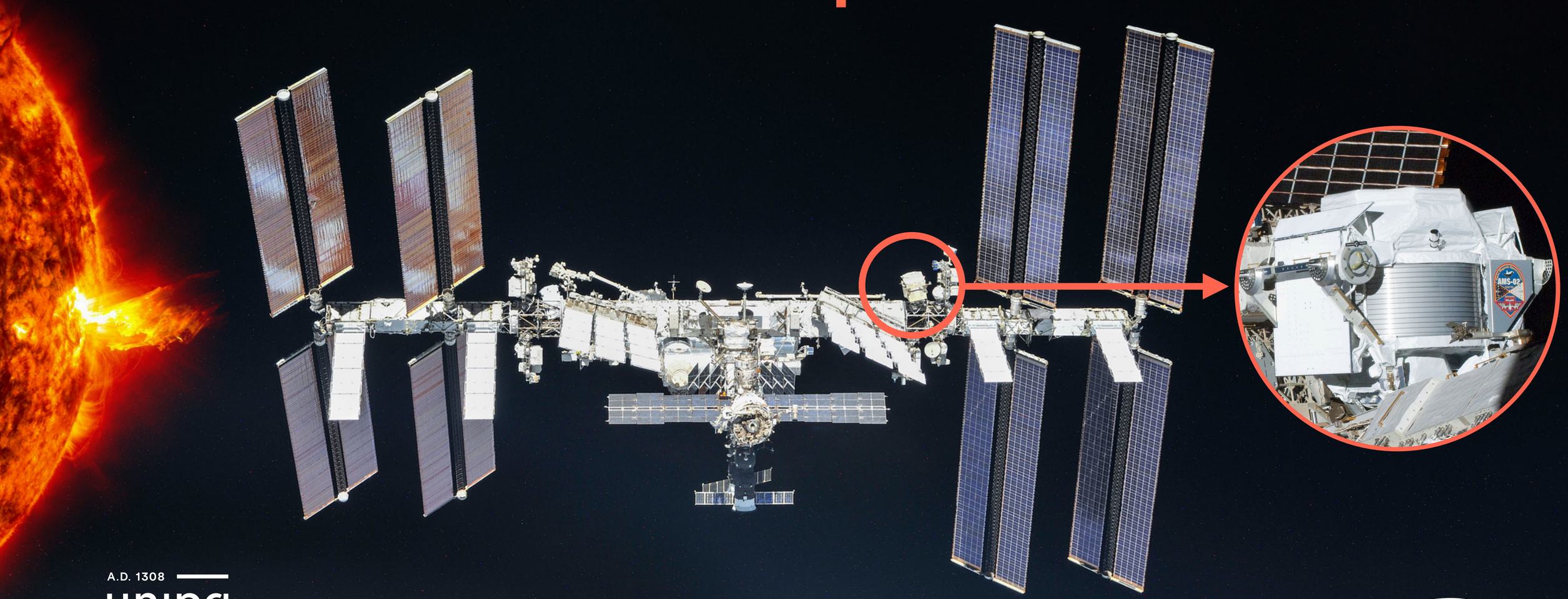
Solar Energetic Particles measured by the AMS-02 experiment



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DIPARTIMENTO DI ECCELLENZA
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AMS Italy 10-10-12025, Roma

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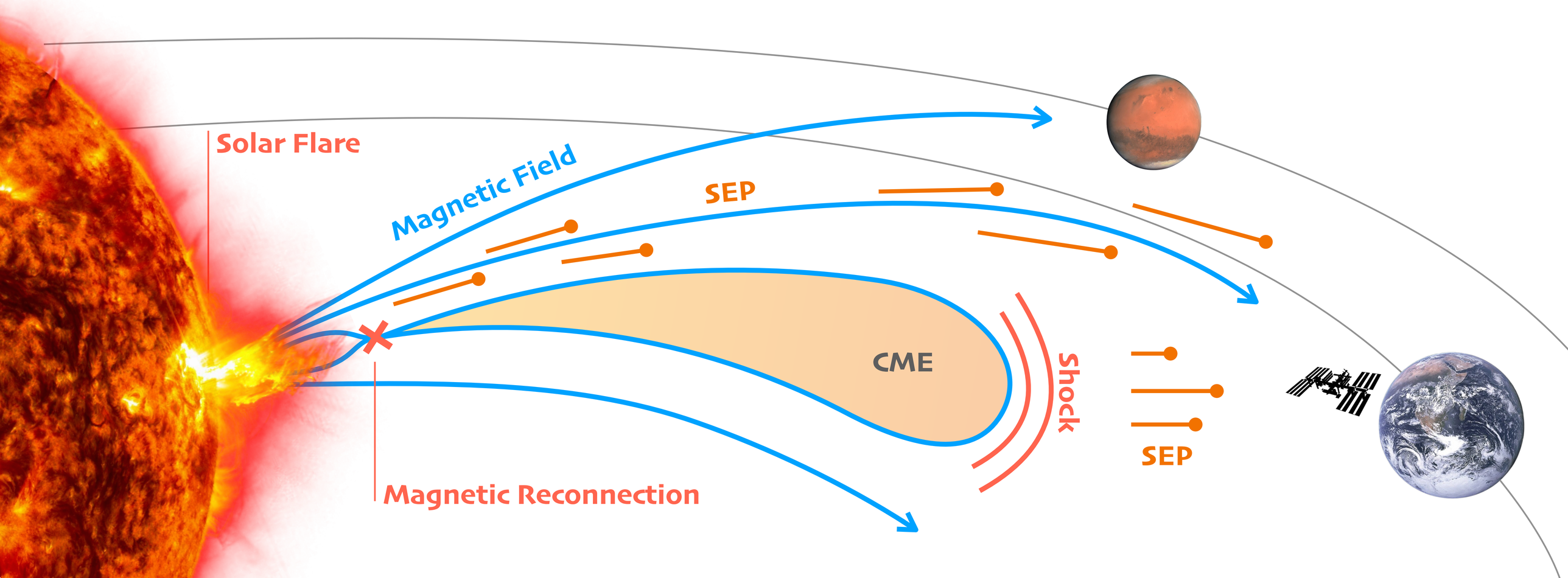
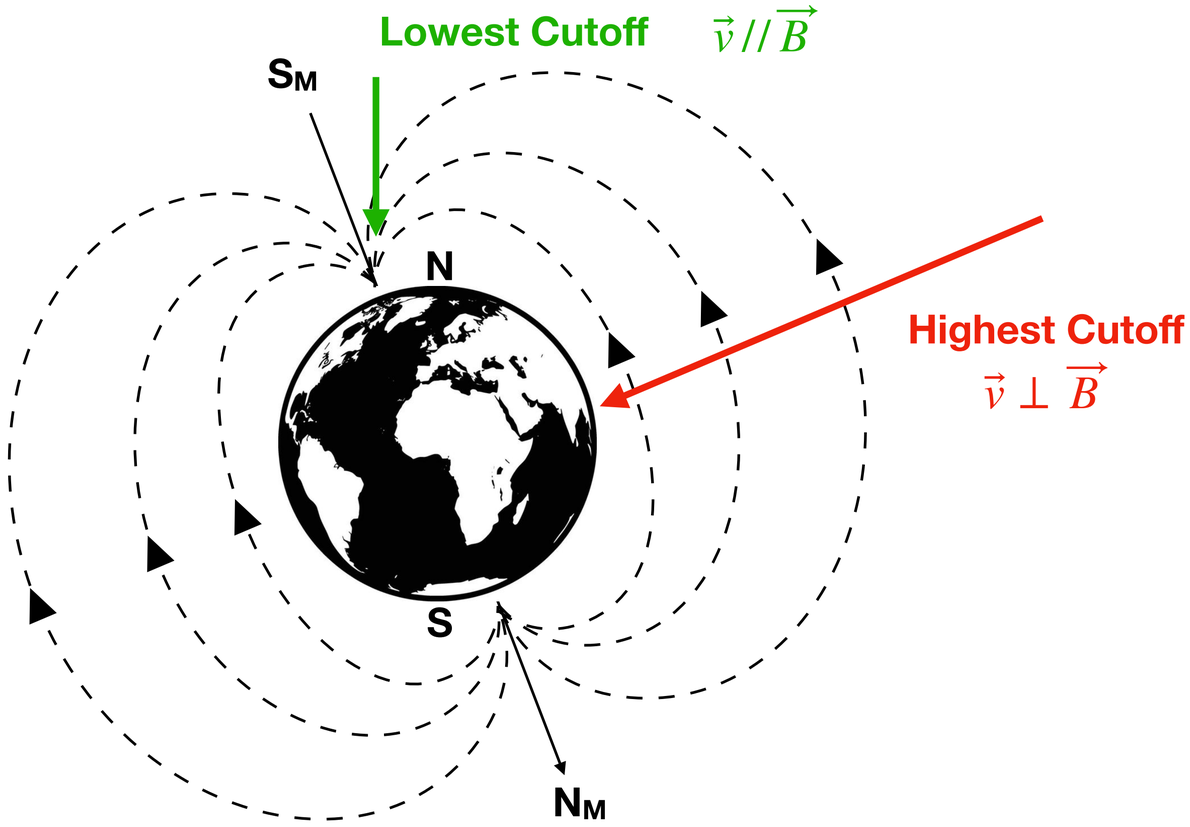
Solar Energetic Particles

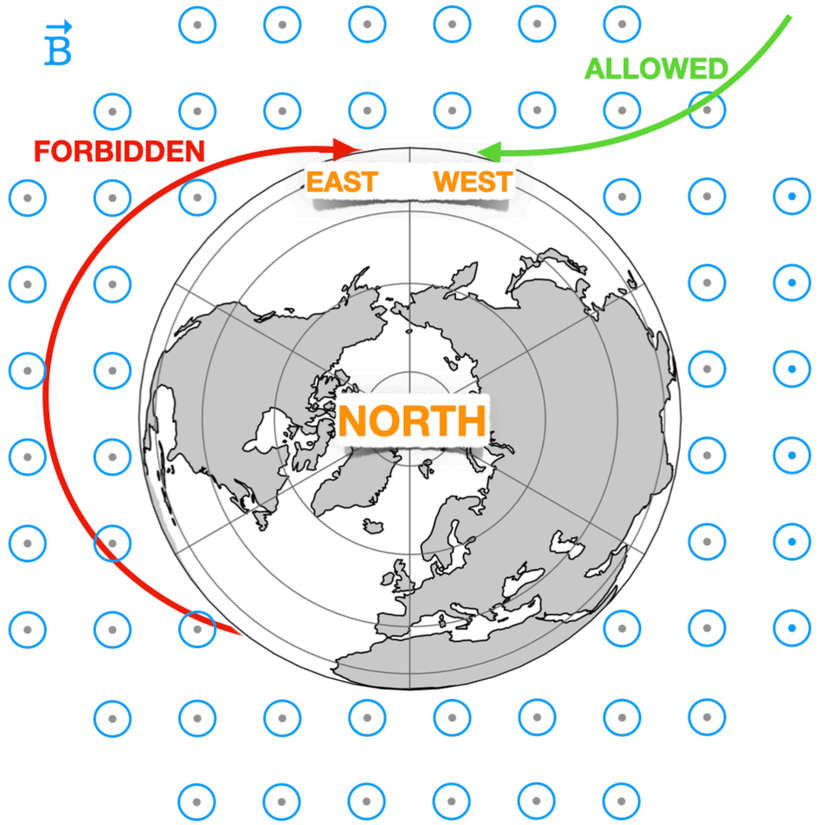
- The Sun produces its own cosmic rays: **Solar Energetic Particles (SEP)**. SEP can be accelerated by **magnetic reconnection** in solar flares and/or **diffusive shock acceleration** in CMEs.
- The **two mechanisms** are thought to generate **different classes** of SEP event on Earth: **impulsive** (ΔT<1 day) and **gradual** (ΔT ~ several days). *Solar Energetic Particles*, Reames 2021



Geomagnetic Rigidity Cutoff

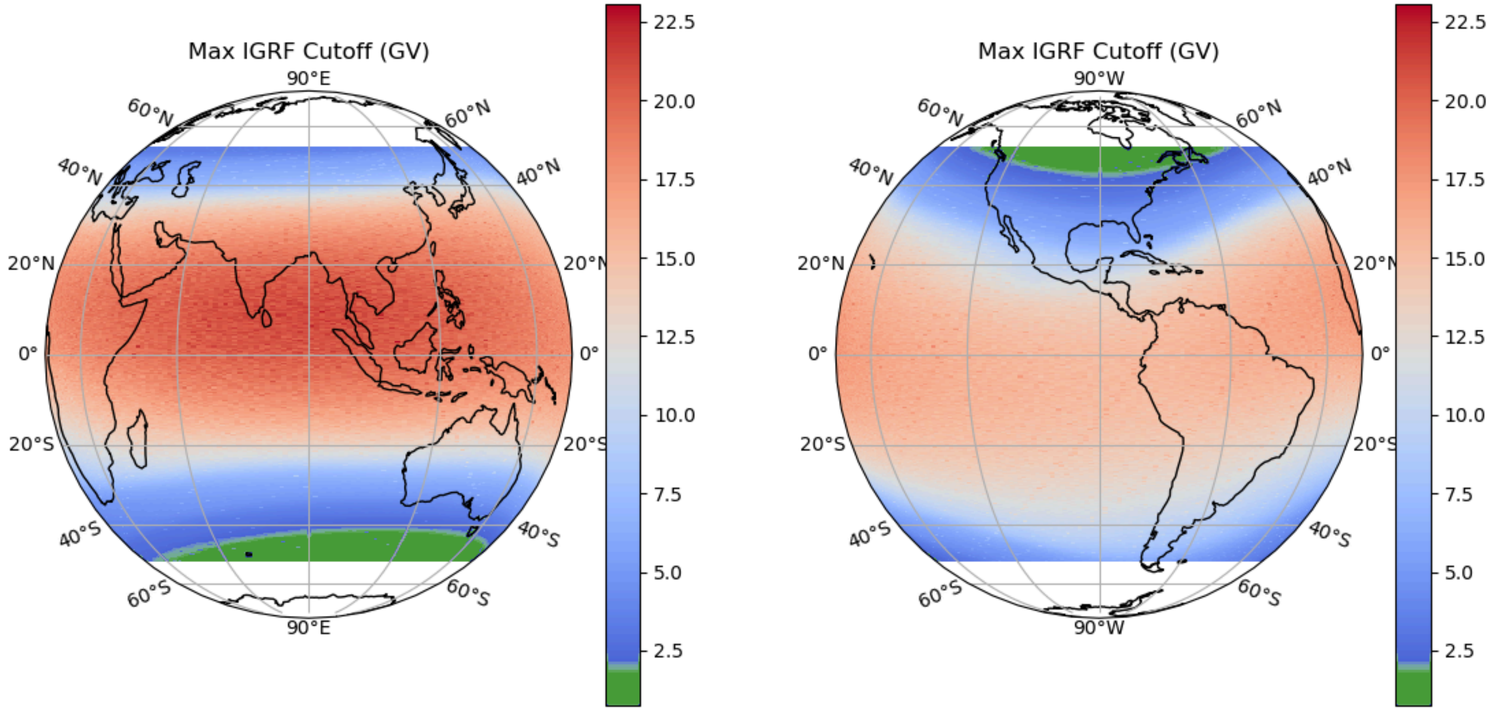
- **Charged CRs** are **deflected** by the geomagnetic field: **minimum rigidity** required to reach Earth.
- The **geomagnetic rigidity cutoff** is a **function** that depends on **position** and, at a given location, on **direction** and **charge** of incoming particles.





Polar-Pass Exposure and cutoff

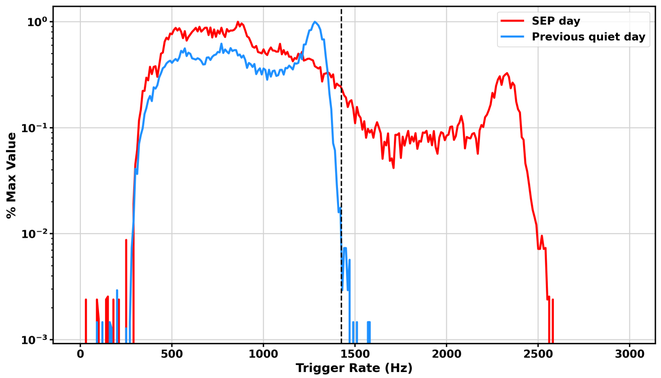
- AMS is **exposed to SEP** only for a **small fraction** of time, near **magnetic poles** (cutoff < 2 GV)
- **Cutoff models** (e.g. Max IGRF) are used in AMS to exclude **secondary/trapped cosmic rays**
- The **cutoff model** we normally use is too **conservative** for a SEP analysis, severely **limiting our statistics** at low rigidities

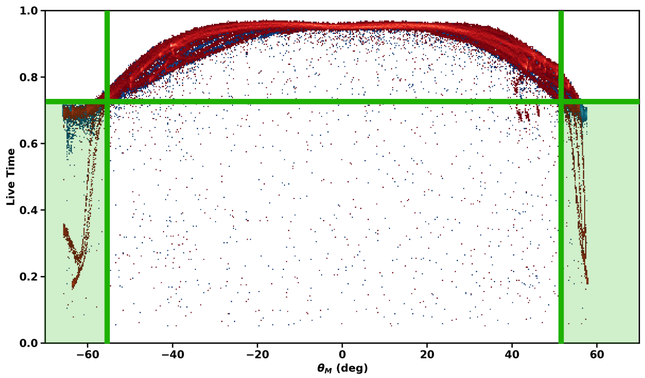


~~**Eliminating** the **above cutoff** cut~~ **Redefining** the **safety factor** for the **rigidity cutoff** improves statistics at low rigidities.

→ **We can try to define a “polar-pass” region using ~~a different variable~~ the cutoff.**

SEP Proton Analysis Roadmap





Without "above cutoff" cut

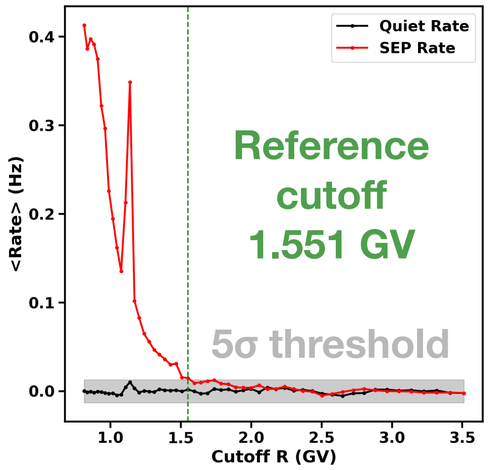
Rate-based threshold

Geomag. Latitude threshold

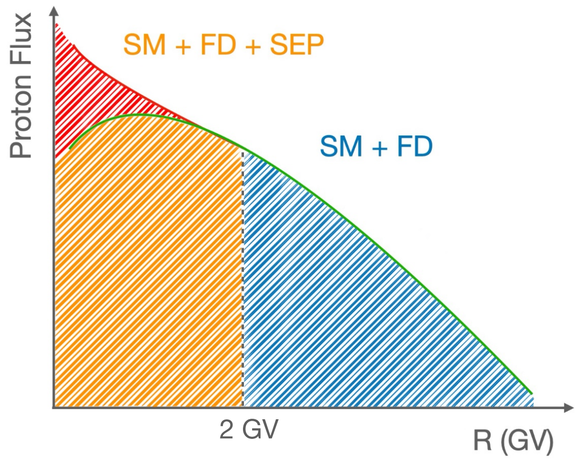
NAIA ntuples → Proton Selection → GCR Background Subtraction → Flux

Cutoff-based threshold

High rigidity normalization

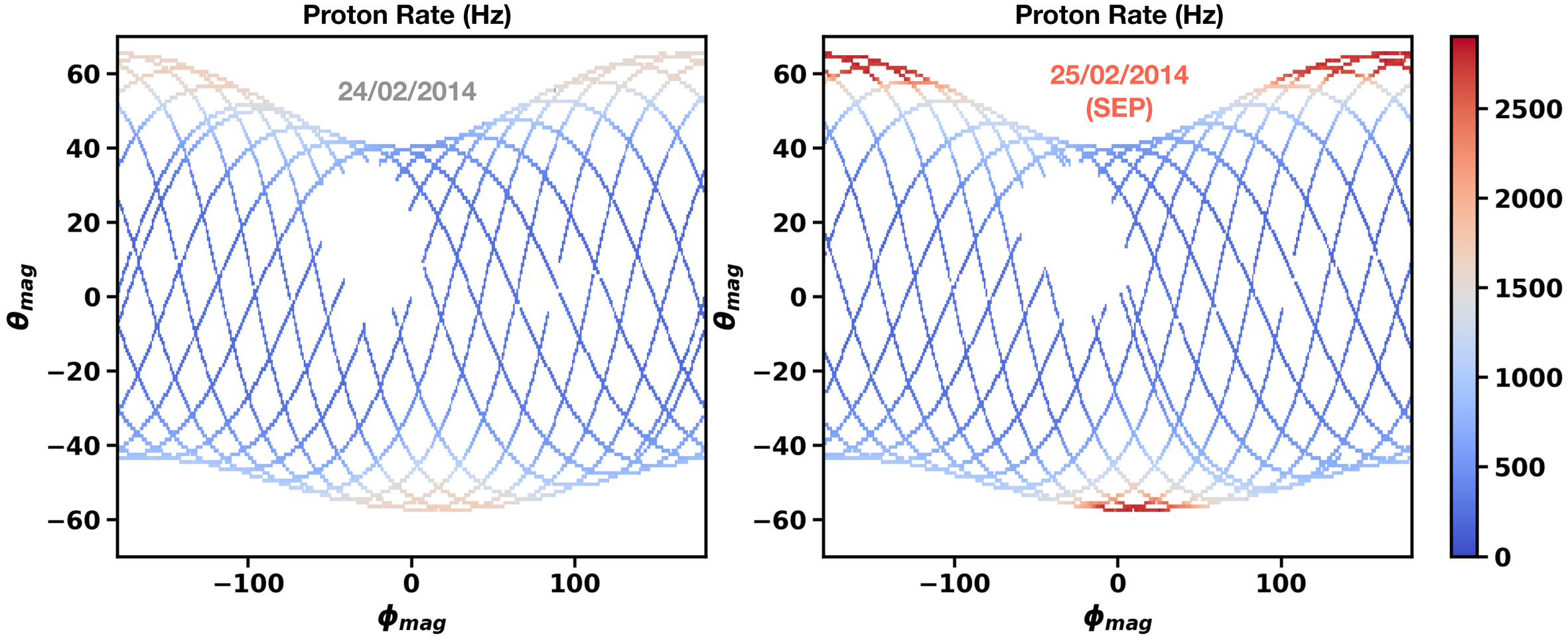


With "above cutoff" cut



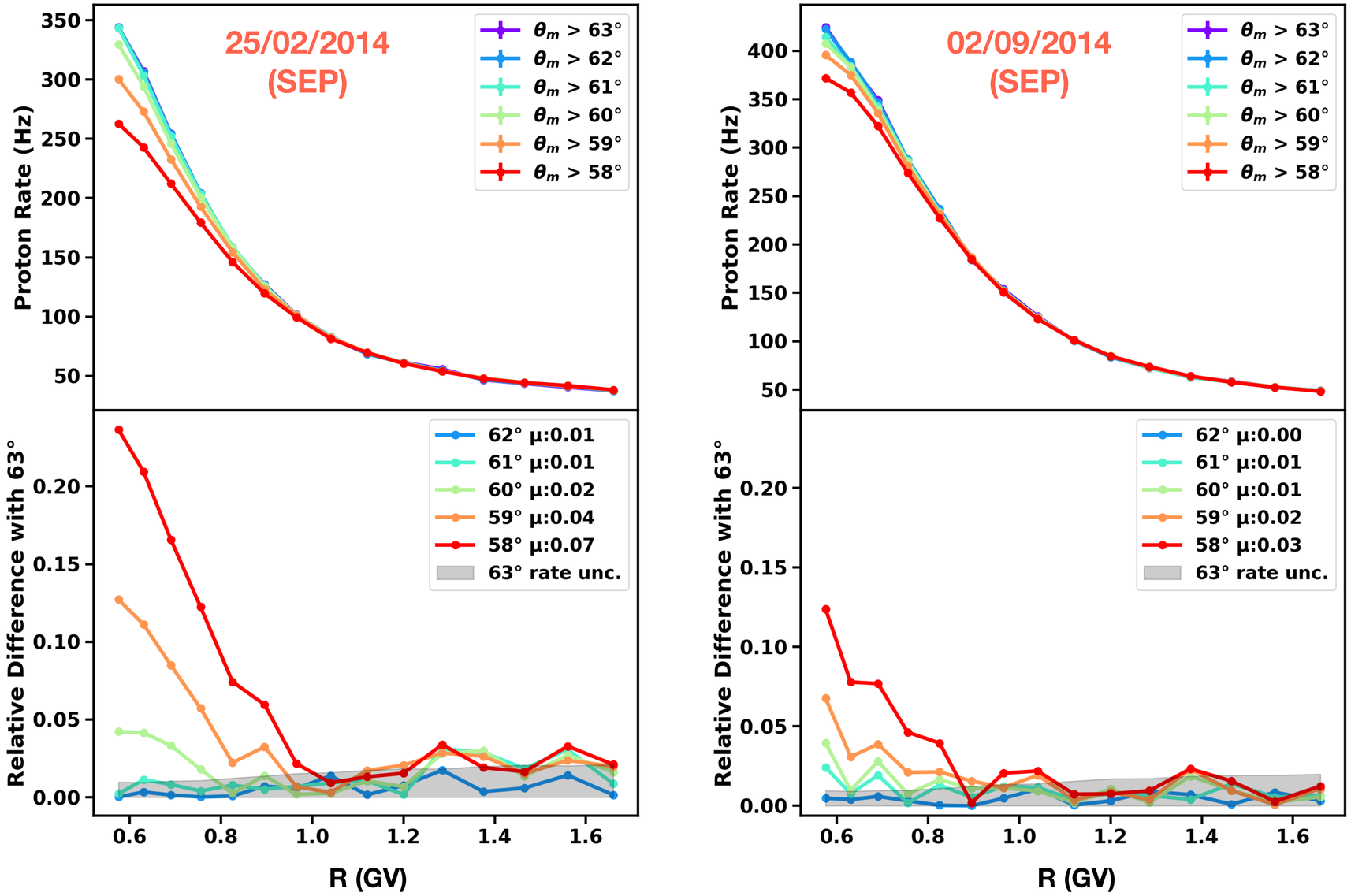
Previous approach: geomagnetic latitude threshold

- The **rate** of proton events is shown in **geomagnetic coordinates before** and **during** an SEP event. Plots are normalised to the maximum value of the rate during the SEP day.
- Is it possible to find an optimal **cut** in **geomagnetic latitude** to select SEPs?

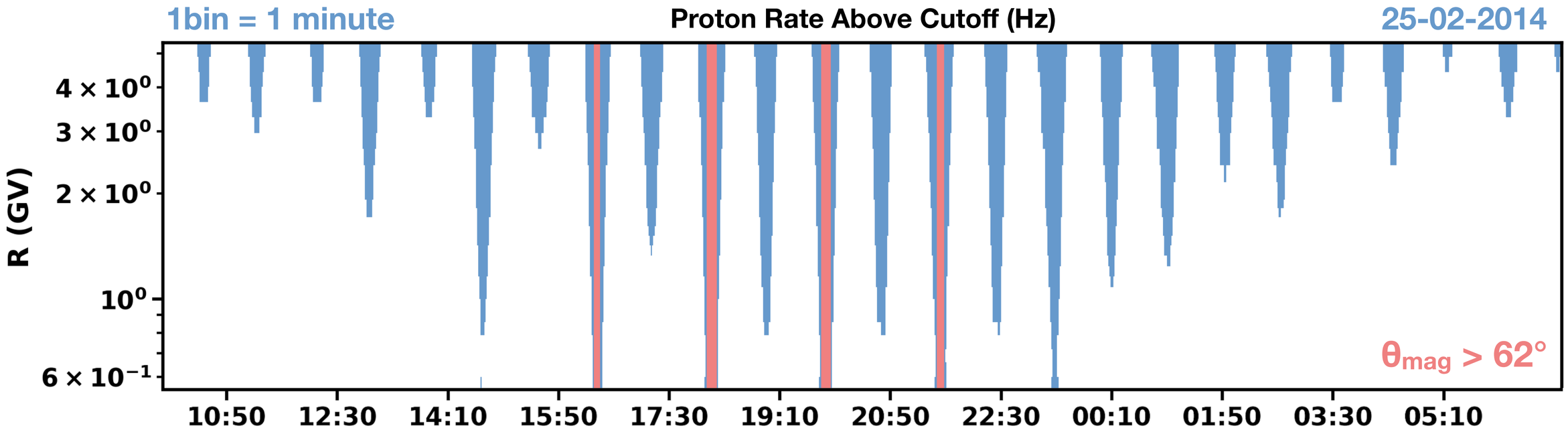


Previous approach: geomagnetic latitude threshold

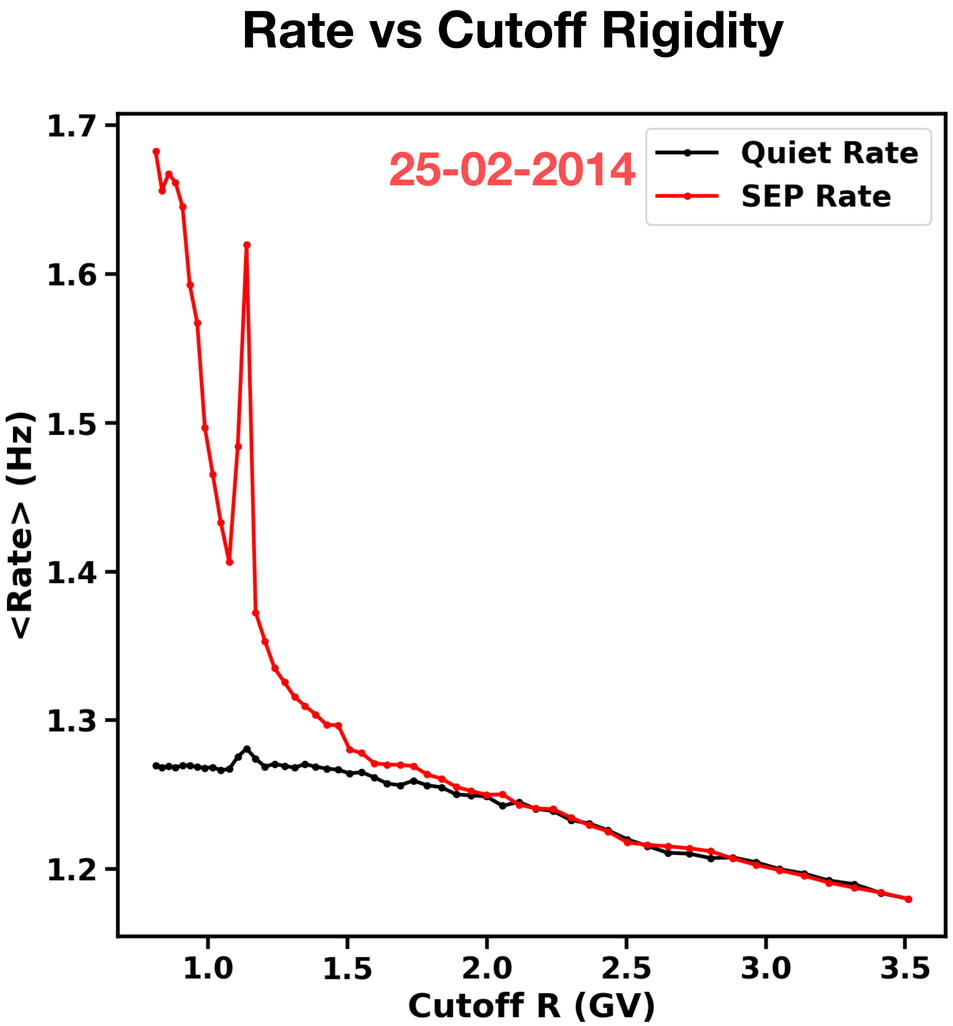
- To select a **threshold** on **geomagnetic latitude**, we studied the **proton rate** at increasing latitudes.
- We selected the value that shows a **relative difference** within **statistical uncertainty** of the rate at θ = 63°.
- **θ = 62°** is an optimal threshold for most of the events.

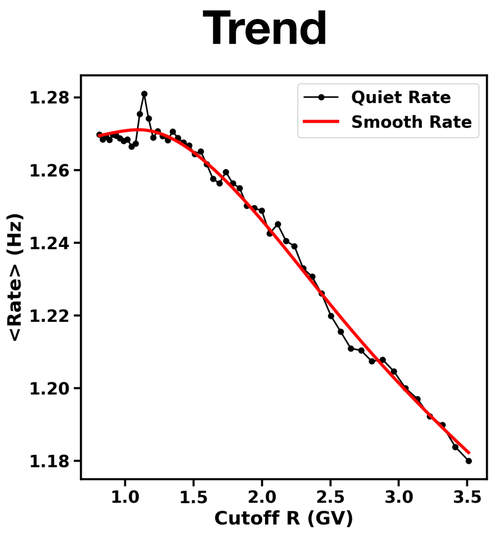


Selected proton rate with previous approach

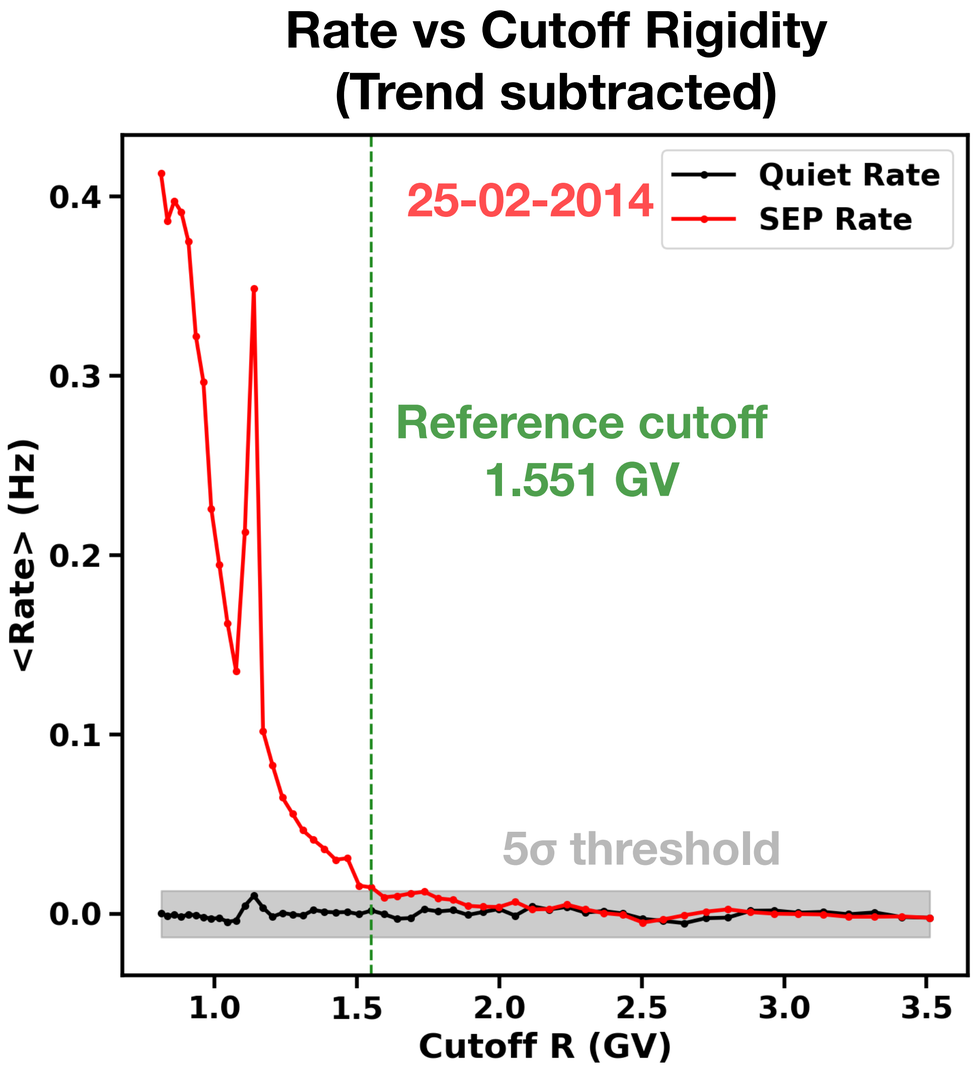


Current approach: reference cutoff

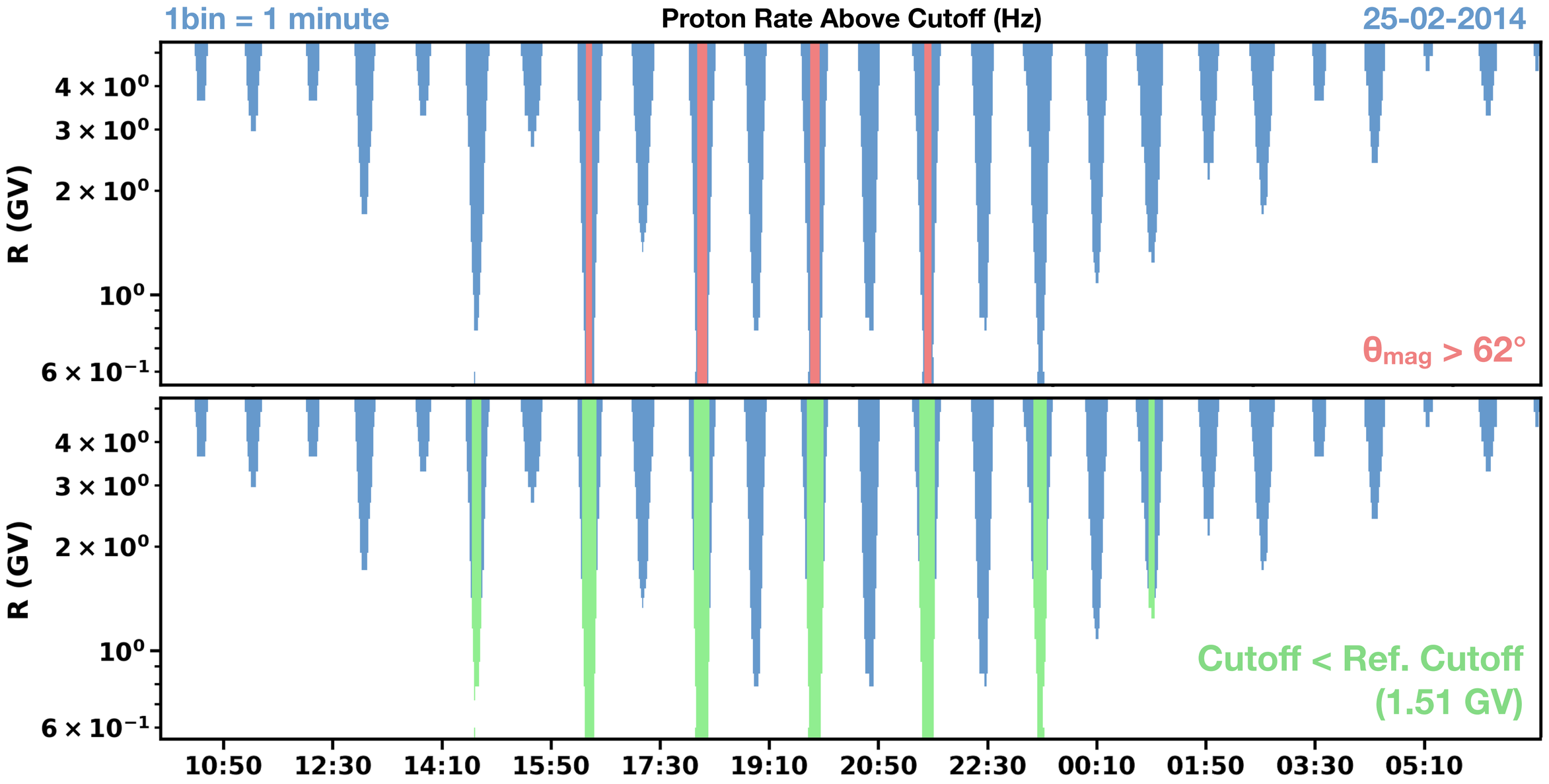




Subtract global trend and find first bin above 5σ of quiet distribution



Comparison with previous approach

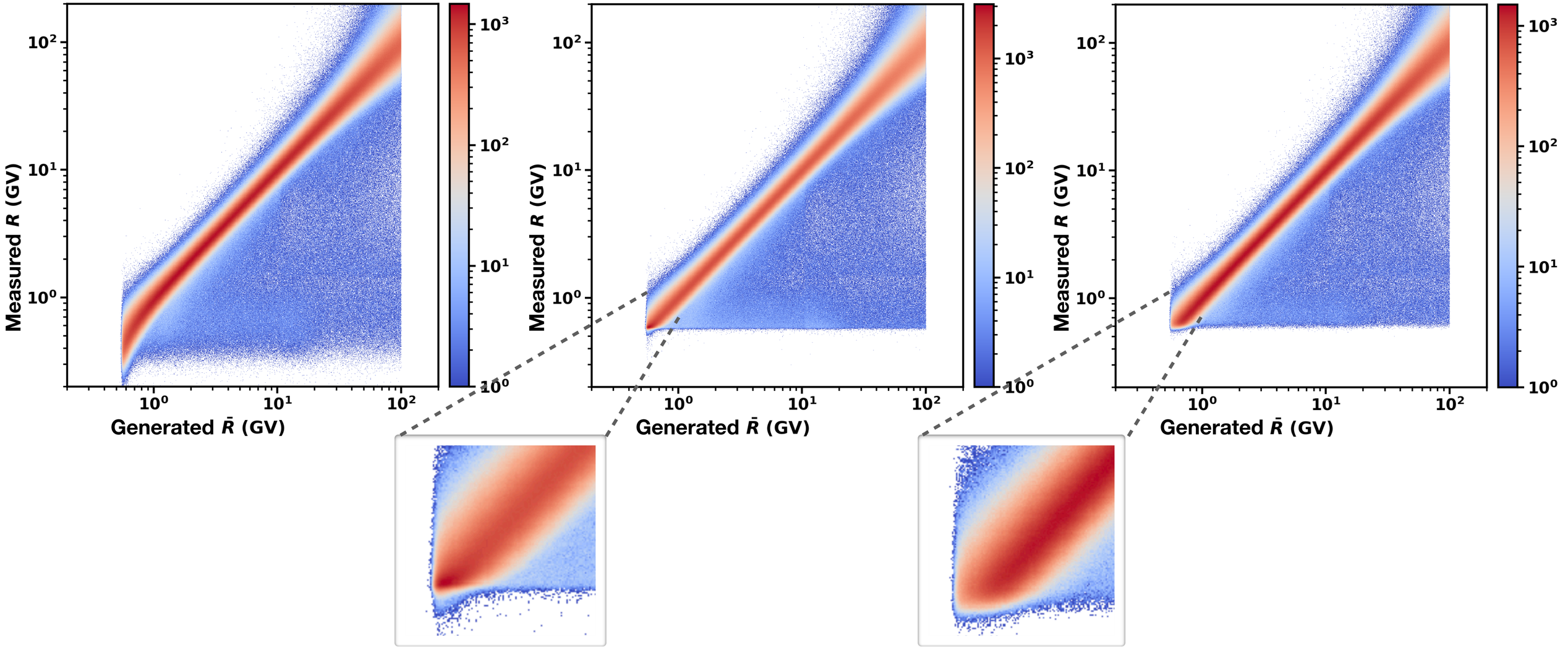


Note on Energy Losses

Migration matrix **without energy loss** correction (GBL)

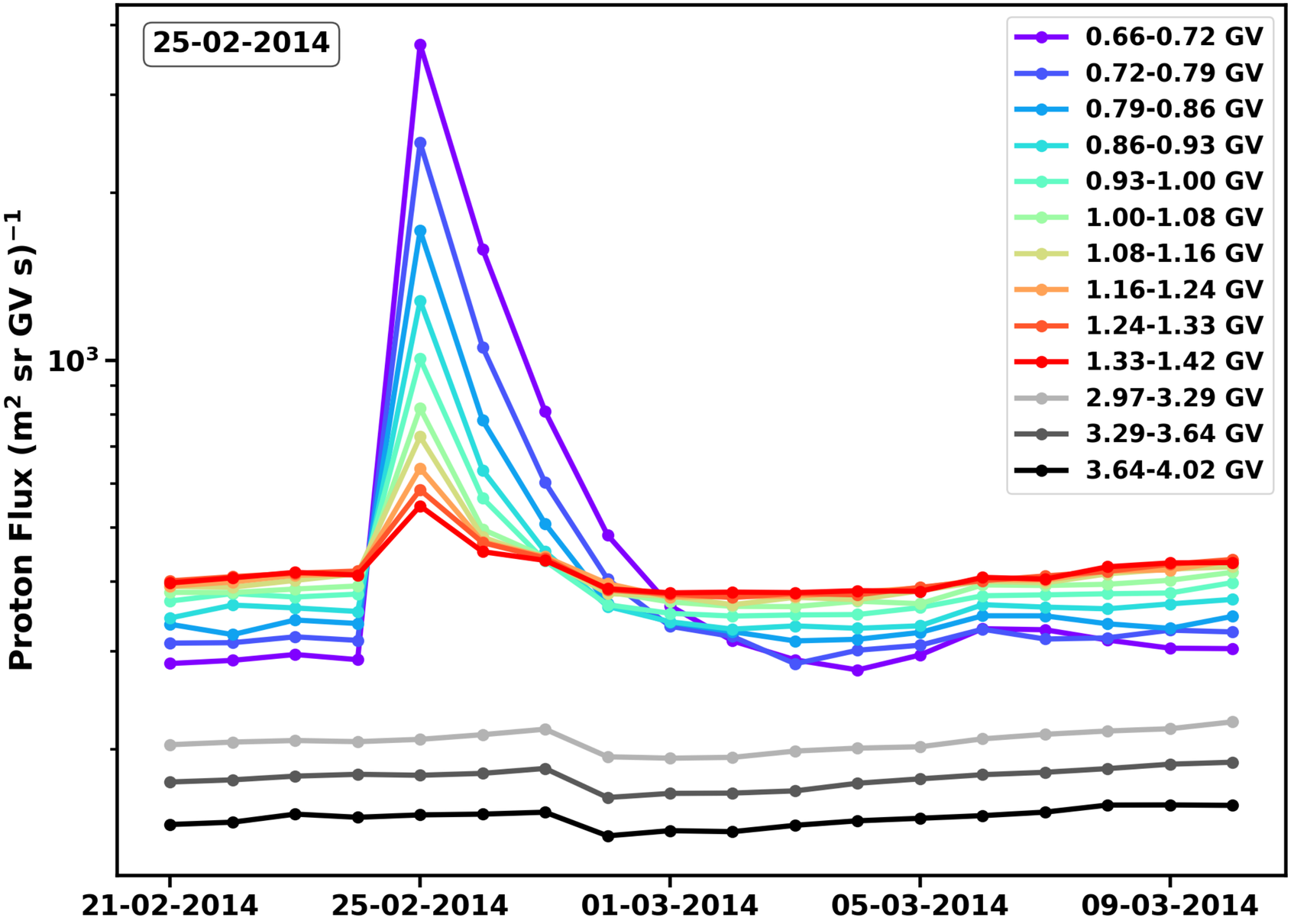
Migration matrix **with global energy loss** correction (GBL)

Migration matrix **with Kalman rigidity**

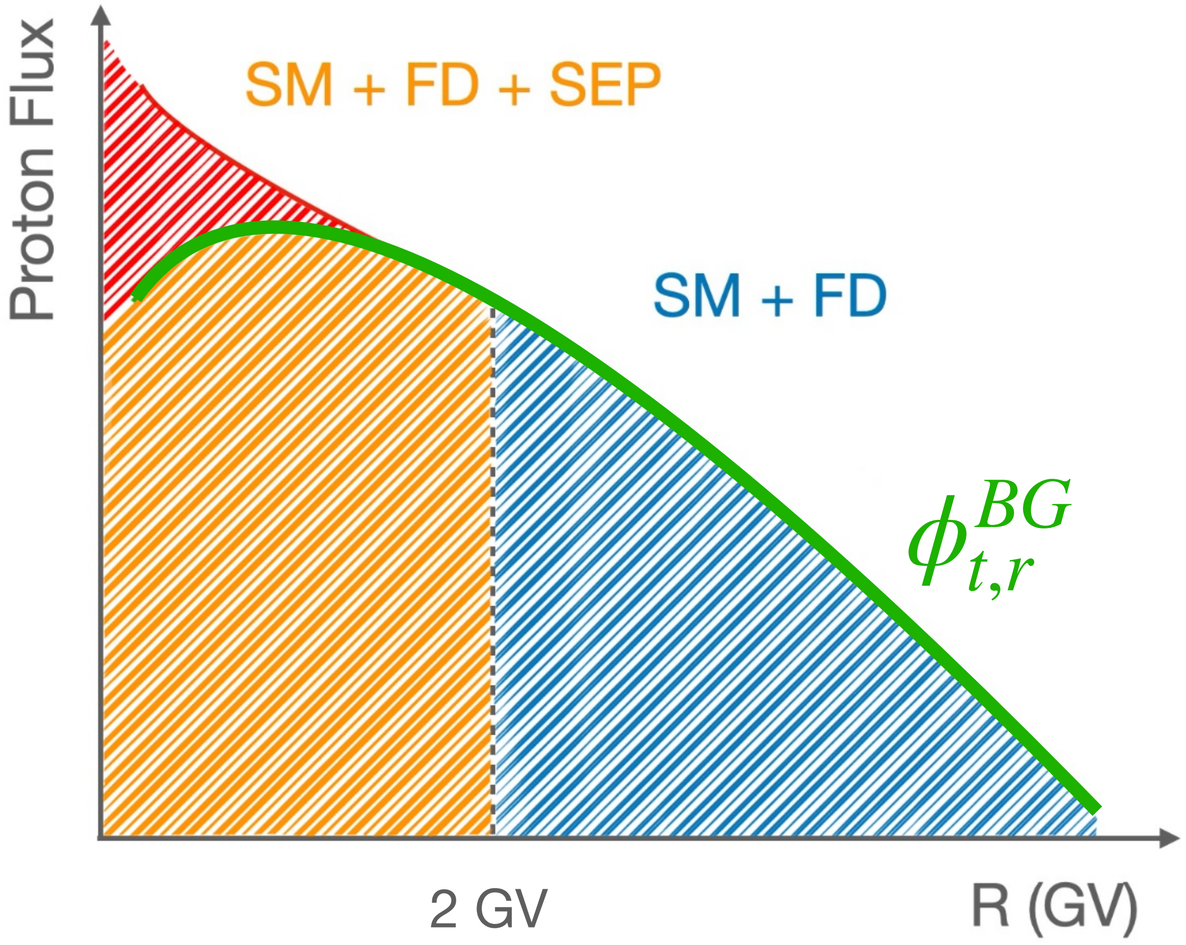


Proton Flux During SEP Event

- **Total proton flux**, for the north polar region.
- The **increase** due to SEPs is **visible** at **low R** (coloured lines), while this contribution is **negligible above** (grey).
- We now need to **subtract** the **GCR background** and **secondary** component.



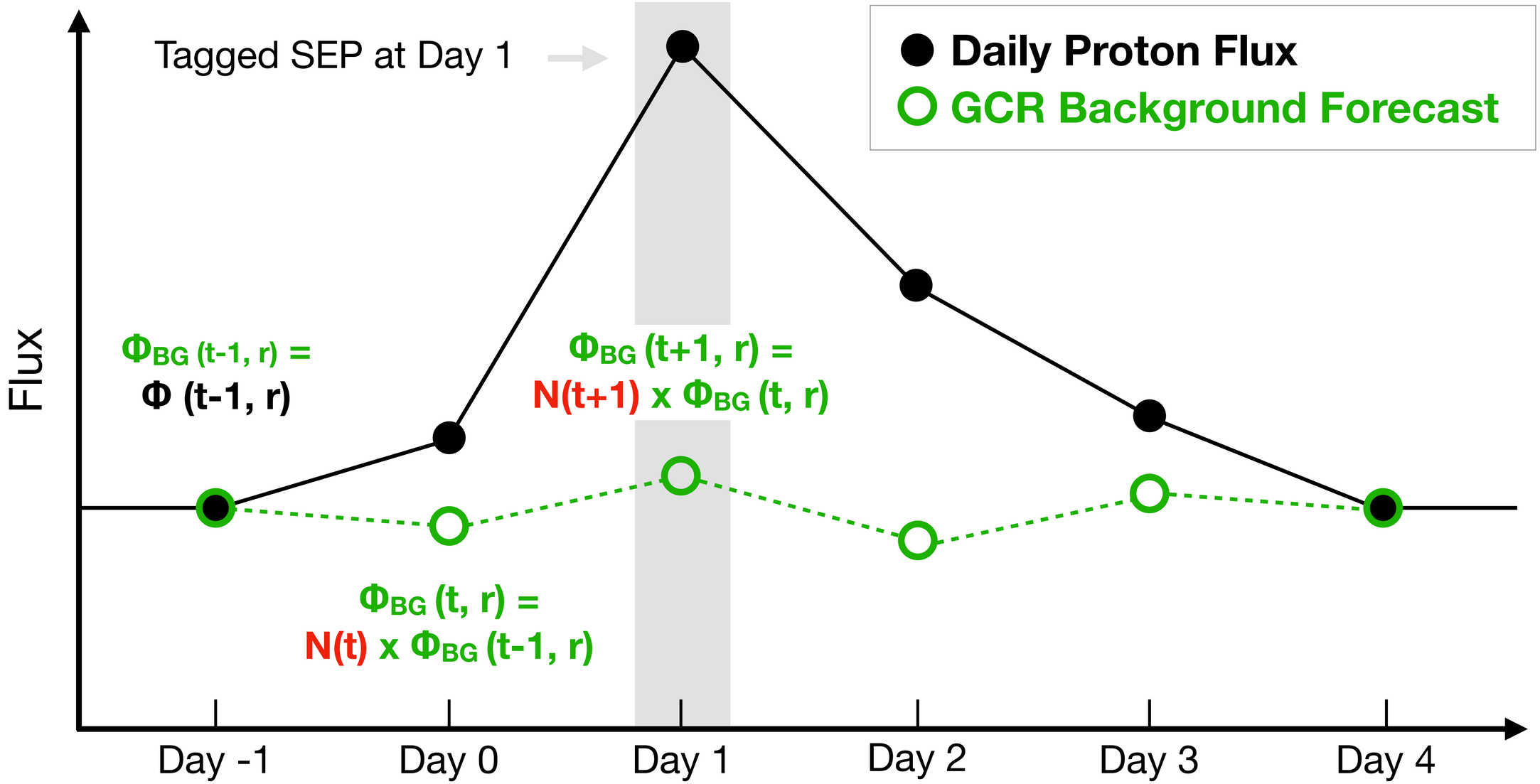
GCR Background Subtraction



$$\phi_{t,r}^{BG} = N_t \times \phi_{t-1,r}^{BG}$$

- **N_t** should include effects of **solar modulation (SM)** and **Forbush decreases (FD)**, but not SEPs.
- The **SEP contribution** to the total flux becomes **negligible** above **~2 GV**.
- The **normalization N_t** can be calculated from the flux at **higher rigidities**, excluding the SEP contribution.

GCR Background Subtraction



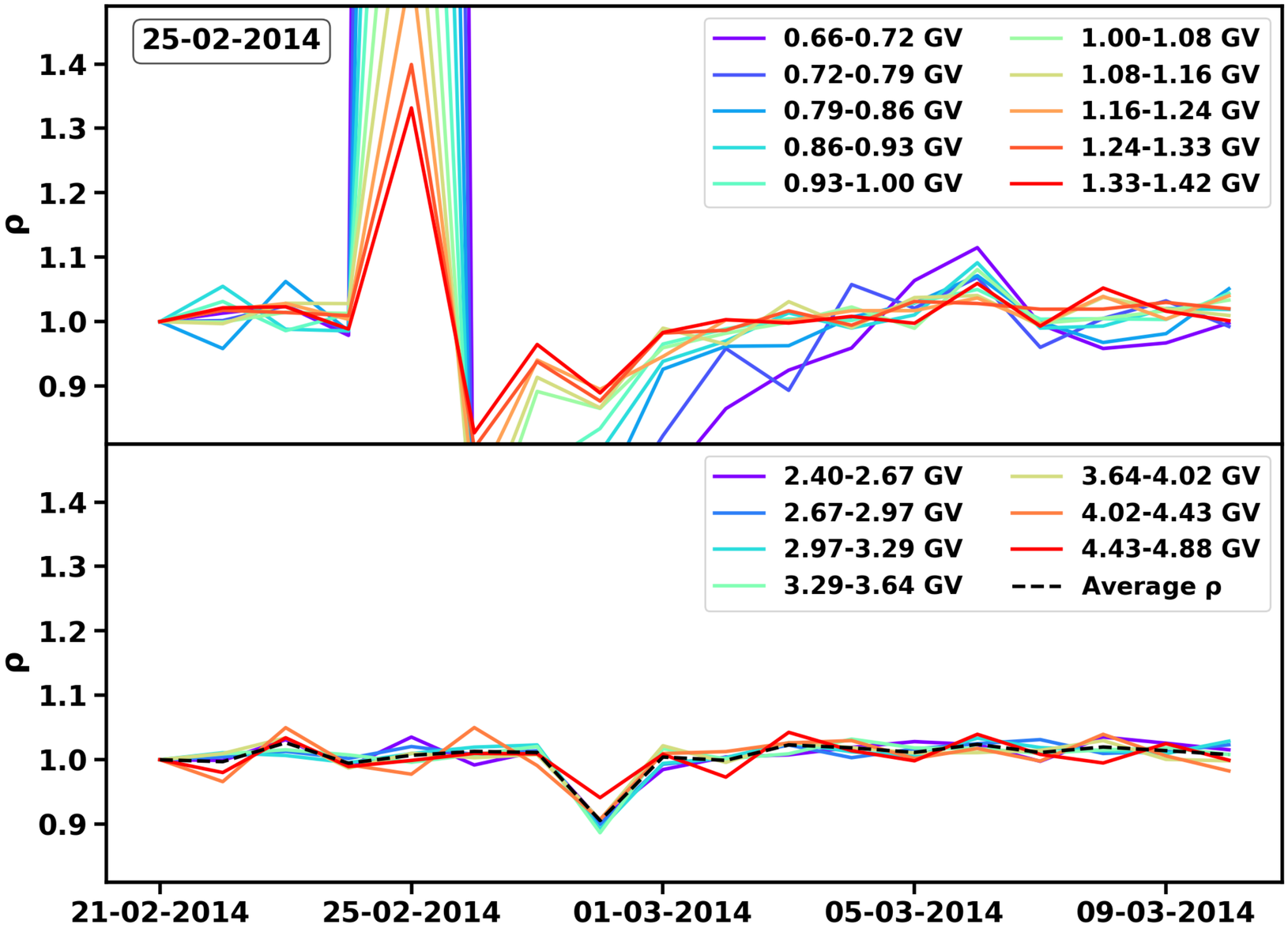
Forecasting Parameter: Ratio with Lag1 Flux

For each time (day) and rigidity bin, ϱ is defined as the **ratio** of the **current** daily flux with the flux of the **previous** day.

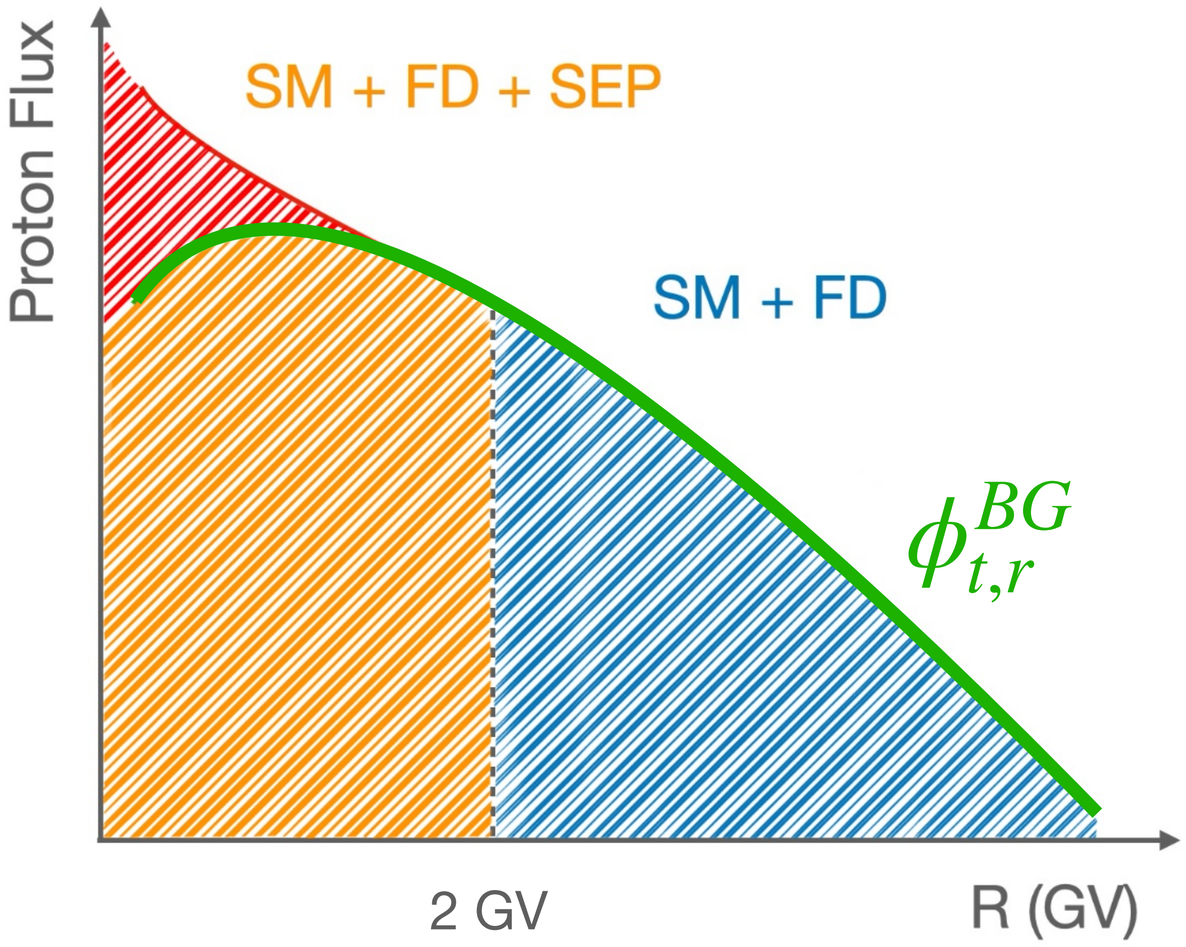
$$\rho_{t,r} = \frac{\phi_{t,r}}{\phi_{t-1,r}}$$

Properties:

- **Stationary**: removes seasonal trend.
- **Rigidity independent** during quiet periods.



Background Normalization



The **normalization N_t** is given by the **average ϱ** parameter, in the rigidity interval ~ **[2.4, 4.8] GV**, above the maximum rigidity reached by SEPs.

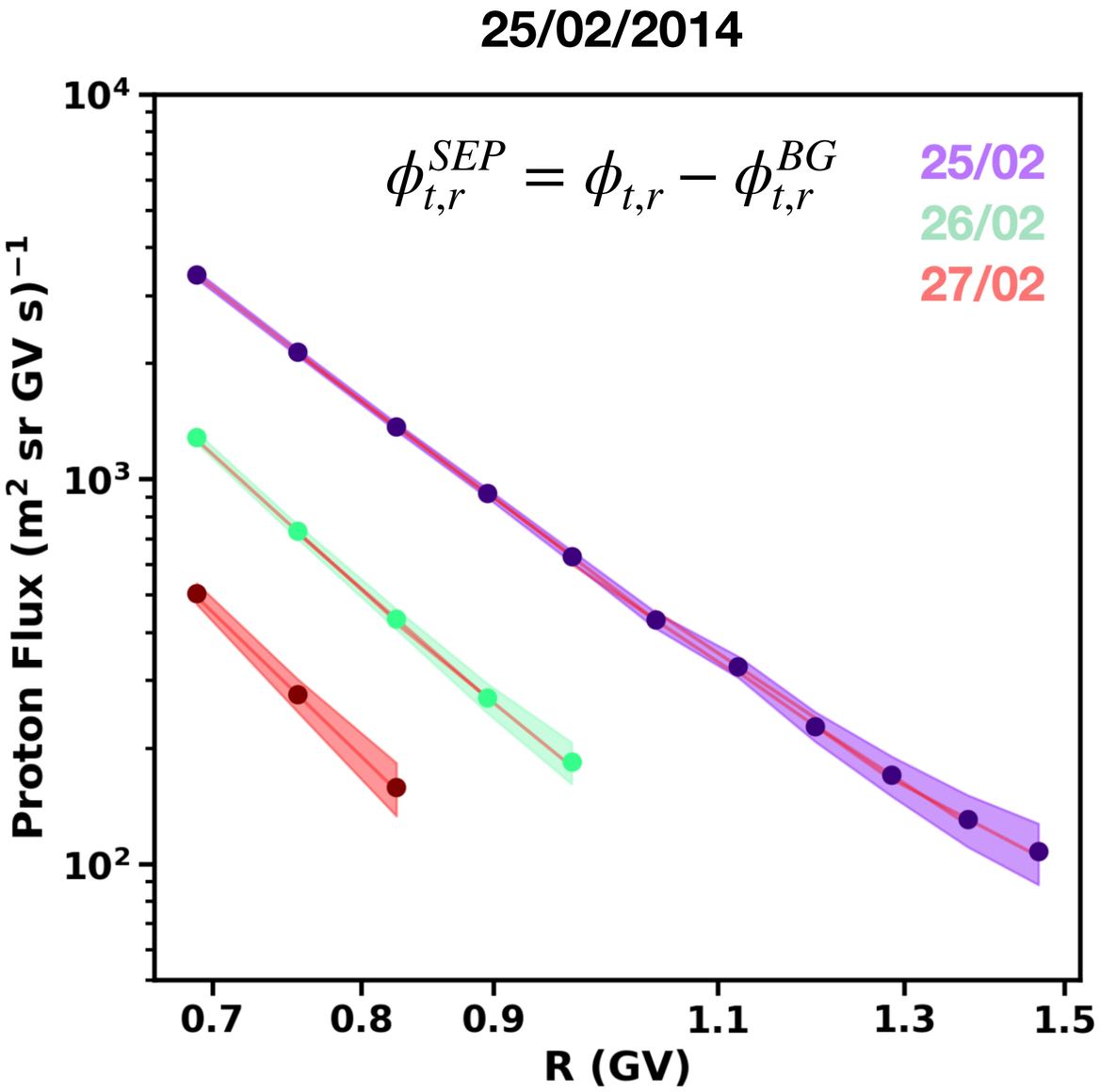
$$N_t = \langle \rho \rangle_t = \frac{1}{7} \sum_{r=10}^{17} \frac{\phi_{t,r}}{\phi_{t-1,r}}$$

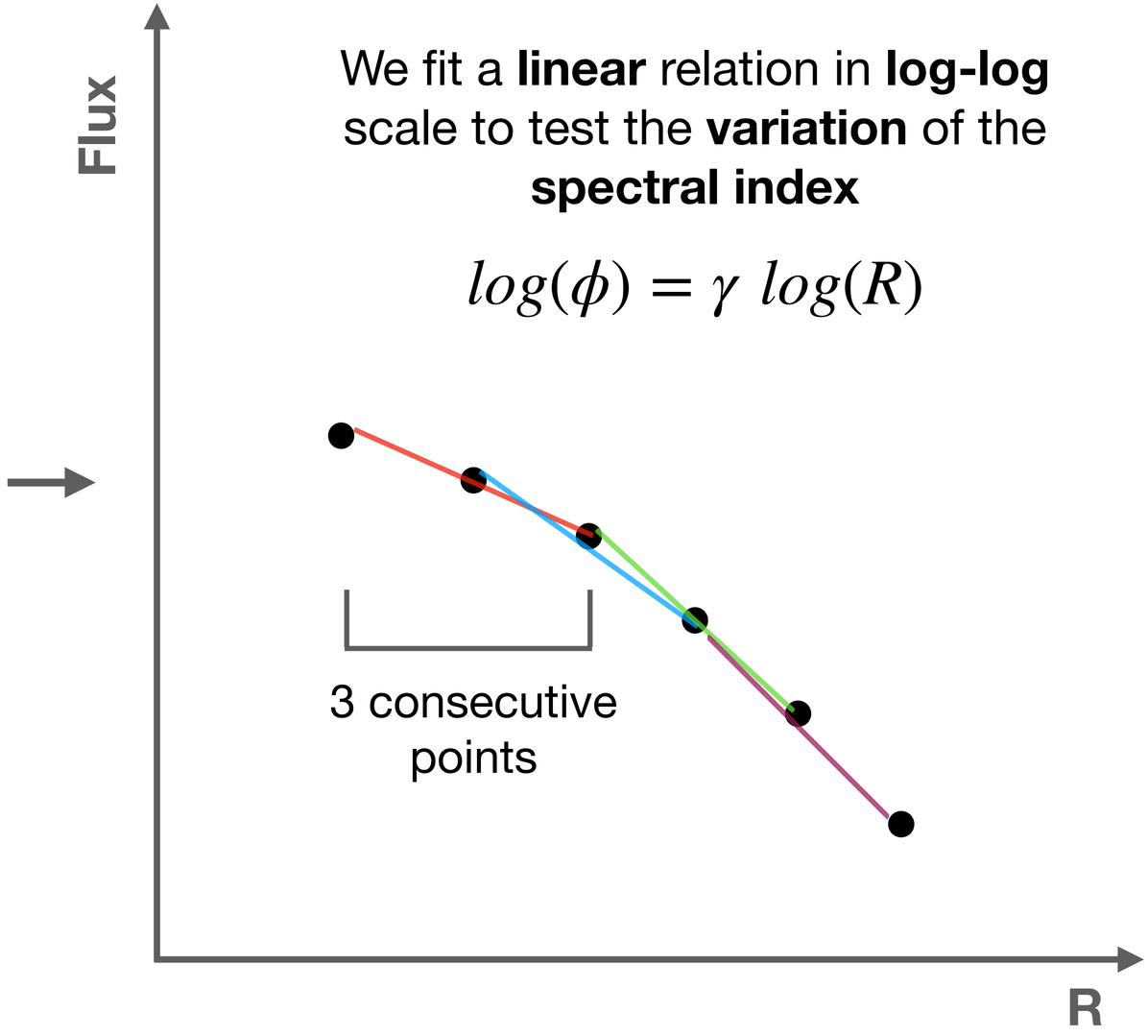
$$\downarrow$$

$$\phi_{t,r}^{BG} = \langle \rho \rangle_t \times \phi_{t-1,r}^{BG}$$

N_t is the same **for any rigidity bin**, thanks to **rigidity independence**.

Background Subtracted SEP Spectra

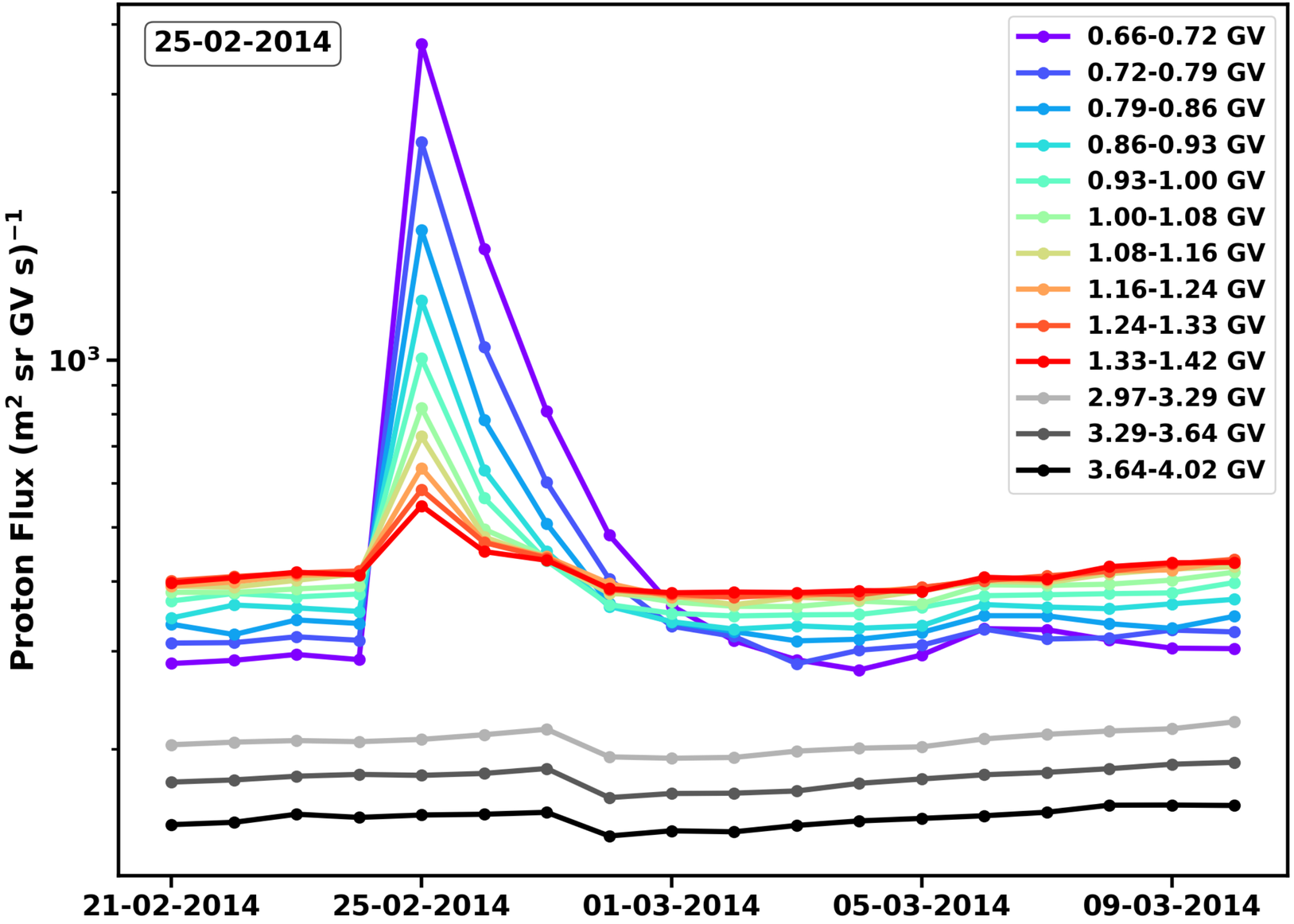




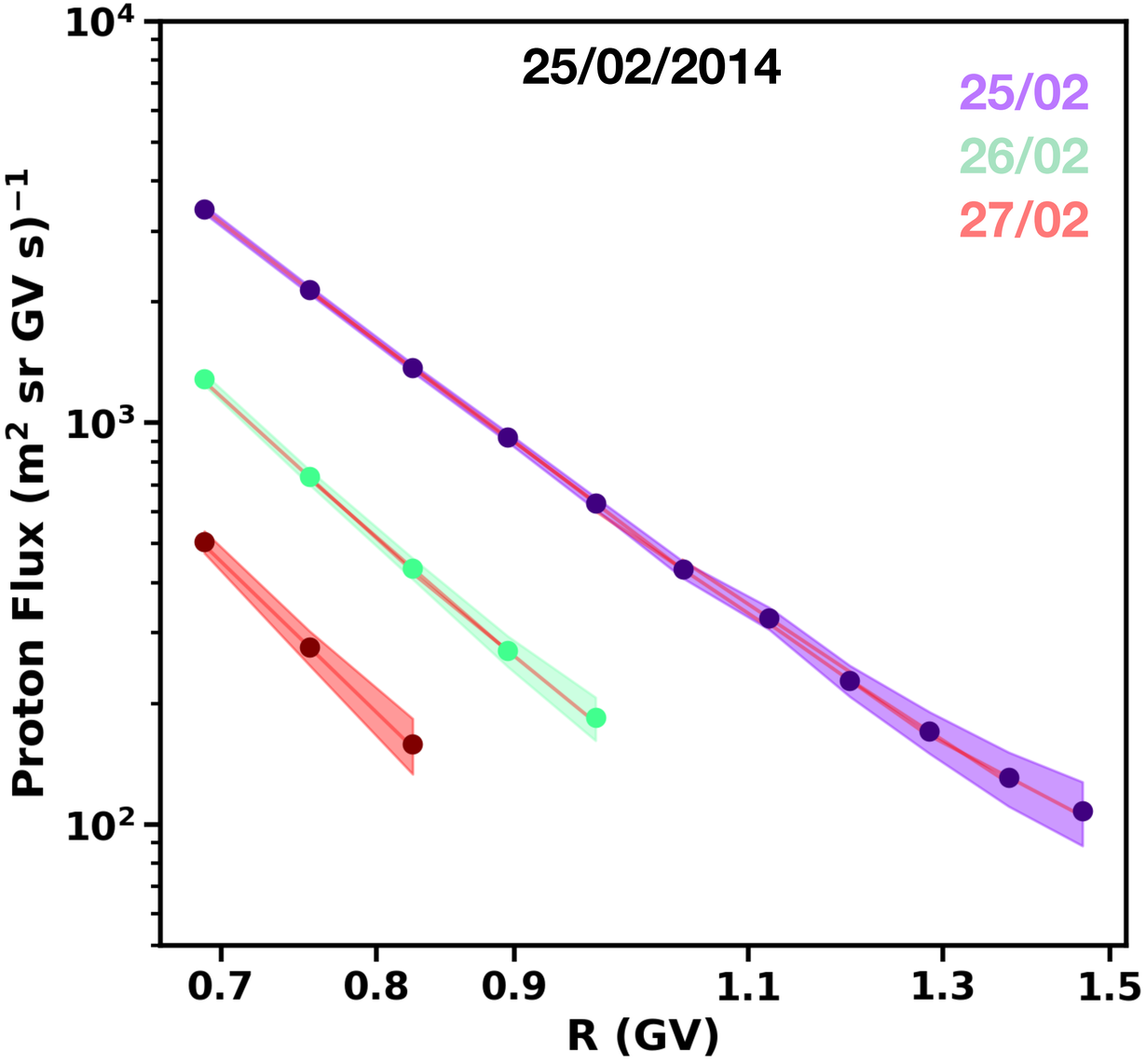
We fit a **linear** relation in **log-log** scale to test the **variation** of the **spectral index**

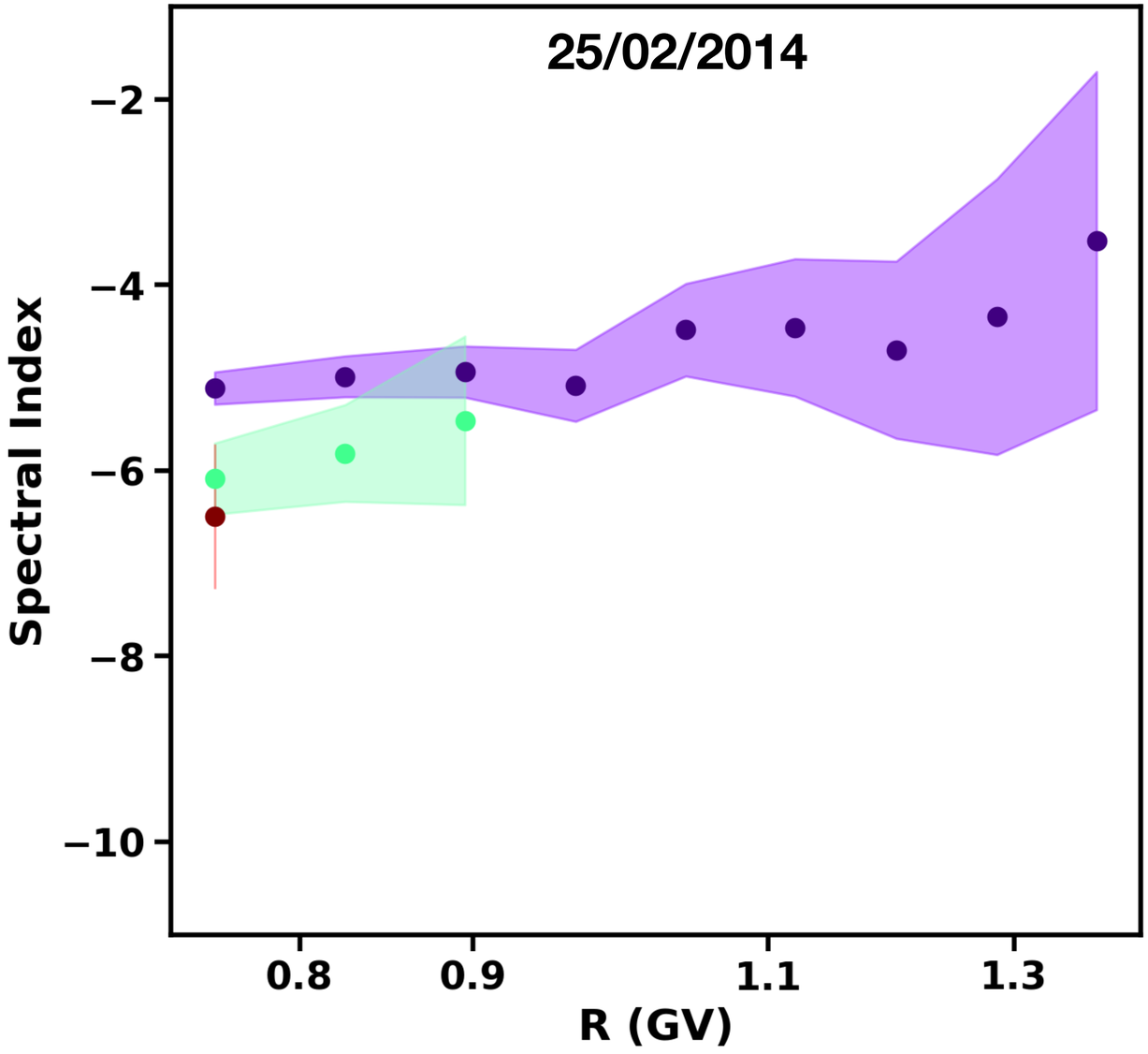
$$log(\phi) = \gamma\ log(R)$$

Rigidity and Time Evolution of SEP Spectra

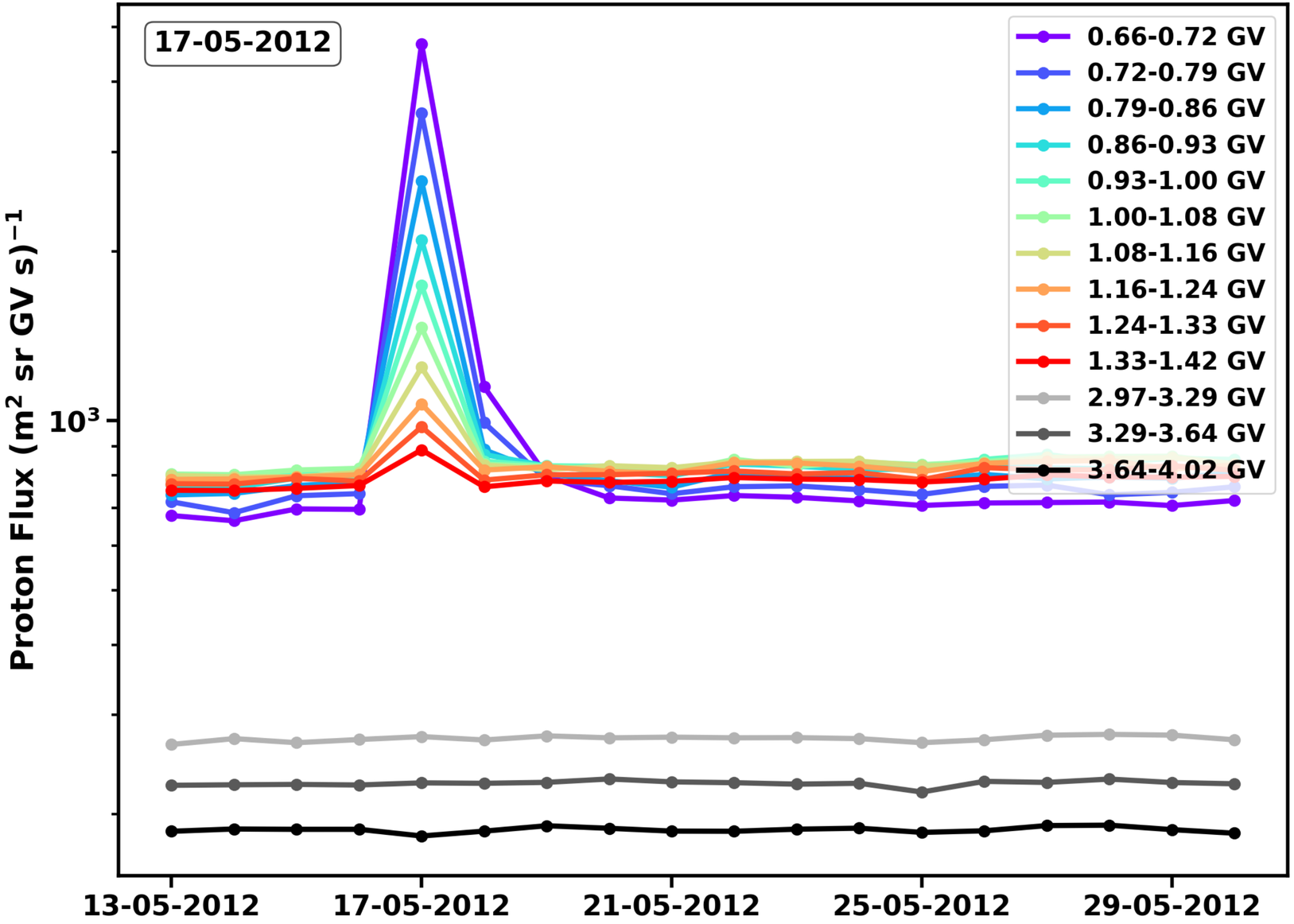


Rigidity and Time Evolution of SEP Spectra

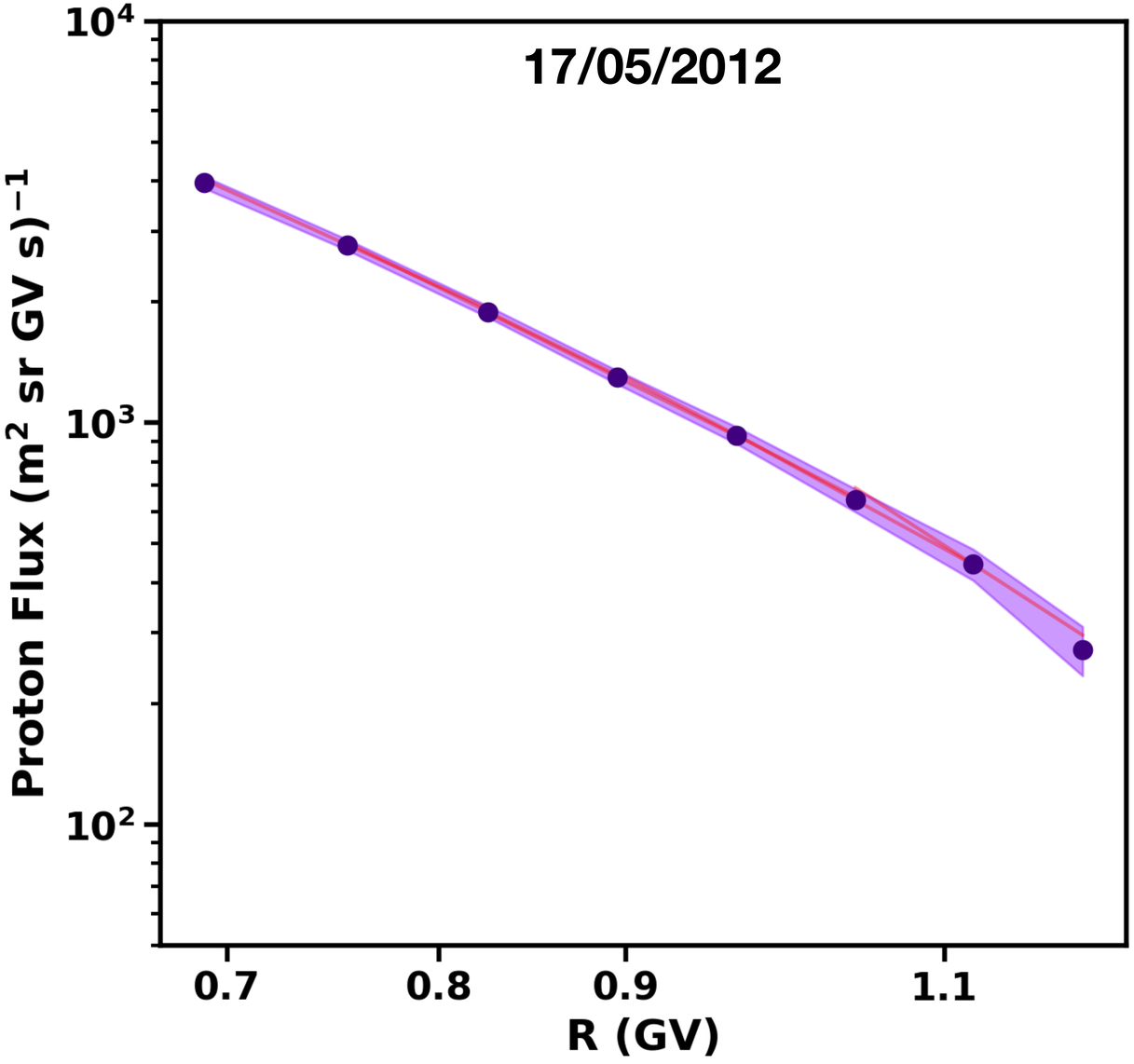


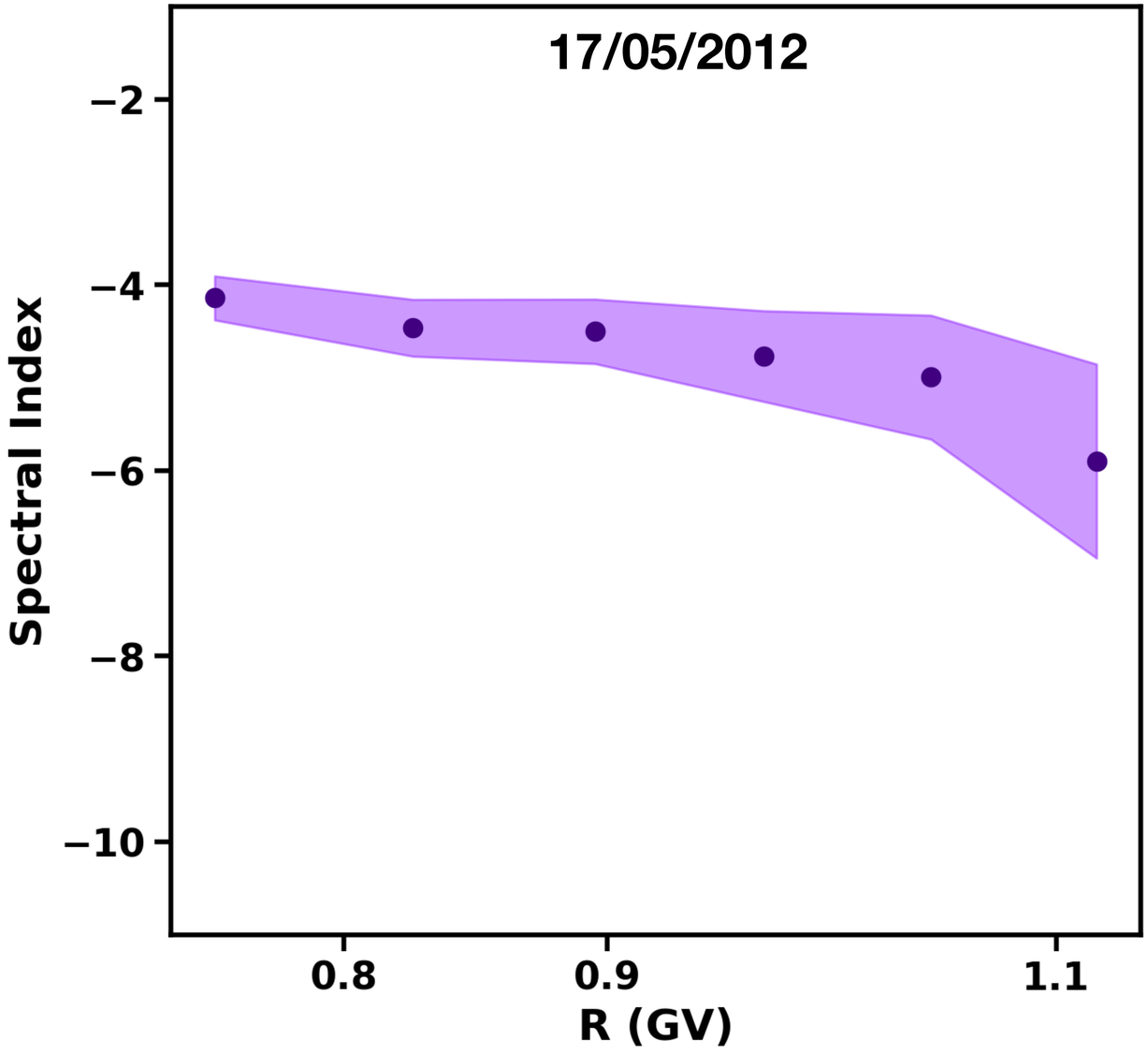


Rigidity and Time Evolution of SEP Spectra

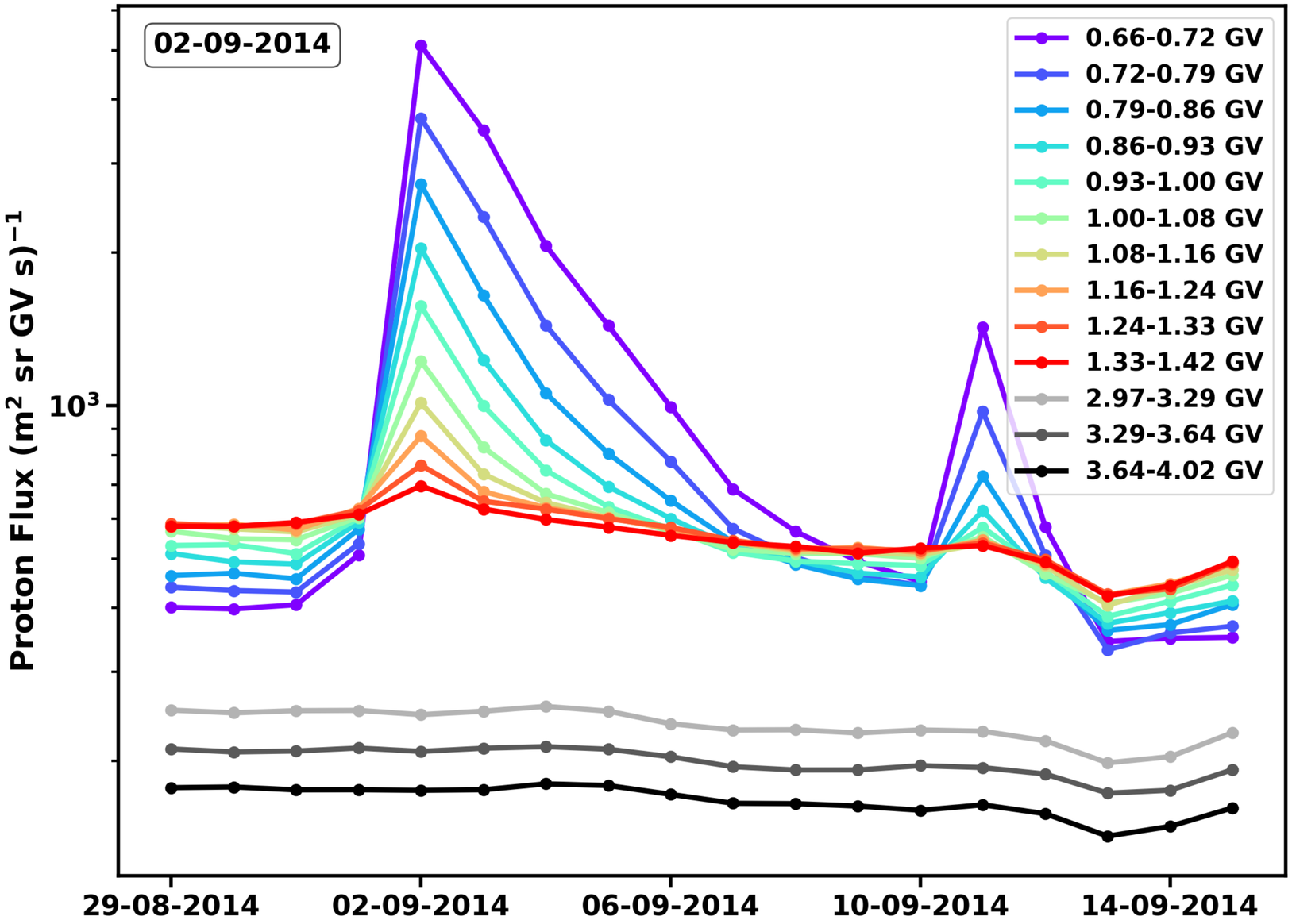


Rigidity and Time Evolution of SEP Spectra

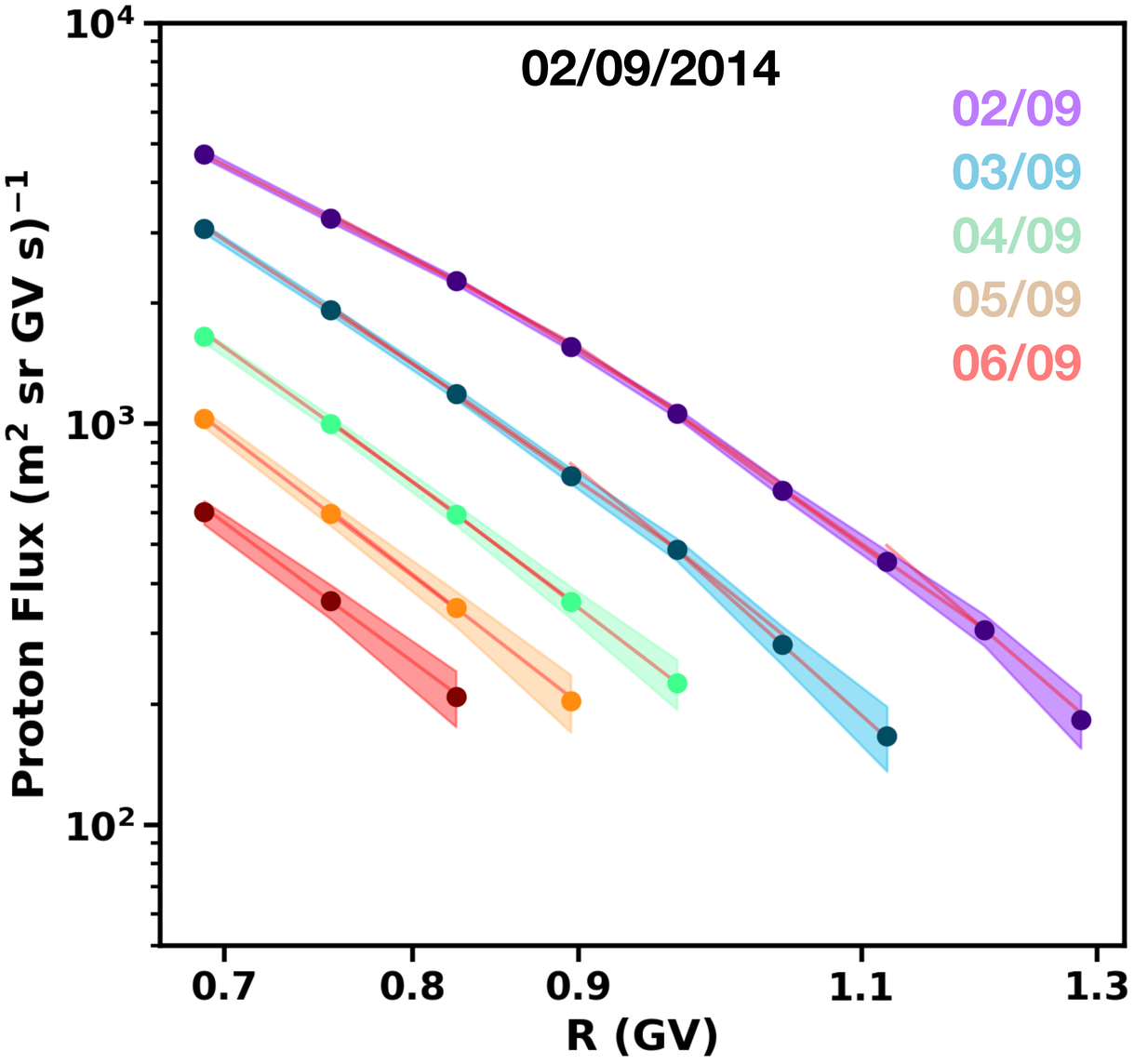


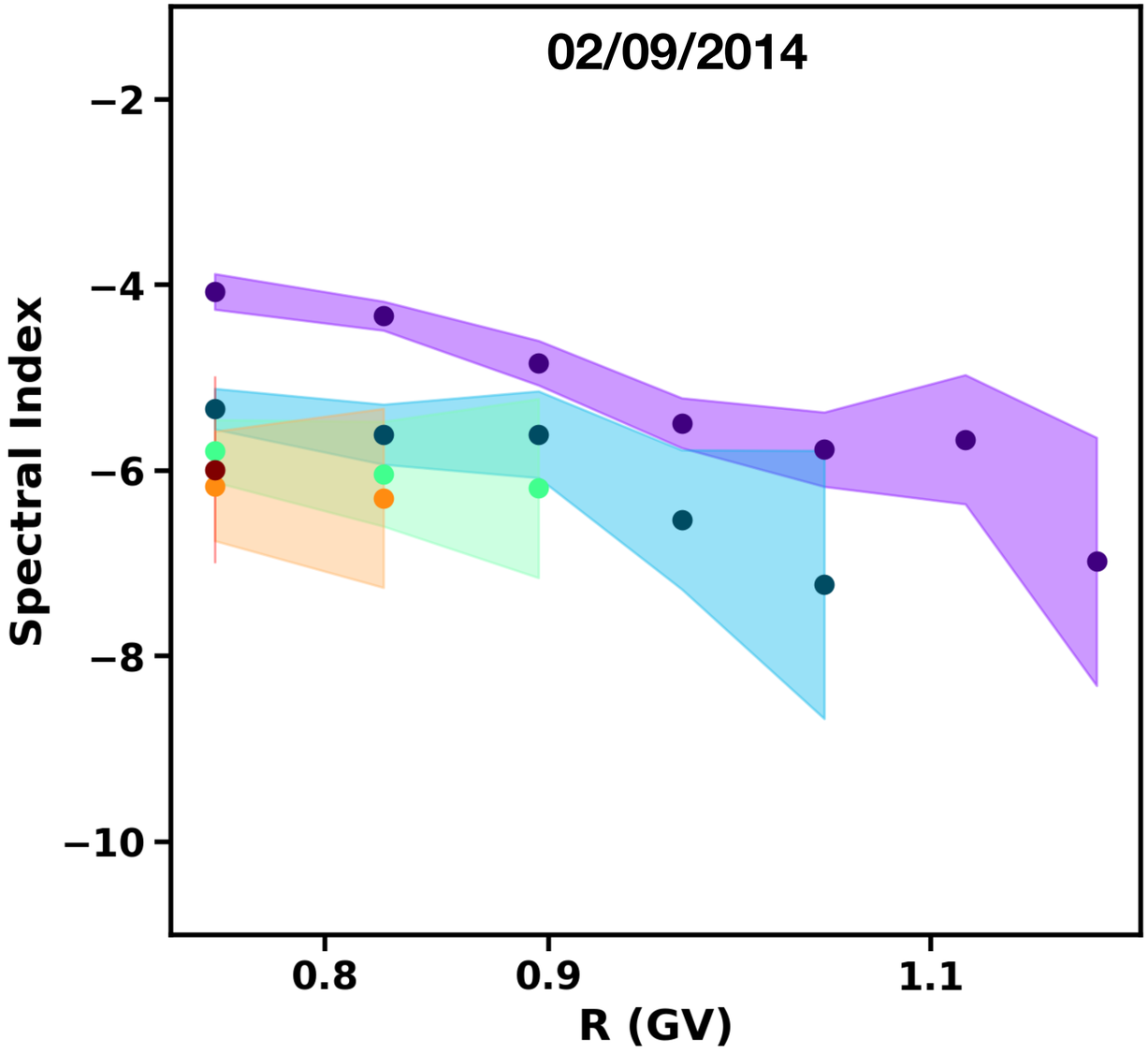


Rigidity and Time Evolution of SEP Spectra



Rigidity and Time Evolution of SEP Spectra



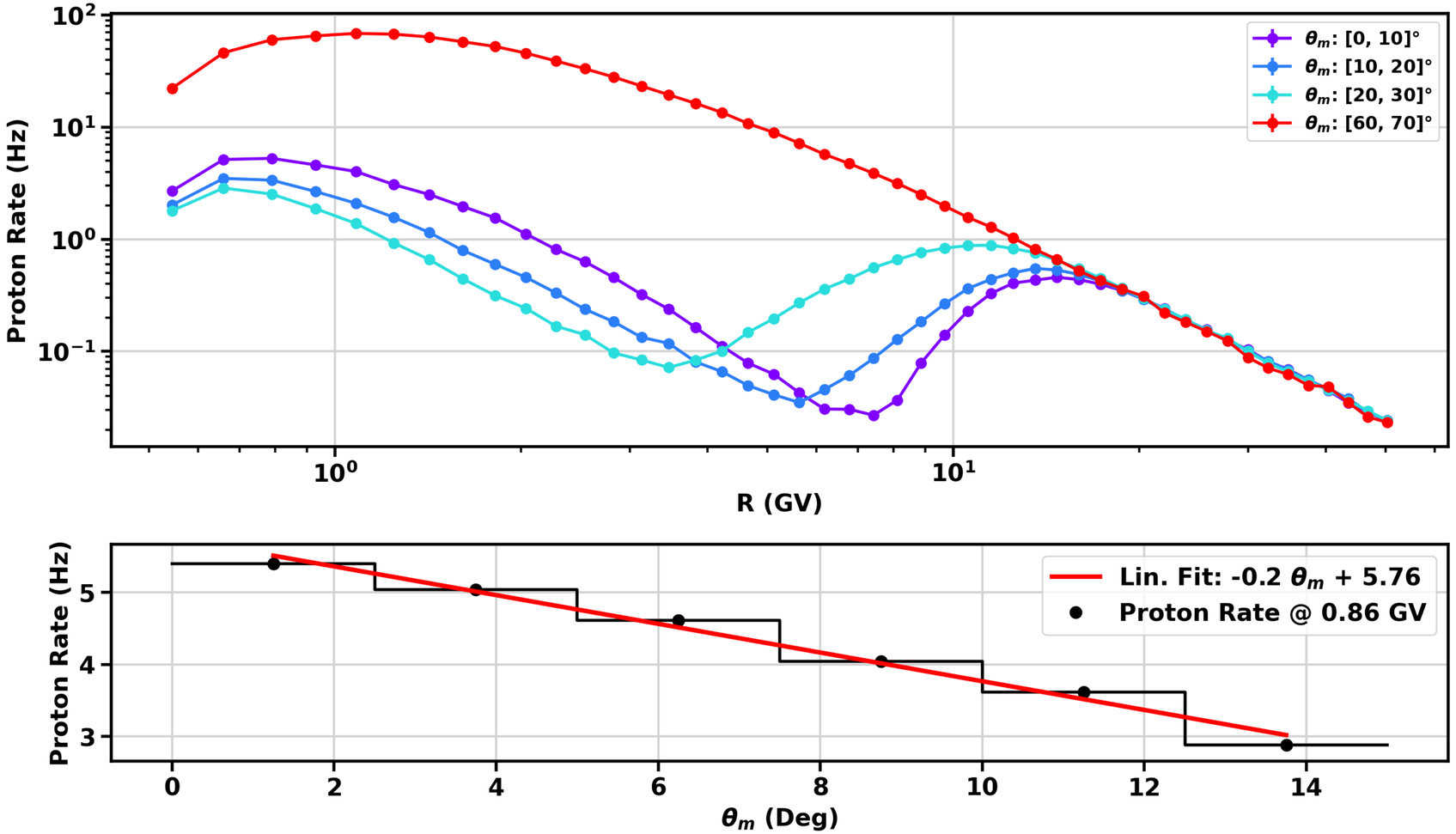


Summary

- **SEPs** can be **accelerated** in two different mechanisms: **magnetic reconnection** and **diffusive shock acceleration**.
- **AMS** can measure the **spectral index** and observe the **temporal evolution** of SEP events at high energy, constraining the **type of acceleration**.
- The production **SEP spectra** with AMS requires a **tailored event selection** and a **robust GCR background subtraction** procedure.
- Many events measured by AMS show a **single power law** spectrum, but a few (backside) show a **rigidity dependence** of the **spectral index**.
- The **SEP fluxes** with AMS can be used to calculate the **radiation dose** absorbed by humans in space during these events.

Proton Rate and Secondary Population

- The **proton rate** at **low geomagnetic latitudes**, including events below cutoff, shows a clear **double spectrum**, due to the presence of secondary protons.
- At **high latitudes** it shows a **mixed spectrum**, including secondaries.



Forecasted Background on Quiet Flux

Distributions of the **relative variation** between **forecasted** background and **measured flux**, during **quiet** periods

$$\frac{\phi^{BG} - \phi}{\phi}$$

[0.50 - 0.55 GV]

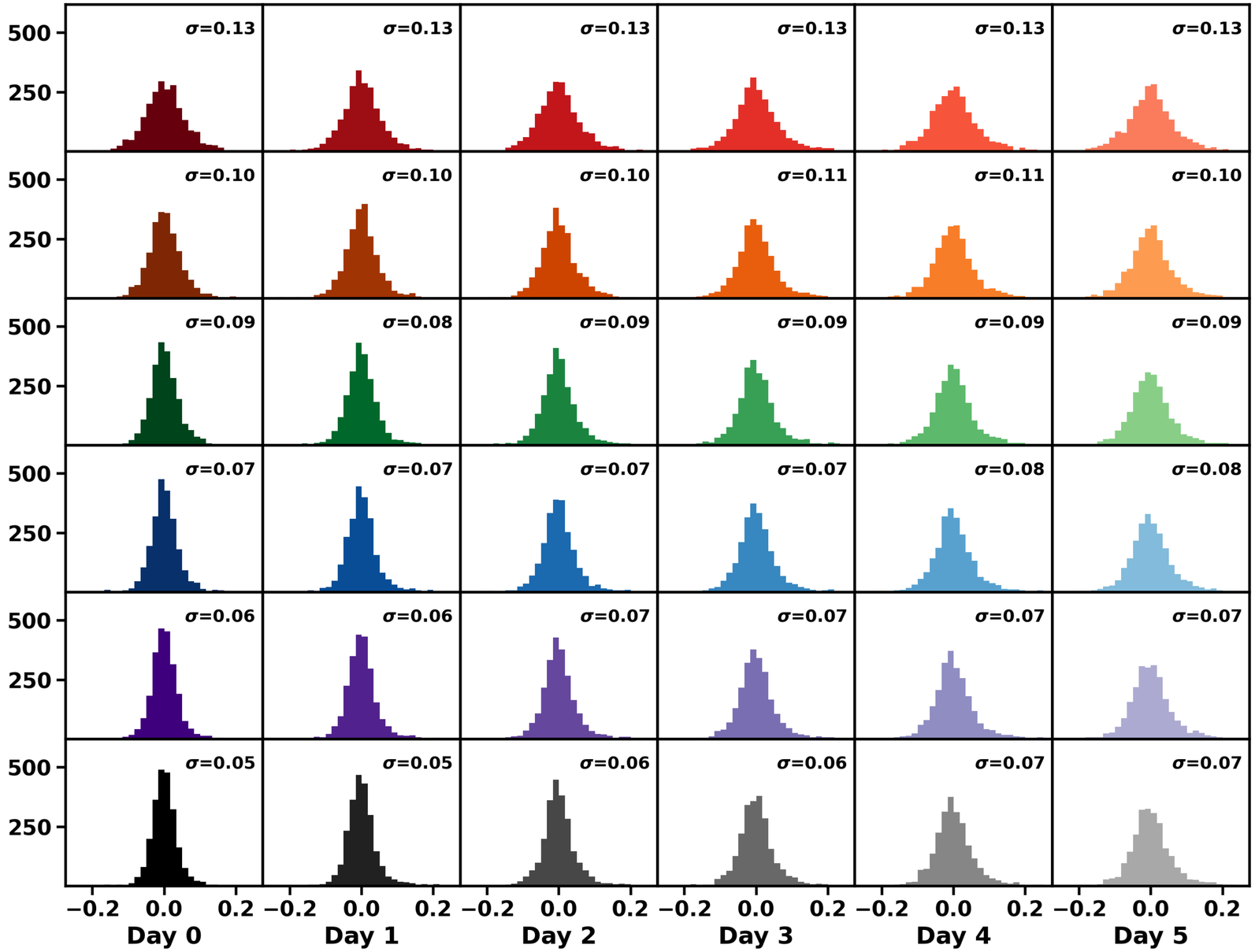
[0.55 - 0.60 GV]

[0.60 - 0.66 GV]

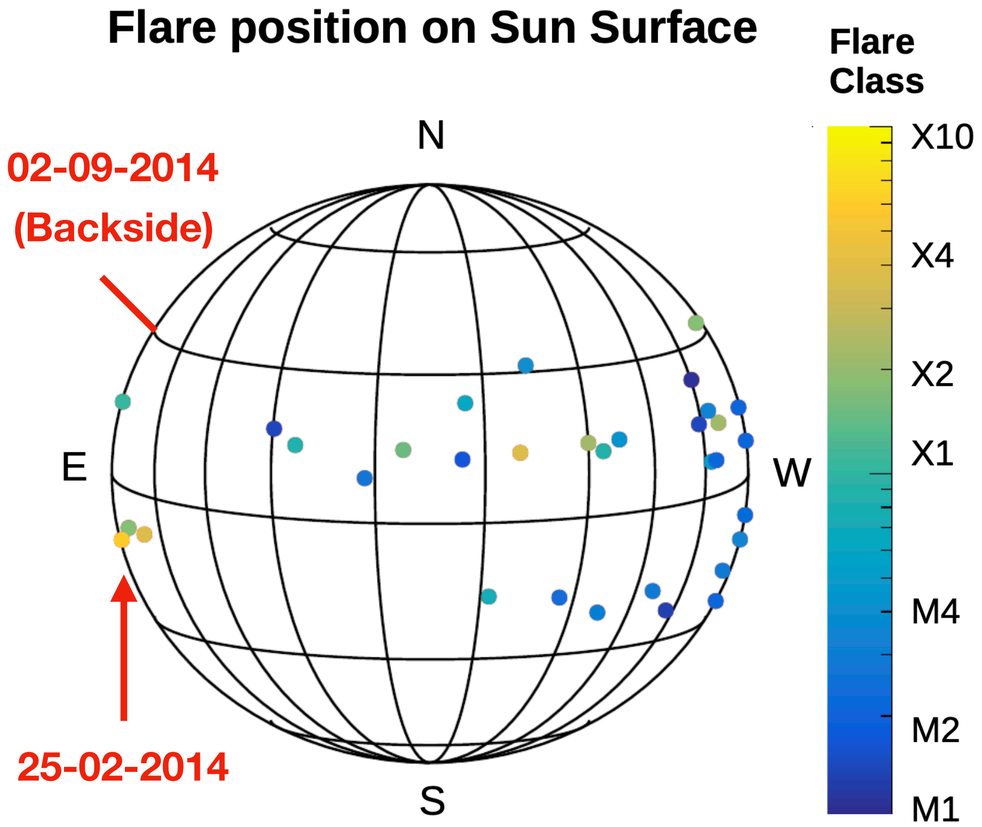
[0.66 - 0.72 GV]

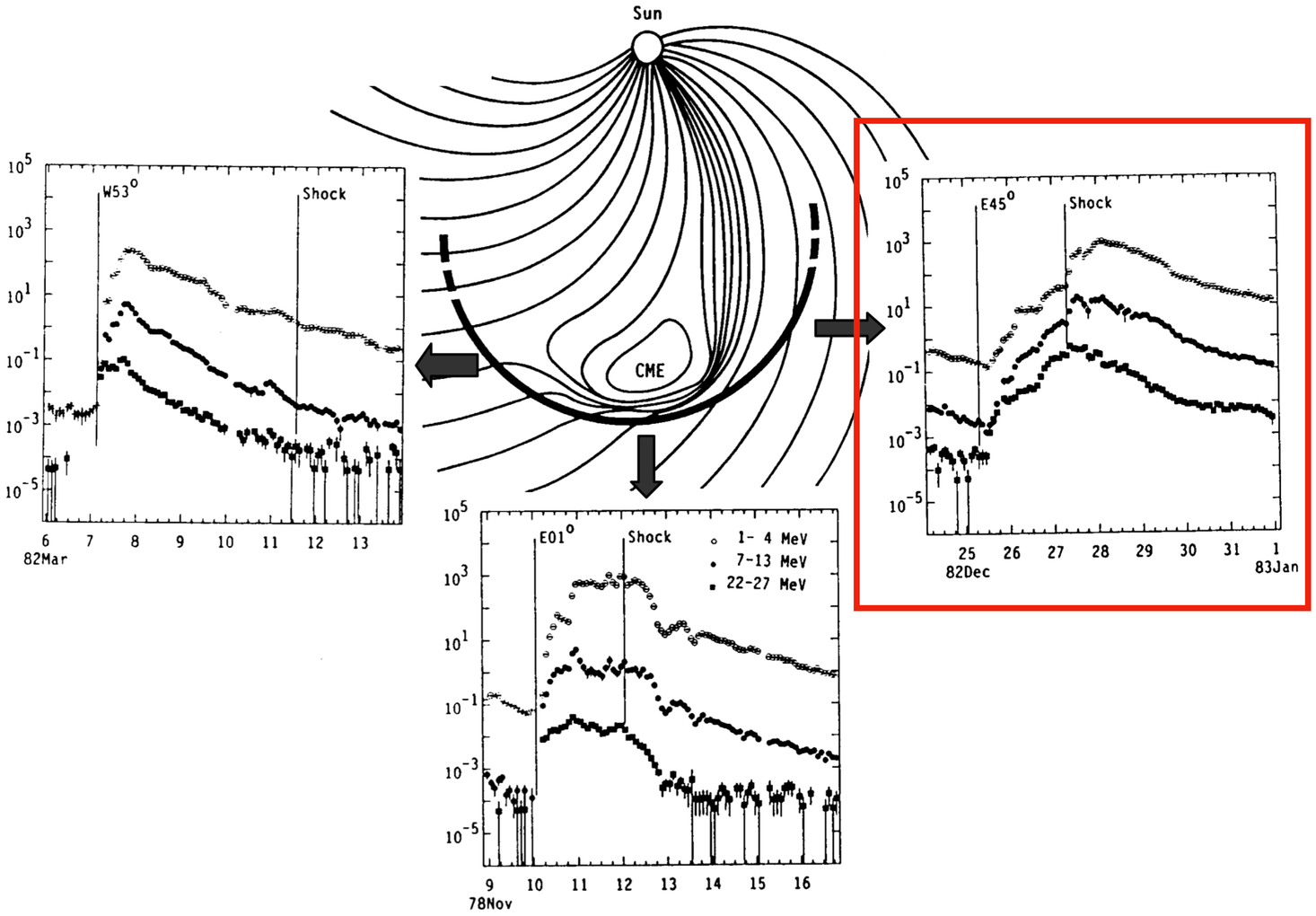
[0.72 - 0.79 GV]

[0.79 - 0.86 GV]



Spectral Fits with AMS at Peak Intensity - Est Side



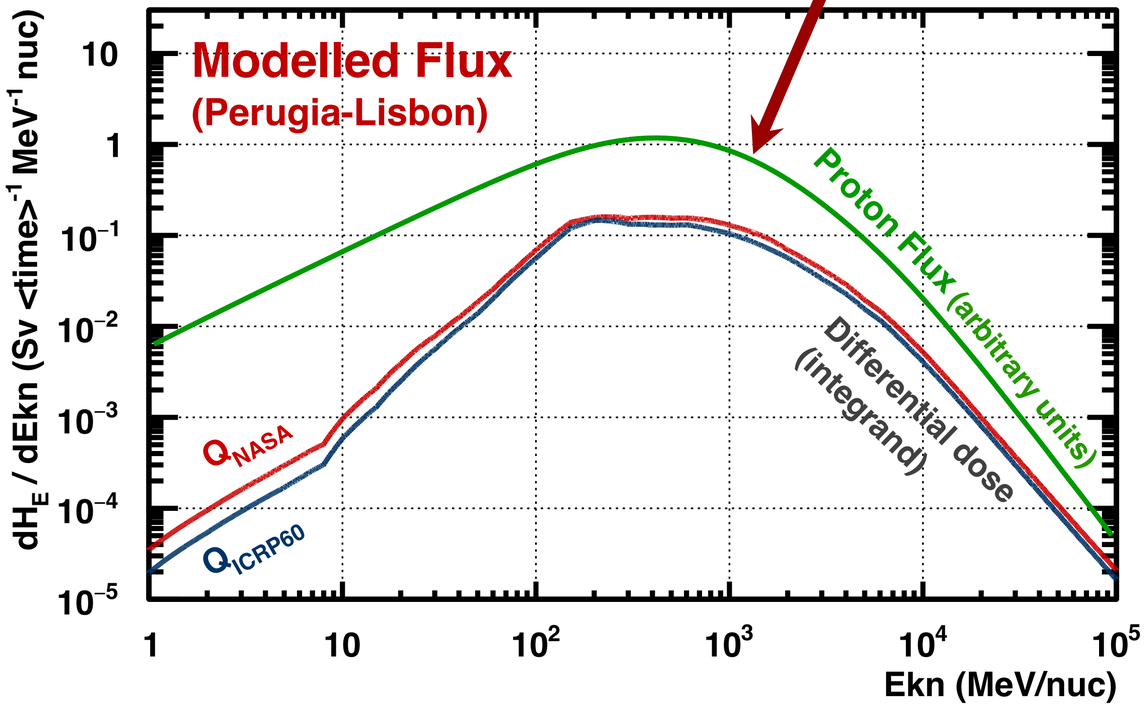


Cane et al. 1988; Reames 1999; Cane and Lario 2006

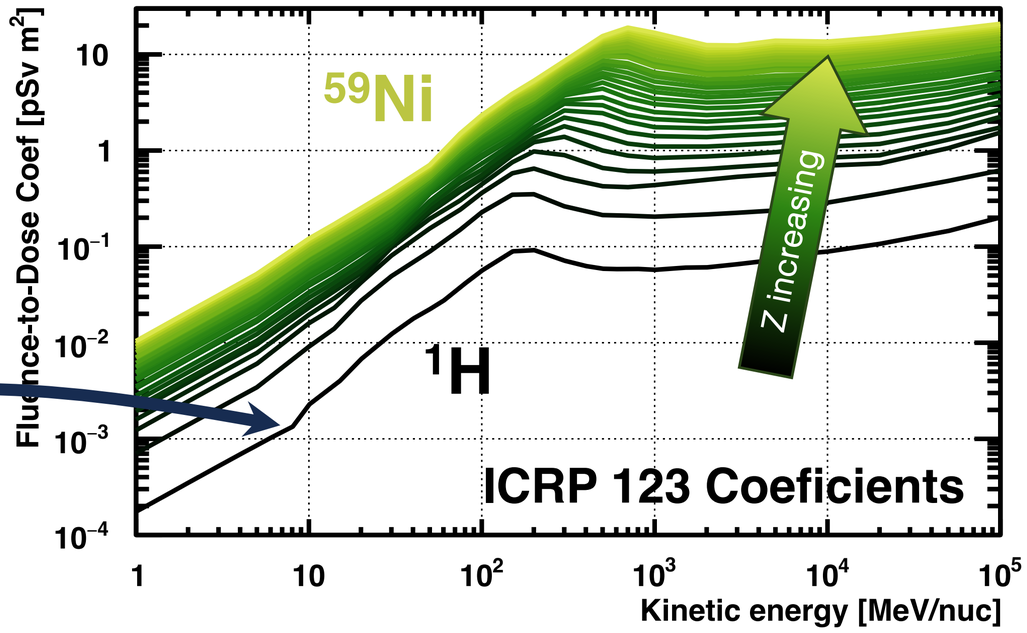
Effective dose equivalent for ISS – New results

Effective Dose Equivalent (weighted for age & gender)

$$H = 4\pi \int_0^\infty \underbrace{Q(E)}_{\text{Quality Factor}} \underbrace{\frac{D}{\Phi}(E)}_{\text{Dose to Fluence}} \int_{\text{Time}} \varphi(E,t)\,\mathrm{d}t\,\mathrm{d}E$$



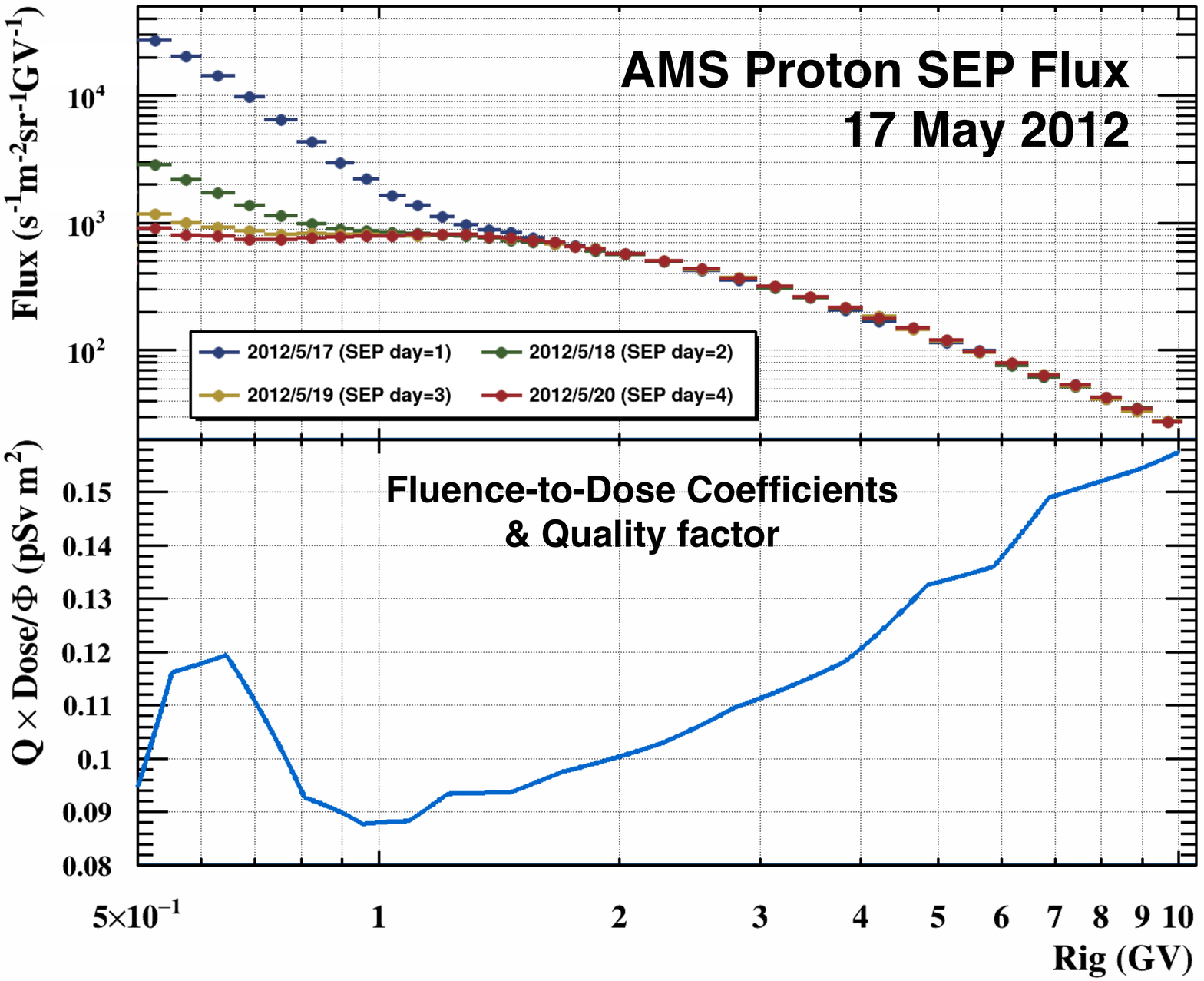
Fluence-to-Dose Coefficients



1. Flux is assumed isotropic.
2. Astronaut is assumed to be naked
3. Deposited energy is expected to be proportional to mass. (Dose is in units of energy / kg)
4. Typical units are Sievert (Sv=m^{2}s^{-2}) or rem (1 Sv = 100 rem)

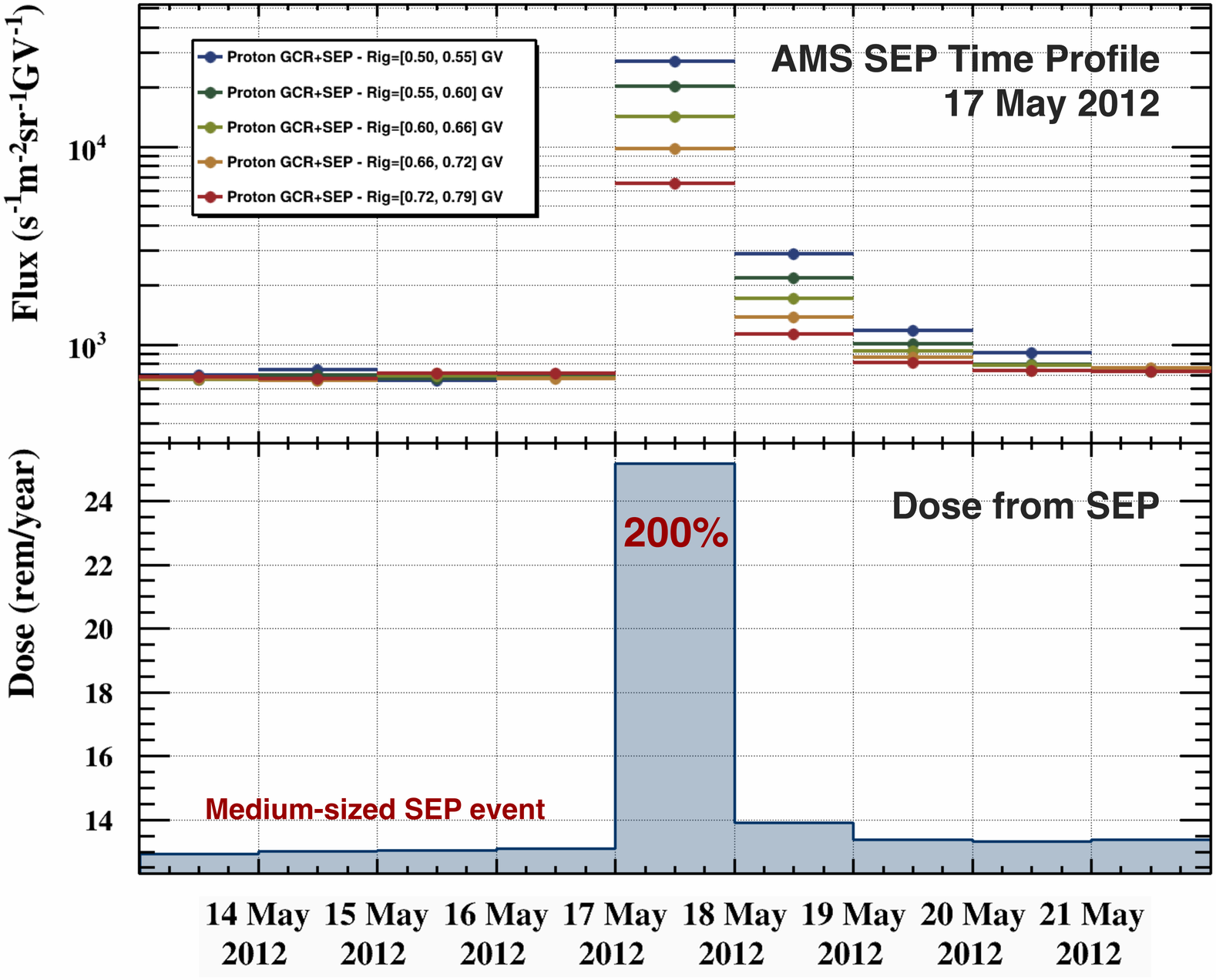
Effective dose equivalent for ISS – New results

Courtesy of Miguel R. Orcinha



Effective dose equivalent for ISS – New results

Courtesy of Miguel R. Orcinha



Effective dose equivalent for ISS – New results

Courtesy of Miguel R. Orcinha