What do we learn by Ground Level Enhancements ?

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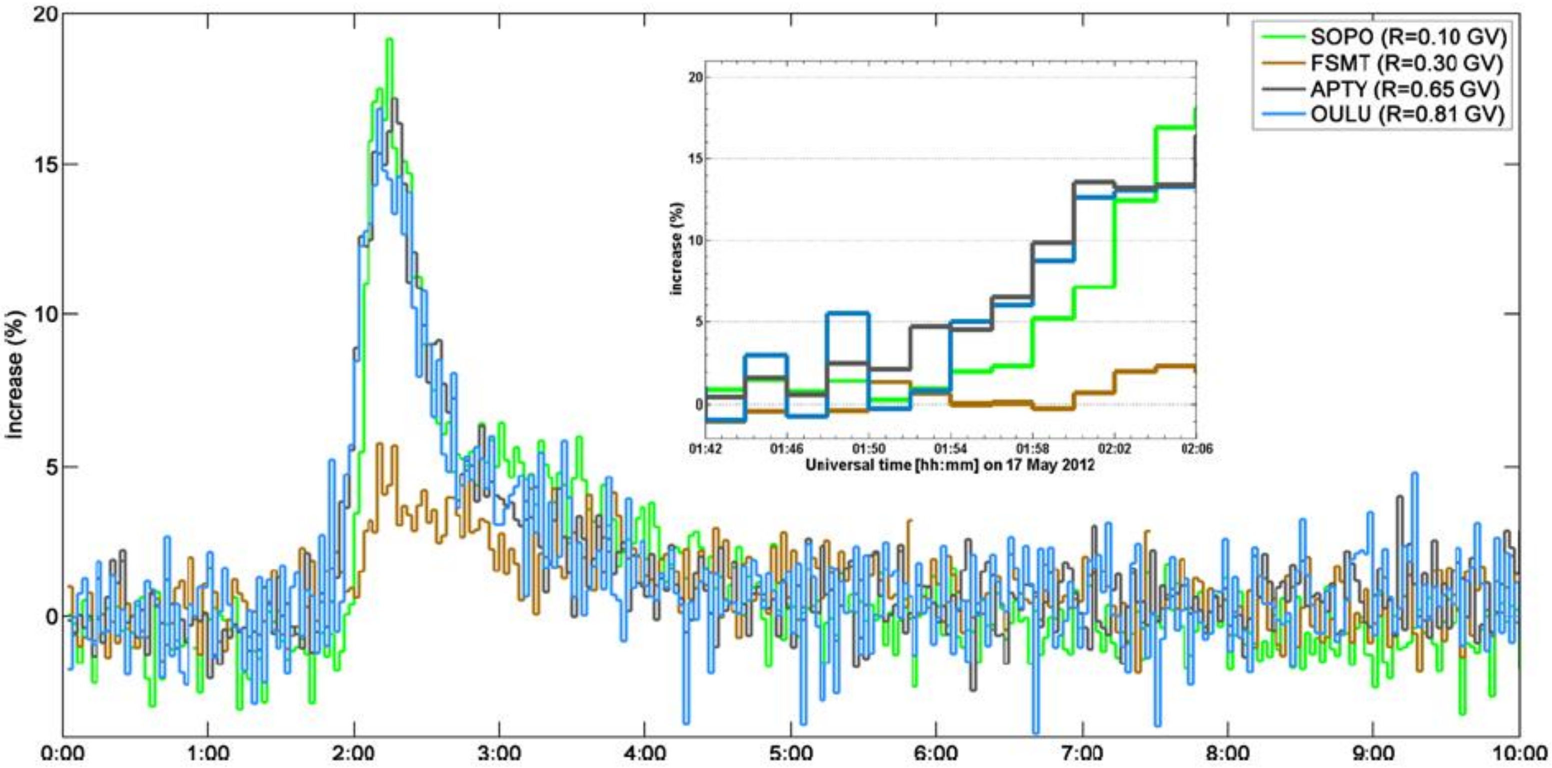
29.09.2022
Athens2World

What is a Ground Level Enhancement ?

Definition



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

> **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** (*<u>high energy</u>*).

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

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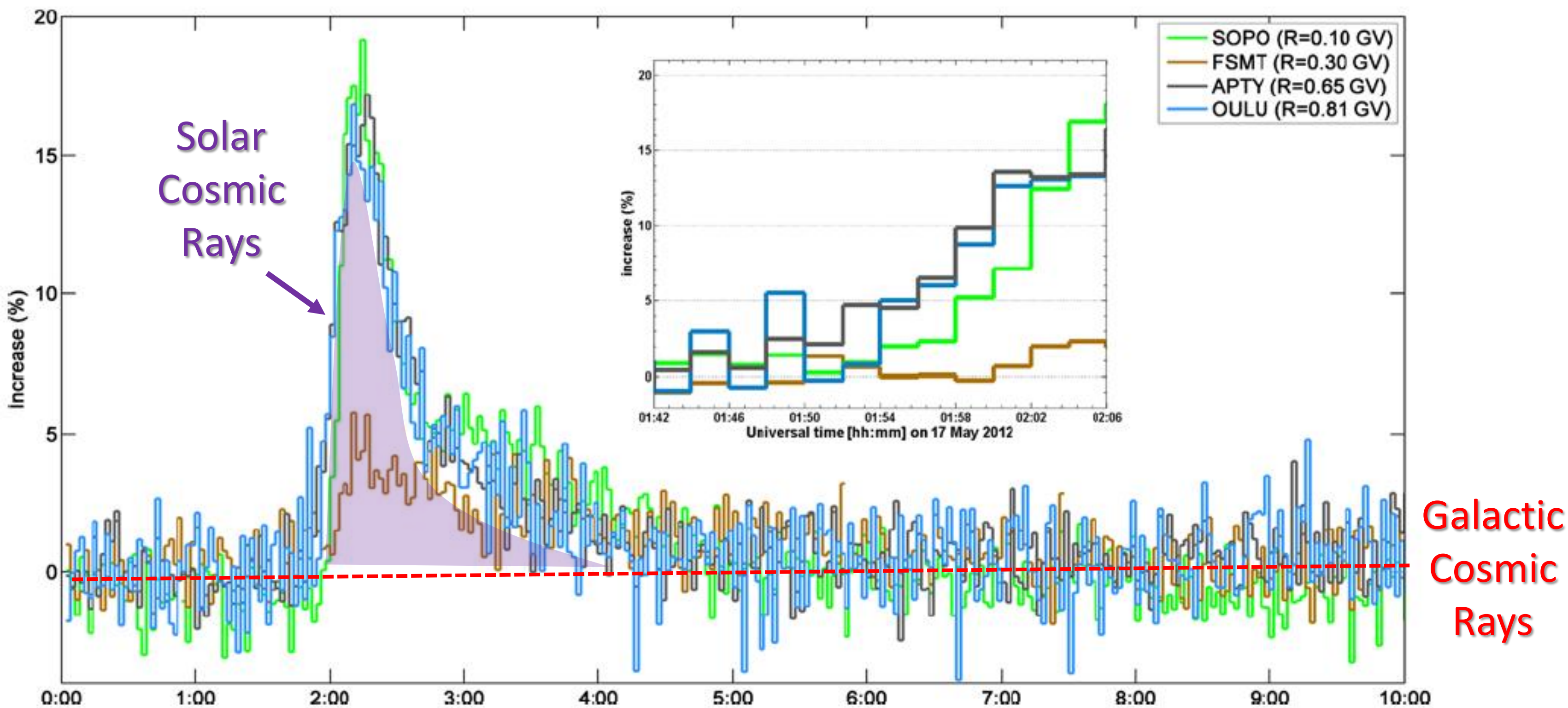

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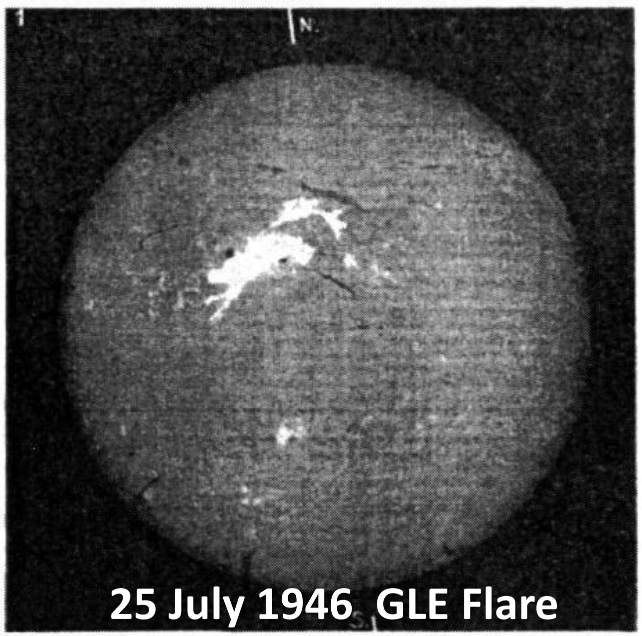
Poluianov et al., *Sol. Phys.*, (**2018**)

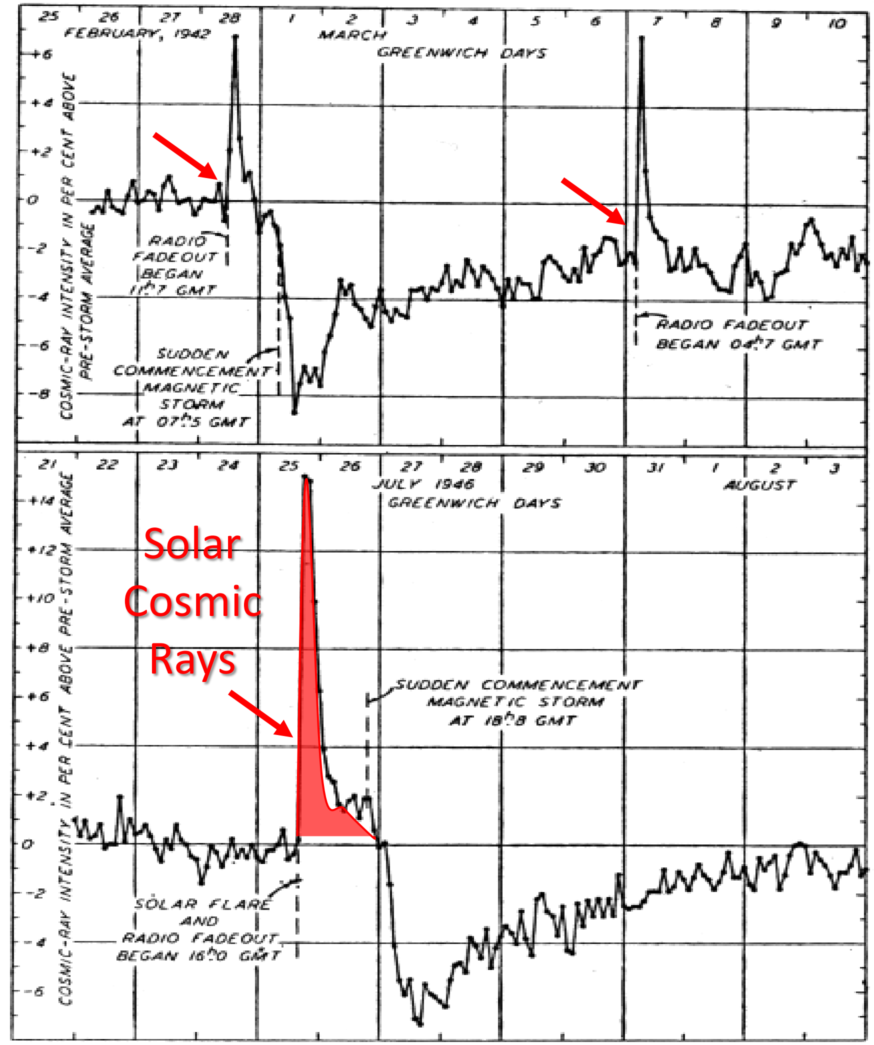
Observations

First ever reported GLEs

Three Unusual Cosmic-Ray Increases Possibly Due to Charged Particles from the Sun

SCOTT E. FORBUSH
*Department of Terrestrial Magnetism,
Carnegie Institution of Washington, Washington, D. C.*
October 10, 1946





Forbush., *Phys. Rev.*, (**1946**)

Observations

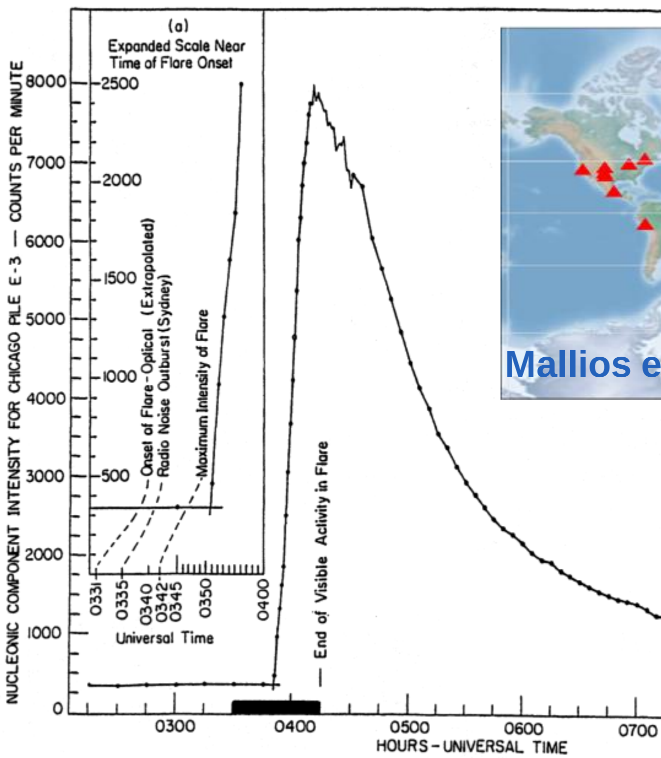
First ever reported GLEs

PHYSICAL REVIEW VOLUME 104, NUMBER 3 NOVEMBER 1, 1956

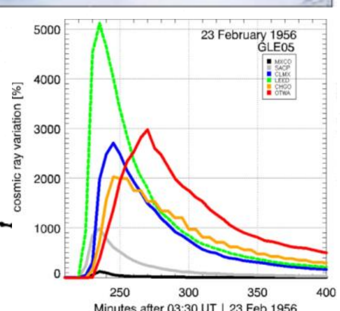
Solar Cosmic Rays of February, 1956 and Their Propagation through Interplanetary Space*

P. MEYER, E. N. PARKER, AND J. A. SIMPSON
Enrico Fermi Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois

(Received July 2, 1956)

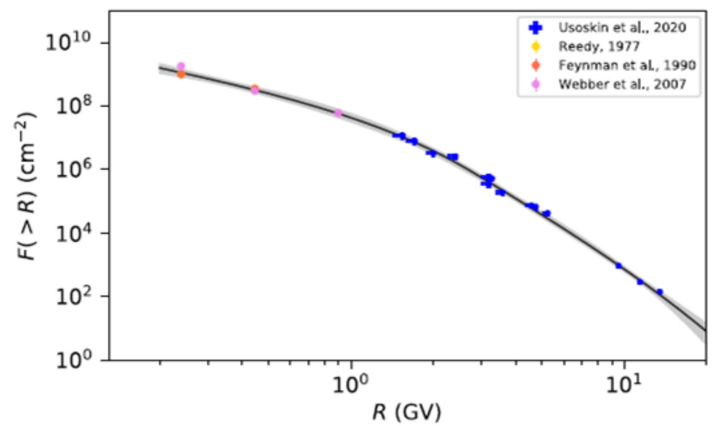


Mallios et al., *JASTP*, (2022)



Meyer, Parker & Simpson., *Phys. Rev.*, (1956)

GLE #05 23-Feb-1956



Usoskin et al., *Astron. Astrophys.*, (2020)

> *First study with NM data* indicating **solar flares** as the **driver of GLEs**

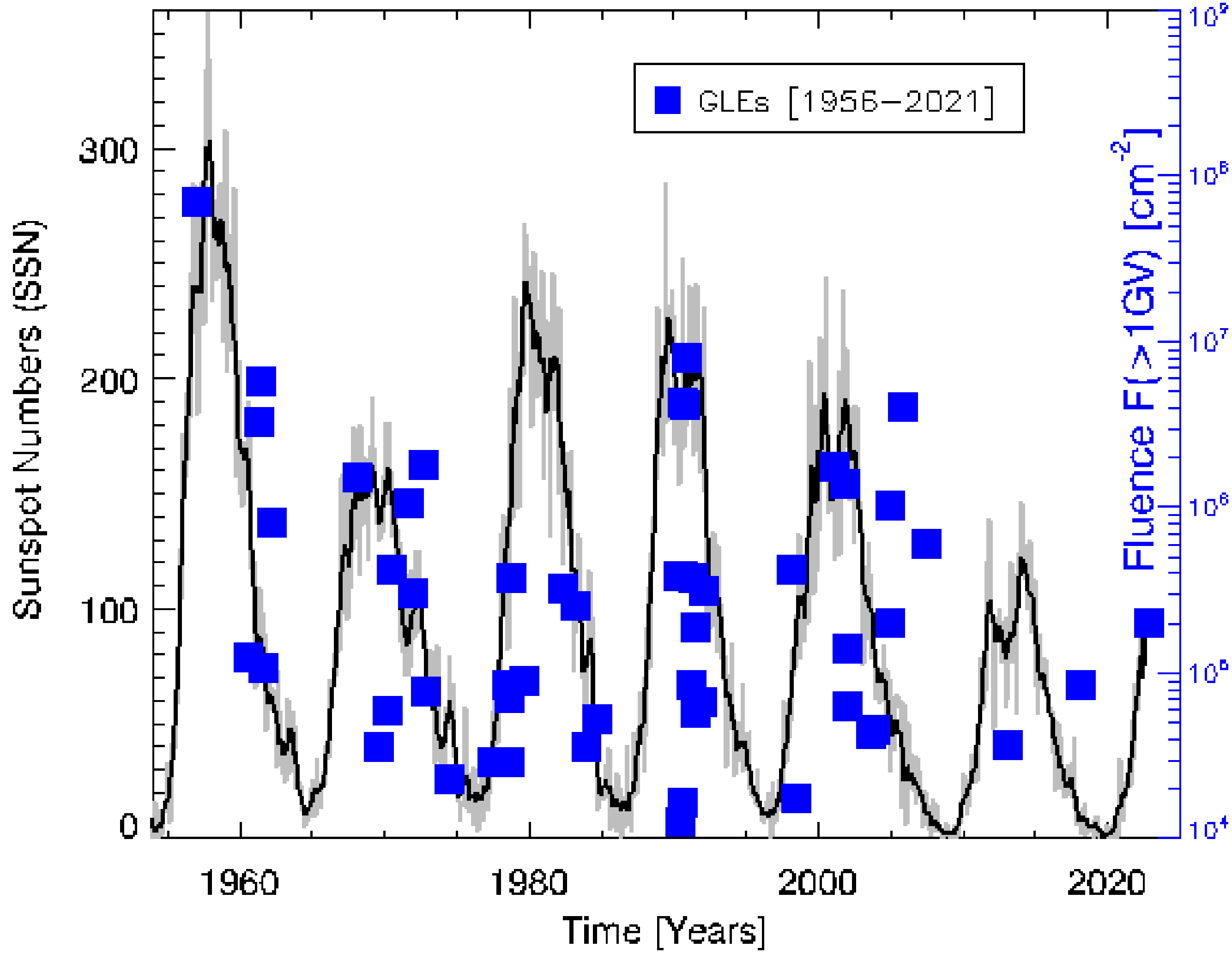
> ***Largest GLE to date***

https://gle.oulu.fi

Observations

When do GLEs take place ? | time distribution

Usoskin et al., *Astron. Astrophys.*, (2020)
Mishev et al., *Sol. Phys.*, (2022)

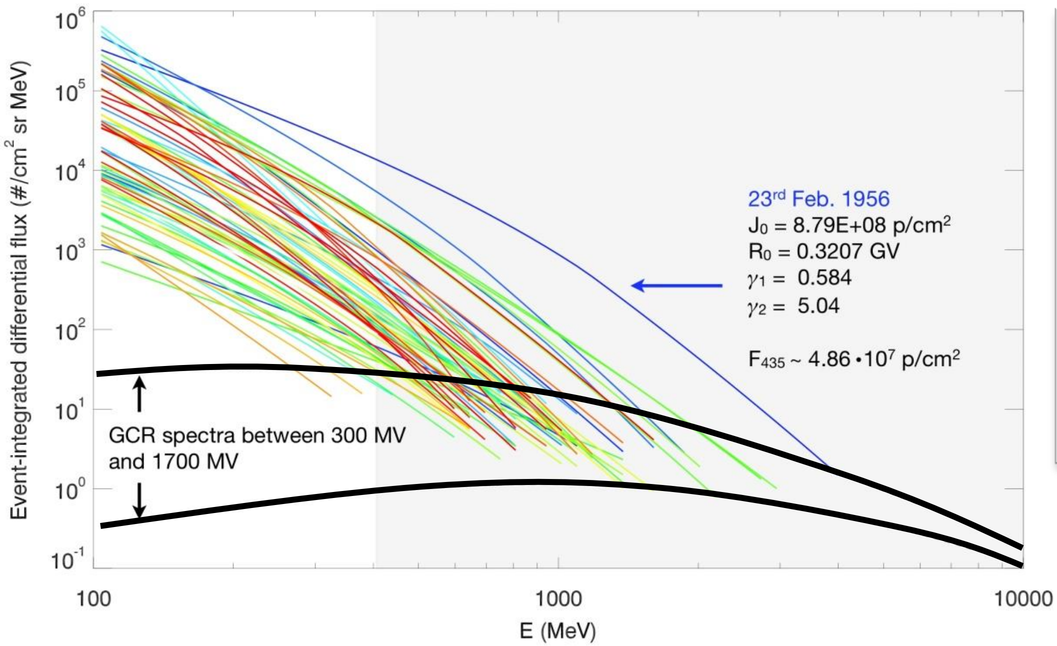


Owens et al., *Sol. Phys.*, (2022)

> Since 1956 there have been only 68 GLEs → ~ 1.04 GLEs/ yr

Observations

Energy | Rigidity

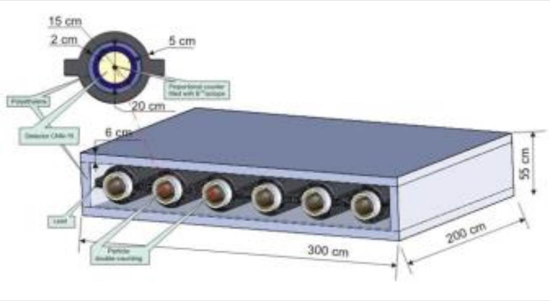


GLEs are *Rare* and *Extreme* SEPs

- ***Rare*** because **since 1956** there have been only ***~1 events per year***
- ***Extreme*** because they need to reach an energy of **E≥433 MeV** in order to be registered on the ground.

Gopalswamy et al., *SSRv*, (**2012**)

> Detecting fast particle is challenging — One needs large instruments to register these rare events => Neutron Monitors

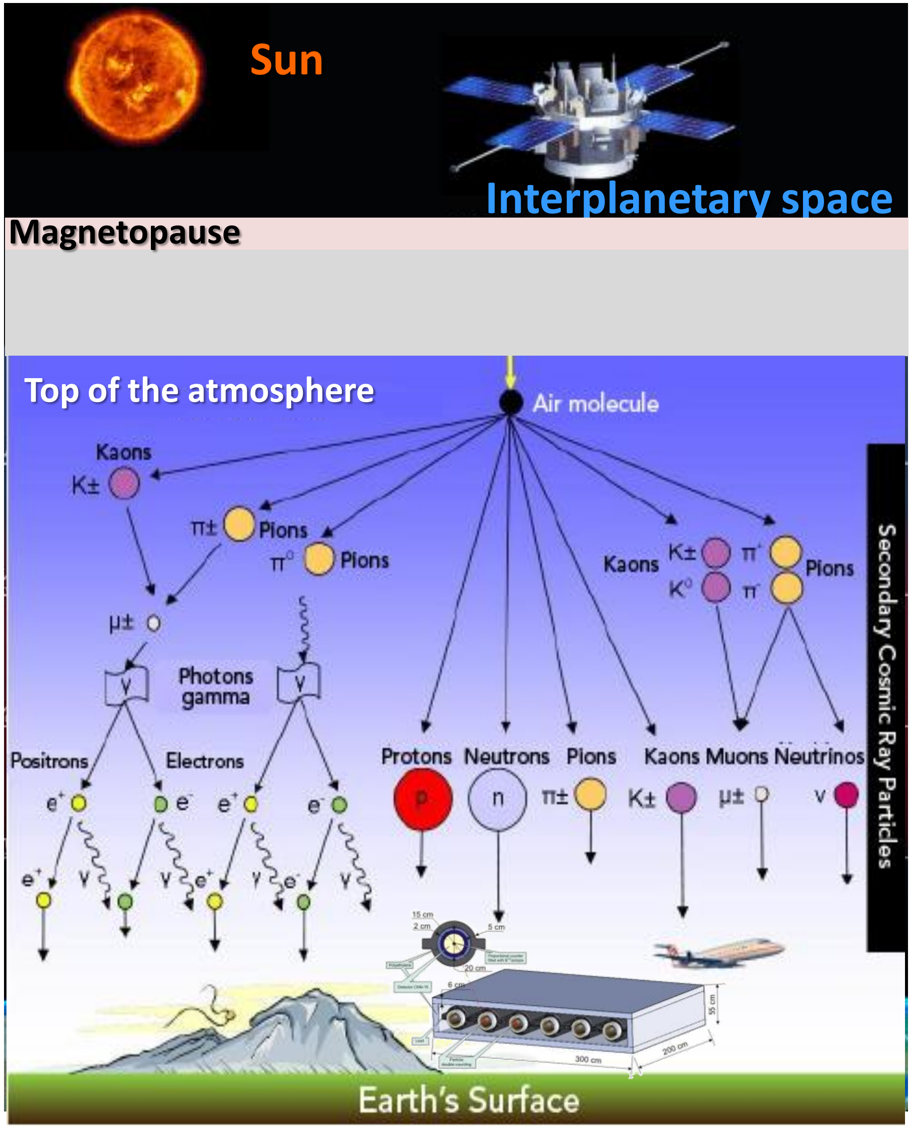


Herbst, *Habilitation Thesis*, (**2021**)

Raukunen et al., *JSWSC*, (**2018**)

Building blocks

From the Sun to the *ground*



> Relativistic particles **accelerated at the Sun**

> Propagation in **interplanetary space**

> Enter the **magnetosphere**

- ***Particle Trajectories bend***

> Enter the atmosphere

- ***Cascade of Secondary Cosmic Rays in the atmosphere***

> Recorded by a **neutron monitor**

Why GLEs ?

Motivation

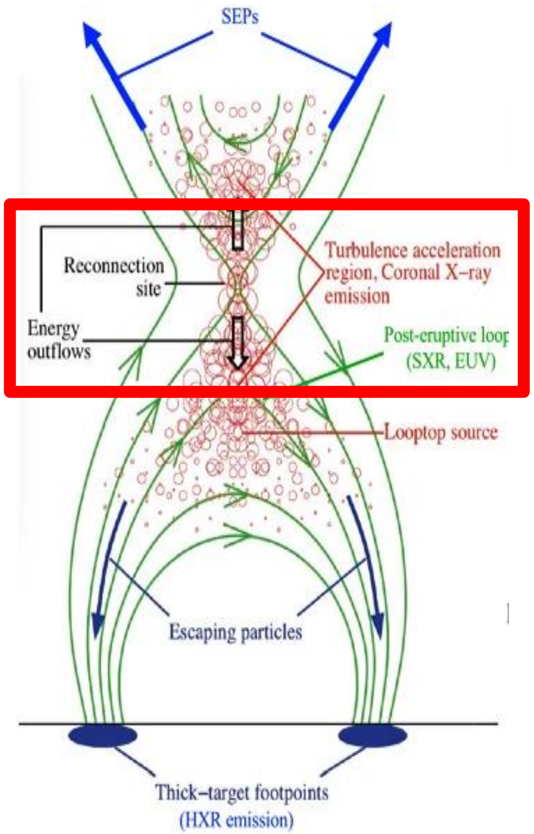
> **Where** do ***relativistic solar energetic particles*** **occur** and under **which mechanism** ?

> The ***early phase*** of the SEP events **close to the time of acceleration**, and the **role of interplanetary transport** is ***minimal*** for the ***first arriving relativistic particles***.

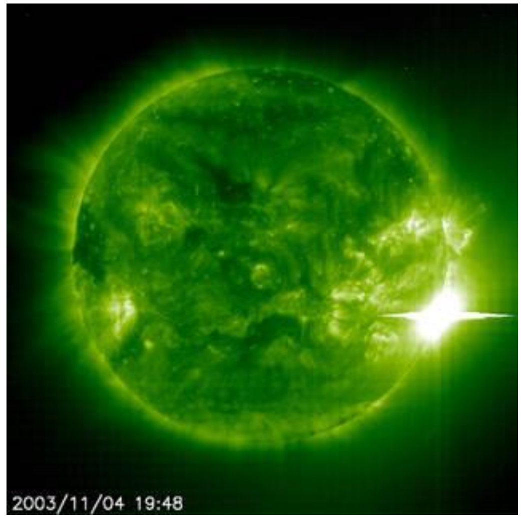
> **GLE events** are most appropriate to shed light into the problem of **particle acceleration**

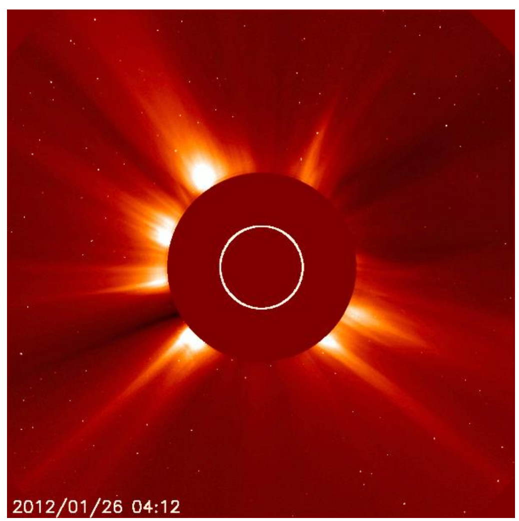
The Sun

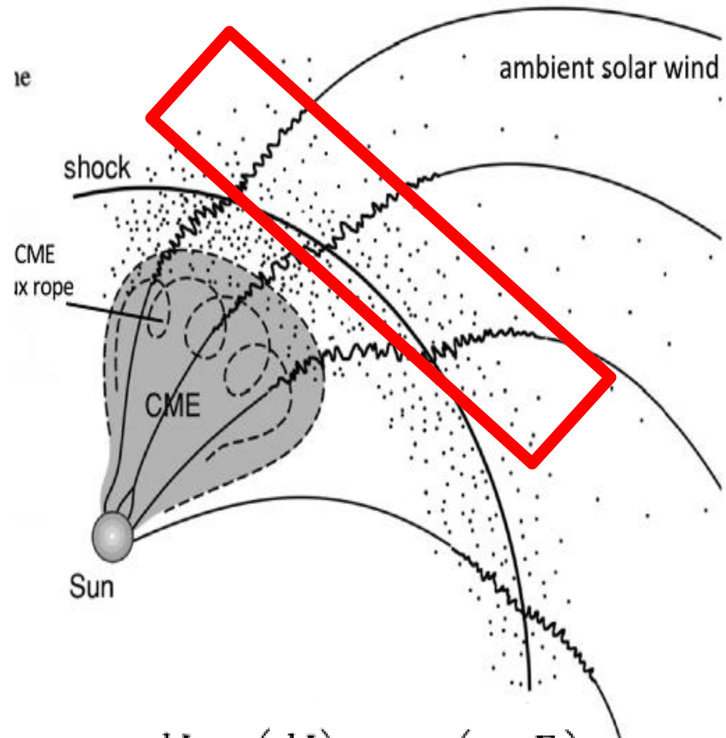
The Sun is the giver of (life) particles



Vlahos et al., *RSTA.*, (**2019**)







$$\frac{dJ}{dE} \propto \left(\frac{dJ}{dE}\right)_0 \exp\left(-\frac{E}{E_0}\right)$$

Ellison & Ramaty, *ApJ.*, (**1985**)

Mikić and Lee, *SSRv.*, (**2006**)

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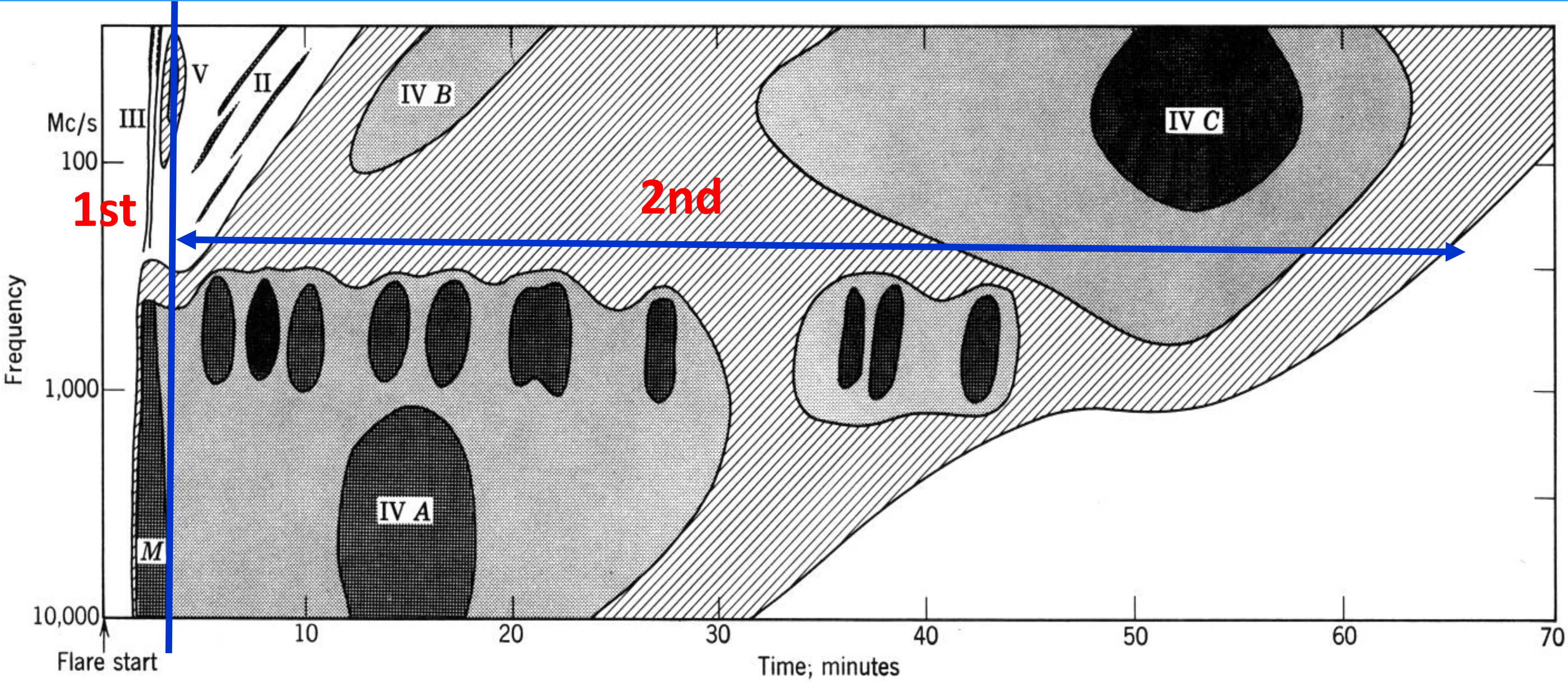


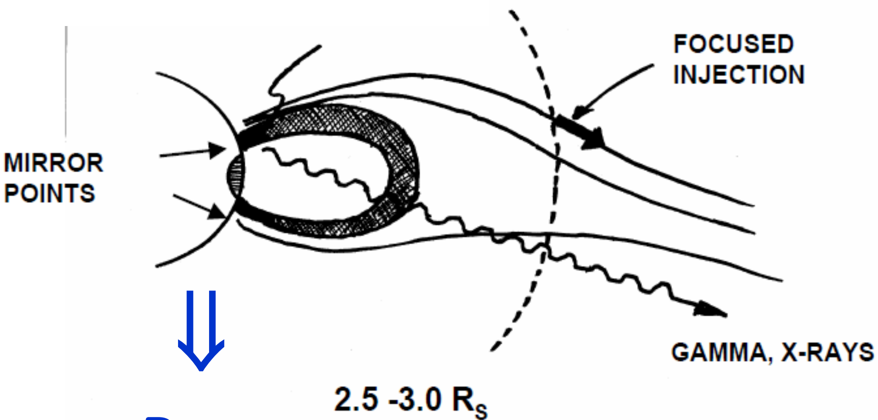
1st ⇒ **Impulsive** ⇓ **Prompt**

2nd ⇒ **Gradual** ⇓ **Delayed**

Wild, Smerd & Weiss, *San. Rev. Astrom Astrophys.*, (**1963**)

Klein, *Frontiers*, (**2021a,b**)

Flare vs CME-shock



⇓

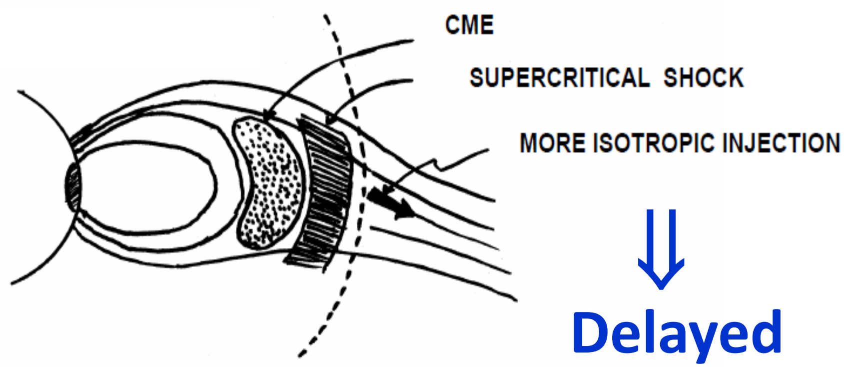
Prompt

in favor of Flare

- > **Powerful flares** are always present
- > Fast **GLE timing** with no (significant) correlation with CME speed or radial distance
- > Presence of **prompt component**
- > **Longitudinal distribution** of the parent flares

in favor of CME

- > **Delay** between the **flare and the particle escape** into interplanetary space
- > **Close connection** with **type II** radio emission
- > **Long injection** comparatively to the impulsive phase of a flash
- > Association with most **powerful CME**
- > Modeling of particle injection and transport: good fitting of intensity time profile and form of energy spectrum



⇓

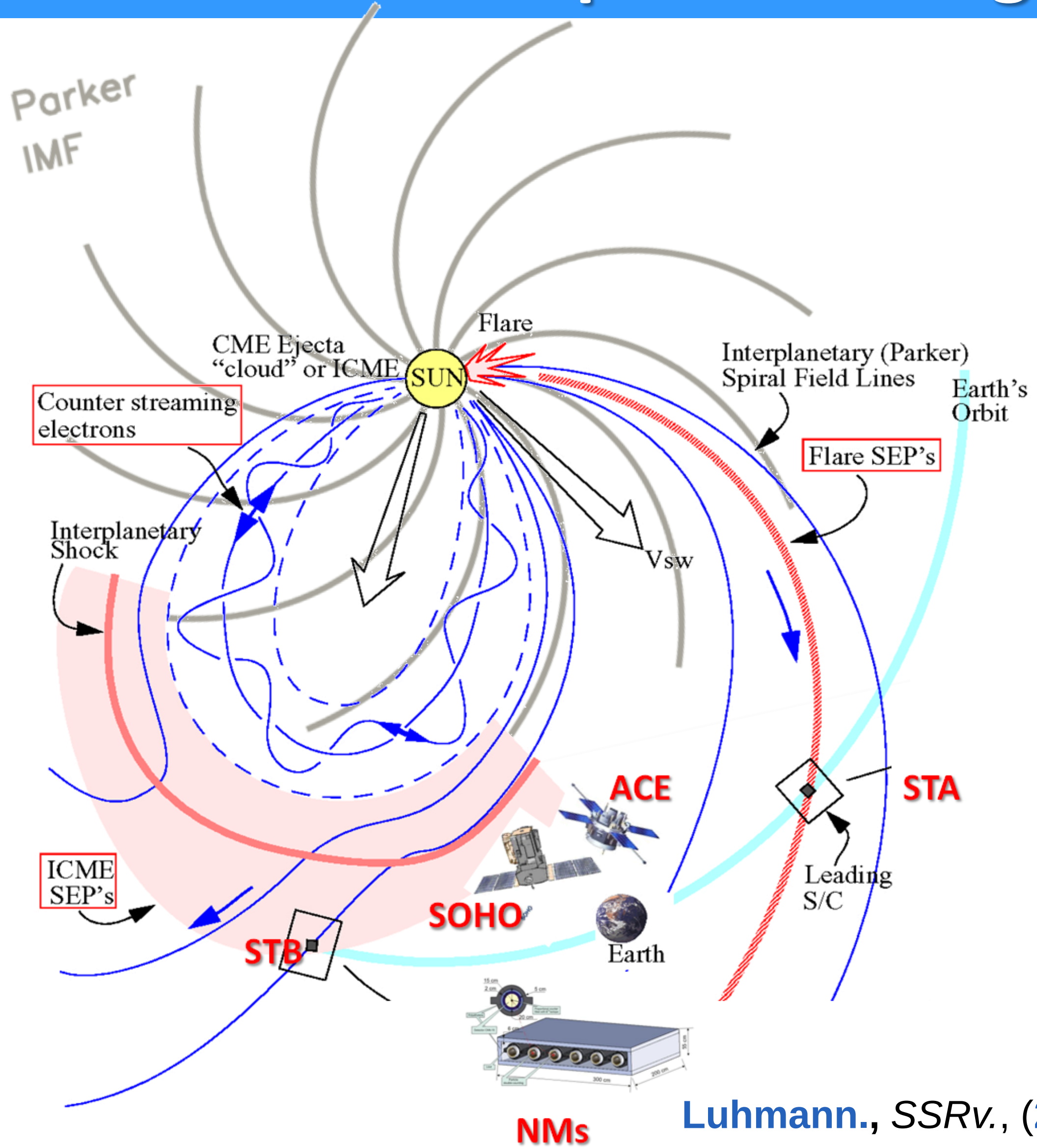
Delayed

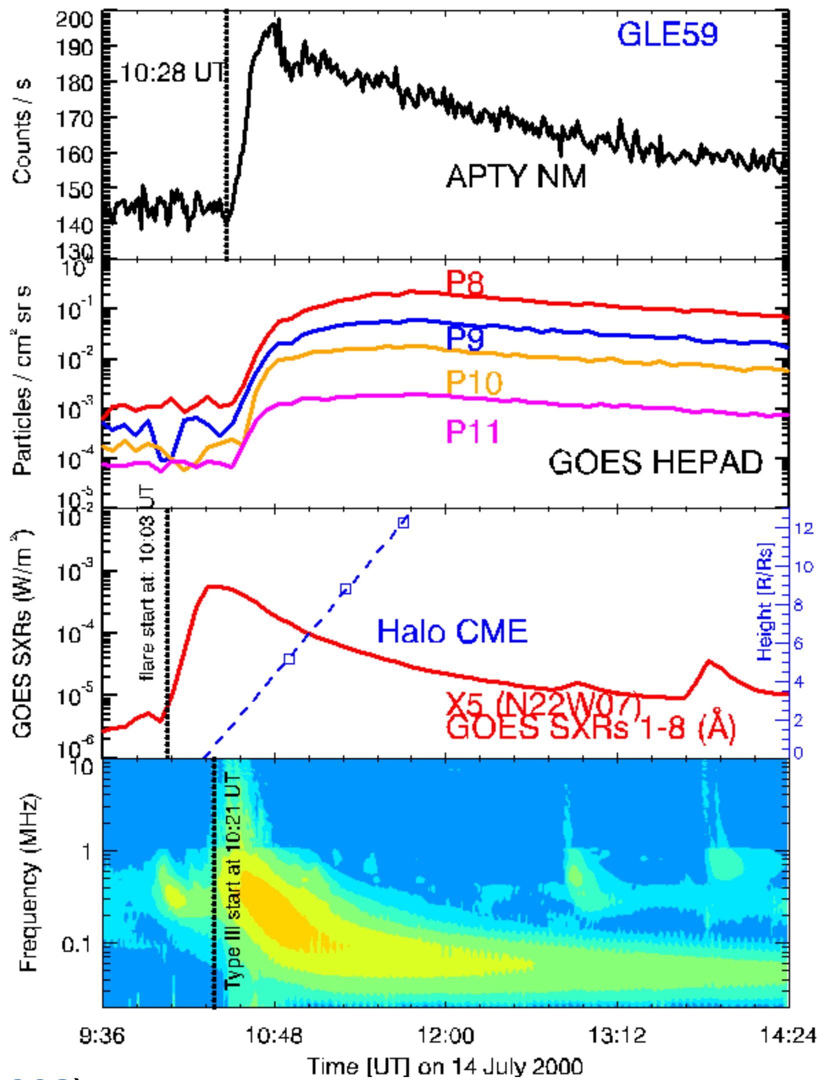
McCracken et al, *SSRv*, (2012)

Vashenyuk et al, *Adv. Space Res*, (2011)

Sun-Earth connection

Transport of Energetic Particles





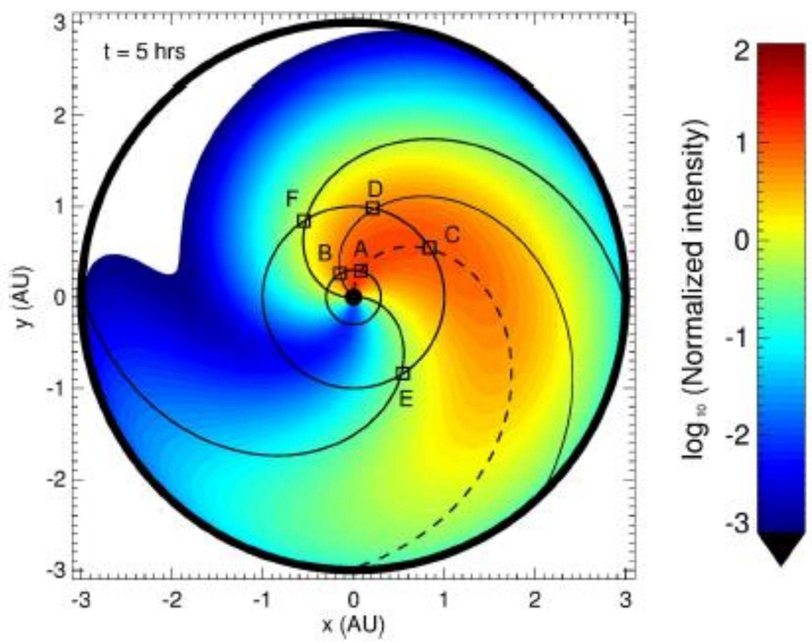
Luhmann., *SSRv.*, (**2008**)

Sun-Earth connection

Transport of Energetic Particles

Roelof, (**1969**);

$$\frac{\partial f}{\partial t} + \nu\mu\frac{\partial f}{\partial z} + \frac{1-\mu^2}{2L}\nu\frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) = q(z,\mu,t)$$



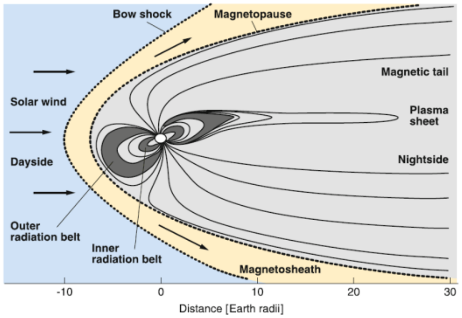
> Representation of the expected **intensity** of the transported **solar particles** at ***different observes*** in the heliosphere.

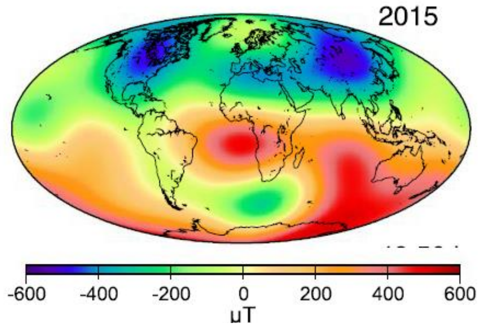
Strauss et al, *ApJ*, (**2017**)

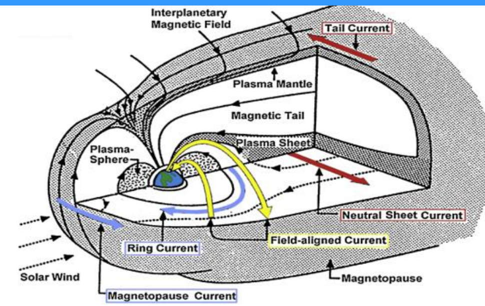
Ruffolo, *ApJ* (**1995**); **Agueda et al**, *Astron. Astrophys.*, (**2014**); **Buetikofer et al**, *ASSL.*, (**2018**),

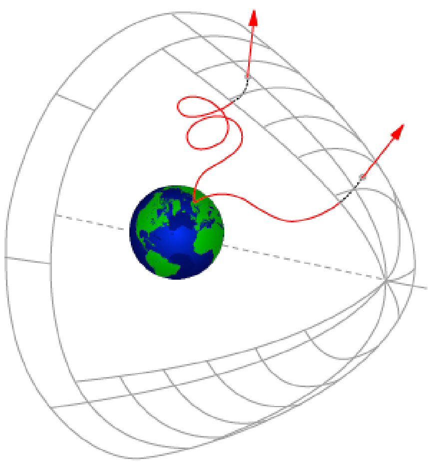
Sun-Earth connection

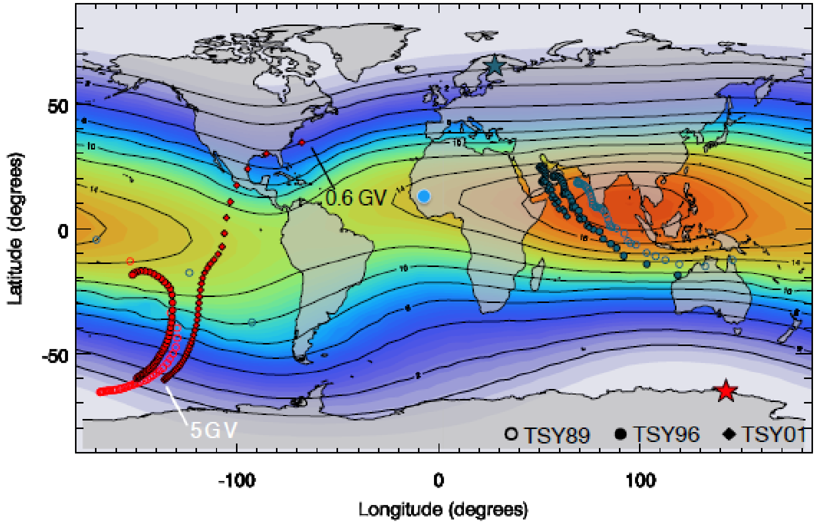
Energetic particles in the geomagnetic field











Smart et al, *SSRv*, **(2006)**

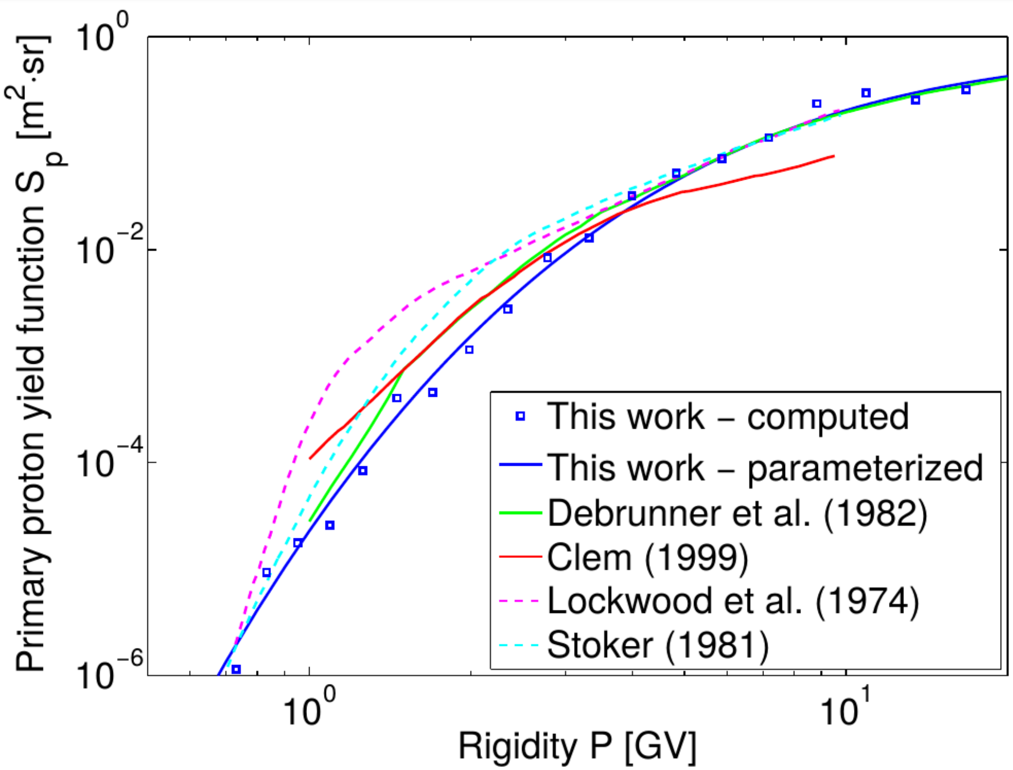
Herbst, *Habil. Thesis*, **(2021)**

> Asymptotic direction: Direction of particle incidence prior to its entry in the geomagnetosphere. It depends on NM location, particle *R* and conditions of magnetosphere.

Sun-Earth connection

Cosmic rays in the atmosphere

> The *transport* of cosmic ray particles in the **Earth's atmosphere** and the **NM detection efficiency for secondary cosmic ray particles** are combined in the neutron monitor ***yield function***.



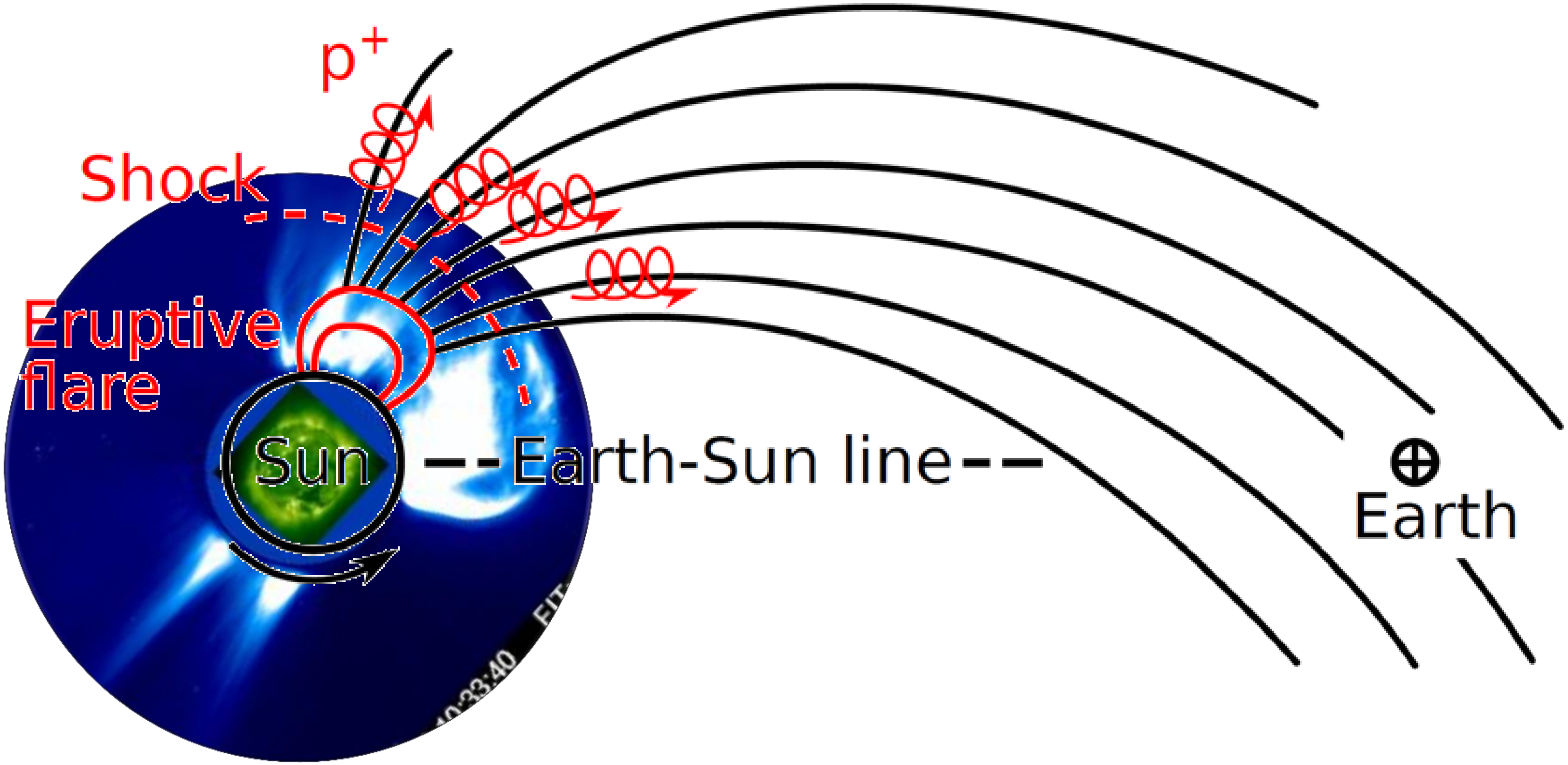
Flückiger et al, *30th ICRC*, (**2008**)

Sun-Earth connection

GLE | Solar storm scenario I

1. Release of magnetic energy @ the Sun

An eruptive event (solar flare and/or CME) occurs



Kusano et al., *IOP*, (**2020**)

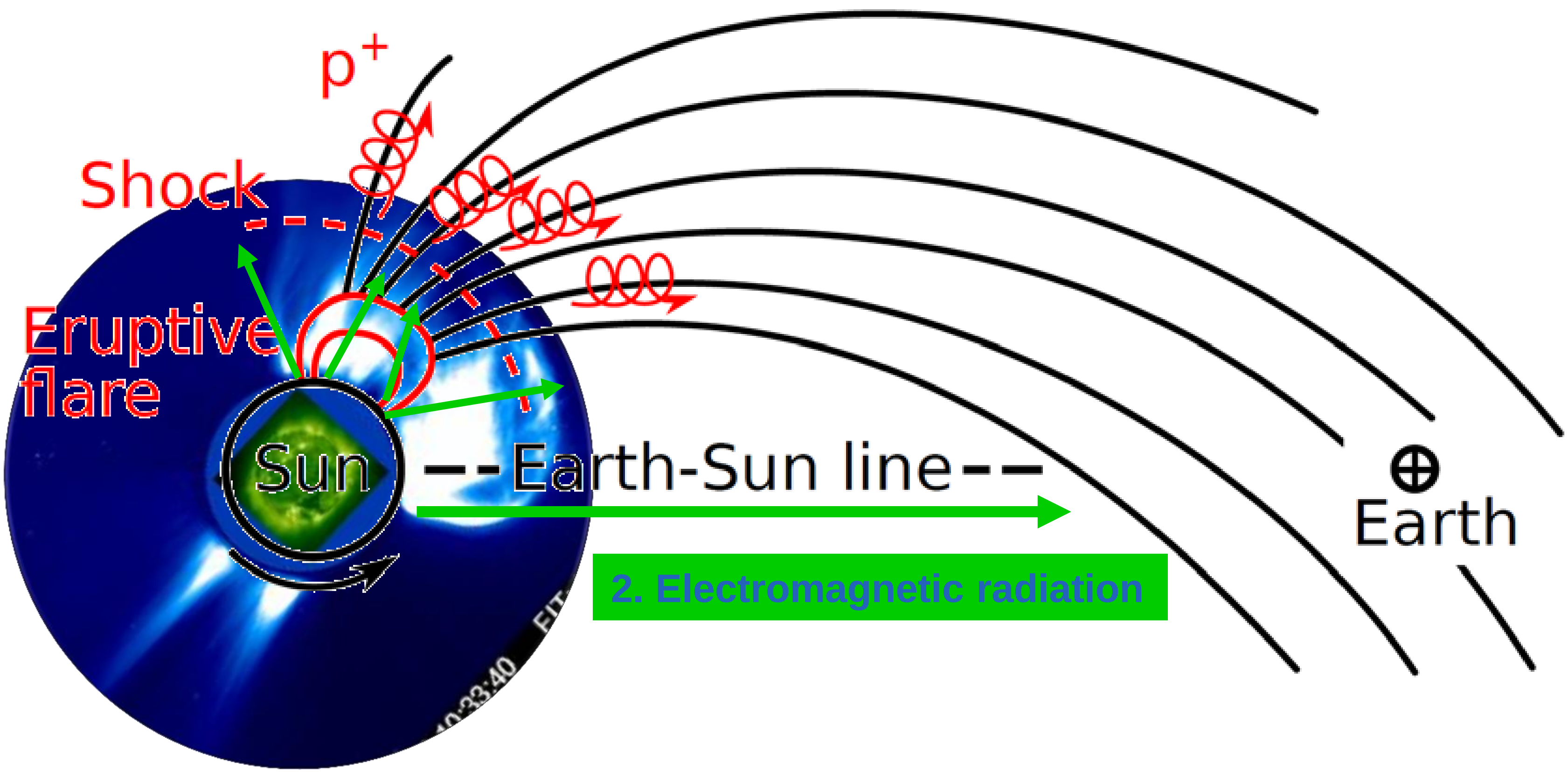
Flueckiger, *NMDB*, (**2017**)

Sun-Earth connection

GLE | Solar storm scenario II

1. Release of magnetic energy @ the Sun

An eruptive event (solar flare and/or CME) occurs



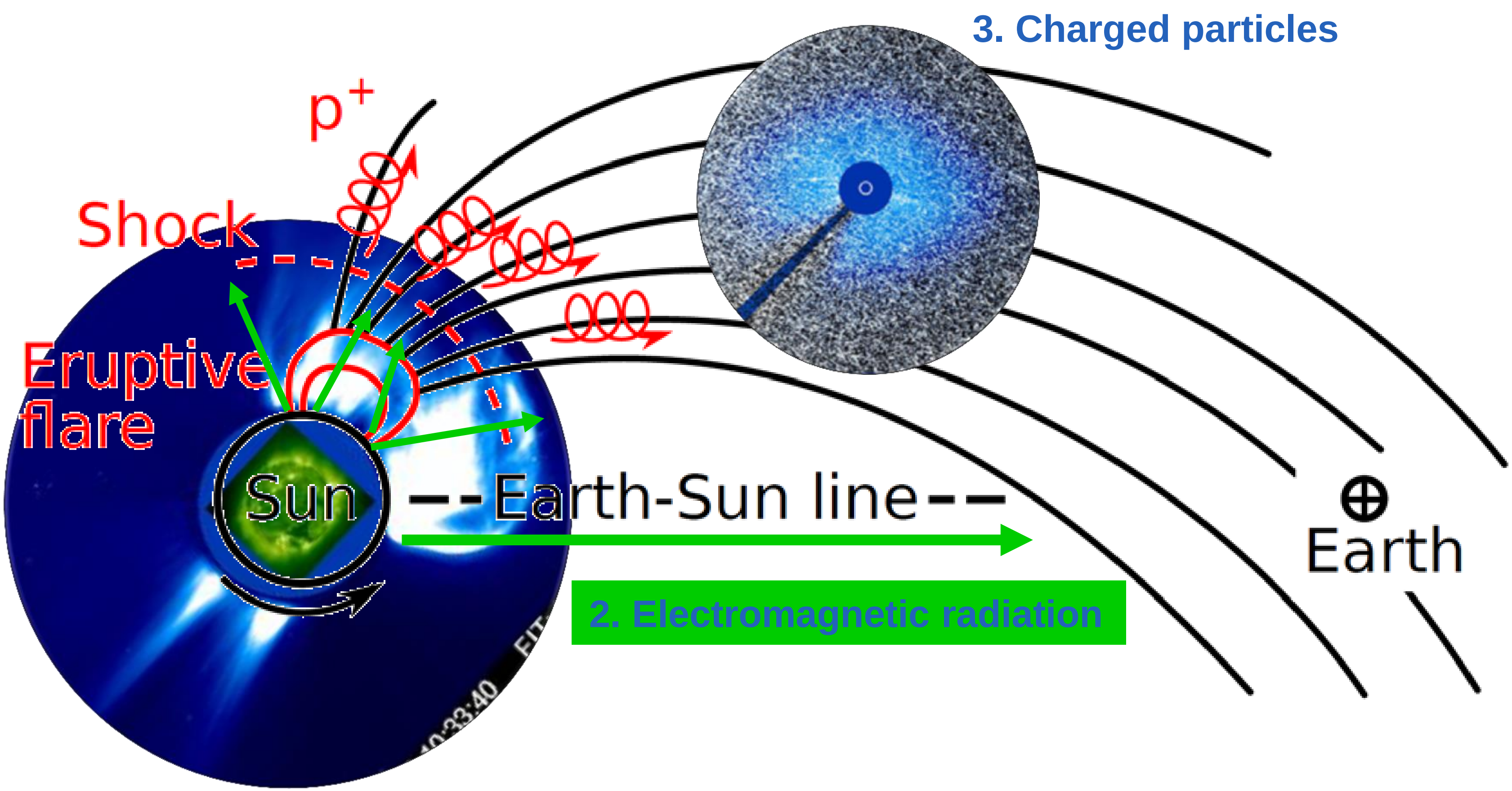
Kusano et al., *IOP*, (**2020**) **Flueckiger**, *NMDB*, (**2017**)

Sun-Earth connection

GLE | Solar storm scenario III

1. Release of magnetic energy @ the Sun

An eruptive event (solar flare and/or CME) occurs



Kusano et al., *IOP*, (**2020**)

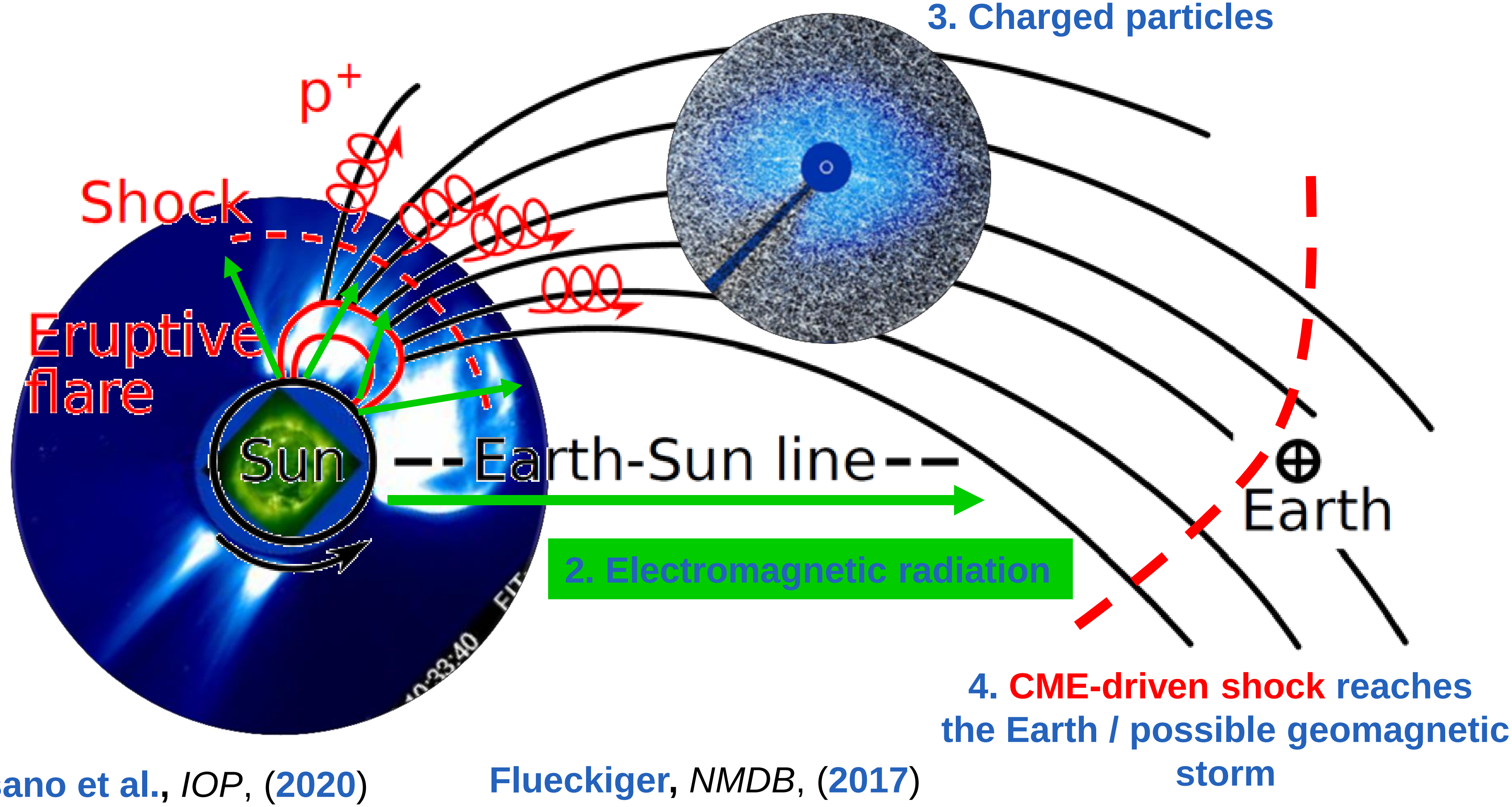
Flueckiger, *NMDB*, (**2017**)

Sun-Earth connection

GLE | Solar storm scenario *IV*

1. Release of magnetic energy @ the Sun

An eruptive event (solar flare and/or CME) occurs

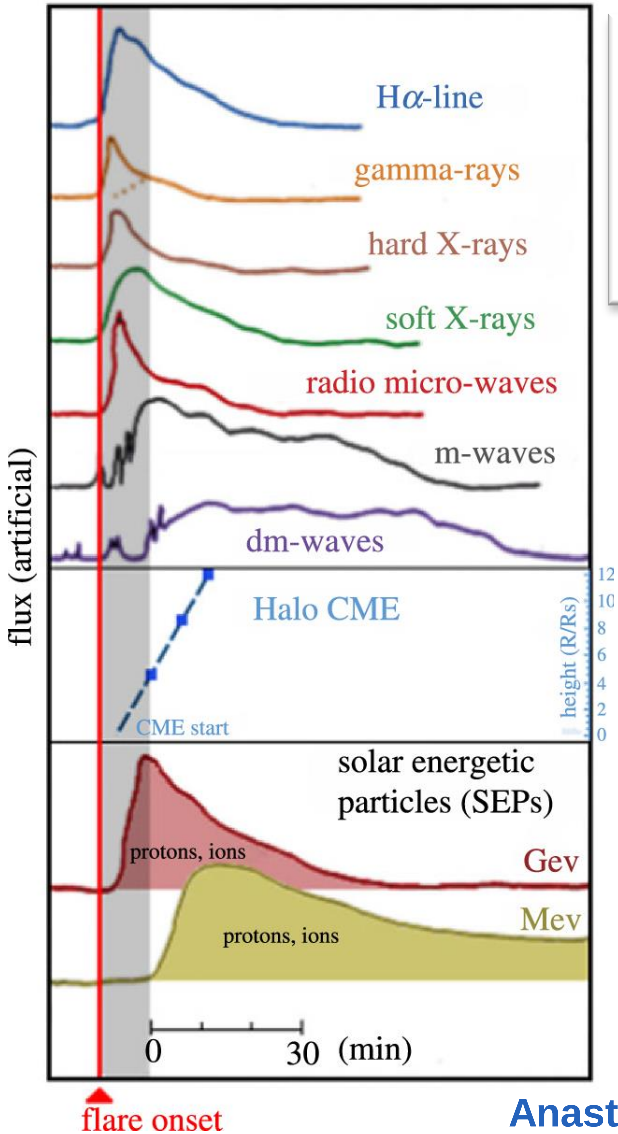


Kusano et al., *IOP*, (**2020**)

Flueckiger, *NMDB*, (**2017**)

Sun-Earth connection

GLE | Solar storm scenario *V*



> Measurements show that for **SEPs / GLEs many different proxies** can have a decisive role.

> Such proxies include, **γ-rays, HXRs, SXRs, radio waves**, **CME characteristics**.

Anastasiadis et al., *RSTA*, (**2019**); **Cliver et al**, *Liv. Rev. Solar Phys.*, (**2022**)

Sun-Earth connection

GLE | Solar storm scenario *V*

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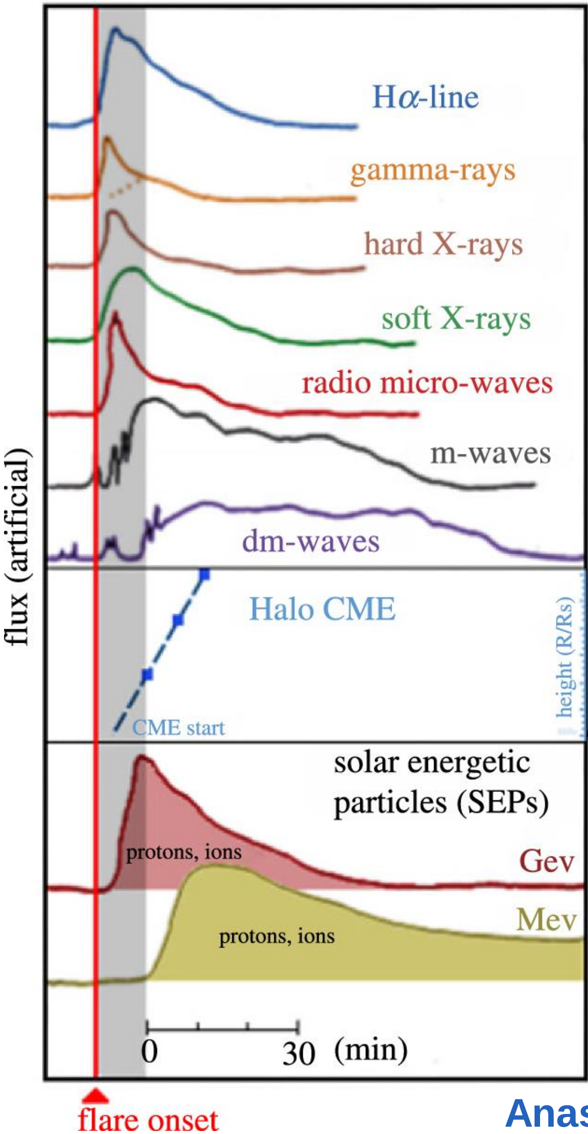
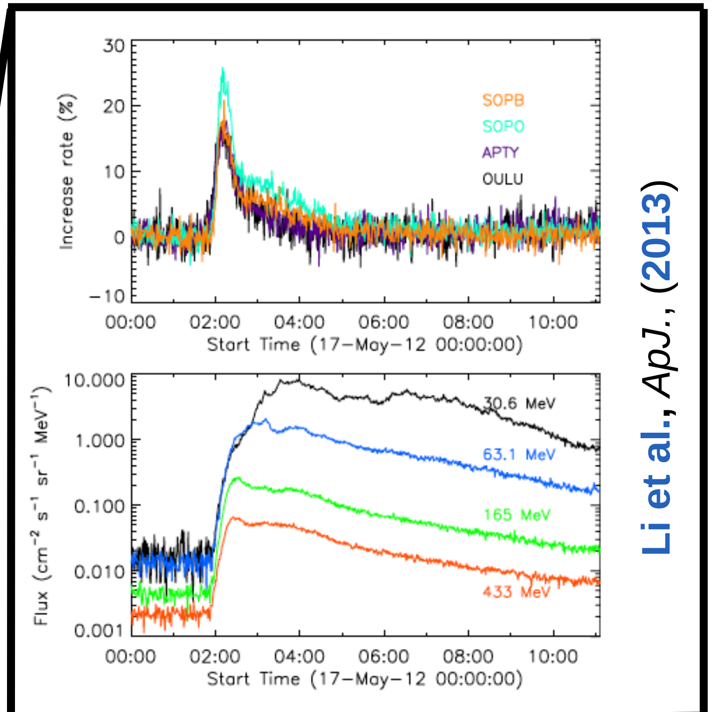




Li et al., *ApJ.*, (**2013**)

> **Particles** of *different energy* arrive at the observer at *different times*.

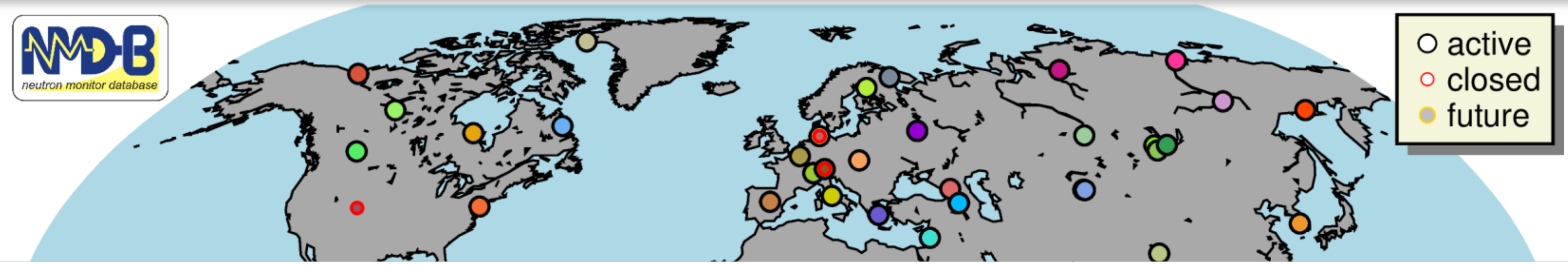
> **Relativistic GLE particles arrive in a few minutes**.

Anastasiadis et al., *RSTA*, (**2019**); **Cliver et al**, *Liv. Rev. Solar Phys.*, (**2022**)

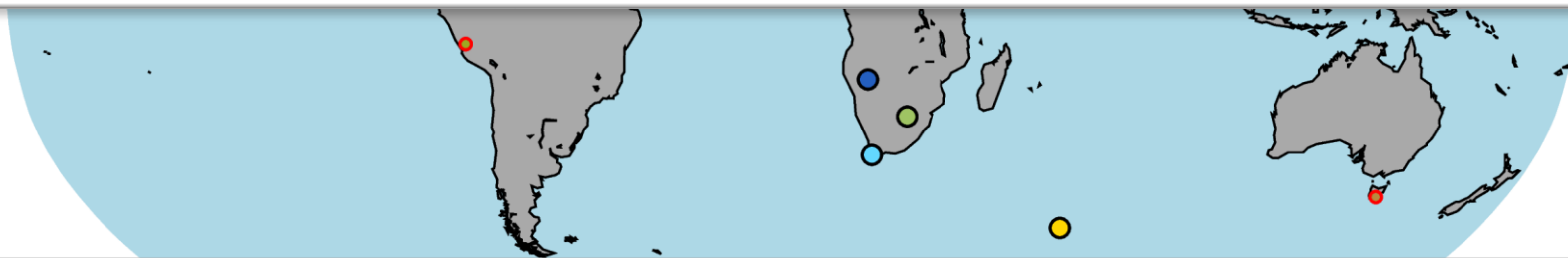
Observations

A Network of Neutron Monitors

> **Neutron monitors** at <u>*different locations*</u> offer a more *complete picture* of the **spatial and energy distribution of the primary particles**.



> The **Network** serves as **a Multi-directional tool**, *revealing the properties of* **primary particles** reaching the Earth's atmosphere.



> The **secondary particles** recorded **at each NM location** *corresponds* **to primaries**:

- with energies covering **a specific part of the primary spectrum** *depending on the cut-off rigidity of the location*
- coming from **a specific set of directions**

Mavromichalaki et al., *Adv. Space Res.*, (2011)

http://www.nmdb.eu

GLE analysis

Modeling | Neutron Monitors

> **Model the response** of an (adequate*) number **of NMs** to *determine* an **optimal fit** for the **SEP spectrum** and the **spatial distribution** at 1 AU.

> ***First step:*** Computation of the **asymptotic directions** and **cut-off rigidity** of NM stations – *simulation of particle propagation in a modeled magnetosphere*

> ***Second step:*** **Initial guess** of the inverse problem (functions need to represent the physical processes involved)

> ***Third step:*** Application of **optimization method** (*energy spectrum, anisotropy axis direction, pitch-angle distribution*)

Many different groups/researchers have **made such enormous efforts** (*not an exhaustive list*: Shea and Smart; Humble et al.; Belov et al.,; Bieber et al., Bombardieri et al.,; Buetikofer et al., Plainaki et al.,; Vashenyuk et al.,; Mishev et al.,Cramp et al., ...).

* *a significant number of NMs with good spatial coverage (distribution) around the world and with high quality data are needed*

GLE analysis

Modeling | Neutron Monitors

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

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

> **PAD**: simple Gaussian

$$G(\alpha(P)) \sim \exp(-\alpha^2/\sigma^2)$$

$$\frac{\Delta N(P_{cut},t)}{N(t)} = \frac{\int_{P_{cut}}^{P_{max}} J_{||sep}(P,t)Y(P)G(\alpha(P),t)dP}{\int_{P_{cut}}^{\infty} J_{GCR}(P,t)Y(P)dP}$$

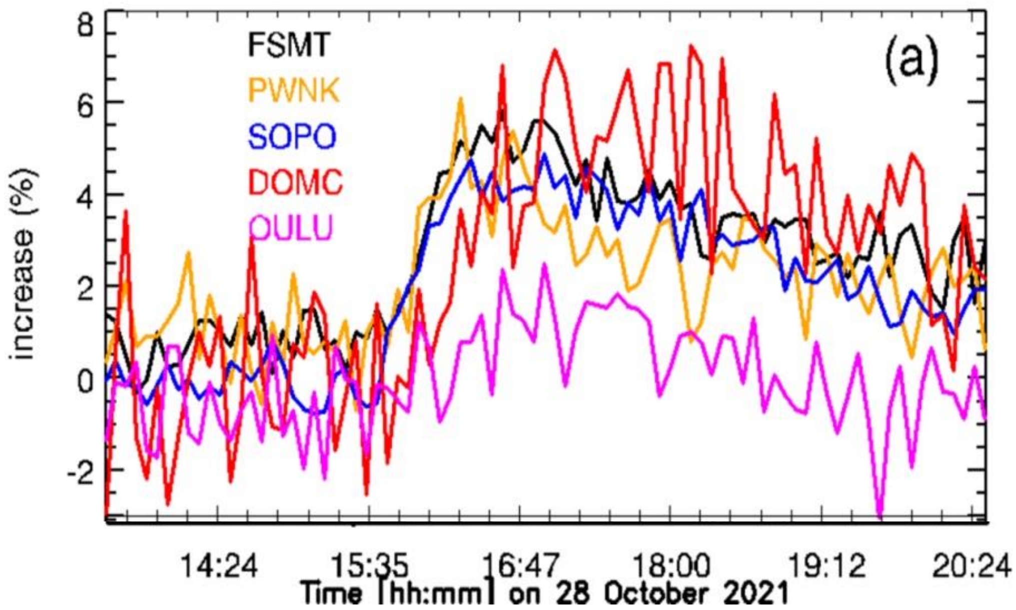
> **NM count-rate:** Inverse, constrained *nonlinear problem*
> Levenberg Marquardt with variable regularization

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

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

Example

GLE73 | 28.10.2021



> **GLE73** revealed a typical **gradual increase**, and **slight anisotropy** during the onset

> The flux remained above the background level for **~ 4.5 hour**

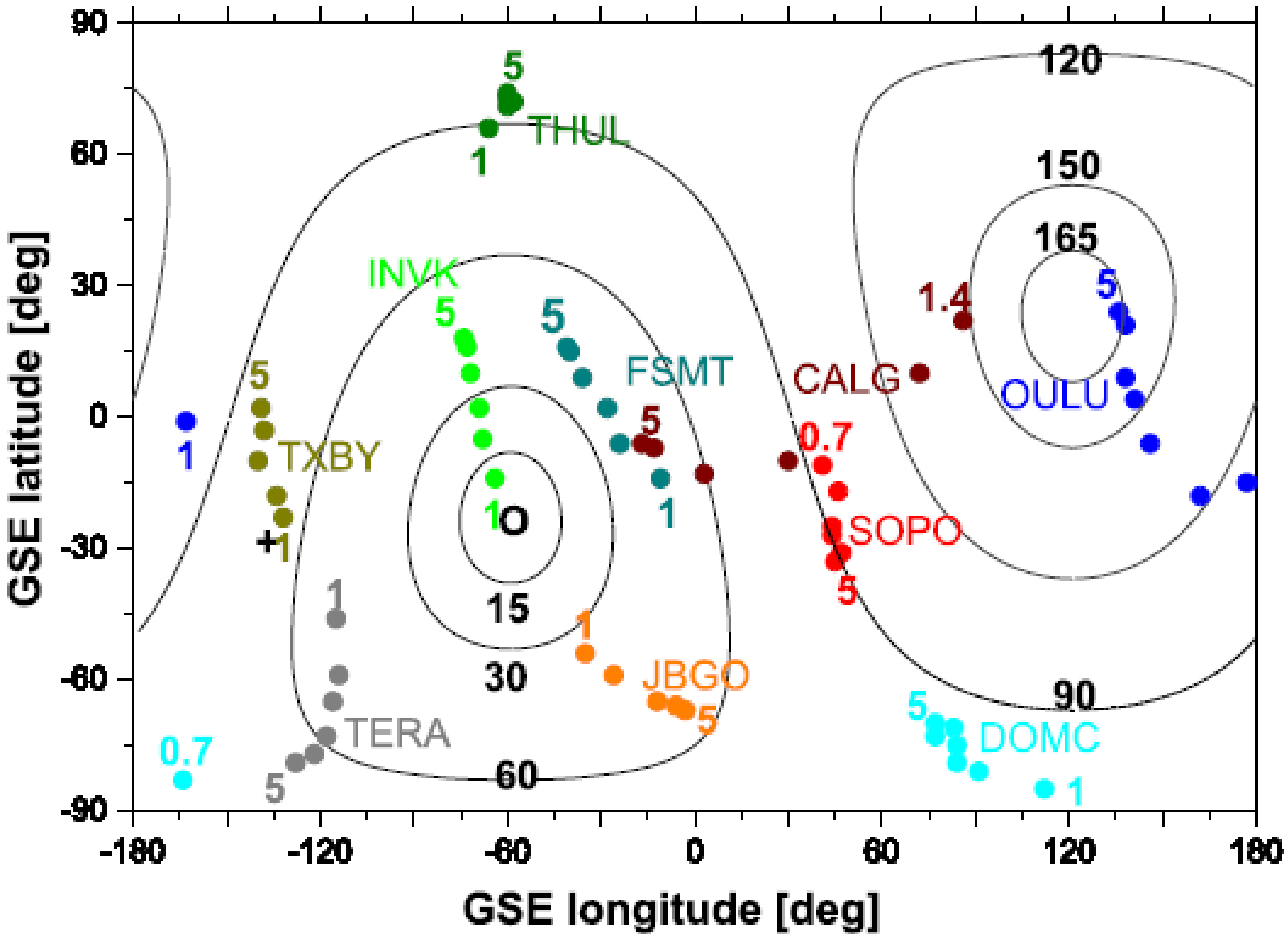
> The NMs situated at polar stations, i.e. **DOMC recorded the greatest count rate**

> The **rise** as shown by the **FSMT**, **SOPO** and **PWNK** NMs intensity time-profile *indicates that energetic protons had reasonable access to the Sun Earth connecting field lines*.

Papaioannou et al., *Astron. Astrophys,*, (**2022**)

Example

GLE73 | 28.10.2021



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

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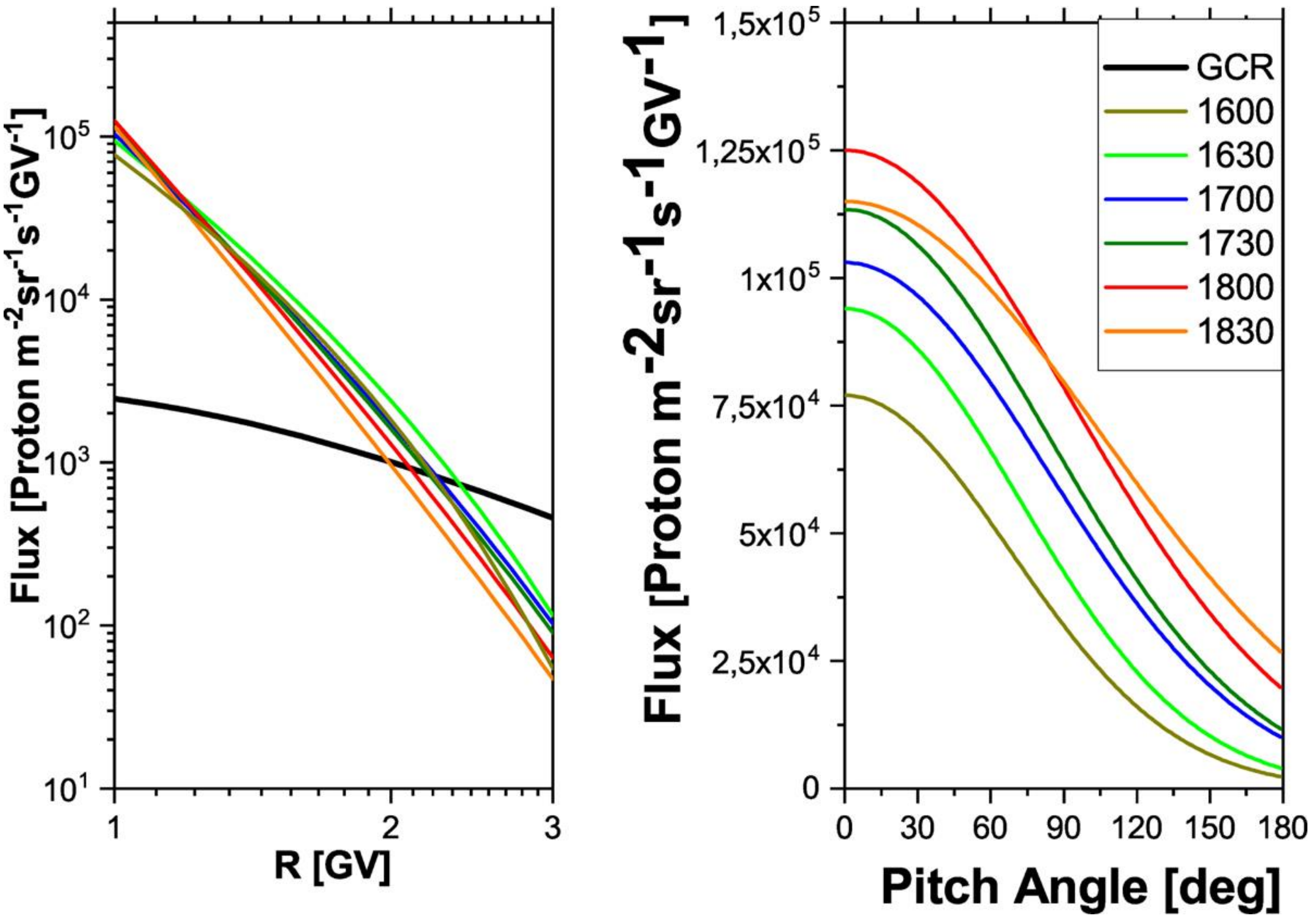

Papaioannou et al., *Astron. Astrophys,,* (**2022**)

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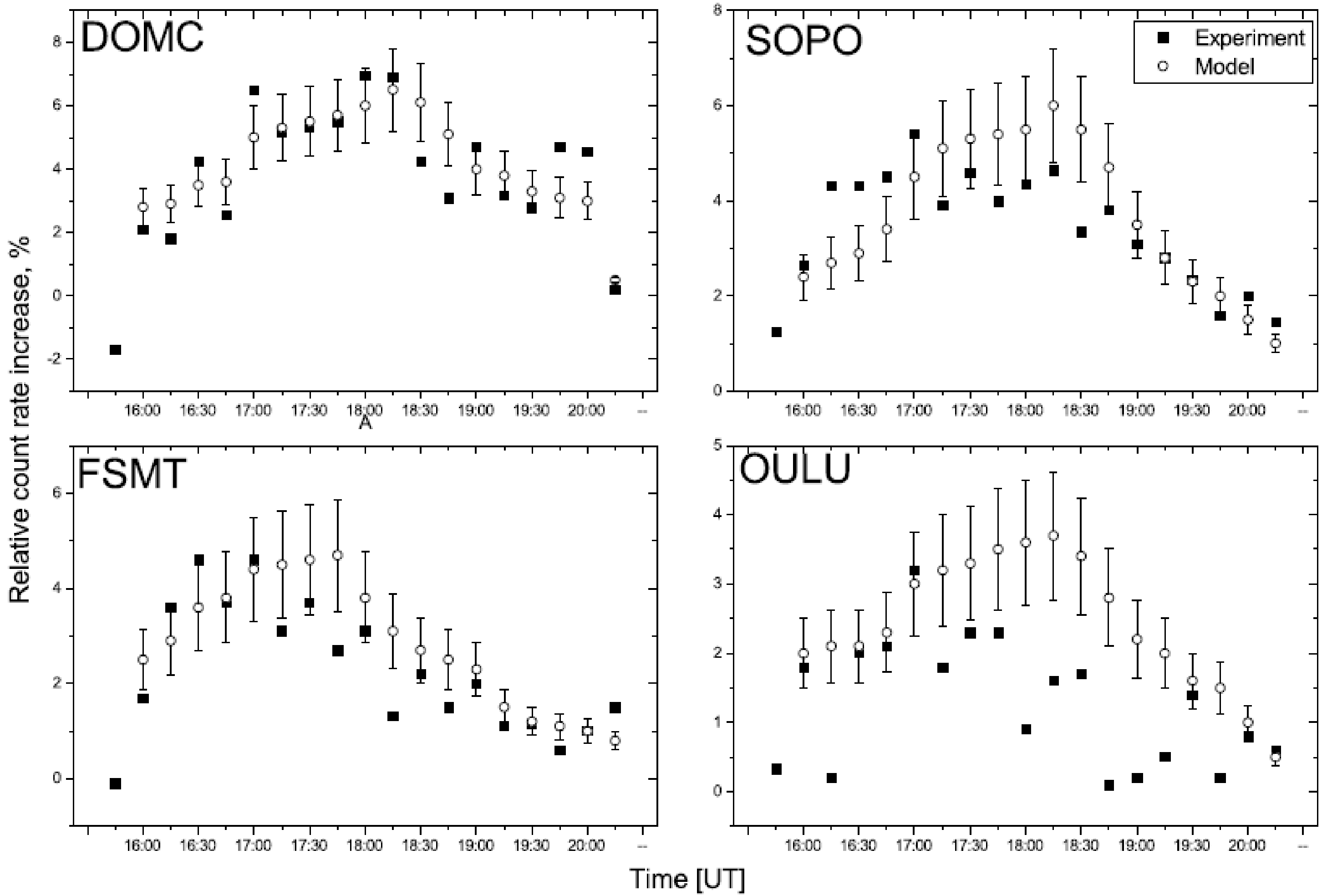
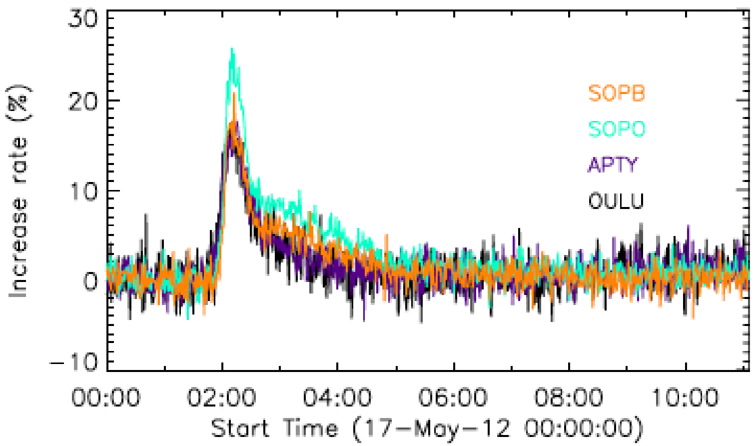


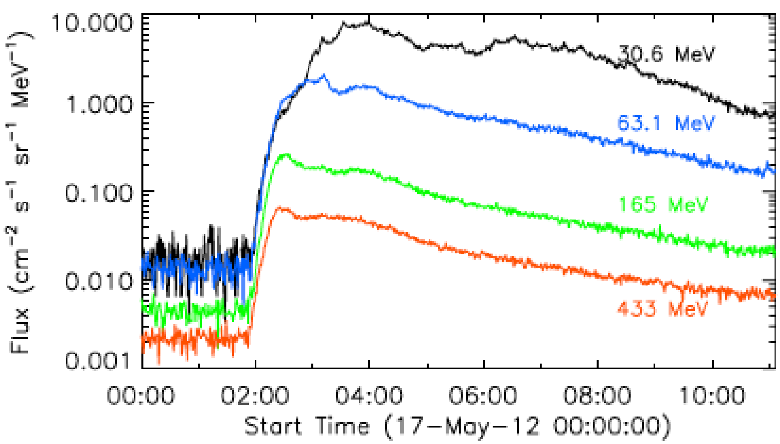
Mishev et al., *Solar Phys.*, (**2022**)

Forecasting Solar Storms

Utilizing the network

Li et al., *ApJ.*, (2013)





> We can make use of ***the particles***

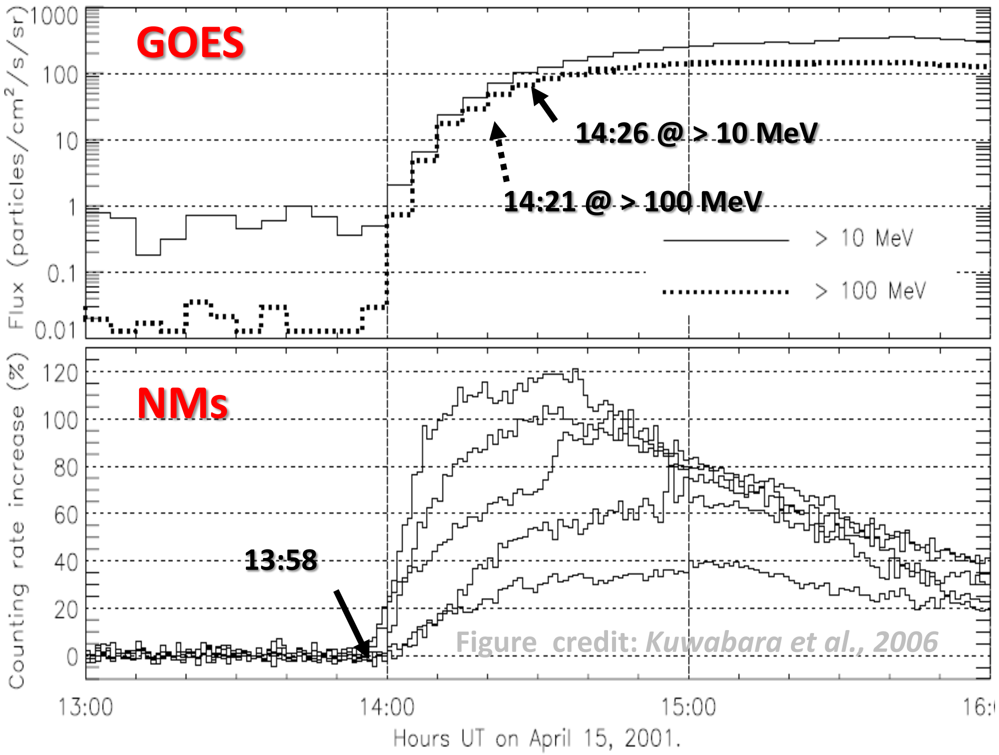
Relativistic protons

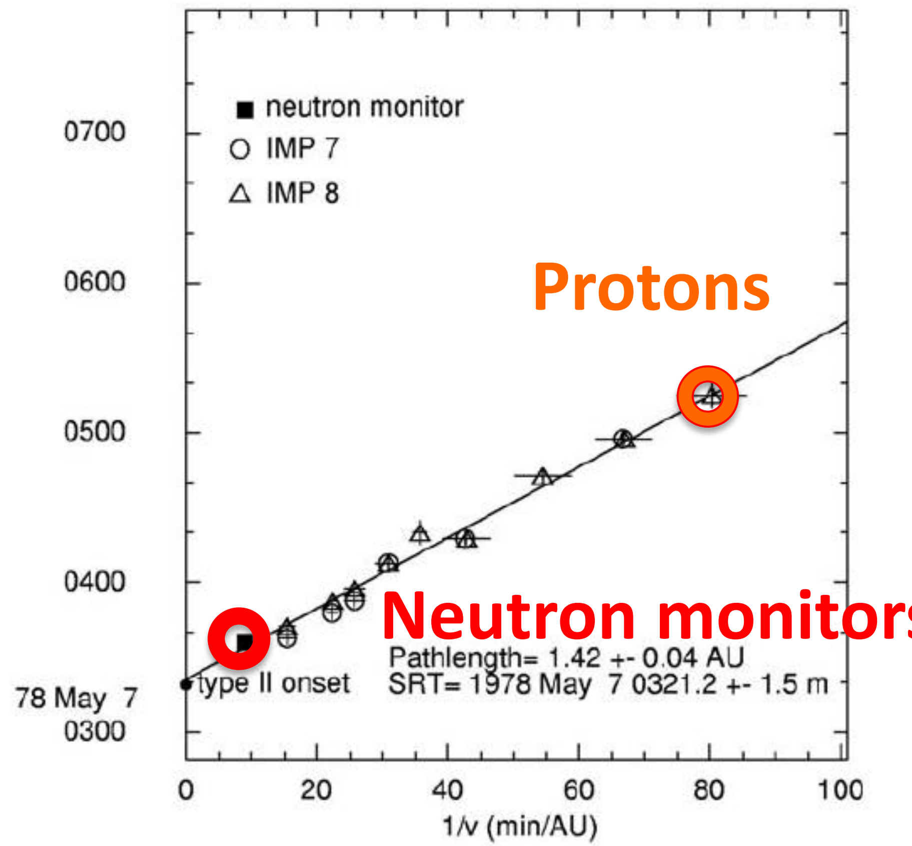
Kuwabara et al., *SW*, (**2006**)

Souvatzoglou et al., *SW*, (**2014**)

Forecasting Solar Storms

Utilizing the network



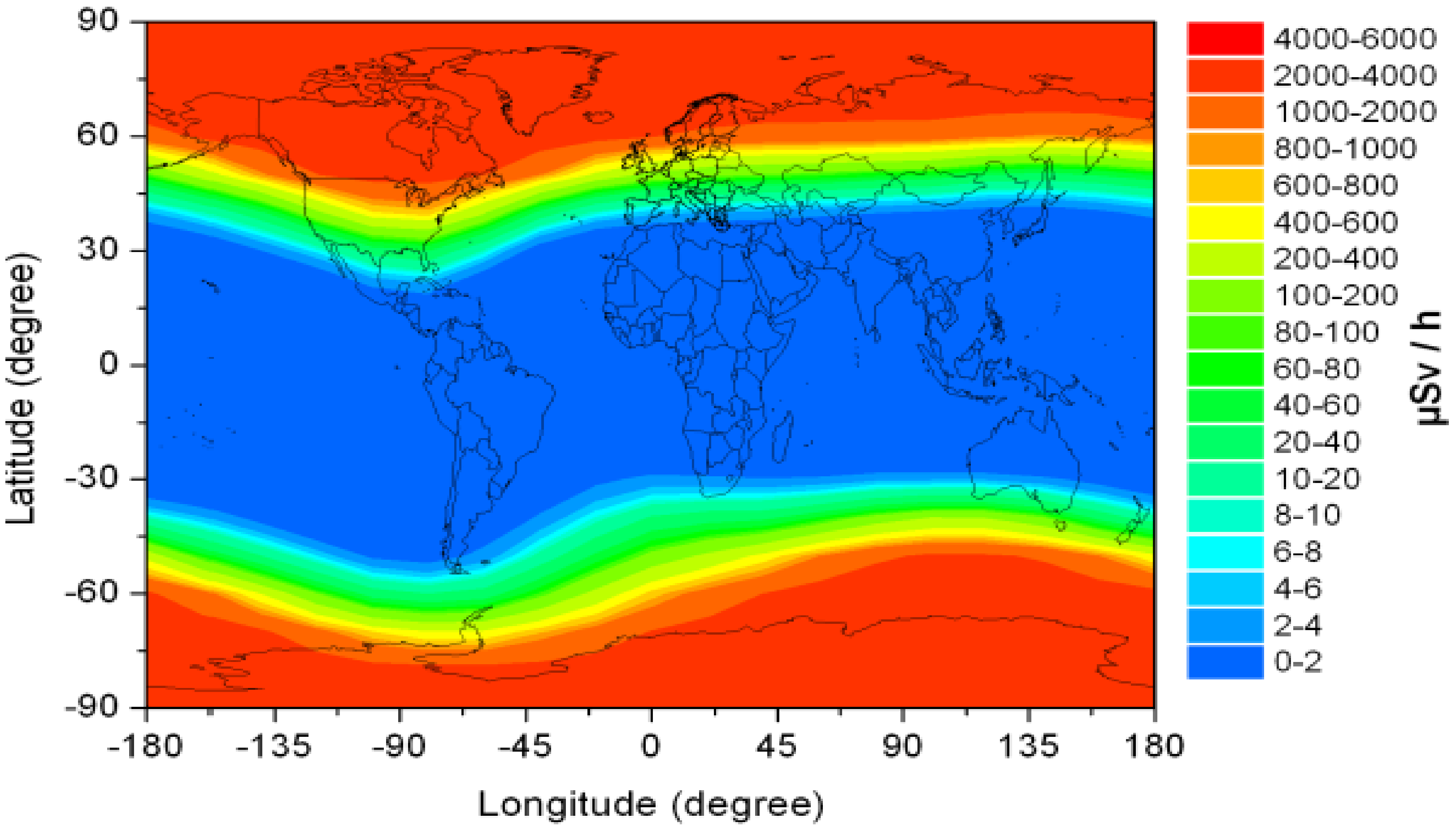


Kuwabara et al., *SW*, (**2006**)

Reames, *ApJ*, (**2009**)

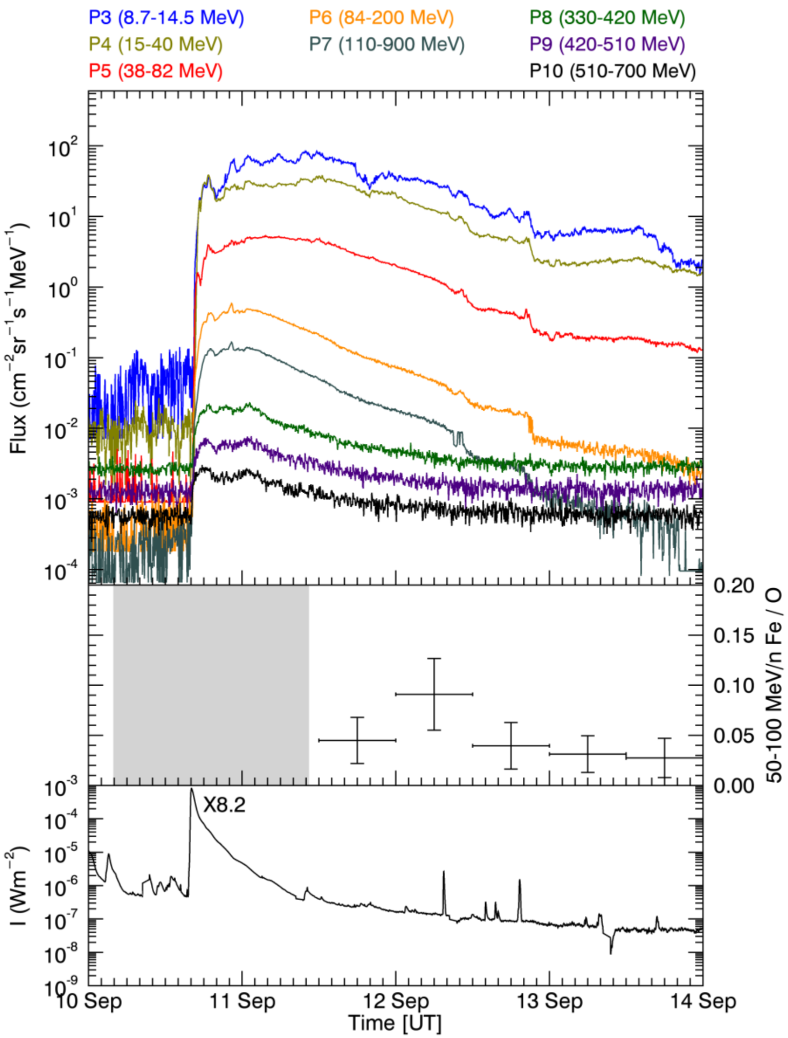
Forecasting Solar Storms

Impact



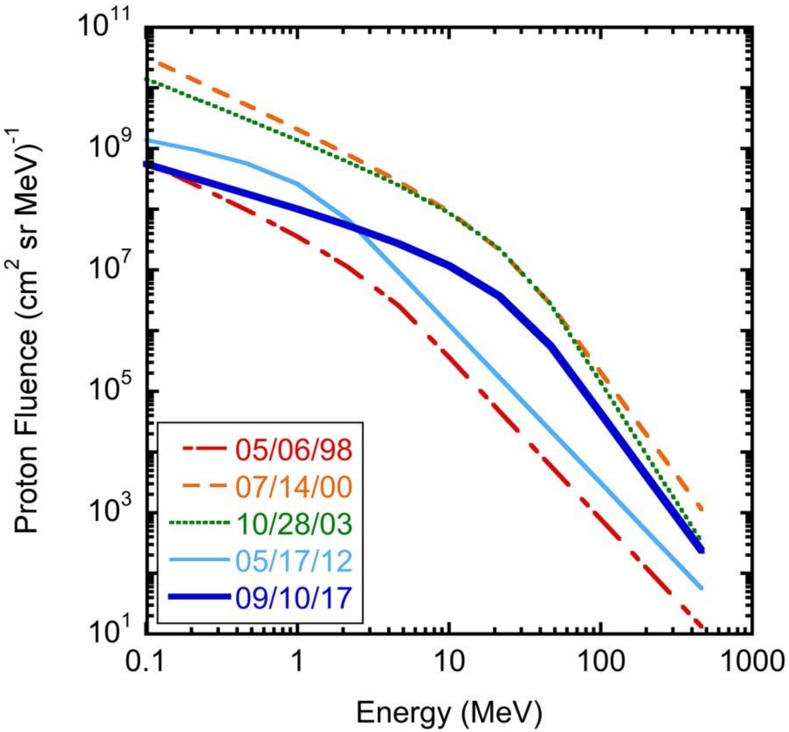
GLEs in the interplanetary space

Spacecraft measurements | GOES



Mishev et al., *ApJ*, (**2018**)

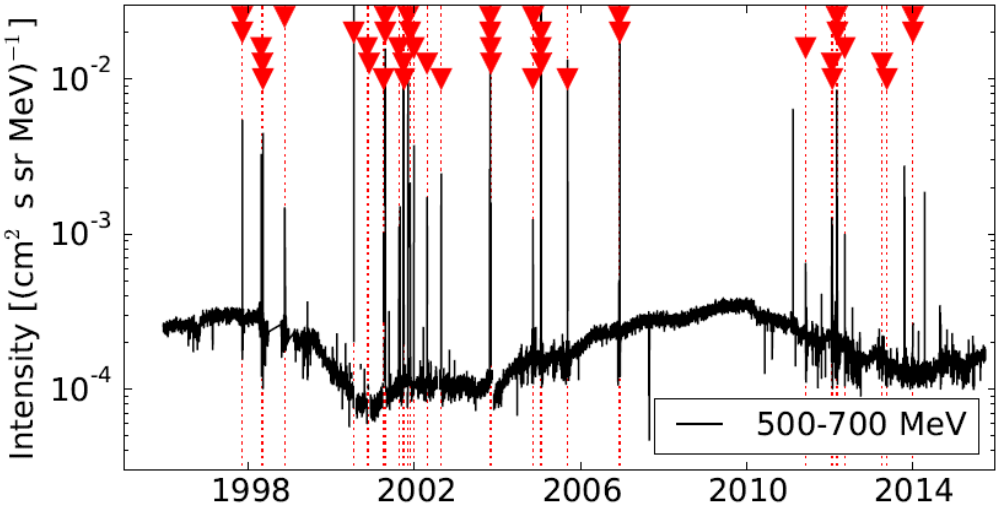
> **GOES:** Carried detectors (**HEPAD**) that could register particles **up to 700 MeV** → Identified several **GLEs (low energy component)** at a range from ~**10-700 MeV**

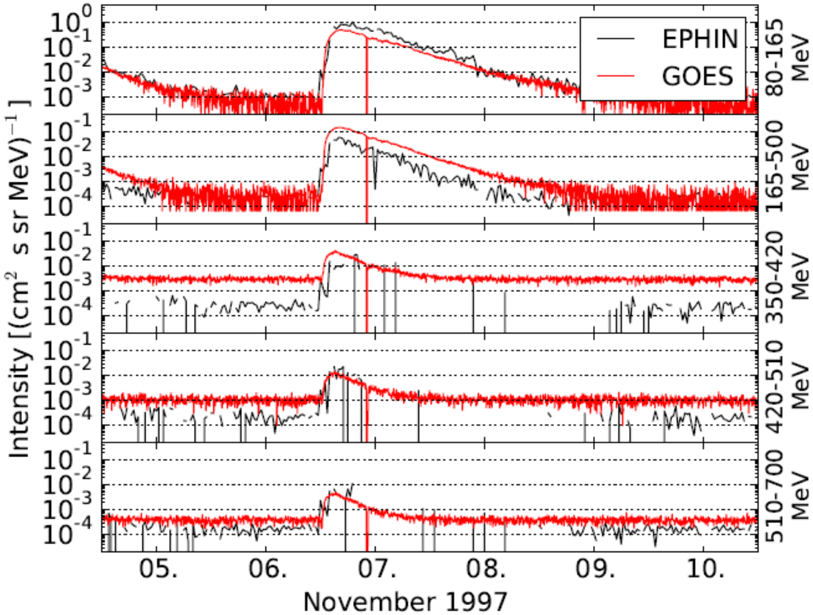


Cohen & Mewaldt, *SW*, (**2018**)

GLEs in the interplanetary space

Spacecraft measurements | SOHO





> SOHO/EPHIN: A recent recalibration showed that **EPHIN** was able to record particles from **500-700 MeV (including two GLEs).**

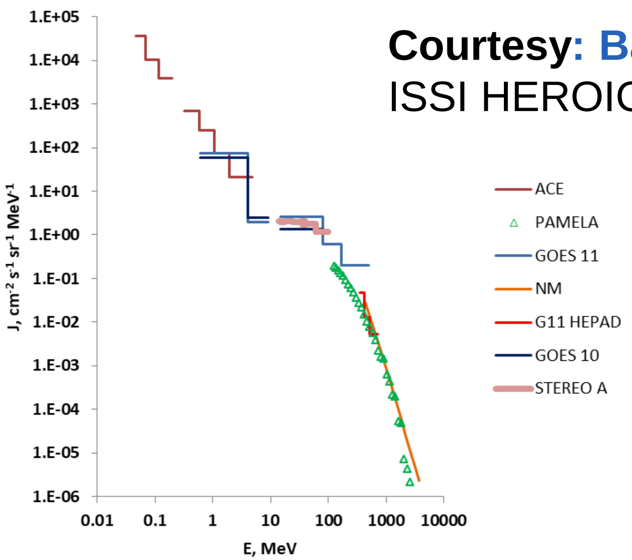
Kuehl et al., *Solar Phys.*, (**2017**)

GLEs in the interplanetary space

Spacecraft measurements | PAMELA & AMS-02

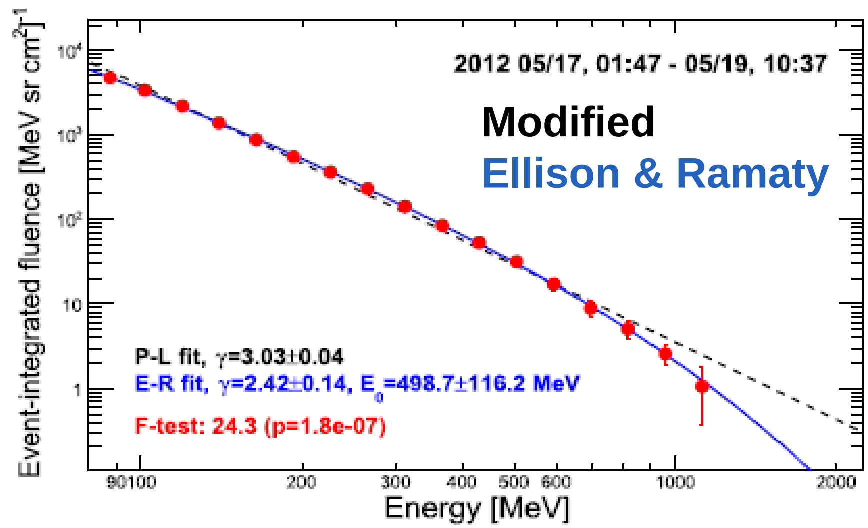
> **PAMELA & AMS-02:** Data from the PAMELA mission and AMS-02 onboard *the International Space Station* (**ISS**), have *provided significant measurements* that **bridge the critical gap** in the spectra from the low-energy (typically up to ~ 100 MeV to the NM range)

20061213 03-05 UT

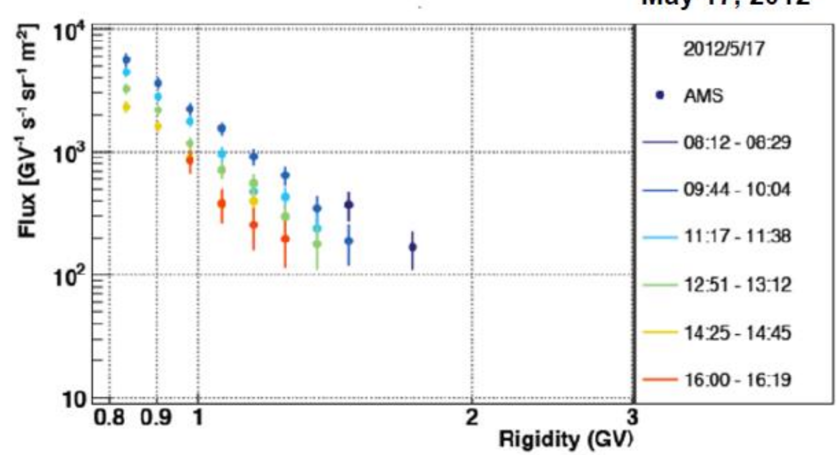


Courtesy: **Basilevskaya**, ISSI HEROIC Team

Bruno et al., *ApJ*, (2018)



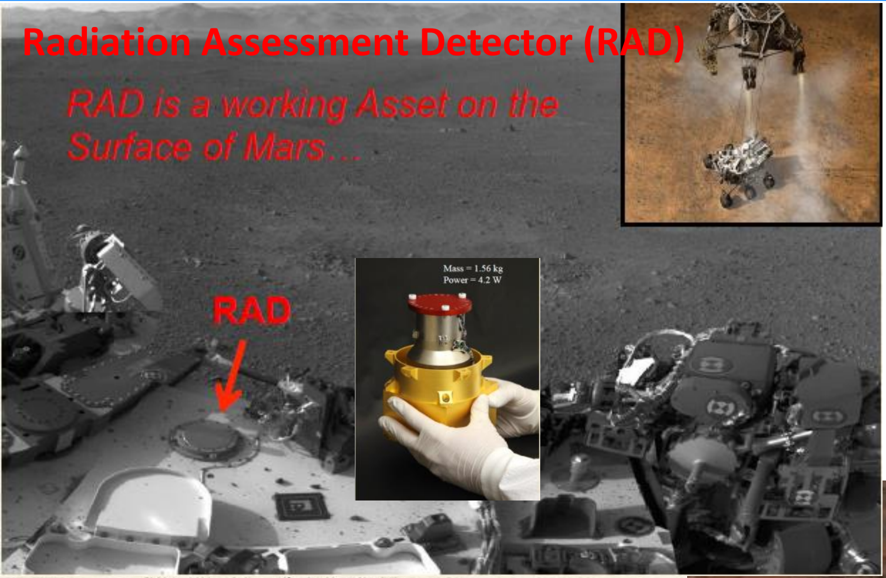
May 17, 2012

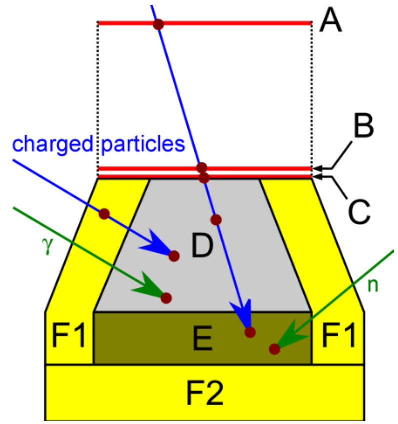


Bindi et al., *ICRC*, (2015)

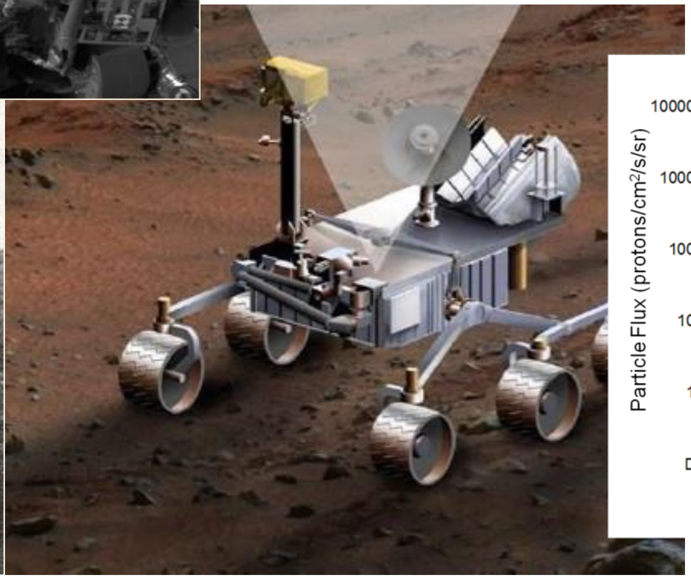
GLEs on other planets

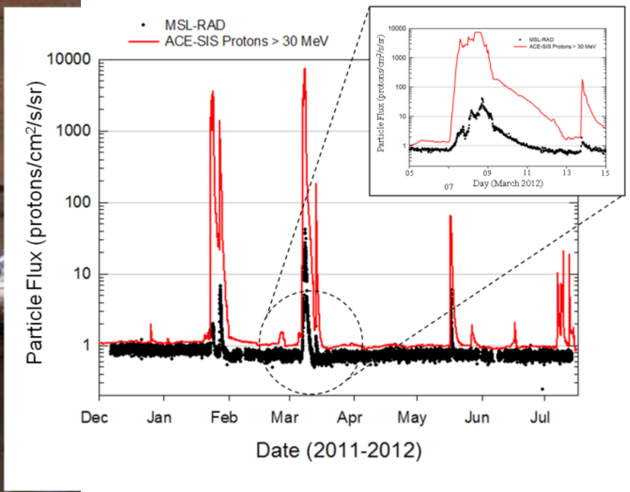
Mars





> **100 years** since the discovery of **Cosmic Rays** from ***Victor Hess*** **RAD** measures for **the first time Cosmic Rays *on the surface of another planet***.

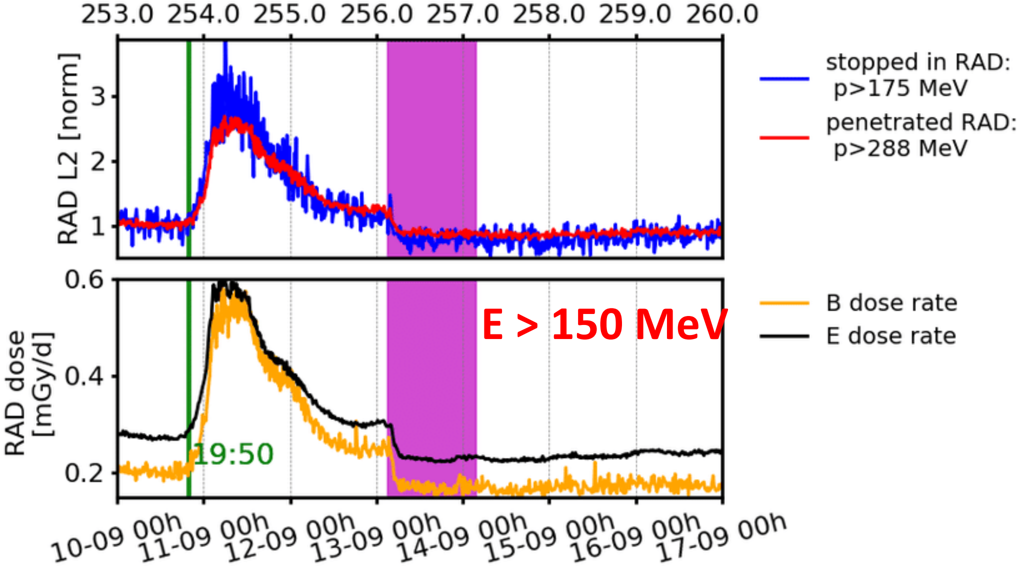




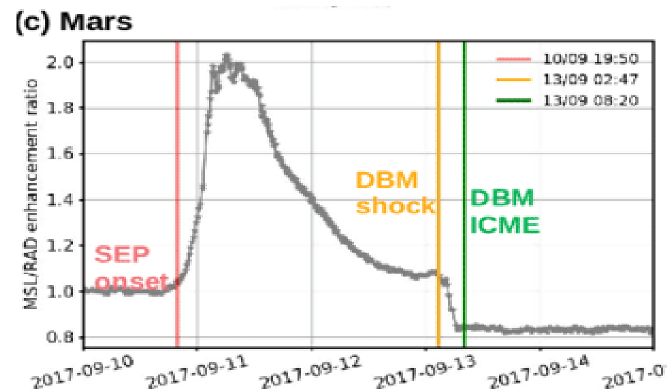
Hassler et al., *Science*, (**2012**)

GLEs on other planets

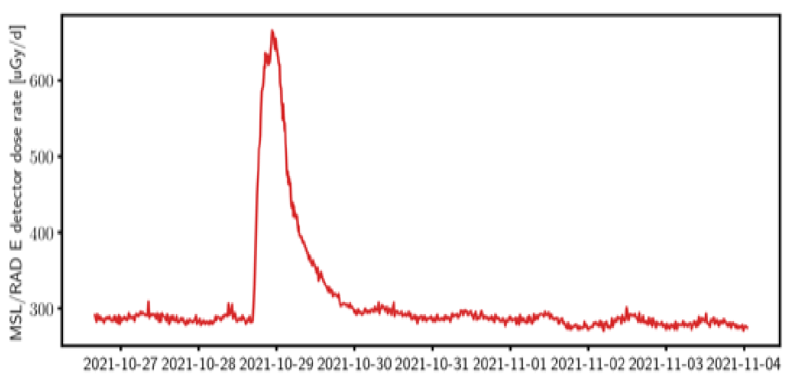
Mars



> GLE72 (10.09.2017)



Guo et al., *SW*, (**2018**)

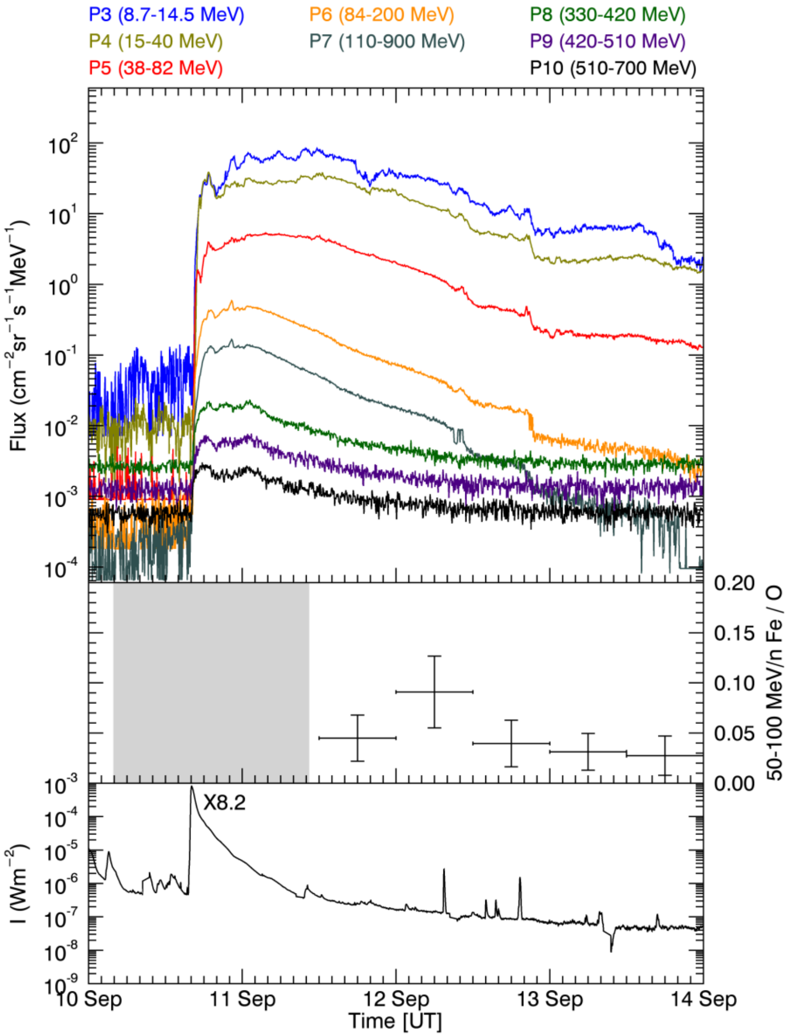


> GLE73 (28.10.2021)

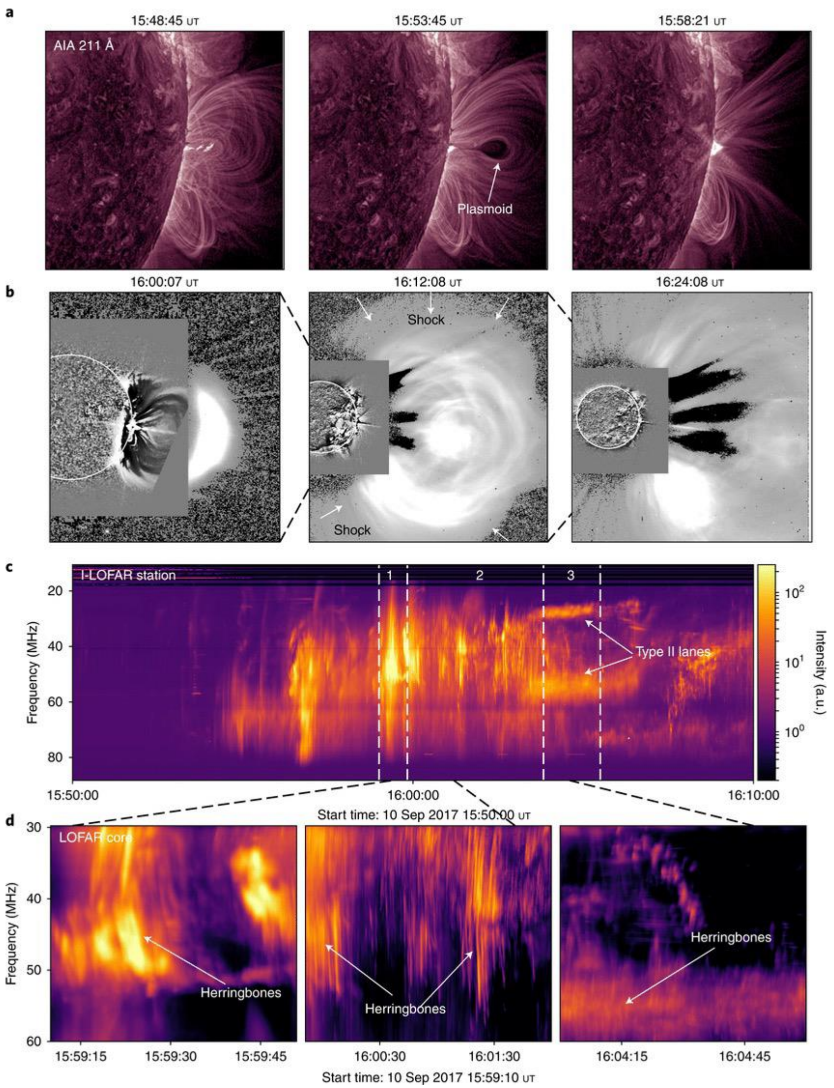
Kouloumvakos et al., *ApJ*, (**2022**) – *in prep.*

Challenges

GLE72 | 10 September 2017



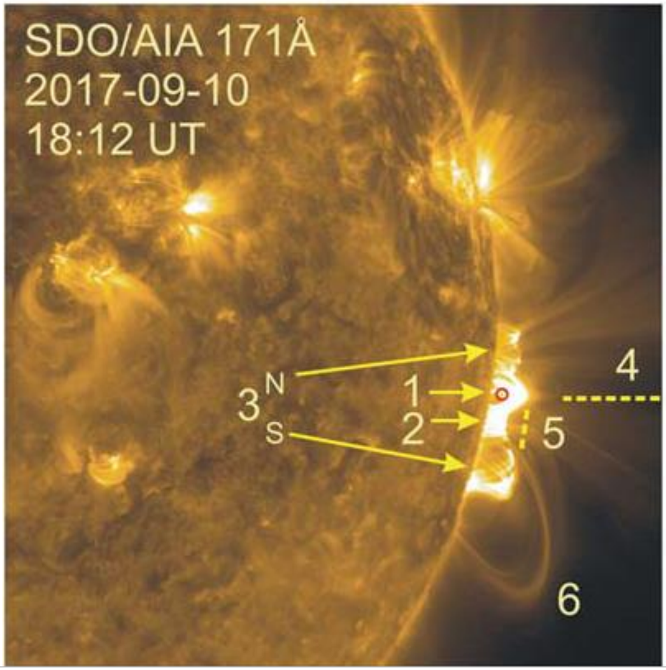
Mishev et al., *ApJ*, (2018)



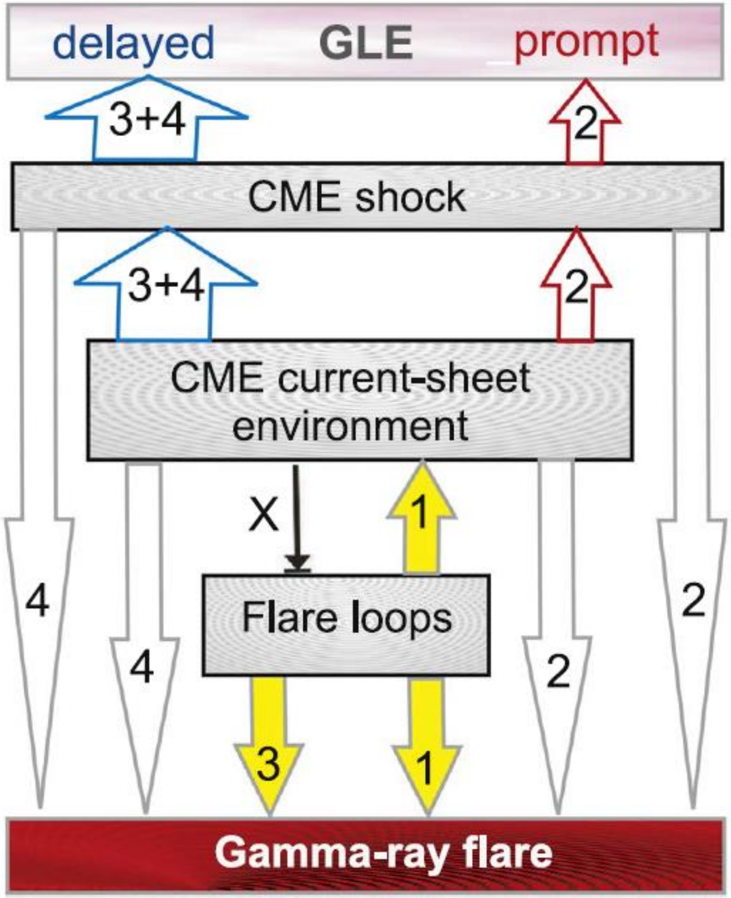
Morosan et al., *ApJ*, (2019)

Challenges

GLE72 | 10 September 2017



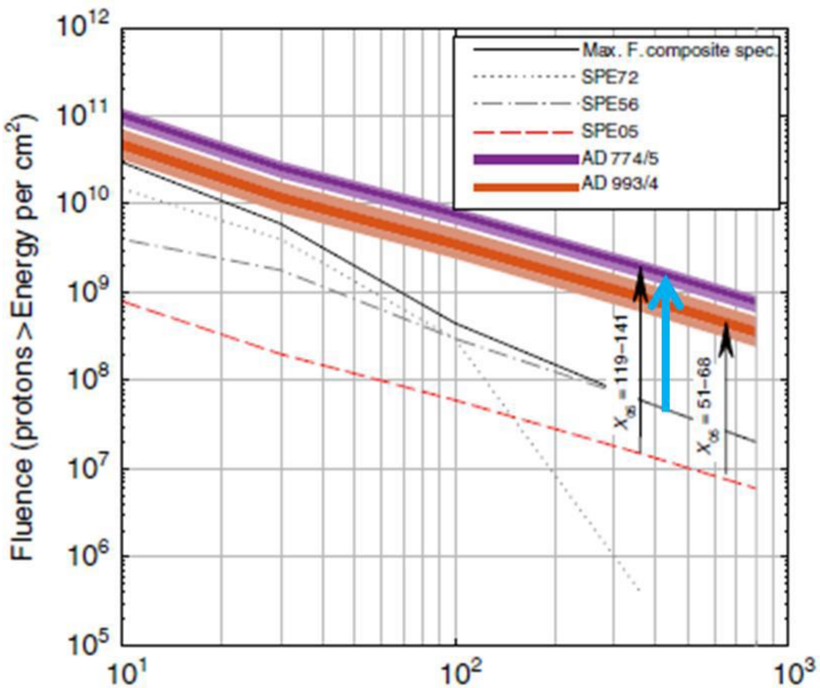
> Multi-wavelength observations of the *flare–CME eruption* reveal **multiple locations where the energetic protons could be produced**. *Data suggest* **four episodes** of the **high-energy proton acceleration at/near the Sun**, *two of which are located around the flare loops*, while *two others are situated in a wider region around the CME-trailing current sheet.*

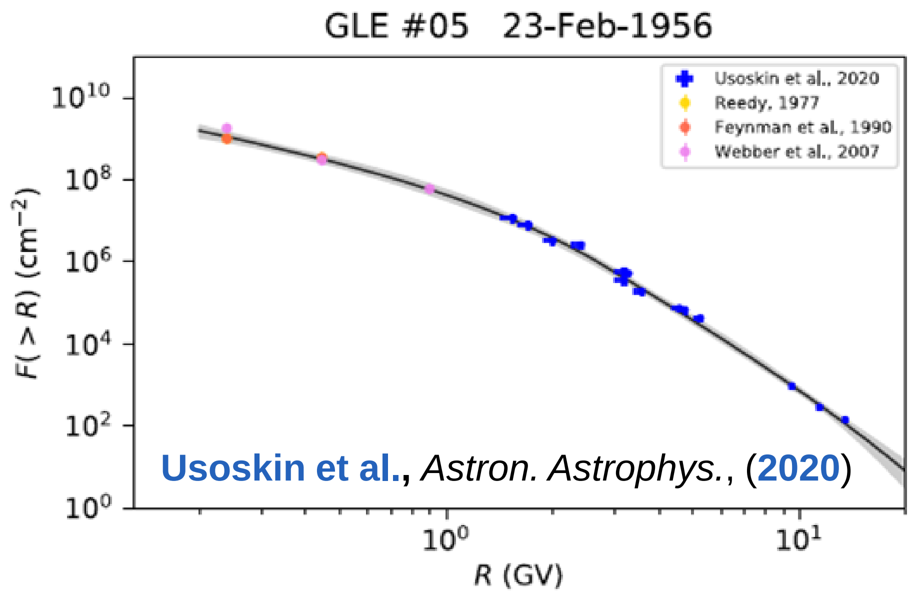


Kocharov et al., *ApJ*, (**2021**)

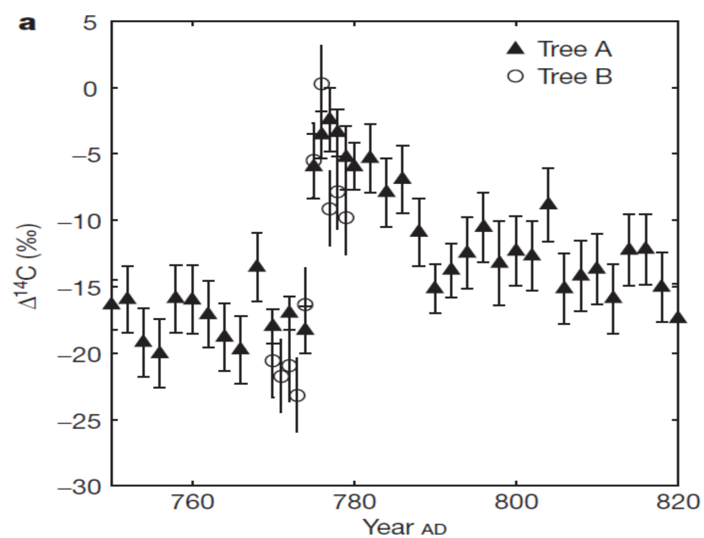
Future directions

GLEs as a stepping stone for *Super Events*





> Solar related "**super-event**" in **ADD774**. Modeled on the basis of a multiplication factor of the measured **GLE05 spectra**

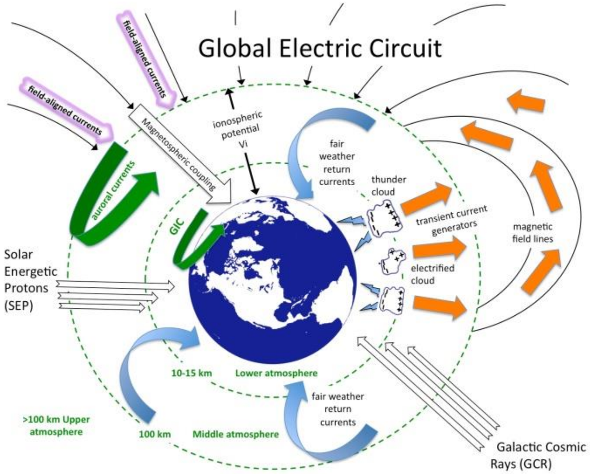


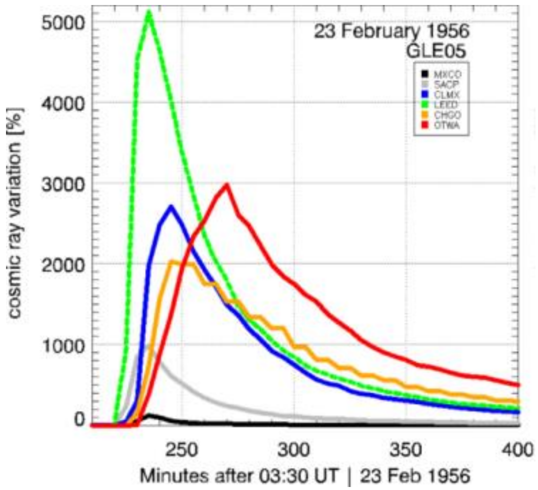
Miyake et al., *Nature*, (**2012**)

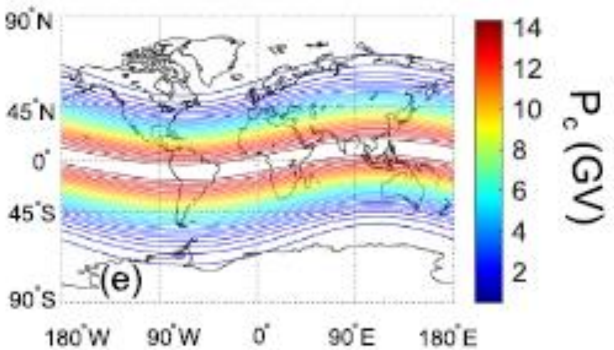
Mekhaldi et al., *Nature*, (**2015**)

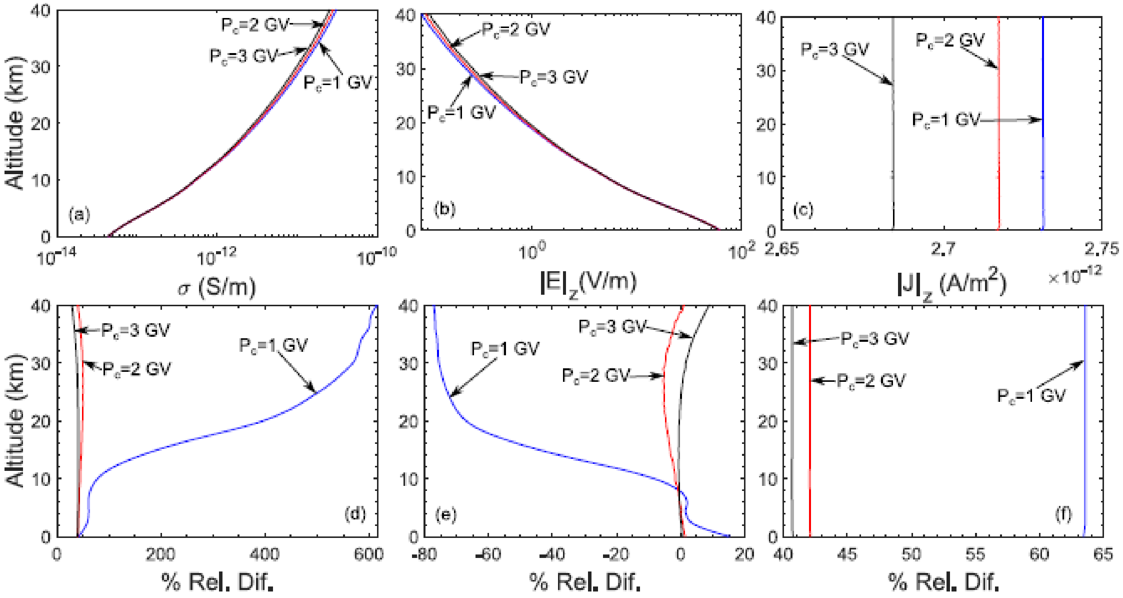
Future directions

GLE contribution to *atmospheric electricity*



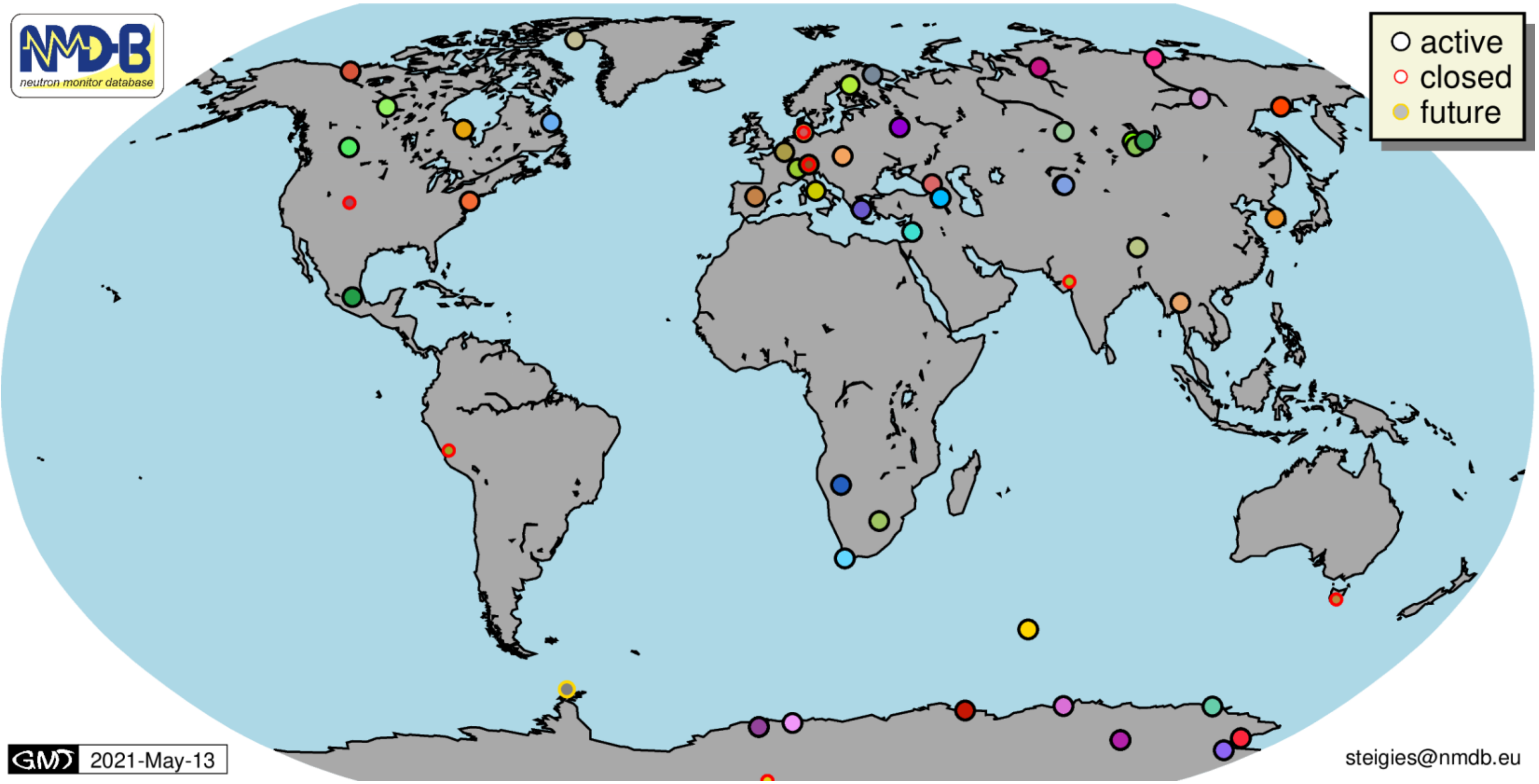






Mallios et al., *JASTP*, (**2022**)

Conclusions



Thank you for your attention