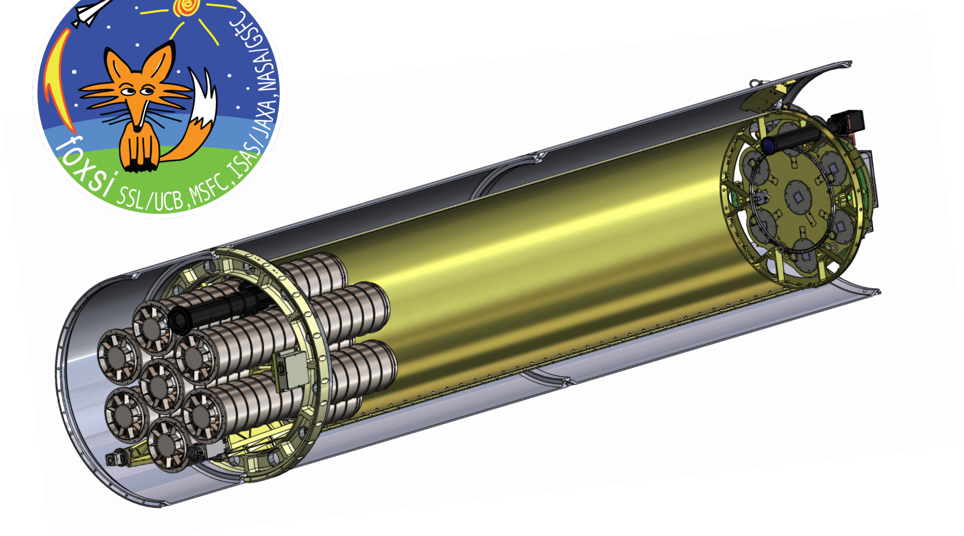
Exploring hot loop plasma with hard X-rays

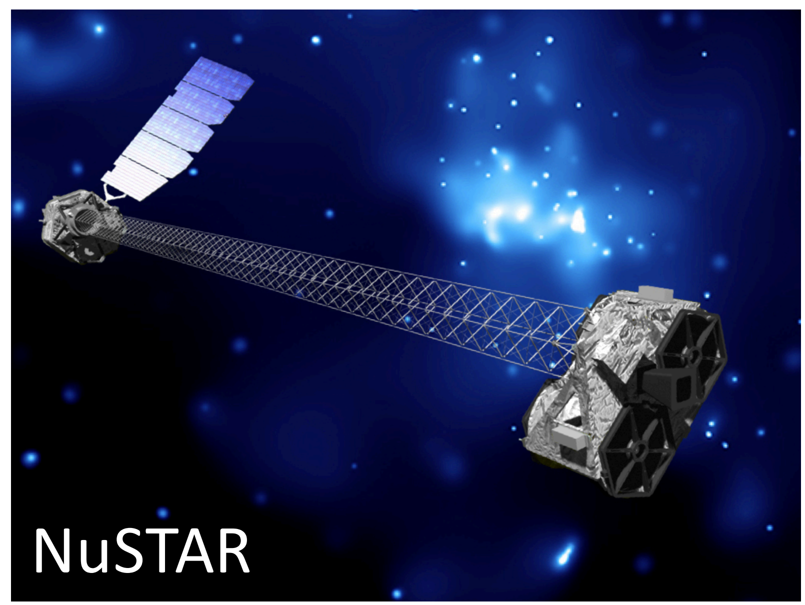
Lindsay Glesener, on behalf of…

Team FOXSI: Shin-nosuke Ishikawa, Säm Krucker, Steven Christe…

Team NuSTAR: David Smith, Iain Hannah, Brian Grefenstette, Hugh Hudson, Paul Wright, Matej Kuhar…

Team EBTEL: Andrew Marsh, Jim Klimchuk, Steve Bradshaw





Preview

Measuring hot plasma with hard X-rays (HXRs)

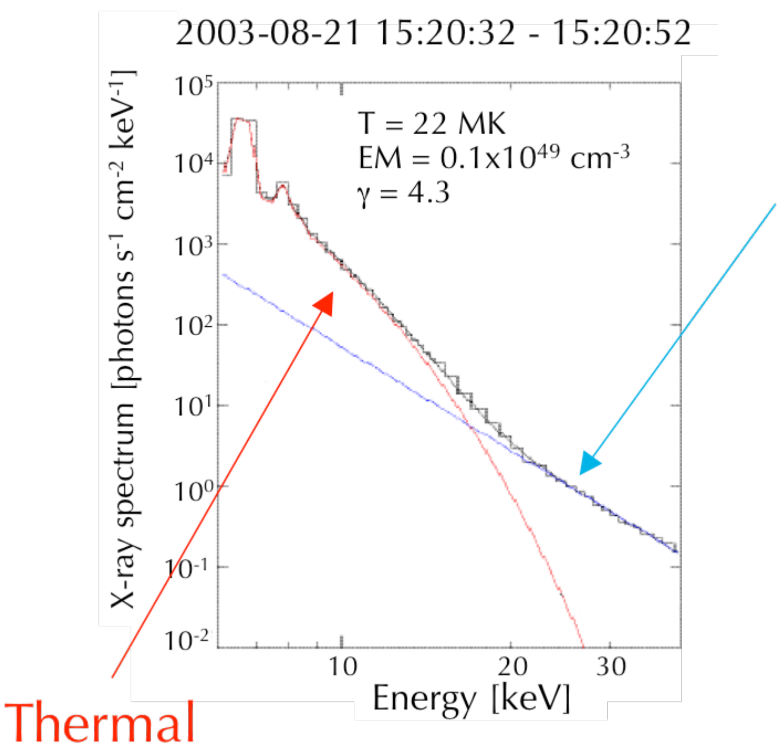
Direct focusing instruments: **FOXSI** and **NuSTAR**

Observations and constraints on hot plasma in quiescent active regions

New HXR accessibility to small flares

Why hard X-rays?

- Hard X-rays are produced immediately and abundantly by hot plasma.
  - “Hot” = minimum 3, 5, 8 MK up to several 10s of MK.
- Fairly direct measure of accelerated electron distributions

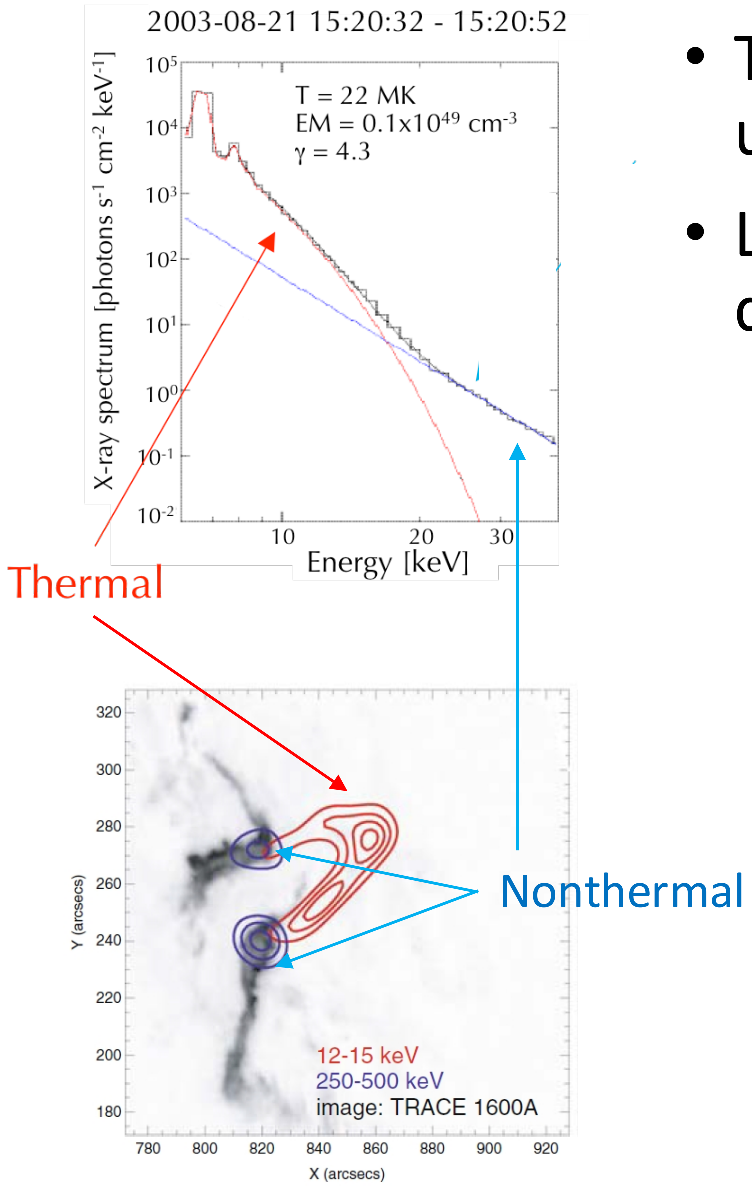


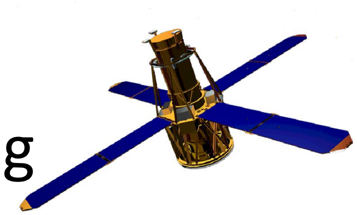
<u>Difficulties:</u>

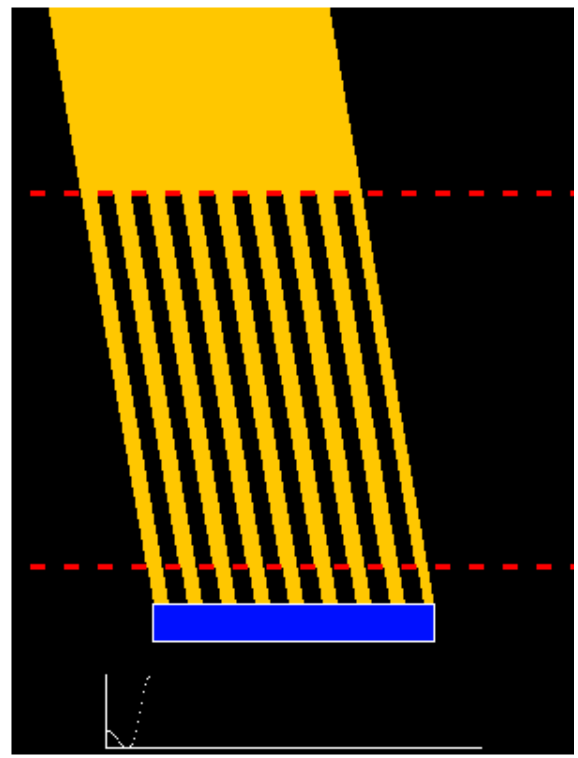
1. Rich, nuanced DEMs require supporting observations at lower energies.
2. Low-energy cutoff (or entire power law) can be hidden beneath thermal component.
3. Resolution few (or several) arcsec

How do we measure HXRs?

- Traditionally, Fourier imaging, were used (e.g. ***RHESSI)***
- Limited sensitivity and imaging dynamic range.

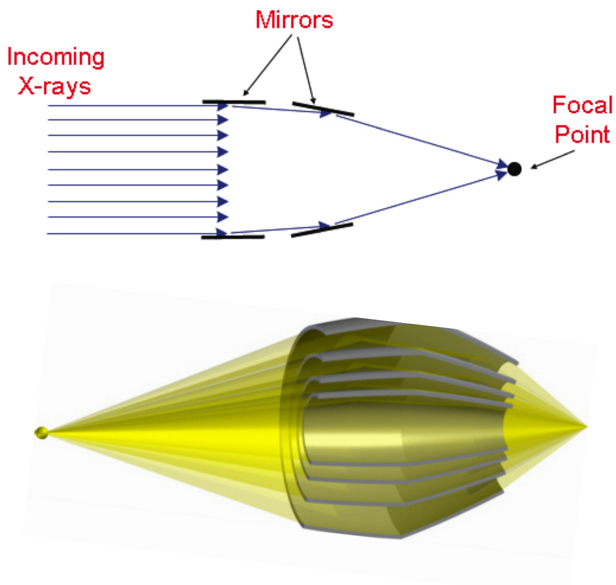


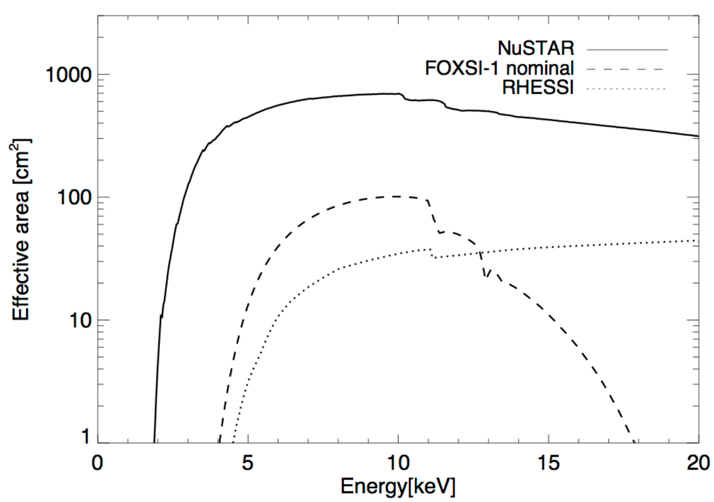


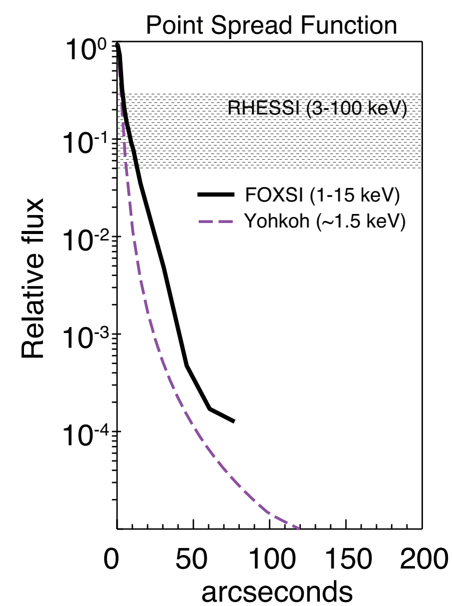


Better hard X-ray sensitivity is now available with ***direct, focusing instruments***.

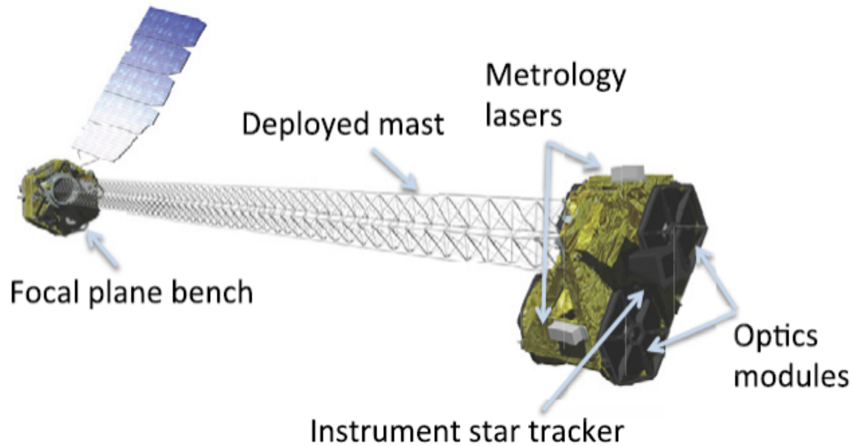
- X-rays can be focused at small, “grazing” angles of incidence
    - Double reflection on a Wolter-1 configuration
- Low background → improved sensitivity
- Point spread function falls steeply, providing improved dynamic range.

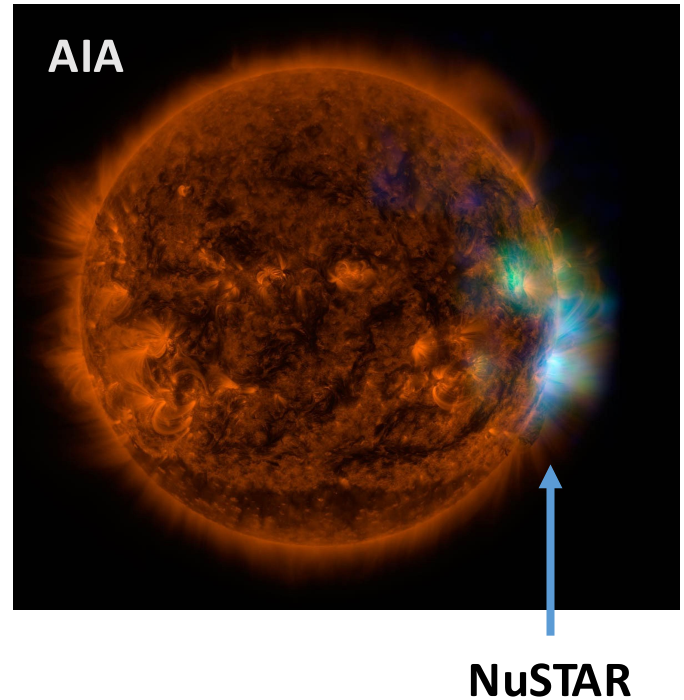






The Nuclear Spectroscopic Telescope Array (NuSTAR)



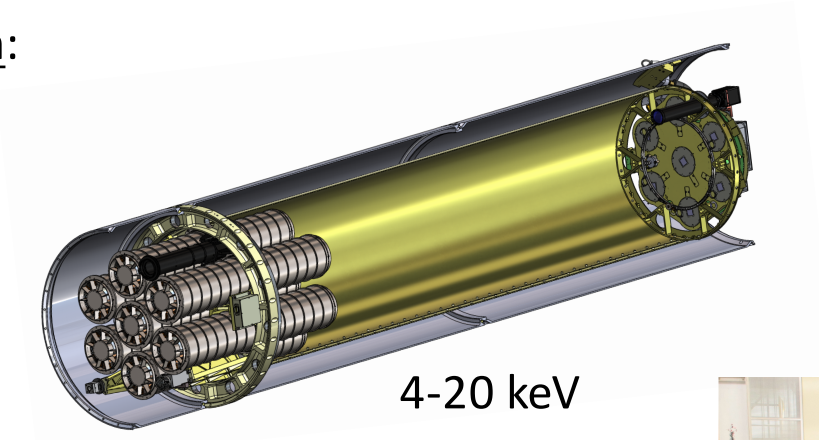


- ***Astrophysics*** spacecraft not optimized for solar pointing
  - 800 cps max throughput → high deadtime
  - 3-79 keV, but most solar observations <10 keV
- Best conditions: targets ≲GOES B5
  - Quiet active regions, small flares
  - Quiet-Sun regions
- Observations are planned 3-4 days in advance (minimum) or as planned coordinations with other spacecraft observing campaigns (better).

Grefenstette et al. (2016)
Hannah et al. (2016)
Kuhar et al. (2017)
Wright et al., accepted
Glesener et al., in revision
Marsh et al., in revision

Focusing Optics X-ray Solar Imager Sounding Rocket

Collaboration:
U.C. Berkeley
NASA/MSFC
NASA/GSFC
JAXA/ISAS



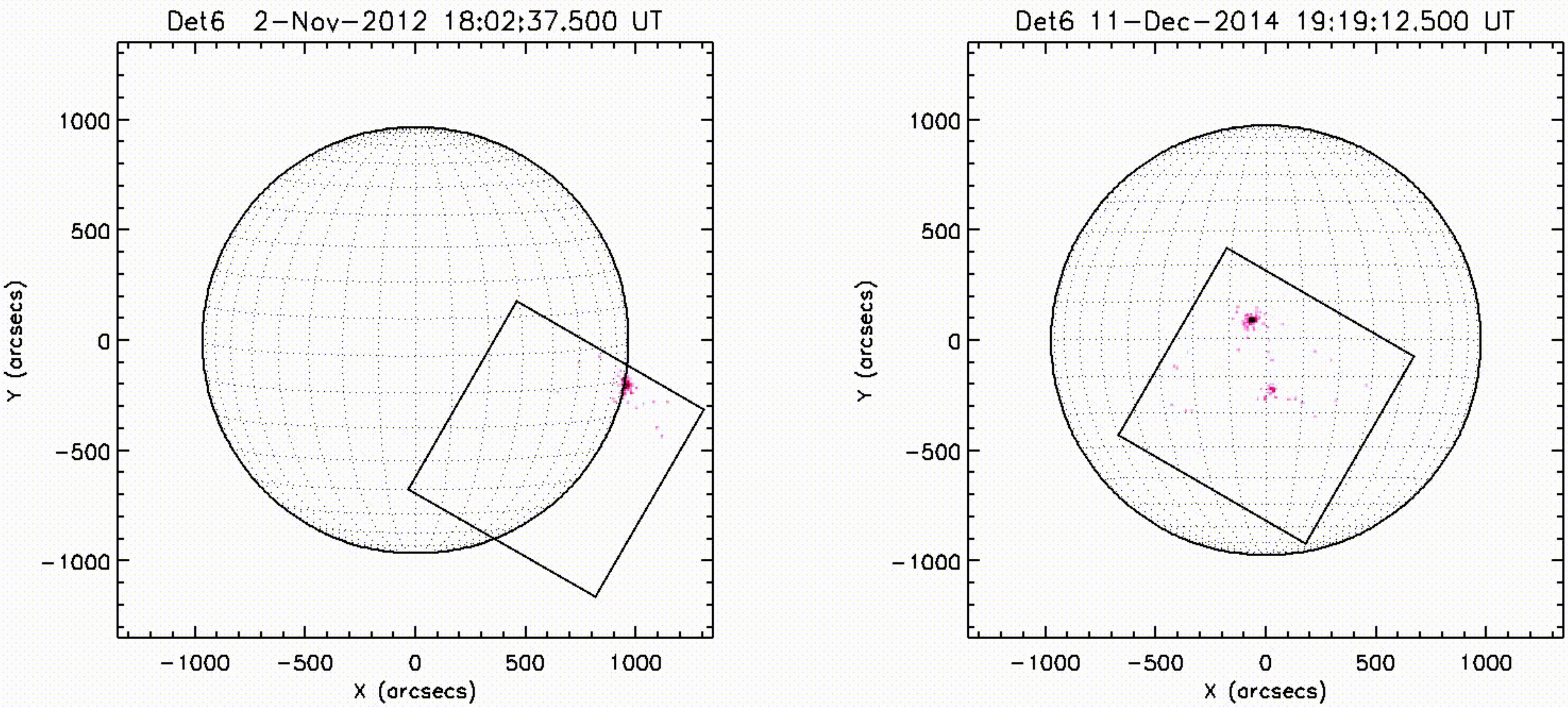
4-20 keV

For FOXSI-3:
University of Minnesota
NAOJ

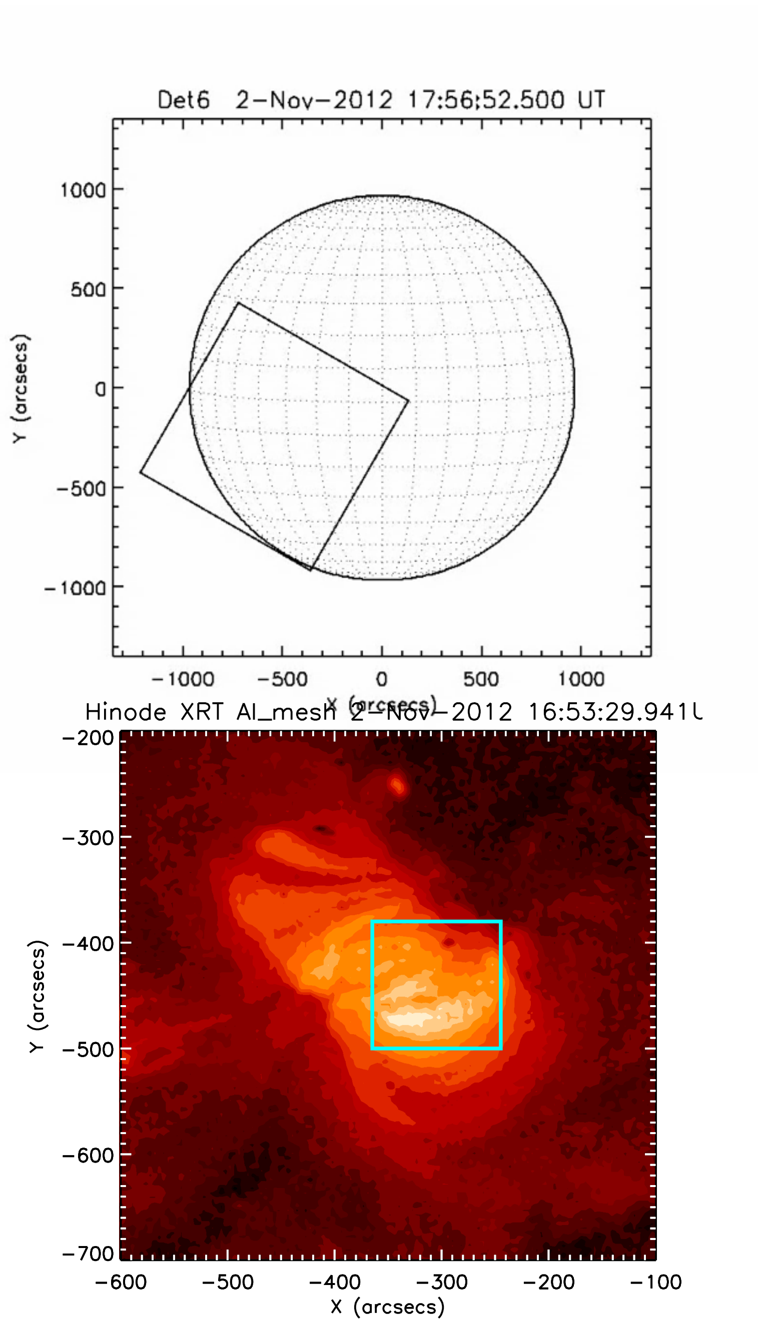
Flights:
- 2012 November 2
- 2014 December 11
- (planned) August 2018

Goals:
- Demonstrate focusing HXR optics optimized for **the Sun**.
- Look for indicators of nanoflares in active regions and the quiet Sun

FOXSI-1 FOXSI-2

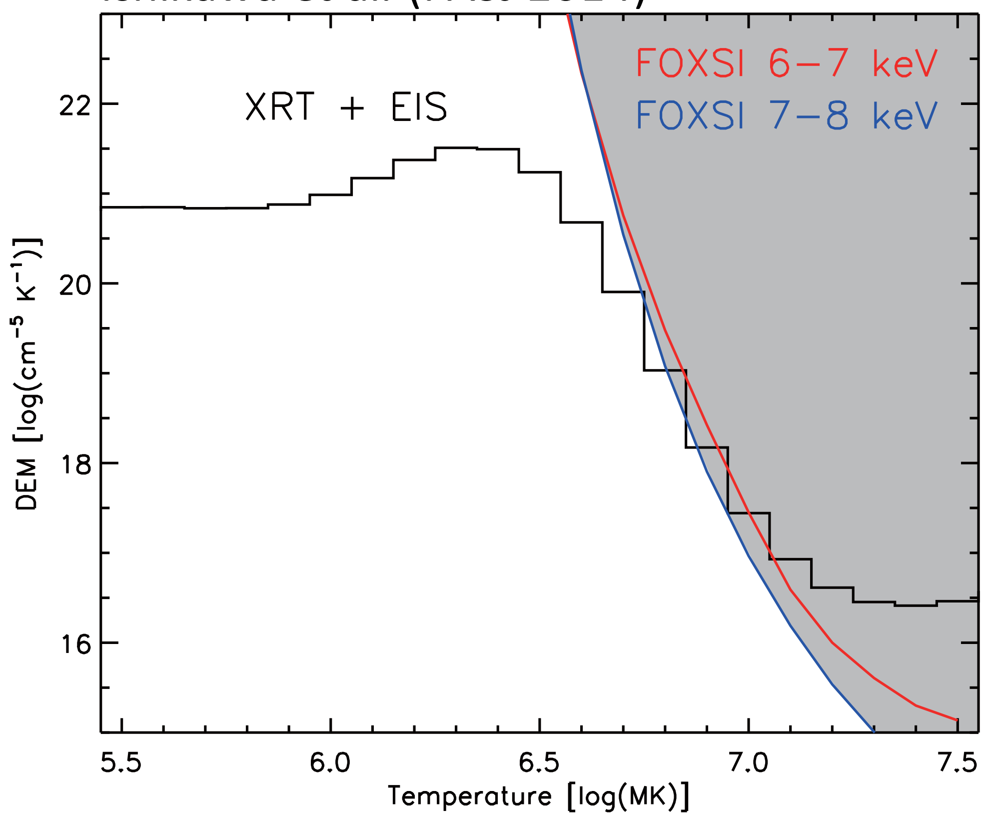


Quiescent active region measurements



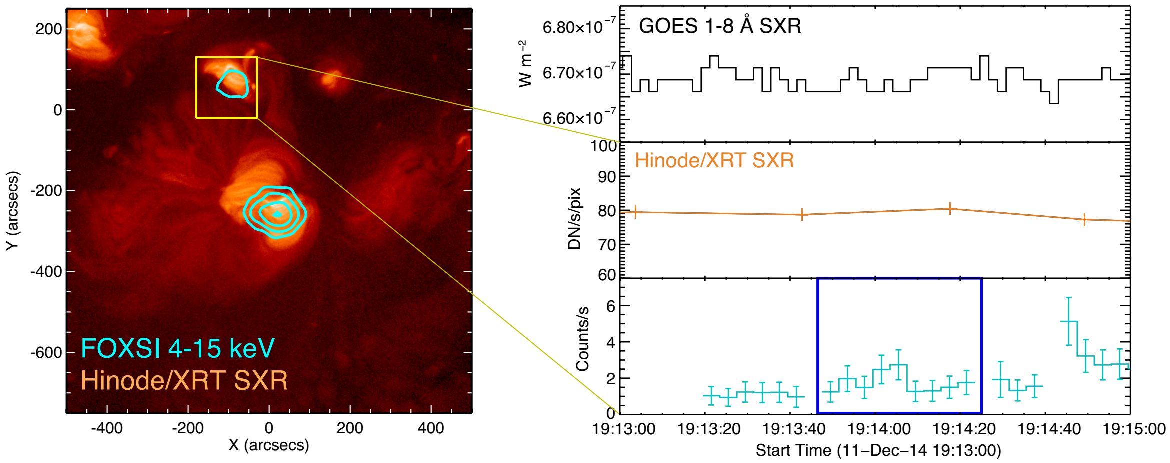
FOXSI-1:
No detectable HXRs. This led to ***constraints*** on DEM (with Hinode)

Ishikawa et al. (PASJ 2014)

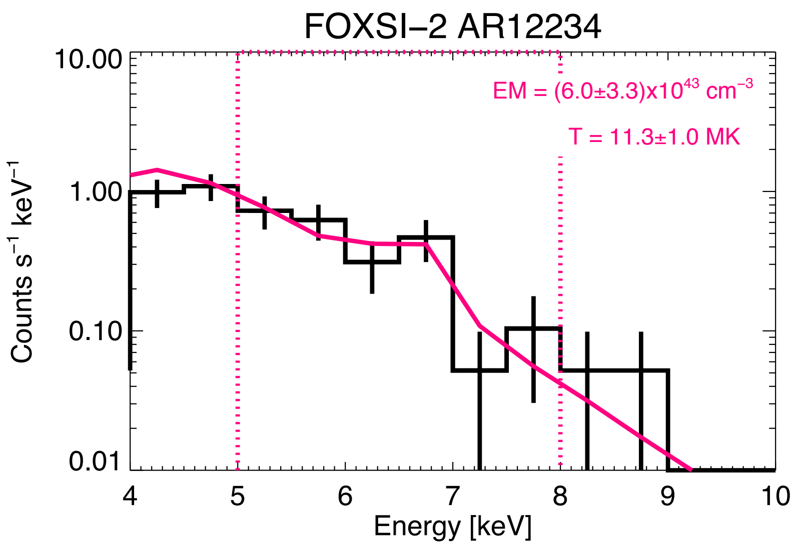


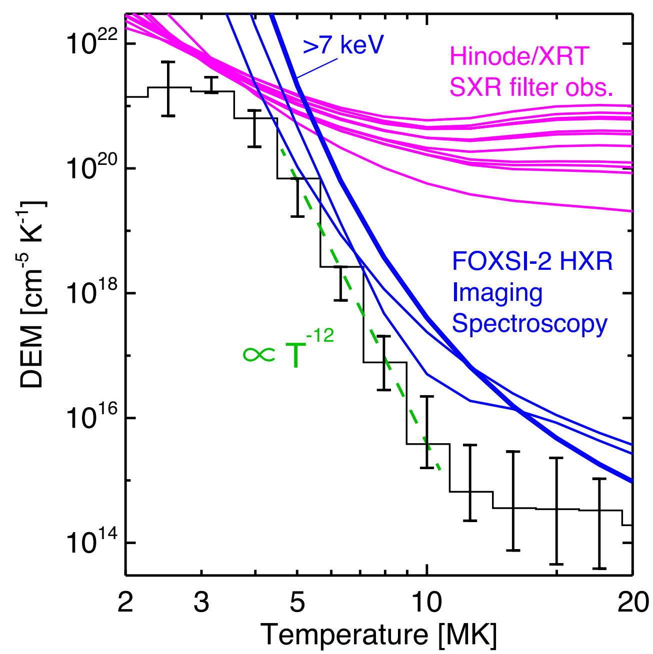
Quiescent active region measurements

FOXSI-2: Clear detection of AR 12234 *when not obviously flaring*



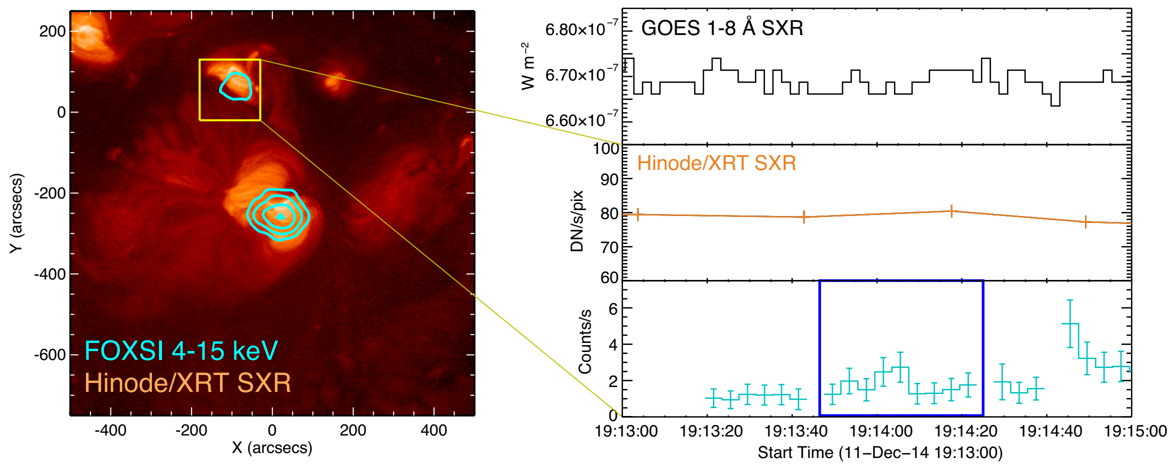
- XRT+FOXSI together measure high-temperature slope of DEM.
- Diverges from power law >10 MK.



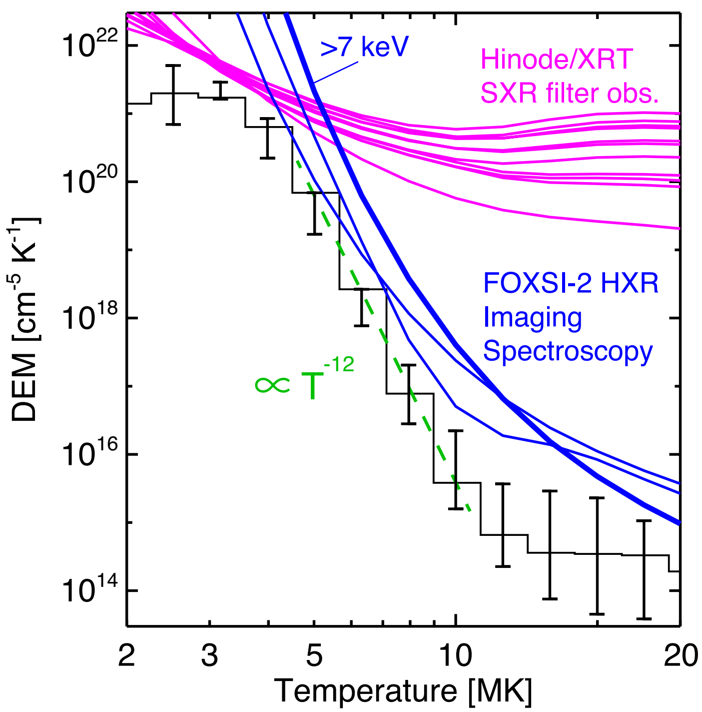


Ishikawa et al. (submitted)

Other explanations for 7-9 keV emission?



We observe
16 photons
in 38 seconds



- Background? No
- Macroscopic event? No
- Cooler part of DEM? No

Ishikawa et al. (submitted)

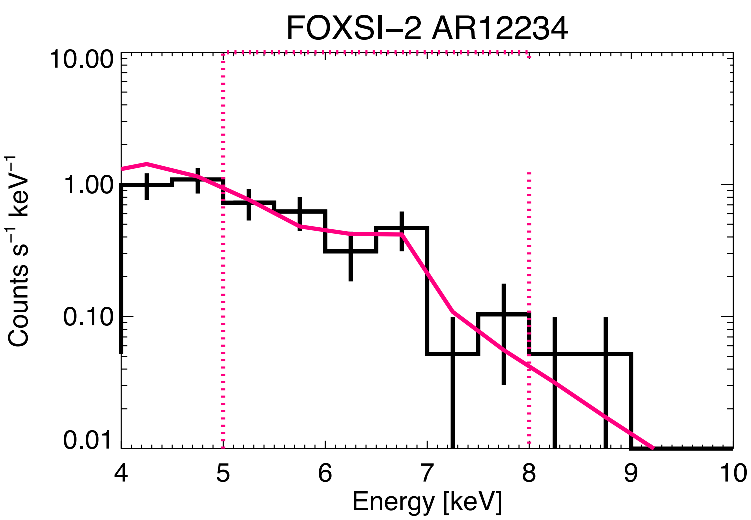
Modeling impulsive heating in AR 12234

Parametric study of impulsive heating events using ***EBTEL*** field-aligned simulations of ***homogenous nanoflares*** throughout the AR.

EBTEL simulation of a single nanoflare → DEM → Time-average the DEM to mimic many homogenous events occurring out of phase → Calculate hard X-ray fluxes using CHIANTI → Fold through instrument response → Compare to FOXSI observed spectrum. Compute goodness-of-fit

Adjustable parameters:

- Heating amplitude and duration
- Heating event frequency
- Filling factor (fit)

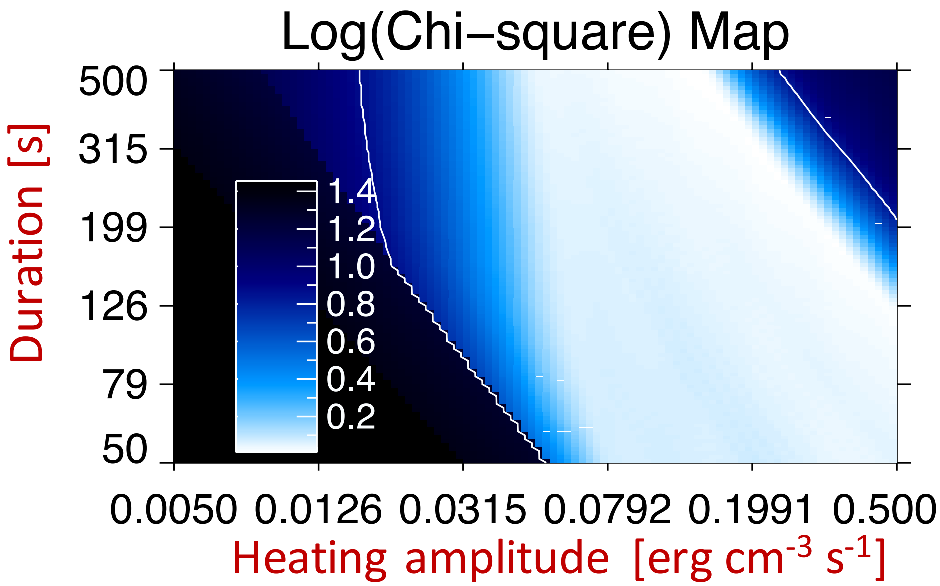


Discard any parameter sets that violate these constraints:

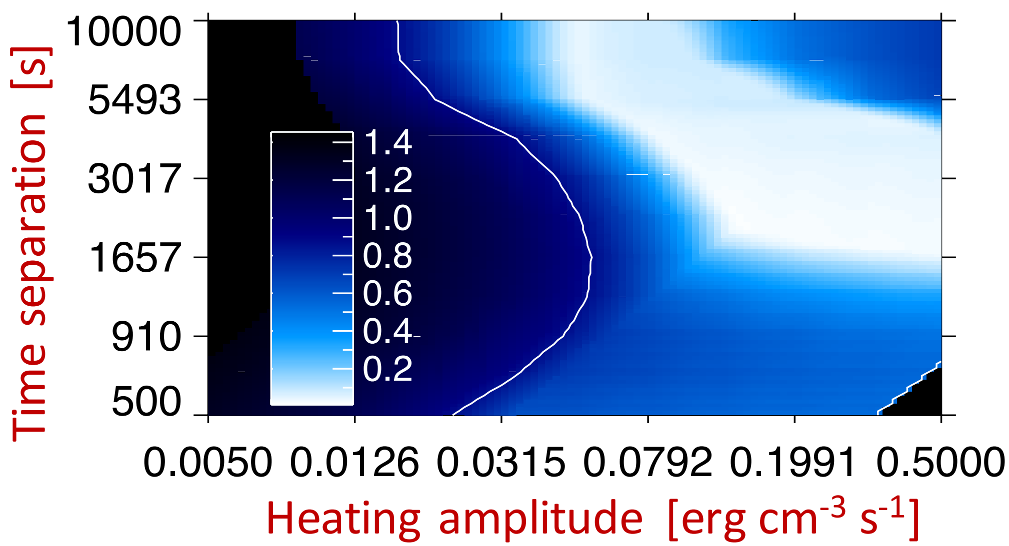
- Time-averaged heating must be <10^8 erg cm^{-2} s^{-1}
- AIA, XRT emission must not be overpredicted

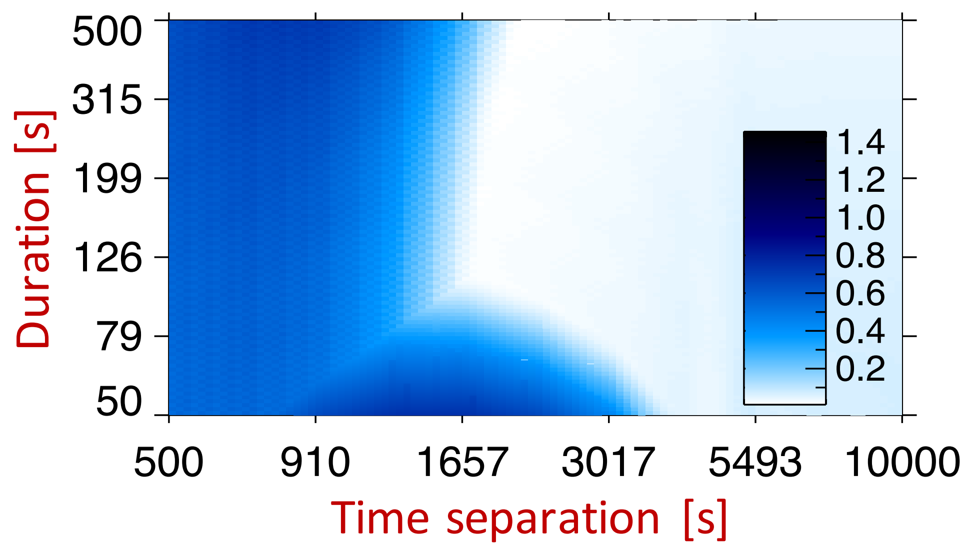
Andrew Marsh et al., in preparation

Results: χ^2 maps across parameters



- Lighter intensities = better fits
- Preference for short, strong events
- Best agreement for event separation of 1600-3000 seconds

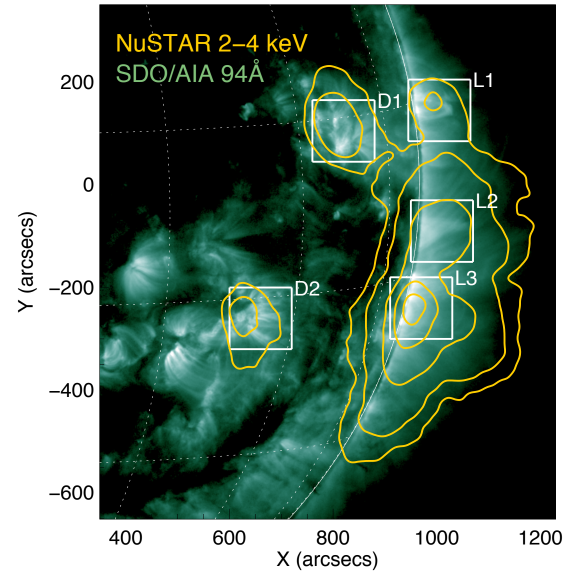




Marsh et al., in preparation

NuSTAR active regions have also been modeled → See Marsh paper

- Longer observations, extending to lower energies
- Data are available for several other ARs; ready for modeling.



Future steps in modeling HXR active region observations:

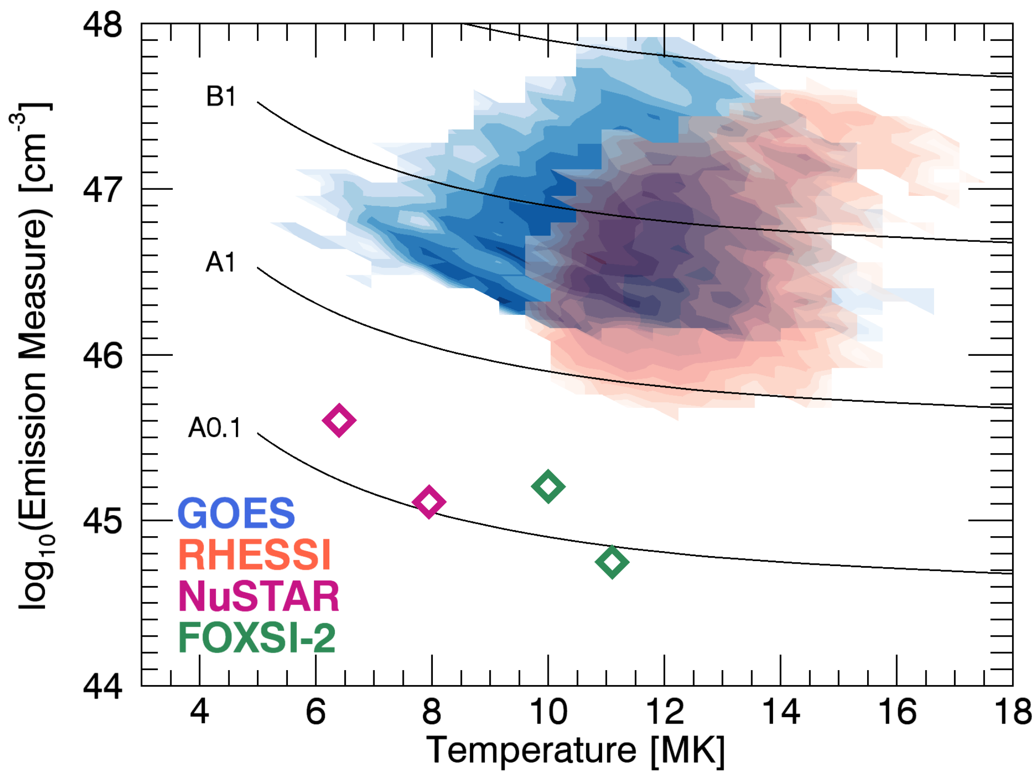
- Include distribution of nanoflares (e.g. power-law in energy)
- Include beam heating in additional to direct heating
- Perform field-aligned simulations
- Model more active regions!

What about macroscopic flares?

- **How do flare energetics scale as we go to small sizes?**
- **Do flares occur everywhere on the Sun?**

- Sub-A class microflares are now being measured.
- Note that the NuSTAR and FOXSI (and RHESSI!) data points represent an isothermal approximation.
- NuSTAR has observed even smaller transient brightenings **in the quiet Sun.**

HXR microflares (and counting...)

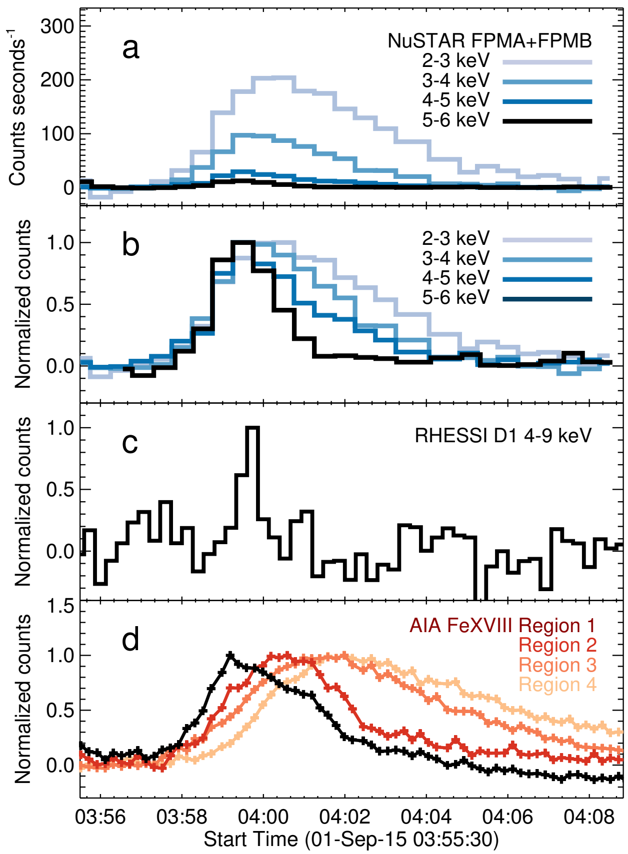


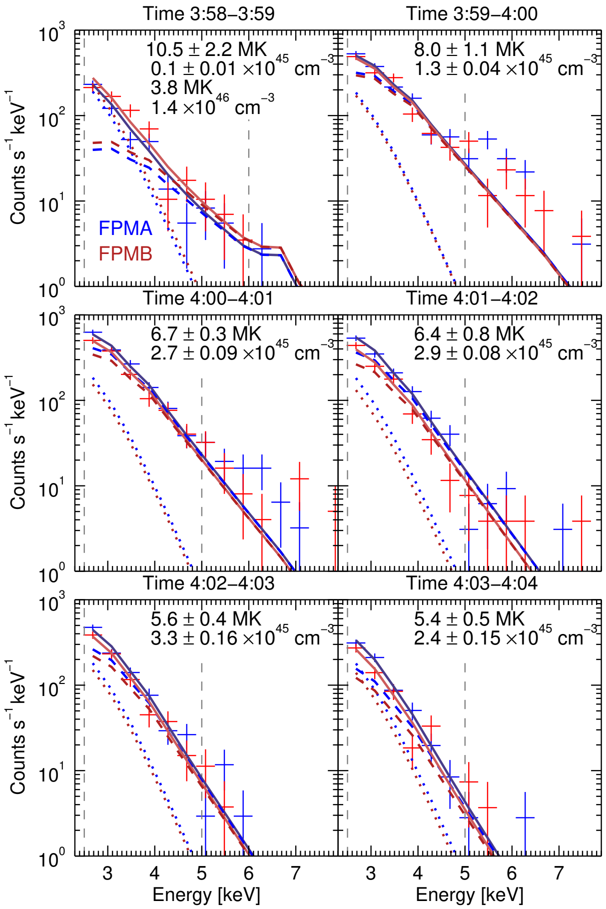
See also:
Wright et al. (2017; accepted)
Glesener et al. (in revision)

Flare on 2015 Sept 01

Estimated A0.2 class flare

- Higher energies peak earlier
- **High-energy excess** in impulsive phase → hotter or nonthermal component required.
- Thermal energy during flare peak is 1.8 x 10^{27} ergs.
- **Similar behavior to that observed in larger flares.**



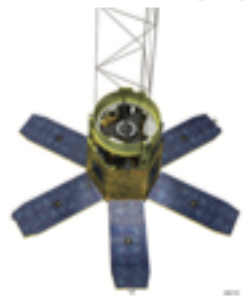


Glesener et al. (in revision)

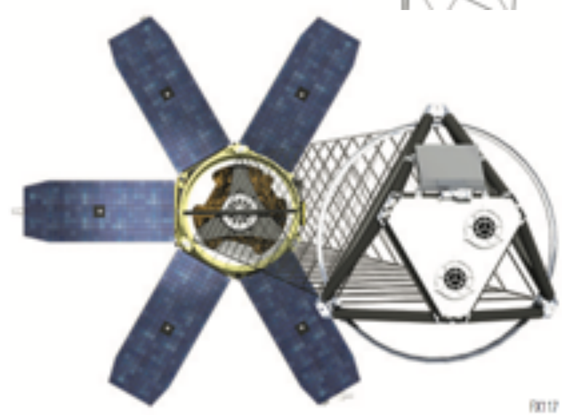
The future…

FOXSI

Focusing Optics X-Ray Solar Imager



Exploring impulsive solar magnetic energy release with direct hard X-ray imaging spectroscopy

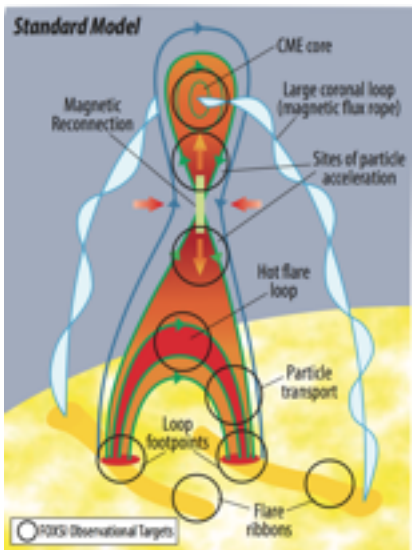


Proposed to NASA's 2016 Heliophysics Small Explorer (SMEX) AO.

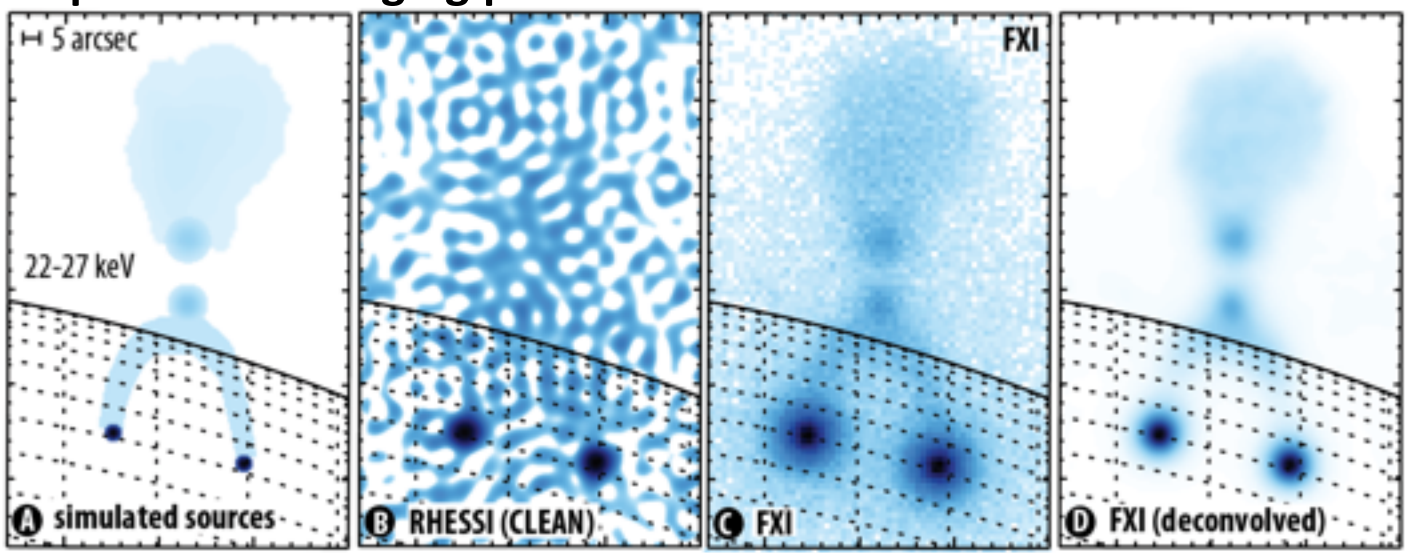
Mission Concept

FOXSI is composed of two instruments:

- **FOXSI X-ray Imager (FXI): Direct focusing hard X-ray instrument.**
- **X-ray Flux Sensor (XFS): Spatially integrated SXR spectroscopy.**



Expected FXI imaging performance

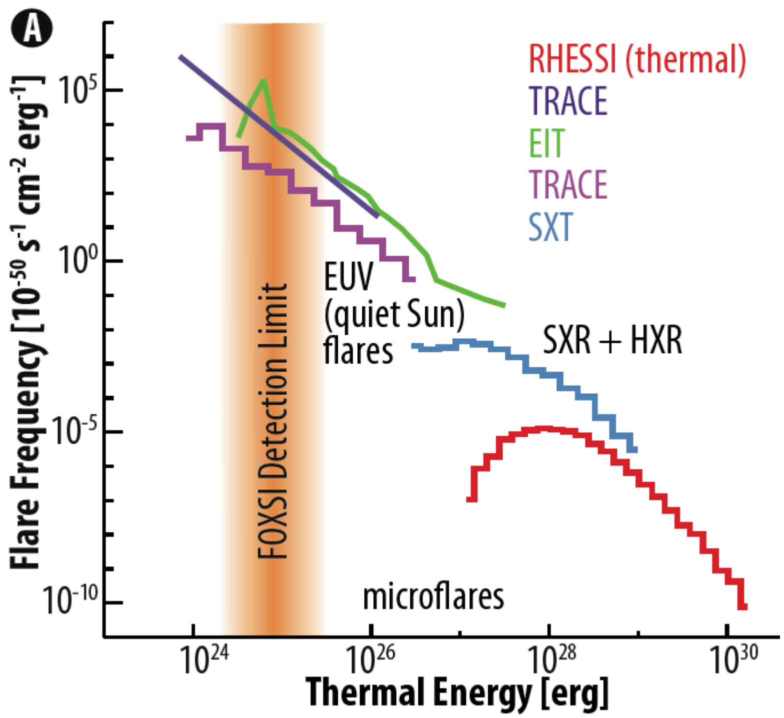


Small flares and active region heating

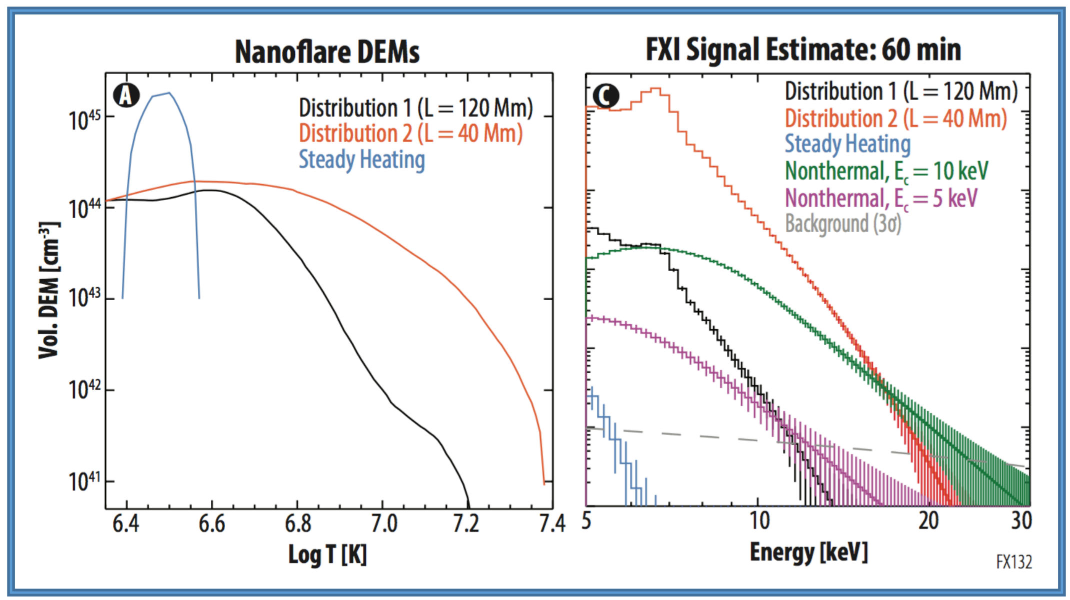
Determine how energy releases processes scale from the smallest to largest flares.

Assess the degree to which impulsive events heat active region corona.

Individual flare sensitivity

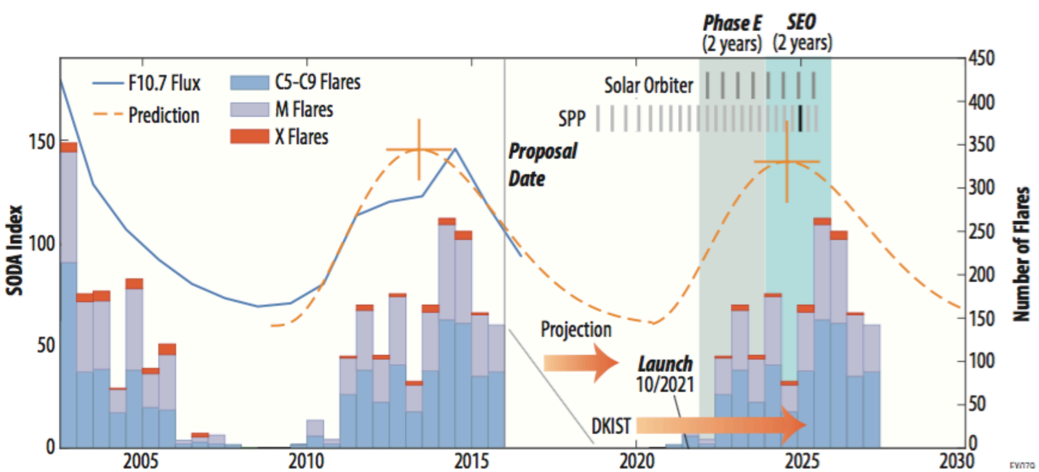


Predicted FOXSI results for ensembles of nanoflares



Distributions based on Lopez Fuentes & Klimchuk (2015, 2016)

FOXSI
Focusing Optics X-Ray Solar Imager



- Proposed launch in 2022
- Two-year primary science phase

- 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)**
- XFS Lead: **Amir Caspi (SwRI)**
- Hardware-providing institutions: **GSFC, MSFC, UCB/SSL, UMN, SwRI, LASP, PAN, Orbital/ATK**

Summary

What can focusing HXR instruments do for you?

High-sensitivity imaging/spectroscopy of small-scale, impulsive energy release on the Sun

What have we observed already?

- Measurement of >10 MK plasma in a quiescent AR. (modeling underway)
- Transient events at scales formerly inaccessible to HXRs
- And much more!

How will we accomplish future observations?

- Observations by **FOXSI and NuSTAR** are ongoing (though rare).
- **A space-based, solar-dedicated instrument is needed.**