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SPACEMON 2025

Space environments monitoring workshop

11-13 June 2025 | ESA/ESTEC

The Multifaceted Impact of the Interplanetary Medium on Space Missions

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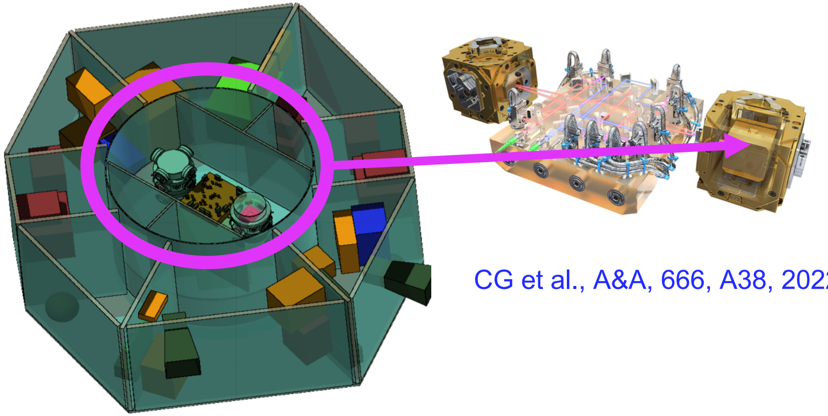
INFN LISA CONSORTIUM metis a-Si:H

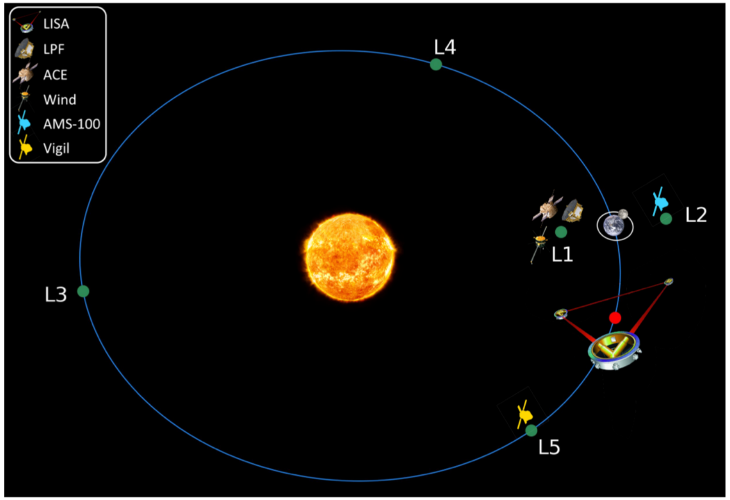
Overview

- **Spacecraft deep charging on board the ESA LISA Pathfinder (LISA-PF) and LISA, the first space interferometer for gravitational waves**. No particle differential flux measurement was allowed by the radiation monitors on board LISA-PF but it will be with LISA up to 400 MeV/n for protons and helium. Precious lessons were learned with LISA-PF on interplanetary physics of galactic cosmic rays (GCRs). On April 1st I was appointed by ESA as a complimentary scientist on the LISA Science Team for the Space Weather area.
- **Solar Orbiter:** EPD/HET particle observations outside the S/C & with the Metis coronagraph below more than 10 g/cm^2 of material. New insights on GCRs but open problems remain on high-energy solar particle detection.
- **HASPIDE-SPACE:** an instrument prototype for high-energy SEP event observations.

LISA-PF and LISA test-mass charging



CG et al., A&A, 666, A38, 2022



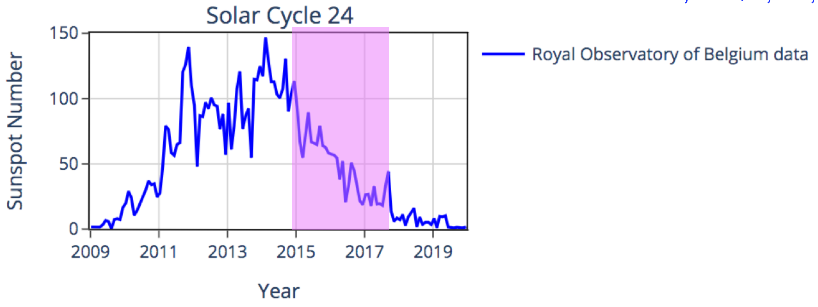
LISA

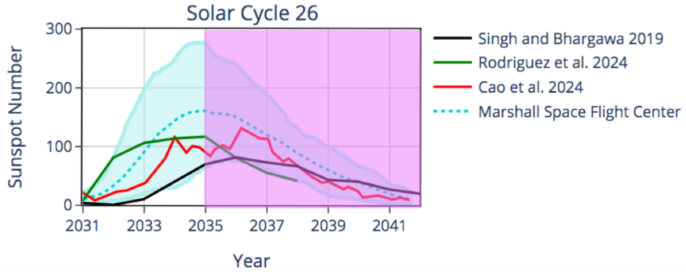
Launch: 2035
Arm: 2.5 10^6 km
Orbit: Heliocentric - 3 S/C trailing Earth at 50 million km
Shielding material: 16 g cm^{-2}

LISA-PF

Launch: 2015
Orbit: L1 - 1.5 million km from Earth
Duration: 1.5 years
Shielding material: 13.8 g cm^{-2}

CG et al., CQG, 42, 095009, 2025

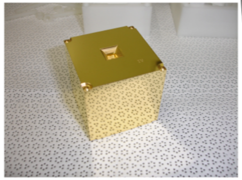




TEST-MASS CHARGING

Estimate of low-energy electron diffraction on gold

OPEN PROBLEMS REMAIN!



Villani M. et al., *Study of quantum electron diffraction for the LISA test-mass charging*
Results in Physics 60 (2024) 107638

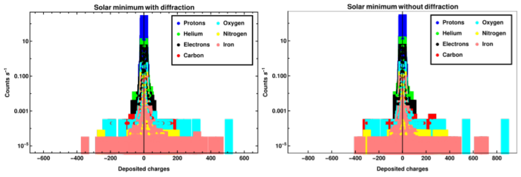


Fig. 14. Charge histogram for the solar minimum simulations. *Left* with diffraction; *right*: without diffraction.

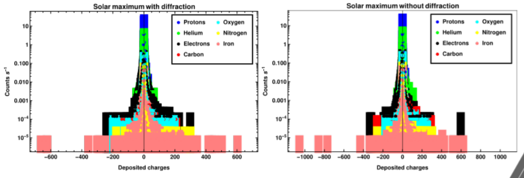
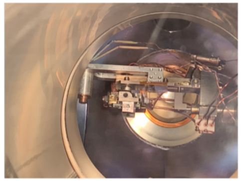
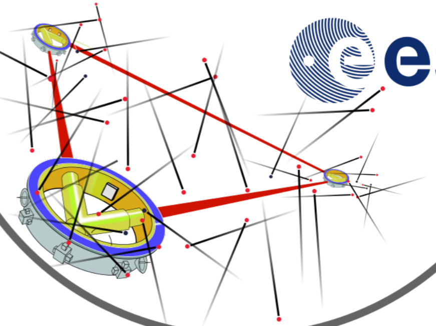


Fig. 15. Same as Fig. 14, for solar maximum.

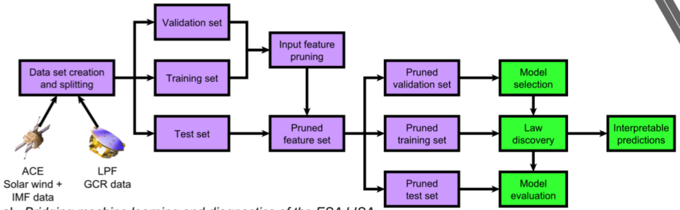
Experimental test
of electron diffraction in progress



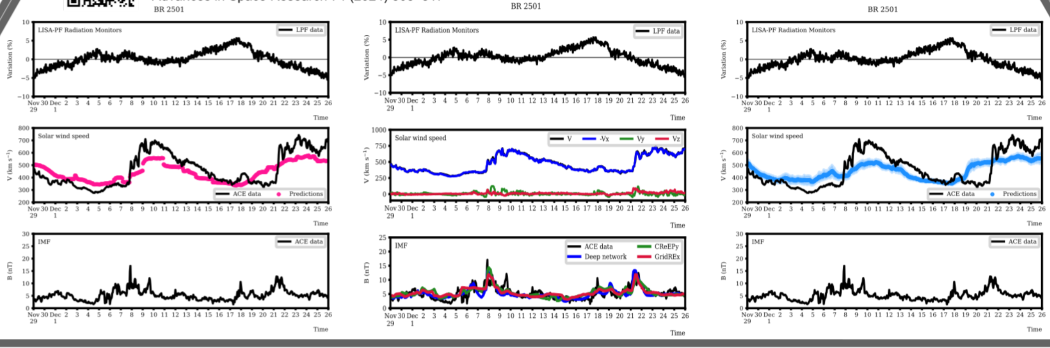


MACHINE LEARNING MODELS

for the recovery of interplanetary plasma parameters for LISA



Sabbatini F., et al., *Bridging machine learning and diagnostics of the ESA LISA space mission with equation discovery via explainable artificial intelligence*
Advances in Space Research 74 (2024) 505–517



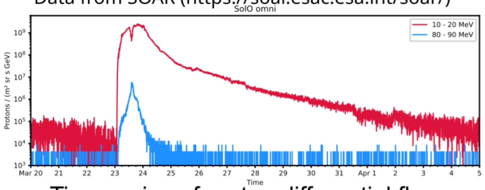
SPACE WEATHER FOR LISA

ESA recognized Space Weather as a formal area of investigation for LISA

Solar Energetic Particle events and their effects on the three LISA satellites remain the main area of investigation.

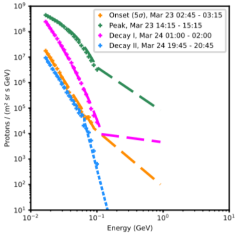
SEP event March 23 2024: a case study

Data from SOAR (https://soar.esac.esa.int/soar/)



Time series of proton differential flux

Proton differential flux during the evolution of the event

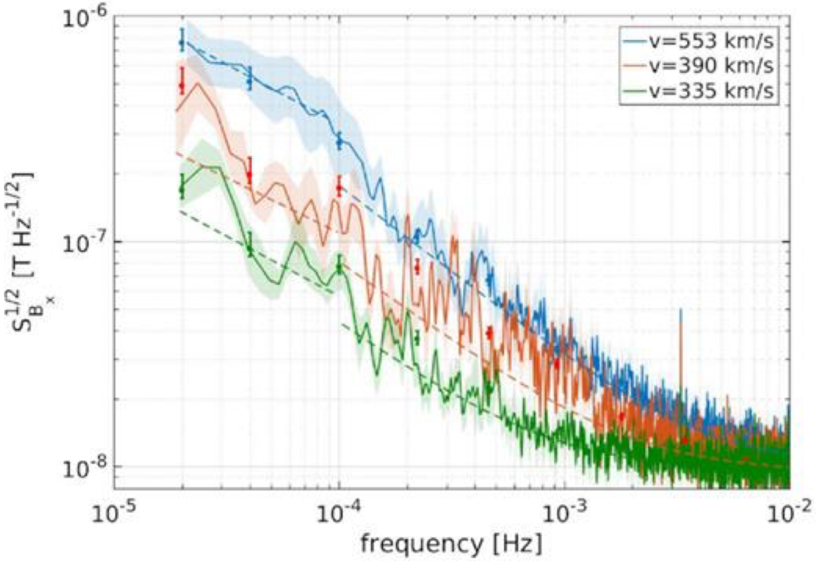


Corresponding tes-mass charging

SEP event March 23-24, 2024	Net (e+/s)	Effective (e/s)
Onset – March 23 02:45 – 03:15 UT	268	281
Peak – March 23 14:15 – 15:15	44808	51332
Decay I – March 24 01:00 – 02:00	62	70
Decay II – March 24 19:45 – 20:45	3	3

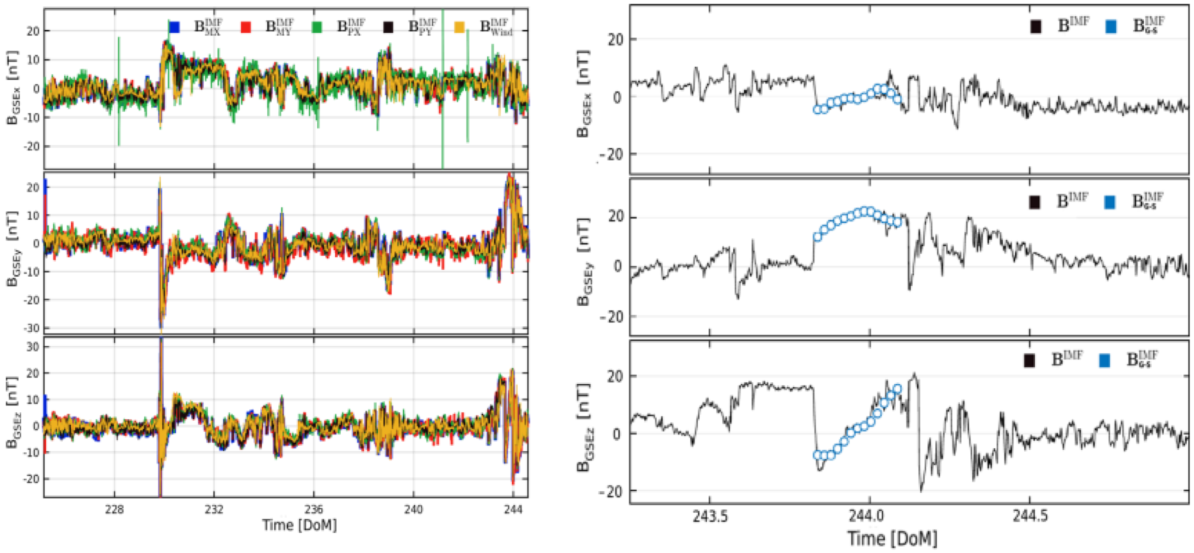
Interplanetary magnetic field

Solar wind speed variations and associated noise



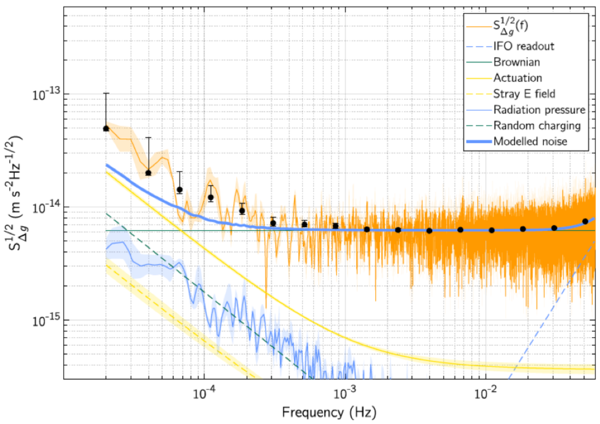
Armano et al., MNRAS, 494, 3014-3027, 2020

Magnetic Cloud passage with LISA-PF magnetometers and Wind



Cesarini et al., JSWSC, 12, 21, 2022
Benella et al., ApJ, 901 (1), 21, 2020

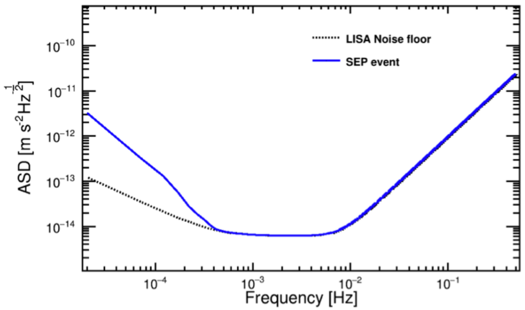
SEP event evolution & TM charging (SEP up to 1 GeV)



LISA-PF acceleration noise
E. Castelli, PhD thesis, 2020

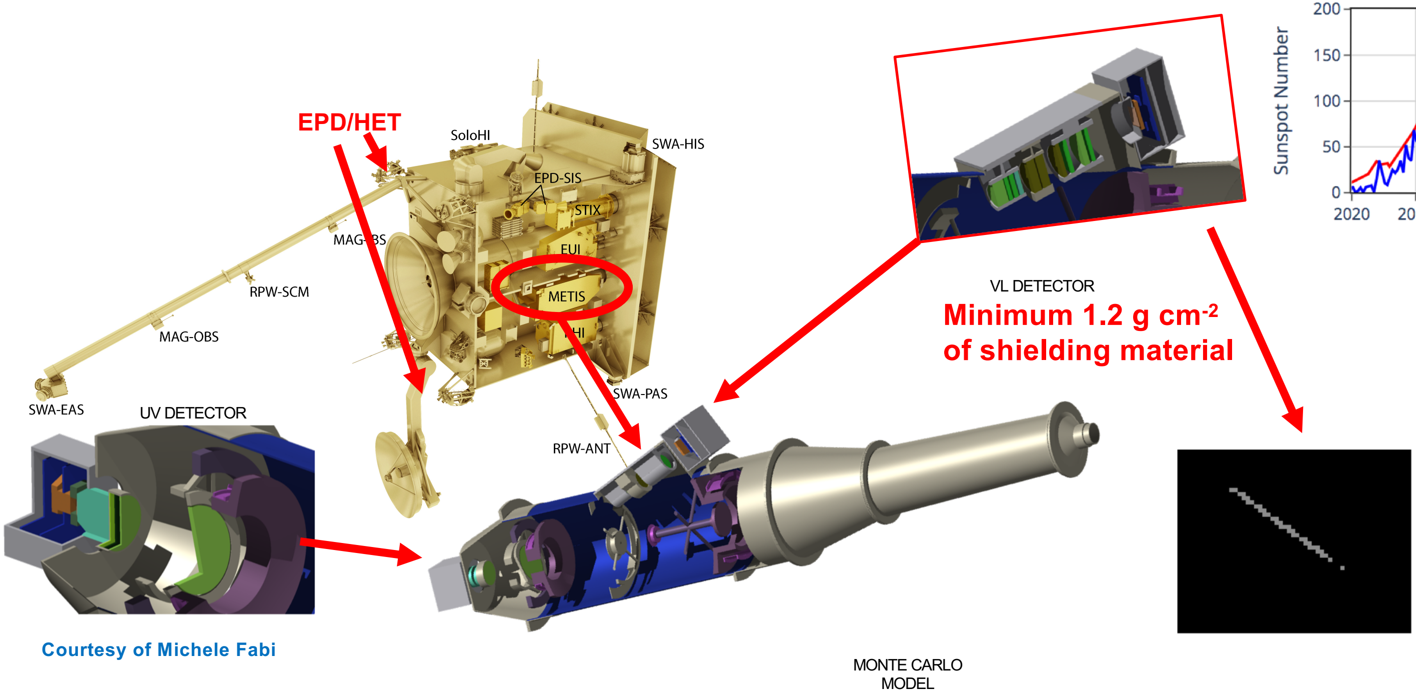
An upper limit to the mission acceleration noise due to SEP TM charging is at 10^{-4} Hz: 9.06×10^{-14} m s^{-2} Hz$^{-1/2}$

Dimiccoli et al., accepted for publication on A&A, 2025 (ESA ITT 10081)

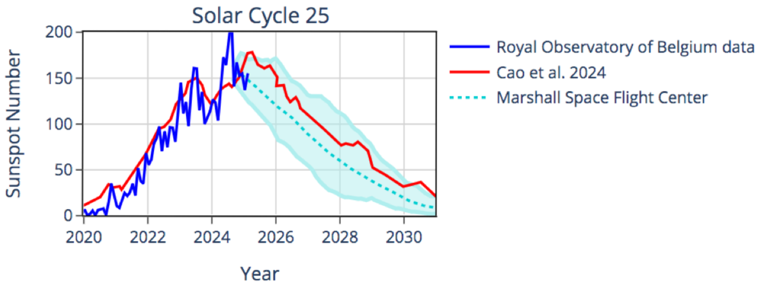


	Net TM charging (e+/s)	Effective TM charging (e/s)	Acceleration noise x10^{-15} (m s^{-2} Hz$^{-1/2}$) @10^{-4} Hz
SEP event July 24-26, 2023			
Onset – July 24 19:00 – 19:30 UT	143	154	0.0986
Peak – July 25 03:00 – 04:00 UT	13635	14580	**0.96**
Decay I – July 25 15:00 – 16:00 UT	269	299	0.137
Decay II – July 26 03:00 – 04:00 UT	259	270	0.131
Decay III – July 26 15:00 – 16:00 UT	6	6	0.0195
SEP event March 23-24, 2024			
Onset – March 23 02:45 – 03:15 UT	268	281	0.133
Peak – March 23 14:15 – 15:15	44808	51332	**1.8**
Decay I – March 24 01:00 – 02:00	62	70	0.0665
Decay II – March 24 19:45 – 20:45	3	3	0.0138

EPD/HET and METIS on board Solar Orbiter

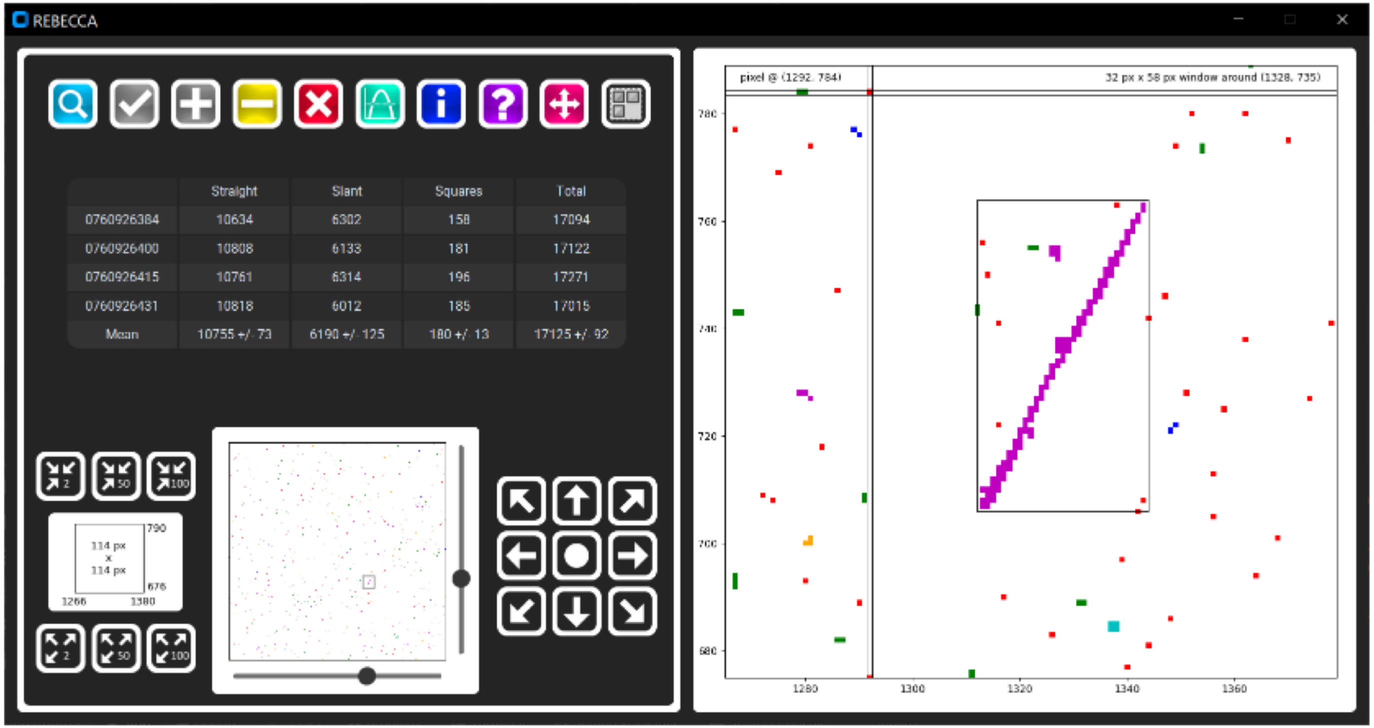


CG et al., A&A, 656, A15, 2021



Metis/Solar Orbiter:
>1.2 g cm^{-2} shielding material
average: > 10 g cm^{-2}
protons and nuclei are stopped below 80 MeV

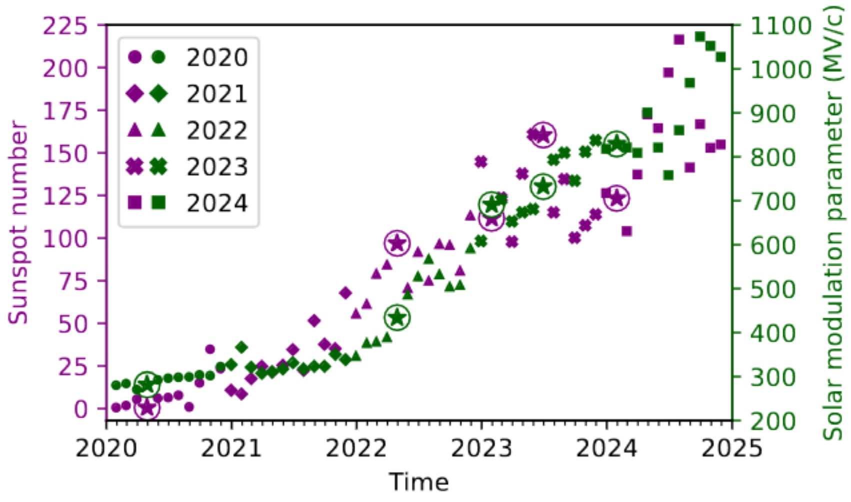
REBECCA



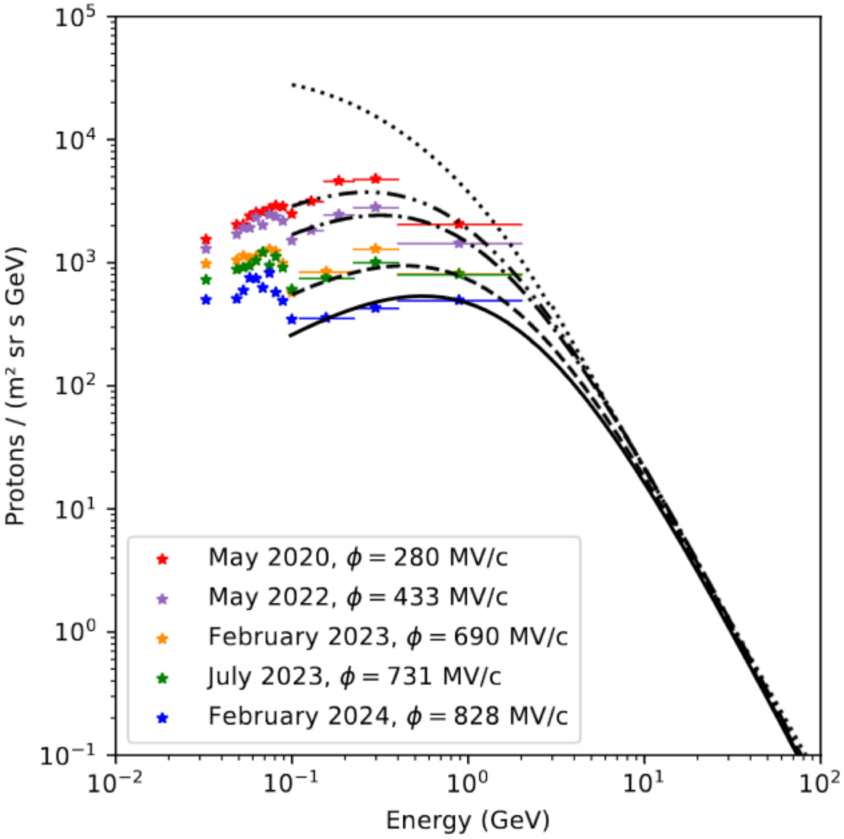
Tool for the visualization and analysis of the Metis cosmic-ray matrices

From F. Sabbatini

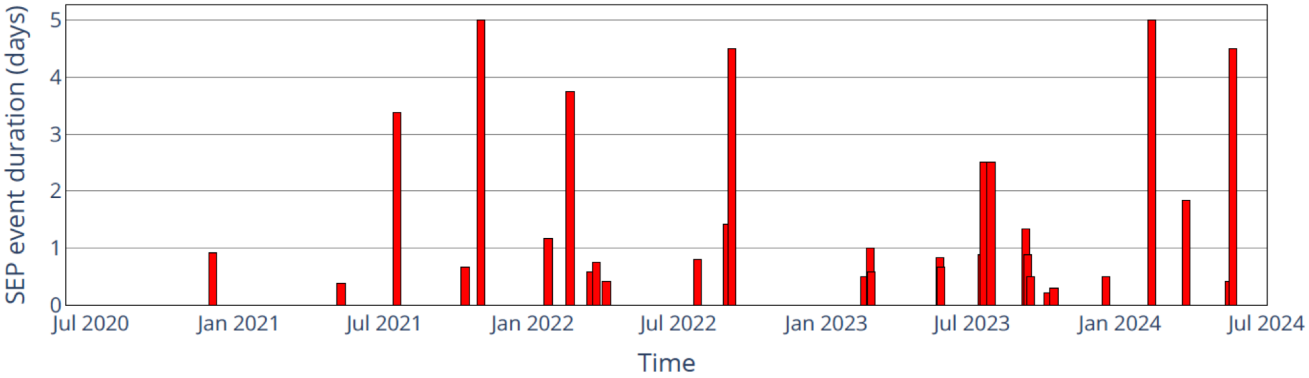
GCR variations during solar cycle 25



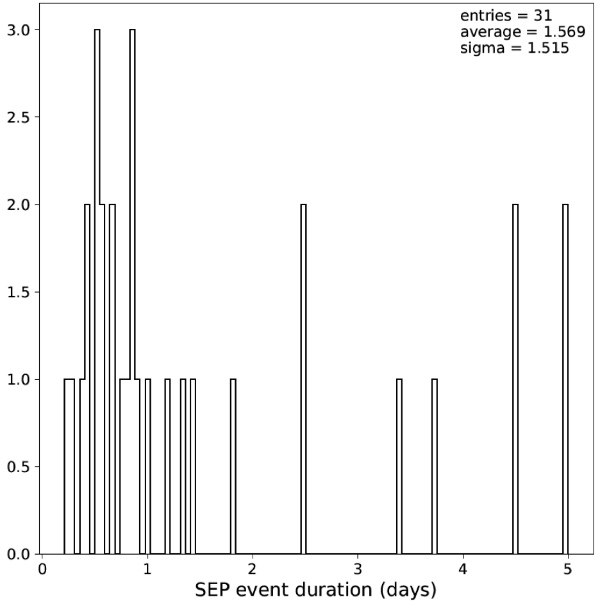
CG et al., to be submitted to A&A



SEP event duration during the present maximum of solar cycle 25

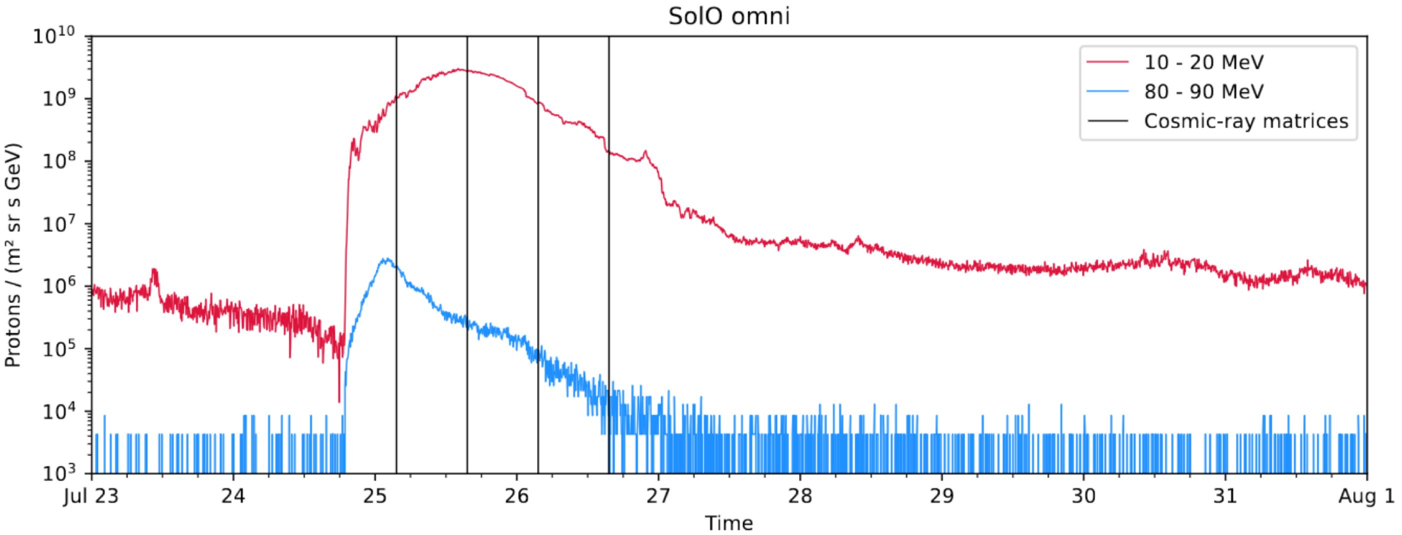


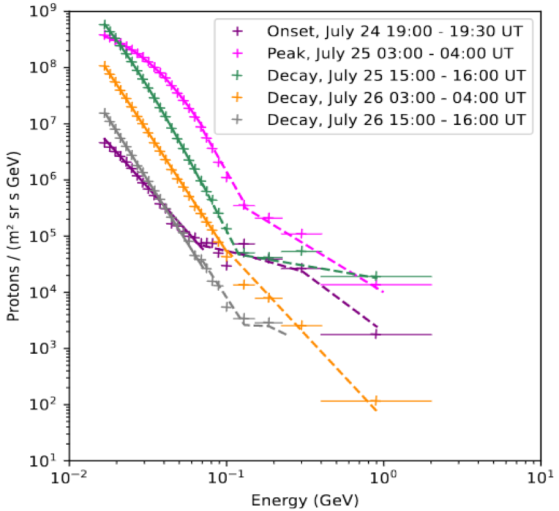
CG et al., CQG, 42, 095009, 2025



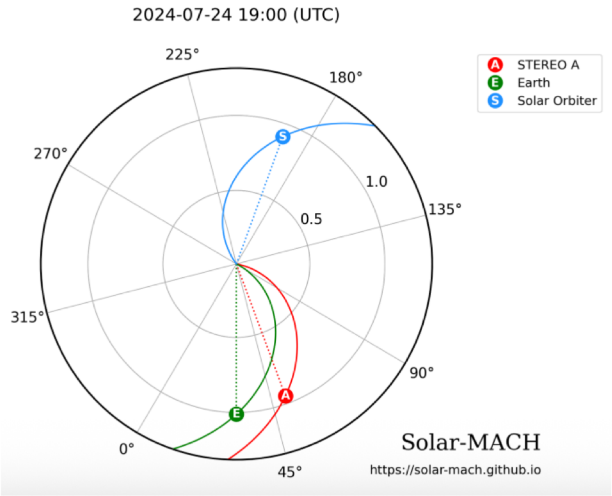
We are only interested in those events associated with particle flux at least 5-σ above GCR background in the energy interval 80-90 MeV, otherwise we would not see any contribution in the TM charging.

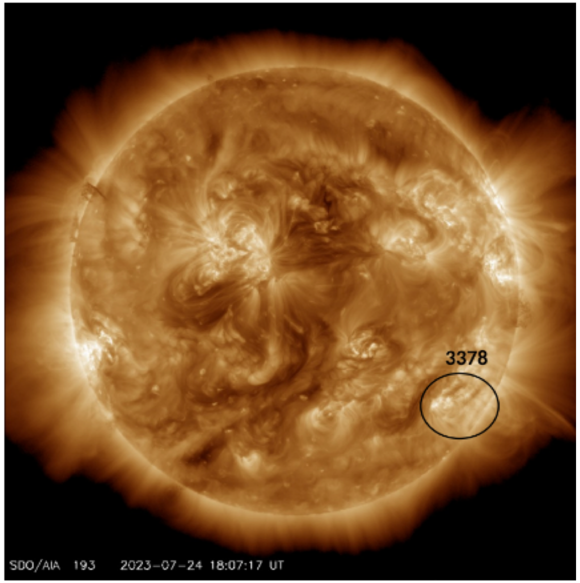
SEP event July 24, 2023

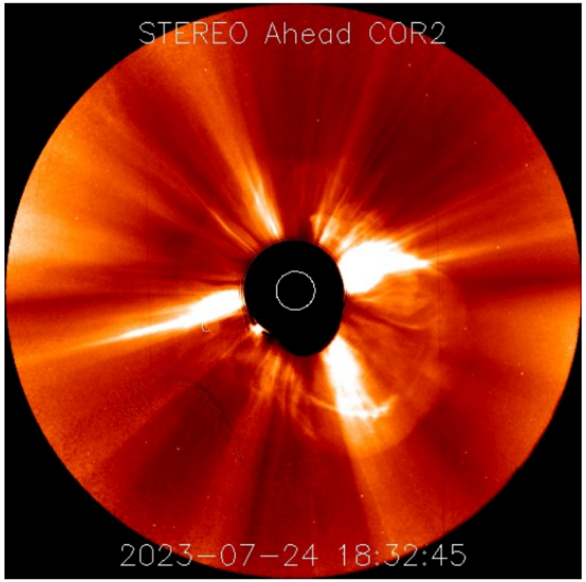


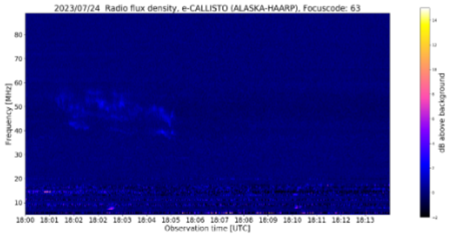


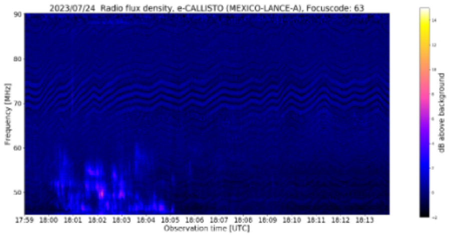
The solar activity associated with the SEP event



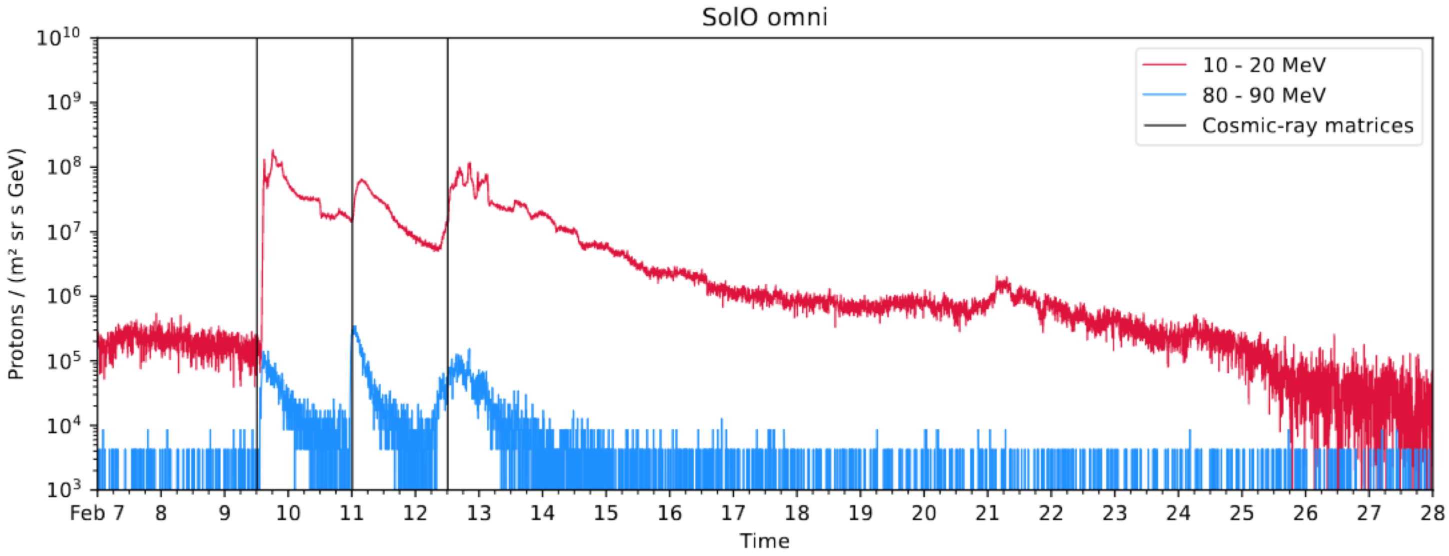


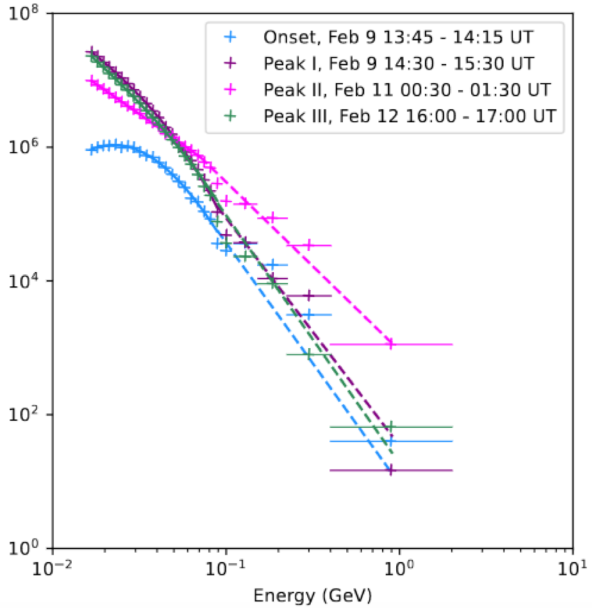




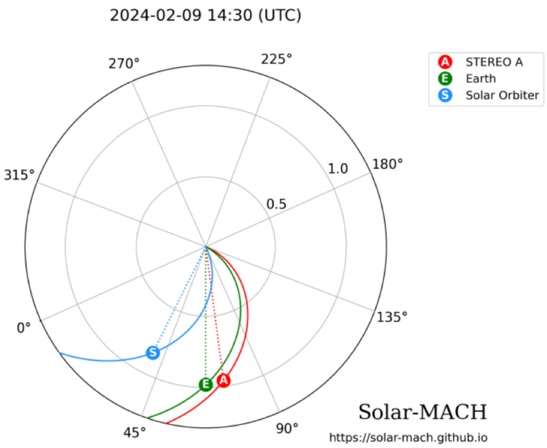


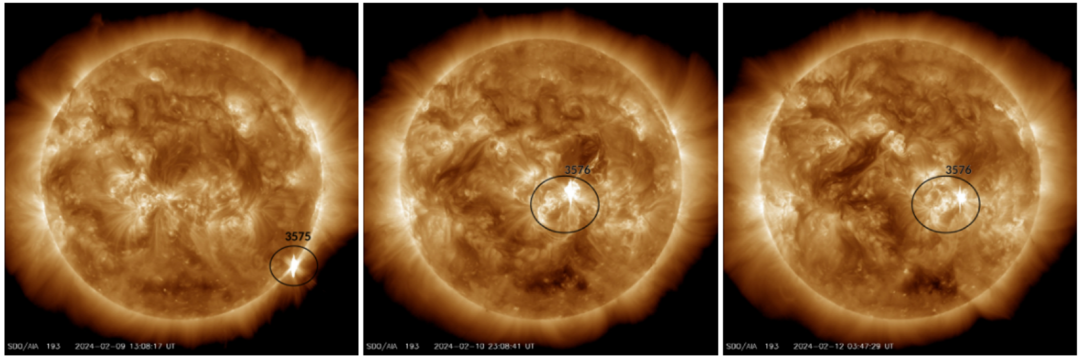
SEP event February 9, 2024

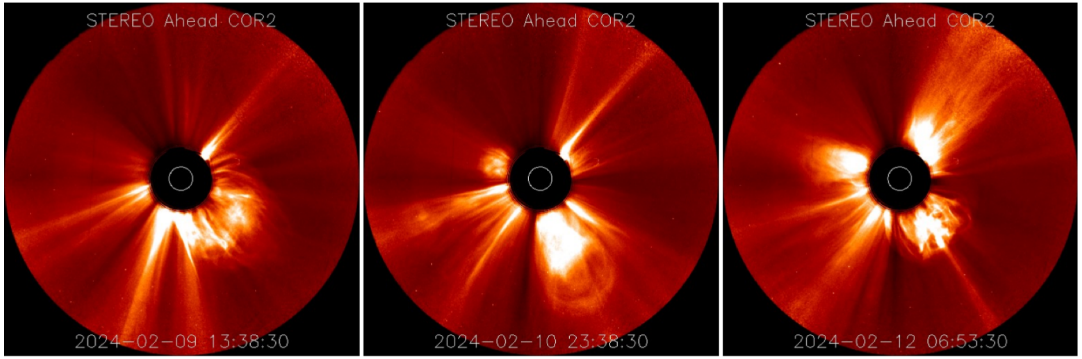


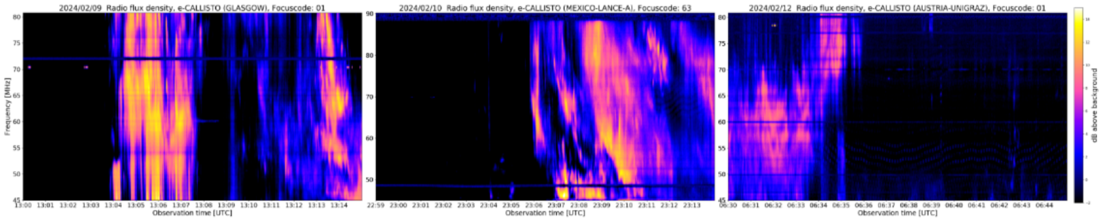


Solar activity associated with the SEP event









GCR and SEP observations in the Metis cosmic-ray matrices

Period	Protons/(cm² sr s) above 100 MeV
May 2020	5111
May 2022	3970
February 2023	2000
July 2023	2154
February 2024	1500

CG et al., to be submitted to A&A

	Straight	Slant	Squares	Total
May 2020 (GCRs) Average	188	79	4	271±22
May 2022 (GCRs) Average	151	57	4	212 ± 6
February 2023 (GCRs) Average	83	36	1	120±5
July 2023 (GCRs) Average	82	32	1	115±4
February 2024 (GCRs) Average	73	28	1	102±3
SEP July 24, 2023 - 19:00-19:30 UT (Onset - Not available)				
SEP July 25, 2023 - 3:00-4:00 UT (Peak) Average	4740	4892	257	9889±19
SEP July 25, 2023 - 15:00-16:00 UT (Decay 1) Average	787	664	47	1498±6
SEP July 26, 2023 - 3:00-4:00 UT (Decay 2) Average	281	183	9	473±11
SEP July 26, 2023 - 15:00-16:00 UT (Decay 3) Average	115	59	2	176±9
SEP February 11, 2024 (peak 2) Average	1536	884	26	2446±13
SEP February 12, 2024 (peak 3) Average	337	217	10	564±13

Simulations of cosmic-ray and SEP secondary particle in the Solar Orbiter S/C

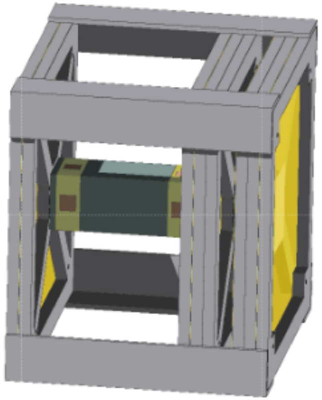
	Number of tracks - 60 s exposure time		
	MC	Observed	ϕ (MV/c)
GCRs			
May 2020	276±39±17	271 ±22	299
May 2022	242±34±16	212 ±6	433
February 2023	118±17±11	120 ±5	701
July 2023	-	115 ±4	731
February 2024	91±13±10	102±3	828

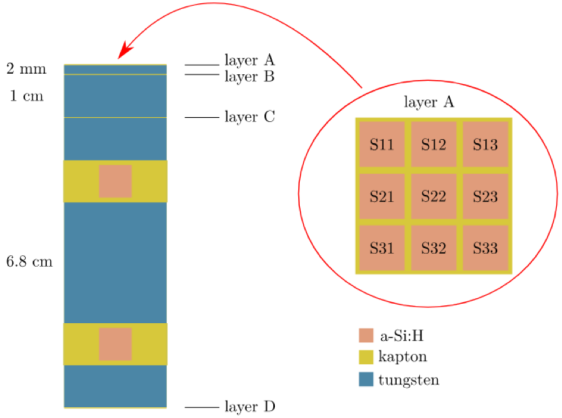
	Number of tracks - 60 s exposure time	
	MC	Observed
	SEPs	GCRs+SEPs
Onset July 24, 2023 19:00-19:30 UT	1524 ±213±39	N. A.
Peak July 25, 2023 3:00-4:00 UT	9960±1394±100	9889±19
Decay 1 July 25, 2023 15:00-16:00 UT	2040±286±45	1498±6
Decay 2 July 26, 2023 3:00-4:00 UT	370±52±19	473±11
Decay 3 July 26, 2023 15:00-16:00 UT	34±5±6	176±9
Onset 9, 2024 13:45-14:30 UT	344±48±19	N. A.
Peak 1 February 9, 2024 14:30-15:30 UT	380±53±20	N. A.
Peak 2 February 11, 2024 00:30-1:30 UT	2400±336±49	2446±13
Peak 3 February 12, 2024 16:00-17:00 UT	400±36±20	564±13

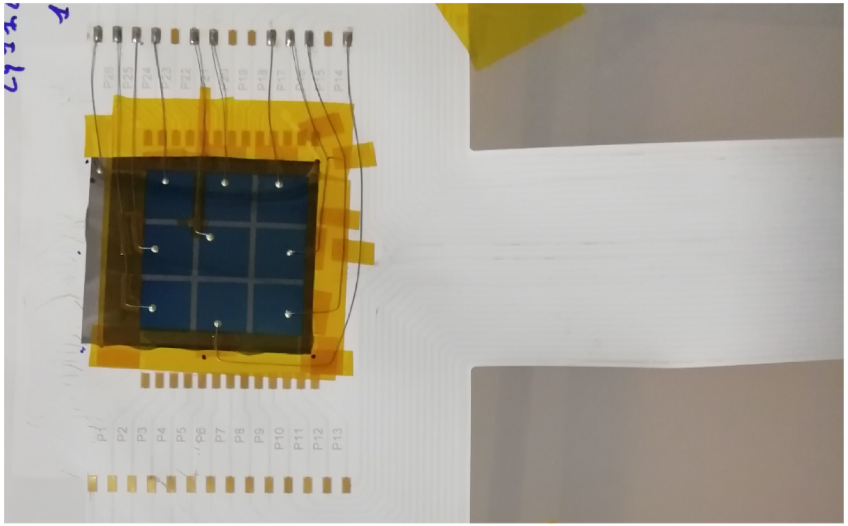
Particle species	Protons (%)	Helium nuclei (%)	e^-e^+ (%)	Heavy nuclei (%)	$\pi^-\pi^+$ (%)	Others (%)
GCRs incident on the S/C	90	8	1	1		
GCRs May 2020 - Metis VL images	80		17		3	
GCRs May 2022 - Metis VL images	77		18		5	
February 2023/July 2023 - Metis VL images	69		23		7	1
February 2024 - Metis VL images	71		17		10	2
SEPs incident on the S/C	99		1			
SEP events - Metis VL images	92-93		7-8			

THE PROTOTYPE OF HASPIDE-SPACE

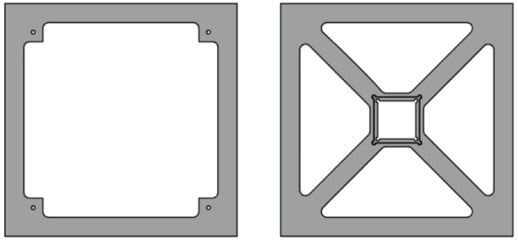
Passive layers are made of tungsten





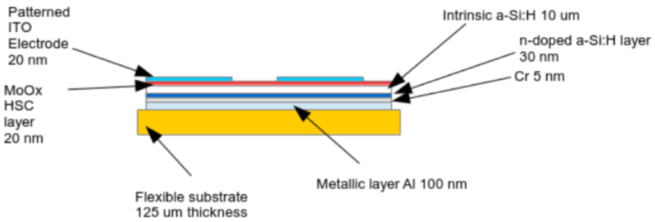


Frame of passive layer

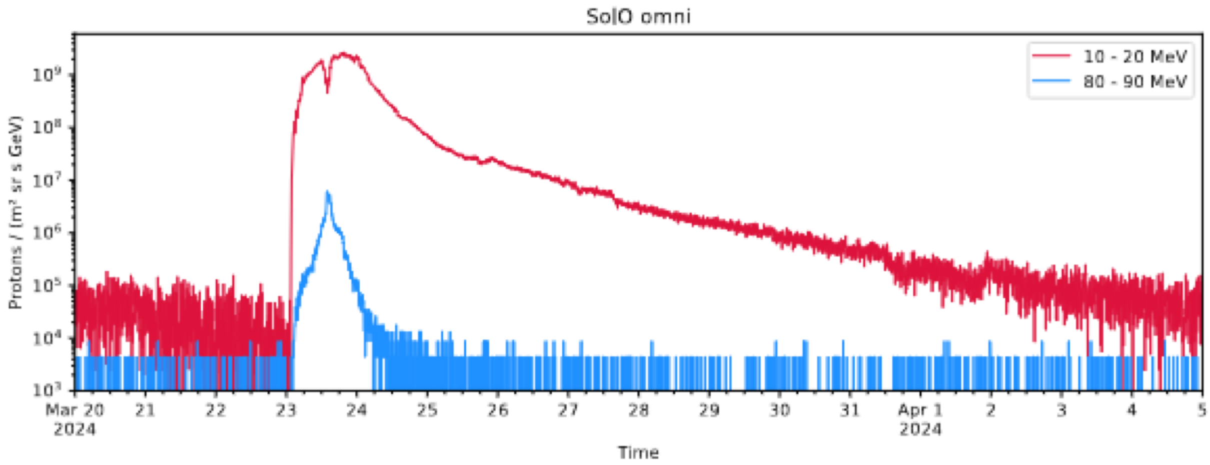


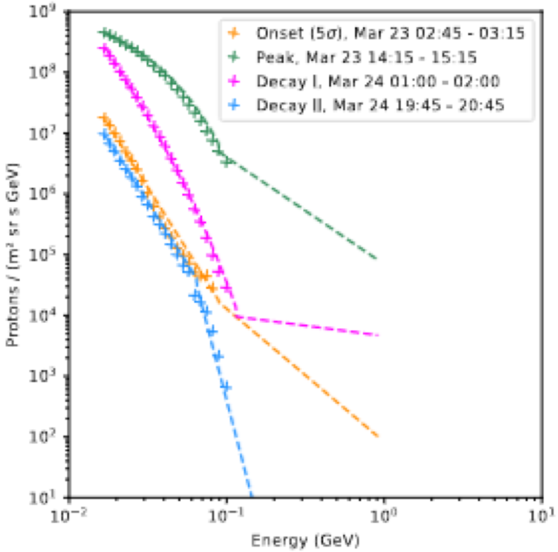
Frame of active layer

Figure 1. Active layer of the HASPIDE-SPACE instrument.

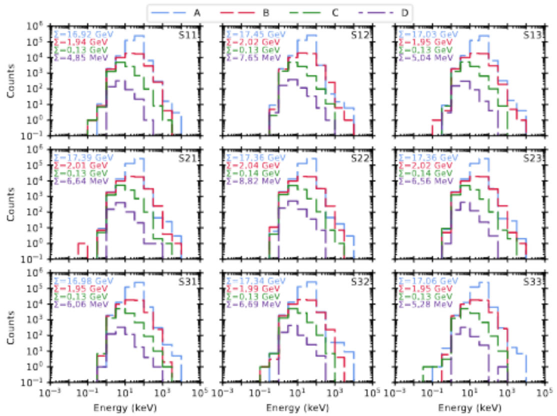


SEP event March 23, 2024



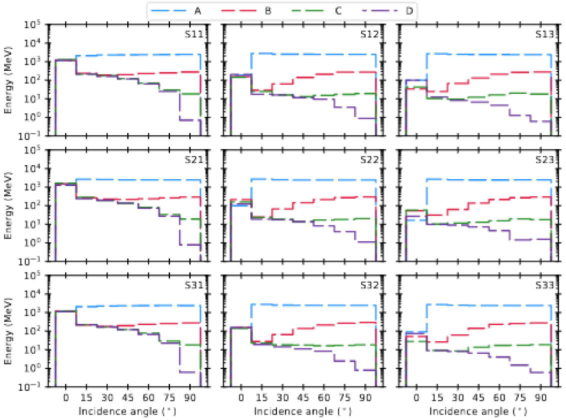


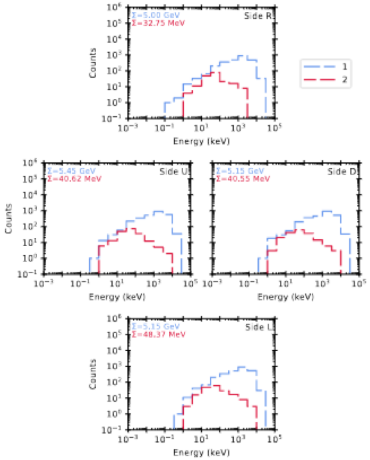
Proton energy losses in the sensors of the instrument



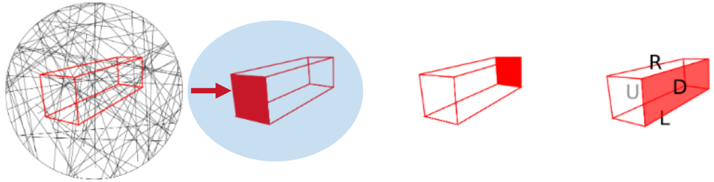
SEP detection for > 100 MeV deposited in 1 s

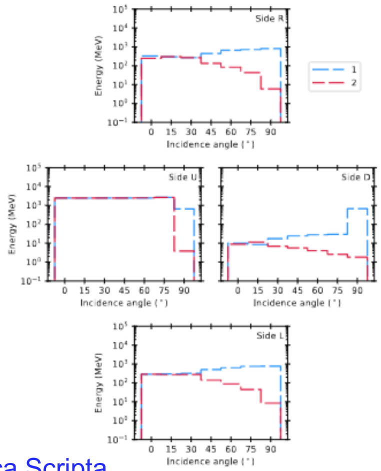
a-Si:H matrix sensors performance





Side sensors





Side sensors

Ionization energy losses of protons in one second at the peak of the March 2024 SEP event in each sensor of HASPIDE for front particle incidence and different angle of incidence. Medium-strong event detection is feasible up to 400-600 MeV depending on the SEP flux spectral index.

CG et al., to be submitted to Physica Scripta

Conclusions

- A detailed study of the test-mass charging for/with LISA Pathfinder allowed us to study the interplanetary physics of GCRs. LISA will provide unique observations of short-term GCRs and SEP events. Aspects of test-mass charging associated with low-energy electrons remain to be investigated.
- Solar energetic particle effects on space missions have been studied with Solar Orbiter EPD/HET & Metis instruments. We have studied the SEP spatial distribution during the evolution of the events and the composition and number of particles outside and inside the S/C. Particle local acceleration masks the effects of adiabatic expansion of GCRs.
- We are building a prototype instrument devoted to low and high energy solar particle measurements: HASPIDE-SPACE.