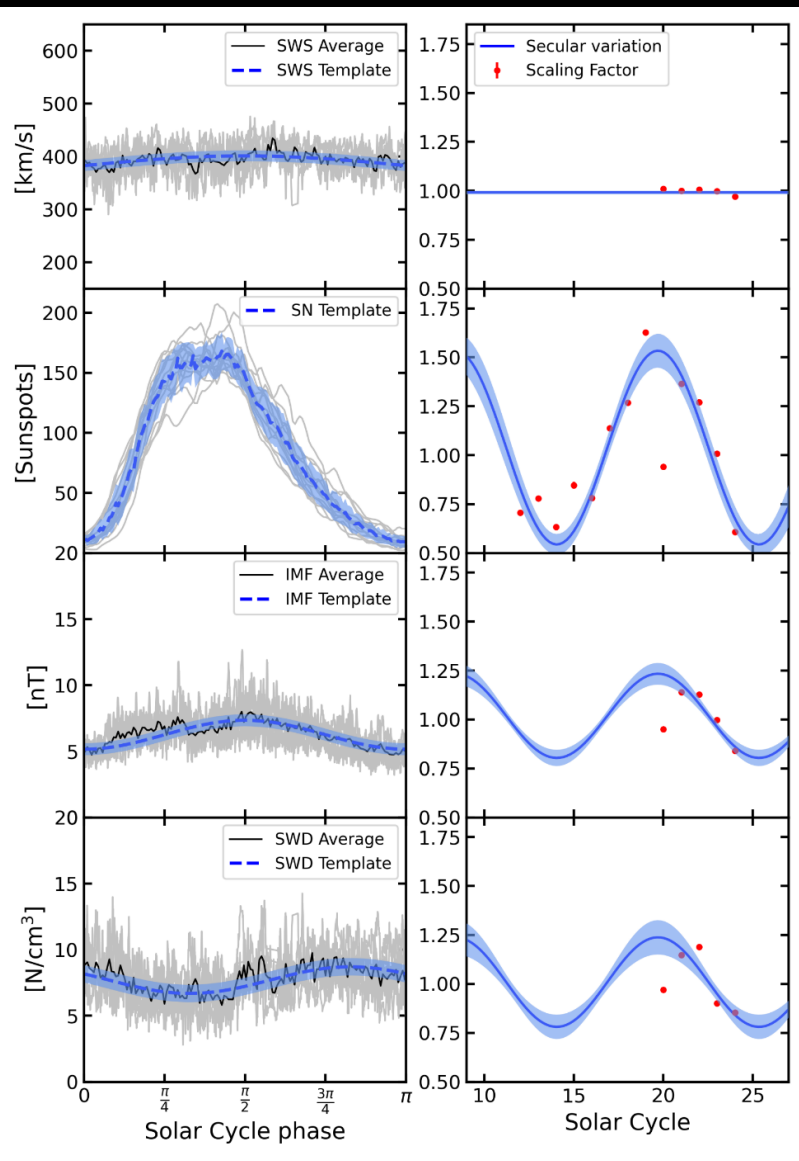Boschini et al. (2022b) Adv. S. Res. *In press*

Forecast

The procedure is used to forecast:
- Sunspot numbers
- Tilt Angle of Neutral Sheet
- IMF
- Solar Wind Speed
- Plasma Density

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

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

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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).**
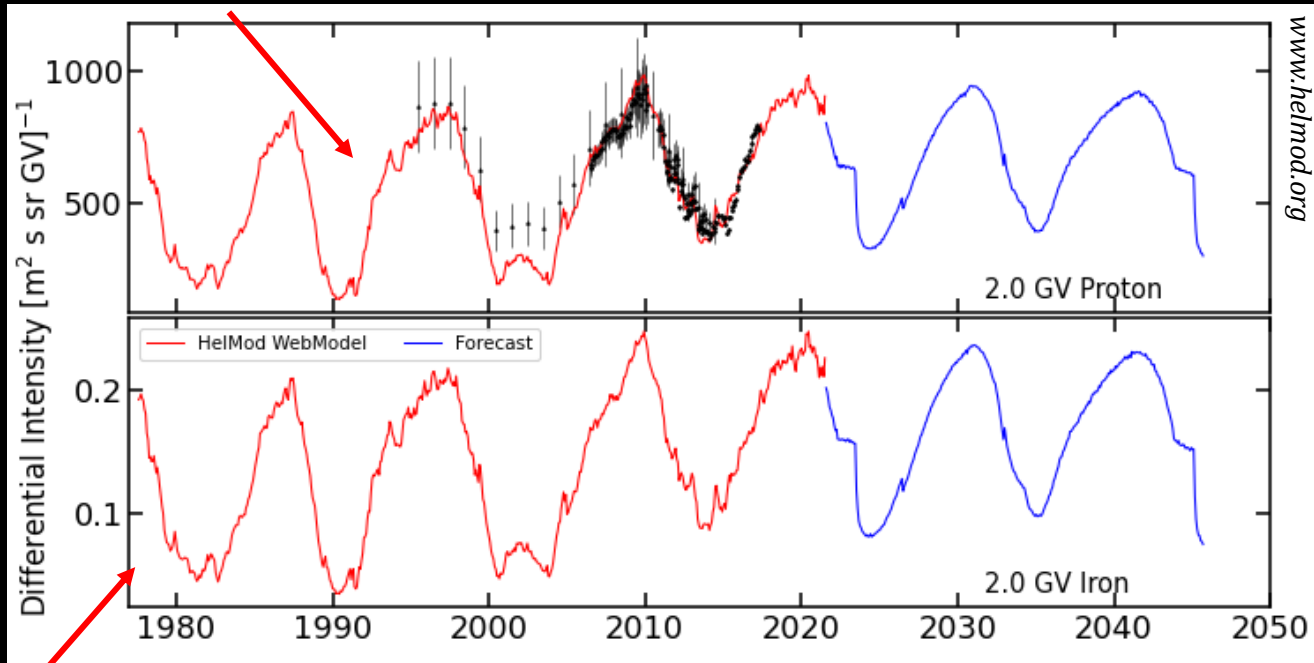
Differential intensity at 2 GV (red is HelMod, Blue is forecasted HelMod)
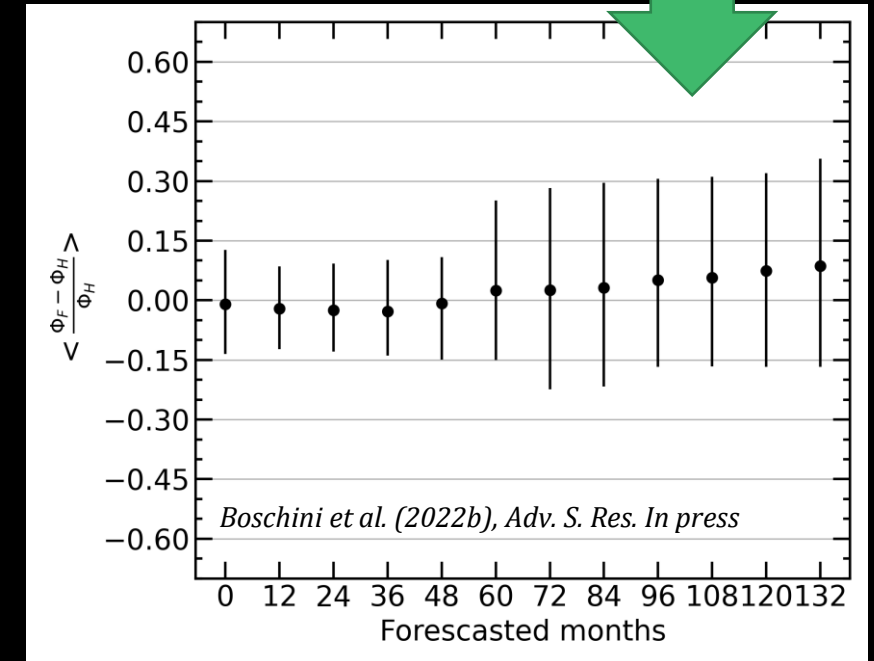
Average Relative difference fluence evalauted with Helmod and with forecast procedure

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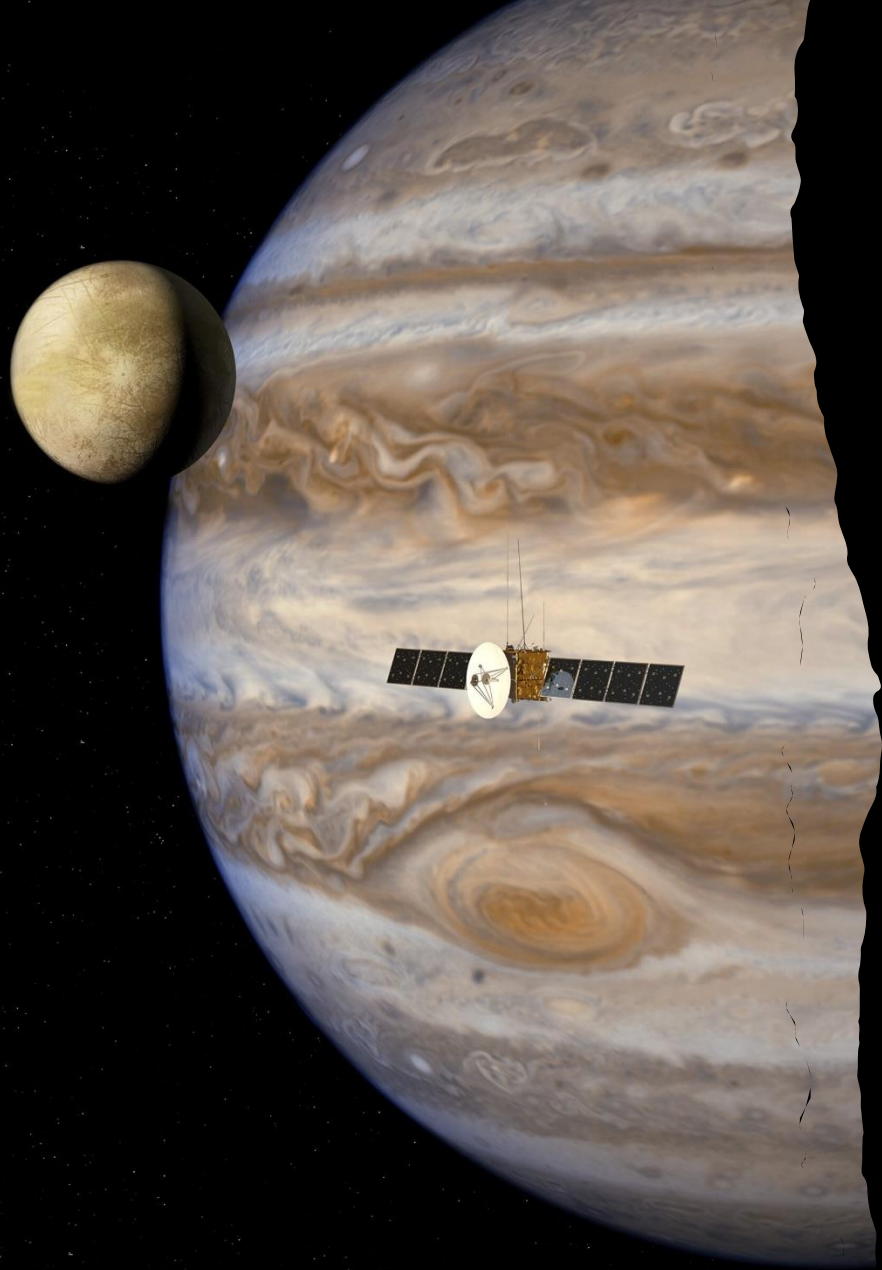
Transfer orbit fluence calculator

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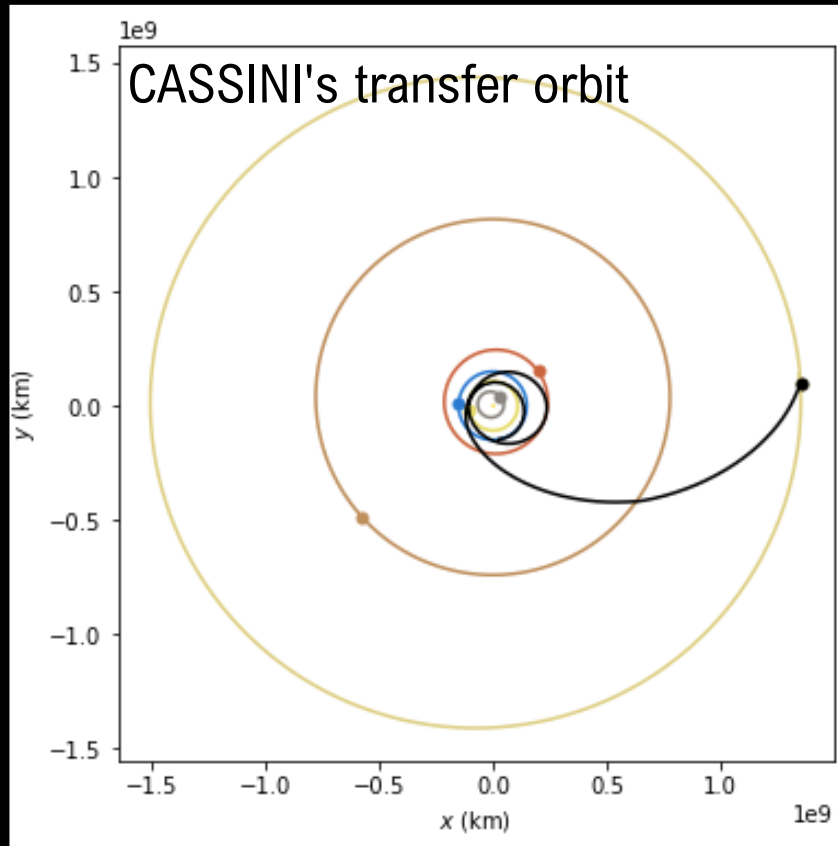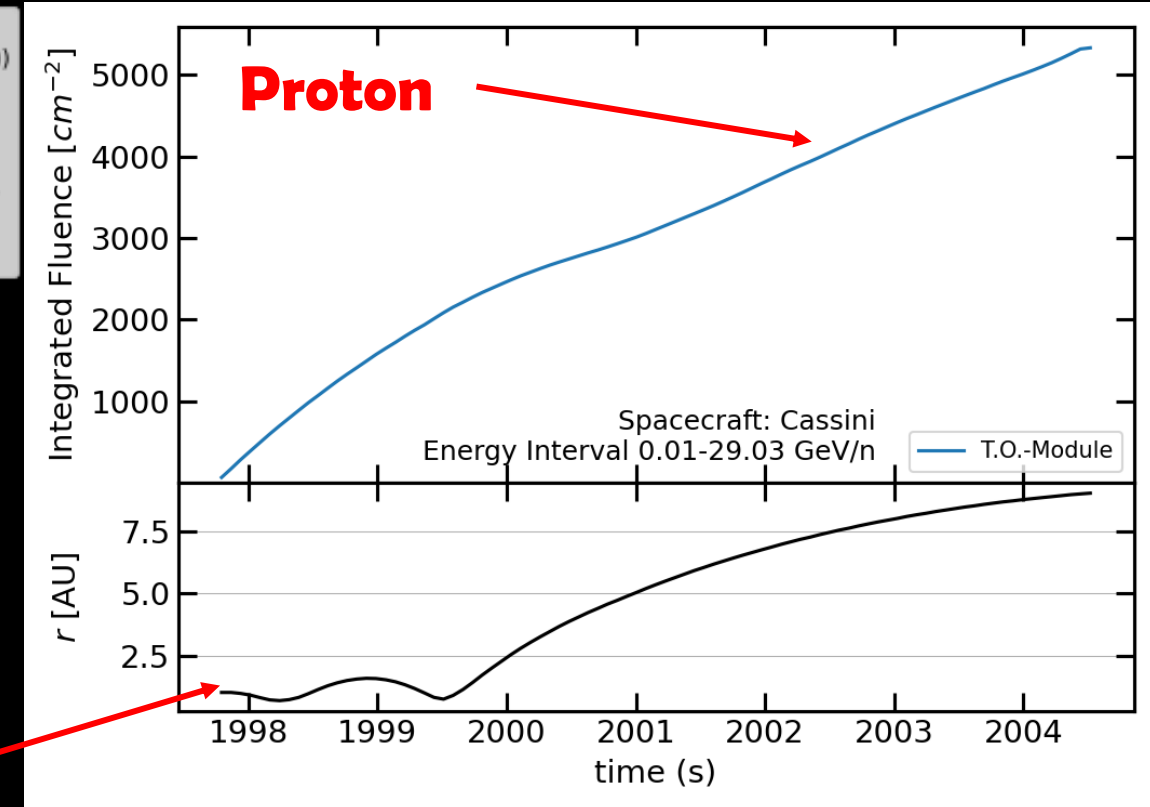
A proper fast calculator is available on HelMod.org to provide an immediate estimation of GCR fluence on transfer orbits provided by the user

Conclusions

For missions in space radiation environment, the long-term modulation is relevant for accounting some type of radiation effects (for instance SEE). Thus, a realistic model is required for planning deep-space missions

- We presented the HelMod Model for the propagation of cosmic rays through the heliosphere. The model reproduces the overall time variation between low and high activity periods as well the observed spatial variation.

- 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.

- The model is provided with a **forecast** tools that allows to predict the GCR fluence for future deep space missions

- New features is available in the web model : **the transfer orbit fluence calculator**

- HelMod is available on-line at *www.helmod.org and through the SR-NIEL framework at www.sr-niel.org*
  In sr-niel HelMod spectral fluences can be combined with SEE cross-section to predict the expected number of SEE - due to GCRs - in future (deep) space missions

Backup slides

Ultra-heavy galactic cosmic rays

Nuclear Composition of Ultra-Heavy Galactic Cosmic Rays

Legend:
Abundance $\times Z^2$ with respect to iron abundance $\times Z_{Fe}^2$
Abundance with respect to iron abundance

UHGCRs

Axis labels: Abundance with respect to iron (y-axis), Atomic number [Z] (x-axis)
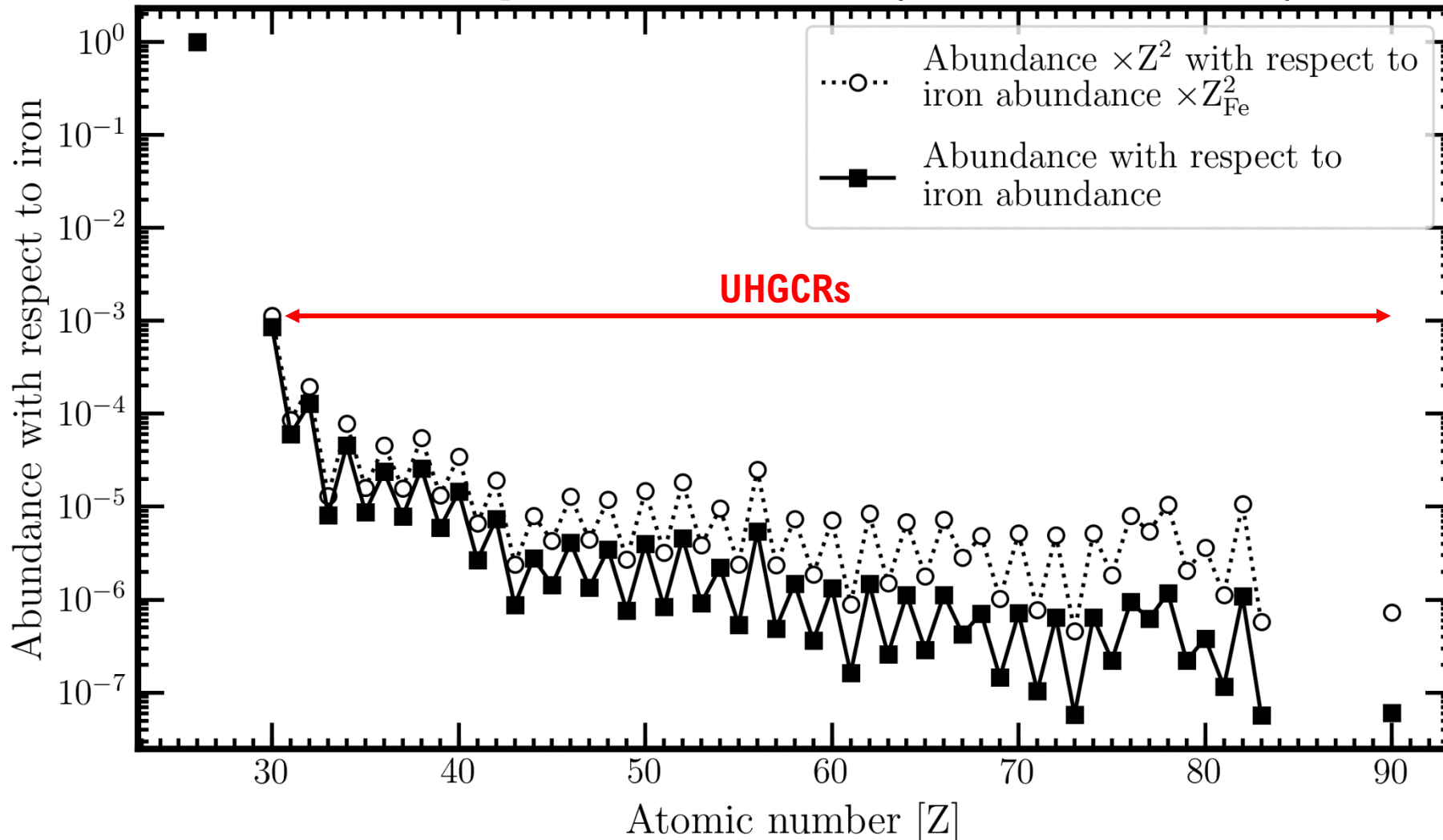
Calculated from GCR modulated spectra at **16.2GeV/n** from the **SPENVIS** website (using the **ISO-15390 model**).

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 $\times Z_{Fe}^2$	Z	Symbol	Abundance with respect to iron abundance	Abundance $\times Z^2$ with respect to iron abundance $\times Z_{Fe}^2$
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 ∼ **0.19%** of the iron abundance

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