Study of short term variations in the cosmic proton fluxes with the AMS-02 experiment

Summary:

- Introduction: Solar Energetic Particles (SEP).
- Phase 1: Production of polar-pass proton fluxes with AMS-02.
- Phase 2: GCR Background Subtraction and SEP Spectra.

Francesco Faldi
AMS-Italy, 16-10-2024

Solar Energetic Particles

- **Solar Energetic Particles (SEPs)** 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

Phase 1

Production of daily “polar-pass” proton fluxes with AMS-02 data

Proton Flux Definition

$$\Phi(t, R) = \frac{N_{selected}(t, R)}{\Delta R \cdot T_{exp}(t, R) \cdot A_{corr}(t, R)}$$

Rigidity: R = p/Z

$N_{selected}$ → Selected counts corresponding to proton events

T_{exp} → Exposure Time in seconds

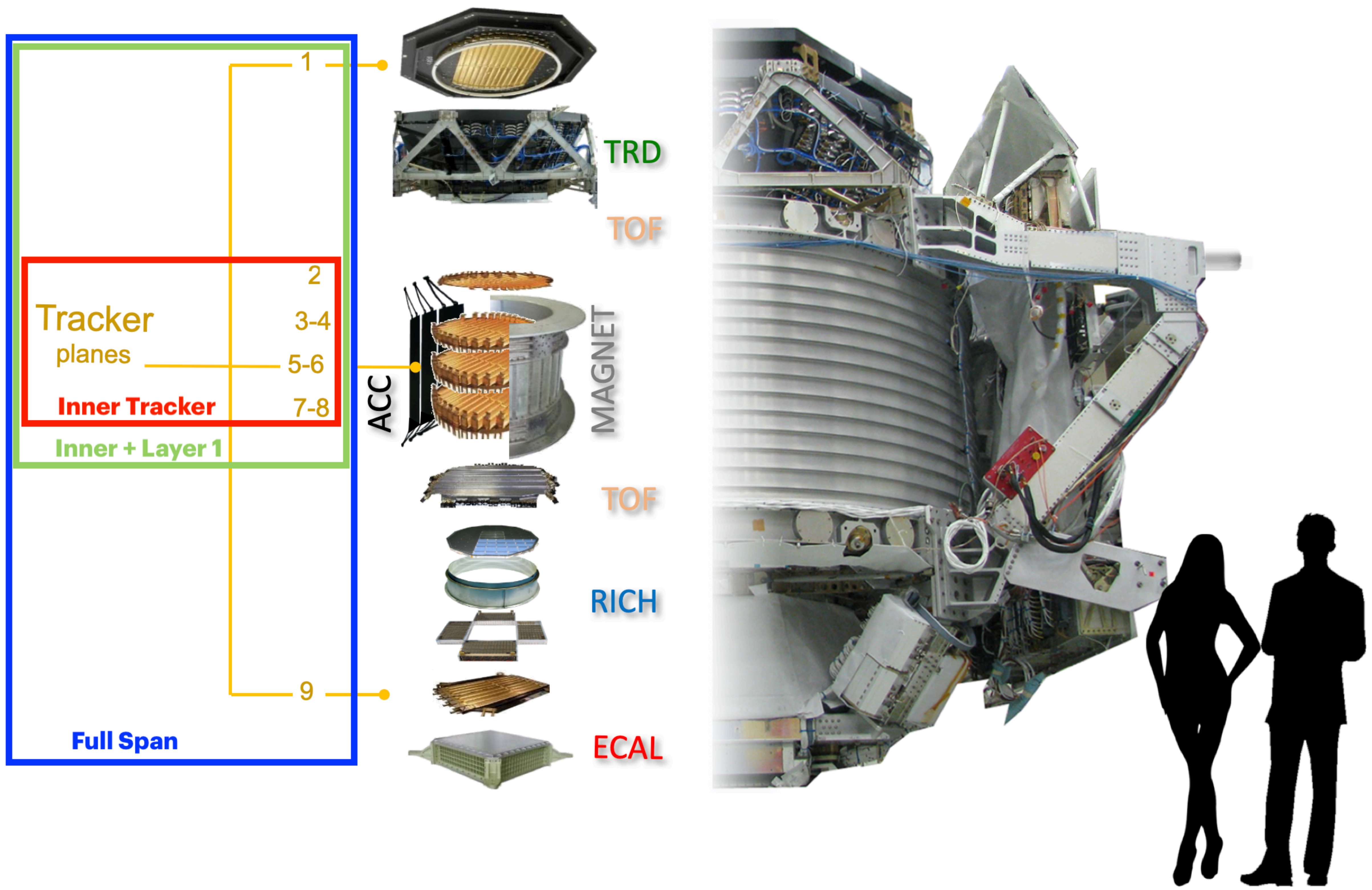
$A_{corr} = A_{geom} \cdot ISS/MC\ Corr$ → Effective Acceptance: Montecarlo Acceptance multiplied by corrections

$ISS/MC\ Corr$ → Efficiencies on Data / Efficiencies on Montecarlo

Unfolding Method: Iterative Folded Acceptance (standard)

Event Selection

- Rigidity Range: **1 - 60 GV**
- Charge Type : Yi Jia (standard)
- Fit Type: GBL (standard)
- **Pass8 Dataset (NAIA Ntuples)**



RTI Cuts

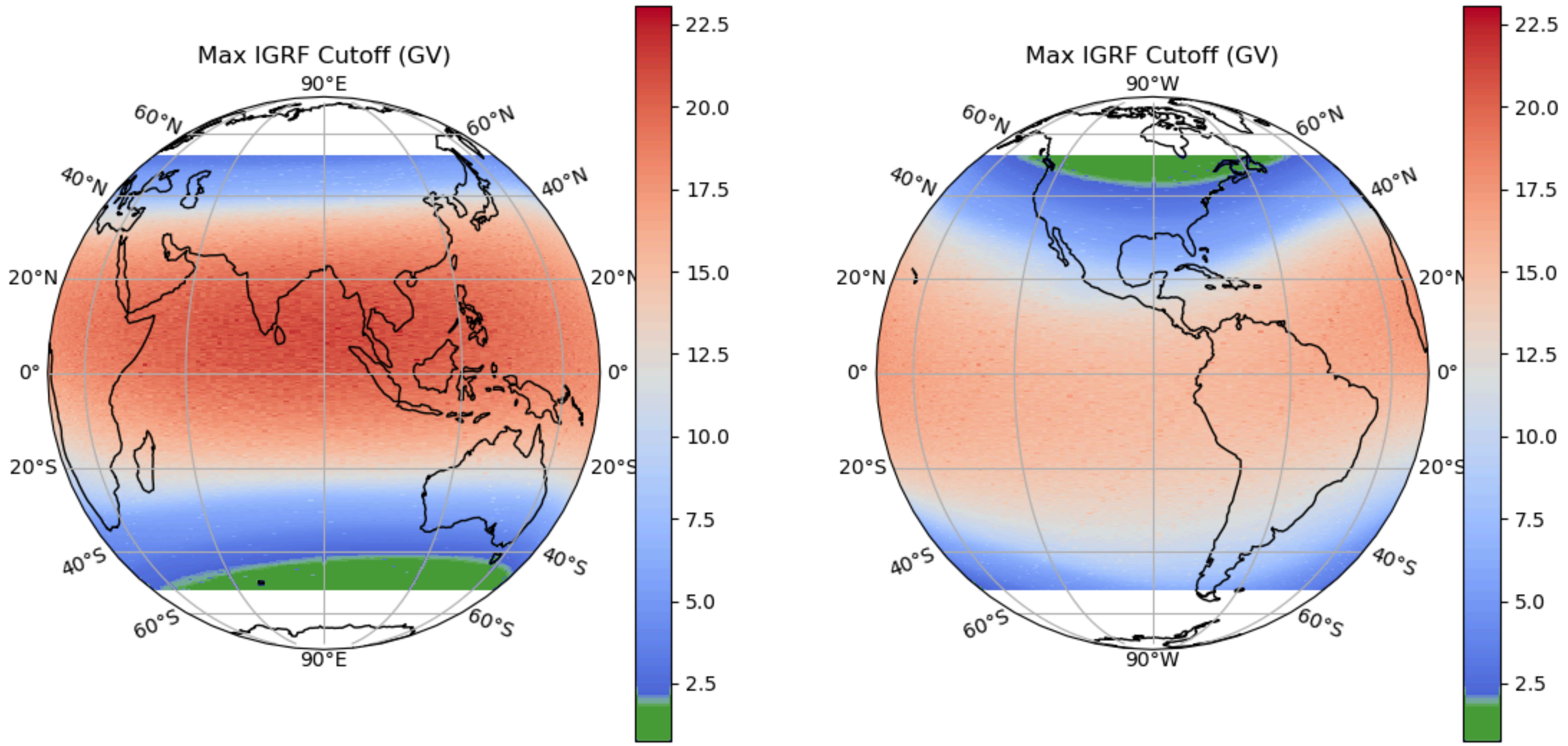
- Livetime Fraction > 0.05
- Zenith Angle < 25
- Not in SAA
- Mean Difference PG-CIEMAT Trk Calib

Physical Cuts

- Any Physical trigger
- Chi2Y < 10 (Inner rigidity)
- Hits on: L2 & (L3|L4) & (L5|L6) & (L7|L8)
- At least 5 Hits in Inner Tracker
- Chi2Y < 10 (InnerL1 rigidity)
- 0.7 < Inner Charge < 1.5
- Inner Charge / Inner Charge RMS < 0.4
- 0.6 < L1 Charge < 2
- Inside Inner Fiducial (InnerL1 rigidity)
- Inside L1 Fiducial (InnerL1 rigidity)
- L1 Normalized Residual < 10
- Beta > 0.4
- 0.5 < Upper ToF Charge < 2.5
- Mass Cut
- InnerL1 Rig > SafetyFactor(R) x IGRF Cutoff

Polar-Pass Selection

- 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 models** we use are too **conservative** for an SEP analysis, severely **limiting our statistics** at low rigidities

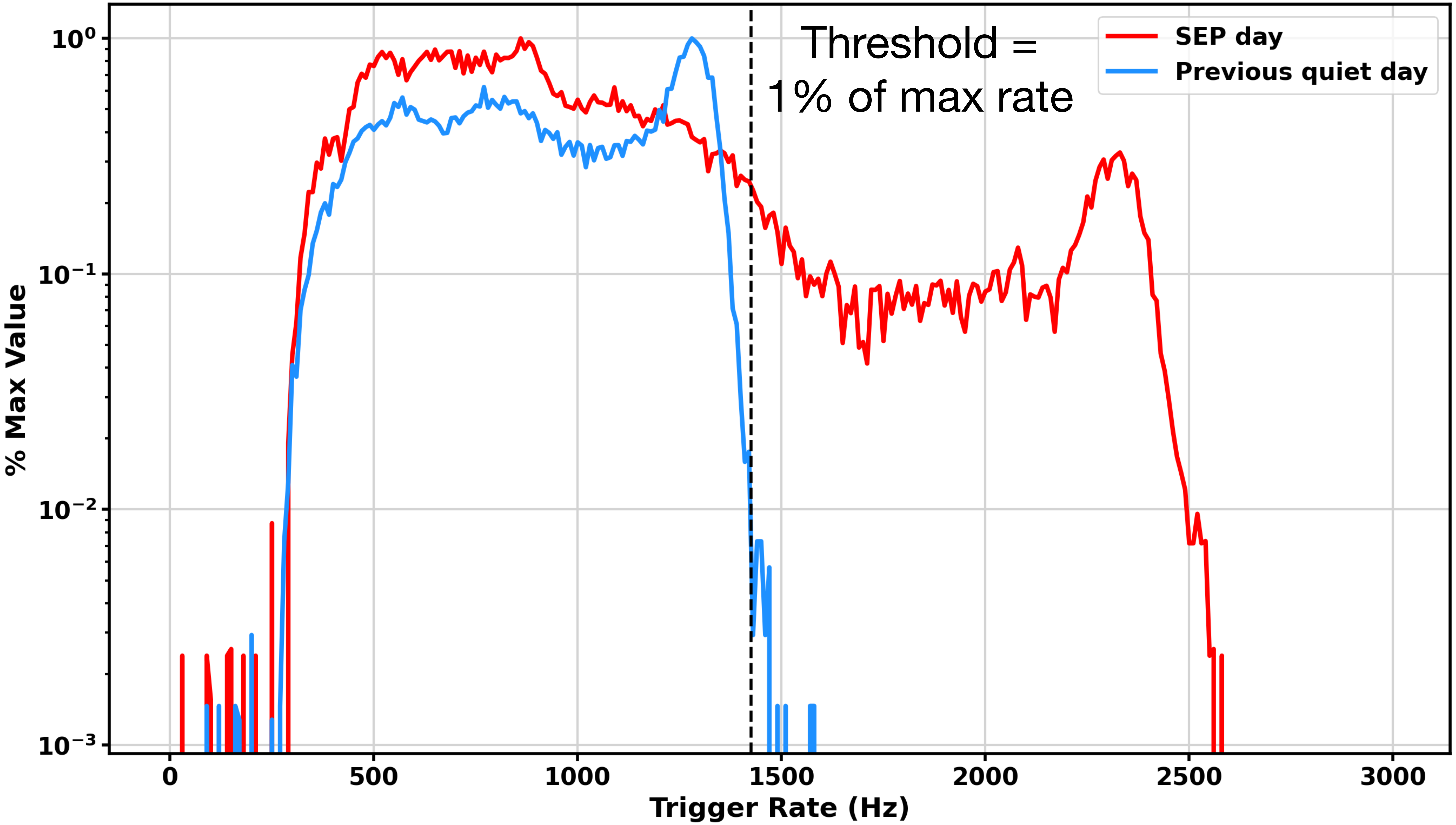


Eliminating the cut on **rigidity cutoff** improves statistics at low rigidities. We can now measure the proton flux from **0.5 GV**.

→ We need to define a "polar-pass" region, using cutoff-independent information.

Polar-Pass Selection

For a given day, we can define the "SEP-sensitive" **polar-pass region**, in geographic **longitude** and **latitude**, by setting the **maximum rate** during a quiet day as threshold.



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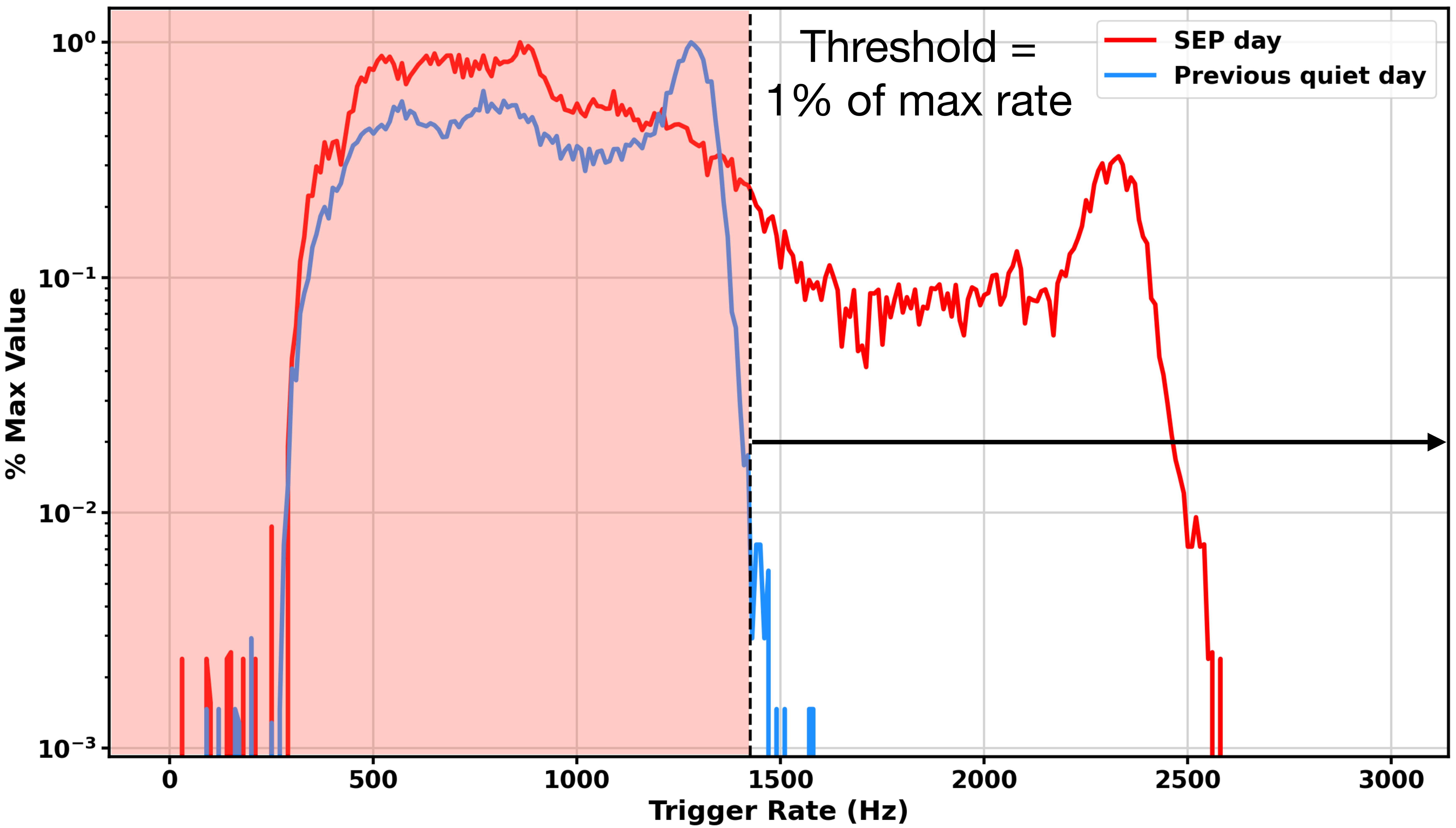
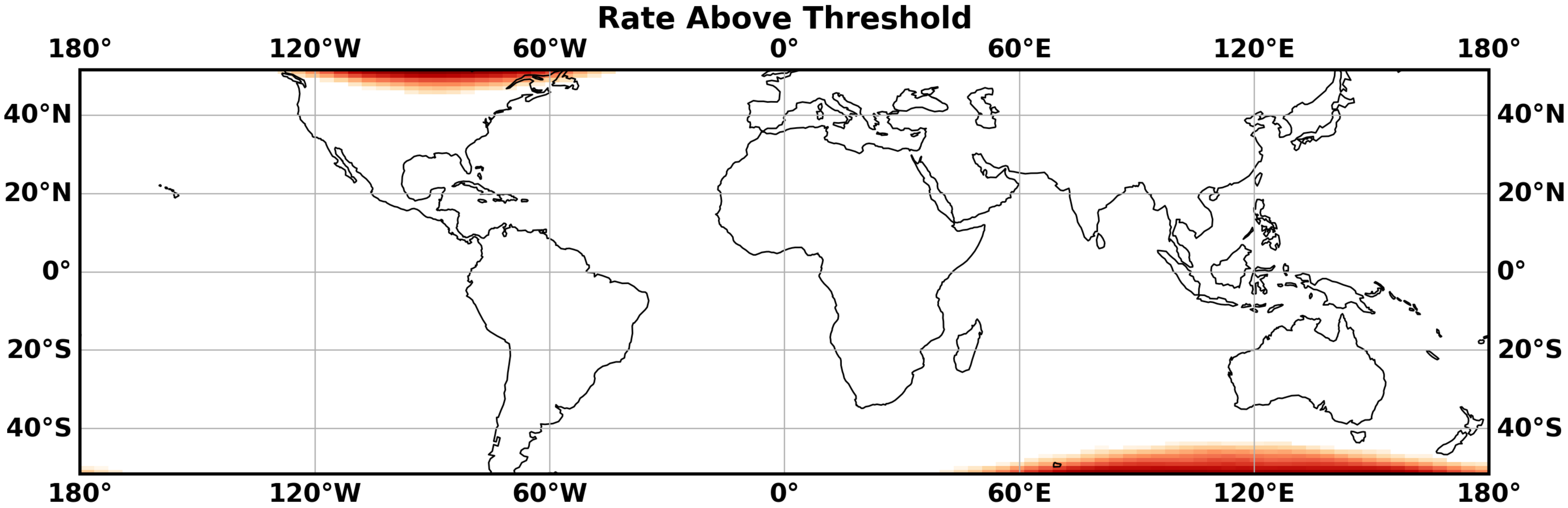


Polar-Pass Selection

We then build a **polar-pass map** by plotting the longitude and latitude for **each event above threshold**.



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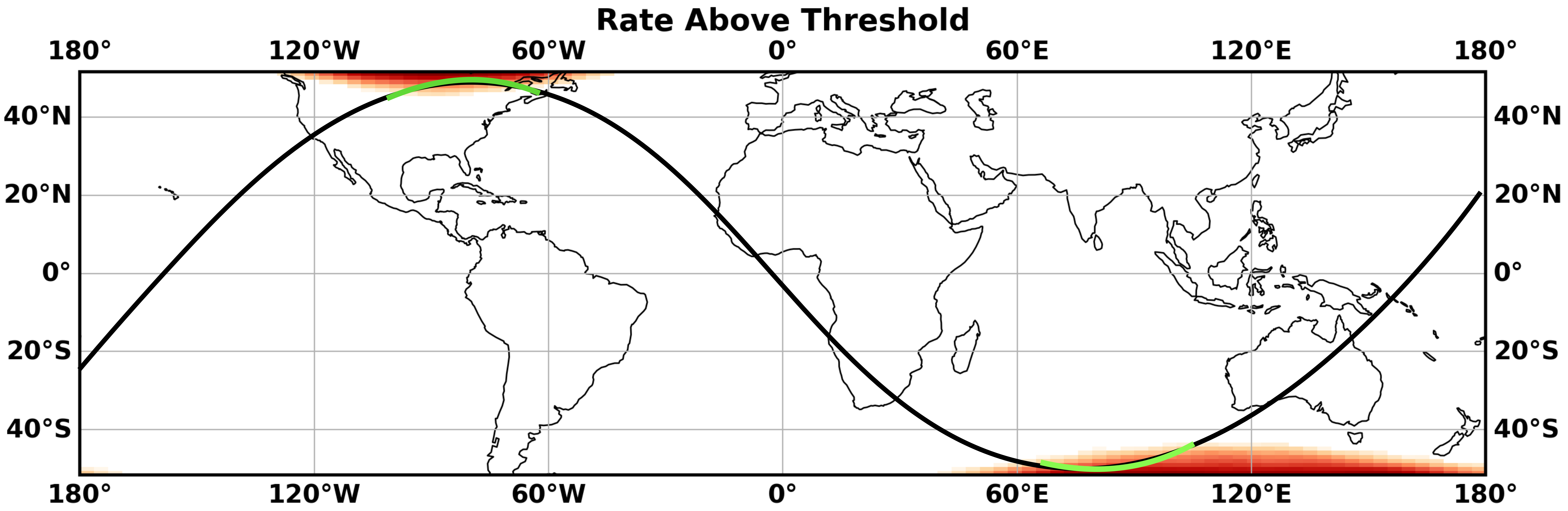
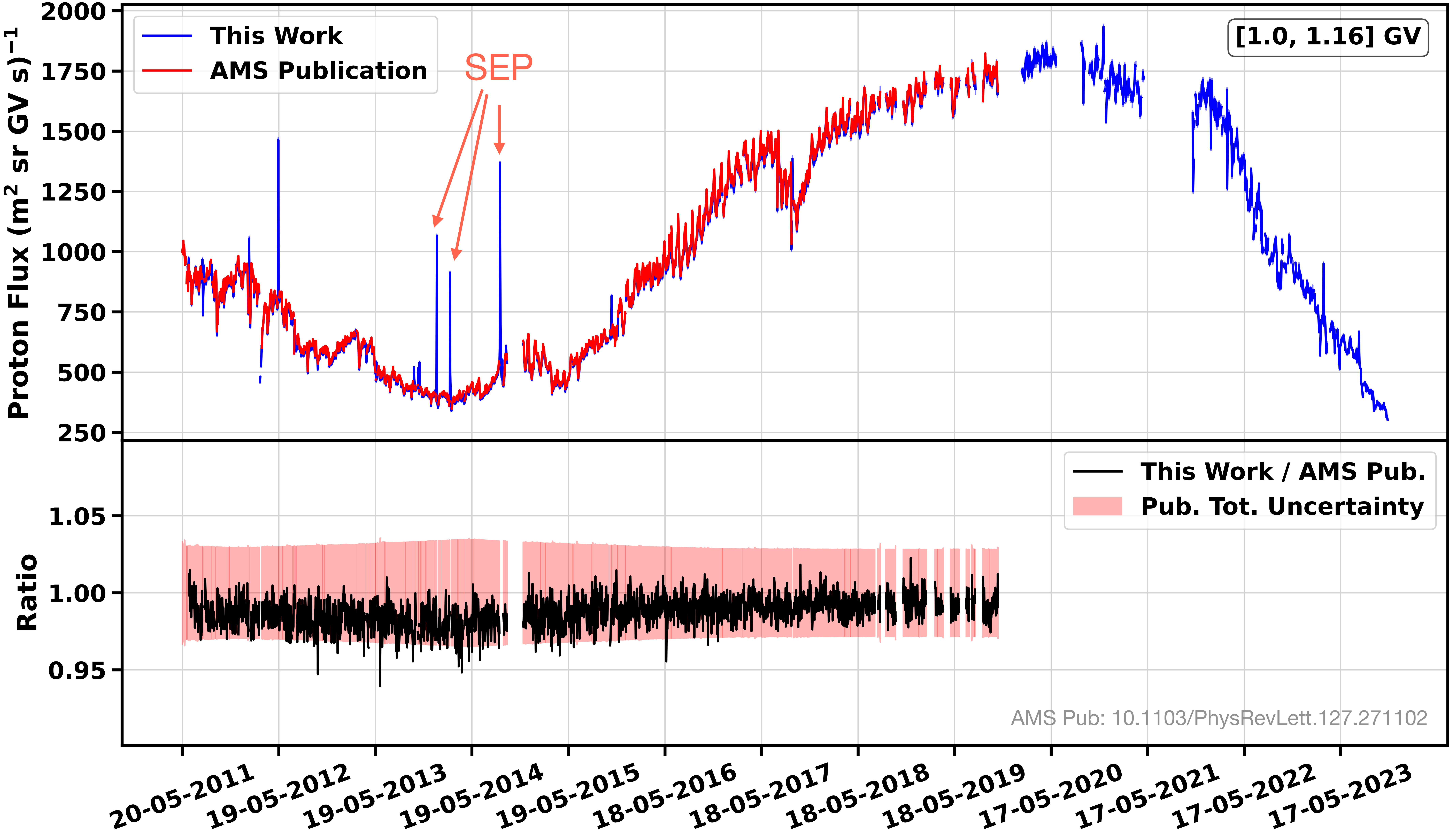


The polar-pass map is used to select events instead of the usual requirement:

InnerL1 Rigidity > SafetyFactor(R) x IGRF Cutoff

Daily Proton Flux - Comparison with Published Results



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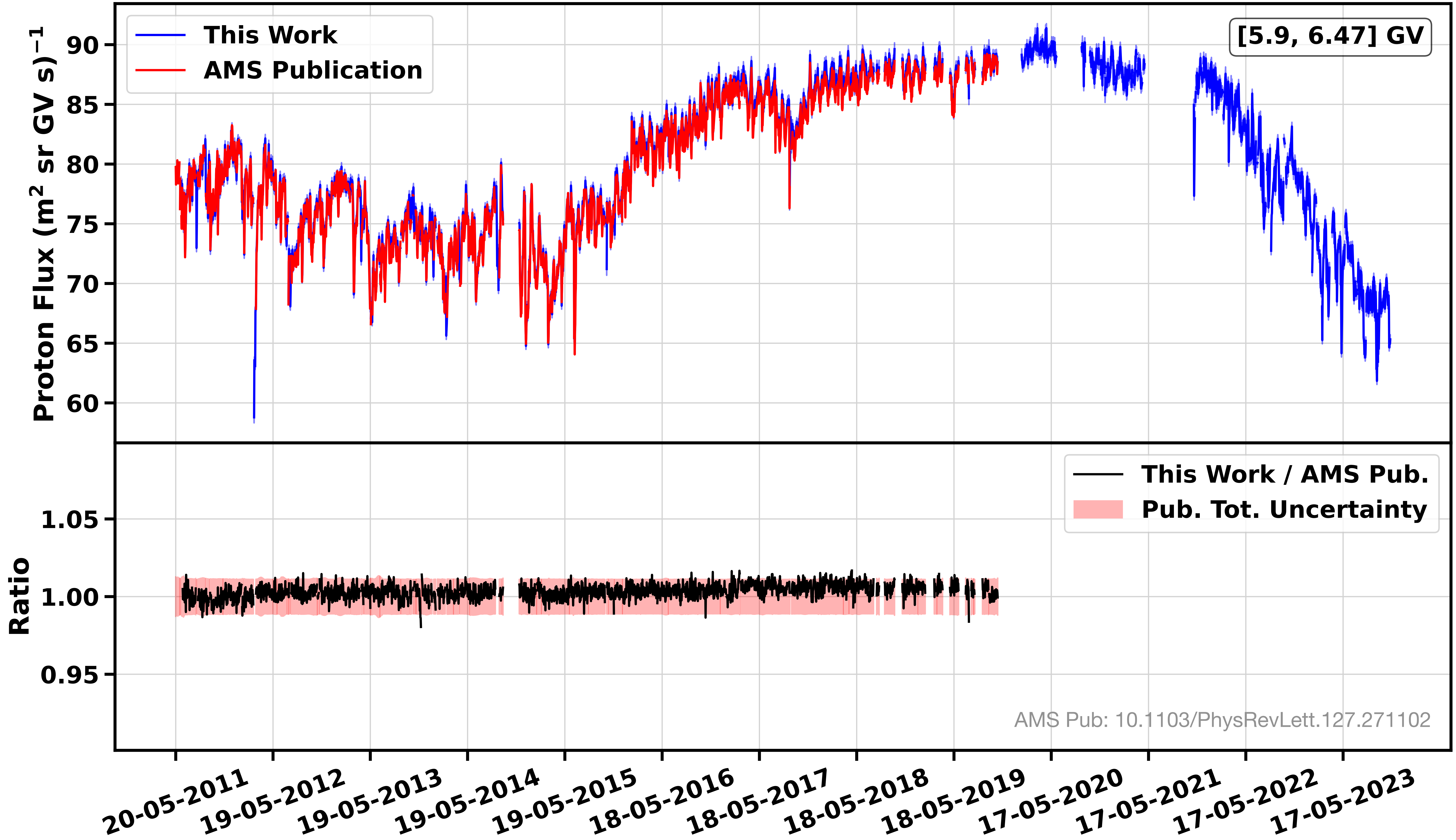
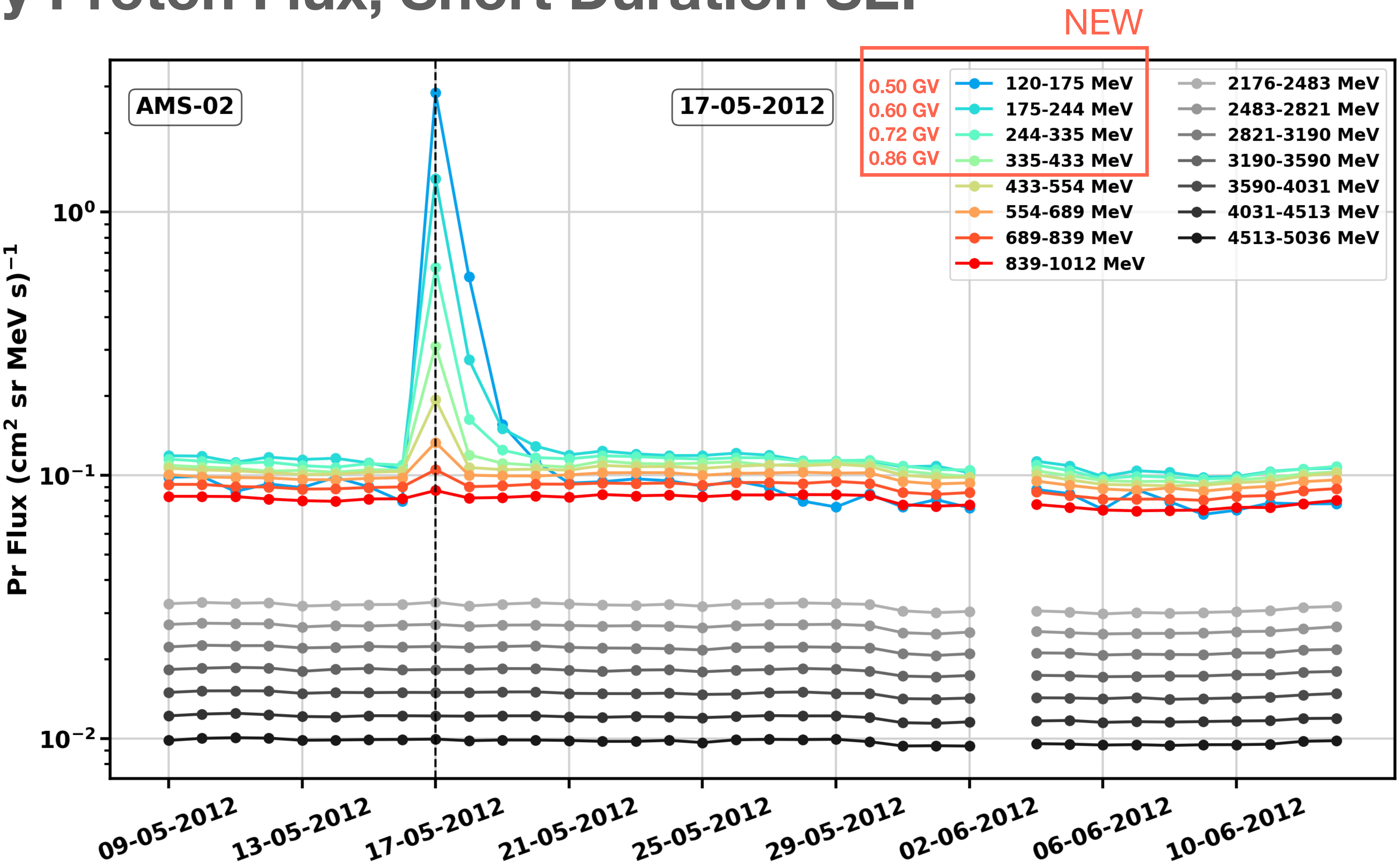
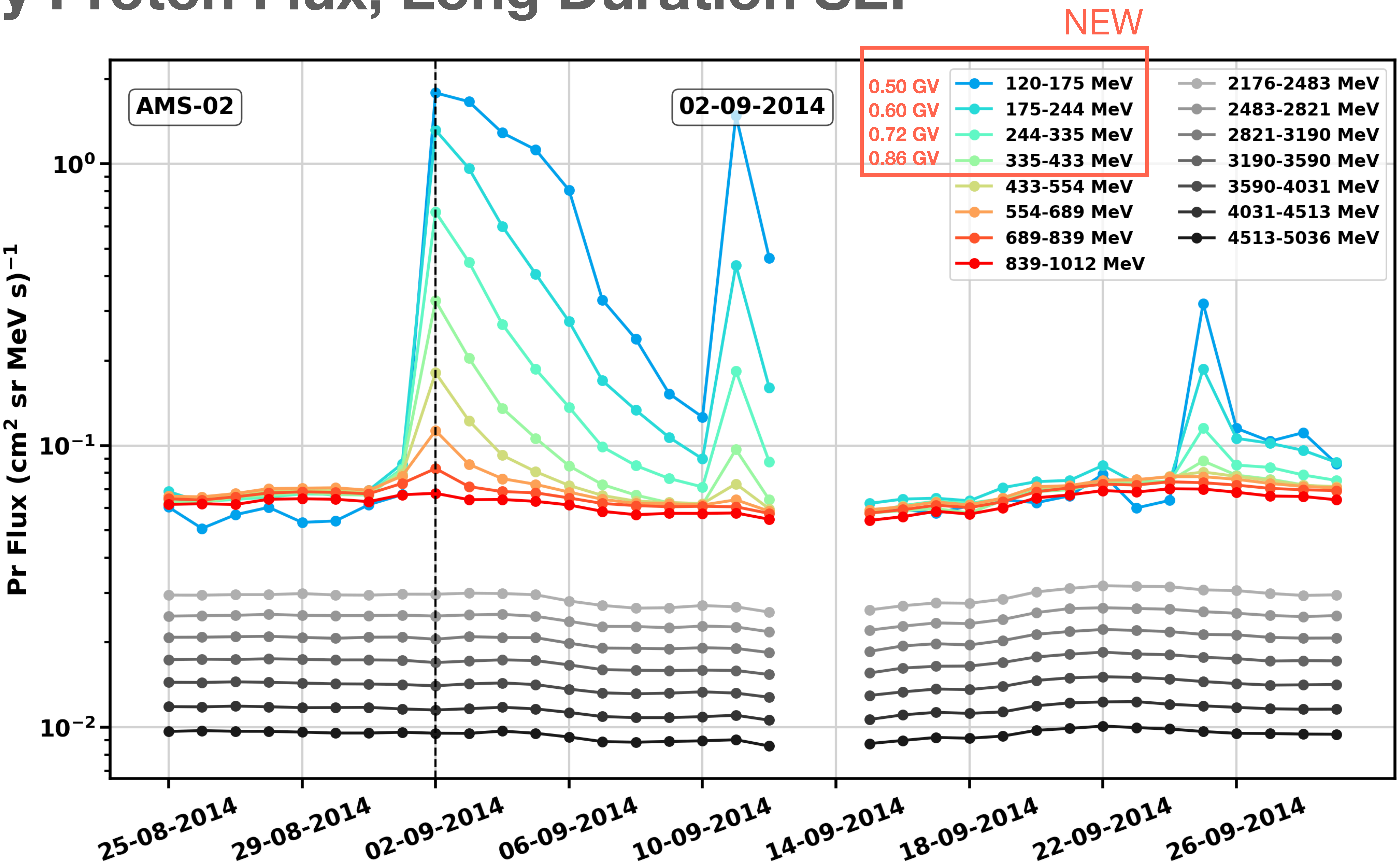


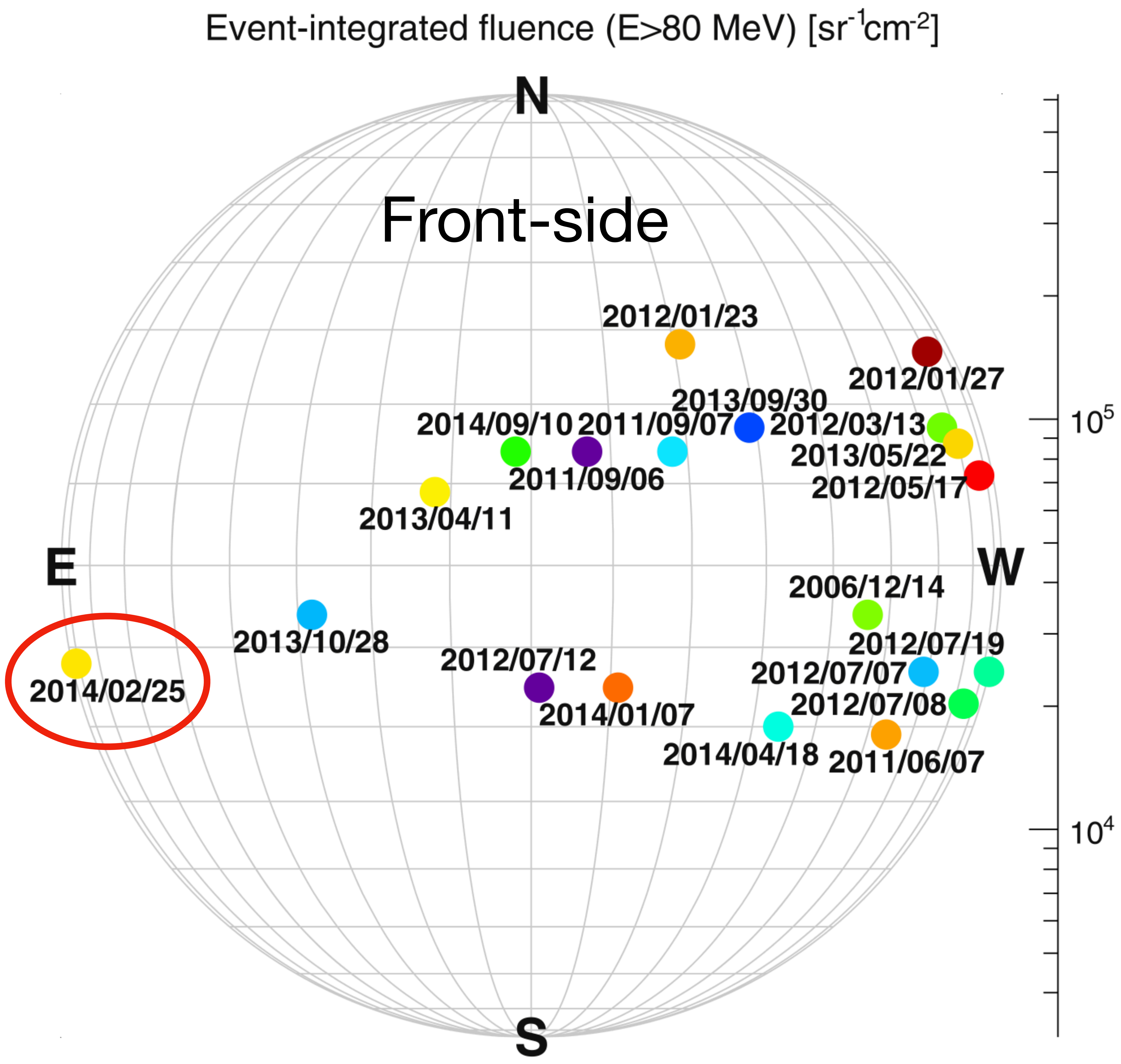
Daily Proton Flux, Short Duration SEP

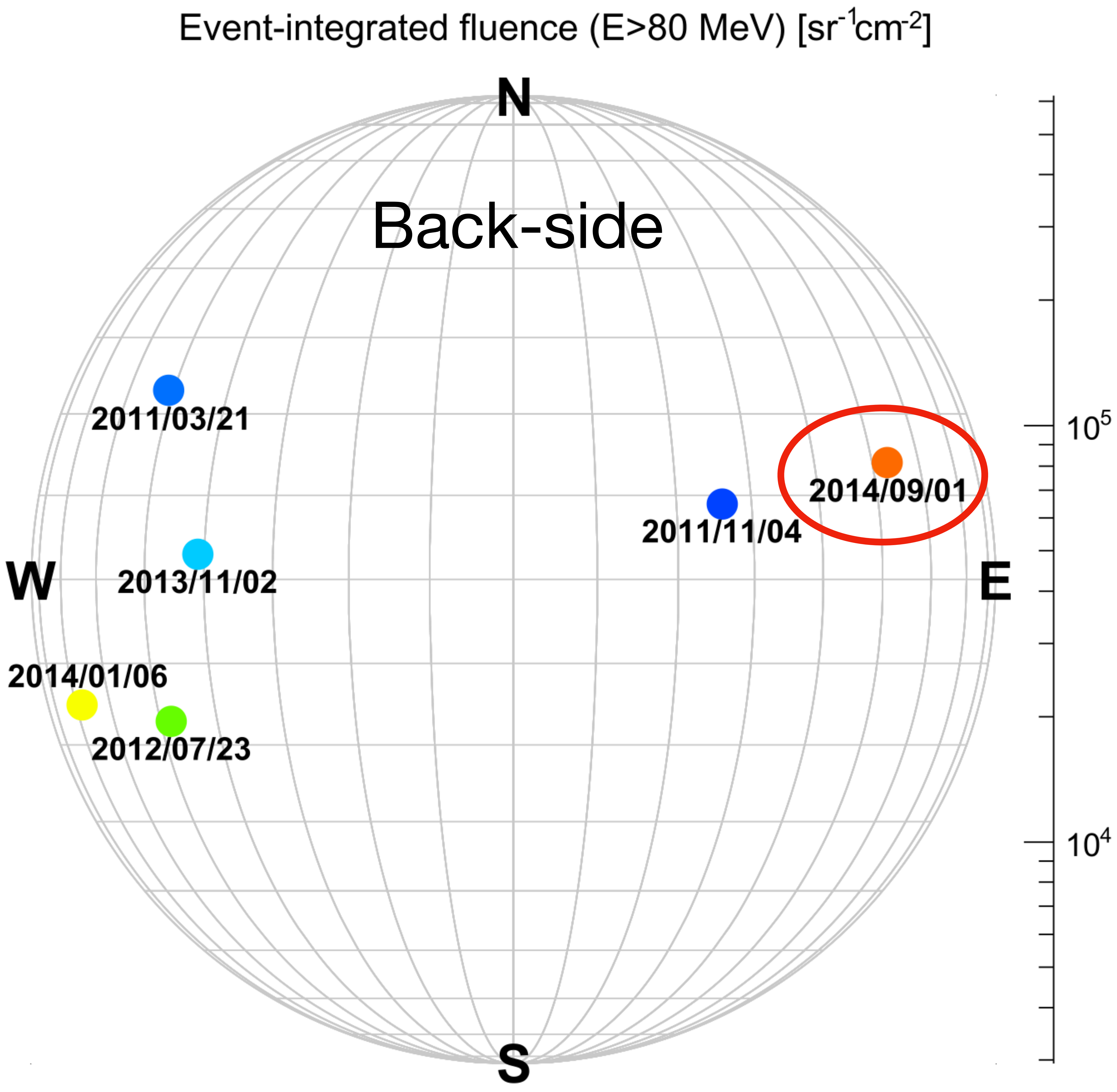


Daily Proton Flux, Long Duration SEP



SEP Events Association with Active Regions





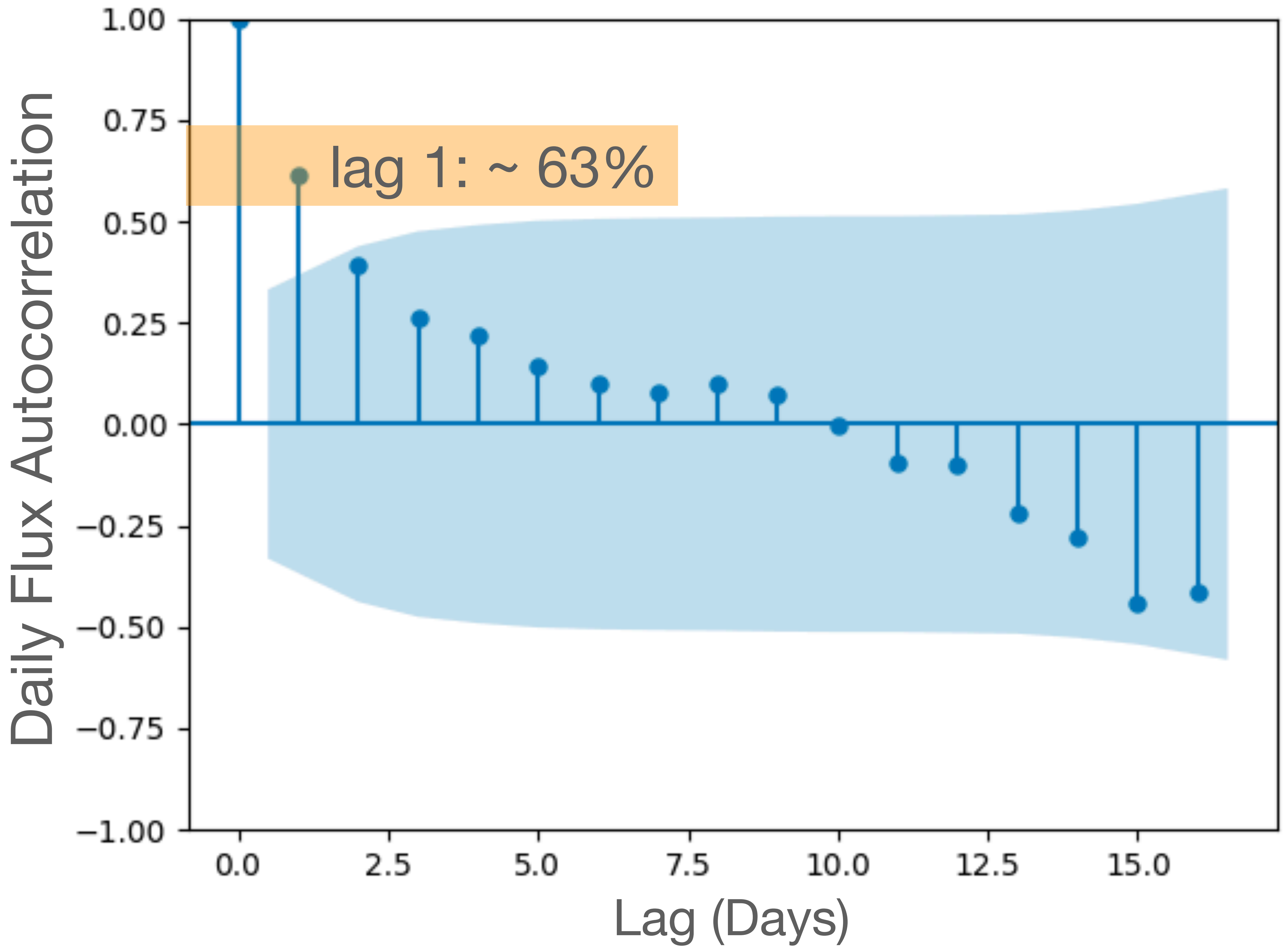
https://doi.org/10.3847/1538-4357/aacc26

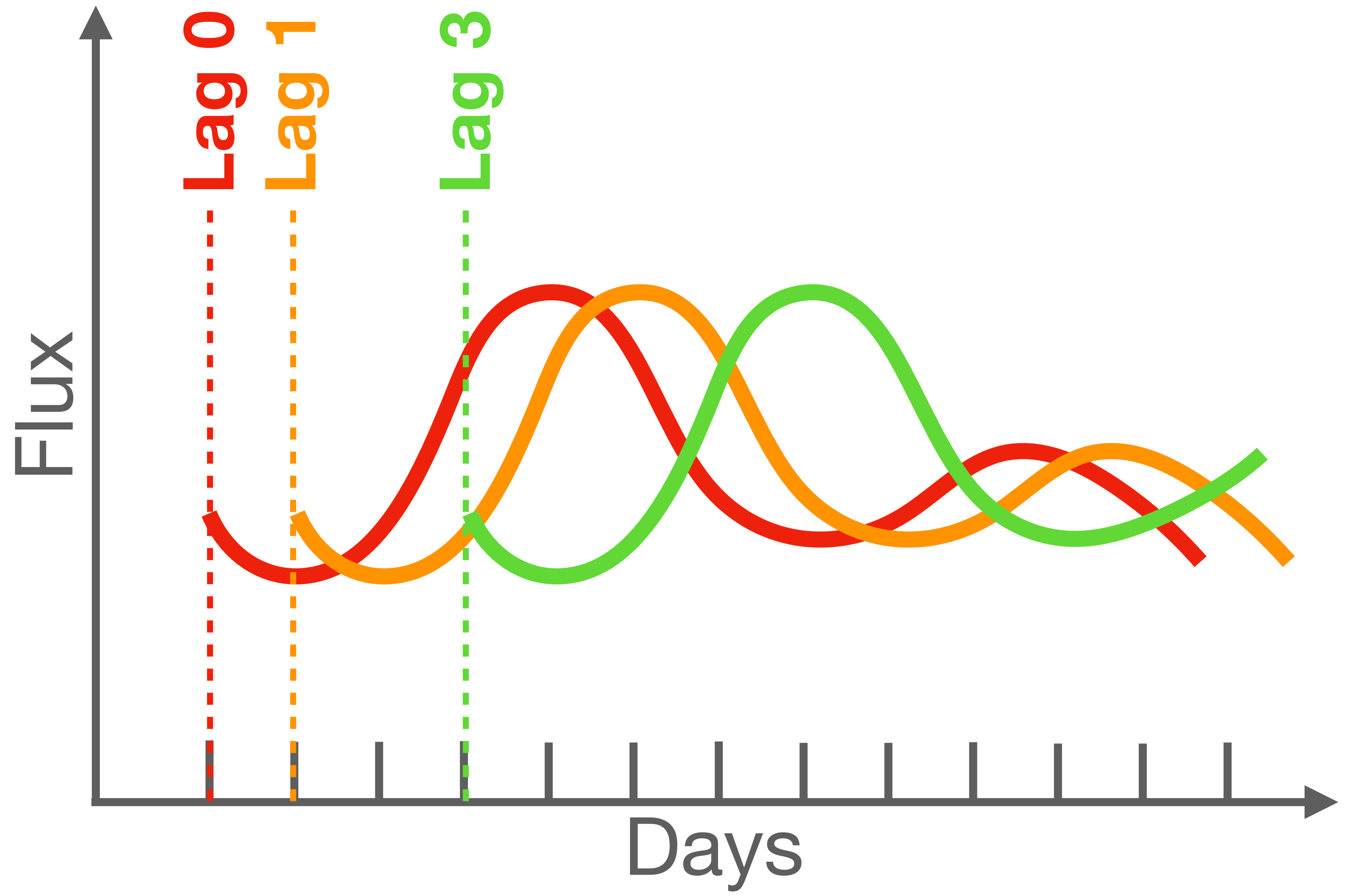
Phase 2

GCR Background Forecasting and Subtraction
and SEP Spectra

GCR Backgorund Forecasting

Autocorrelation is the **correlation** of a signal with a **delayed copy of itself** as a function of delay, called **lag**.

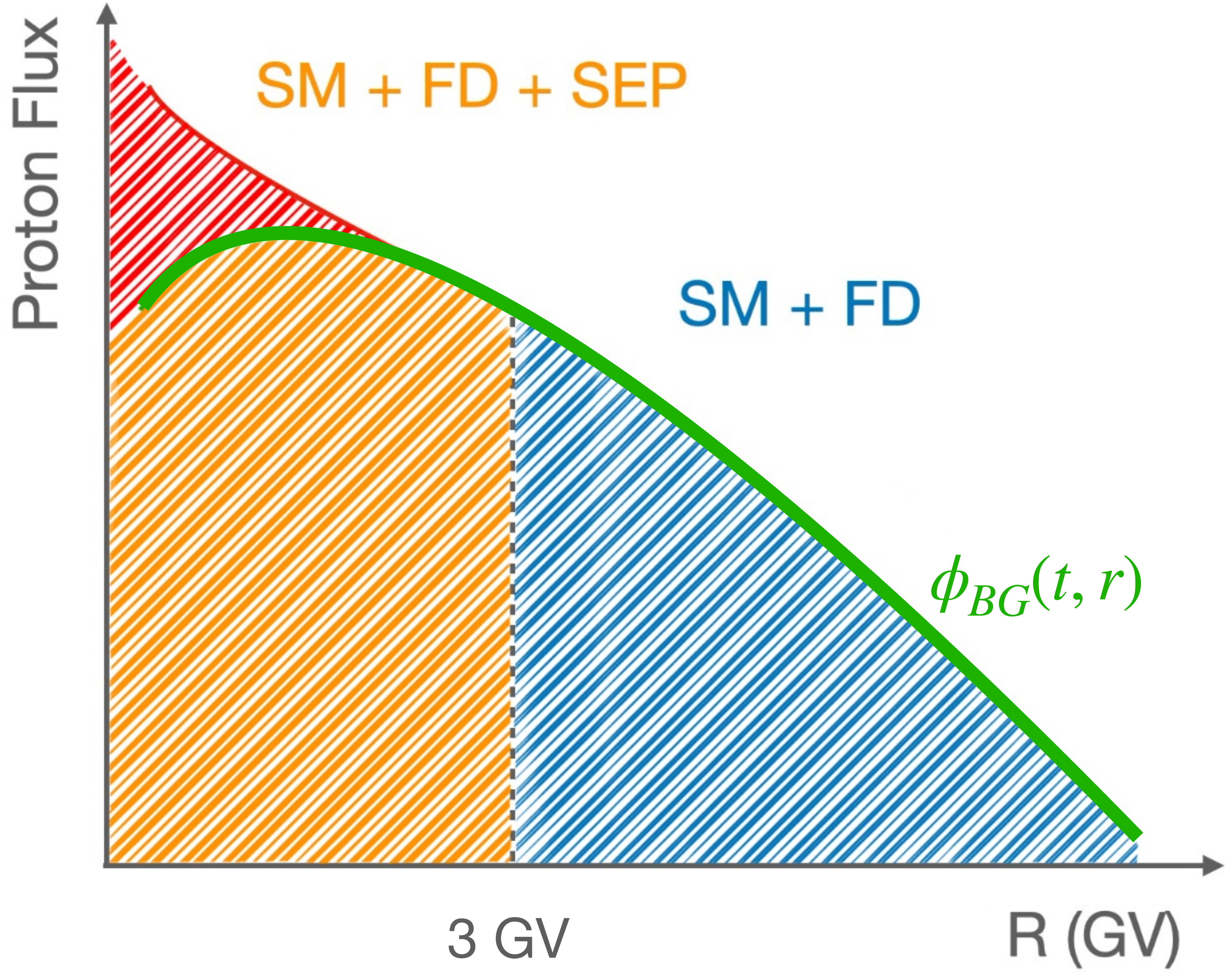




The **proton flux**, at a given day, is strongly **correlated** to the flux on **previous day**

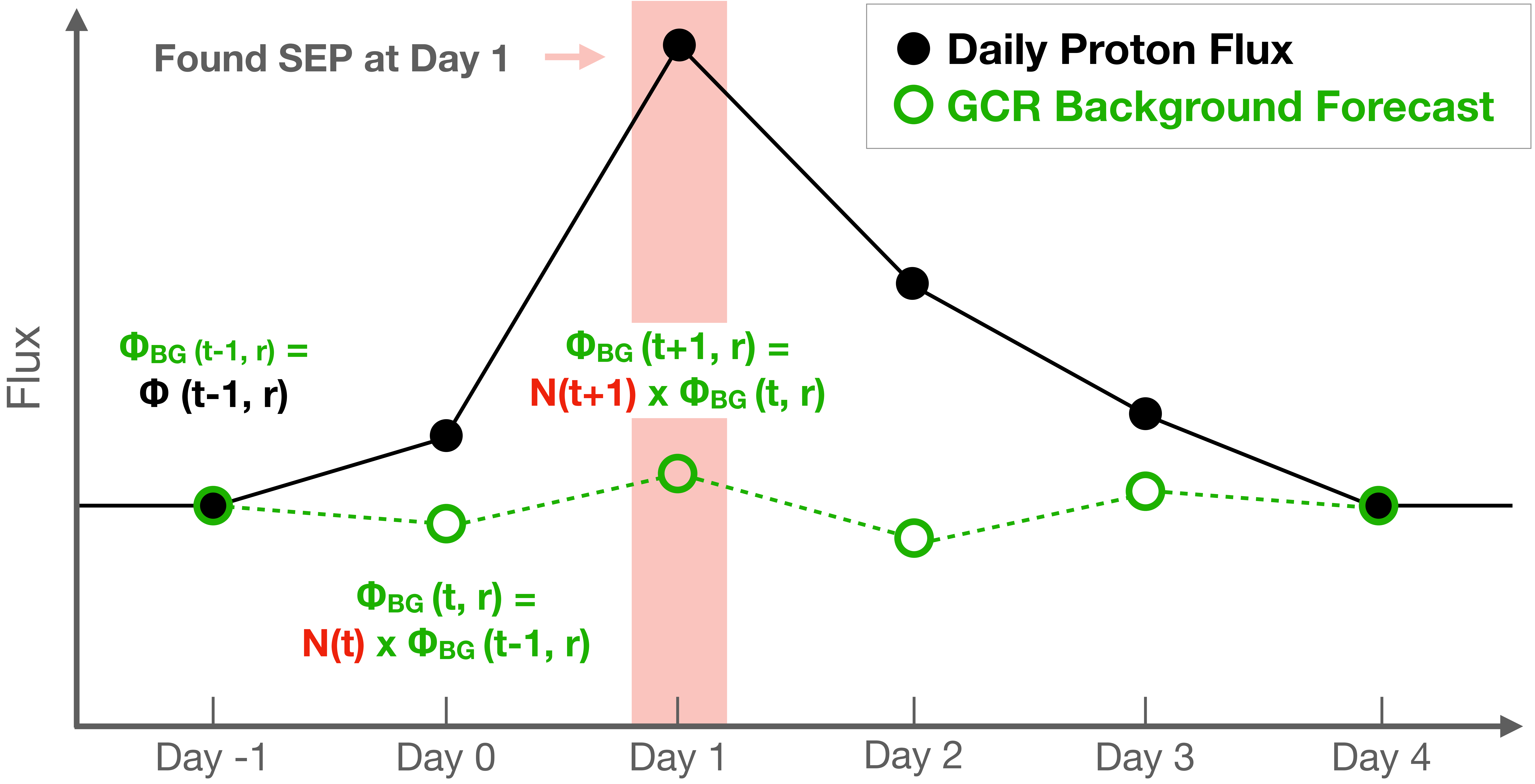
$$\phi_{BG}(t, r) = N(t) \times \phi_{BG}(t\text{-}1, r)$$

Background Normalization

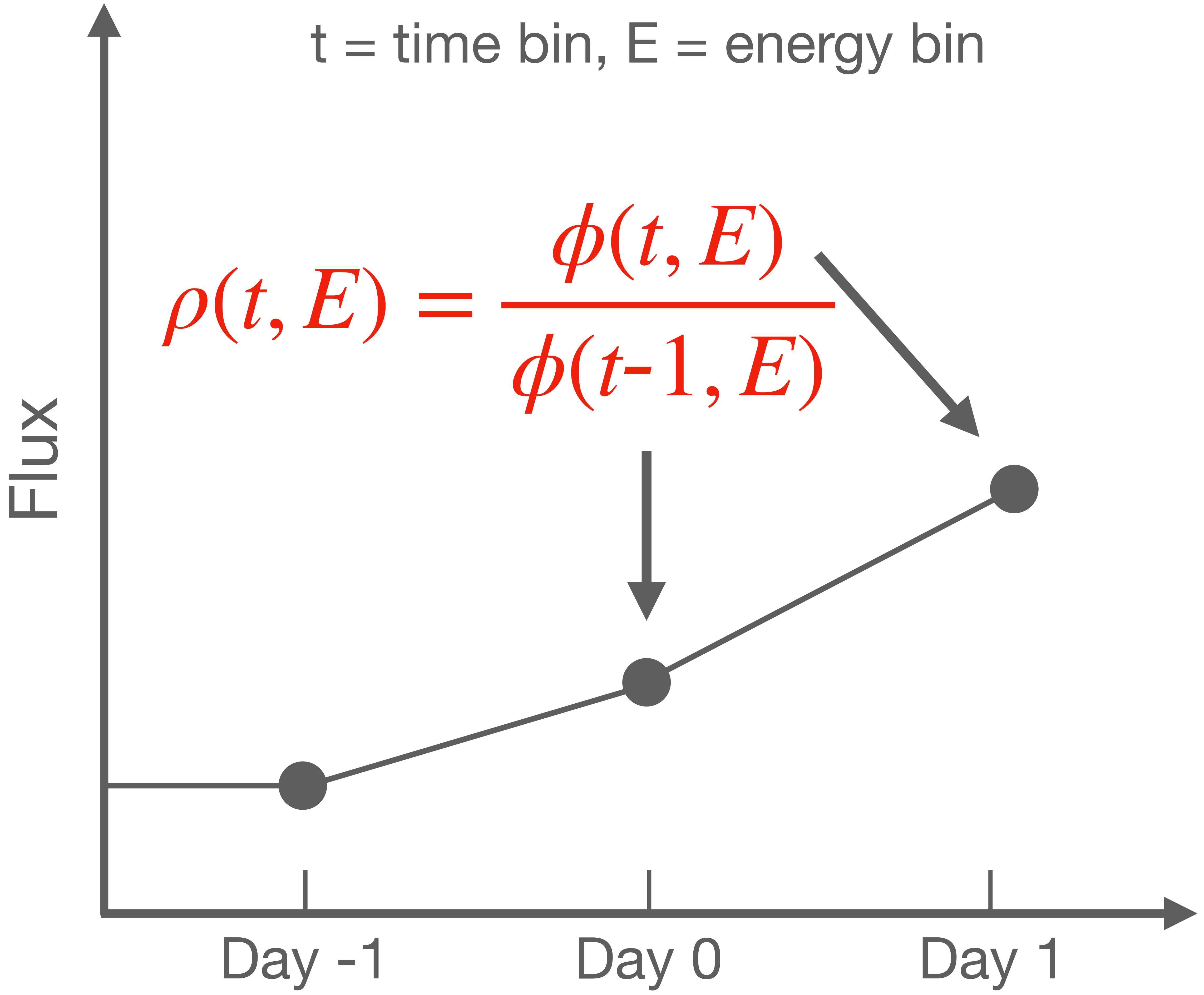


- **N(t)** should include effects of **solar modulation (SM)** and **Forbush decreases (FD)**, but not SEPs.
- The **SEP contribution** to the total flux becomes **negligible** above **3 GV**.
- The **normalization N** can be calculated from the flux at **higher rigidities** (> 3 GV), excluding the SEP contribution.

GCR Background Forecast



Forecast Parameter: Ratio with Lag1 Flux

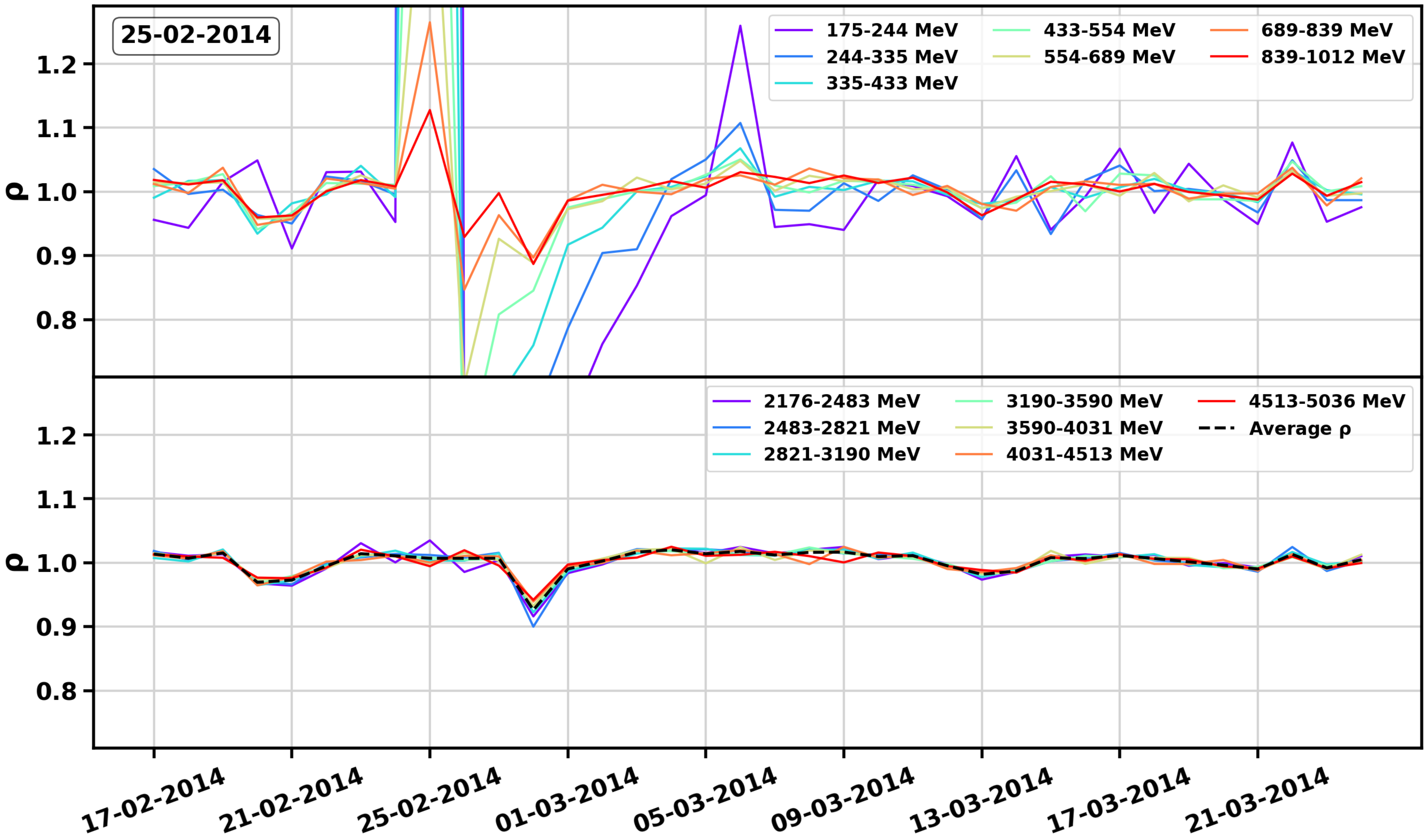


For each time (day) and rigidity bin, ϱ is defined as the **ratio** of the **current** daily flux with the flux of the **previous** day.

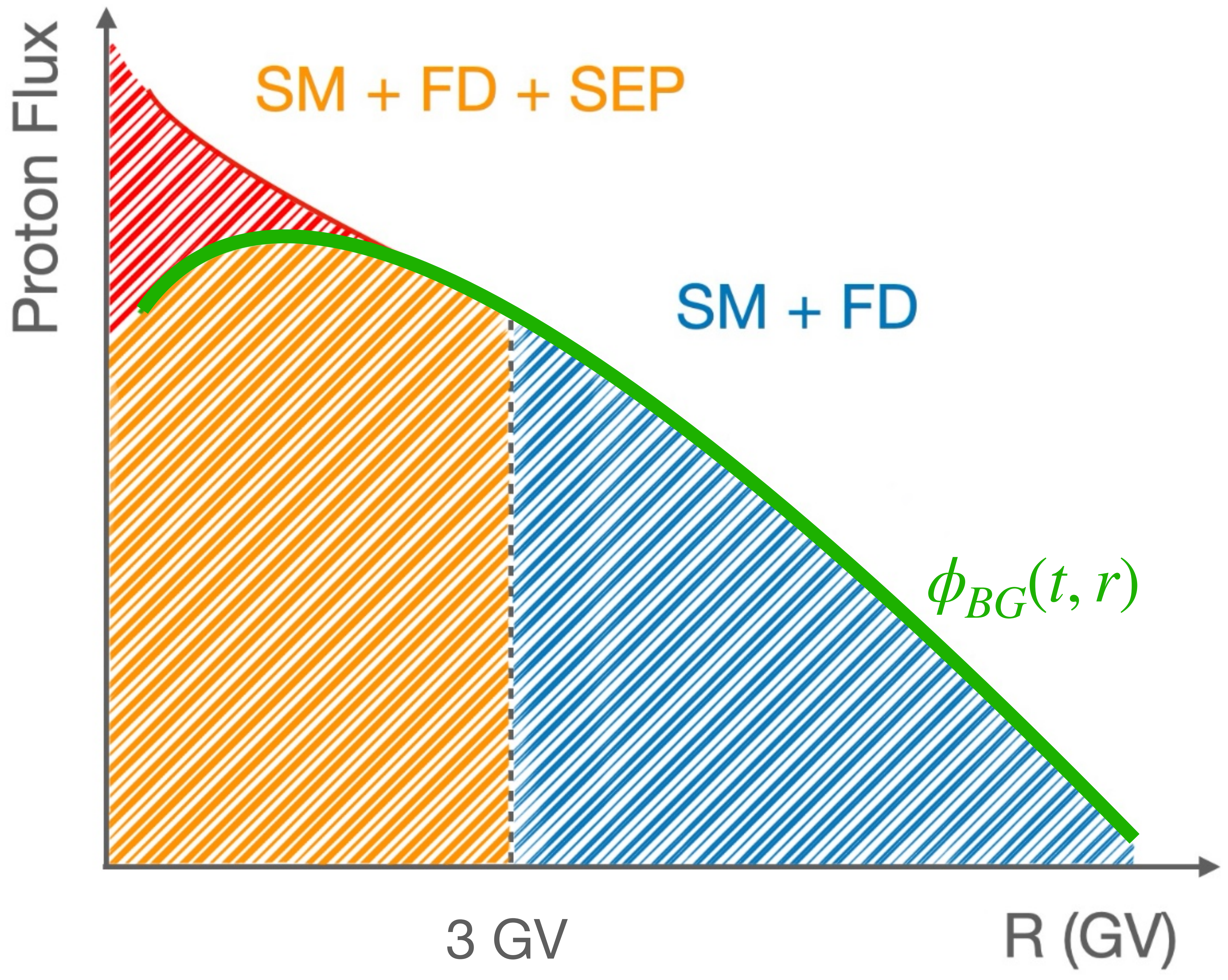
Properties:

- **Stationary**: removes seasonal trend. It is still time dependent, i.e. solar modulation and Forbush decreases are preserved.
- **Rigidity independent** during quiet periods: unique normalization factor for every rigidity bin.

Forecast Parameter: Ratio with Lag1 Flux



Background Normalization



The **normalization N(t)** is given by the **average** of the ϱ parameter, in the rigidity interval ~ **[3, 6] GV**, above the maximum rigidity reached by SEPs.

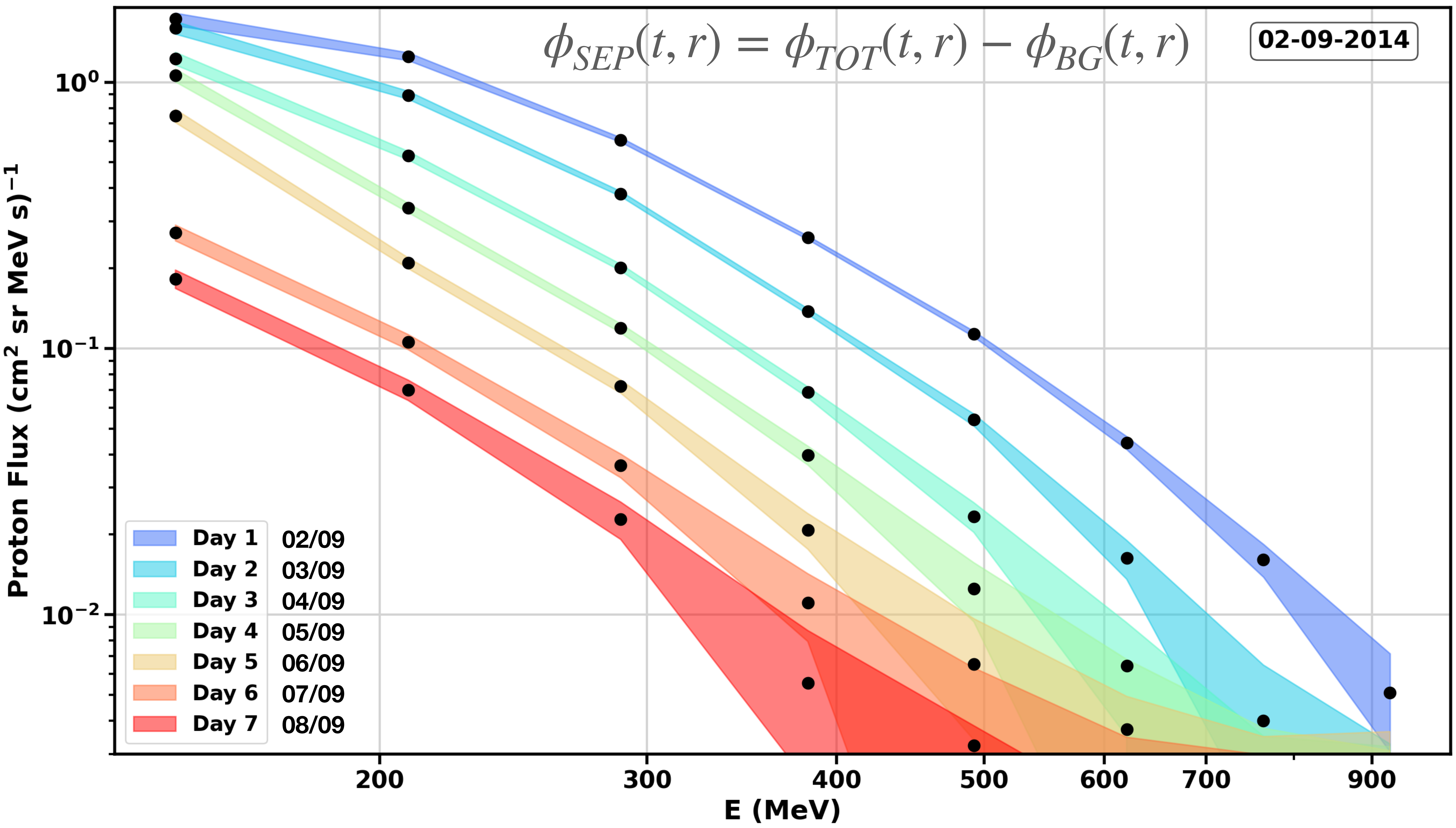
$$N(t) = < \rho(t) > = \frac{1}{7} \sum_{r=10}^{17} \frac{\phi(t, r)}{\phi(t\text{-}1, r)}$$

$$\phi_{BG}(t, r) = < \rho(t) > \times \phi_{BG}(t\text{-}1, r)$$

N(t) is the same **for any rigidity bin**, thanks to **rigidity independence**.

Background Subtracted SEP Spectra

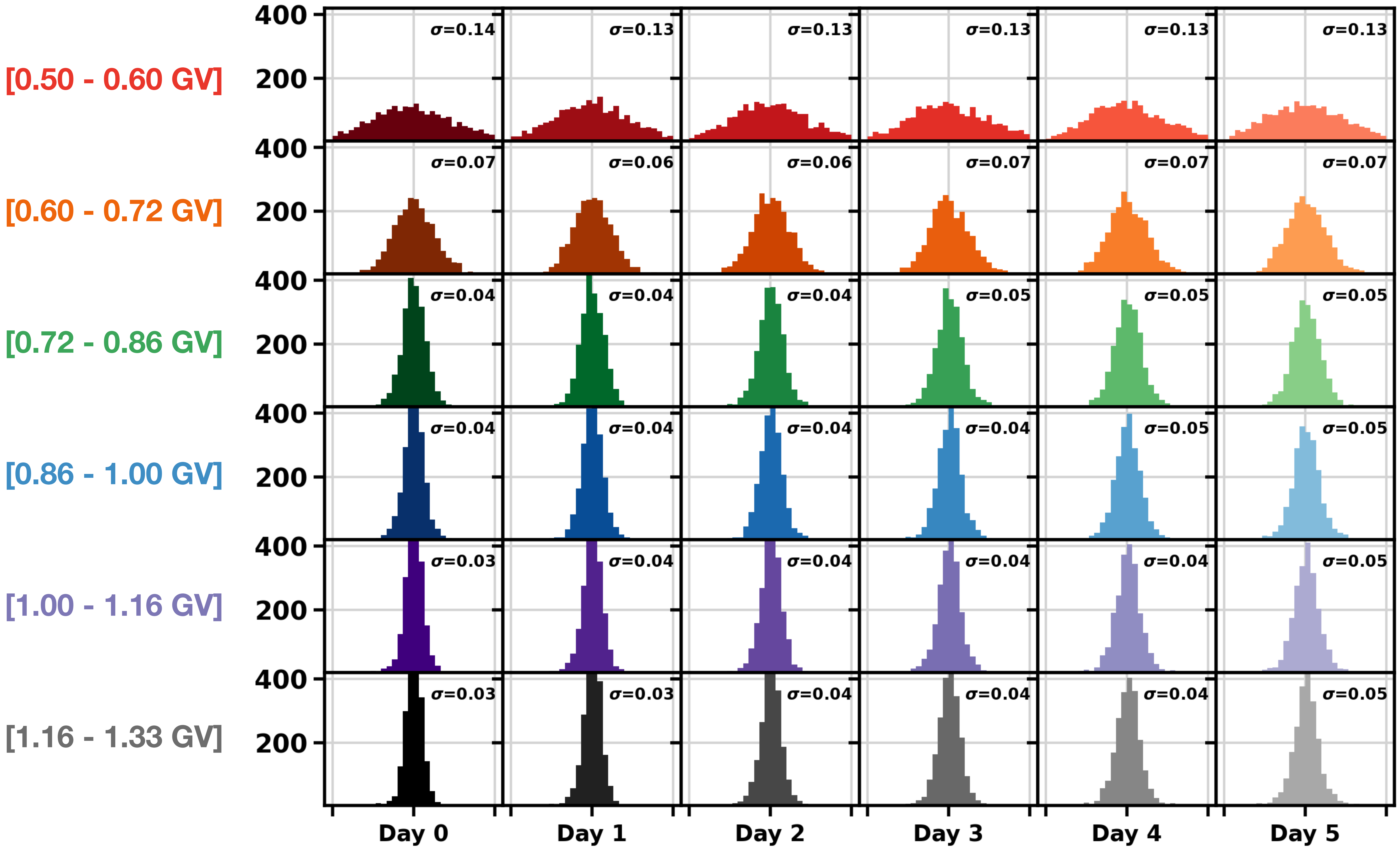
The **SEP only** flux is the **subtraction** of the **background** from the **total** flux.



Forecasted Background on Quiet Flux

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

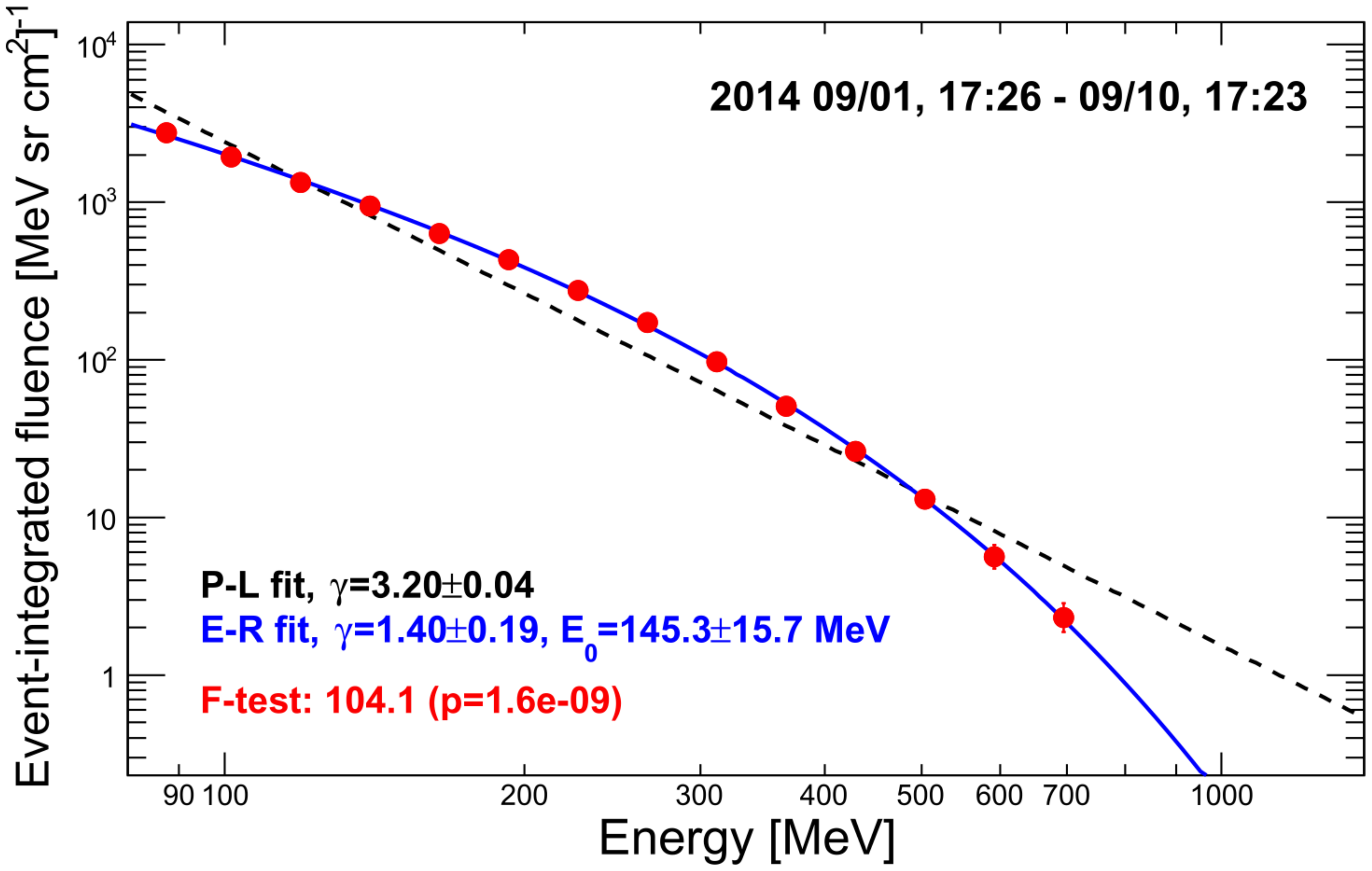
$$\frac{\phi_{BG} - \phi}{\phi}$$



Spectral Fit Functions

The **Ellison-Ramaty** function describes a **power law** with **exponential rollover**, typical of **diffusive shock acceleration** with limited spatial and temporal extension.

$$\Phi_{ER}(E) = AE^{-\gamma} \exp\left(-\frac{E}{E_r}\right)$$

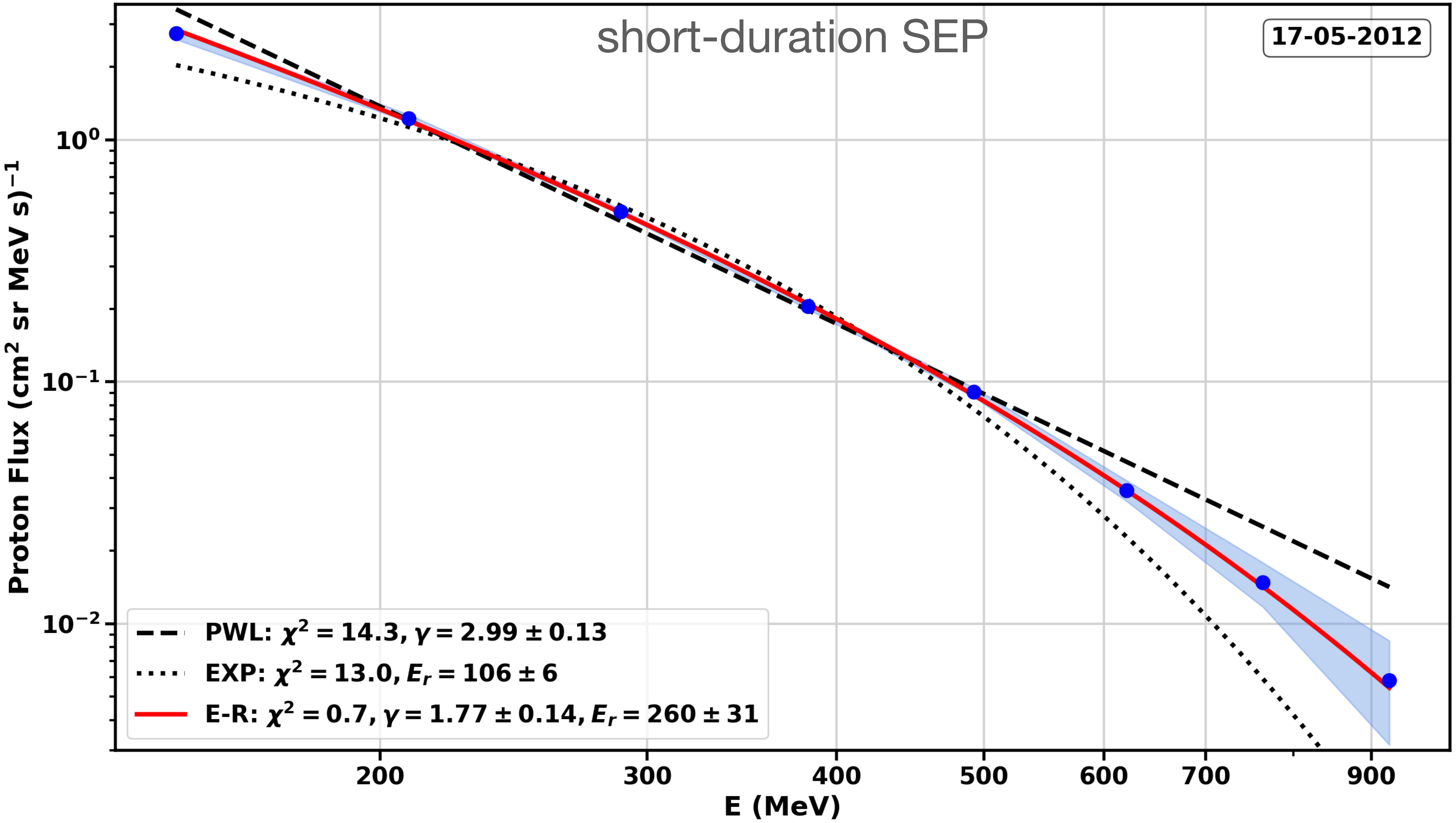


- The function has been used on **Pamela** data (event-integrated fluence) to perform a fit of **SEP spectra**.
- The results are in **agreement** with the **DSA** hypothesis.

https://doi.org/10.3847/1538-4357/aacc26

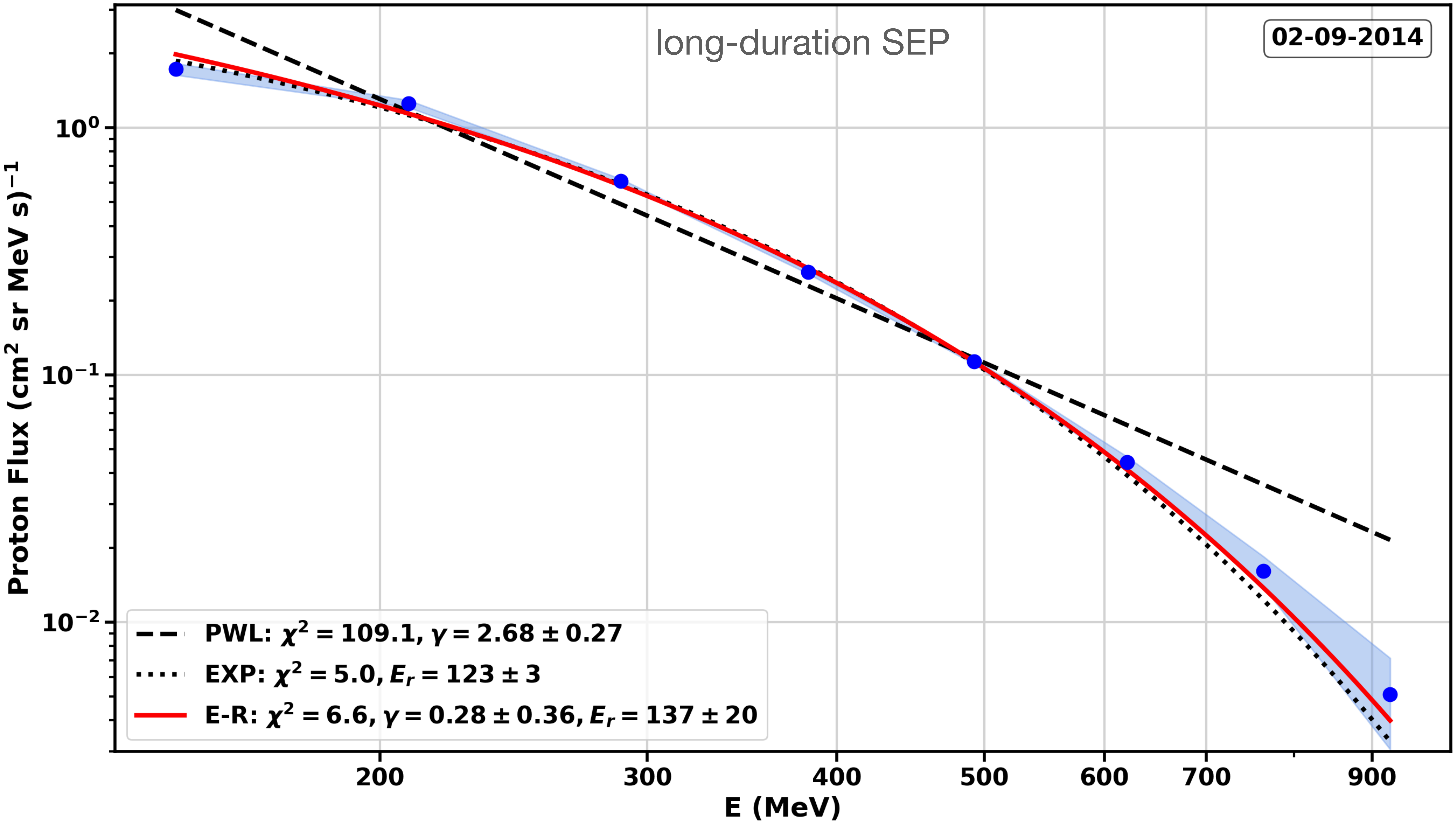
Spectral Fits with AMS at Peak Intensity

Background-subtracted SEP spectra are **fitted** with the **Ellison-Ramaty** function (red) and its asymptotic limits: single **power law** (dashed) and **exponential** (dotted).



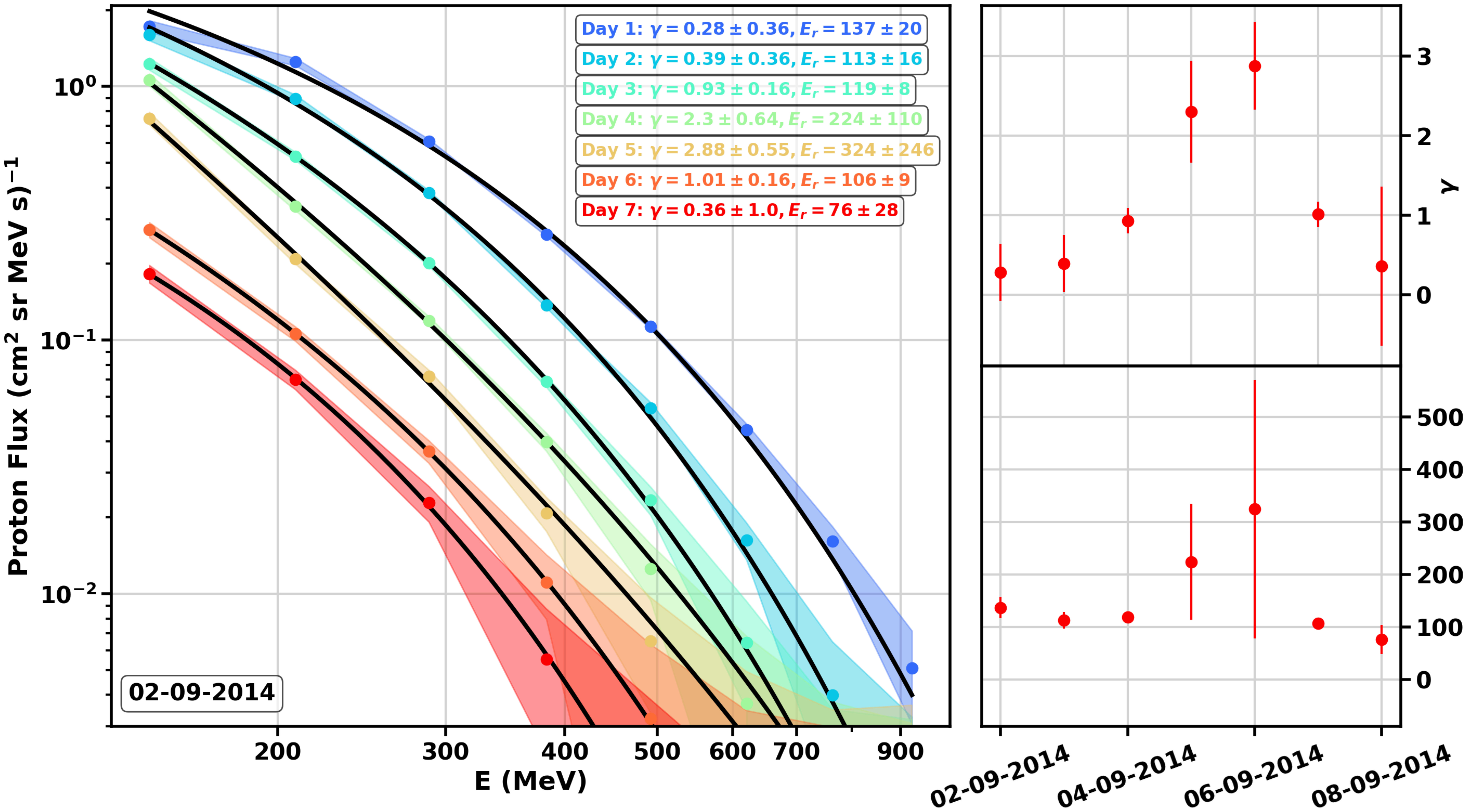
Our result **supports** the presence of an **exponential rollover**, which might be related to the spatial and temporal limits of **diffusive shock acceleration**, in agreement with PAMELA results.

Spectral Fits with AMS at Peak Intensity



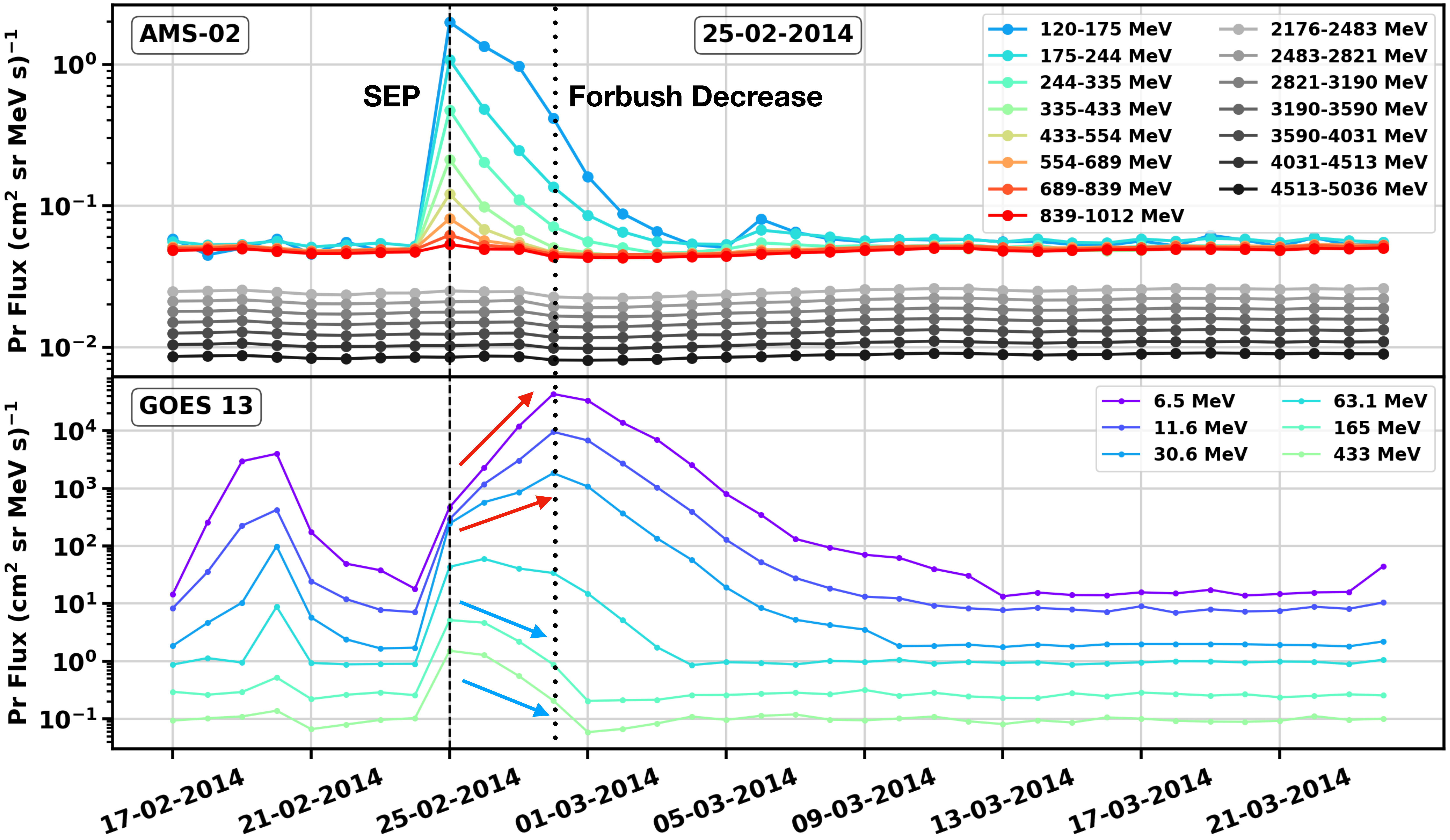
Spectral Index Temporal Evolution

Fitting the Ellison-Ramaty function to the **consecutive daily spectra** of a given SEP event shows that the **spectral index increases**.



Spectral Index Temporal Evolution

- The **spectral softening** is **consistent** with the measurements from the **GOES** observatory at the lowest energies.
- The delayed **source** at low energy might be interplanetary protons **accelerated** by the **shock front** of the CME.



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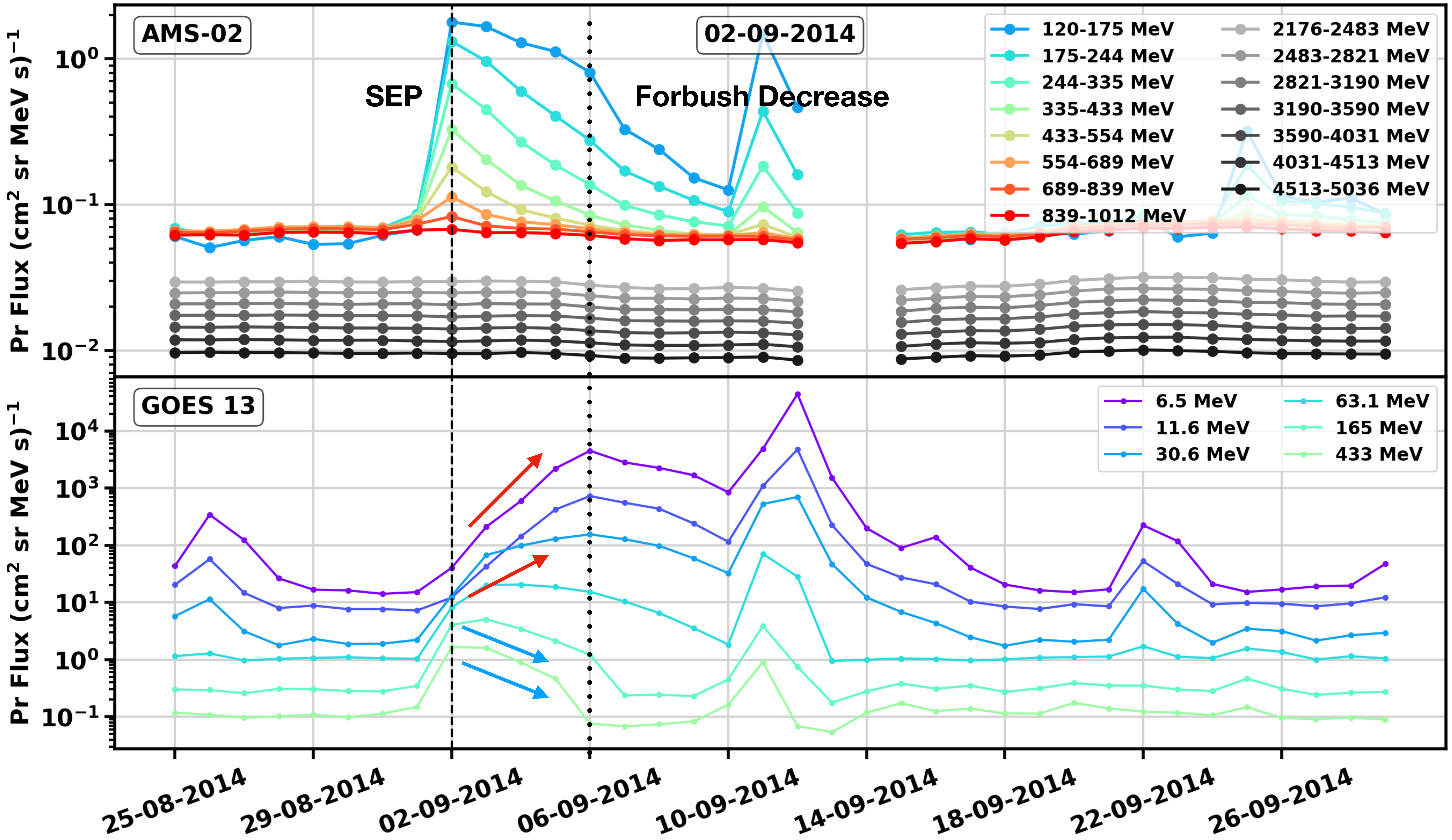


Summary

- The **daily proton flux** is compatible with the recent publication.
- Improved **selection** for SEP protons with **polar-pass regions** to maximise statistics at low energy.
- An **algorithm** to **forecast** and **subtract** the **GCR background** was developed for the polar-pass flux, in order to obtain SEP-only spectra.
- Fitted each SEP spectrum at peak intensity with “**power law + exp. rollover**”.
- Spectral **temporal evolution** of a given SEP events shows **spectral softening** at **low energy**.
- The spectral softening is **supported** by the comparison with **GOES**.

Backup

SEP Events Found With AMS

#	Start Time	Flare Class
1	2011 Jun 07	M2
2	2011 Aug 04	M9
3	2011 Aug 09	X6
4	2011 Sep 07	
5	2011 Sep 23	X1
6	2011 Nov 04	
7	2012 Jan 23	M8
8	2012 Jan 28	X1
9	2012 Mar 07	**X5**
10	2012 Mar 13	M7
11	2012 May 17	M5
12	2012 Jun 16	M1
13	2012 Jul 07	X1
14	2012 Jul 12	X1
15	2012 Jul 17	M1
16	2012 Jul 23	
17	2012 Sep 28	C3
18	2012 Nov 08	
19	2013 Mar 05	M1
20	2013 Apr 11	M6
21	2013 Apr 24	
22	2013 May 23	M5
23	2013 Jun 23	M2
24	2013 Oct 11	
25	2013 Oct 28	
26	2013 Nov 02	
27	2013 Dec 28	C9
28	2014 Jan 06	X1
29	2014 Feb 25	X4
30	2014 Apr 18	M7
31	2014 Sep 02	
32	2014 Sep 11	X1
33	2014 Sep 25	
34	2015 Oct 24	M7
35	2017 Jul 14	M2
36	2017 Sep 07	M5
37	2017 Sep 12	**X8**
38	2022 Feb 17	
39	2022 Mar 28	M4
40	2023 Mar 13	
41	2023 Jul 16	M5
42	2023 Jul 24	
43	2023 Sep 01	M1

Layer 1 Pickup Efficiency

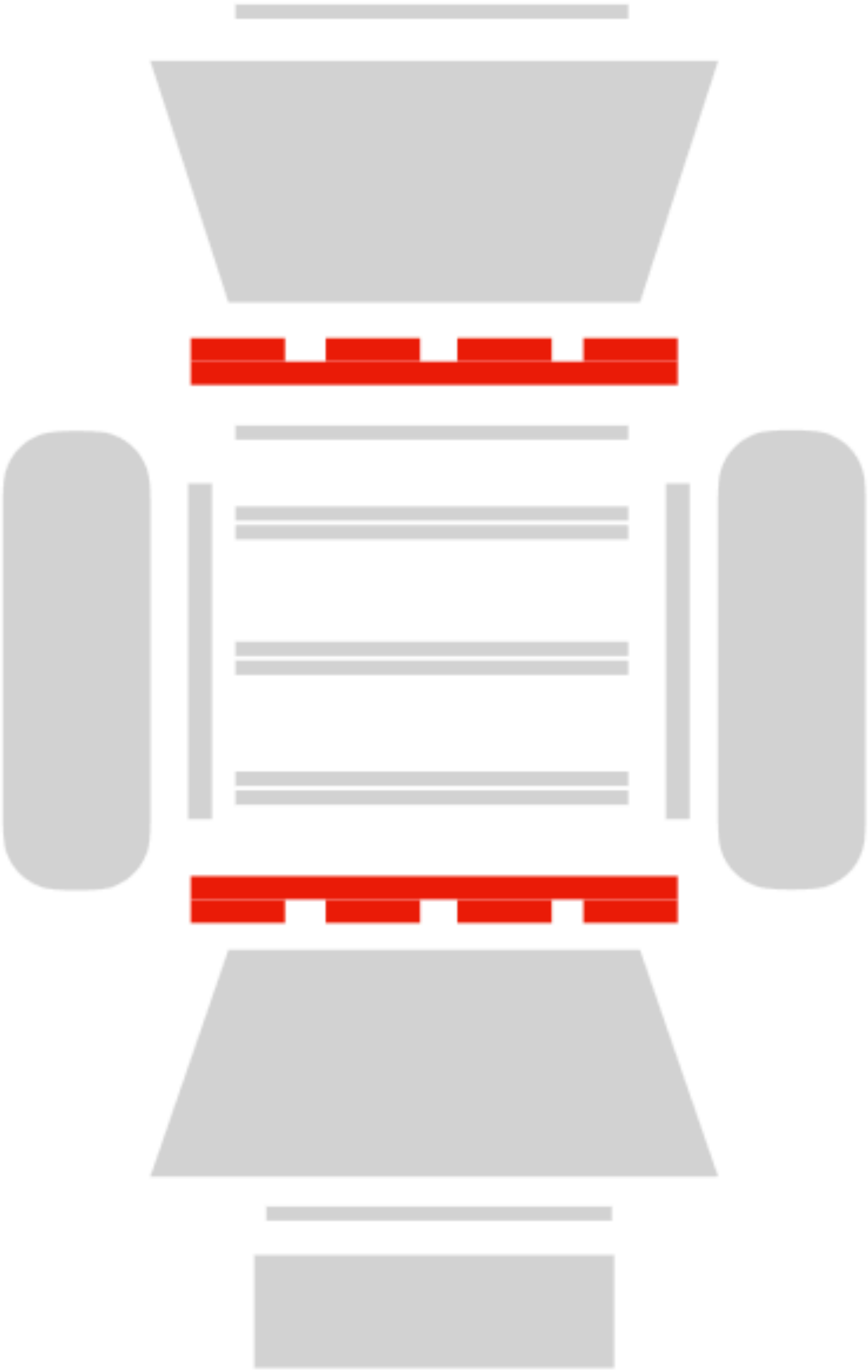
Denominator

- RTI cuts (see event selection)
- Any Physical trigger
- Chi2Y < 10 (Inner rigidity)
- Hits on: L2 & (L3|L4) & (L5|L6) & (L7|L8)
- At least 5 Hits in Inner Tracker
- 0.7 < Inner Charge < 1.5
- Inner Charge / Inner Charge RMS < 0.4
- Beta > 0.4
- 0.5 < Upper ToF Charge < 1.7
- Mass Cut (Inner rigidity)
- 0.5 < Lower ToF Charge < 1.7
- Less than 5 ToF Clusters
- ToF Chi2 Coo < 2
- Only one inner track
- No ACC fired
- Match Inner TRD Fit
- Inner Rigidity > SafetyFactor(R) x IGRF Cutoff

Numerator

- Denominator
- Chi2Y < 10 (InnerL1 rigidity)
- 0.6 < L1 Charge < 2
- Inside Inner Fiducial (InnerL1 rigidity)
- Inside L1 Fiducial (InnerL1 rigidity)
- L1 Normalized Residual < 10

ToF Efficiency



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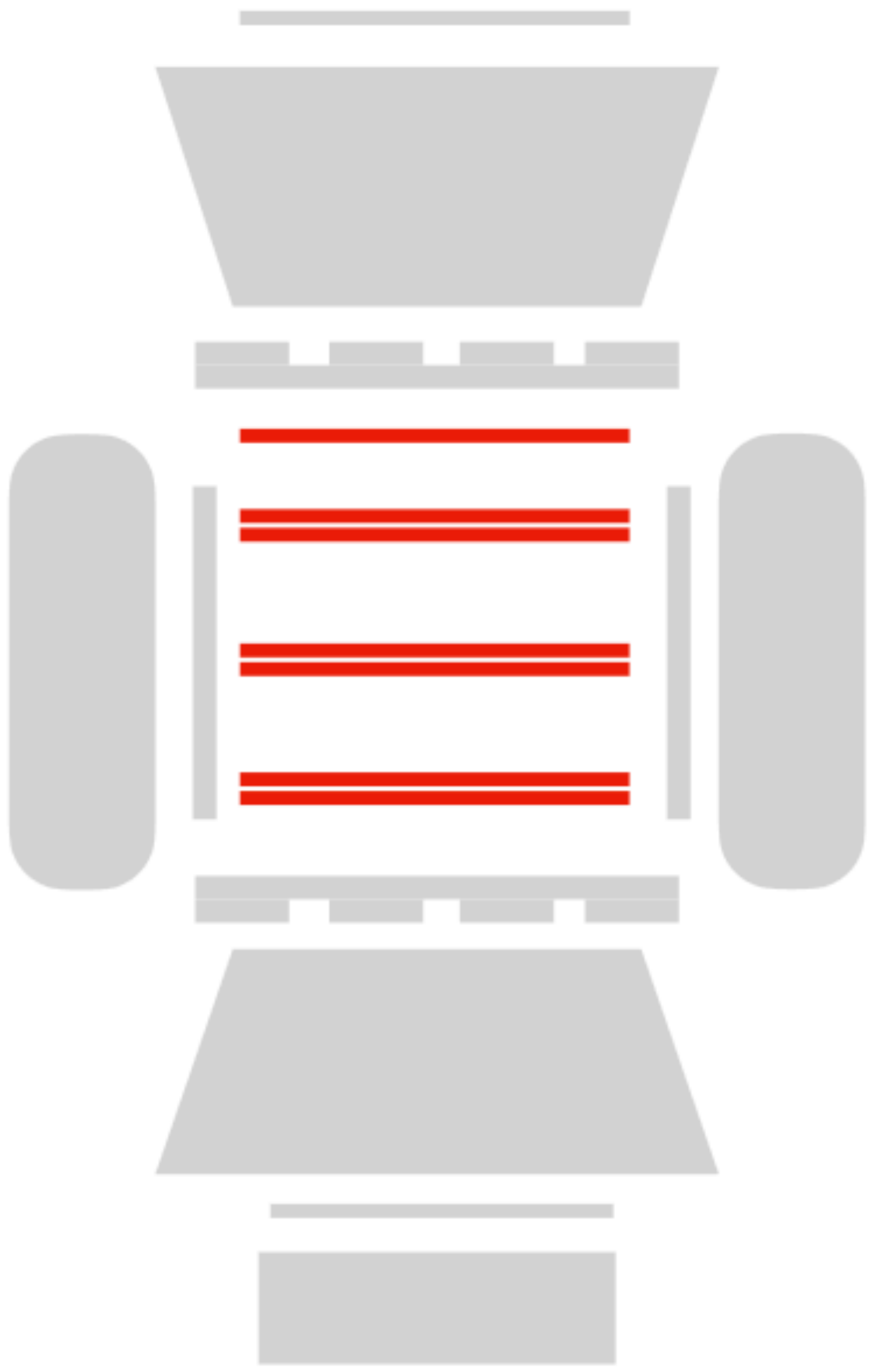
- Inner Charge / Inner Charge RMS < 0.4
- $0.6 <$ L1 Charge < 2
- Inside Inner Fiducial (InnerL1 rigidity)
- Inside L1 Fiducial (InnerL1 rigidity)
- L1 Normalized Residual < 10
- InnerL1 Rigidity $>$ SafetyFactor(R) x IGRF Cutoff

Numerator

- Denominator
- Beta > 0.4
- $0.5 <$ Upper ToF Charge < 2.5

Inner Tracker Efficiency



Denominator

- RTI cuts (see event selection)
- Any Physical trigger
- 0.6 < L1 Charge < 2
- Beta > 0.4
- 0.5 < Upper ToF Charge < 1.5
- Lower ToF Charge > 0.5
- ToF Chi2 Coo < 2
- ToF Chi2 Time < 2
- ToF Track Inside Inner Fiducial
- ToF Track Inside L1 Fiducial
- TRD Track Inside L1 Fiducial
- Less than 5 ToF Clusters
- InnerL1 Rigidity > SafetyFactor(R) x IGRF Cutoff

Numerator

- Denominator
- Chi2Y < 10 (Inner rigidity)
- Hits on: L2 & (L3|L4) & (L5|L6) & (L7|L8)
- At least 5 Hits in Inner Tracker
- 0.7 < Inner Charge < 1.5
- Inner Charge / Inner Charge RMS < 0.4

Trigger Efficiency

PhysBPatt

Bit	Description
1	Unbiased Charged (prescale: 1/100)
2	Single Charge
3	Normal Ion
4	Slow Ion
5	Electron
6	Photon
7	Unbiased EM (prescale: 1/1000)

Den: 1 || 7

Num: 2 ||...|| 6

Denominator

- RTI cuts (see event selection)
- Chi2Y < 10 (Inner rigidity)
- Hits on: L2 & (L3|L4) & (L5|L6) & (L7|L8)
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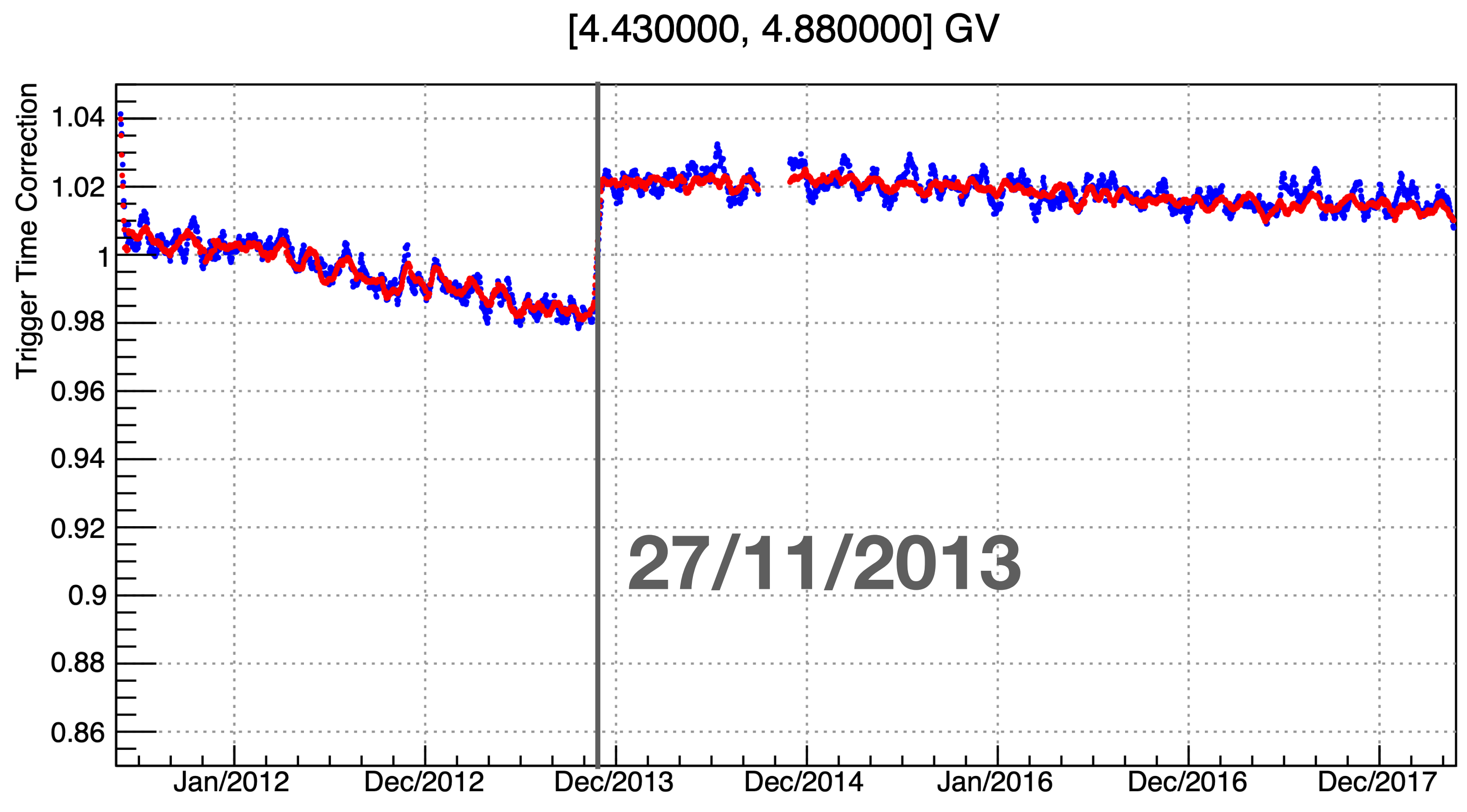
- Inside L1 Fiducial (InnerL1 rigidity)
- L1 Normalized Residual < 10
- Beta > 0.4
- 0.5 < Upper ToF Charge < 2.5
- Mass Cut
- InnerL1 Rigidity > SafetyFactor(R) x IGRF Cutoff
- Unbiased Trigger (PhysBPatt & 01000001)

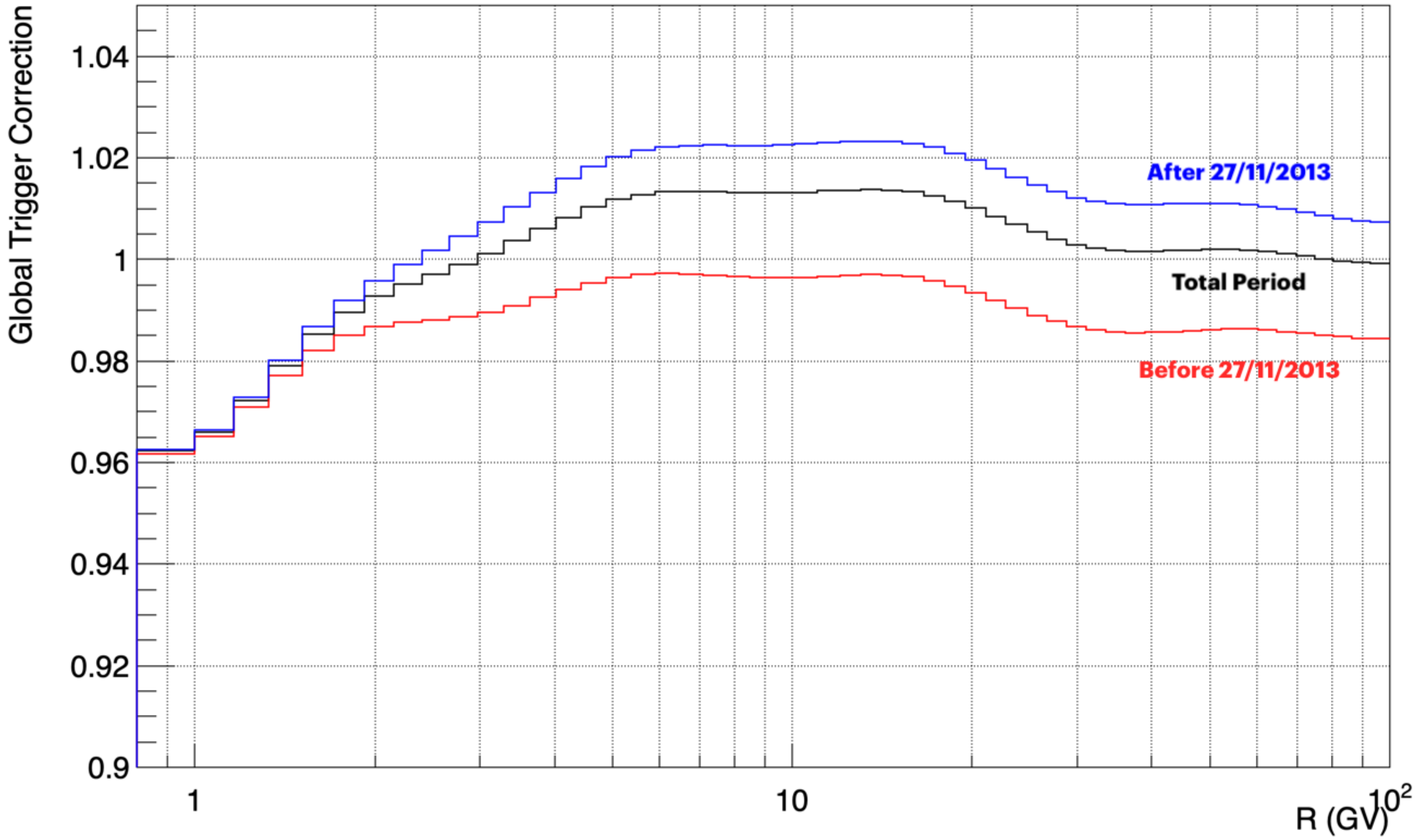
Numerator

- Denominator
- Any Physical trigger

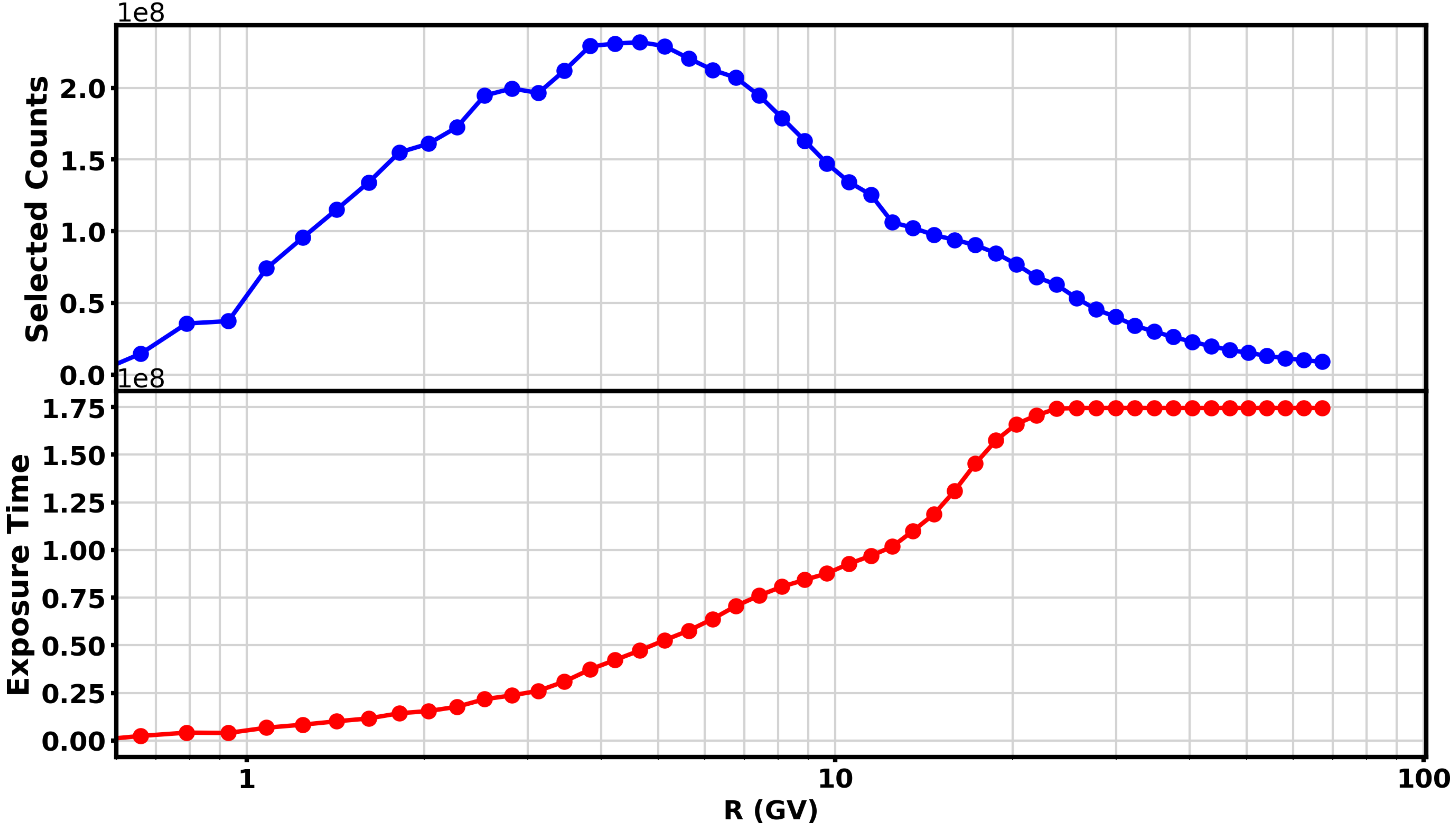
Global Trigger Correction

Trigger efficiency changes after ToF PMT reconfiguration: we use two different global corrections (before and after).

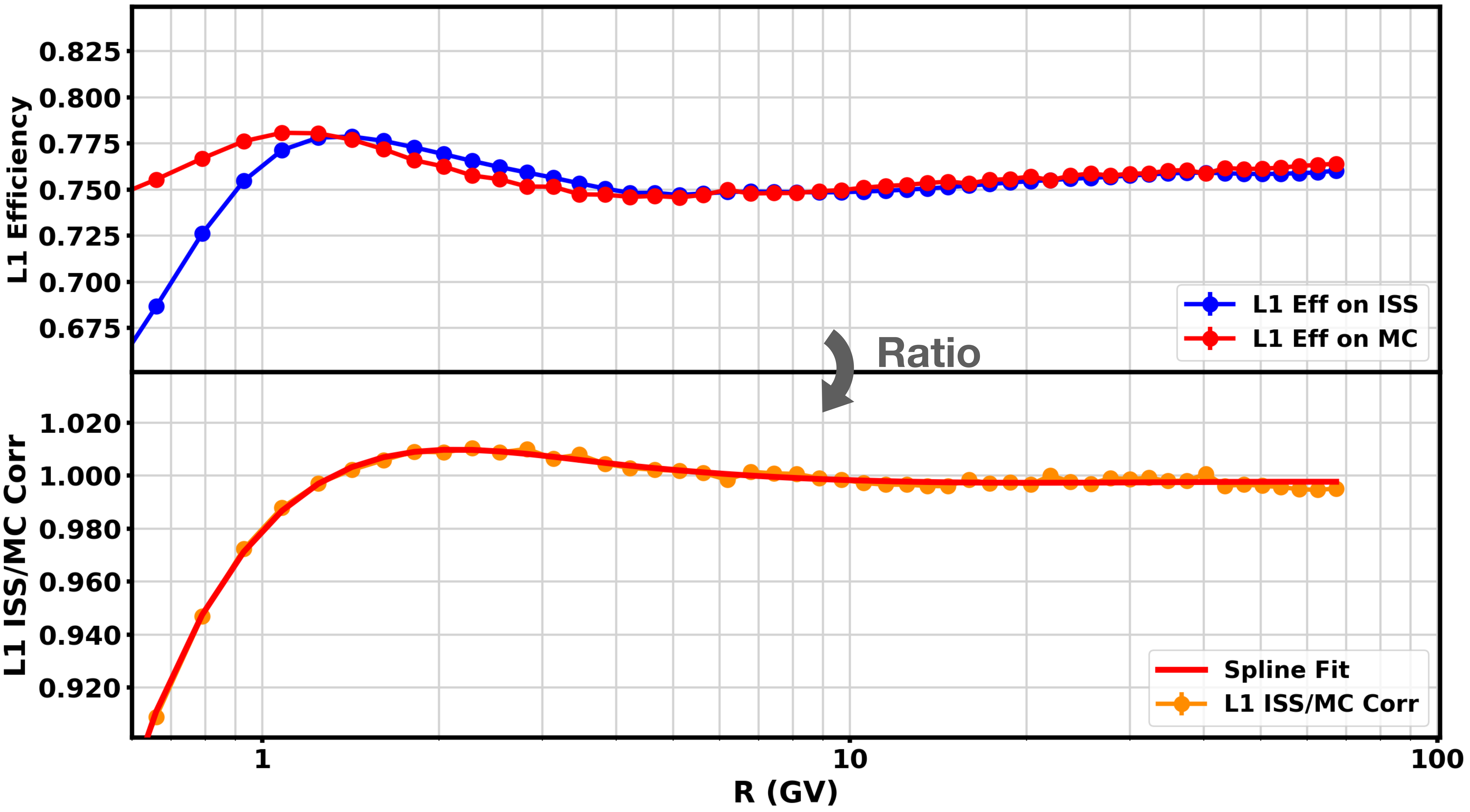




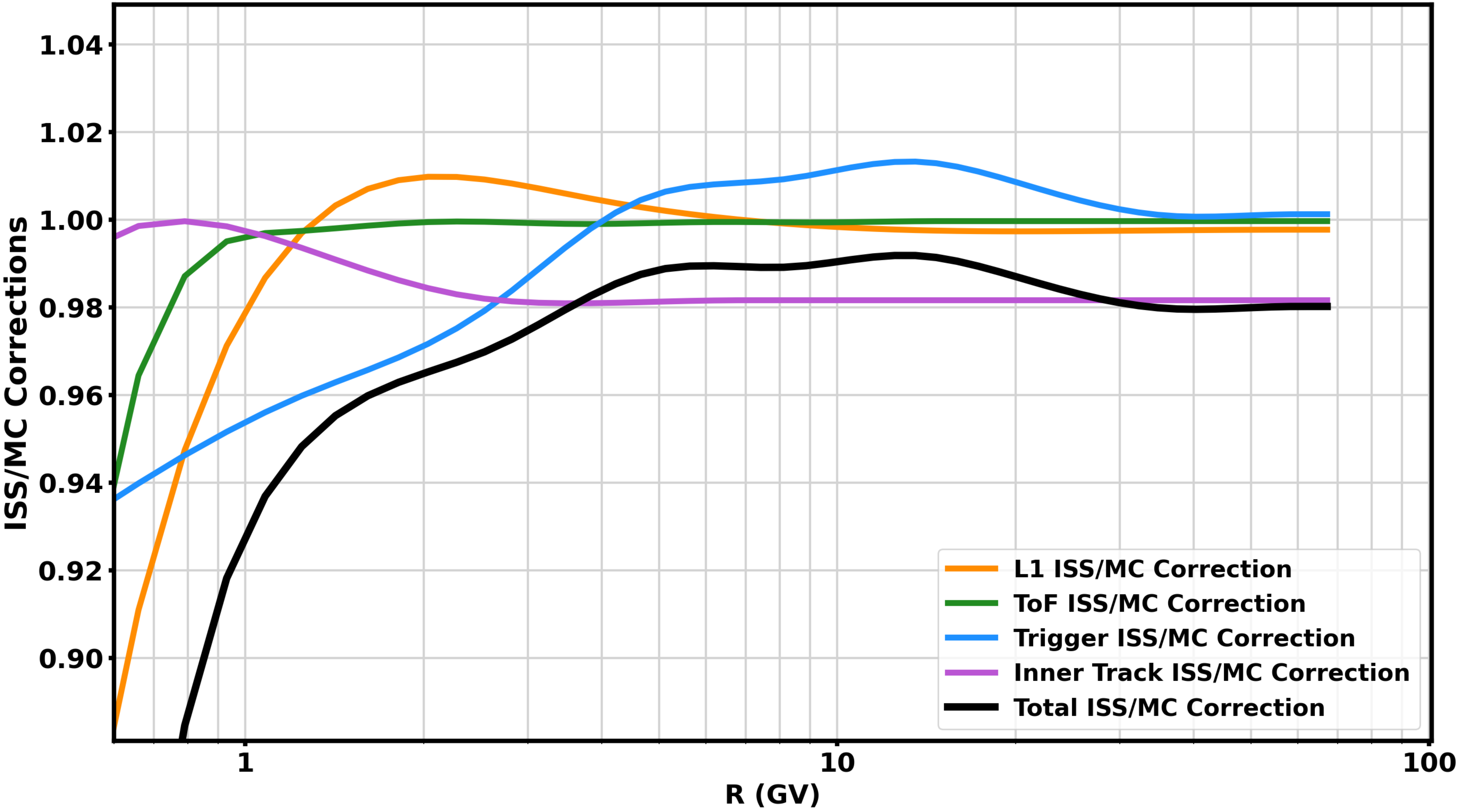
Selected Counts and Exposure Time



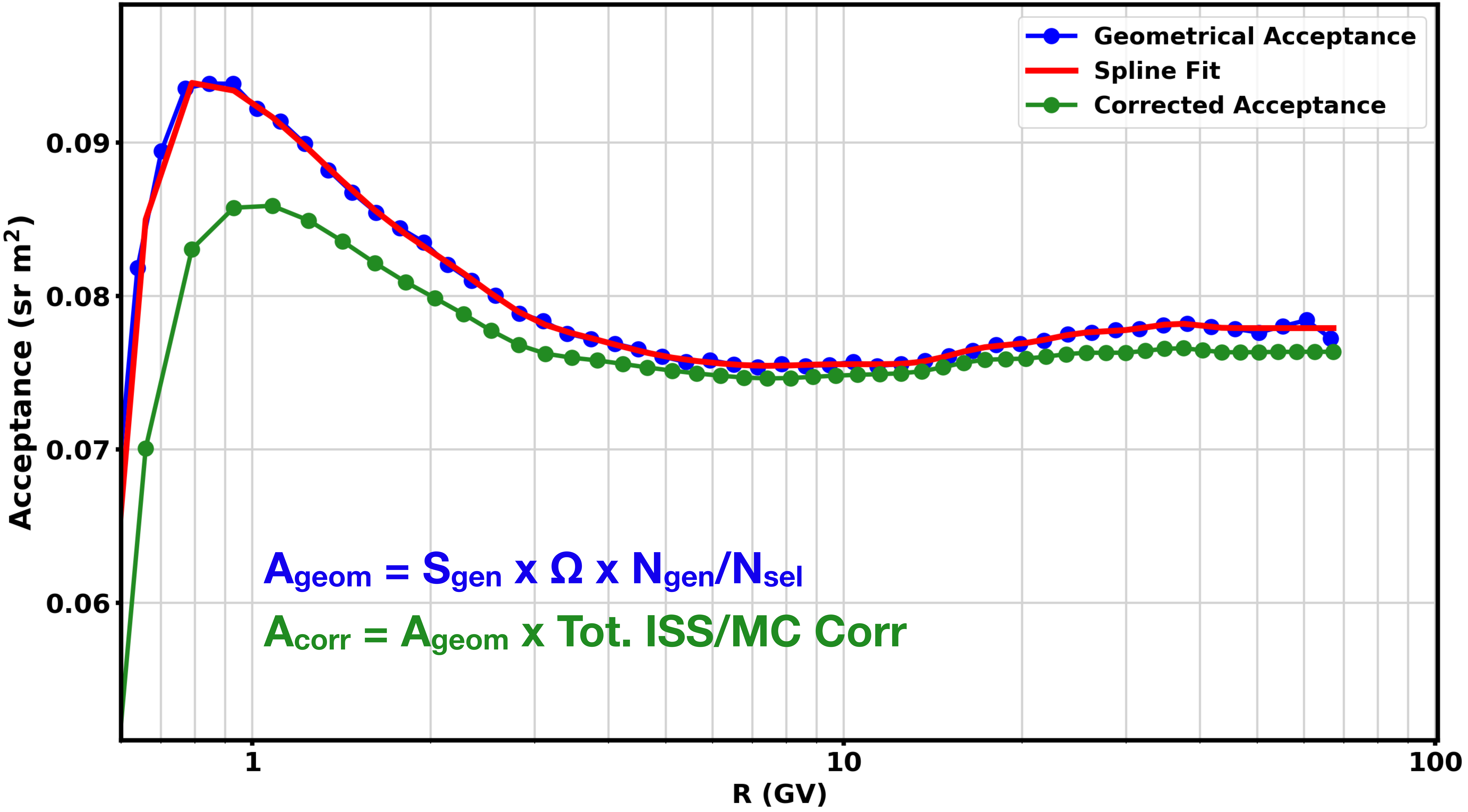
Layer 1 Efficiencies and Correction



ISS/Montecarlo Corrections



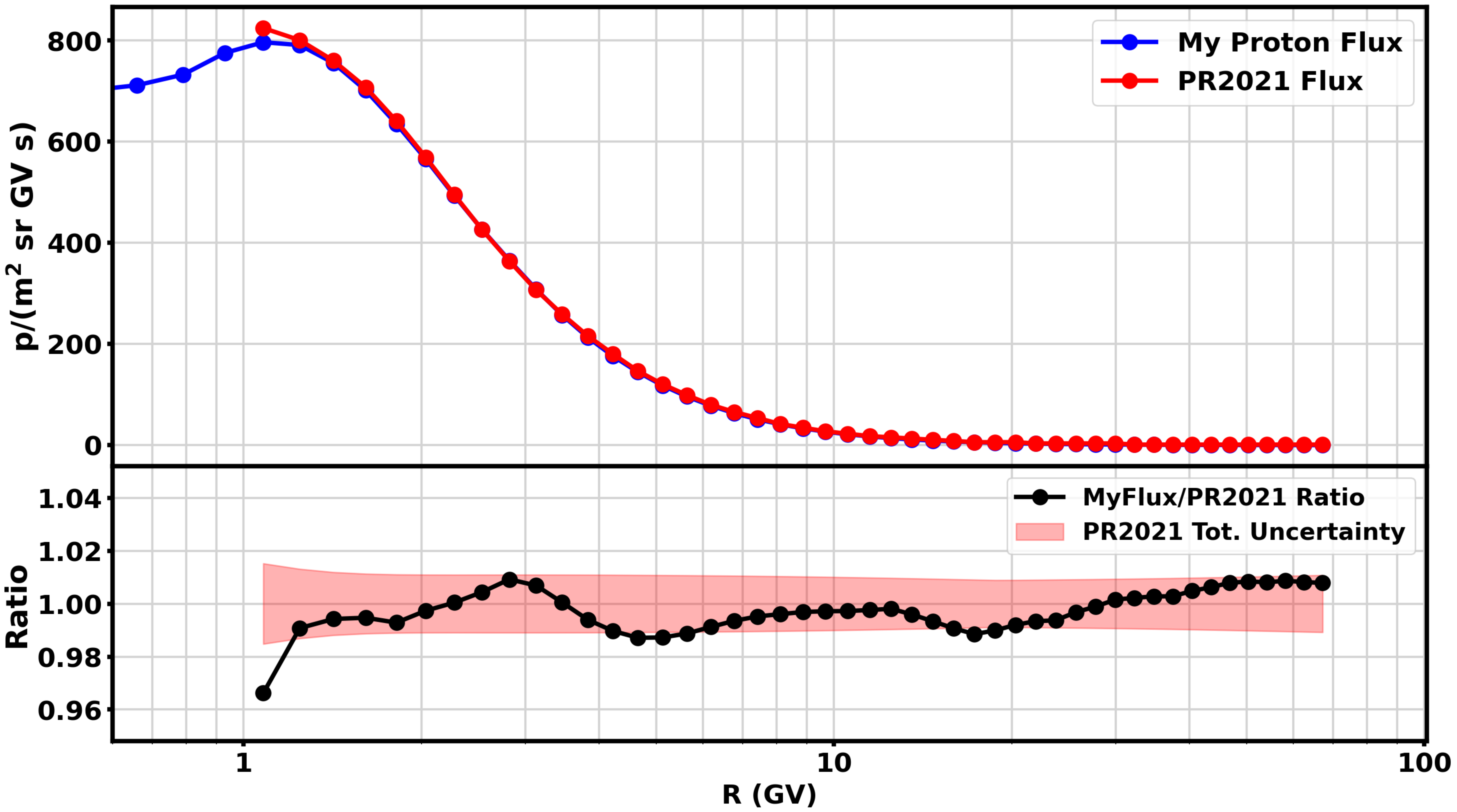
Acceptance



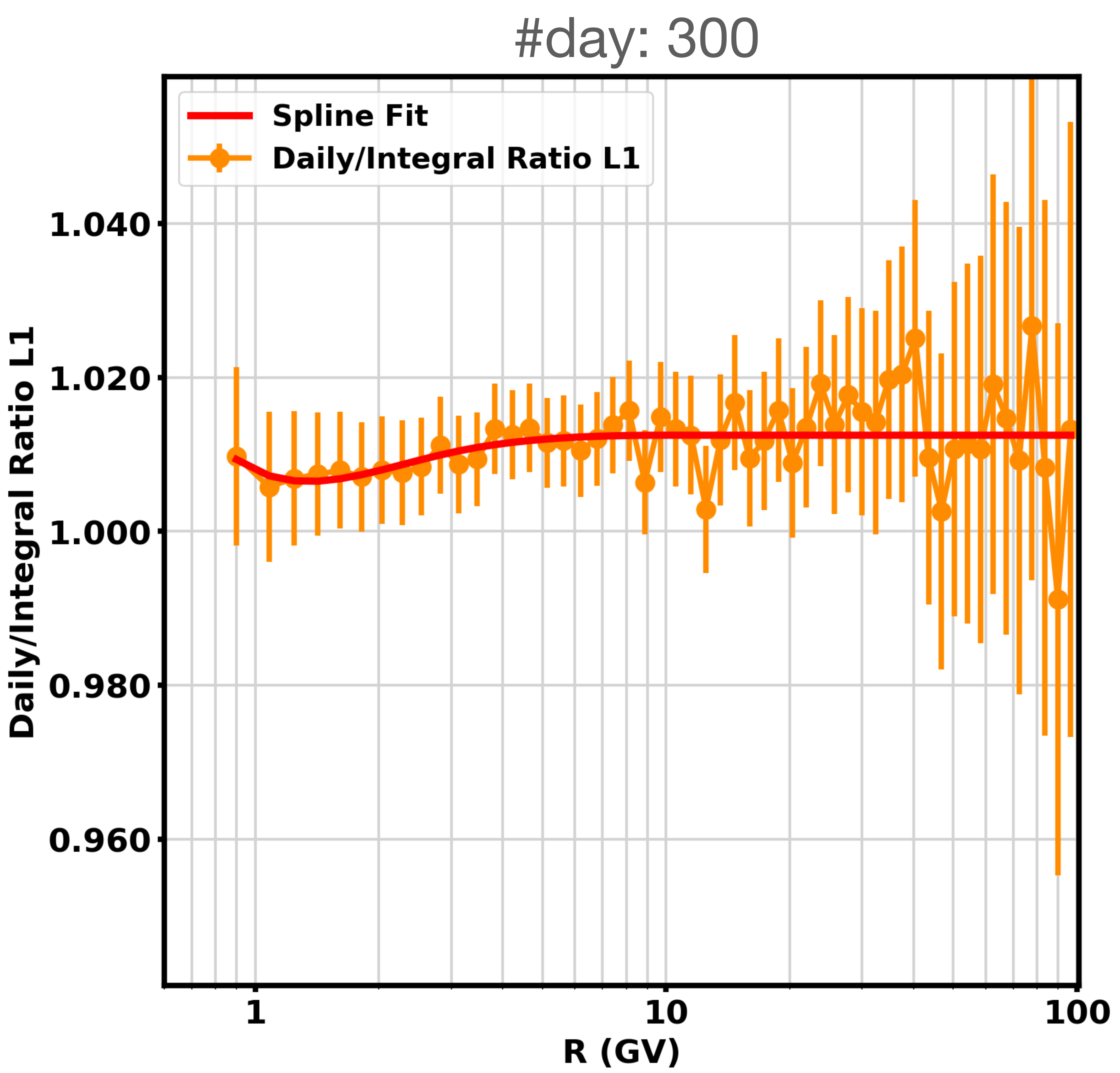
$A_{geom} = S_{gen} \times \Omega \times N_{gen}/N_{sel}$

$A_{corr} = A_{geom} \times$ Tot. ISS/MC Corr

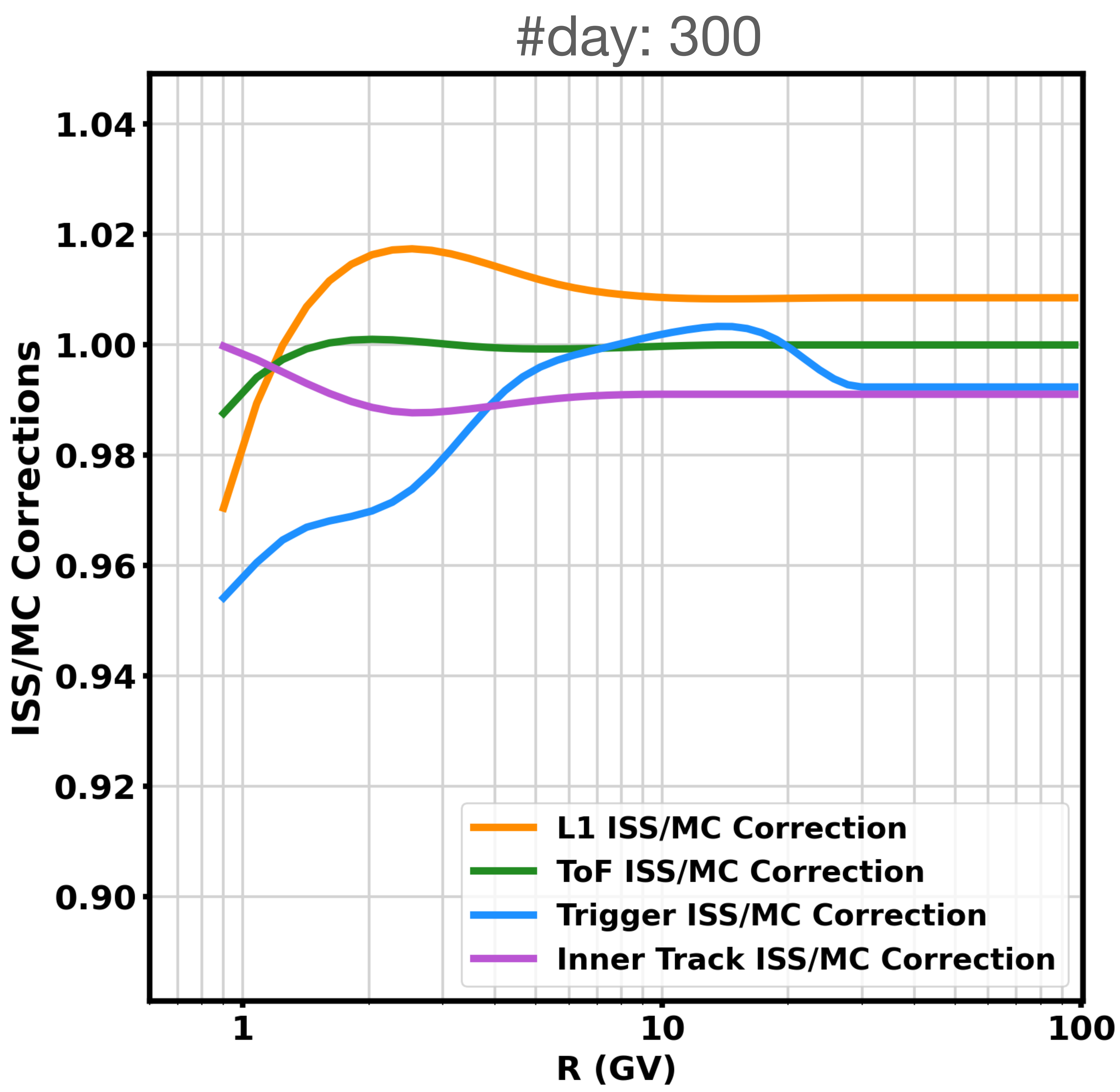
Integral Flux - Comparison with PR 2021



Daily ISS/Montecarlo Corrections



Compute Daily/Integral ratio and fit with spline (3 knots) up to 20 GV



Daily Corr = Integral Corr x Spline