Solar flare science with smallsats: possibilities and challenges

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Monitoring the High Energy Sky with Small Satellites

Brno, Czech Republic

September 2022

Introduction: The Sun and solar flares

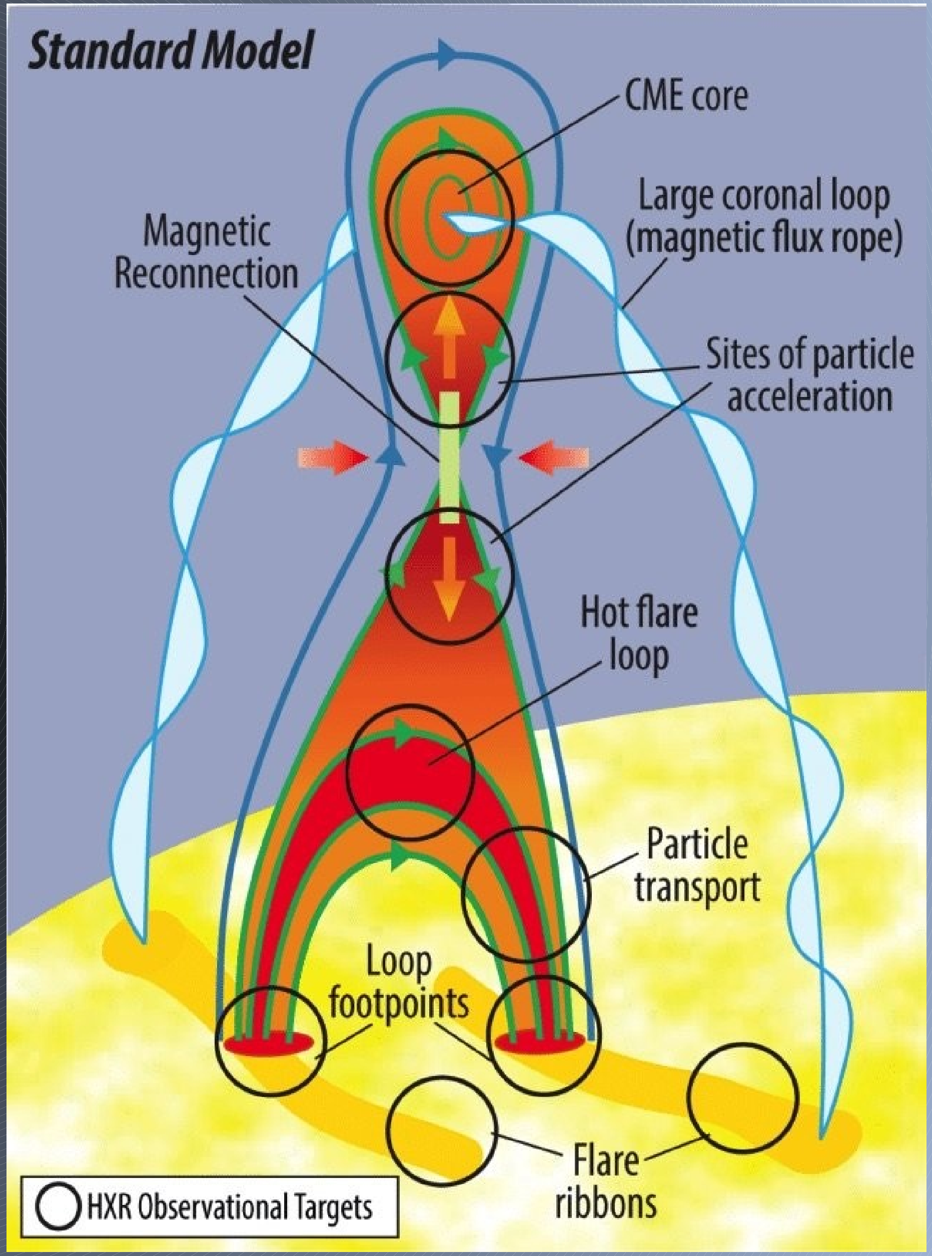
- Solar flares are impulsive, unpredictable eruptions that release large amounts of energy at the solar surface.

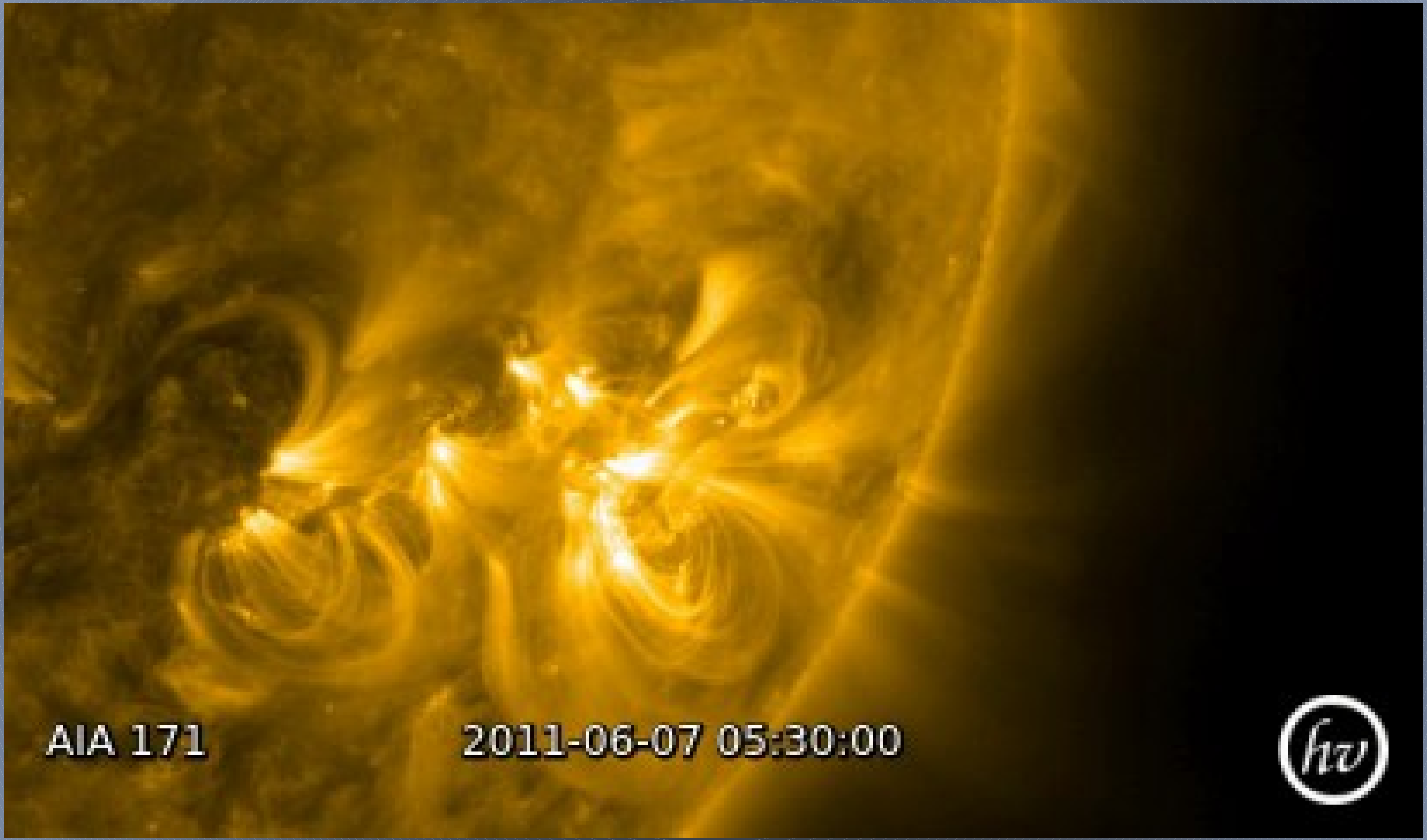
- They are the result of magnetic reconnection in the solar corona, which leads to both direct heating of local plasma and the acceleration of particles to high energies.

- During flares, X-ray flux from the Sun can increase by several orders of magnitude.

- Large flares are closely associated with coronal mass ejections (CMEs), where plasma is jettisoned into space.

- Flares produce emission throughout the EM spectrum, from radio waves to white light, UV, X-ray and gamma-ray wavelengths.

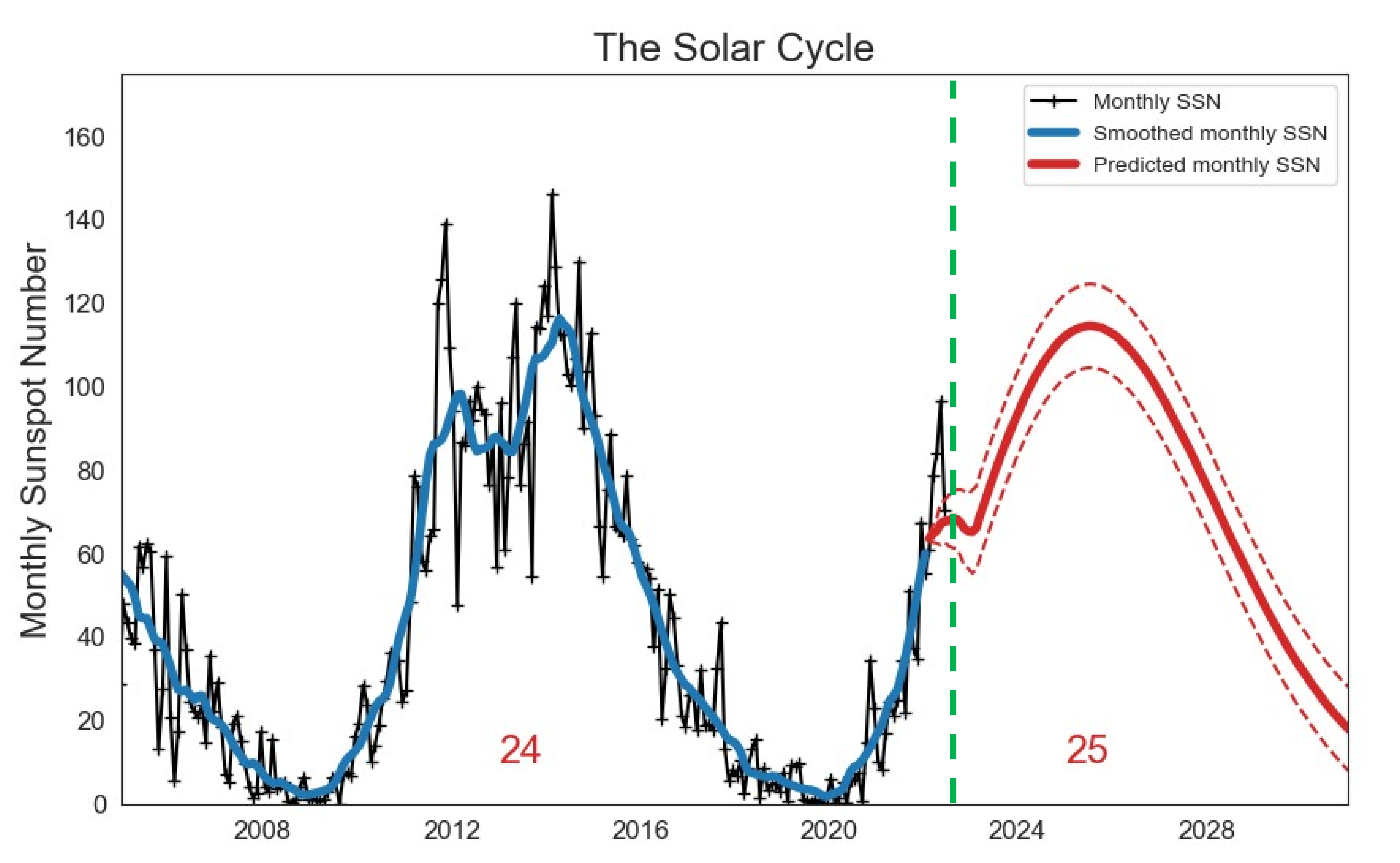




Make your own solar movies at: helioviewer.org

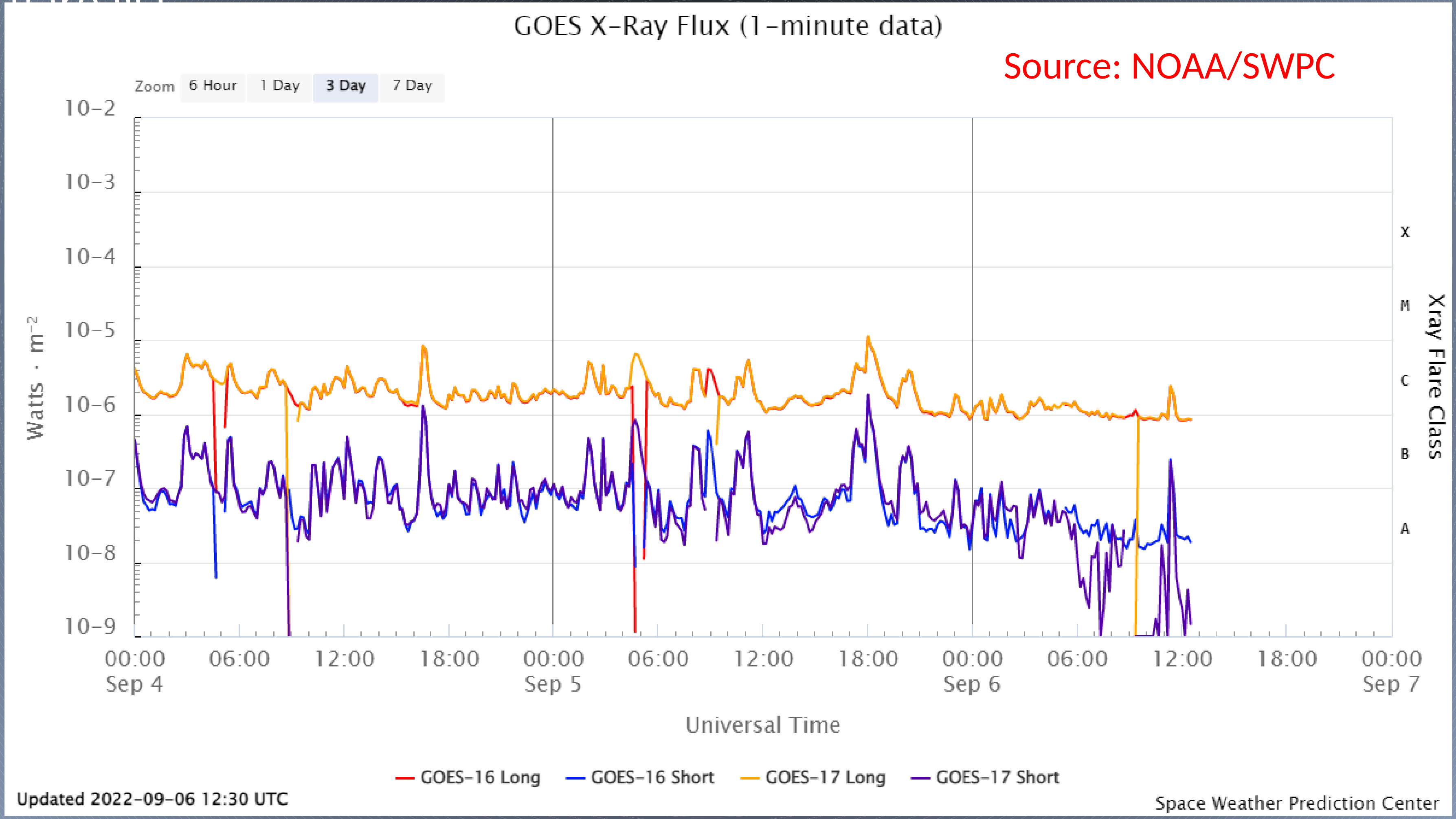
The solar activity cycle

The Sun follows an 11-year activity cycle. We are currently in the rising phase of Cycle 25. Activity is predicted to peak in 2025 – 2026.



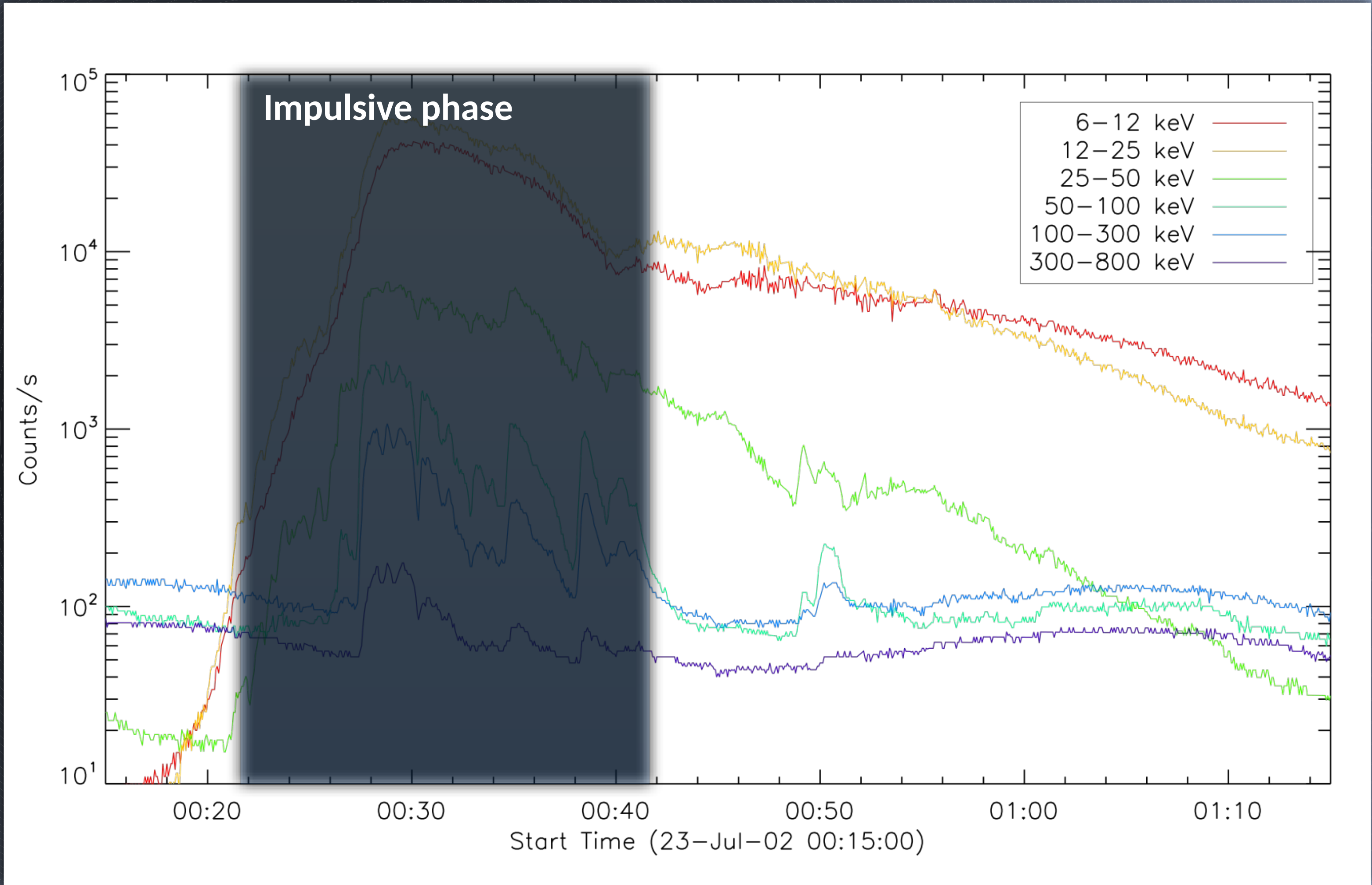
Solar flux monitoring

We have constant X-ray flux monitoring of the Sun via the GOES/XRS instruments. GOES is located in geostationary orbit and has a continuous view of the Sun. The GOES flux is traditionally used to classify the magnitude of solar flares, e.g. 'M5' or 'X2'. Sometimes we refer to the 'GOES flare list'



Solar flare temporal evolution

- Solar flares exhibit rapid evolution and fine time-structure. A ‘typical’ solar flare is often divided into two phases, an impulsive phase, and a decay phase.
- Most significant particle acceleration, and therefore hard X-ray and gamma-ray emission occurs during the impulsive phase, which may last ~10-30 minutes.
- This is followed by a gradual phase that is dominated by thermal emission. In this phase, hot flare plasma



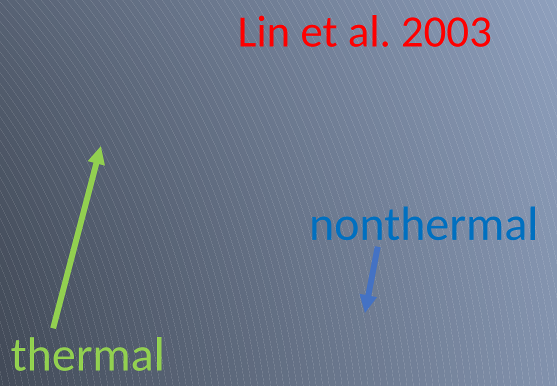
RHESSI temporal profile of the X5-class 2002 July 23 solar flare between 6 keV - 800 keV. The ‘impulsive phase’ lasts approximately 20 minutes for this large flare.

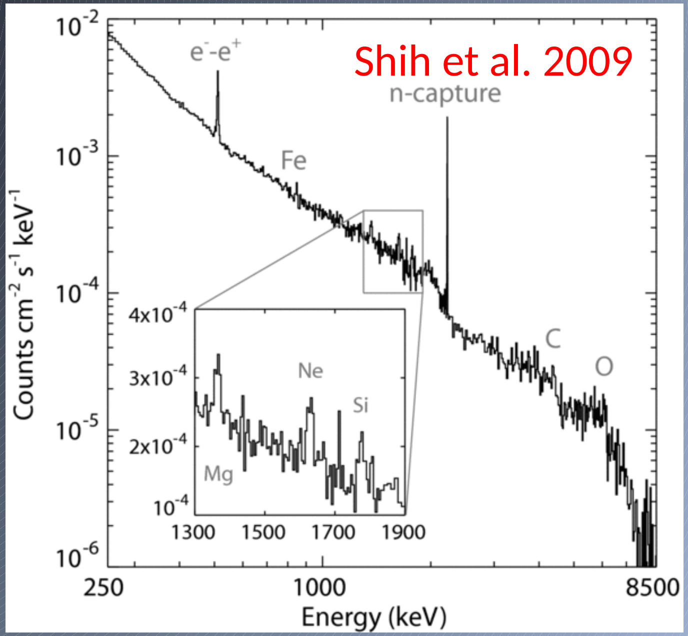
Solar flare energy spectra

- Two of the most fundamental components of a flare energy spectrum are 1) a thermal bremsstrahlung component at low (<25 keV) energies, and 2) a non-thermal thick-target bremsstrahlung component at high (>25 keV) energies. Understanding these tells us about the flare plasma temperature, and the amount of nonthermal energy released.

- Large flares can produce substantial emission above 100 keV. At these high energies, ions and neutrals also become important, producing a number of emission lines.

- A classic example of this is the X4.8 flare from 2002 July 23 (see right). This flare exhibited substantial >300 keV emission, including substantial line emission.





Challenges posed by solar flares

The unpredictability of flares

- It is not yet possible to predict exactly when and where a flare will occur. Flare forecasting currently takes the form of a binary yes/no prediction within a certain time interval (often the next 24 hours).

- There are many operational flare forecasting methods, but to date have only demonstrated moderate skill.

Leka et al. 2019

Comparison of flare forecasting methods, each offering a binary prediction of whether an >M1 class solar flare will occur in the next 24 hours. Various skill score metrics are shown.

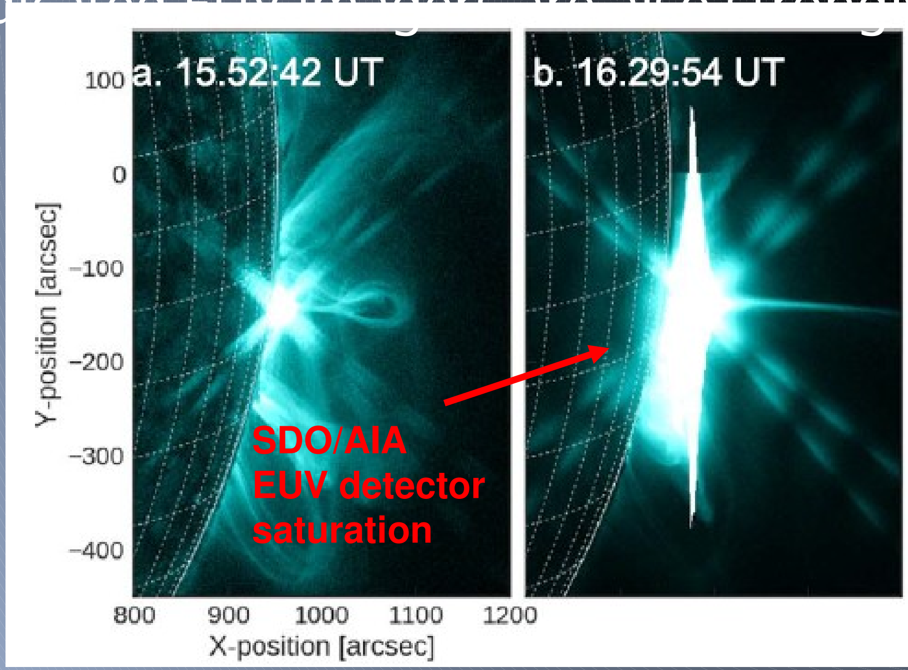
- Even today, one of the most successful predictors of future flare activity in a solar active region is that flares have recently occurred.

Handling flare fluxes: 2017-09-10 X8.2 flare

This very large X-class flare was observed by GOES, RHESSI, and Fermi. Causes strong pulse pileup effects in the sunward Fermi/GBM detectors. Two lower energy counts are incorrectly recorded as a single high energy count.

Even using thick attenuators, RHESSI livetime is at ~30%, while GBM is < 10%.

Solar-dedicated EUV imagers are also strongly saturated.



Dominated by < 10 keV emission

Attenuator activations

Pileup

Attenuator activations

Solar flare science opportunities with smallsats

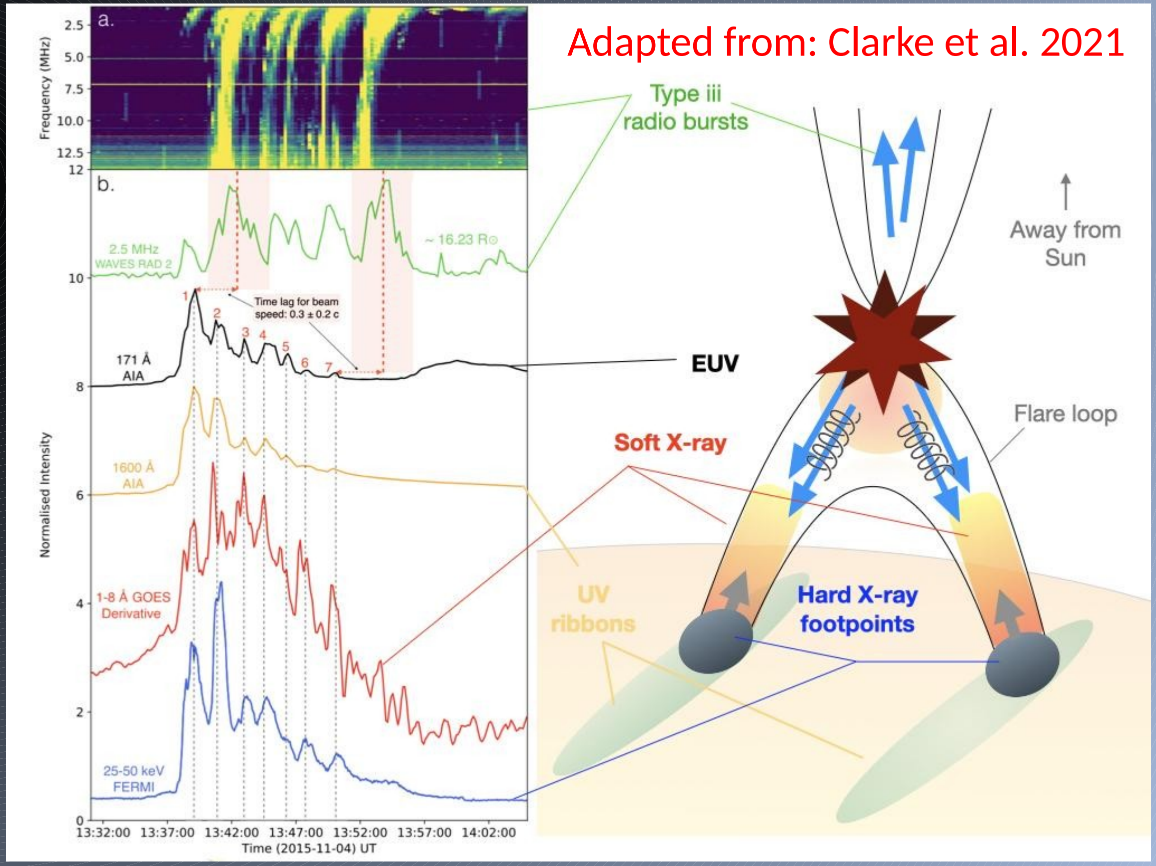
Quasi-periodic pulsations (QPPs) in flare emission

Solar flares are highly variable in time, often displaying quasi-periodic behavior on short timescales. This behavior can be observed throughout the EM spectrum, from radio waves to X-rays and gamma-rays. High time resolution data from smallsats can be especially useful for detecting and understanding this phenomenon.

Typical periods of QPPs are often in the 10-20s range. Similar processes occur on other stars, so we can exploit the solar-stellar connection.

Fermi/GBM is already used to study this phenomenon in X-rays.

Future missions can provide more solar coverage and enable more detections. This is especially critical since the retirement of RHESSI (2002 – 2018).



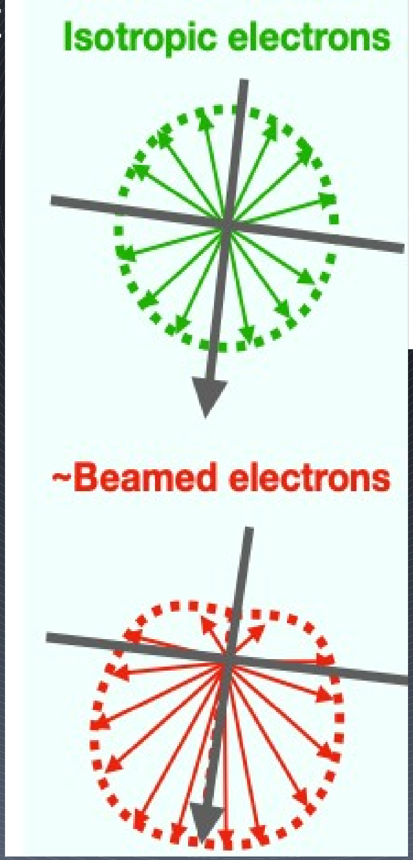
Adapted from: Clarke et al. 2021

Directivity of solar flare X-rays

Currently the directivity of solar flare X-ray emission is unknown. In other words, how beamed is non-thermal electron emission? Historically we have only had Earth-based measurements.

Now, we can use the fact that Solar Orbiter/STIX is outside of the Sun-Earth line. Combined with X-ray sensitive spacecraft at Eart … es in the X-ray spectrum to test this.

Differences in the power-law index of spectra from different viewing angles would indicate anisotropic emission.



Credit: N. Jeffrey, S. Krucker, L. Hayes et al. 2022

Power law slope

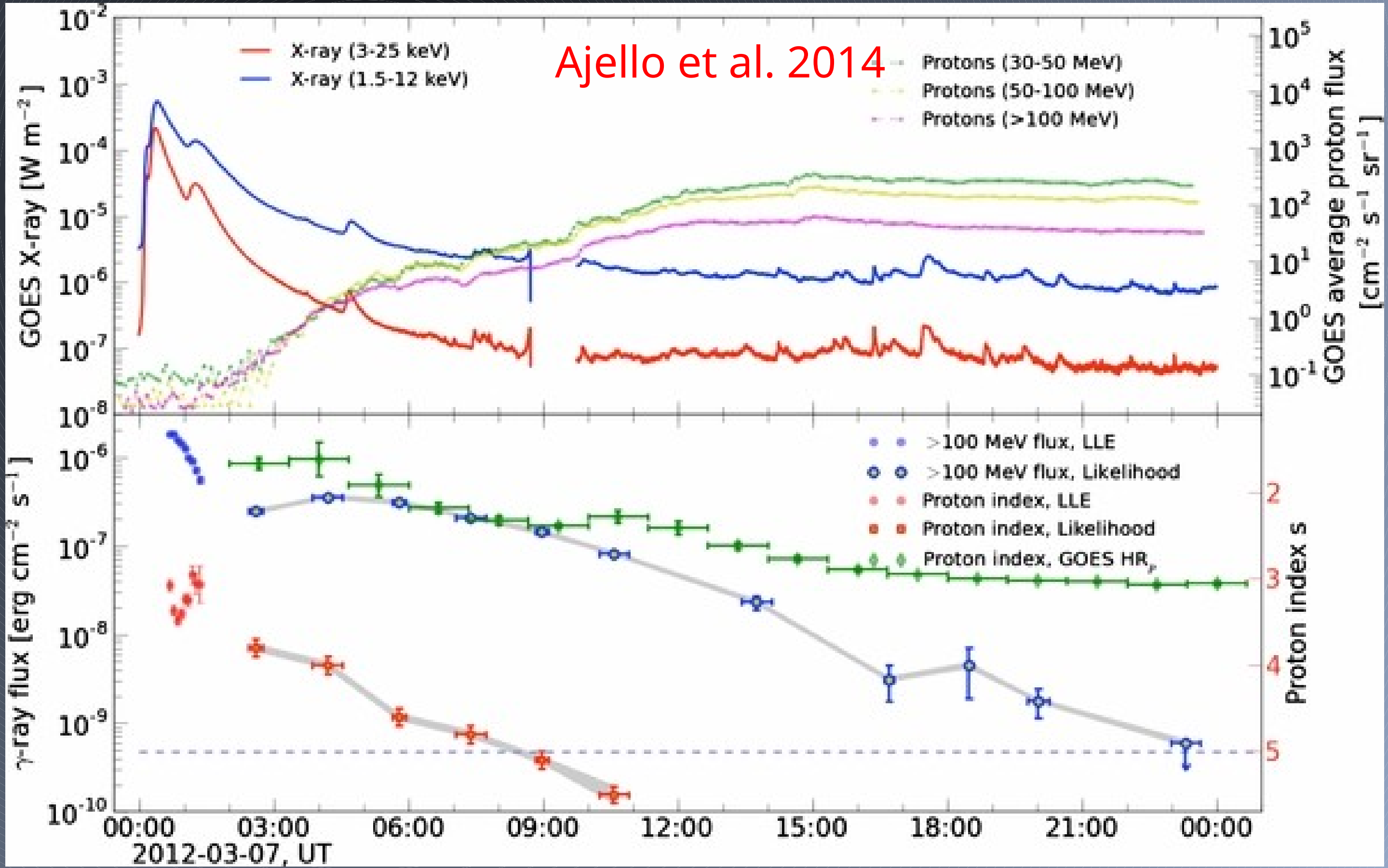
Solar flare high energy gamma-ray emission

- Fermi/LAT has shown that larger flares sometimes produce > 30 MeV gamma-ray emission, which can last much longer than the flare impulsive phase (e.g. Ajello et al. 2014, Pesce-Rollins et al. 2015).

- The nature and spatial location of this long-duration gamma-ray emission is still unclear.

- It may be related to shocks occurring in CMEs associated with these flares.

- Most likely not co-spatial with impulsive phase HXR emission.



Summary

- Solar flares are an important consideration for any smallsat mission. They present operational challenges but are also an opportunity to pursue science questions.
- Flares are unpredictable and can generate very high fluxes throughout the electromagnetic spectrum, especially at EUV, X-ray, and gamma-ray wavelengths. This can lead to instrument saturation, as well as unanticipated data volumes.
- Instruments with high time resolution are ideal for studying the time-variability of flares, in particular oscillations and pulsations.
- For X-ray instruments, there is an opportunity to perform stereoscopic observations together with the STIX instrument on solar orbiter. This can help address the directivity of nonthermal flare emission.