Long-term correlation between Solar activity and Cosmic-ray fluxes

Nicola Tomassetti
Università degli Studi di Perugia

Solar Modulation and Dark Matter Workshop
14-19 Novembre 2021 - IFPU Trieste, Italy

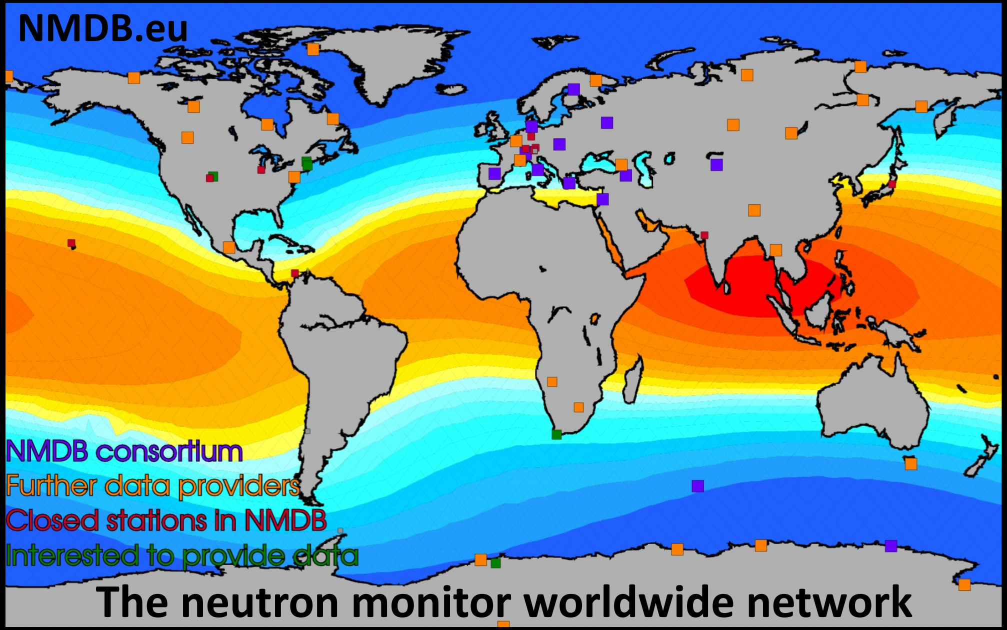
A.D. 1308
unipg
DIPARTIMENTO
DI FISICA E GEOLOGIA

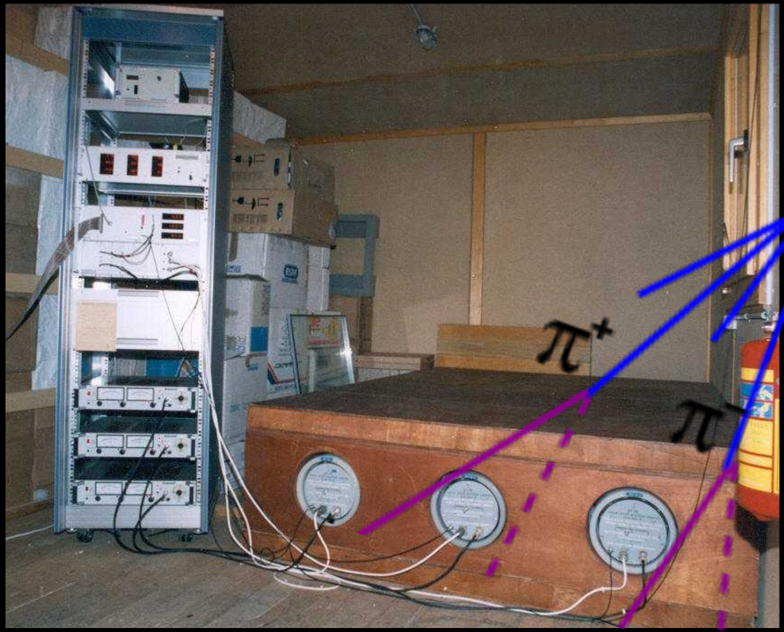
Università degli Studi di Perugia

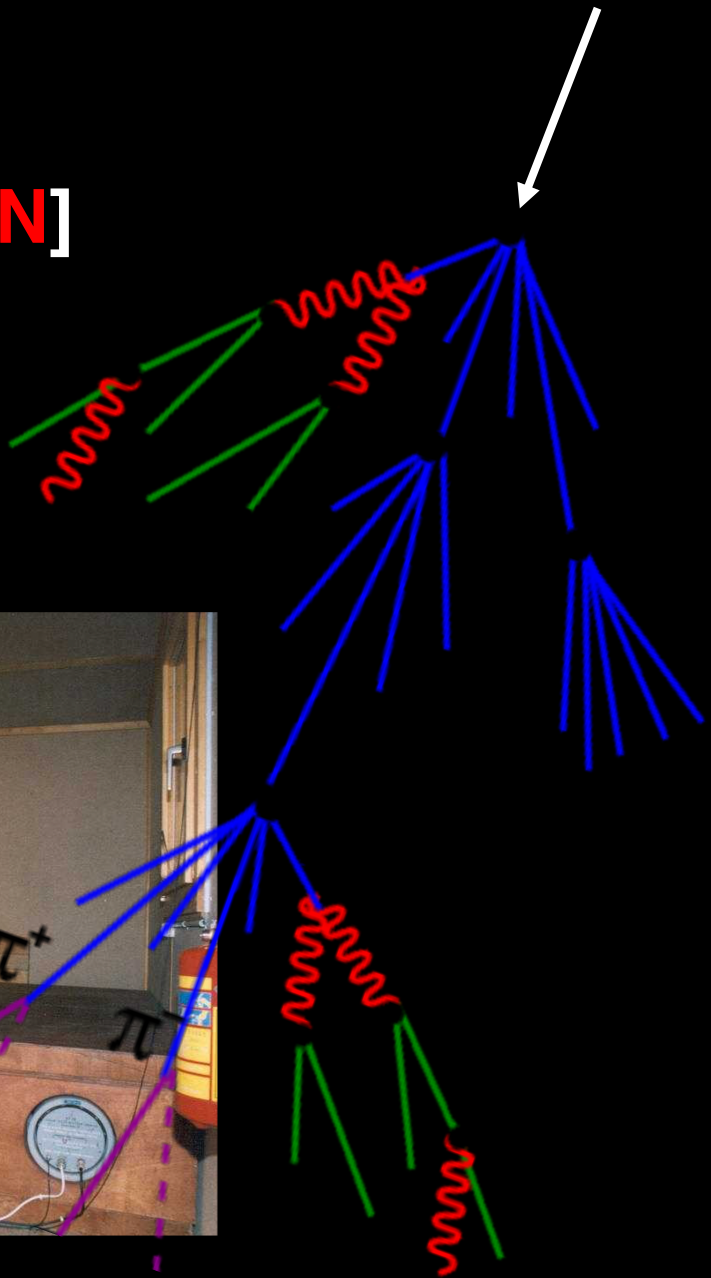
C.R.I.S.P. ASI-UniPG 2019-2-HH.0

What we have investigated

Cross-correlation between Solar activity [SSN] and Cosmic ray fluxes [Neutron Monitors] over [5] Solar Cycles [20-24]

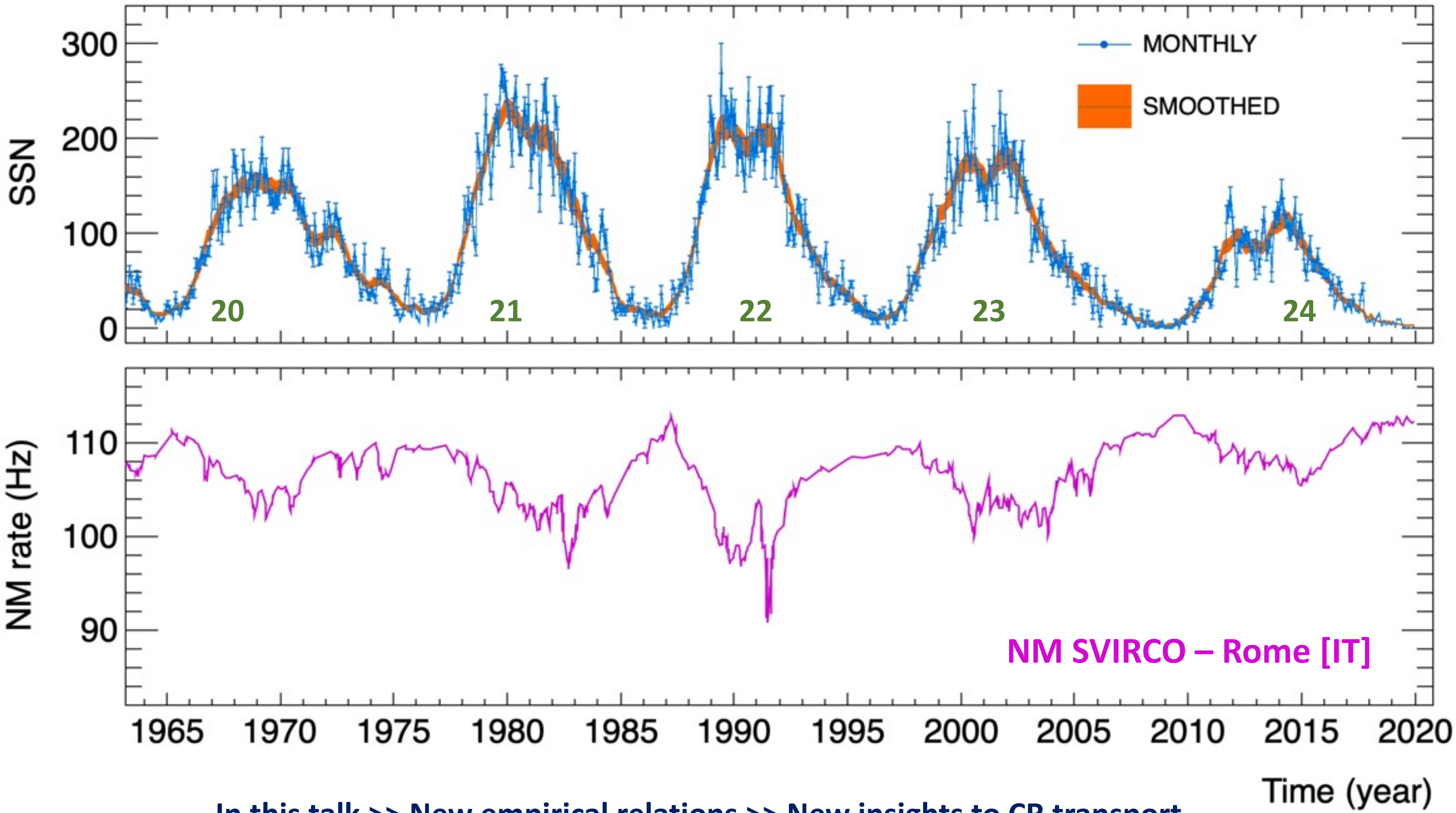






Solar activity, Neutron Monitor rates, Cosmic-ray modulation

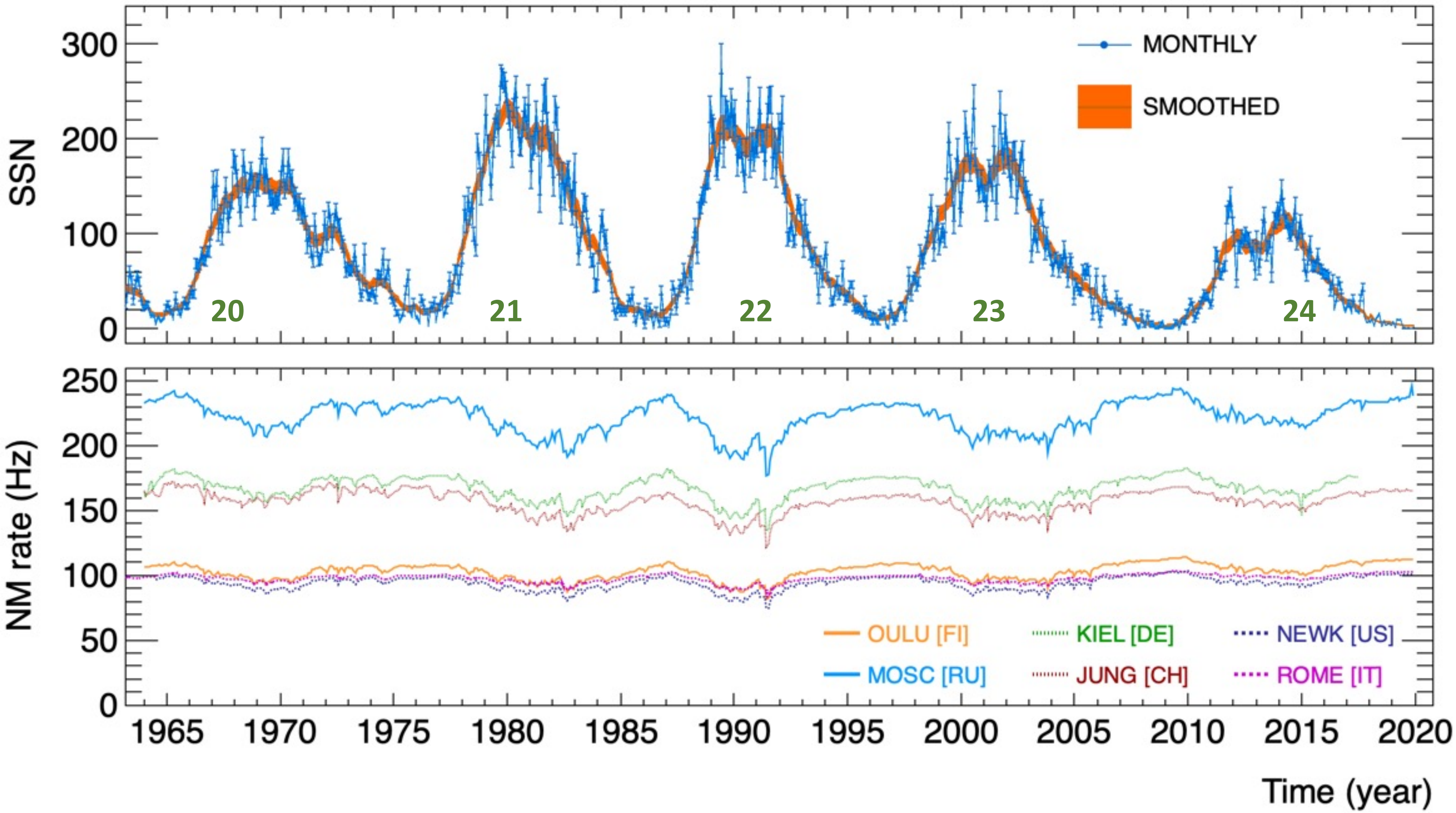
the anticorrelation plot



In this talk >> New empirical relations >> New insights to CR transport

Solar activity, Neutron Monitor rates, Cosmic-ray modulation

the anticorrelation plot



Relation between neutron monitor rates and varying cosmic-ray fluxes

Counting rate of neutron monitor "d" at epoch t

$$\Gamma^d(t) = \int_0^\infty \sum_{k=CRs} H_k^d(E) \cdot Y_k^d(E) \cdot J_k(t,E)$$

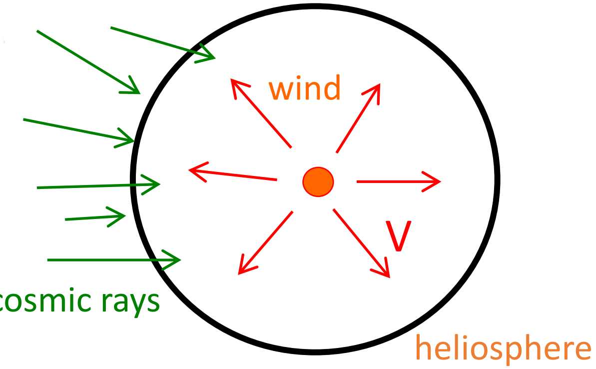
NM counting rate — geomagnetic transmission — NM yield function — The varying CR fluxes

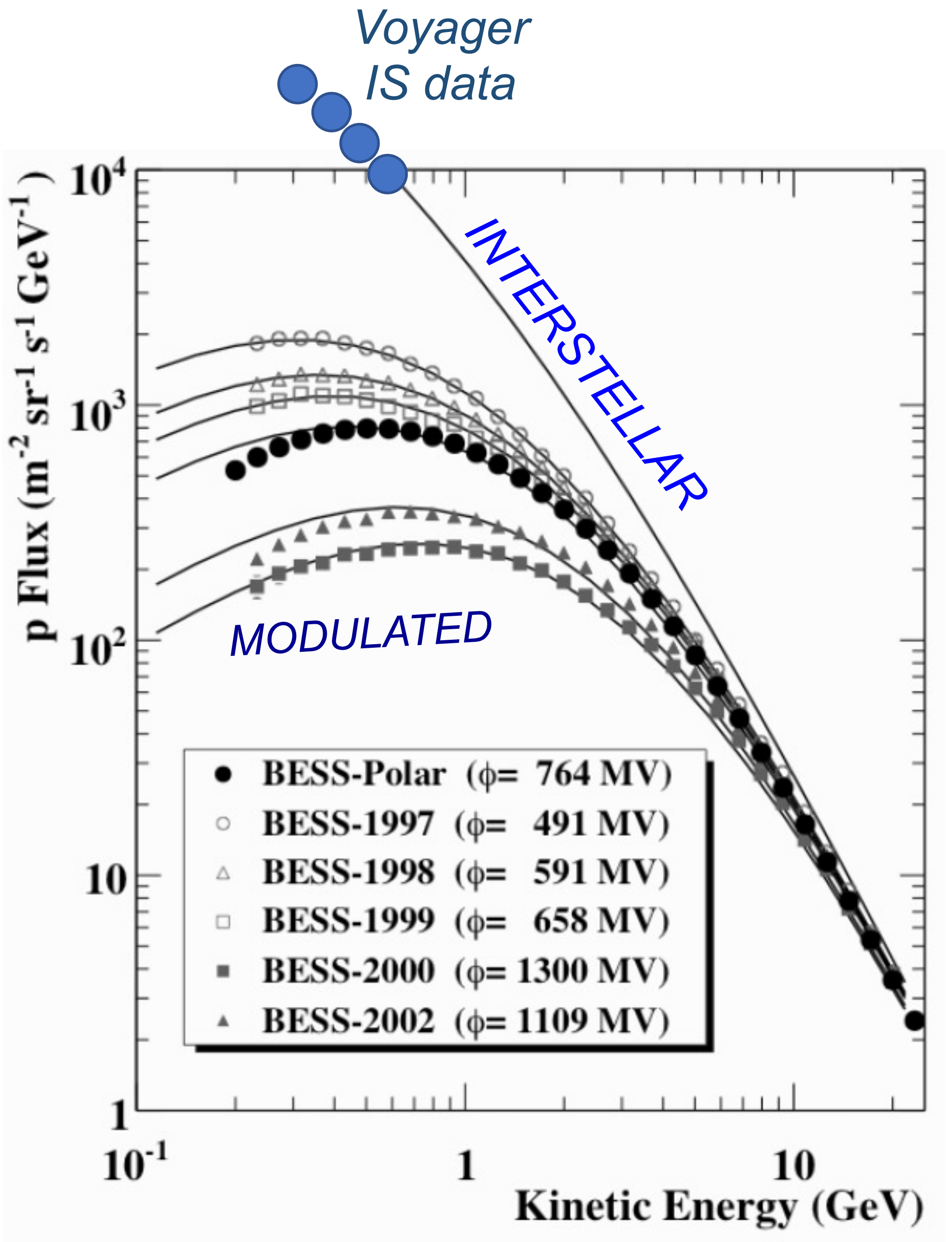
Modeling J(t,E) in the simplest way: FFA

When entering the heliosphere, CRs are slowed down by the expanding wind. Force-Field: *energy loss per charge unit* ϕ

$$J(E) = \frac{(E+m_p)^2 - m_p^2}{(E+m_p+\frac{|Z|}{A}\phi)^2 - m_p^2} \times J^{IS}\left(E + \frac{|Z|}{A}\phi\right)$$

$$E = E^{IS} - \frac{|Z|}{A}\phi.$$





Relation between neutron monitor rates and varying cosmic-ray fluxes

From ground: counting rates of different NMs at different location

NM station	NEWK	OULU	KIEL	JUNG	ROME
Detector type	9-NM64	9-NM64	18-NM64	3-NM64	20-NM64
Location	Newark US	Oulu FI	Kiel DE	Jungfraujoch CH	Rome IT
Coordinates	39.68 N 75.75 W	65.05 N, 25.47 E	54.34 N, 10.12 E	46.55 N, 7.98 E	41.86 N, 12.47 E
Altitude	50 m	15 m	54 m	3570 m	0 m
Cutoff	2400 MV	810 MV	2360 MV	4500 MV	6270 MV

From space: direct GCR flux measurements of various elements

PAMELA [p, He]

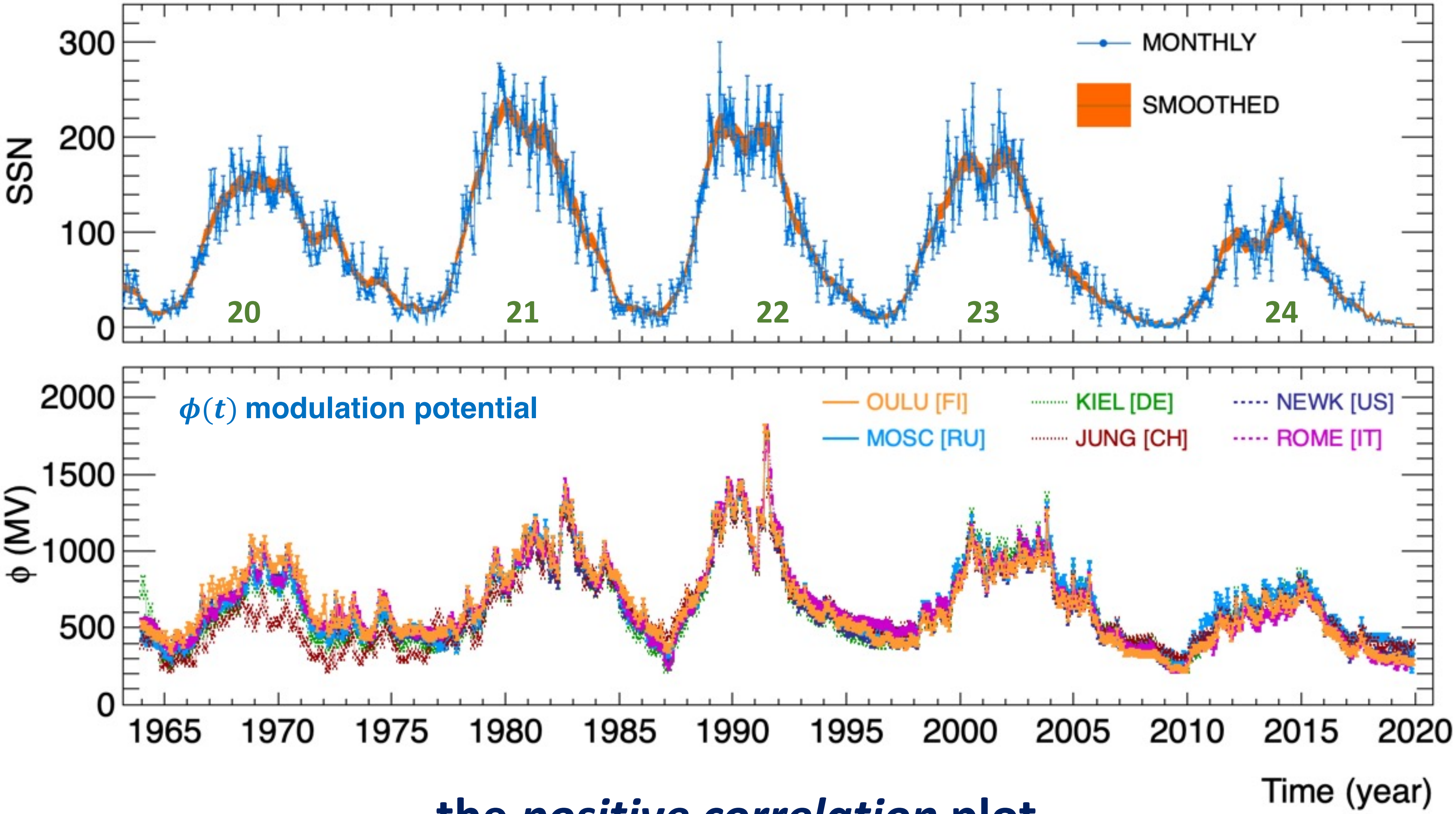
AMS / ISS [p, He]

EPHIN / SOHO [p]

CRIS / ACE (C)

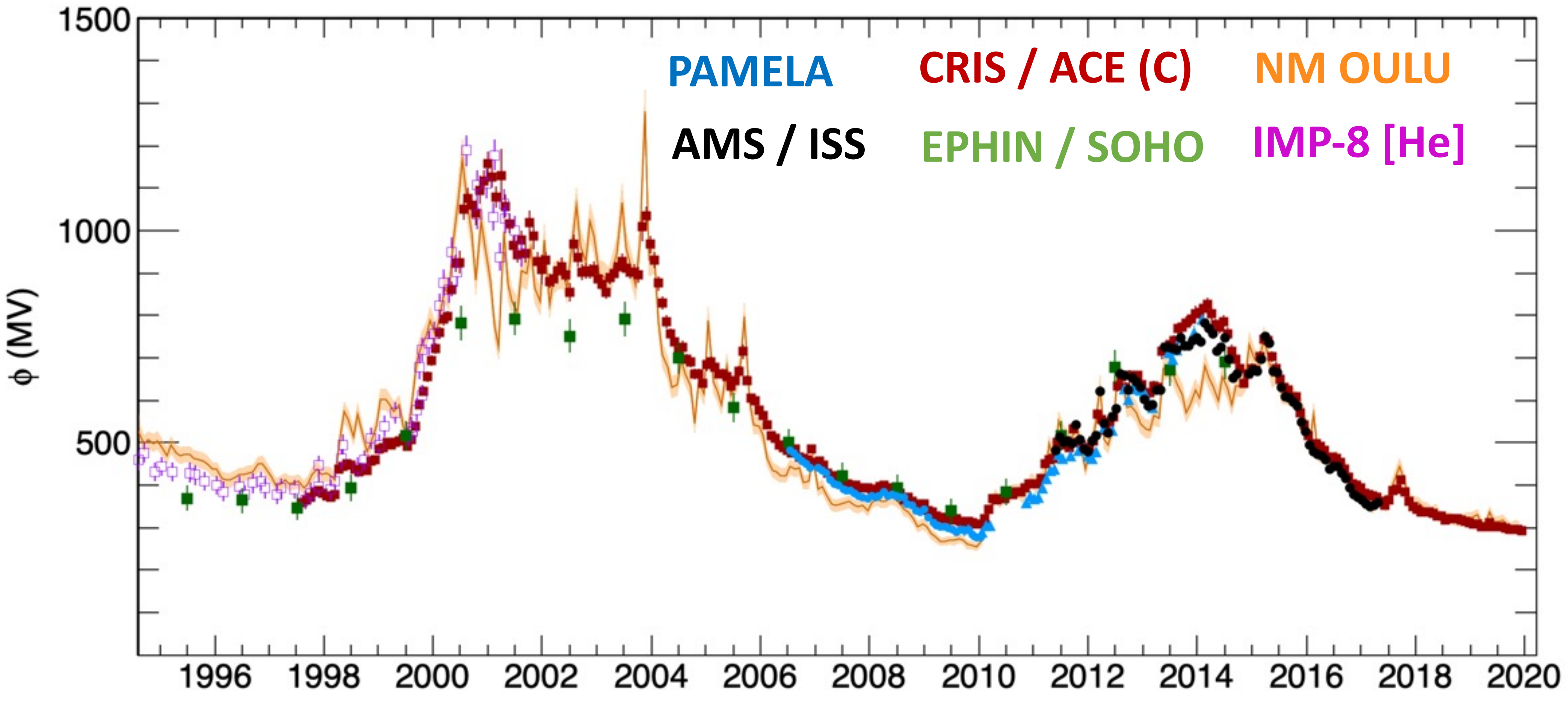
IMP-8 [He]

Solar activity and Cosmic-ray modulation



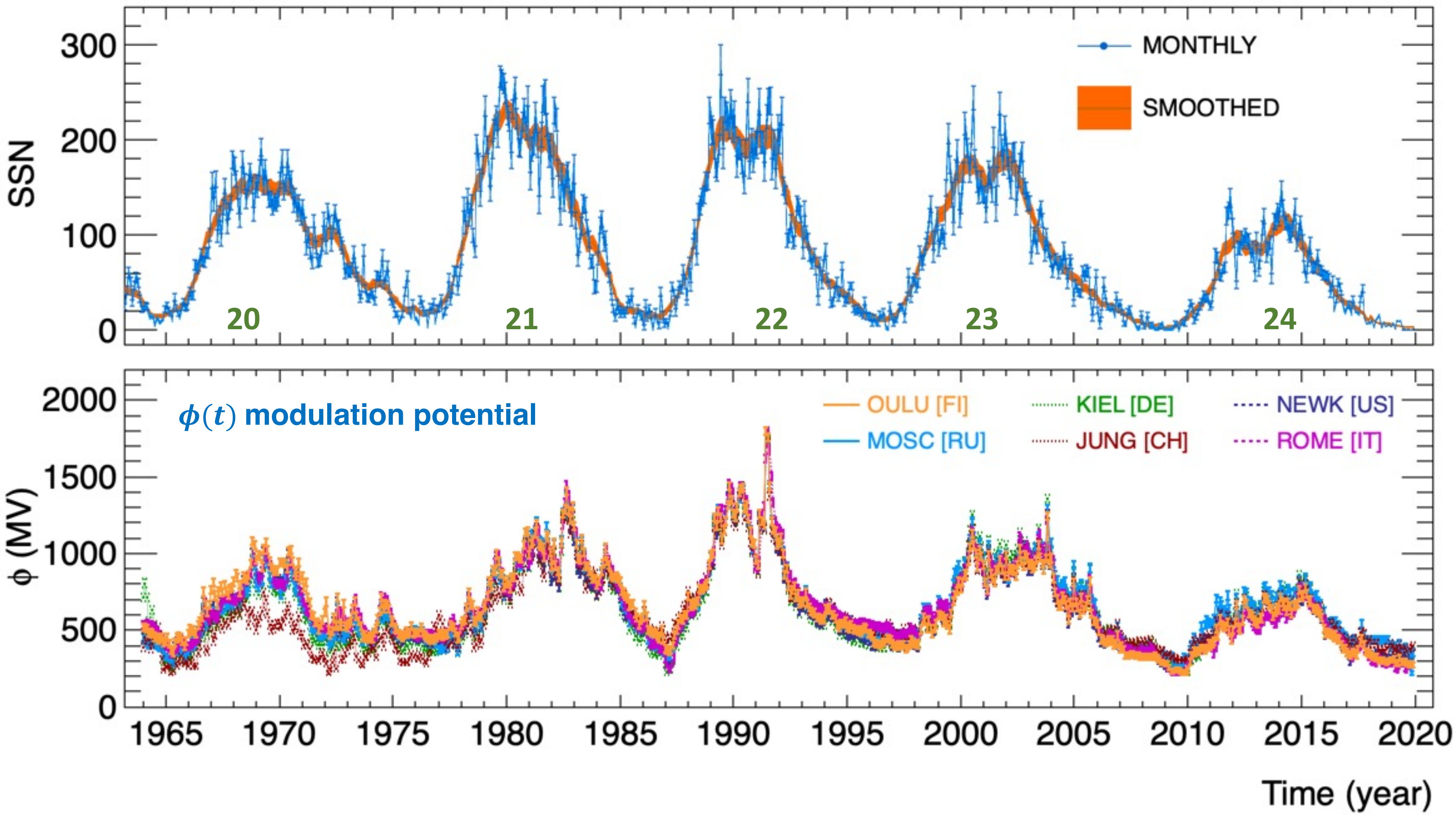
the *positive correlation* plot

Solar activity and Cosmic-ray modulation



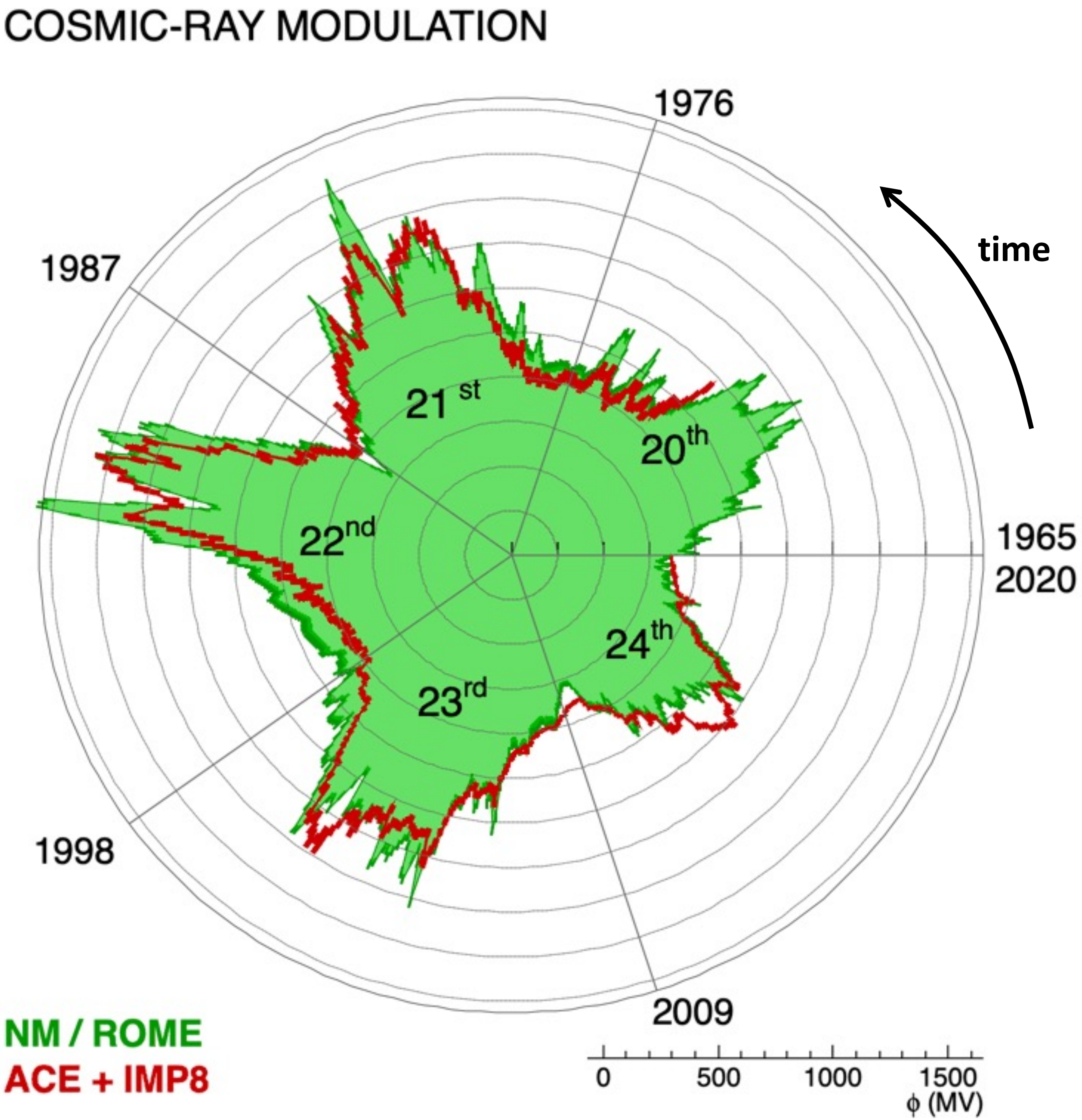
Comparing NM data with direct CR measurements in space

Lag between Solar activity and Cosmic-ray modulation



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

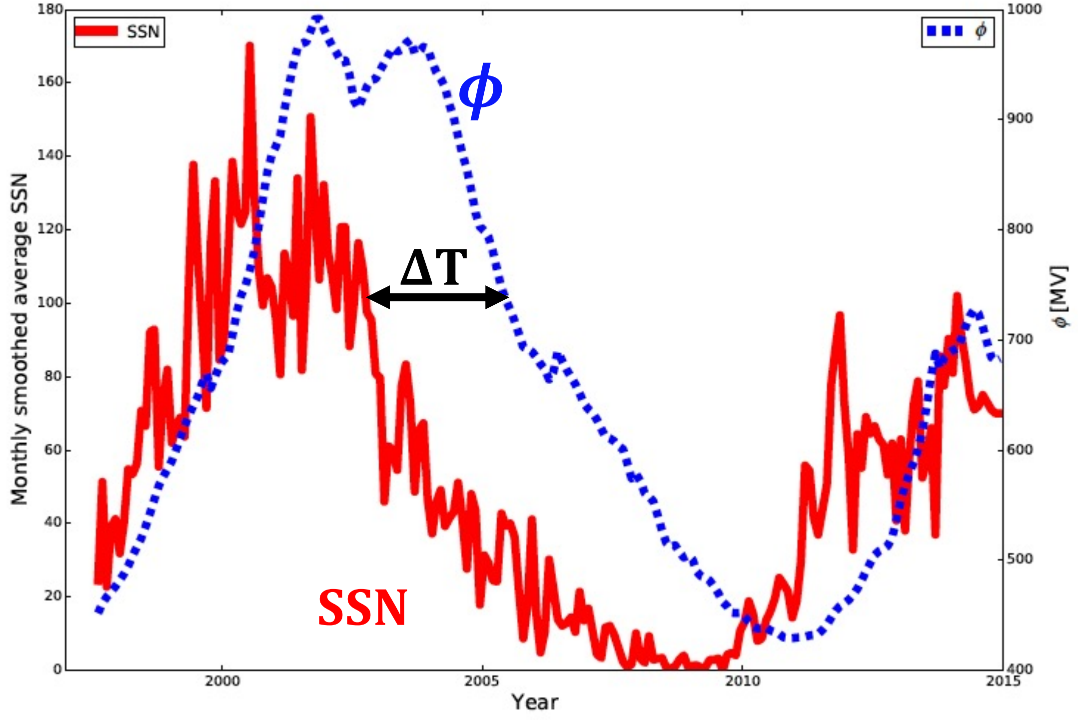
$\phi(t)$
$SSN(t)$

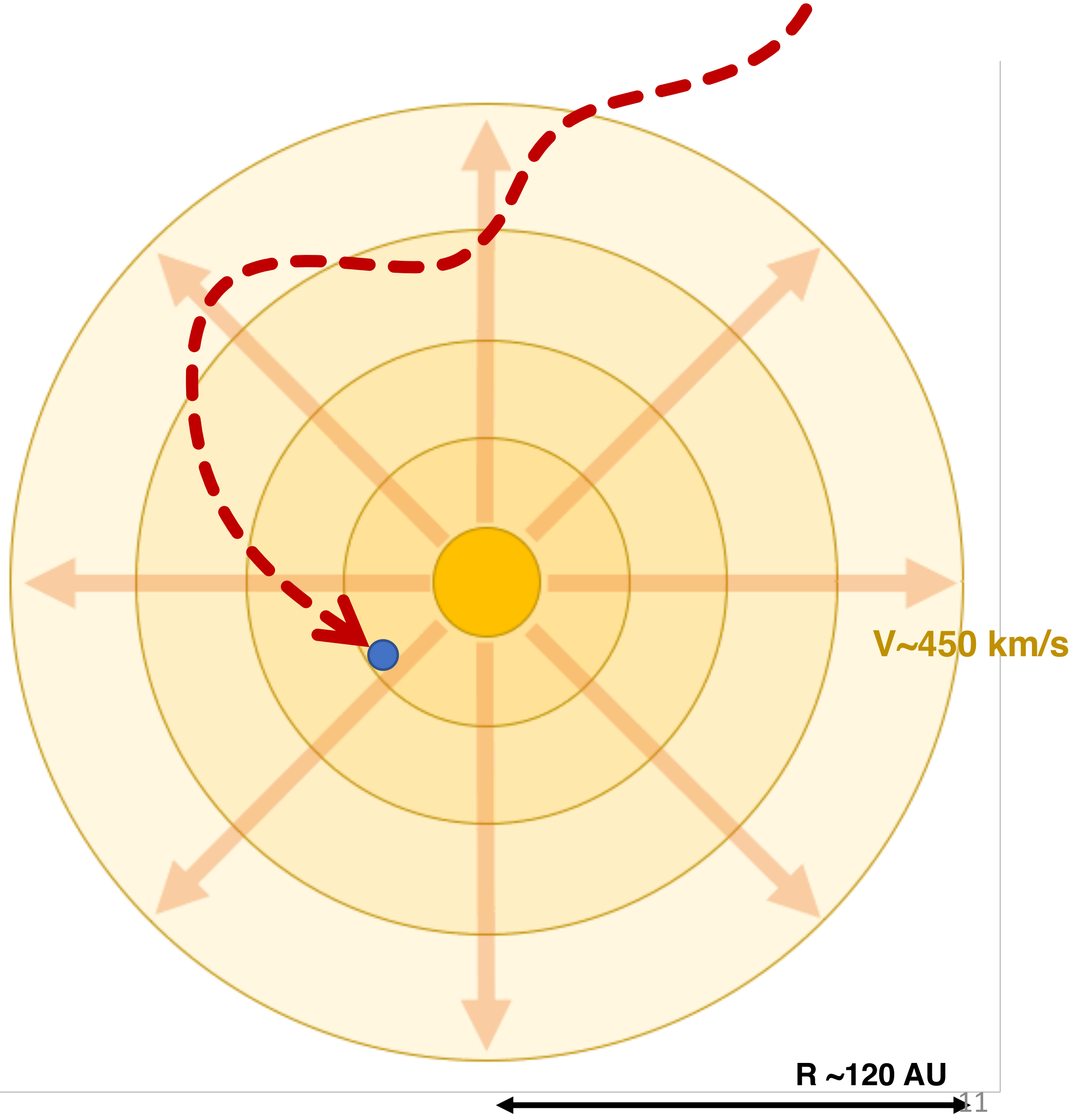

COSMIC-RAY MODULATION
1976
1987
1965
2020
1998
2009
21 st
20th
22nd
23rd
24th
time
NM / ROME
ACE + IMP8
0
500
1000
1500
ϕ (MV)

Time Lag between Solar Activity and Modulation

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

Example: lag between ϕ and SSN (magnified)

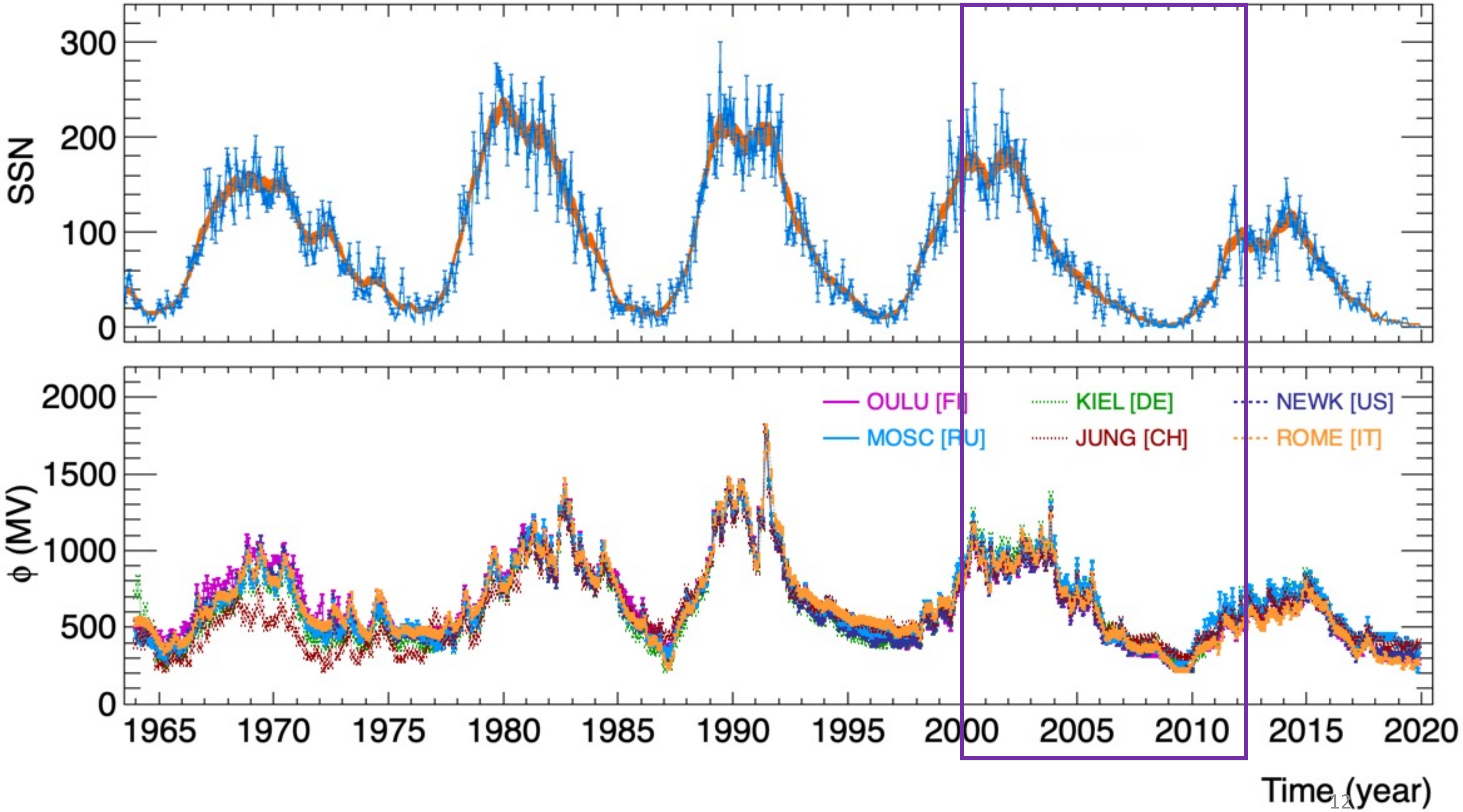




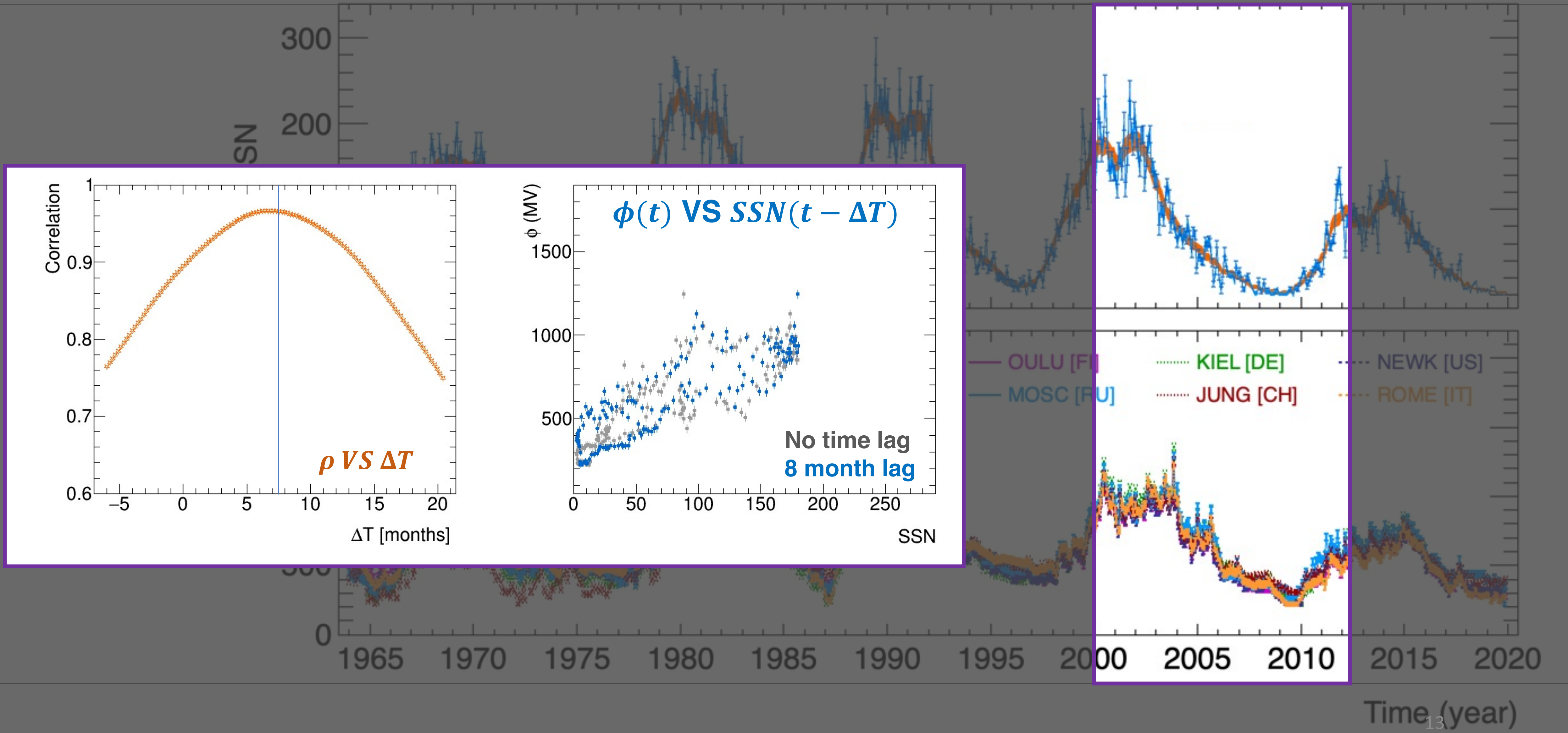
NT+ 2017, ApJ 849 L32: we incorporated the lag in a numerical model of CR tranpsort in heliosphere. Using space CR data, we found: $\Delta T \approx 8\, months$

Other studies with NM reported: $\Delta T \approx 0\ to\ 20\, months$ (?)
Different lags from different cycles? ODD/EVEN effects?

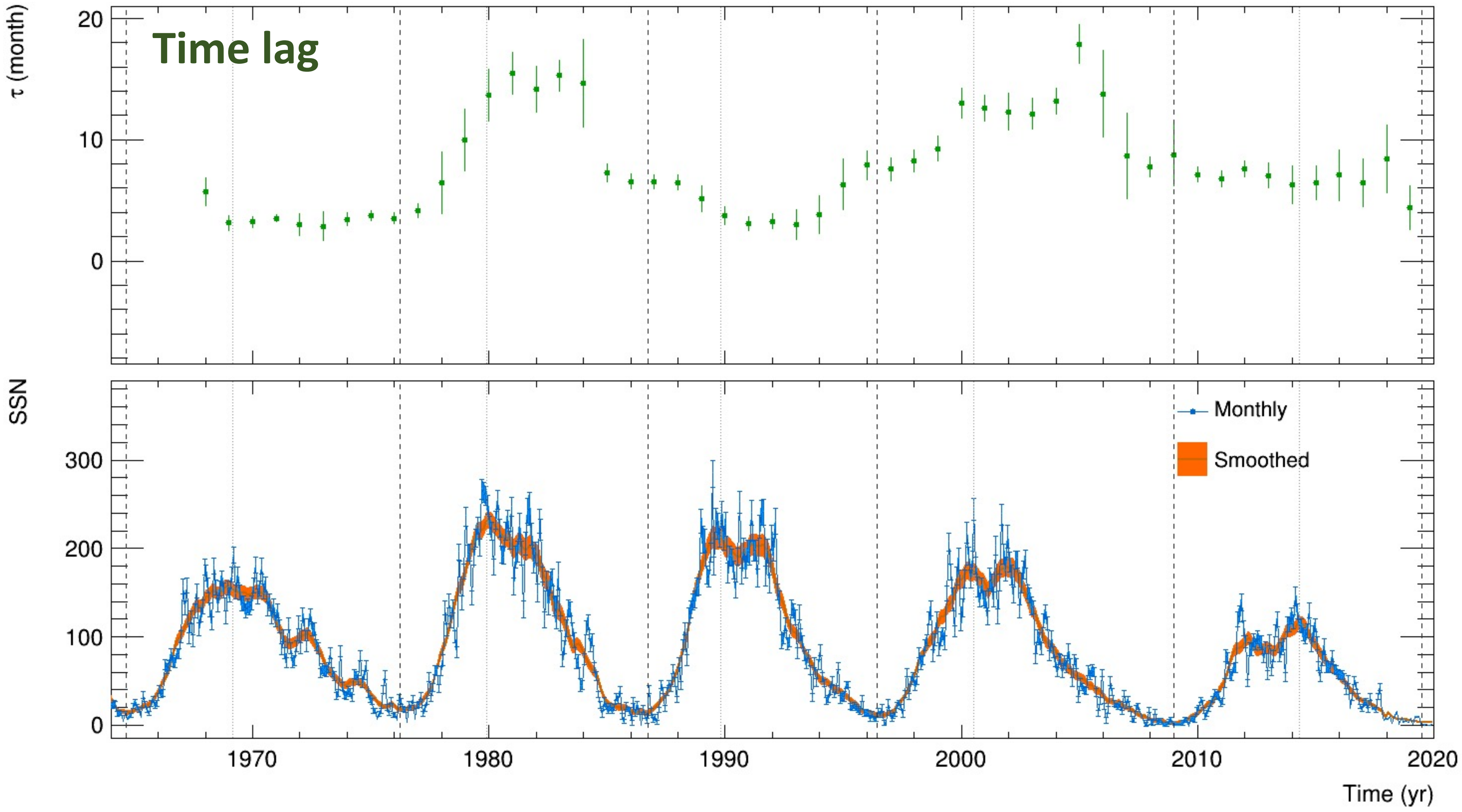
Time Lag between Solar Activity and Modulation



Time Lag between Solar Activity and Modulation

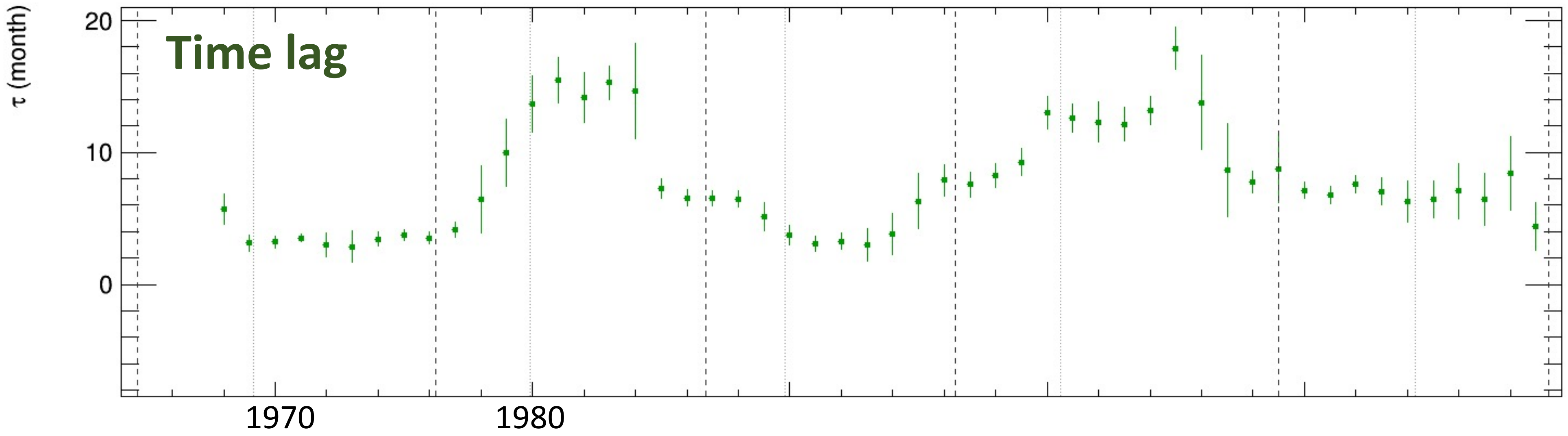


Evolution of the Lag over the Solar Cycle



- ✓ A lag ΔT of a few months improves the correlation between $\phi(t)$ and $SSN(t-\Delta T)$
- ✓ The best time-lag parameter is seen to *evolve* over time, with the changing solar activity.

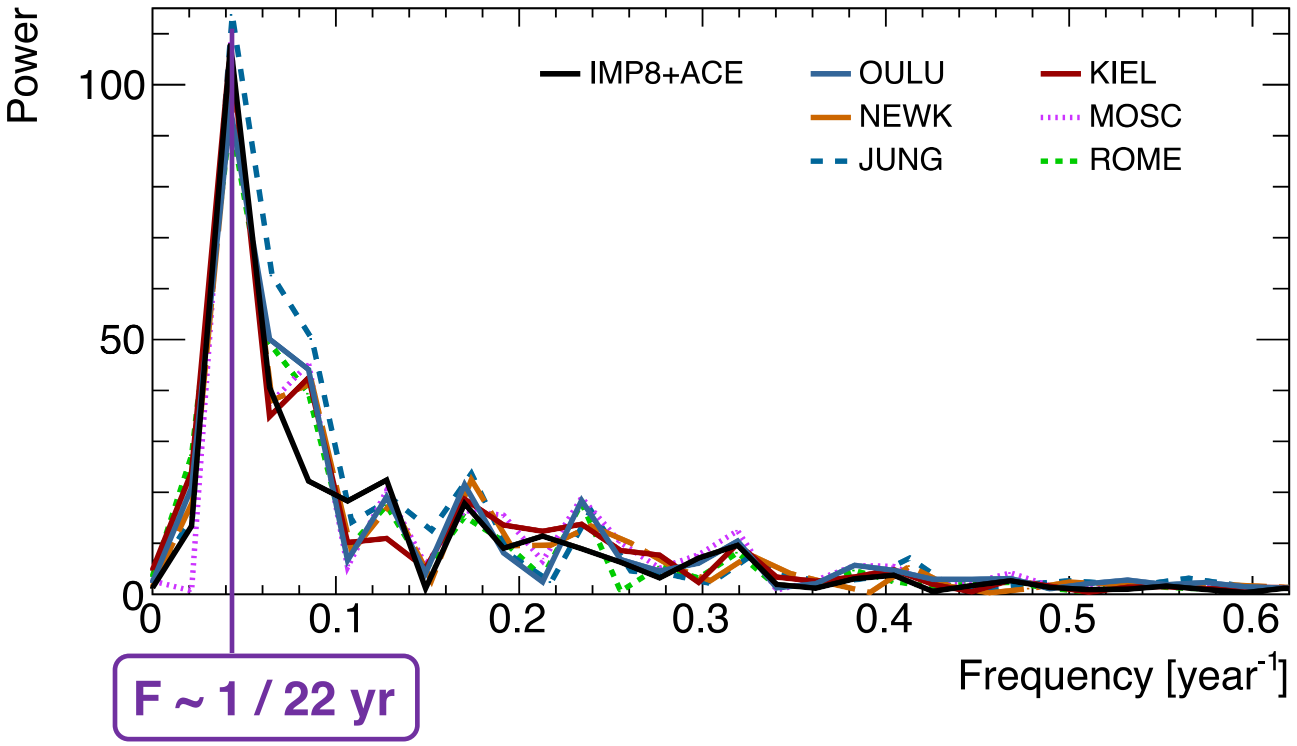
Evolution of the Lag over the Solar Cycle



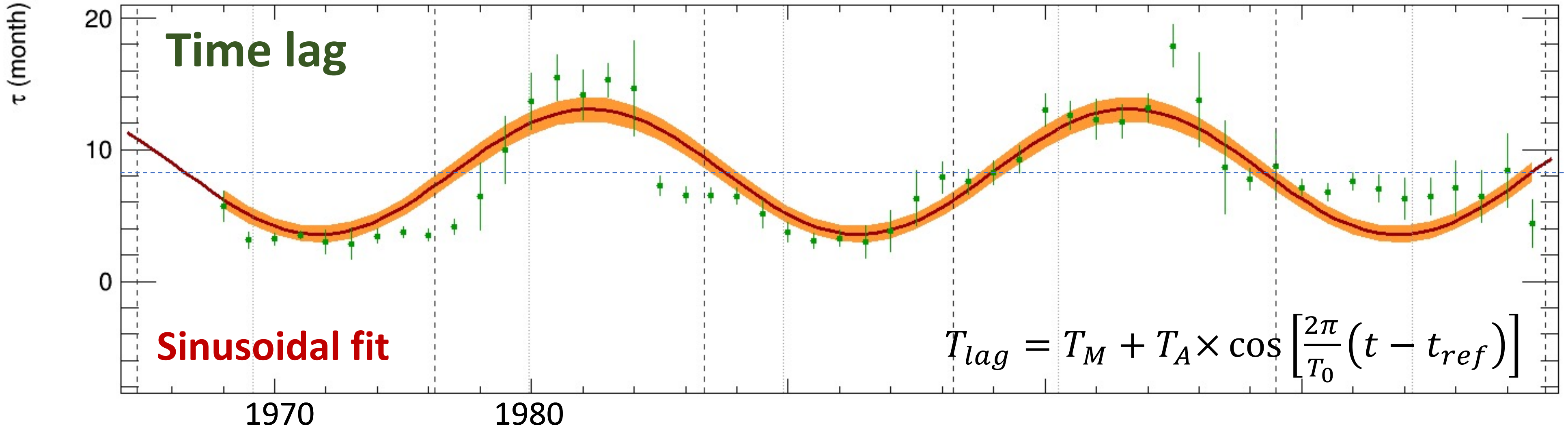
from time domain…
to frequency domain

Fast Fourier Transform →

Main periodicity:
T ~ 22 yr !!!



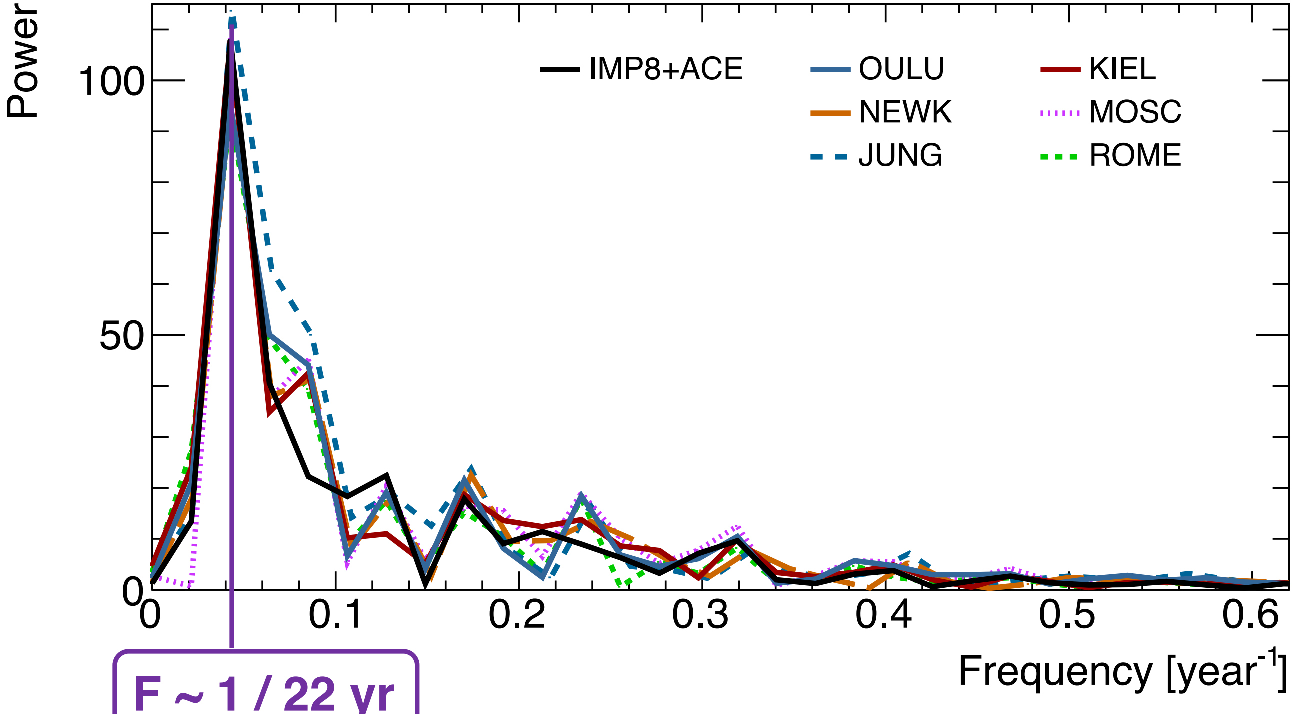
Evolution of the Lag over the Solar Cycle



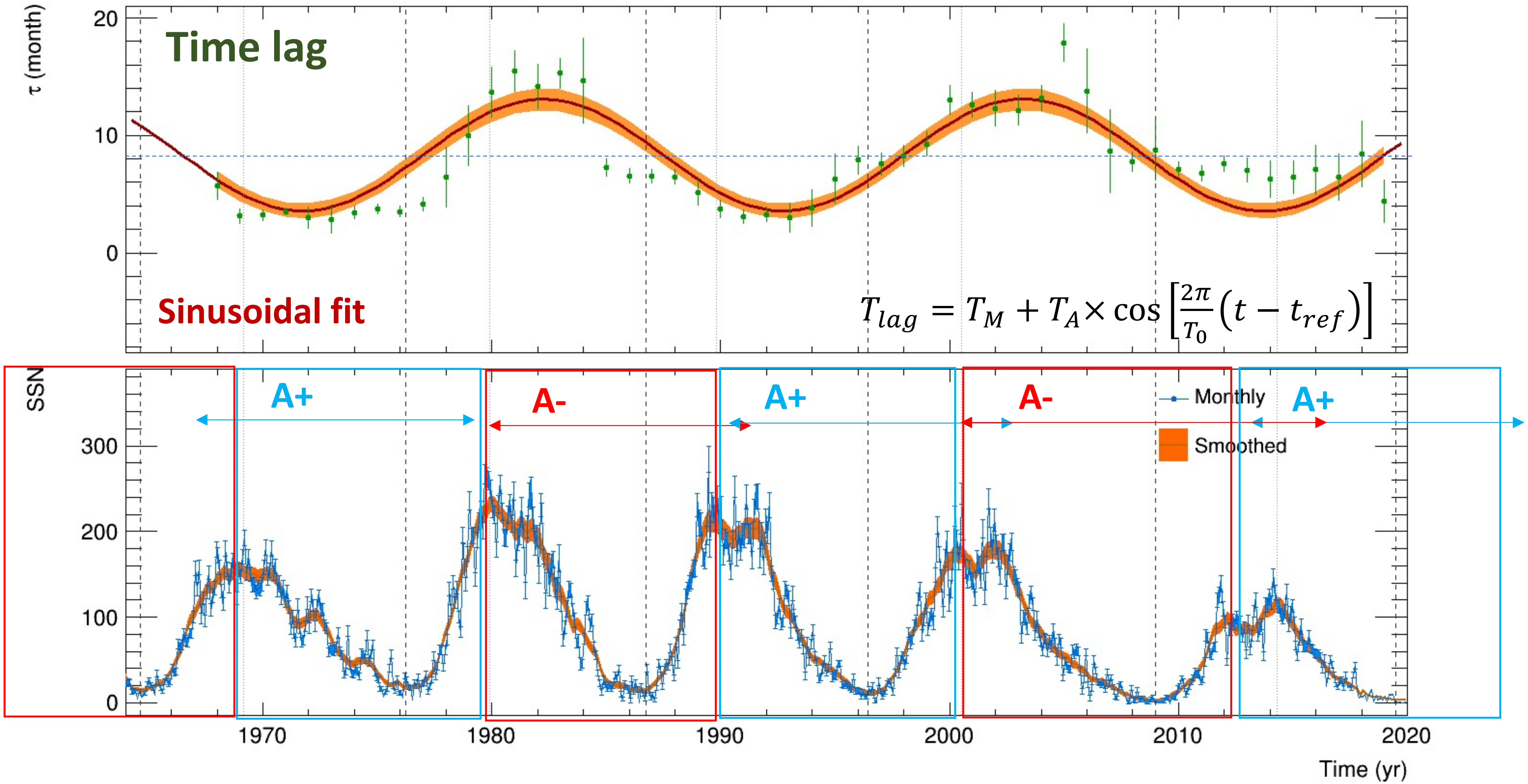
from time domain…
to frequency domain

Fast Fourier Transform →

Main periodicity:
T ~ 1 / 22 yr !!!



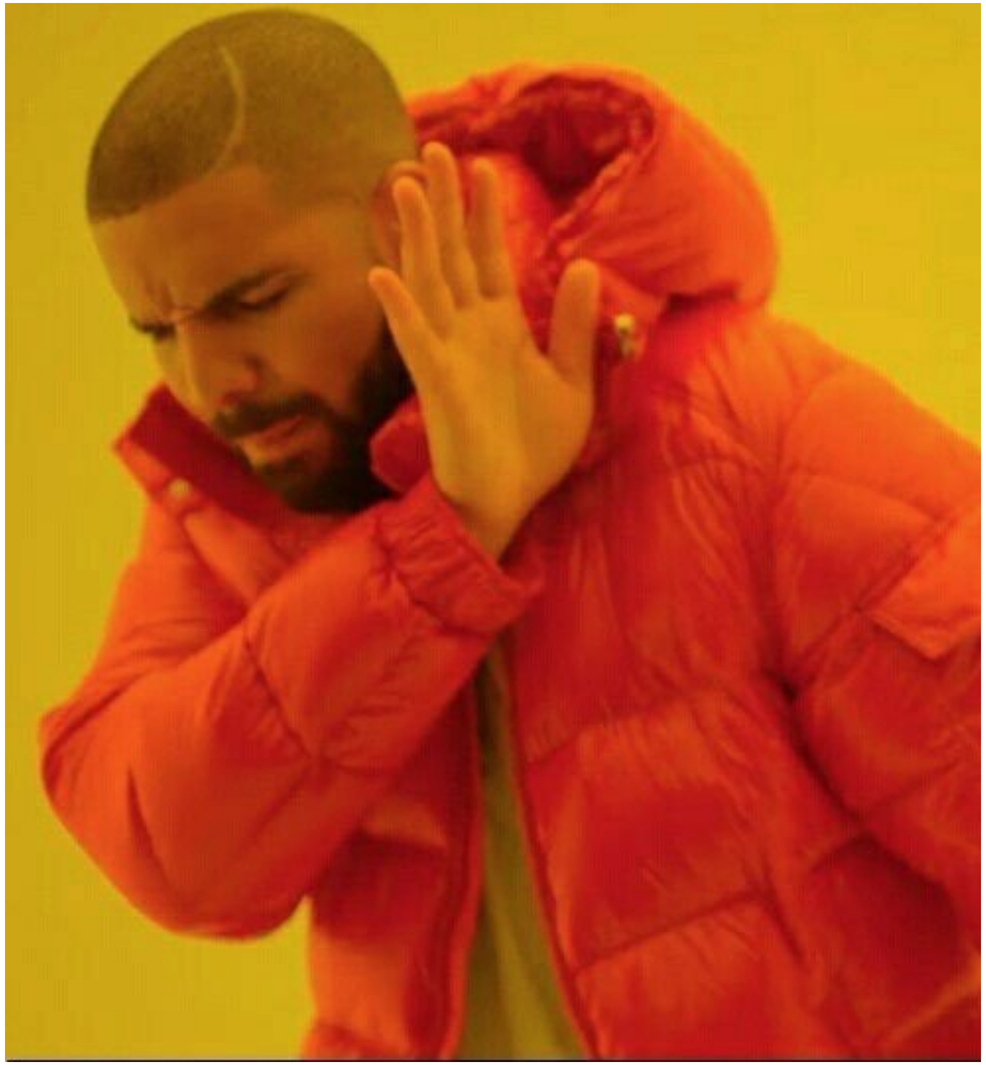
Evolution of the Lag over the Solar Magnetic Cycle

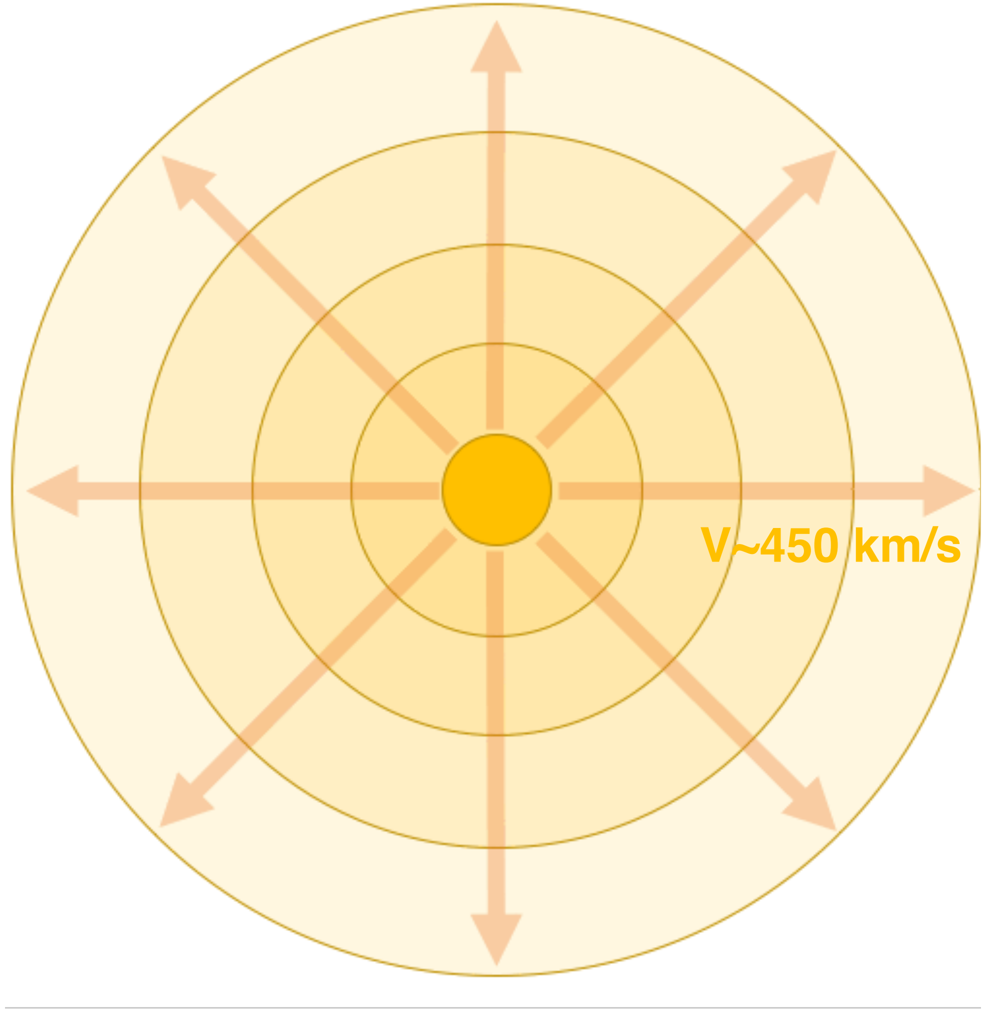


The time-lag appear correlated with the 22-yr magnetic cycle of the Sun.

Different lags are observed under periods of negative or positive polarity

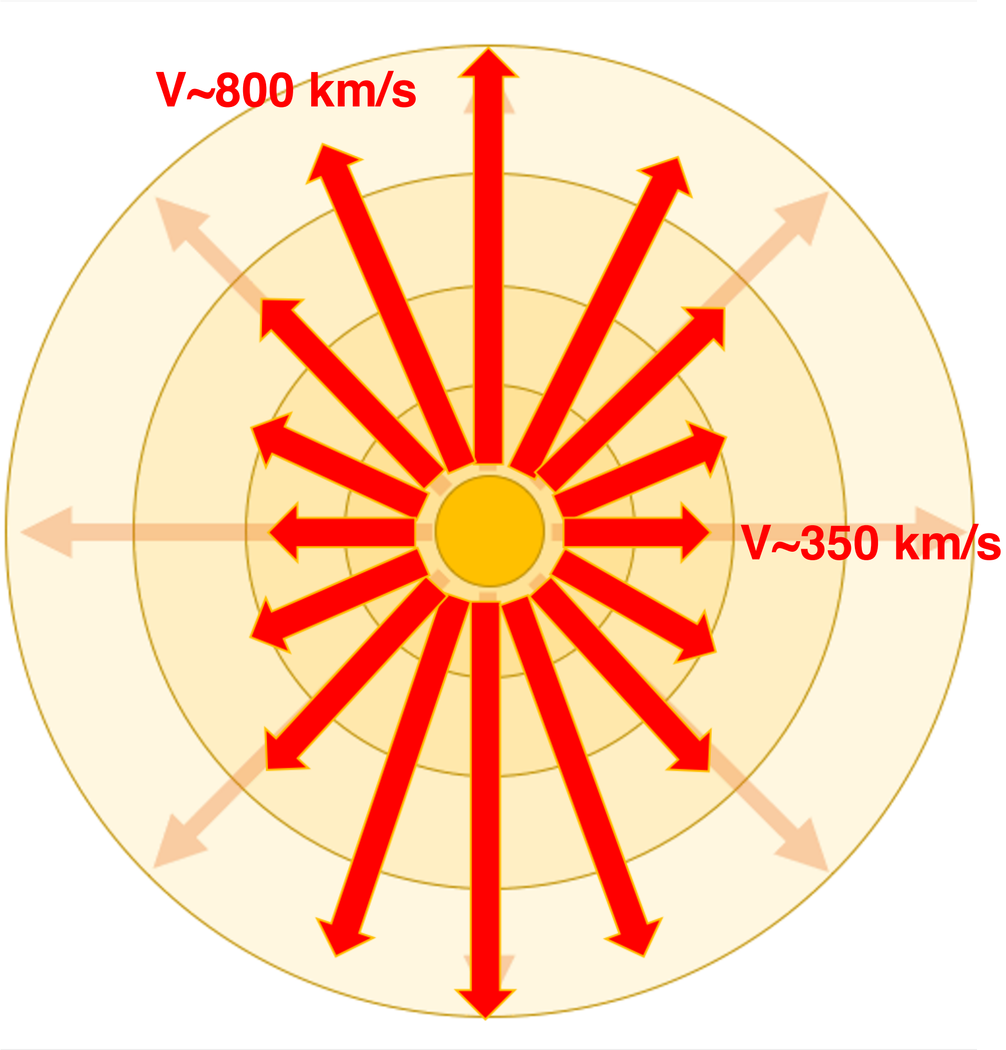
The solar Wind profile





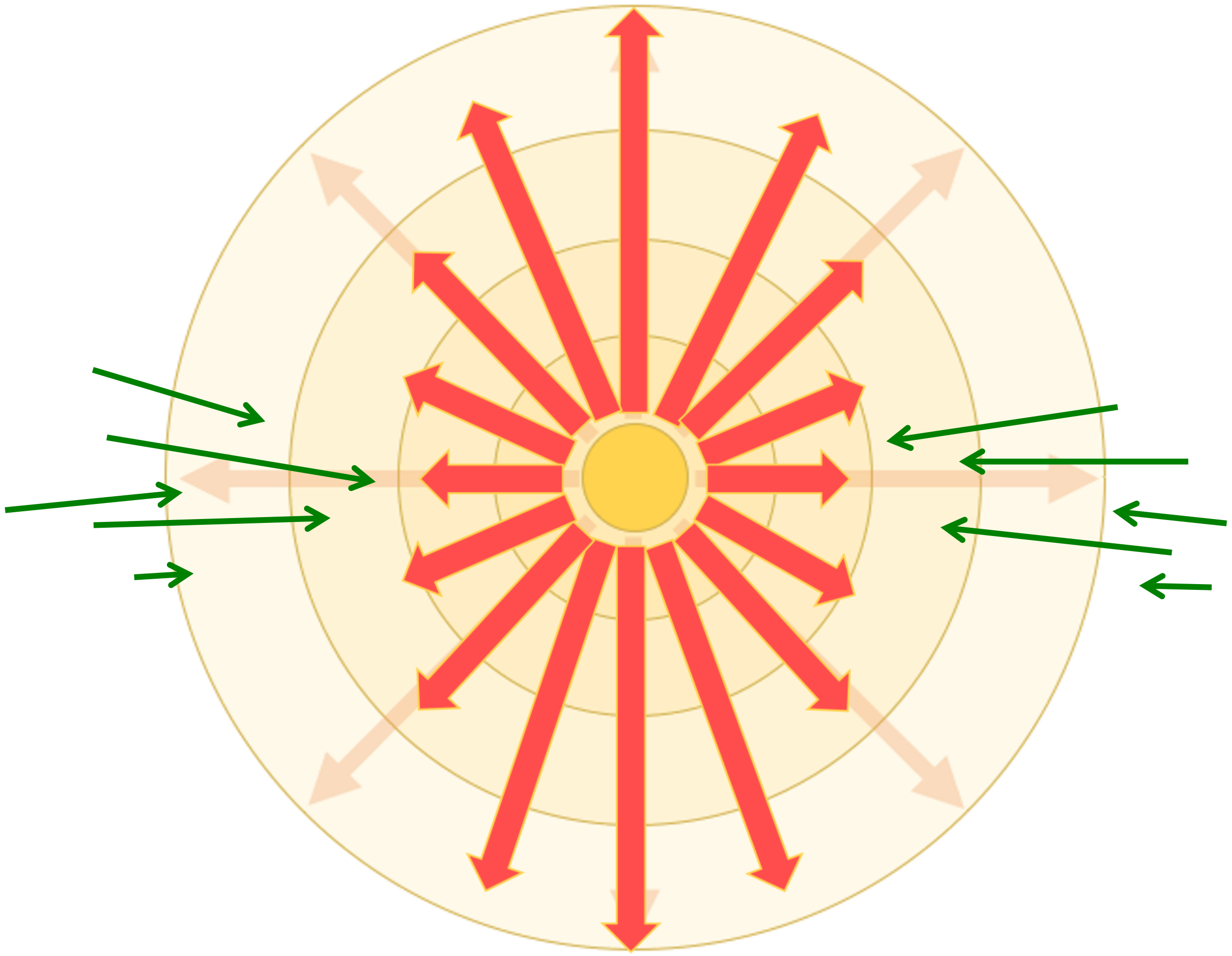
radially symmetric wind

The solar Wind profile



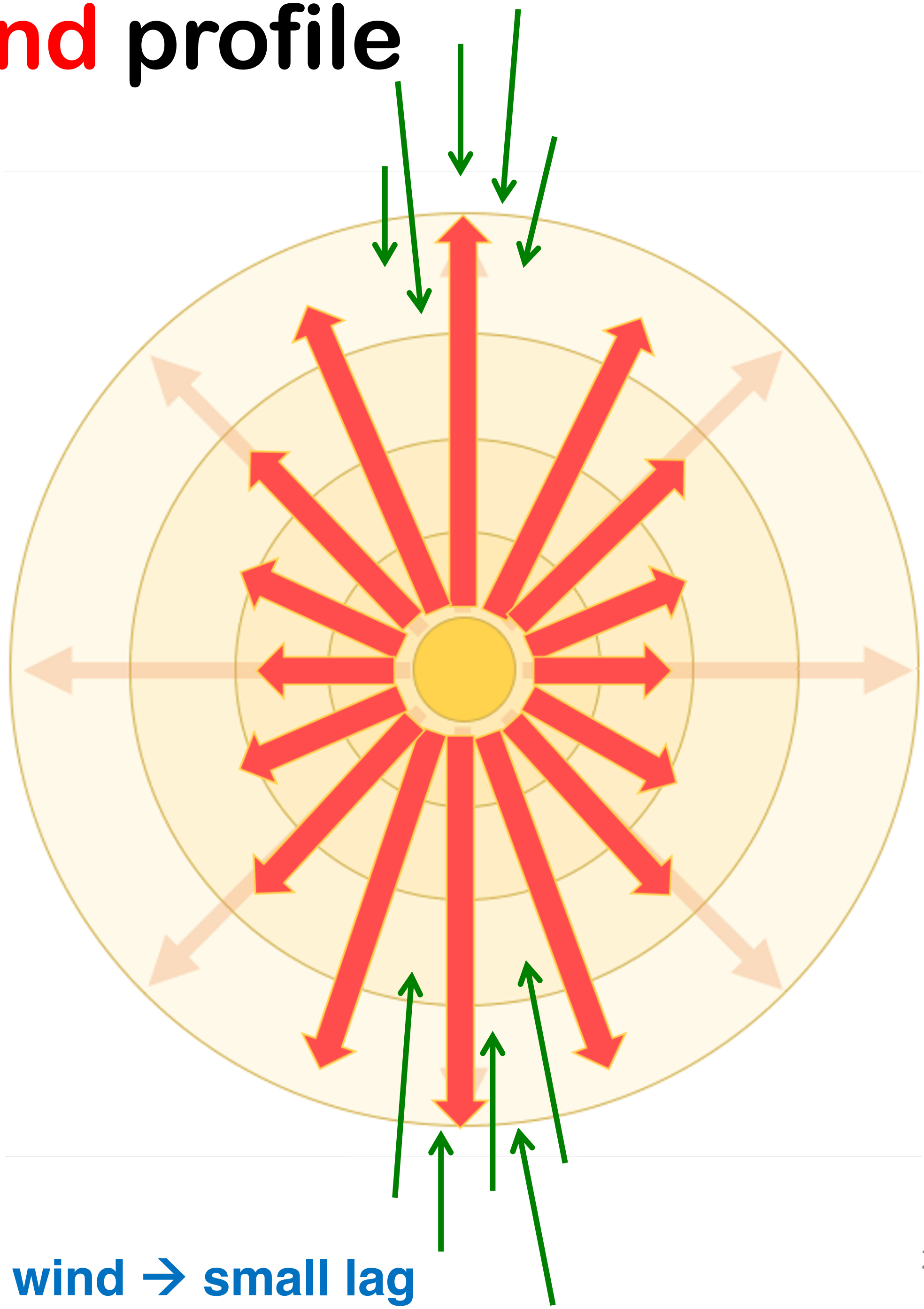
latitudinal profile $V(\theta)$ based on data

The solar Wind profile



Cosmic rays from equators → test a region with slow wind → large Lag

The solar **Wind** profile

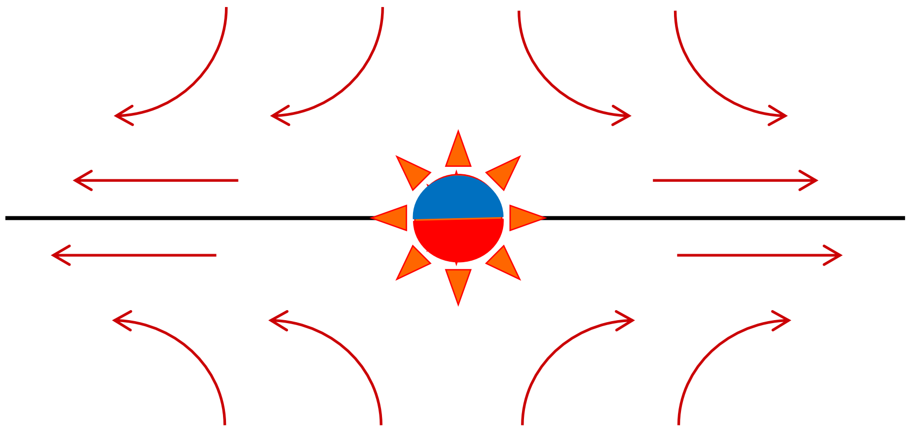


Cosmic rays from poles → test a region with fast wind → small lag

Heliospheric B-Field

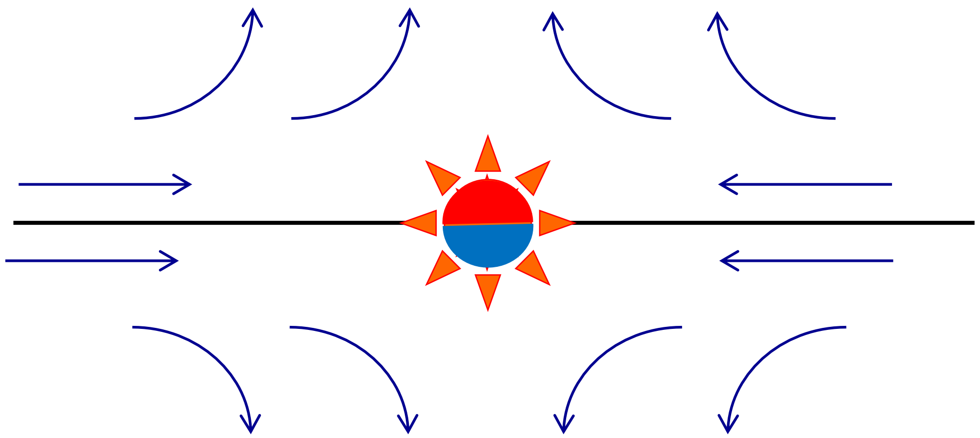
CRs experience drift motion through the large scale B-field of heliosphere, a magnetic dipole.

A+ positive polarity



CRs reach us passing from poles
They encounter fast wind
Short time lag: ~ 3-6 months

A- negative polarity



CRs reach us passing from equator
They encounter slow wind
Long time lag : ~ 9-13 months

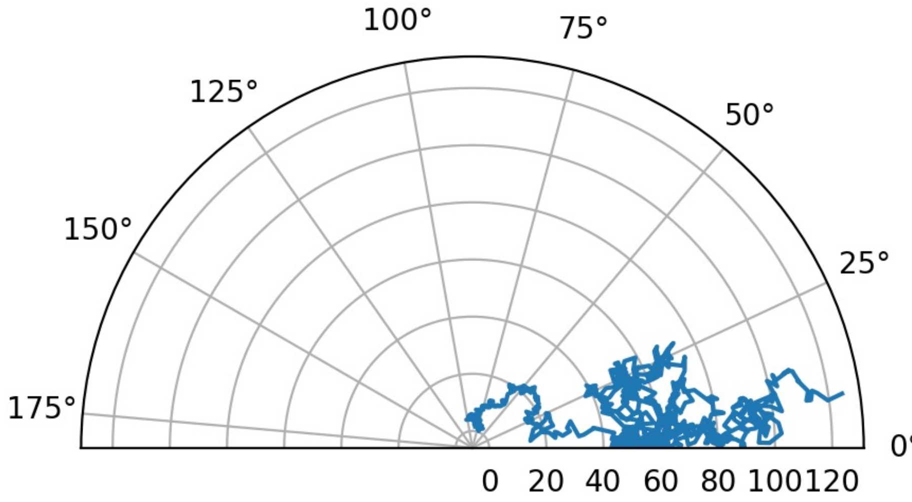
Heliosphere is a magnetic spectrometer. It selects/suppresses anti/particles from given directions

The evolution of the time-lag with the solar cycle is a remarkable signature of charge-sign dependent drift in the transport of CRs through the Heliosphere

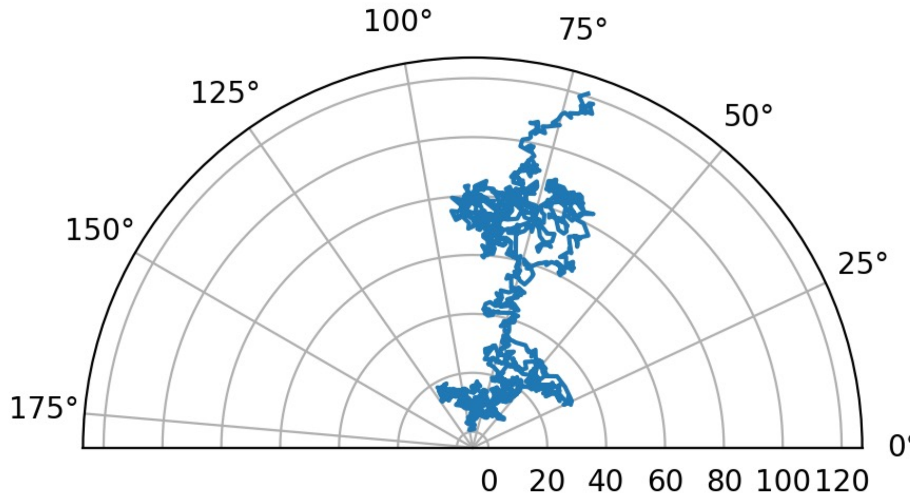
Heliospheric B-Field

CRs experience drift motion through the large scale B-field of heliosphere, a magnetic dipole.

A+ positive polarity



A- negative polarity



Monte-Carlo simulations of CR trajectories including drift motion

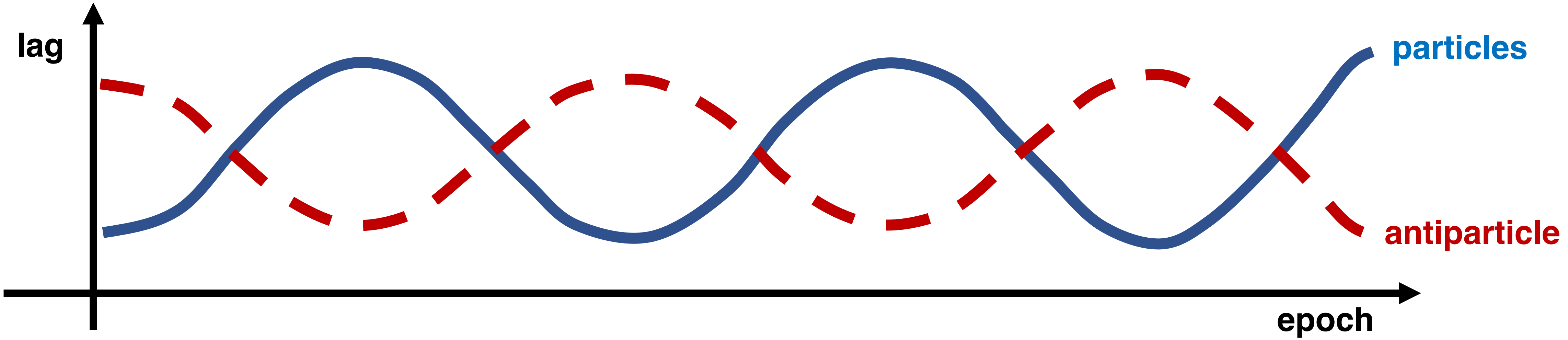
The evolution of the time-lag with the solar cycle is a remarkable signature of <u>charge-sign dependent drift</u> in the transport of CRs through the Heliosphere

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

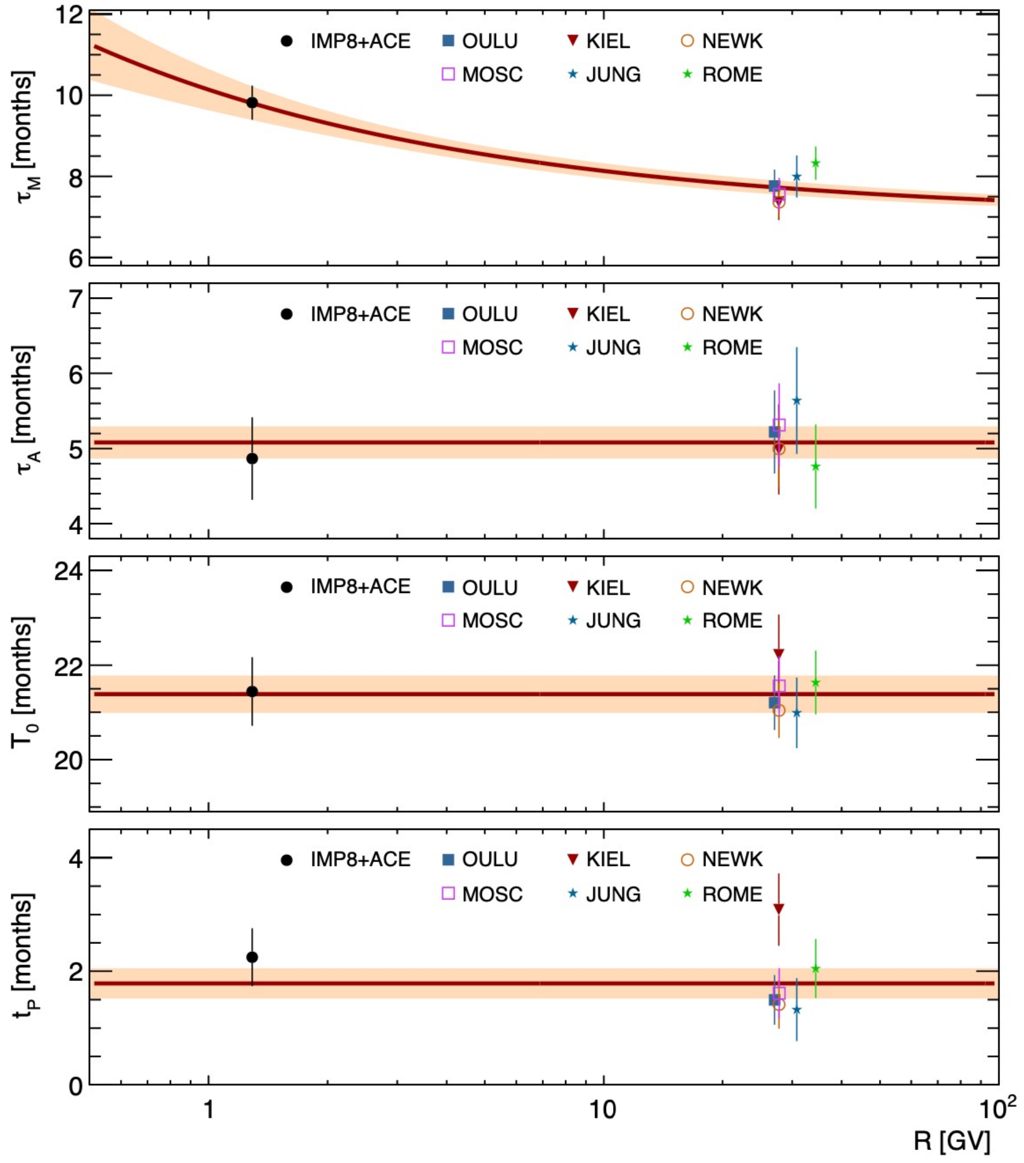
- **During A+ polarity states, CR protons come to us through the polar regions. Fast wind, short lag.**
- **During A- polarity states, CR protons come to us through the equators. Slow wind, large lag.**

Thus, the observed evolution of the time-lag is a remarkable signature (and independent evidence) of charge-sign dependent drift in the modulation of cosmic rays in the Heliosphere

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



Rigidity dependence?



Semi-empirical formula to describe lag evolution

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

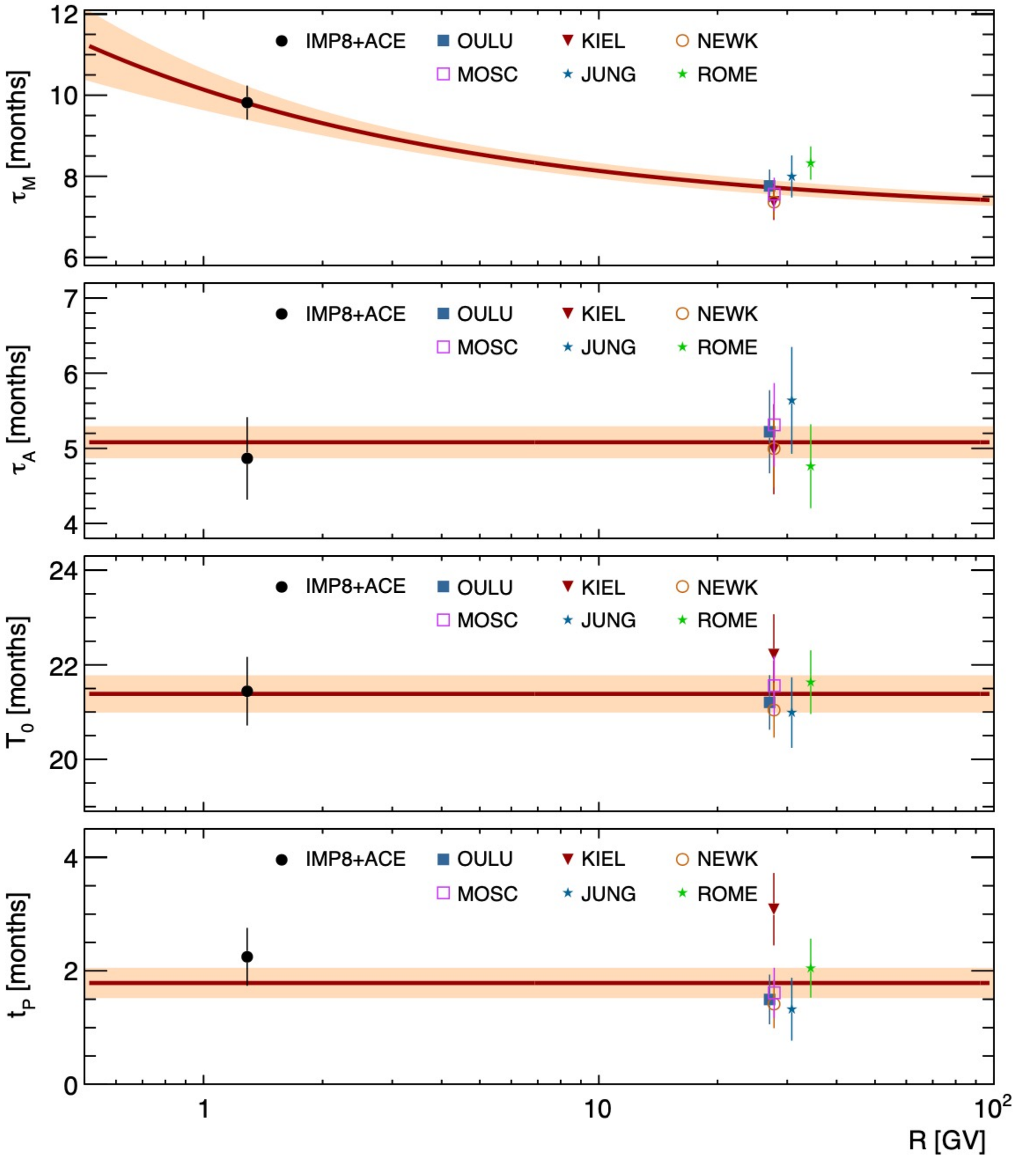
Determine the free parameters for the many time series (6 NM stations + space data)

Determine the mean GCR rigidity R for data set

- **IMP+ACE ➔ use data at 1 GV**
- **NM ➔ data at ~25-30 GV (from their GMF cutoff)**

Plot best-fit parameters as function of rigidity

Rigidity dependence?



Semi-empirical formula to describe lag evolution

$$\tau^d(t) = \tau_M^d + \tau_A^d \cdot \cos\left[\frac{2\pi}{T_0^d}\left(t - t_P^d\right)\right]$$

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

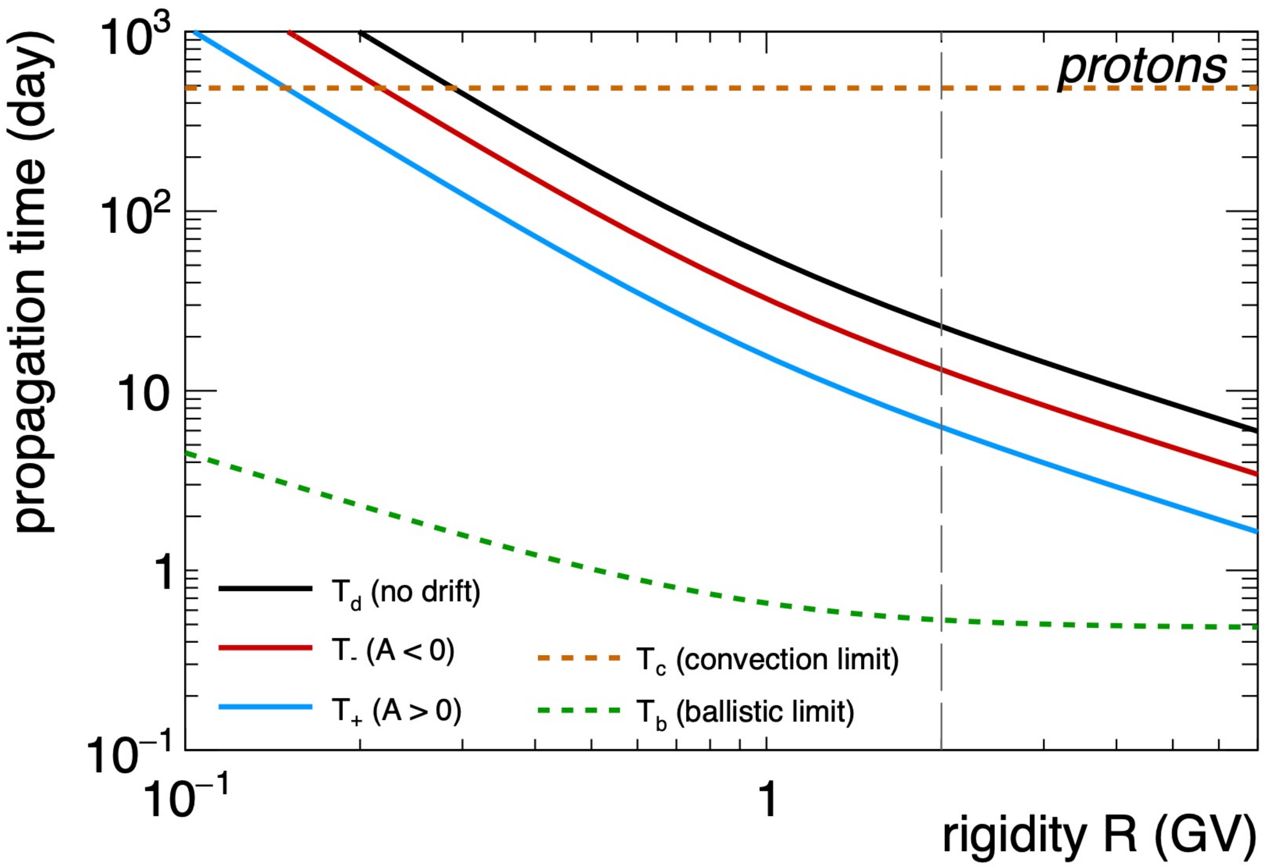
Determine the mean GCR rigidity R for data set

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

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

Rigidity dependence?

The propagation time of GCR in heliosphere is rigidity dependent and charge-sign dependent



$$T_d \approx \int_{r_0}^{L} \frac{r}{3K} dr$$

$$K \sim \beta R^{\alpha}$$

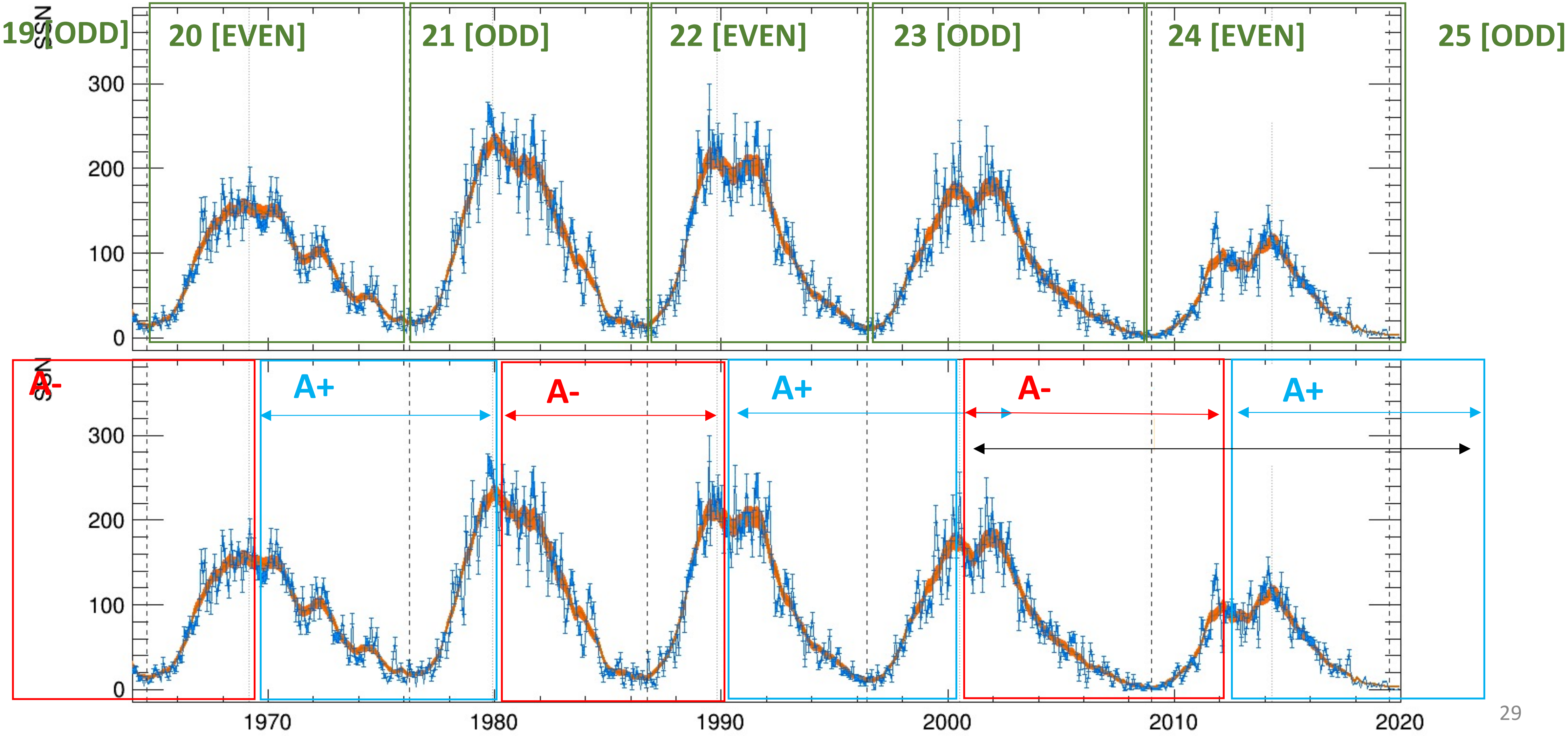
$$\rightarrow \; T_d \sim \beta^{-1} R^{-\alpha}$$

[See Strauss et al. ApJ 735, 83 (2011), O'Gallagher ApJ 197, 495 (1975)]

On the activity / magnetic solar cycles

Magnetic cycle: from **max** to **max**, T~22 yrs [A+/A- sequences]

Activity cycle: from **min** to **min**, T~11 yrs [**number** sequences]



Evidence for a time Lag in cosmic-ray modulation

The modulation parameter $\phi(t)$ appears to be correlated with the sunspot no. $SSN(t)$.

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

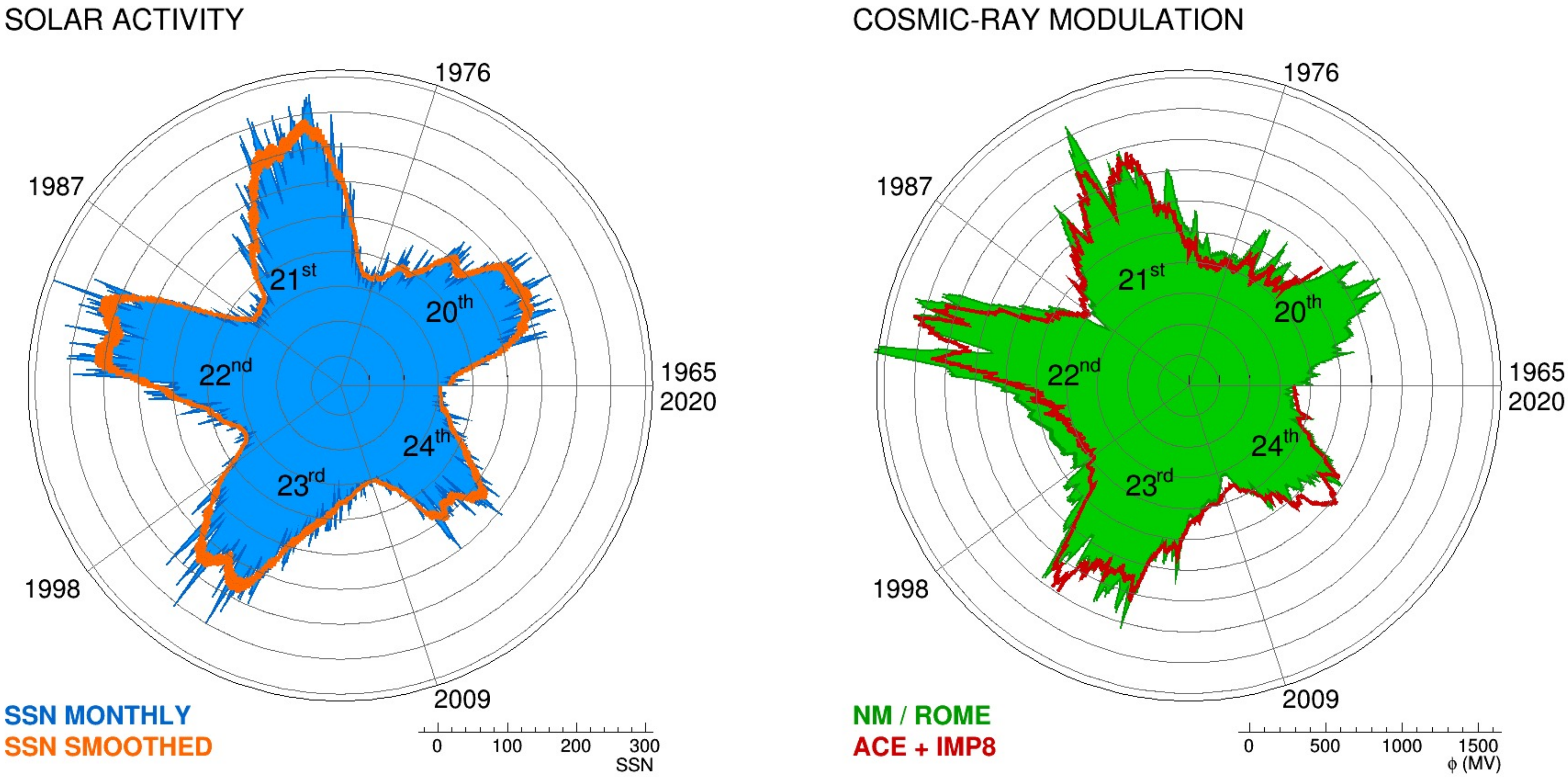
- NT+ 2017, ApJ 849 L32: Evidence for **8-month** lag using CR data from space (**2000-2013**)
  Theoretical interpretation, use of a «retarded» Parker's equation

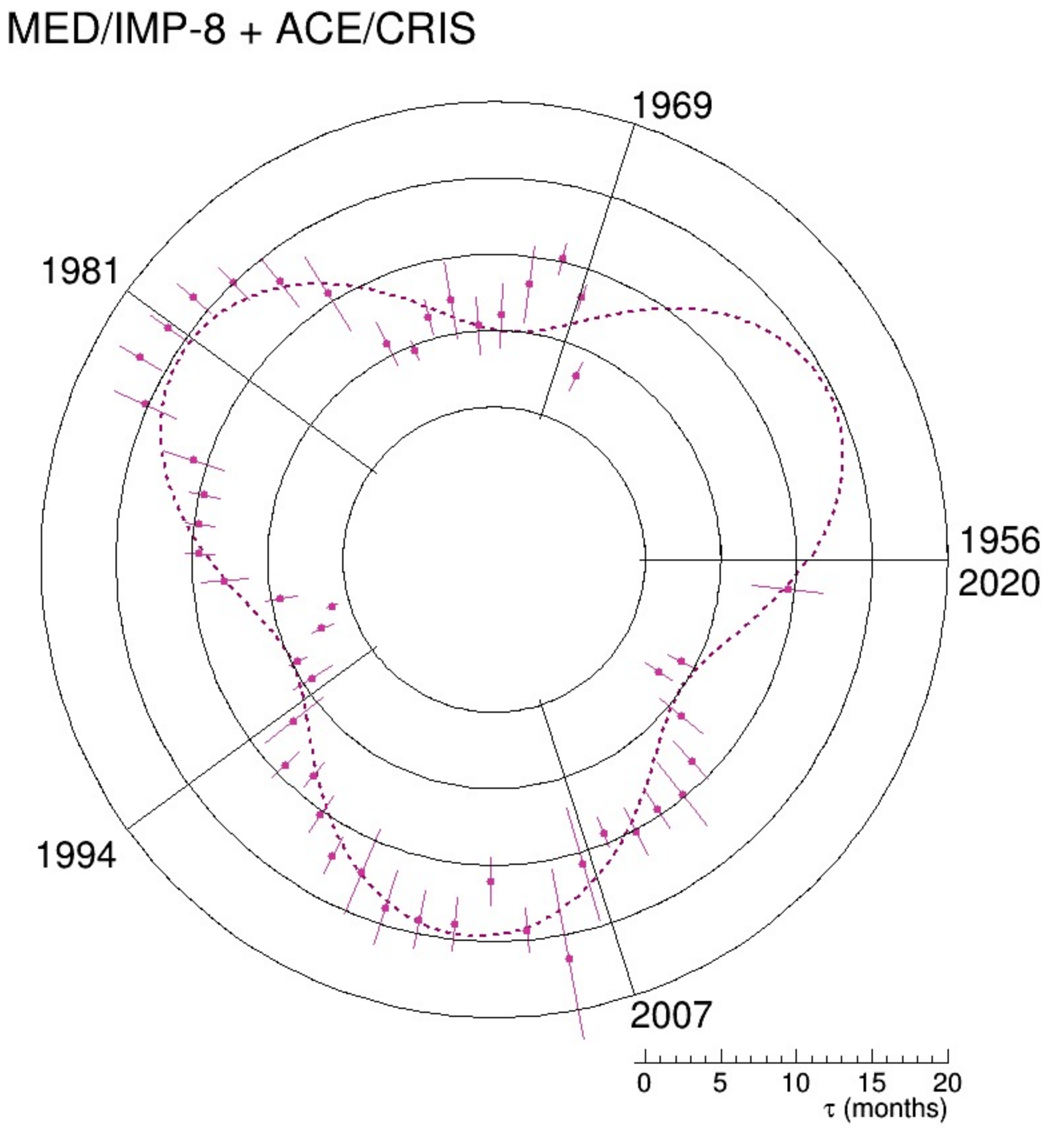
- Badwhar O'Neil 2014: Time lags of **~5-15 months** observed in Neutron-Monitor data
- Chowdhury et al 2016 Time lags of ~0-17 months between NM and SSN.

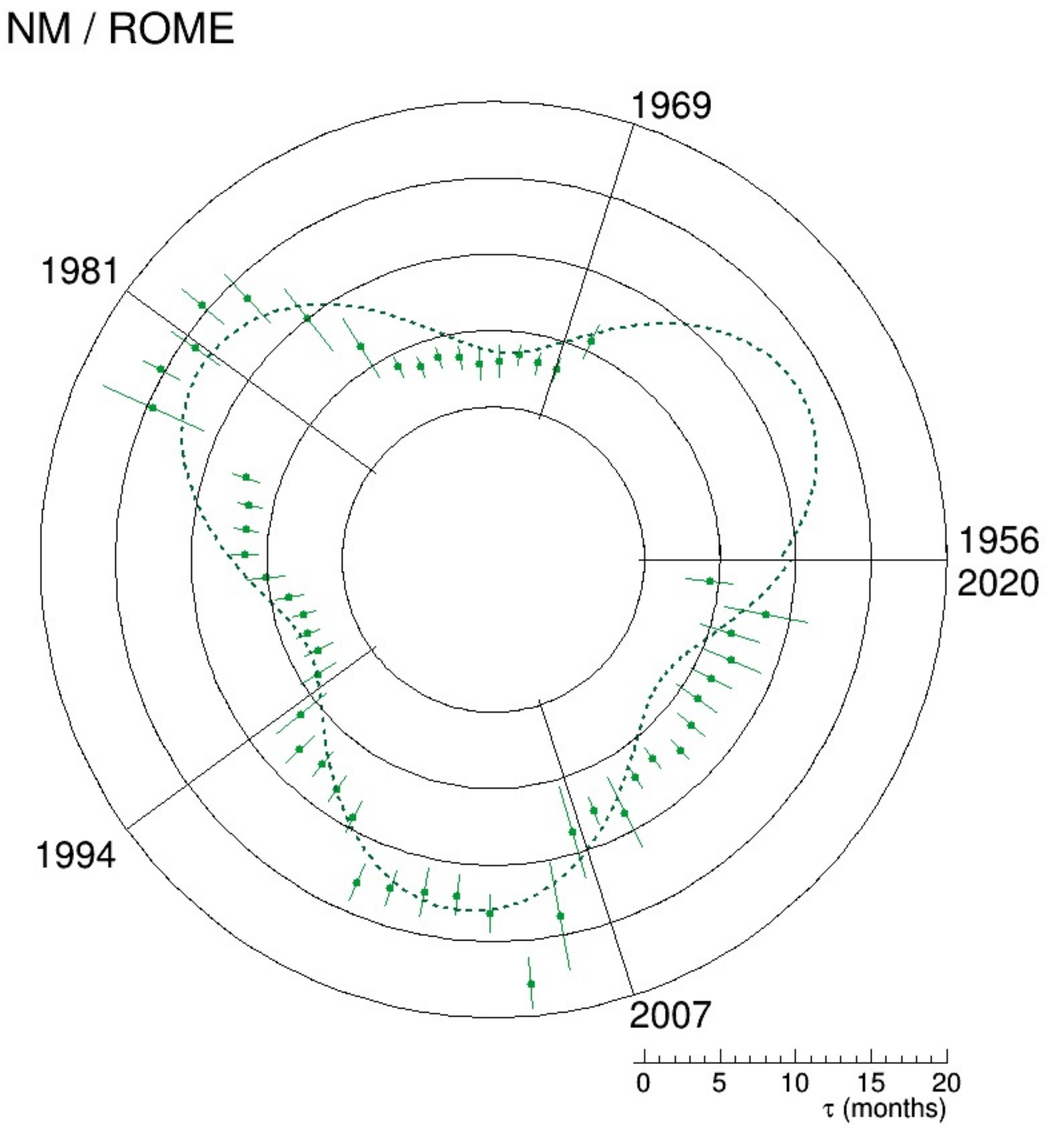
- Nimmyk 95, Badruddin 13 Different lags for different Solar Cycle numbers. Odd/Even effect?

- **Different lags for different solar cycles**
- **Discrepancies between different study**

==> Maybe the lag changes over the solar cycle?


SOLAR ACTIVITY
1976
1987
1965
2020
1998
2009
21st
20th
22nd
24th
23rd
SSN MONTHLY
SSN SMOOTHED
0
100
200
300
SSN
COSMIC-RAY MODULATION
1976
1987
1965
2020
1998
2009
21st
20th
22nd
24th
23rd
NM / ROME
ACE + IMP8
0
500
1000
1500
ϕ (MV)


MED/IMP-8 + ACE/CRIS
1969
1981
1956
2020
1994
2007
0 5 10 15 20
τ (months)


NM / ROME
1969
1981
1956
2020
1994
2007
0 5 10 15 20
τ (months)