

Active region temperature diagnostics with FOXSI-2 and Hinode/XRT



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Introduction - Non-flaring AR DEM

Temperature structure of active regions
not during flares:

A few MK main component

+ additional high-temperature component?

as the heating signature (Klimchuk et al. 2008)

Differential Emission Measure (DEM) estimation:

EUV (EIS, AIA, ..) & X-ray (XRT, RHESSI, ..)

XRT multi-filter observations have

a good sensitivity for a few MK

High uncertainty for >10 MK

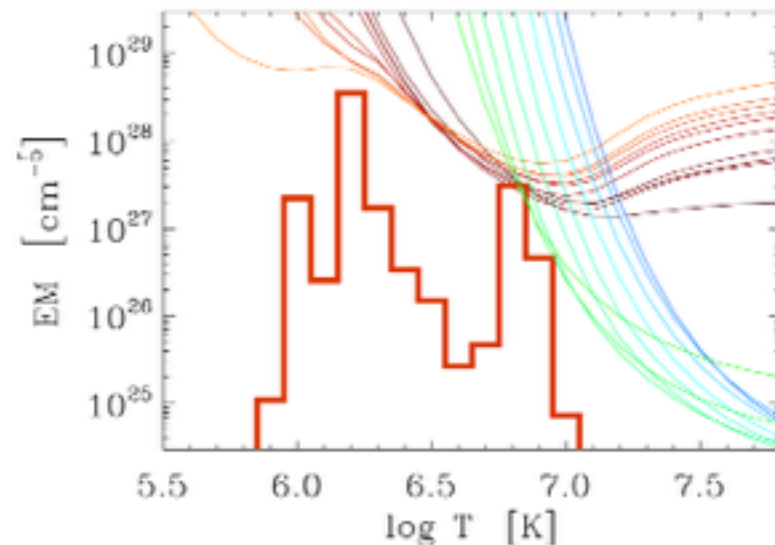
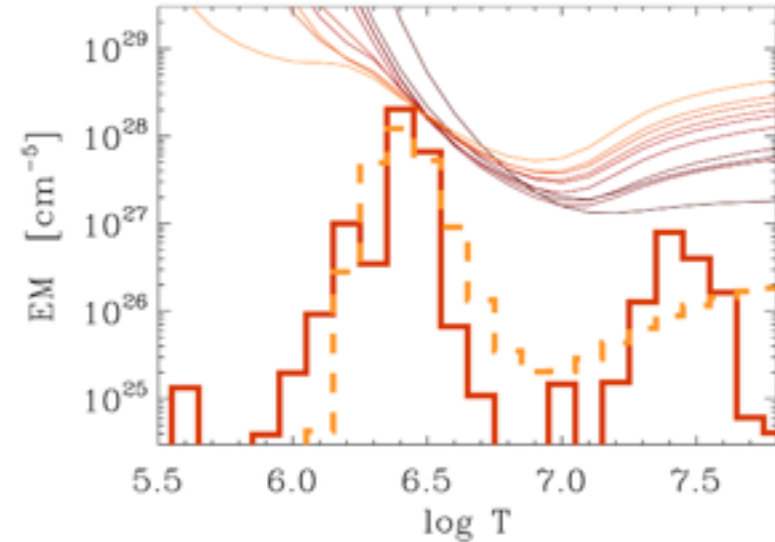
(Winebarger et al. 2012, ..)

RHESSI observations performed a significant role
to constrain high-temperature component

Upper limit only, because of sensitivity limitation

High-sensitivity observations are necessary

→ X-ray focusing optics : FOXSI, NuStar, ..



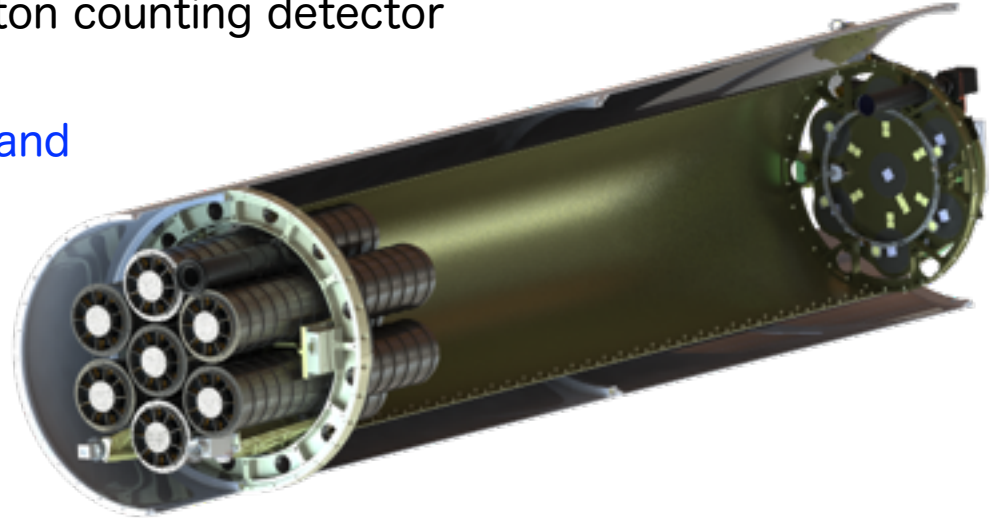
(Schmelz et al. 2009, ApJ)

Focusing Optics Solar X-ray Imager (FOXSI)

- Rocket experiment for first **HXR imaging & spectroscopy** using focusing optics
-> **good capability to estimate plasma temperature especially for >10 MK**

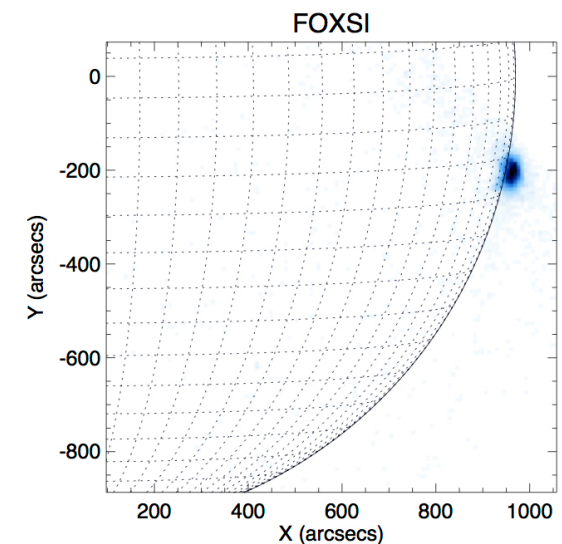
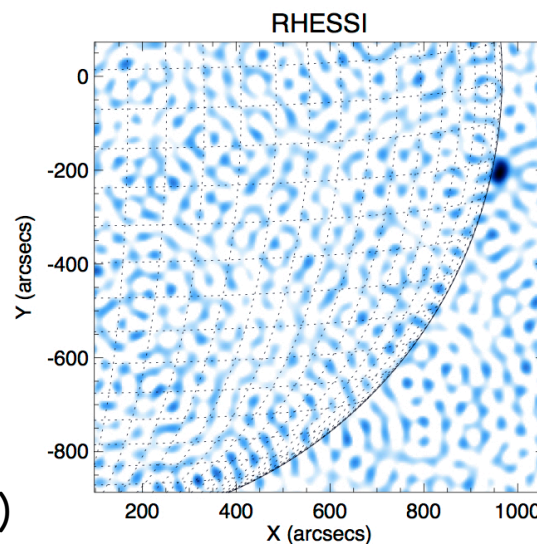
Grazing incidence telescope + photon counting detector

- Energy range : 4-20 keV
- **Optimized to solar observations and good livetime**
- Position resolution $\sim 9''$
- FOV : $960'' \times 960''$
- Duration : ~ 400 s



- Successful 2 flight :
FOXSI-1 November 2012
FOXSI-2 October 2014

- FOXSI-1 detected a microflare and high-sensitivity is shown



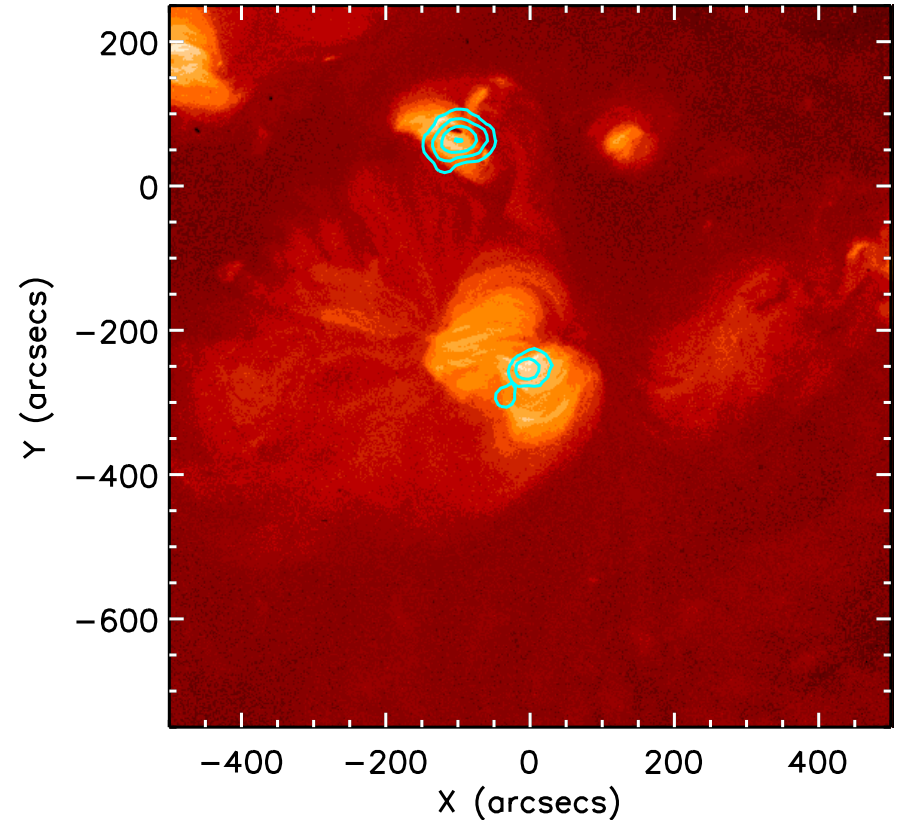
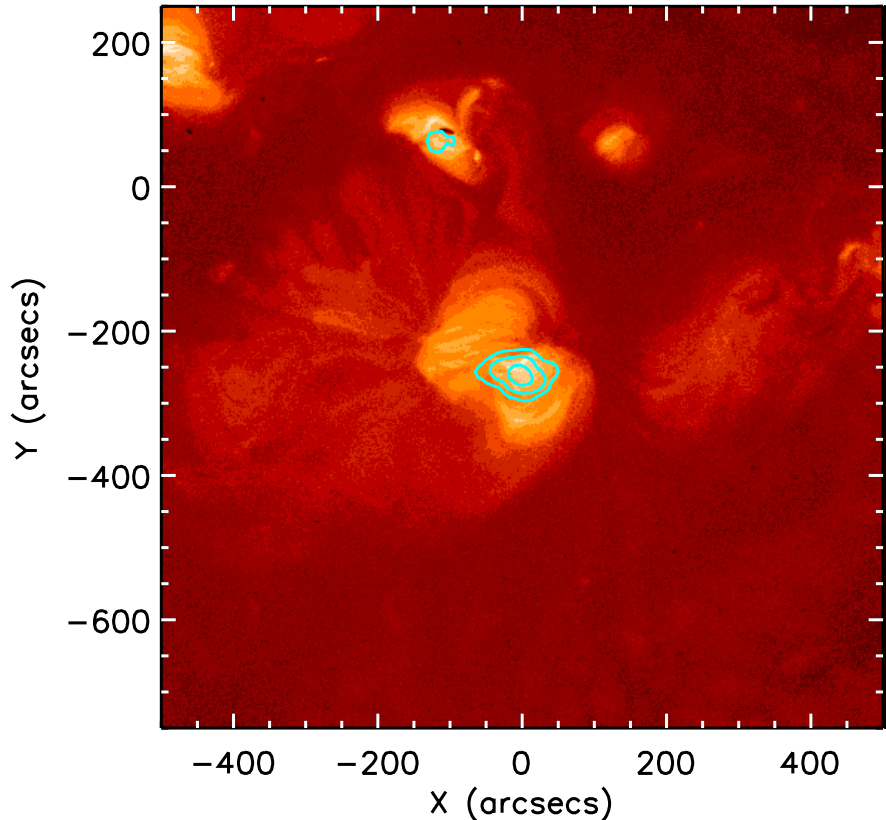
(Krucker et al. 2014)

FOXSI-2 disk center observations

~5 minutes later

FOXSI-2 19:13:46.5-19:14:25
(38.5 s)

FOXSI-2 19:18:50.5-19:19:23.2
(32.7 s)



By looking at FOXSI-2 4-15 keV, X-rays from the south AR become weaker, and those from the north AR become stronger

Time variations of the two ARs

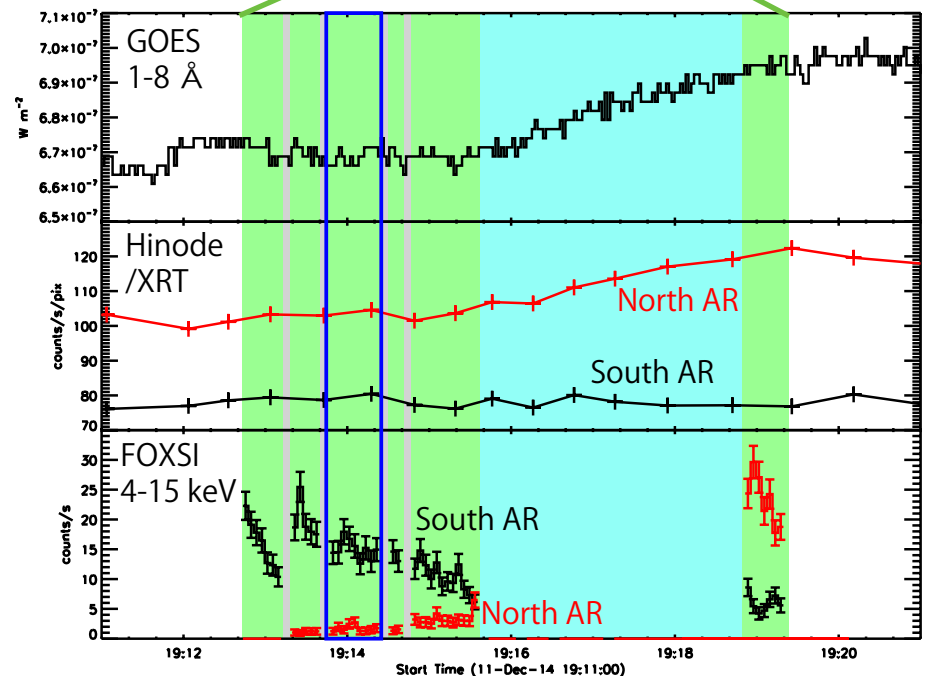
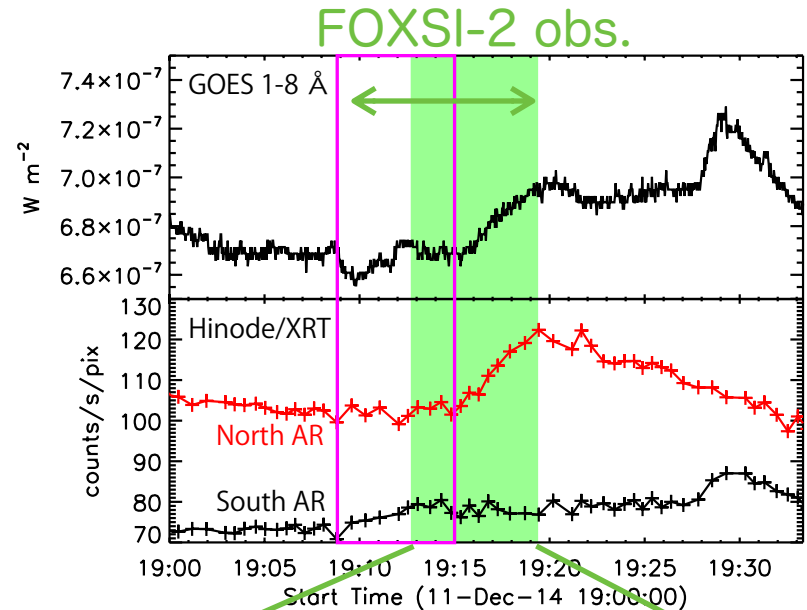
We compared lightcurves of XRT flare patrol data (Ti-poly), GOES, FOXSI-2

A flare occurs at ~19:15 at the north AR

→ Successful HXR detection from an AR with no obvious GOES or XRT flare before 19:15

The south AR was already flaring at the beginning of the FOXSI observation

We estimated DEM of the north AR before the flare start



Time variations of the two ARs

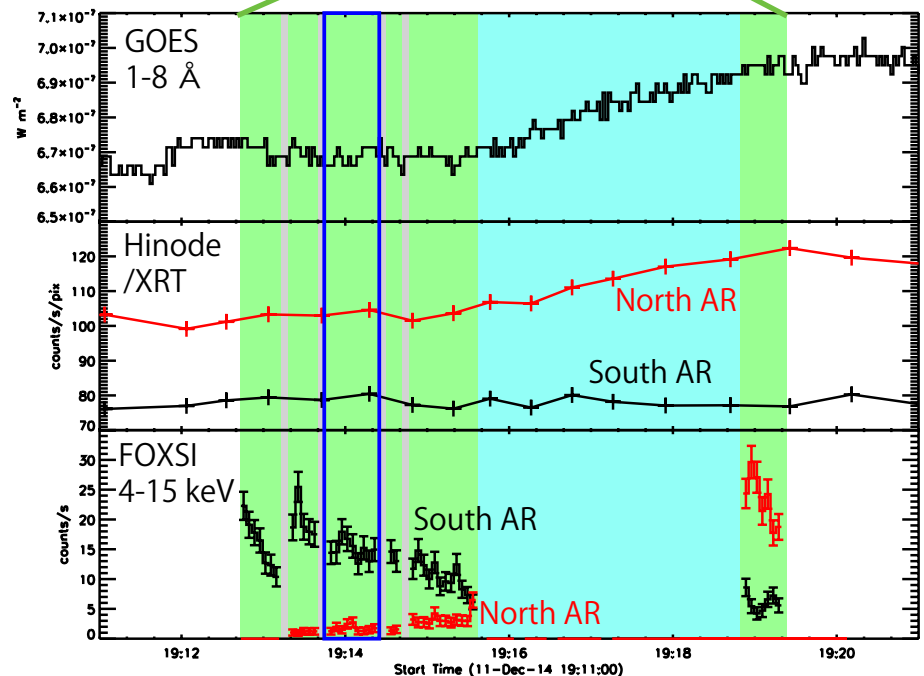
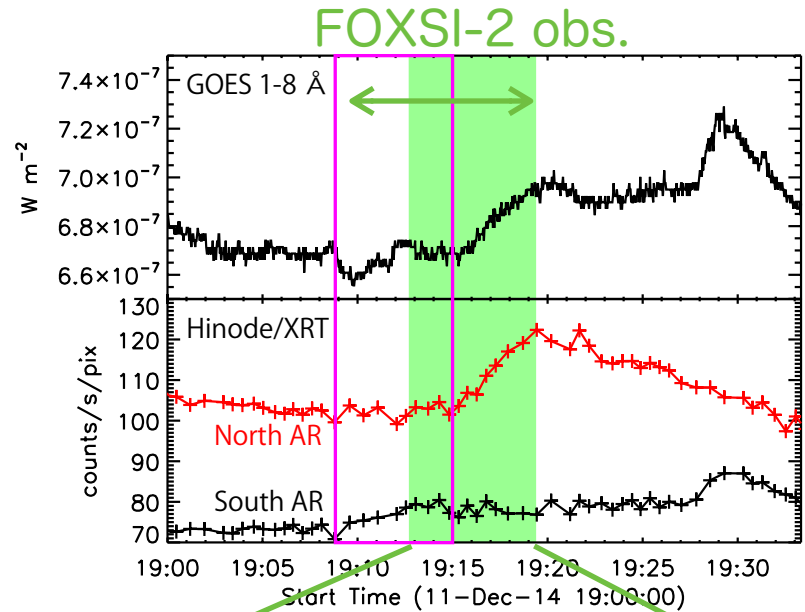
XRT observations
during the FOXSI flight :
Multi-filter observations
(11 filter pairs)
1 complete set \sim 6 min.
9 min. cadence

Hinode pointing center was
at the quiet Sun
-> no AR observations by EIS

XRT multi-filter observation
19:08:56-19:14:57

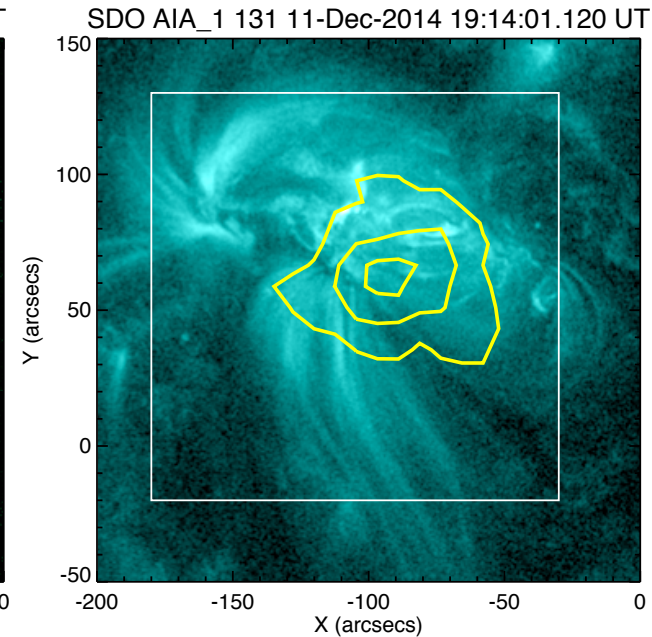
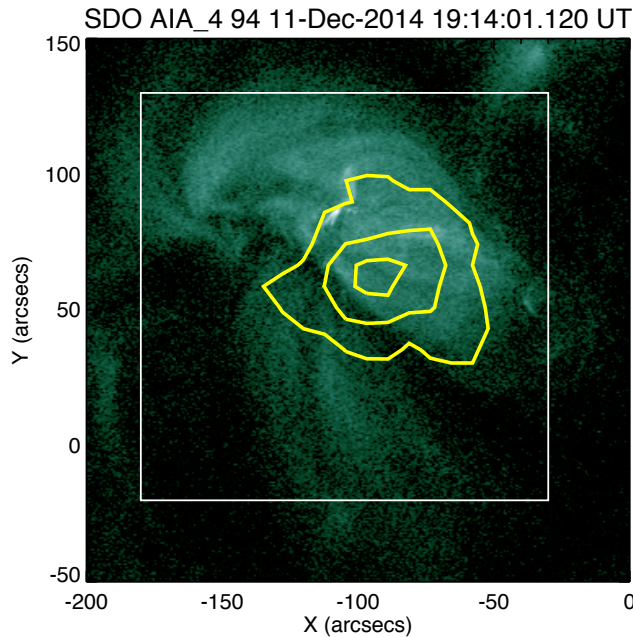
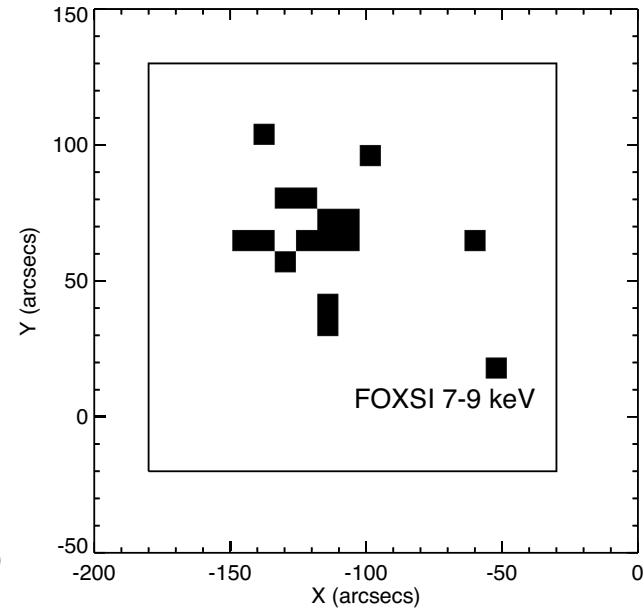
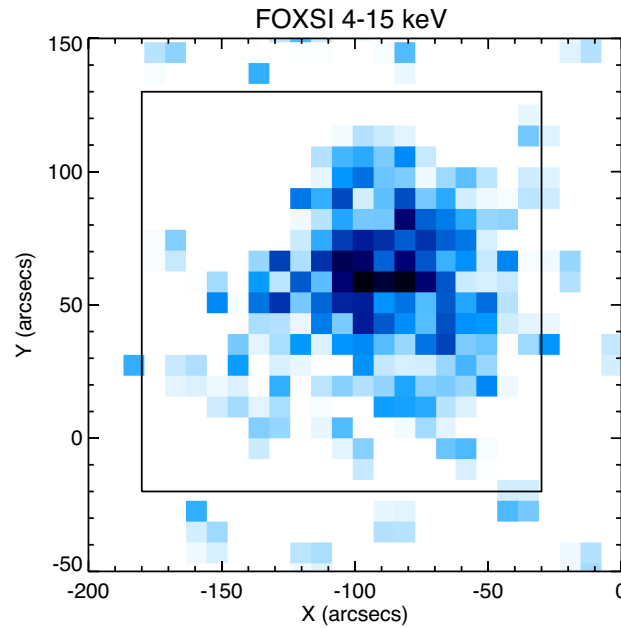
FOXSI-2 19:13:46.5-19:14:25

We assumed time variation is
negligible during these durations



Images of the target AR

- > 100 photons are detected by FOXSI
- 7-9 keV emissions are detected (16 photons)



DEM Reconstruction

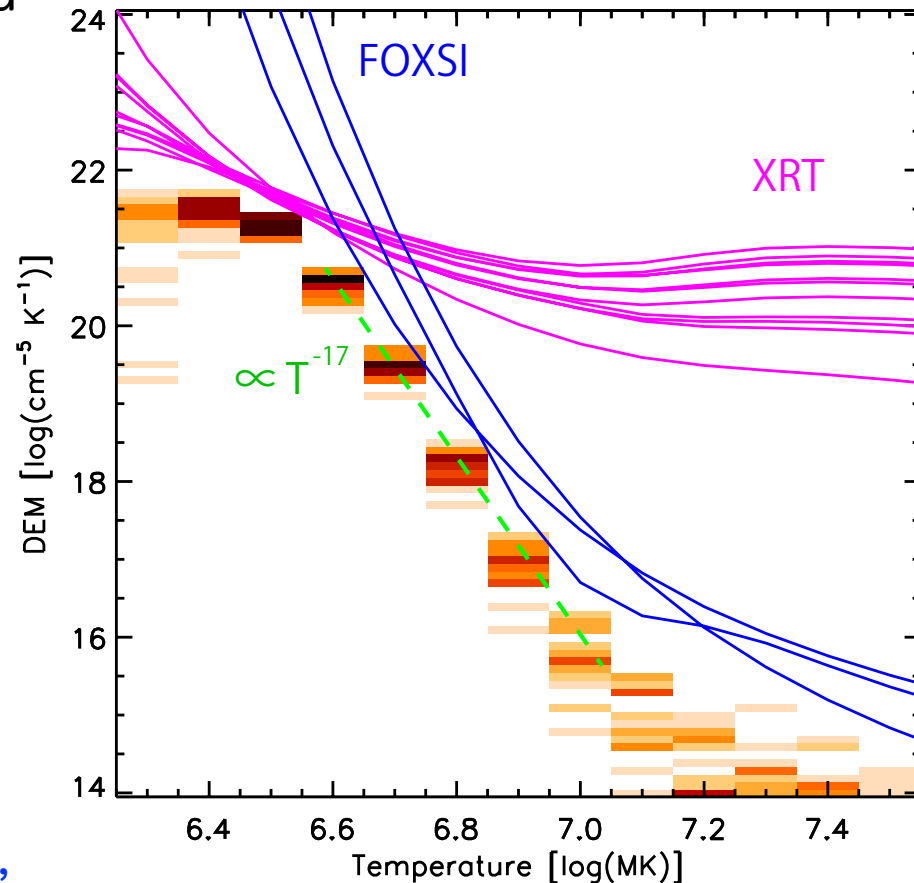
Using XRT_DEM_iterative2.pro in SSW
(χ^2 fitting, spline function, Monte Carlo run)
 χ^2 within 10 times minimum are plotted

FOXSI-2 5-6, 6-7, 7-9 keV counts
are used for the combined DEM
(not upper limit!)

Good DEM estimation is achieved
for wide temperature range with the
combination of XRT and FOXSI

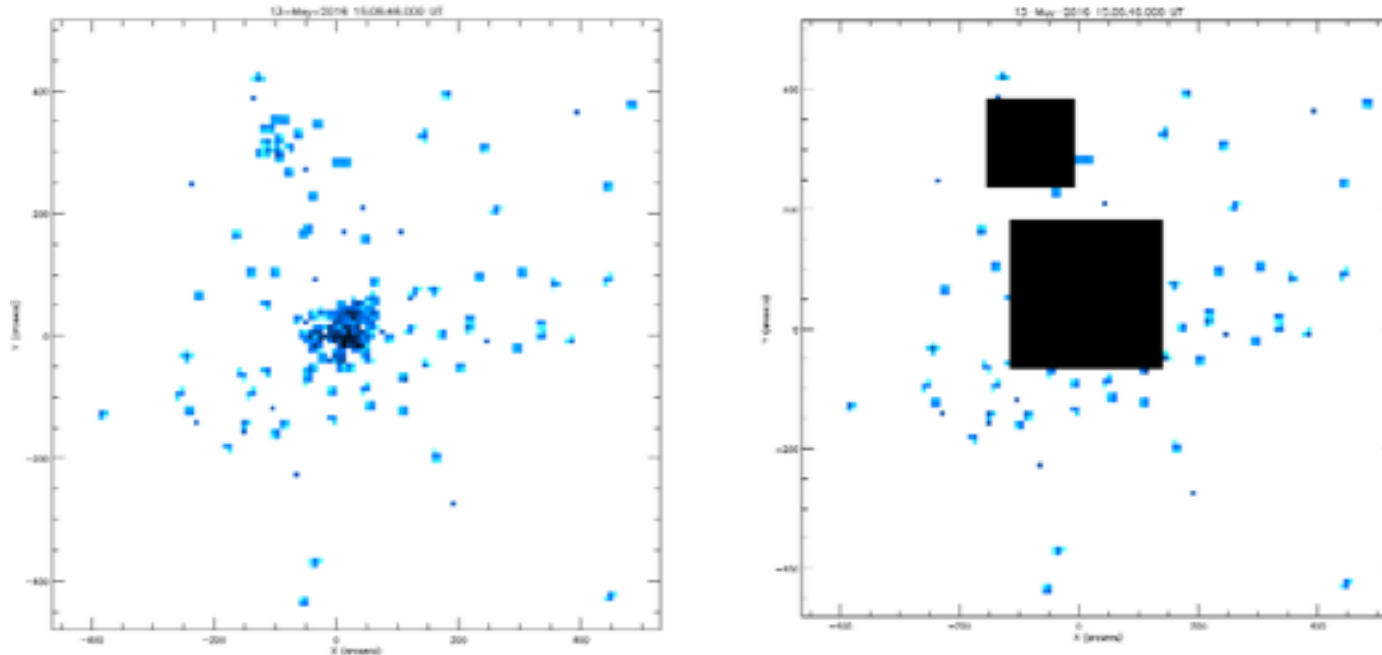
High energy slope of the DEM
is very steep, about -17

>10 MK plasma is strongly constrained,
but still suggested by the FOXSI 7-9 keV



7-9 keV counts are really from the non-flaring AR?

We checked the possibility if those counts are just background

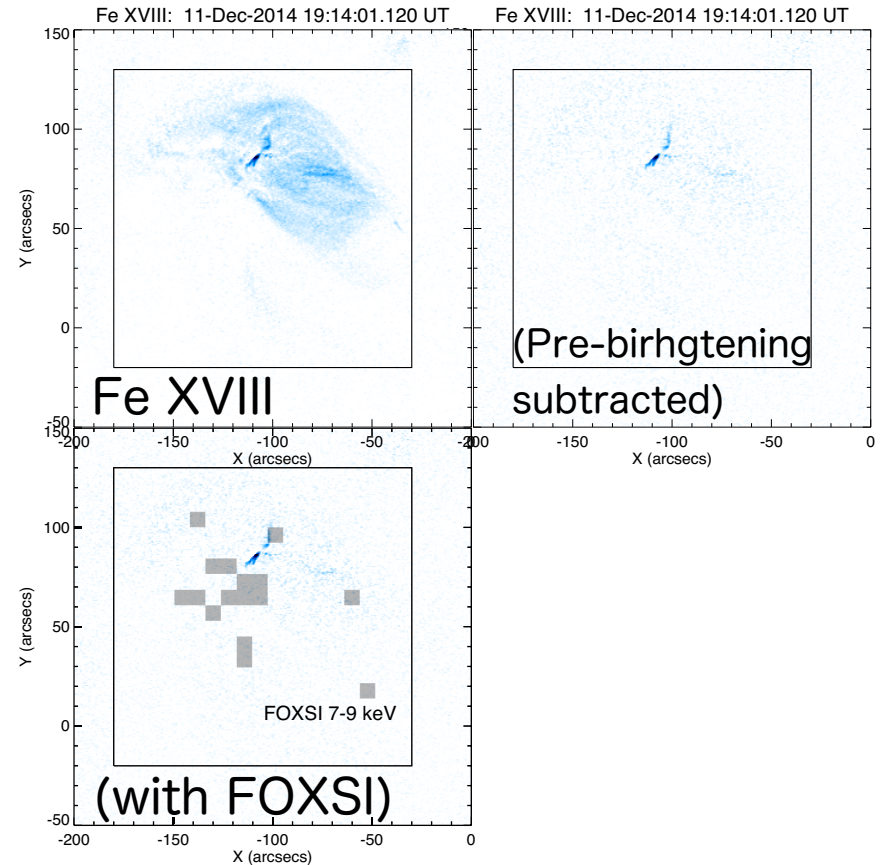
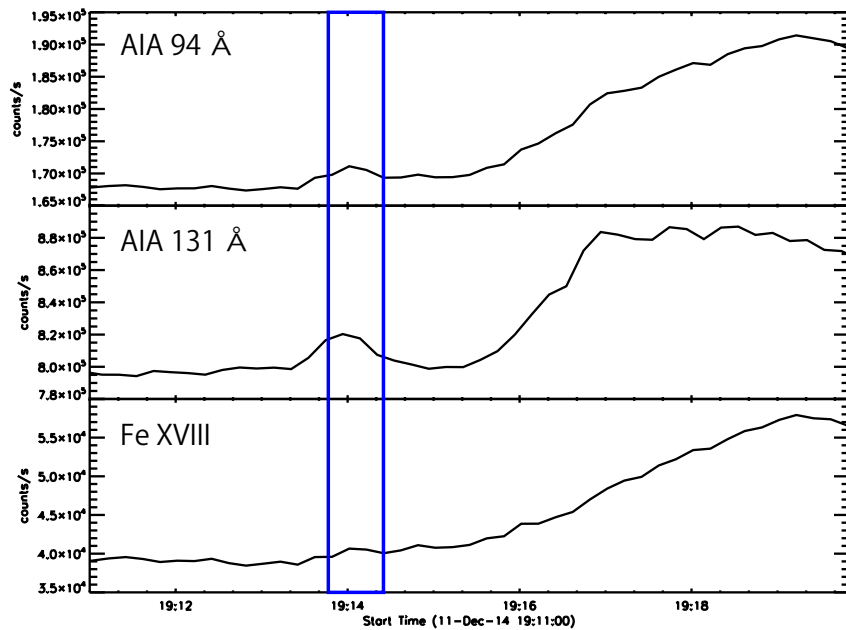


FOXSI 7-9 keV counts in the whole FOV

After the masking the two ARs, the averaged background counts are 1.58 (+/-1.26) counts/ROI including quiet Sun emission ghost rays from the ARs -> **16 counts are significant detection**

7-9 keV counts are really from the non-flaring AR?

We checked the possibility if those counts are associated with detected brightening event; we found a tiny AIA brightening

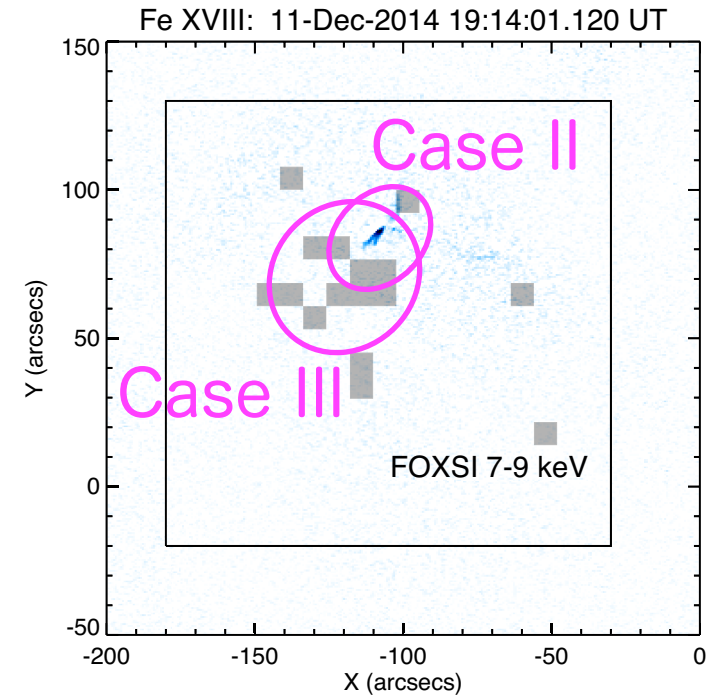


Estimated XVIII image shows a weak brightening of a loop, but the FOXSI 7-9 keV counts are much wide spread

3 cases of the origin of the 7-9 keV counts

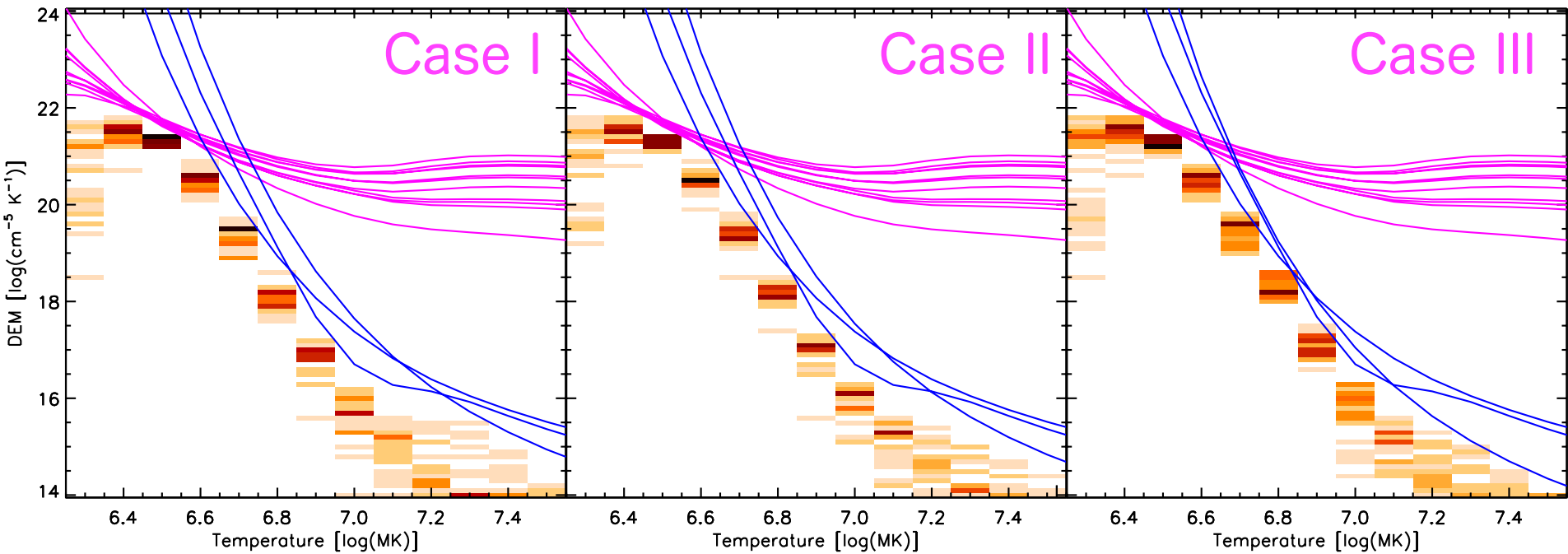
Some of the 7-9 keV counts might be associated with the AIA brightening or background

We investigated 3 cases with max/mid/min photons are from the target and compared the DEM solutions



	From AR, not flare [photons]	From AIA brightening [photons]	Background [photons]	Description
Case I	16	0	0	Extreme case; all the photons are from the target AR, non-flaring emission
Case II	12.5	2	1.5	Estimation: Half photons inside HPD x flare loop are from the flare (2/4), and average background
Case III	4	9	3	Extreme case: All photons inside 50'' circle after 20'' shift are from the flare, and background counts are double the average

DEMs with the 3 cases



- DEM solution does not change so much
- Hot (> 10 MK) component is still required to explain even with the case III

Summary

By the rocket experiment FOXSI-2, we successfully performed HXR imaging and spectroscopy from an AR during the time duration with no obvious GOES or XRT flare

We estimated the DEM with XRT multi-filter observations and HXR imaging spectroscopy, and the combination of Hinode/XRT and FOXSI-2 produced the good DEM estimation over the wide temperature range ($\log T = 6-7.5$)

The DEM slope at the high temperature was very steep

Significant detection of 7-9 keV photons suggests the existence of > 10 MK plasma