

# Observations of solar energetic particle events with Solar Orbiter and friends

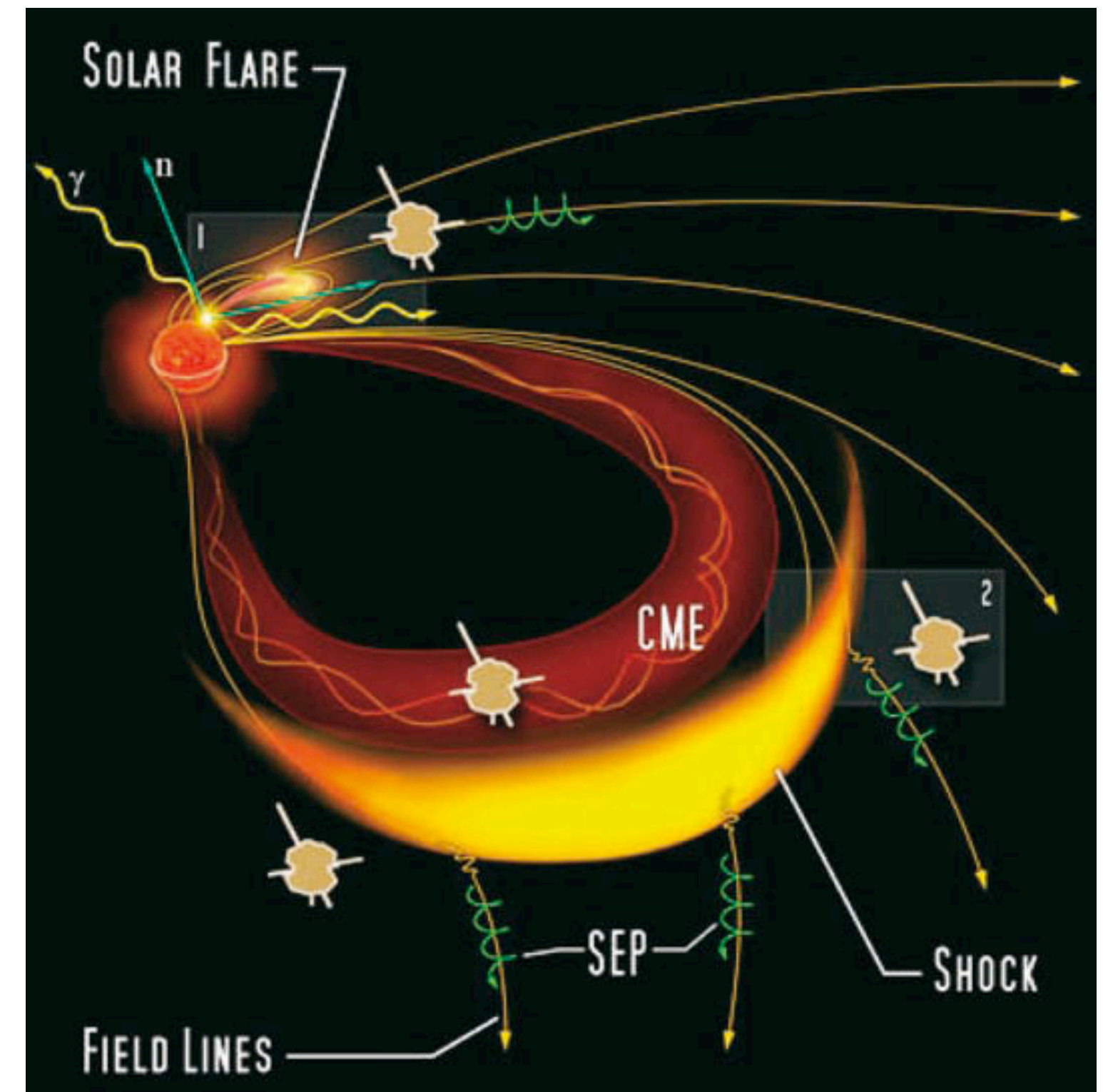
New results and open-source analysis tools



# 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

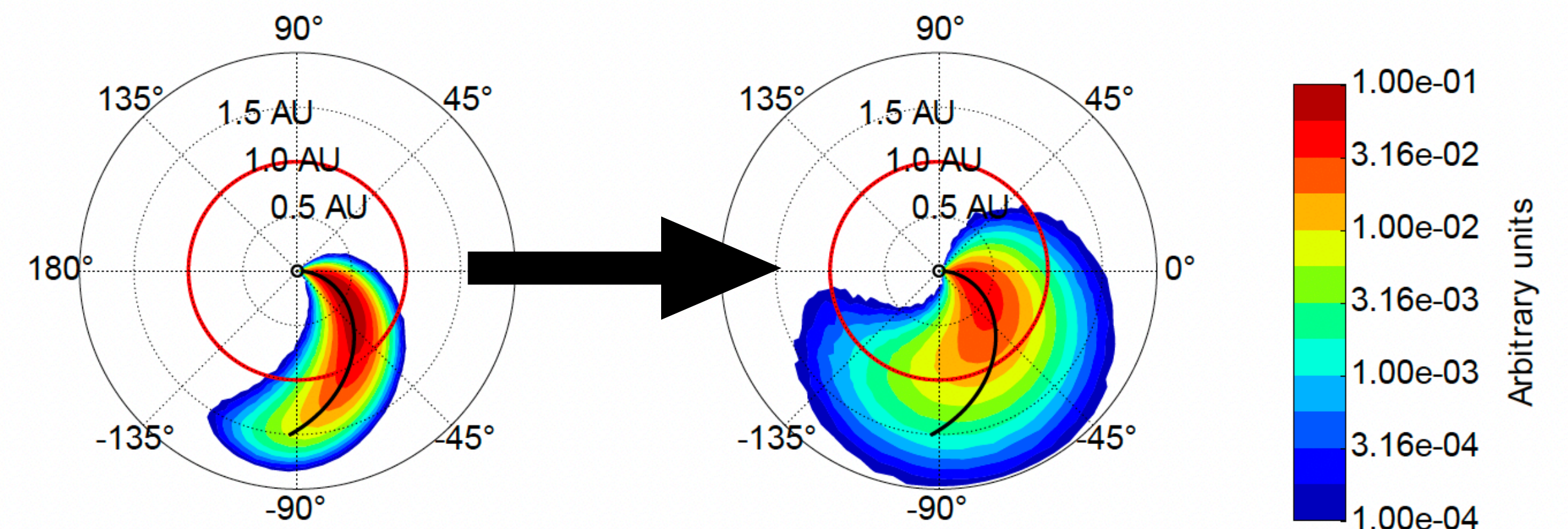
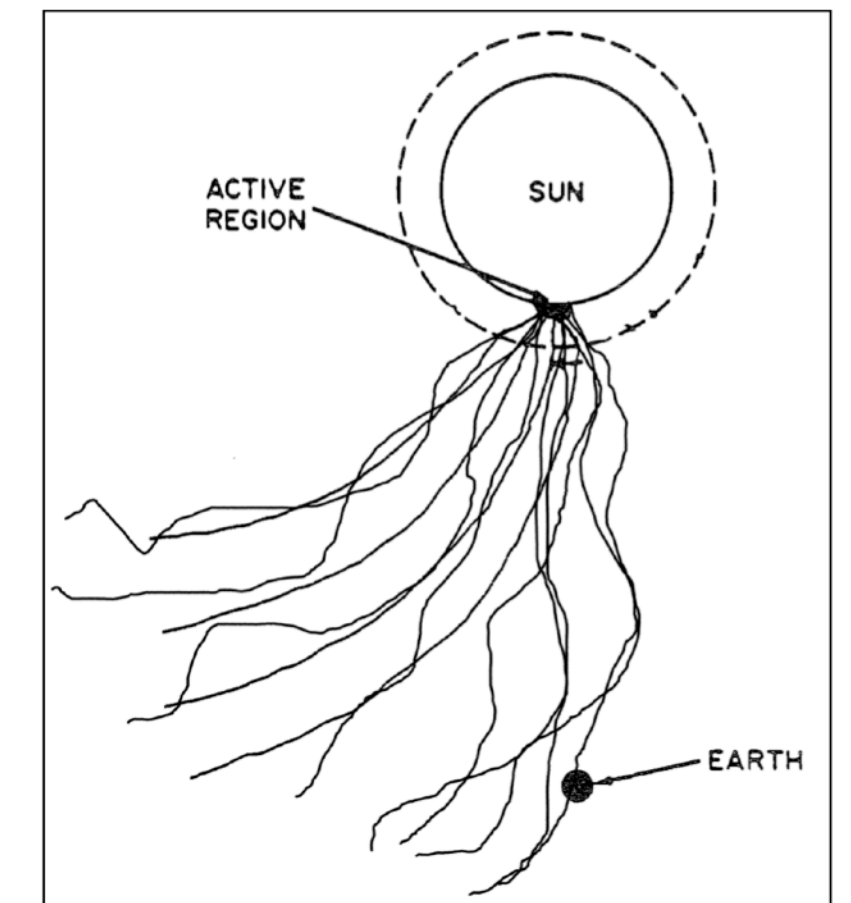
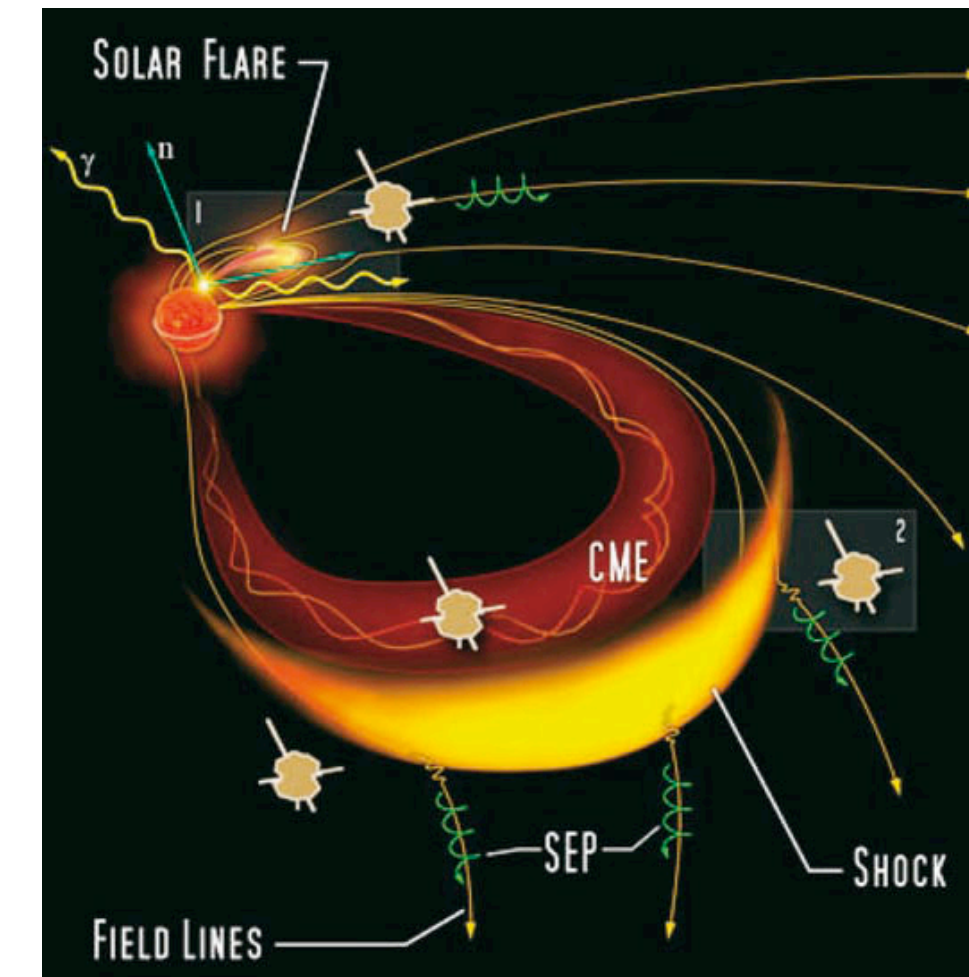




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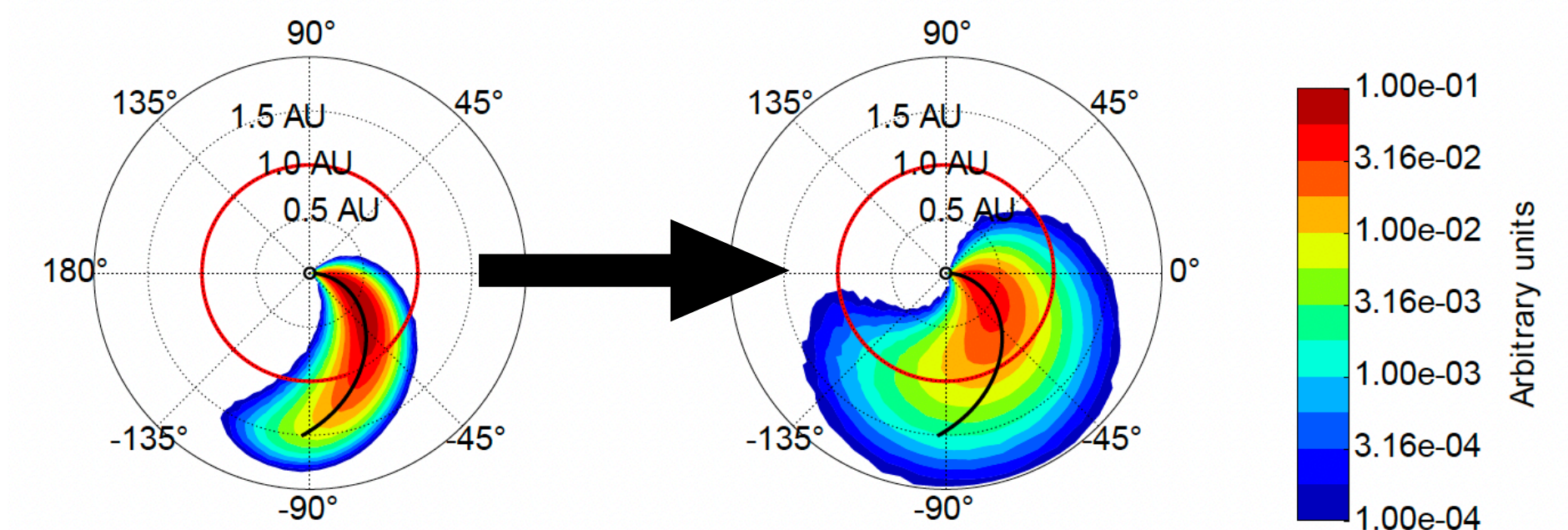
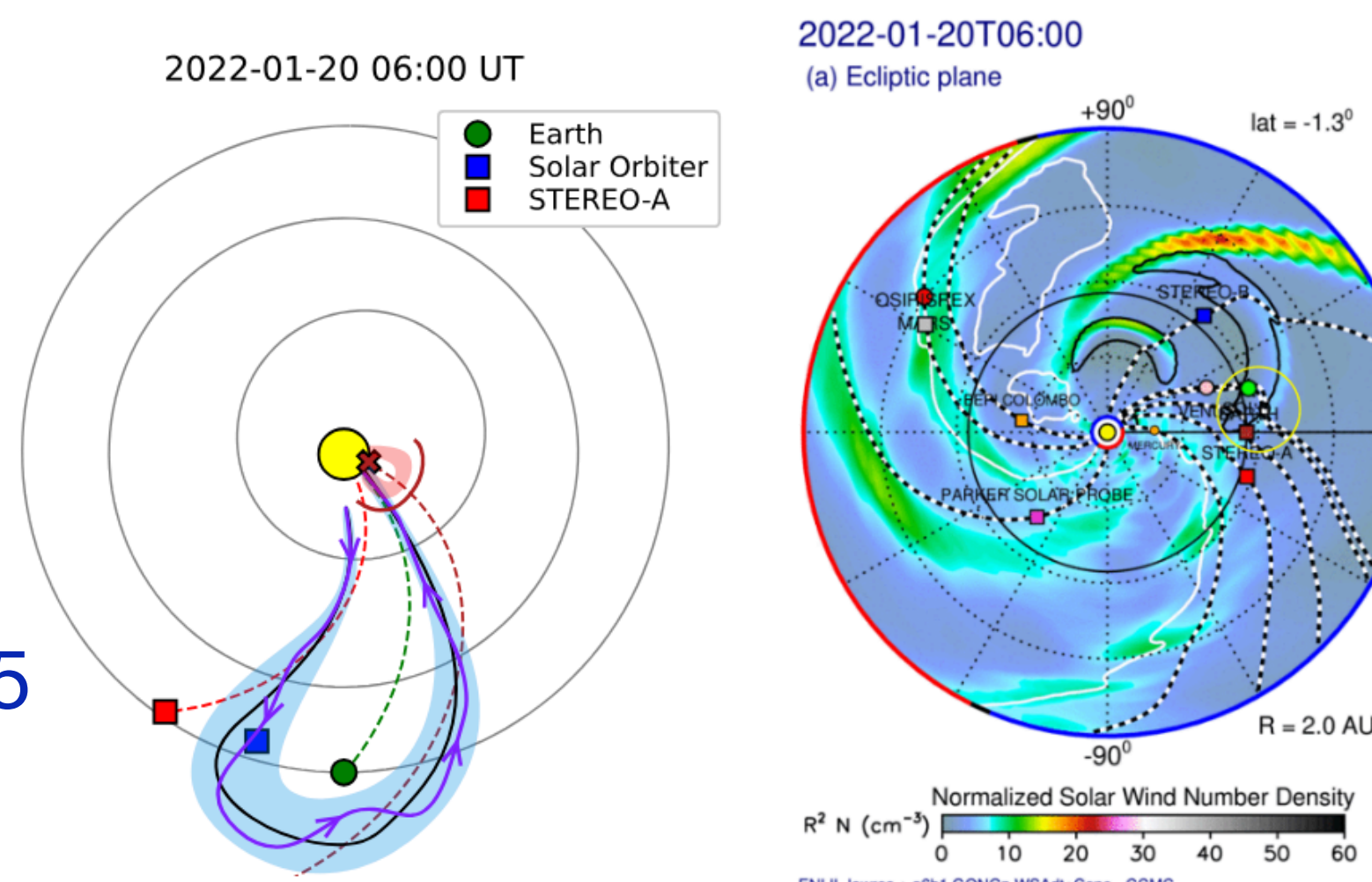
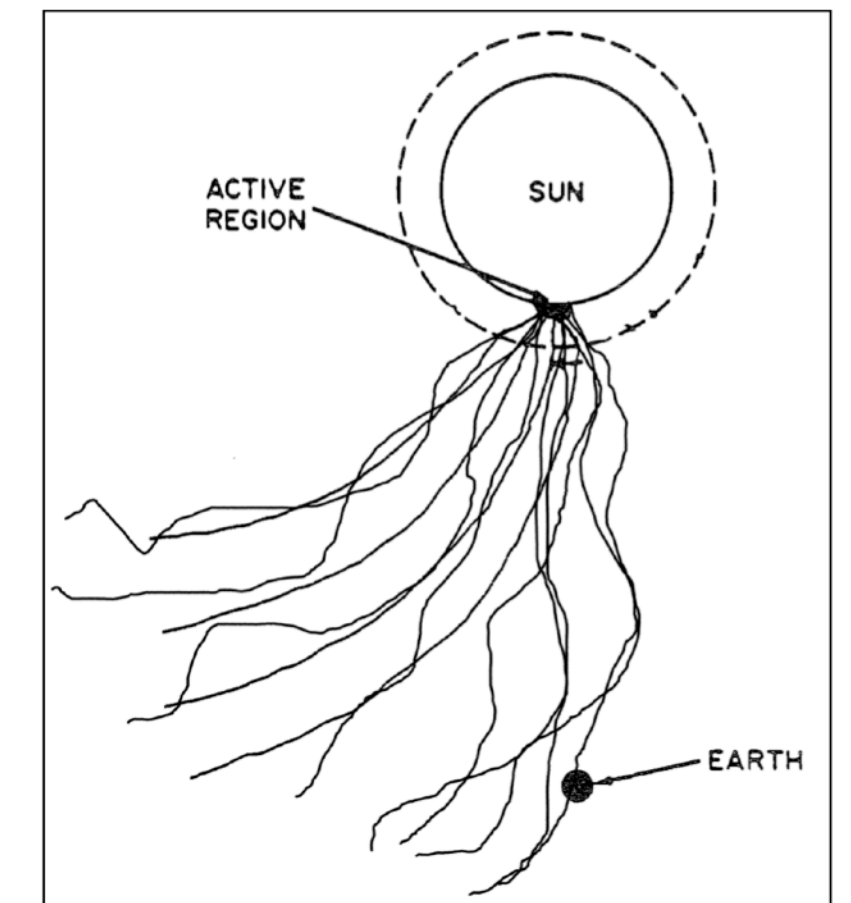
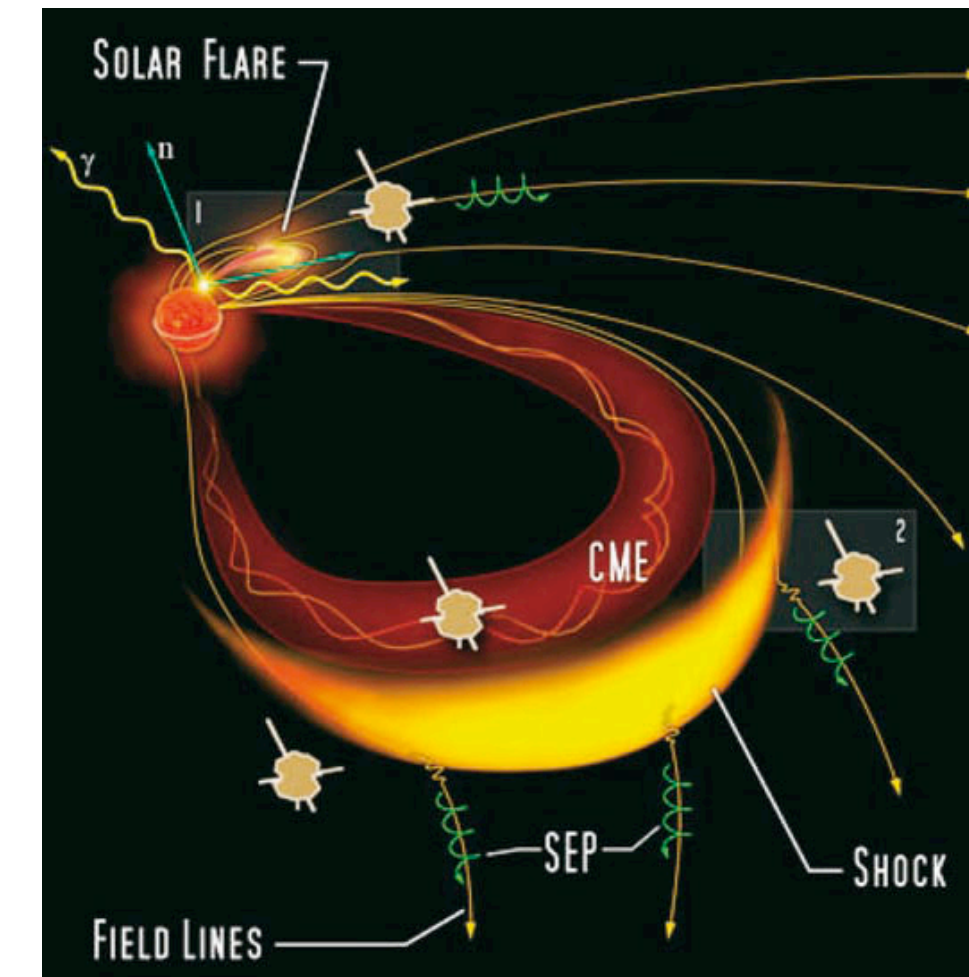




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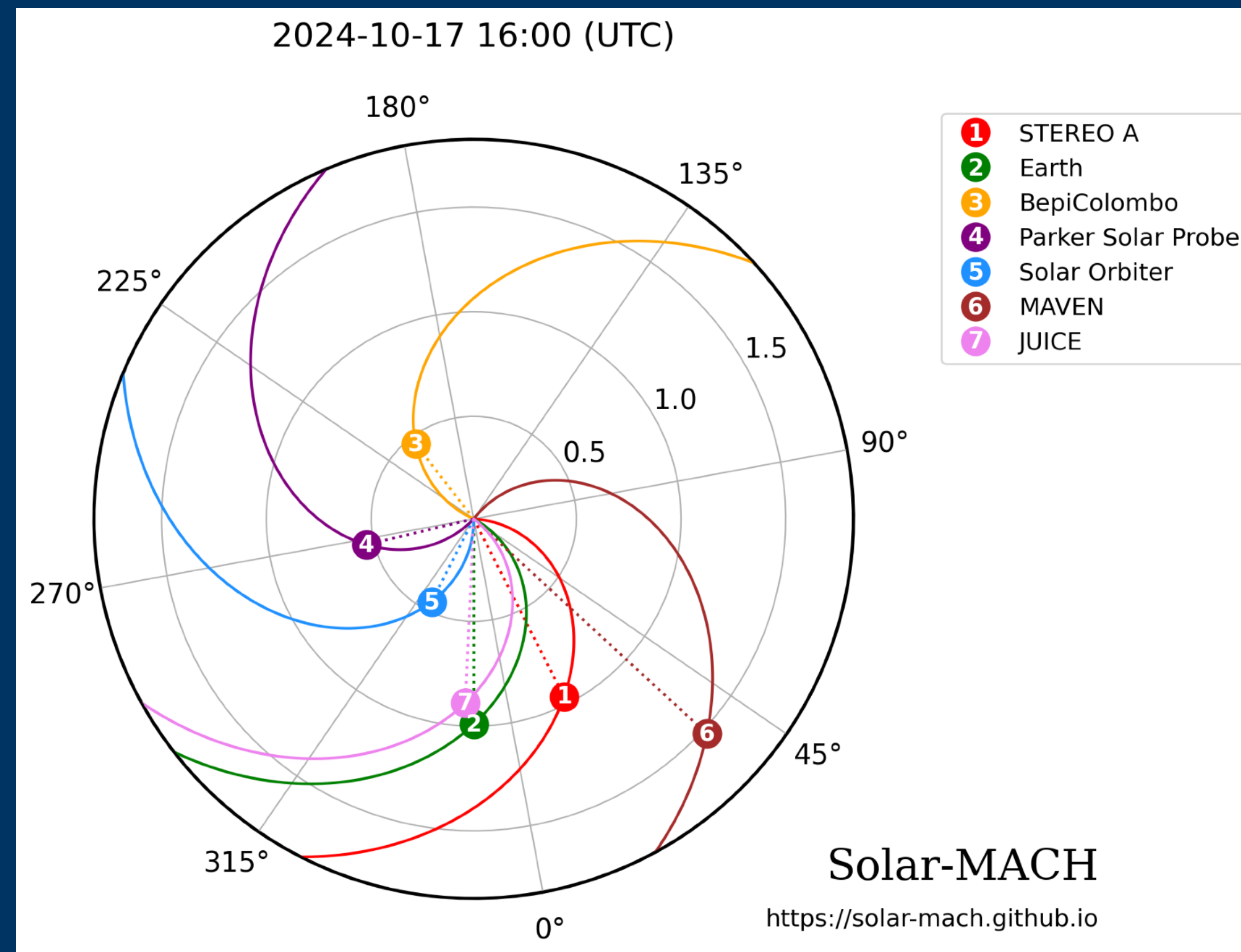


Rodríguez-García+ 2025

Laitinen+ 2016



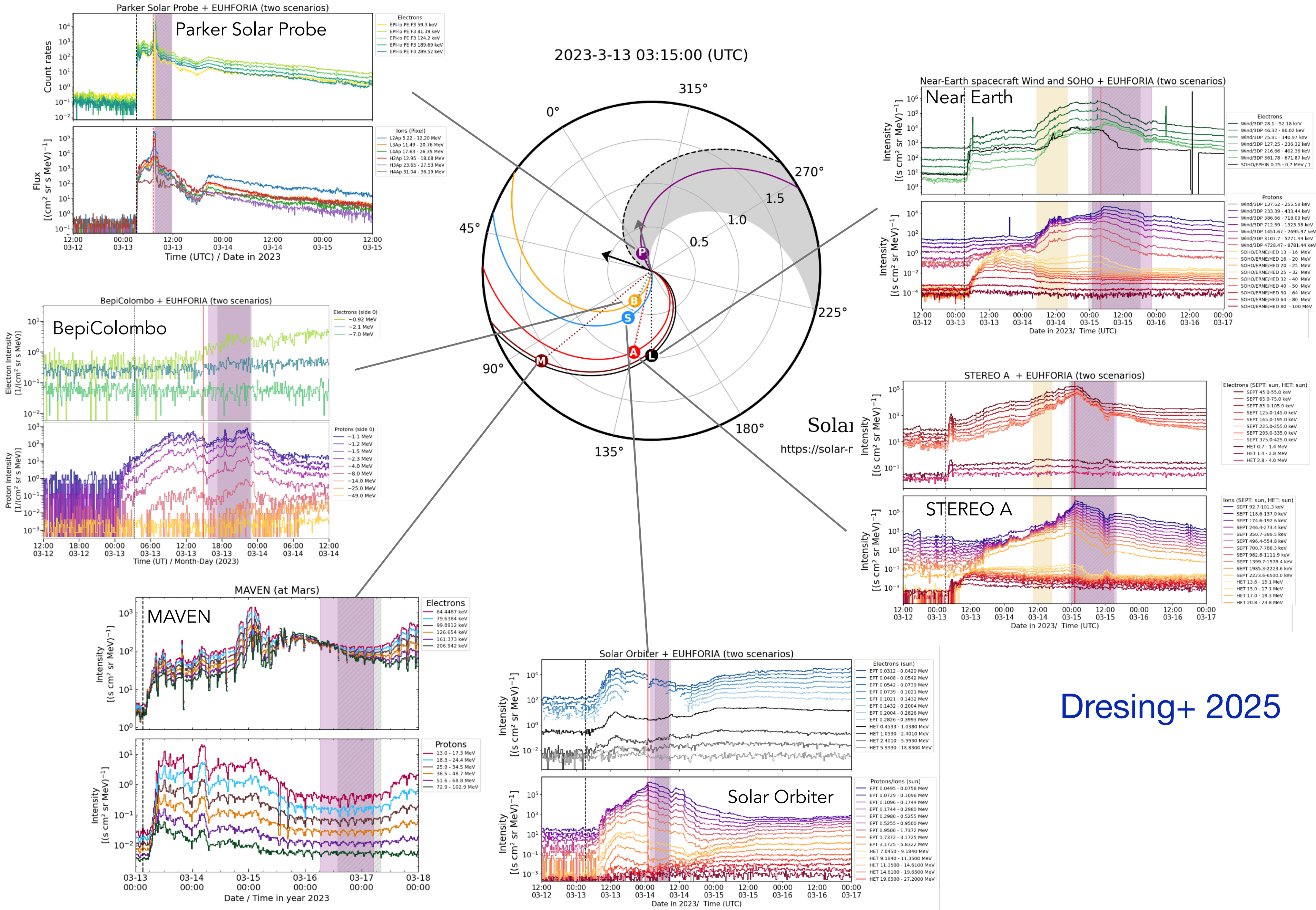
# Multi-Spacecraft observations with the new fleet





# 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!

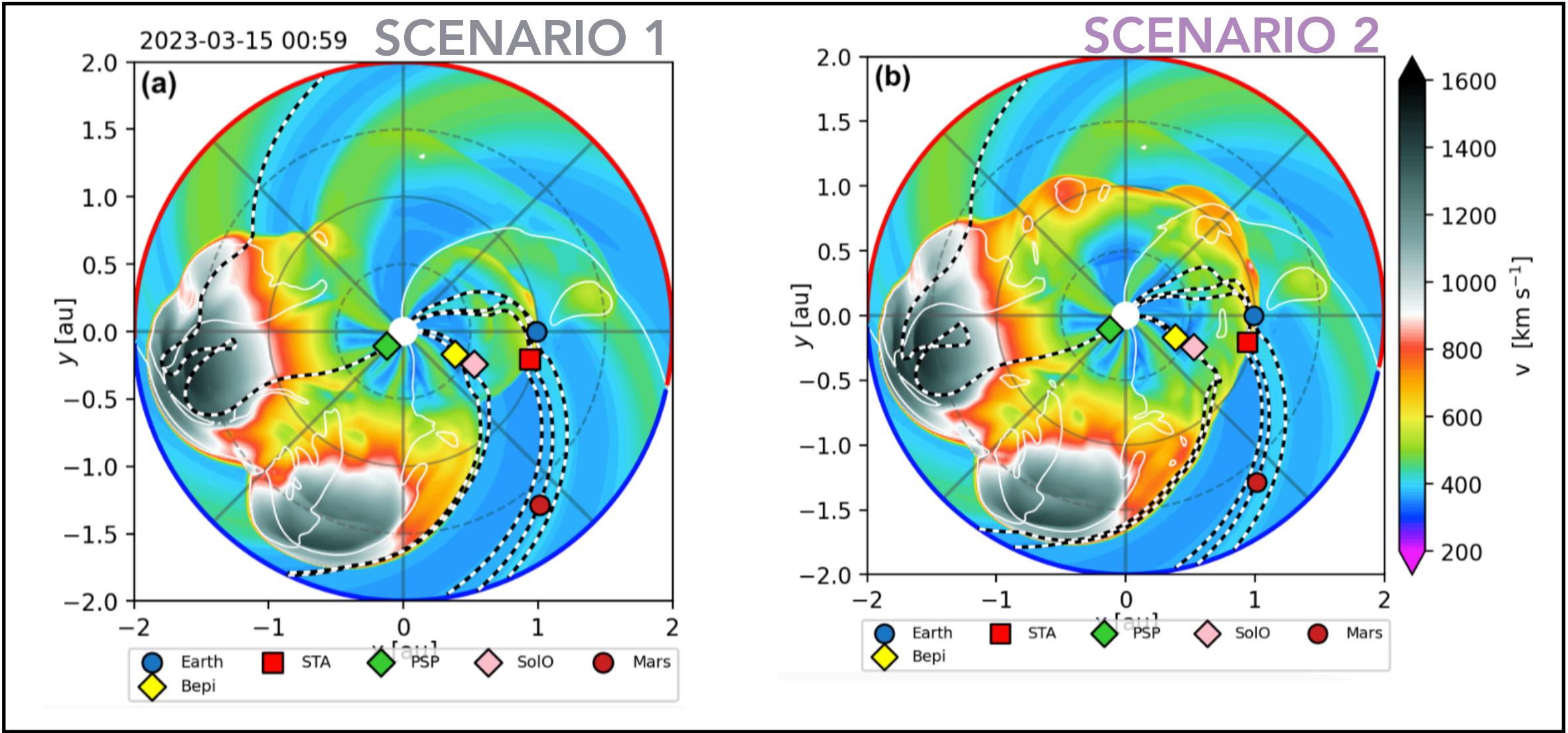


Dresing+ 2025

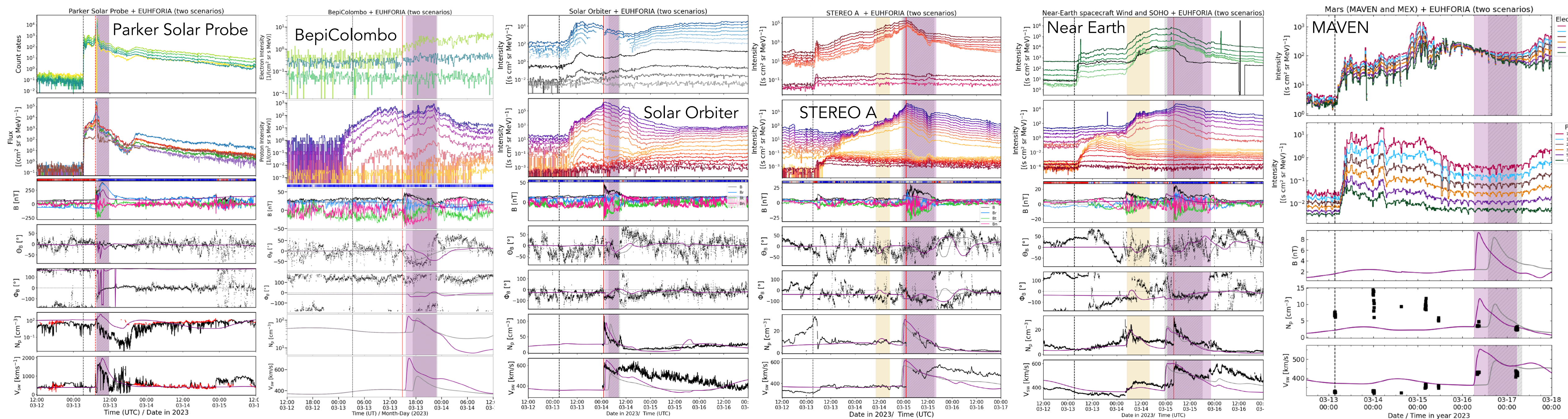


# WIDESPREAD SEP EVENT OF 13 MARCH 2023

- **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

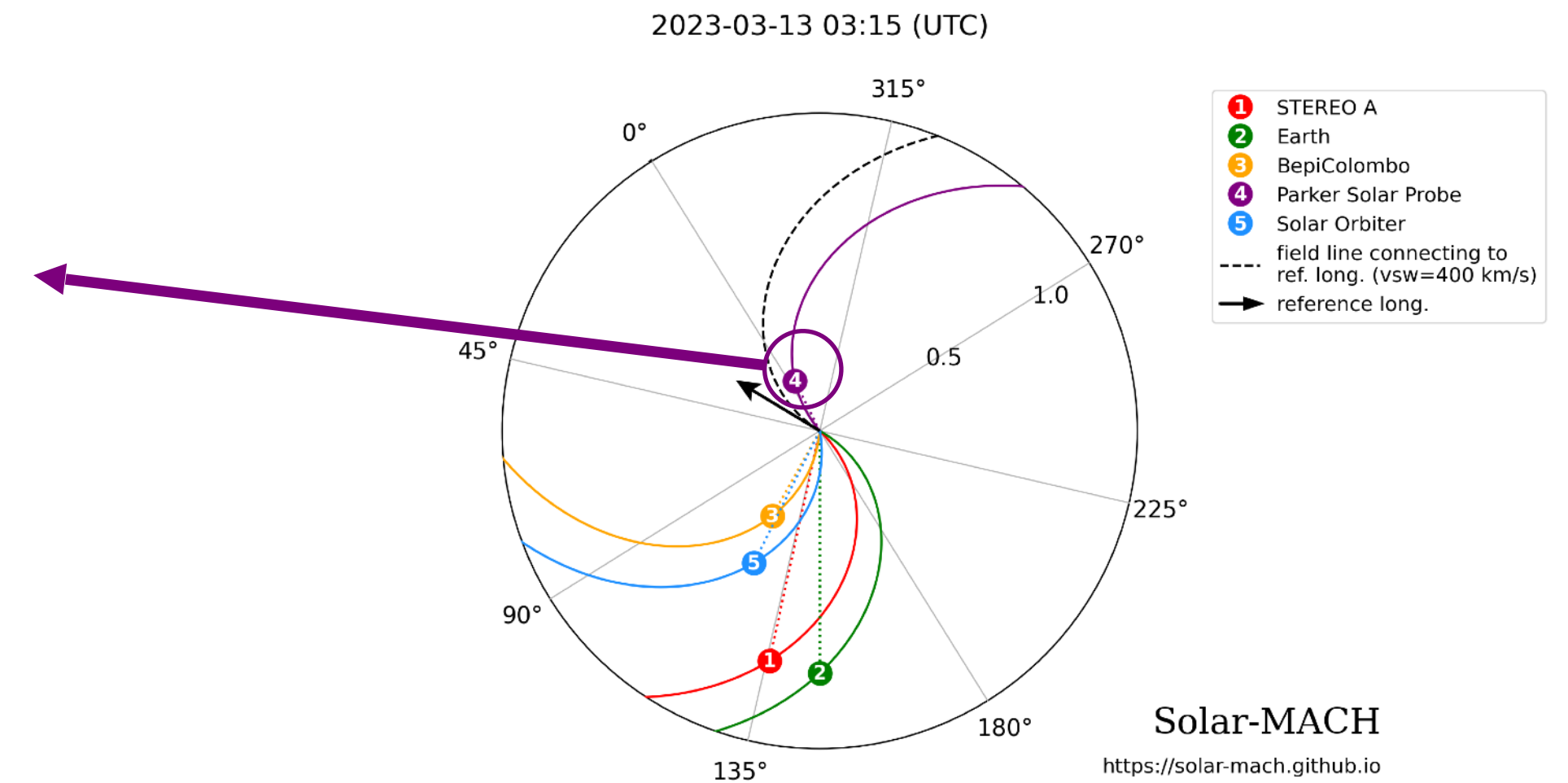
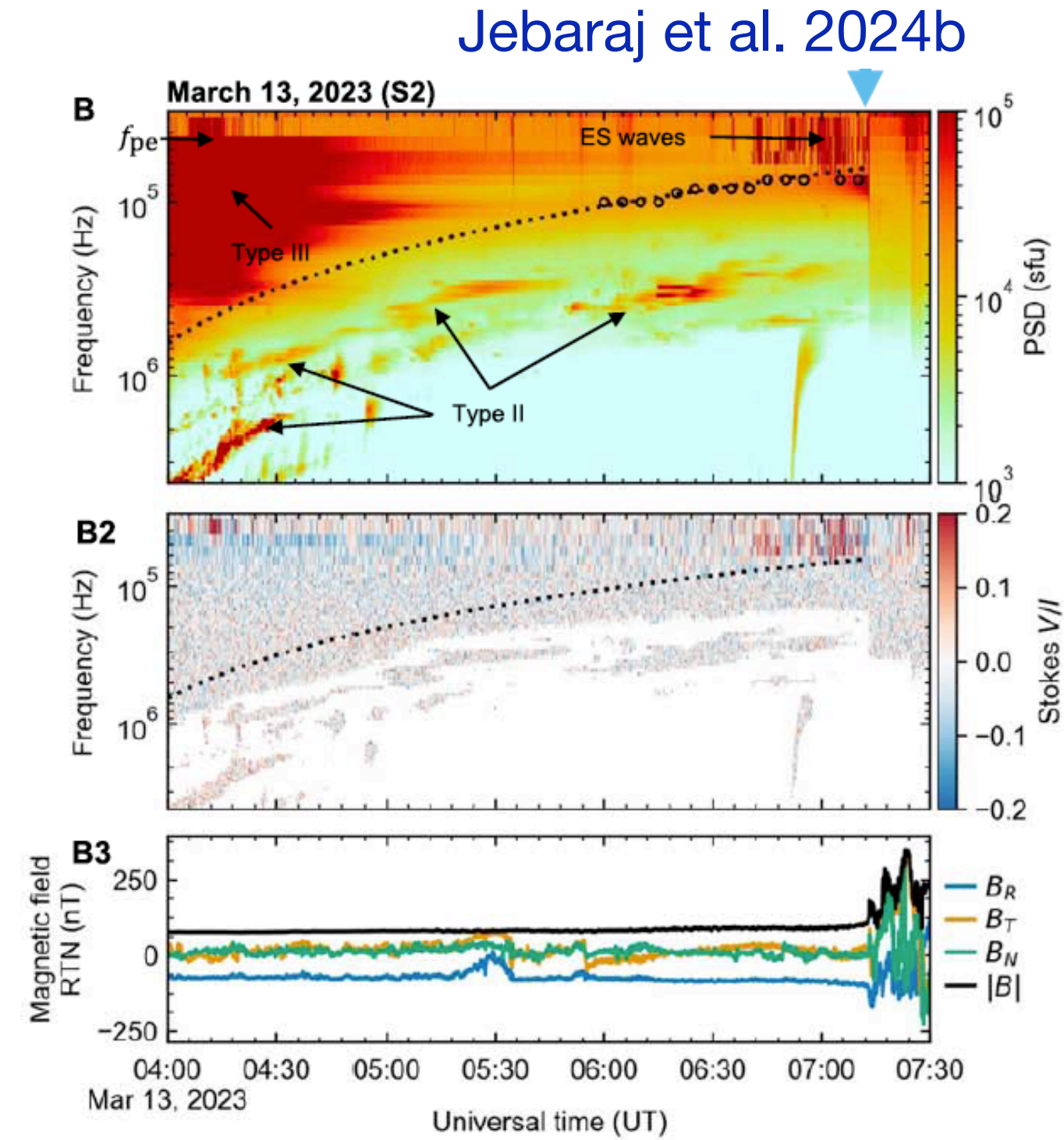
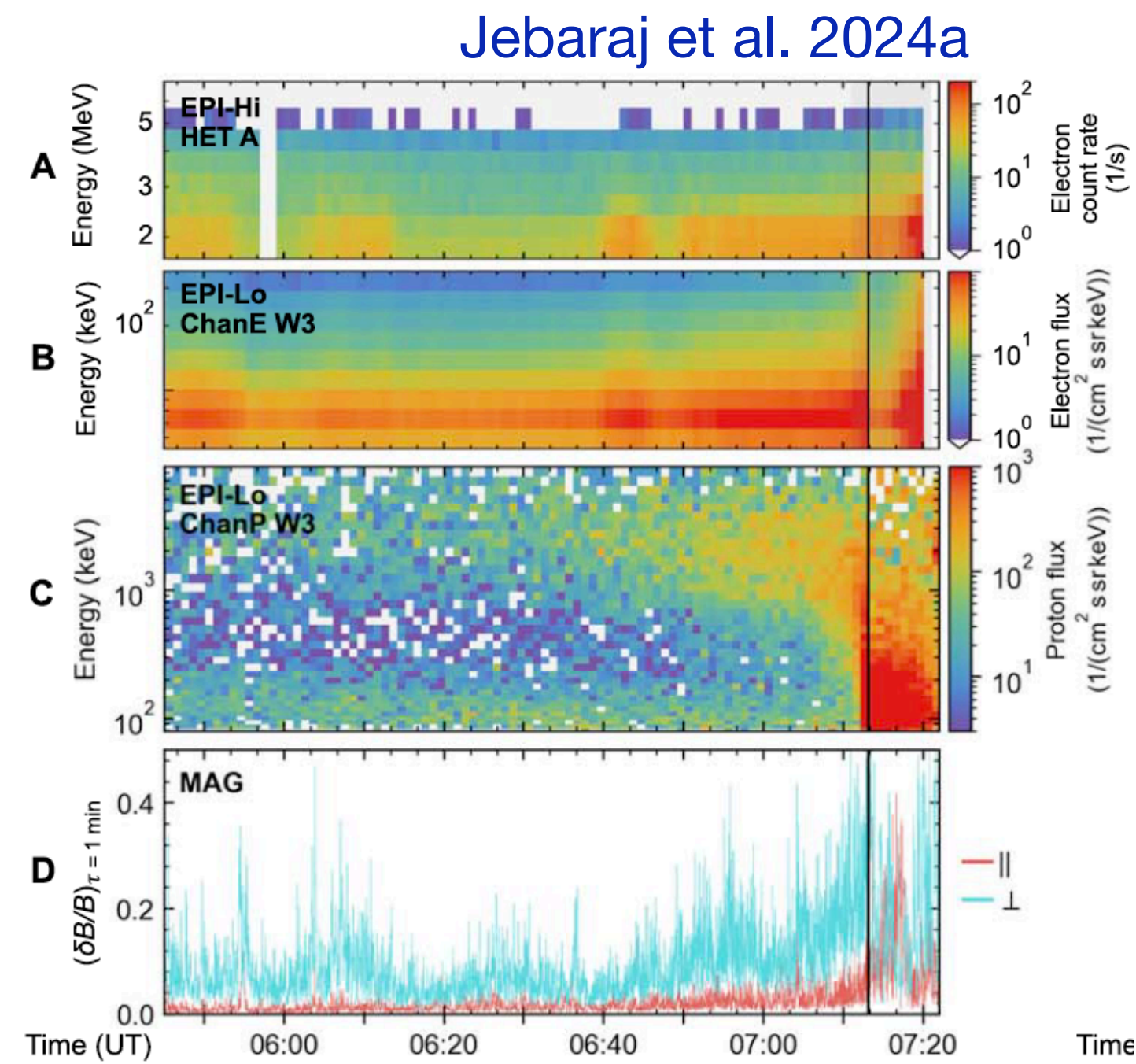


Dresing+ 2025, see also Wijzen+ 2025

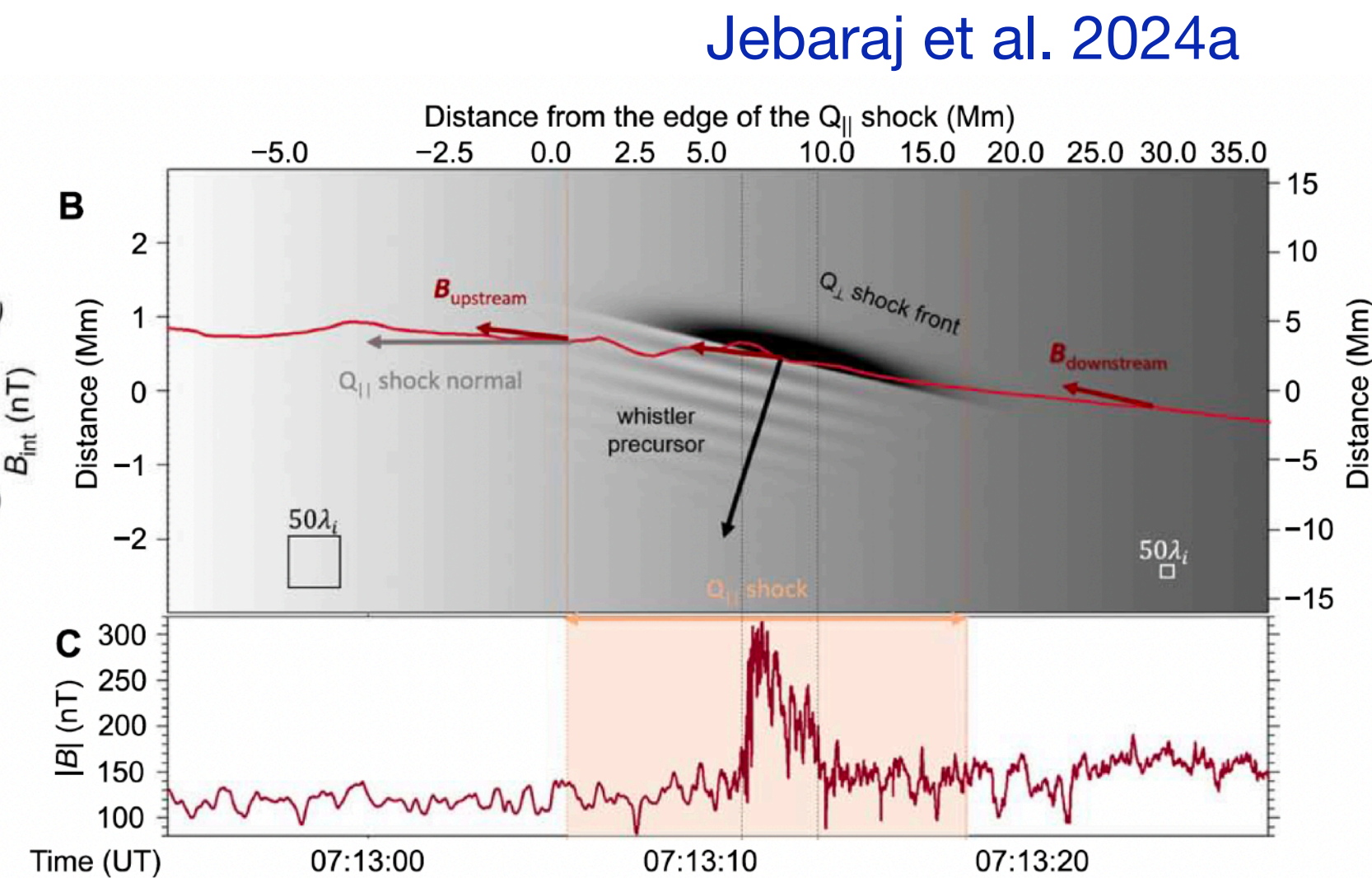
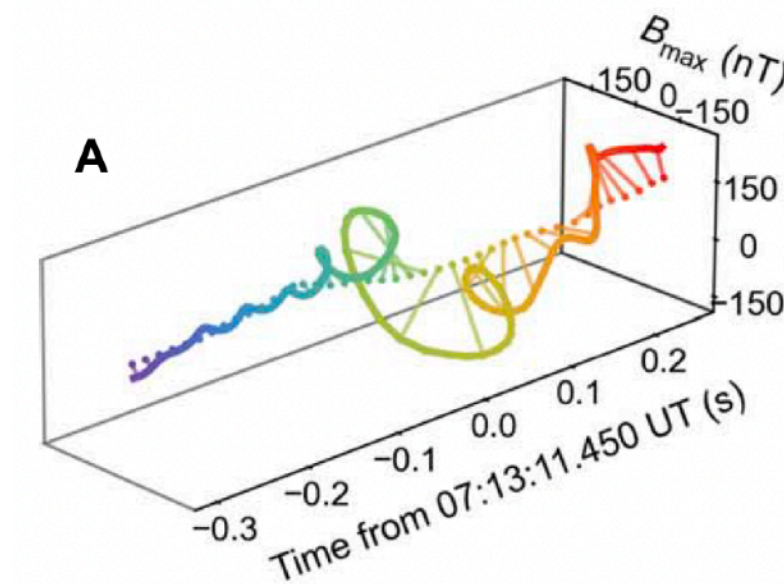




# 13 March 2023 event: In-situ observations of electron acceleration at the coronal shock



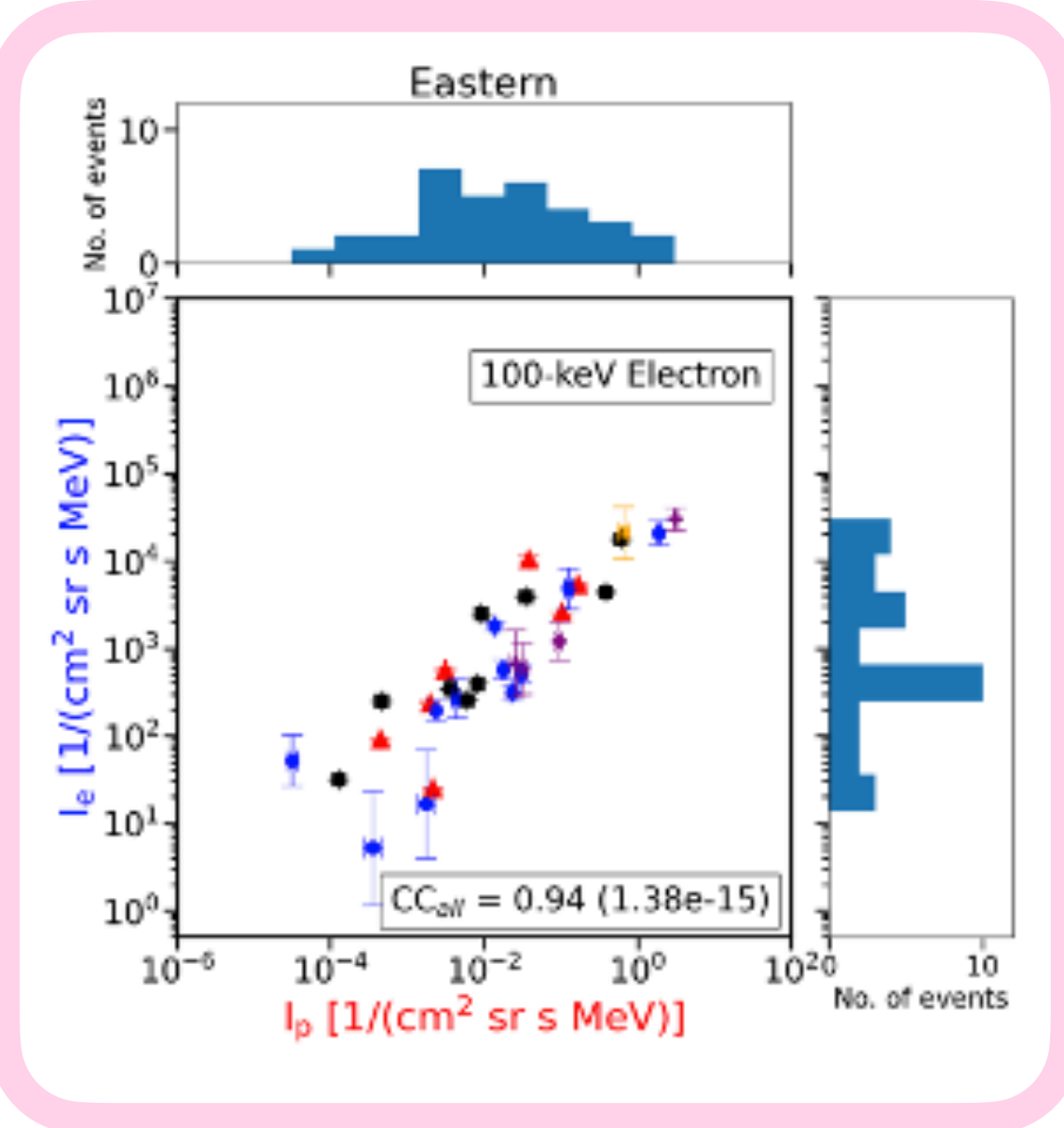
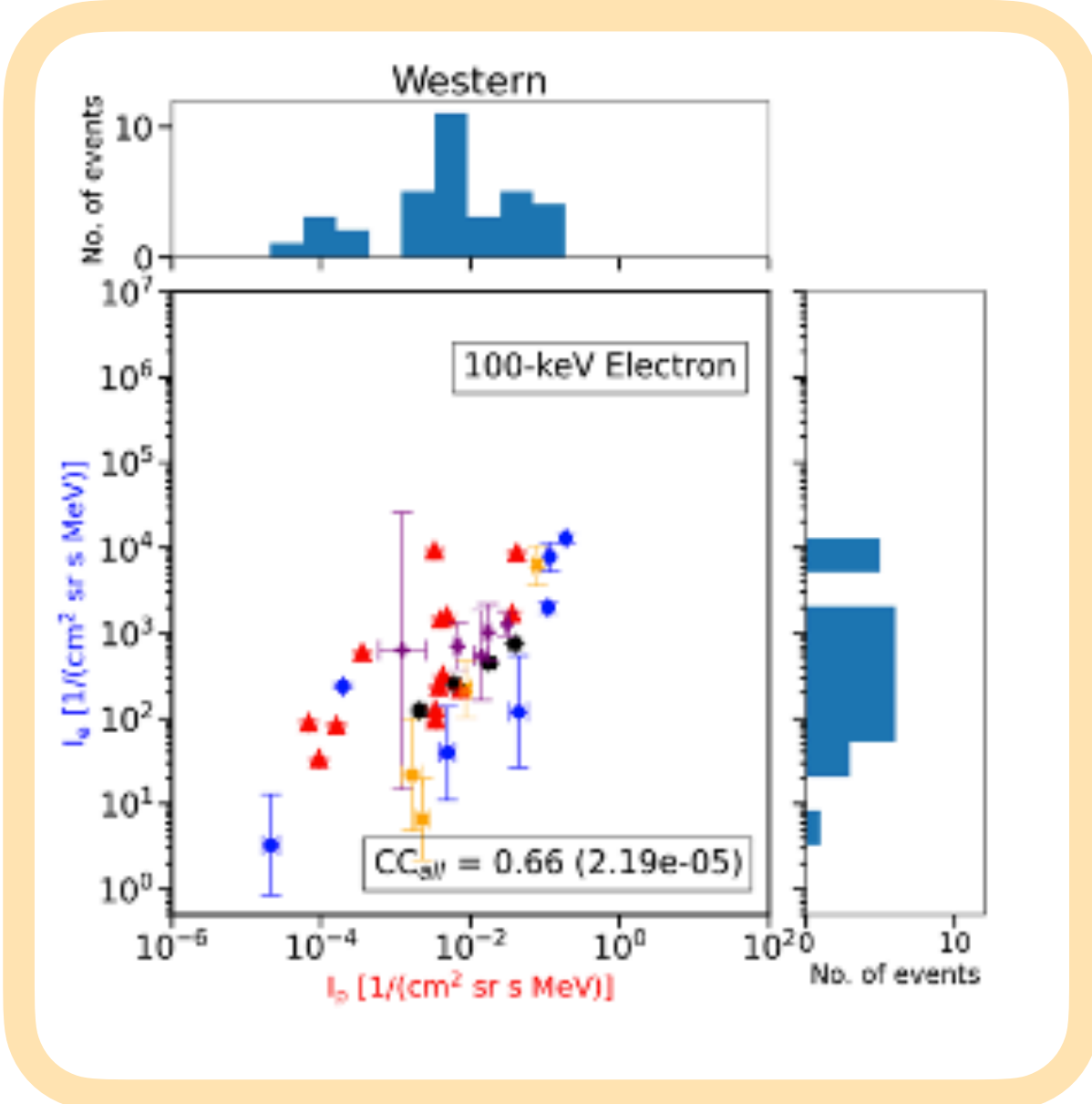
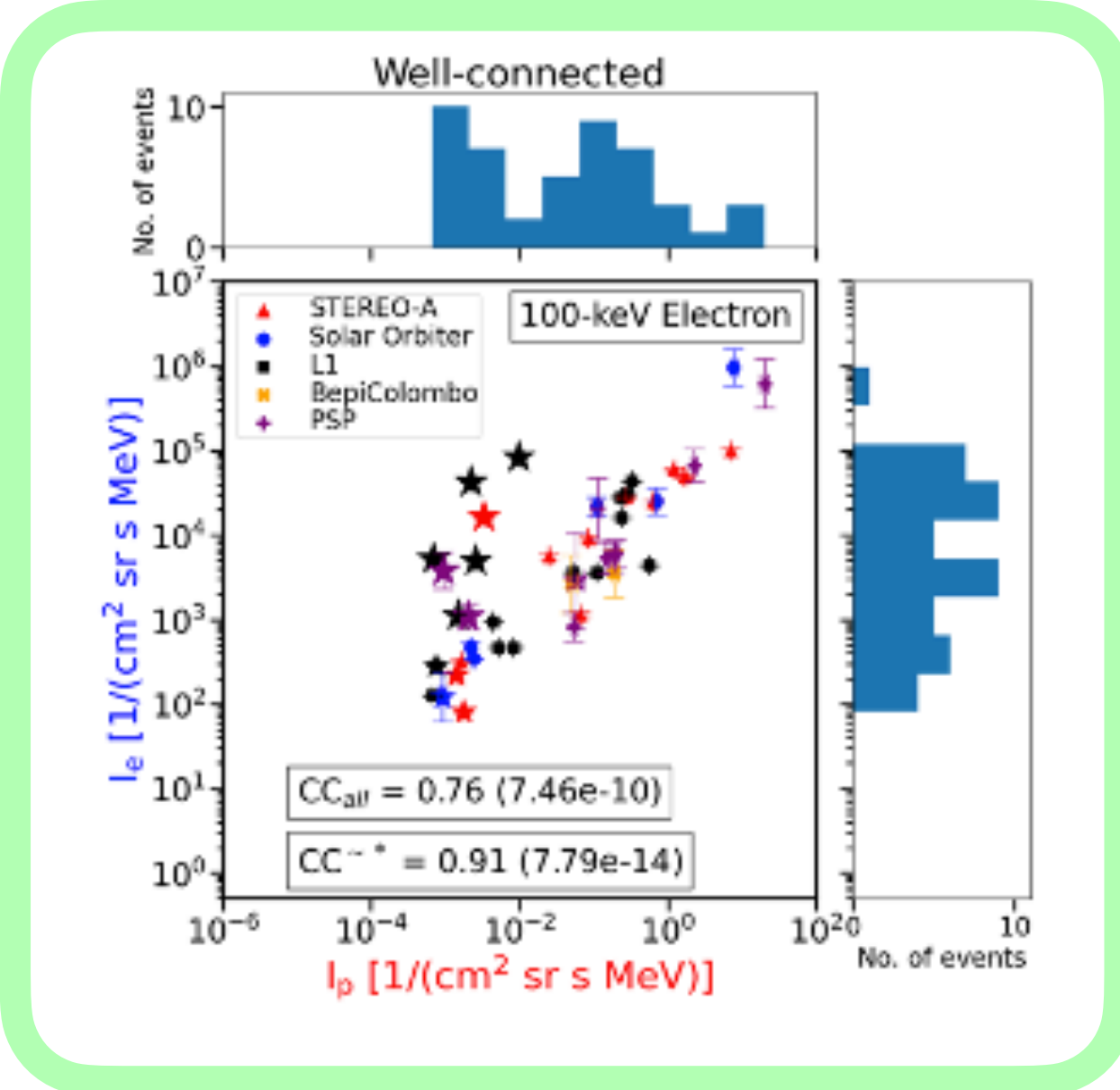
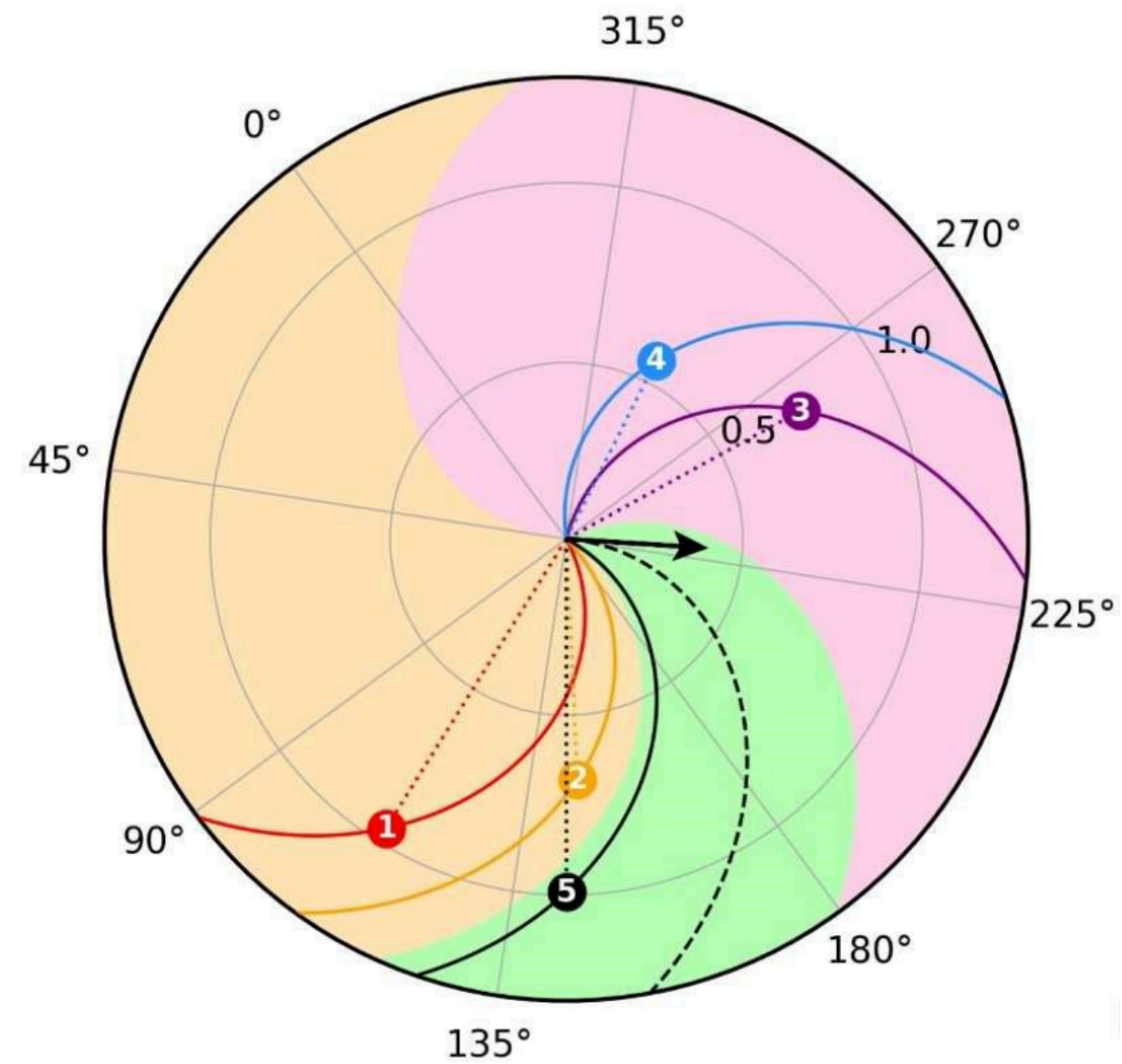
- March 13 2023 in-situ shock at PSP: One of the fastest CME-driven shocks ever (~2800 km/s, Jebaraj et al. 2024a).
- In-situ electron acceleration up to ultra-relativistic energies (6 MeV) could be confirmed
- A local perpendicular configuration of the globally parallel shock was likely key to sustained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





# Correlation of electron and proton peak intensities

100 keV electrons vs. 25-40 MeV protons



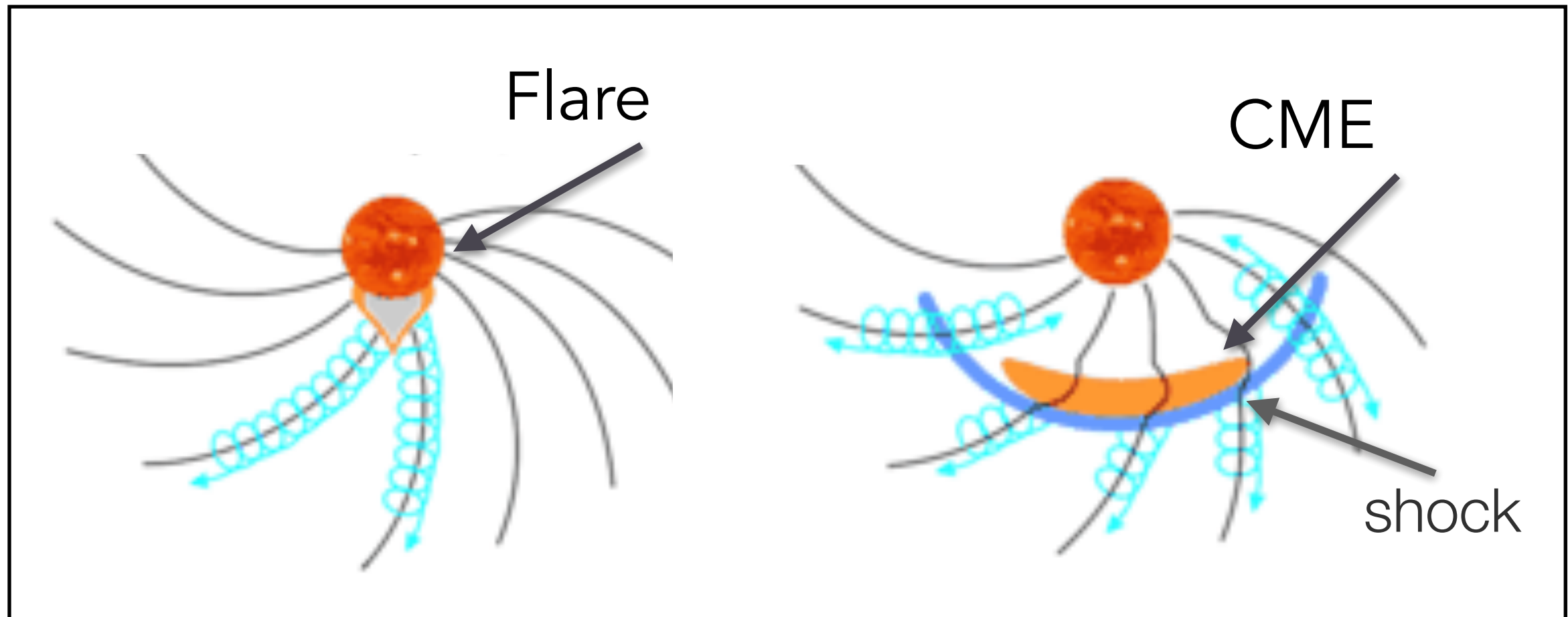
Solar Orbiter

Parker Solar Probe

STEREO A

SOHO/Wind

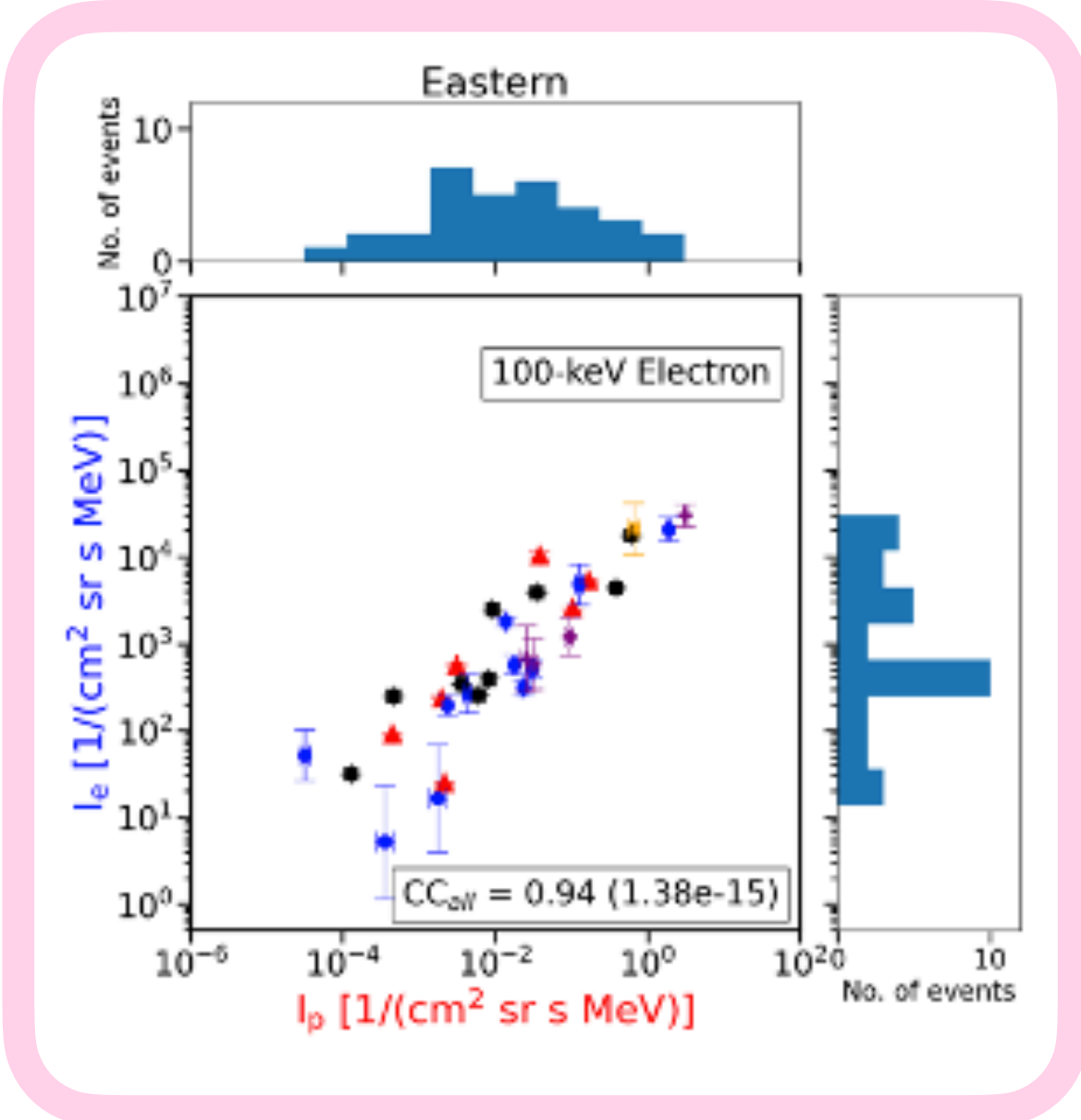
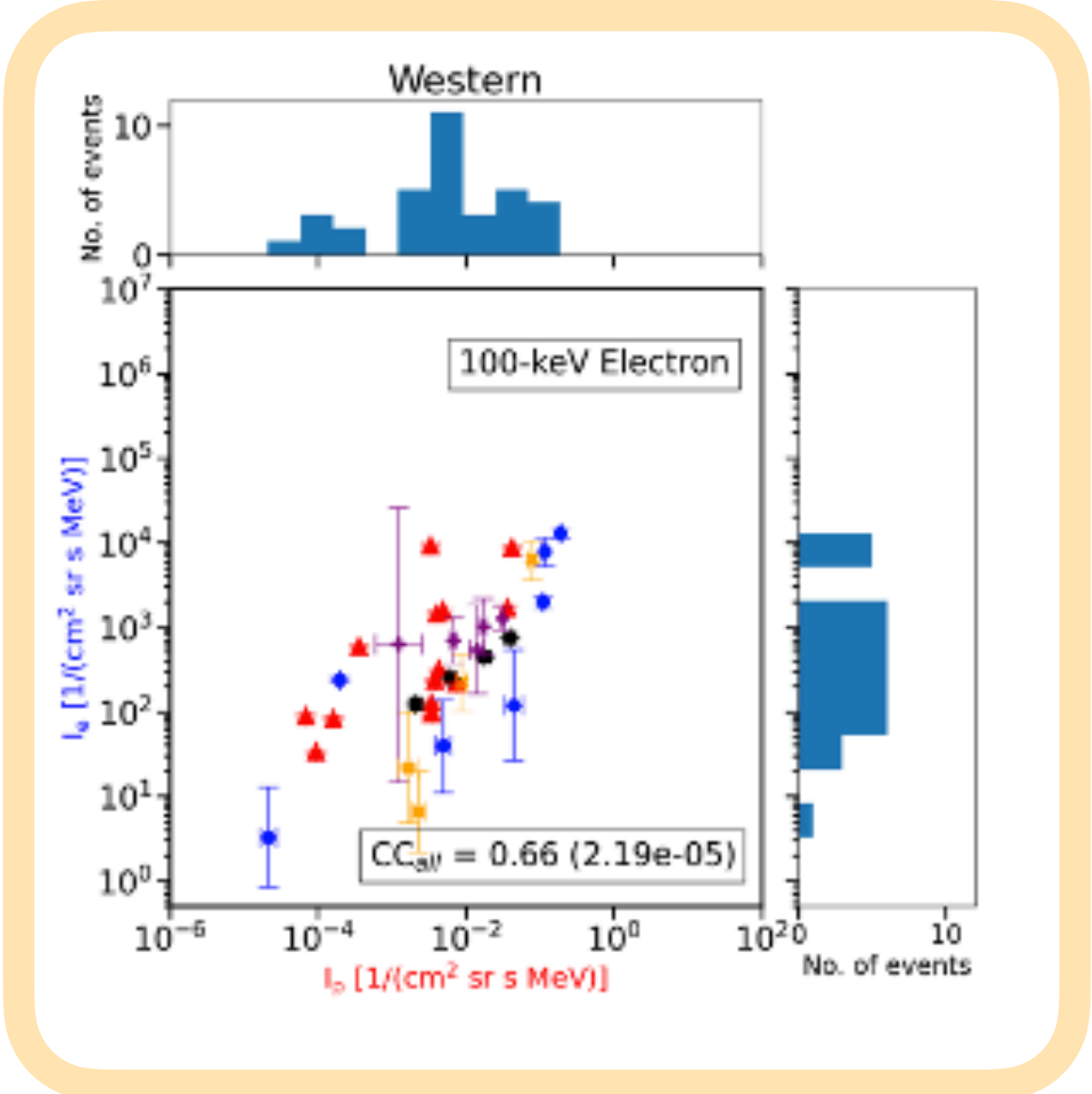
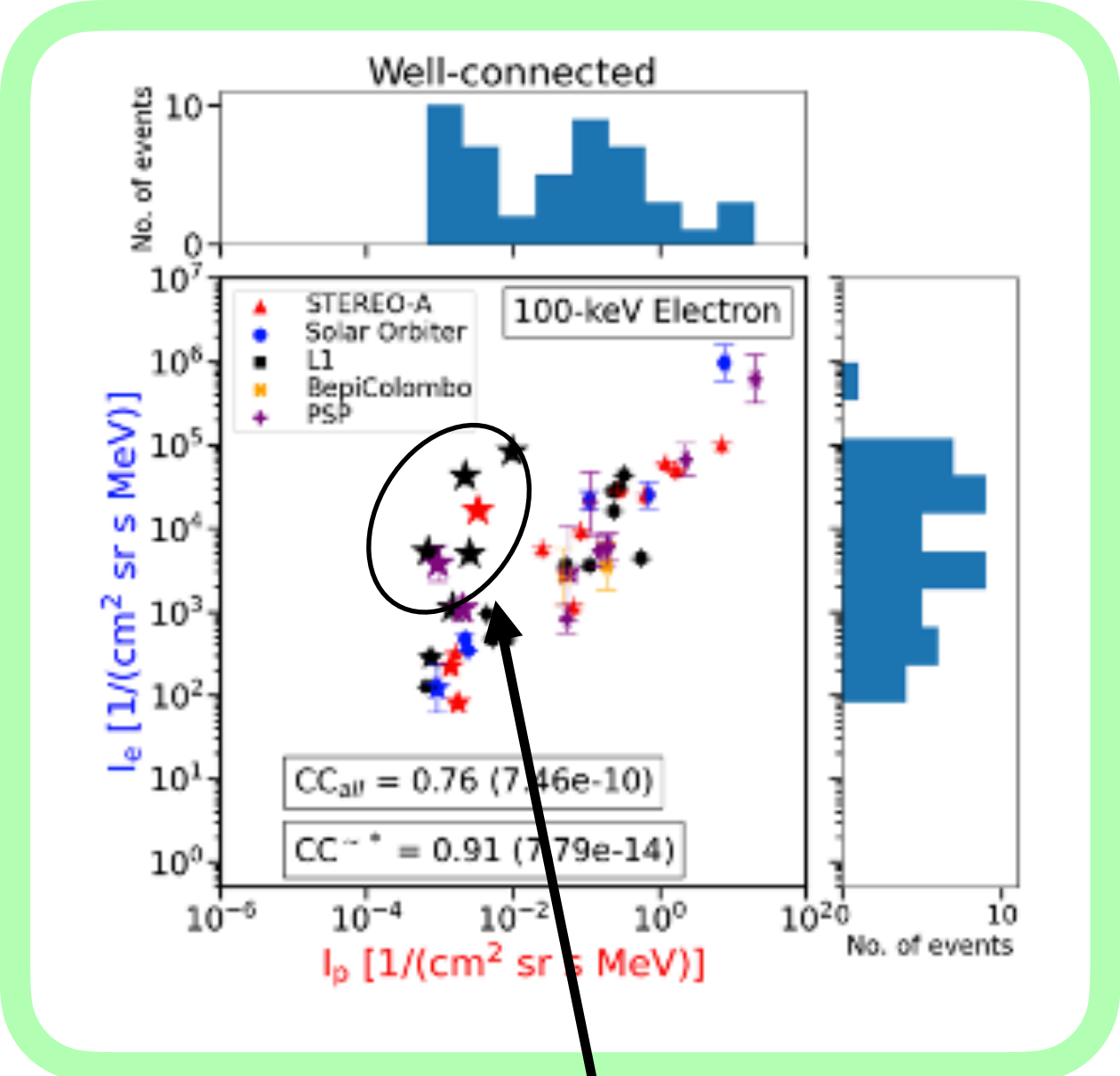
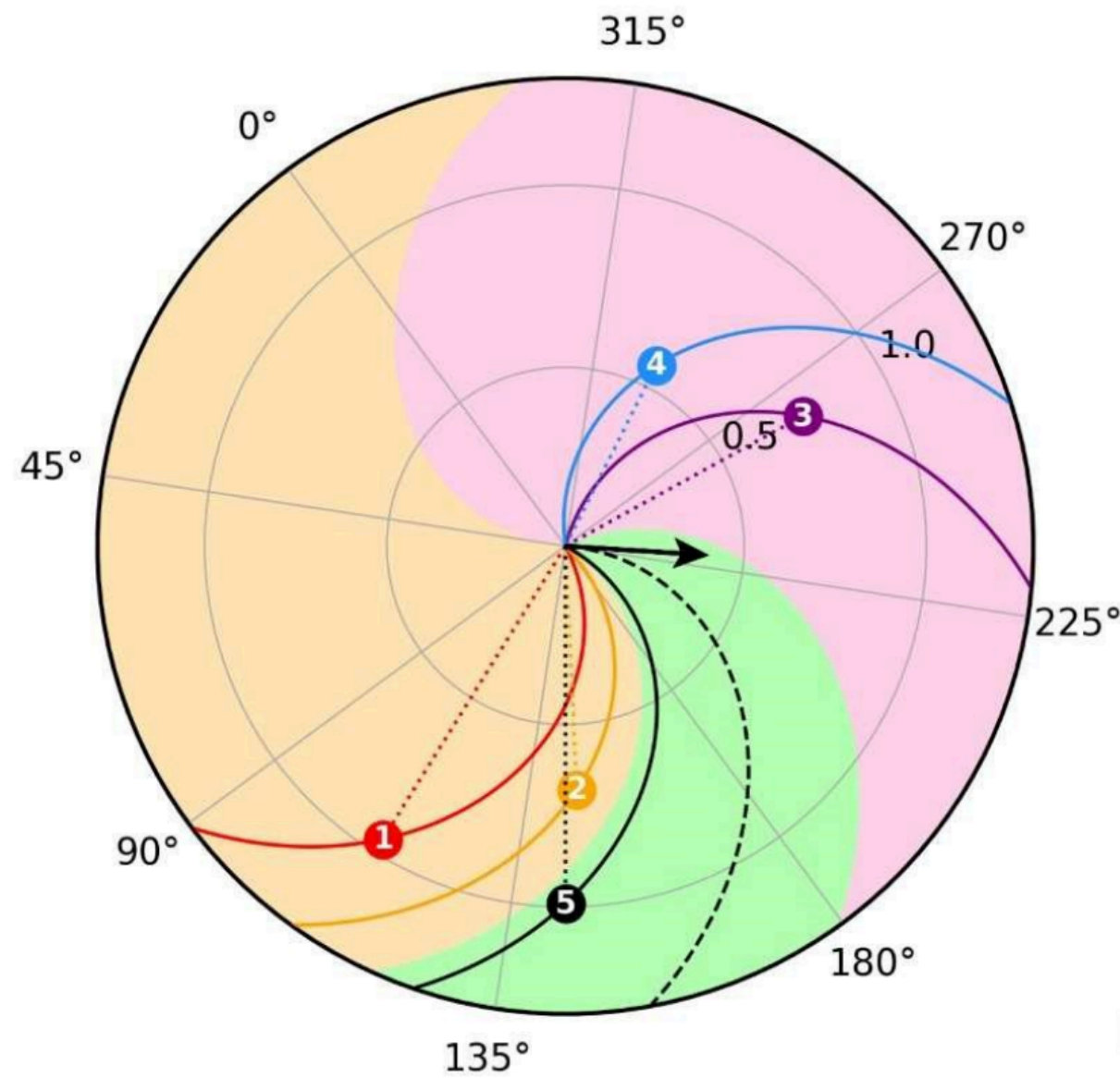
BepiColombo



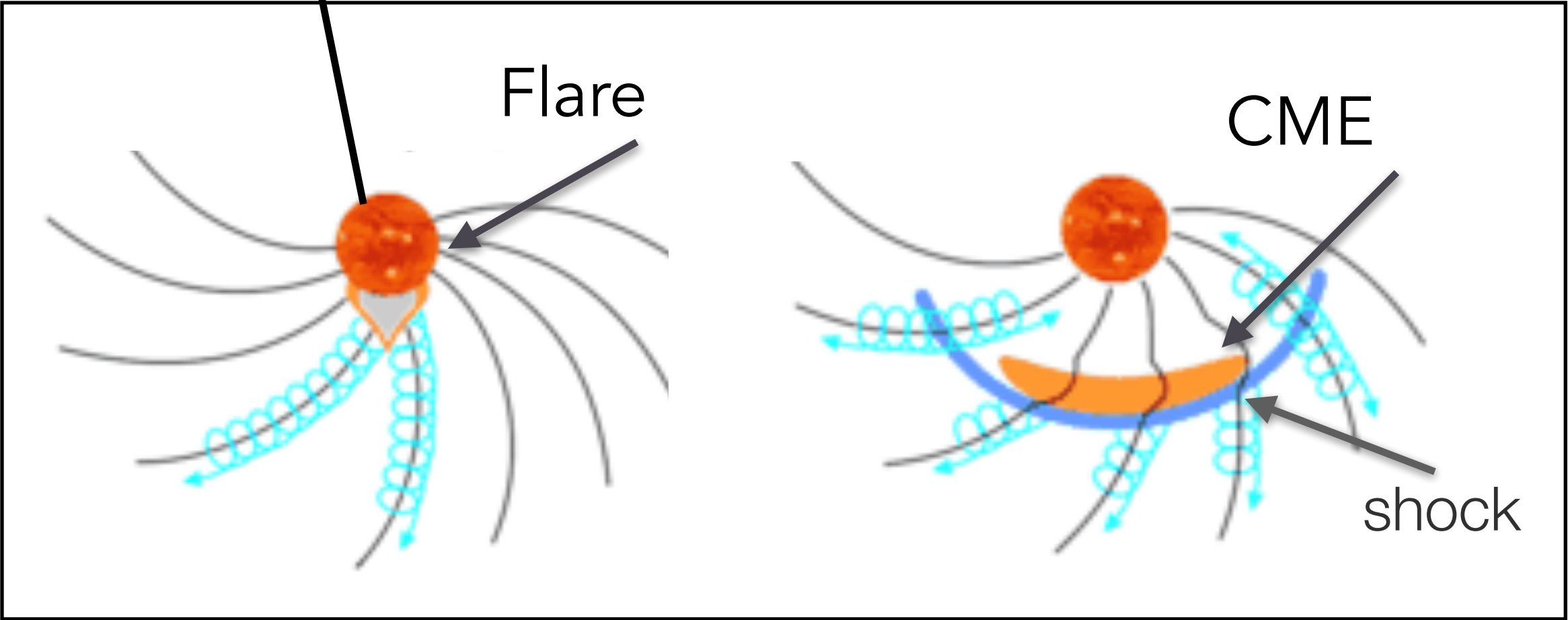
Farwa et al. 2025

# Correlation of electron and proton peak intensities

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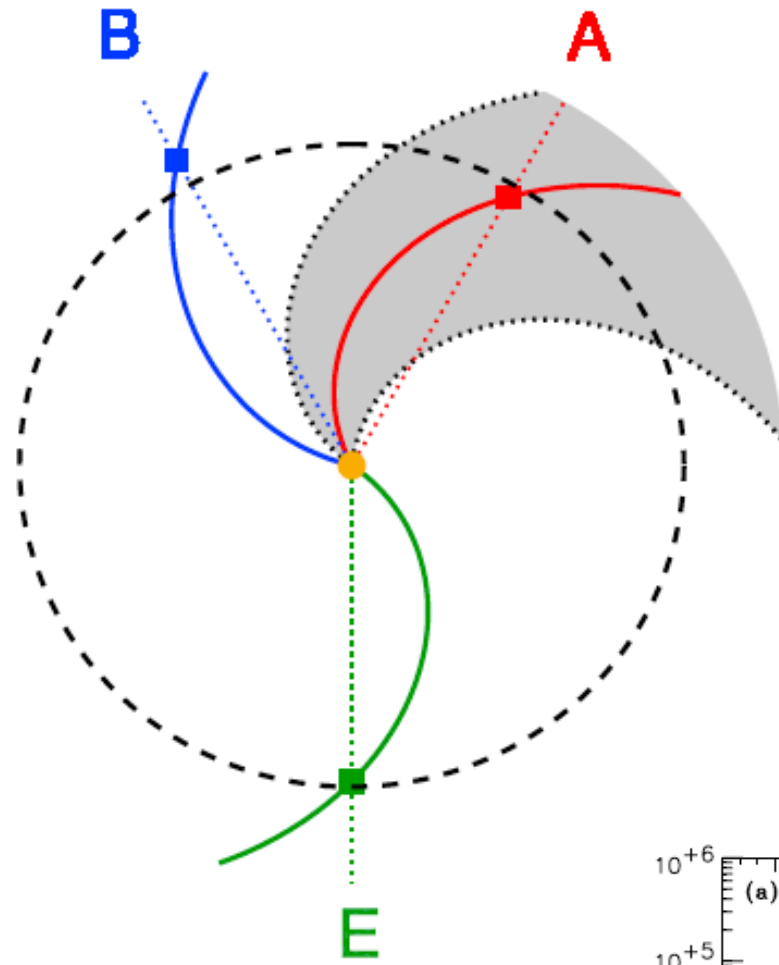
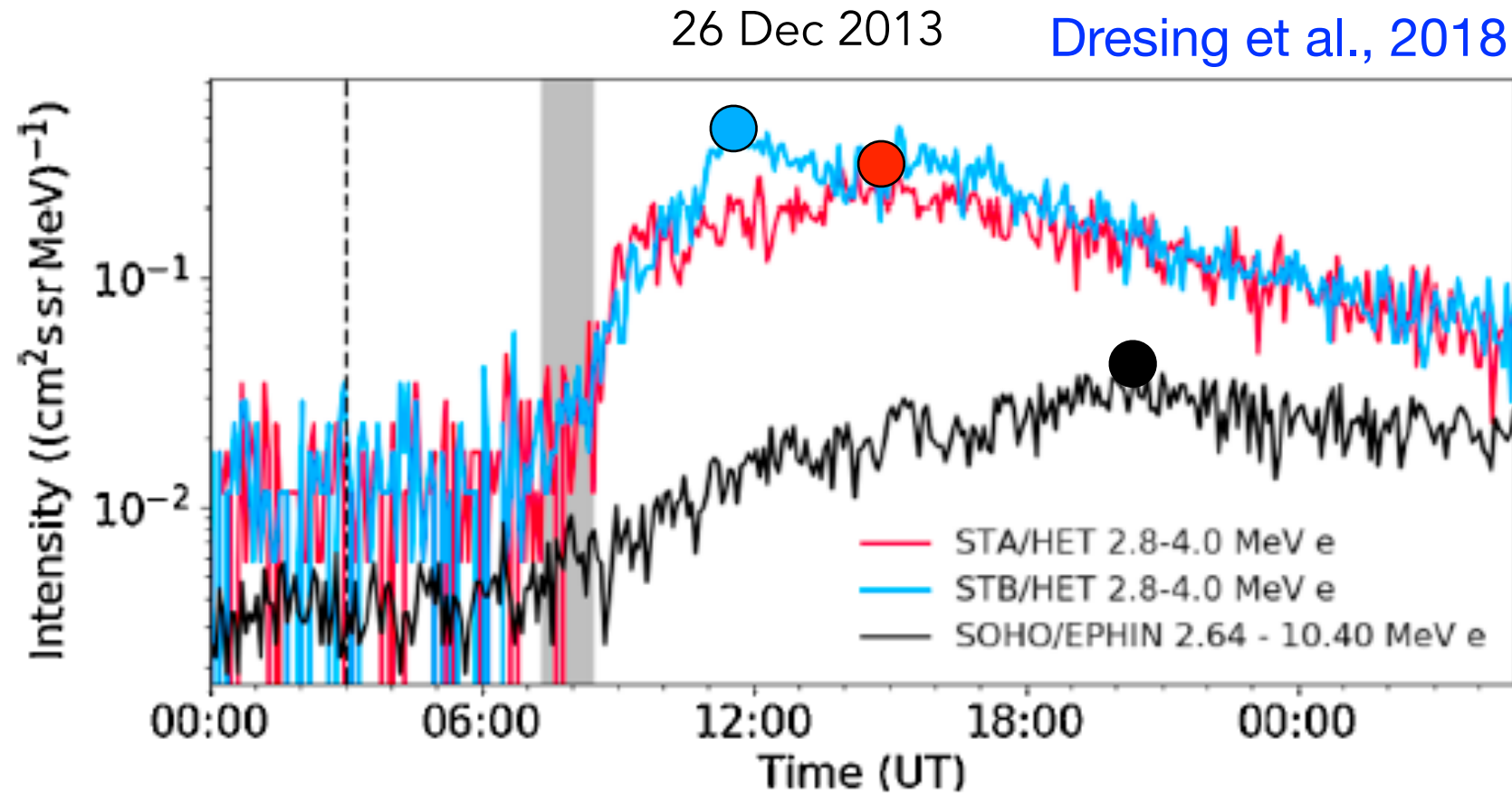
- Solar Orbiter
- Parker Solar Probe
- STEREO A
- SOHO/Wind
- BepiColombo



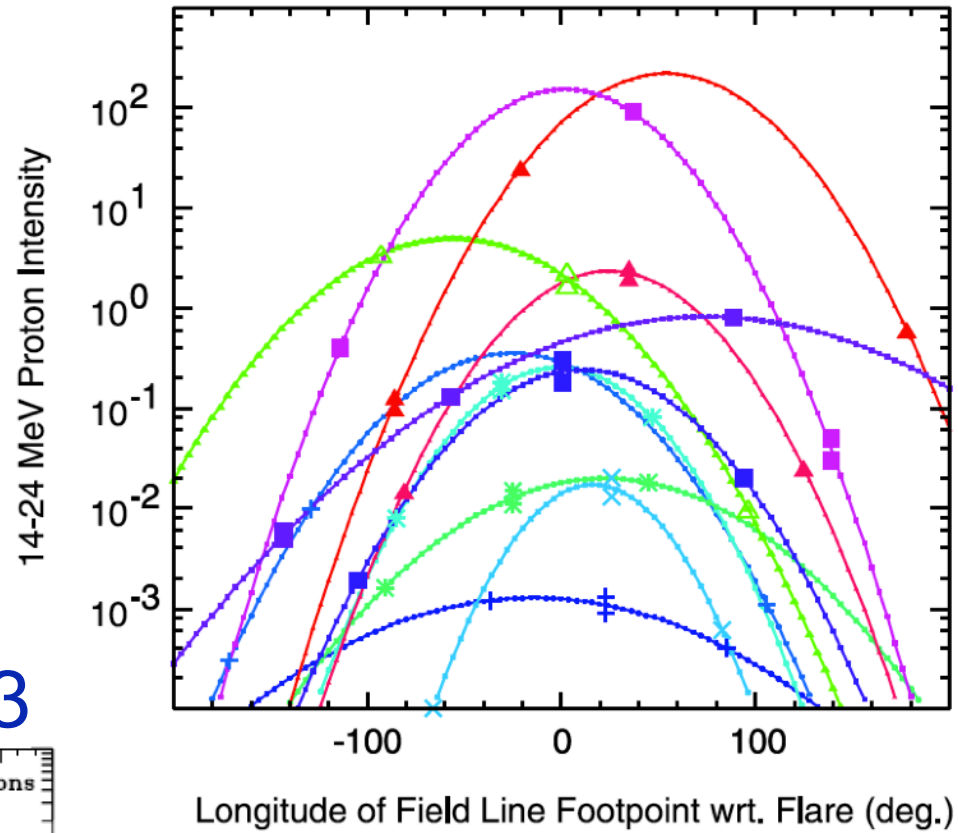
Farwa et al. 2025



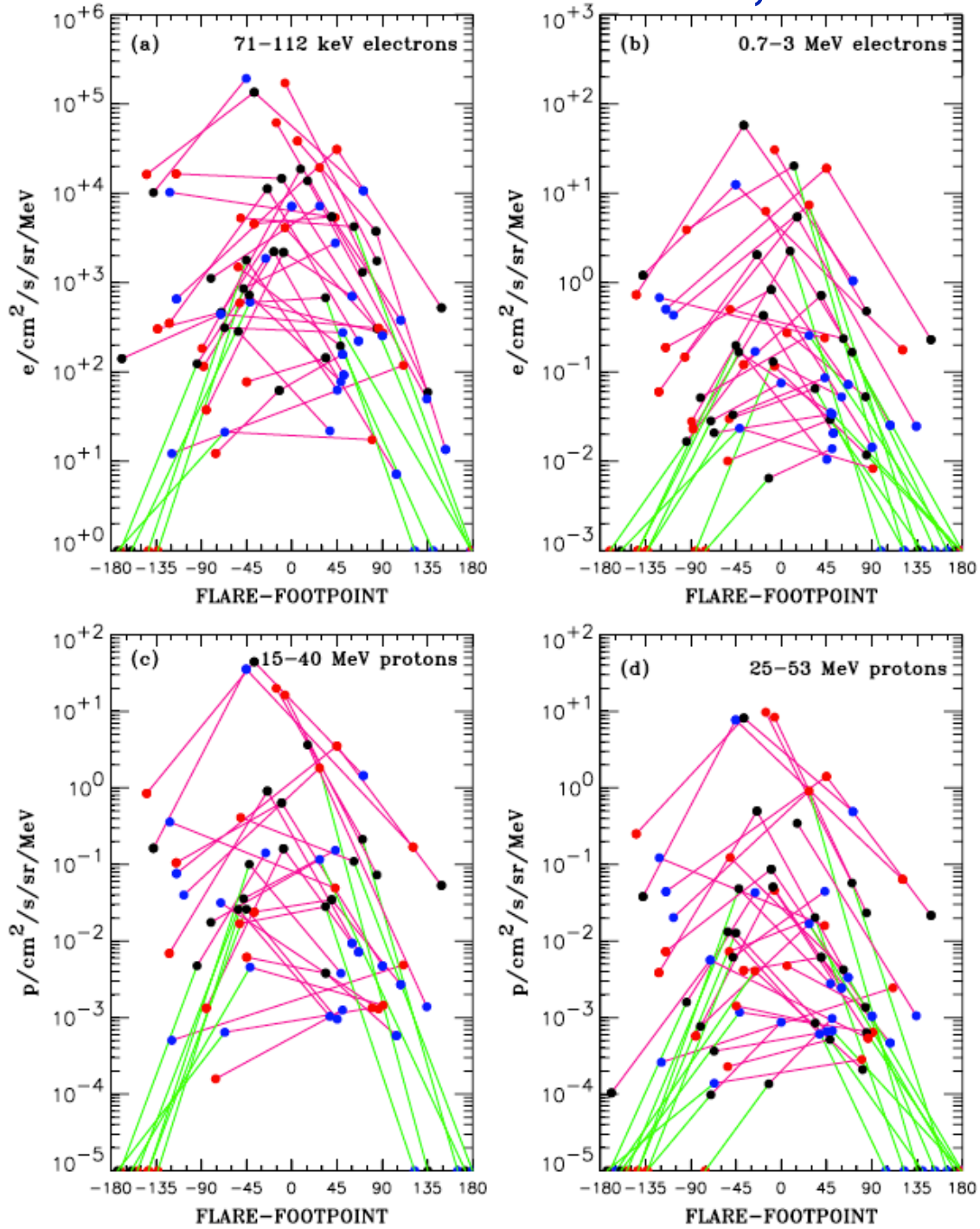
# CHARACTERIZING THE LONGITUDINAL DISTRIBUTION OF SEPs<sub>s</sub>



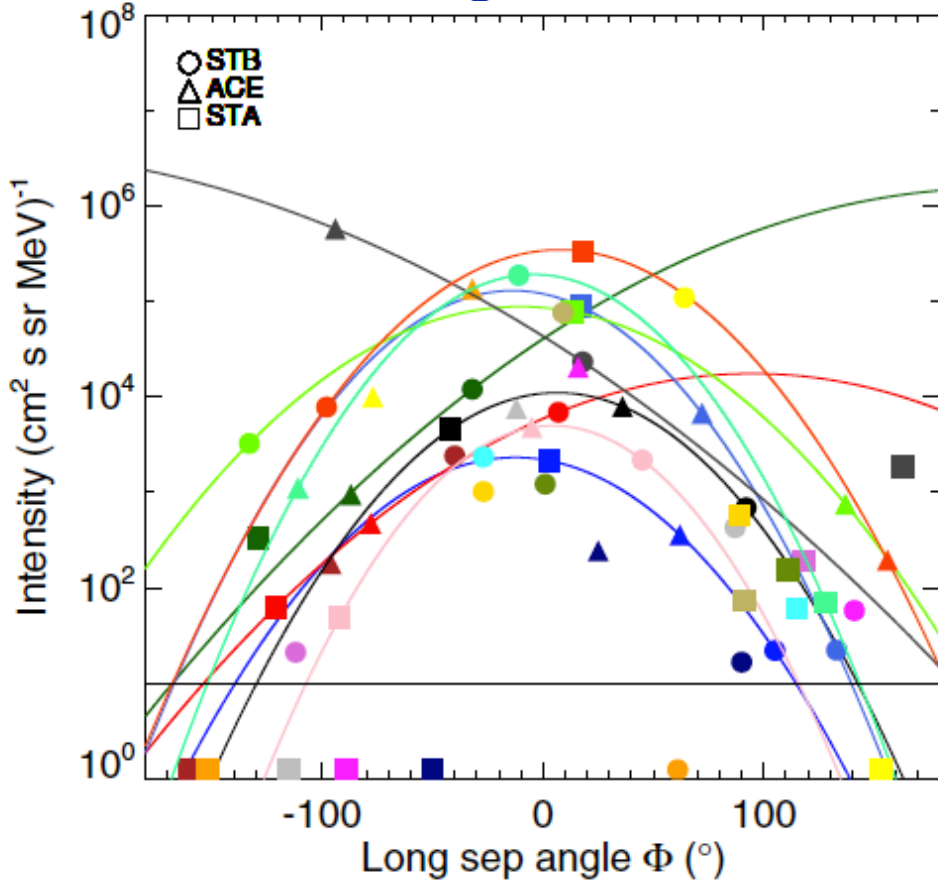
Richardson et al., 2014



Lario et al., 2013



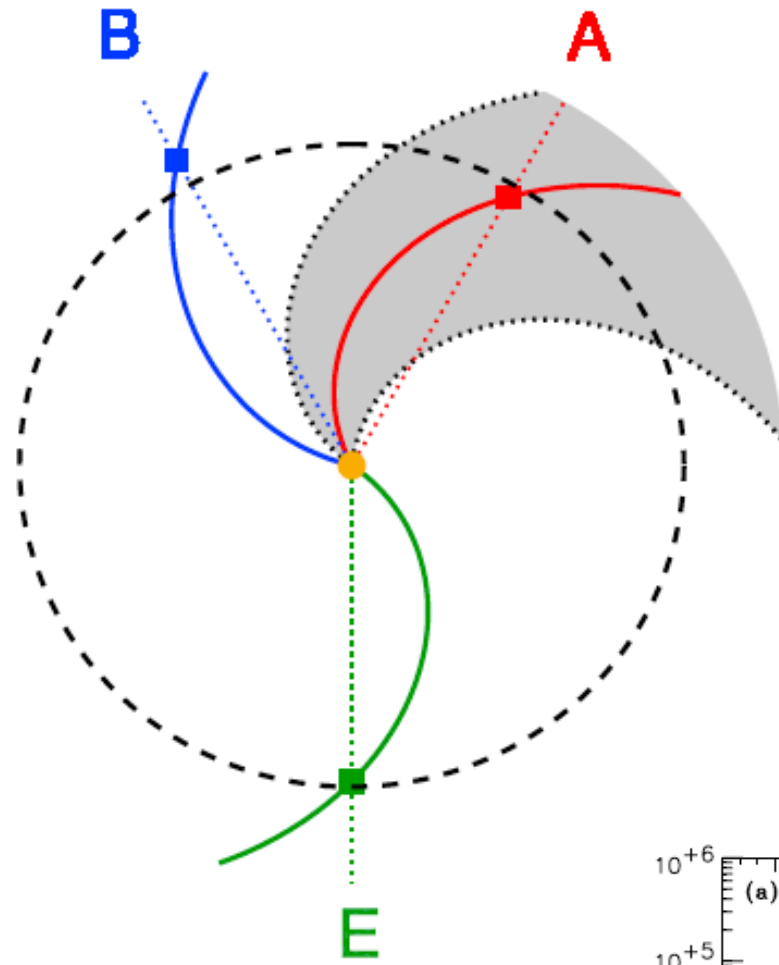
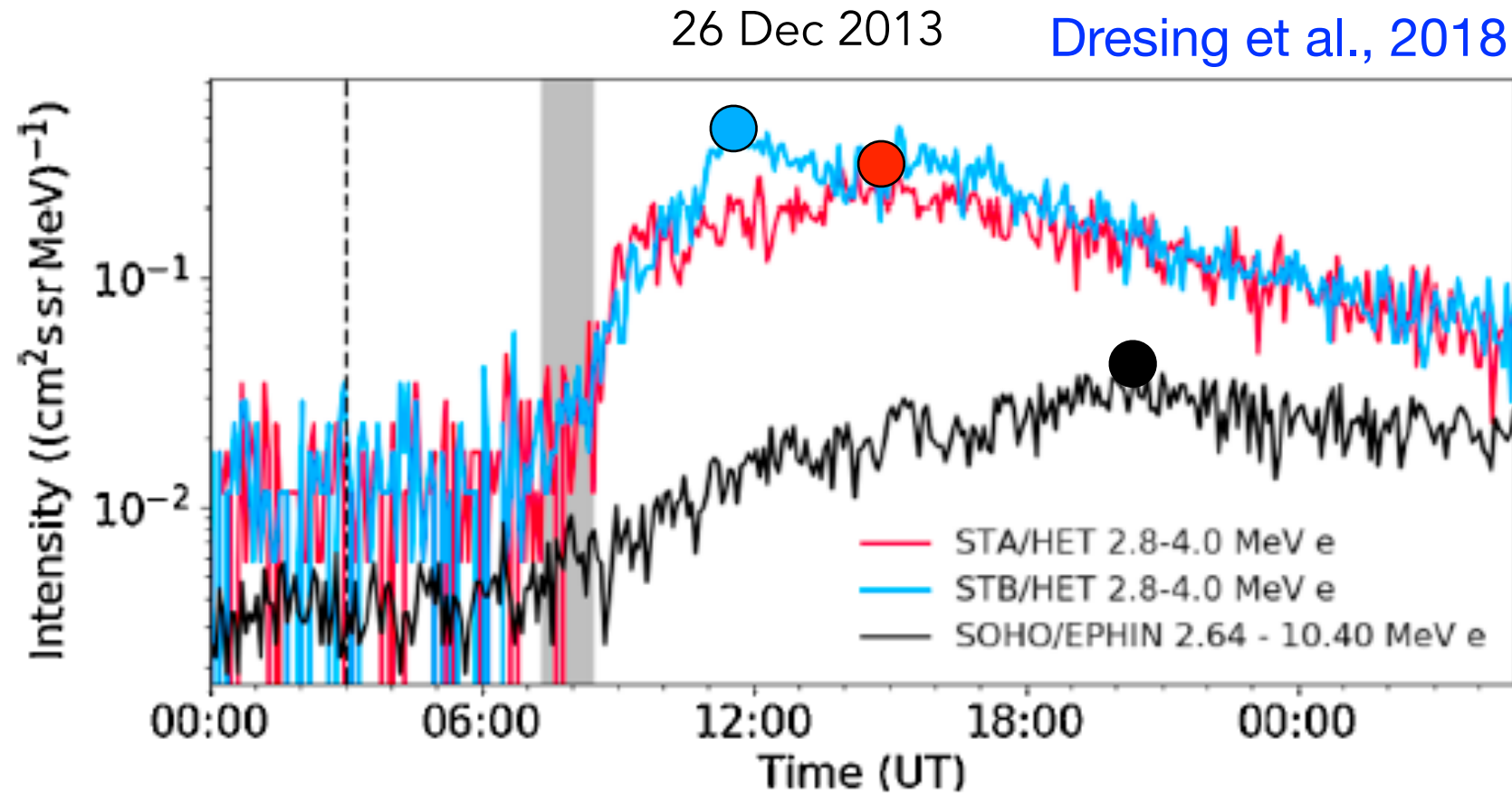
Dresing et al., 2014



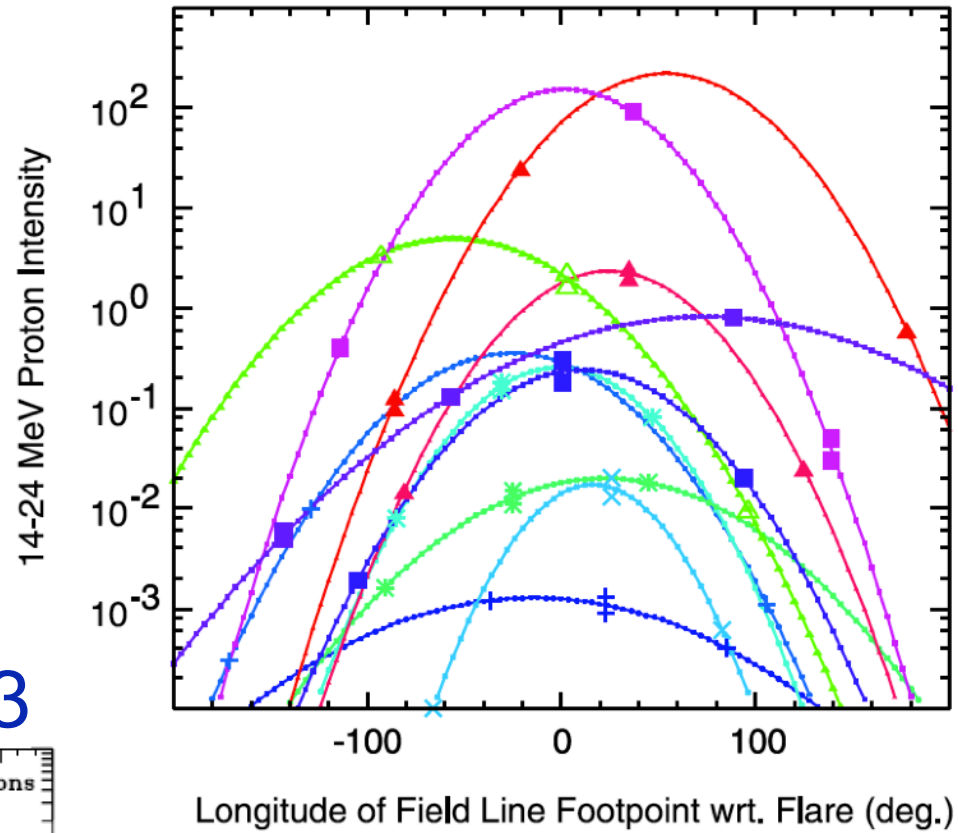
Previously: usually only 3 points available



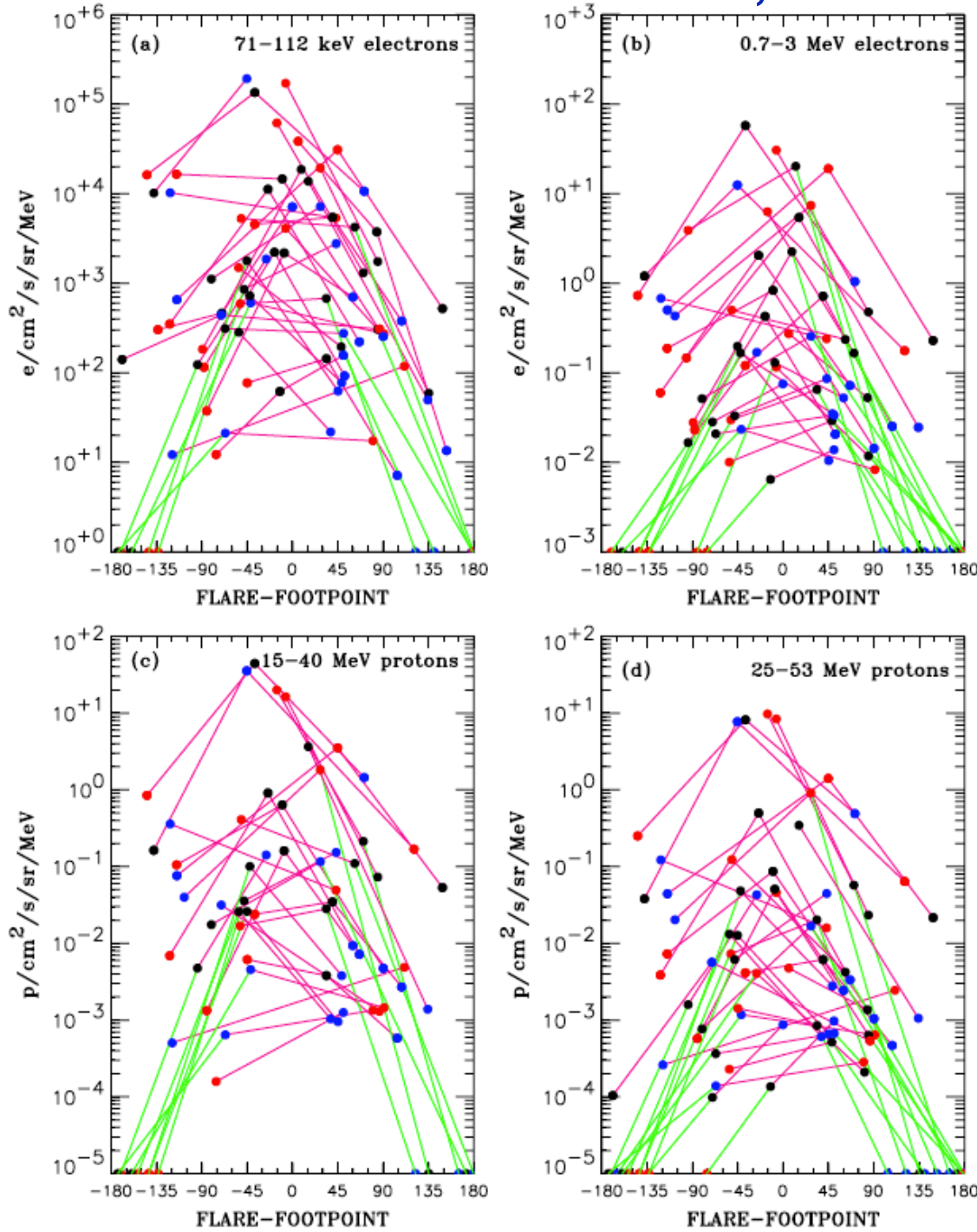
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Richardson et al., 2014

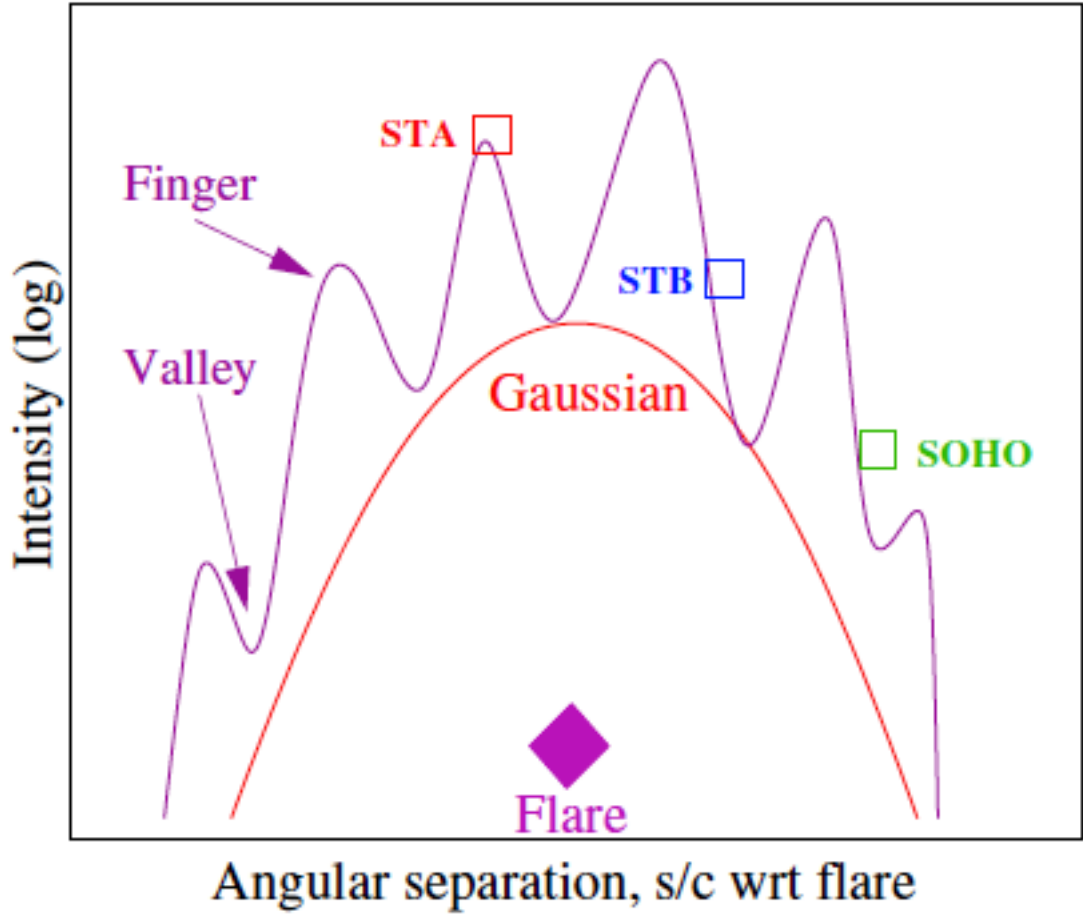


Lario et al., 2013



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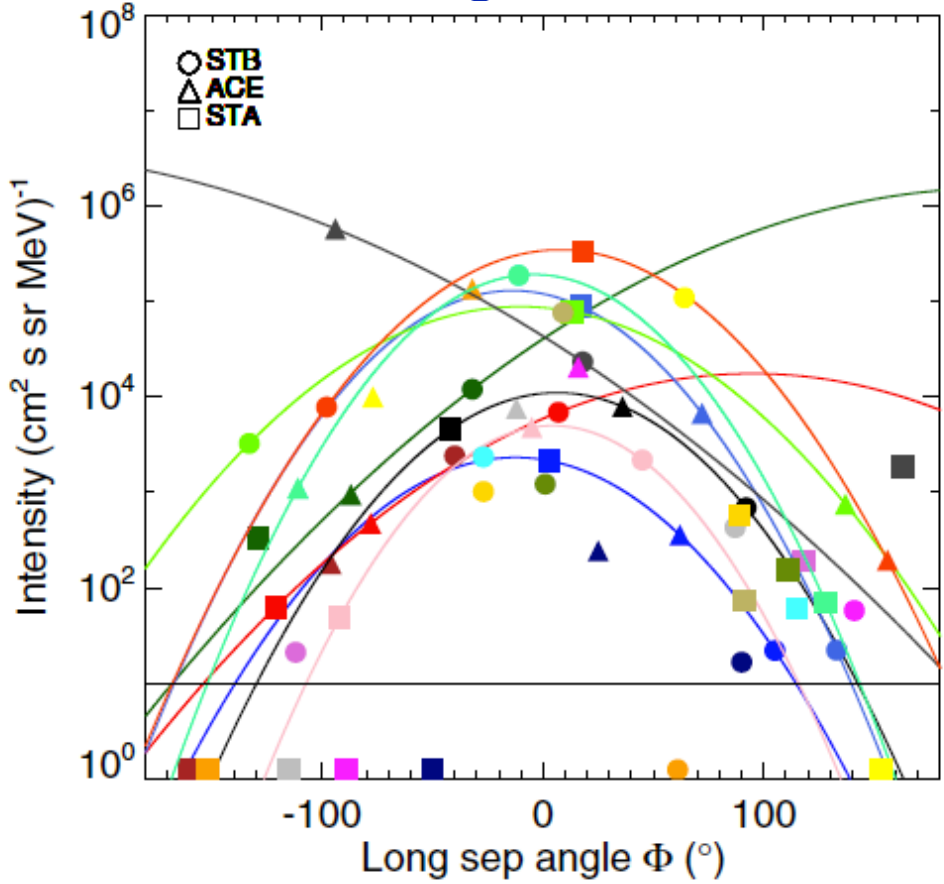
Klassen et al., 2016



## PROBLEMS:

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

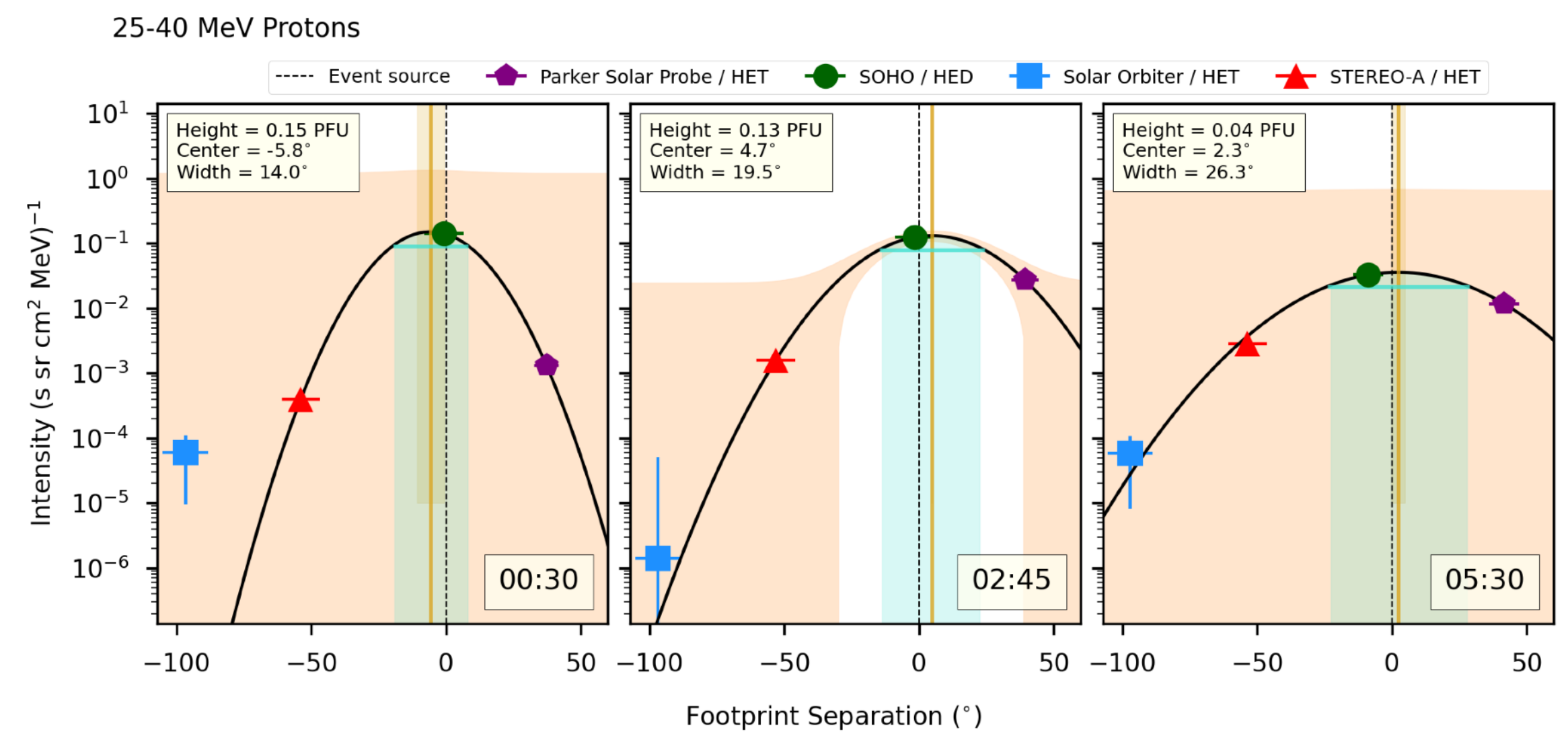
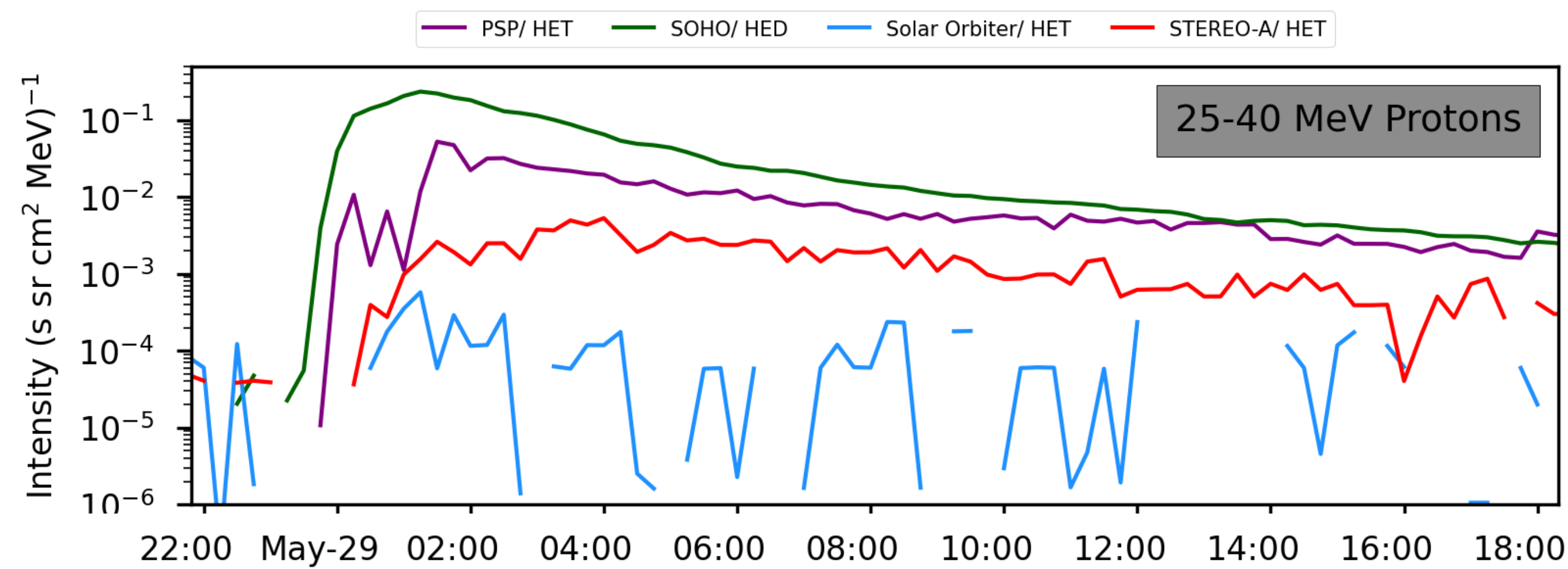
Dresing et al., 2014



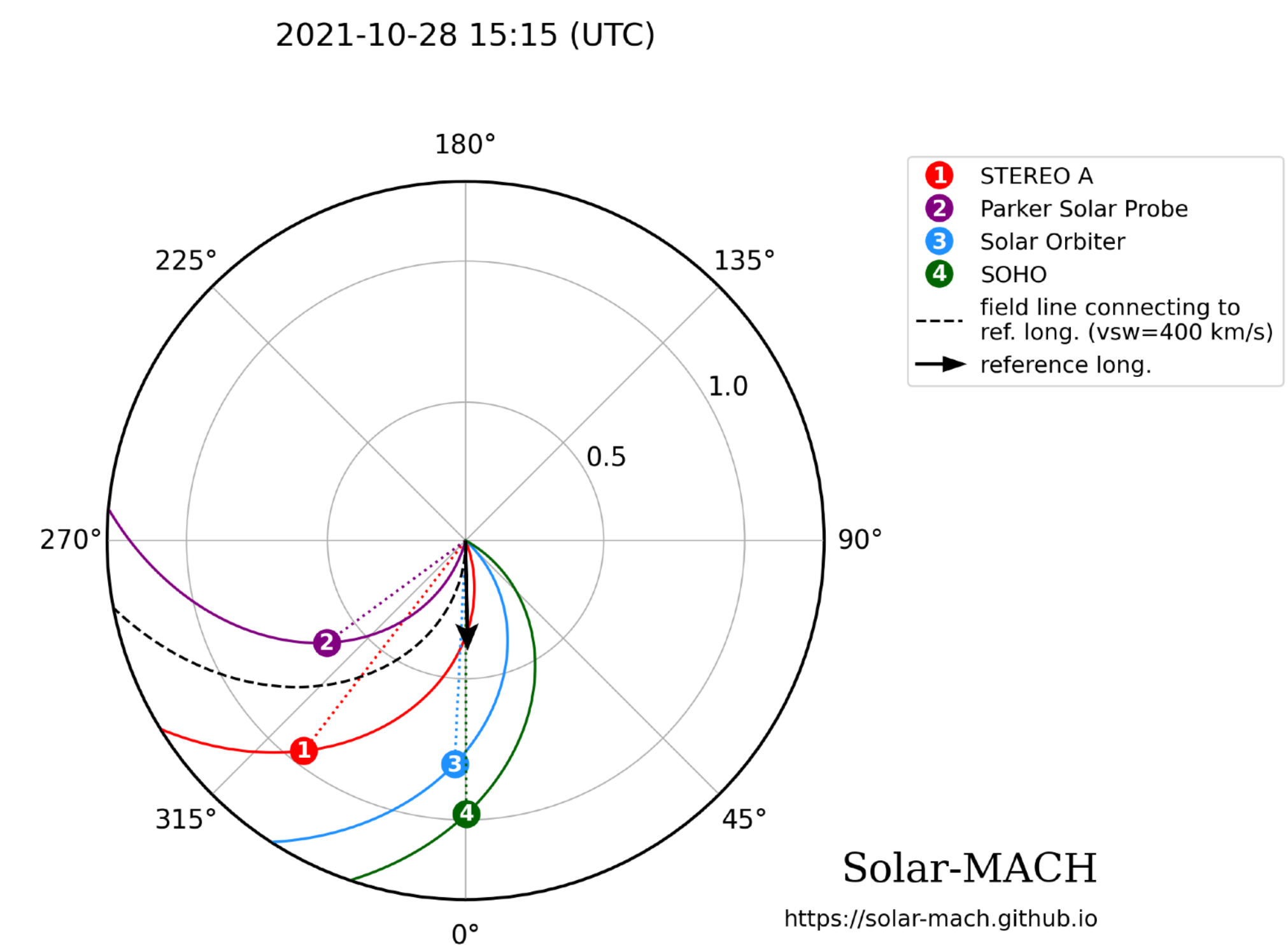


# CHARACTERIZING THE LONGITUDINAL DISTRIBUTION OF SEPs

... MAKING USE OF MORE SPACECRAFT!



Plots from J. Lang

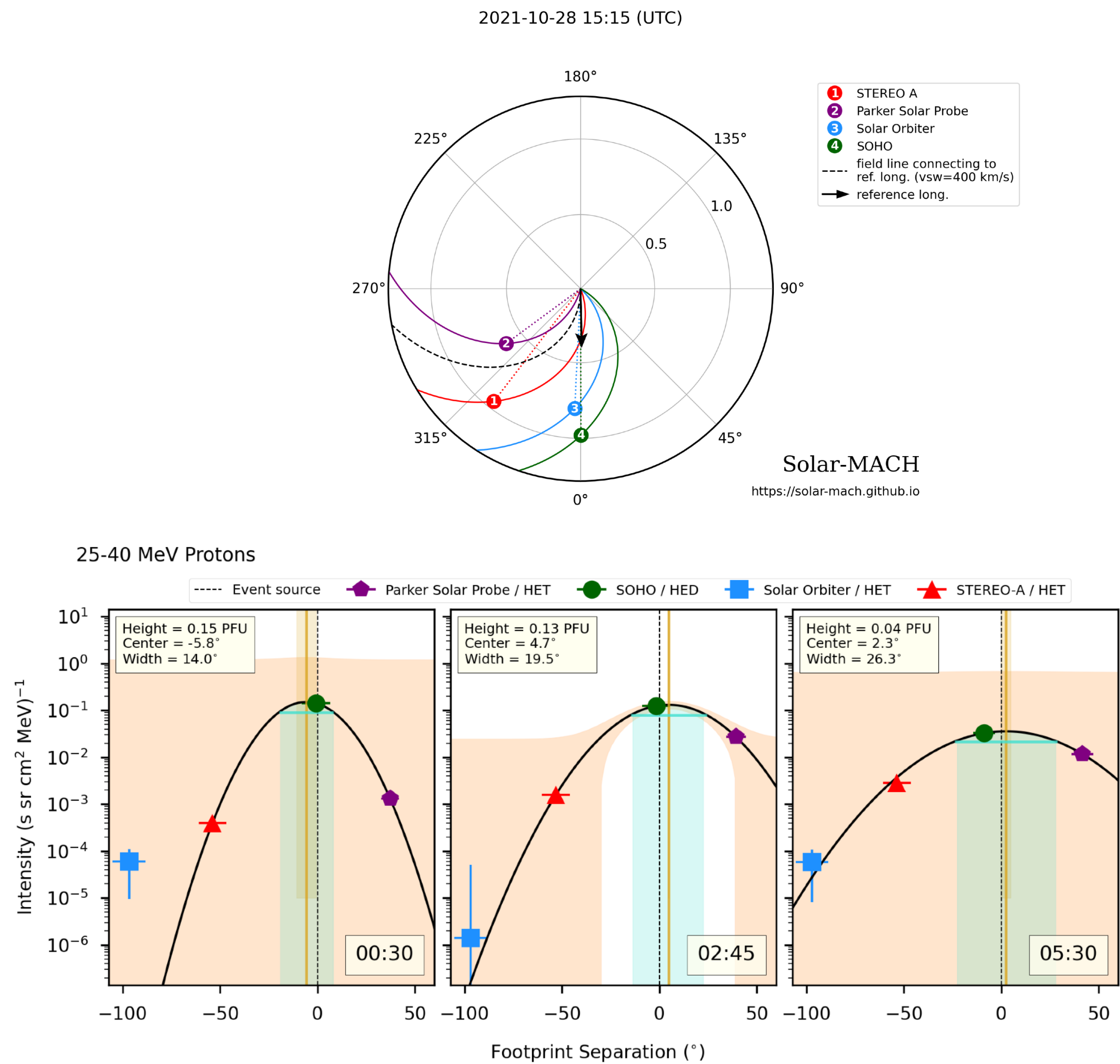
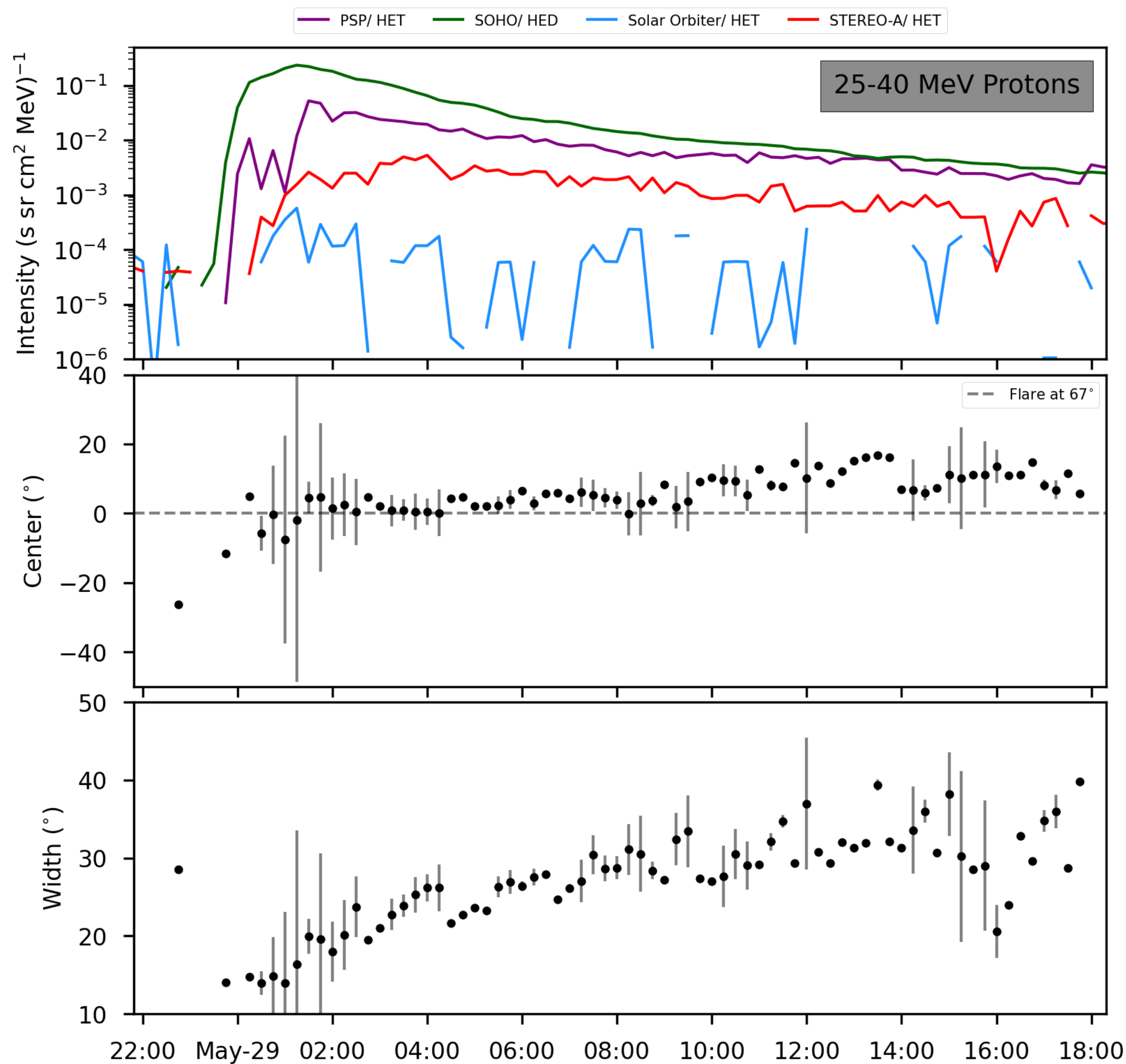


- Challenges:
- Different instrumentation
  - Intercalibration
  - Radial scaling (e.g., Rodríguez-García+ 2023)



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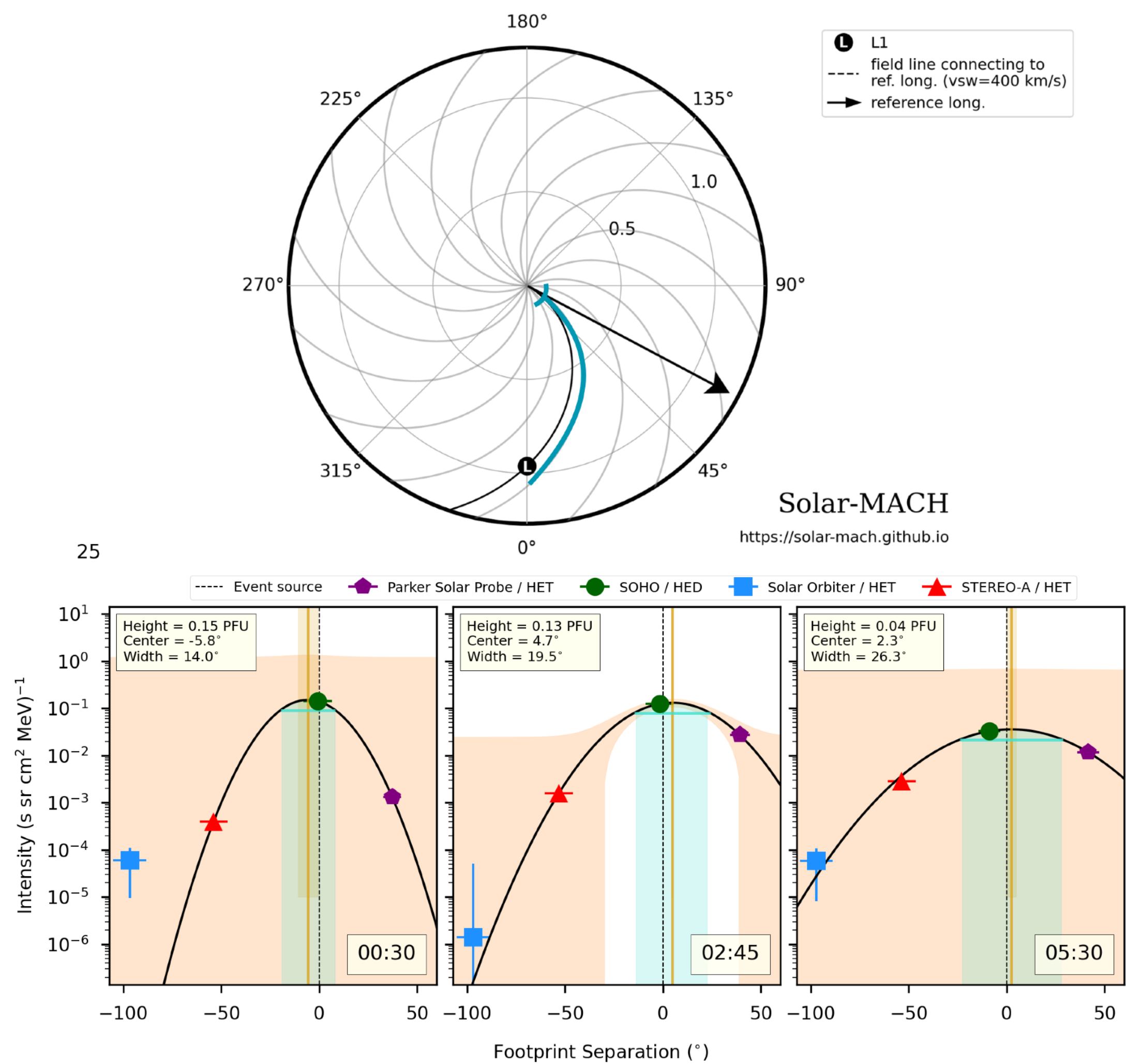
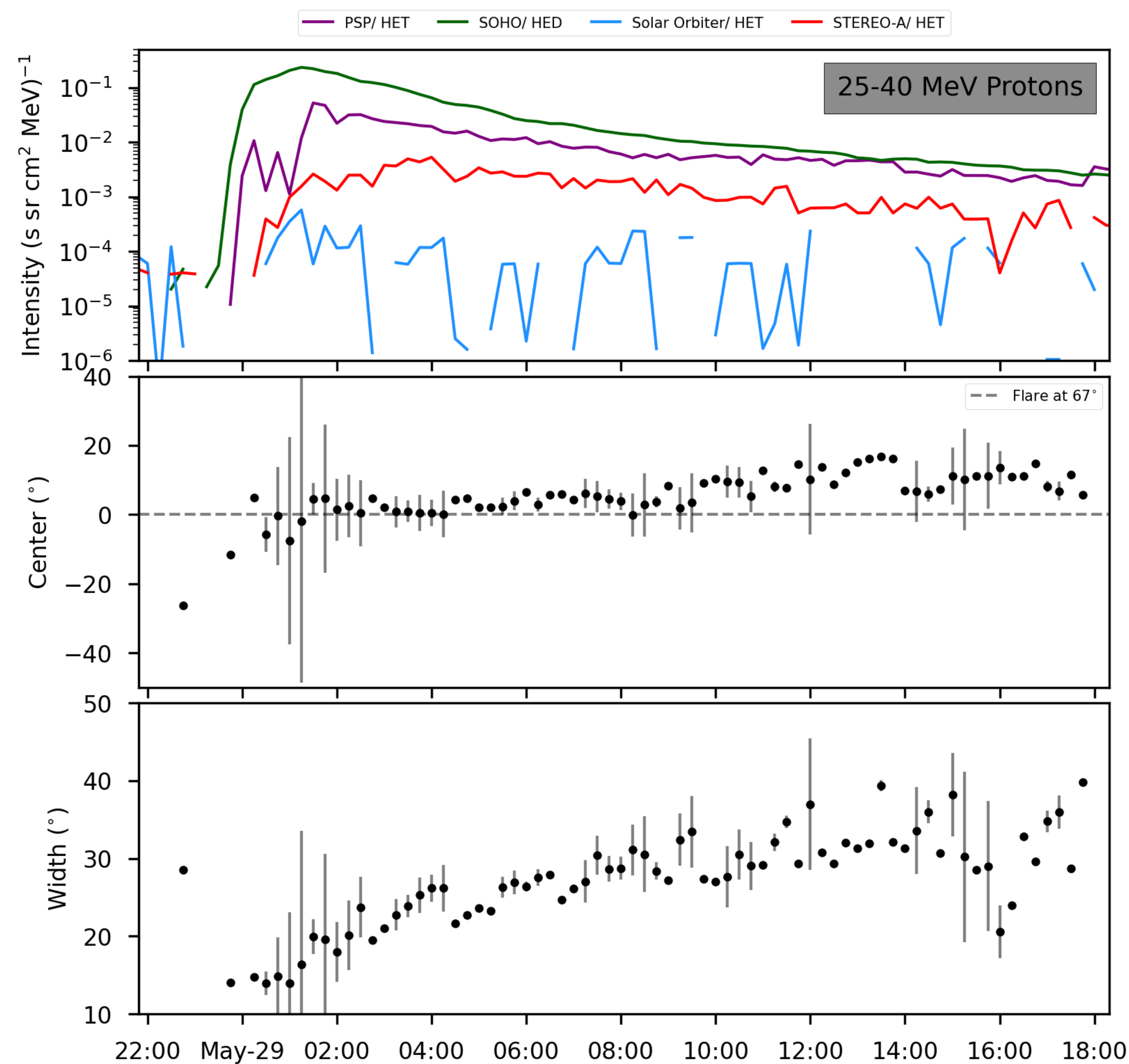


Plots from J. Lang



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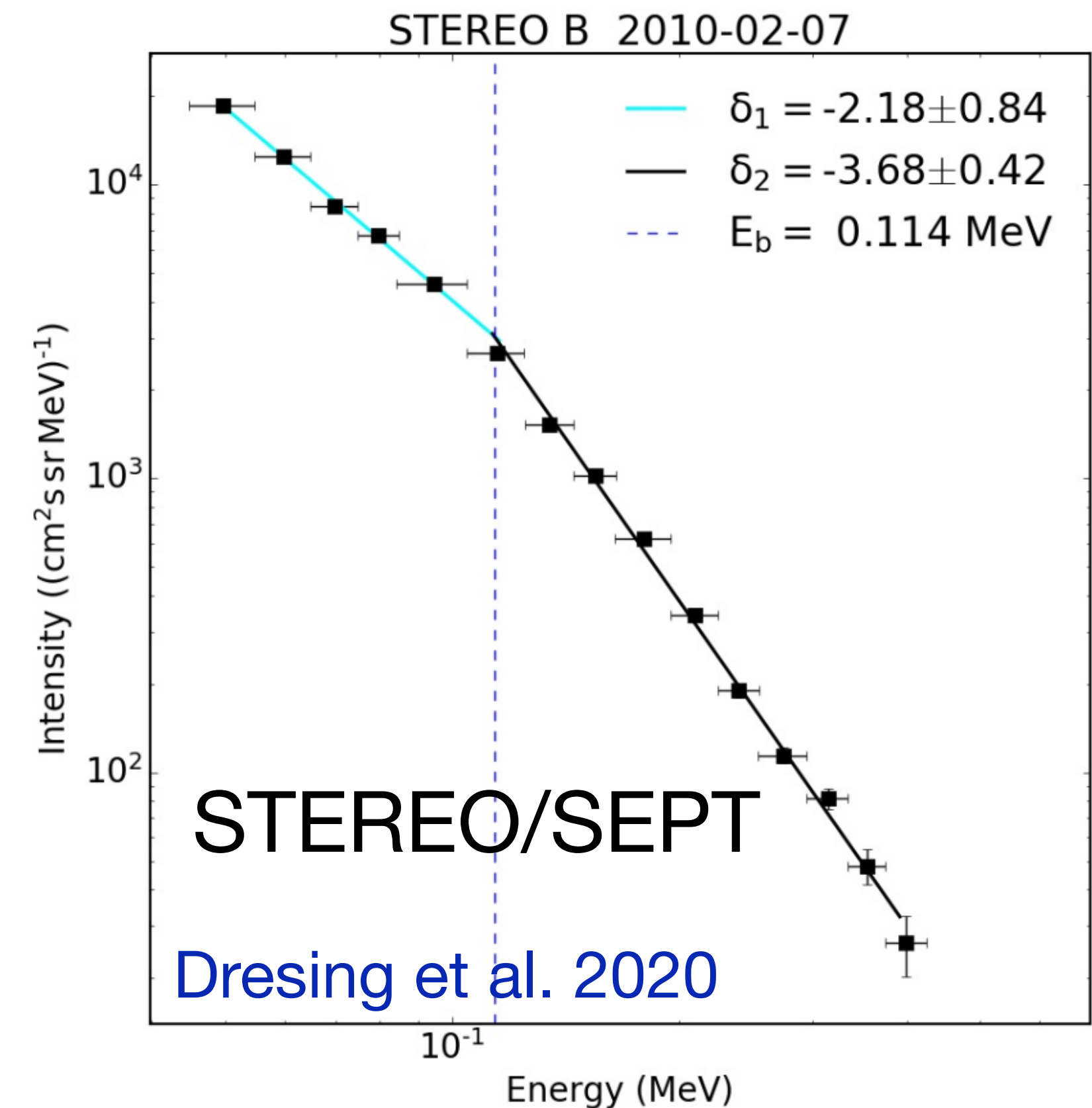
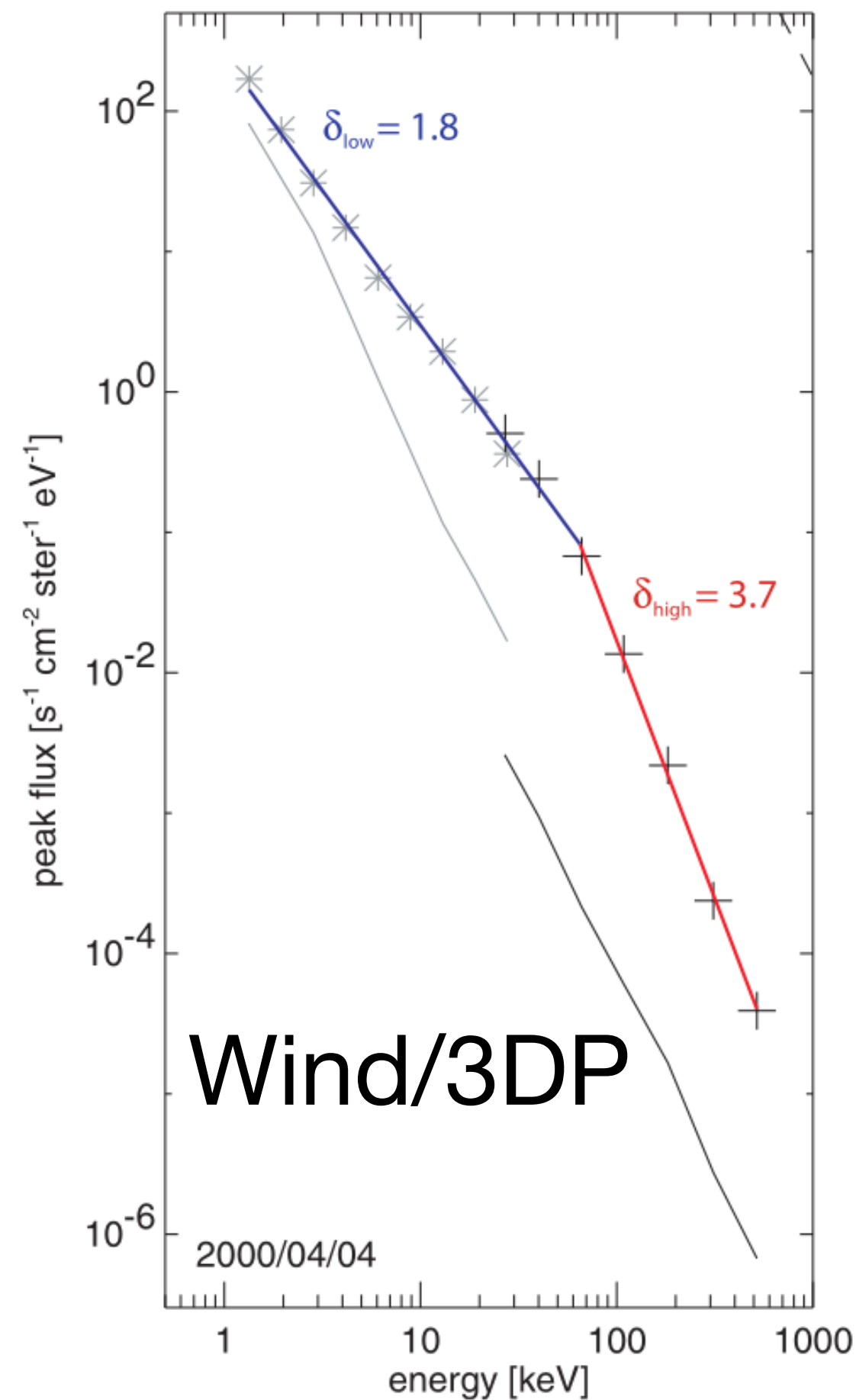


Plots from J. Lang



# Energy spectra: before Solar Orbiter

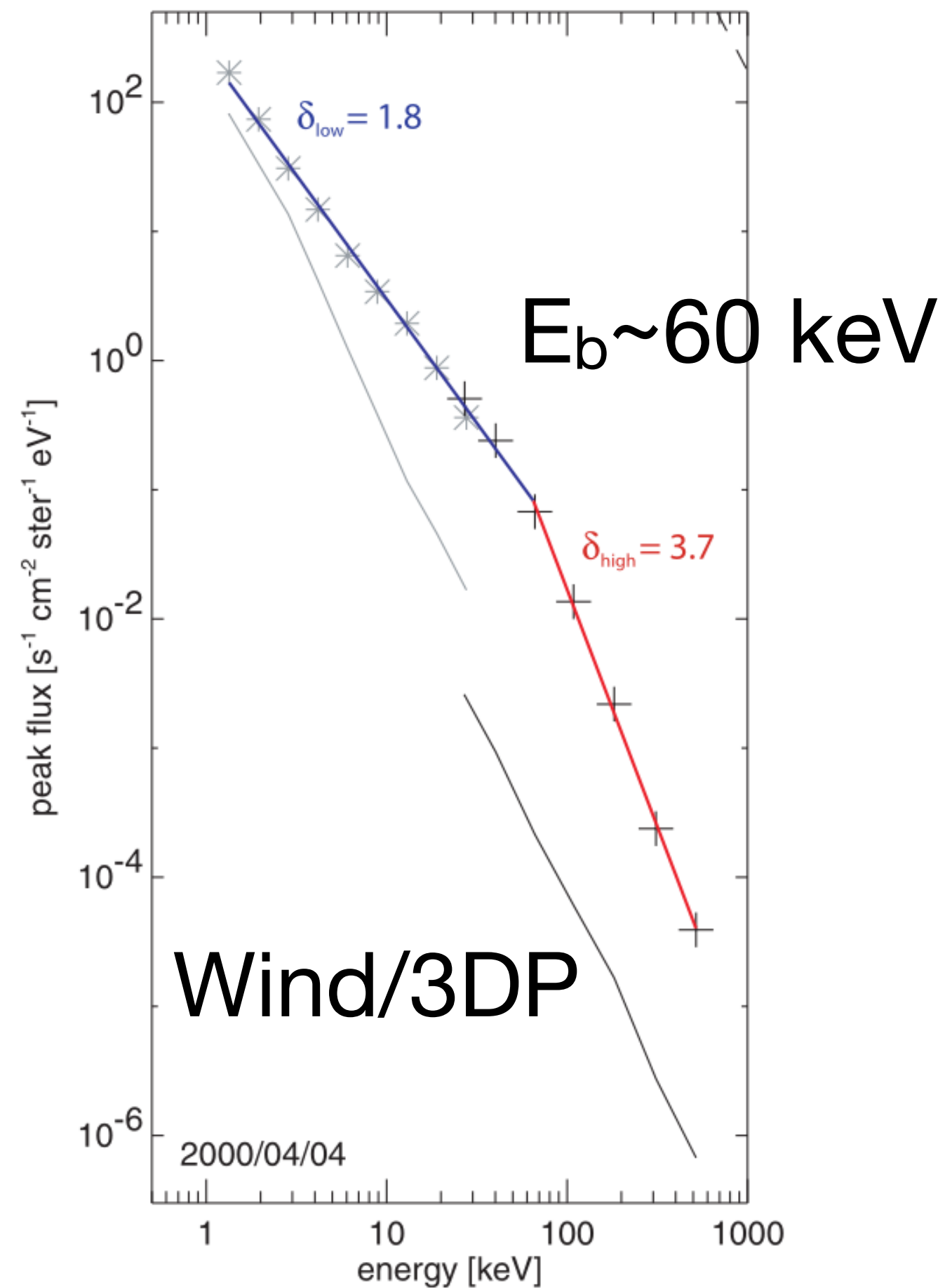
Krucker et al. 2009



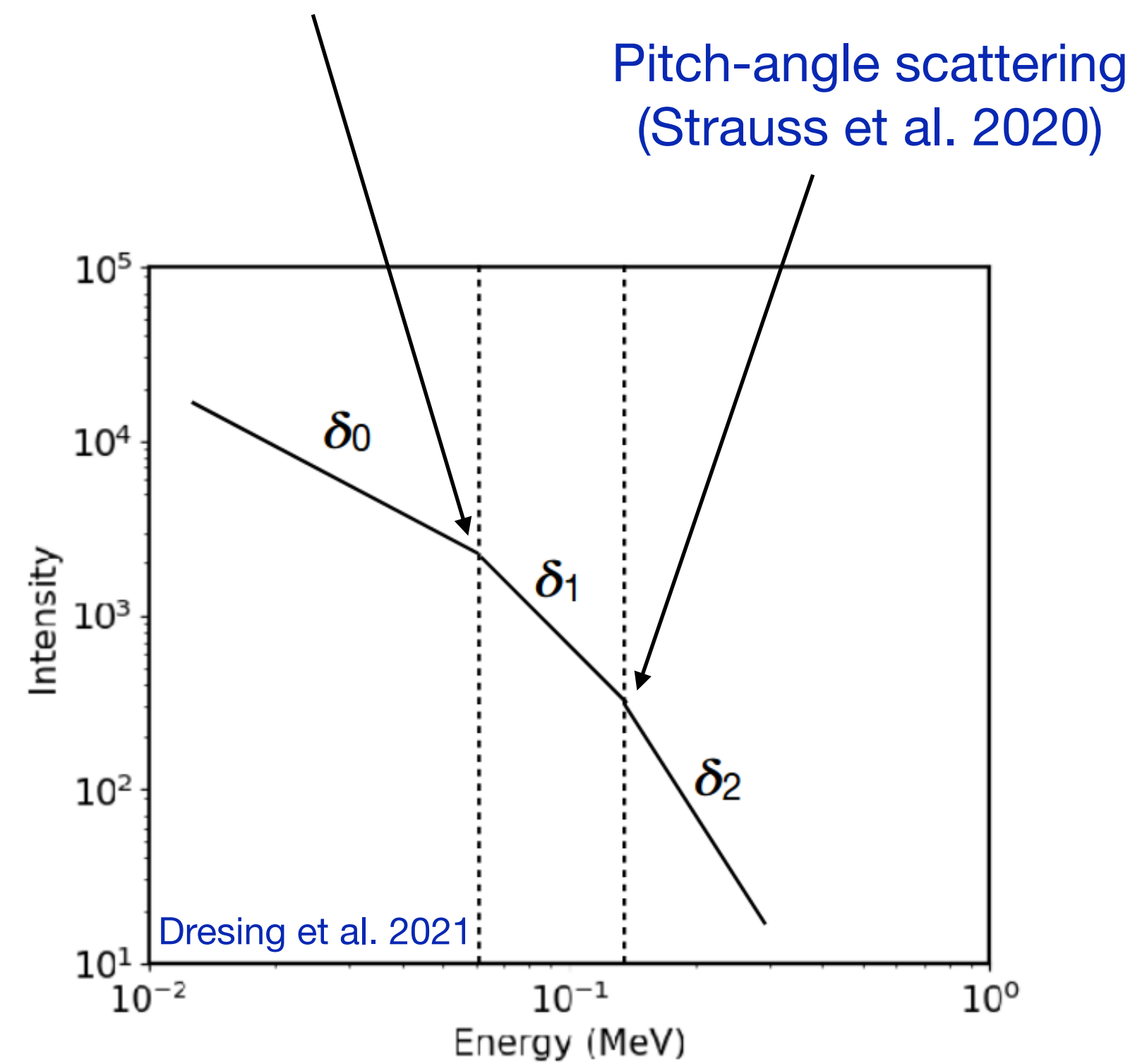


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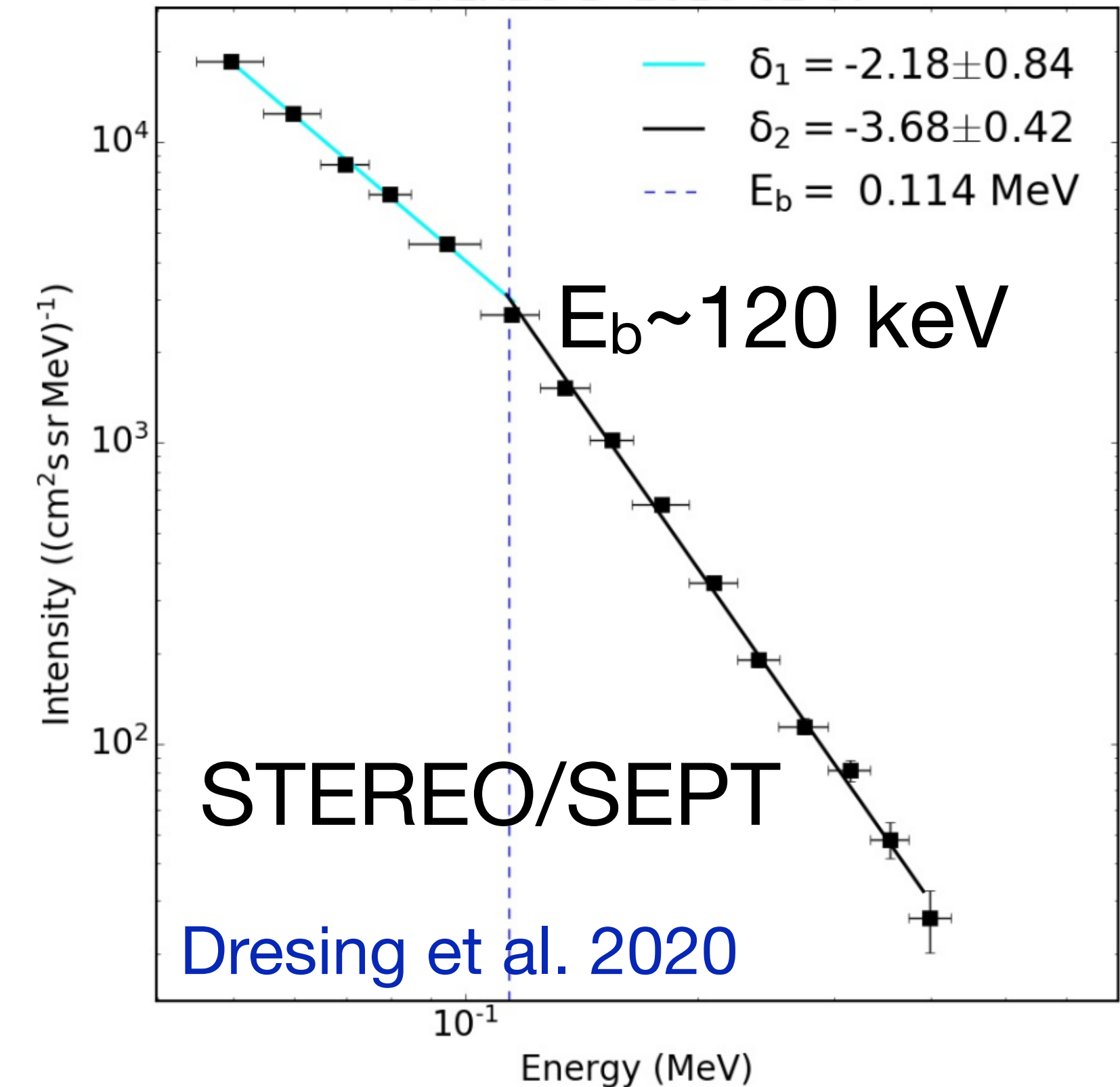
Krucker et al. 2009



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



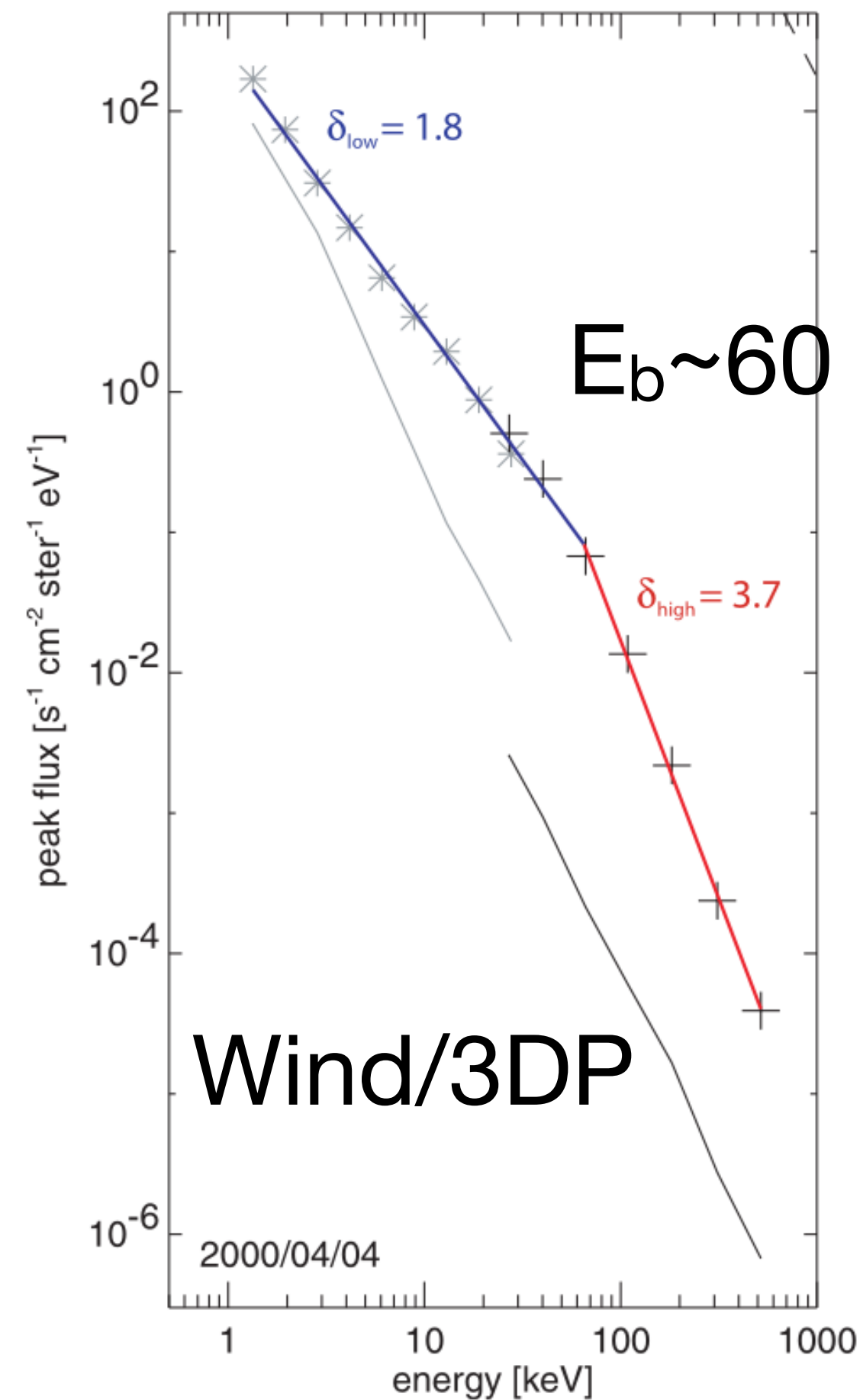
STEREO B 2010-02-07



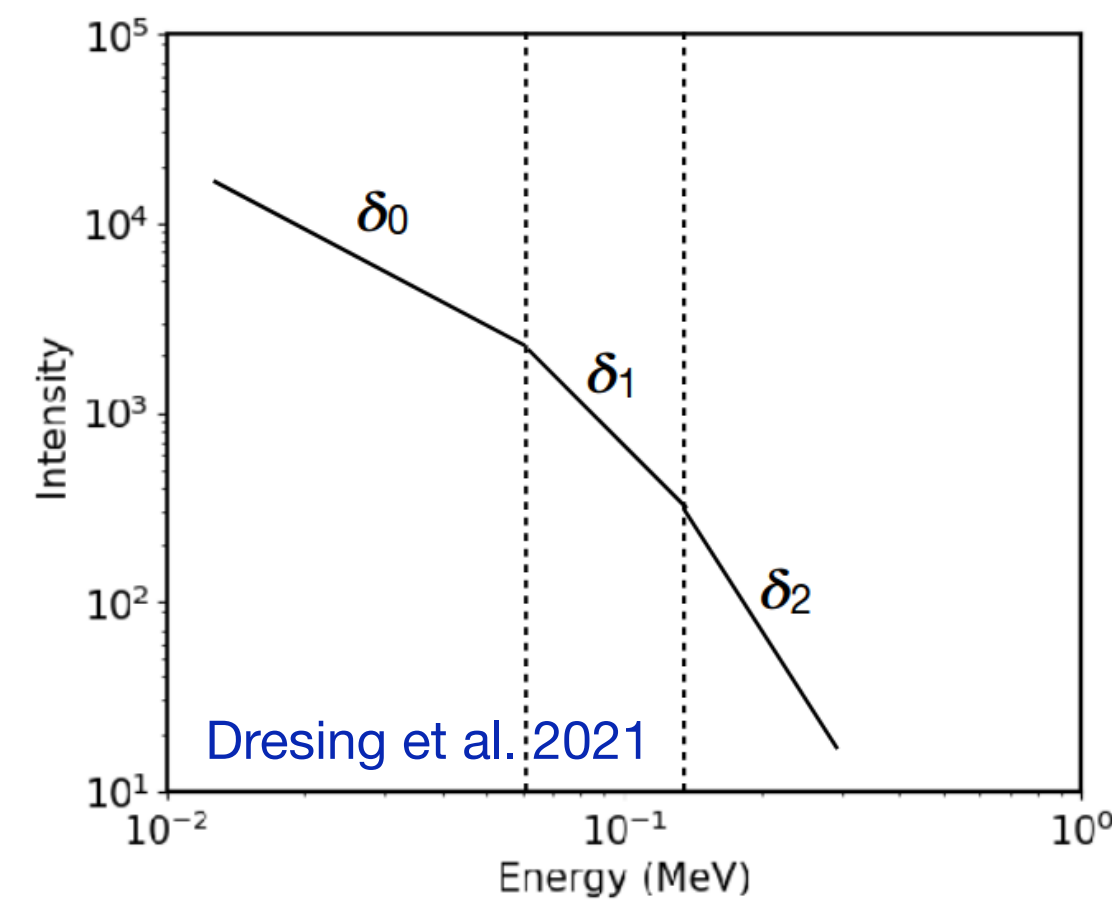
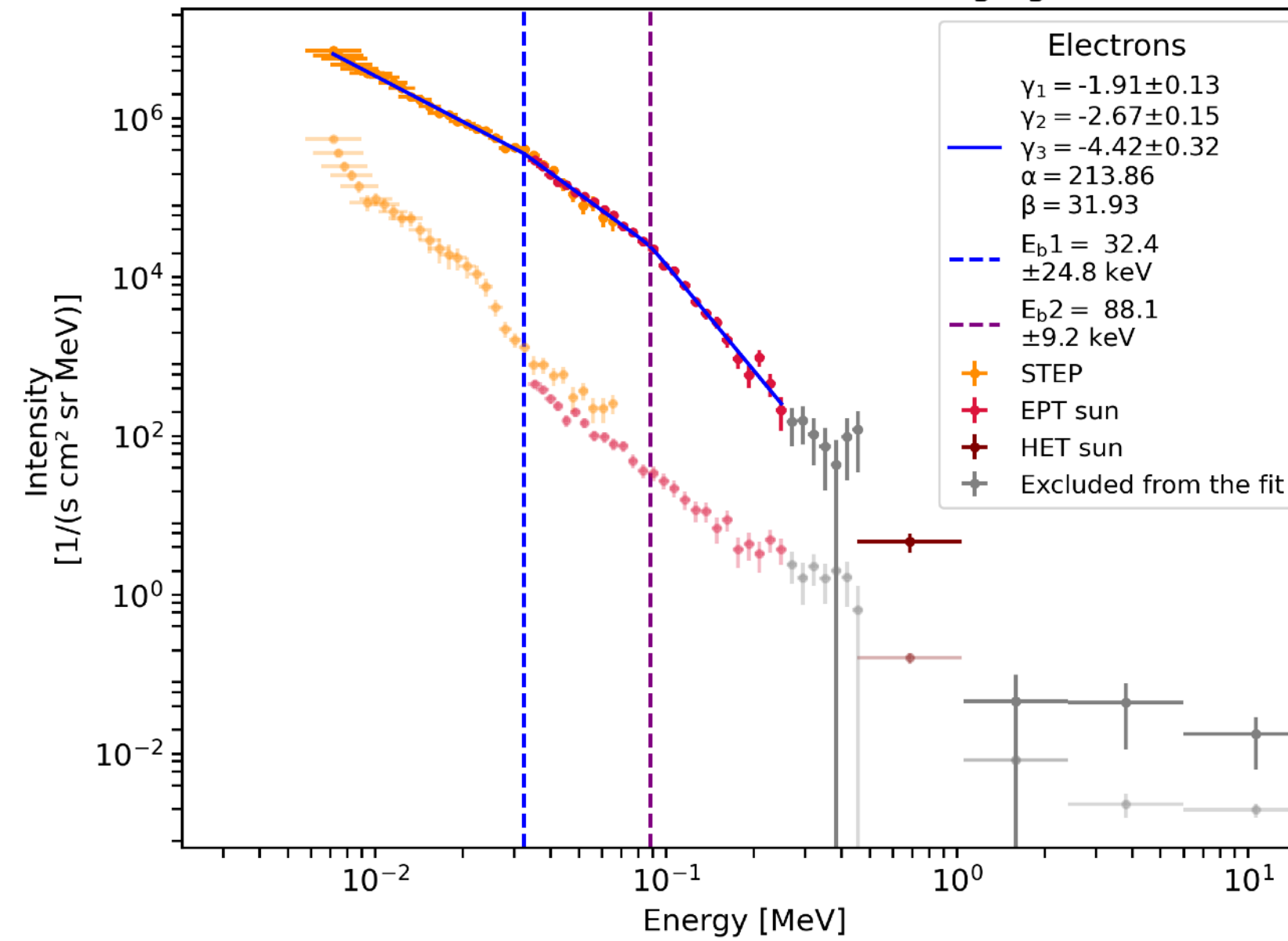


# Energy spectra with Solar Orbiter/EPD

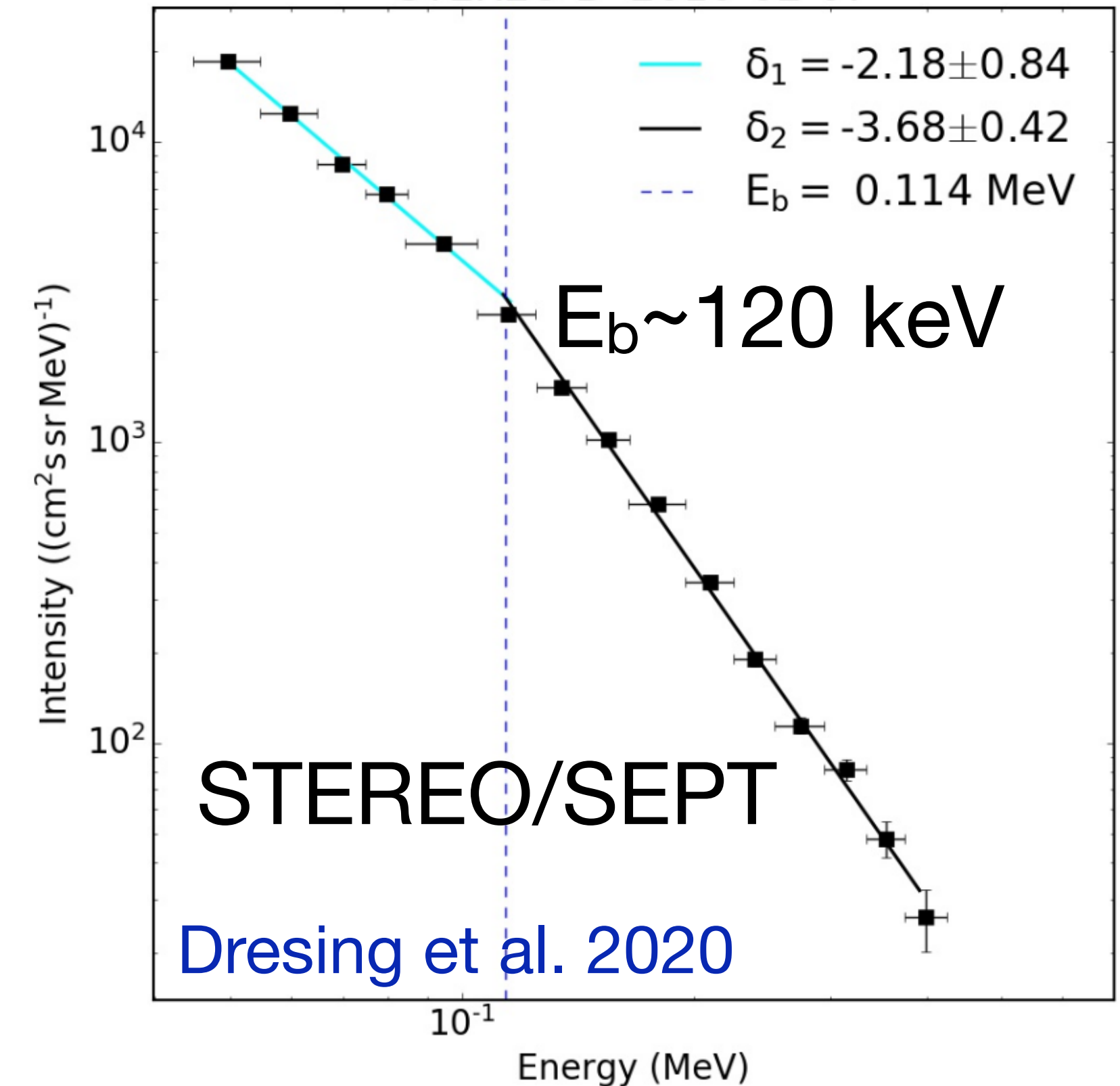
Krucker et al. 2009



Solar Orbiter (R = 0.81 au) peak spectrum  
2022-12-01 07:24 1min averaging



STEREO B 2010-02-07

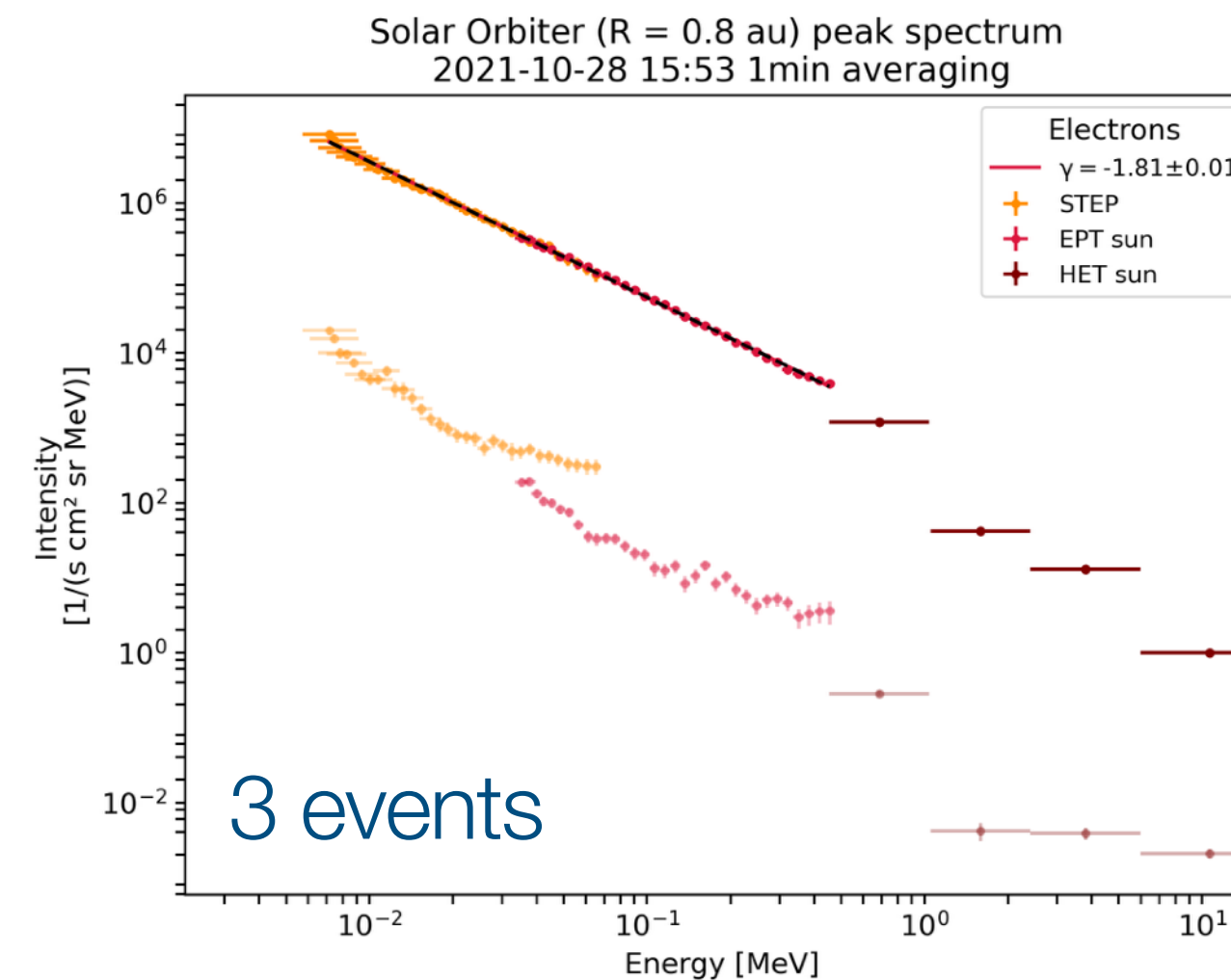
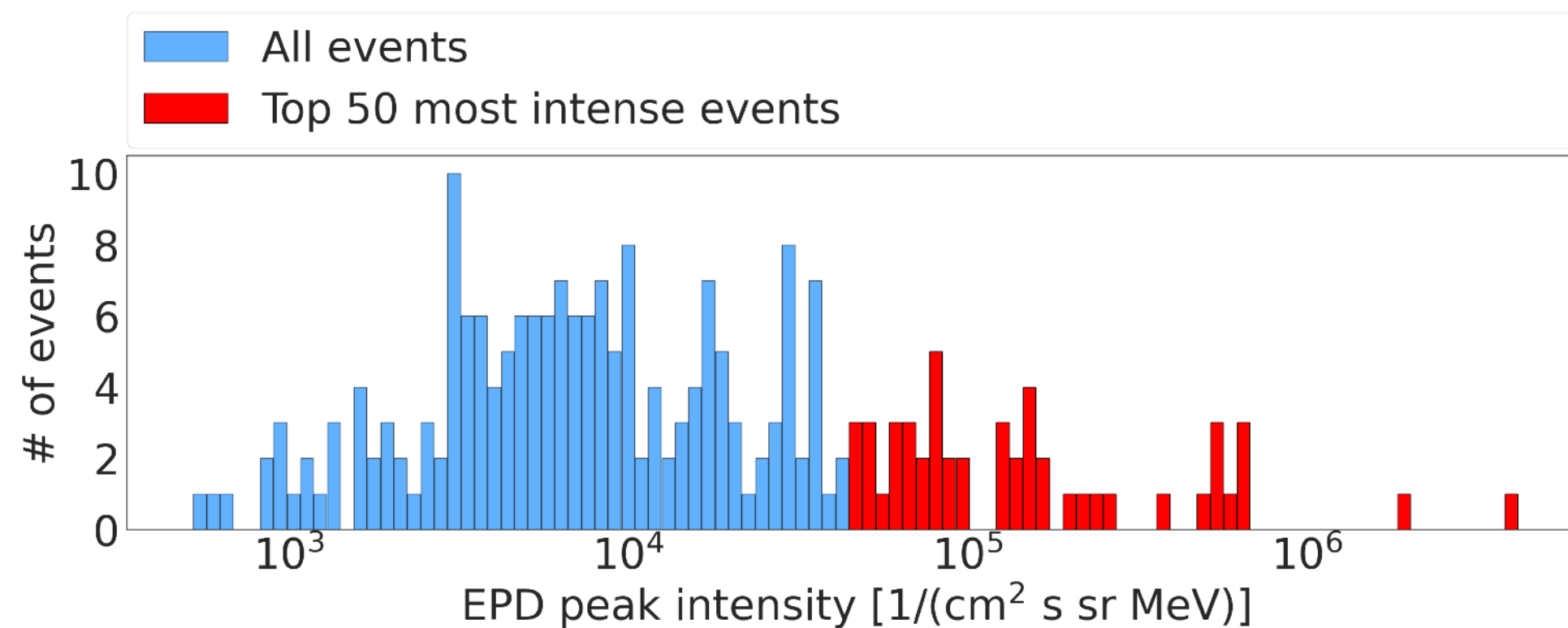




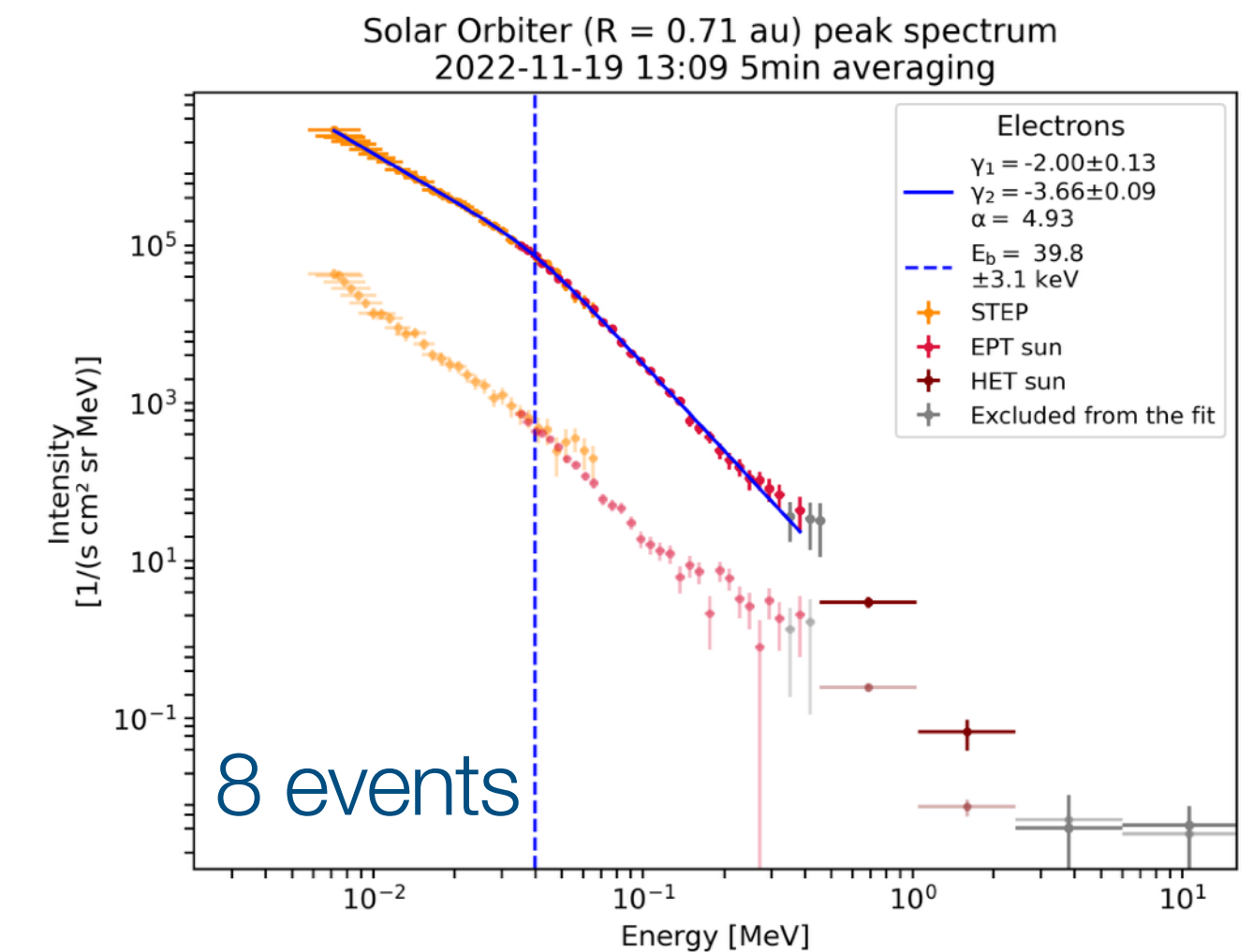
# Energy spectra with Solar Orbiter / EPD

Statistical analysis of peak intensity spectra of solar energetic electron events

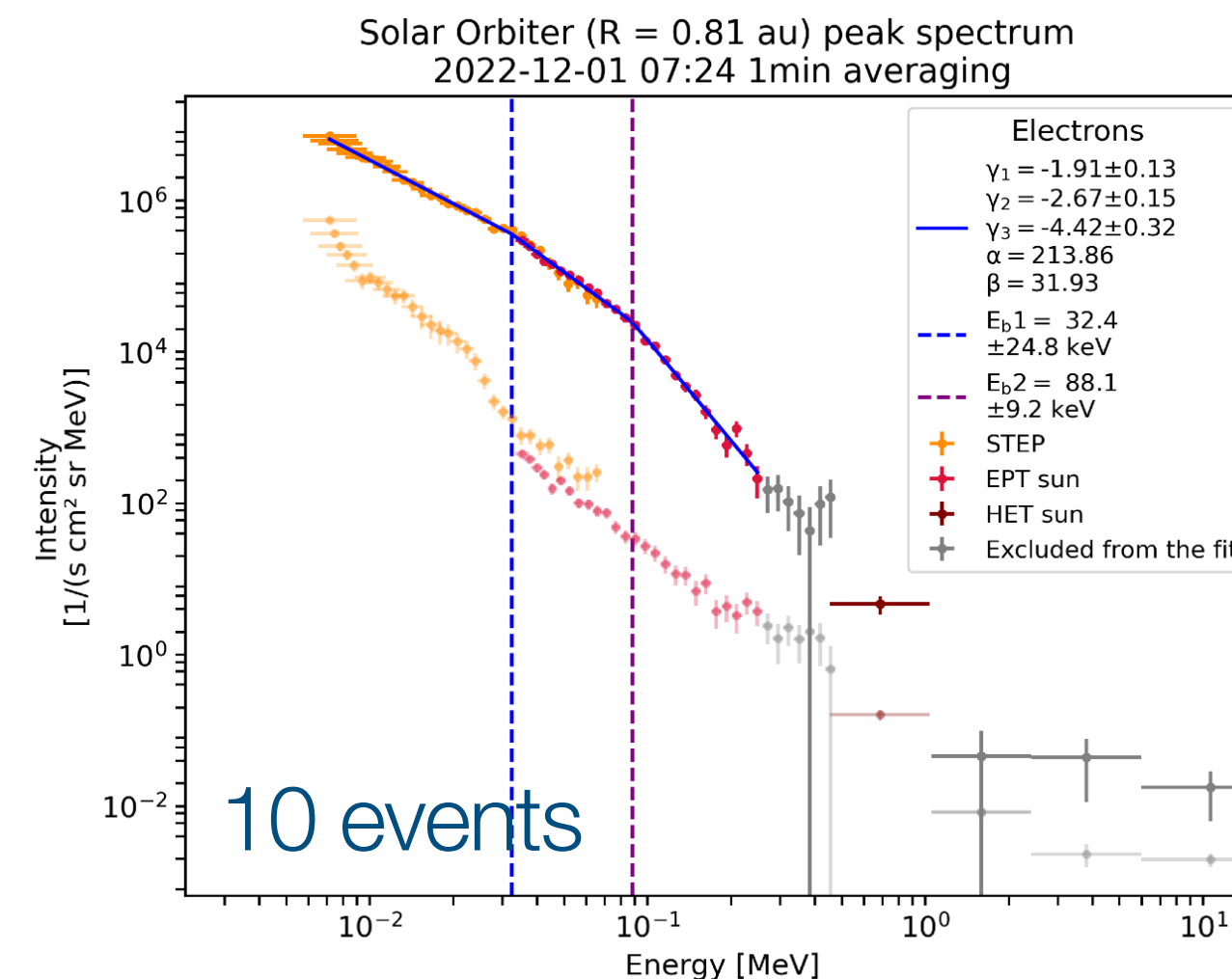
Based on the CoSEECat catalog (Warmuth+ 2025, submitted)



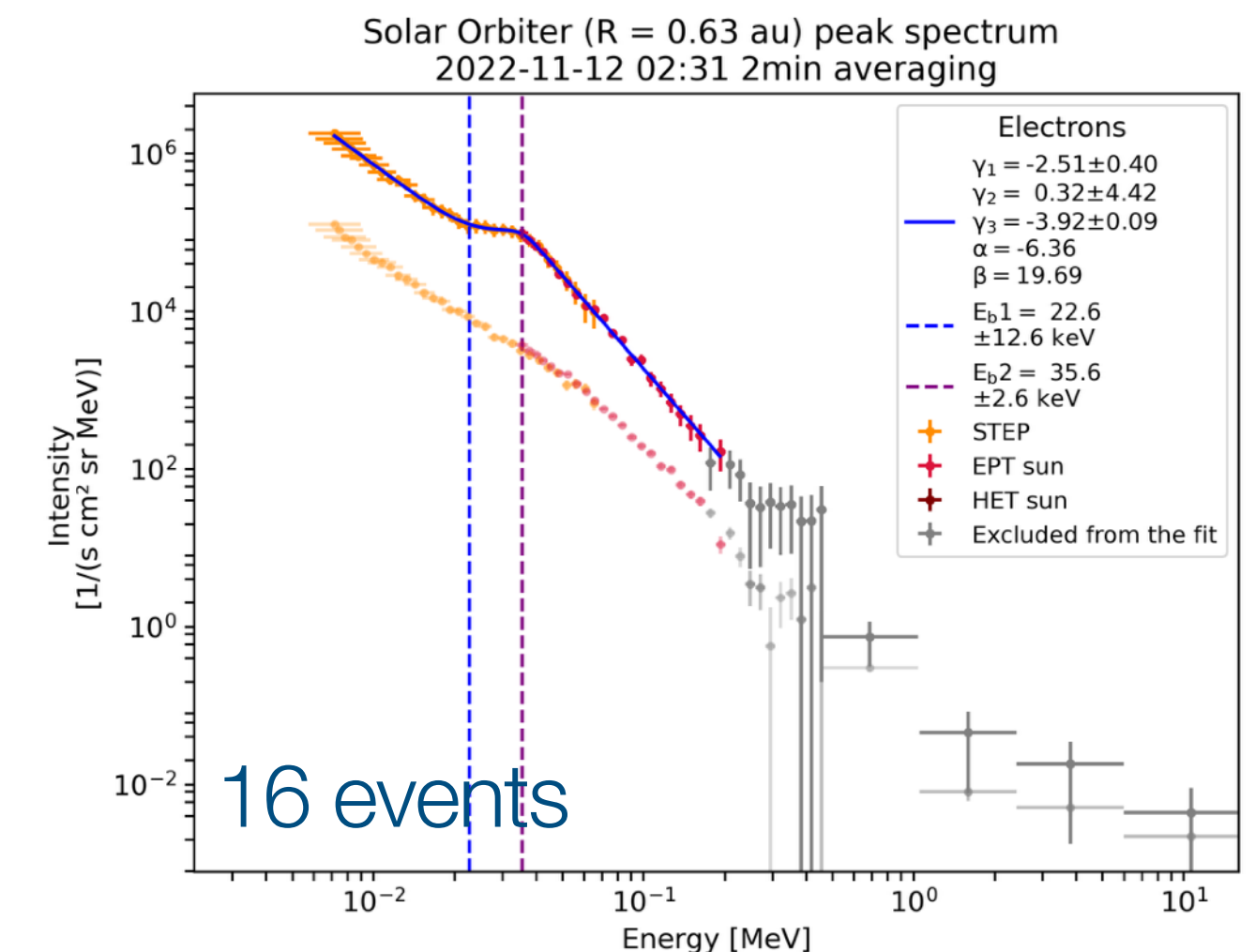
3 events



8 events



10 events



16 events

Fedeli et al. 2025,  
to be submitted



# SEP analysis tools of SERPENTINE and SOLER

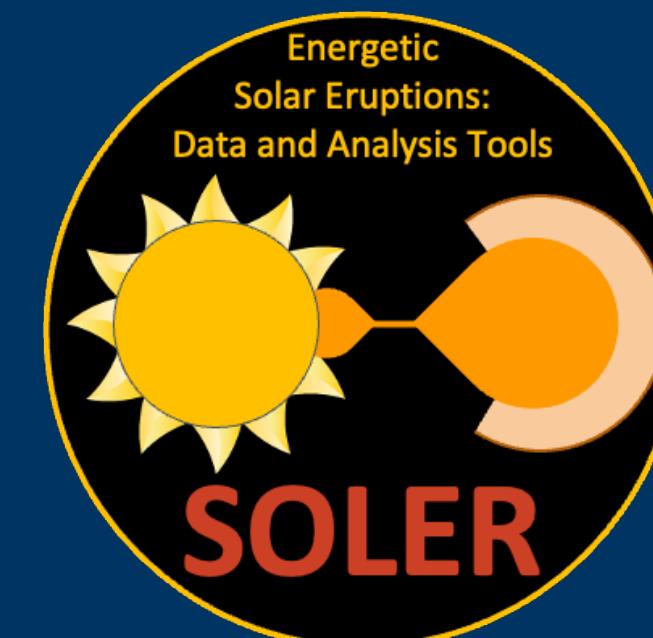




## SERPENTINE: Solar energetic particle analysis platform for the inner heliosphere

(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

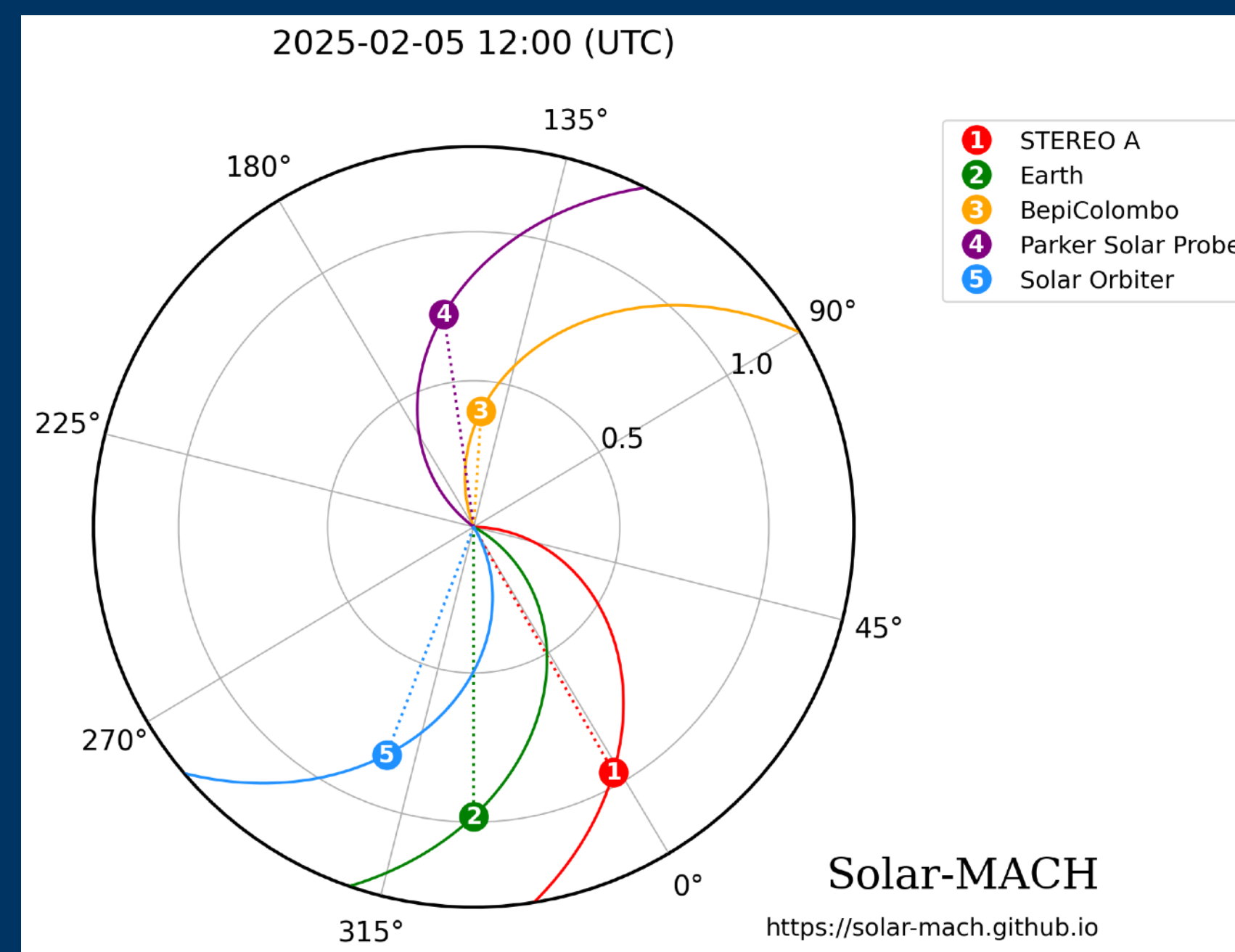


## SOLER: Energetic Solar Eruptions: Data and Analysis Tools

(EU Horizons Europe; 2024–2027)

- five partners

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





# Multi-sc SEP event catalog of solar cycle 25

SERPENTINE  
Data Center

Home Catalogs L3 Datasets API

Solar Energetic Particle Analysis  
platform for the Inner Heliosphere

Solar cycle 25 SEP Events Catalog

Catalog description

This catalogue contains multi-spacecraft solar energetic particle (SEP) events, which were observed with the new spacecraft fleet in solar cycle 25. The catalog comprises key SEP characteristics observed by five different observer locations as provided by Solar Orbiter, Parker Solar Probe, STEREO A, Wind and SOHO (at the Lagrangian point 1), and BepiColombo. The catalog focuses on large events, which show energetic proton increases above 25 MeV observed at least at two spacecraft. The catalogue provides not only key parameters of the proton event but also the same parameters for 1 MeV and 100 keV electrons, respectively.

Select time range

Start date 2020-11-29

End date 2023-05-16

Reset

Select spacecraft

	Include	Require
BepiColombo	<input checked="" type="checkbox"/>	<input type="checkbox"/>
L1 (SOHO/Wind)	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Parker Solar Probe	<input checked="" type="checkbox"/>	<input type="checkbox"/>
STEREO A	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Solar Orbiter	<input checked="" type="checkbox"/>	<input type="checkbox"/>

Additional filters

Add new...

No additional filters

Order by

Event date/time (id)

Using spacecraft

Maximum

Direction

Ascending

Reset all filters

Export as CSV file

Selected 45 entries

Previous 1 2 Next

Show 25 entries per page

ID	Spacecraft	Channel	Event date/ Onset date [UTC]	Flare time/ Onset time [UTC]	Flare location/ S/C location (Carrington lat., lon. [deg])	Flare class (GOES)	Radial distance [au]	SEP peak date [UTC]	SEP peak time [UTC]	SEP peak flux [cm <sup>-2</sup> s <sup>-1</sup> sr <sup>-1</sup> MeV <sup>-1</sup> ]	e <sup>+</sup> /p ratio e <sup>+</sup> : ~0.5 MeV p: 25-40 MeV	Radio type II burst	Associated CMEs/IP shocks	Comm
SEP-C25-0001			2020-11-29	12:34:00	-23, 266	M4.4						PSP, STEREO- A, Wind, GB	CME-0001a CME-0001b	Later fl observ 13:01
	L1 (SOHO/Wind)	p 25 MeV e <sup>+</sup> 100 keV	2020-11-29 2020-11-29	<=20:47:30 <=16:30:00	1, 348		0.98	2020-11-30 2020-11-30	20:45:00 23:30:00	3.63e-02 4.56e+03	2.02e+02		WIND-2020120210	Gradu increas Gradu
	Parker Solar Probe	e <sup>+</sup> 1 MeV p 25 MeV	2020-11-29 2020-11-29	<=16:30:00 13:30:00	4, 252		0.81	2020-11-30 2020-11-30	23:30:00 03:30:00	1.77e+00 4.64e+00				Only 1h resolut availab not in r orienta
		e <sup>+</sup> 100 keV	2020-11-29	13:47:30				2020-11-29	>=20:35:00	>=1.99e+04				Intensi rising s local p peak r later di data ga not in r orienta
	STEREO A	p 25 MeV e <sup>+</sup> 100 keV e <sup>+</sup> 1 MeV	2020-11-29 2020-11-29 2020-11-29	15:30:00 <=13:37:30 <=13:54:00	7, 291		0.96	2020-11-29 2020-11-29 2020-11-29	23:25:00 22:35:00 20:25:00	1.81e-01 6.11e+03 2.86e+00	2.72e+01		STEREO-2020120107 STEREO-2020120318	
	Solar Orbiter	p 25 MeV e <sup>+</sup> 100 keV e <sup>+</sup> 1 MeV	2020-11-29 2020-11-29 2020-11-29	14:03:30 13:27:00 13:35:00	-5, 111		0.88	2020-11-29 2020-11-29 2020-11-29	18:25:00 15:55:00 15:55:00	1.41e-01 3.03e+03 8.03e+00	1.70e+02			
SEP-C25-0002			2020-12-07	15:46:00	-25, 249	C7.4						PSP, STEREO-	CME-0002a	

SERPENTINE  
Data Center

Home Catalogs L3 Datasets API

Solar Energetic Particle Analysis  
platform for the Inner Heliosphere

SEP-C25-0001  
November 29, 2020

Science case  
Widespread event

Flare date/time [UTC]  
2020-11-29 12:34:00

Flare Carrington latitude  
-23°

Flare comments  
Later flare observed at 13:01

Flare class (GOES)  
M4.4

Flare Carrington longitude  
266°

Radio type II bursts  
PSP, STEREO-A, Wind, GB

Decametric type II burst  
Start time [UT]  
13:00

Frequency range  
20-3.5 MHz

Metric type II burst  
Start time [UT]  
12:57

Frequency range  
25-180 MHz

Radio comments  
RSTN

End time [UT]  
13:40

End time [UT]  
13:22

Imaging available  
NRH

STEREO A  
L1  
BepiColombo  
Parker Solar Probe  
Solar Orbiter

field line connecting to  
ref. long. (vsw=400 km/s)

reference long.

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

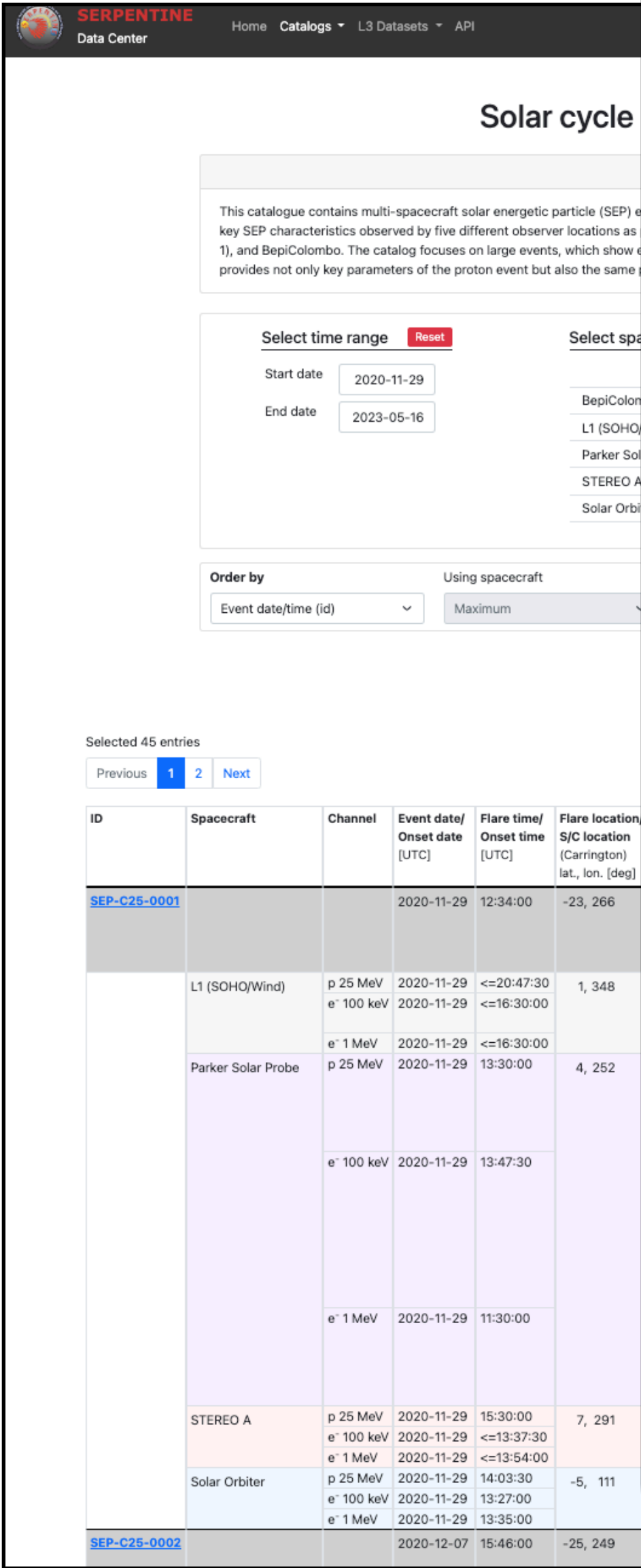
	L1 (SOHO/Wind)	Parker Solar Probe	STEREO A	Solar Orbiter
Radial distance [au]	0.98	0.81	0.96	0.88
Carrington latitude [deg]	1	4	7	-5
Carrington longitude [deg]	348	252	291	111
e <sup>+</sup> (~1 MeV) / p (25-40 MeV) ratio	2.02e+02	—	2.72e+01	1.70e+02
p 25 MeV				
Onset date [UTC]	2020-11-29	2020-11-29	2020-11-29	2020-11-29
Onset time [UTC]	<=20:47:30	13:30:00	15:30:00	14:03:30
Averaging used for onset [min]	5	60	4	5
Sector used for onset	—	A	—	sun
Peak date [UTC]	2020-11-30	2020-11-30	2020-11-29	2020-11-29
Peak time [UTC]	20:45:00	03:30:00	23:25:00	18:25:00
Peak flux [cm <sup>-2</sup> s <sup>-1</sup> sr <sup>-1</sup> MeV <sup>-1</sup> ]	3.63e-02	4.64e+00	1.81e-01	1.41e-01
Averaging used for peak [min]	10	60	10	10
Sector used for peak	—	A	—	sun
Inferred injection date [UTC]	2020-11-29	2020-11-29	2020-11-29	2020-11-29
Inferred injection time [UTC]	20:09:25	13:00:48	14:53:28	13:31:14
Spiral length used for inferred injection time [au]	1.16	0.89	1.13	0.99
Solar wind speed [km/s]	359	—	363	—
Comments		Only 1h resolution available. PSP not in nominal orientation		
e <sup>+</sup> 100 keV				
Onset date [UTC]	2020-11-29	2020-11-29	2020-11-29	2020-11-29
Onset time [UTC]	<=16:30:00	13:47:30	<=13:37:30	13:27:00
Averaging used for onset [min]	60	5	3	2
Sector used for onset	0	3 (sun)	north	sun
Peak date [UTC]	2020-11-30	2020-11-29	2020-11-29	2020-11-29
Peak time [UTC]	23:30:00	>=20:35:00	22:35:00	15:55:00
Peak flux [cm <sup>-2</sup> s <sup>-1</sup> sr <sup>-1</sup> MeV <sup>-1</sup> ]	4.56e+03	>=1.99e+04	6.11e+03	3.03e+03
Averaging used for peak [min]	60	10	10	10
Sector used for peak	7	7 (asun)	sun	sun
Inferred injection date [UTC]	2020-11-29	2020-11-29	2020-11-29	2020-11-29
Inferred injection time [UTC]	16:12:40	13:31:41	13:20:39	13:12:17
Spiral length used for inferred	1.16	0.89	1.12	0.99



see also  
Dresing+ 2024



# Multi-sc SEP event catalog of solar cycle 25

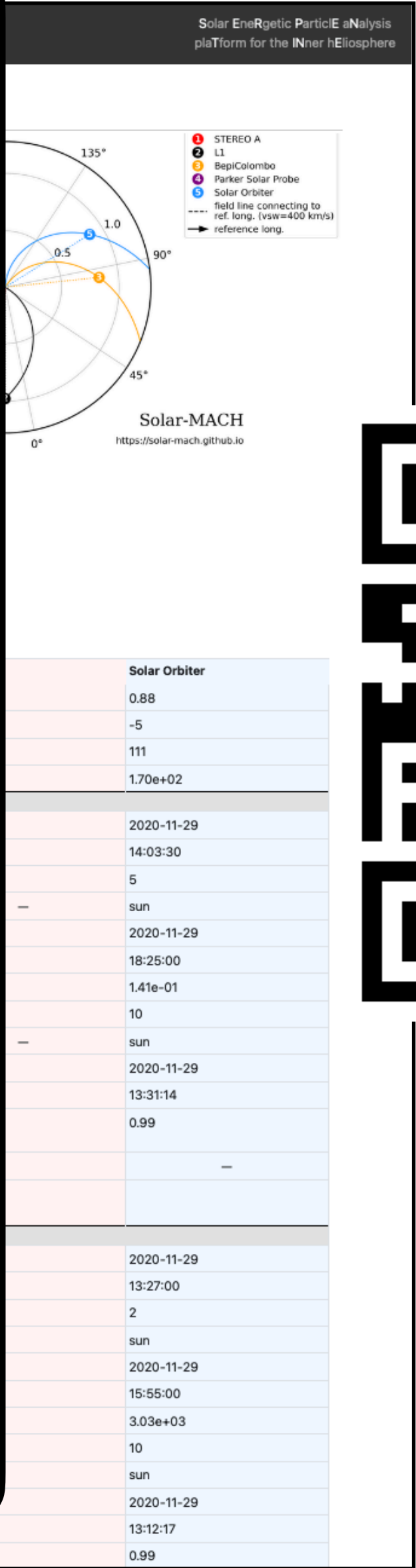


The catalog includes SEP observations from 5 observer locations:

- 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

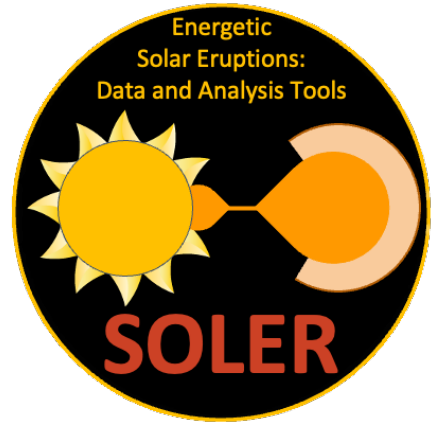
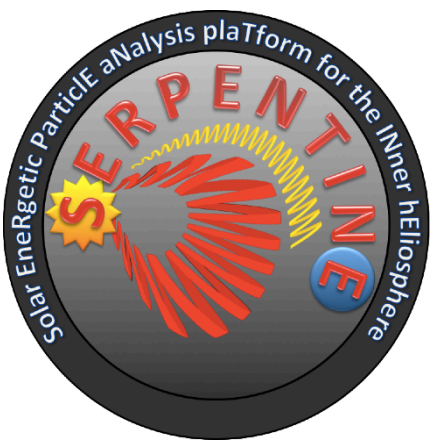


see also  
Dresing+ 2024



# Technical objectives of SERPENTINE and SOLER

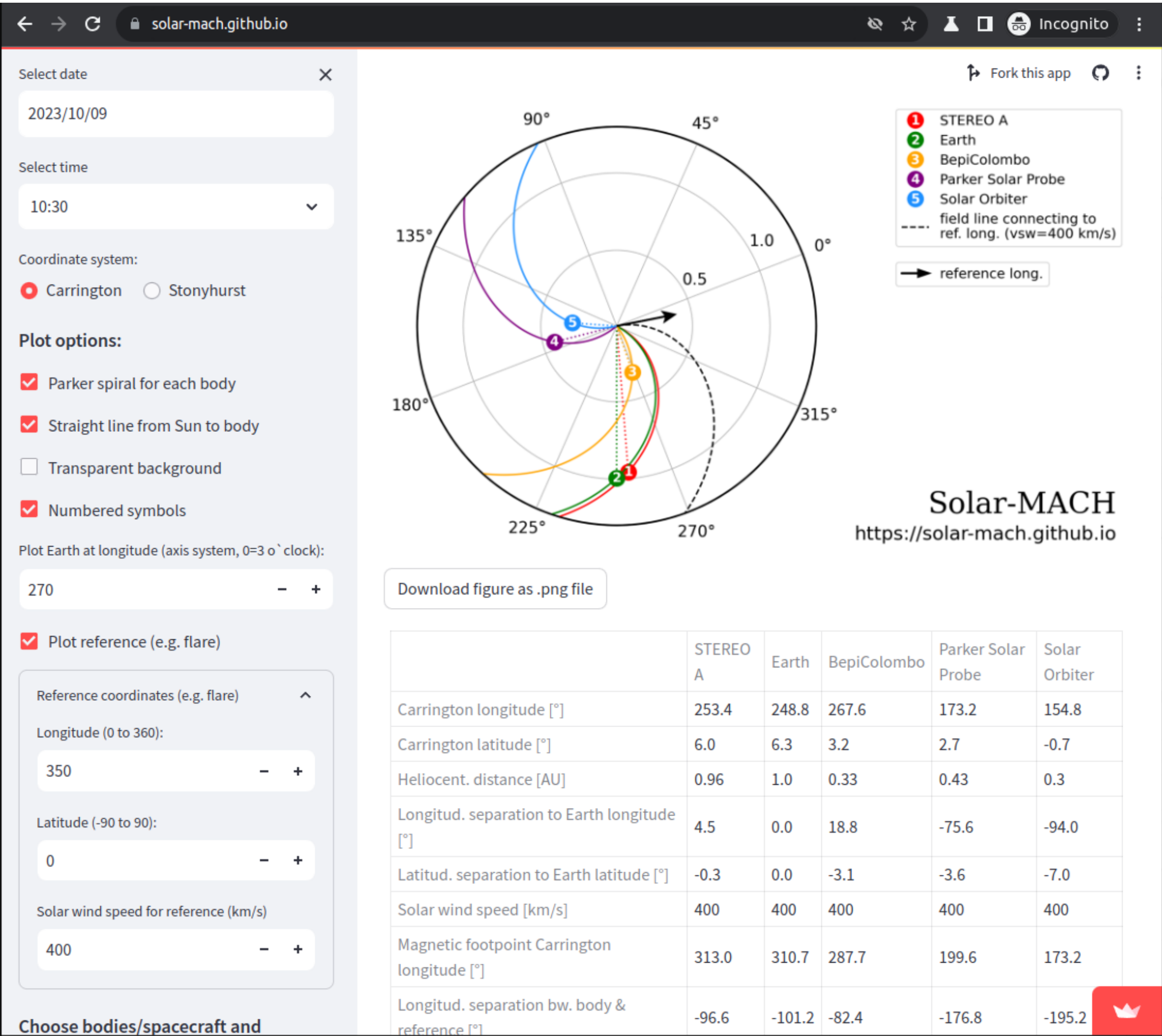
Development of analysis and modeling tools for the scientific community



Event catalogs and datasets:



SERPENTINE/SOLER Jupyter HUB:



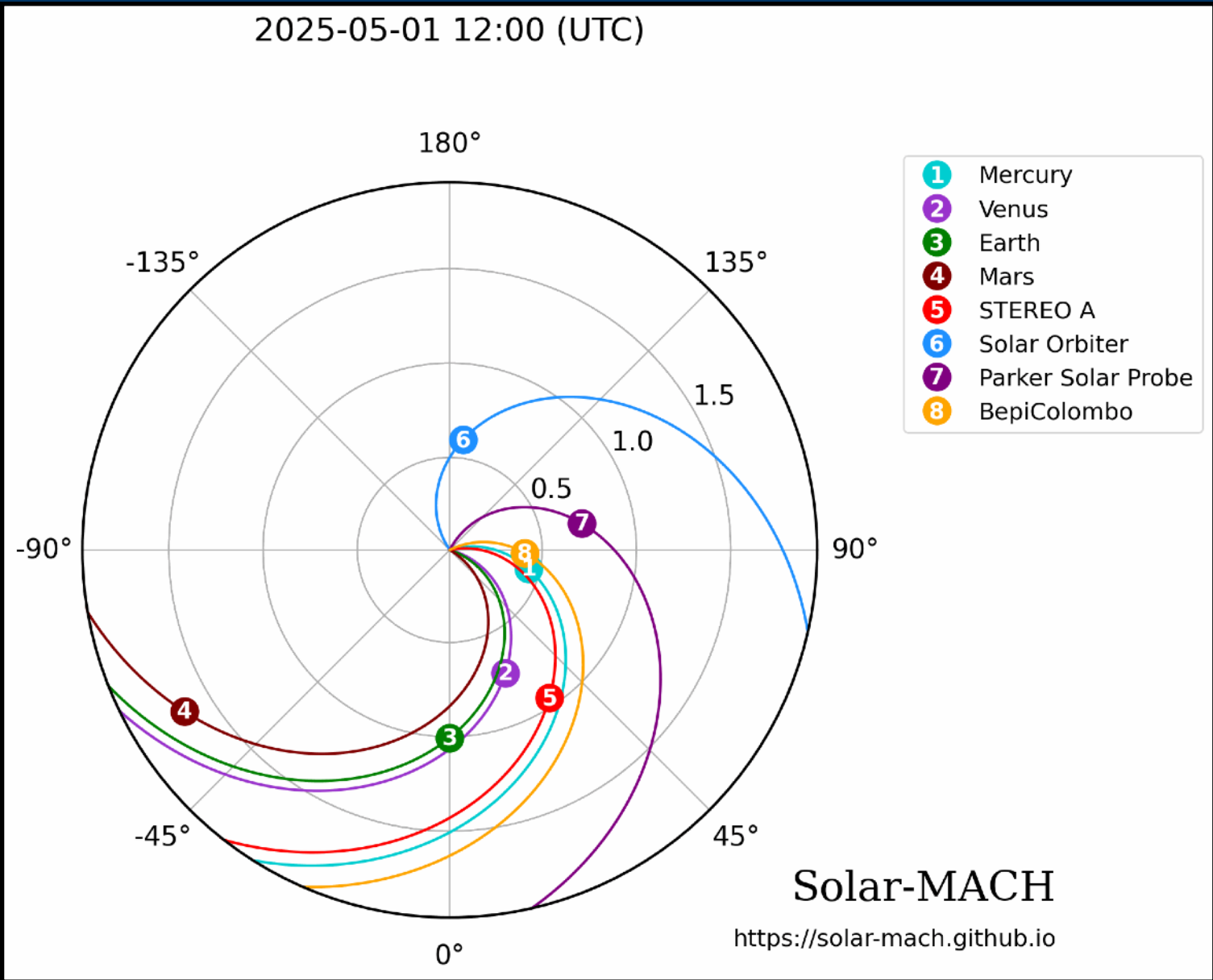


# SERPENTINE Tools

**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](https://doi.org/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](https://doi.org/10.3389/fspas.2022.1073578)

SERPENTINE/SOLER  
Jupyter HUB:



```
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

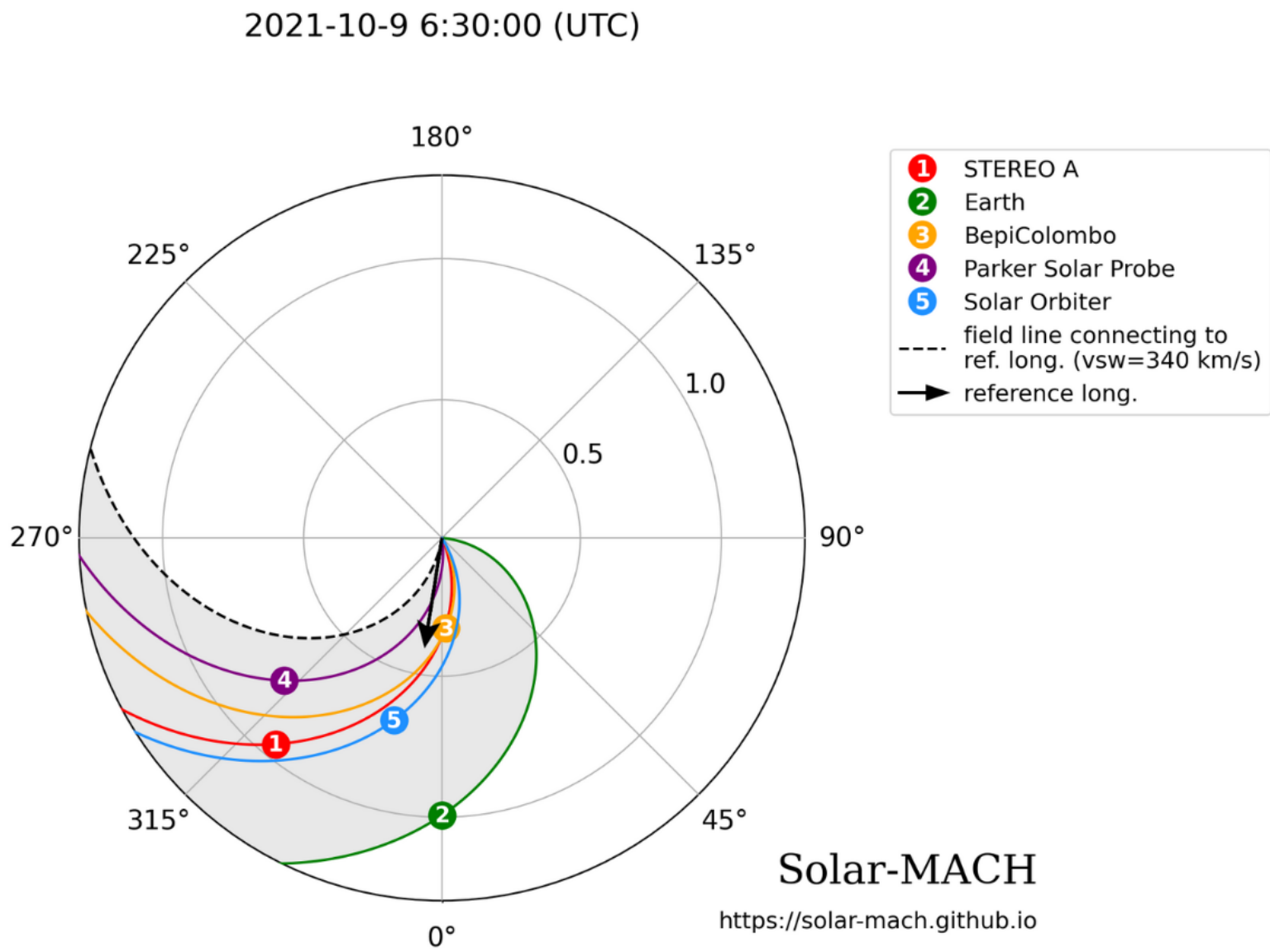
In addition, we explicitly provide all available plotting options:

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:

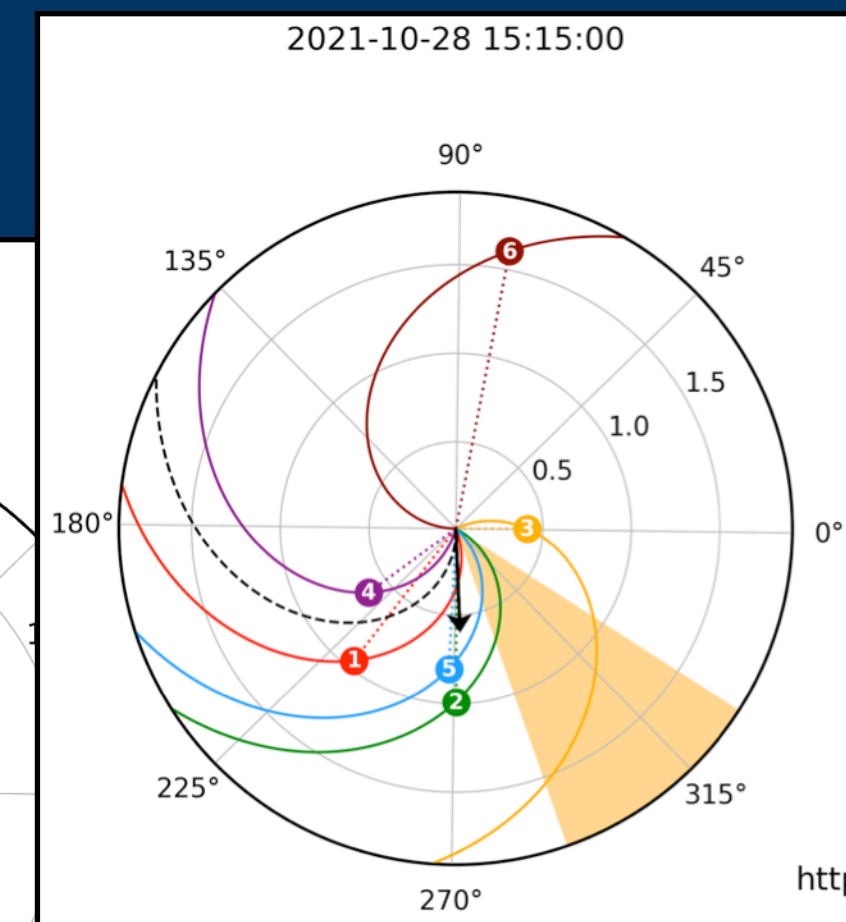
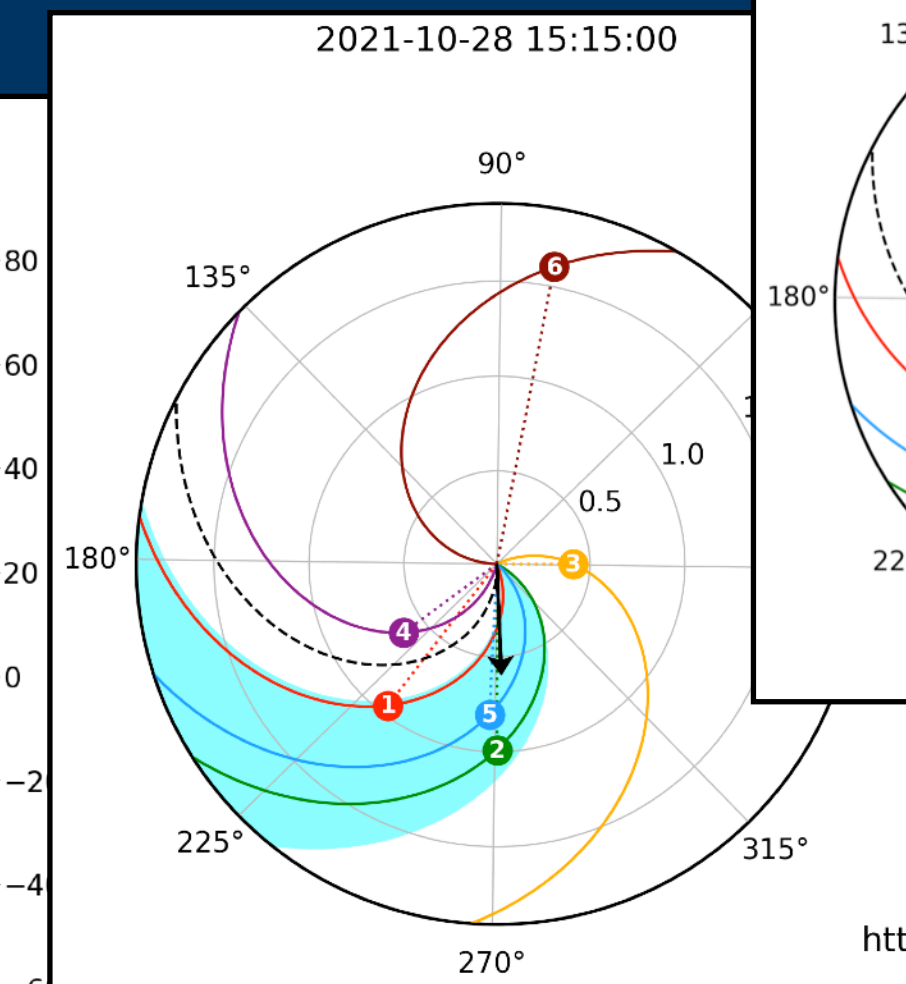
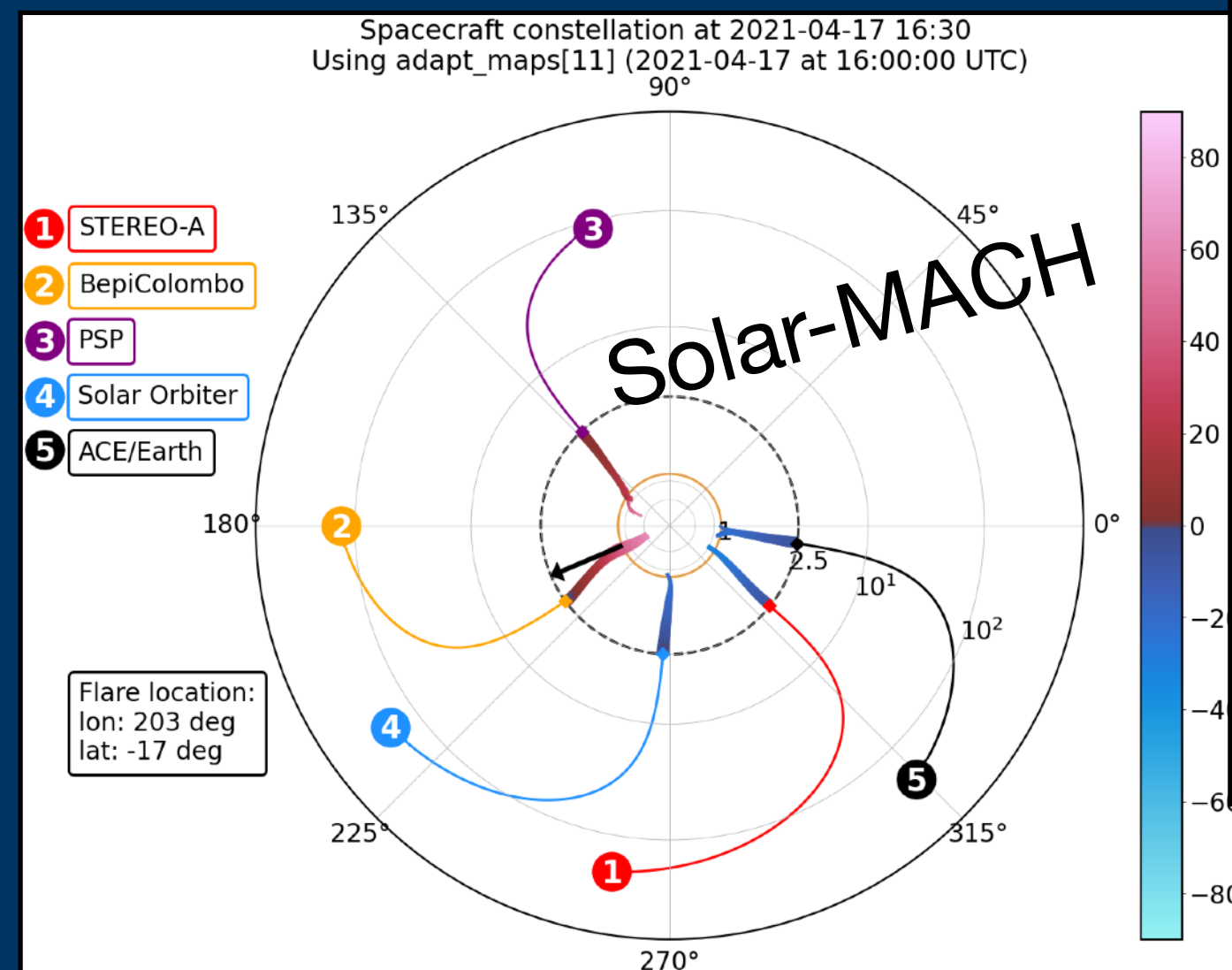
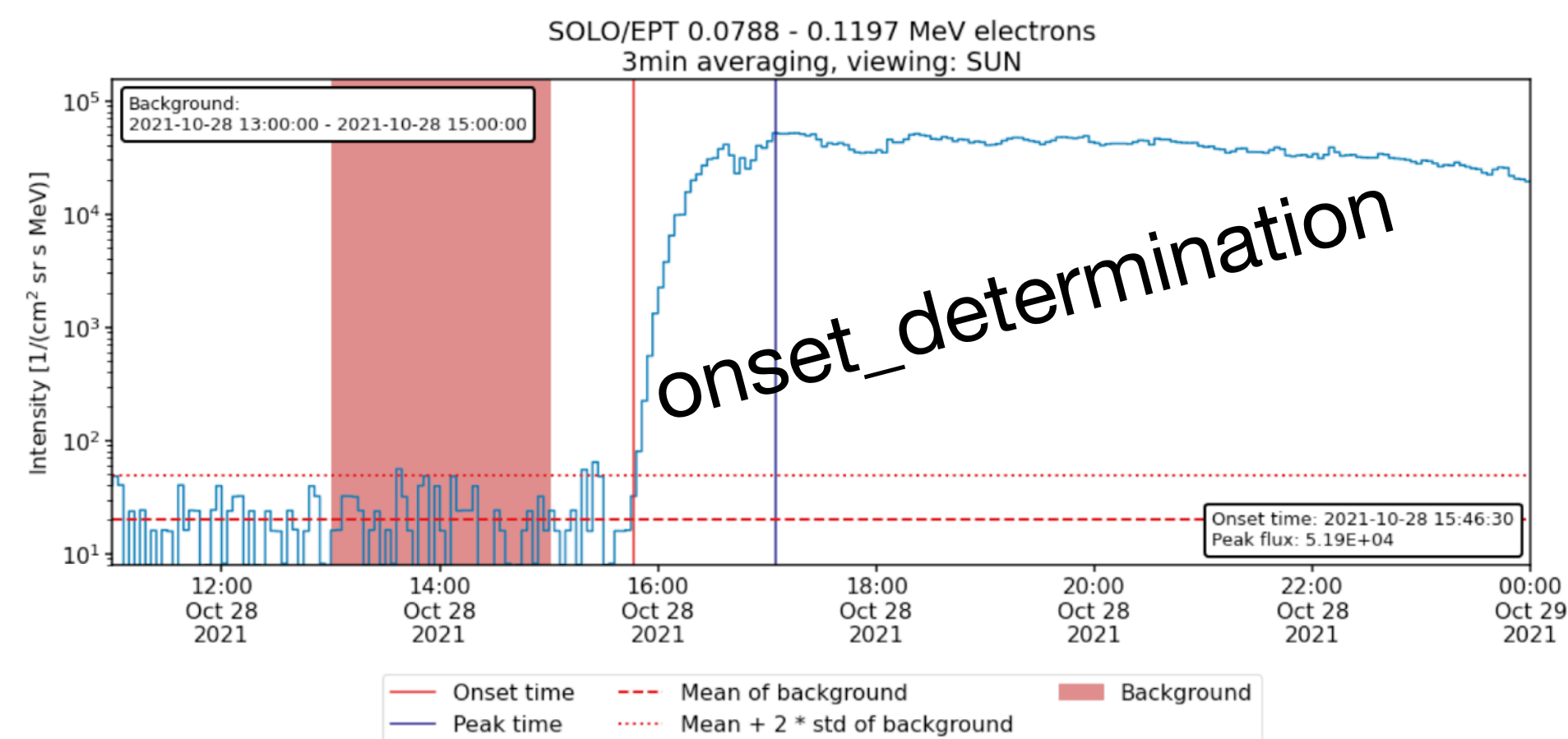
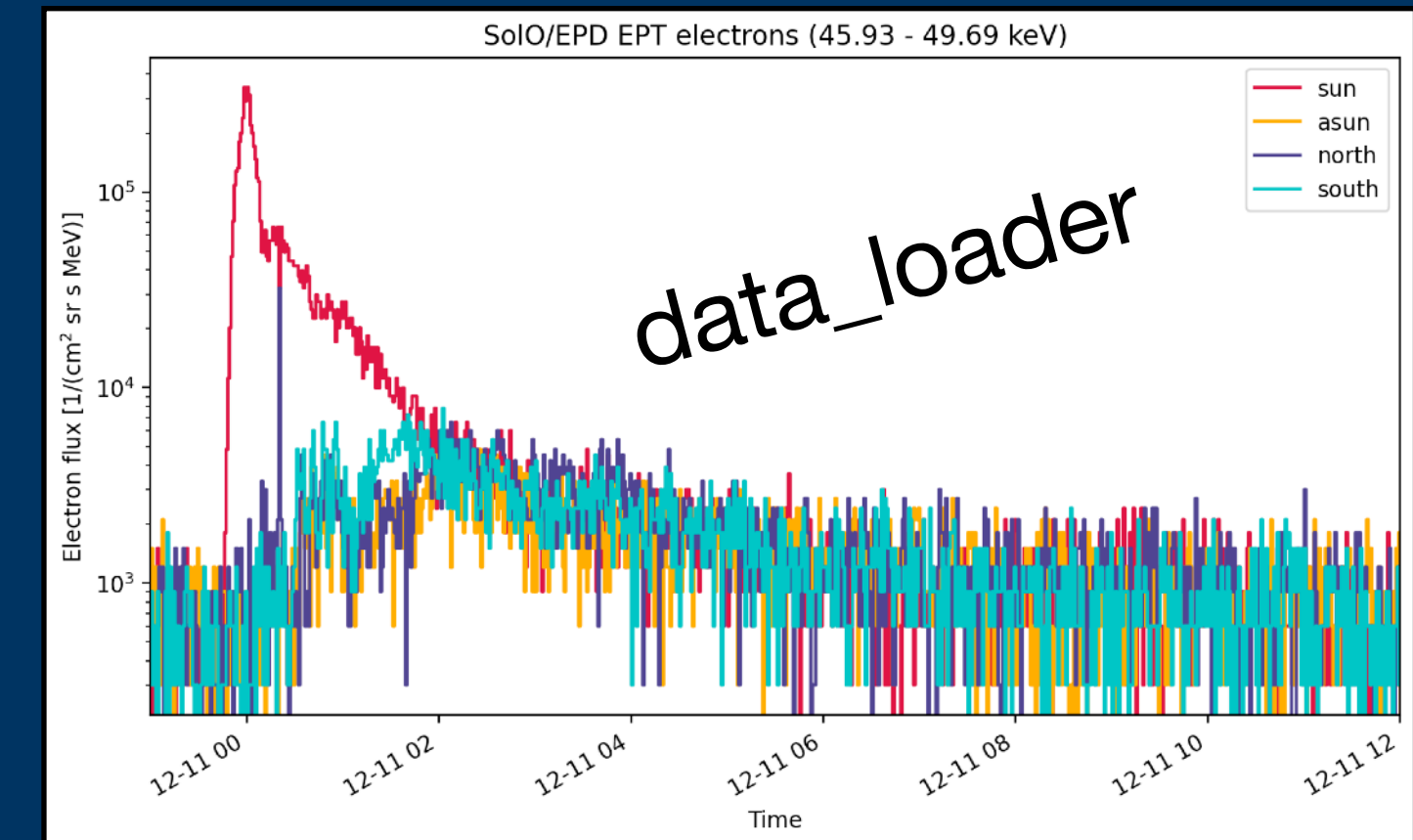
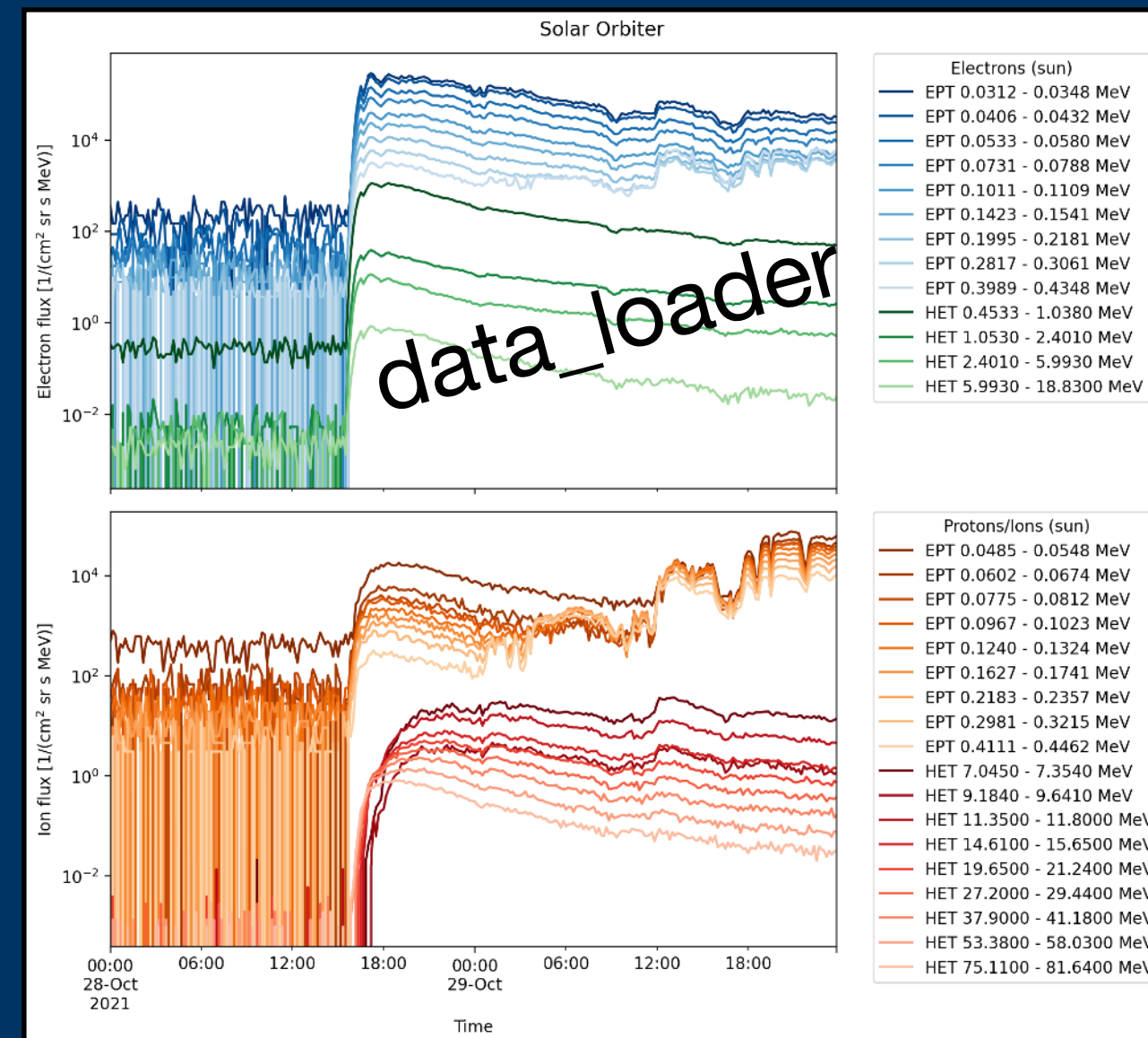
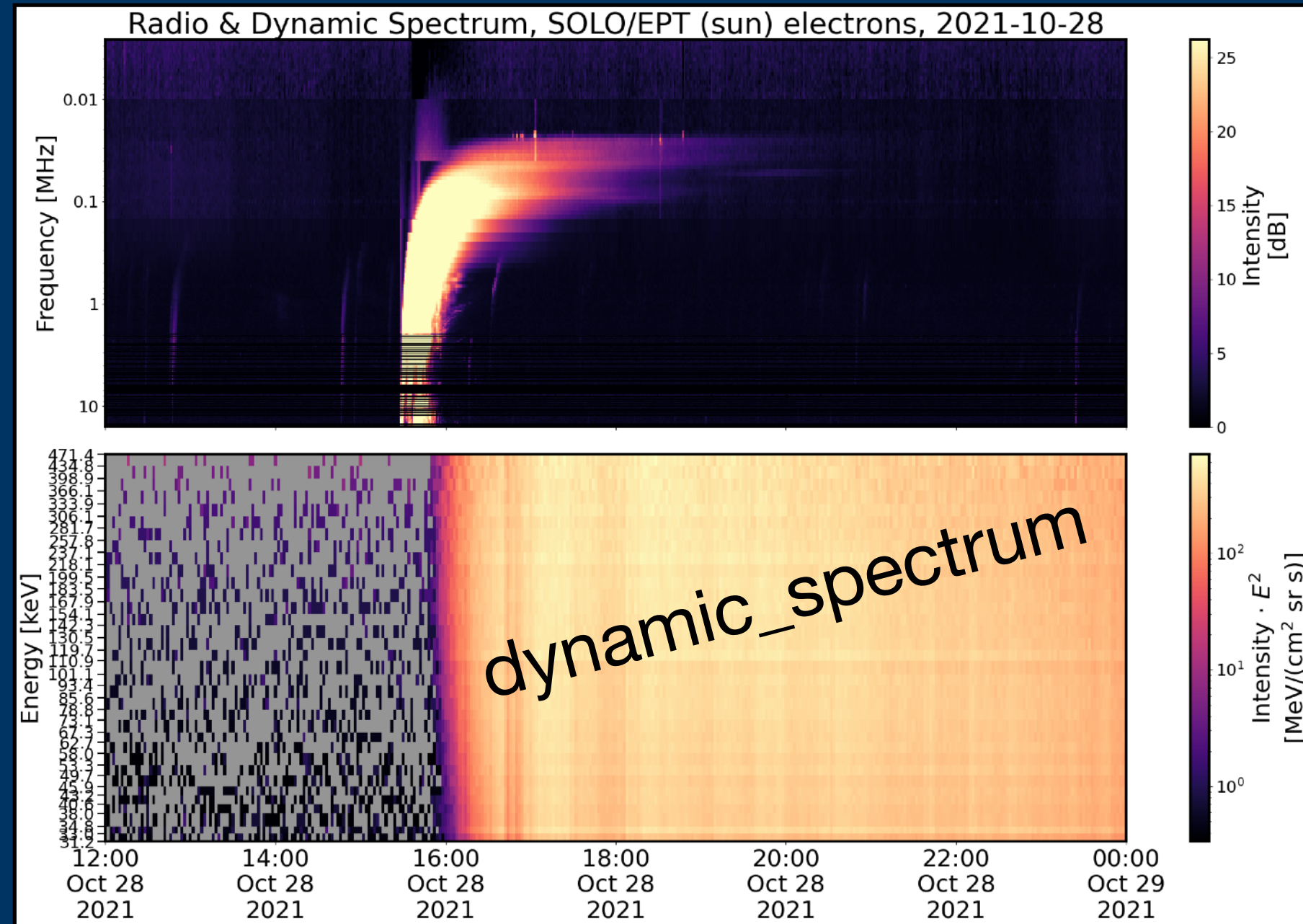
```
In [7]: sm.coord_table
```

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 magnetic 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

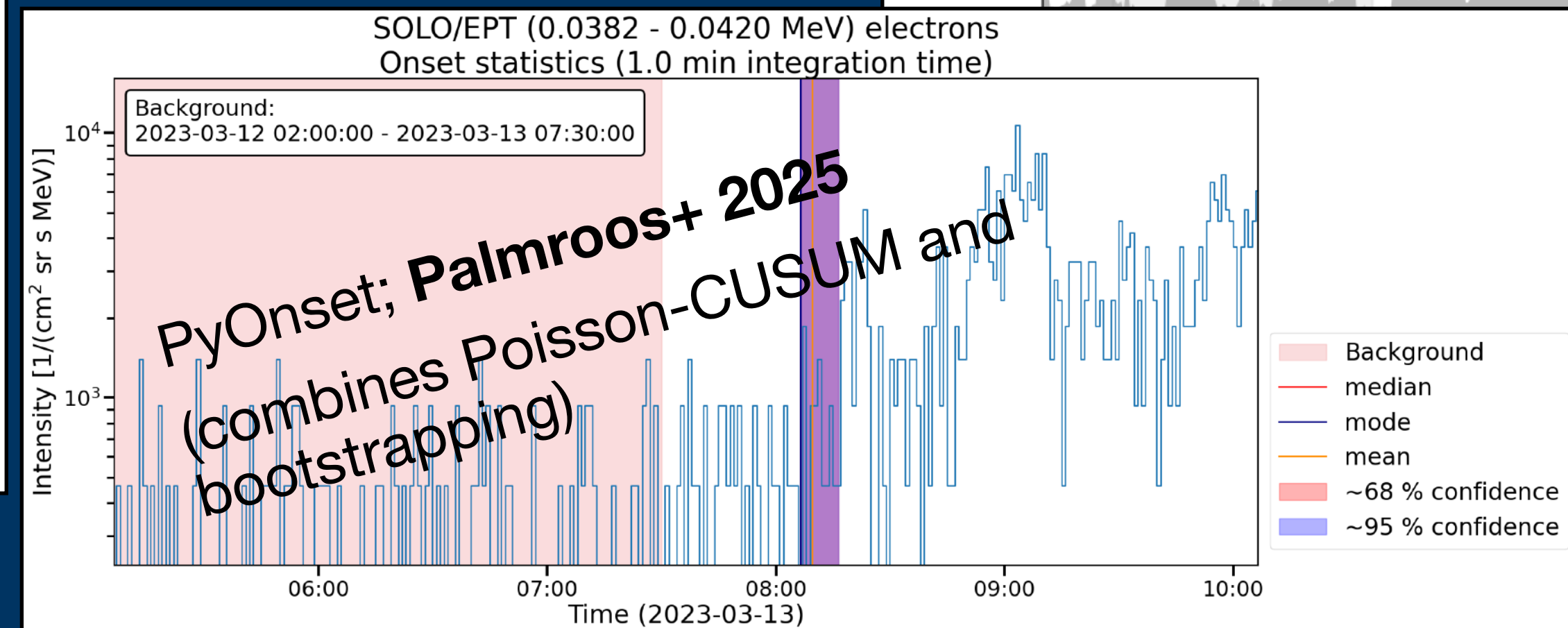
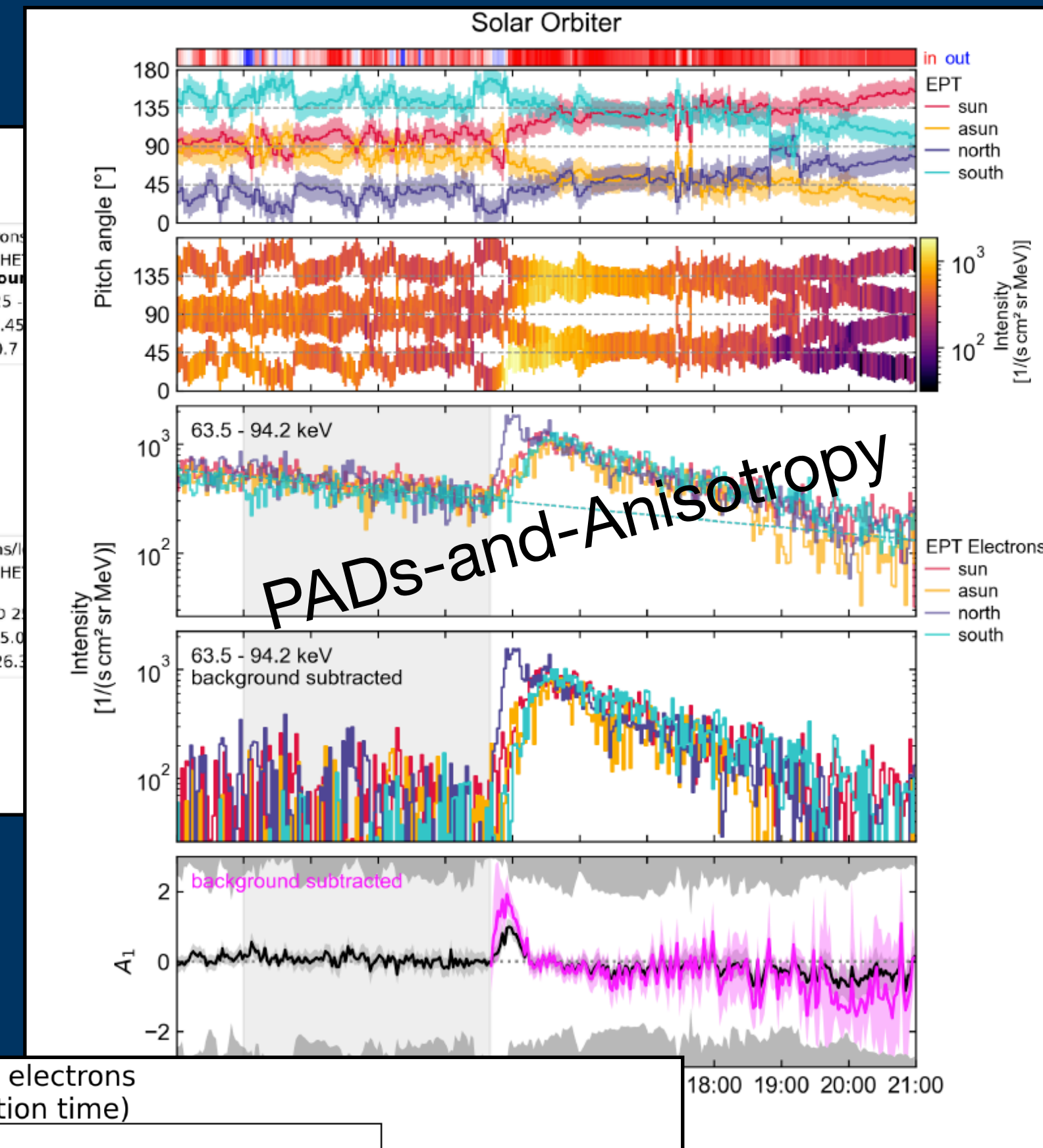
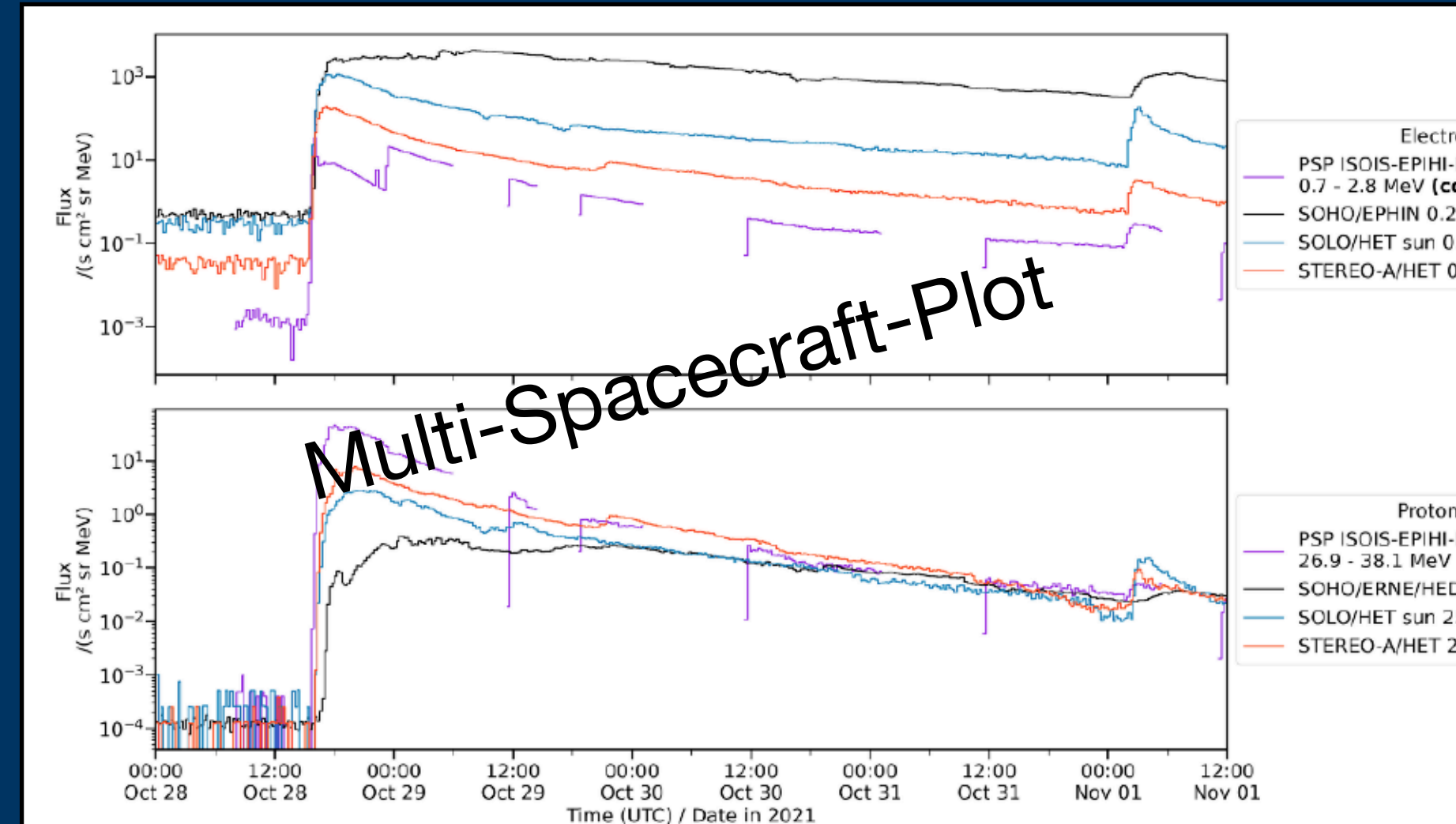
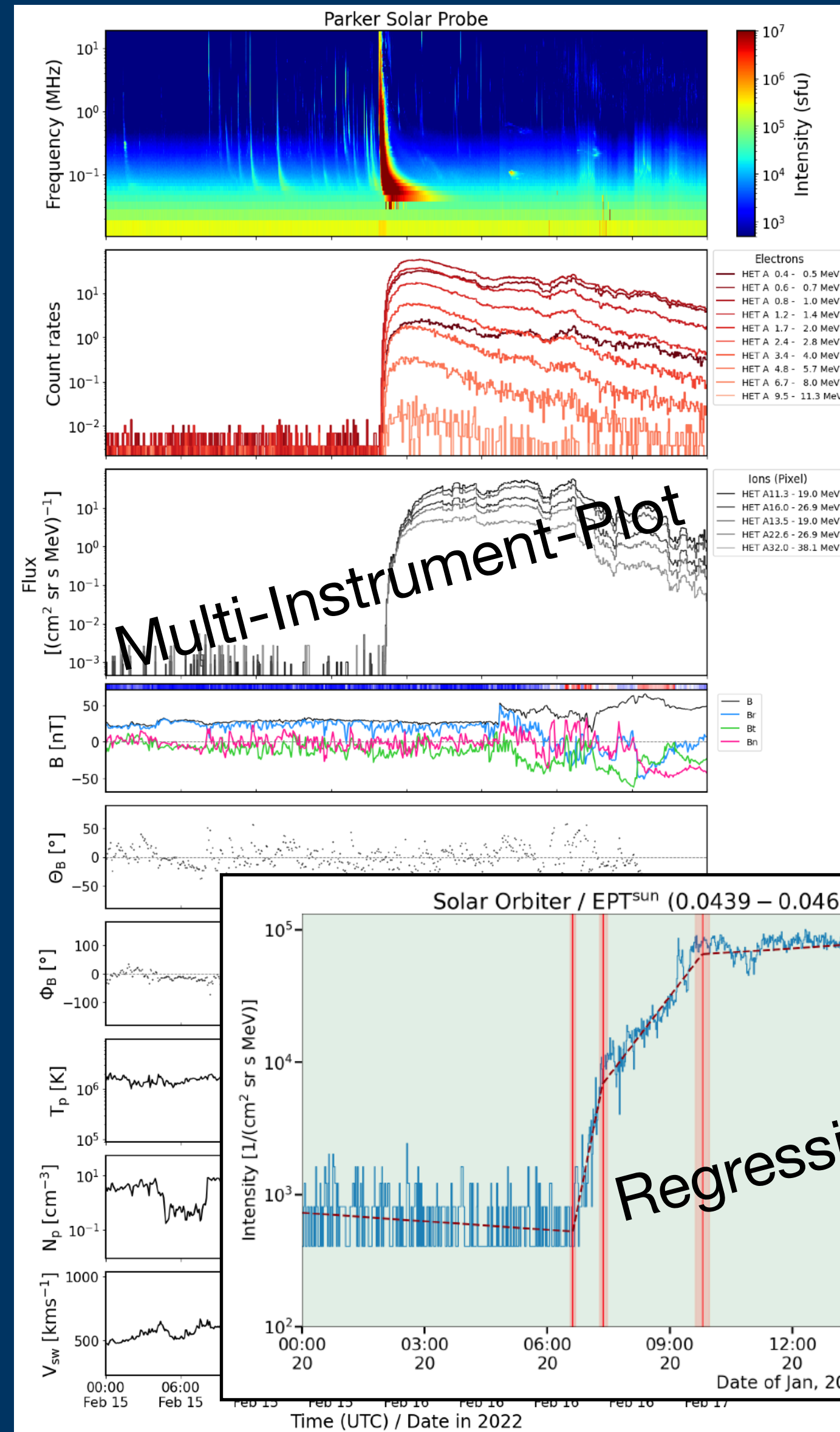


# SERPENTINE's SEP analysis Tools



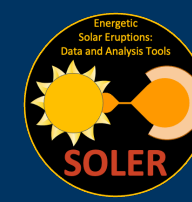


# SOLER's SEP analysis Tools





# Summary



These projects have received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004159 and No 101134999. 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.

- 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/SOLAR Jupyter HUB:

