Multi-Point Observations of the 9 October 2024 SEP Event: Implications for Solar Energetic Particle Forecasting at Mars

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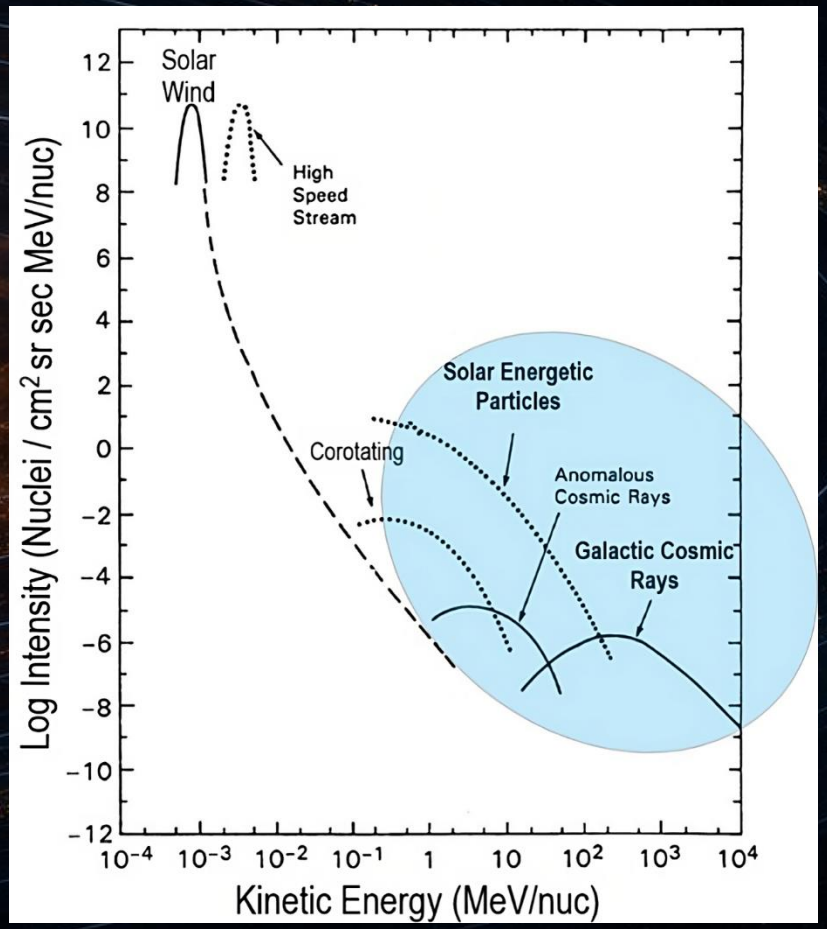
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WRMISS-2026 , Prague

Solar Energetic Particle Events

SEPs are high-energy particles accelerated during solar eruptions, particularly by CME-driven shocks and solar flares. They can reach spacecraft, Earth, the Moon, and Mars on operationally relevant time scales.

Why forecasting matters?



Spectra of oxygen ions in the near-Earth interplanetary space, showing the contributions of different populations (Mewaldt et al., 2001)

Current Limitations in SEP Forecasting at Mars

Limited magnetic connectivity between Mars and existing heliospheric spacecrafts

Incomplete observational coverage of the Sun–Mars system

MAVEN and MSL/RAD provide local SEP detection at Mars, but not upstream advance warning.



RESEARCH QUESTION

Can near-Earth observations be used to forecast SEP events at Mars?

We investigate intense SEP events observed by MSL/RAD and the potential for forecasting using near-Earth systems such as **REleASE**.

NEAR-EARTH OBSERVATIONS
(SOHO and STEREO-A)

REleASE
SEP FORECAST

MARS SURFACE
(MSL/RAD)

WE STUDY THE WHOLE MSL MISSION

1 CRUISE PHASE
Earth → Mars

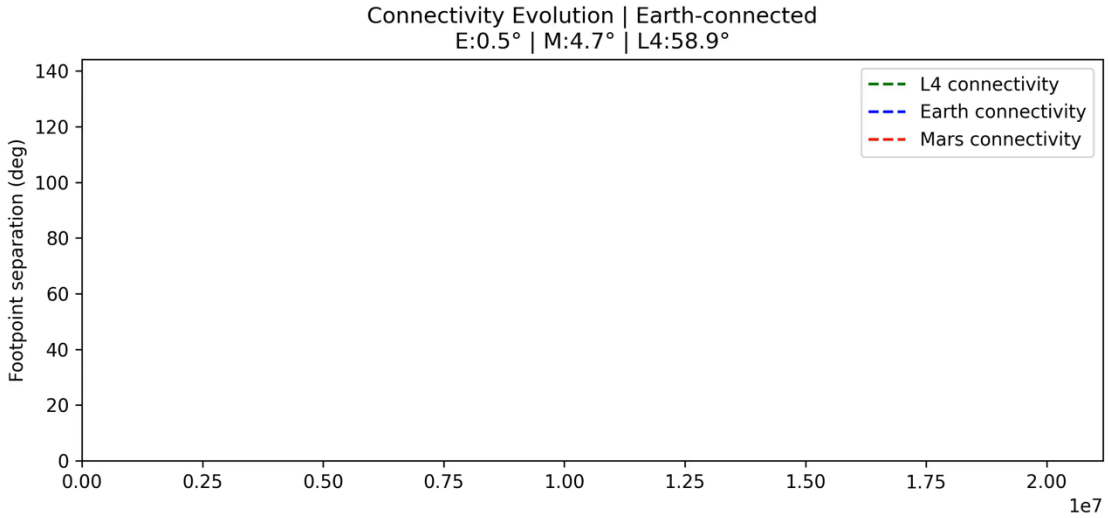
Can near-Earth observations provide **advance warning** for a spacecraft traveling to Mars?

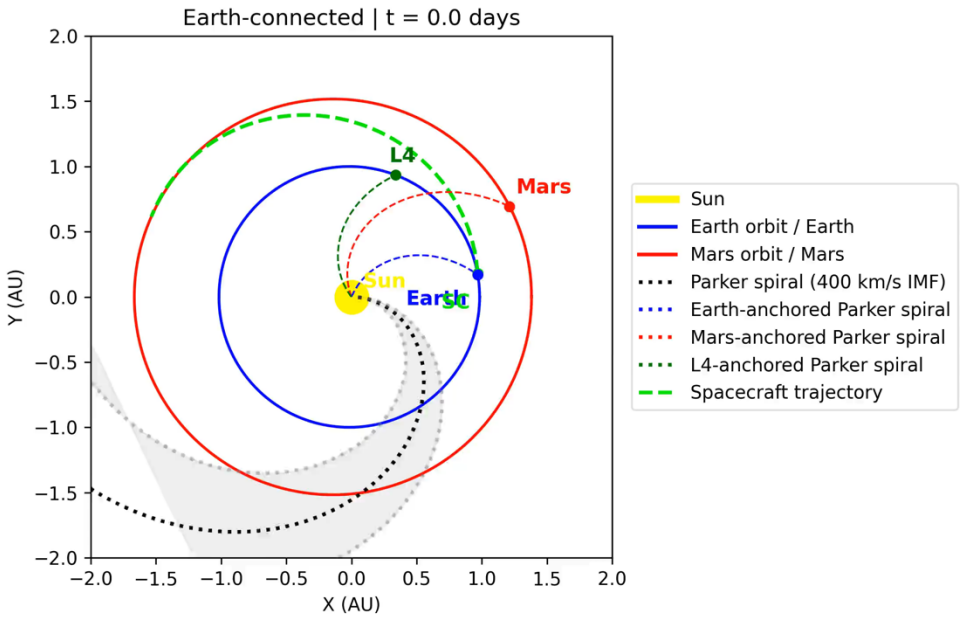
2 MARTIAN SURFACE
MSL/RAD

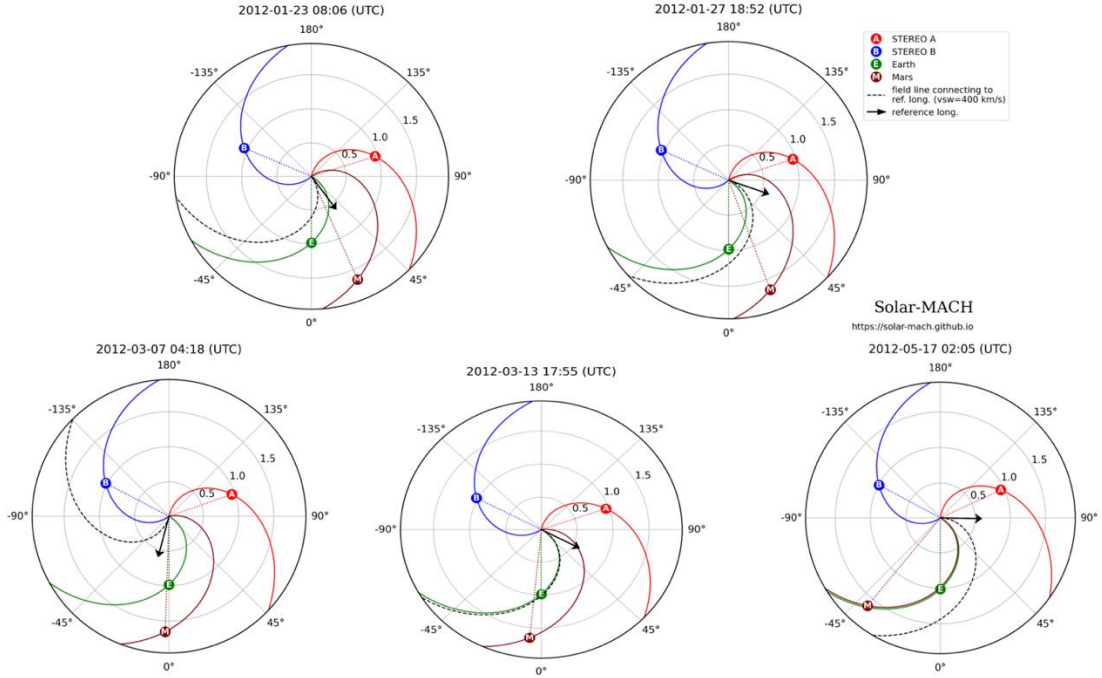
Can near-Earth observations provide **advance warning** of SEP events before they are detected at the Martian surface?

We check the **magnetic connectivity** between near-Earth observers and Mars, then use **RELeASE** to forecast SEP events at Earth and compare their timing at Mars. Can this provide **advance warning** for astronauts?

SEP Forecasting Geometry During Earth–Mars Hohmann Transfer Cruise



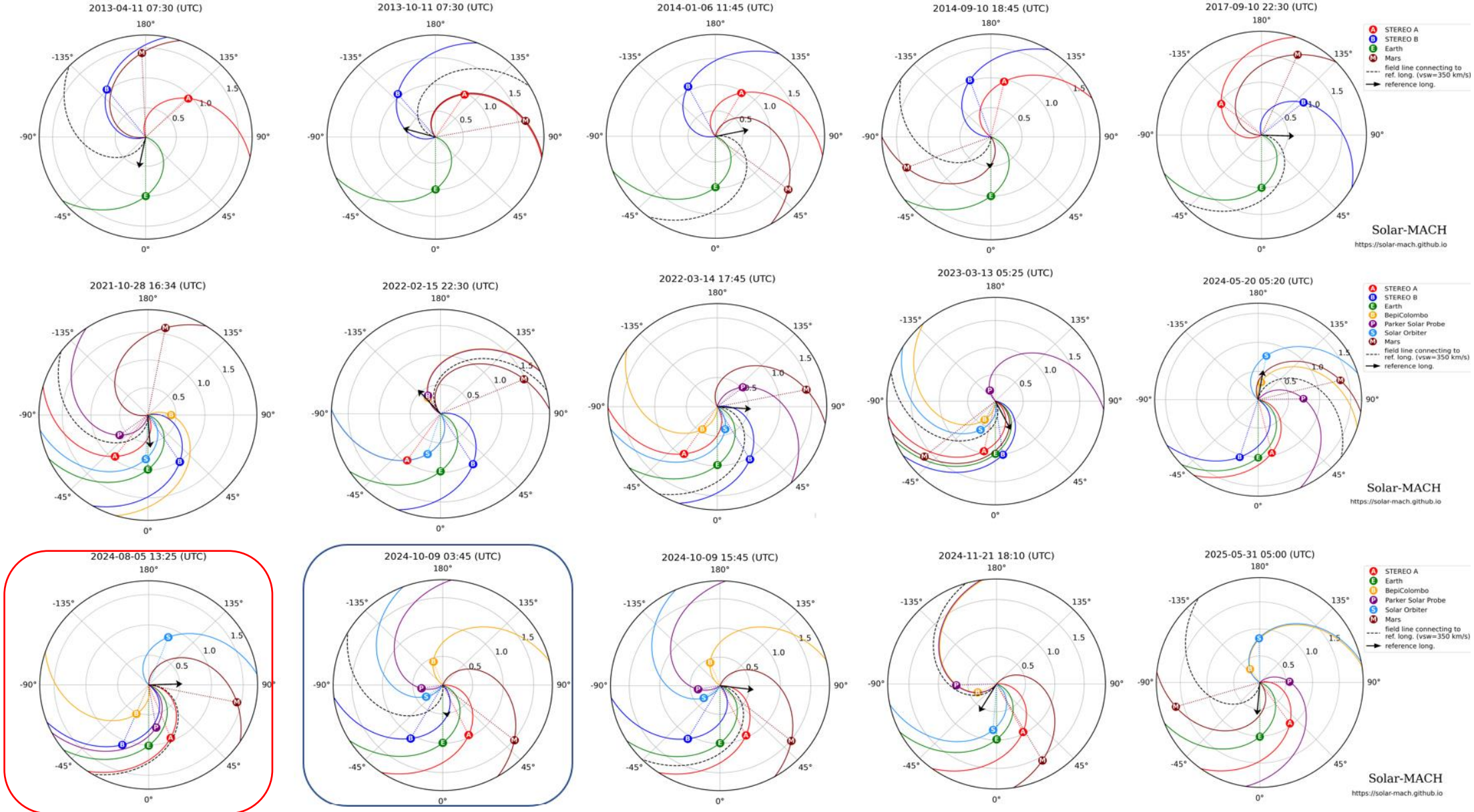




Onset time	Type	Lat - Long	**Earth-Source magnetic footpoint separation**	Mars-Source FP
2012-01-23	M8.7	N28W36	**25.1°**	91.0°
2012-1-27	X1.7	N27W71	**9.9°**	53.4°
2012-03-07	X5.4	N17E15	**76.3°**	116.6°
2012-03-13	M7	N18W62	**0.6°**	35.7°
2012-05-17	M5.1	N12W89	**25.9°**	27.7°

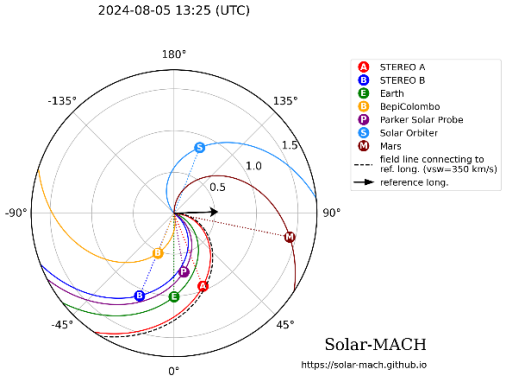
SEPs on the Martian Surface

Can Earth-Based REleASE (Relativistic Electron Alert System for Exploration) Forecasts Provide Advance Warning for Astronauts at Mars?

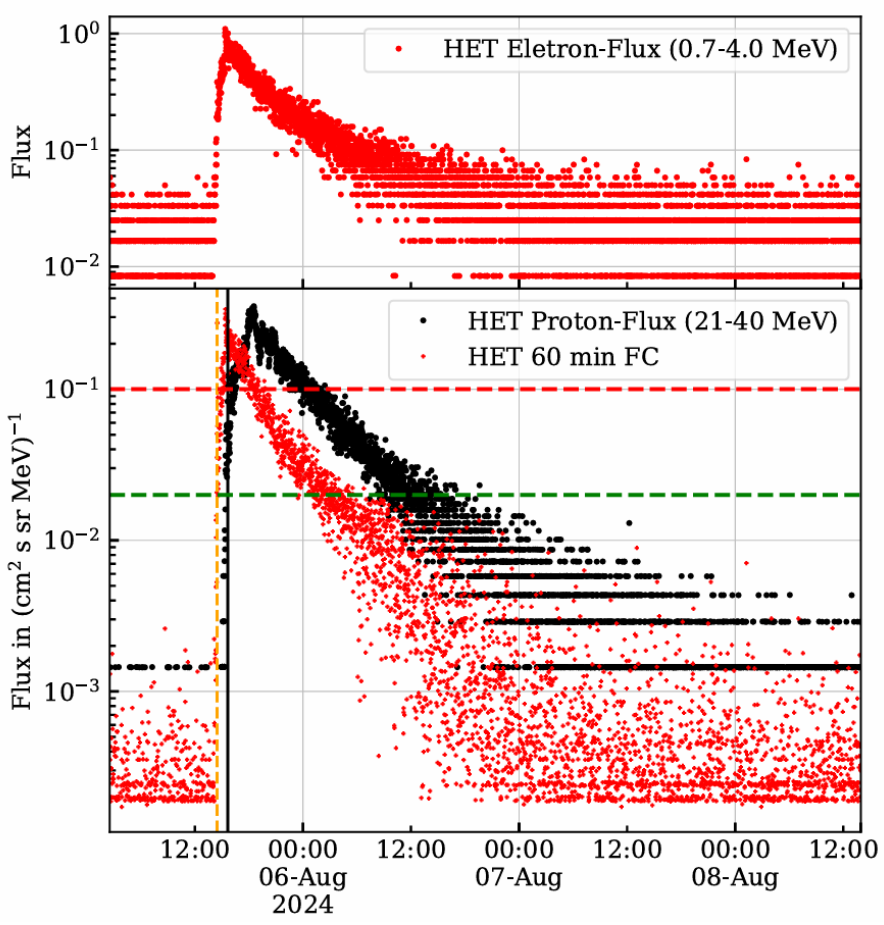


REleASE Forecast at Earth (5 Aug 2024 event)

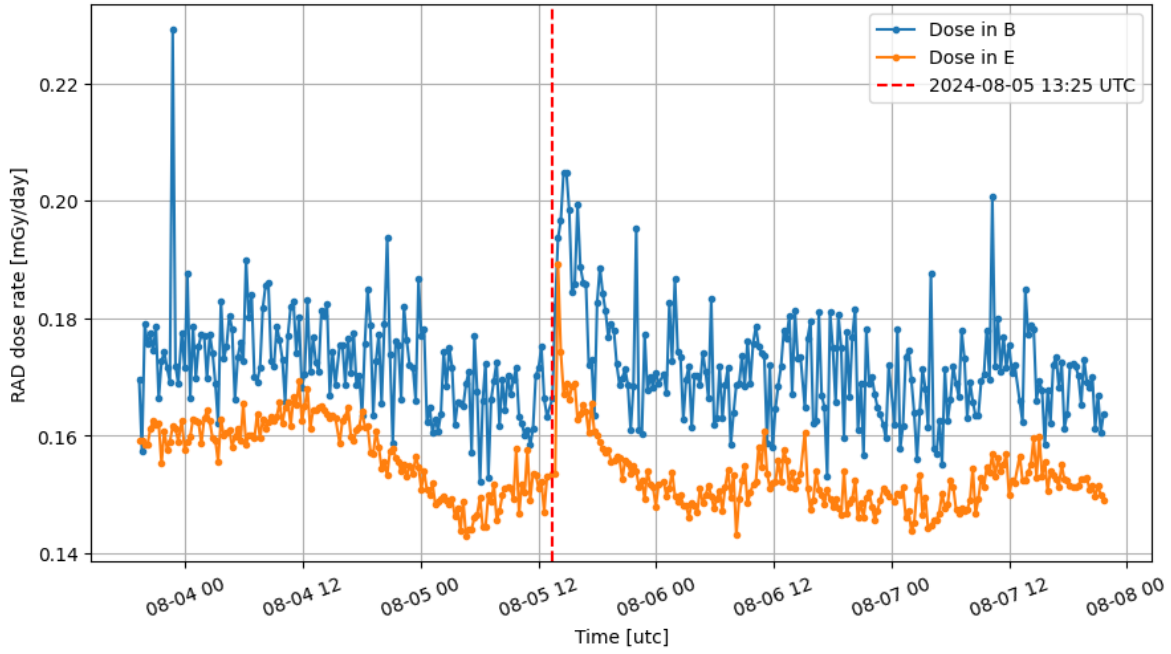
REleASE provides real-time SEP forecasts by using near-Earth measurements of near-relativistic electrons to predict the subsequent proton flux.



STEREO_A REleASE system : **14:29**

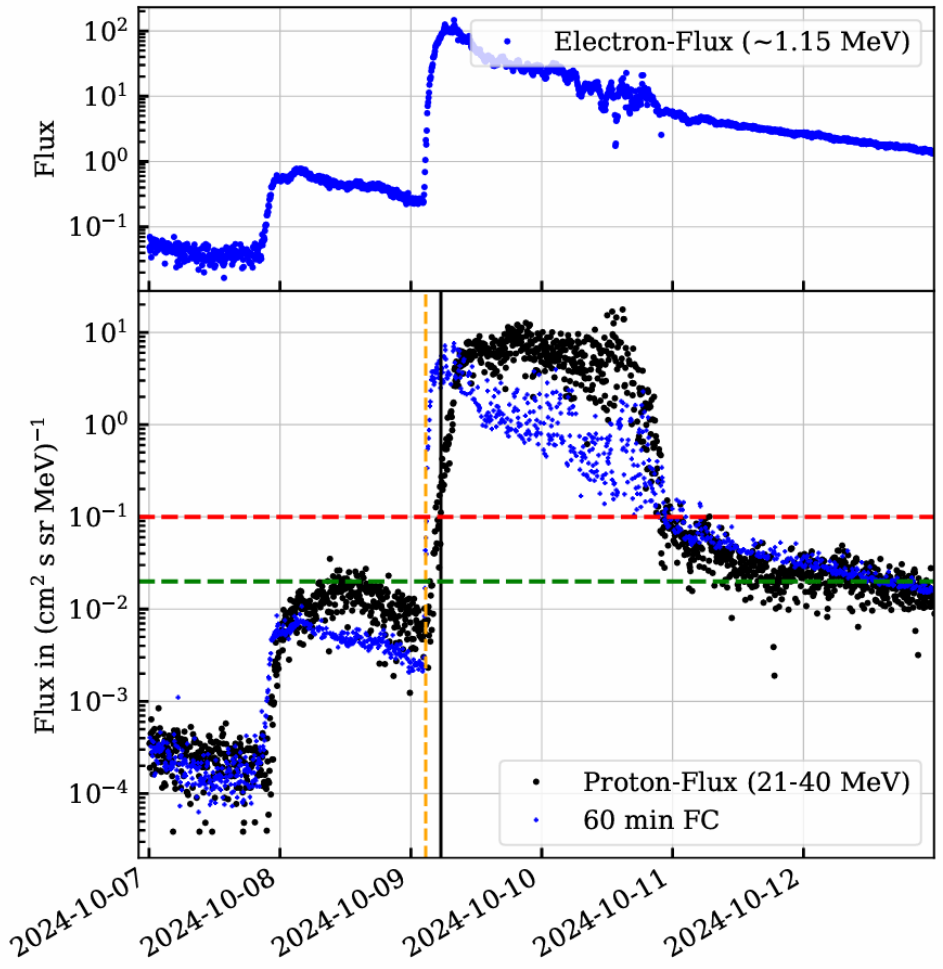


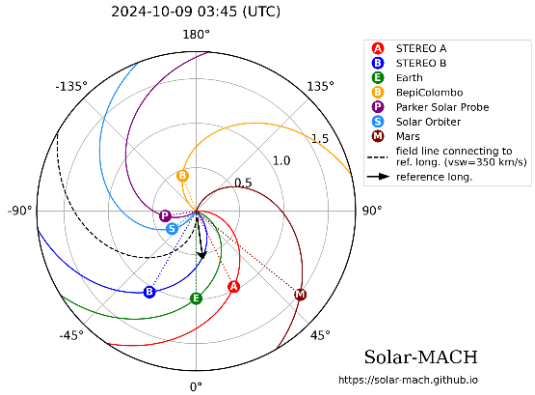
SEPs Onset on Mars: **13:25**



REleASE Forecast at Earth (9 Oct 2024 event)

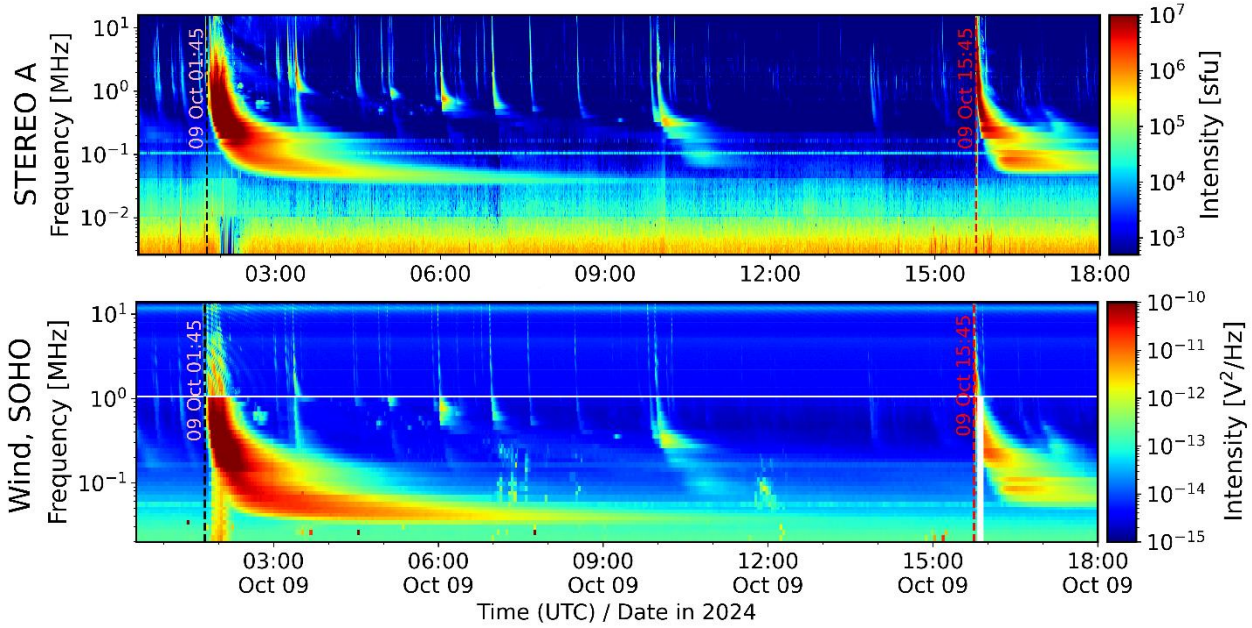
SOHO REleASE system: **02:45** (Henrik Dröge)





Real-time STEREO-A S/WAVES beacon radio fluxes (Arik Posner (2025)) :

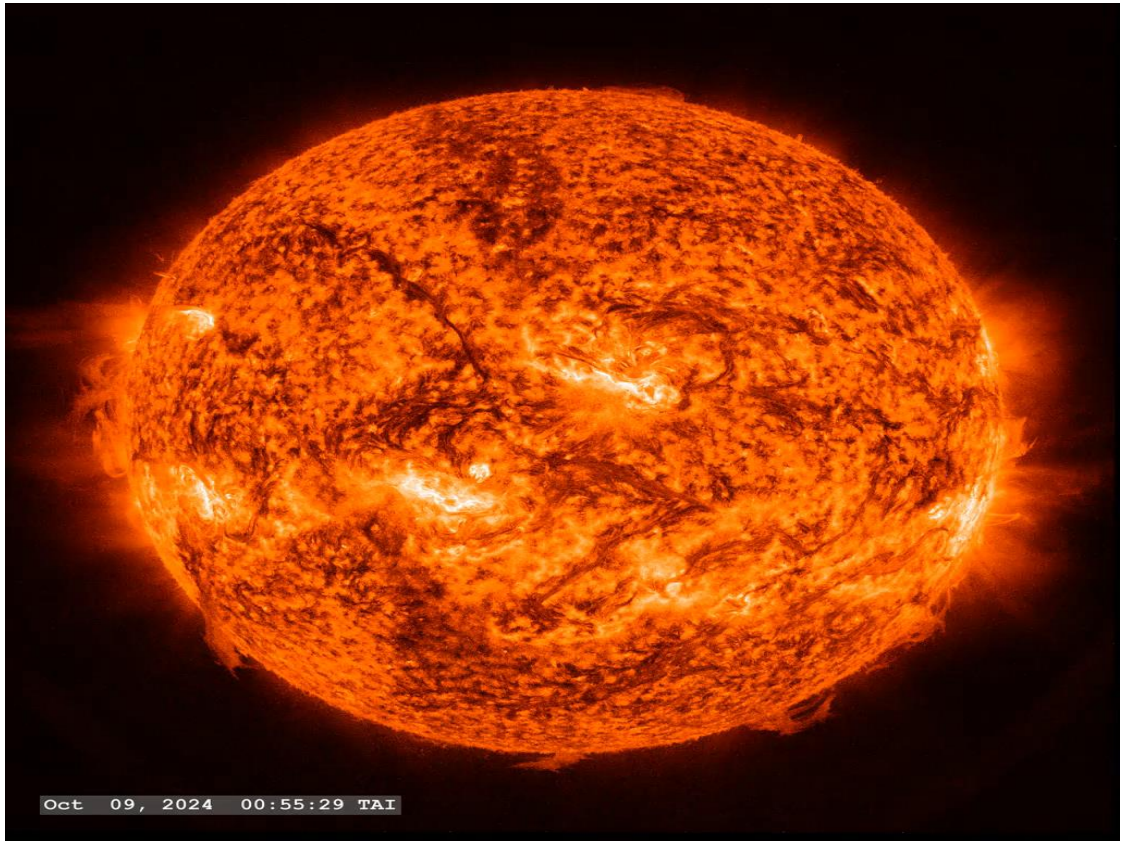
Onset tine: 01:48



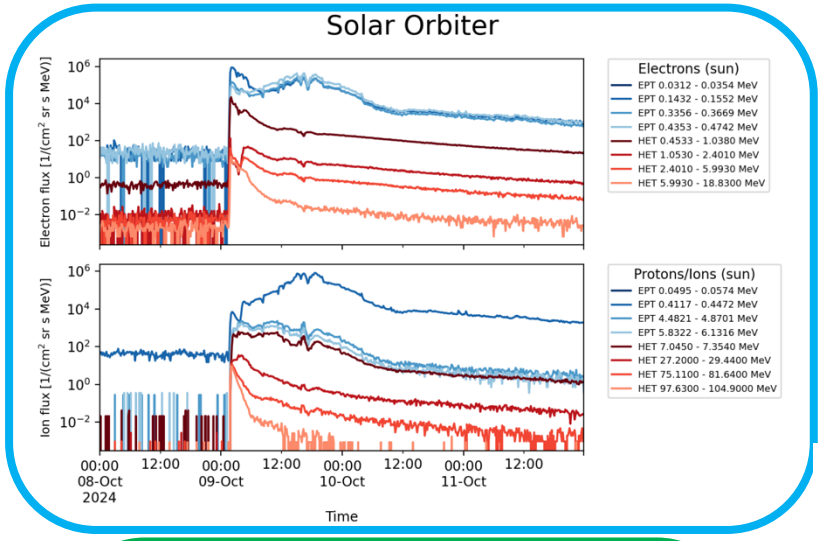
SEP Onset at the Martian Surface: 9 Oct 2024 **03:45**

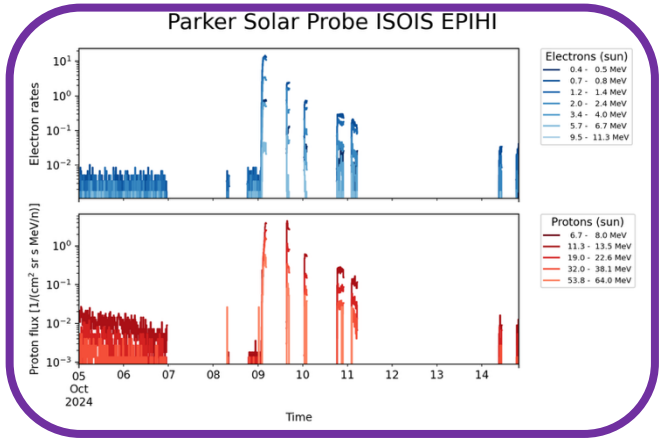
9 Oct 2024 Event (X1.8 Flare (AR 3848))

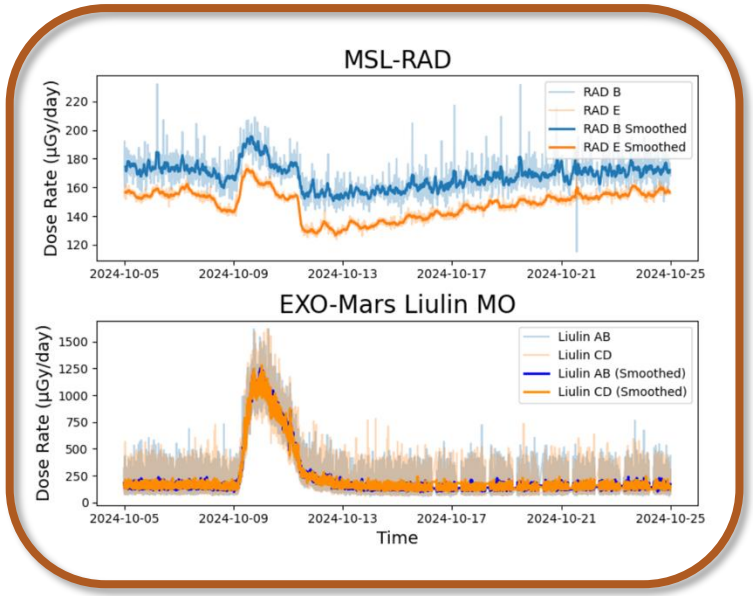
Parameter	Value	Notes
CME Launch Time	2024-10-09 01:56 UTC	Associated with X1.8 flare from AR 13848
Source Active Region	NOAA AR 13848	Identified source of flare and CME
Latitude	+12° (North)	Heliographic latitude (positive = North)
Longitude	+10° (West)	Stonyhurst longitude (positive = West of central meridian)
Initial Speed	1435 km/s	From coronagraph kinematic fit
Acceleration	-52 m/s^2	Slowing down (decelerating CME)
Source Description	Near central meridian, strong flare, CME with shock	Good magnetic connectivity with Earth, STEREO-A

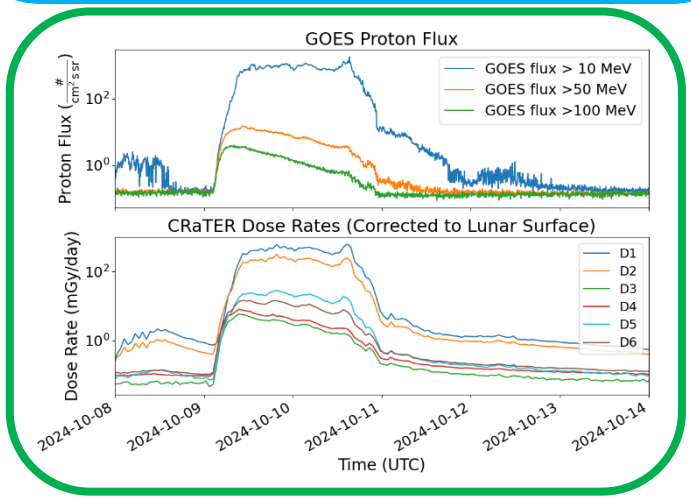


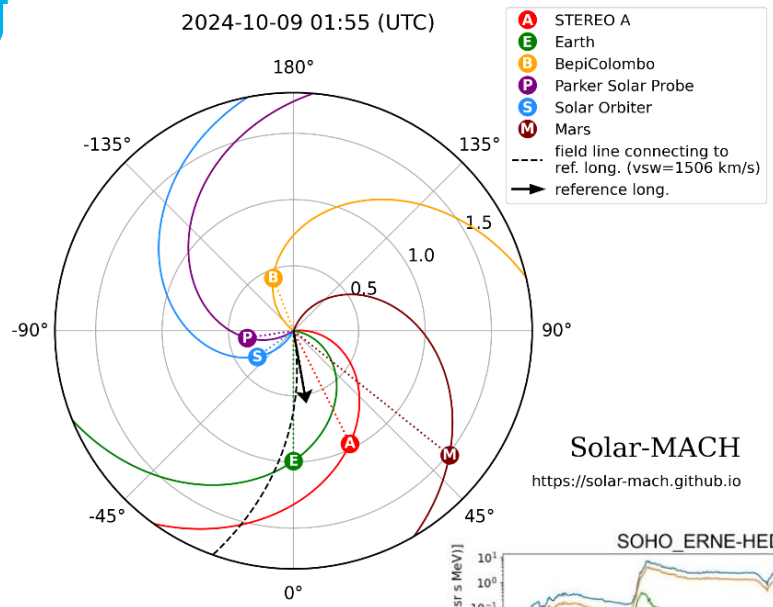
credit :NASA's Scientific Visualization Studio





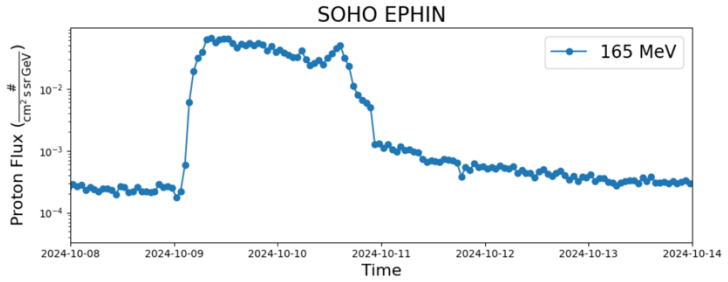


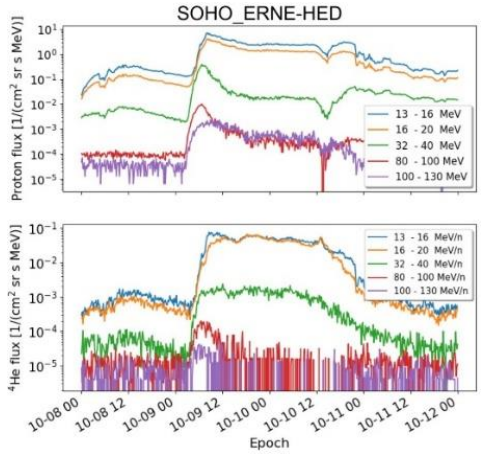


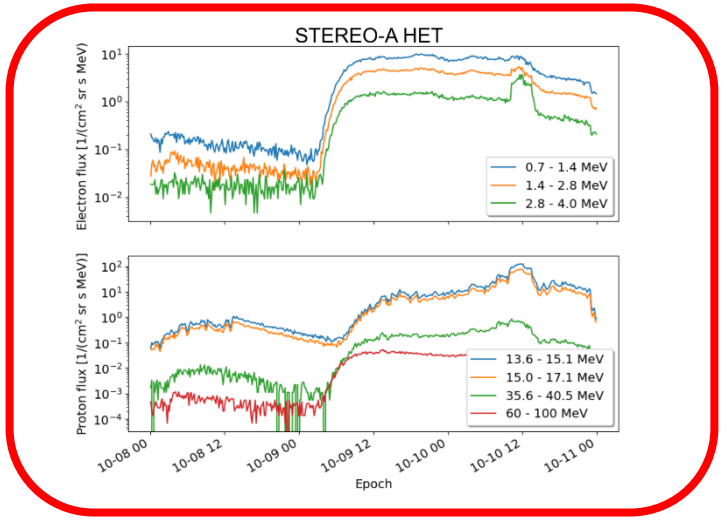


Solar-MACH

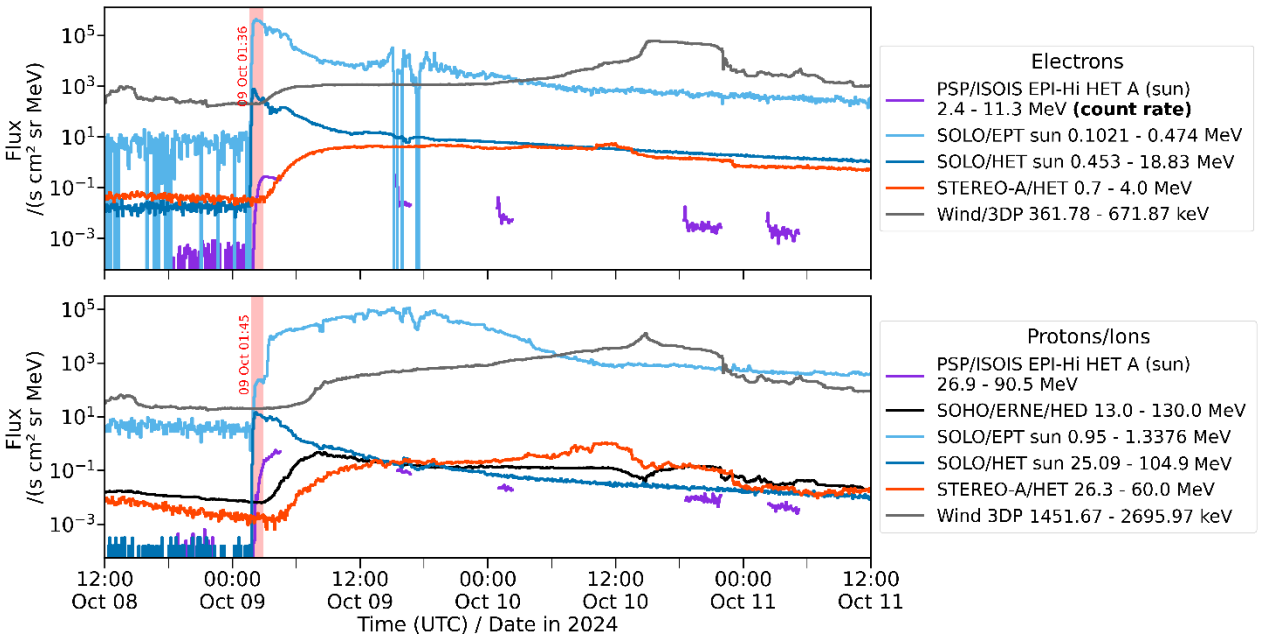
https://solar-mach.github.io

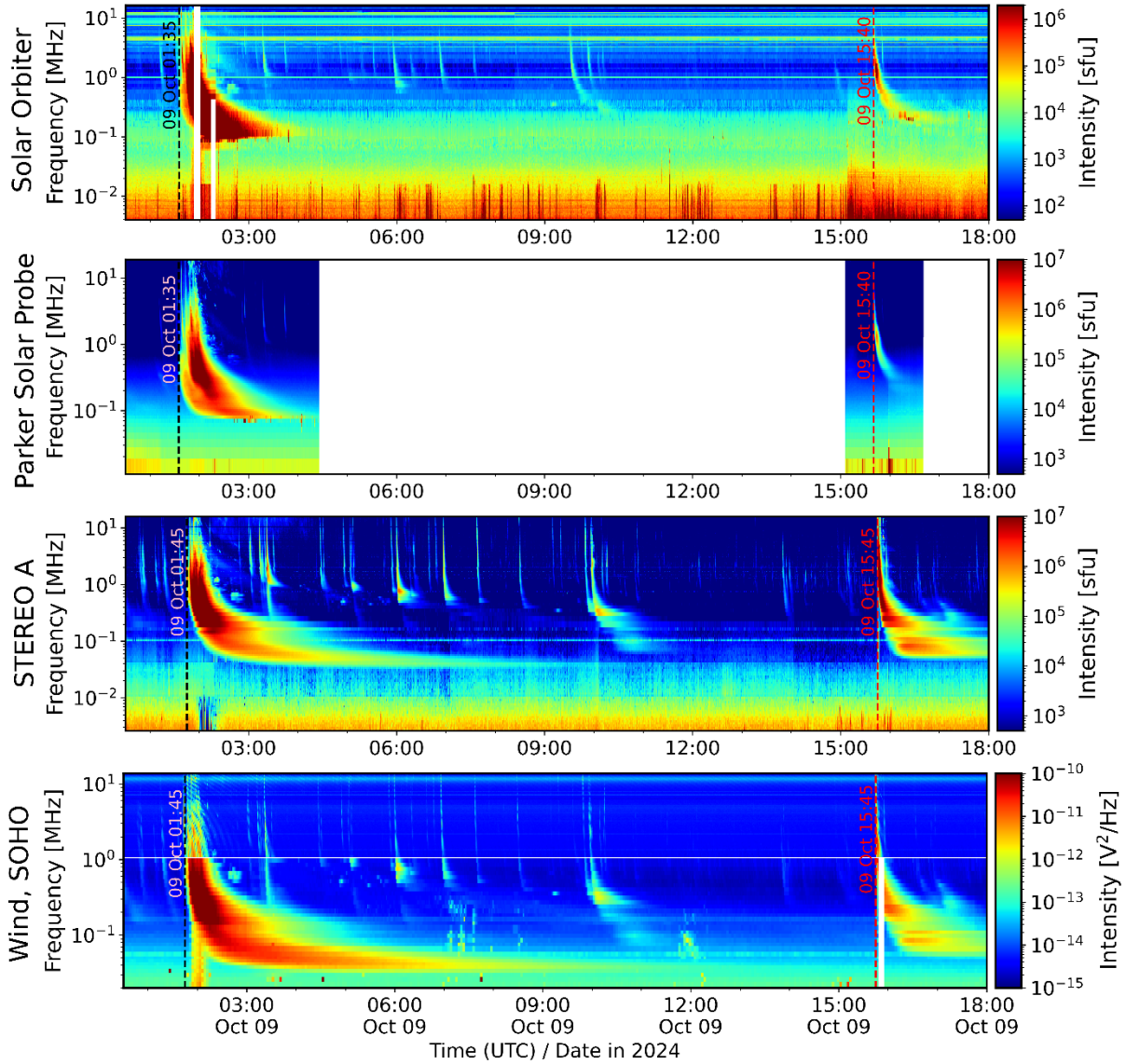






Overview of the 9 October 2024 event





9 Oct 2024 SEP event at Mars

Strong SEP enhancement across Mars instruments

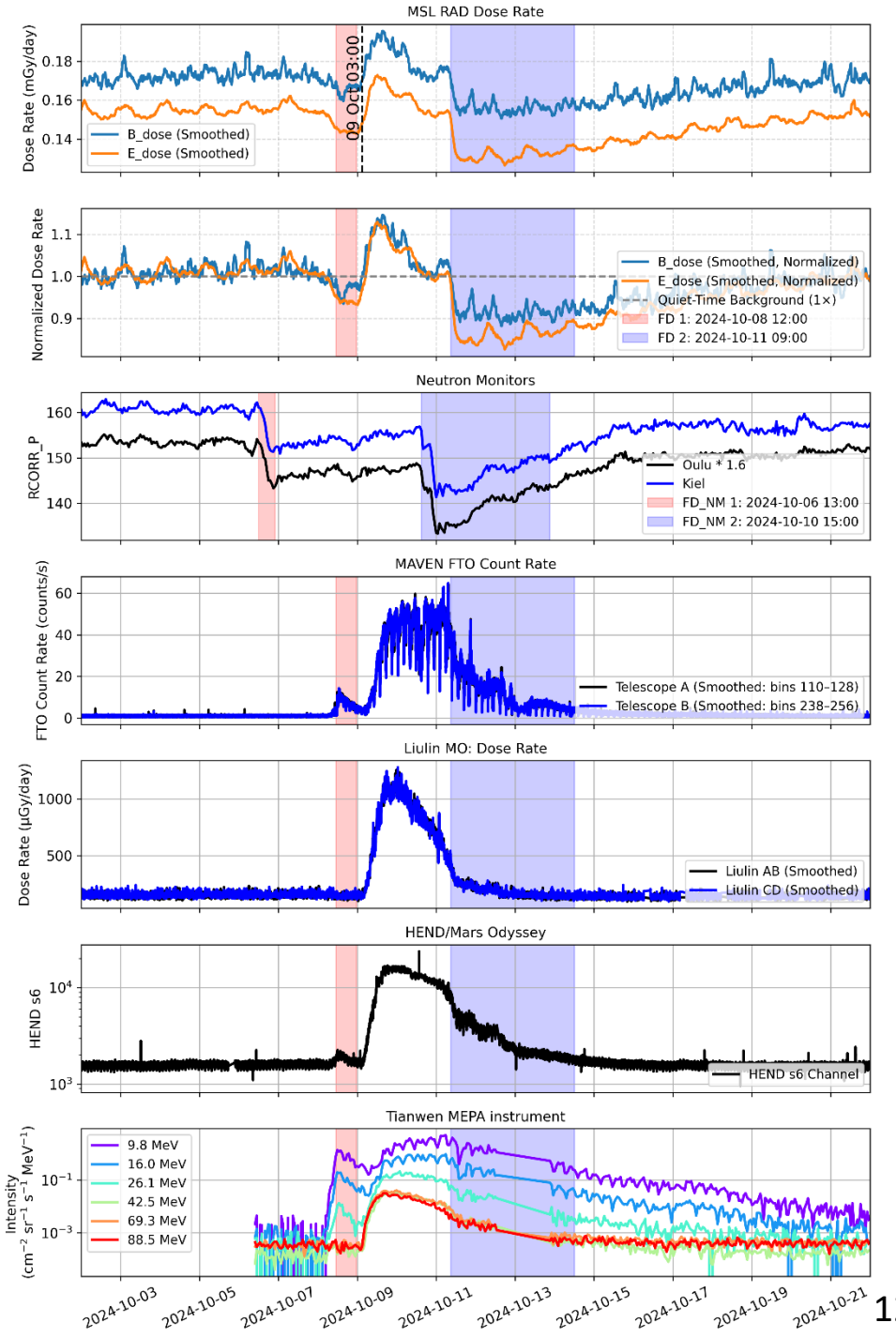
- **RAD clearly shows the SEP enhancement and two Forbush decreases (FD1 & FD2).**

- **Oulu & Kiel neutron monitors clearly show the corresponding GCR decreases at Earth.**

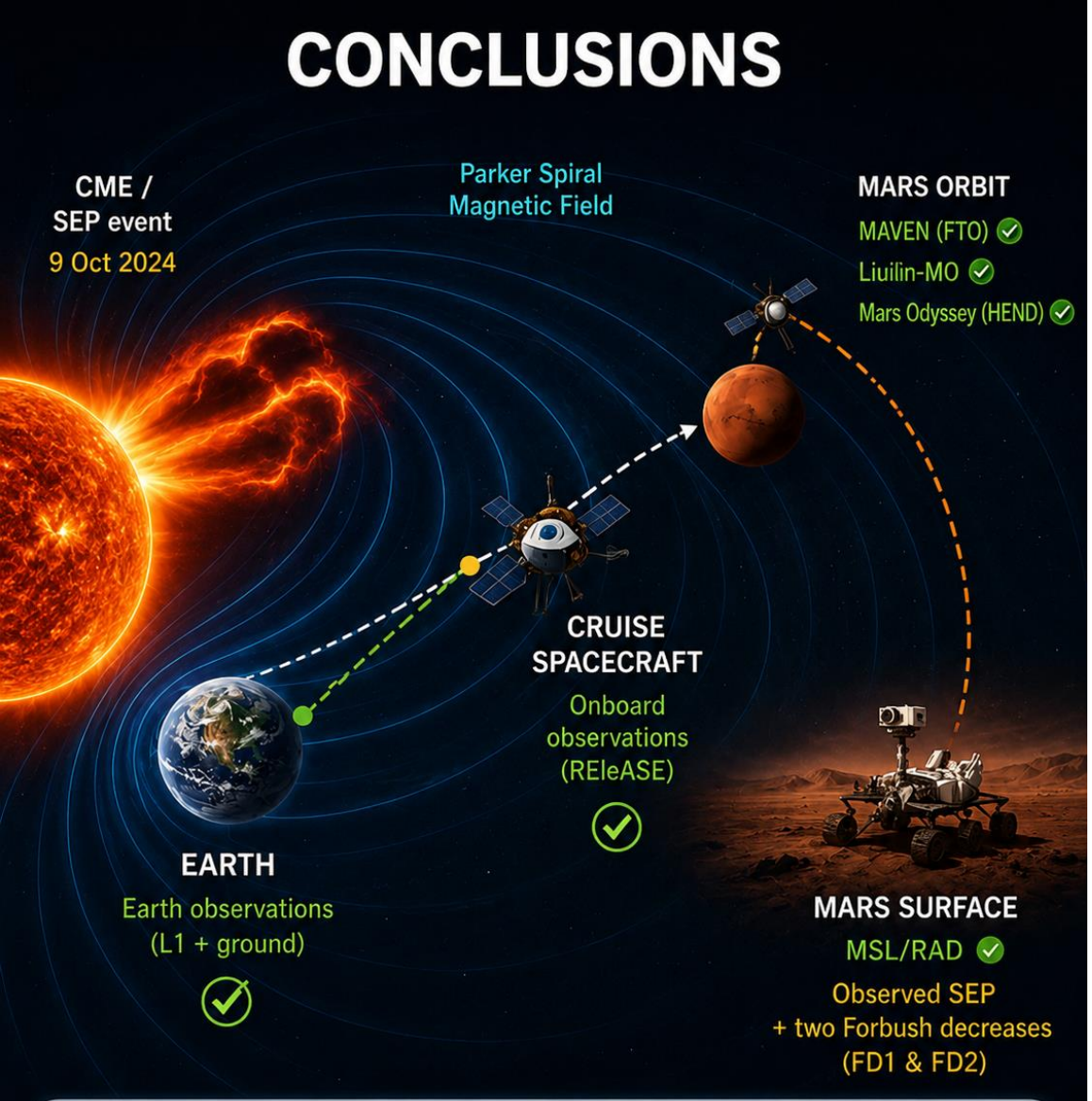
- **FD signatures are less clearly resolved in MAVEN/FTO and HEND, where the strong SEP contributi can mask the underlying GCR decrease.**

- **No clear FD in Liulin-MO aboard ExoMars TGO:**
the reduction in the GCR component is likely masked by the strong SEP contribution to the measured dose rate.

FD visibility depends strongly on instrument energy response, measured quantity, location, and atmospheric/spacecraft shielding.



CONCLUSIONS



Reliable Mars forecasting therefore requires magnetic connectivity + multipoint observations + particle transport information + local/onboard monitoring.

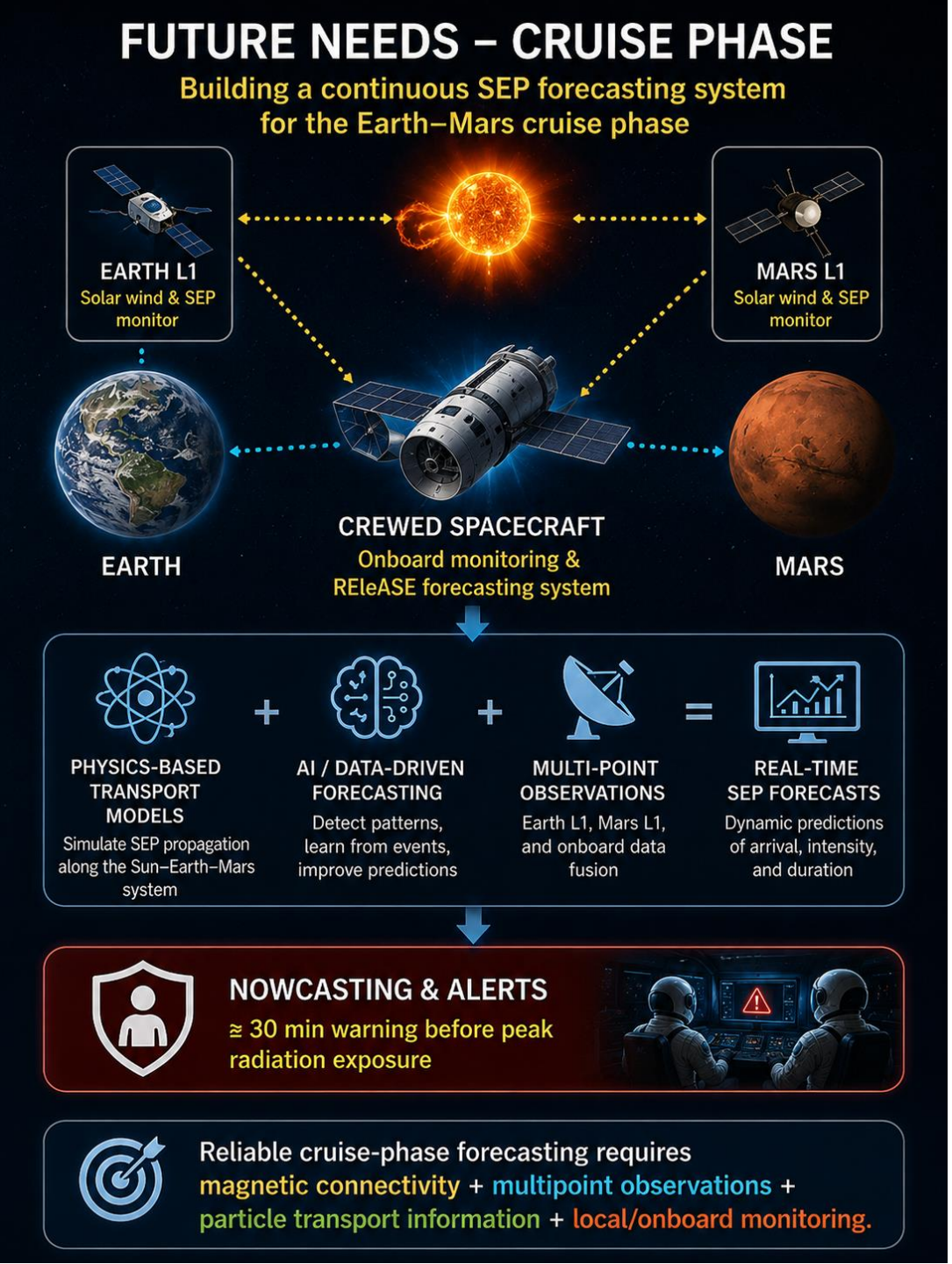
Forecasting SEP events at Mars remains challenging and strongly event-dependent.

Magnetic connectivity is a key factor, but favorable connectivity alone does not guarantee a successful forecast.

SEP propagation is more complex than nominal Parker-spiral geometry: evolving CME-driven shocks, scattering, field-line meandering, and cross-field transport can strongly affect particle arrival at Mars.

Even poorly connected events can reach Mars, while well-connected events may not provide sufficient warning time.

During October 2024 event, MSL/RAD observed both the SEP event and two distinct Forbush decreases



Cruise Phase

Hohmann–Parker effect

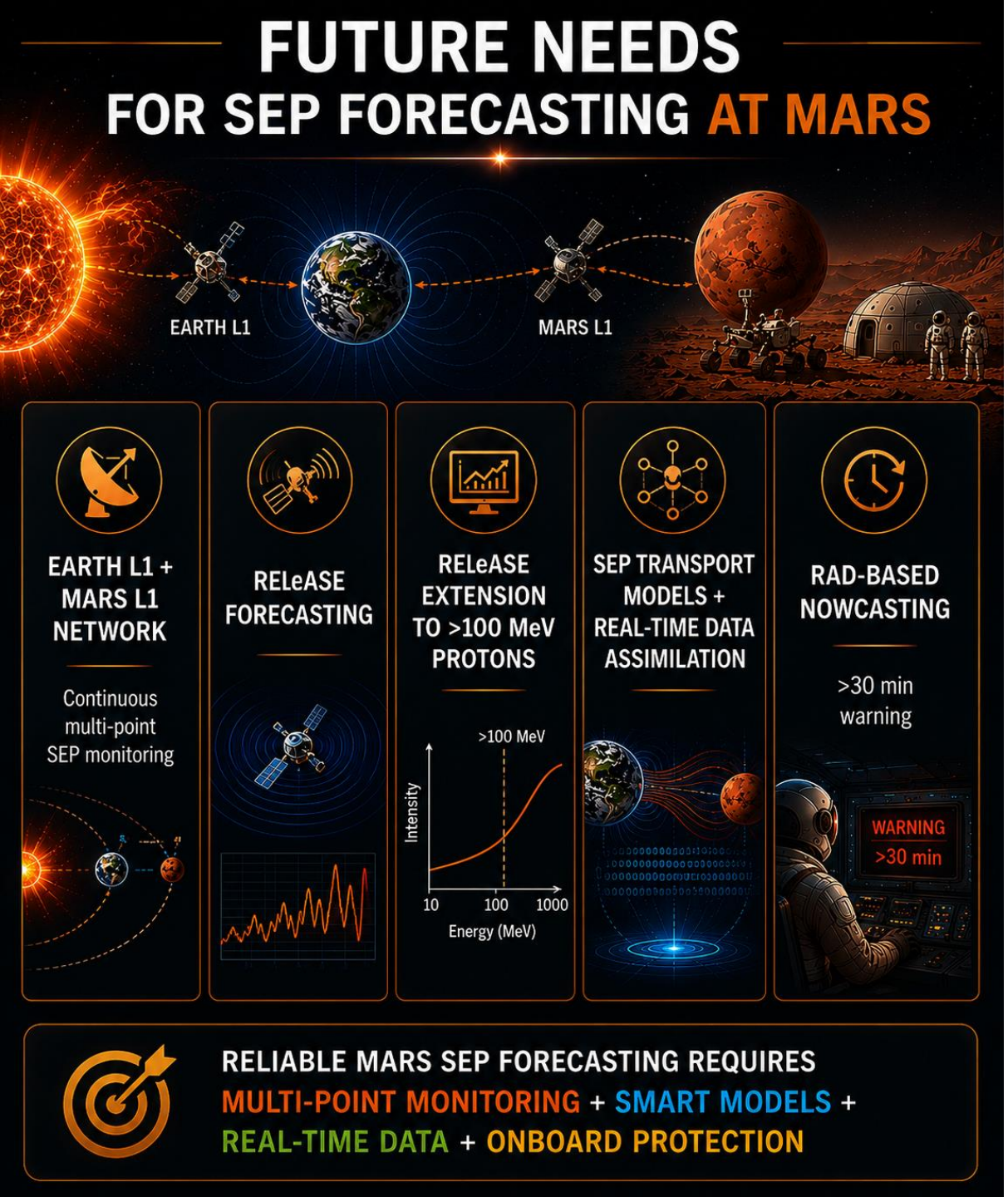
Favorable Earth/Mars magnetic connectivity can enable Earth-based REleASE forecasting.

Onboard REleASE

Autonomous early warning using relativistic electrons.

RAD-based nowcasting

Local warning before peak radiation exposure when advance forecasting fails .



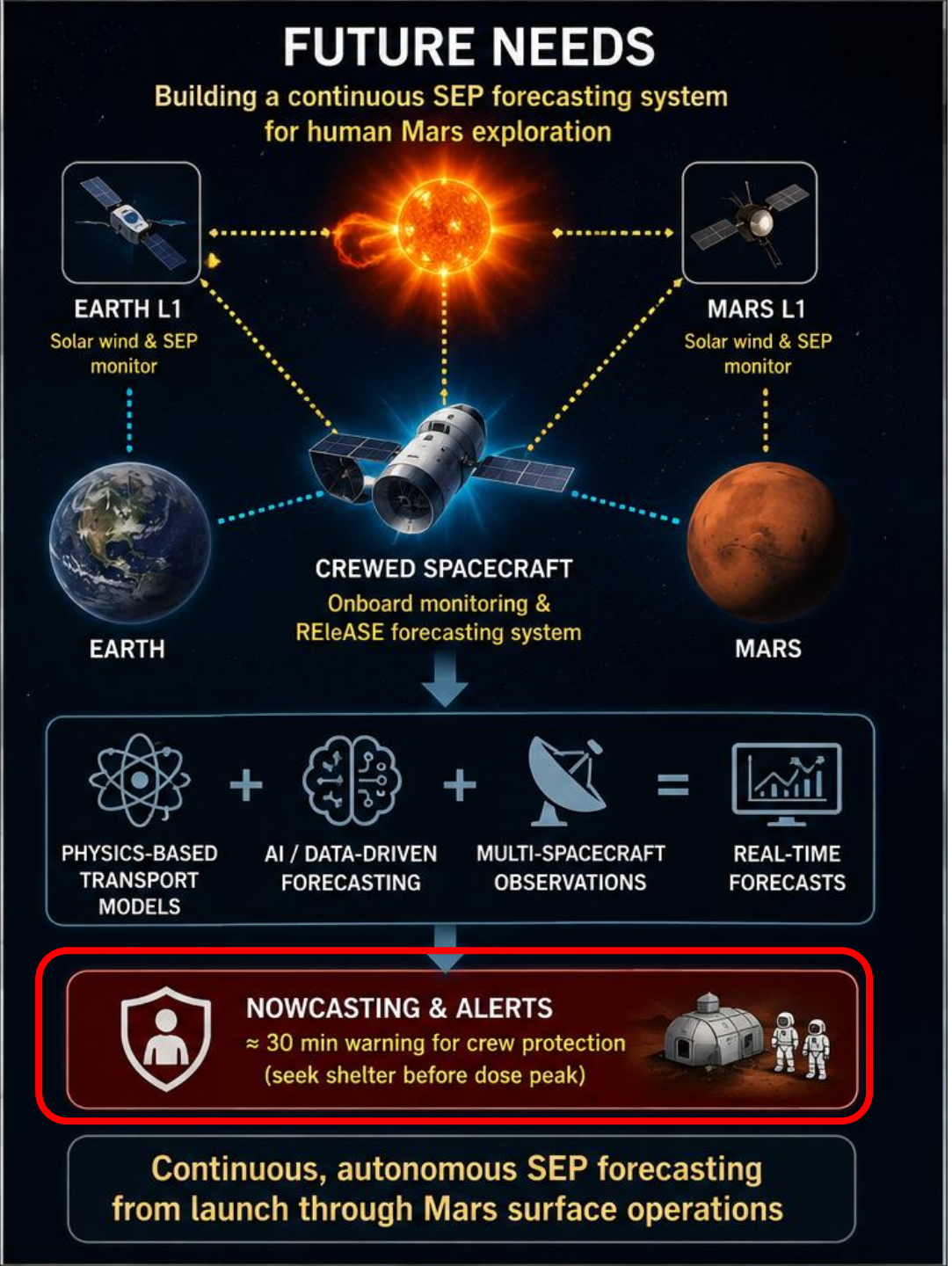
Earth L1 + Mars L1 Network
Continuous multi-point coverage for SEP forecasting at Mars.

REleASE Extension to Higher Energies
Extend REleASE forecasting to >100 MeV protons relevant to Martian surface exposure.

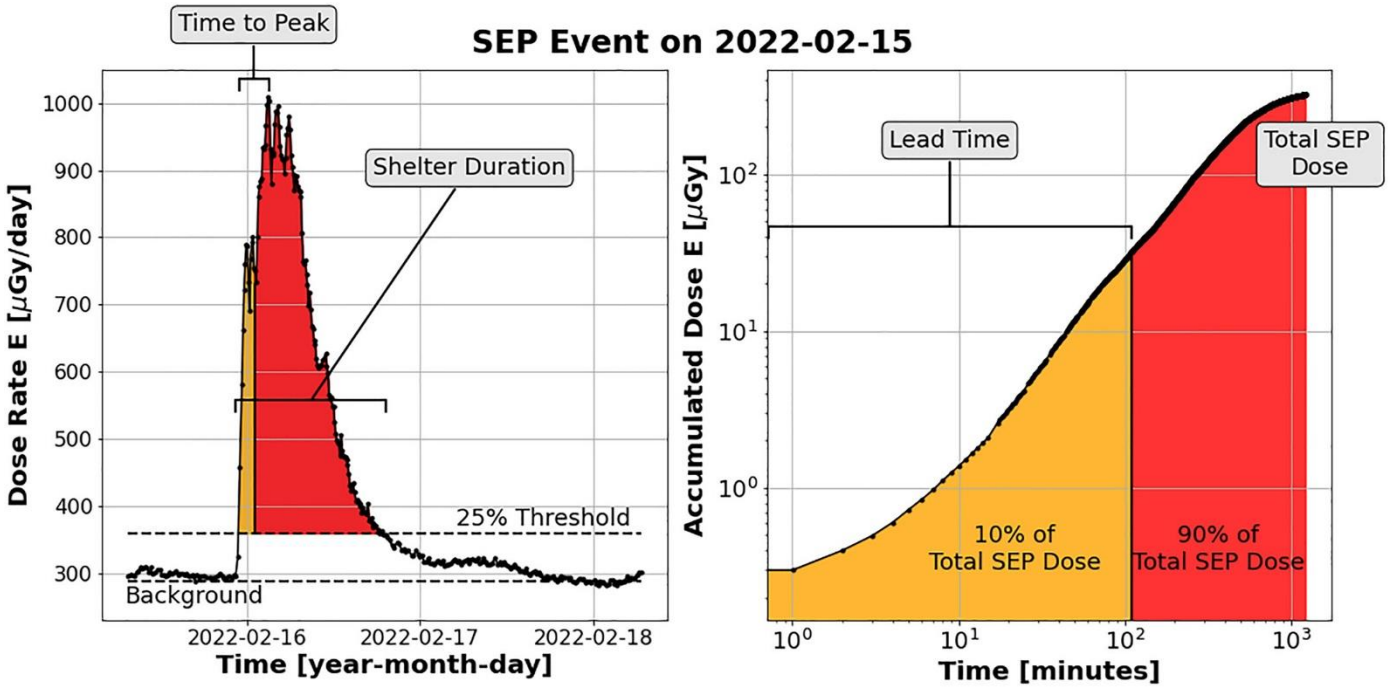
SEP Transport Models
Account for magnetic connectivity and cross-field transport.

Real-Time Data Assimilation
Combine observations from Earth and Mars for improved forecasting.

Local RAD-Based Nowcasting
Final protection layer with >30 min warning before peak radiation exposure.



Extending MSL/RAD operations and deploying RAD-type instruments on Mars-transfer spacecraft could provide autonomous SEP nowcasting, potentially reducing astronaut radiation exposure by up to 90% when advance forecasting fails.



Löwe, J. L., Khaksari, S., et al. (2025). Nowcasting Solar Energetic Particle Events for Mars Missions.

CONCLUSIONS

Forecasting SEP events at Mars is challenging and strongly event-dependent.

Magnetic connectivity is important, but not sufficient for reliable forecasting.

SEP transport is complex: evolving CME-driven shocks, particle scattering, field-line meandering, and cross-field transport strongly influence particle arrival at Mars.

Poorly connected events can still affect Mars, while well-connected events may not provide enough warning time.

A robust warning system requires multiple layers: connectivity analysis, multi-point observations, transport modeling, onboard monitoring, and local nowcasting.

Magnetic connectivity tells us where forecasting may work — but SEP transport determines whether it actually does.

FUTURE NEEDS



CRUISE PHASE

Onboard REleASE-type forecasting
Autonomous early warning using relativistic electrons.



MARTIAN SURFACE

Dedicated Mars–Sun L1 monitor
Continuous upstream space weather monitoring for Mars.



EARTH L1 + MARS L1

Continuous forecasting along the Earth–Mars trajectory
Distributed warning network.



MULTI-POINT OBSERVATIONS + TRANSPORT MODELS

Multi-spacecraft observations combined with SEP transport models
Account for evolving connectivity and cross-field transport.



REAL-TIME DATA ASSIMILATION

Real-time multi-point data assimilation
Integrate observations from Earth, Mars, and the spacecraft.

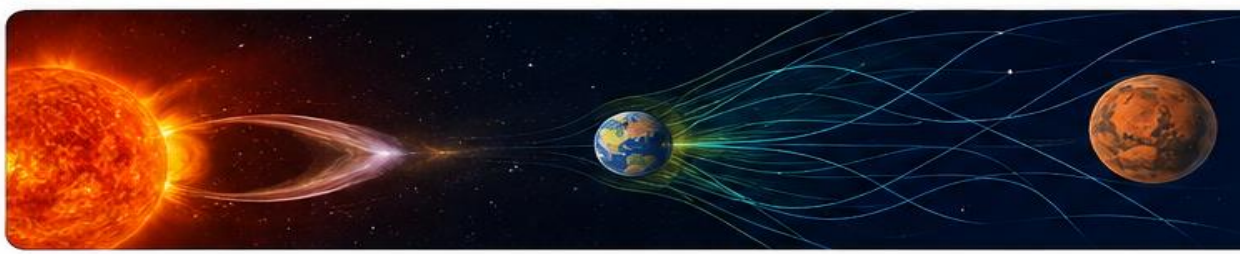


OPERATIONAL SEP NOWCASTING

Operational SEP nowcasting
≥30 min warning before peak radiation exposure for crew sheltering.

Extending MSL/RAD operations and deploying RAD instruments on Mars transfer spacecraft could enable SEP nowcasting, potentially reducing astronaut SEP dose by up to 90% during worst-case scenarios when forecasting does not work.





THANK YOU FOR LISTENING!

ANY QUESTIONS?