UNIVERSITY OF TURKU

Observations of solar energetic particle events with Solar Orbiter and friends

New results and open-source analysis tools

Nina Dresing, University of Turku, Finland

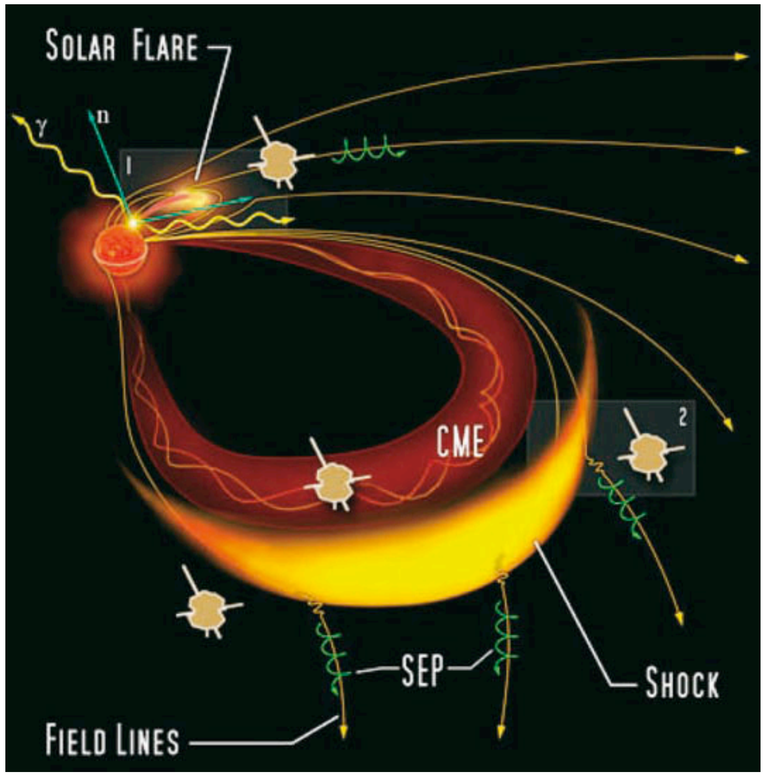
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HaDEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004159 and 101134999.

Funded by the European Union

Multi-Spacecraft Observations of SEP events

Why?

- **Determine the role of flare vs. shock in SEP acceleration**
- Disentangle source and transport effects
- Understand perpendicular transport
- Understand the role of interplanetary transients



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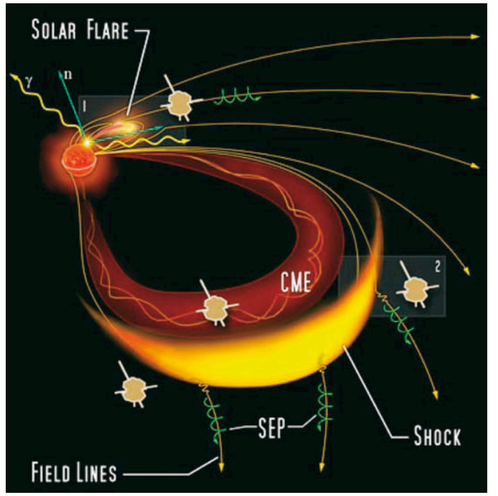

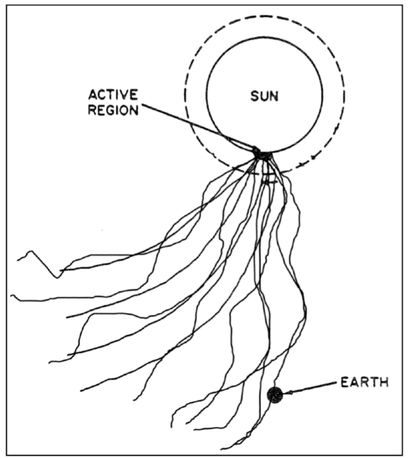

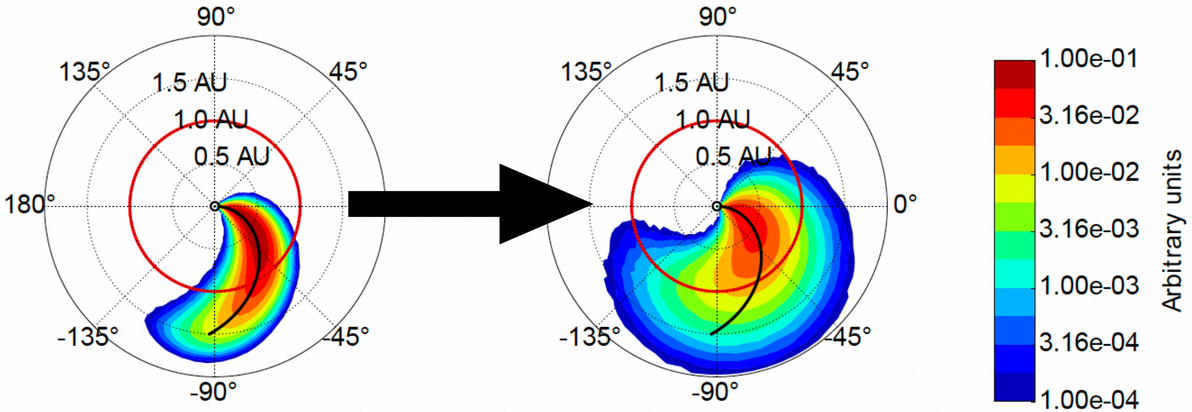

Laitinen+ 2016

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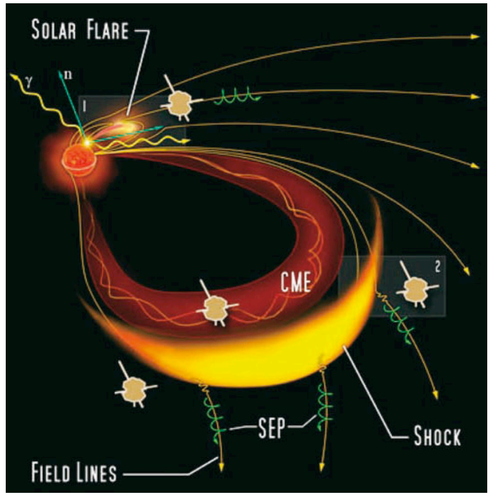

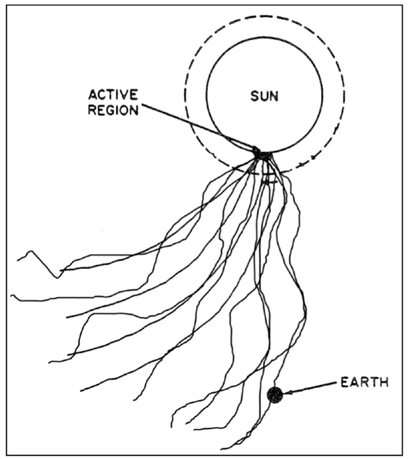

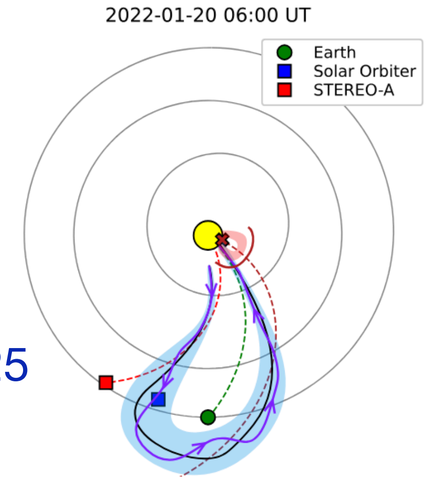

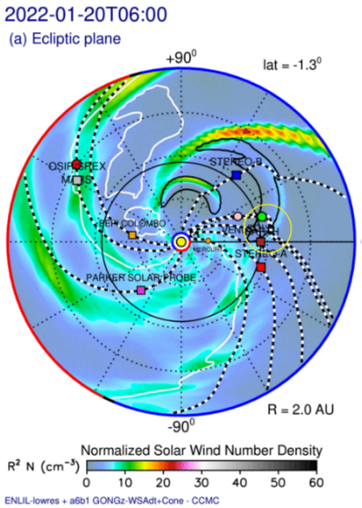

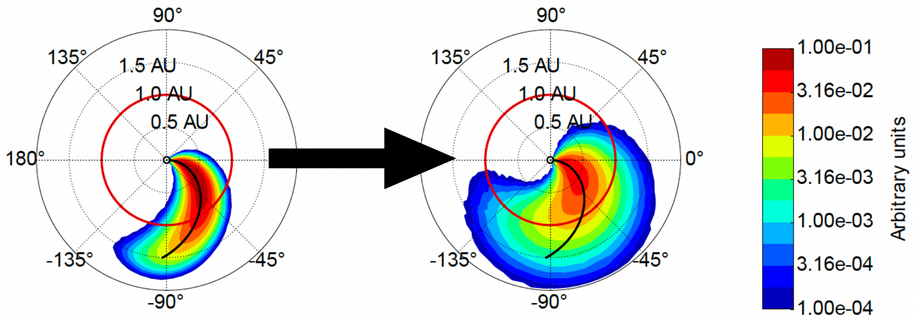

Rodríguez-García+ 2025

Laitinen+ 2016

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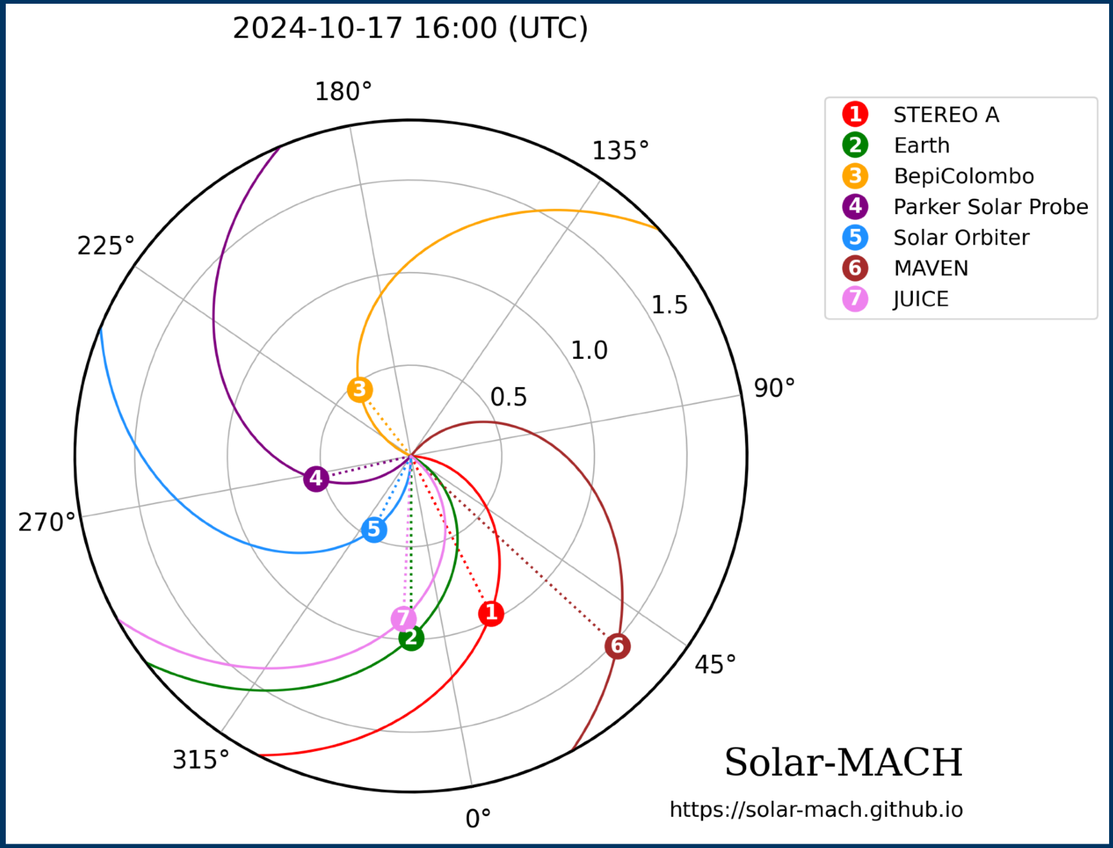
Multi-Spacecraft observations with the new fleet



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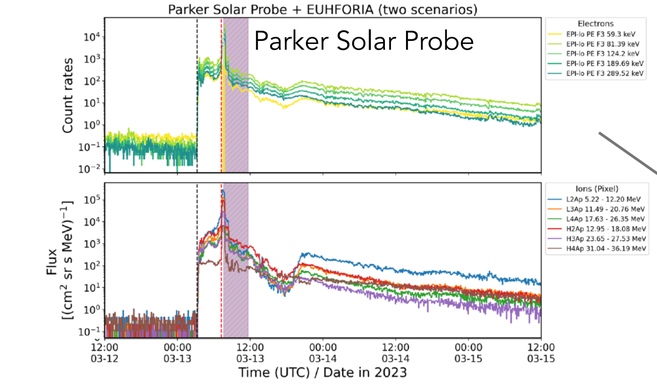
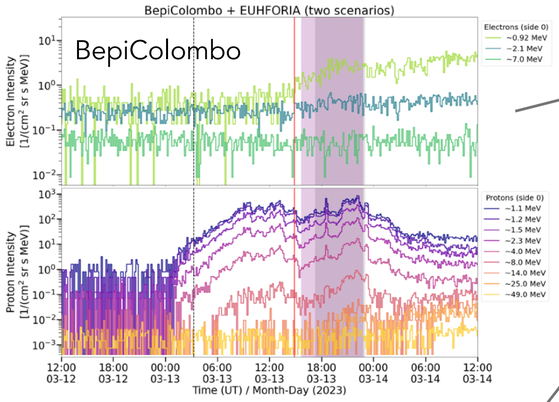
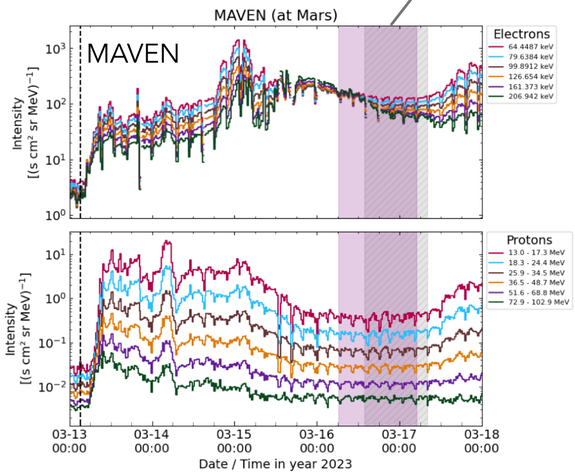
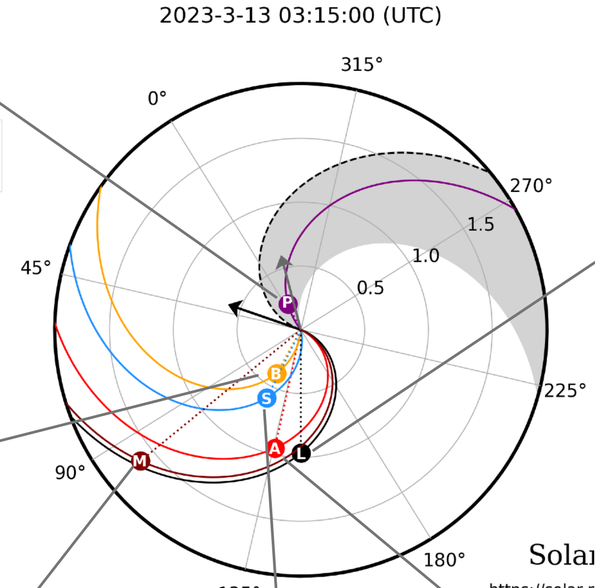
WIDESPREAD SEP EVENT OF 13 MARCH 2023

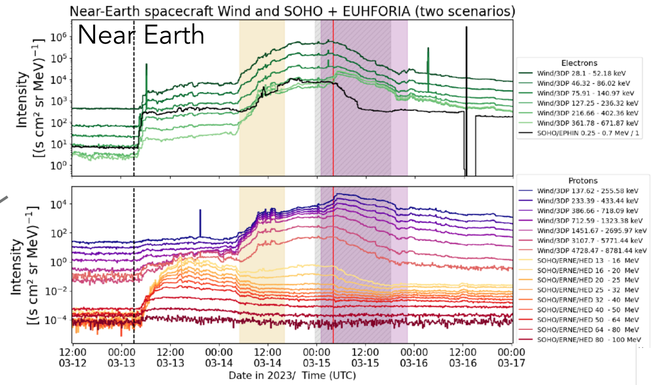
- SEP event observed all around the Sun at **six well-separated locations**: Parker Solar Probe, Solar Orbiter, BepiColombo, STEREO A, SOHO/Wind, MAVEN
- In-situ shock and energetic storm particle (ESP) event detected at all five inner-heliospheric observers!

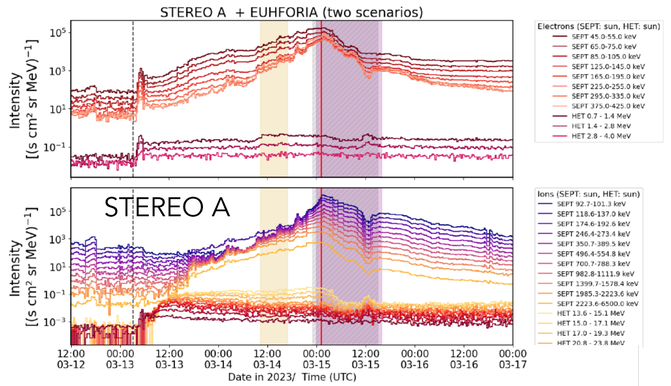


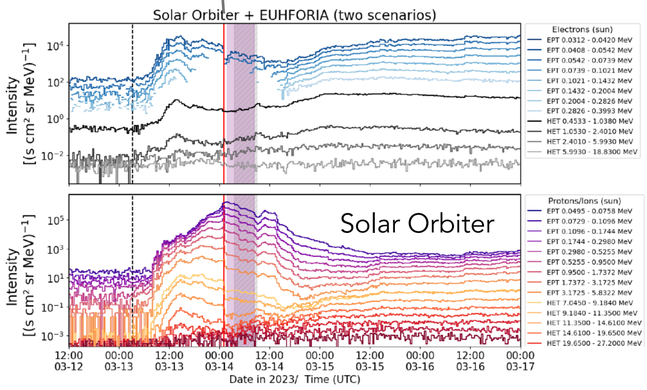












Dresing+ 2025

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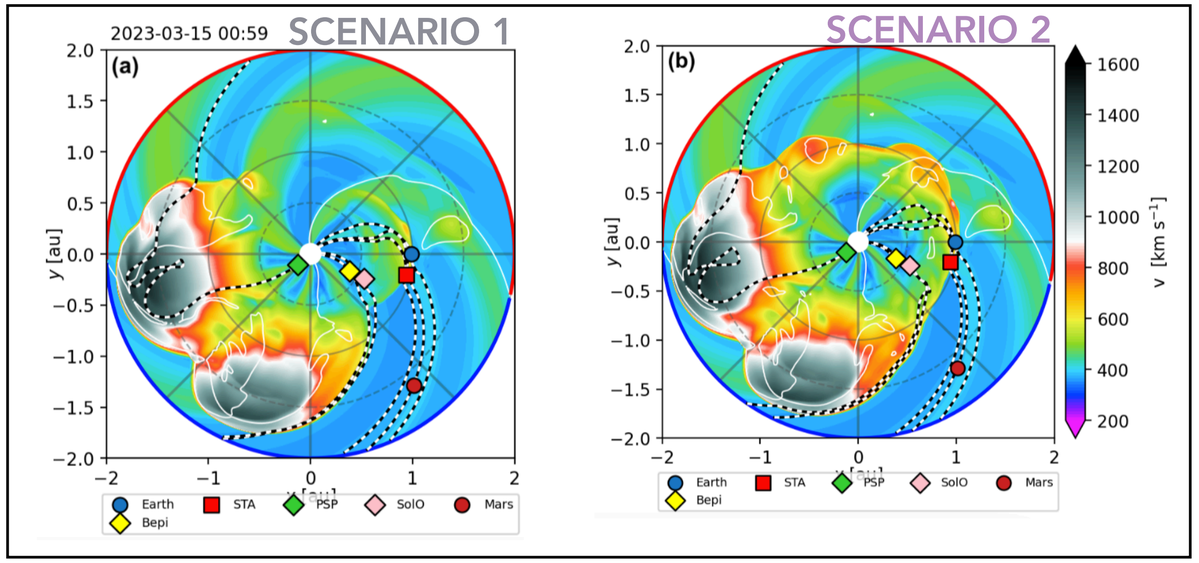
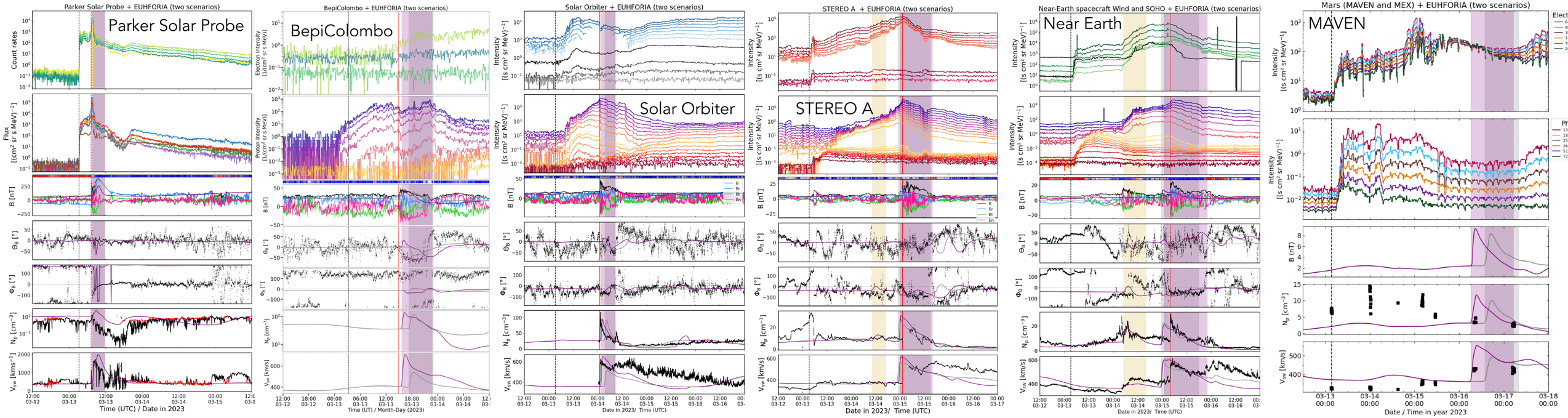
WIDESPREAD SEP EVENT OF 13 MARCH 2023

- **SCENARIO 1**: A pre-event CME (CME-5) creates the ESP event of the Earth-sided observers
  - works only with a higher density CME
- **SCENARIO 2**: A circumsolar (partly freely-propagating) shock



Dresing+ 2025, see also Wijsen+ 2025



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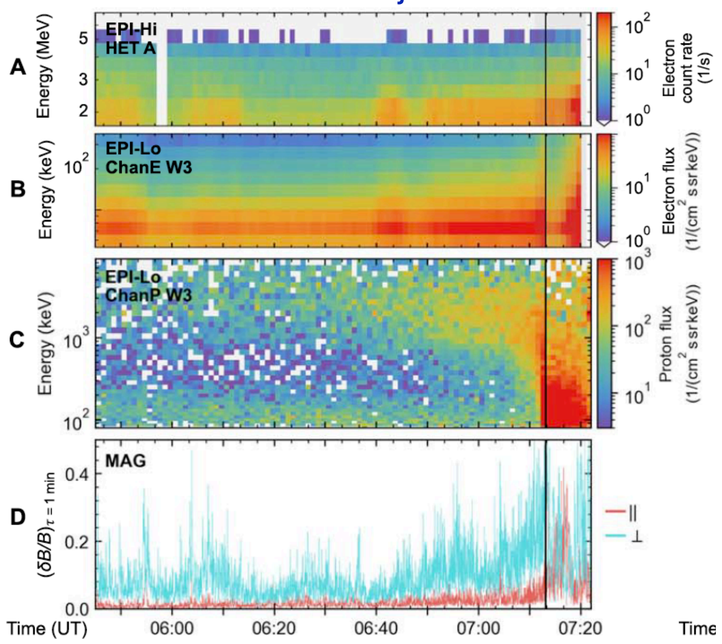
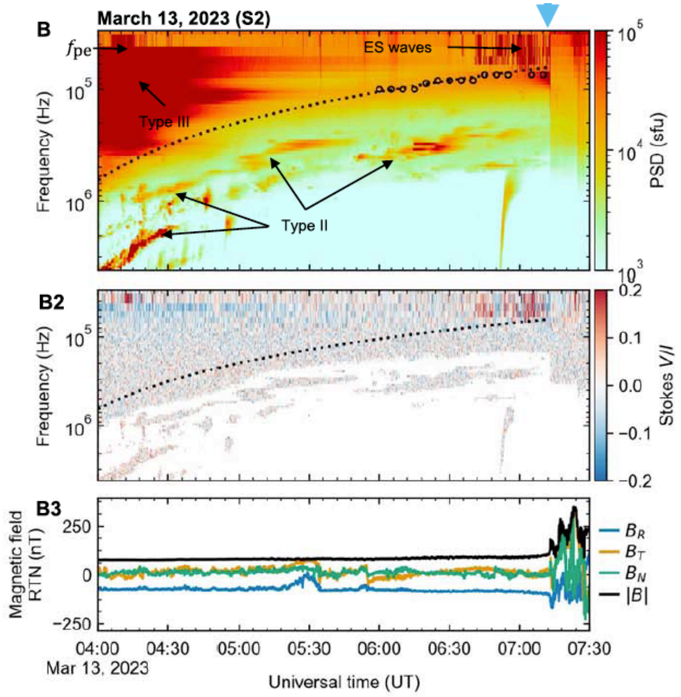
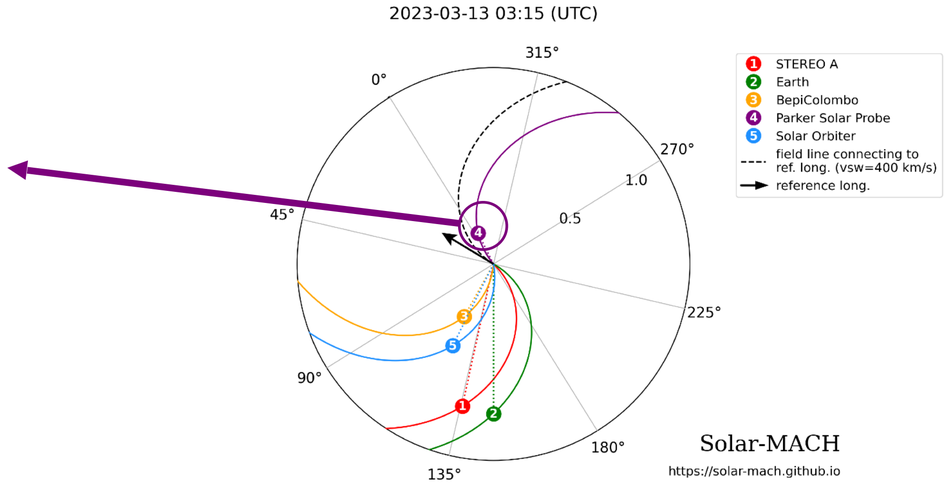
13 March 2023 event: In-situ observations of electron acceleration at the coronal shock

Jebaraj et al. 2024a



Jebaraj et al. 2024b





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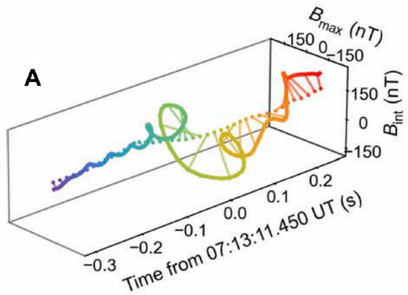

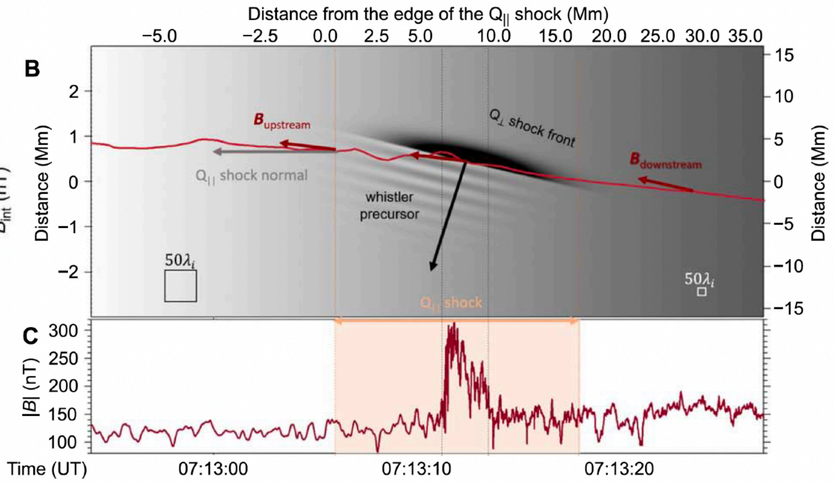

- March 13 2023 in-situ shock at PSP: One of the fastest CME-driven shocks ever (~2800 km/s, Jebaraj et al. 2024a).
- In-situ electron acceleration up to ultra-relativistic energies (6 MeV) could be confirmed
- A local perpendicular configuration of the globally parallel shock was likely key to sustained electron acceleration
- First-ever direct measurements of synchrotron-emitting heliospheric traveling shocks (Jebaraj et al. 2024b)!

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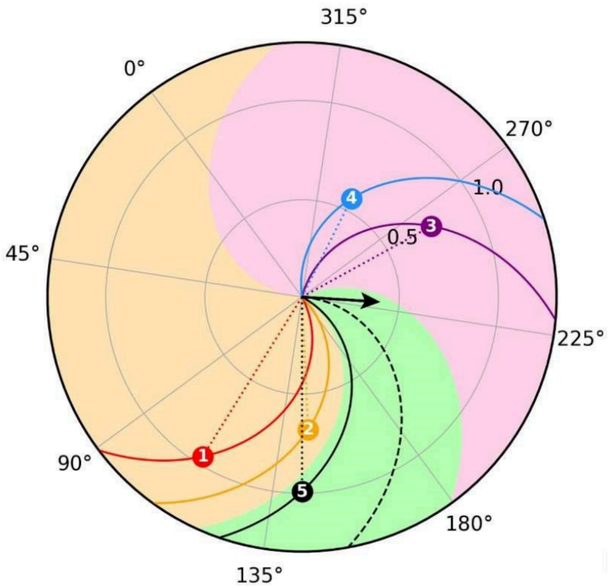
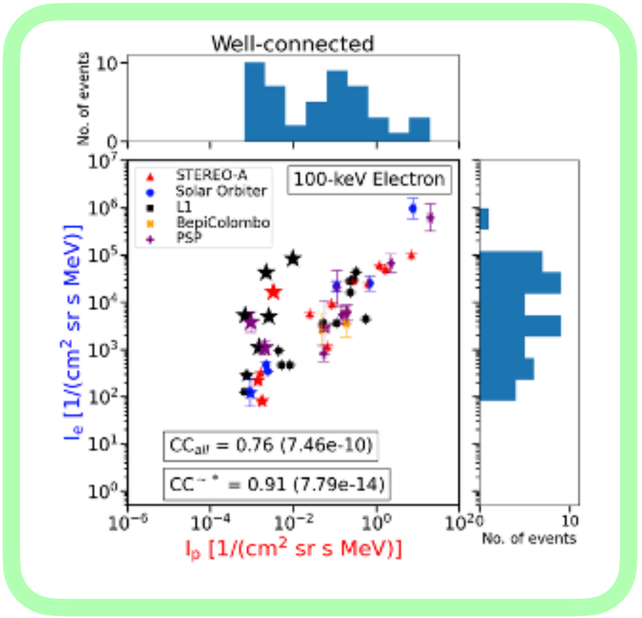
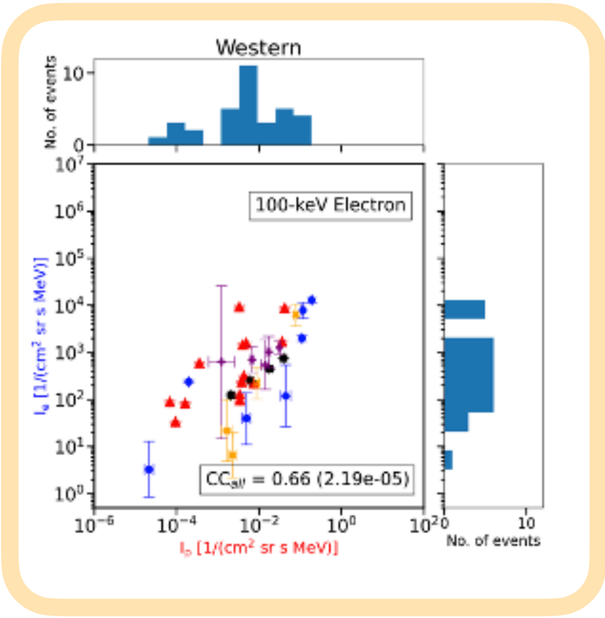
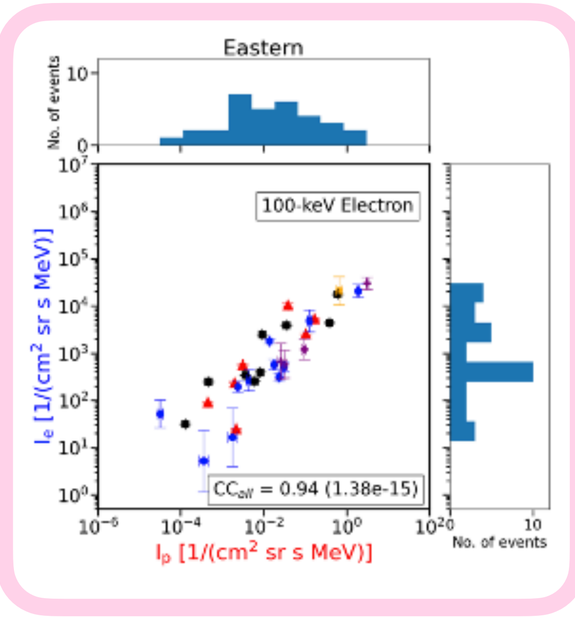
Correlation of electron and proton peak intensities



100 keV electrons vs. 25-40 MeV protons







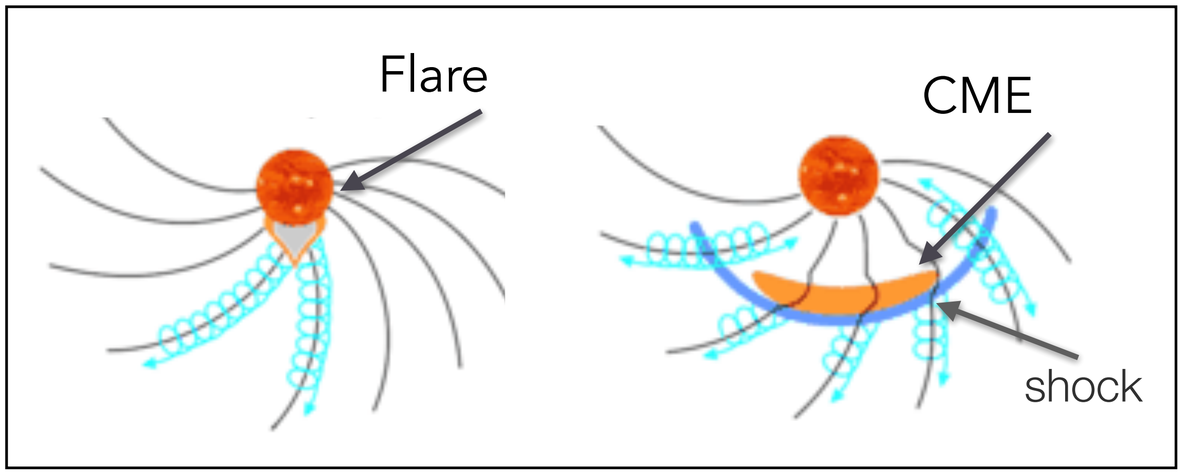
Solar Orbiter

Parker Solar Probe

STEREO A

SOHO/Wind

BepiColombo



Farwa et al. 2025

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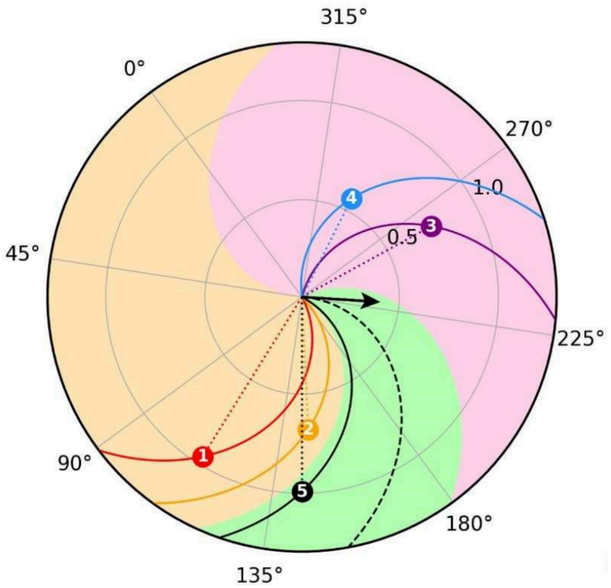

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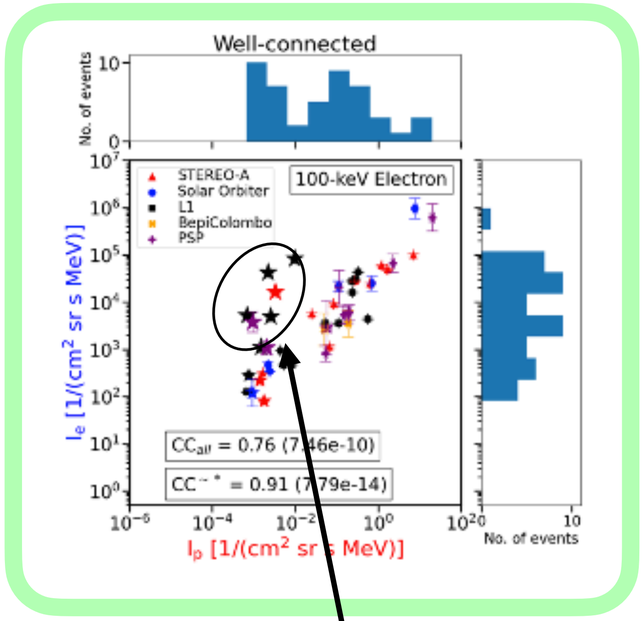

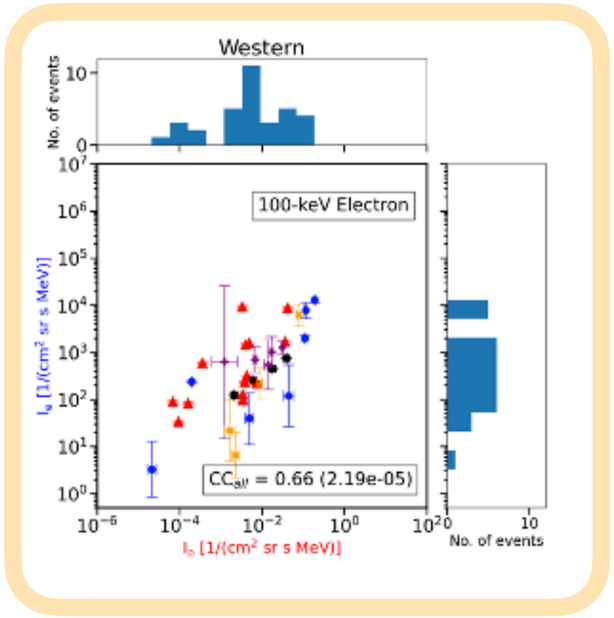

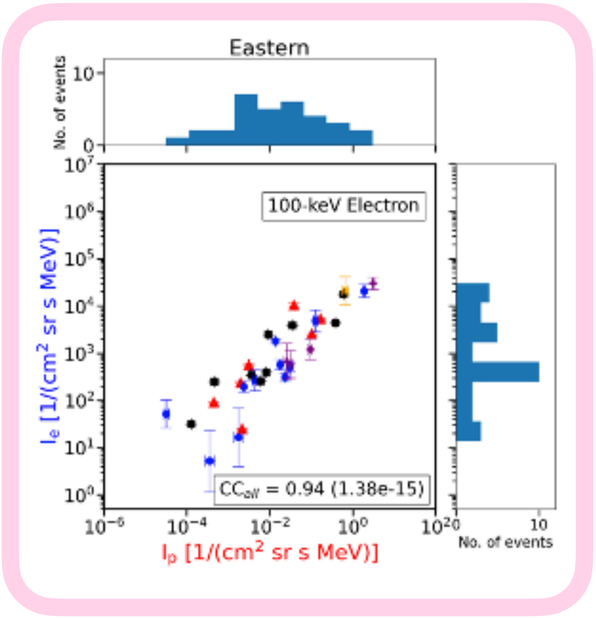

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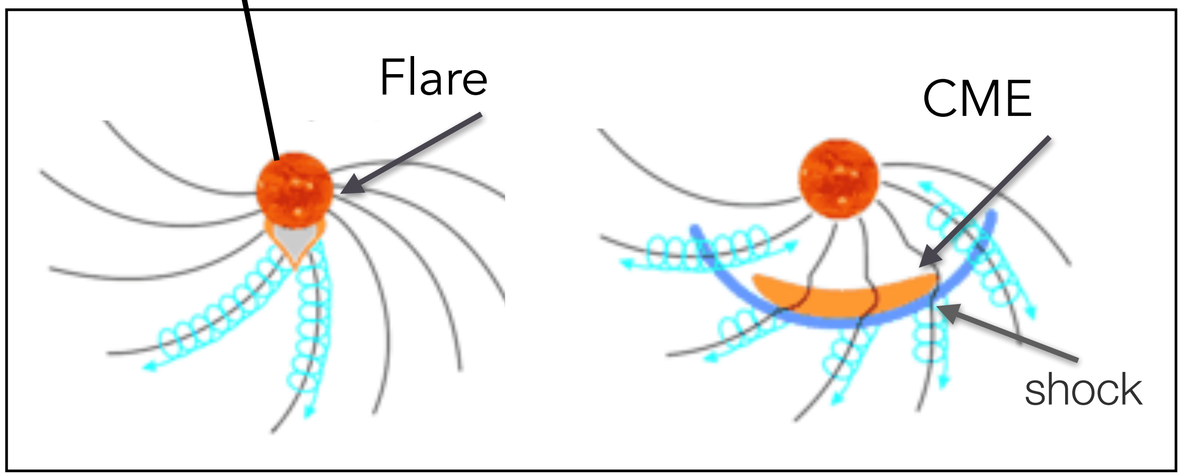
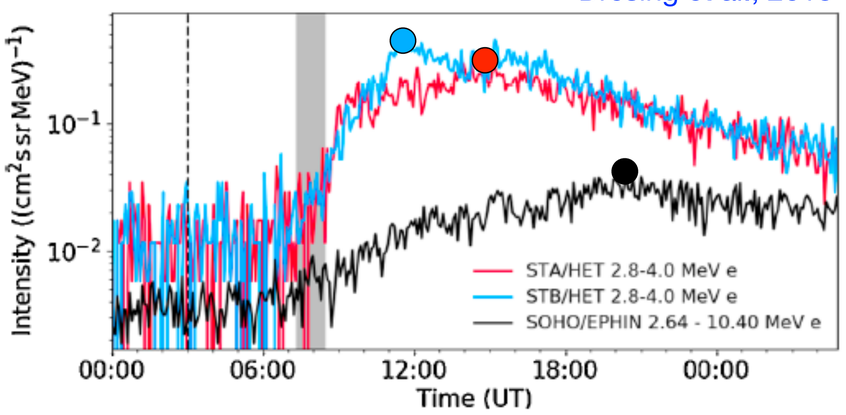
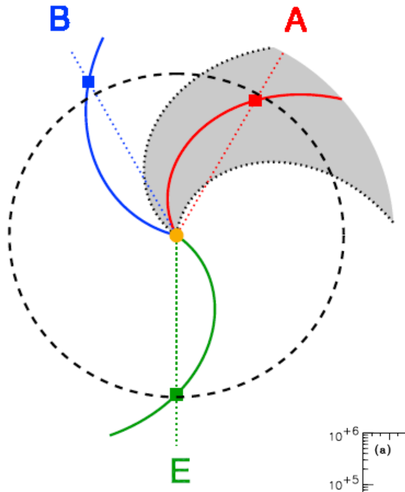


Farwa et al. 2025

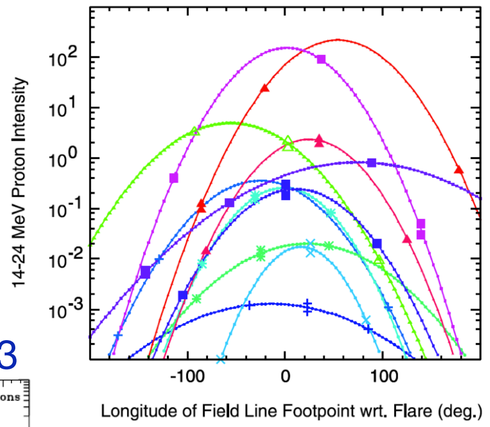
CHARACTERIZING THE LONGITUDINAL DISTRIBUTION OF SEPs

26 Dec 2013 Dresing et al., 2018



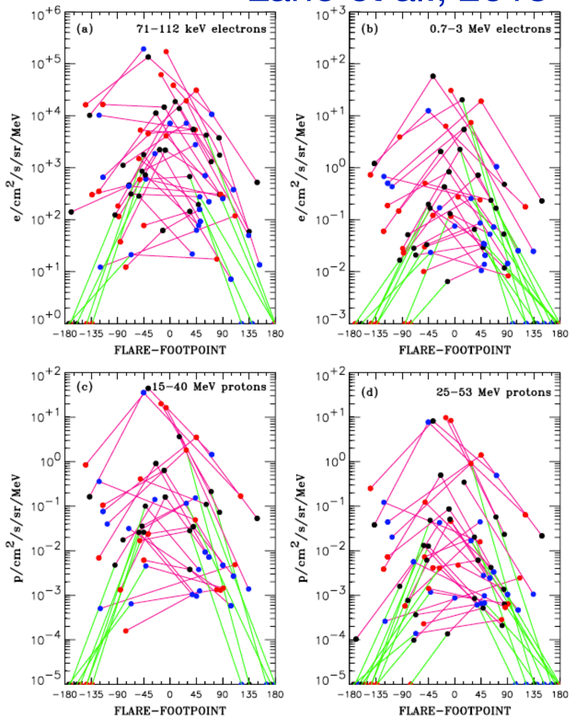


Richardson et al., 2014

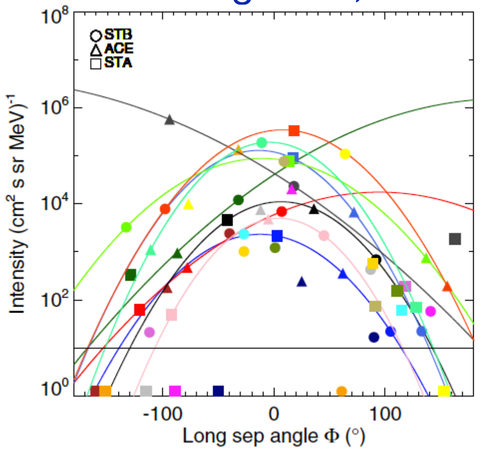


Previously: usually only 3 points available

Lario et al., 2013



Dresing et al., 2014



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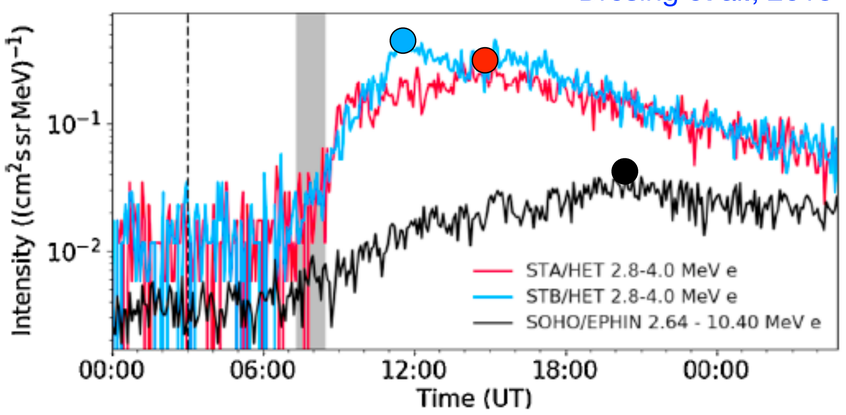
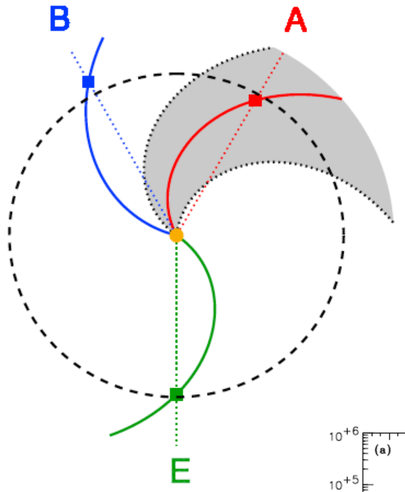
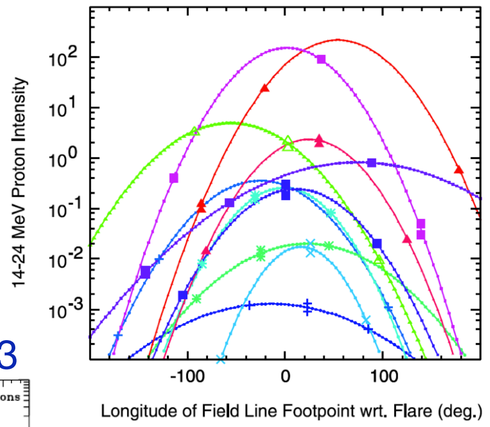
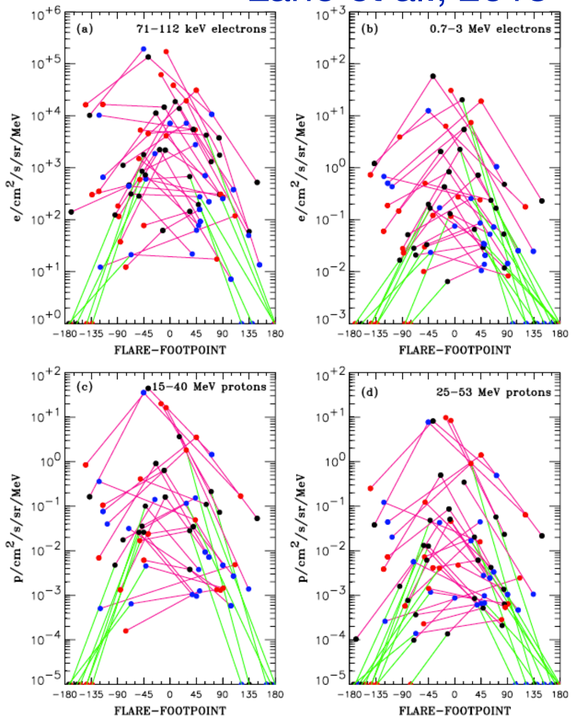




Richardson et al., 2014



Lario et al., 2013



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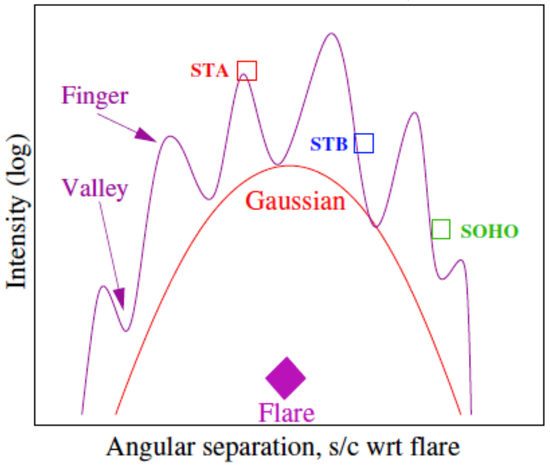
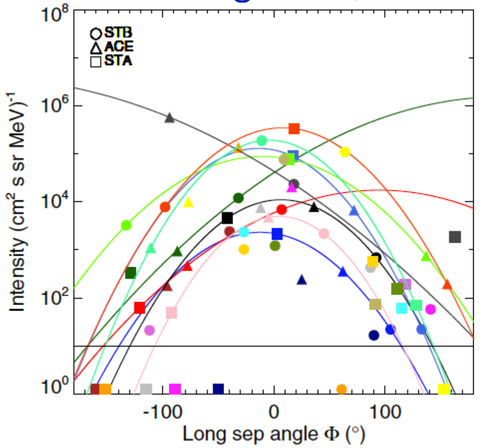
Klassen et al., 2016



PROBLEMS:

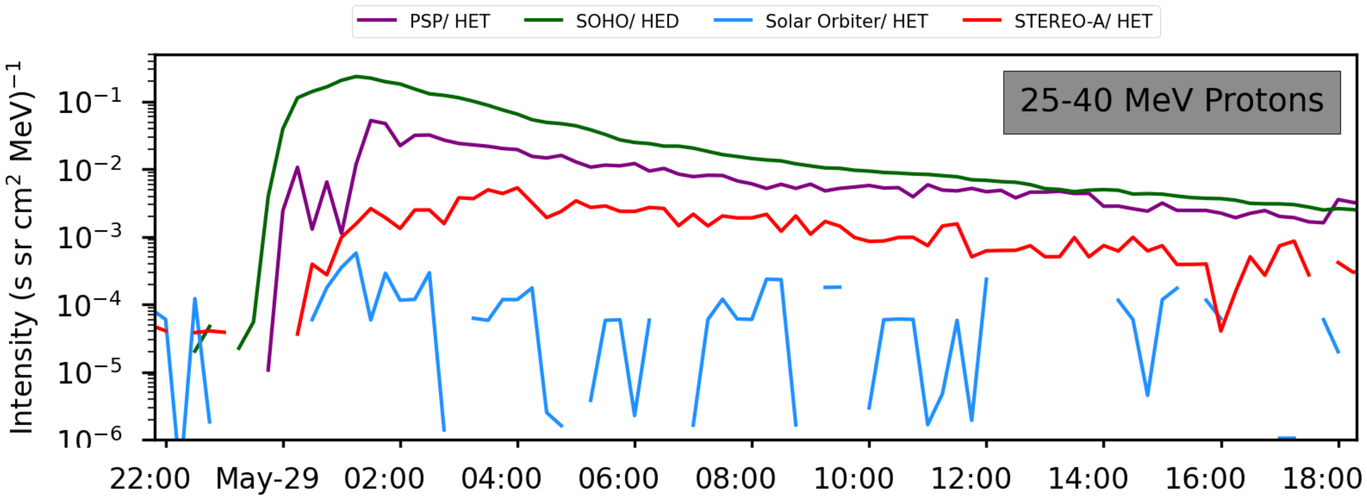
- The intensity peaks happens at different times
- **The real distribution might be non-Gaussian**

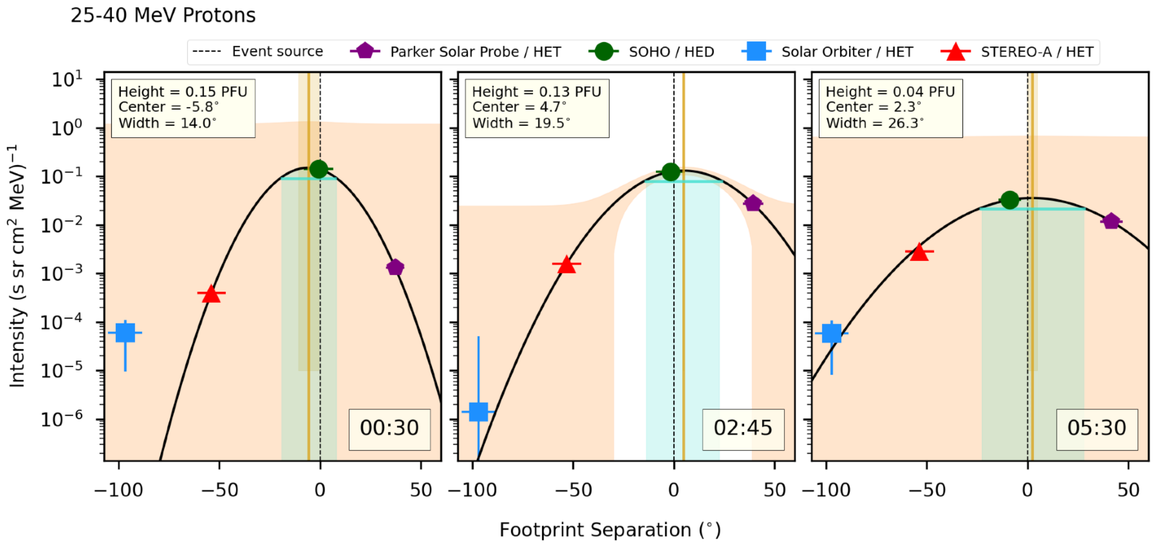
Dresing et al., 2014



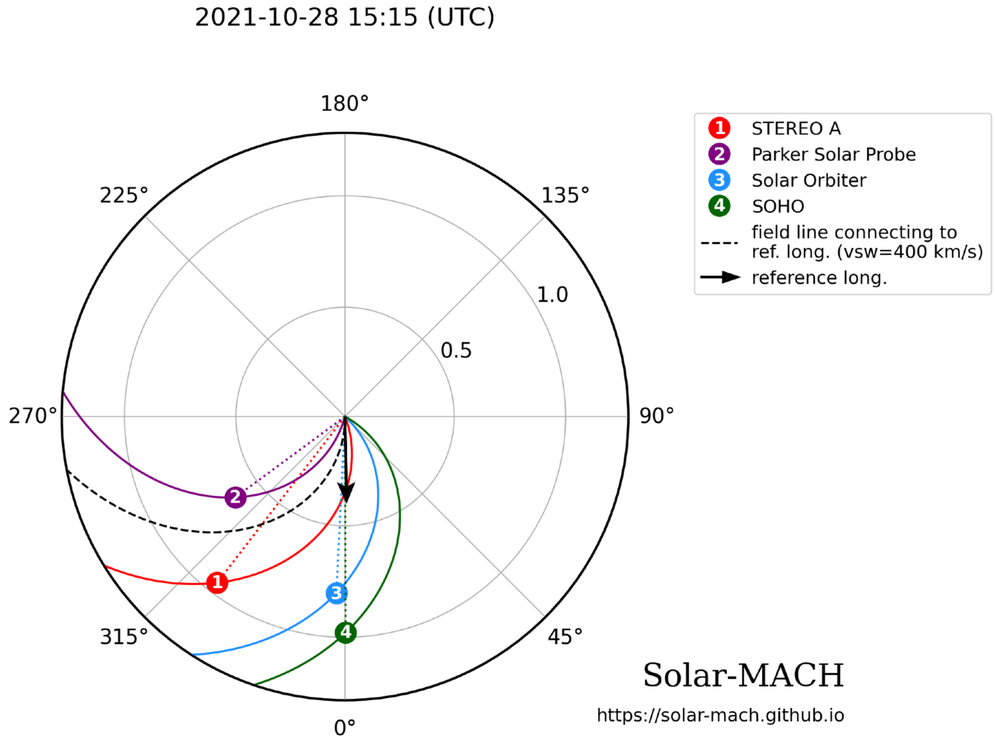
CHARACTERIZING THE LONGITUDINAL DISTRIBUTION OF SEPs

… MAKING USE OF MORE SPACECRAFT!





Plots from J. Lang



Challenges:

- Different instrumentation
- Intercalibration
- Radial scaling (e.g., Rodríguez-García+ 2023)

CHARACTERIZING THE LONGITUDINAL DISTRIBUTION OF SEPs

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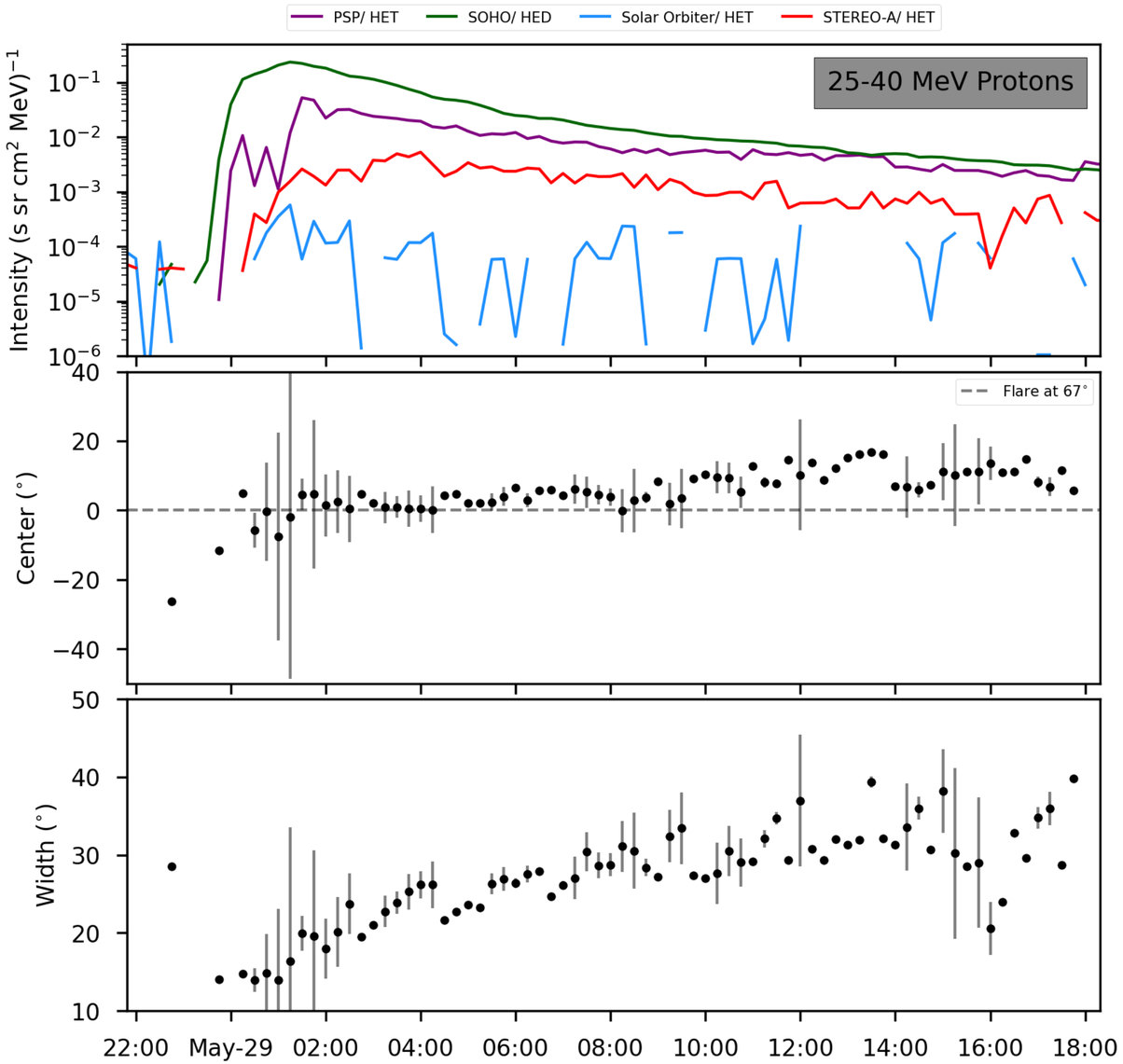

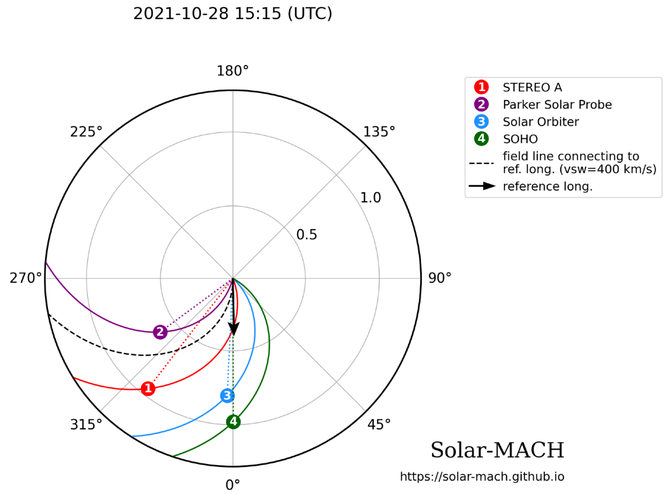

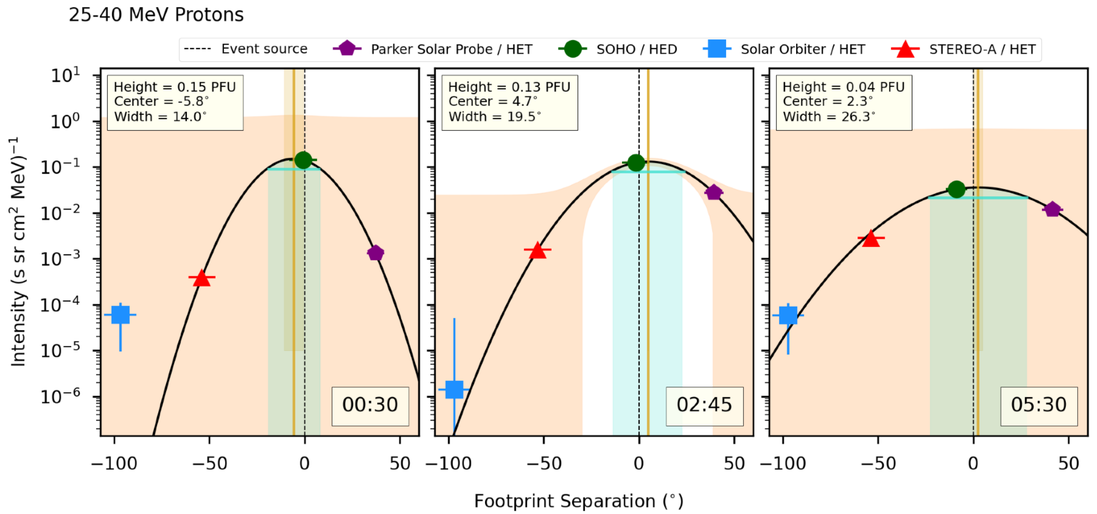

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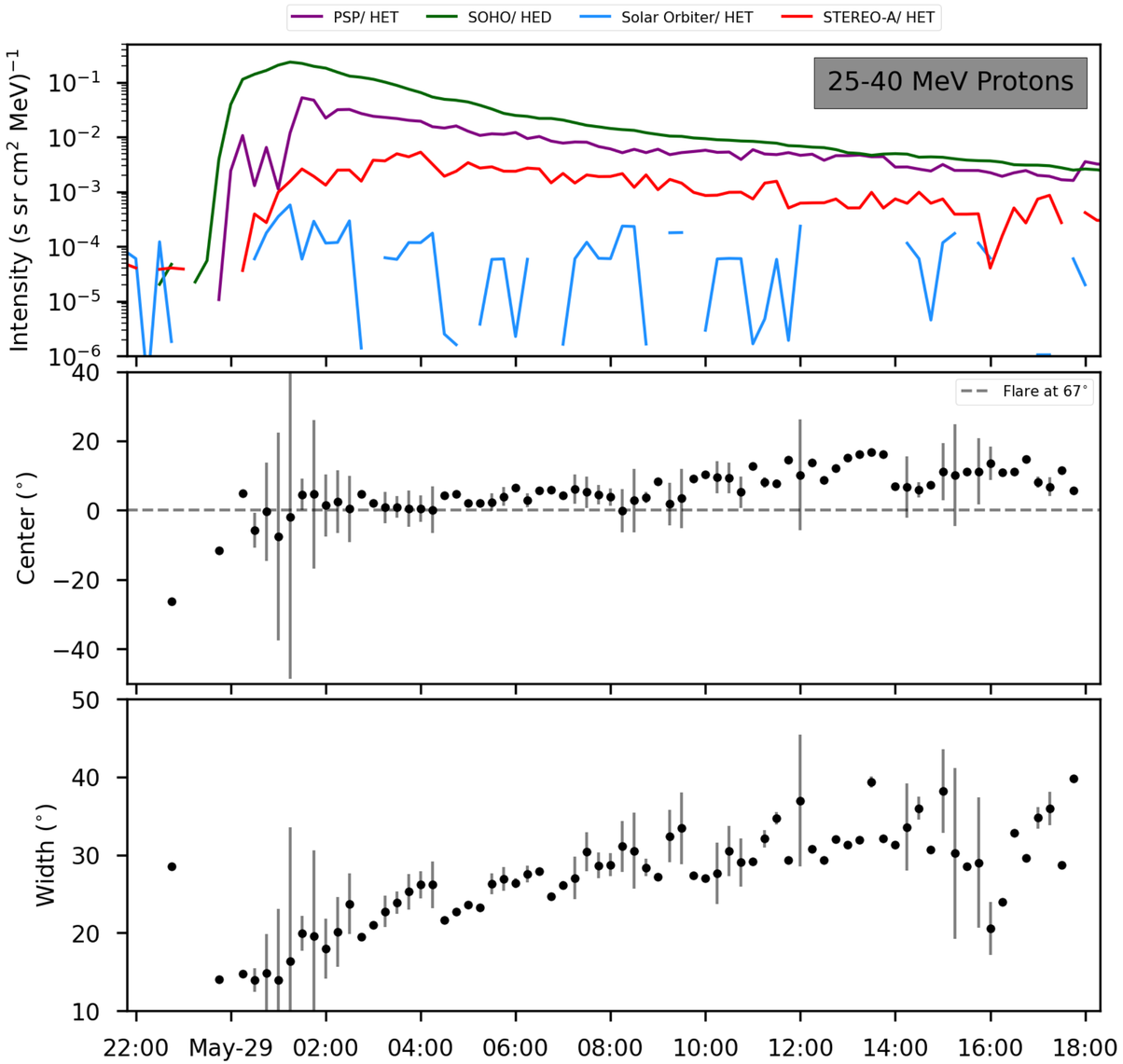
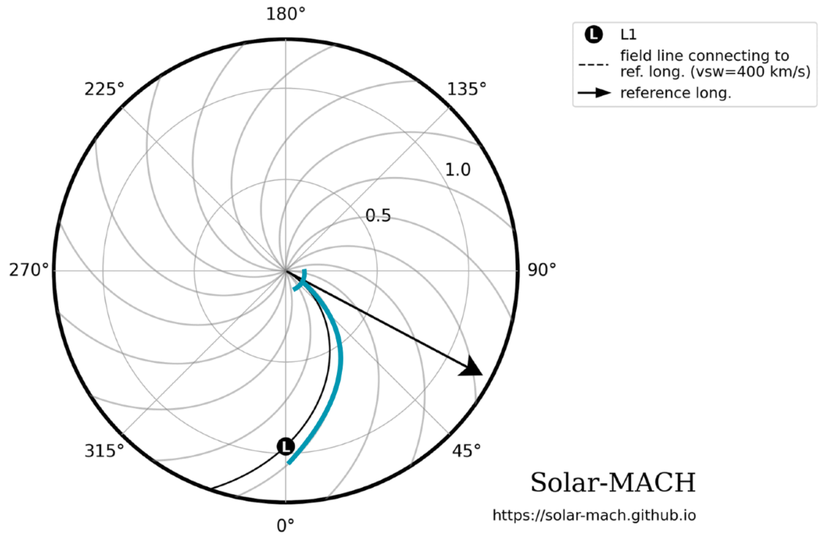
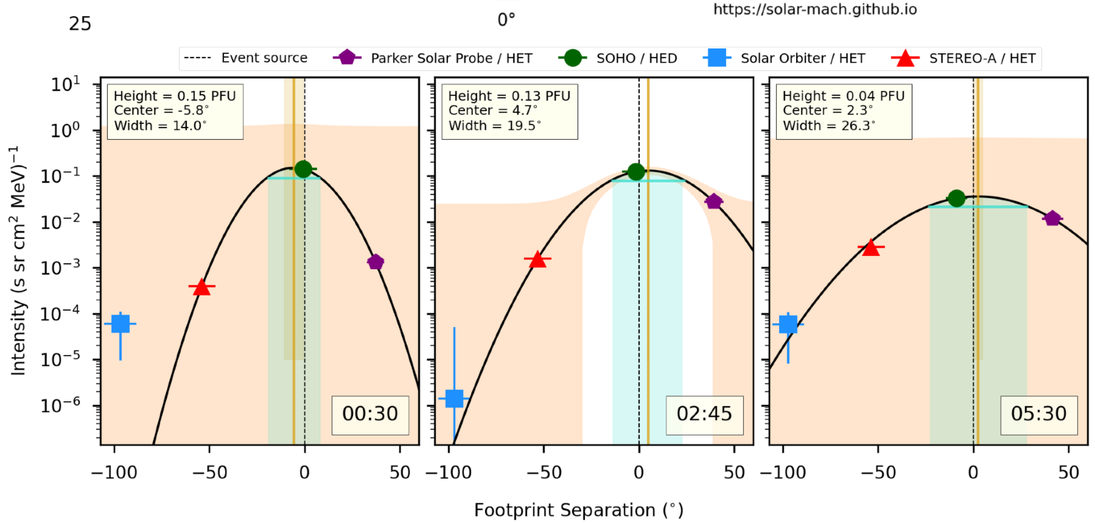


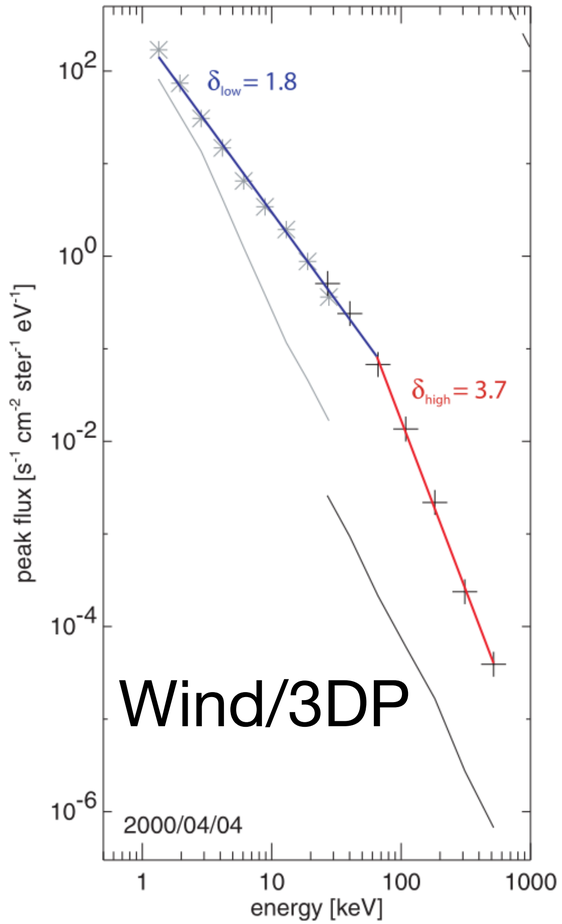


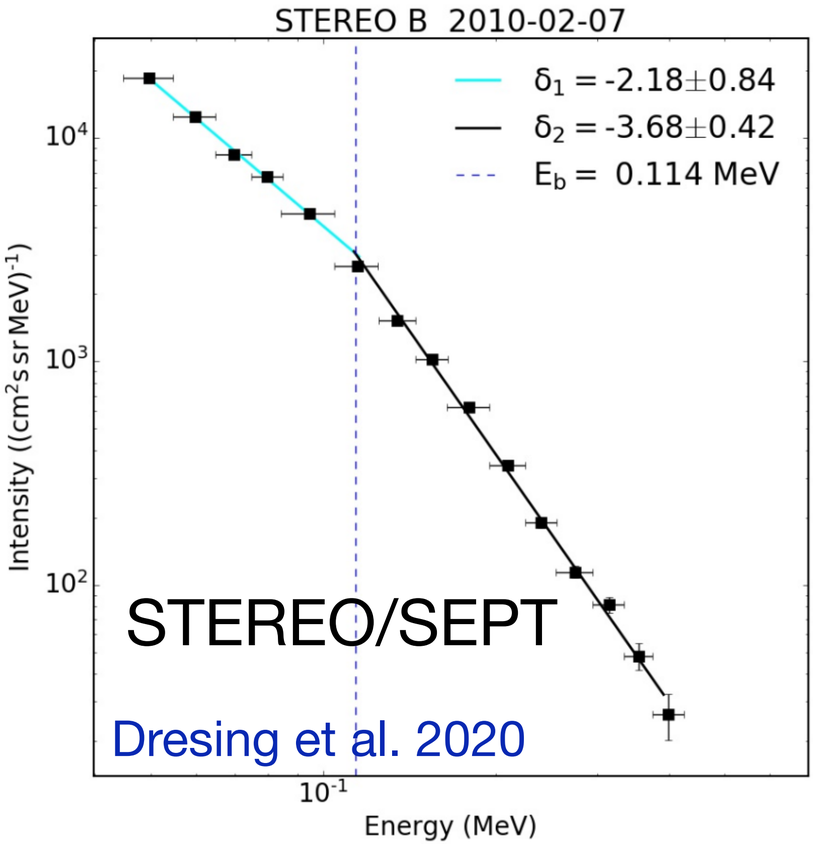


Plots from J. Lang

Energy spectra: before Solar Orbiter

Krucker et al. 2009





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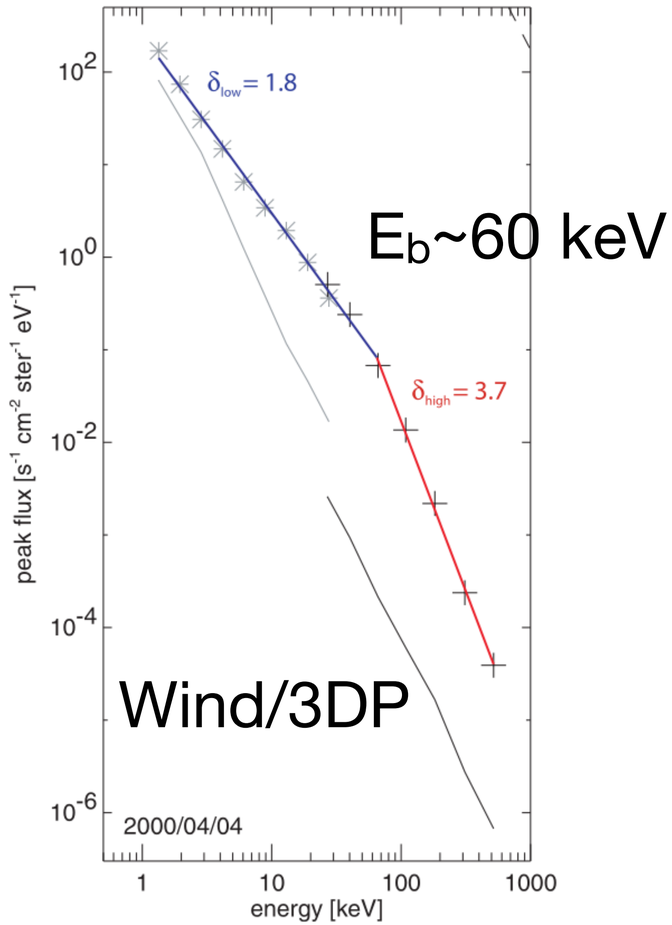
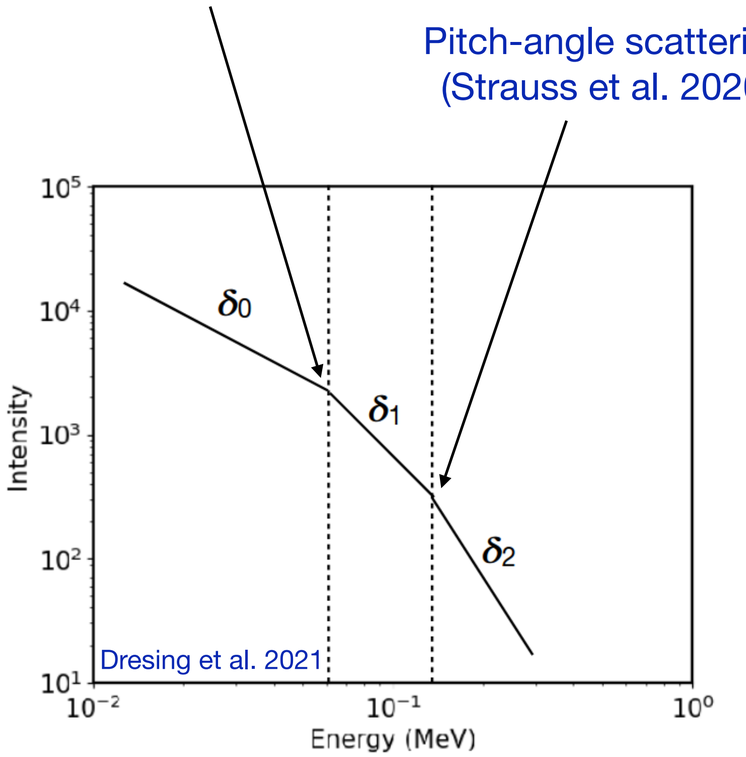
Energy spectra: before Solar Orbiter

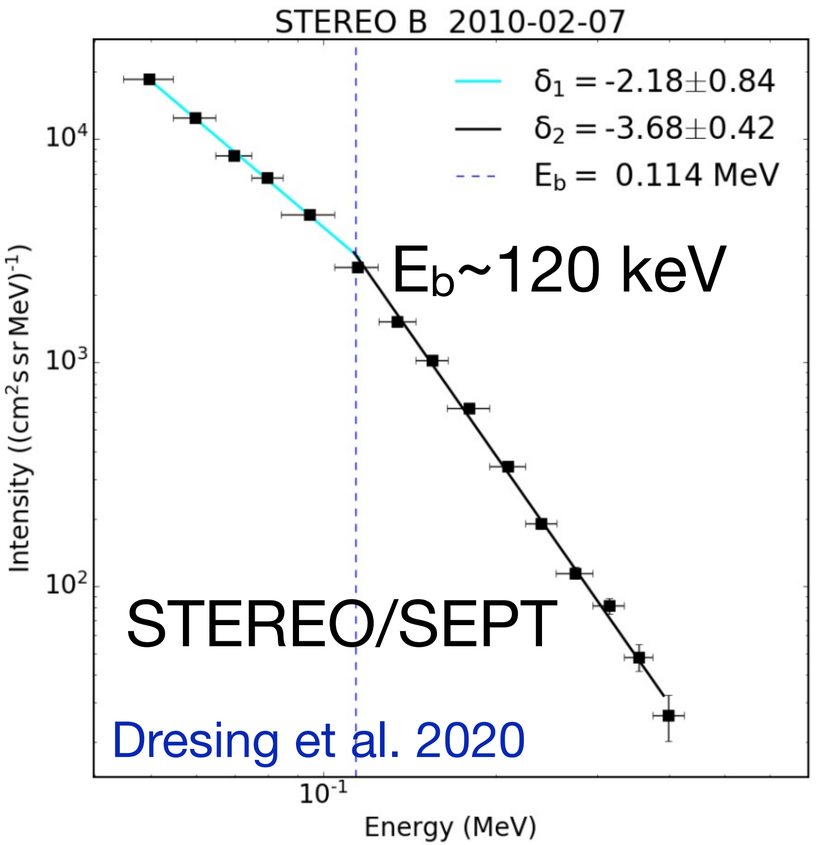
Krucker et al. 2009



Langmuir-wave generation
(e.g. Kontar & Reid 2009)

Pitch-angle scattering
(Strauss et al. 2020)





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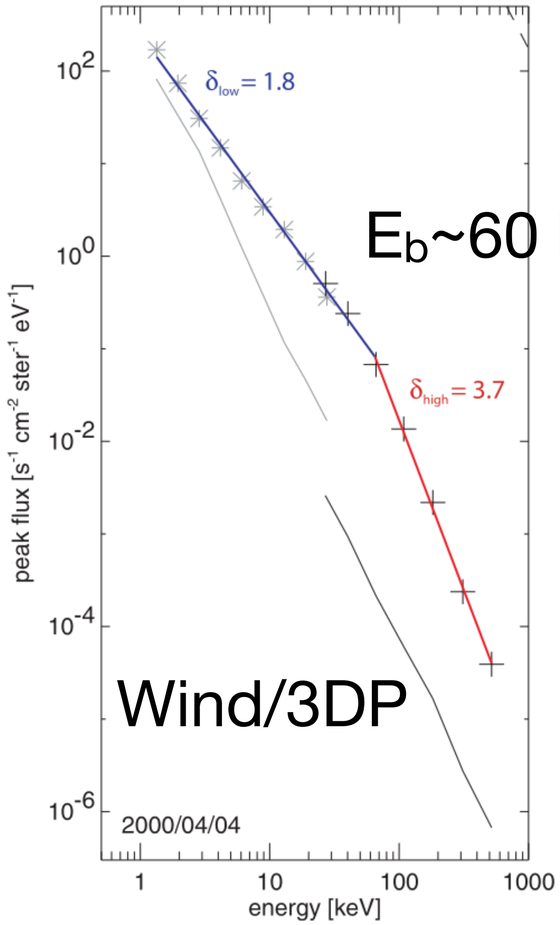
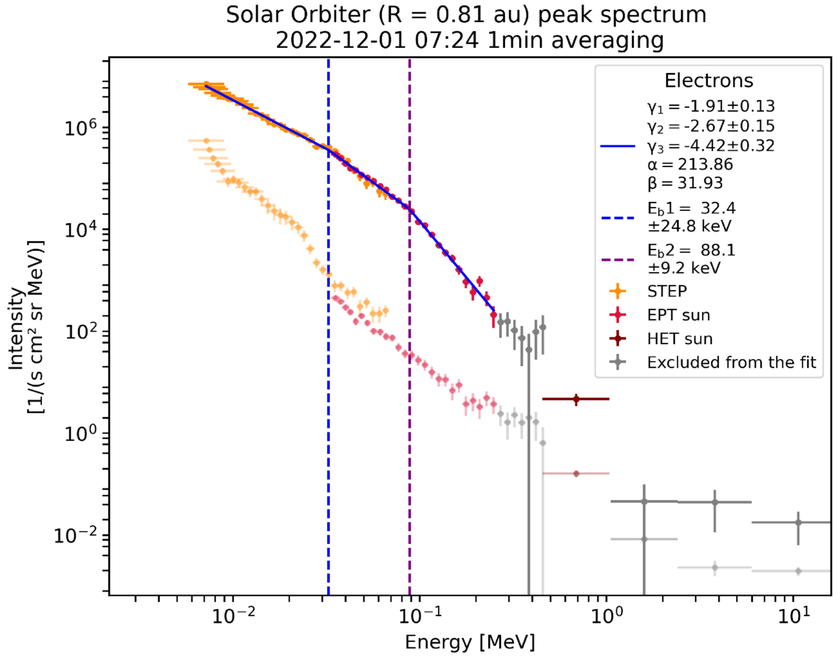
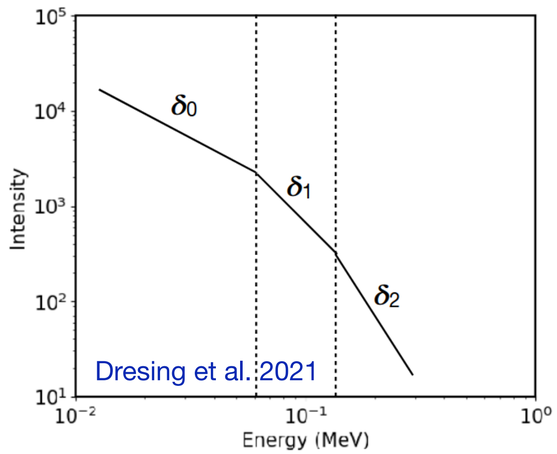
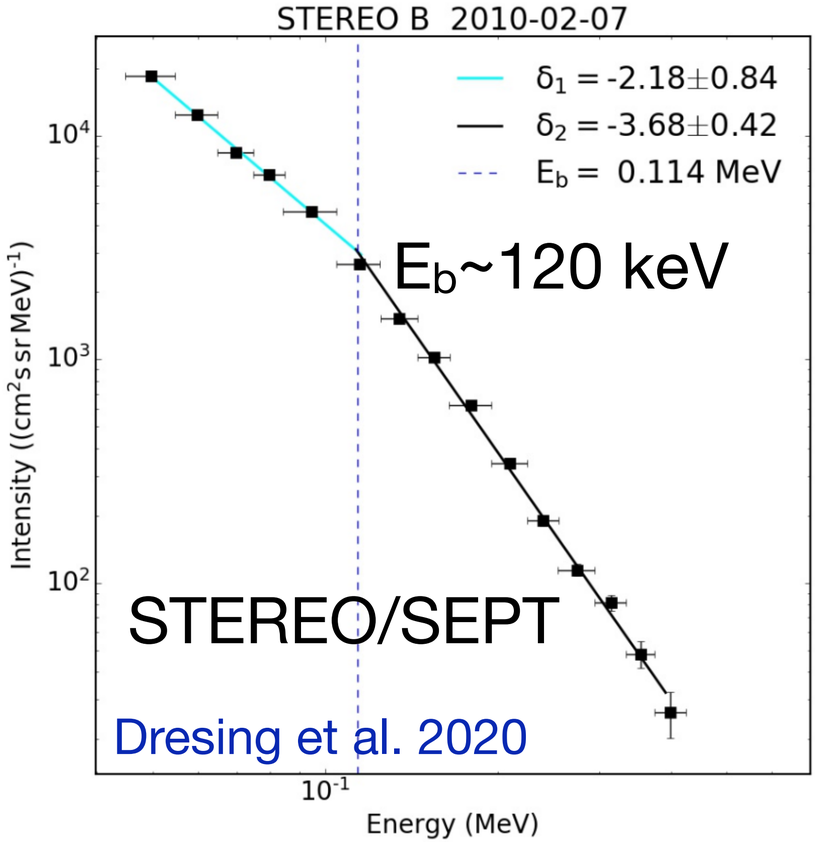
Energy spectra with Solar Orbiter/EPD

Krucker et al. 2009









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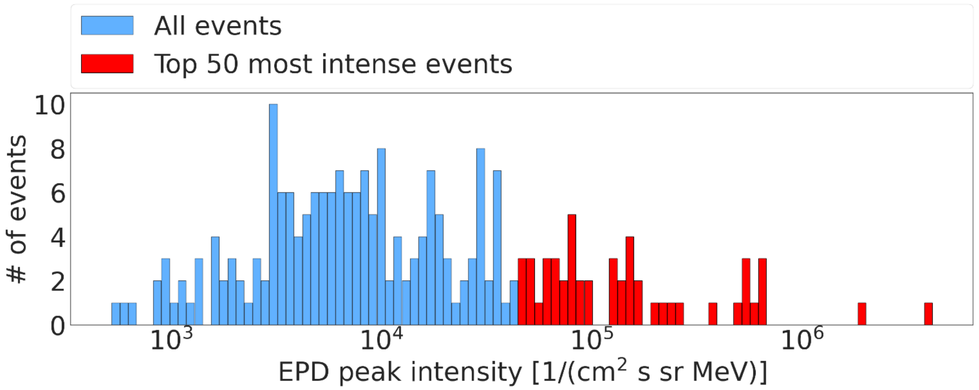
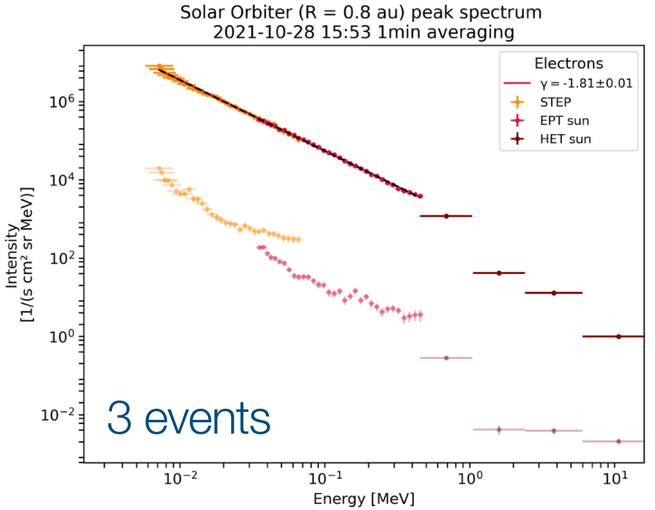
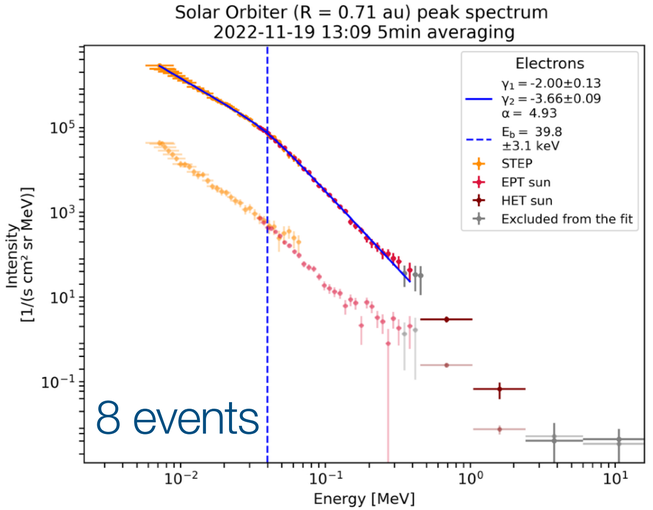
Energy spectra with Solar Orbiter / EPD

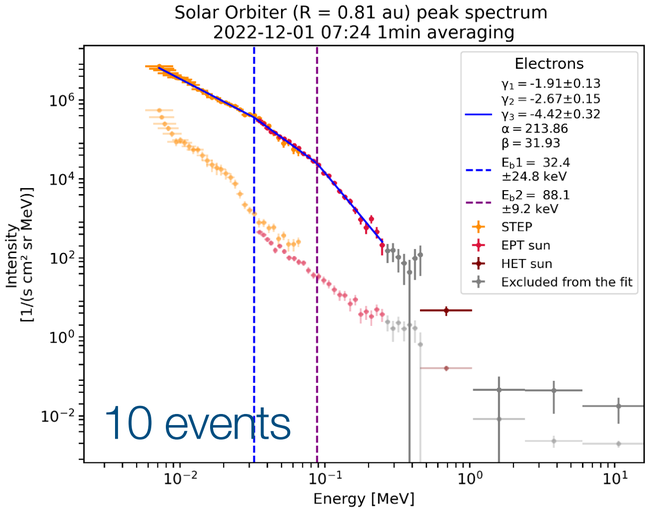
Statistical analysis of peak intensity spectra of solar energetic electron events

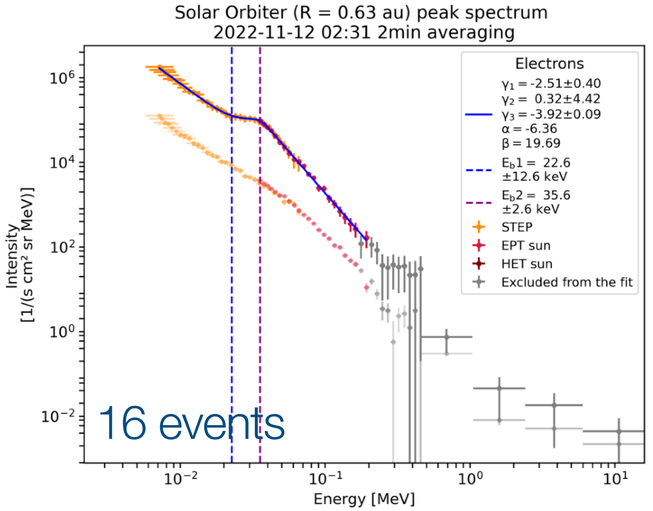
Based on the CoSEEcat catalog (Warmuth+ 2025, submitted)











Fedeli et al. 2025, to be submitted

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SEP analysis tools of SERPENTINE and SOLER

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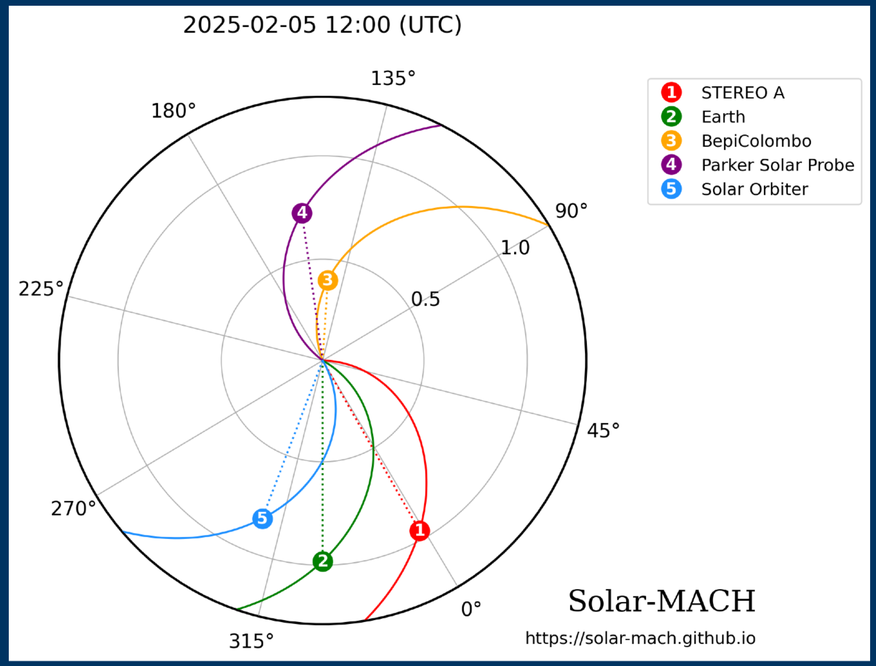
SERPENTINE: Solar energetic particle analysis platform for the inner heliosphere

(EU Horizons 2020; 2021–2024)

- six partners
- SERPENTINE studied very **high energy particles emitted from the Sun** during solar eruptions – Particle acceleration and transport processes



SOLER: Energetic Solar Eruptions: Data and Analysis Tools

(EU Horizons Europe; 2024–2027)

- five partners
- SOLER investigates the **most energetic phenomena occurring at the Sun**: their interrelations, variability and energy partitioning

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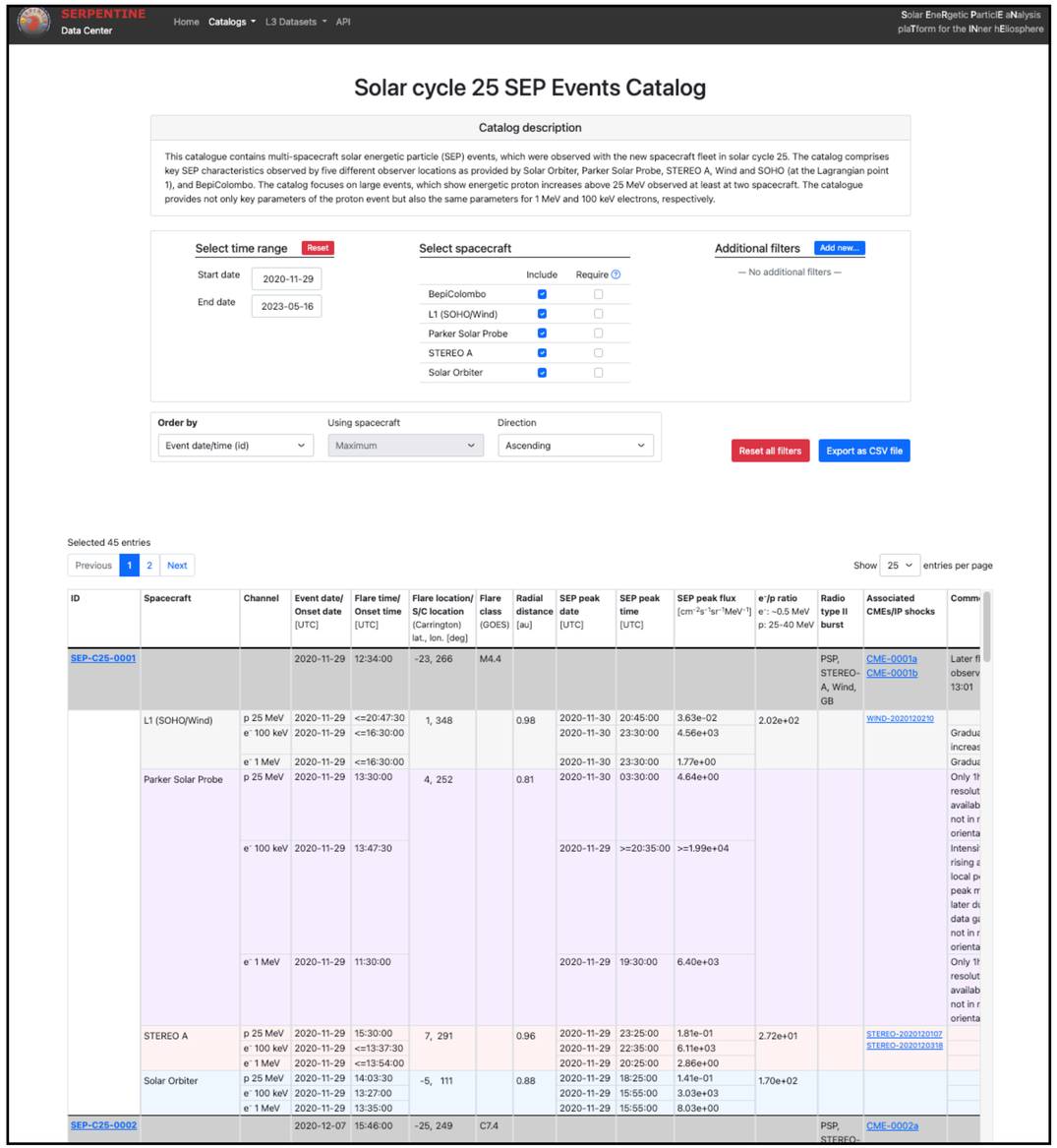
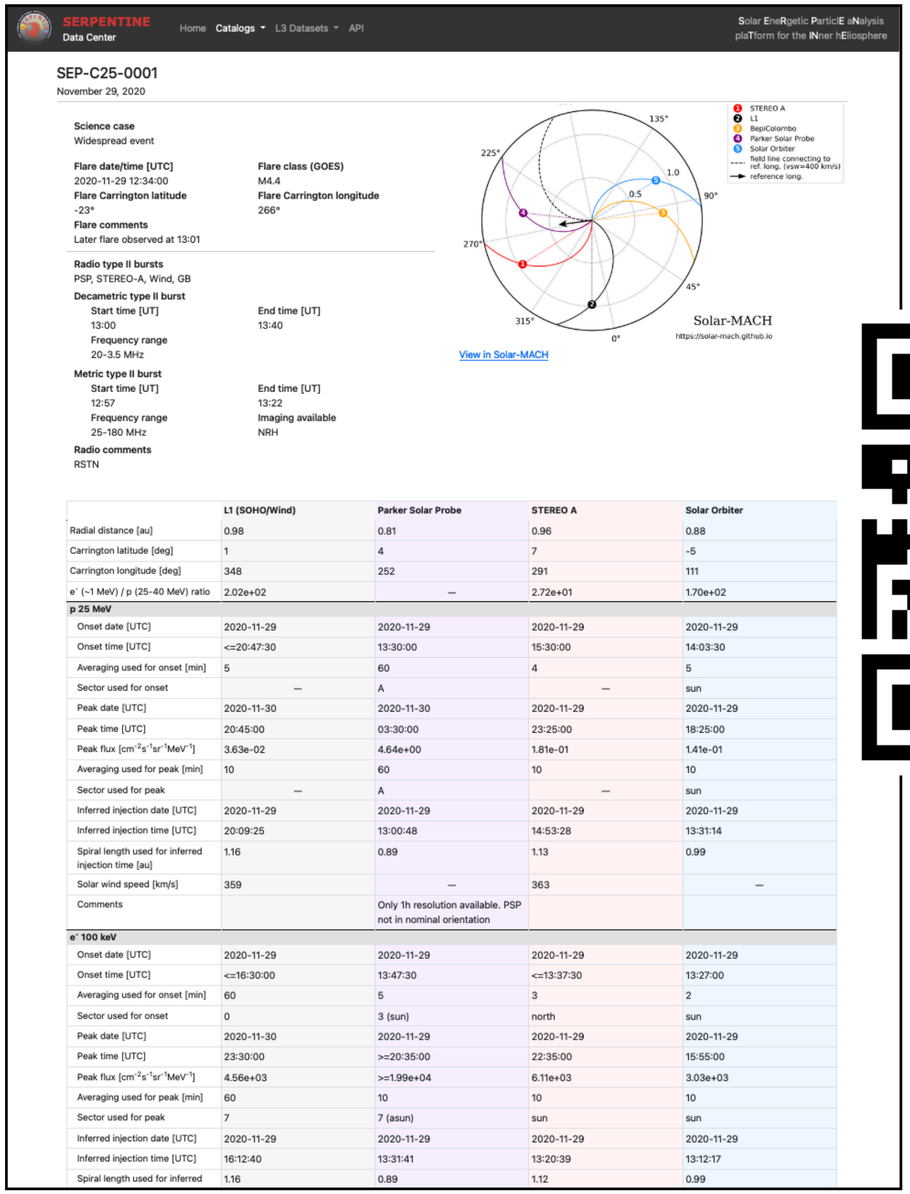
Multi-sc SEP event catalog of solar cycle 25

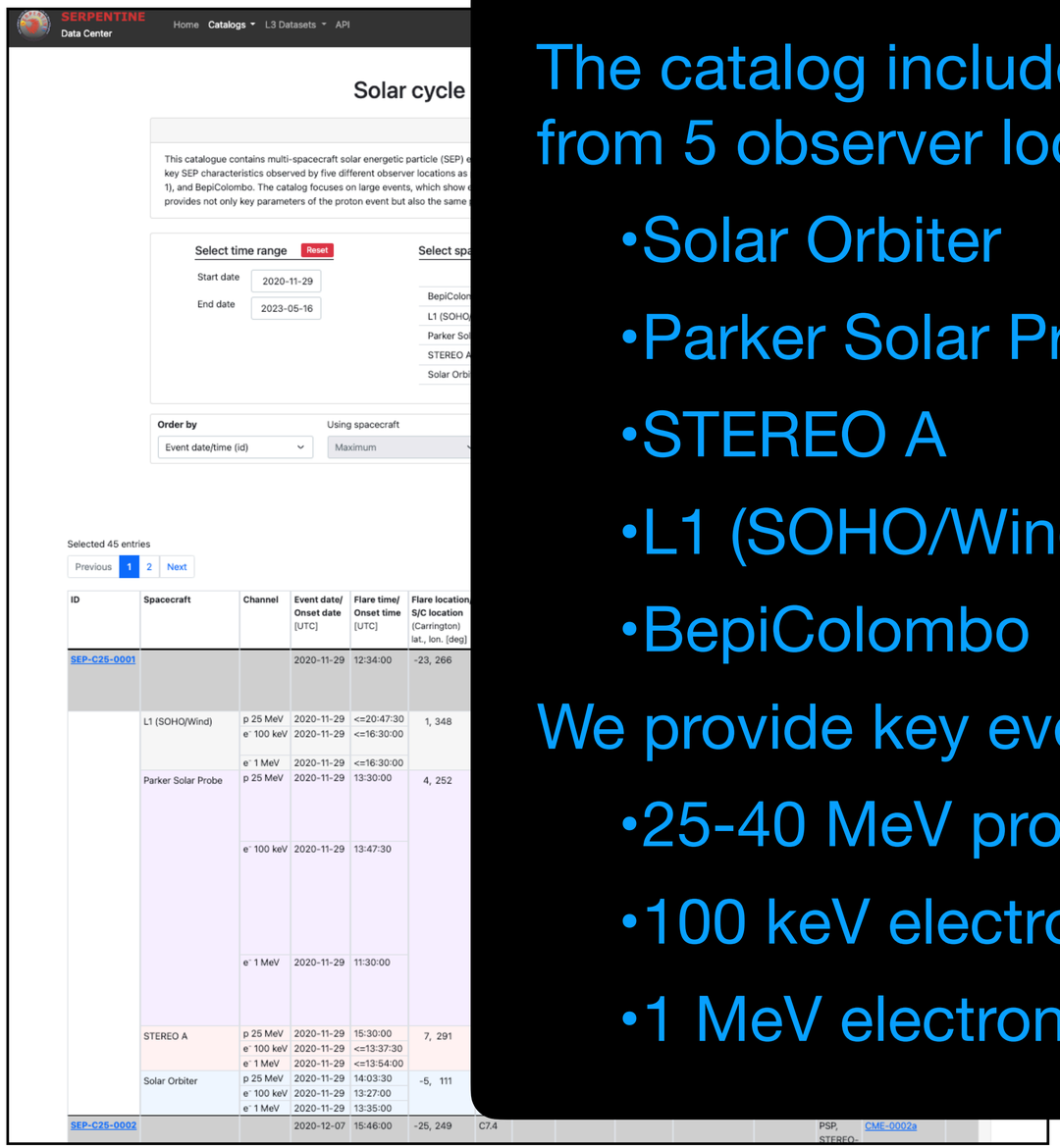




see also
Dresing+ 2024

Nina Dresing, University of Turku, Finland

Multi-sc SEP event catalog of solar cycle 25

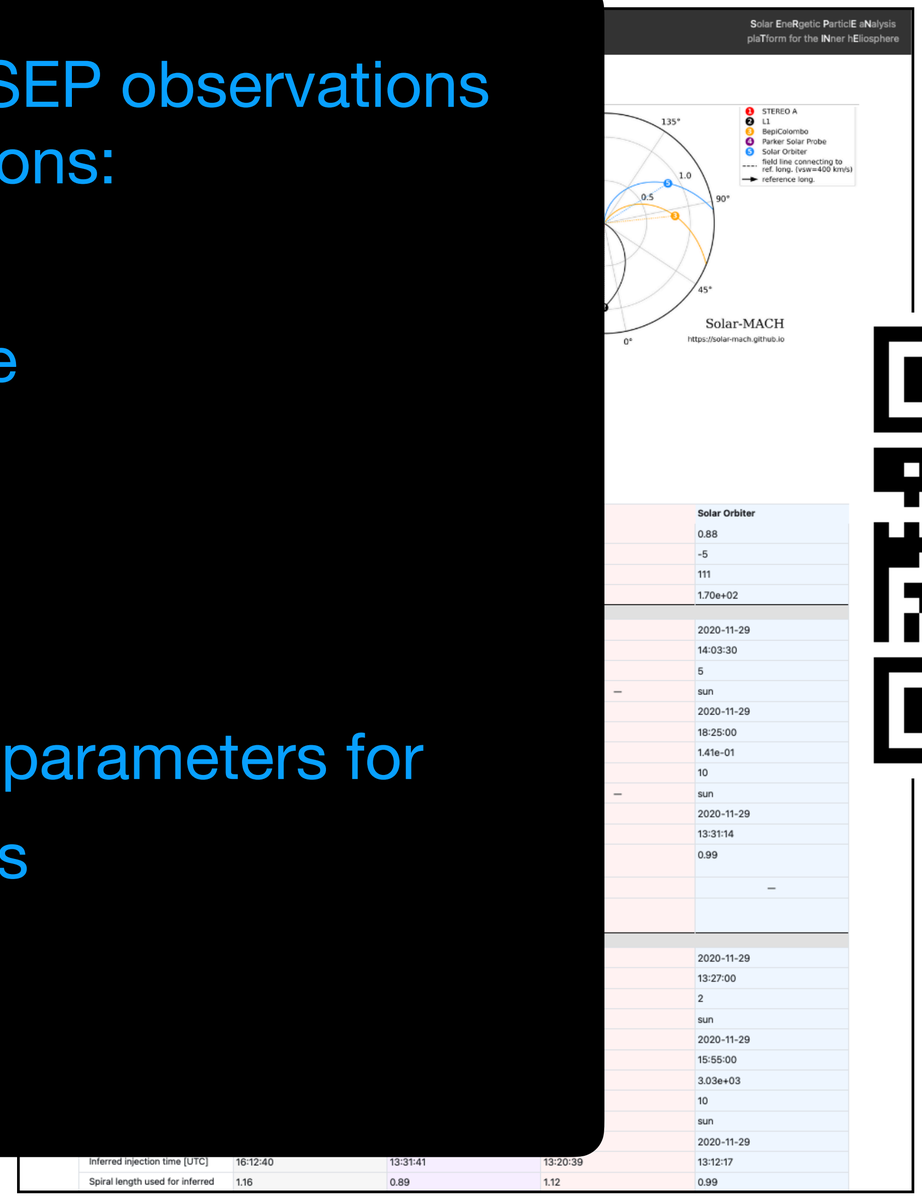


The catalog includes SEP observations from 5 observer locations:

- Solar Orbiter
- Parker Solar Probe
- STEREO A
- L1 (SOHO/Wind)
- BepiColombo

We provide key event parameters for

- 25-40 MeV protons
- 100 keV electrons
- 1 MeV electrons



see also Dresing+ 2024

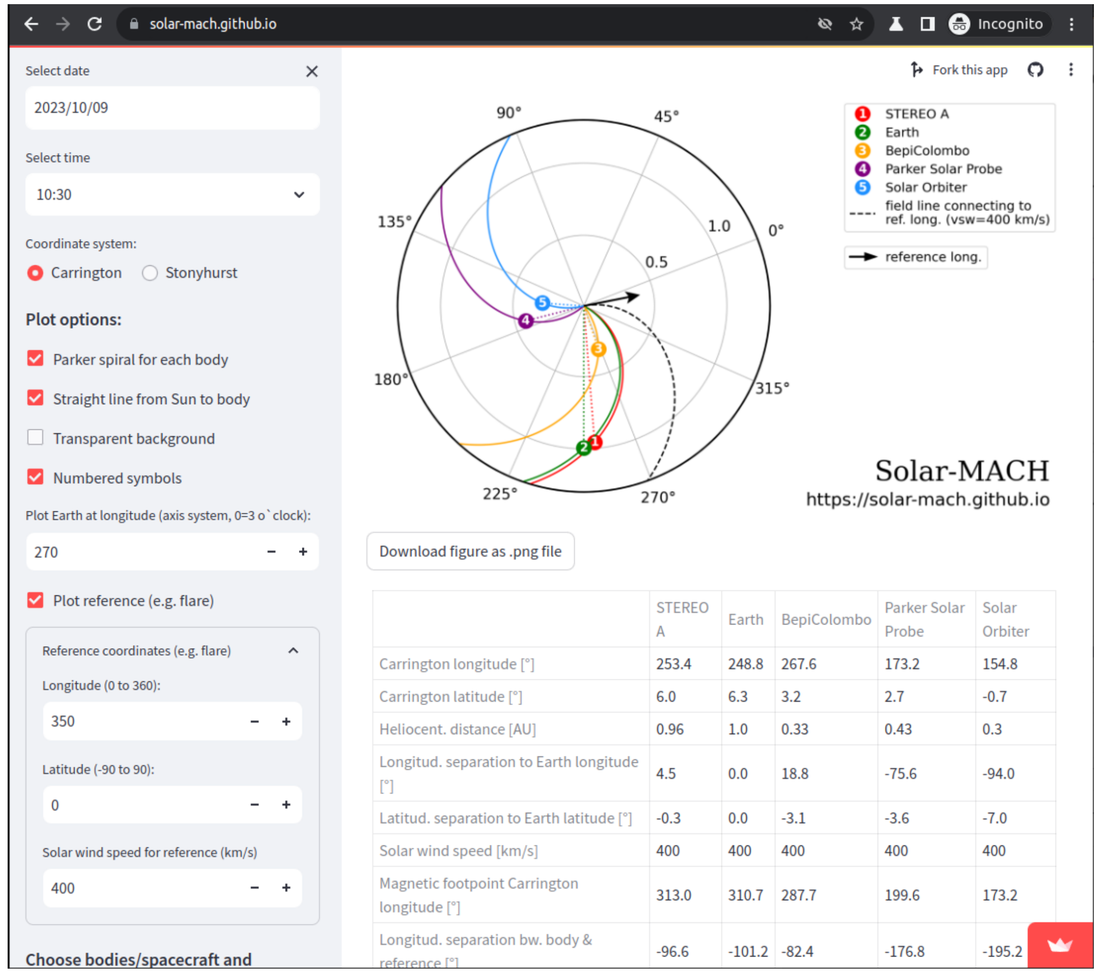
Nina Dresing, University of Turku, Finland

Technical objectives of SERPENTINE and SOLER

Development of analysis and modeling tools for the scientific community

Event catalogs and datasets:

SERPENTINE/SOLER Jupyter HUB:



	STEREO A	Earth	BepiColombo	Parker Solar Probe	Solar Orbiter
Carrington longitude [°]	253.4	248.8	267.6	173.2	154.8
Carrington latitude [°]	6.0	6.3	3.2	2.7	-0.7
Heliocent. distance [AU]	0.96	1.0	0.33	0.43	0.3
Longitud. separation to Earth longitude [°]	4.5	0.0	18.8	-75.6	-94.0
Latitud. separation to Earth latitude [°]	-0.3	0.0	-3.1	-3.6	-7.0
Solar wind speed [km/s]	400	400	400	400	400
Magnetic footpoint Carrington longitude [°]	313.0	310.7	287.7	199.6	173.2
Longitud. separation bw. body & reference [°]	-96.6	-101.2	-82.4	-176.8	-195.2

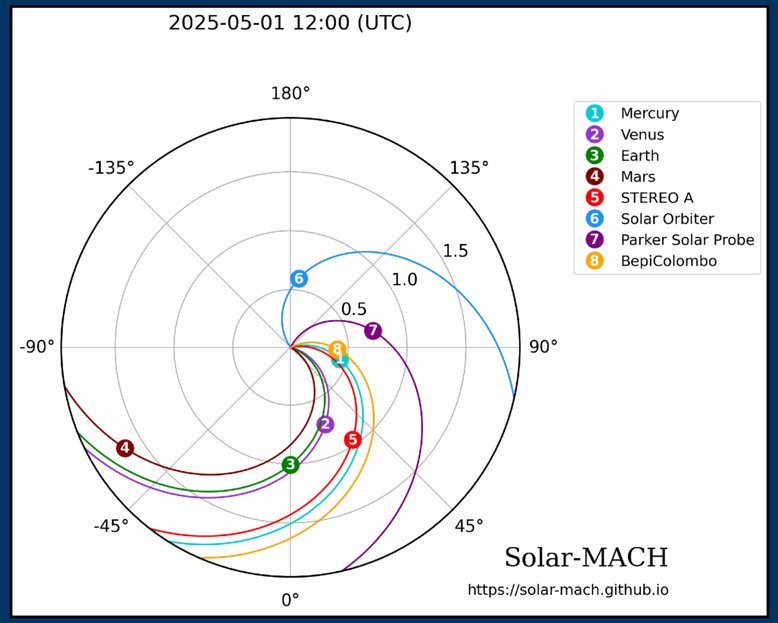
Nina Dresing, University of Turku, Finland

SERPENTINE Tools

Gieseler et al. (2023). Solar-MACH: An open- source tool to analyze solar magnetic connection configurations. Front. Astronomy Space Phys. doi:10.3389/fspas.2022.1058810

Palmroos et al. (2022). Solar energetic particle time series analysis with Python. Front. Astronomy Space Phys. doi:10.3389/fspas.2022.1073578

SERPENTINE/SOLER Jupyter HUB:



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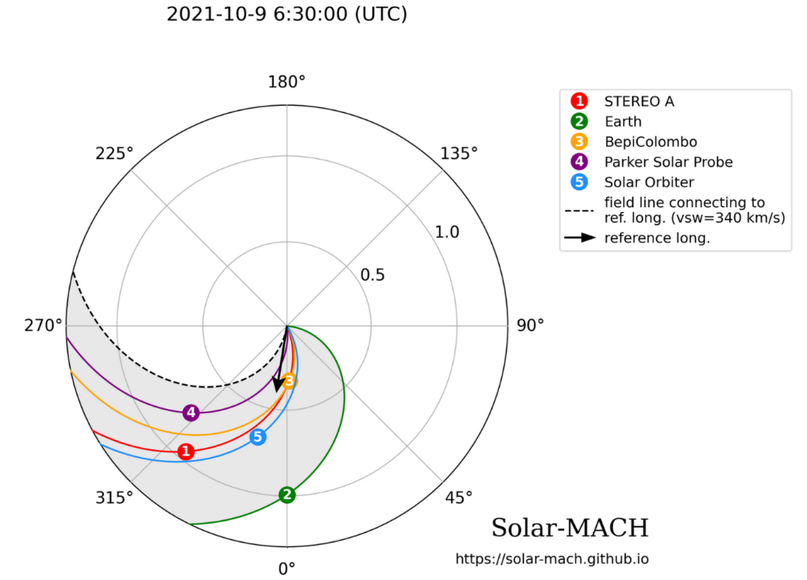
```
In [1]: from solarmach import SolarMACH

Provide the necessary options:

In [2]: body_list = ['STEREO-A', 'Earth', 'BepiColombo', 'PSP', 'Solar Orbiter']
        vsw_list = [380, 290, 300, 340, 362]  # values from Lario et al. 2022, doi:10.3847/1538-4357/ac6efd
        date = '2021-10-9 6:30:00'

The default coordinate system is Carrington coordinates, alternatively one could select the Earth-centered Stonyhurst coordinate system:

In [3]: coord_sys = 'Stonyhurst'      # 'Carrington' (default) or 'Stonyhurst'

Now we also want to indicate the position and direction of a flare, and the (assumed) solar wind speed at its location:

In [4]: reference_long = 351          # Carrington longitude of reference (None to omit)
        reference_lat = 0             # Carrington latitude of reference (None to omit)
        reference_vsw = 340           # define solar wind speed at reference

In addition, we explicitly provide all availabe plotting options:

In [5]: plot_spirals = True           # plot Parker spirals for each body
        plot_sun_body_line = False    # plot straight line between Sun and body
        long_offset = 270             # longitudinal offset for polar plot; defines where Earth's longitude is (by default 27
        numbered_markers = True       # plot each body with a numbered marker

Finally, initializing and plotting with these options.

In [6]: sm = SolarMACH(date, body_list, vsw_list, reference_long, reference_lat, coord_sys)

        sm.plot(plot_spirals=plot_spirals, plot_sun_body_line=plot_sun_body_line, long_offset=long_offset,
                reference_vsw=reference_vsw, numbered_markers=numbered_markers,
                long_sector=[351, 85], long_sector_vsw=[340, 290], long_sector_color='lightgrey')
```

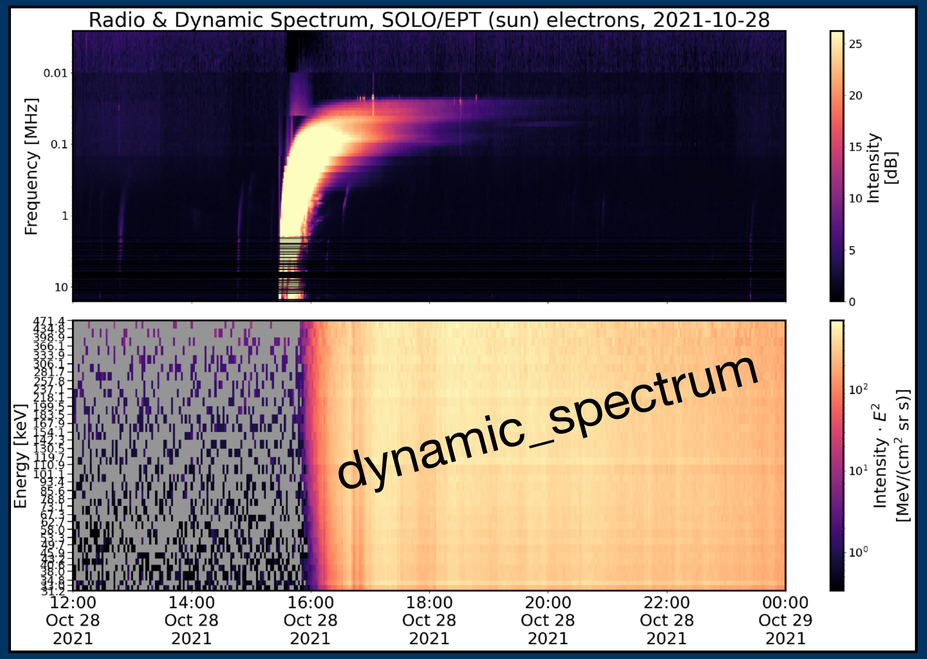


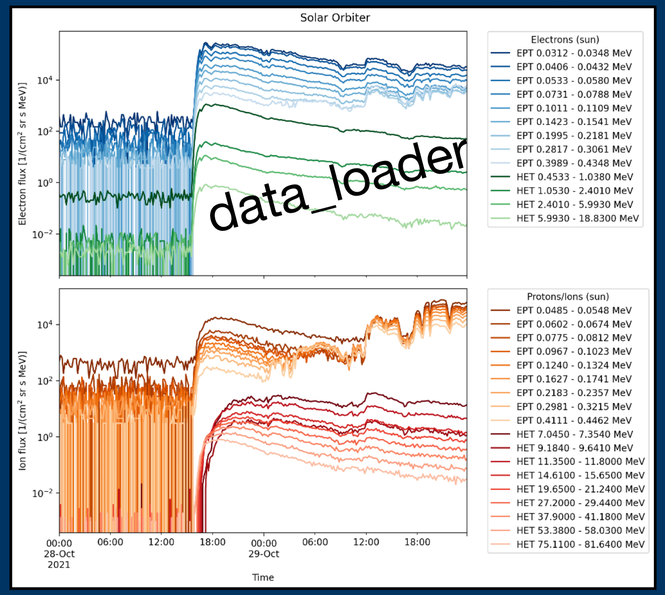
All the data can also be obtained as a Pandas DataFrame for further use:

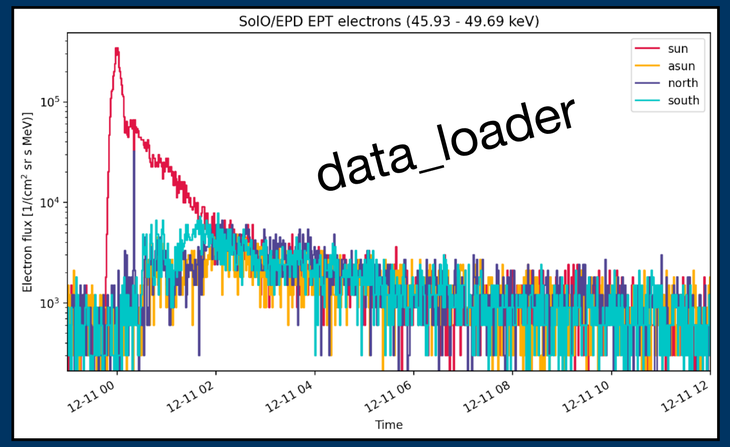
```
In [7]: sm.coord_table
Out[7]:
```

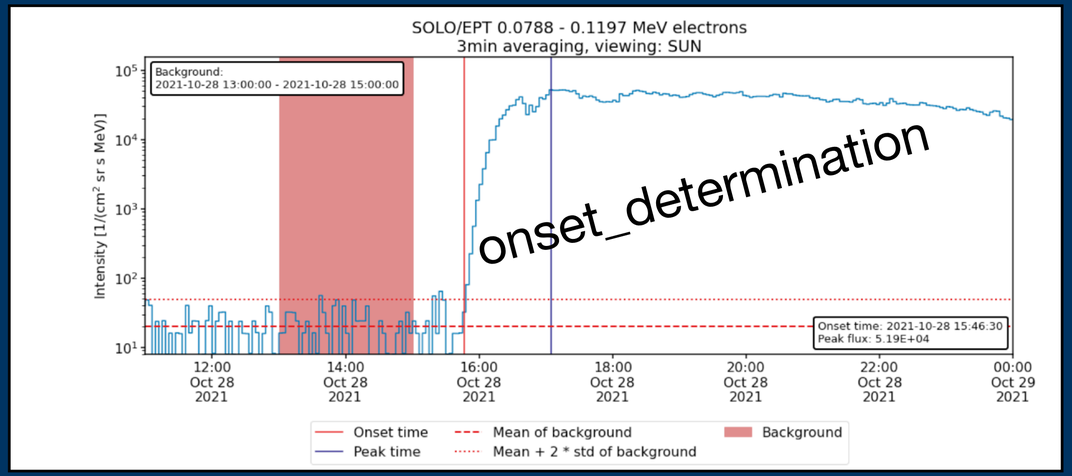
	Spacecraft/Body	Stonyhurst longitude (°)	Stonyhurst latitude (°)	Heliocentric distance (AU)	Longitudinal separation to Earth's longitude	Latitudinal separation to Earth's latitude	Vsw	Magnetic footpoint longitude (Stonyhurst)	Longitudinal separation between body and reference_long	Longitudinal separation between body's mangetic footpoint and reference_long	Latitudinal separation between body and reference_lat
0	STEREO-A	-38.917004	7.276757	0.957026	-38.917005	1.009886	380	23.300249	-389.917004	32.300249	7.276757
1	Earth	0.000001	6.266871	0.998914	0.000000	0.000000	290	85.360062	-350.999999	94.360062	6.266871
2	BepiColombo	2.551346	2.176375	0.330621	2.551344	-4.090496	300	29.803439	-348.448654	38.803439	2.176375
3	PSP	-47.855146	3.694387	0.765364	-47.855148	-2.572484	340	8.154330	-398.855146	17.154330	3.694387
4	Solar Orbiter	-14.772829	2.339315	0.678619	-14.772830	-3.927556	362	31.915162	-365.772829	40.915162	2.339315

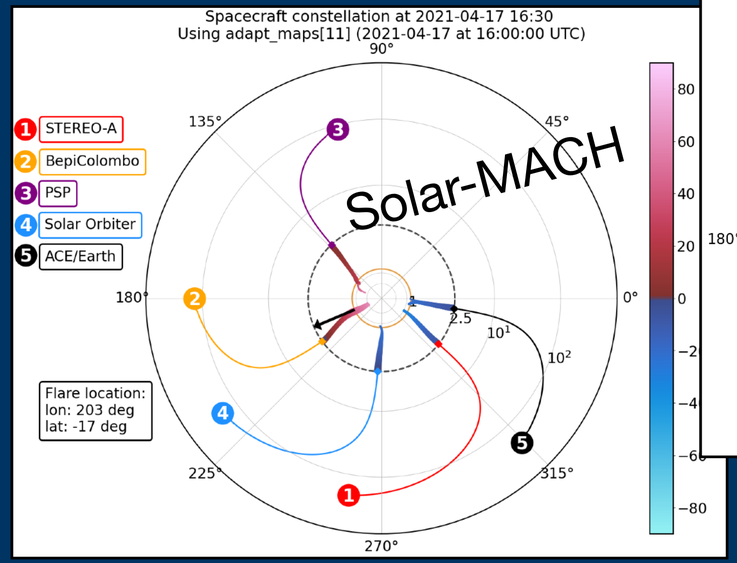
SERPENTINE's SEP analysis Tools

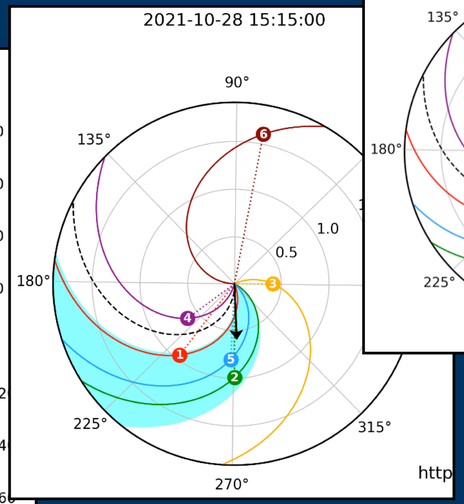


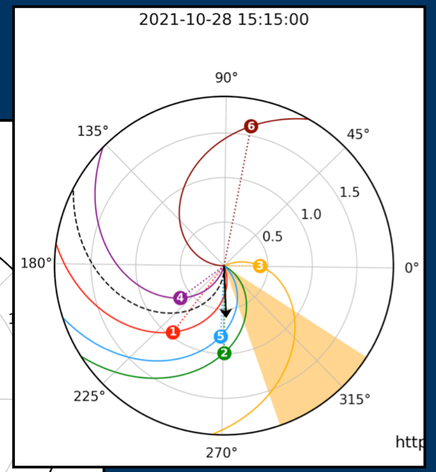












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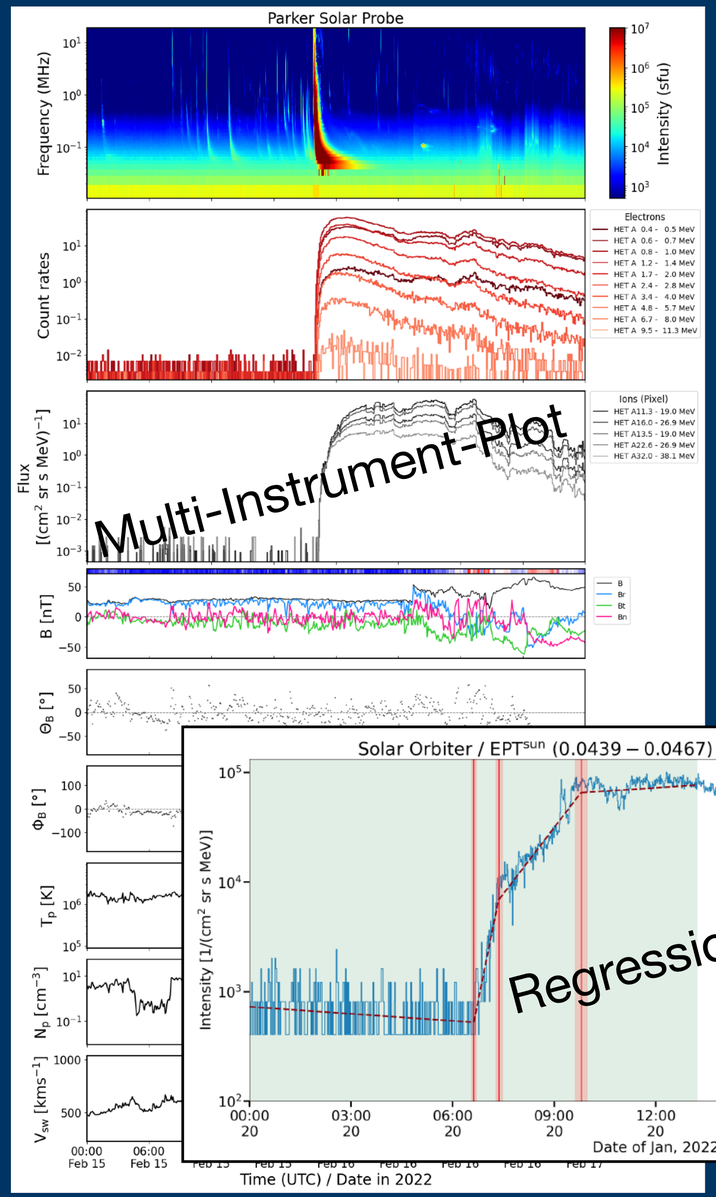
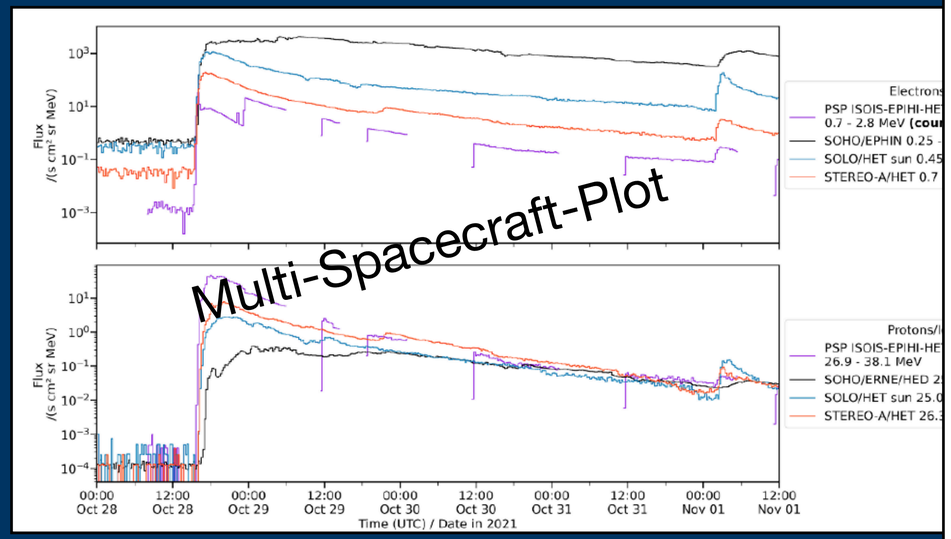
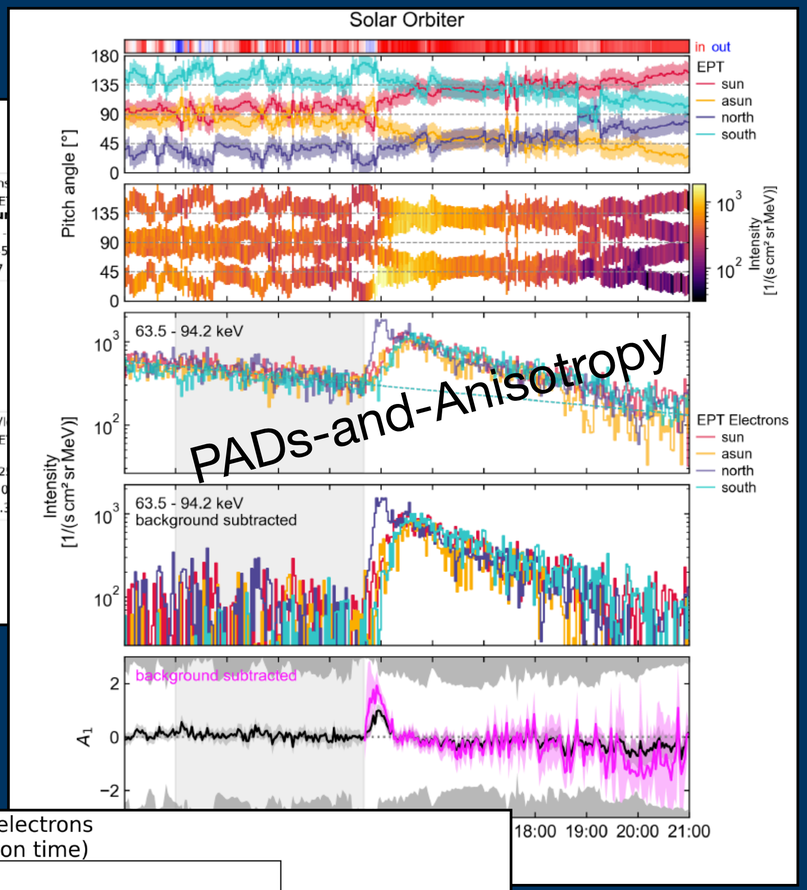
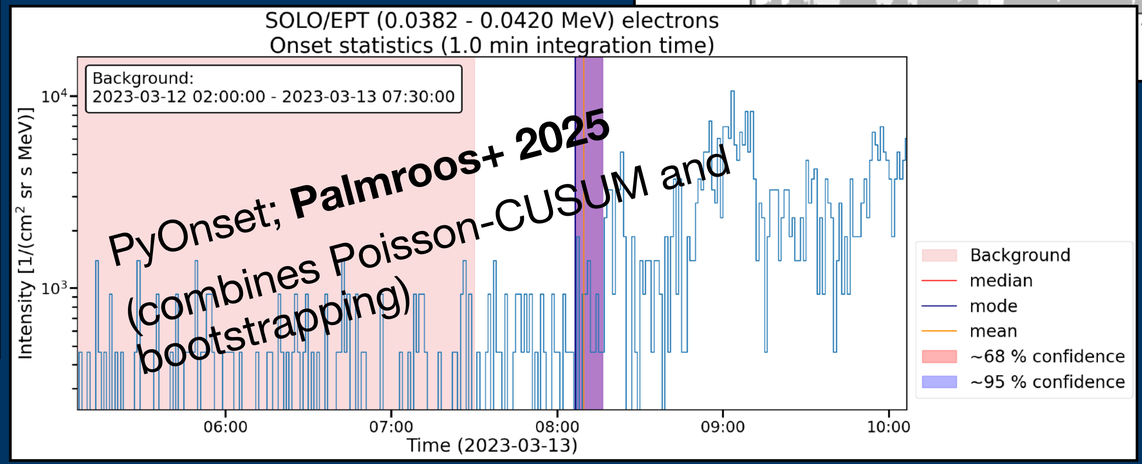
SOLER's SEP analysis Tools









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Summary

- Solar Orbiter is part of an unprecedented spacecraft fleet opening new avenues to study solar energetic particle events
  - Disentangle source and transport effects
  - Characterize the longitudinal distribution of SEPs (and soon also the latitudinal distribution)

- Solar Orbiter's excellent energetic particle detector (EPD) allows to push the limits of energy spectra analysis
  - New insights into SEP transport effects
  - Opens the door to connect energy spectra with remote sensing observations of potential source regions

---

- Various energetic particle and in-situ analysis tools provided by the SERPENTINE and SOLER EU projects available at https://hub-route-serpentine-soler.2.rahtiapp.fi/

All tools also on GitHub:

- https://github.com/serpentine-h2020/serpentine
- https://github.com/soler-he
- https://github.com/jgieseler/solarmach
- https://github.com/Christian-Palmroos/PyOnset

Event catalogs and datasets:

SERPENTINE/SOLER Jupyter HUB:

Funded by the European Union

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