

# HelMod: cosmic rays fluence at solar system planets and for deep space missions

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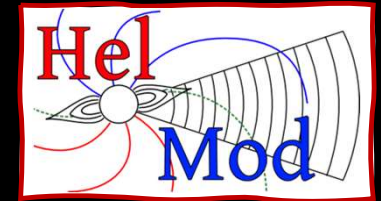
# HelMod: The Cosmic ray model for space radiation environment

A Reliable modelling and forecasting of GCR radiation should provide:

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

HelMod is available as online calculator at [www.helmod.org](http://www.helmod.org)

# HelMod: The Cosmic ray model for space radiation environment



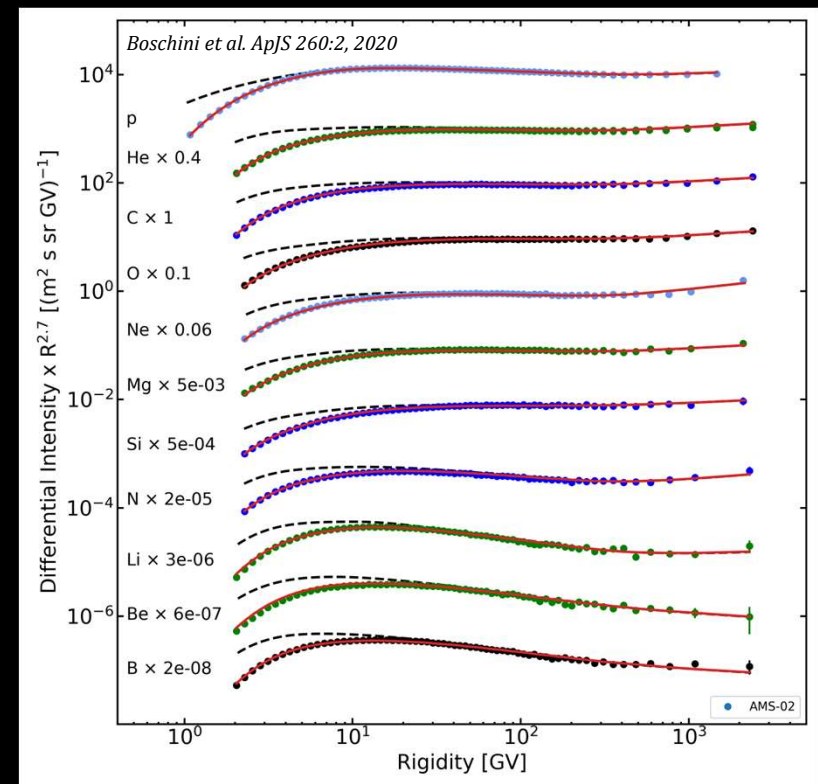
HelMod is a Monte Carlo Code that evaluate modulated spectrum in the heliosphere for:

- 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 in press 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  $Z \leq 28$   
*Boschini et al. ApJS 260:2, 2020*



# HelMod: The Cosmic ray model for space radiation environment

## Recent milestone publications

- Boschini et al. Adv. S. Res. *In press* (2022) *Forecasting of cosmic rays intensities with HelMod Model.*
- Boschini et al. Adv. S. Res. 64(12):2459 (2019) *The HelMod model in the works for inner and outer heliosphere: From AMS to Voyager probes observations.*
- Boschini et al. Adv. S. Res. 62(10):2859 (2018) *Propagation of Cosmic Rays in Heliosphere: the HelMod Model.*
- Bobik et al. JGR. 2016, 121(5) *On the forward-backward-in-time approach for Monte Carlo solution of Parker's transport equation: One-dimensional case.*
- Bobik et al. Adv. Ast., ID 793072 (2013) *Latitudinal Dependence of Cosmic Rays Modulation at 1 AU and Interplanetary Magnetic Field Polar Correction.*
- Bobik et al. ApJ 745:132 (2012) *Systematic Investigation of Solar Modulation of Galactic Protons for Solar Cycle 23 Using a Monte Carlo Approach with Particle Drift Effects and Latitudinal Dependence.*

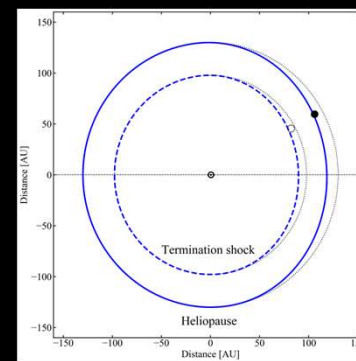
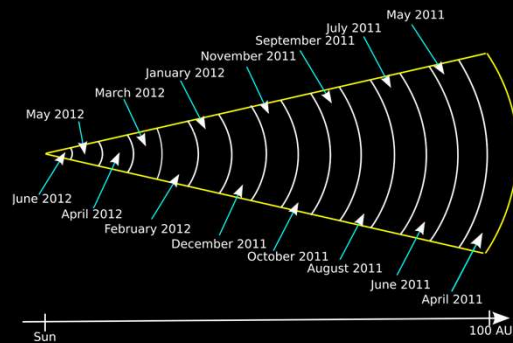
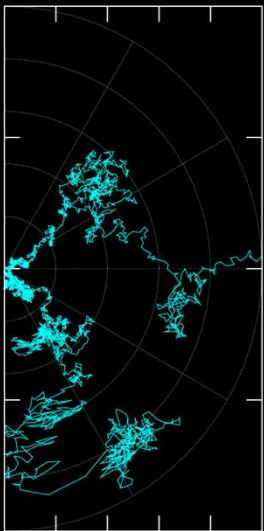
# HelMod: The Cosmic ray model for space radiation environment

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

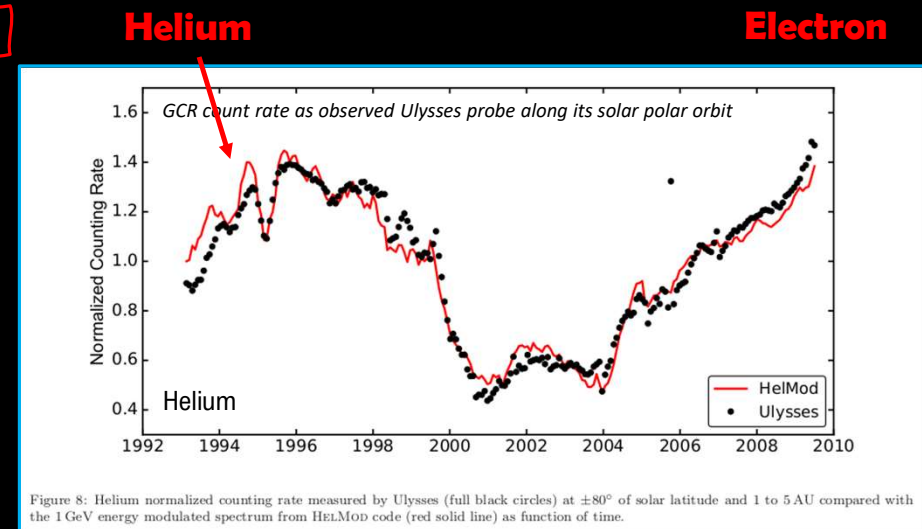
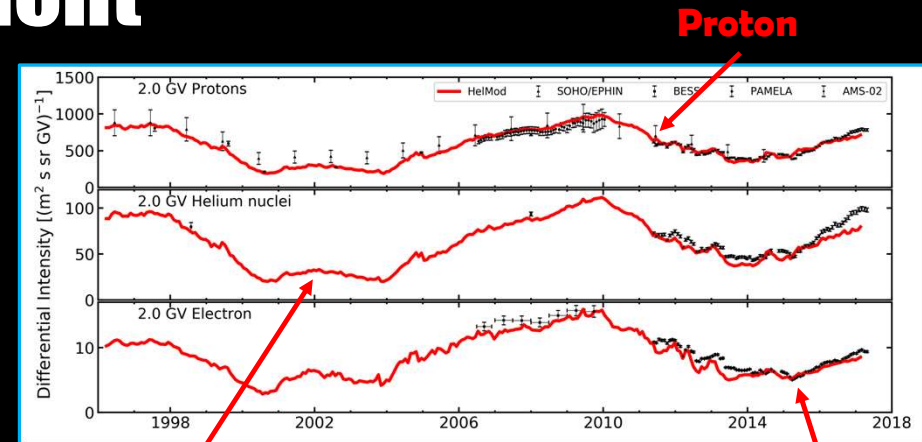
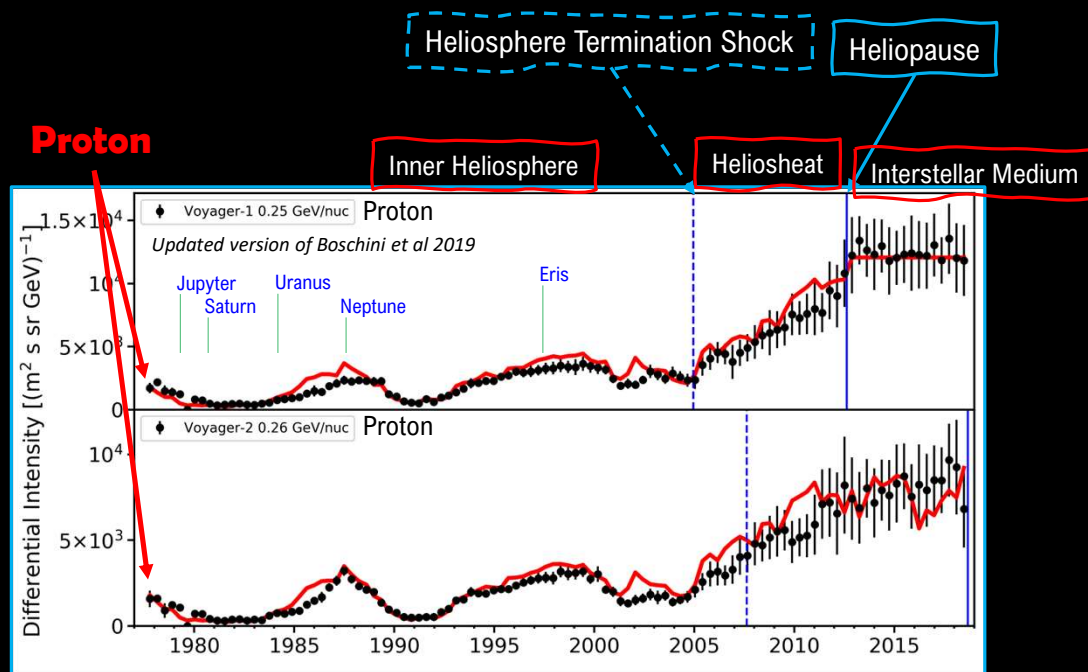
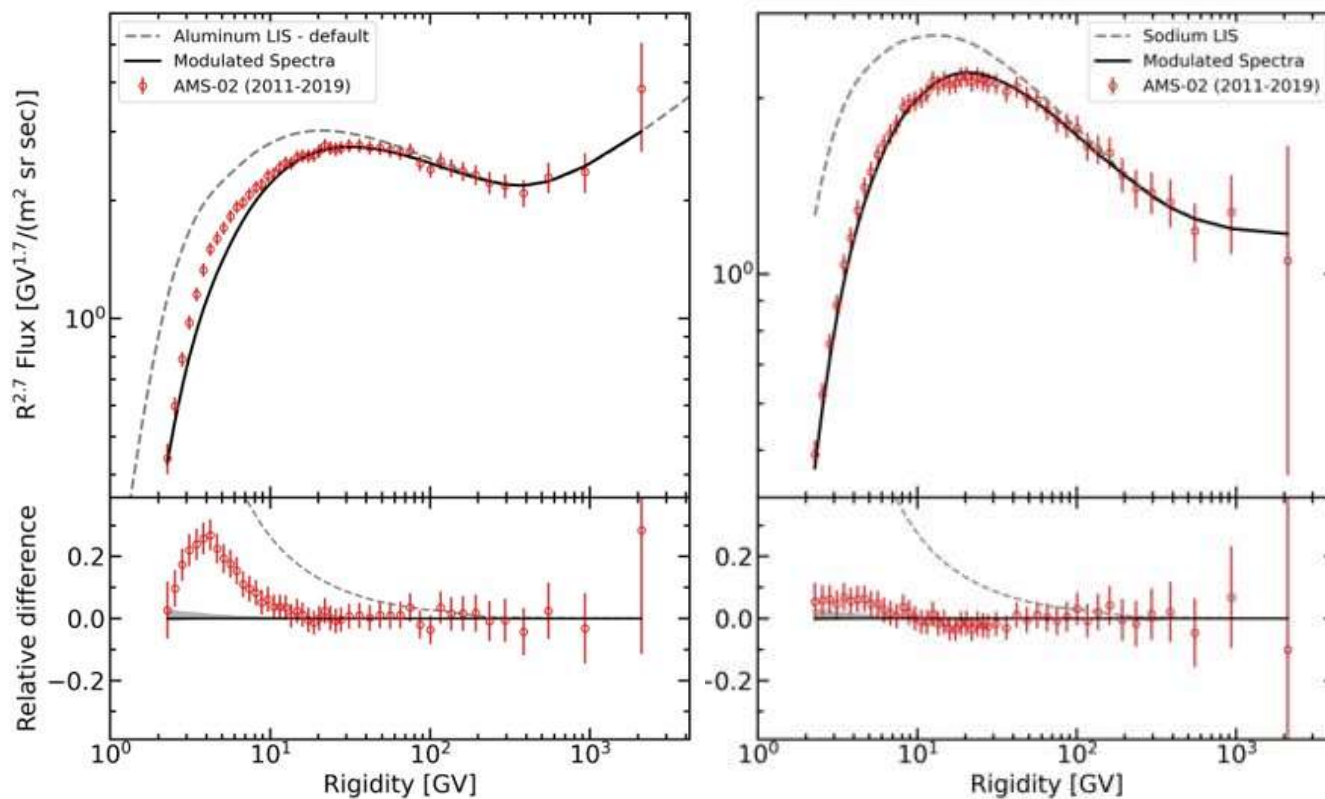


Figure 8: Helium normalized counting rate measured by Ulysses (full black circles) at  $\pm 80^\circ$  of solar latitude and 1 to 5 AU compared with the 1 GeV energy modulated spectrum from HELMOD code (red solid line) as function of time.

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

Boschini et al, to be appear on ApJ 2022 - arXiv:2202.09928



the sodium spectrum agrees well with the standard scenario,

The Al spectrum shows a significant excess.

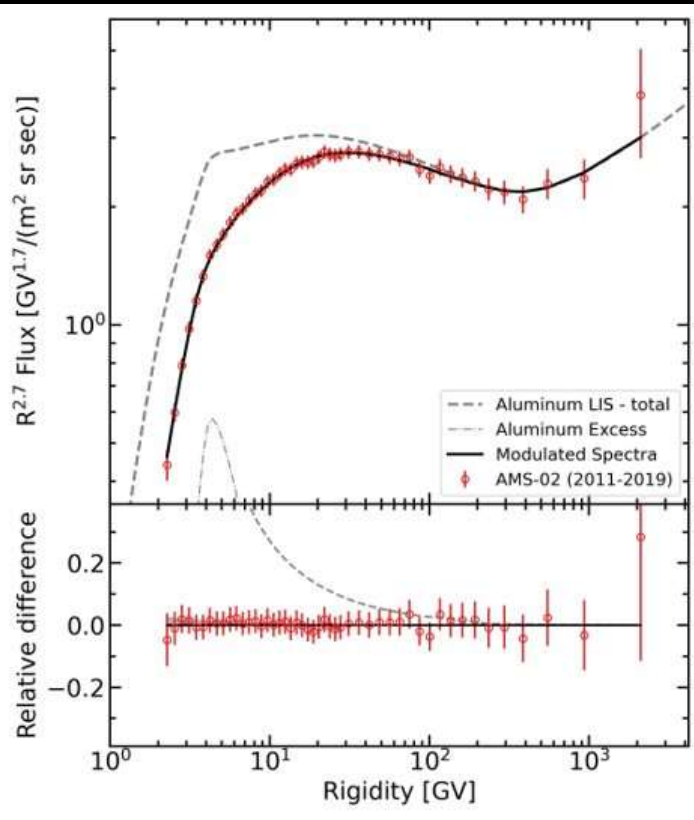
Other excess were found in F, Li and Fe

Boschini et al ApJ 889:167 2020

Boschini et al ApJ 913:5 2021.

Boschini et al ApJ 925:108 2022

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

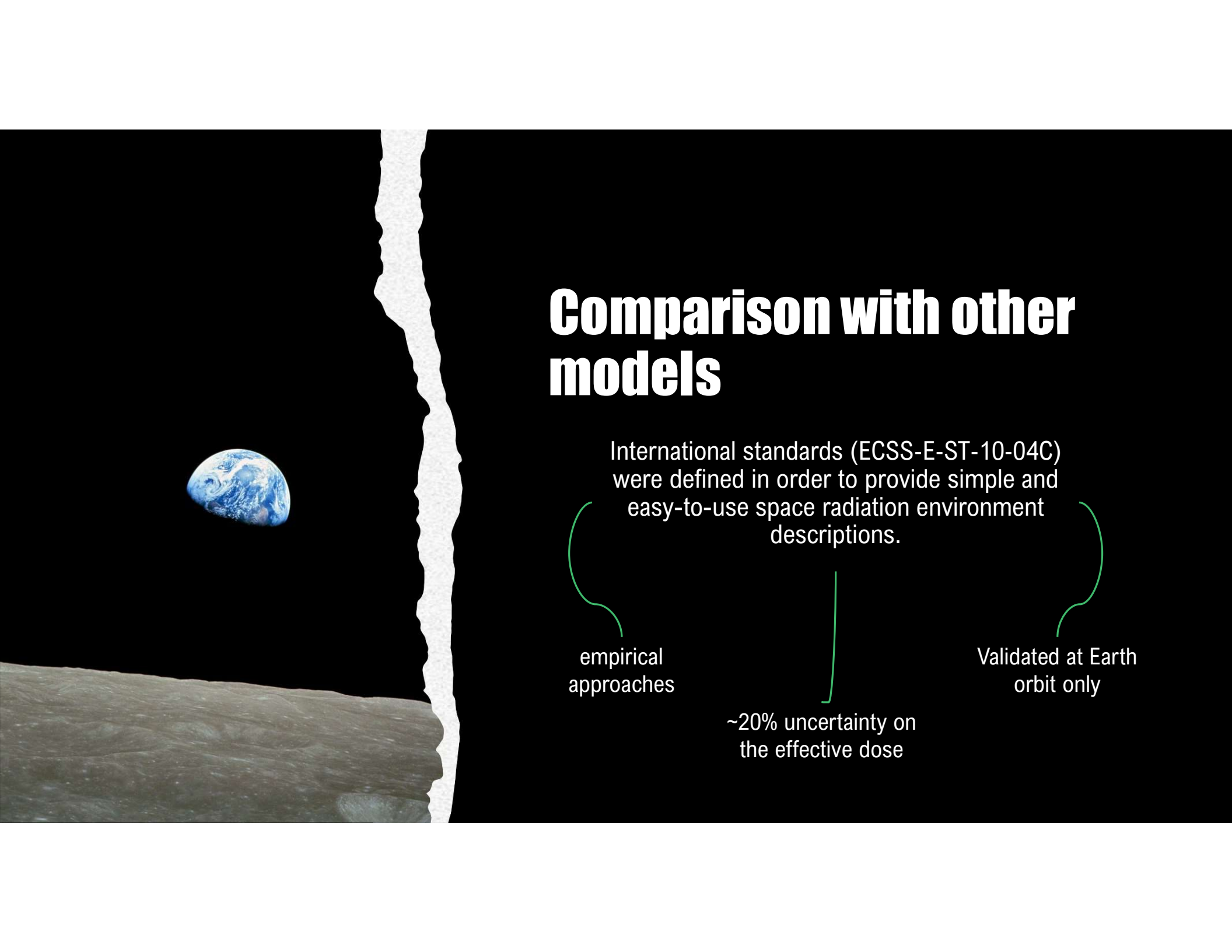


There are four possible physical reasons of the observed excess in the Al spectrum

- (i) an incorrect spectrum of  $^{28}\text{Si}$ , the major progenitor of  $^{26,27}\text{Al}$
- (ii) errors in the total inelastic cross sections of Al
- (iii) errors in the isotopic production cross sections of  $^{26,27}\text{Al}$
- (iv) an additional local component of primary Al

Cannot account for such excess -  
arXiv:2202.09928

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*

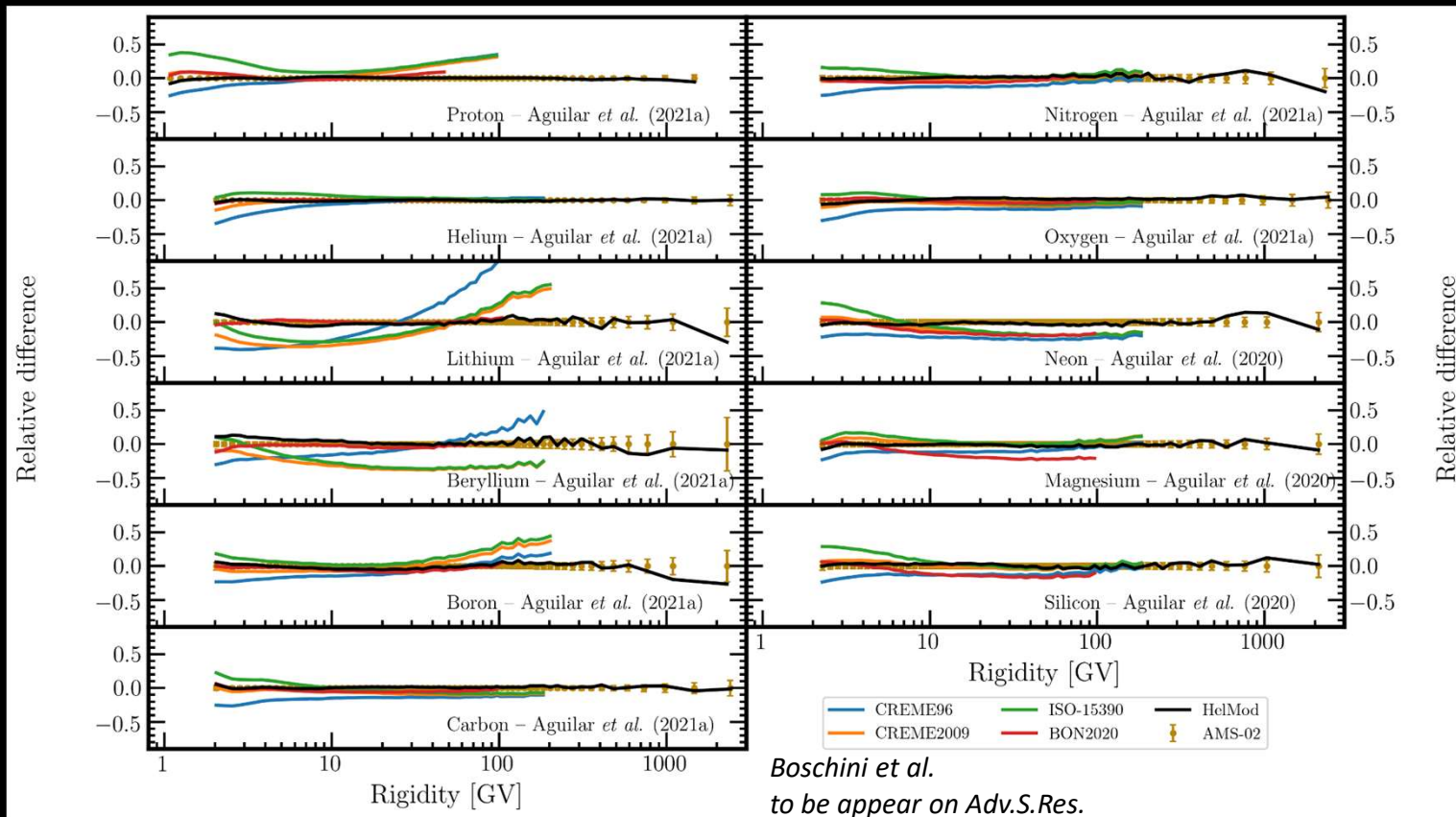
*ISO-DLR A simplified version of the ISO-15390 model, modified in order to reduce the number of free parameters to one  
Matthia, D., Berger, T., Mrigakshi, A.I., Reitz, G., Adv. Space Res. 51: 329-338, 2013*

Cosmic Ray Effects on MicroElectronics Code (CRÈME) GCR model is based on Nymmik *et al.* (1992)  
*CRÈME96* – Tylka *et al.* 1997 *IEEE Transactions on Nuclear Science* 44(6), 2150–2160.  
*CRÈME2009* – update of *CRÈME96* (<https://creme.isde.vanderbilt.edu/>)

*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

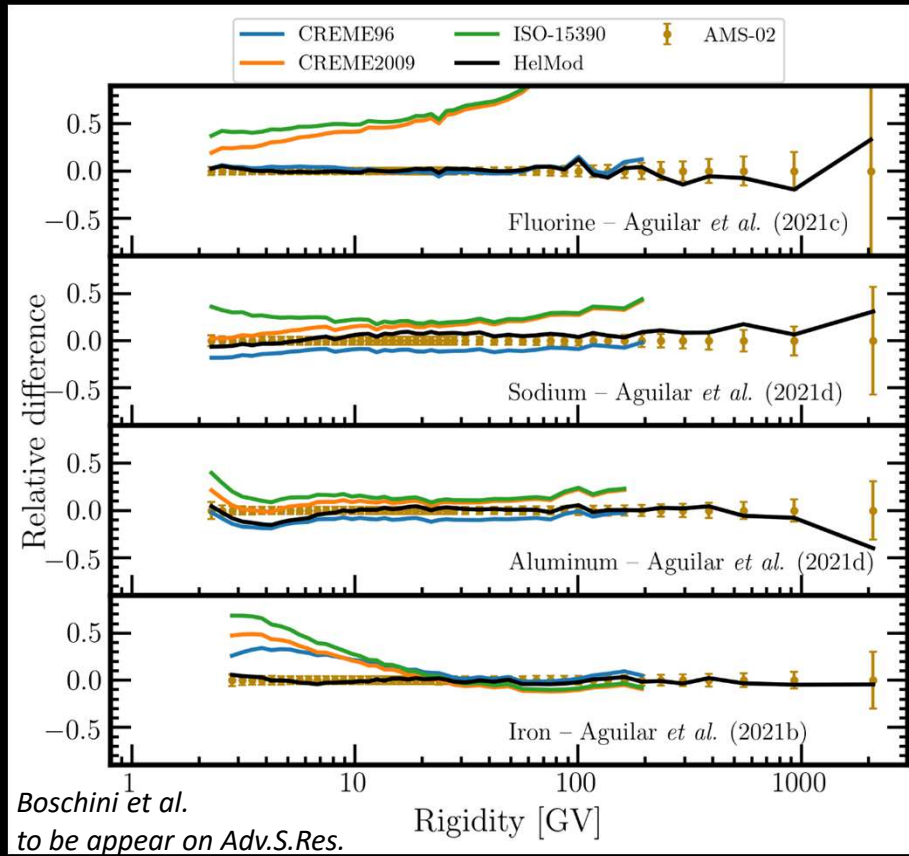
# Comparison with other models

Including ISO 15390 discussed in  
Sect. 9.3 *ECSS-E-ST-10-04C* (2020)



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

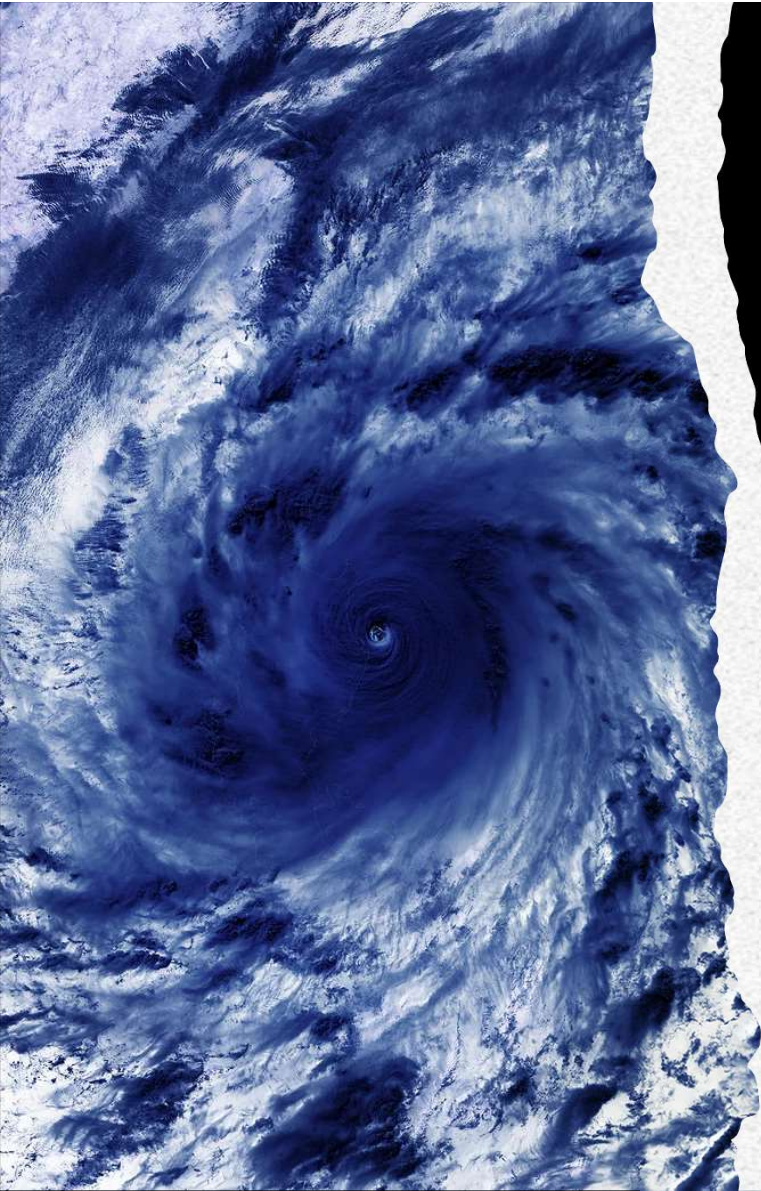
# Comparison with other models



HelMod was found to achieve a good agreement over the full set of experimental data with, typically,  $\Delta\Phi$  within  $\pm 2.5\%$  and RMS within 5%.

Usually larger or, in a few cases, much larger values for  $\Delta\Phi$  and  $\eta$ RMS 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

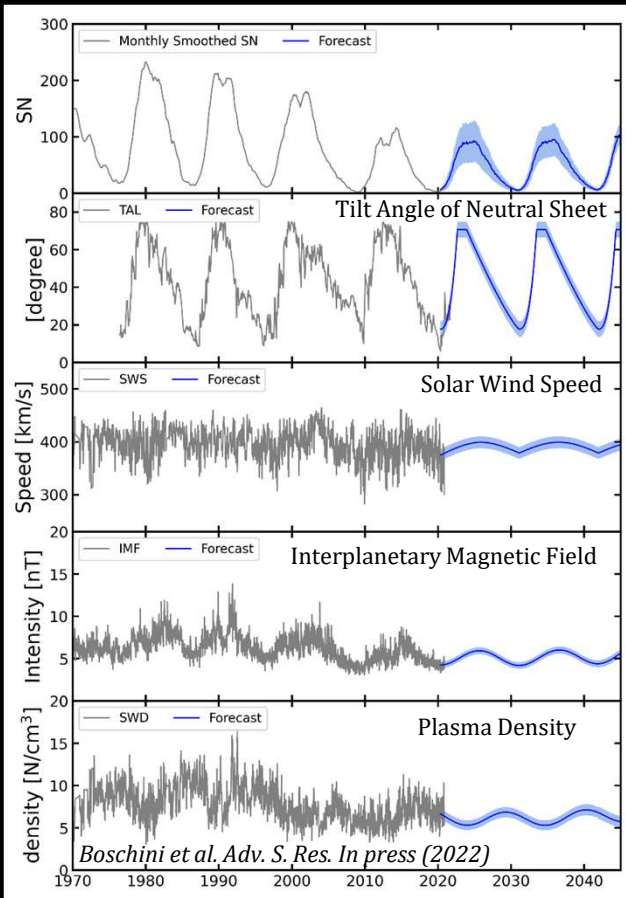
The modulated GCR intensity is directly predicted employing the heliospheric parameters such as sunspot numbers, solar wind speed & density,...



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

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

# Forecast



The procedure is used to forecast:

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

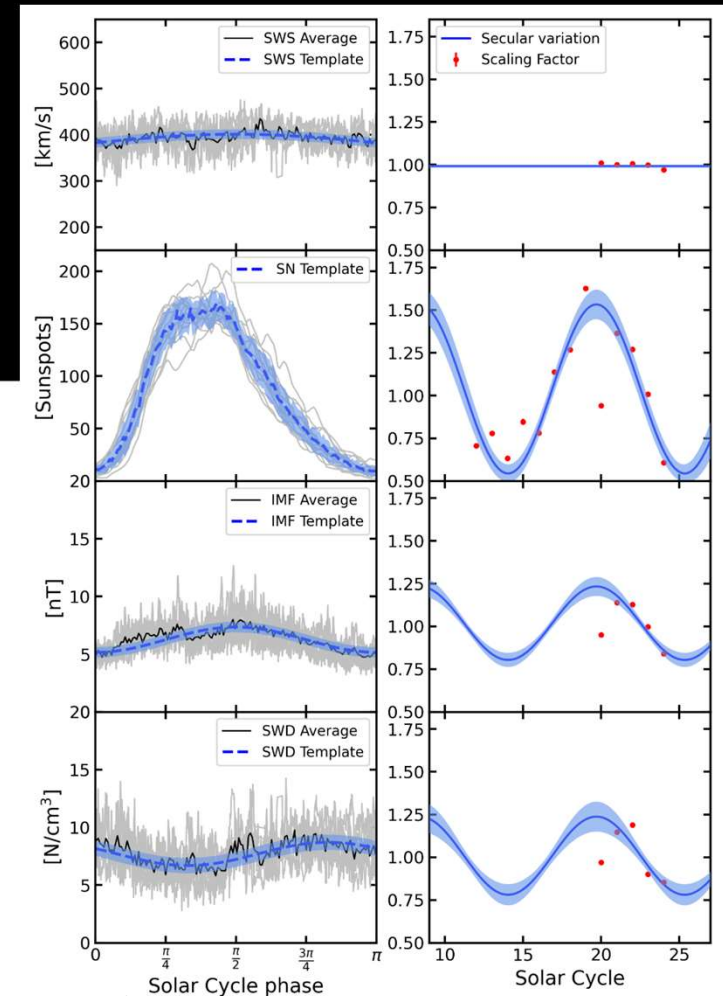
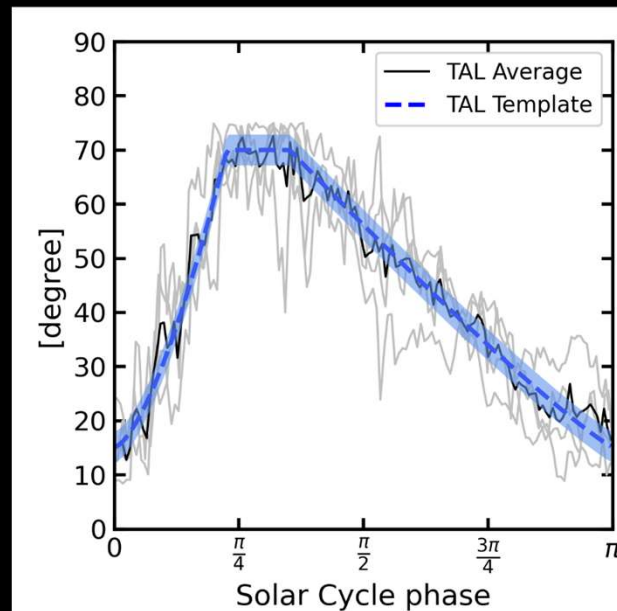
The procedure can optimize the forecast up to 3-5 years using the measured parameters of last 3 years

# Forecast

The procedure is described in Boschini et al. (2022)

we consider the activity of last 12 solar cycle to create a template of the average cyclic variation

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



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

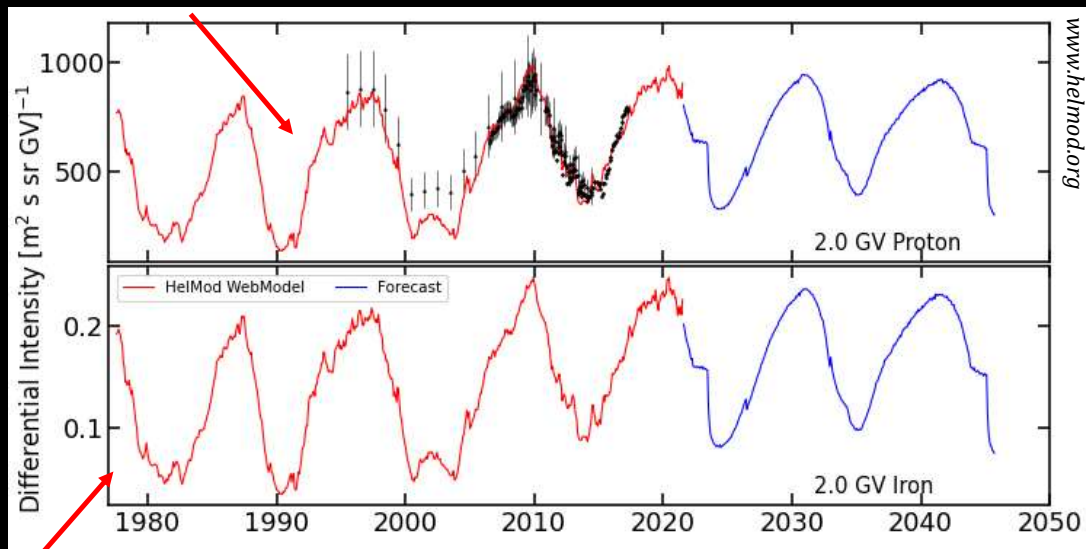
# Forecast

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 discrepancies between the two are due to the forecasting method itself.

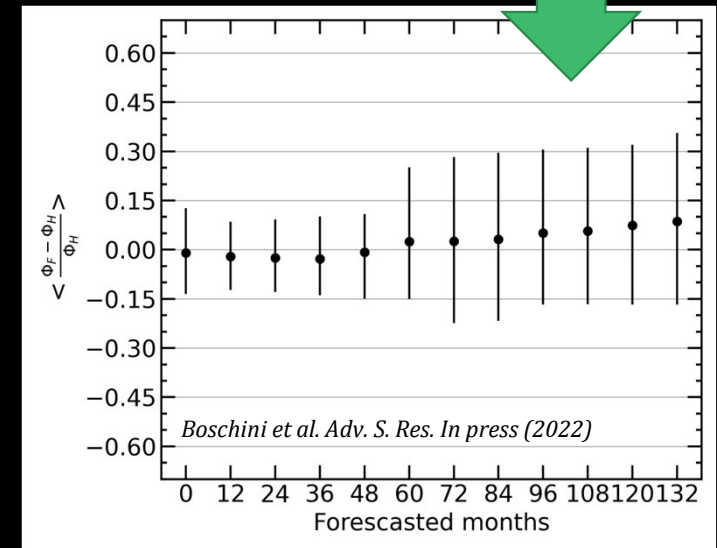
The forecasting procedure can reproduce HelMod fluences with an accuracy:

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

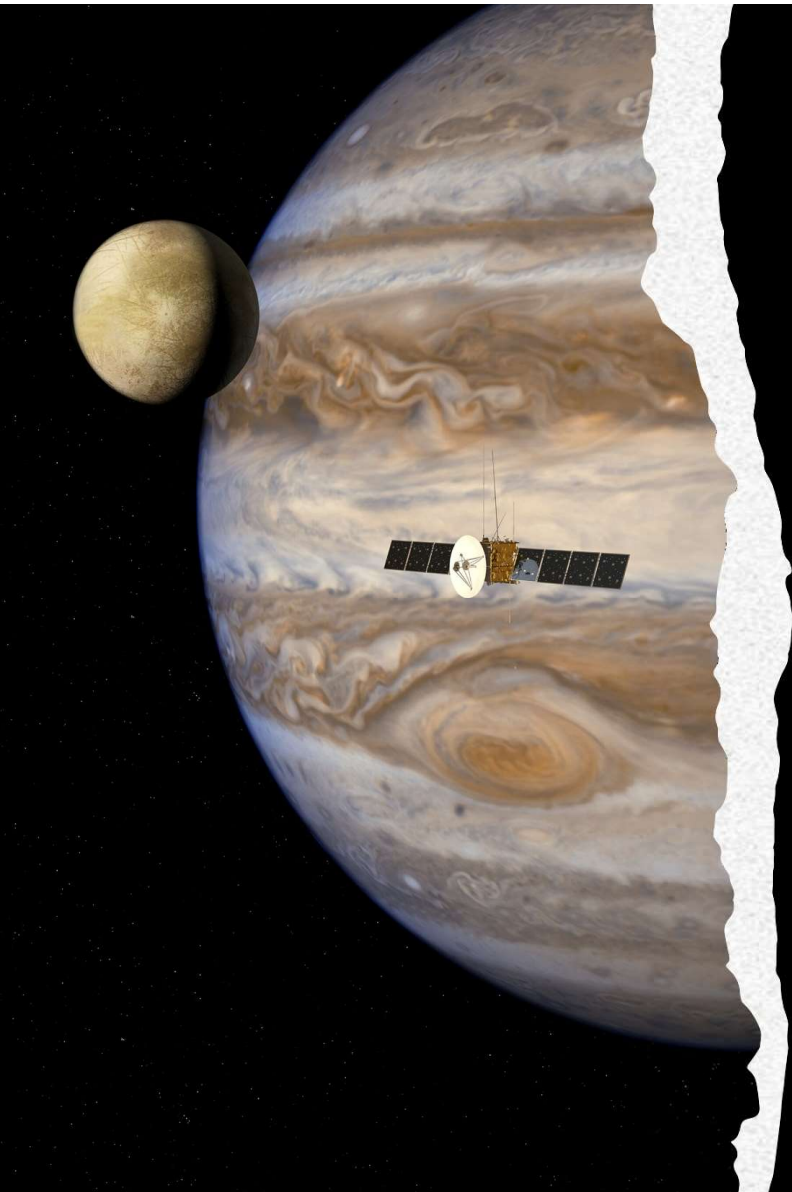
## Proton



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



Average Relative difference fluence evaluated with Helmod and with forecast procedure



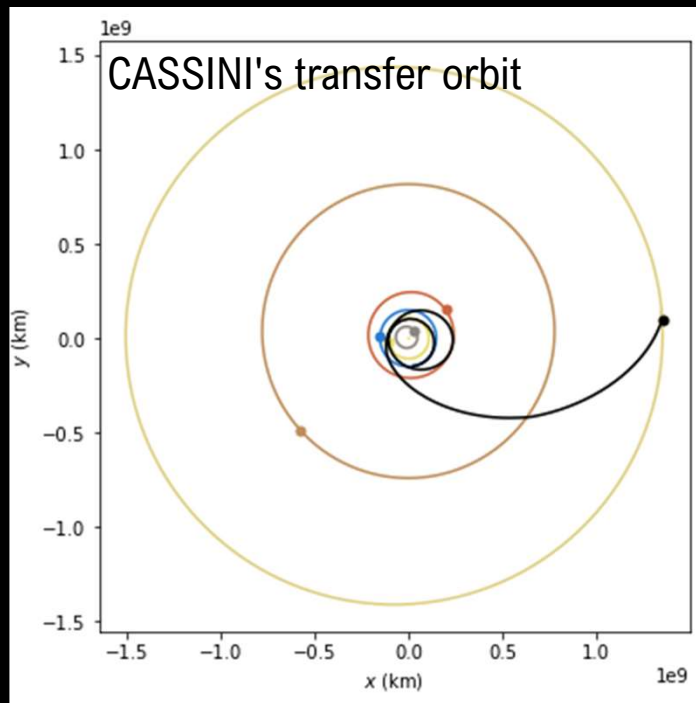
# Transfer orbit fluence calculator

GCR spectra increase with increasing the solar distance.

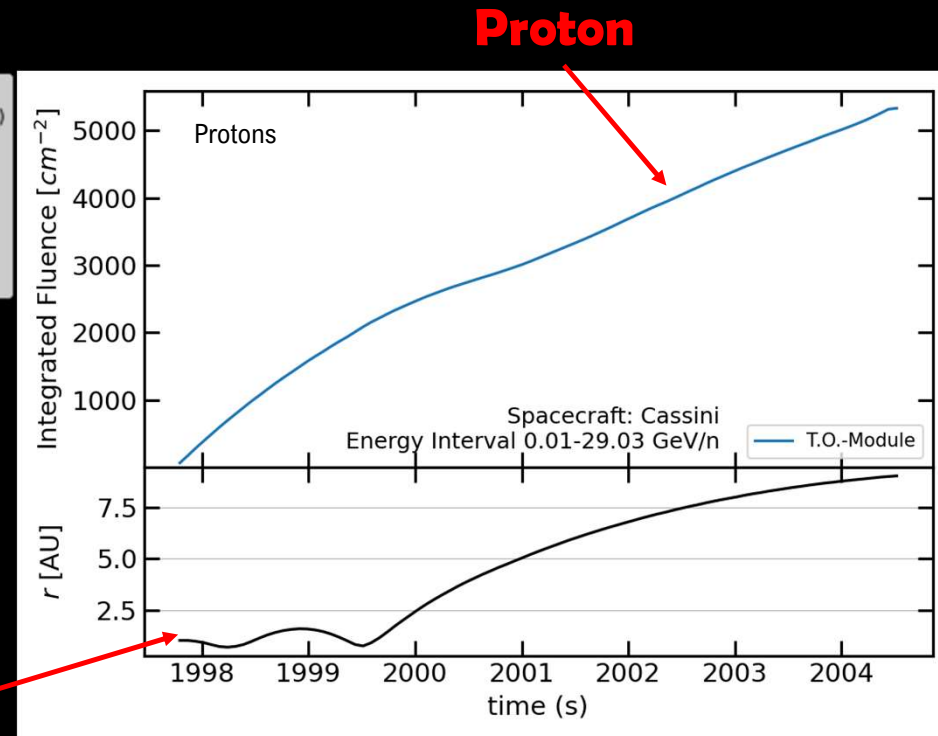
This gradient depends on solar activity and global magnetic field polarity

# Transfer orbit fluence calculator

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

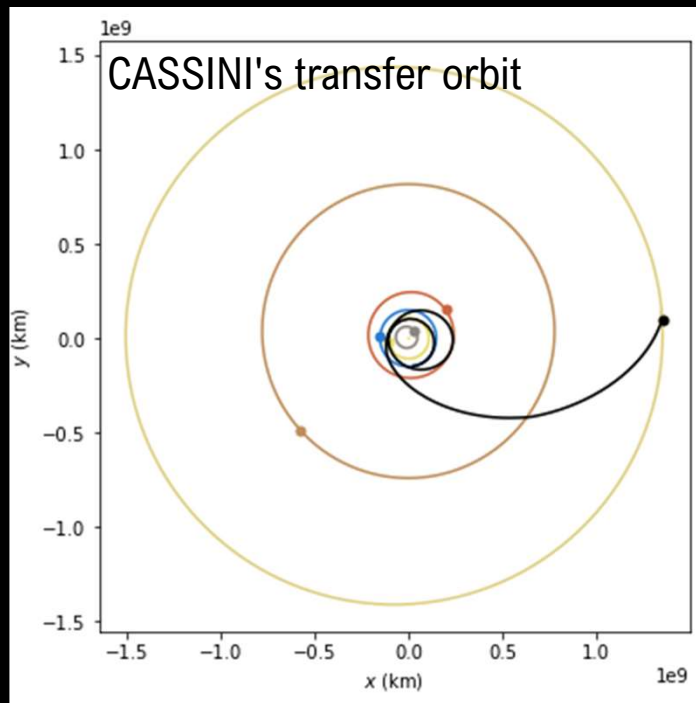


Radial distance  
of Transfer Orbit

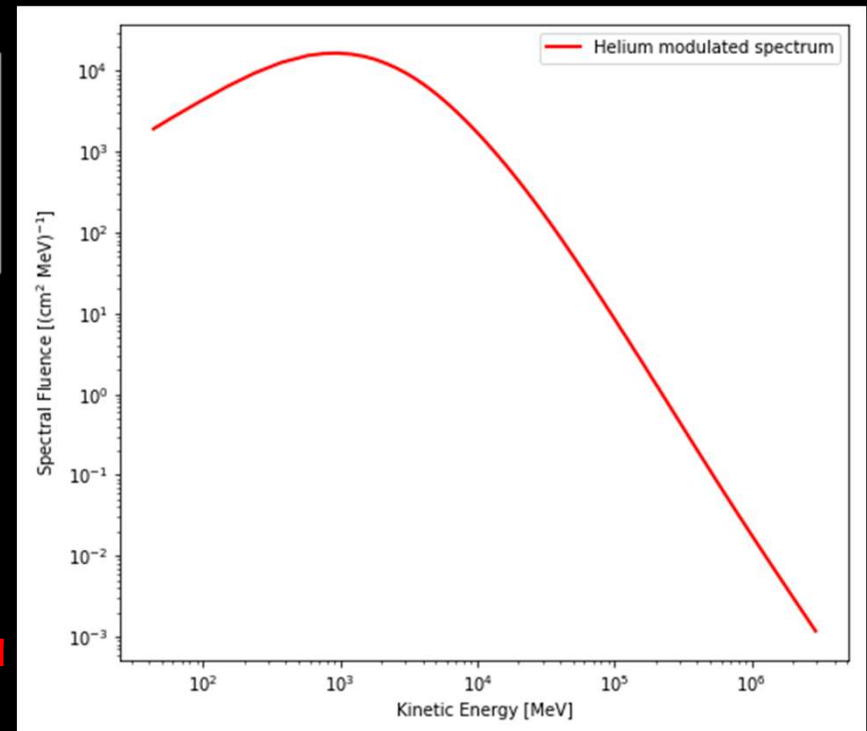


# Transfer orbit fluence calculator

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

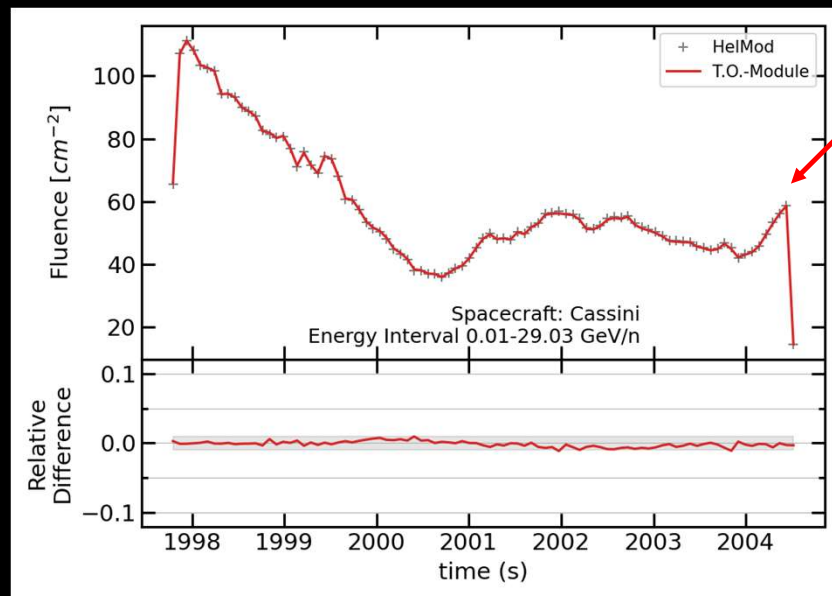


**Differential  
Fluence**

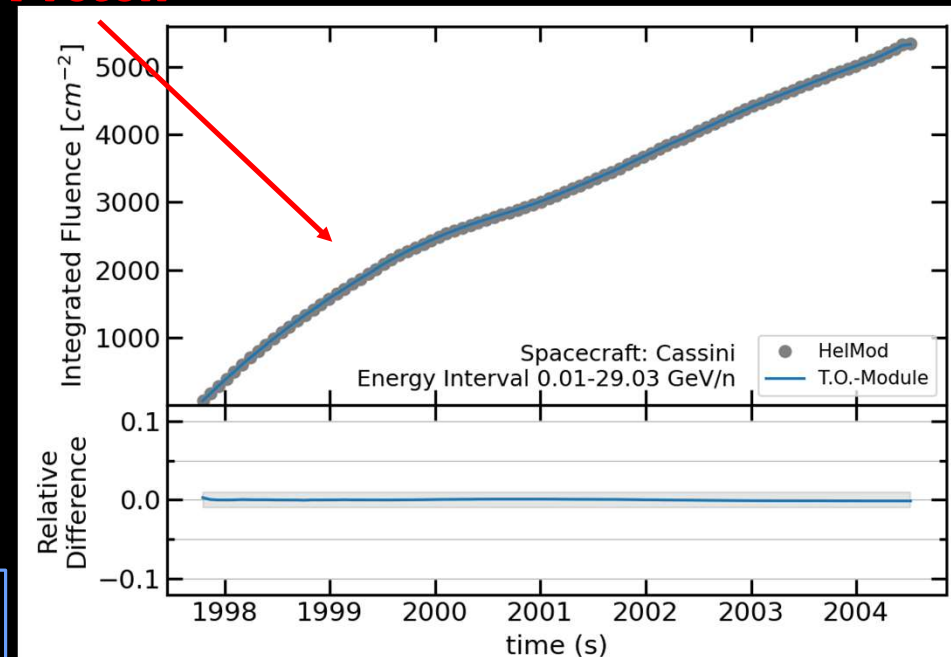


# Transfer orbit fluence calculator

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



**Proton**



The accuracy of the calculator compared the full simulation is at few percent level

# Conclusions

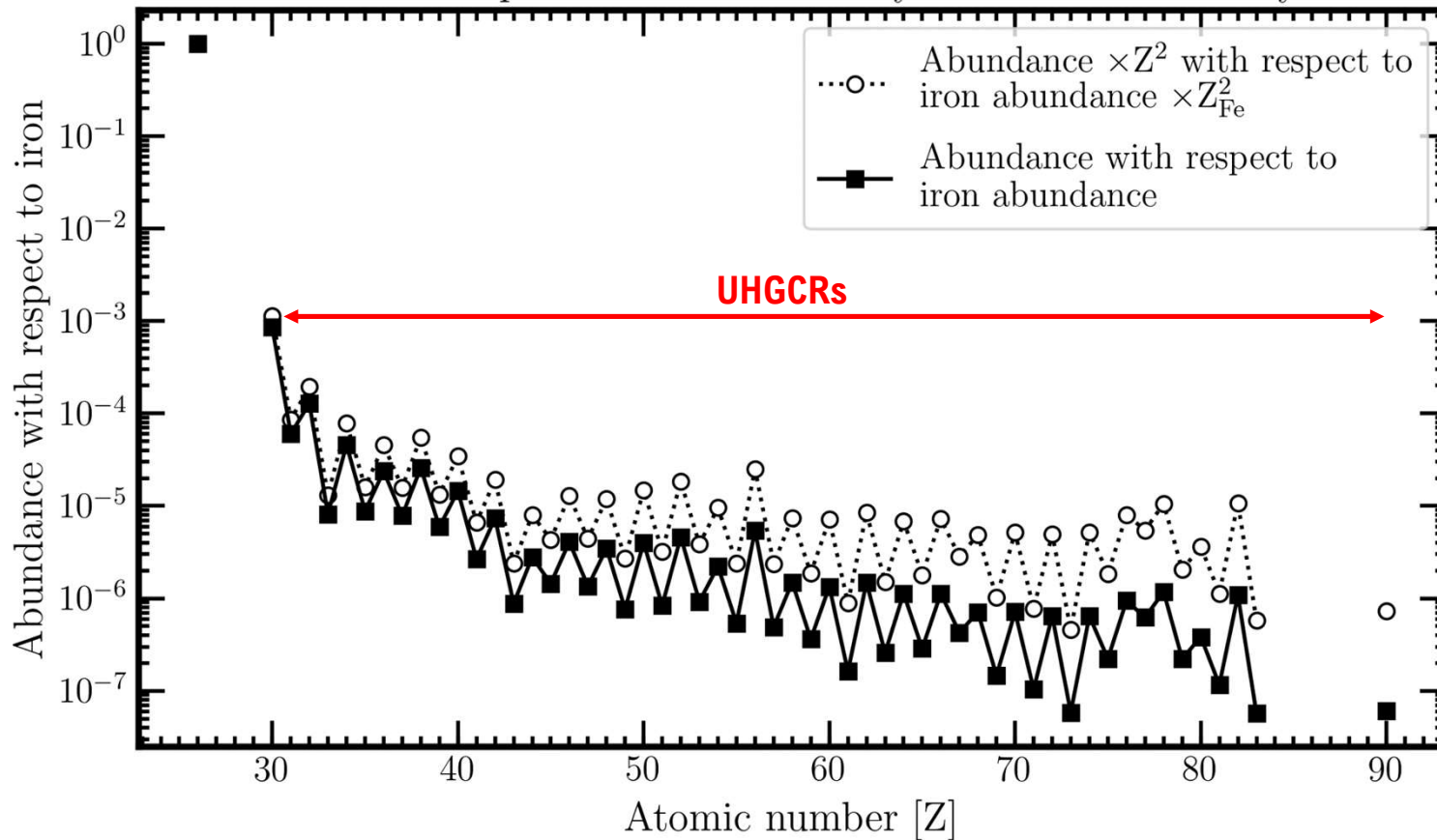
For missions in space radiation environment, the long-term modulation is relevant for accounting some type of radiation effects (for instance SEE). Thus, a realistic model is required for planning missions

- We presented the **HelMod Model** for the propagation of Cosmic rays through the heliosphere.
- The model reproduce 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 allow to predict the GCR fluence for future deep space missions
- **HelMod is available on-line at [www.helmod.org](http://www.helmod.org) and through the SR-NIEL framework ([www.sr-niel.org](http://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
- New features is available in the web model : **the transfer orbit fluence calculator**

**Backup slides**

# Ultra-heavy galactic cosmic rays

Nuclear Composition of Ultra-Heavy Galactic Cosmic Rays



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

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

# Ultra-heavy galactic cosmic rays

| Z     | Symbol | Abundance<br>with respect to<br>iron abundance | Abundance $\times Z^2$<br>with respect to<br>iron abundance $\times Z_{\text{Fe}}^2$ | Z  | Symbol | Abundance<br>with respect to<br>iron abundance | Abundance $\times Z^2$<br>with respect to<br>iron abundance $\times Z_{\text{Fe}}^2$ |
|-------|--------|------------------------------------------------|--------------------------------------------------------------------------------------|----|--------|------------------------------------------------|--------------------------------------------------------------------------------------|
| 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

# Measurements of UHGRs abundances w.r.t. Fe

03/05/2022

Data retrieved from CRDB (<https://lpsc.in2p3.fr/crdb>)

Relative Abundances with respect to Fe

