Energetic particles and X-rays with EPD and STIX on Solar Orbiter

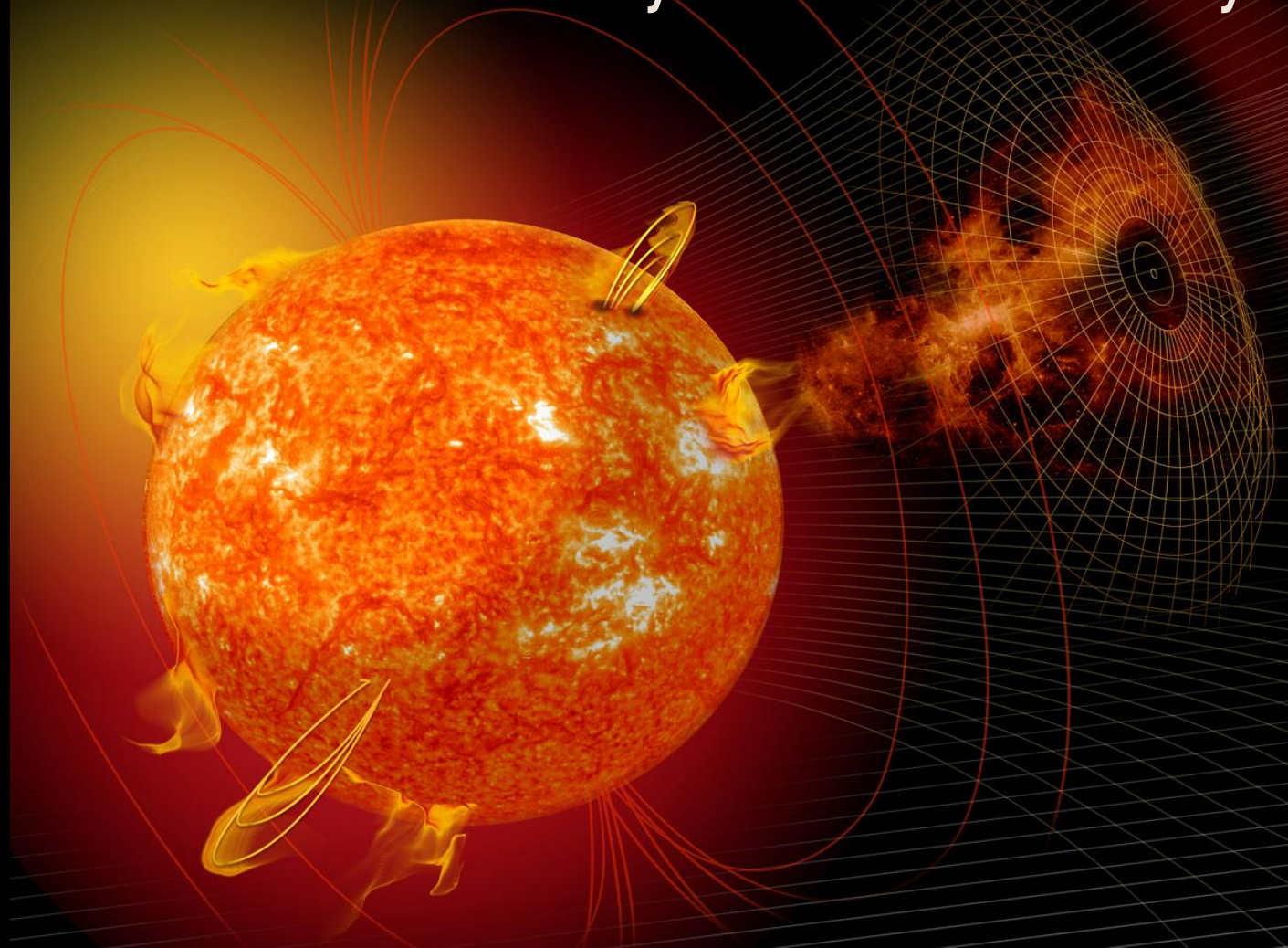
Solar Orbiter
Summer School 2022
Sète

Sophie Musset
ESA/ESTEC

Solar Orbiter scientific objectives

How does the Sun create and control the heliosphere, and why does solar activity change with time?

Müller. et al (2020)



What drives the solar wind and where the coronal magnetic field originate from?

How do solar transients drive heliospheric variability?

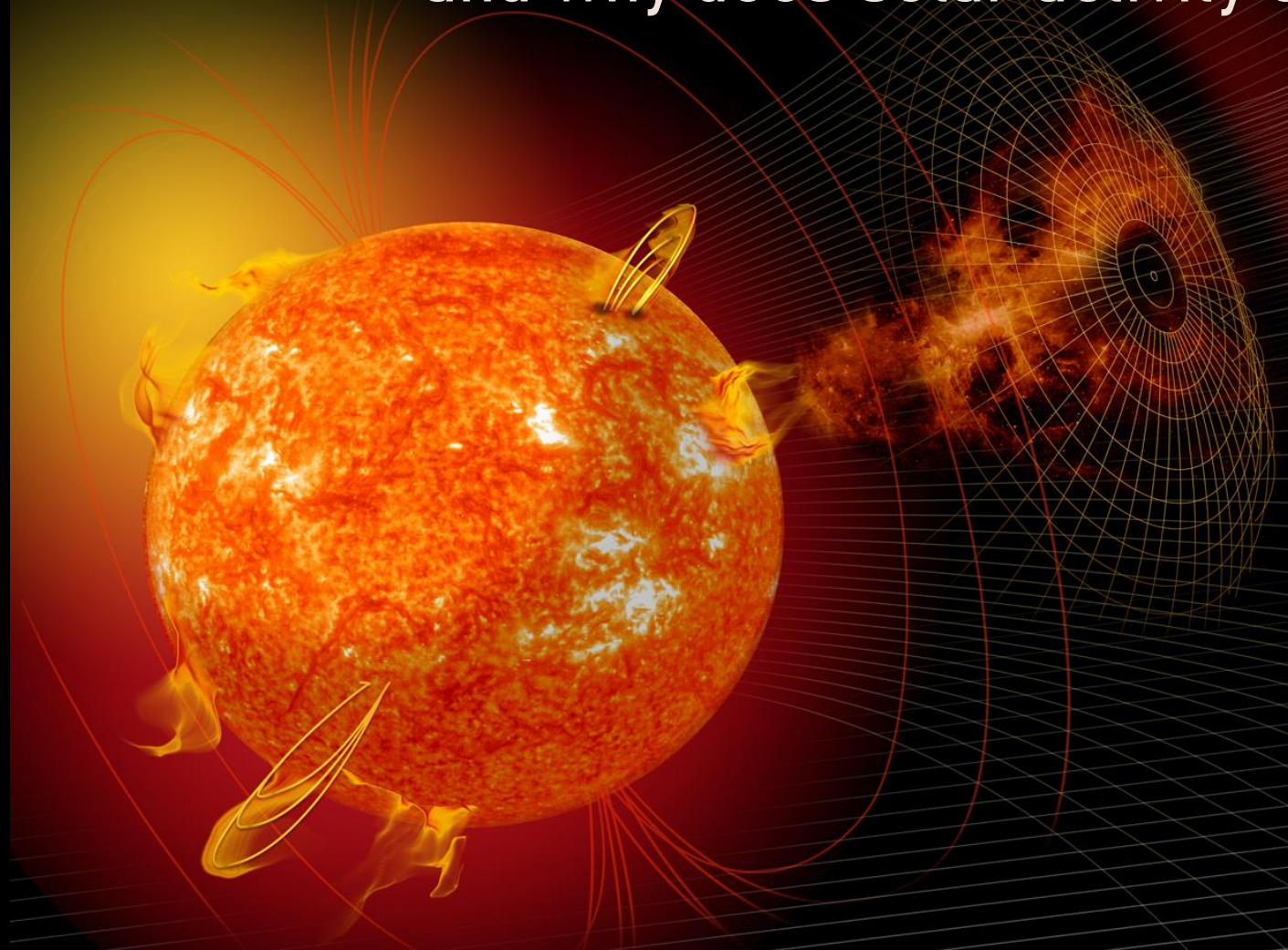
How do solar eruption produce energetic particle radiation that fills the heliosphere?

How does the solar dynamo work and drive connections between the Sun and the heliosphere?

Solar Orbiter scientific objectives

How does the Sun create and control the heliosphere, and why does solar activity change with time?

Müller. et al (2020)



What drives the solar wind and where the coronal magnetic field originate from?

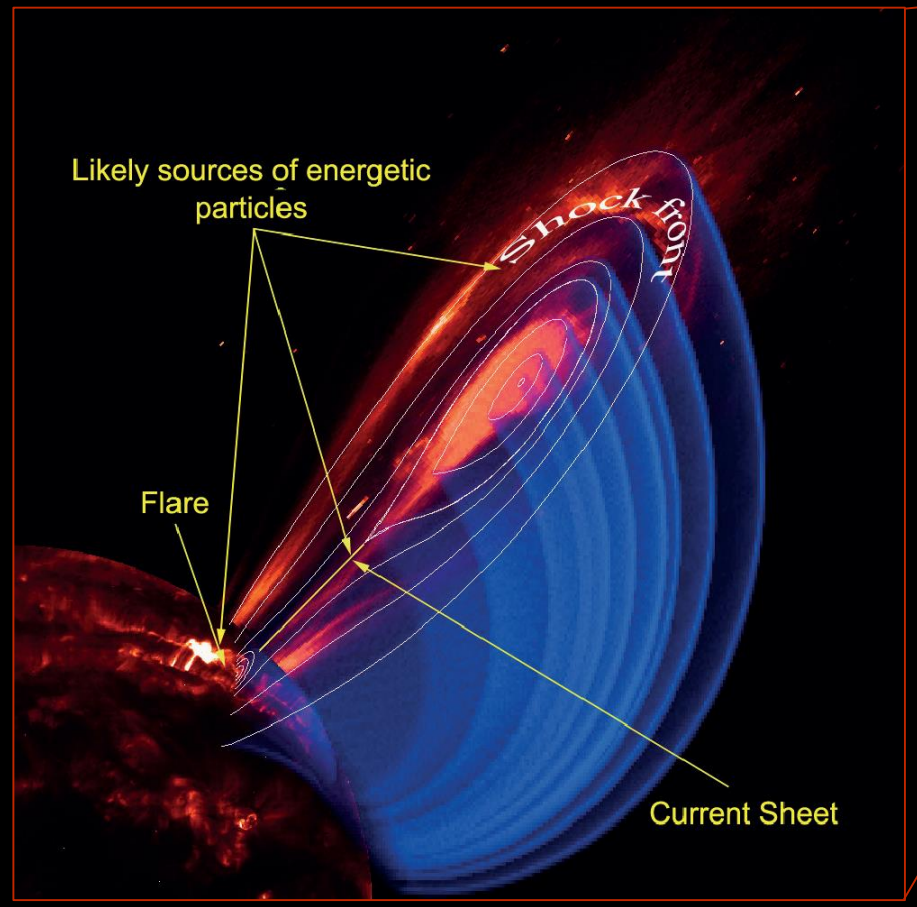
How do solar transients drive heliospheric variability?

How do solar eruption produce energetic particle radiation that fills the heliosphere?

How does the solar dynamo work and drive connections between the Sun and the heliosphere?

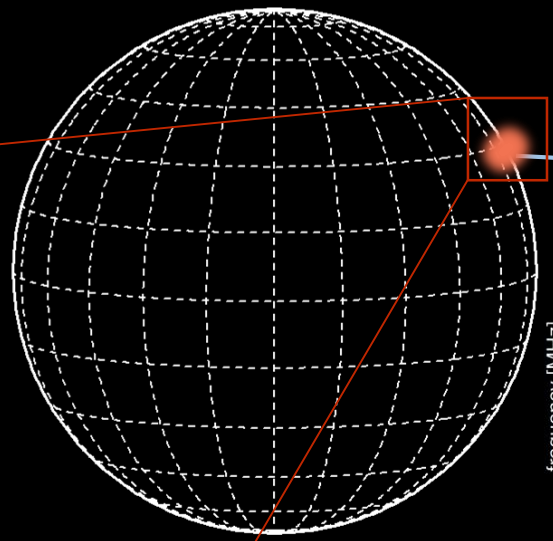
How do solar eruptions produce energetic particle radiation that fills the heliosphere?

- How and where are energetic particles accelerated at the Sun?



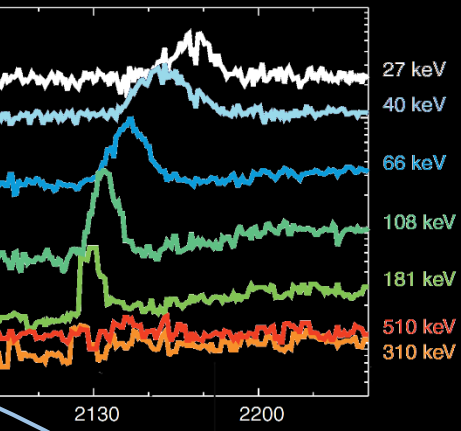
From NASA's Solar Sentinels STDT report

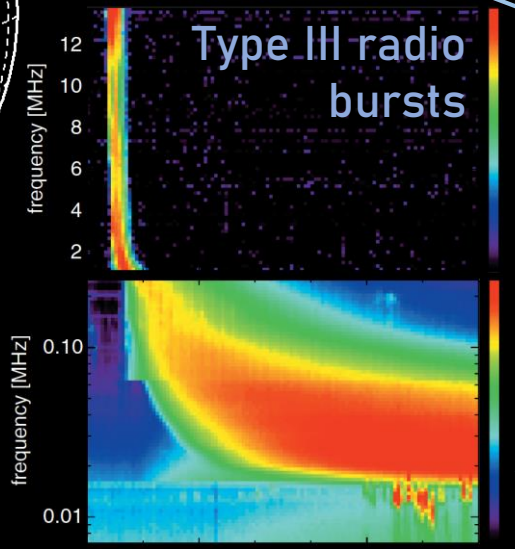
Müller. et al (2020)



Energetic particles

In-situ measurements

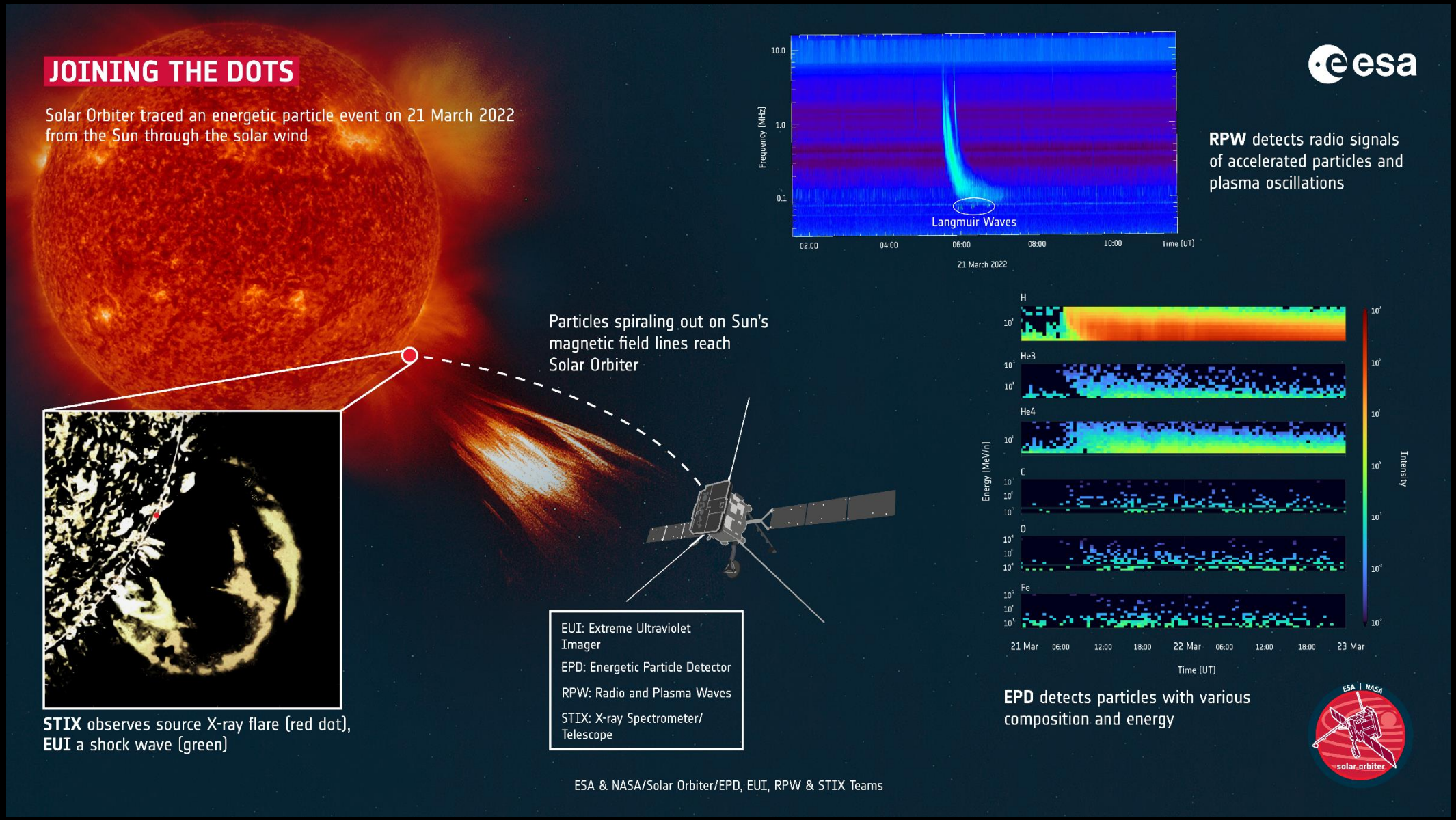




Adapted from Krucker et al (2011)

- How are energetic particles released from their sources and distributed in space and time?
- What are the seed populations for energetic particles?

How do solar eruptions produce energetic particle radiation that fills the heliosphere?



Payload

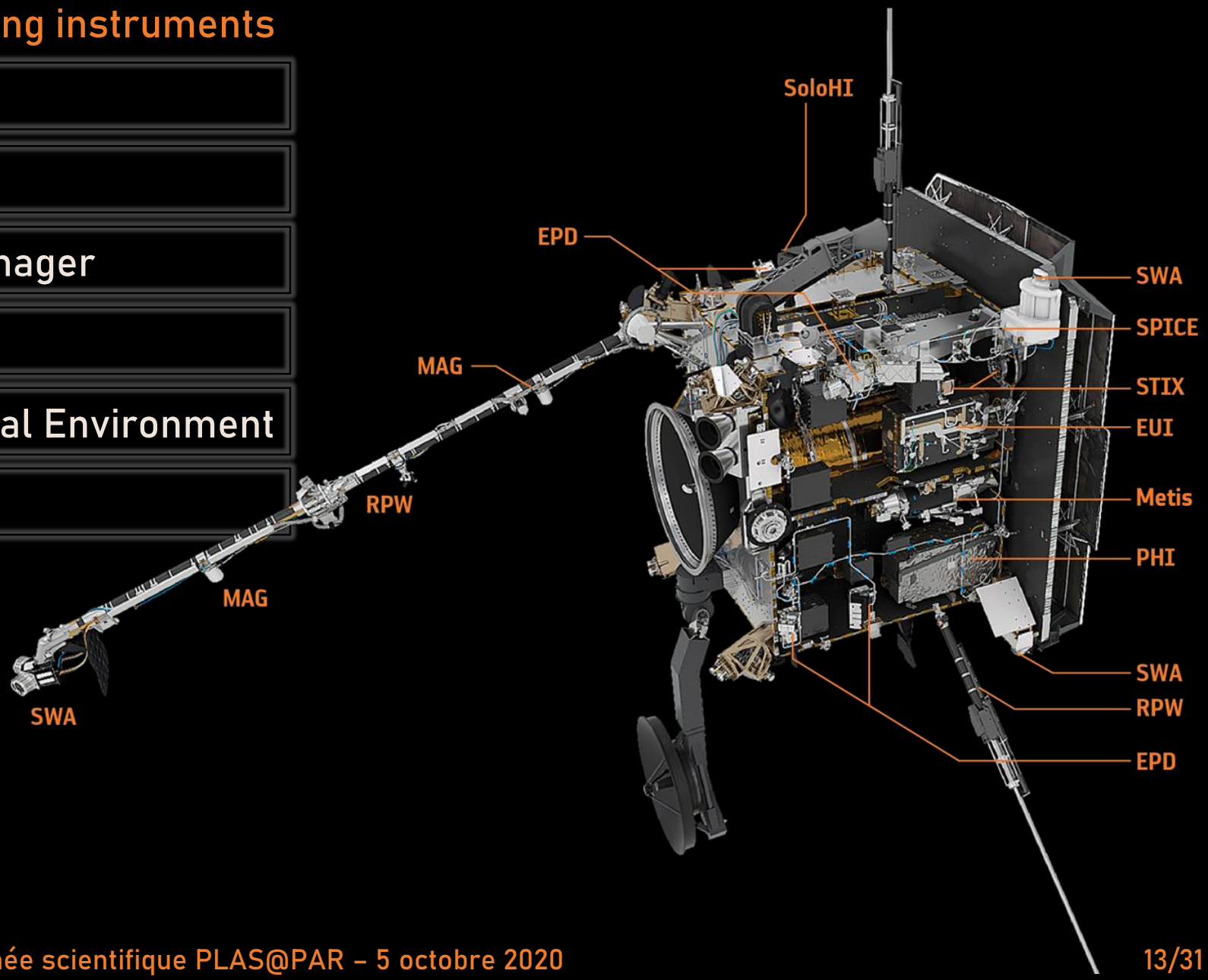
Müller et al (2020)

6 remote-sensing instruments

- EUI: Extreme Ultraviolet Imager
- Metis: Coronagraph
- PHI: Polarimetric and Helioseismic Imager
- SoloHI: Heliospheric Imager
- SPICE: Spectral Imaging of the Coronal Environment
- STIX: X-ray Spectrometer/Telescope

4 in-situ instruments

- EPD: Energetic Particle Detector
- MAG: Magnetometer
- RPW: Radio and Plasma Waves
- SWA: Solar Wind Analyser



Payload

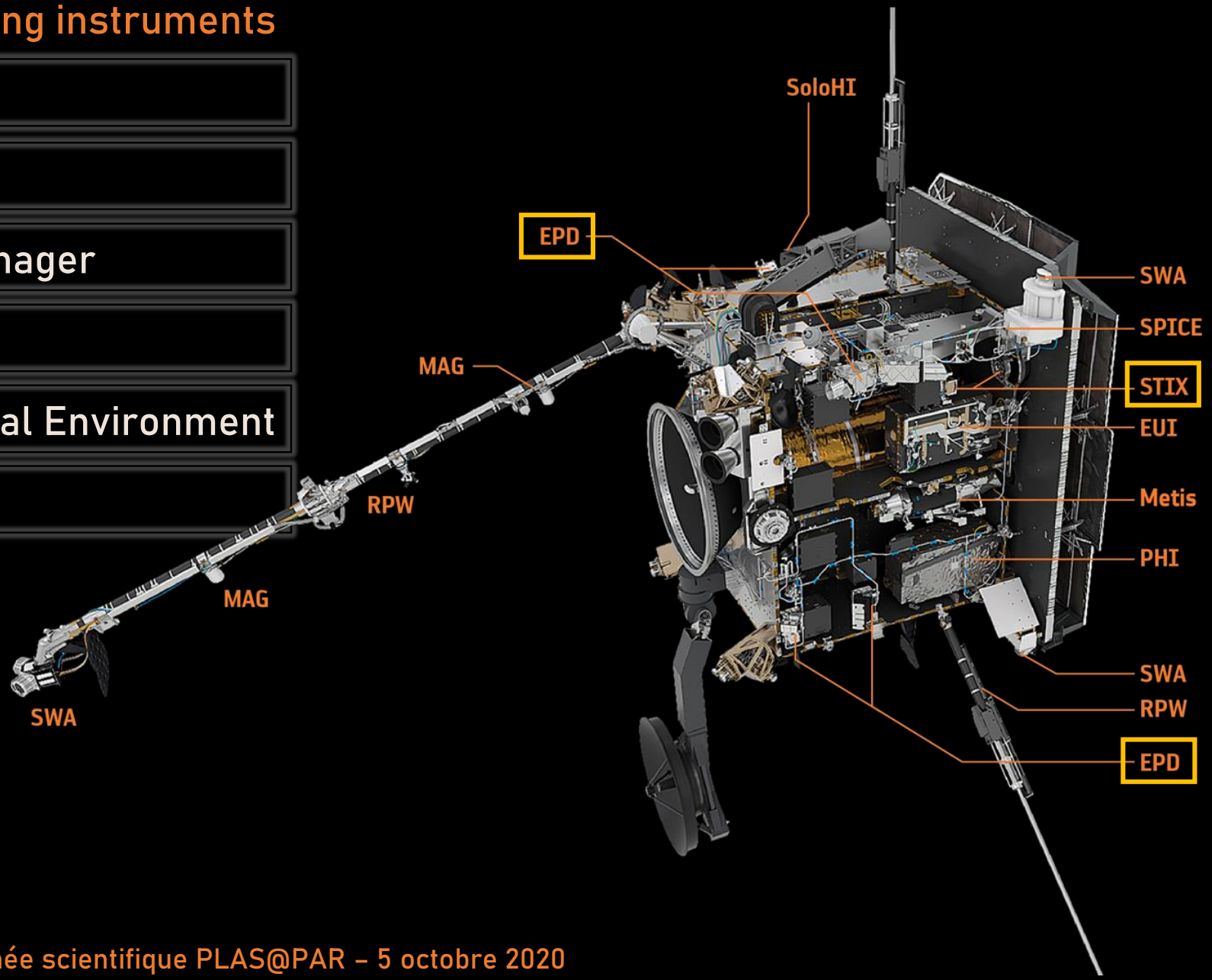
Müller et al (2020)

6 remote-sensing instruments

- EUI: Extreme Ultraviolet Imager
- Metis: Coronagraph
- PHI: Polarimetric and Helioseismic Imager
- SoloHI: Heliospheric Imager
- SPICE: Spectral Imaging of the Coronal Environment
- STIX: X-ray Spectrometer/Telescope

4 in-situ instruments

- EPD: Energetic Particle Detector
- MAG: Magnetometer
- RPW: Radio and Plasma Waves
- SWA: Solar Wind Analyser



EPD: Energetic Particle Detector

Rodriguez-Pacheco et al. (2020)

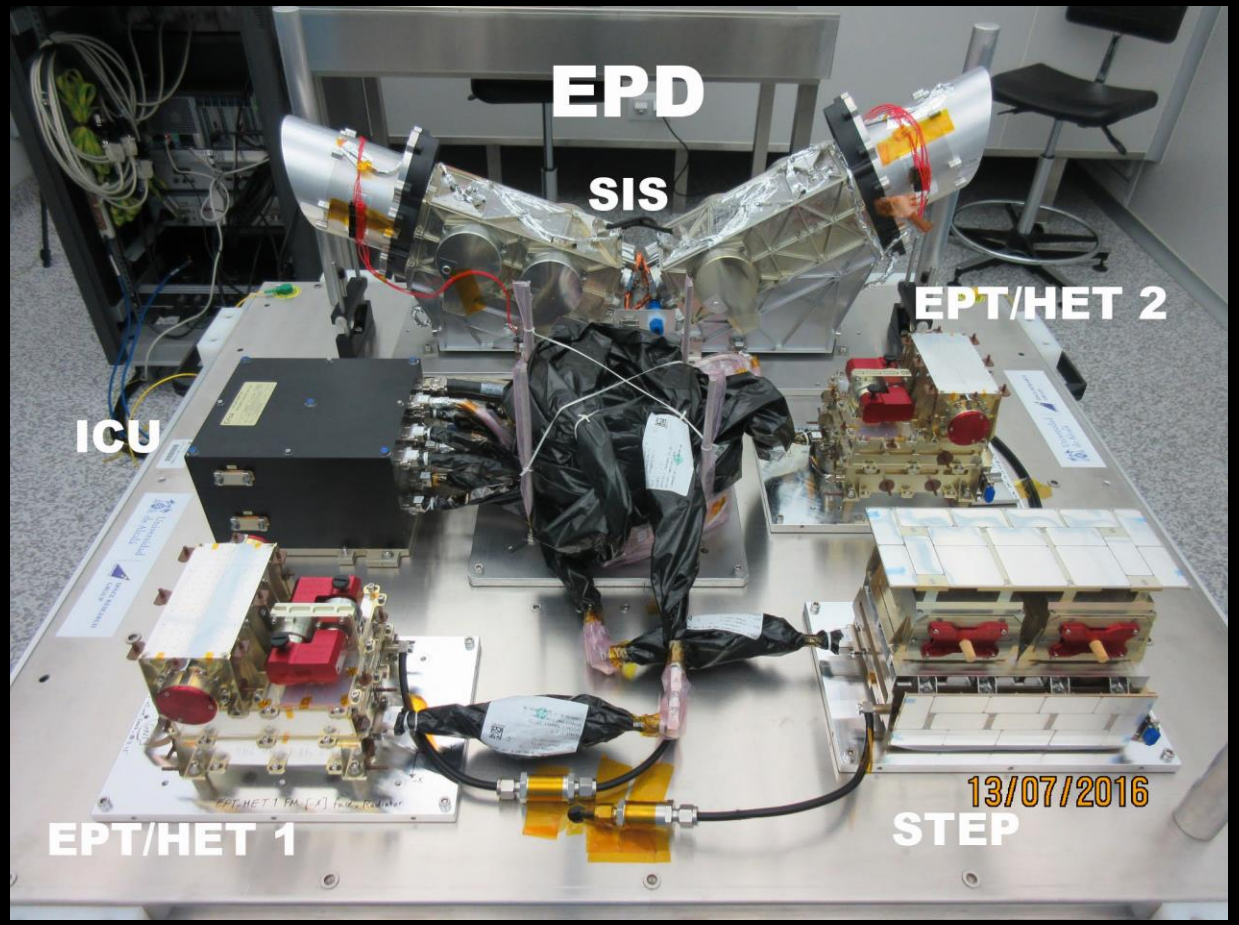
Need to measure energetic particles in-situ with:

- Broad range of energies and composition
- High time resolution
- Directional information

And…

- Get close to the Sun
- Complementary in-situ measurements (magnetic field, plasma parameters…)

➔ The EPD suite of instruments



EPD: Energetic Particle Detector

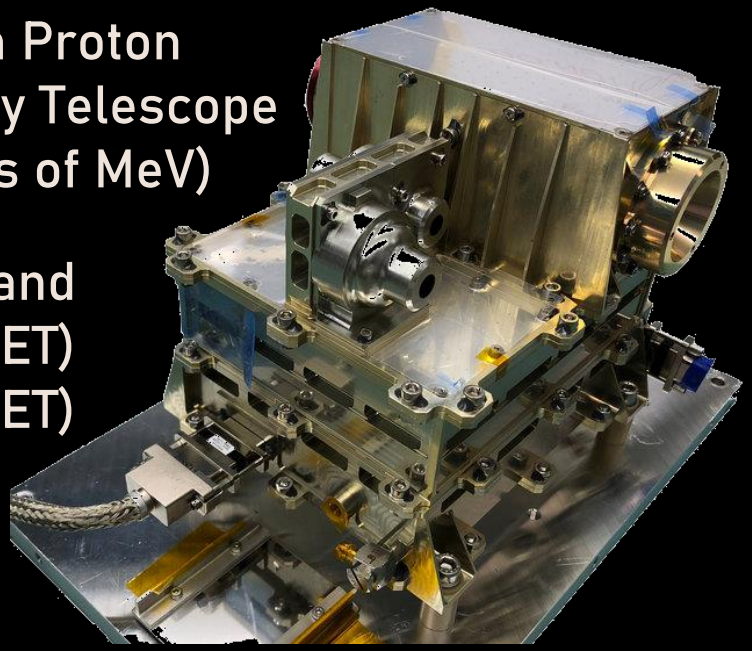
Rodriguez-Pacheco et al. (2020)

SIS: Suprathermal Ion Spectrograph
(14 keV/n-20.5 MeV/n)

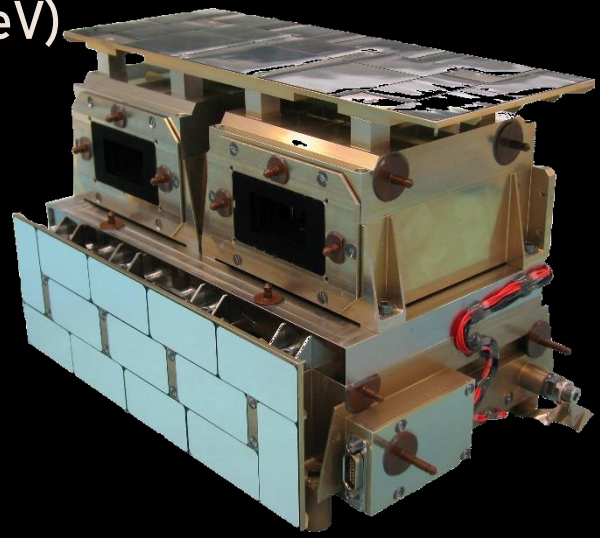
He-Fe between energies
just above the solar wind
to multi MeV/n energies

EPT/HET: Electron Proton
Telescope/High Energy Telescope
(25 keV to hundreds of MeV)

Energetic electrons and
protons (EPT/HET)
Heavy ions (HET)



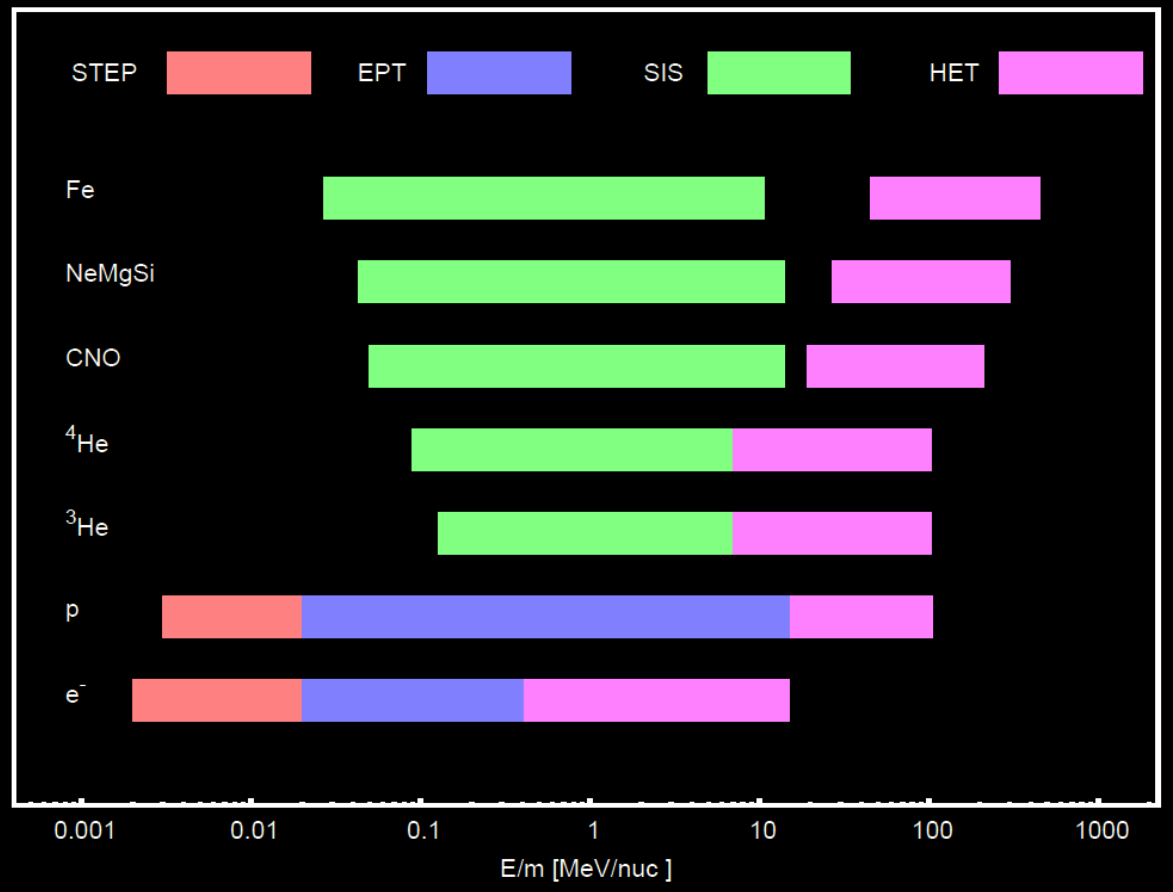
STEP: SupraThermal Electrons and Protons
(2-80 keV)



Protons and
electrons at
supra-thermal
energies

EPD: Energetic Particle Detector

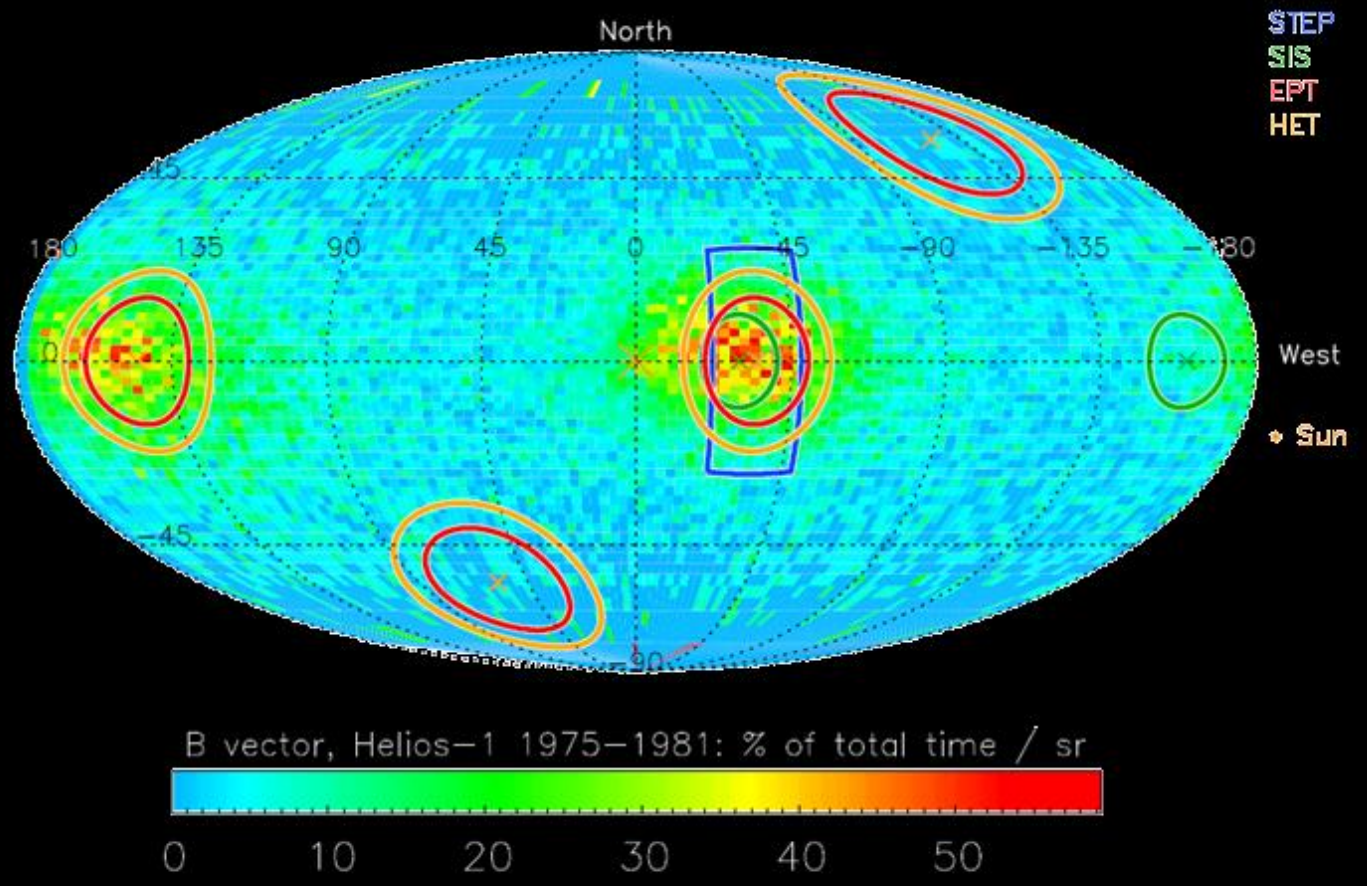
Rodriguez-Pacheco et al. (2020)



Energy coverage of EPD for different species

EPD: Energetic Particle Detector

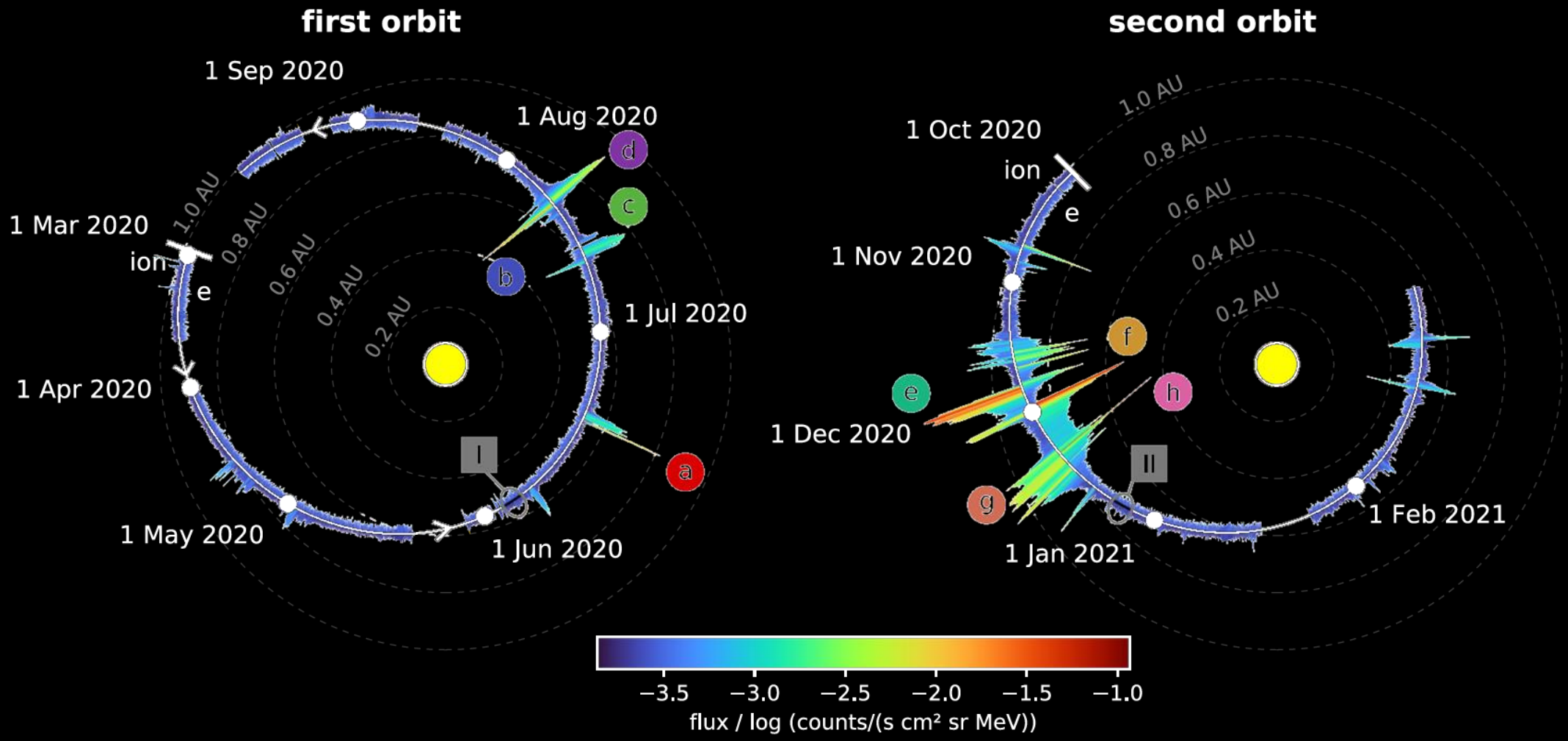
Rodriguez-Pacheco et al. (2020)



Field of view for the different EPD sensors
→ Directional information

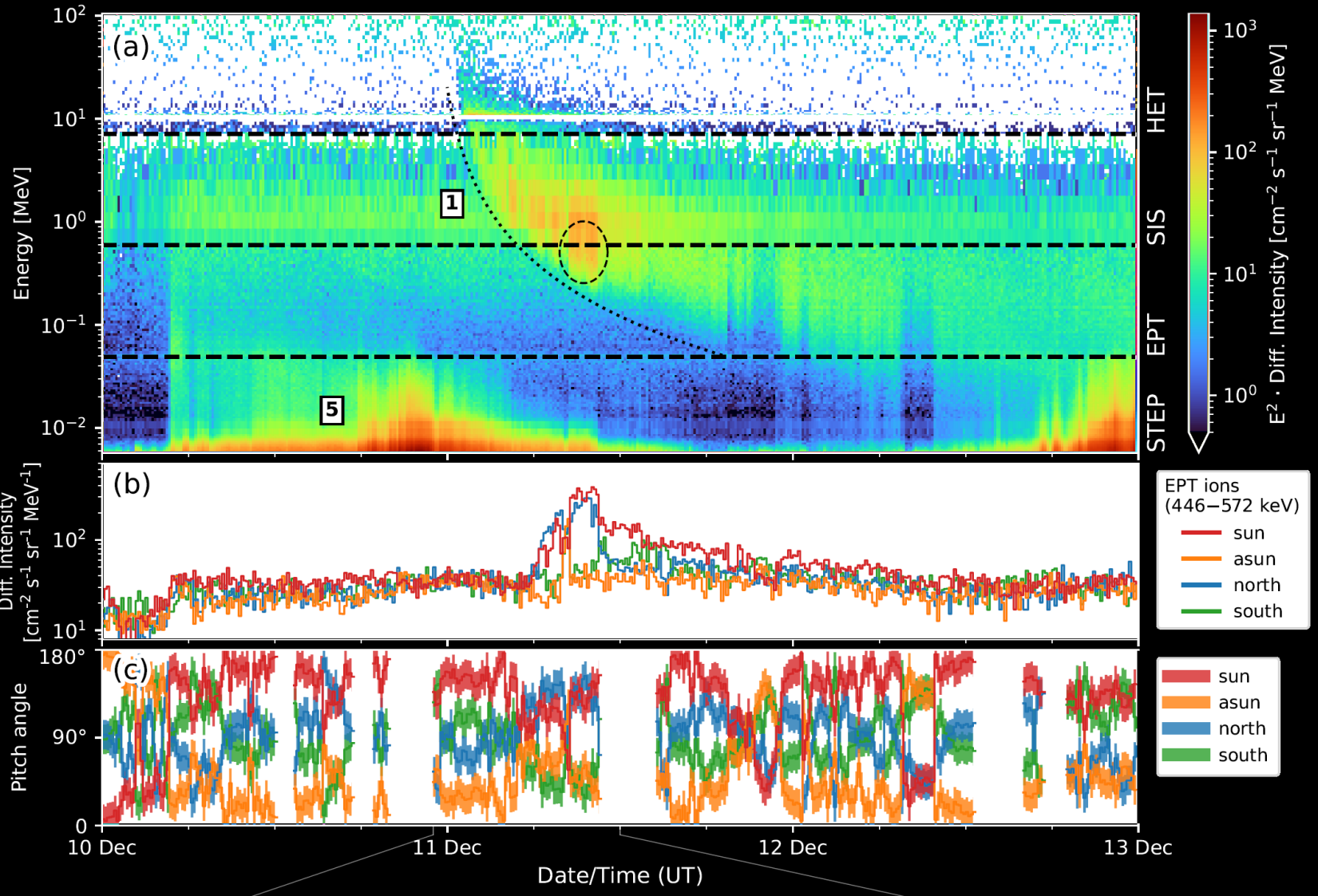
EPD: Energetic Particle Detector

Ions: 124-218 keV
Electrons: 54-101 keV



Wimmer-Schweingruber et al. (2021)

EPD: Energetic Particle Detector



Ions

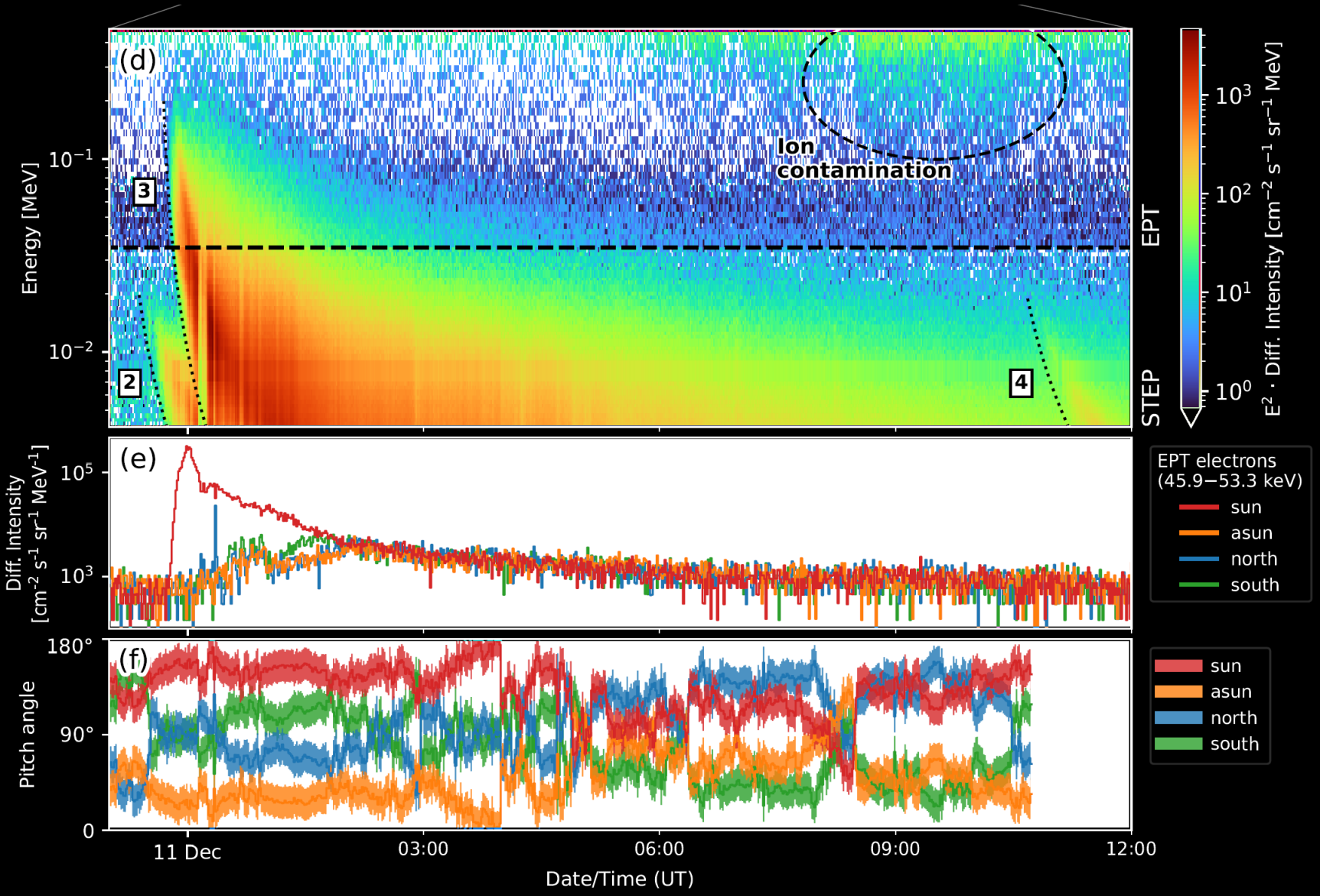
Spectrogram

Sectored intensity time profiles

Pitch angle coverage

Wimmer-Schweingruber et al. (2021)

EPD: Energetic Particle Detector



Electrons

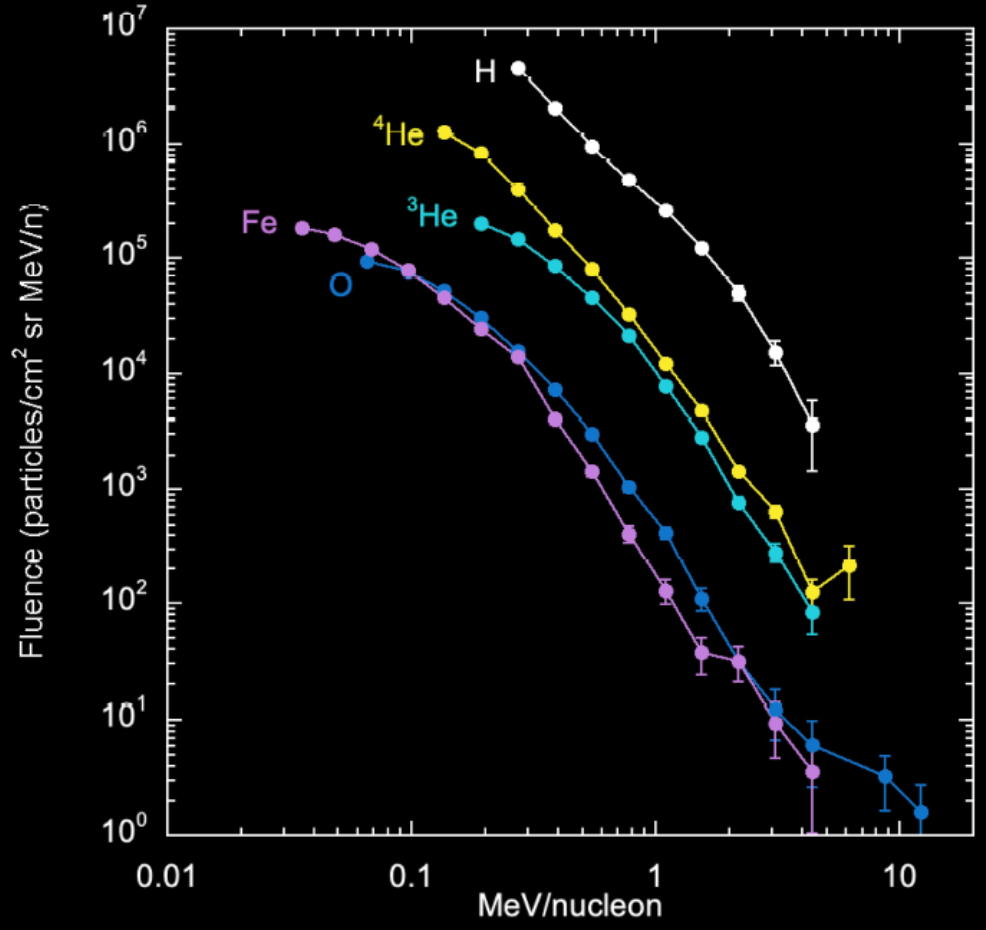
Spectrogram

Sectored intensity time profiles

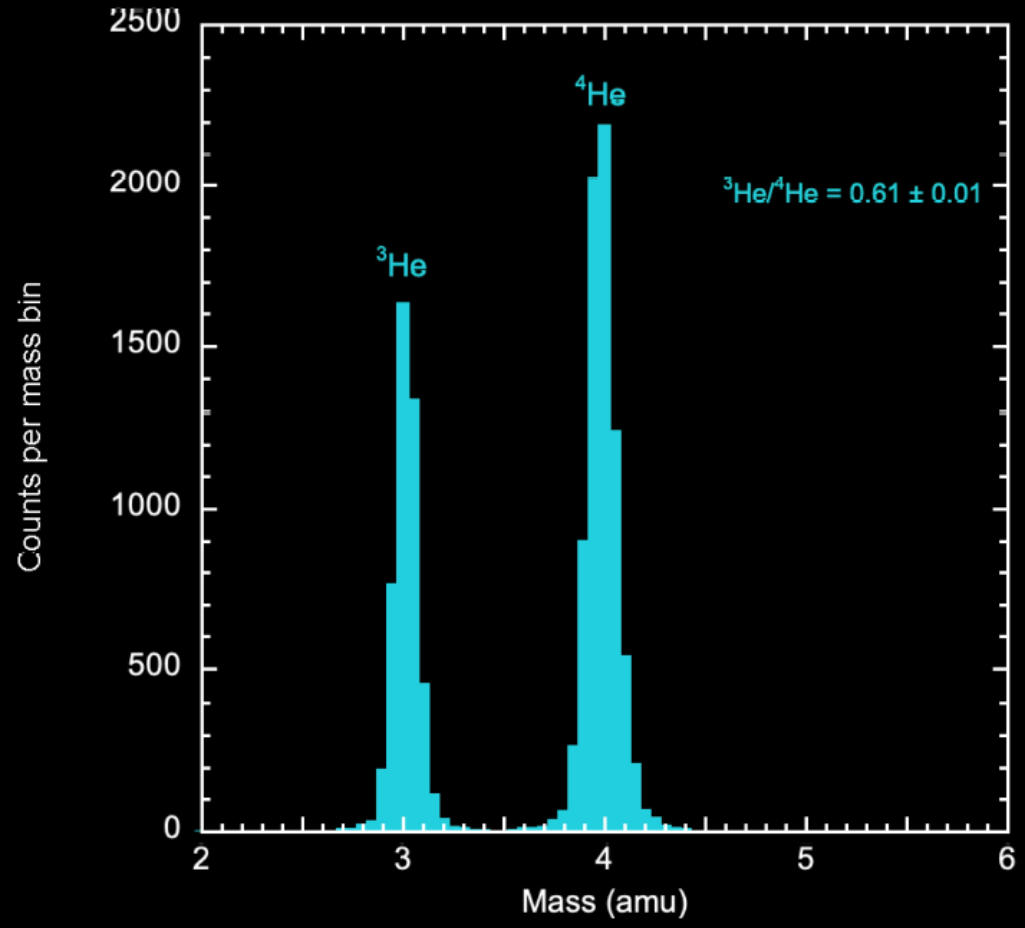
Pitch angle coverage

Wimmer-Schweingruber et al. (2021)

EPD: Energetic Particle Detector



Fluence for selected species in the 21 July 2020 event



Mass histogram

Mason et al. (2021)

EPD: Energetic Particle Detector

Calibrated data = L2 data sets

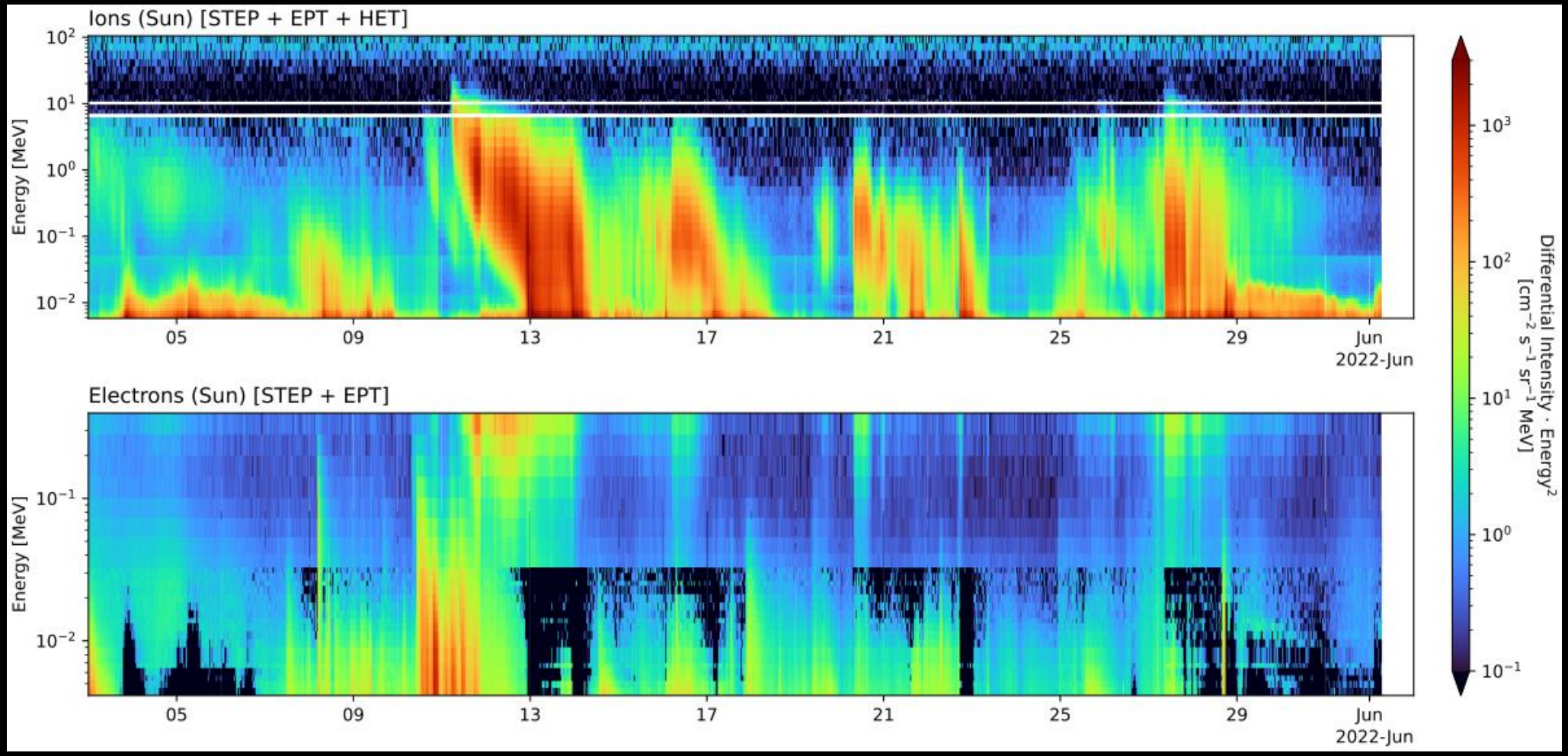
- On SOAR
- Also at https://espada.uah.es/epd/data/archive with preview plots
- Quicklook summary plots available at https://espada.uah.es/epd/data/plots/quicklook
- AMDA, propagation tool…

→ Read documentation for caveats in the data
→ Ask the instrument team!

Level 3 data (e.g. pitch angle distribution) will be distributed as well in the future

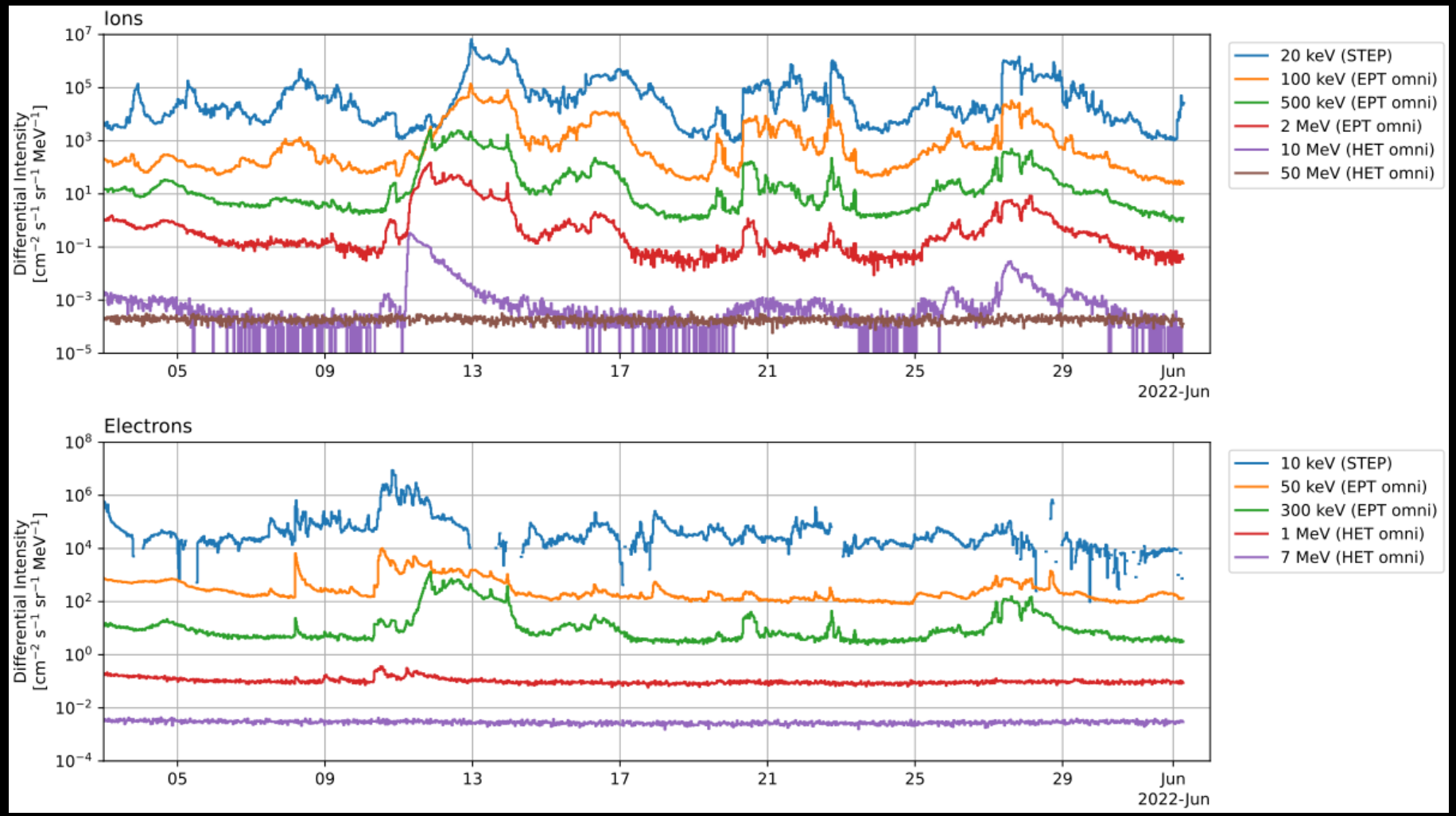
EPD: Energetic Particle Detector

Combined dynamic spectra for energetic ions and electrons as measured by STEP, EPT and HET in the sunward looking direction (along the average Parker spiral)

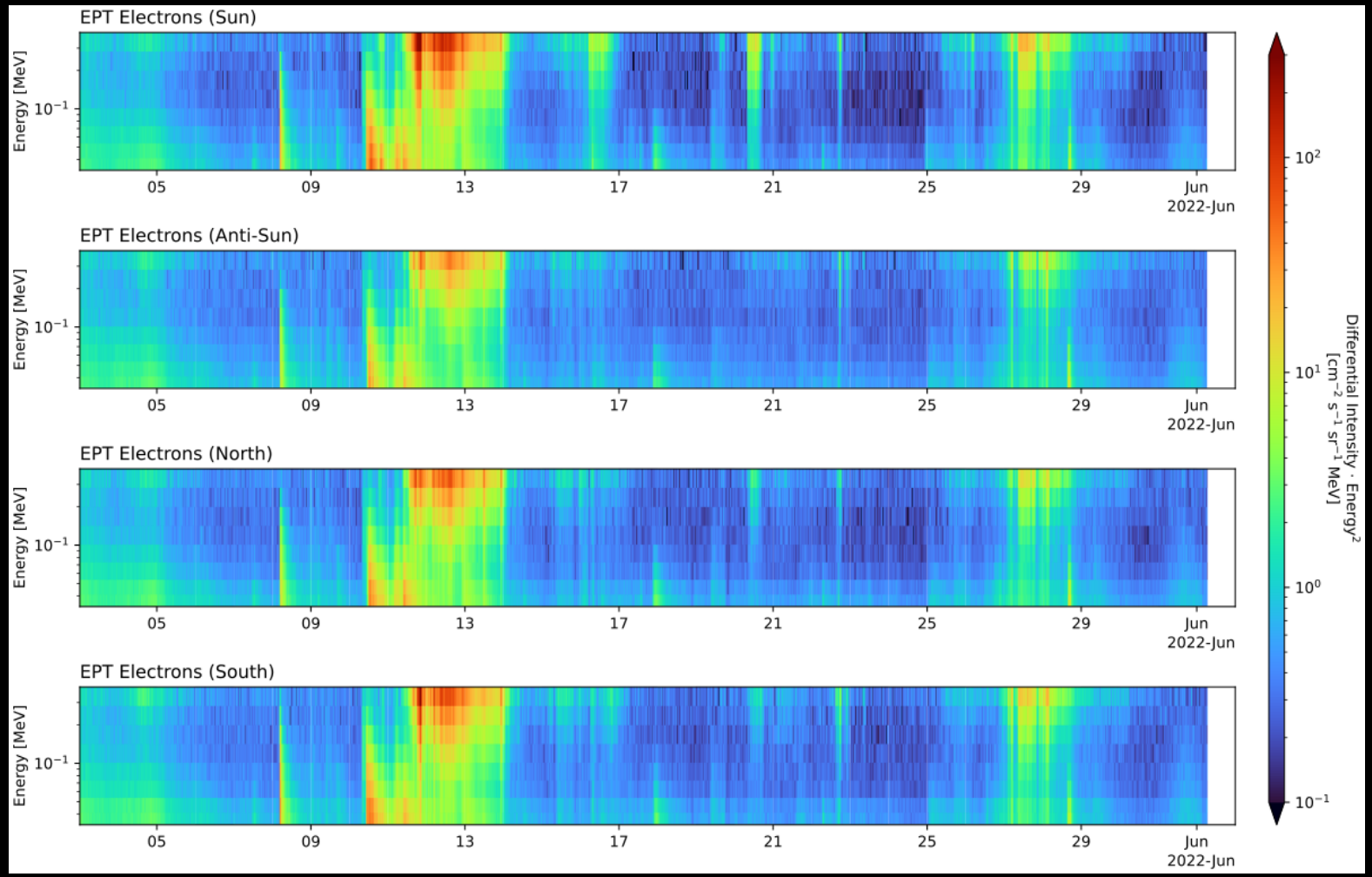


EPD: Energetic Particle Detector

Time series for energetic ion and electron intensities for selected particle energies. EPT and HET omnidirectional intensities are calculated by averaging the measurements of the four telescopes.

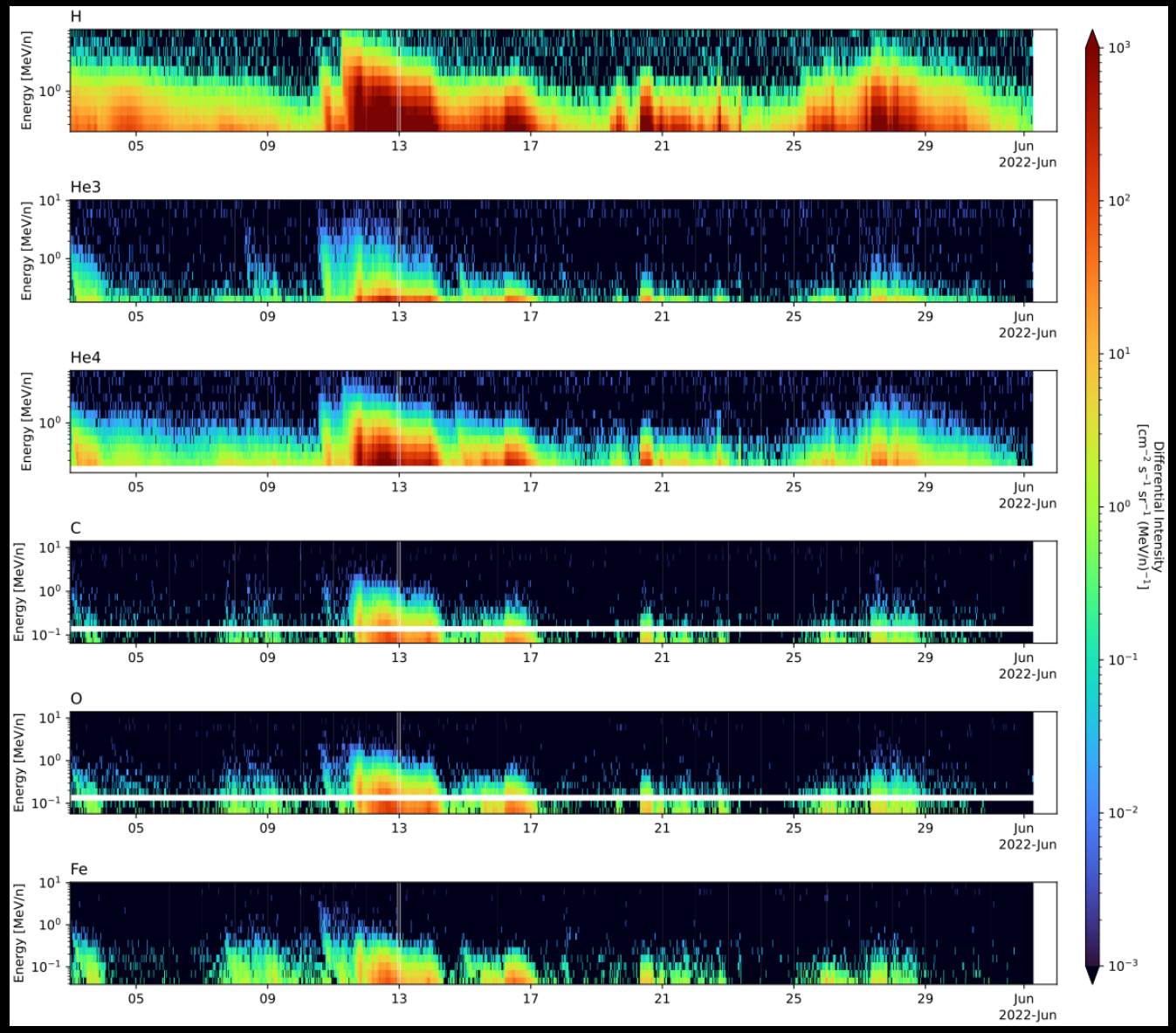


EPD: Energetic Particle Detector



Dynamic spectra for energetic electrons observed by all EPT telescopes.
EPT sun and anti-sun telescopes look along the average Parker spiral in opposite directions.
EPT north and south telescopes point respectively towards the north and south ecliptic hemispheres.

EPD: Energetic Particle Detector



Dynamic spectra for selected ion species as measured by the SIS A telescope (looks sunward in the direction of the average Parker spiral)

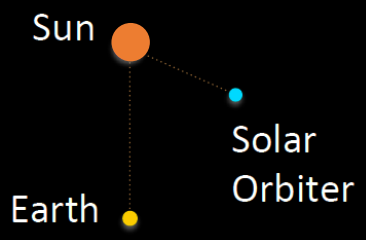
STIX: X-ray Spectrometer/Telescope

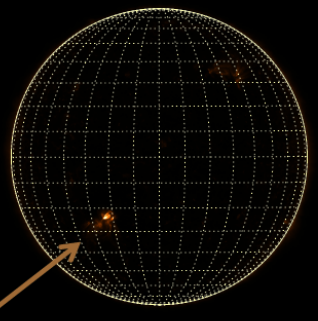
Krucker et al. (2020)

PI: Samuel Krucker, FHNW

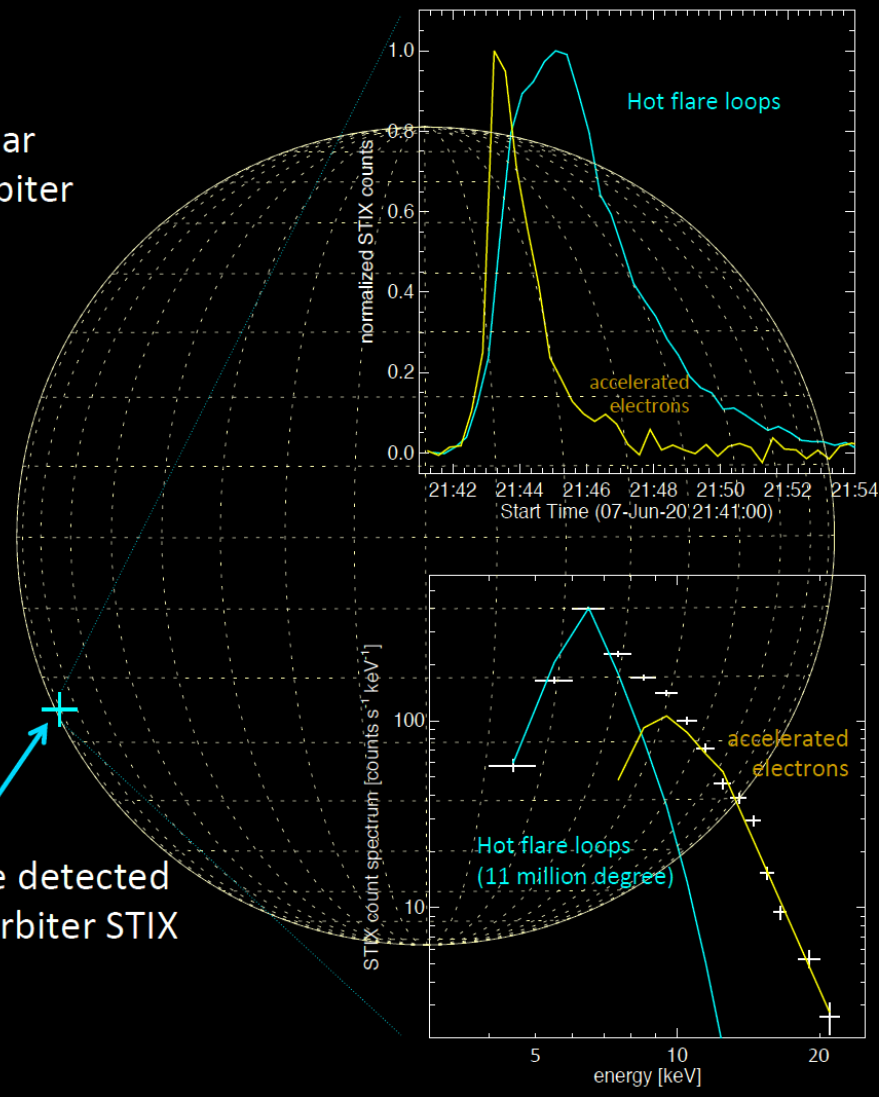
- Spectroscopy of X-ray emission in 4-150 keV energy range
- Indirect imaging (Fourier-based)

Distribution in space, time and energy of X-ray emitting energetic electrons in the solar atmosphere





Solar flare seen from Earth with SDO

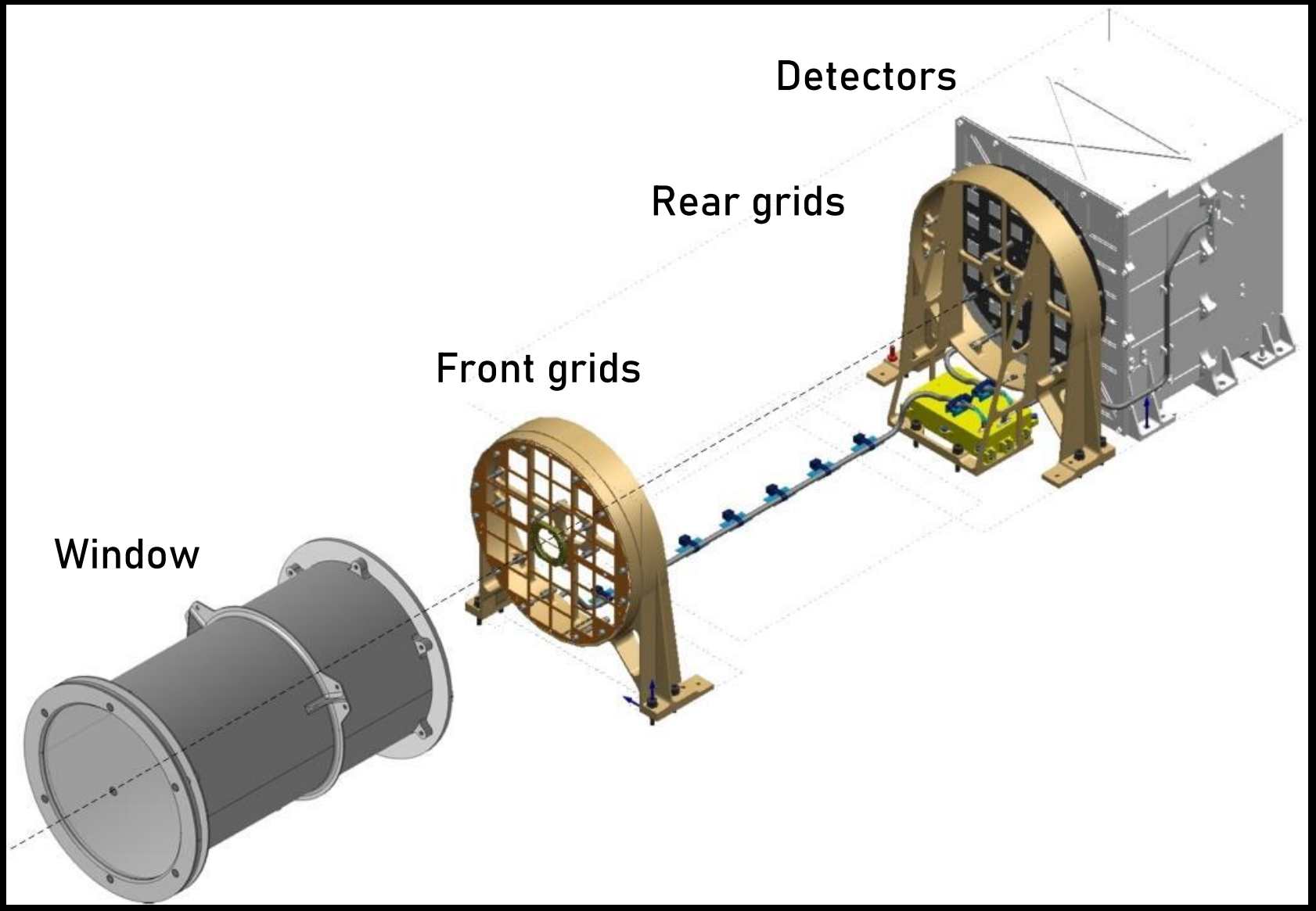


Same flare detected by Solar Orbiter STIX

Flare position, lightcurves and spectrum in X-ray, on June 7 2020.

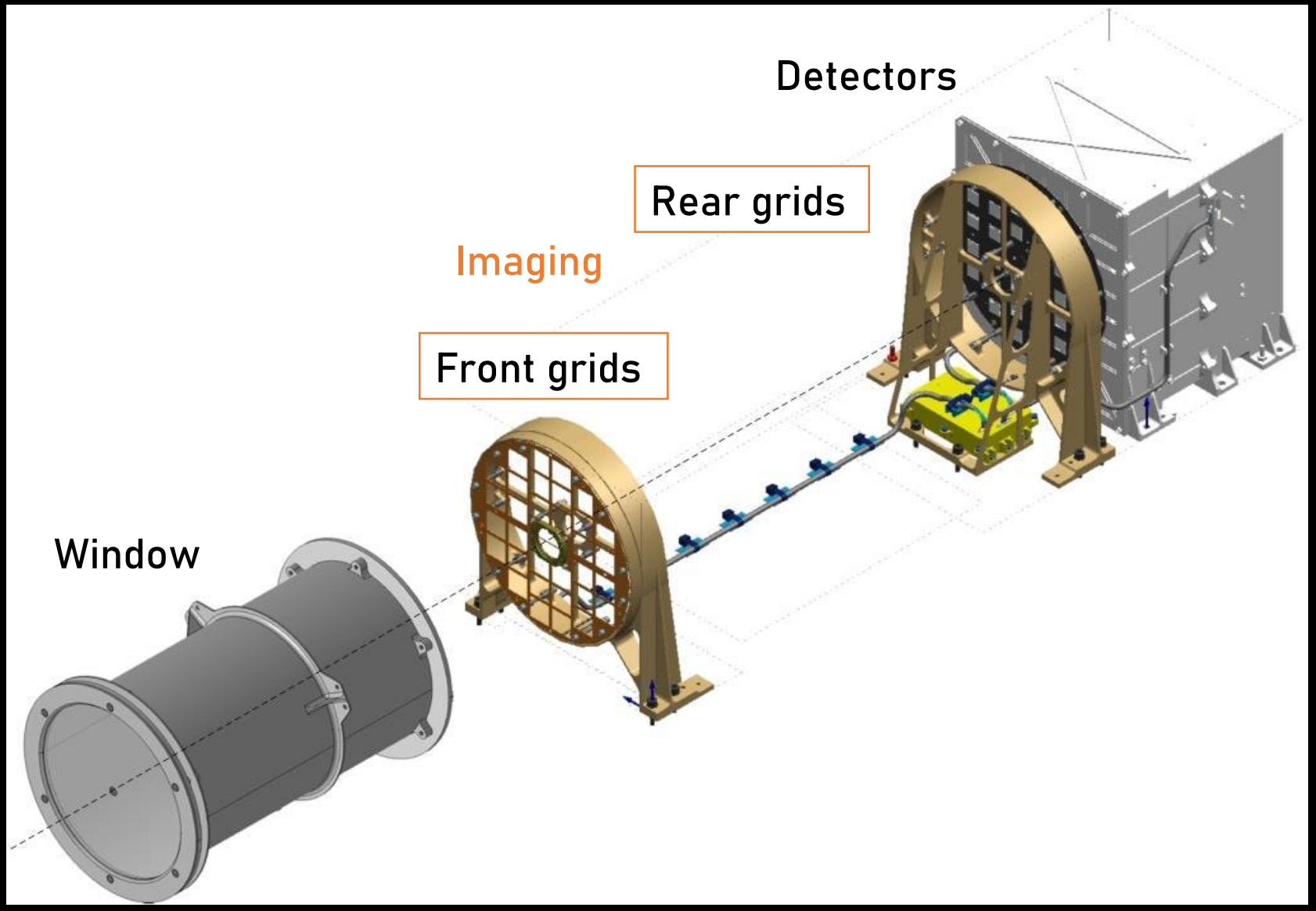
STIX: Spectrometer/Telescope Imaging X-rays

Krucker et al. (2020)



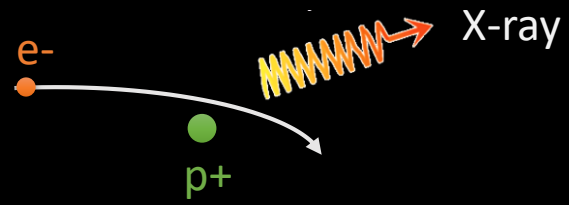
STIX: Spectrometer/Telescope Imaging X-rays

Krucker et al. (2020)



STIX: Spectrometer/Telescope Imaging X-rays

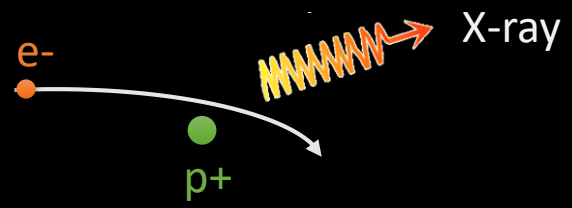
What do we see with X-rays?



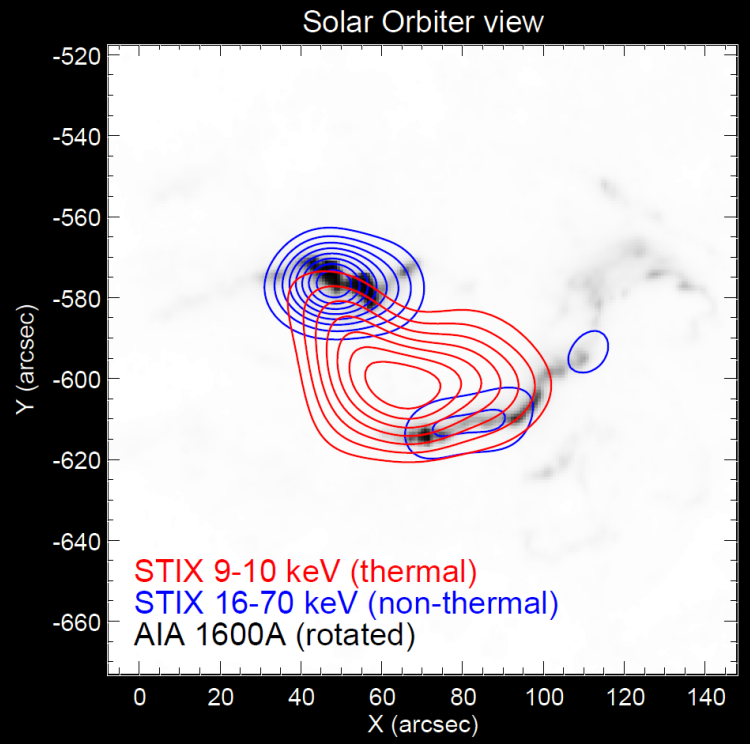
Bremsstrahlung emission

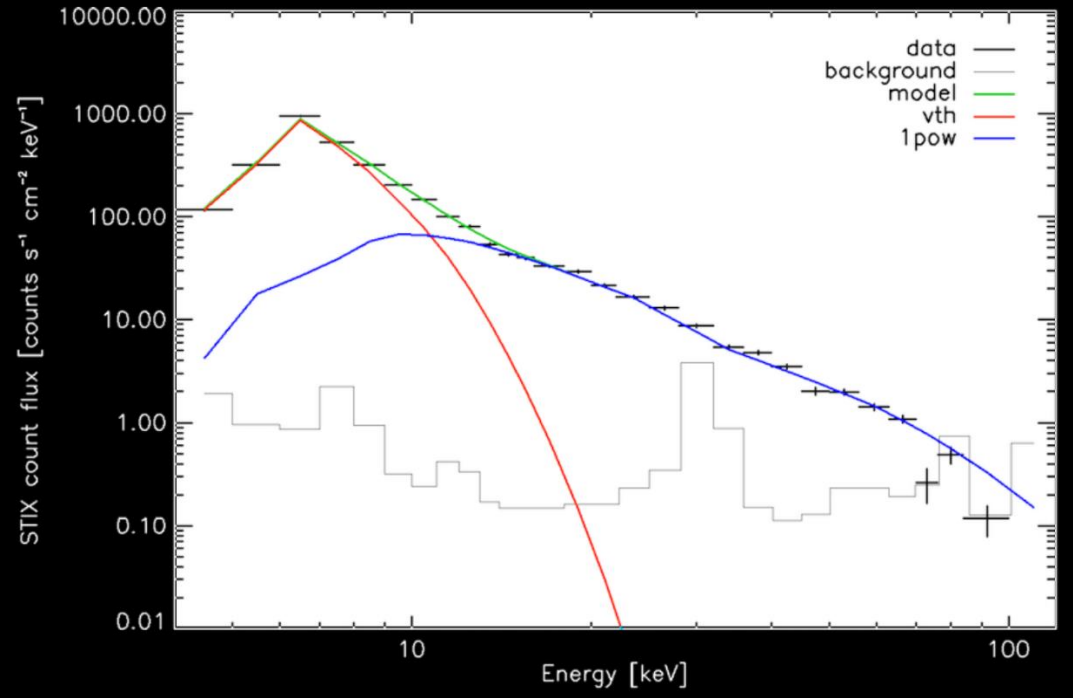
STIX: Spectrometer/Telescope Imaging X-rays

What do we see with X-rays?



Bremsstrahlung emission

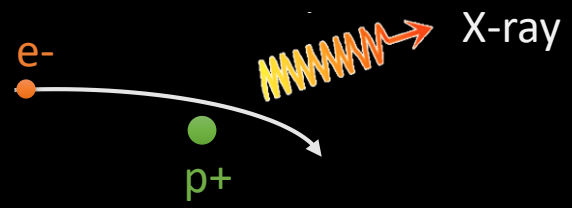




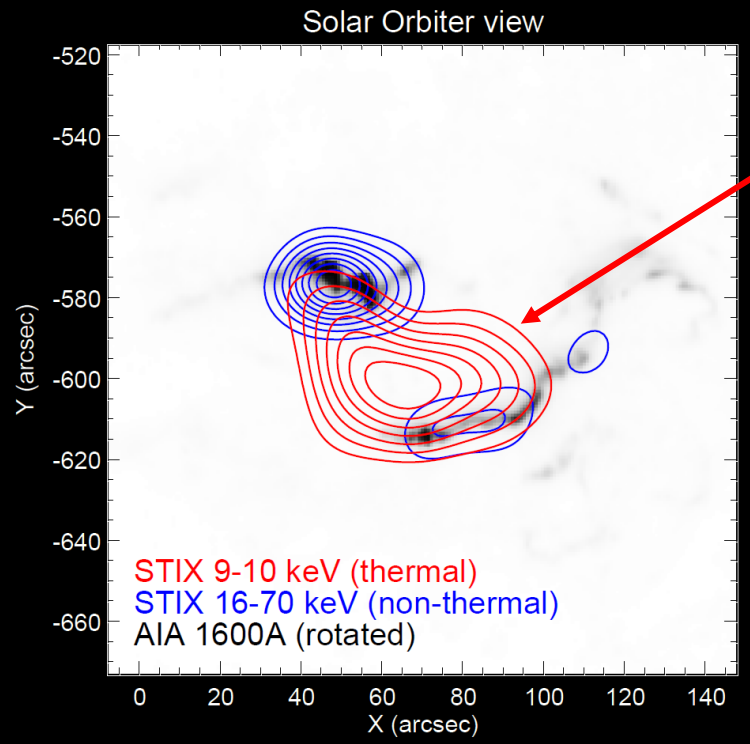
From Klein et al. (accepted)

STIX: Spectrometer/Telescope Imaging X-rays

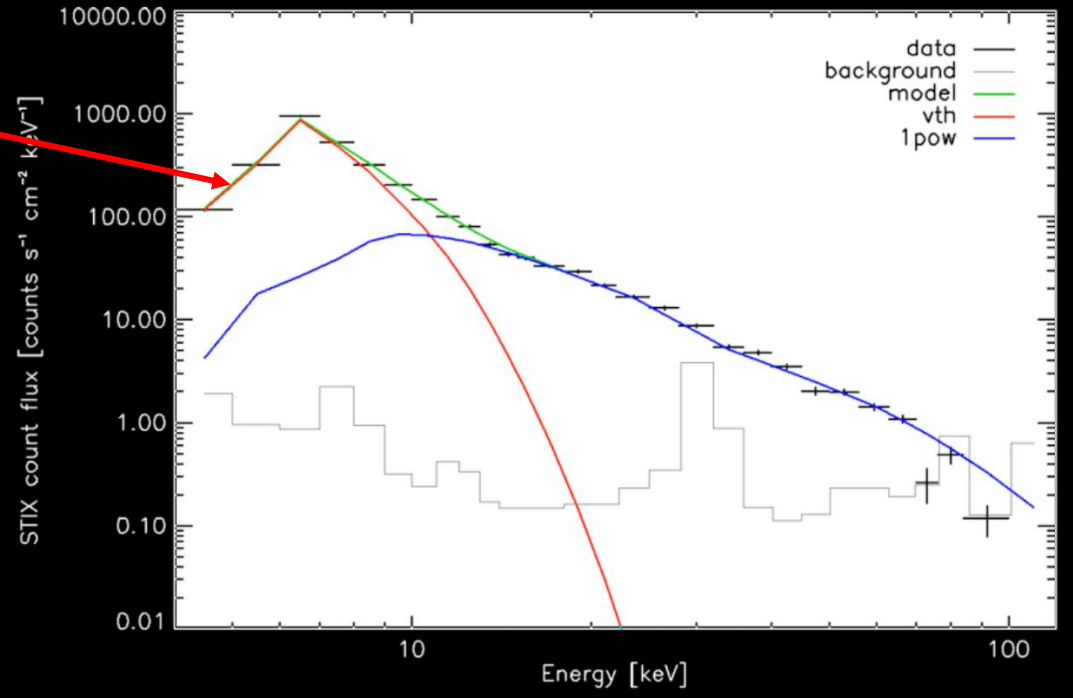
What do we see with X-rays?



Bremsstrahlung emission



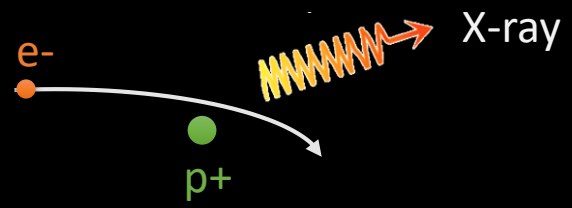
Hot plasma
"thermal emission"
in loops



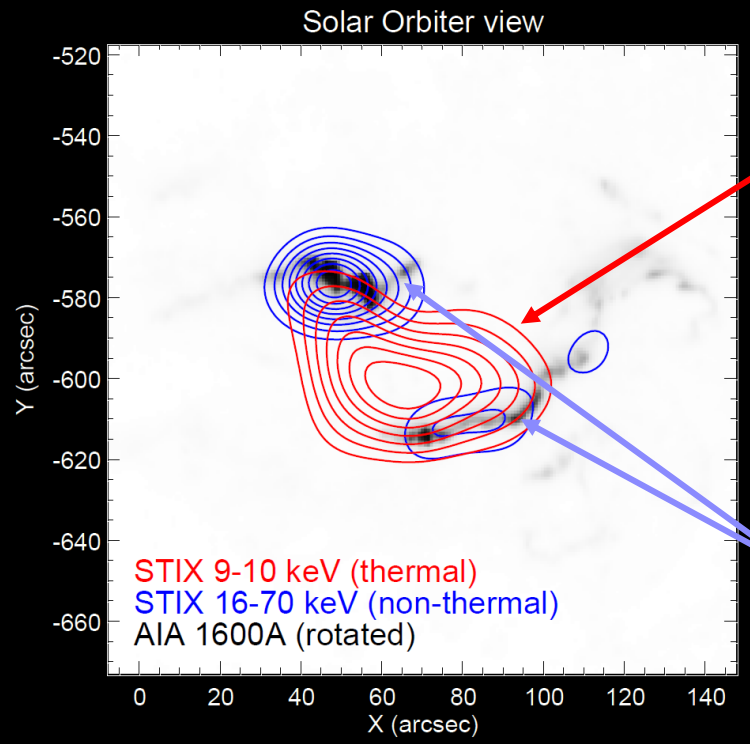
From Klein et al. (accepted)

STIX: Spectrometer/Telescope Imaging X-rays

What do we see with X-rays?

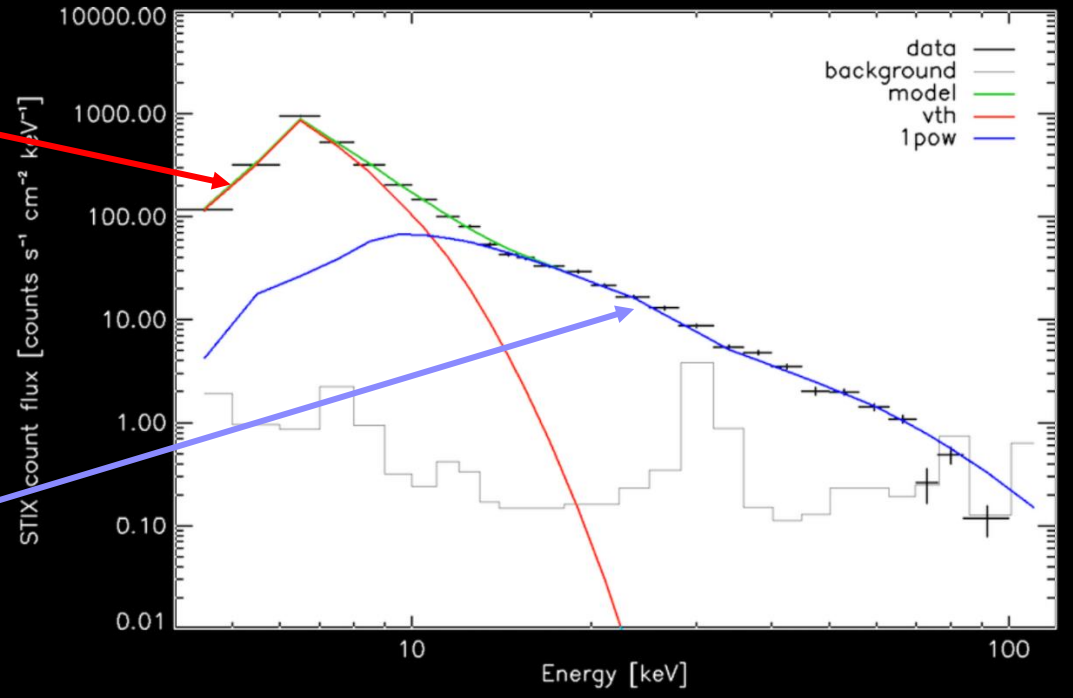


Bremsstrahlung emission



Hot plasma
"thermal emission"
in loops

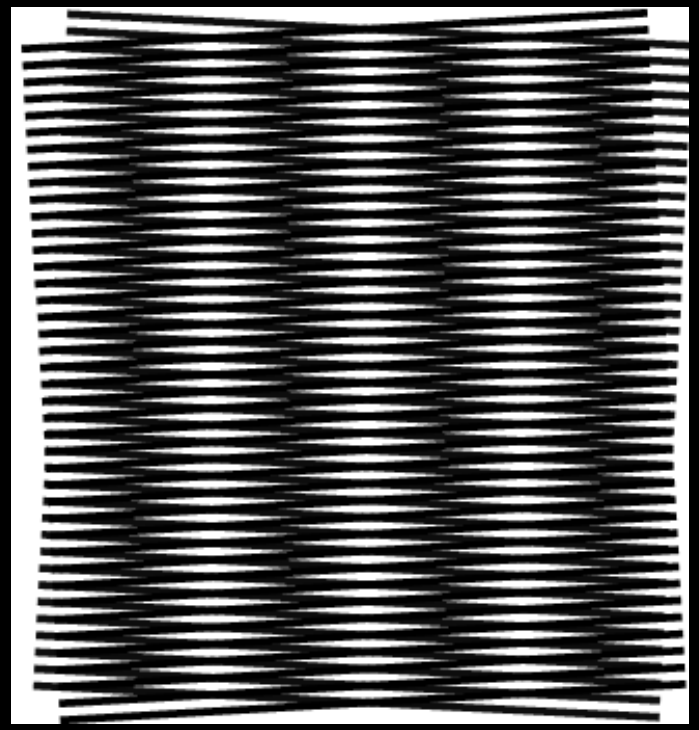
Energetic
electrons
"non-thermal
emission"
In footpoints



From Klein et al. (accepted)

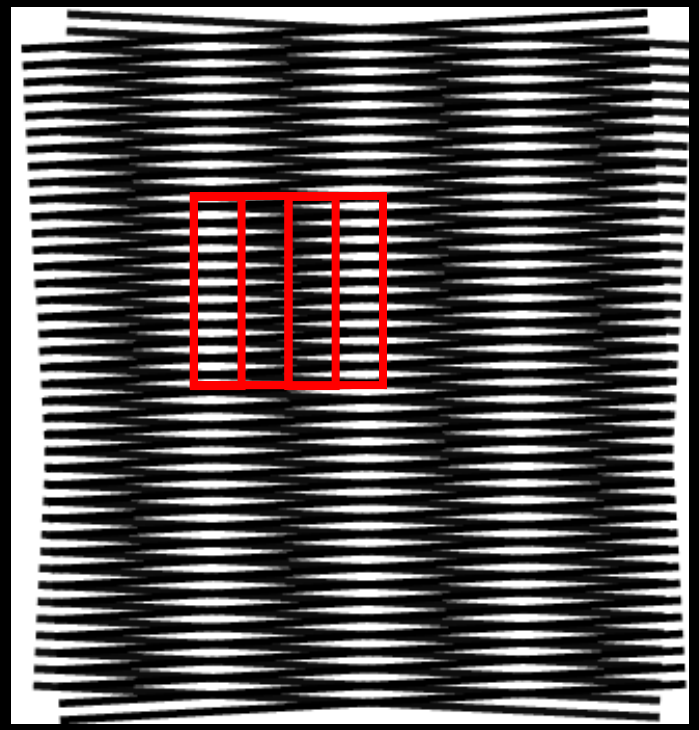
STIX: Spectrometer/Telescope Imaging X-rays

Imaging: two grids to create a moiré pattern

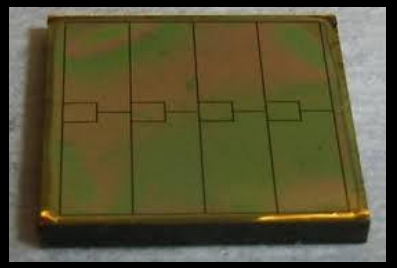


STIX: Spectrometer/Telescope Imaging X-rays

Imaging: two grids to create a moiré pattern

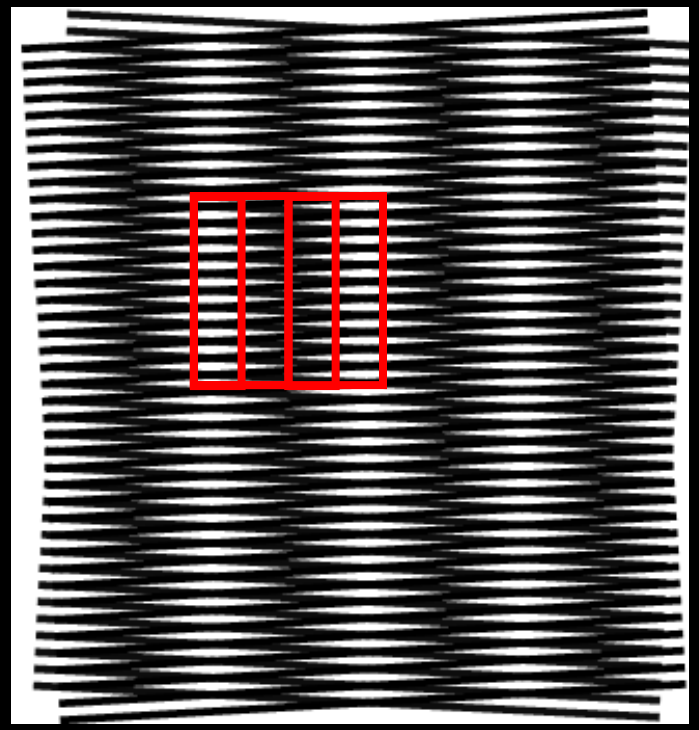


STIX pixels

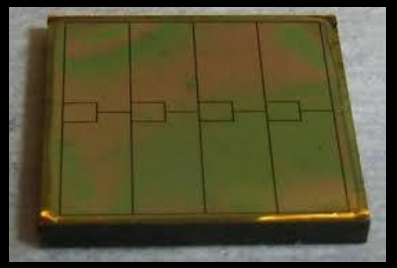


STIX: Spectrometer/Telescope Imaging X-rays

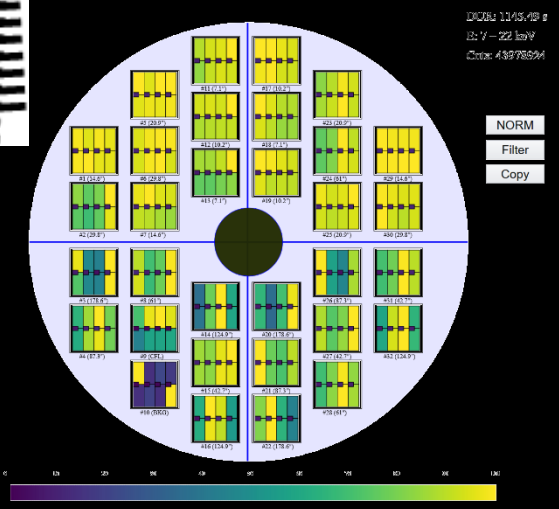
Imaging: two grids to create a moiré pattern



STIX pixels

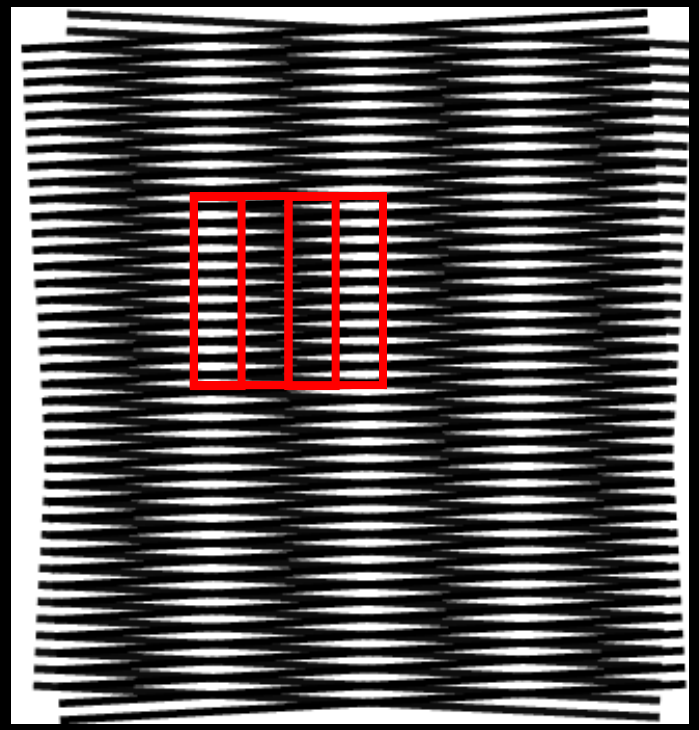


8.8 mm

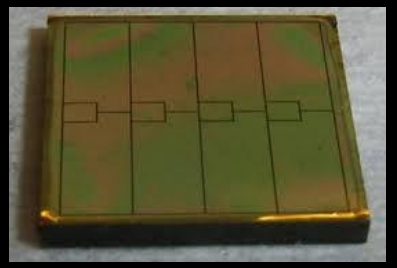


STIX: Spectrometer/Telescope Imaging X-rays

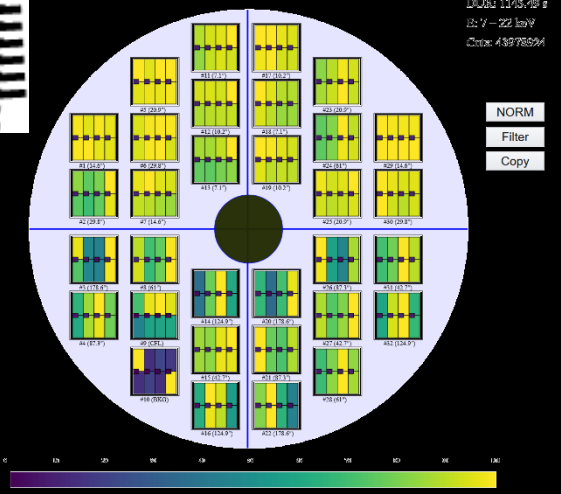
Imaging: two grids to create a moiré pattern



STIX pixels



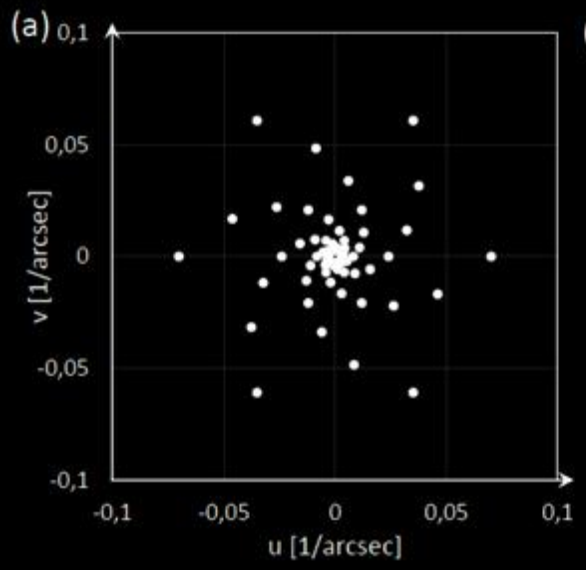
8.8 mm

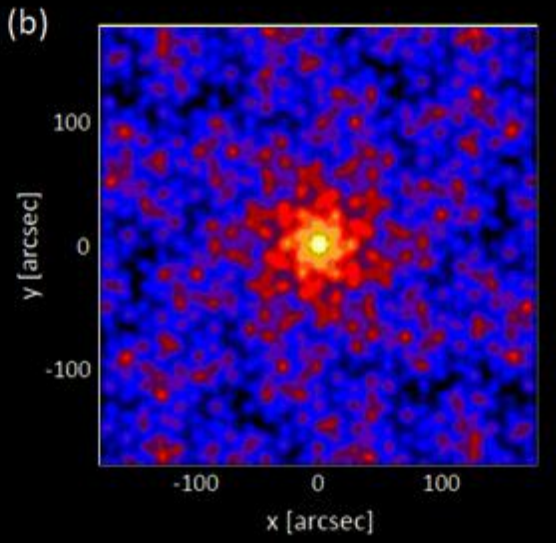


Average pitch of the grid
→ One spatial scale (resolution)

Orientation (average angle) of the grid
→ One direction in space

One moiré pattern
= one visibility in the Fourier space



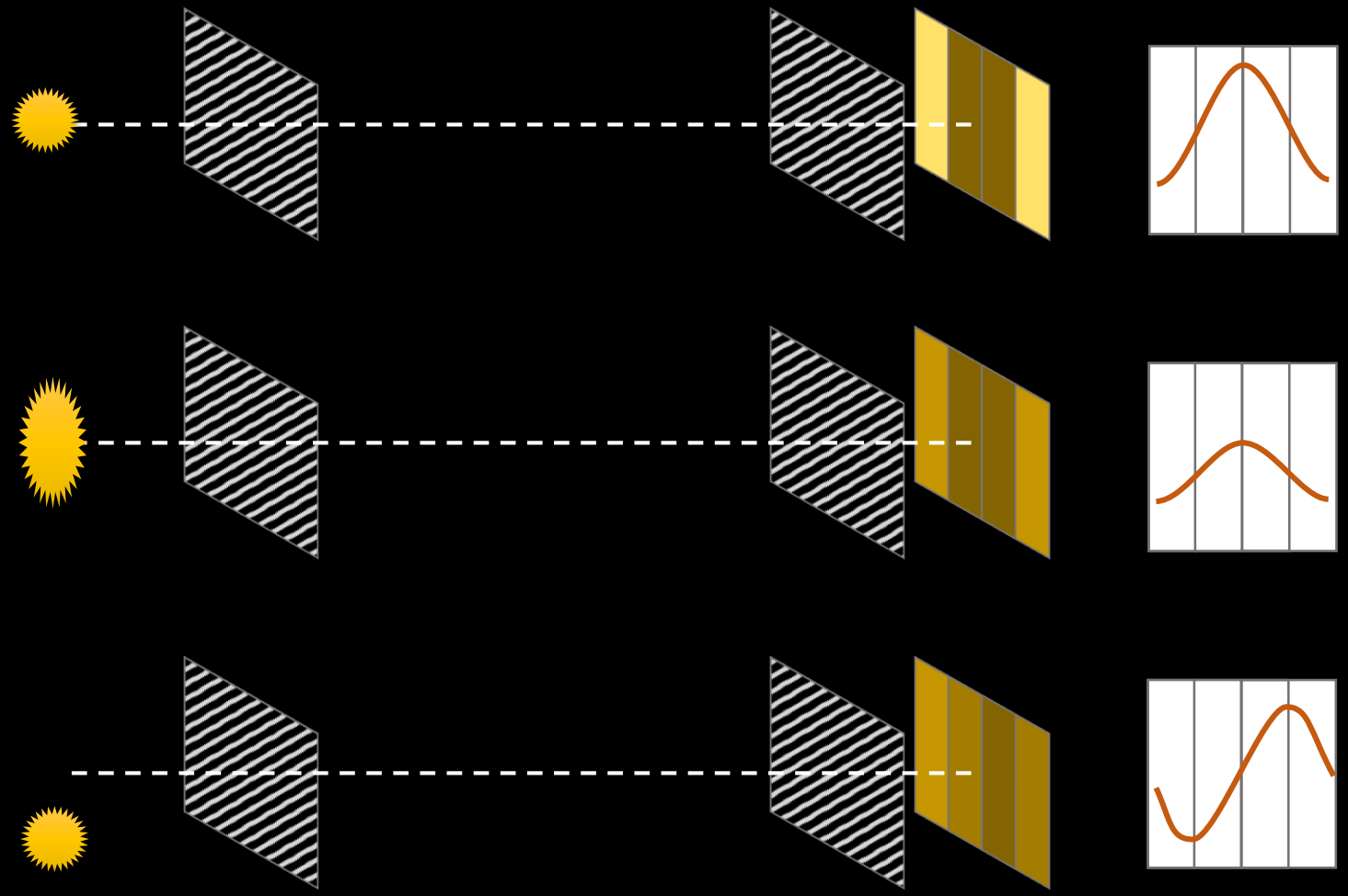


STIX: Spectrometer/Telescope Imaging X-rays

The moiré pattern amplitude and phase depend on the source size and location

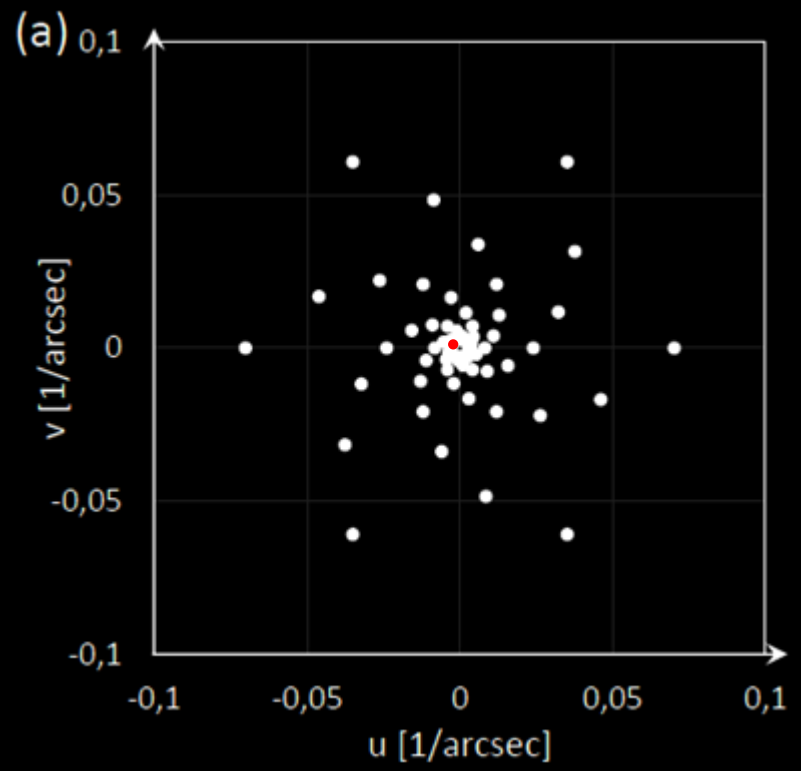
Extended source

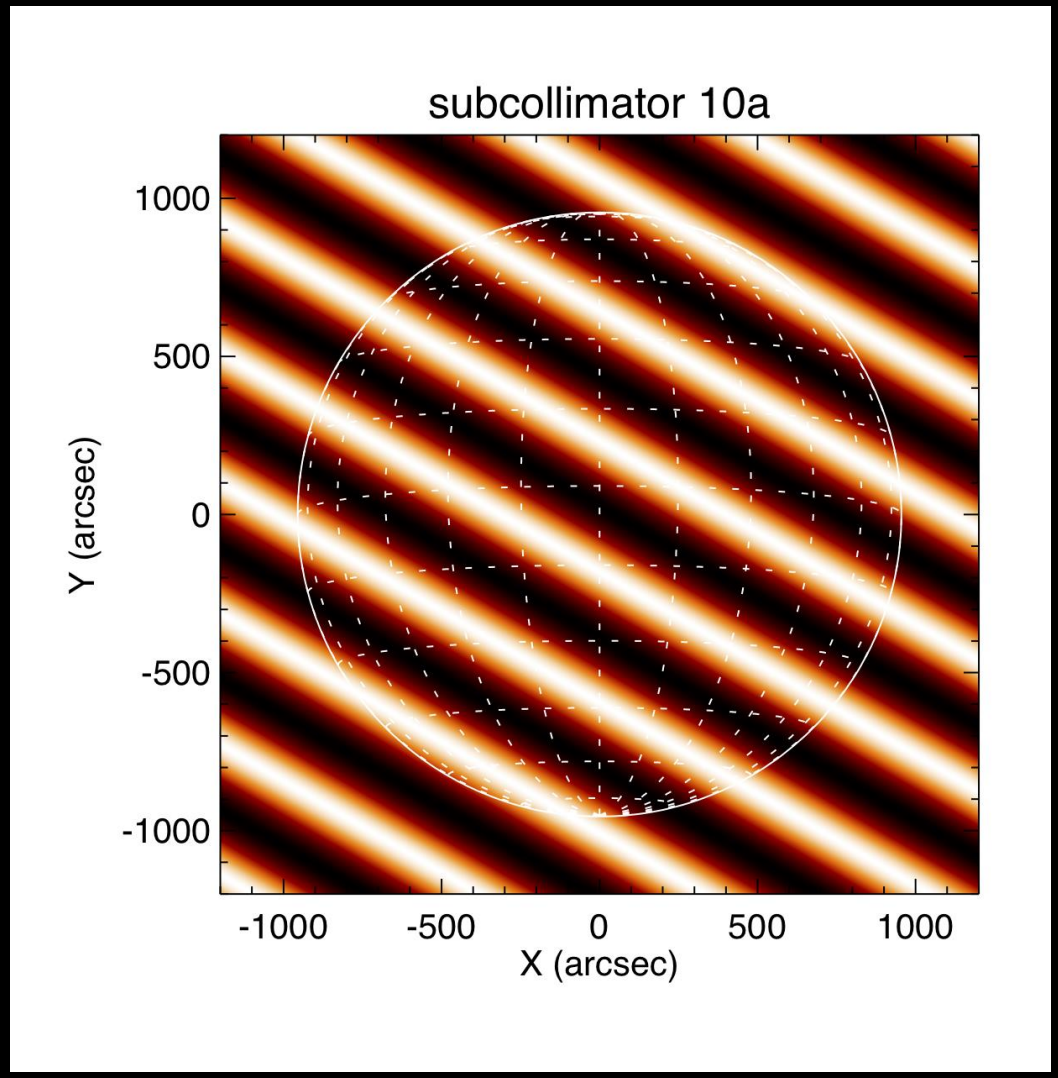
Off-axis source



STIX: Spectrometer/Telescope Imaging X-rays

STIX = 30 visibilities

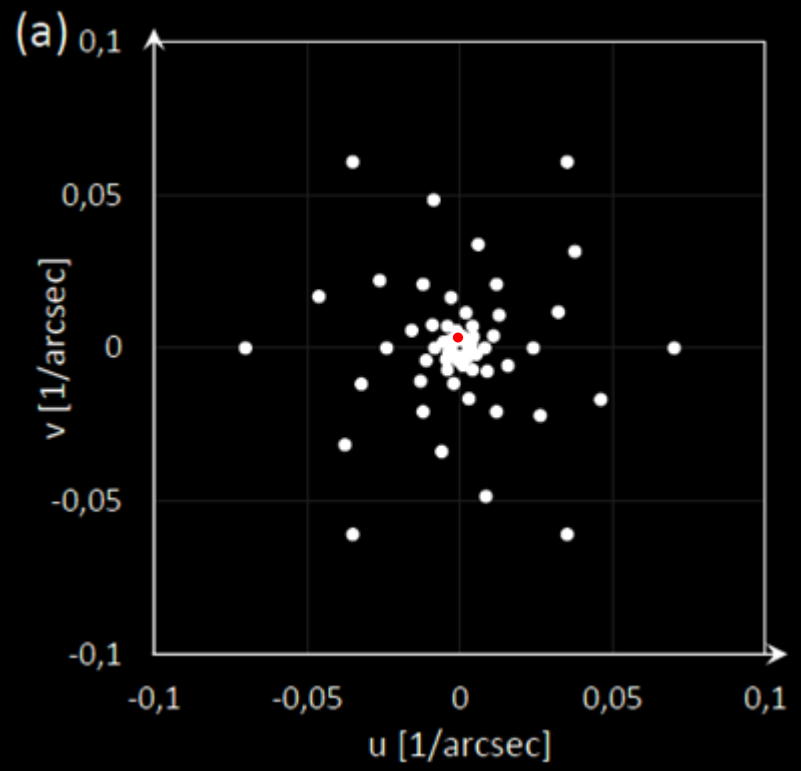


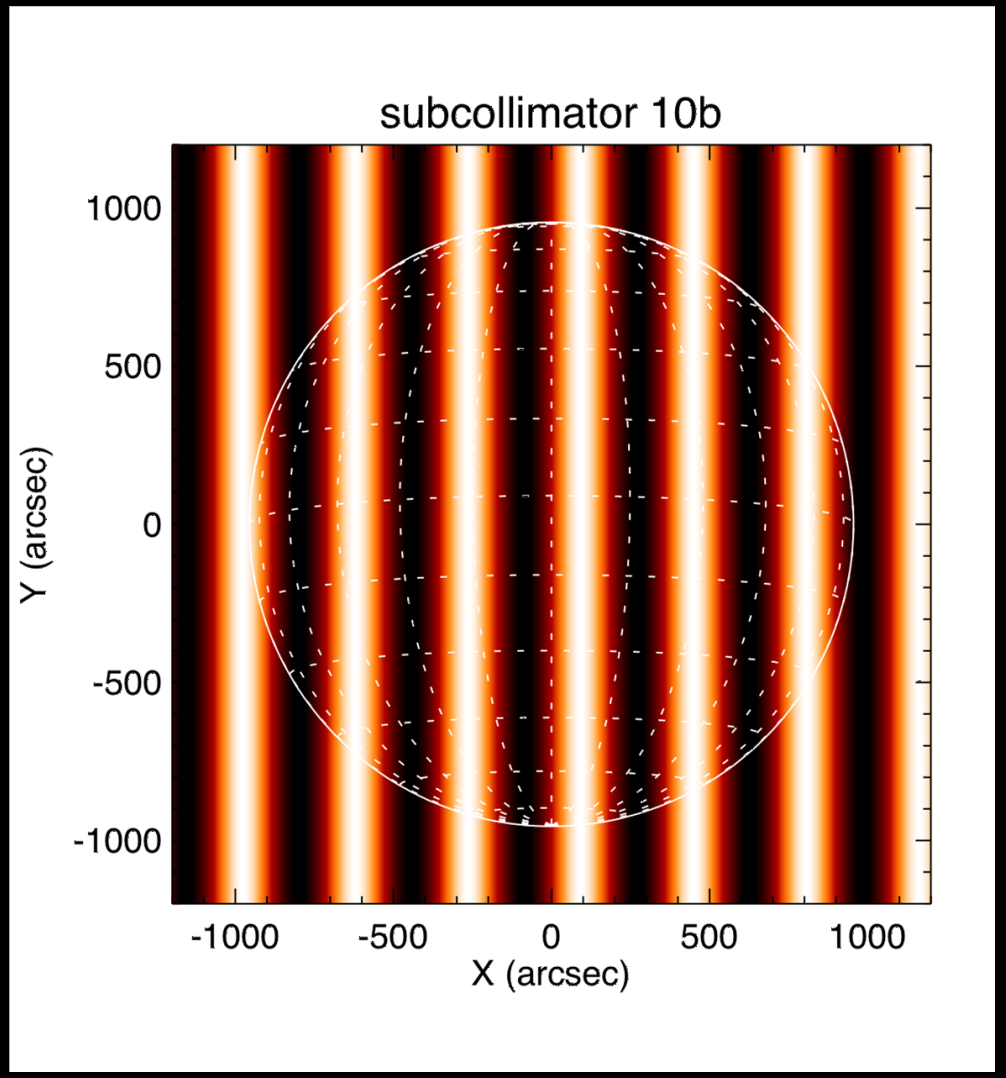


Courtesy of S. Krucker

STIX: Spectrometer/Telescope Imaging X-rays

STIX = 30 visibilities

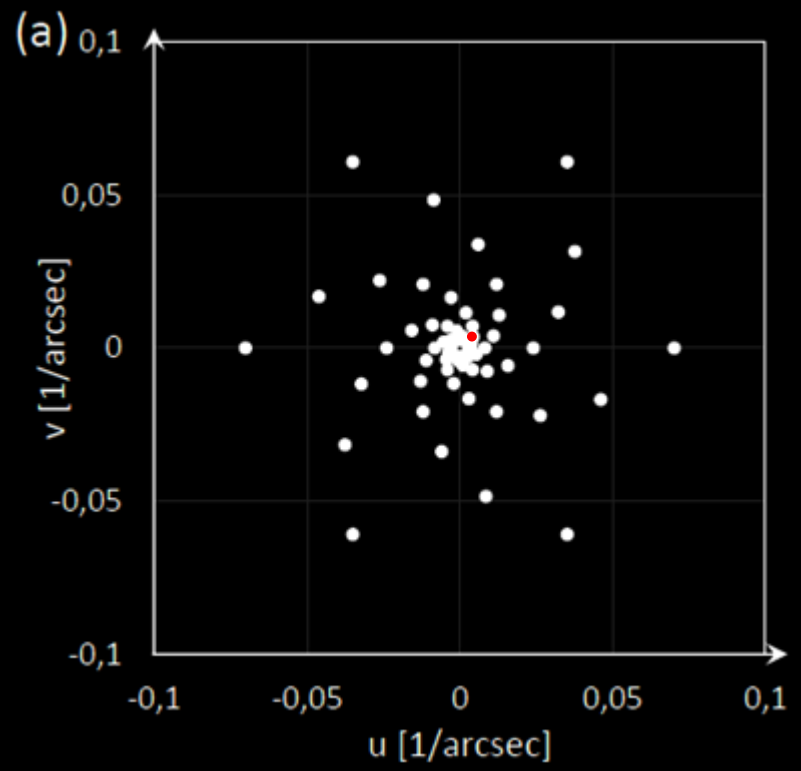


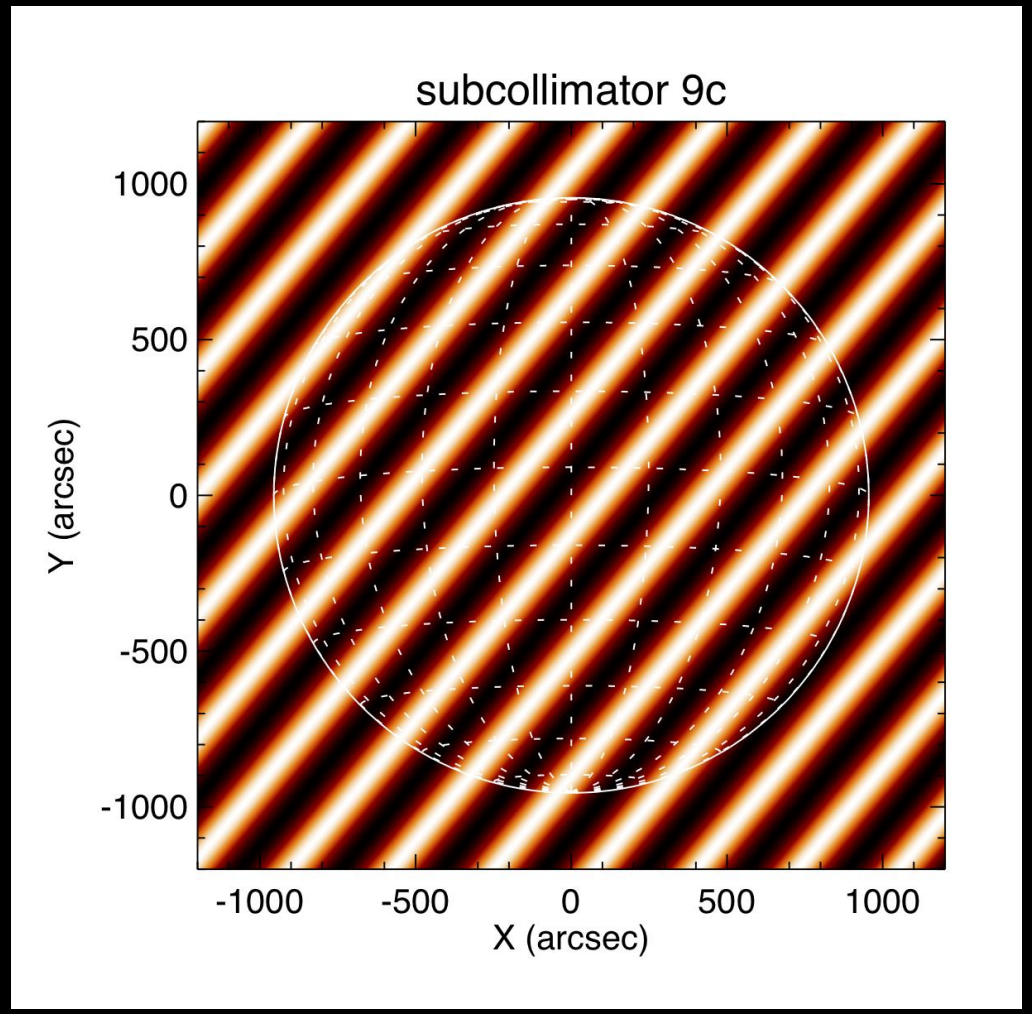


Courtesy of S. Krucker

STIX: Spectrometer/Telescope Imaging X-rays

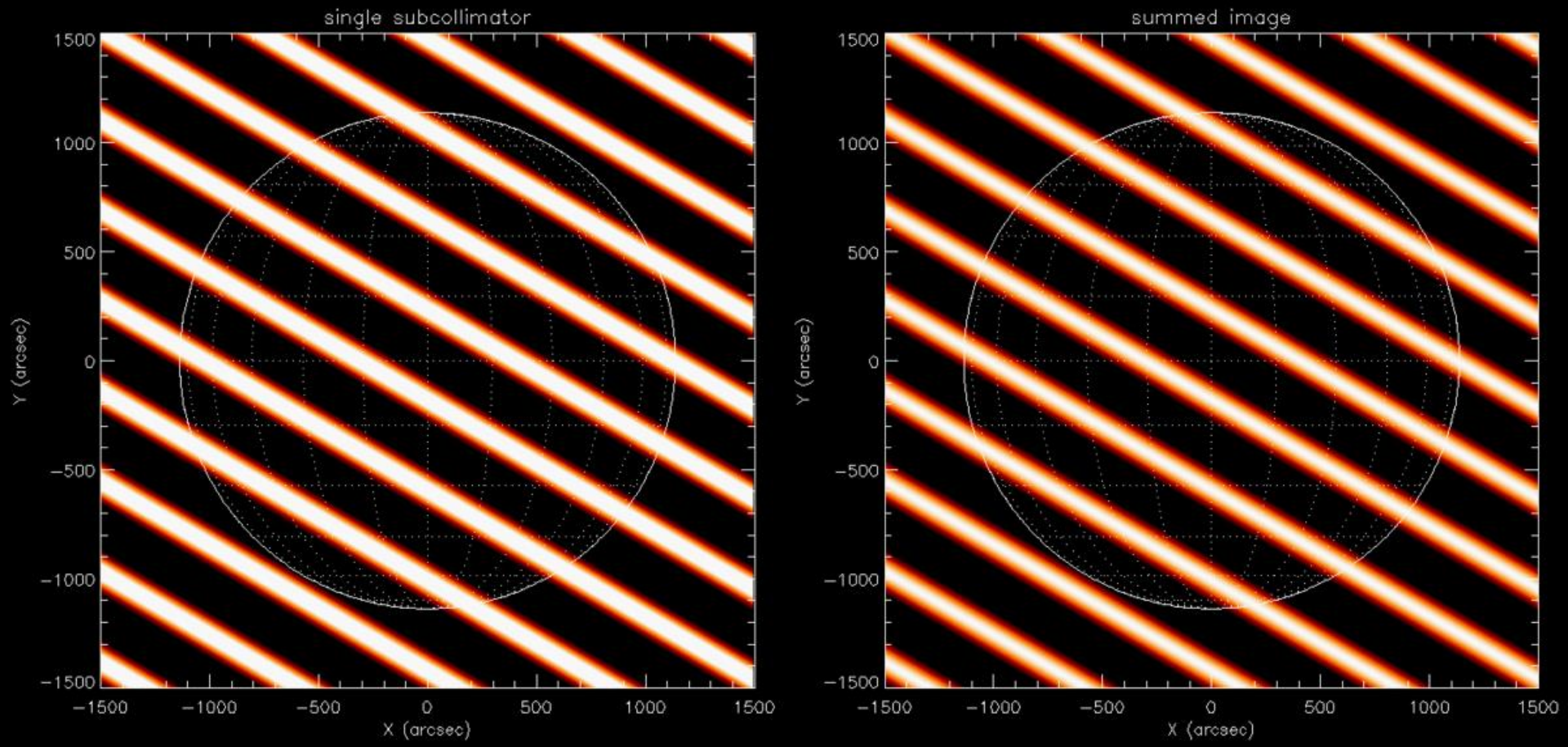
STIX = 30 visibilities





Courtesy of S. Krucker

STIX: Spectrometer/Telescope Imaging X-rays



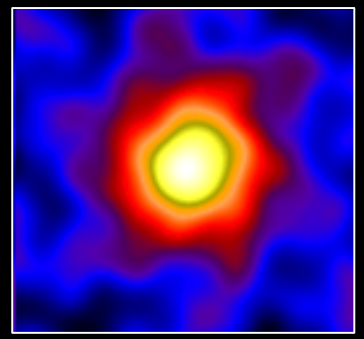
Flare of April 17, 2021

Courtesy of S. Krucker

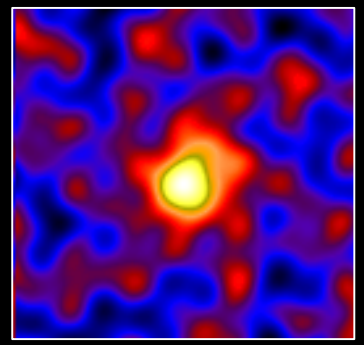
STIX: Spectrometer/Telescope Imaging X-rays

Imaging algorithms

Backprojection = Fourier transform



Natural weighting



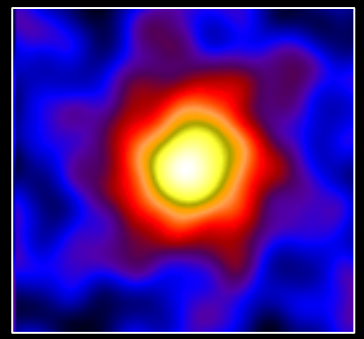
Uniform weighting

Source + instrument response

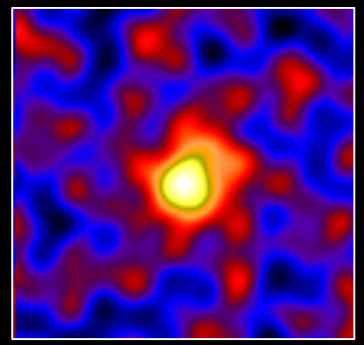
STIX: Spectrometer/Telescope Imaging X-rays

Imaging algorithms

Backprojection = Fourier transform



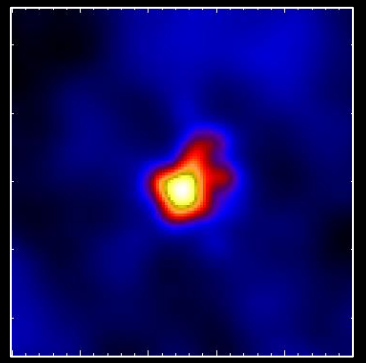
Natural weighting

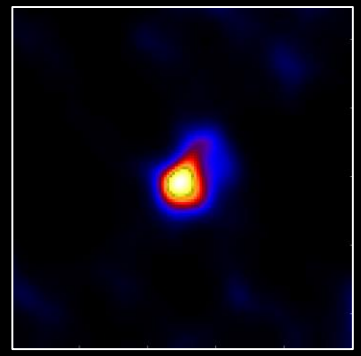


Uniform weighting

Source + instrument response

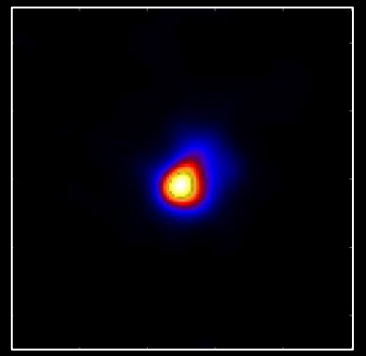
CLEAN algorithm

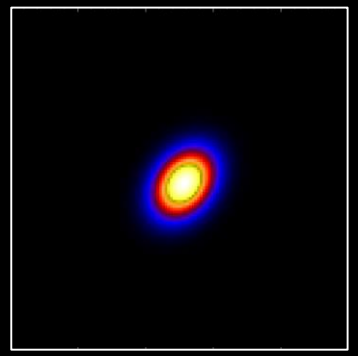




Maximum Entropy Method

Expectation Maximization



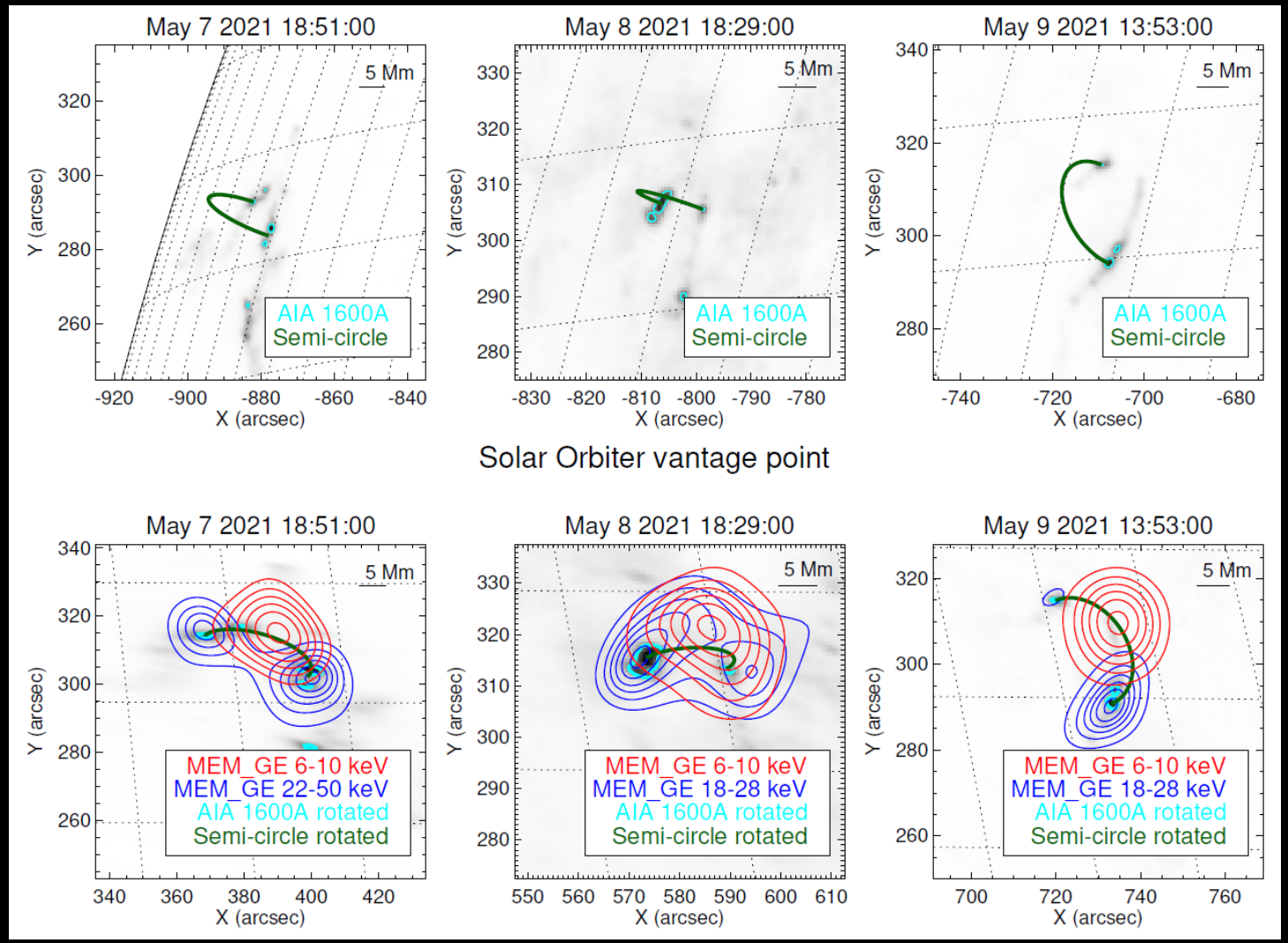


Visibility Forward Fit

STIX: Spectrometer/Telescope Imaging X-rays

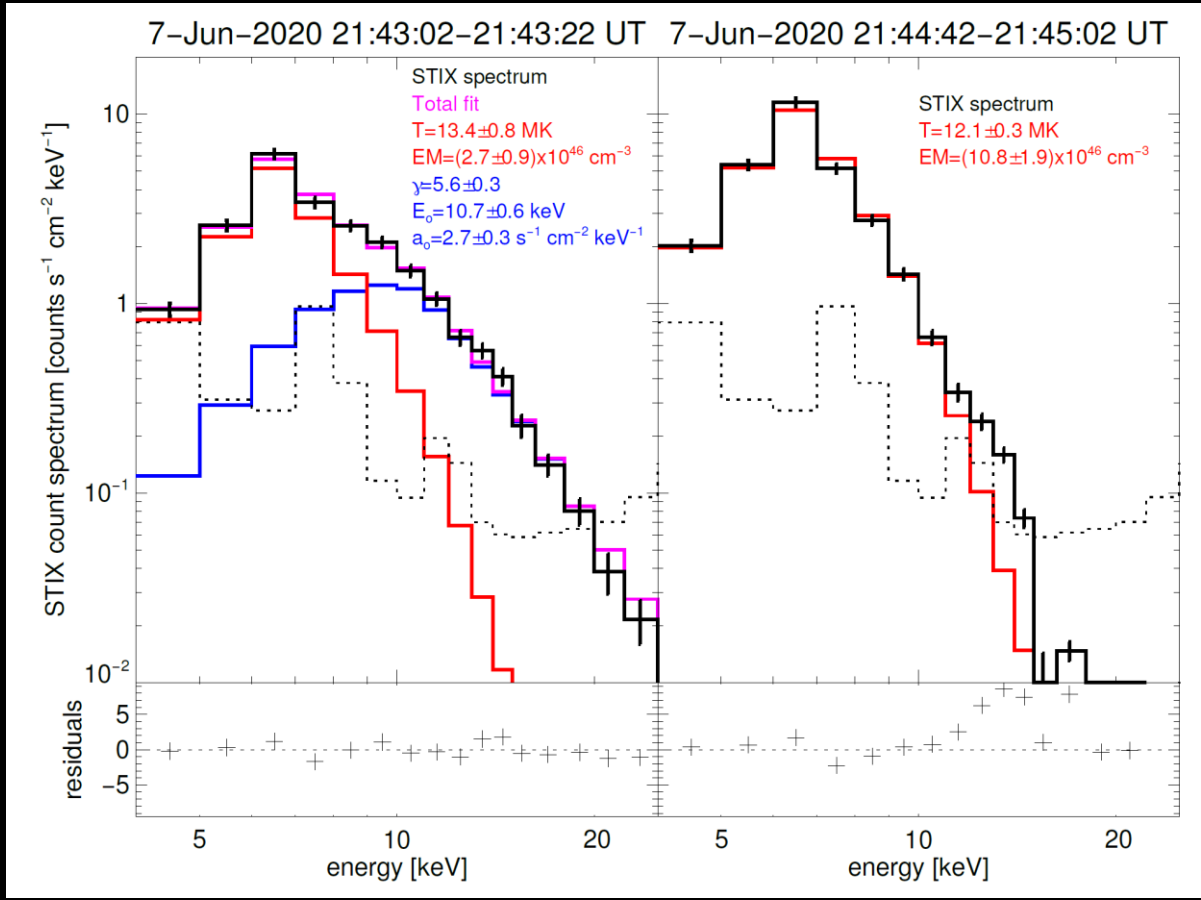
Comparing Solar Orbiter observations with “Earth-based” observatories (e.g. SDO)

→ The challenge of rotation & projection



Massa et al. (in revision)

STIX: Spectrometer/Telescope Imaging X-rays



Battaglia et al. (2021)

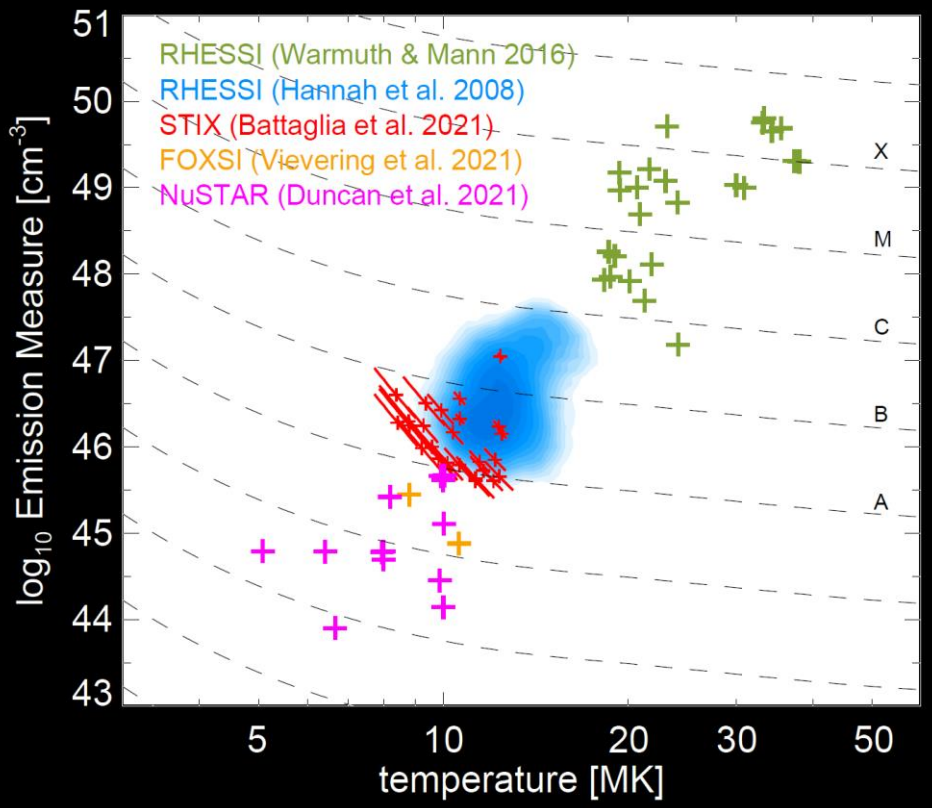
X-ray spectroscopy with STIX

- 30 energy bins
- Lowest cadence 0.1 sec

Spectral distribution of energetic particles
→ To be compared to spectral distribution of energetic electrons in-situ (EPD)

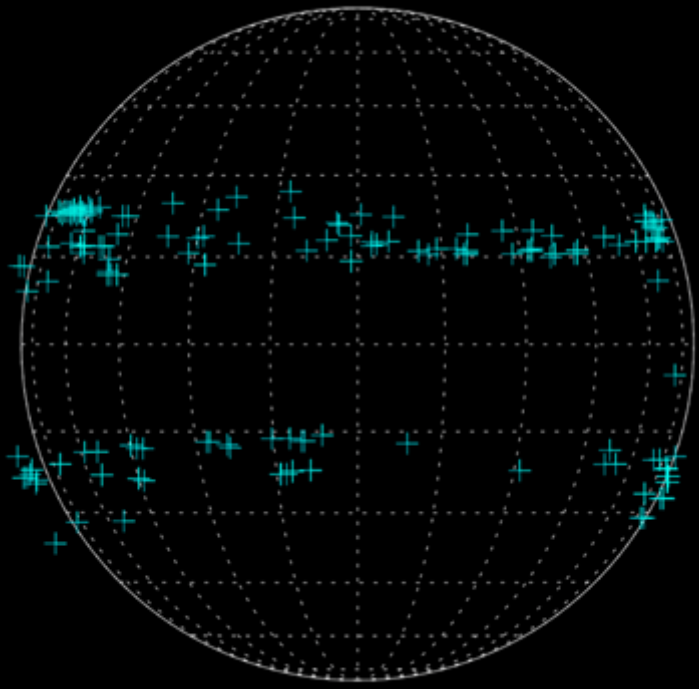
STIX: Spectrometer/Telescope Imaging X-rays

STIX flares



STIX microflares during commissioning phase

Battaglia et al. (2021)

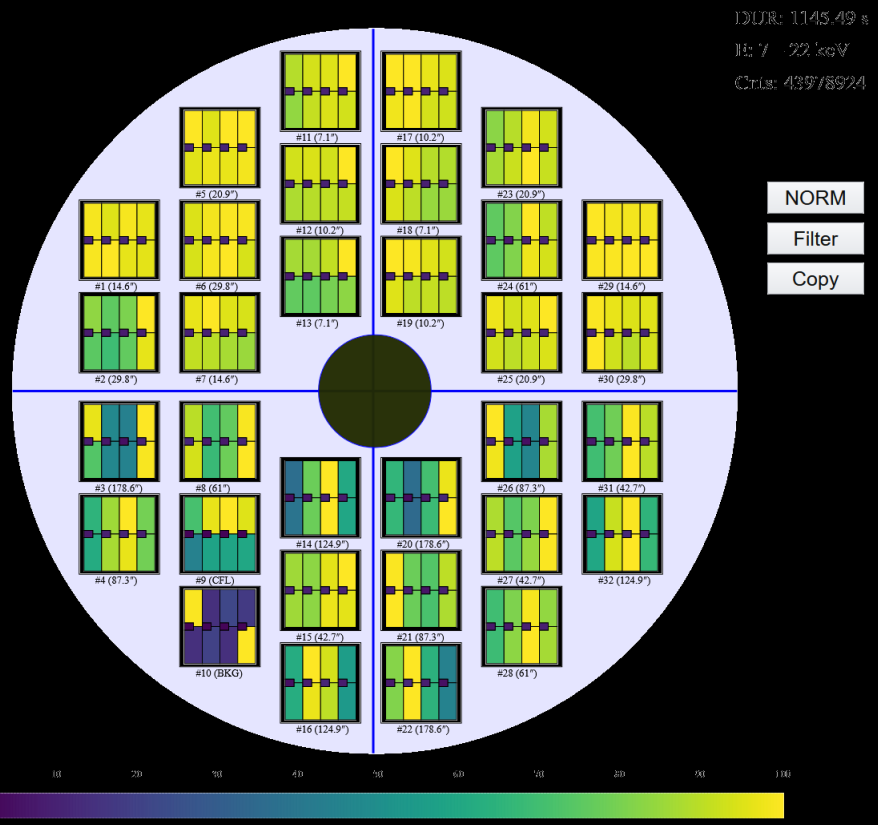


264 flares detected by STIX in 2021

STIX flare list:
https://datacenter.stix.i4ds.net/view/flares/list

STIX: Spectrometer/Telescope Imaging X-rays

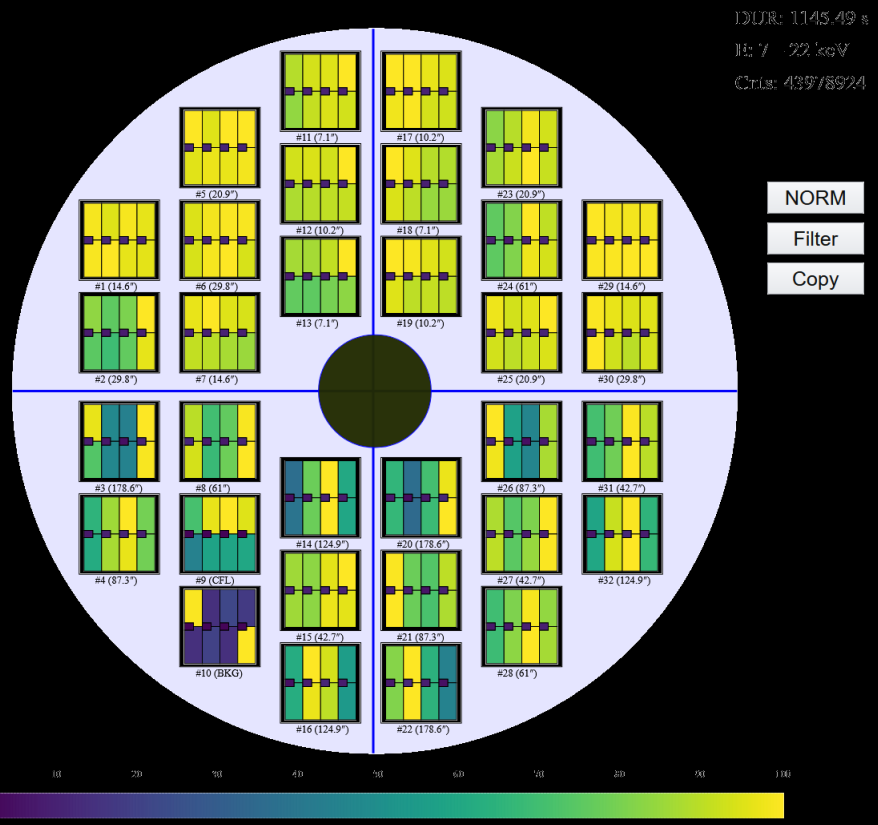
✓ STIX is observing (almost) all the time since January 2021
Because of low telemetry, not all data is downloaded from the spacecraft.



For interesting time intervals (i.e. during flares), “pixel data” is downloaded: counts in different pixels over time
→ Necessary to reconstruct images
→ Different time binning can be requested

STIX: Spectrometer/Telescope Imaging X-rays

✓ STIX is observing (almost) all the time since January 2021
Because of low telemetry, not all data is downloaded from the spacecraft.

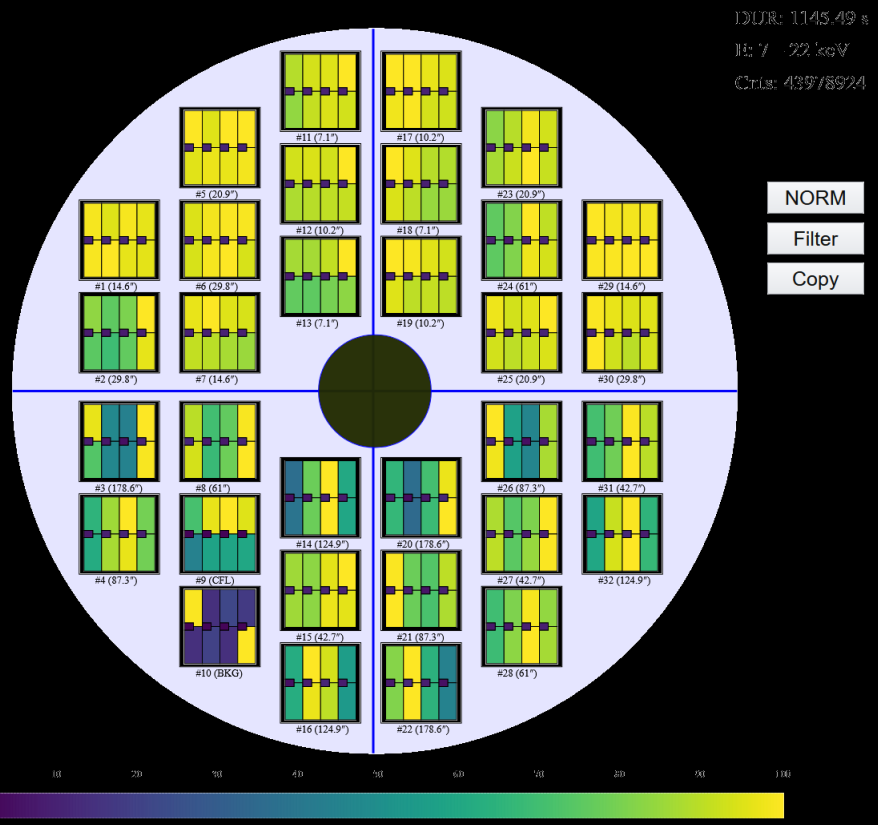


For interesting time intervals (i.e. during flares), “pixel data” is downloaded: counts in different pixels over time
→ Necessary to reconstruct images
→ Different time binning can be requested

At other times, “spectrogram data” is downloaded
→ Counts summed over pixels and detectors
→ No imaging
→ Different time binning possible

STIX: Spectrometer/Telescope Imaging X-rays

✓ STIX is observing (almost) all the time since January 2021
Because of low telemetry, not all data is downloaded from the spacecraft.



For interesting time intervals (i.e. during flares), “pixel data” is downloaded: counts in different pixels over time
→ Necessary to reconstruct images
→ Different time binning can be requested

At other times, “spectrogram data” is downloaded
→ Counts summed over pixels and detectors
→ No imaging
→ Different time binning possible

YOU can request data for your favorite flare (stored for a few weeks in onboard memory)

STIX: Spectrometer/Telescope Imaging X-rays

✓ STIX is observing (almost) all the time since January 2021

Because of low telemetry, not all data is downloaded from the spacecraft.
Low latency data is used to produce quicklooks (~ updated daily):
https://datacenter.stix.i4ds.net/view/plot/lightcurves

More about STIX data in the remote-sensing hands-on session

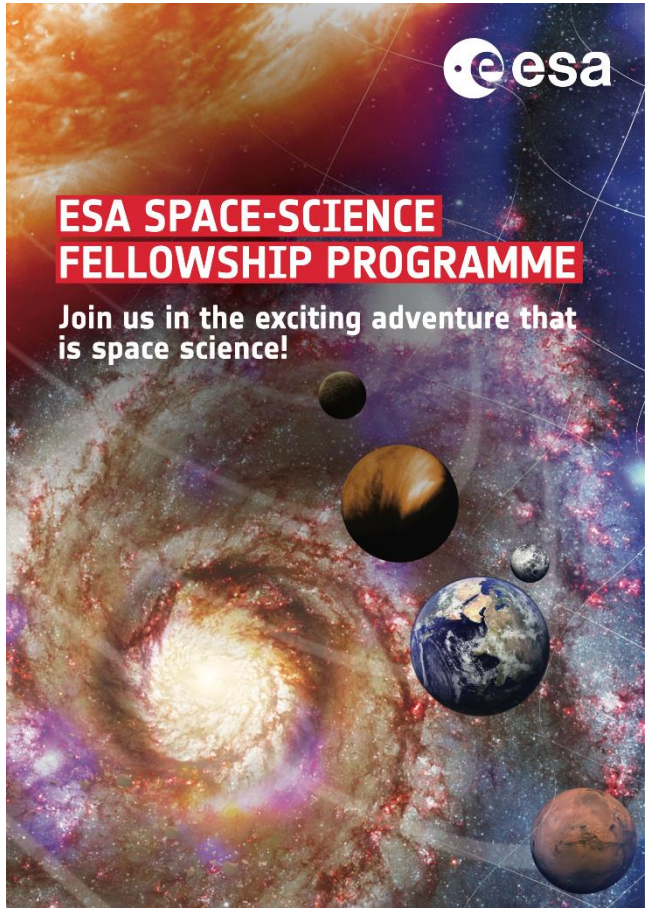
Science data include pixel data (L1) and spectrogram data (L4)
You can request data (will give the data set priority to be downloaded)
Request form:
https://datacenter.stix.i4ds.net/view/datareq/form

Ask the team for help analyzing the data set: software and data format still evolving at this point

Data access: the data is publicly accessible (practically) as soon as it is downloaded from the spacecraft (on the STIX data center at the moment)

Authorship policy: no need to include the STIX PI or STIX team. Only include authors who actually contributed to the study.

ESA Science Research Fellowship



- **What?**

➤ **independent postdoctoral fellowship for ESA State nationals**
➤ research project covering any topic in space science
➤ 2 + 1 years (proposal for 3rd year extension)

- **Where?**

➤ ESTEC (Netherlands), ESAC (Spain) or STScI (USA)

- **Why?**

➤ **100% research time** (optionally <20% functional work, e.g. archive/data science, citizen science, operations, calibration, communication)
➤ insights into ESA environment & activities
➤ mentoring from senior ESA Science Faculty members
➤ training available (e.g. spacecraft design, soft skills, management)
➤ 3000-4200€ net monthly salary (depending on location & experience)
➤ comprehensive health coverage

Website: https://www.cosmos.esa.int/web/space-science-faculty/opportunities/research-fellowships

contact: yannis.zouganelis@esa.int