Interpretation of the AMS time-dependent data

A.D. 1308
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DIPARTIMENTO
DI FISICA E GEOLOGIA

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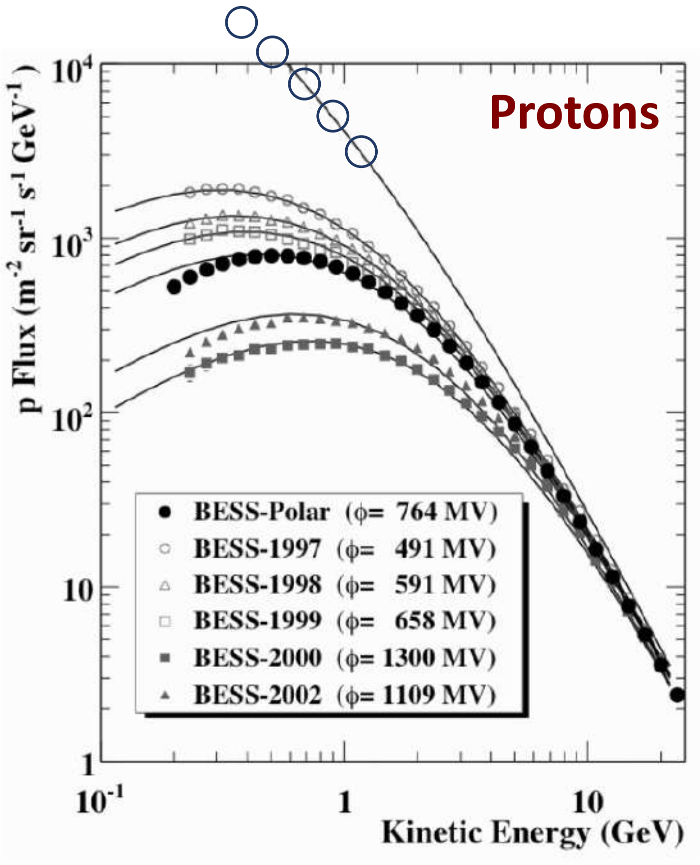
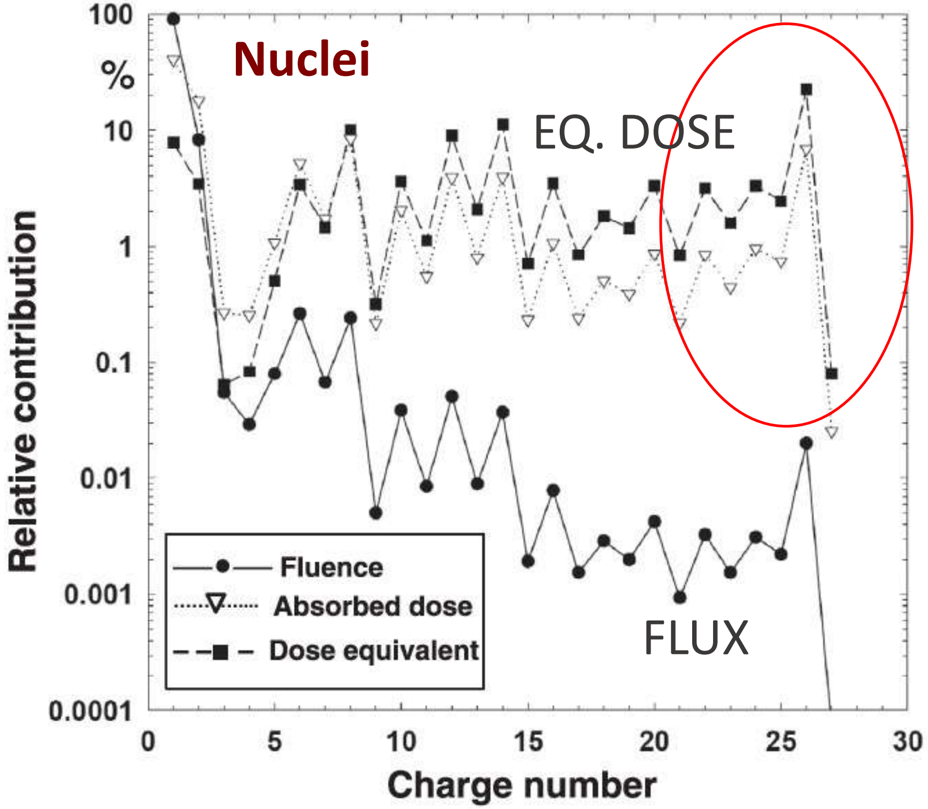
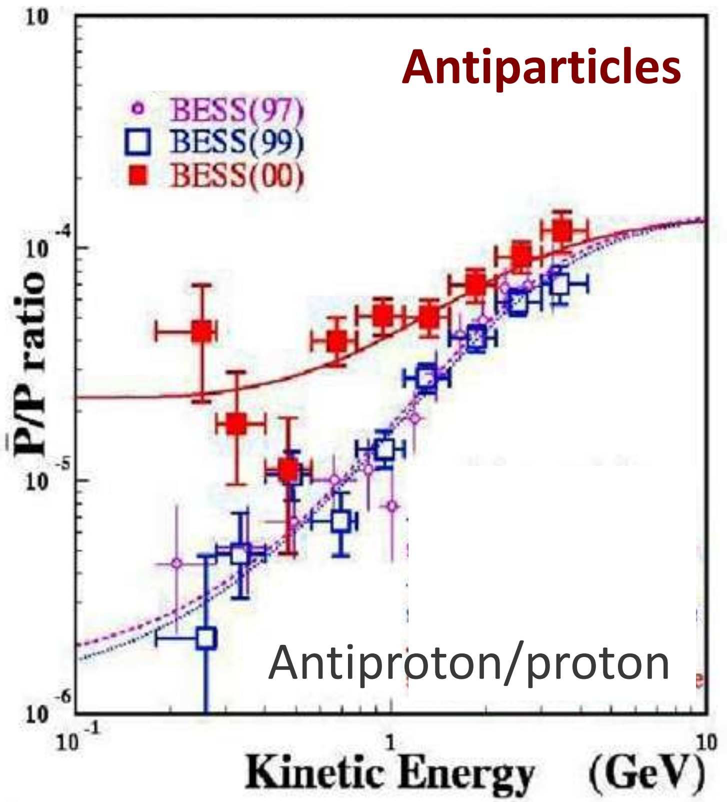
Solar modulation: what to look at and why







Dominant in GCRs. Best data.
To probe GCR transport

Important source of radiation
To assess radiation dose

Messengers for new physics
Precious source of information

Some recent efforts & results

E. Fiandrini, N. Tomassetti, B. Bertucci, F. Donnini, M. Graziani, B. Khiali, A. Reina Conde, *"Numerical modeling of cosmic rays in the heliosphere: Analysis of proton data from AMS-02 and PAMELA"*, Phys. Rev. D 104, 023012 (2021)

B. Khiali, B. Bertucci, E. Fiandrini, N. Tomassetti, *"Recent progress in solar modulation modeling in light of new cosmic-ray data from AMS-02"*, Nuovo Cimento 43 C, 78 (2020) + Paper in preparazione (2023).

PG+BO+RM2
Metodo stocastico/RW: simulazioni MC di pseudo-particelle

N. Tomassetti, B. Bertucci, E. Fiandrini, *"Temporal evolution and rigidity dependence of the solar modulation lag of Galactic cosmic rays"*, Physics. Rev. D 106, 103022 (2022) [arXiv:2210.05693]

PG - analisi multi-correlative

N. Tomassetti F. Barao, B. Bertucci, E. Fiandrini, M. Orcinha, *"Numerical modeling of cosmic-ray transport in the heliopshere and interpretation of the proton-to-helium ratio in Solar Cycle 24"*, Adv. Space Res. 64 (2019) 2477-2489 [arXiv:1906.11477]

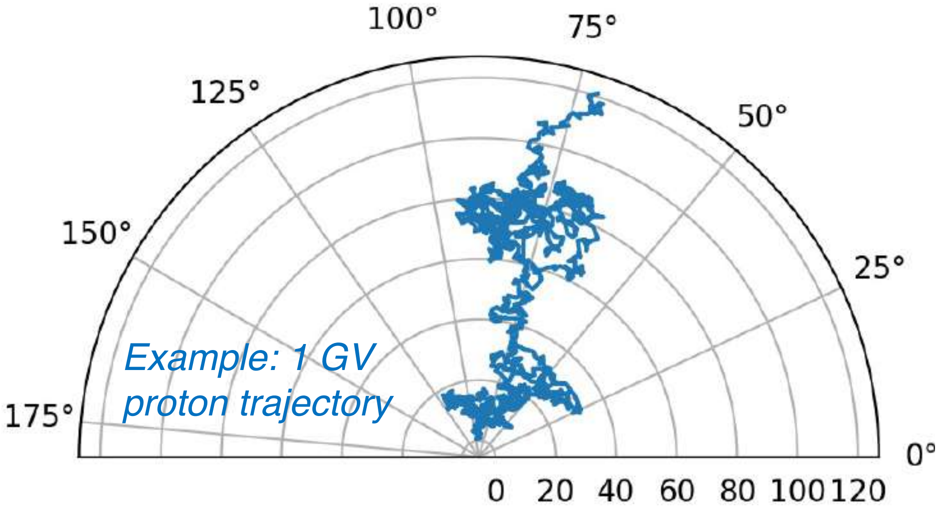
PG+Lisbon
integrazione numerica eq. trasporto

Solar Modulation Calculations

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

Stochastic method

The solution is obtained by sampling of MC generated pseudo-particle trajectories. (Fiandrini et al. 2021)



CR transport parameters

Free parameters that regulate the processes of CR tranport in heliosphere, e.g. diffusion and drift.

connection

Heliospheric input parameters

Parameters that capture the conditions of the heliospheric plasma (the medium where CRs move throught) at a given epoch

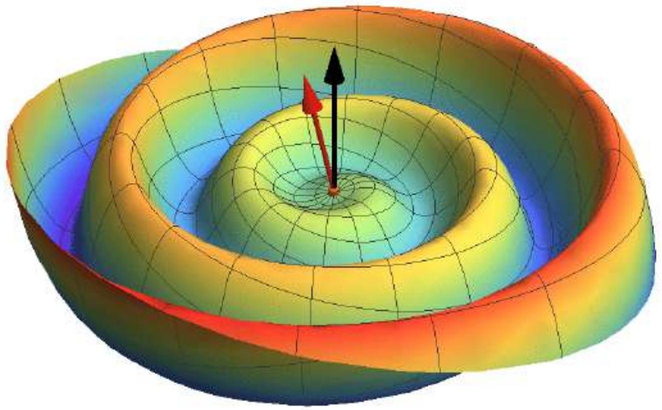
- *IMF intensity*
- *IMF polarity*
- *IMF Tilt Angle*

Heliospheric input parameters

Fiandrini et al 2021

Determined from observations of the solar or interplanetary B field

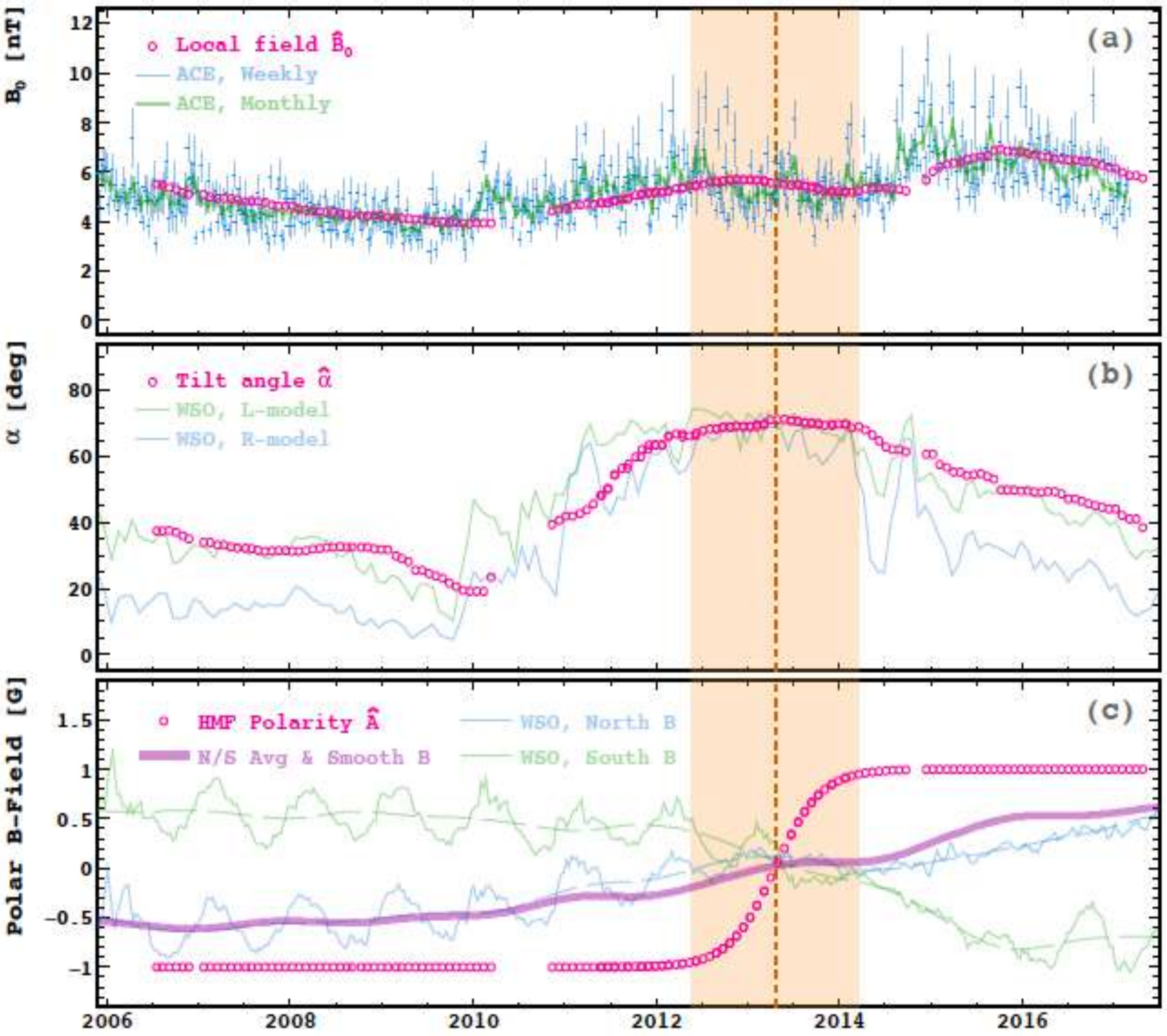
$$\{B_0(t), \alpha(t), \hat{A}(t)\}$$



Intensity B_0

Tilt angle α

Polarity $\hat{A}$



Transport parameters

Time-dependent coefficients of the diffusion tensor:

Parallel:

$$K_{\parallel} = \frac{\beta c}{3} \times K_0 \frac{(R/R_0)^a}{(B/B_0)} \left[\frac{(R/R_0)^h + (R_b/R_0)^h}{1 + (R_b/R_0)^h} \right]^{\frac{b-a}{h}}$$

Normalization

Slope @ R< Rb

Break rigidity

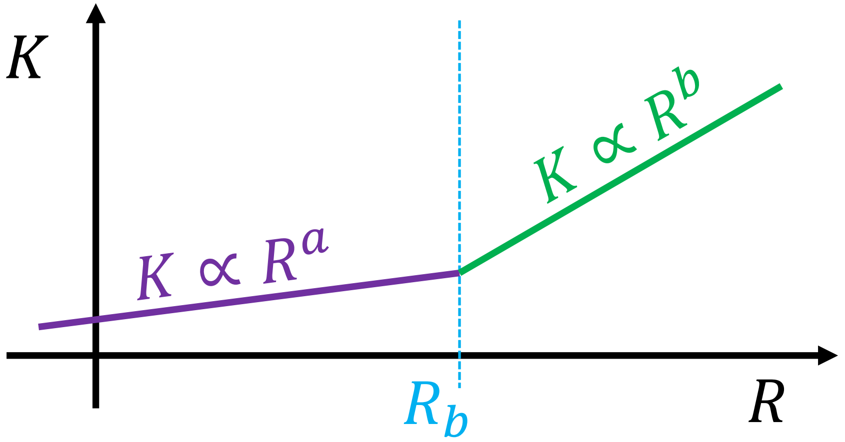
Slope @ R> Rb

Perpendicular:

$$K_{\perp} = \xi K_{\parallel}$$

Mean free path $\lambda(t, R)$, from $K = \frac{\beta c}{3} \lambda$

Basic set: $\{K_0(t), a(t), b(t)\}$

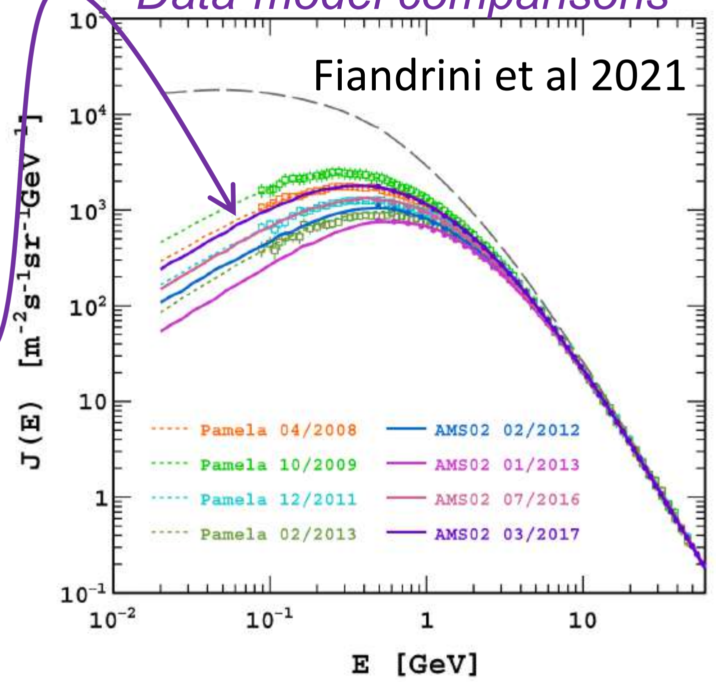


Data driven calculation of CR transport

$$\vec{q}(t) = \{K_0, a, b, B_0, \alpha, \hat{A}\} \qquad \chi^2 = \chi^2(\vec{q})$$

CR transport (K_0, a, b) *IMF conditions* ($B_0, \alpha, \hat{A}$)

Data-model comparisons

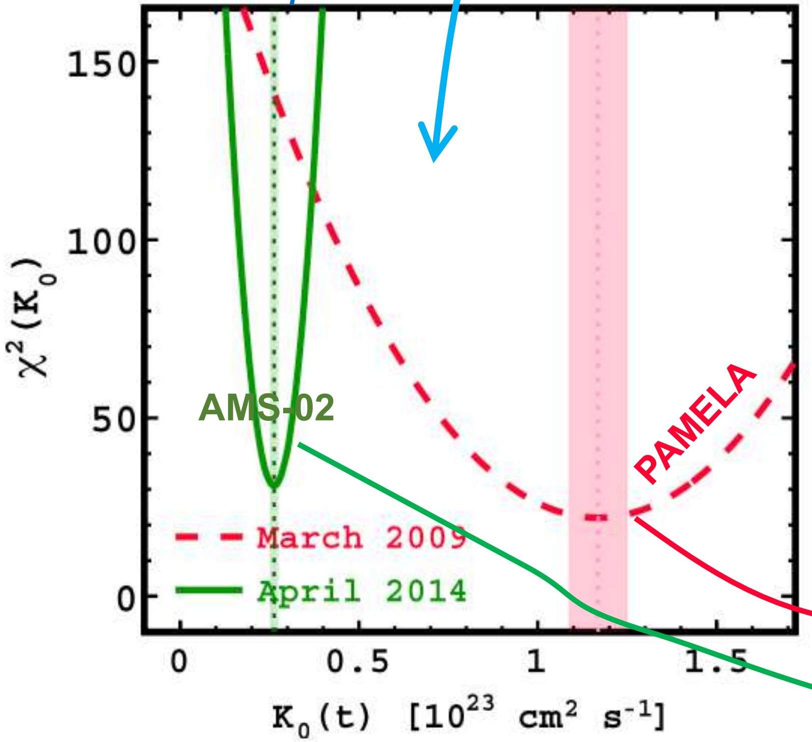


Misure di AMS-02 e PAMELA *modello numerico*

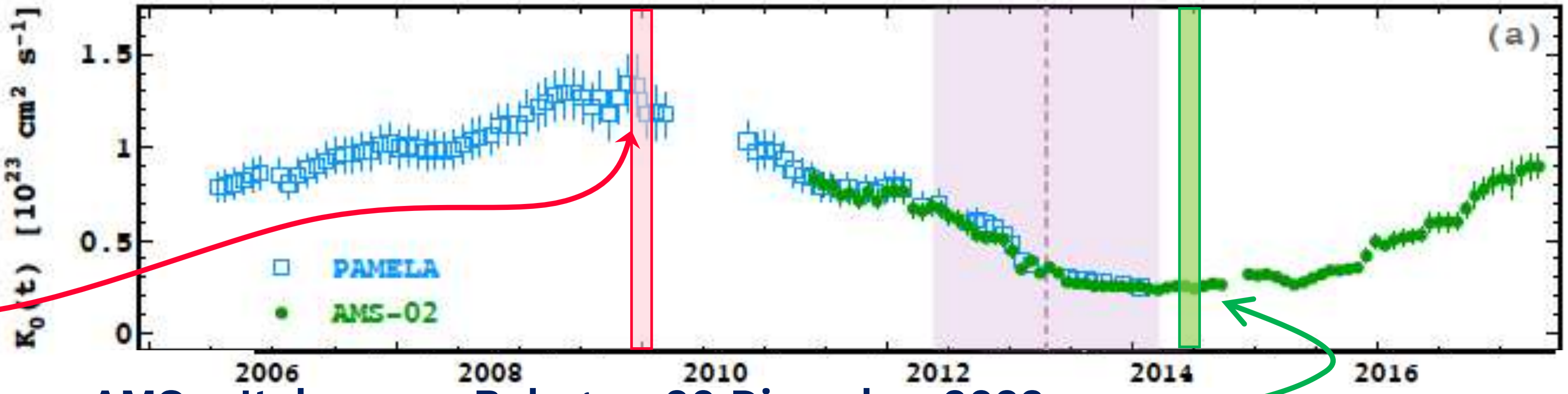
$$\chi^2(\vec{q}) = \sum_i \frac{[J_d(E_i,t) - J_m(E_i,\vec{q})]^2}{\sigma^2(E_i,t)}$$

Valutazione delle incertezze

Chi square as function of K0

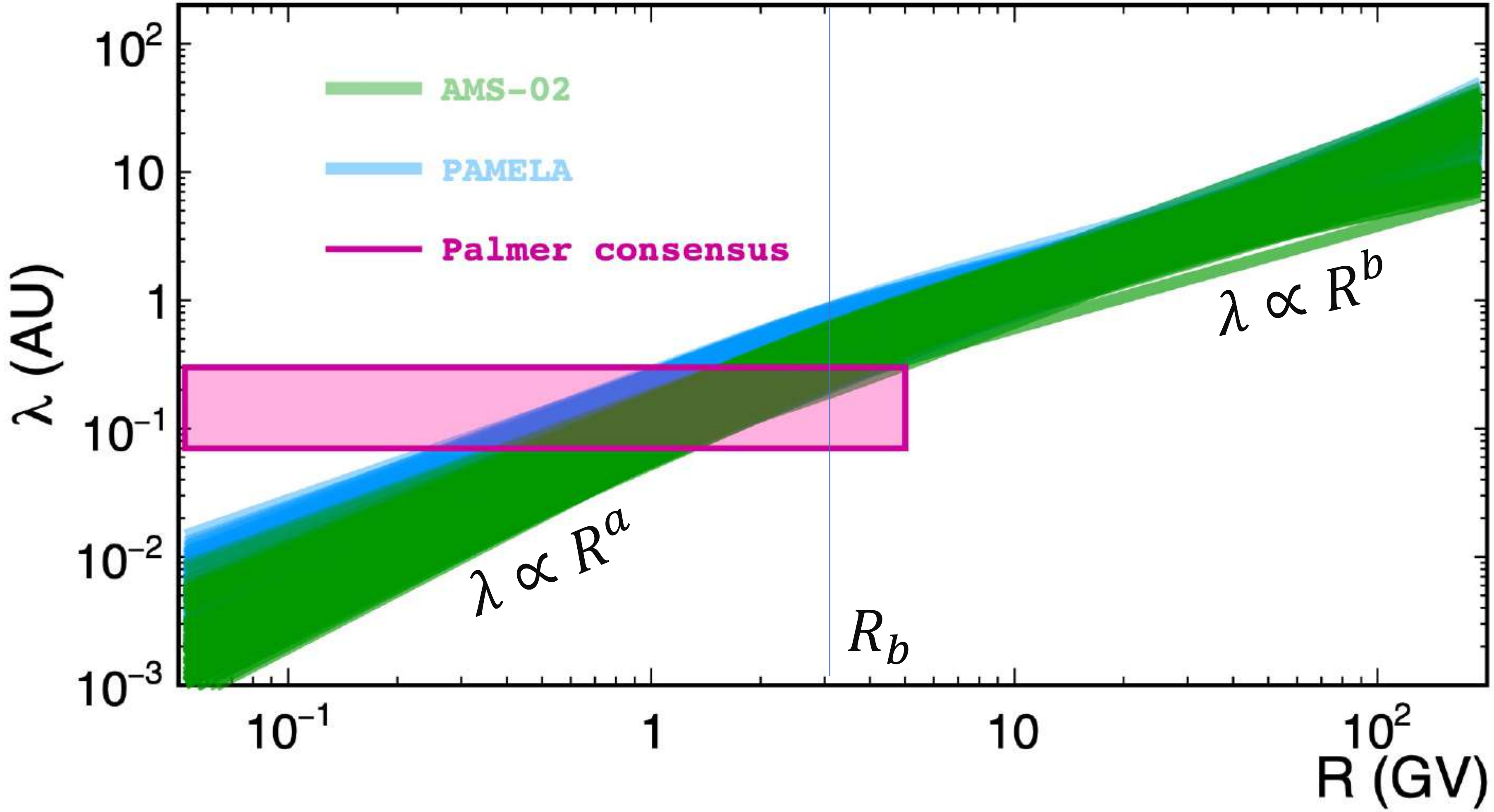


Temporal dependence of K_0, as part of $\vec{q} = \{K_0(t), a(t), b(t)\}$.



Data driven calculation of CR transport

$$K(t,R) = \frac{\beta c}{3} \lambda(t,R)$$



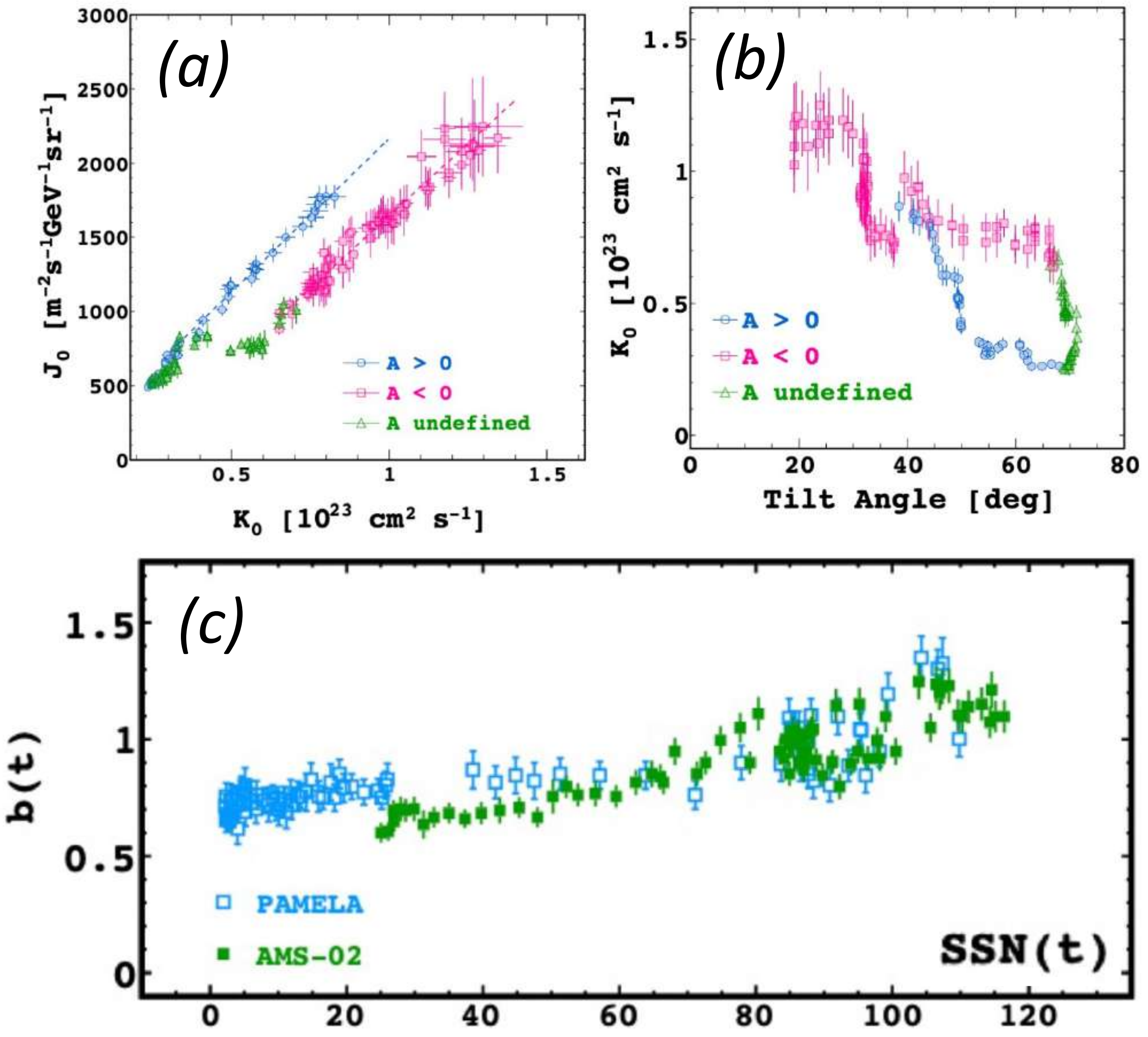
Correlation analyses

Correlations between solar/diffusion parameters show hystheresis and loops revealing various physics phenomena:

(a) Charge-sign dependence

(b) Time lag of CRs in response to changing conditions of the IMF

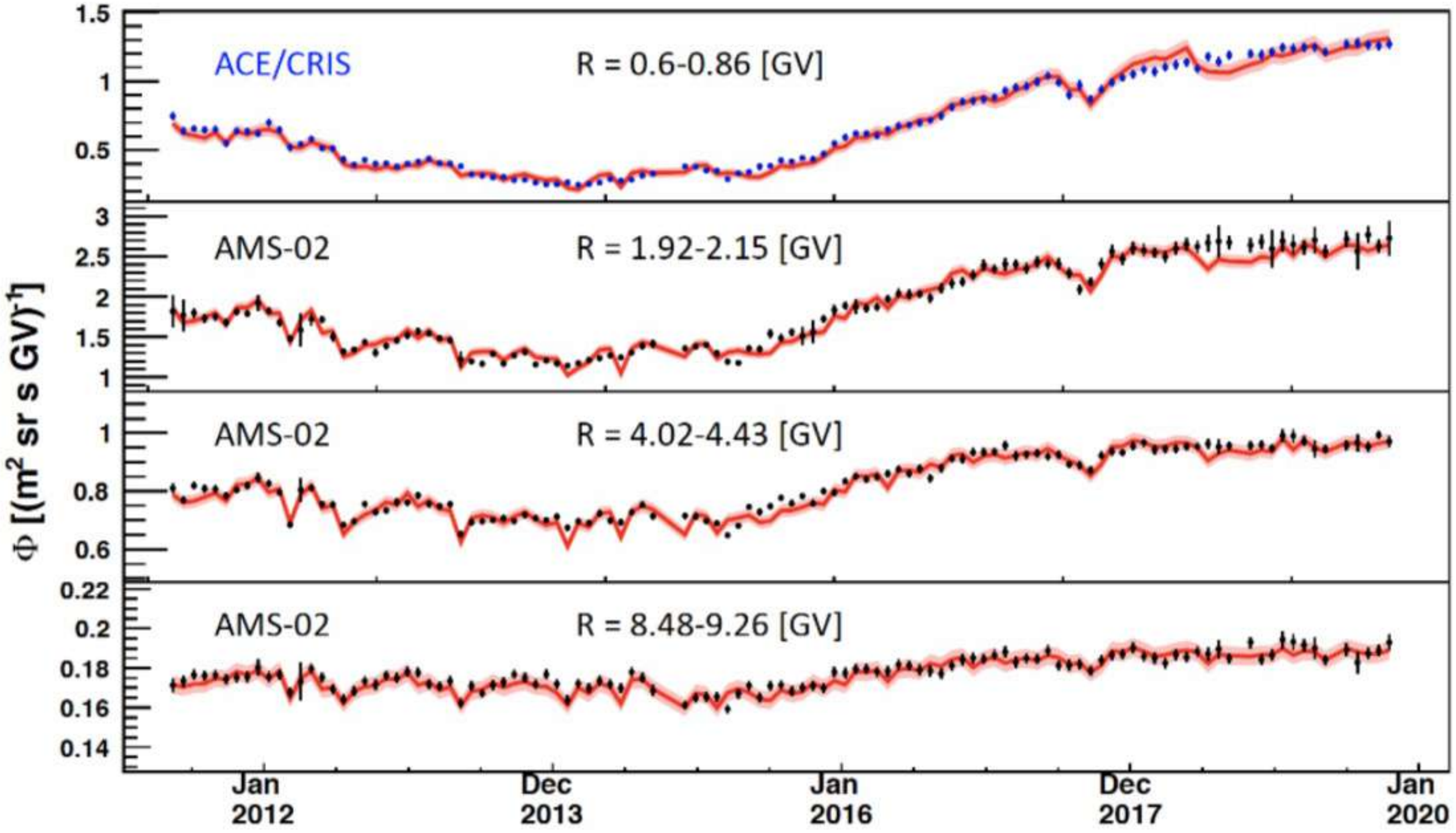
(c) Variability of the IMF turbulence

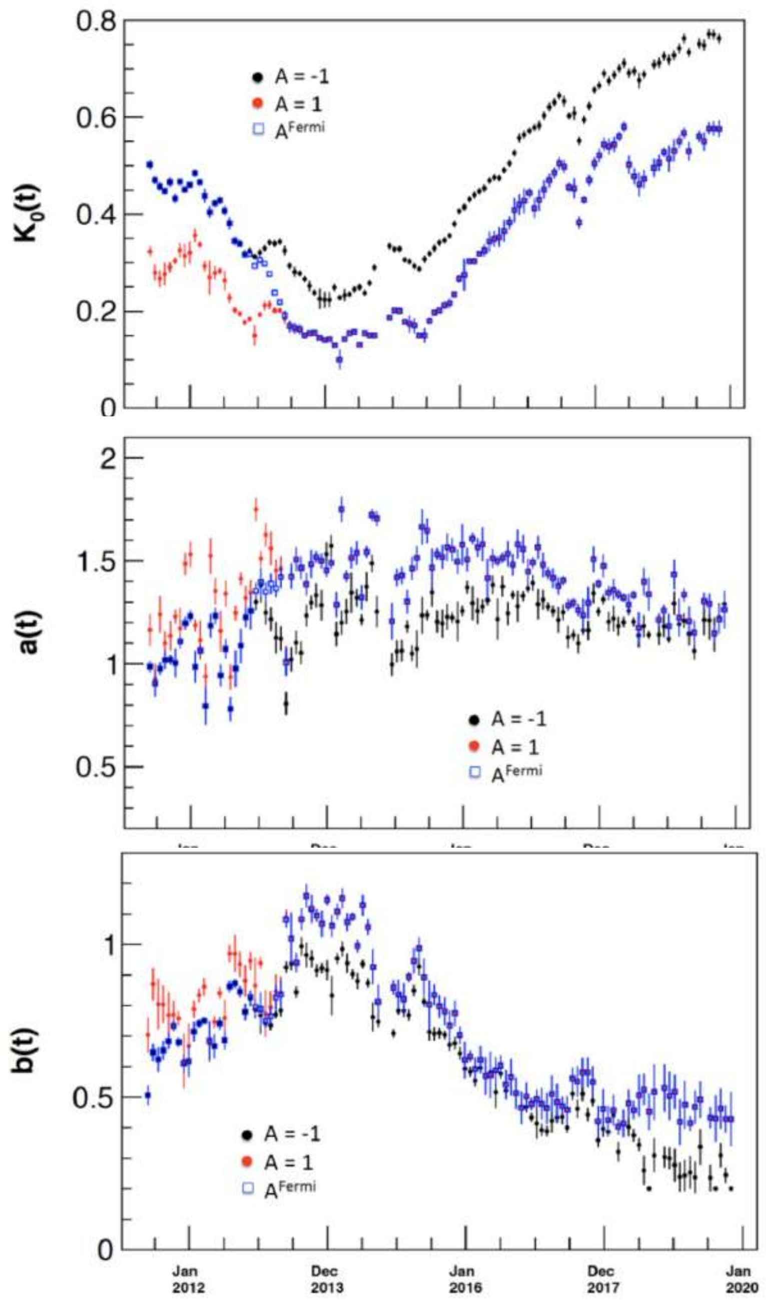


Results with CR nuclei

A. Reina Conde et al.

- ✓ Evolution of B, C, O vs Time and Rigidity
- ✓ Parameter determined from from C data: ACE/CRIS & AMS-02
- ✓ Testable predictions for B, B/C or other species and ratios

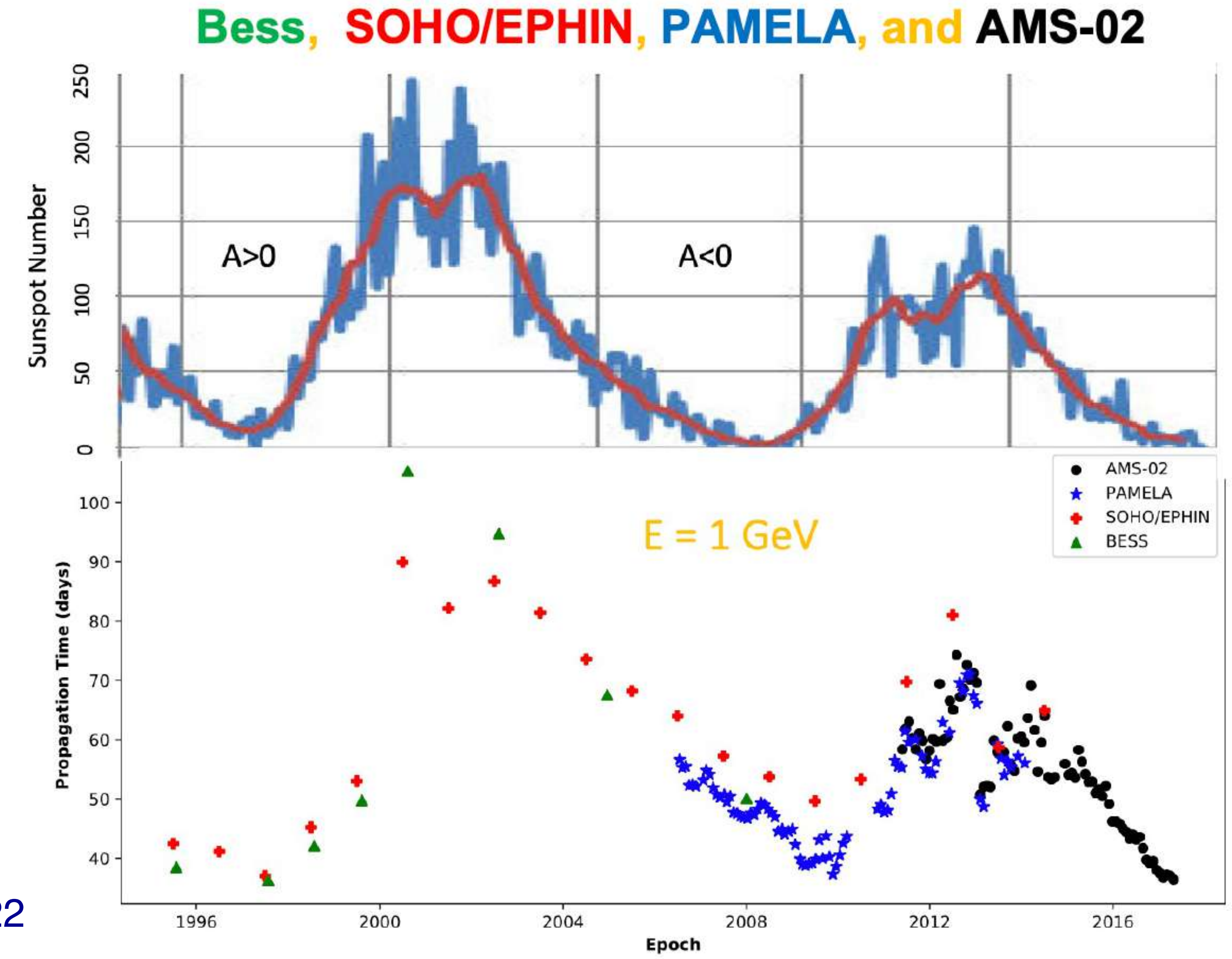




Evolution of the CR propagation times

Data-driven calculation of the CR propagation times and energy losses and how they *evolve* over the solar cycle.

Example: 1 GeV CR protons spend 40 to 100 days in the heliosphere, on average



B. Khiali+ ECRS-2022

Calculations of times and energies

B. Khiali et al.

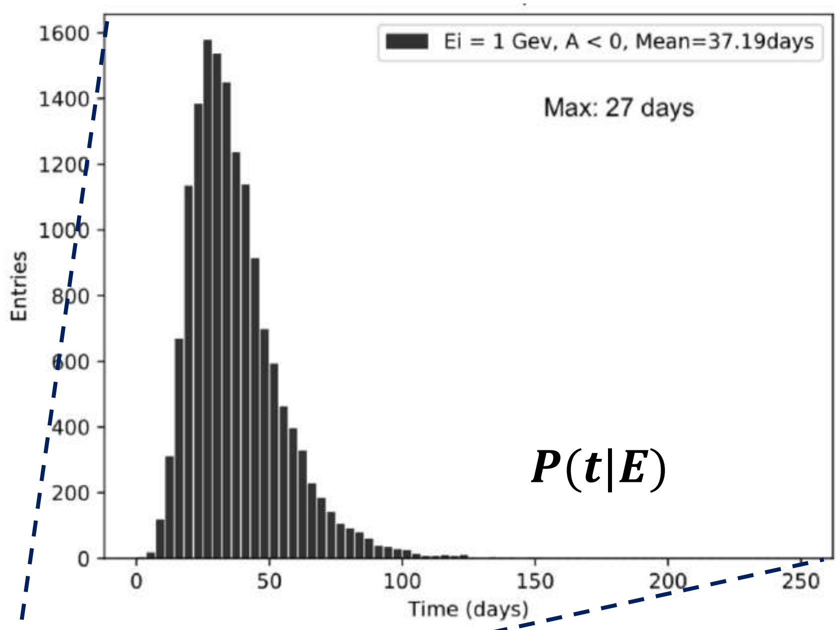
Simulation of 1 GeV protons (arrival energy).

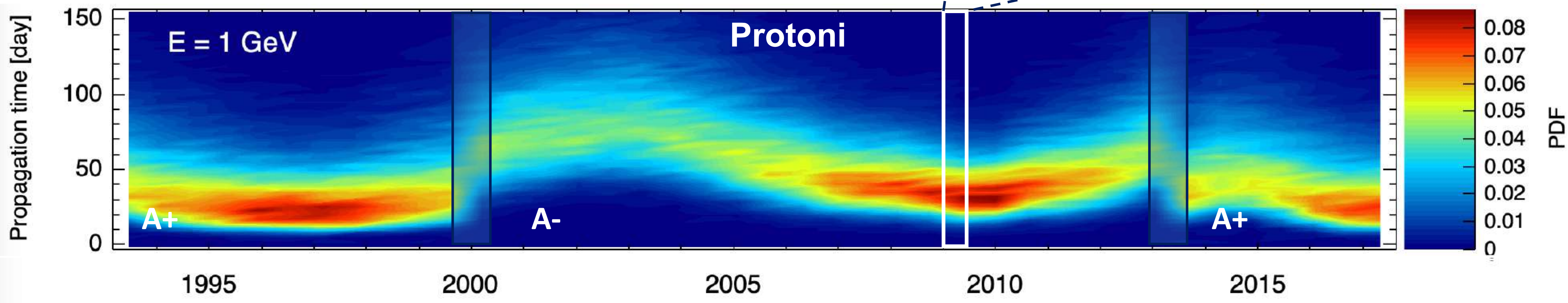
Model calibrated over an entire 22yr polarity cycle (Data from AMS, PAMELA, EPHIN/SOHO, BESS)

Propagation time: **time spent by CR protons in the heliosphere if they are detected near-Earth with $E_f = 1\ GeV$.**

Energy loss fraction: **loss of initial energy E_i by CRs due to adiabatic cooling $\eta = (E_i - E)/E_i$.**

Probability density functions $P(t|E)$ & $P(\eta|E)$

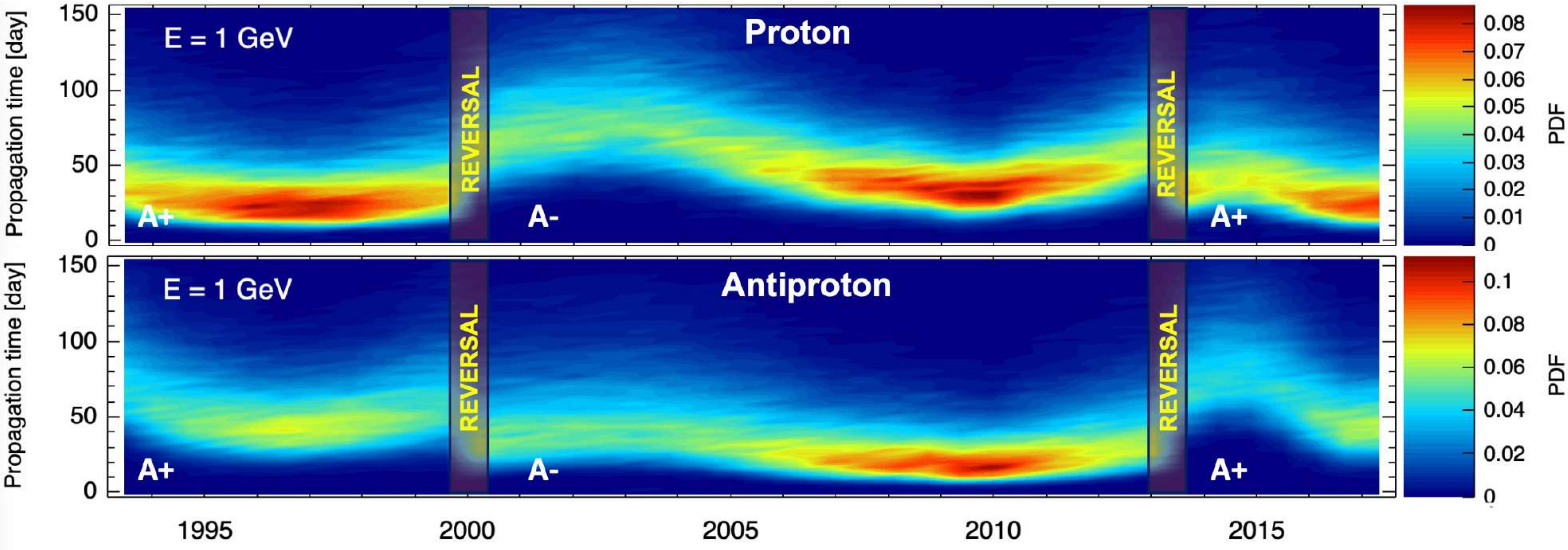




Calculations of times and energies

B. Khiali et al.

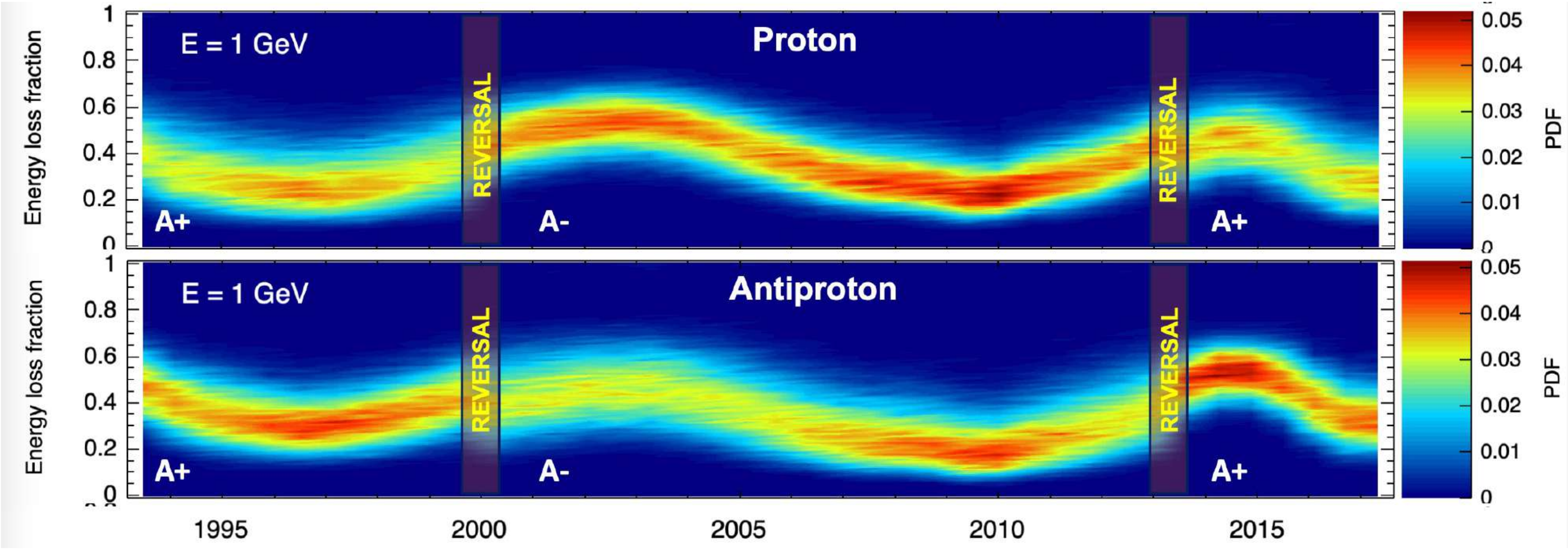
Propagation times of 1 GeV protons and antiprotons



Calculations of times and energies

B. Khiali et al.

Energy loss fraction of 1 GeV protons and antiprotons

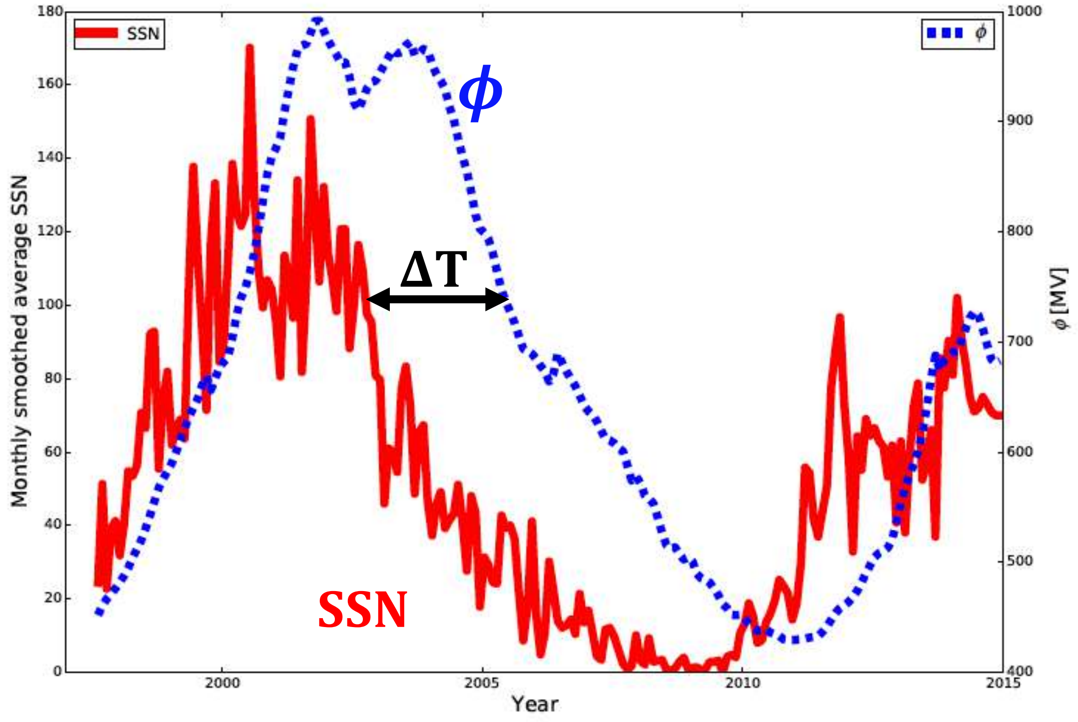


Investigation of the time lag

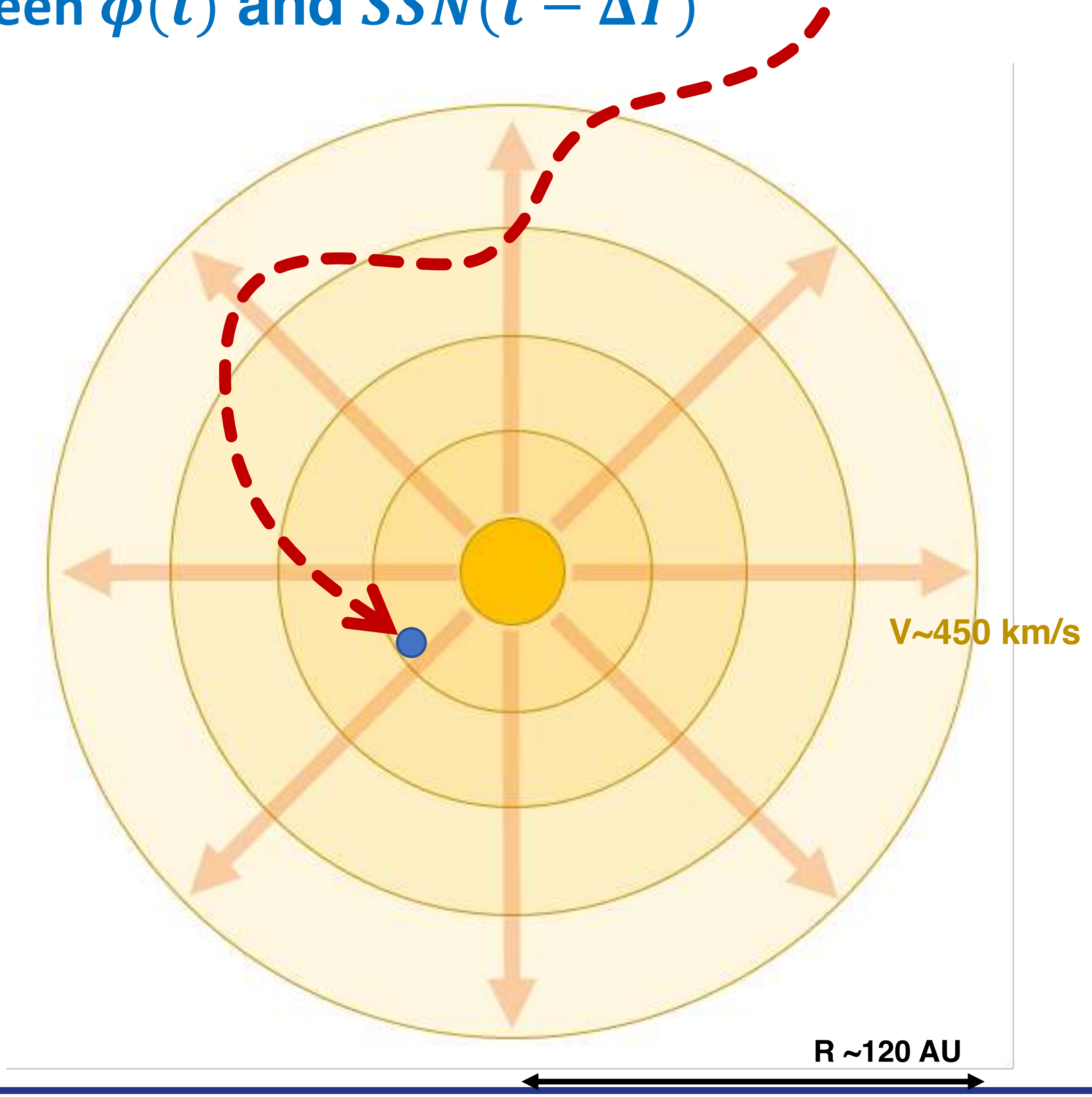
NT et al. 2022

The best correlation is between $\phi(t)$ and $SSN(t - \Delta T)$

Example: lag between ϕ and SSN (magnified)

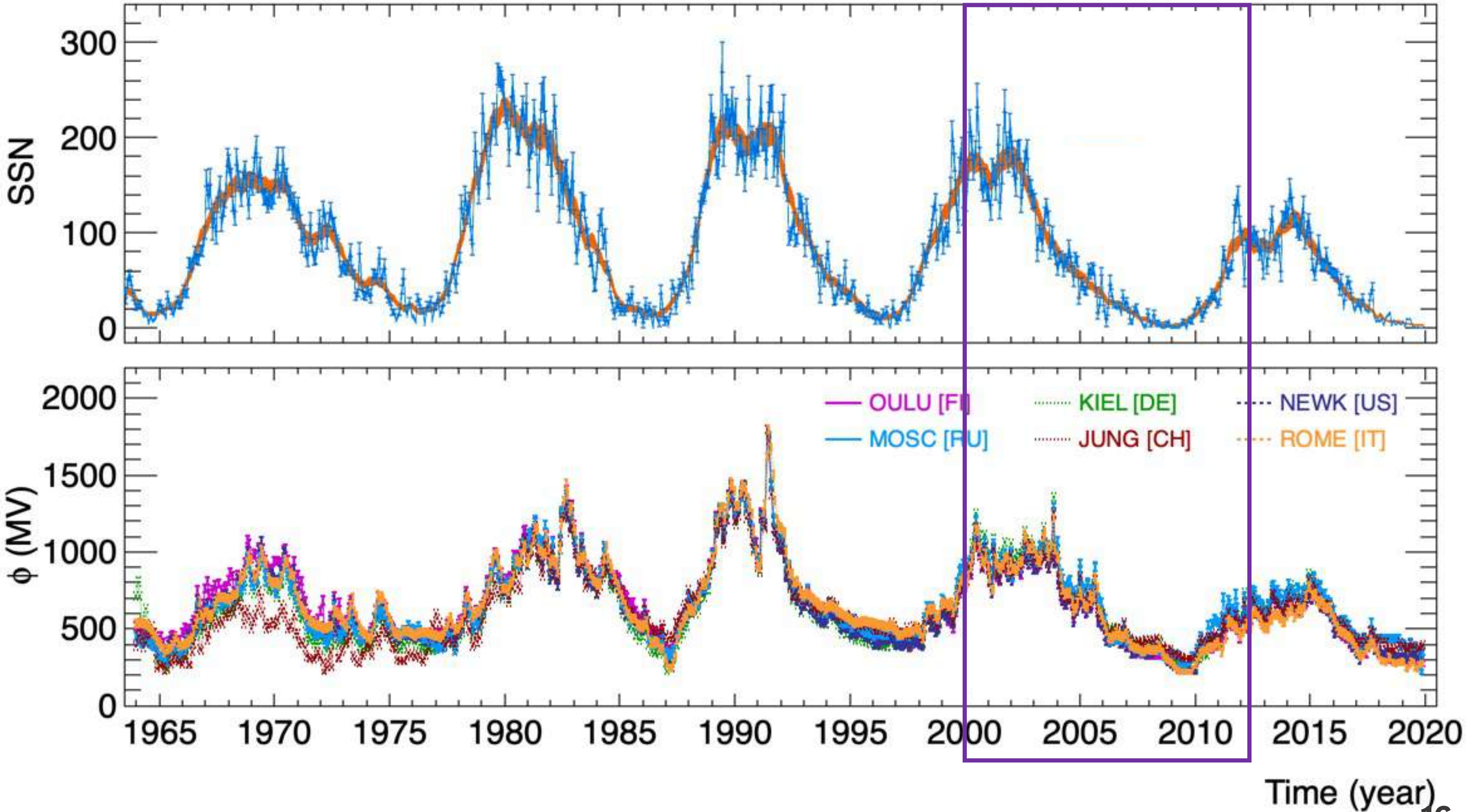


NT+ 2017, ApJ 849 L32: lag incorporated in CR transport model. Using CR data from space: $\Delta T \approx 8\, months$



Time Lag between Solar Activity and Modulation

NT et al. 2022



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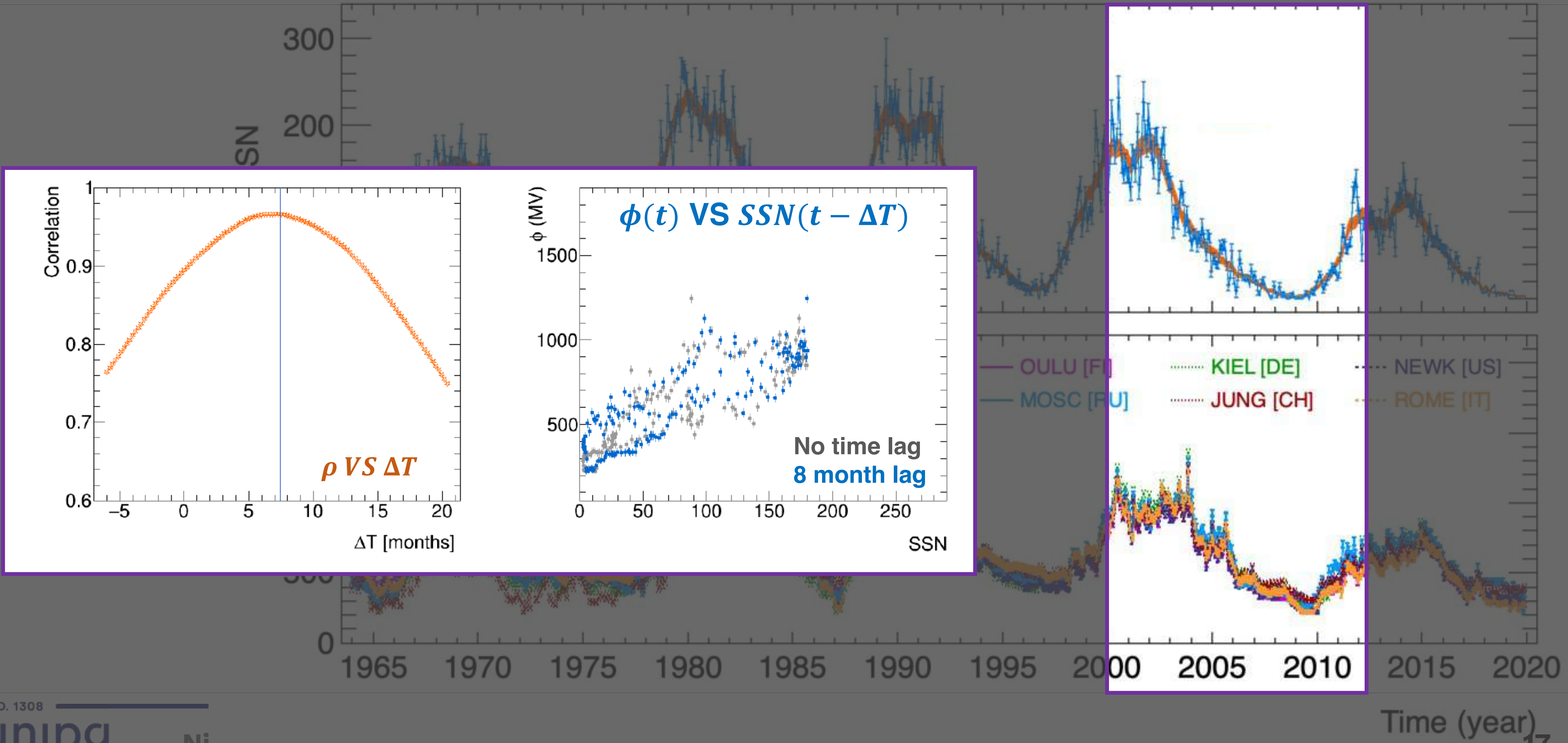
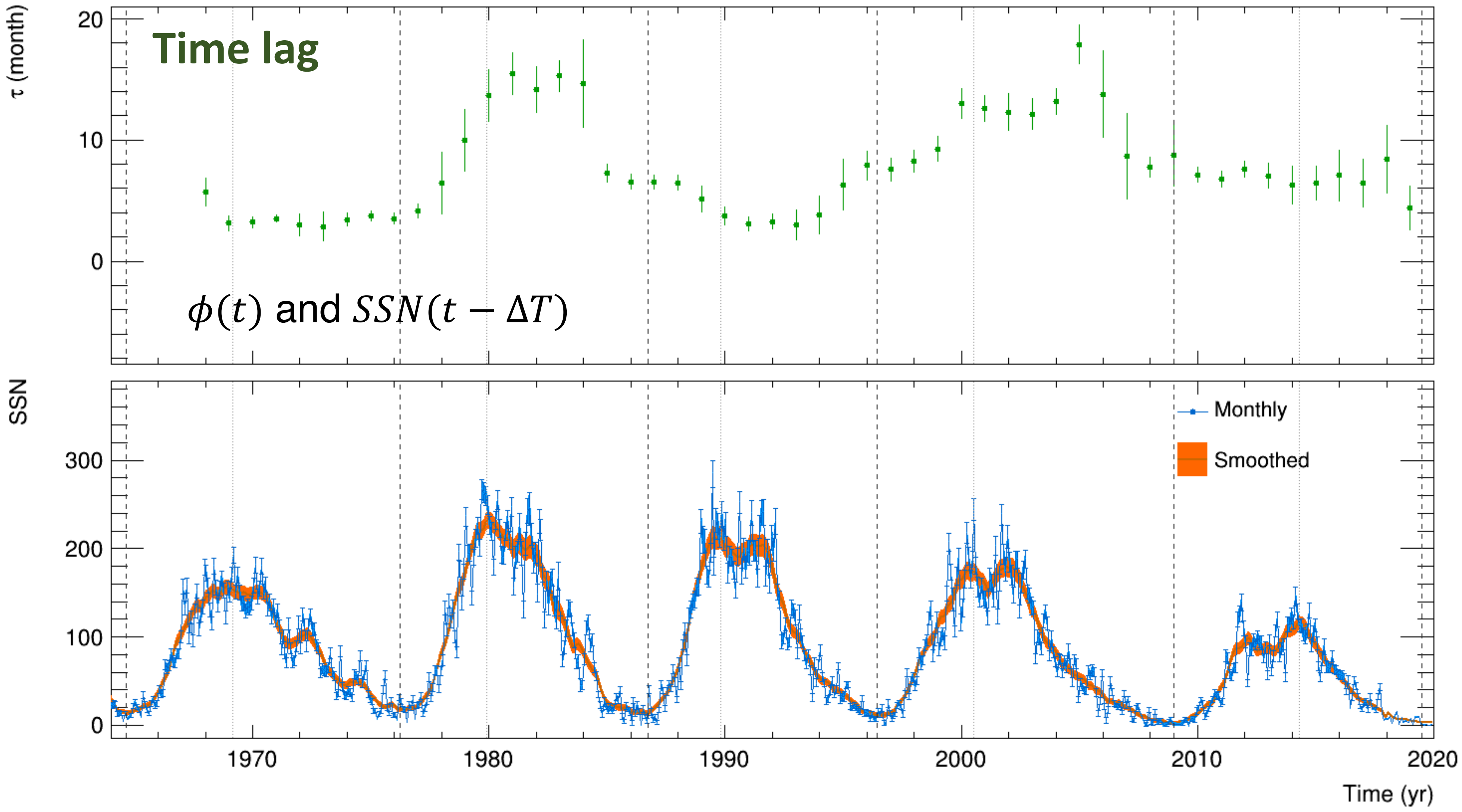
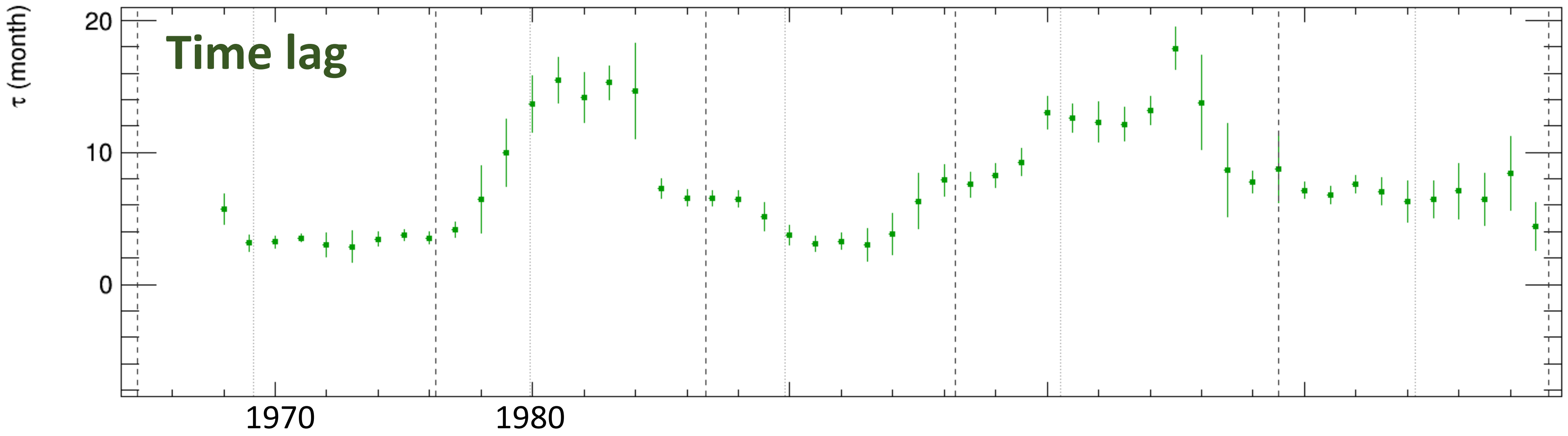


Evolution of the Lag over the Solar Cycle

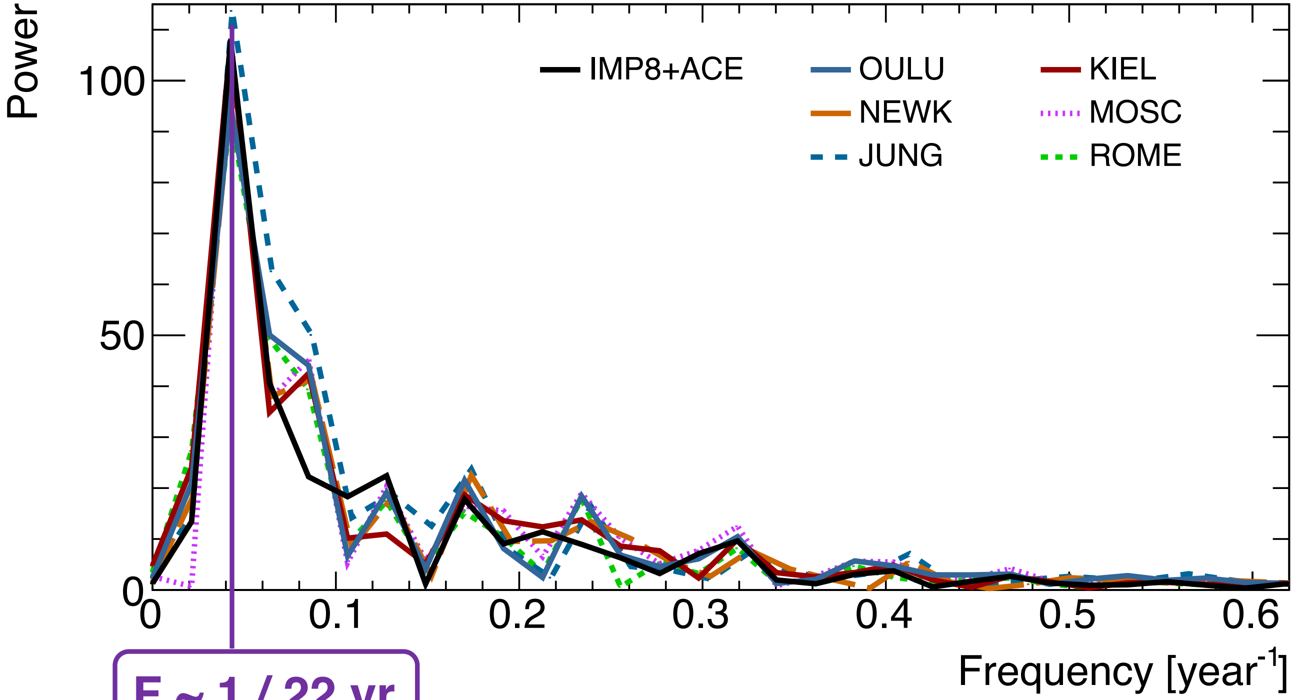


Evolution of the Lag over the Solar Cycle



from time domain…
to frequency domain

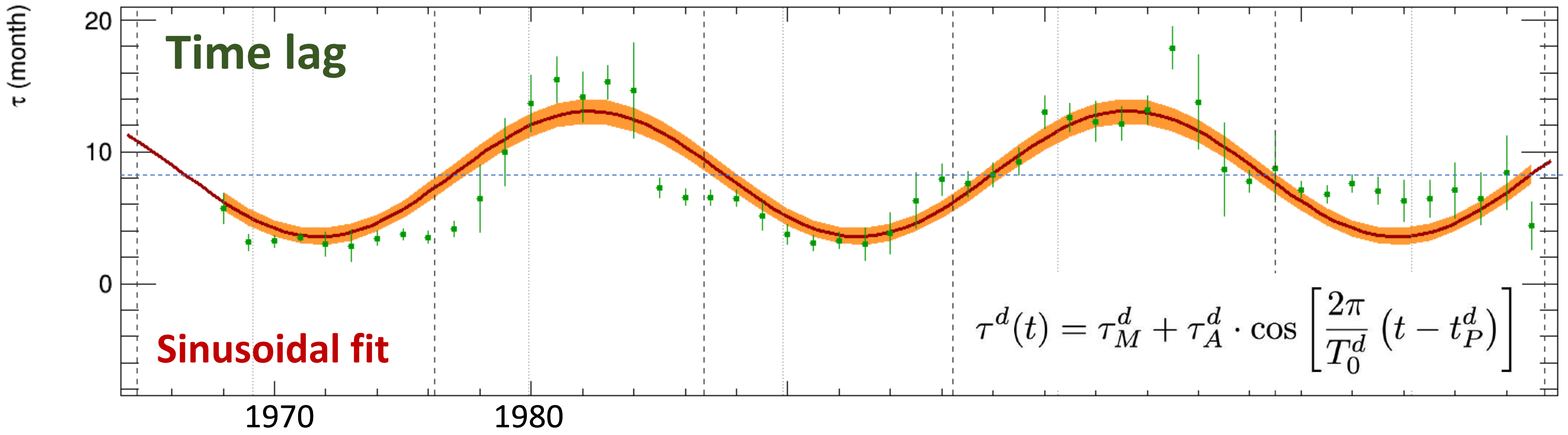
Fast Fourier Transform →



Main periodicity:
T ~ 22 yr !!!

F ~ 1 / 22 yr

Evolution of the Lag over the Solar Cycle



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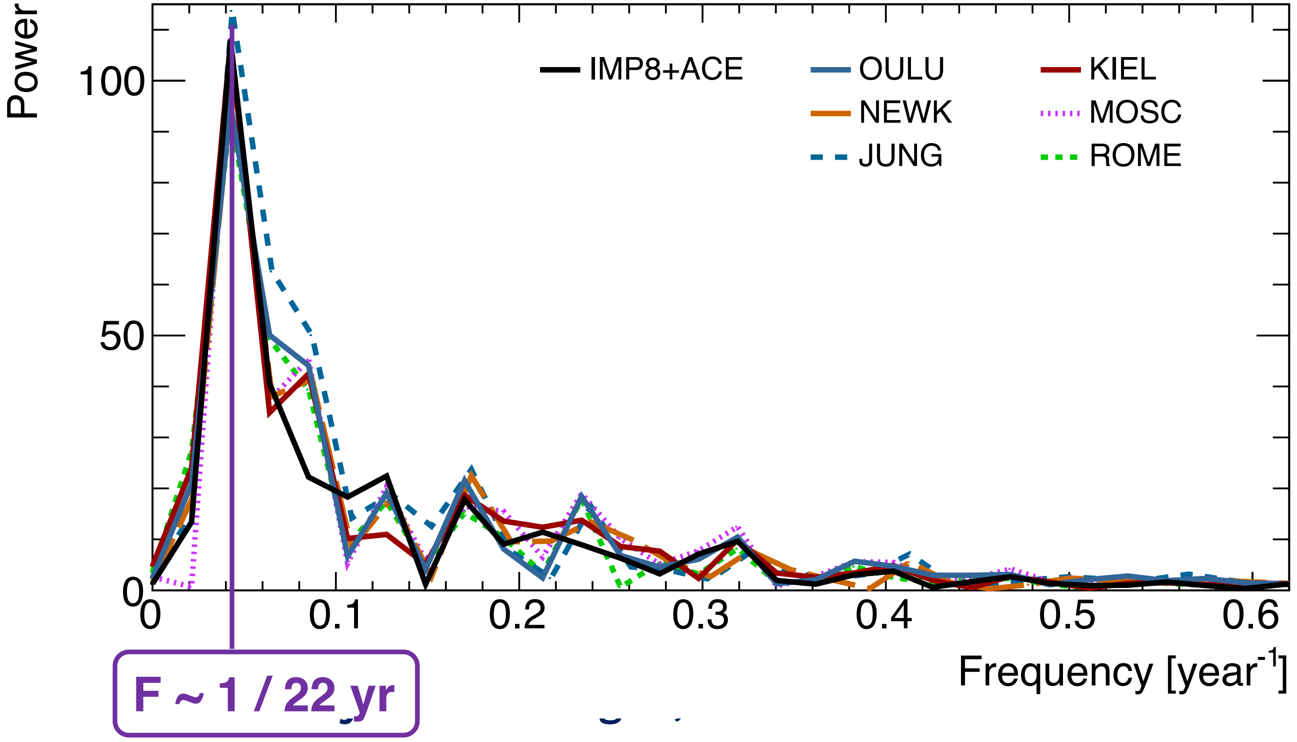
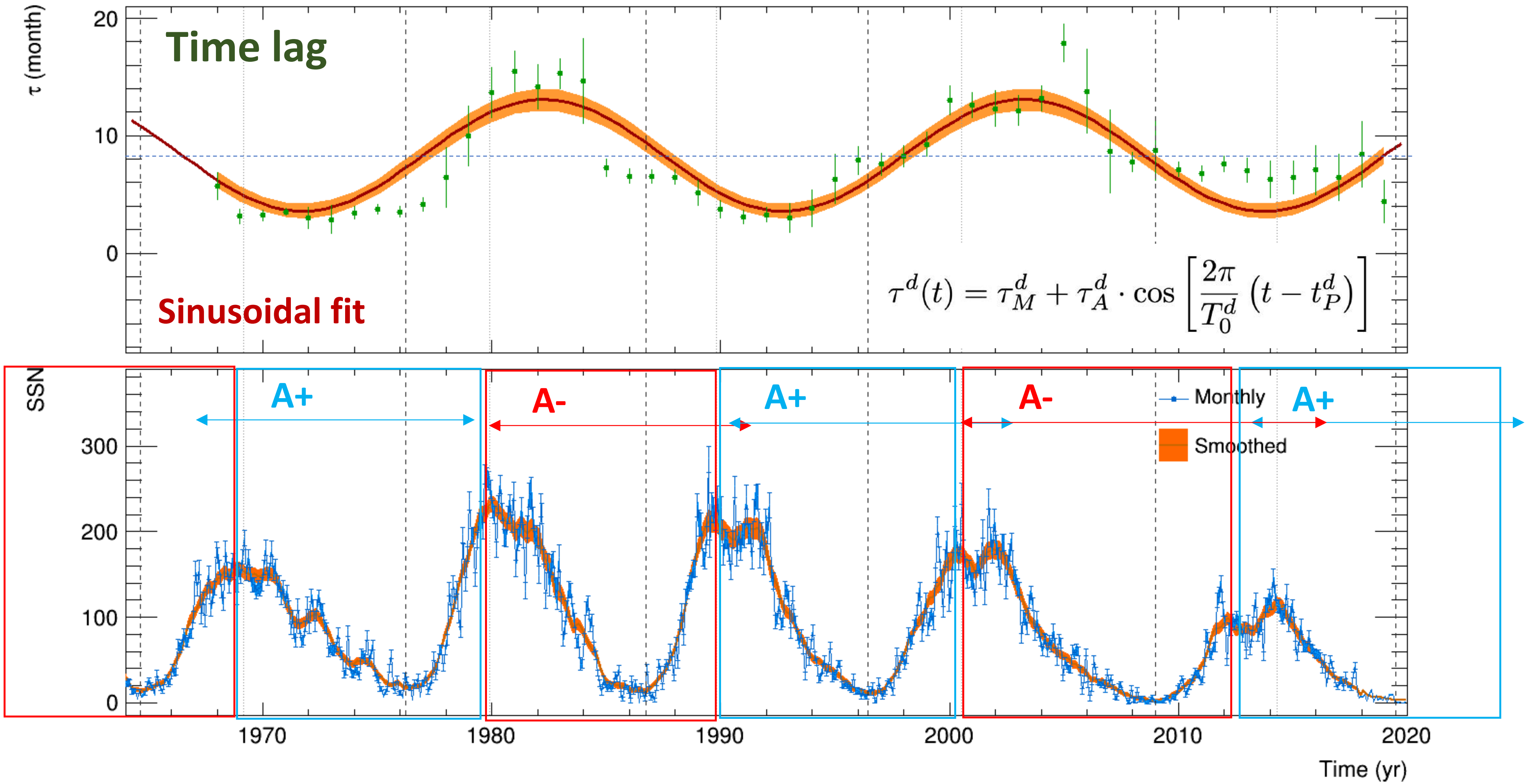


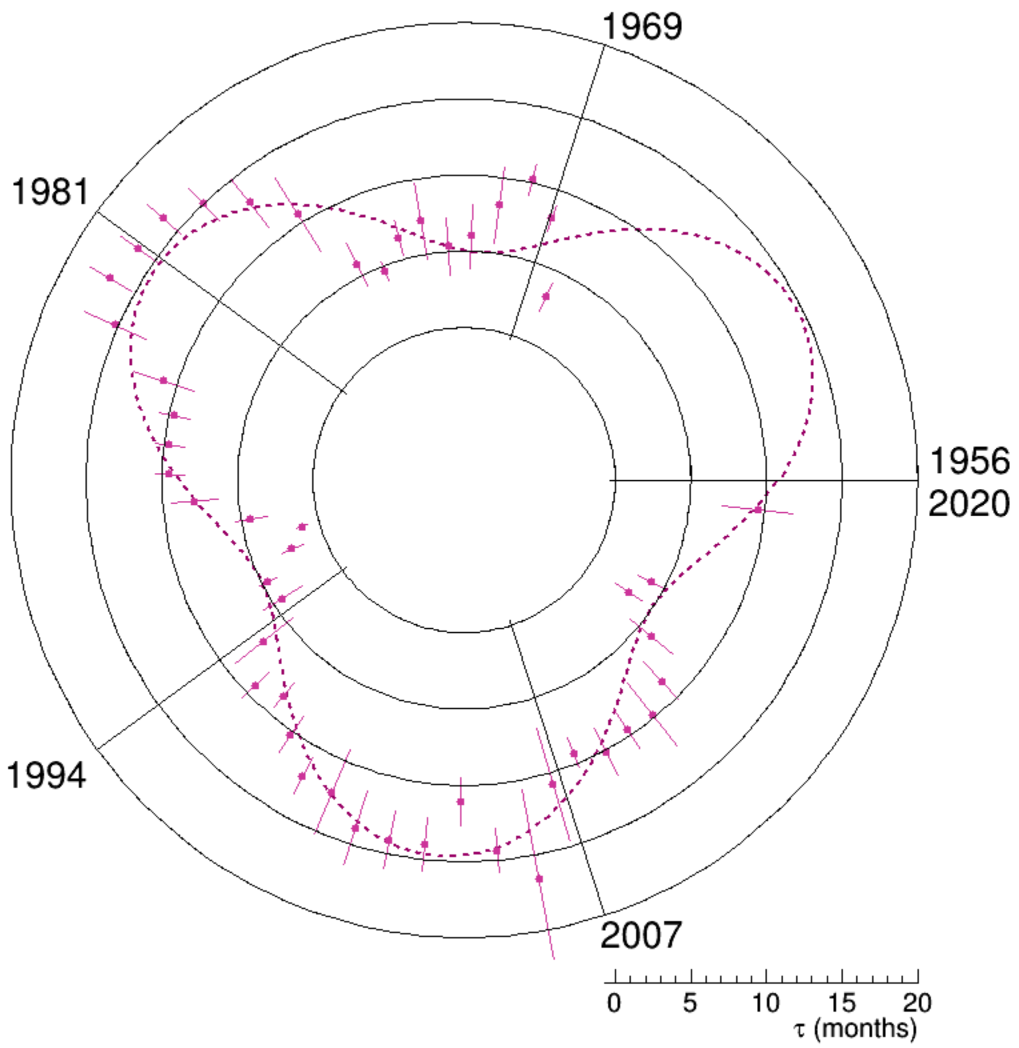
Evolution of the Lag over the Solar Cycle



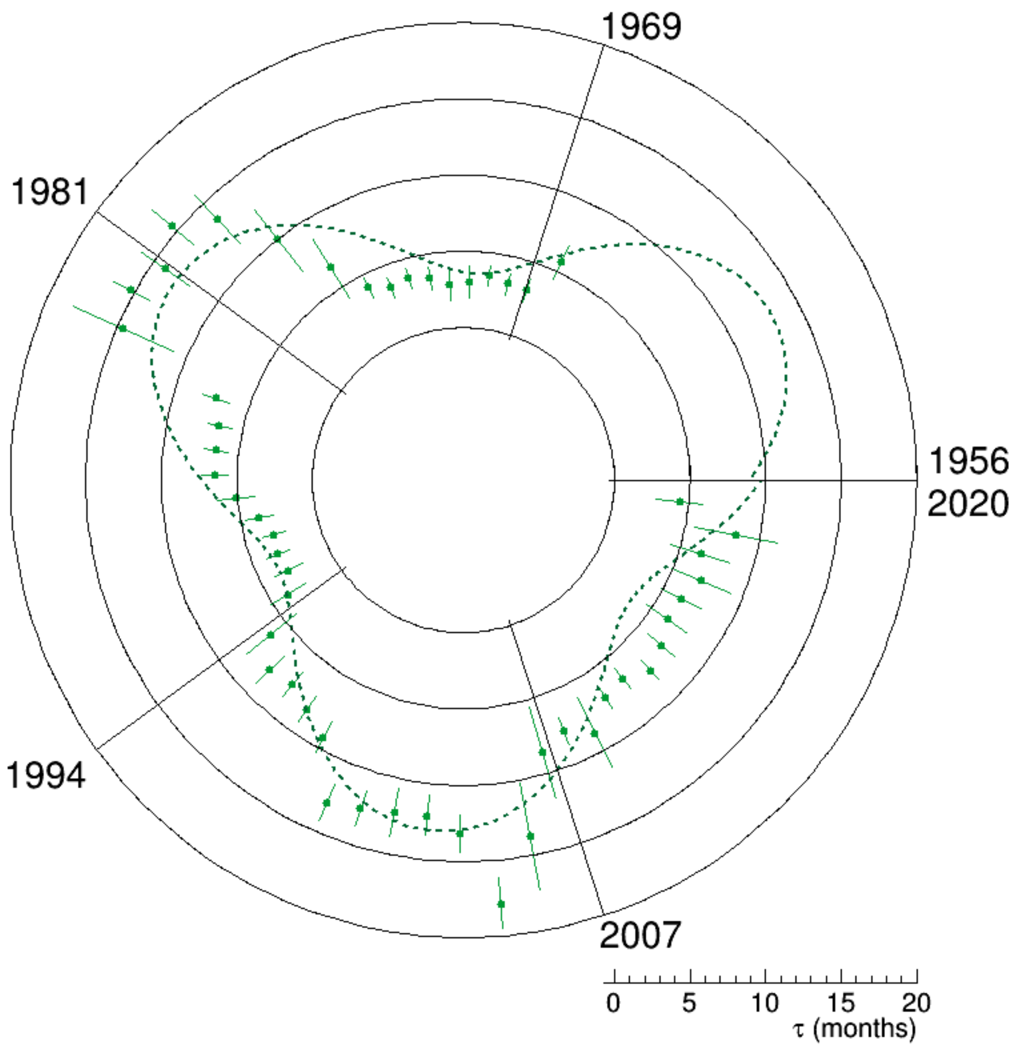
The time-lag appear correlated with the 22-yr magnetic cycle of the Sun.

Evolution of the Lag over the Solar Cycle

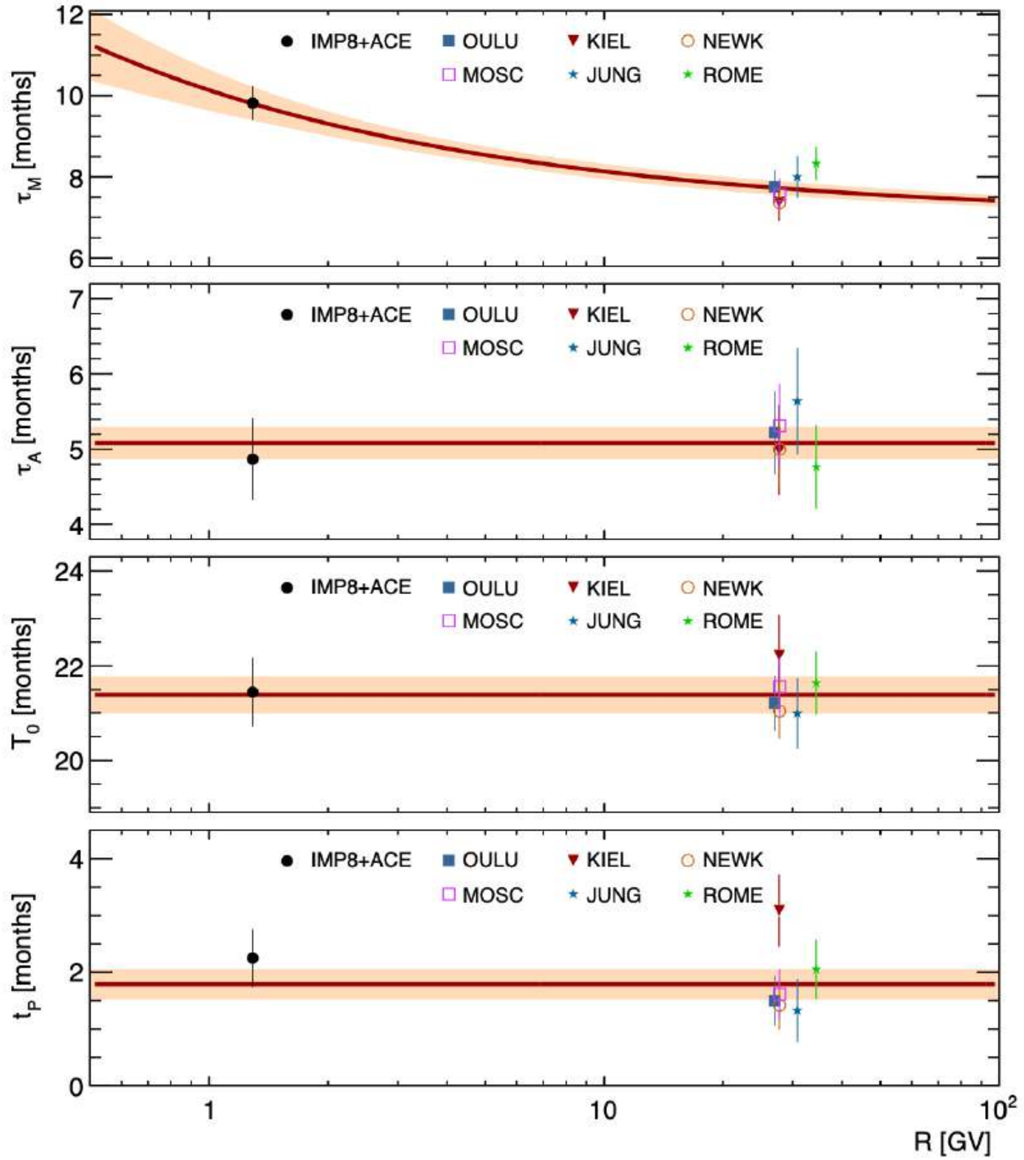
MED/IMP-8 + ACE/CRIS



NM / ROME



Rigidity dependence of the Lag



Semi-empirical formula to describe lag evolution

$$\tau^d(t) = \tau^d_M + \tau^d_A \cdot \cos\left[\frac{2\pi}{T^d_0}\left(t - t^d_P\right)\right]$$

Determine the free parameters for the many time series (6 NM stations + space data)

Determine the mean GCR rigidity R for data set

All parameters except τ_M are independent on R. Tm decreases with rigidity

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

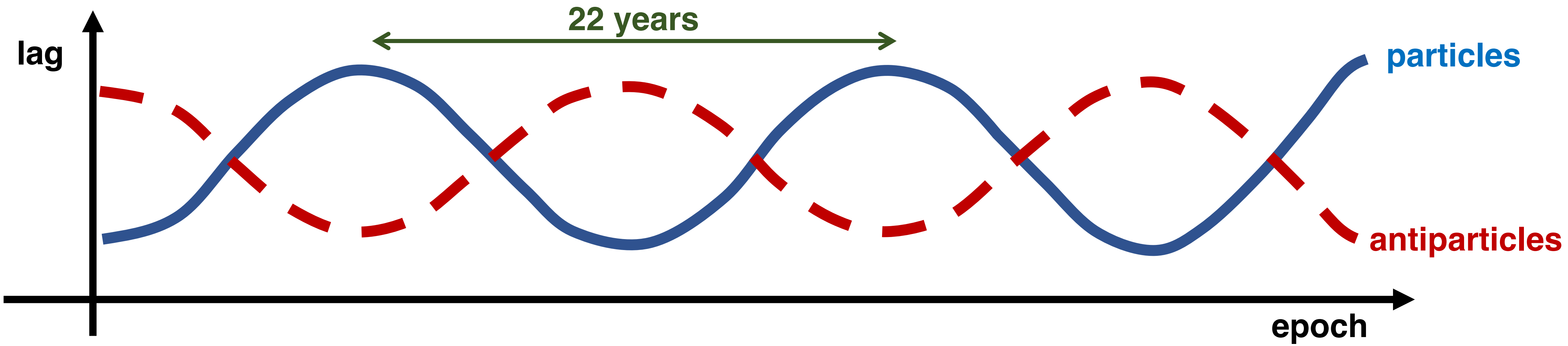
Predictions for antiparticles

The heliosphere is a giant magnetic spectrometer. It acts at selecting/suppressing trajectories.

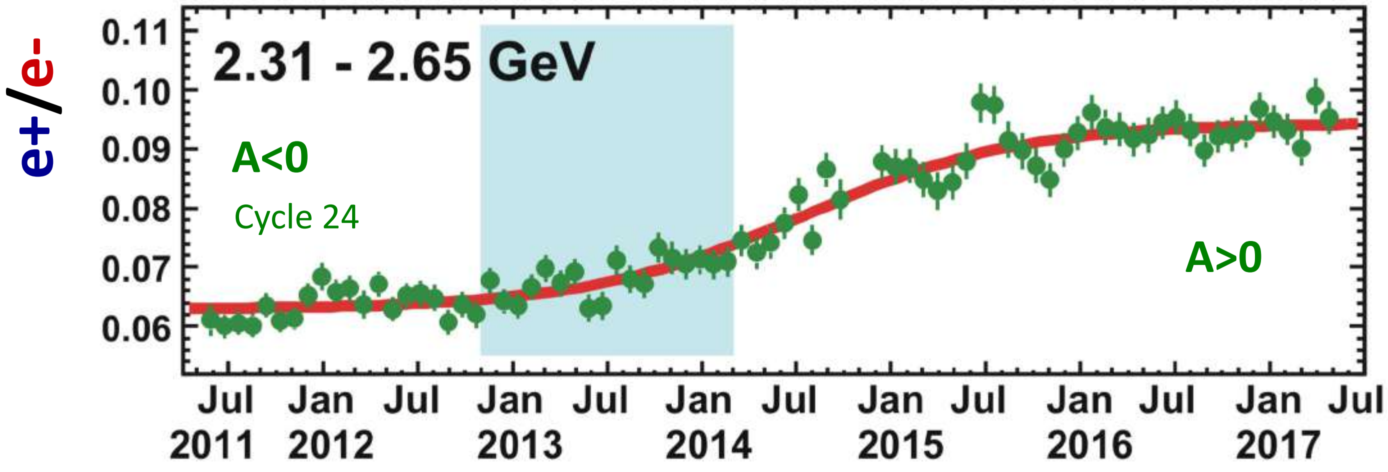
- **During A+ polarity states, CR protons come to us through the polar regions. Fast wind, short lag.**
- **During A- polarity states, CR protons come to us through the equators. Slow wind, large lag.**

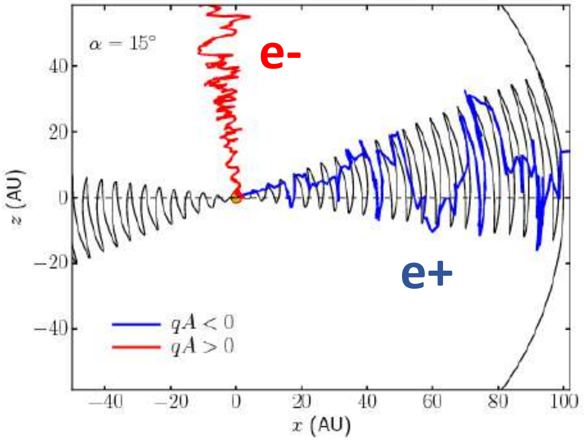
The observed evolution of the lag is a signature of charge-sign dependent drift. Its rigidity dipendence may be related to the CR propagation times (and to spectrum of IMF turbulence)

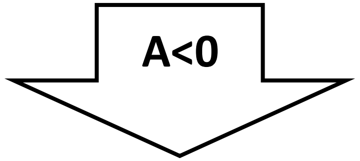
$$\tau_{lag} = \tau_M \pm \tau_A \times \cos\left[\frac{2\pi}{T_0}(t - \tau_P)\right]$$

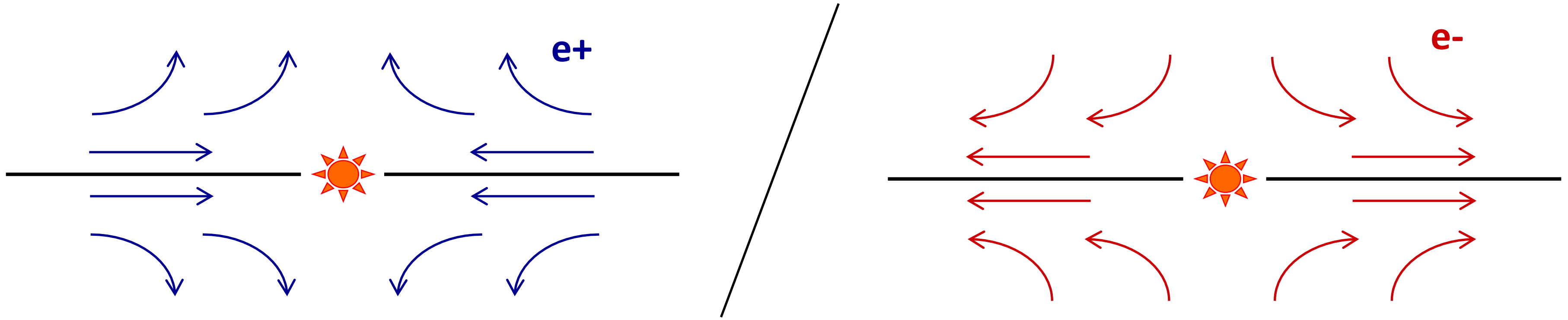


Insights from antimatter/matter ratios: drift









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