Energy Spectra of Solar Energetic Electron Events Observed with Solar Orbiter

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Overview

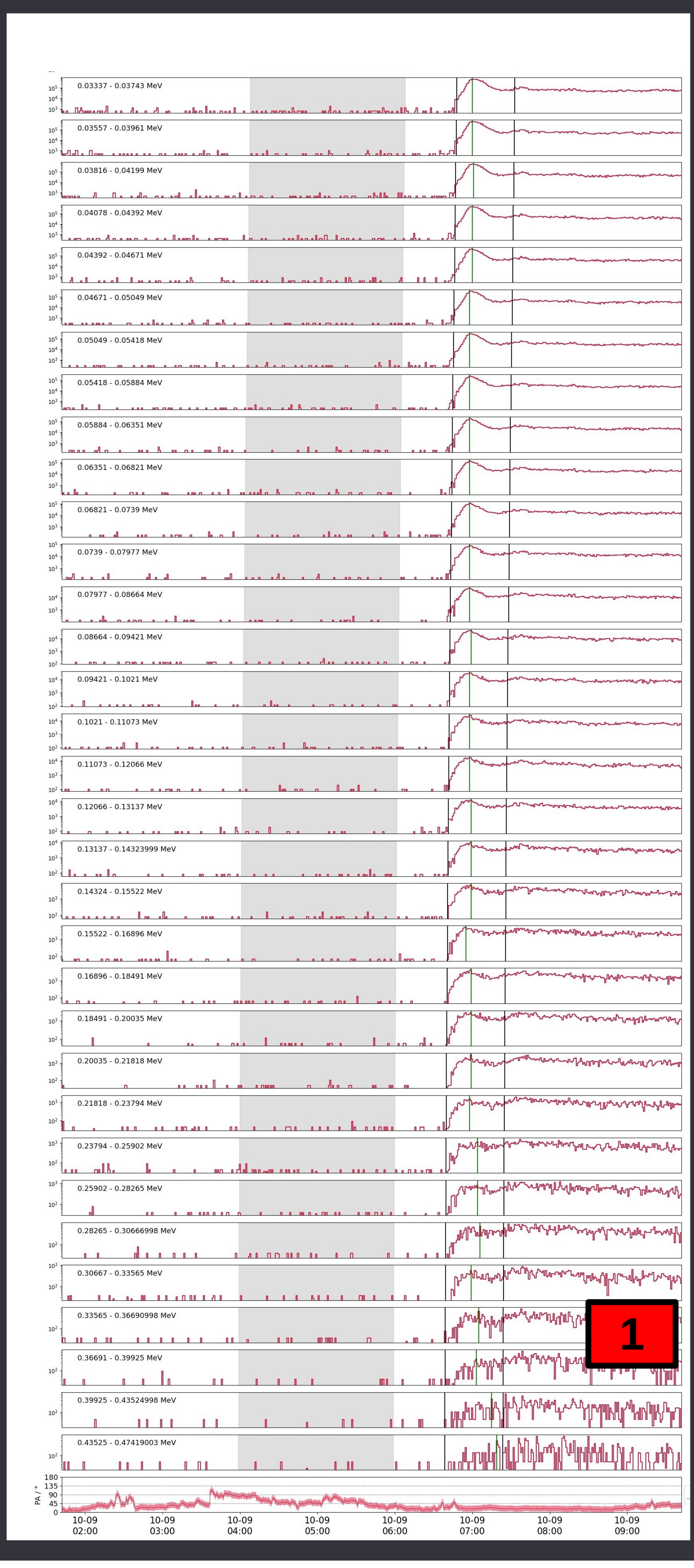
Our analysis focuses on solar energetic electrons (SEEs). We use the novel measurements of the Energetic Particle Detector (EPD) on board the Solar Orbiter (SolO) spacecraft. The combination of EPD's subunits STEP, EPT, and HET offers an unprecedented energy coverage (from the suprathermal to relativistic range).
The novel data from EPD, together with SolO's varying distances to the Sun, allows us to characterise features of the energy spectra of SEEs better than ever before and to pin down interplanetary transport effects.

We determine the peak intensity spectra of the most intense SEE events (intensities above 5 X 10[5] /s cm[2] sr MeV measured at 43 keV) from an event list compiled by the SolO multi-instrument consortium.

Methodology: Peak intensity determination

We use newly developed techniques, taking into account velocity dispersion as well as the pitch angle coverage of the instruments to determine peak intensity spectra (Fig. 1). We characterise the spectral features of each event by fitting the energy spectra (STEP + EPT) with five mathematical models (see Fig. 3-6 for examples). We determine the peak intensity for each energy channel of STEP, EPT and HET, which occur at different times due to velocity dispersion (green vertical lines Fig. 1).
The pre-event background (gray area Fig. 1) is subracted from the peak intensity.
EPT data is corrected for ion contamination.
We only use the 9 centremost pixels of STEP to align the STEP measurements with the instrument opening of EPT.
Energy channels are excluded if:
- The peak intensity does not exceed the background intensity plus 3 times the standard deviations of the background.
- The absolute value of the uncertainty of the bg subtracted flux peak divided by the bg subtracted peak is less than 0.5
- There is a data gap of more than 10% in the time frame during which we are searching for the peak intensity.

We also take into account the pitch angle coverage of the instruments (bottom panel Fig.1) by calculating a quality factor, which gives us an indication of how well the particle beam is measured by the instruments.



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The mathematical models and fits

We fit the energy spectrum of each event with 5 different mathematical models:

$$I(E) = I_0\left(\frac{E}{E_0}\right)^{\gamma_1}$$

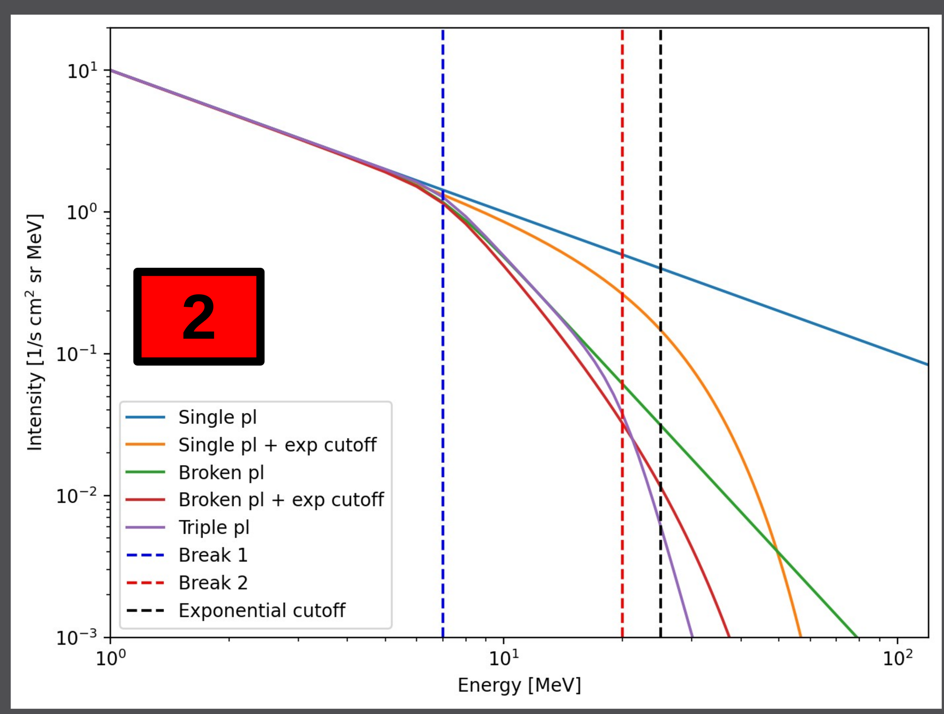
$$I(E) = I_0\left(\frac{E}{E_0}\right)^{\gamma_1}\left(\frac{E^\alpha + E_b^\alpha}{E_0^\alpha + E_b^\alpha}\right)^{\frac{\gamma_2-\gamma_1}{\alpha}}$$

$$I(E) = I_0\left(\frac{E}{E_0}\right)^{\gamma_1} e^{-\left(\frac{E}{E_c}\right)^2}$$

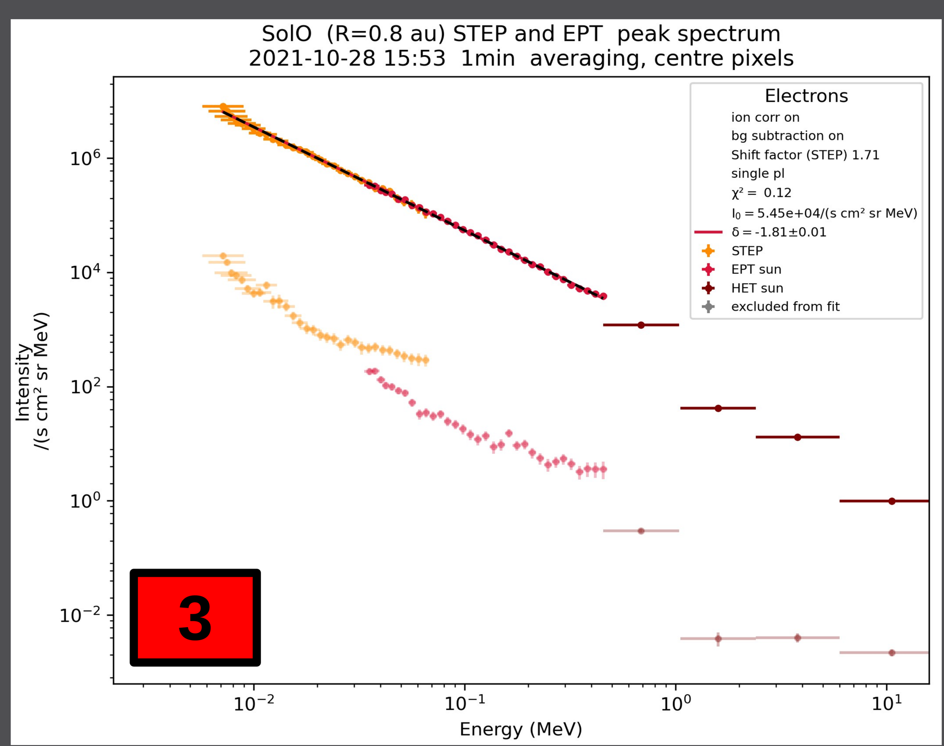
$$I(E) = I_0\left(\frac{E}{E_0}\right)^{\gamma_1}\left(\frac{E^\alpha + E_b^\alpha}{E_0^\alpha + E_b^\alpha}\right)^{\frac{\gamma_2-\gamma_1}{\alpha}} e^{-\left(\frac{E}{E_c}\right)^2}$$

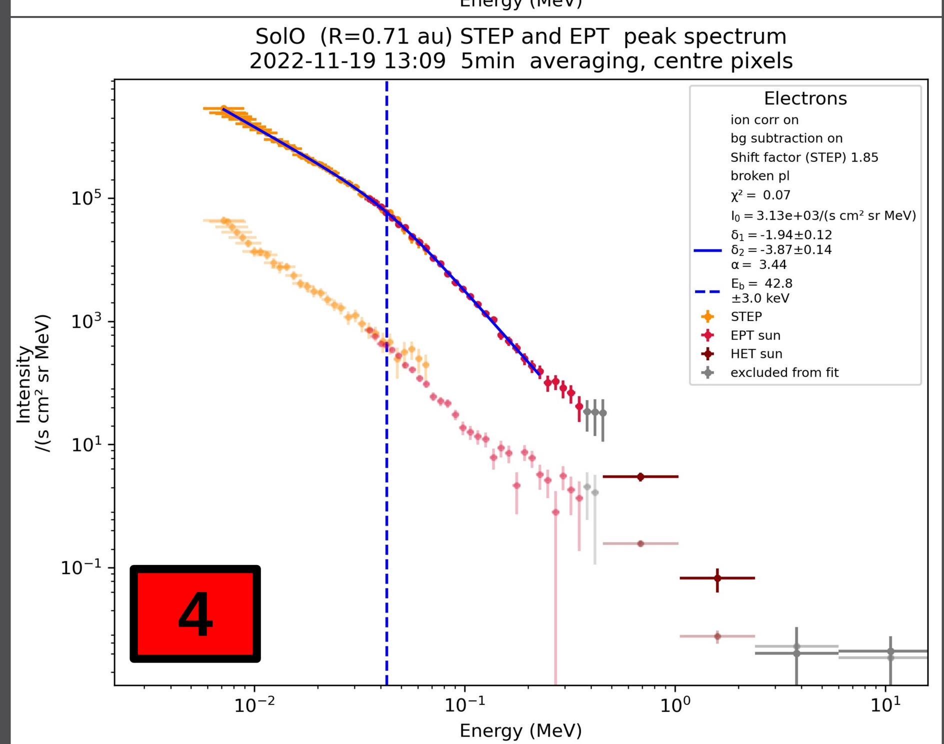
$$I(E) = I_0\left(\frac{E}{E_0}\right)^{\gamma_1}\left(\frac{E^\alpha + E_{bl}^\alpha}{E_0^\alpha + E_{bl}^\alpha}\right)^{\frac{\gamma_2-\gamma_1}{\alpha}}\left(\frac{E^\beta + E_{bh}^\beta}{E_0^\beta + E_{bh}^\beta}\right)^{\frac{\gamma_3-\gamma_2}{\beta}}$$

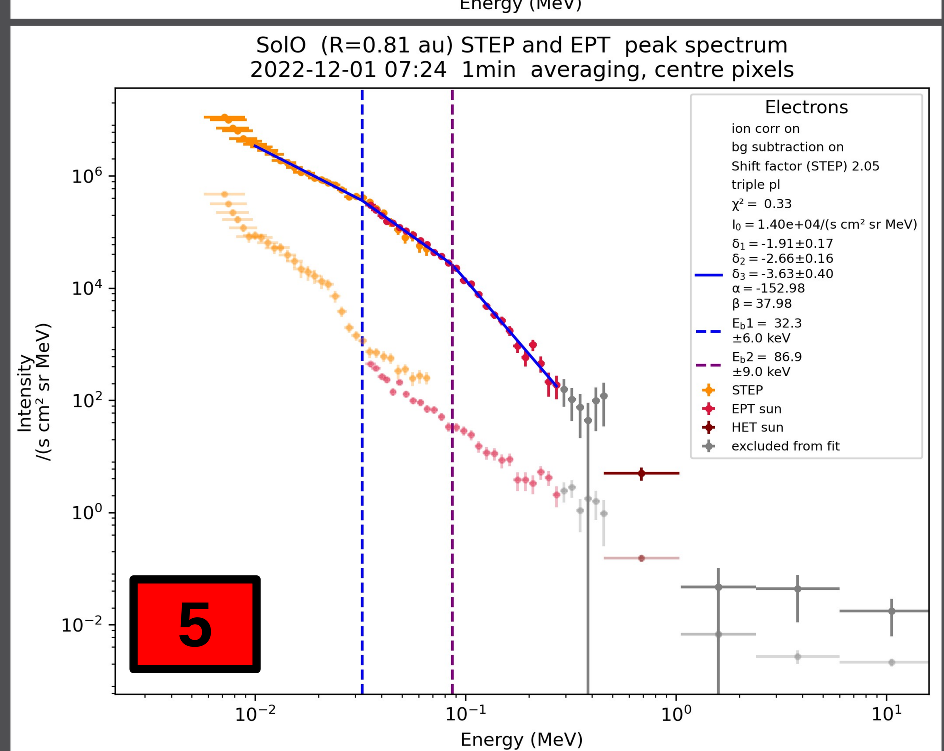
Examples of the functions above are shown in fig.2

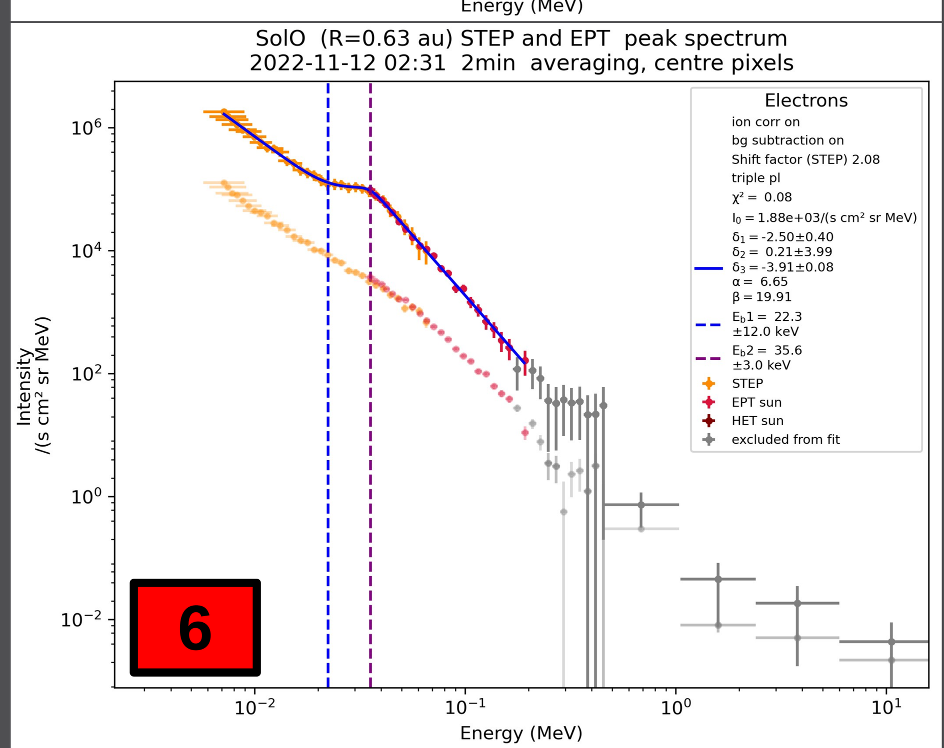


We choose the best fit based on the reduced χ^2









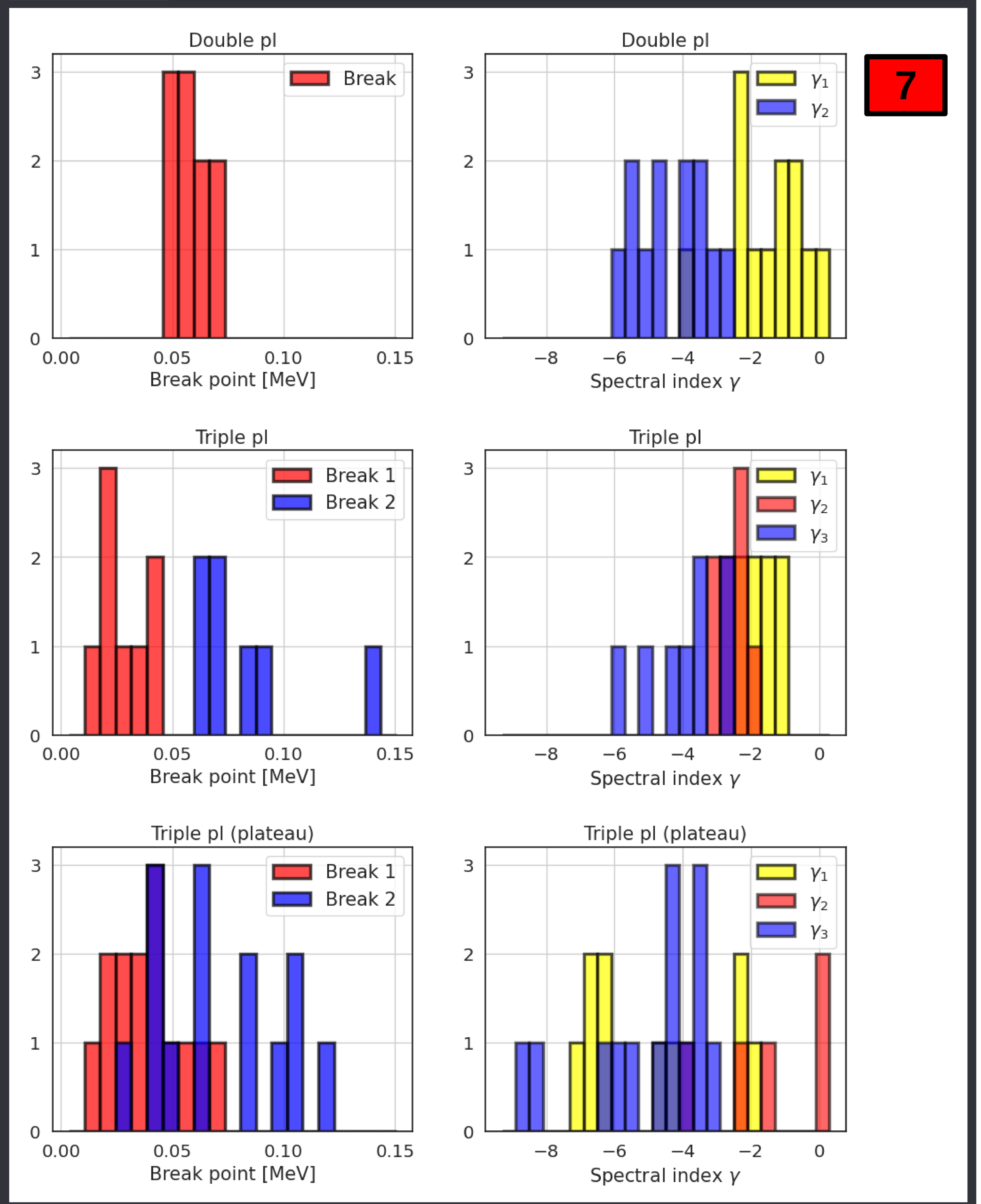
Results

We found 50 events with intensities above 5 X 10[5] /s cm[2] sr MeV measured at 43 keV from the event list compiled by the SolO multi-instrument consortium. We were able to fit the spectra (STEP + EPT) of 36 events in total. Events were excluded based on irregular spectral shapes, that made it impossible to produce a reliable fit.

We find that SEE spectra have different spectral shapes and can be desribes by different mathematical models. We found that the majority of the spectra exhibit at least one spectral break (fig. 4-6, 7 and Table). More than 60% of the events can be fit with a triple power-law.
We separate the triple power-law-fits into two categories:
1. Spectra that becomes progressively sofer after each of the two breaks (fig. 5)
2. Spectra that exhibit a "plateau" or hardening after the first break (fig. 6)

Our results are summarised in the table below. The distribution of the spectral breaks and spectral indices are shown if fig. 7.

	Single pl	Double pl	Double pl + Exp cutoff	Triple pl	Triple pl (plateau-like)
# of events	1	12	1	8	14
<Break 1> [keV]	-	74.7±12.5	46.5±0.0	23.4±4.1	35.9±7.6
<Break 2> [keV]	-	-	-	97.6±17.7	67.4±22.8
<γ1>	-1.8±0.01	-1.7±0.7	-3.0±06	-1.9±0.6	-6.8±4.4
<γ2>	-	-4.6±0.6	-1.2±1.8	-2.7±0.2	0.4±3.0
<γ3>	-	-	-	-5.1±0.5	-4.1±2.1



Summary and Discussion

The wide energy range of EPD allows us to find two separate spectral breaks withing one spectrum and fit it with a triple power-law function. From previous studies we know that spectral breaks of ~60 keV seem to be associated with Langmuir wave generation, supported by an anti-correlation between intensities and break energies (Krucker et al., 2009). Pitch anglle scattering is believed to cause spectral breaks at ~120 keV (Strauss et al. 2020; Dresing et al, 2020)
Our results for the spectral breaks and indices of the double power-law fits are comparable to the results of Kruker et al. 2009 (Eb ~ 60 keV, $\gamma_1 = -1.9 \pm 0.3$ and $\gamma_2 = -3.6 \pm 0.7$ Krucker et al., 2009). We could not however find an anti-correlation between the intensities and spectral breaks, likely due to the small numeber of events in our analysis.
The second break as well as γ_2 and γ_3 in our triple power-law fits are comparable to the values Dresing et al. 2020.
The first break energy of our triple power-law fits is however much lower than other break found before. The break could potentially be caused by sudden changes in the magnetic field and the pitch angle coverage of the instruments. We calculate a quality factor to describe how well the instruments cover the beam of particles, and according to our calculations, these low energy breaks appear to be real.