WP2: Multi-spacecraft SEP event analyses

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and the SERPENTINE team

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SERPENTINE User Workshop, Sep 5-9, Kiel, Germany

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CONTENT

- **What is WP2 about?**
  - **… and what will it provide for SERPENTINE users?**

- SEP event analysis tools:
  - Dynamic spectra
  - Data loaders and SEP time series plots
  - SEP Onset analysis
  - Inferring the SEP injection time
    - Interactive Time Shift Analysis (TSA)
  - Spacecraft constellation plotter tool Solar-MACH

All WP2 tools are Python software that comes with Jupyter Notebooks

These provide application examples and also serve as documentation

- Cycle 25 multi-spacecraft SEP event catalog

WP2: ANALYSIS OF MULTI-SPACECRAFT SEP EVENTS

WP2 addresses all three science questions:

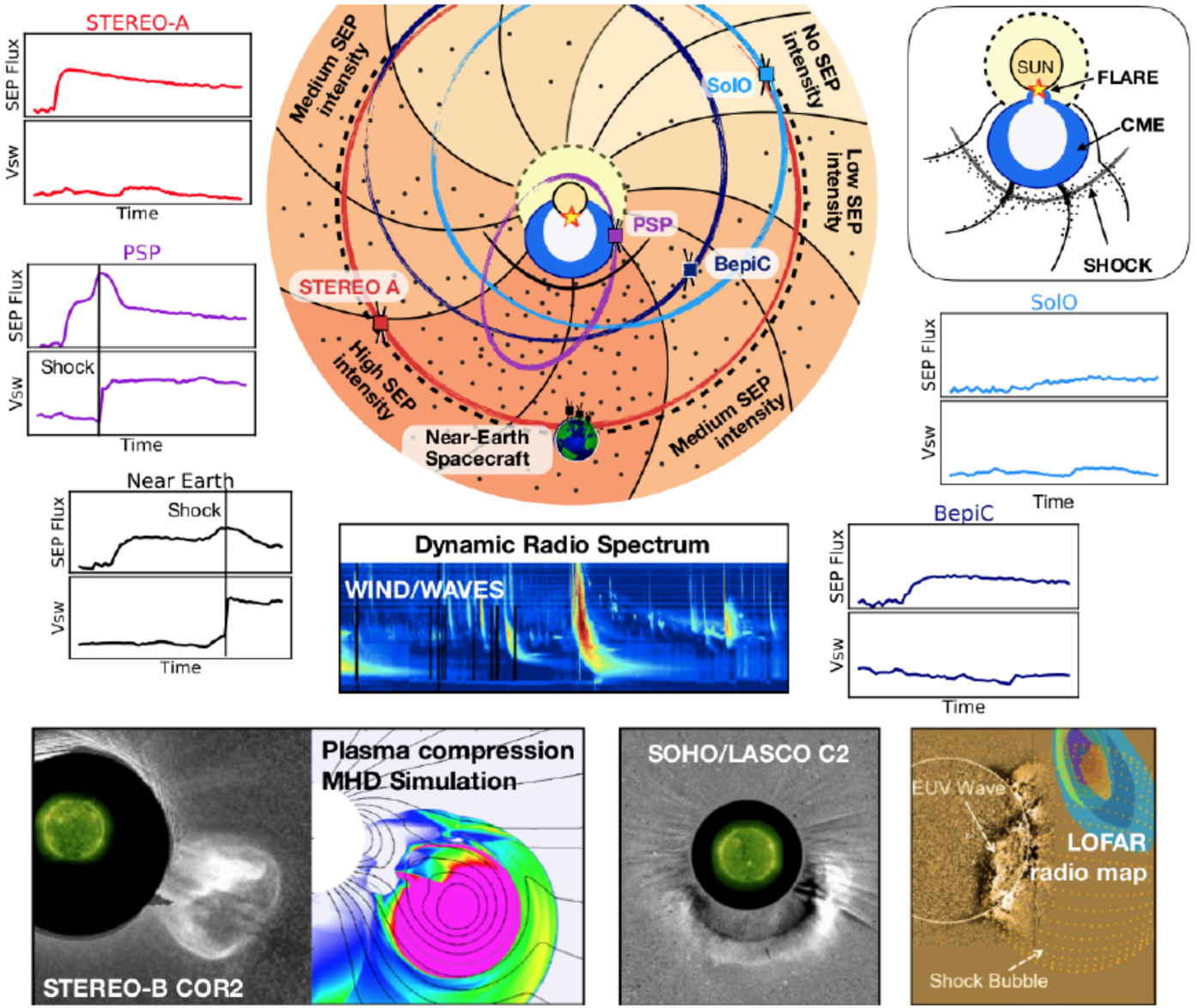
Q1: Causes for widespread SEP events?

Q2: Shock acceleration mechanisms for ions?

Q3: Role of shocks in electron acceleration?

T1: SEP event catalogs

T2: Tools for SERPENTINE analysis platform



ANALYSIS OF SOLAR ENERGETIC PARTICLE (SEP) EVENTS

One of the main questions of SEP physics is still:

What are the relative contributions of flare vs. shock?

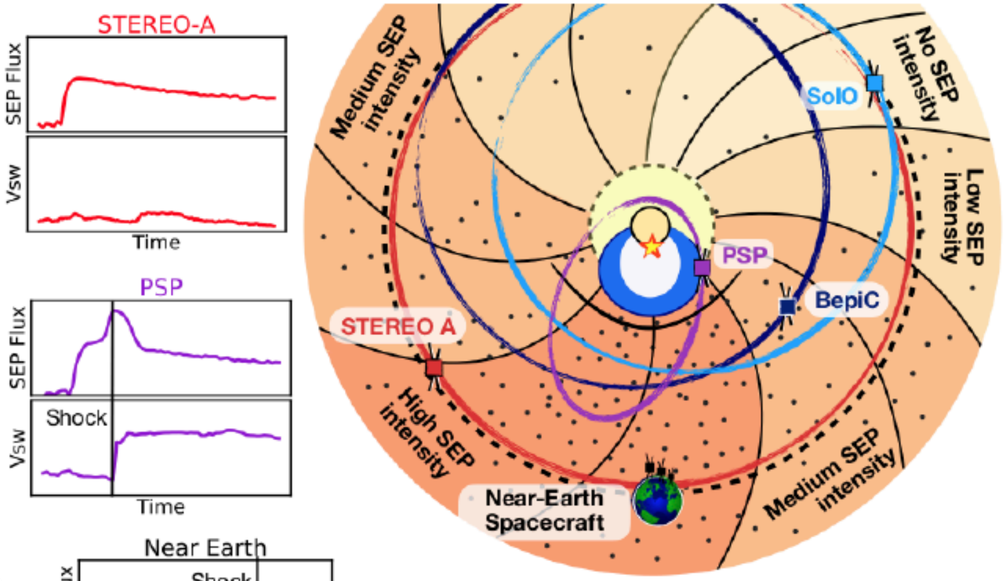
Careful analysis of SEP characteristics

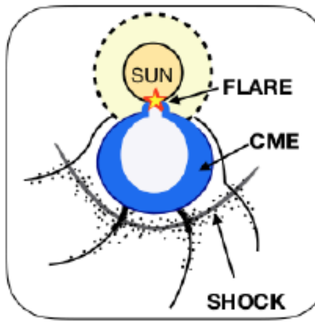
+

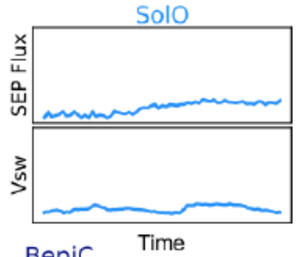
Connect SEP observations with observations of potential acceleration sites / phenomena at the Sun

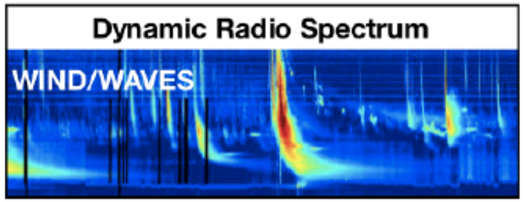
+

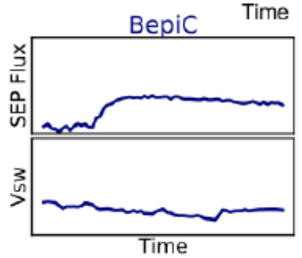
Make use of multi-spacecraft observations

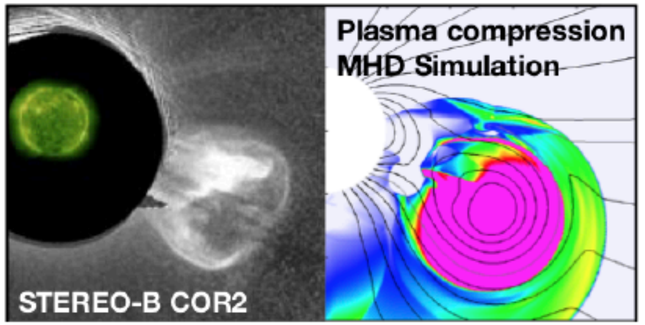


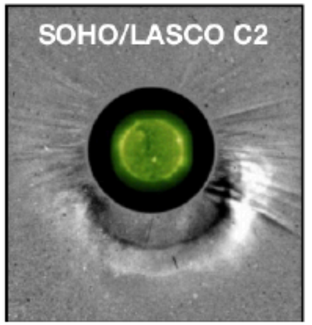


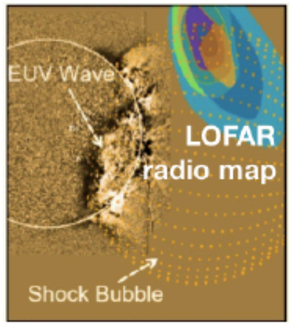












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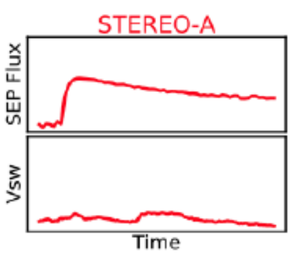
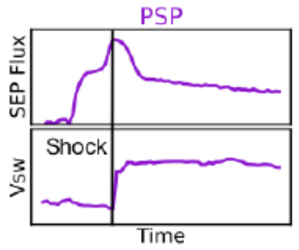
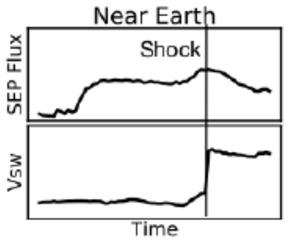
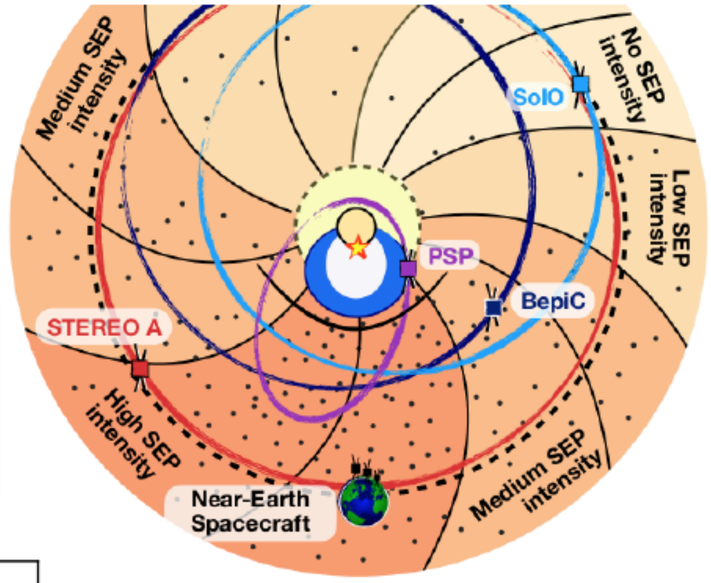
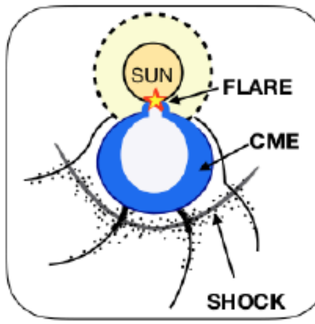
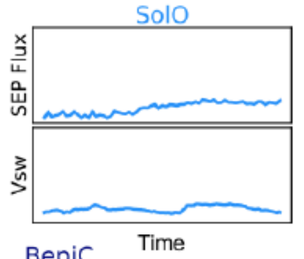


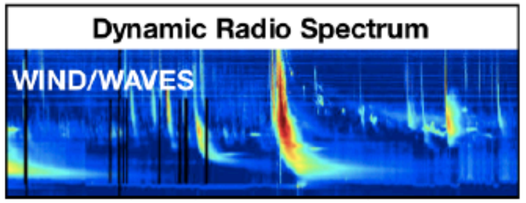


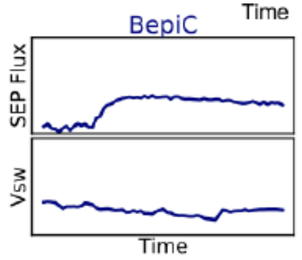


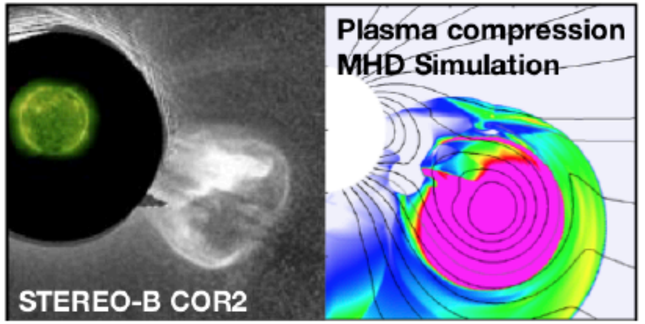


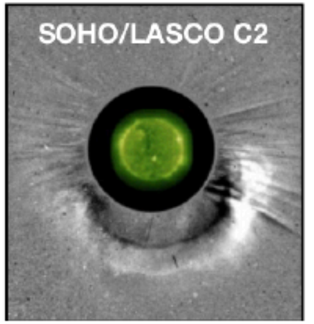


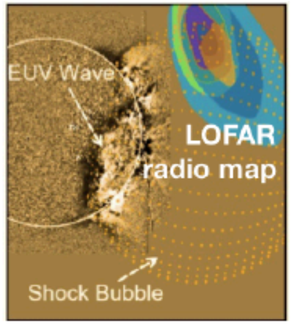






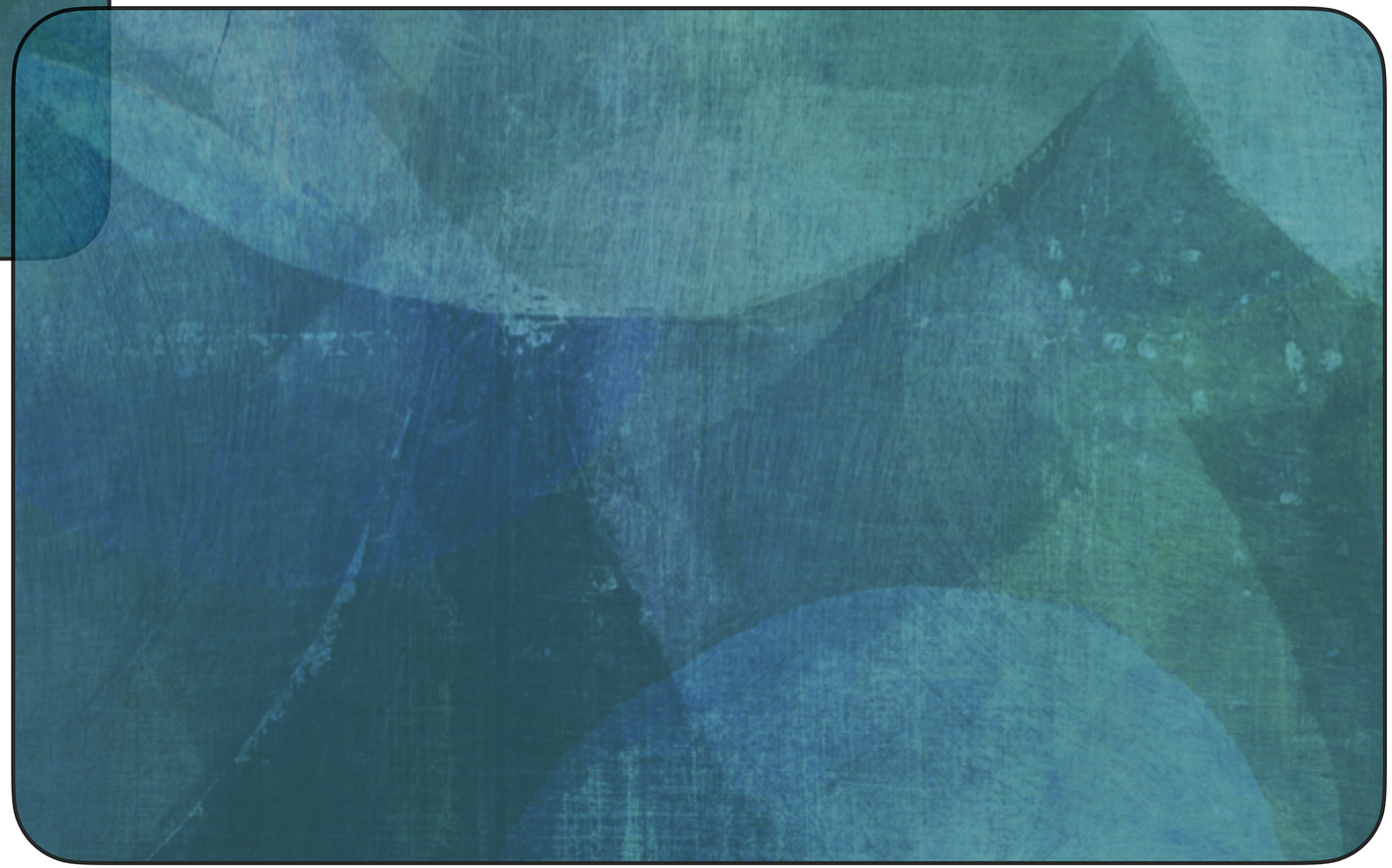






ANALYSIS OF SOLAR ENERGETIC PARTICLE (SEP) EVENTS

- SEP intensities
  - Study the SEP event using
    - different energy channels
    - different particle species
    - different viewing directions



ANALYSIS OF SOLAR ENERGETIC PARTICLE (SEP) EVENTS

- SEP intensities
  - Study the SEP event using
    - different energy channels
    - different particle species
    - different viewing directions

- How energetic is the event?
- Is the SEP event time profile impulsive or gradual?
- Is it seen in electrons and protons?
- Do we characteristics for a good magnetic connection to the source? For example,
  - velocity dispersion
  - anisotropy
- Do we see hints of instrumental issues / contamination?

CONTENT

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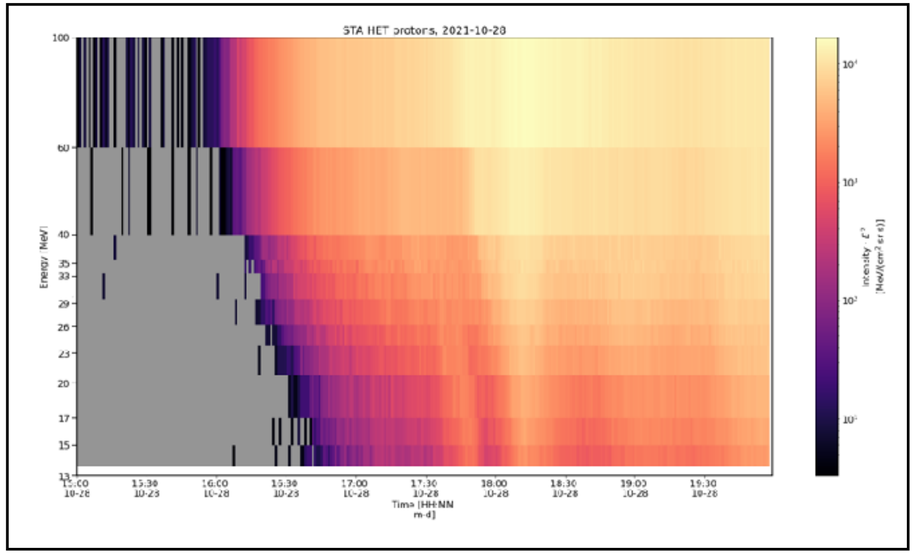
  - **… and what will it provide for SERPENTINE users?**

- SEP event analysis tools:
  - **Dynamic spectra**
  - Data loaders and SEP time series plots
  - SEP Onset analysis
  - Inferring the SEP injection time
    - Interactive Time Shift Analysis (TSA)
  - Spacecraft constellation plotter tool Solar-MACH

- Cycle 25 multi-spacecraft SEP event catalog

TOOL: DYNAMIC SPECTRA



- All our SEP tools:
- directly download the data files from the internet and store them locally on your computer
- Load the data into pandas dataframes (Python structures)
- Load all viewing directions at once (if available)

- Select spacecraft/instrument/(viewing direction) from drop-down menu
- Chose time interval
- Optional: time averaging, color map

All WP2 tools come as Jupyter notebooks

jupyter dynamic_spectrum Last Checkpoint: Yesterday at 2:59 PM (autosaved)

File Edit View Insert Cell Kernel Widgets Help — Not Trusted — Python 3 (ipykernel)

Run Code

In [1]:
```
from onset_functions import *
import onset_widgets as w
```

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)
```

Spacecraft: STEREO-A
Sensor: HET
Viewing:
Species: protons

Set the data path and date range to load data:

In [3]:
```
# The path to where data is located / to be downloaded (by default the current directory)
data_path = f"/Users/dresing/data"

# Format of date: year, month, day
startdate = datetime.date(2021, 10, 28)
enddate = datetime.date(2021, 10, 29)

# Set the time range for the plot:
plot_range = ["2021-10-28 15:00", "2021-10-28 19:59"]
#plot_range = ["2021-04-17 15:00", "2021-04-17 19:59"]

# Set the averaging period, or leave to None to not resample data
# averaging should be a pandas-compatible string, e.g. '1h', '2min', '15s'
averaging = "1min"

# Select the color map used for the plot, by default 'magma'
# for avavailable options, cf. https://matplotlib.org/stable/tutorials/colors/colormaps.html
cmap = 'magma'  # e.g. 'jet', 'viridis', 'magma'
```

Just run, don't edit:

]:
```
# Get event data:
Event_class = Event(spacecraft=w.spacecraft_drop.value, sensor=w.sensor_drop.value,
                    data_level='l2', species = w.species_drop.value,
                    start_date=startdate, end_date=enddate,
                    data_path=data_path)
```

]:
```
Event_class.dynamic_spectrum(w.view_drop.value, cmap=cmap, xlim=plot_range, resample=averaging)
```

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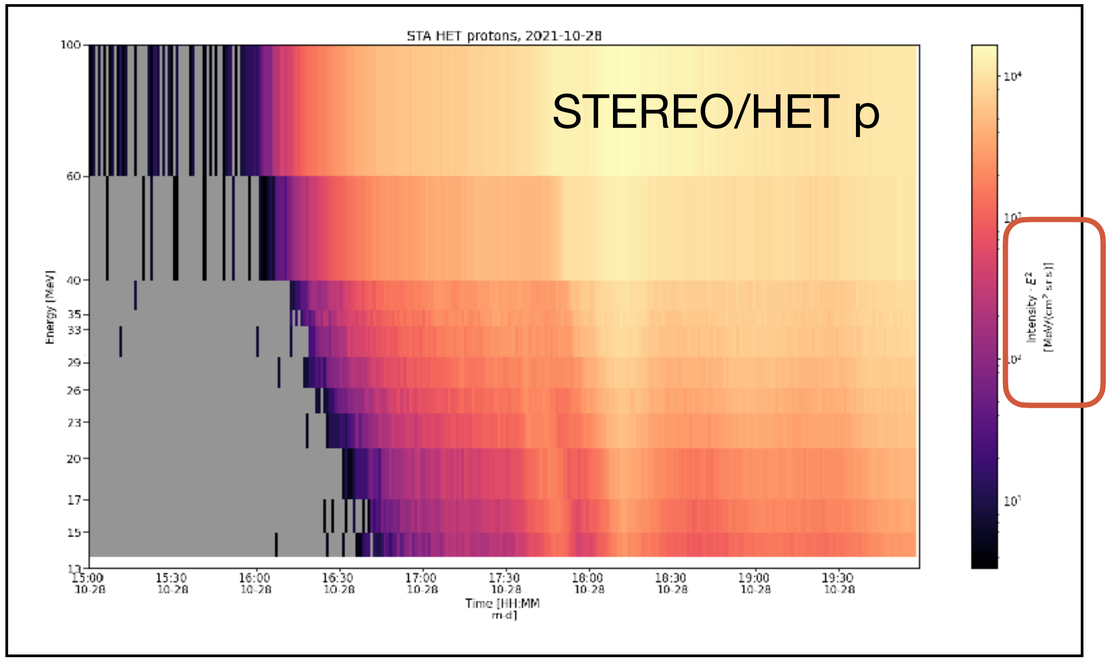
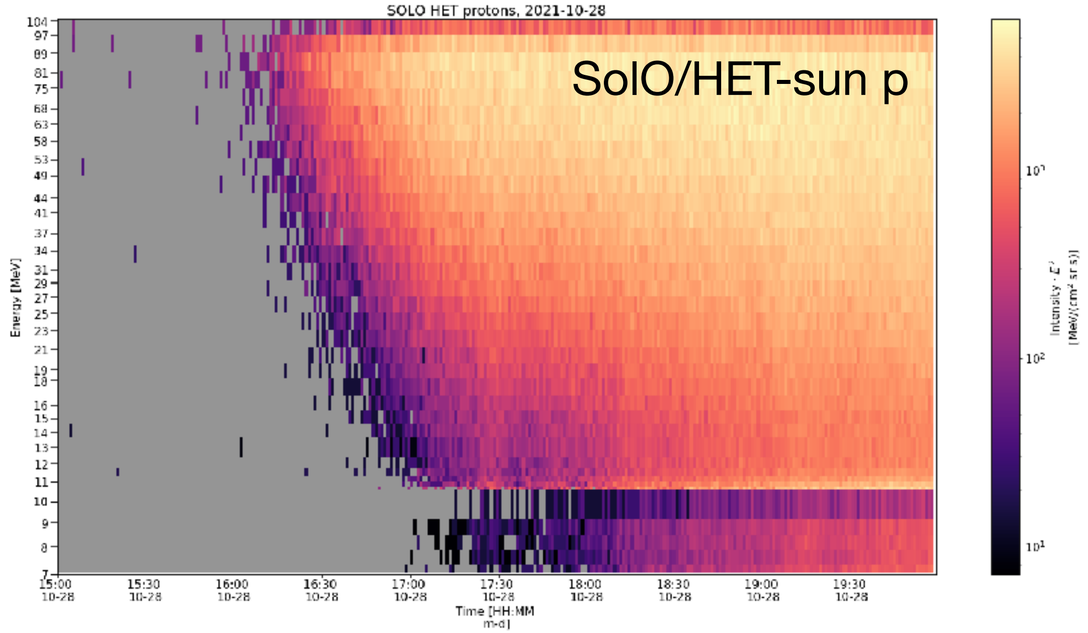
TOOL: DYNAMIC SPECTRA

First Ground Level Enhancement (GLE) event of solar cycle 25 (28 Oct 2021)





Color axis scaled with E^2

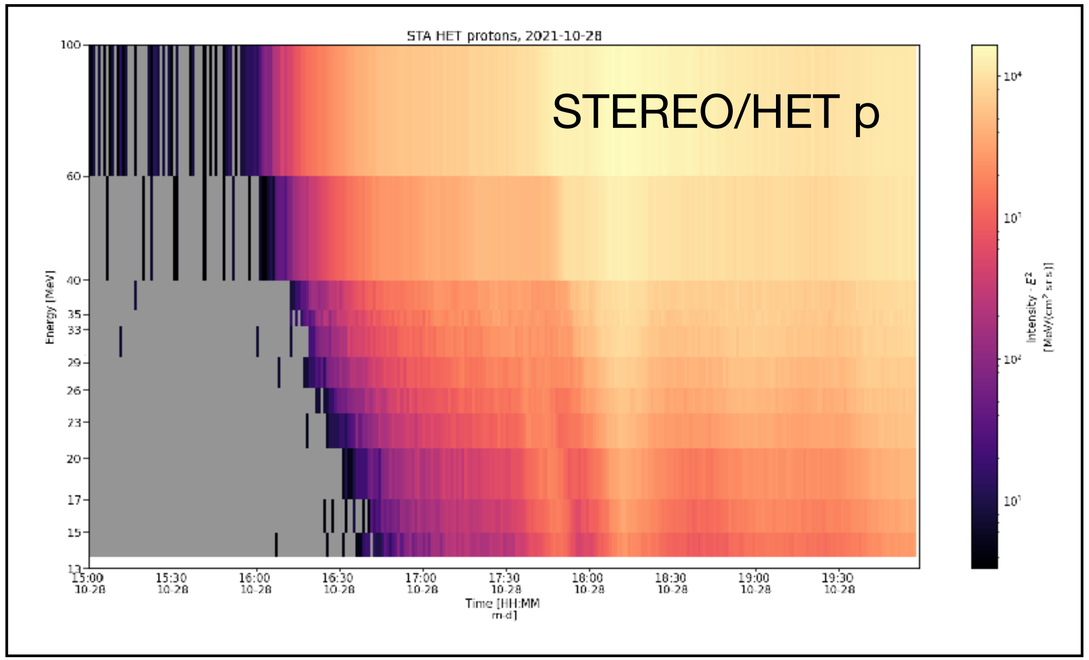
- ✓ How energetic is the event?
- ✓ Is it seen in electrons and protons?
- ✓ velocity dispersion

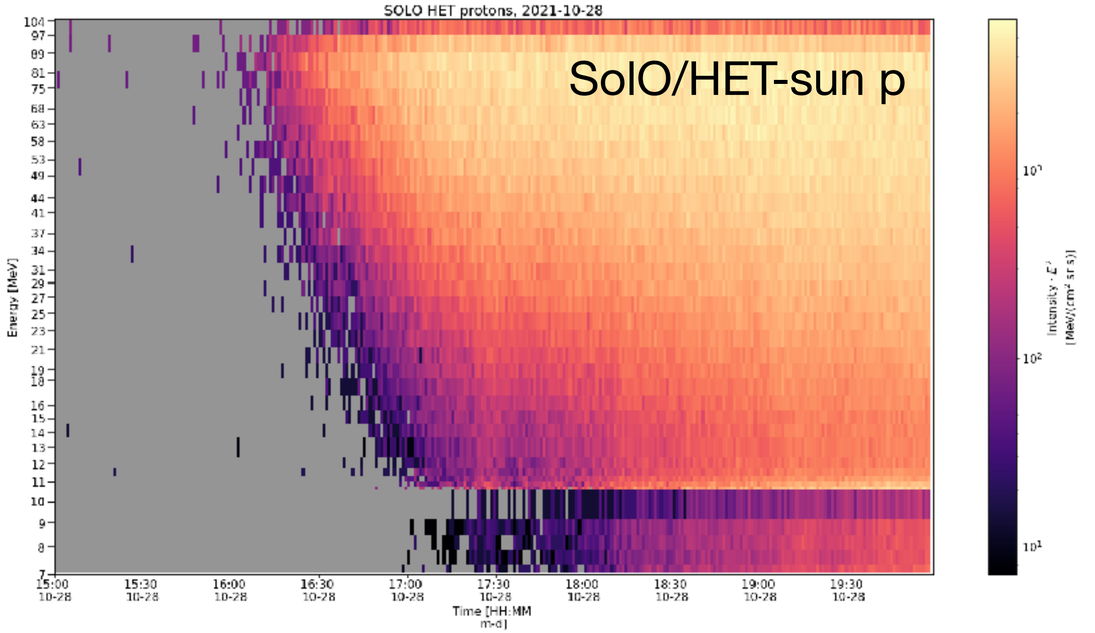
Currently implemented:

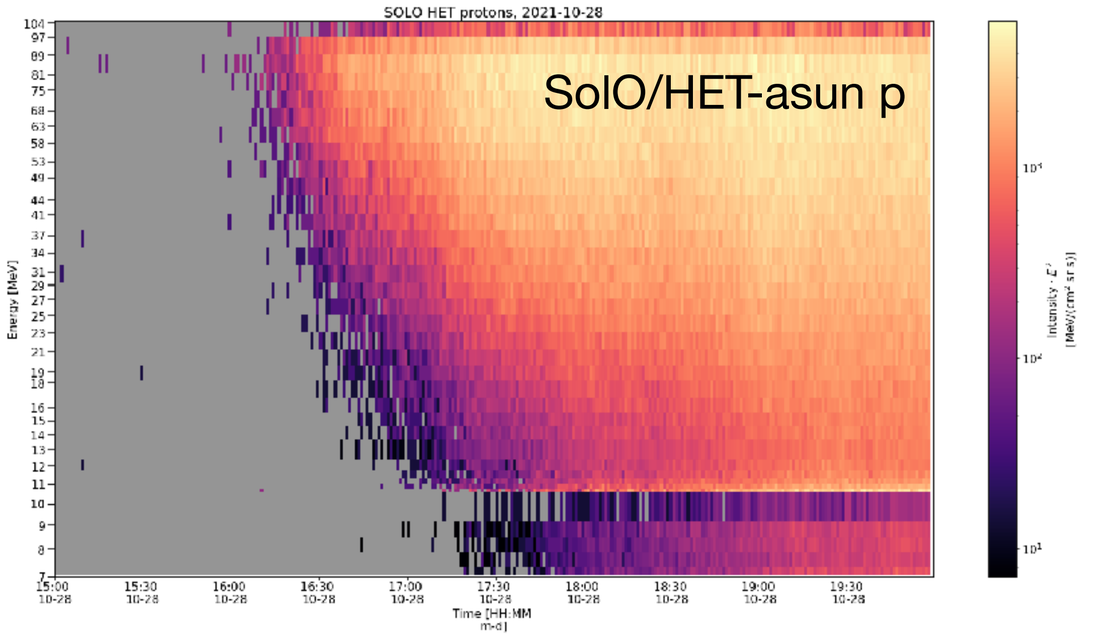
- ➤ Electron and proton/ion intensities from:
  - ➤ STEREO A & B: SEPT, HET
  - ➤ SolO: EPT, HET
  - ➤ SOHO: ERNE-HED
    - ➤ All available viewing directions

TOOL: DYNAMIC SPECTRA

First Ground Level Enhancement (GLE) event of solar cycle 25 (28 Oct 2021)







- ✓ How energetic is the event?
- ✓ Is it seen in electrons and protons?
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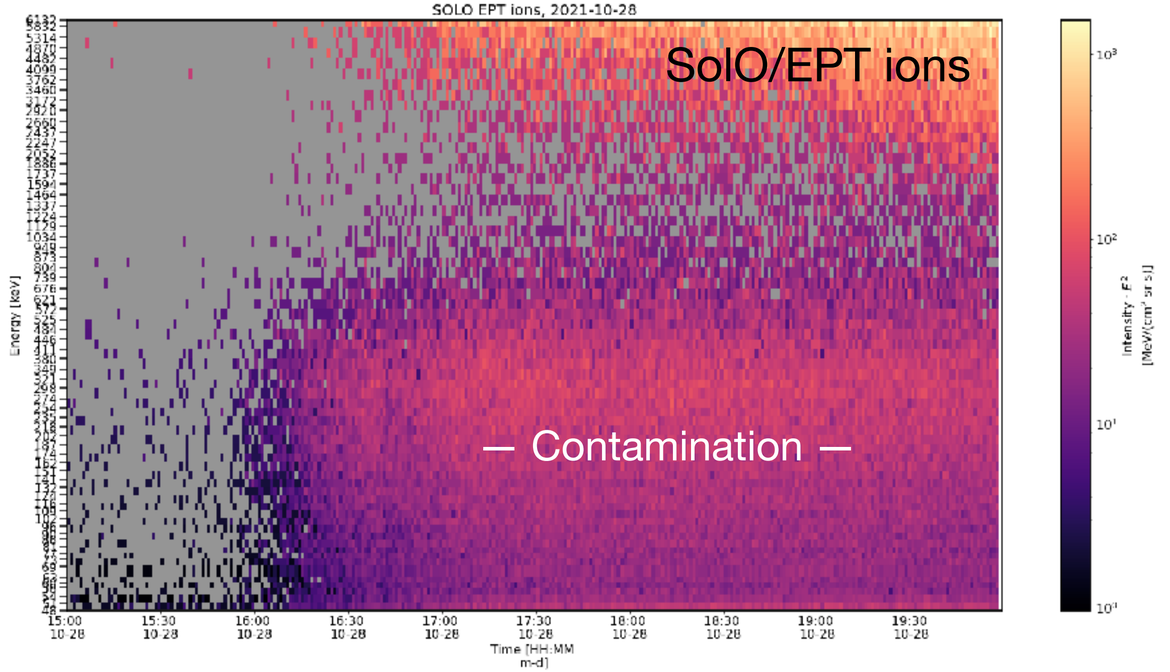
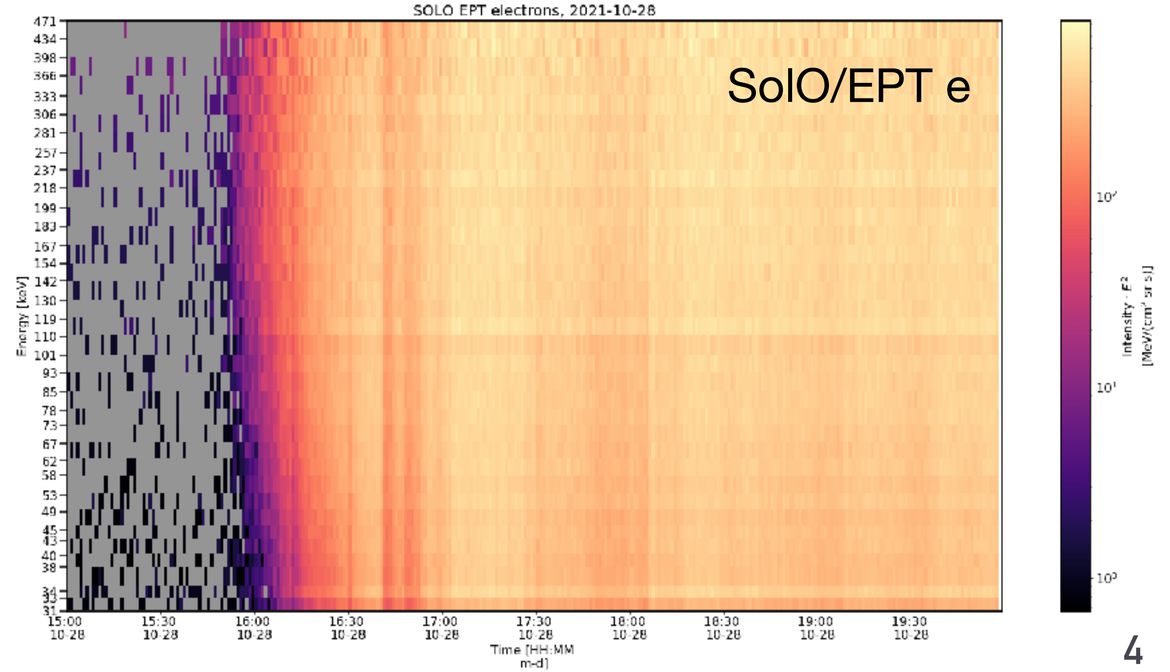
- ✓ (anisotropy)

TOOL: DYNAMIC SPECTRA

First Ground Level Enhancement (GLE) event of solar cycle 25 (28 Oct 2021)

- ✓ How energetic is the event?
- ➤ Is the SEP event time profile impulsive or gradual?
- ✓ Is it seen in electrons and protons?
- ✓ velocity dispersion
- ✓ (anisotropy)
- ✓ instrumental issues / contamination?





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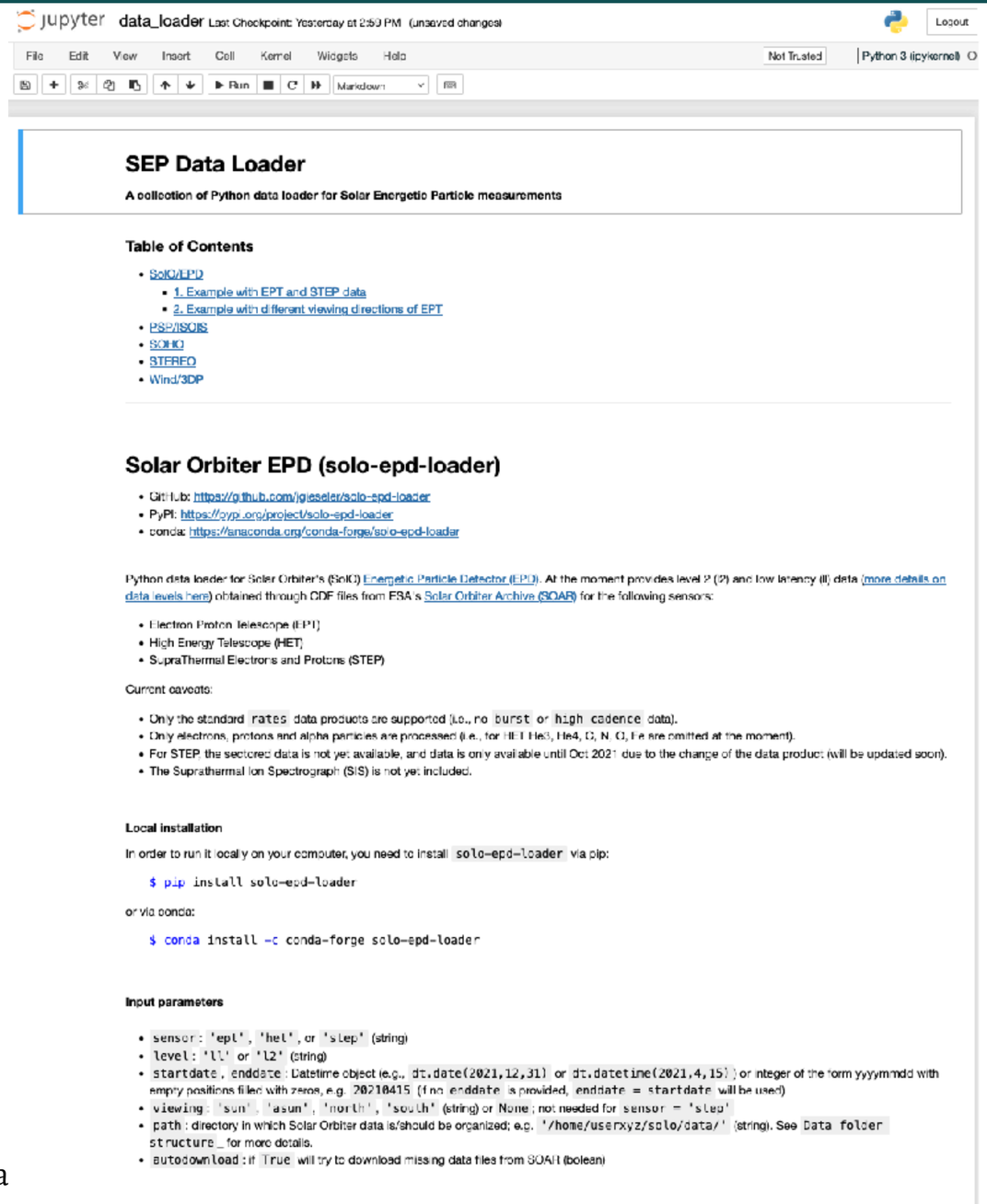
TOOL: DATA LOADERS (AND TIME SERIES PLOTS)



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SEP Data Loader

A collection of Python data loader for Solar Energetic Particle measurements

Table of Contents

- SolO/EPD
  - 1. Example with EPT and STEP data
  - 2. Example with different viewing directions of EPT
- PSP/ISOIS
- SOHO
- STEREO
- Wind/3DP

Solar Orbiter EPD (solo-epd-loader)

- GitHub: https://github.com/jgieseler/solo-epd-loader
- PyPI: https://pypi.org/project/solo-epd-loader
- conda: https://anaconda.org/conda-forge/solo-epd-loader

Python data loader for Solar Orbiter's (SolO) Energetic Particle Detector (EPD). At the moment provides level 2 (L2) and low latency (ll) data (more details on data levels here) obtained through CDF files from ESA's Solar Orbiter Archive (SOAR) for the following sensors:

- Electron Proton Telescope (EPT)
- High Energy Telescope (HET)
- SupraThermal Electrons and Protons (STEP)

Current caveats:

- Only the standard `rates` data products are supported (i.e., no `burst` or `high cadence` data).
- Only electrons, protons and alpha particles are processed (i.e., for HET He3, He4, C, N, O, Fe are omitted at the moment).
- For STEP, the sectored data is not yet available, and data is only available until Oct 2021 due to the change of the data product (will be updated soon).
- The Suprathermal Ion Spectrograph (SIS) is not yet included.

Local installation

In order to run it locally on your computer, you need to install `solo-epd-loader` via pip:

```
$ pip install solo-epd-loader
```

or via conda:

```
$ conda install -c conda-forge solo-epd-loader
```

Input parameters

- `sensor` : `'ept'`, `'het'`, or `'step'` (string)
- `level` : `'ll'` or `'l2'` (string)
- `startdate`, `enddate` : Datetime object (e.g., `dt.date(2021,12,31)` or `dt.datetime(2021,4,15)`) or integer of the form yyyymmdd with empty positions filled with zeros, e.g. `20210415` (if no `enddate` is provided, `enddate = startdate` will be used)
- `viewing` : `'sun'`, `'asun'`, `'north'`, `'south'` (string) or `None`; not needed for `sensor = 'step'`
- `path` : directory in which Solar Orbiter data is/should be organized; e.g. `'/home/userxyz/solo/data/'` (string). See `Data folder structure` for more details.
- `autodownload` : if `True`, will try to download missing data files from SOAR (boolean)

- Downloads data files
- Reads in files (also cdf files) into pandas dataframes
- plots various energetic particle datasets (and more)

Currently implemented:

- Electron and proton/ion intensities from:
  - SolO: EPT, HET, (STEP until Oct 2021)
  - PSP: EPI-Hi/HET, EPI-Lo
  - STEREO A & B: SEPT, HET, LET (unsectored), (MAG, MAGB)
  - SOHO: ERNE-HED, EPHIN, (CELIAS)
  - Wind: 3DP SST
    - All available viewing directions

TOOL: DATA LOADERS (AND TIME SERIES PLOTS)

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```
$ conda install -c conda-forge solo-epd-loader
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Input parameters

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- `level` : `'ll'` or `'l2'` (string)
- `startdate`, `enddate` : Datetime object (e.g., `dt.date(2021,12,31)` or `dt.datetime(2021,4,15)`) or integer of the form yyyymmdd with empty positions filled with zeros, e.g. `20210415` (if no `enddate` is provided, `enddate = startdate` will be used)
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- `autodownload` : if `True`, will try to download missing data files from SOAR (boolean)

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Run Markdown

Importing and general settings

In [1]:
```
import datetime as dt
import numpy as np
import os
import pandas as pd
import warnings
from matplotlib import pyplot as plt
from solo_epd_loader import epd_load

# omit Pandas' PerformanceWarning
warnings.simplefilter(action='ignore', category=pd.errors.PerformanceWarning)
```

Define some general options:

In [2]:
```
# set your local path where you want to save the data files:
path = f"{os.getcwd()}/data/"
#data_path = f"/Users/dresing/data"

# whether missing data files should automatically downloaded from SOAR:
autodownload = True

# define some optional plotting settings
color = {'sun': 'crimson', 'asun': 'orange', 'north': 'darkslateblue', 'south': 'c'}  # define SolO/EPD colors
```

1. Example with EPT and STEP data

Define some basic options:

In [118]:
```
# format of date: year, month, day
startdate = dt.datetime(2021, 10, 28)
enddate = dt.datetime(2021, 10, 29)

#startdate = dt.datetime(2022, 2, 15)
#enddate = dt.datetime(2022, 2, 22)

# Set the time range for the plot:
#plot_range = ["2021-10-28 15:00", "2021-10-28 19:59"]


# change time resolution to get smoother curve
resample = '5min'

# define viewing direction of telescope (for EPT & HET)
viewing = 'sun'
```

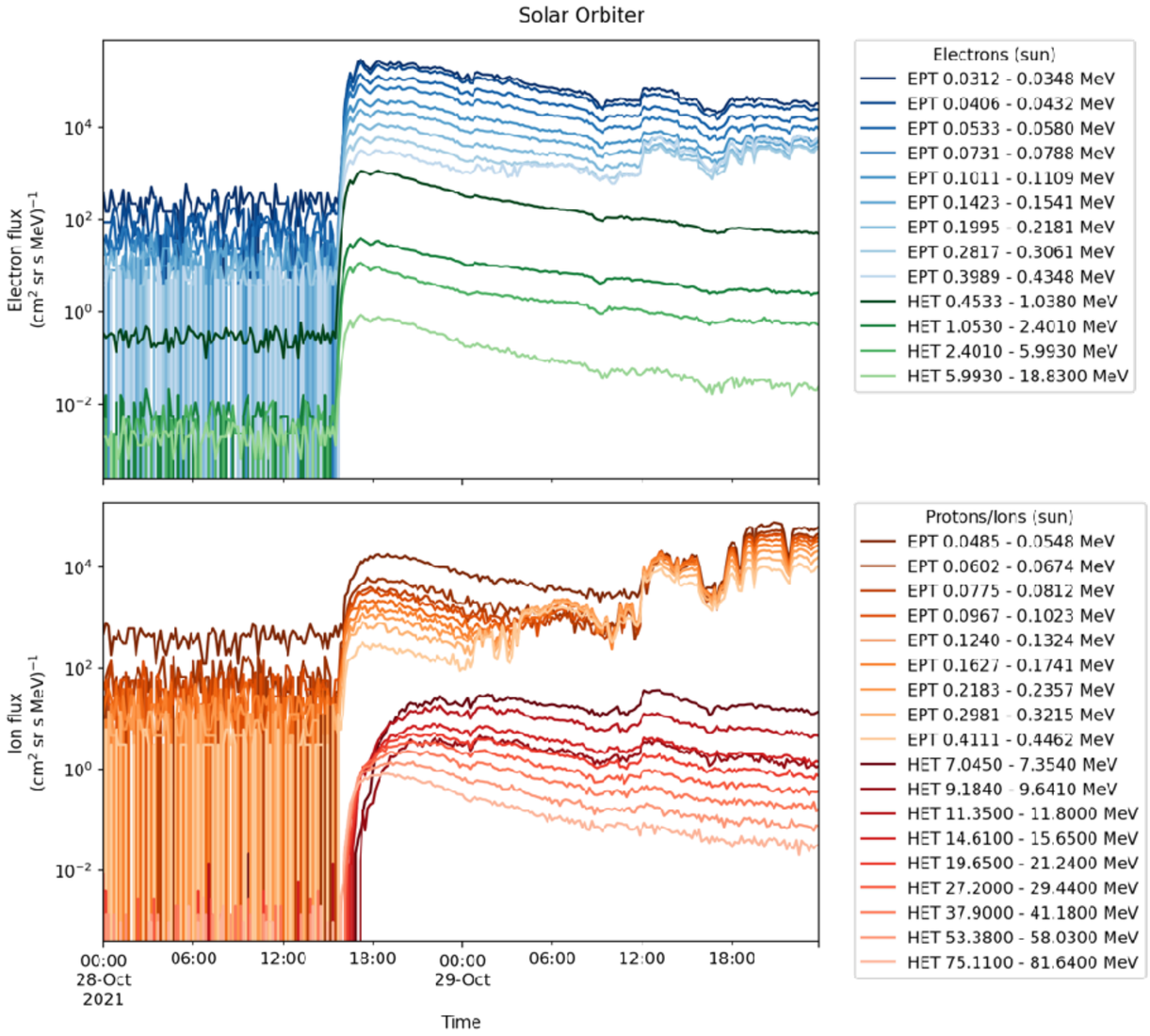
Obtain the data, downloading them to `path` if needed:

Get info on energy channels:

In [124]:
```
energies_ept
```

Out[124]:
```
{'H Bins Text': array([['7.0450 - 7.3540 MeV'],
                       ['7.3540 - 7.8900 MeV'],
                       ['7.8900 - 8.4840 MeV'],
                       ['8.4840 - 9.1840 MeV'],
                       ['9.1840 - 9.6410 MeV'],
                       ['10.6000 - 10.7400 MeV'],
                       ['10.7400 - 10.9800 MeV'],
                       ['10.9800 - 11.3500 MeV'],
                       ['11.3500 - 11.8000 MeV'],
                       ['11.8000 - 12.4300 MeV'],
                       ['12.4300 - 13.6800 MeV'],
                       ['13.6800 - 14.6100 MeV'],
                       ['14.6100 - 15.6500 MeV'],
                       ['15.6500 - 16.8200 MeV'],
                       ['16.8200 - 18.2000 MeV'],
```

TOOL: DATA LOADERS (AND TIME SERIES PLOTS)



Importing and general settings

In [1]:
```
import datetime as dt
import numpy as np
import os
import pandas as pd
import warnings
from matplotlib import pyplot as plt
from solo_epd_loader import epd_load

# omit Pandas' PerformanceWarning
warnings.simplefilter(action='ignore', category=pd.errors.PerformanceWarning)
```

Define some general options:

In [2]:
```
# set your local path where you want to save the data files:
path = f"{os.getcwd()}/data/"

# whether missing data files should automatically downloaded from SDAR:
autodownload = True

# define some optional plotting settings
color = {'sun': 'crimson', 'asun': 'orange', 'north': 'darkslateblue', 'south': 'c'}  # define SolO/EPD colors
```

1. Example with different viewing directions of EPT electrons

Define some basic options:

In [4]:
```
# define start and end date of data to load (year, month, day):
startdate = dt.datetime(2020, 12, 10)
enddate = dt.datetime(2020, 12, 11)

# define the sensor to use:
sensor = 'ept'

# define data level to use ('l2' or 'll'):
level = 'l2'
```

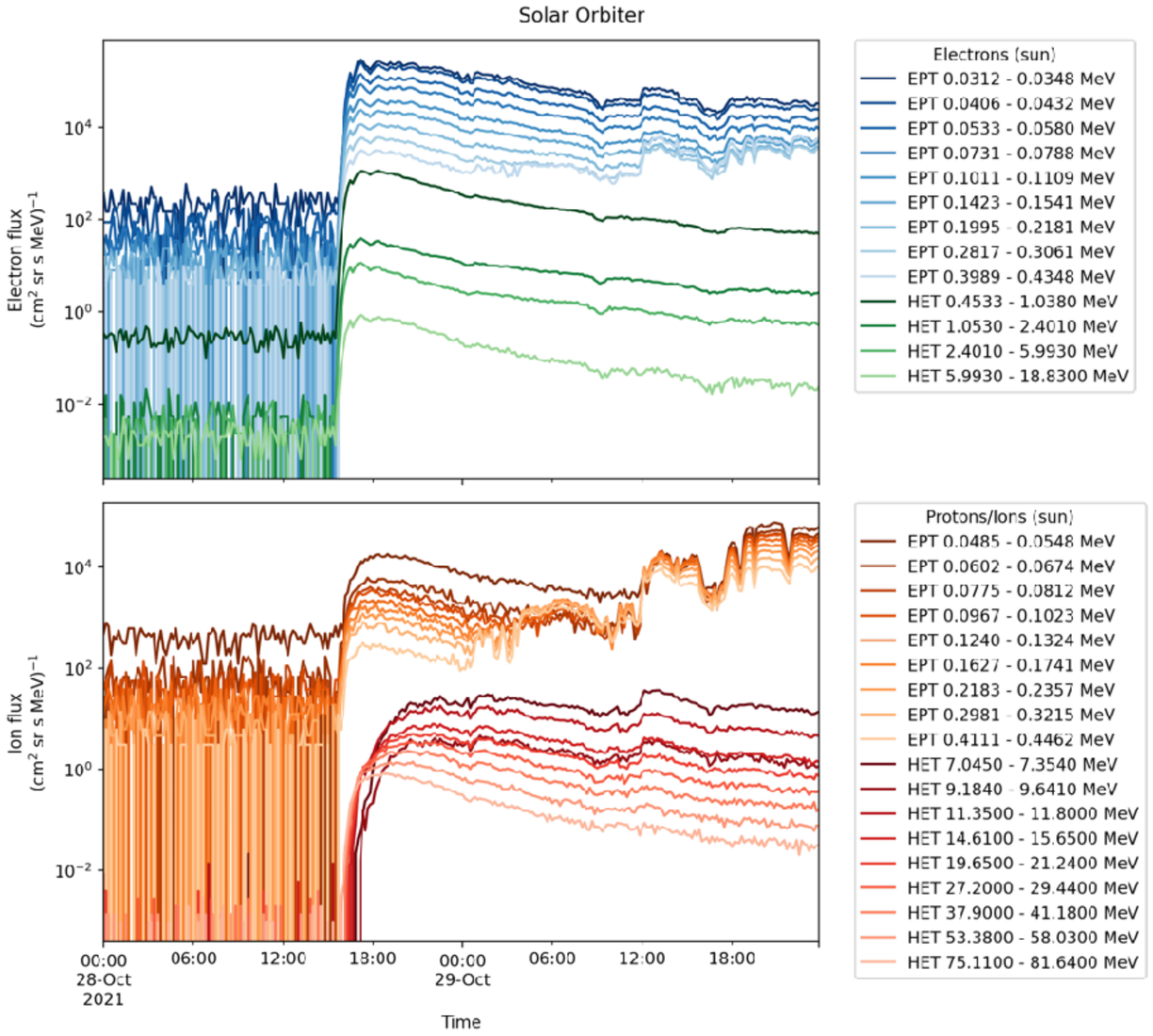
Obtain the data, downloading them to `path` if needed:

In [5]:
```
# load data
df_protons_sun, df_electrons_sun, energies = epd_load(sensor=sensor, level=level, startdate=startdate,
                                                      enddate=enddate, viewing='sun',
                                                      path=path, autodownload=True)
df_protons_asun, df_electrons_asun, energies = epd_load(sensor=sensor, level=level, startdate=startdate,
                                                        enddate=enddate, viewing='asun',
                                                        path=path, autodownload=True)
df_protons_south, df_electrons_south, energies = epd_load(sensor=sensor, level=level, startdate=startdate,
                                                          enddate=enddate, viewing='south',
                                                          path=path, autodownload=True)
df_protons_north, df_electrons_north, energies = epd_load(sensor=sensor, level=level, startdate=startdate,
                                                          enddate=enddate, viewing='north',
                                                          path=path, autodownload=True)
```

Make the plot:

In [6]:
```
# energy channel to use; cf. "energies" for the energies
channel = 6
```

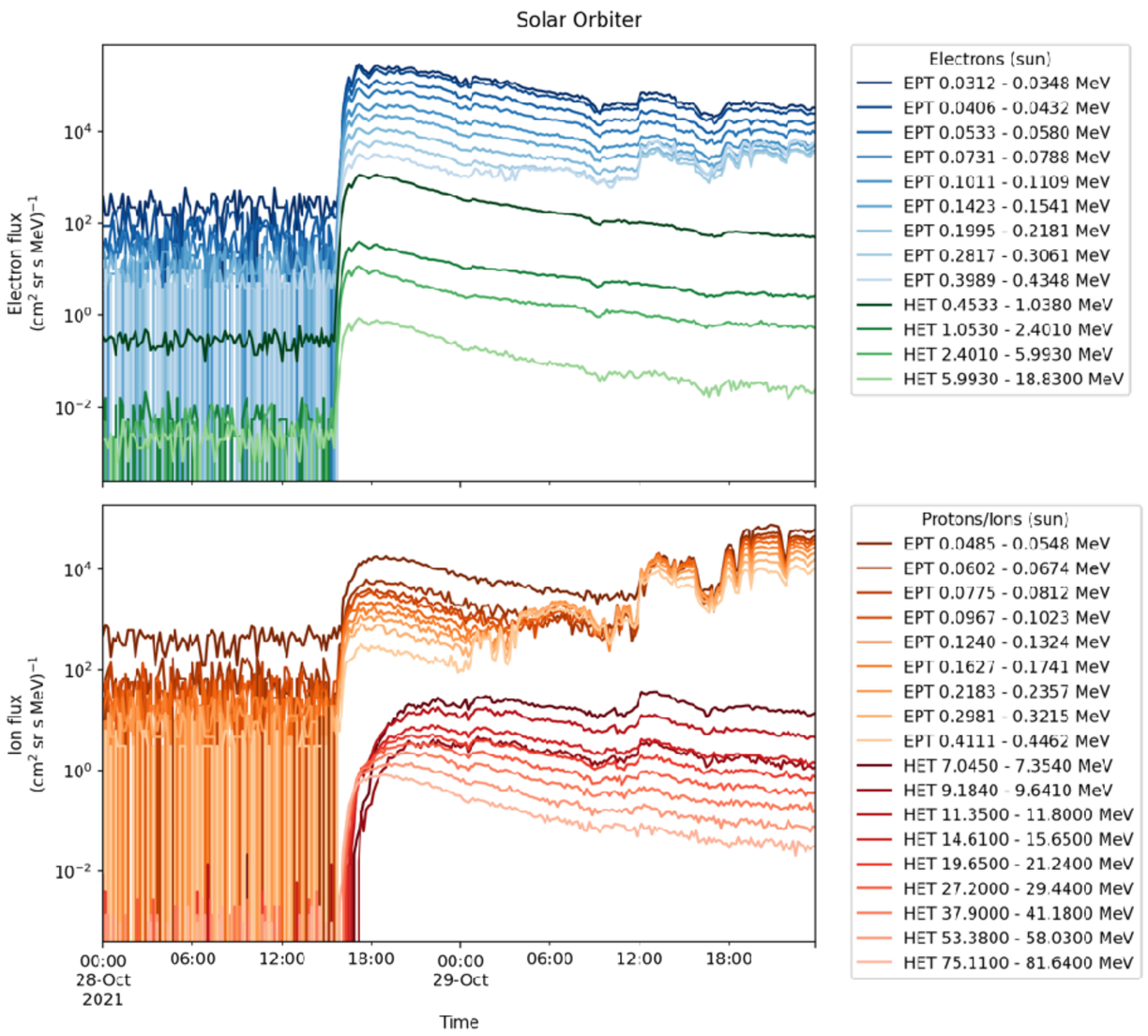
TOOL: DATA LOADERS (AND TIME SERIES PLOTS)



Time series analyses:

- ✓ How energetic is the event?
- ✓ Is the SEP event time profile impulsive or gradual?
- ✓ Is it seen in electrons and protons?

TOOL: DATA LOADERS (AND TIME SERIES PLOTS)

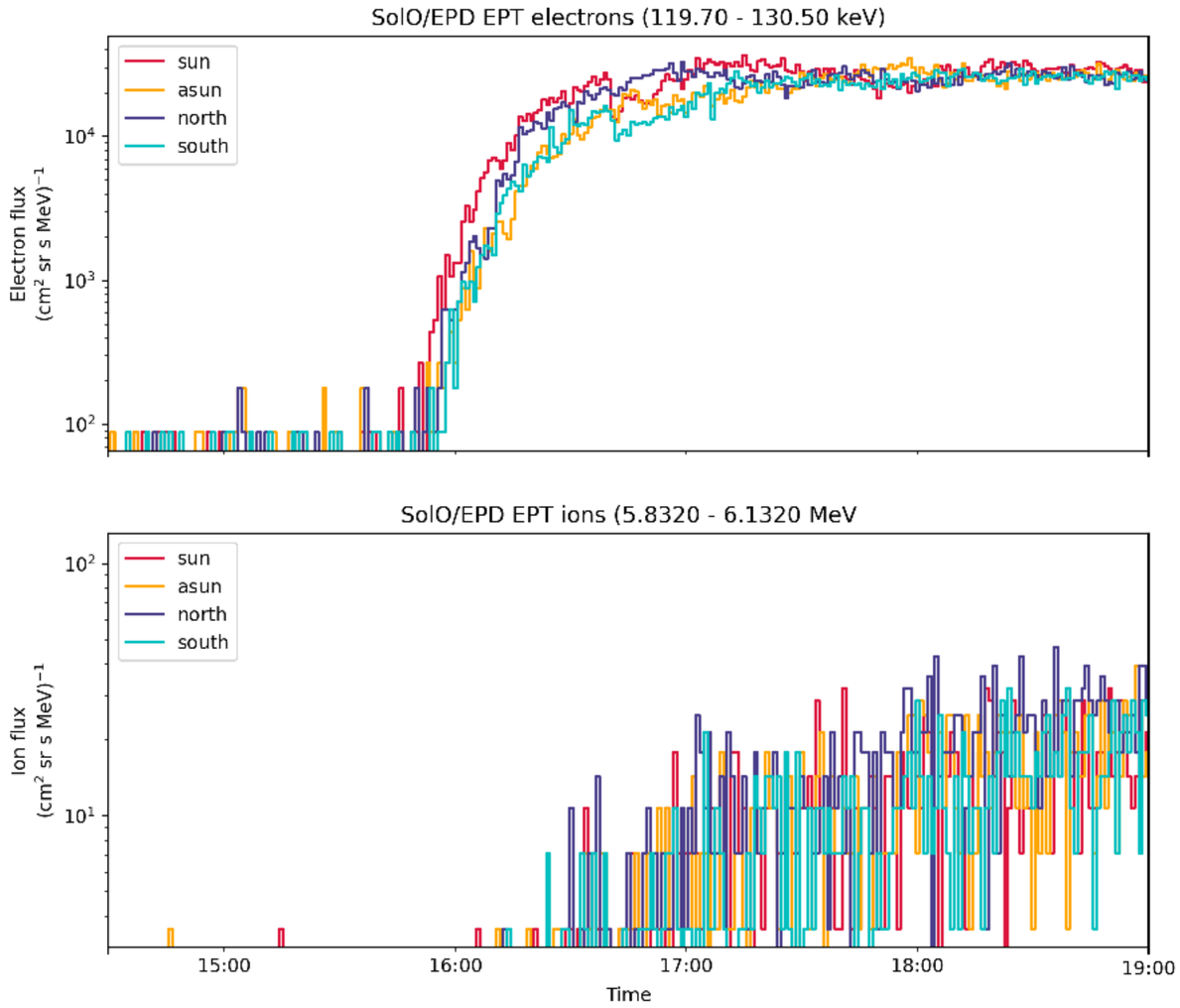


Time series analyses:

- ✓ How energetic is the event?
- ✓ Is the SEP event time profile impulsive or gradual?
- ✓ Is it seen in electrons and protons?
- ✓ Do we see characteristics for a good magnetic connection to the source? For example,
  - ✓ (velocity dispersion)
  - ✓ anisotropy
- ✓ (Do we see hints of instrumental issues / contamination?)

TIME SERIES

Time series analyses:

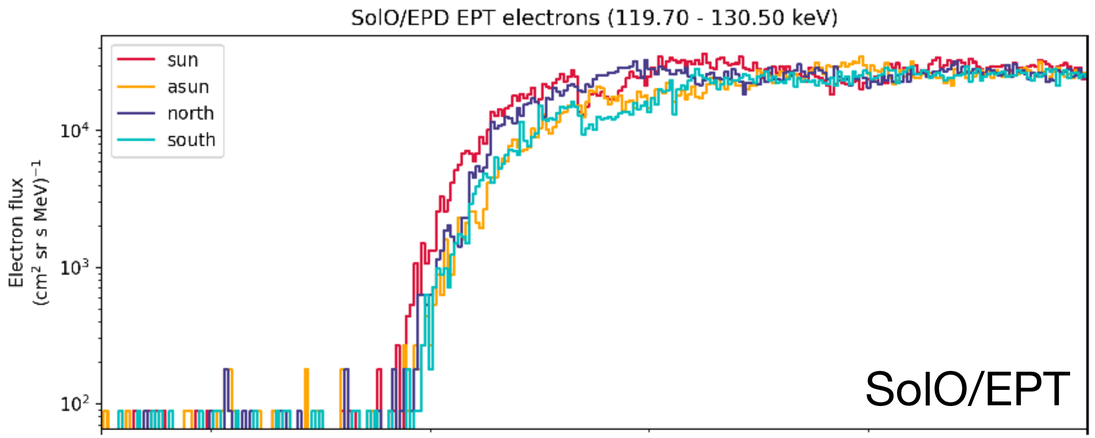


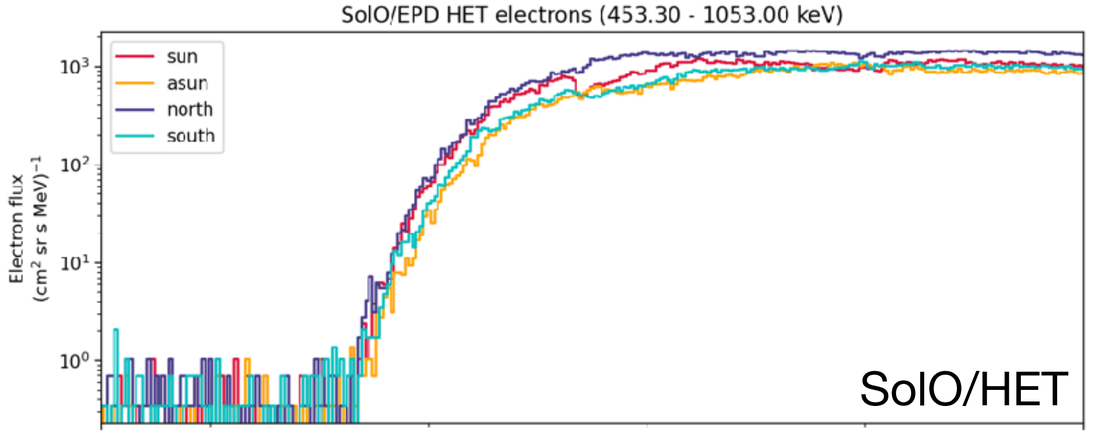
- ✓ How energetic is the event?
- ✓ Is the SEP event time profile impulsive or gradual?
- ✓ Is it seen in electrons and protons?
- ✓ Do we see characteristics for a good magnetic connection to the source? For example,
  - ✓ (velocity dispersion)
  - ✓ anisotropy
- ✓ (Do we see hints of instrumental issues / contamination?)

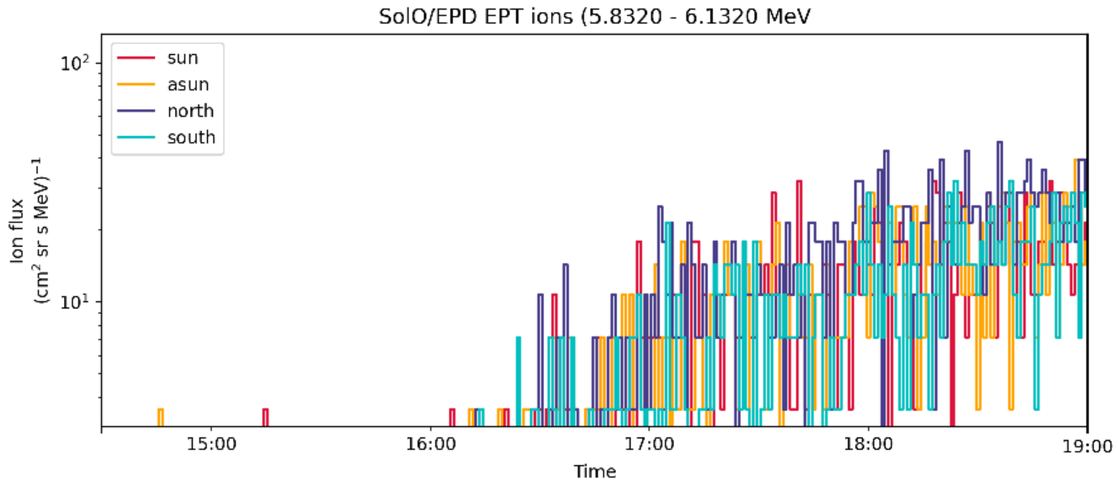
TIME SERIES

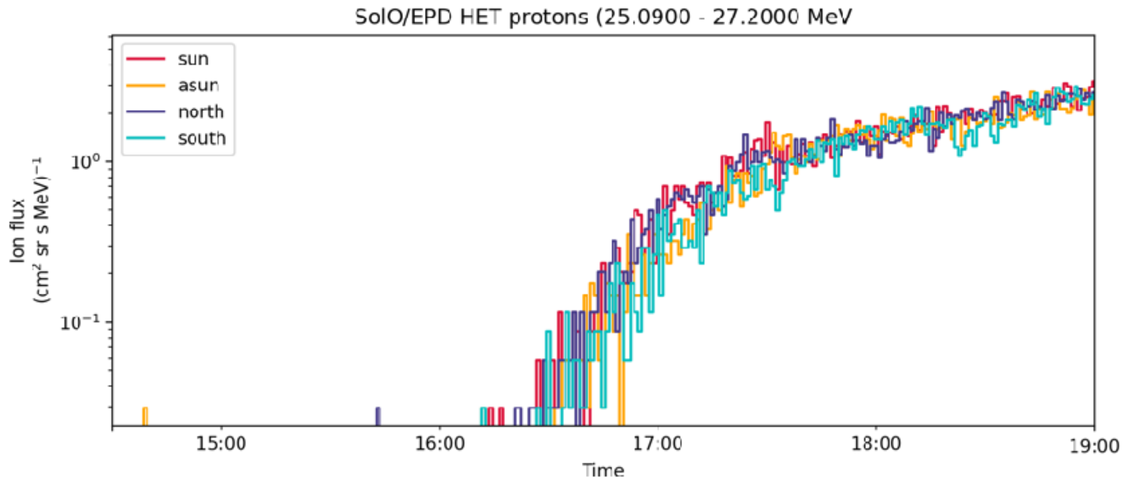
Time series analyses:

Sectored intensities of electrons and protons at different energies









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    - Interactive Time Shift Analysis (TSA)
  - Spacecraft constellation plotter tool Solar-MACH

- Cycle 25 multi-spacecraft SEP event catalog

ANALYSIS OF SOLAR ENERGETIC PARTICLE (SEP) EVENTS

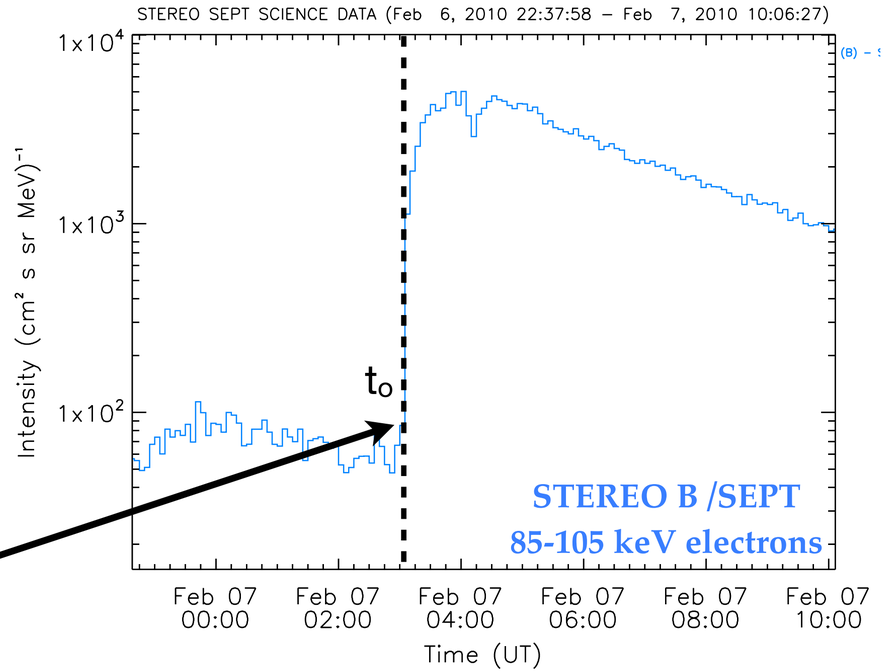
Goal: Connect SEP observations with observations of potential acceleration sites / phenomena at the Sun

Timing analyses

We want to connect the SEPs with their potential solar sources (e.g., flare, jets, radio bursts, EUV waves, CME)

➤ We need to infer the solar release time (injection time) of the SEPs

➤ Therefore, we first need to determine the SEP **onset time** at the spacecraft



ONSET OF SEP EVENTS – THE POISSON CUSUM METHOD

The Poisson-CUSUM (CUmulative SUM) method is a statistical quality control scheme

It cumulates the difference S (CUSUM) between the observed intensities I_i and a reference value k

$$S_i = \max(0, I_i - k + S_{i-1})$$

μ, σ = mean & std. of pre-event background

$$\mu_d = \mu + 2\sigma$$

$$k = \frac{\mu_d - \mu}{\ln(\mu_d) - \ln(\mu)}$$

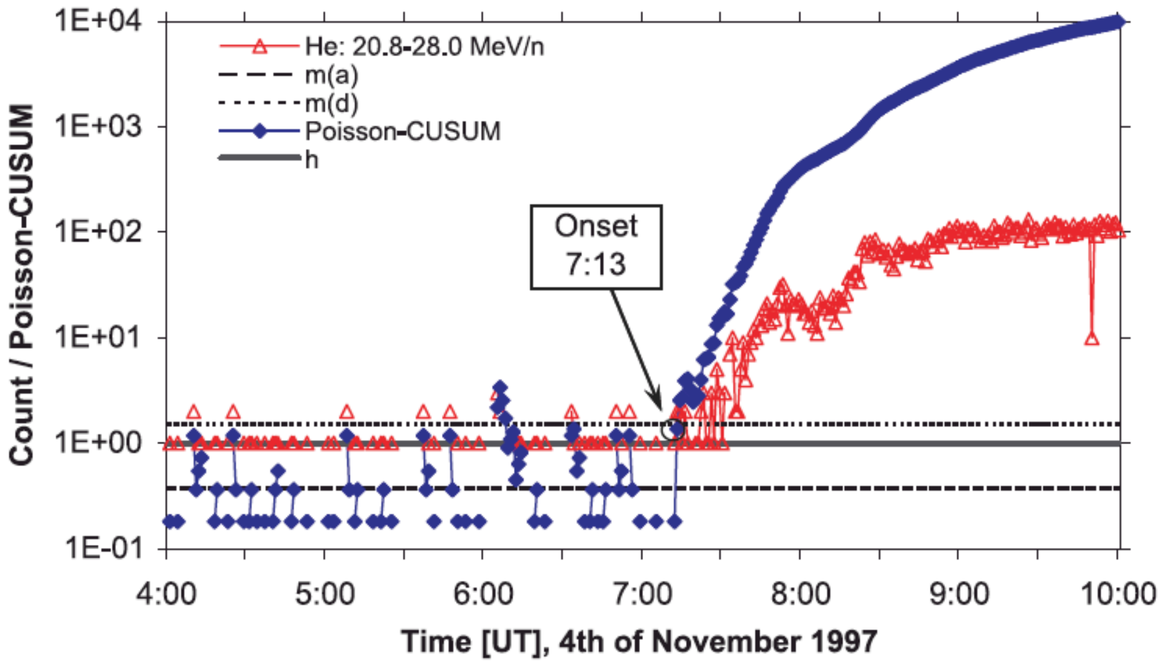
Decision threshold h (used to trigger an event:)

$k<1: h=1$

$k \geq 1: h=2$

An out of control signal is triggered when: $S_i > h$

Huttunen-Heikinmaa et al. (2005)

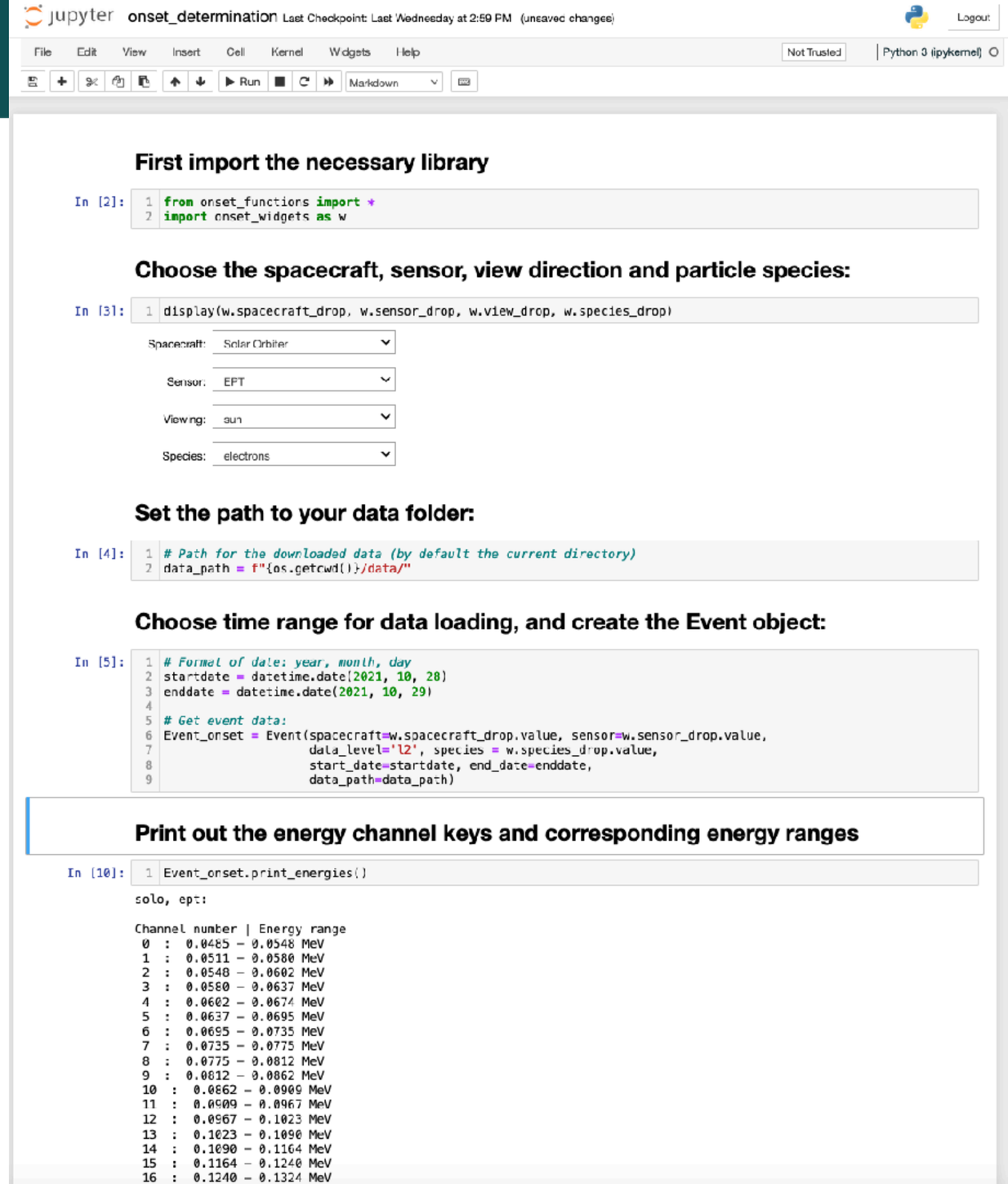


The onset is found if the following data points of a defined window length w (e.g., a window of w=30 min) also satisfy $S_{i...i+w} > h$

SEP ONSET TOOL

Currently implemented:

- Electron and proton/ion intensities from:
  - STEREO A & B: SEPT, HET
  - SolO: EPT, HET
  - SOHO: ERNE-HED, EPHIN
    - All available viewing directions



SEP ONSET TOOL

Uses the Poisson CUSUM method and provides:

- Onset time
- Peak time (within plot interval, after onset)
- Peak intensity
- Background mean and std

Flexible and quick change of

- energy channels
- viewing directions
- Time averaging
- Background interval
- Plot range

UNIVERSITY OF TURKU Nina Dresing

jupyter onset_determination Last Checkpoint: Last Wednesday at 2:59 PM (autosaved) Logout

File Edit View Insert Cell Kernel Widgets Help No: Trustec Python 3 (ipykernel)

Run Markdown

```
output = Event_onset.output

##### >Energy channels< #####
0.0380 - 0.0497 MeV
##############################

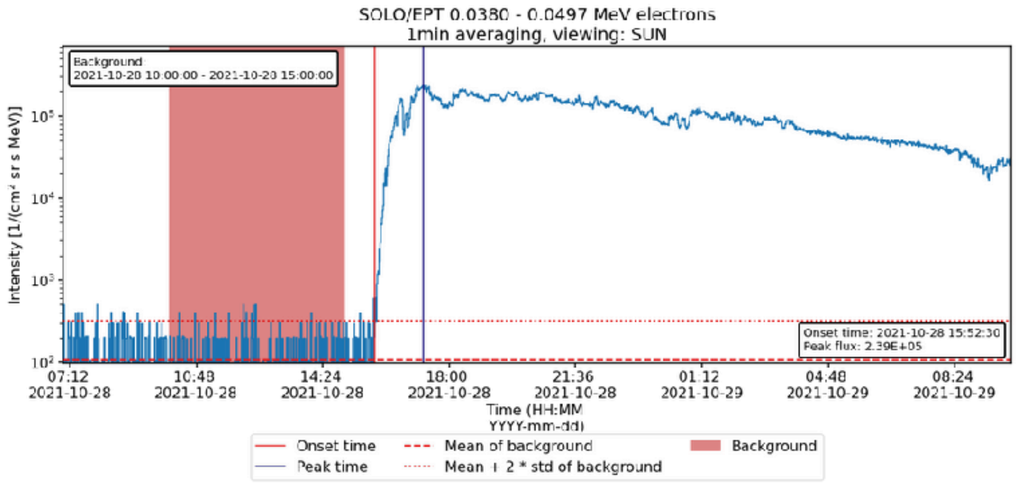
##### >Flux peak< #####
                          flux
Time
2021-10-28 17:15:30  239012.28125
#######################

##### >Onset time< #####
2021-10-28 15:52:30
#######################

##### >Mean of background intensity< #####
104.241615
#########################################

##### >Std of background intensity< #####
106.31322
#########################################

##### >Particle species< #####
electrons
##############################
```



output is a dictionary, that contains 'flux_series', 'onset_stats', 'onset_found', 'onset', 'peak_flux', 'peak_time', 'fig' and 'bg_mean'

In [45]:

```
print(f"Onset: {output['onset'].round(freq='s')}")
print(f"Peak flux: {output['peak_flux']:.2e}")
print(f"Peak time: {output['peak_time'].round(freq='s')}")
print(f"Bg mean: {output['bg_mean']:.2e}")
```

```
Onset: 2021-10-28 15:55:30
Peak flux: 7.98e+00
Peak time: 2021-10-28 22:24:30
Bg mean: 5.10e-03
```

CONTENT

- **What is WP2 about?**
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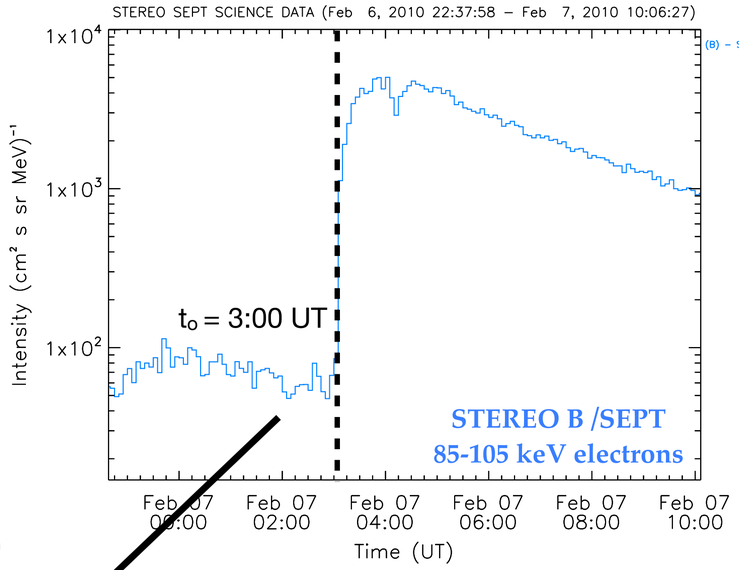
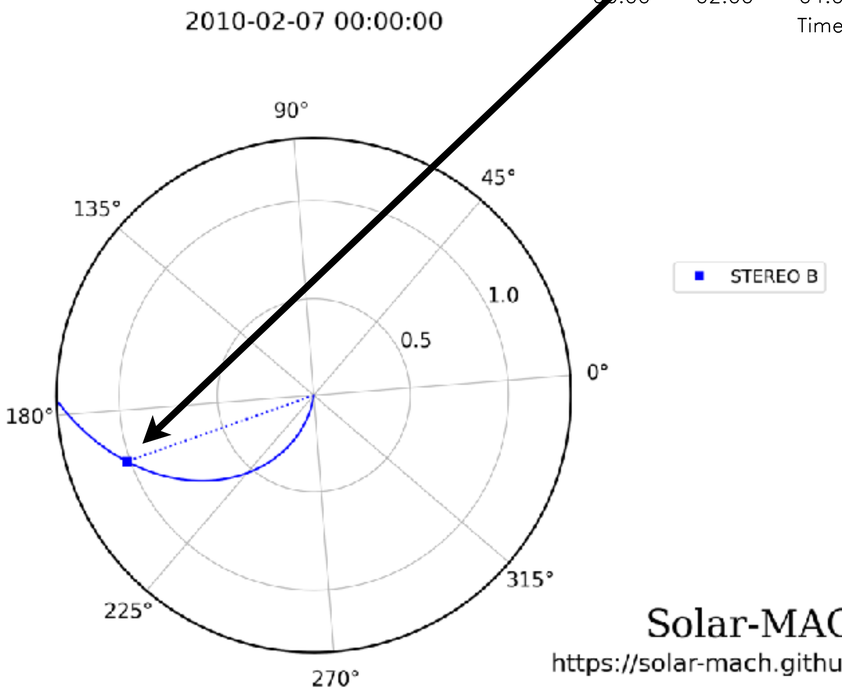
    - Interactive Time Shift Analysis (TSA)
  - Spacecraft constellation plotter tool Solar-MACH

- Cycle 25 multi-spacecraft SEP event catalog

INFERRED SEP INJECTION TIME – TIME SHIFT ANALYSIS (TSA)

- Determine SEP onset time ✓ t_o = 3:00 UT
- Infer SEP injection time
  1. **Determine the travel path length of the SEPs**
  2. Determine the particle speed
  3. Calculate particle propagation time and subtract from onset time



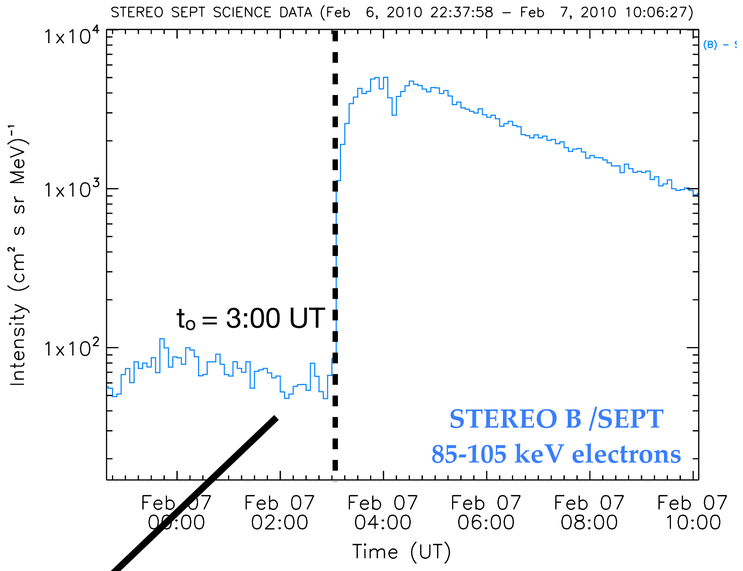


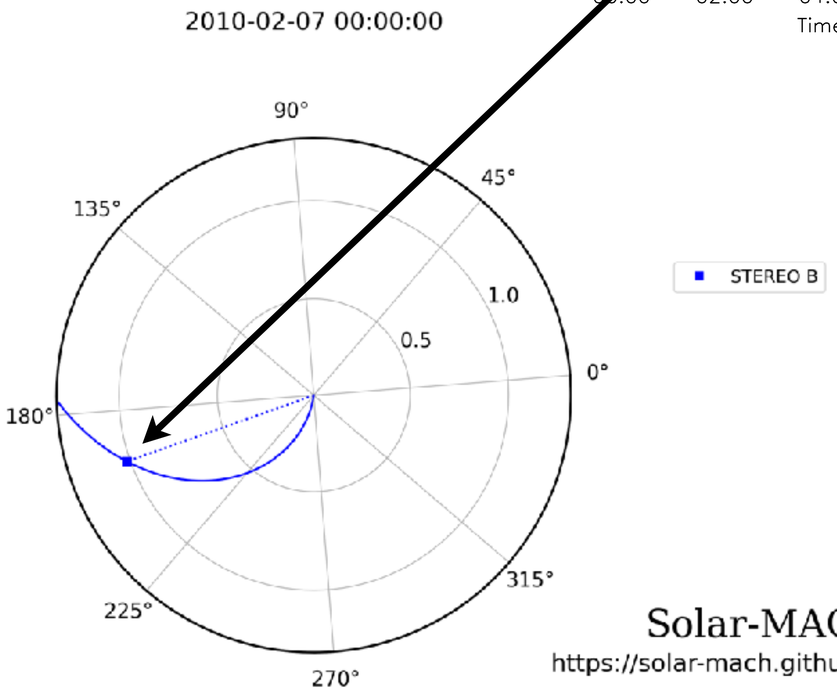
INFERRED SEP INJECTION TIME – TIME SHIFT ANALYSIS (TSA)

- Determine SEP onset time ✓ t_o = 3:00 UT
- Infer SEP injection time
  1. **Determine the travel path length of the SEPs**
  2. Determine the particle speed
  3. Calculate particle propagation time and subtract from onset time

Future tool:

```
SEP_injection_time(to, energy,
                   species='electrons',
                   spacecraft='Solar Orbiter',
                   vsw=400)
```





TOOL: INTERACTIVE TIME SHIFT ANALYSIS

Selection of data set as in the onset tool

(drop-down menu)

Allows to determine a common path length of the SEPs (assuming they were injected at the same time)

Currently implemented:

- Electron and proton/ion intensities from:
  - STEREO A & B: SEPT, HET
  - SolO: EPT, HET
  - SOHO: ERNE-HED, EPHIN
    - All available viewing directions

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

```
In [2]: 1 display(w.spacecraft_drop, w.sensor_drop, w.view_drop, w.species_drop)
```

Spacecraft: Solar Orbiter

Sensor: EPT

Viewing: sun

Species: electrons

Set the data path and date range to load data:

```
In [19]: 1 # The path to where data is located / to be downloaded (by default the current directory)
         2 data_path = f"{os.getcwd()}/data/"
         3
         4 # Format of date: year, month, day
         5 #startdate = datetime.date(2021, 10, 28)
         6 #enddate = datetime.date(2021, 10, 29)
         7 startdate = datetime.date(2022, 1, 18)
         8 enddate = datetime.date(2022, 1, 19)
```

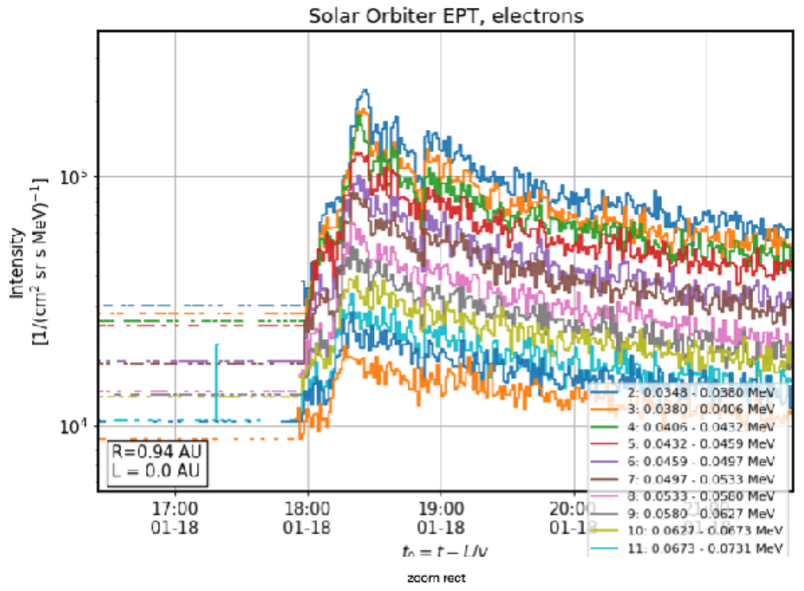
```
In [35]: 1 # Select the channels to be plotted (first, last, step), end-exclusively (use None to choose all)
         2 channels = (2, 14) #(1, 11, 2)
         3
         4 %matplotlib widget
         5 Event_class.tsa_plot(w.view_drop.value, selection=channels, resample=averaging)
```

```
INFO: Obtained JPL HORIZONS location for Solar Orbiter (spacecraft) [-144 [sunpy.coordinates.ephemeris]
```

Path length L [AU]: 0.00

Normalize

Figure 1



TOOL: INTERACTIVE TIME SHIFT ANALYSIS

Original data

```
In [35]:
# Select the channels to be plotted (first, last, step), end-exclusively (use None to choose all)
channels = (2, 14) #(1, 11, 2)

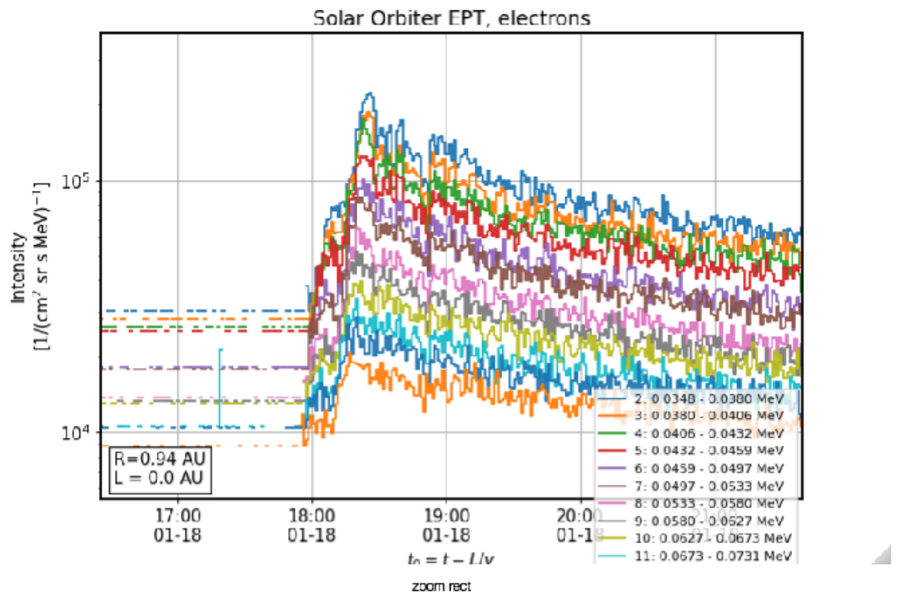
%matplotlib widget
Event_class.tsa_plot(w.view_drop.value, selection=channels, resample=averaging)
```

```
INFO: Obtained JPL HORIZONS location for Solar Orbiter (spacecraft) (-144 [sunpy.coordinates.ephemeris]
```

Path length L [AU]: 0.00

☐ Normalize

Figure 1



Normalized data

```
In [35]:
# Select the channels to be plotted (first, last, step), end-exclusively (use None to choose all)
channels = (2, 14) #(1, 11, 2)

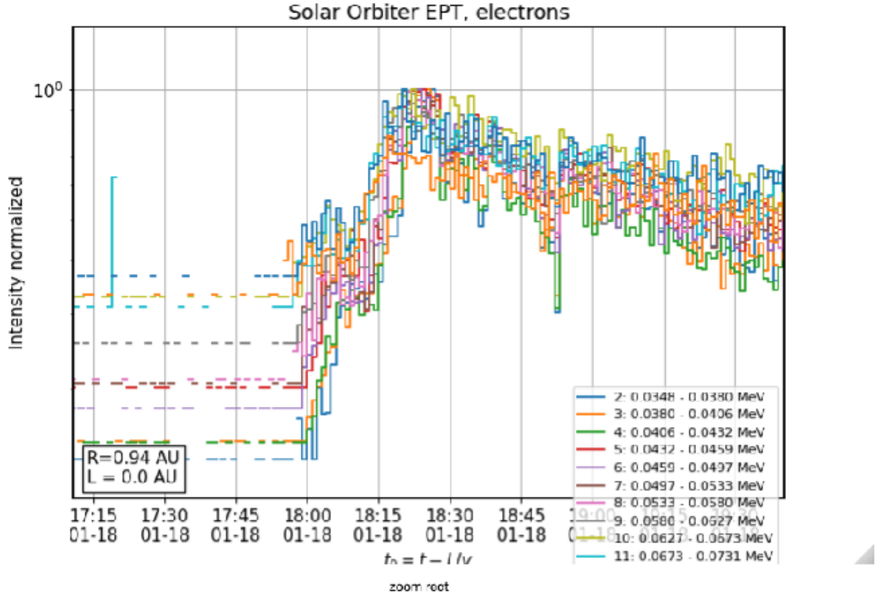
%matplotlib widget
Event_class.tsa_plot(w.view_drop.value, selection=channels, resample=averaging)
```

```
INFO: Obtained JPL HORIZONS location for Solar Orbiter (spacecraft) (-144 [sunpy.coordinates.ephemeris]
```

Path length L [AU]: 0.00

☑ Normalize

Figure 1



TOOL: INTERACTIVE TIME SHIFT ANALYSIS

shifted data (L=0.5 AU)

```
In [35]:
# Select the channels to be plotted (first, last, step), end-exclusively (use None to choose all)
channels = (2, 14) #(1, 11, 2)

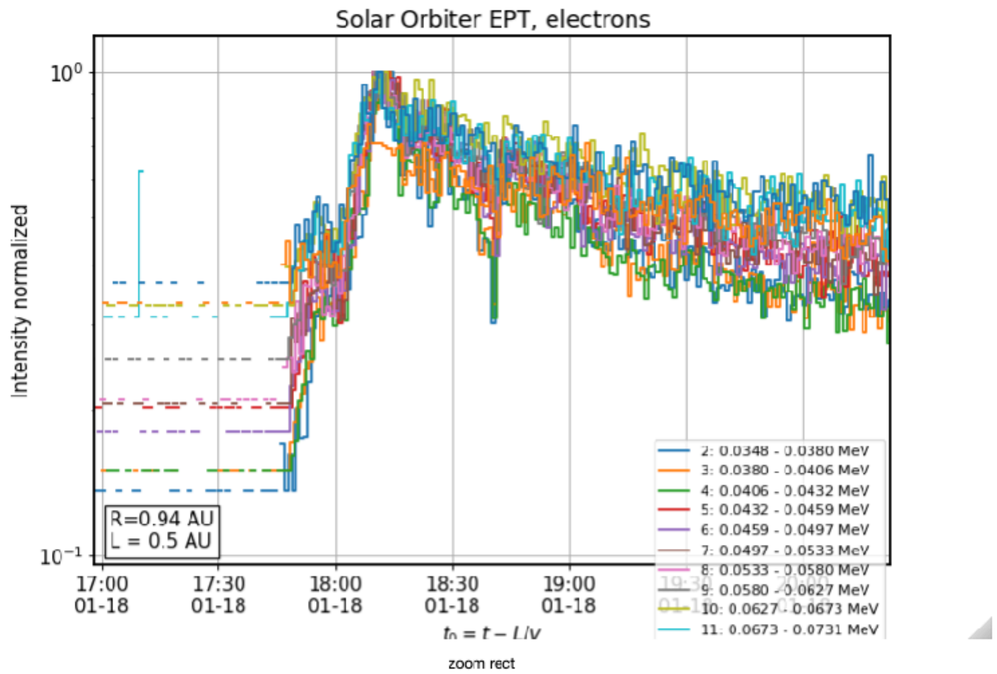
%matplotlib widget
Event_class.tsa_plot(w.view_drop.value, selection=channels, resample=averaging)
```

```
INFO: Obtained JPL HORIZONS location for Solar Orbiter (spacecraft) (-144 [sunpy.coordinates.ephemeris]
```

Path length L [AU]: 0.50

Normalize

Figure 1



final result: shifted data (L=1.1 AU)

```
In [35]:
# Select the channels to be plotted (first, last, step), end-exclusively (use None to choose all)
channels = (2, 14) #(1, 11, 2)

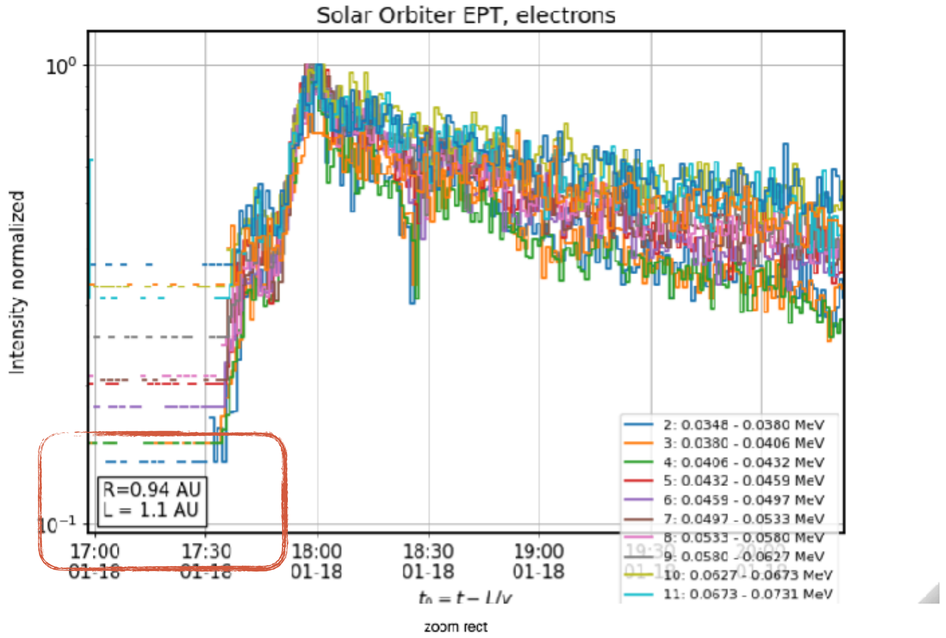
%matplotlib widget
Event_class.tsa_plot(w.view_drop.value, selection=channels, resample=averaging)
```

```
INFO: Obtained JPL HORIZONS location for Solar Orbiter (spacecraft) (-144 [sunpy.coordinates.ephemeris]
```

Path length L [AU]: 1.10

Normalize

Figure 1



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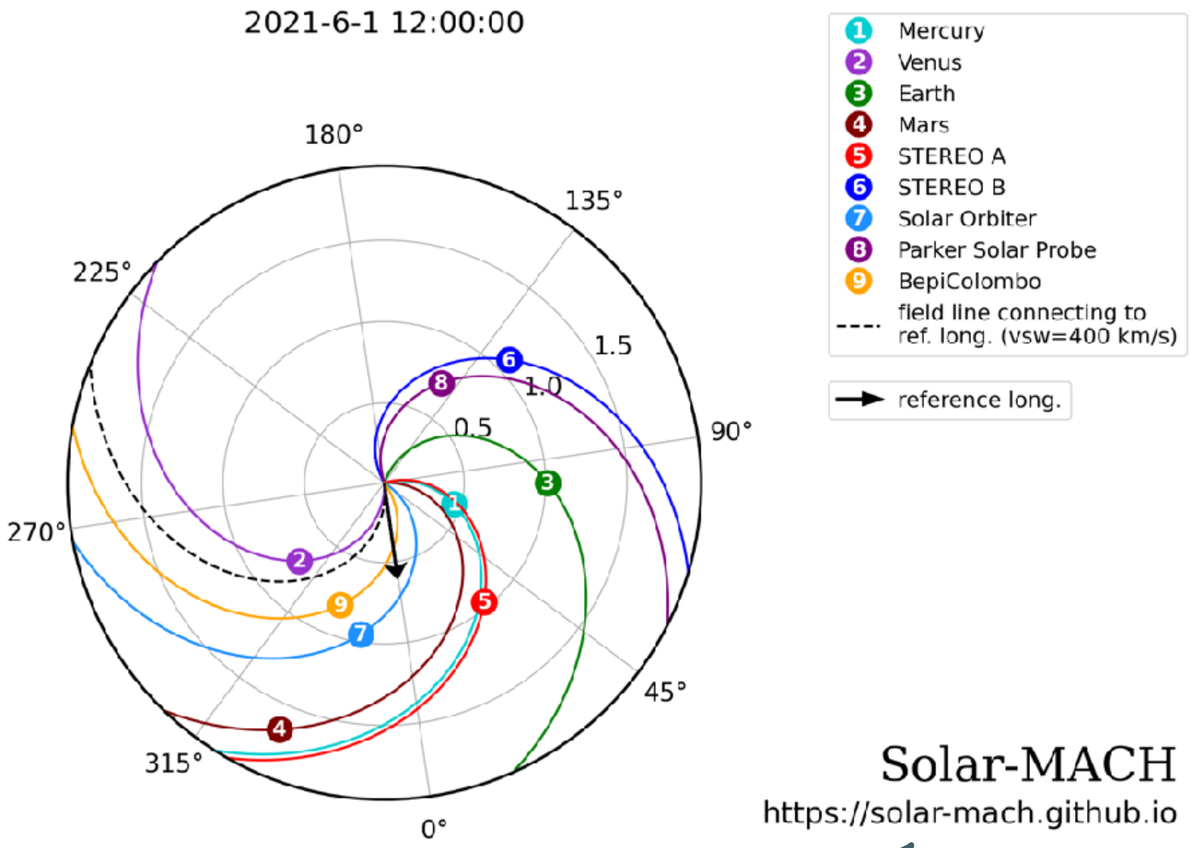
THE SOLAR-MACH TOOL: A MULTI-SPACECRAFT CONSTELLATION PLOTTER

- To know the spacecraft constellation is essential to study multi-spacecraft SEP events
- Solar-MACH:
  - Locations of selected bodies and spacecraft
  - Nominal Parker spiral field lines connecting the bodies with the Sun (using provided solar wind speed)
  - Carrington or Stonyhurst coordinate system
  - Reference longitude (e.g., location of a flare) and its corresponding Parker field line
  - A coordinate table with spacecraft locations, separation angles, and backmapped magnetic footpoint locations at the Sun



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

Online version of the tool

THE SOLAR-MACH TOOL: A MULTI-SPACECRAFT CONSTELLATION PLOTTER

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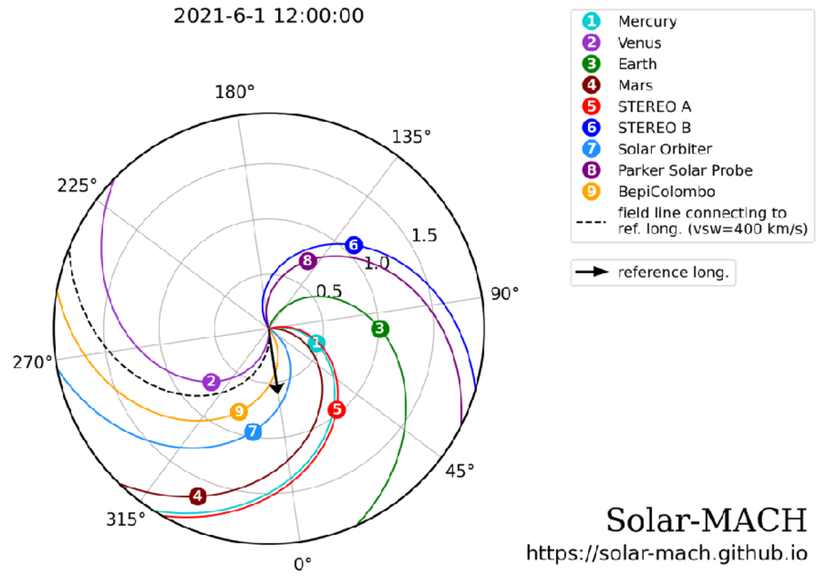


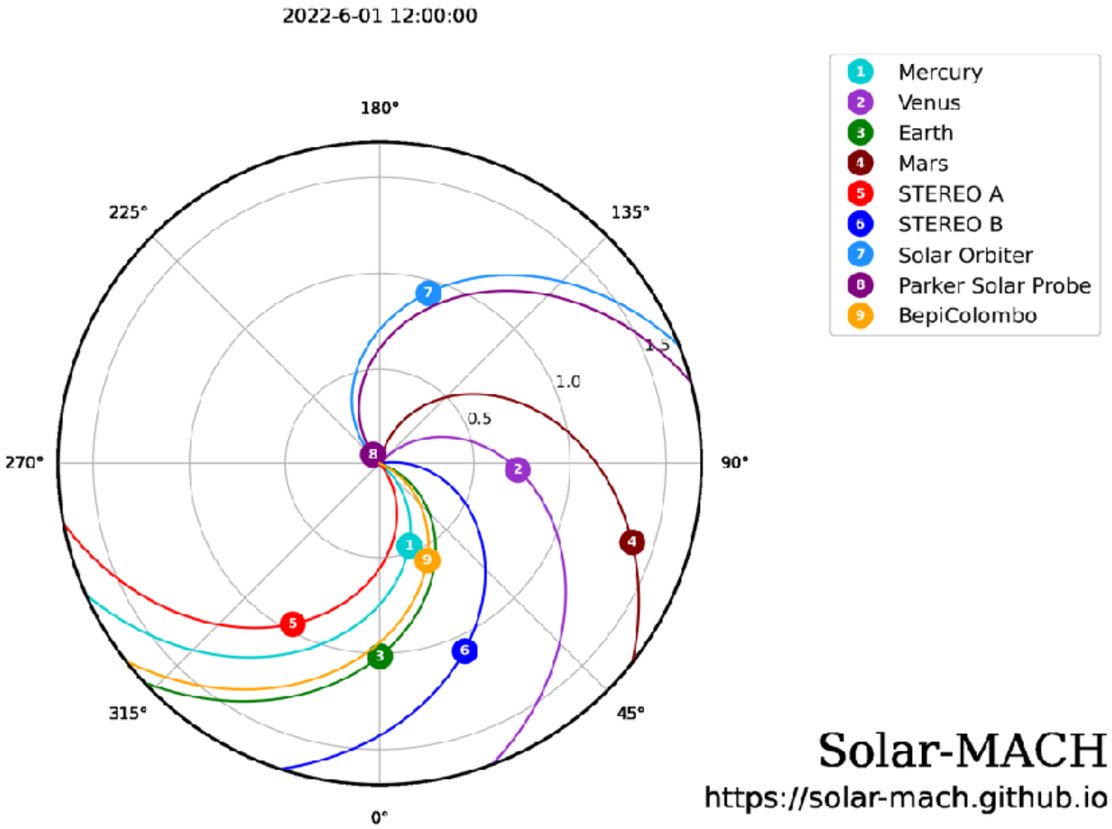
	Spacecraft/Body	Carrington Longitude (°)	Carrington Latitude (°)	Heliocentric Distance (AU)	Longitudinal separation to Earth's longitude	Latitudinal separation to Earth's latitude	Vsw	Magnetic footpoint longitude (Carrington)	Longitudinal separation between body and reference_long	Longitudinal separation between body's mangetic footpoint and reference_long	Latitudinal separation between body and reference_lat
0	Mercury	64.6	-3.4	0.5	-17.2	-2.8	350	96.6	64.6	96.6	-3.4
1	Venus	304.3	-2.4	0.7	-137.4	-1.8	350	354.7	-55.7	-5.3	-2.4
2	Earth	81.7	-0.6	1.0	0.0	0.0	350	152.9	81.7	152.9	-0.6
3	Mars	328.7	-4.6	1.7	-113.0	-4.0	350	85.0	-31.3	85.0	-4.6
4	STEREO A	31.7	-6.0	1.0	-50.1	-5.4	350	99.3	31.7	99.3	-6.0
5	STEREO B	126.3	4.5	1.1	44.6	5.1	350	202.5	126.3	-157.5	4.5
6	Solar Orbiter	342.9	-1.0	1.0	-98.8	-0.4	350	49.7	-17.1	49.7	-1.0
7	PSP	142.0	3.2	0.7	60.3	3.8	350	192.3	142.0	-167.7	3.2
8	BepiColombo	332.0	-3.5	0.8	-109.8	-2.9	350	28.6	-28.0	28.6	-3.5

THE SOLAR-MACH TOOL: A MULTI-SPACECRAFT CONSTELLATION PLOTTER

The Solar-MACH notebook illustrates various use cases and contains some more advanced applications, like

- Creating movies of a longer time period
- Analyzing a list of events
- Customizing the plot

It also contains an extension to perform backmapping below the source surface using a Potential Field Source Surface (PFSS) model



THE CORONAL MAGNETIC FIELD AND BACKMAPPING CLOSE TO THE SUN

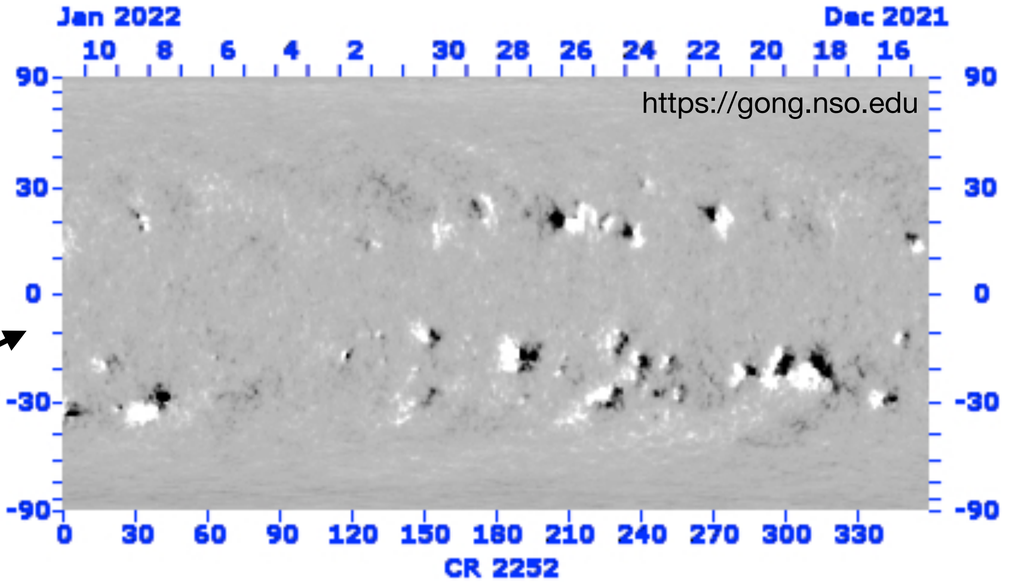
A Potential Field Source Surface (PFSS) model* assumes a current-free corona:

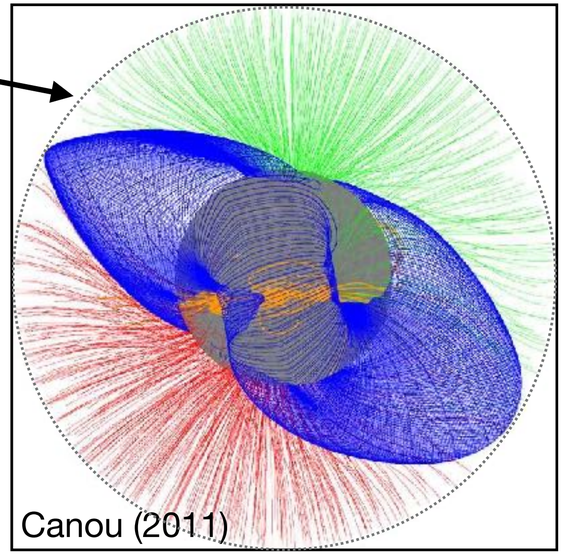
$$\nabla \cdot B = 0; \nabla \times B = 0$$

and extrapolates the magnetic field lines from the solar surface (lower boundary) to the Source Surface (SS, upper boundary)

Lower boundary: the magnetic field at the solar surface provided by a magnetogram map

Upper boundary: often assumed to be at 2.5 R_S, all field lines above are forced to be radial





*initially developed by Schatten, Wilcox & Ness (1969) and Altschuler & Newkirk (1969)

THE CORONAL MAGNETIC FIELD AND BACKMAPPING CLOSE TO THE SUN

Two-step backampping using ballistic and PFSS* backmapping

ABBREVIATIONS
PS: Photosphere
SS: Source Surface
FP: Footpoint
P: Polarity

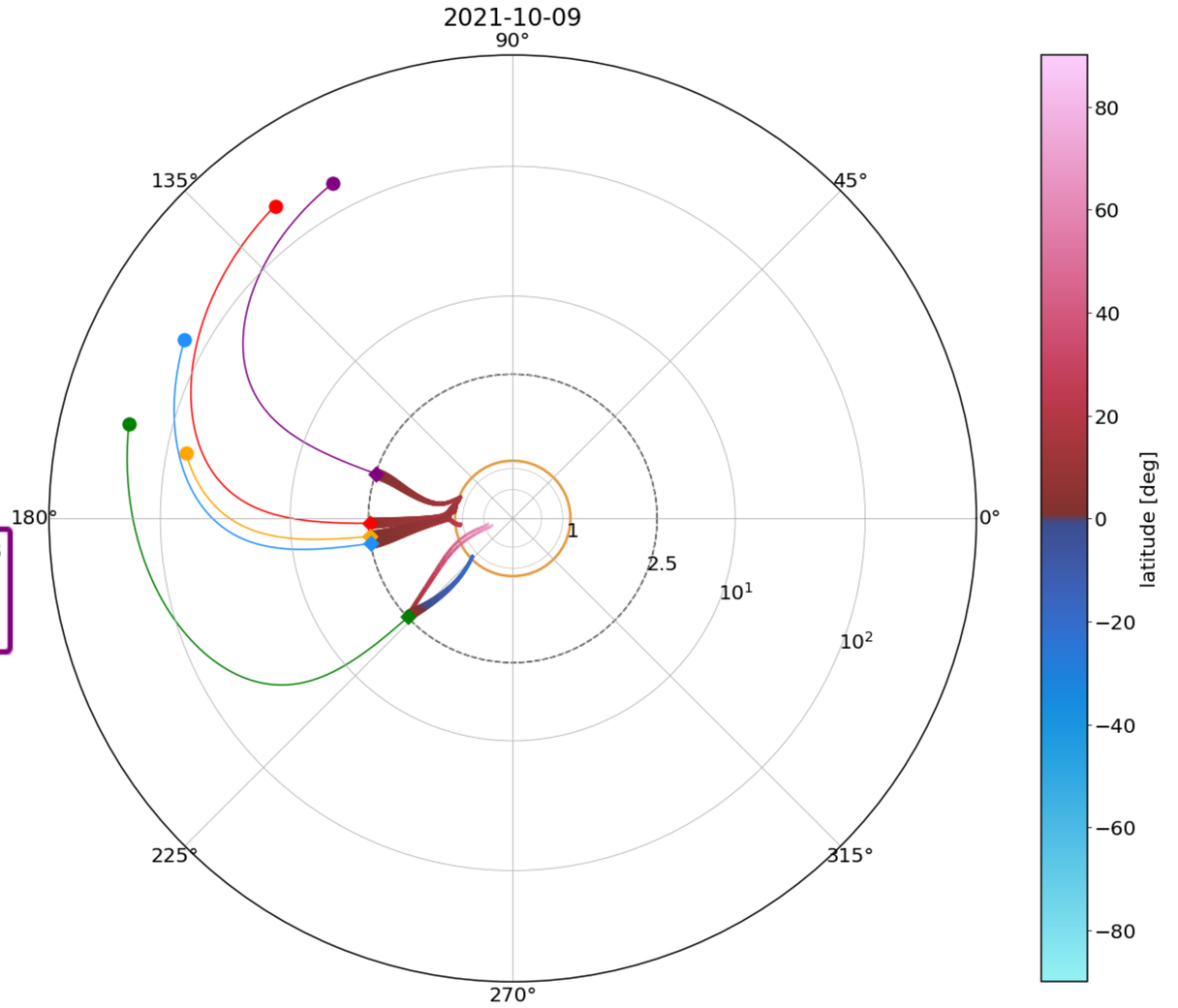
STEREO A, sw=400 km/s
PS FP = (159.2,14.6)
SS FP = (181.9,7.3)
P: 1

Earth, sw=400 km/s
PS FP = (223.3,-19.8)
SS FP = (223.3,6.3)
P: -1

BepiColombo, sw=400 km/s
PS FP = (171.5,11.8)
SS FP = (187.2,2.2)
P: 1

Parker Solar Probe, sw=400 km/s
PS FP = (156.8,15.9)
SS FP = (161.9,3.7)
P: 1

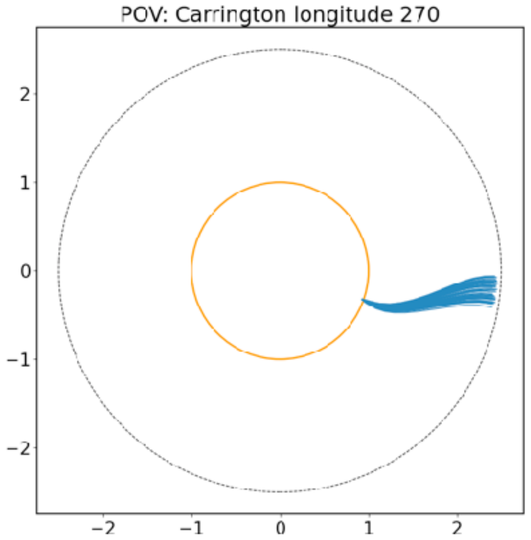
Solar Orbiter, sw=400 km/s
PS FP = (171.5,11.8)
SS FP = (190.0,2.4)
P: 1

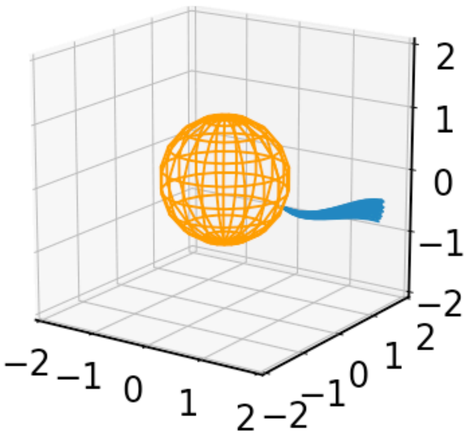


*using the pfsspy package

THE SOLAR-MACH TOOL AND ITS PFSS EXTENSION

Various different projections available that allow to investigate the field lines below the source surface in detail





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Solar Orbiter, sw=400 km/s
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SS FP = (190.0,2.4)
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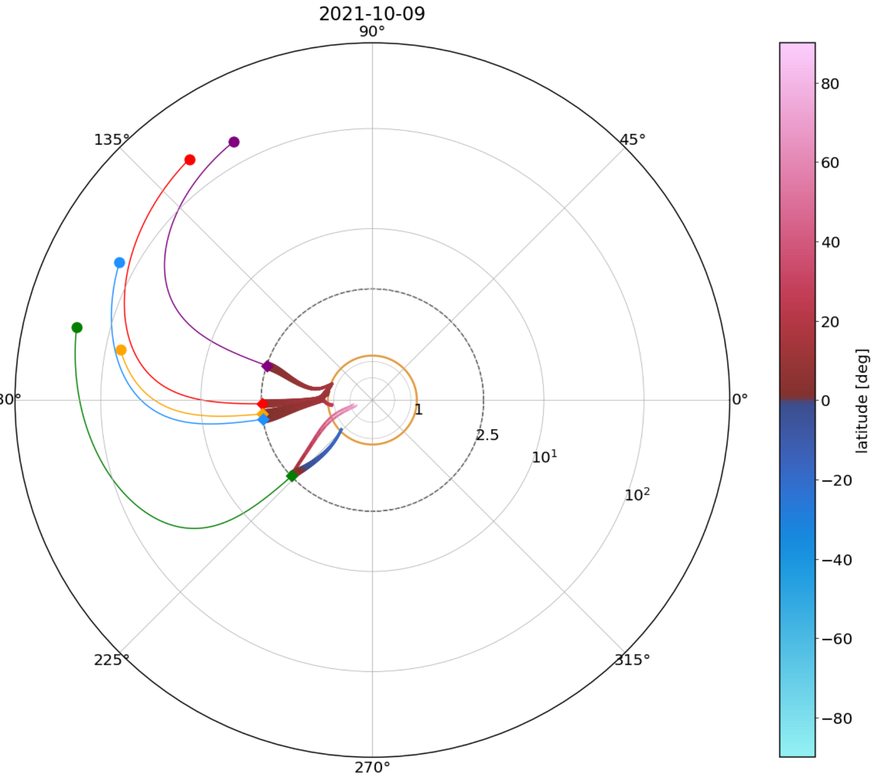


CONTENT

- What is WP2 about?
  - … and what will it provide for SERPENTINE users?

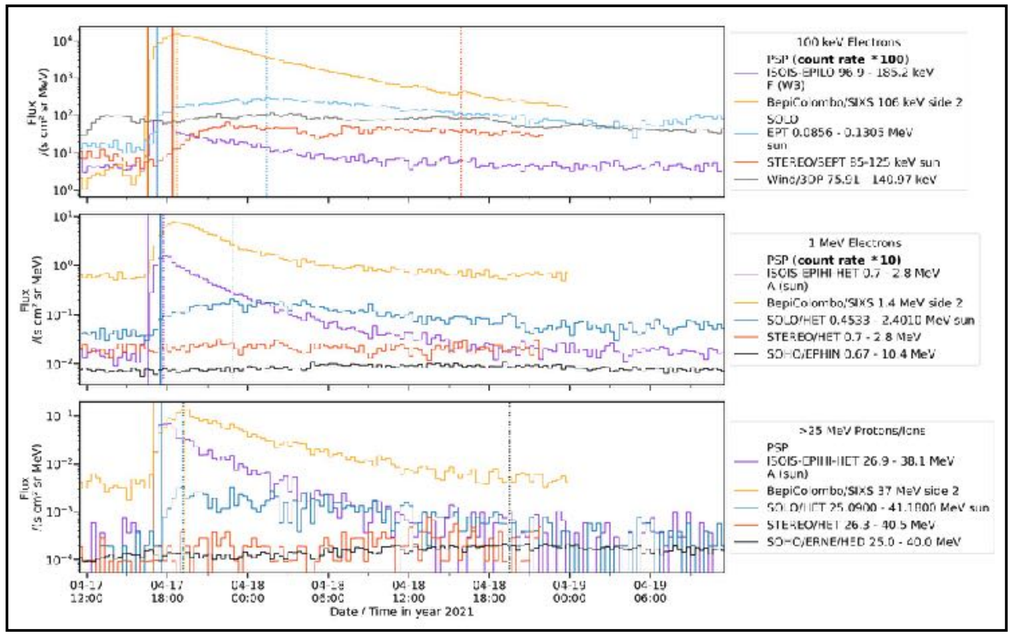
- SEP event analysis tools:
  - Dynamic spectra
  - Data loaders and SEP time series plots
  - SEP Onset analysis
  - Inferring the SEP injection time
    - Interactive Time Shift Analysis (TSA)
  - Spacecraft constellation plotter tool Solar-MACH

- **Cycle 25 multi-spacecraft SEP event catalog**

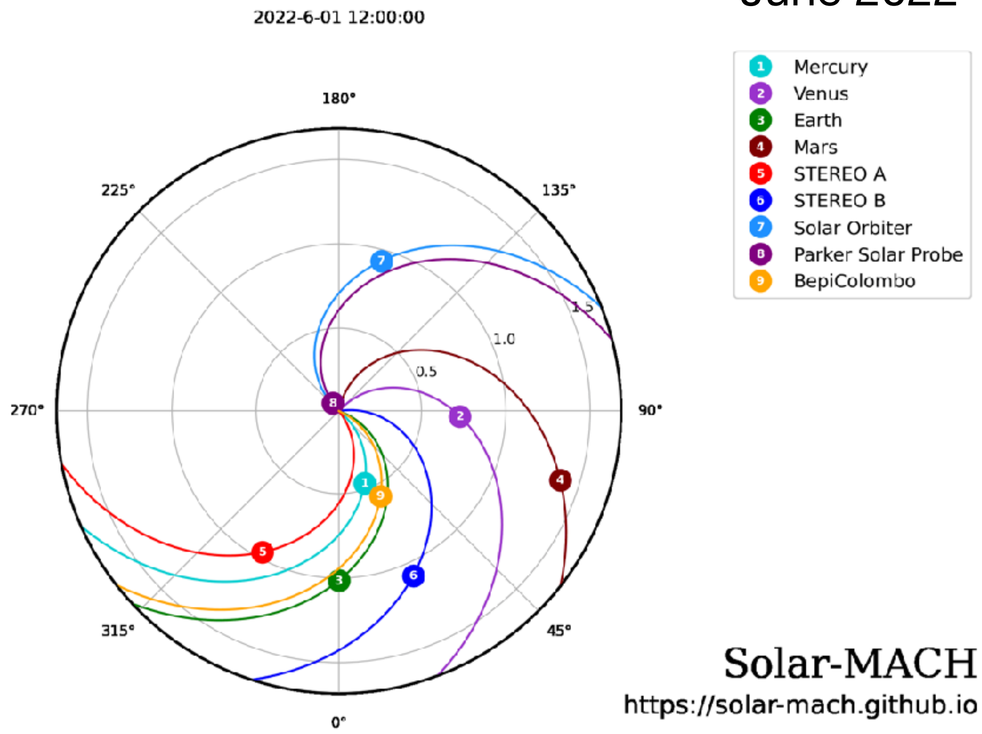
CYCLE 25 MULTI-SPACECRAFT SEP EVENT CATALOG

Multi-spacecraft catalog of large SEP events in solar cycle 25 (coming soon)

Contains all events with of >25 MeV protons at ≧ two observers



June 2022

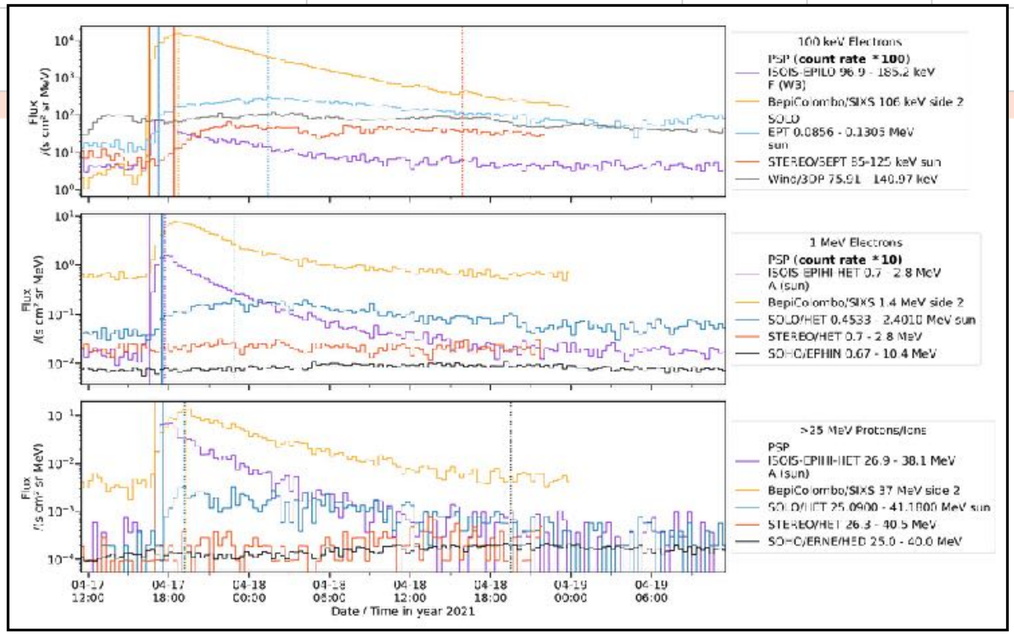


Solar-MACH
https://solar-mach.github.io

Future tool: Multi-spacecraft SEP plots

CYCLE 25 MULTI-SPACECRAFT SEP EVENT CATALOG

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	WP2		WP2	WP2		WP2			WP2							
2	Event number	Event identifier	Event start date (yyyy-mm-dd)	Science case ("")	Observer identifier	Observer	S/C distance (au)	S/C Carrington longitude (deg)	S/C Carrington latitude (deg)	Solar-MACH link	flare date (yyyy-mm-dd)	flare time (HH:MM:SS)	flare Carrington longitude	flare Carrington latitude	Goes class	Flare comments ("")
3																
5																
6	1	SEP-C25-0001	2020-11-29	"widespread event"	SEP-C25-0001-SOLO	SOLO	0,88	117	-5	https://share.streamlit.io/jgieseler/solar-mach?date=20201111&time=1330&bodies=STEREO+	2020-11-29	11:24:00	338	-20	C1.6	
7					SEP-C25-0001-PSP	PSP	0,81	259	4							
8					SEP-C25-0001-STA	STEREO-A	0,96	297	7							
9					SEP-C25-0001-WIND	Wind	0,99	355	1							
10					SEP-C25-0001-SOHO	SOHO	0,99	355	1							
11					SEP-C25-0001-BEPI	BepiColombo	0,83	91	-4							
12	2	SEP-C25-0003	2020-12-07	"PSP-STA, and STA-Earth similarily separated in longitude "		SOLO		12	-5	https://share.streamlit.io/jgieseler/solar-mach?date=20201207&time=1645&bodies=STEREO+A&bodies=Earth&bodies=BepiColombo&bodies=Parker+Solar+Probe&bodies=Solar+Orbiter&speeds=400&sp	2020-12-07	15:46:00	249	-25	C7.4	
13						PSP		150	4							
14						STEREO-A		192	6							
15						Wind		249	0							
16						SOHO		249	0							
17						BepiColombo		346	-4							



>25 MeV protons observed by at least 2 spacecraft

CYCLE 25 MULTI-SPACECRAFT SEP EVENT CATALOG

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	WP2		WP2	WP2		WP2			WP2							
2	Event number	Event identifier	Event start date (yyyy-mm-dd)	Science case ("")	Observer identifier	Observer	S/C distance (au)	S/C Carrington longitude (deg)	S/C Carrington latitude (deg)	Solar-MACH link	flare date (yyyy-mm-dd)	flare time (HH:MM:SS)	flare Carrington longitude	flare Carrington latitude	Goes class	Flare comments ("")
3																
5																
6	1	SEP-C25-0001	2020-11-29	"widespread event"	SEP-C25-0001-SOLO	SOLO	0,88	117	-5	https://share.streamlit.io/jgieseler/solar-mach?date=20201111&time=1330&bodies=STEREO+	2020-11-29	11:24:00	338	-20	C1.6	
7					SEP-C25-0001-PSP	PSP	0,81	259	4							
8					SEP-C25-0001-STA	STEREO-A	0,96	297	7							
9					SEP-C25-0001-WIND	Wind	0,99	355	1							
10					SEP-C25-0001-SOHO	SOHO	0,99	355	1							
11					SEP-C25-0001-BEPI	BepiColombo	0,83	91	-4							
12	2	SEP-C25-0003	2020-12-07	"PSP-STA, and STA-Earth similarily separated in longitude "		SOLO		12	-5	https://share.streamlit.io/jgieseler/solar-mach?date=20201207&time=1645&bodies=STEREO+A&bodies=Earth&bodies=BepiColombo&bodies=Parker+Solar+Probe&bodies=Solar+Orbiter&speeds=400&sp	2020-12-07	15:46:00	249	-25	C7.4	
13						PSP		150	4							
14						STEREO-A		192	6							
15						Wind		249	0							
16						SOHO		249	0							
17						BepiColombo		346	-4							

Onset date (yyyy-mm-dd)	Onset time (HH:MM:SS)	Averaging used for onset (min)	Sector used for onset ("")	Peak date (yyyy-mm-dd)	Peak time (HH:MM:SS)	Peak flux	Averaging used for peak (min)	Sector used for peak ("")	Inferred injection time (HH:MM:SS)	Pathlength used for inferred injection time (au)	proton event comment ("")

Parameters provided for: 25 MeV protons, 1 MeV electrons, and 100 keV electrons

CYCLE 25 MULTI-SPACECRAFT SEP EVENT CATALOG

	A	B	C	D	E	F	G	H	I	
1	WP2		WP2	WP2		WP2			WP2	
2	Event number	Event identifier	Event start date (yyyy-mm-dd)	Science case ("")	Observer identifier	Observer	S/C distance (au)	S/C Carrington longitude (deg)	S/C Carrington latitude (deg)	Solar-MACH link
3										
5										
6	1	SEP-C25-0001	2020-11-29	"widespread event"	SEP-C25-0001-SOLO	SOLO	0,88	117	-5	https://share.streamli mach?date=2020111
7					SEP-C25-0001-PSP	PSP	0,81	259	4	
8					SEP-C25-0001-STA	STEREO-A	0,96	297	7	
9					SEP-C25-0001-WIND	Wind	0,99	355	1	
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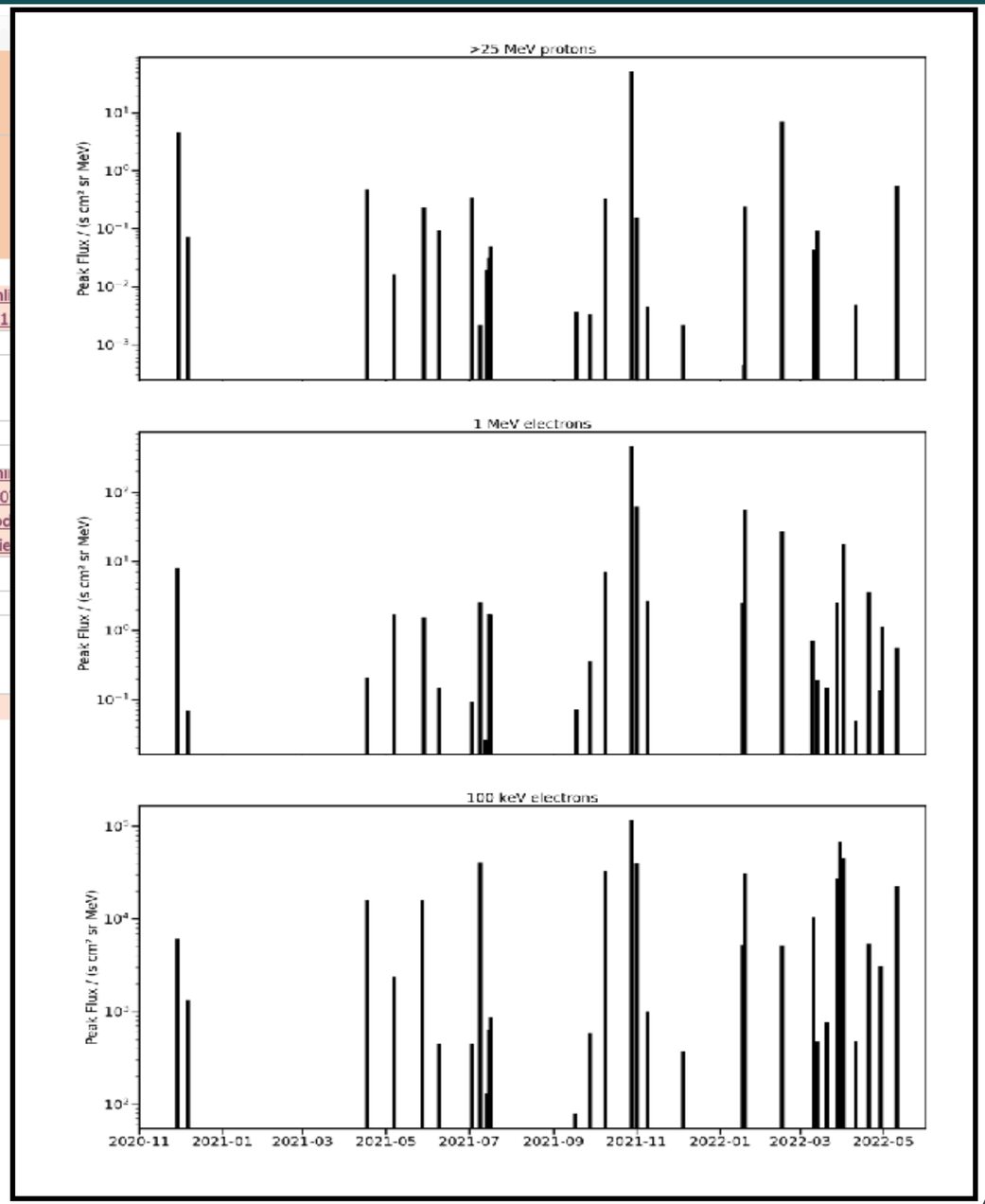
12	2	SEP-C25-0003	2020-12-07	"PSP-STA, and STA-Earth similarily separated in longitude "		SOLO		12	-5	https://share.streamli mach?date=2020120 A&bodies=Earth&boc r+Solar+Probe&bodie
13						PSP		150	4	
14						STEREO-A		192	6	
15						Wind		249	0	
16						SOHO		249	0	
17						BepiColombo		346	-4	

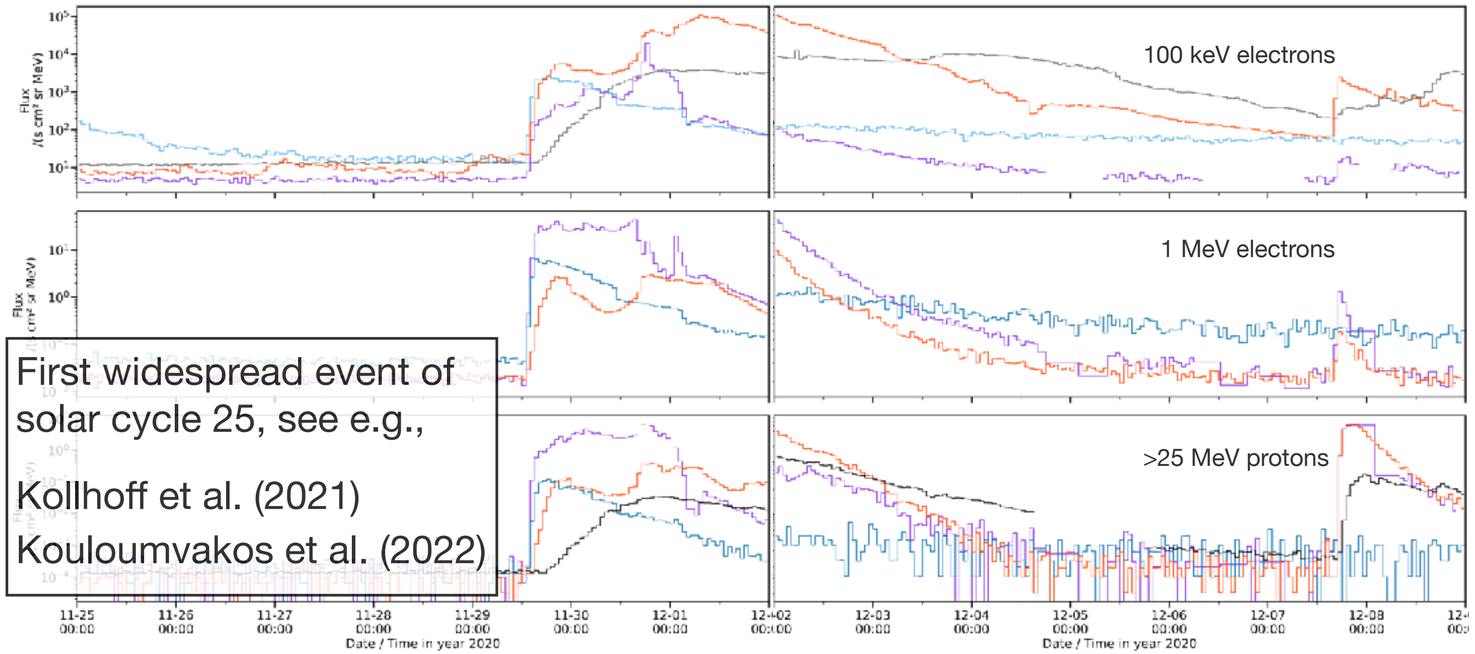


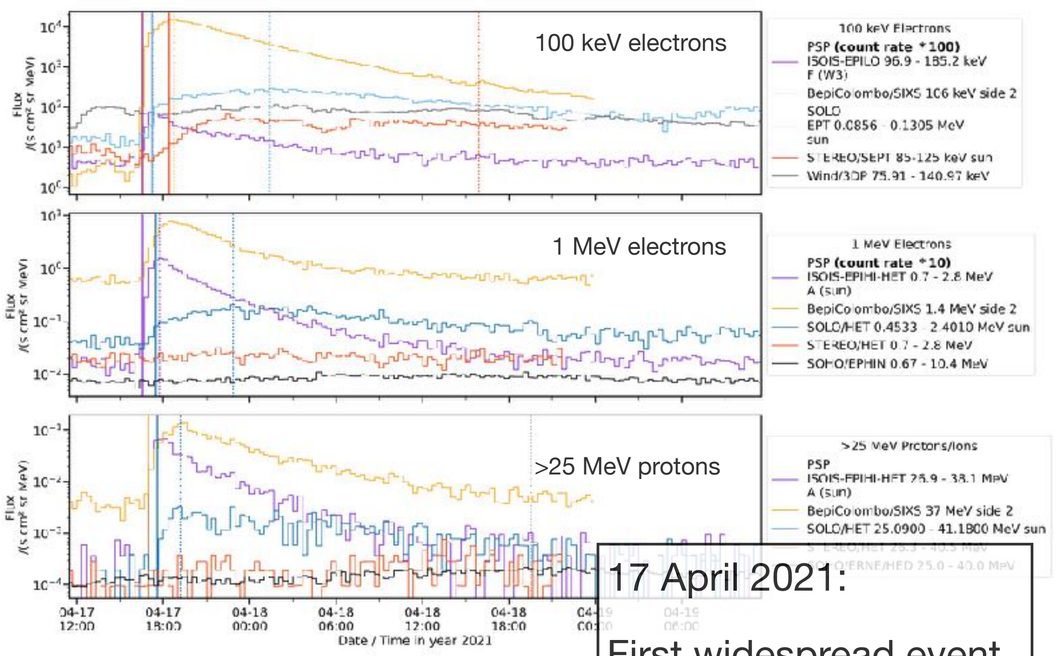
Solar activity picked up

33 Events until June 13 2022

23 events until March 14 (Version one of the list)

> 25 MEV PROTON EVENTS OF SOLAR CYCLE 25





First widespread event of solar cycle 25, see e.g.,

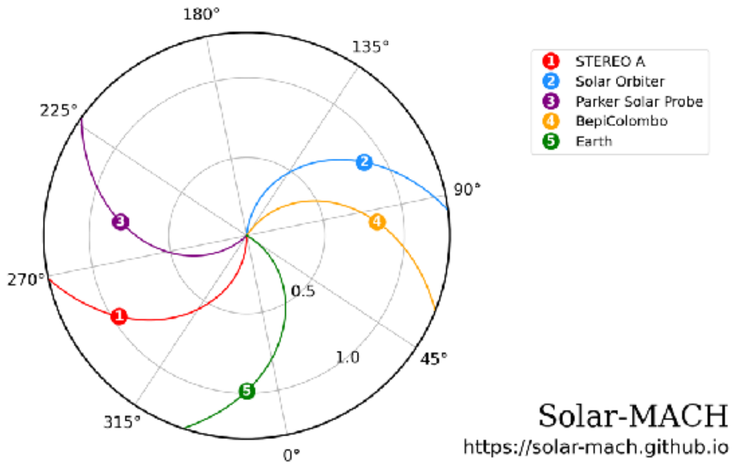
Kollhoff et al. (2021)

Kouloumvakos et al. (2022)

17 April 2021:

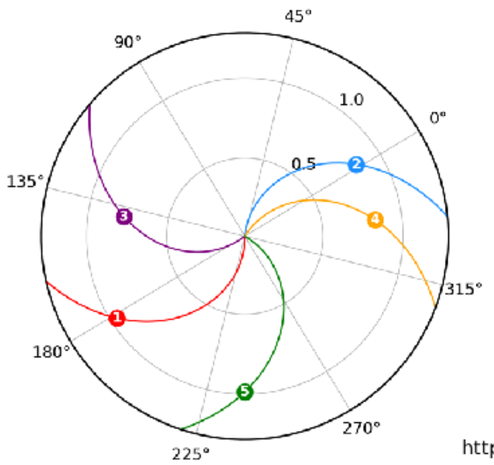
First widespread event observed with 5 well-separated observers!

2020-11-29 11:30

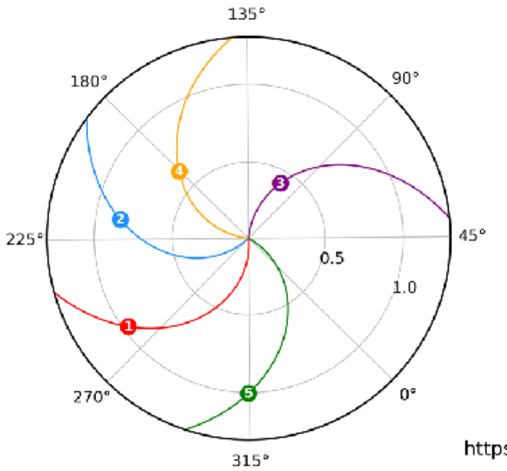


Solar-MACH
https://solar-mach.github.io

2020-12-07 19:15



2021-04-17 16:00



Solar-MACH
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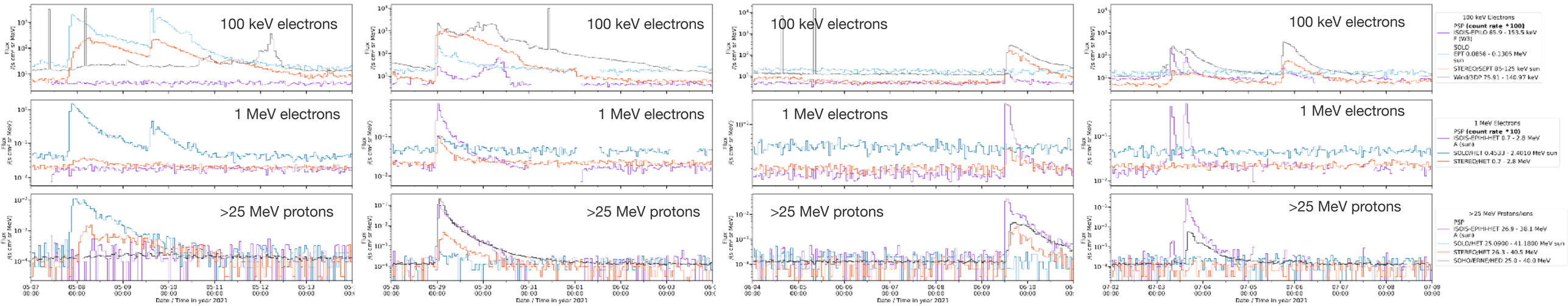
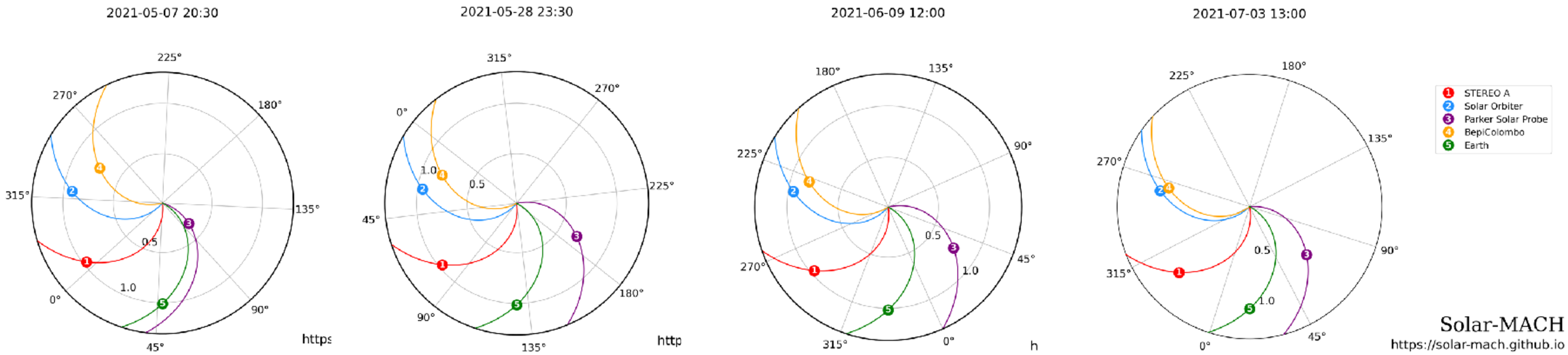
> 25 MEV PROTON EVENTS OF SOLAR CYCLE 25

Energetic ‘short’ duration events





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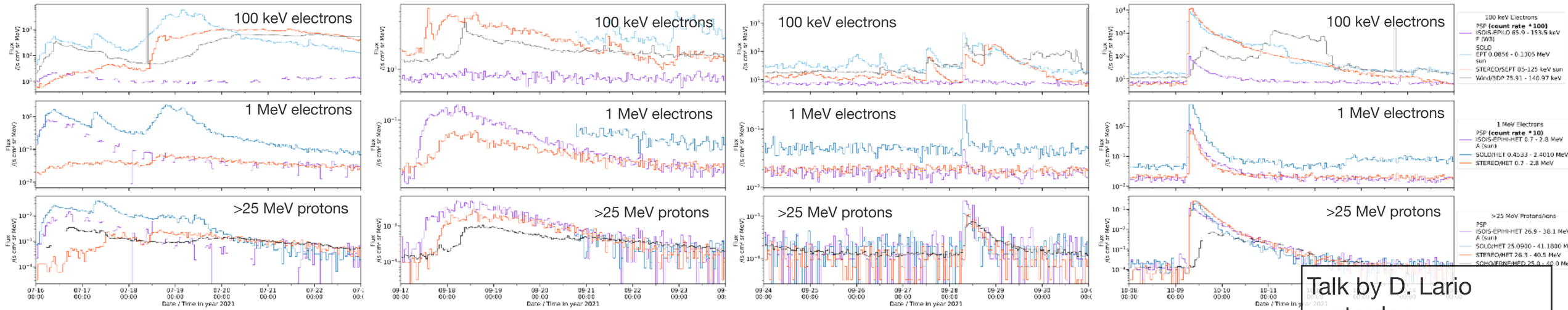


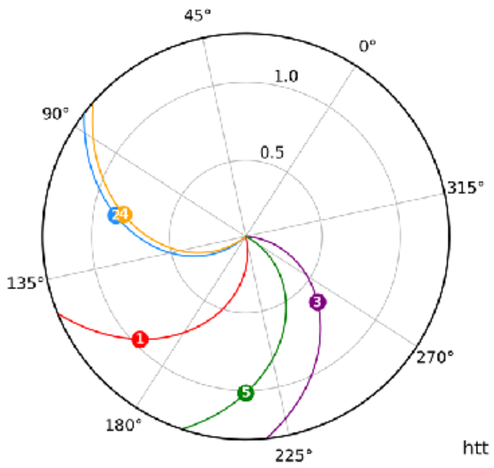
Consecutive / mixing events

closely spaced observers

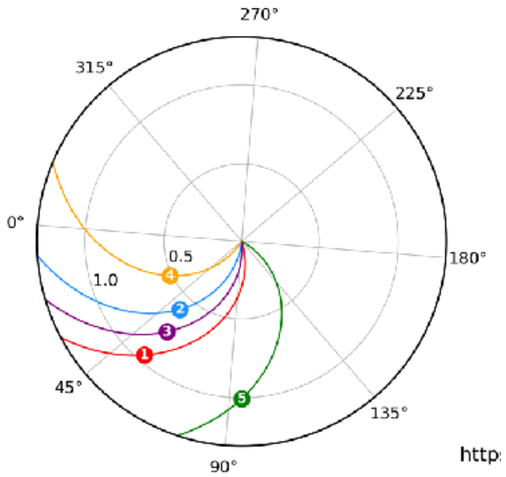
Talk by D. Lario yesterday

Talk by N. Wijsen today

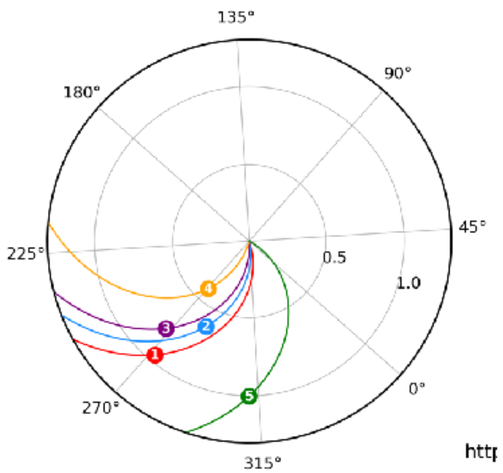
2021-07-16 00:00



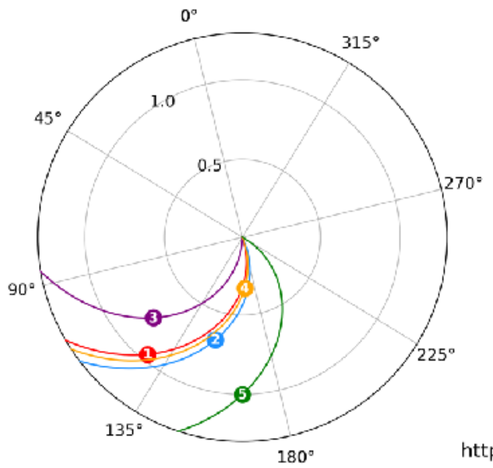
2021-09-17 10:00



2021-09-28 06:00



2021-10-09 06:00



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

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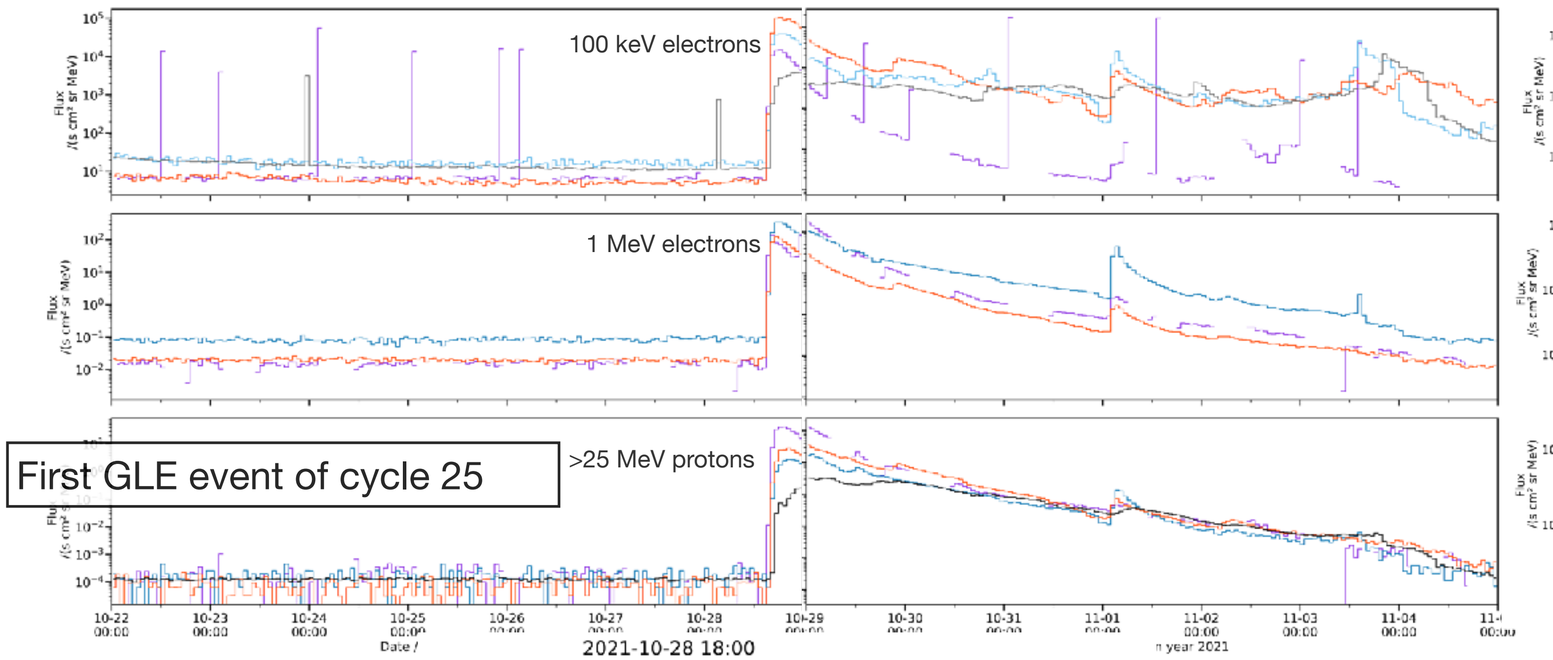
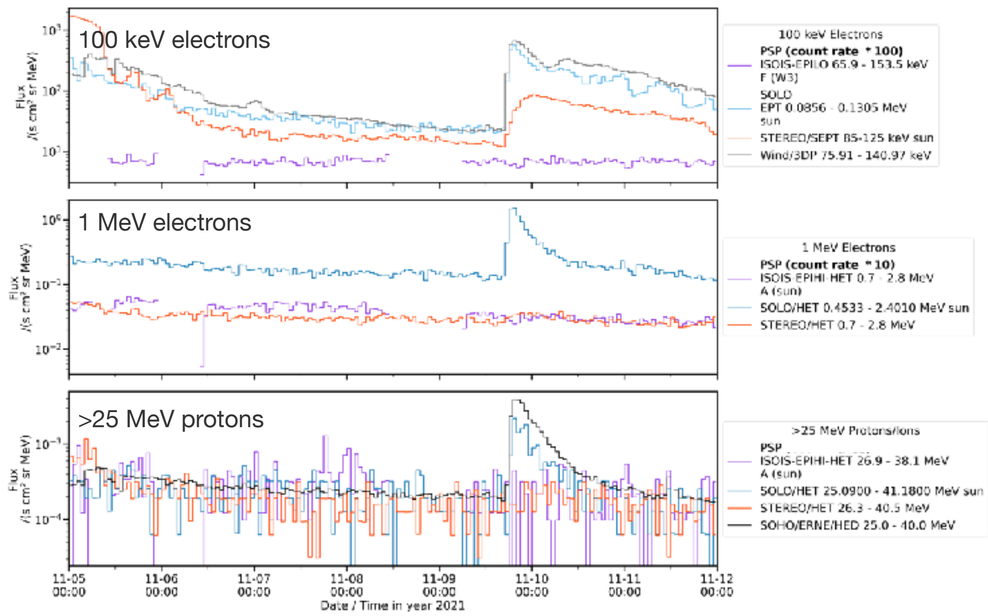
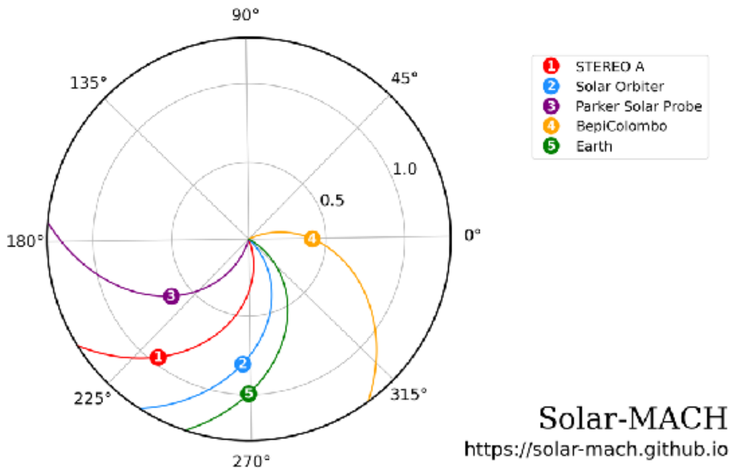


First GLE event of cycle 25

2021-10-28 18:00

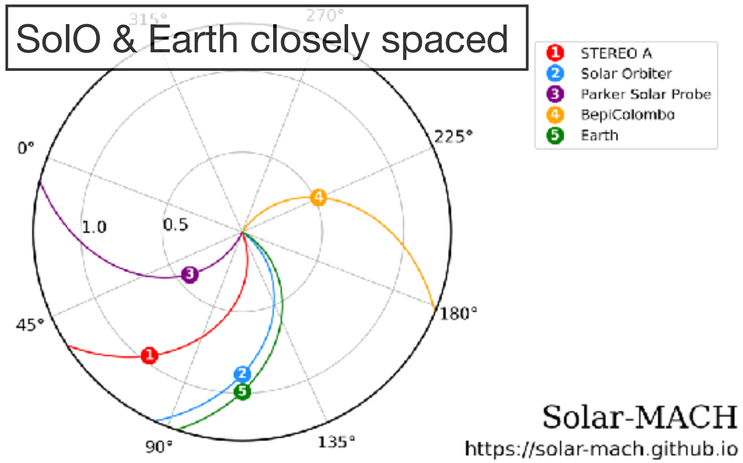


2021-11-09 18:00



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

SolO & Earth closely spaced



Solar-MACH
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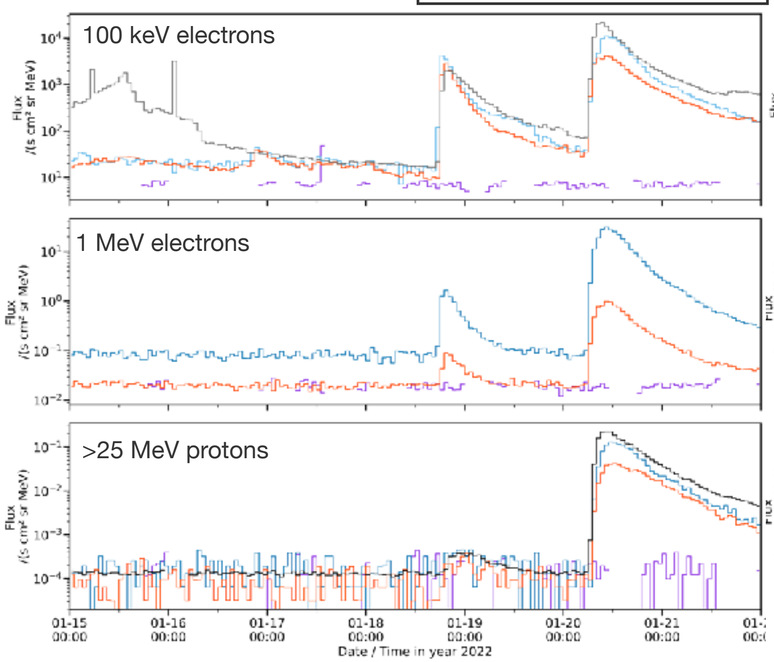
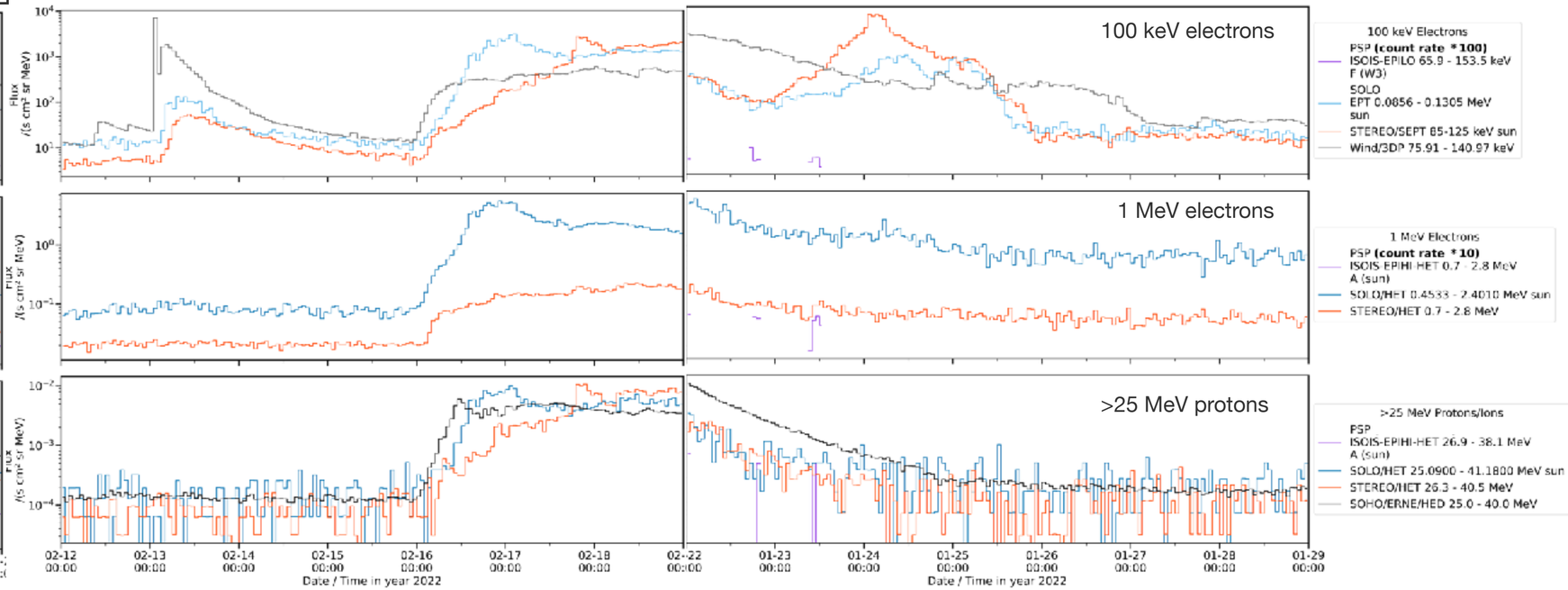
> 25 MEV PROTON EVENTS OF SOLAR CYCLE 25

Short-lasting event



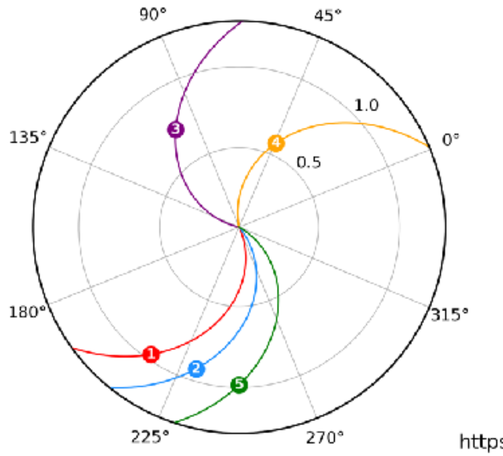
2022-01-20 08:00

Long-lasting event



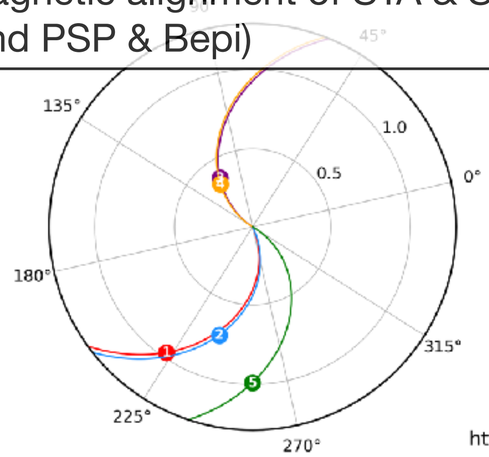
2022-02-15 23:00

Magnetic alignment of STA & SolO (and PSP & Bepi)



1 STEREO A
2 Solar Orbiter
3 Parker Solar Probe
4 BepiColombo
5 Earth

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



1 STEREO A
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5 Earth

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

SUMMARY

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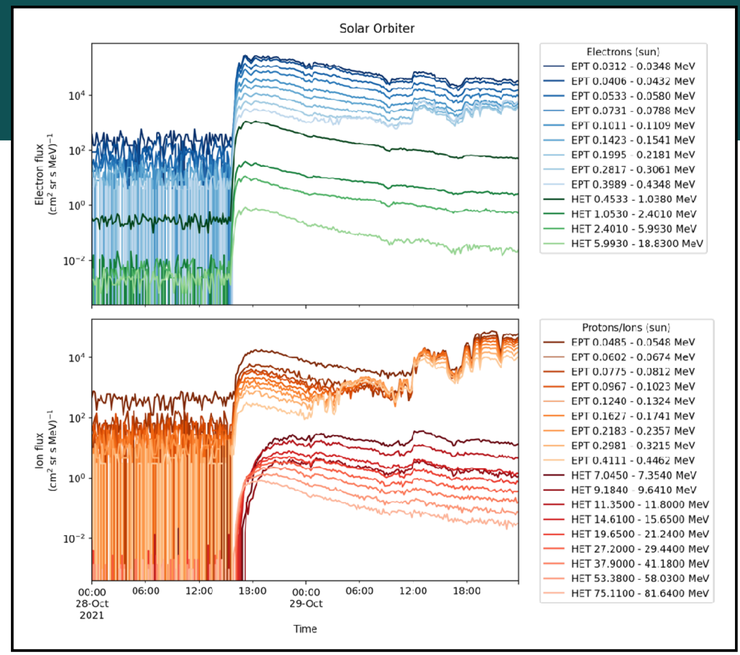
  - **SEP data loaders & advanced time series plots**
  - SEP dynamic spectrogram plots
  - SEP onset determination
  - Interactive time shift analysis
  - Solar-MACH spacecraft configuration plotter and PFSS extension



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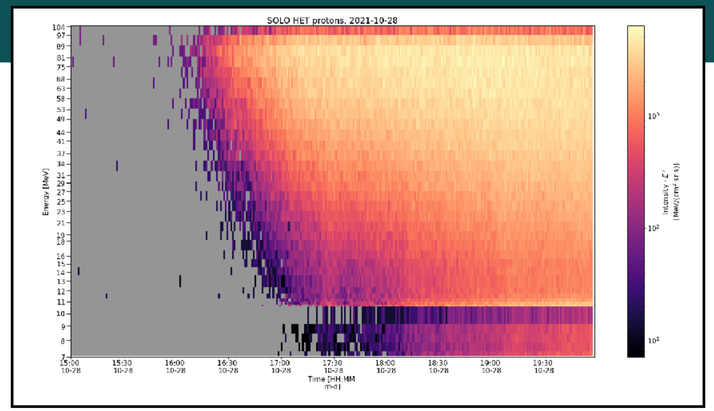

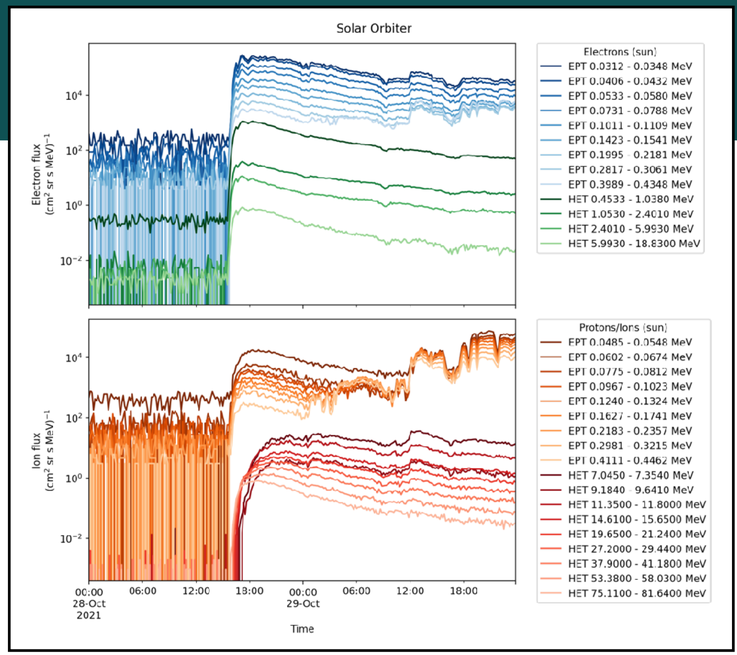

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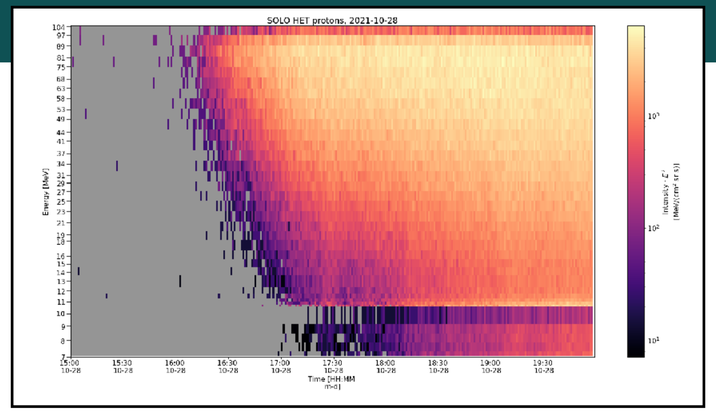
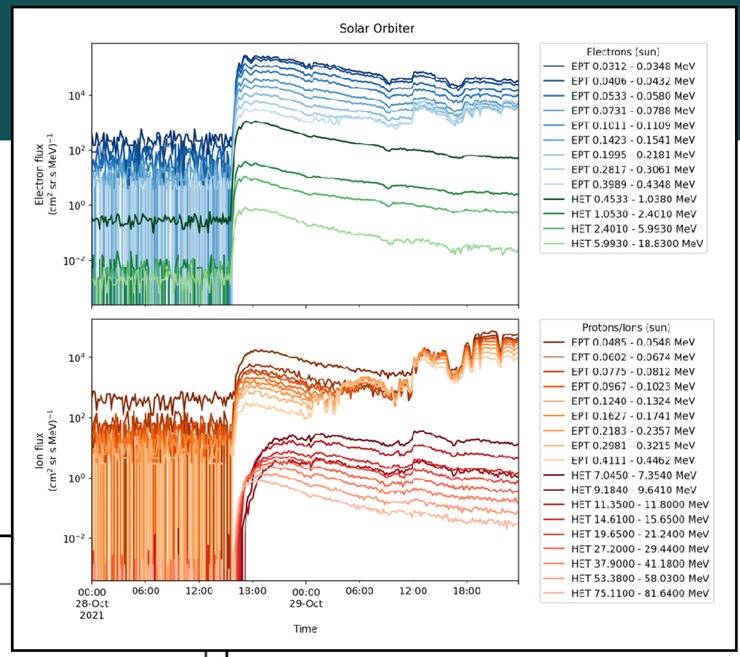
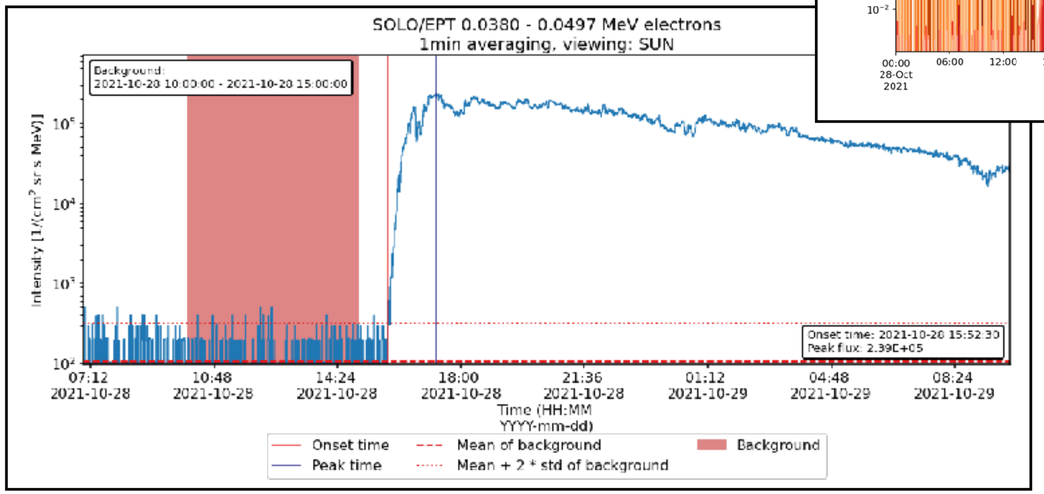
  - **SEP onset determination**
  - Interactive time shift analysis
  - Solar-MACH spacecraft configuration plotter and PFSS extension







SUMMARY

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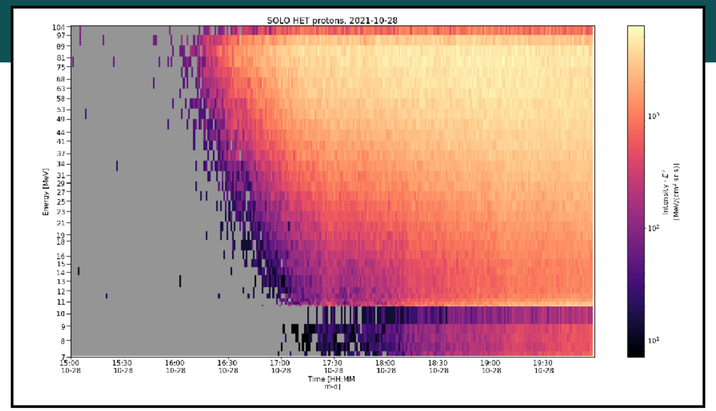

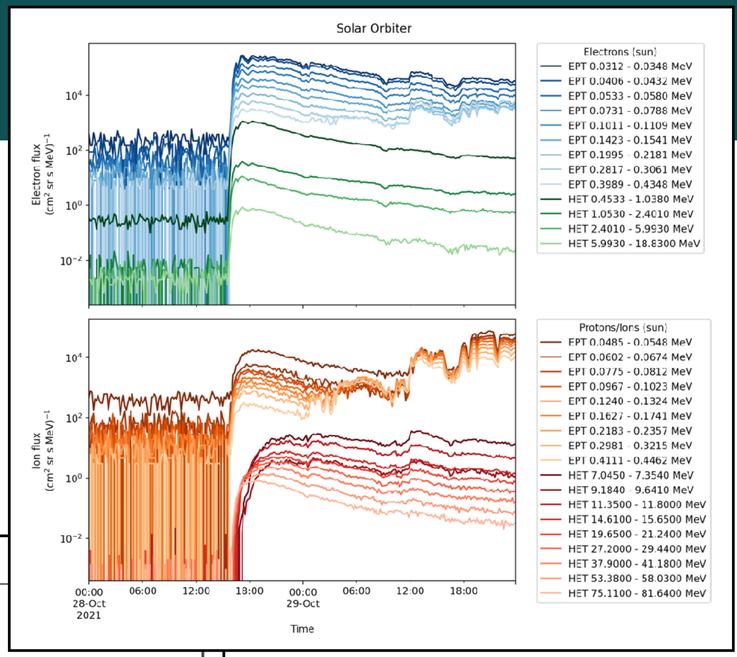

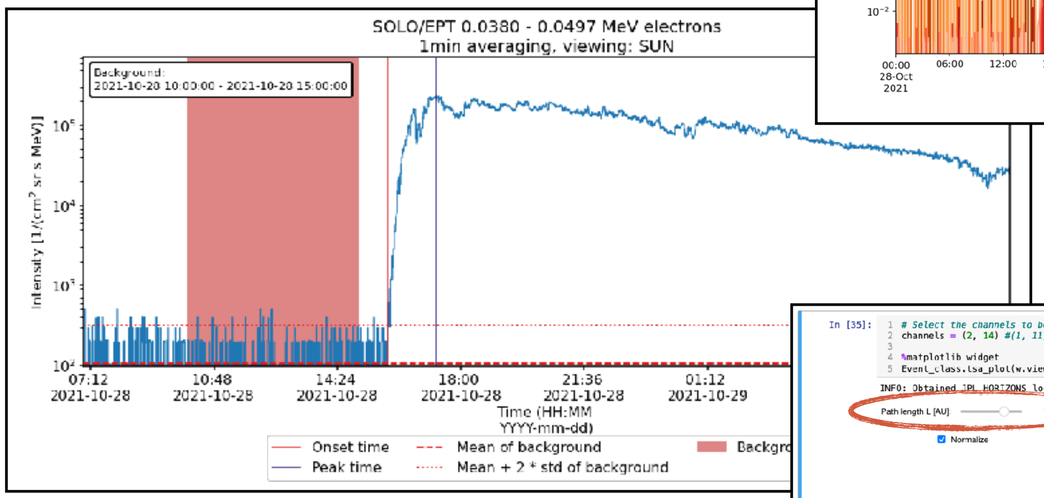

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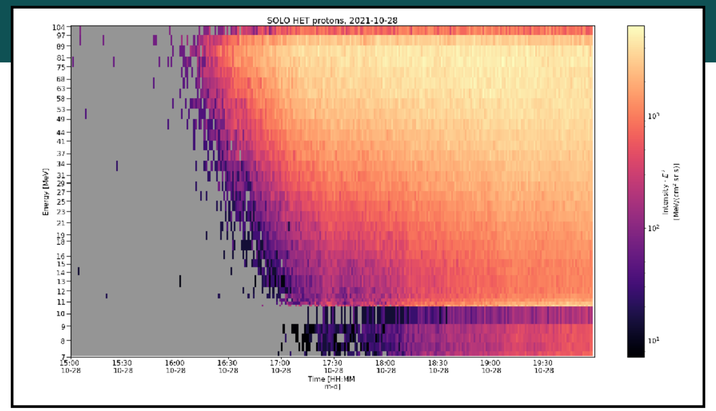
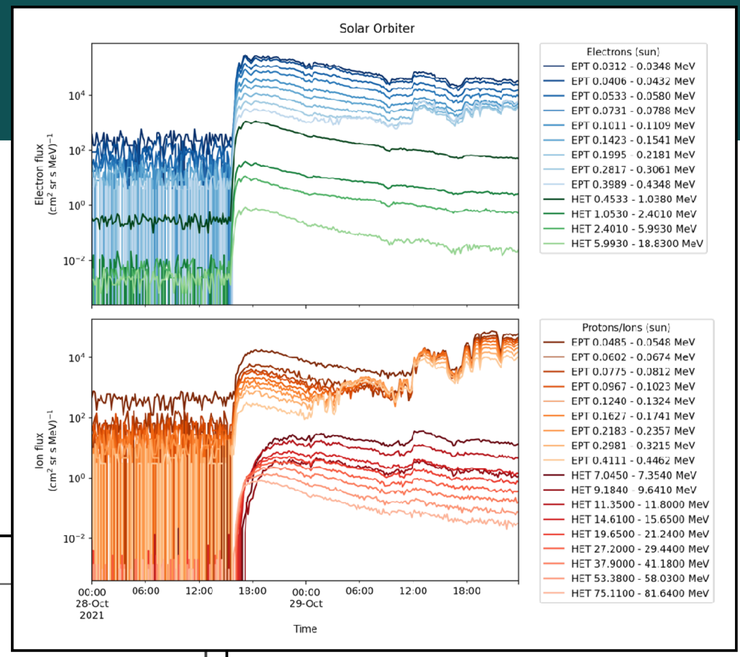
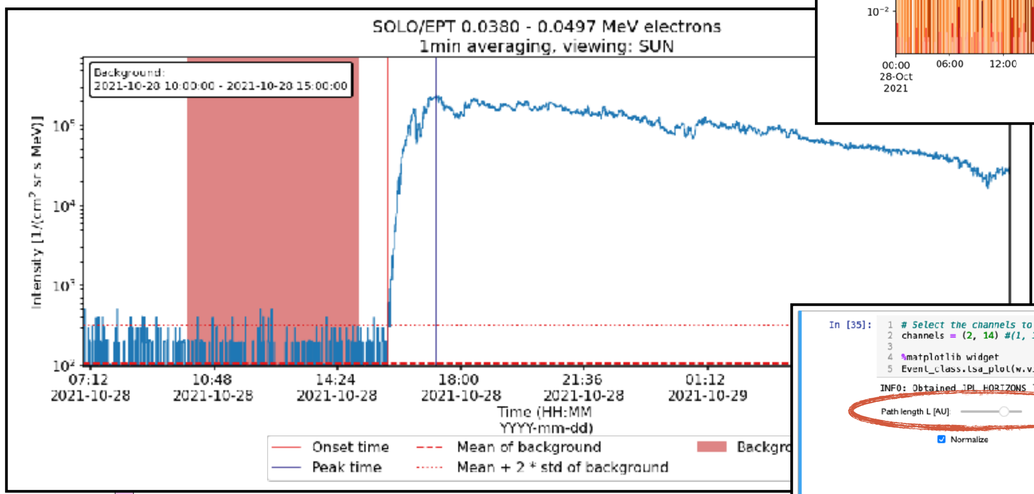
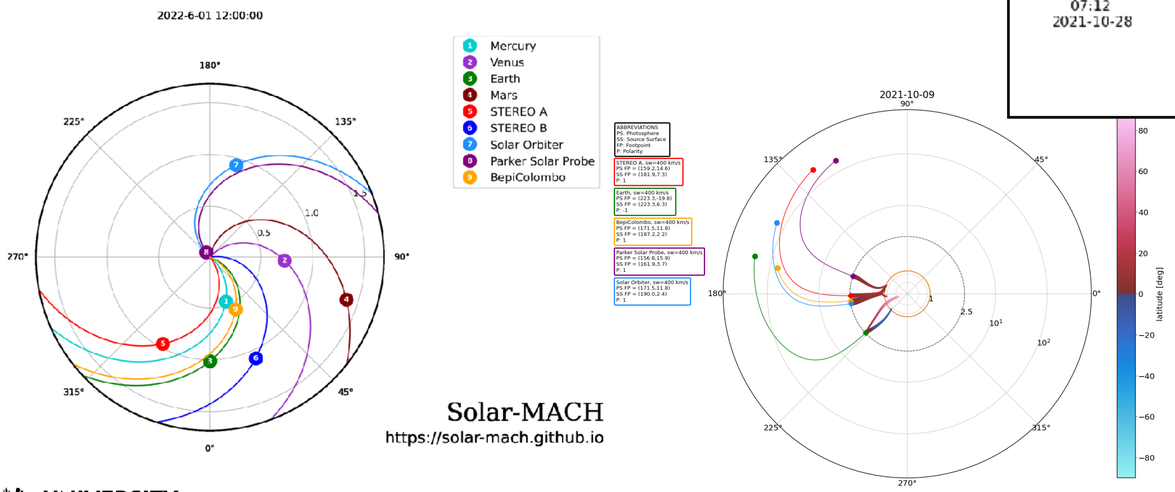




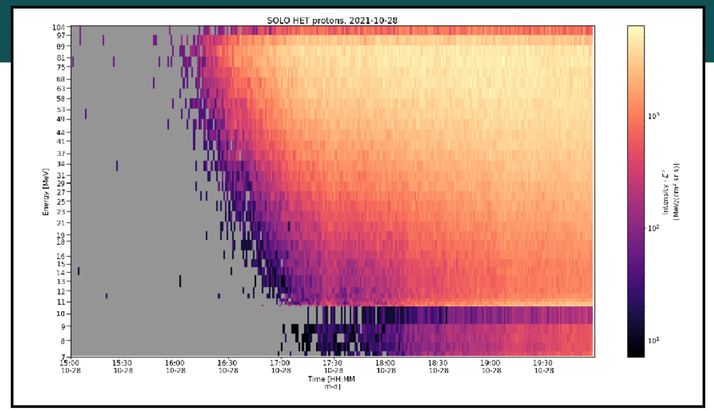


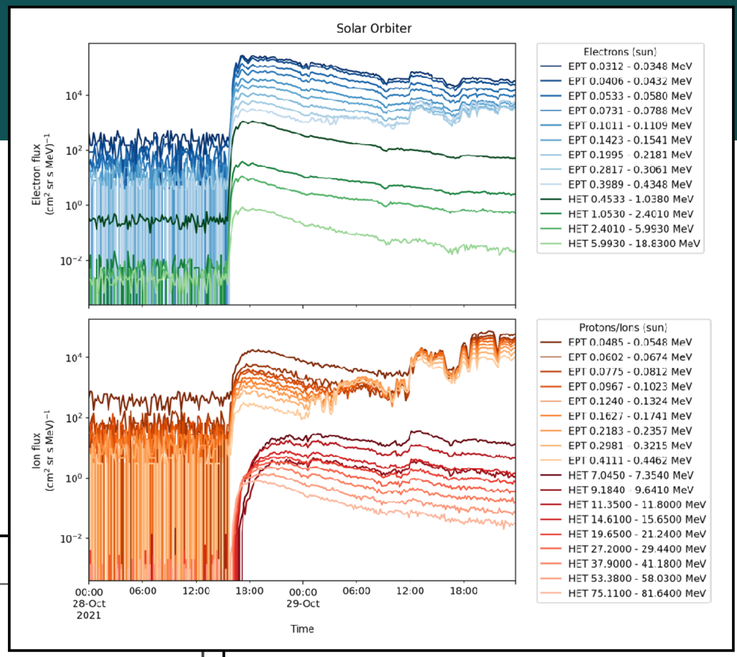


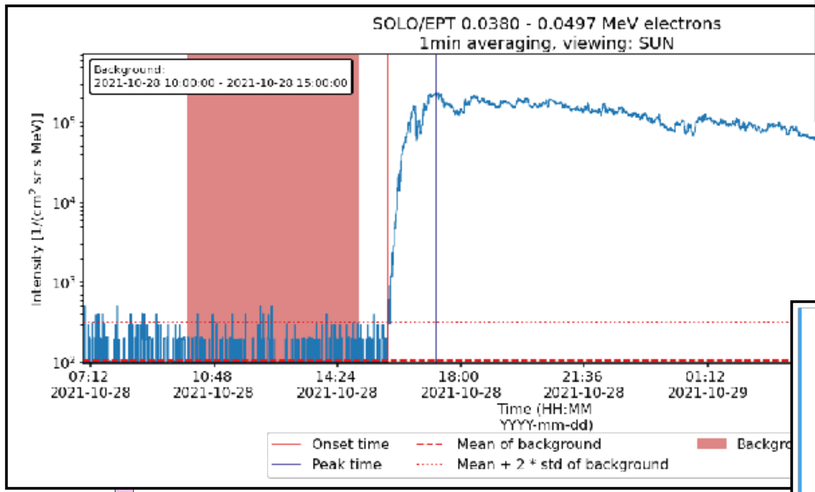
UNIVERSITY OF TURKU
Nina Dresing

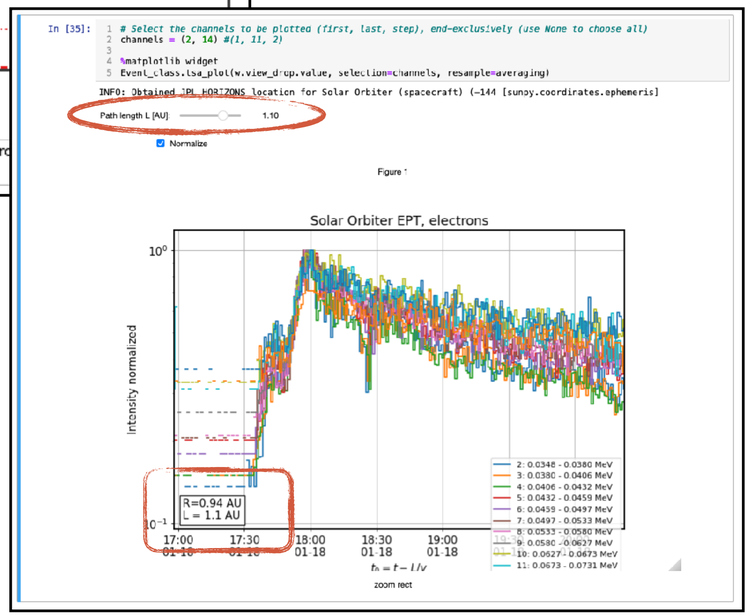
SUMMARY

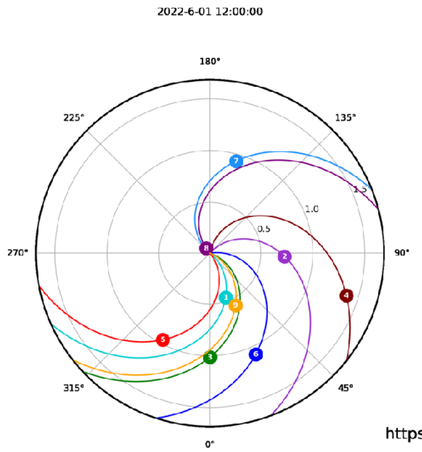
- Disclaimer: this is not high-level software ;-)
- We are looking forward to feedback!
- Please let us know if run into problems using the tools!

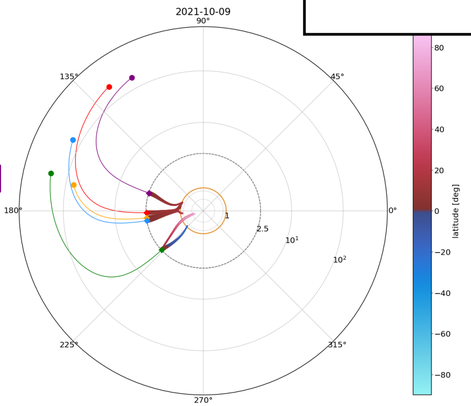












Solar-MACH
https://solar-mach.github.io