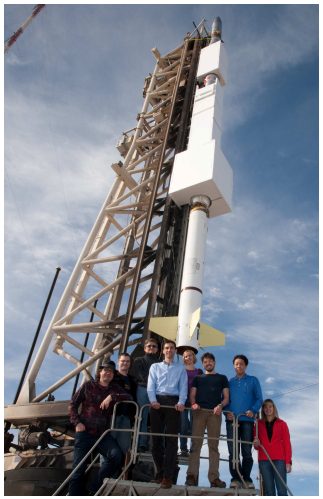


The FOXSI sounding rocket campaigns

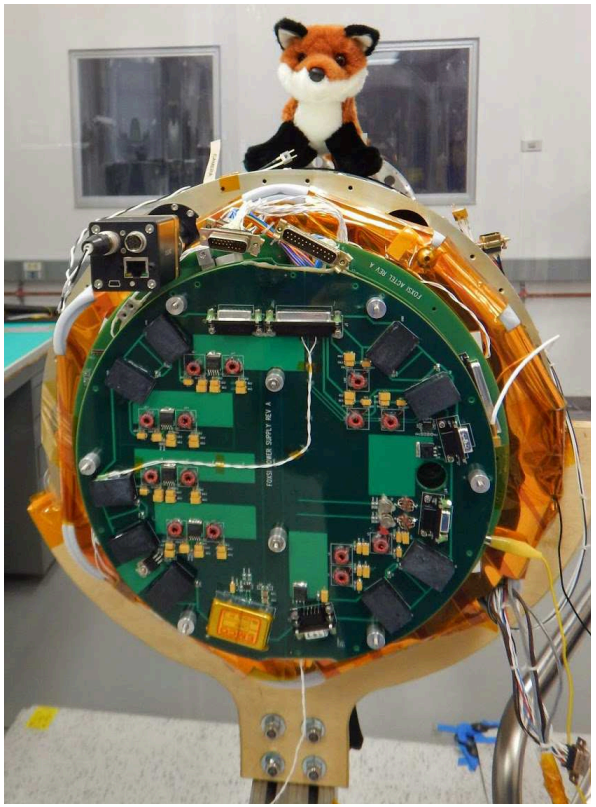
Lindsay Glesener, Säm Krucker, Steven Christe, Shin-nosuke Ishikawa, Brian Ramsey, Mikhael Gubarev, Tadayuki Takahashi, Shin Watanabe, Juan Camilo Buitrago Casas, Juliana Vievering

…and the rest of team FOXSI!

Univ. of Minnesota, Univ. of California-Berkeley, NASA/MSFC, JAXA/ISAS, NASA/GSFC

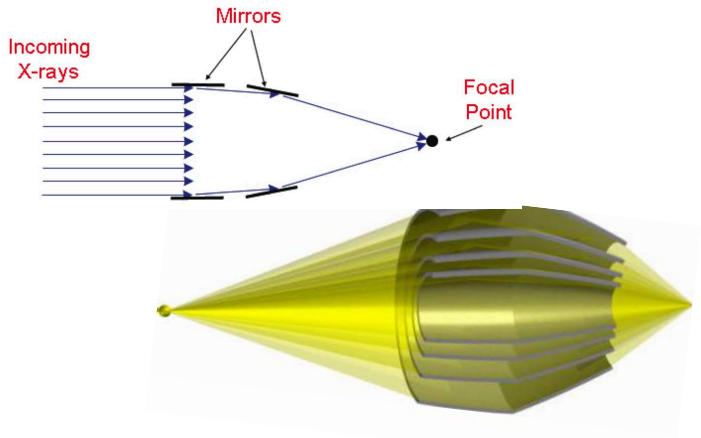
The journey of the FOXSI rocket

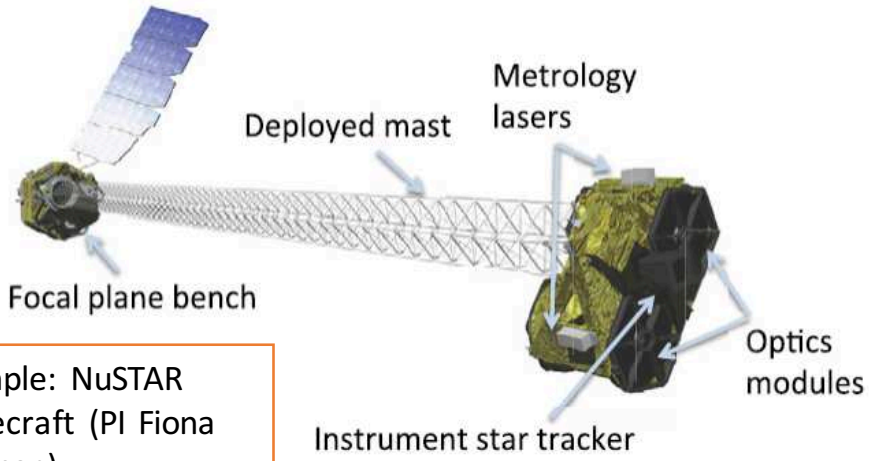
- Intro to FOXSI
- Instrument and capabilities
- First two flights
- FOXSI-1 and FOXSI-2 **microflares**
- **Active region DEM** analysis
- Plans for **FOXSI-3**



The appeal of focusing optics…

- X-rays can be focused at small, “grazing” angles of incidence (<0.5 deg)
- Wolter-1 configuration: double reflection





Example: NuSTAR spacecraft (PI Fiona Harrison)

Photons are collected on a small volume → lower background → improved sensitivity

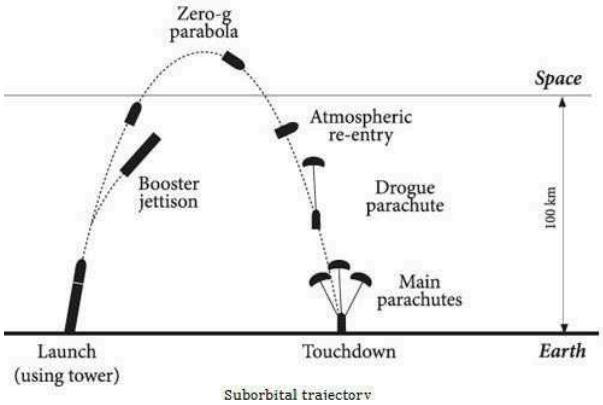
Point spread function falls steeply → improved dynamic range.

Focusing Optics X-ray Solar Imager Sounding Rocket

- Sounding rocket: ~6.5 minute observation time

- Flights:
  - **November 2, 2012**
  - **December 11, 2014**
  - **(planned) Summer 2018**

- Funding from NASA Low Cost Access to Space



Credit: Copenhagen Suborbitals

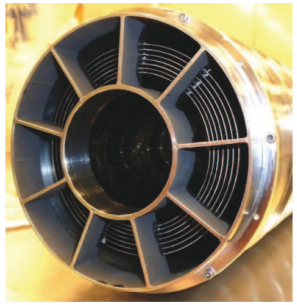
- **Goal:** Demonstrate the use of focusing optics to measure hard X-rays from the Sun.

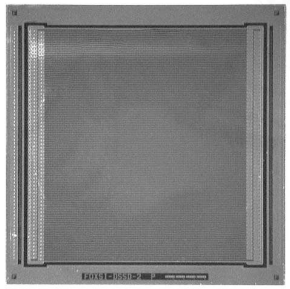
- **Goal:** Look for hard X-rays from "nanoflares" and characterize their energy content.

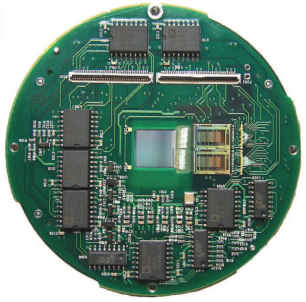
- **Goal:** Measure high-temperature components of active region emission measures.

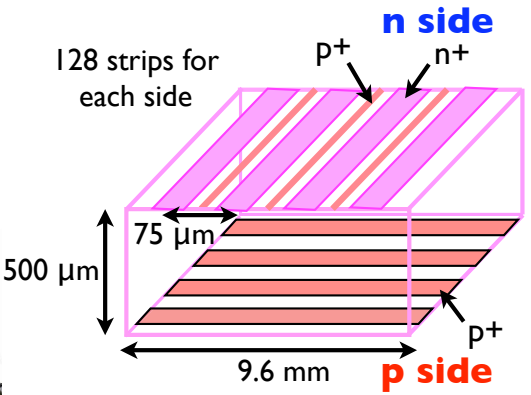
FOXSI Rocket Components

- Replicated Ni optics from NASA/Marshall
- Wolter-I shape
- Nested sets of 7 or 10
- FWHM ~5 arcsec
- HPD 25” (on-axis)







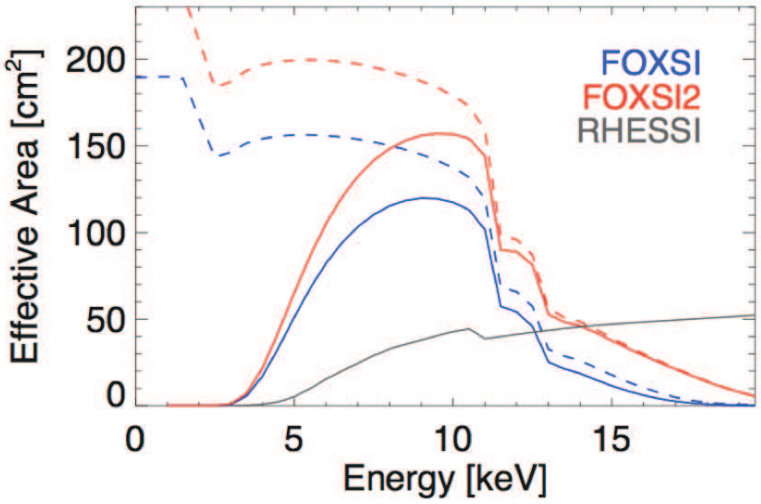


- 7 double-sided Si or CdTe strip detectors from ISAS
- 75 um pitch (60 for CdTe), 500 um thick
- Read out by low-power, low-noise ASICs

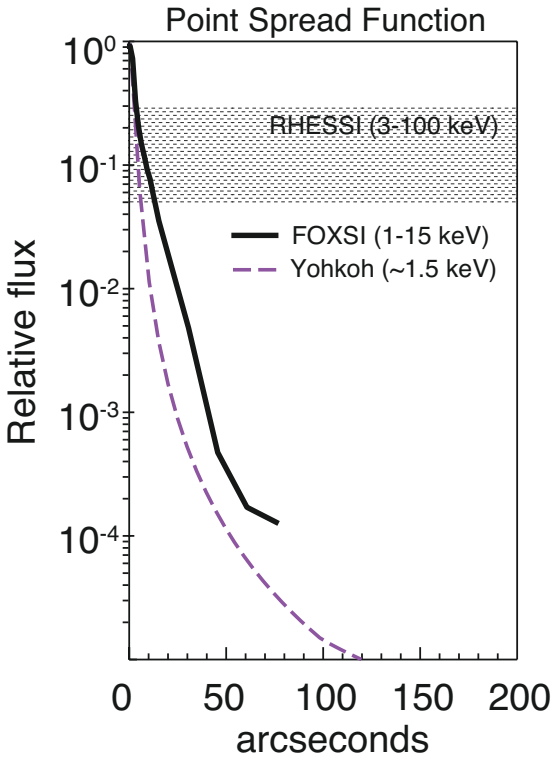
New for FOXSI-2:

- **Additional mirrors**
- **CdTe detectors**
- **Visible-light Solar Aspect & Alignment System**

Measurement capabilities



Energy Range	4 to 15 keV
Energy Resolution	0.5 keV
FOV	¼ Sun (16 x 16 arcmin^2)
Angular Resolution	~9'' FWHM
Effective Area	~3 x RHESSI at 10 keV (120 cm^2)
Dynamic Range	~10 x RHESSI (~100) (for source separation of 30'')

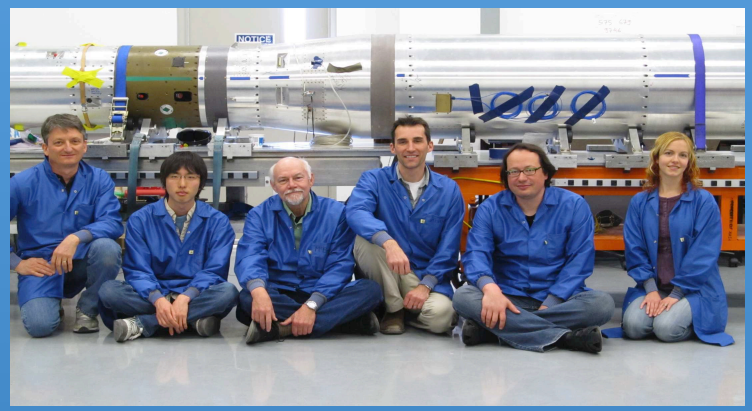


Launch campaigns: FOXSI-1 and FOXSI-2

White Sands Missile Range, New Mexico

FOXSI-1: Nov 2, 2012

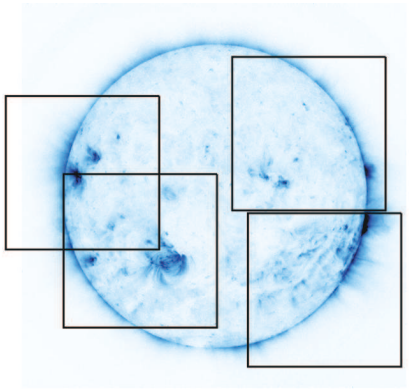
- 6.5 min observation time
- Obs. >150 km, apogee 340 km
- Successful first flight!
- **First focused images of the Sun above 5 keV.**
- Reduced sensitivity due to thermal blanket motion + 1 displaced optic.



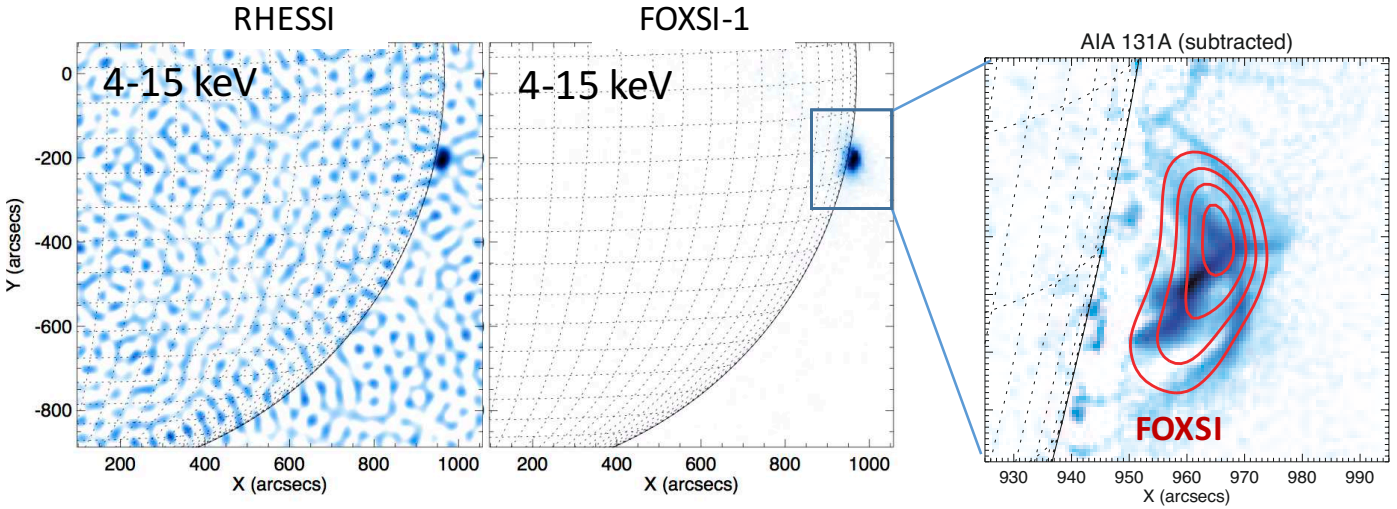
FOXSI-2: Dec 11, 2014

- Successful 2nd flight
- Replaced 2 Si with CdTe
- Upgraded 2 optics modules with 3 small-diameter shells
- **Increased sensitivity**, mainly >10 keV

2012 November 02: *FOXSI-1* flight



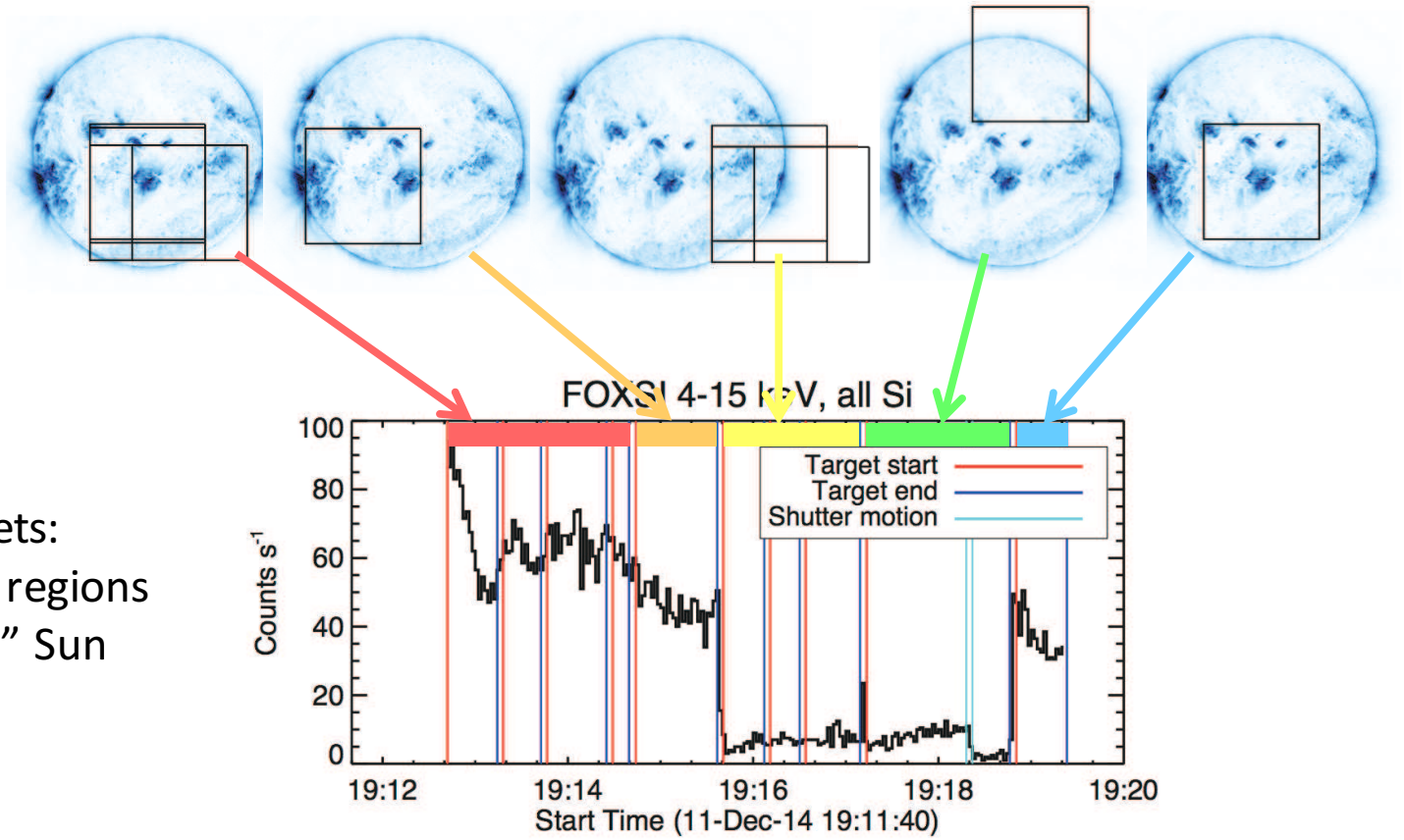
AIA 94A **2012 Nov 2**
Launch 17:55 UTC



Krucker, Christe, Glesener, et al., ApJL 2014

First focused image of the Sun in hard X-rays! (>5 keV)

2014 December 11: *FOXSI-2* flight

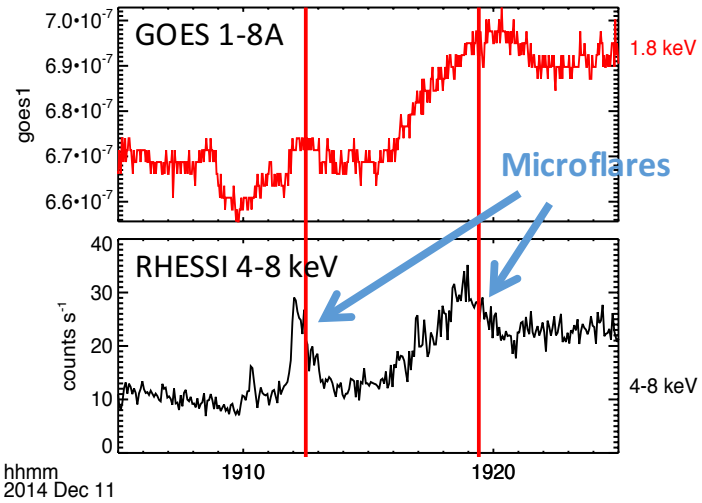


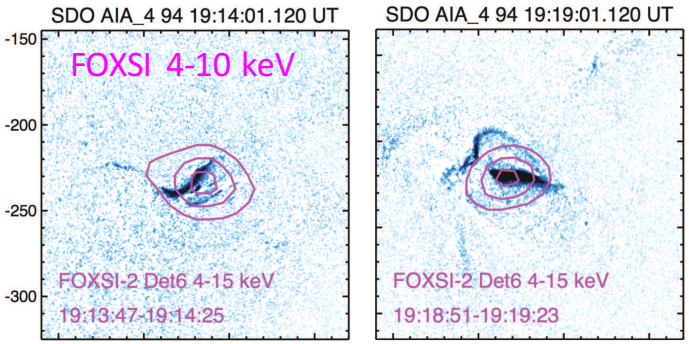
Targets:

- Active regions
- "Quiet" Sun

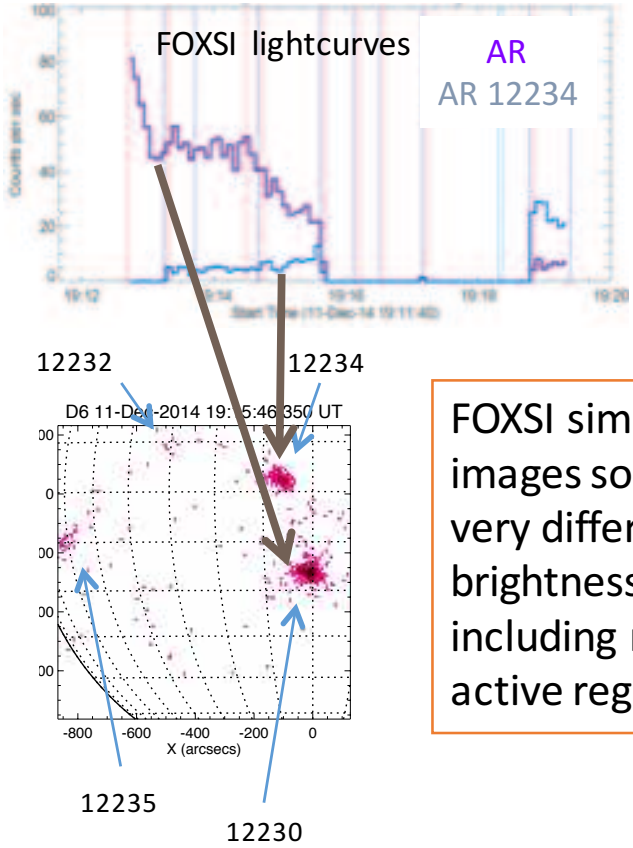
2014 December 11: *FOXSI-2* flight

Two more microflares!



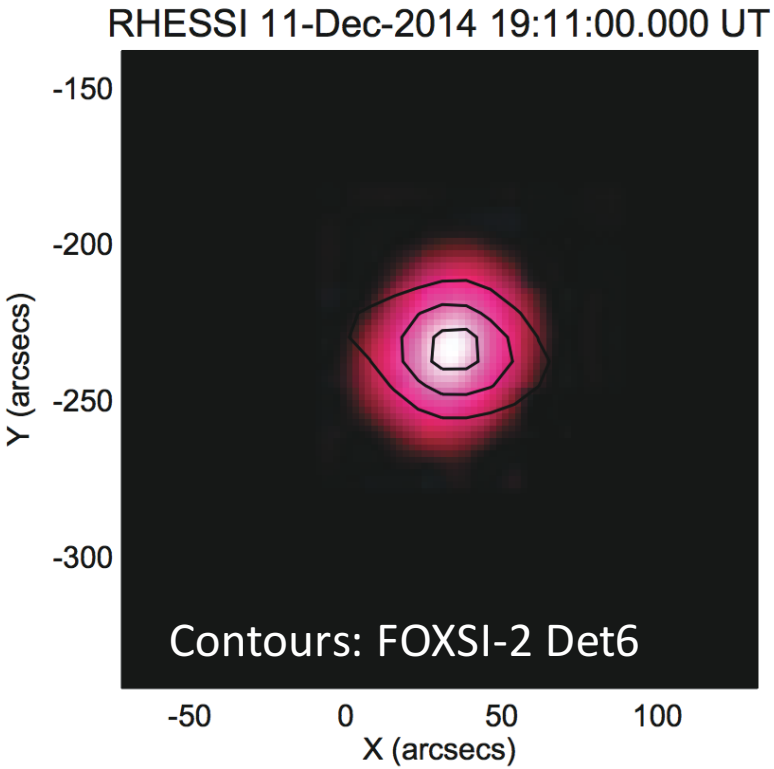


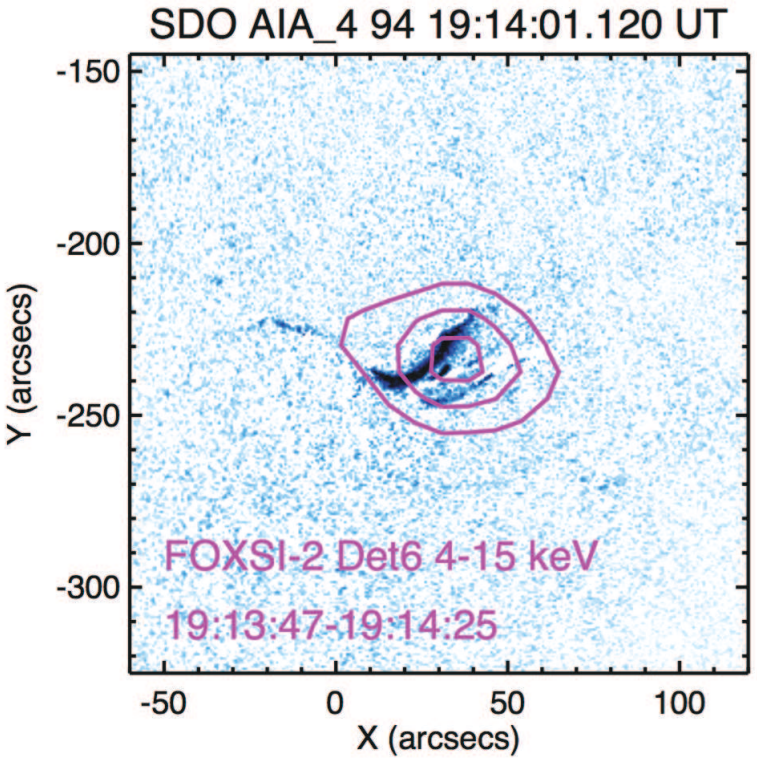
Flare in AR 12230 Flare in AR 12234



FOXSI simultaneously images sources of very different brightnesses, including nonflaring active regions.

FOXSI-2 microflare #1 (of 2)



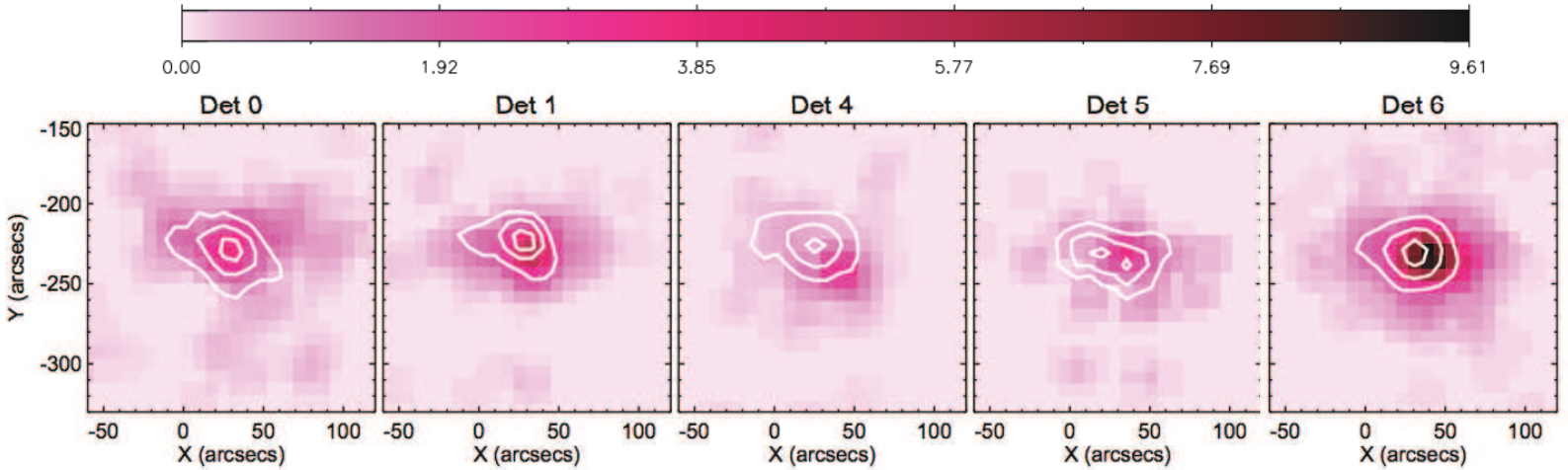


- RHESSI: 3 min, Detectors: 6,7,8,9
- FOXSI: 38 seconds, Detector 6
- Energy: 4-15 keV

FOXSI locations found by coalignment with RHESSI.

Analysis by Julie Vievering

Imaging spectroscopy for each Si detector



Pink intensity: 4 - 5.5 keV

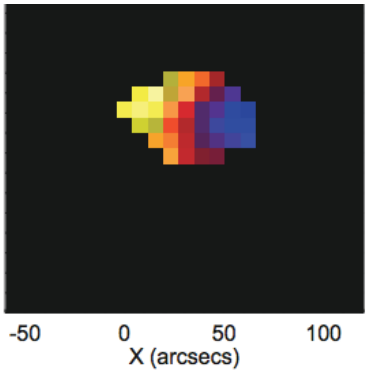
White contours: 6 - 10 keV

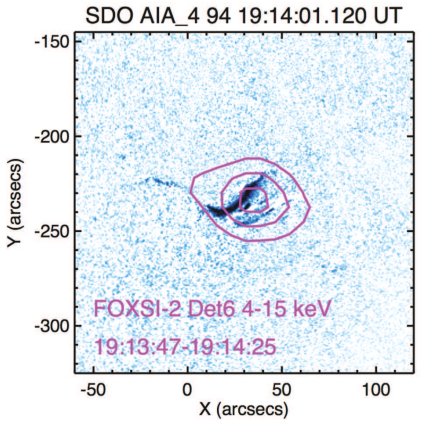
	Det 0	Det 1	Det 4	Det 5	Det 6
Low E:	(**35**, -230)	(**27**, -231)	(**31**, -239)	(**33**, -239)	(**38**, -234)
High E:	(**30**, -230)	(**18**, -232)	(**25**, -228)	(**25**, -233)	(**29**, -232)

- High-energy centroids are further east in every detector.

→ Suggests higher temperatures to the east

Ratio of high to low





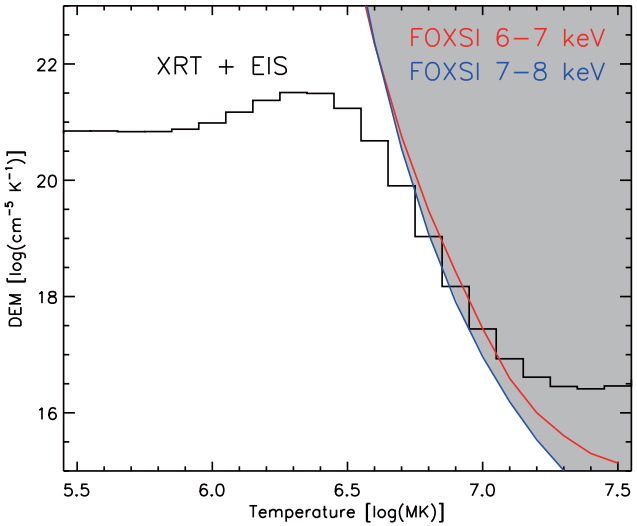
Imaging spectroscopy of an A0.5 flare!

Analysis by
Julie Vievering

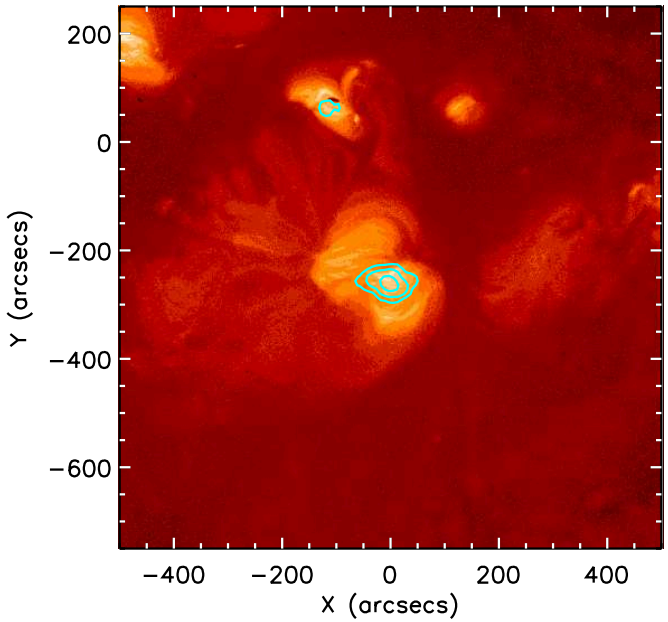
Analysis by Shin-nosuke Ishikawa

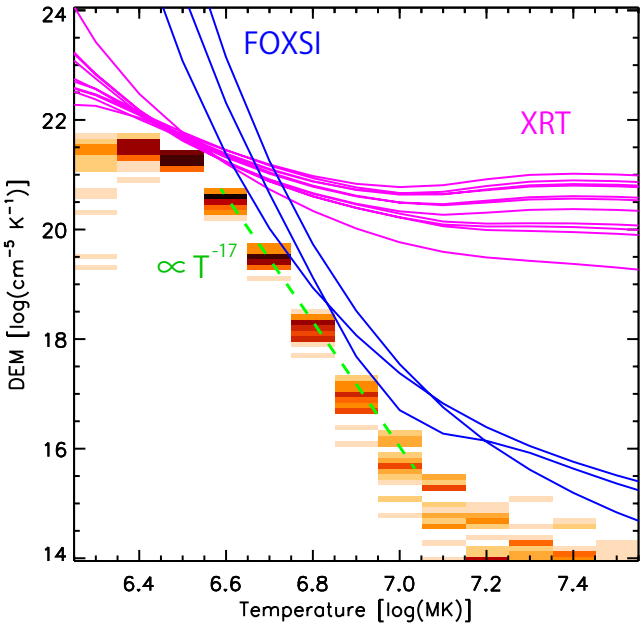
Quiescent active region measurements

- FOXSI-1 looked at quiet active regions, but did not measure any signal.
- FOXSI-1's instrument response was used to construct constraints for AR DEM analysis (with Hinode).



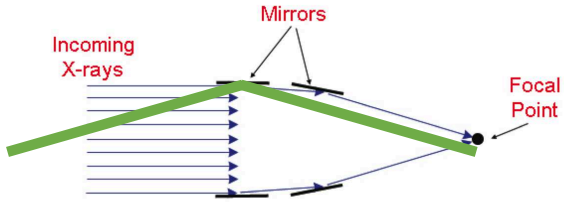
- FOXSI-2 has a clear detection of AR 12234 when not flaring.
- With XRT+FOXSI, high-temperature slope of DEM is measured.

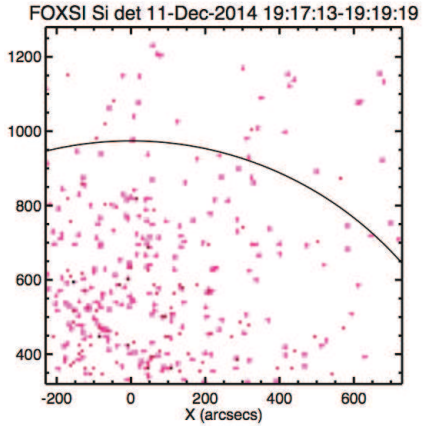


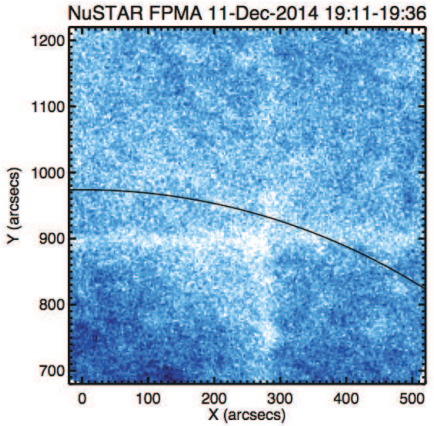


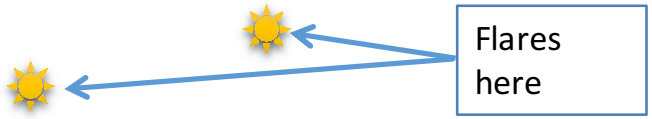
Quiet Sun HXR signal? Not yet!

All focused HXR Quiet Sun observations so far are dominated by “ghost rays” from sources outside FOV.









What's new for FOXSI-3?

- **FOXSI-3 is funded**, flight expected in 2018.

- Upgrade 2 more modules to 10 mirrors.
  - (4 at 10 shells; 3 at 7 shells)

- Detector set:
  - 6 CdTe detectors with slight changes
  - 1 Si detector sensitive to ***soft*** X-rays
    - Noriyuki Narukage @ NAOJ and Shin-nosuke Ishikawa @ ISAS

- Add a **pre-collimator to block ghost rays**
  - Several styles currently under trade, including long, thin "blade" style and shorter "honeycomb" style.

Conclusions

- FOXSI's technology and scientific promise have been demonstrated in two successful rocket flights.

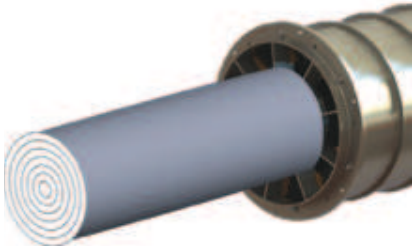
- FOXSI is now a mature technology. Each successive rocket flight serves to develop new capabilities and perform new science.

On to a spacecraft!

Extra

How to block ghost rays?

Collimating baffle



- Pros:
  - Effectively attenuates low-energy ghost rays from most off-axis source positions.
- Cons:
  - Length and mass
  - Sensitive alignment

Azimuthal blocker

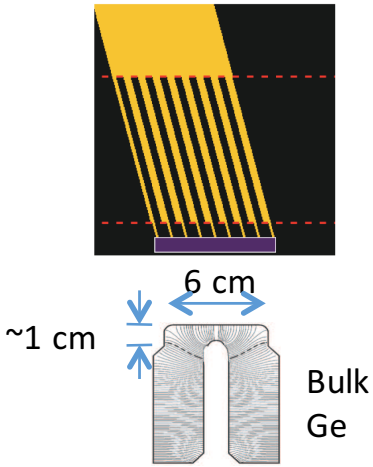
- Pros:
  - Effectively attenuates low-energy ghost rays from part of the Sun.
- Cons:
  - Requires roll control
  - Small loss in effective area
  - Cannot block >1 source
  - Requires more calibration

One or (likely) both methods will be demonstrated on FOXSI-3.

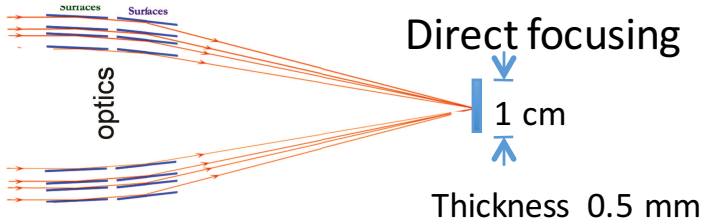
- FOXSI-3 flight funded and anticipated for summer 2018.

Hard X-ray detector backgrounds

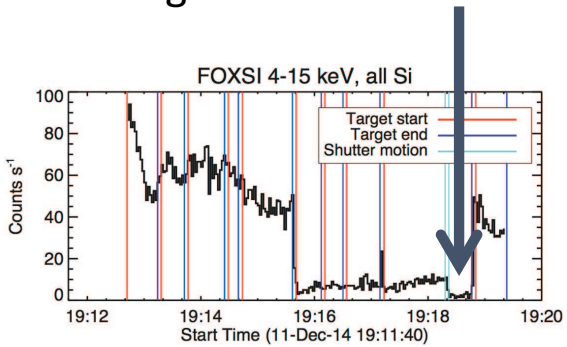
RHESSI method
(traditional; indirect)



- RHESSI background on Dec. 11 **~0.8 counts s^{-1} keV^{-1} $detector^{-1}$**

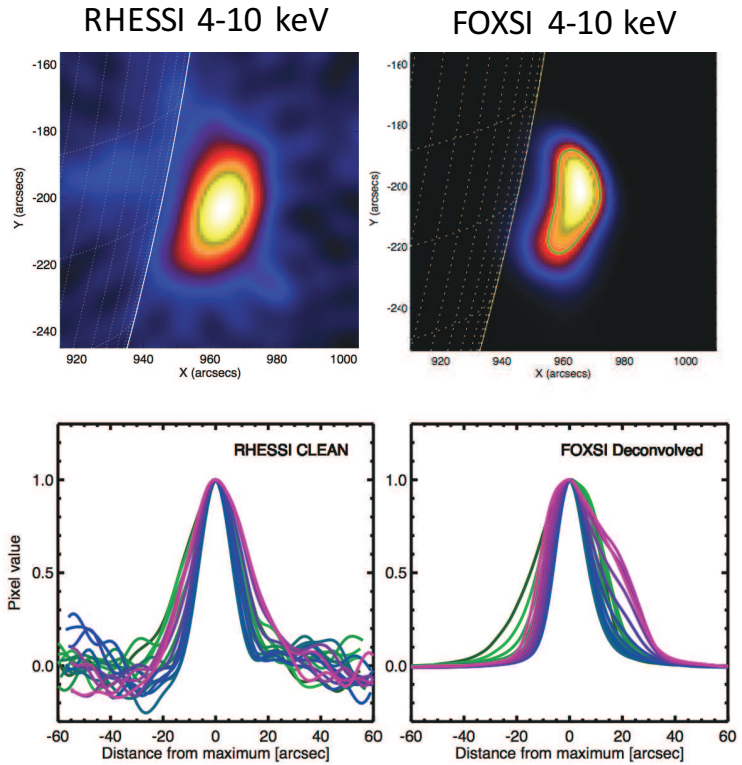


FOXSI-2 flight included 24 s with shutters inserted

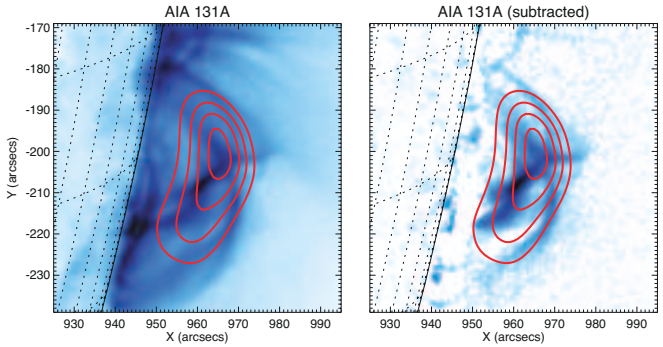


- Nonsolar background is **~0.03 counts s^{-1} keV^{-1} $detector^{-1}$**
- Nonsolar background **within HPD** is **~2 x 10^{-5} counts s^{-1} keV^{-1} $detector^{-1}$**

Deconvolved *FOXSI-1* flare image



Compare with SDO/AIA images of hot flaring loop (extreme ultraviolet)



Glesener, Krucker, Christe et al., *in preparation*