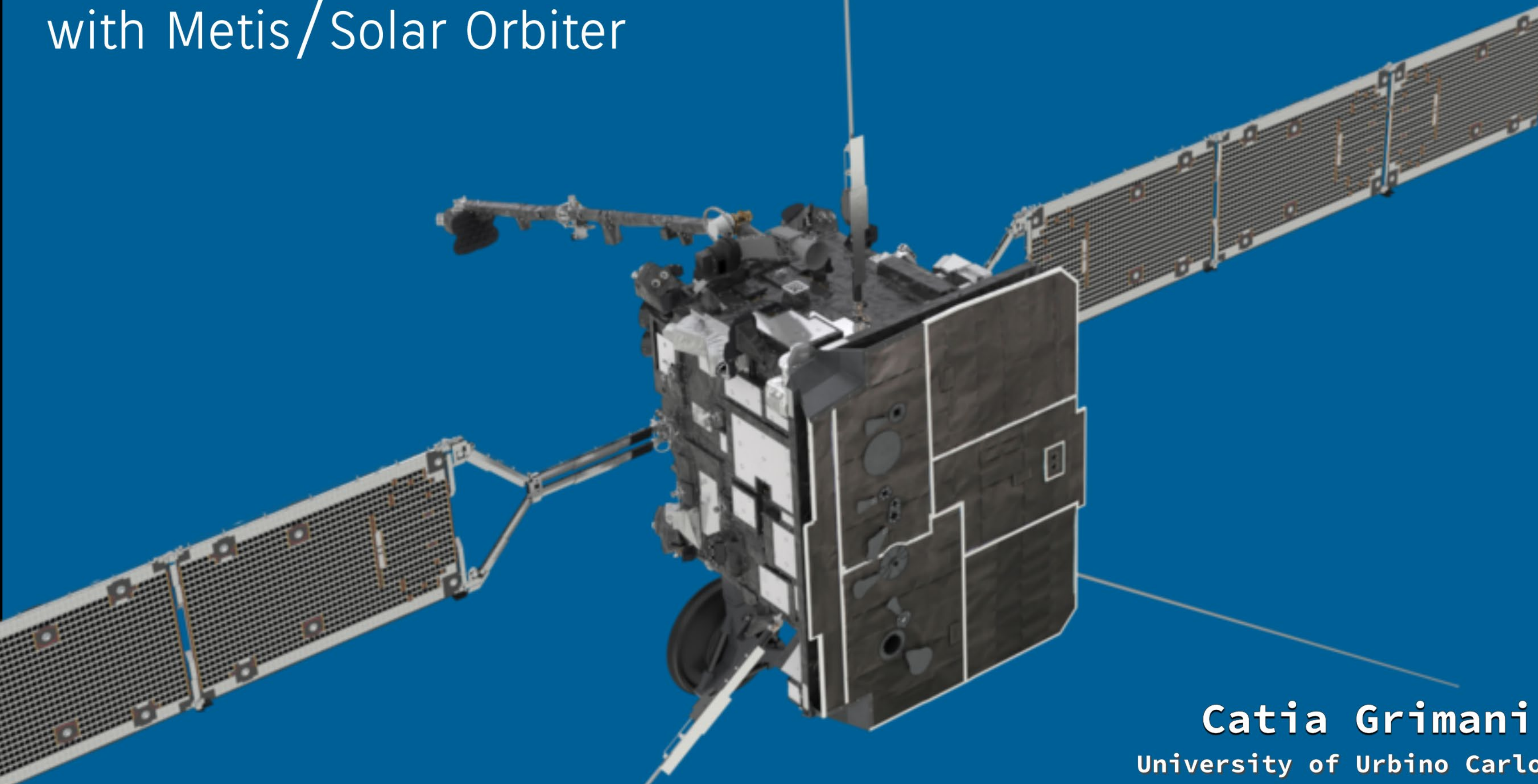
Observations of galactic cosmic rays and solar energetic particles with Metis/Solar Orbiter

9th Metis Worskhop Catania



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INFN Florence, Italy
and the Metis Cosmic Rays Topical Team

1506 UNIVERSITÀ DEGLI STUDI DI URBINO CARLO BO

INFN

ESA | NASA solar orbiter

Jan 24 – 26, 2024
Museo Diocesano di Catania
Catania (Italy)

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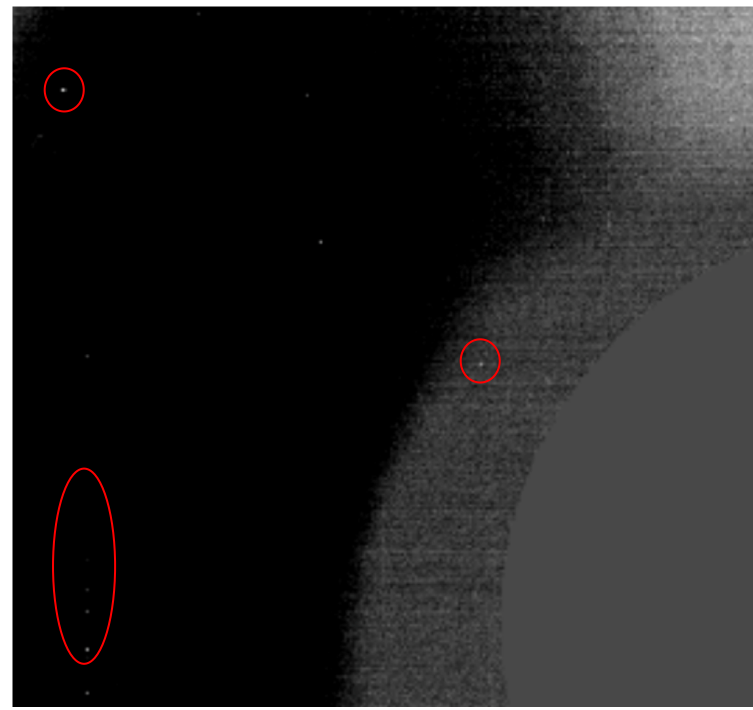
BACKGROUND AND MOTIVATIONS

- The research activities of the *Metis Cosmic Rays Topical Team* concern the monitoring of the high-energy particles deep within the Solar Orbiter S/C for instrument diagnostics, however some cosmic-ray physics can be carried out with this work.
- The Metis cosmic-ray matrices play the role of detectors of galactic cosmic rays and solar energetic particles during different phases of the solar cycle 25.
- First activity: visual analysis of the cosmic-ray matrices.
- Second activity: Monte Carlo simulations **(input fluxes and geometry).**
- Metis VL and UV instrument simulations **with FLUKA (CERN release).**
- Galactic cosmic-ray fluxes have been studied in 2020, 2022 and 2023. The first SEP event above the GCR background has been observed on February 25, 2023.



SOLAR ACTIVITY AND EPD/HET COSMIC-RAY DATA

From the analysis of:
Ly-□ index
F10.7 cm
SSN
Recorded in the last 70 years

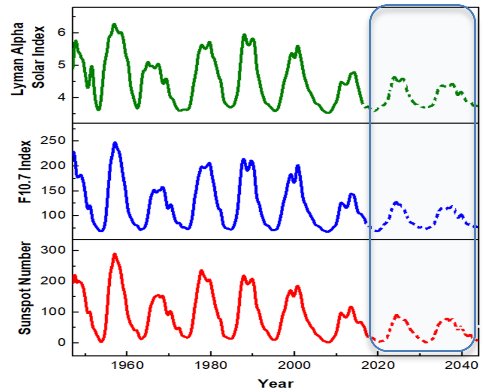
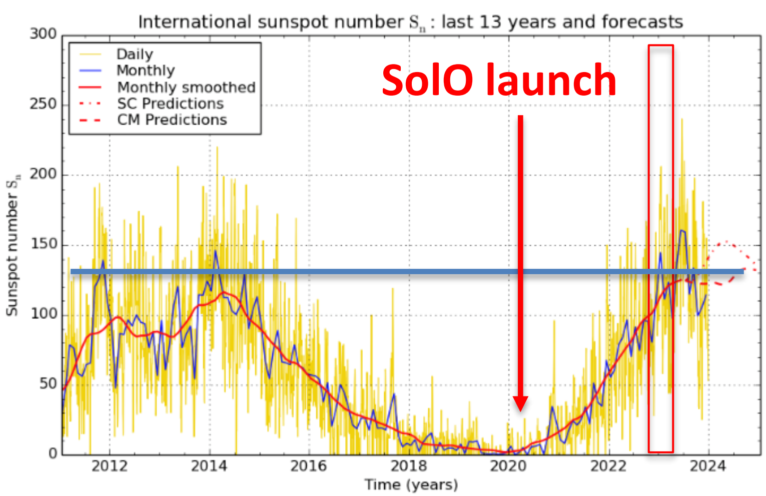


Fig. 5 Monthly variations of the observed and predicted (dotted) values of the sunspot numbers, F10.7 cm index and Lyman alpha index

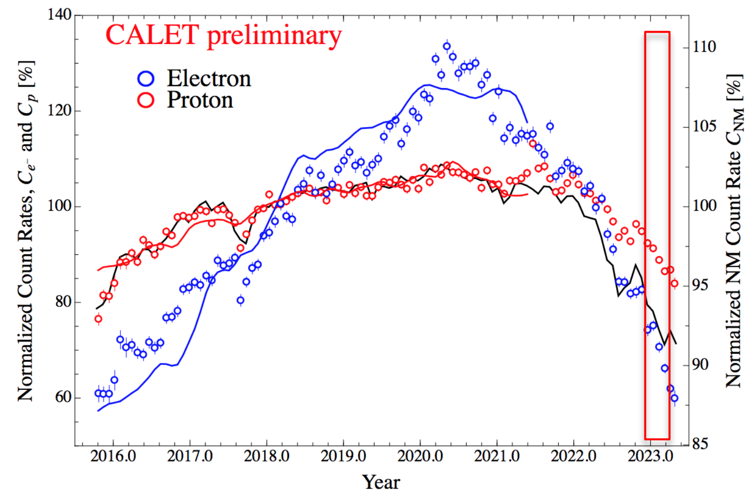
Singh & Bhargawa
Astrophys. Space Sci. , 364, 12, 2019

https://www.sidc.be/silso/datafiles



SILSO graphics (http://sidc.be/silso) Royal Observatory of Belgium 2024 January 1

Adriani et al., ICRC, 1253, 2023



MODEL PREDICTIONS of GCR ENERGY SPECTRA

Agenzia Spaziale Italiana

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

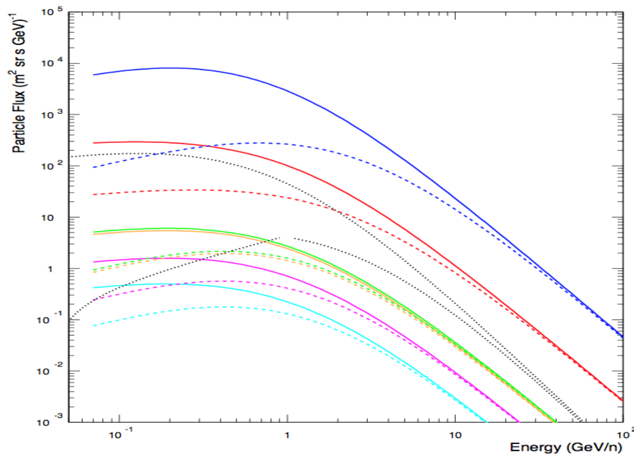
Gleeson and Axford, Ap. J., 154, 1011, 1968

$$\frac{J(r,E,t)}{E^2-E_o^2} = \frac{J(\infty,E+\Phi)}{(E+\Phi)^2-E_o^2}$$

ϕ_m=□□ MV/c

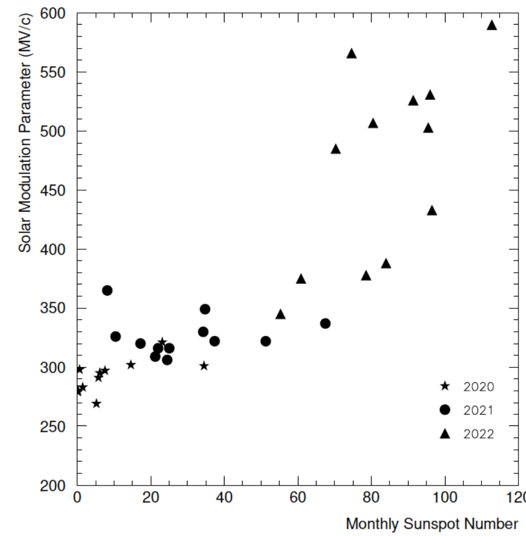
ϕ_M=□□ MV/c

NO DRIFT INCLUDED not needed during positive polarity periods



ESA ITT 10081

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



J(∞,E+Φ□IS Spectrum

From Burger, R. A., Potgieter, M. S., & Heber, B. 2000, JGR, 105, 27447

http://cosmicrays.oulu.fi/phi/Phi_mon.txt

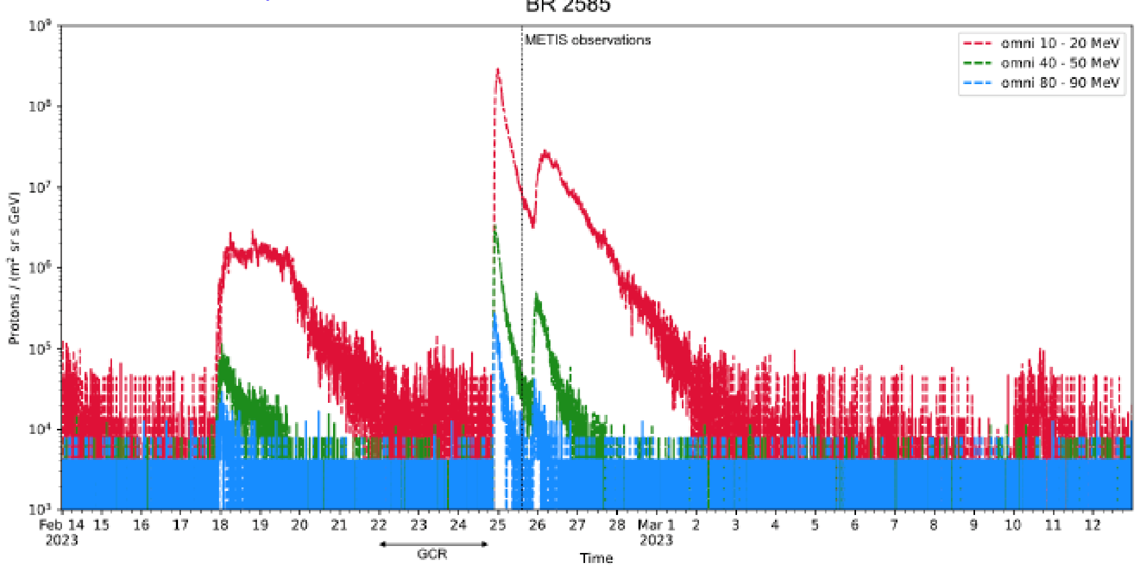
$$F(E) = A\,(E+b)^{-\alpha}\,E^{\beta} \quad \text{particles } (\mathrm{m}^2\ \mathrm{sr\ s\ GeV\ n}^{-1})^{-1},$$

Papini, CG & Stephens, Nuovo Cimento, 1996

EPD/HET DATA DURING THE BR2585

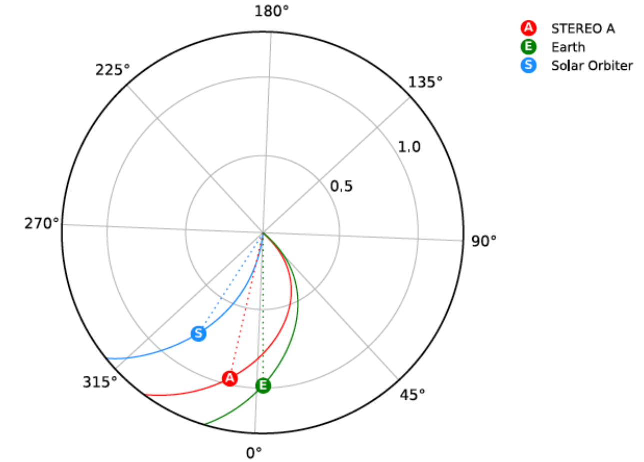
90 MeV particles: onset 21:00 UT
10 MeV: 21:11 UT

From SEPPEL by F. Sabbatini



EPD/HET data from http://soar.esac.esa.int/soar/#home

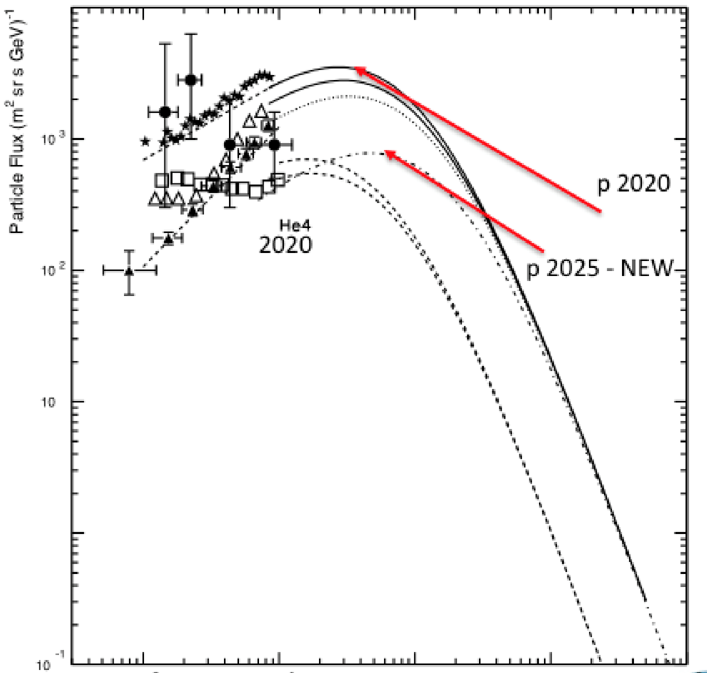
2023-02-24 21:00:00 (UTC)



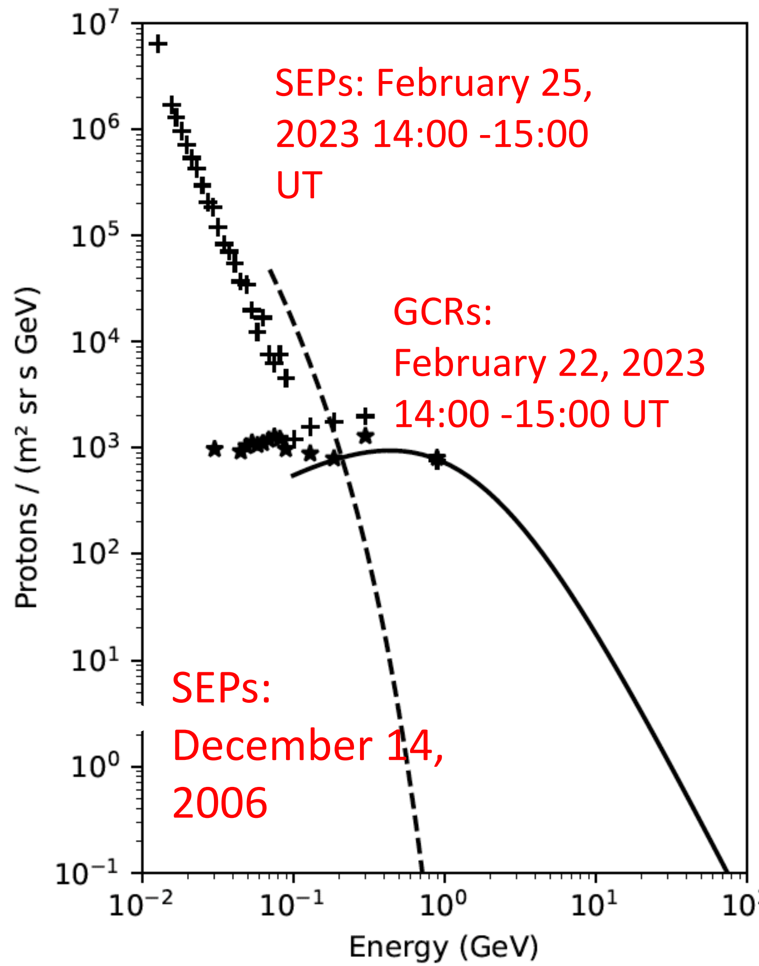
https://solar-mach.github.io/

Solar Orbiter: 0.77 AU from the Sun
0.54 AU from Earth
(-32° in Longitude)

PROTON DIFFERENTIAL FLUX DURING THE BR 2585



CG et al.; A&A, 2021
https://arxiv.org/abs/2104.13700

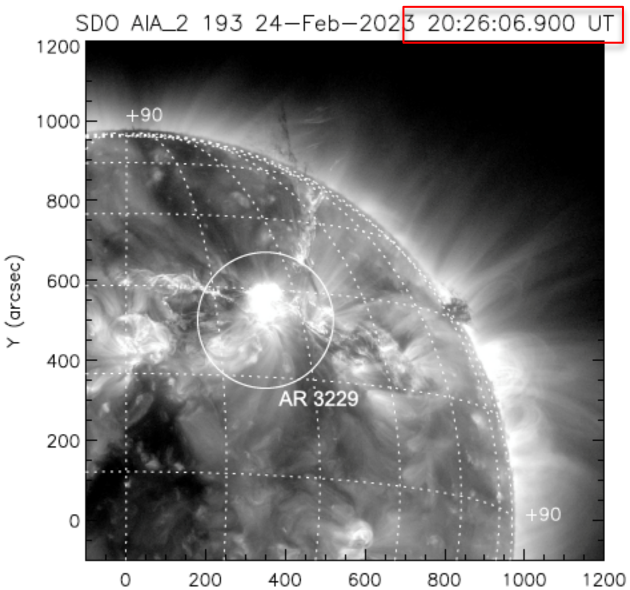


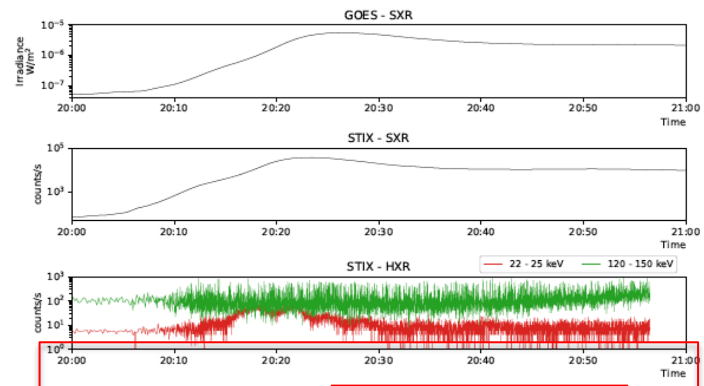
ϕ_m=□□ MV/c

http://soar.esac.esa.int/soar/#home

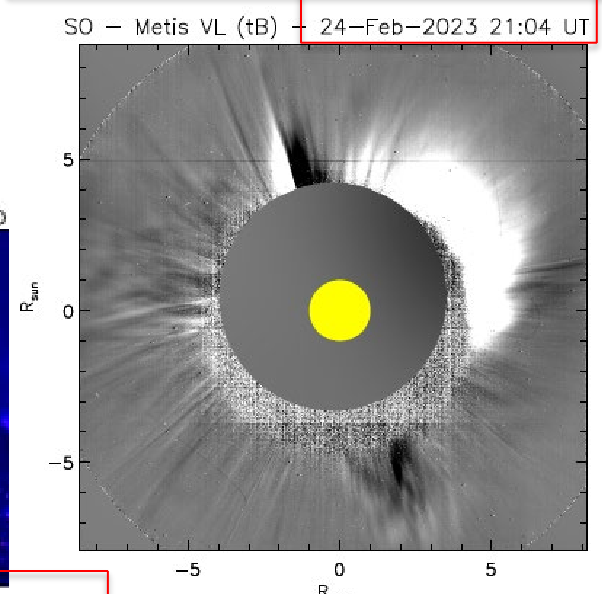
ACTIVITY ON THE SUN ASSOCIATED WITH THE SEP EVENT

Filament eruption 20:03 UT
AR 3229
NW quadrant of the Sun
Long:18°
Lat:25°

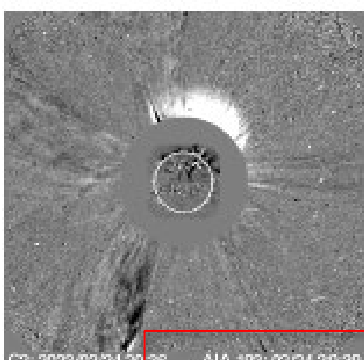


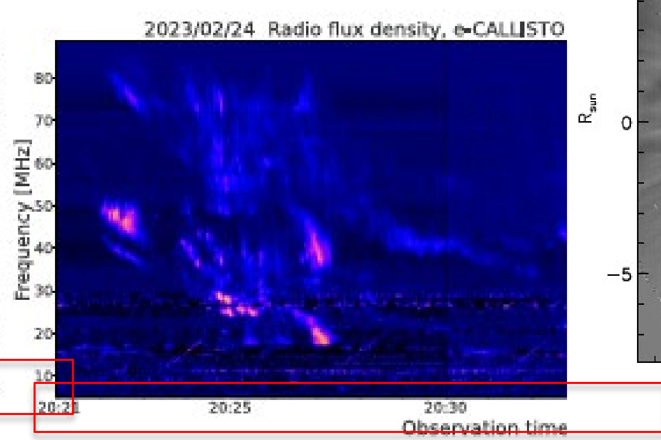


Flare M3.7
20:07 UT
Soft x-ray peak
at 20.23 UT on GOES
and at 20:26 on STIX



Halo CME
1336 km s^{-1}

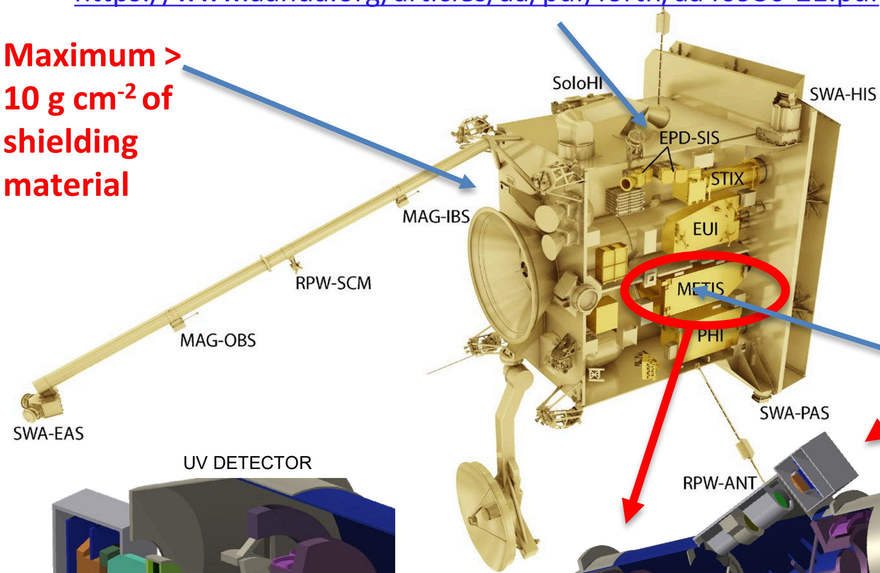


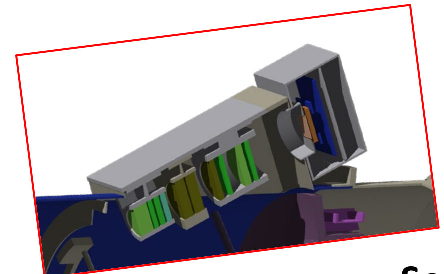


THE METIS CORONAGRAPH ON BOARD SOLAR ORBITER

CG et al.; https://arxiv.org/abs/2104.13700
https://www.aanda.org/articles/aa/pdf/forth/aa40930-21.pdf

Maximum > 10 g cm^{-2} of shielding material



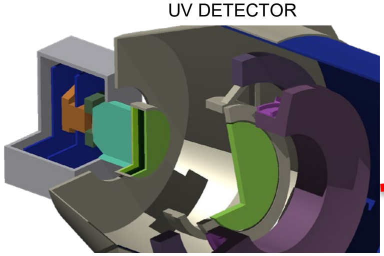


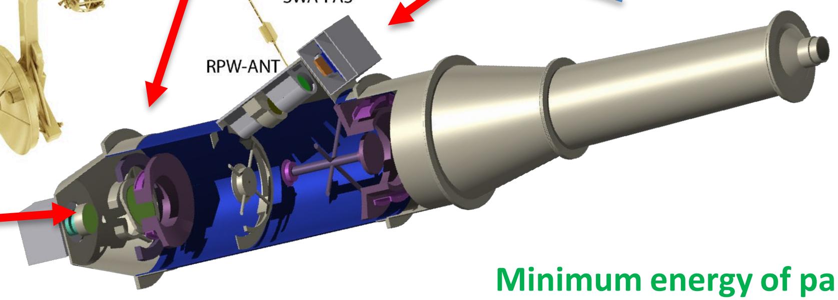
VL DETECTOR

Minimum 1.2 g cm^{-2} of shielding material

Solar Orbiter S/C simulation geometry with FLAIR

UV DETECTOR

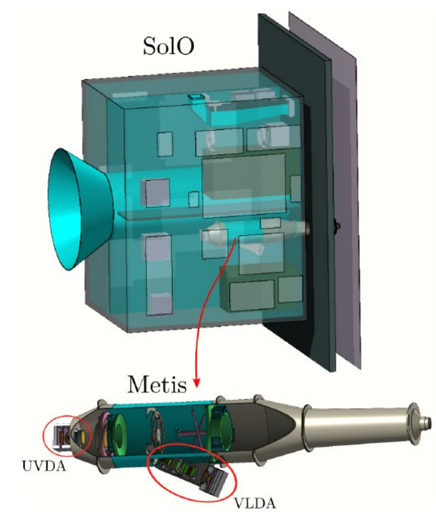




MONTE CARLO MODEL

Courtesy of M. Fabi

Minimum energy of particles crossing the cosmic-ray matrices > 90 MeV/n



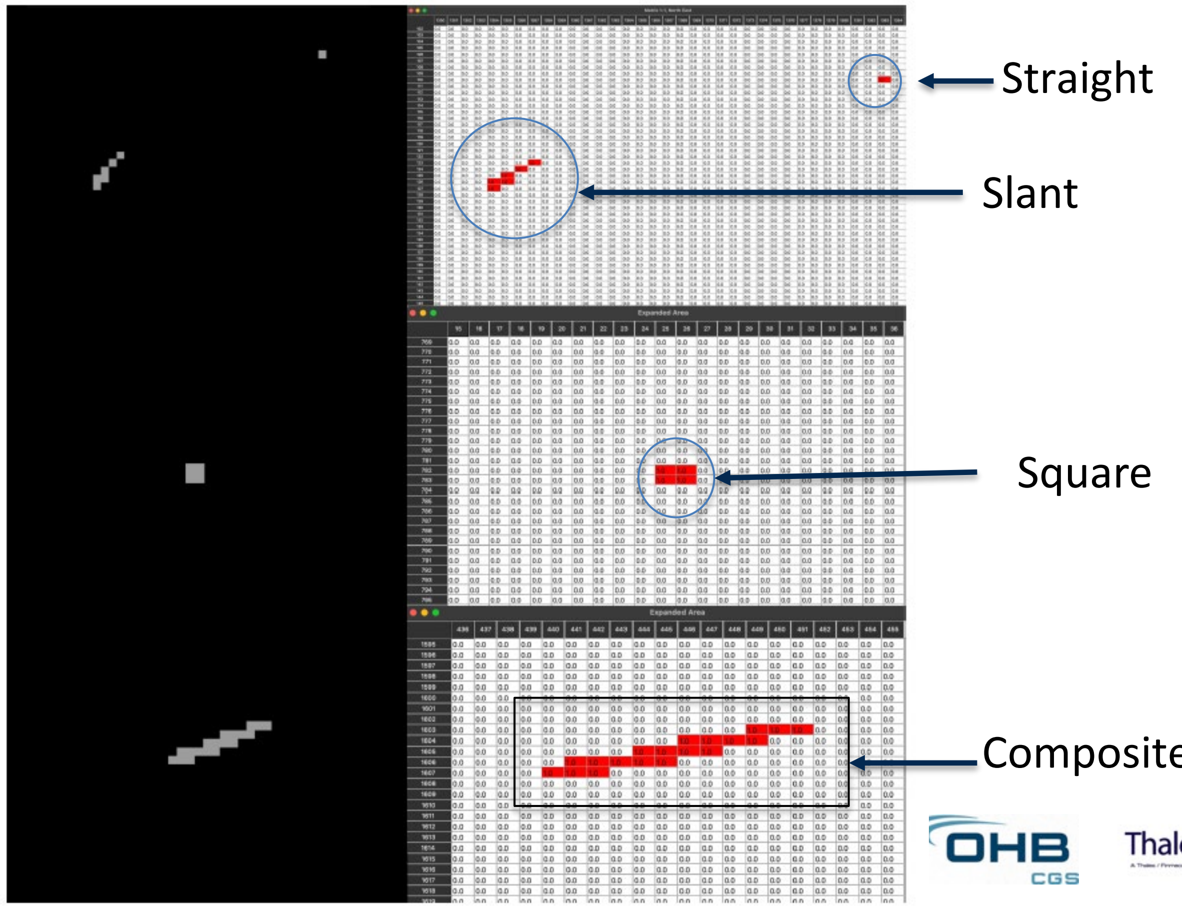
Antonucci et al., A&A 642 (A10), 2020
Romoli et al.;
https://www.aanda.org/articles/aa/pdf/forth/aa40930-21.pdf

VISUAL ANALYSIS OF COSMIC-RAY TRACKS IN THE METIS COSMIC-RAY MATRICES

2048x2048 pixels

10 μm x 10 μm x 4.45 μm: GF per pixel 401 μm^2 sr. 10^{-5} of the pixel sample are noisy

Particle track reconstruction with fv (left) and APViewer (right) by A. Persici



6 cosmic-ray matrices

3 – February 22, 2023

14:00 -15:00 UT

3 – February 25, 2023

14:00 -15:00 UT

Each matrix:

12 frames of 30 s

Total exposure time: **6 minutes**

RESULTS OF THE PARTICLE TRACK ANALYSIS

Number of particle tracks for 60 s exposure time of the cosmic-ray matrices (visual analysis)

The number of observed tracks depends on algorithm and single pixel (0.94) efficiencies

In a previous paper we have demonstrated that the overall efficiency is equivalent (37%) to the number of particles generated by primary and secondary cosmic rays

	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
February 2023 (GCRs+SEPs) Average	108	51	2	161±5

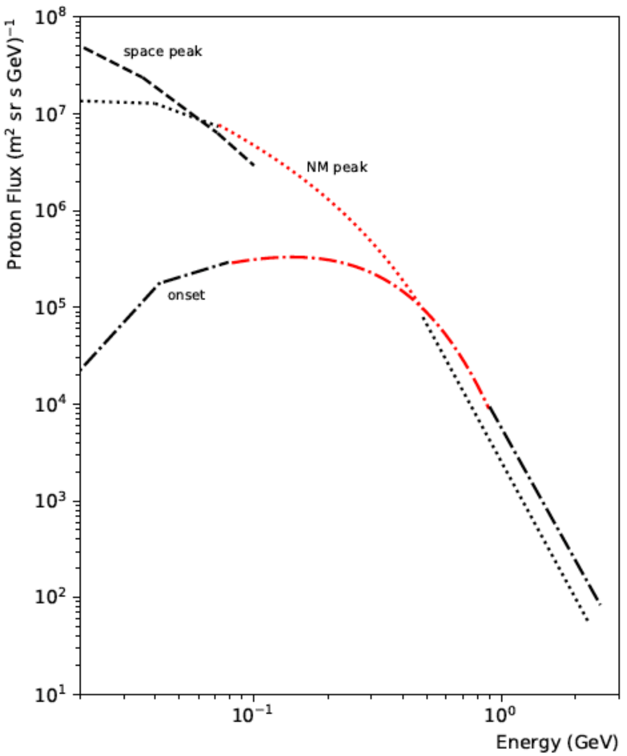
	MC	Observed	$\phi_{estimated}$ (MV/c)	ϕ_{real} (MV/c)
GCRs				
May 2020	276±39±17	271 ±22	300	299
May 2022	242±34±16	212 ±6	340	433
February 2023	118±17±11	120 ±5	650	?
GCRs+SEPs				
February 25, 2023	143±20±12	161 ±5		

Number of particle tracks for 60 s exposure time of the cosmic-ray matrices from visual analysis and Monte Carlo (MC) simulations

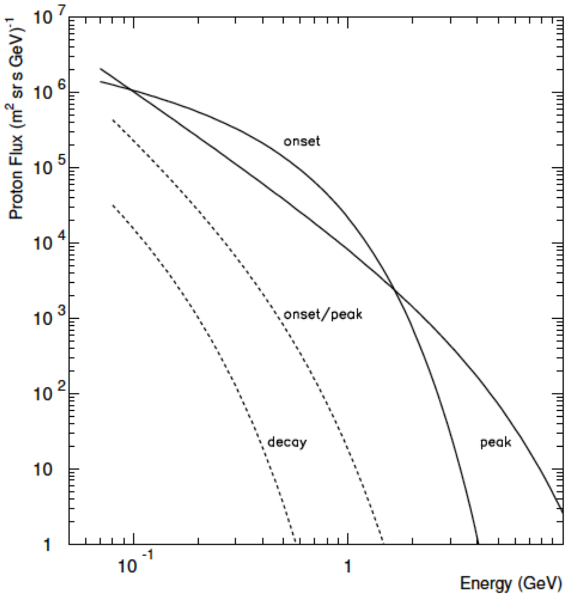
Particle composition with incident protons only:
GCRs: 69% protons, 21% e^-, 4% π^-, 3% π^+, 2% e^+ and 1% μ^-
SEPs: 92% protons, 8% e^-

The estimate that the difference between simulations and analysis of SEPs may be associated with the actual spatial distribution of SEPs not exactly isotropic during the decay phase of the event

COMPARISON WITH PREVIOUS WORK



SEP event October 28, 2021



SEP events December 13-14, 2006

Number of particle tracks in the cosmic-ray matrices during SEP events estimated with Monte Carlo simulations for 60 s exposure time

SEP event	VL detector	UV detector
December 13, 2006 (onset)	24600	56400
December 13, 2006 (peak)	11600	30800
December 14, 2006 (onset/peak)	1380	1980
December 14, 2006 (decay)	180	201
October 28, 2021 (onset)	12960	28680
October 28, 2021 (NM peak)	9000	13380
October 28, 2021 (HET peak)	38400	60000

CG et al.; A&A, 677, A45, 2022

CONCLUSIONS

- Our work allows us to correlate cosmic-ray/SEP measurements incident on the spacecraft with instrument performance and deep charging during the mission operations.
- The number of spurious pixels is unchanged since the mission launch (10^{-5} of the whole pixel sample). The cosmic-ray tracks in the VL images decreased by more than a factor of two after the mission launch.
- The VL instrument on-board algorithm and pixel efficiencies remove a number of tracks equivalent to those generated by rare cosmic rays.
- **Metis can play the role of a proton monitor.** We have tested the optimum capability of Metis to monitor both GCR and SEP protons.