May 30th, 2024

Automation Framework for XGEO Space Environment Resiliency

Space Weather Impact Mitigation

Improving Space Weather Modeling for Satellite Space Environment Awareness

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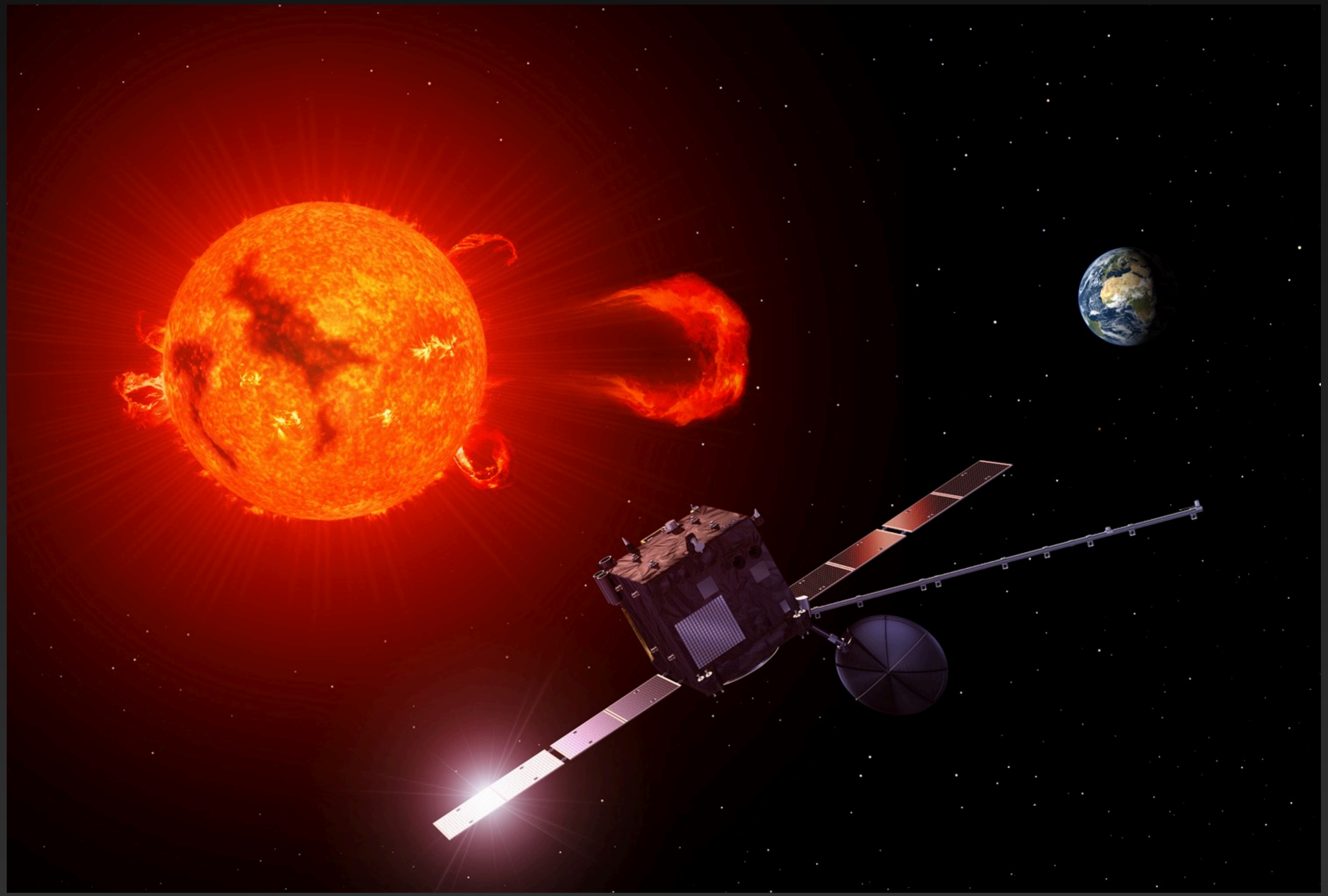
Department of Mechanical and Aerospace Engineering, UF



In collaboration with

Dr. Christopher Petersen & Faraz Abed Azad
Department of Mechanical and Aerospace Engineering, UF

AFOSR Center of Excellence for Assured Autonomy in Contested Environments

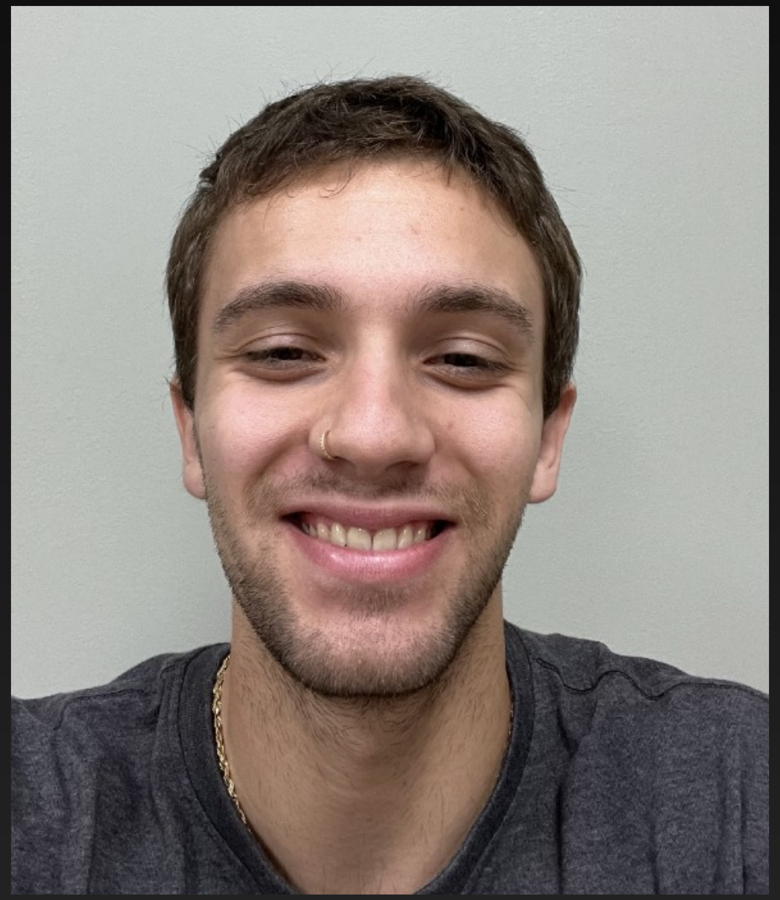

Natalie Perez and Gabriella Araujo

SWIFT Lab Students

Space Weather Impacts, Forecasting and Transit

PhD Students:

- David Galarza
- Nick Furioso



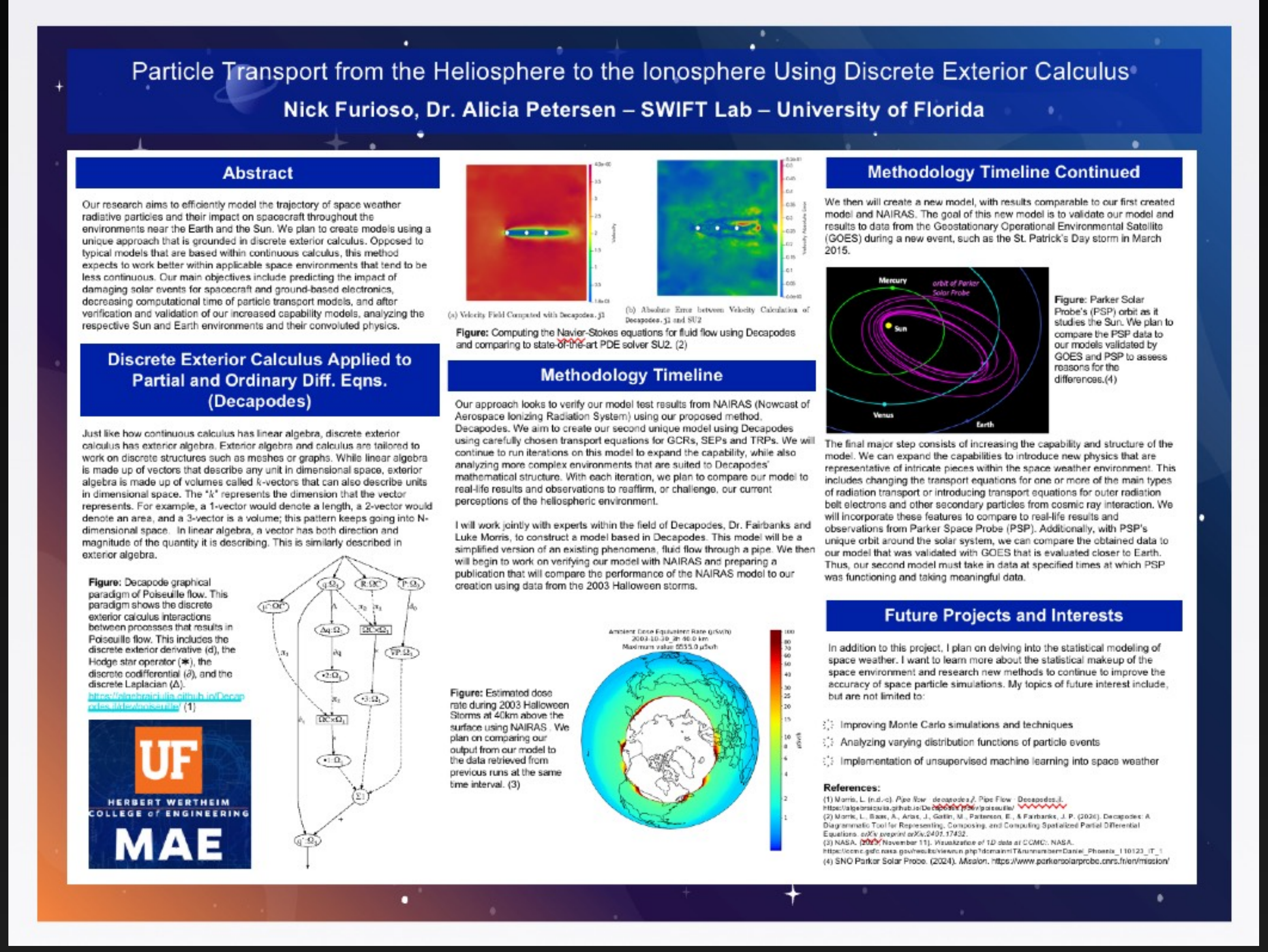
Undergraduate Students:

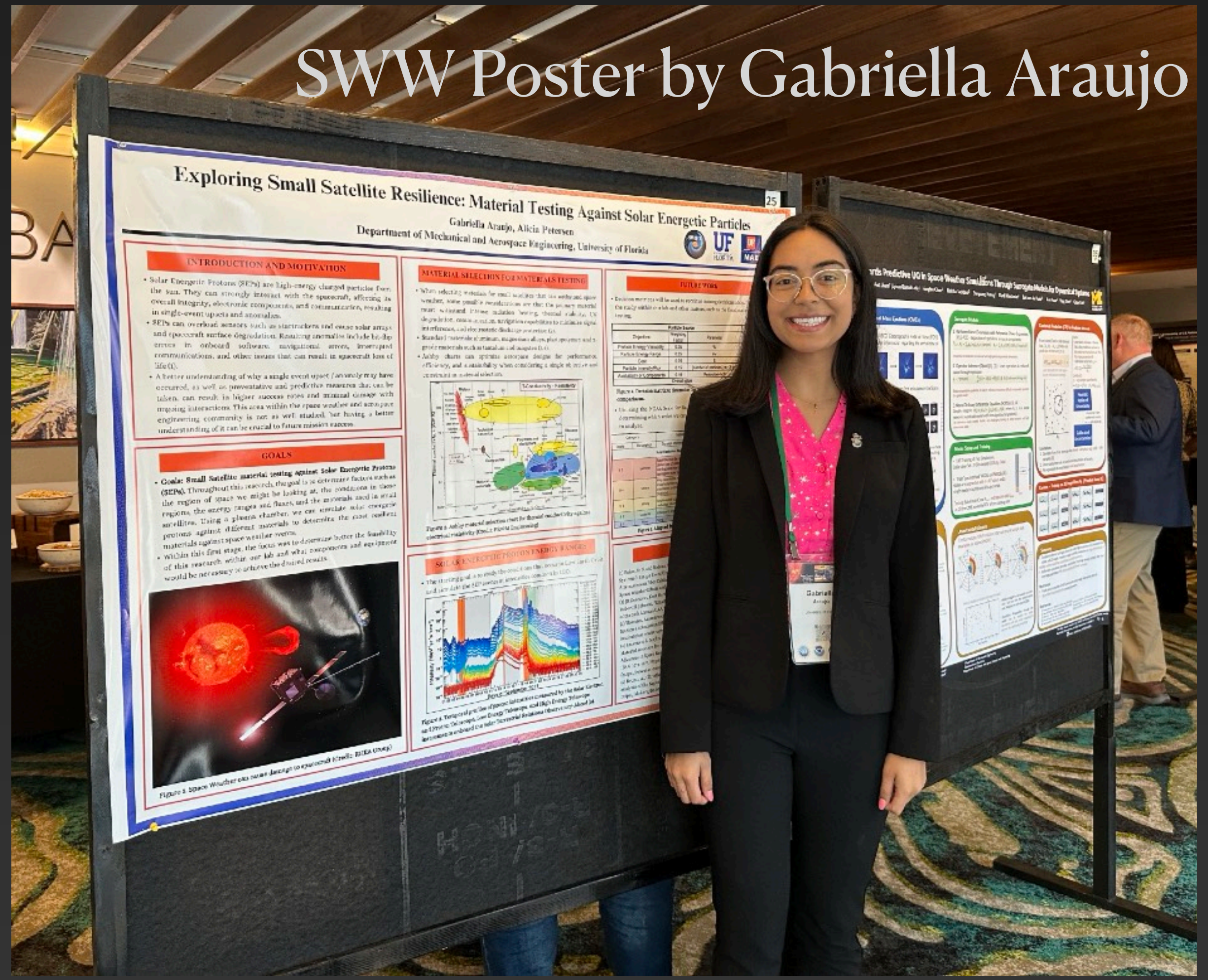
- Gabriella Araujo, Natalie Perez, Nathaniel Marcelin and Eric Steiner

SWIFT Lab Presentations

- American Geophysical Union Fall Meeting 2023
  - Alicia K. Petersen, “Suprathermal Electrons: Keys to the HMF”
- SciTech/Spaceflight Mechanics 2024
  - Alicia K. Petersen and Gabriella Araujo, “Active Space Weather Monitoring of Energetic Particles”
  - Faraz Abed Azad, Alicia K. Petersen, and Christopher Petersen, “Autonomous Satellite Operational Mode Switching for Anomalies and Space Weather Effects Mitigation”
- Space Weather Workshop 2024
  - Nicholas Furioso, Alicia K. Petersen, “Particle Transport from the Heliosphere to the Ionosphere Using Discrete Exterior Calculus”
  - Gabriella Araujo, Alicia K. Petersen, “Exploring Small Satellite Resilience: Material Testing Against Solar Energetic Particles”
- AIAA Student Conference - March 2024
  - Natalie Perez, “Reviewing Known Mitigation Methods for Space Weather’s Effects on Spacecrafts”
- Upcoming Solar Heliospheric Interplanetary Environment Meeting August 2024
  - Alicia K. Petersen, title TBD.
  - David Galarza, Alicia K. Petersen, “HelioSTET: Modeling Suprathermal Electron Transport in the Heliospheric Magnetic Field”
  - Nicholas Furioso, Alicia K. Petersen, “Particle Transport from the Heliosphere to the Ionosphere Using Discrete Exterior Calculus”

SWW Poster by Nick Furioso

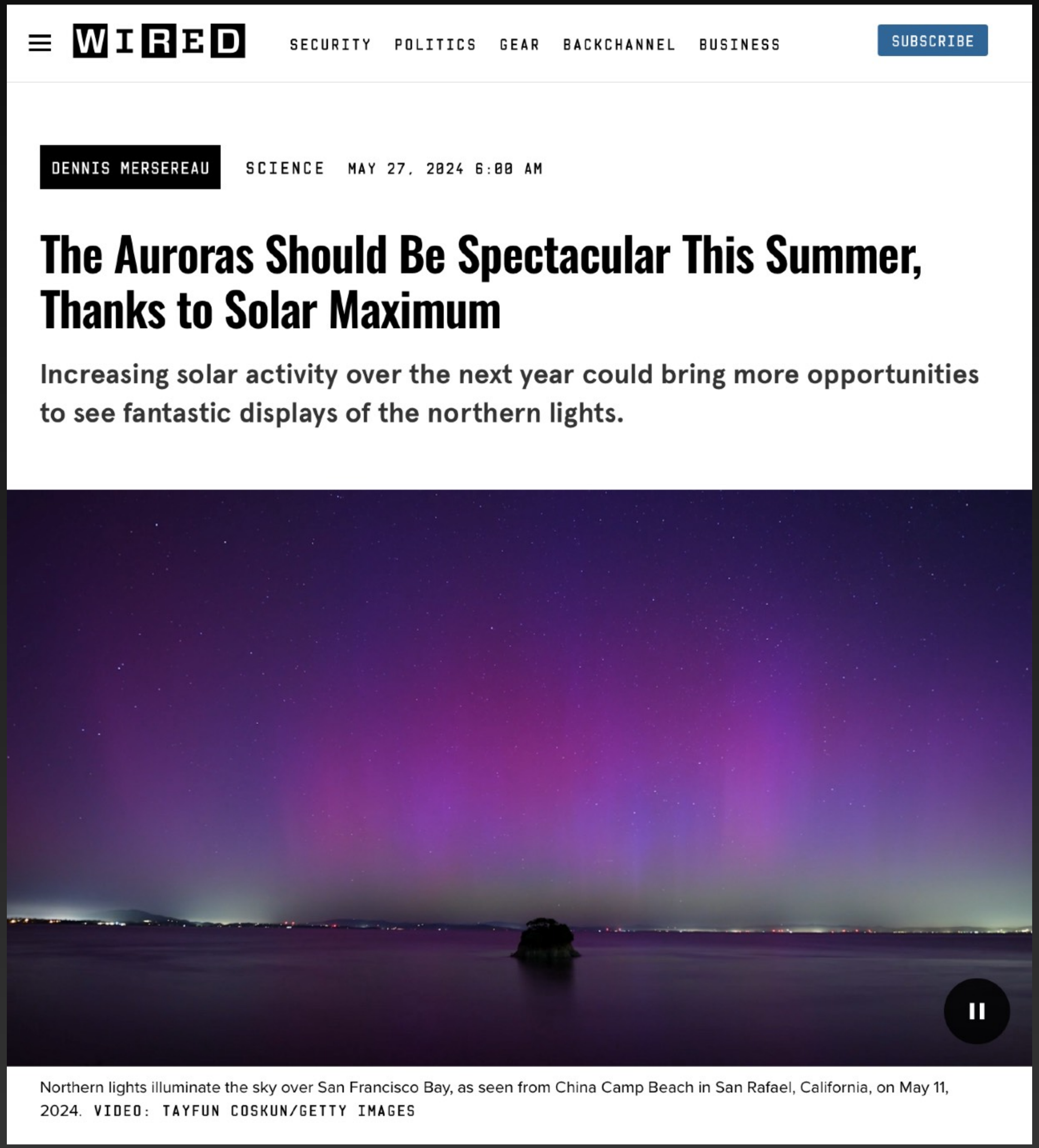




SWW Poster by Gabriella Araujo

Space Weather during Solar Maximum

Space weather has recently been making national news as we are currently in solar maximum within the 11-year solar cycle.

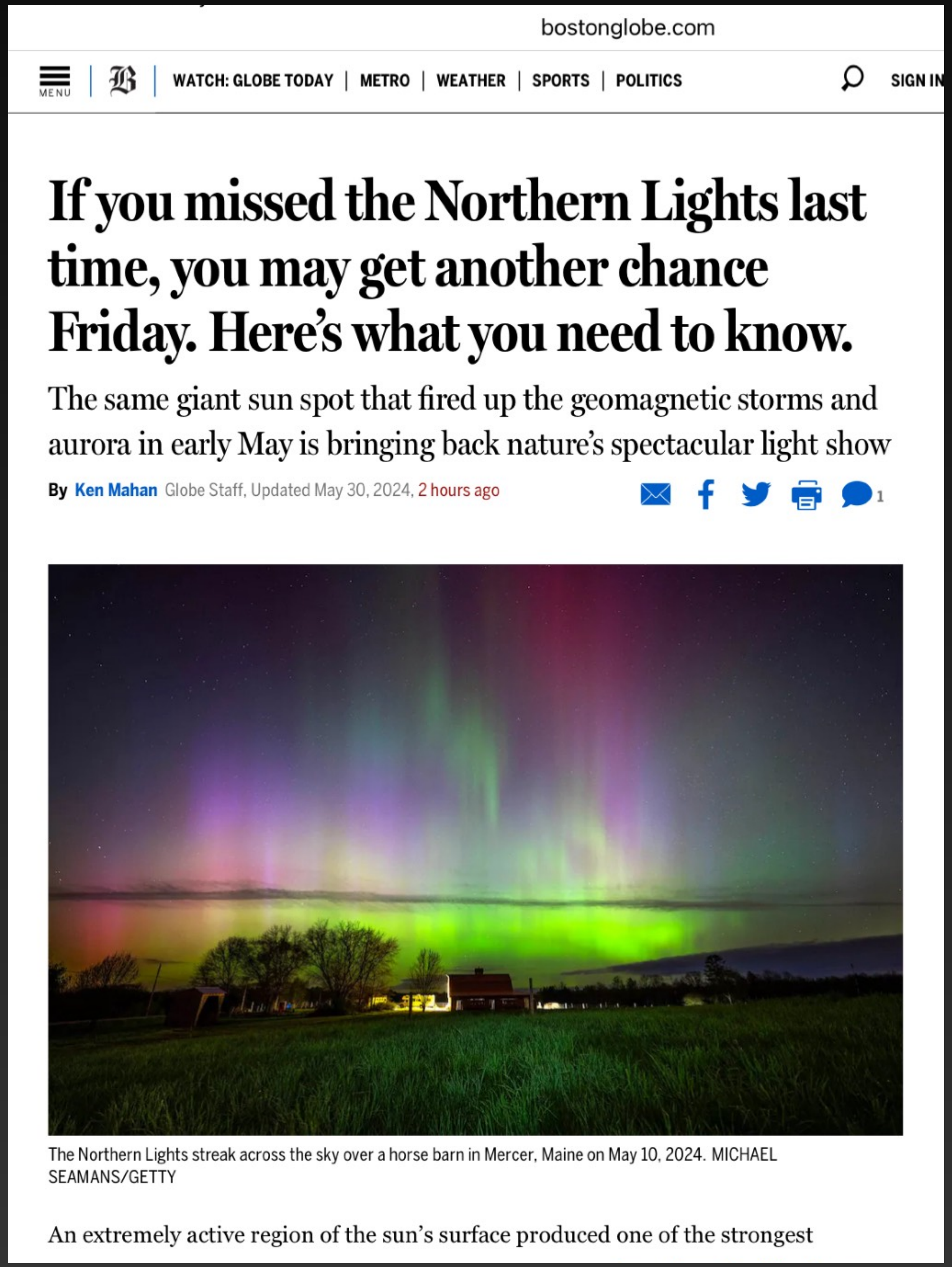

SECURITY POLITICS GEAR BACKCHANNEL BUSINESS SUBSCRIBE

DENNIS MERSEREAU SCIENCE MAY 27, 2024 6:00 AM

The Auroras Should Be Spectacular This Summer, Thanks to Solar Maximum

Increasing solar activity over the next year could bring more opportunities to see fantastic displays of the northern lights.

Northern lights illuminate the sky over San Francisco Bay, as seen from China Camp Beach in San Rafael, California, on May 11, 2024. VIDEO: TAYFUN COSKUN/GETTY IMAGES


bostonglobe.com

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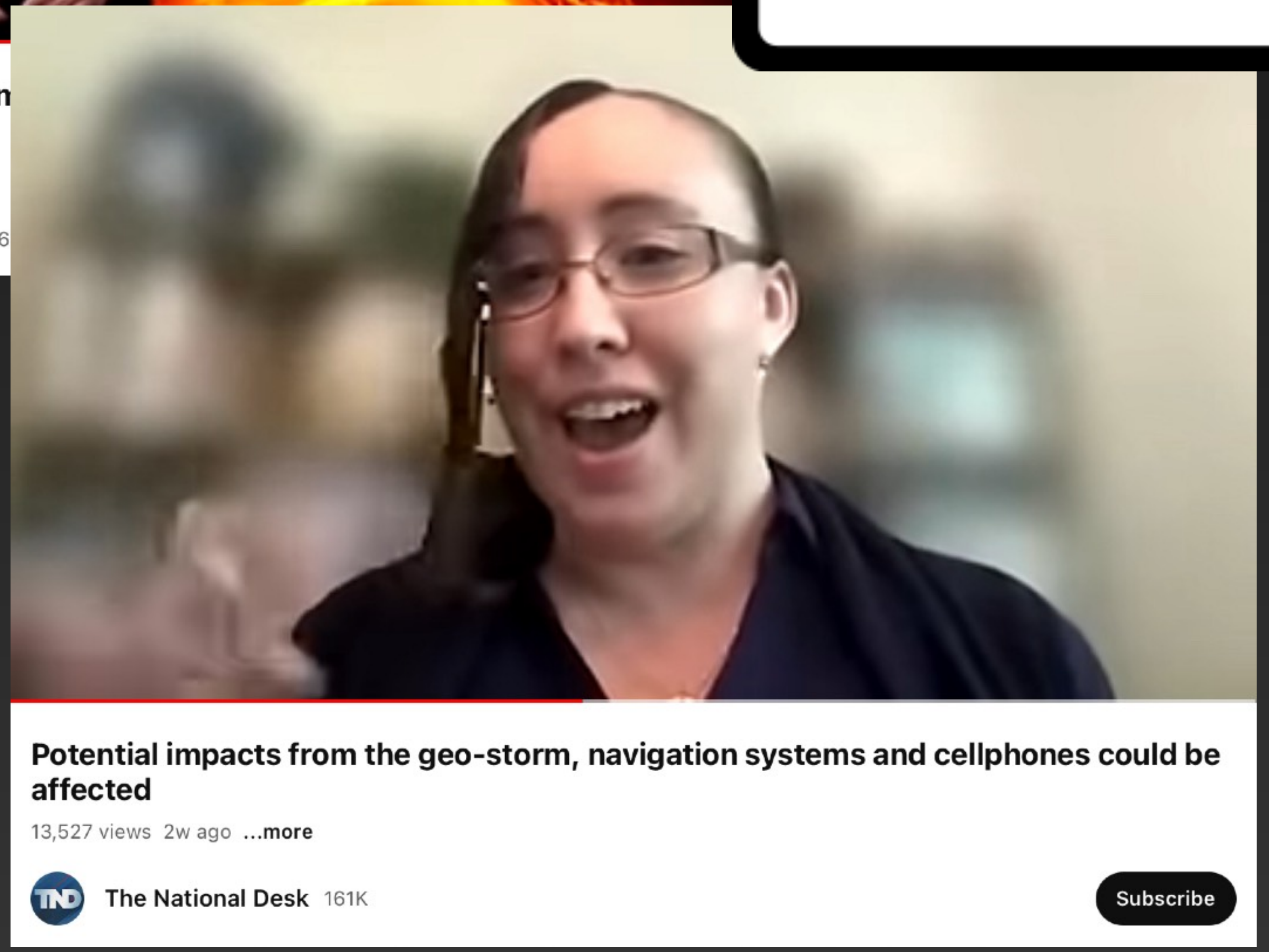
If you missed the Northern Lights last time, you may get another chance Friday. Here's what you need to know.

The same giant sun spot that fired up the geomagnetic storms and aurora in early May is bringing back nature's spectacular light show

By Ken Mahan Globe Staff, Updated May 30, 2024, 2 hours ago

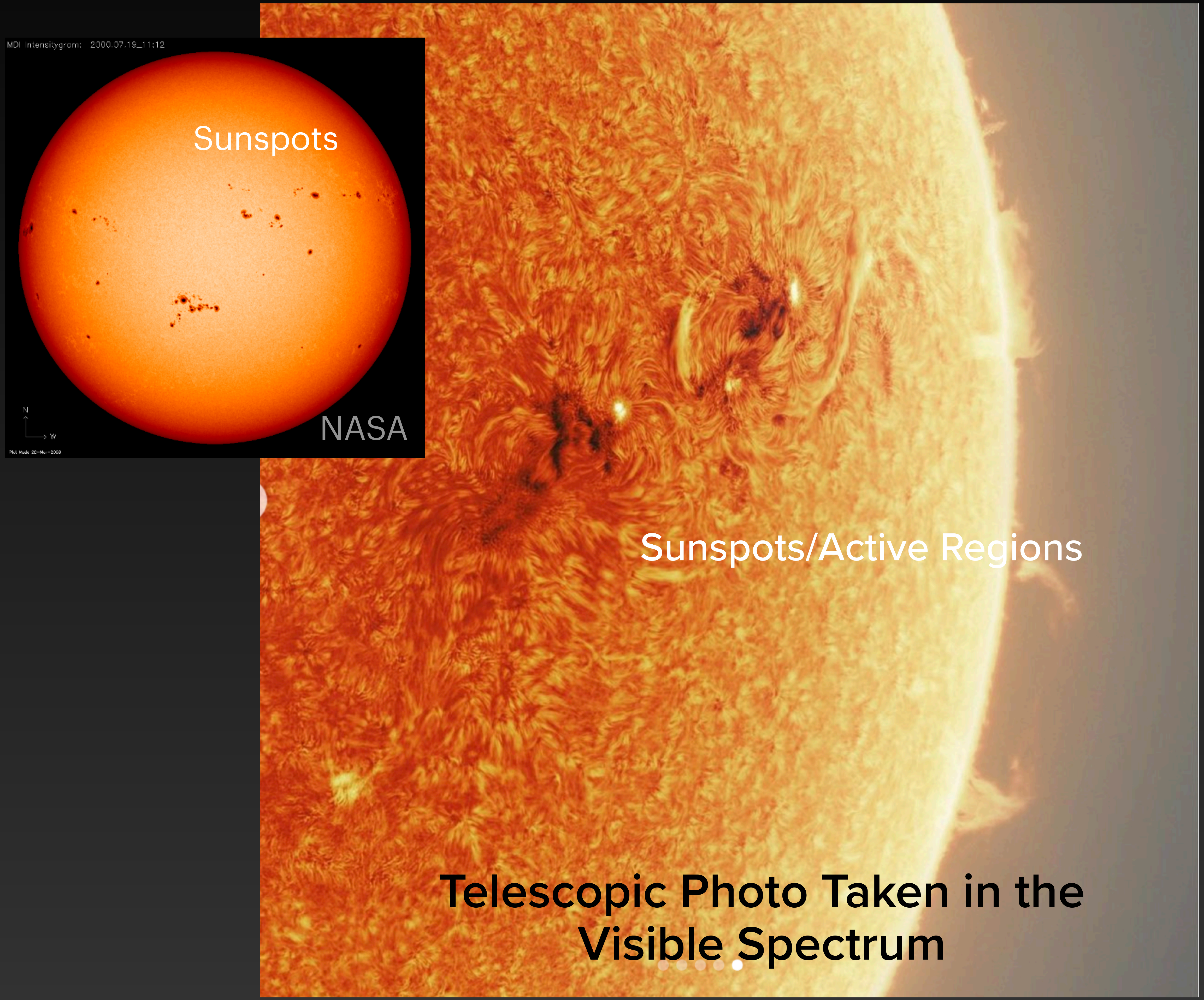
The Northern Lights streak across the sky over a horse barn in Mercer, Maine on May 10, 2024. MICHAEL SEAMANS/GETTY

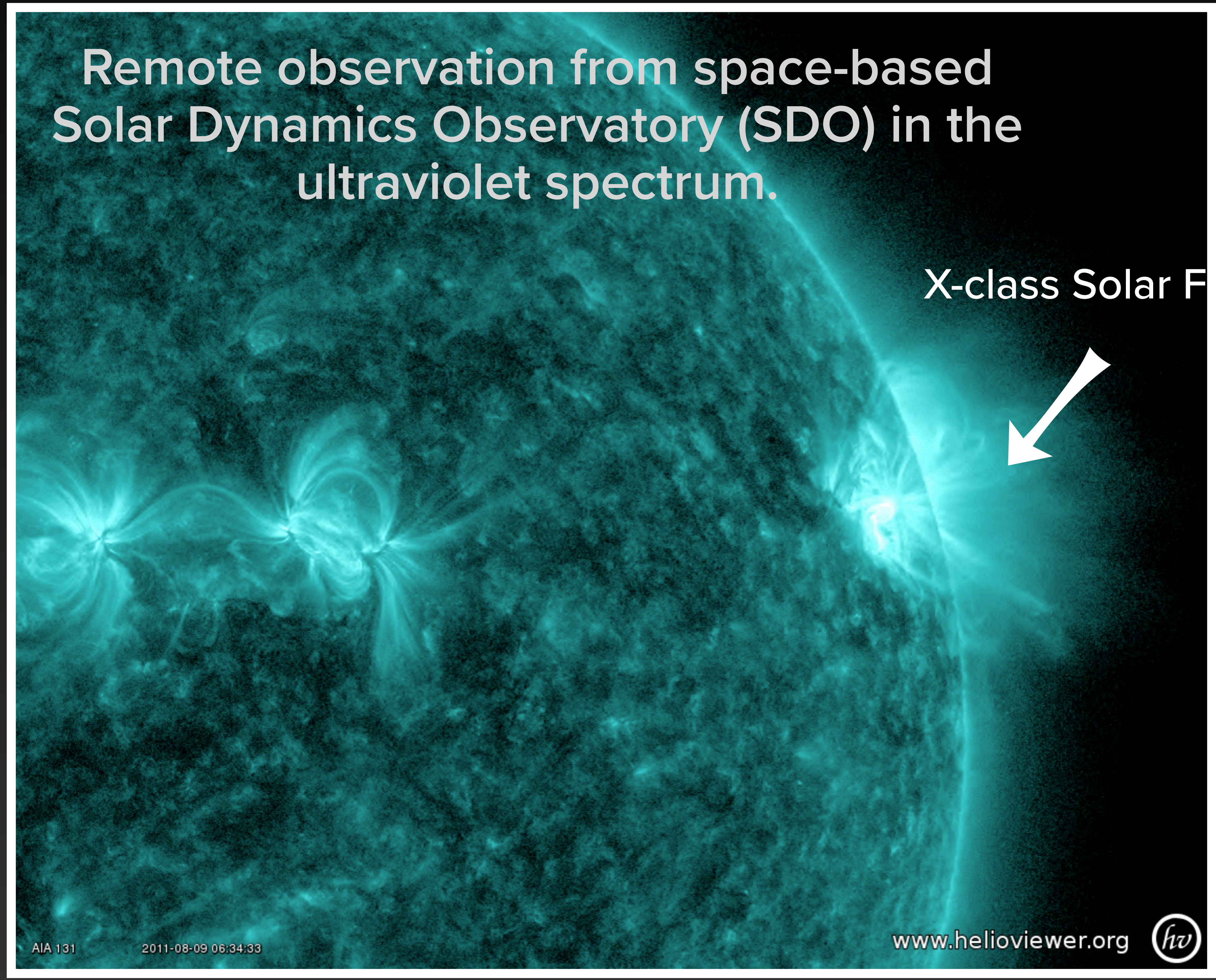
An extremely active region of the sun's surface produced one of the strongest



https://youtube.com/watch?v=4LWqhCoMQoU&si=0VqCVCxSVv8E1tBq

Space Weather drivers such as solar flares, solar energetic particles (SEPs) and coronal mass ejections (CMEs) originate in active regions on the solar surface.





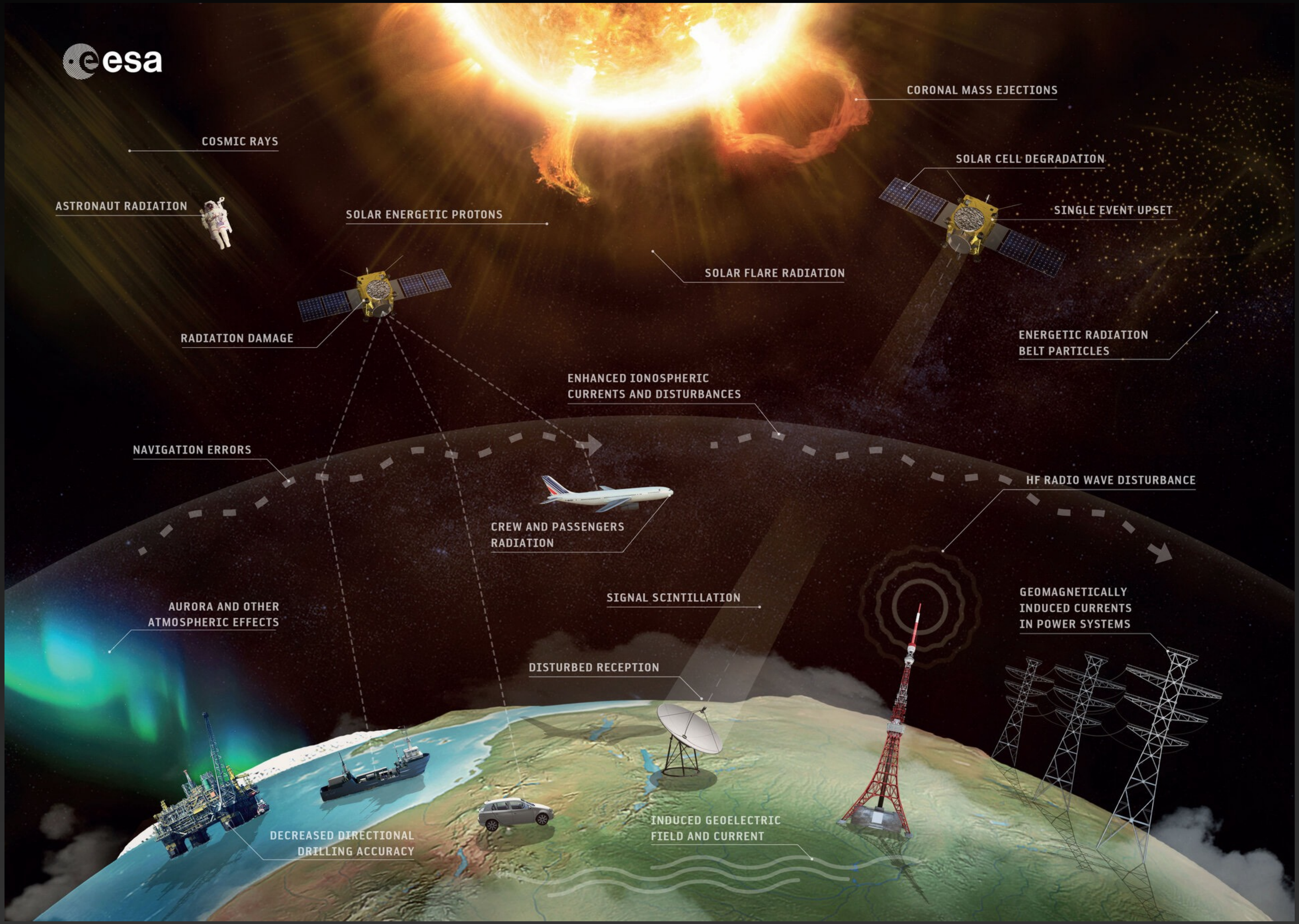
Prof. Alicia K. Petersen
AFOSR Center of Excellence for Assured Autonomy

UF Department of Mechanical & Aerospace Engineering
UNIVERSITY of FLORIDA

[Andrew McCarthy, @Cosmic_Background]

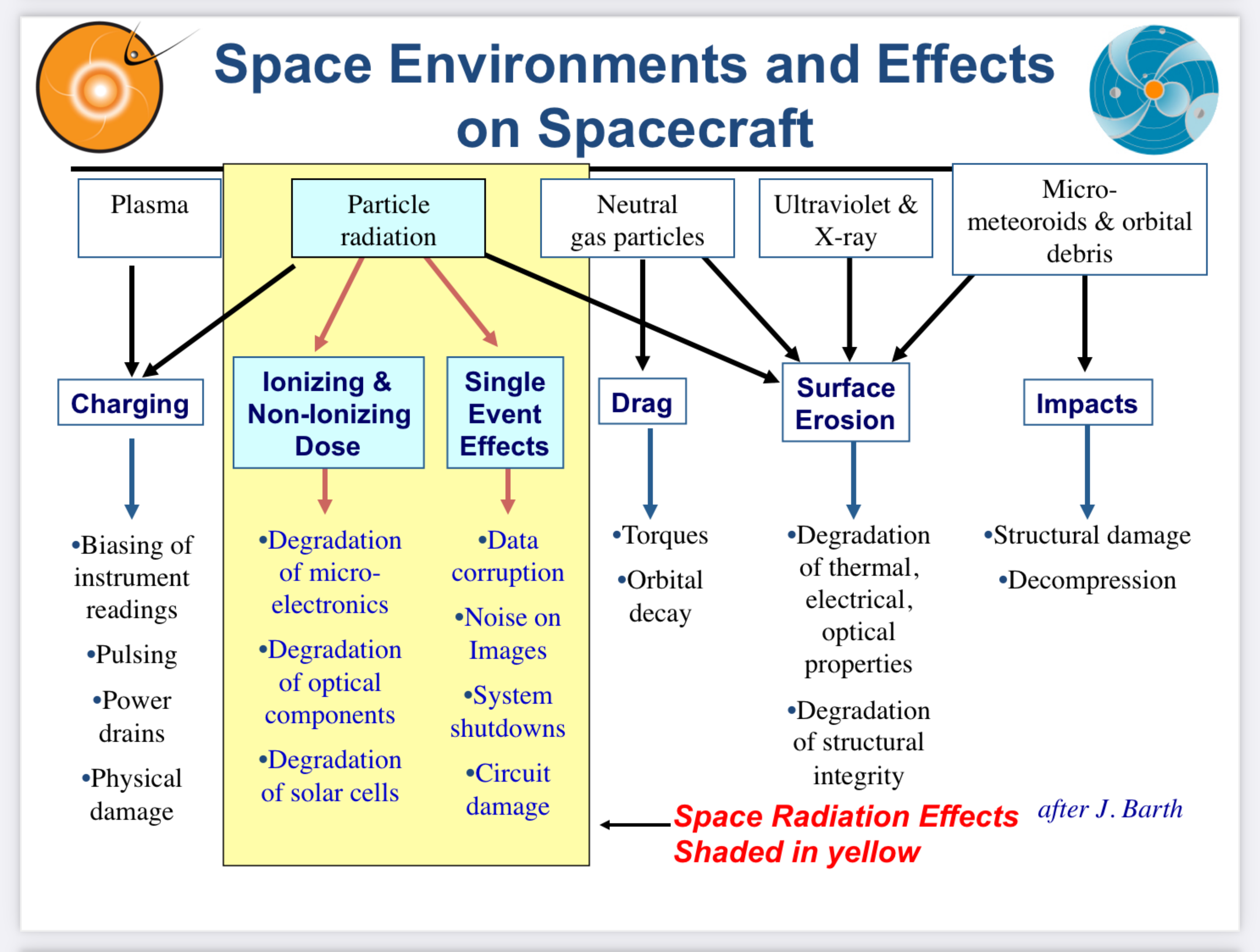
Effects of Space Weather at Earth

- Aurora Borealis & Aurora Australis
- Damage to Spacecraft Hardware and Electronics
- Geomagnetic Storms
  - Dramatic Changes to Currents, Electric Fields and Earth's Magnetic Fields in Earth's Space Environment
  - Increases Ionization in Earth's Ionosphere
  - Increases Density, Especially in LEO
    - Increases Satellite Drag
  - Influx of High Energy Protons and Electrons
  - Influx of Radiation Belt Particles
  - Influx of heavy ions (C, O, Fe, etc.)
- Damage to the Power Infrastructure on the Ground
- Satellite, Radio & HF Communications Interference
  - Greatly impact error in GNSS signals and timing
- Increased Harmful Ionizing Radiation in Polar Regions
  - Affects Polar Aeronautical Flights
  - Harms Astronauts in LEO onboard the ISS



Primary Hazards to Spacecraft

- Spacecraft Charging
- Single Event Upsets
- Ionizing Radiation
- Other concerns include increased drag, communications interference, loss of GPS, …

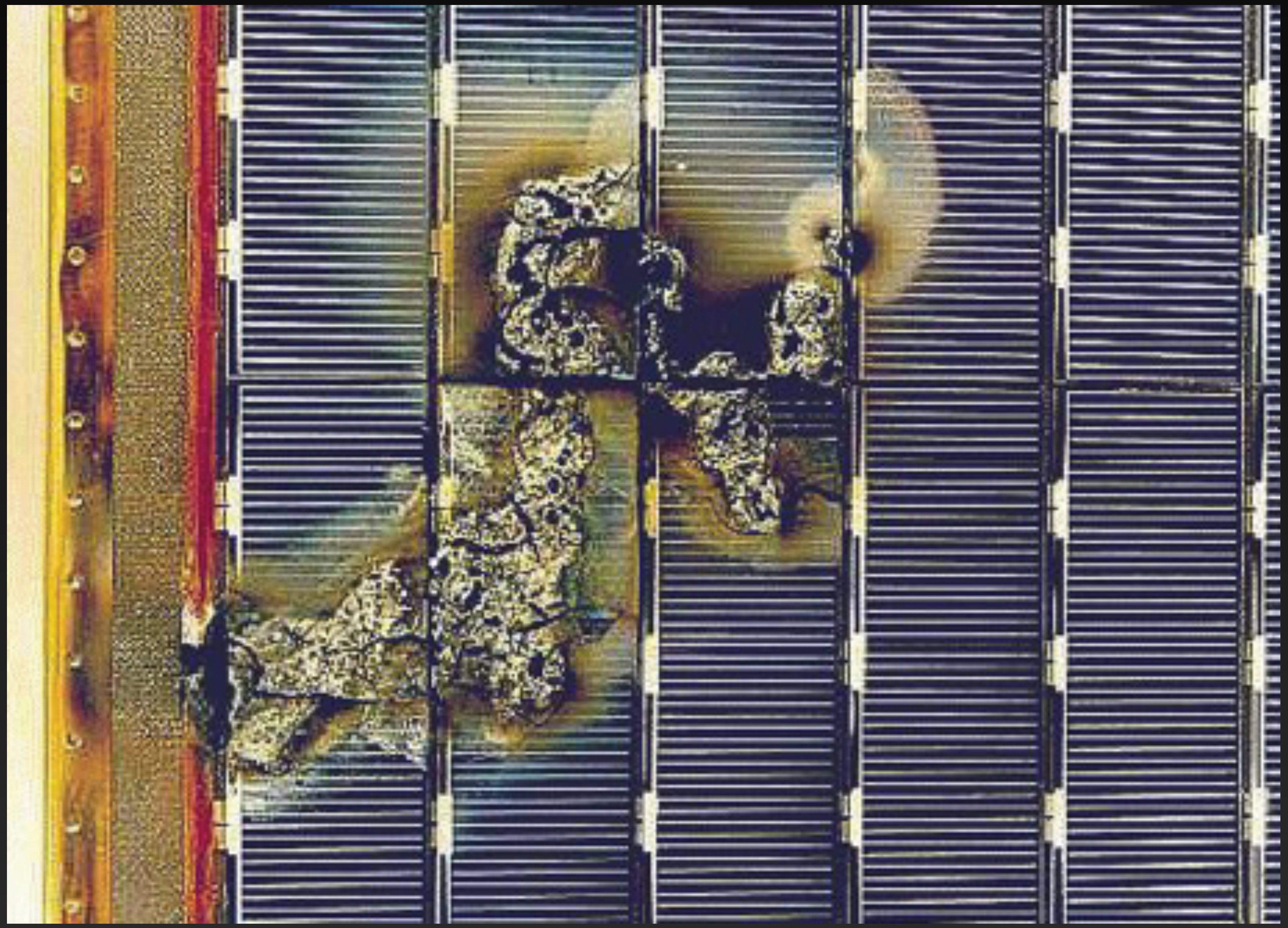


Primary Hazards to Spacecraft

- Spacecraft Charging
  - When the electric potential of a spacecraft increases due to changes in the near-spacecraft space environment.
    - Caused by an influx of charged particles
    - Increases during geomagnetic storms
    - Increases the susceptibility of the onboard systems to energetic particles,
    - Causes harm to the electronics and solar panels through arcing and shorts,
- Single Event Upsets
- Ionizing Radiation
- Other concerns include increased drag, communications interference, loss of GPS, …

Spacecraft Electronics Damage from Arcing

- Arcing = Induced electric currents that jump across electronics panels or circuits.
  - Essentially static electricity in space
  - Result: Burnt out electronics
- The smaller the circuitry, the smaller the induced current needs to be to do damage
- Spacecraft charging: The greater the spacecraft's electric potential, the more free electrons are available for arcing.



[ESA]

Primary Hazards to Spacecraft

- Spacecraft Charging
- Single Event Upsets
  - Direct impact of high energy particles that penetrates through a spacecraft into the electronics and hardware
    - Caused by Solar Energetic Particles
      - Electrons and Protons
    - Also caused by Galactic Cosmic Rays
      - Energetic particles from stars outside our solar system
- Ionizing Radiation
- Other concerns include increased drag, communications interference, loss of GPS, ...

Primary Hazards to Spacecraft

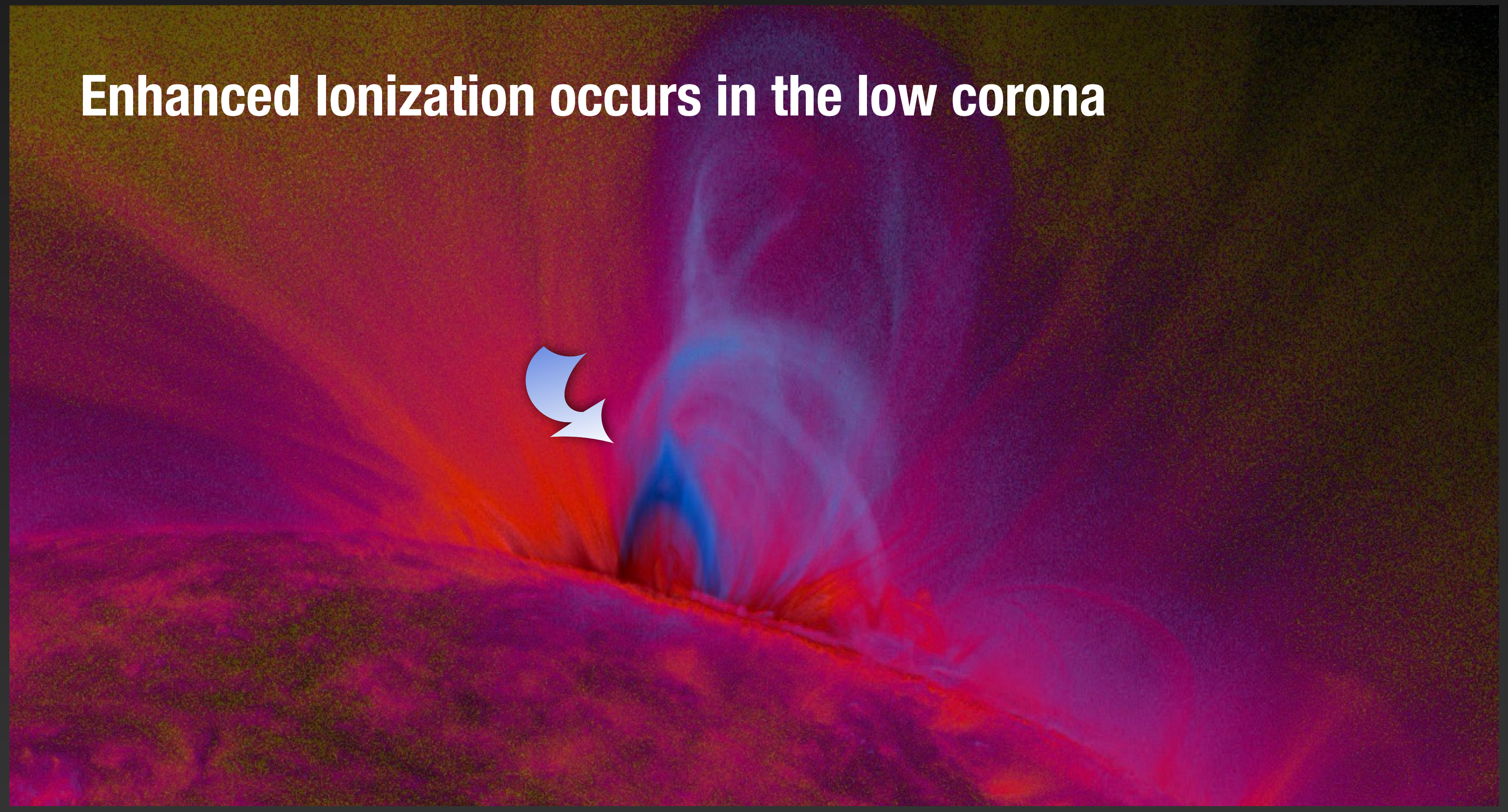
- Spacecraft Charging
- Single Event Upsets
- Ionizing Radiation
  - Increases due to increased trapped particles
    - From SEPs
    - During geomagnetic storms due to particle influx from CMEs
  - Degradation over time
    - Degradation of micro-electronics
    - Degradation of optical components
- Other concerns include increased drag, communications interference, loss of GPS, ...

[ccmc.gsfc.nasa.gov/RoR_WWW/SREDI/2014/SEP_YZheng_20140602.pdf]

Solar Energetic Particles (SEPs)

SEPs refer to either solar energetic protons or solar energetic particles. Sometimes they're called solar particle events (SPEs).

- SEPs tend to be accelerated in the higher corona, in nearly collisionless plasmas and their acceleration sites are "invisible" in remote observations of E-M spectra.



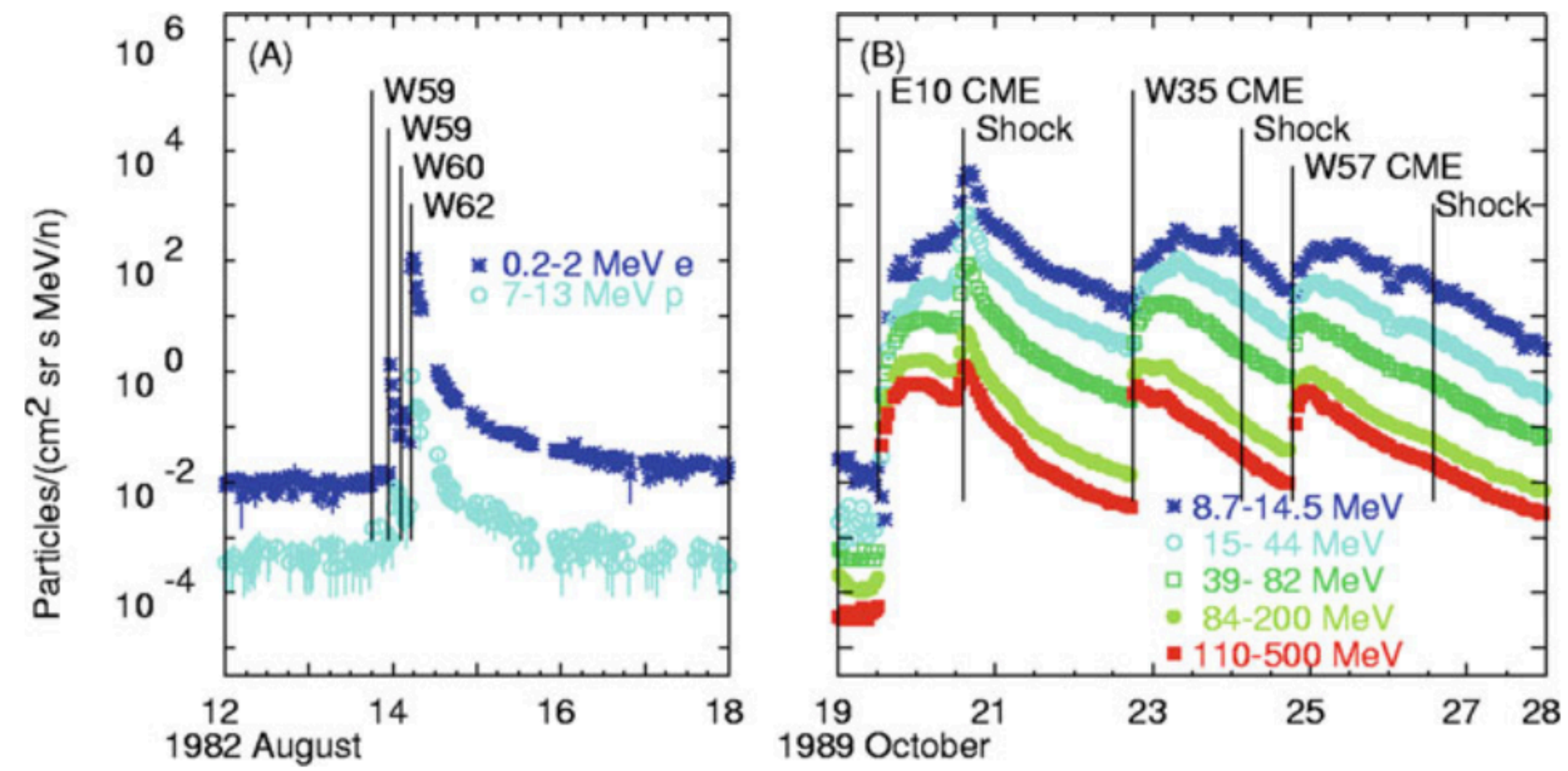
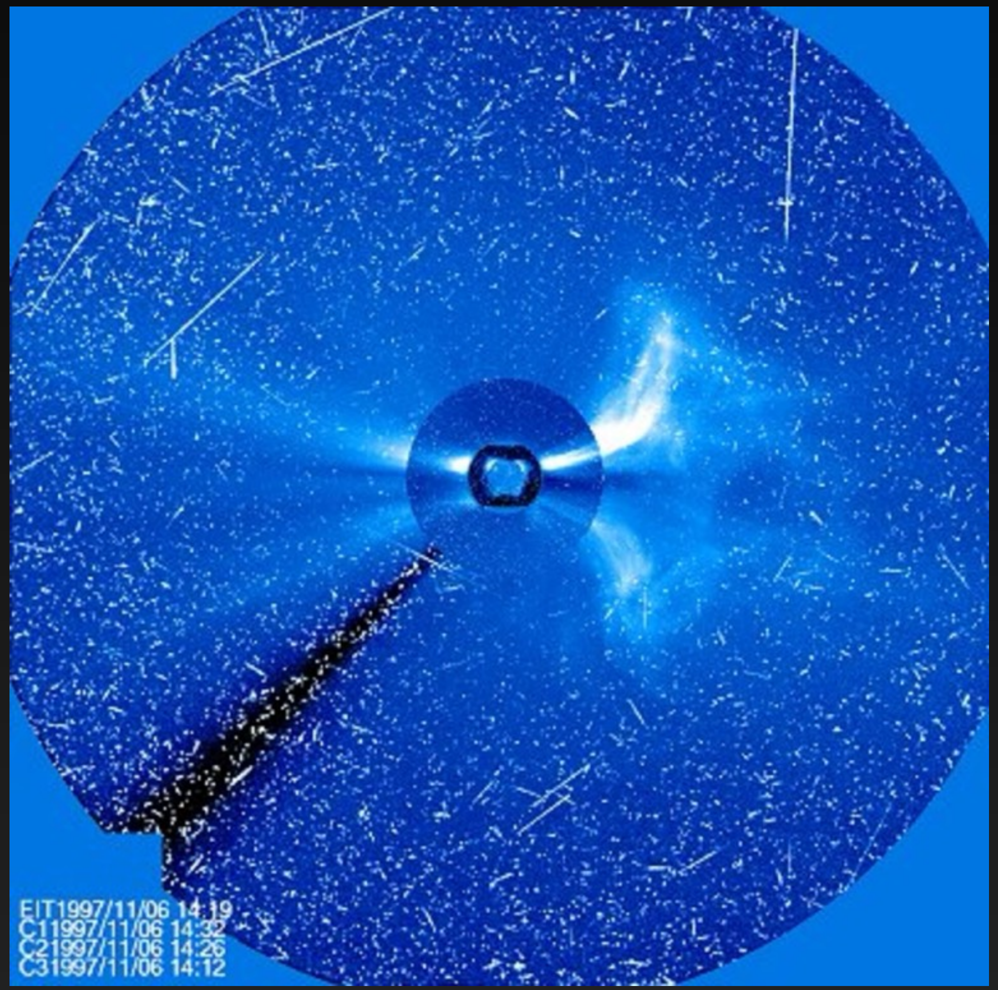


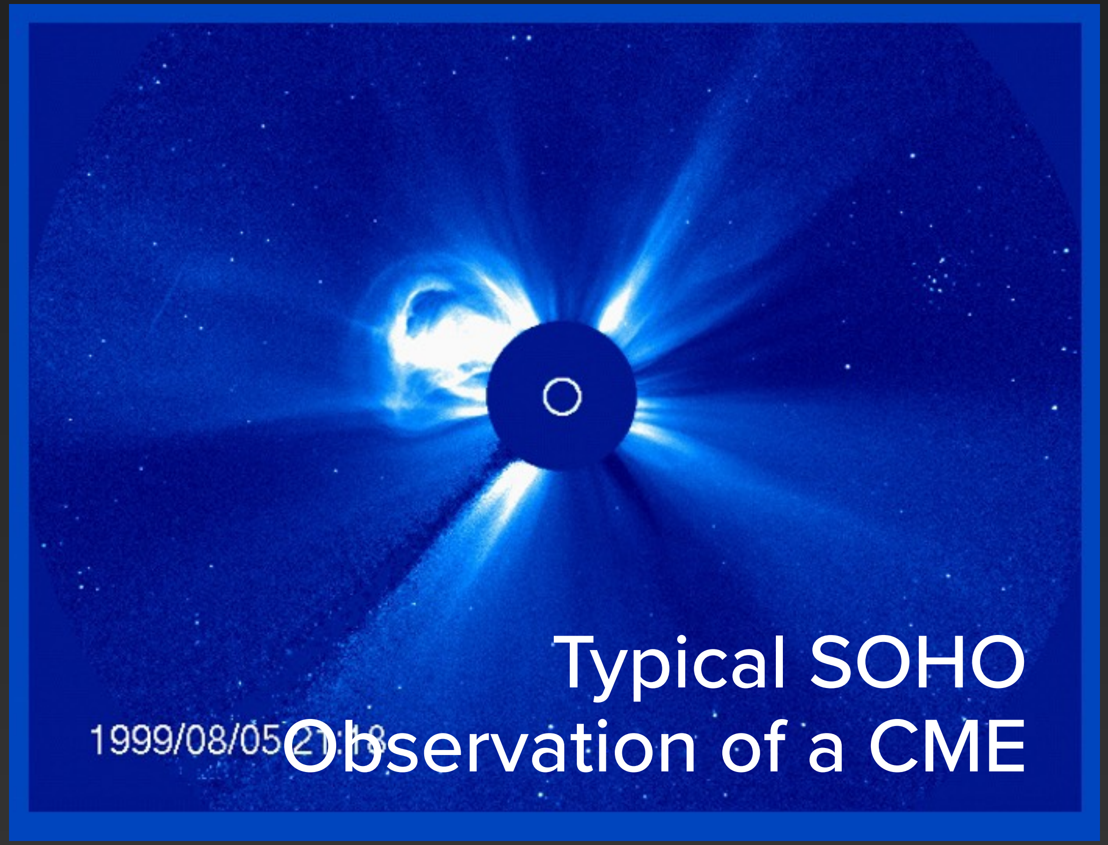
Fig. 1.5 Particle intensities are shown for a series of (**a**) impulsive and (**b**) gradual or long-duration SEP events at similar time and intensity scales. Flags labeled with the source longitude indicate the onset times of the events; also shown are the times of shock passage near Earth. Proton (or electron) energies are listed. It is difficult to obtain comparable proton energies because impulsive events are much less energetic (Reames 1999 © Springer)

[AIA observations of coronal loops, 131 Å and 171 Å differenced composite]

SEP Impacts Can Vary Depending on Orbit

SOHO Observation of a CME while being bombarded by SEPs





Typical SOHO Observation of a CME

- Ground Level Enhancements (GLEs) are types of SEPs (typically >500 MeV/nuc) which penetrate through the Earth's Magnetosphere-Ionosphere-Thermosphere, therefore affecting regions including LEO orbits.
- GEO orbits receive high influxes of energetic protons during SEP events.
    - This is the regime where NOAA's GOES spacecraft continually monitor SEPs and NOAA Space Weather Prediction Center's forecasts are based on these observations.
- In XGEO domains, a spacecraft will leave the protection of Earth's magnetosphere and will receive the full impact of an influx of ionized high energy particles during an SEP event.

Gradual vs Impulsive SEPs

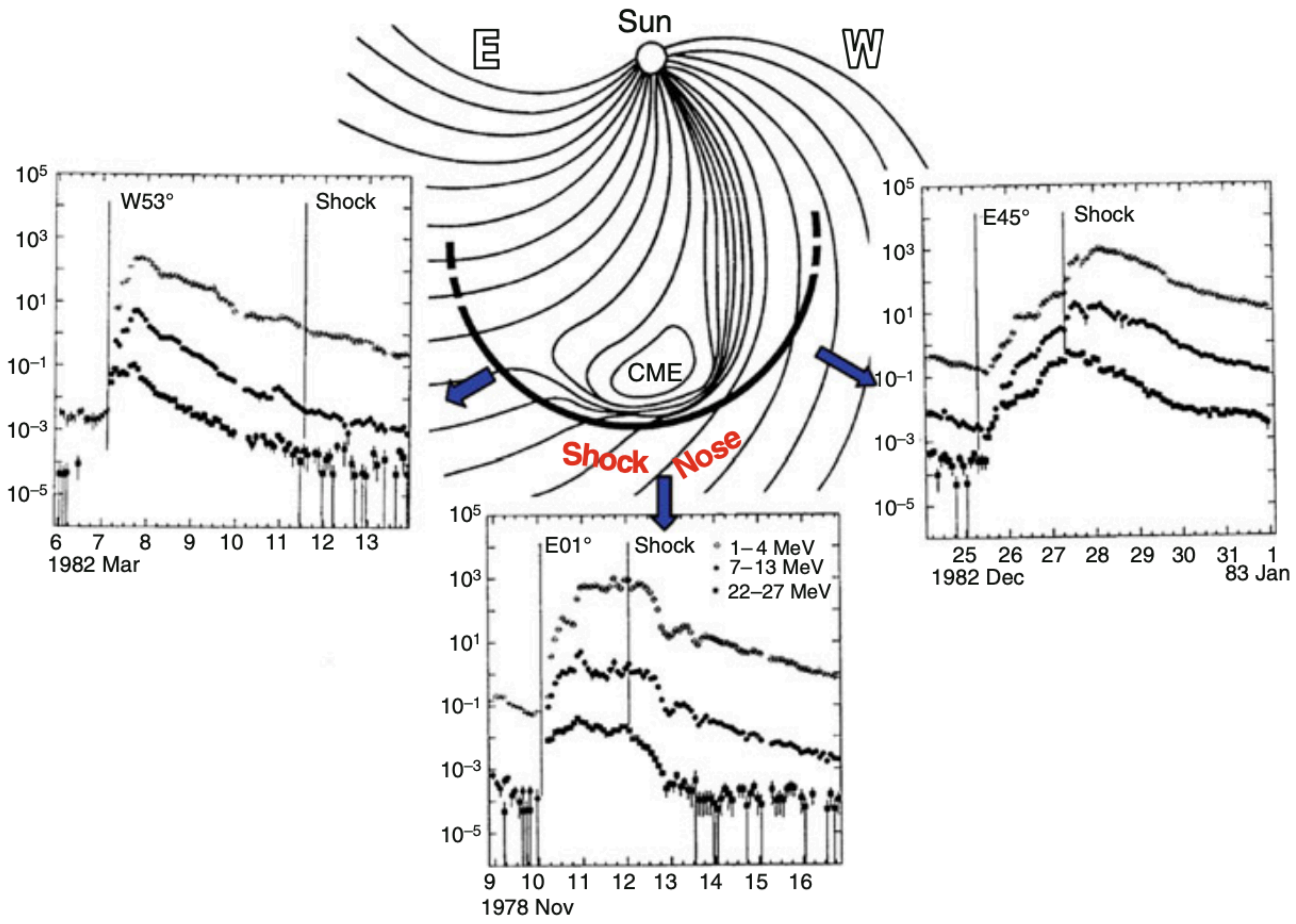
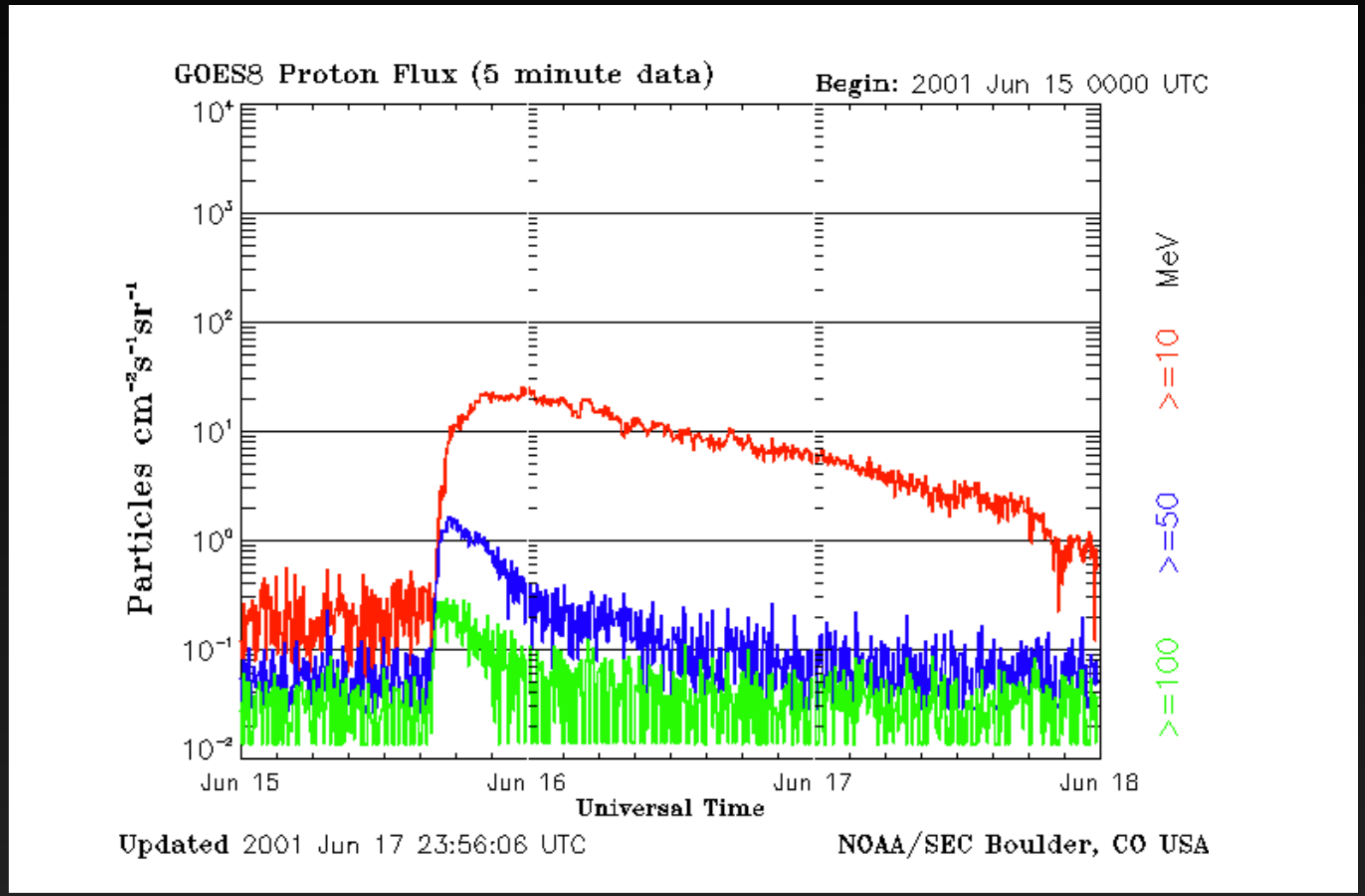


Fig. 2.2 Variation of the appearance of typical SEP events is shown as viewed from three solar longitudes (see text; after Reames 1999 © Springer; see also Cane et al. 1988, Reames et al. 1996)

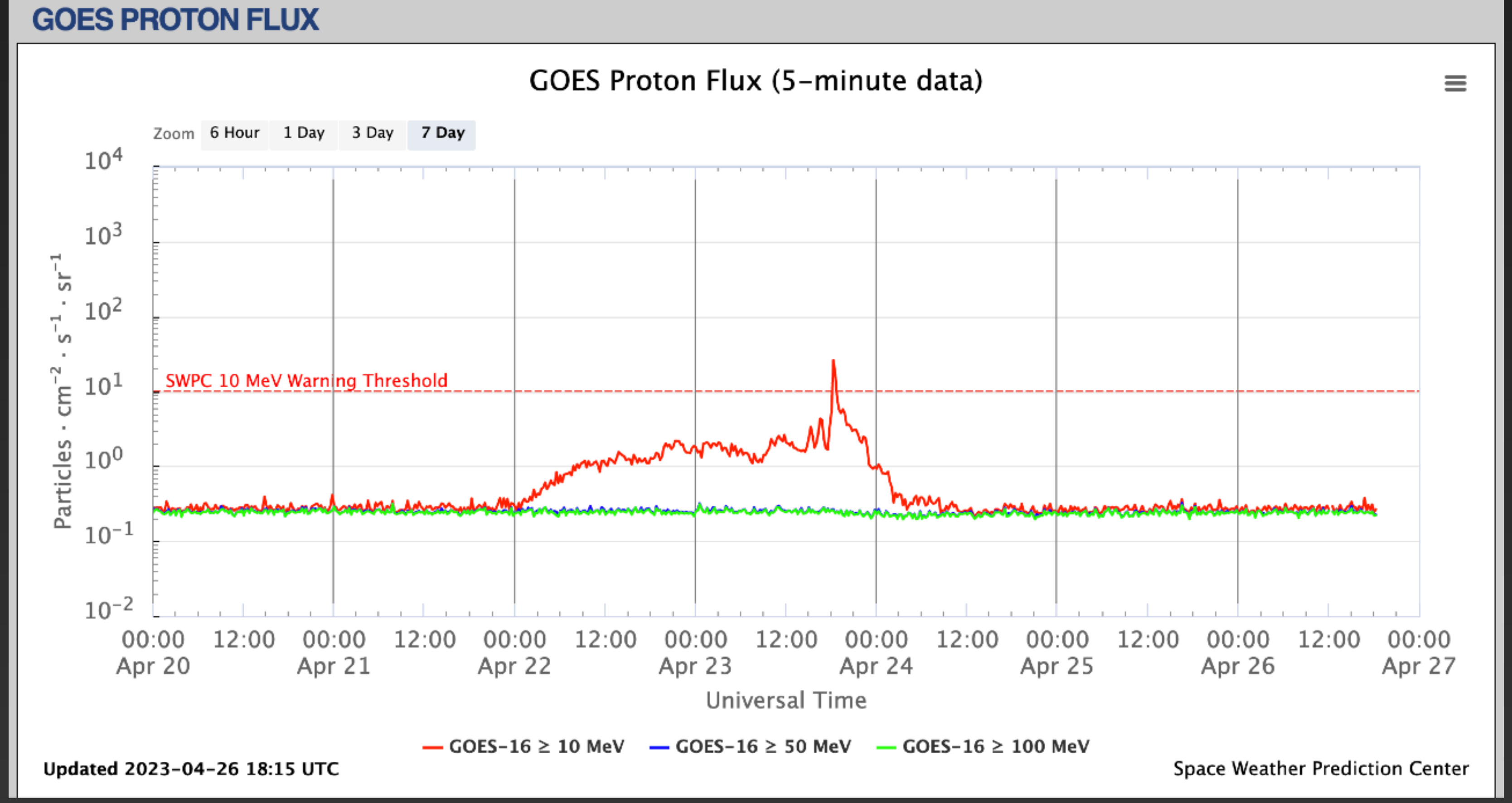
SEPs travel through the solar system along the Sun's hemispheric magnetic field and are classified as gradual or impulsive.

- Gradual SEPs are generally shock-accelerated SEPs and are long-duration.
- Impulsive SEPs are generally flare-accelerated SEPs and have sharp rise phases.
- The effects of the acceleration location and the initial particle population are active areas of research.

Potential for Onboard SEP Detection



Goal: Early in the event, based on onboard observations, effectively forecast the intensity and duration of the SEPs.



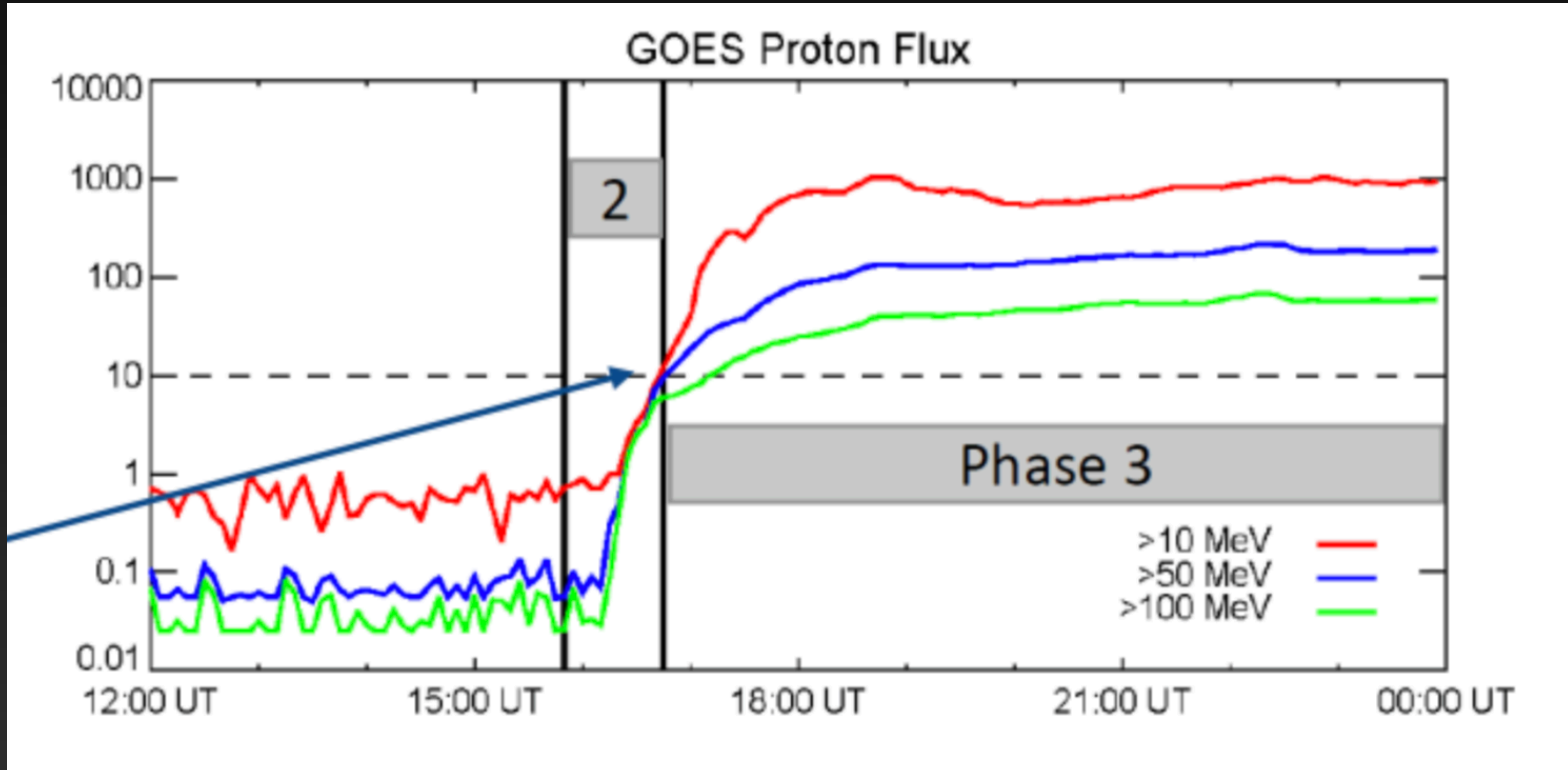


Figure from Rachel Hock-Mysliwiec, Space Weather Workshop, 3 Apr 2019

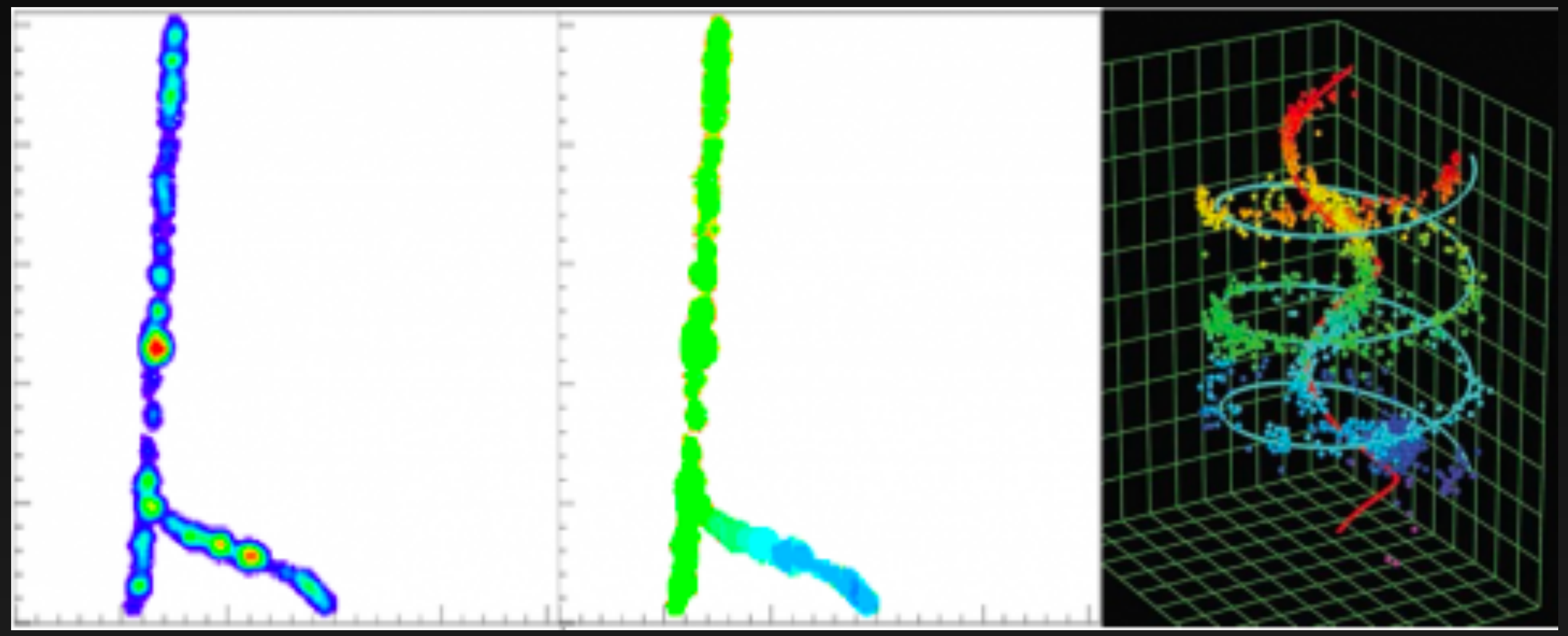
ADEPT = SEP Real-Time Forecast Tool Developed by Stephen White and others at AFRL RVBXD

Onboard Detection using TimePIX-based Instrumentation

Available Off-the-shelf and customizable small particle detectors.

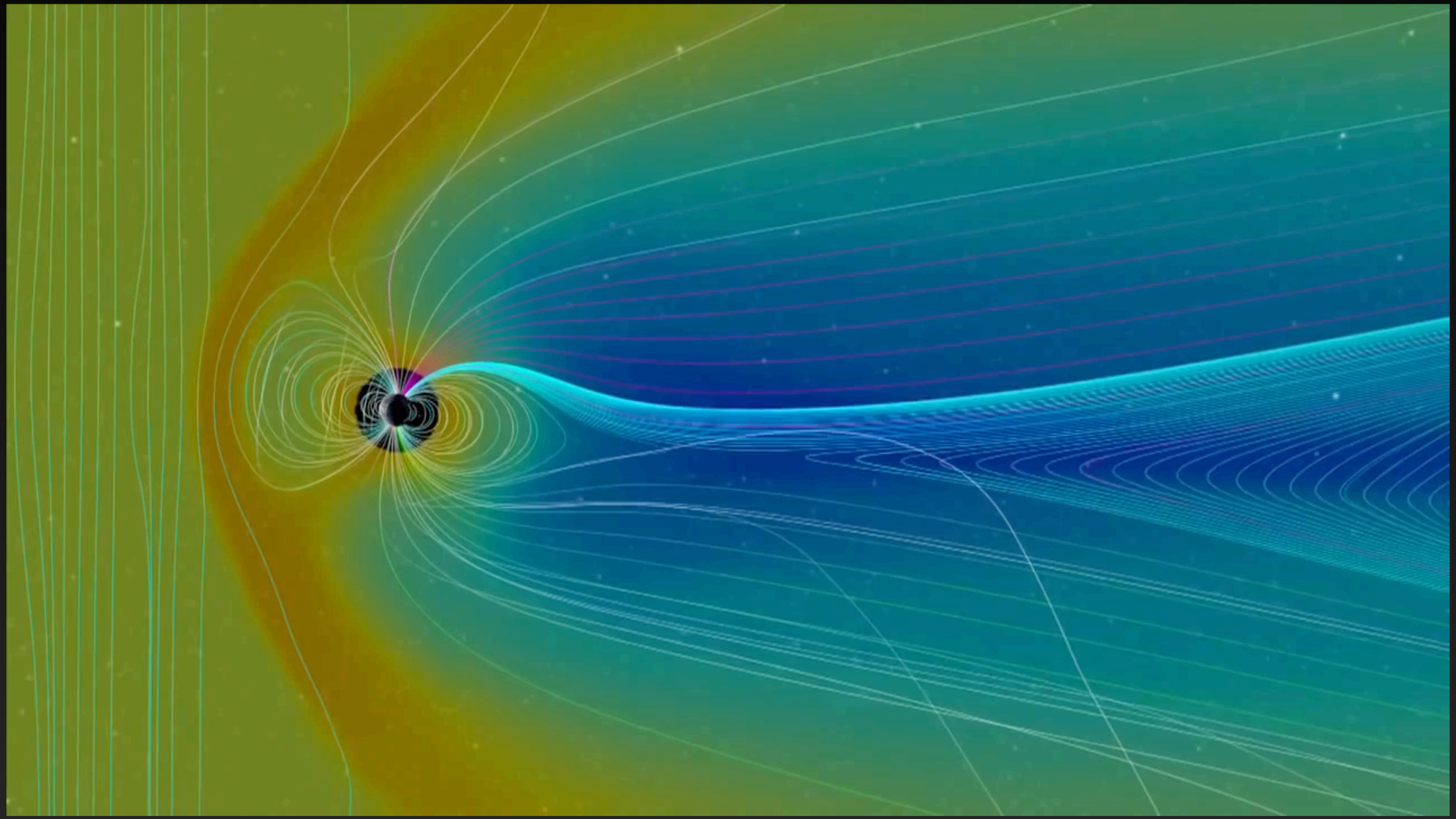
TimePIX3 Space

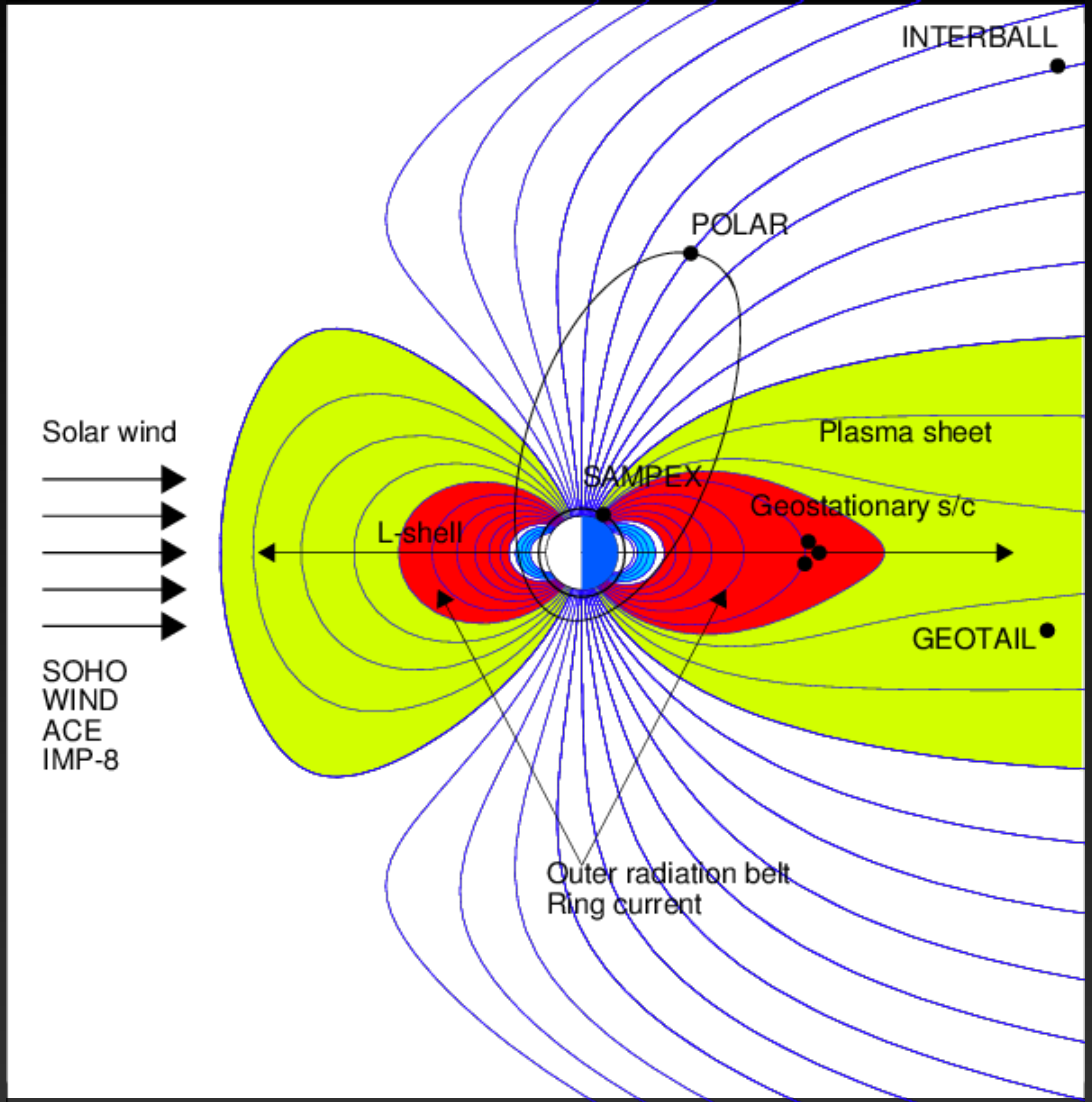
- Plug & Play
- Configurable
- Flight-tested
- Vacuum-compatible
- We're working on configuring them into particle detector made of multiple sensors.



3D Particle Tracking with Advacam TimePIX3

XGEO - Outside the Earth’s Magnetosphere





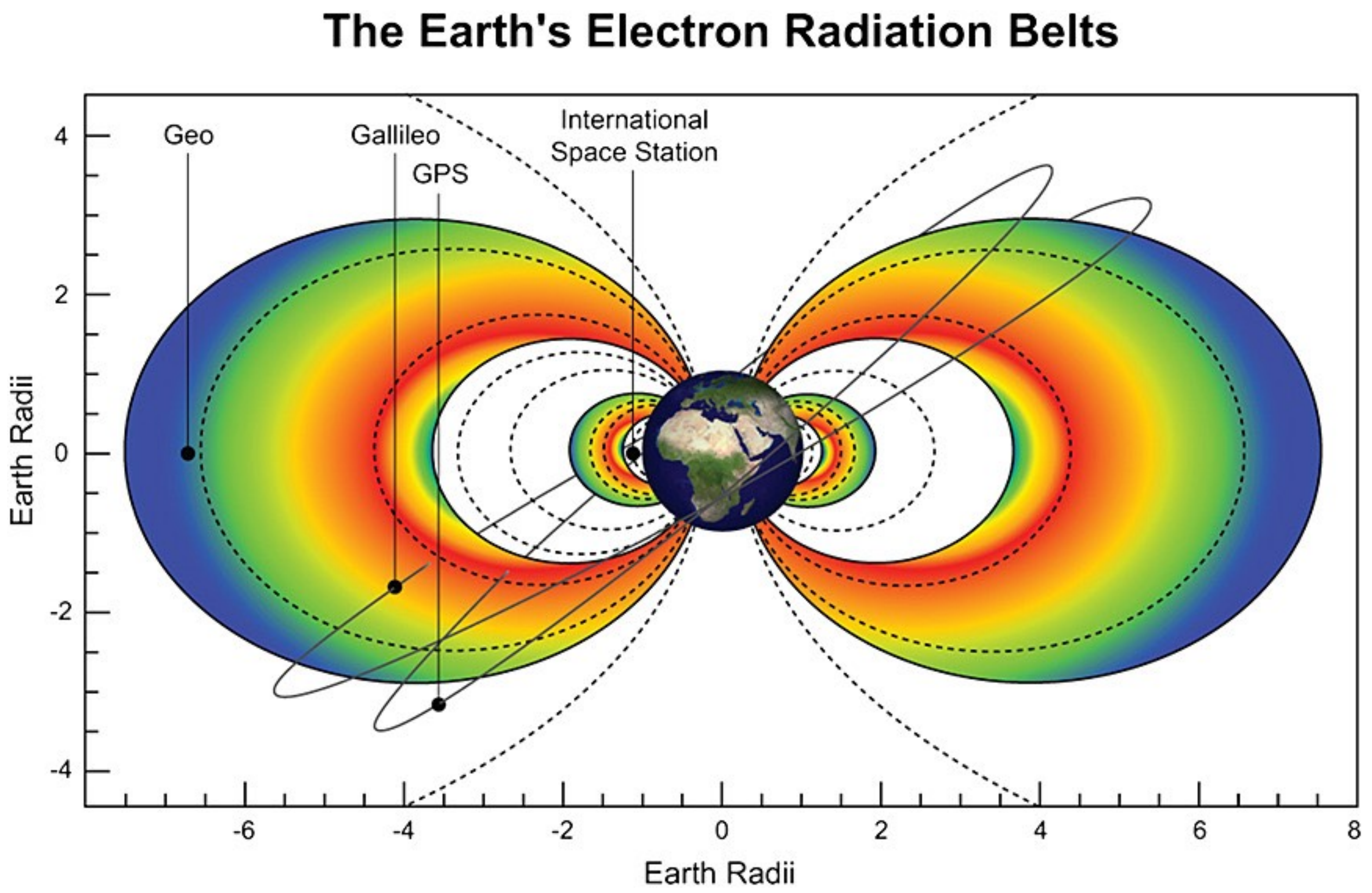
Where your spacecraft is located, changes the environment in consideration and the corresponding space weather concerns.

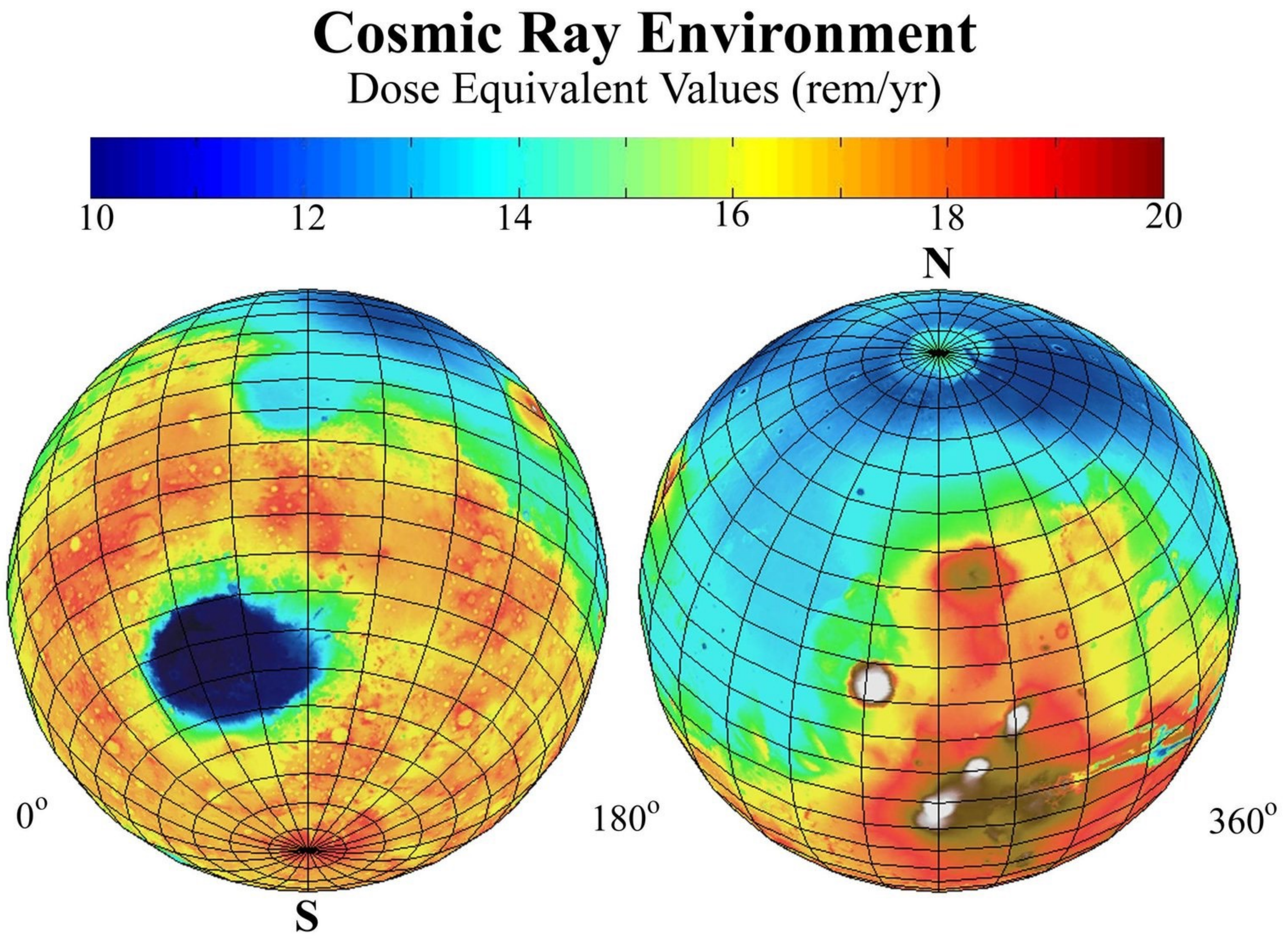
[Space Weather Modeling Framework Simulation Results]

[Tuija Pulkkinen, University of Michigan]

Mapping the Energetic Particles and Ionizing Radiation

How do we identify "avoidable regions"?





[Horne, Space Weather, 2013]

[https://www.jpl.nasa.gov/images/pia03480-estimated-radiation-dosage-on-mars]

Defining the Accumulated Risk

In spacecraft decision-making, we aim to characterize the accumulated risk due to space weather for any given trajectory.

- Methodology
  - Create a "map" of energetic particles, and radiation hazards, through which a spacecraft trajectory is mapped.
  - Such a map can be ready on-board and later updated or scaled using recent observations or forecasts as needed and as available.
    - Flexible to needs, information sources and communication schedules.
  - The accumulated risk can then be calculated for use in autonomous decision-making by calculated the total flux of particles throughout the trajectory over the chosen path and time.

Defining the Accumulated Risk

In spacecraft decision-making, we aim to characterize the accumulated risk due to space weather for any given trajectory.

- Version 1:
  - Spherical shell map of propagated SEPs and radiation at a given atmospheric height using the NAIRAS model.
    - Use: Extrapolate radially inward or outward for a given trajectory.
    - Assume evolution of the mapping is minimal over the trajectory of the spacecraft.
    - Designed for radiation doses for flights rather than spacecraft.

Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS)

- Our Decapodes approach will be verified using results from NAIRAS
- NAIRAS inputs: GOES and neutron monitor count rates, vertical geomagnetic cutoff rigidity, and atmospheric depth
- NAIRAS outputs: Equivalent dose rate, integral LET (Linear Energy Transfer) flux, and other flux values for varying slab levels
- NAIRAS uses a combination of:
  1. Fitting input GOES proton and alpha differential non-flux spectral data to constants for the SEP transport differential equation
  2. CISM-Dartmouth to get dynamic values for the geomagnetic cutoff rigidity
  3. HZETRN for the transport of SEP particles through the atmosphere
- Using these results, you can find regions of avoidance for spacecraft near or within the Earth's atmosphere
- The accompanying figure shows how you could map the dangerous areas for spacecraft to occupy in real-time
- Additionally, trajectories can be put in for altitudes greater than 40 kilometers and get dosage rates.

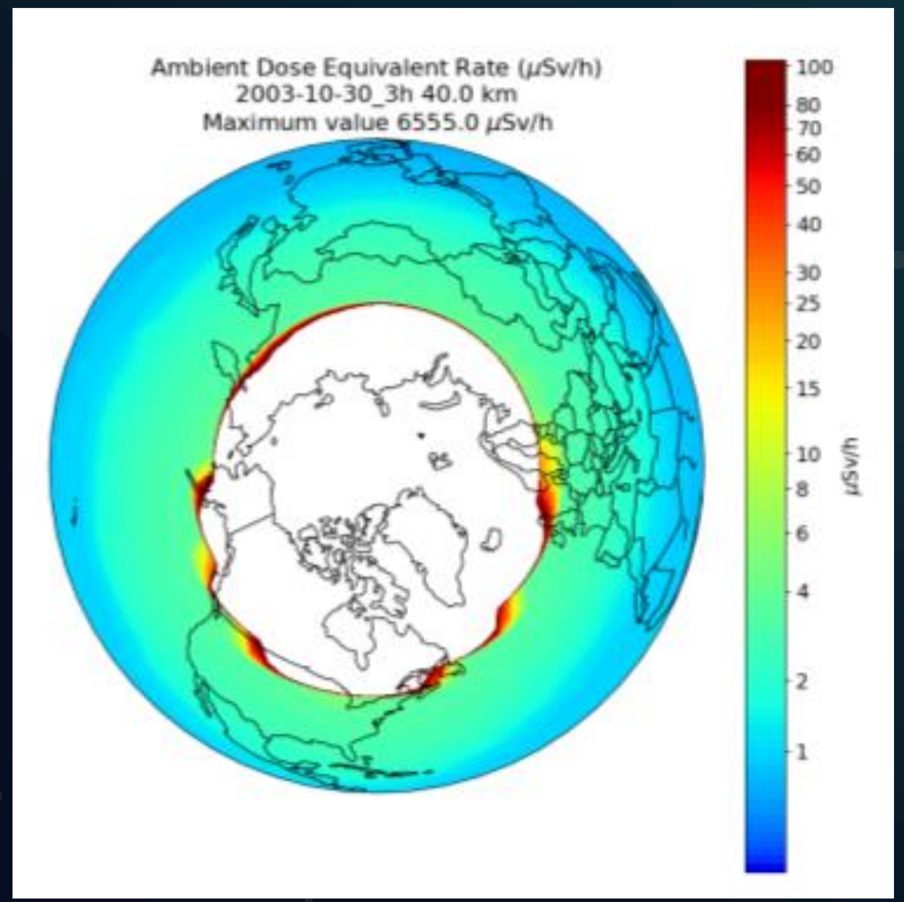


Figure: Estimated dose rate during 2003 Halloween Storms at 40km above the surface using NAIRAS. In our model, we plan to expand capability from only 40km (2)

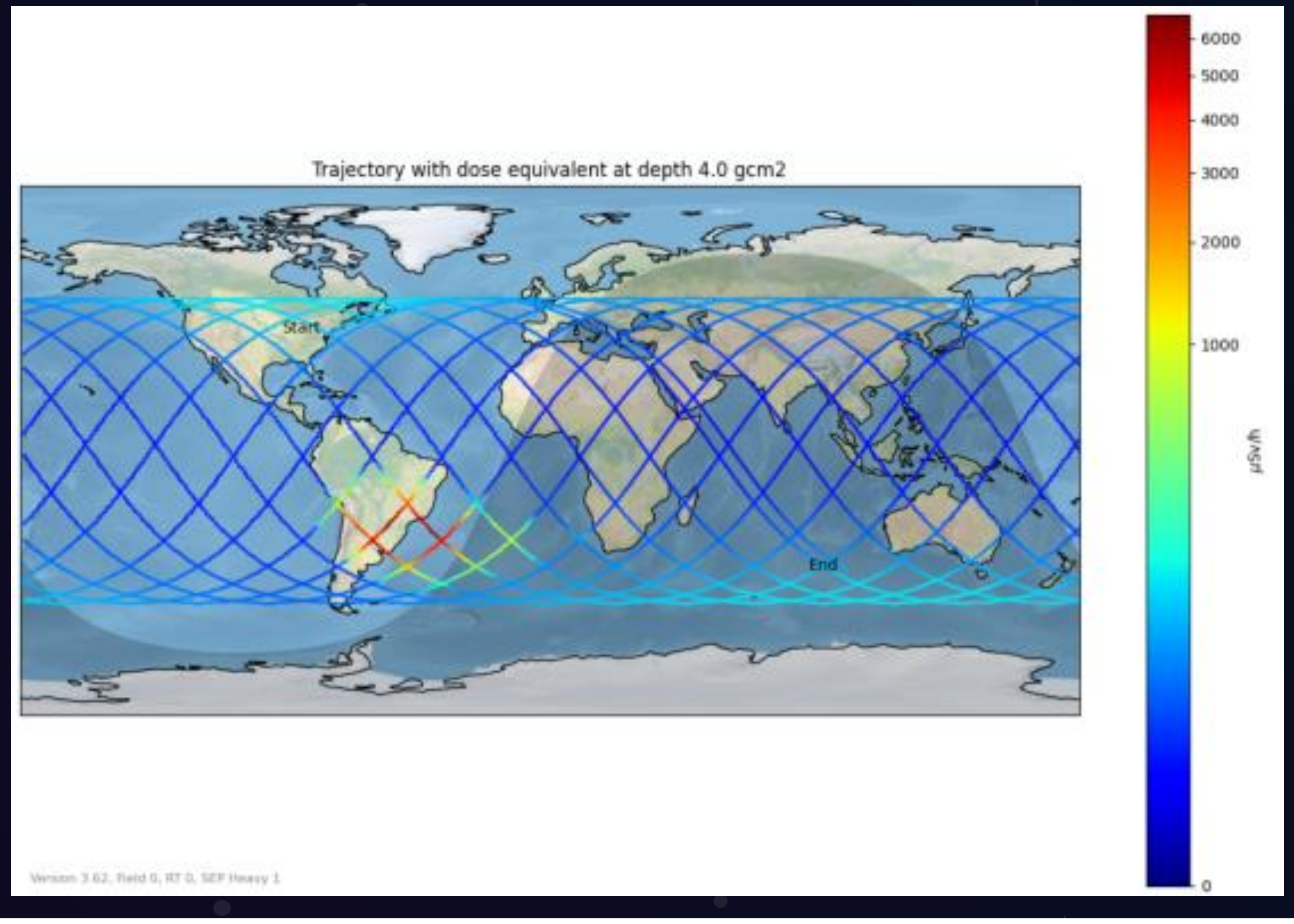


Figure: Dose equivalent for a given trajectory path that averages at an altitude of 424 km (3)

References:
(2) NASA. (2023, November 11). *Visualization of 1D data at CCMC:*. NASA. https://ccmc.gsfc.nasa.gov/results/viewrun.php?domain=IT&runnumber=Daniel_Phoenix_110123_IT_1
(3) NASA. (n.d.). *Visualization of 1D data at CCMC:*. Run Information. https://ccmc.gsfc.nasa.gov/results/viewrun.php?domain=IT&runnumber=Richard_Nederlander_050824_IT_10

Defining the Accumulated Risk

In spacecraft decision-making, we aim to characterize the accumulated risk due to space weather for any given trajectory.

- Version 1:
  - Spherical shell map of propagated SEPs and radiation at a given atmospheric height using the NAIRAS model.
    - Use: Extrapolate radially inward or outward for a given trajectory.
    - Assume evolution of the mapping is minimal over the trajectory of the spacecraft.
    - Designed for radiation doses for flights rather than spacecraft.
  - Continuing onto Version 2 for improved results optimized for space environment outputs.

Defining the Accumulated Risk

In spacecraft decision-making, we aim to characterize the accumulated risk due to space weather for any given trajectory.

- Version 2:
  - 3D map of trapped energetic particles and ionizing radiation for a typical geomagnetic storm using the IRENE model.
    - Use: Calculate the total the particle flux that the trajectory crosses through.
    - Current simplifying assumption: The evolution of the mapping is minimal over the trajectory of the spacecraft.
      - True for some particle populations, not true for others.
    - Define the "avoidable regions" based on a typical event, and weight the risk if initial incoming observations indicate actual risk is higher or lower than typical.

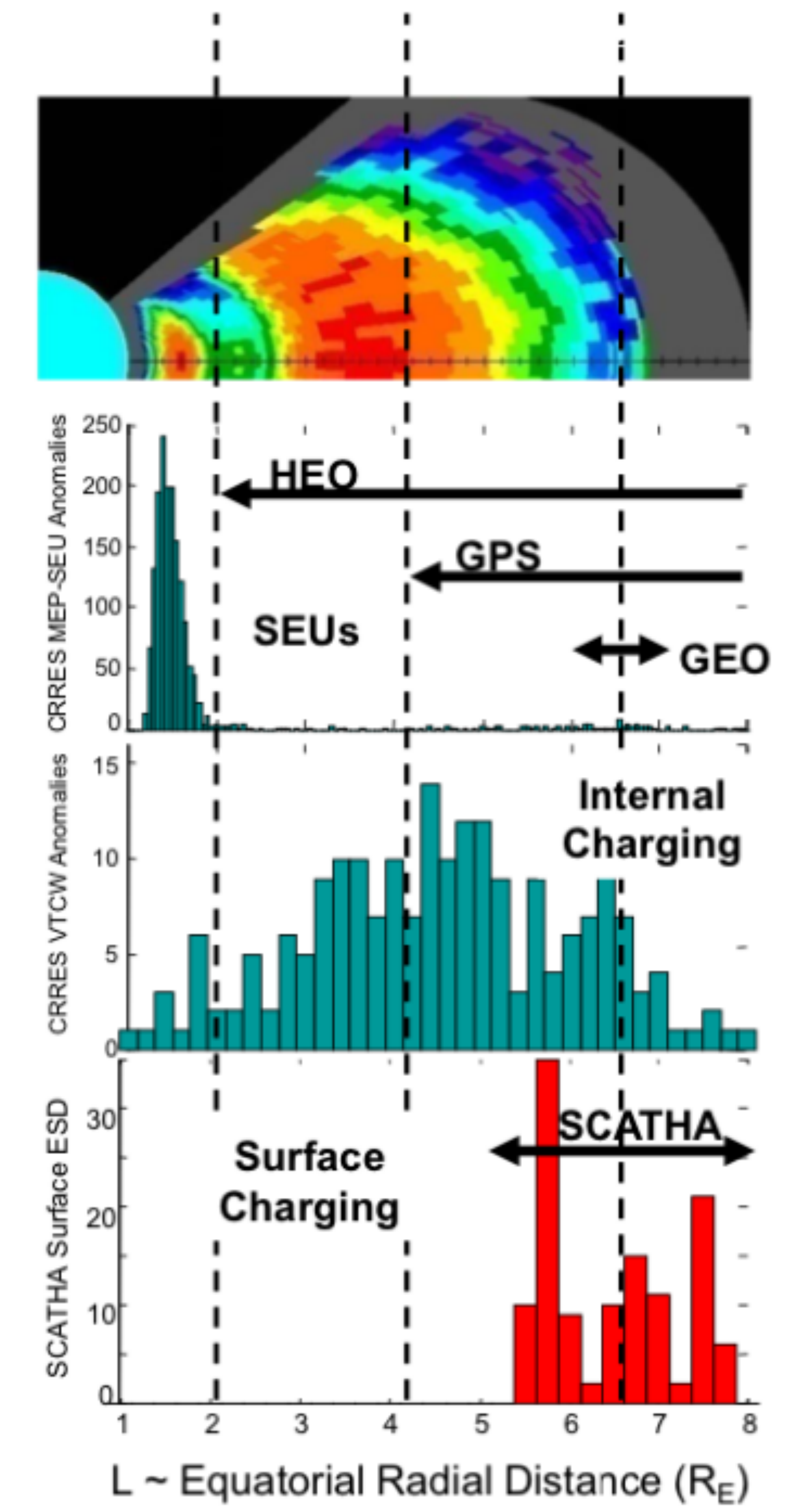
IRENE (International Radiation Environment Near Earth) AE9/AP9/SPM Radiation Environment Model

- Different L-shell distances yield different dominant radiation or particle populations.
- IRENE couples several models of particle flux and radiation dose.
- IRENE was actually initially developed at AFRL in collaboration with LANL and MIT.

Priority	Species	Energy	Location	Sample Period	Effects
1	Protons	>10 MeV (> 80 MeV)	LEO & MEO	Mission	Dose, SEE, DD, nuclear activation
2	Electrons	> 1 MeV	LEO, MEO & GEO	5 min, 1 hr, 1 day, 1 week, & mission	Dose, internal charging
3	Plasma	30 eV – 100 keV (30 eV – 5 keV)	LEO, MEO & GEO	5 min, 1 hr, 1 day, 1 week, & mission	Surface charging & dose
4	Electrons	100 keV – 1 MeV	MEO & GEO	5 min, 1 hr, 1 day, 1 week, & mission	Internal charging, dose
5	Protons	1 MeV – 10 MeV (5 – 10 MeV)	LEO, MEO & GEO	Mission	Dose (e.g. solar cells)

(indicates especially desired or deficient region of current models)

[https://www.vdl.afrl.af.mil/programs/ae9ap9/files/package/Ae9_Ap9_SPM_Users_Guide.pdf]

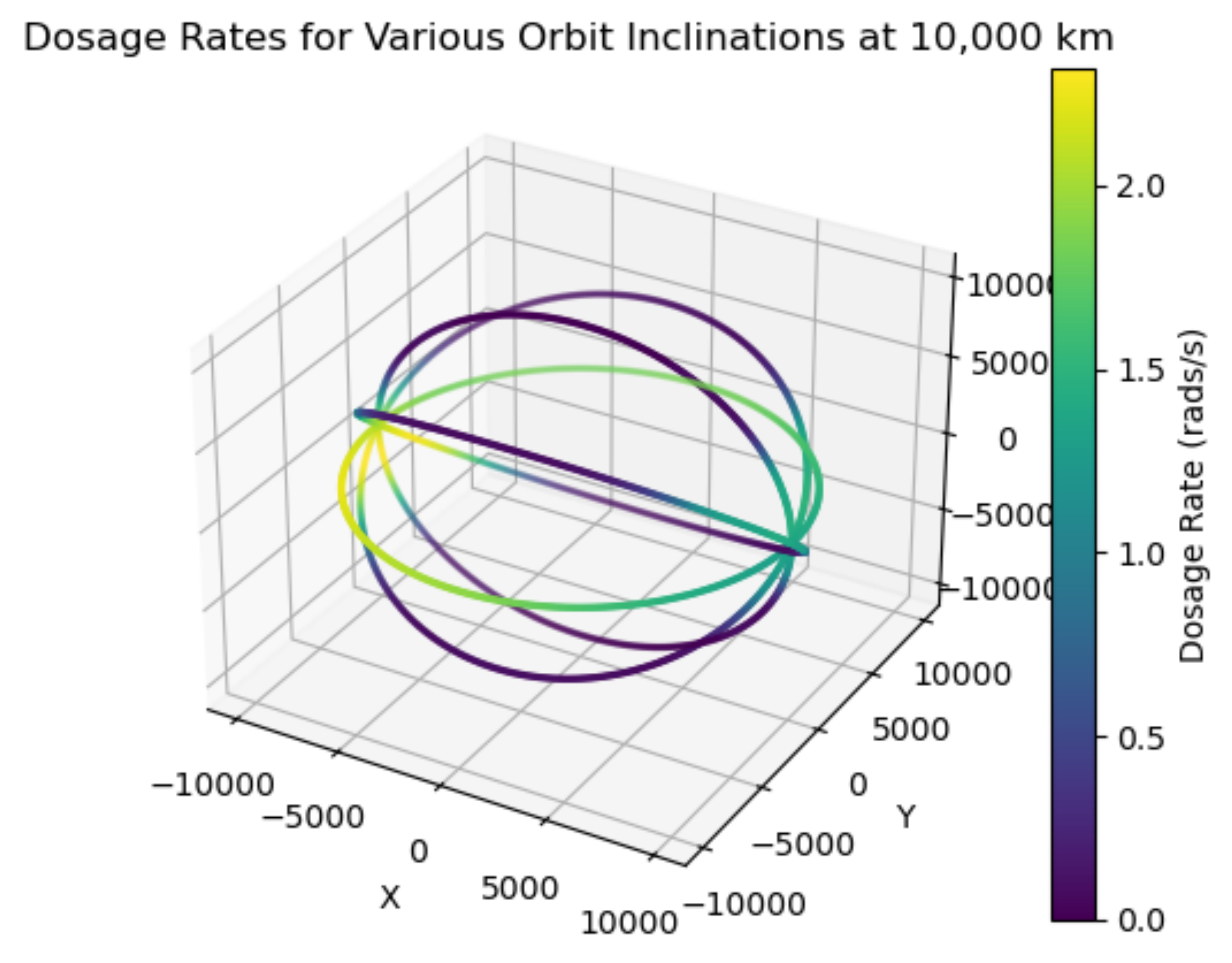


[Ginet et al. 2013] [lws-set.gsfc.nasa.gov]

IRENE: AP9/AE9/SPM

Model of Trapped Particle Transport in the upper atmosphere and the near-Earth space environment to predict ionizing radiation dose and energetic particle flux.

- Current:
  - Creating maps of predicted ionizing radiation and energetic particle flux



Example Accumulated Risk along Trajectories at 10,000 km

[van den Berg, Space Science Review, 2020]

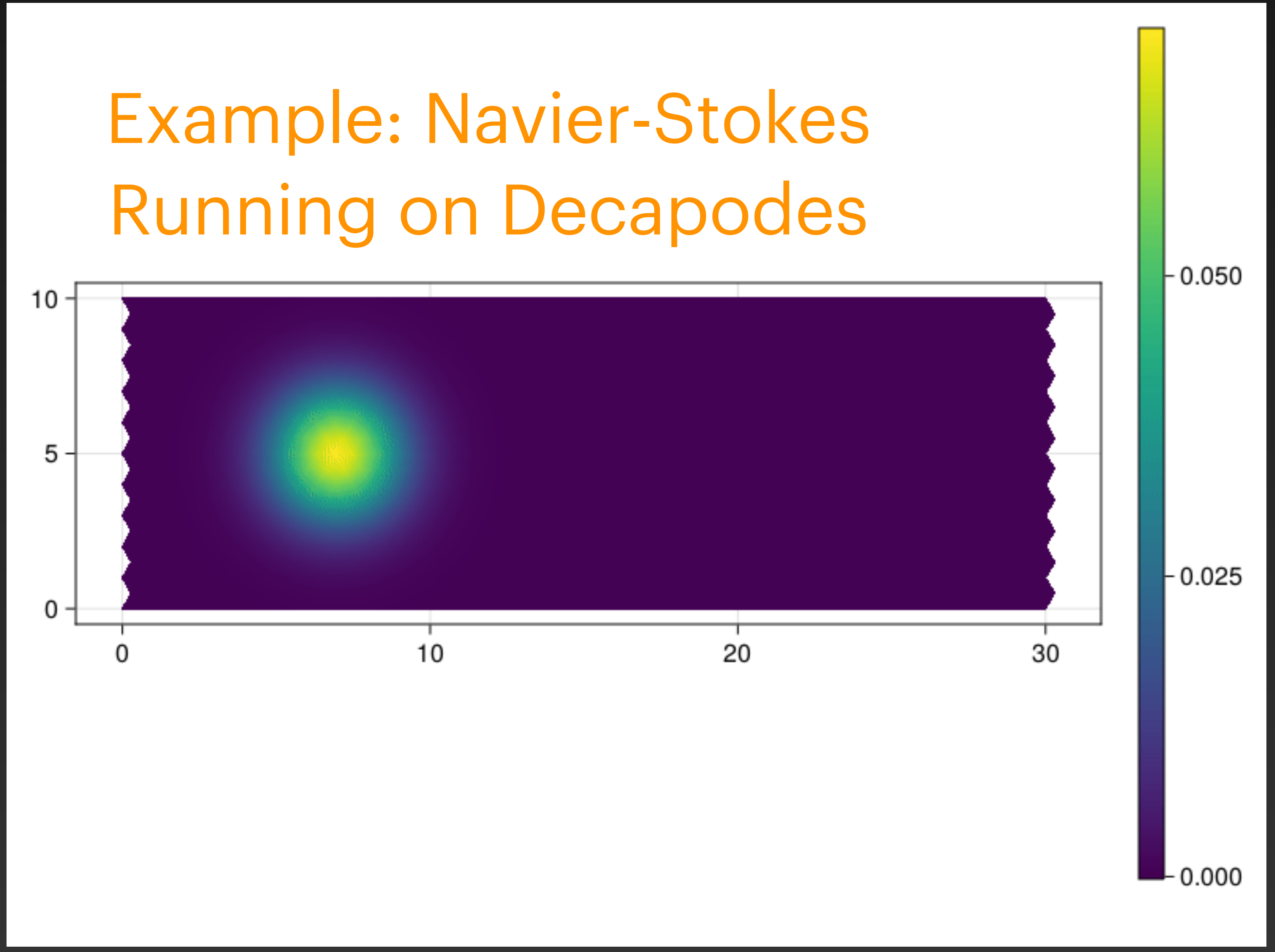
Defining the Accumulated Risk

In spacecraft decision-making, we aim to characterize the accumulated risk due to space weather for any given trajectory.

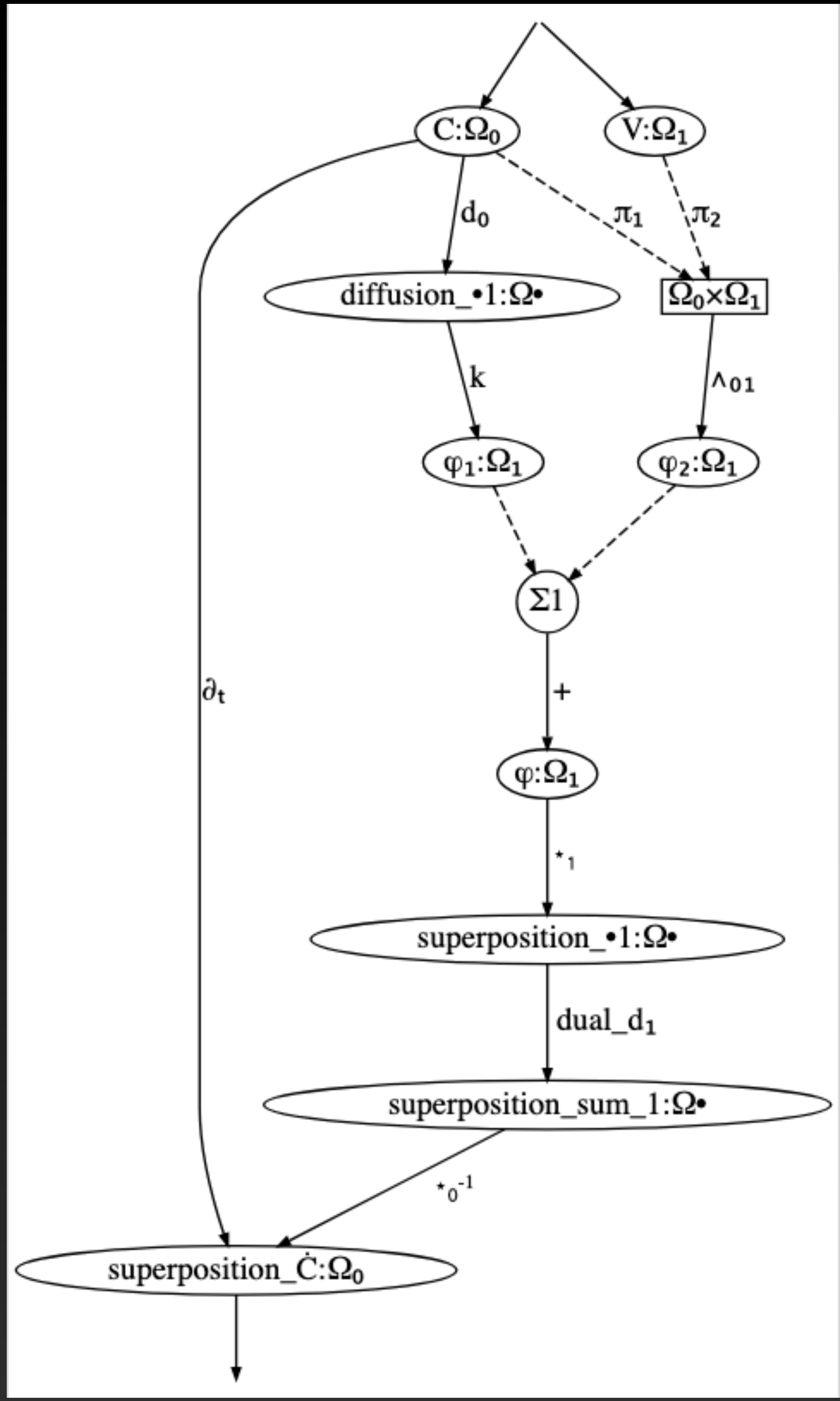
- Potential Future Developments:
  - Improve input conditions to correspond specifically to the current event forecast.
    - Couple HMF SEP modeling of inner HMF transport to create potential accumulated risk maps.
  - Compare accumulated risk maps from different available models evaluating effectiveness for use in autonomous decision-making.
    - Test implementation timescales for use in more realistic autonomous decision-making.
  - Reach out to IRENE team about model use, potential development and potential collaborations.

SEP Transport Modeling

- In a collaboration with Dr. James Fairbanks and Luke Morris (UF CISE) using DECAPODES, we're developing our own SEP transport model. Designed to be implemented in 3D space on the Sun's heliospheric magnetic field to model SEPs and electrons arriving at Earth.



- DECAPODES uses Discrete Exterior Calculus, which uses k-forms to evaluate differential equations and is therefore flexible and quickly adaptable to new geometries and new applications.

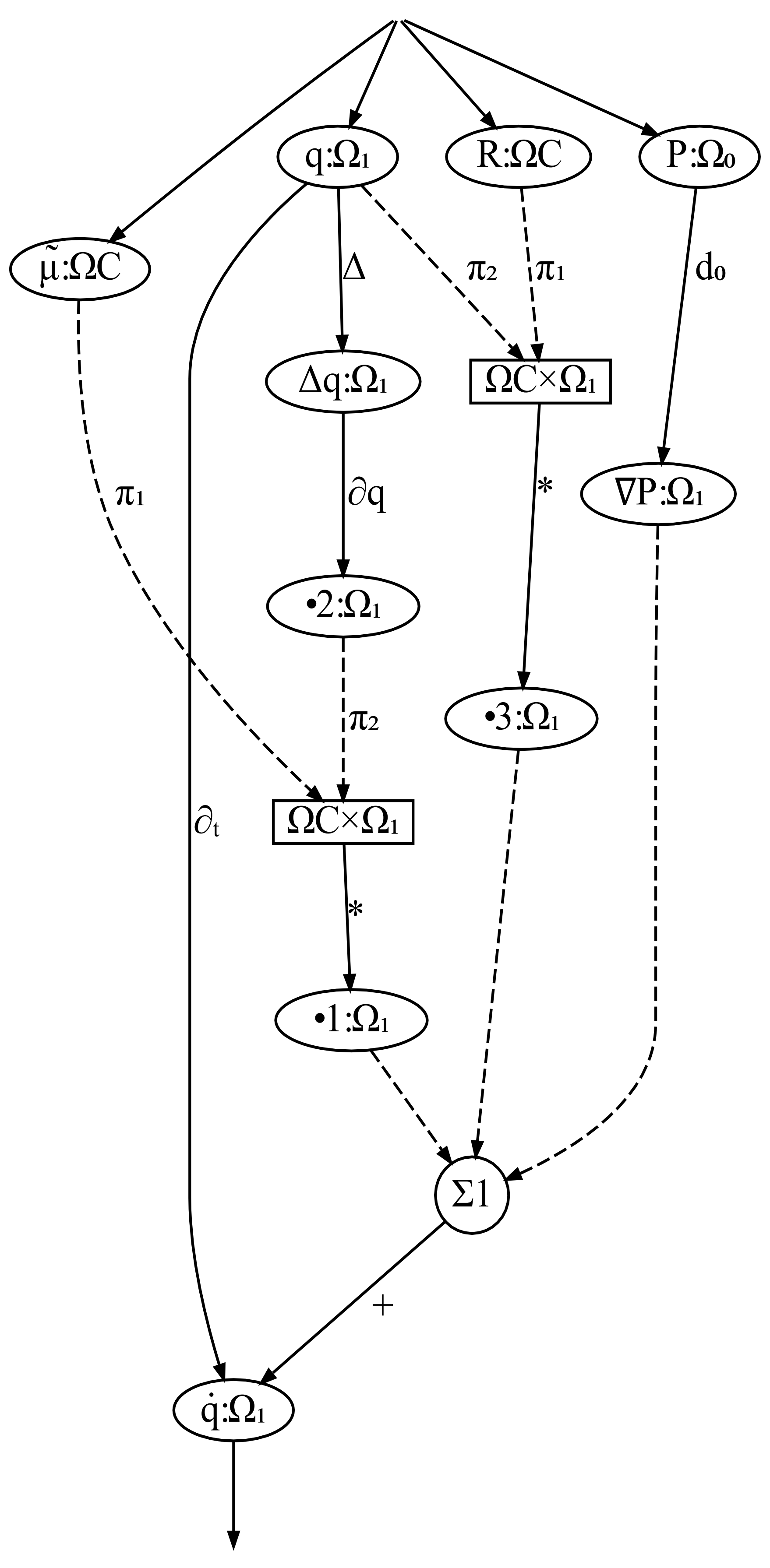


[van den Berg, Space Science Review, 2020]

Discrete Exterior Calculus Applied to Partial and Ordinary Differential Equations (Decapodes)

- ➢ Just like how continuous calculus has linear algebra, discrete exterior calculus has exterior algebra
- ➢ Exterior algebra and calculus are tailored to work on discrete structures such as meshes or graphs
- ➢ Linear algebra is made up of vectors that describe any unit in dimensional space
- ➢ Exterior algebra is made up of volumes called k-vectors that can also describe units in dimensional space
- ➢ The “k” represents the dimension that the vector represents. For example, a 1-vector would denote a length, a 2-vector would denote an area, and a 3-vector is a volume
- ➢ This pattern keeps going into N-dimensional space
- ➢ In linear and exterior algebra, a vector has both direction and magnitude
- ➢ Exterior calculus has distinct operations
- ➢ Each operation can be expressed in linear calculus

Figure: Decapode graphical paradigm of Poiseuille flow. This paradigm shows the discrete exterior calculus interactions between processes that results in Poiseuille flow. This includes the discrete exterior derivative (d), the Hodge star operator ($*$), the discrete codifferential (∂), and the discrete Laplacian (Δ). https://algebraicjulia.github.io/Decapodes.jl/dev/poiseuille/ (1)



References:
(1) Morris, L. (n.d.-c). *Pipe flow · decapodes.jl*. Pipe Flow · Decapodes.jl. https://algebraicjulia.github.io/Decapodes.jl/dev/poiseuille/

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UNIVERSITY of FLORIDA

SEP Transport

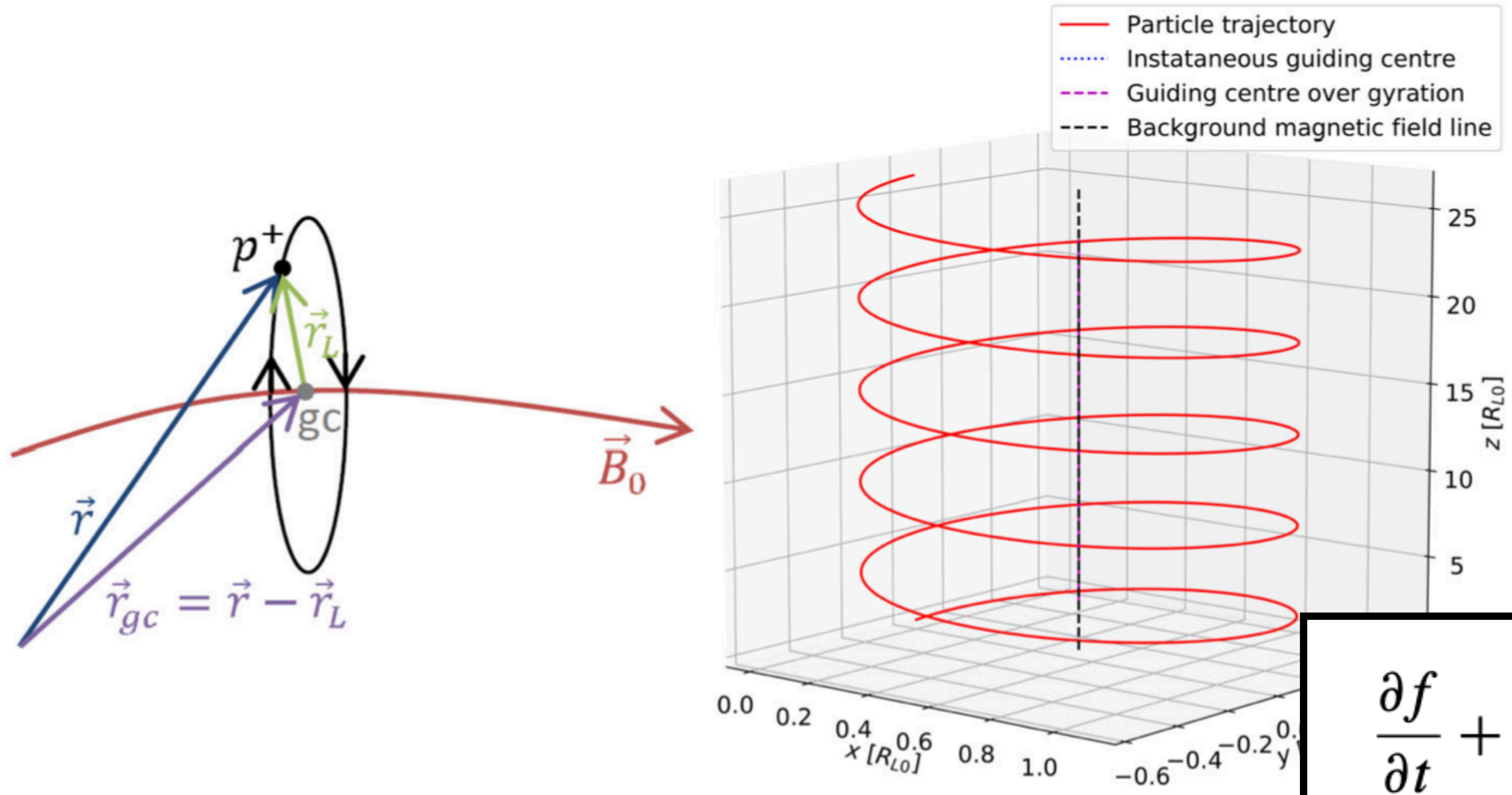


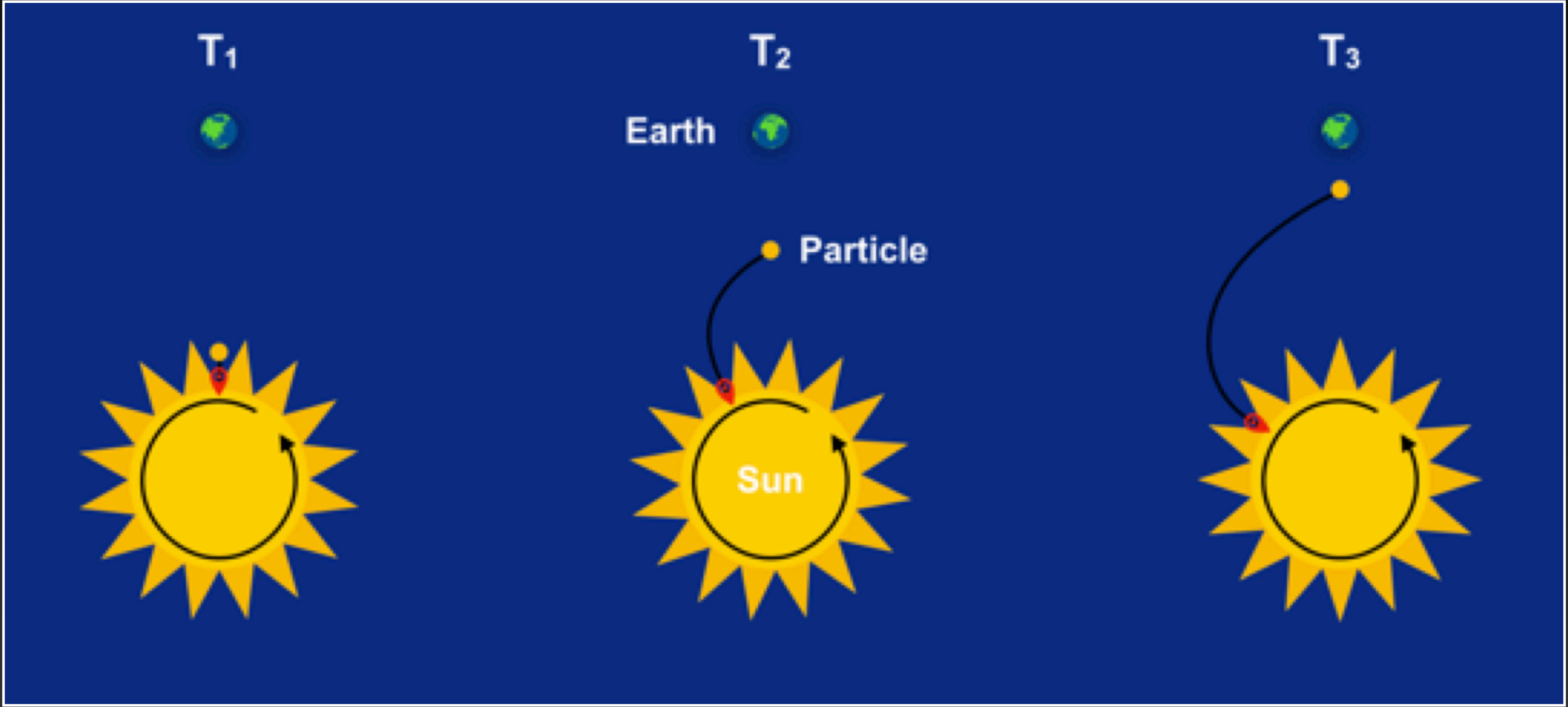
Fig. 1 *Left:* Illustration of a proton's position (blue vector), guiding centre (purple vector), and directional Larmor radius (green vector) during its gyration (black circle, with arrows indicating the direction of rotation) around the background magnetic field line (red vector). This figure was adapted from Northrop (1961). *Right:* Simulation of a proton in a constant and uniform magnetic field performed with a fourth-order Runge-Kutta scheme. The trajectories of the particle (solid red) and its guiding centre (dotted blue: Eq. (7); dashed purple: running average of the particle's position over a gyration) are shown, together with a single background magnetic field line (dashed black; coinciding with the guiding centre)

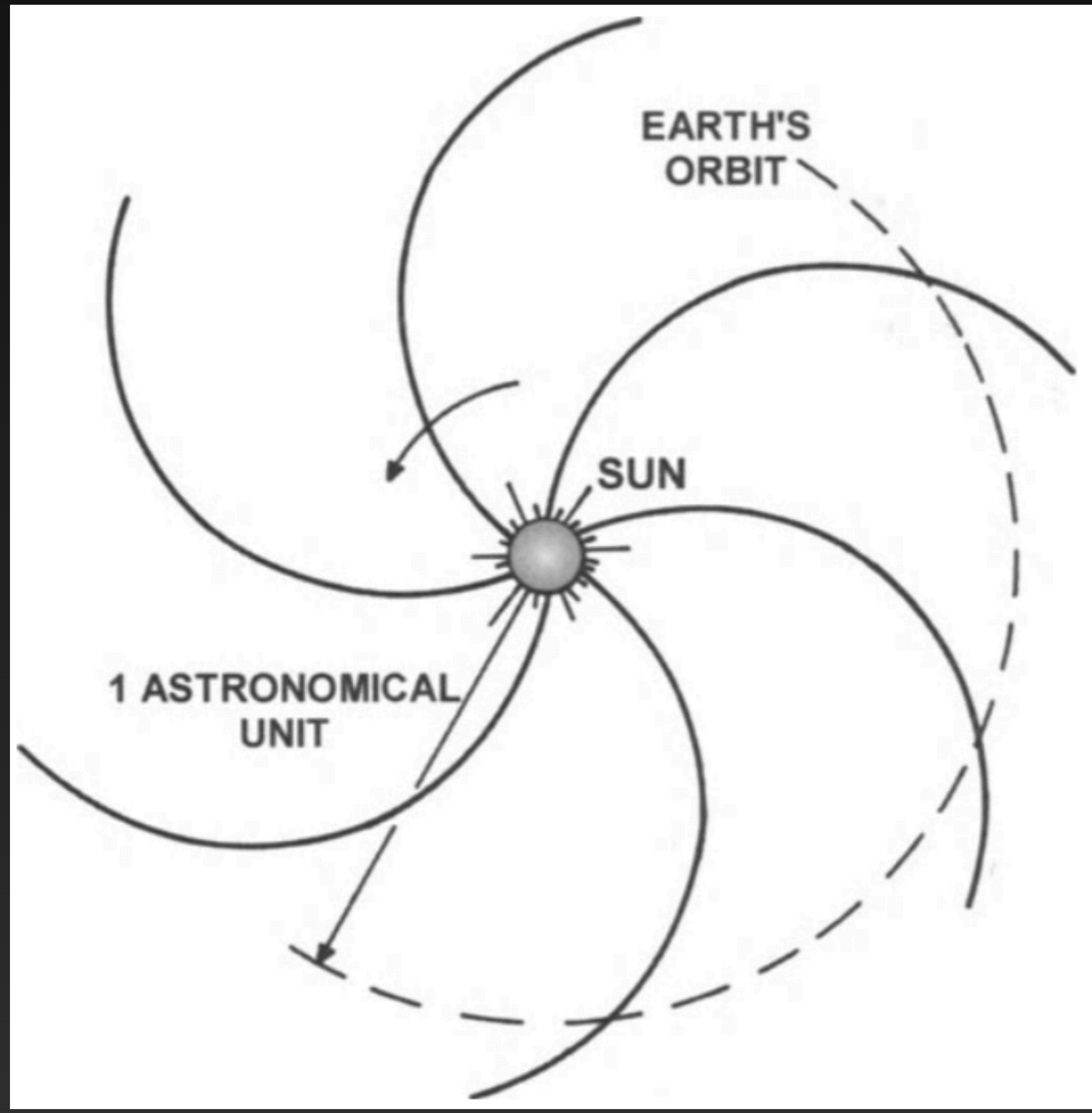
Roelof's 1969 Focused Transport Equation for SEPs

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial s}\left[\mu v f\right] + \frac{\partial}{\partial \mu}\left[\frac{(1-\mu^2)v}{2L(s)} f\right] = \frac{\partial}{\partial \mu}\left[D_{\mu\mu}\frac{\partial f}{\partial \mu}\right],$$

Further Applications of Modeling Development Using Decapodes

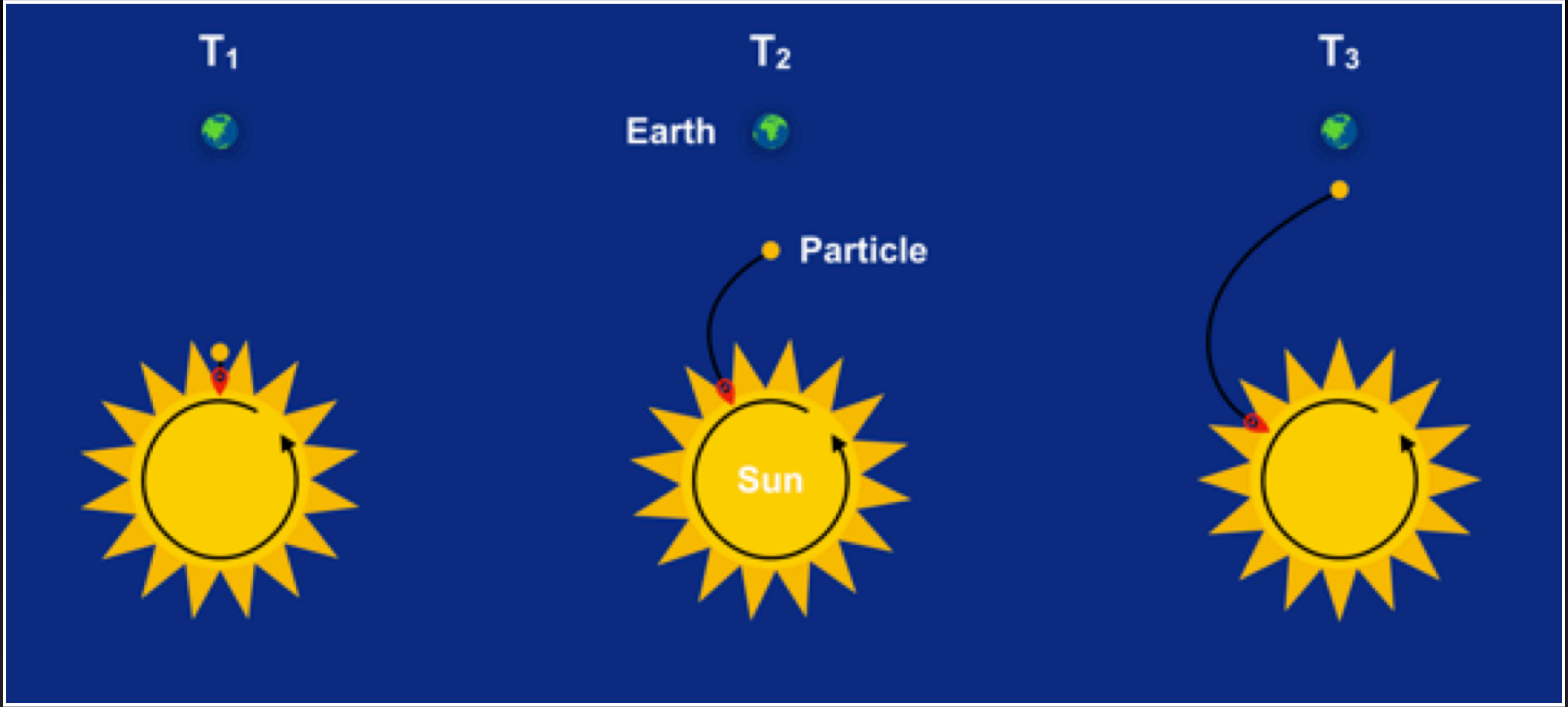
SEPs and CMEs travel along and impact the shape of the Sun's heliospheric magnetic field (HMF). Improving modeling the HMF and teasing out the properties of particle events which are determined during propagation, aid in forecasting the differences between events.



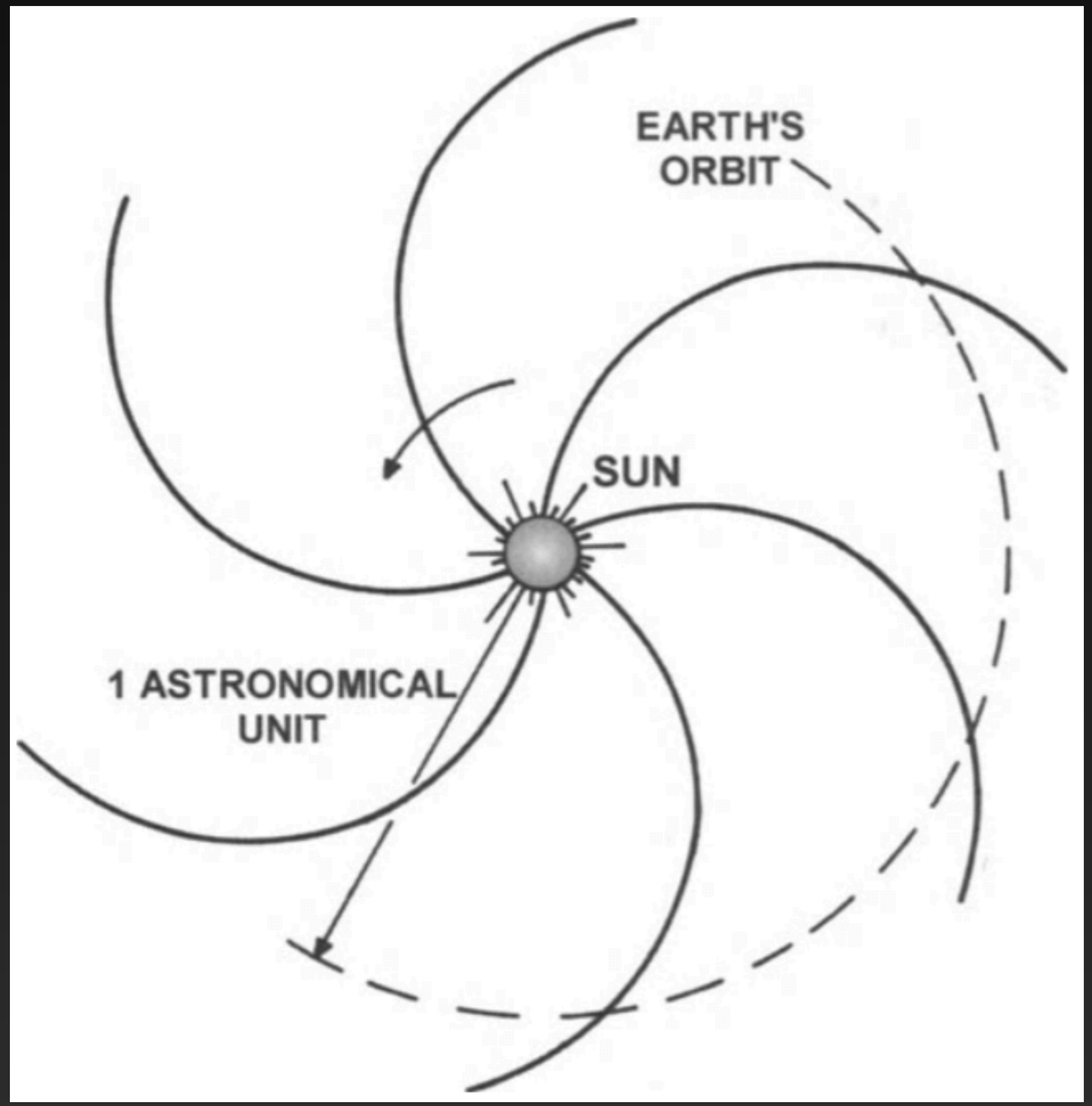


The Parker spiral approximates the shape of the HMF.

Further Applications of Modeling Development Using Decapodes



- Sunlight travels at ~300,000 km/s radially outward from the Sun, reaching Earth after ~8.3 minutes.
- SEPs travel along the HMF and reach Earth on the order of hours.
- Solar wind particles travel 400-900 km/s, reaching Earth in 3-5 days.
- Though the solar wind travels radially outward from the Sun, the path of solar wind particles and the subsequent HMF are curved like a sprinkler.



The Parker spiral approximates the shape of the HMF.

Space Weather Impact Mitigation

Thank You!

Any Questions?

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