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INFN PERUGIA
Istituto Nazionale di Fisica Nucleare
Sezione di Perugia

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eSWW

Solar Activity and Galactic Cosmic Rays: A Comprehensive Model for Long-Term Forecasting

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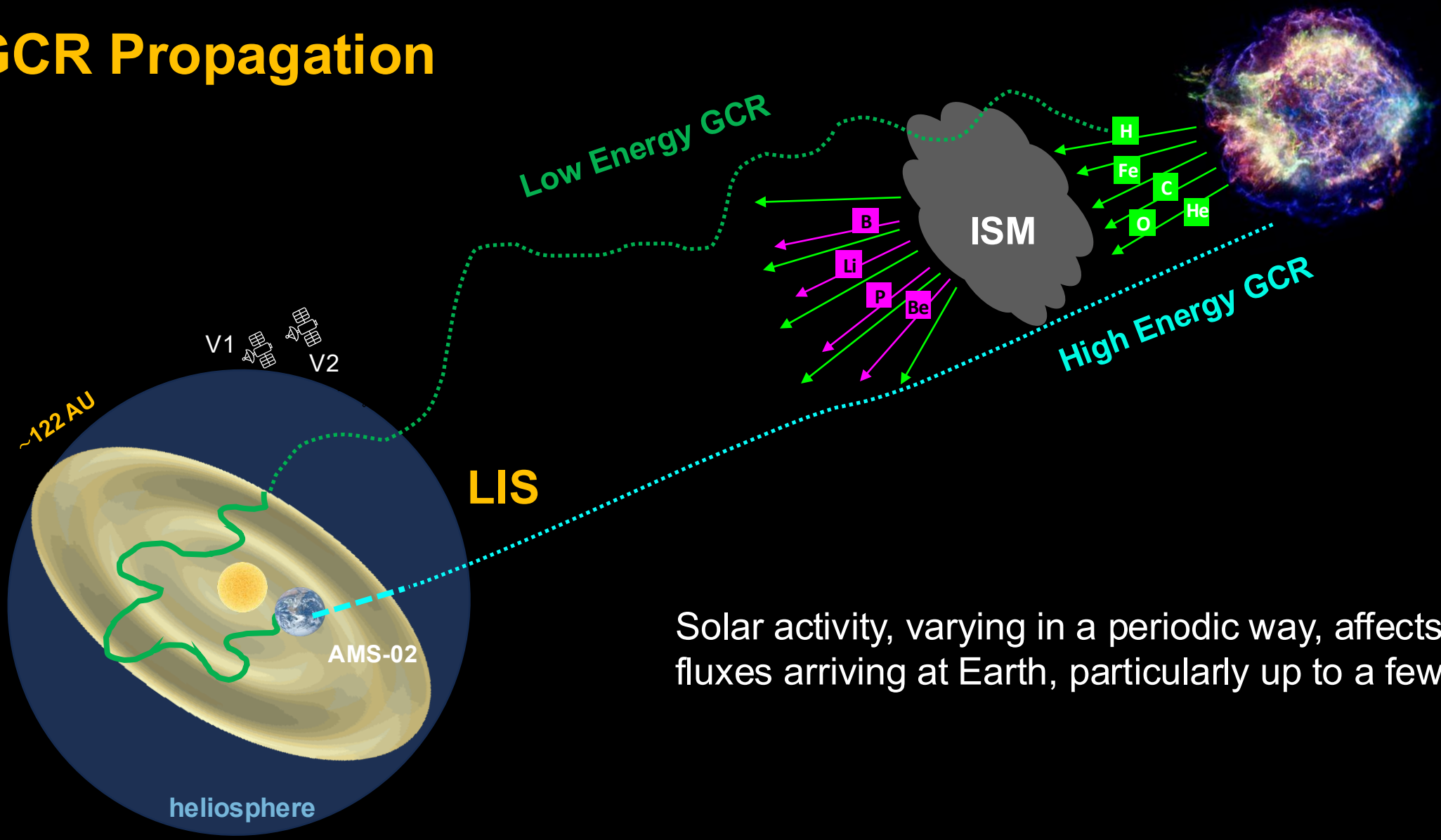
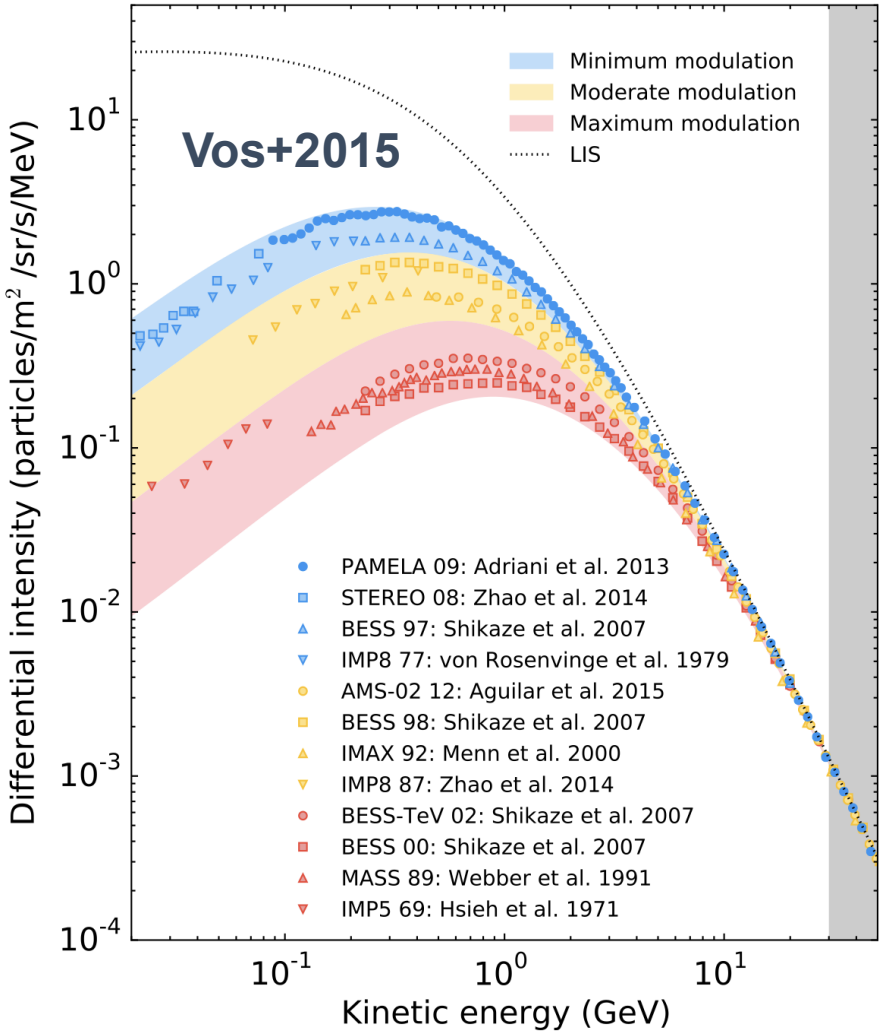
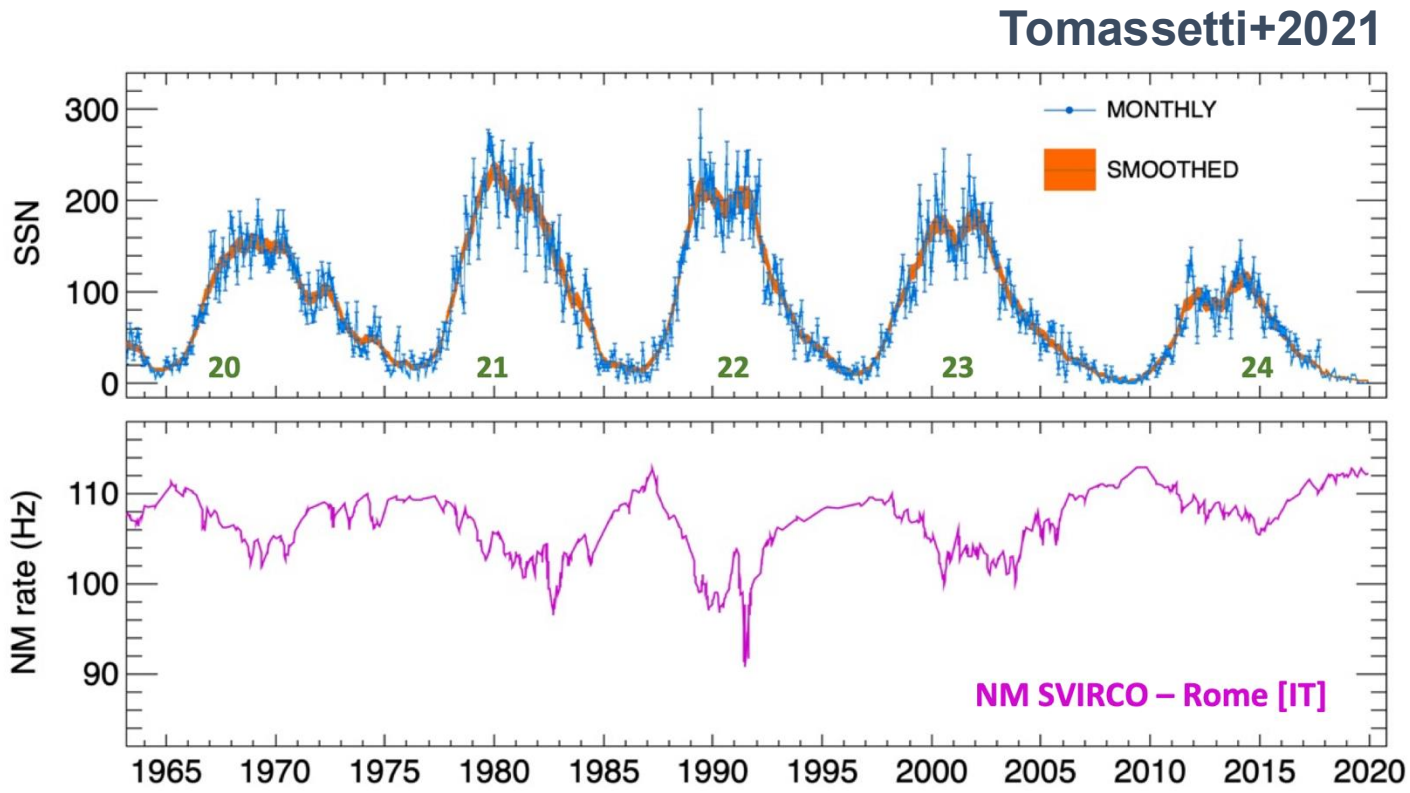
GCR Propagation



Solar activity, varying in a periodic way, affects cosmic-ray fluxes arriving at Earth, particularly up to a few tens of GV.

Solar modulation



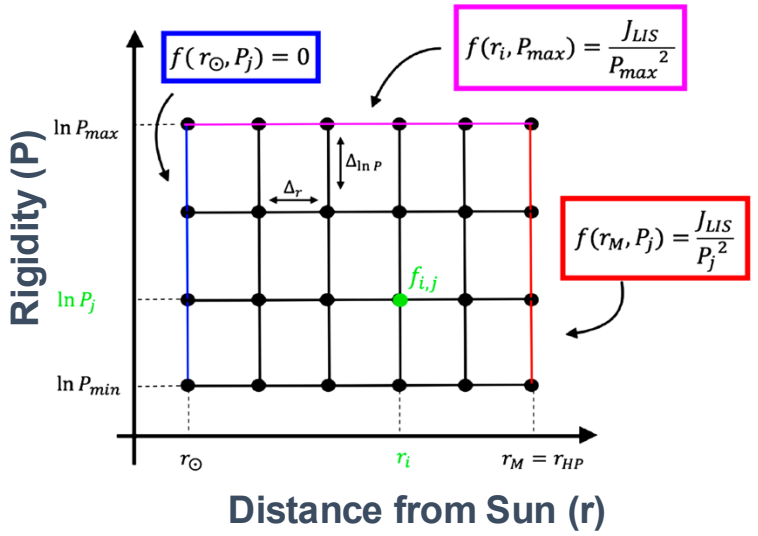


The Parker's Transport Equation

Solar modulation is caused by the long-term variations in solar activity (cycle).
It relates to the physics of particle transport in the turbulent heliospheric plasma.
The basic phenomenology is captured by Parker's transport equation.

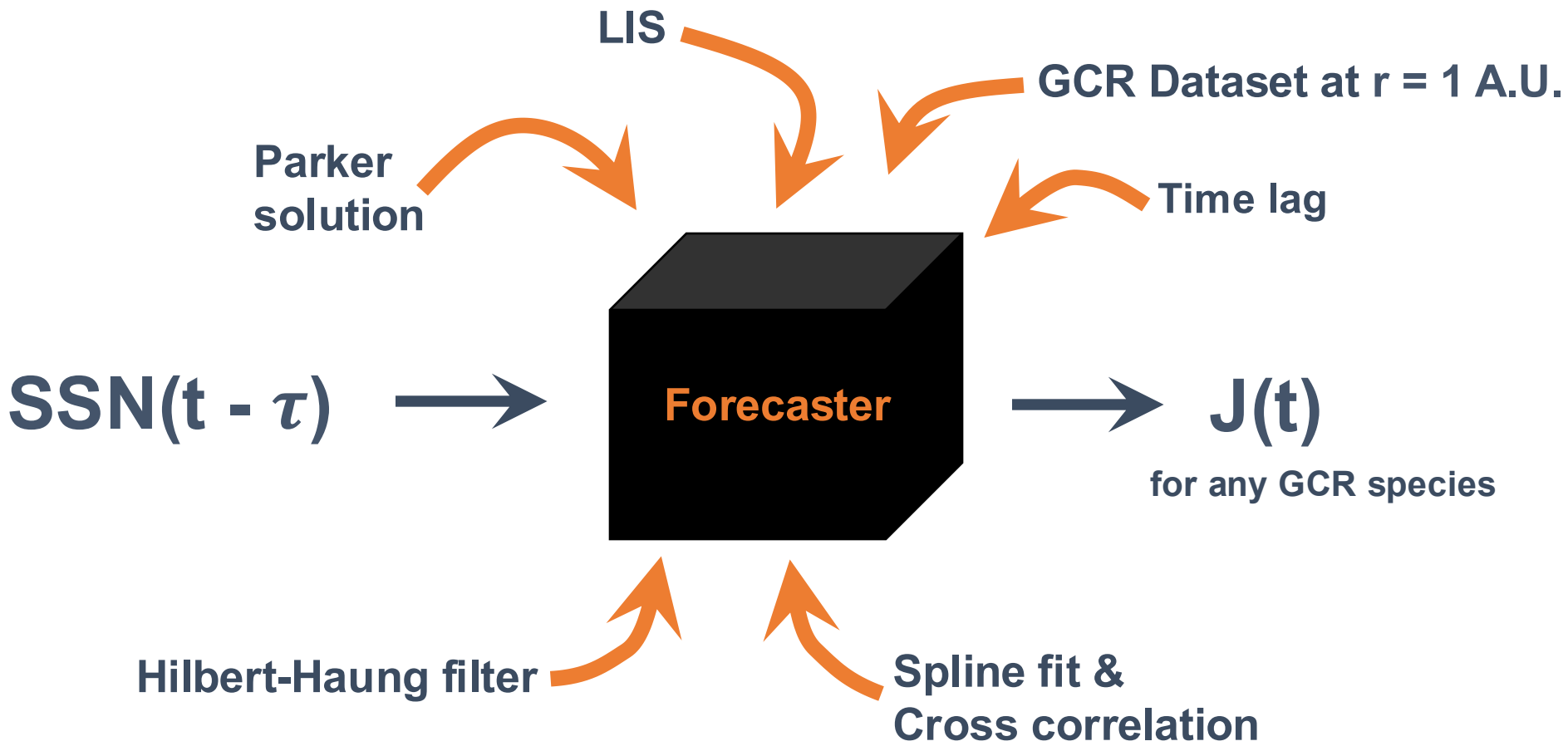
$$\underbrace{\frac{\partial f}{\partial t}}_{\text{Flux}} = \underbrace{\nabla \cdot [\mathbf{K} \cdot \nabla f]}_{\text{Diffusion}} - \underbrace{\mathbf{V} \cdot \nabla f}_{\text{Advection}} - \underbrace{\langle \mathbf{v}_D \rangle \cdot \nabla f}_{\text{Particle drift}} + \underbrace{\frac{1}{3}(\nabla \cdot \mathbf{V})\frac{\partial f}{\partial \ln p}}_{\text{Energy losses}} + \underbrace{Q(\mathbf{r}, p, t)}_{\text{Source}}$$

- **Analytical methods** (Force-Field)
- **Numerical methods:**
  - Crank-Nicolson algorithm (1-D)
- **Stochastic methods**:
  - 3D model of heliosphere (High computational cost)



The LXPG model

Pelosi D. et. al., A forecasting framework for galactic cosmic ray flux in space weather applications, Adv. Space Res. 76(9), 5700–5713 (2025).



- **ML** (Du+2025, Long Short Term Memory strategy)

The Numerical Solution

1D Parker transport equation **solved numerically via Crank–Nicolson scheme**, assuming LIS (Pelosi et al. 2025), constant solar wind speed *V*, and effective diffusion coefficient *K*.

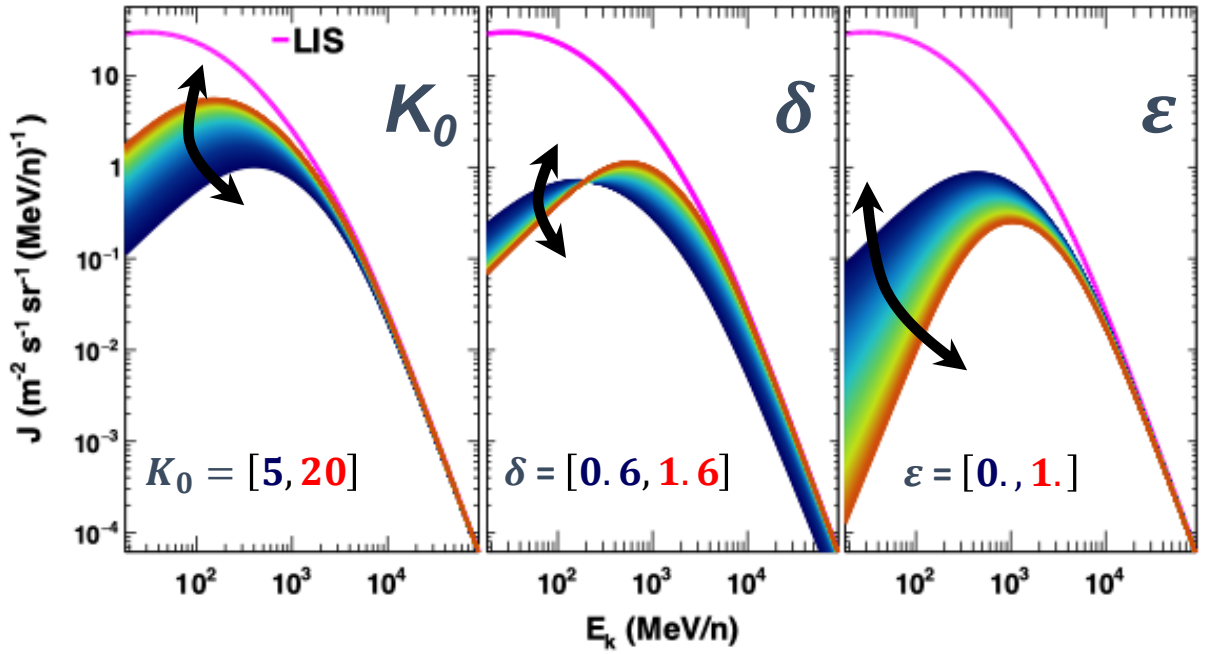
$$K\frac{\partial^2 f}{\partial r^2} + \left(\frac{2K}{r} - V - V_c\right)\frac{\partial f}{\partial r} - \frac{2V_c}{r}f + \frac{2V}{3r}\frac{\partial f}{\partial \ln p} = 0$$

$$K(t) = K_0(t)\,\beta\left(\frac{P}{1\ \mathrm{GV}}\right)^{\delta(t)} \qquad V_c(t) = \varepsilon(t)\cdot V$$

The **effective term** ε introduces an additional advection component $V_c = \varepsilon * V$, without an adiabatic loss counterpart, which helps shape the solution in the sub-GeV energy region.

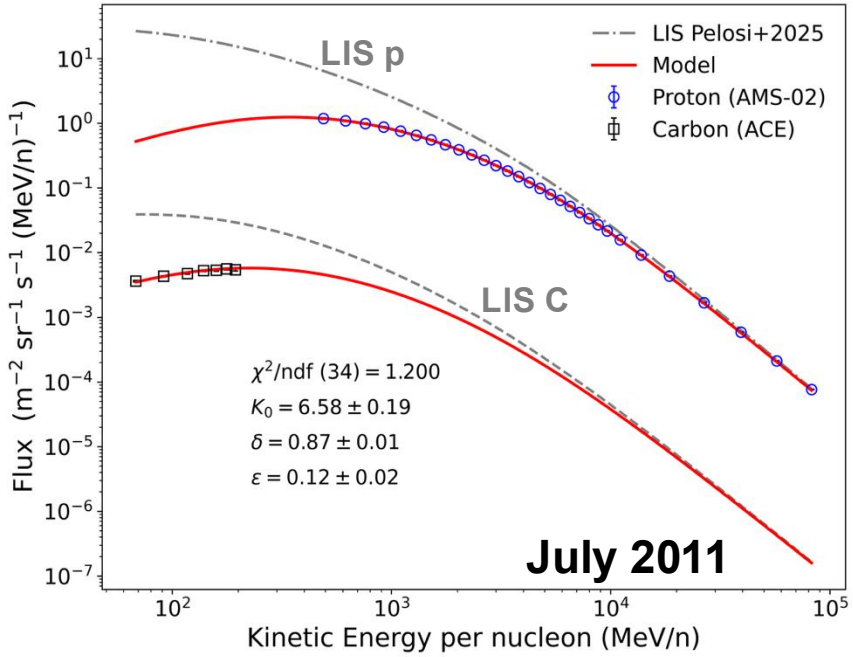
K_0, δ, ε are the parameters used to describe the flux at any given moment.

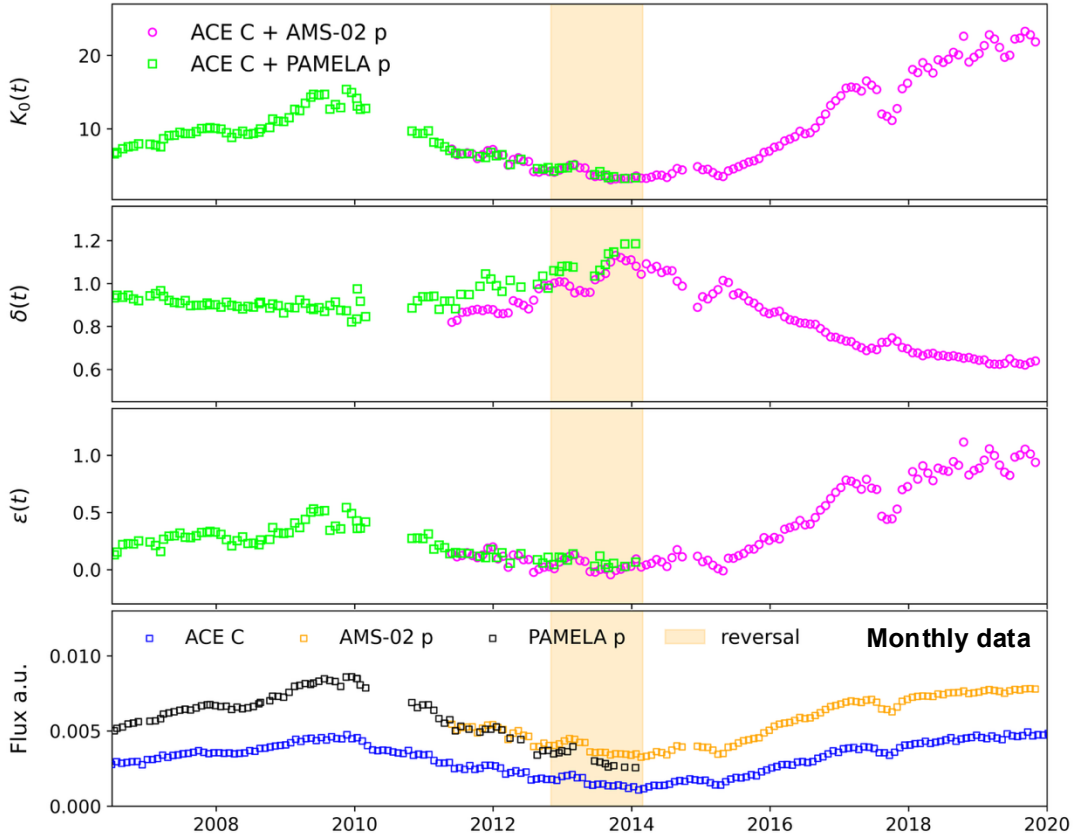
Flux shape — single parameter effect



Parameter Time-series

Combined monthly AMS-02 (protons), PAMELA, and ACE (carbon) data to improve statistics and extend energy range for better parameter constraints.



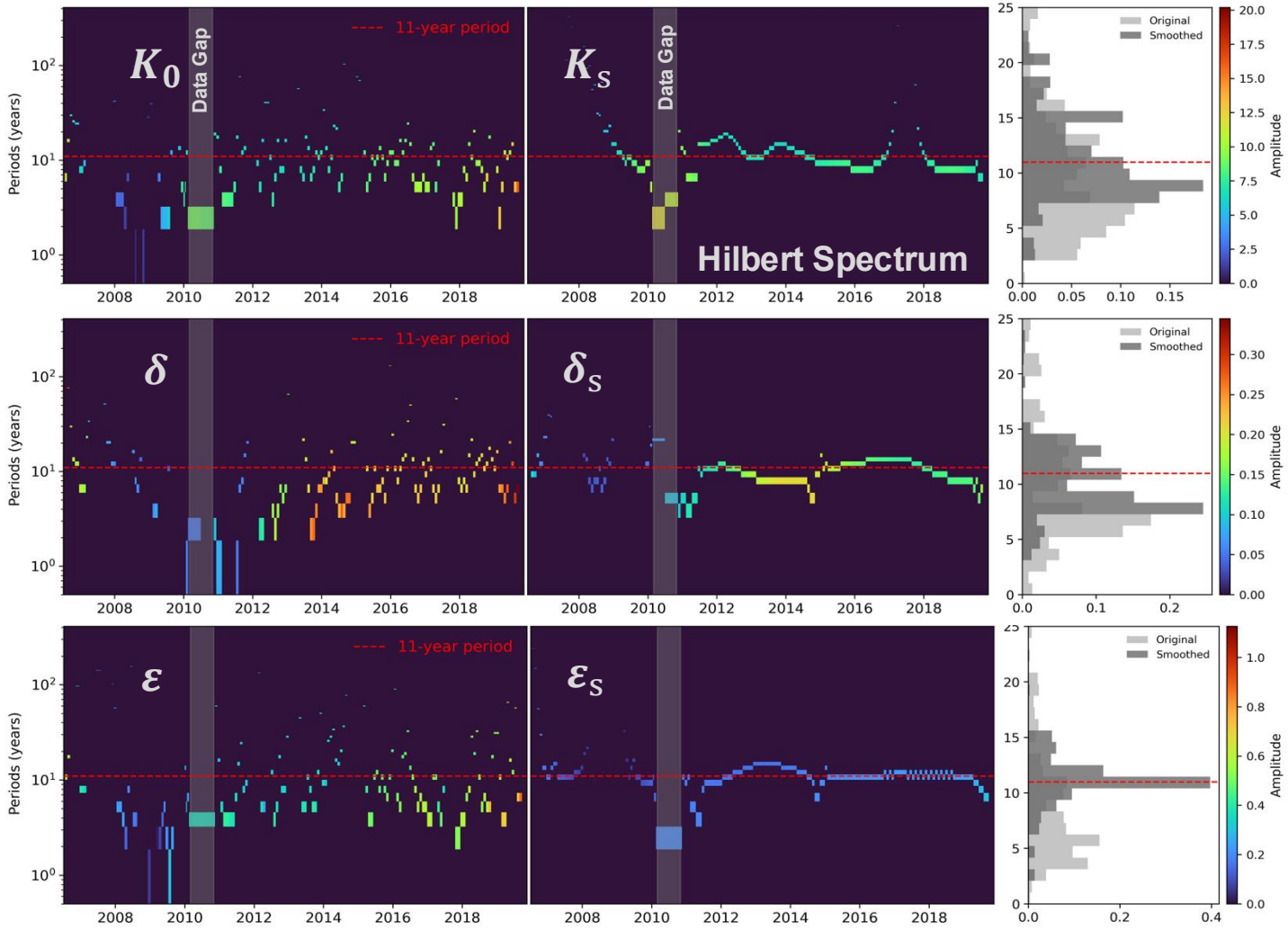


$$\chi^2(K_0,\delta,\varepsilon) = \sum_s \sum_j \sigma_{s,j}^{-2} \left[\hat{J}_s^j - \frac{1}{\Delta P_j} \int_{P_j}^{P_{j+1}} J_s(P, K_0, \delta, \varepsilon)\, dP \right]^2$$

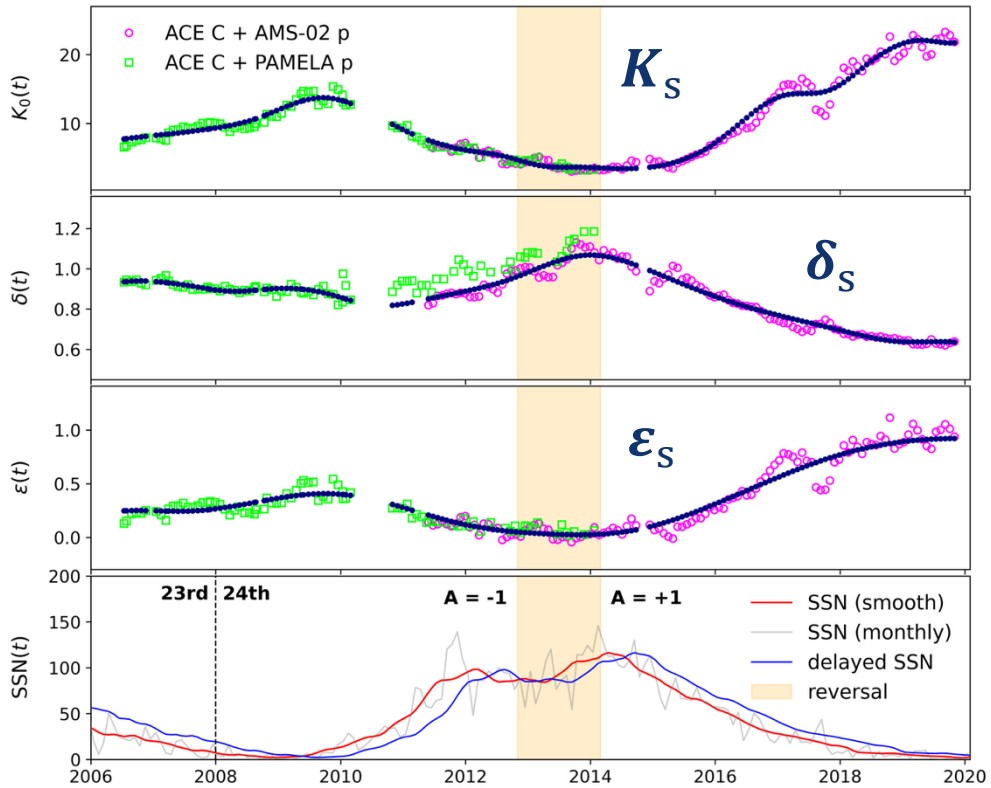
- s: GCR species
- j: Rig bins
- $\hat{J}_s^j$: Data
- $J_s(P, K_0, \delta, \varepsilon)$: Model based on LIS of the s-GCR

Hilbert-Haung filter

$$K_0(t) = \sum_{k=1}^{N} c_k(t) + r(t) \qquad K_S(t) = \sum_{k \in N} c_k(t) + r(t)$$



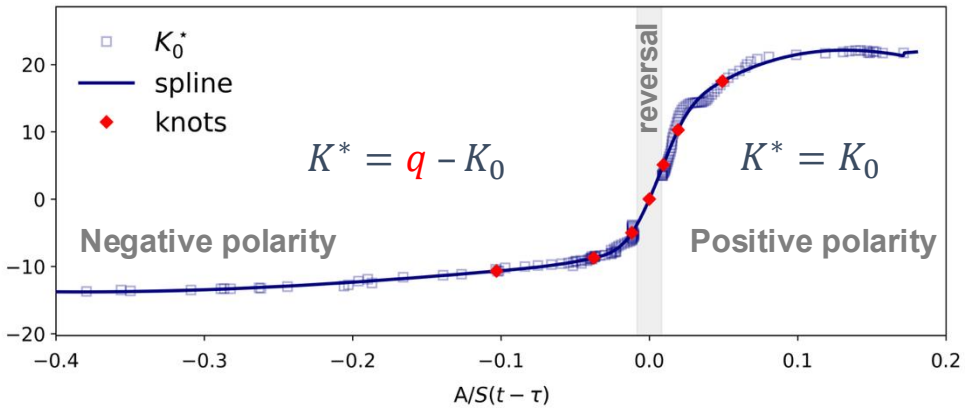
Hilbert–Huang transform with EMD optimization (11-yr solar cycle reference) for robust **long-term mode extraction**, minimizing short-term solar transient signatures.

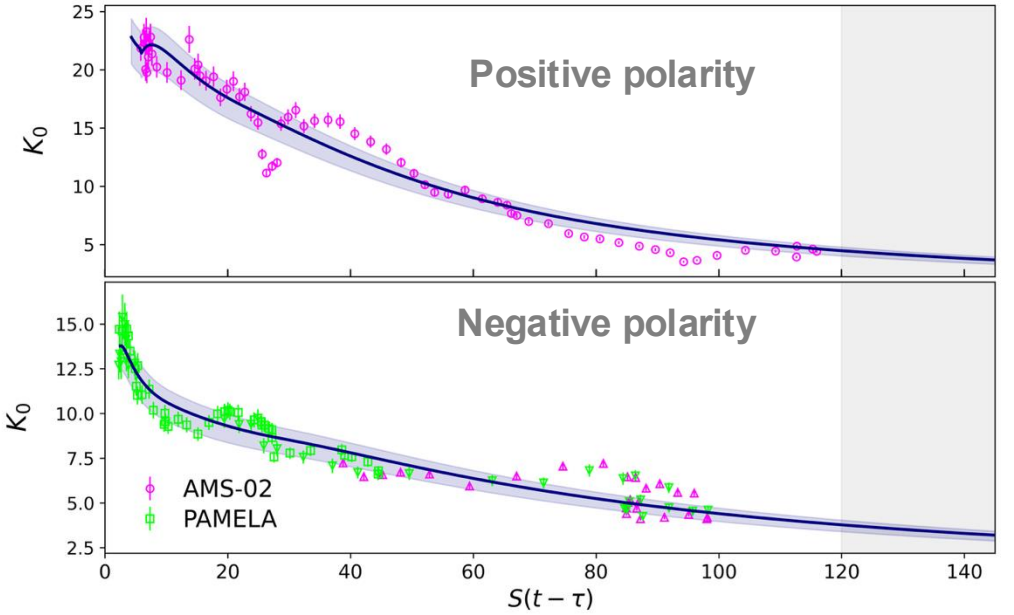


Spline fit and Cross correlation

Tomassetti+Phys. Rev. D, 2022

$$\tau(t) = \tau^0_{\mathrm{Min}} + \tau^0_M + \hat{q}\,\tau_A \cos\left[\frac{2\pi}{T_0}(t - t_P)\right]$$





Preliminary uncertainties

- **Heliospheric lag** between smoothed SSN and GCR data explicitly included S(t - τ).
- **B-spline fit** across both polarity phases (A / S(t - τ)) ensures smoothness and **continuity and smooth transition through reversal**.
- Fit minimizes loss-function $\mathcal{L}$ optimizing knots ($\mathcal{N}$) and biases($\vec{q}$)

$$\mathcal{L}(\, f(\vec{q})\,,\, \mathcal{N}\,) = \chi^2_{ndf}\,(f) + \int f''(x)^2\, dx$$

$$\mathcal{L}_{min}\big(f(q, \mathcal{N})\big)$$

- **Cross-correlation functions** quantifies parameter–SSN relationships.

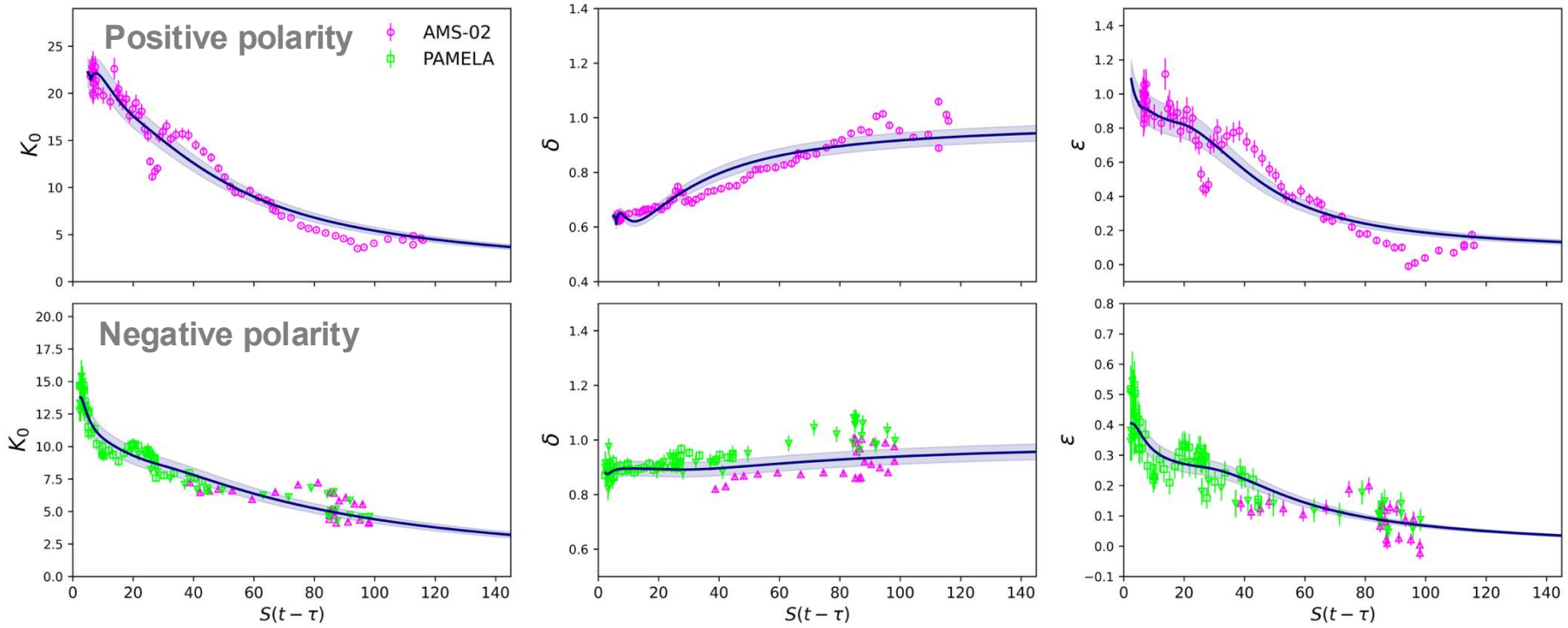
Spline fit and Cross correlation

Bootstrap technique used to evaluate uncertainties:

- Resampling using fitted errors and correlations
- Apply filter and spline fitting to each realization.
- Use the spread of the resulting distribution as the final uncertainty.

$$S(t-\tau) \xrightarrow{\vec{f}} \begin{pmatrix} K_0(t) \\ \delta(t) \\ \varepsilon(t) \end{pmatrix} \xrightarrow{\text{model}} J(P,t) + \sigma$$

for any GCR species

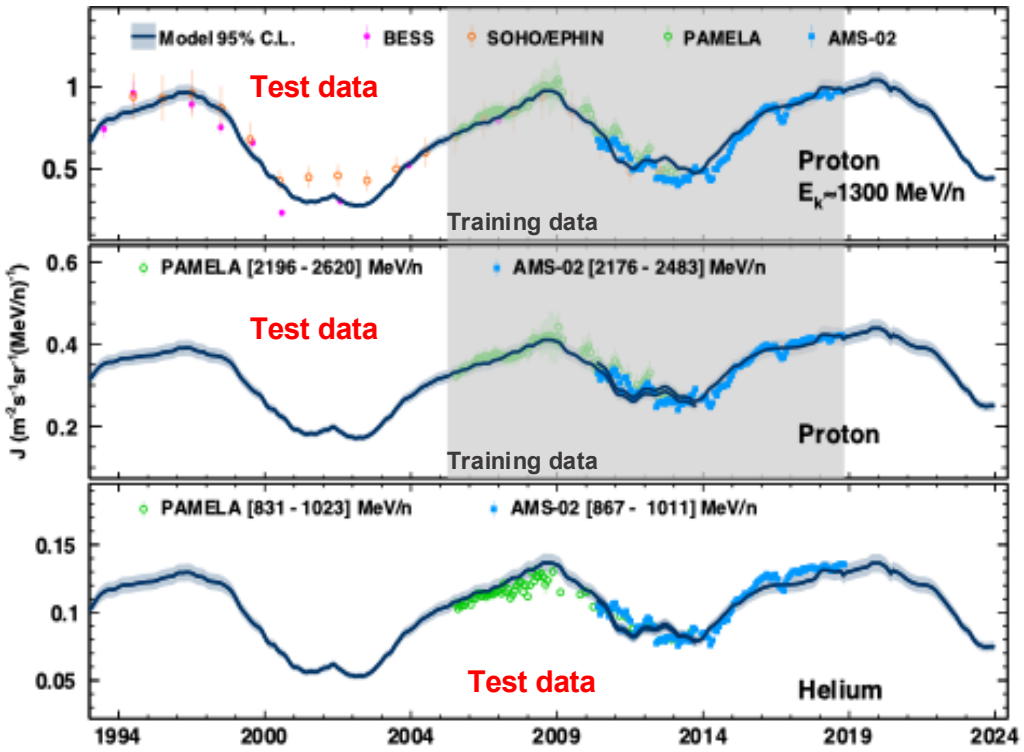


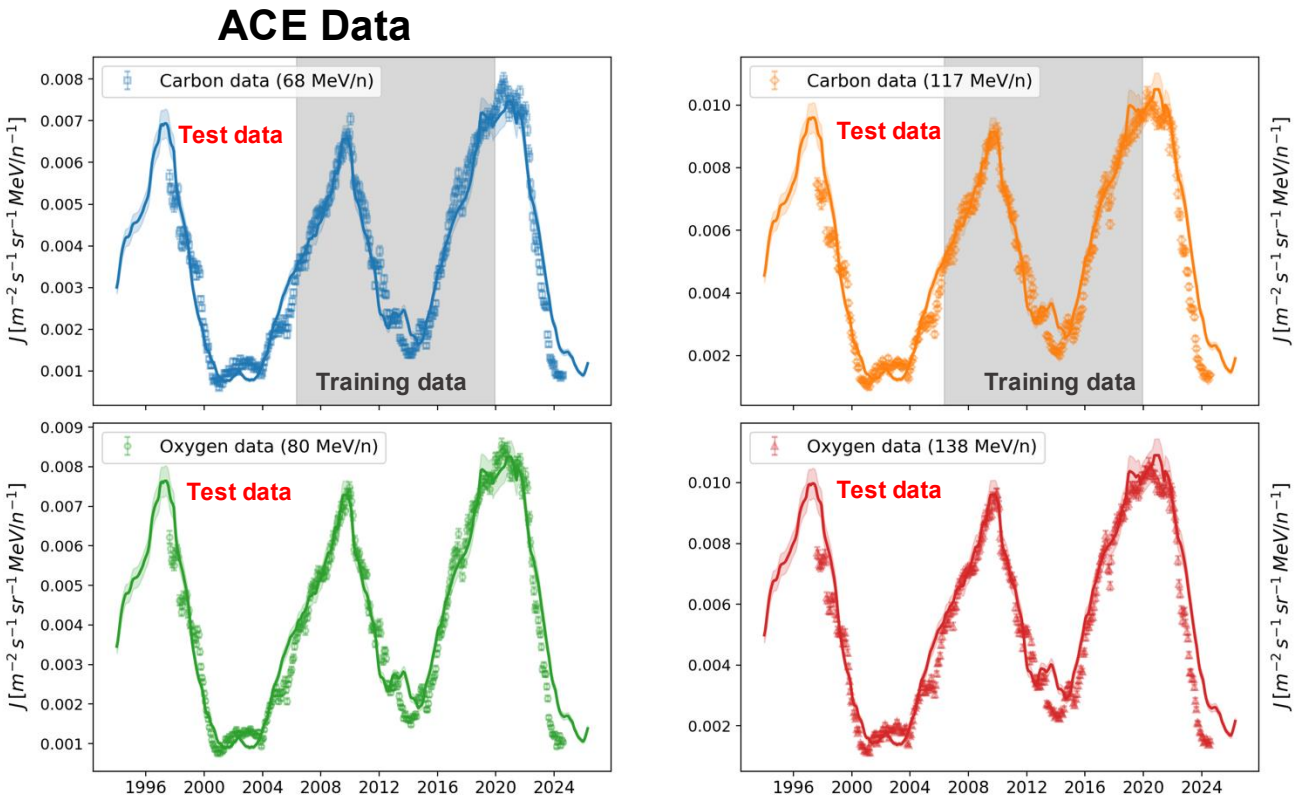
Preliminary uncertainties

Performances

Paper in preparation

Robust performance across data from several experiments, species, and energy ranges; consistent reconstruction through multiple solar cycles.





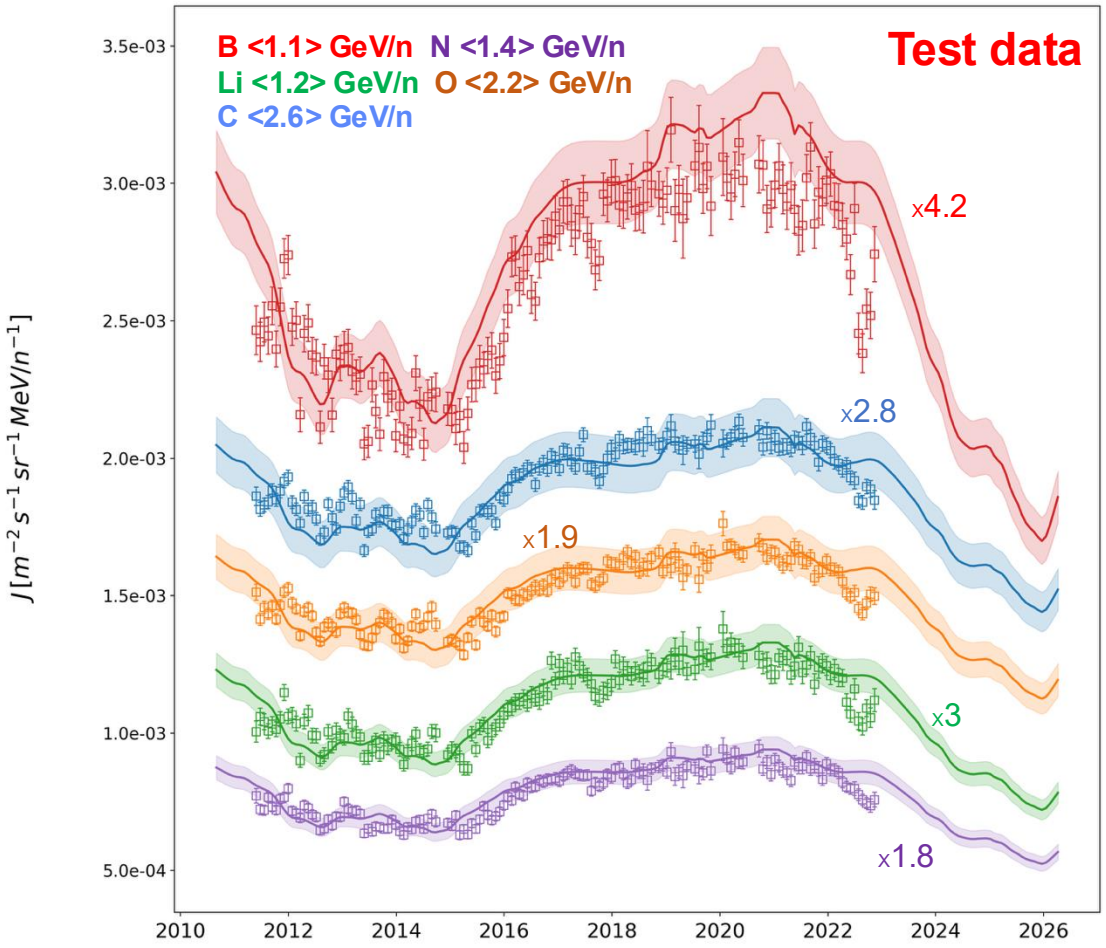
*Model uncertainty preliminary

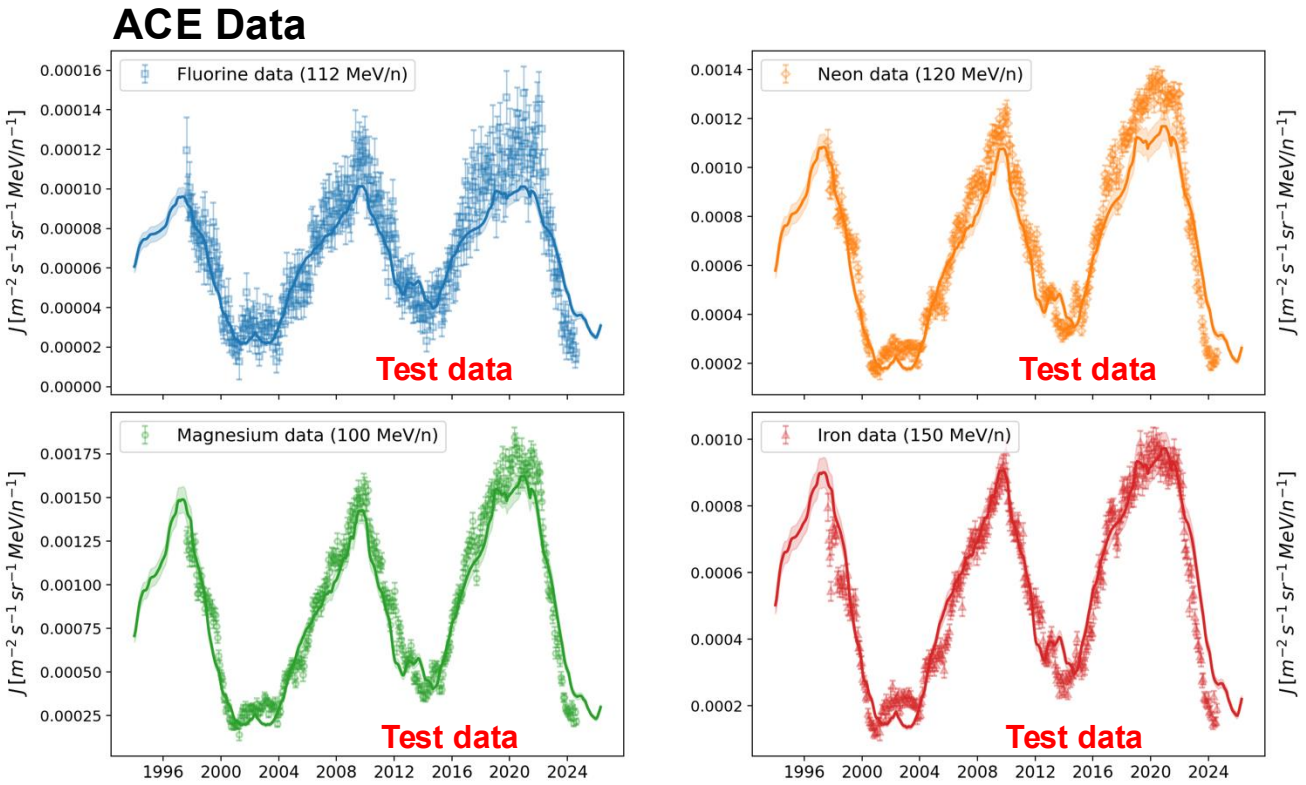
Performances

Paper in preparation

- LIS from Boschini+2017

AMS-02 Phys. Rev. Lett. 134, 051001 (2025)





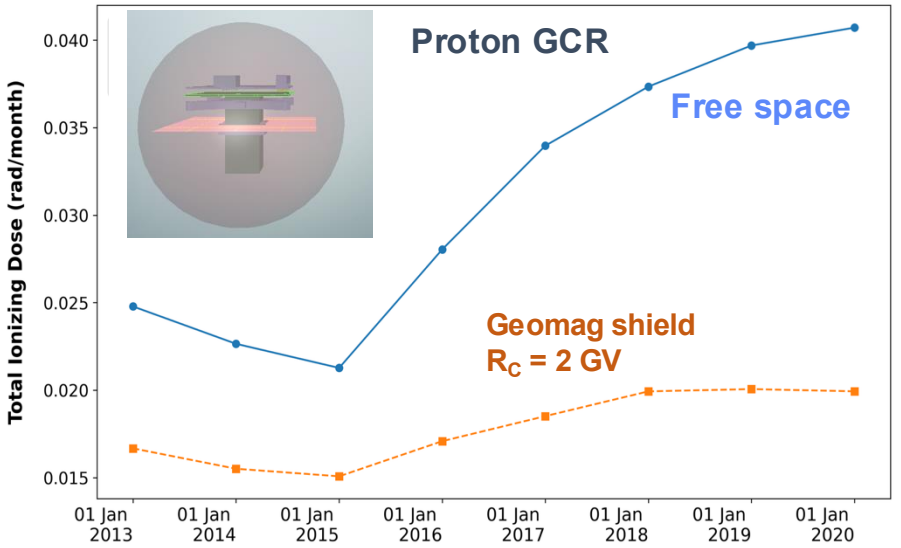
*Model uncertainty preliminary

Space Weather Applications

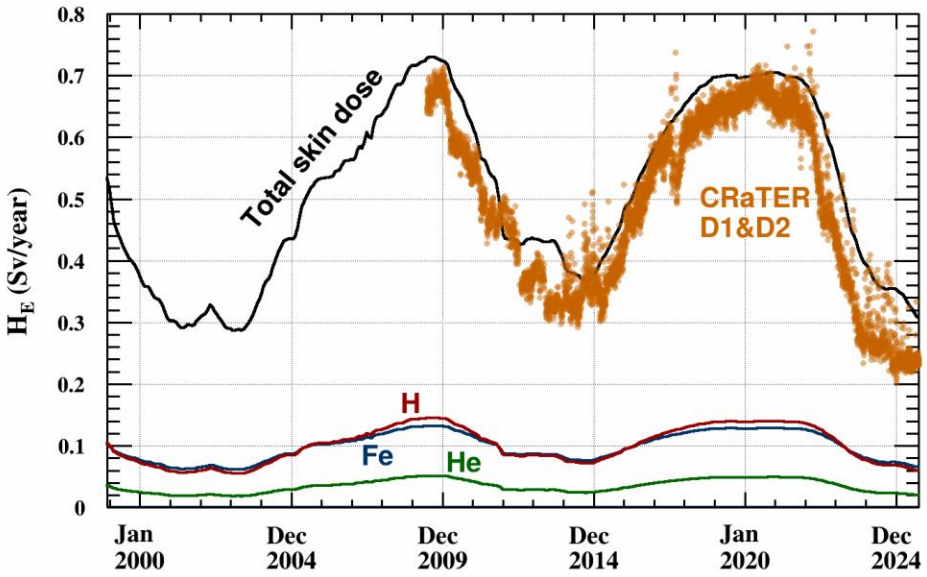
MRADSIM®
Alpat+2024

- Framework can be extended for long-term GCR predictions, integrating SSN forecast models (Penza+2021, Asikainen+2023).
- Space Weather applications**:** preliminary tests coupling **LXPG model** with **GEANT4** for **dose simulations** (MRADSIM, BEAMDIE s.r.l.).

Toy CubeSat geometry: PCB Board as target dose estimates (LXPG + MRADSIM)



Credits M.Orcinha



For details on **dose and geomagnetic cutoff studies**, see **M. Orcinha's talk – SWR5, 30 Oct 2025:**
"Cosmic radiation near Earth: Impact of solar activity and the geomagnetic field in long-term modelling of dose from cosmic radiation in space."

Conclusion

- The model effectively reproduces **multichannel cosmic-ray data** across several **energy ranges and epochs.**
- Demonstrates strong **predictive capability** through SSN-driven modulation and time-delay effects.
- Supports **space weather forecasting** and **dose assessment** for both **humans and spacecraft systems**, enabling long-term predictive applications.

Next Steps

- Investigate **radial dependence** of flux modulation.
- Incorporate more suitable physical solar proxies (e.g. **open solar flux**)
- Refine **time-lag studies** as explored in Pelosi+PoS(ICRC2025)