FOXSI

Focusing Optics X-Ray Solar Imager

SMEX proposal

Albert Y. Shih (NASA/GSFC)

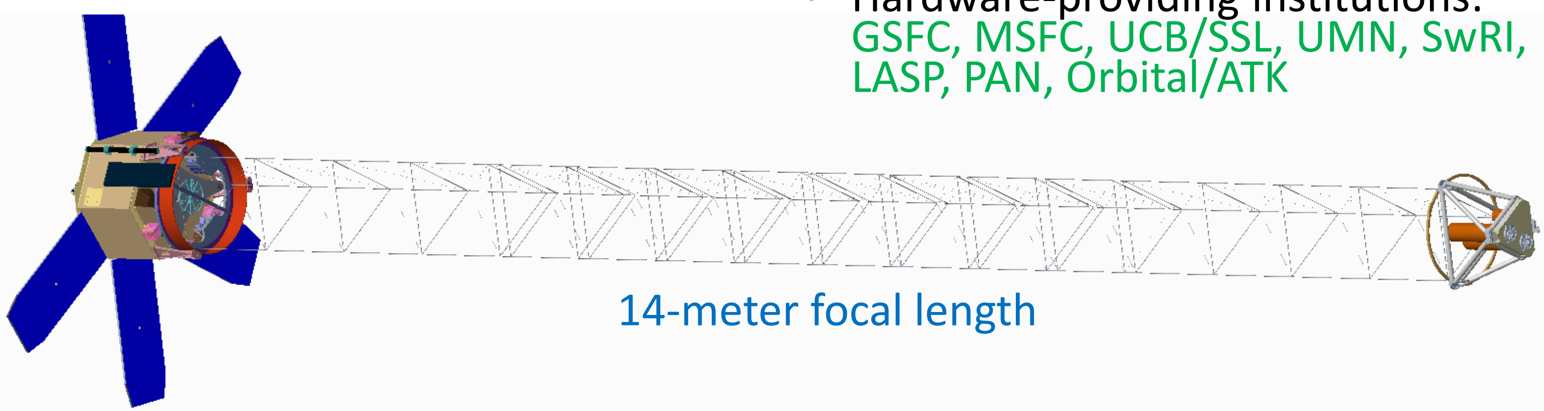
on behalf of the *FOXSI* SMEX team

2016 July 27

Focusing Optics X-ray Solar Imager (*FOXSI*) SMEX concept

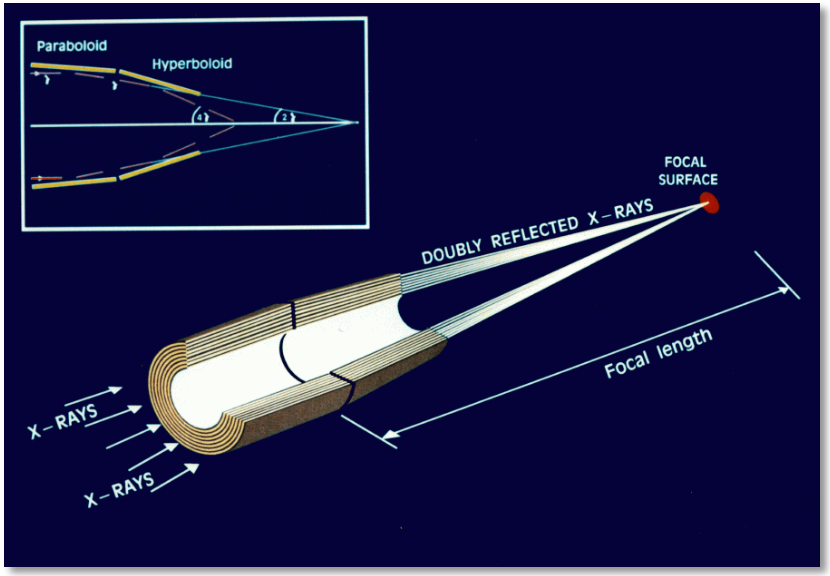
- *FOXSI* uses direct imaging of hard X-rays to obtain the high sensitivity and high dynamic range needed to make breakthrough observations
- *FOXSI* combines:
  - State-of-the-art grazing-incidence mirrors, with <8" FWHM angular resolution
  - Pixelated solid-state detectors, with high-count-rate capability
- 2-year prime mission during the rise of solar cycle 25

- PI: Steven Christe (GSFC)
- Deputy PI: Albert Shih (GSFC)
- Project scientist: Säm Krucker (UCB/SSL, FHNW)
- Instrument scientist: Lindsay Glesener (UMN)
- Imaging scientist: Pascal Saint-Hilaire (UCB/SSL)
- Detector scientist: Wayne Baumgartner (GSFC)
- Hardware-providing institutions: GSFC, MSFC, UCB/SSL, UMN, SwRI, LASP, PAN, Orbital/ATK



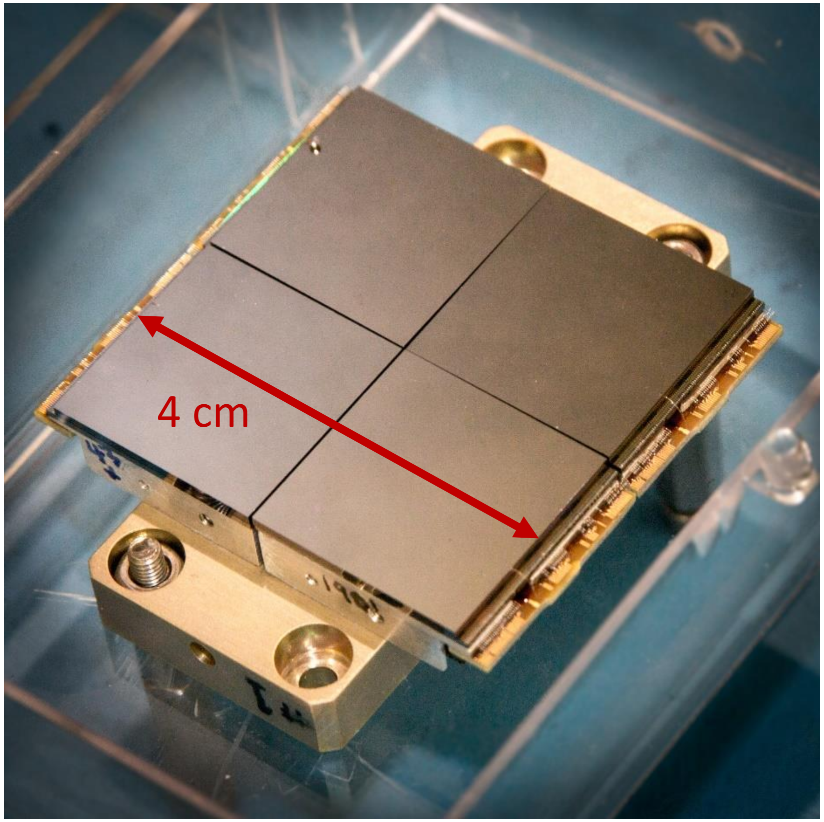
Grazing-incidence optics

- X-rays reflect at very shallow angles
  - Paraboloid and hyperboloid shells focus X-rays
  - Nested shells for energy range and effective area
- Electroformed nickel replicated optics
  - High angular resolution: ~5” FWHM
  - Better angular resolution than glass optics, but heavier
- Heritage
  - *FOXSI* sounding rocket
  - *HERO/HEROES* balloon
  - Delivered to *ART-XC*



Pixelated solid-state detectors

- Match high-resolution optics with pixelated solid-state detectors that can handle high count rates
- Detector arrays
  - CdTe detectors using the HEXITEC ASIC built by RAL
  - 2×2 array is 4 cm on a side
  - Pixel pitch: 250 µm
  - Spectral resolution: <~1 keV FWHM
  - Can count up to 10,000 counts/s in each pixel
- Ongoing detector development at GSFC



How *FOXSI* works

- Direct HXR imager, but still tags individual photons!
  - Aspect system for high-cadence pointing knowledge
  - Relaxes control requirements on the 14-meter boom
  - Maximum flexibility for data analysis
- Direct imaging has significantly improved imaging dynamic range over indirect imaging
  - ≥20:1 at 20” separation
  - ≥1000:1 at 45” separation
- Two telescopes
  - Energy range: ~3–75 keV
  - One telescope optimized for nonthermal emission
    - Attenuators to manage count rate
  - Other telescope optimized for thermal emission
    - Thinner attenuators
- Partial-Sun FOV of 9’×9’
  - Pointing targets will be defined regularly and on demand by science team
  - Have to concerned about stray light from sources outside the FOV

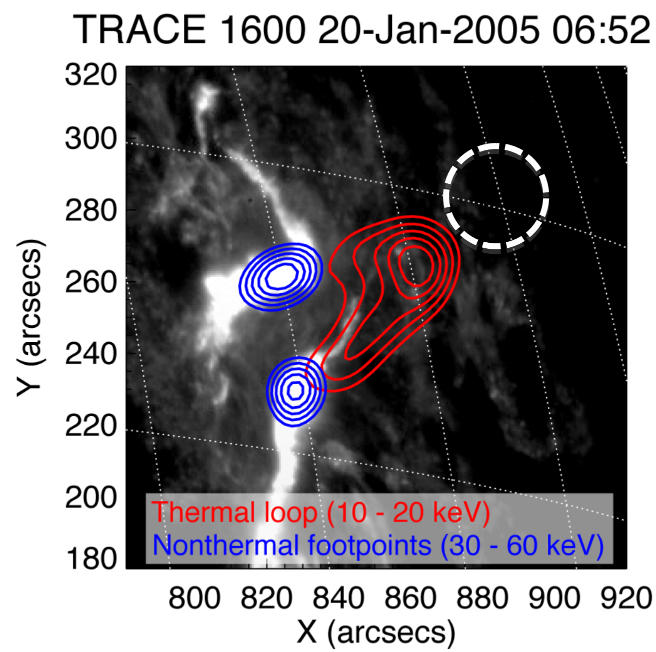
FOXSI science questions

- How are particles accelerated at the Sun?
  - Where are electrons accelerated and on what time scales?
  - What fraction of electrons are accelerated out of the ambient medium?
  - Where do escaping flare-accelerated electrons originate?
- How do solar plasmas get heated to high temperatures?
  - What is the energy input of accelerated electrons into the chromosphere and the corona?
  - How do super-hot coronal plasmas originate and evolve?
  - How much do flare-like processes heat the quiescent corona?
- How does magnetic energy release on the Sun lead to flares and eruptions?
  - How does coronal energy release and the resulting accelerated particles drive the evolution of flares and associated magnetic structures?
  - How do energy-release processes scale from the smallest bursts to the largest flares?

Where are electrons accelerated?

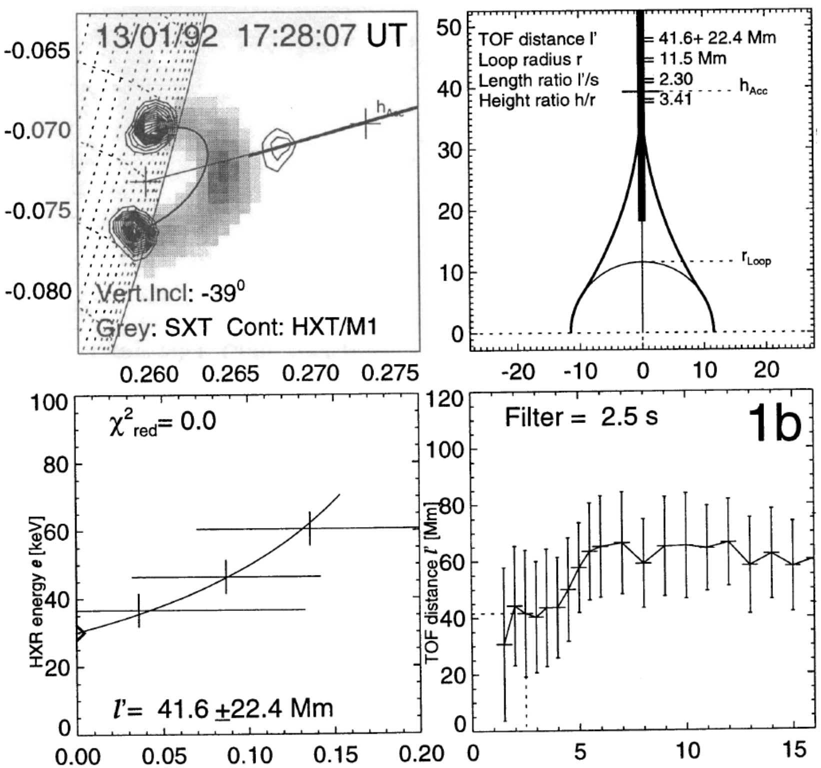
- Electrons accelerated in the corona are difficult to observe given the low ambient densities
  - The thin-target emission in the corona is much fainter than the thick-target emission from the chromospheric footpoints
  - Sources have typically been studied only in flares where the footpoints are occulted by the solar limb
- Recent observations have raised the possibility of significant chromospheric acceleration of electrons
- *FOXSI* will have:
  - The dynamic range to observe coronal sources in the presence of bright footpoints
  - The imaging spectrocopic capability to disentangle the effects of transport on the accelerated energy spectrum

Challenging to observe coronal acceleration regions



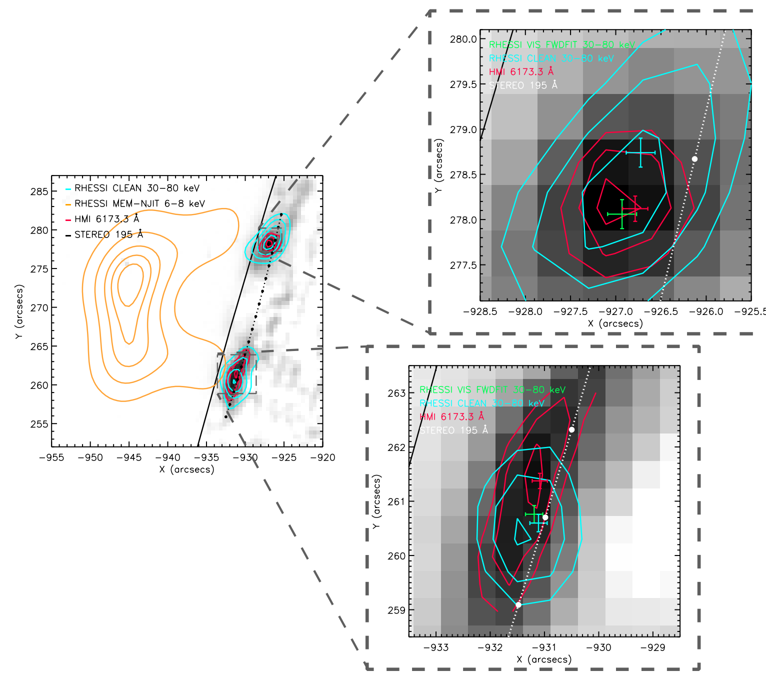
Dashed circle indicates where an above-the-looptop source might be, but is invisible without sufficient dynamic range

Time-of-flight studies support coronal acceleration



(Aschwanden et al. 1996)

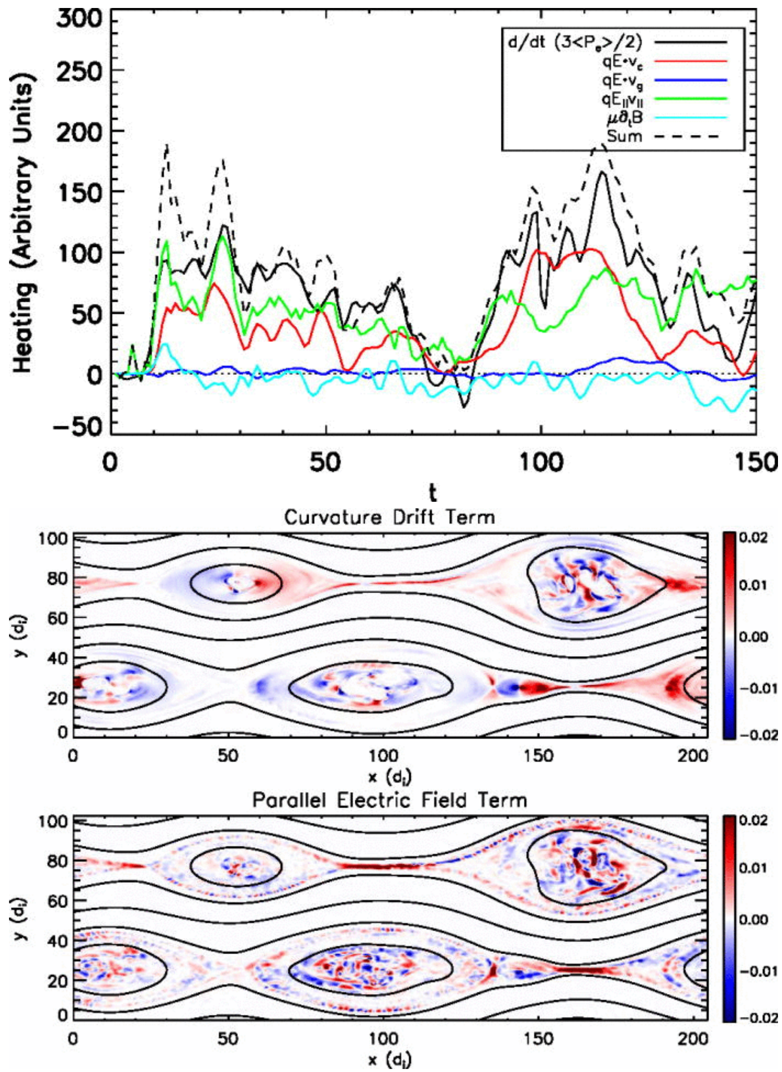
Absolute height determination suggests chromospheric acceleration



(Martínez Oliveros et al. 2012)

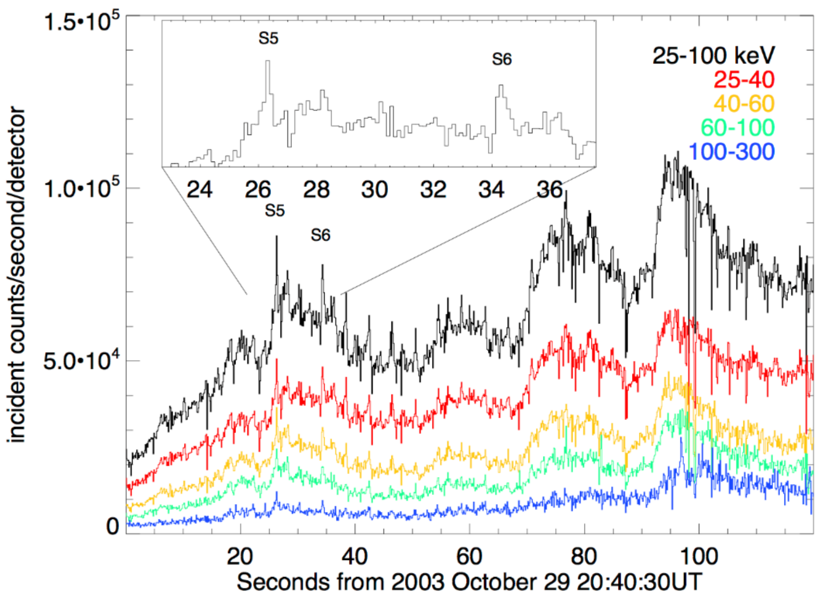
What are the acceleration time scales?

- Flares can exhibit hard X-ray (HXR) spikes with durations down to ~0.1 s
  - Morphology of individual spikes may be different from overall flare
  - Difficult to produce both high-quality time profiles and images when using indirect imaging
- As one explanation, burstiness is predicted by merging magnetic islands (see right)
  - Spike time scales are consistent with model predictions
  - Studying spikes individually can constrain models
- *FOXSI* will have:
  - High-time-resolution direct imaging of HXR variations in flares

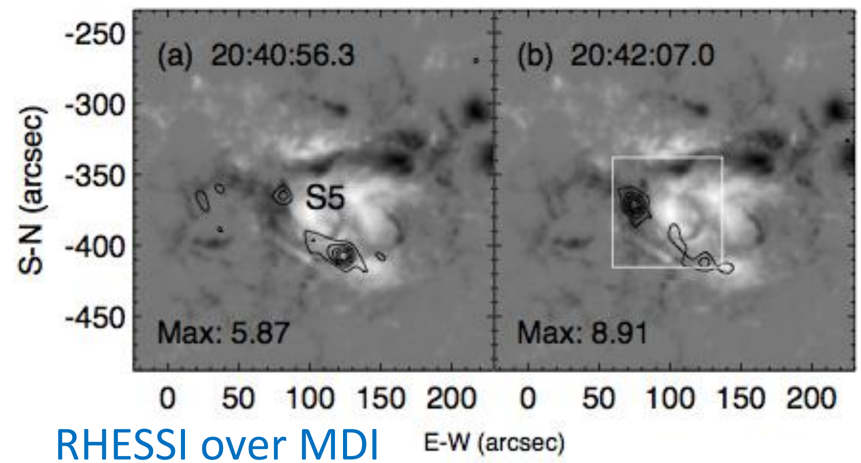


(Dahlin, Drake, & Swisdak 2014)

Flare time profile showing <~1-second HXR spikes



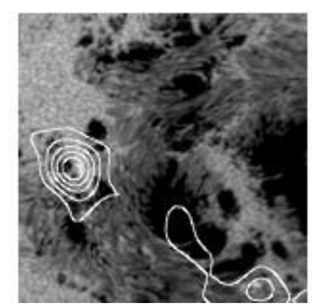
Imaging to compare morphology of spikes



RHESSI over MDI

RHESSI over infrared

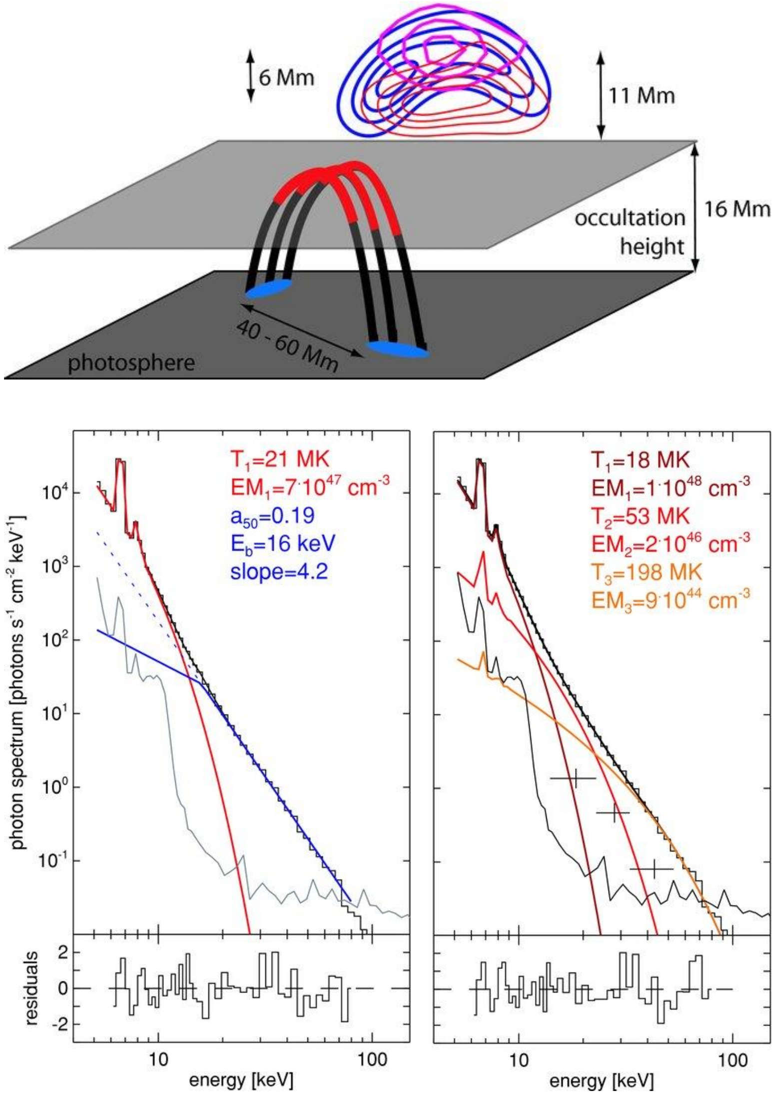
(c) 20:42



(Qiu et al. 2012)

What fraction of electrons are accelerated?

- Observations of the coronal acceleration region indicate that a significant fraction of the electrons, perhaps all of them, are accelerated
  - Such efficient acceleration puts strong constraints on acceleration and transport models
  - Past studies (e.g., right) needed occultation of the bright footpoints by the solar limb
- *FOXSI* will have:
  - The dynamic range to observe coronal sources in the presence of bright footpoints and obtain detailed spectra

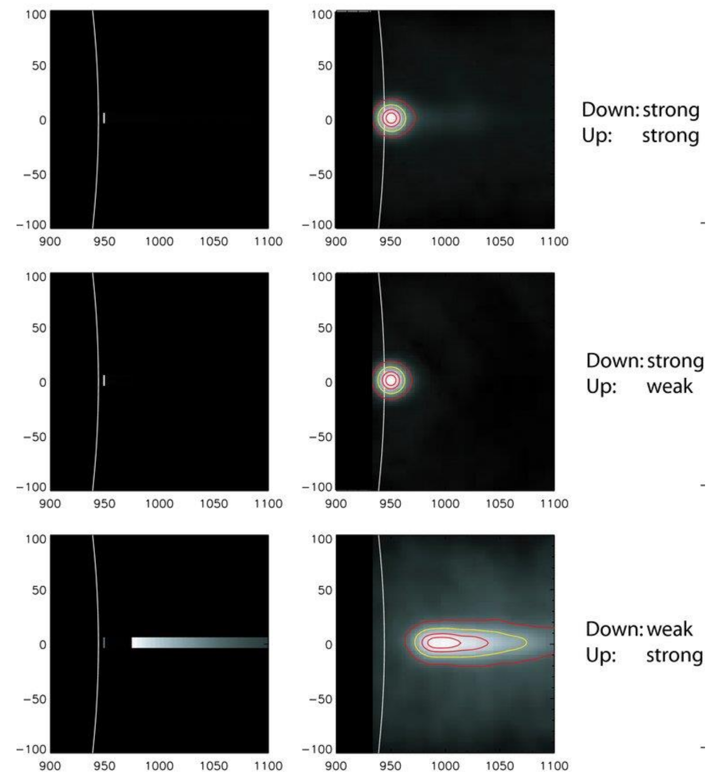


(Krucker et al. 2010)

Where do escaping flare-accelerated electrons originate?

- Flare-associated electron beams escape the Sun, but the connection to the flare process itself is unclear
  - Type III bursts provide good timing information, but lack spectral and spatial information
  - The coronal thin-target emission is much fainter than other flare emission
- *FOXSI* will have:
  - The sensitivity and the dynamic range to observe emission from escaping electron beams and compare against flare spectra and locations

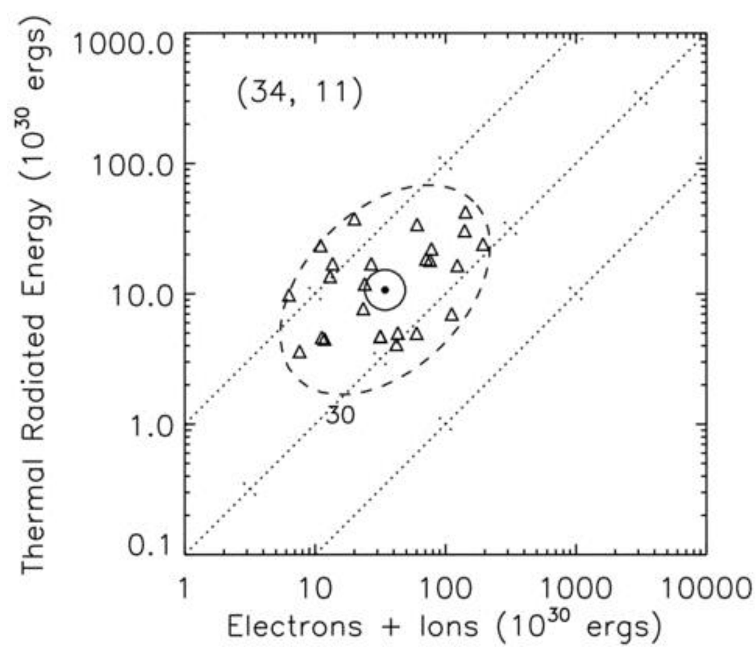
Simulations of RHESSI images show the limitations of indirect imaging



(Saint-Hilaire et al. 2009)

What is the energy input of accelerated electrons into the chromosphere and corona?

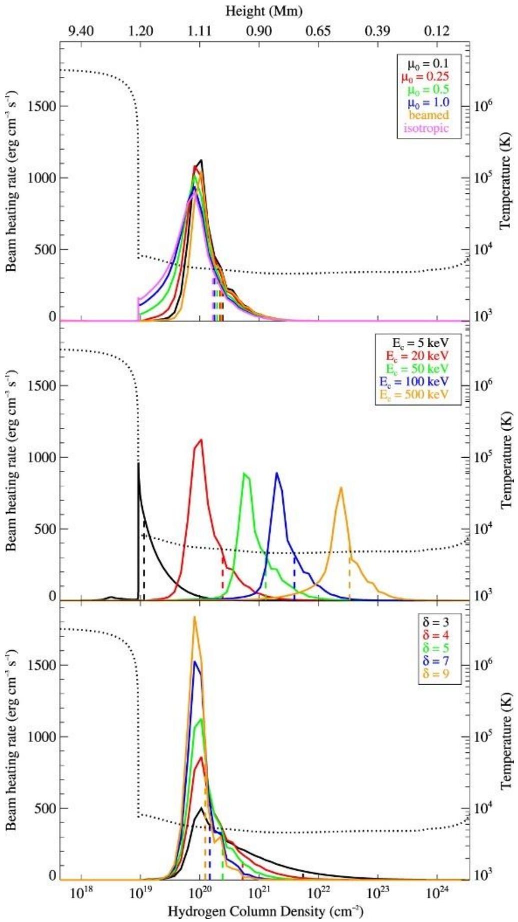
- In large flares, the total thermal radiated energy is comparable to the total energy in accelerated particles (see right)
  - Energy in the form of particles may be the primary source of plasma heating
  - Determining the total energy content in particles without imaging is challenging, particularly in small flares, due to obscuration of the low-energy nonthermal spectrum by thermal emission
- *FOXSI* will have:
  - True imaging spectroscopy to discriminate the nonthermal electron energy spectrum in footpoints from the thermal emission fro the flare loop
  - The sensitivity and dynamic range to observe the nonthermal electron energy spectrum in coronal sources



(Emslie et al. 2012)

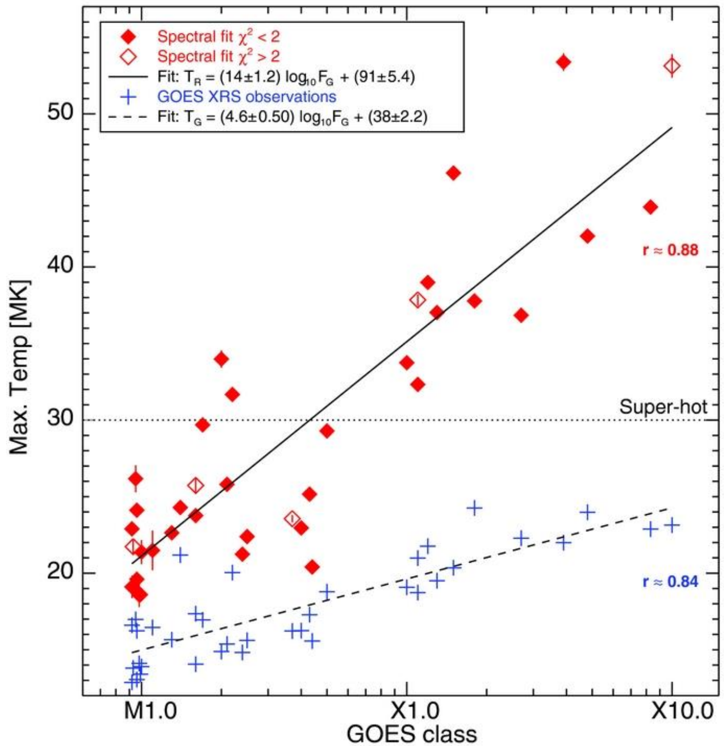
How do super-heated coronal plasmas originate and evolve?

- It is still undetermined how flares produce extremely hot plasma
  - The hottest plasmas cannot be quantified via EUV or soft X-ray observations
  - Models such as RADYN indicate that accelerated particles can be responsible for such extreme heating
- *FOXSI* will have:
  - High-time-resolution spectroscopy to obtain the accelerated electron energy spectra for input to models
  - True imaging spectroscopy to obtain the spatial distribution and evolution of flare plasmas as a function of temperature



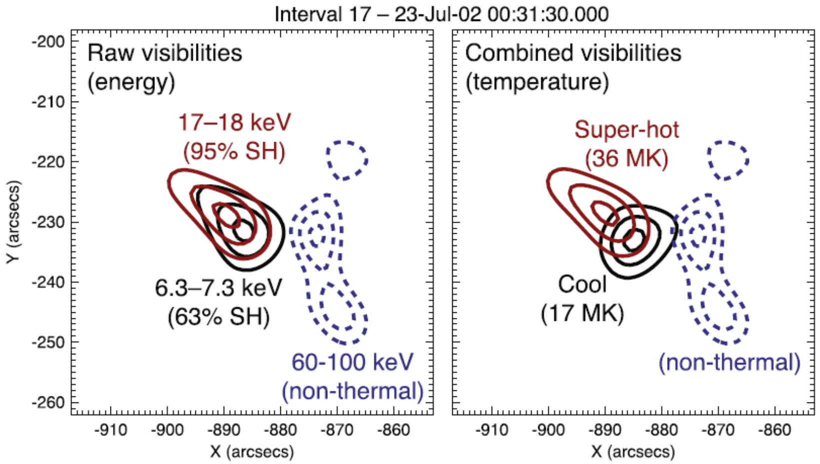
(Allred, Kowalski, & Carlsson 2015)

X-class flares tend to have "super-hot" (>~30 MK) plasmas



(Caspi, Krucker, & Lin 2014)

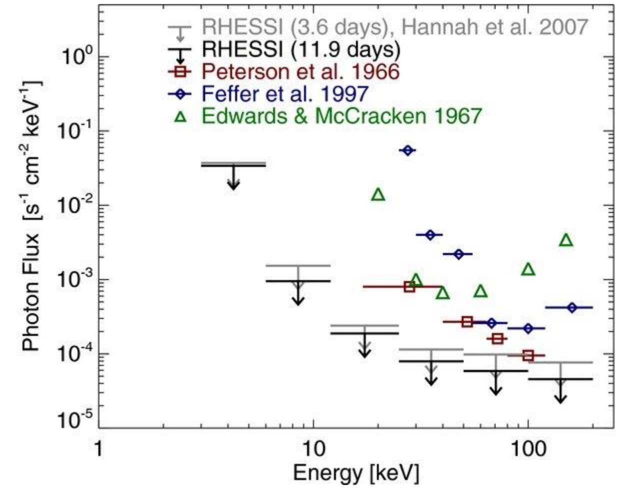
Flare plasmas at different temperatures can have different distributions in space

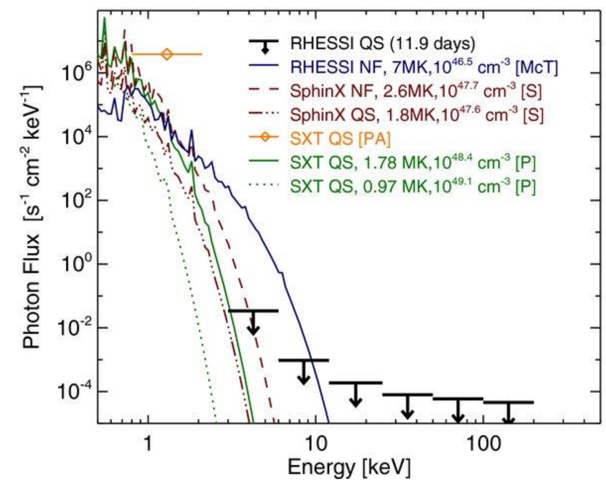


(Caspi et al. 2015)

How much do flare-like processes heat the quiescent corona?

- Flare-like energy release and particle acceleration may be responsible for the hot temperatures in active regions and the quiet Sun
  - Very challenging to study without high sensitivity or direct imaging
- *FOXSI* will have:
  - The sensitivity to observe the thermal distributions in active regions
  - True imaging and sensitivity to search for nonthermal signatures in the quiet Sun

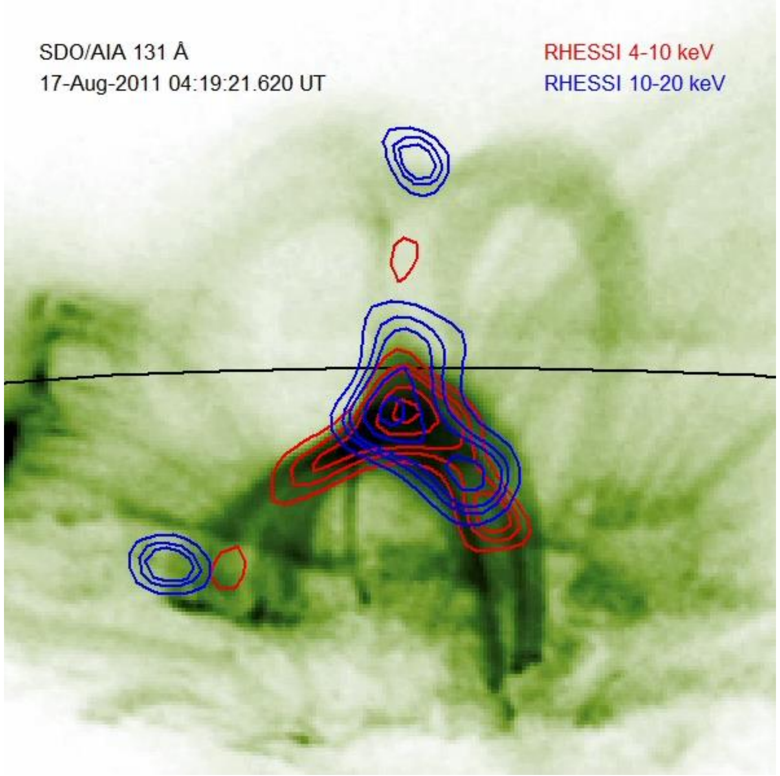




(Hannah et al. 2010)

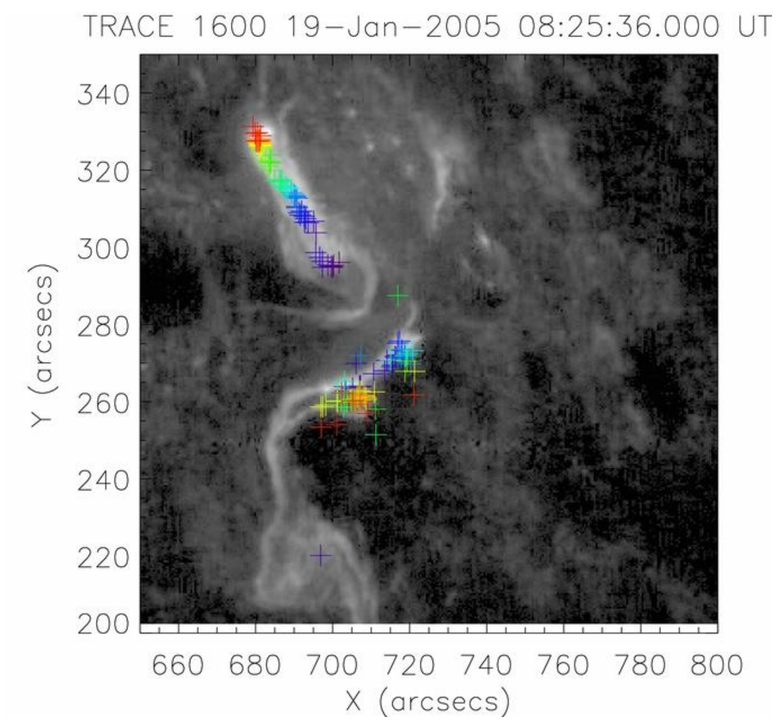
How does coronal energy release and the resulting accelerated particles drive the evolution of flares and associated magnetic structures?

- X-ray signatures can show where energy is released, not just where it is deposited
  - The locations of energy release are fundamental to understanding the evolution of flares and related phenomena and validating models
- *FOXSI* will have:
  - Direct imaging to determine the morphology and evolution of energy-release regions
  - True imaging spectroscopy to discriminate between the effects of acceleration and transport on evolution



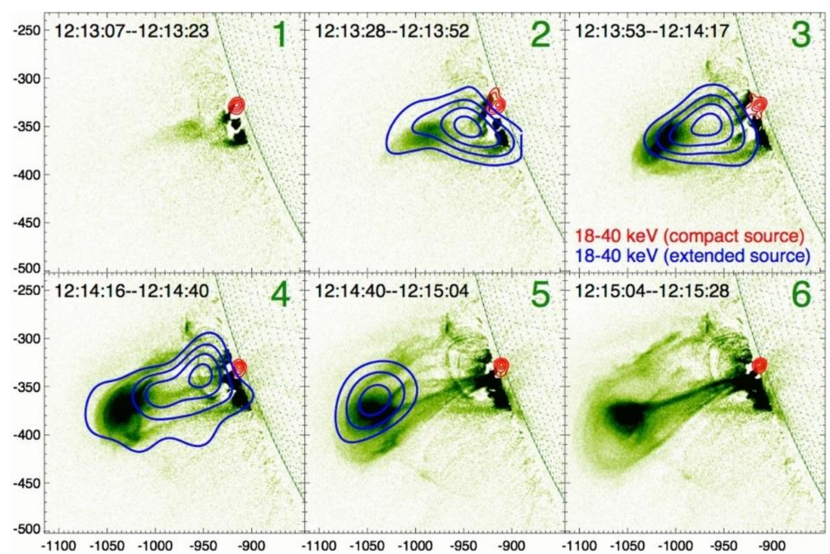
(Su et al. 2013)

Observing footpoint motions can test whether slow MHD waves can explain evolution



(Inglis & Dennis 2012)

Observation of nonthermal electrons in a CME core and their evolution

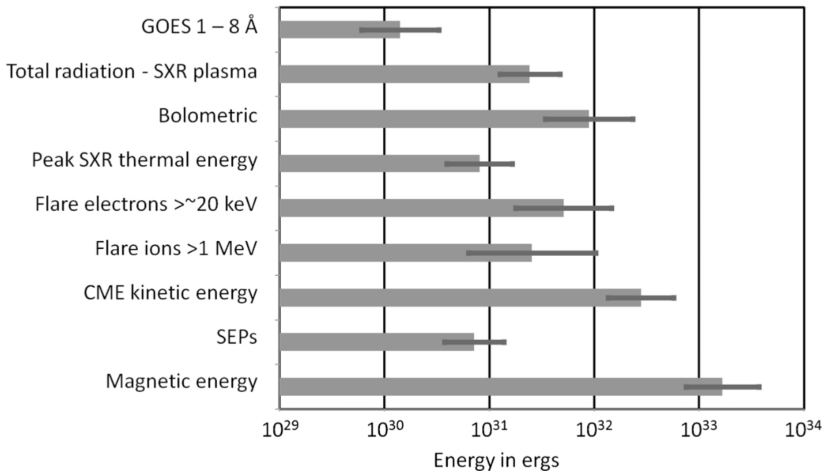


(Glesener et al. 2013)

How do energy-release processes scale from the smallest bursts to the largest flares?

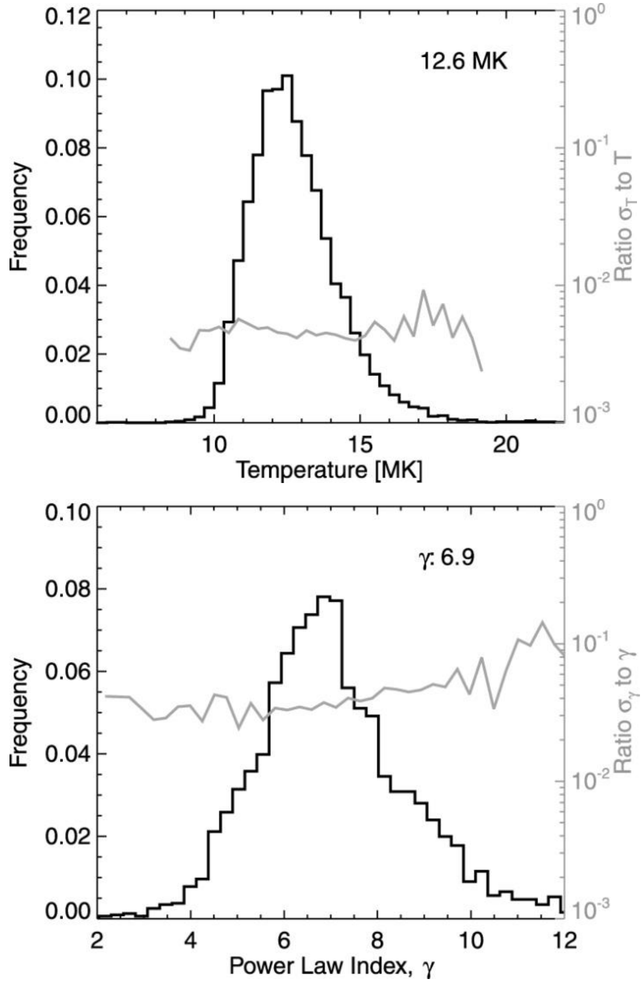
- The physics of flares is not scale invariant
  - The largest solar eruptive events are well observed, but smaller flares are not simply scaled-down versions
  - Understanding the scale dependence of the high-energy aspects of flares is critically needed
- *FOXSI* will have:
  - True imaging spectroscopy to obtain accurate estimates of electron energetics and thermal energetics
  - The sensitivity to extend energetics studies to much smaller flares

Average breakdown of energetics for six solar eruptive events in solar cycle 23

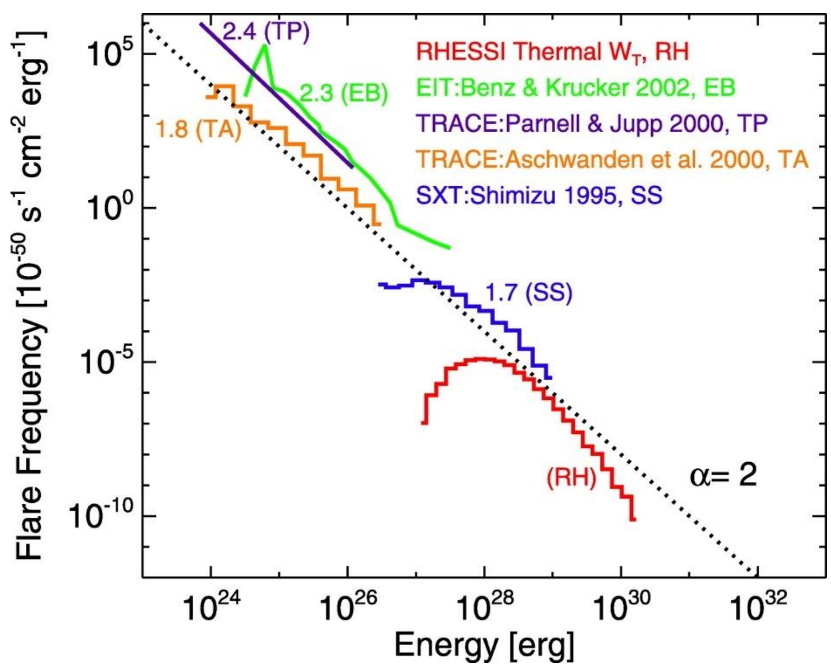


(Emslie et al. 2012)

Microflare temperatures are similar to large flares, but spectral indices are steeper



Small end of microflare distribution obscured by instrumental selection effects



(Hannah et al. 2008)

Summary

- *FOXSI* will break new ground via direct imaging of the hard X-ray corona
- *FOXSI* will observe the full range of HXR emission, from large flares to the quiet Sun
- Simulations are underway to predict qualities and sensitivities of the various types of observations
- The *FOXSI* team and friends will be hard at work on the proposal for the next two months, so send cookies!