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FOXSI Sounding rocket flights and Solar microflare observations

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Universities Space Research Association
NASA Marshall Space Flight Center

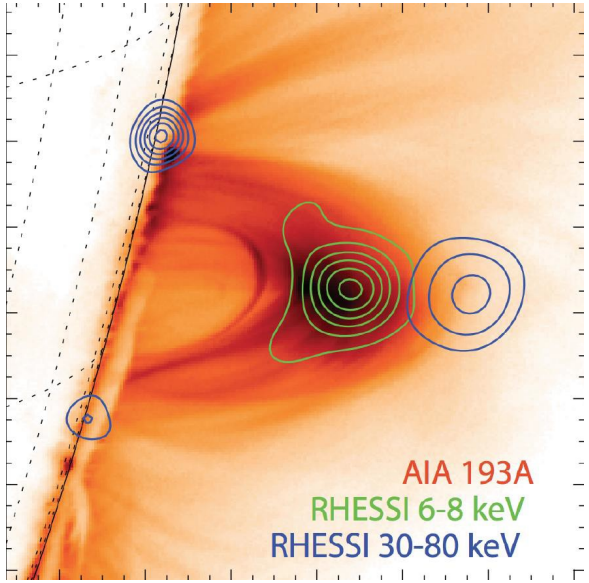
5th Asia Pacific Solar Physics Meeting

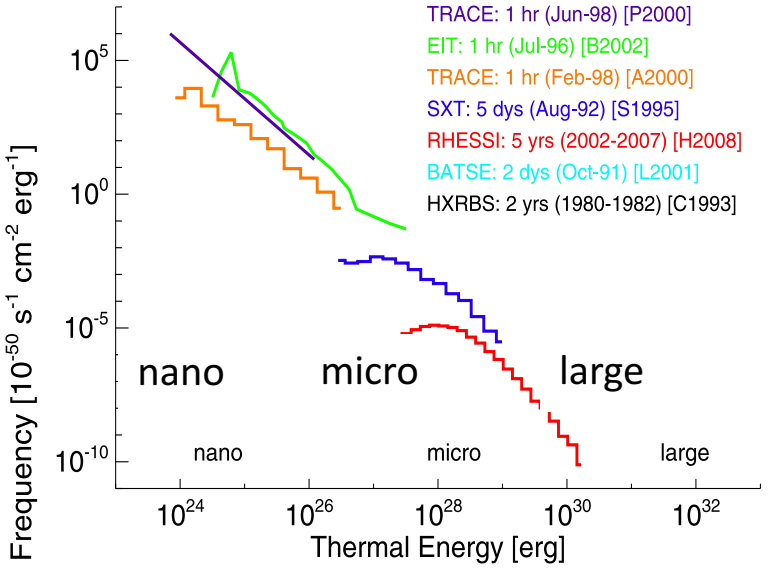
Pune, 5 Feb 2020

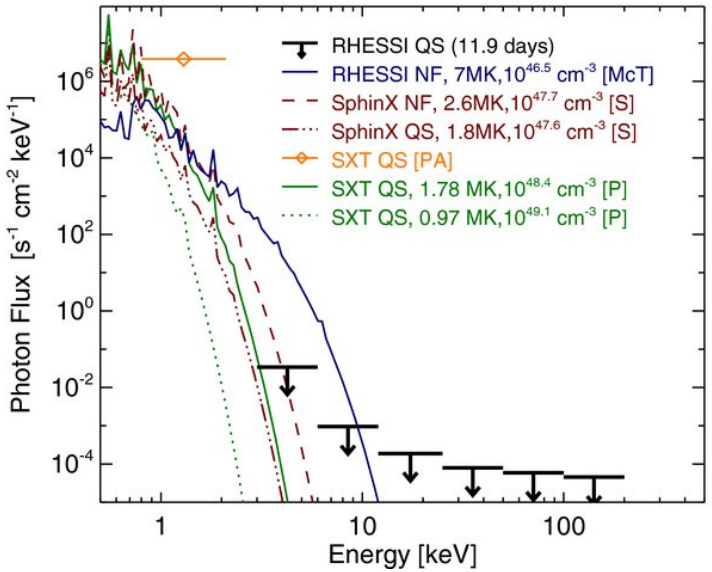
Outline

- Overview of FOXSI sounding rocket experiment
- Successful Flight campaigns and coordinated FOXSI-2 microflare observations
- Temperature response functions for FOXSI-2
- Combined **Differential Emission Measure** (DEM) analysis - to determine the amount of plasma in the line of sight that emits the radiation as a function of temperature
- Estimates of thermal energy
- Summary

High-energy aspects of the Sun beyond RHESSI







Lingering questions…

Where and how does particle acceleration occur?

What is the role of small-scale energy release in heating coronal plasmas?

How quiet is the Sun in HXRs?

Need for…

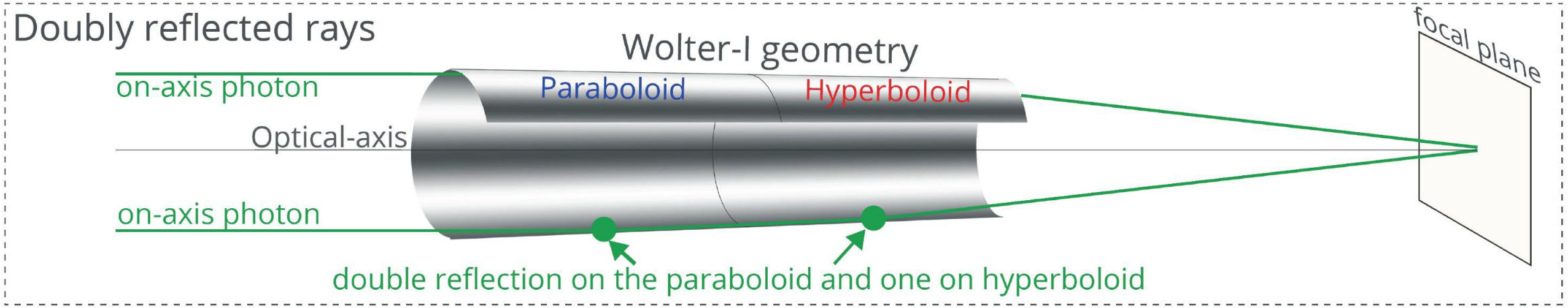
Better sensitivity

Increased imaging dynamic range

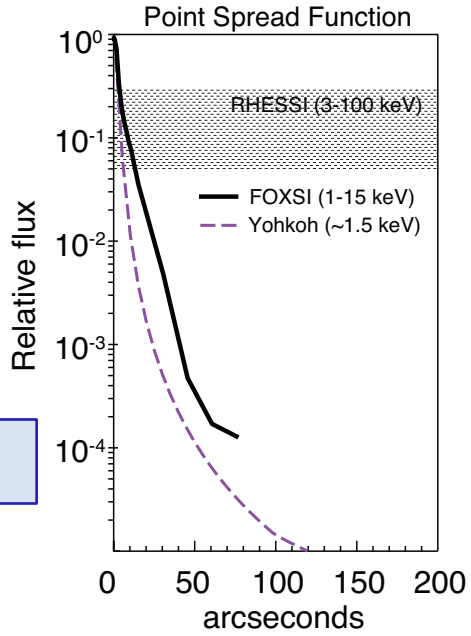
Fine time resolution

Focusing Optics X-ray Solar Imager (FOXSI)

First solar dedicated Hard X-ray (HXR) telescope with direct focusing optics

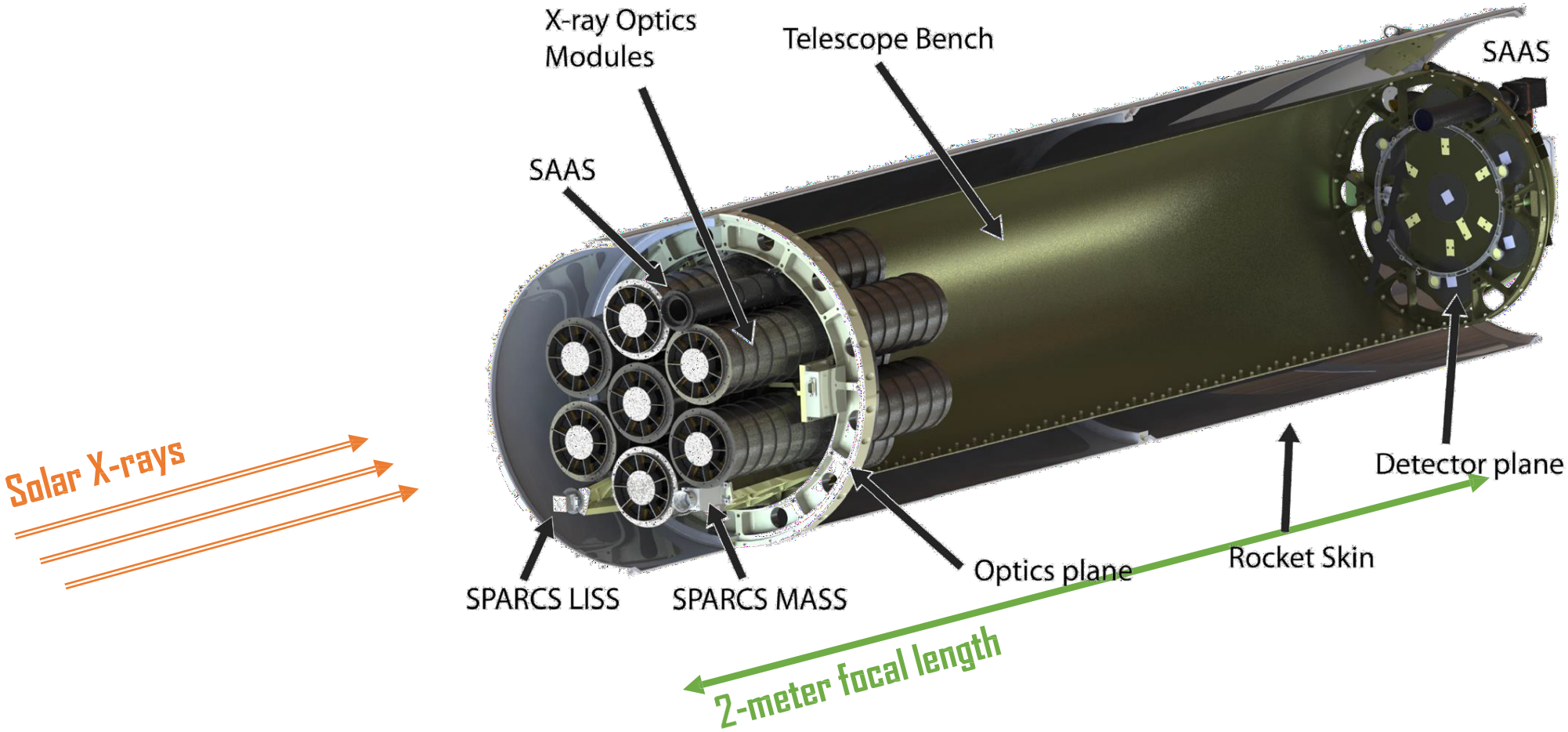


1. Photons are collected on a small volume for – **high Signal to Noise**
2. Point spread function falls steeply, providing improved dynamic range.



Main Goal of FOXSI: Demonstrate use of focusing optics for observing the Sun in hard x-rays

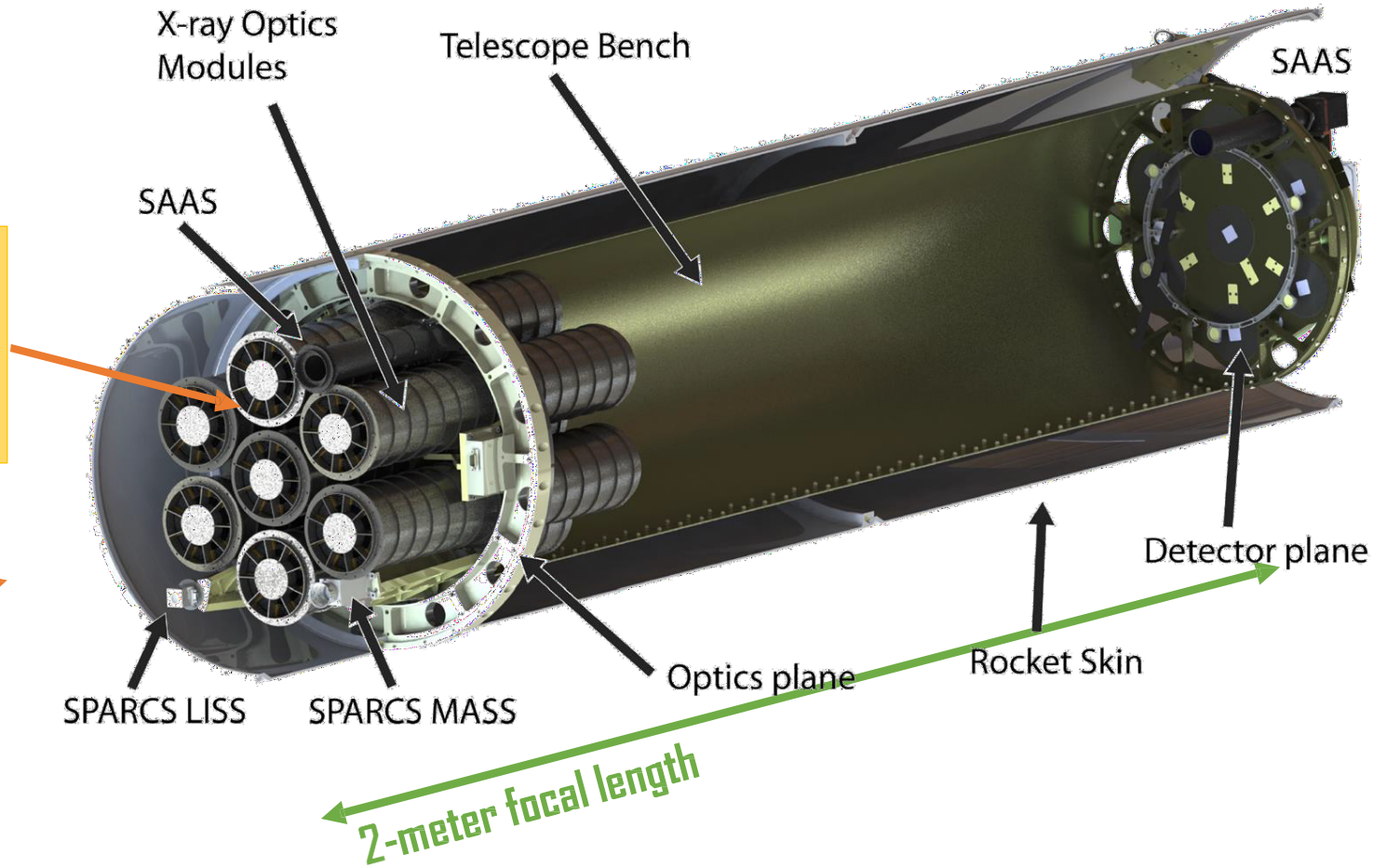
FOXSI sounding rocket experiment



FOXSI sounding rocket experiment

- Replicated Ni optics
- Wolter-I shape
- Nested sets of 7 or 10
- FWHM ~5”

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

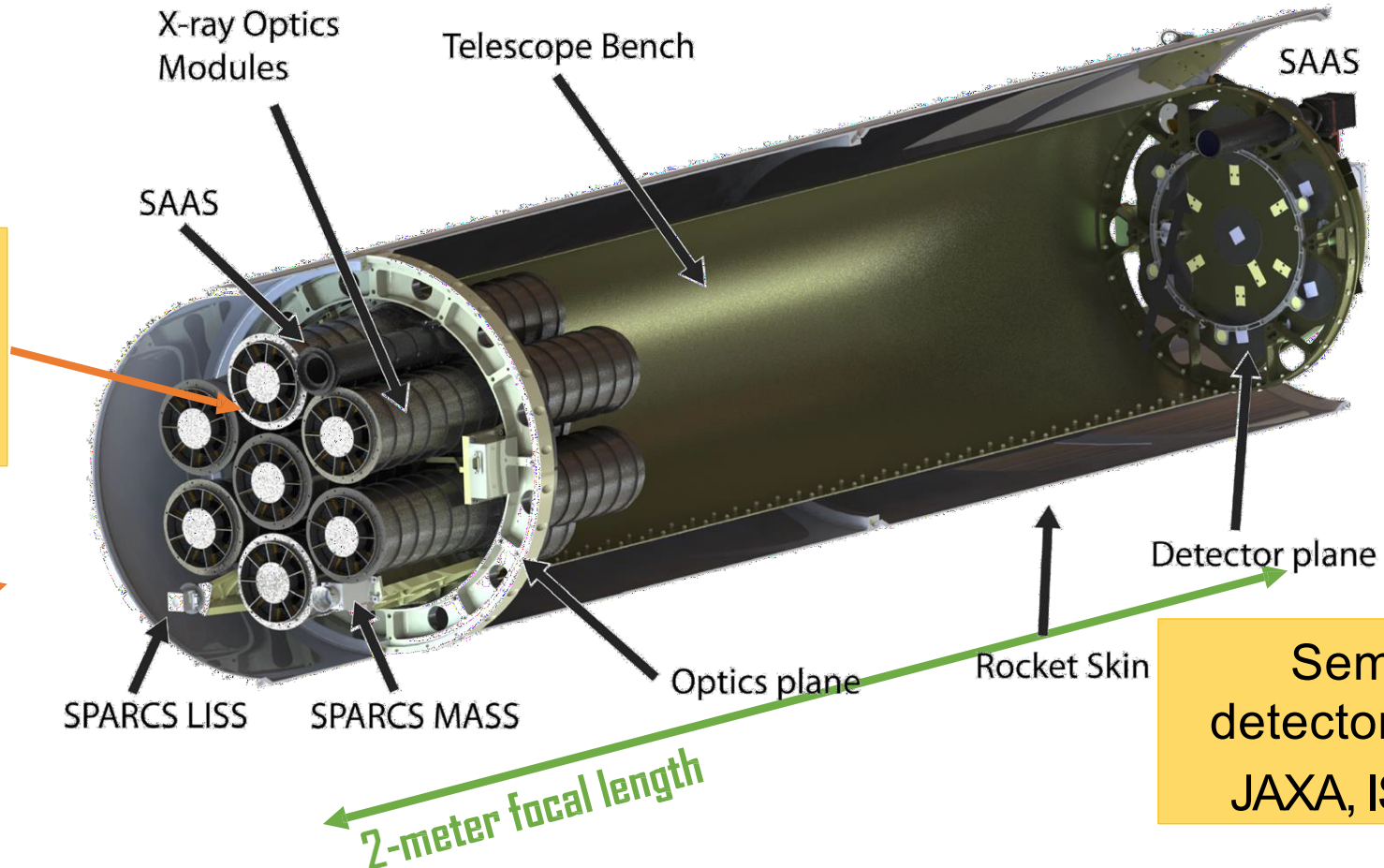


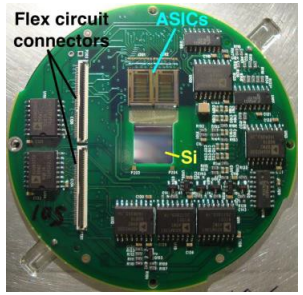
Krucker et al, SPIE, 2013
Christe et al, 2015
Buitrago-Casas et al, 2017

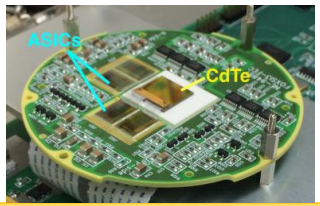
FOXSI sounding rocket experiment

Energy range : 4 to 20 keV

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







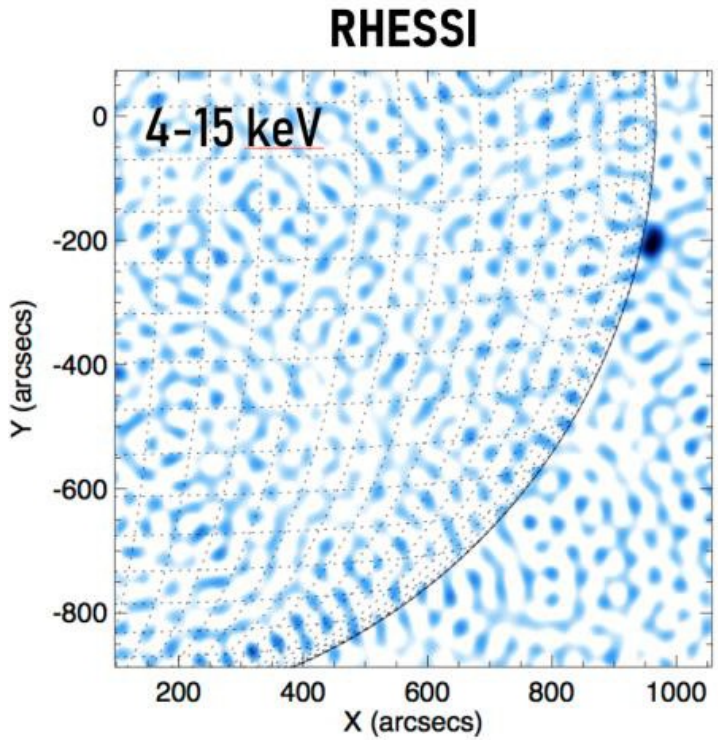
Semi-conductor detectors (Si and CdTe), JAXA, ISAS, Kavli IPMU

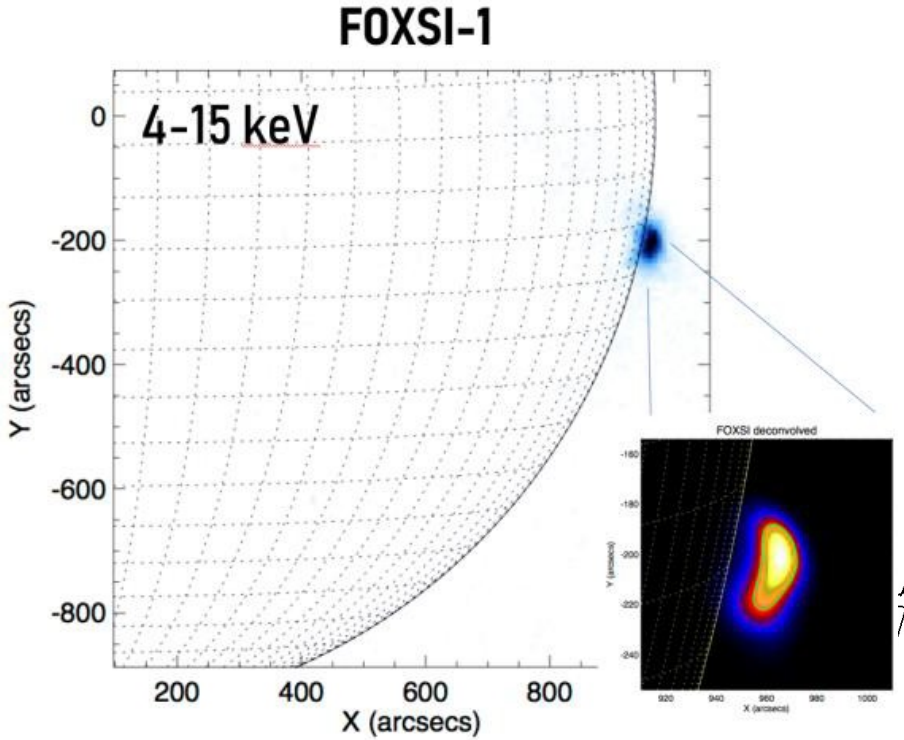
- Double-sided Si or CdTe strip detectors
- Read out by low-power, low-noise ASICs

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





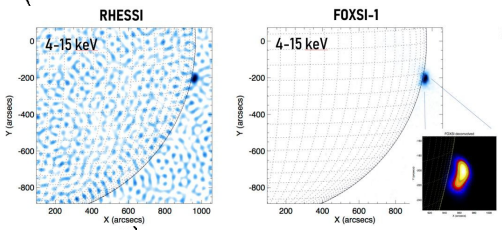
FOXSI-1 (2012)
First focused image of the solar HXR

Krucker et al, 2014
Ishikawa et al, 2014

★ White Sands Missile Range

FOXSI sounding rocket: past campaigns

Major upgrades:
Additional optic shells, CdTe detectors



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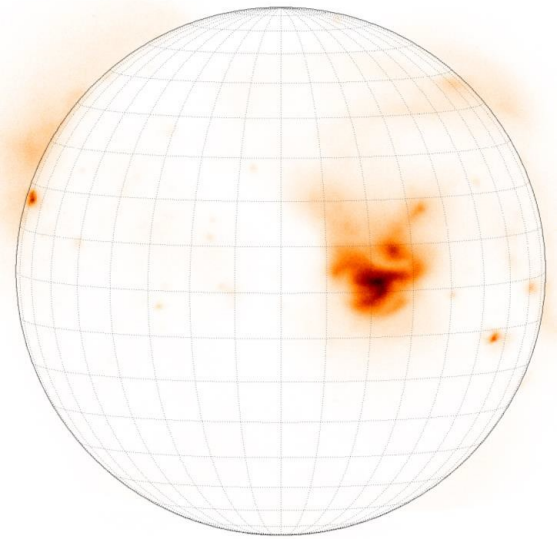
Ishikawa et al, Nature Astronomy, 2017
Athiray et al, ApJ (in revision)
Vievering et al, in prep

FOXSI-2(2014)
1. Observation of quiet ARs
2. Two microflares, an order of magnitude fainter than previous observations

FOXSI sounding rocket: past campaigns

Major upgrades:
SXR detector
Collimator



Major upgrades:
Additional optic shells, CdTe detectors

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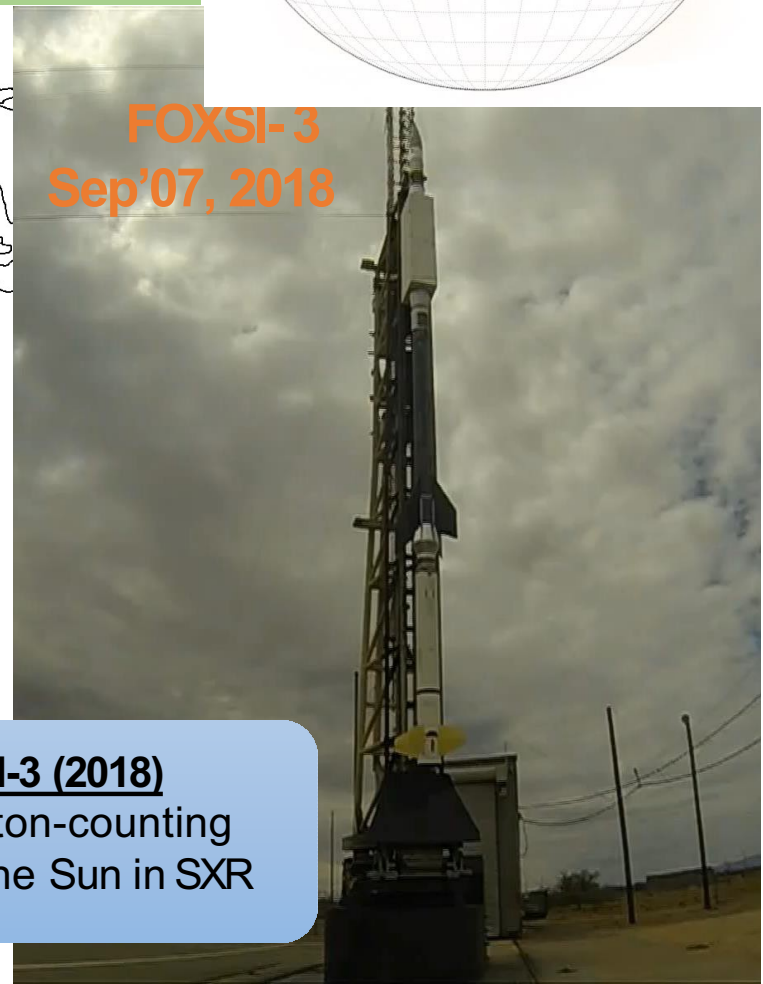

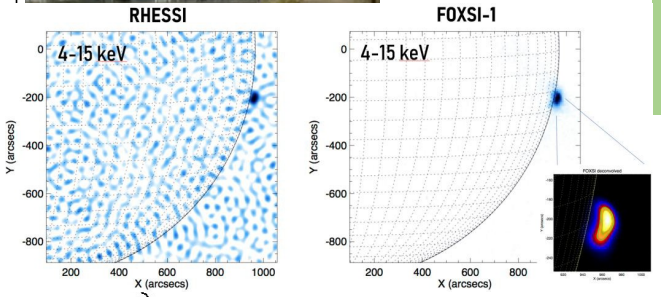

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Vievering et al, in prep

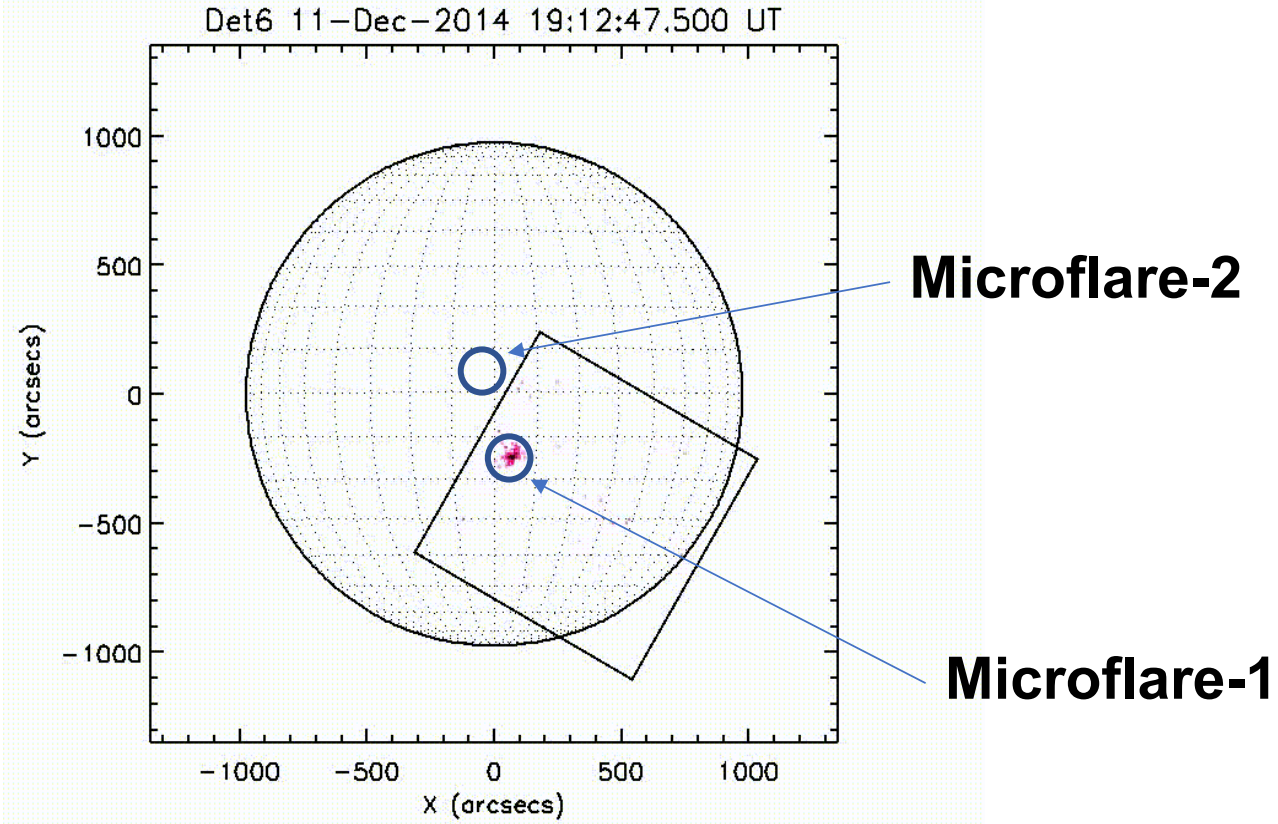
FOXSI-3 (2018)
First photon-counting image of the Sun in SXR

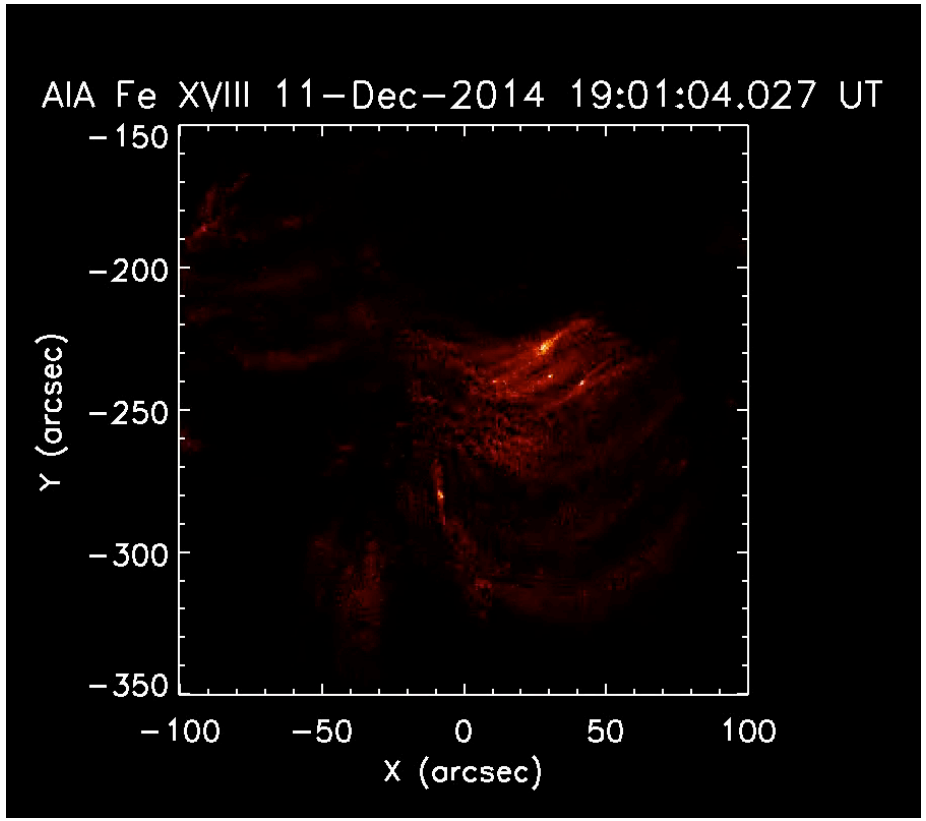
Musset et al, 2019

Solar microflares with FOXSI-2 rocket

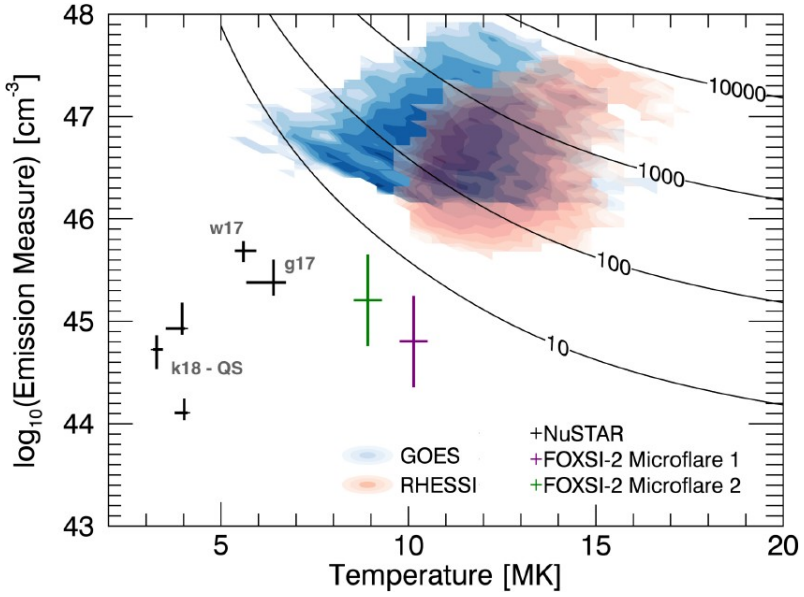
Observations during second flight ~(6.5mins)

- **Two solar microflares**
- Coordinated observations : Hinode/XRT, SDO/AIA, IRIS, VLA



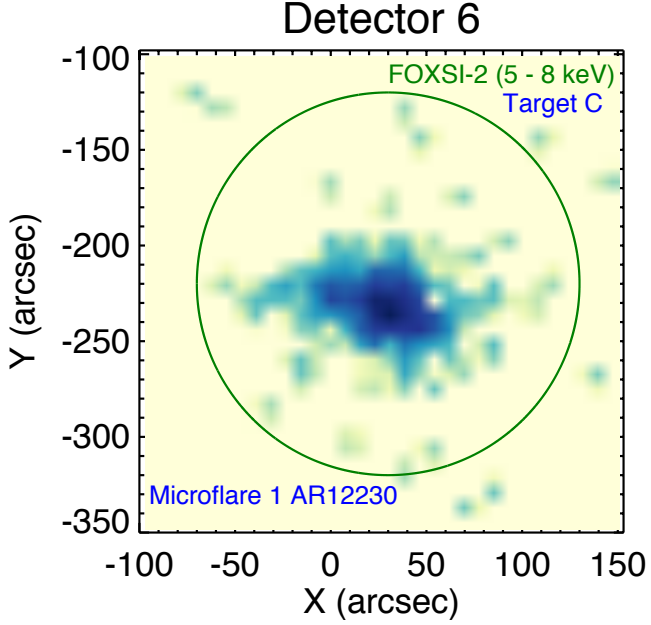


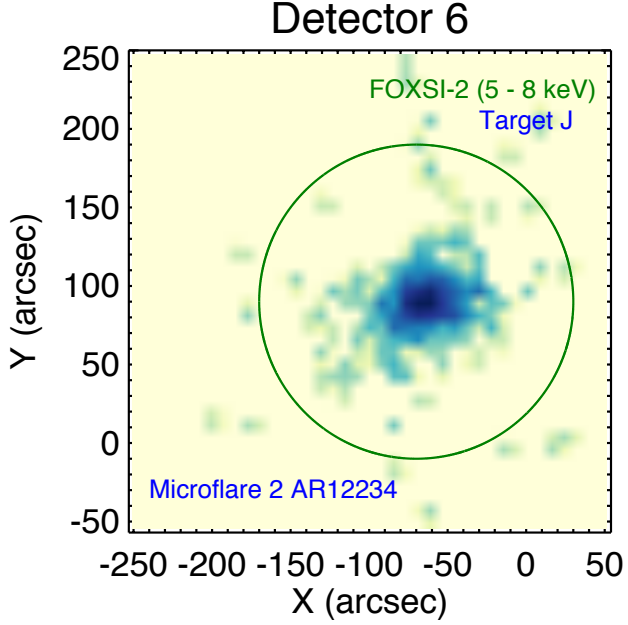
FOXSI-2 microflares

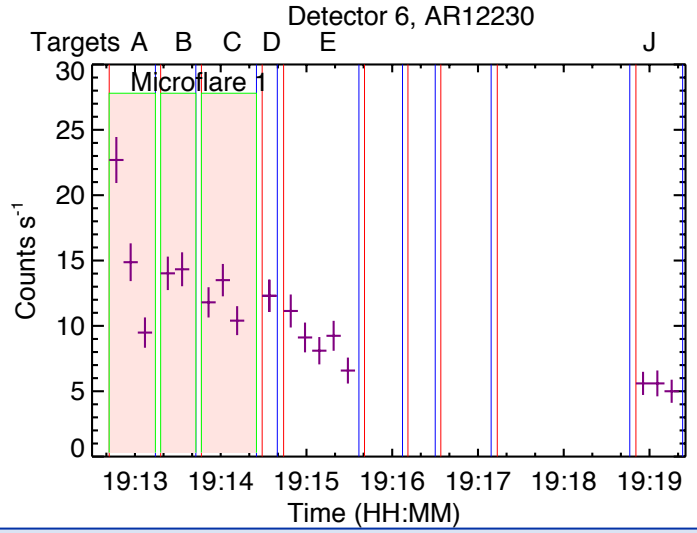


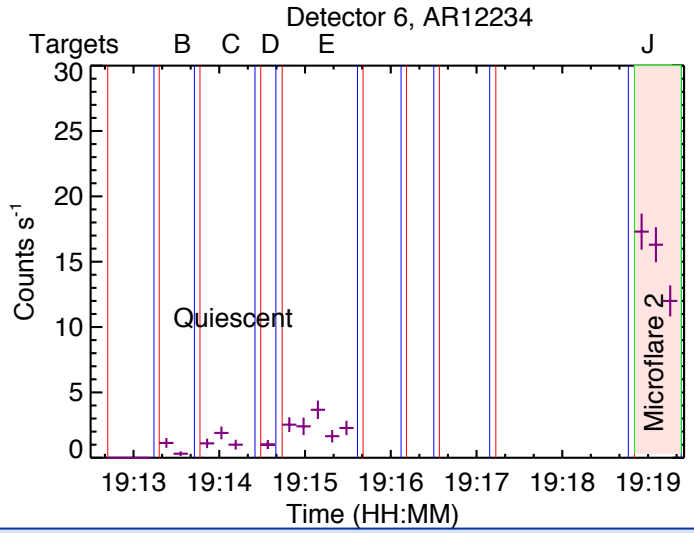
Vievering (2019, Phd Thesis)

Background subtracted GOES X-ray flux indicate sub A-class microflares





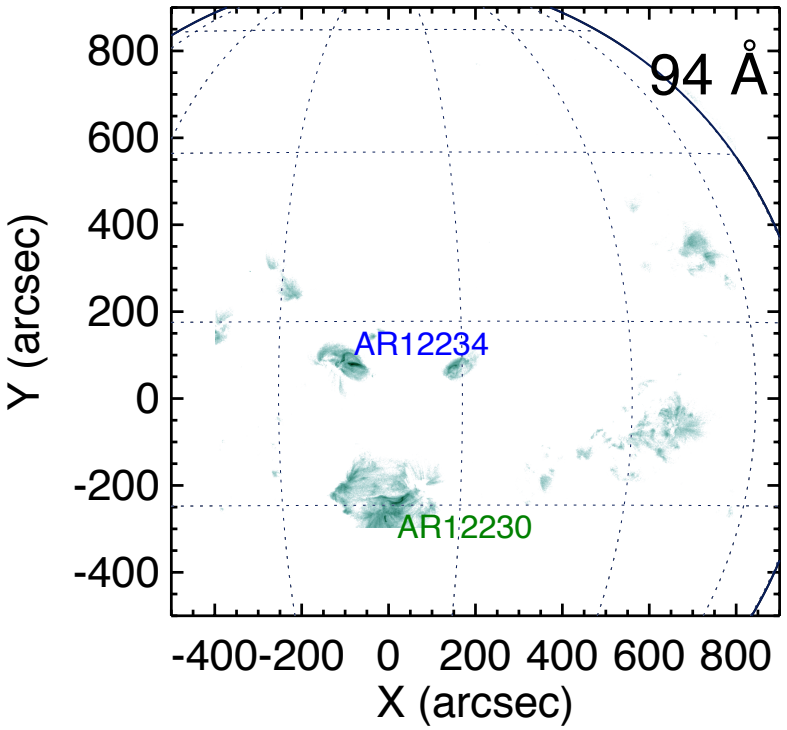




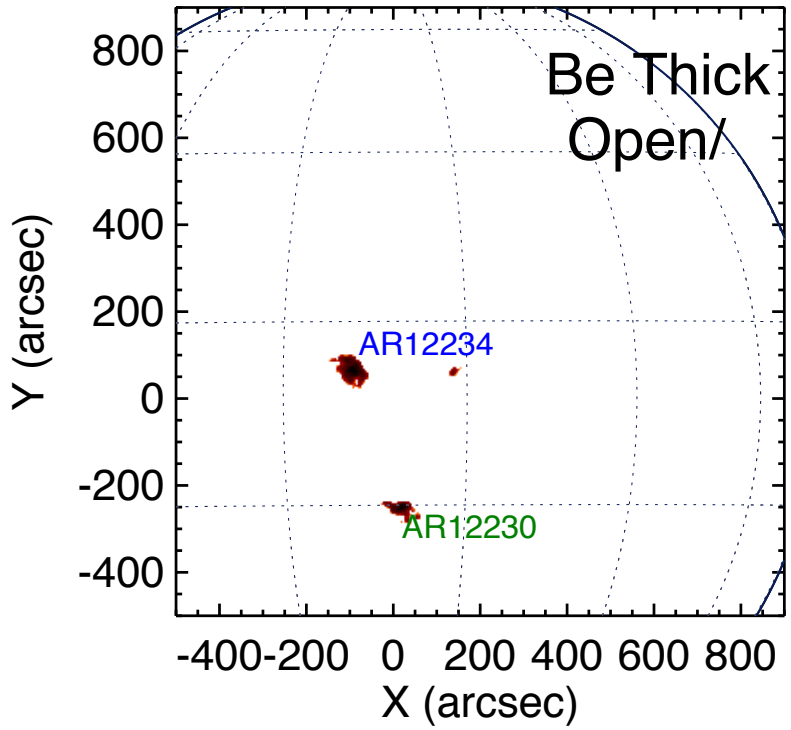
- FOXSI allows us to image **an order of magnitude fainter microflares** than observed by solar X-ray instruments

Data summary for DEM analysis

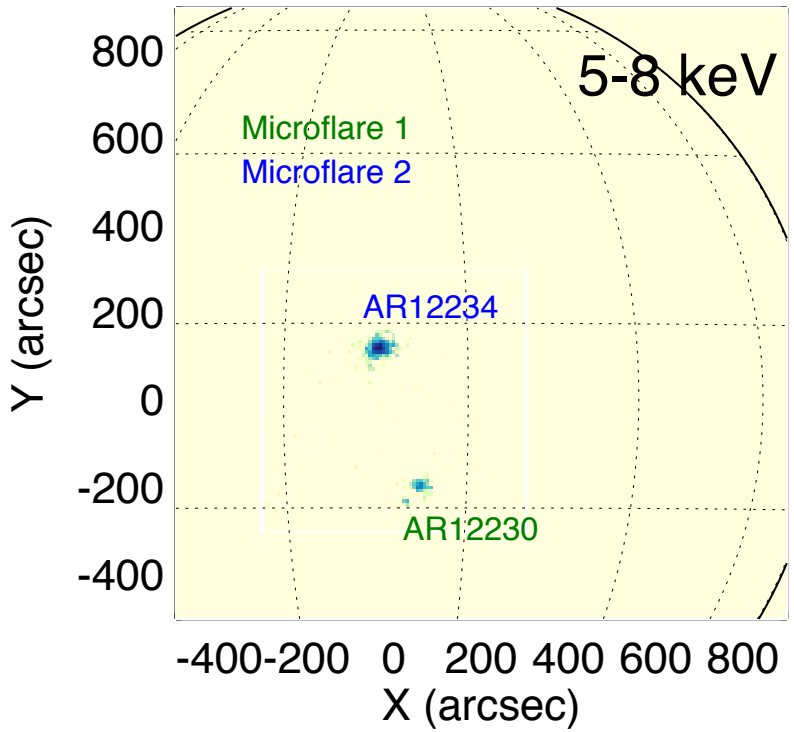
SDO/AIA



Hinode/XRT



FOXSI-2 (Detector 6)



EUV (5 Channels)

SXR (9 filter combinations)

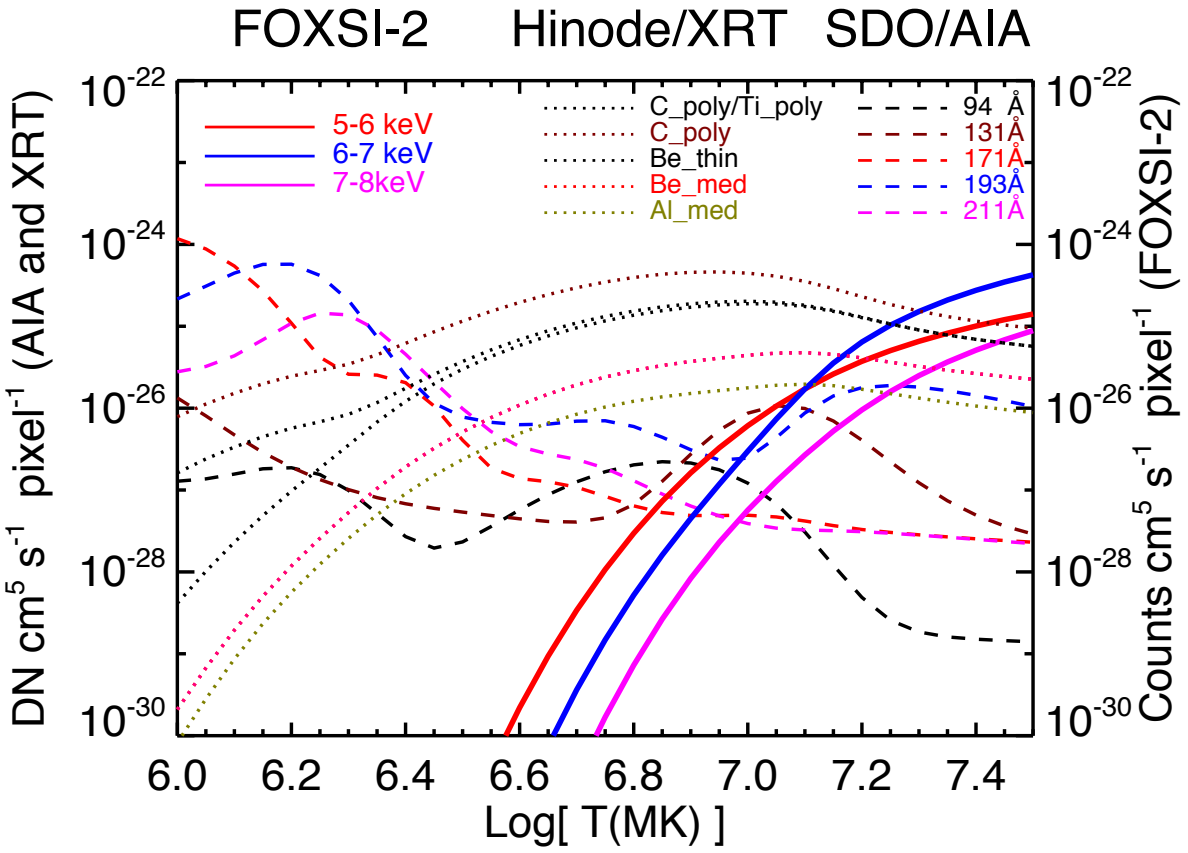
HXR (5 to 8 keV)

- Brightening in EUV, SXRs and HXRs clearly suggest a multi-thermal plasma
- **Unique dataset** suitable for “Differential Emission Measure analysis”

Temperature response function

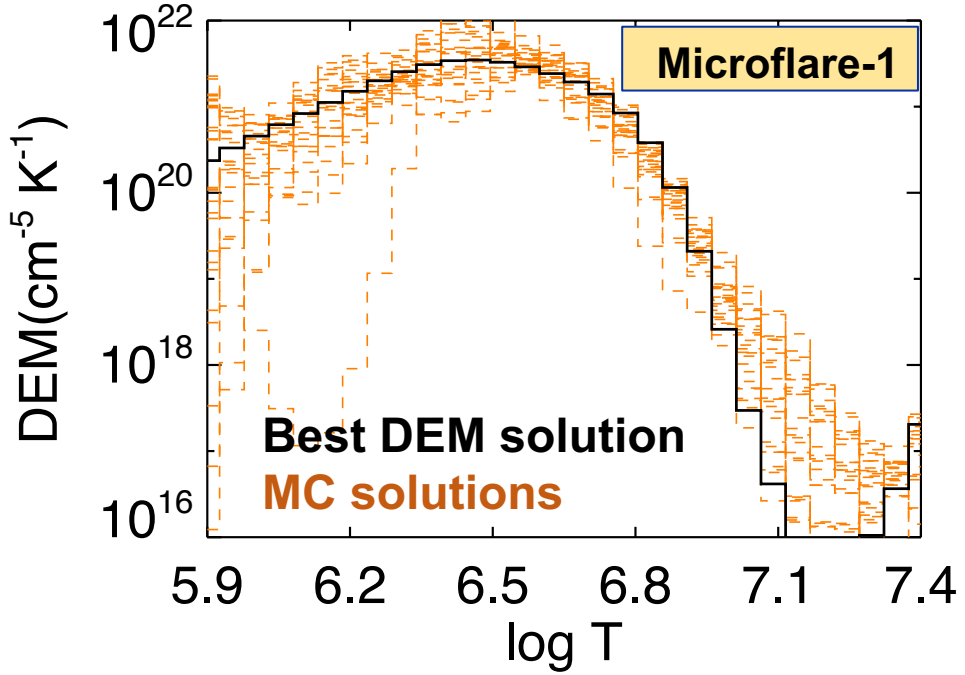
Instruments' ability to detect plasma at different temperatures

- AIA & XRT - Standard solar soft routines
- FOXSI-2
  1. **Instrument response** : Optics effective area, Detectors spectral response matrix, Thermal blankets
  2. **Synthetic Solar spectrum** at different isothermal temperatures (1 to 30 MK)
  3. **Temperature response** is created by folding the synthetic spectra through instrument response to get the expected counts



- FOXSI is sensitive to temperatures > 5 MK
- Good overlap in temperature sensitivity for all the instruments

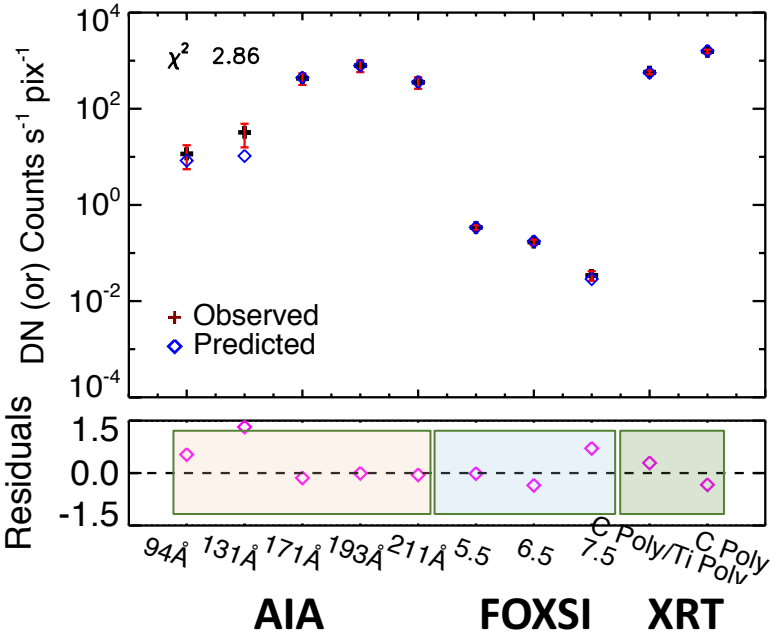
Note: Pixel sizes are different for each instrument

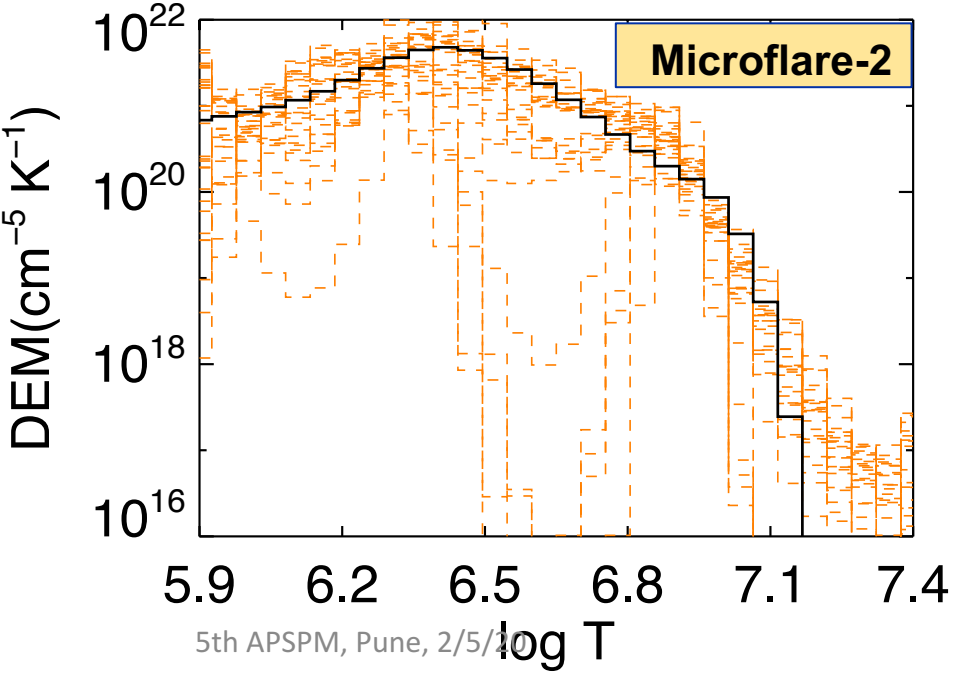


Combined DEM analysis

$$\text{Flux}_i = \text{Response}(T_{i,j}) \cdot \text{DEM}(T_j)$$

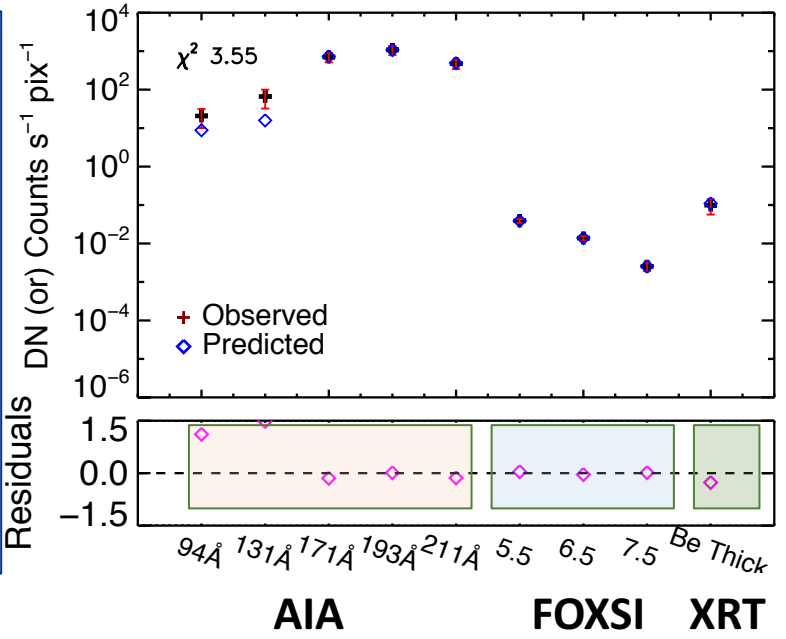
unknown



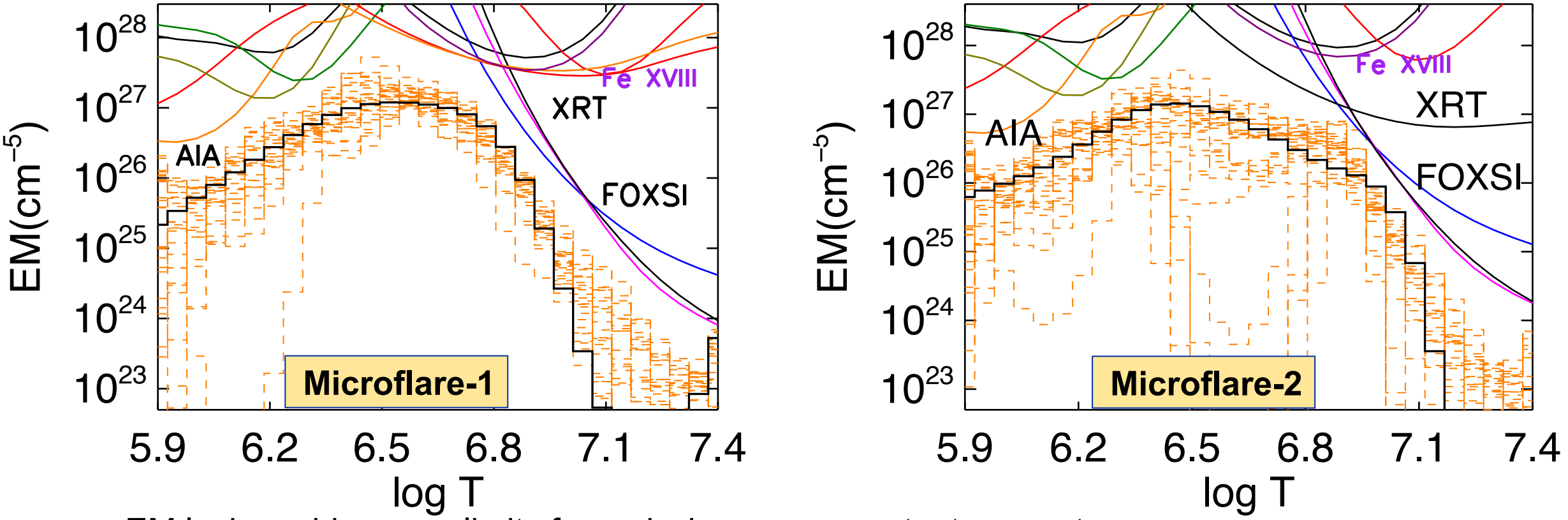


Hinode-XRT DEM inversion

- Forward fitting using non-linear least squares
- Monte Carlo simulations to emulate errors



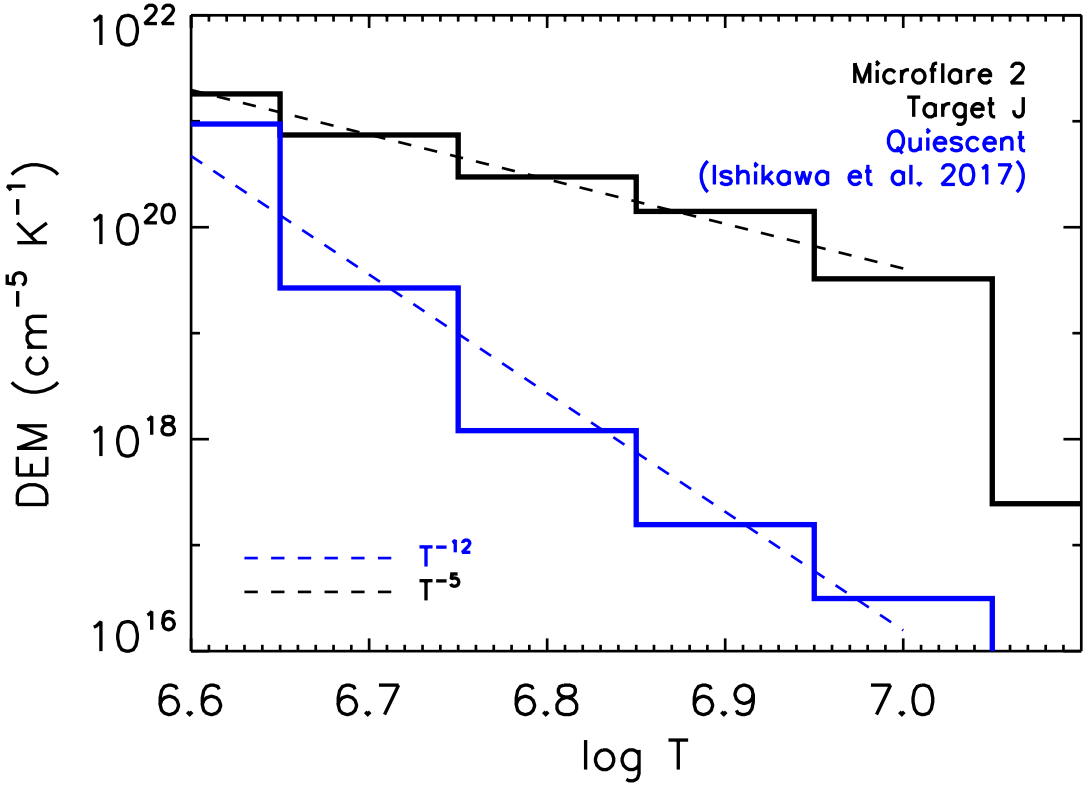
Combined DEM analysis : EM loci curves

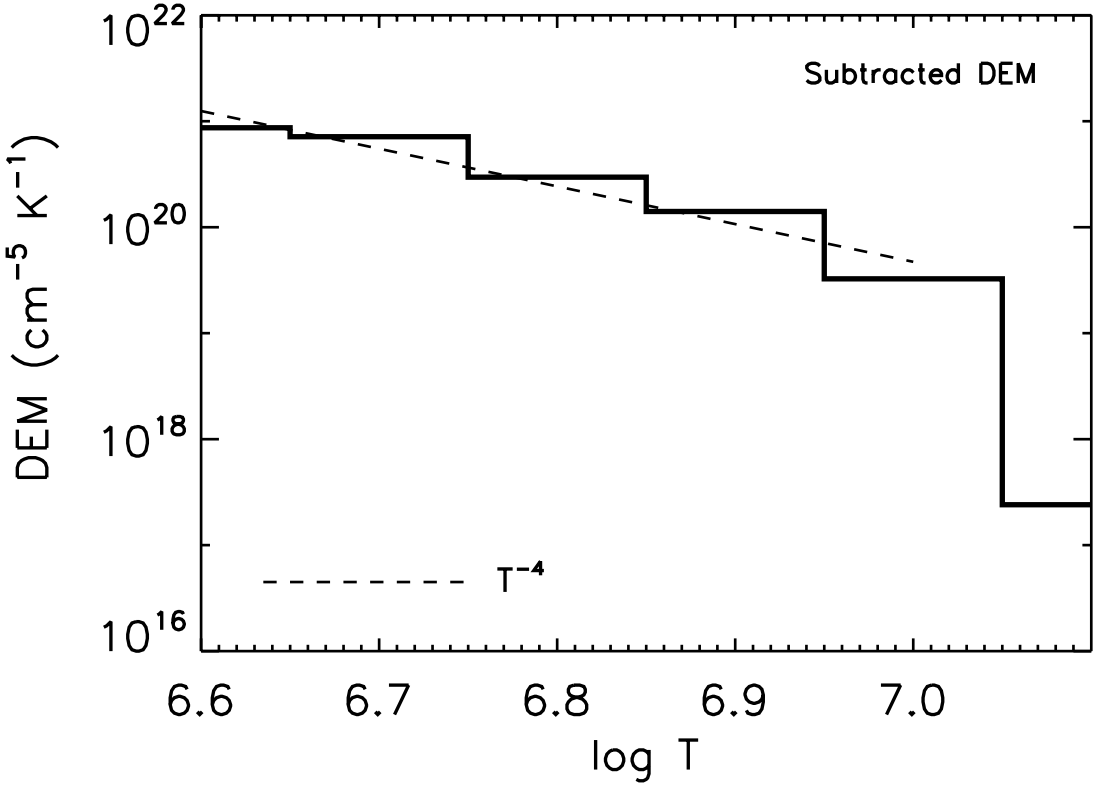


EM loci provide upper limits for emission measure at a temperature

Including FOXSI can **better constrain high temperature emission than AIA & XRT alone**

Comparison of flaring emission vs quiescent emission





- Background emission peaks at 2– 4 MK
- **Microflares have excess emission above 5 MK**

Thermal energy estimates

		Thermal energy (x 10^{28} erg) Multi-thermal plasma	Thermal energy (x 10^{28} erg) Isothermal plasma
Microflare-1	Target A	5.1	1.4
	Target B	4.9	1.5
	Target C	5.1	1.2
Microflare-2	Target J	1.6	1.0

Multi-thermal DEM provides a more comprehensive E_{th} estimates than isothermal approximation

- RHESSI microflares : 10^{26} – 10^{30} erg (Hannah et al., 2008)
- NuSTAR microflares : 10^{27} – 10^{28} erg (Wright et al., 2017)

Summary

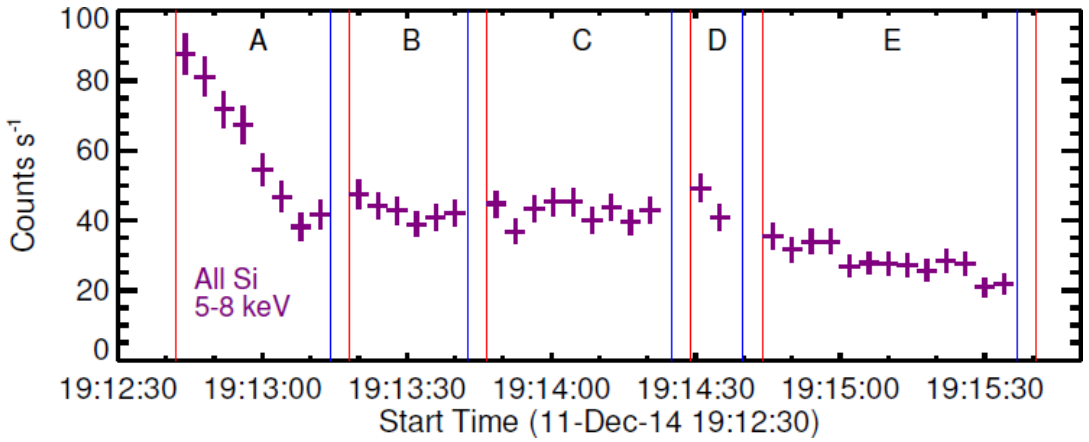
- We produced DEMs for two sub-A class microflares jointly observed by FOXSI-2, XRT, and AIA
- Coordinated FOXSI-2 observations are **one of the few definitive measurements of the plasma temperature distribution above 5MK** in microflares
- These microflares have significant emission above 5 MK
- Multi-thermal DEM analysis provides a more comprehensive thermal energy estimates than isothermal approximation
- Small scale energy releases are important to consider for coronal heating

Acknowledgement : FOXSI was funded by NASA's Low Cost Access to the Space program, grant NNX11AB75G.

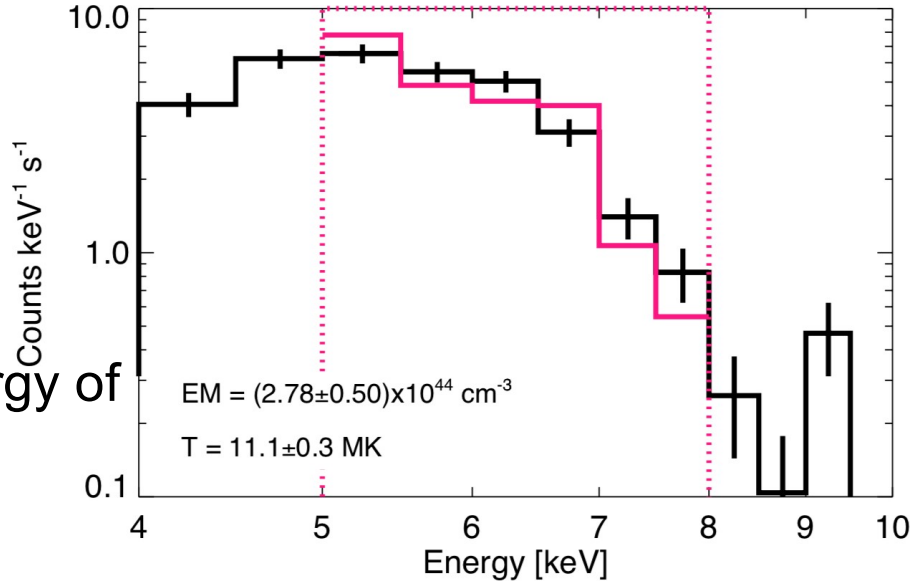
- Thank you

Complexity in a FOXSI microflare

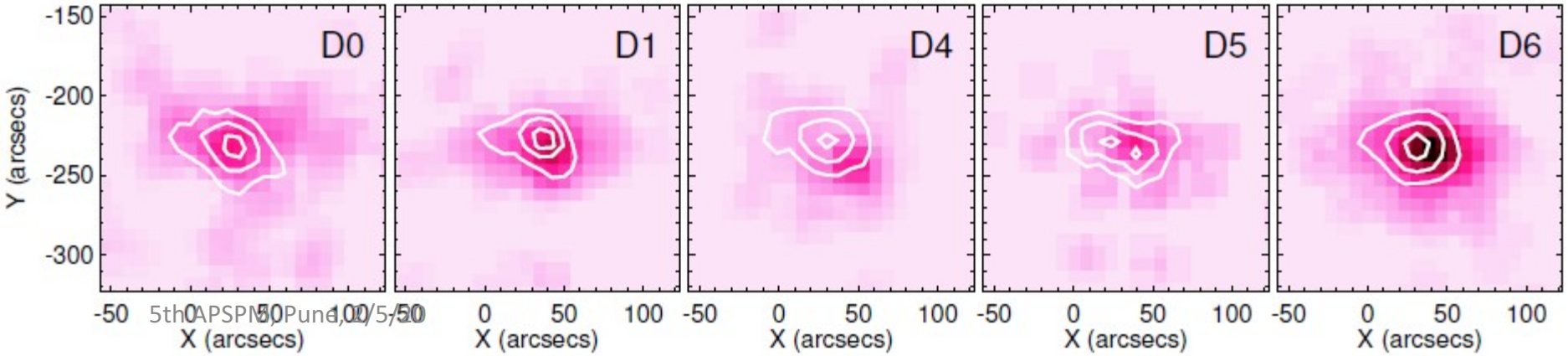
FOXSI-2 first microflare: Estimated GOES class: A0.5



Spectroscopy: Isothermal fit → Thermal energy of



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

Viveringet al, in prep + thesis (2019)

Flight Data Analysis

Instrument response:

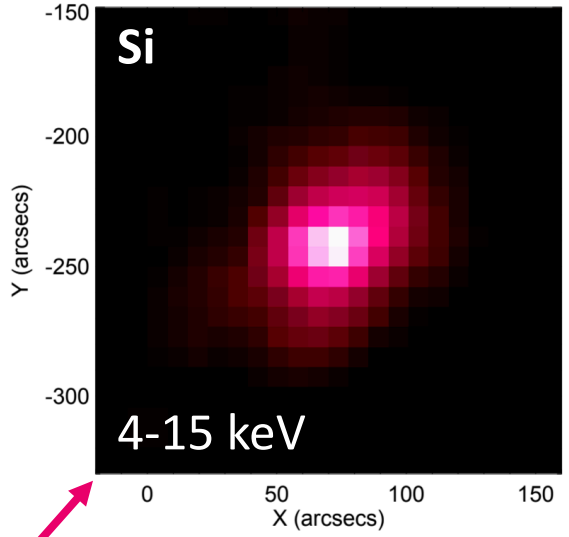
- No major nondiagonal contributions
- Convolve response with gaussian probability distribution account for **finite energy resolution**

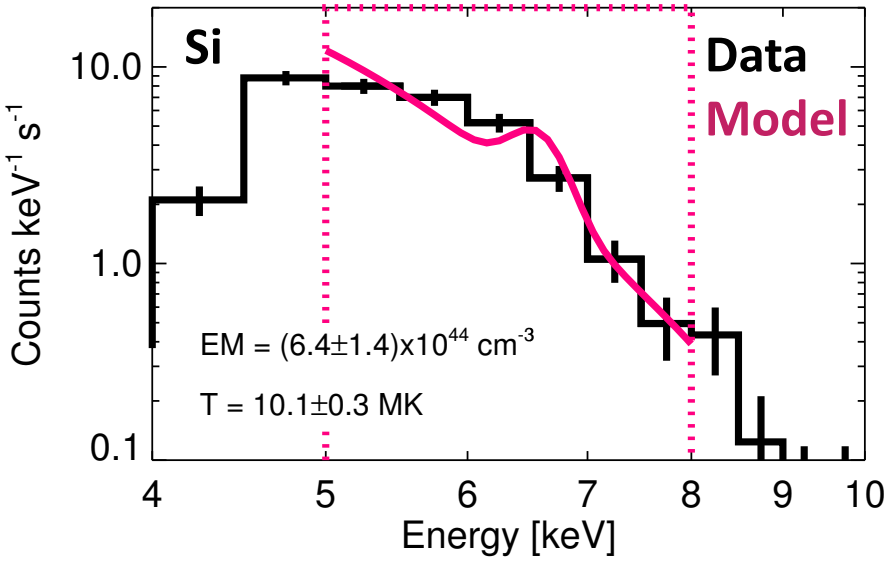
Note finer pixel size for CdTe

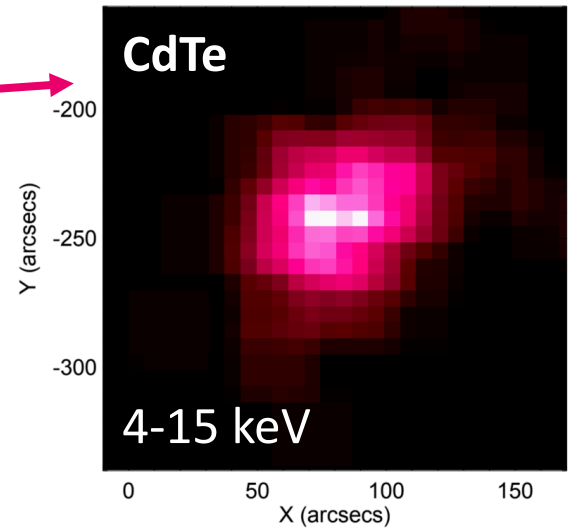
Spectral modeling of CdTe data shows results that are **consistent with Si data.**

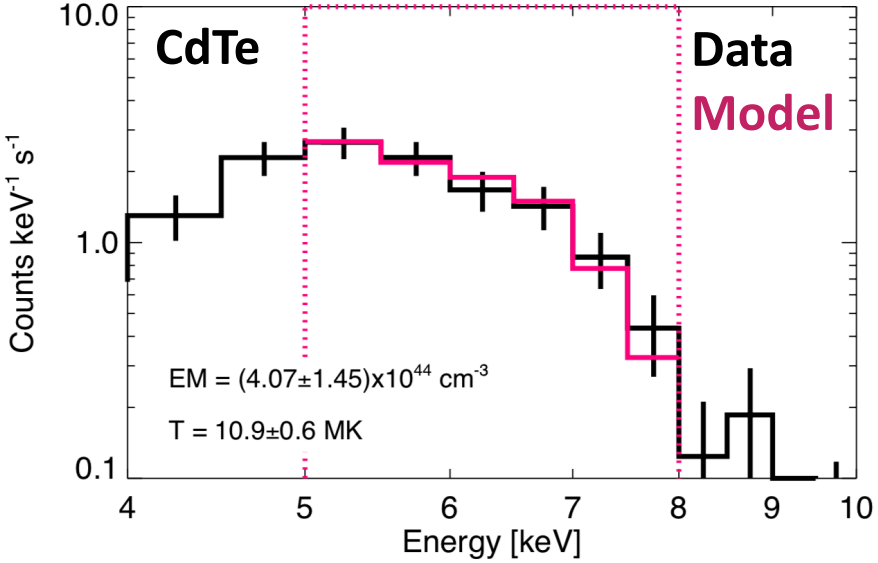
FOXSI-2 First Microflare

(optically thin thermal bremsstrahlung model)





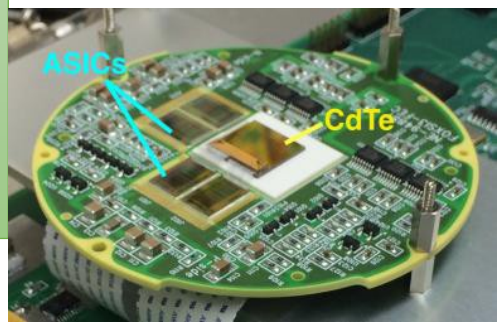




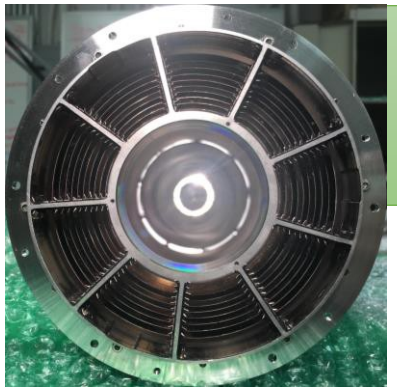
Vievering et al 2019 (Thesis) (In preparation)

FOXSI-3 upgrades

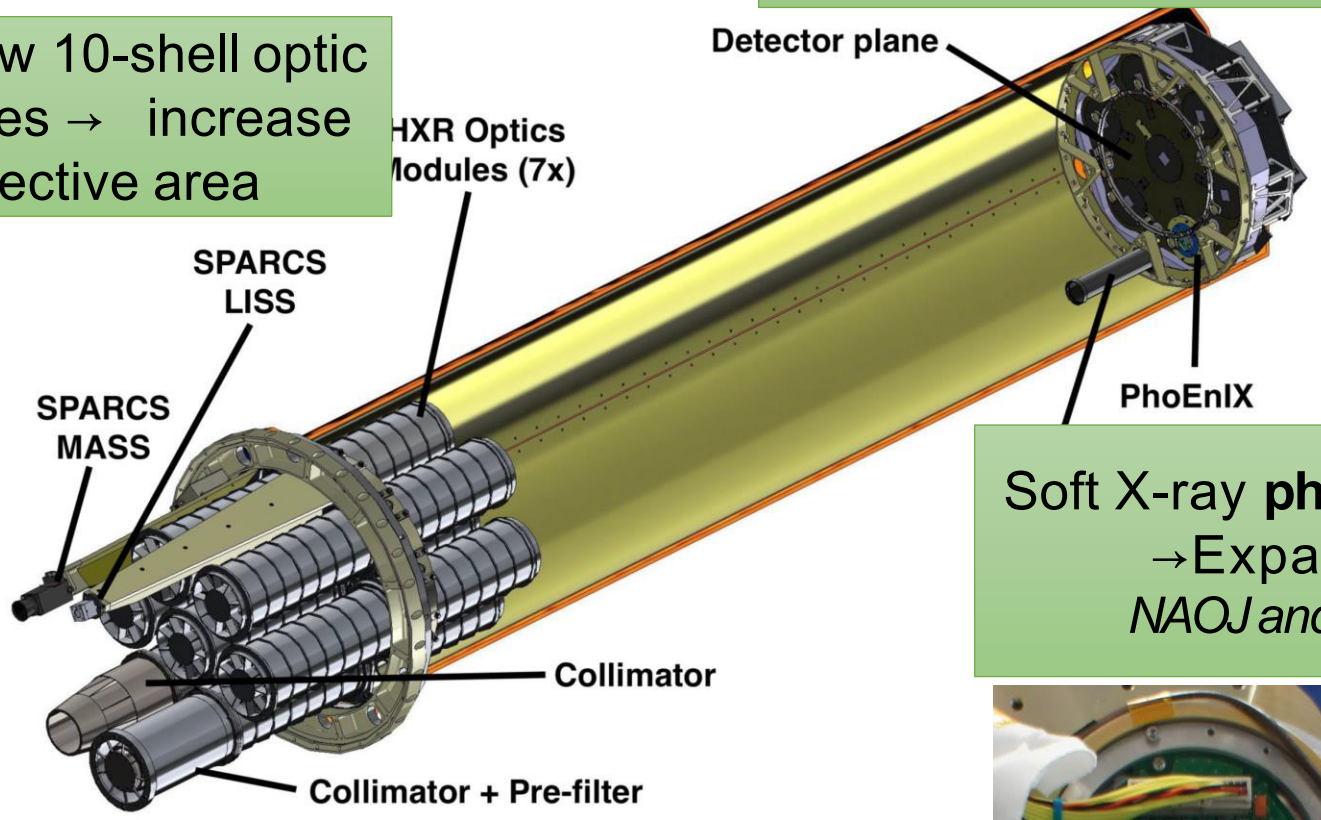
Two new CdTe detectors
→ increase efficiency at high energies
JAXA/ISAS and Kavli IPMU



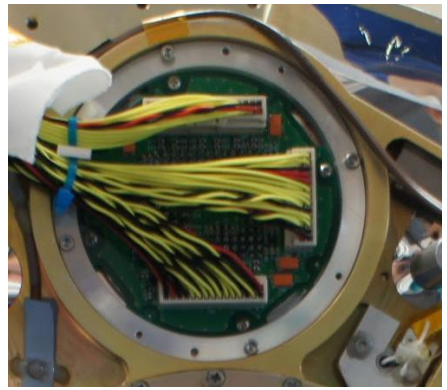
Ishikawa et al, 2016
Furukawa et al, 2019



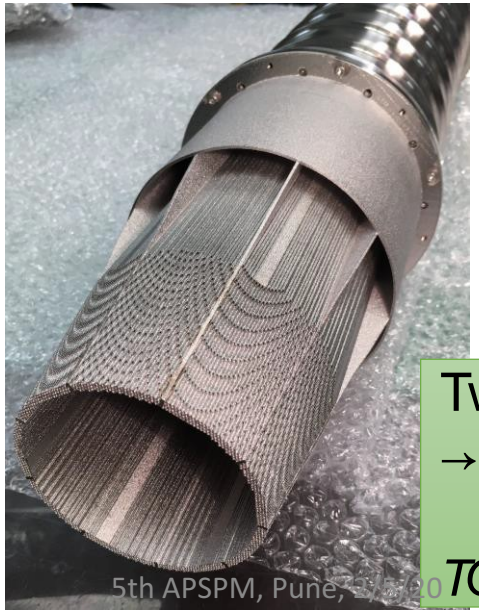
Two new 10-shell optic modules → increase effective area



Soft X-ray **photon-counting** detector
→Expand energy range
NAOJ and Nagoya University



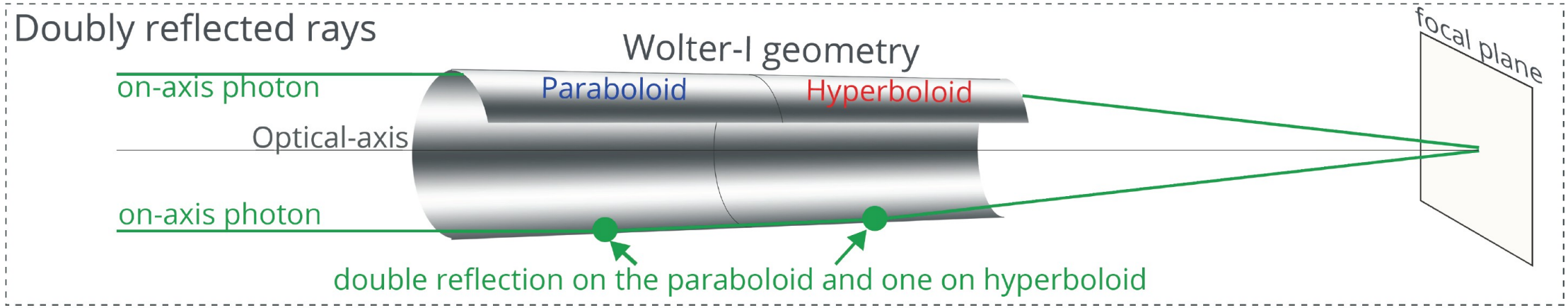
Narukage et al, SPIE, 2017



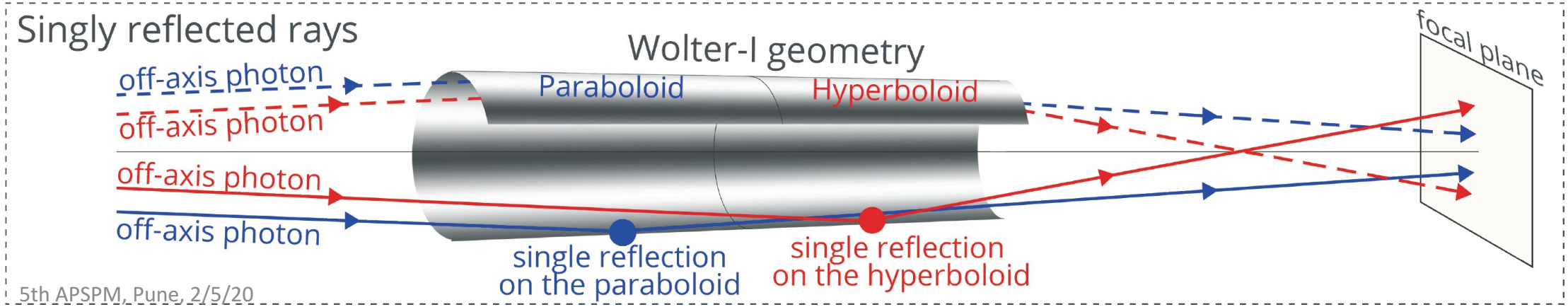
Two collimators
→reduce the ghost ray background
TORAY

Buitrago-Casas, SPIE, 2017

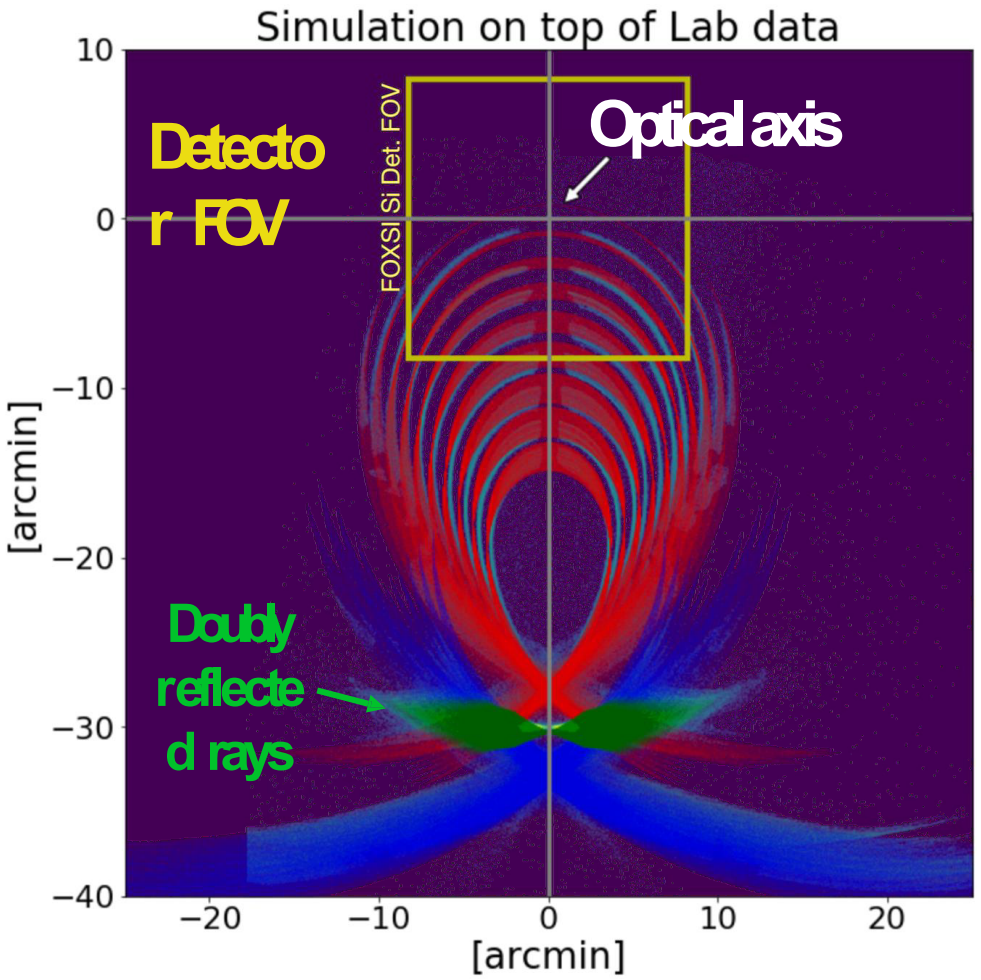
Reducing the ghost ray background



Ghost-rays



Reducing the ghost ray background



Lab measurement of the ghost ray background

- Point spread function of a FOXSI 7-shell module

at the ***Stray Light Facility*** at ***Marshall Space Flight Center***:

- X-ray source at 100 meters from the optics
- Source is 30 arcmin off axis

Ray-tracing simulation of ghost rays

→ **Match the lab measurements**

History of each simulated ray is tracked

→ **Information on the origin of the ghost rays**