UMN: Lindsay Glesener (PI), P.S. Athiray, S. Musset, J. Vievering, L. Davis
UCB: S. Courtade, J.-C. Buitrago Casas, S. Krucker, G. Dalton, P. Turin
MSFC: B. Ramsey, S. Bongiorno
GSFC: D. Ryan, S. Christe
Georgia Tech: Z. Turin
Kavli IPMU: T. Takahashi, K. Furukawa
ISAS: S. Watanabe, T. Kawate
NAOJ: N. Narukage
Nagoya Univ.: S. Ishikawa, I. Mitsuishi
Tokyo Univ. of Science: K. Hagino

Investigating high energy processes in the solar atmosphere with the FOXSI sounding rocket

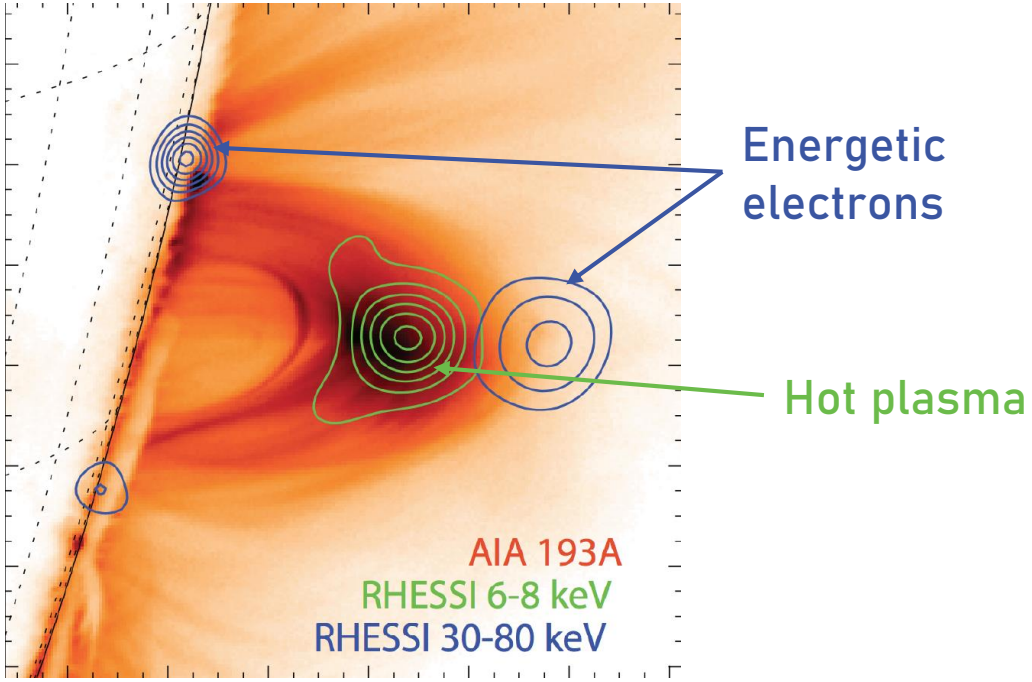
University of Minnesota

Sophie Musset,
University of Minnesota
And the FOXSI-3 Team

IRIS-10 Workshop
Bengaluru, Nov. 8. 2019

Science from solar X-ray diagnostics

How are particles accelerated during solar flares?



EUV (image) and hard X-ray (contours) during a flare (Krucker & Battaglia, 2013)

Science from solar X-ray diagnostics

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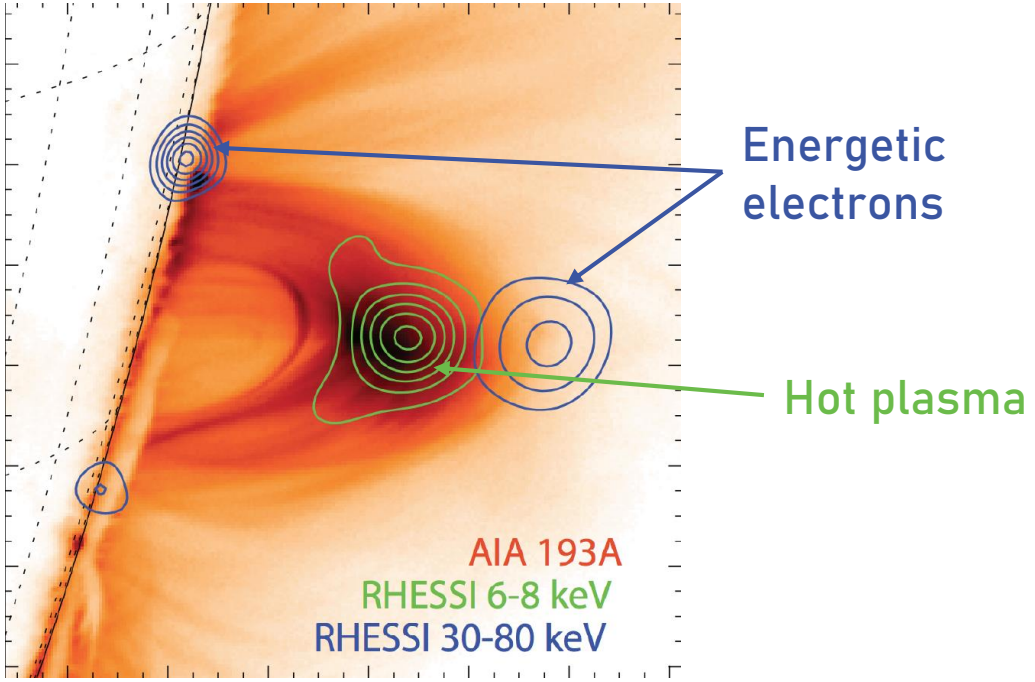

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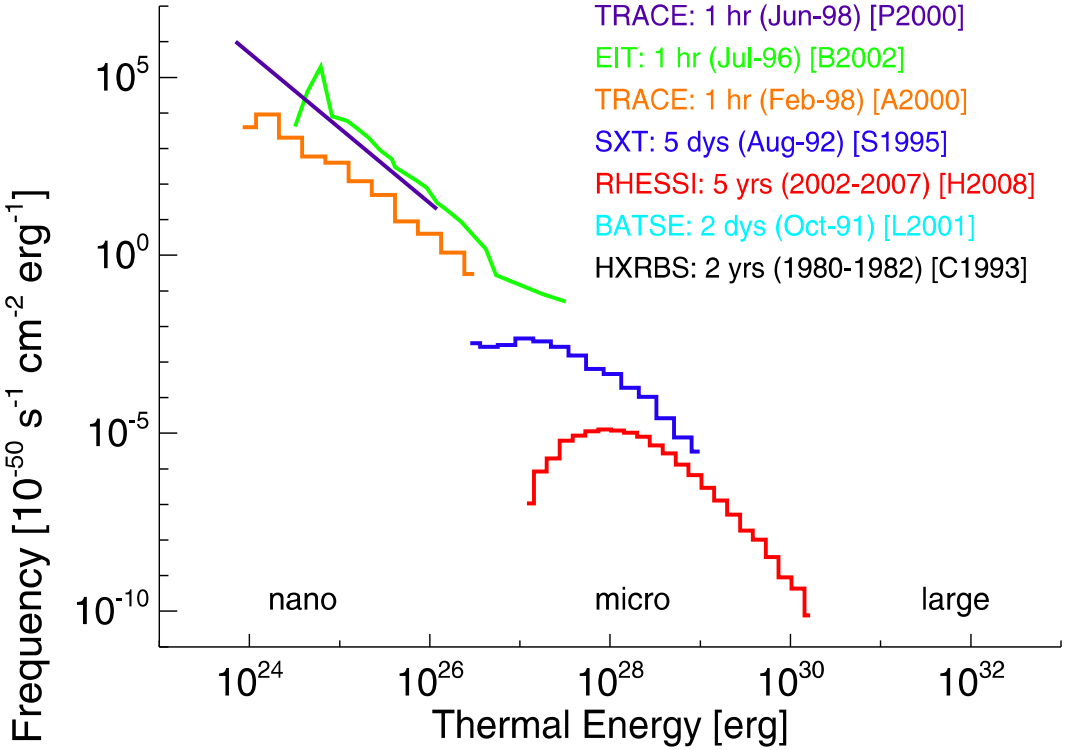
How does the solar corona get heated to millions of degrees?



Flare energy distribution (Hannah et al, 2011)

Science from solar X-ray diagnostics

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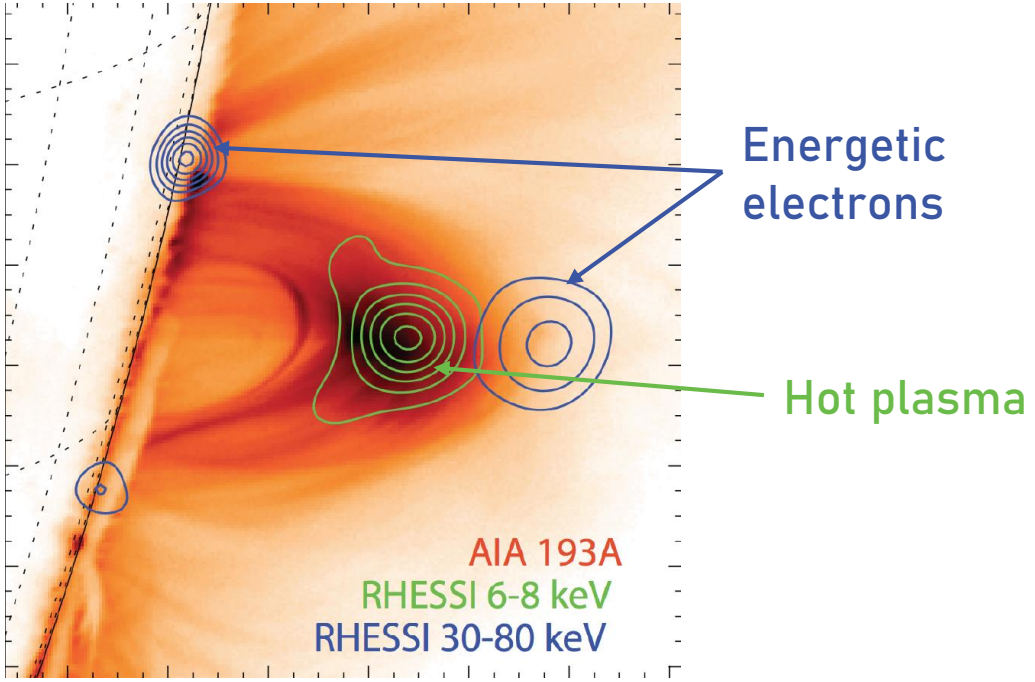

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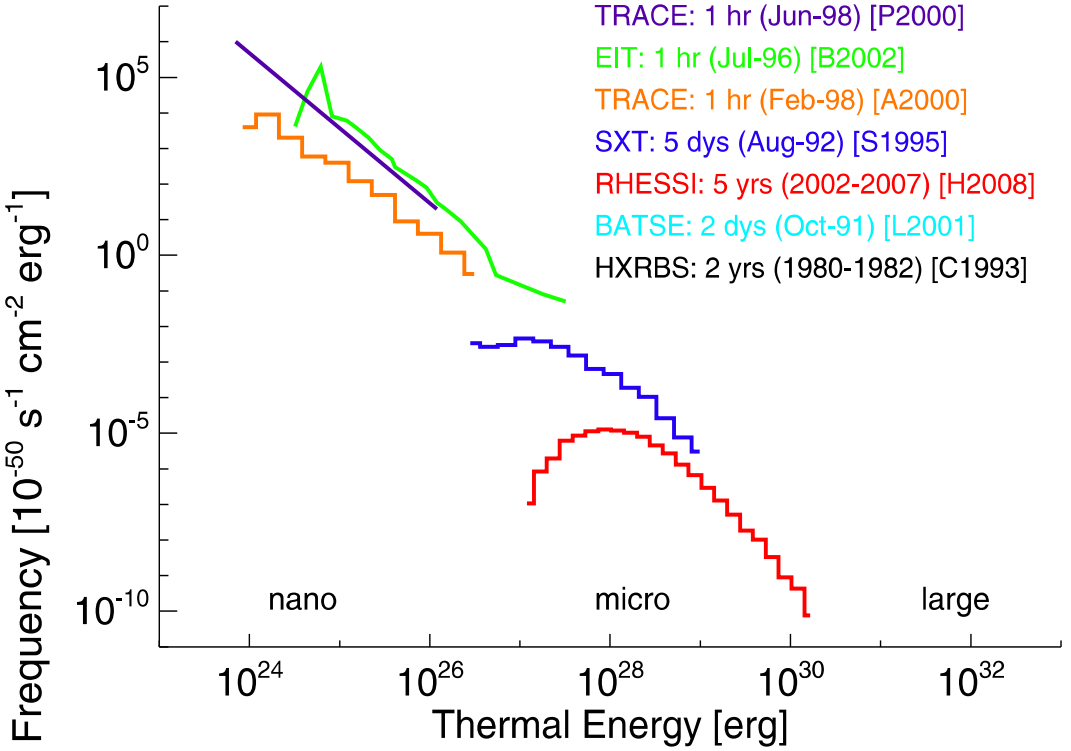


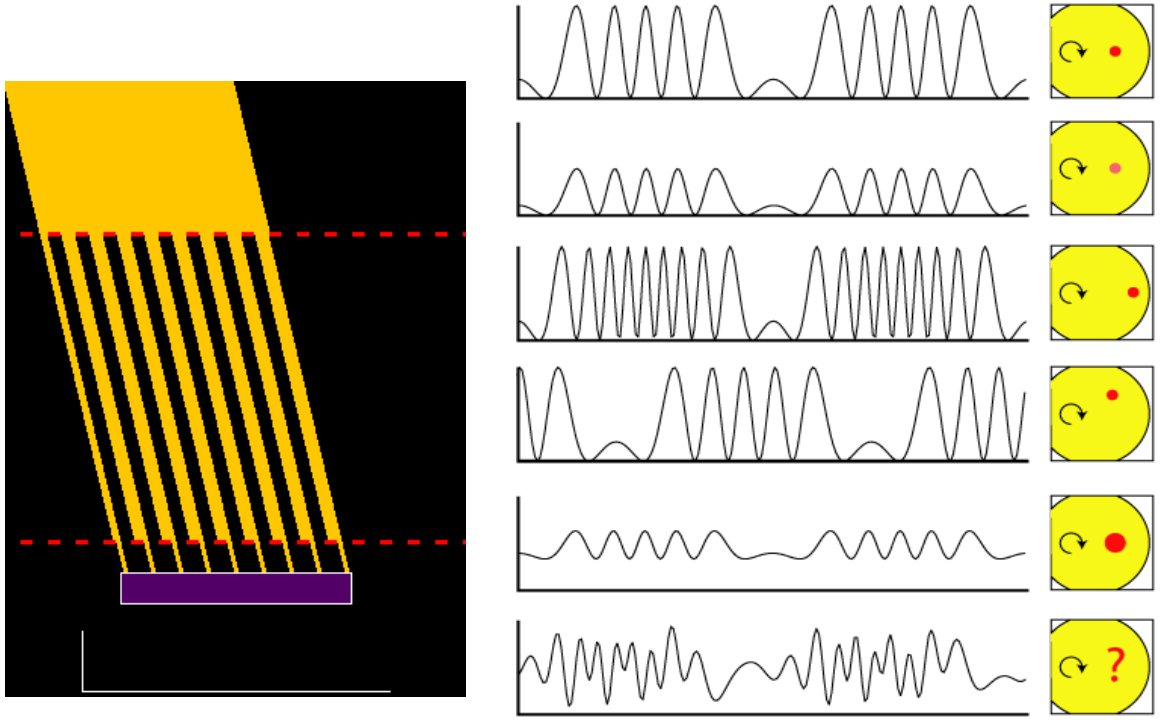
Flare energy distribution (Hannah et al, 2011)

Need for solar hard X-ray (HXR) observations with good sensitivity and dynamic range

The need for X-ray focusing optics

RHESSI 2002 – 2018

Reuven Ramaty High Energy Solar Spectroscopic Imager



Indirect imaging method (modulation by rotation)
High background (large detectors)
➔ Limited sensitivity and dynamic range

The need for X-ray focusing optics

RHESSI 2002 – 2018

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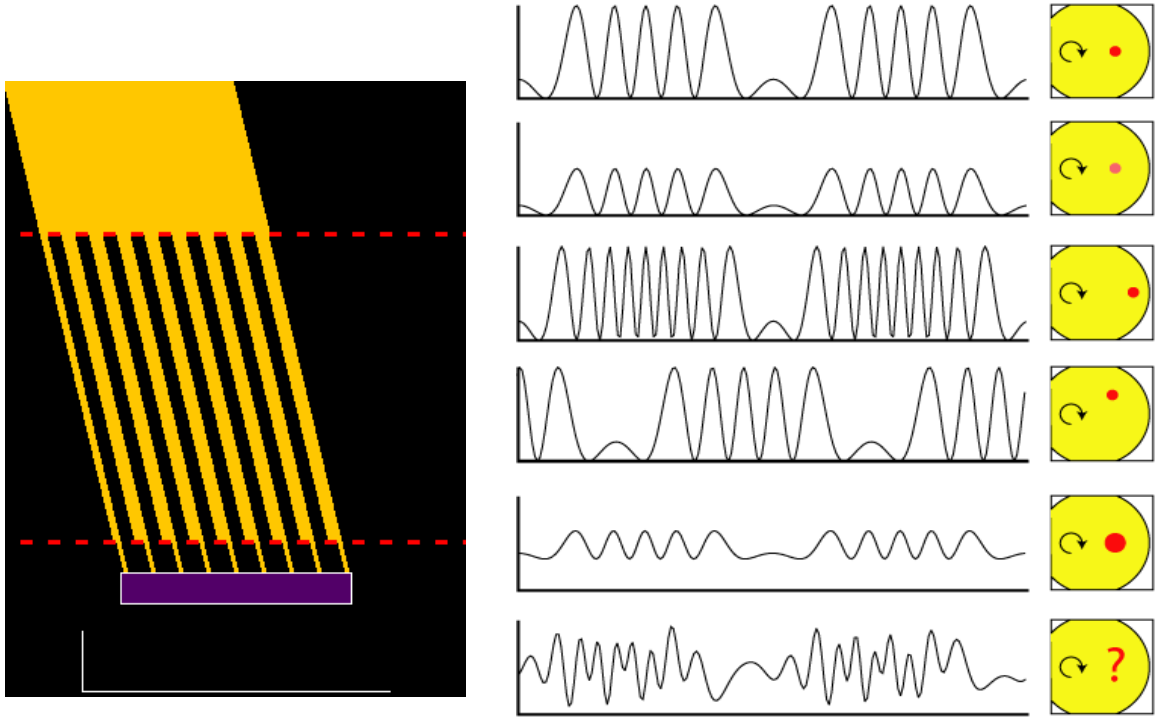
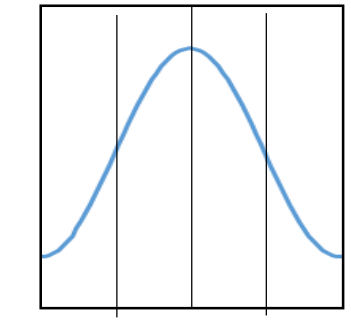
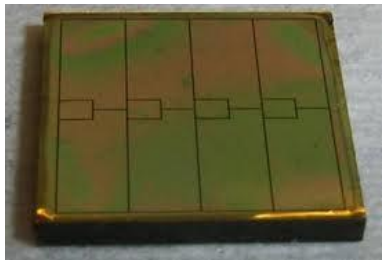


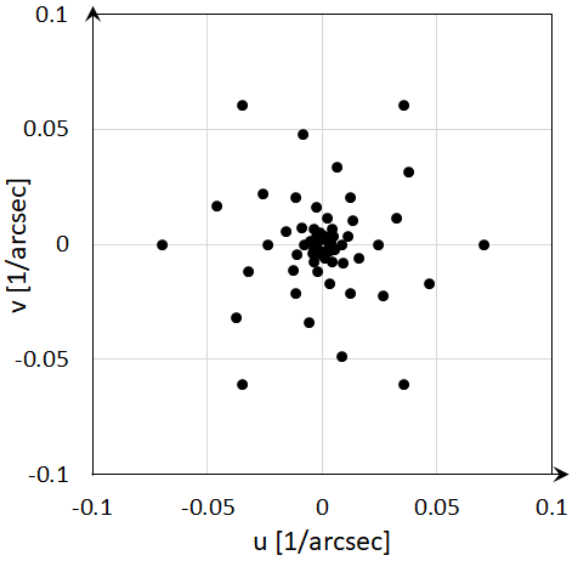
Indirect imaging method (modulation by rotation)
High background (large detectors)
➔ Limited sensitivity and dynamic range

STIX 2021 – ?

Spectrometer/Telescope for Imaging X-rays

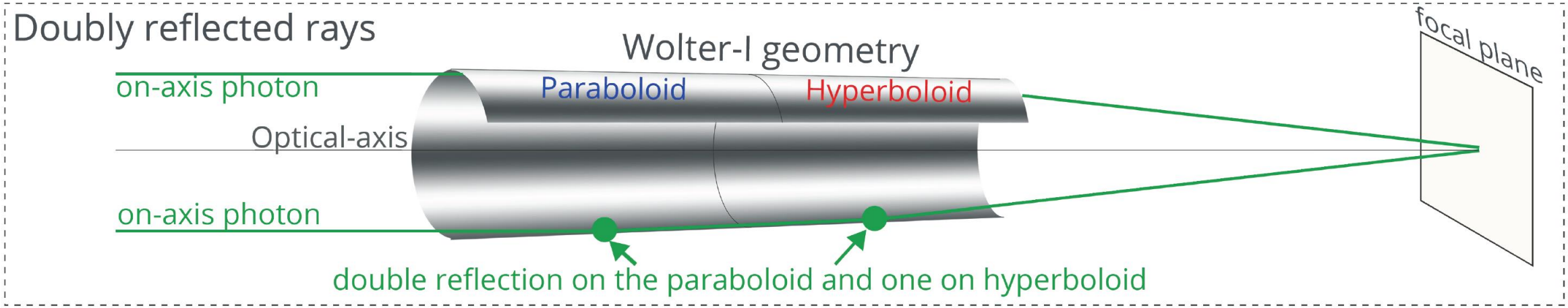




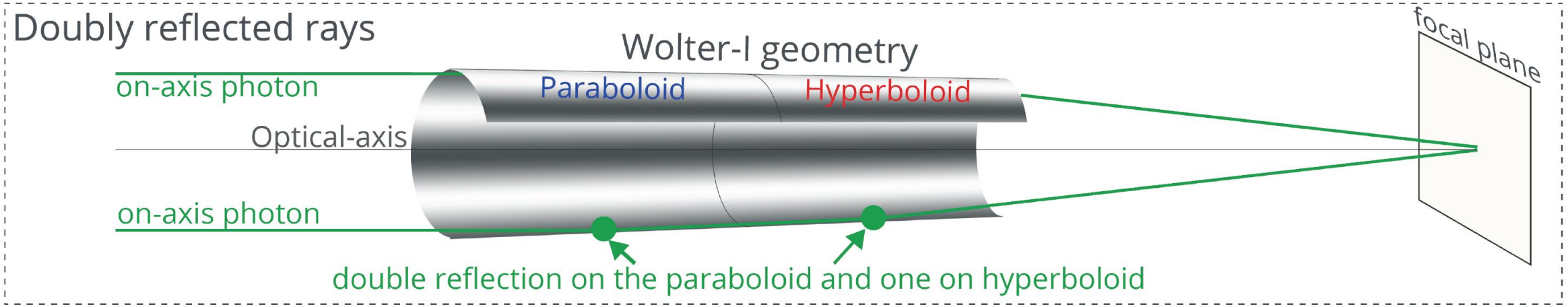


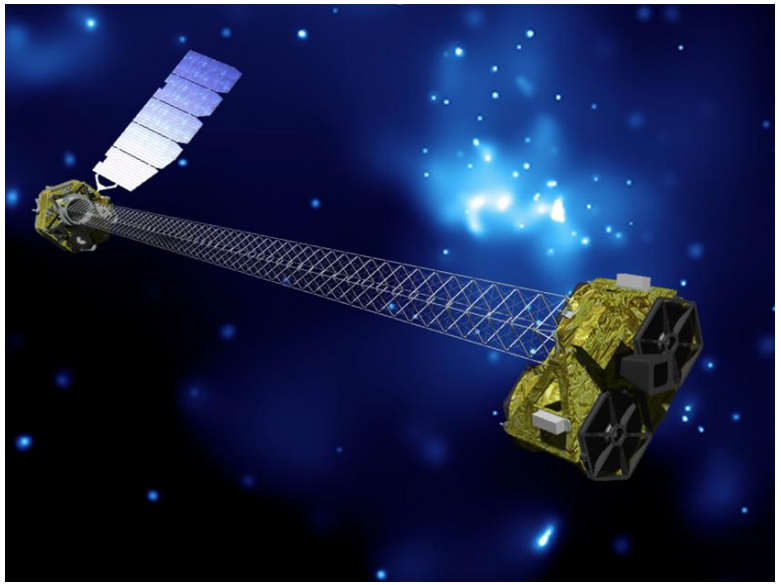
Indirect imaging method (measure of visibilities with moiré patterns)
➔ Limited dynamic range, limited coverage of the Fourier plane

Focusing optics for Hard X-ray observations



Focusing optics for Hard X-ray observations





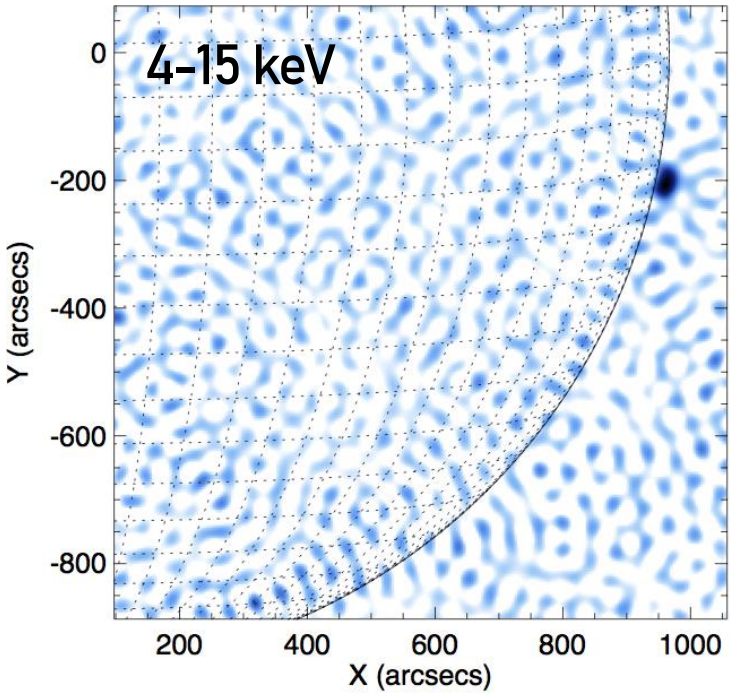
NuSTAR is the first focusing optics X-ray spaceborne telescope
→ NOT optimized for solar observations

The Focusing Optics X-ray Solar Imager (FOXSI)
sounding rocket demonstrates
focusing X-ray imaging and spectroscopy of the Sun

Focusing optics for Hard X-ray observations

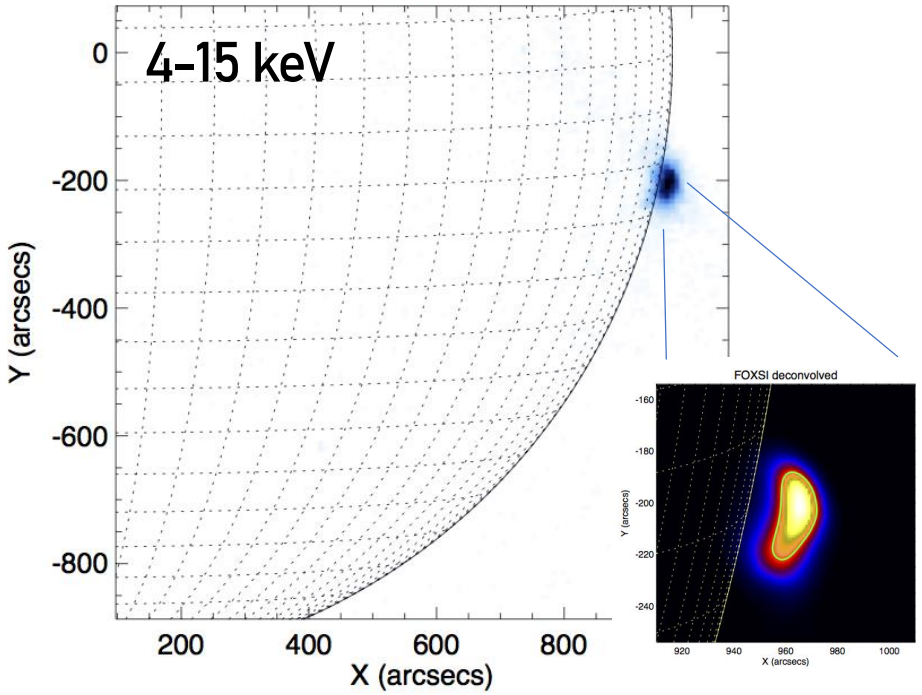
The Focusing Optics X-ray Solar Imager (FOXSI) sounding rocket demonstrates focusing X-ray imaging and spectroscopy of the Sun

RHESSI



Indirect (Fourier-based) imaging method

FOXSI-1



Focused image of the same event

Krucker et al, 2014

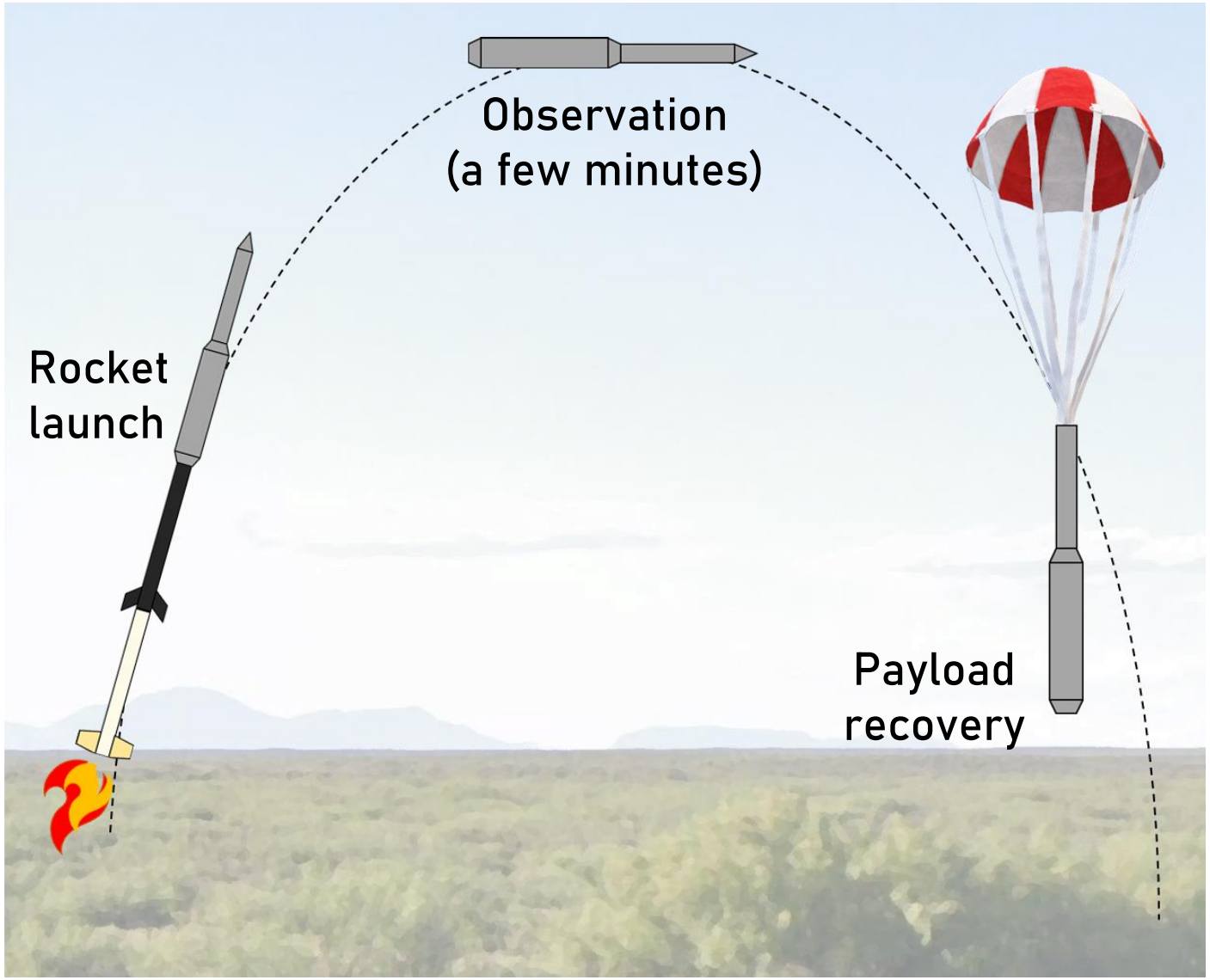
The FOXSI sounding rocket program

NASA sounding rockets:
An opportunity to demonstrate capabilities of new technologies for space applications

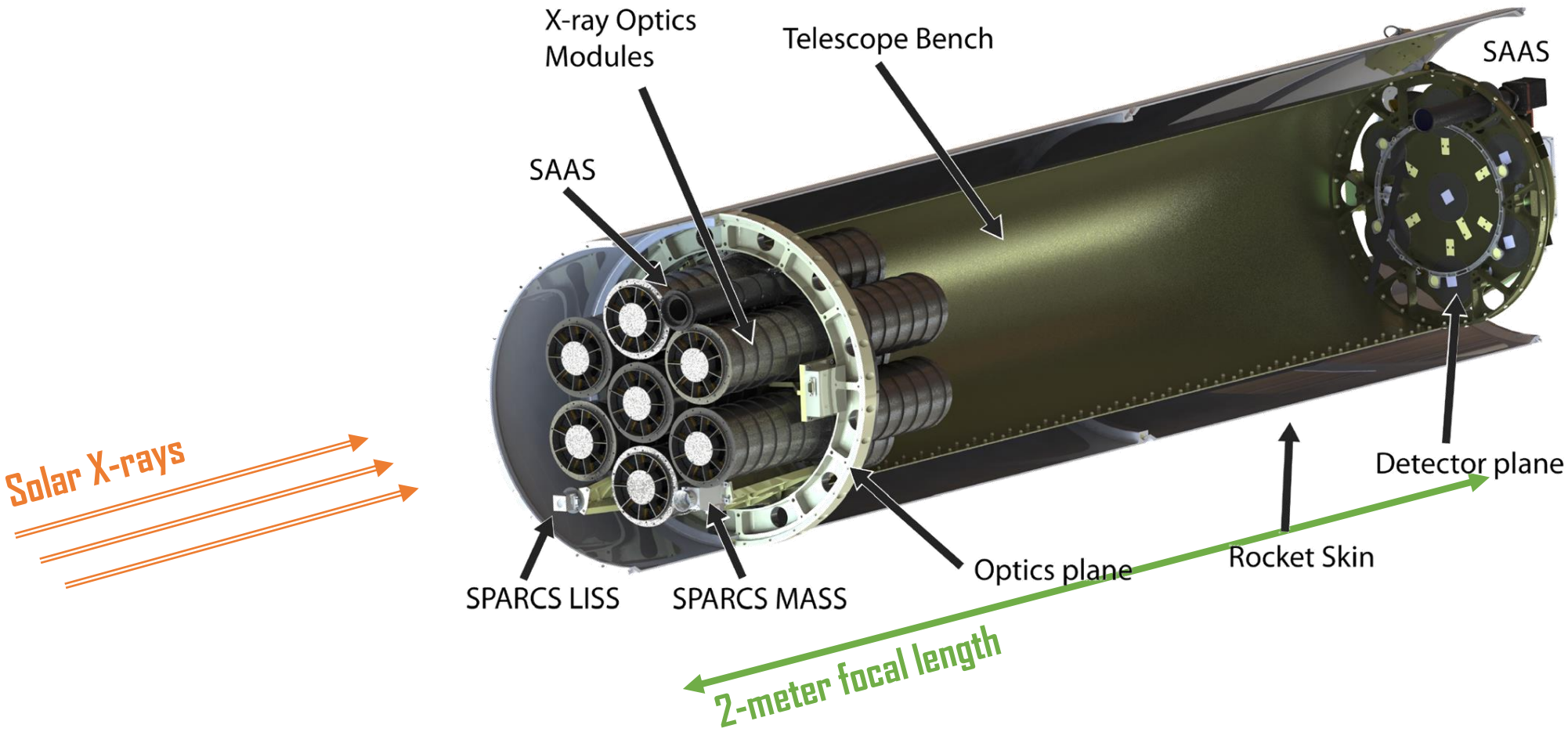
Benefits:

- Lower cost
- Increase of "Technology Readiness Level" of experiment
- Opportunity for student and early career scientist involvement in hardware

FOXSI sounding rocket flew in 2012, 2014 and 2018



FOXSI sounding rocket experiment



FOXSI sounding rocket experiment

X-ray optic modules:
Nested shells of grazing incidence optics
NASA Marshall Space Flight Center

Krucker et al, SPIE, 2013
Christe et al, 2015
Buitrago-Casas et al, 2017

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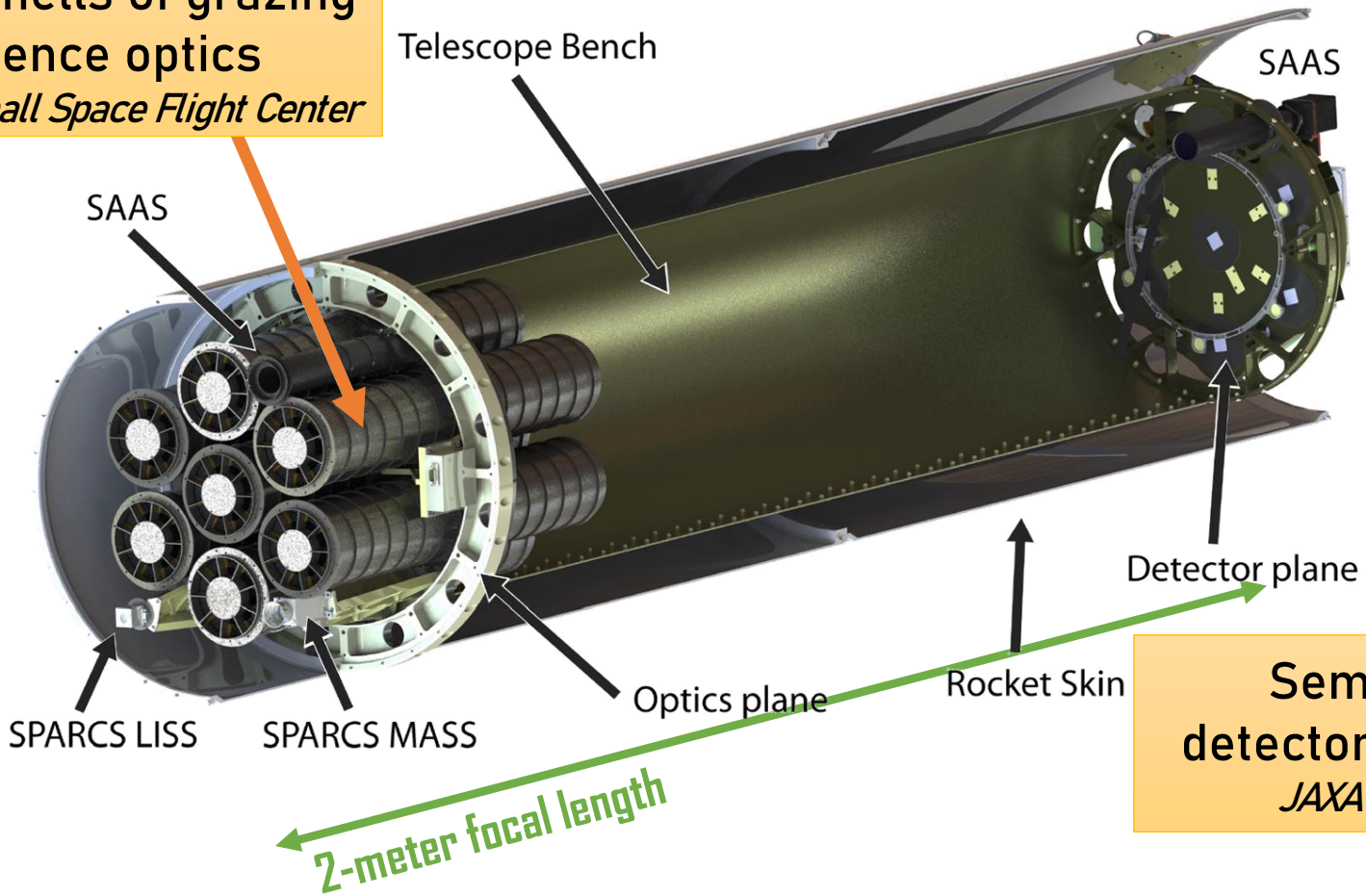
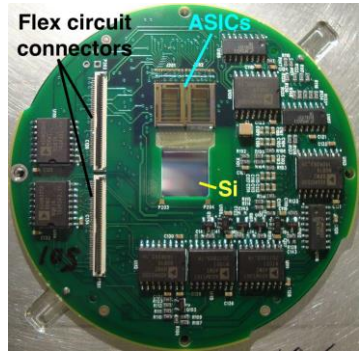
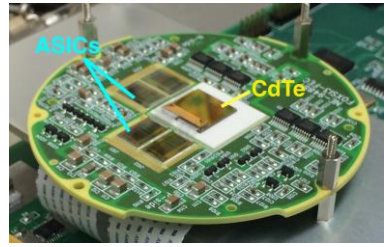




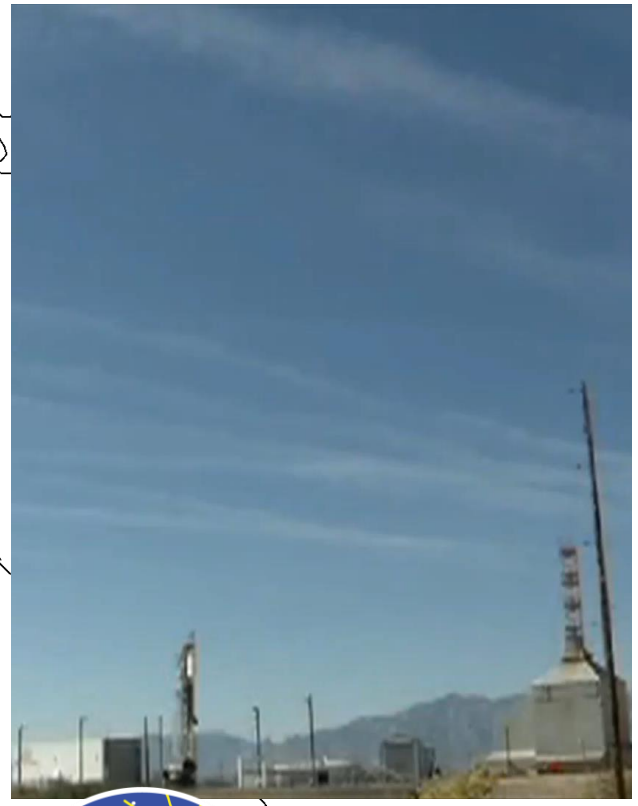


Semi-conductor detectors (Si and CdTe),
JAXA ISAS, Kavli IPMU

Krucker et al, SPIE, 2013
Christe et al, 2015
Buitrago-Casas et al, 2017

Ishikawa et al, 2016
Athiray et al, 2017

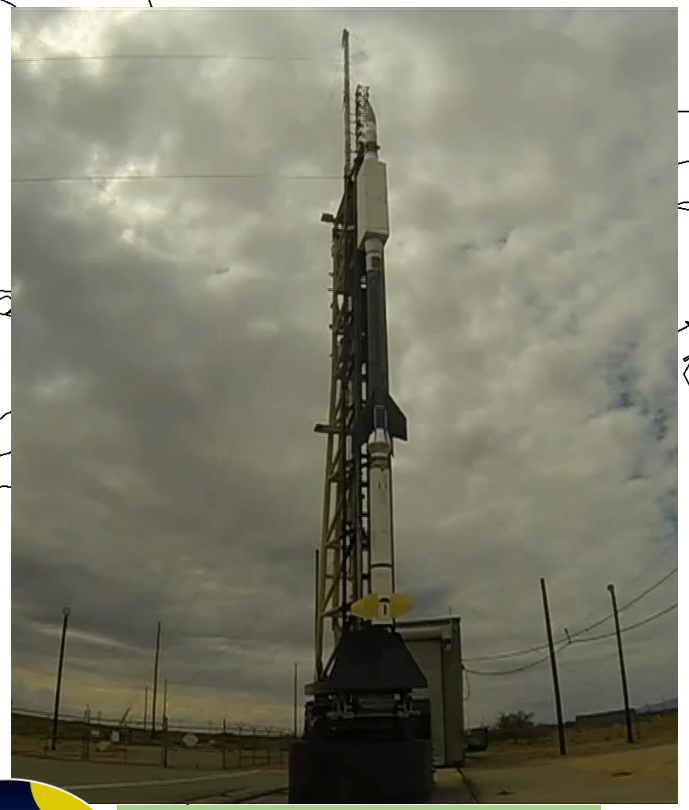
FOXSI sounding rocket: past campaigns



FOXSI-1
Nov. 2, 2012

FOXSI-2
Dec. 11, 2014

FOXSI-3
Sep. 7, 2018

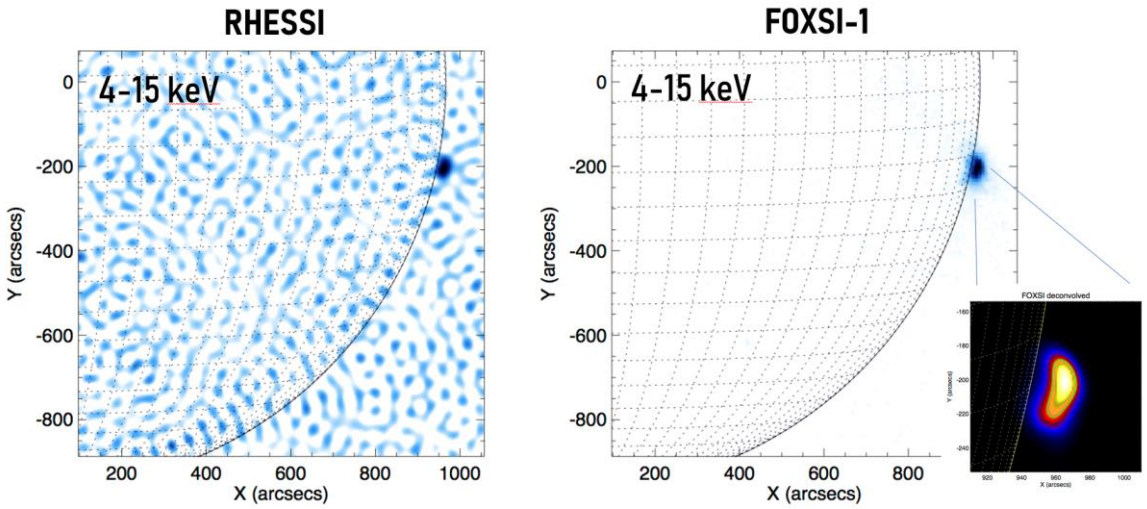


★ White Sands Missile Range

Major upgrades:
Additional optic shells
CdTe detectors

Major upgrades:
SXR detector
Collimator

FOXSI sounding rocket: past campaigns

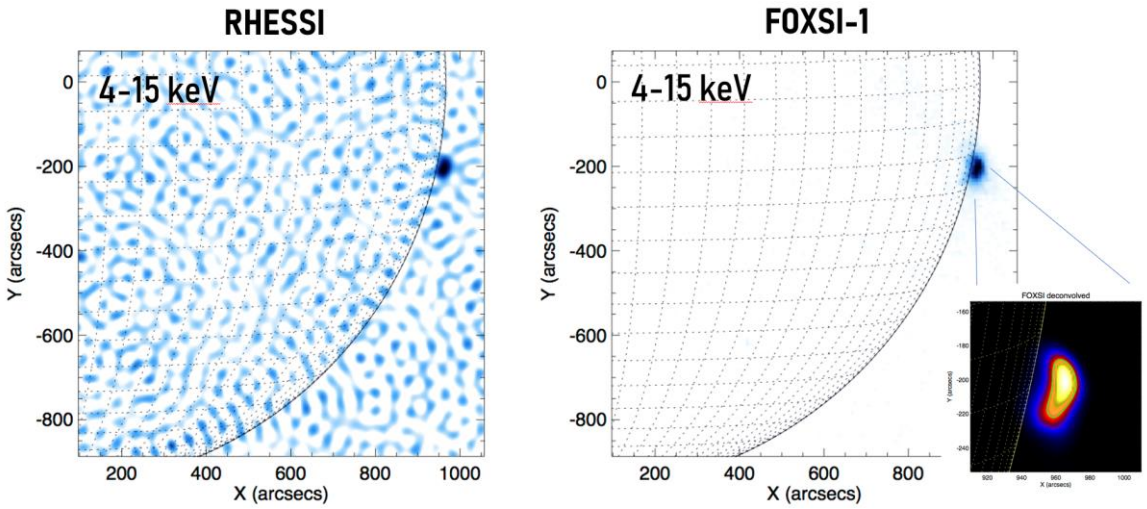


Glesener et al, SPIE, 2016

FOXSI-1 (2012)
First focused image of the solar HXR

Krucker et al, 2014
Ishikawa et al, 2014

FOXSI sounding rocket: past campaigns



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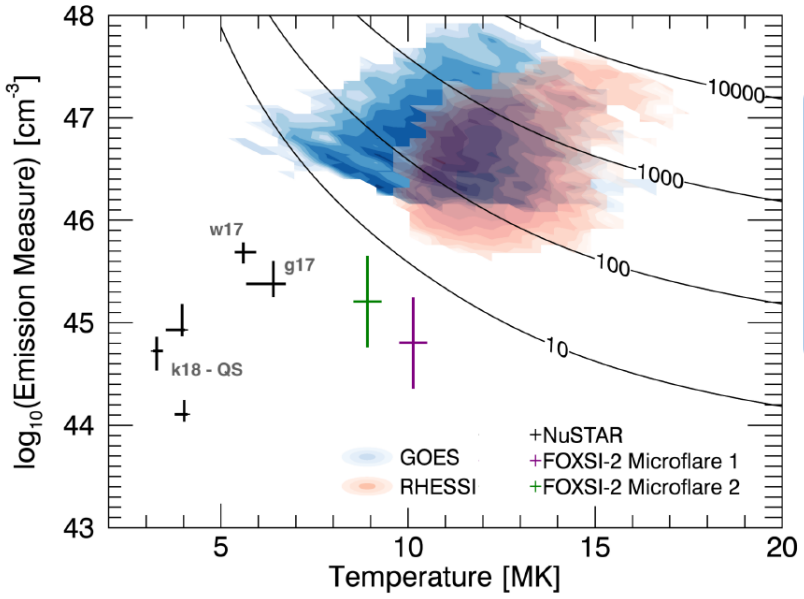
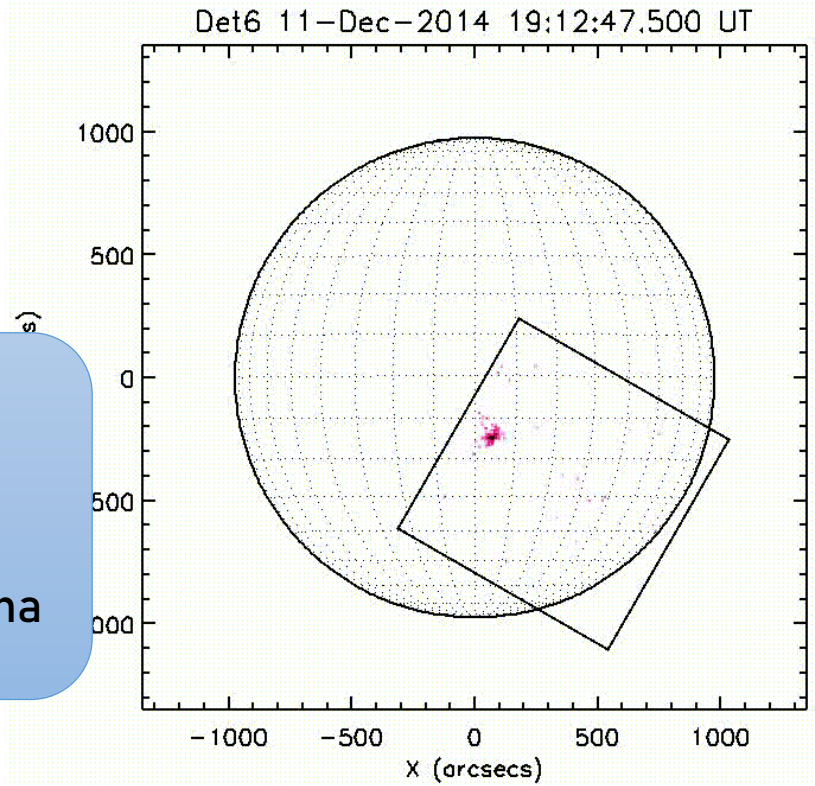
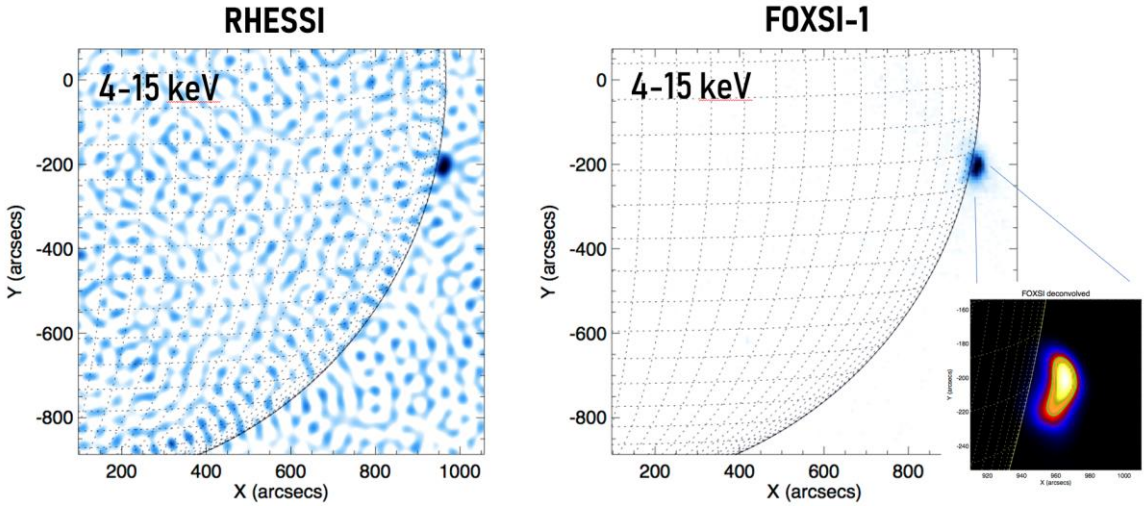


FOXSI-2 (2014)
Observation of two microflares, on order of magnitude fainter than previous observations
+ detection of nanoflare heated plasma in active region

Ishikawa et al, Nature Astronomy, 2017
Athiray et al, in rev.
Vievering et al, in prep



FOXSI sounding rocket: past campaigns



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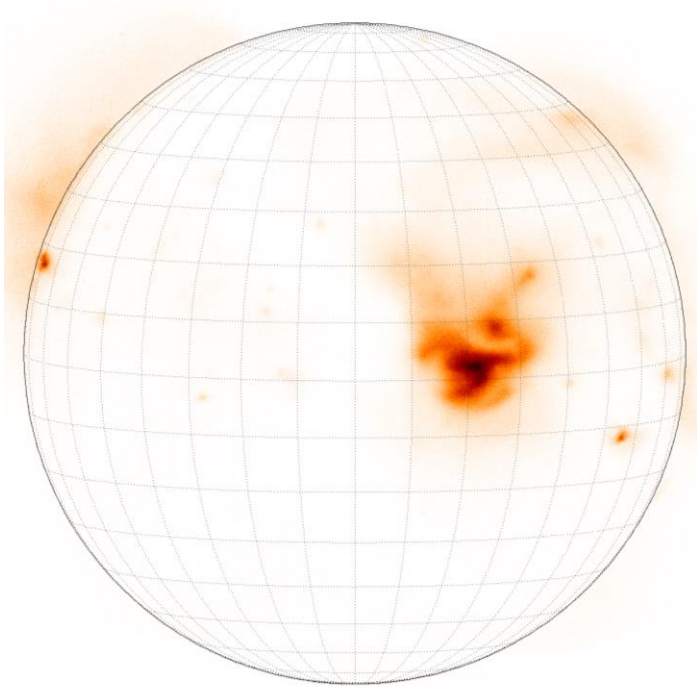
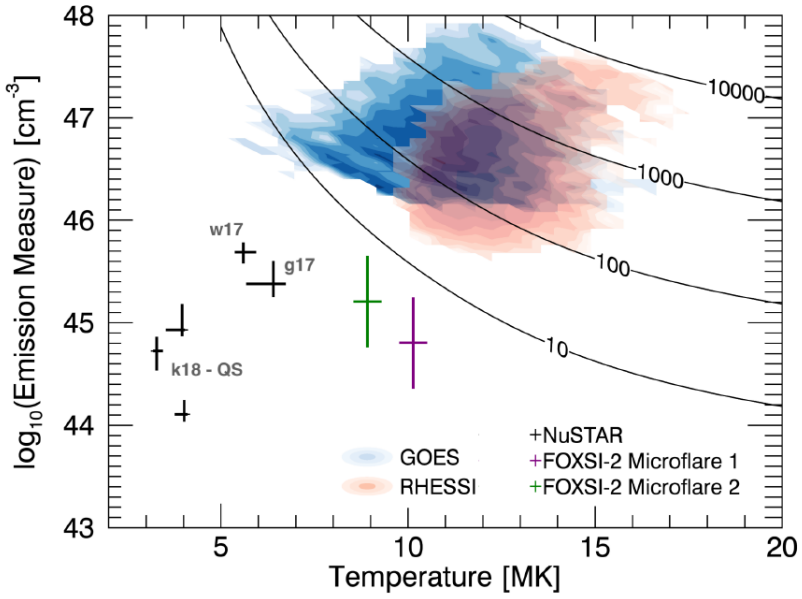
Glesener et al, SPIE, 2016





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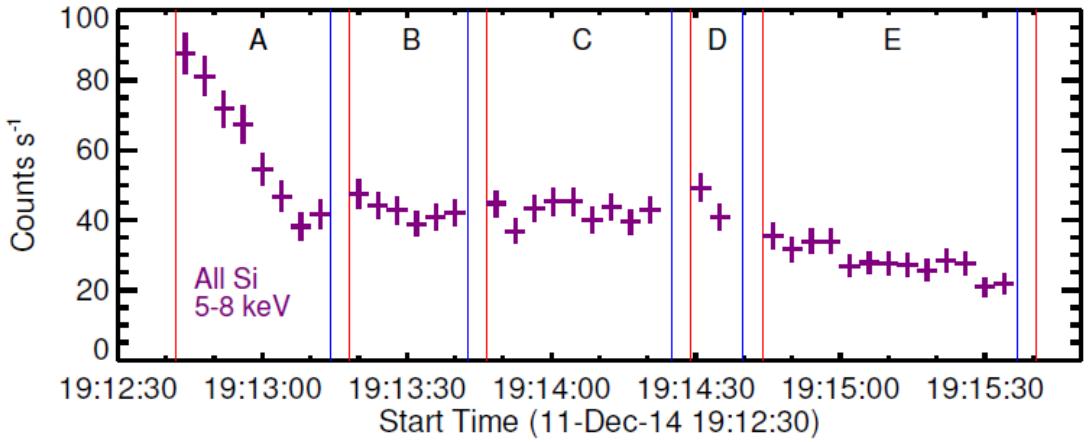
Vievering et al, in prep

FOXSI-3 (2018)
First photon-counting image of the Sun in SXR

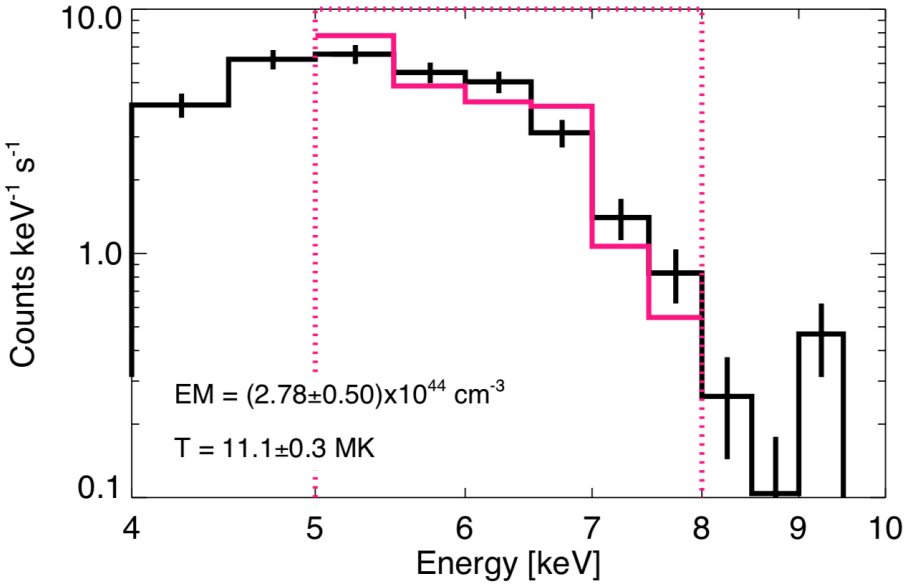
Musset et al, 2019

Complexity in a FOXSI microflare

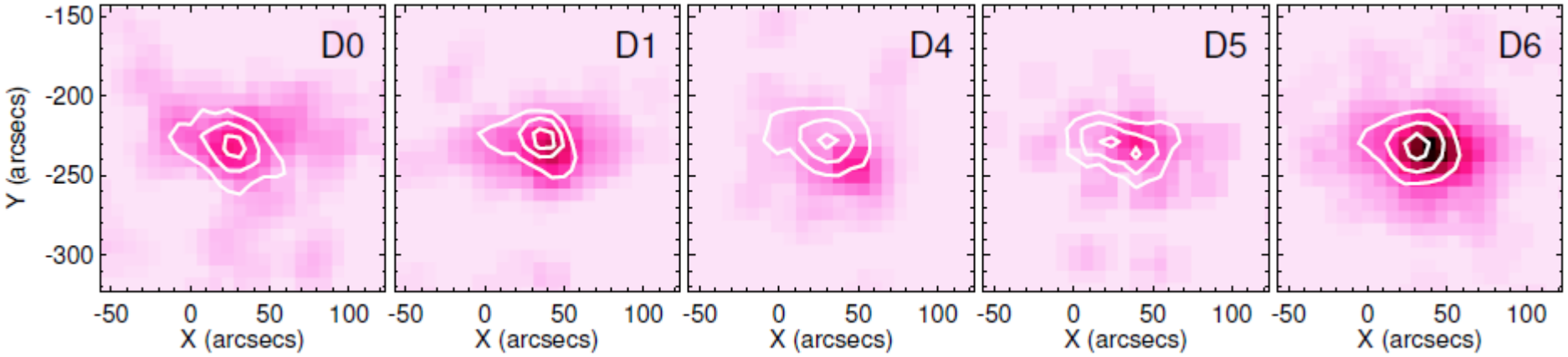
FOXSI-2 first microflare: Estimated GOES class: A0.5



Spectroscopy: Isothermal fit



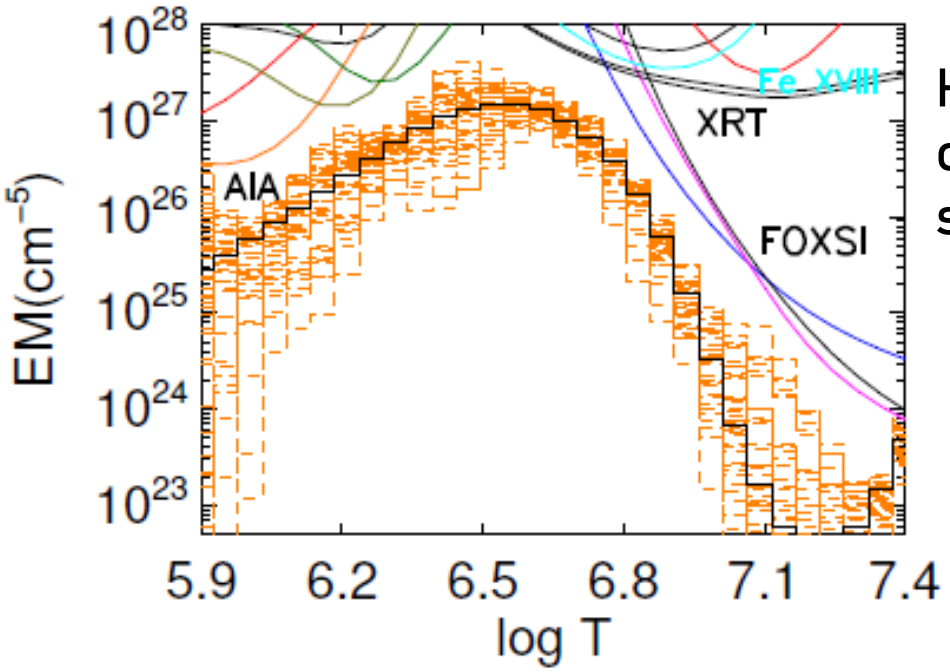
Imaging spectroscopy: Centroids at higher energy are located ~7" east of the low-energy, suggesting high temperature plasma (energy release)



Images: 4-5.5 keV
Contours: 6-15 keV

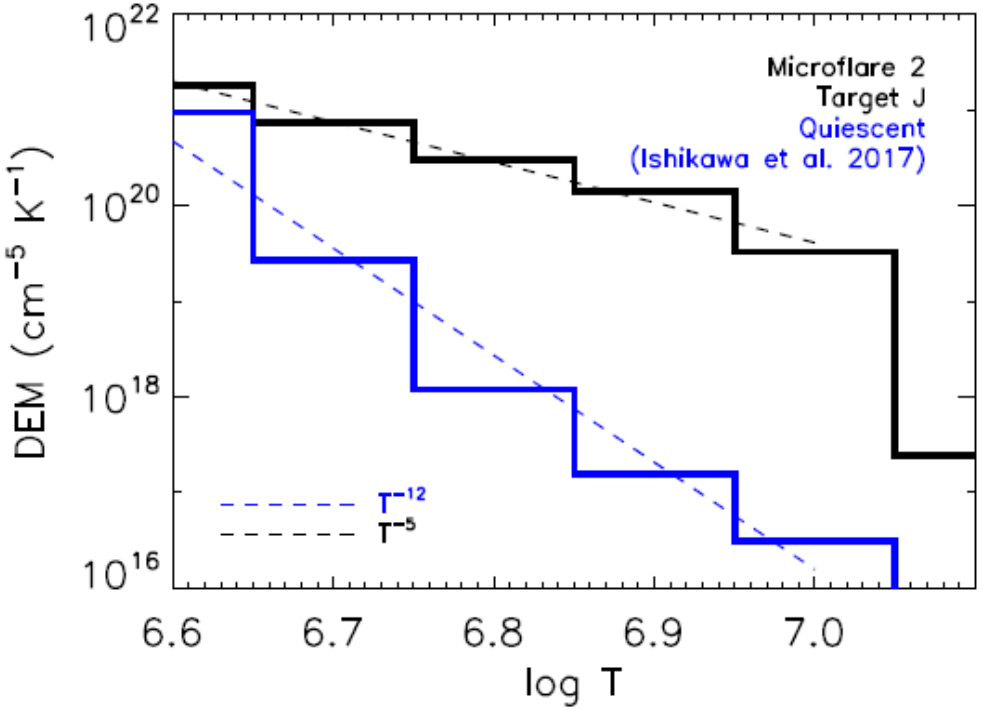
Vievering et al, in prep + thesis (2019)

Heating in FOXSI microflares



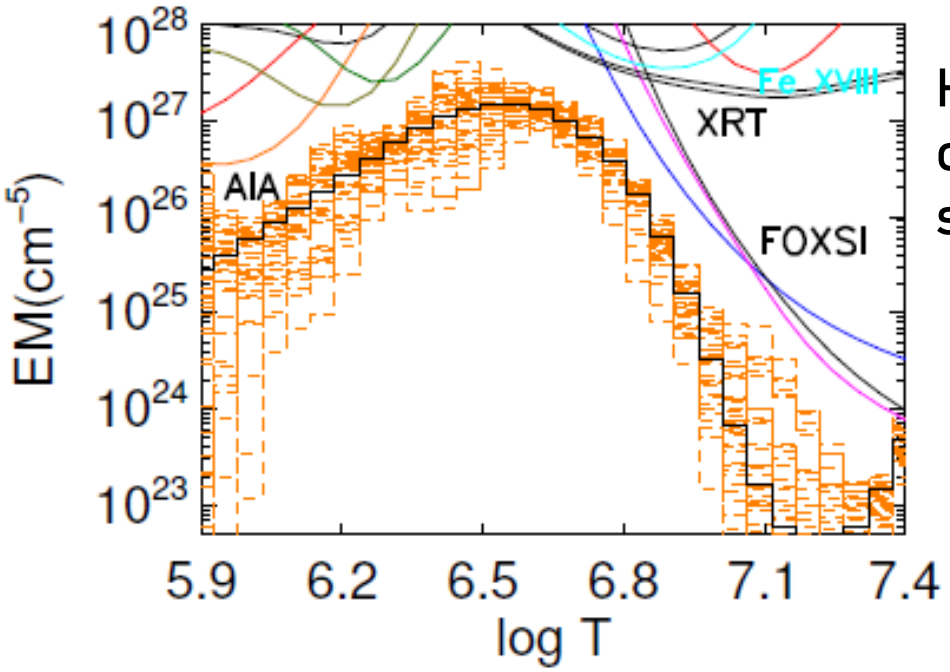
HXR are needed to constrain high-energy slope of DEMs

Microflares have excess emission above 5 MK



Athiray et al, in rev.

Heating in FOXSI microflares



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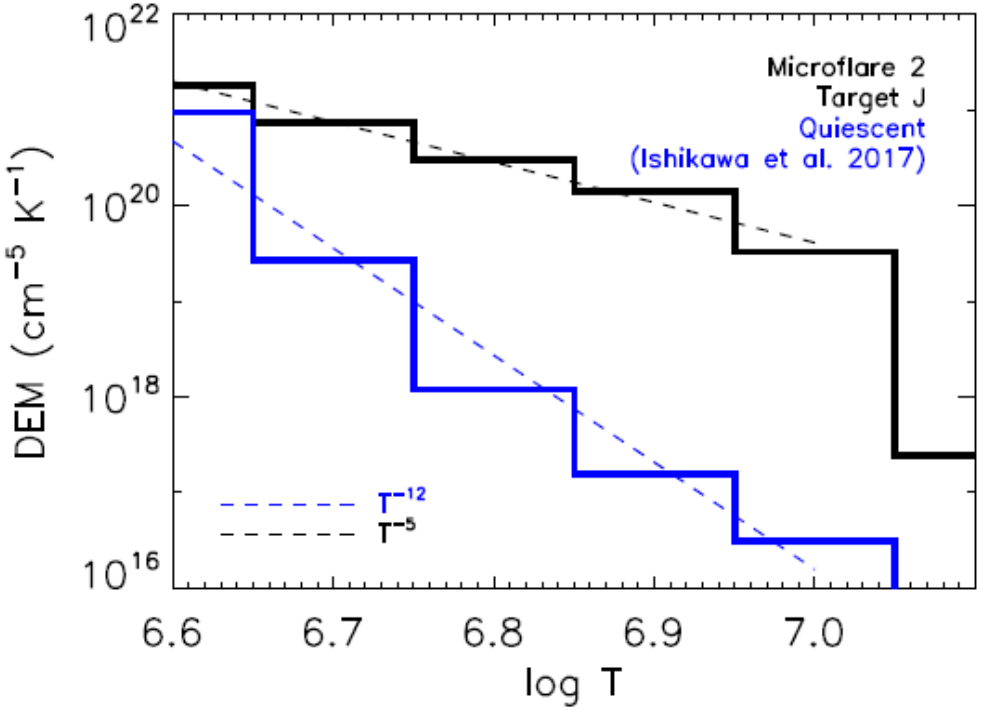


Thermal energy estimates

	Multithermal	Isothermal
Microflare 1	$5.1^{+0.6}_{-0.6} \times 10^{28}$ ergs	$1.2^{+0.1}_{-0.1} \times 10^{28}$ergs
Microflare 2	$1.6^{+0.6}_{-0.7} \times 10^{28}$ergs	$1.0^{+0.1}_{-0.1} \times 10^{28}$ergs

Athiray et al, in rev.

Multithermal DEM provides estimates of the higher thermal energy than the isothermal approximation

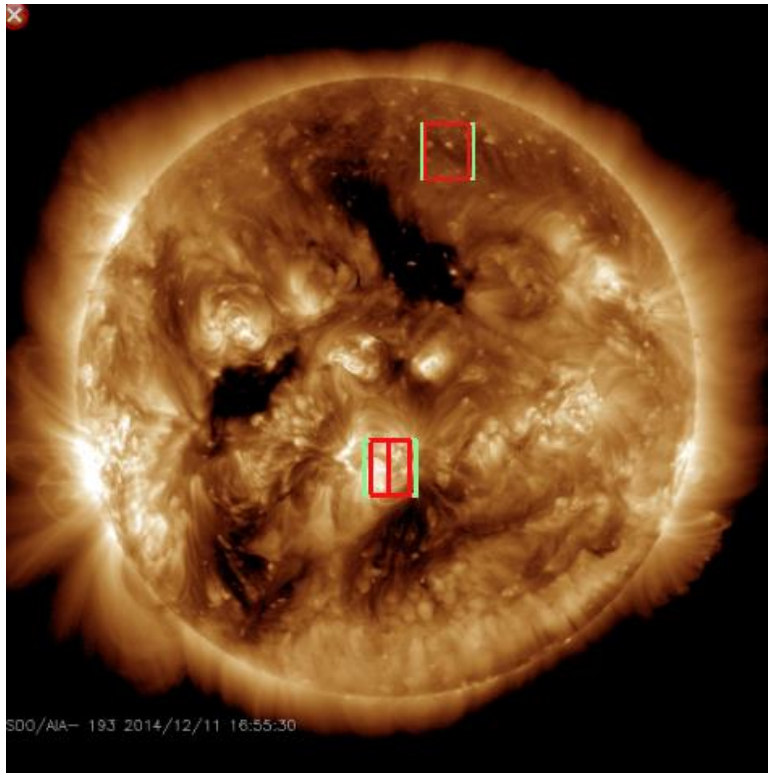
➔ Small scale energy releases are important to consider for coronal heating

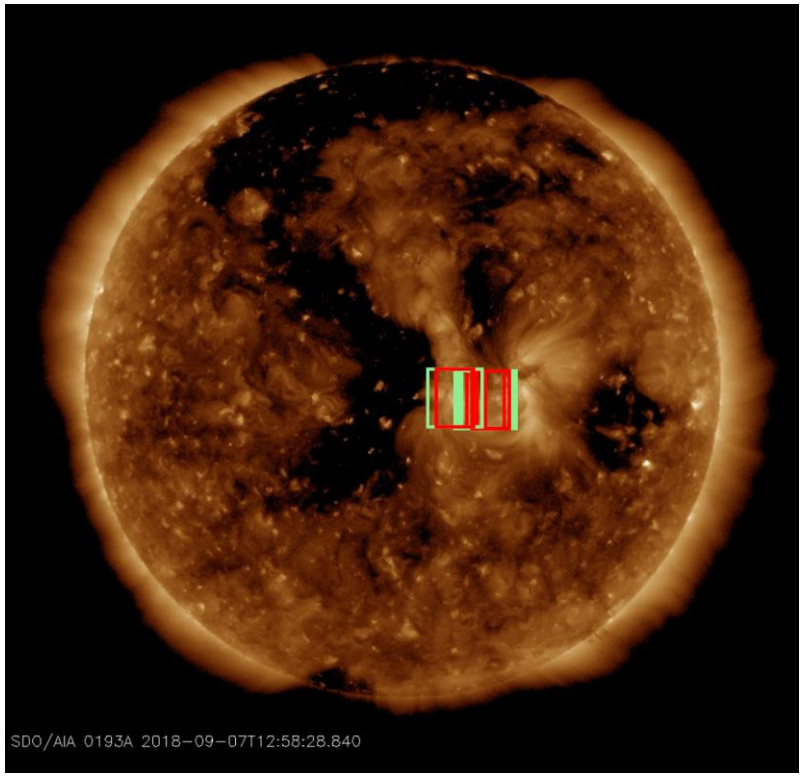
FOXSI coordination with IRIS

FOXSI-2 and FOXSI-3 were coordinated with IRIS

IRIS in raster mode, SJI filters: 1330, 1400, 2796, 2832 A

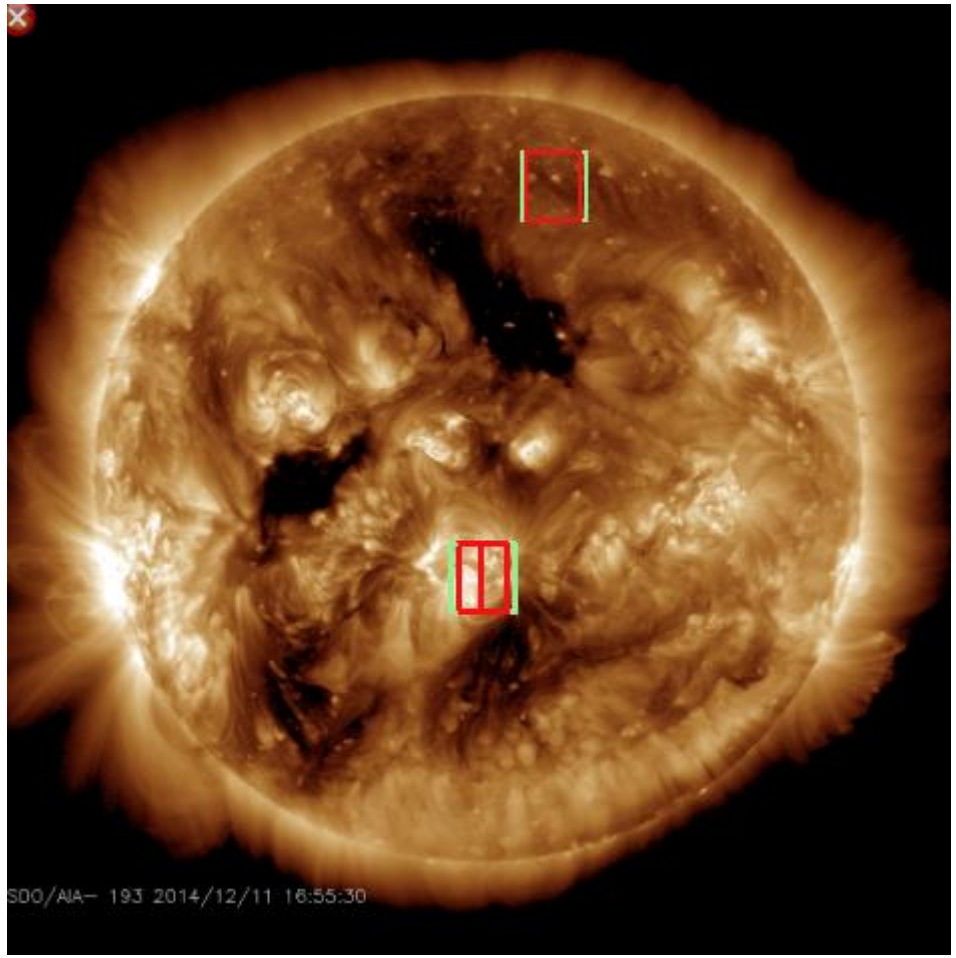
FOXSI launch windows are 1 hour-long → Repeated fast coarse scans during launch window
→ Also single dense scans before and after the launch window

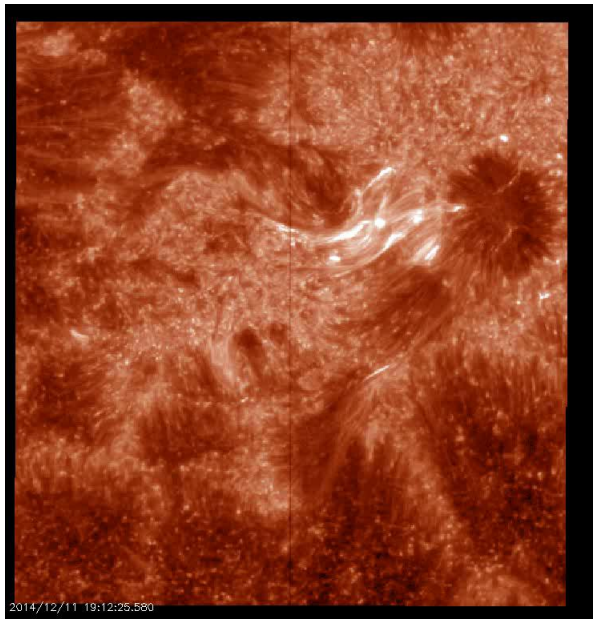


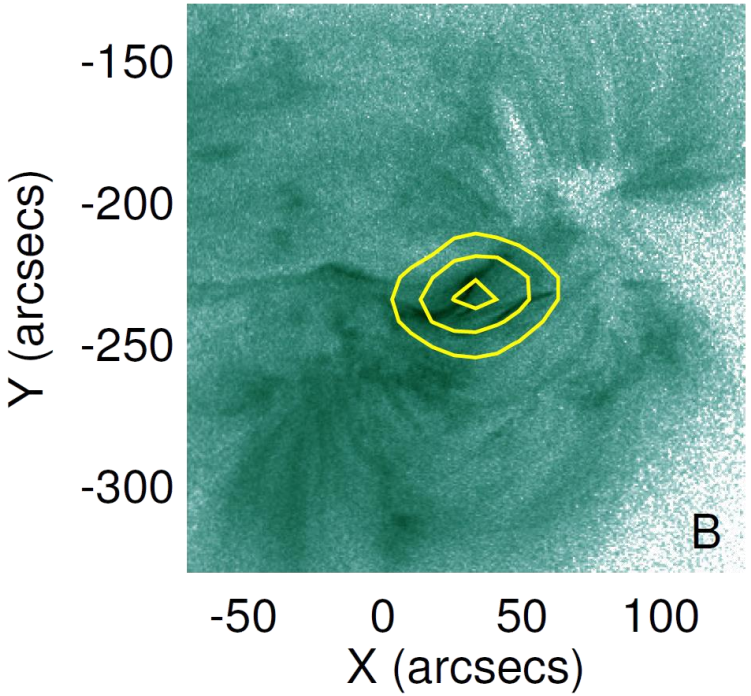


FOXSI coordination with IRIS

FOXSI-2 coordinated IRIS observations



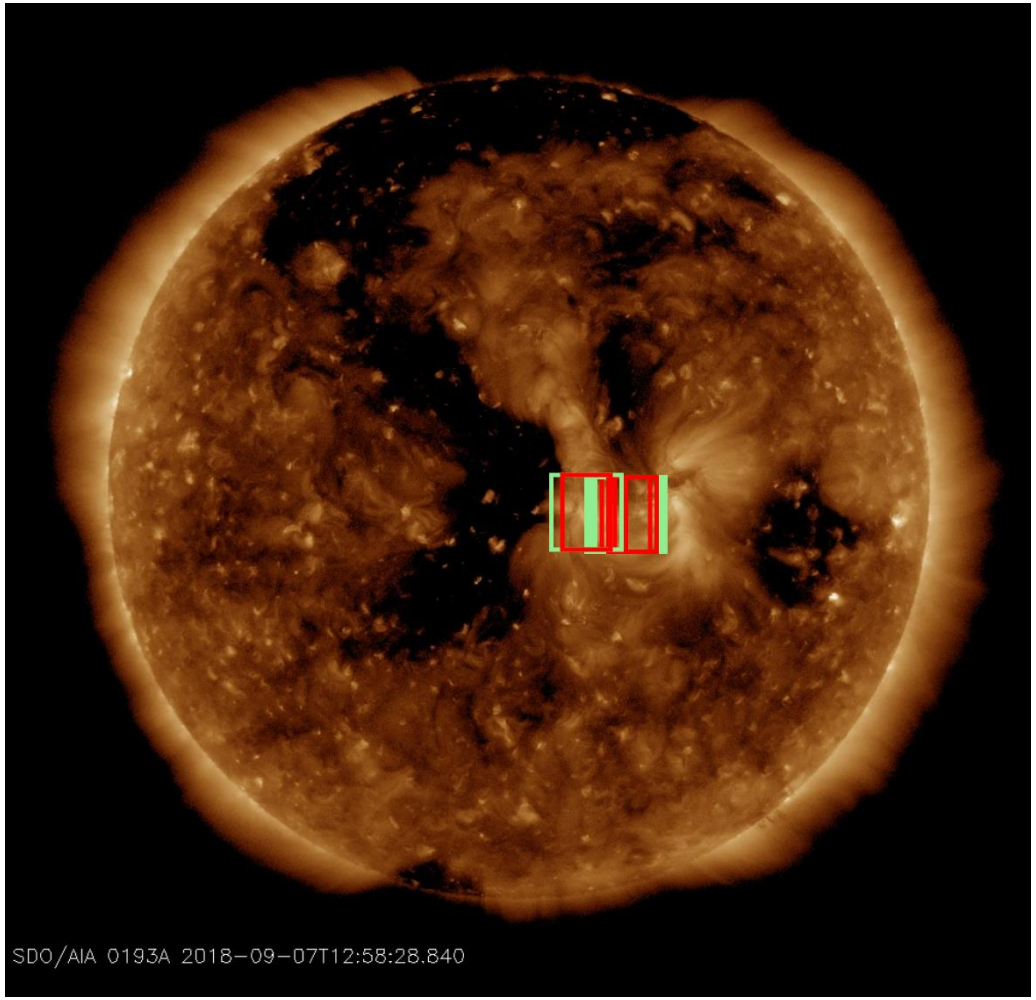


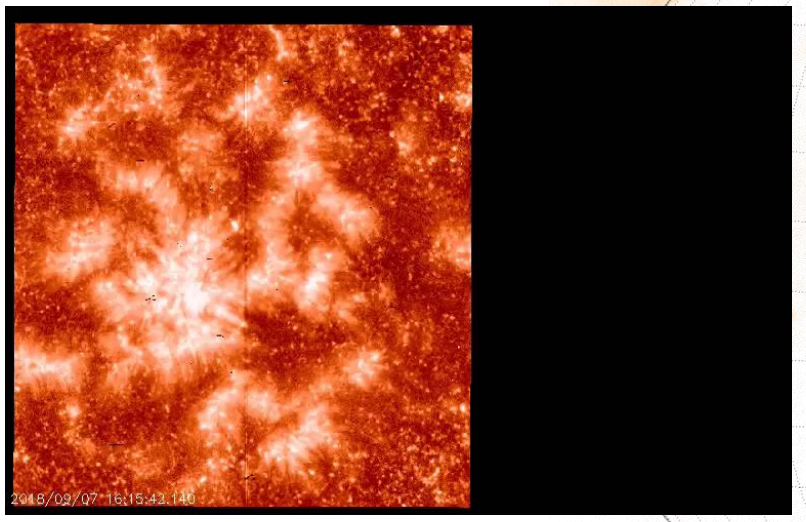


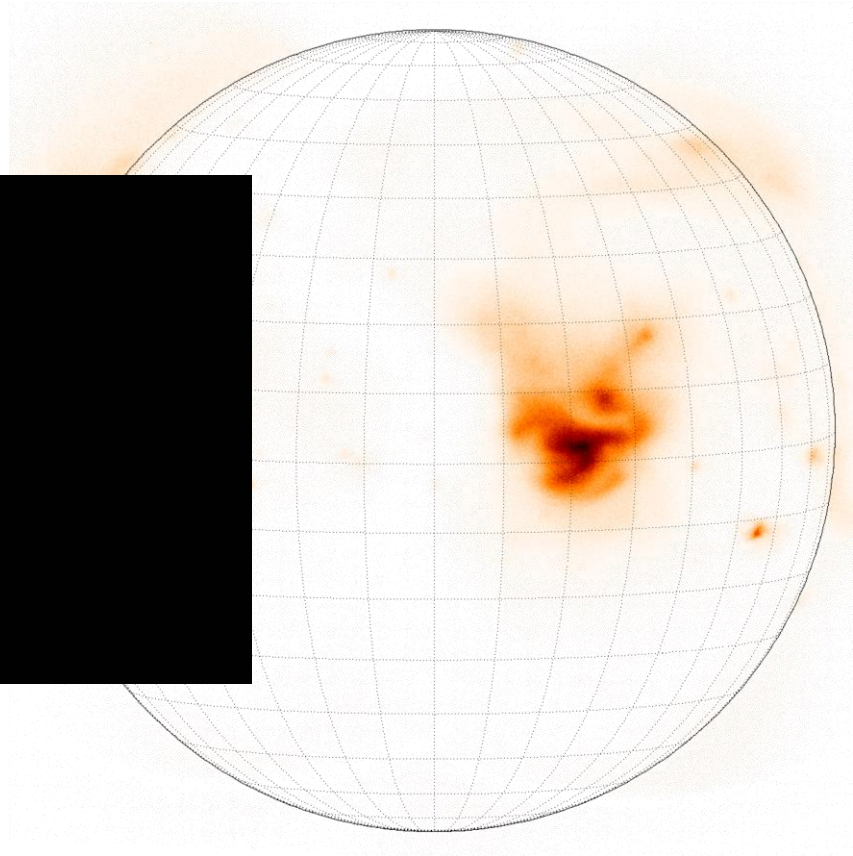
FOXSI 4-15 keV contours on AIA 94A image (Vievering, 2019, thesis)

FOXSI coordination with IRIS

FOXSI-3 coordinated IRIS observations







FOXSI coordination with IRIS

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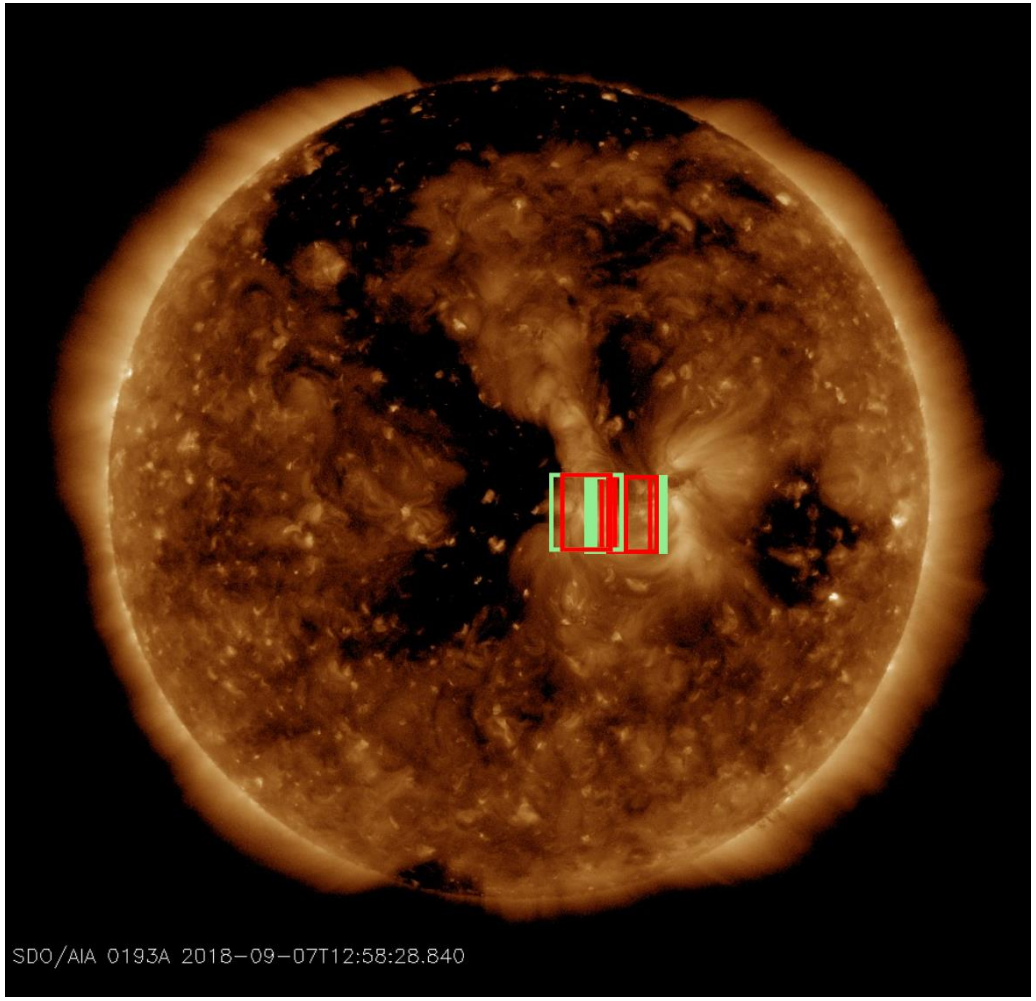

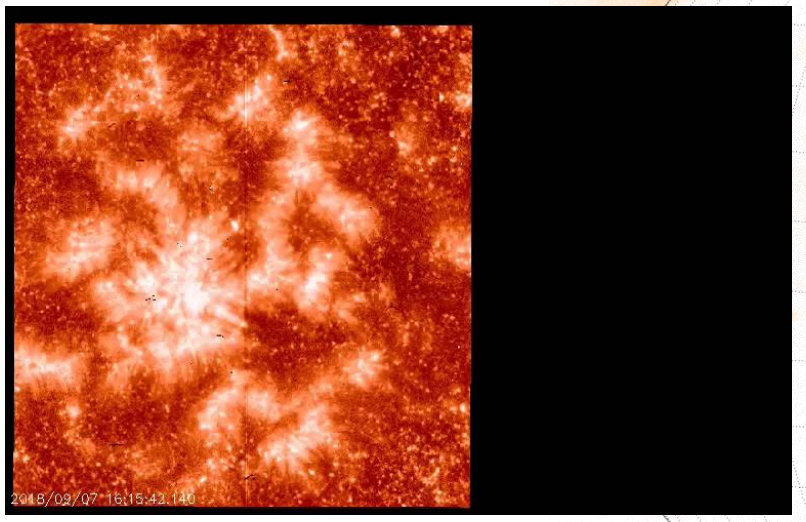

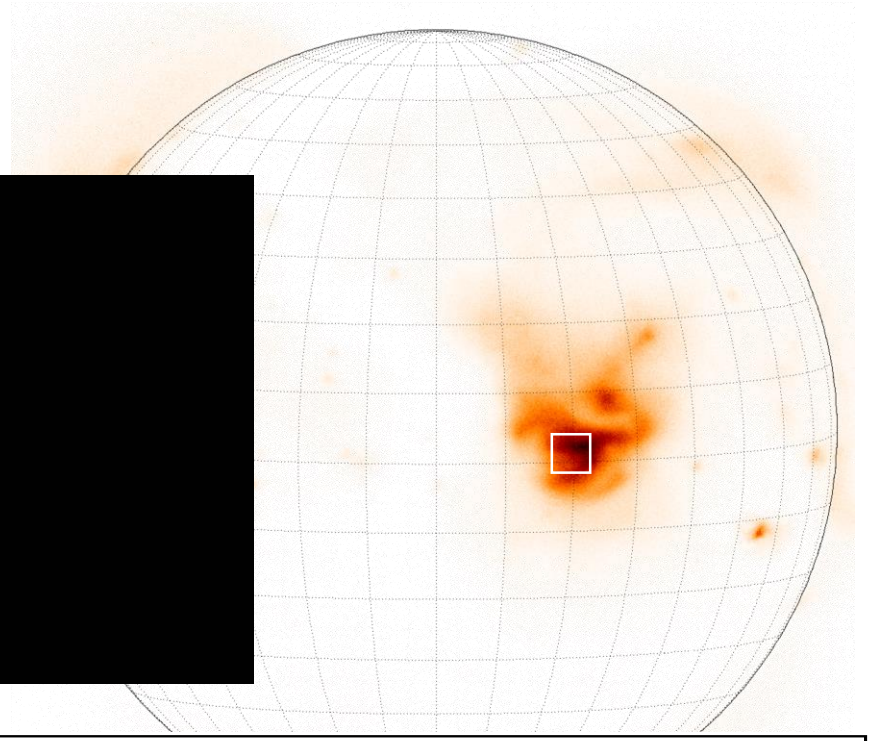

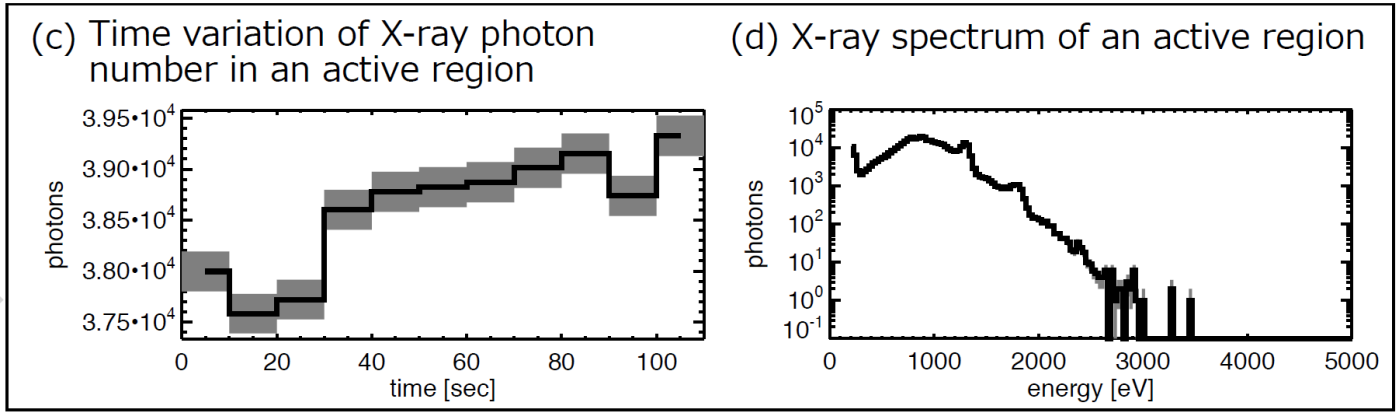

The future of FOXSI

Next challenges for solar HXR focusing telescopes:
High spatial resolution
Flare observations (> microflares)

FOXSI-4

To be proposed to NASA LCAS (today!)

PI: Lindsay Glesener, University of Minnesota

- High resolution optics
- High-rate detectors
- Flare campaign

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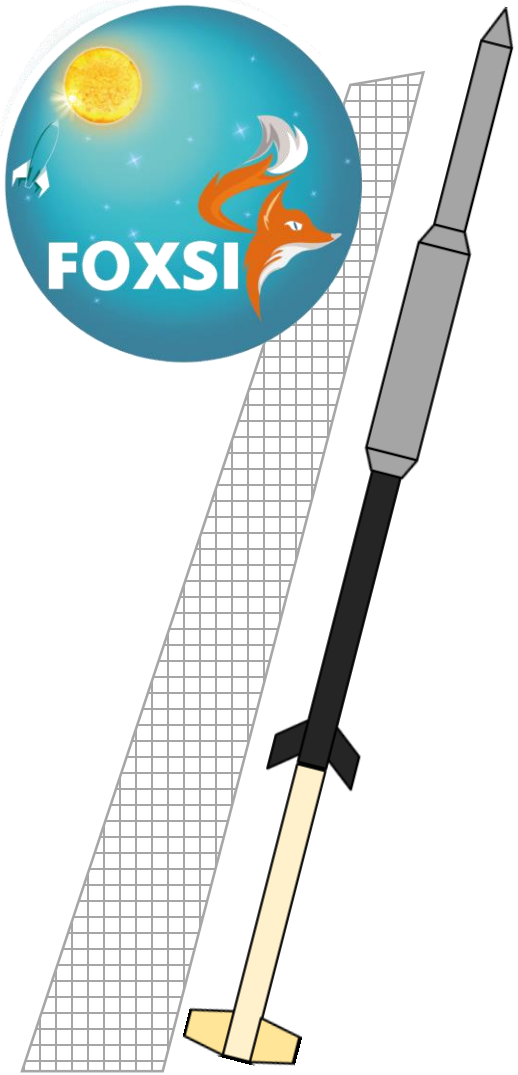
The Focusing Optics X-ray Solar Imager (FOXSI) sounding rocket demonstrated focusing X-ray imaging and spectroscopy of the Sun
+ need for a long focal length (high energies)

Fundamentals of Impulsive Energy Release in the Corona Explorer
proposed to Heliophysics MidEx in 2019
PI: Albert Shih, GSFC

→ 3 instruments:
- FOXSI-like HXR telescope
- SXR spectrometer
- EUV imager

Proposed FOXSI-4



Main FOXSI-4 developments:
- Flare campaign
- High-resolution optics

Flare campaign:

Waiting a few hours per day for 2 weeks, for a flare above C5 (detection with real-time GOES X-ray data)

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Bonus: possible coordination with another solar sounding rocket!
→ Hi-C (high resolution EUV images)

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High resolution optics:

Developed at Marshall Space Flight Center and Nagoya University

Conclusion

FOXSI sounding rocket program

- The Focusing Optics X-ray Solar Imager (FOXSI) sounding rocket demonstrated *focusing X-ray imaging and spectroscopy* of the Sun and solar *SXR photon counting*
- Science results from FOXSI observations include detection of microflare complexity and heated plasma

Next challenges of the FOXSI sounding rocket experiment:

Flare observation:
- Flare campaigns for NASA sounding rockets
- High rates

High resolution HXR imaging:
Development of polishing methods to enhance spatial resolution

Focusing optics in future solar X-ray telescopes:

- PhoENiX spacecraft: photon counting SXR imaging spectroscopy
- FIERCE: proposition for a NASA MidEx, includes a FOXSI-type telescope (2 modules)