Fachhochschule
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X-ray view on solar flare accelerated electrons

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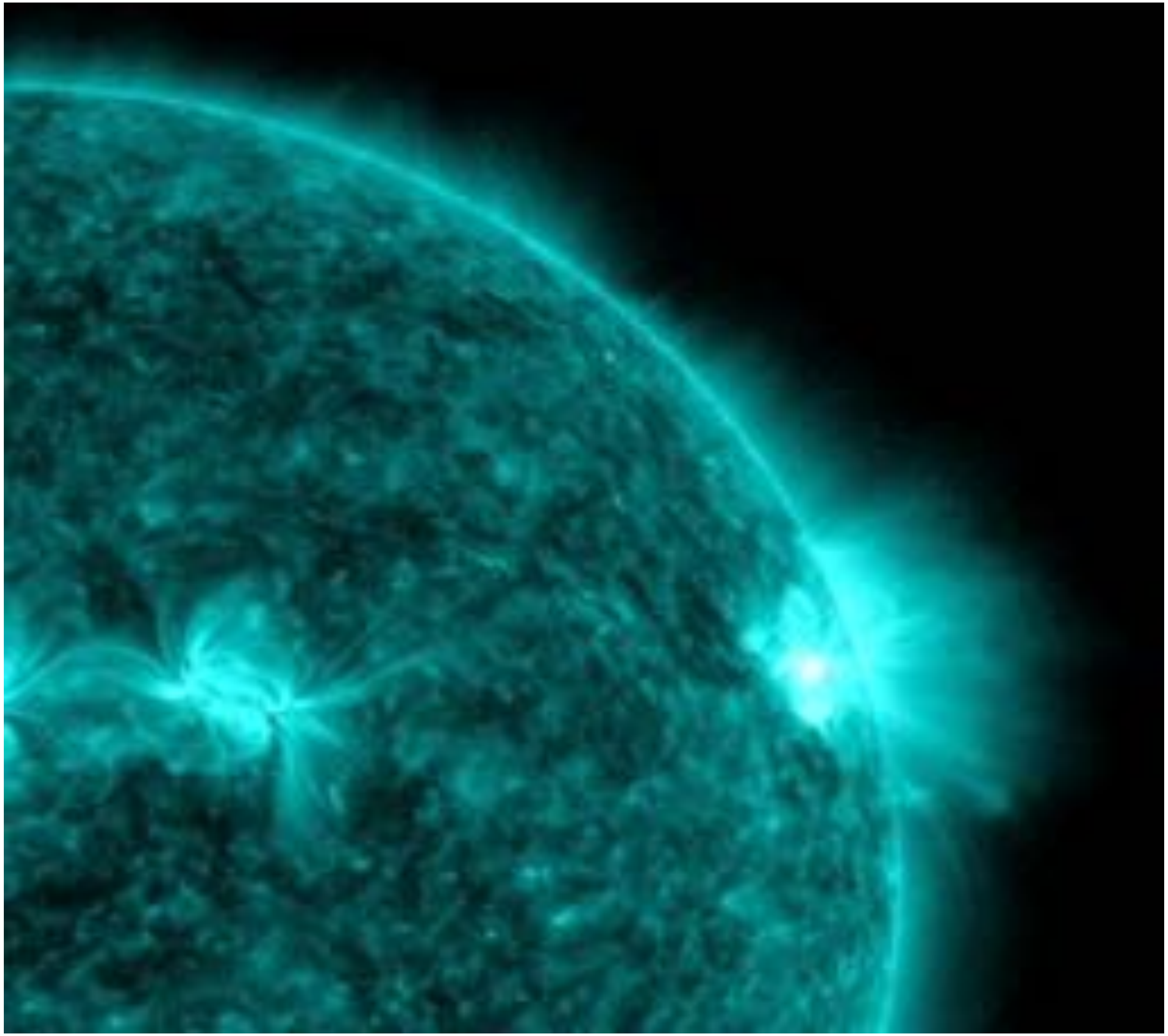
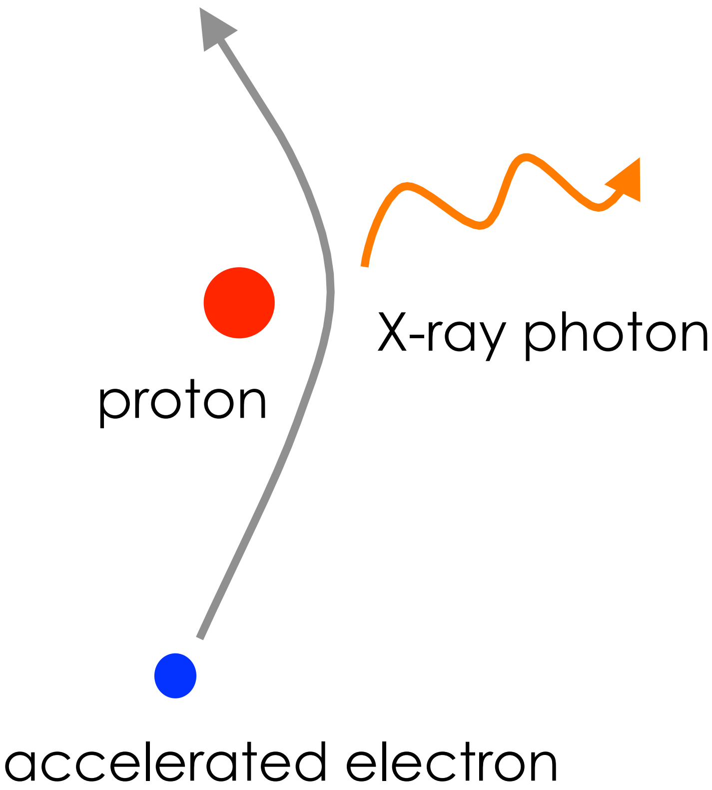


Why X-rays?

Emission mechanism: bremsstrahlung



X-ray intensity (at a given photon energy) depends on:

- accelerated electron flux density
- ambient plasma density
- does NOT depend on magnetic field strength

$$\boxed{I(\epsilon)} = \frac{1}{4\pi R^2} \int_{\epsilon}^{\infty} \langle \boxed{n} V \boxed{F} \rangle (E) \boxed{\sigma(\epsilon, E)} dE$$

(Brown 1971, Holman et al. 2011)

X-ray flux spectrum at Earth
Ambient plasma density
Electron flux
X-ray bremsstrahlung cross-section

Some questions regarding electron acceleration in solar flares

1) Where are electrons accelerated? → X-ray images

2) How are electrons accelerated?

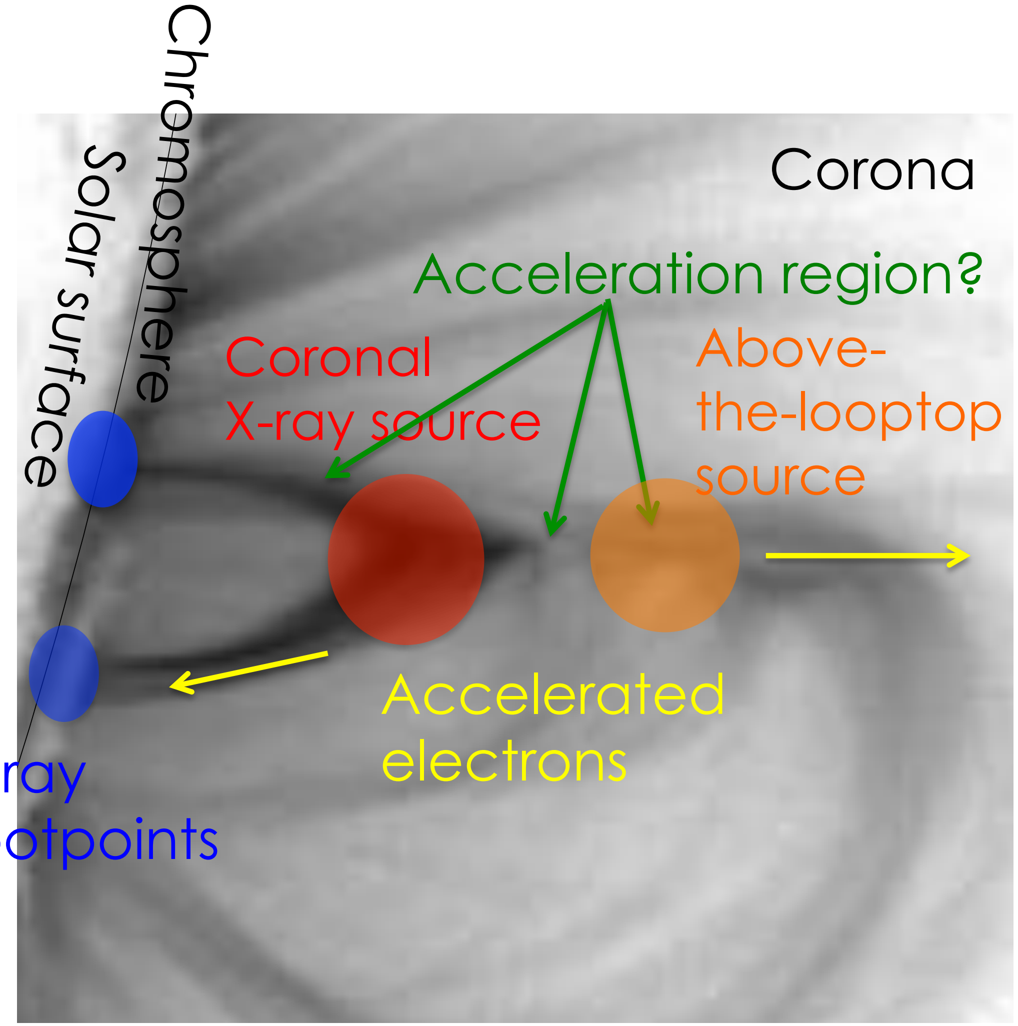
3) How much energy is contained in accelerated electrons?

→ X-ray spectra

4) What are the time scales of electron acceleration? → X-ray lightcurves

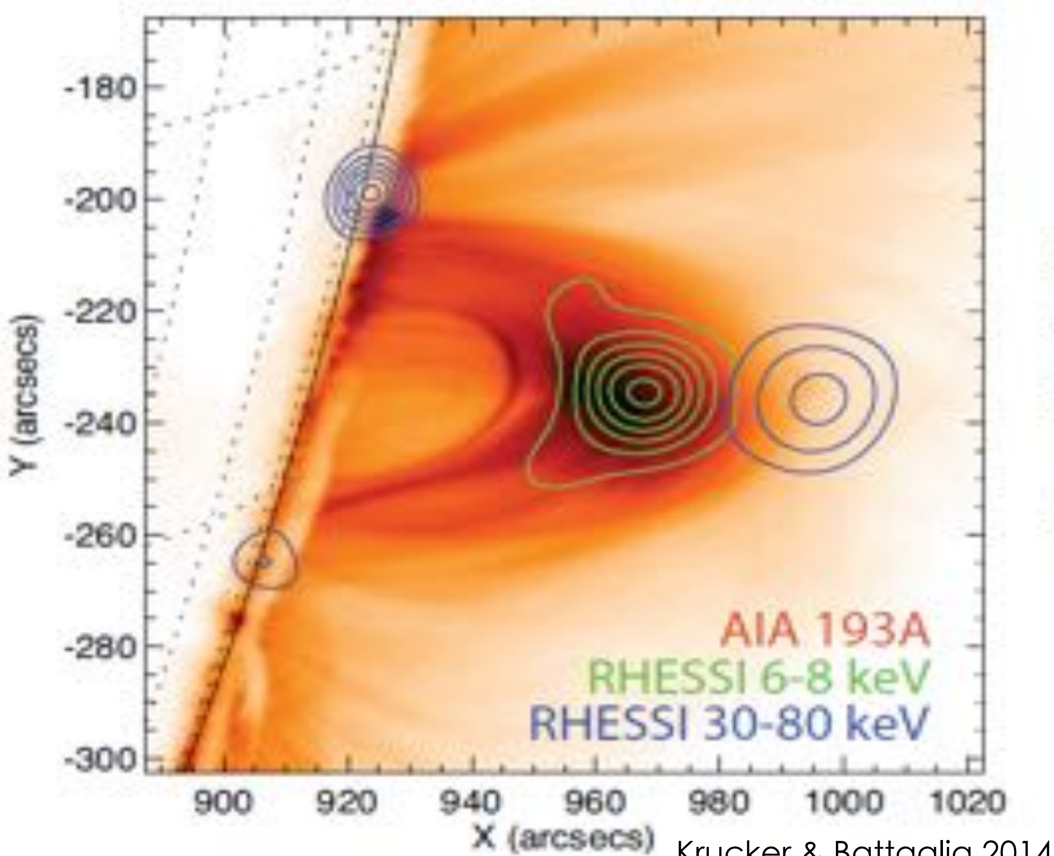
5) How are electrons transported in the corona? → X-ray images and spectra

X-rays in the standard solar flare scenario - imaging



Sketch of the standard scenario overlaid on extreme UV-Image

6-8 keV: soft X-rays (SXR)
30-80 keV: hard X-rays (HXR)

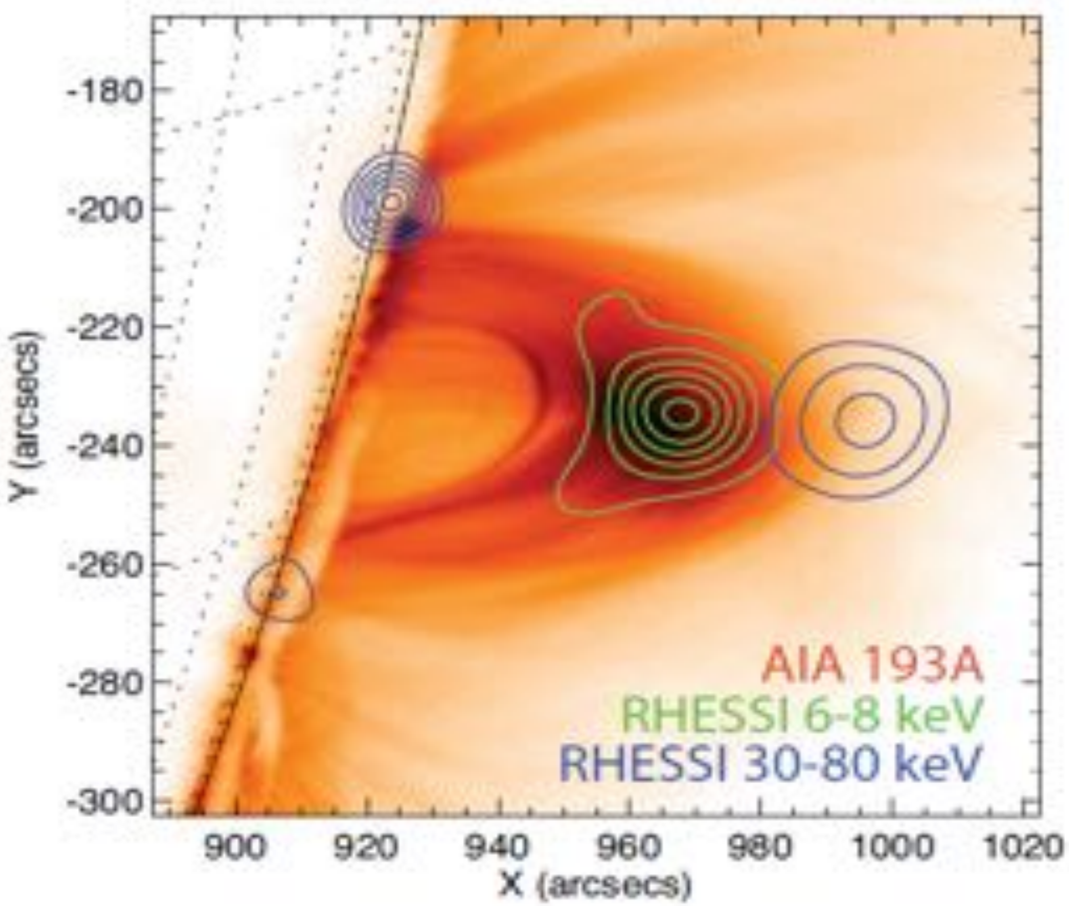


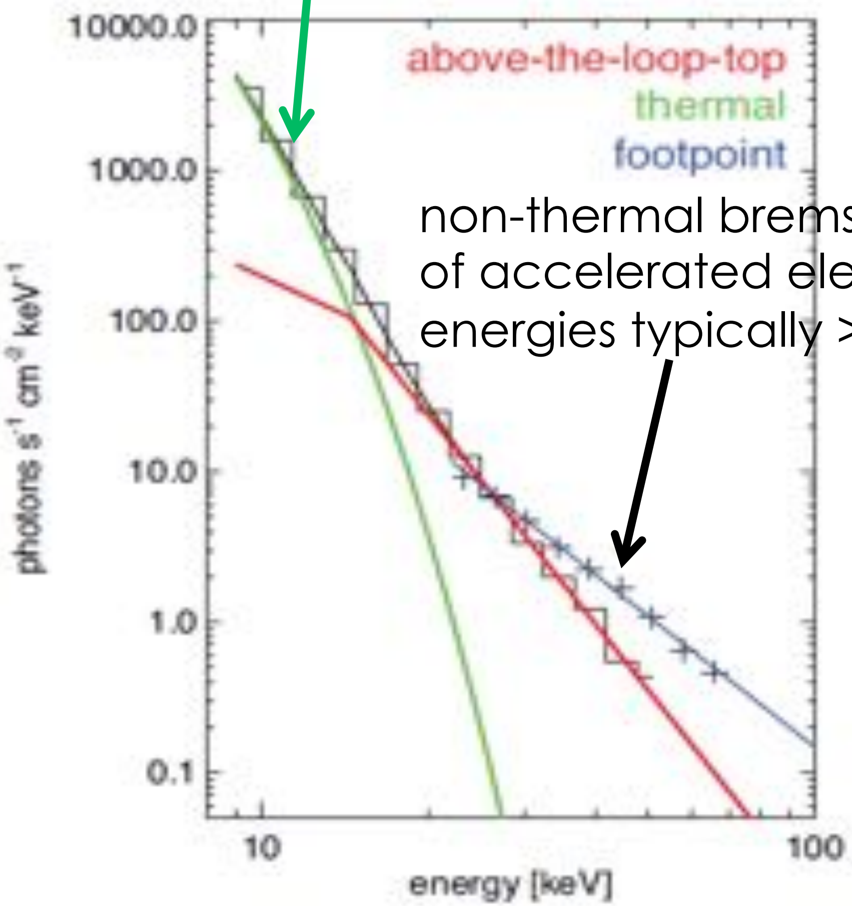
Krucker & Battaglia 2014

X-ray image contours overlaid on extreme UV-image

X-rays: spectroscopy

thermal bremsstrahlung T~10-25 MK



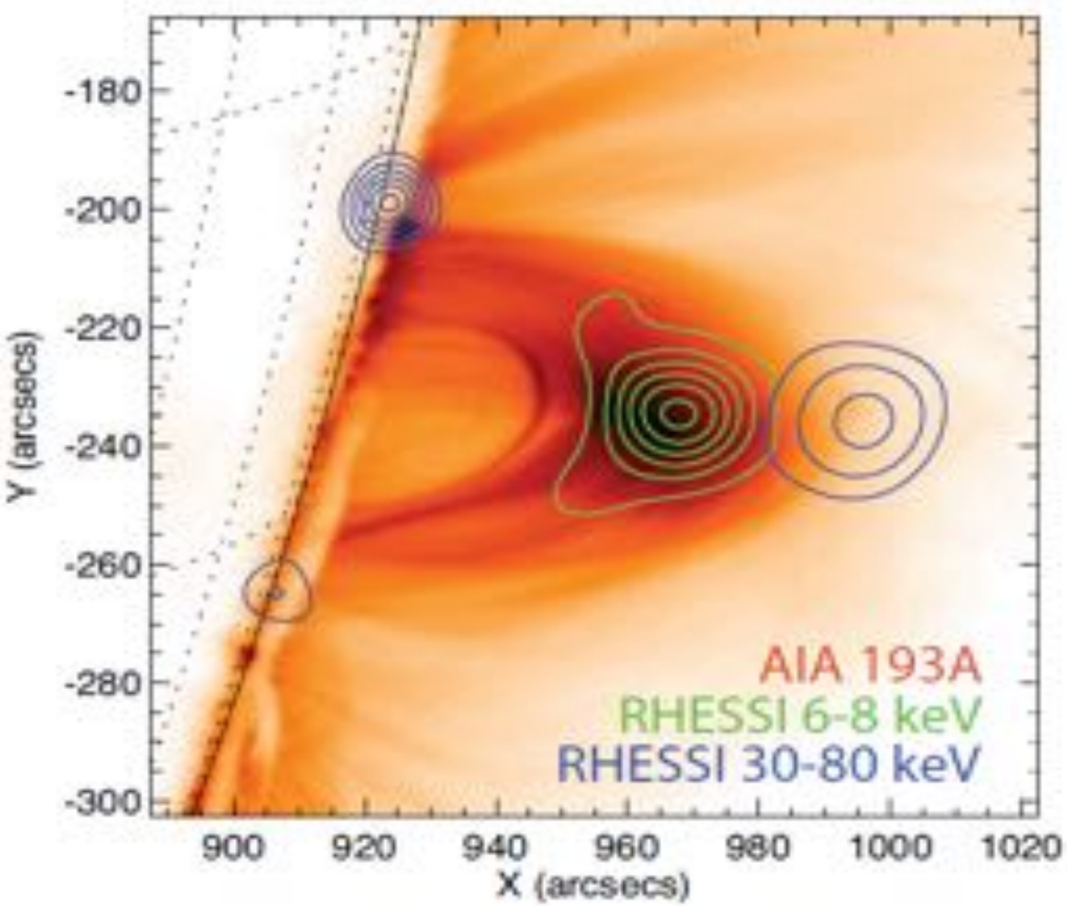


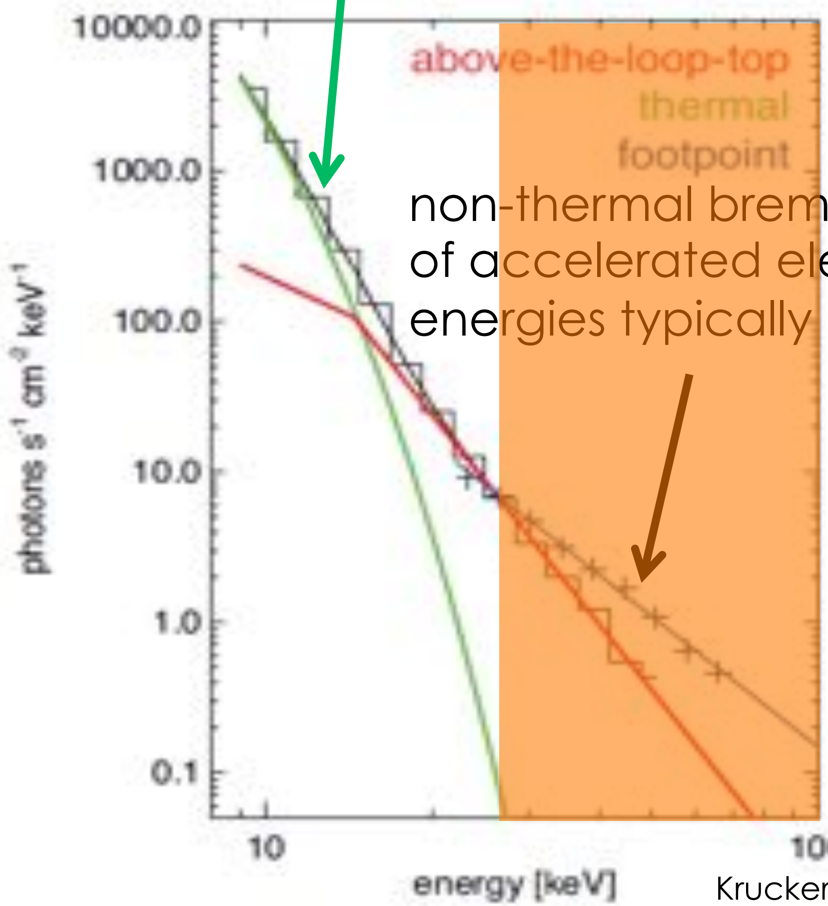
non-thermal bremsstrahlung of accelerated electrons with energies typically > 10 keV

Krucker & Battaglia 2014

X-rays: spectroscopy

thermal bremsstrahlung T~10-25 MK





non-thermal bremsstrahlung of accelerated electrons with energies typically > 10 keV

Krucker & Battaglia 2014

→ photon energies > 20 keV of interest for studying flare accelerated electrons

Spectrum often described as a power-law with photon index γ: $f(\varepsilon) \sim \varepsilon^{-\gamma}$

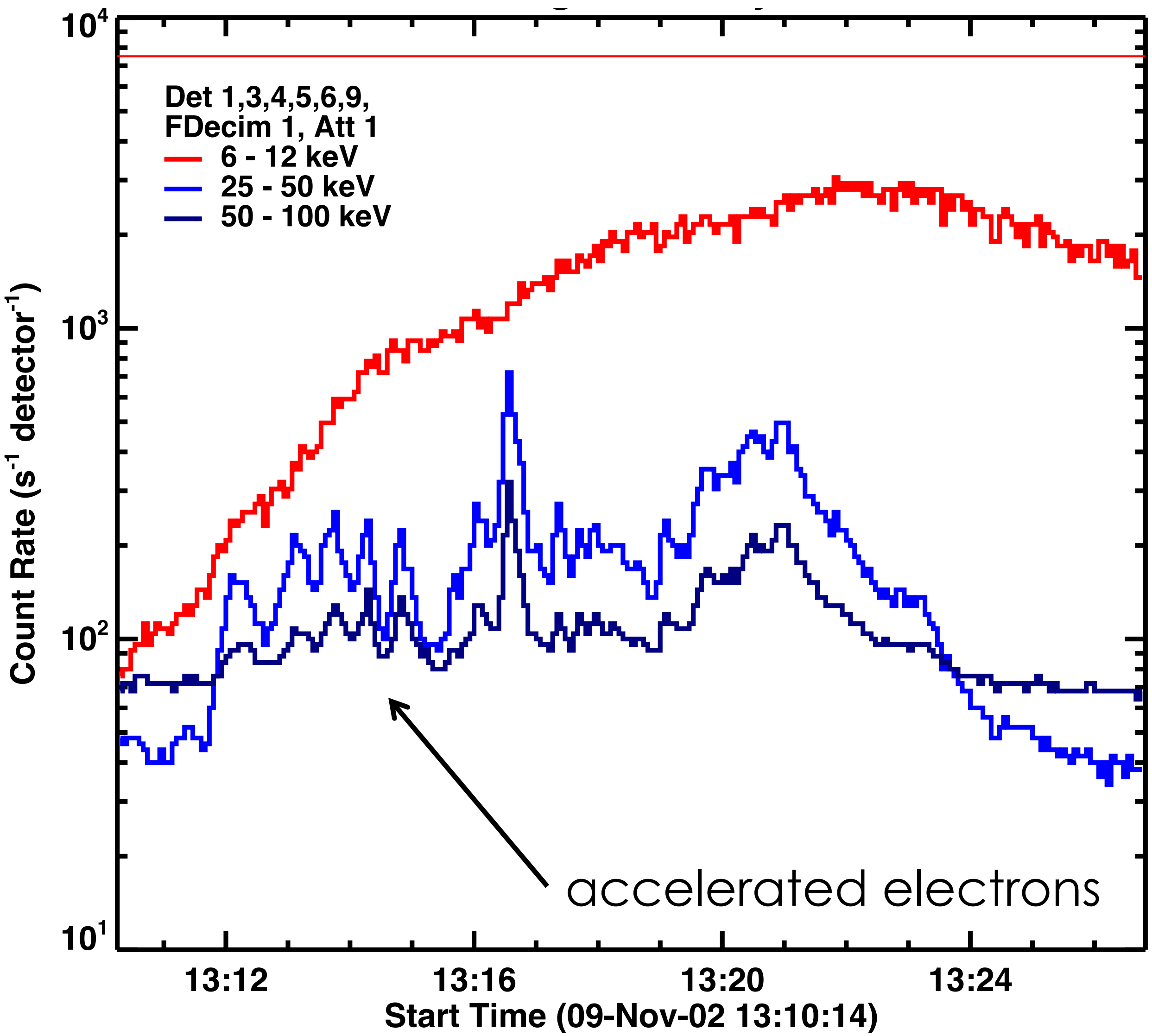
X-rays time evolution

Generally (with MANY exceptions)

low photon energies:
gradual evolution, heating and cooling of ambient plasma

higher photon energies:
impulsive evolution, signatures of accelerated electrons

photon energies > 20 keV of interest for studying flare accelerated electrons



Some questions regarding electron acceleration in solar flares

1) Where are electrons accelerated? → X-ray images

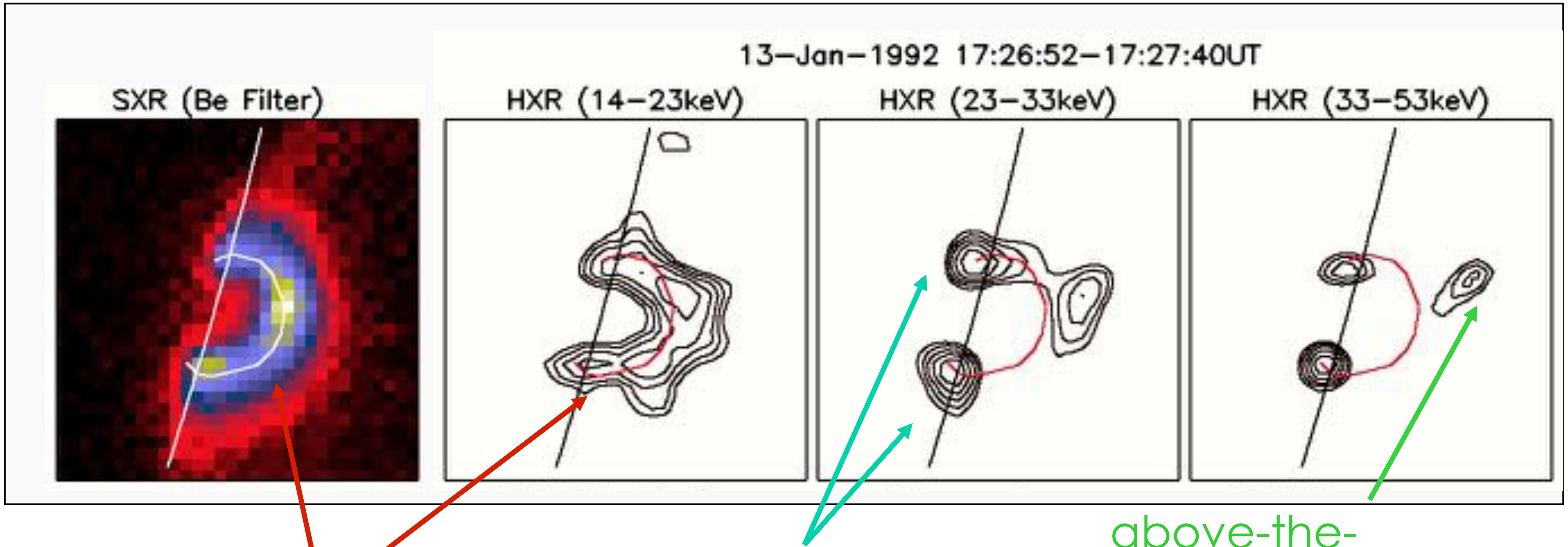
2) How are electrons accelerated?

3) How much energy is contained in accelerated electrons? → X-ray spectra

4) What are the time scales of electron acceleration? → X-ray lightcurves

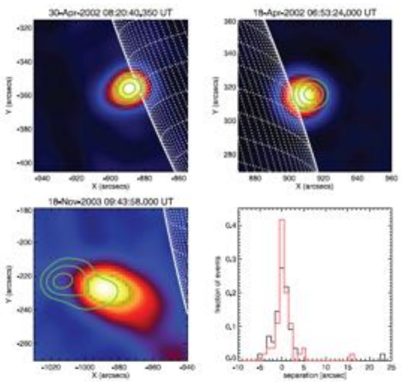
5) How are electrons transported in the corona? → X-ray images and spectra

1) Where are electrons accelerated?

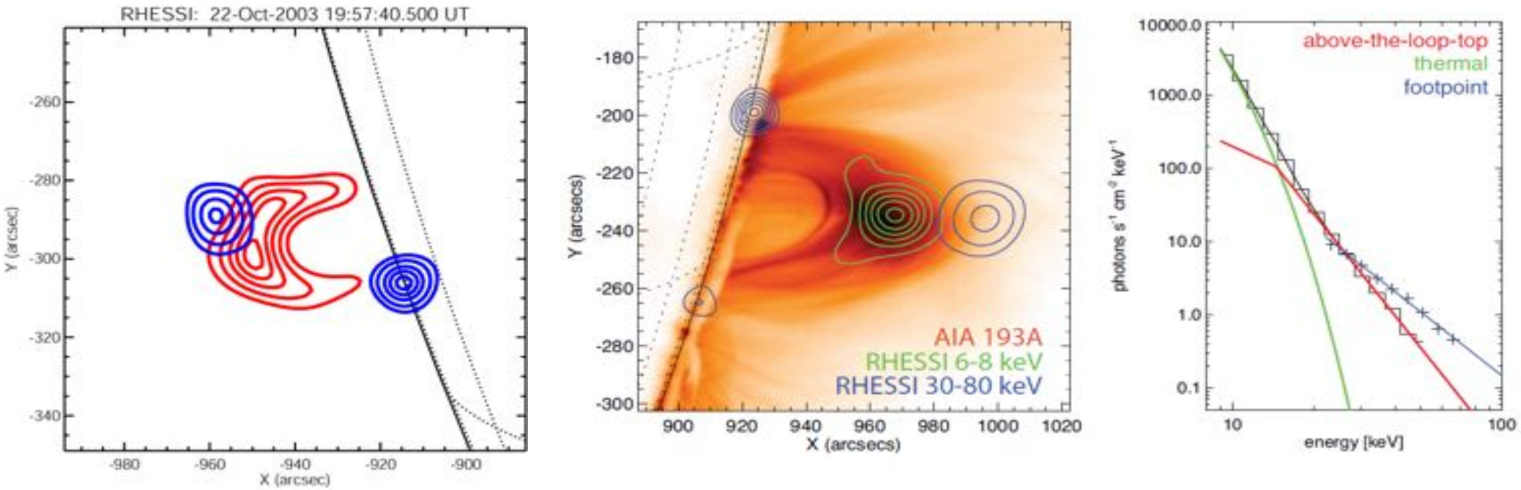


Masuda et al. 1994: first observation of a HXR source in the corona with Yohkoh → now interpreted as signature of accelerated electrons

Krucker & Lin 2008: HXR emission in most of the studied coronal sources with RHESSI,
but mostly co-spatial with SXR source



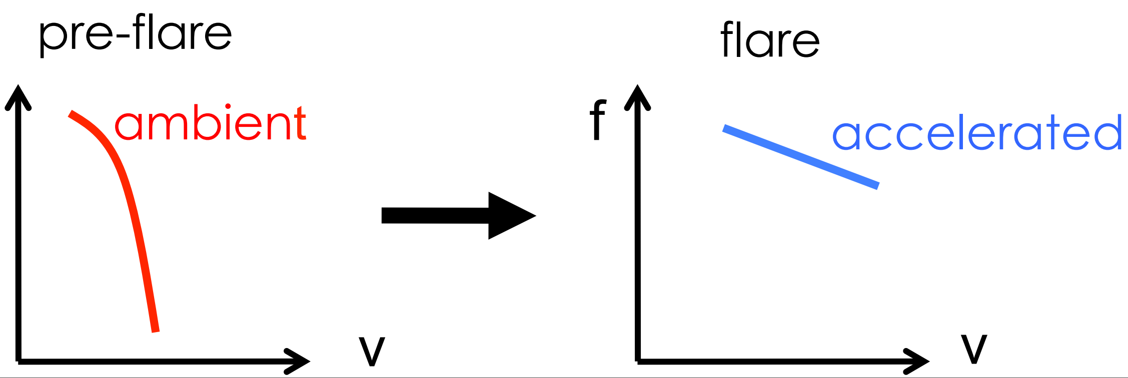
Above the loop-top-source is the acceleration region



Krucker et al. 2010
& Krucker & Battaglia 2014

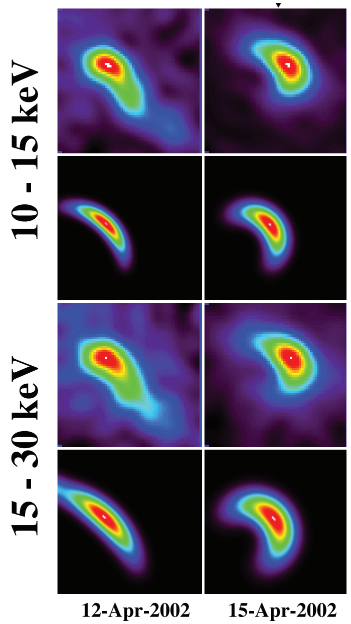
Low ambient density & strong X-ray source → very large number of accelerated electrons

→ Entire plasma is accelerated (non-thermal) in bulk energization process



Electron acceleration along the loop

- Some flares show loop structure up to high energies
- Loop length increases energy
- Observations can be explained with a model, featuring an extended acceleration region



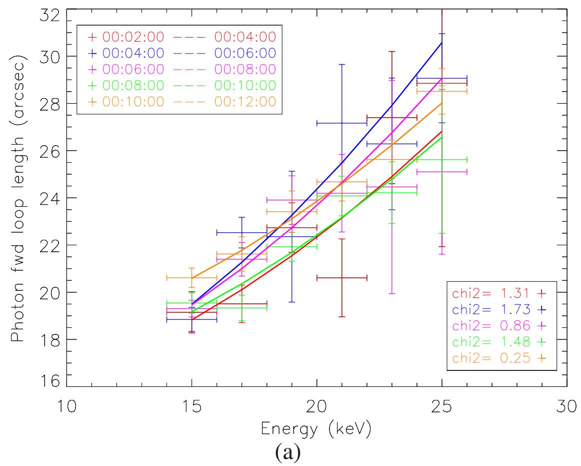
CLEAN

vis_fwdfit

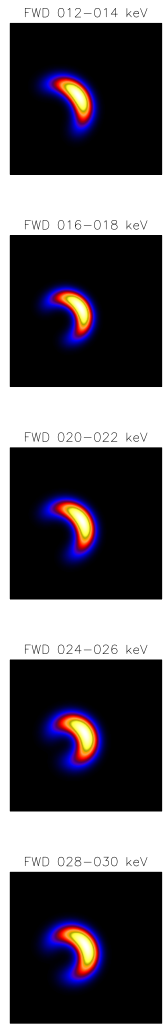
CLEAN

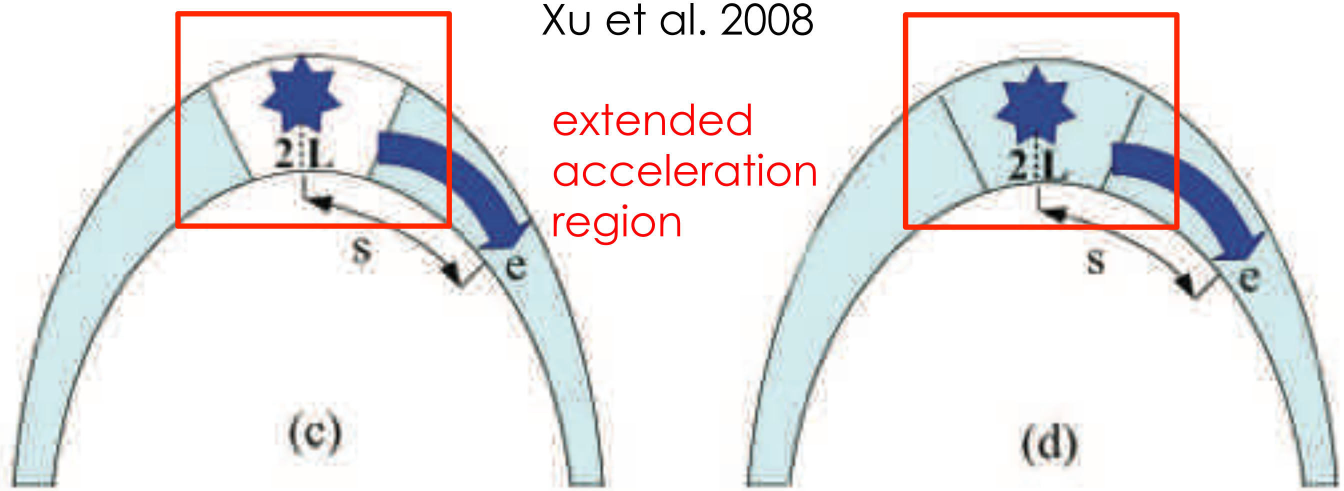
vis_fwdfit

Xu et al. 2008



Guo et al. 2012





Some questions regarding electron acceleration in solar flares

1) Where are electrons accelerated? → X-ray images

2) How are electrons accelerated?

3) How much energy is contained in accelerated electrons? → X-ray spectra

4) What are the time scales of electron acceleration? → X-ray lightcurves

5) How are electrons transported in the corona? → X-ray images and spectra

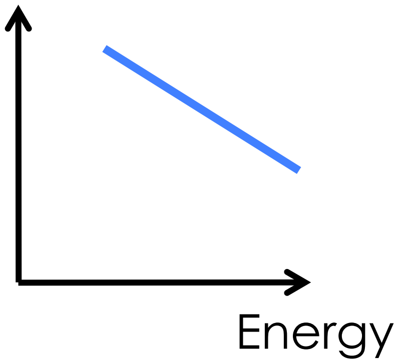
3) How much energy is contained in accelerated electrons?

Simplest approach: “cold thick target model” (Brown 1971)

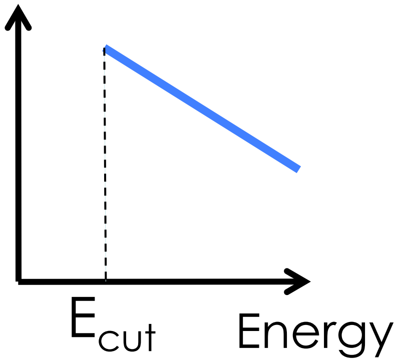
Electrons are completely stopped in a very dense = thick target, where electron energy E > kT of the target = “cold” target

$$I(\epsilon) = \frac{1}{4\pi R^2}\int_{\epsilon}^{\infty} \langle nVF\rangle(E)\,\sigma(\epsilon, E)\,dE$$

observed photon spectrum



inferred electron spectrum $F_0(E)$



Total power: $P = \int_{\boxed{E_{cut}}}^{\infty} E F_0(E)\,dE$

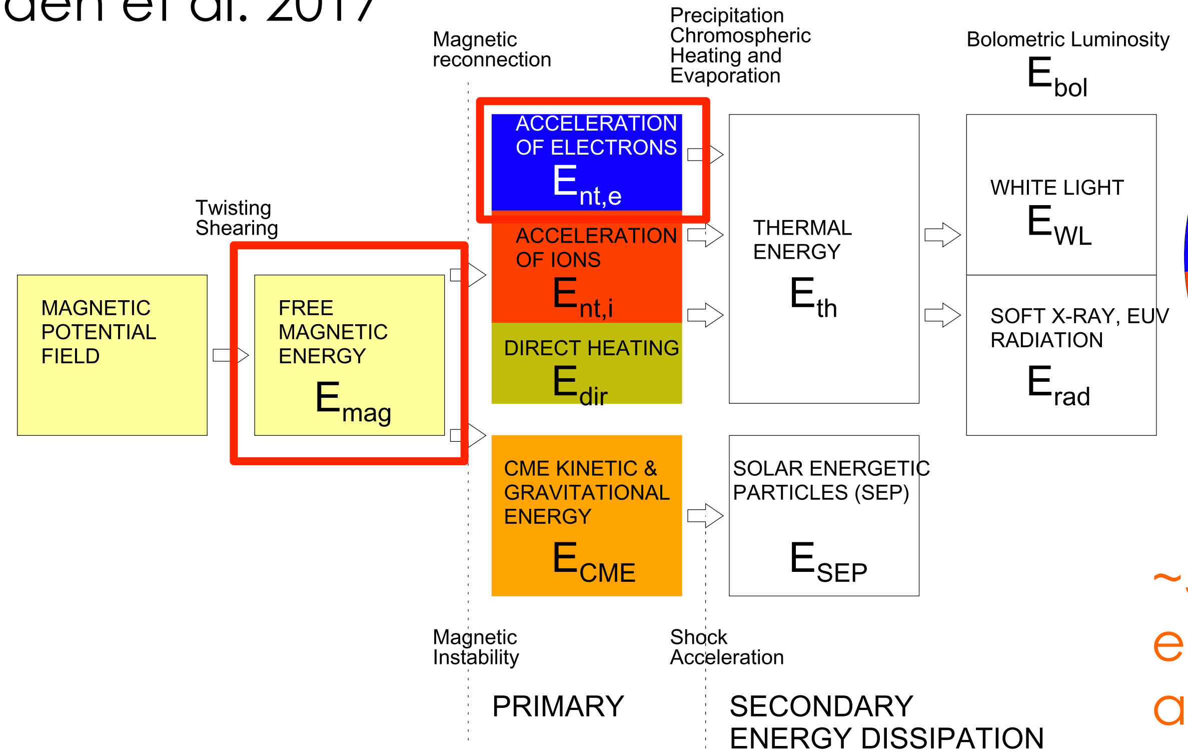
Problems with this approach:

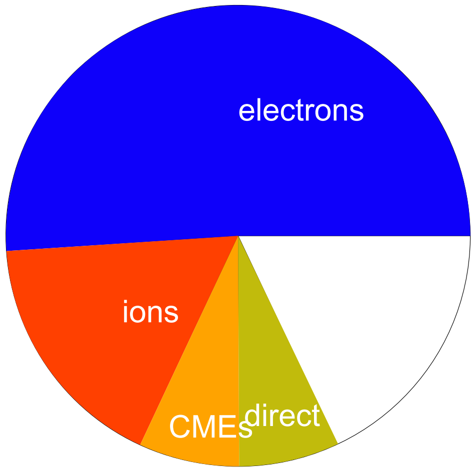
P depends strongly on E_{cut}, target may not be cold

New developments using a “warm” target, e.g. Kontar et al. 2015

So, how much energy *IS* contained in accelerated electrons?

Aschwanden et al. 2017





~50% of magnetic free energy goes into accelerated electrons

Based on several extensive statistical studies
Used warm thick target, average E_{cut} = 6 keV
Latest, but probably not *last* word on flare energy partition!

Some questions regarding electron acceleration in solar flares

1) Where are electrons accelerated? → X-ray images

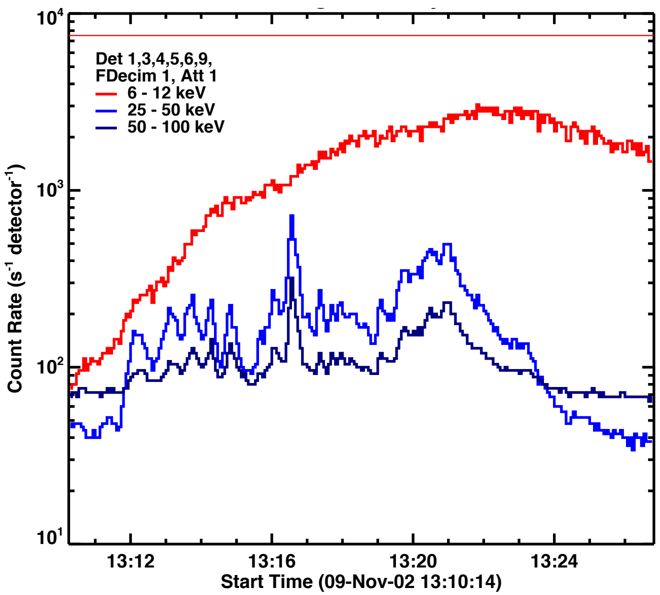
2) How are electrons accelerated?

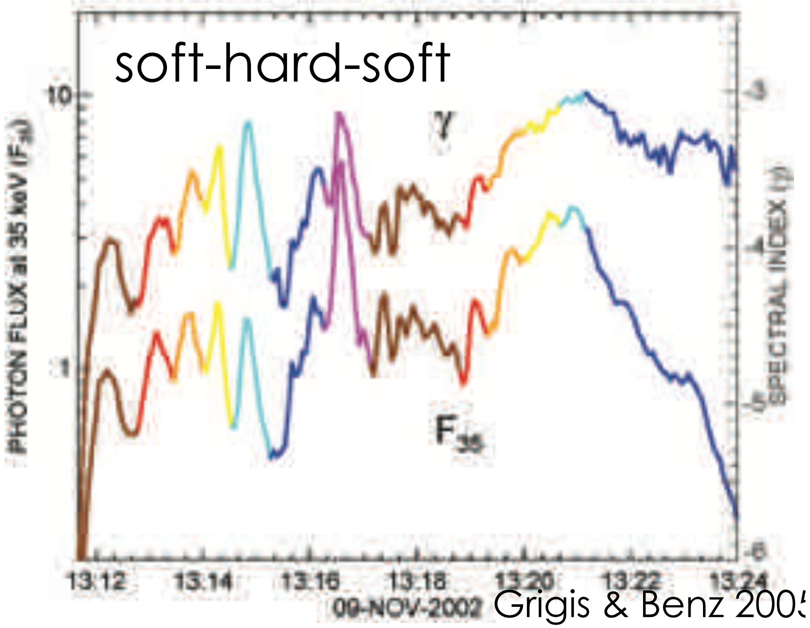
3) How much energy is contained in accelerated electrons? → X-ray spectra

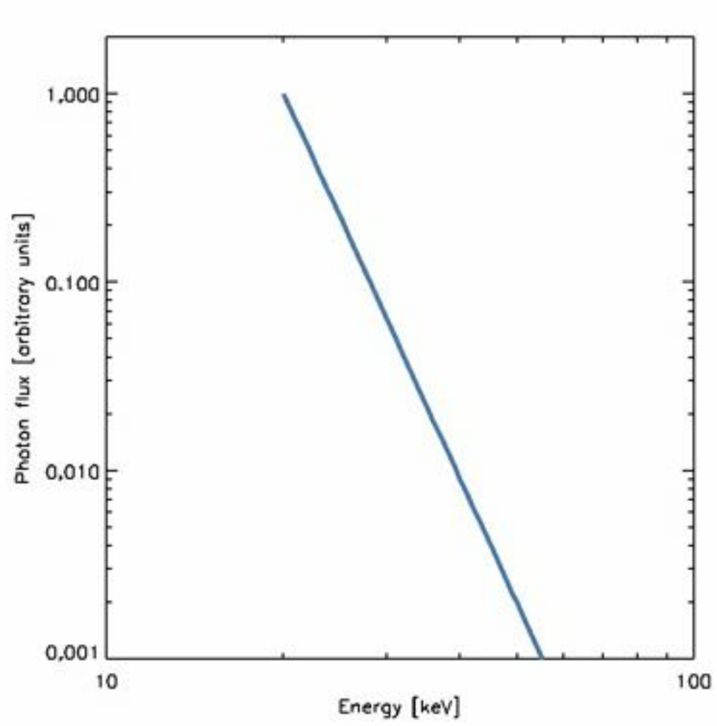
4) What are the time scales of electron acceleration? → X-ray lightcurves

5) How are electrons transported in the corona? → X-ray images and spectra

4) What are the time scales of electron acceleration?



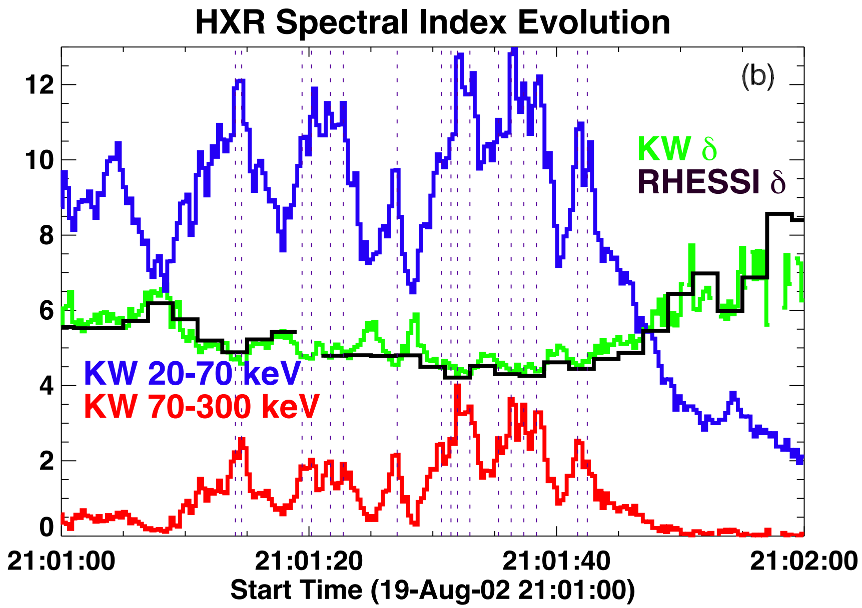


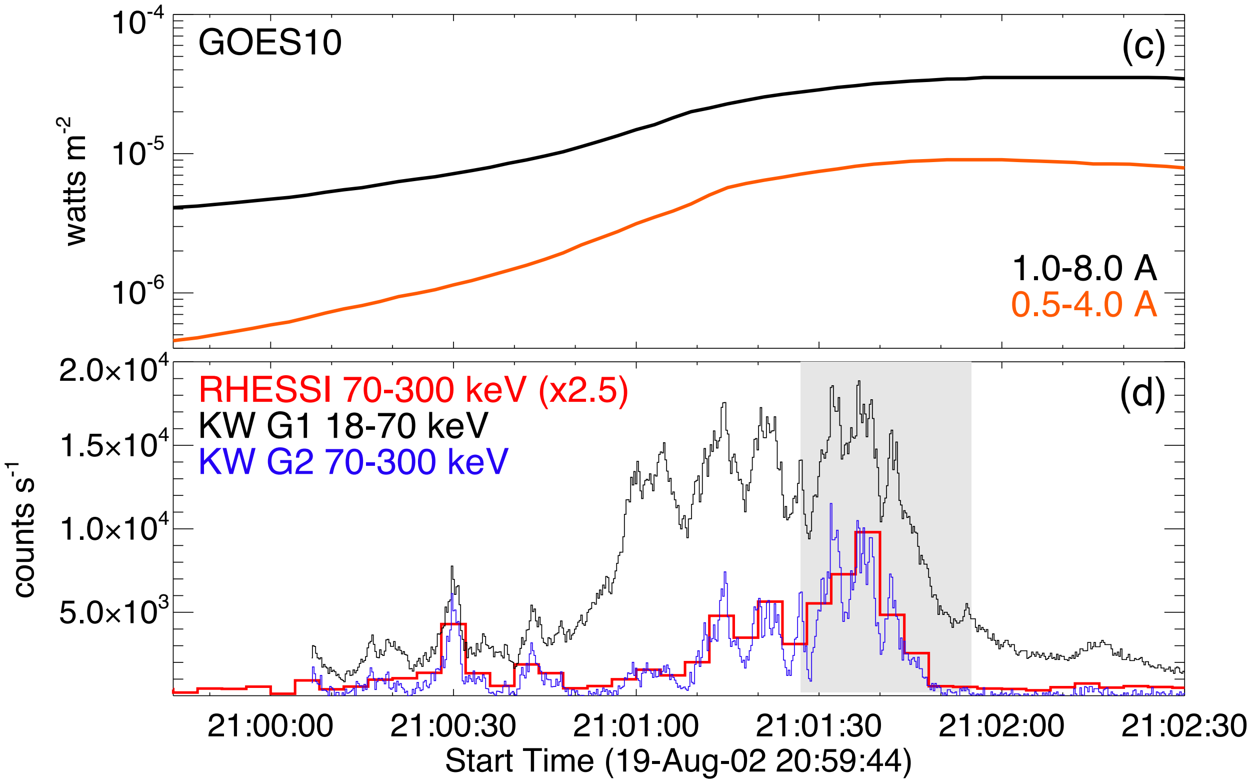


Multiple HXR bursts in short succession, each associated with spectral hardening,
→ individual acceleration events
RHESSI time resolution: 4 seconds (2 seconds) → acceleration time scales possibly not resolved

Glesener & Fleishman 2018:

acceleration time scales < 1s in joint flare observation with RHESSI & Konus-Wind





Some questions regarding electron acceleration in solar flares

1) Where are electrons accelerated?

Above the loop-top?
Along the loop?
Both?

2) How are electrons accelerated?

3) How much energy is contained in accelerated electrons?

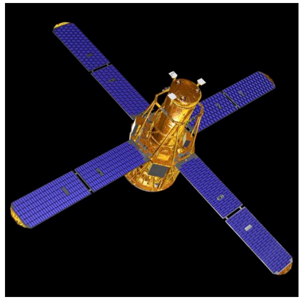
~ 50% of magnetic free energy?

4) What are the time scales of electron acceleration?

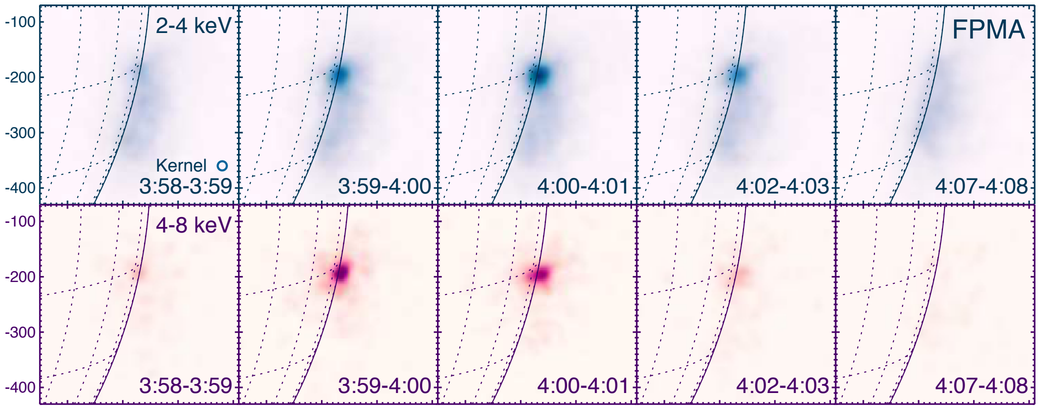
sub-second?

5) How are electrons transported in the corona?

The past, present, and future of X-ray solar flare studies



- To conclusively answer the question summarized earlier we need
  - Imaging at high (~ arcsec) spatial resolution: RHESSI until 2018,
  - *Imaging with large dynamic range*
  - Spectroscopy at high spectral (~ 1 keV) resolution: RHESSI until 2018, Fermi (Konus-Wind)
  - High temporal (< 1s) resolution: Konus-Wind
  - Energy coverage from a few keV up to a few 100 keV: RHESSI, Konus-Wind, Fermi
  - *High sensitivity for studying the smallest flares: NuSTAR*



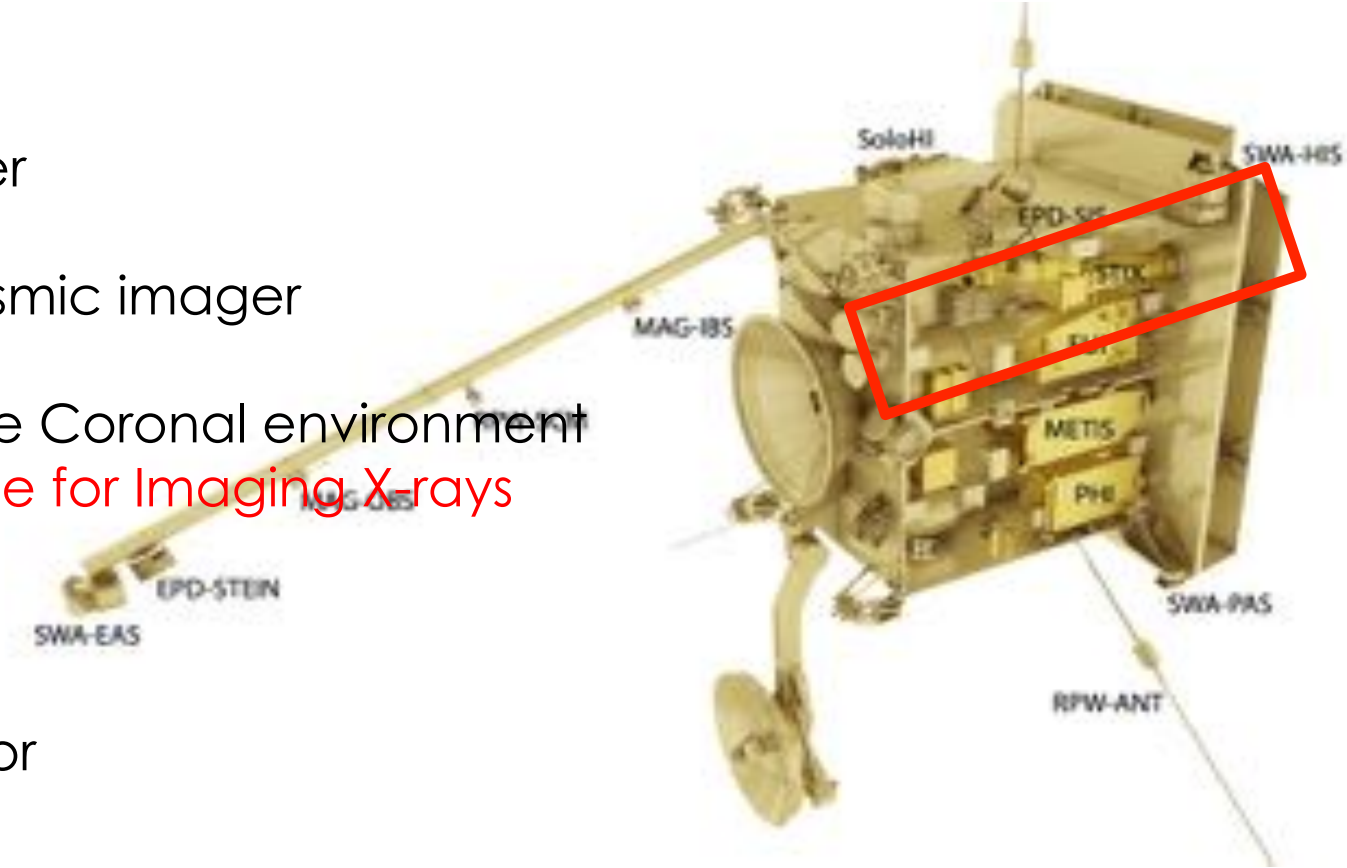
Glesener et al. 2017:
faintest ever observed HXR flare
GOES class ~ A0.1

Upcoming X-ray imaging-spectrometer: STIX on Solar Orbiter

Solar Orbiter: ESA mission to study how the Sun forms, shapes and affects the heliosphere
Launch: February 5 2020

Remote sensing instruments:

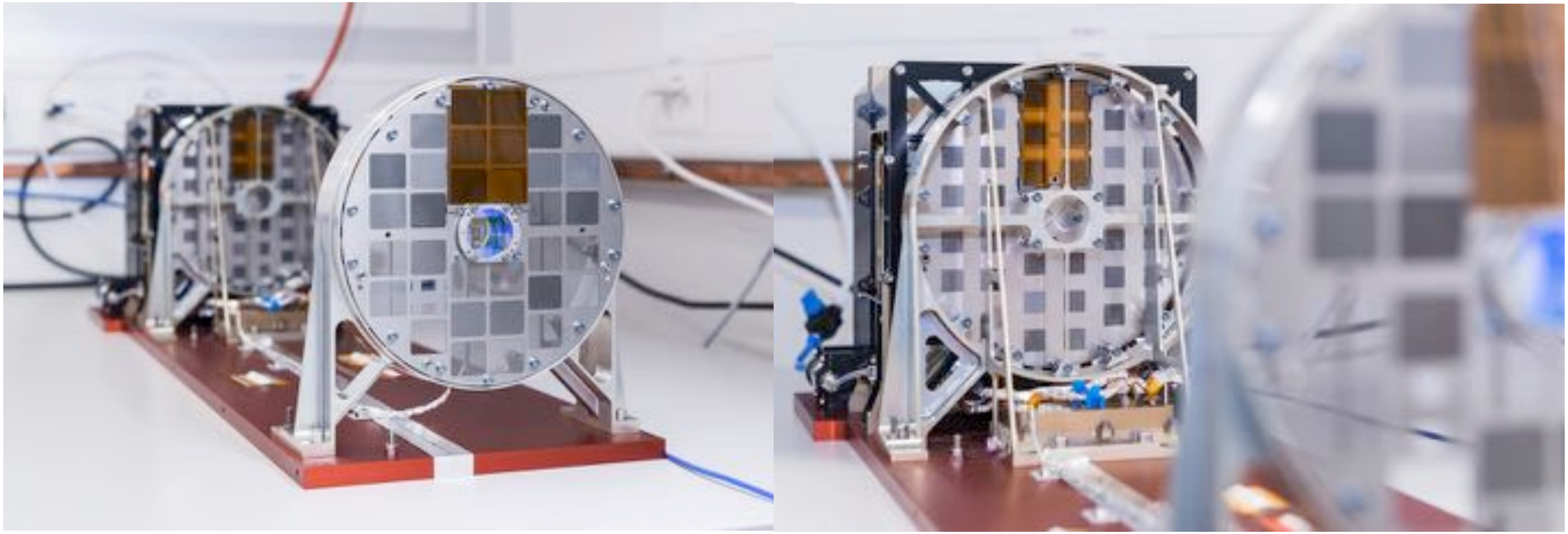
- EUI: Extreme Ultraviolet Imager
- Metis: Coronagraph
- PHI: Polarimetric and Helioseismic imager
- SoloHI: Heliospheric imager
- SPICE: Spectral Imaging of the Coronal environment
- STIX: Spectrometer / Telescope for Imaging X-rays



In-situ instruments:

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

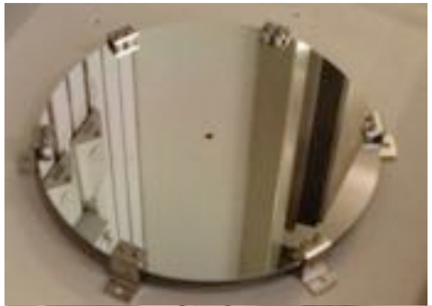
STIX on solar orbiter



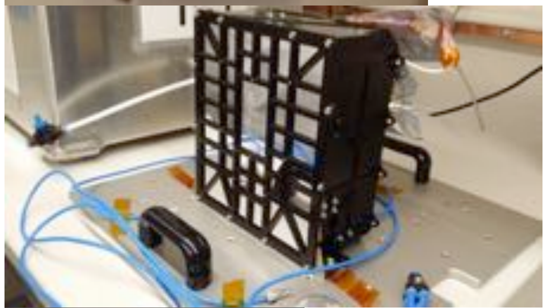
32 CdTe detectors, 1 cm^2 detector area
Energy range 4 – 150 keV
Energy resolution 1-15 keV
Time resolution: nominally < 1s, telemetry-dependent
Fourier imager with spatial resolution ~ 7 arcsec @ 1 AU

University of Applied Sciences
Northwestern Switzerland

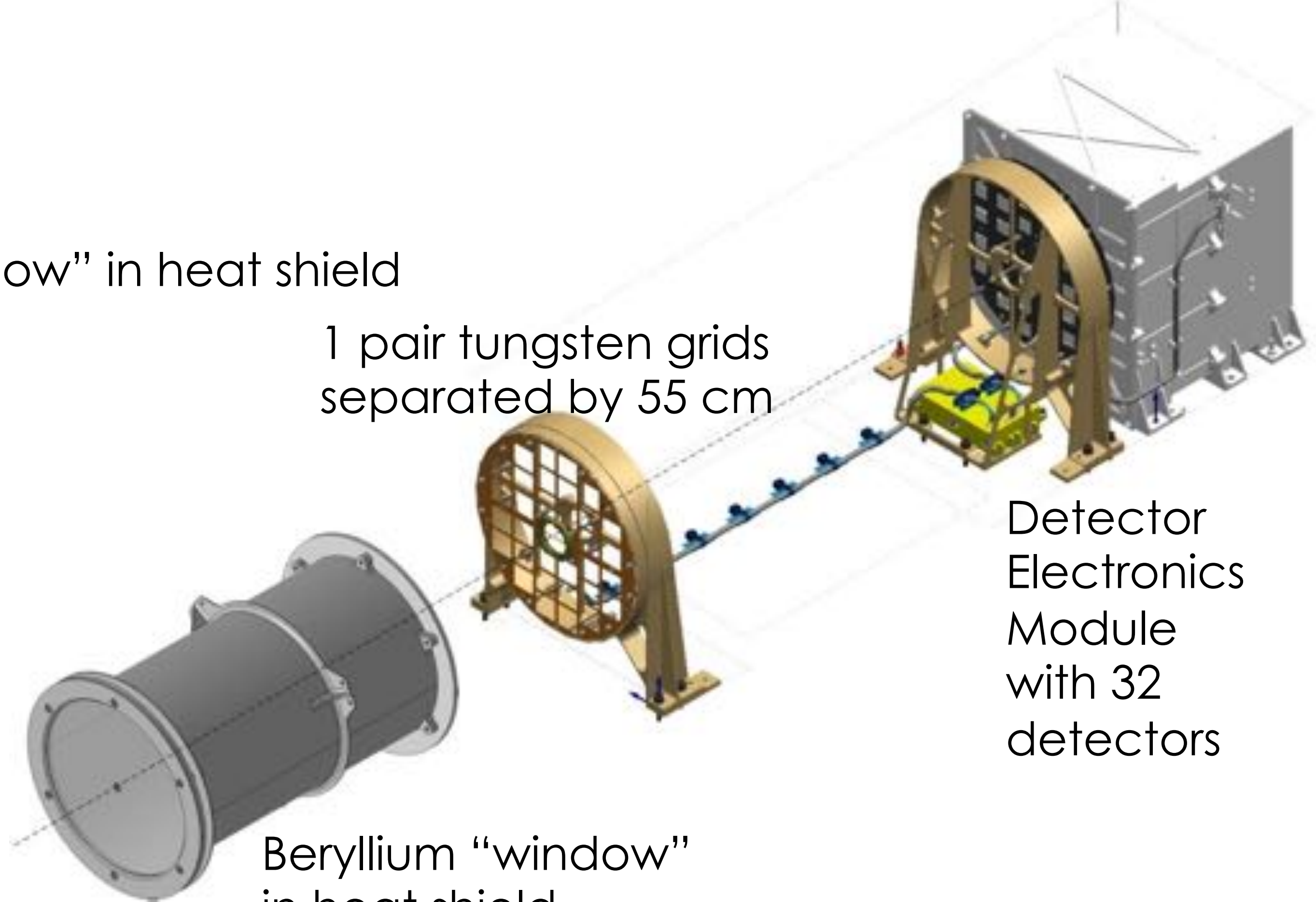
STIX components



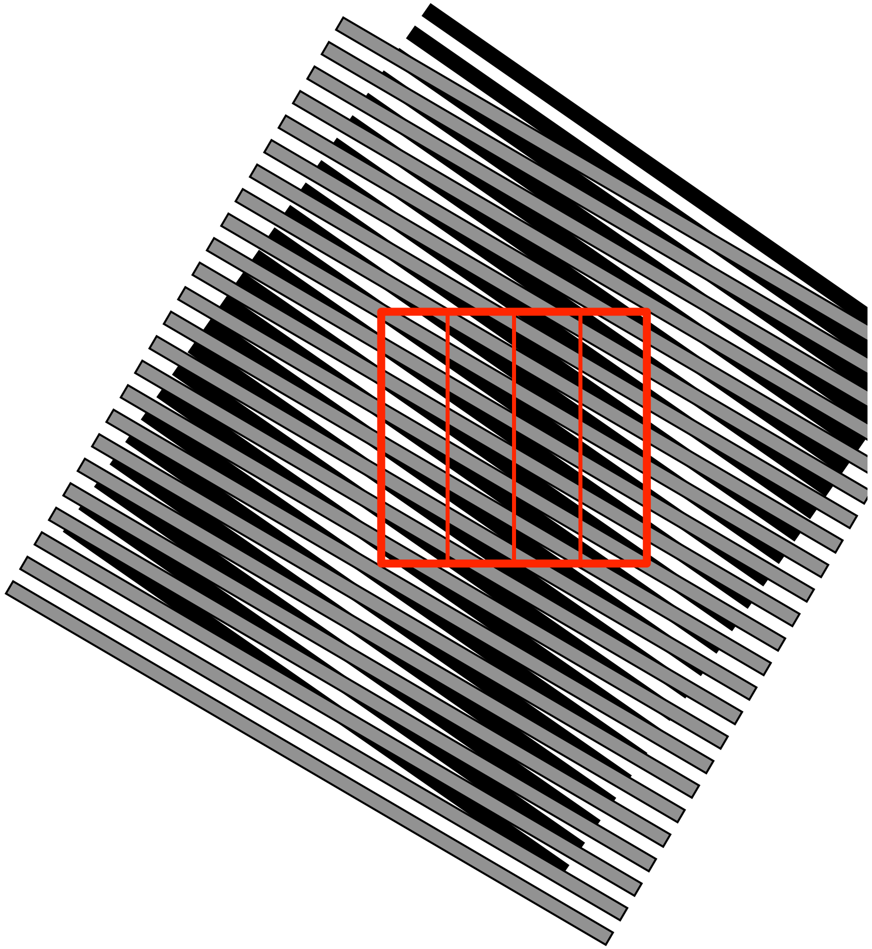
Beryllium “window” in heat shield

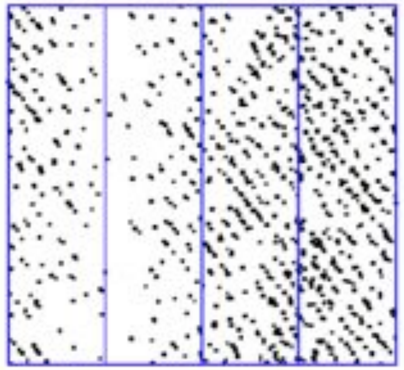


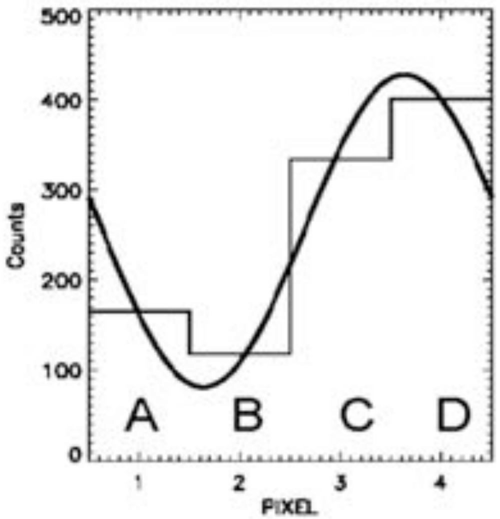
32 CdTe detectors,
1 cm^2 detector area
→ energy range 4 – 150 keV, resolution 1-15 keV

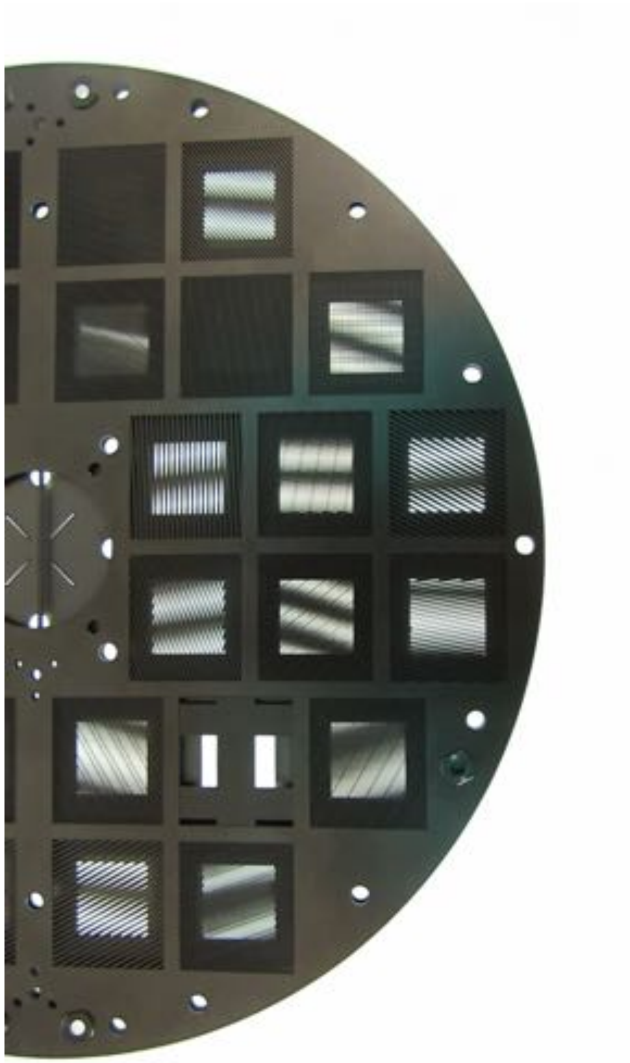


STIX imaging



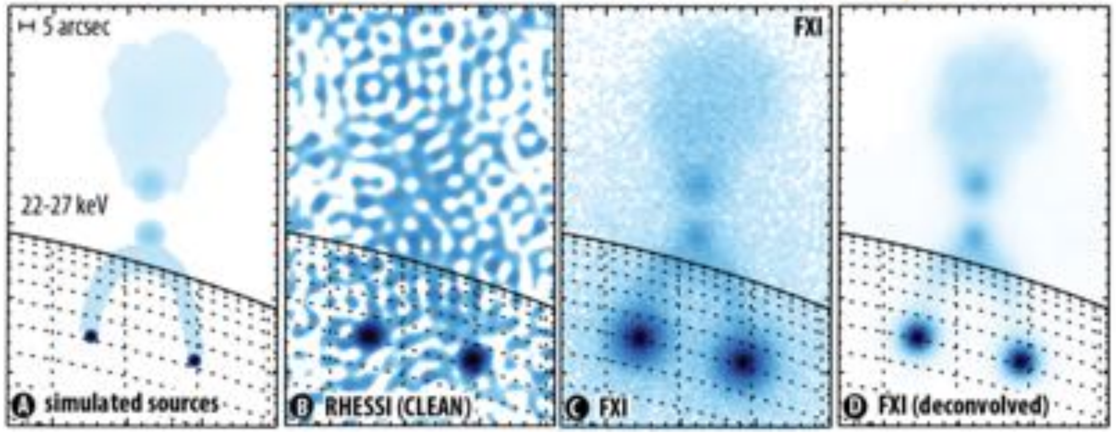






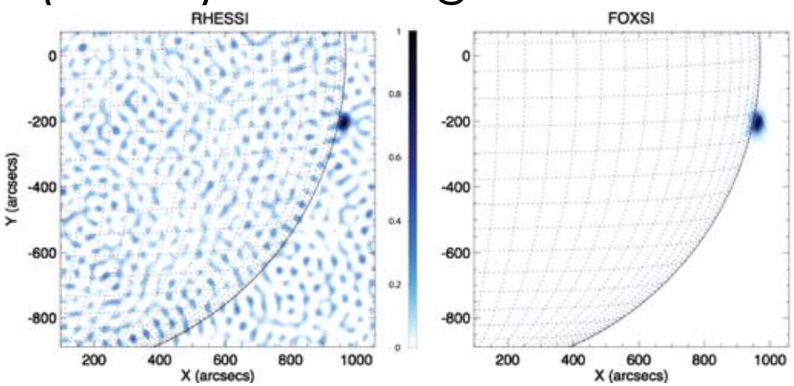
Other developments

- We currently have no solar-dedicated X-ray imager and spectrometer
- STIX (from 2020) will have similar capabilities as RHESSI
- Still missing high dynamic range imaging → difficult to observe X-rays from low-density regions such as the (suspected) acceleration regions



→ focusing optics

Flare observed with RHESSI and the Focusing Optics X-ray Solar Imager (FOXSI) sounding rocket

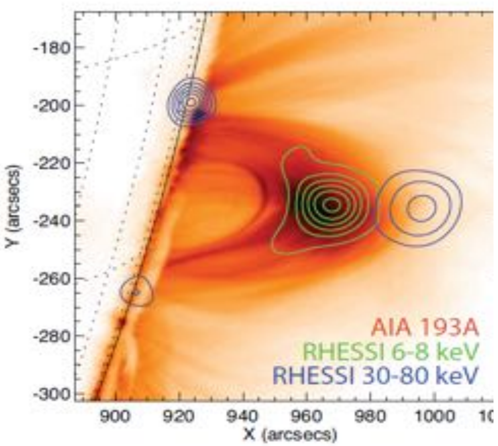


Simulation of a flare observed with a (hopefully future!) solar dedicated focusing optics space mission (The FOXSI team, AGU 2017)

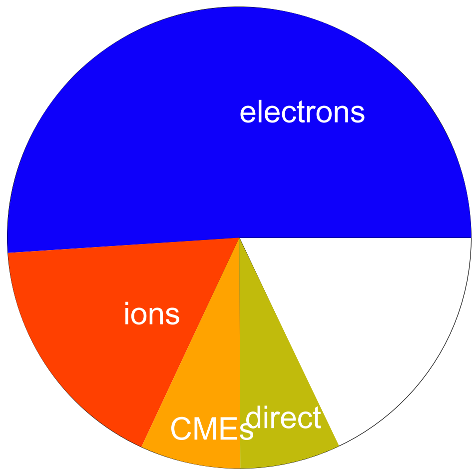
Krucker et al. 2014

Summary

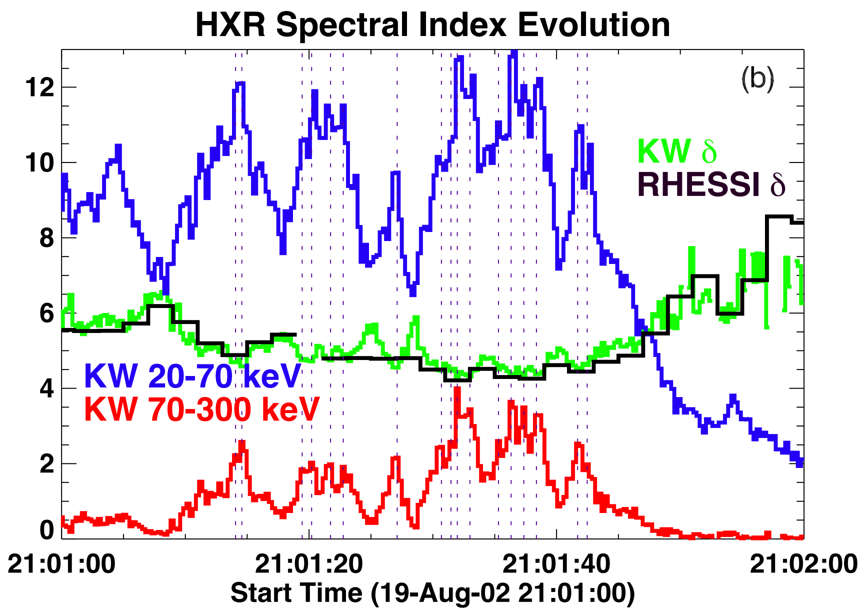
- X-ray observations provide crucial insight into electron acceleration and transport in solar flares
- A lot of progress has been made in the past ~20 years
- For a complete picture of the flaring process, multi-wavelength observations are needed (see talk by G. Fleishman)



Krucker & Battaglia 2014



Aschwanden et al. 2017



Glesener & Fleishman 2018