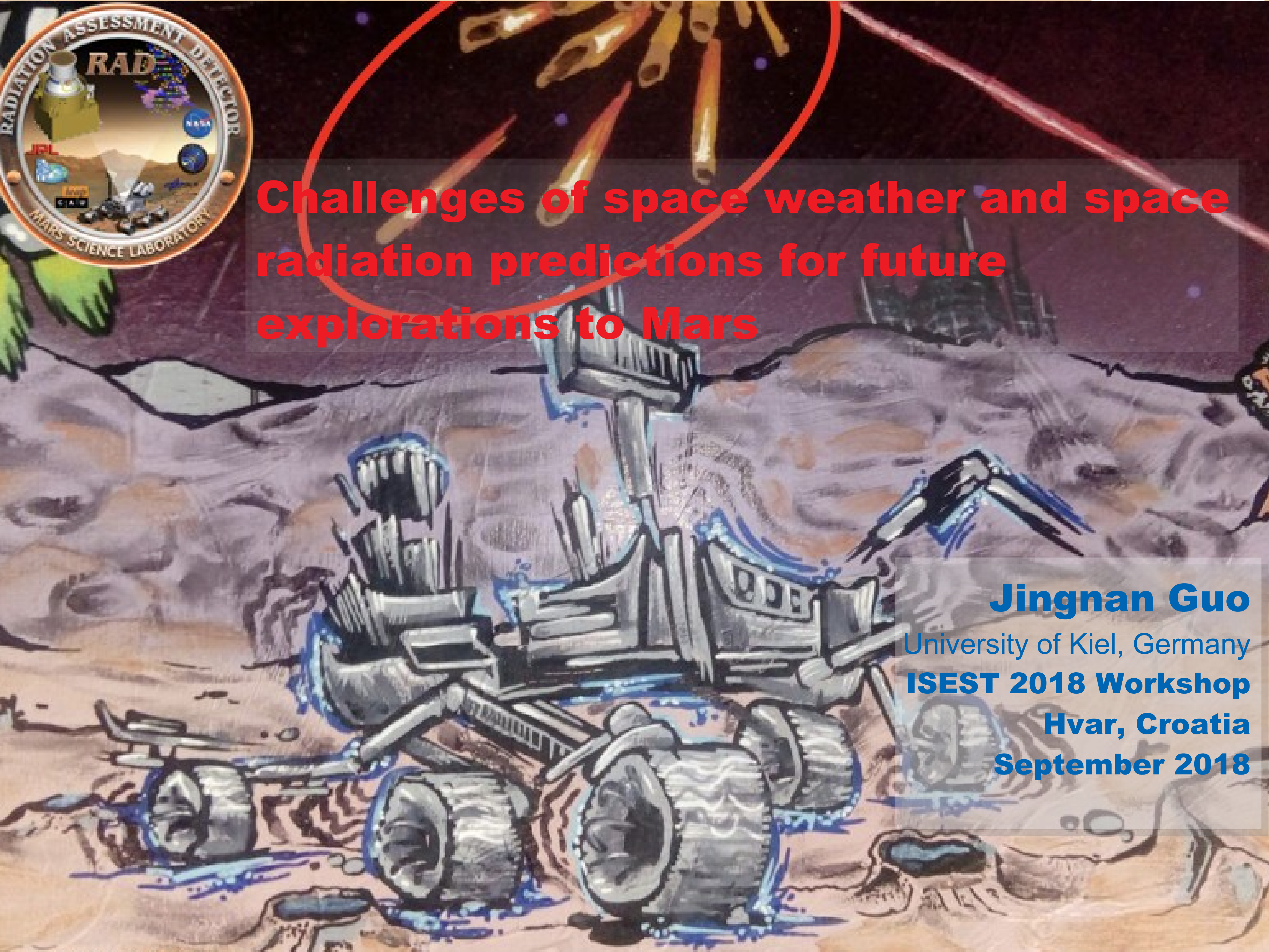
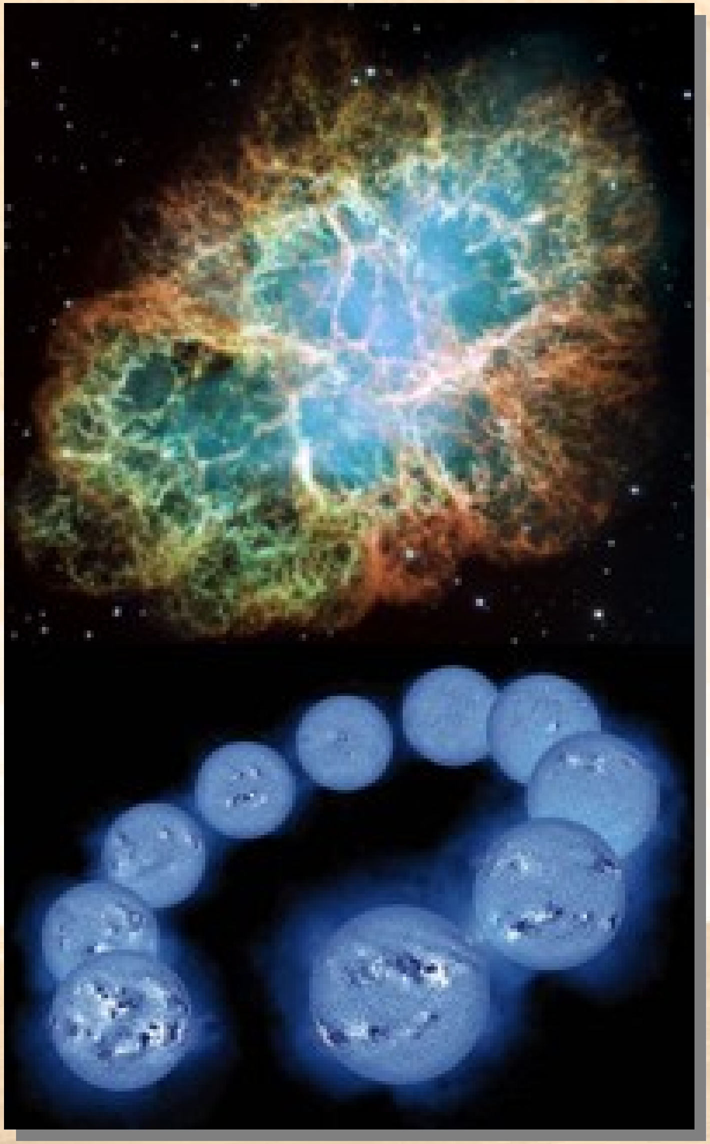


Challenges of space weather and space radiation predictions for future explorations to Mars

Jingnan Guo
University of Kiel, Germany
ISEST 2018 Workshop
Hvar, Croatia
September 2018

Particle Radiation Sources in Space and on Mars



Galactic Cosmic Rays:

Very high energies, modulated by heliospheric activities, highly penetrating, but predictable (Guo+2018, AJ / JSWSC **Implementing a** Mars surface radiation **environment tool under europlanet project: http://radmaree.irap.omp.eu**)

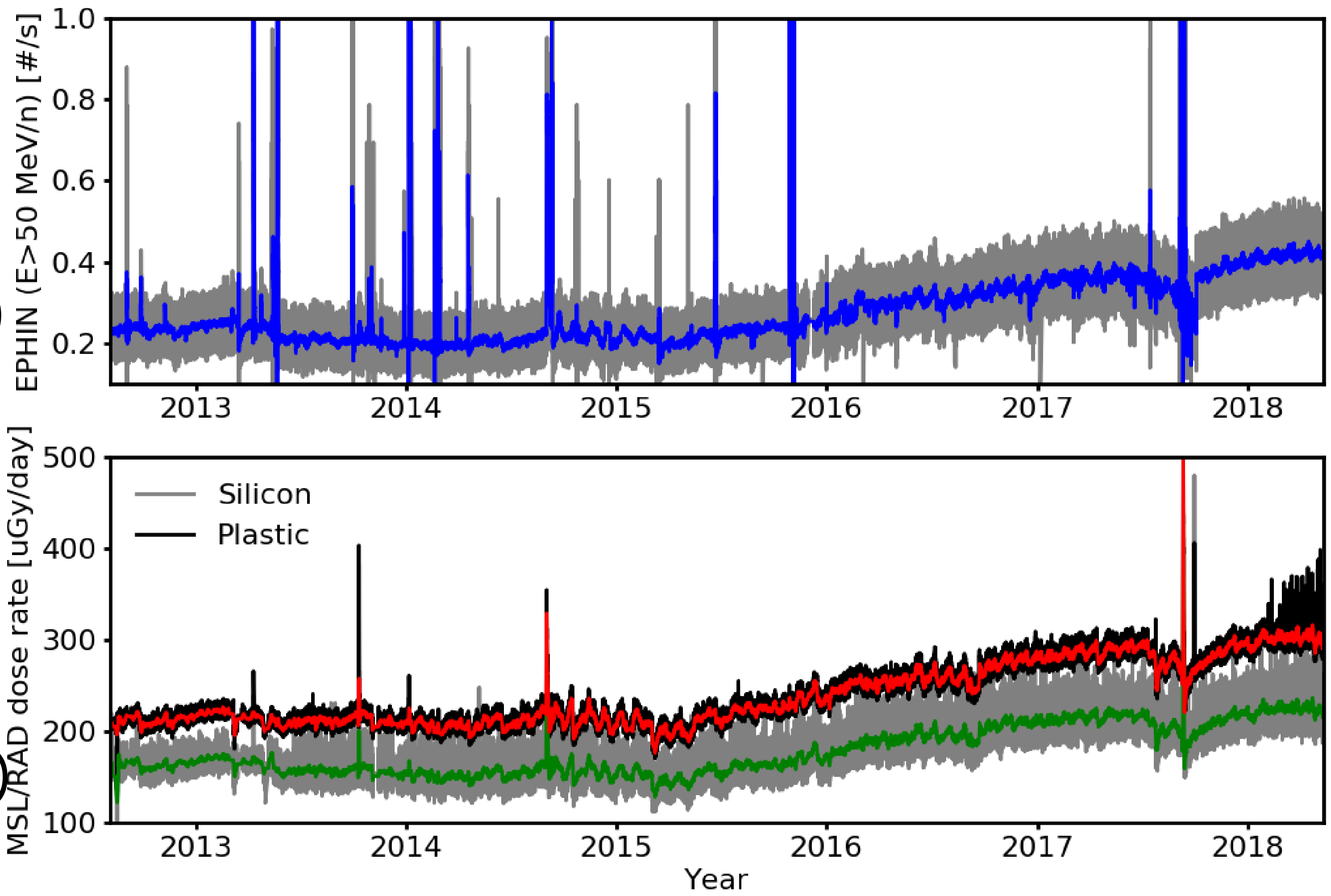
Solar Energetic Particles:

sporadic, variable, dynamic, high dose deposit in deep space. (more easily shielded due to their lower energies)

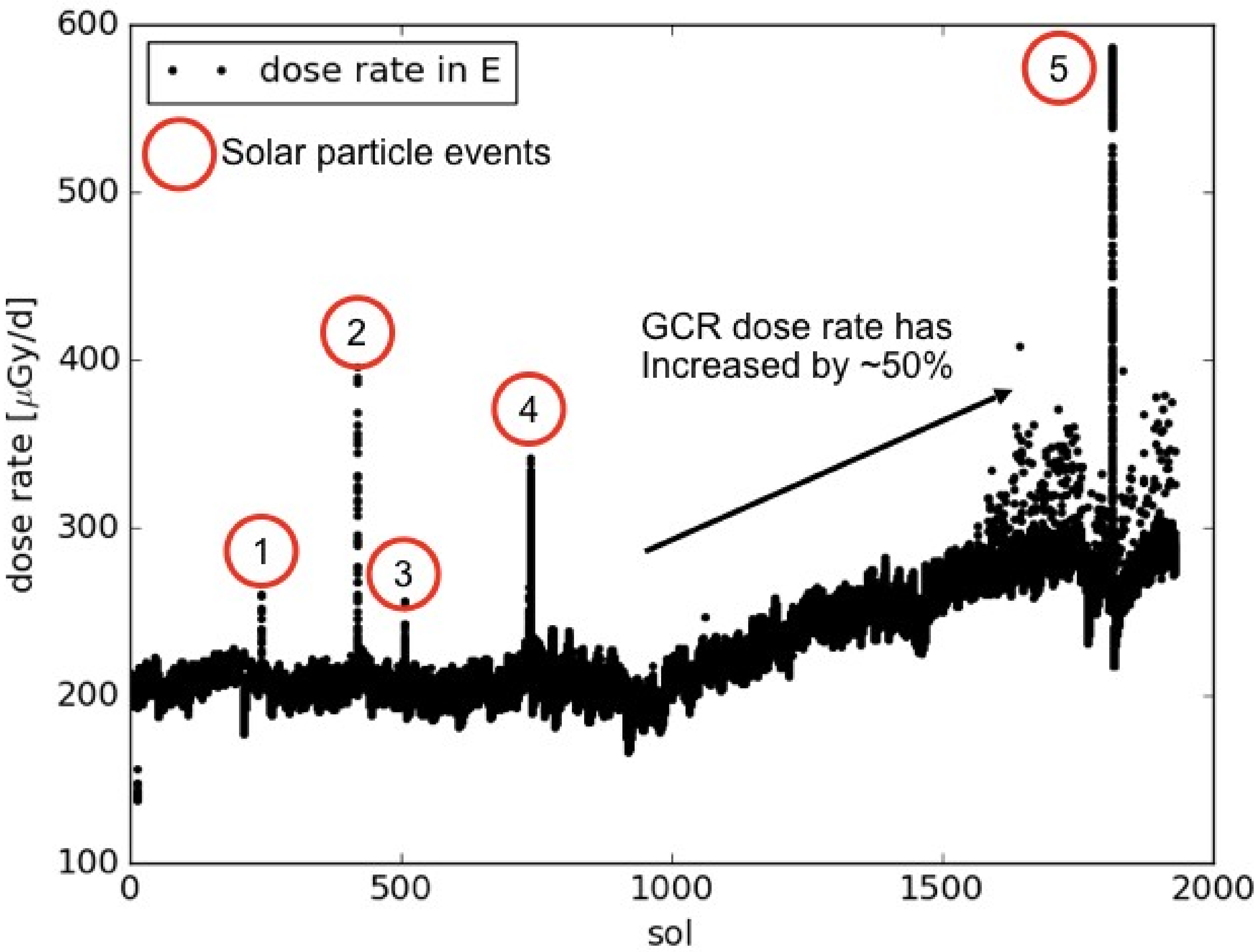
Particle flux at Earth (L1) and on Mars (August 2012 - May 2018)

EPHIN/SOHO @ Earth

MSL/RAD @ Mars



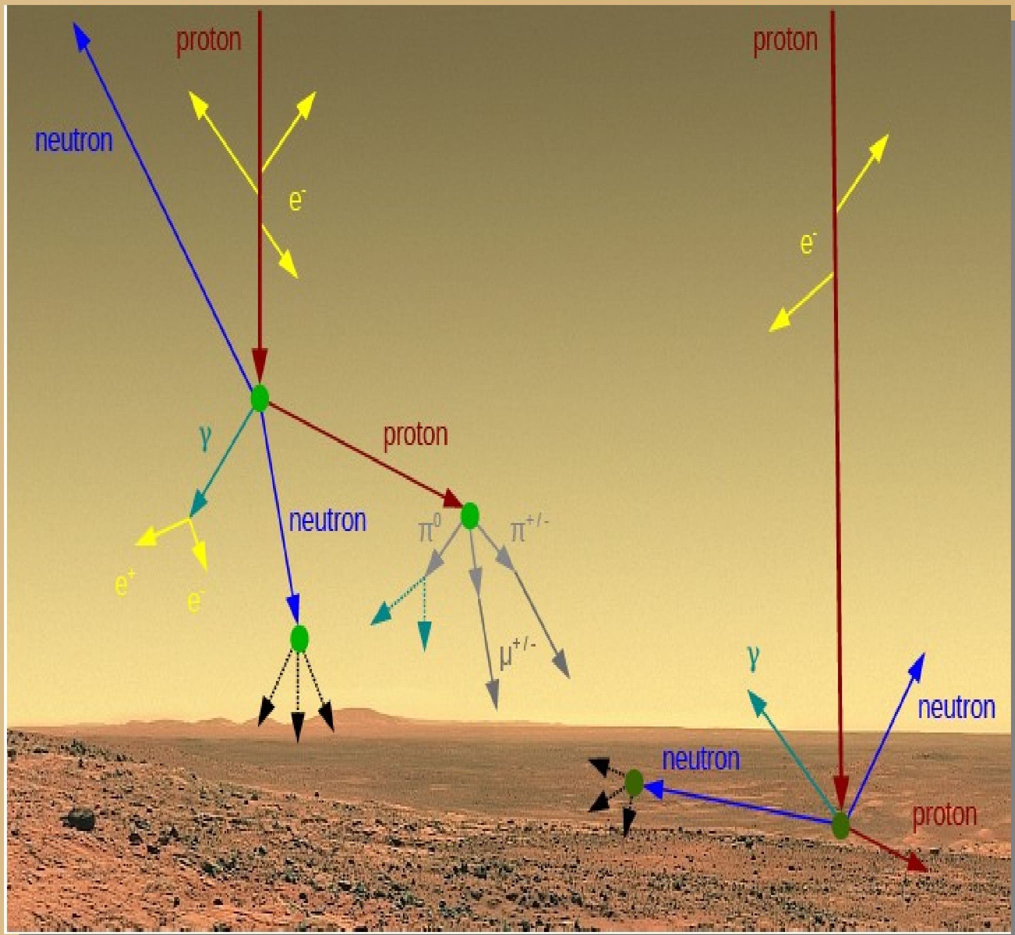
GCR bk + SPEs on Mars



Particles interact with the Martian atmosphere

Radiation Assessment Detector (RAD) on the Mars Science Laboratory (MSL) observed several solar particle events (**SPEs**) on the surface of Mars. **Their onset times and spectra are different from those observed at near Earth** due to:

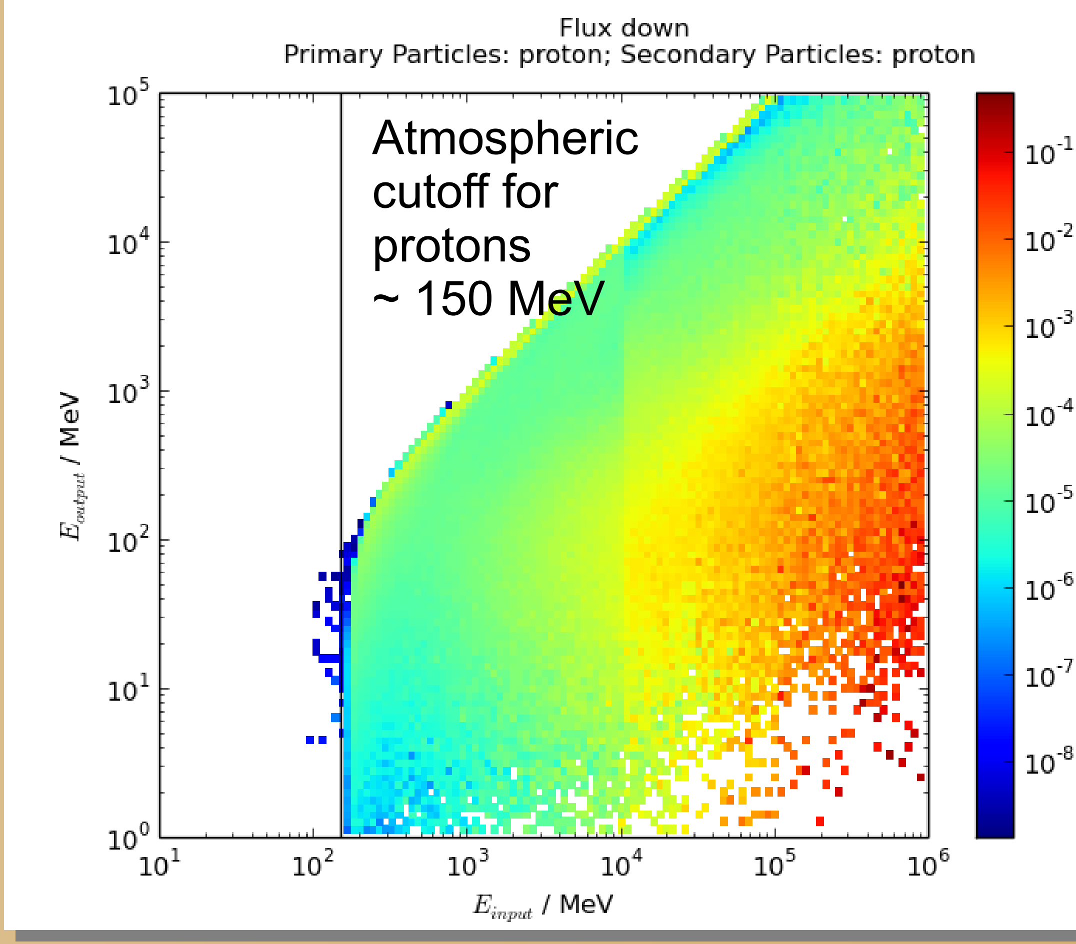
- the atomic and nuclear **interaction** of particles with the Martian **atmosphere**
  - which has been modeled and extracted into functions (e.g., Guo et al 2018 AJ)
- different **magnetic connection** to the particle acceleration sites (at the flares, and/or CMEs and shocks)
- **Cross-field transportation effects** on particles as they propagate through the heliosphere



Particles interact with the Martian atmosphere

RAD observed several SPEs on the surface of Mars. Their onset times and spectra are different from those observed at near Earth due to:

- the atomic and nuclear **interaction** of particles with the Martian **atmosphere**
  - which has been modeled and extracted into functions (e.g., **Guo et al 2018 AJ)**
- 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



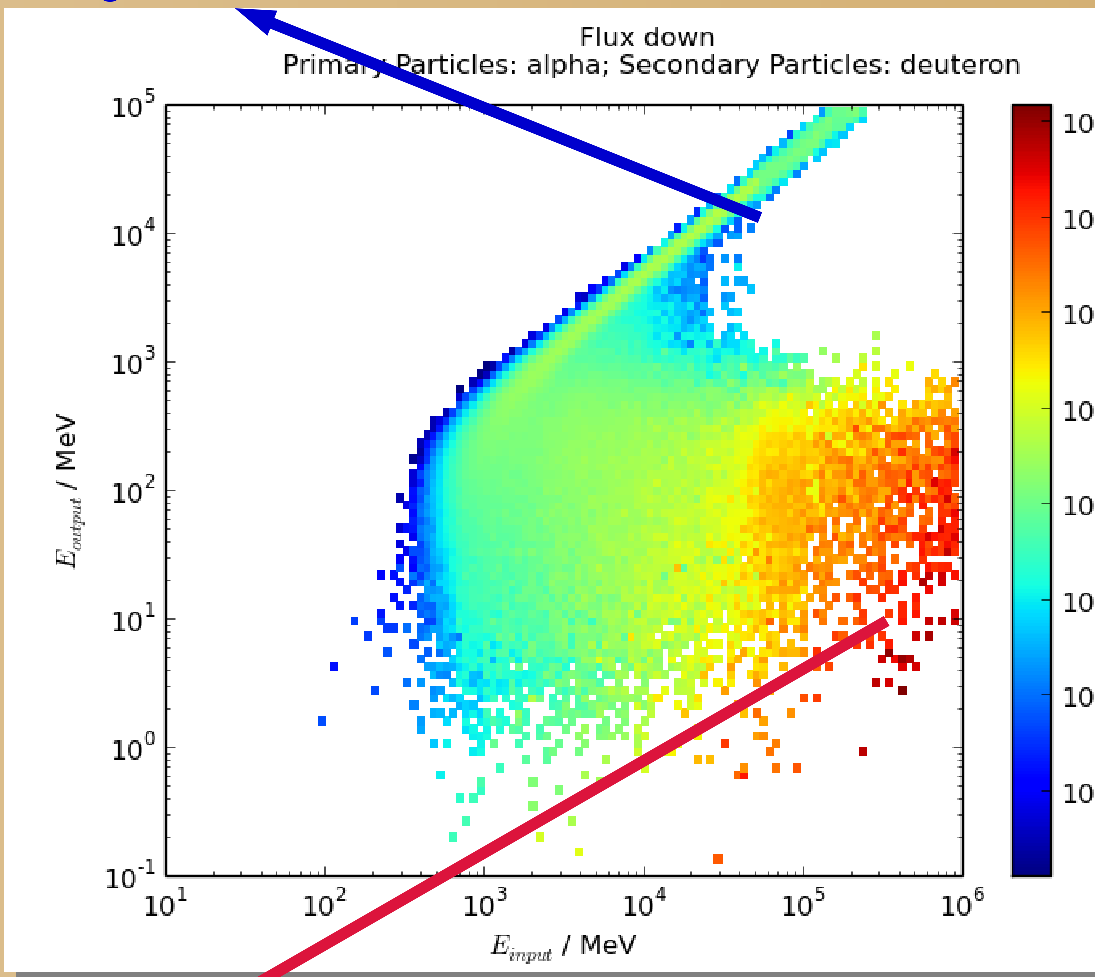
Proton arriving at Mars → secondary protons on the surface

Particles interact with the Martian atmosphere

RAD observed several SPEs on the surface of Mars. Their onset times and spectra are different from those observed at near Earth due to:

- the atomic and nuclear **interaction** of particles with the Martian **atmosphere**
  - which has been modeled and extracted into functions (e.g., **Guo et al 2018 AJ)**
- 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

Fragmentation



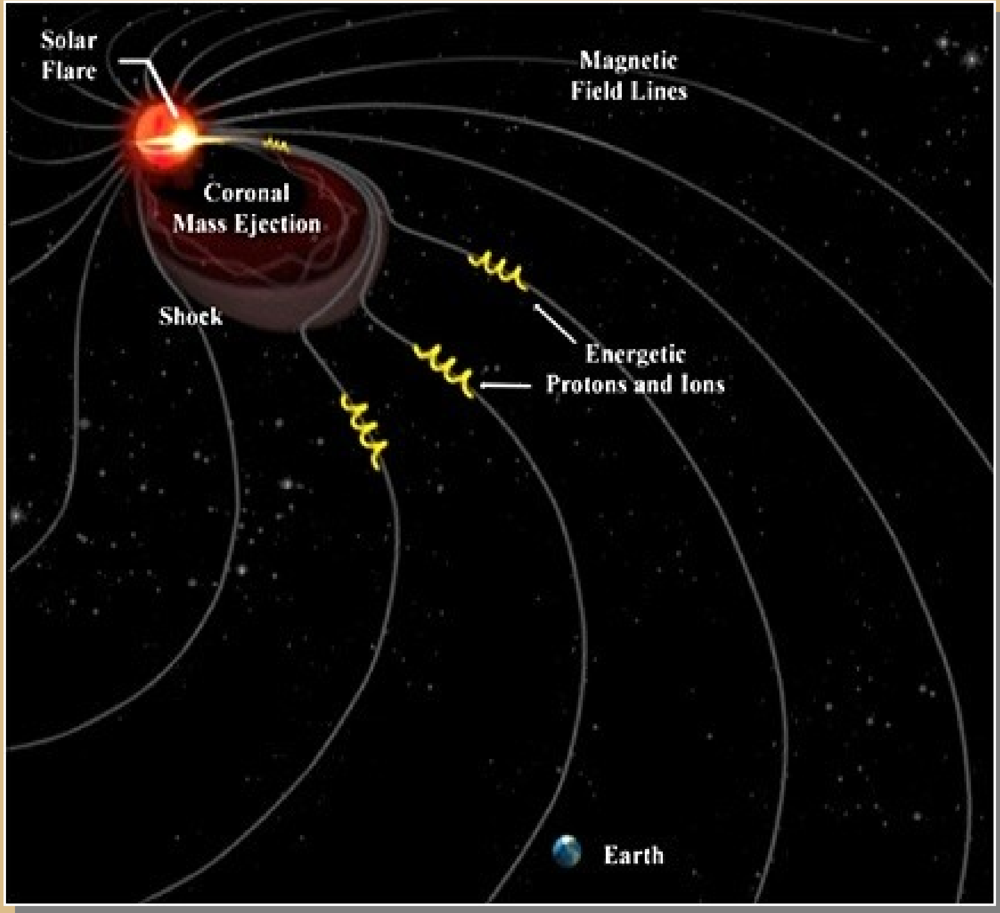
Spallation

^{4}He arriving at Mars → ^{2}H on the surface

Particle injection at the Sun and particle transport in the heliosphere

RAD observed several **SPEs** on the surface of Mars. Their onset times and spectra are different from those observed at near Earth due to:

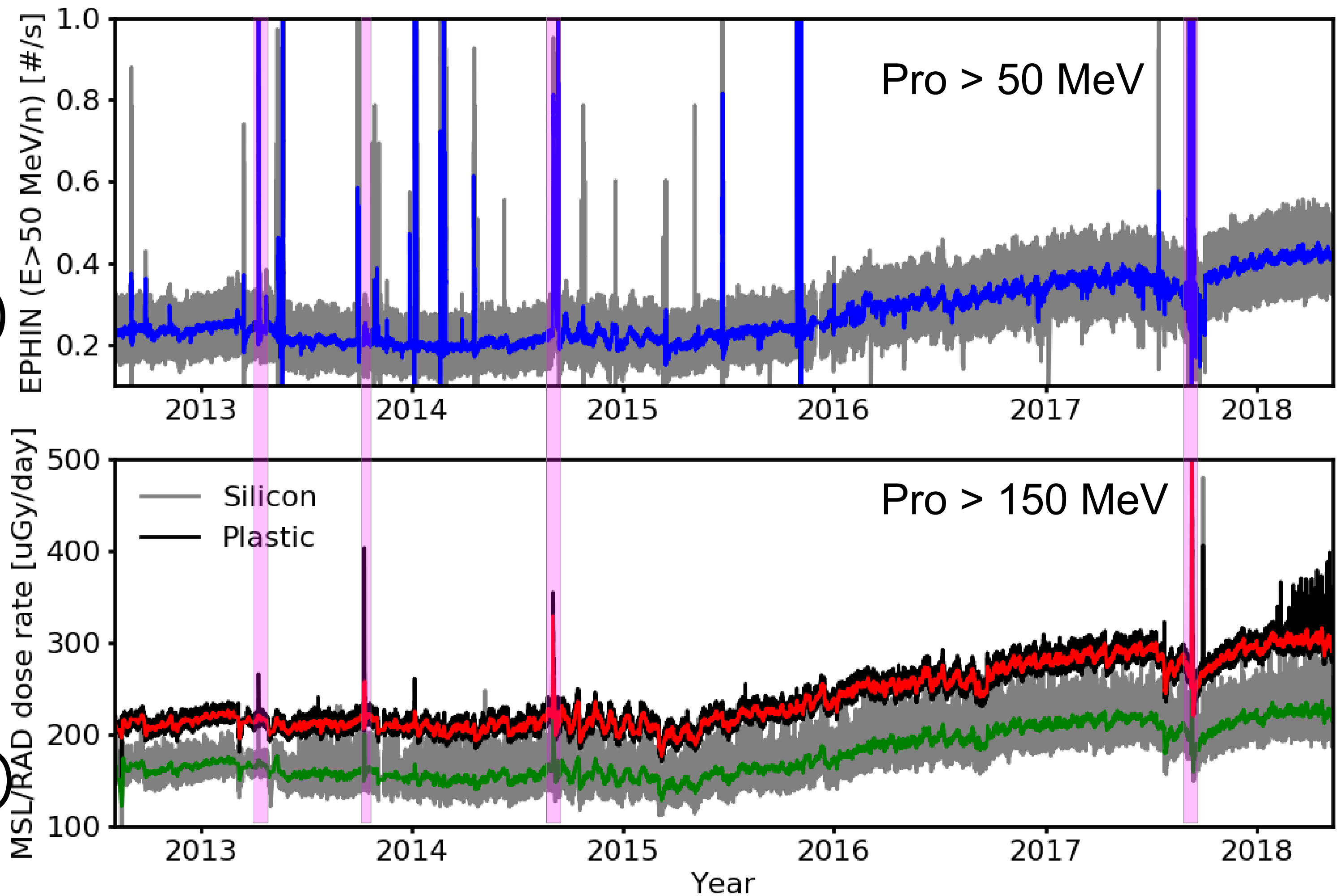
- the atomic and nuclear **interaction** of particles with the Martian **atmosphere**
  - which has modeled and extracted into functions (e.g., Guo et al 2018 AJ)
- different **magnetic connection** to the particle acceleration sites (flares, and/or CMEs and shocks)
- **Cross-field transportation effects** on particles as they propagate through the heliosphere

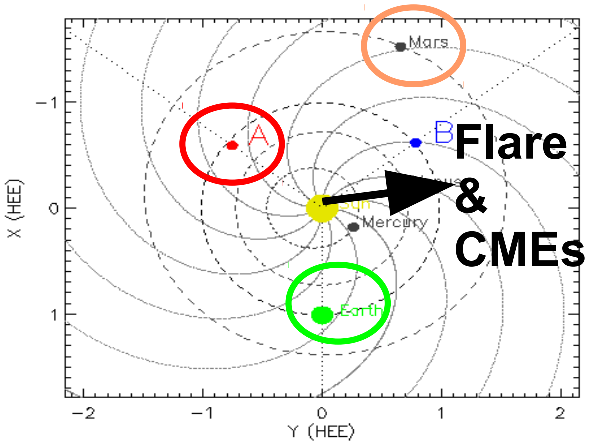


The same SEP events are seen with different flux and spectra at Earth and at Mars

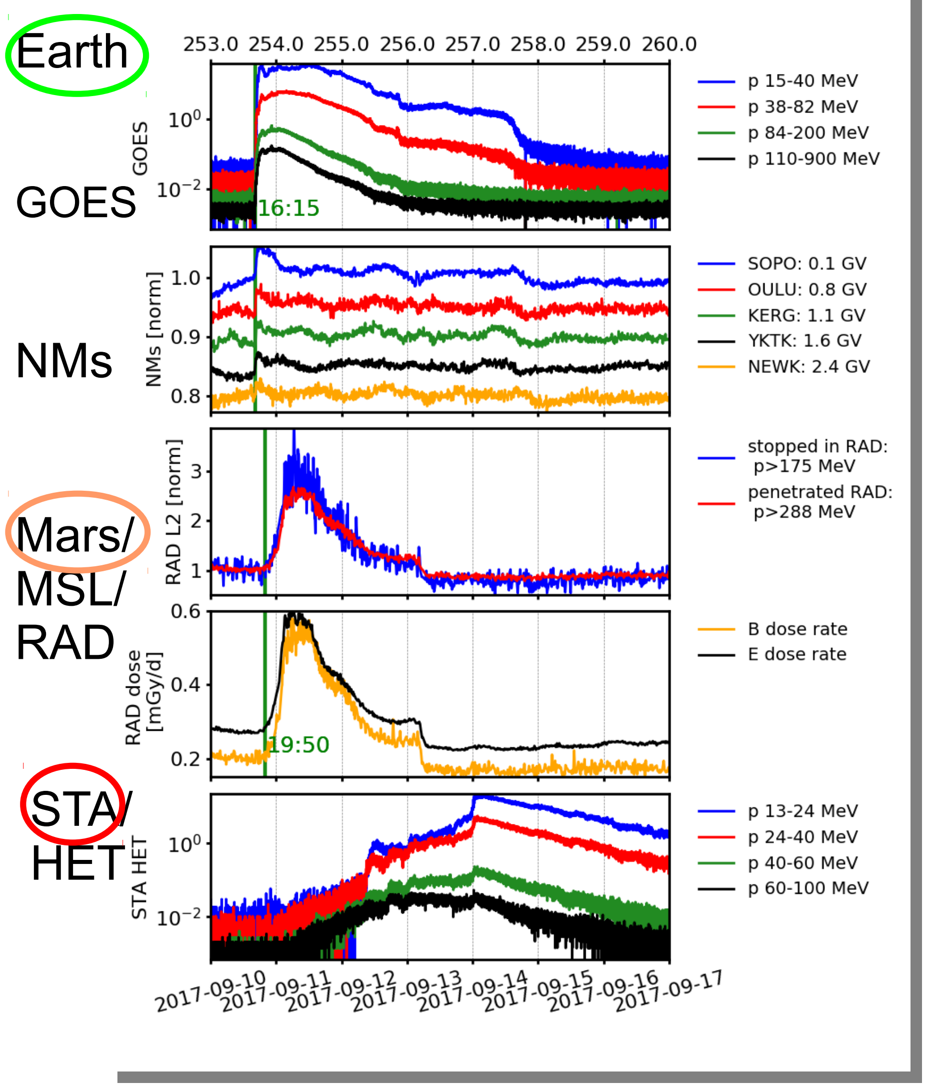
EPHIN/SOHO @ Earth

MSL/RAD @ Mars





The first GLE observed on two planets: 2017-09-10 event with SEPs (>100 MeV) arriving at Earth, Mars and STEREO-A



Earth

- The onset of protons > 100 MeV seen by GOES at Earth is at about **16:15** on 2017-09-10.
- SEPs were also registered as a ground level enhancement (GLE) seen by multiple neutron monitors with cutoff rigidities of about 3 GV (~2 GeV protons)

Mars

- Mars magnetic foot point is ~150 degrees from the flare.
- The earliest onset at Mars is about **19:50** and this has been the biggest GLE at Mars seen by the Radiation Assessment Detector (RAD) since the landing of the Curiosity rover.
- Considering the atmospheric cutoff and the RAD detector response function, particles with > ~300 MeV arrived at Mars.
- *We are working on retrieving the SEP spectra at Mars on top of the atmosphere from surface measurement.*

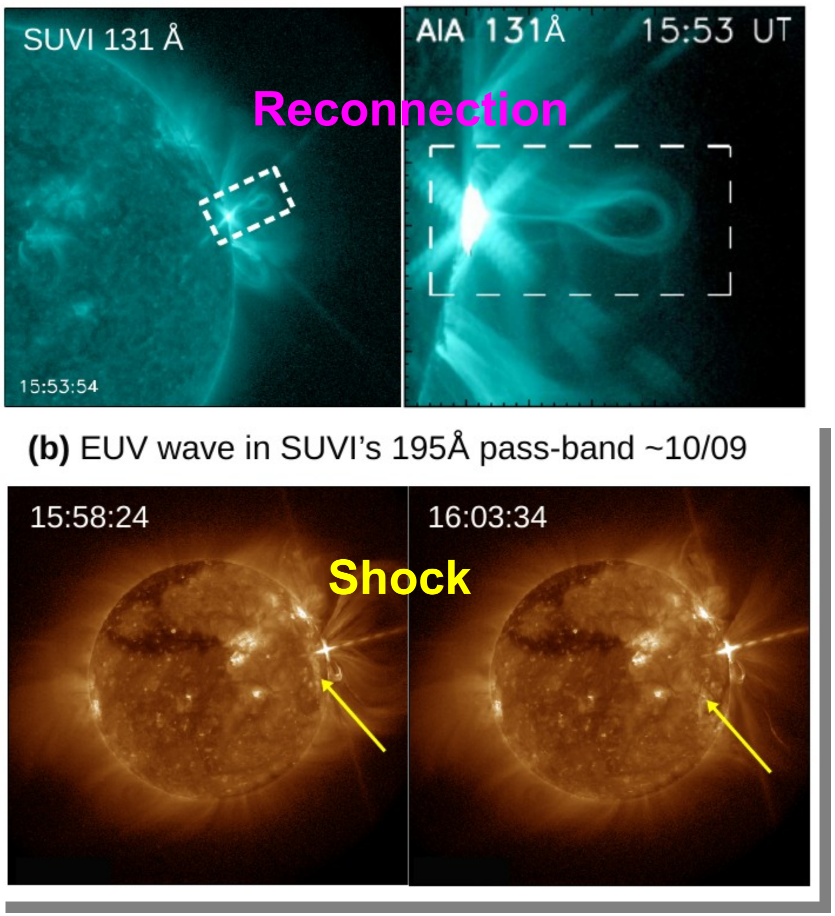
STEREO-A

- STA foot point is >~200 degrees away from flare and still detected particles ~ 100 MeV.
- The SEPs arriving at STA are likely transported there across Interplanetary Magnetic Field (IMF) lines via diffusion and scattering as STA was at the back side of the flare and CME shock.

The 10 September Flare, Flux Rope, and Initial Acceleration of Particles

(a) Flare, current sheet and the MFR ~10/09 15:53

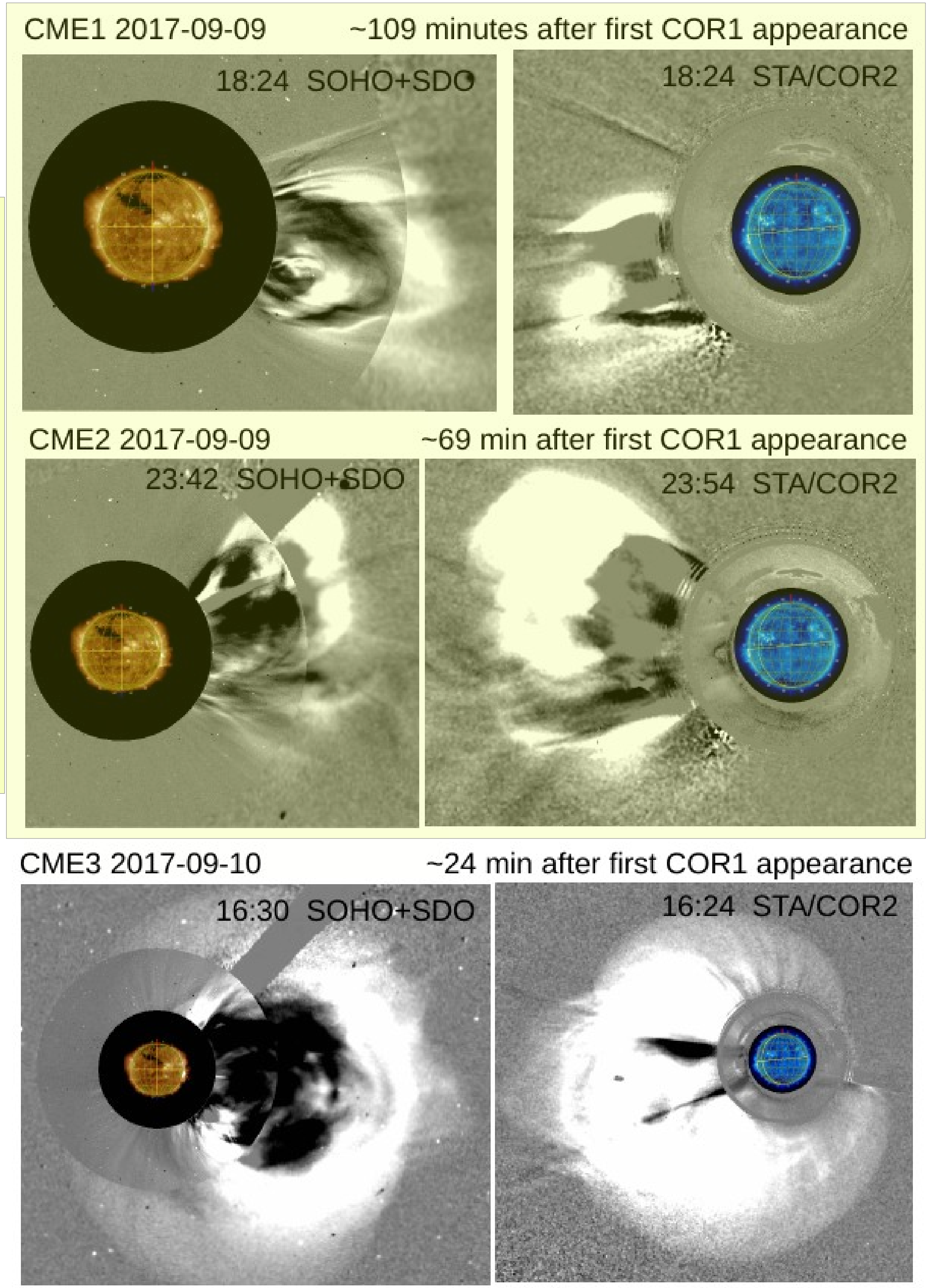
(b) EUV wave in SUVI's 195Å pass-band ~10/09

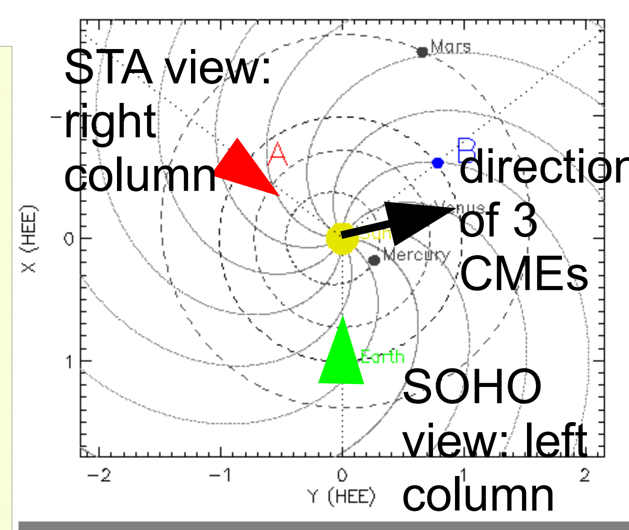


Warren+ 2017;
Seaton and Darnel , 2018;
Guo+ 2018;
Veronig+ 2018…
(EUV wave: T. Podladchikova talk later)

- From the clear onset time of relativistic particles, a release time around 16:00 UT can be inferred for 1 GeV protons.
- This timing matches reasonably well with the final eruption of the flux rope and the X-ray bursts (*RHESSI & FERMI: two broad X-ray bursts centered at 15:57 and 16:10 UT.*).
- However, the timing of the initial signature of the shock and the reconnection process was very close (both starting around 15:53) and it is yet difficult to tell whether the shock or magnetic reconnection (flare) contributed more to the initial acceleration of particles.

Coronagraph obs. also shows the launch of **another 2 CMEs** half a day before this extreme event launched into similar directions.

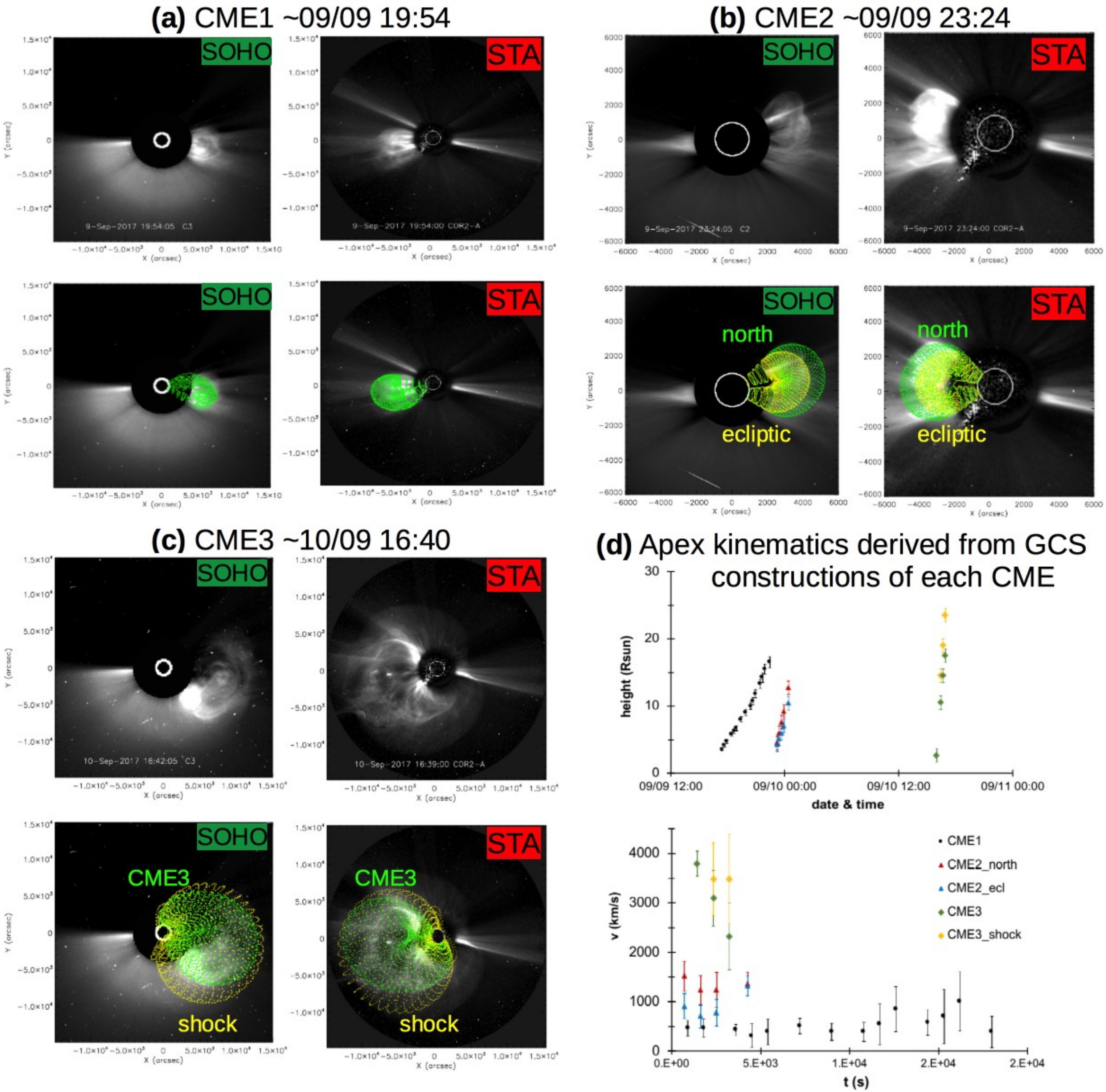




Using the GCS model, we constructed the initial 3D geometry and kinematics of the 3 CMEs based on both STA and SOHO coronagraph images.

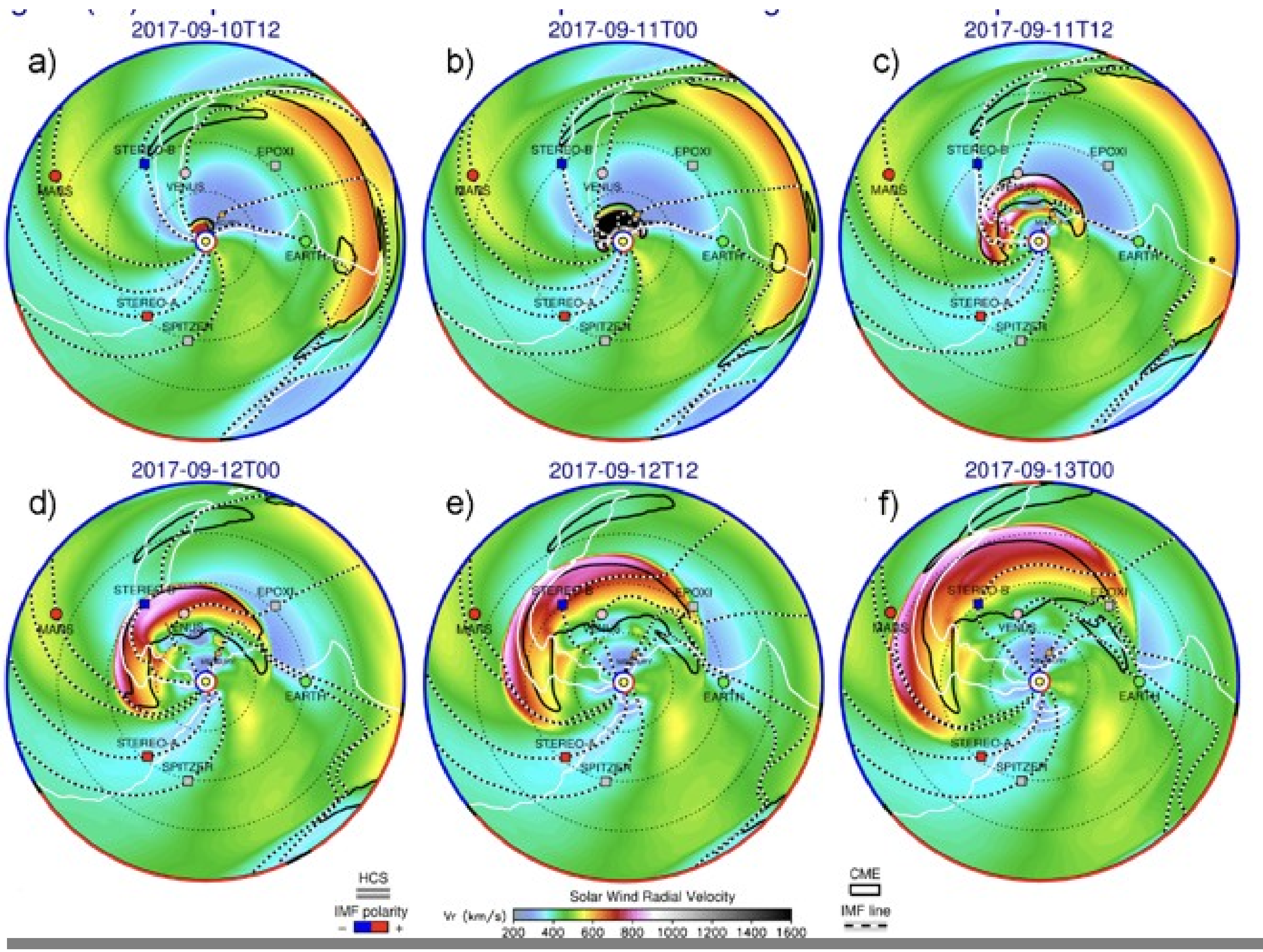
GCS fitting of the kinematics of the 3 CMEs

Given V_cme3 >> V_cme2 > V_cme1, the later CMEs were likely catching up and interacting with the earlier ones.



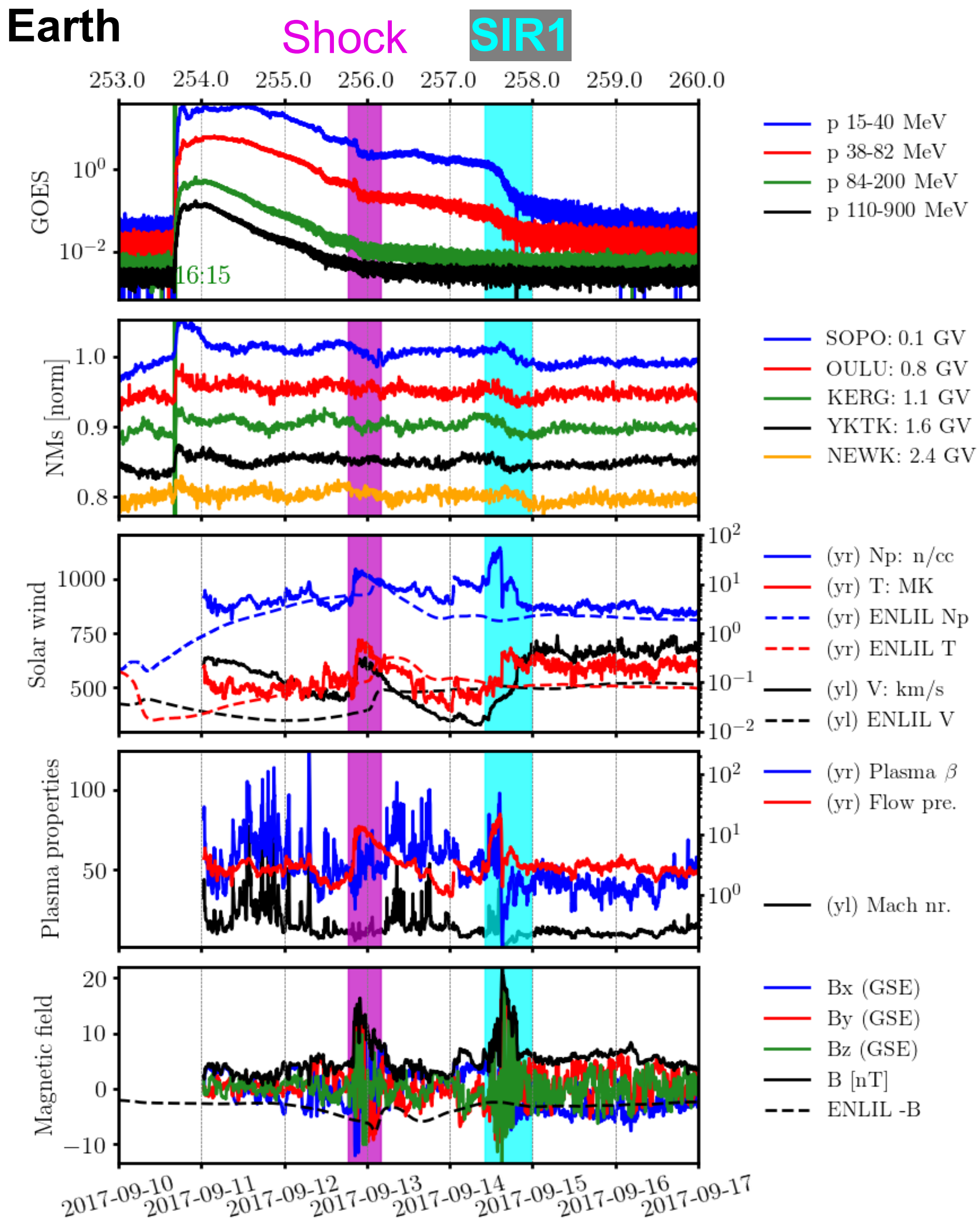
Modeling the Propagation of the ICME event

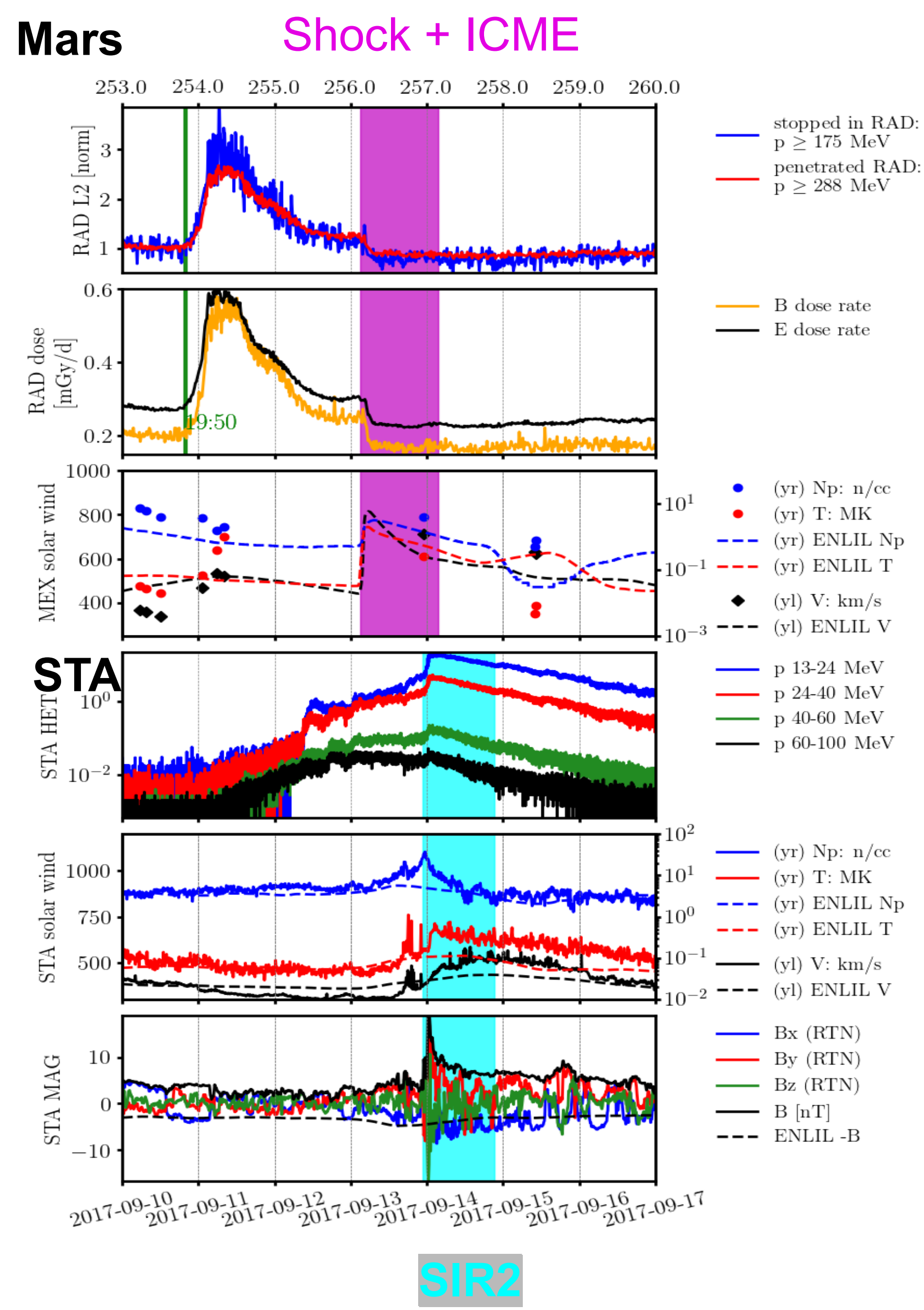
- The ICME driven shock reached Earth at 18:30 on 12 September ~50.5hr after launch.
- The ICME hit Mars ~59 hr after launch at 02:50 UT on 13 September 2017
- Using input parameters of only the 3rd (the one associated with the GLE event), neither WSA ENLIL+Cone nor DBM could predict the correct arrival time at both planets.
  - The interplanetary propagation conditions (SW speed and the drag force) are different in two directions.
  - In particular, the interaction of the 3 CMEs in the direction of Mars changed the kinematics of the ICME propagation.
  - Towards Earth, the shock is not driven by an ejecta.



Input 3 CMEs with tweaked SW parameters into the ENLIL model could finally match with in situ obs.

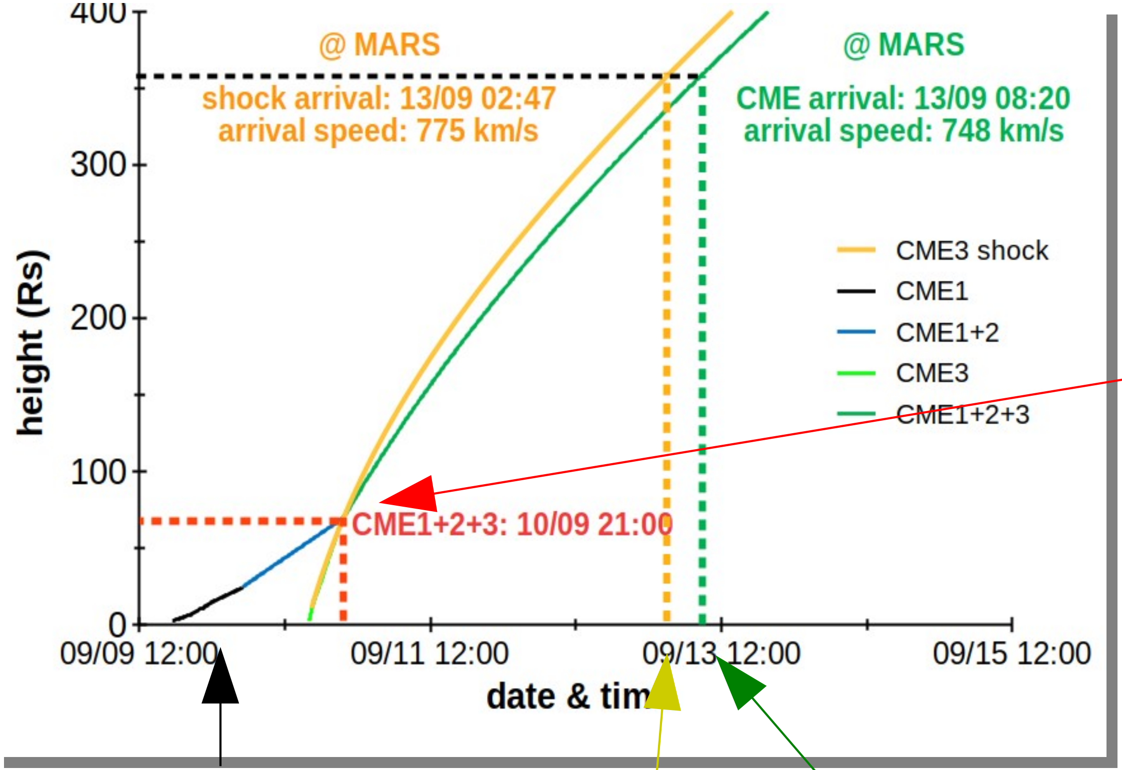
In situ data of at Earth, Mars and STA





Data-constrained DBM Modeling of the propagation and interaction of the 3 CMEs

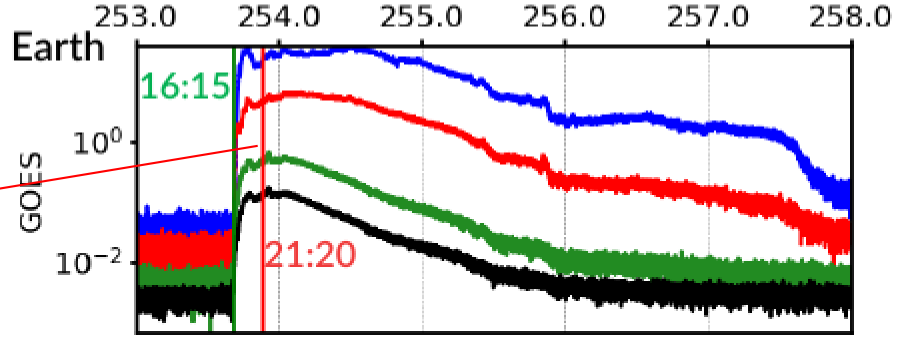
During the CME collision, CME mass merged as an entity and the two colliding bodies continued their propagation further with the momentum conserved [Temmer et al., 2012]



CME1+CME2

Shock arrival

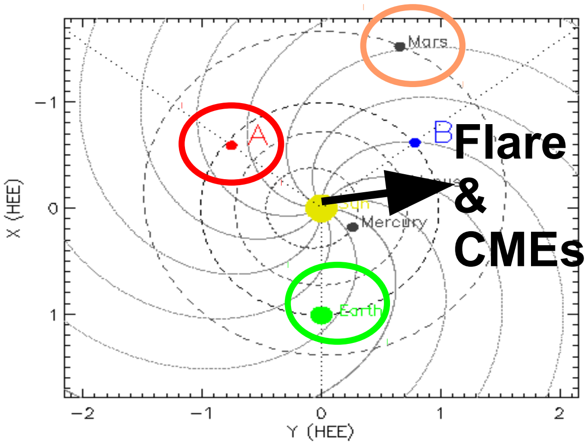
ICME (CME123) arrival at Mars

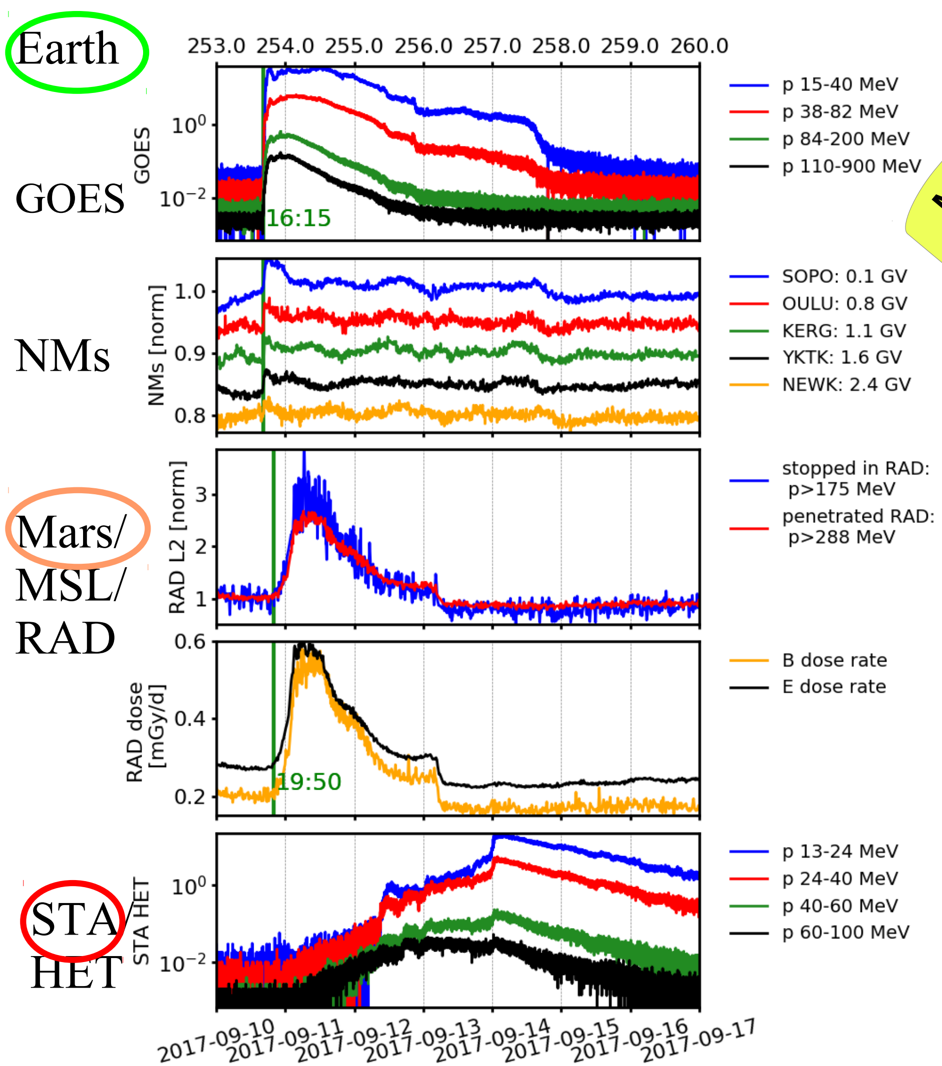


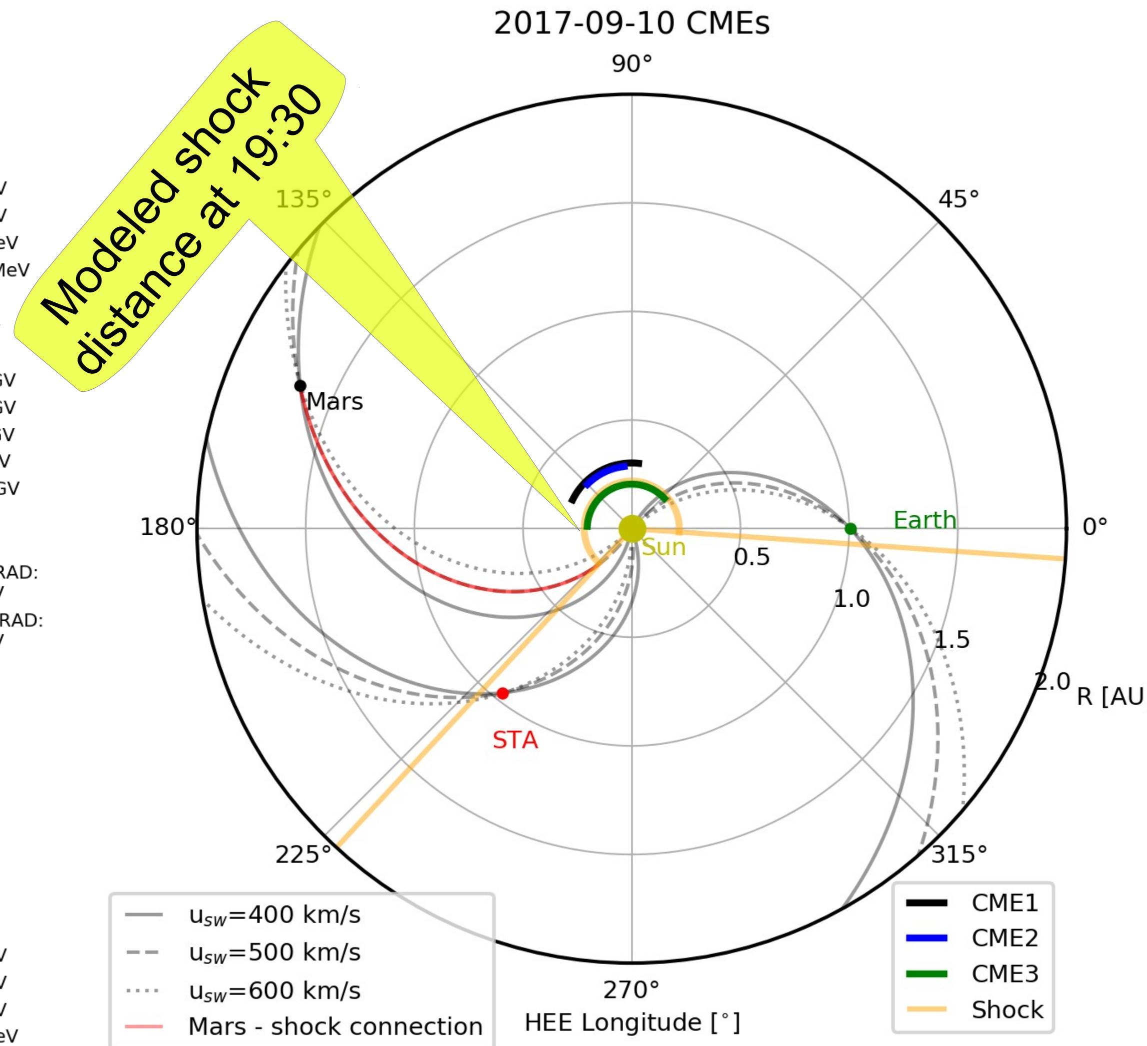
Merging of 3 CMEs at ~21:00 may be providing more seed particles for an enhanced flux ~21:20 as observed in situ at Earth.

Reason for particle arriving at Mars?

- cross-field drift?
- direct magnetic connection?
- Both?...and even other reasons?



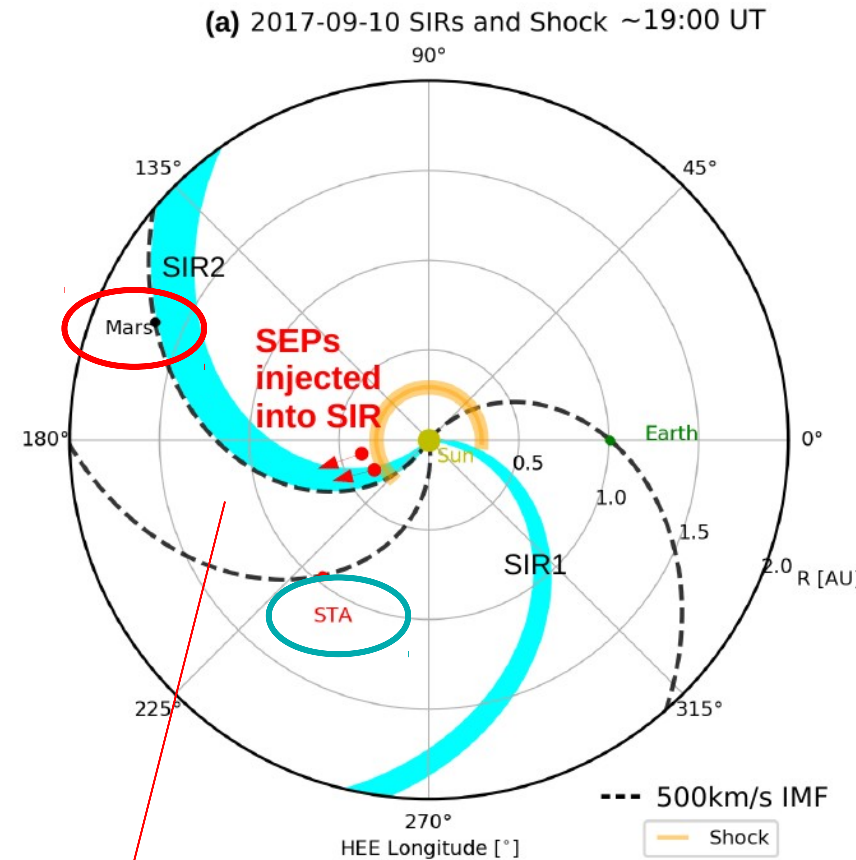


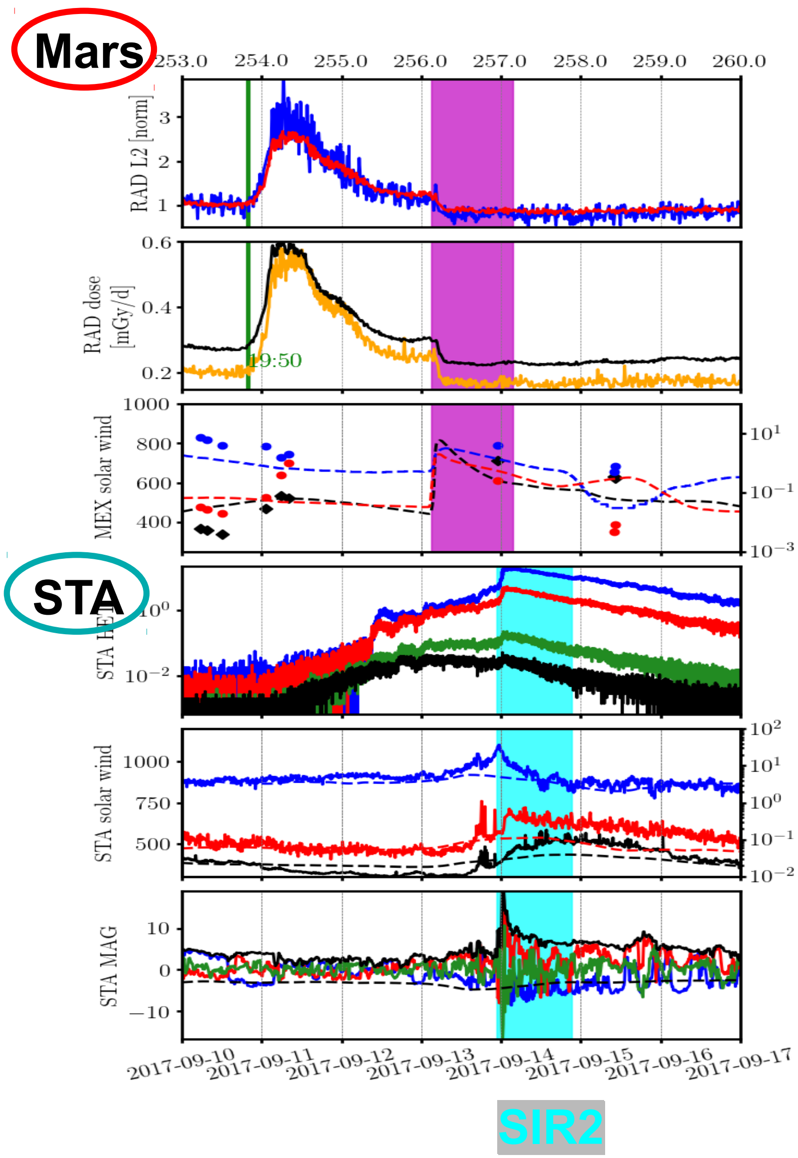


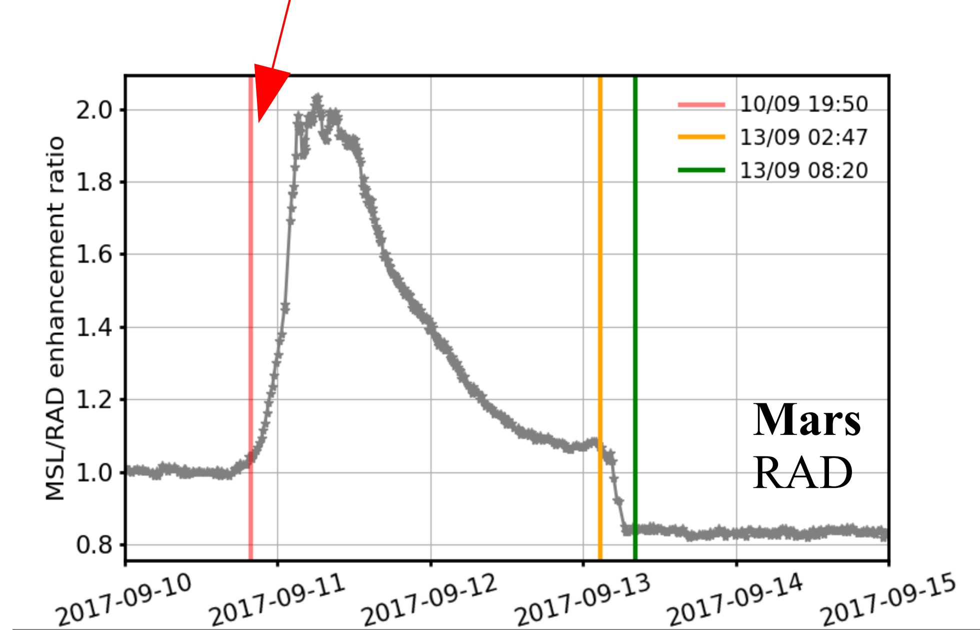
For direct connection:
Shock ½ width ~117°

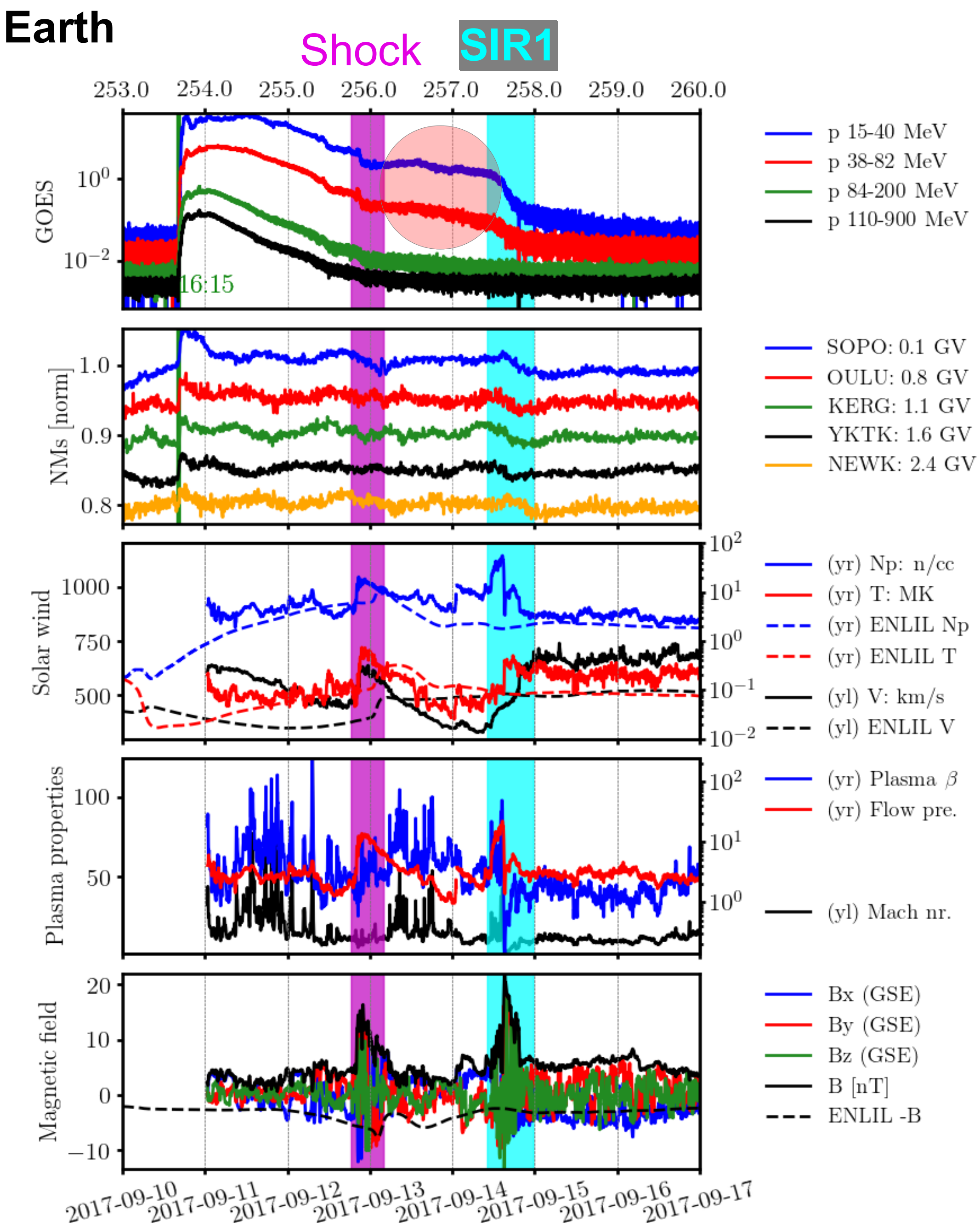
A Streaming Interaction Region (SIR) detected at STA was back-shifted to the Mar location. The expected arrival time at Mars is coincident with the SEP onset time at Mars.

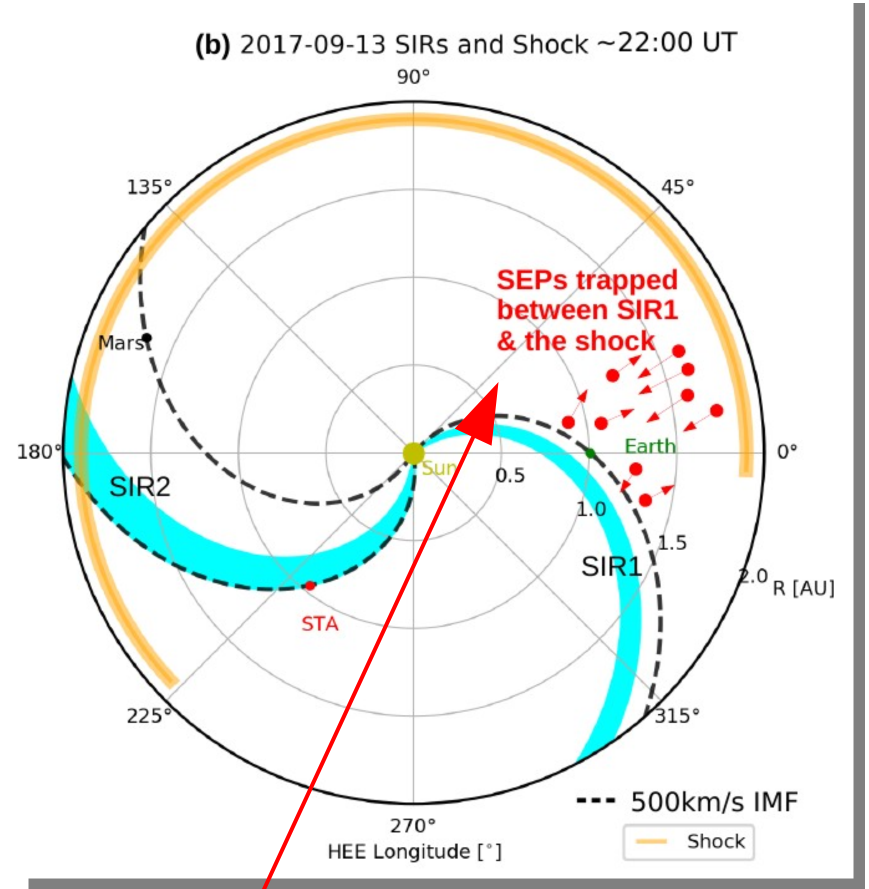
- The shock was rather wide and particles were directly injected into the SIR structure.
- This structure co-rotates with the Sun and favored the particle onset at Mars and enhanced the SEP flux at STA.







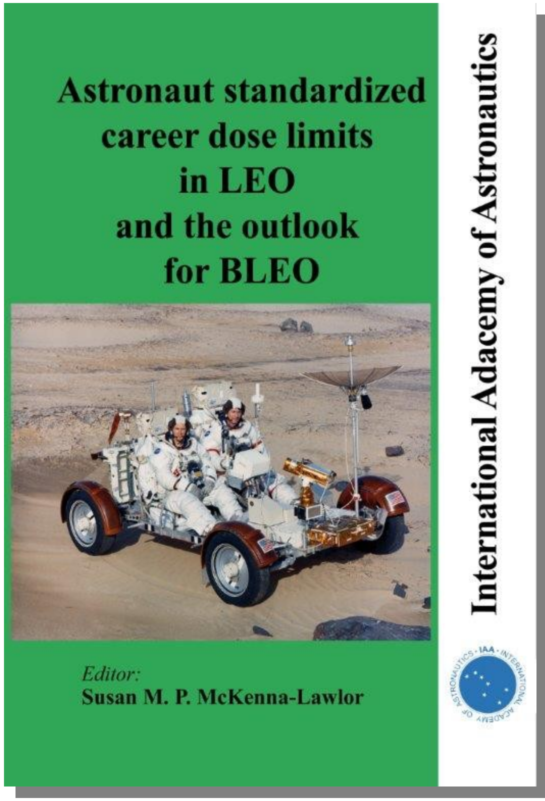




- The SIR arrived at Earth ~ 1.5 days after the CME shock passed Earth.
- SEPs were trapped between these two structures causing a plateau profile in the GOES SEP flux.
- Perpendicular diffusion could be strongly damped at magnetic discontinuities (e.g Strauss+ 2016)

Guo et al 2018, Space Weather, 16, 1156

Outlook for space weather and space radiation predictions for space explorations



GCR radiation is easier to predict, but hard to shield.
Its radiation level is anti-correlated with the heliospheric activity and needs to be better measured and quantified.
Modeling radiation under different shielding environment (varying atmospheric conditions or different spacecraft shielding) with more precise GCR spectra input is important. (book in preparation).

SEP radiation are rather difficult to predict, but easier to shield, which highlights the importance of the timely and precise forecast.
Synergistic analysis of the remote-sensing and in-situ measurements combined with modeling tools is helping us to better understand and possibly forecast extreme space weather conditions for human explorations in space.

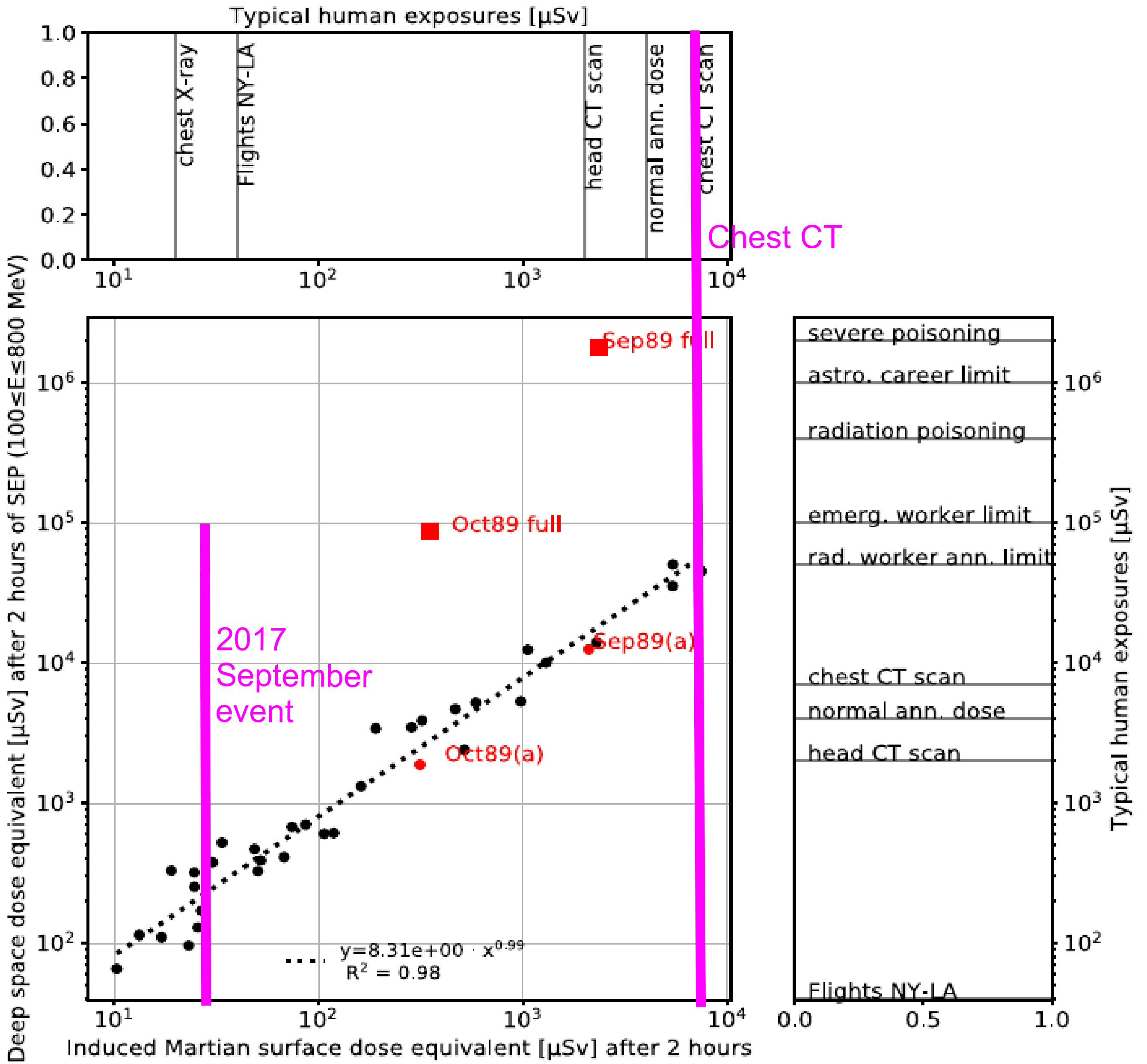
To forecast SEP events, it is important and necessary to consider:

- The **acceleration and injection** of the particles at the Sun and the continuous acceleration by the ICME driven shock in the interplanetary (IP) space.
- The heliospheric position of the spacecraft and its **magnetic connection** to the injection site (flare and/or shock front).
- Scattering and cross-field **transport** of particles in the IP space.
- The **shielding** configuration of the local environment, e.g., the spacecraft material or the planet atmosphere shielding.

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

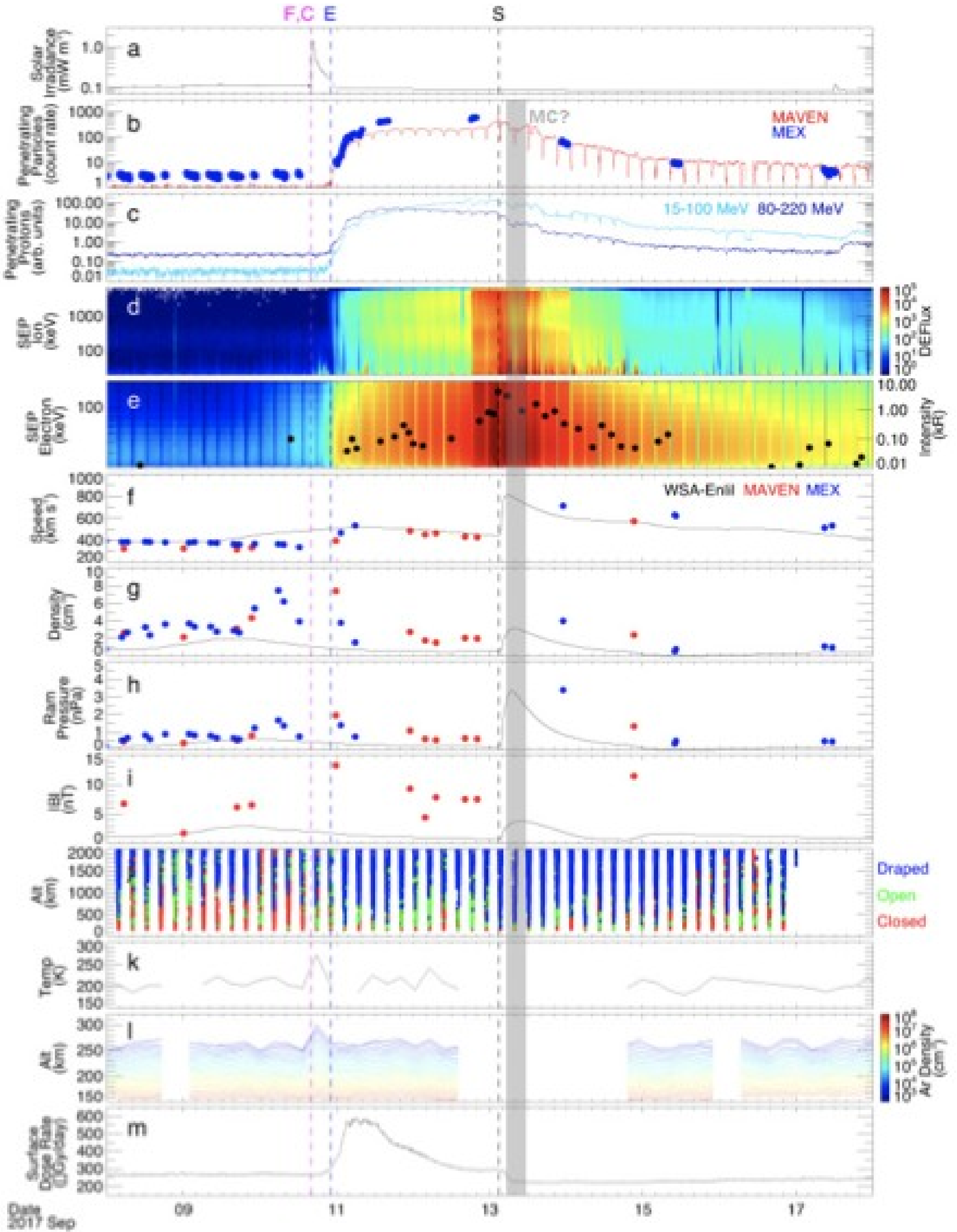
SEP >100MeV (~ inside a spacecraft)

(2 hours)



SEP dose equivalent on Mars (2 hours)

More details in Guo et al 2018 AJ

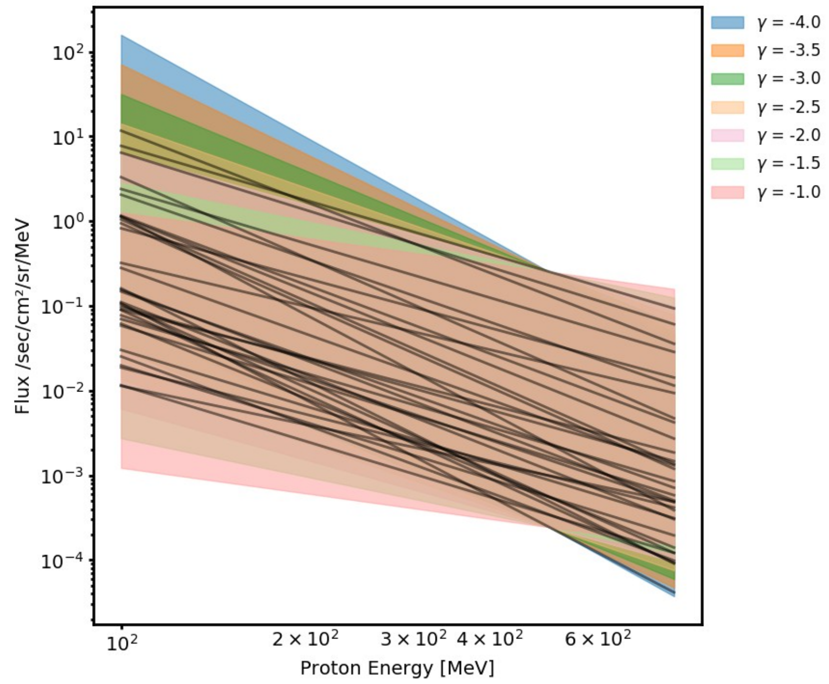

F,C E
S
Solar Irradiance (mW m⁻²)
Penetrating Particles (count rate)
MC?
MAVEN
MEX
Penetrating Protons (arb. units)
15-100 MeV 80-220 MeV
SEP Ion (keV)
DEFlux
SEP Electron (keV)
Intensity (kR)
Speed (km s⁻¹)
WSA-Enlil MAVEN MEX
Density (cm⁻³)
Ram Pressure (nPa)
\|B\| (nT)
Alt (km)
Draped
Open
Closed
Temp (K)
Alt (km)
Ar Density (cm⁻³)
Surface Dose Rate (Gy/day)
Date 2017 Sep
09
11
13
15
17

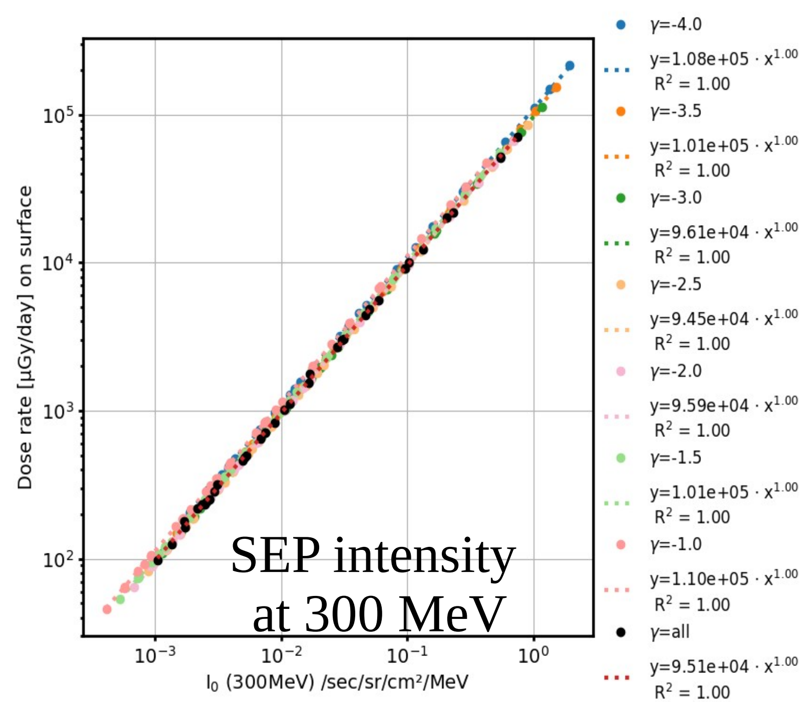
Open discussion 1

- **FD at Mars**: MSL/RAD has been measuring FDs at Mars since 2012 (Guo et al 2018 A&A). We have studied their statistics and modeled the energy dependent atmospheric response to incoming particles. So the measured magnitude of the FDs can be empirically converted into that on top of the atmosphere. Such FD data combined with models (e.g., ForMOD) may be able to give us valuable information on CME structures and their evolution in the IP space. We are also looking at recurrent FDs and their causes

Open discussion 2

- Inverting high energy **SEP spectra at Mars**
- Using the modeled response function of particle interactions with Mars atmosphere, we have found some <u>beautiful</u> correlation between the SEP flux and surface radiation dose.
- → from the surface measurement of dose rate, we can obtain valuable information of the intensity and spectra shape of SEPs arriving at Mars.





A parametric study of dose rate dependence on SEP spectral properties

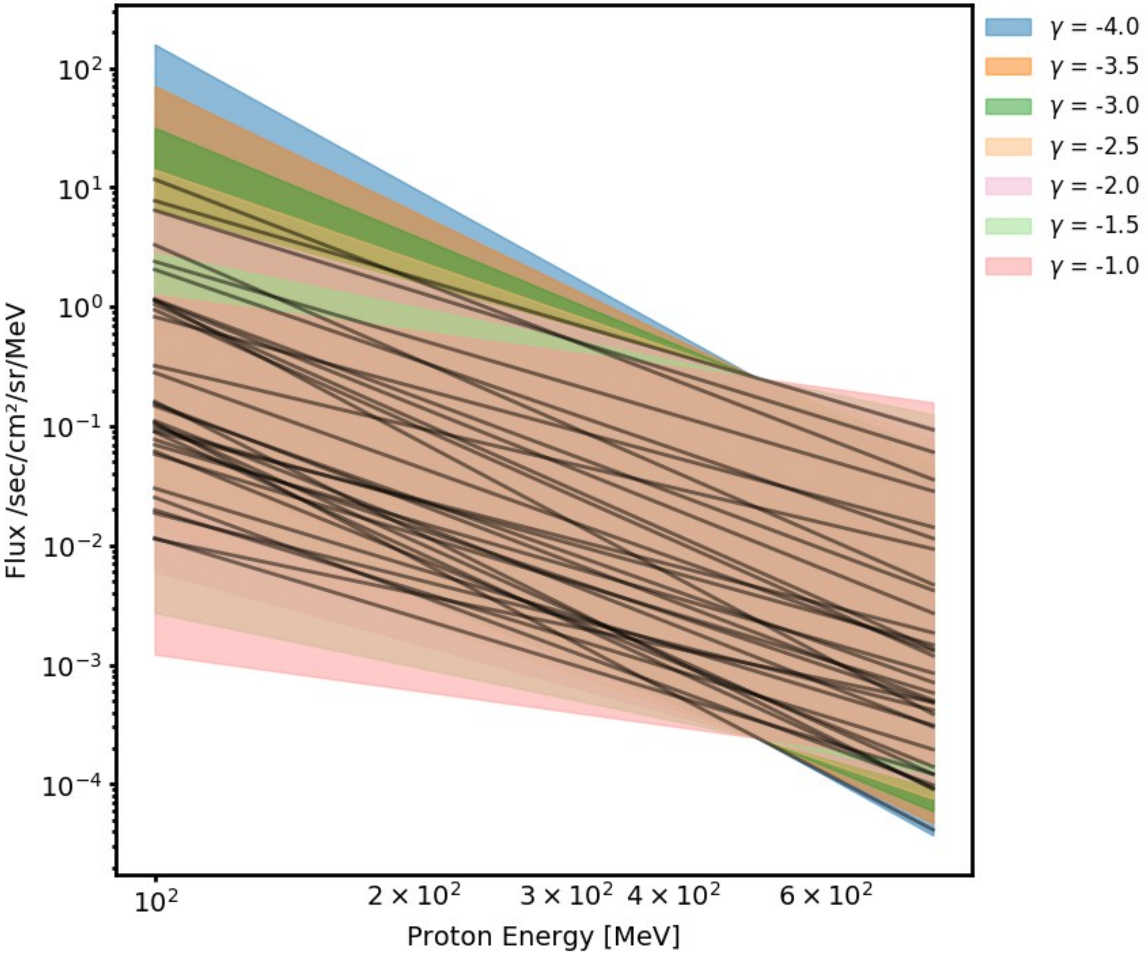
1) Re-generate a new set of SEP spectra using a fixed power-law index; the surface radiation dose rate of these events with the same power-law index is calculated for each event.

2) The above step is repeated for different power-law index in the range [-4,-3.5,-3,-2.5,-2,-1.5,-1]

3) The surface dose rate versus SEP intensities (at certain energy E0) for each power-law case is plotted and fitted.

4) The above procedure 1)-3) is repeated for SEP energy range of 100-800 MeV as well as 15-1000 MeV range.

Generating parameterized input SEP spectra

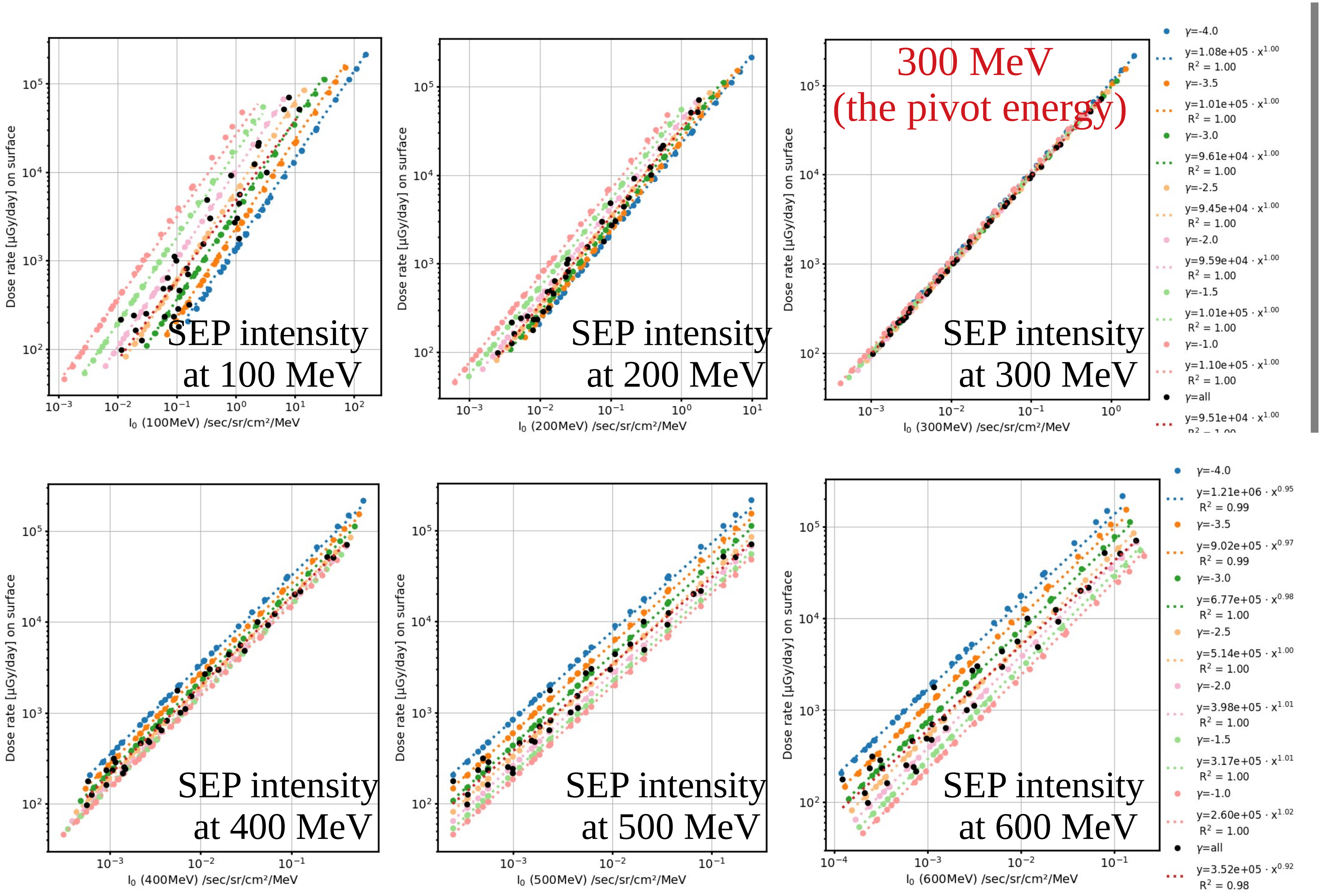


100 – 800 MeV SEP spectra

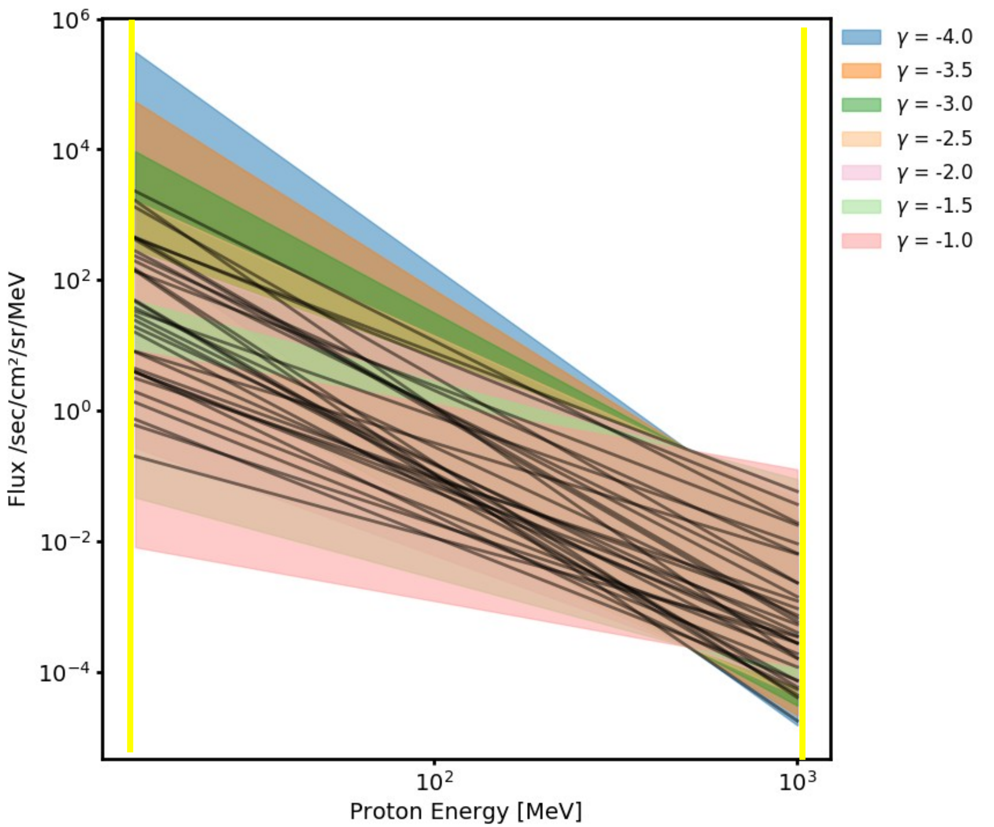
Black lines are original event spectra while the shaded areas mark the parameterized spectra with different power-law indices

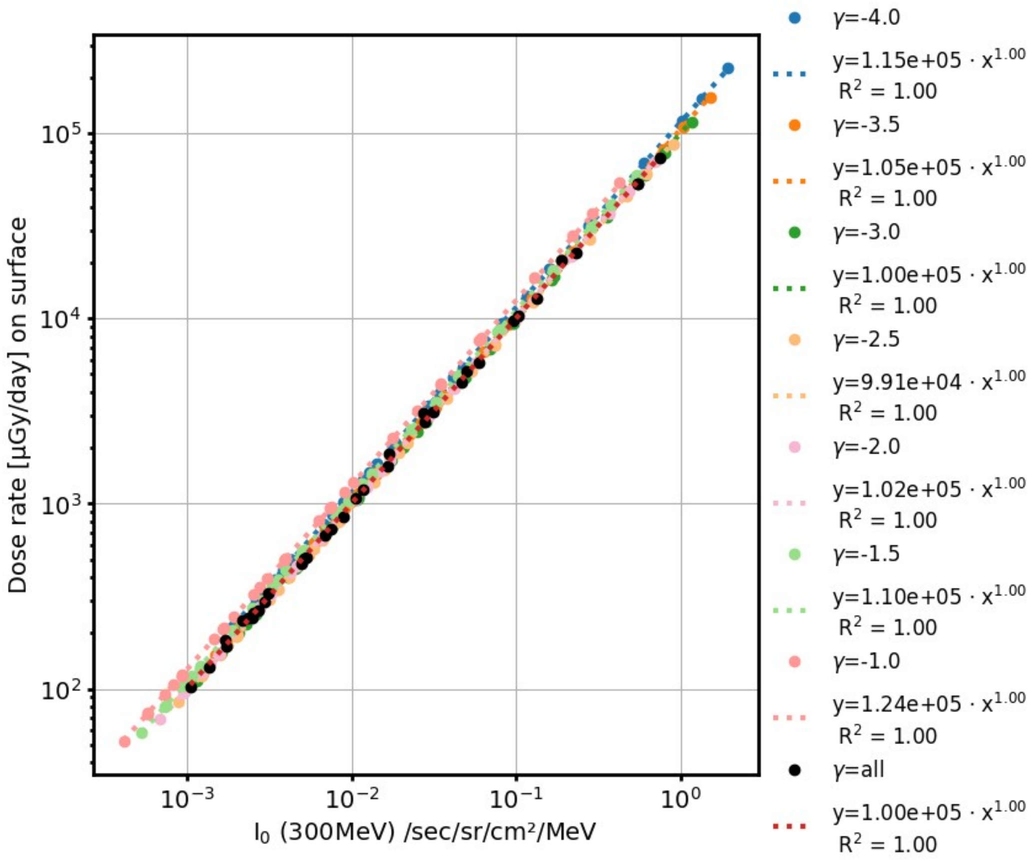
(The fixed energy flux for generating the new spectra is 500 MeV, but this is trivial...)

Dose rate versus SEP intensity at different energies



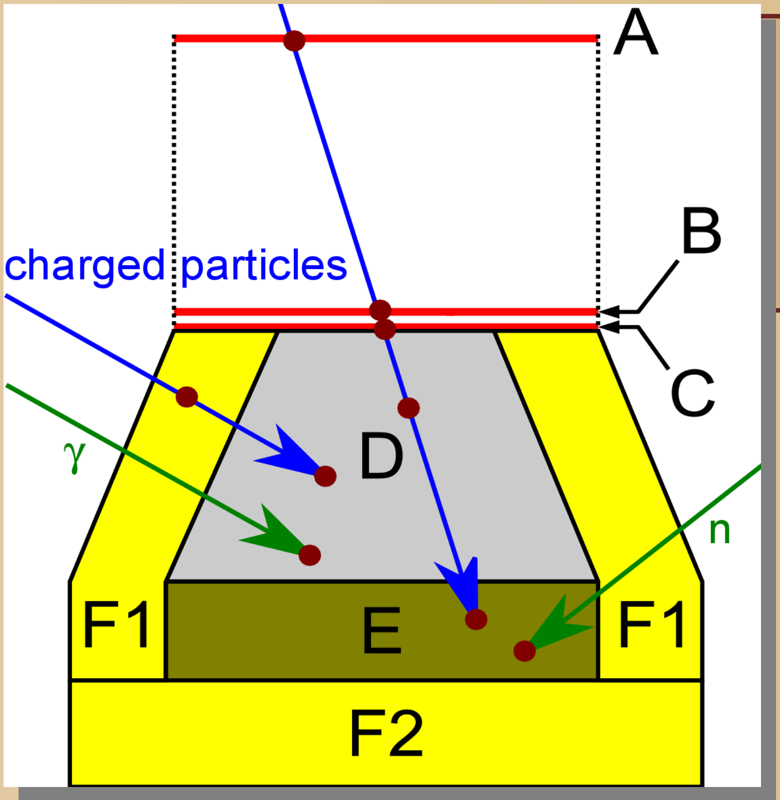
The result is also valid for SEP with power-law spectra between 15 – 1000 MeV



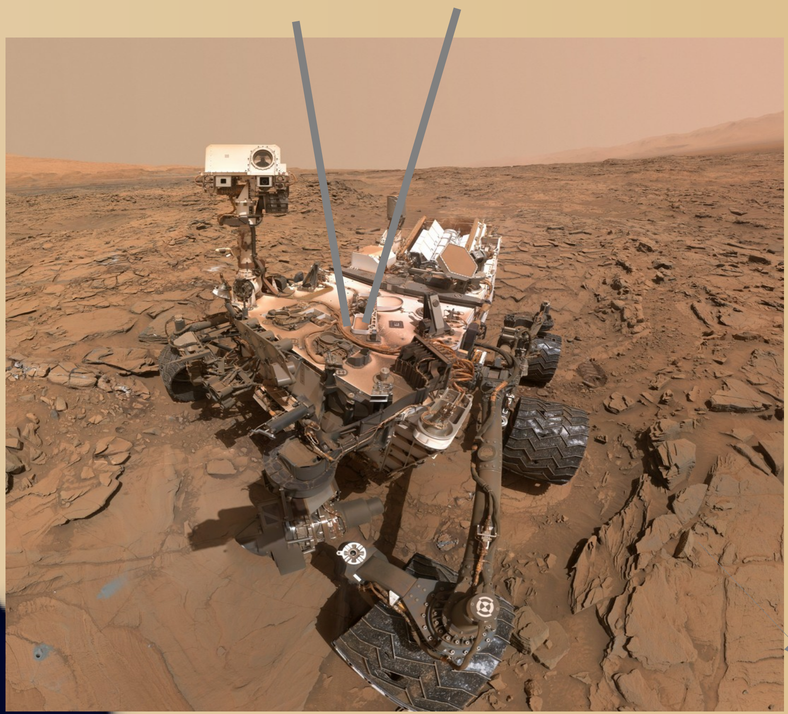


15 – 1000 MeV SEP spectra

The Radiation Assessment Detector (RAD)

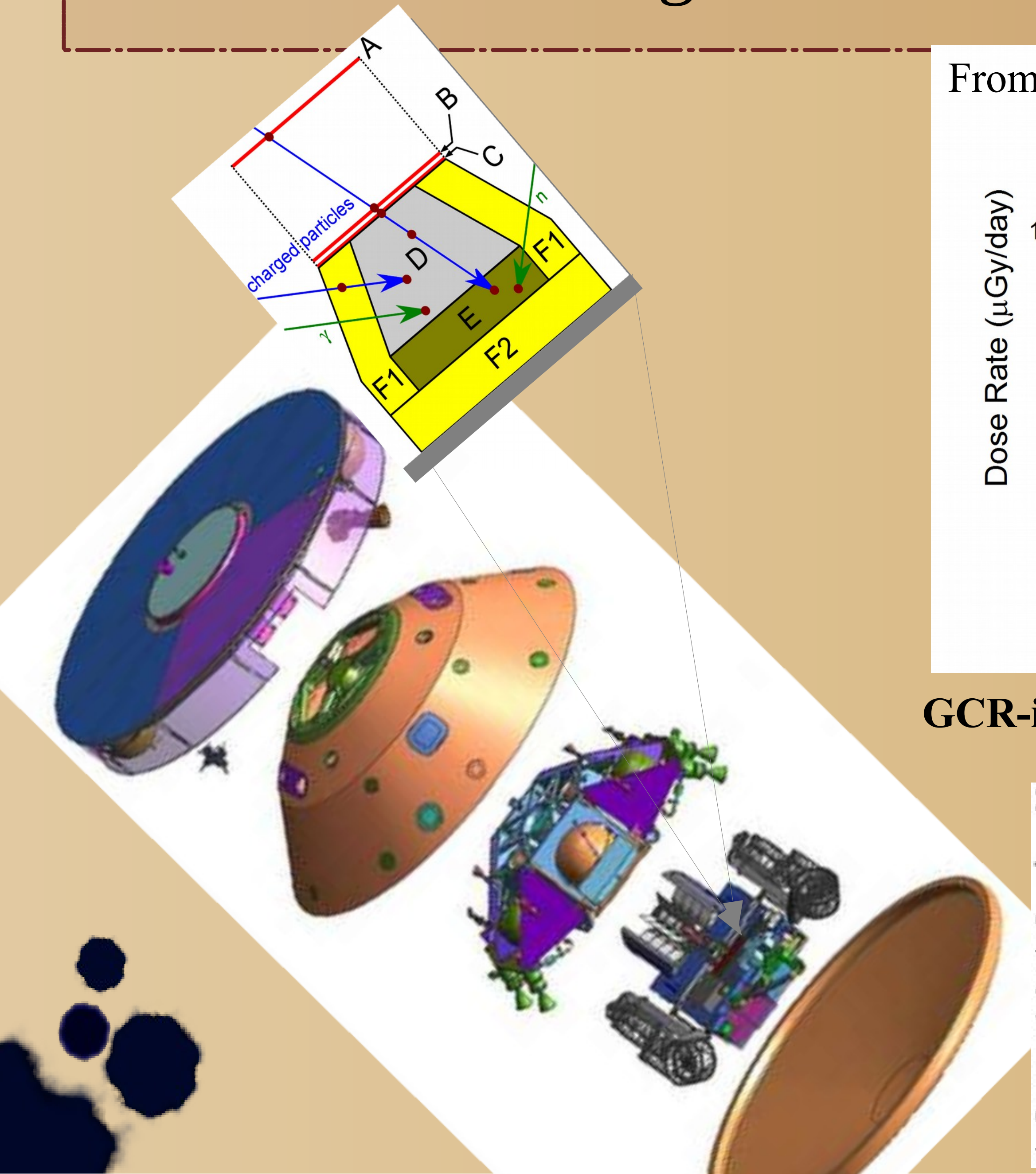


- RAD landed on Mars in August 2012 and has been measuring the Martian Radiation Environment for 6 years (~2 Martian years).
- RAD is an energetic particle detector measuring galactic cosmic rays, solar energetic particles, and their secondary particles generated in the Martian atmosphere.
- RAD contains 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.

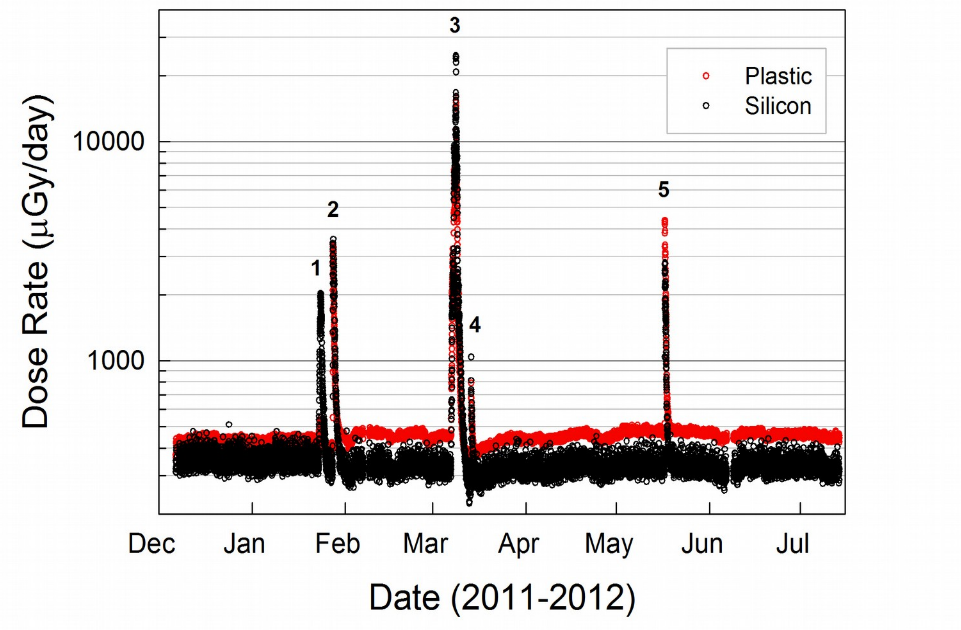


A selfi of the curiosity rover on Mars.

Radiation inside a spacecraft in deep space measured during **the cruise phase to Mars**



From **Zeitlin et al 2013, Science**

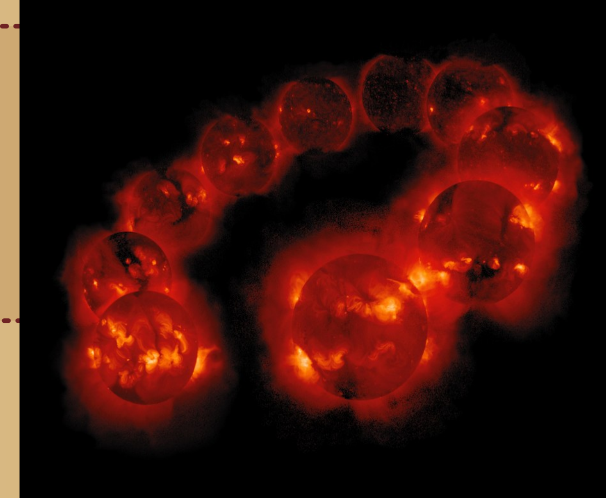


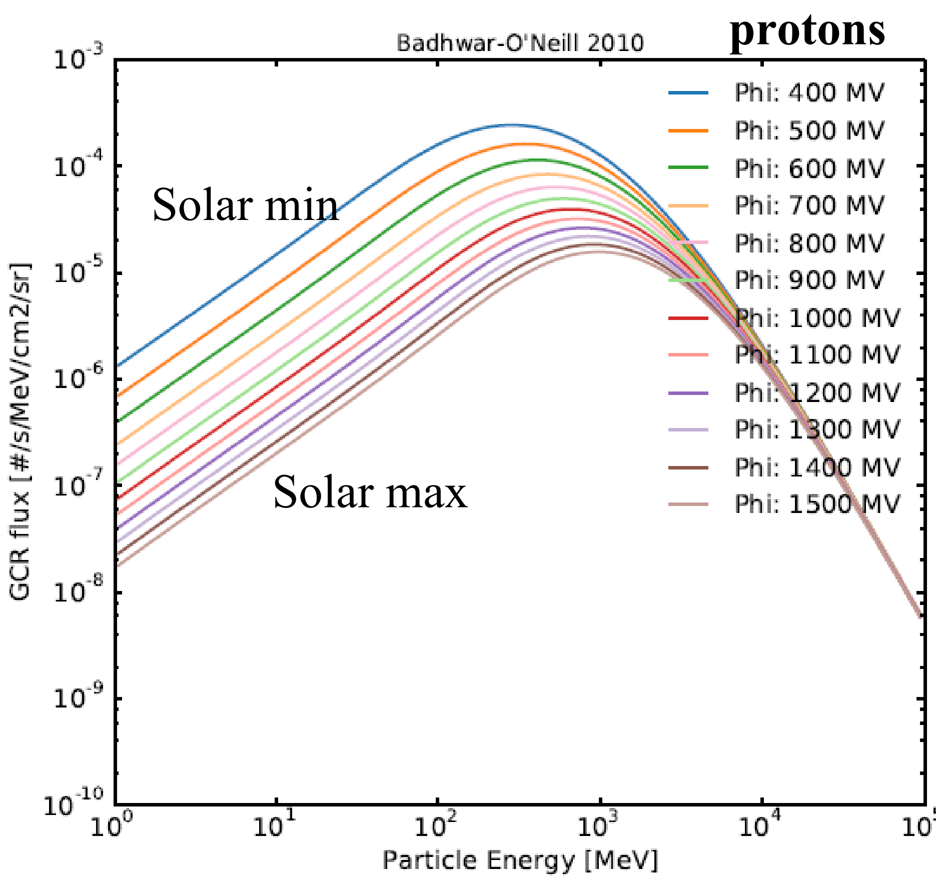
GCR-induced dose rate: ~0.481 uGy/day

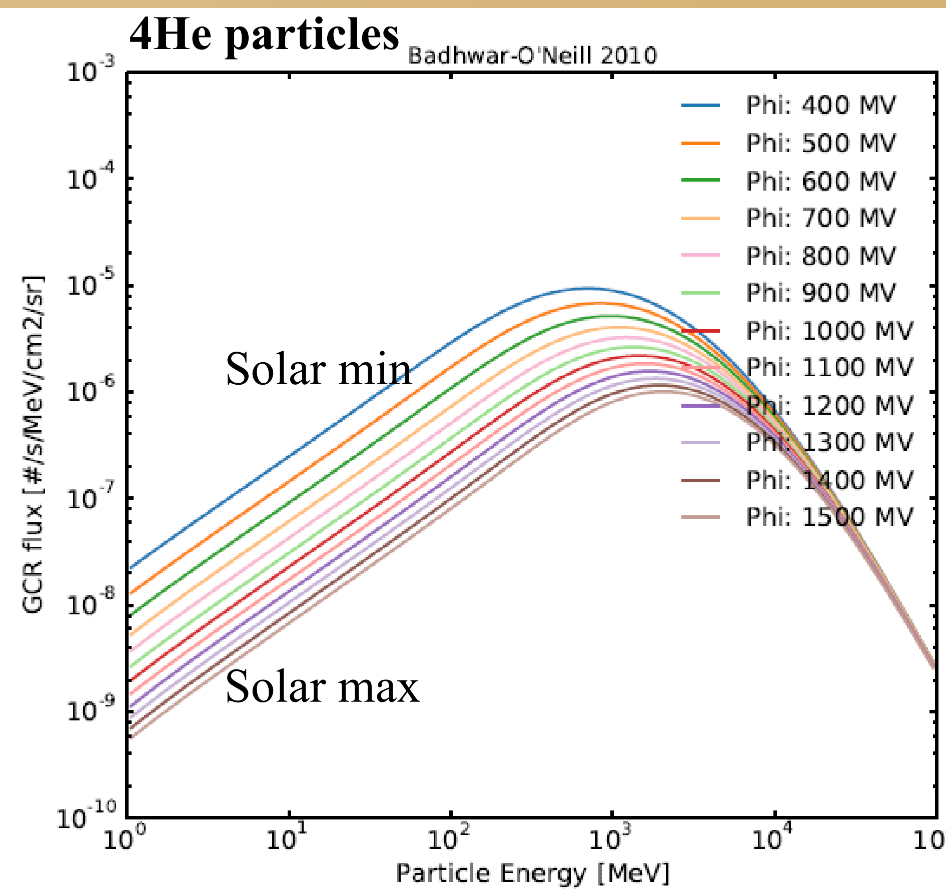
SEP events.

Time period (2012)	Integrated dose equivalent (mSv)
23 to 29 January	4.0
7 to 15 March	19.5
17 to 18 May	1.2
Cruise SEP Total	24.7

How about the GCR radiation under different solar modulation conditions?

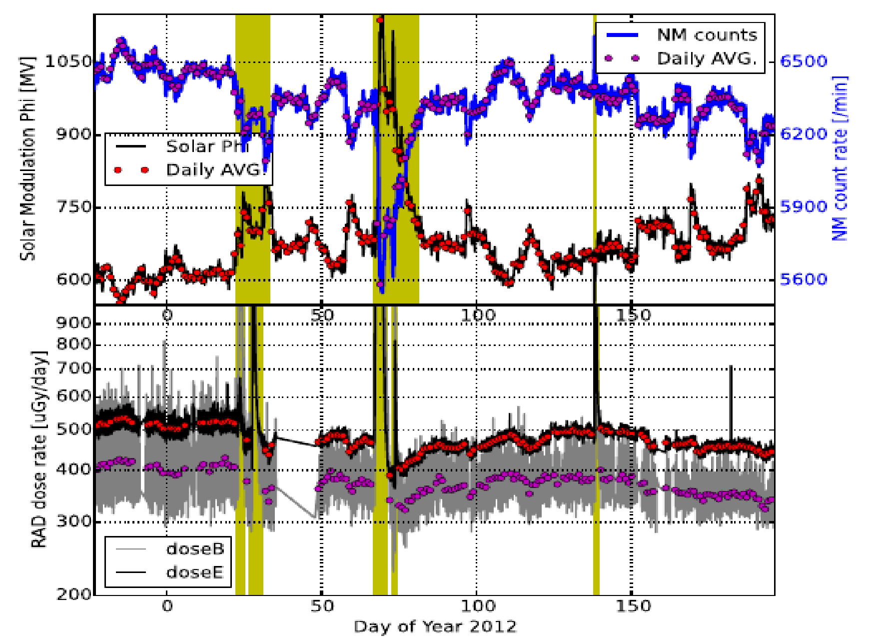




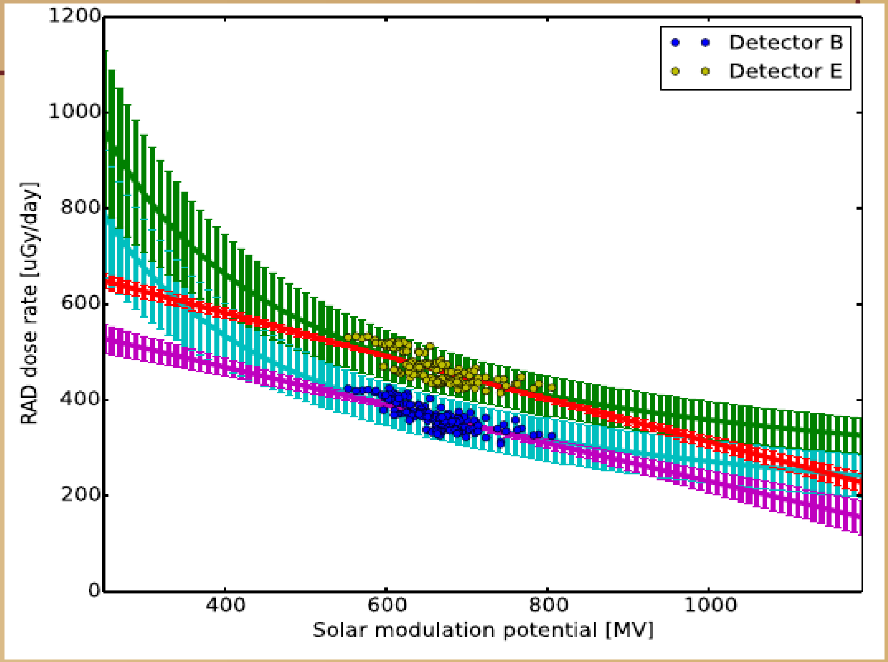


Badwahr O' Neil 2010 model

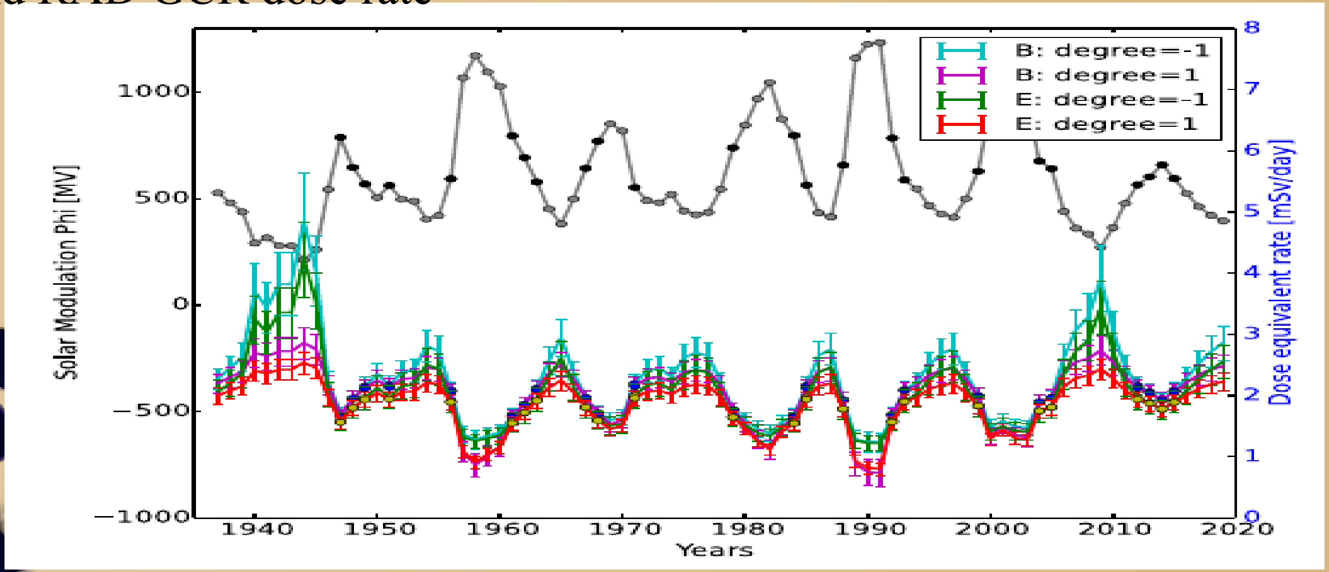
Empirical predictions of **GCR-radiation** during the **cruise to Mars under different solar modulation conditions**



Anti-correlation of solar modulation and RAD GCR dose rate



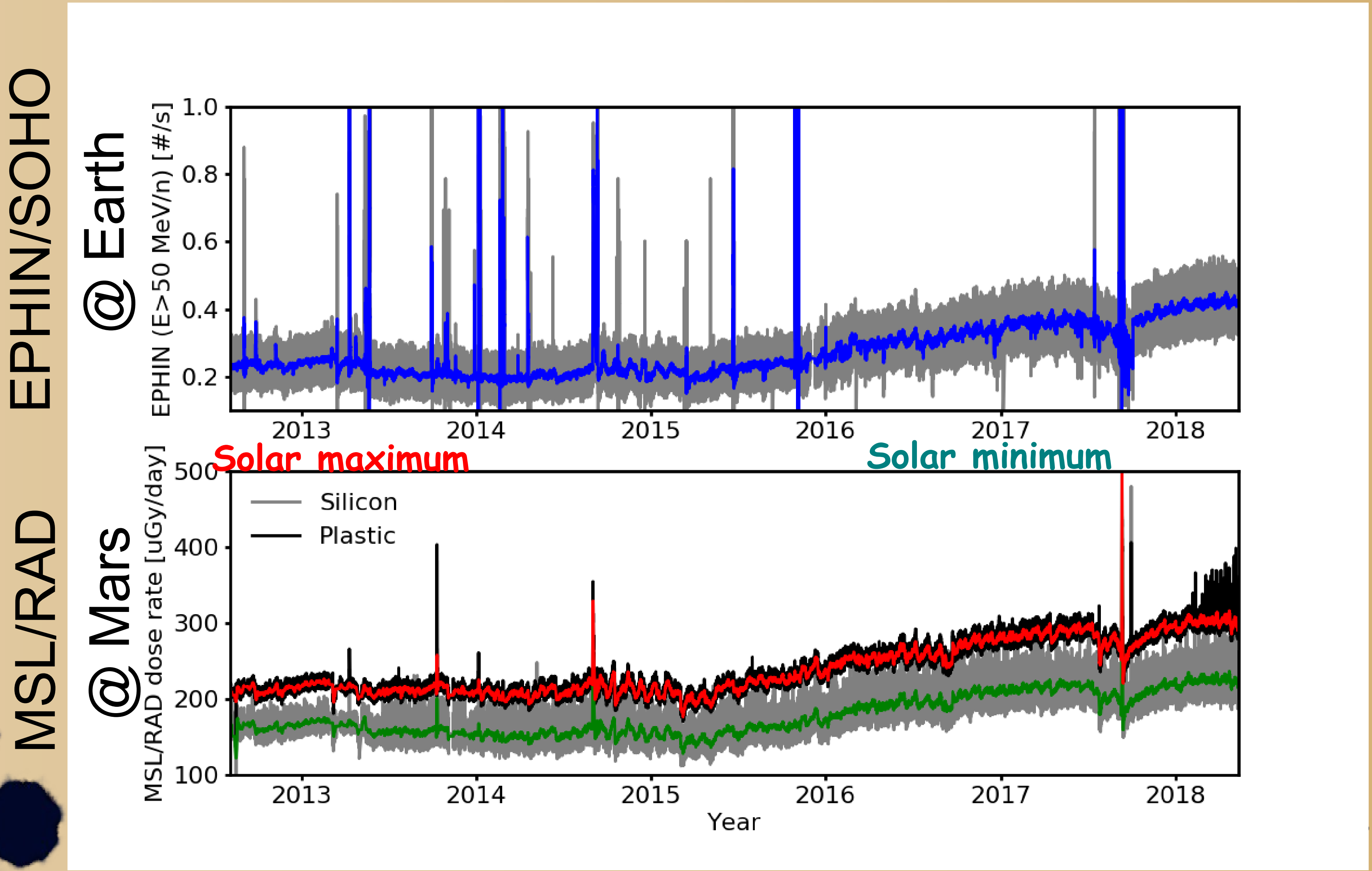
Quantify and extrapolate this correlation



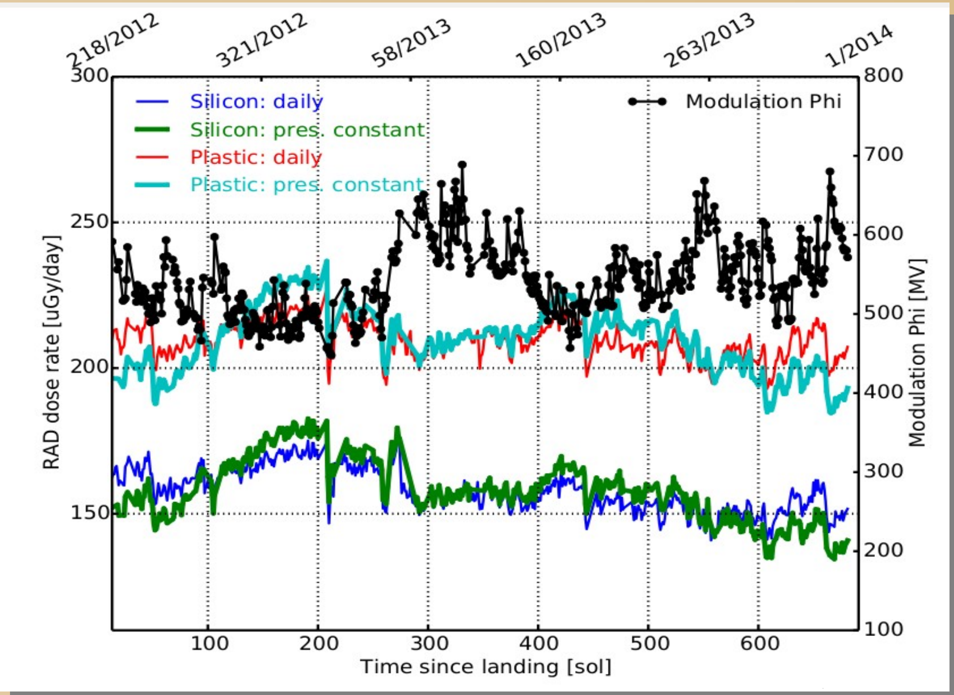
Empirical model of the dose rate during different solar modulation conditions.
More measurements are needed to constrain the model.

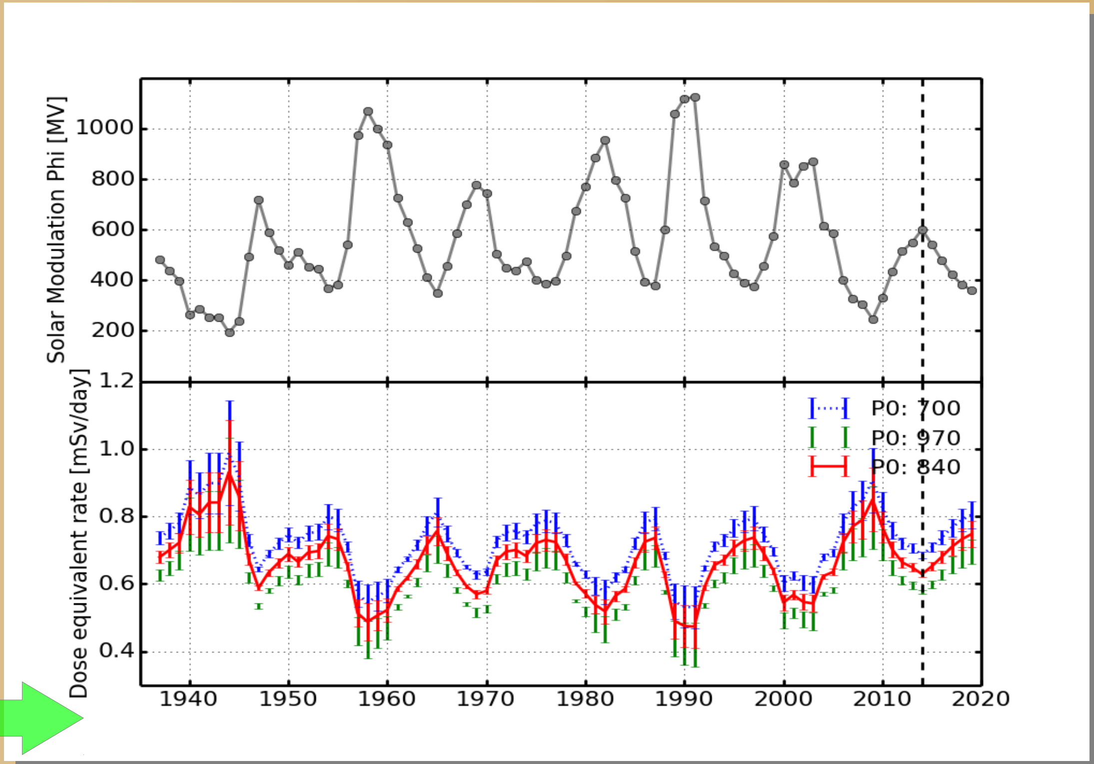
Guo et al 2015 A&A

On the surface of Mars, GCR-radiation is also modulated by the solar activity and has been increasing as solar activity decreases in recent years



Empirical predictions of **GCR-radiation** on Mars surface **under different solar modulation conditions**





The long-term heliospheric modulation of the surface radiation is isolated by subtracting the variation induced by seasonal pressure changes.

Guo et al 2015b, ApJ

Based on the modulation-dose rate correlation, we can 'predict' the Martian surface radiation under different solar modulation conditions.

GCR radiation for a typical mission to Mars

Solar minimum: cruise (224+237)*3 + Mars (458*0.8) ~ **1.75 Sv**
Solar maximum: cruise(224+237)*1.2 + Mars (458*0.5) ~ **0.78 Sv**