TIME-DEPENDENT PROPAGATION TIMES AND ENERGY LOSSES OF PROTONS IN THE HELIOSPHERE:

A SOLAR MODULATION MODELLING IN LIGHT OF NEW COSMIC-RAY DATA FROM OBSERVATIONS

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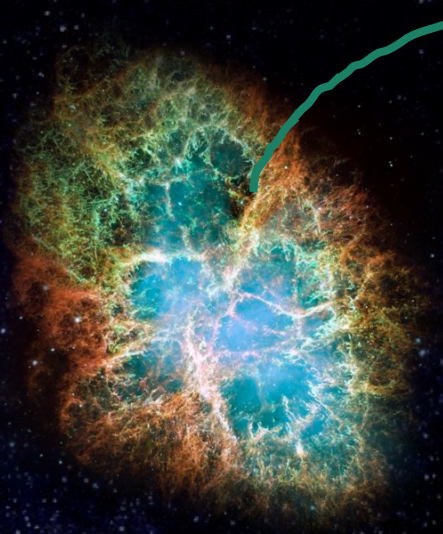
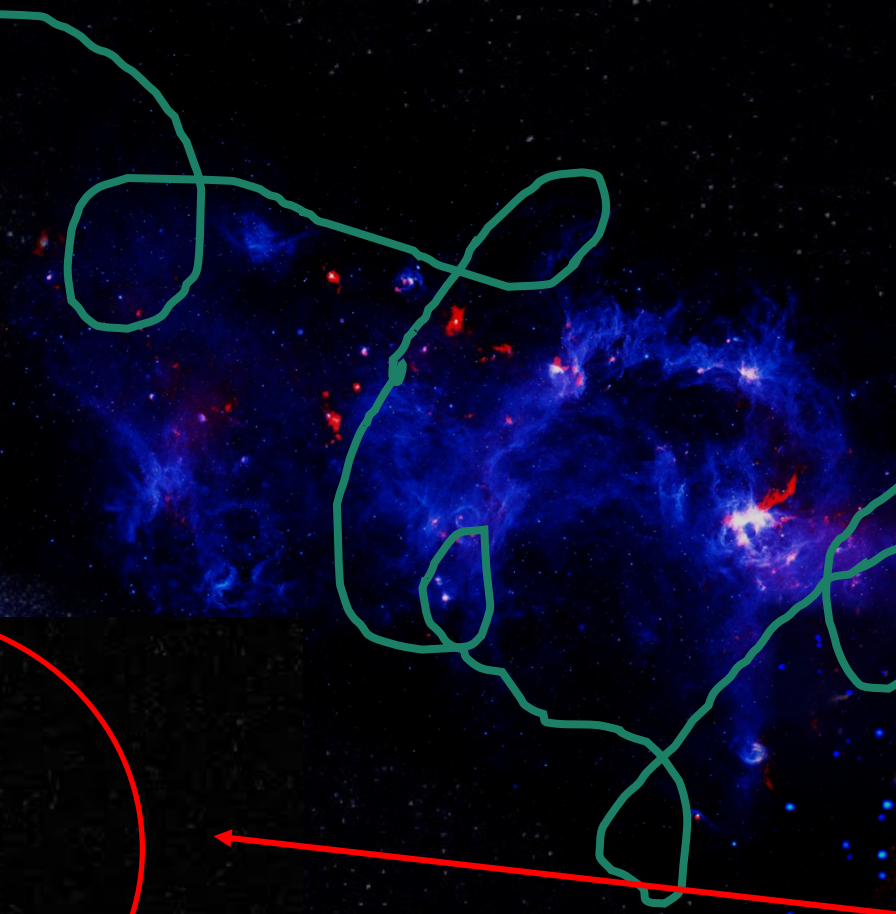
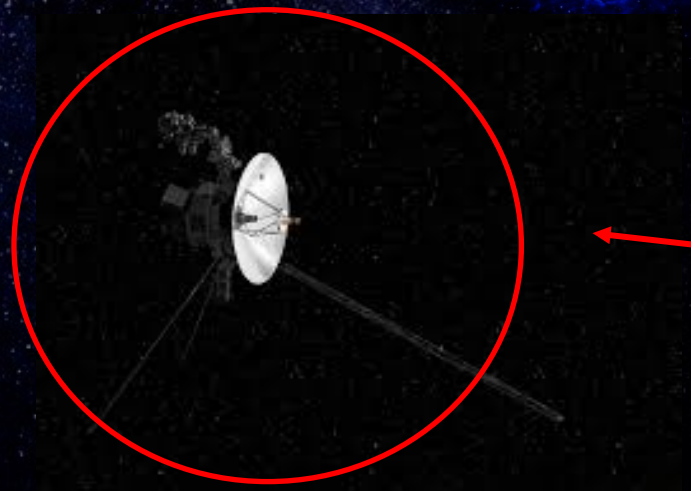
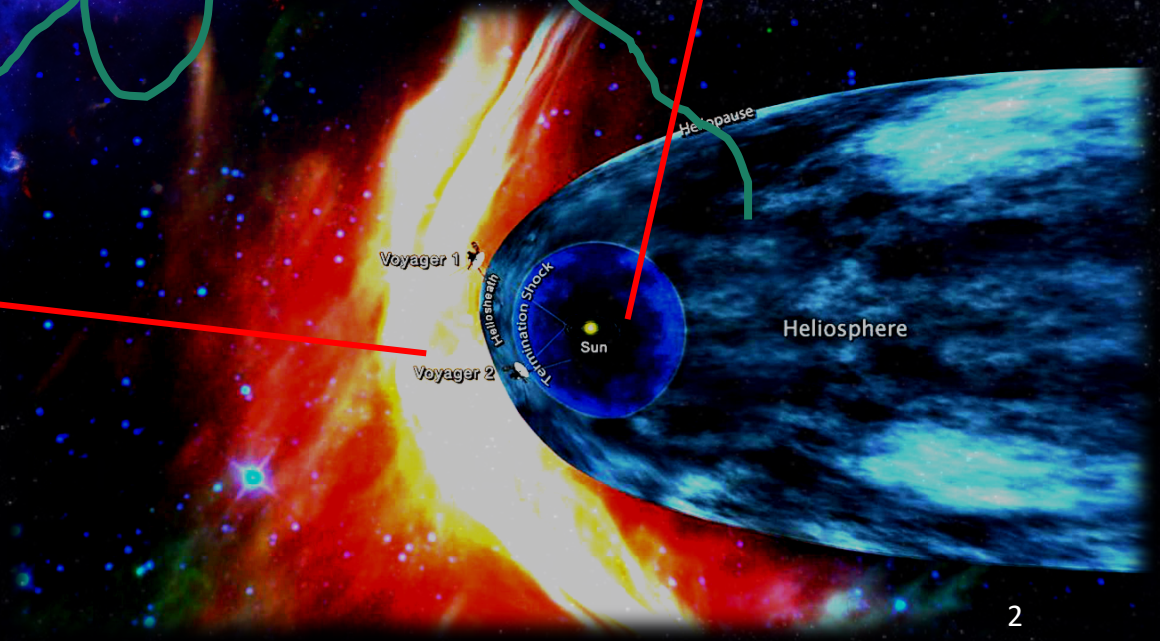
Galactic Cosmic Rays



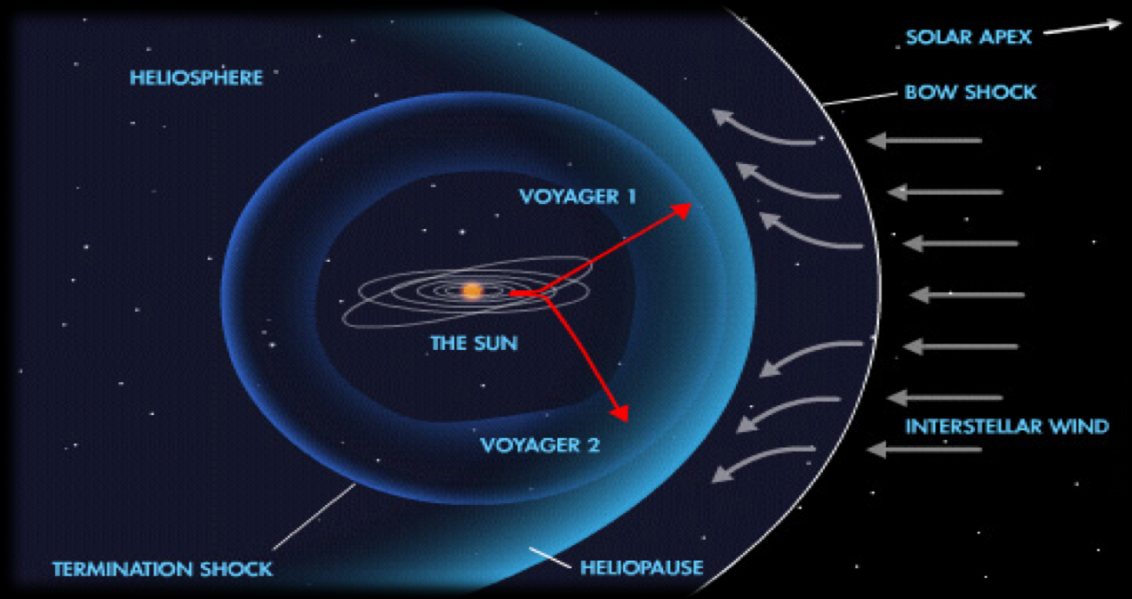






The galactic cosmic rays enter the heliosphere through a combination of diffusion (random walk) and drift

Solar Modulation



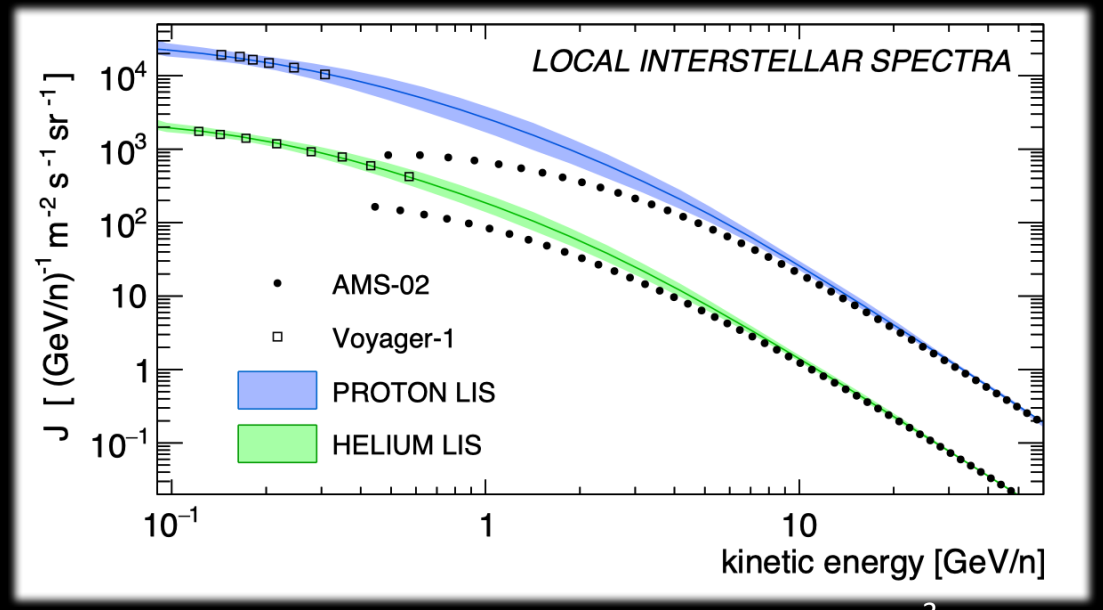
Main attributes:

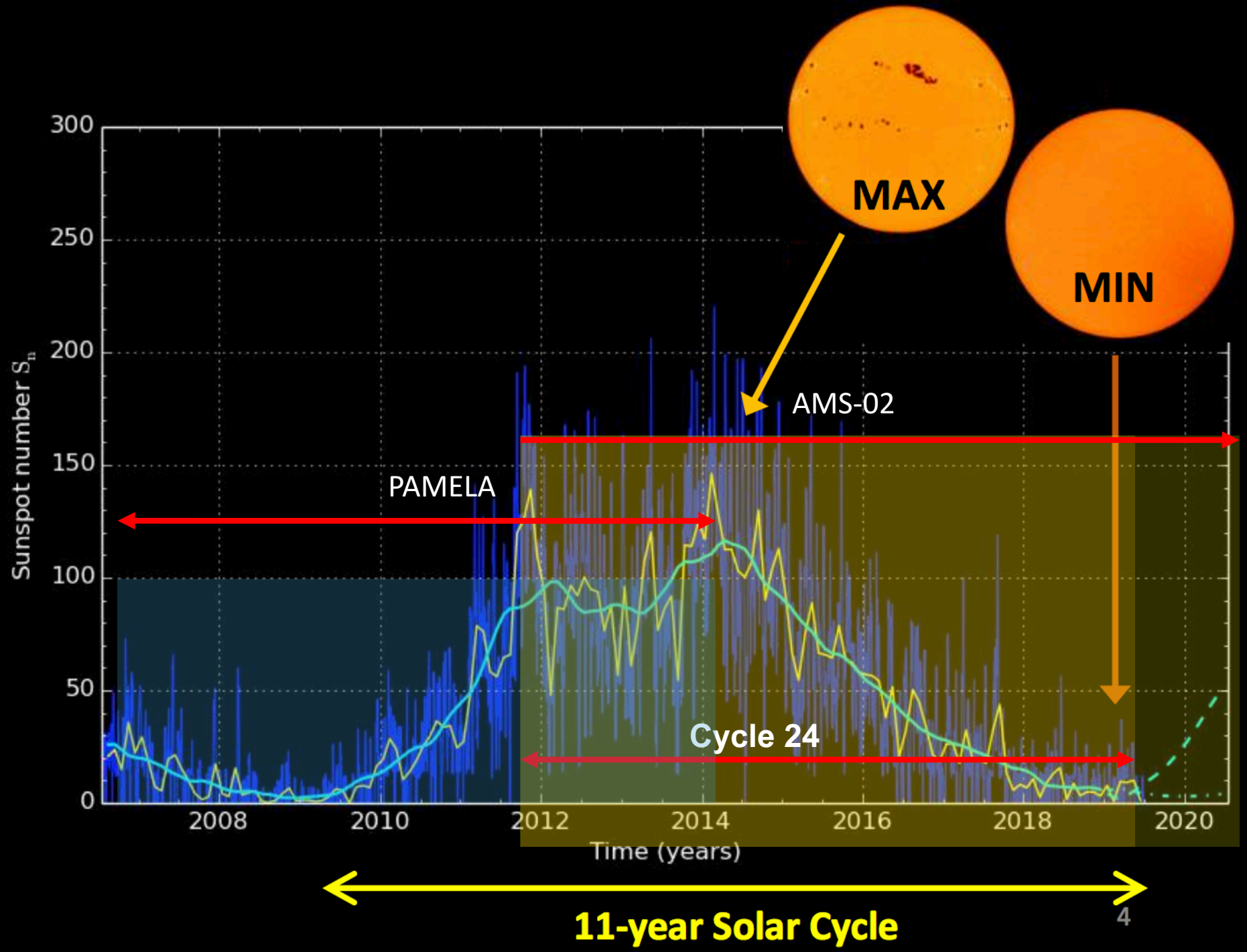
- Out-flowing Solar wind
- Frozen-in turbulent Magnetic Field
- Cyclic time-dependent activity

- This leads to significant global and temporal variations in their intensity and in their energy as a function of position inside the heliosphere.
- This process is identified as the **solar modulation** of cosmic rays .

The Golden Age:

Data from Interstellar medium taken by Voyager 1 & 2




MAX
MIN
AMS-02
PAMELA
Cycle 24
Sunspot number S_n
300
250
200
150
100
50
0
2008
2010
2012
2014
2016
2018
2020
Time (years)
11-year Solar Cycle

Propagation in the heliosphere

The Parker evolution equation for the cosmic ray density

Diffusion
Small-scale Magnetic field irregularities

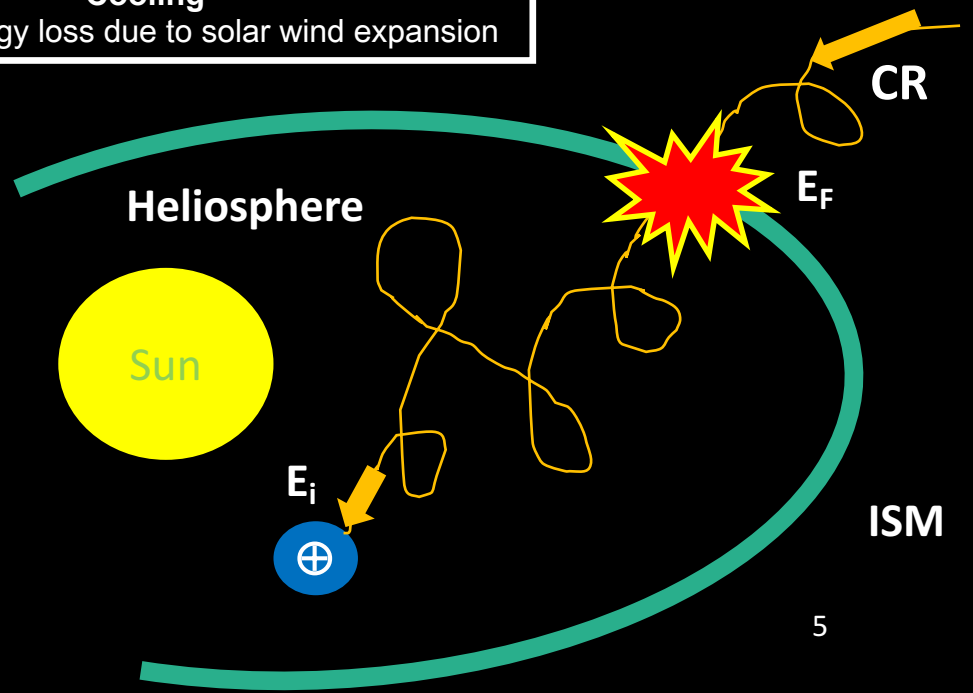
Drifts
Large-Scale B field, (gradients & curvature)

Sources
Galactic CRs from interstellar space

$$\frac{\partial f}{\partial t} = \nabla.[K.\nabla f] - V.\nabla f - < vD >.\nabla f + \frac{1}{3}(\nabla.V)\ \frac{\partial f}{\partial \ln p} + Q(r,p,t)$$

Convection
Solar wind moving out from the Sun

Cooling
Adiabatic energy loss due to solar wind expansion

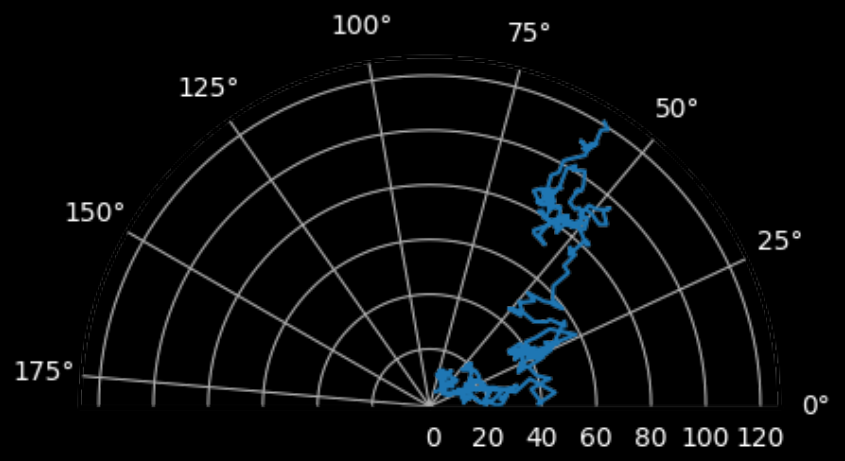


- **Numerical integration with ∂/∂t=0 solves the Stochastic Differential Equation approach with a backward time integration based on SOLARPROP. [Kappl, Comp. Phys. Comm. 207 (2016) 386–399]**

Propagation Model

The calculations

- *Parker equation for the cosmic ray (CR) density in the heliosphere*
- *Stochastic method: Monte-Carlo simulation of CR trajectories*
- *Grid scan over free parameters and statistical data analysis*



Example: 1 GeV proton trajectory

Key data

- *Voyager-1: the CR proton flux outside the heliosphere (LIS)*
- *AMS-02: monthly variations of the CR proton fluxes since 2011*
- *PAMELA: monthly variations of the CR proton fluxes since 2006*

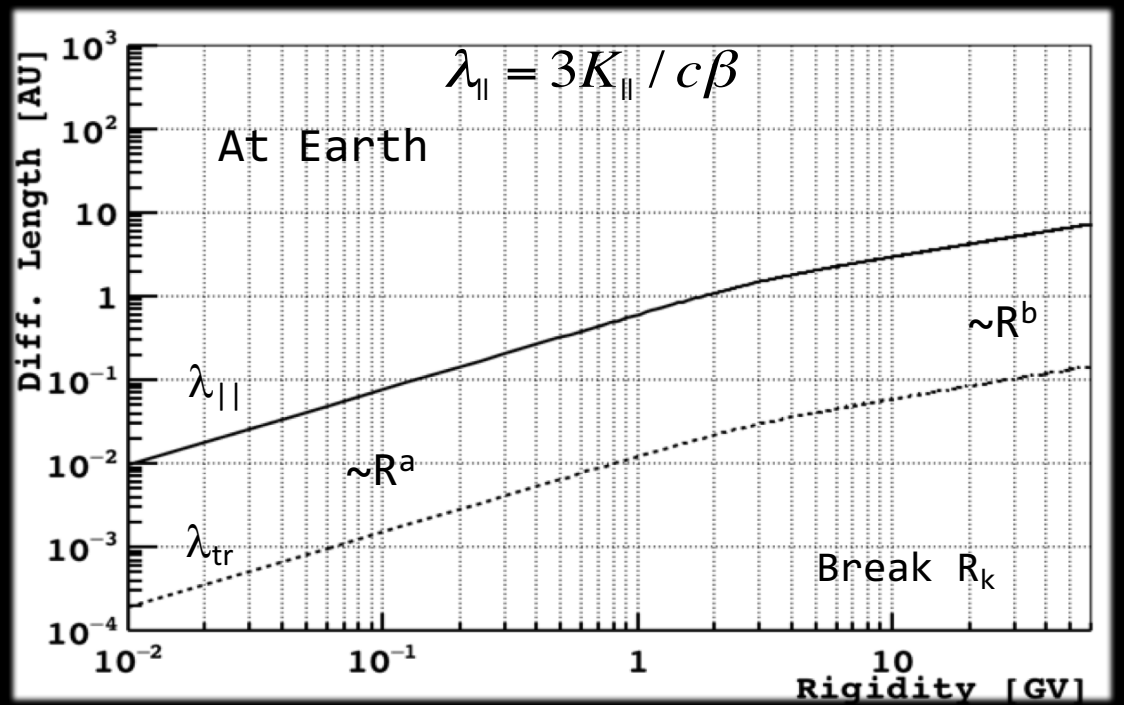
Key ingredients

1. Rigidity- and time-dependent diffusion: K(R, t)

$$K(R,t) = \begin{cases} K_0(t) R_k^{a(t)} & (R_k < 3GV) \\ K_0(t) R_k^{b(t)} & (R_k > 3GV) \end{cases}$$

2. Improved 2D description of the heliosphere

3. Time-dependent B-field, current sheet, solar wind



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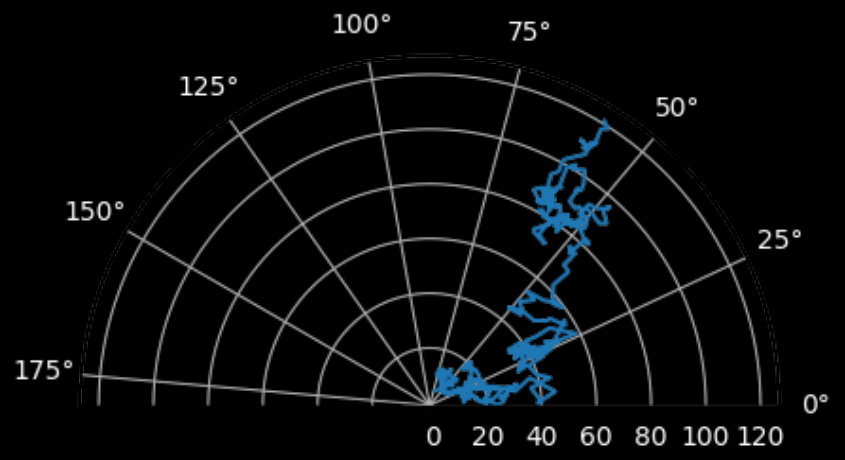


Example: 1 GeV proton trajectory

The model has 6 parameters:

1. Tilt Angle $\alpha_T(t)$,
2. HMF at Earth $B_0(t)$,
3. Polarity of the HMF A(t),

Fix the HS status at a given epoch

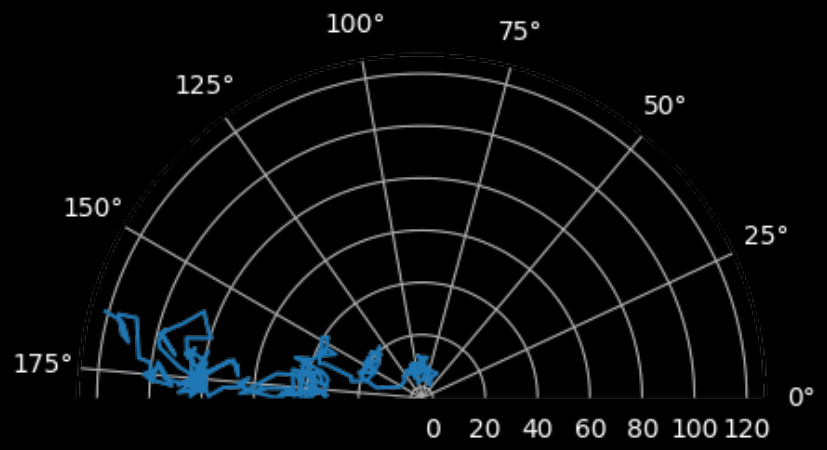
4. Diffusion coefficient normalization $K_o(t)$,
5. Diffusion spectral indices, *a(t)* and *b(t)*, and R_k respectively
6. The break was fixed at R_k = 3 GV

Fit the data

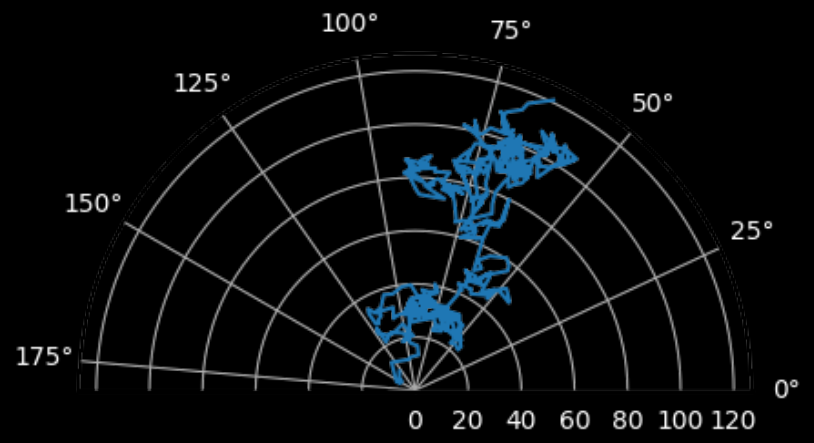
Propagation Model

Key results

- ✓ ***Data-driven determination of the key diffusion parameters as function of time***
- ✓ ***Relations between the CR diffusion parameters and solar activity indices***
- ✓ ***Inter-relations among the CR parameters***

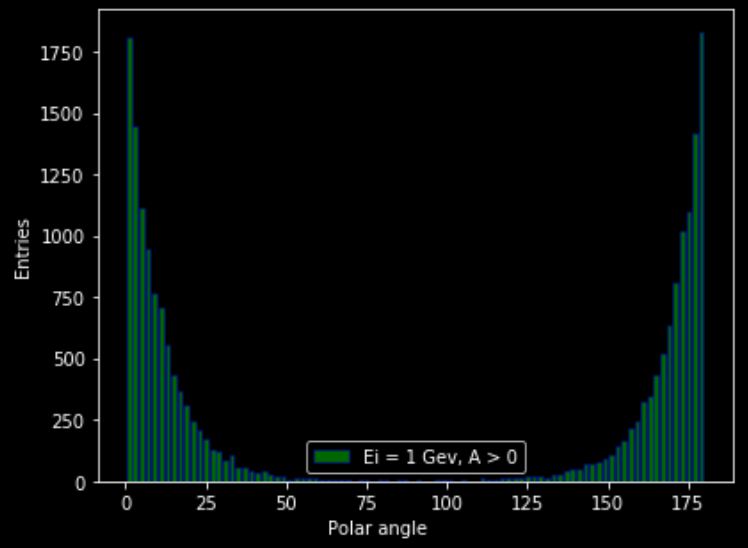


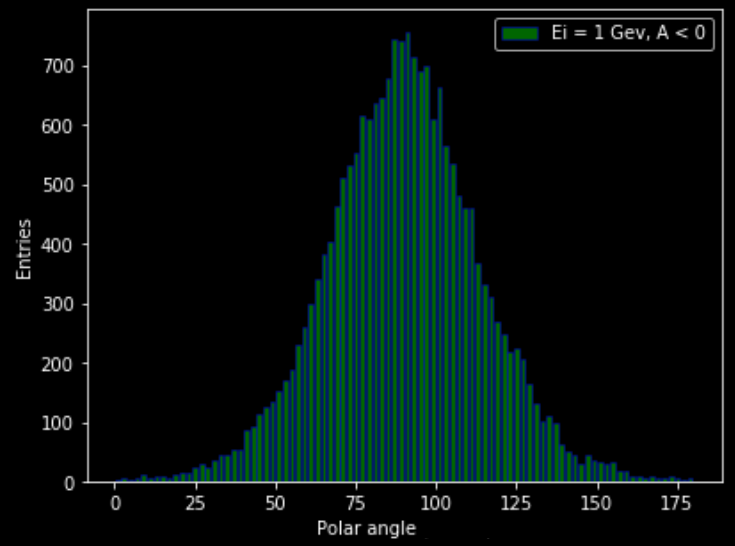
A > 0



A < 0

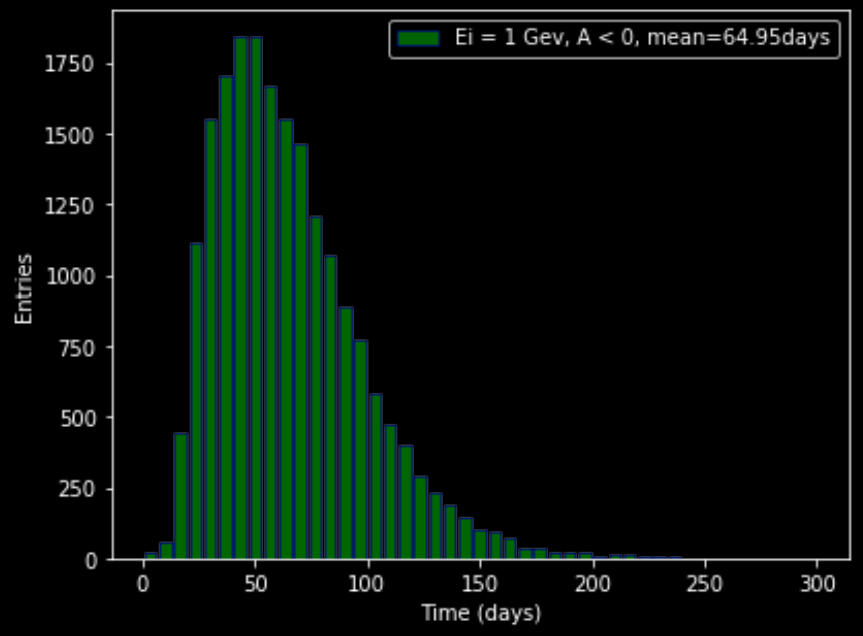
Proton trajectories in different polarities

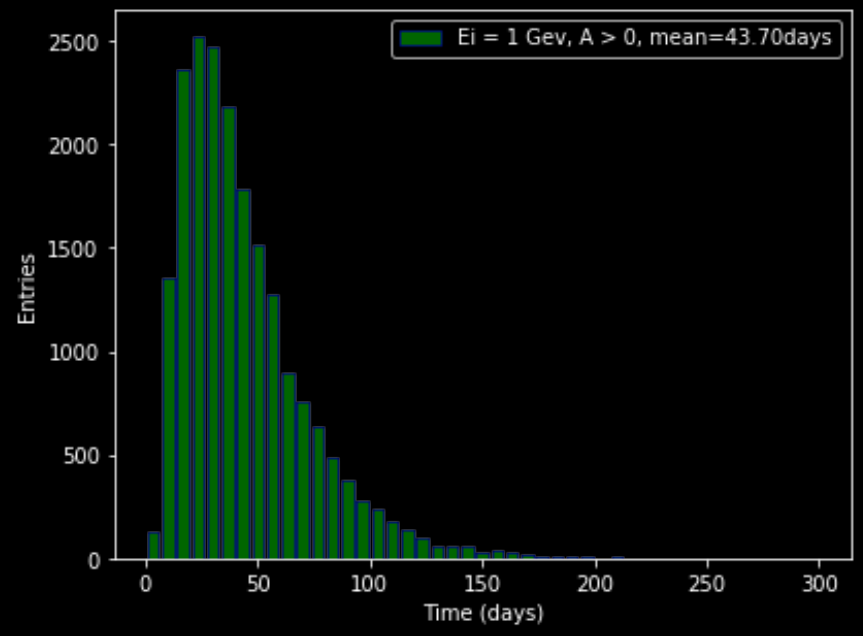


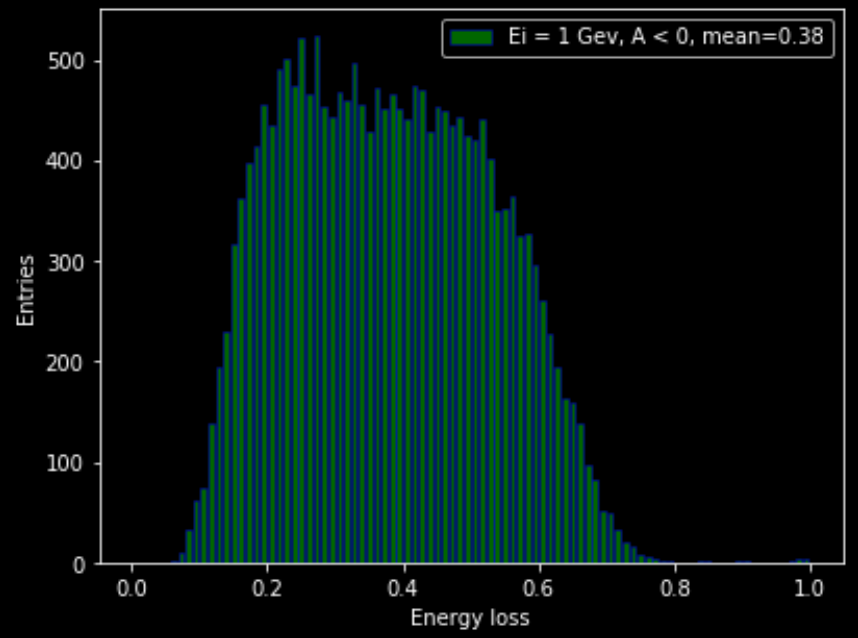


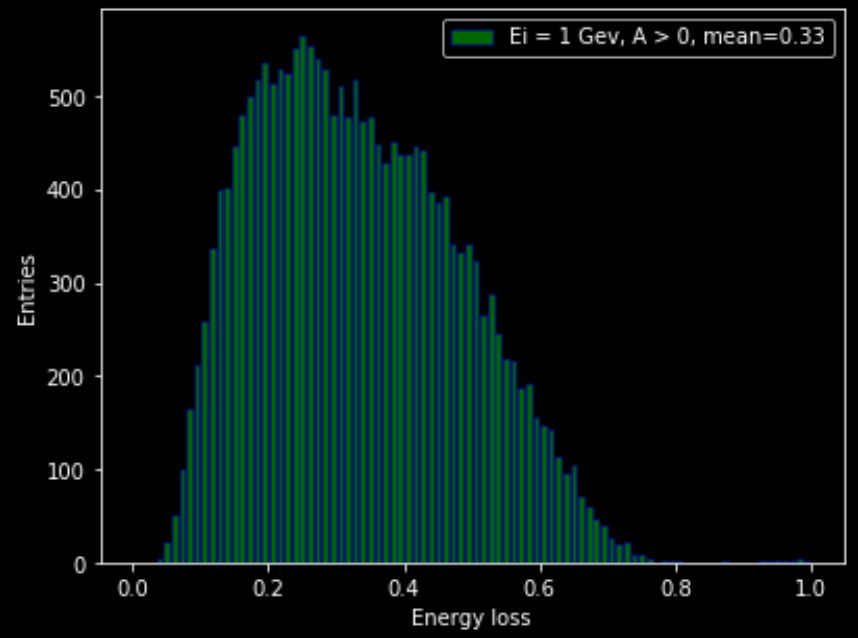
In the A > 0 drift cycle, GCR protons generally drift from the polar regions to reach Earth, whereas, in the A < 0 cycle, they mainly drift along the Heliospheric Current Sheet

Propagation Model









Binned Propagation time

This is consistent with general drift considerations: For the A < 0 cycle, the protons that reach Earth have to drift inward along the heliospheric current sheet (HCS), taking a much longer time to reach Earth than protons which simply drift toward Earth from the polar regions in the A > 0 cycle.

Binned Energy Loss

E_F= At the boundary

E_i= Near the Earth

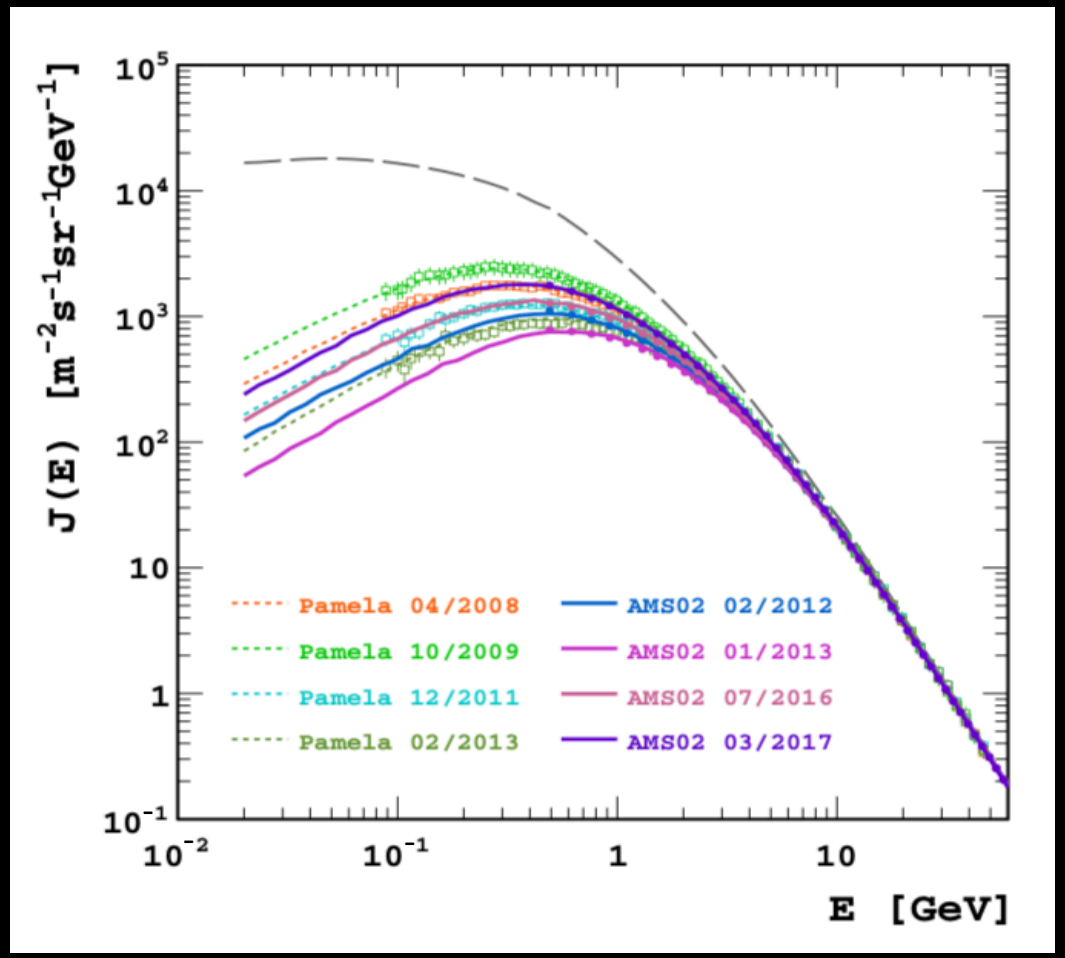
Energy Loss= $\frac{E_F - Ei}{E_F}$

Results: Application to AMS and PAMELA

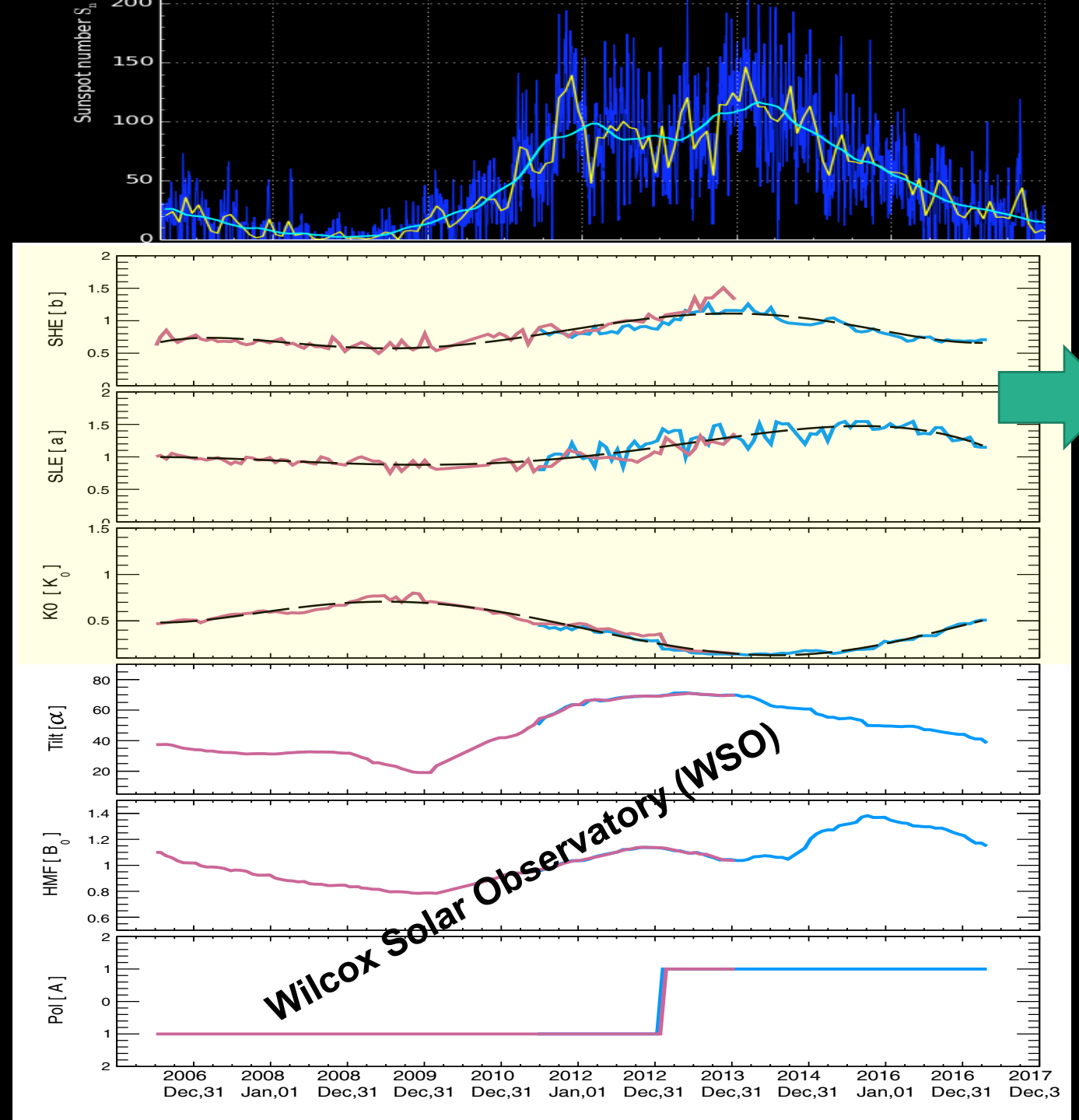
The new precise data from AMS02 and PAMELA experiments offer a unique possibility to study the solar modulation over a long period of time

The model was applied to:

- **Bartel-rotation averaged Pamela data sets from 2006/6 to 1/2014 [ApJ 742 (2011) 10, ApJ 765 (2013) 91]**
- **Bartel-rotation averaged AMS02 data sets from 2011/7 to 2017/6 [PRL 121 (2018) 0511**



Fiandrini et al. 2021
Phys.Rev. D. 104, 023012



Results: Application to AMS and PAMELA

A set of modulated proton fluxes were produced over the points of a discrete 6-D grid of model parameters:

- α (5°, 75°) with step 5°
- B_0 (0.7, 1.5) in units of 5 nT with step 0.1
- Polarity A = 1 and -1
- K_0 (0.1, 0.9) with step 0.1 in units of 1.678 x 10^{23} cm^2s^{-1}
- *a* (0.45, 1.4) with step 0.05
- *b* (0.45, 1.65) with step 0.05

Total of 1.215×10^6 models fluxes $J_m(E,q)$ with 2×10^3 pseudo-particles for each of the 60 energy bins from 20 MeV to 200 GeV with log step, one for each of the parameters vector q (a, B_0, A, K_0, a, b)

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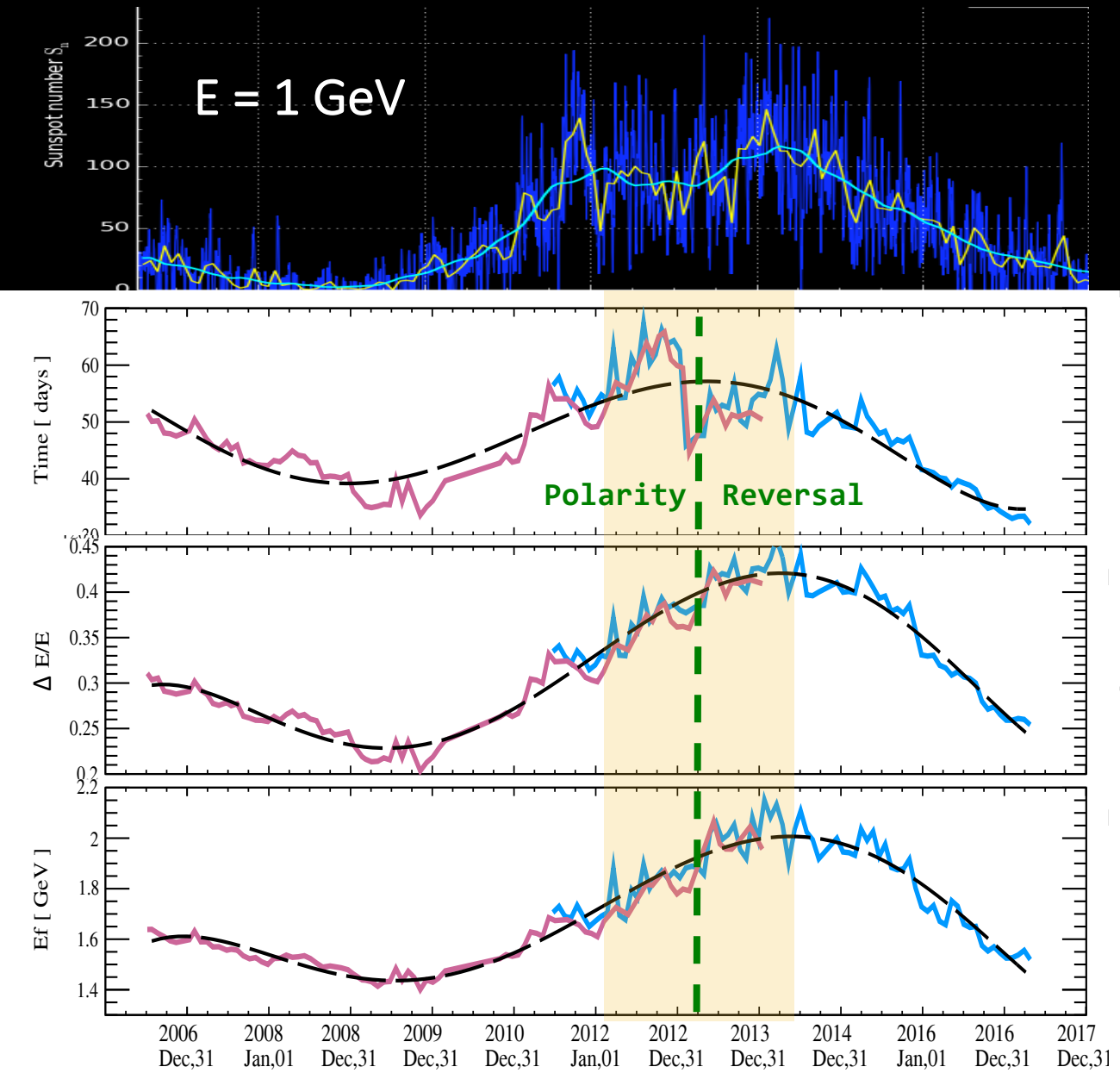
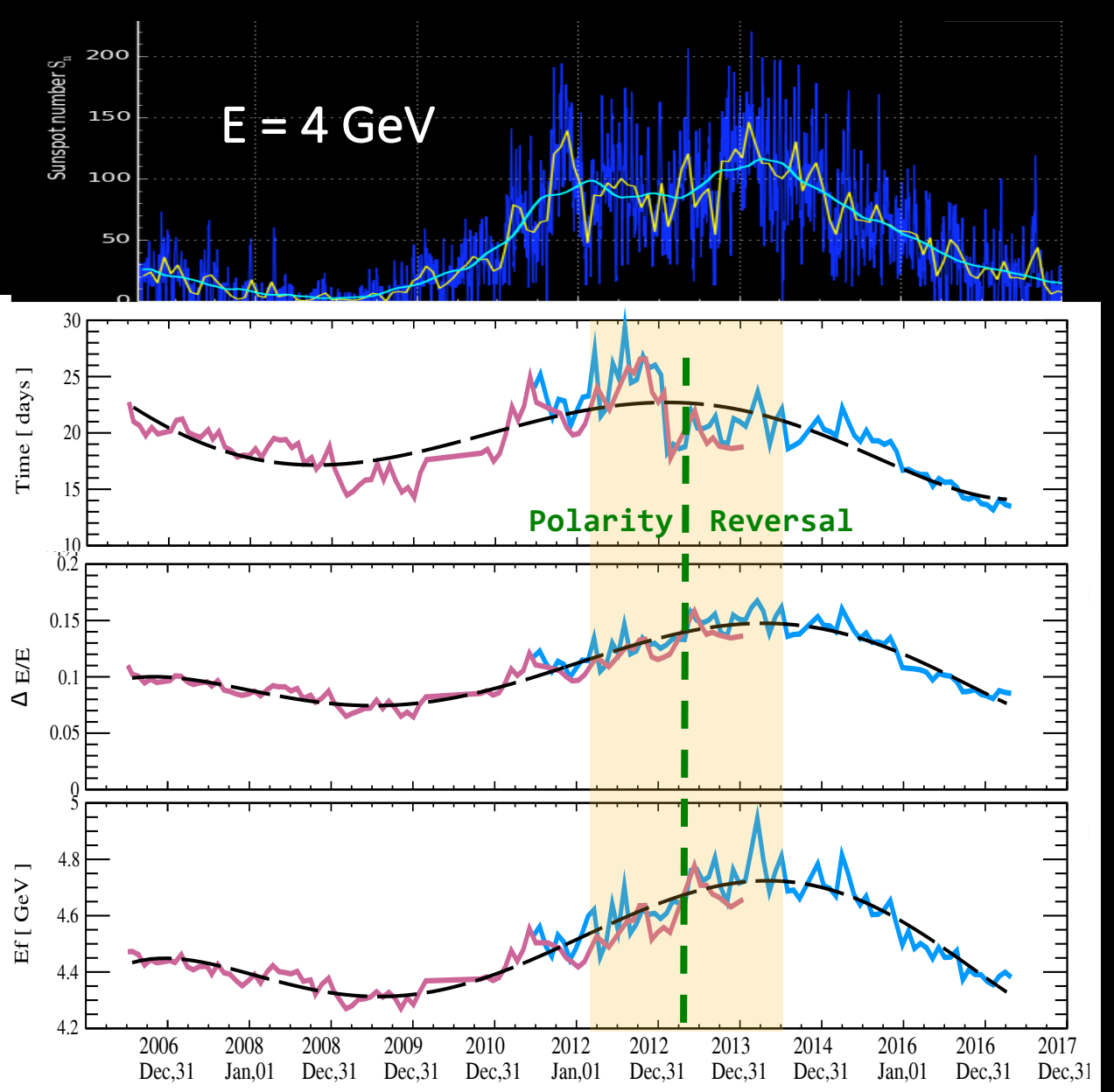
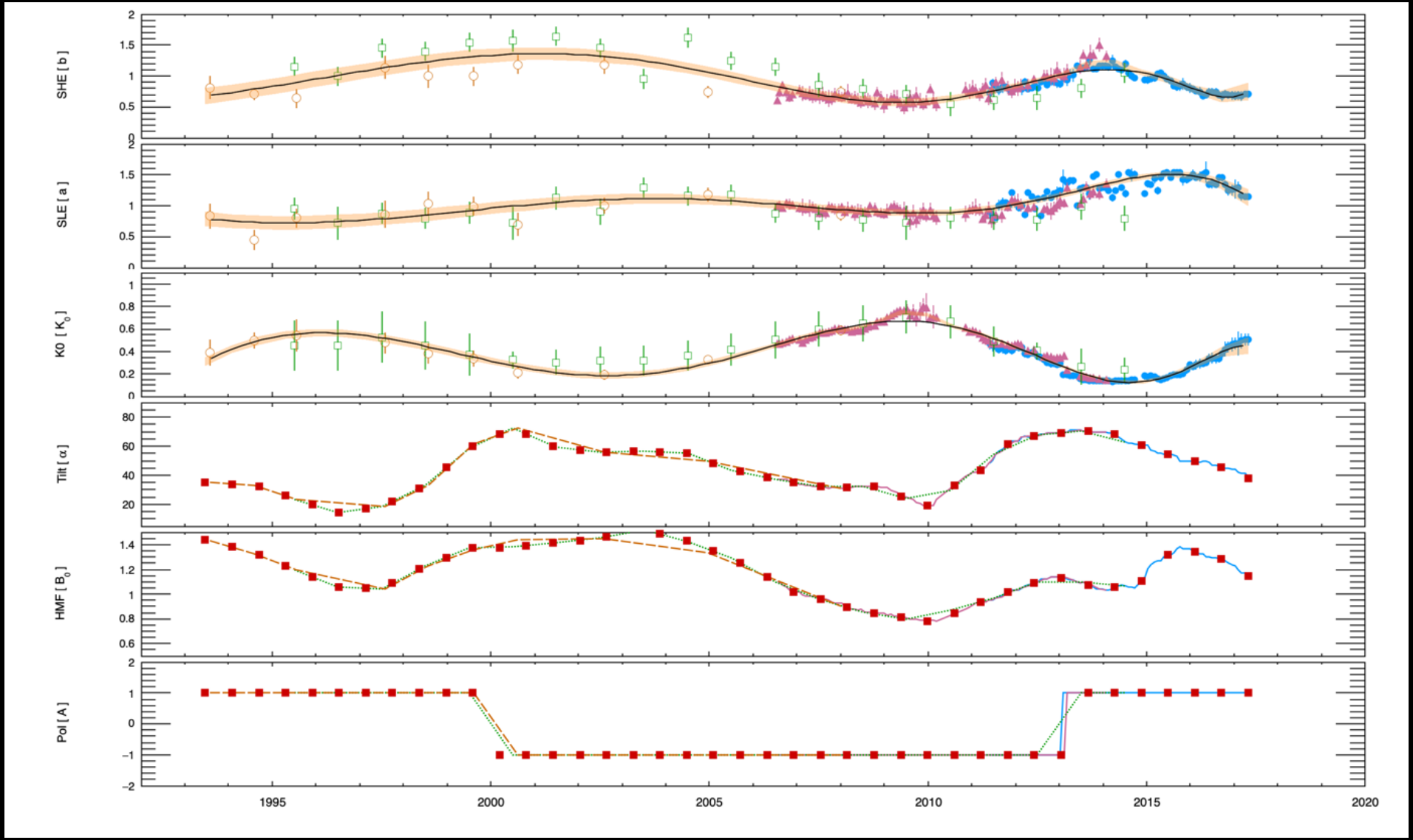
Results: Application to AMS and PAMELA





Applying the model for Bess, SOHO/EPHIN, PAMELA, and AMS-02



By N. Tomassetti

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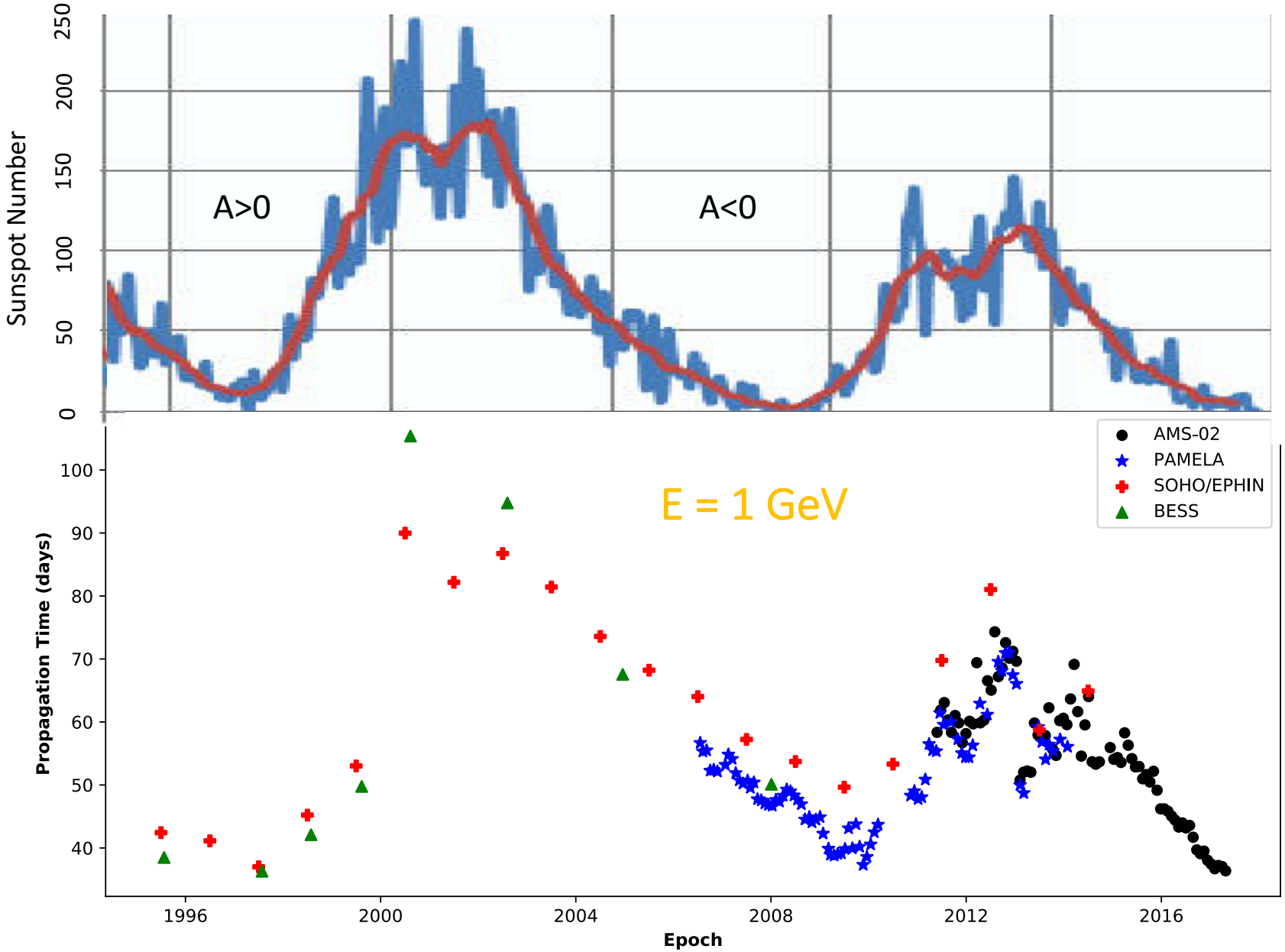

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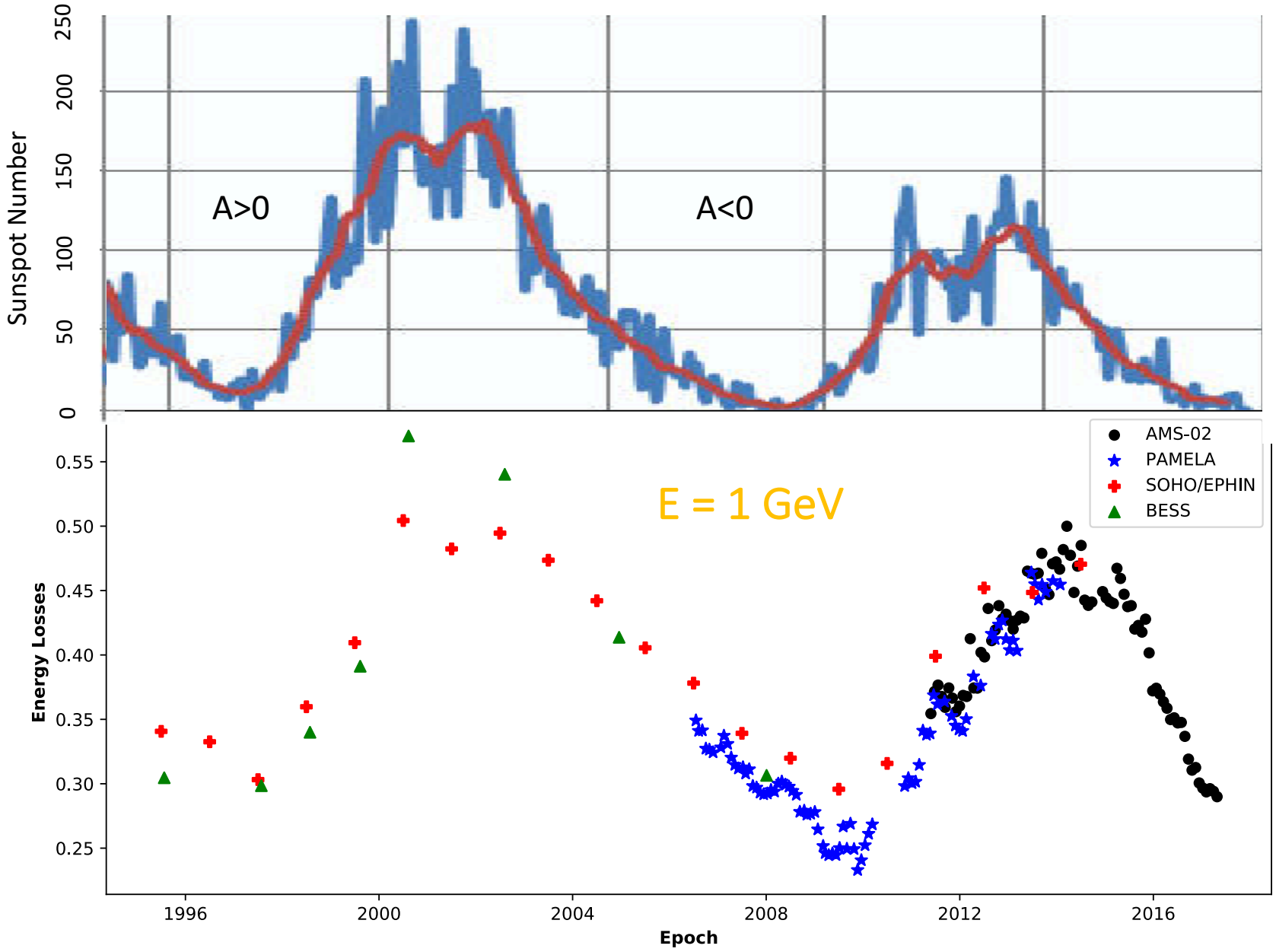
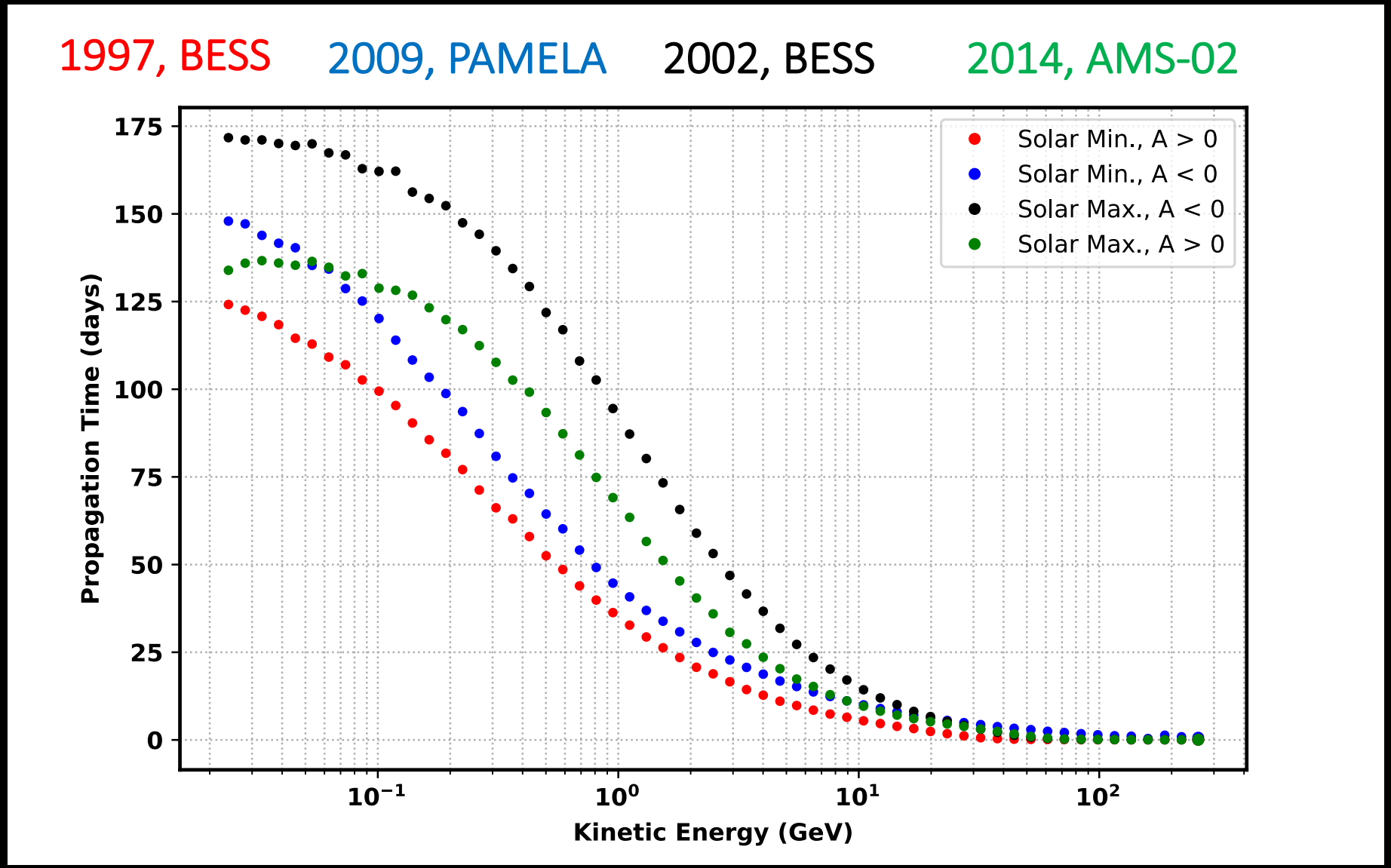
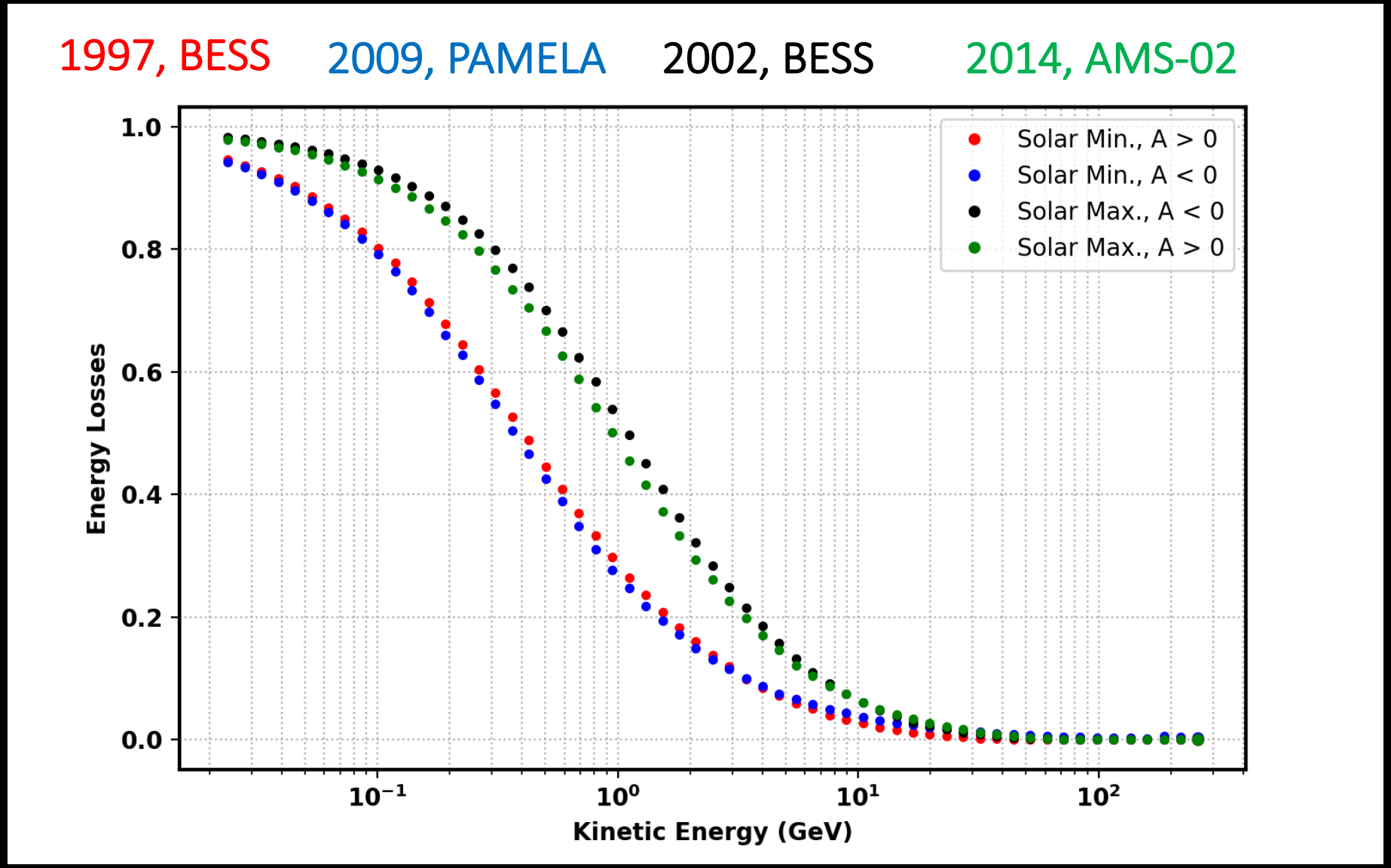


Results: Energy at Earth- Propagation Time



Results: Energy at Earth- Energy Losses



Conclusions

- We use a stochastic model where we simulate particle trajectories.

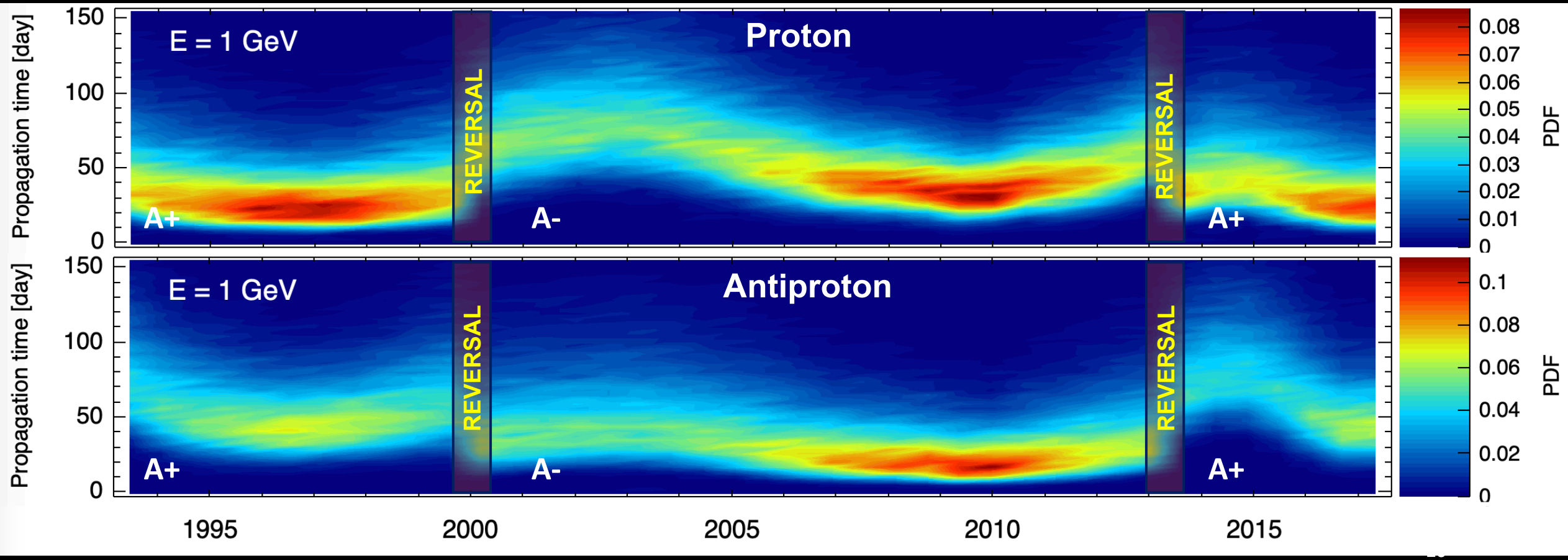
- The model (the parameters of CR diffusion) is tuned to the observational time dependent CR fluxes: AMS-02, PAMELA, BESS, and SOHO/EPHIN, covering solar cycles

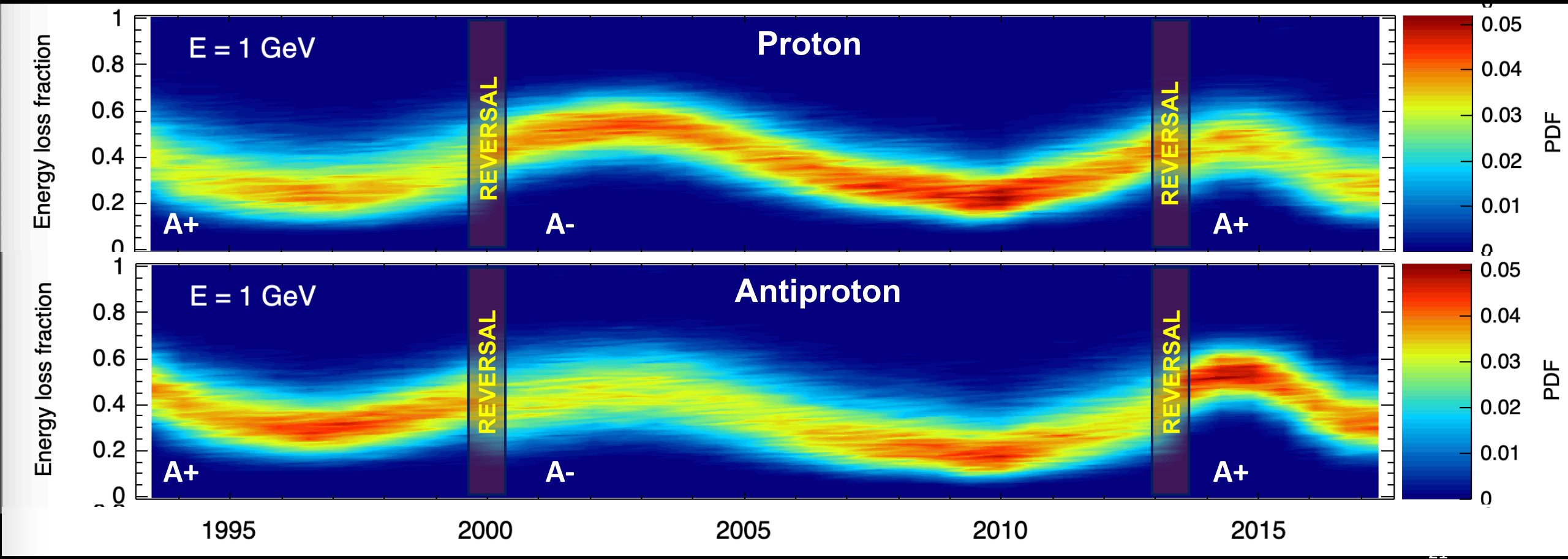
- Other physical inputs of the model are taken from direct observations of the Sun (WSO: tilt, B-field intensity, polarity)

- We are looking at particle trajectories, propagation times of CRs, and their energy losses, using our model that is global tuned over a large time interval

- The evolution of CR propagation time and their energy losses are correlated with solar activities

Back-up Slides …


Proton
E = 1 GeV
REVERSAL
REVERSAL
A+
A-
A+
Propagation time [day]
150
100
50
0
PDF
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Antiproton
E = 1 GeV
REVERSAL
REVERSAL
A+
A-
A+
Propagation time [day]
150
100
50
0
PDF
0.1
0.08
0.06
0.04
0.02
0
1995
2000
2005
2010
2015


E = 1 GeV
Proton
REVERSAL
REVERSAL
A+
A-
A+
Energy loss fraction
PDF
E = 1 GeV
Antiproton
REVERSAL
REVERSAL
A+
A-
A+
Energy loss fraction
PDF
1995
2000
2005
2010
2015