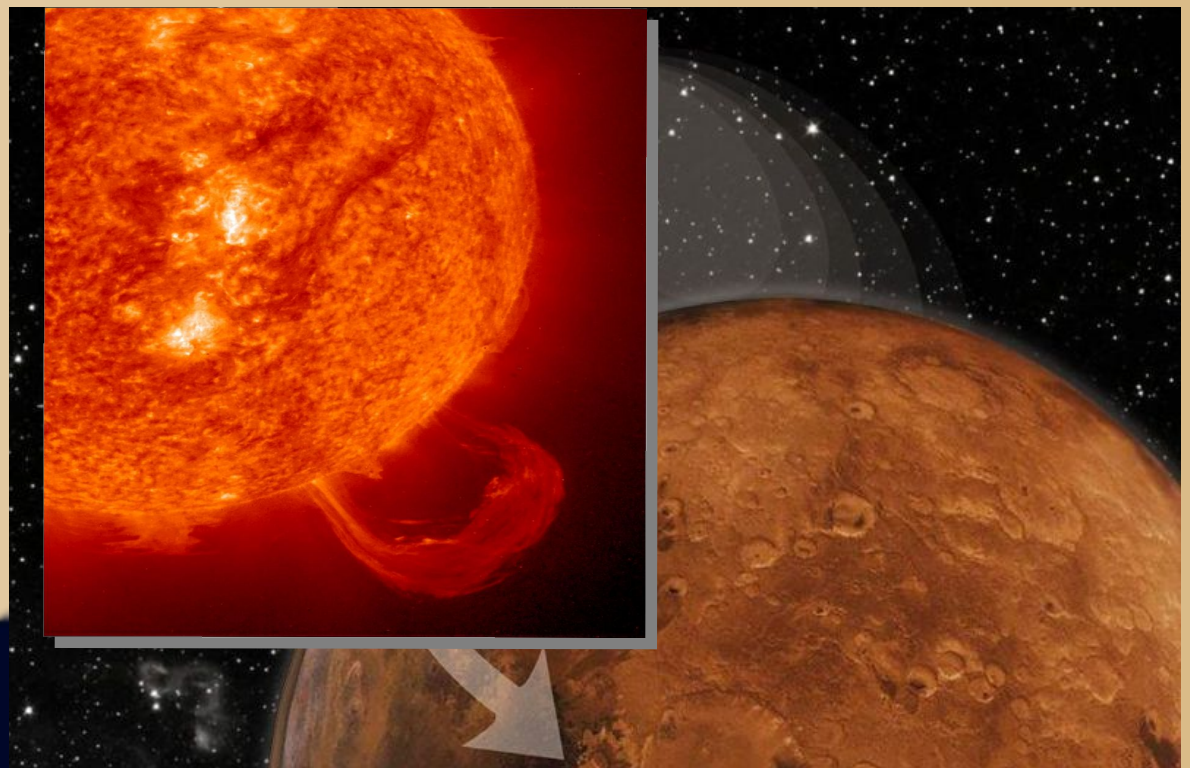
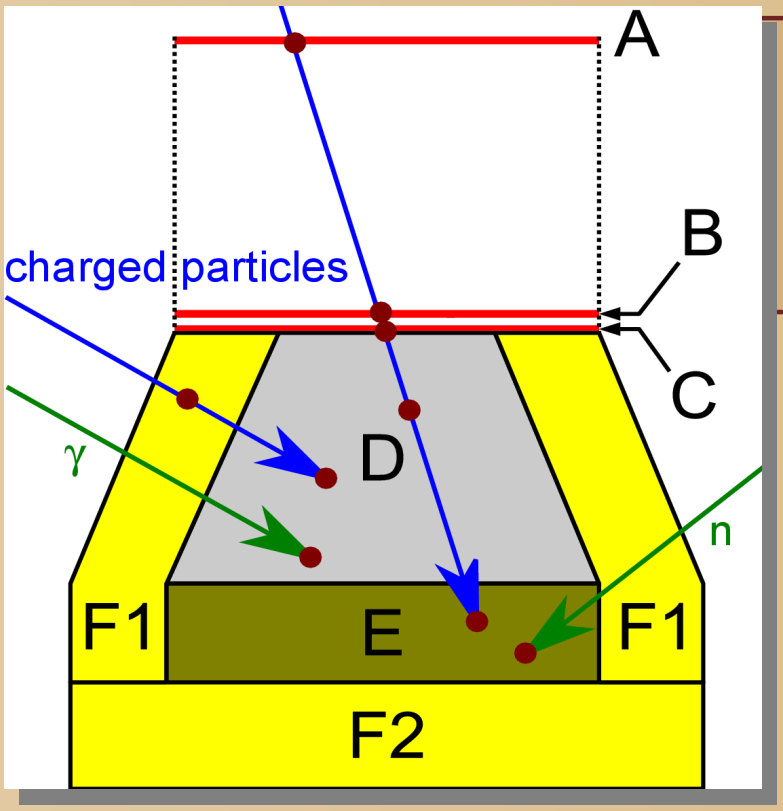
A generalized approach to model the spectra and radiation dose rate of solar particle events on the surface of Mars

Jingnan Guo, Cary Zeitlin, Robert F. Wimmer-Schweingruber, and the MSL/RAD team

*University of Kiel, Germany

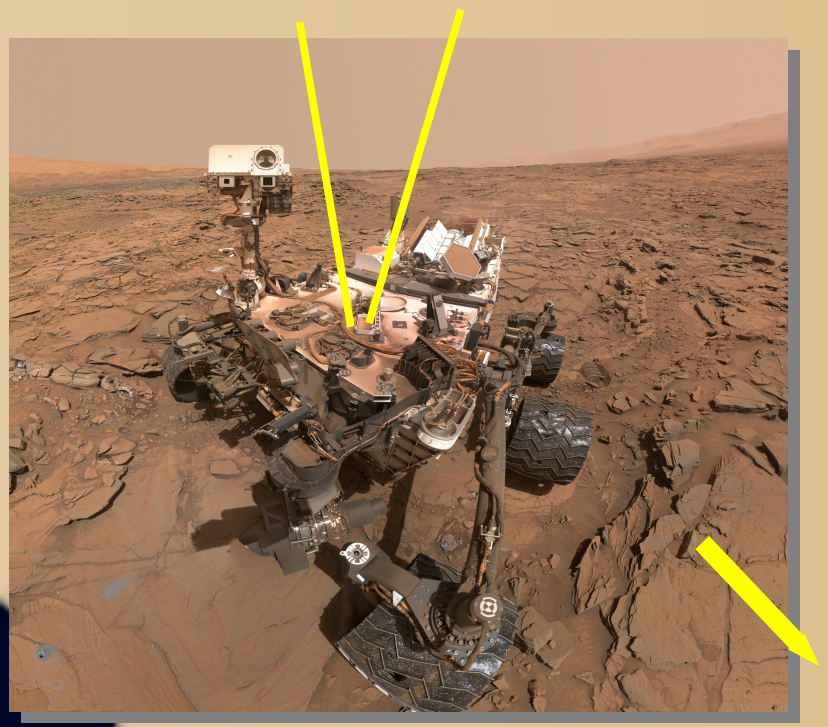


September 2017
WRMISS
Torino
Italia



Radiation Assessment Detector (RAD) provides the first measurement of high energetic particle flux on Mars!

- RAD is an energetic particle detector measuring **galactic cosmic rays**, **solar energetic particles**, and their secondary particles generated in the atmosphere.
- RAD contains 6 detectors, **A, B, and C** are **silicon diodes** (each 300 um thick) arranged as a telescope.
- The other three (**D, E, and F**) are **scintillators**.
  - **D**: 2.8 cm thick CSI
  - **E**: 1.8 cm thick hydrogen-rich plastic,
  - Both D and E are efficient for **neutral particles**
  - **F**: 1.2 cm thick plastic; **anti-coincidence**
- Dose rates (deposited energy by particles) are measured in both silicon and plastic detectors.



A selfi of the curiosity rover on Mars.

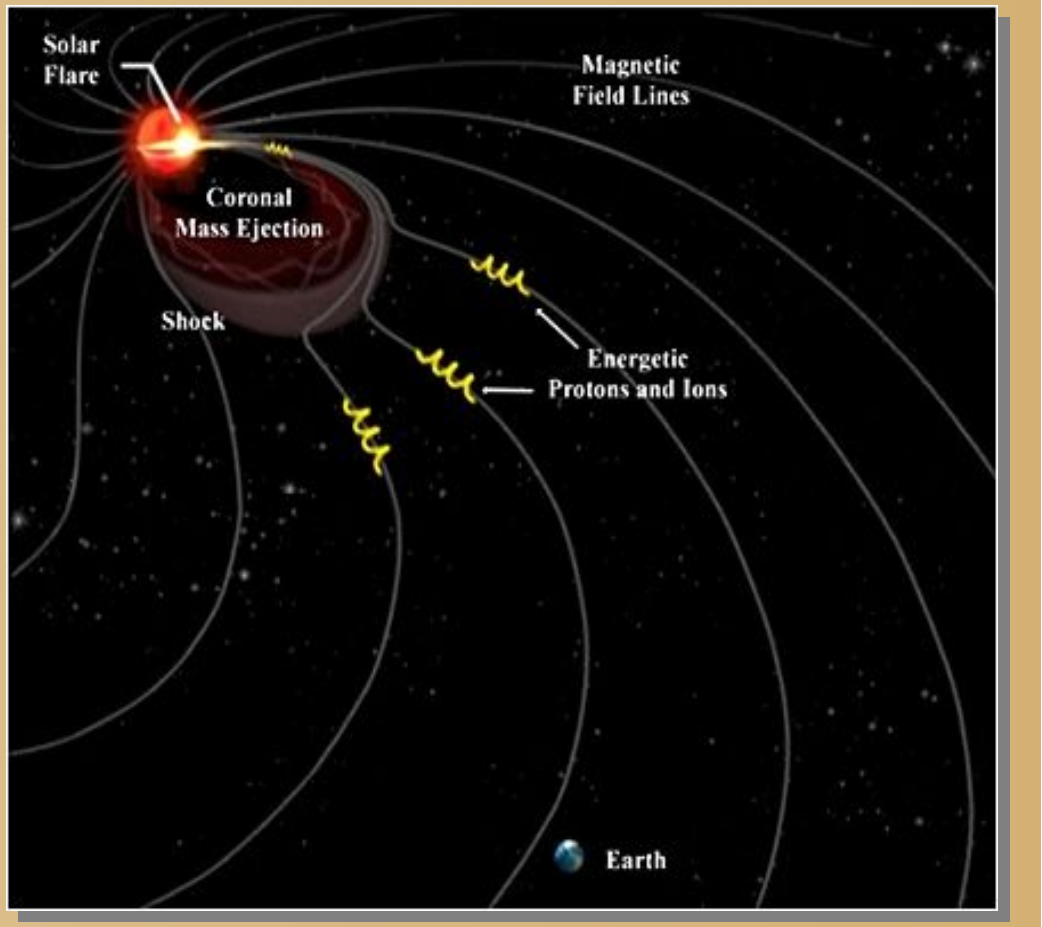
MSL/RAD GCR measurement

- **The solar and heliospheric conditions** strongly influence the radiation environment during the cruise to and on Mars
  - Studied the **correlation** of **heliospheric modulation** and RAD measured **GCRs** and modeled the GCR dose rate during other solar (extreme) conditions (WRIMISS2015; Guo et al 2015 A&A; Guo et al 2015 ApJ);
  - The **atmosphere** anti-modulates the GCR doses and how such atmospheric **shielding** depends on the **heliospheric** modulation of the GCRs (WRMISS2016; Rafkin et al 2014; Guo et al 2017 JGR).
  - Short term modulations of the GCR by **ICMEs** and SIRs cause sudden depression in the GCR fluxes resulting in **Forbush** Decreases have been studied both statistically and individually at Mars and compared to those at Earth (Guo et al 2017 A&A, Forstner et al 2017 JGR, submitted).
  - Please ask/write us for more details afterwards if you were interested.

MSL/RAD SEP measurement

RAD observed several solar particle events (**SPEs**) during the cruise phase and on the surface of Mars. Their onset times and spectra are different from those observed at near Earth due to:

- different **magnetic connection** to the particle acceleration sites (at the flares, and/or CMEs and shocks)
- **Cross-field transportation effects** on particles as they propagate through the heliosphere
- the atomic and nuclear **interaction** of particles with the Martian **atmosphere**



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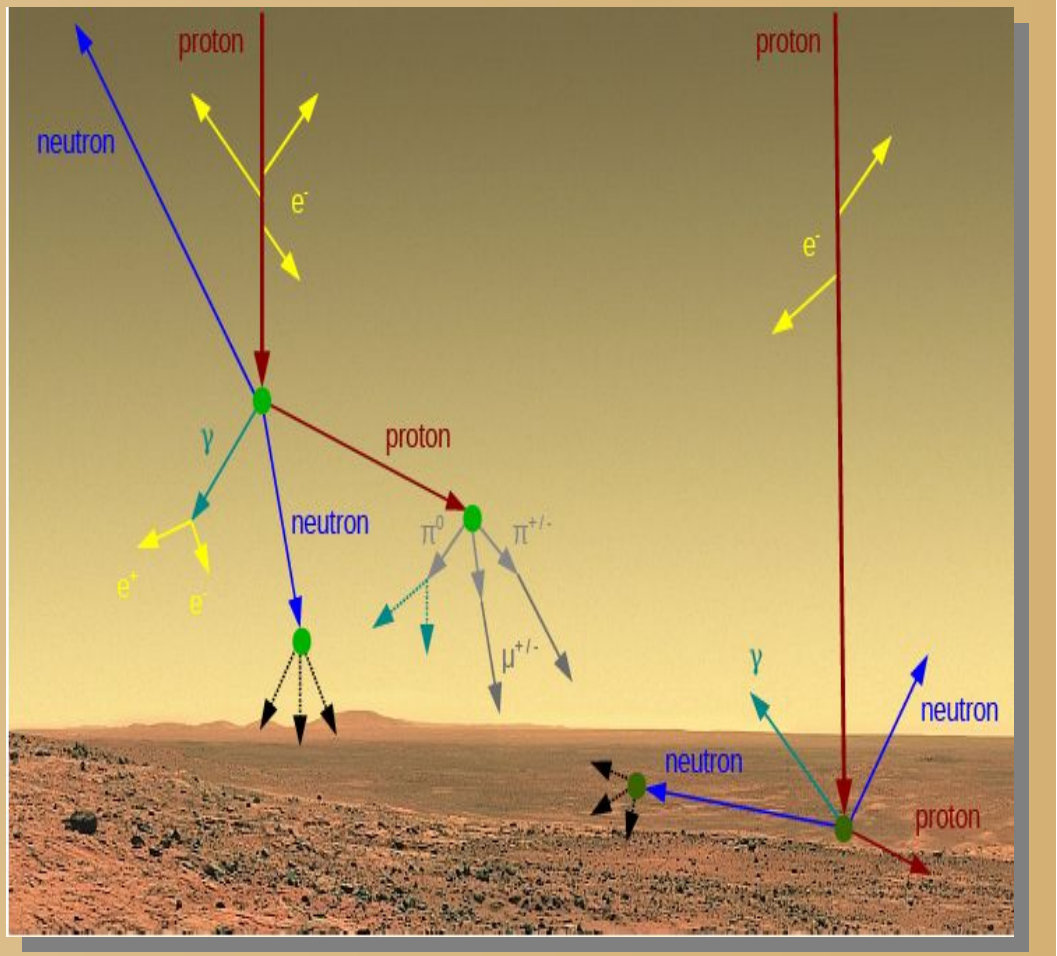
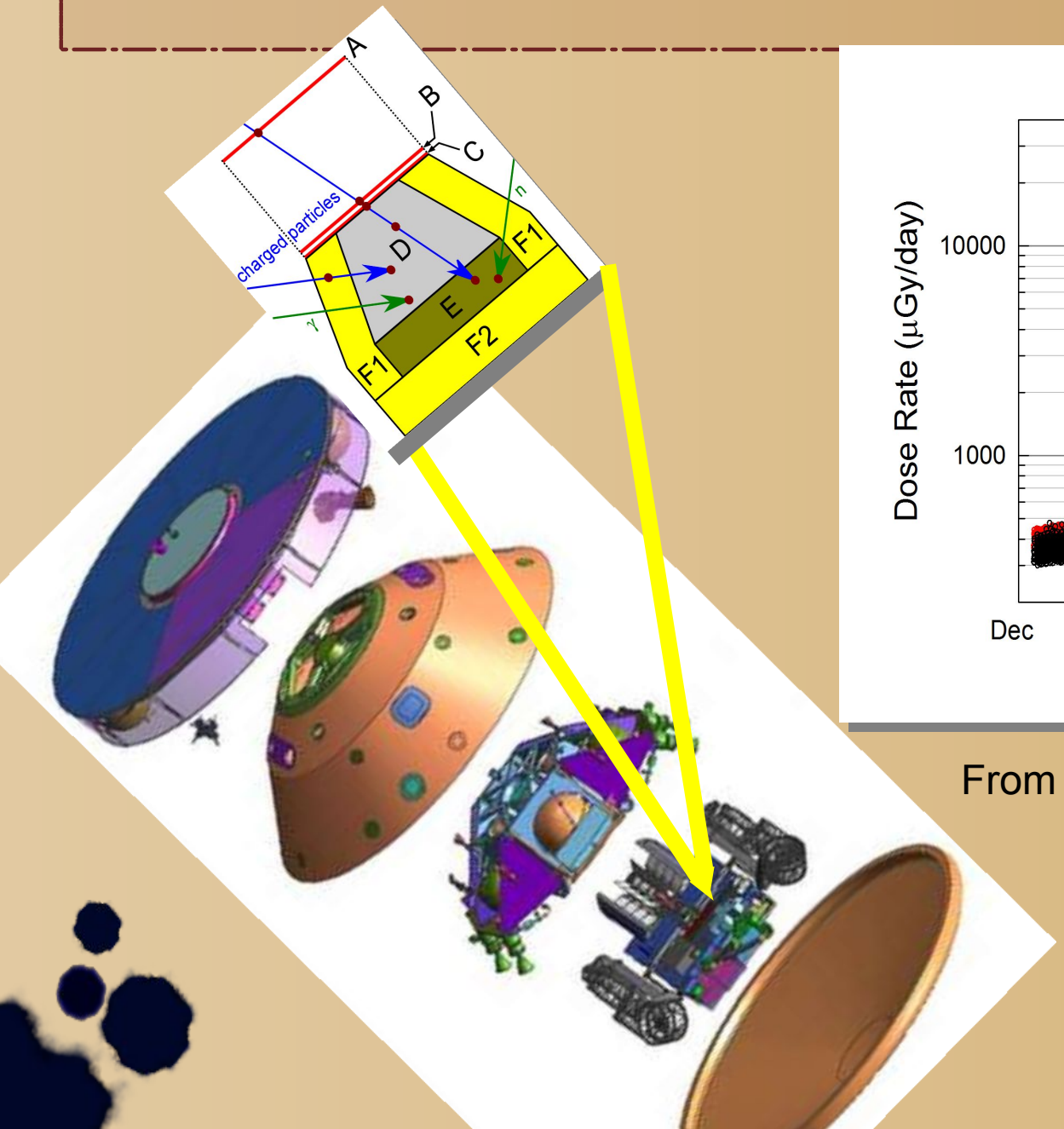
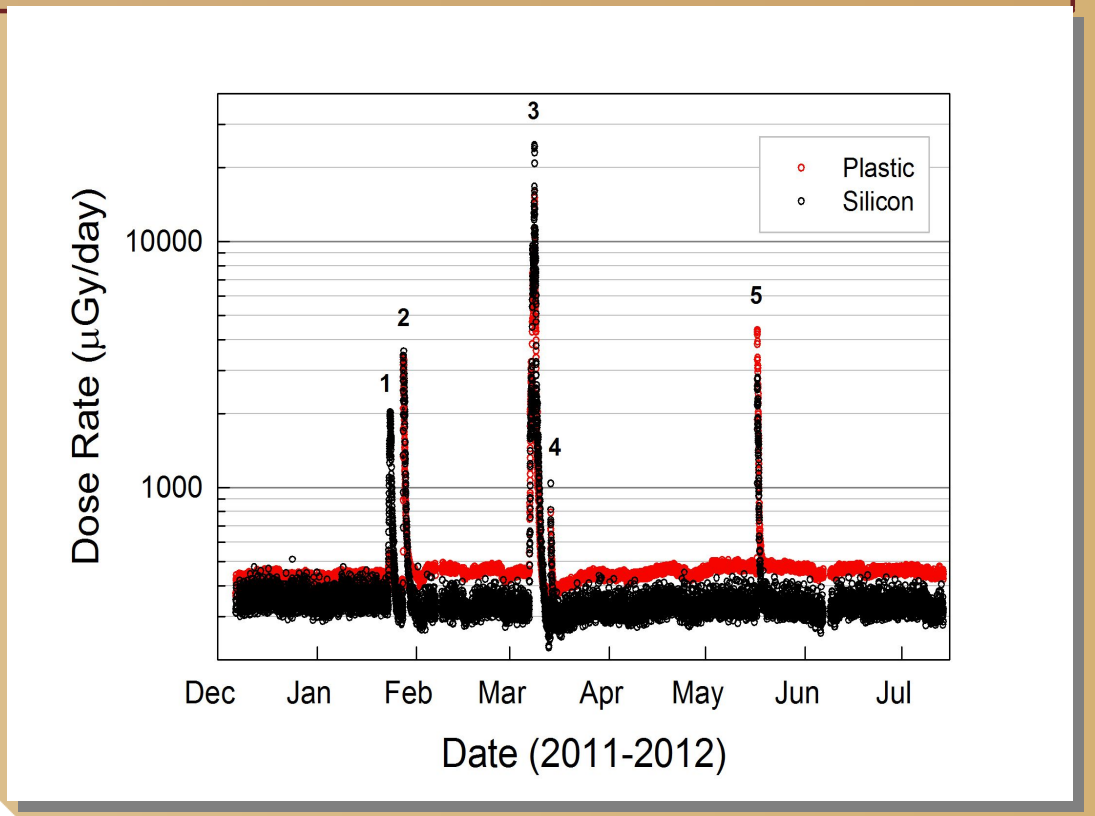


SEP Measurement during the cruise phase



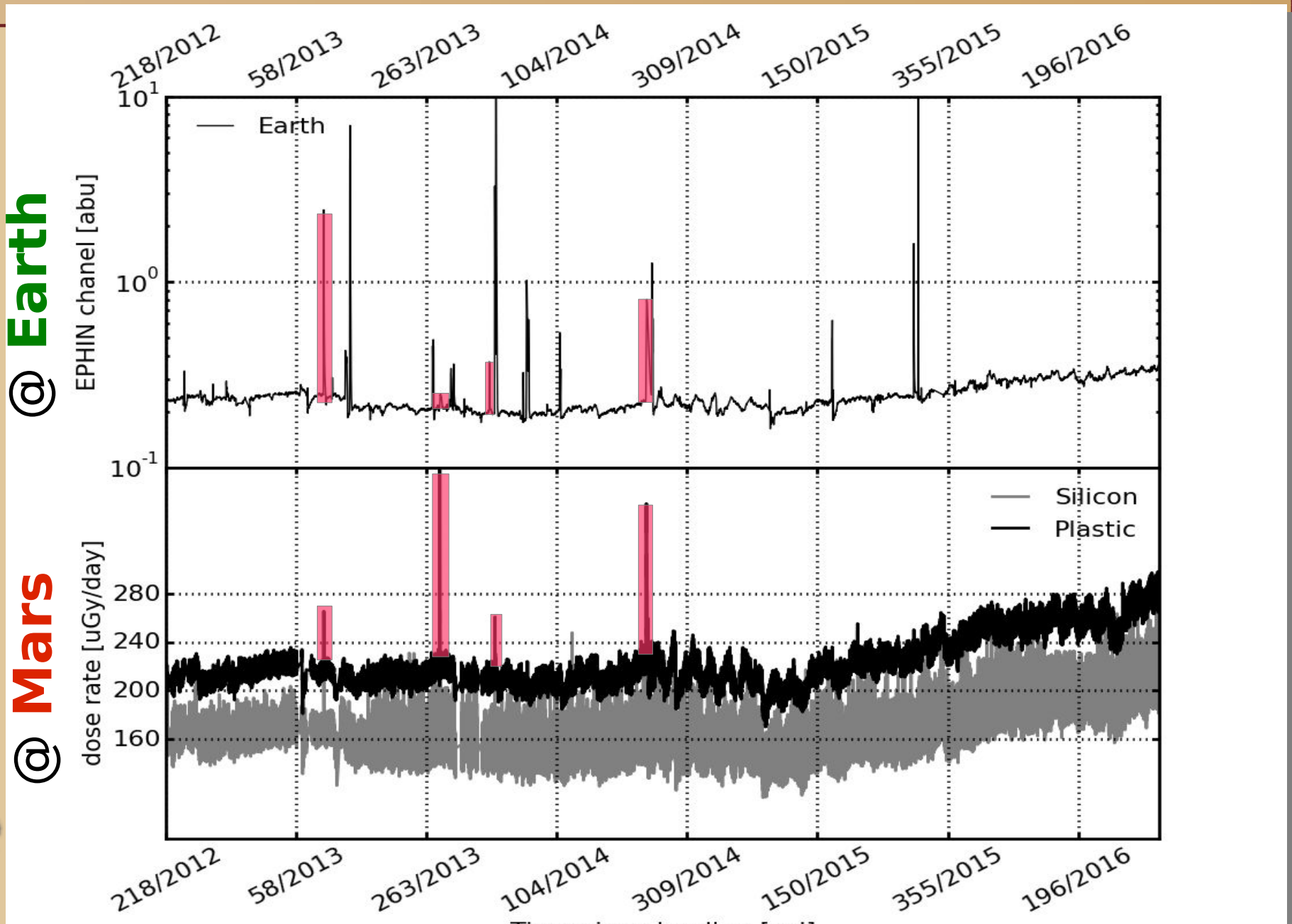


From Zeitlin et al 2013, Science

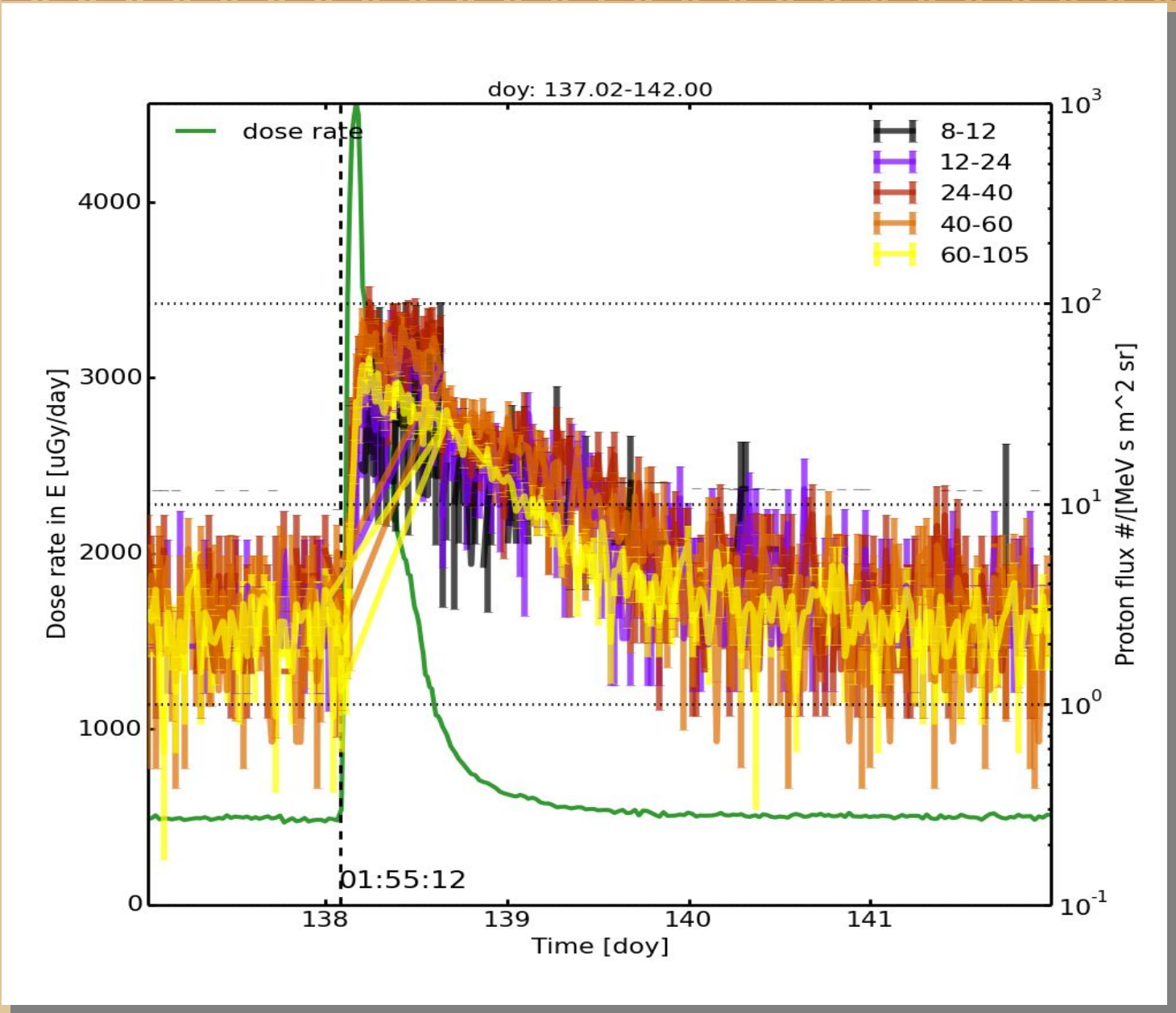
SEPs on the surface of Mars

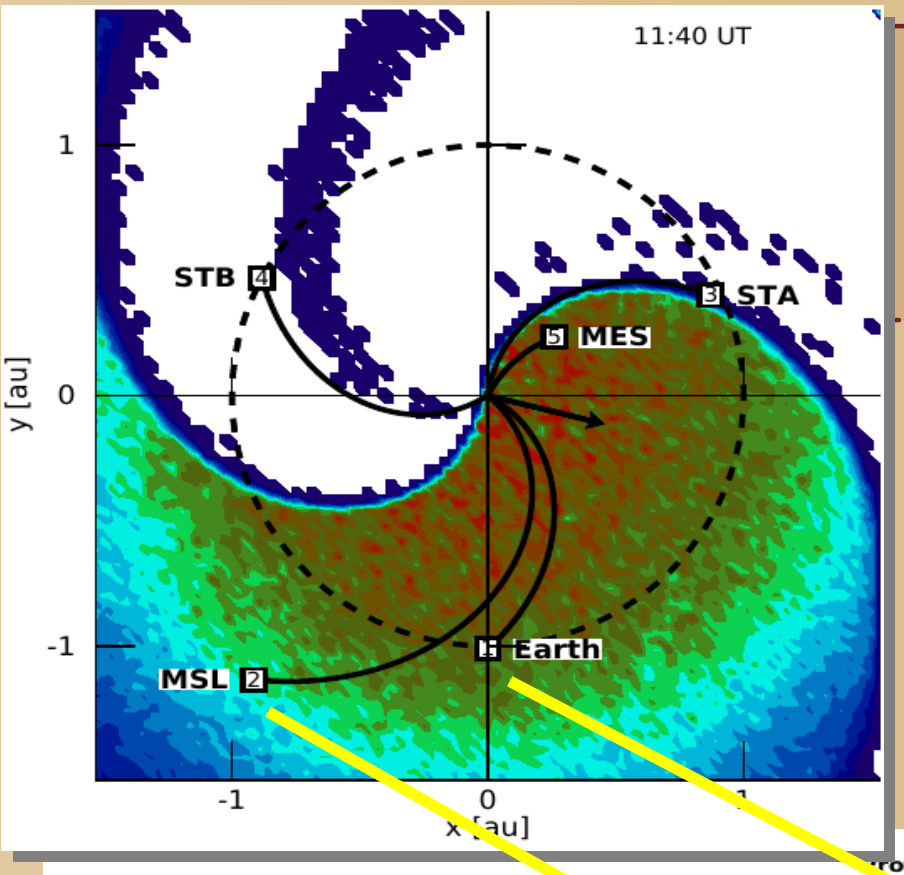
EPHIN/SOHO @ **Earth**

MSL/RAD @ **Mars**



E.g., 2012 May 17th event (cruise phase)
RAD measurement behind the sc shielding

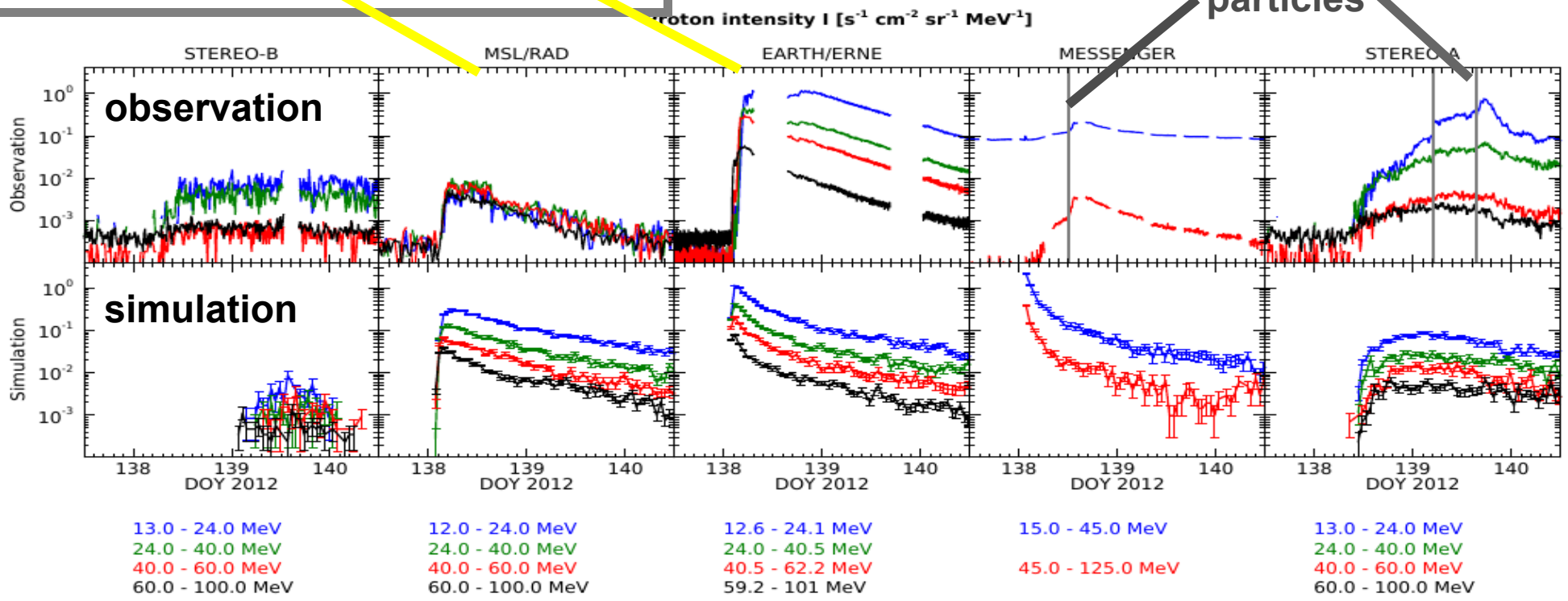




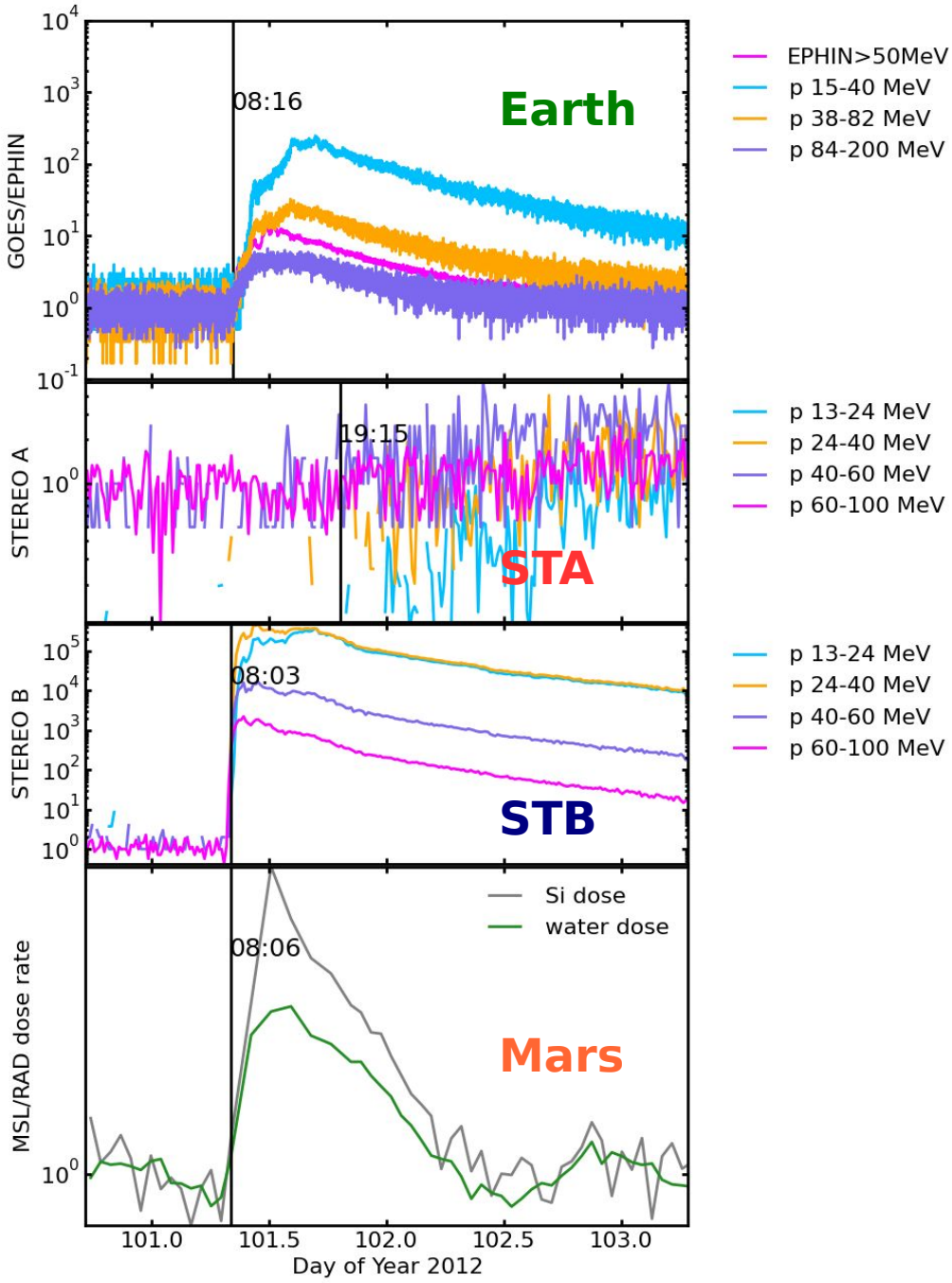
We modeled the SPE from the origin at the Sun using a 3D particle transport code

Barttarbee, Guo, Dalla et al 2017, A&A, coming soon

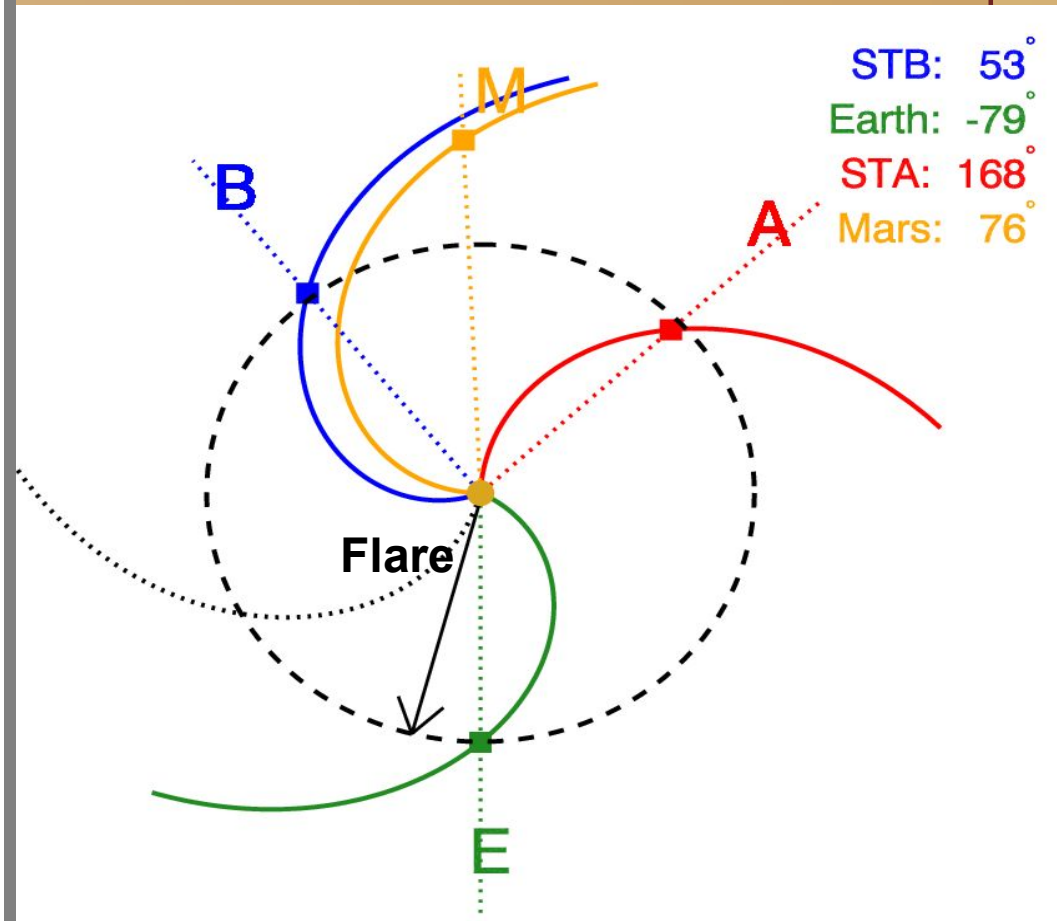
ICME shock related lower-energy particles



11/04/2013 SEP



First SPE seen on the surface of Mars!
A wide-spread event

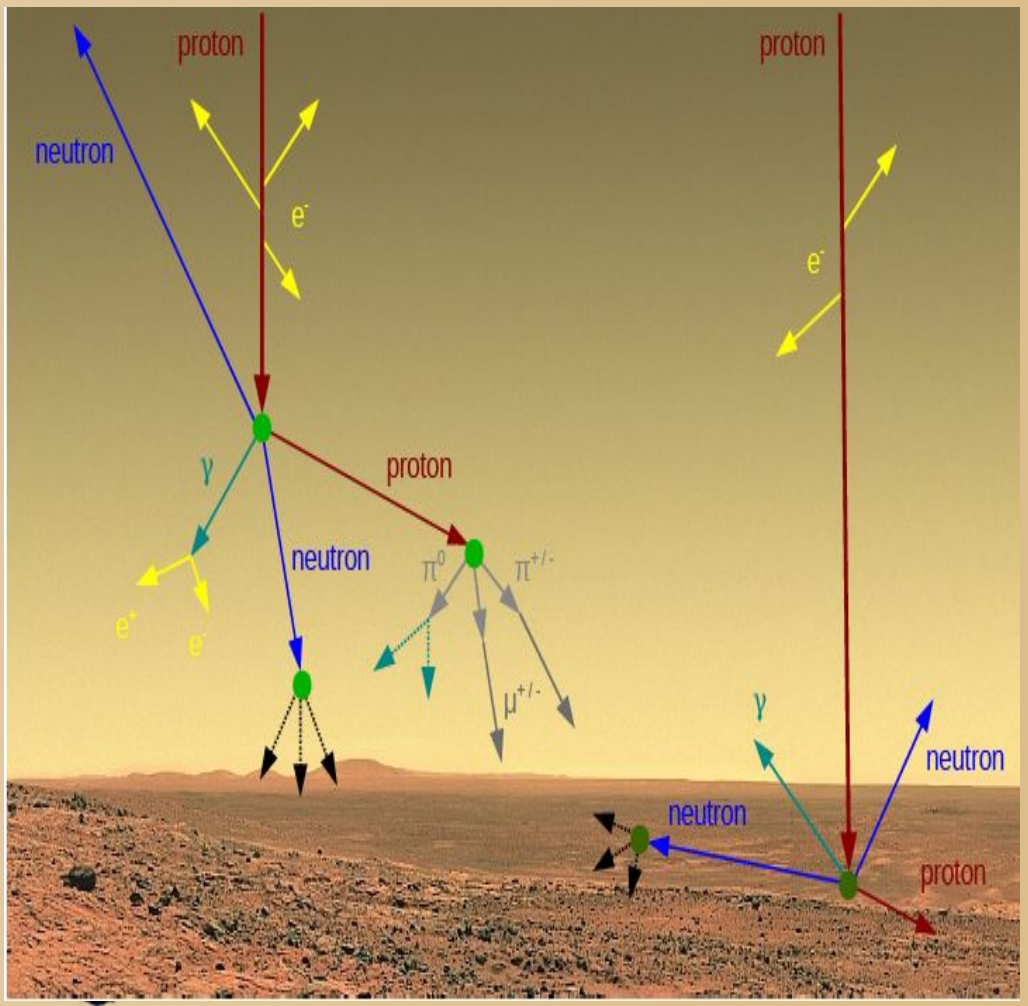


To forecast SEP events, it is important and necessary to analyze:

(1) the **heliosphere** position of the spacecraft, its connection to the flare/ICME-shock, the propagation of particles through turbulent interplanetary (IP) magnetic fields... the continuing acceleration by the ICME driven shock in the IP space with dynamic magnetic field conditions (turbulence, reconnection...)

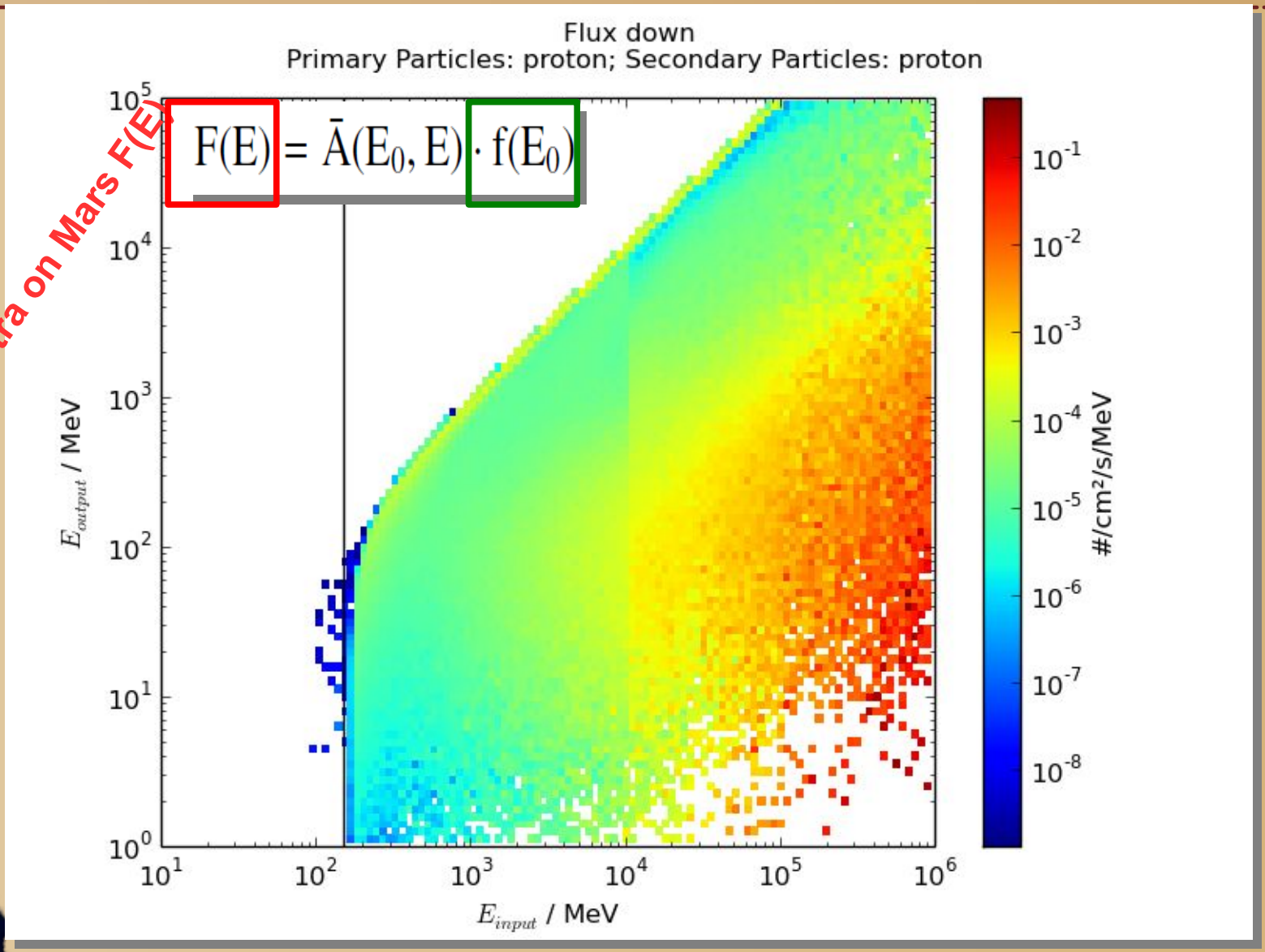
(2) the **shielding** configuration of the local environment and the viewing angle of the detectors, e.g., the spacecraft material or the planet atmosphere shielding

The GEANT4-based model applied to Mars



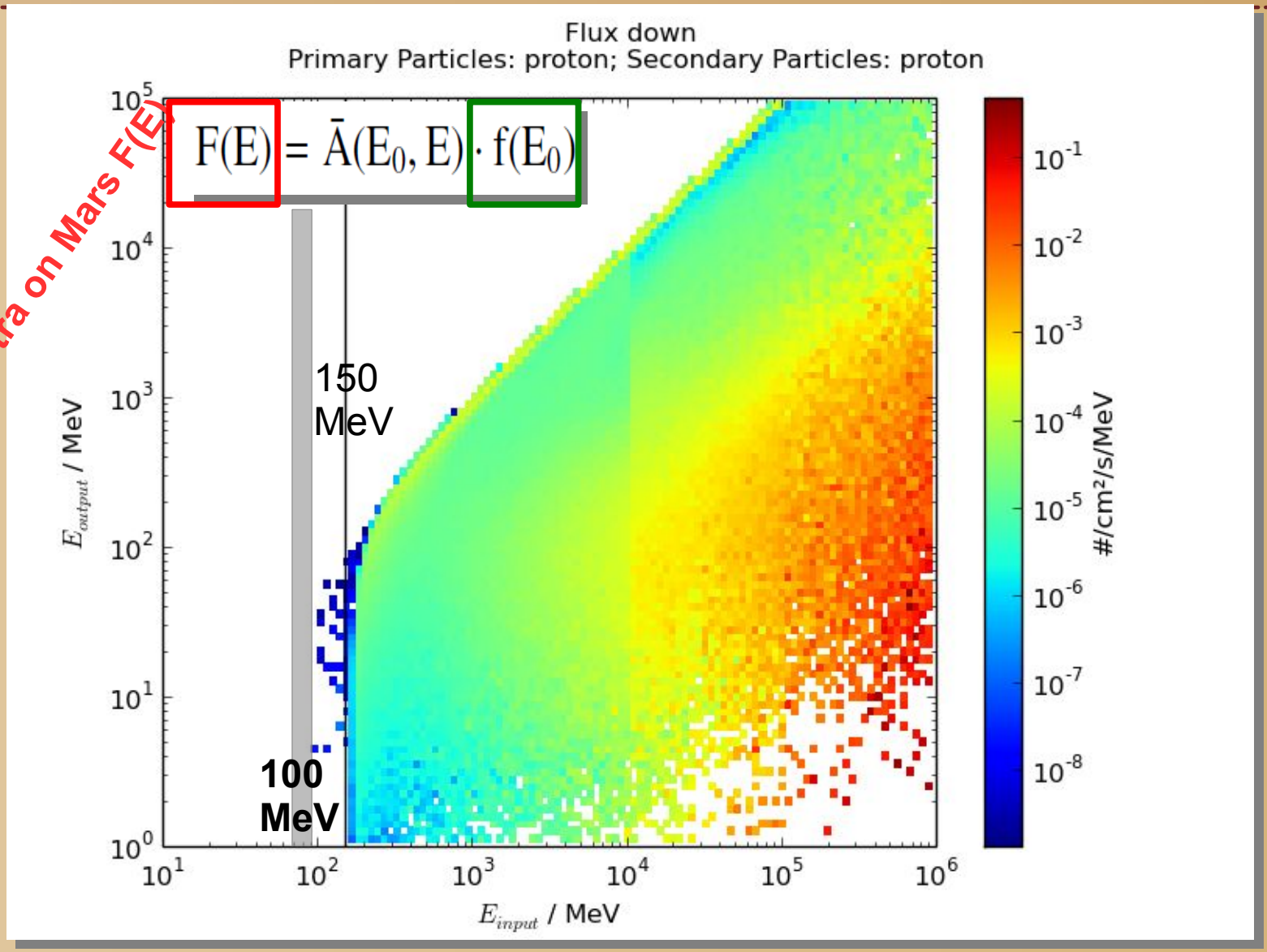
- PLANETOCOSMICS
- Electromagnetic interactions are loaded from emstandard_pt4 physics list
- Hadronic interactions are based on QGSP_BIC_HP list
- Ion hardronic interactions are provided by the PHITS
- Validated by Matthia et al 2016 & Appel et al 2017 JGR

Atmospheric modification of the spectra: illustrated by a 2D histogram (built via nuclear Monte Carlo simulations)



proton spectra in interplanetary space

Atmospheric modification of the spectra: illustrated by a 2D histogram (built via nuclear Monte Carlo simulations)



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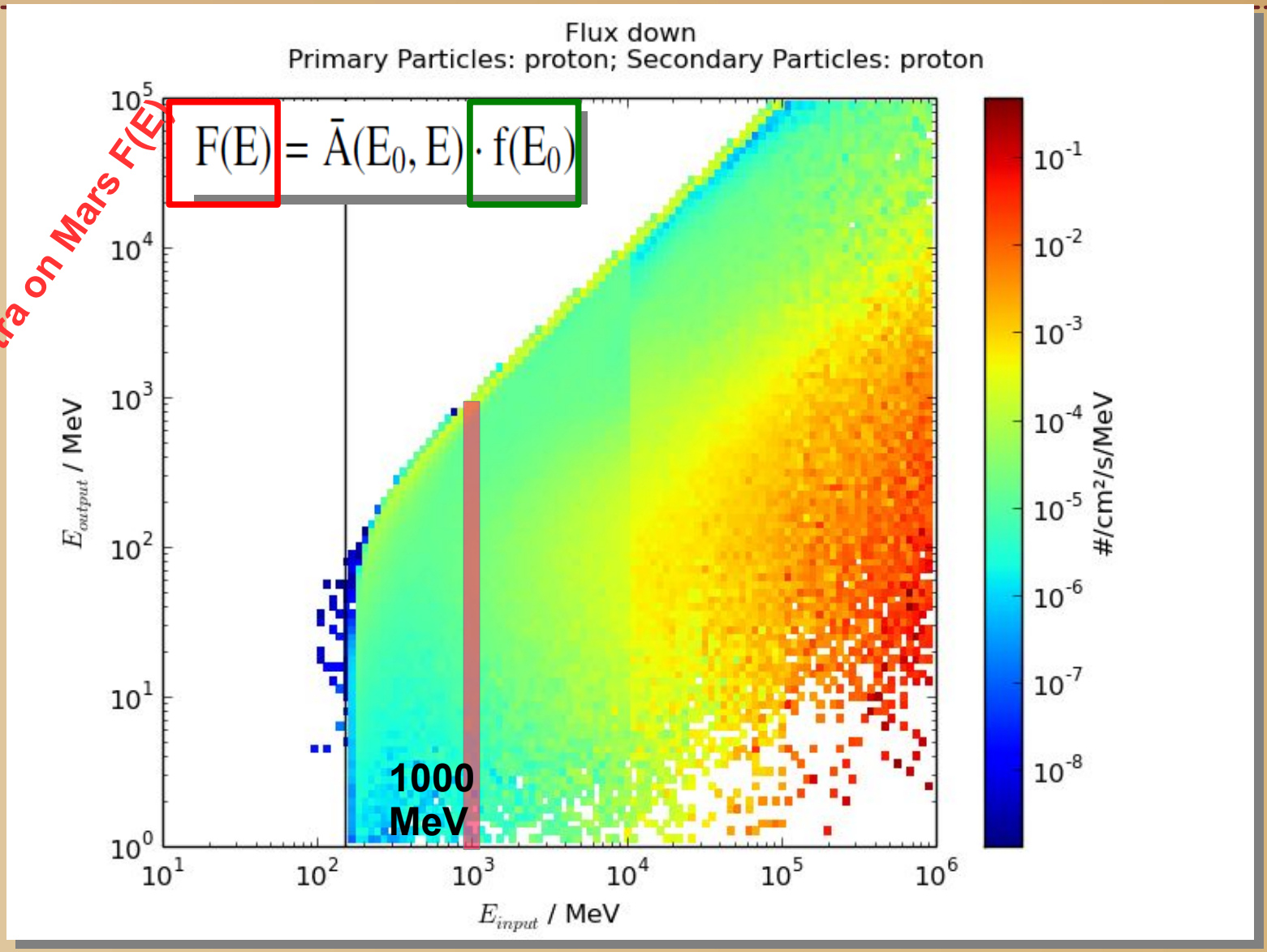


proton spectra in interplanetary space

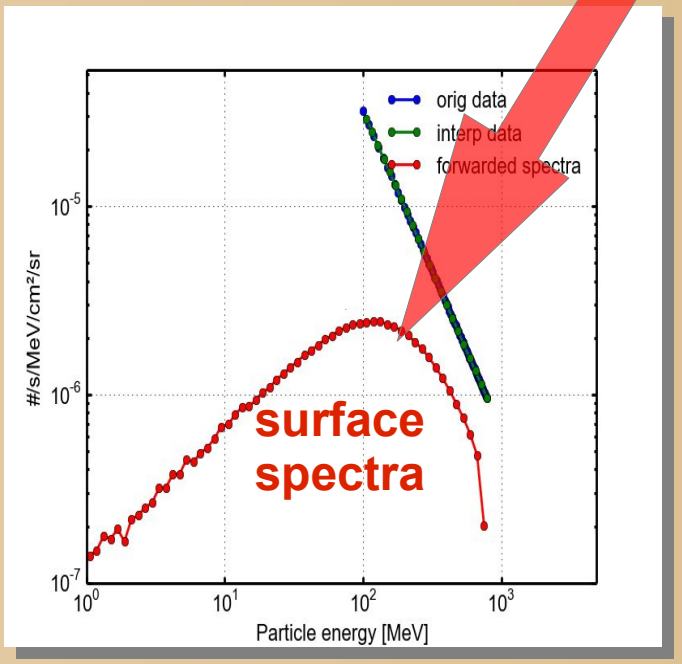
PLANETOMATRIX

$$F_{\sigma j-dn}(E_j) = \sum_i \bar{A}_{\sigma ij-dn}(E_0, E) \cdot f_i(E_0)$$

- Each Matrix is built
  - for each depth (1, 2, 3 … 25 g/cm2) through the atmosphere
  - for most primary-secondary pairs, e.g, p→mu-, He→e- ...
  - for both upward or downward directions of the secondary
- The secondary flux can be then calculated by
  - (1) multiplying the incoming flux with the corresponding matrix
  - (2) summing up the same secondary generated by different primary contributions (only protons and helium ions considered here)
- The dose rate can be calculated from all secondaries.

Forward modeling the surface spectra: Fast and Easy

$$F(E) = \bar{A}(E_0, E)\, f(E_0)$$



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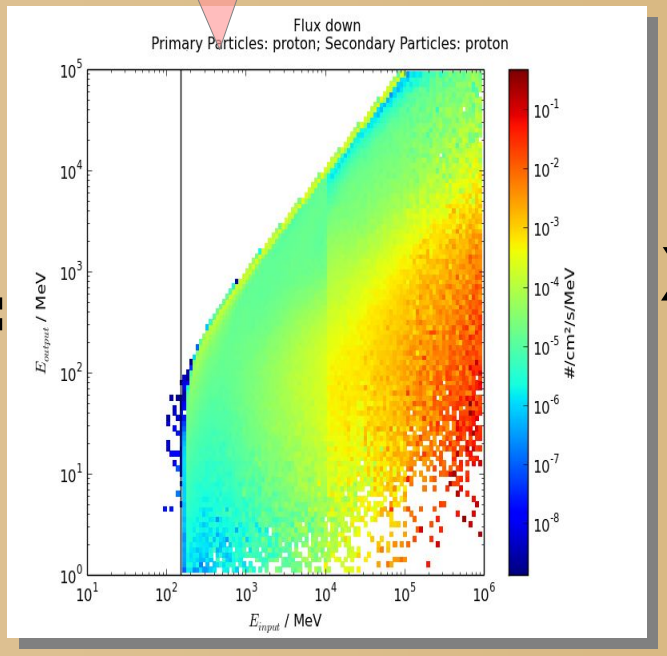
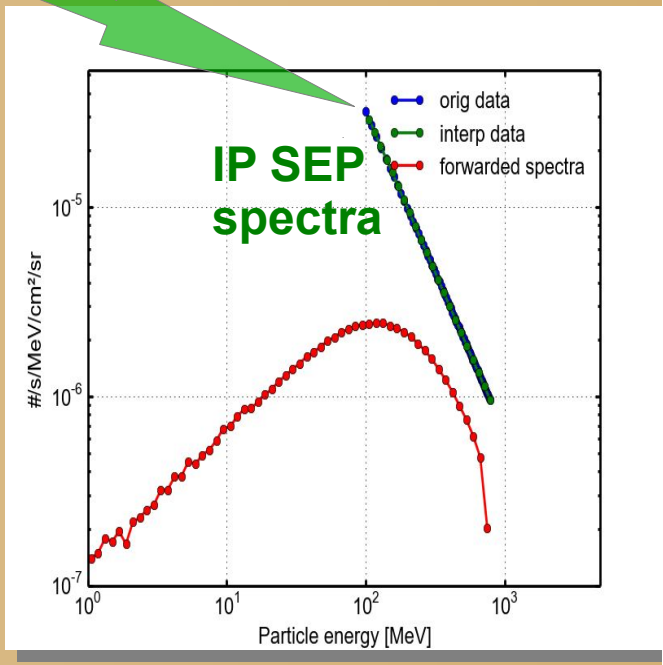
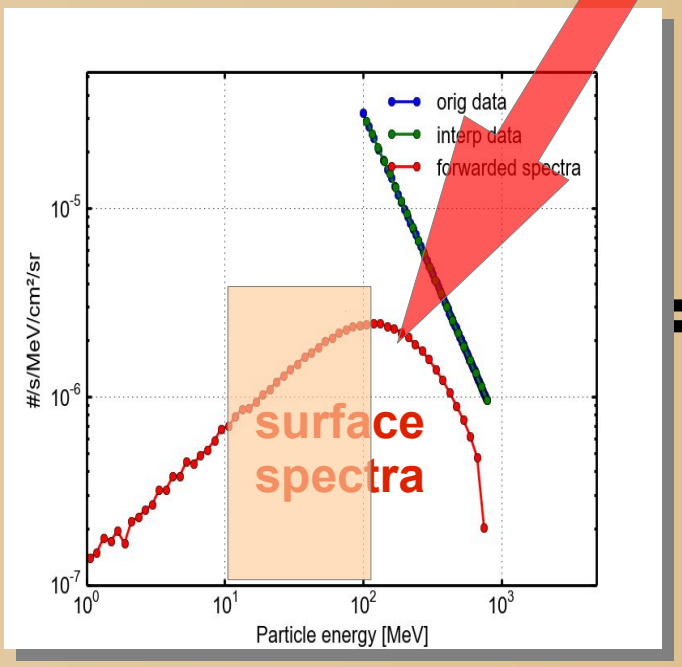


X



Inversion? Well…

$$F(E) = \bar{A}(E_0, E)\, f(E_0)$$



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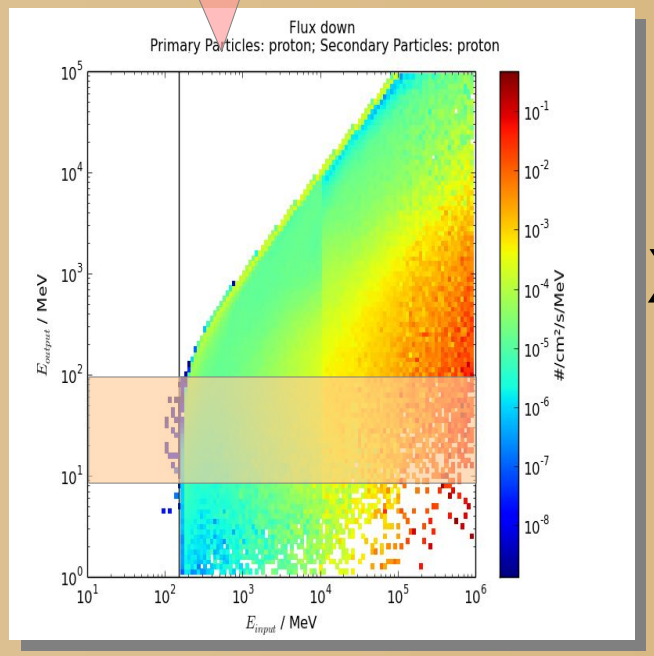
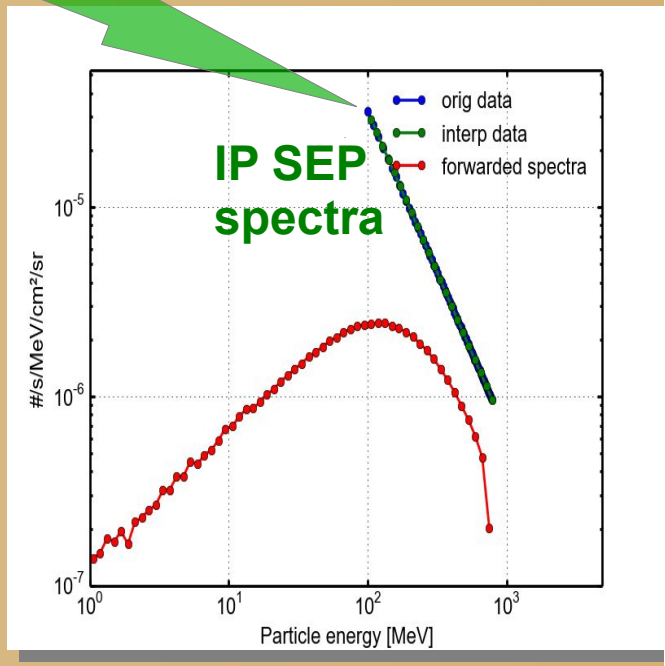


X

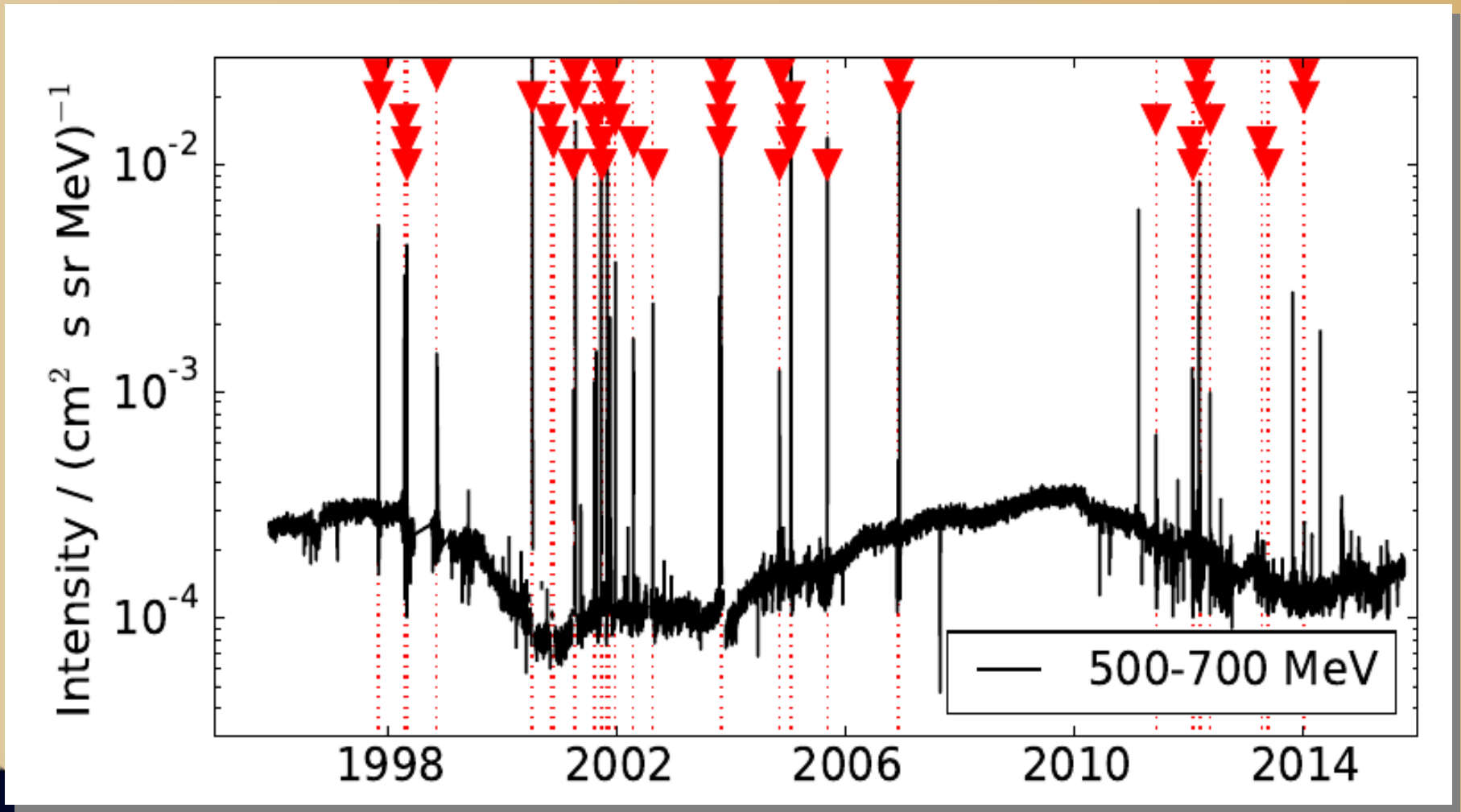


Stopping proton spectra (10-100 MeV) measured by RAD

?

Direct inversion is very difficult !!!
And it is not relevant for radiation on Mars

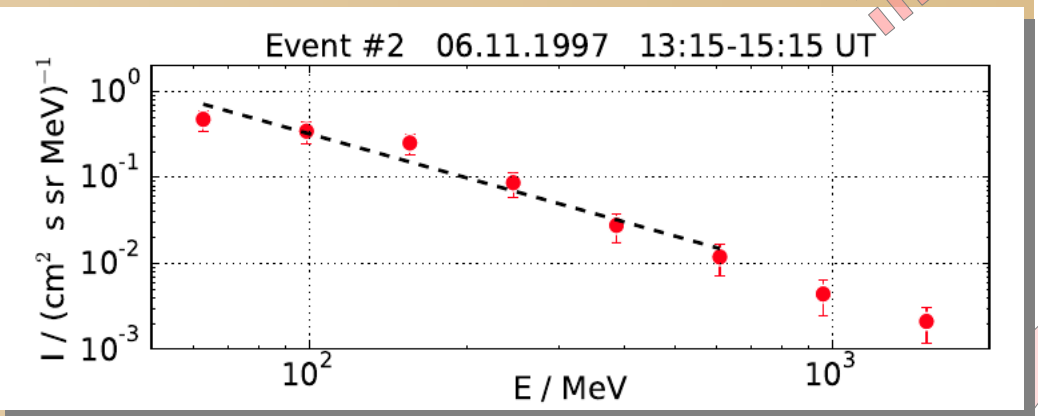
High-energy SEP events during 20 years of SOHO obs.



Kuehl et al 2016

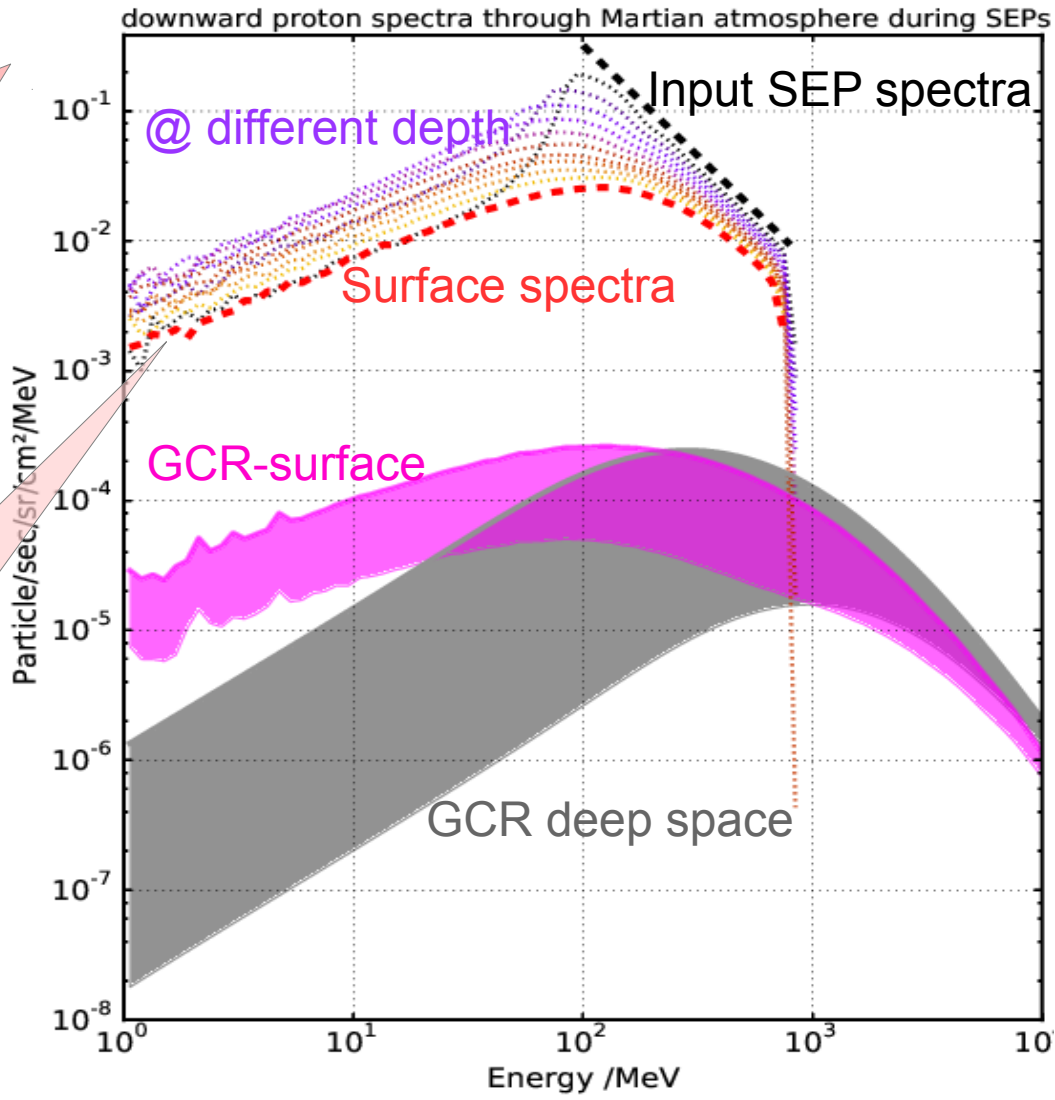
Modeling the Mars surface spectra and dose rate using 30+ power-law shaped SEP events observed at Earth

The input spectra is selected to be a set of **SOHO/EPHIN** events fitted with a power-law of 100-800 MeV,e.g.,

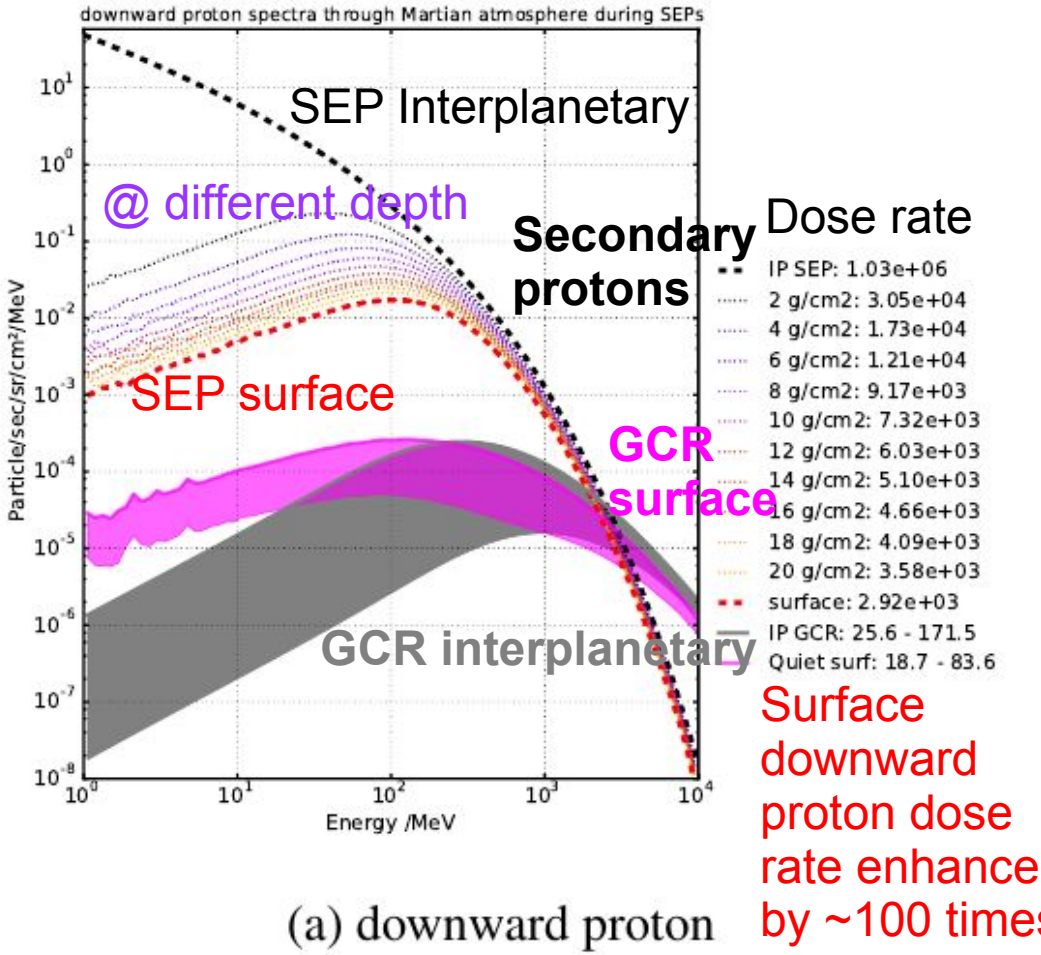


$$I(E) = I_0 \cdot (E/E_0)^{\gamma}$$

An example of induced surface proton spectra from the SEPs, compared to quiet GCR spectra in deep space and on the surface of Mars

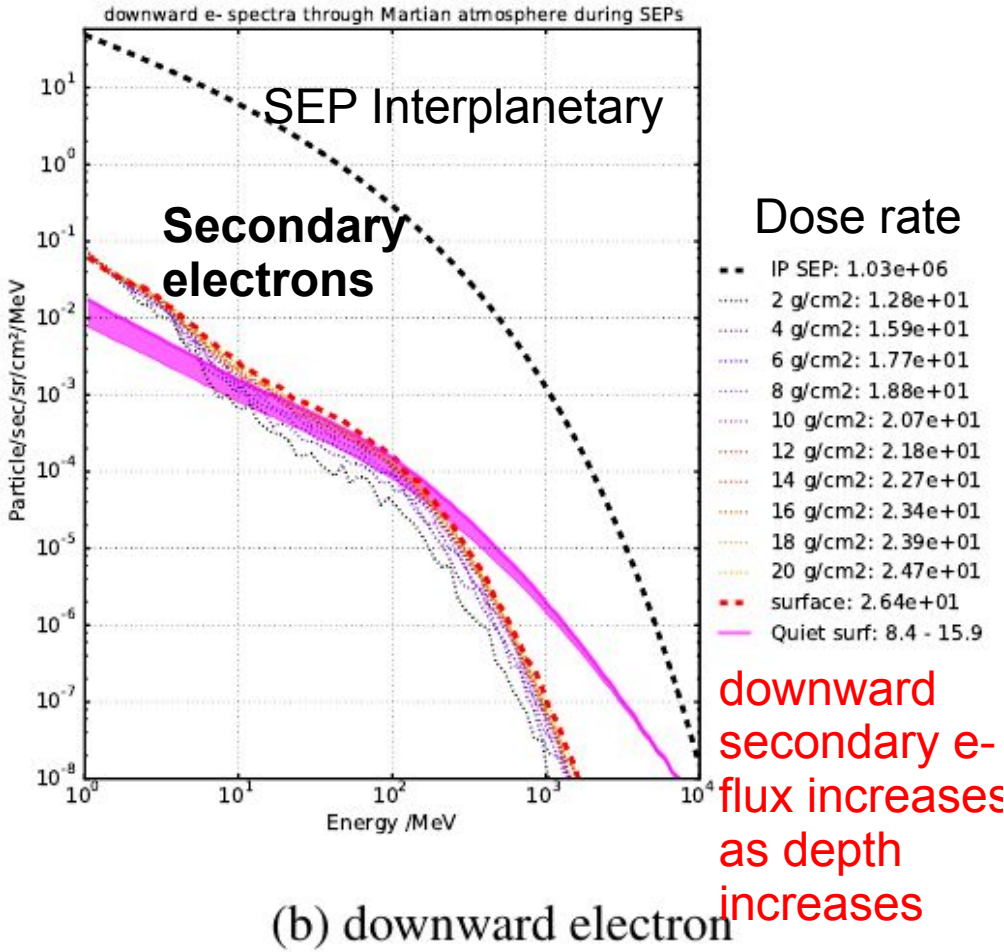


Also studied (non-power law) **full SEP spectra**, e.g., Oct89 event



(a) downward proton

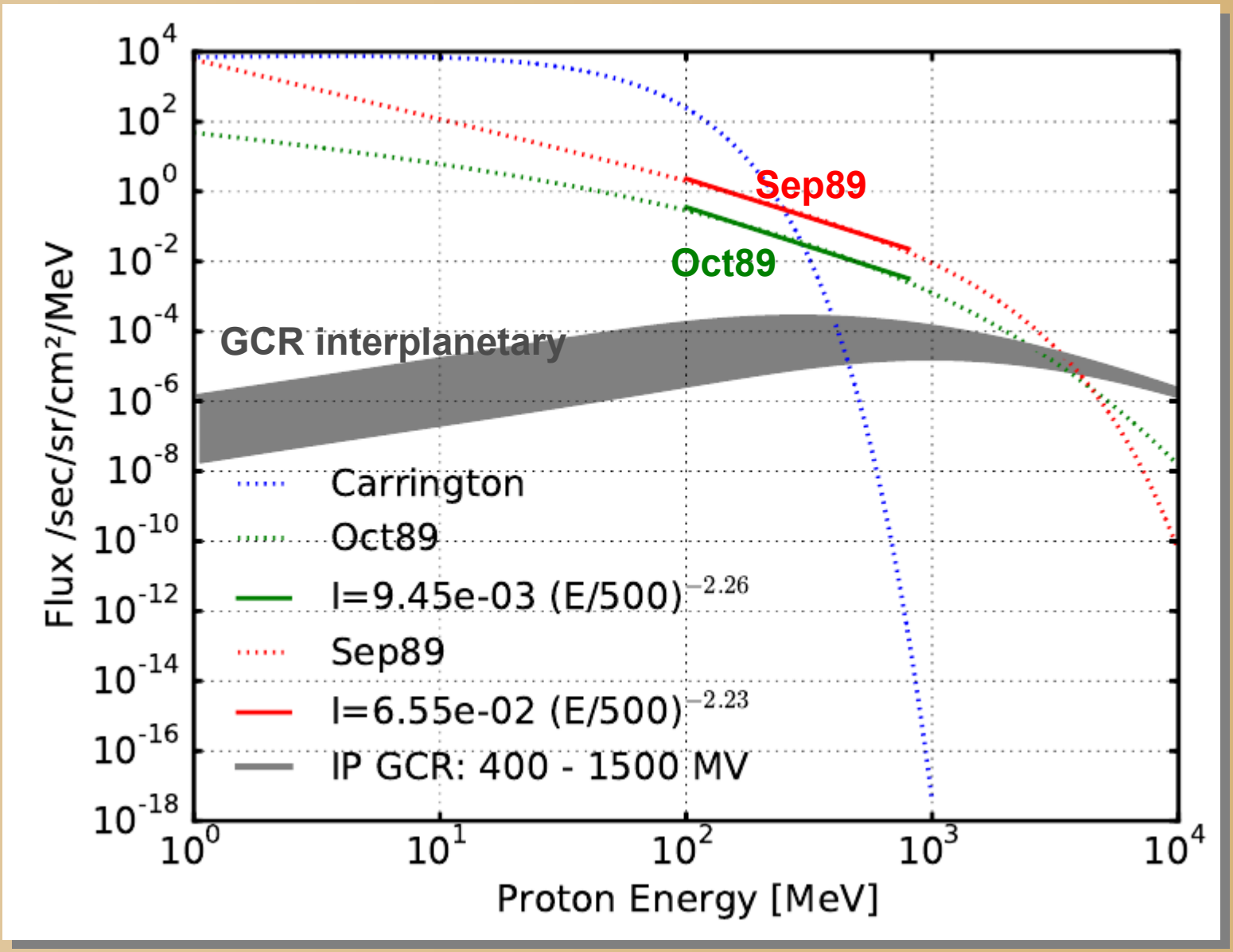
Surface downward proton dose rate enhanced by ~100 times



(b) downward electron

downward secondary e- flux increases as depth increases

Comparison between the full spectra and 100-800 MeV power-law range



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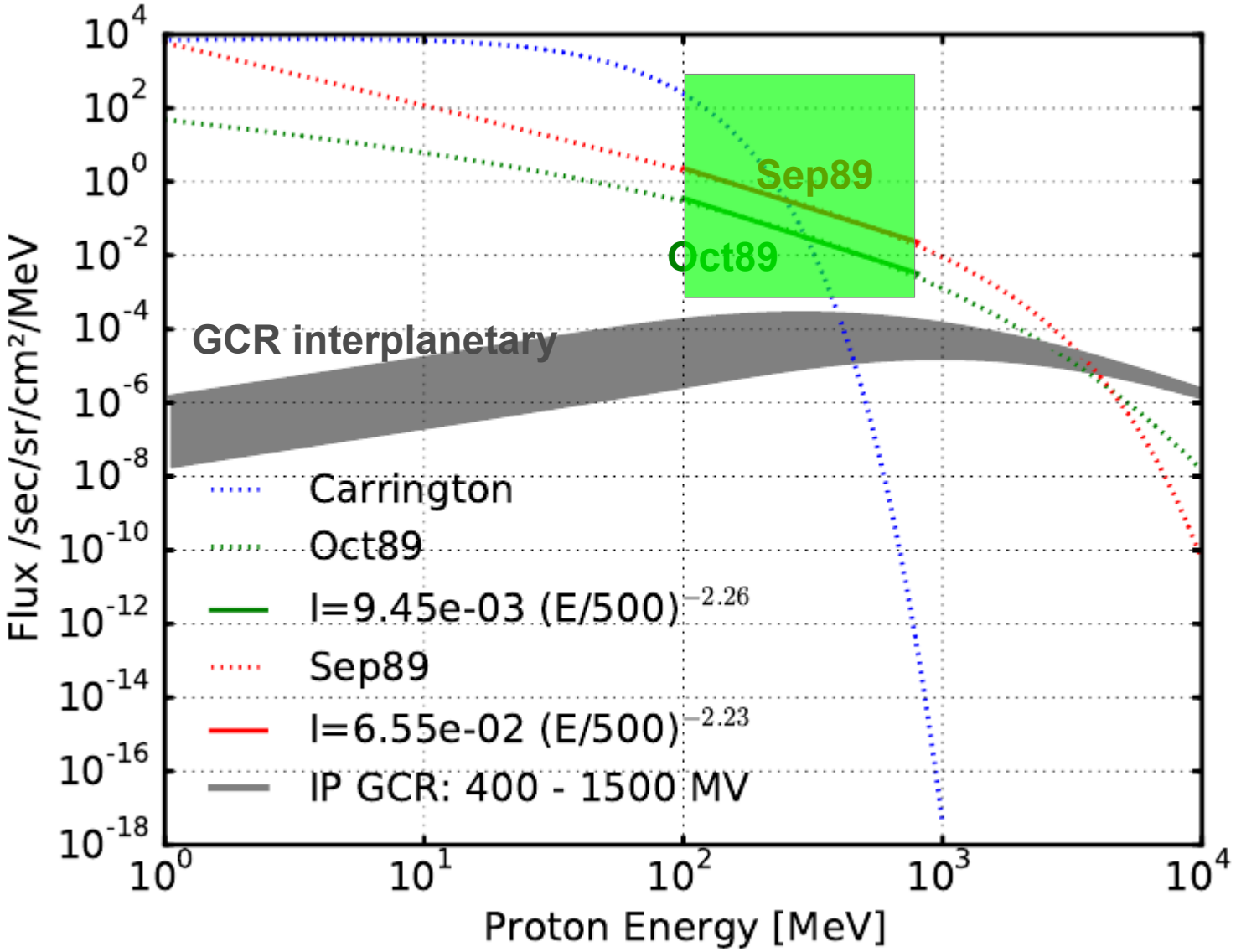
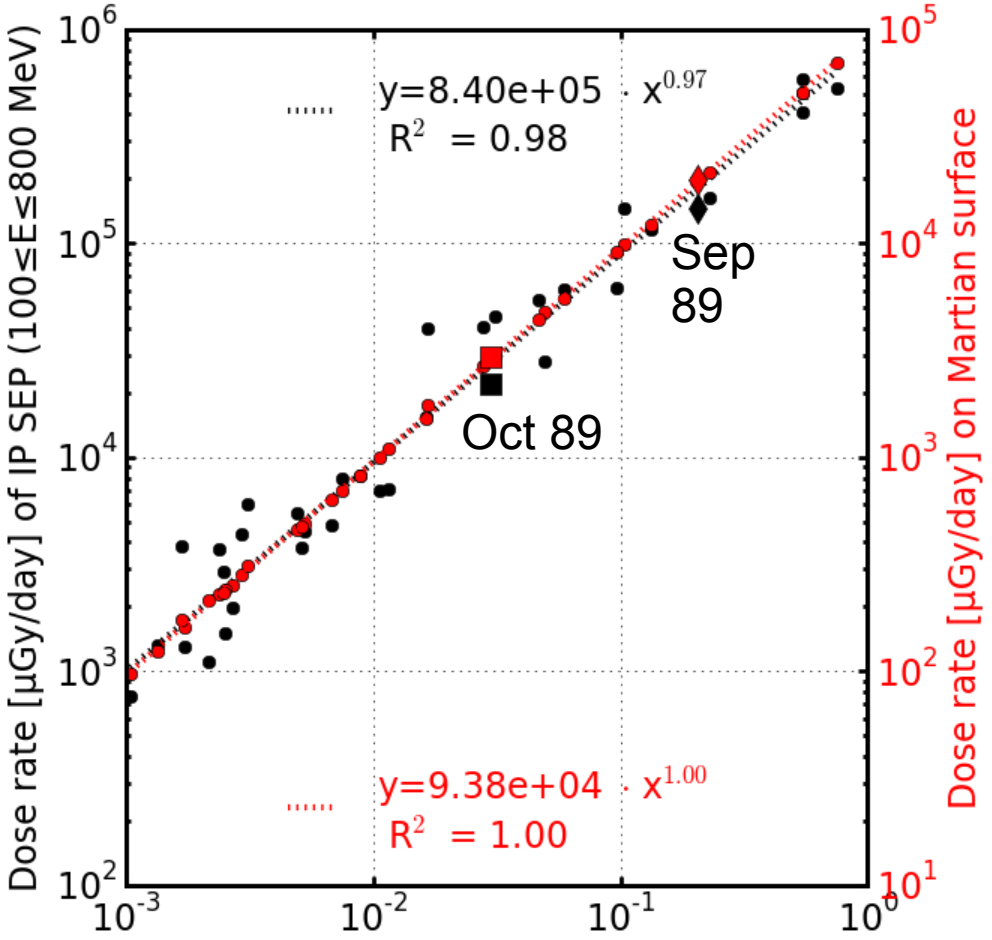


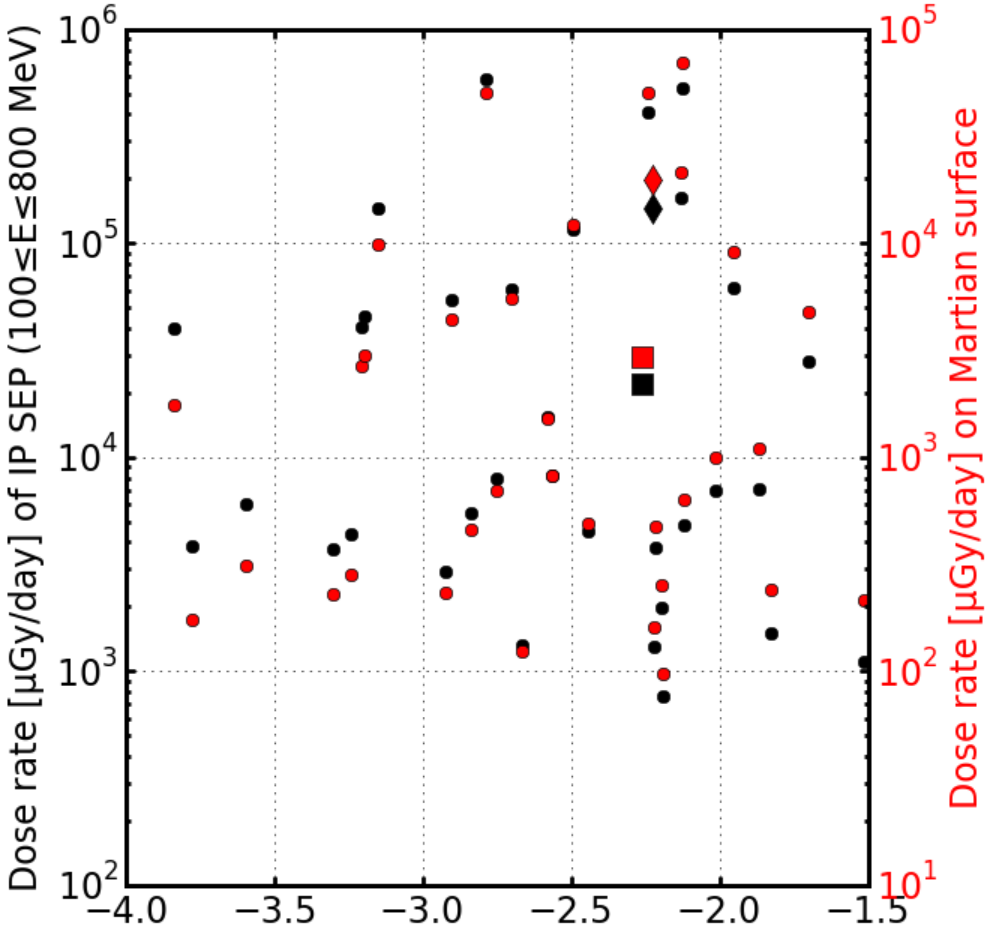
In deep space, the 100-800 MeV range of the Sep89 event results in only 0.69% of the dose rate of the full spectra.

However the dose rate induced by these SEPs contributes to 93% of the total surface dose rate.

Good correlation between surface total dose rate and spectra intensity of the 30+ historical SPEs (power-law from 100-800 MeV) → **The RAD measured dose rate can be used to infer the intensity of a power-law SEP spectra.**



IP SEP Intensity at 300 MeV



Power-law index

More details in Guo et al 2017, ApJ

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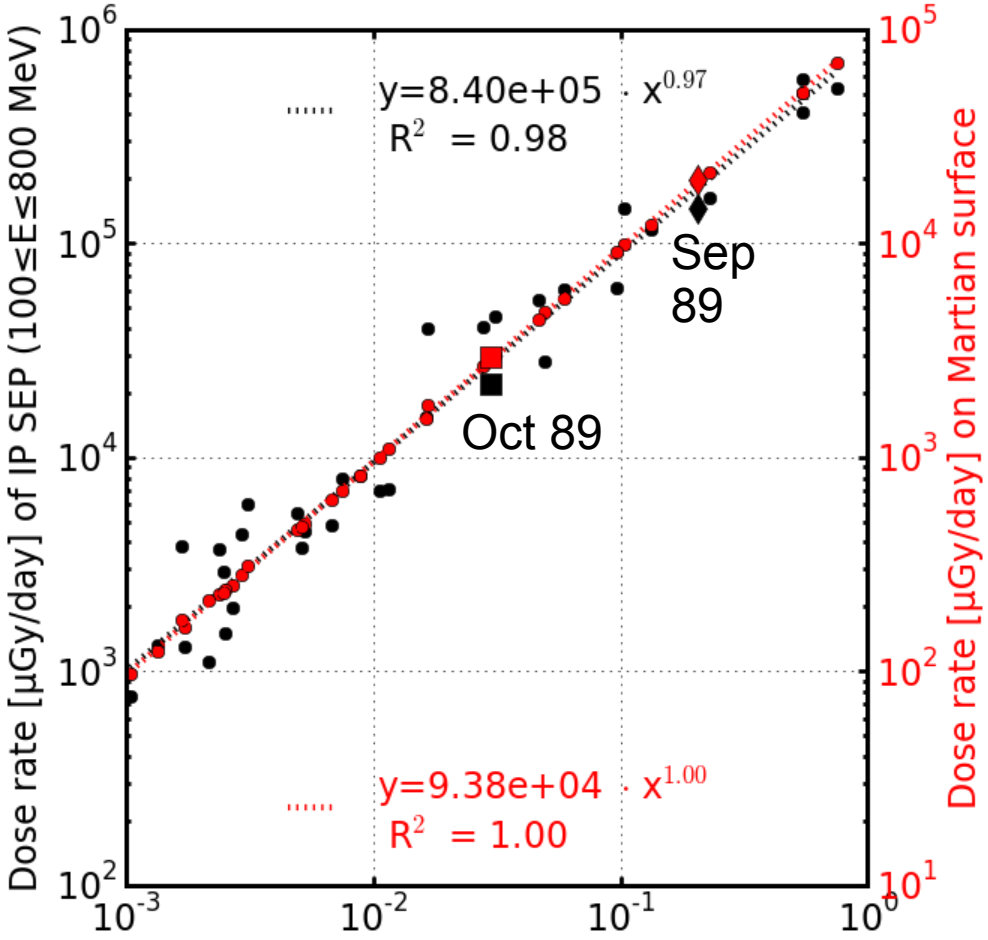

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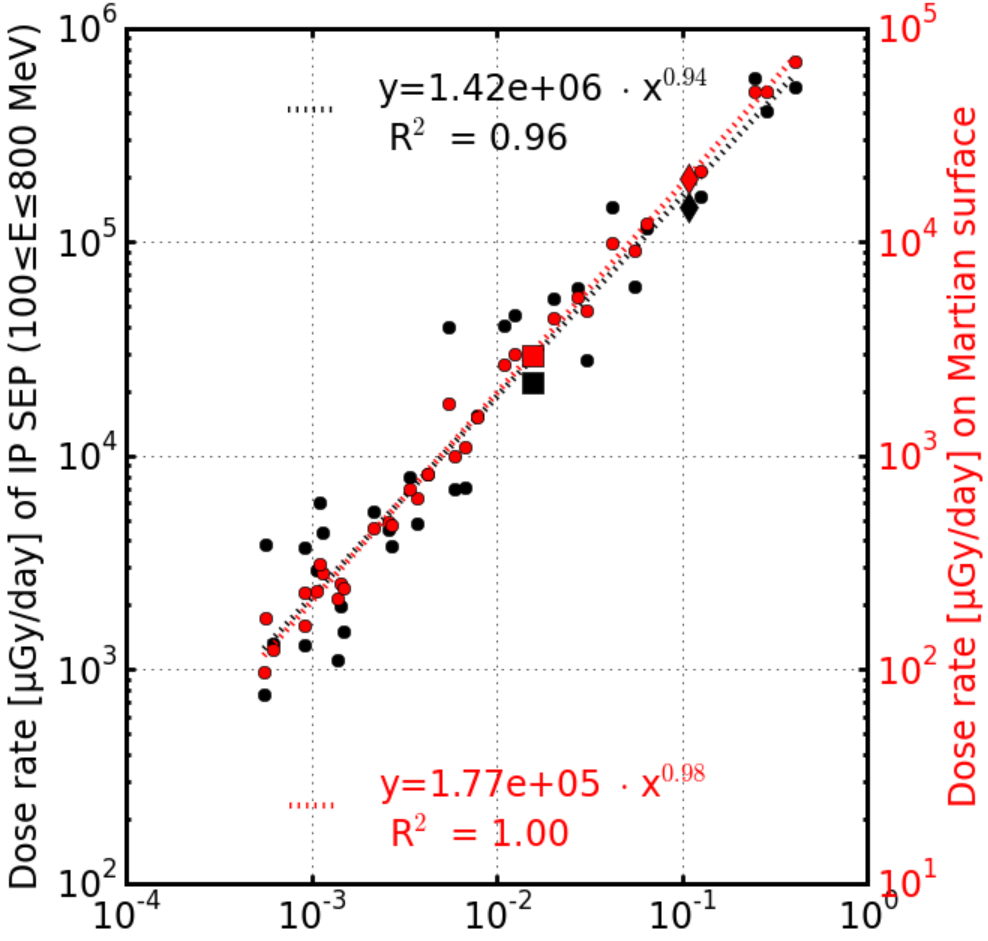

IP SEP Intensity at 400 MeV

More details in Guo et al 2017, ApJ

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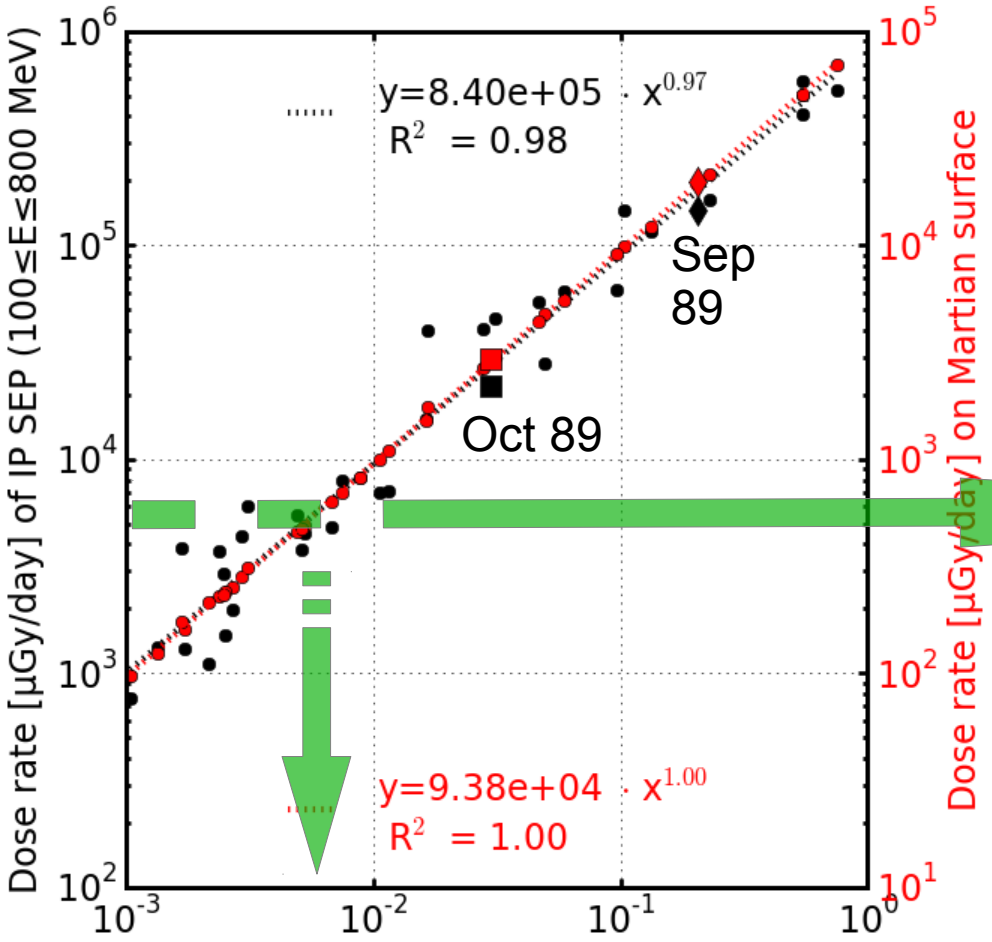
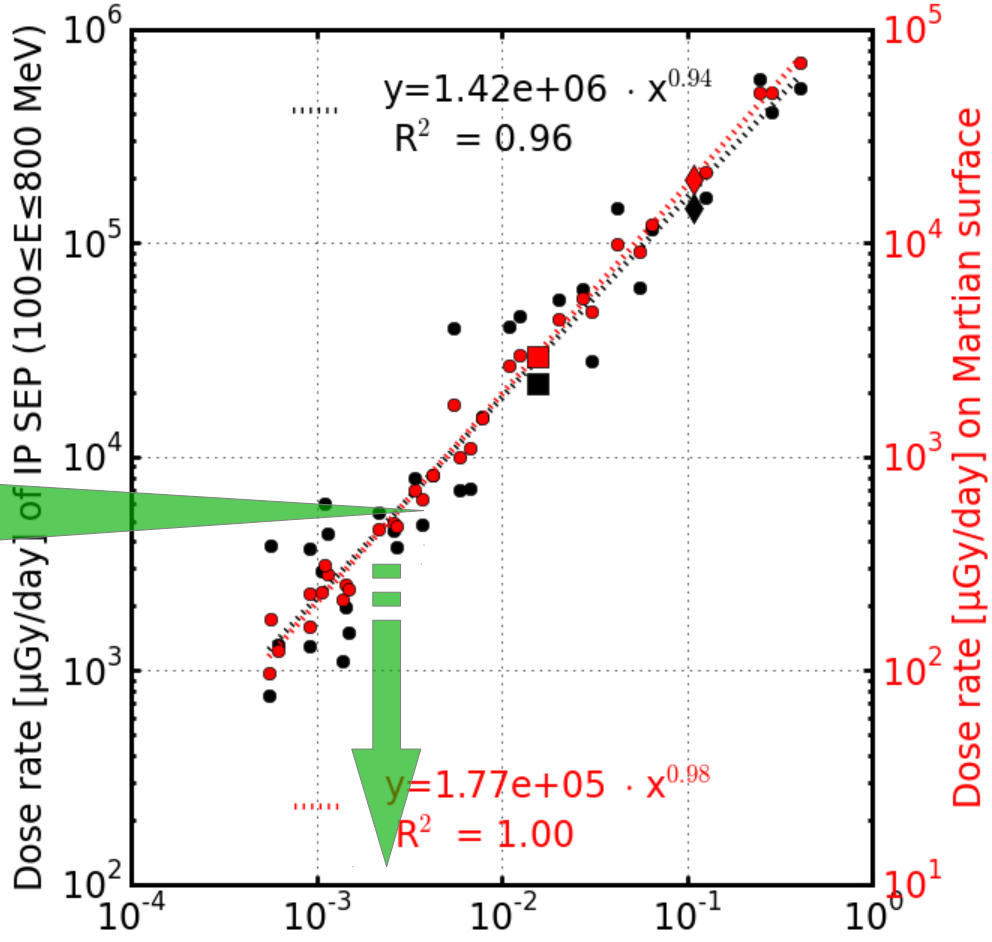


IP SEP Intensity at 300 MeV

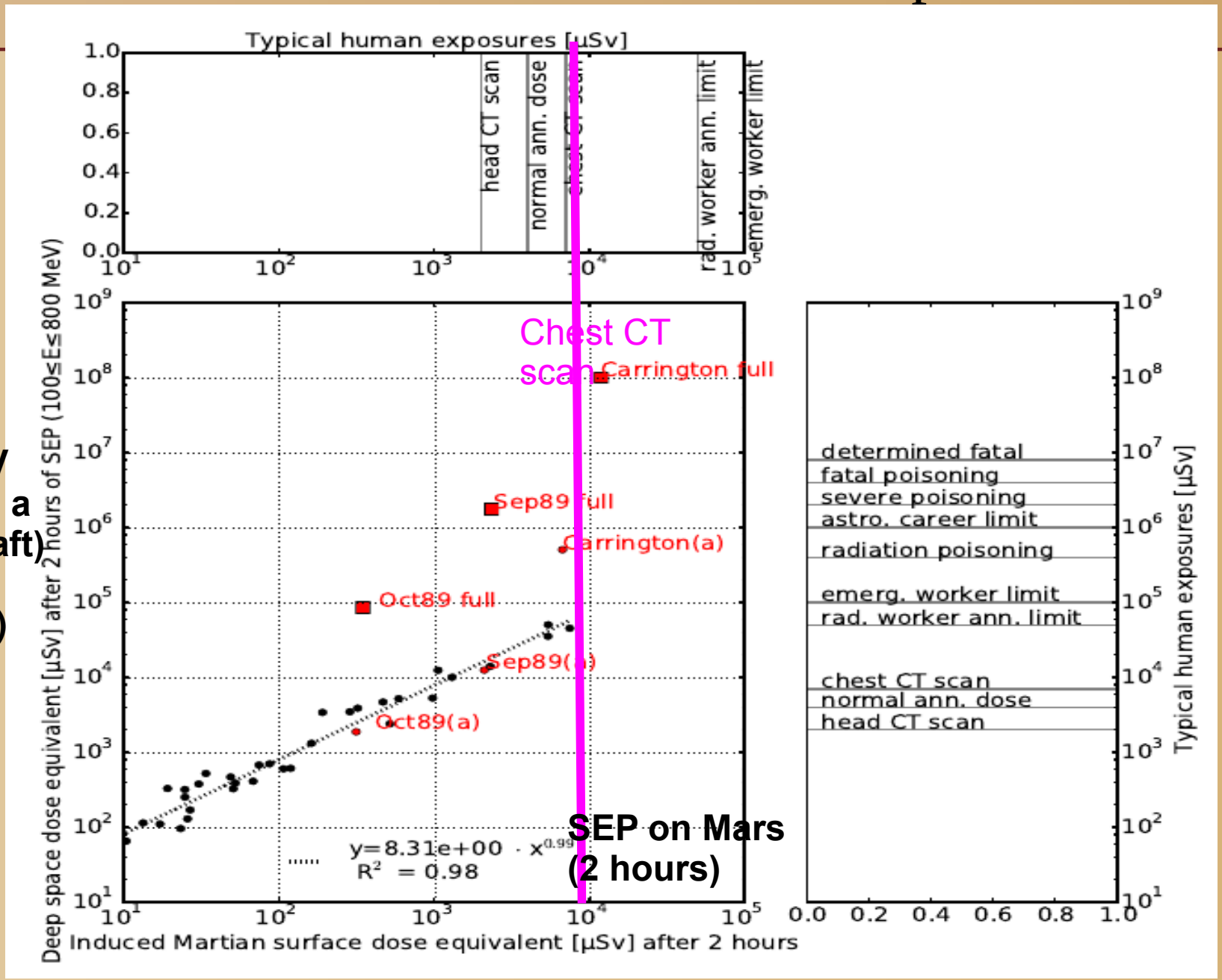


IP SEP Intensity at 400 MeV

SEP radiation dose equivalent (2 hours) on the surface Mars & inside a spacecraft

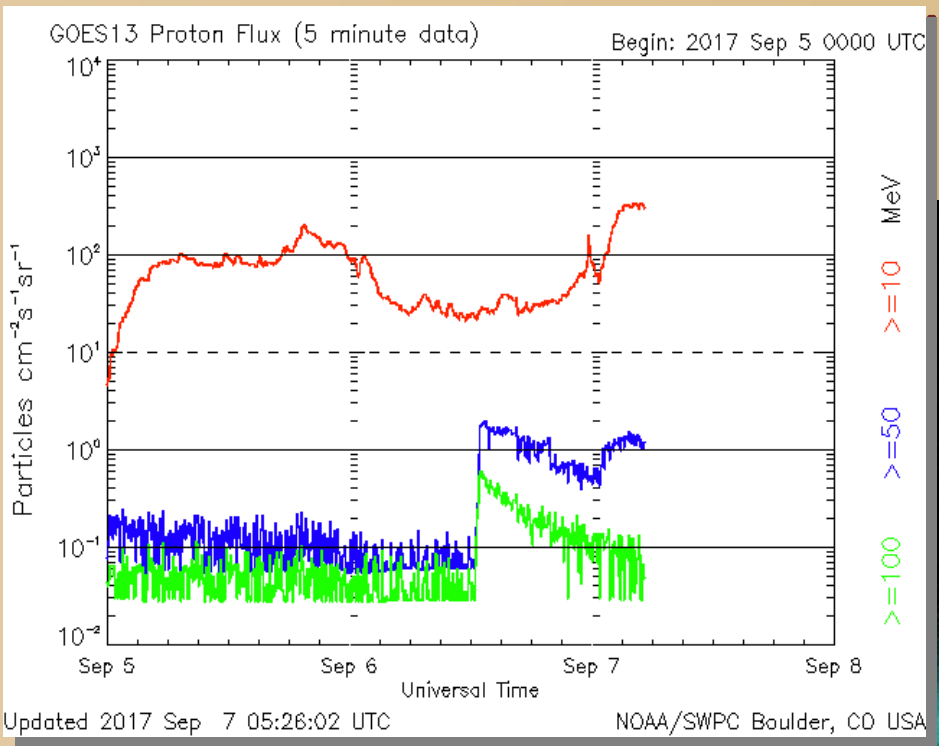
SEP >100MeV (~ inside a spacecraft)

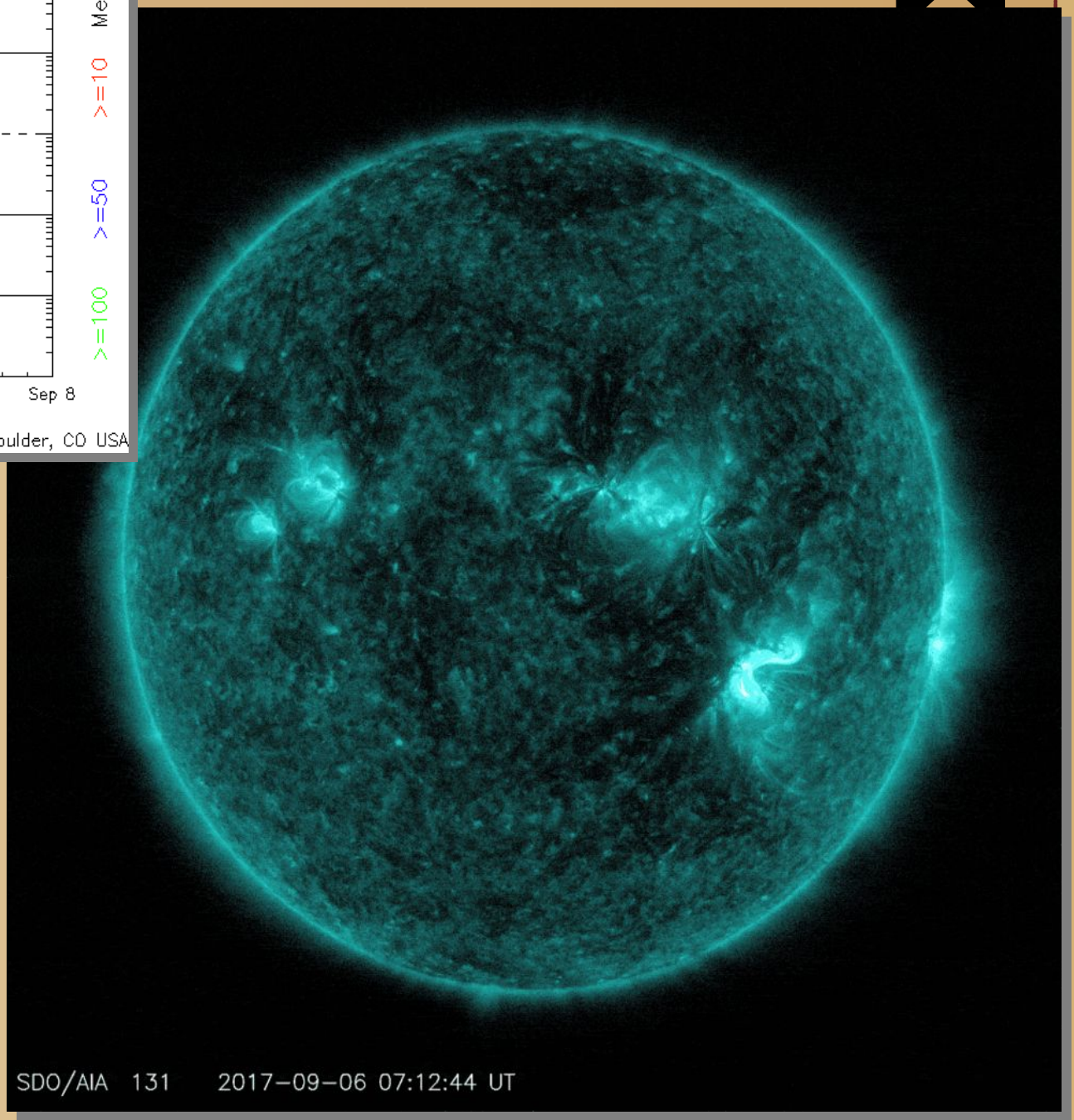
(2 hours)



Summary and Conclusion

- We have developed a generalized approach to model the Martian surface (and also different depths of the atmosphere) radiation environment which can simplify the simulations from hours down to seconds for any given SEP (and helium ion) spectra.
- We have provided some benchmark and convenient formulas for estimating the Martian surface radiation environment induced by power-law shaped SEPs.
- SEP induced dose and dose equivalent rates in deep space are very **different** from those on the surface of Mars due to the Martian **atmospheric modification** of the incoming particle spectra.
  - The 2-hour accumulated dose on the surface of Mars of any of the extreme SPEs (observed near Earth in the last 20 years) is less than 10 mSv, i.e., less than (or equivalent to) a chest CT scan.
- **To predict the SEP-induced radiation environment on Mars, it is probably sufficient to have a detector monitoring the 100-800 MeV proton intensities towards Mars.**
- The work is supported by DLR's grant to the Christian Albrechts University, Kiel. We thank Daniel Mattiä at the Germany Space Agency (DLR) for helping to set up the PLANETOCOSMICS and the BON models.

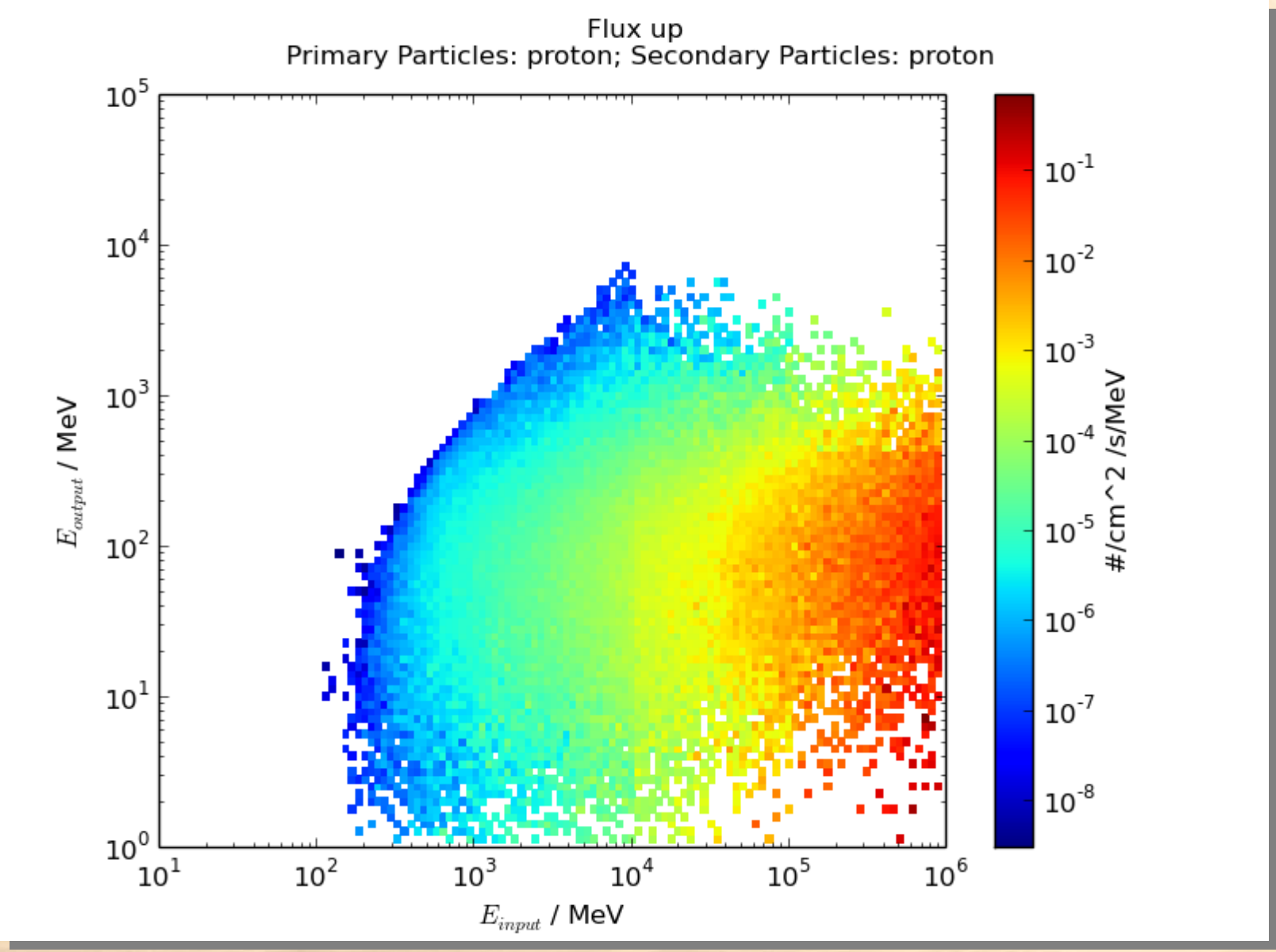




Flare onset:
2017-09-06 09:30

GOES proton:
2017-09-06 12:00

Proton → Upward proton matrix



Proton → Downward neutron matrix