Searching for faint solar HXRs with NuSTAR

Iain G. Hannah[1]

[1]University of Glasgow

B. W. Grefenstette[2], D. M. Smith[3], L. Glesener[4,5], S. Krucker[4,6], H. S. Hudson[1,4], K. K. Madsen[2], A. J. Marsh[3], S. M. White[7], P. Wright[1], M. Kuhar[6], A. Caspi[8], A. Y. Shih[9], J. Vogel[10] & NuSTAR SSC

[2]Caltech, [3]UC Santa Cruz, [4]UC Berkeley, [5]Minnesota, [6]FHNW, [7]AFRL, [8]SWRI, [9]NASA/GSFC, [10]LLNL

AIA+XRT+NuSTAR
29-Apr-2015

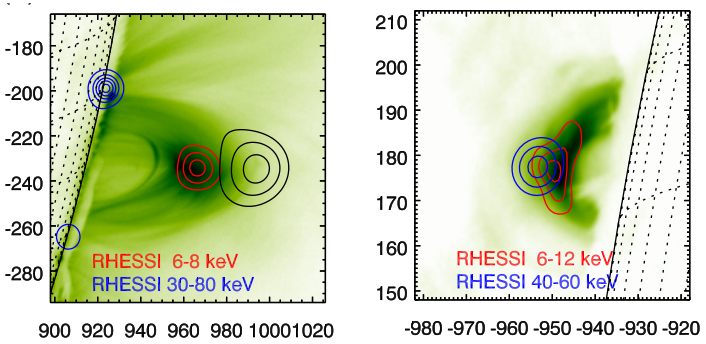
iain.hannah@glasgow.ac.uk

Overview

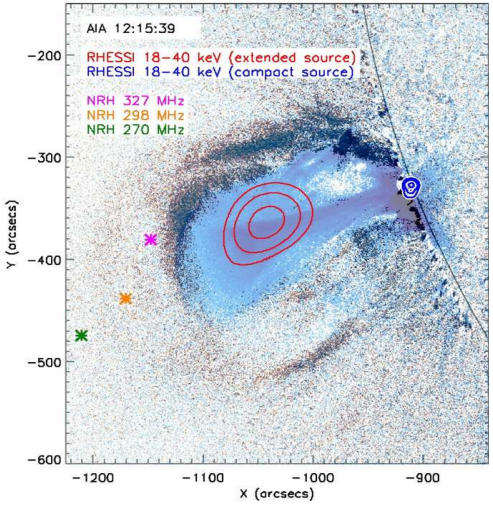
- **X-rays: crucial diagnostic of energy release in the Sun's atmosphere**
  - Thermal (lines + continuum) & non-thermal properties
- **RHESSI does this for X-Class flares down to A, B microflares**
- **To go beyond RHESSI need higher sensitivity & dynamic range**
  - Coronal energy release site, escaping/Type III electrons, CME accelerated electrons (trapped, current sheet, shocks) etc
  - Accelerated electrons in <A microflares, high temperature and non-thermal nanoflares
  - Axions (see Hugh Hudson or Julia Vogel)
- **NuSTAR provides a unique HXR sensitivity for observing the Sun**
  - But not the dynamic range & tricky to use the full sensitivity.
    - Need occulted footpoints & loop for coronal sources
    - Need lower levels of activity on whole solar disk

Coronal Sources

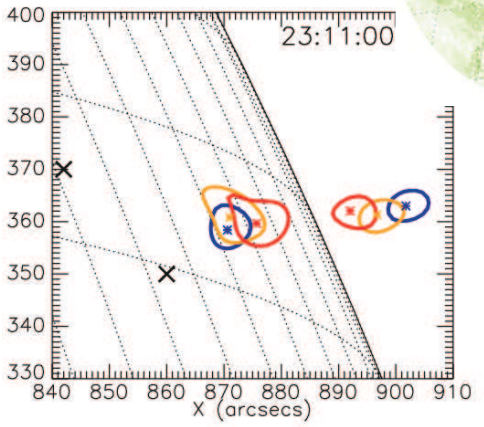
- **Normally only see bright HXR footpoints and infer coronal properties – want to directly probe the faint coronal sources**
  - Accelerating, trapping, escaping electrons



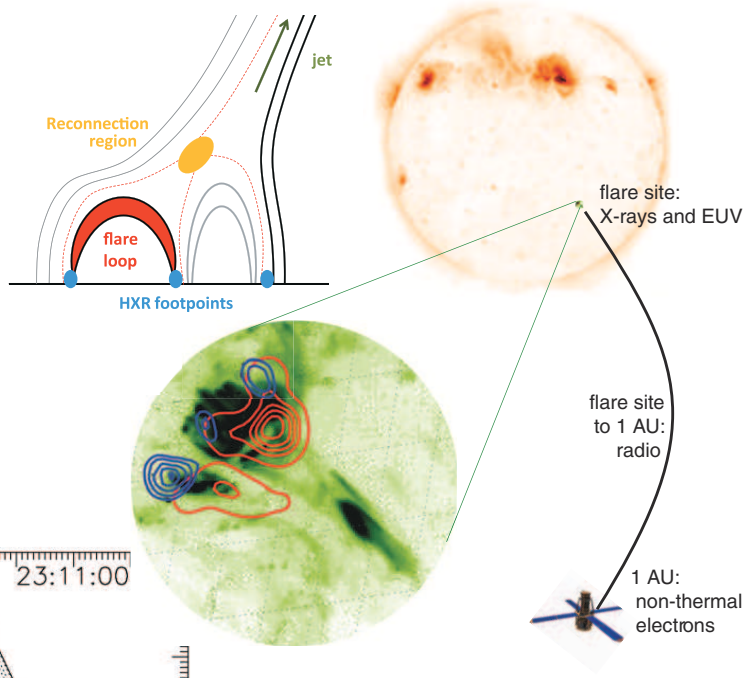
Oka et al. 2015

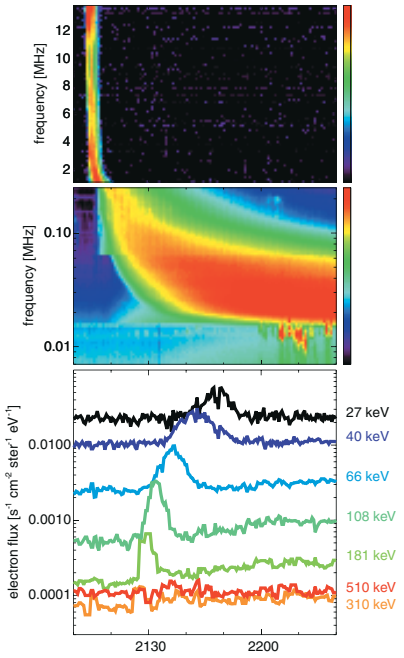


Bain et al. 2012



Sui & Holman 2003



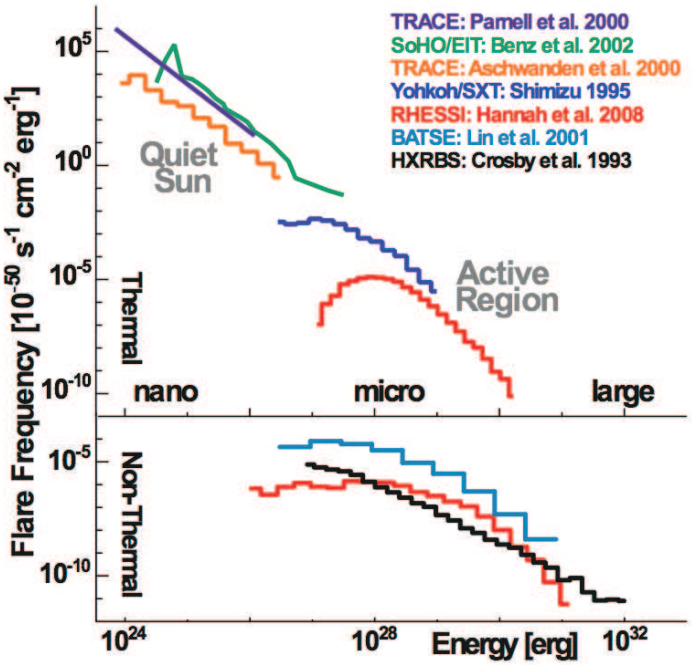


Krucker et al. 2011

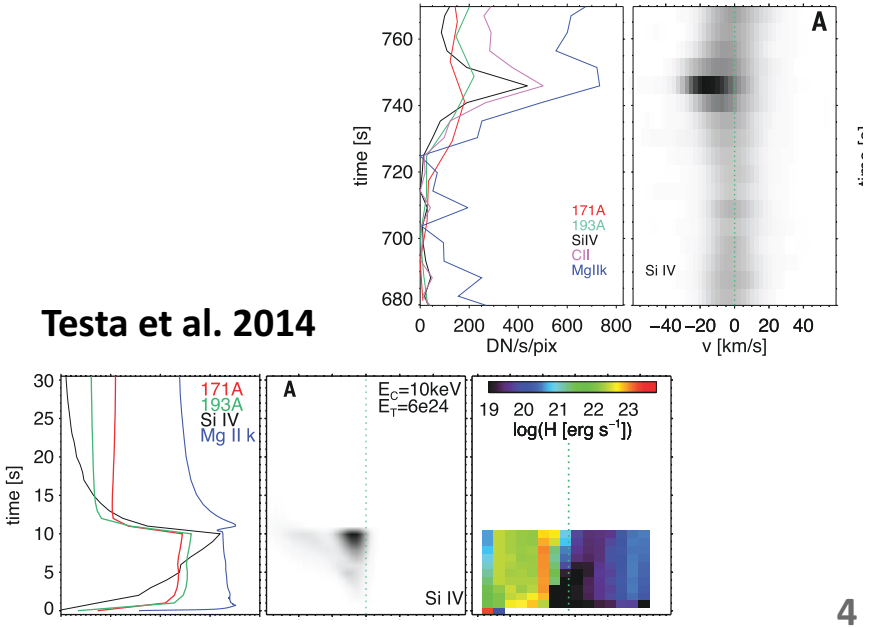
Smaller Non-thermal Flares

- **RHESSI microflares (A, B-GOES class) have HXR non-thermal emission**
- **Impulsive heating events in EUV/SXR**
  - Sometimes called “nanoflares”
  - SphinX <A-Class flares (Sylwester et al. 2009, Gburek et al. 2011)
- **Can these smaller events also accelerate electrons?**
  - Weak HXR signal not detected (yet)
  - Non-thermal clues from radio
  - Indirect evidence from IRIS UV & RADYN simulations (Testa et al. 2014)

Hannah et al. 2011

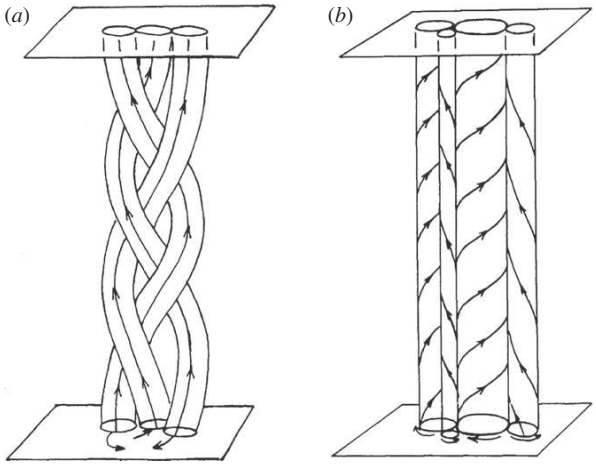


Testa et al. 2014



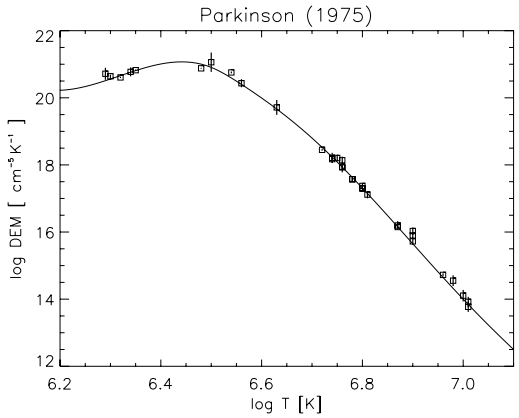
Quiescent & Non-thermal?

- **Are Parker's nanoflares small impulsive events, that heat and accelerate electrons?**
  - Events so small & frequent cannot distinguish them individually (e.g. Glencross et al. 1975)
  - Appears "non-flaring"/quiescent

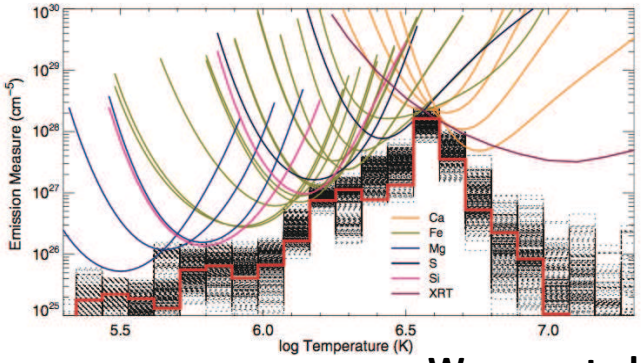


Parker 1988

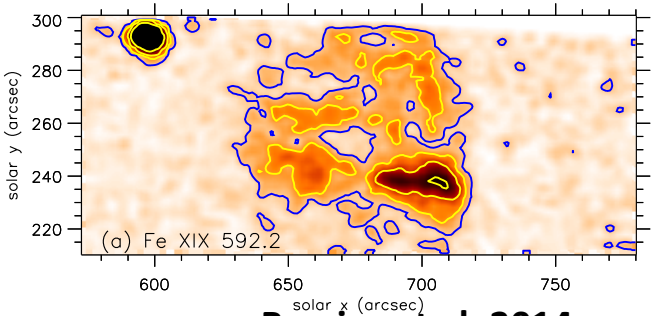
- **Detect via their impact on the DEM**
  - Models of the DEM and high T (>5MK) component (e.g. Sturrock et al. 1990, Cargill 1994)
  - EUV obs, but limited X-ray data and get very steep DEMs - need SXR & HXR



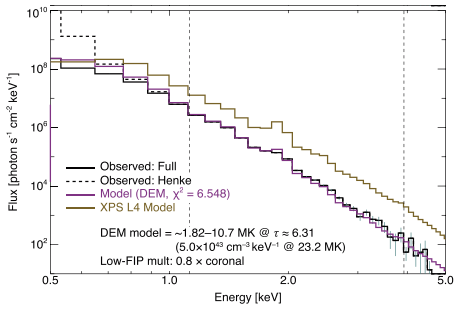
Del Zanna & Mason 2015



Warren et al. 2011



Brosius et al. 2014

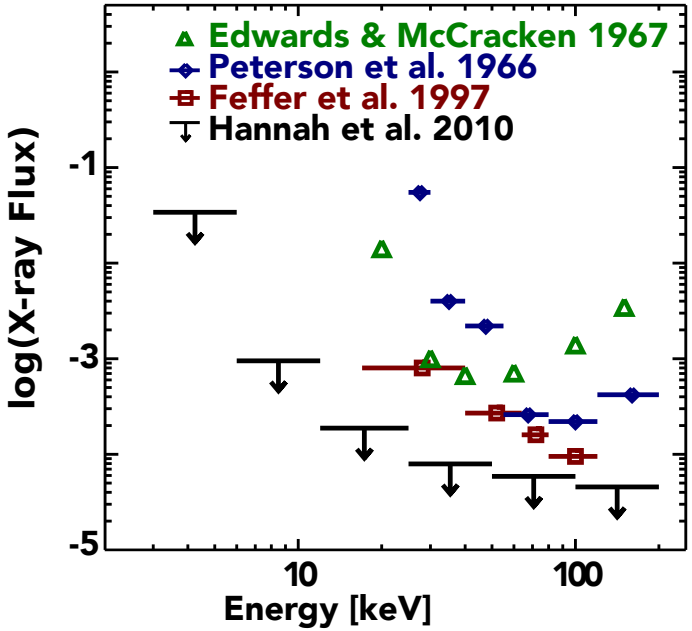


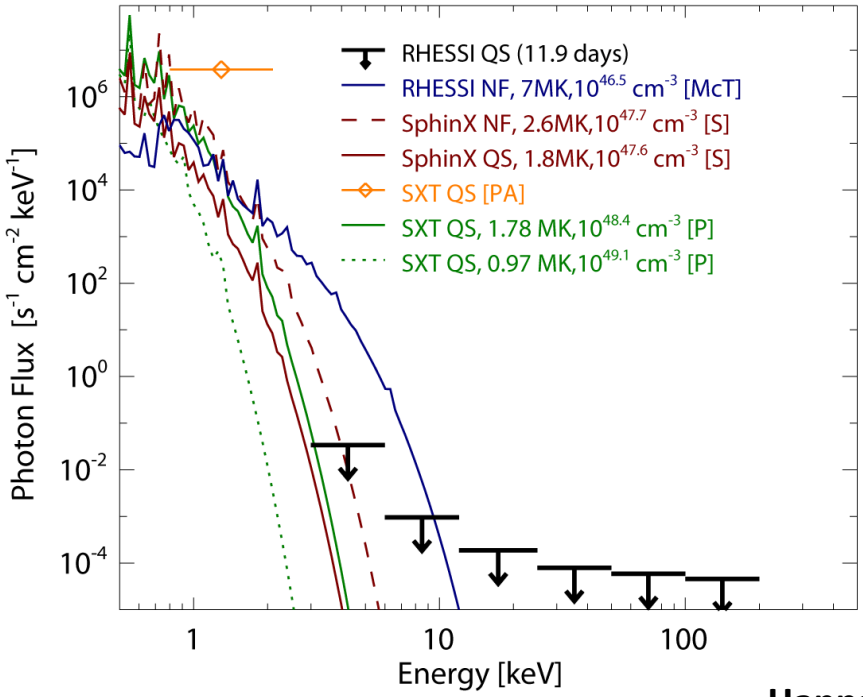
Caspi et al. 2015

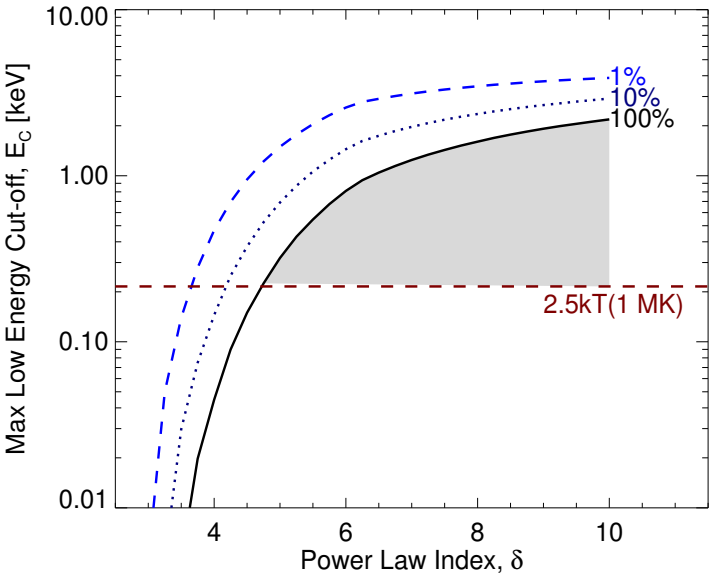
Quiescent & Non-thermal?

- **Detect via their weak HXR emission from non-flaring ARs or Quiet Sun**

- **But RHESSI not sensitive enough**
  - ARs 6-8MK (McTiernan 2009)
  - QS HXR limits (Hannah et al. 2007, 2010)







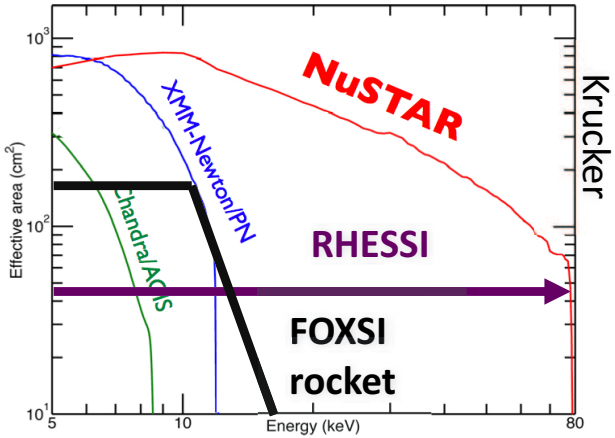
Hannah et al. 2010

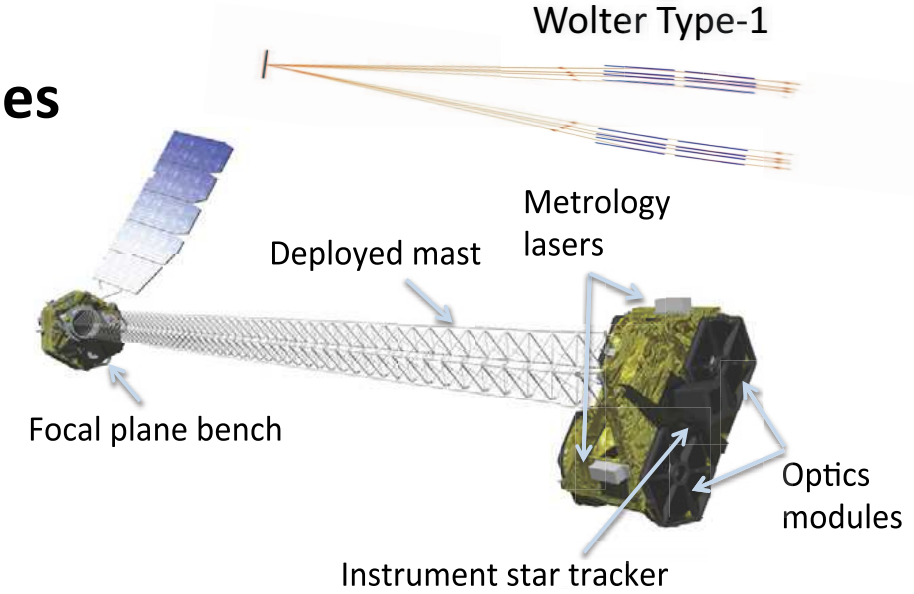
So….

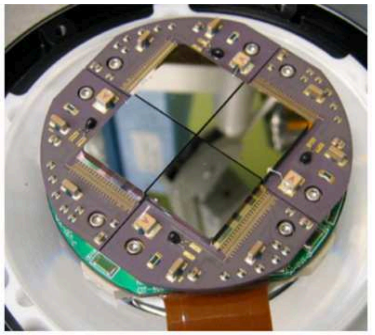
- **Many exciting science targets but need high sensitivity (with low background) and high dynamic range X-ray imaging spectroscopy**
  - Coronal emission weak relative to footpoints
  - Weak emission from the hottest and non-thermal in small events
- **Have FOXSI-1, FOXSI-2, FOXSI-3 and…..**
  - See Christe/Glesener/Krucker but “only” sounding rockets so far
- **Sensitive SXR spectrometers would also be very useful**
  - Cubesats (like MinXSS) and MaGIXS sounding rocket
- **Have NuSTAR**
  - Highly capable of solar observing but not optimized
    - Main targets not in the solar system
    - High sensitivity but not the dynamic range

NASA's NuSTAR

- **Astrophysics HXR imaging spectrometer**
  - Nuclear Spectroscopic Telescope Array
  - Launched June 2012 (Harrison et al. 2013)
  - x20 RHESSI's effective area at 10keV
- **Two (A+B) grazing incidence telescopes**
  - 10 m focal length
  - 12'x12' FOV (FWHM: 18")
- **Detectors per telescope module:**
  - 2.5-78 keV (5.0 - 0.15Å)
  - Four 32 x 32 pixel detector
  - Max throughput: 400 cnts s^{-1} mod^{-1}
  - Output is eventlist: E,t,x,y per X-ray
    - And pixel grade info

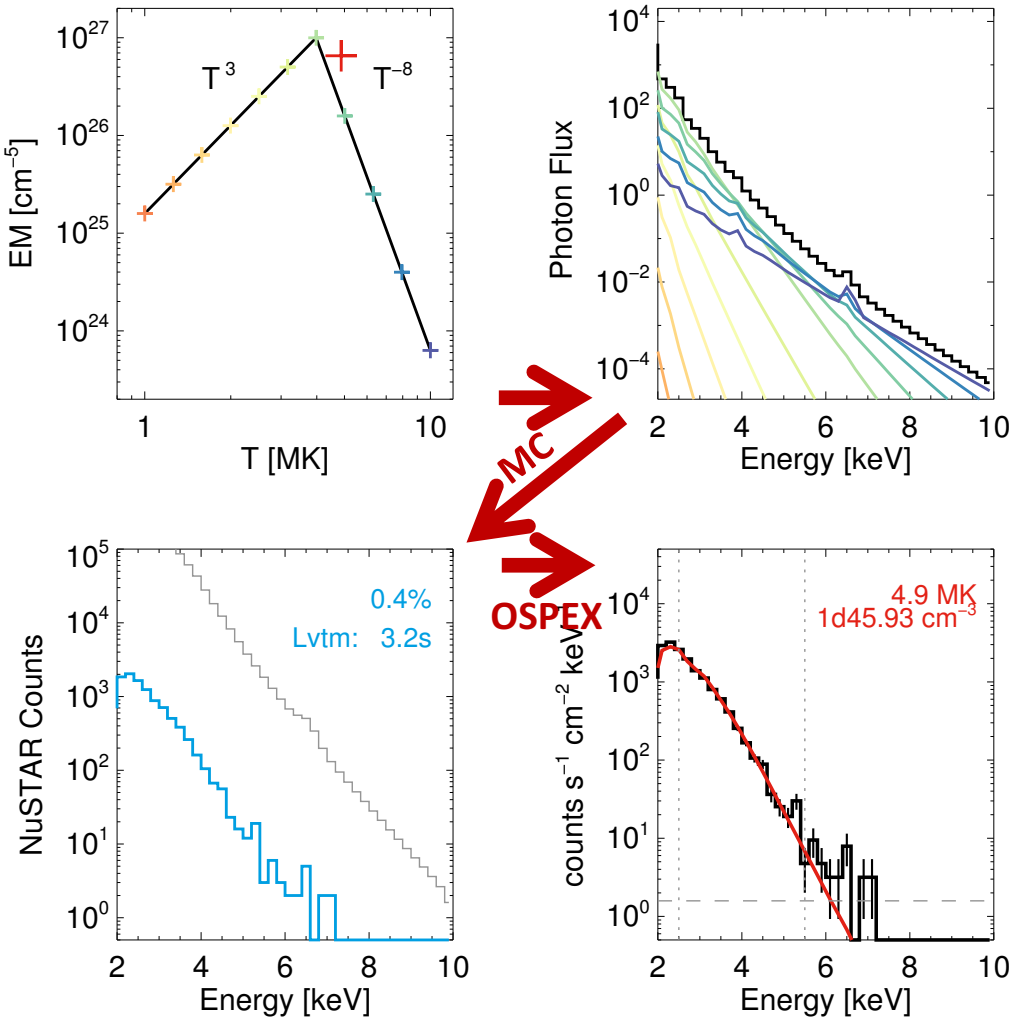






NuSTAR Solar Challenges

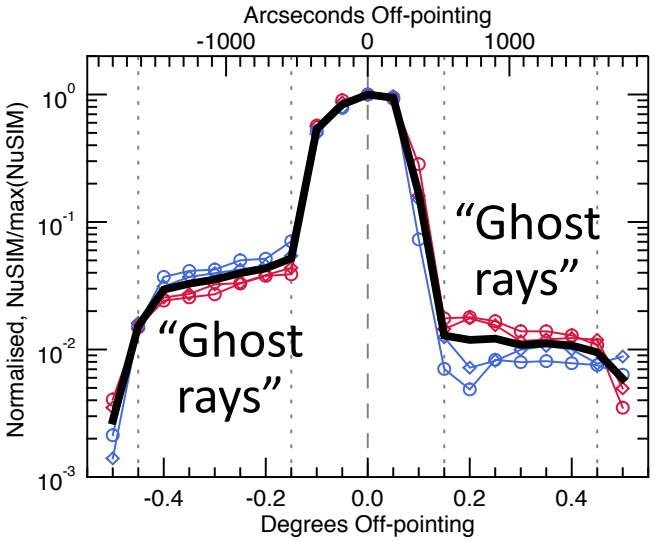
- **Highly capable but not optimised for solar pointing**
  - Limits ability to use full sensitivity
- **Low detector throughput rate**
  - High deadtime which limits the spectral dynamic range
  - But additional grade info helps with pile-up
- **Pointing about 1’ off and changes - manually align data**
  - And software pipeline designed for non-solar



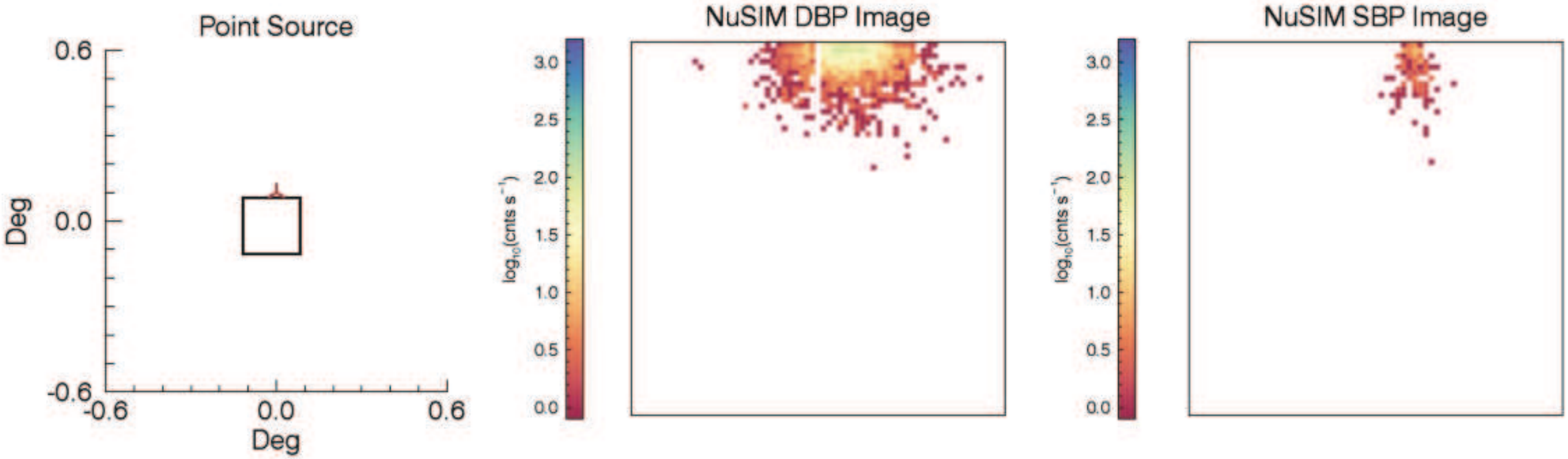
Limited spectral dynamic range from short effective exposure (low livetime)

NuSTAR – Ghost Rays

- **"Ghost rays": single-bounce photons, mostly from sources outside the FOV**
  - Madsen et al. 2015
- **Weak (1/100th) compared to properly focused double-bounce photons**
  - But problematic if bright sources outside FOV (livetime worse)



Grefenstette et al. 2016

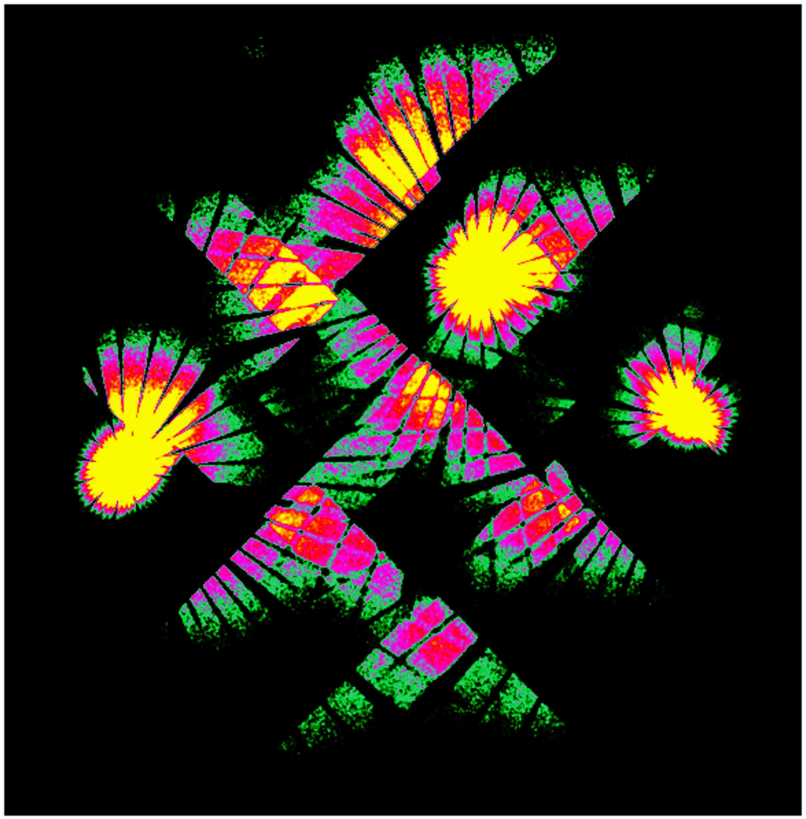


Simulated NuSTAR off-axis response to bright point source

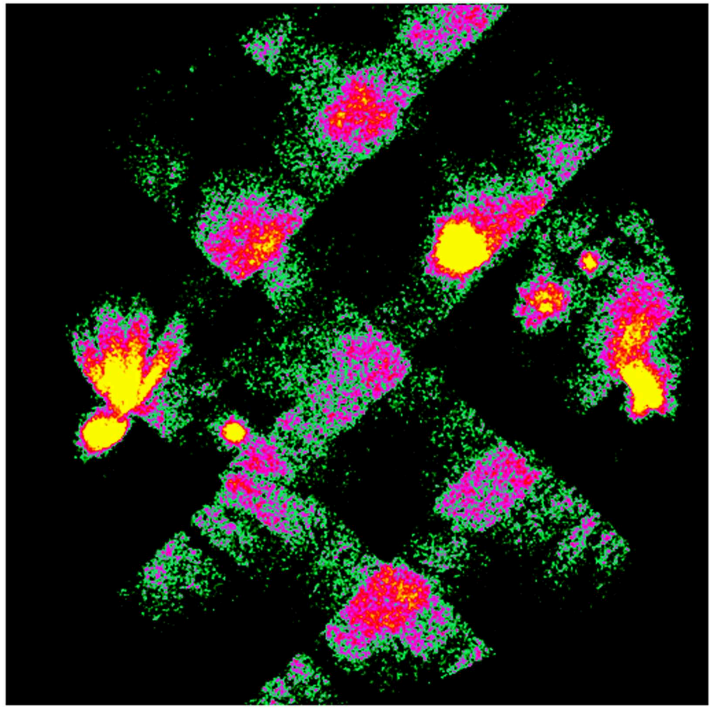
NuSTAR – Ghost Rays

- **If know sources outside FOV can simulate the ghost ray pattern**

Grefenstette et al. 2016



Simulate ghost-ray pattern



Apr-2015 full disk mosaic observation

NuSTAR Solar So Far

#	Date	Orbits (≈hr)	Target(s)	+
0	10 Sep 2014	2	Pathfinder/engineering test	
1	1 Nov 2014	4	ARs near limb/occulted North Pole	
2	11 Dec 2014	1	Limb AR North Pole	FOXSI-2
3	29 Apr 2015	2	Full disk mosaics	Hinode/XRT
4	1/2 Sep 2015	8	Partial Disk Mosaic Limb/occulted AR	
5	19 Feb 2016	3.5	Limb/occulted AR	
6	22 Apr 2016	4	Limb/occulted AR Non-flaring AR	Hinode/XRT IRIS
7	26/27 Jul 2016	4	Limb/occulted AR Non-flaring AR/Quiet disk center	

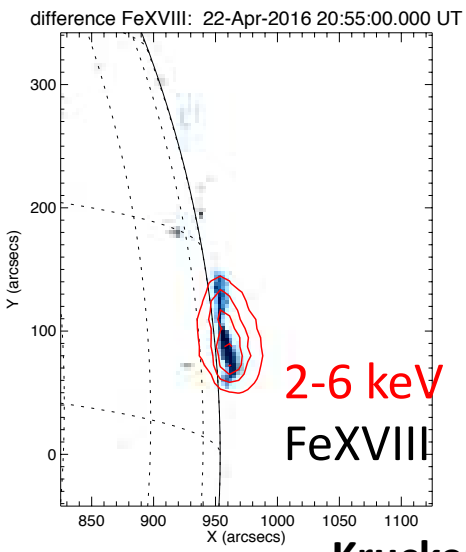
http://ianan.github.io/nsigh_all/

Grefenstette et al. 2016 ApJ 826, 20 - Overview of #0-3
Hannah et al. 2016 ApJ 820 L14 - Covers some of #1

NuSTAR Occulted ARs

- **Need ARs to be behind the limb (and flaring)**
- **Several observations from NuSTAR**
  - Loops & High coronal sources so far

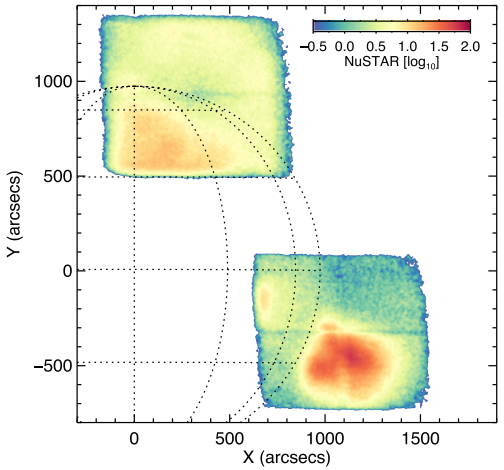
22-Apr-2016



Krucker

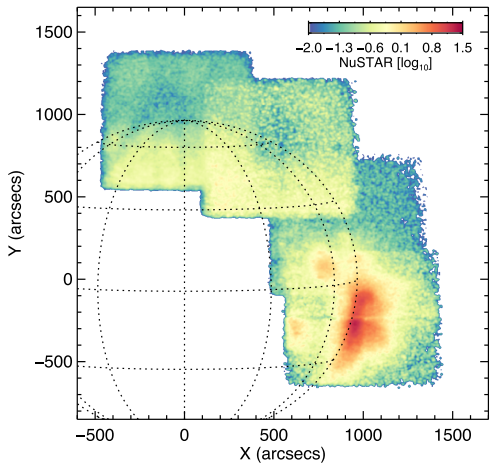
Background blue/green/yellow are ghost-rays from bright AR outside the FOV

11-Dec-2014

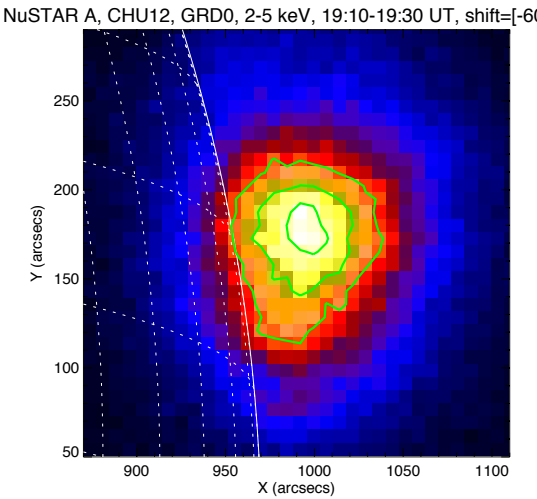


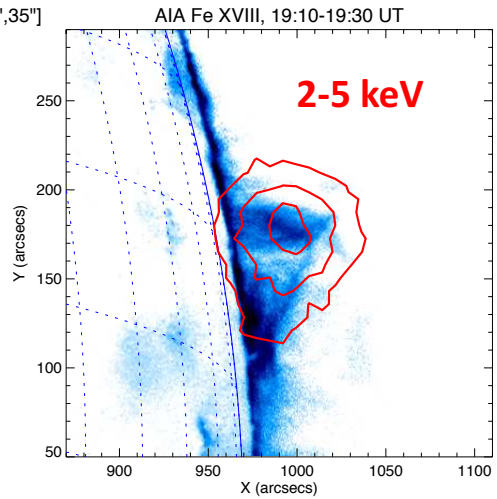
Grefenstette et al. 2016

01-Nov-2014



19-Feb-2016

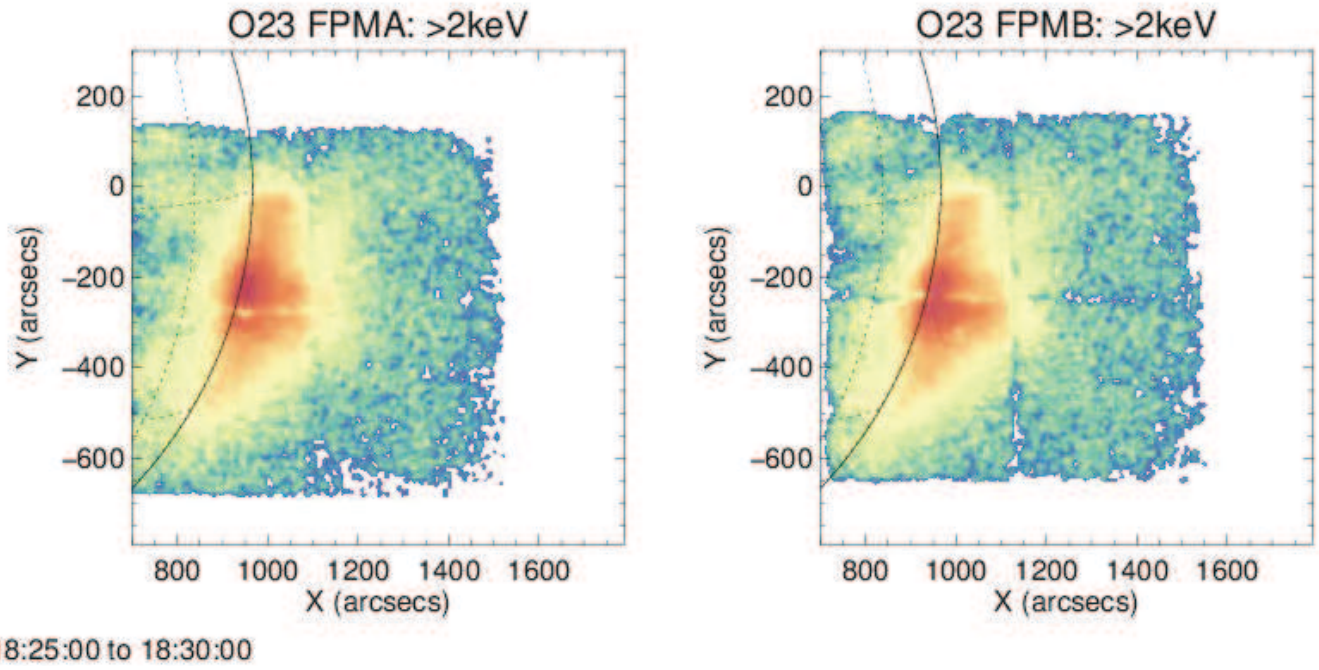




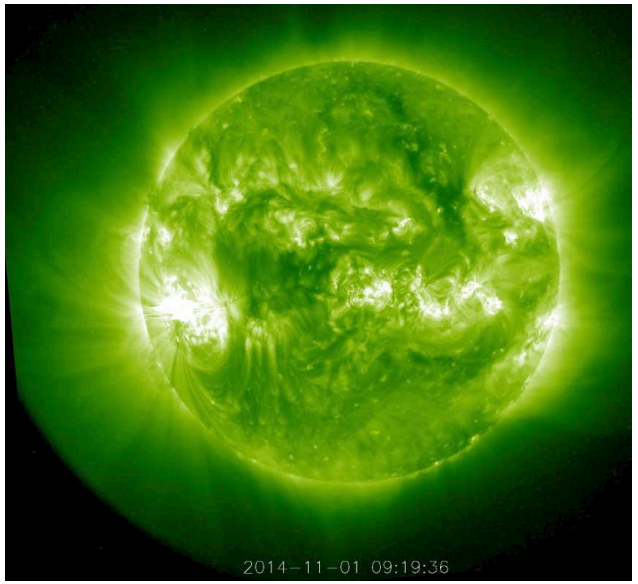
Krucker/Glesener

NuSTAR High Coronal Source: 01-Nov-2014

- **Not changing as pointing drifts & same source in both telescopes**
  - So not ghost rays
- **Large flare from AR12192 from 10hrs before**
  - Can still get a 4MK post-flare loop that long afterwards?

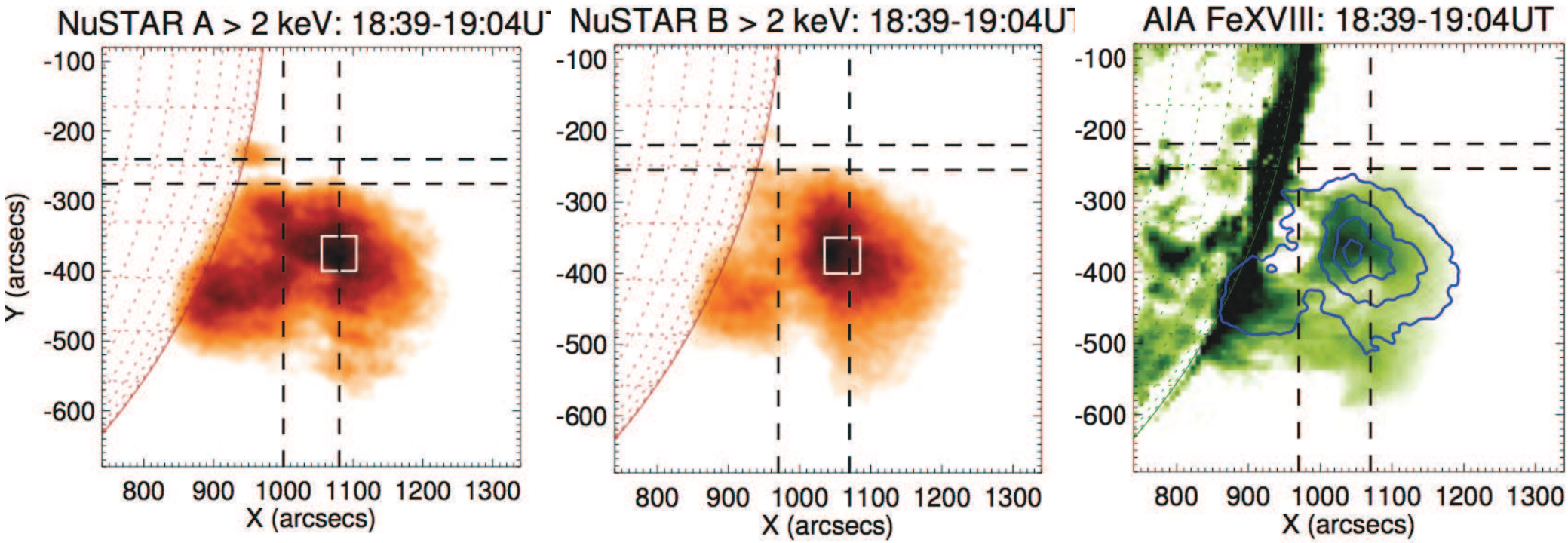


STEREO-A/EUVI 195Å 09:20UT



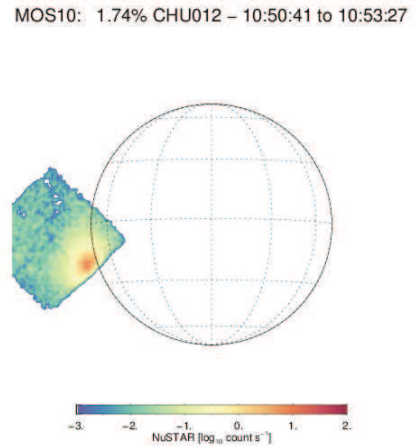
NuSTAR High Coronal Source: 11-Dec-2014

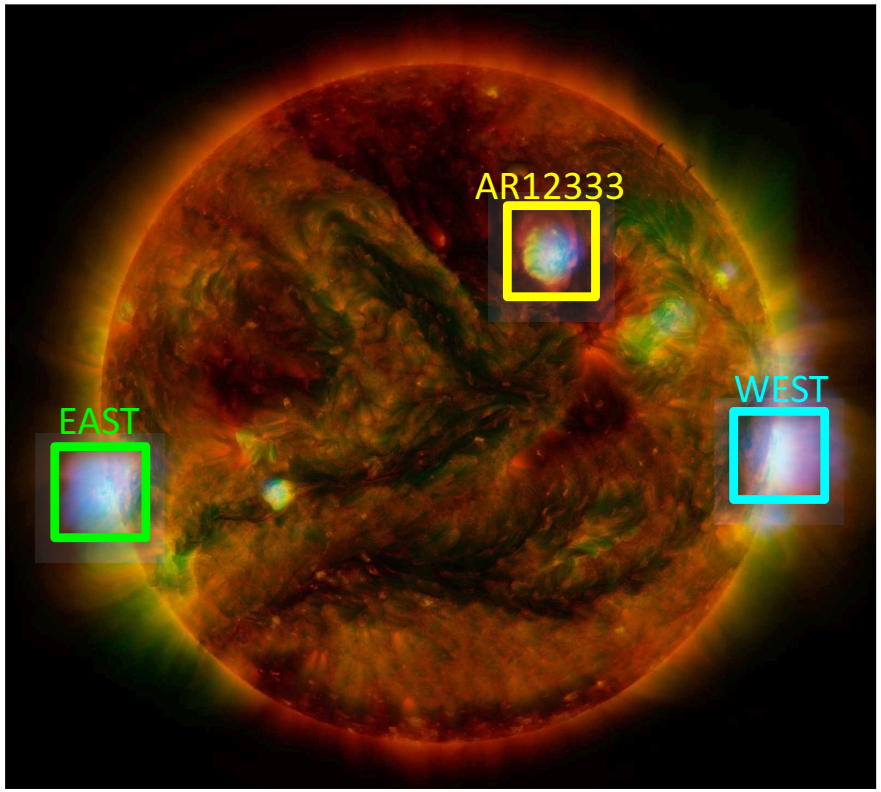
- See Matej Kuhar's talk Fri afternoon WG3
- 4MK post-flare loops associated with earlier large occulted flare

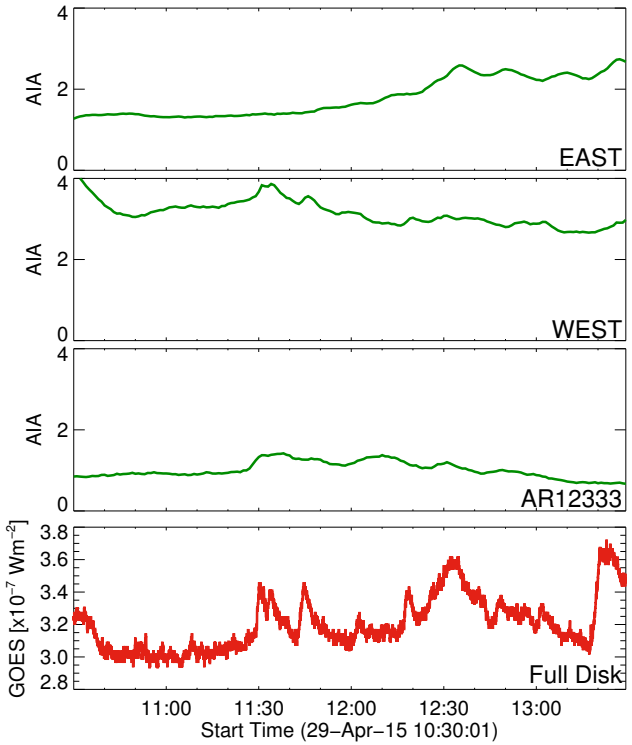


NuSTAR Microflare: 22-Apr-2015

- **During two full disk mosaics caught microflaring ARs**
  - 17 tiles, few mins per tile
- **Combined HOP with Hinode/XRT**
  - Full disk multi-filter 10:30, 13:30
  - AR12333 high cadence multi-filter

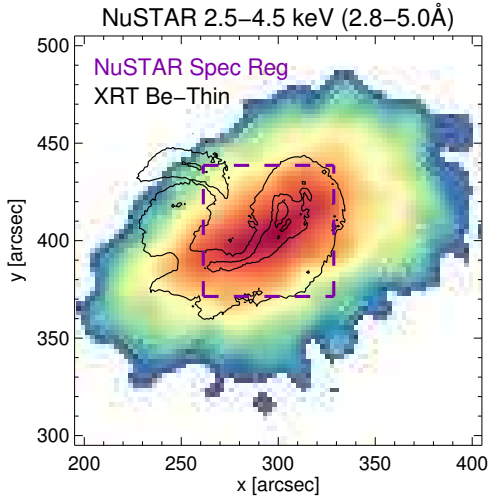


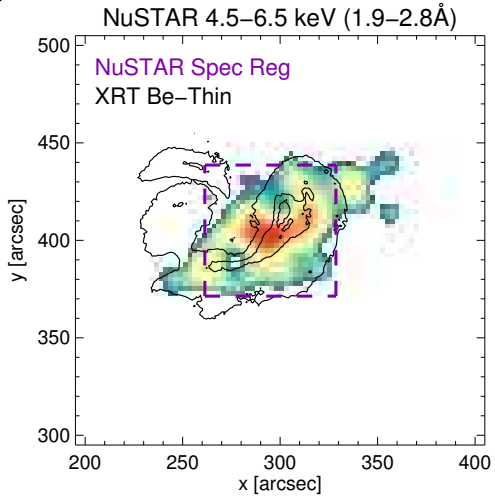


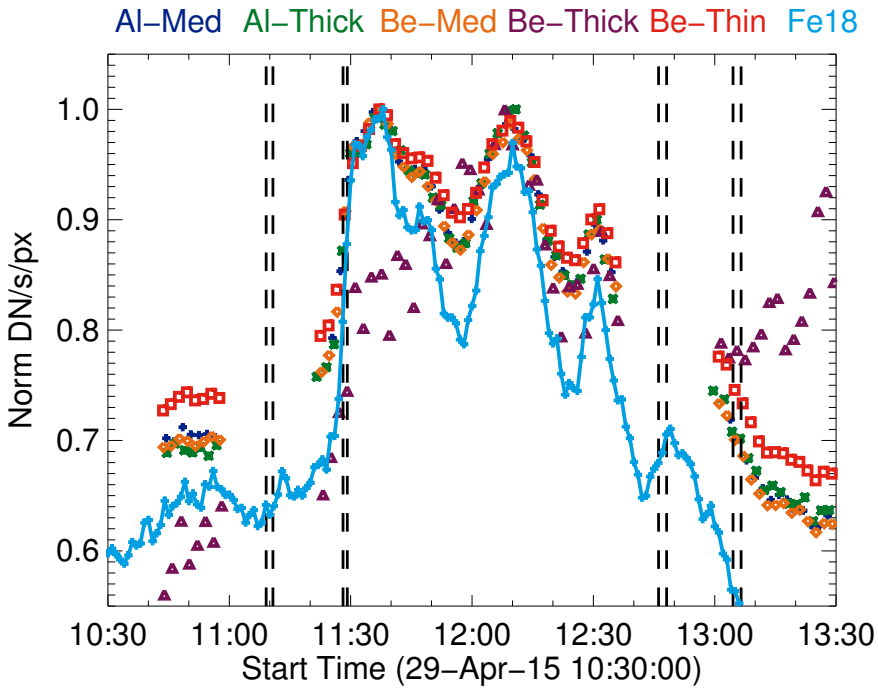


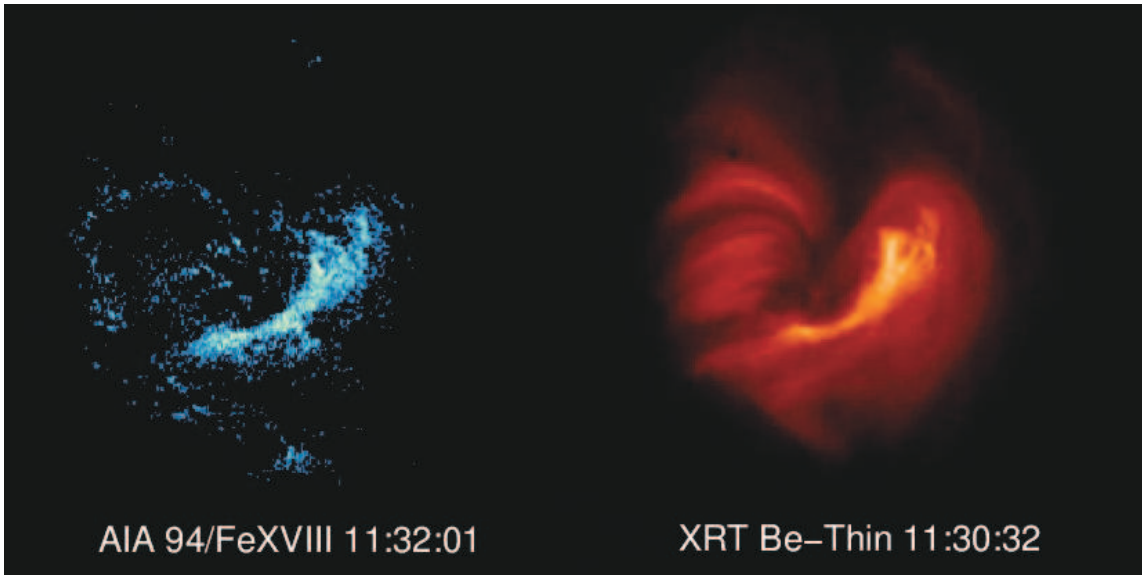
<A1 Microflares in AR 12333

- **NuSTAR saw region 4 times**
  - Once during impulsive rise



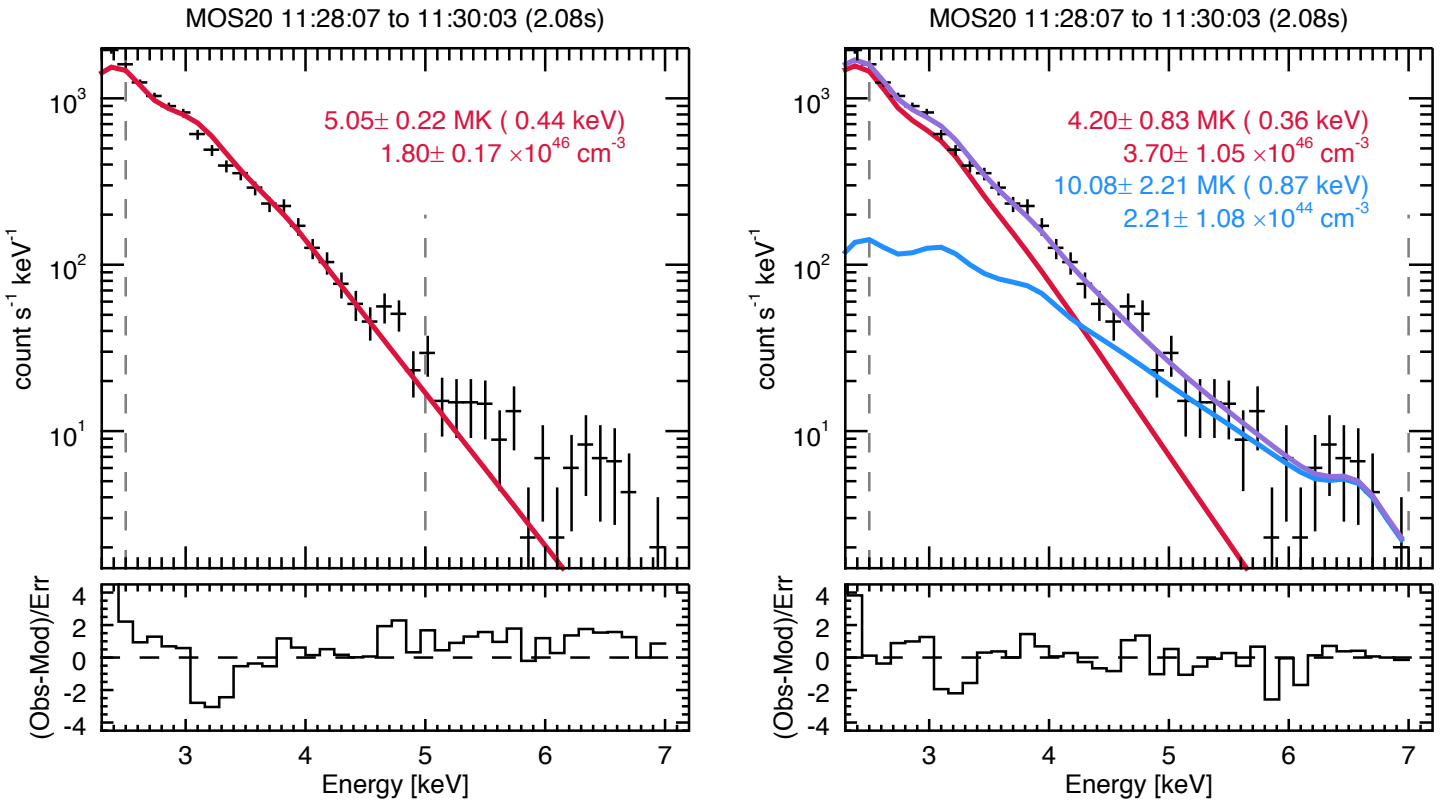






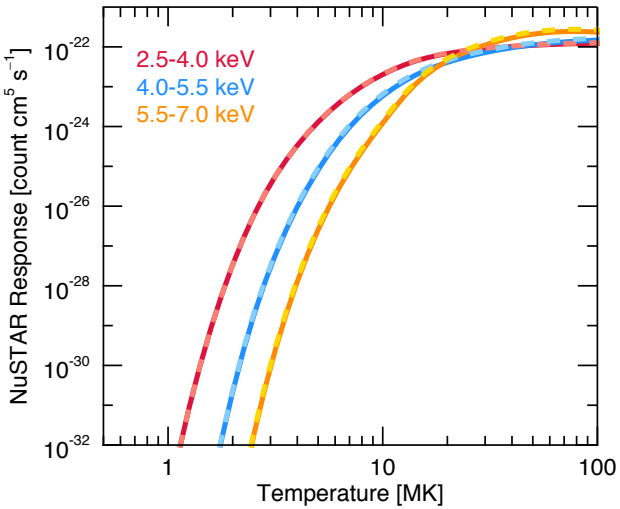
NuSTAR Microflare Spectra

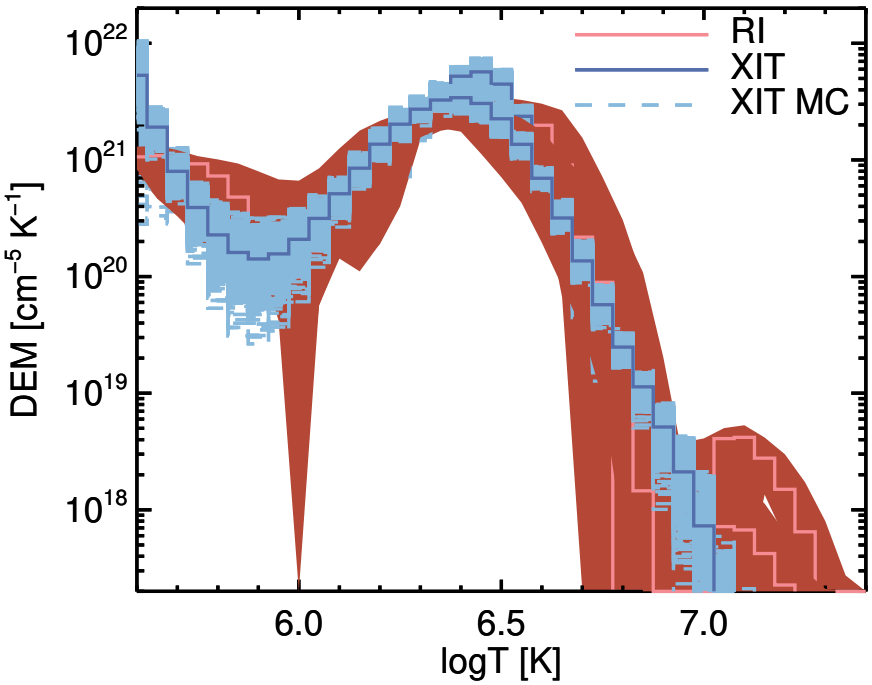
- **At the impulsive time, NuSTAR spectrum not isothermal**
  - Using XSPEC with APEC model
  - Other 3 times fitted well by isothermal 3-3.5 MK
  - No counts >7 keV due to short effective exposure

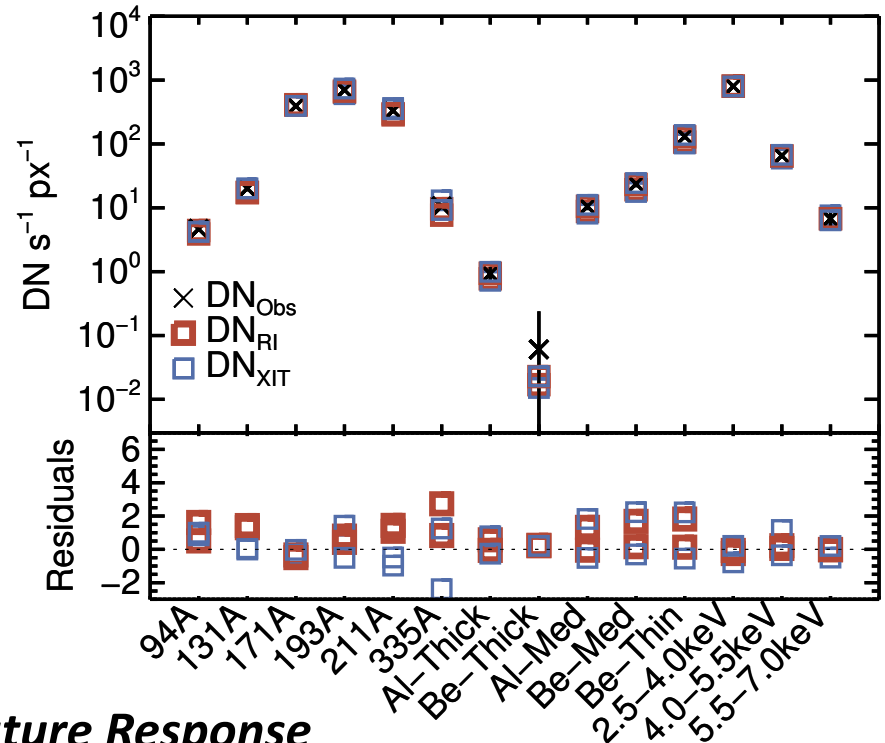


Microflare DEM: NuSTAR, AIA & XRT

- **NuSTAR purely thermal so can produce temperature response to calculate DEM**
  - XRT Iterative (Weber) and Regularized Inversion (Hannah & Kontar)
- **Better DEM if use x2(ish) XRT response**
  - Schmelz et al. 2015, Chueng et al. 2014



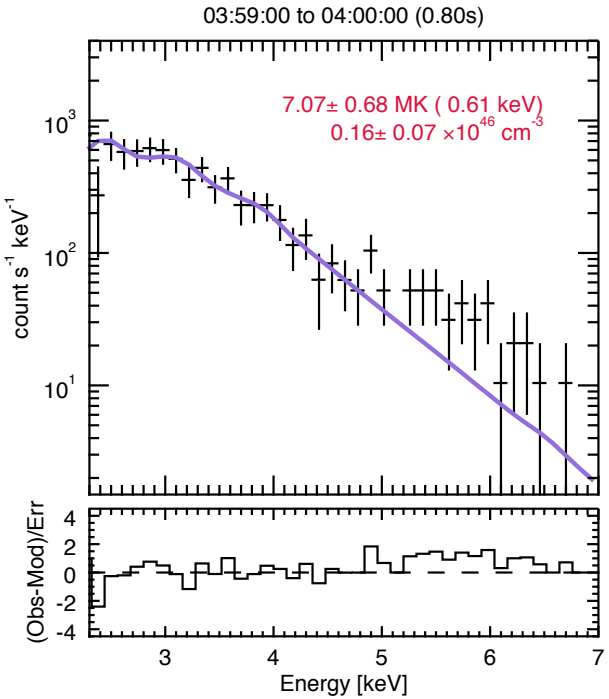


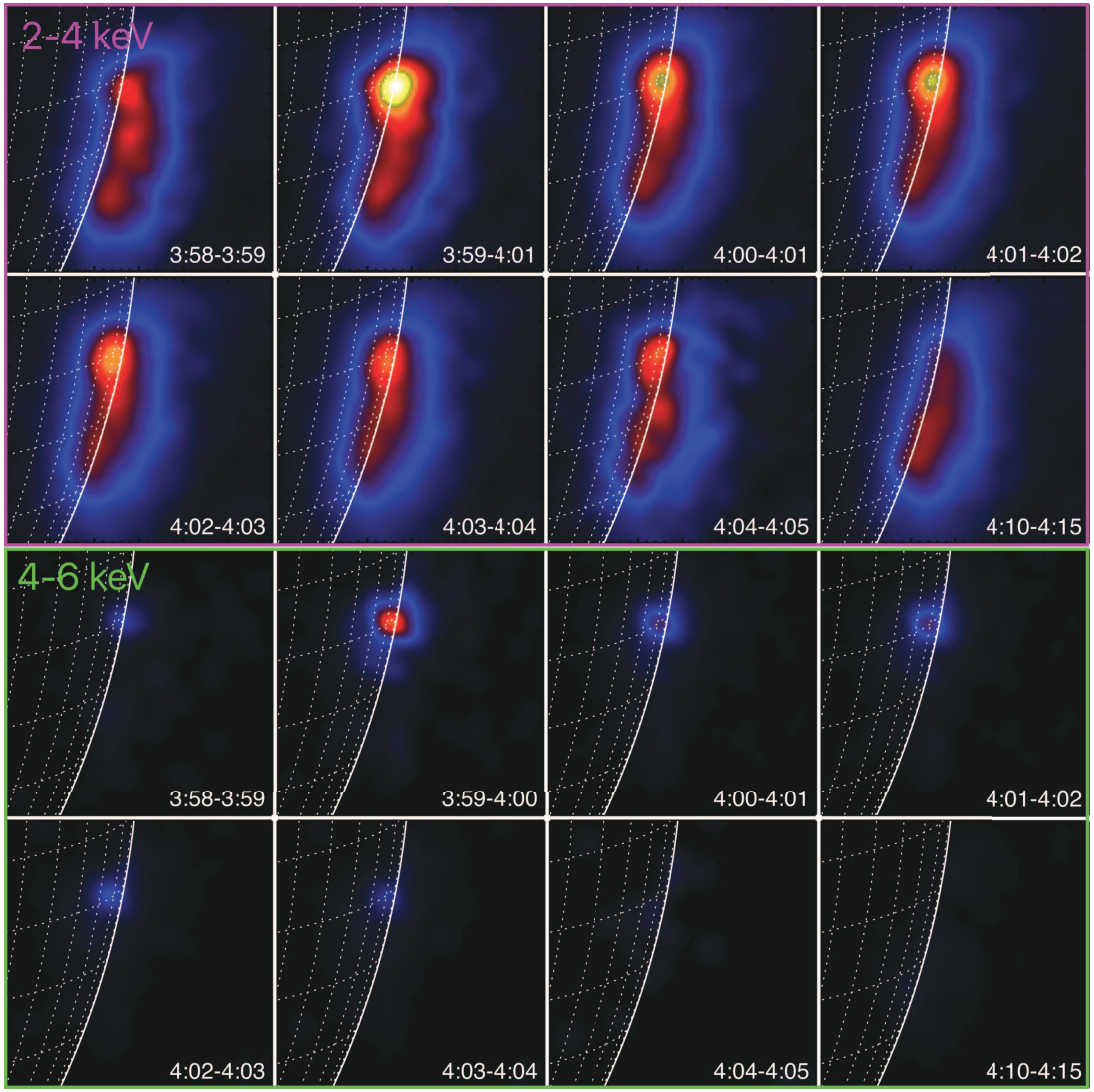


x2 XRT Temperature Response

NuSTAR Microflare: 01-Sep-2015

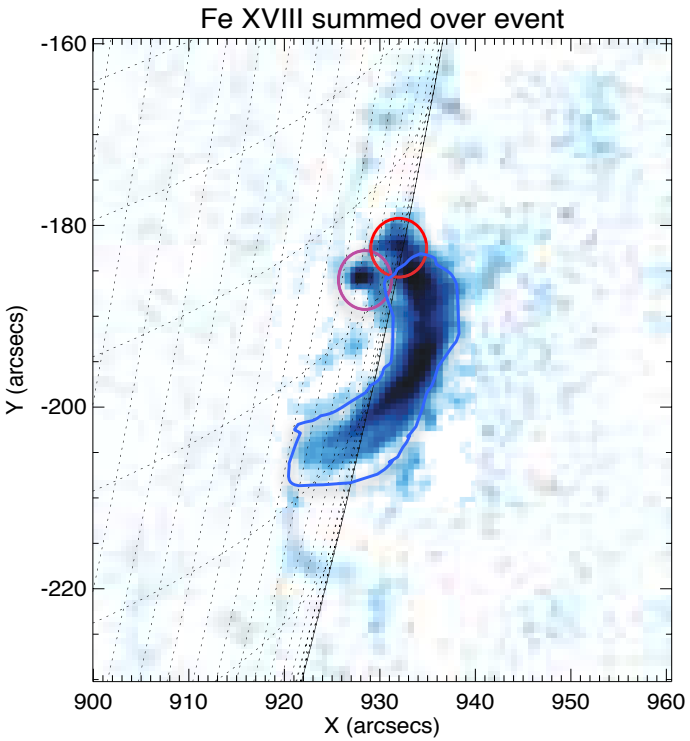
- Lindsay Glesener working on this event <A1
- Small limb flare but NuSTAR caught full time evolution

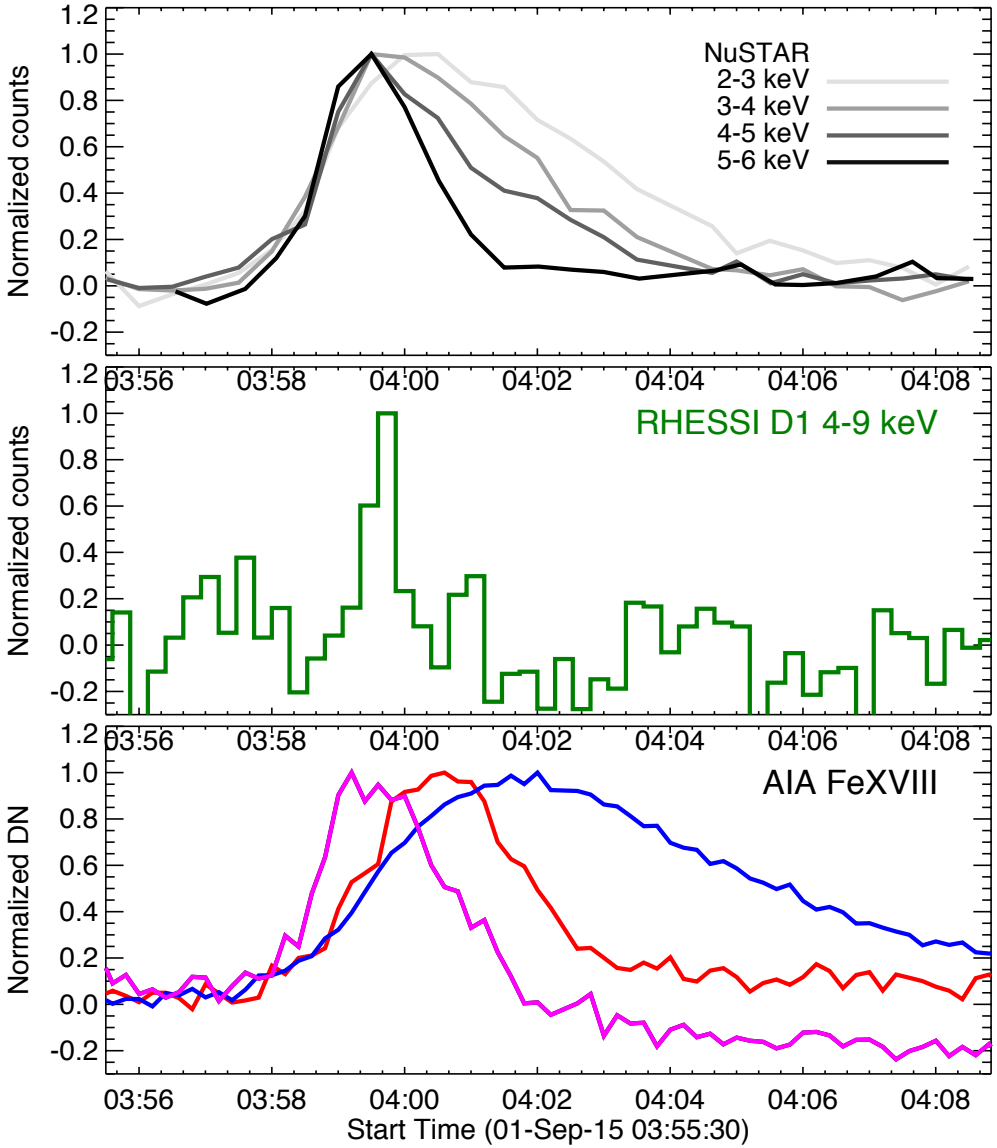




NuSTAR Microflare: 01-Sep-2015

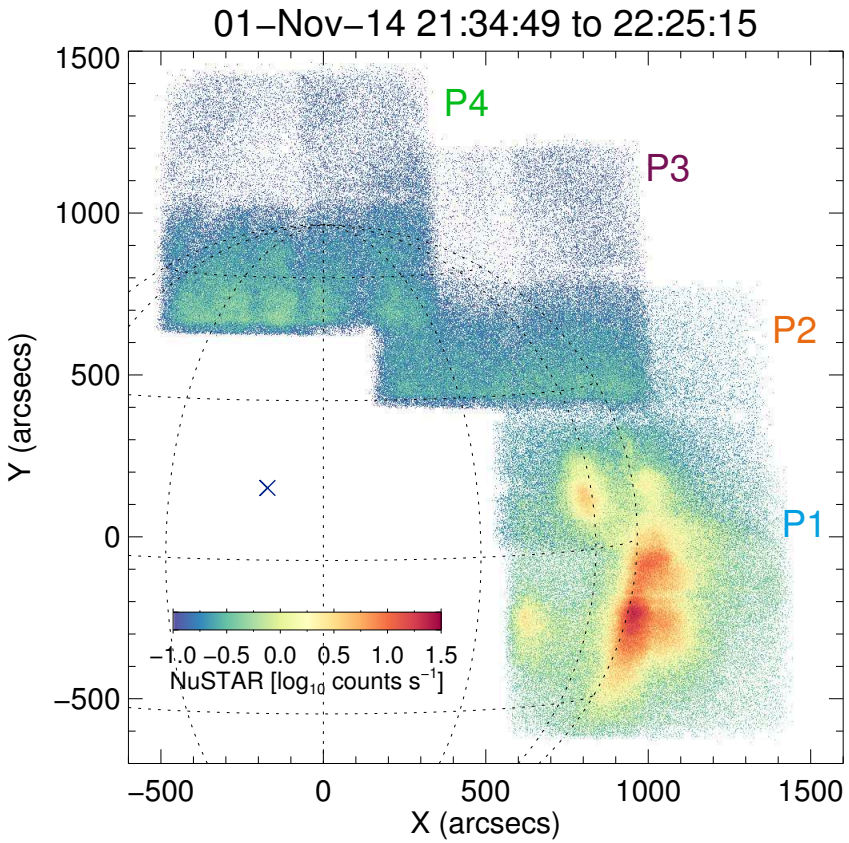
- **Higher energy peaks first**
- **AIA FeXVIII northern footpoints brightens with NuSTAR**



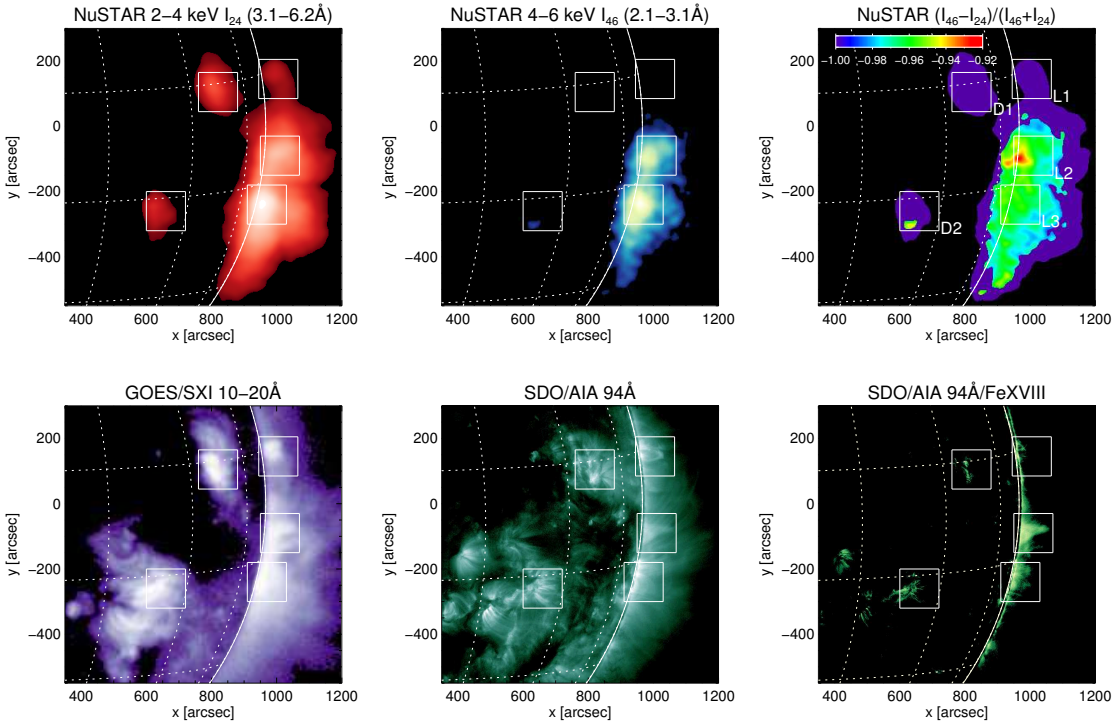


NuSTAR Non-flaring AR: 01-Nov-2014

- **From Hannah et al. 2016 ApJ 820 L14**
- **Four limb pointings that caught non-flaring ARs**



NuSTAR image >2 keV
Four pointings (P1 to P4) combined

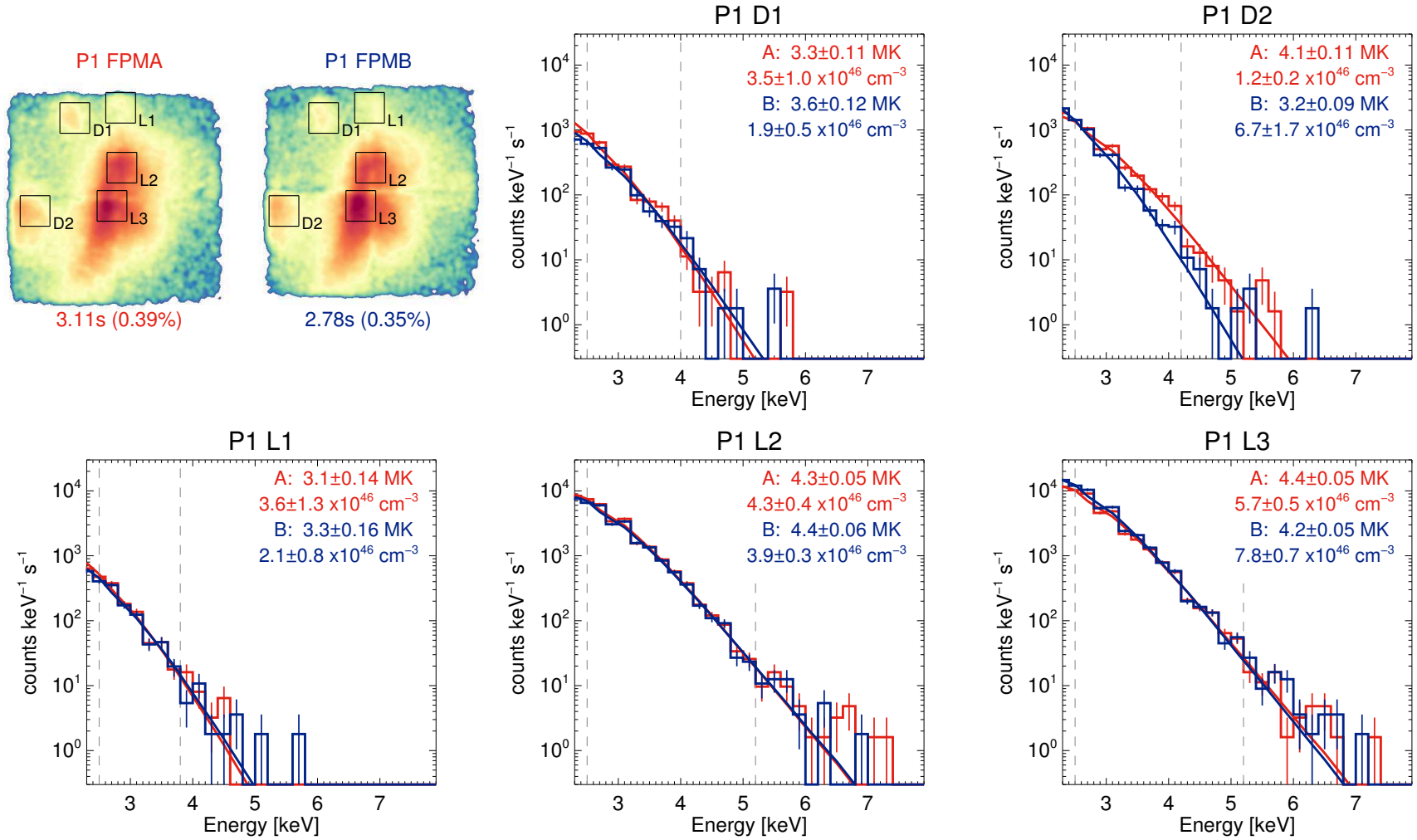


Hannah et al. 2016

NuSTAR matches EUV/SXR structures

NuSTAR Non-flaring AR: 01-Nov-2014

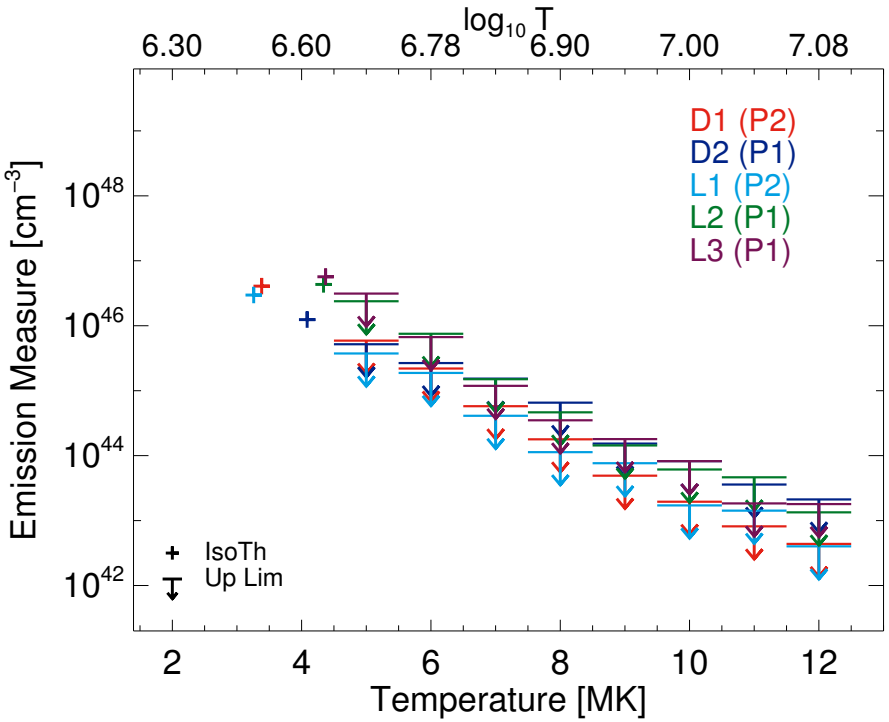
- **Well fitted by single isothermal but limited dynamic range**
  - Virtually nothing >6keV (Grade 0 – pileup minimized spectra)

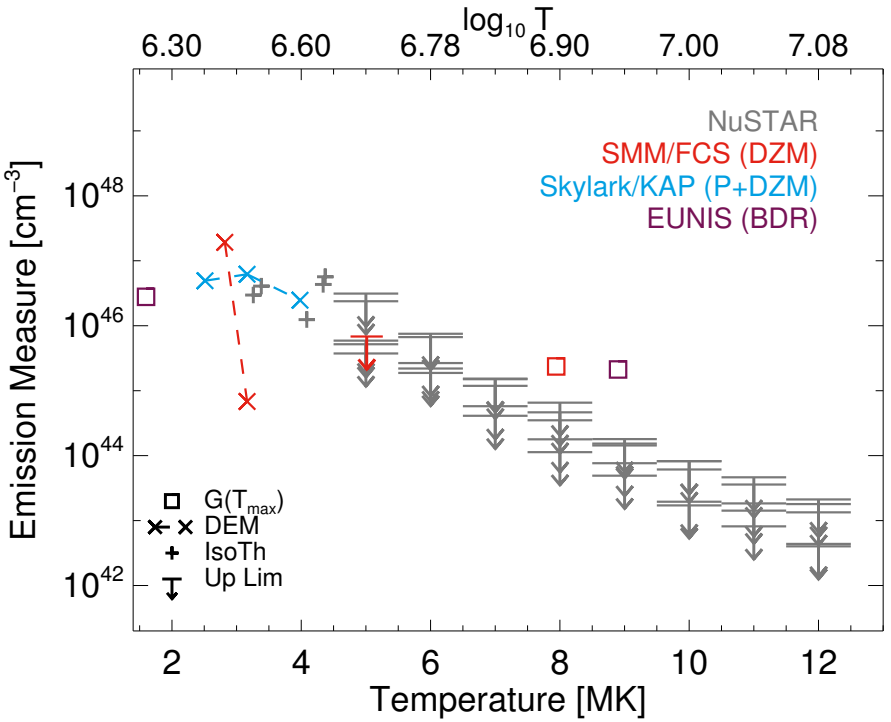


Hannah et al. 2016

NuSTAR Non-flaring AR: 01-Nov-2014

- **Can place limits on higher temperature emission**
  - Consistent or better than previous observations

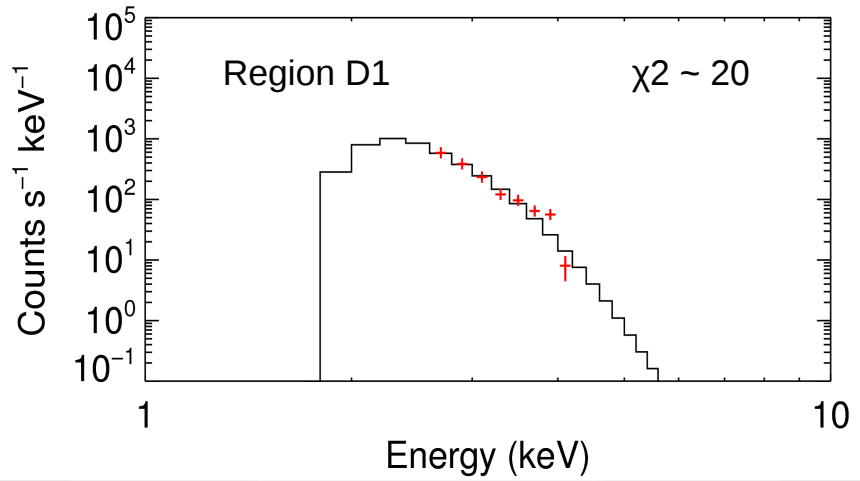


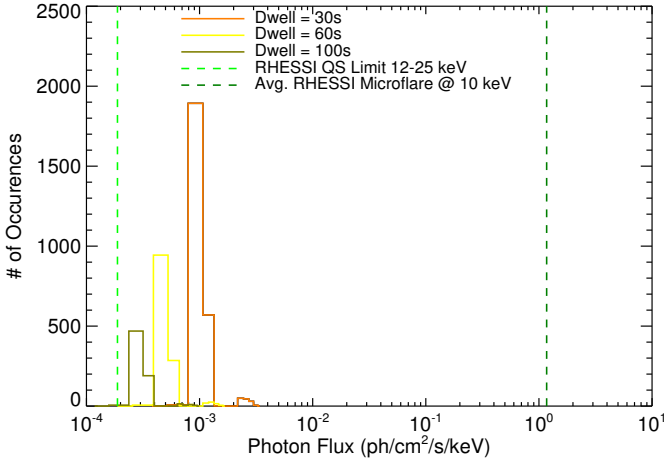


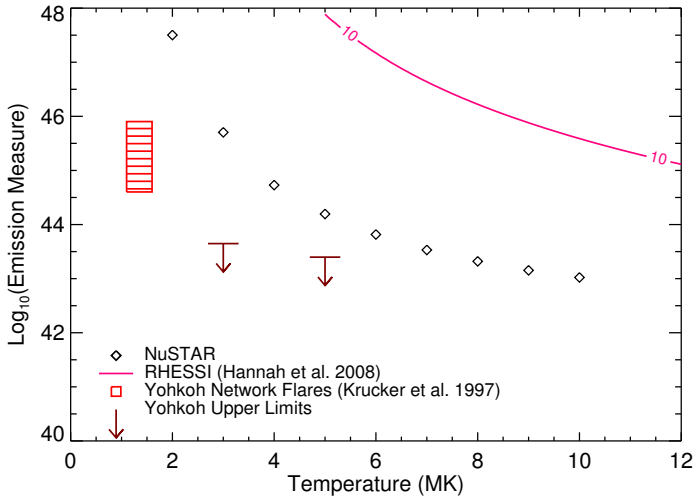
Hannah et al. 2016

NuSTAR NF AR & Quiet Sun Transients

- **Andrew Marsh has been working on constraining nanoflare properties in various non-flaring regions**
  - Using EBTEL for the NuSTAR Non-flare 01-Nov-2014 data
  - Set thermal and non-thermal limits for NuSTAR quiet Sun data







Summary & Future

- **NuSTAR provides a unique X-ray sensitivity for observing the Sun**
  - Highly capable if not optimized for the Sun
    - Grefenstette et al. 2016 ApJ 826, 20
  - Better NuSTAR sensitivity approaching solar minimum
  - Optimal targets: single weak AR and Quiet Sun (AR-free)
- **Some interesting results from first solar observations**
  - High Coronal Sources
  - Thermal spectra & limits of non-flaring active regions
    - Hannah et al. 2016 ApJ 820 L14
  - Thermal spectra of small microflares
  - Quiet Sun transients
  - More to come with current/future solar data
- **X-rays are great but we need more observations of them**
  - XRT, RHESSI, NuSTAR, FOXSI, MaGIXS, CubeSats, GOES, FOXSI-SMEX...