High energy proton recordings during GLE74 on 11 May 2024

A. Papaioannou, A. Mishev, I. Usoskin, B. Heber, R. Vainio, N. Larsen, M. Jarry, A.P. Rouillard, N. Talebpour Sheshvan, M. Laurenza, M. Dumbović, G. Vasalos, J. Gieseler, S. Koldobskiy, O. Raukunen, C. Palmroos, M. Hörlöck, M. Köberle, R. Wimmer-Schweingruber, A. Anastasiadis, P. Kühl, E. Lavasa

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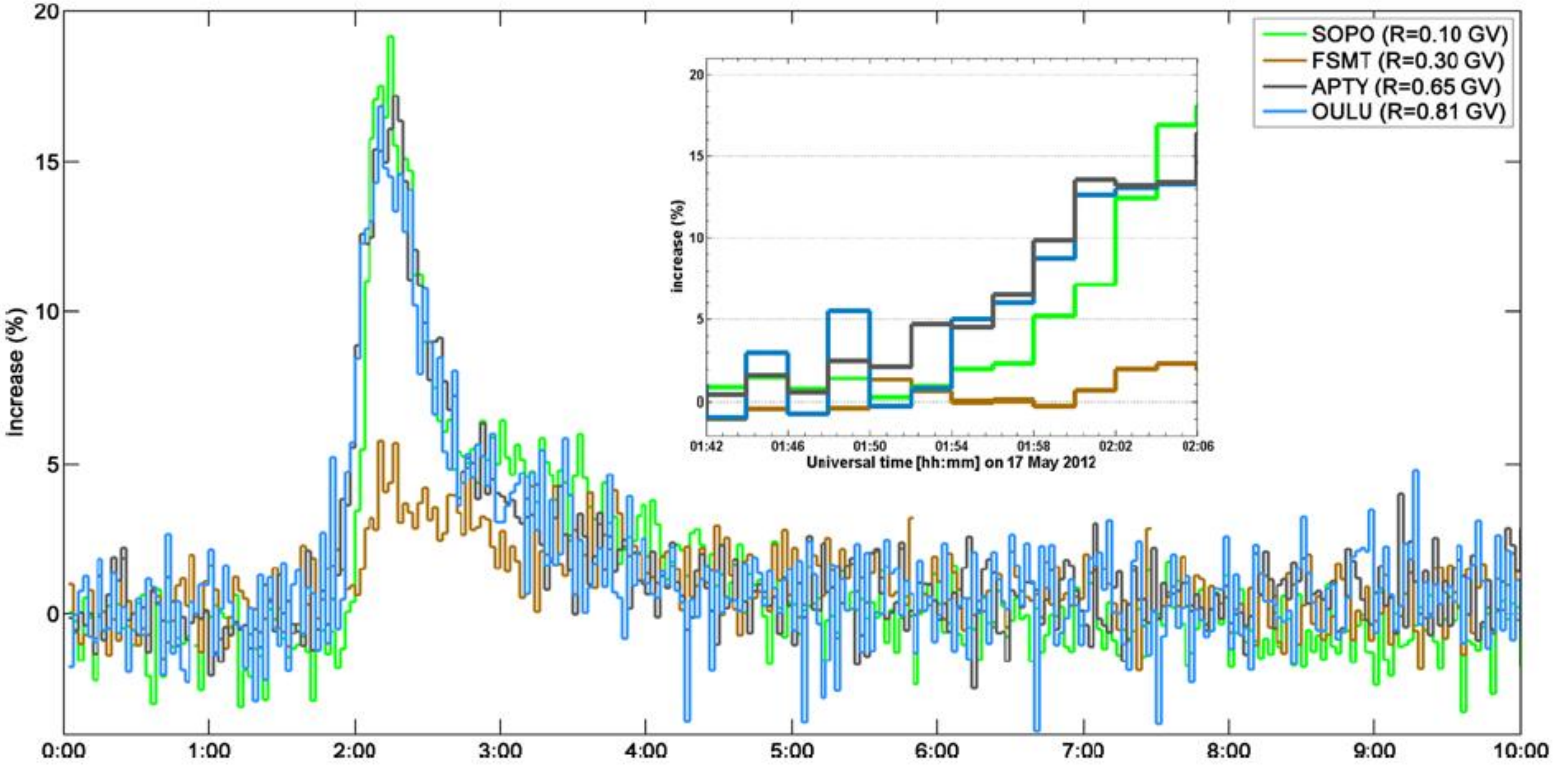
Overview of Ground Level Enhancements (GLEs)

Papaioannou et al., *Sol. Phys.*, (2014)



Poluianov et al., *Sol. Phys.*, (2018)

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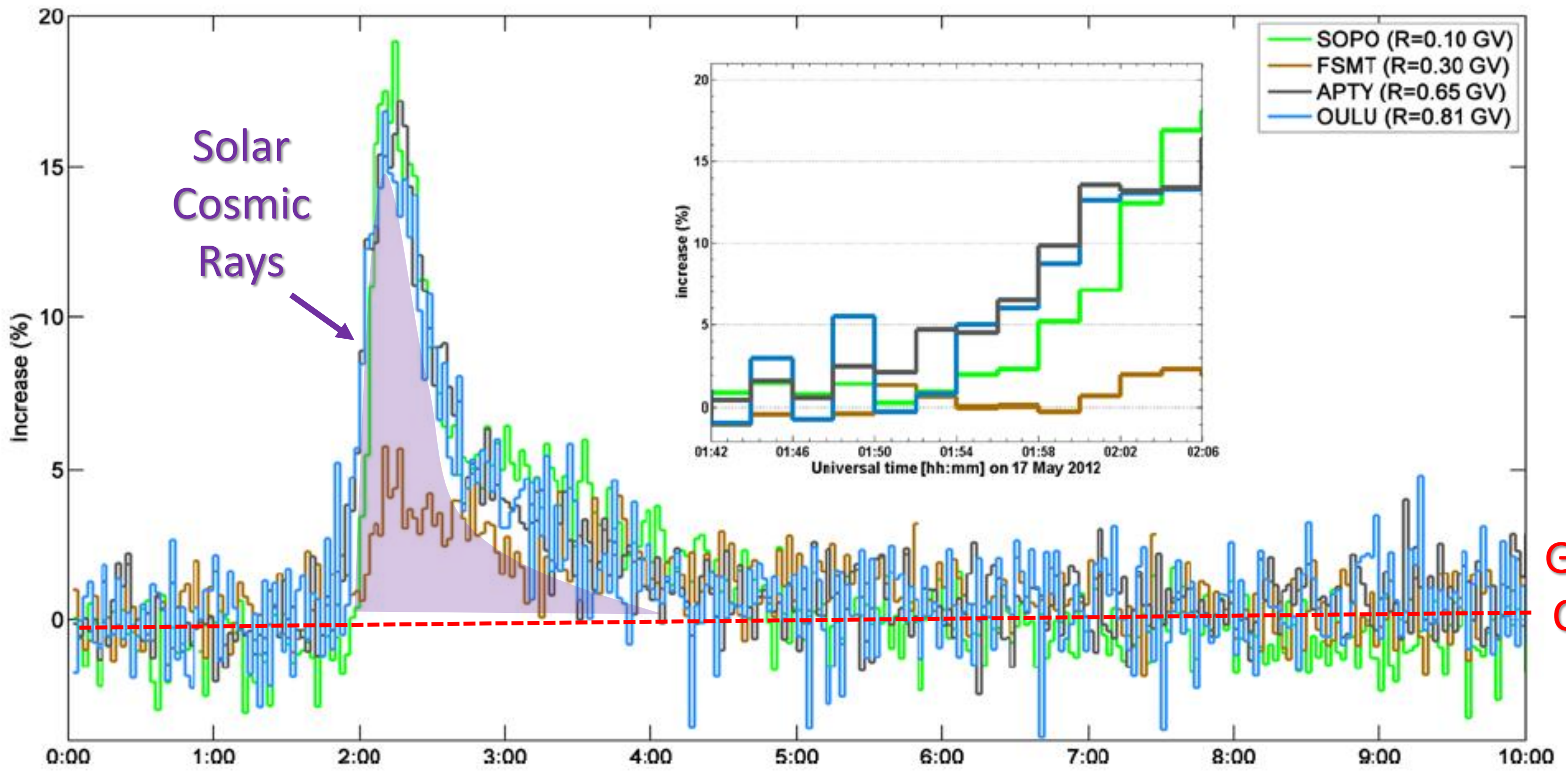
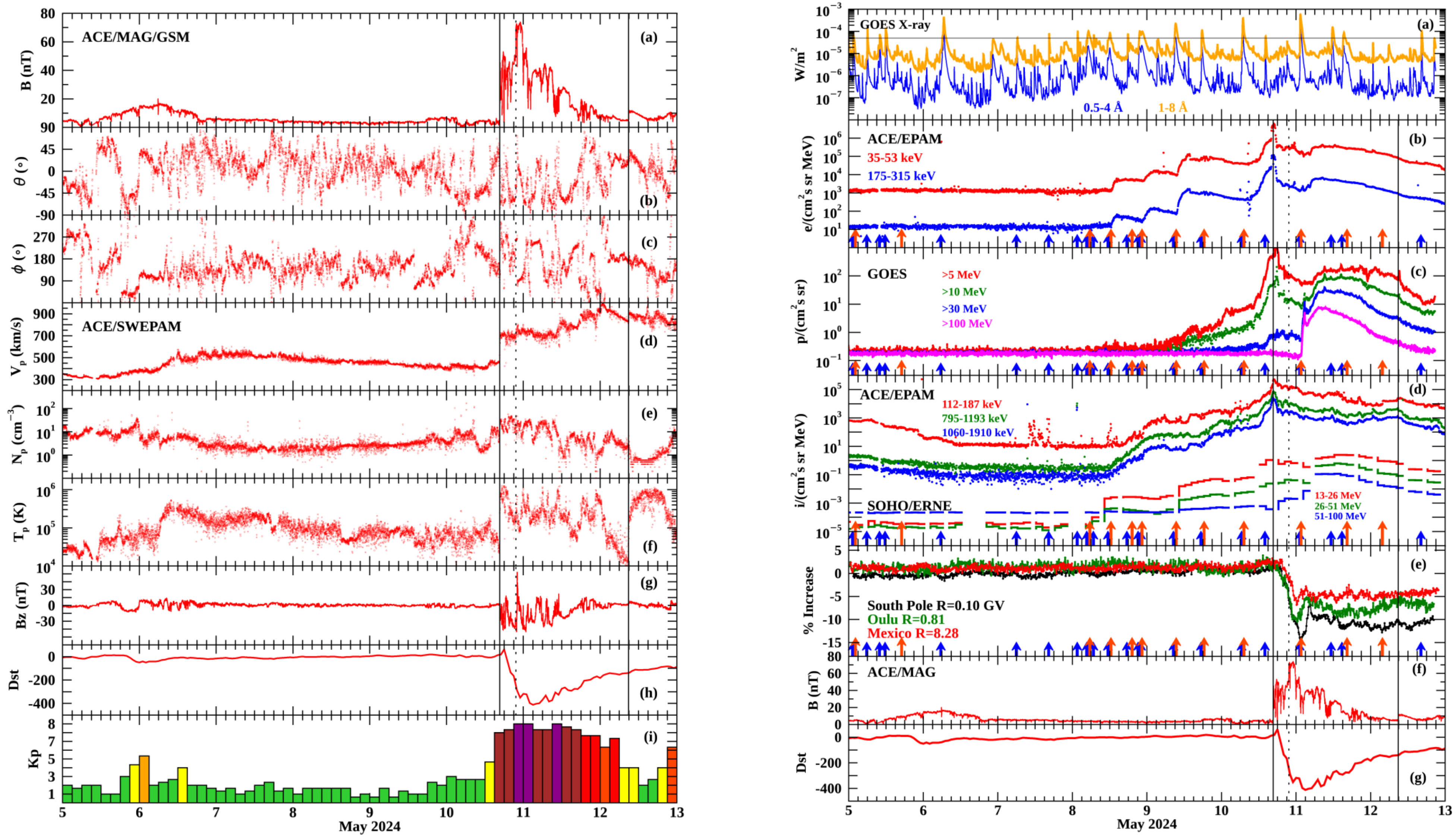


Poluianov et al., *Sol. Phys.*, (2018)

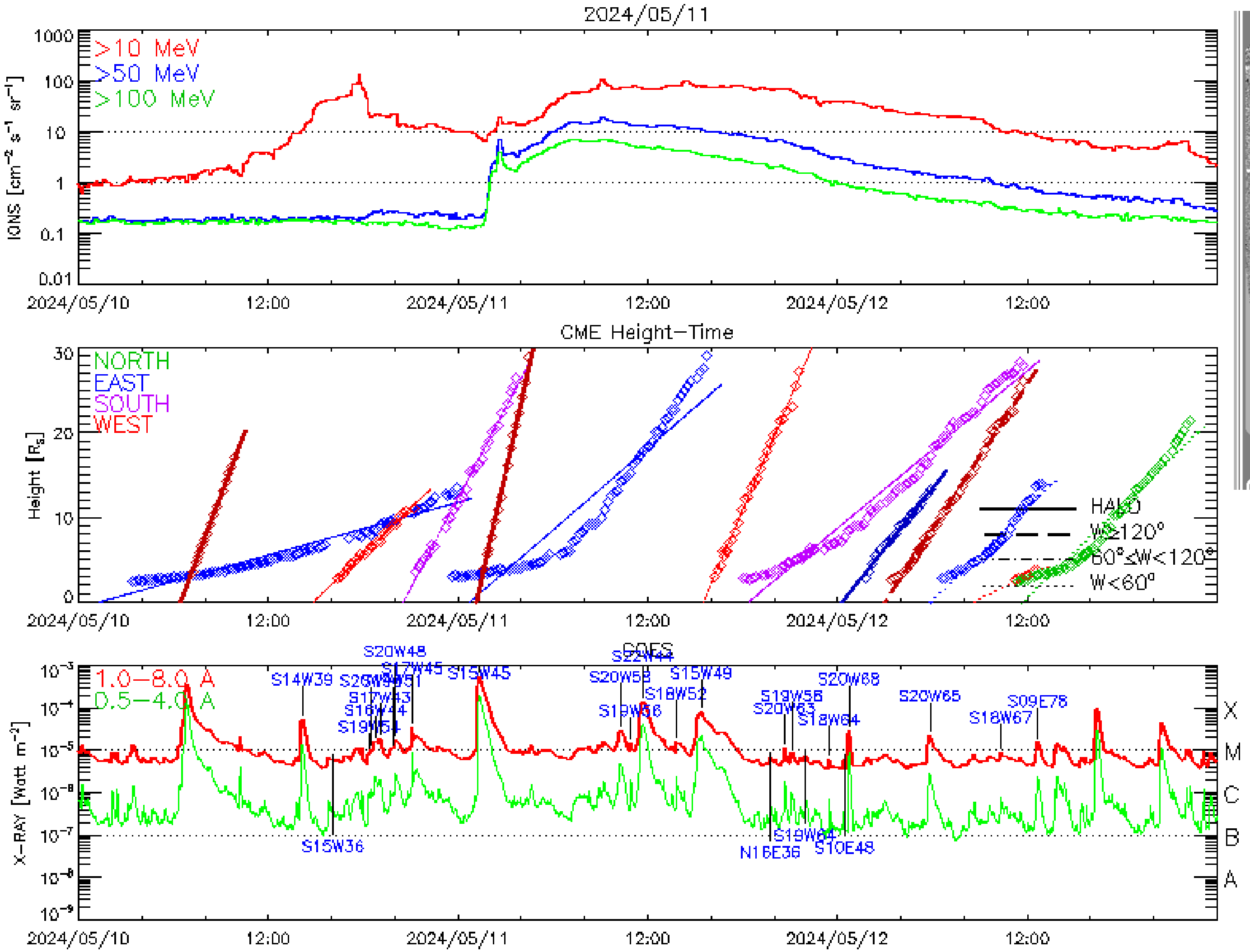
> **Ground-level enhancements** (**GLEs**) are **short-term increases** of the **cosmic ray intensity** registered at the ground by *particle detectors*. These **particles originate @ the Sun** and **are very fast** (*high energy*).

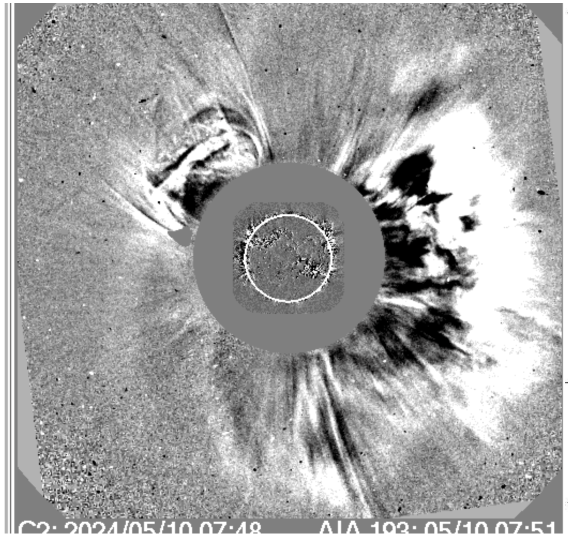
Background of GLE74

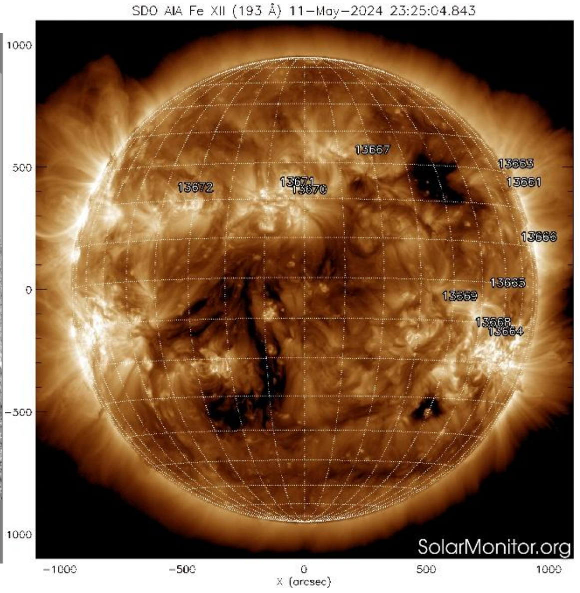


Courtesy: David Lario

Background of GLE74



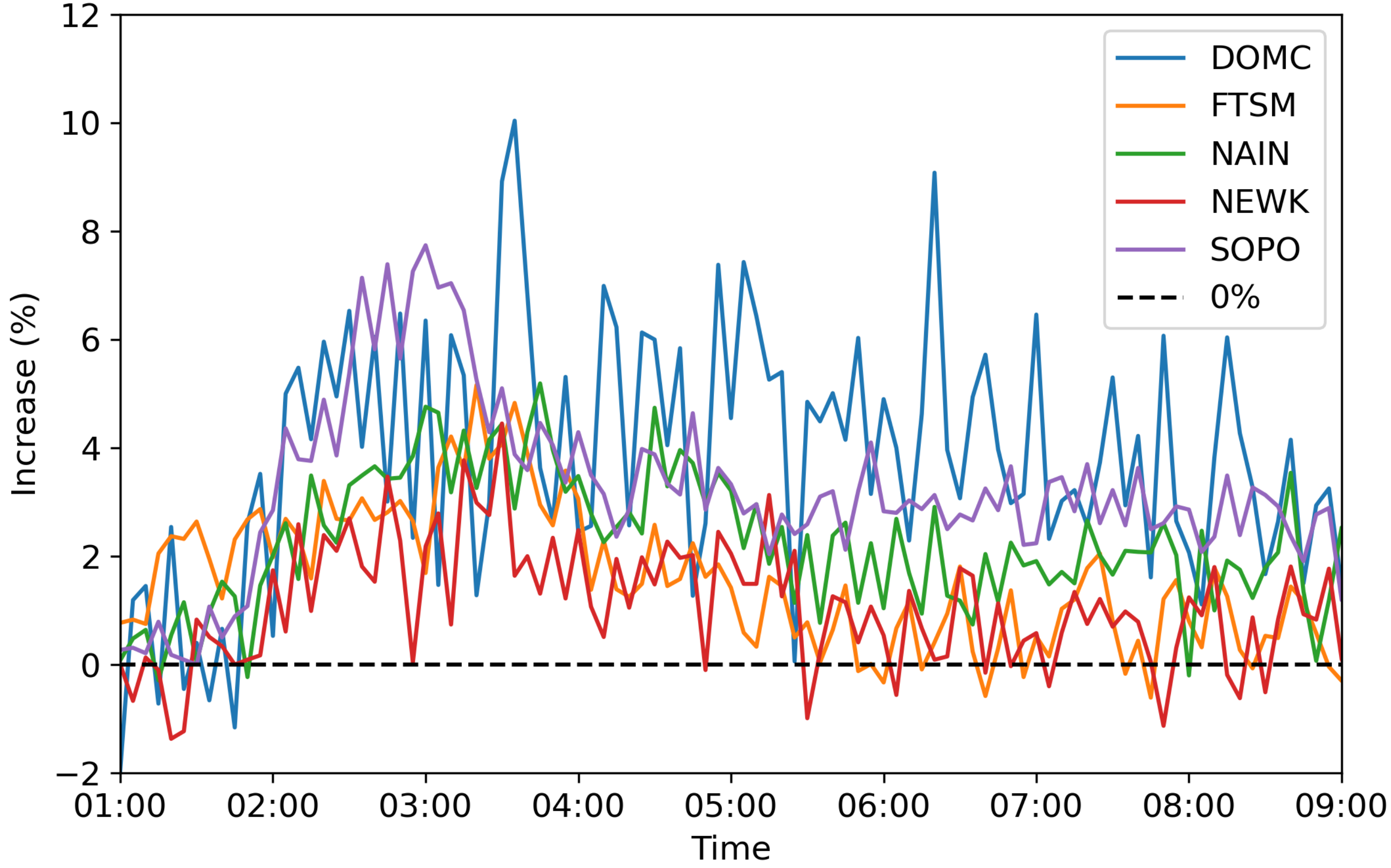




> **X5.8 (S15W55) flare** from NOAA AR13668

> **Fast (1614 km/s) halo CME**

GLE74 | Neutron Monitors | *Observations*



> The high-altitude, high-latitude stations **DOMC** and **SOPO** are more sensitive than most NMs as they can detect lower-energy particles. These stations recorded the highest flux intensity during **GLE74**. **DOMC-> 10% & SOPO -> 7.74%**

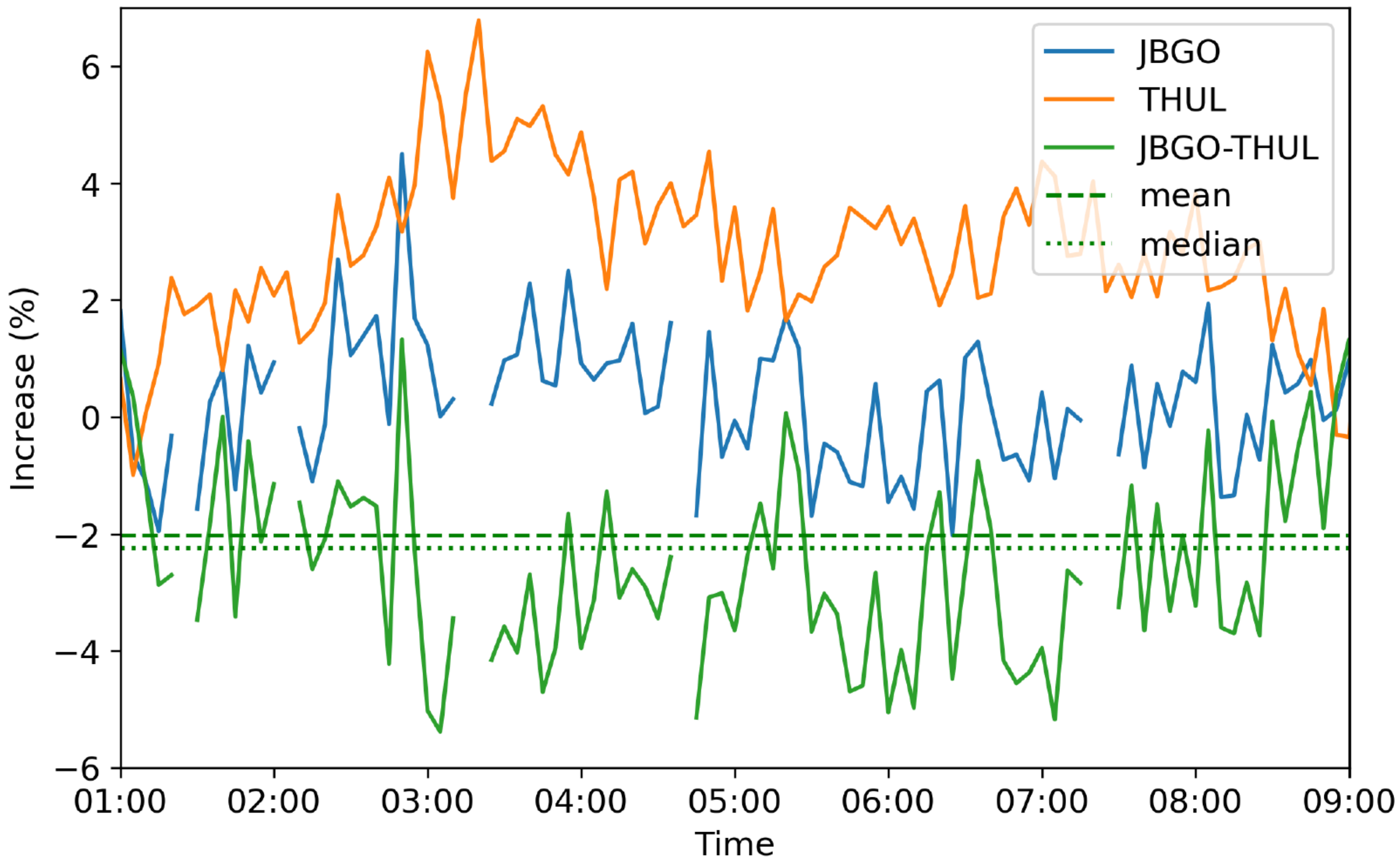
> Additionally, the bare neutron monitors at these locations (**DOMB** and **SOPB**) captured the most pronounced signals of solar particles for this event (**16% & 8.92% respectively**).

> *Inspection of the NM data from various neutron monitor stations* around the world indicated the presence of particles with rigidity of up to ~**2 GV**.

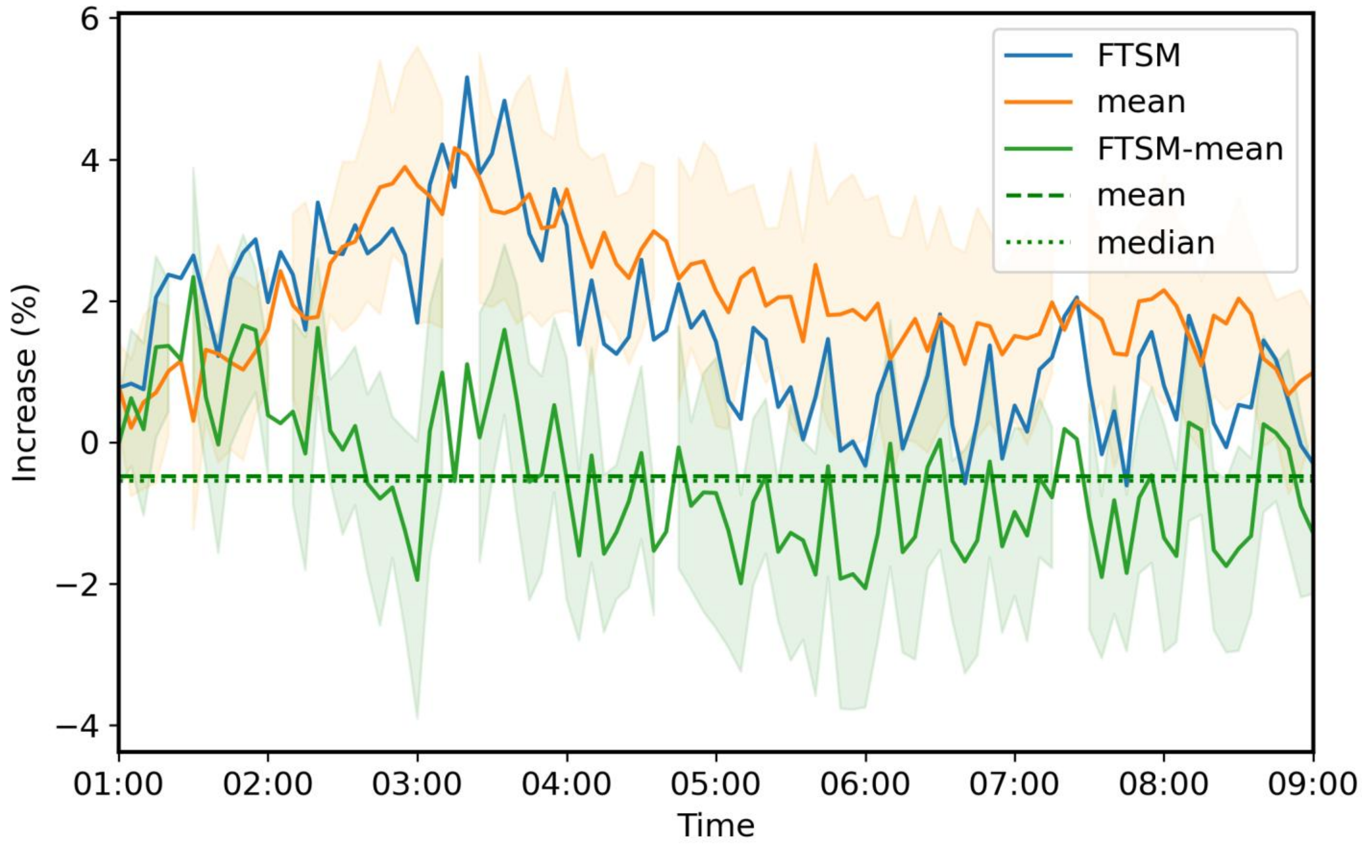
GLE74 | Neutron Monitors | *Observations*

> The count rates of **two high latitude NMs** - **Thule** (THUL, 75.6◦ N) and **Jang Bogo** (JBGO, 74.6◦ S) — which share similar characteristics, with a vertical cutoff rigidity of 0.0 GV and site altitudes of 260 m and 30 m, respectively.

> Since the two NMs *have similar energy responses*, the different traces result from ***the anisotropy of the incoming solar particles***.



GLE74 | Neutron Monitors | *Observations*



> Next, **11 NM** stations with a nominal cutoff rigidity **RC <1.4 GV** were used.

- *Apatity (APTY, Inuvik (INVK), Jang Bongo (JBGO), Mawson (MWSN), Nain (NAIN), Oulu (OULU), Peawanuck (PWNK), Terre Adelie (TERA), Thule (THUL), and Tixie Bay (TXBY)* led to an **averaged "mean" NM response** – trace in **orange color**
- *Fort Smith (FSTM)* – trace in **blue color**

> **Spectra**: Modified power-law in rigidity

$$J_{||}(P) = J_0(P)^{(\gamma+\delta\gamma(P-1))}$$

> **PAD**: Double Gaussian

$$G(\alpha) \approx \exp(-\alpha^2/\sigma_1^2) + B \cdot \exp(-(\alpha-\pi)^2/\sigma_2^2)$$

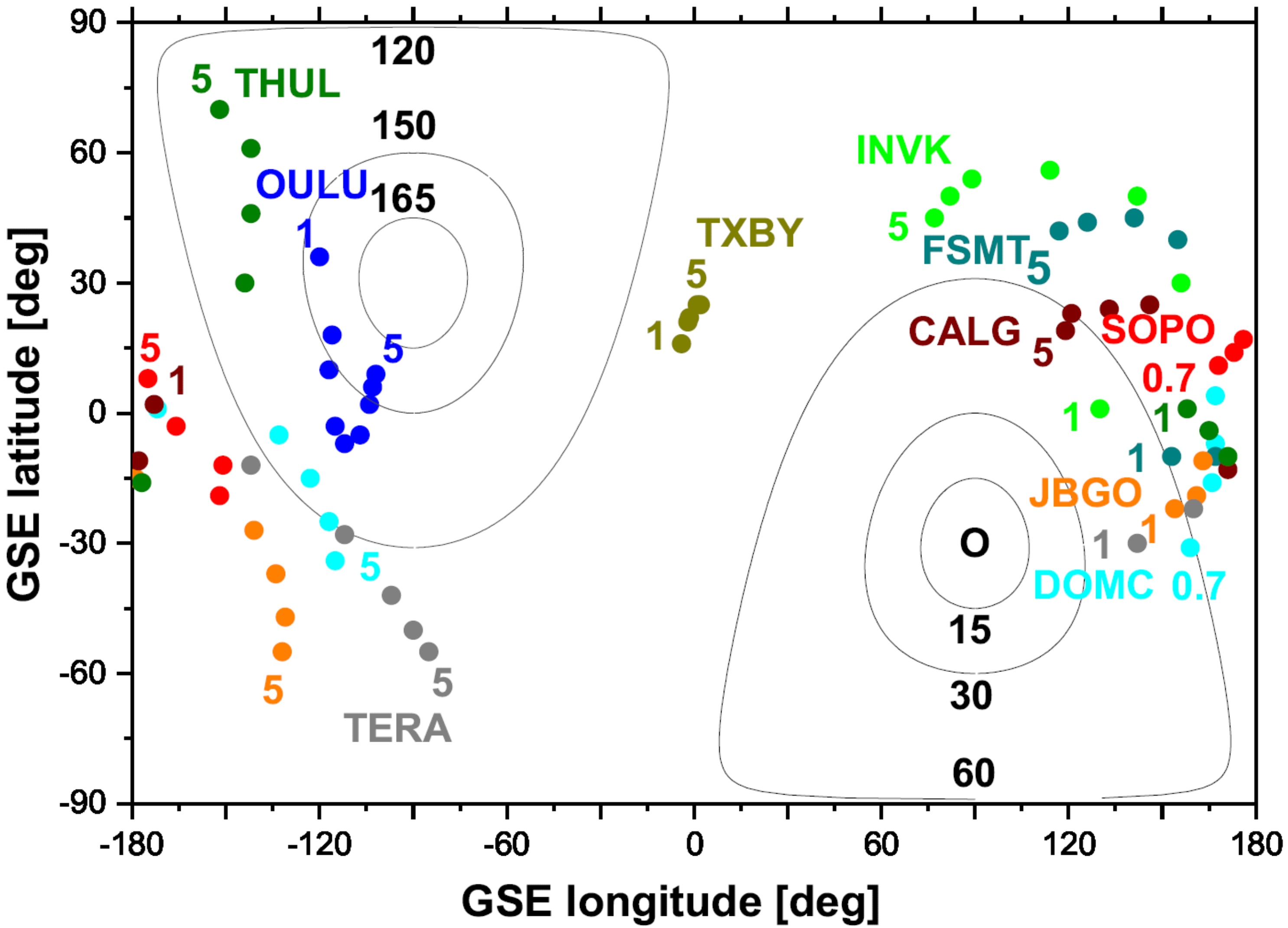
$$\frac{\Delta N}{N}(P_{\mathrm{cut}}, t) = \frac{\int_{P_{\mathrm{cut}}}^{P_{\max}} J_{\mathrm{SEP}}(P,t) S(P) G(\alpha,t) A(P) dP}{\sum_i \int_{P_{\mathrm{cut}}}^{\infty} J_{\mathrm{GCR}_i}(P,t) S_i(P) dP}$$

> **NM count-rate:** Inverse, constrained *nonlinear problem*
> Levenberg Marquardt with variable regularization

$$\mathcal{F} = \sum_{i=1}^{m} \left[\left(\frac{\Delta N_i}{N_i} \right)_{\mathrm{mod.}} - \left(\frac{\Delta N_i}{N_i} \right)_{\mathrm{meas.}} \right]^2$$

Mishev et al., *Solar Phys.*, (2022) and references within

GLE74 | Neutron Monitors | *Modeling*



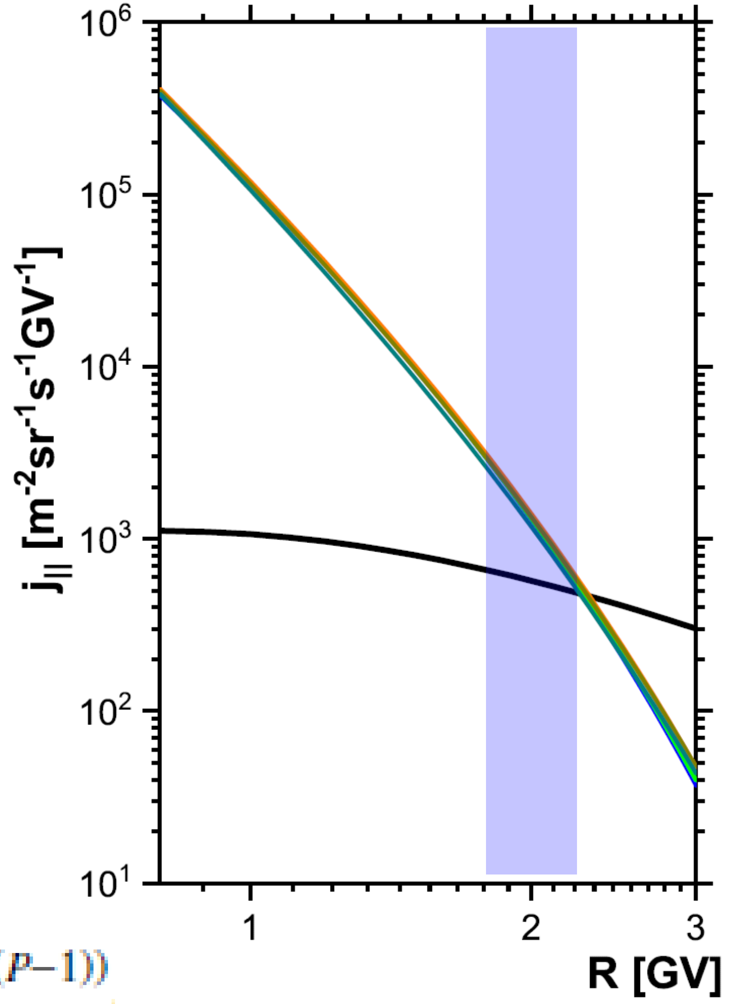
> ***Asymptotic directions***

- *Internal magnetic field: IGRF*
- *External magnetic field: TSY01S*

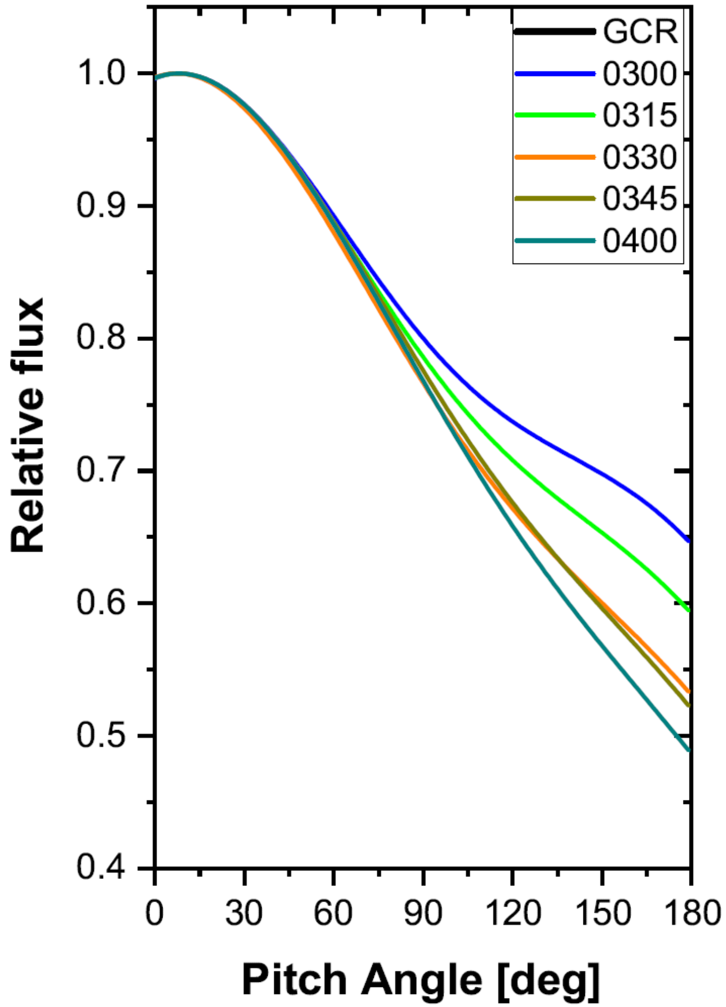
> ***Inputs for TSY01S***

- *Solar wind speed (v),*
- *y and z components of the interplanetary magnetic field (IMFy and IMFz),*
- *Solar wind dynamic pressure (Pdyn),*
- *Dst index,*
- *G2 and G3*

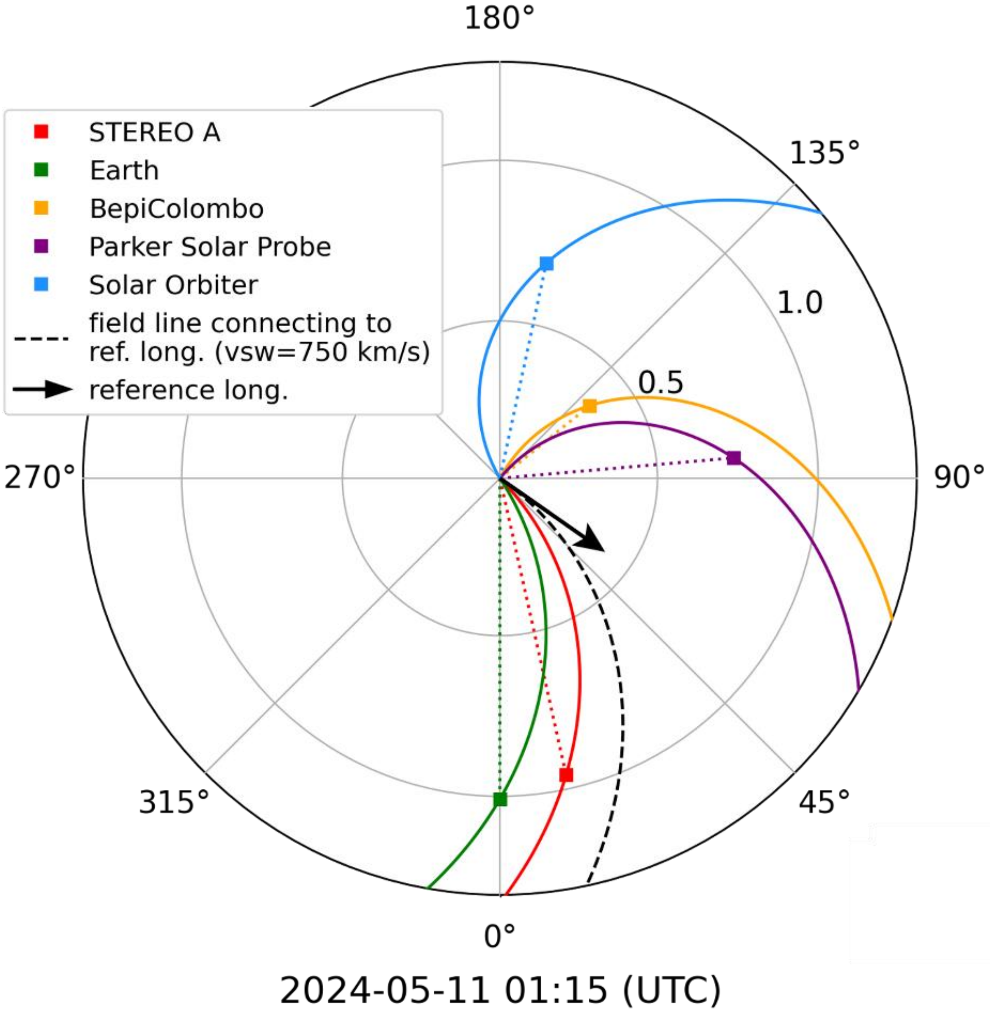
GLE74 | Neutron Monitors | *Modeling*



$$J_{||}(P) = J_0(P)^{(\gamma+\delta\gamma(P-1))}$$



GLE74 | Spacecraft observations

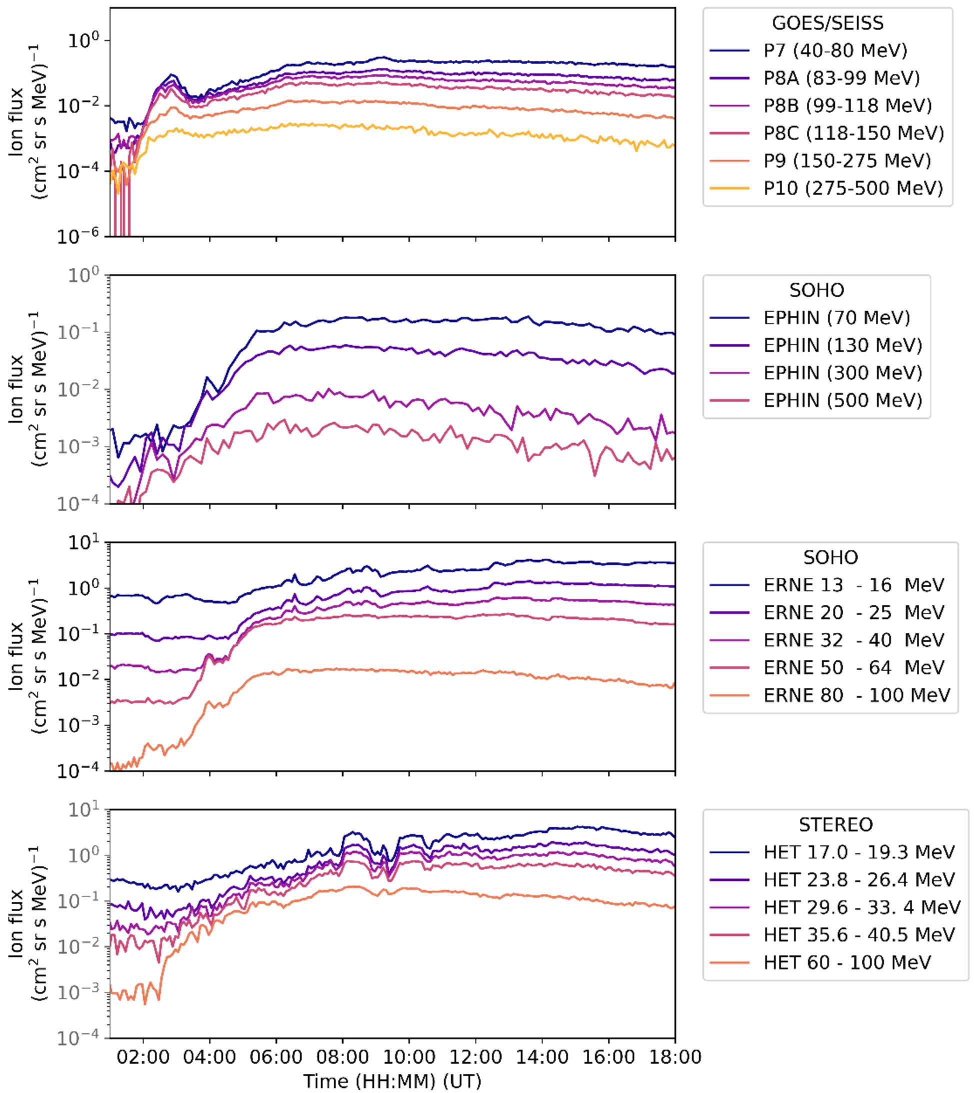


> View of the heliographic equatorial plane from solar north, showing the *positions of various spacecraft* on **11 May 2024** at **01:15 UT**.

> The Parker spirals are shown for each spacecraft.

> *Vsw ~ 750 km/s* has been used

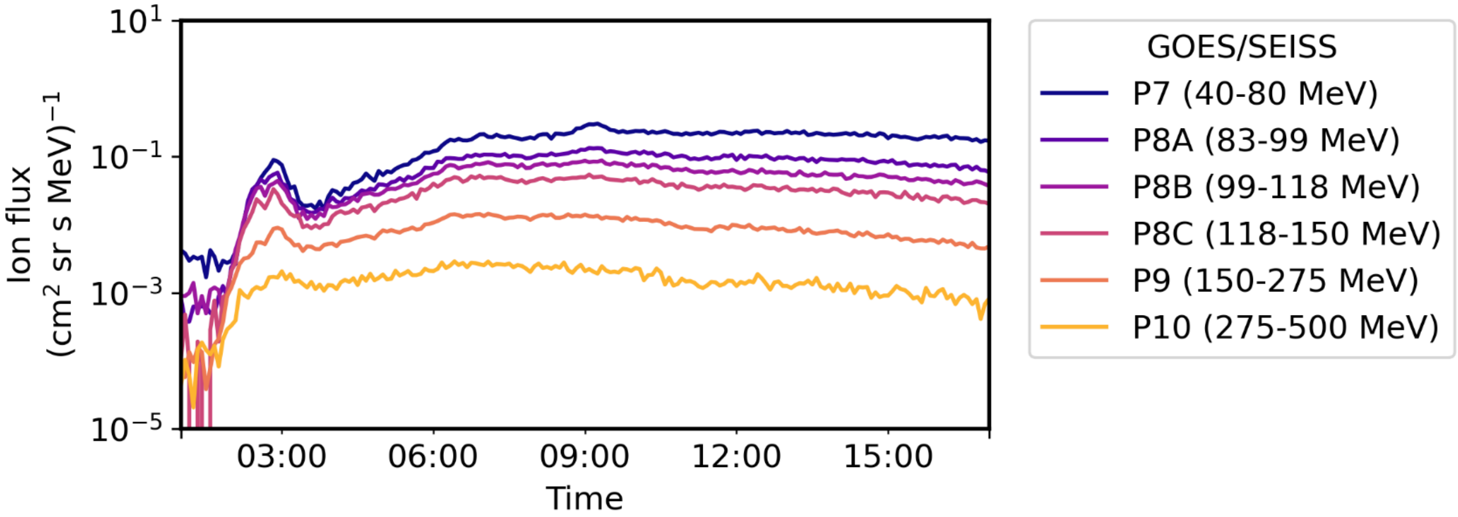
GLE74 | Spacecraft observations

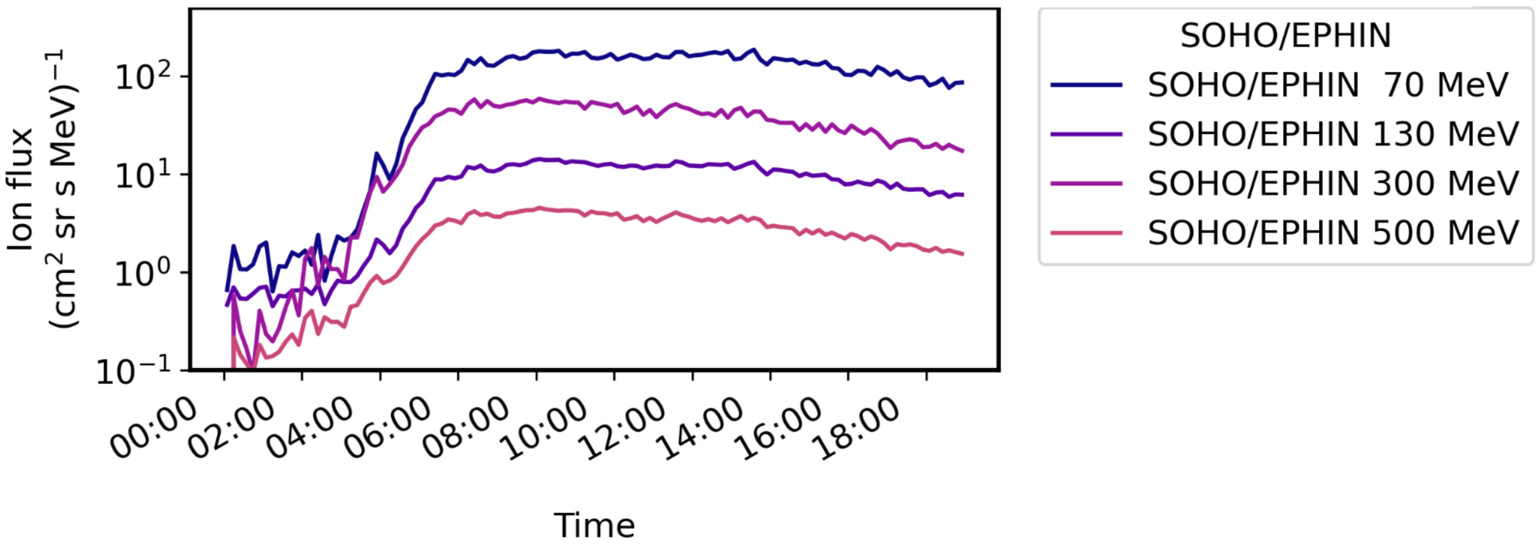


> The time history of SEP measurements during **GLE74** as recorded (from top to bottom):

- ***GOES/SEISS*** (40–500 MeV)
- ***SOHO/EPHIN*** (70-500 MeV)
- ***SOHO/ERNE*** (13-100 MeV)
- ***STEREO-A/HET*** (17-100 MeV)

GLE74 | Spacecraft observations

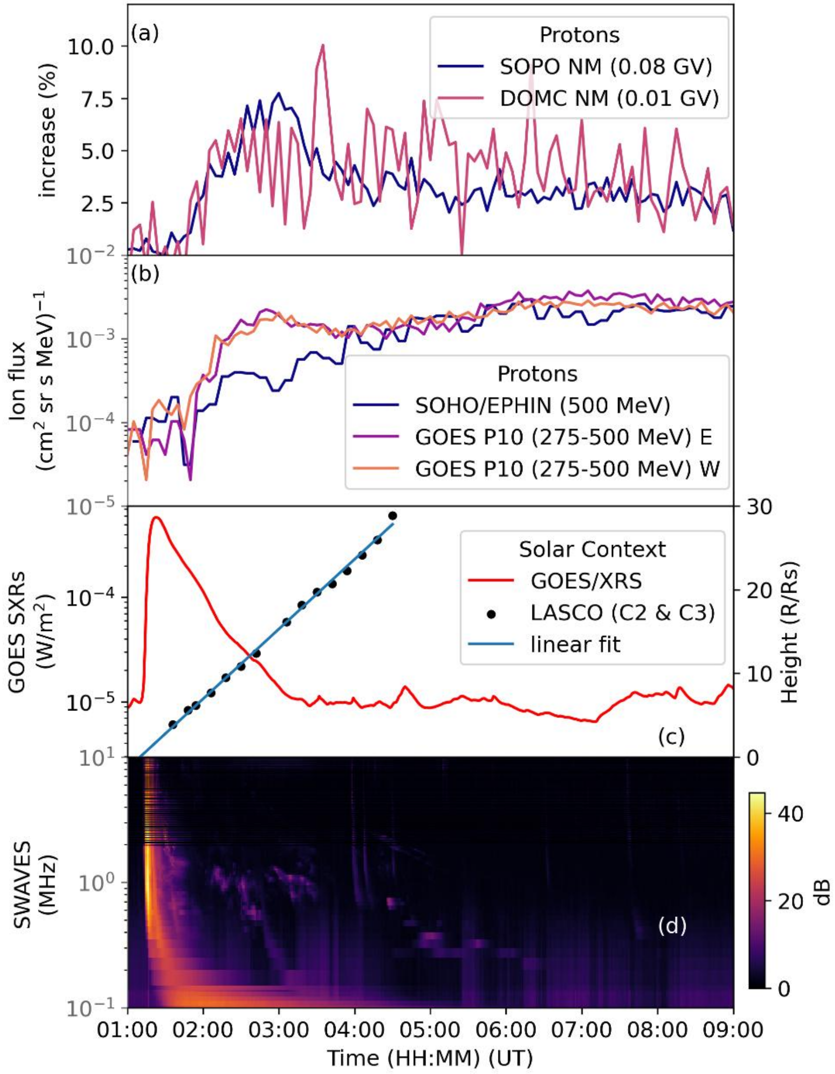




> **High-energy protons** at each spacecraft seem to have a prompt increase:

- **GOES/P10** (275–500 MeV) has an onset time at **01:15 UT±5min**
- **SOHO/EPHIN** (at 500 MeV) records the event at **01:24 UT±10min**.

Overall GLE74



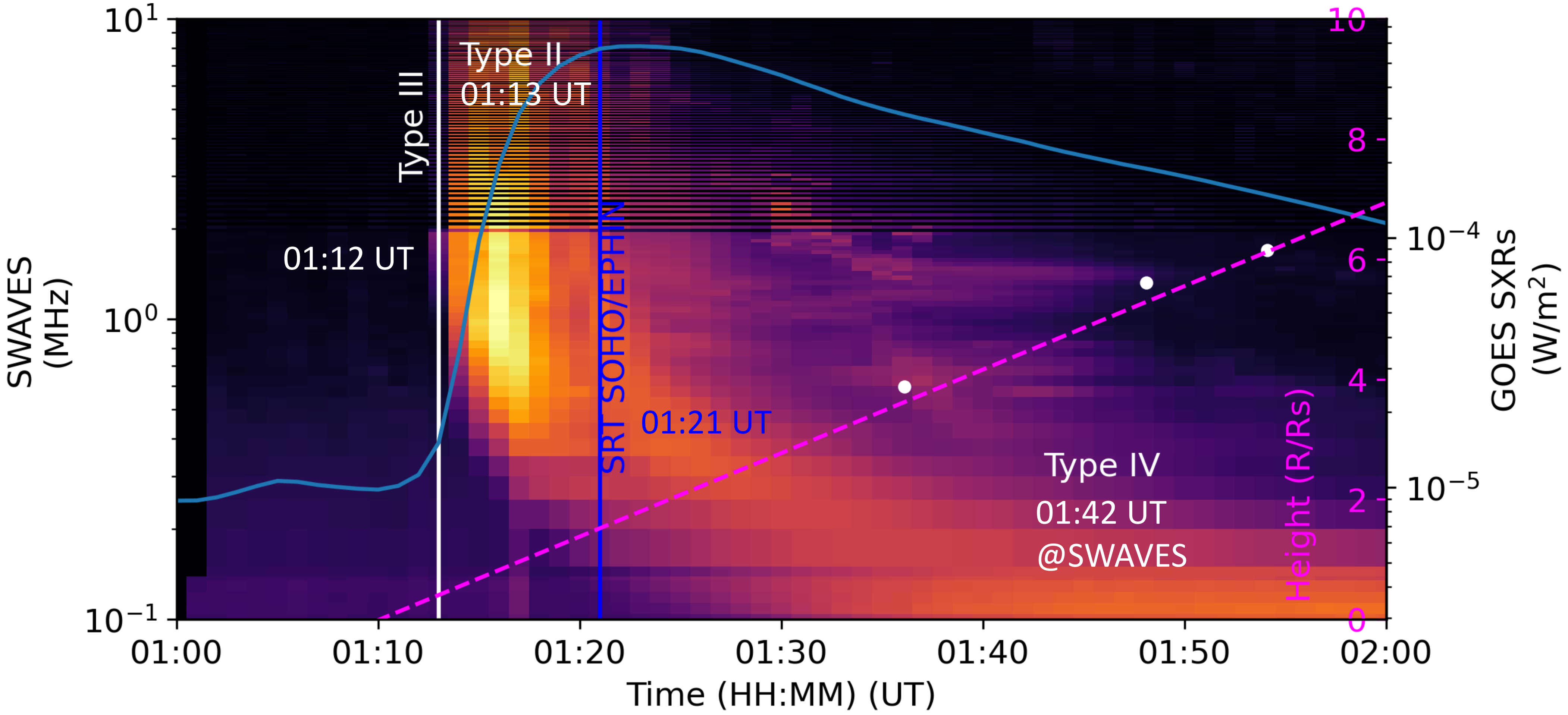
> Panel (a): Count rate increase (in percent) of SOPO and DOMC NMs based on 5-minute de-trended NM data**.**

> Panel (b): SOHO/EPHIN and GOES/SEISS proton flux.

> Panel (c): SXR flux observed by GOES, denoting an X5.8 solar flare (red curve; left axis). The height time of the CME evolution is shown with the black circles from measurements at the plane-of-sky near the CME leading edge (taken by the LASCO CME CDAW catalog). The solid blue line is a linear fit to the height and extrapolated back to the surface of the Sun.

> Panel (d): Dynamic radio spectrum observed by STEREO-A/WAVES (SWAVES)

GLE74 | Relation to Solar Sources



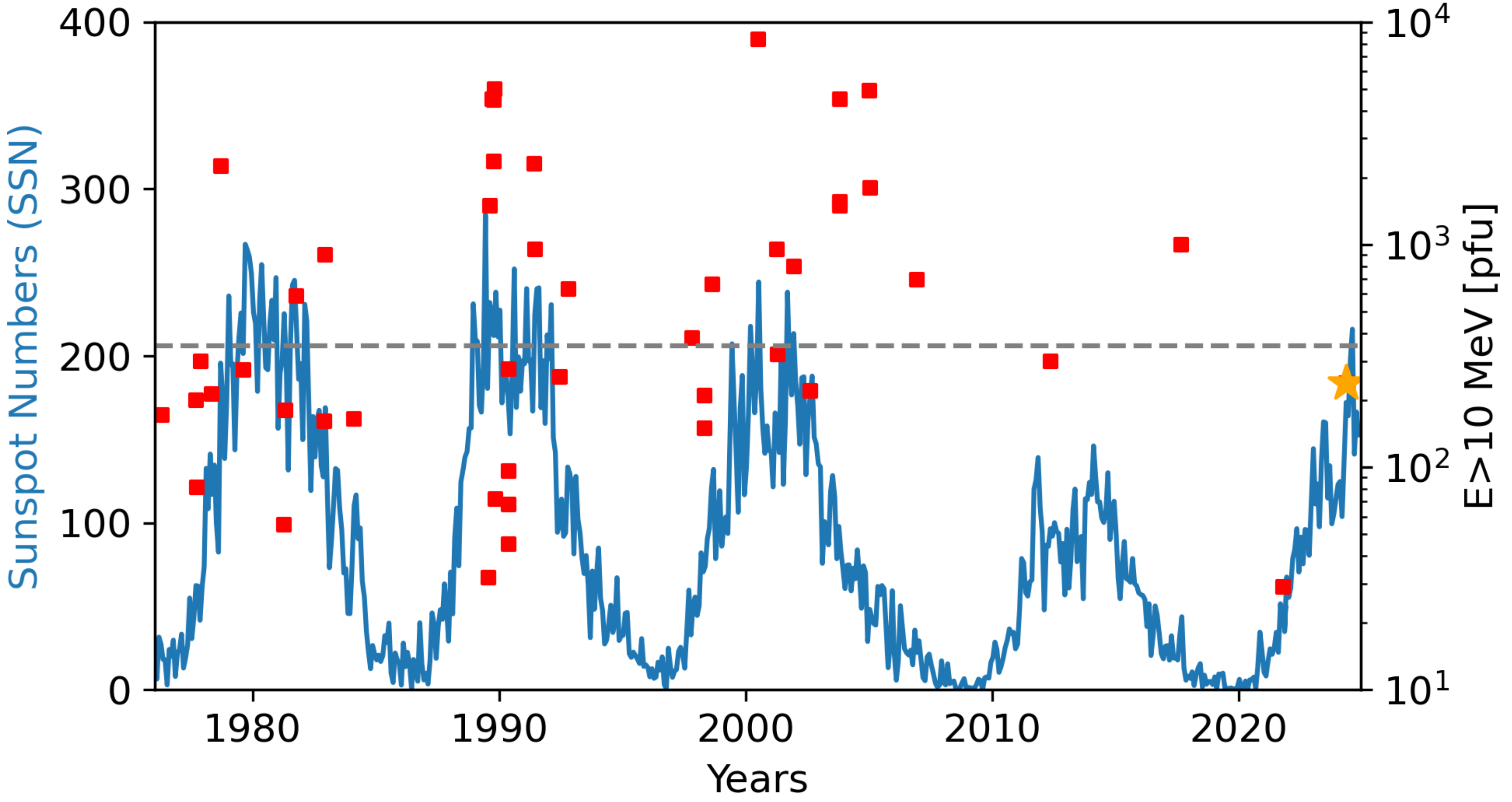
GLE74 | Relation to Solar Sources

Table 2. Timeline of events for GLE74.

Event	Time [UT]
SXR onset	01:10 (1min)
Type III onset (first of the group)	01:12 (1sec)
Type II onset	01:13 (1sec)
GOES/SEISS onset (E=275–500 MeV)	01:15 (5min)
SRT (E=500 MeV)	01:21 (10min)
SXR peak	01:23 (1min)
SOHO/EPHIN onset (E=500 MeV)	01:24 (10min)
Type IV (Metric)	01:25 (1min)
GLE onset at South Pole	01:35 (5min)
CME first observation in LASCO/C2	01:36 ($\sim$5min)

Notes. All times are Earth times, and propagation times for electromagnetic emissions have been considered in this table as explained in the text. The numbers in parentheses denote the time resolution of the measurements used.

GLE74 | Comparison to other GLEs



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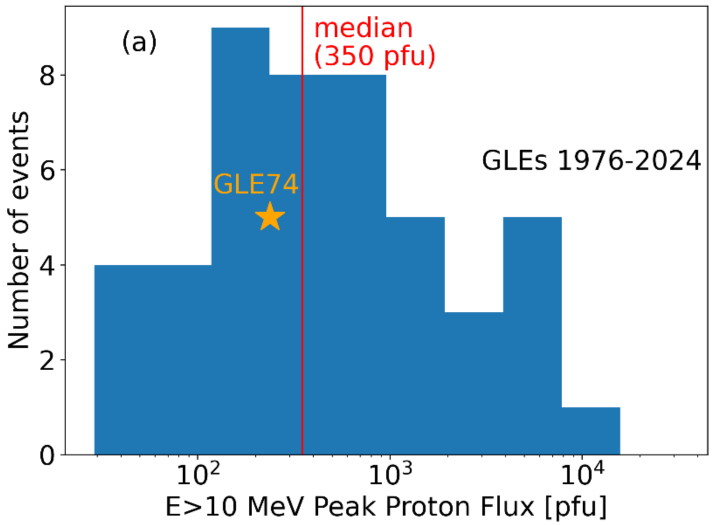
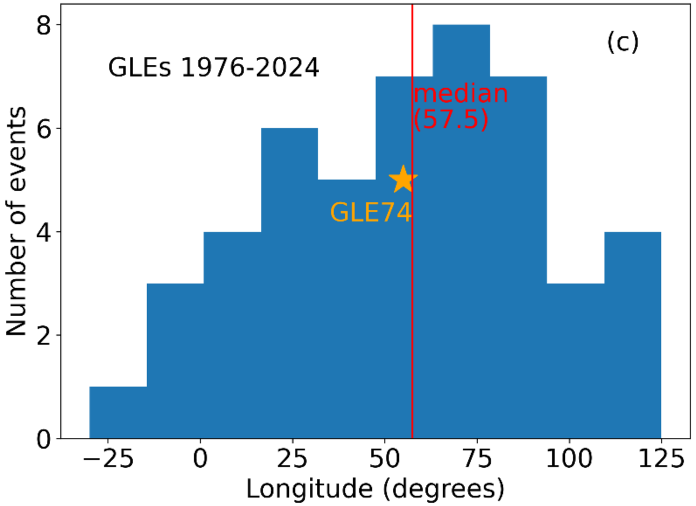
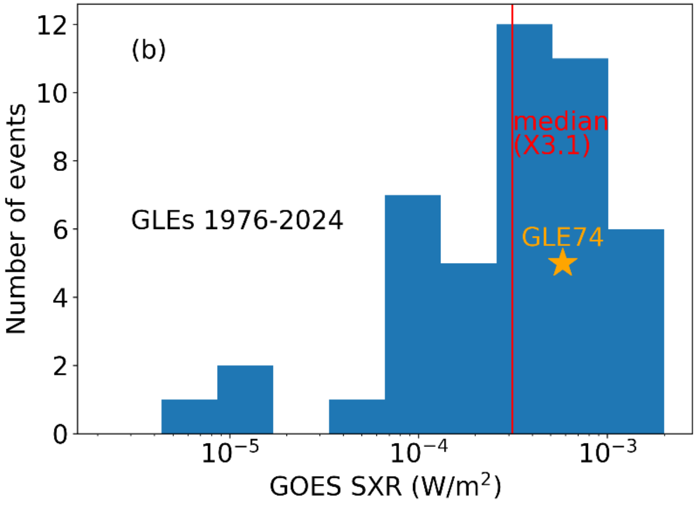
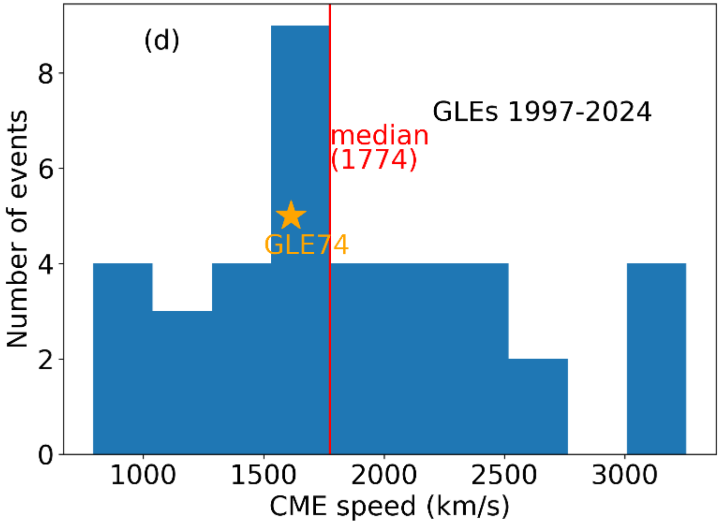








Event	Longitude [degrees]	SXR $[\mathrm{W/m^2}]$	CME speed [km/s]	I_P [pfu]
GLE74	55	X5.8	1614	238
Median	57.5	X3.1	1530	350

Summary

> The **main results** of the study are:

1. During the main phase of **GLE74**, the rigidity spectrum exhibit *moderate hardness*, with slopes (**γ**) ranging from approximately **5** to ~**6.3**.

2. A notable spectral rollover (**δγ**), characterized by *a steepening in the high rigidity/ energy region*, was observed. This steepening gradually weakened over time but never completely disappeared.

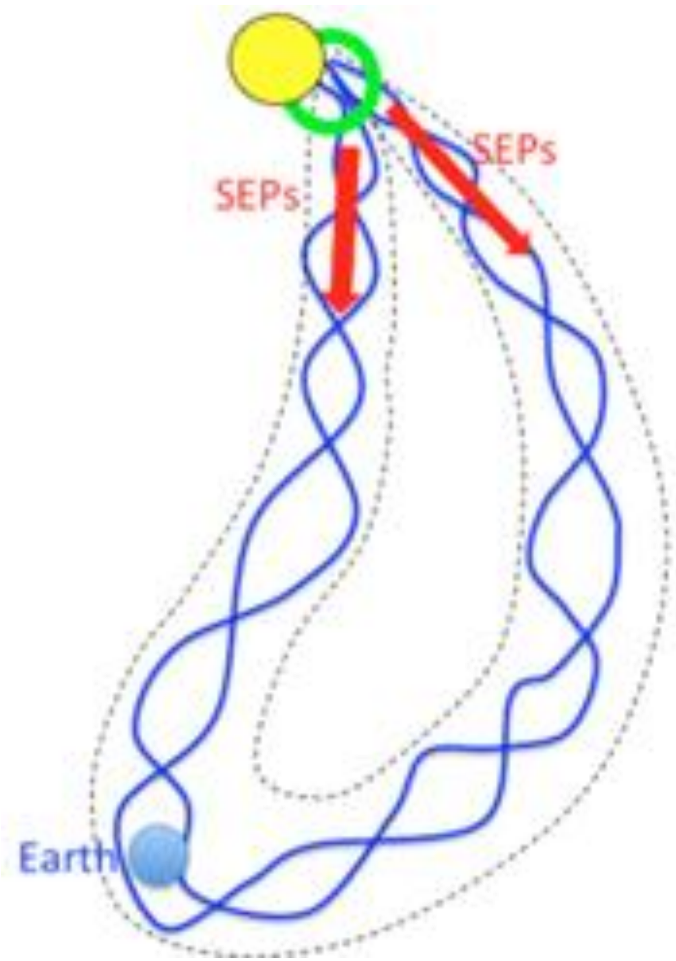
3. A **notable SEP flux from anti-Sun direction** was detected, **exhibiting a relatively broad angular distribution**—rather than a narrow, beam-like pattern particularly during the main phase of the event, when particle flux reached its peak.

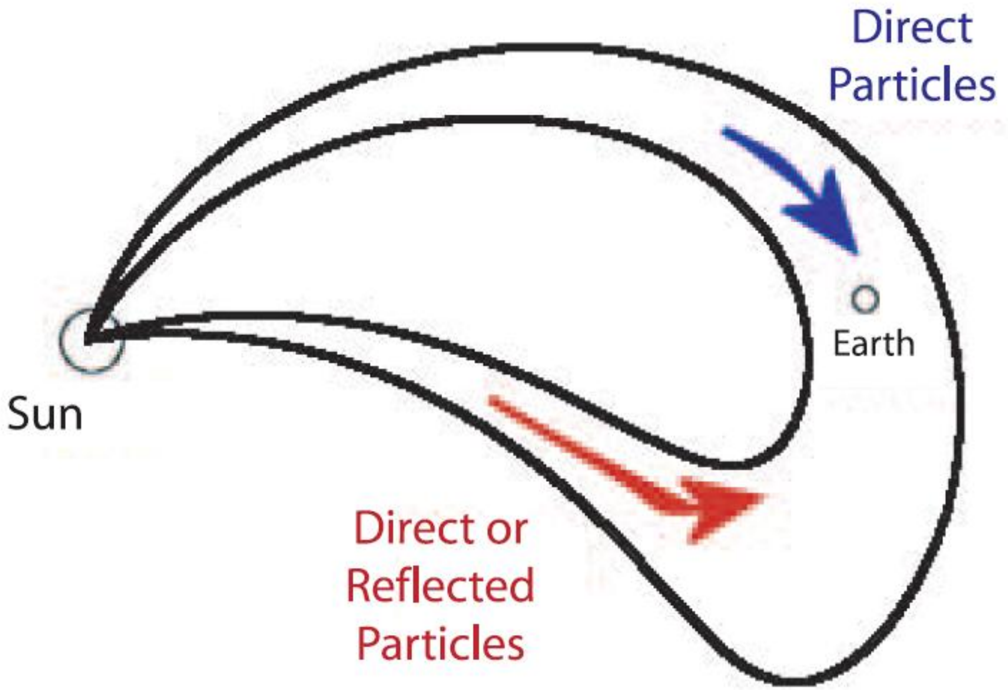
4. The **SRT** of the **very high-energy particles onboard SOHO** (EPHIN; E=500 MeV) was found to be **~01:21 UT,** and around this SRT the CME-driven shock was located at a height of **~1.8 (±0.2) Rsun**.

5. A series of **type III bursts** (starting at 01:12 UT), a **type II** (onset at 01:13 UT) and a **type IV** (onset at SWAVES at 01:42 UT) burst were identified in conjunction to **GLE74**.

Discussion

"A notable SEP flux from ***anti-Sun direction was detected****, exhibiting a relatively broad angular distribution—rather than a narrow, beam-like pattern particularly during the main phase of the event, when particle flux reached its peak"*





Ruffolo et al., *ApJ.*, (**2006**)

Rouillard et al., *ApJ.*, (**2016**)

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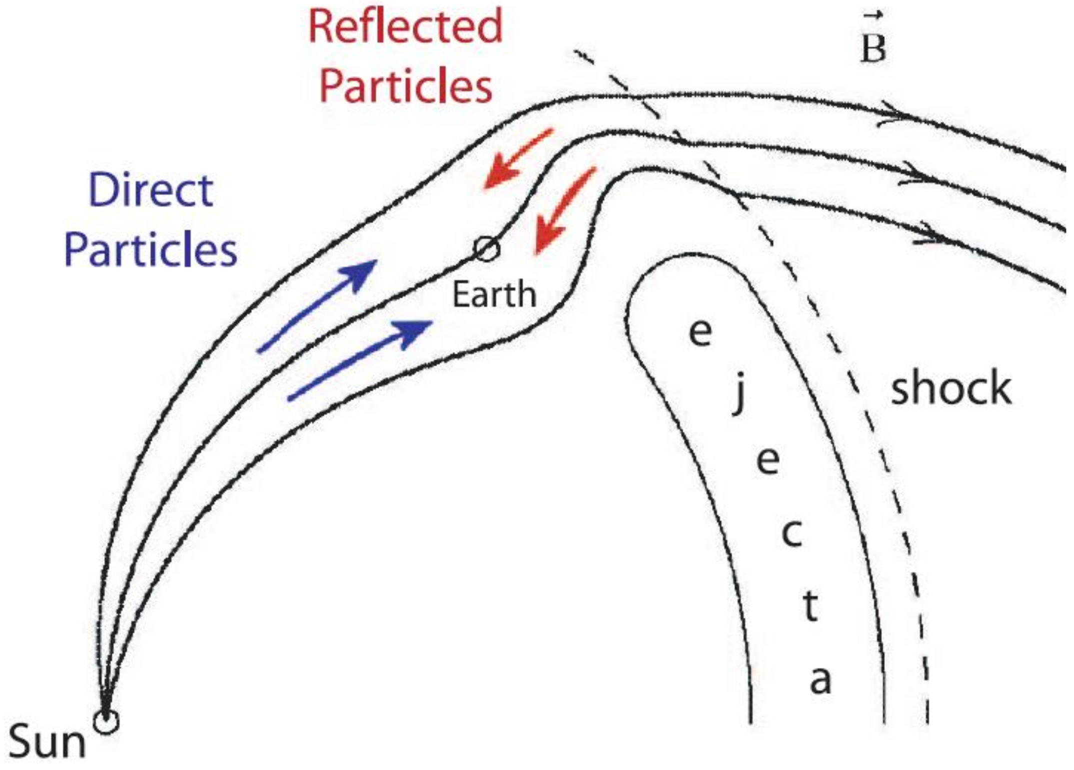


Ruffolo et al., *ApJ.*, (2006)

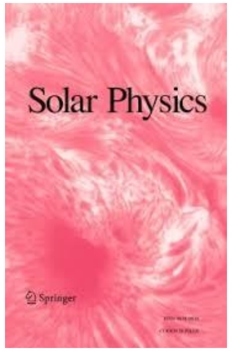
Conclusions

> The **anti-Sun flux** is suggestive of certain magnetic field configurations that may have contributed to these observed fluxes.

<u>The presence of multiple CMEs and their interplanetary counterparts prior to and during GLE74 is further suggestive of such possibilities</u>

> The **SRT of the near-relativistic particles** at **01:21 UT(±10min)** agrees with the actual SXR peak flux time (**01:23 UT±1min**), indicating a delay between the energetic (rising) phase of the flare. Additionally, near the SRT the CME-driven shock was located at a height of **~1.8 (±0.2) Rsun**.

See presentation by **Manon Jarry** today !



The high-energy protons of the ground level enhancement (GLE74) event on 11 May 2024

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Thank you for your attention