Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

Investigation of CR heliospheric propagation models during Forbush Decrease with GPU parallelization

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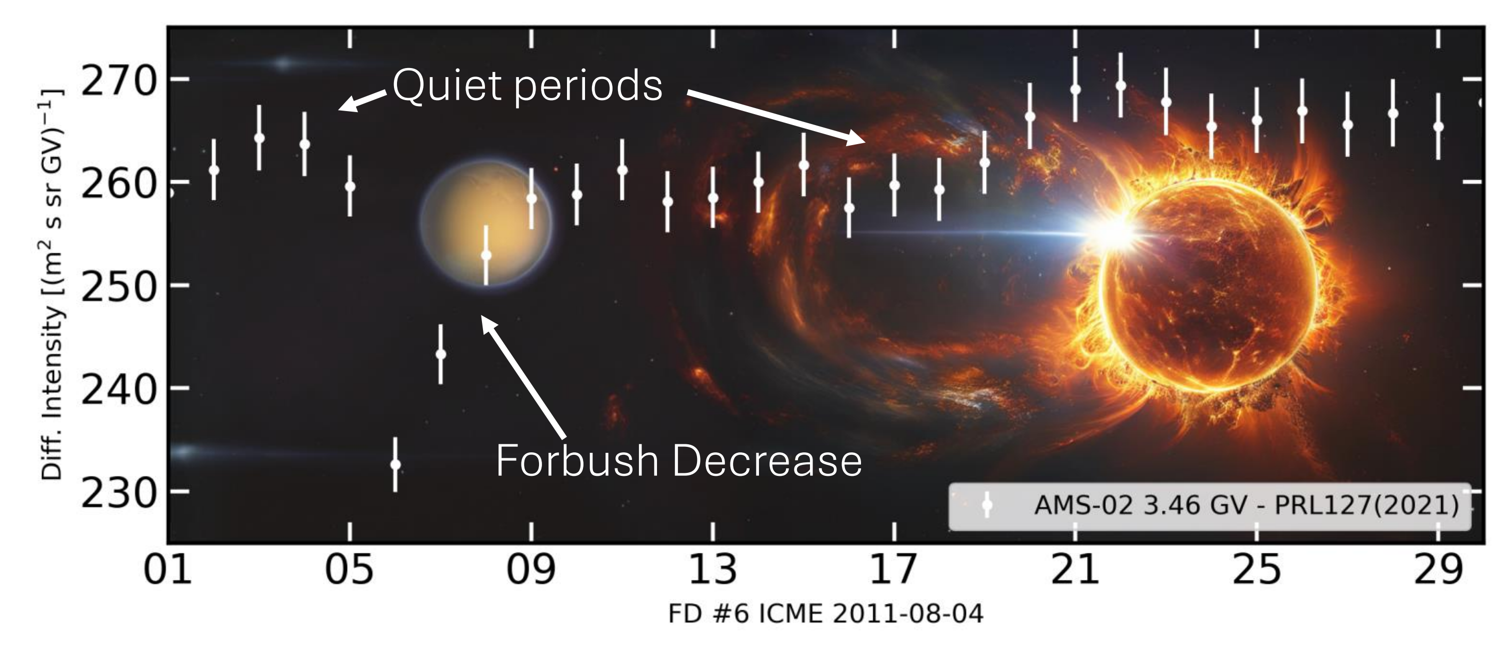
Scientific Rationale

Coronal Mass Ejection (CME) -> expulsion of plasma from the Sun that locally alter the properties of the interplanetary medium.

***Forbush Decrease* (FD)** -> a sudden (local) reduction of the Cosmic Rays (CR) intensity due to CME passage that may take several days to be recovered.

AMS-02 measured 142 FD (5/2011->10/2019).

The measured spectra allow for analyzing FD behaviour at different rigidity intervals with unprecedented accuracy.



Is it possible to infer general properties of particle propagation in the interplanetary medium using a phenomenological approach?

The computational model

We use a modified version of HelMod

www.helmod.org

Monte Carlo Code solving a set of Stochastic Differential Equations (SDE) equivalent to Parker Transport Equations.

Diffusion — Advective — Adiabatic loss — Drift

$$\frac{\partial U}{\partial t} = \frac{\partial}{\partial x_i}\left(K^S_{ij}\frac{\partial U}{\partial x_j}\right) + \frac{1}{3}\frac{\partial V_{sw,i}}{\partial x_i}\frac{\partial}{\partial T}\left(\alpha_{rel} T U\right) - \frac{\partial}{\partial x_i}\left[\left(V_{sw,i} + v_{d,i}\right)U\right]$$

Parker Transport Equation

Fokker-Plank-like equation

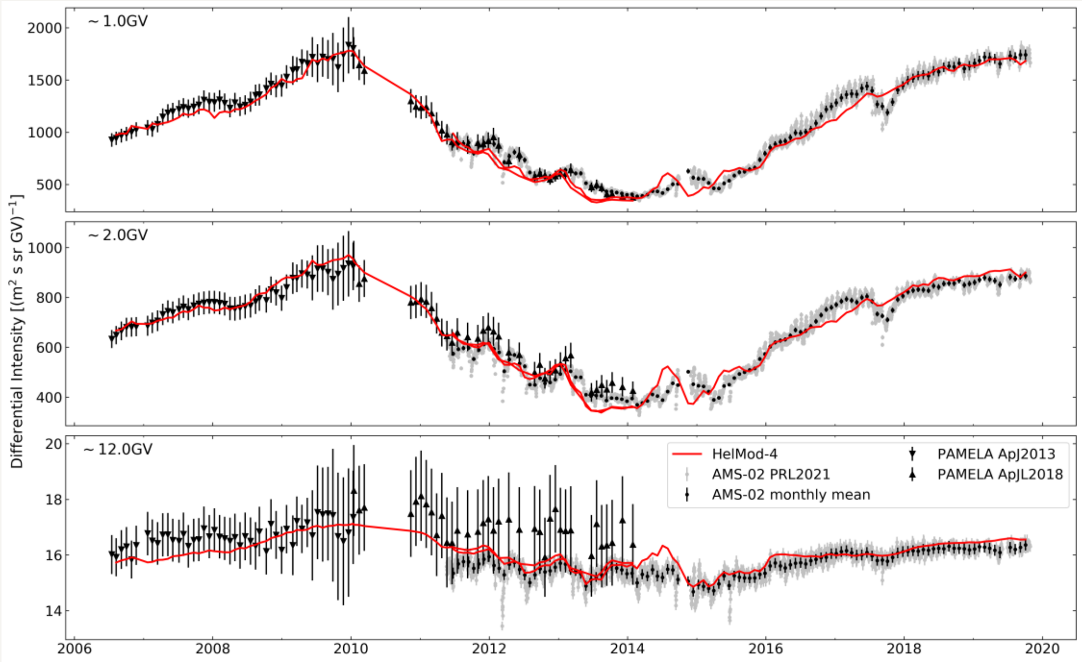
Ito's formula

$$\frac{\partial U}{\partial s} = \sum_i A_{B,i}(s,y)\frac{\partial U}{\partial y_i} + \frac{1}{2}\sum_{i,j} C_{B,ij}(s,y)\frac{\partial^2 U}{\partial y_i \partial y_j} - L_B U + S$$

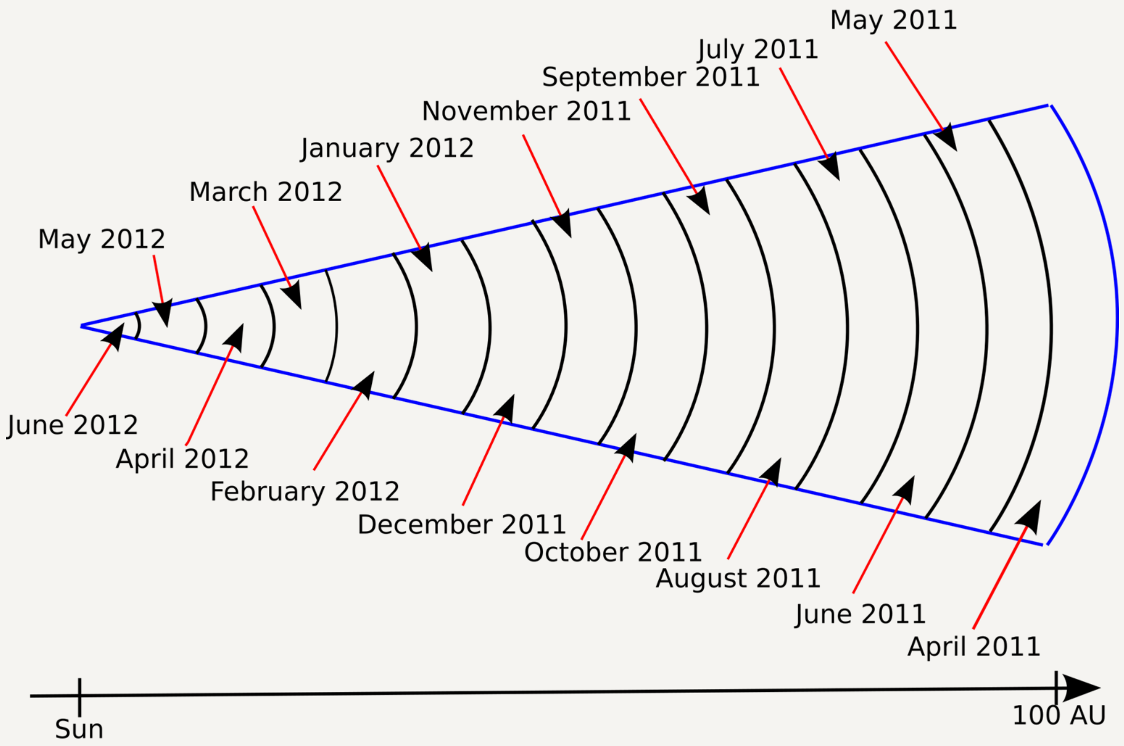
Stochastic Differential Equations

(MC backward in time numerically integrated)

Model parameters are tuned along a complete 22-year solar cycle using CR proton.
The same parametrization is then applied to all nuclei.



The computational model



We divide the Heliosphere in 15 regions, each one equivalent to the average of solar activity in the periods before the experiment

The Heliosphere radius and shape varies with time, according with the Sun Activity

Details of the model HelMod-4 (v5.1) can be found in *Boschini et al. Adv. Space Res. (2024)*

Parameters in each region are

- *Tilt angle of the Neutral Sheet*
- *Magnetic Field Magnitude at Earth*
- *Solar Wind Speed*
- *Diffusion coefficients*

http://wso.stanford.edu
Wilcox Solar Observatory

https://omniweb.gsfc.nasa.gov/
database

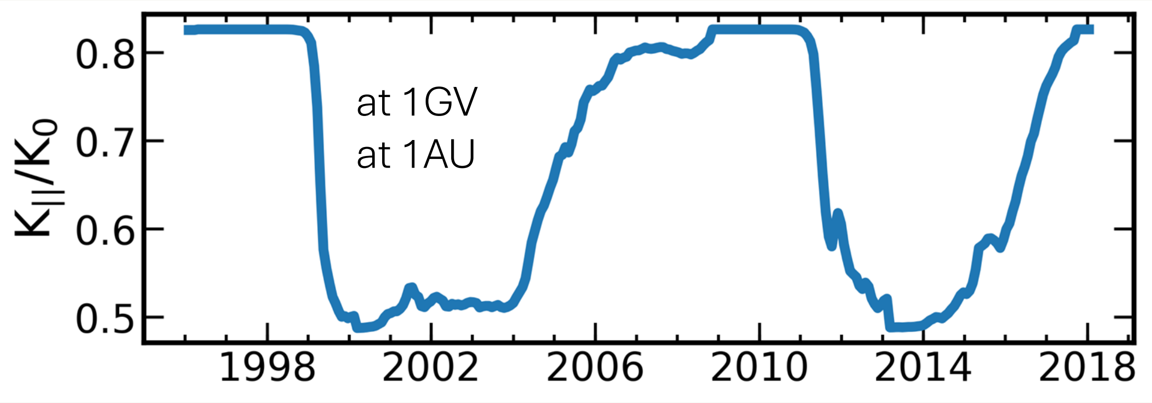
The computational model

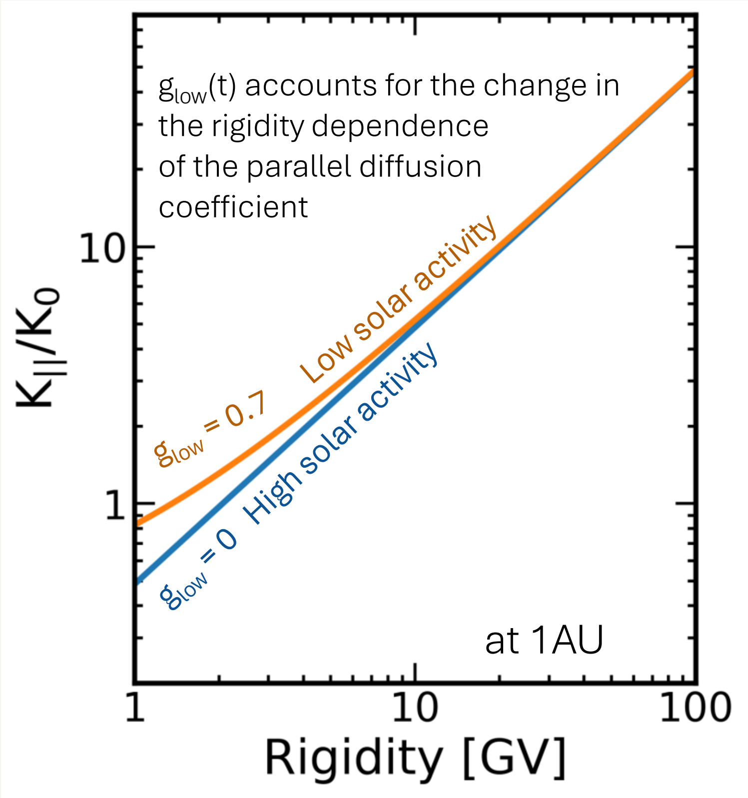
Parametrization of diffusion coefficients:

$$\frac{K_{\parallel}}{K_0} = \frac{\beta}{3}\left[\frac{P}{1\,GV} + g_{low}(t)\right]\left(1 + \frac{r}{1\,AU}\right)$$

$$K_{\perp,i}/K_{\parallel} = \rho_i$$

P is rigidity in GV



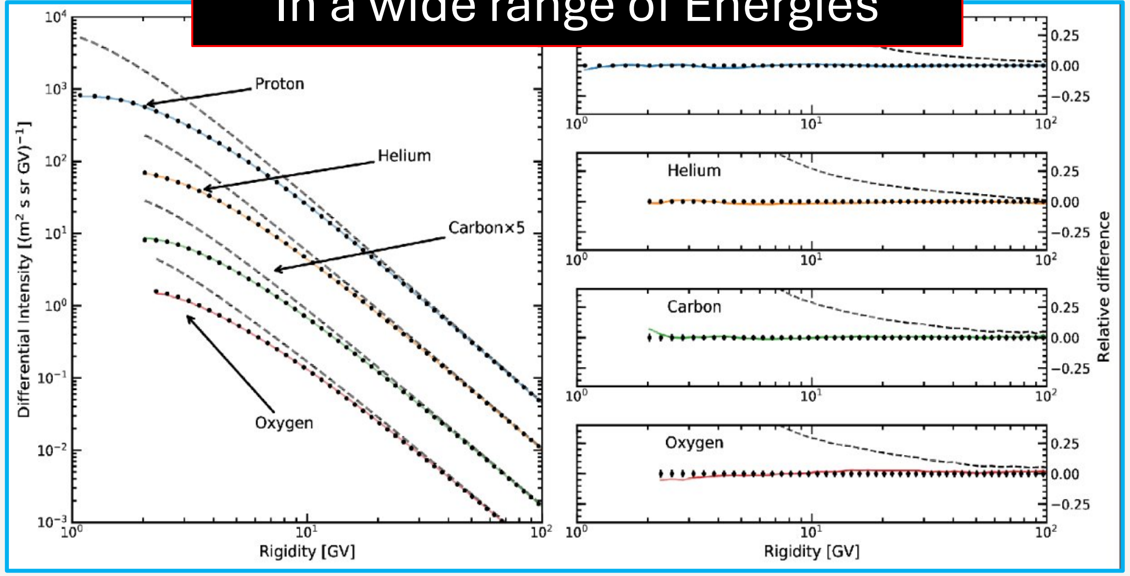


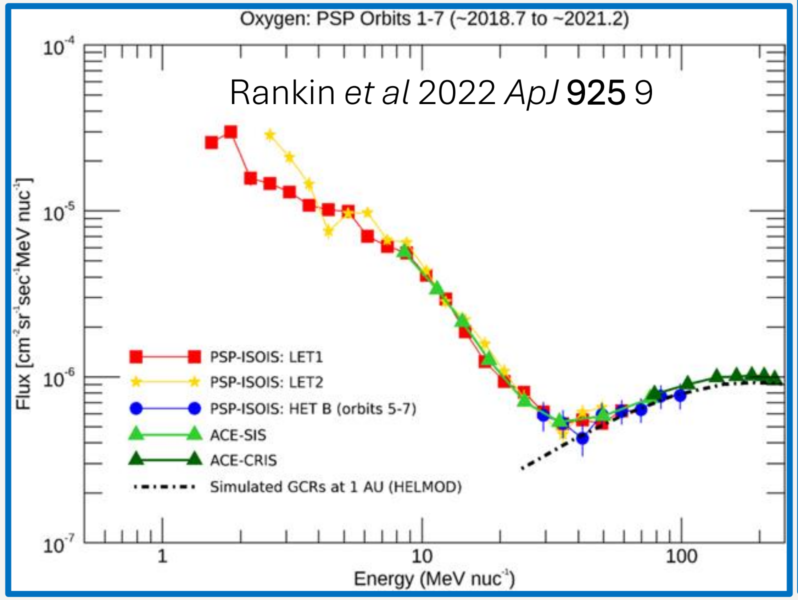
$K_0(t)$ is the diffusion parameter obtained using cosmic ray fluxes measured with neutron monitor at different latitudes.

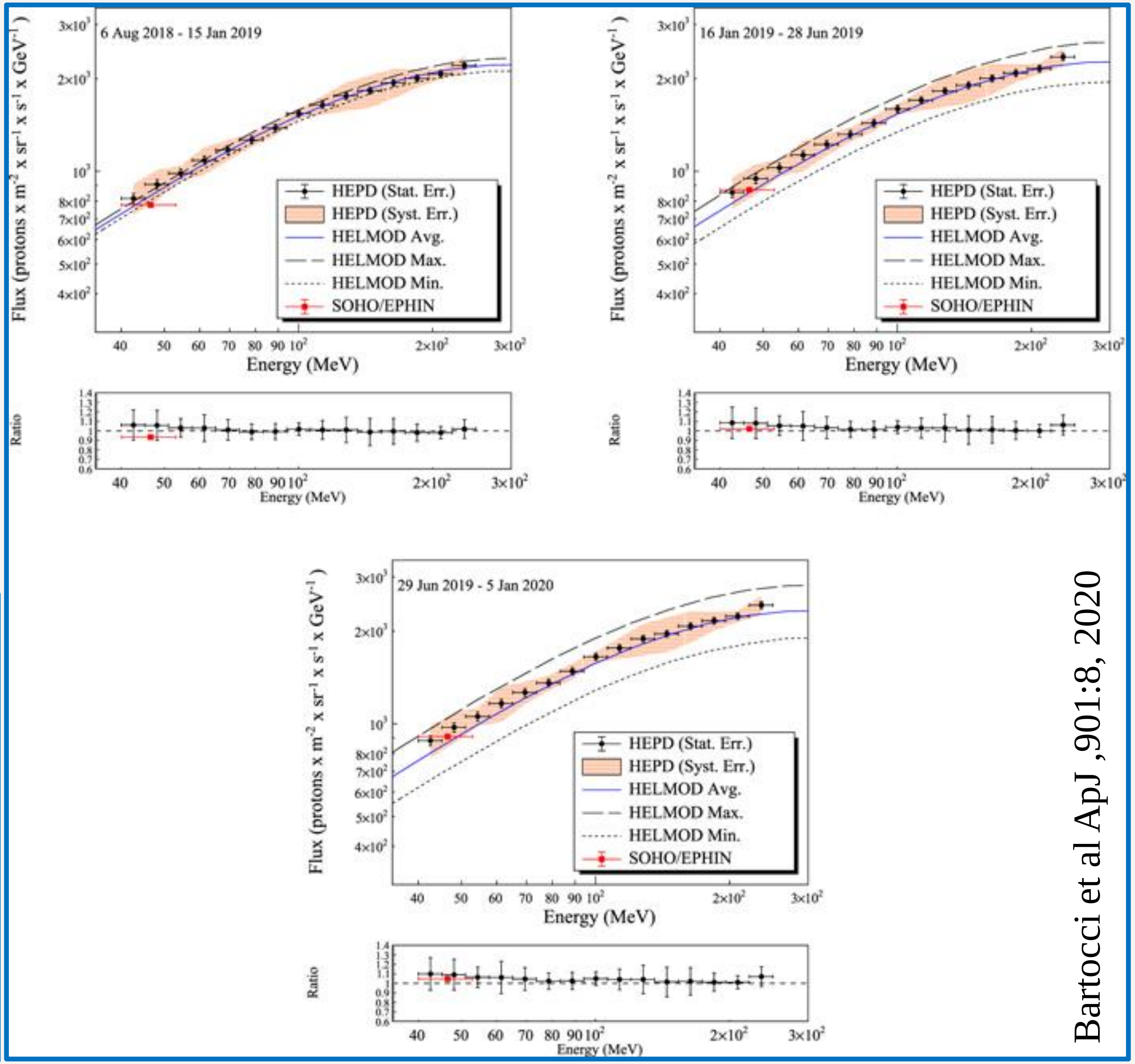
see
Bobik et al. ApJ 745:132 (2012)
Bobik et al. AdsAst,ID 793072 (2013)
Boschini et al. Adv. S. Res. (2017,2019,2022,2024)

HelMod reproduces Ions:

In a wide range of Energies



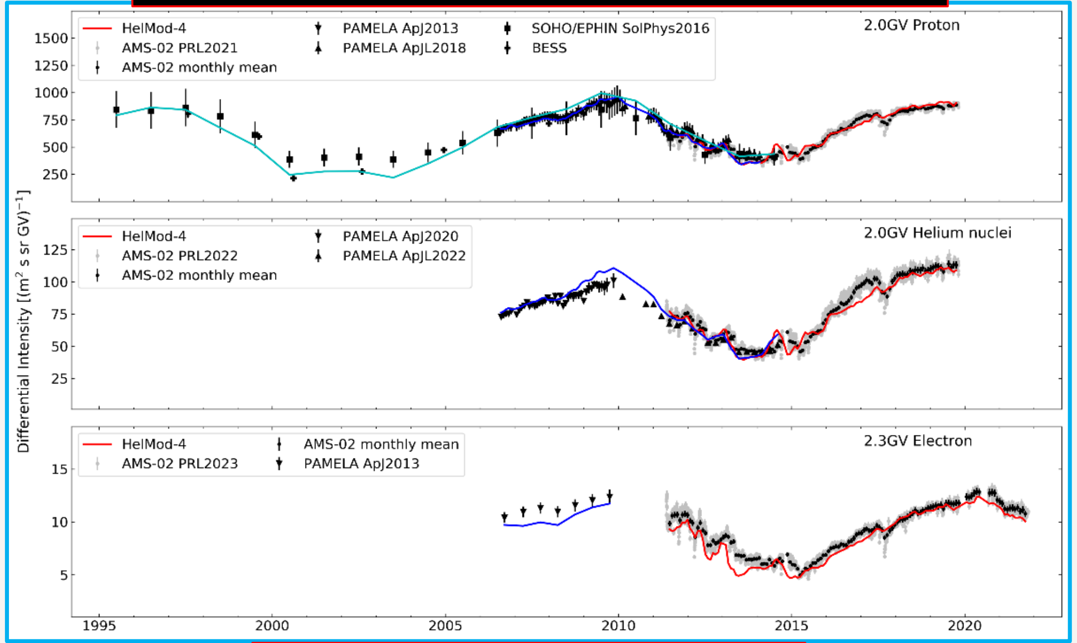




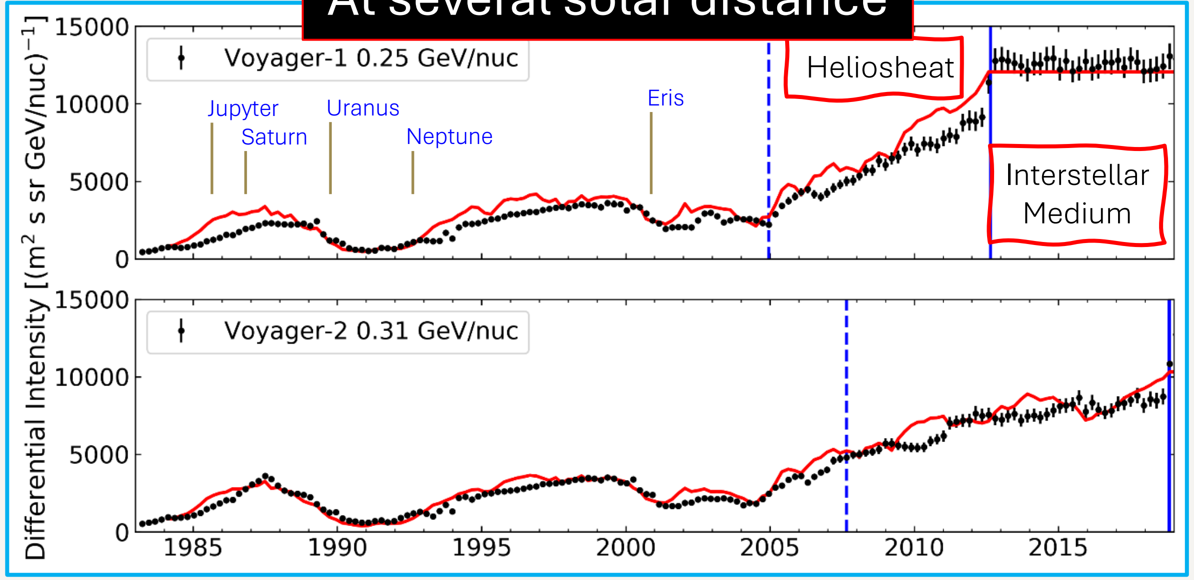
Bartocci et al ApJ ,901:8, 2020

HelMod reproduces Ions:

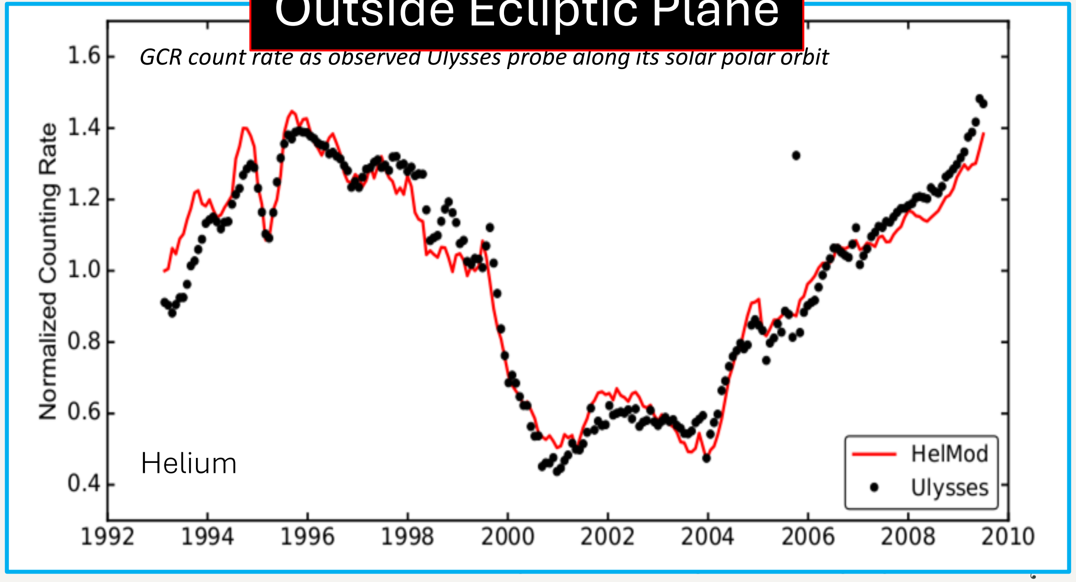
For different solar activities



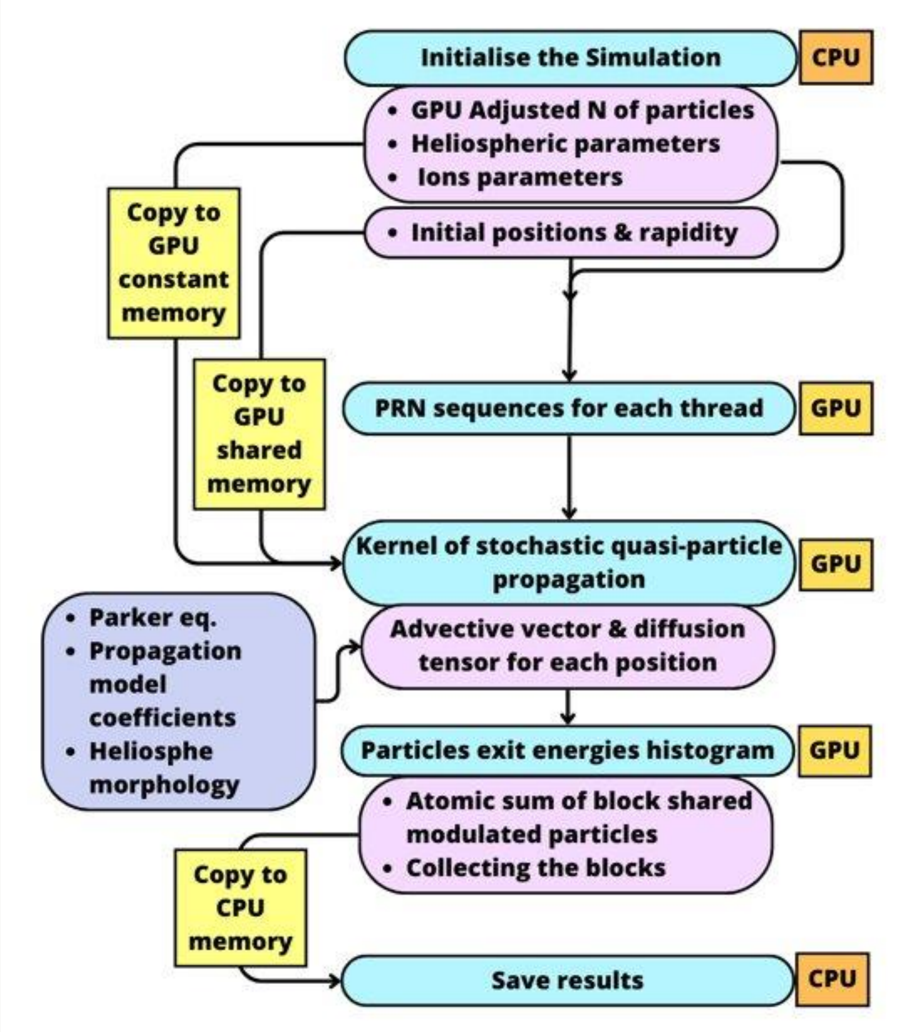
At several solar distance



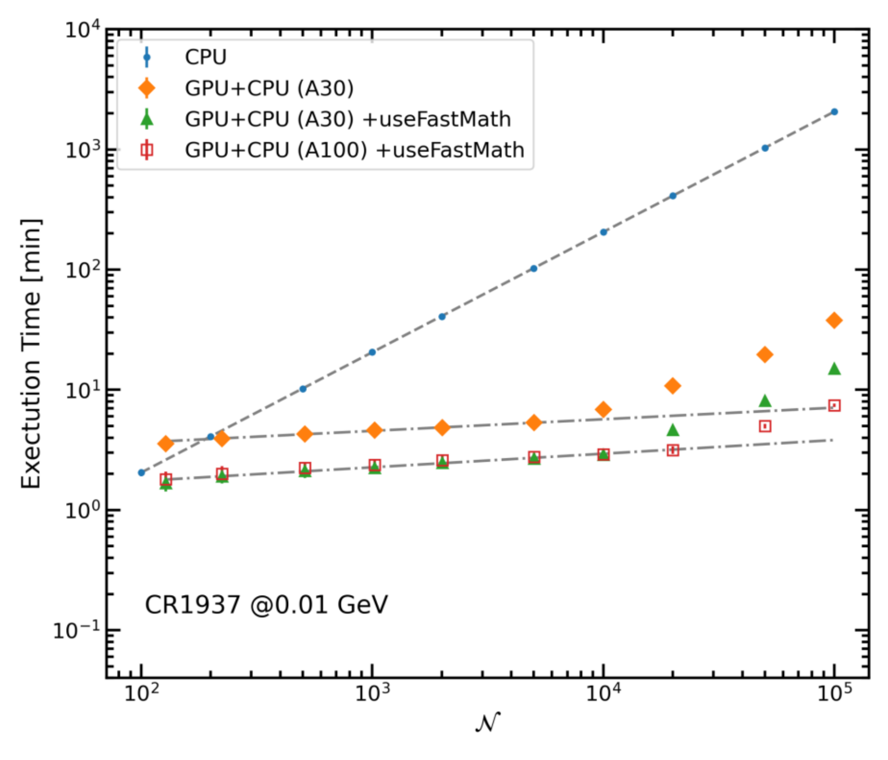
Outside Ecliptic Plane



GPU implementation and performances



The SDE integration algorithm is well suited to work with HPC architecture involving GPUs.

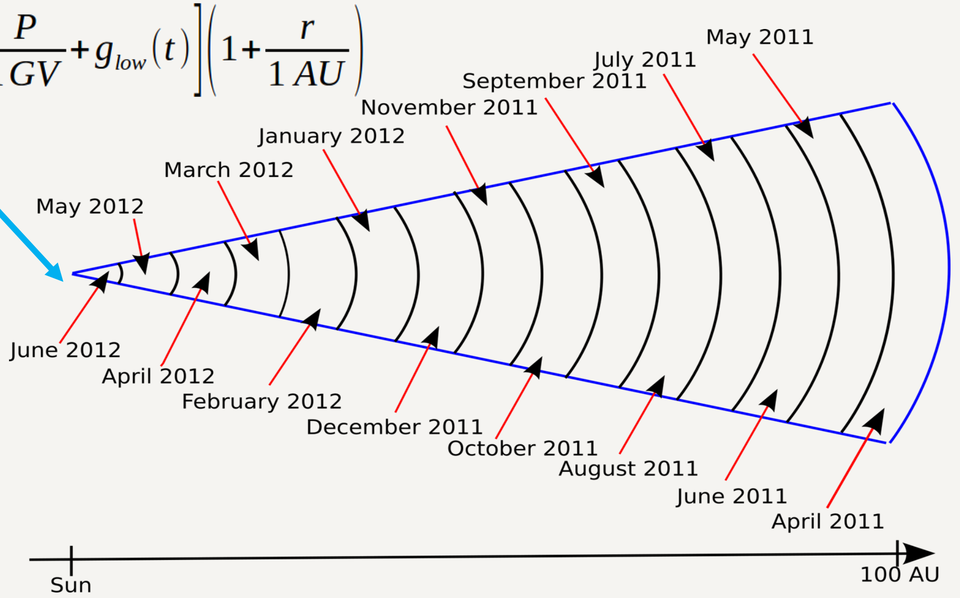


The computational time is dramatically reduced opening to new studies (see Boschini et al 2024). *Yet, there is room further to reduce the computational time through code optimization.*

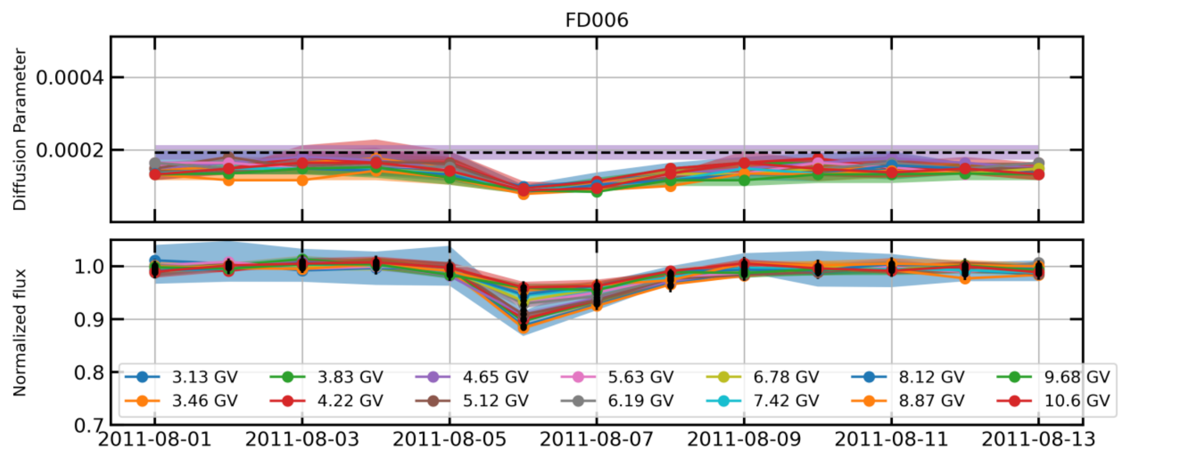
Methodology

$$\frac{K_{\parallel}}{K_0}=\frac{\beta}{3}\left[\frac{P}{1\,GV}+g_{low}(t)\right]\left(1+\frac{r}{1\,AU}\right)$$

In this work, we modify the value of K_0 parameter in the first shell (i.e. ~5 AU) emulating the effect of a local perturbation around Earth and not affecting the rest of the heliosphere



Using a scanning strategy we vary the value of K_0 for each energy and day independently to fit AMS-02 daily spectra from 3 to 10 GV



FD	Type	Time	MAR	Ampl
006	ICME	2011/08	16.6	13.6
010	ICME	2011/10	48.5	10.3
017	ICME	2012/03	33.5	35.1
058	ICME	2014/02	33.5	10.0
121	ICME	2017/09	22.8	17.7

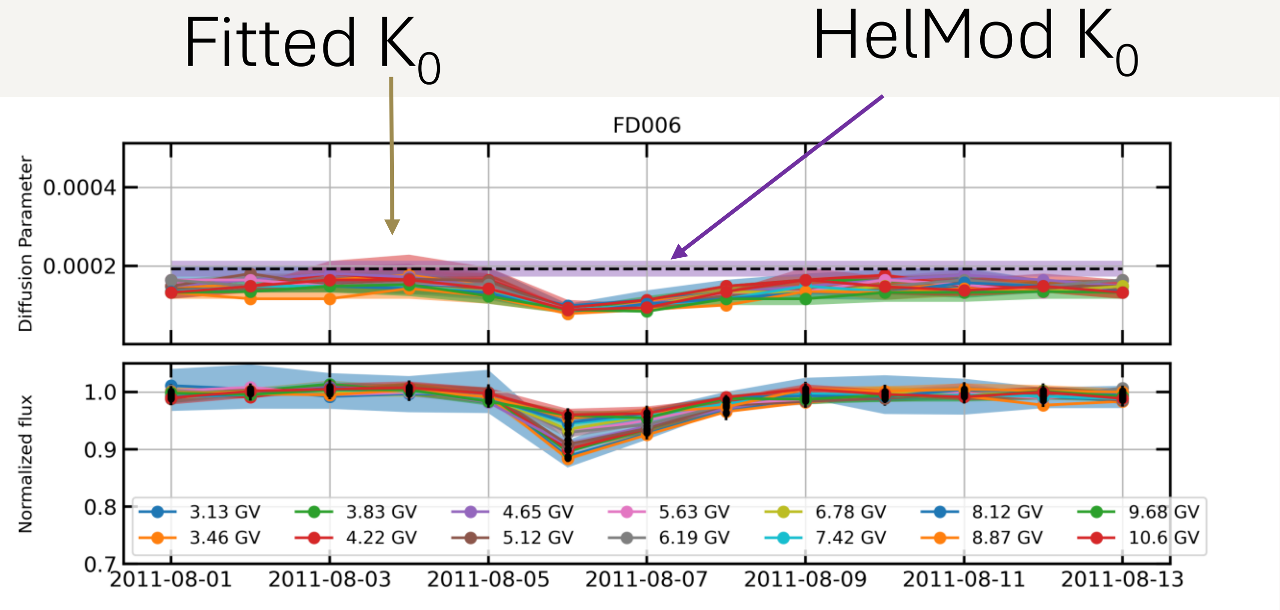
Events from Wang et al ApJ 950:23, 2023.

We apply our study to the five most relevant FD events seen by AMS-02. **For each FD we select a time windows that influence up to 4 quiet days before and after the event.**

Preliminary results

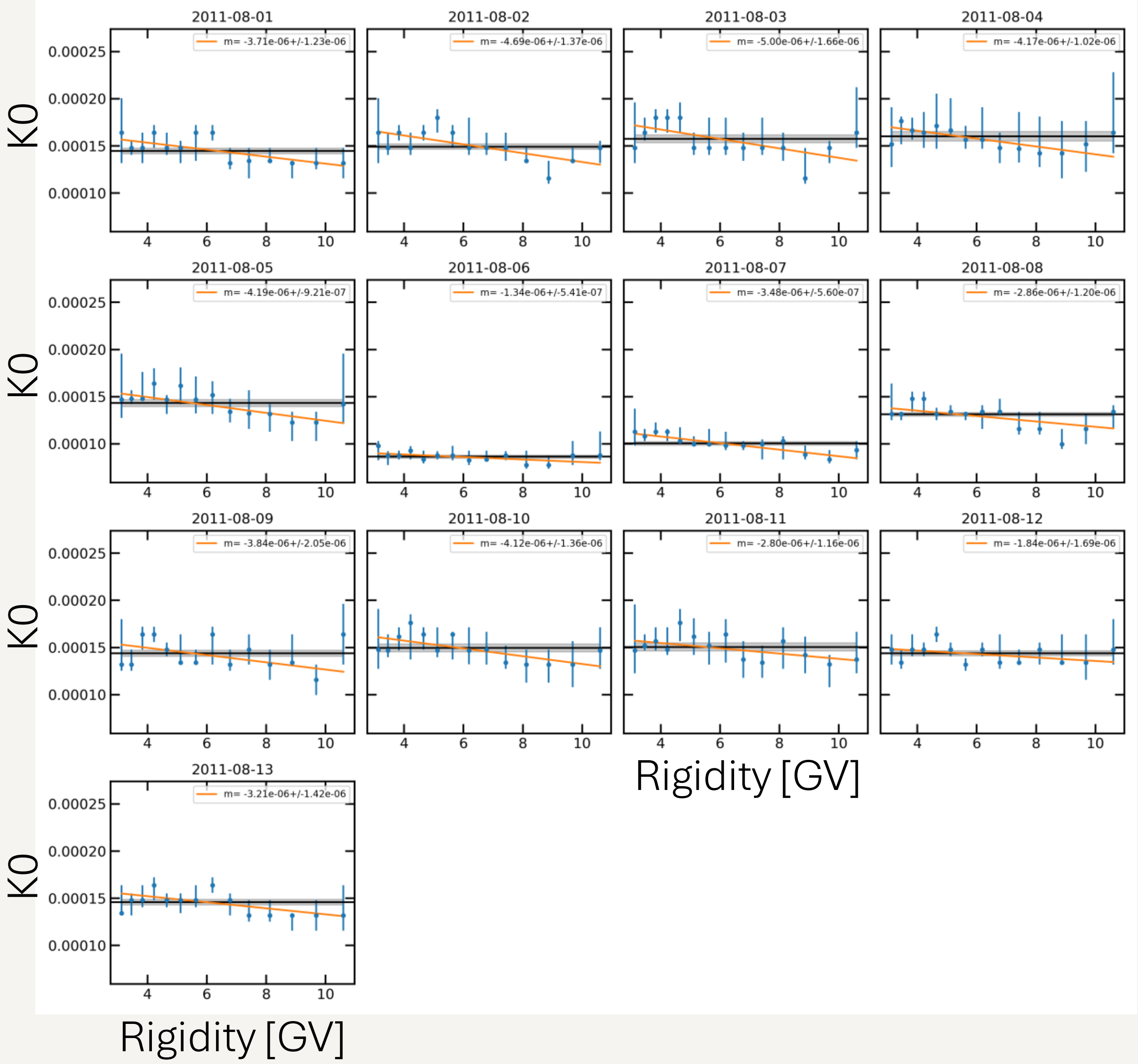
We notice that the daily K_0

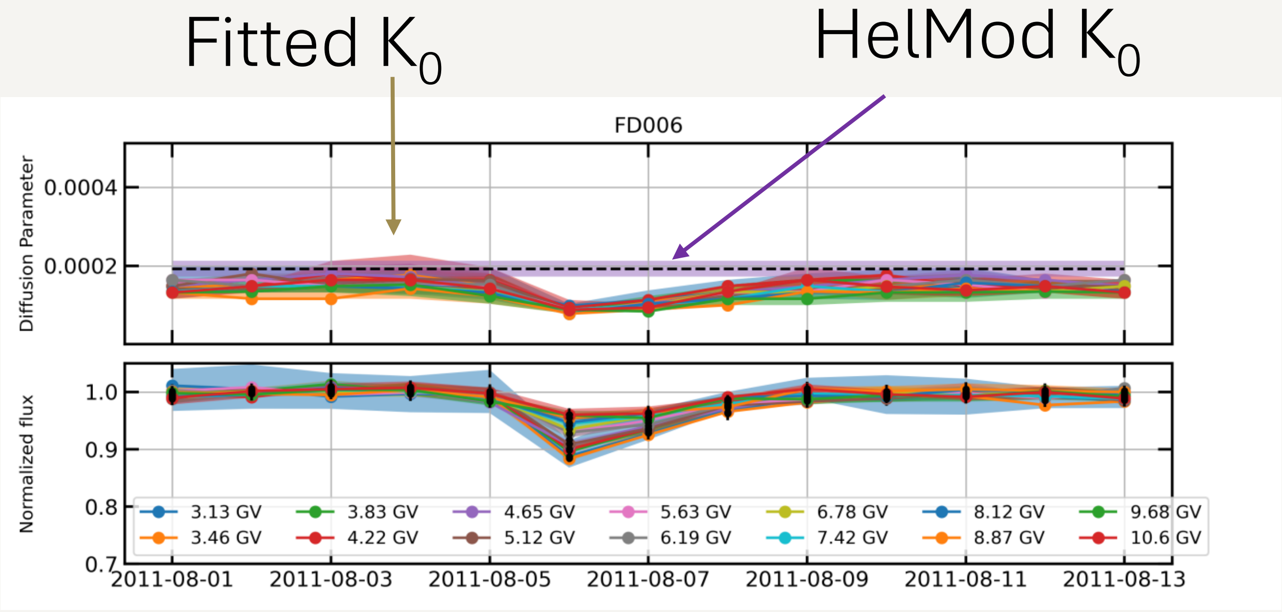
1. decrease following the forbush decrease
2. has similar values for all considered rigidities



Black point = AMS-02 normalized data
Color band = Simulations best fit

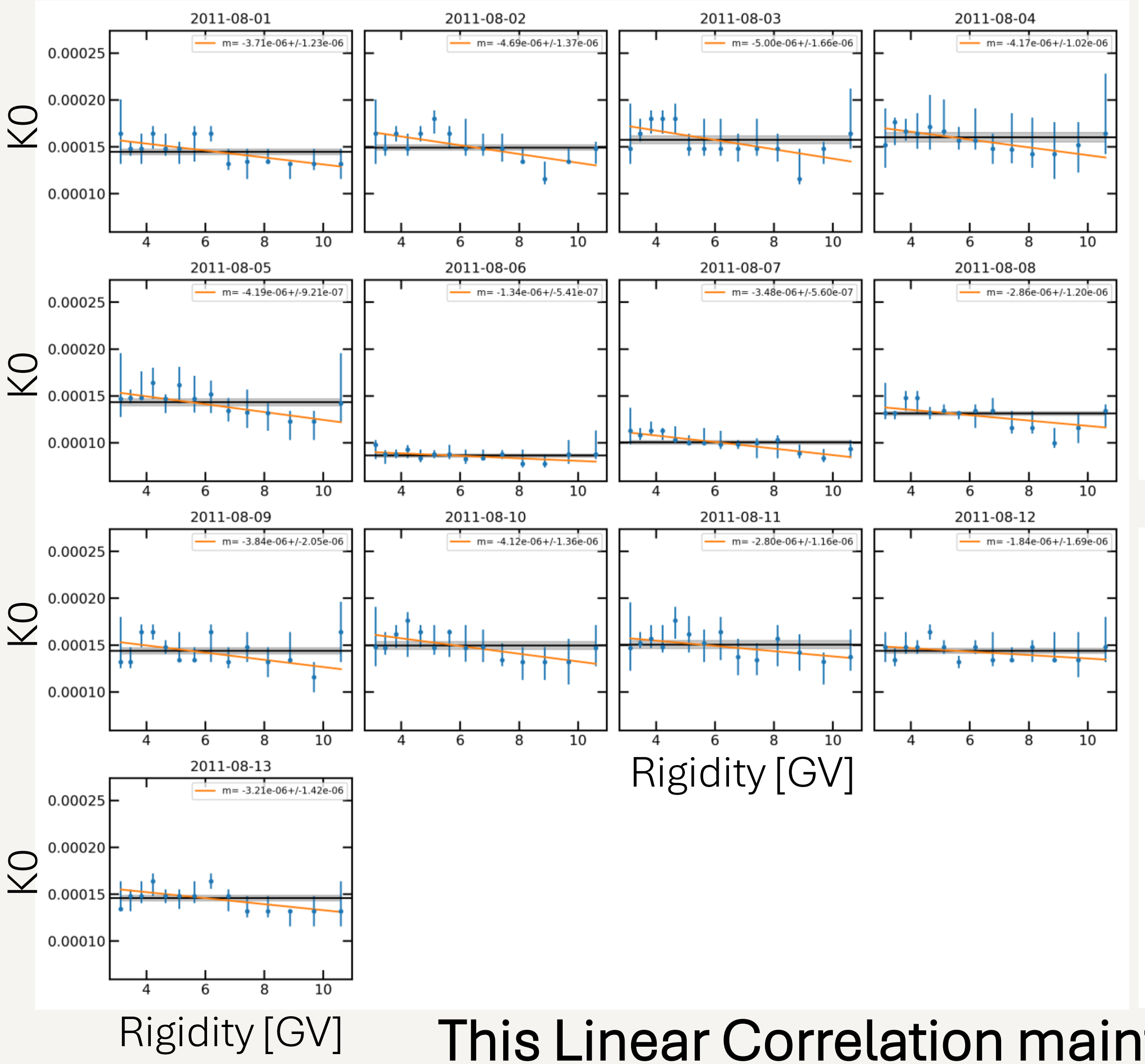
Preliminary results

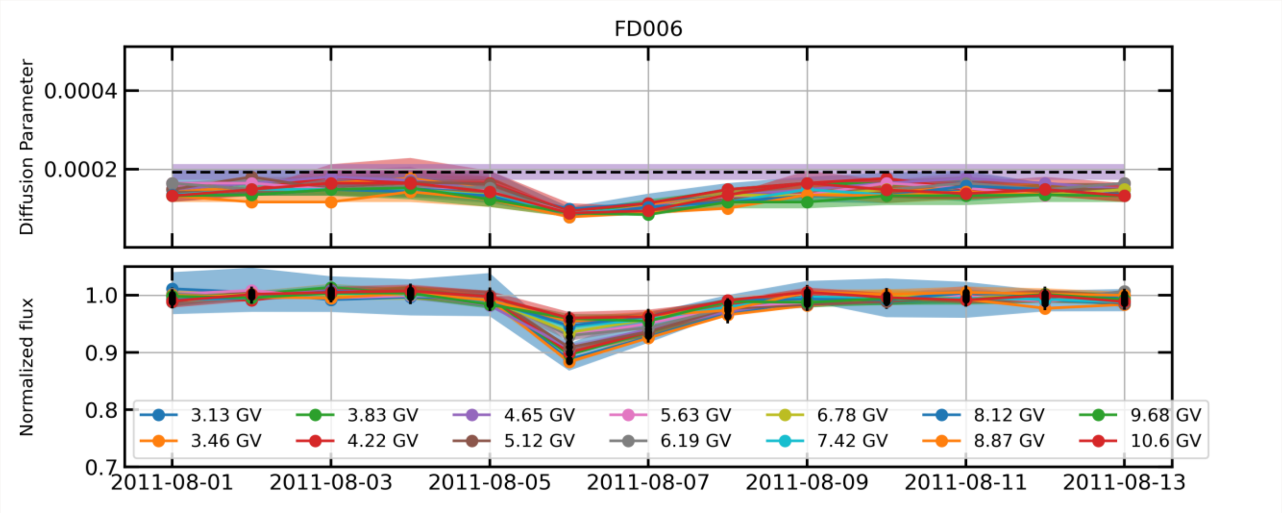


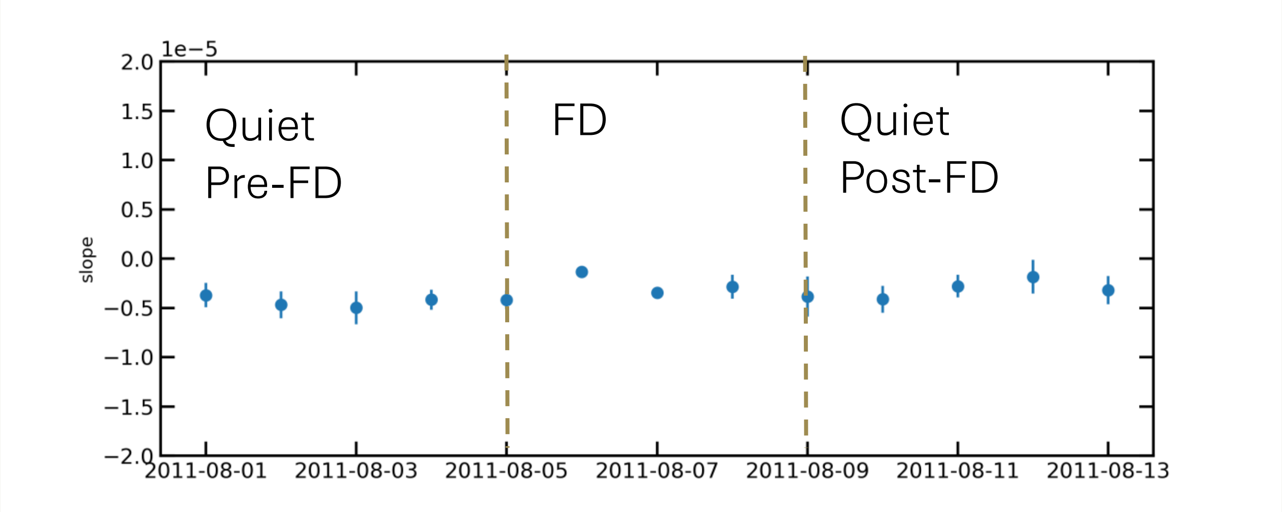


We found a linear correlation between K_0 and Rigidity. This may be due to LIS uncertainties or an incorrect rigidity dependence of diffusion tensor.

Preliminary results



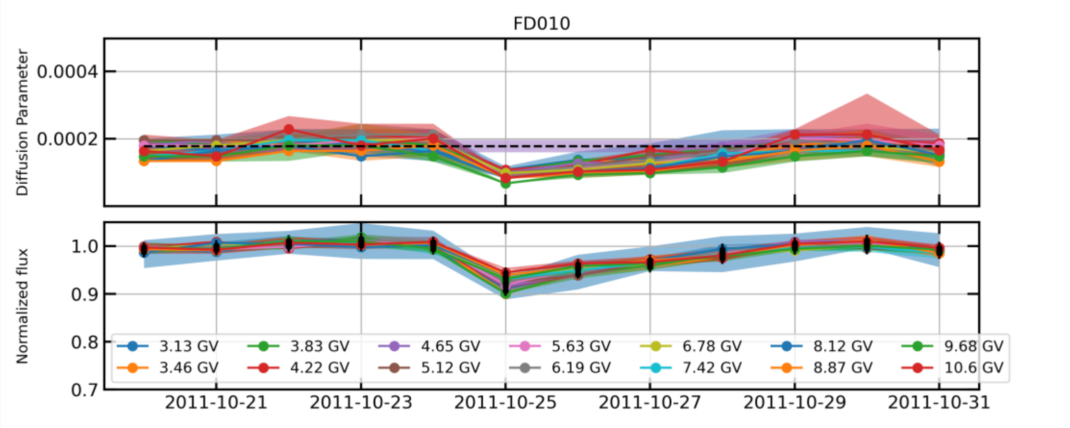


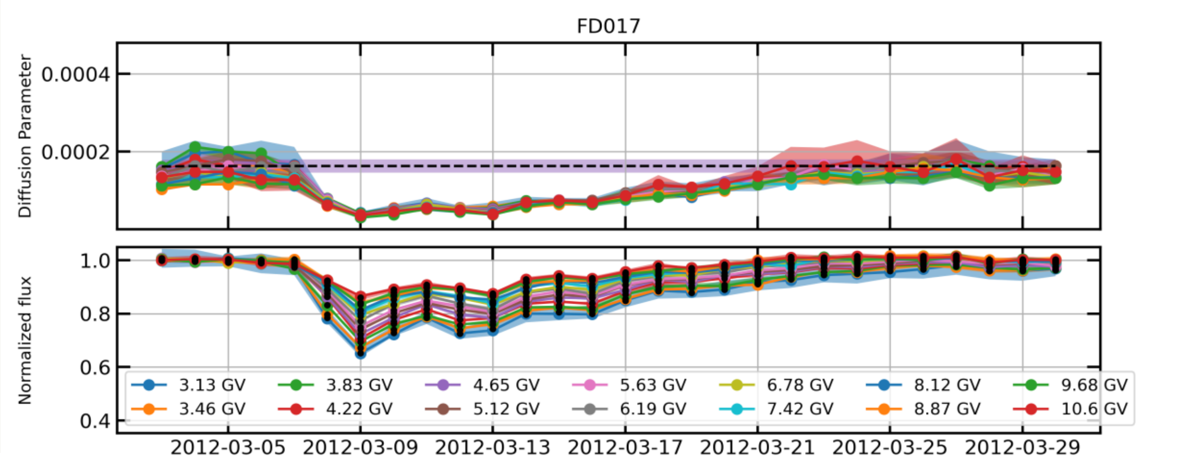


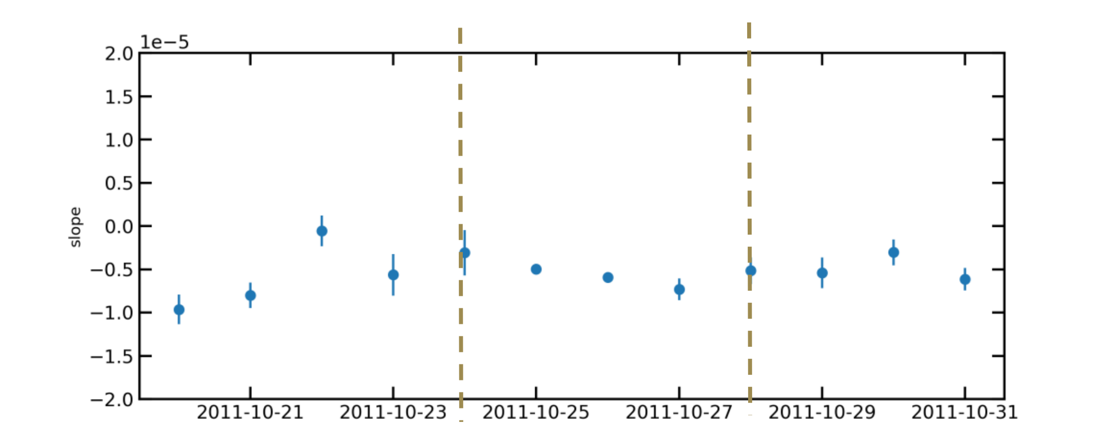
This Linear Correlation maintains the same slope both quiet and perturbed days.

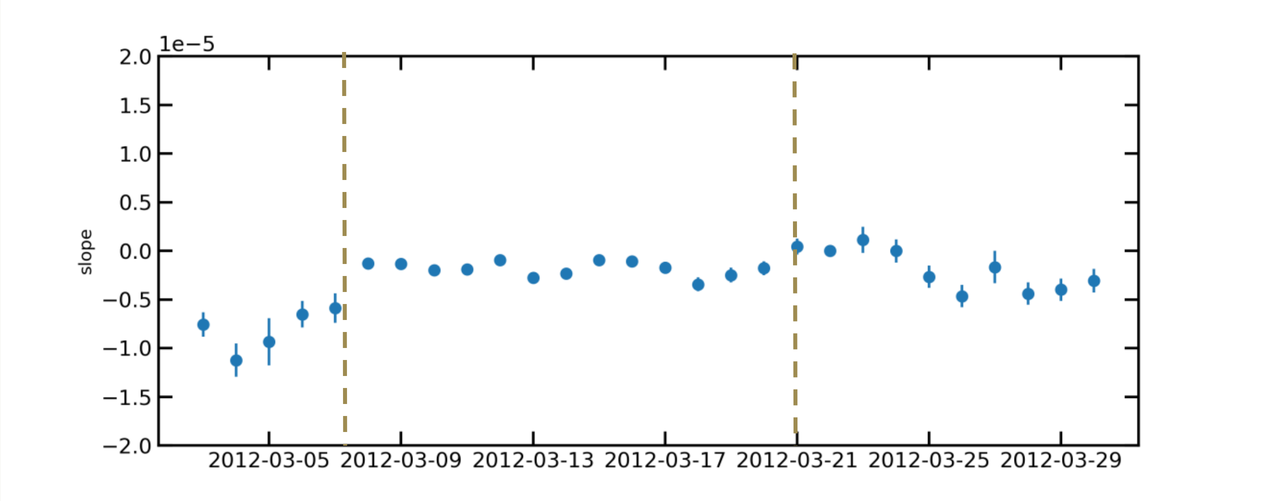
Preliminary results

Similar results are observed on others FD of the sample









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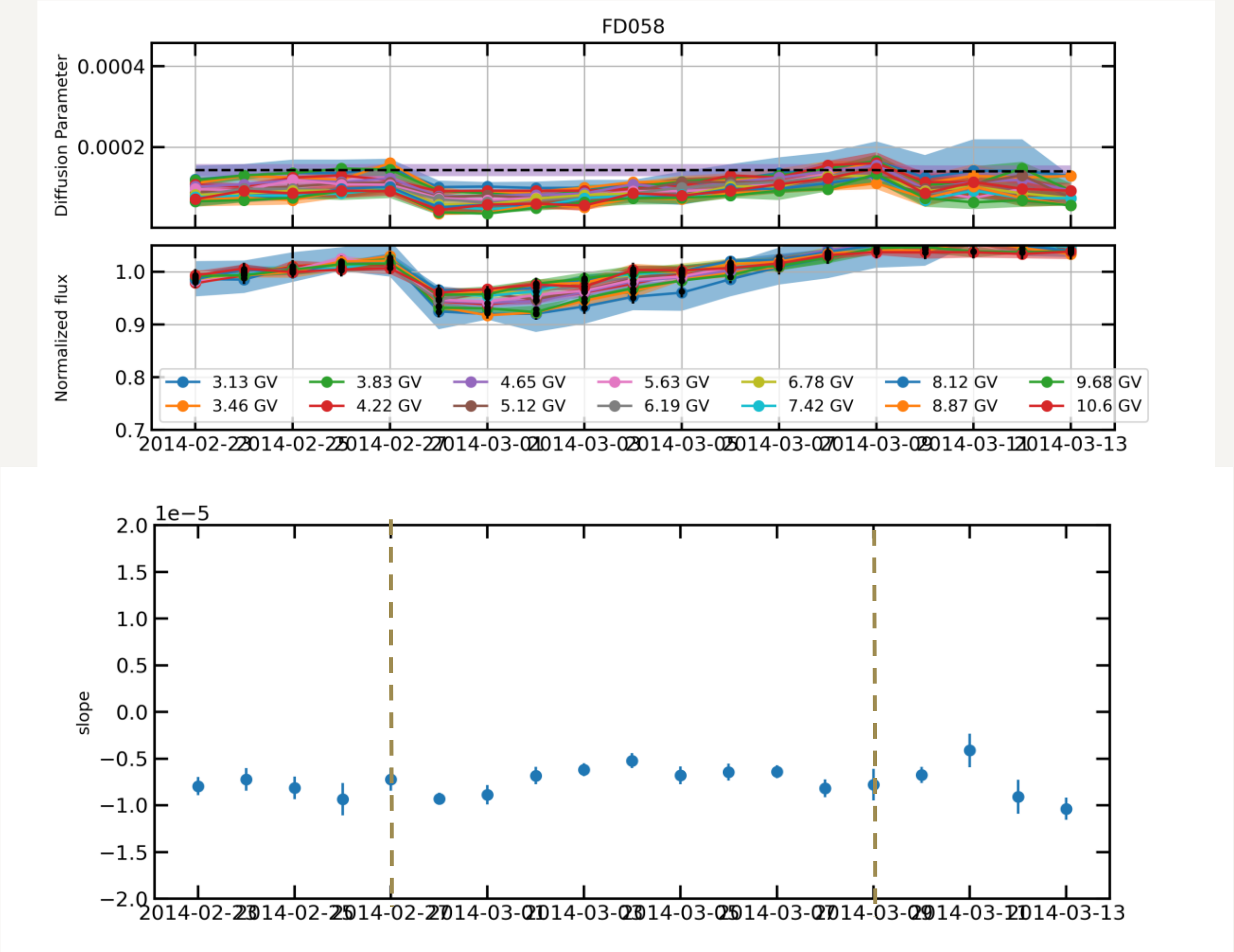

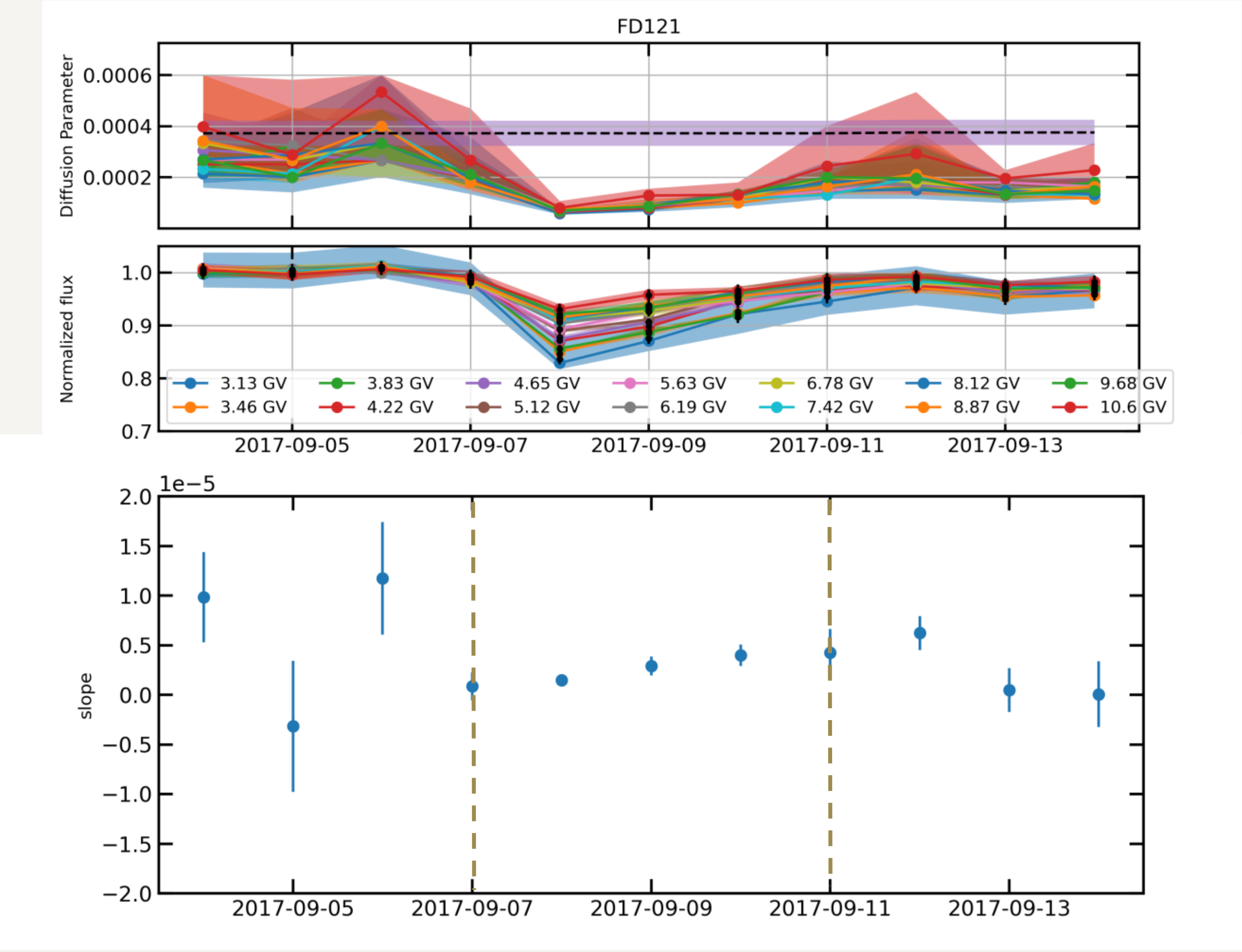

This Linear Correlation maintains the same slope both quiet and perturbed days.

Comments and Conclusions

- We studied the values change of the diffusion parameter of the HelMod Model during a Forbush Decrease at different rigidities.
- We found similar value of diffusion parameter for different rigidities.
- The relative difference between best K_0 values at different rigidities are not affected by perturbation causing the FD.
- This may be an indication that diffusion tensor description is the same for quiet and perturbed period .
- The study of FD perturbed spectra may allow to inferr general properties of diffusive medium.

Thanks for your attention

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