European Commission

Horizon 2020
European Union funding
for Research & Innovation

Solar energetic particle analysis platform for the inner heliosphere

A Research and Innovation Action

Rami Vainio for the SERPENTINE Team

2023-06-27

UNIVERSITY OF TURKU

UNIVERSITÉ TOULOUSE III PAUL SABATIER

C A U
Kiel University
Christian-Albrechts-Universität zu Kiel

Imperial College London

HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

Universidad de Alcalá

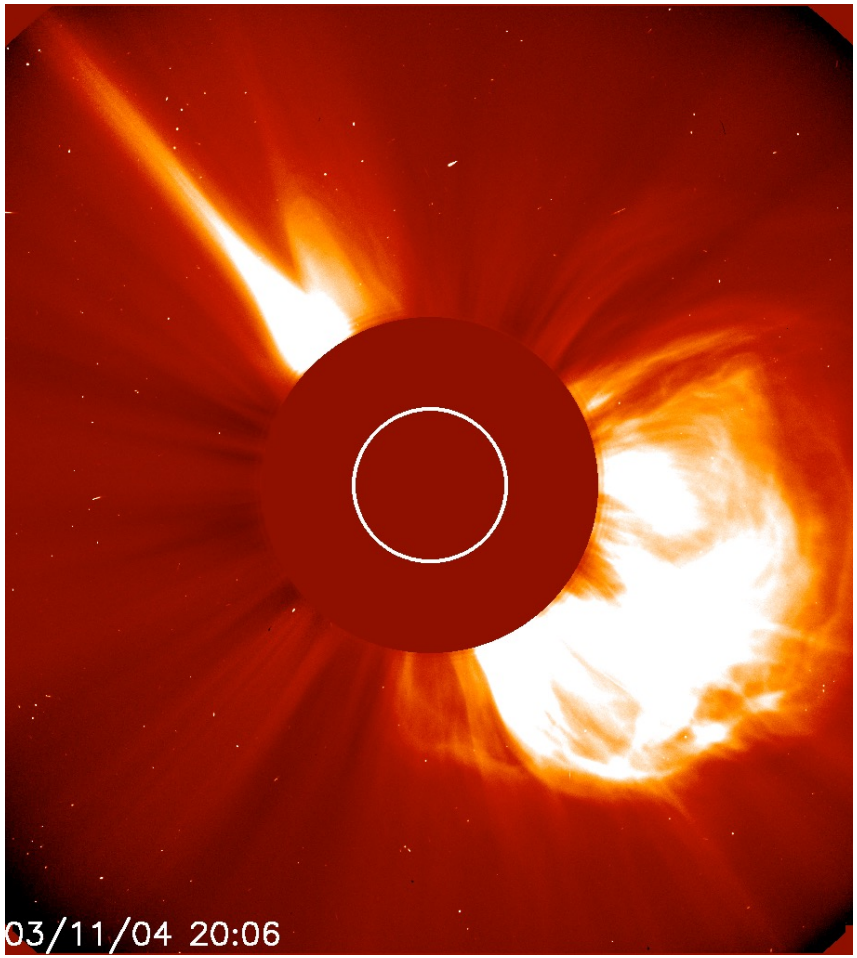
SERPENTINE Consortium

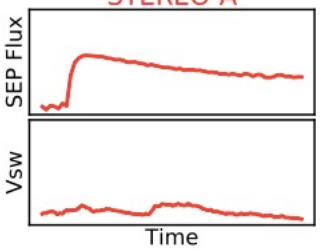
1. University of Turku (coordinator), FI (UTU)
2. University of Kiel, DE (CAU)
3. Paul Sabatier University, Toulouse, FR (UPS)
   - IRAP as a connected third party
4. Imperial College London, UK (Imperial)
5. University of Helsinki, FI (UH)
6. University of Alcala, ES (UAH)

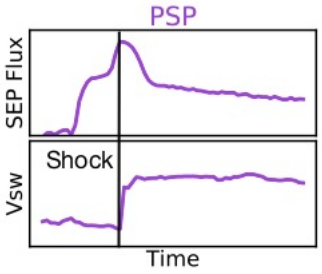
Project idea

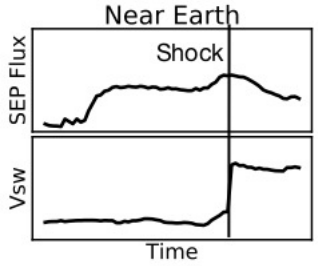
SERPENTINE

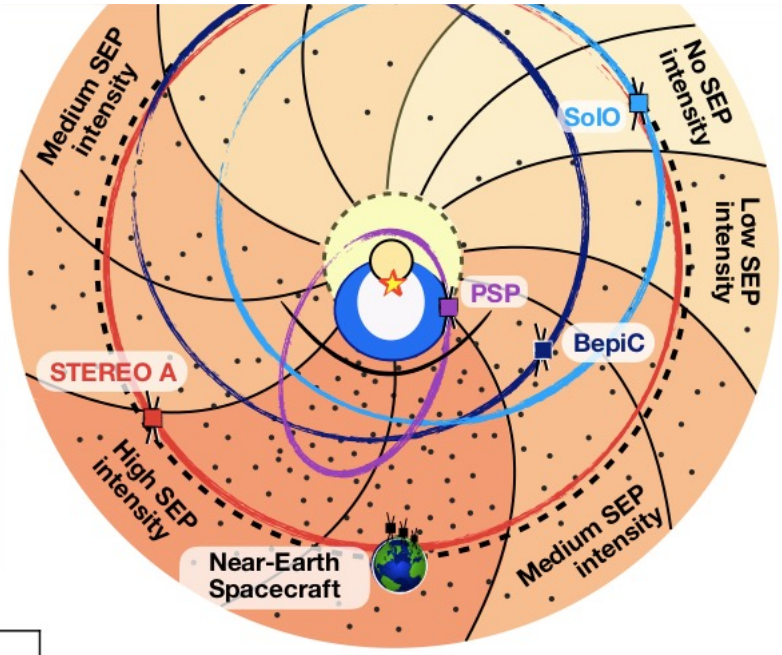
- Studies very high energy particles emitted from the Sun during solar eruptions
  - Particle acceleration processes
  - Particle transport processes
- Provides the community with data analysis tools
- Utilizes observations from recently launched space missions to the inner heliosphere
  - Parker Solar Probe
  - Solar Orbiter
  - BepiColombo

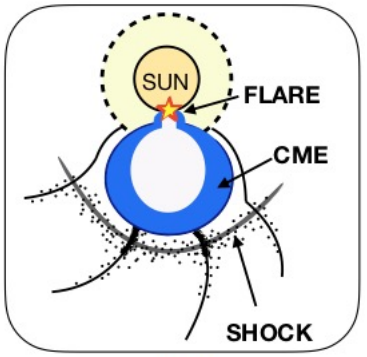


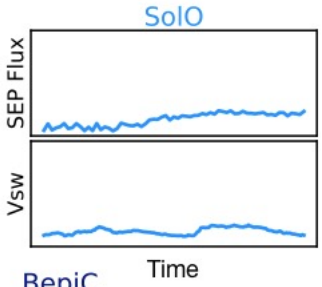

STEREO-A
SEP Flux
Vsw
Time

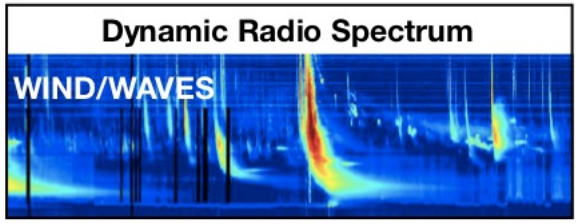

PSP
SEP Flux
Shock
Vsw
Time

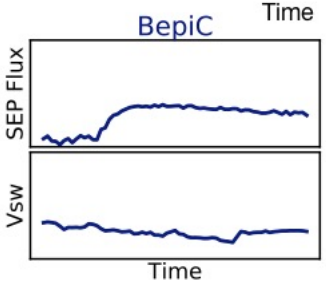

Near Earth
SEP Flux
Shock
Vsw
Time

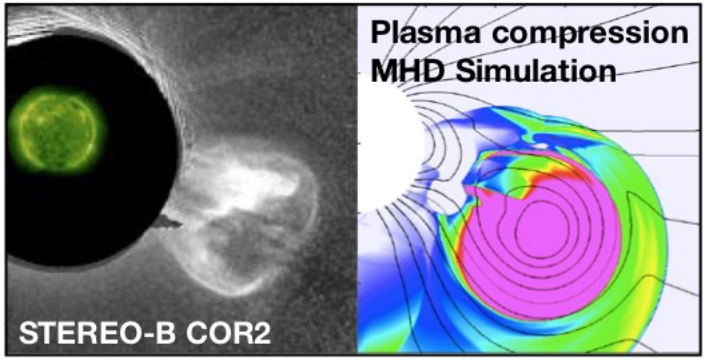

Medium SEP intensity
No SEP intensity
Low SEP intensity
SolO
PSP
BepiC
STEREO A
High SEP intensity
Near-Earth Spacecraft
Medium SEP intensity

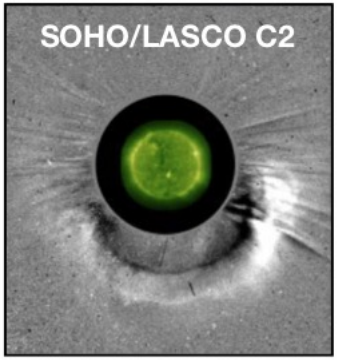

SUN
FLARE
CME
SHOCK

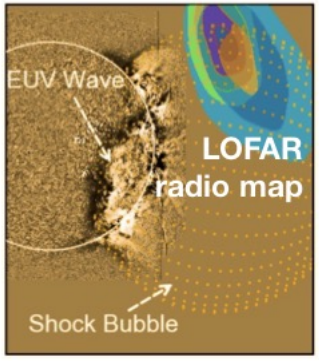

SolO
SEP Flux
Vsw
Time


Dynamic Radio Spectrum
WIND/WAVES

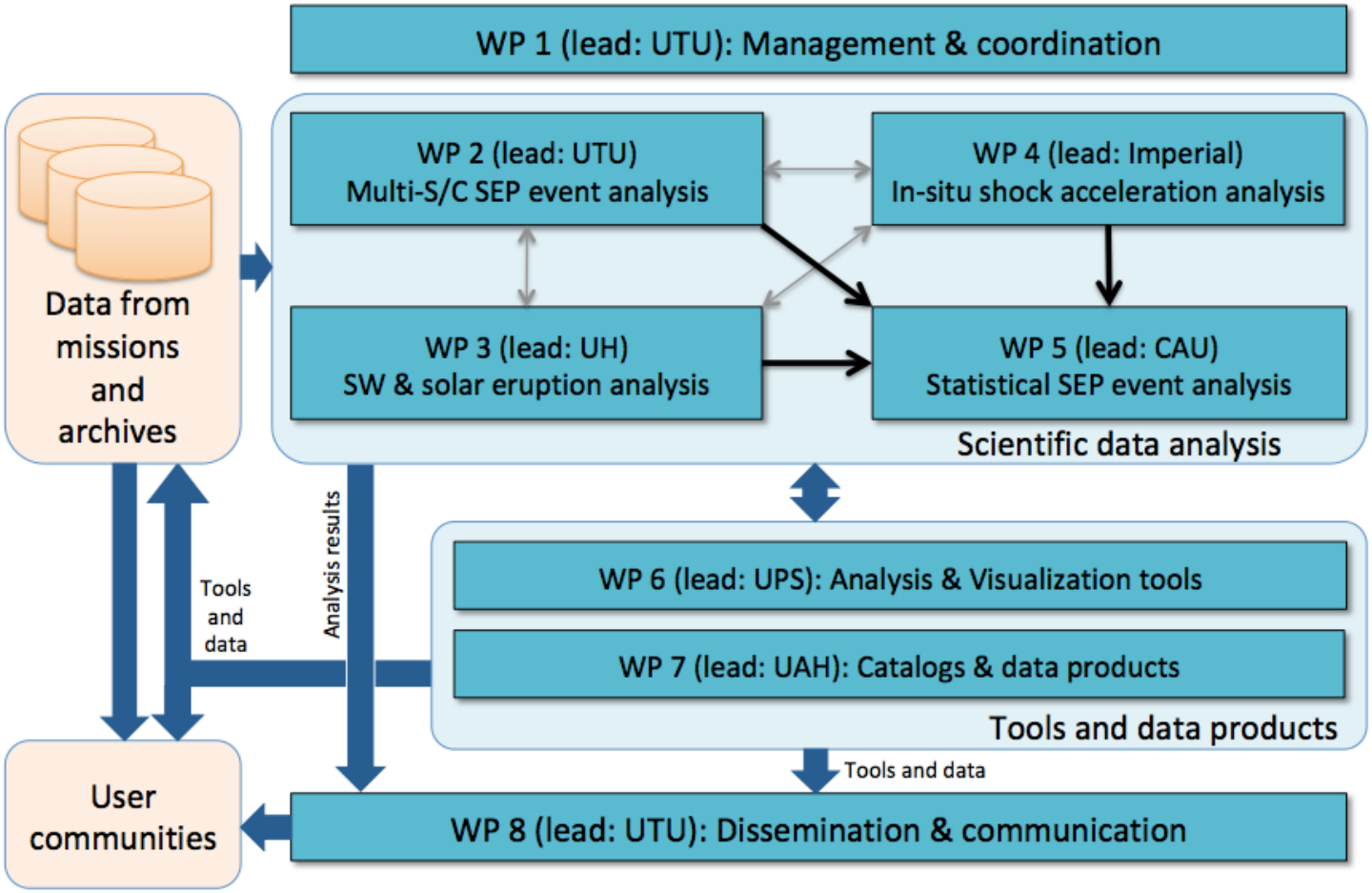

BepiC
SEP Flux
Vsw
Time


Plasma compression
MHD Simulation
STEREO-B COR2

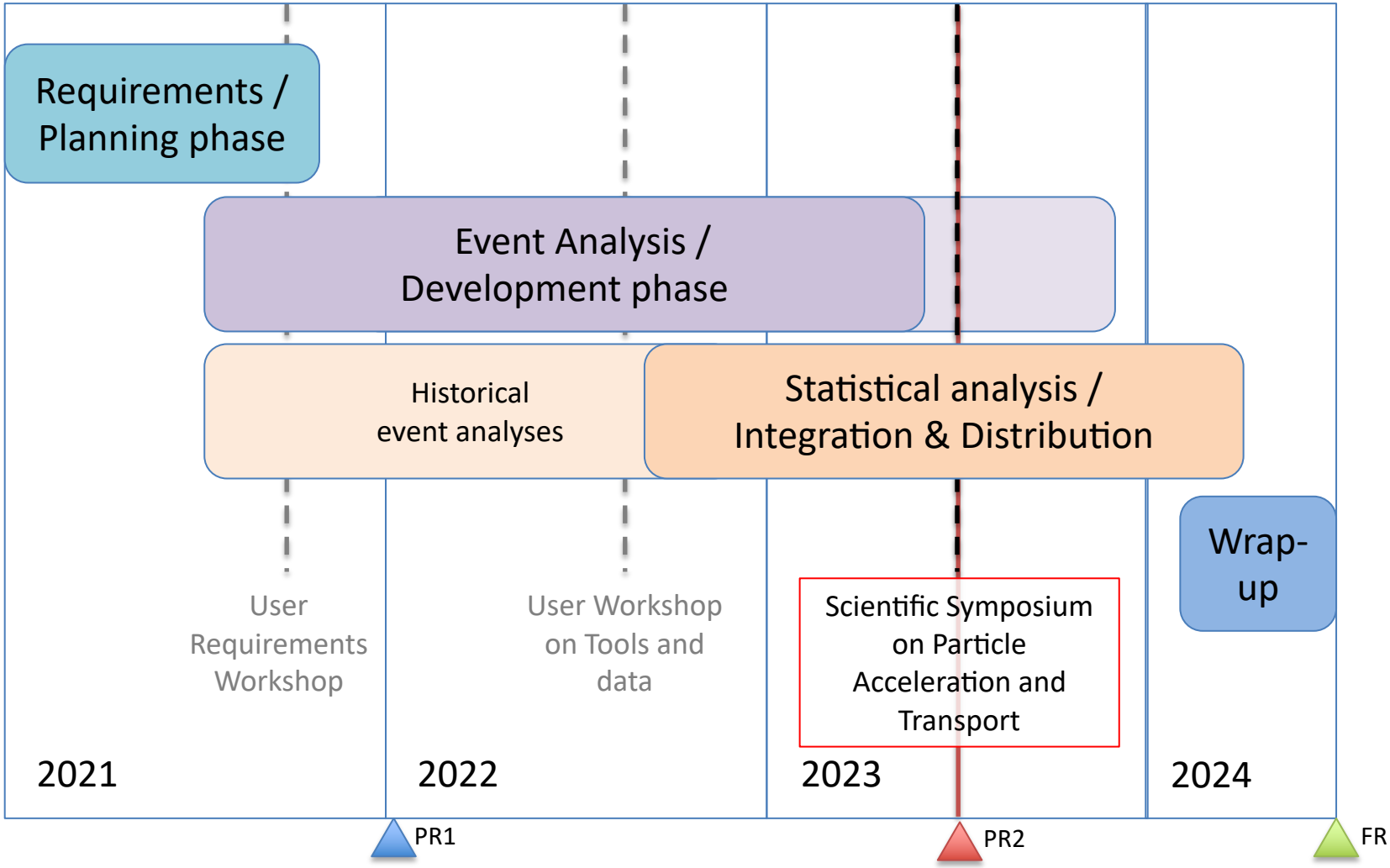

SOHO/LASCO C2


EUV Wave
LOFAR
radio map
Shock Bubble

Work Plan


WP 1 (lead: UTU): Management & coordination
WP 2 (lead: UTU)
Multi-S/C SEP event analysis
WP 4 (lead: Imperial)
In-situ shock acceleration analysis
WP 3 (lead: UH)
SW & solar eruption analysis
WP 5 (lead: CAU)
Statistical SEP event analysis
Scientific data analysis
Data from missions and archives
Tools and data
Analysis results
WP 6 (lead: UPS): Analysis & Visualization tools
WP 7 (lead: UAH): Catalogs & data products
Tools and data products
Tools and data
User communities
WP 8 (lead: UTU): Dissemination & communication

Overall schedule 01/2021—06/2024



Science questions

Primary objective: obtain answers to the following science questions:

Q1: What are the primary causes for widespread SEP events observed in the heliosphere?

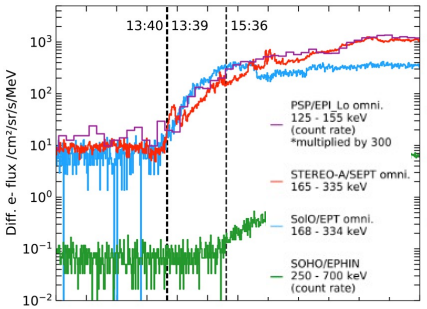
Q2: What are the shock acceleration mechanisms responsible for accelerating ions from thermal/suprathermal energies to near-relativistic energies in the corona and in the interplanetary medium?

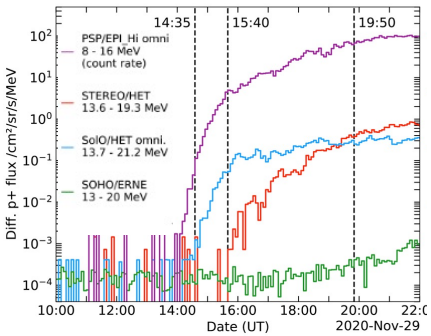
Q3: What is the role of shocks in electron acceleration in large gradual and widespread events? How does it relate to ion acceleration and what is its importance relative to flare acceleration?

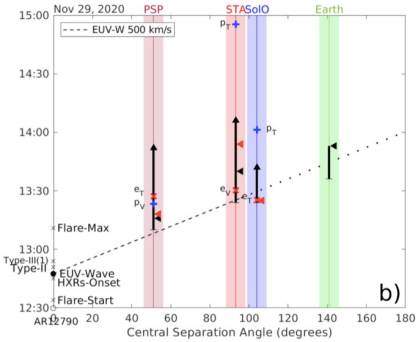
Q1: primary causes of widespread events

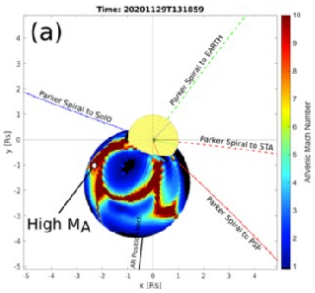
- *Kollhoff et al (2021, A&A) and Kouloumvakos et al (2022, A&A):*
  - Multi-S/C analysis of the first widespread SEP event of SC 25
  - Data supports the key role of the shock as the source of particles
  - Particle fluxes in the most remote observer (Earth) due to diffusion
- *Dresing et al (2023, A&A)*:
  - Multi-S/C analysis of the second widespread event of SC 25
  - Electron release times consistent with shock expansion to connected field line, protons delayed
  - Consistent with multiple sources as one cause of widespread events

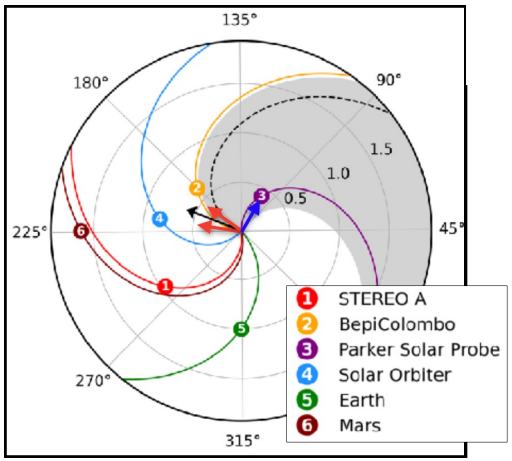
→ **Multiple causes for widespread events**





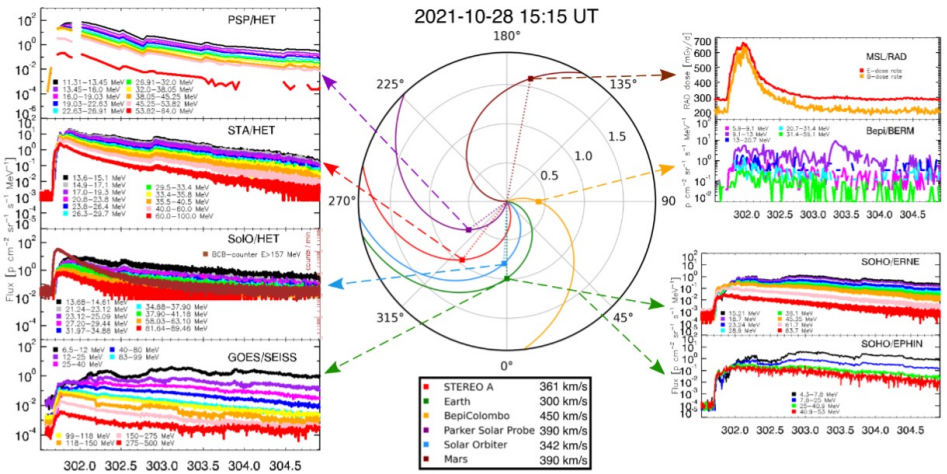


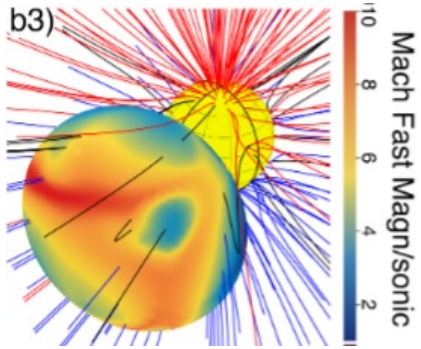


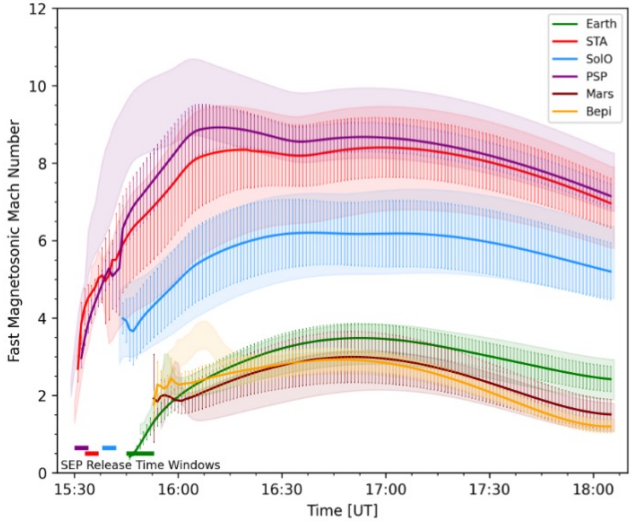


Q2: ion acceleration mechanisms at shocks

- Multi-S/C events of Nov 2020 and Apr 2021 support ion acceleration at shocks through timing analysis
- *Papaioannou et al. (2022, A&AL) and Kouloumvakos et al. (2023, A&A submitted):* The first GLE of SC 25 (29 Oct 2021)
  - proton release at the Sun consistent with the diffusive shock acceleration of deca–hecto-MeV protons



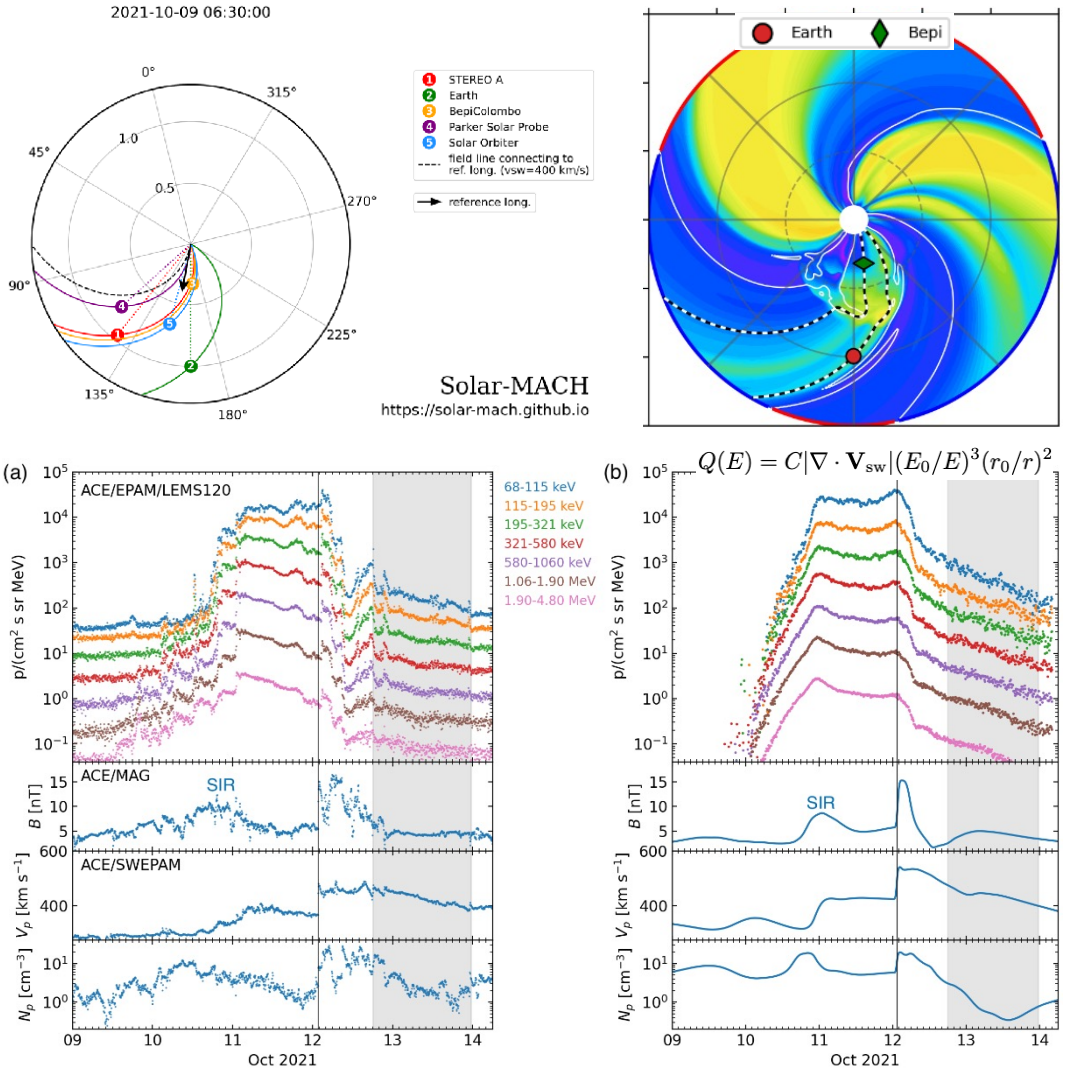




Q2: ion acceleration mechanisms at shocks

- *Lario et al. (2022: ApJ); Jebaraj et al. (2023, A&A, in press); Wijsen et al. (2023, ApJ, in press):* The Oct 9, 2021, event
  - Structured solar wind important for interplanetary shock acceleration
  - Particle injection at the shock proportional to the compression at the shock is able to fully explain the details of the time profiles

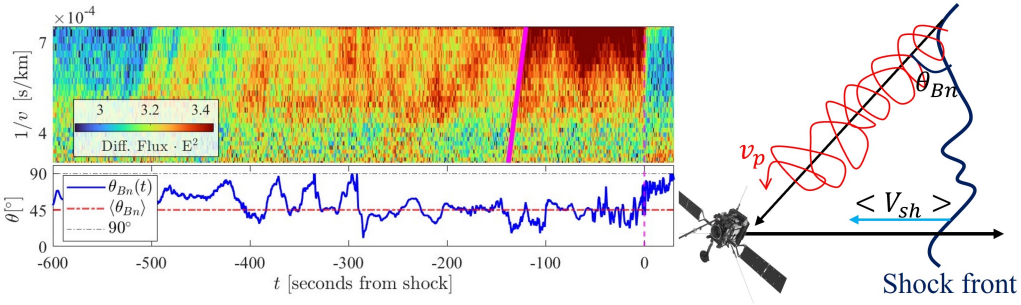
→ Strong evidence for diffusive shock acceleration

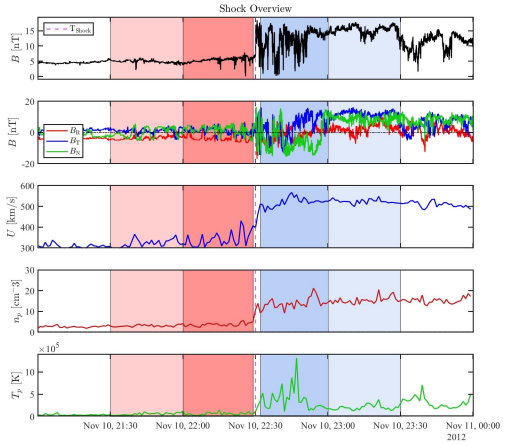


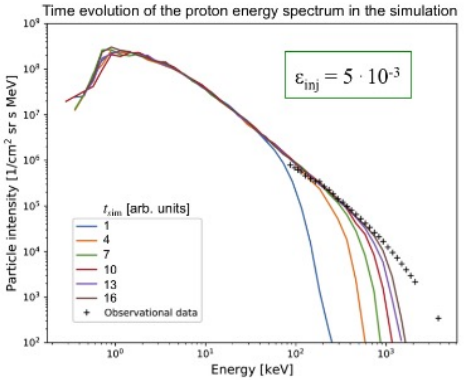
Wijsen et al. (2023, ApJ, in press)

Q2: ion acceleration mechanisms at shocks

- Local vs. global structures have been assessed by
  - *Trotta et al. (2023, MNRAS)*: shocklets in an interplanetary shock
  - *Trotta et al. (2023: PRL, submitted)*: imprints of fine-structured shock in upstream particle intensities
  - *Afanasiev et al. (2023: A&A, submitted)*: role of self-generated waves and time history



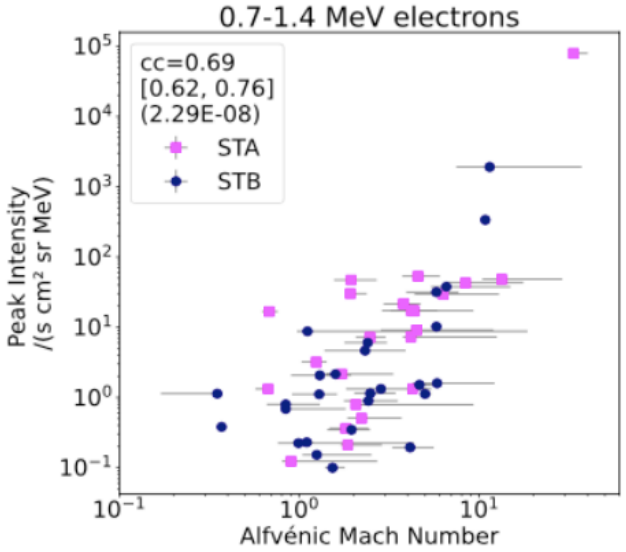




- Local structures seem to have a strong effect at suprathermal energies, but at higher energies, a more averaged shock structure dominates → to be confirmed with a larger sample

Q3: role of shocks in electron acceleration

- *Dresing et al. (2022, ApJL)*
  - MeV electrons in fast-CME-related events are shock accelerated
  - Flares probably contribute at lower energies
- *Talebpour Sheshvan et al. (2023, A&A)*
  - MeV electrons in interplanetary shocks in fast shocks observed by STEREO A
  - Not common phenomenon at 1 AU
  - Analysis of inner heliospheric measurements will be important



- *Jebaraj et al. (2023, A&A, in press)*
  - October 9, 2021, event shows that MeV electrons have a prolonged injection at the shock
  - Prompt component probably associated with the flare
- Solid evidence on the shock origin of MeV electrons at least in large gradual events
- ~100-keV electrons have stronger (relative) flare contribution

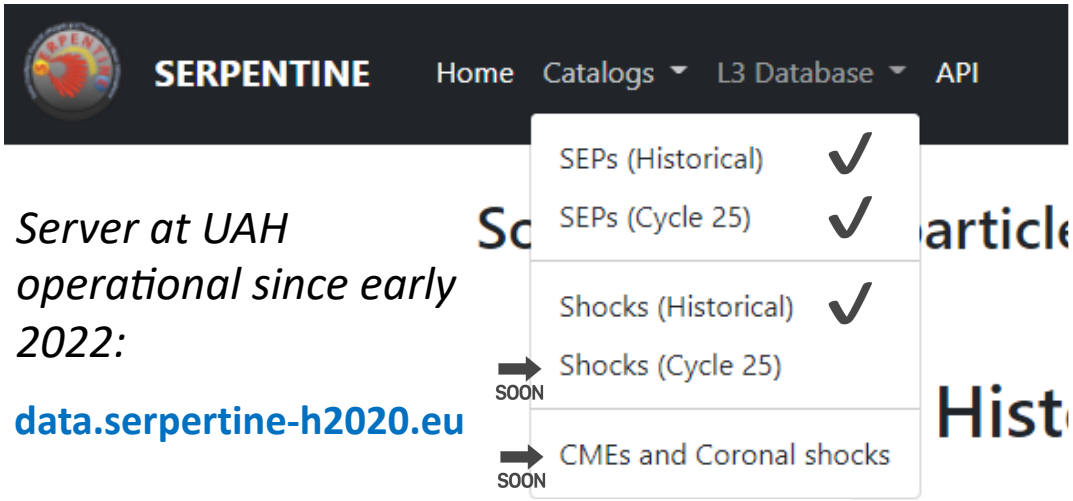
Technical objectives

T1: Produce and distribute catalogues of single- and multi-S/C SEP events and in-situ shock events.

T2: Provide an analysis platform with the data and tools for advanced analysis along with visualization of the modeled heliospheric state.

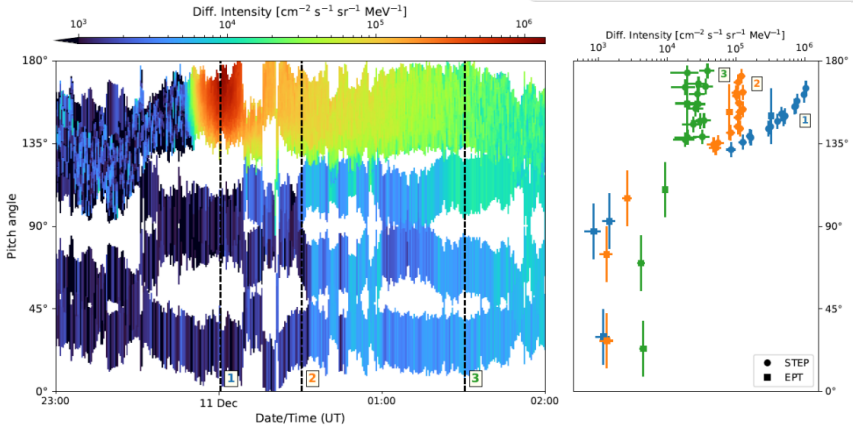
T3: Produce and deliver high-level and multi-instrument datasets for energetic particles and the necessary ancillary data.

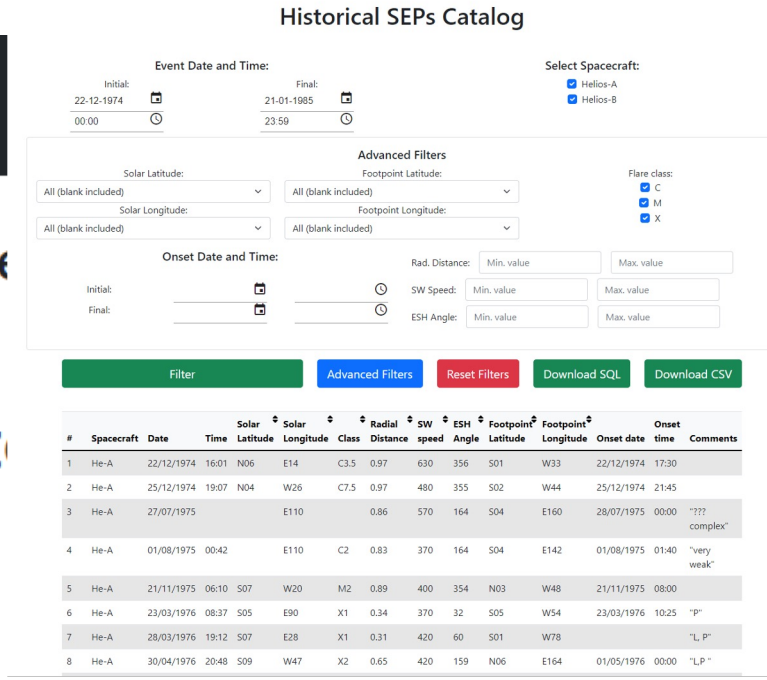
Server for catalogues and L3 data products



Server at UAH operational since early 2022:

data.serpertine-h2020.eu

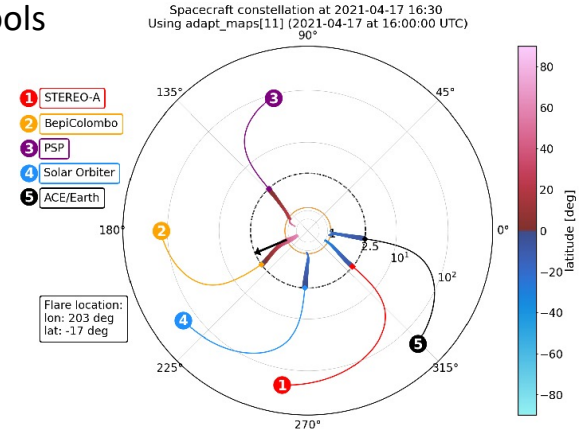




First level-3 datasets coming soon

Tools for data analysis

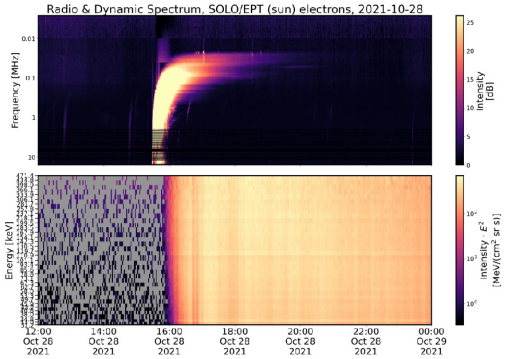
Python tools



Choose spacecraft, sensor, viewing direction and particle species from the drop-down menu:

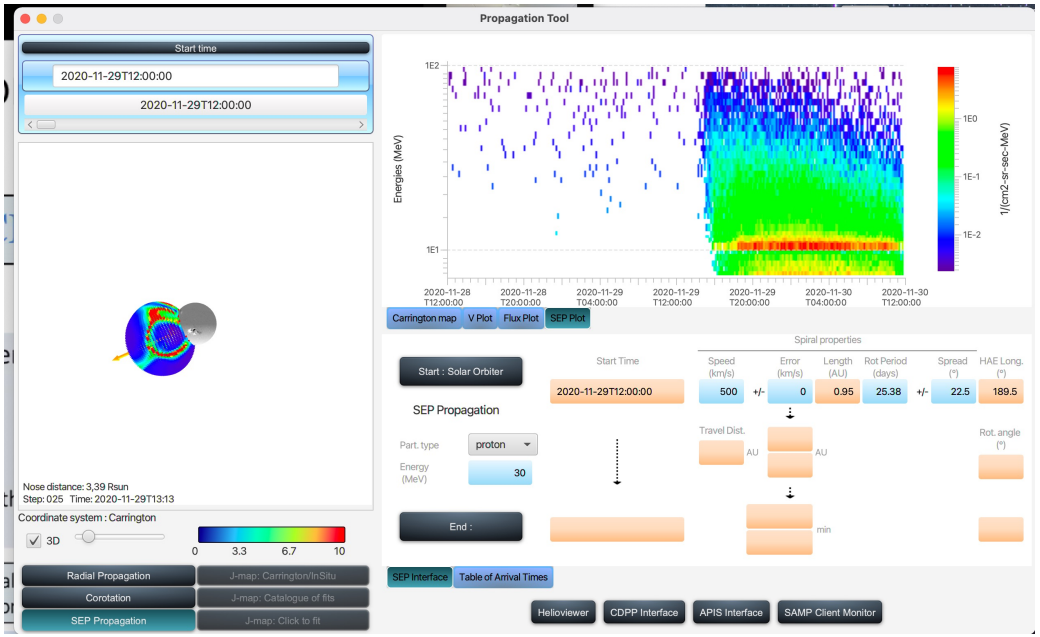
```
In [2]: display(w.spacecraft_drop, w.sensor_drop, w.view_drop, w.species_drop)
        display(w.radio_drop)
```

Spacecraft: Solar Orbiter
Sensor: EPT
Viewing: sun
Species: electrons
Plot radio spectrum for: STEREO-A



Several tools being developed: SolarMACH, SEPPy, Tools hosted by UPS-IRAP

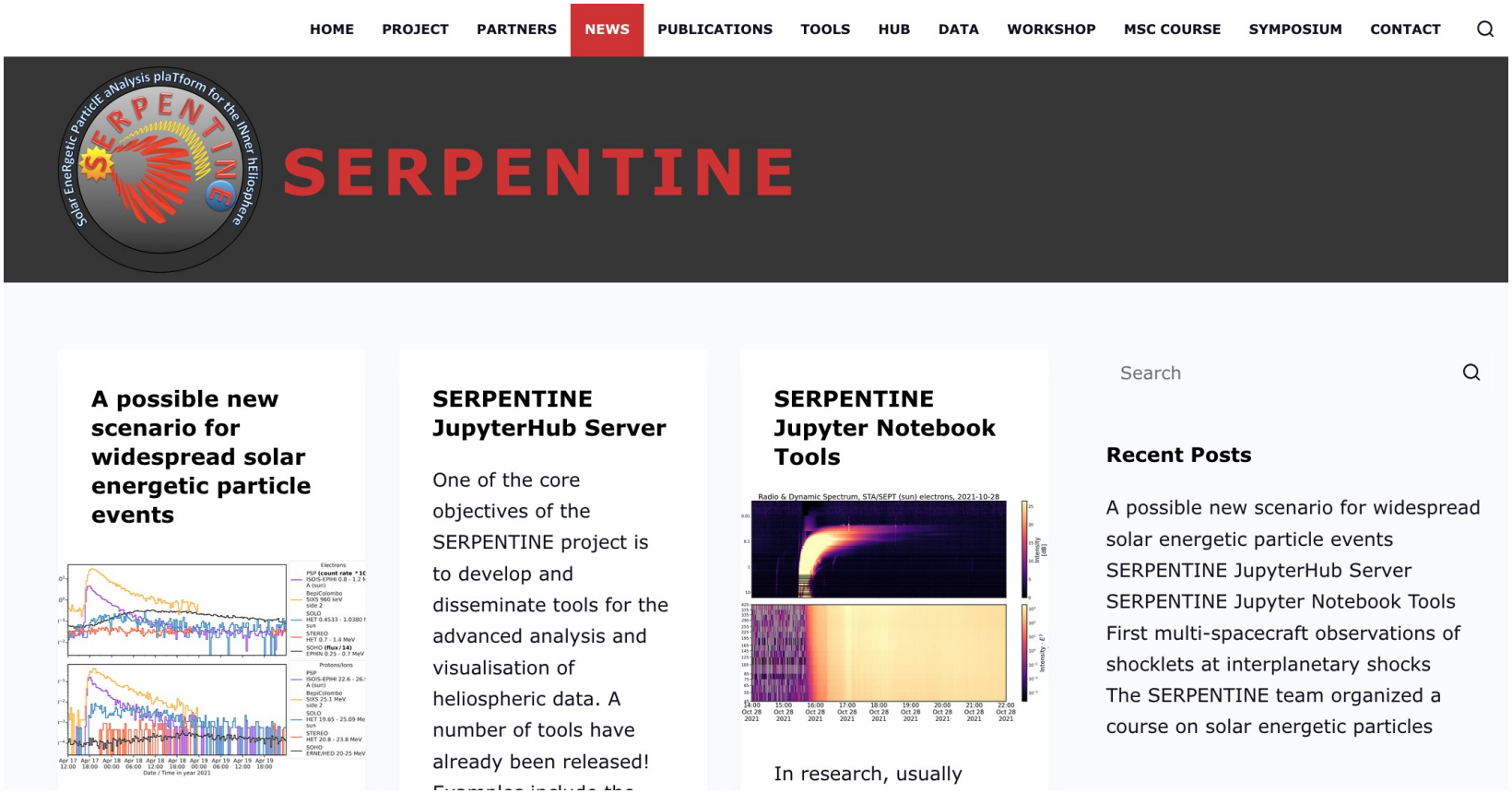
Jupyter Notebooks in GitHub and SERPENTINE Hub



Access the Python tools through: **serpentine-h2020.eu**

Visit the SERPENTINE website

https://serpentine-h2020.eu



Conclusions

- SERPENTINE project has delivered a number of science results and tools for the community
- Continues still one year, adding analysis results and tools, and improving the existing ones
- We are always open for collaboration!
- **We wish you all a very fruitful symposium!**