FOXSI-2 Solar Microflares : Multi-instrument Differential Emission Measure Analysis

P. S. Athiray

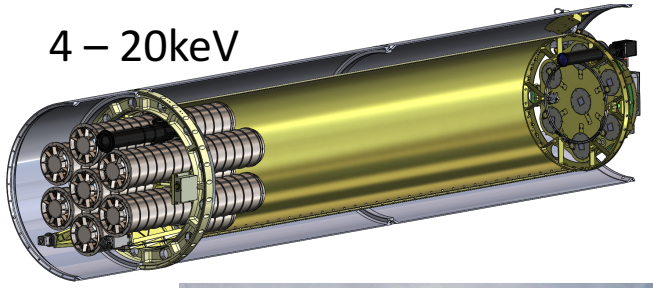
NASA Marshall Space Flight Center

Lindsay Glesener, Juliana Vievering, Juan Camilo Buitrago-Casas,
Shin-nosuke Ishikawa, Andrew Inglis, Noriyuki Narukage,
Daniel Ryan, Steven Christe, Sophie Musset,
Säm Krucker

Outline

- Overview of FOXSI-2 coordinated 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

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

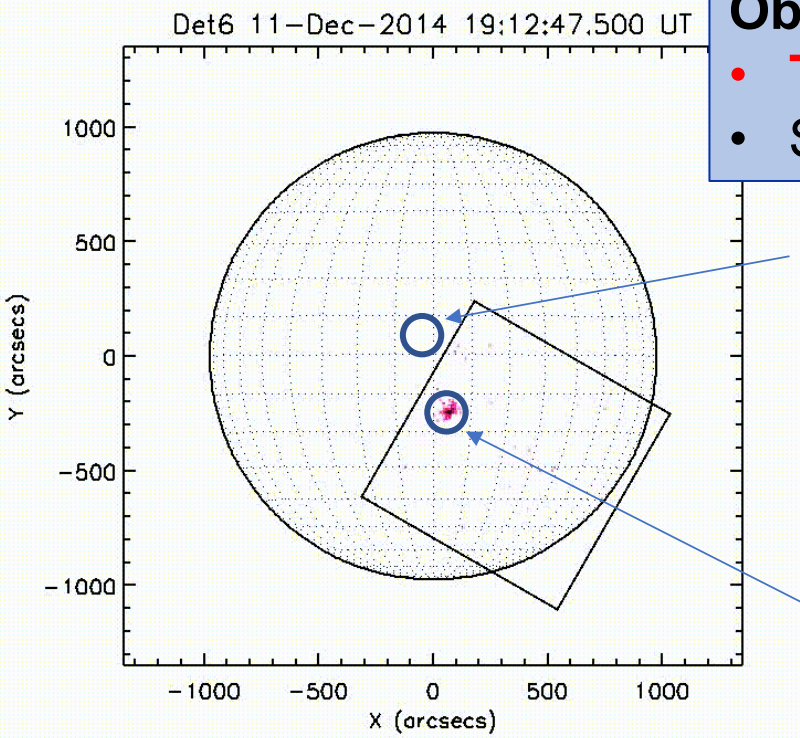


FOXSI-2

Launched on December 11, 2014
from White Sands Missile Range

Instrumentation

- Seven direct focusing X-ray optics modules paired with double sided strip detectors



Observations during second flight ~(6.5mins)

- **Two solar microflares**
- Several active regions

Microflare-2

Microflare-1

Coordinated observations

Hinode/XRT, SDO/AIA,

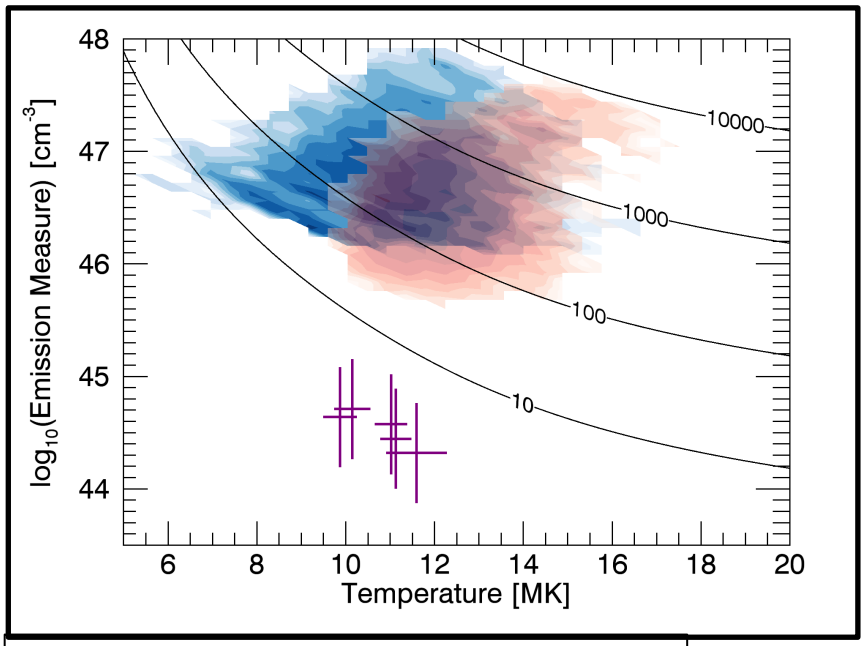
IRIS, VLA

Objectives of this work

Estimate

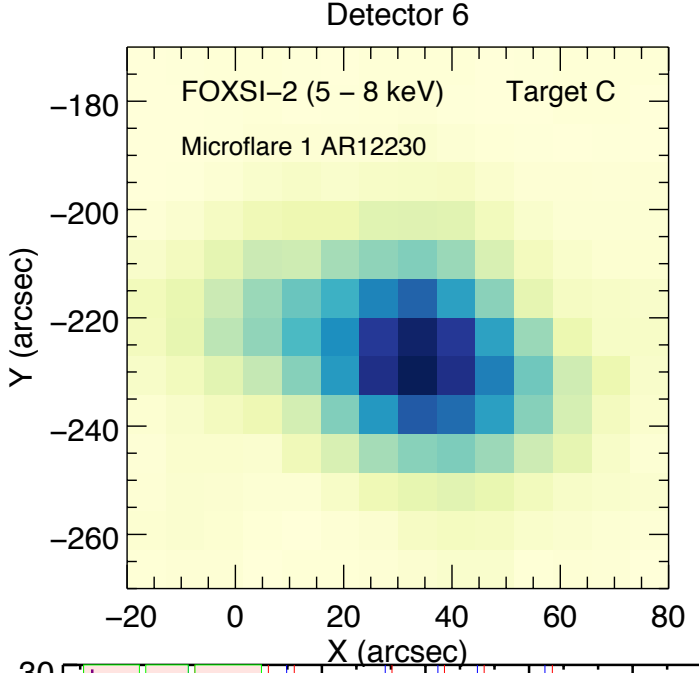
1. Plasma temperature distribution for microflares observed by FOXSI-2
2. Combined DEM : FOXSI-2, XRT, AIA
3. Thermal energy

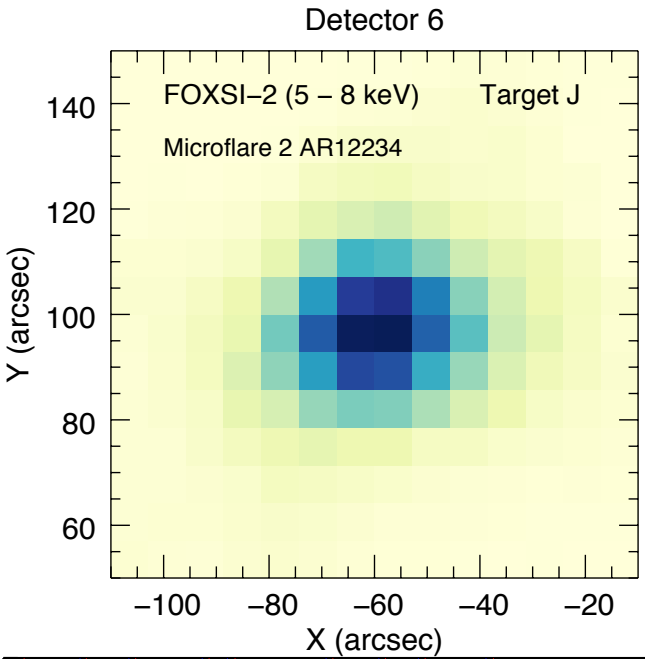
FOXSI-2 microflares

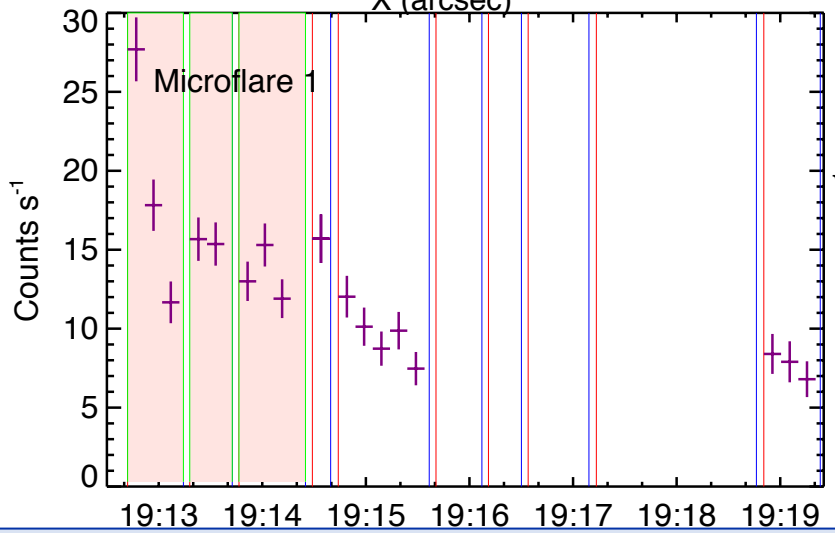


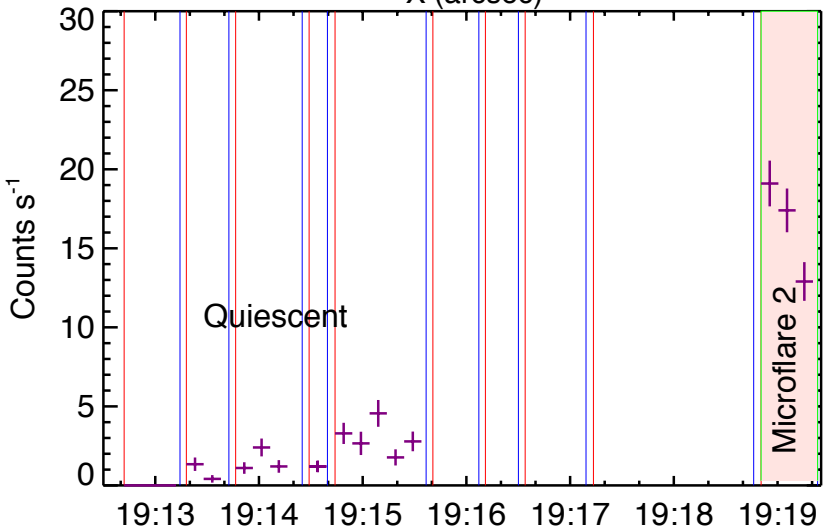
GOES - Hannah et al. 2008
RHESSI - Hannah et al. 2008
FOXSI-2 - microflare-1

Vievering et al., (In preparation)
(204.04 Poster Session II – 11 June 2019)





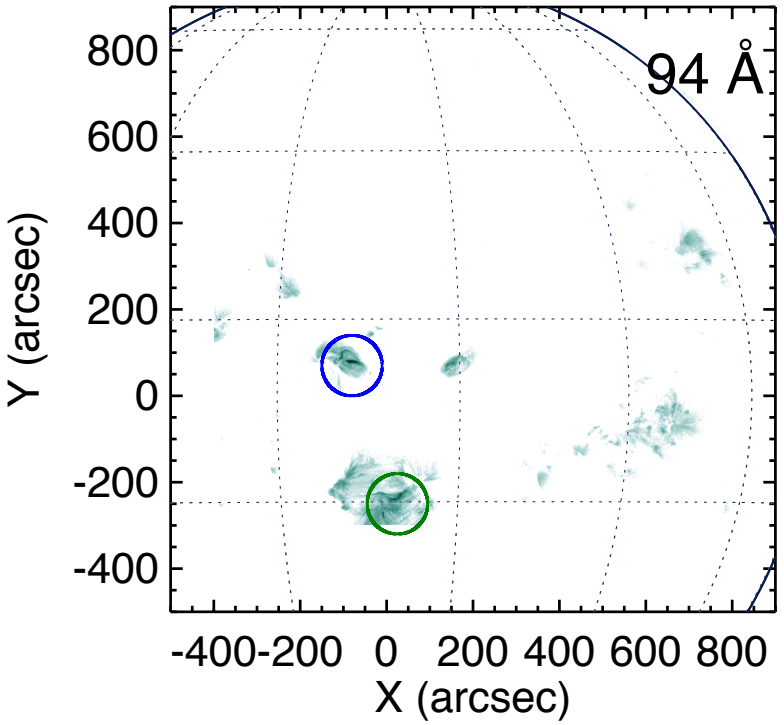




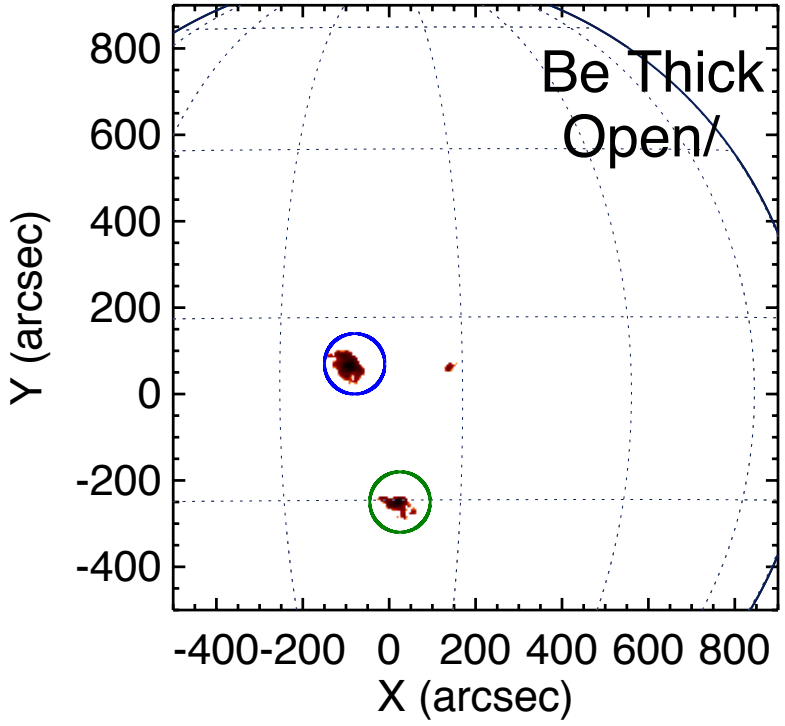
- Background subtracted GOES X-ray flux indicate sub A-class microflares
- FOXSI allows us to image **an order of magnitude fainter microflares** than observed by solar X-ray instruments

Data summary for DEM analysis

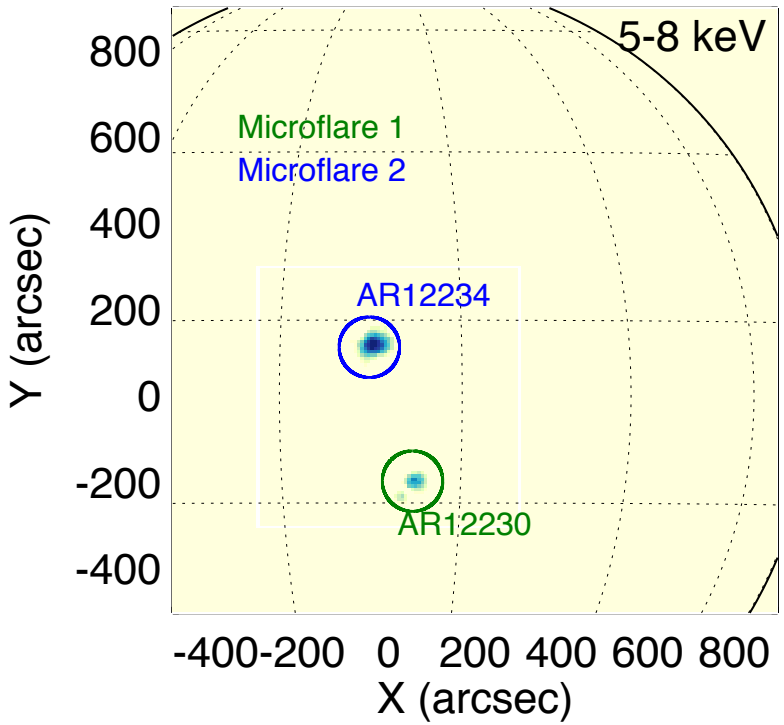
SDO/AIA



Hinode/XRT



FOXSI-2 (Detector 6)



EUV (5 Channels)

SXR (9 filter combinations)

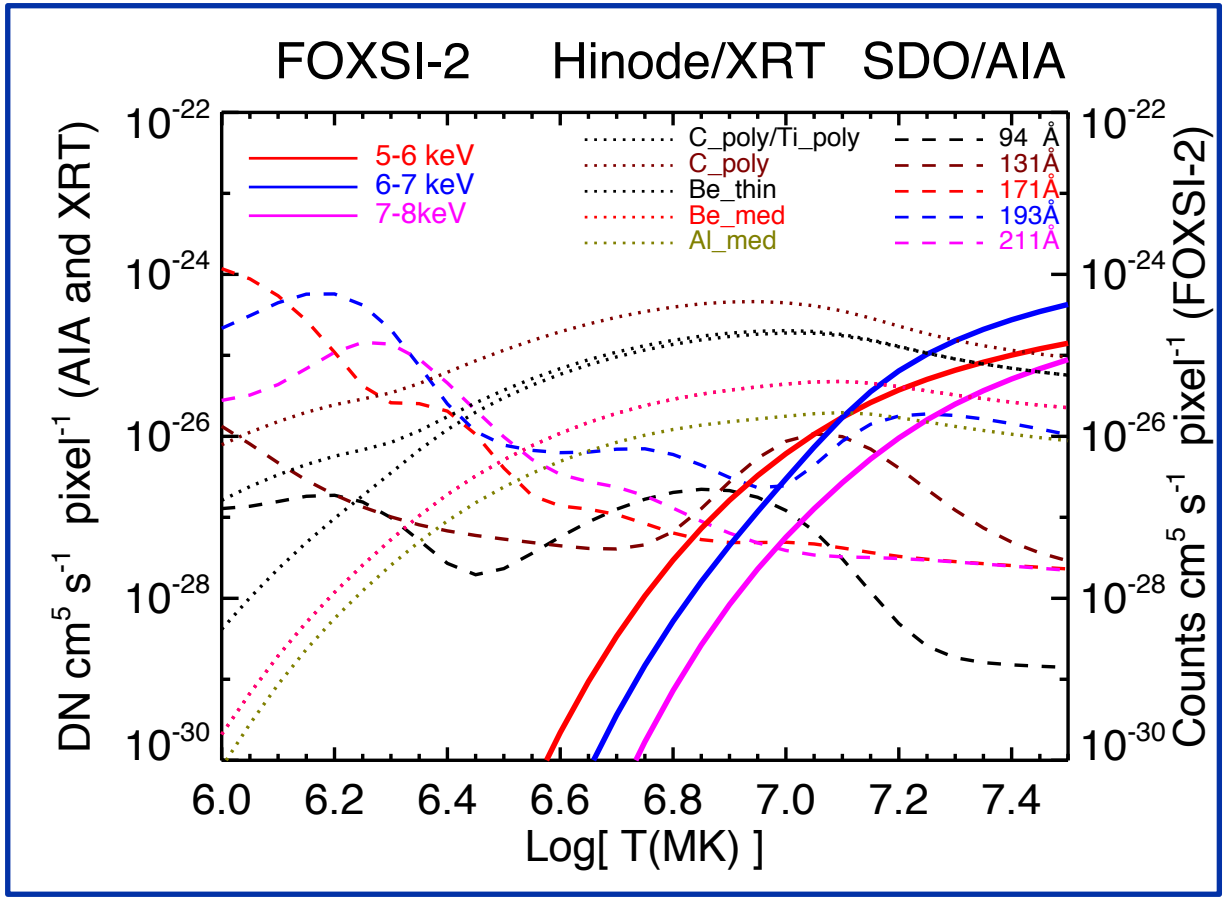
HXR (5 to 8 keV)

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

Temperature response function

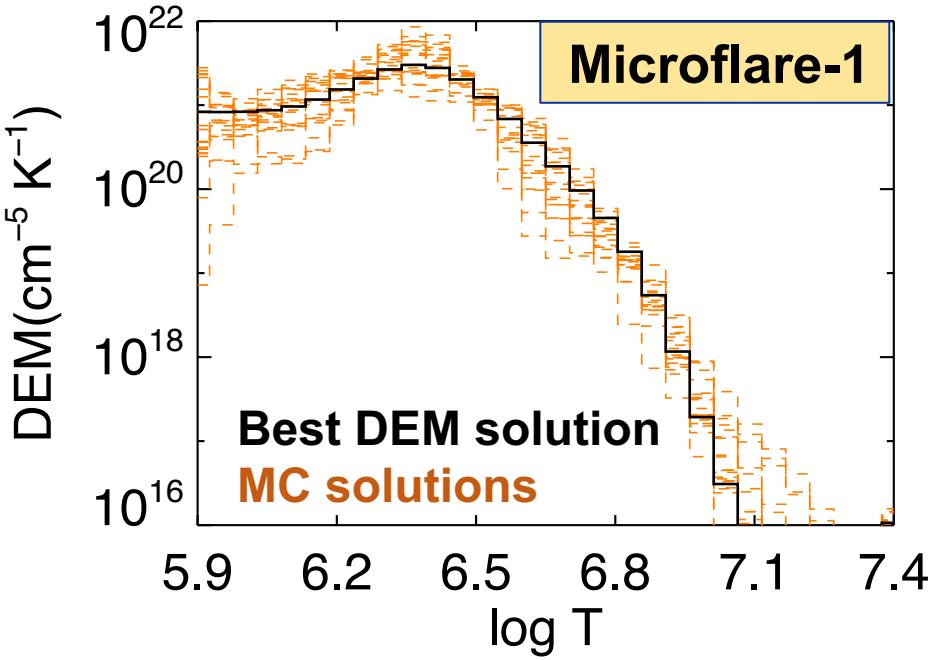
Instruments' ability to detect plasma at different temperatures

- 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

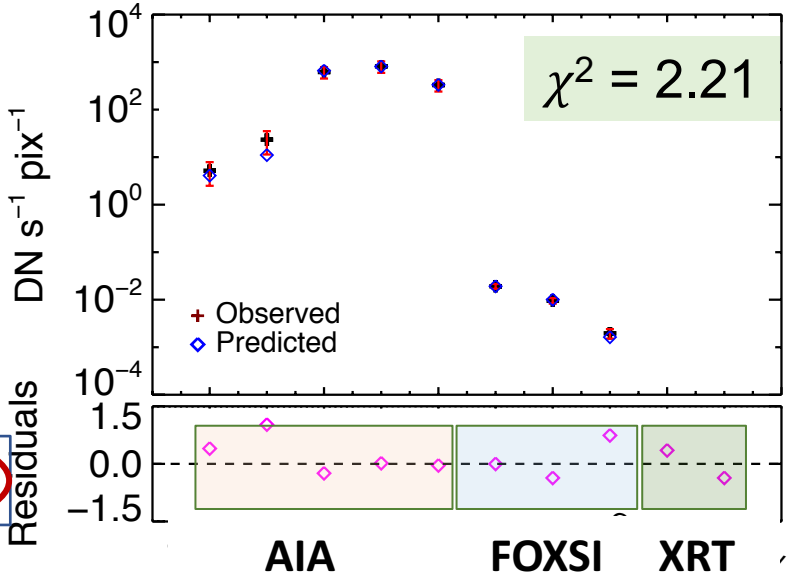
Note: Pixel sizes are different for each instrument

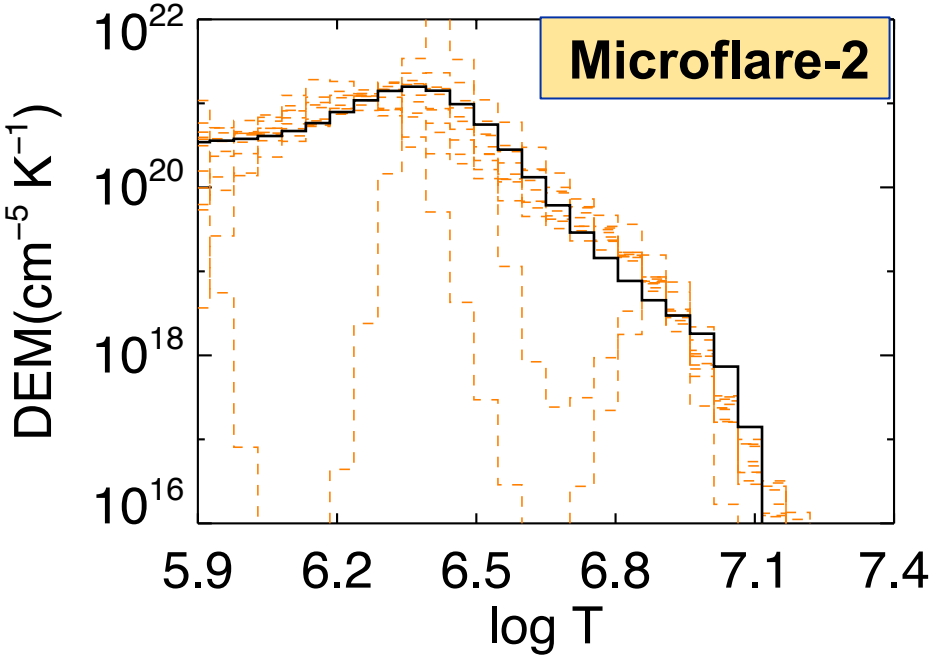


Combined DEM analysis

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

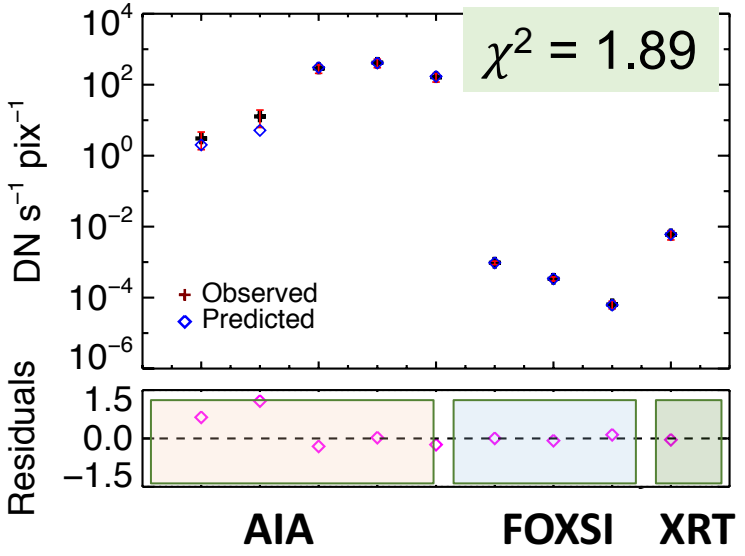
unknown



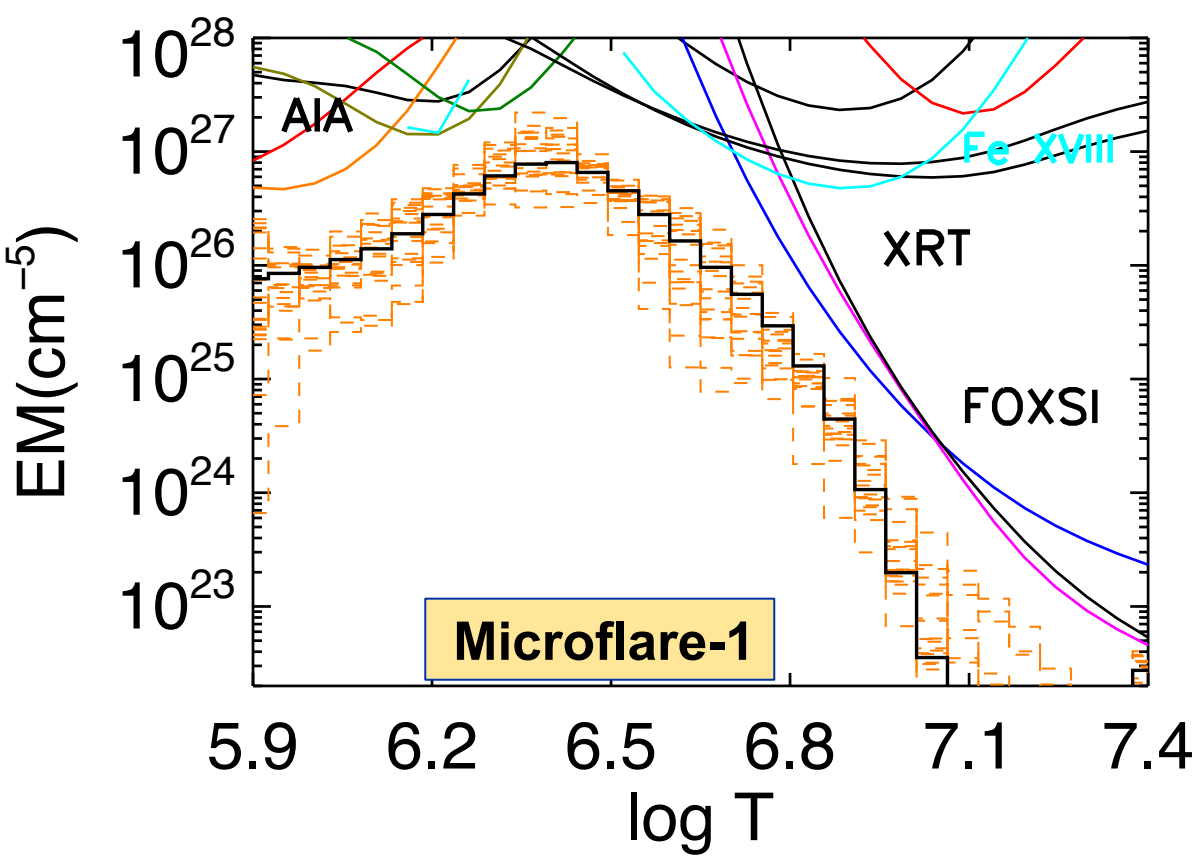


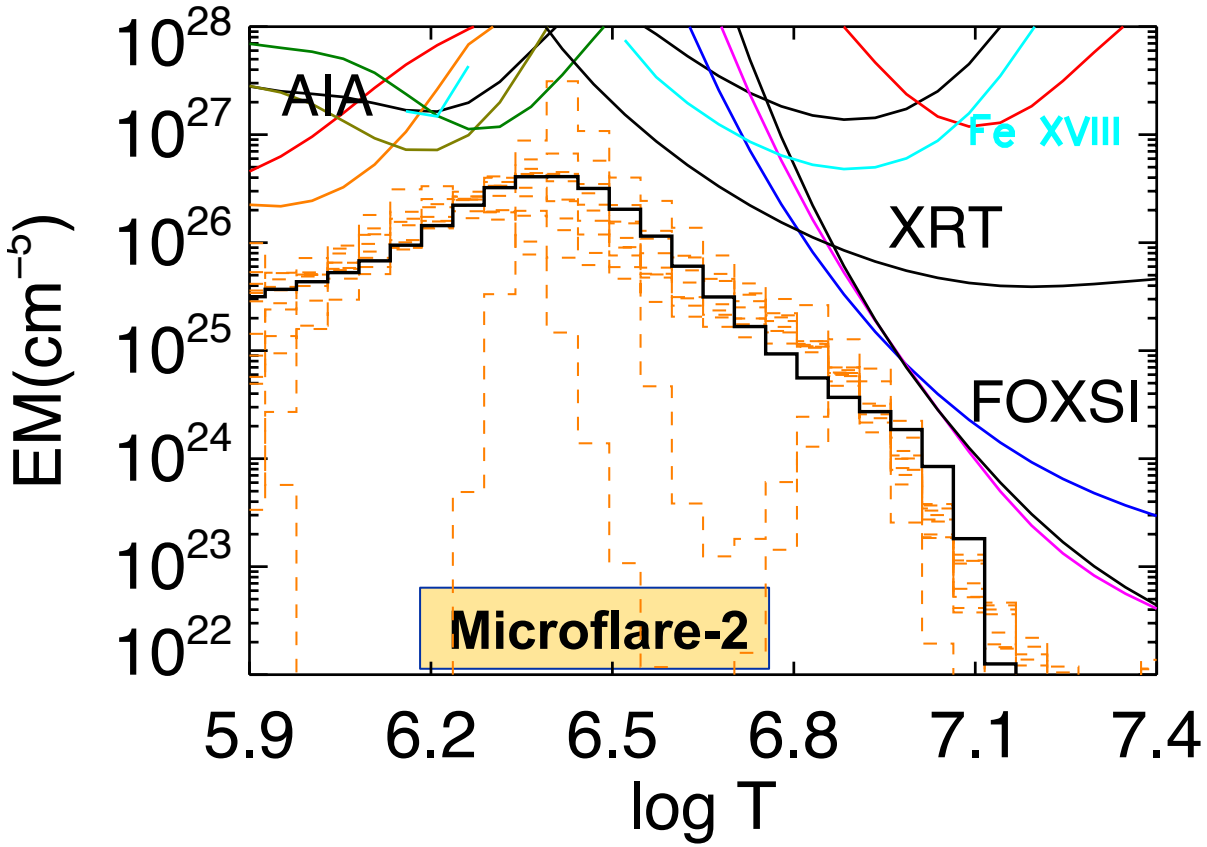
Hinode-XRT DEM inversion

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



Combined DEM analysis : EM loci curves

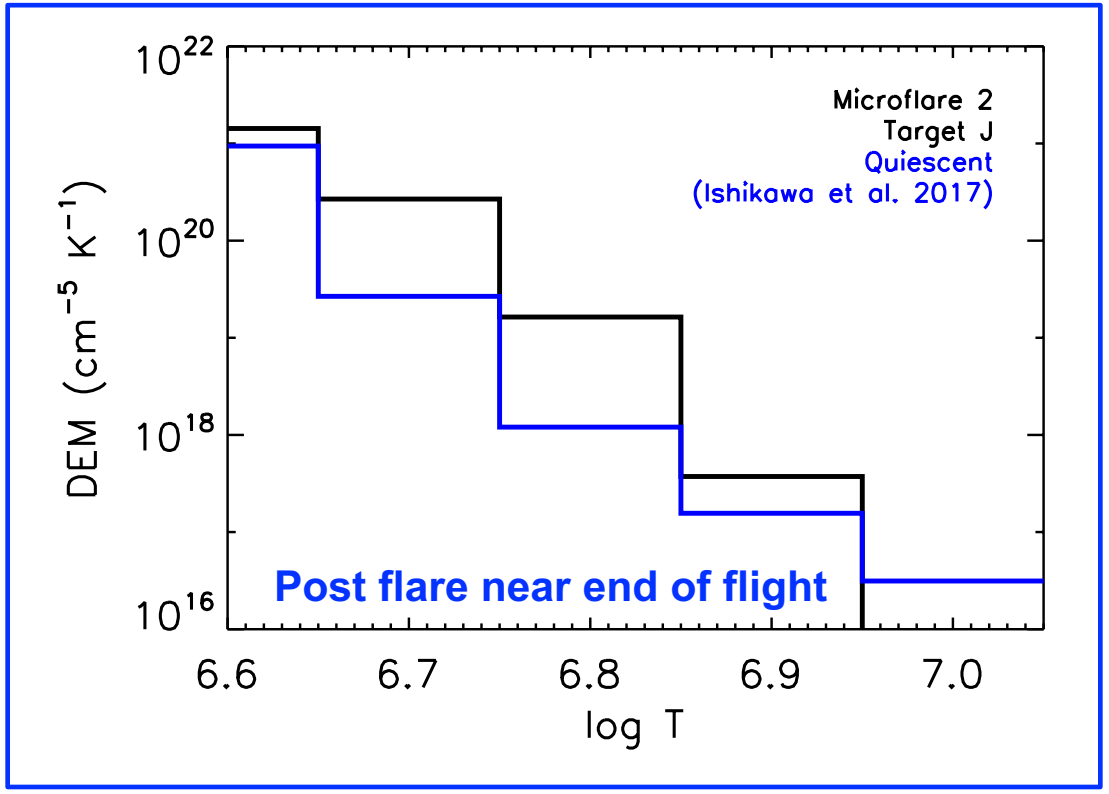


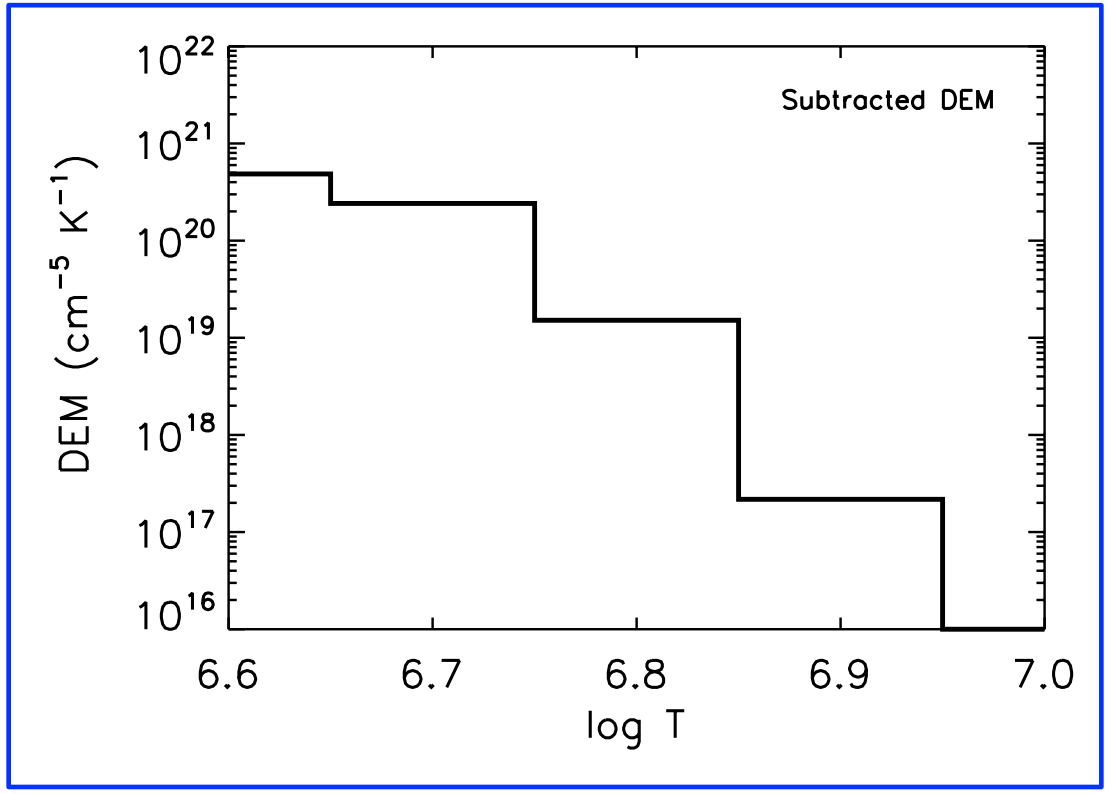


EM loci provide upper limits for emission measure at a temperature

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	Pointing 1	0.8 to 1.5	0.5 to 1.1
	Pointing 2	0.8 to 1.5	**See Vievering et al., 204.04 Poster Session II**
	Pointing 3	0.8 to 1.6	
Microflare-2	Pointing 1	0.6 to 1.1	

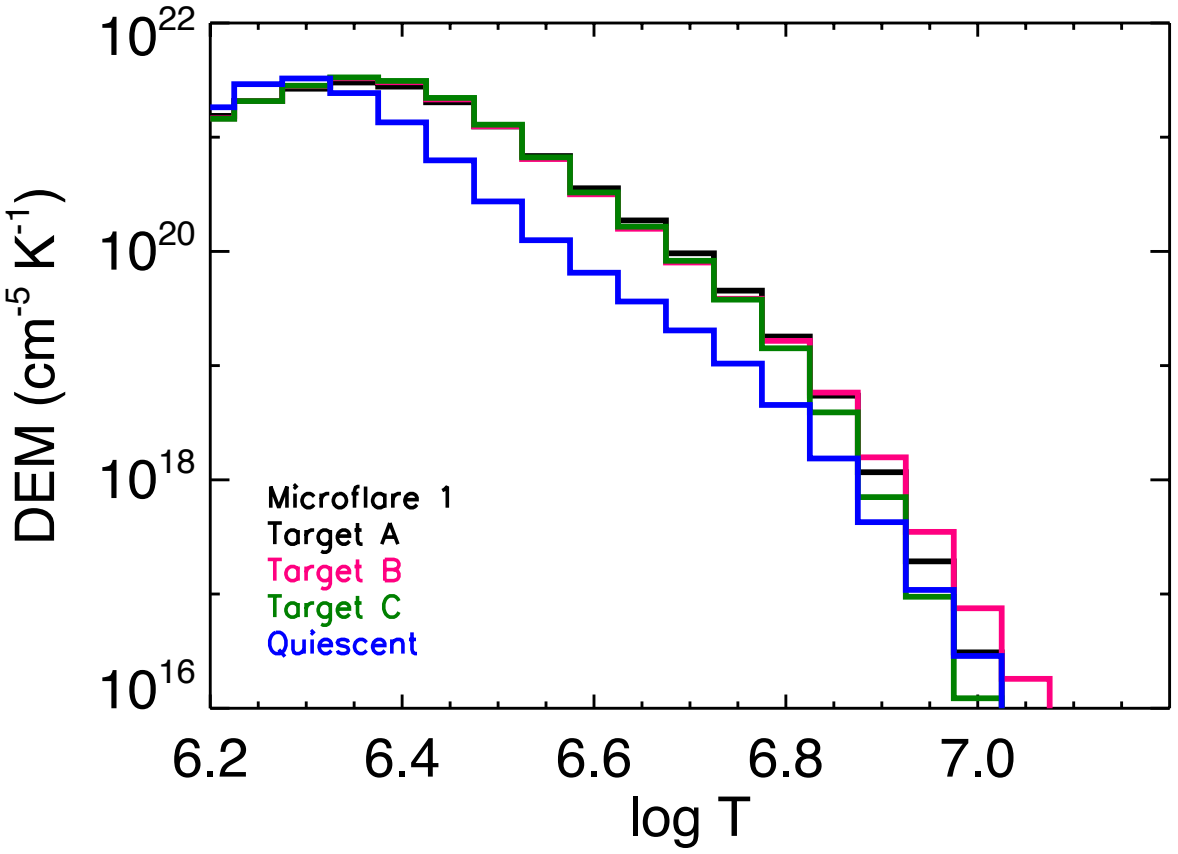
Multi-thermal DEM provides a more comprehensive E_{th} estimates than isothermal approximation

- 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. Special thanks to **Mr. Lance Davis** of the Univ. Of Minnesota and FOXSI team.


10^{22}
10^{20}
10^{18}
10^{16}
DEM (cm^{-5} K^{-1})
Microflare 1
Target A
Target B
Target C
Quiescent
6.2
6.4
6.6
6.8
7.0
log T