USING AMS DATA TO MODEL COSMIC RAY PROPAGATION IN THE HELIOSPHERE

Stefano Della Torre, Ph.D.
INFN Sez. Milano-Bicocca - Italy
Stefano.dellatorre@mib.infn.it

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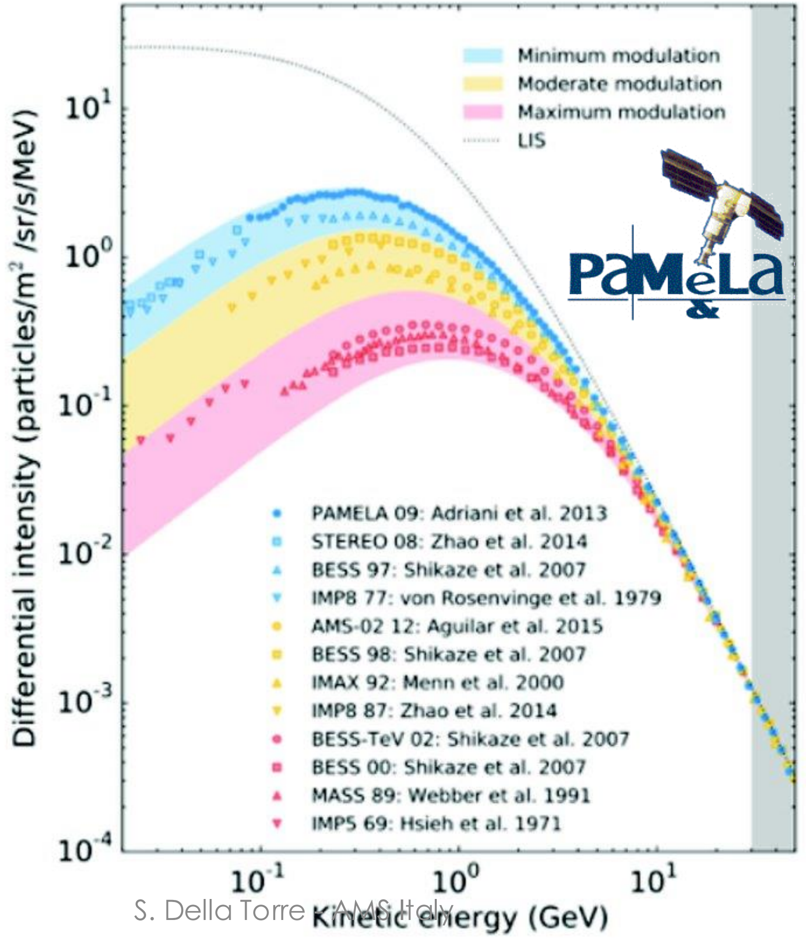
OUTLINE

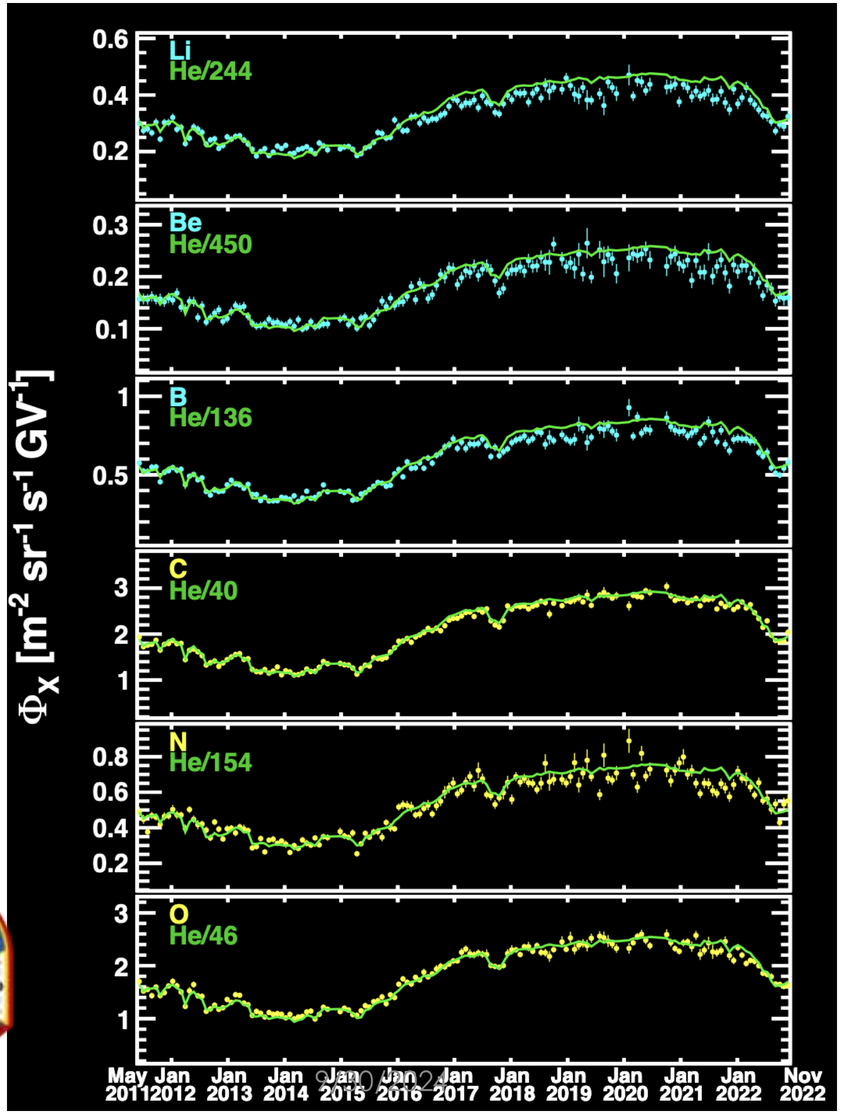
- Brief introduction to Solar Modulation and to Heliosphere
- Cosmic Rays Transport in the Heliosphere
- Applications and implications

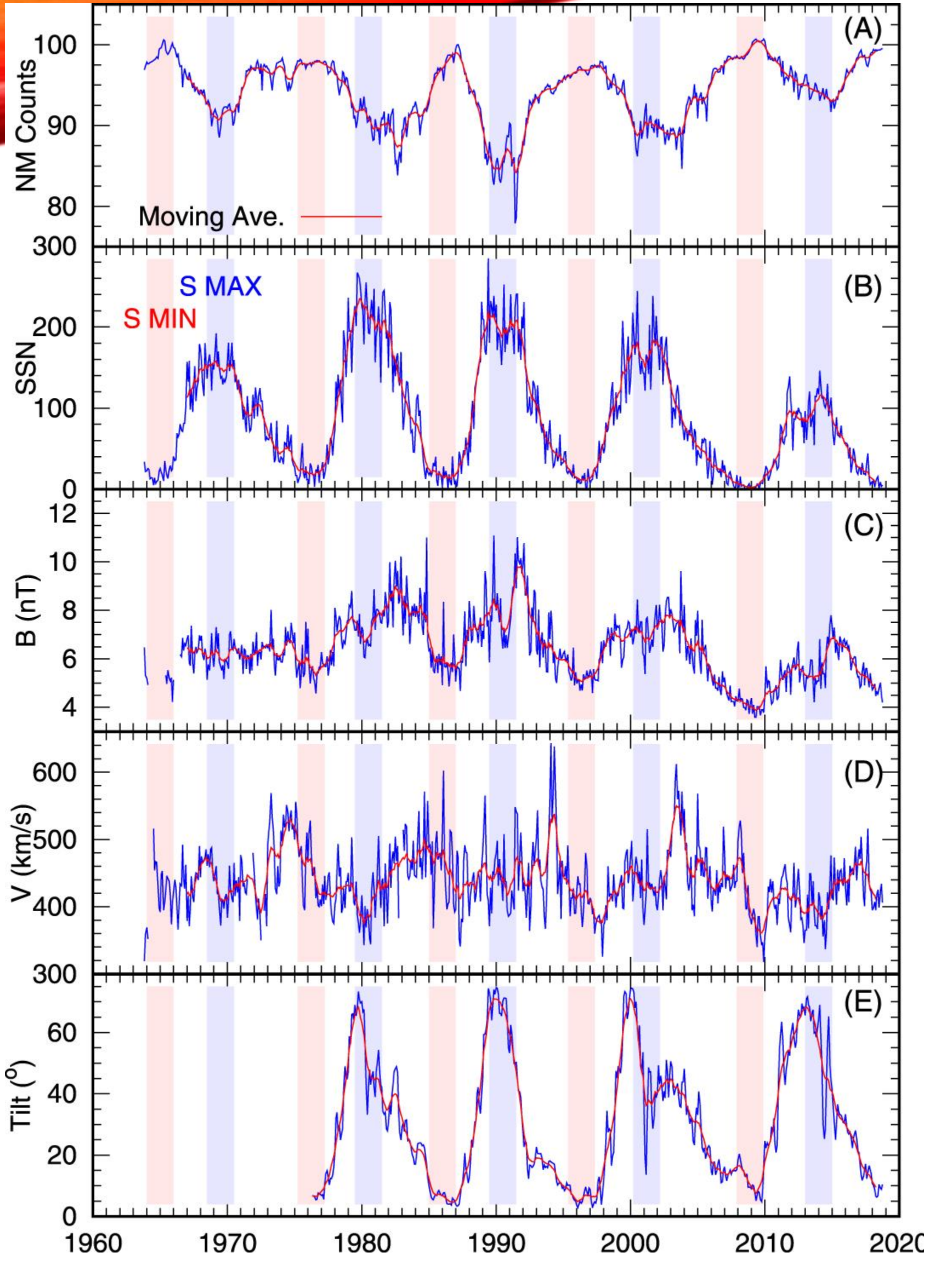
DEFINITION #1: SOLAR MODULATION

Solar Modulation is Energy dependent and is effective <30 GeV/nuc



Solar Modulation affect all Ions in a similar way

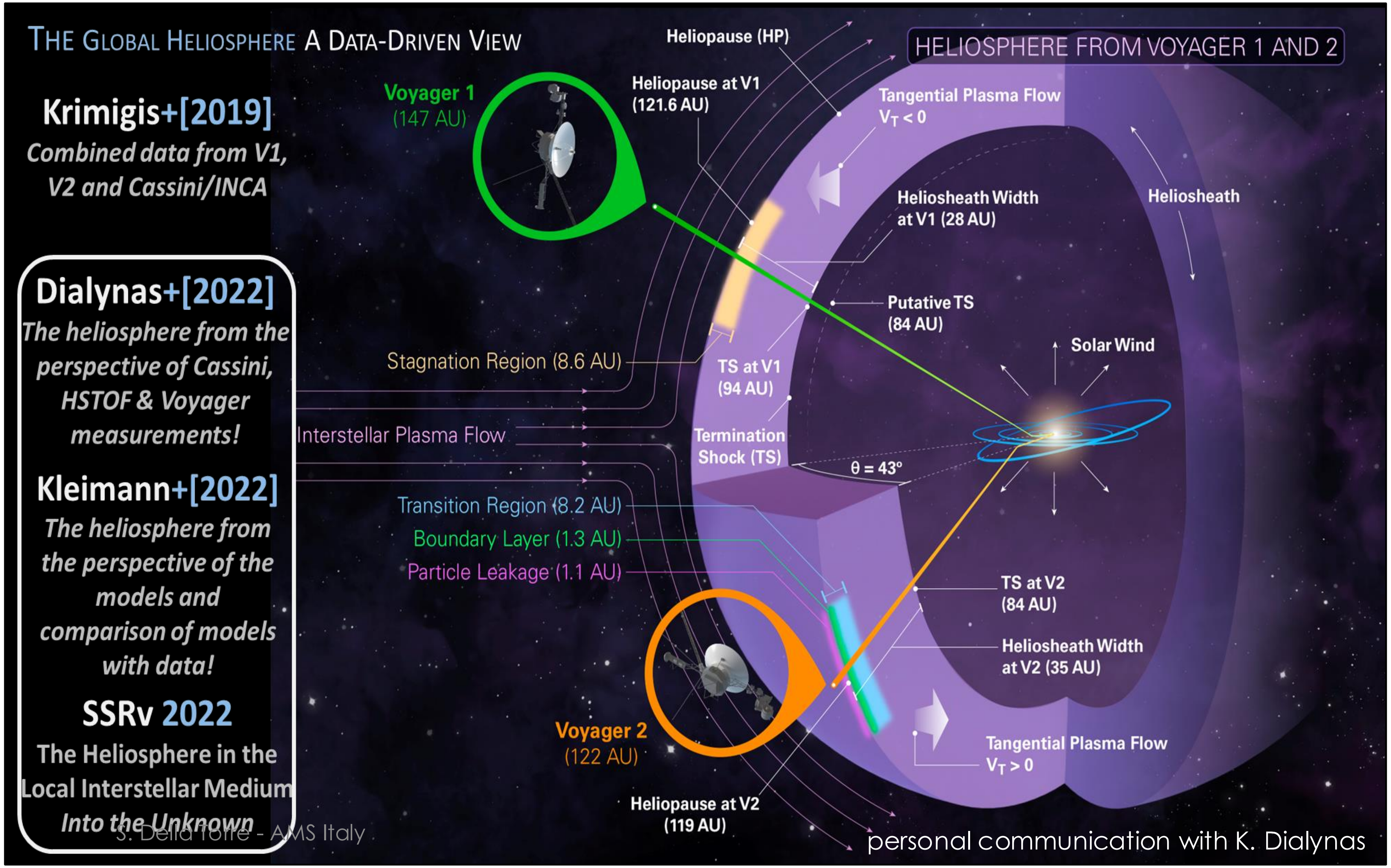




The temporal variation is anti-correlated in time with parameters inferred from solar observations...

therefore, whatever the cause of the variability, it is linked to our star.

DEFINITION #2: THE HELIOSPHERE

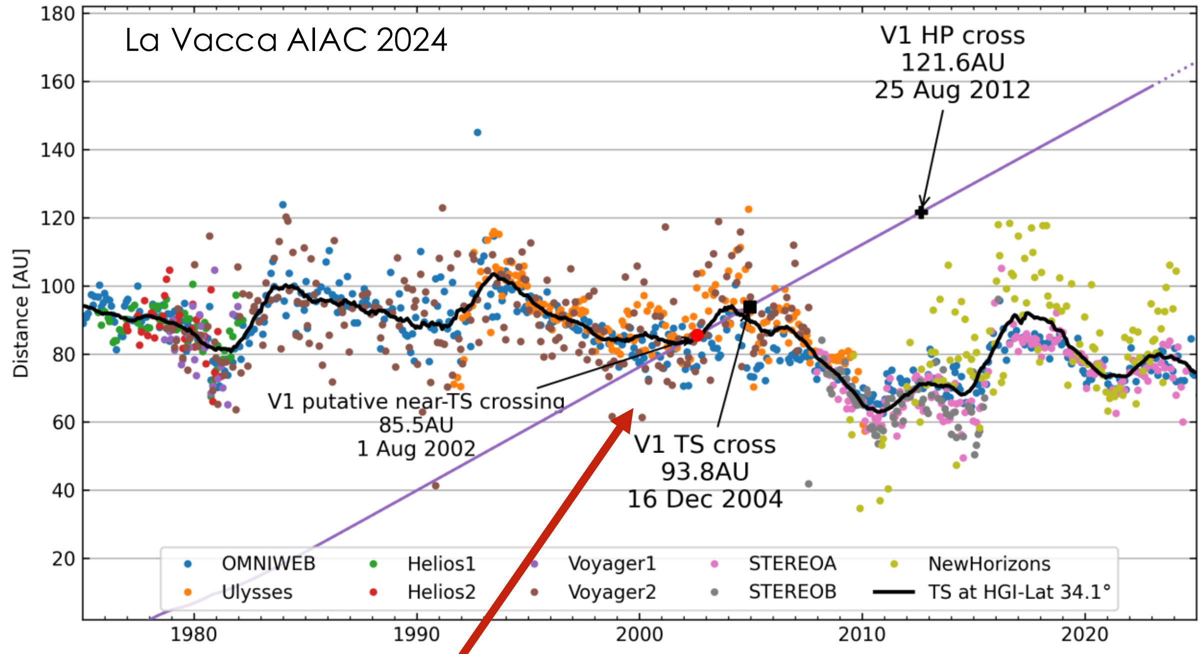


personal communication with K. Dialynas

Simple definition: Region of space directly influenced by Sun dynamics

Plasma emitted by the Sun (solar wind) transport the magnetic field defining the shape and dimension of the heliosphere

HELIOSPHERE BOUNDARIES MOVES AS FUNCTION OF TIME

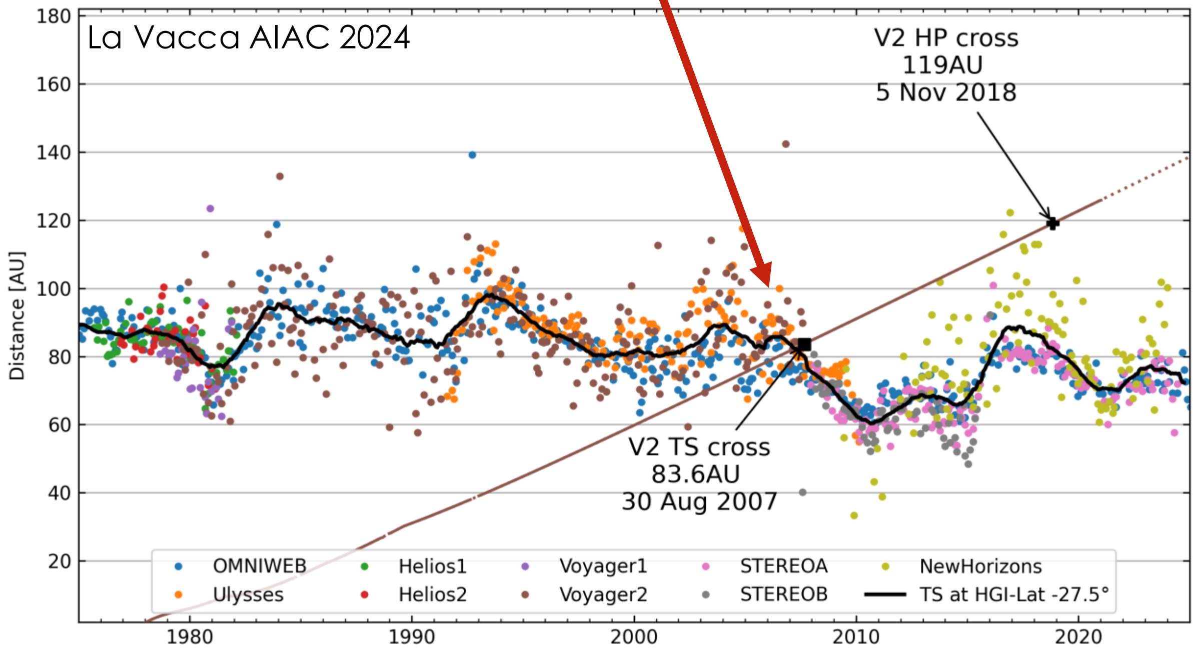


At Voyager 2 latitude:

- Moving average 2-years amplitude applied to the average

Estimated TS cross

- 80.0AU on 30 Aug 2007



At Voyager 1 latitude:

- Moving average 2-years amplitude applied to the average

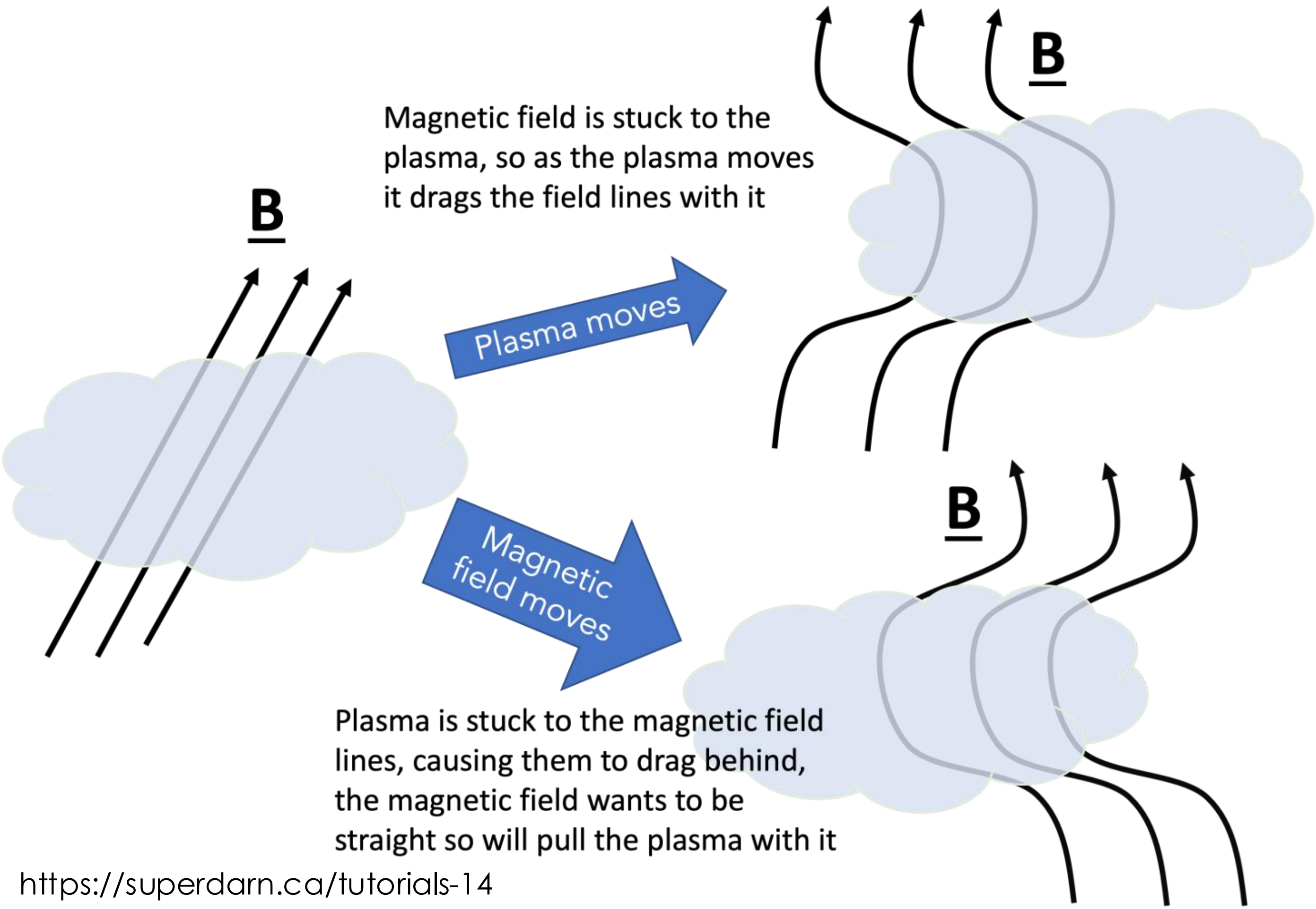
Estimated TS cross

- 89.5AU on 16 Dec 2004

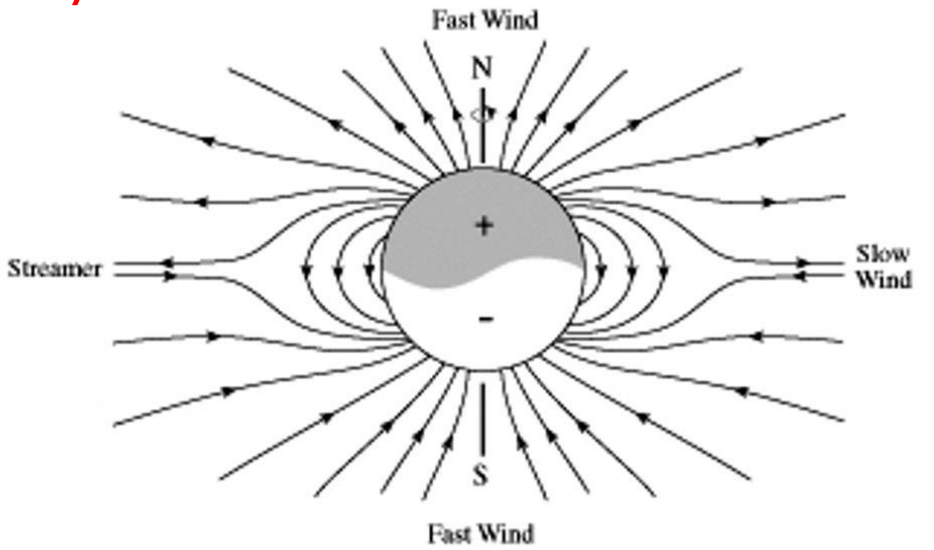
Sun has a magnetic field

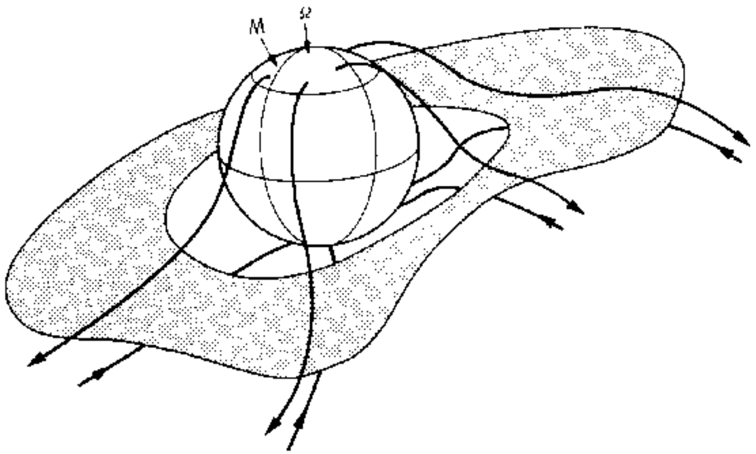
Sun emits a plasma flow (solar wind)

Sun Magnetic field permeate the heliosphere by means of solar wind



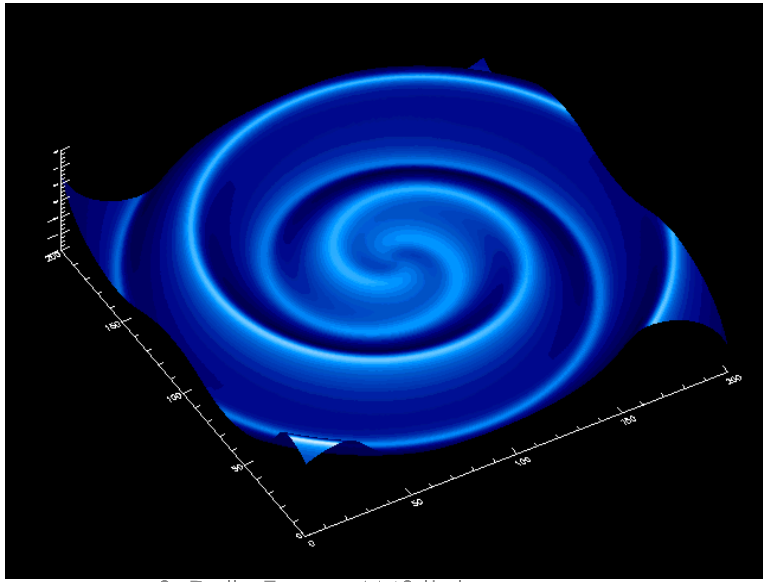
https://superdarn.ca/tutorials-14





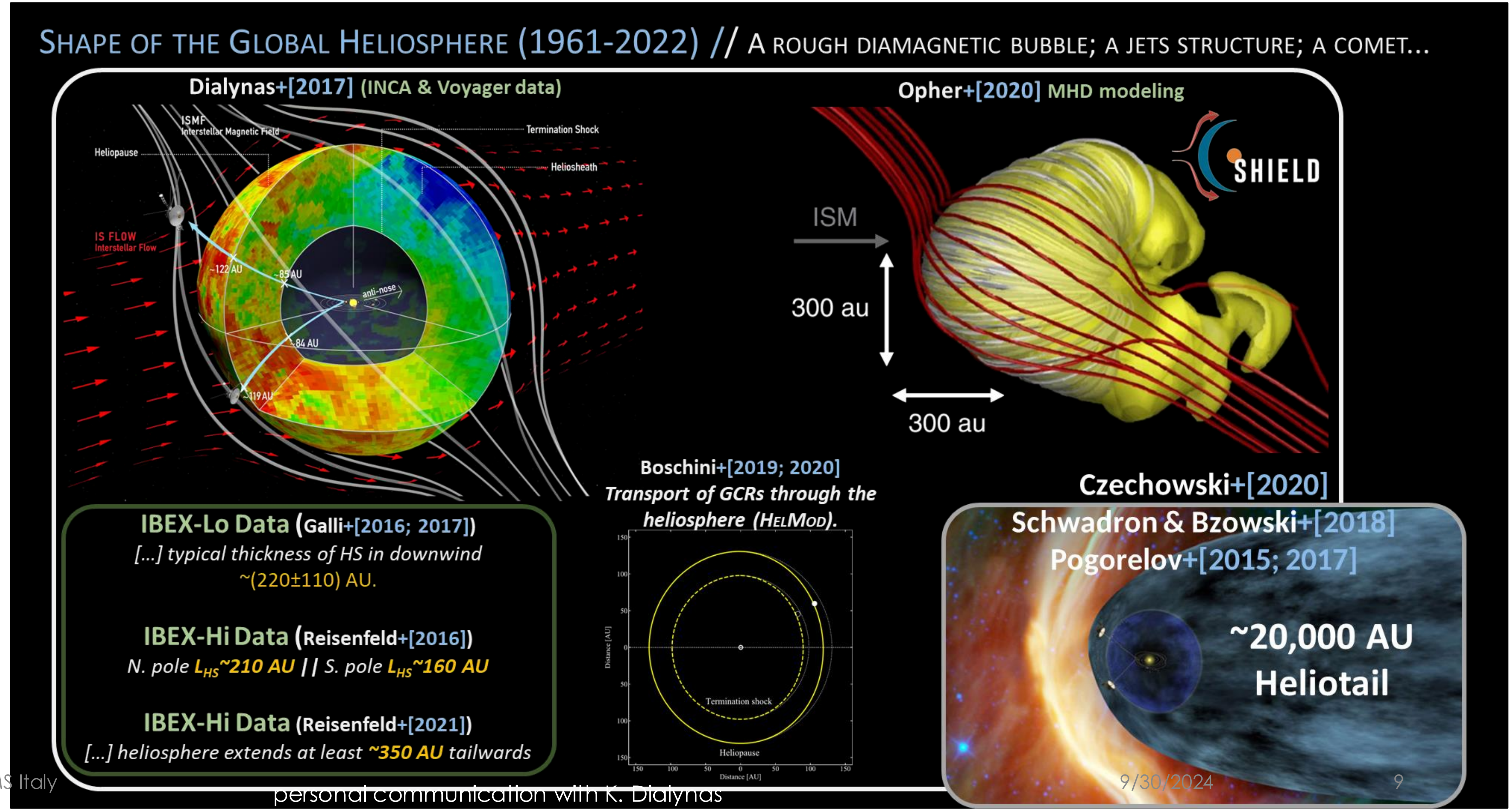
Solar wind expansion creates the Neutral Current Sheet that divide heliosphere in two hemisphere of opposite solar polarity

This sheet is more tilted with increasing of solar activity



Due to Solar rotation field line create na Archimedean spiral also known as “Parker Spiral”

The global shape of the heliosphere is still debated.



personal communication with K. Dialynas

CR TRANSPORT IN THE HELIOSPHERE

What cause Solar Modulation?

Modulation along horizzontal line

Vertical reduction in intensity

Energy loss
e.g. Force-Field Model

Convection-diffusion

Solar modulation consists of both of these processes that act simultaneously

Caballero-Lopez & Moraal JGR 2004

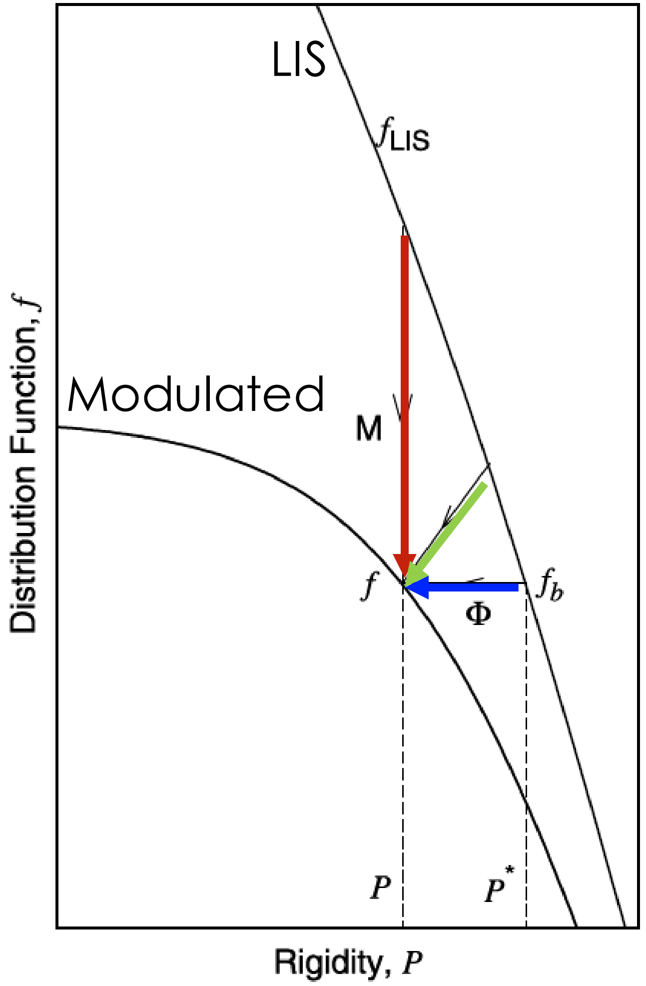


Figure 1. Graphical representation of the description of the modulation with the force field solution (horizontal line) and the convection-diffusion solution (vertical line). The sloped line represents the actual modulation as a combination of intensity reduction and energy loss.

Parker Equation

Parker (1965) proposed a Fokker-Planck like equation to describe the passage of charged particle in interplanetary medium

$$\frac{\partial U}{\partial t} = -\nabla \cdot (U\vec{V}) + \nabla \cdot \left[\tilde{K} \cdot \nabla U\right] + \frac{(\nabla \cdot \vec{V})}{3} \frac{\partial}{\partial T} \left(\alpha_{rel} T U\right)$$

U = particle density for unit space and kinetic energy

Convection

Presence of the solar wind moving out from the Sun

Diffusion

Small Scale Magnetic Field irregularity

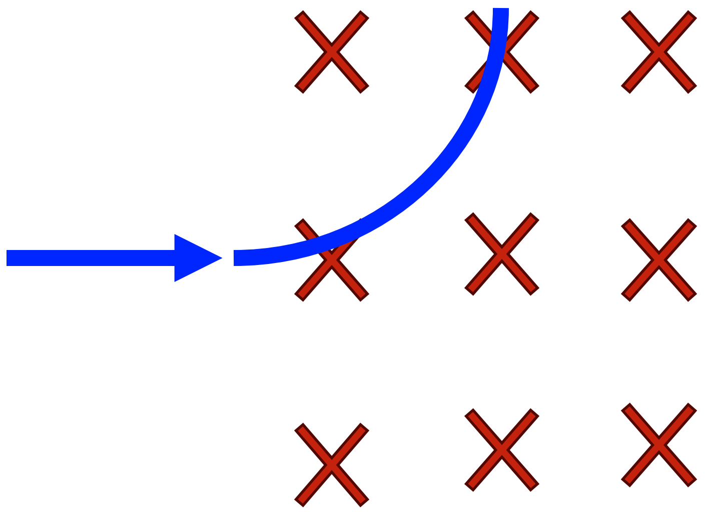
Drift

Large Scale structure of magnetic field (e.g. gradients)

Energetic Loss

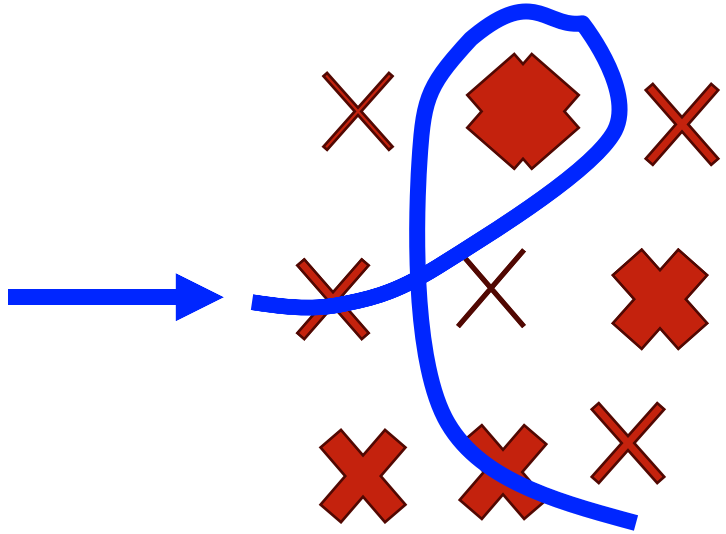
Due to adiabatic expansion of the solar wind

DIFFUSION IN TURBULENT MAGNETIC FIELD



Uniform magnetic field

Motion defined by Lorentz's equation



Nonuniform magnetic field

Motion is not well defined

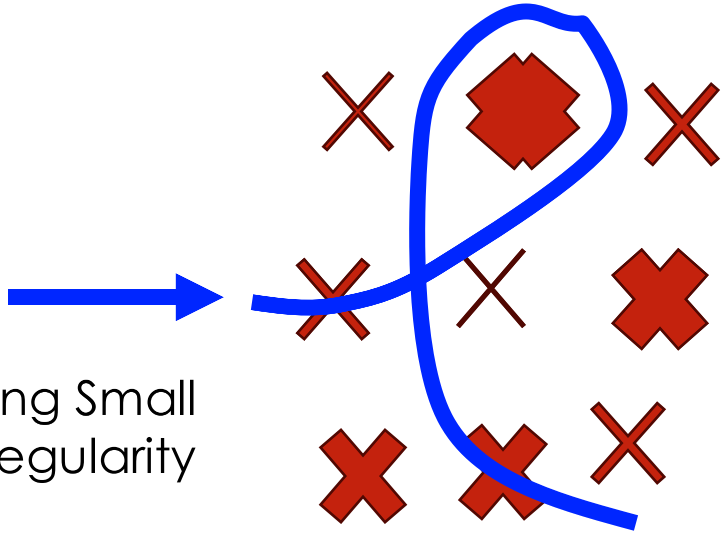
DIFFUSION IN TURBULENT MAGNETIC FIELD

$$\frac{\partial U}{\partial t} = \nabla \cdot [\tilde{K} \cdot \nabla U]$$

$$\hat{\kappa} = \begin{pmatrix} \kappa_{\|} & 0 & 0 \\ 0 & \kappa_{\perp} & \kappa_A \\ 0 & -\kappa_A & \kappa_{\perp} \end{pmatrix}$$

Diffusion due to scattering Small Scale Magnetic Field irregularity

Drift motion due to Large Scale structure of magnetic field



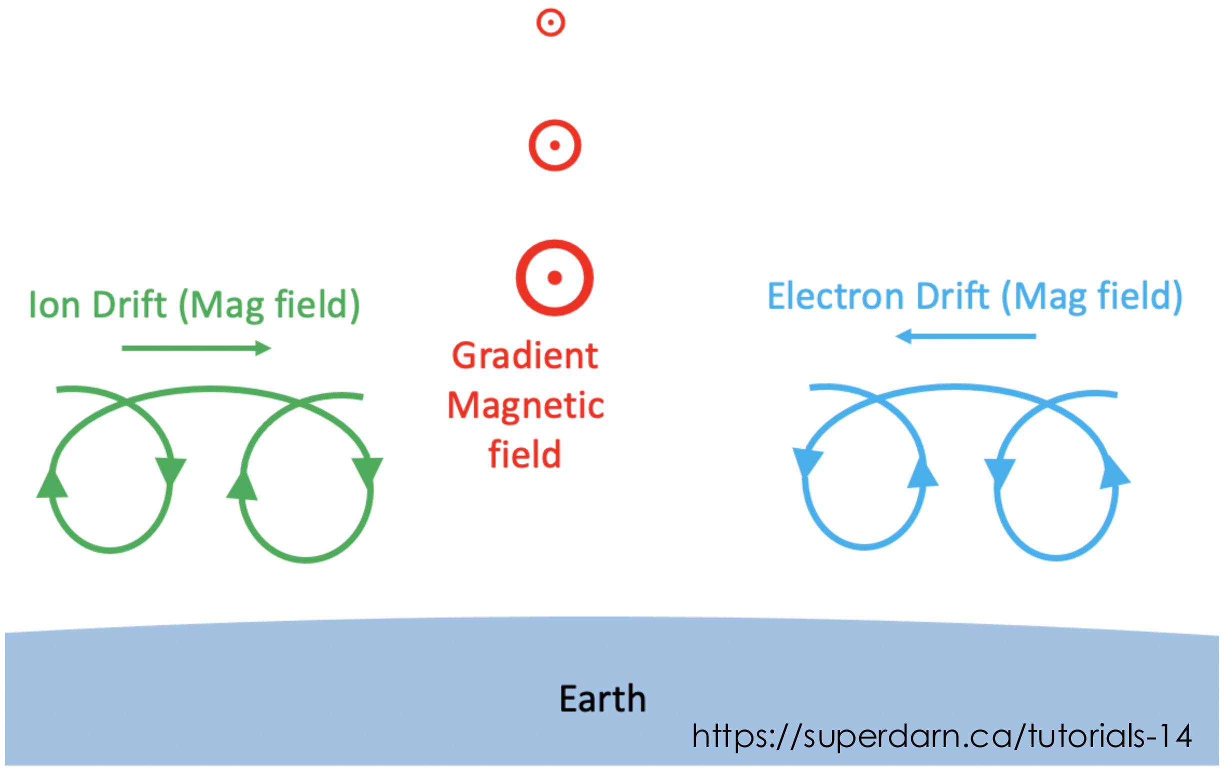
Nonuniform magnetic field

Motion is not well defined

MAGNETIC DRIFT

$$\hat{\kappa} = \begin{pmatrix} \kappa_{\|} & 0 & 0 \\ 0 & \kappa_{\perp} & \kappa_A \\ 0 & -\kappa_A & \kappa_{\perp} \end{pmatrix}$$

Drift motion due to Large Scale structure of magnetic field



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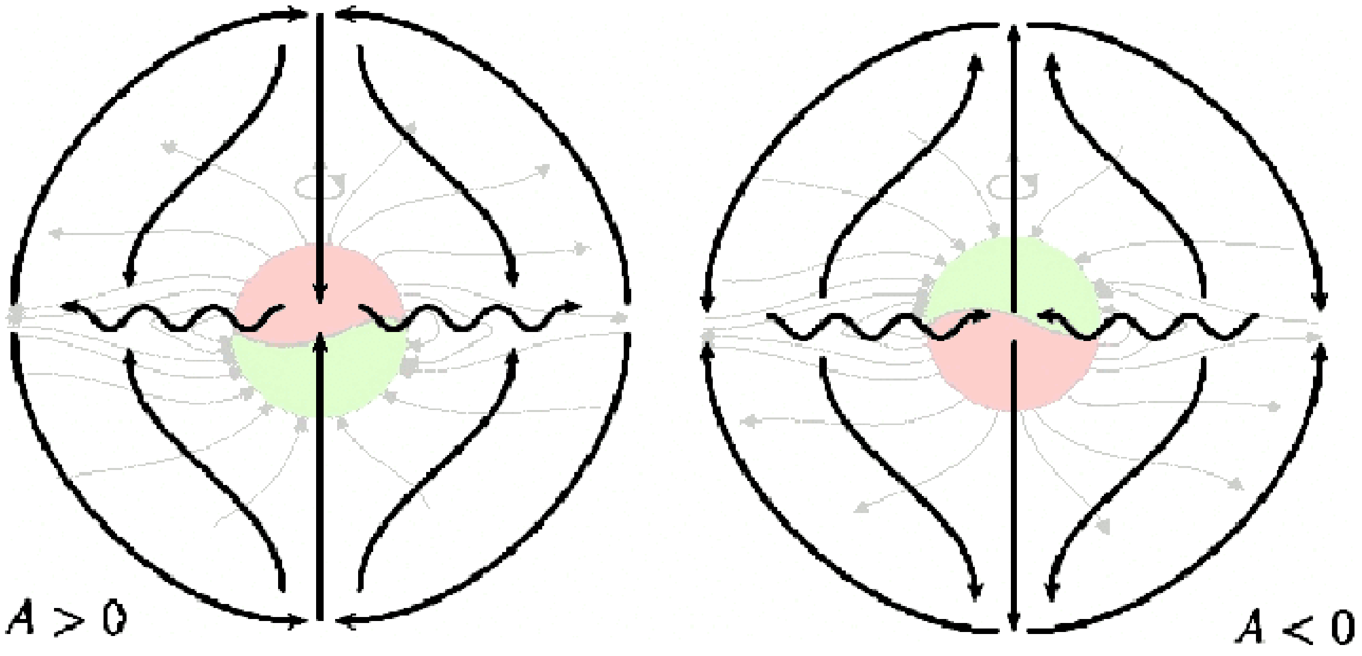
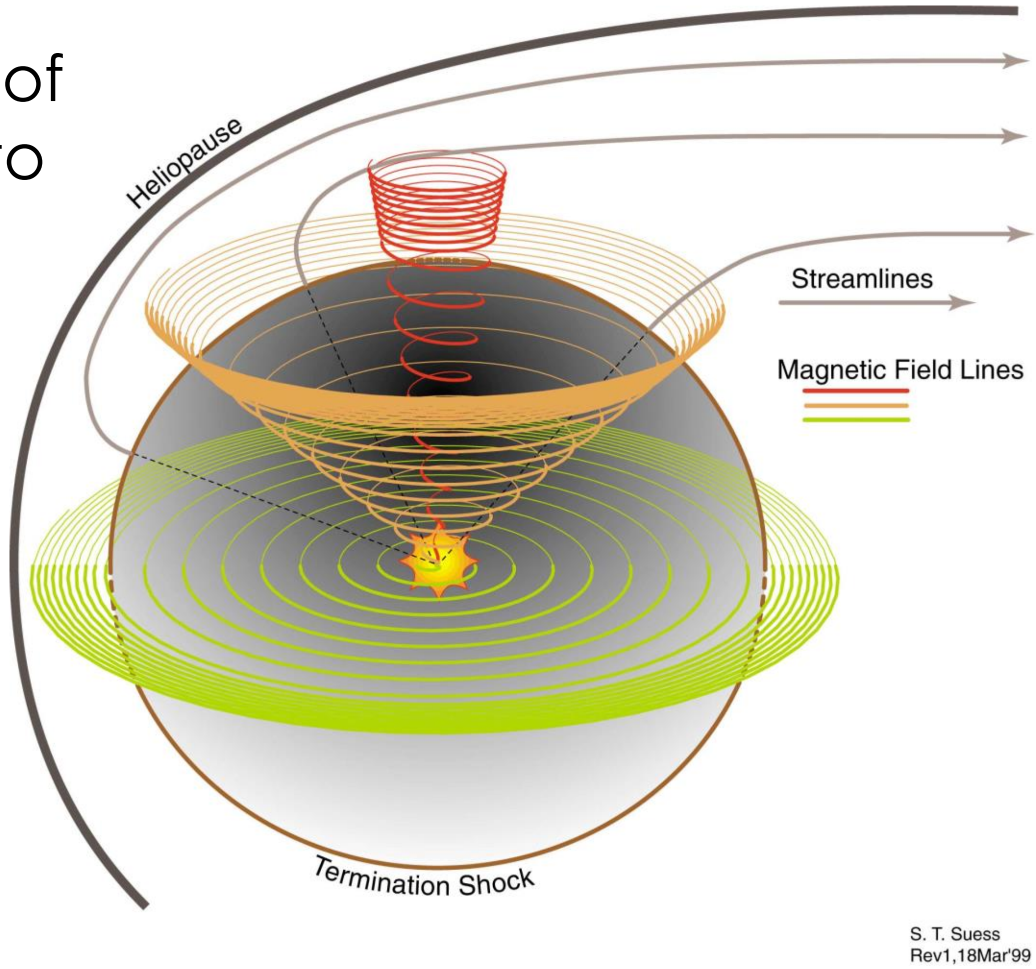
MAGNETIC DRIFT IN THE HELIOSPHERE

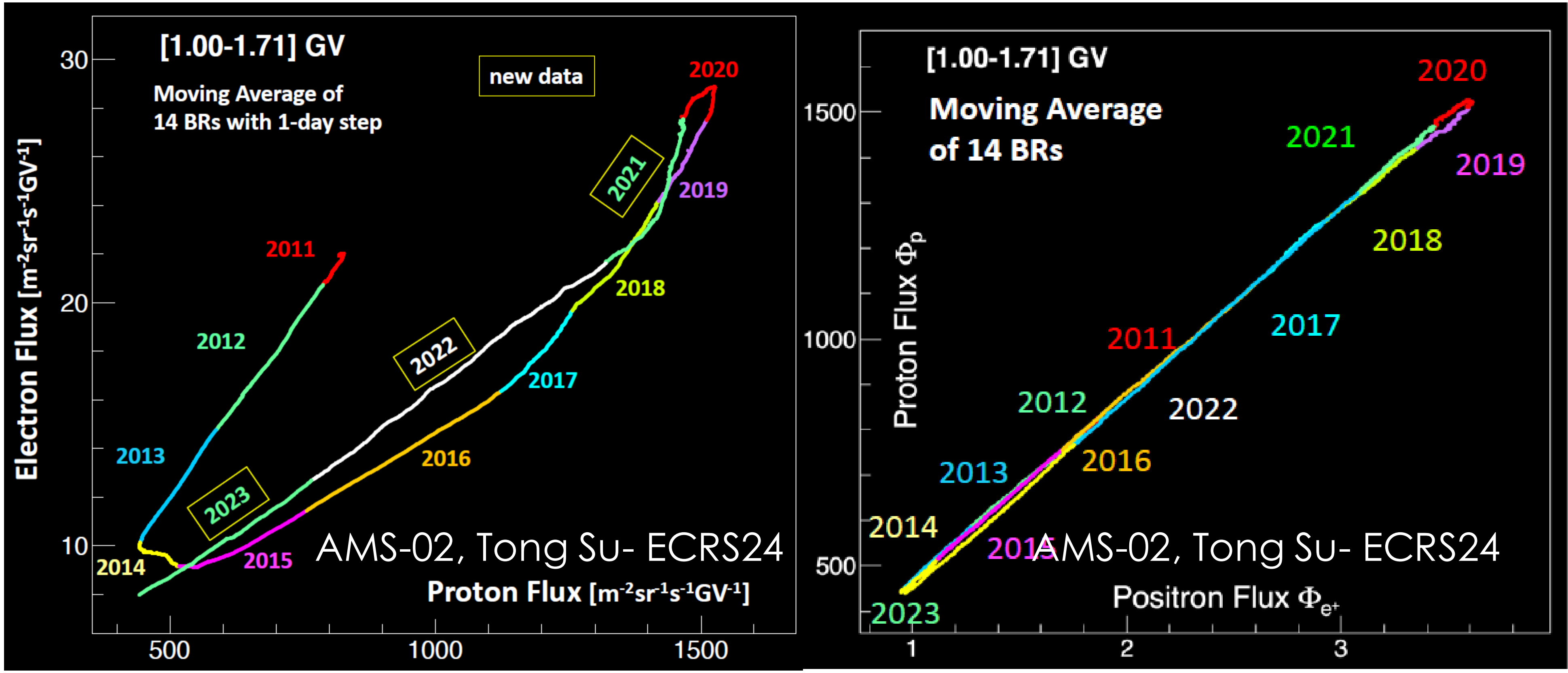
Inside the heliosphere, drift motion create flown of particles from/toward the inner part according to the solar polarity & particle charge





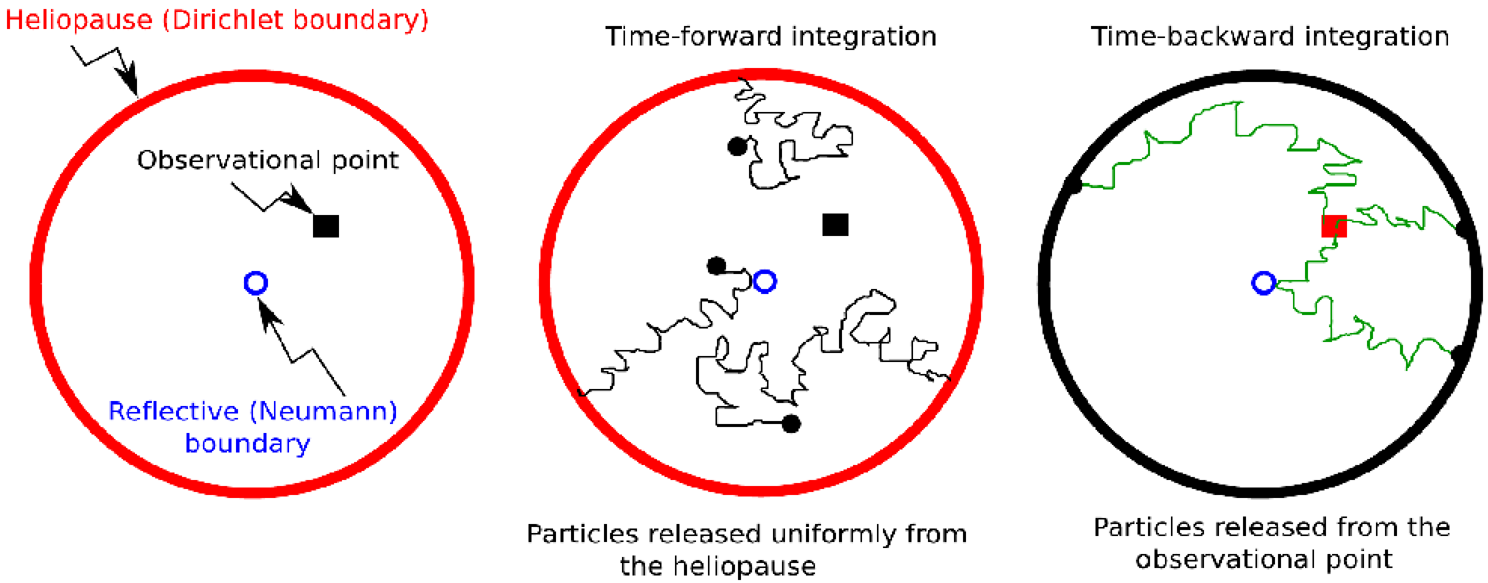
MAGNETIC DRIFT IN THE HELIOSPHERE

This process affect differently particles with opposite charge

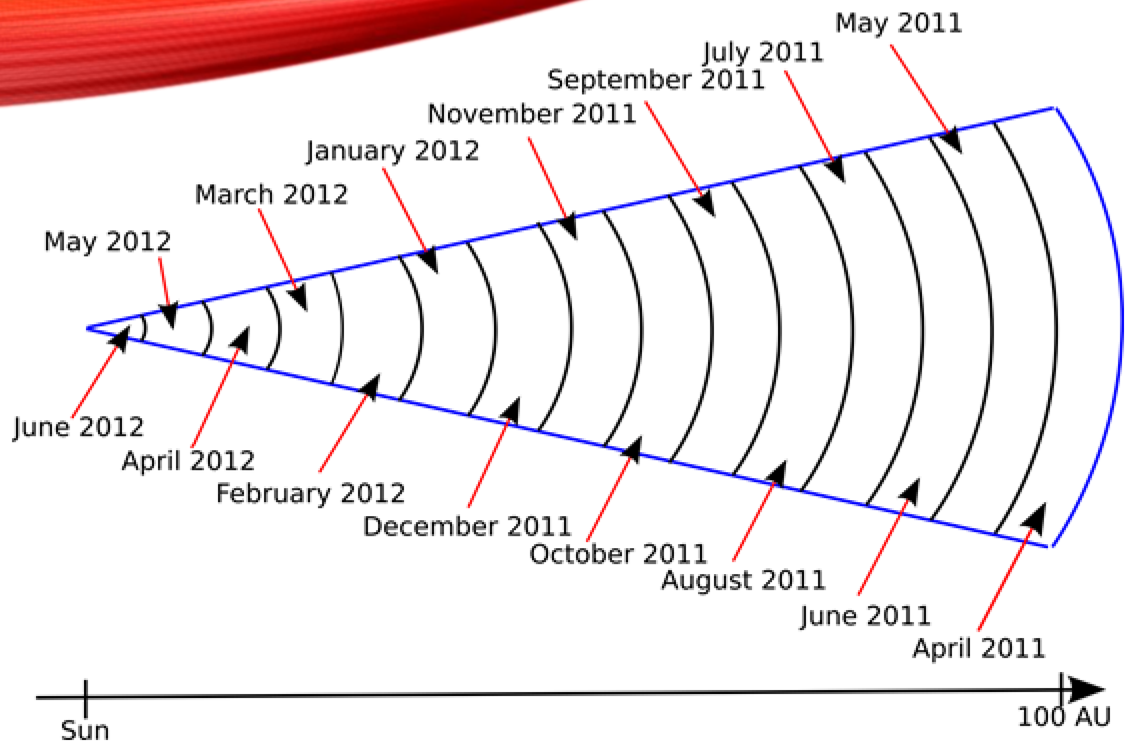


THE HELIOSPHERE MODULATION MODEL

Is a Monte Carlo code that solves numerically the Parker equation in a 2D approximation with the *backward-in-time Stocastic Differential Equation (SDE)* approach.



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

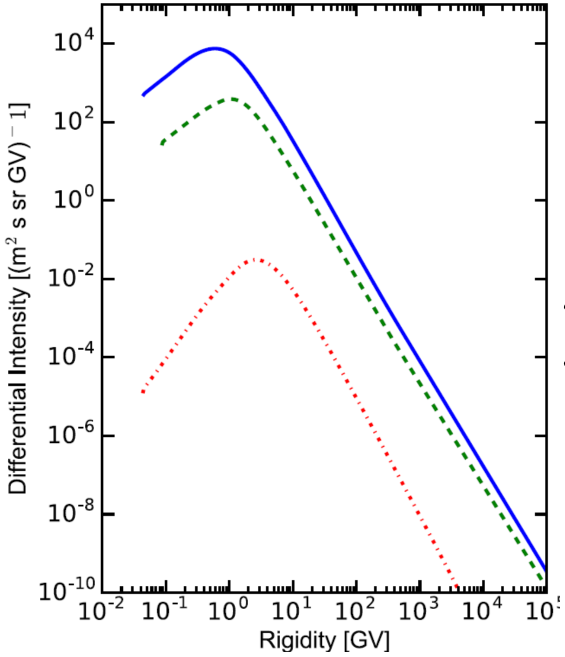
Solar Wind Speed

Diffusion coefficients

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

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

HelMod provide the transformation functions needed to modify the Local Interstella Spectra (i.e. outside heliosphere) into modulated spectra



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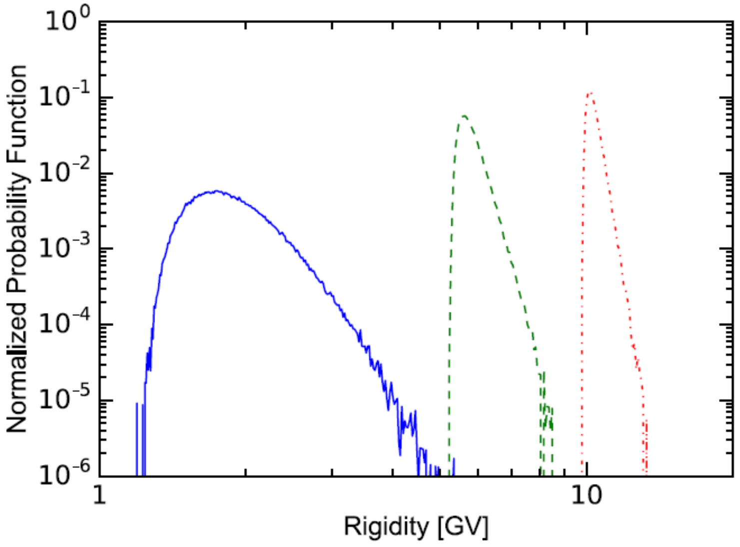

Figure 2. Computed normalized probability function $G(R_0|R)$ for $R_0 = 1.1$, 5.1, and 9.7 GV (left to right) evaluated for AMS-02 proton binning during the period 2011–2014; see the text for details.

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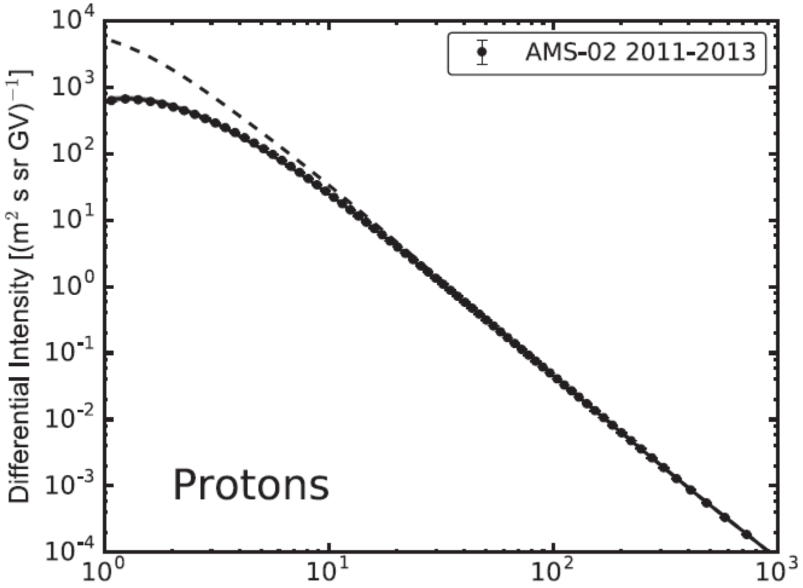
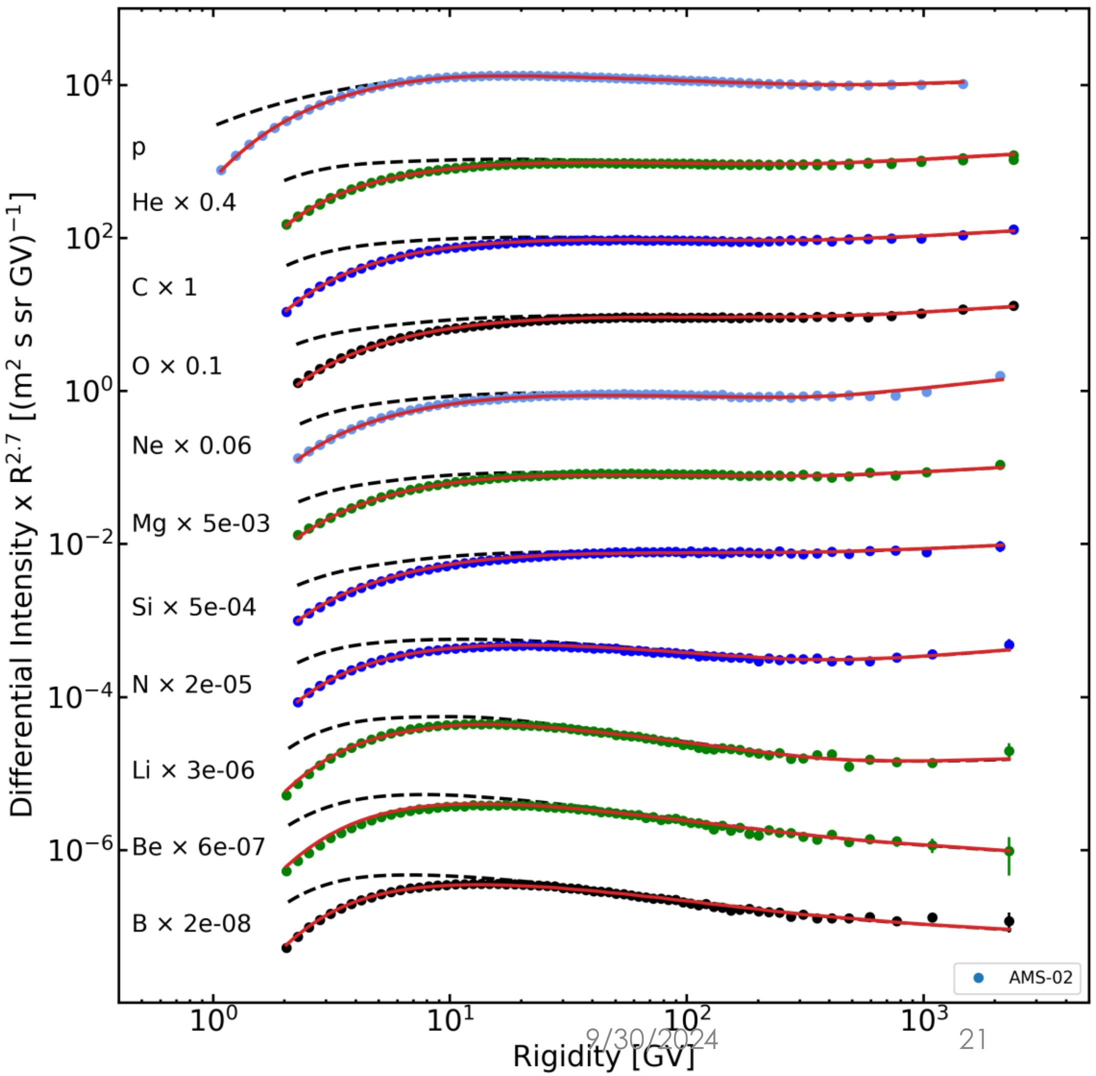


LIS is a critical element in evaluating the modulated spectra

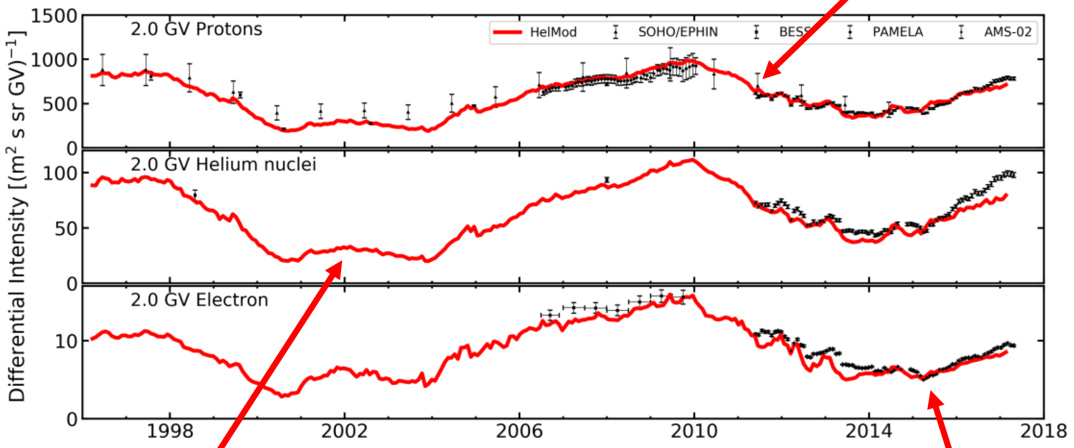
The GALPROP-HelMod join effort allow to intercalibrate the two model in a energy region without direct measurements (outside heliosphere)



HelMod can reproduce ions:

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

Proton



Helium

Electron

Heliosphere Termination Shock

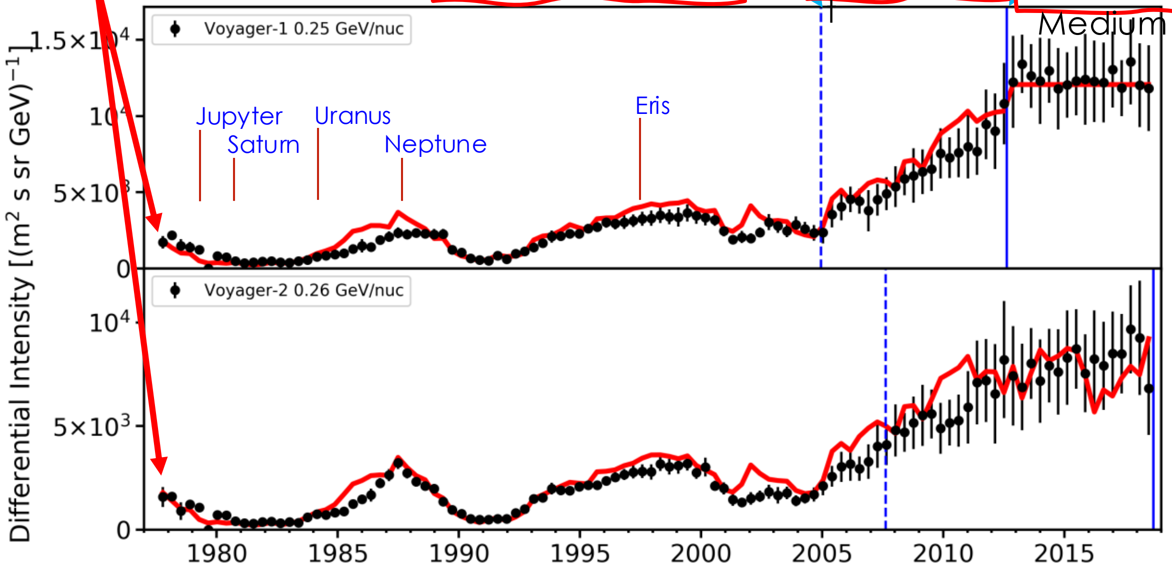
Heliopause

Proton

Inner Heliosphere

Helioshea

Interstellar Medium



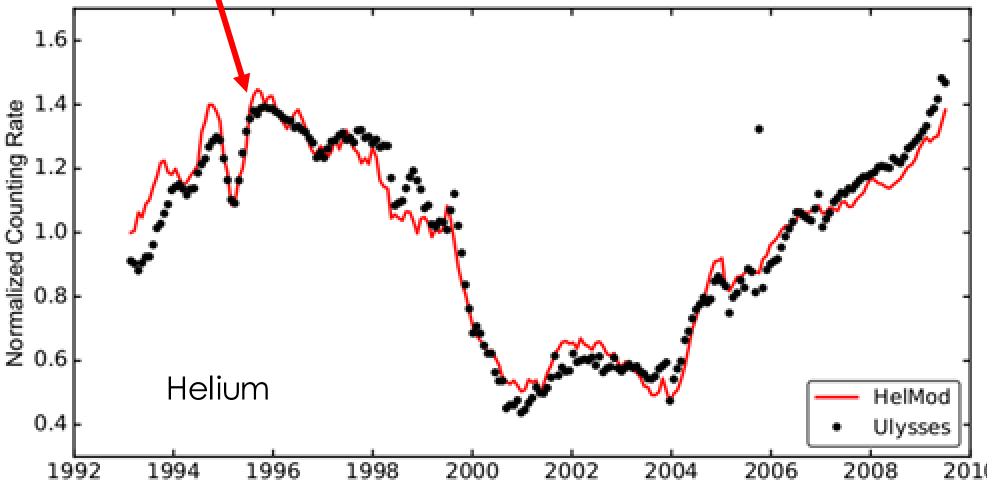
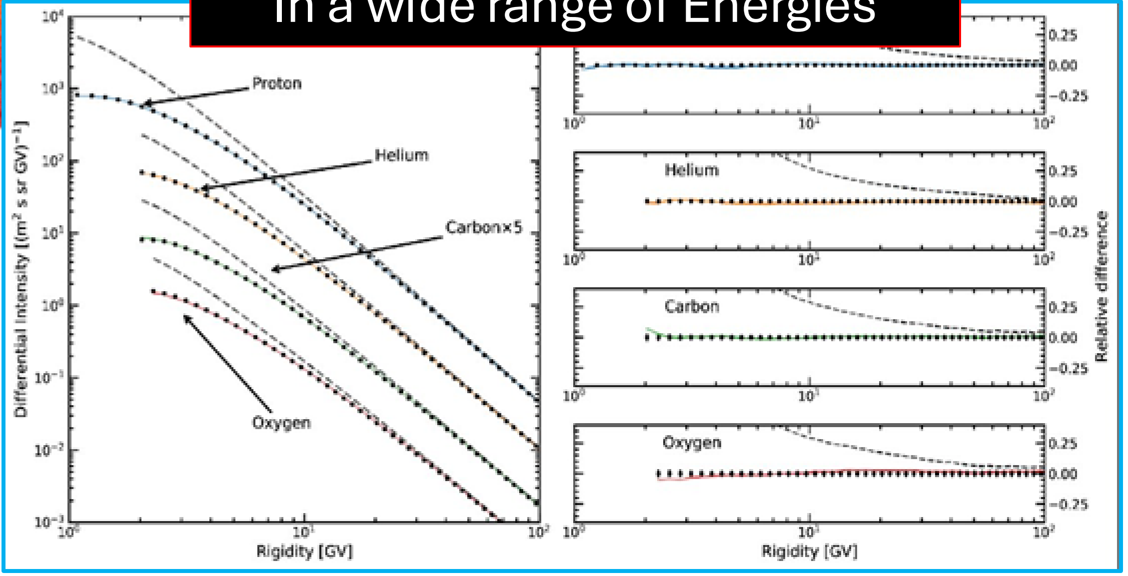
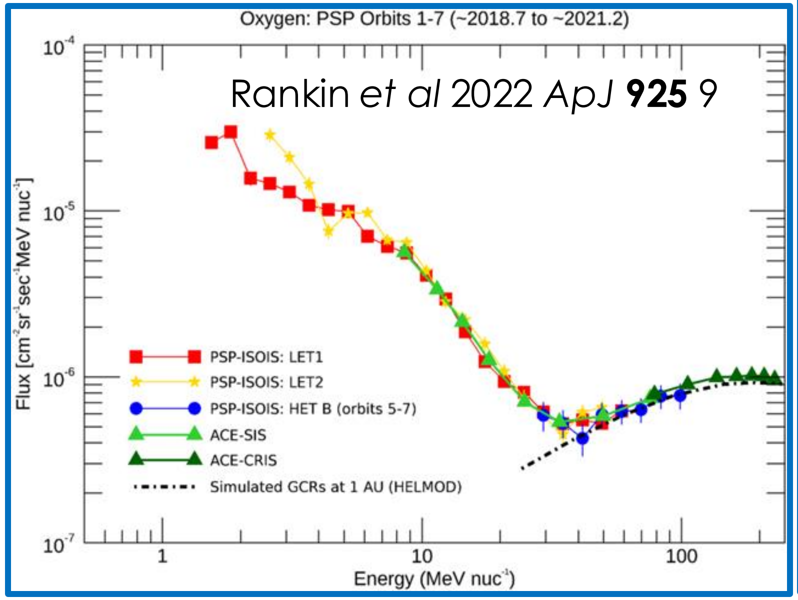


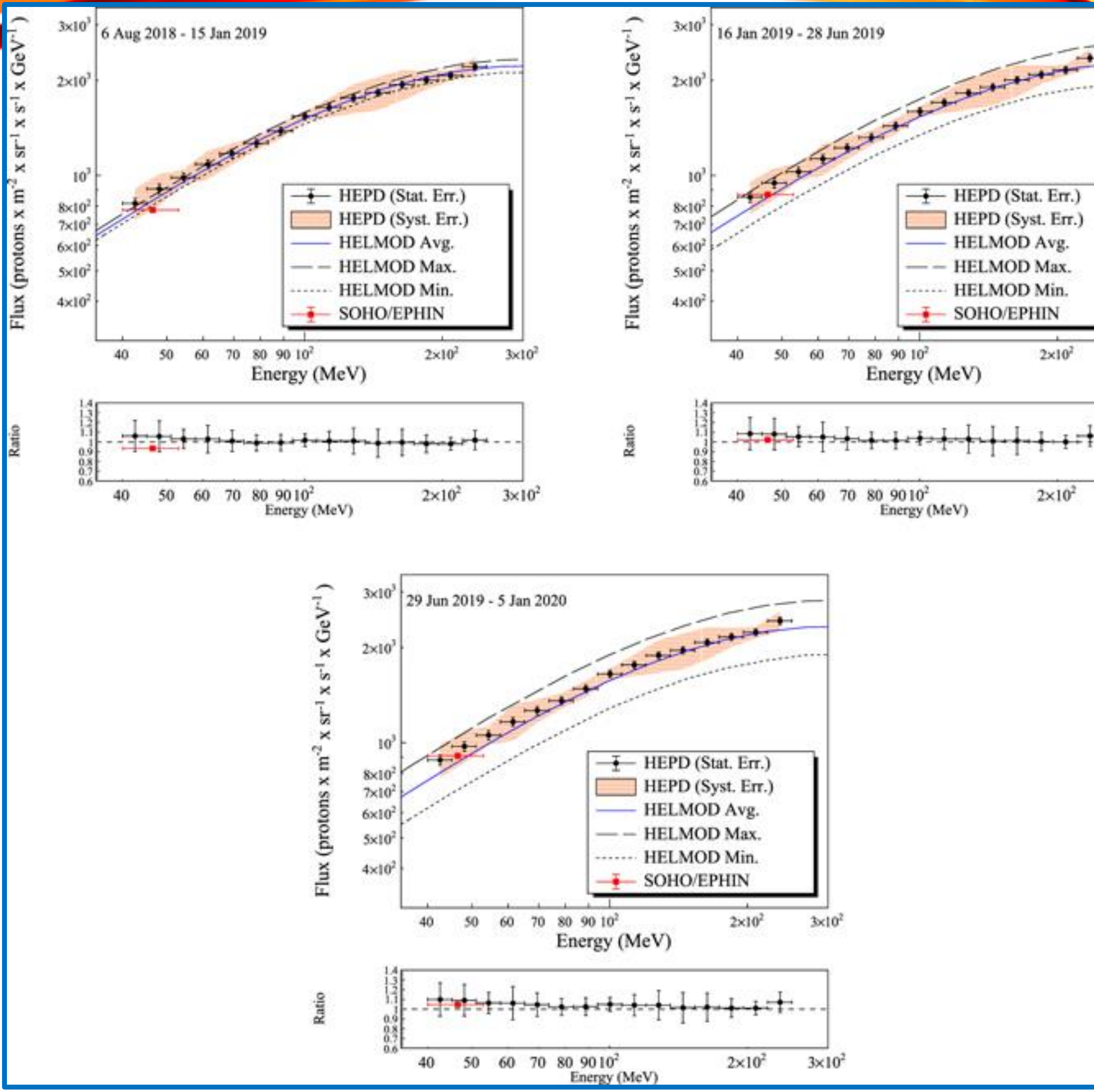
Figure 8: Helium normalized counting rate measured by Ulysses (full black circles) at ±80° of solar latitude and 1 to 5 AU compared with the 1 GeV energy modulated spectrum from HelMod code (red solid line) as function of time.

In a wide range of Energies





Rankin *et al* 2022 *ApJ* **925** 9



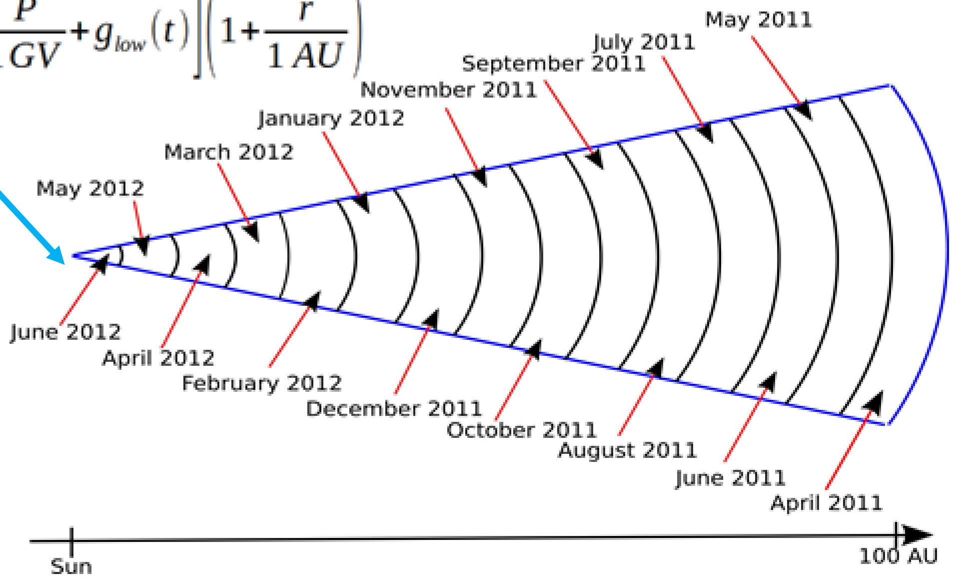
Bartocci et al ApJ ,901:8, 2020

APPLICATIONS AND IMPLICATIONS

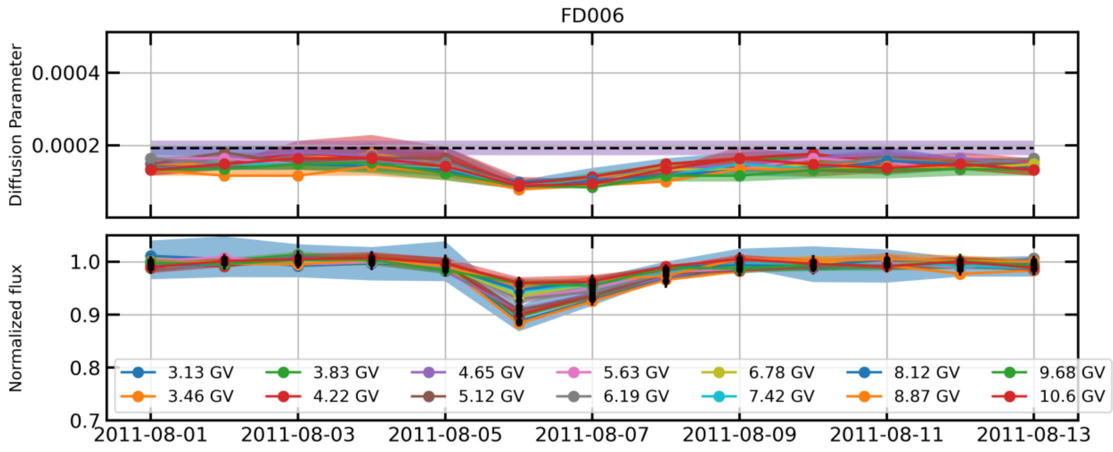
METHODOLOGY

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

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



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.

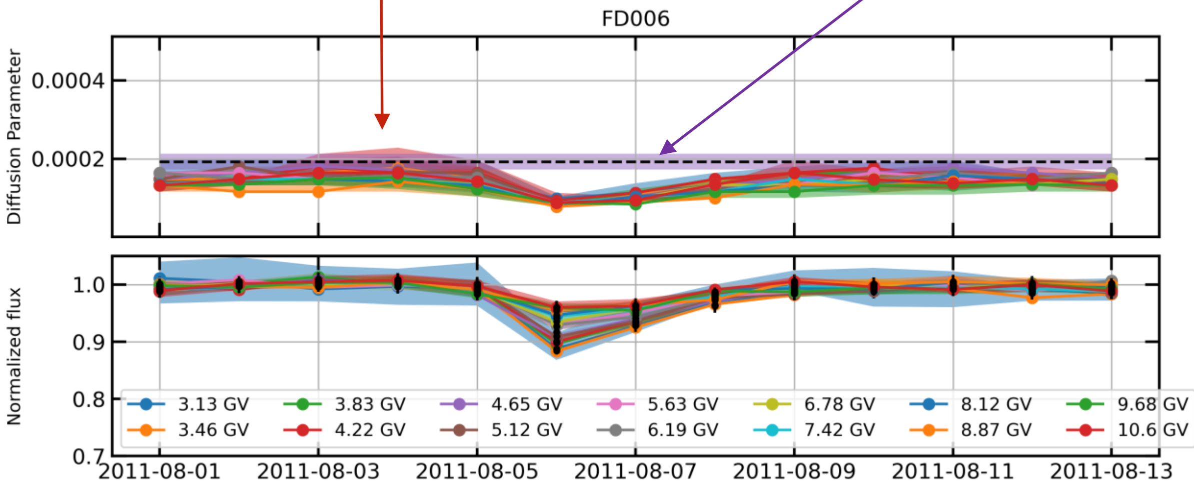
We apply our study to the five most relevant FD events seen by AMS-02. **For each FD we select a time windows that influence up to 4 quiet days before and after the event.**

PRELIMINARY RESULTS

We notice that the daily K_0

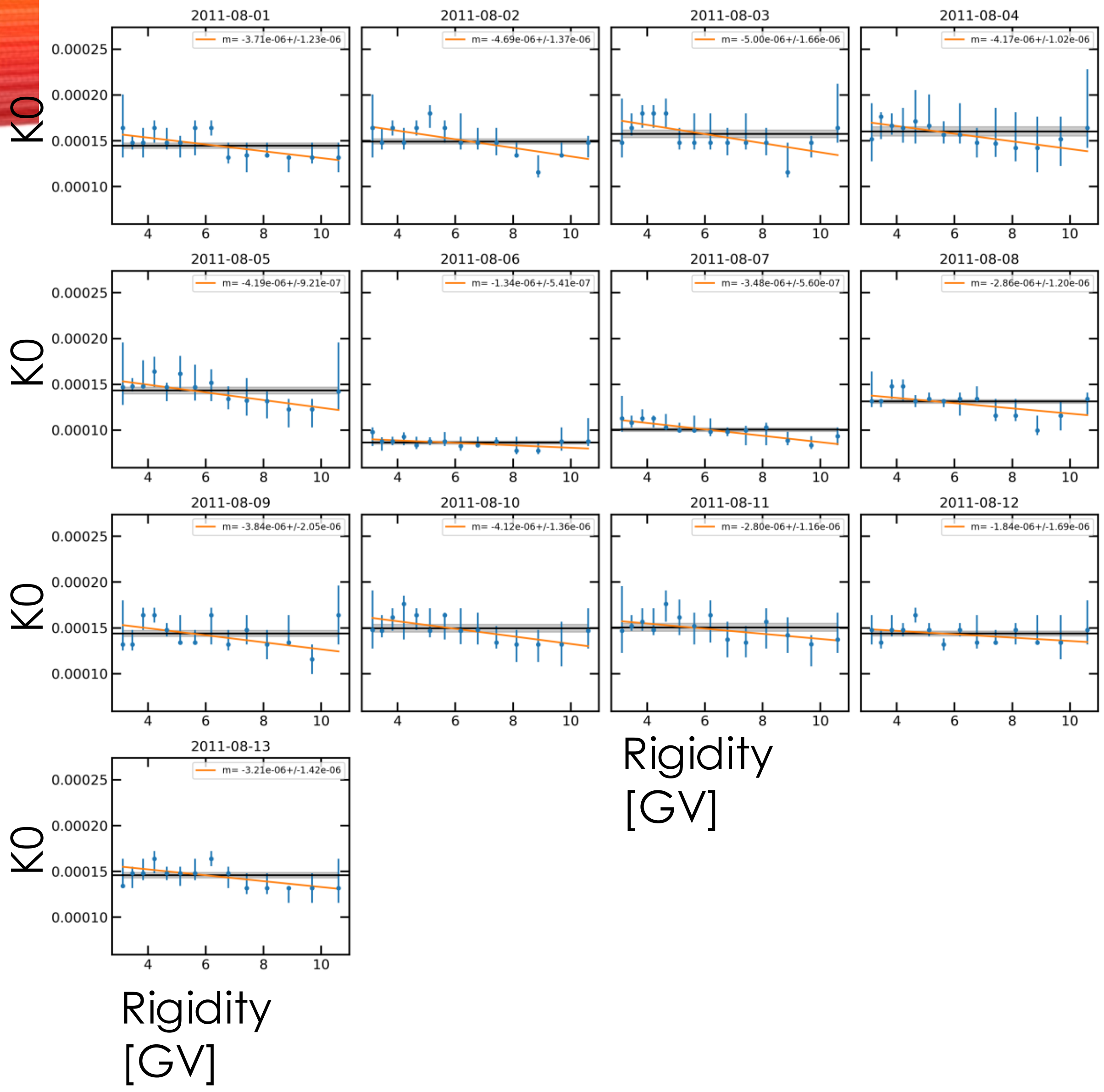
1. decrease following the forbush decrease
2. has similar values for all considered rigidities

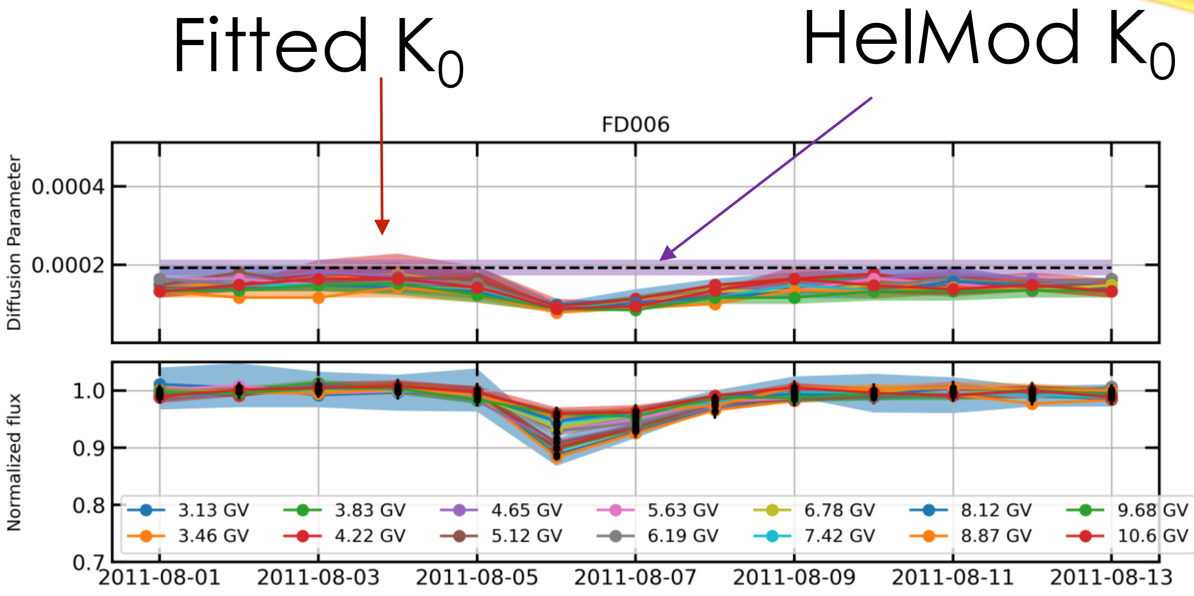
Fitted K_0 HelMod K_0



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

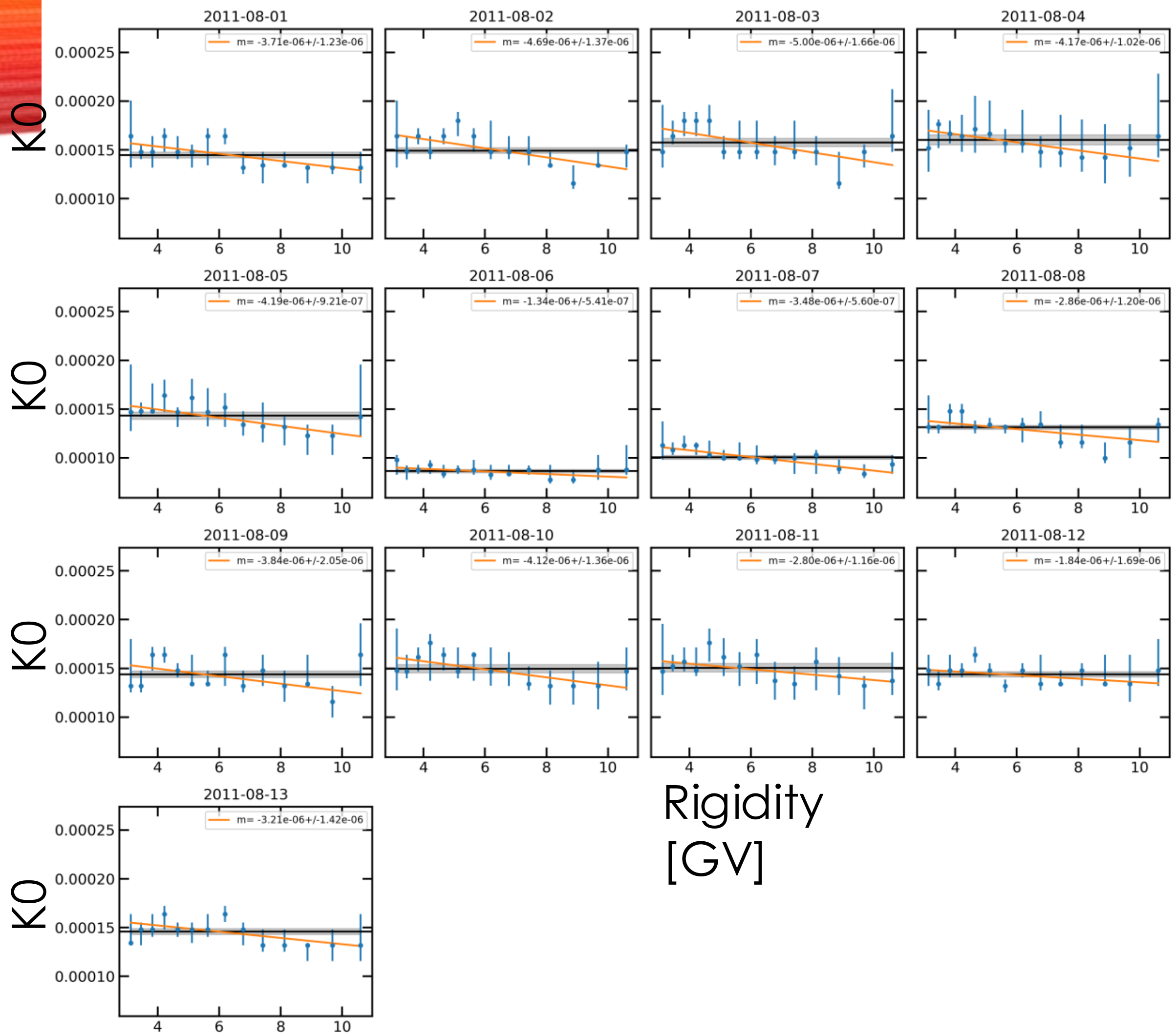
PRELIMINARY RESULTS



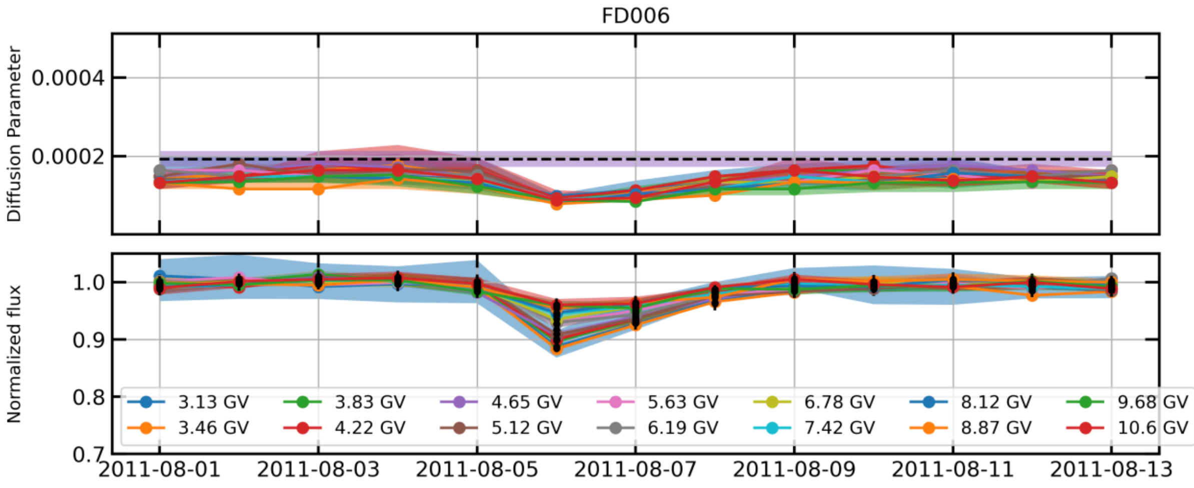


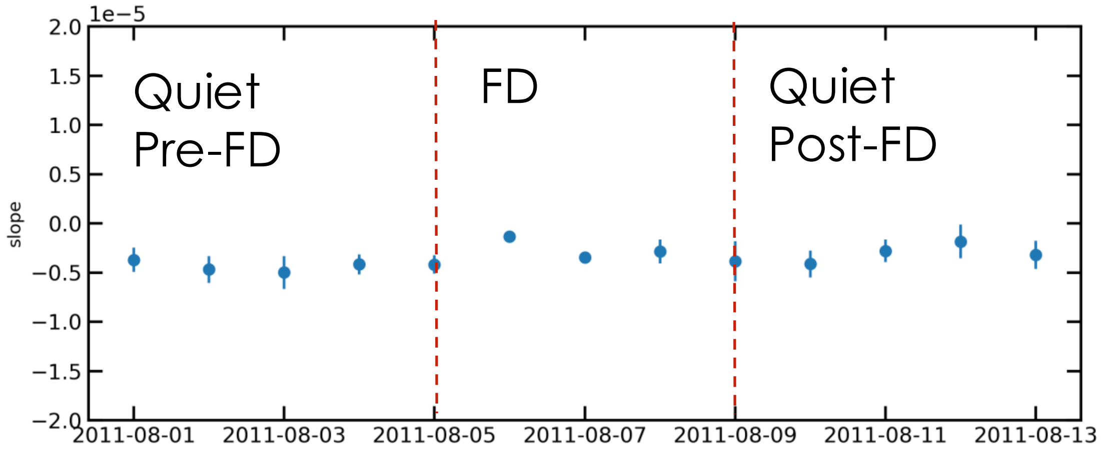
We found a linear correlation between K_0 and Rigidity. This may be due to LIS uncertainties or an incorrect rigidity dependence of diffusion tensor.

PRELIMINARY RESULTS



Rigidity [GV]

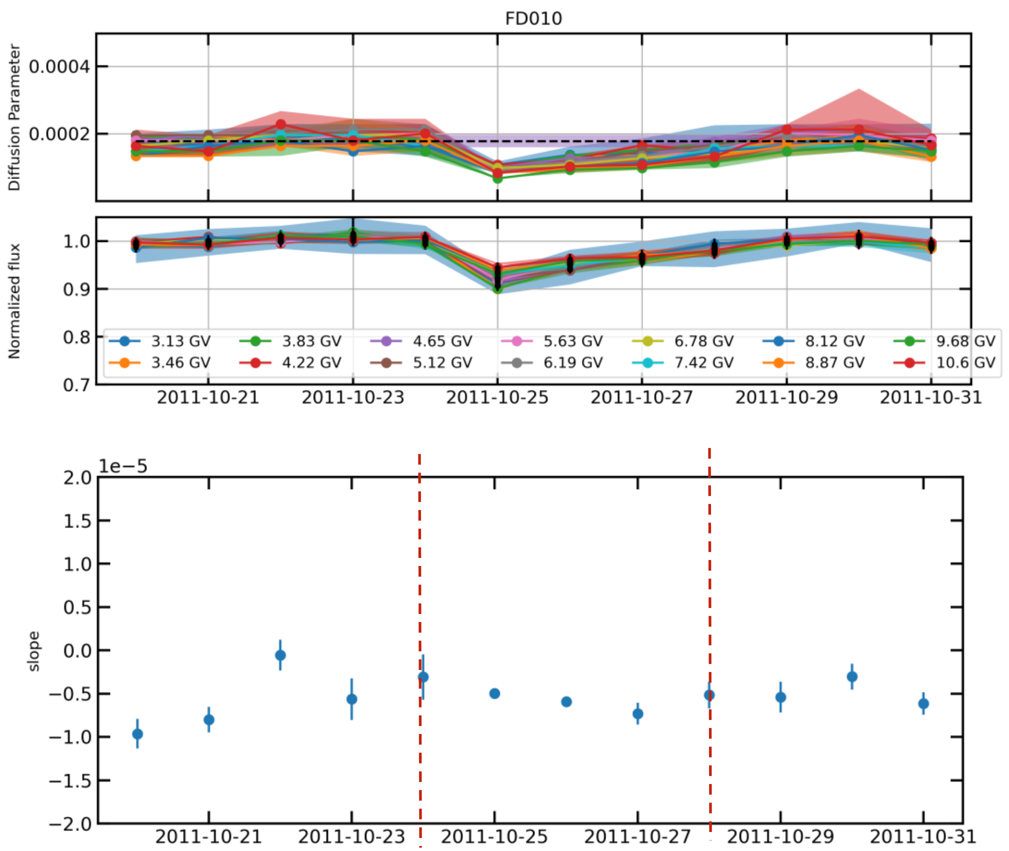


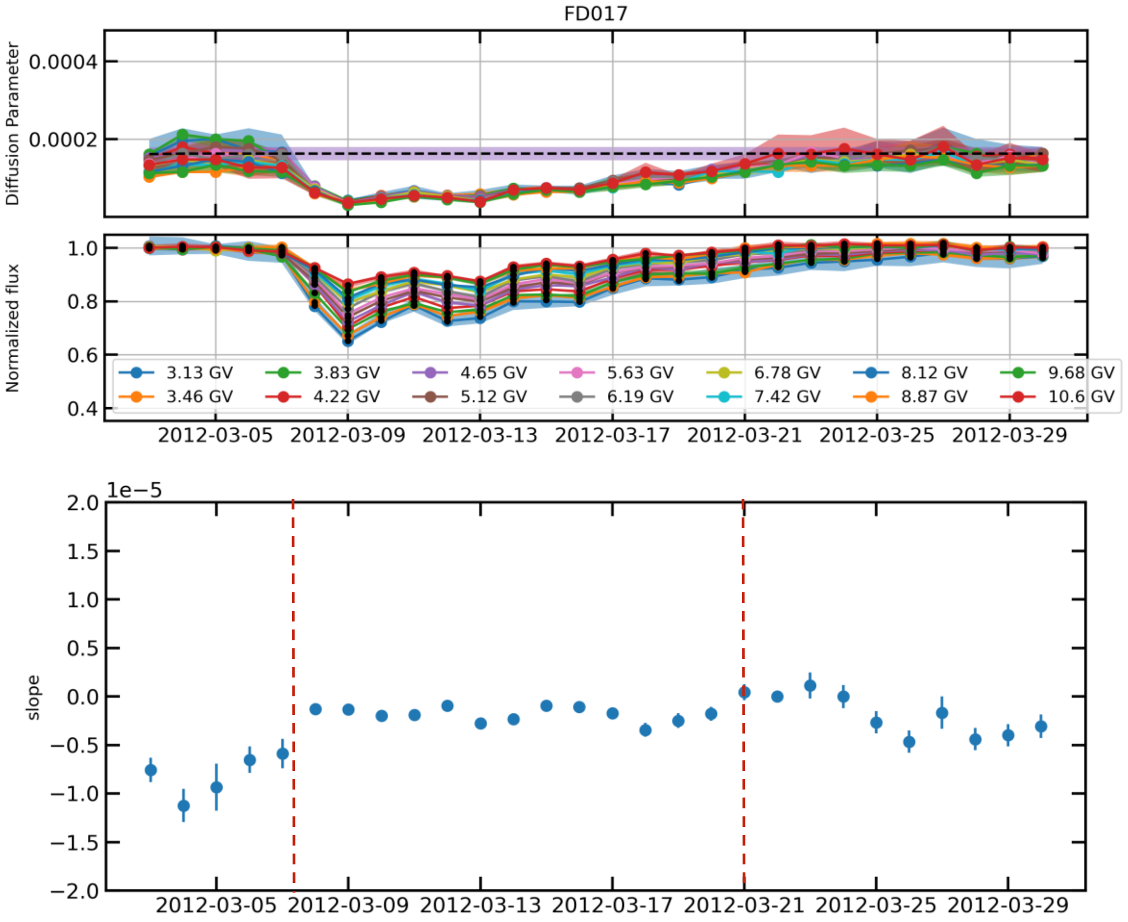


This Linear Correlation maintains the same slope both quiet and perturbed days.

PRELIMINARY RESULTS

Similar results are observed on others FD of the sample





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PRELIMINARY RESULTS

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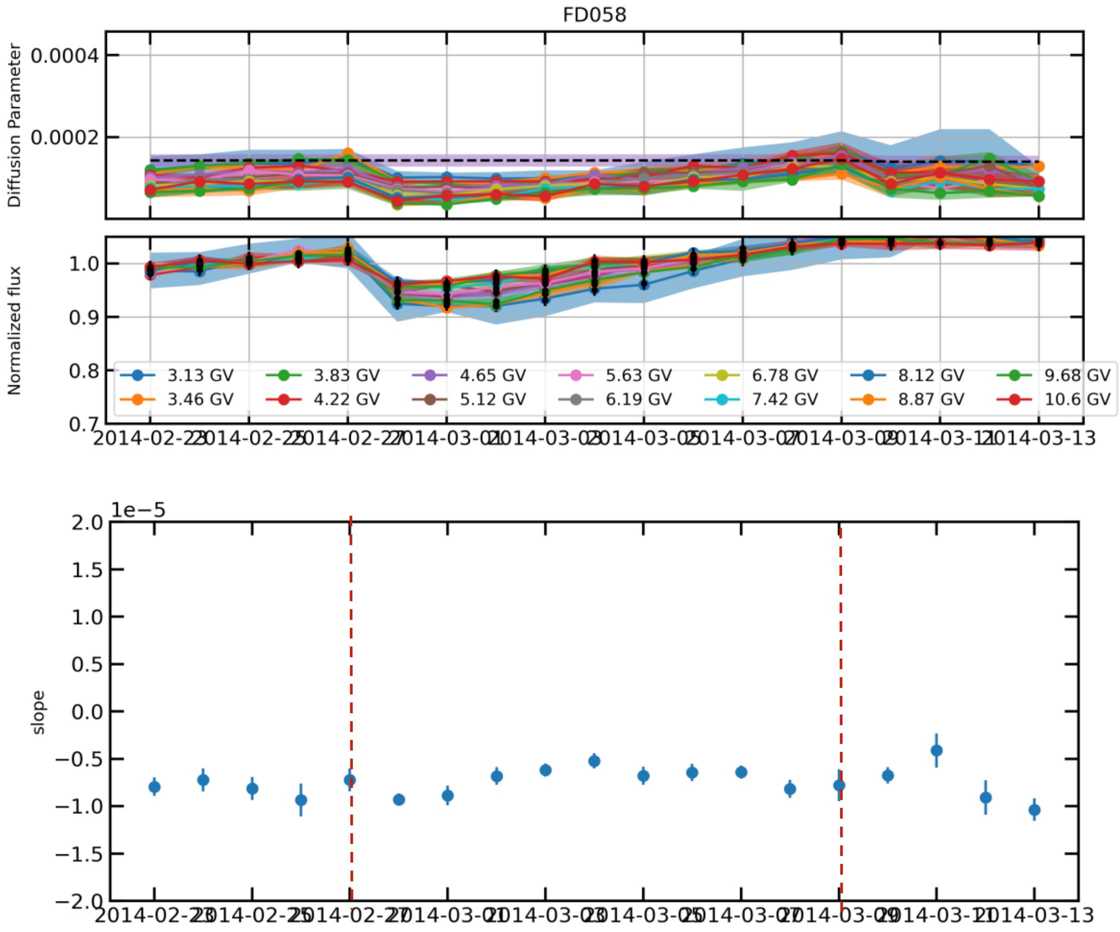
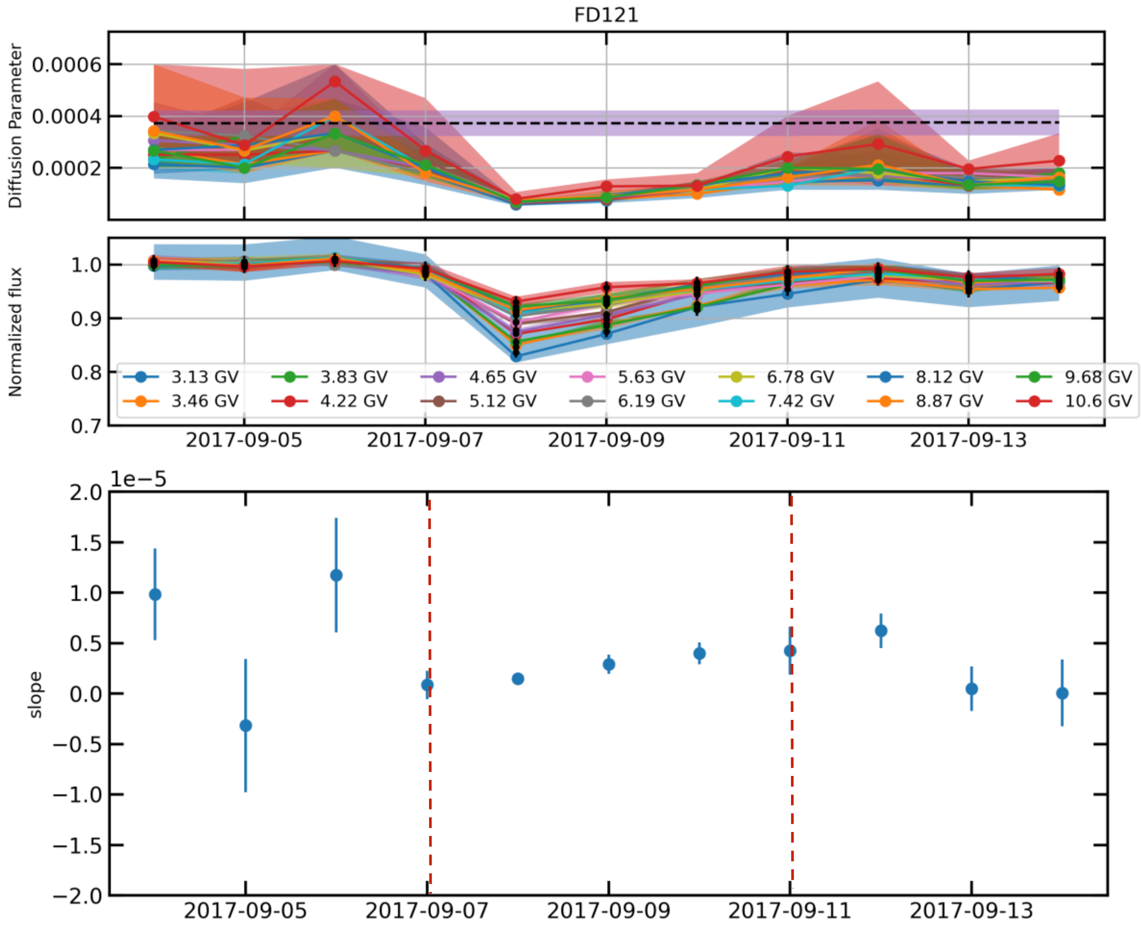
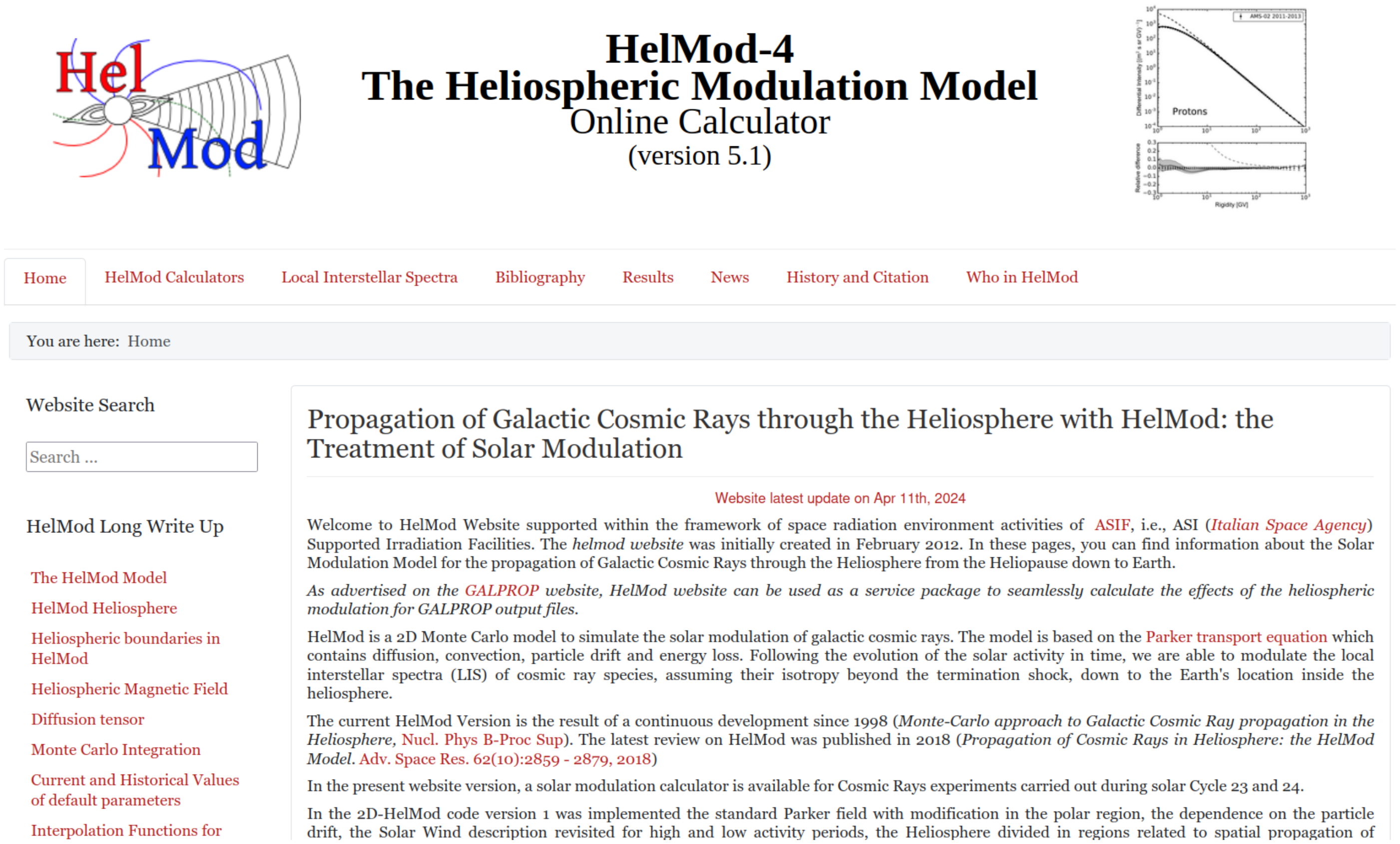




This Linear Correlation maintains the same slope both quiet and perturbed days.

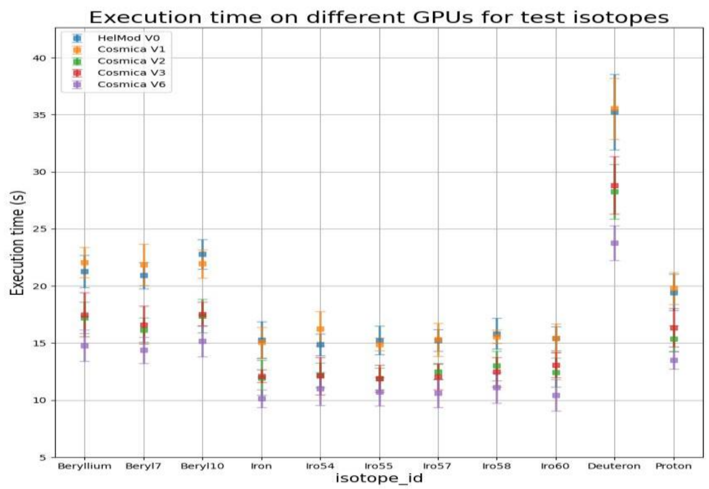
WEBSITE

We developed a website where selected results from HelMod are provided to users

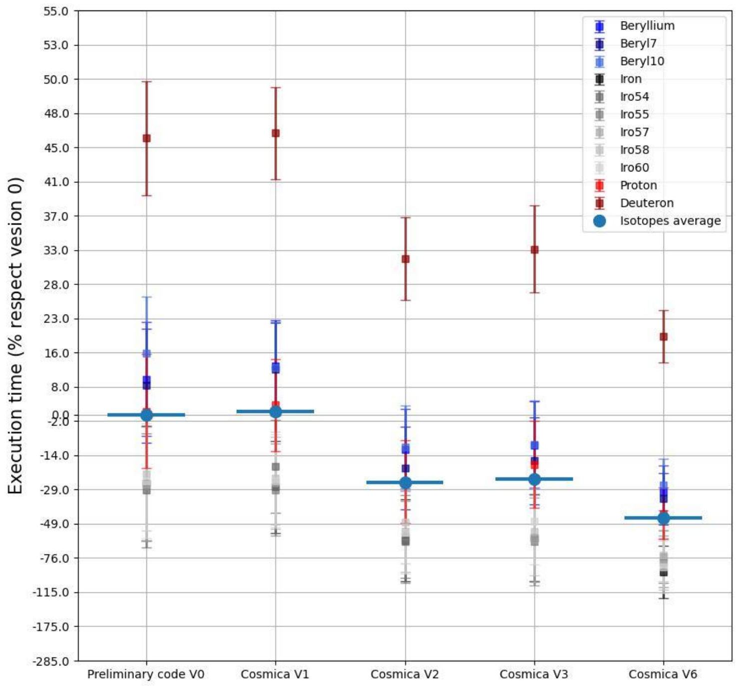


Is under development a new service that allows to run "customized" HelMod Simulation on MiB GPU local Farm

COSMICA AND BEYOND



Execution time of code versions



-50%

We are working on the next generation of modulation code, that exploit the potential of GPUs

The objectives are

a) Made the code to run faster and optimized on GPU (and HPC in general) - *in work*
b) Set up and analysis environment to search for modulation parameters with state-of-art algorithm – *started with Ca' Foscari university*
c) Review the model descriptions with state-of-art theories – *planned*
d) Make the code public for world-wide collaboration toward a common mantained Modulation model – planned

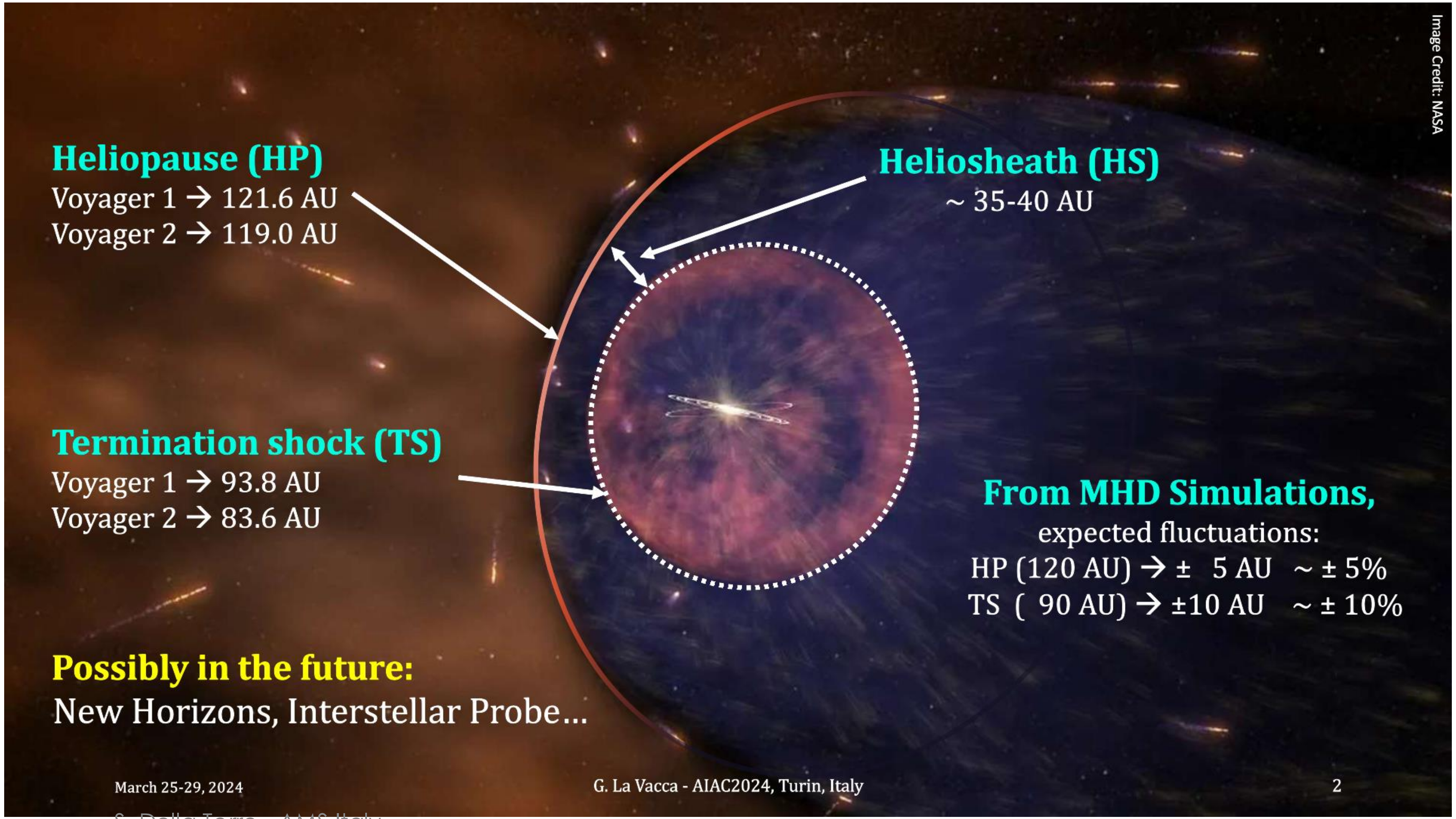
SPOKE 3
Astrophysics
& Cosmos Observations

CONCLUSIONS

- Solar modulation is an interesting phenomena that involves several disciplines
- The study of Solar modulation allows to better understand the space close to Earth
- An accurate model for solar modulation is needed in order to study fine structures in actual measurement
- New model and tools are in development, so stay tuned or propose yourself for collaboration

THANKS FOR THE ATTENTION

DEFINITION #2: THE HELIOSPHERE

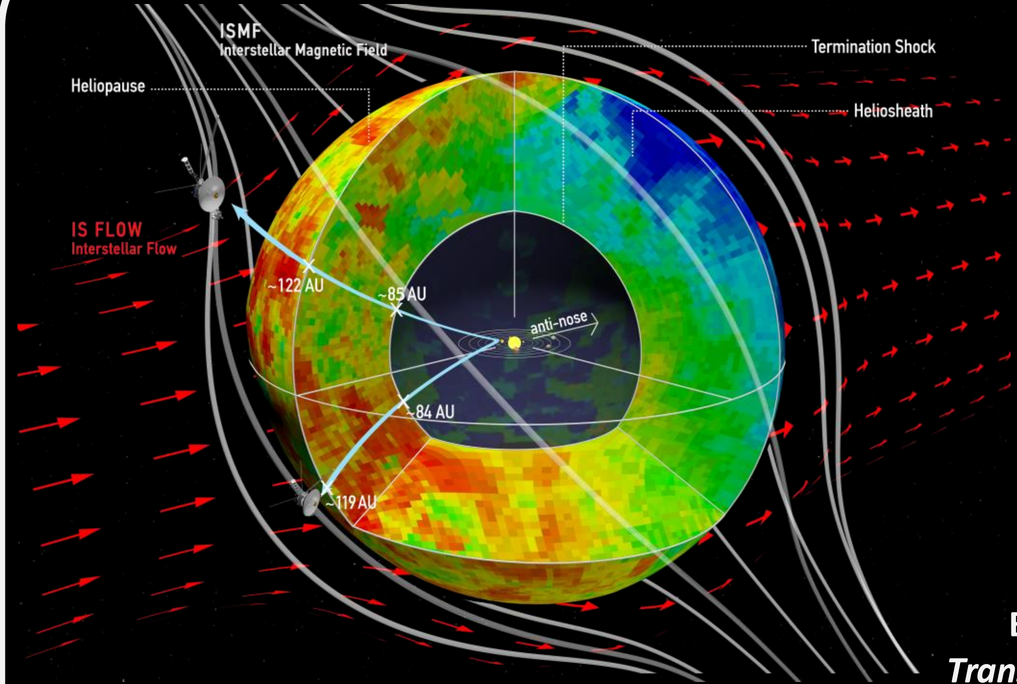


Simple definition: Region of space directly influenced by Sun dynamics

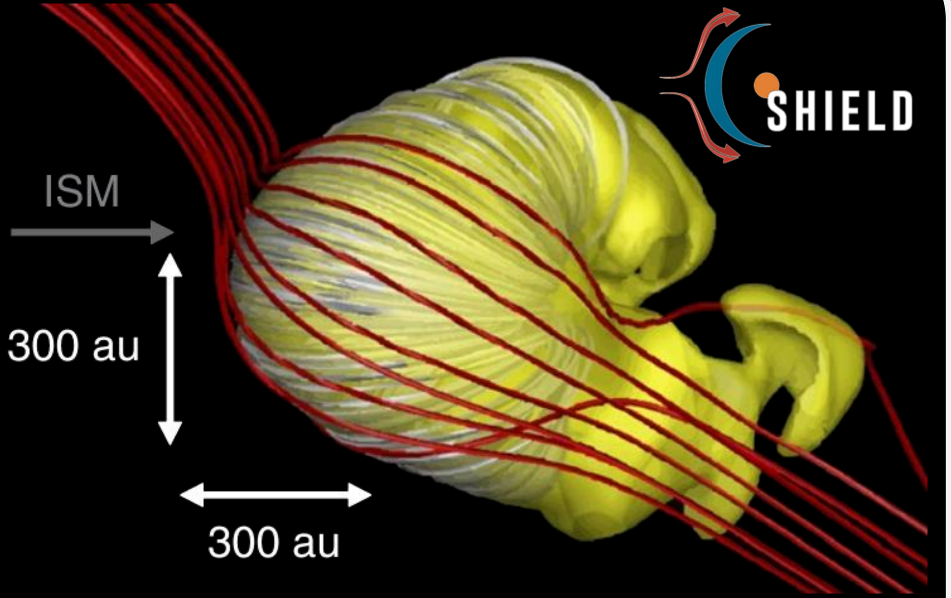
Plasma emitted by the Sun (solar wind) transport the magnetic field defining the shape and dimension of the heliosphere

Shape of the Global Heliosphere (1961-2022) // A rough diamagnetic bubble; a jets structure; a comet...

Dialynas+[2017] (INCA & Voyager data)



Opher+[2020] MHD modeling



IBEX-Lo Data (Galli+[2016; 2017])

[...] typical thickness of HS in downwind
~(220±110) AU.

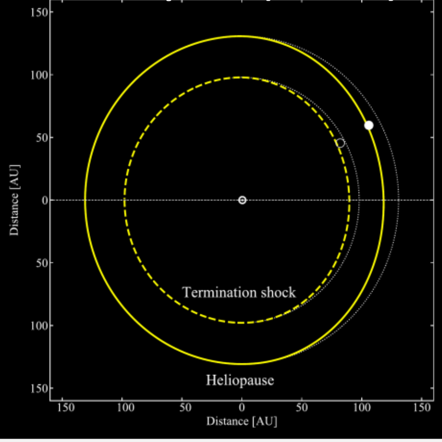
IBEX-Hi Data (Reisenfeld+[2016])

N. pole ***L_{HS}~210 AU*** *|| S. pole* ***L_{HS}~160 AU***

IBEX-Hi Data (Reisenfeld+[2021])

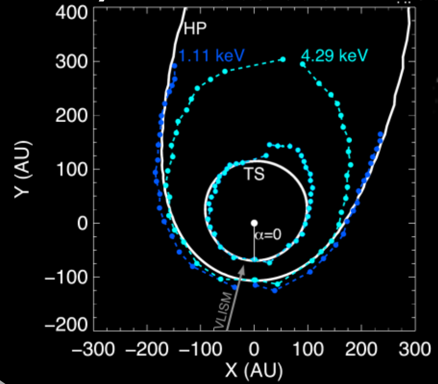
[...] heliosphere extends at least ***~350 AU*** *tailwards*

Boschini+[2019; 2020]
Transport of GCRs through the heliosphere (HelMod).

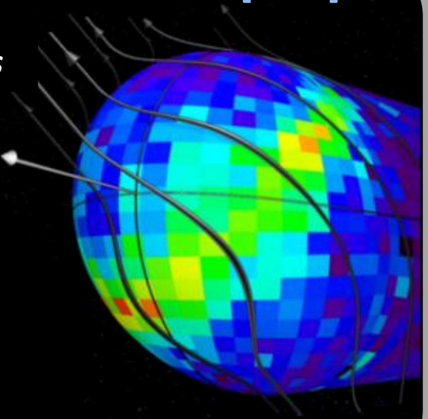


Intermediate Configuration

Zirnstein+[2018]
IBEX/ENA trace back times



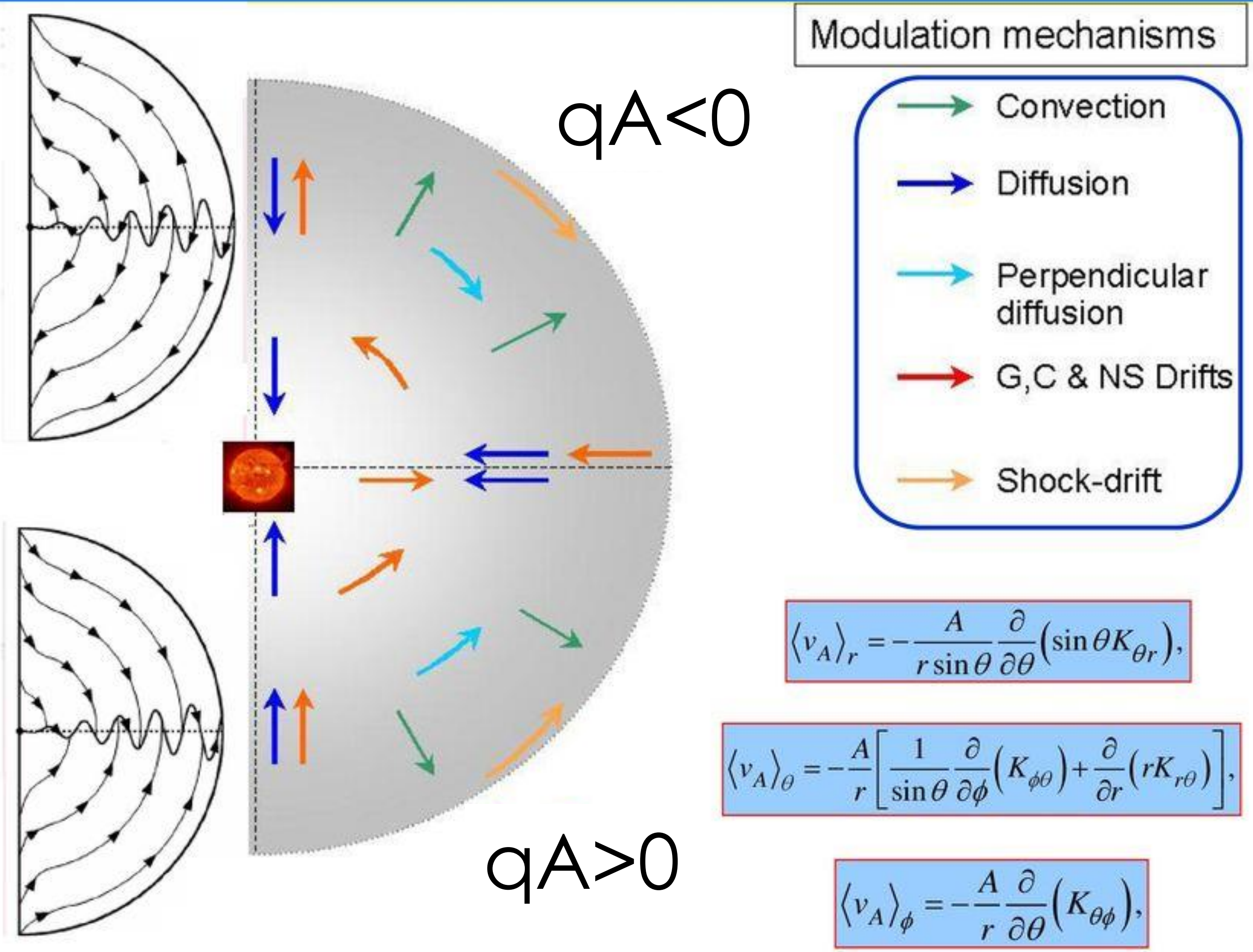
McComas+[2013]



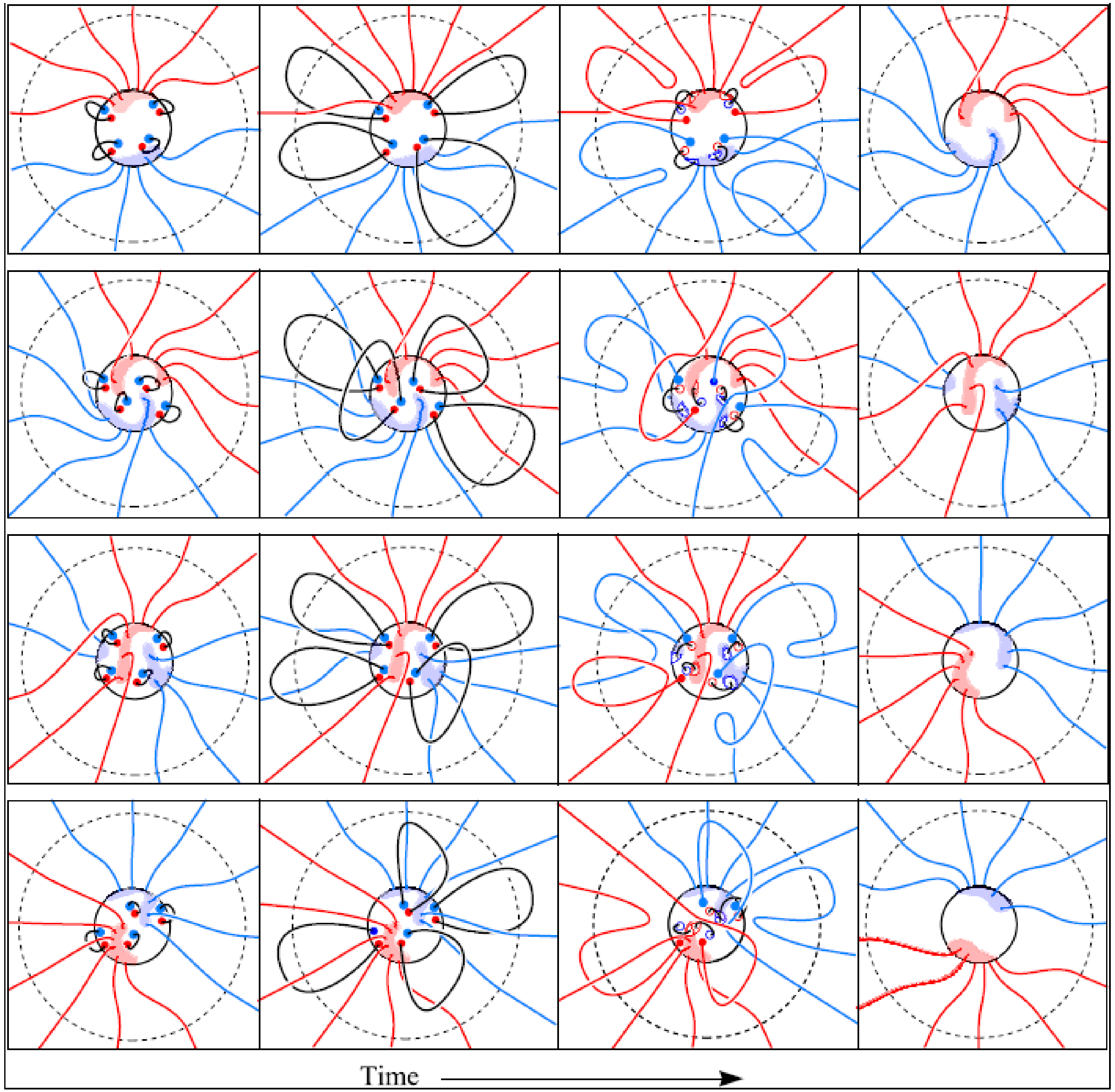
Conceptual illustration of modulation processes

qA<0 Maggiore capacità di penetrazione ai equatore, svuotamento della regione Polare

qA>0 Maggiore capacità di penetrazione ai poli, svuotamento della regione equatoriale



Solar Activity change the sun configuration continously



Equazione del trasporto – Parker 1965

$$\frac{\partial U}{\partial t} = -\nabla \cdot (U\mathbf{V}) + \nabla \cdot \left[\vec{K} \cdot \nabla U\right] + \frac{(\nabla \cdot \mathbf{V})}{3} \frac{\partial}{\partial T} (\alpha_{rel} T U)$$

L'equazione del trasporto fa parte delle equazioni di Fokker-Planck

$$\partial_t F = -\sum_i \partial_i [A_i(\mathbf{x}, t) F] + \frac{1}{2} \sum_{i,j} \partial_i \partial_j \{[\tilde{\mathbf{D}}(\mathbf{x}, t)]_{ij} F\}$$

Advettivo (Convettivo, Deriva)

Diffusione

STOCHASTIC DIFFERENTIAL EQUATION

Si definiscono SDE equazioni della tipologia:

Drift term

Diffusion term

$$\frac{dx(t)}{dt} = a(x,t) + b(x,t)\zeta(t)$$

Funzioni continue

Termine di rumore - Funzione a variazione

STOCHASTIC DIFFERENTIAL EQUATION

Formalismo di Itò

Drift term Diffusion term

$$dx(t) = a(x,t)dt + b(x,t)dW(t)$$

Processo di Wiener

W (t) representing the Wiener process; a time stationary stochastic Lévy process where the time increments have a Normal distribution with a mean of zero (i.e. a Gaussian distribution) and a variance of dt ; dW (t) = W (t + dt) − W (t) ∼ N (0, dt). In fact, the Wiener process can be understood as the integral of the stochastic Equation, i.e. in its differential form we have dW (t) = ζ (t)dt . See especially the introduction by Gardiner

STOCHASTIC DIFFERENTIAL EQUATION

In forma integrale

$$x(t) = x_0 + \int_0^t a(x, t')dt' + \int_0^t b(x, t')dW(t')$$

normal (Riemann or Lebesgue) integral

Itò-type stochastic integral.

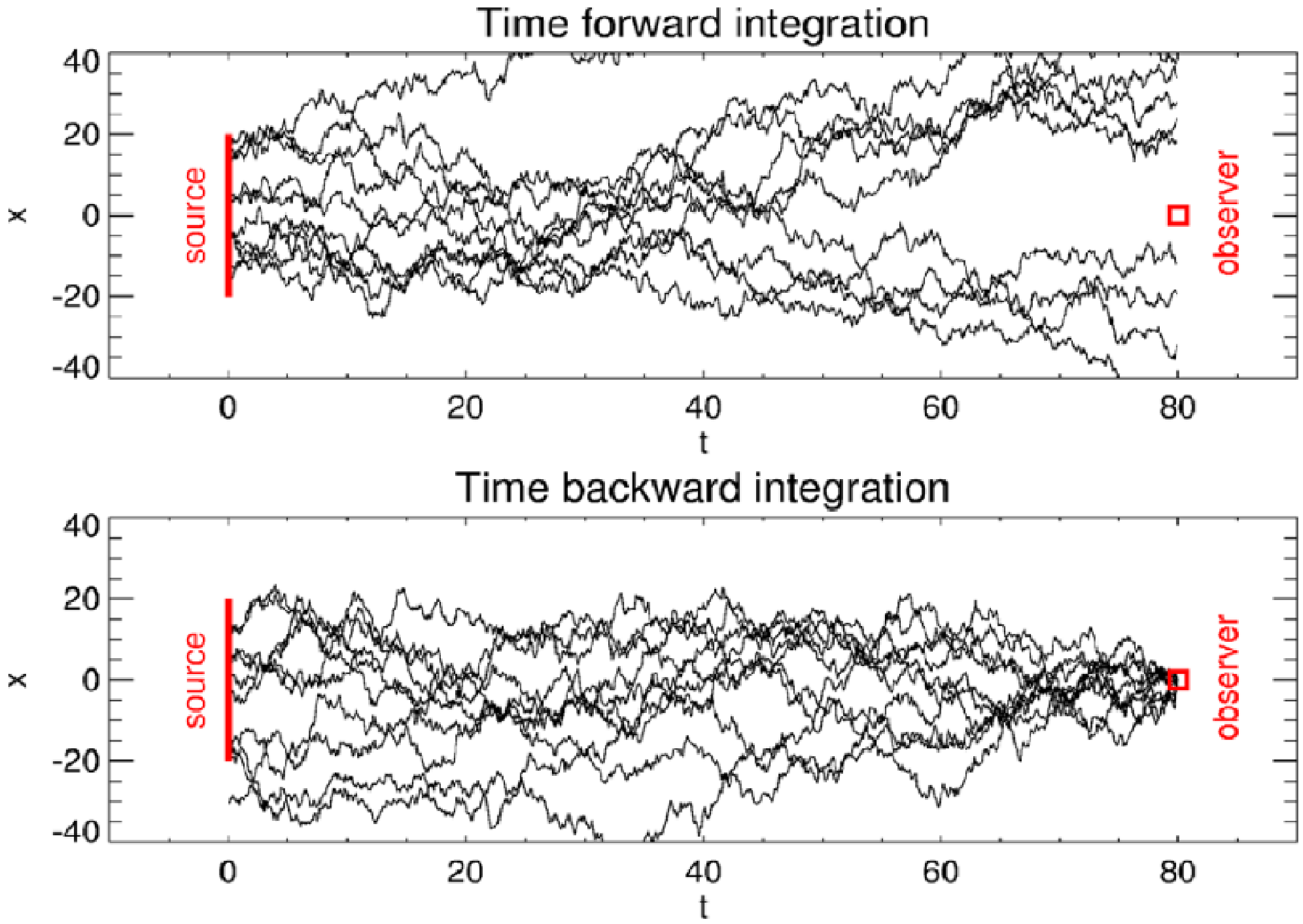
Non l'unico modo di calcolare l'integrale, ma certamente quello più facile da computare

Integrabile numericamente con uno schema Eulero - Maruyama

$$x(t+\Delta t) = x(t) + a(x,t)\Delta t + b(x,t)\Delta W(\Delta t)$$

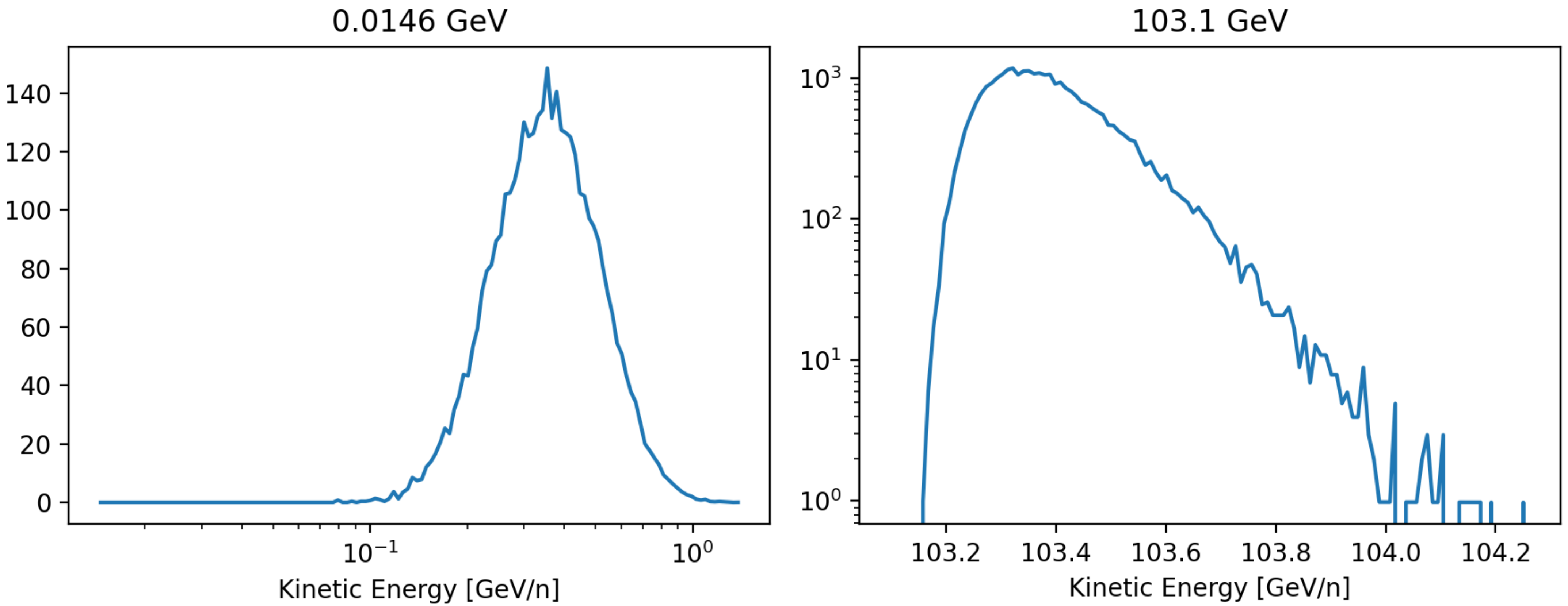
$$\Delta W(\Delta t) = \sqrt{\Delta t} \cdot \Lambda(t),$$

$\Lambda(t)$ is a simulated Gaussian distributed pseudo-random number (PRN).



Il sistema evolve Pseudo-particelle

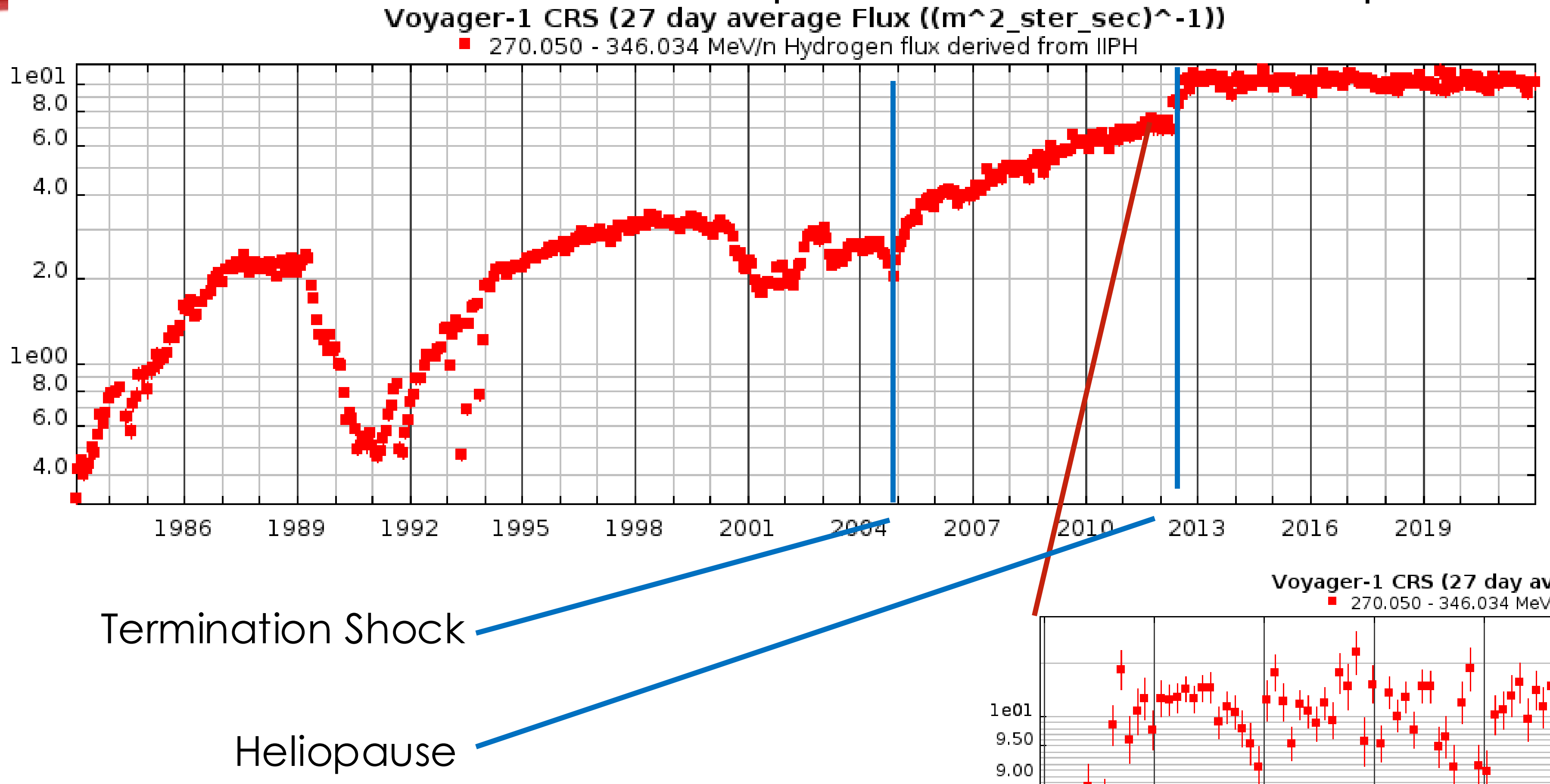
Evoluzione di un elemento della densità dello spazio delle fasi
L'integrazione di una singola pseudo-particela non è significativa.

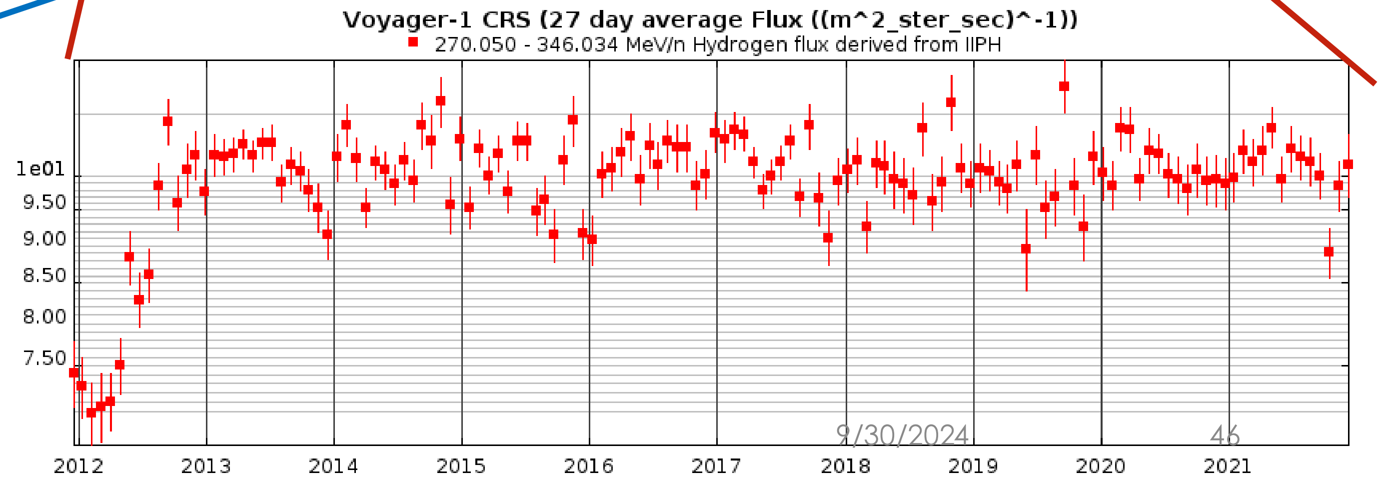


Occorre un gran numero di realizzazioni indipendenti al fine di avere una sorta di distribuzione di probabilità di trasmissione tra sorgente e osservatore (*quasi-funzioni di green*)

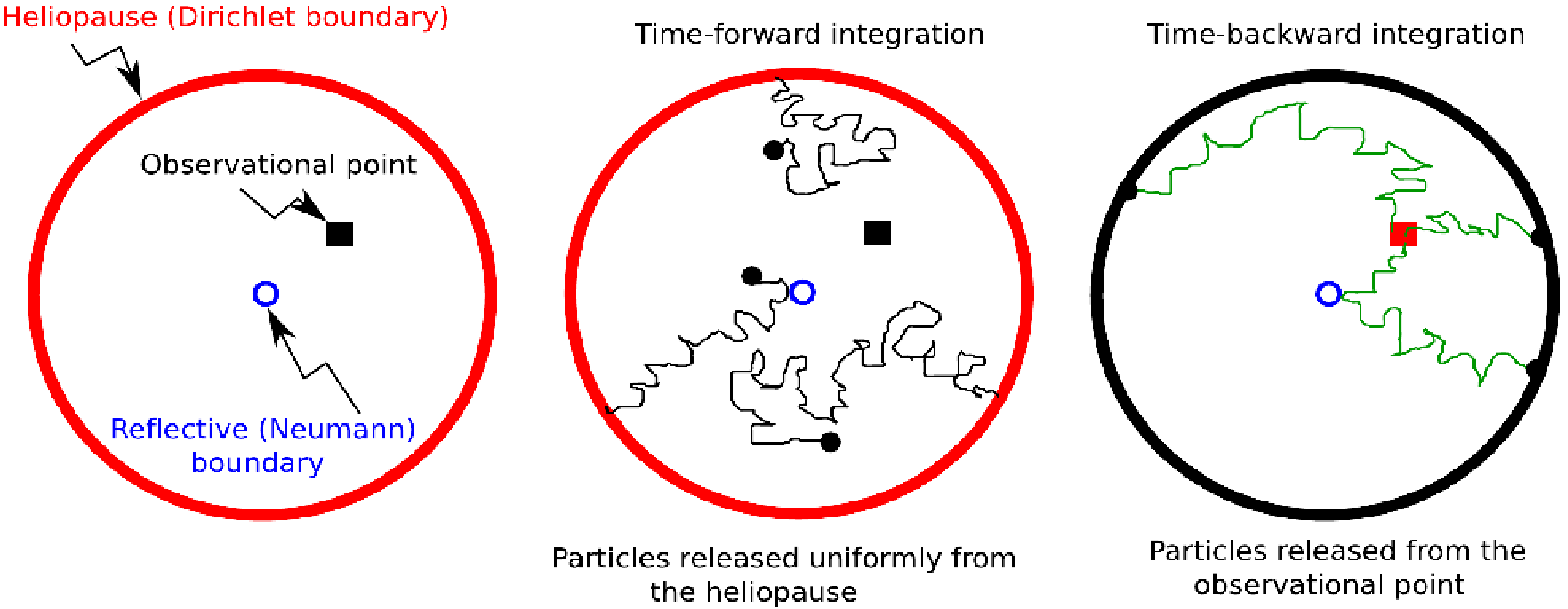
I CONFINI DEL MODELLO

Le Sonde Voyager sono le uniche sonde uscite dall'Eliosfera e hanno potuto confermare che oltre l'eliopausa NON si osserva più Modulazione Solare





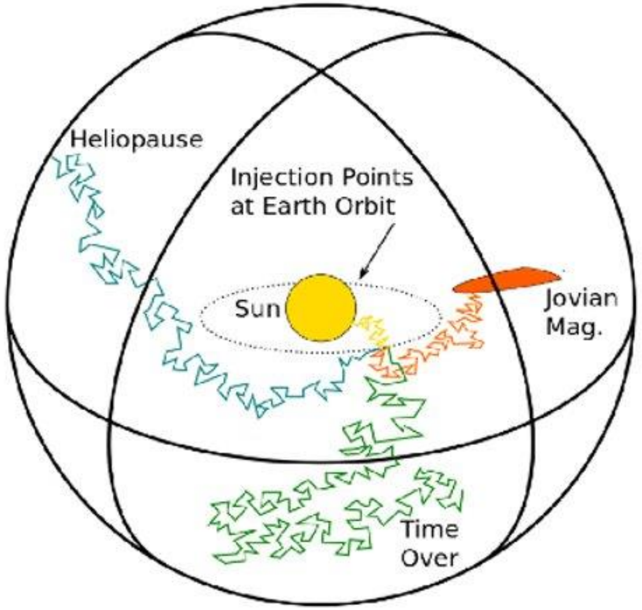
Se rivediamo il Metodo MC alla luce del nostro Caso Fisico (i.e. Trasporto dei raggi cosmici)



P. Dunzlaff et al. / Computer Physics Communications 192 (2015) 156–165

SDE n-dimensionale

$$dx_i = a_i(x_i, s)ds + \sum_{j=1}^{n} b_{ij}(x_i, s)dW_i(s)$$



Backward Kolmogorov equation - Fokker Plank Equation

$$-\frac{\partial \rho(x_i, s)}{\partial s} = \sum_{i=1}^{n} a_i(x_i, s)\frac{\partial \rho(x_i, s)}{\partial x_i} + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij}(x_i, s)\frac{\partial^2 \rho(x_i, s)}{\partial x_i \partial x_j}$$

Forward Kolmogorov equation - Fokker Plank Equation

$$\frac{\partial \rho(x_i, t)}{\partial t} = -\sum_{i=1}^{n} \frac{\partial}{\partial x_i}[\tilde{a}_i(x_i, t)\rho(x_i, t)] + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} \frac{\partial^2}{\partial x_i \partial x_j}[\tilde{C}_{ij}(x_i, t)\rho(x_i, t)].$$

$$\frac{\partial U}{\partial t} = -\nabla \cdot (U\vec{V}) + \nabla \cdot [K^S \cdot \nabla U] + \frac{(\nabla \cdot \vec{V}_{sw})}{3}\frac{\partial}{\partial T}(\alpha_{rel} TU)$$

$$\frac{\partial F}{\partial t} = \frac{1}{2}\sum_{i,j}[BB^\top]^{ij}\frac{\partial^2 F}{\partial x_i \partial x_j} + \sum_i A_B^i \frac{\partial F}{\partial x_i} + LF.$$

$$dx_i = A_B^i dt + \sum_j B^{ij} d\omega_j.$$

$$A_B^r = \frac{1}{r^2}\frac{\partial r^2 K_{rr}}{\partial r} + \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}(\sin\theta K_{\theta r}) + \frac{1}{r\sin\theta}\frac{\partial K_{\phi r}}{\partial\phi} - V_{sw} - V_{dr}$$

$$A_B^\theta = \frac{1}{r^2}\frac{\partial r K_{r\theta}}{\partial r} + \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}\left(\frac{K_{\theta\theta}\sin\theta}{r}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\phi}(K_{\phi\theta}) - \frac{V_{d\theta}}{r}$$

$$A_B^\phi = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\frac{rK_{r\phi}}{\sin\theta}\right) + \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}\left(\frac{K_{\theta\phi}}{r}\right) + \frac{1}{r^2\sin^2\theta}\frac{\partial}{\partial\phi}(K_{\phi\phi}) - \frac{V_{d\phi}}{r\sin\theta}$$

$$A_B^T = \frac{2}{3}\frac{\alpha T V_{sw}}{r}$$

$$BB^\top = \begin{bmatrix} 2K_{rr} & \frac{2K_{r\theta}}{r} & \frac{2K_{r\phi}}{r\sin\theta} \\ \frac{2K_{\theta r}}{r} & \frac{2K_{\theta\theta}}{r^2} & \frac{2K_{\theta\phi}}{r^2\sin\theta} \\ \frac{2K_{\phi r}}{r\sin\theta} & \frac{2K_{\phi\theta}}{r^2\sin\theta} & \frac{2K_{\phi\phi}}{r^2\sin^2\theta} \end{bmatrix}$$

$$L = \frac{2V_{sw}}{r}\left(\frac{1}{3}\frac{\partial\alpha T}{\partial T} - 1\right).$$

$$\Delta r = \left[\frac{1}{r^2}\frac{\partial r^2 K_{rr}}{\partial r} + \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}(K_{\theta r}\sin\theta)\right]\Delta t - [V_{SW} + v_{drift,r}]\Delta t + (2K_{rr})^{1/2}\omega_r\sqrt{\Delta t},$$

$$\Delta\theta = \left[\frac{1}{r^2}\frac{\partial r K_{r\theta}}{\partial r} + \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}\left(\frac{K_{\theta\theta}\sin\theta}{r}\right) - \frac{V_{drift,\theta}}{r}\right]\Delta t + \frac{2K_{r\theta}}{r\sqrt{2K_{rr}}}\omega_r\sqrt{\Delta t} + \left[\frac{2K_{\theta\theta}}{r^2} - \frac{2K_{r\theta}^2}{r^2 K_{rr}}\right]^{1/2}\omega_\theta\sqrt{\Delta t},$$

$$\Delta T = \frac{\alpha_{\rm rel} T V_{SW}}{3r}\Delta t,$$

$$L = \frac{2V_{sw}}{r}\left(\frac{1}{3}\frac{\partial\alpha_{\rm rel} T}{\partial T} - 1\right),$$

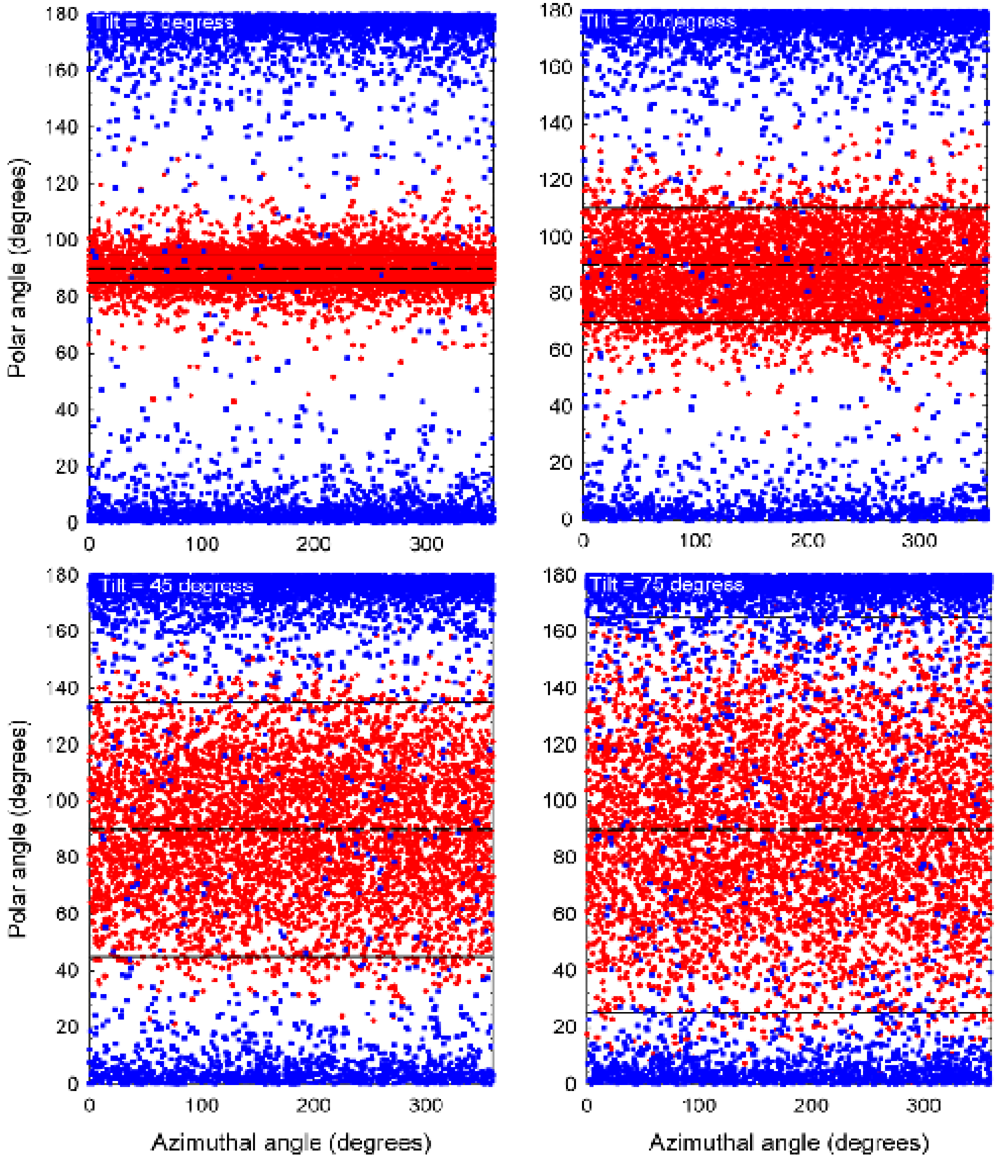
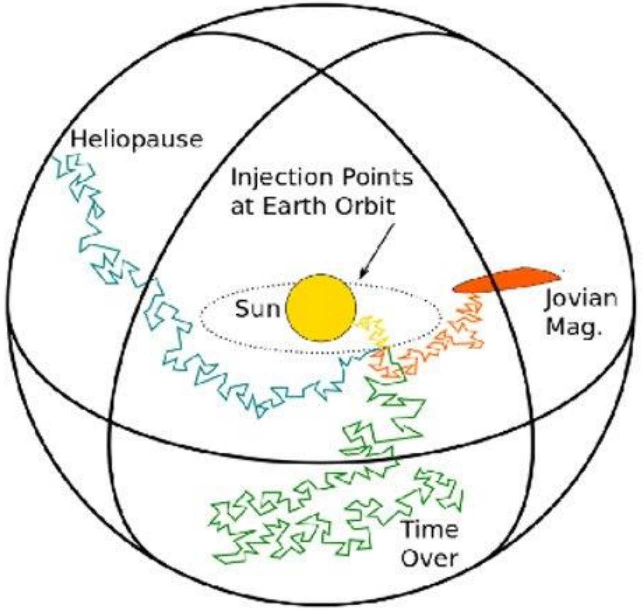


Fig. 7 Illustrating drift effects in the heliosphere by plotting the exit position of protons in the so-called $A > 0$ (*blue*) and $A < 0$ (*red*) drift cycles for various tilt angles. The *solid* and *dashed lines* show the latitudinal extend of the wavy HCS, with the different tilt angles indicated on each panel. The figure is taken from Strauss et al. (2012). With permission of Springer



Usando il Codice Monte Carlo per cercare gli "exit point"

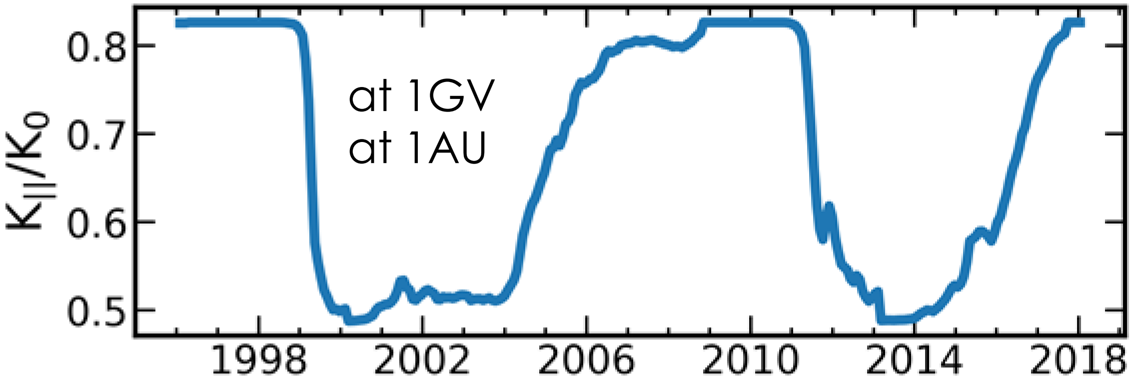
DIFFUSION TERM

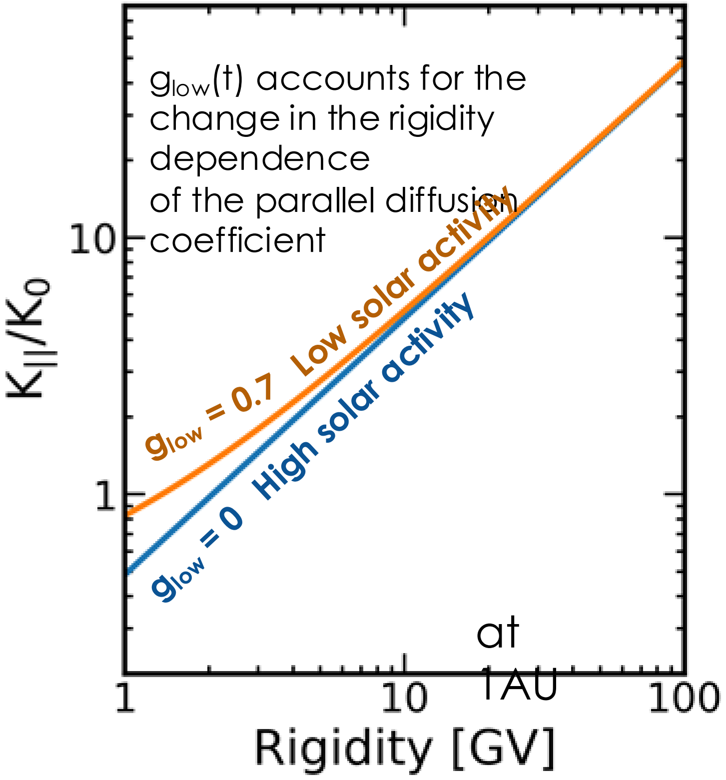
Parametrization of diffusion coefficients:

P is rigidity in GV

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

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



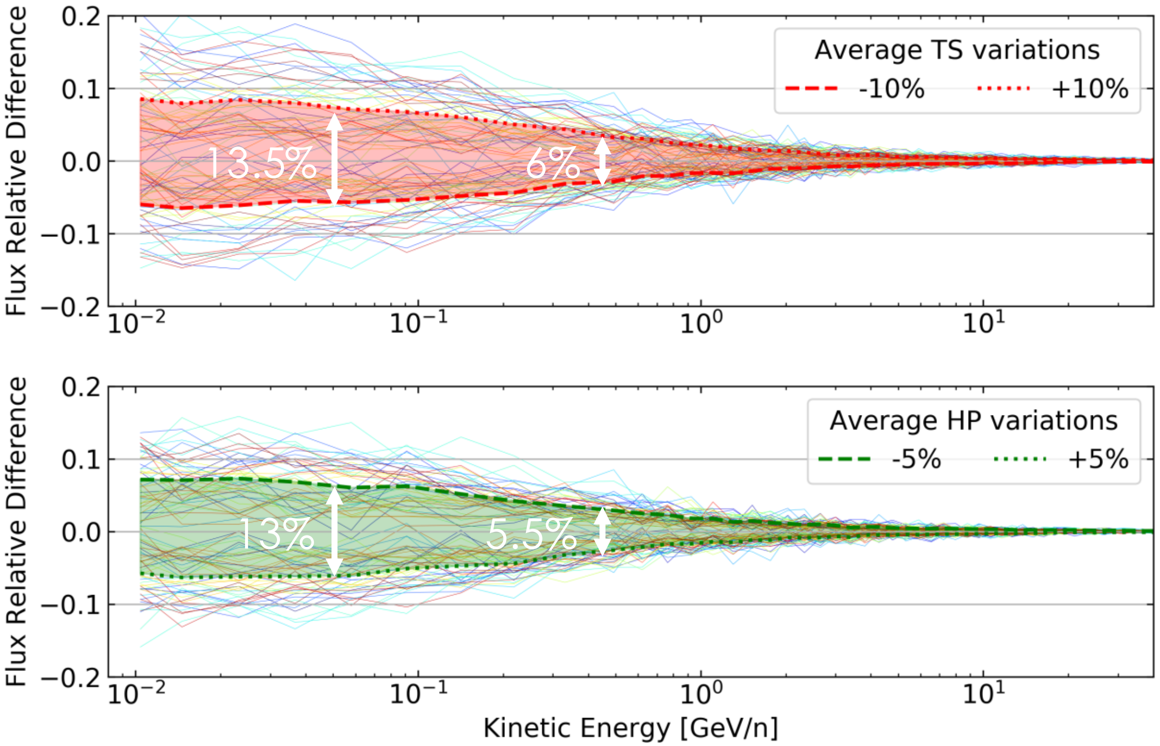


$K_0(t)$ is the diffusion parameter obtained using cosmic ray fluxes measured with neutron monitor at different latitudes.

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)

EFFECTS OF TS & HP TIME-VARIATIONS ON GCR MODULATION

www.helmod.org



The accurate prediction of the solar modulation of GCRs requires a time-dependent heliosphere structure

Some degeneracy with GCR transport properties

→ "A priori" knowledge of TS & HP time variation is needed.

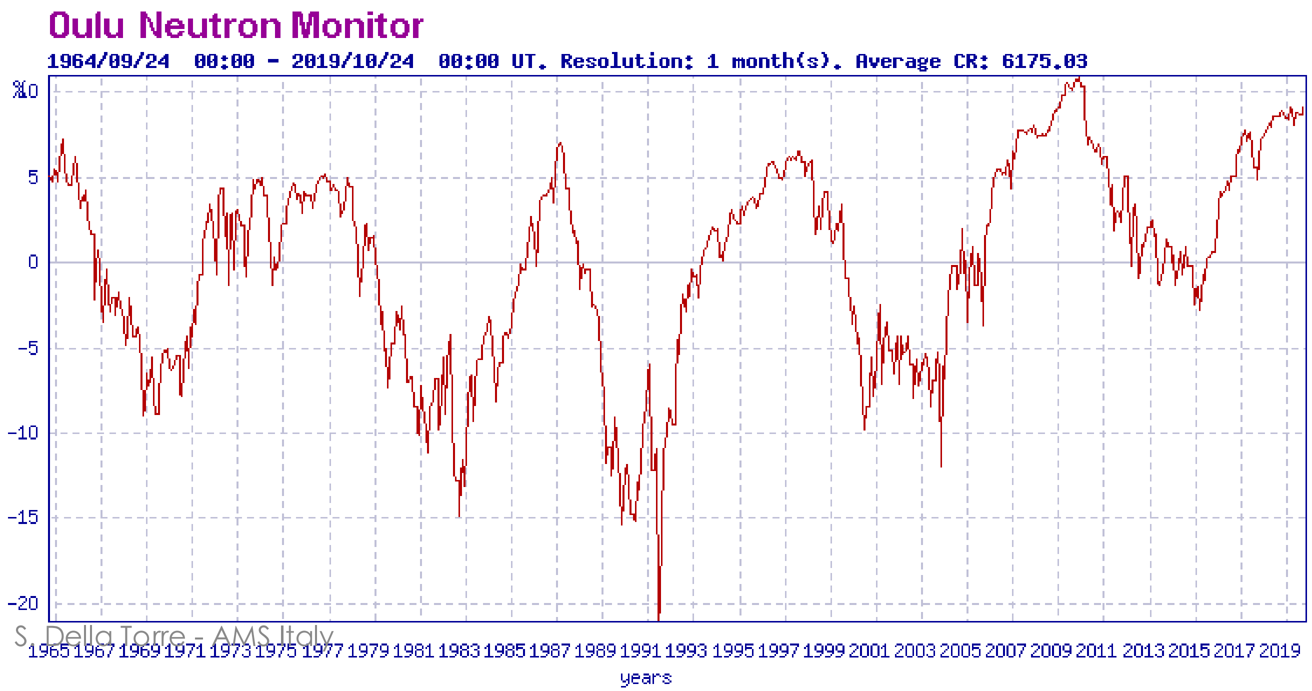
GCR solar modulation usually calculated on Carrington rotation time intervals:

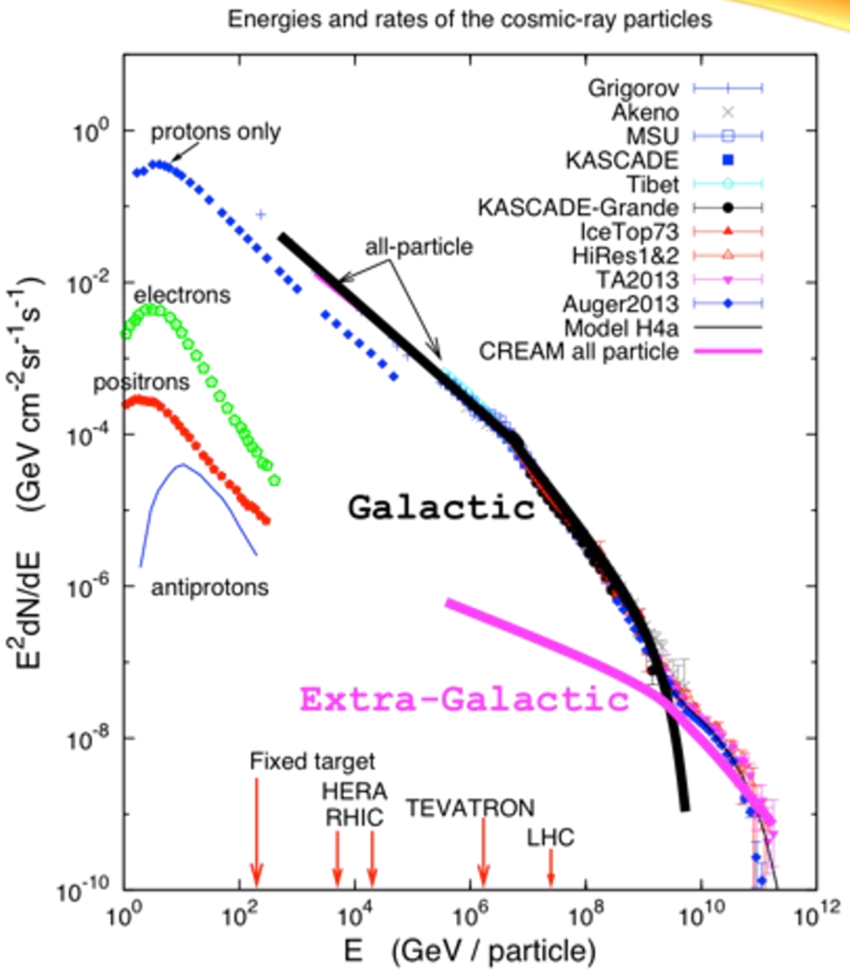
→ no large time resolution needed

- impact on the long-term variation of cosmic rays
- appreciable effects at energies ≤1 GeV/n

AFTER >100Y OBSERVATIONS

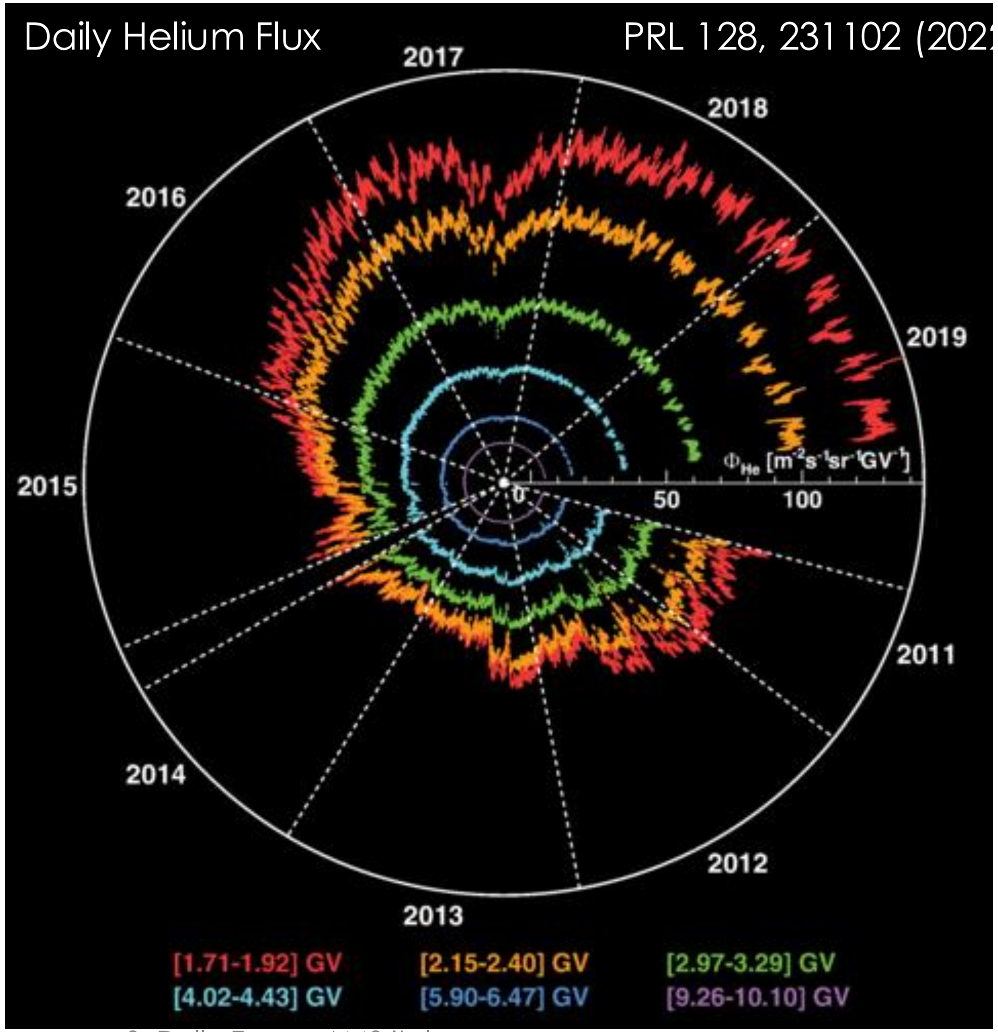
Nowadays we improved our knowledge on cosmic rays (CR) thank to a global network of observatory both on ground and on space





The intensity of CR varies with time with a cycle of 11y (22y considering solar polarity)

CR SOLAR MODULATION MEASUREMENTS



PAMELA, on space from 2006 to 2016, and AMS-02, on International Space Station (ISS) since 2011, represented a *game changer* in this field.

They provide the highest quality Cosmic ion measurements in the GV region.

They provide high quality CR spectra