Leibniz-Institut für
Astrophysik Potsdam

AIP

DLR

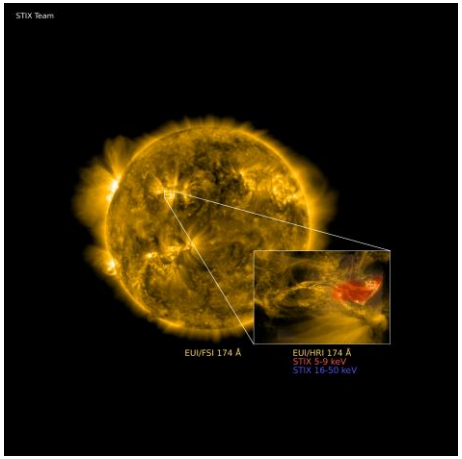
Combining in-situ and remote-sensing data from Solar Orbiter to study particle acceleration and transport in the heliosphere

Alexander Warmuth
and the joint STIX-EPD-EUI-RPW-Metis-SoloHI working group

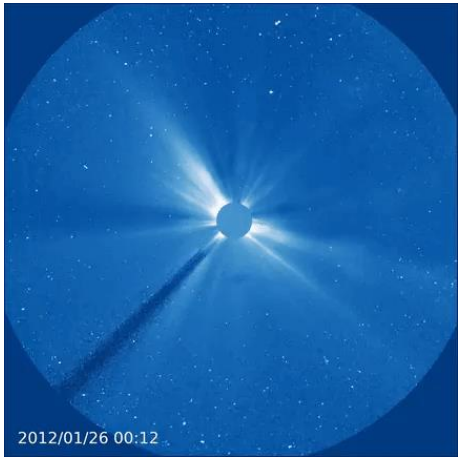
Solar Orbiter Community Building Webinar – 5 March 2025

Energetic particles on the Sun and in the heliosphere

- our Sun is the most energetic particle accelerator in the solar system
- energetic particles (ions and electrons) precipitate onto Sun and are injected into space
- acceleration in flares (magnetic reconnection) and CME-driven shock waves
- Solar Energetic Electrons (SEEs):
  - can be detected in-situ as well as remotely (hard X-rays and radio)
  - however: many open questions

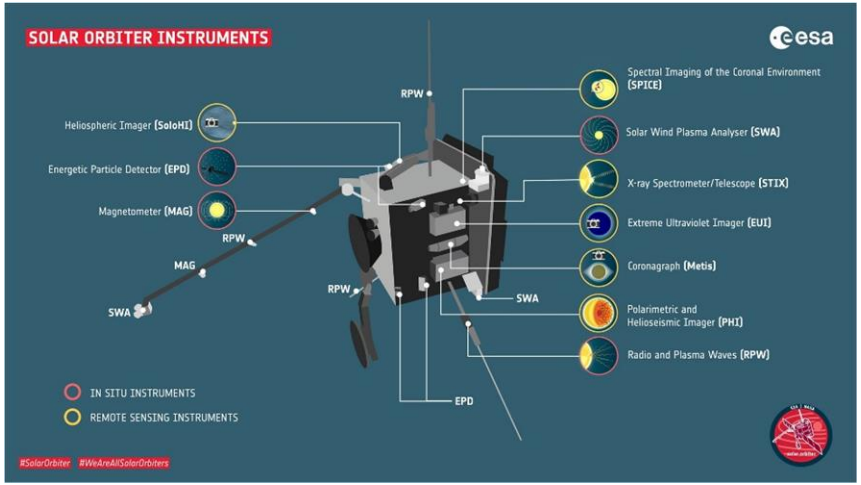


(ESA)



(ESA)

Solar Orbiter‘s unique capabilities: linking the Sun to the heliosphere



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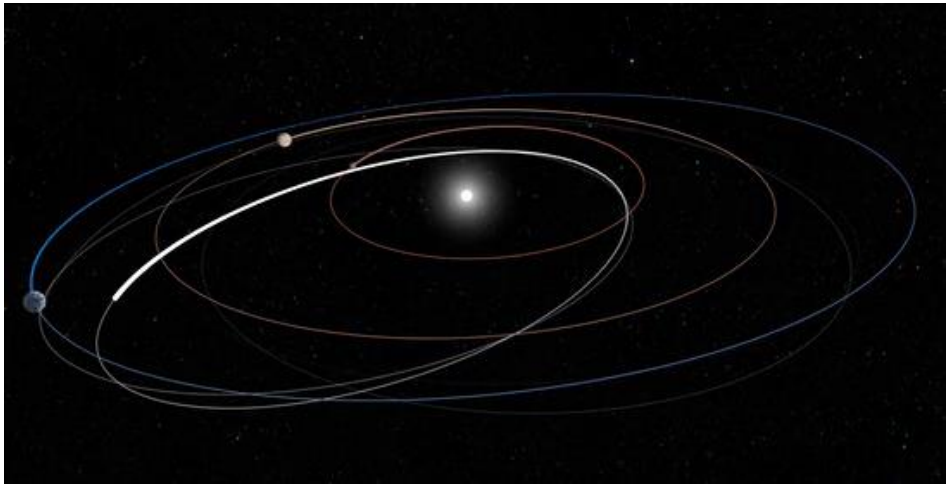
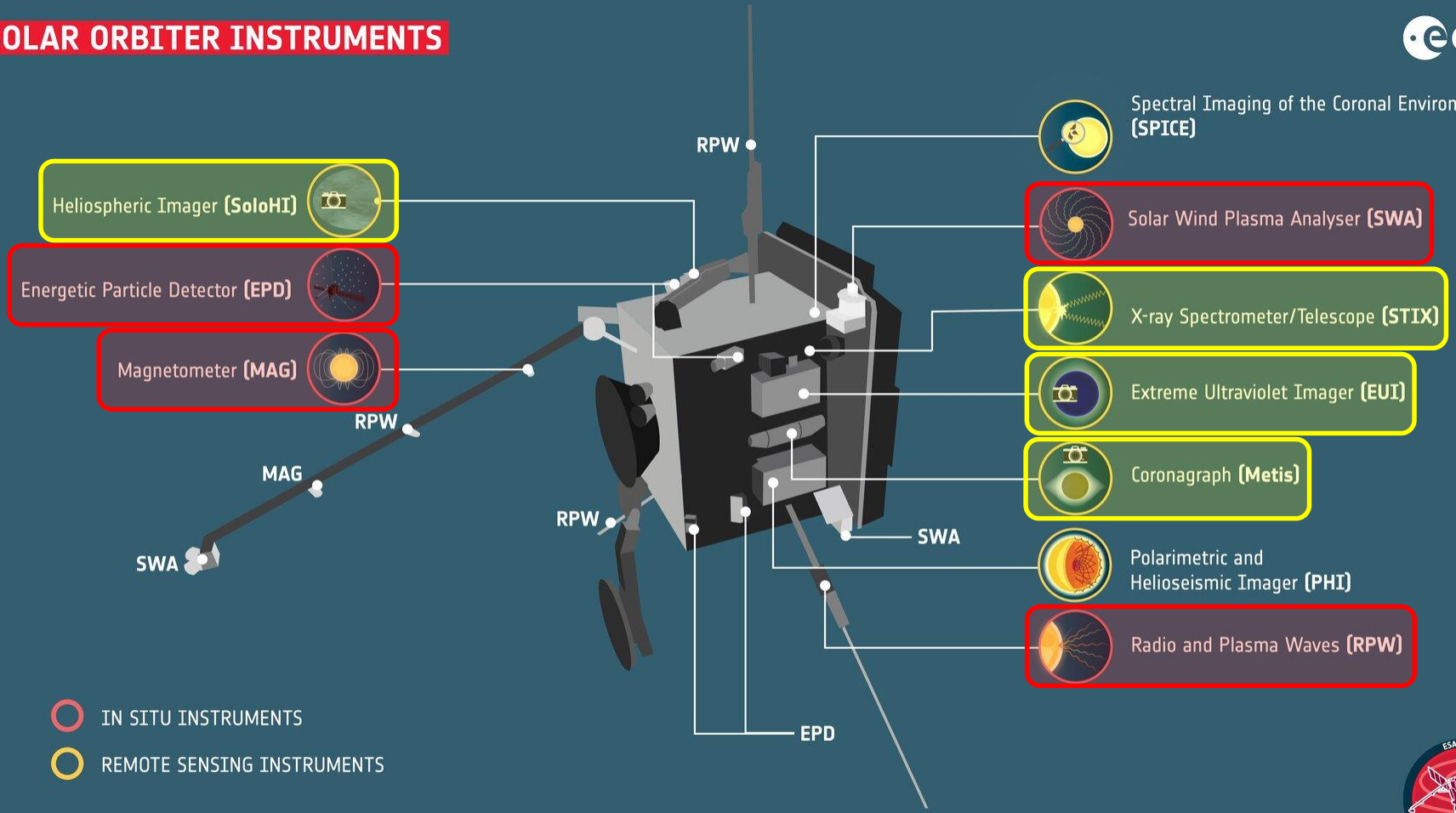


(ESA)

- combining remote-sensing and in-situ observations
- sampling different locations in the inner heliosphere

SOLAR ORBITER INSTRUMENTS



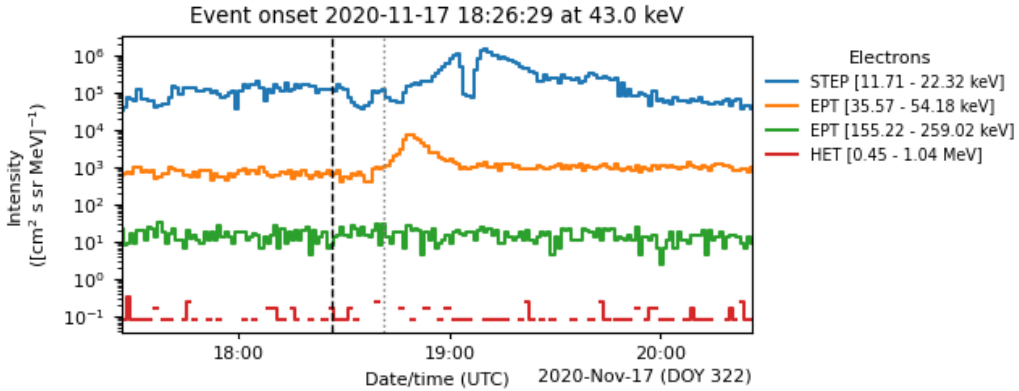
#SolarOrbiter #WeAreAllSolarOrbiters

Joint working group

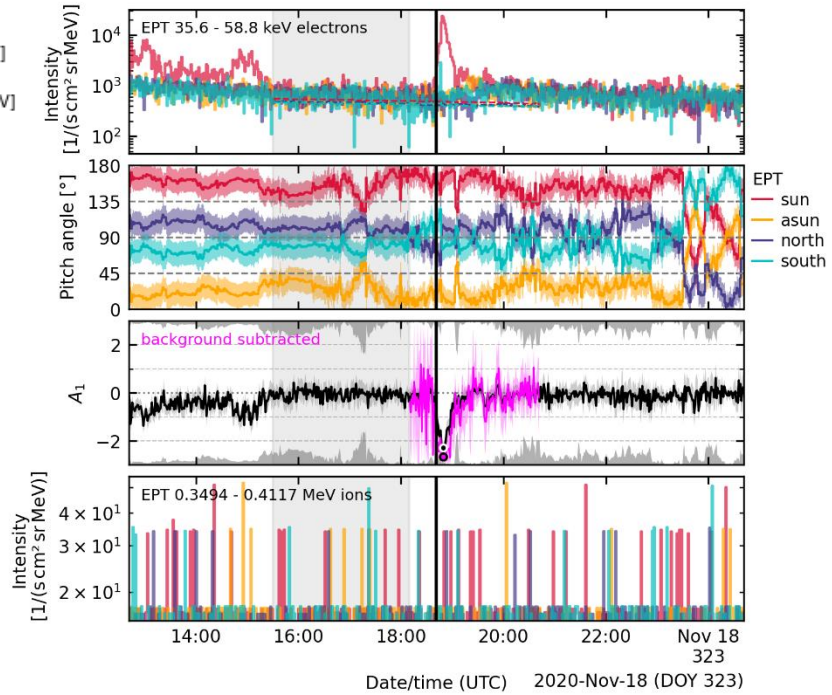

- compile comprehensive event catalogue of all SEEs recorded by EPD and associated solar events
- conduct statistical studies of SEEs
- members:

Frederic Schuller, Song Tan, Jake Mitchell, Raúl Gómez Herrero, Ignacio Cernuda, Fernando Carcaboso, Daniel Pacheco, Javier Rodríguez-Pacheco, Glenn Mason, Nina Dresing, Annamaria Fedeli, Aleksi Yli-Laurila, Robert Wimmer-Schweingruber, Alexander Kollhoff, Sebastian Fleth, Sam Krucker, Andrea Battaglia, Hannah Collier, Sophie Musset, Laura Rodríguez-García, Matthieu Kretzschmar, Nicole Vilmer, David Paipa, Milan Maksimovic, Antonio Vecchio, Krzysztof Barczynski, Luciano Rodriguez, Daria Shukhobodskaia, Manon Jarry, Alexis Rouillard, Radoslav Bucik, George C. Ho, David Lario, Karl-Ludwig Klein, Frederic Effenberger, Vratislav Krupar, Oleksiy Dudnik, Hamish Reid, Camille Lorfing, Xu Zigong, Silvio Giordano, Catia Grimani, Federico Landini, Giuliana Russano, Clementina Sasso, Marco Romoli

Measuring solar energetic electrons with the Energetic Particle Detector (EPD)



(R. Gómez-Herrero/EPD team)

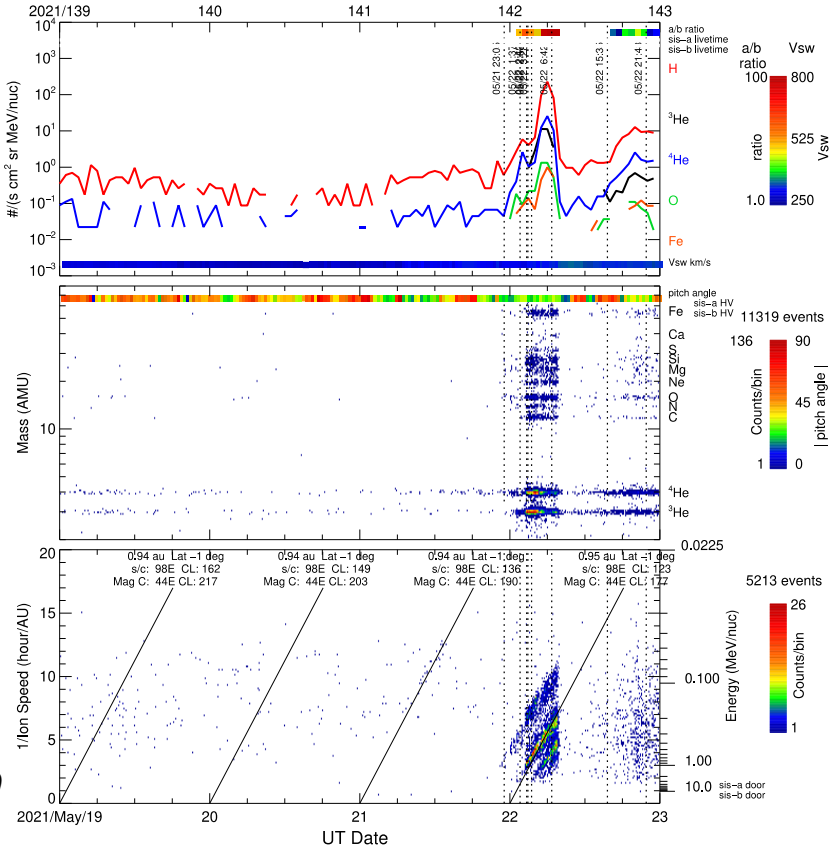


(N. Dresing/EPD team)

- covers electrons in range 2 keV – 80 MeV (STEP, EPT, HET)
- constrains anisotropy (EPT)
- measures composition of ions (SIS)

Measuring the composition of associated energetic ions

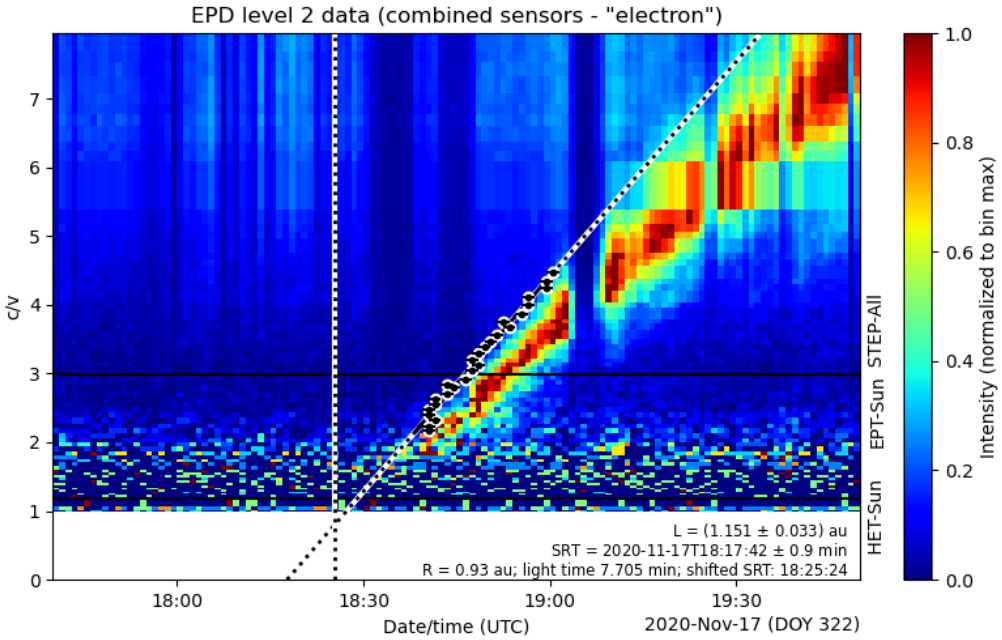
- ion composition measured by EPD/SIS
- impulsive events:
  - enriched in ^{3}He and Fe
  - reconnection-related
- gradual events:
  - no significant enhancements
  - shock-related



(G. Mason/EPD-SIS team)

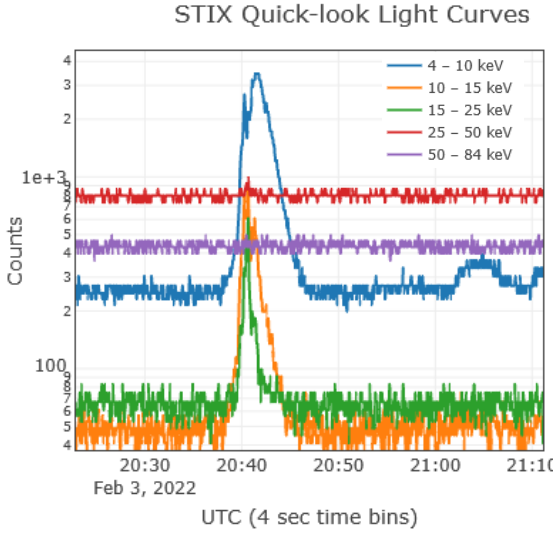
Inferring SEE injection times at the Sun with EPD

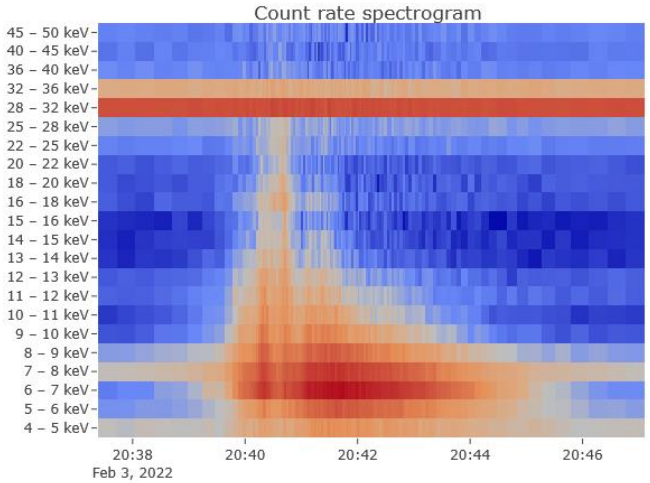
- Time-shift analysis (TSA):
  - use single energy channel
  - assume propagation along Parker spiral
- Velocity dispersion analysis (VDA):
  - assume simultaneous acceleration
  - fit onset times at many energy channels
  - obtain injection time and path length

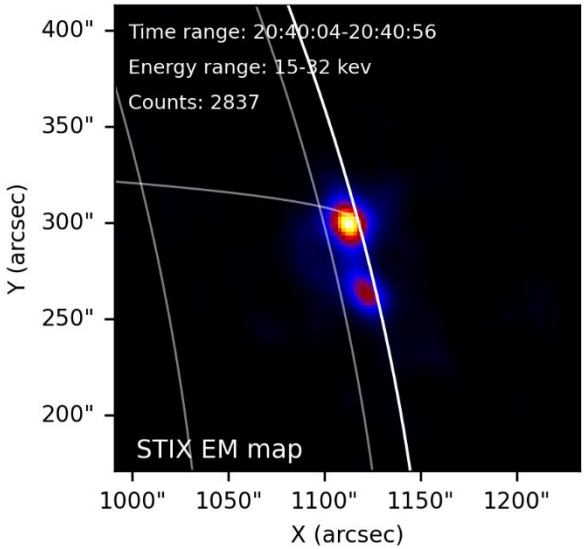


(R. Gómez-Herrero/EPD team)

Observing solar flares with the Spectrometer/Telescope for Imaging X-rays (STIX)



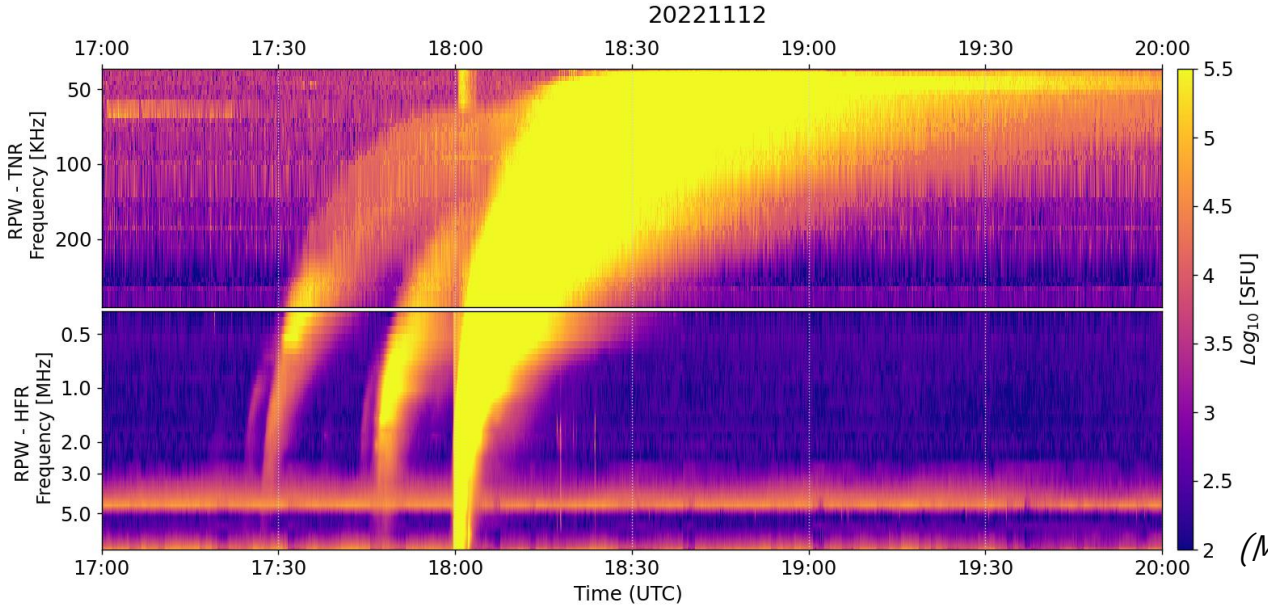




(STIX team)

- imaging spectroscopy in hard X-rays (4-150 kev)
- constrains thermal plasma and energetic electrons
- quick-look lightcurves, spectrograms, images

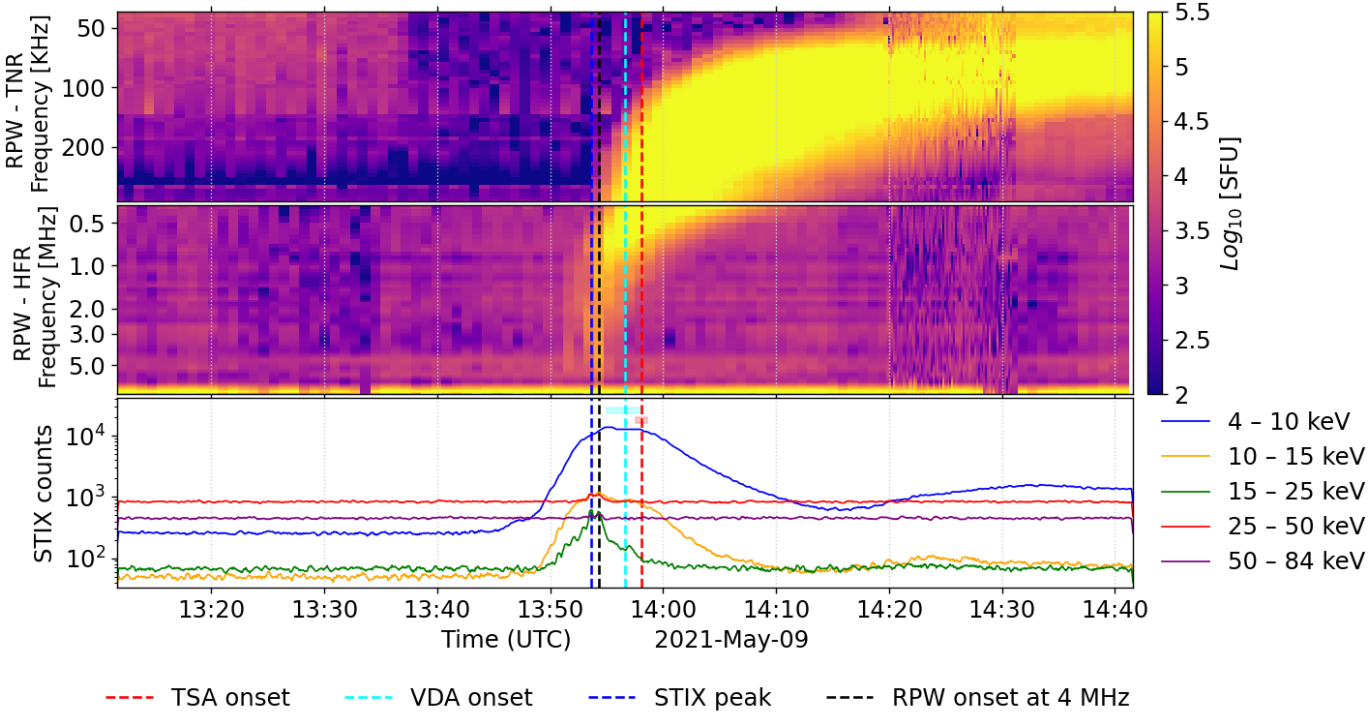
Observing solar radio bursts with the Radio and Plasma Wave instrument (RPW)



(M. Kretzschmar/RPW team)

- dynamic radiospectra from 16 MHz down to 4 kHz (corona to IP space)
- type III bursts trace propagation of energetic electron beams
- type II burst are signatures of shock waves

Associating SEE events with STIX X-ray flares and RPW type III bursts

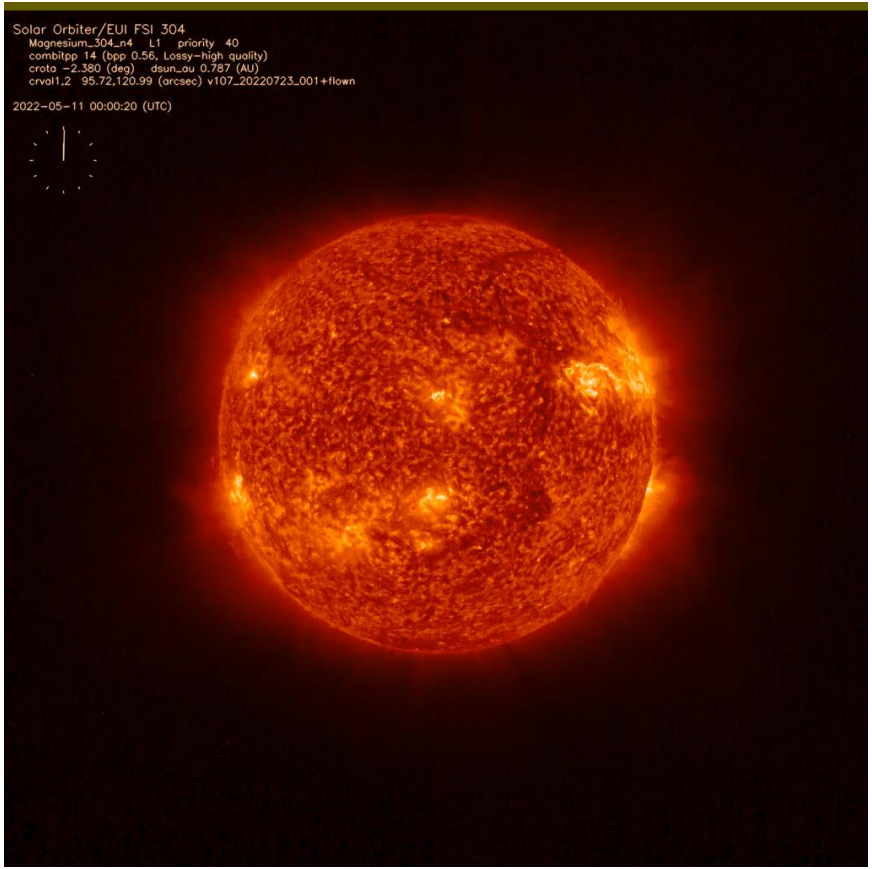


(M. Kretzschmar/RPW team)

- association based on inferred injection times

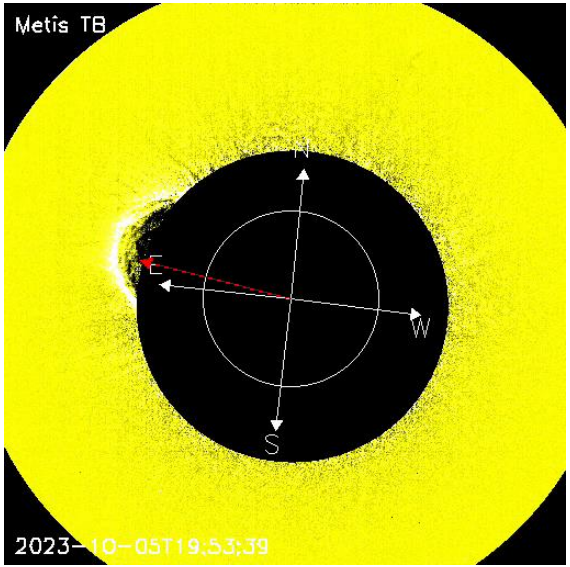
Identifying associated EUV flares and eruptions with the Extreme Ultraviolet Imager (EUI)

- full-disk EUV images covering chromosphere (304 Å) and corona (174 Å)
- search for associated EUV events
- identify eruption type (if any)
- provide location and active region association

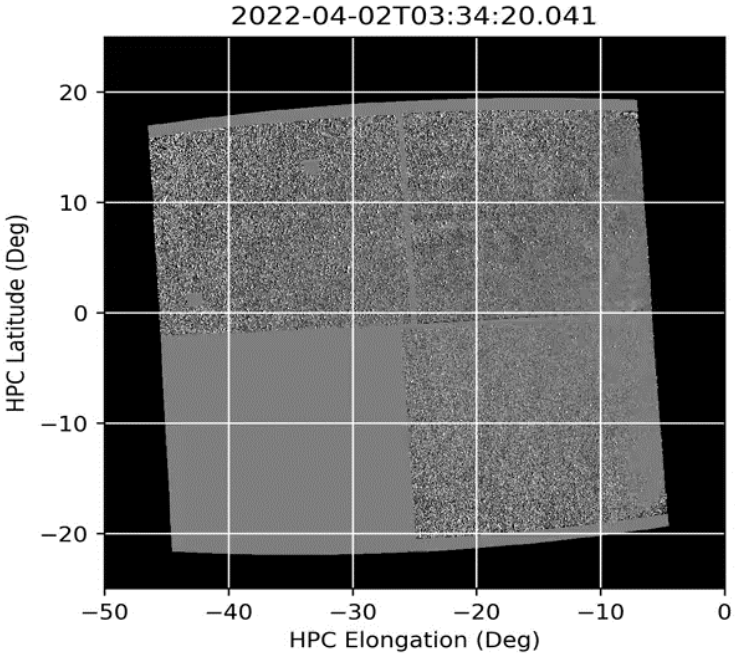


(EUI team)

Characterizing associated CMEs with the Metis coronagraph and the Solar Orbiter Heliospheric Imager (SoloHI)



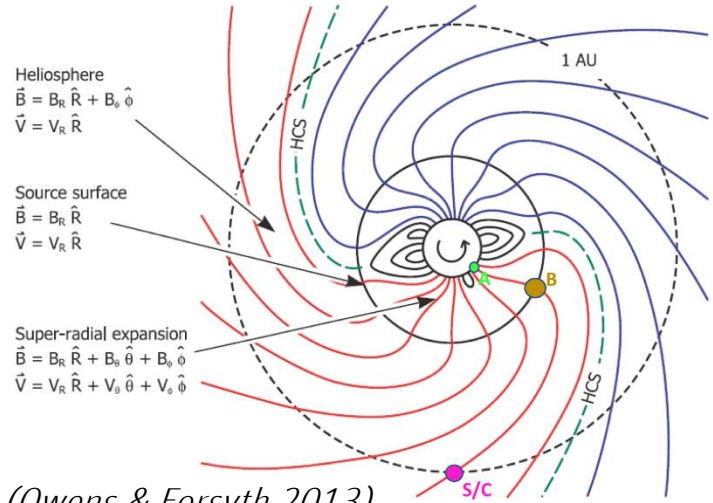
(Metis team)



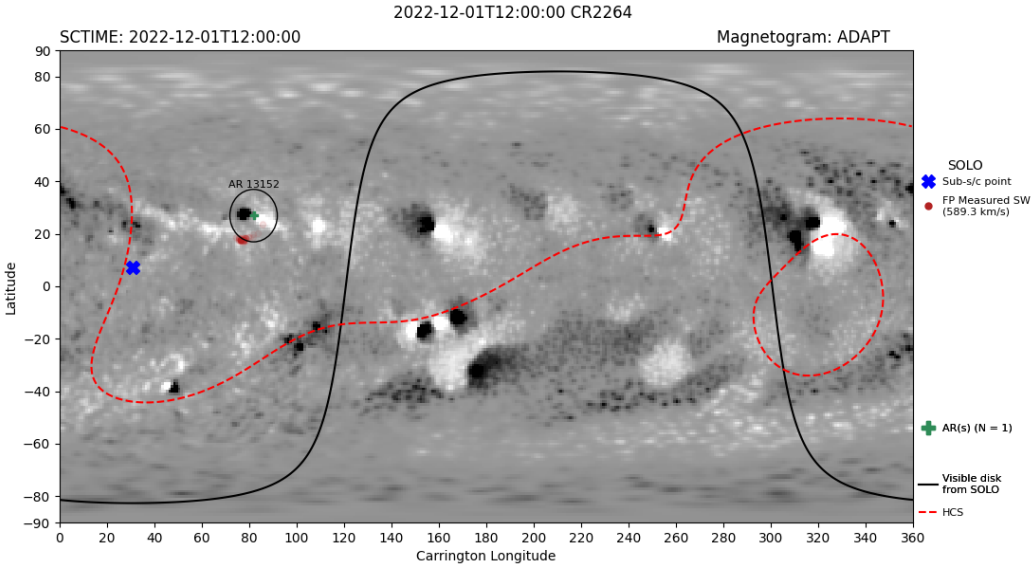
(C. Mac Cormack/ SoloHI team)

- VL & UV imaging of corona (Metis), WL imaging of inner heliosphere (SoloHI)
- search for associated CMEs, measure parameters (speed, width, launch time, etc.)

Establishing the magnetic connectivity

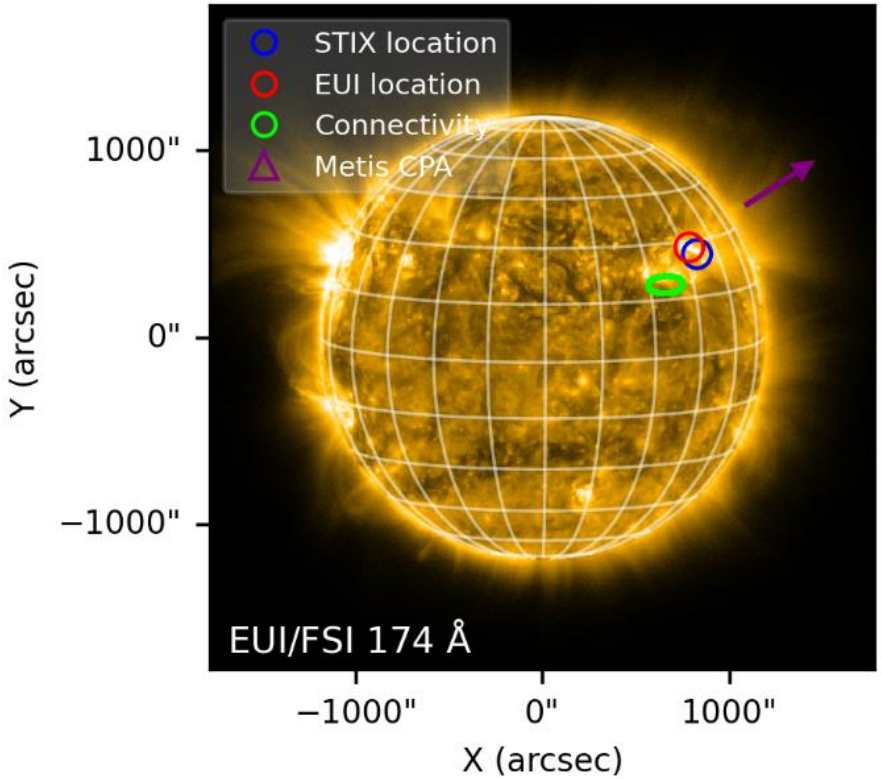


(Owens & Forsyth 2013)



- Magnetic Connectivity Tool: **http://connect-tool.irap.omp.eu/**
- get footpoint of connecting field line from magnetogram and solar wind speed

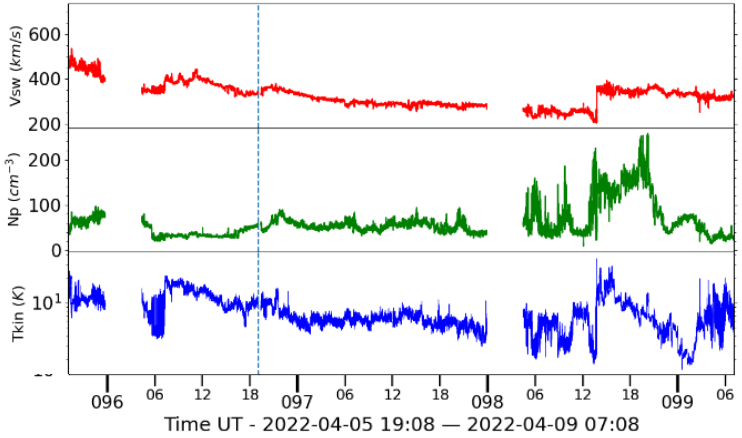
Flare source positions, magnetic connectivity, CME direction: STIX, EUI, connectivity tool, Metis



(S. Tan/STIX team)

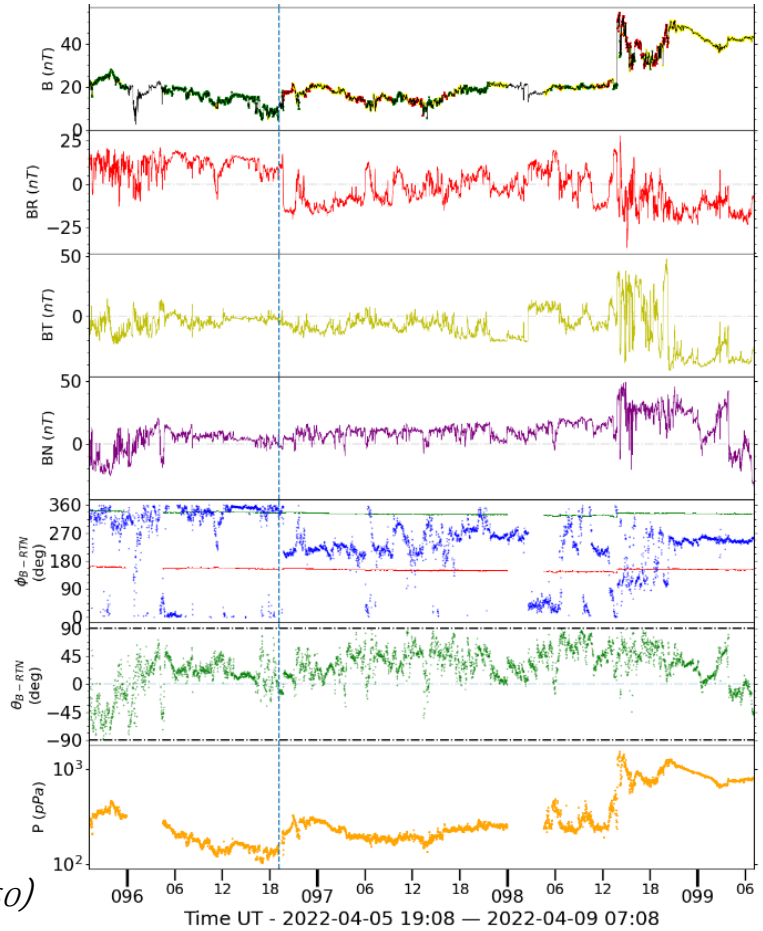
Interplanetary context: SWA & MAG

solar wind parameters



- characterize conditions in IP medium
  - measure solar wind speed
  - identify IP structures

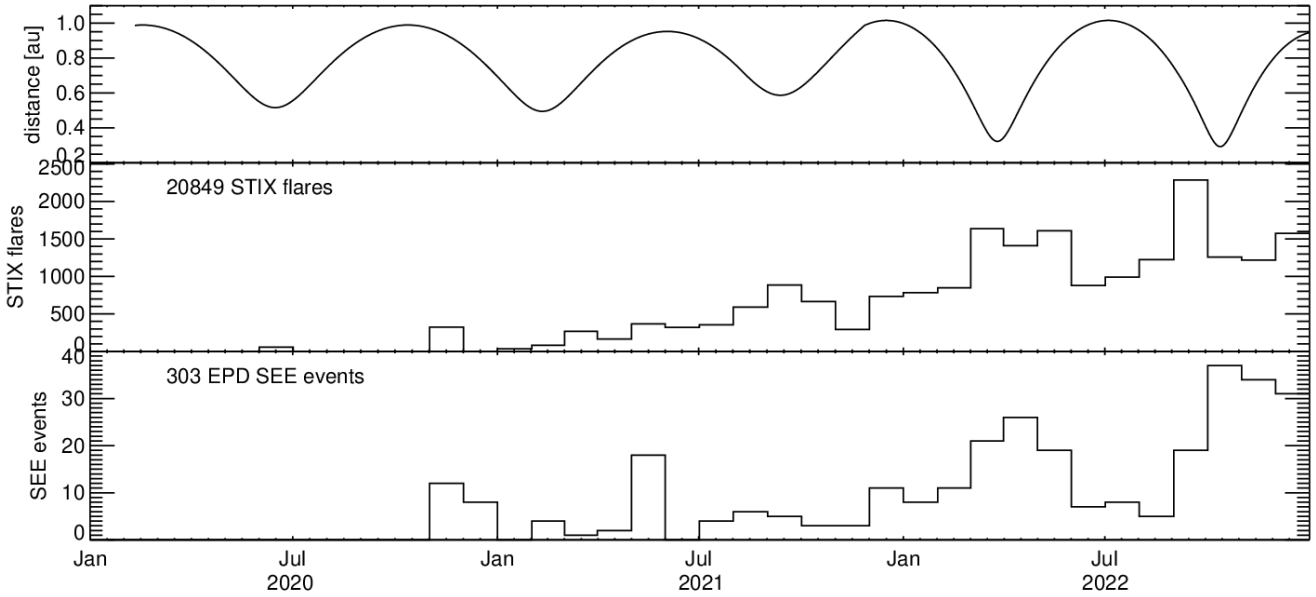
IP magnetic field parameters

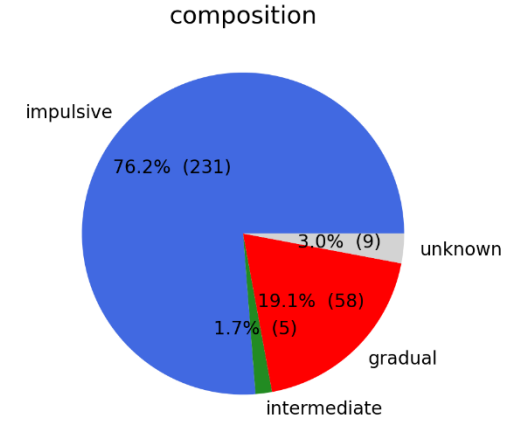


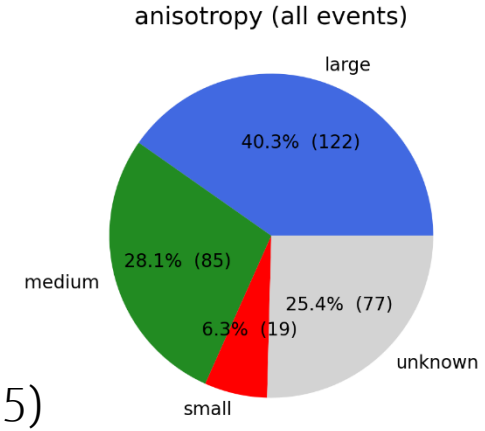
(F. Carcaboso)

The Comprehensive Solar Energetic Electron event Catalogue (CoSEE-Cat)

Event sample and basic characteristics

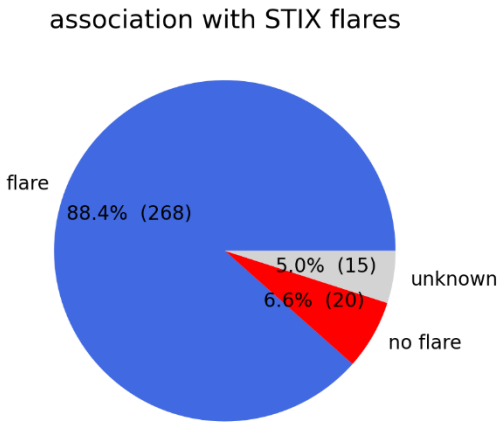


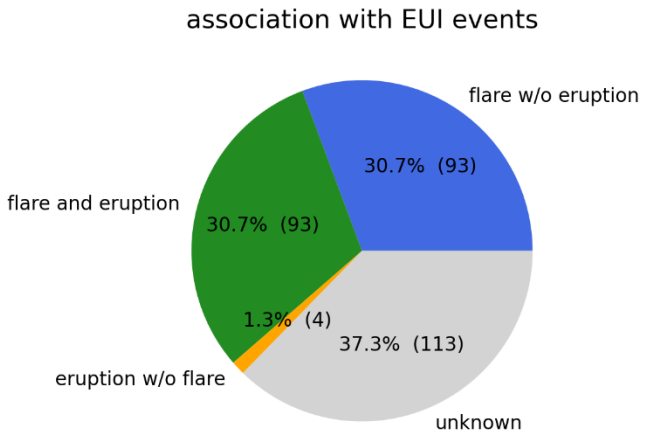


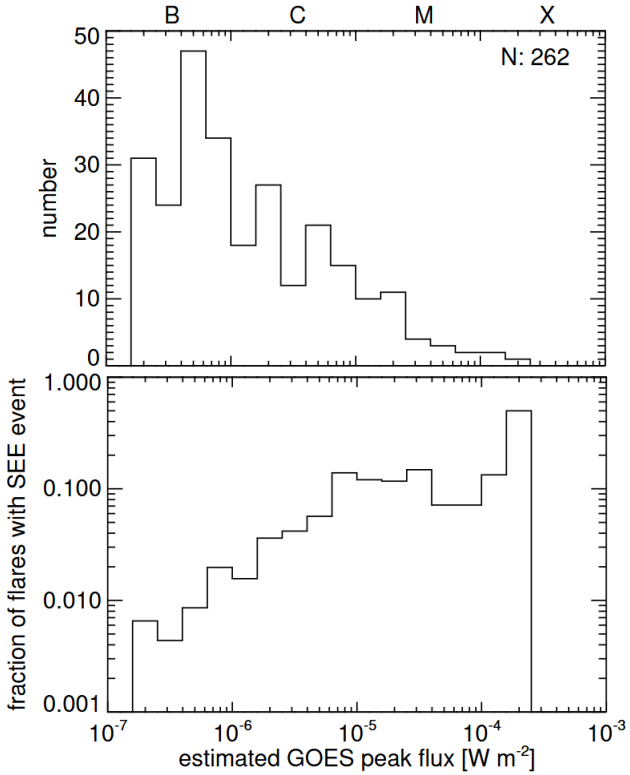


- Nov 2020 – Dec 2022: 303 EPD SEE events (630 until Jan 2025)

Associations with flares

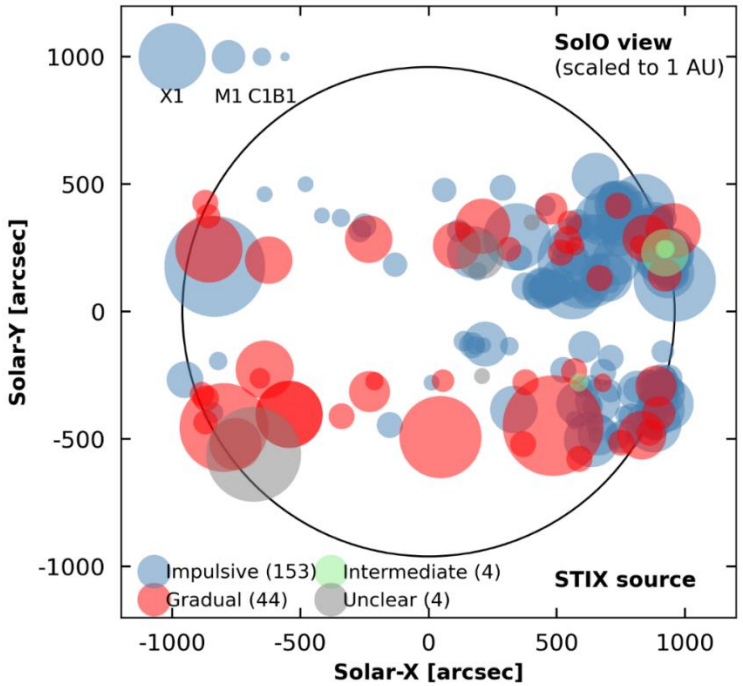


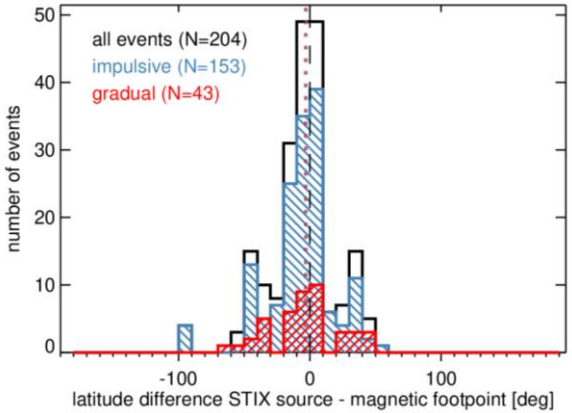


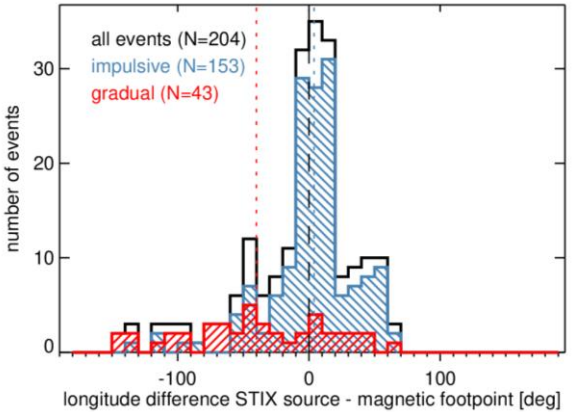


- high association with STIX flares and EUI flares/eruptions
- SEE association rises with peak X-ray flux

Results on source positions and connectivity

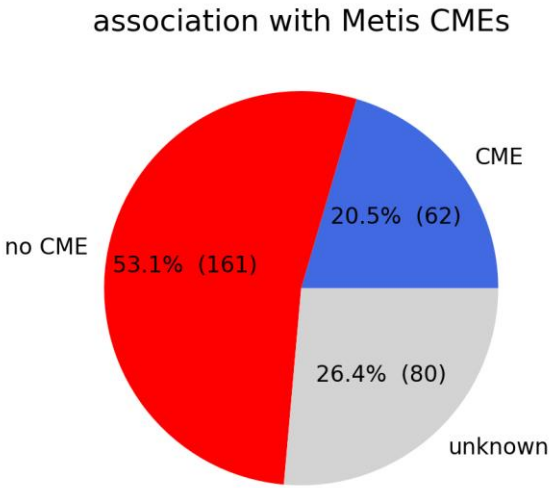


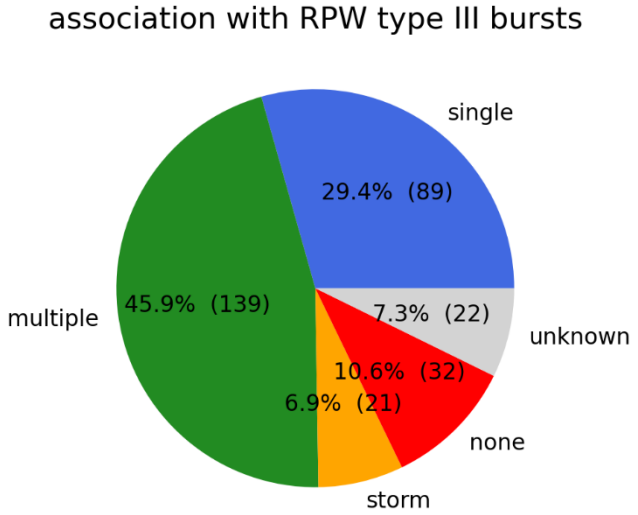




- magnetic connectivity is important for impulsive events, not for gradual ones

Associations with CMEs and type III radio bursts

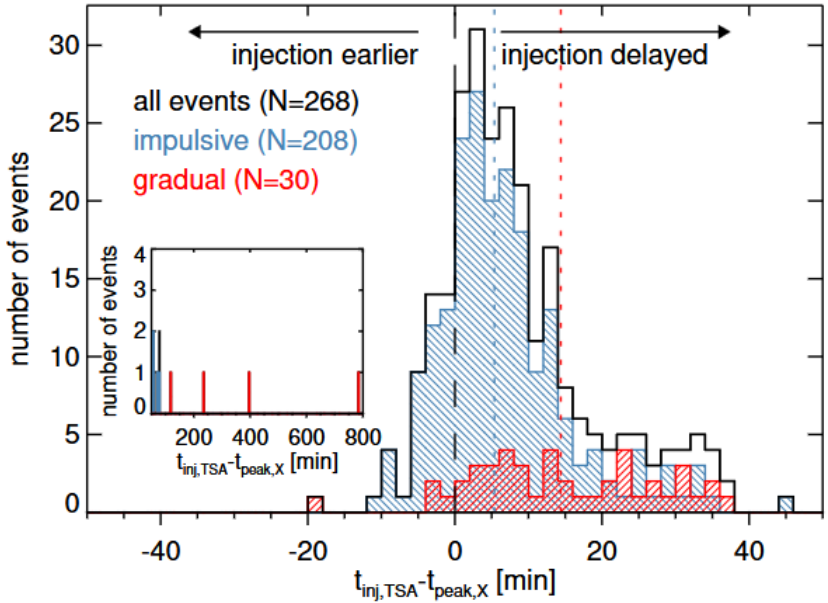




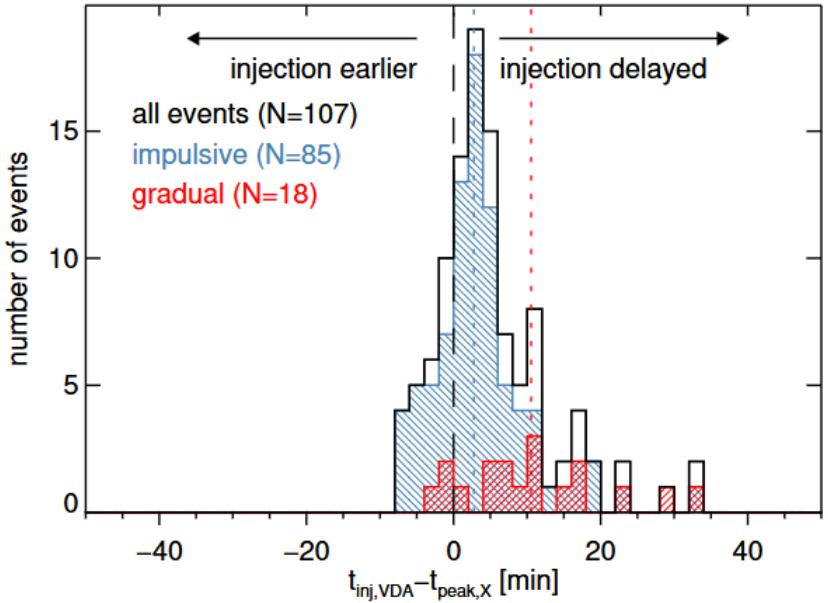
- higher CME association for gradual events
- high association with type III bursts

Time difference between electron injection and nonthermal X-ray peak

time-shift analysis

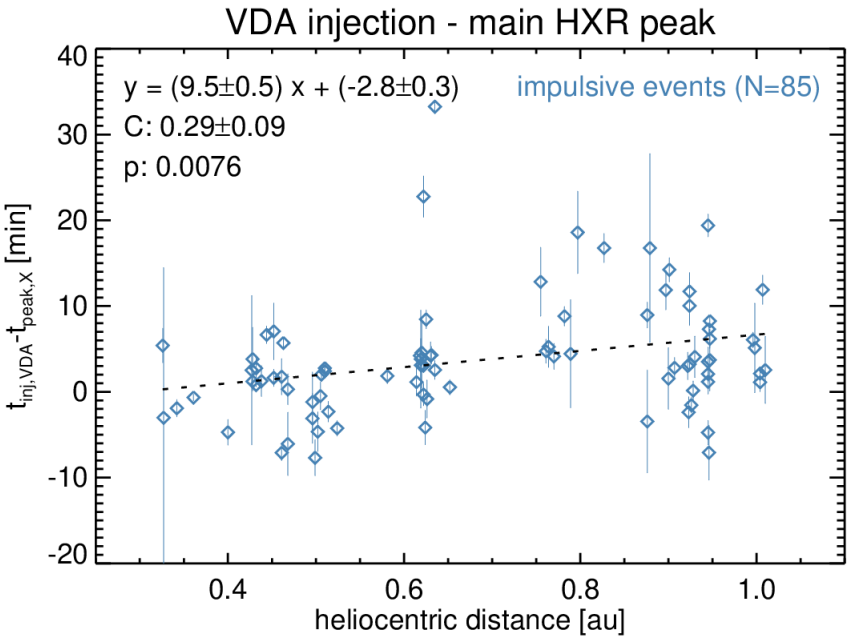


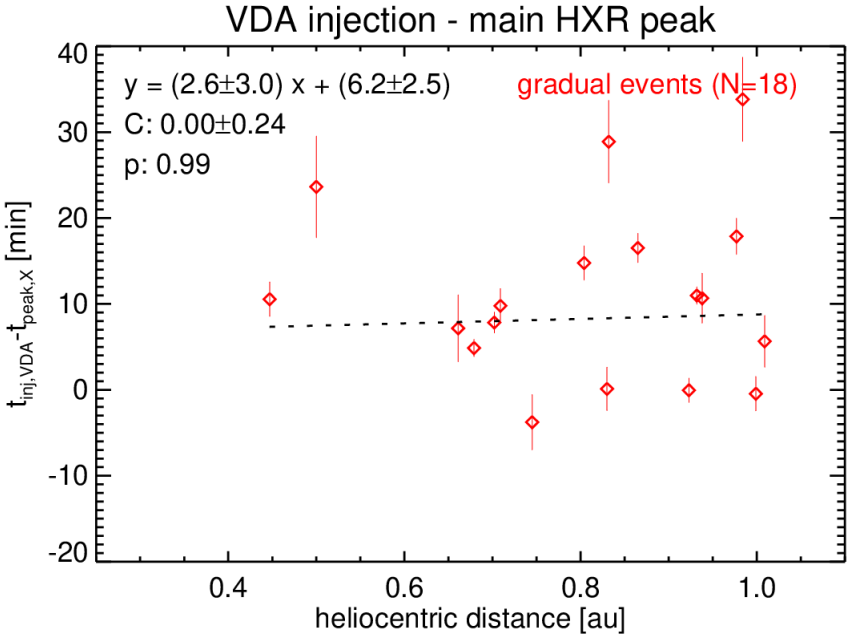
velocity dispersion analysis



- impulsive events show significantly better temporal association with flares

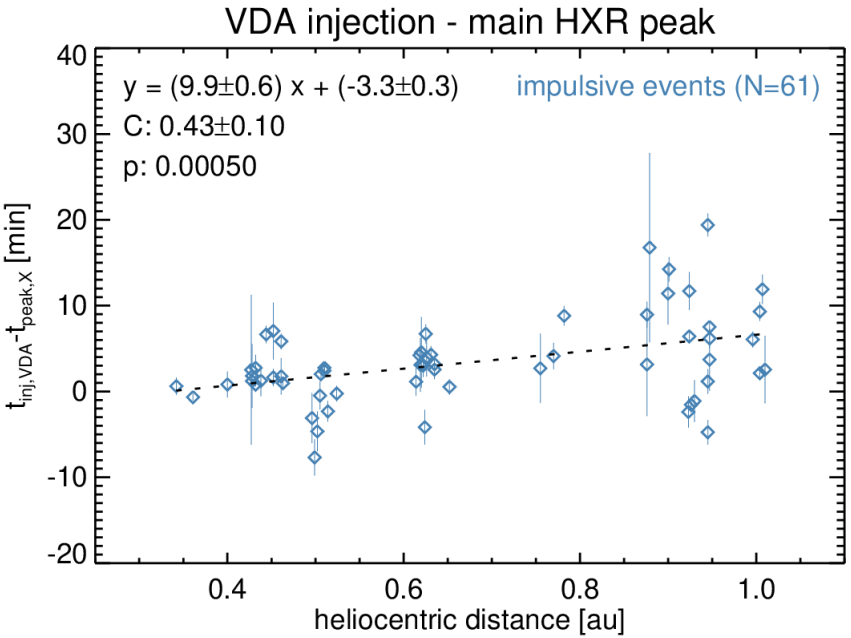
Time differences vs. distance: impulsive and gradual events

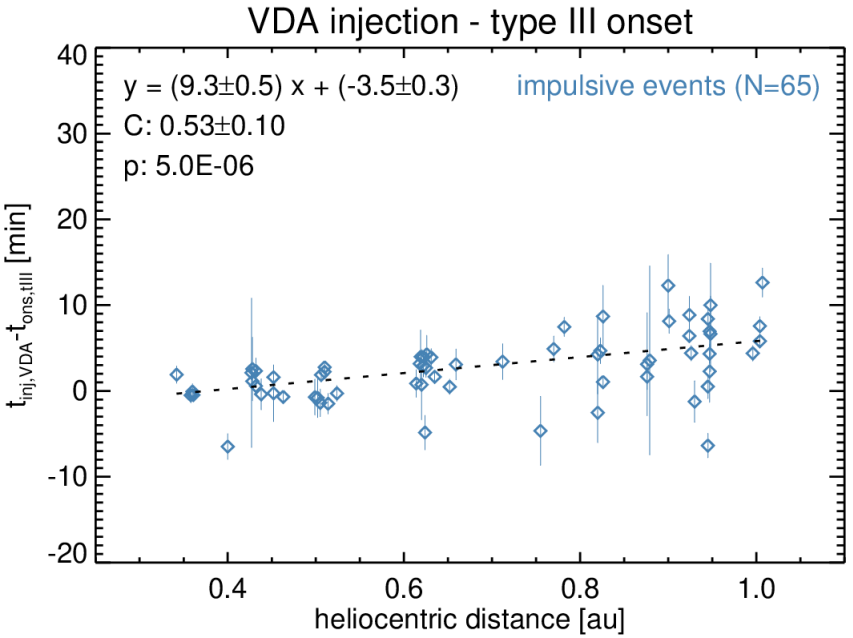




- weak trend of apparently increasing injection time delay for impulsive events
- no trend for gradual events

Time differences vs. distance: impulsive events, simple IP conditions





- fewer outliers, clearer trend of apparently increasing injection time delay

Summary and Outlook

- Solar Orbiter provides unique capabilities to study particle acceleration and transport in the heliosphere
- first opportunity to separate acceleration from propagation effects
- strong support for flare-related origin of impulsive SEE events

Next steps:

- publish the CoSEE catalogue and first statistical results
- keep CoSEE-Cat updated
- perform spectral analysis with STIX and EPD
- include in-situ electron observations from other locations in the heliosphere