Fachhochschule
Nordwestschweiz

Multi-wavelength observations of electron energization in solar flares

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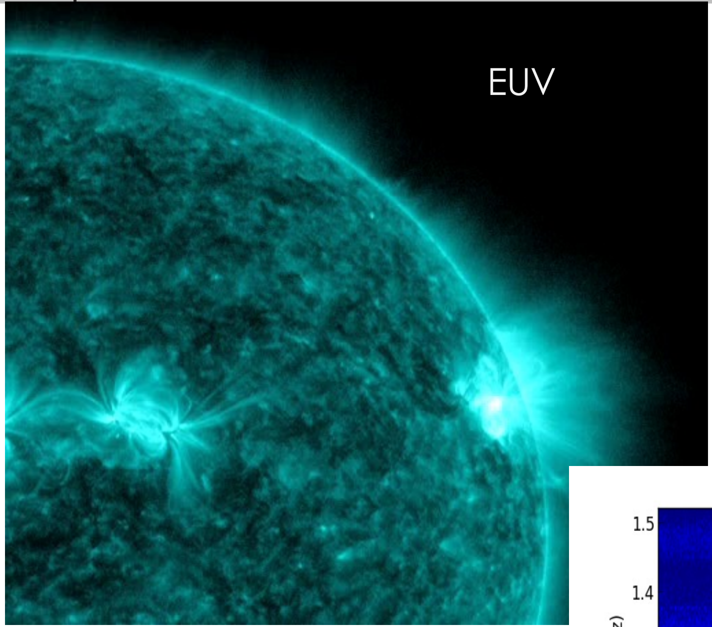
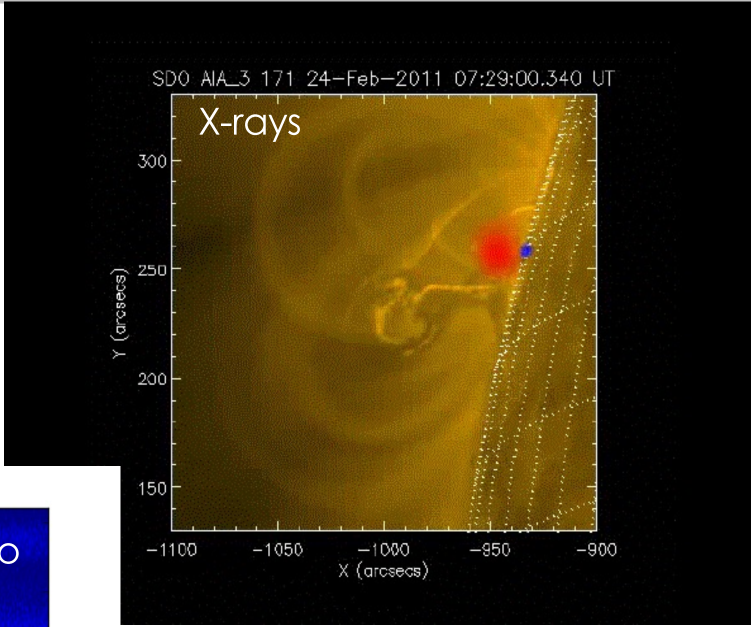
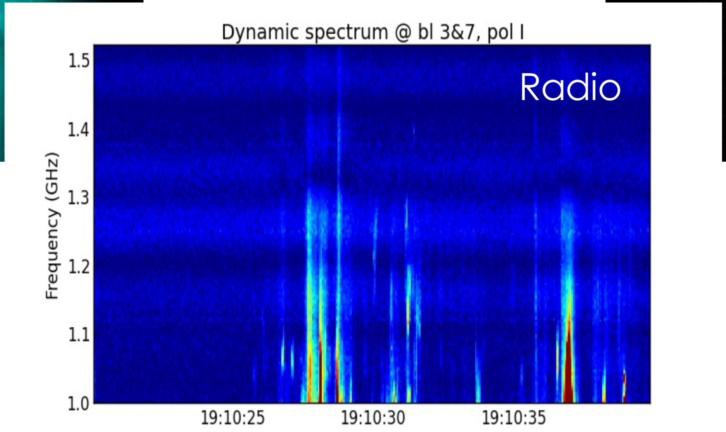

EUV


SDO AIA_3 171 24-Feb-2011 07:29:00.340 UT
X-rays
300
250
200
150
Y (arcsecs)
−1100
−1050
−1000
−950
−900
X (arcsecs)


Dynamic spectrum @ bl 3&7, pol I
Radio
Frequency (GHz)
1.5
1.4
1.3
1.2
1.1
1.0
19:10:25
19:10:30
19:10:35

Outline

1. Open questions surrounding electron energization in flares
2. Multi-wavelength signatures of energetic electrons
3. Locations of electron energizations
4. Spectral signatures of electron energizations
5. A change of perspective
6. Summary
7. Questions

1. Open questions surrounding electron energization in flares

Where are electrons accelerated?

How are electrons accelerated?

What are the **timescales** of electron energization?

How much **energy** is contained in accelerated electrons?

How are electrons **transported** in the corona?

How does the atmosphere **react** to flare energy input?

1. Open questions surrounding electron energization in flares

Where are electrons accelerated?

How are electrons accelerated?

What are the **timescales** of electron energization?

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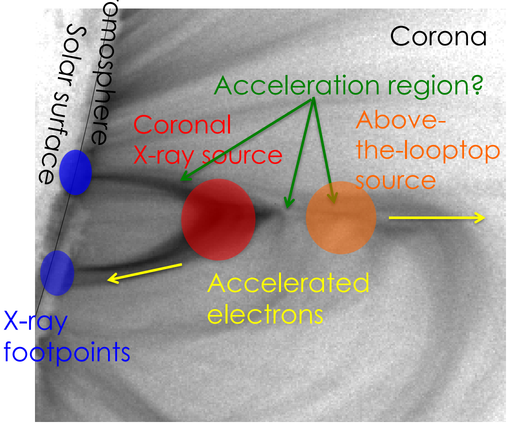
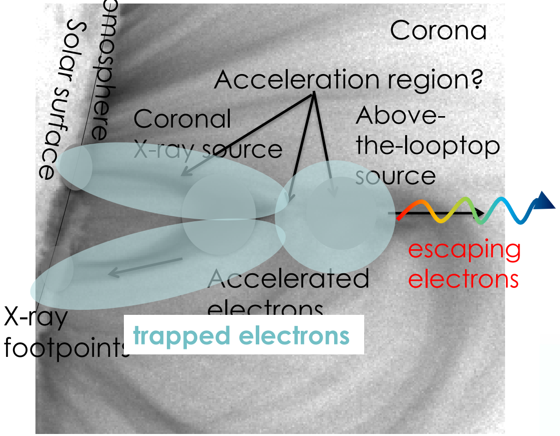
How are electrons **transported** in the corona?

How does the atmosphere **react** to flare energy input?

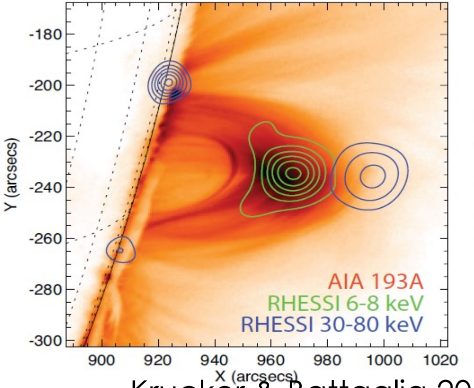
2. Multi-wavelength signatures of energetic electrons

X-ray emission in the standard flare scenario

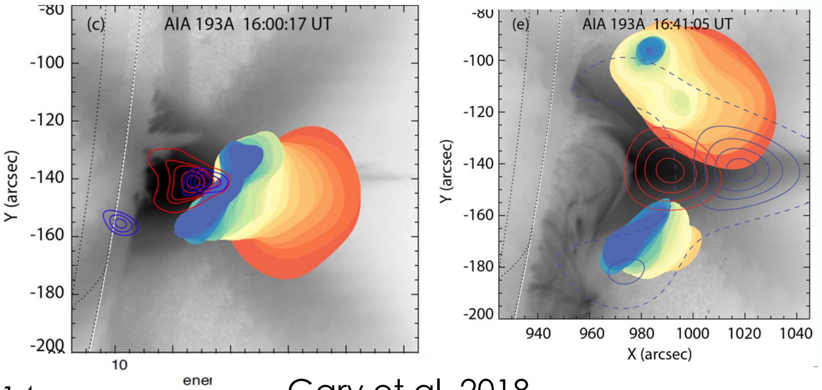




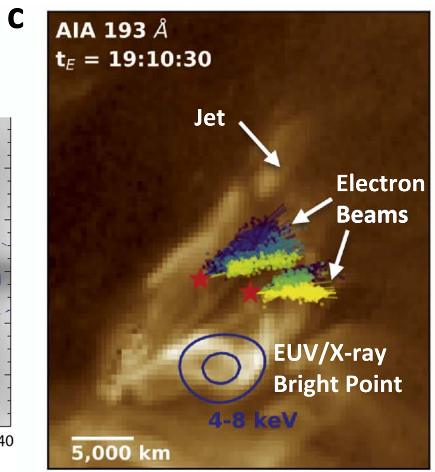
Radio emission in the standard flare scenario



Krucker & Battaglia 2014



Gary et al. 2018



Chen et al. 2018

3. Locations of electron energization

Important for

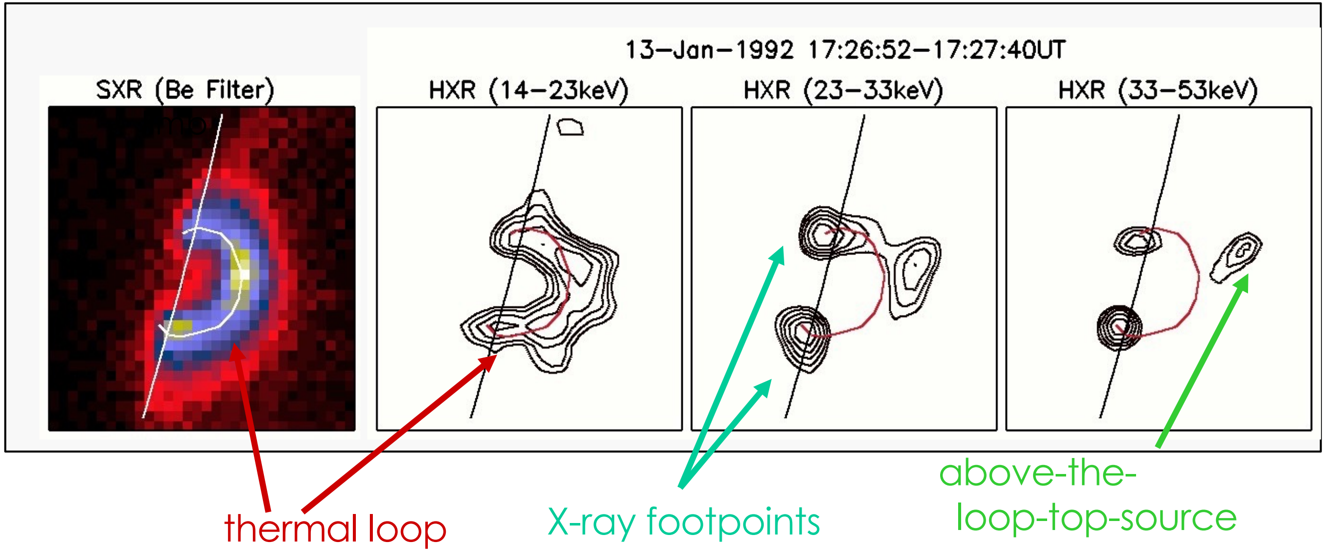
- Flare geometry and morphology
- Relation between reconnection and acceleration
- Atmospheric response

Challenges

- Instrument sensitivity and dynamic range
- Angular resolution
- Temporal resolution

3. Locations of electron energization

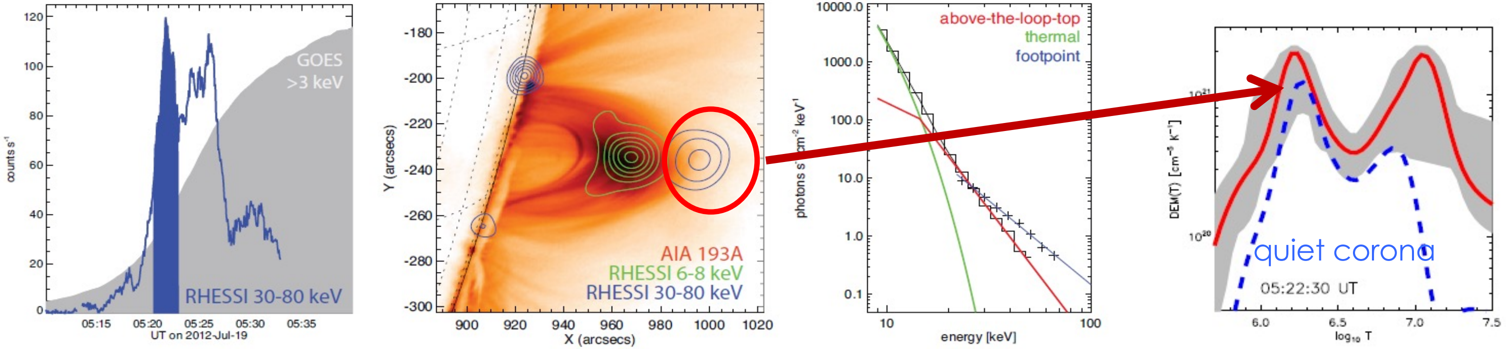
Above the loop-top-source as acceleration region



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

X-ray
EUV

3. Locations of electron energization
Bulk acceleration in the above-the-loop-top source

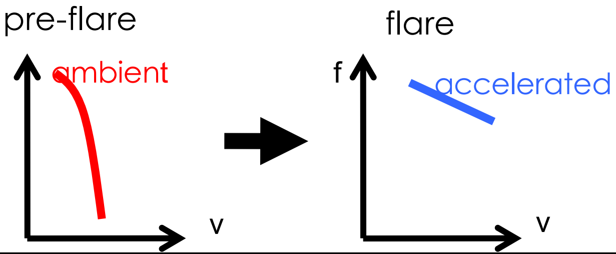


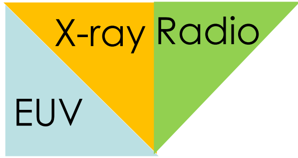
Krucker & Battaglia 2014

- RHESSI imaging spectroscopy to infer density of accelerated electrons: $n_{nt} \sim 10^9$ cm^{-3}
- SDO/AIA differential emission measure analysis to determine ambient density n_0

→ ratio n_{nt}/n_0 is close to 1

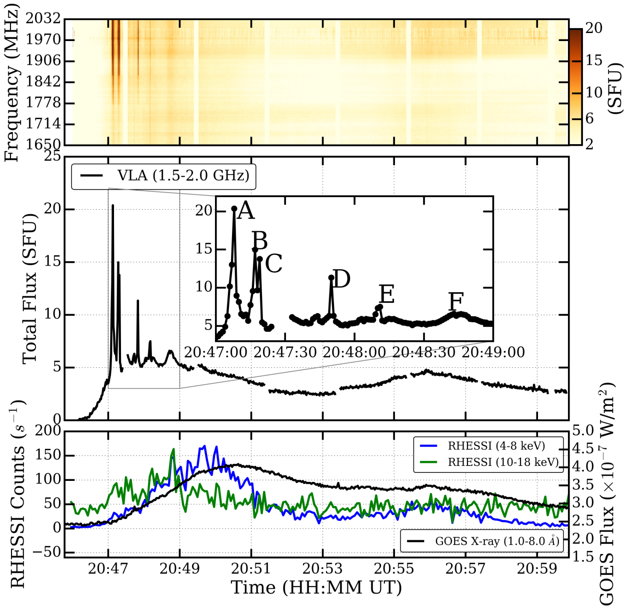
Interpretation: Entire plasma is accelerated (non-thermal) in bulk energization process
Above the loop-top-source is acceleration region

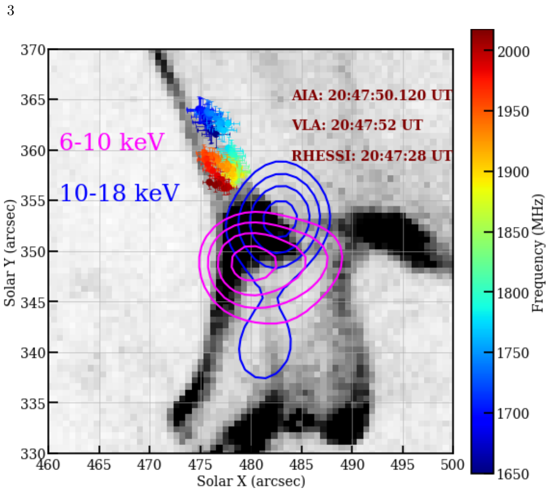




3. Locations of electron energization

Multiple acceleration sites

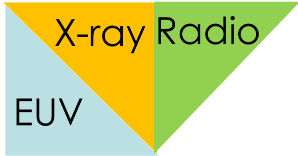




(D)

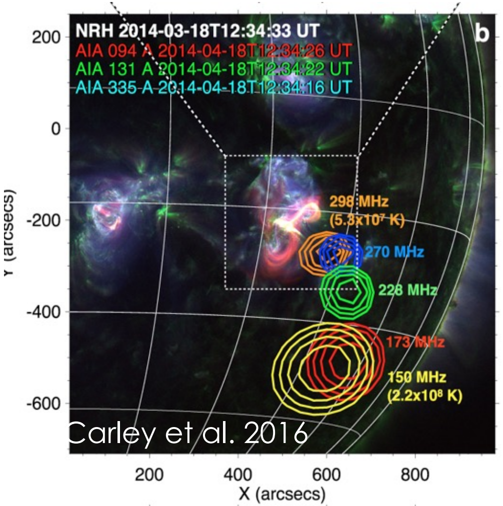
Sharma et al. 2020

Imaging and spectroscopy
→ different electron populations

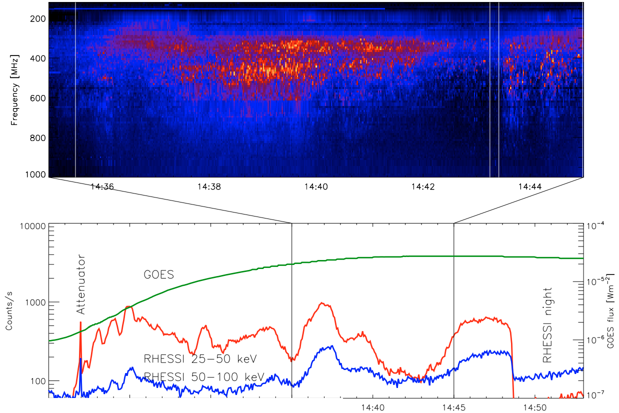


3. Locations of electron energization

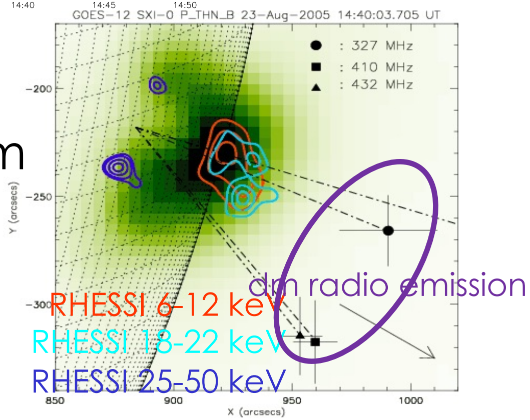
Multiple acceleration sites

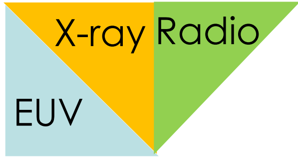


Type III burst associated with an erupting flux rope (Carley et al. 2016)



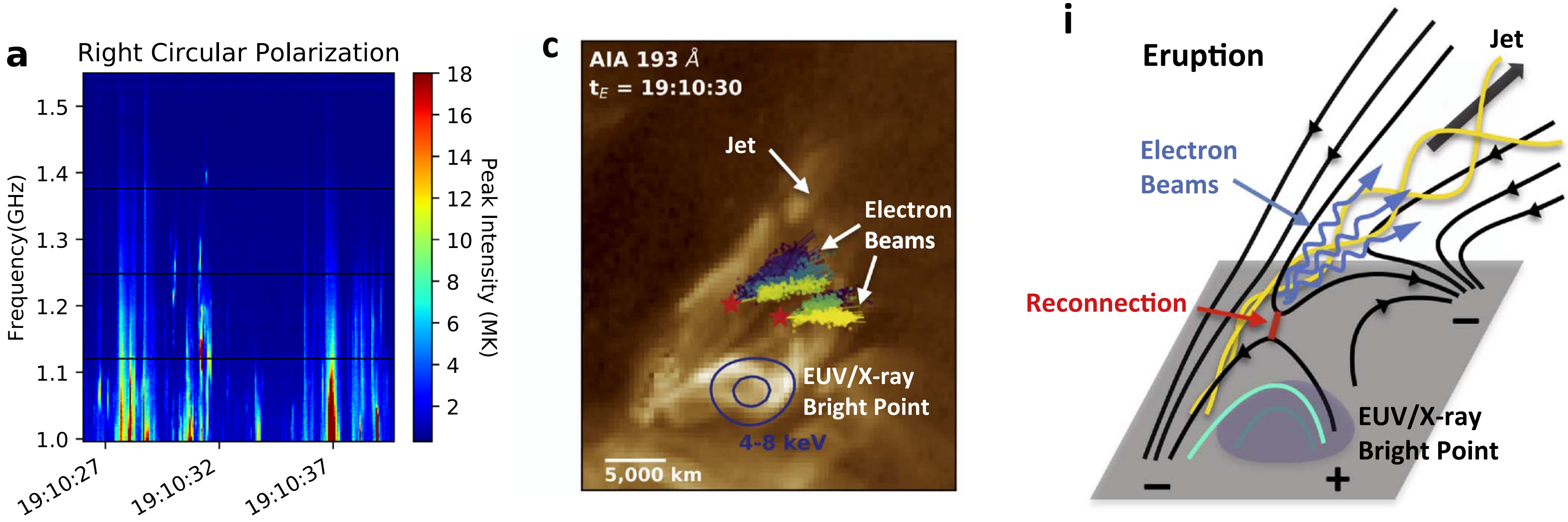
Decimetric spikes from above the flare site (Battaglia & Benz 2009)





3. Locations of electron energization

The reconnection region itself?



Chen et al. 2018

4. Spectral signatures of electron energization

Important for

- Total energetics
- Thermal – nonthermal energy partition
- Acceleration mechanism
- Atmospheric response

Challenges

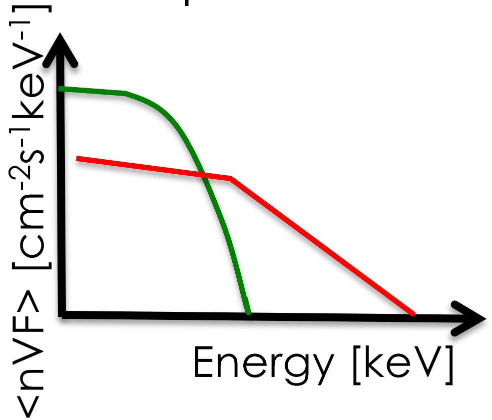
- Energy coverage
- Spectral inversion / fitting models
- Low energy cutoff

X-ray

4. Spectral signatures of electron energization

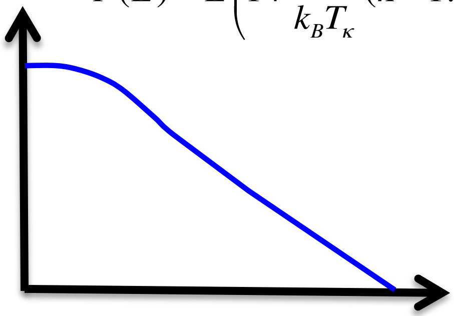
Spectral models and the kappa-distribution

Thermal + power-law



T, EM, δ, flux normalization, E_{cut}

$$F(E) \propto E\left(1+\frac{E}{k_B T_\kappa}(\kappa-1.5)\right)^{-(\kappa+1)}$$



→ T_κ, EM_κ, κ

Why kappa?

- Single analytic function to describe whole spectrum
- No cutoff needed
- Found in multiple RHESSI observations (e.g. Kasparova & Karlicky 2009, Oka et. al. 2013/2015)
- Supported by stochastic acceleration models

(e.g. Bian et al 2014)

X-ray

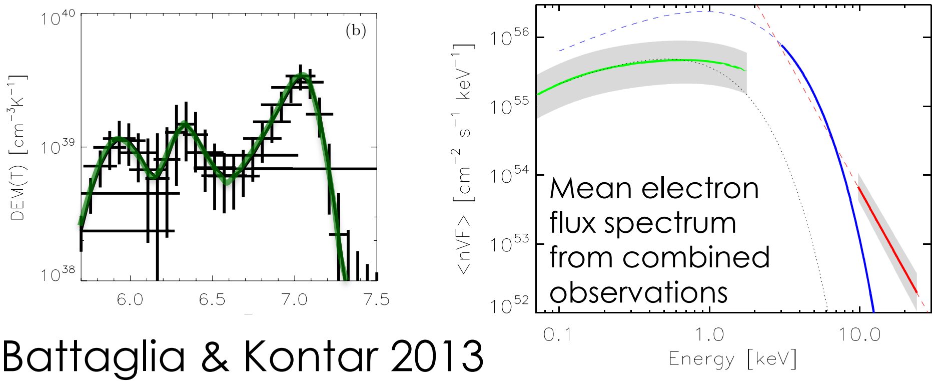
EUV

4. Spectral signatures of electron energization

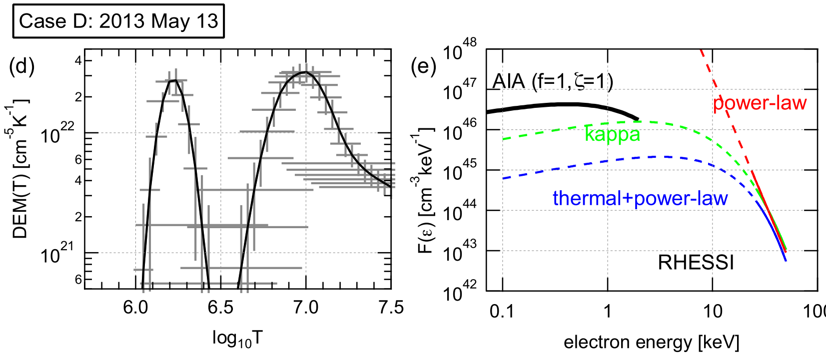
Electron spectra from combined EUV and X-ray *observations*

<nVF> is directly related to DEM: $$\boxed{\langle nVF\rangle} = \frac{2^{3/2}E}{(\pi m_e)^{1/2}} \int_0^\infty \frac{\boxed{\xi(T)}}{(k_B T)^{3/2}} \exp(-E/k_B T)\, dT.$$

Combining AIA with RHESSI we can extend the energy range down to ~ 0.1 keV



Battaglia & Kontar 2013



Oka et al. 2015

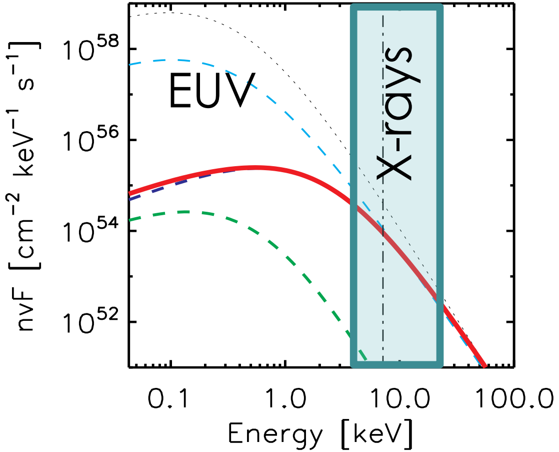
X-ray

EUV

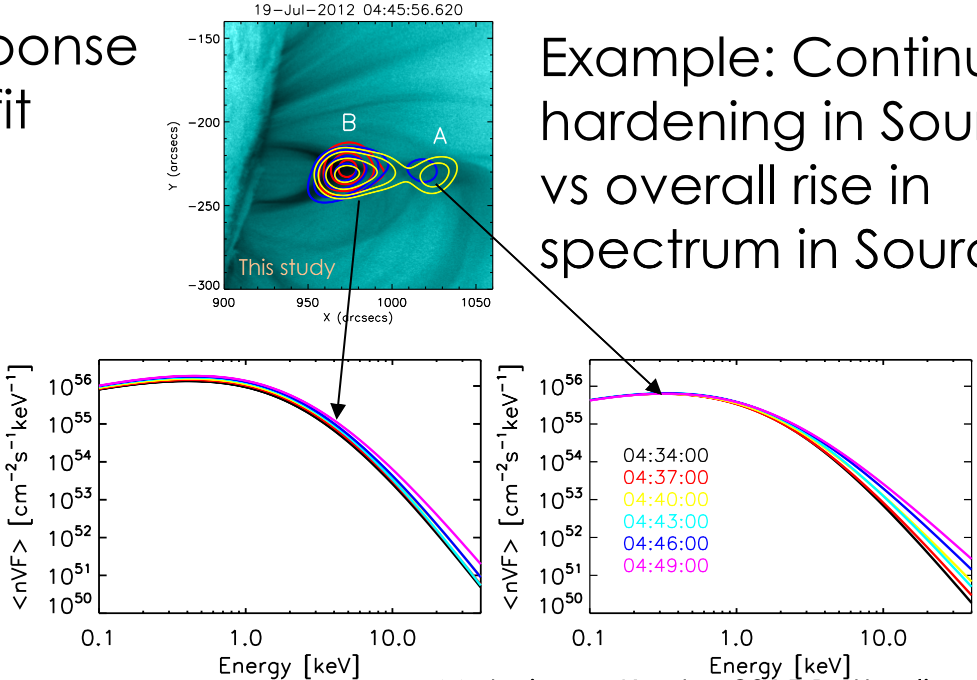
4. Spectral signatures of electron energization

Electron spectra from combined EUV and X-ray fitting

Combine AIA and RHESSI response matrix into one and forward-fit kappa-distribution



Example: Continuous hardening in Source A vs overall rise in spectrum in Source B

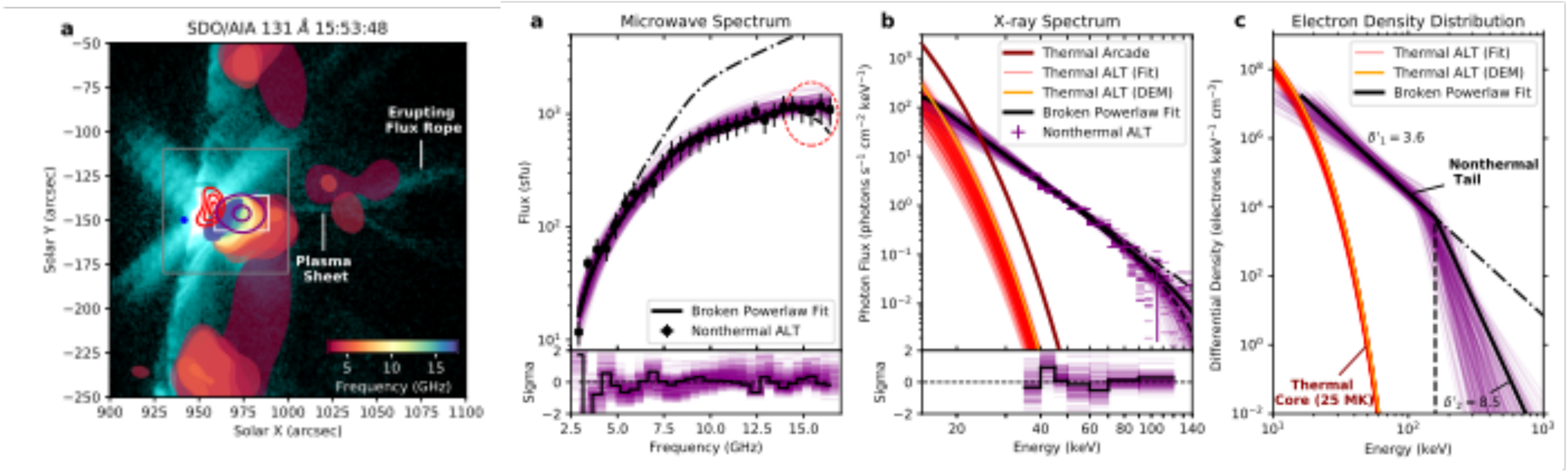


Motorina & Kontar 2015,Battaglia et al. 2019

X-ray Radio

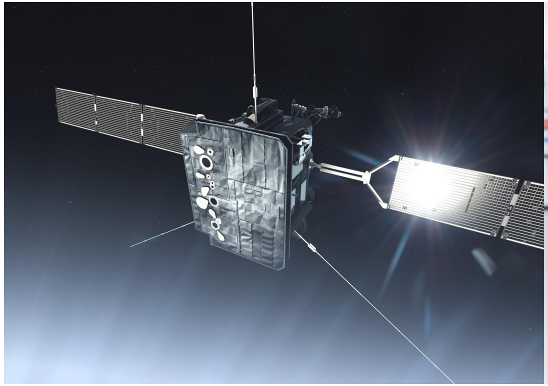
4. Spectral signatures of electron energization

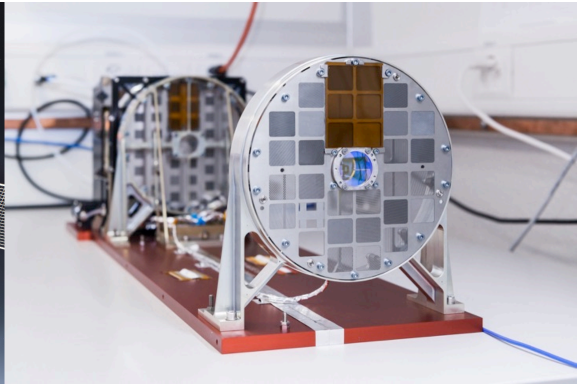
Electron spectra from joint X-ray and radio fitting



Chen et al. 2021

5. A change of perspective





The Spectrometer/Telescope for Imaging X-rays (STIX)

32 CdTe detectors
30 grid pairs
Imaging via Moiré patterns (Fourier imaging)

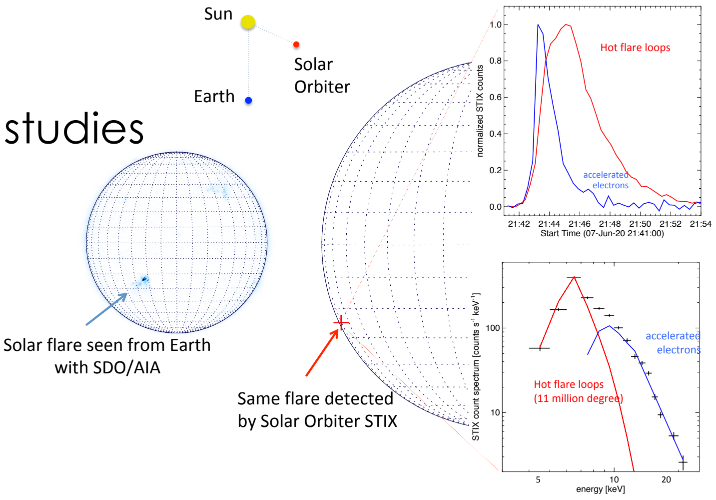
Energy range	4 – 150 keV
Energy resolution	1 keV at lowest energies
Temporal resolution	1 s (nominal)
Angular resolution	7 arcsec (at 1 AU)

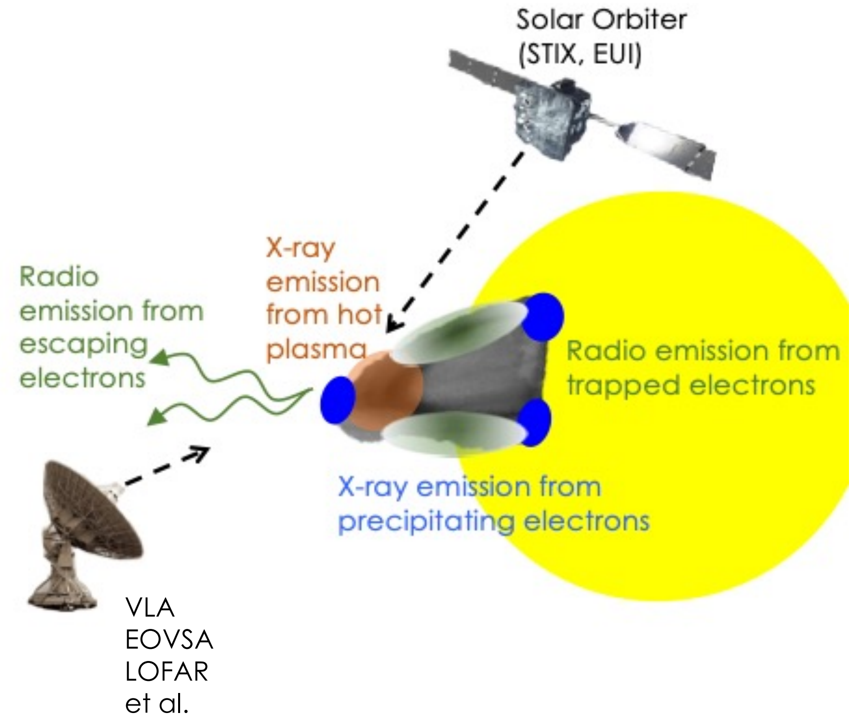
5. A change of perspective

Electron energization in 3D with STIX

Two different viewing angles

- First pseudo-3D model of electron energization in solar flares
- Directivity studies

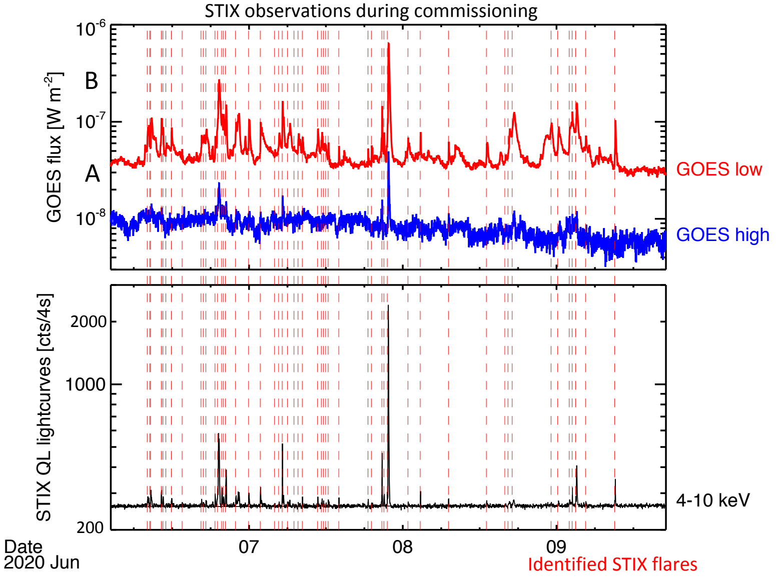




5. A change of perspective

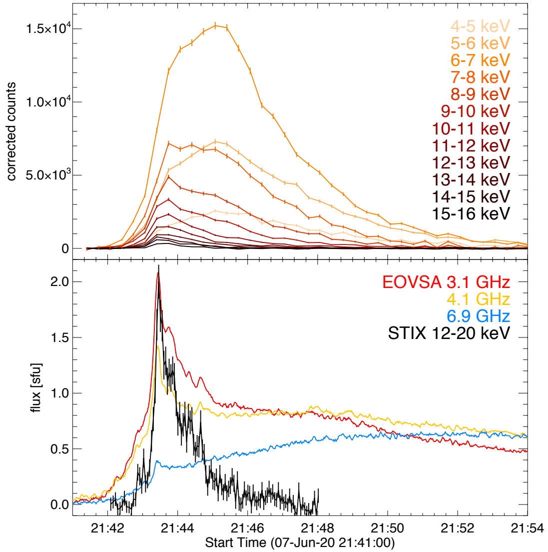
STIX sees flares!

Several hundred flares observed so far



First results from STIX:

Poster by Jonas Saqri
Talk by Alexander Warmuth (Q6)



6. Summary

Multi-wavelength imaging and spectroscopy allows us to study many aspects of electron energization in flares, such as where, when, and how electrons are energized, to what energies, and how these energies are partitioned.

Solar Orbiter adds a new perspective: Combining STIX X-ray observations with radio observations from Earth provides a quasi-3D picture of electron energization.

7. Questions?