FLARE ENERGY RELEASE AT SMALL SCALES

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Solar Flare Energy Release (SolFER) DRIVE Center

Webinar Series

May 15, 2020

How much FLARE ENERGY RELEASE is there AT SMALL SCALES ?

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OUTLINE

- In large flares, thermal and nonthermal energies are ***huge***.
- Small flares seem ***less energetic*** (in nonthermal electrons), even for their scales.
- ***But is this actually true?***

Time →

Large flares → Small flares → Smaller → Smaller → Smaller

GOES
Class: M9

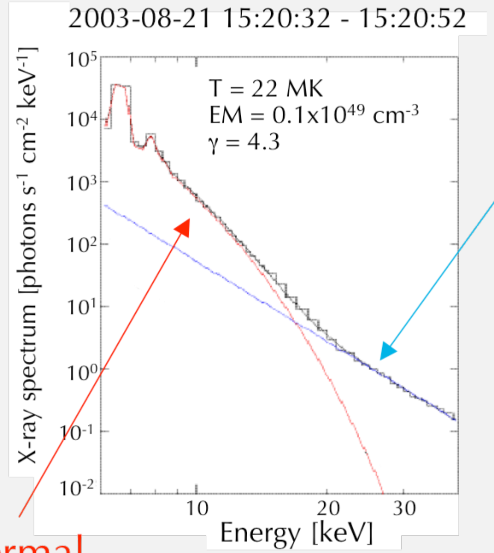
THIS IS HOW THE SLIDES ARE ORGANIZED

RHESSI

Standard measure of flare brightness in X-rays

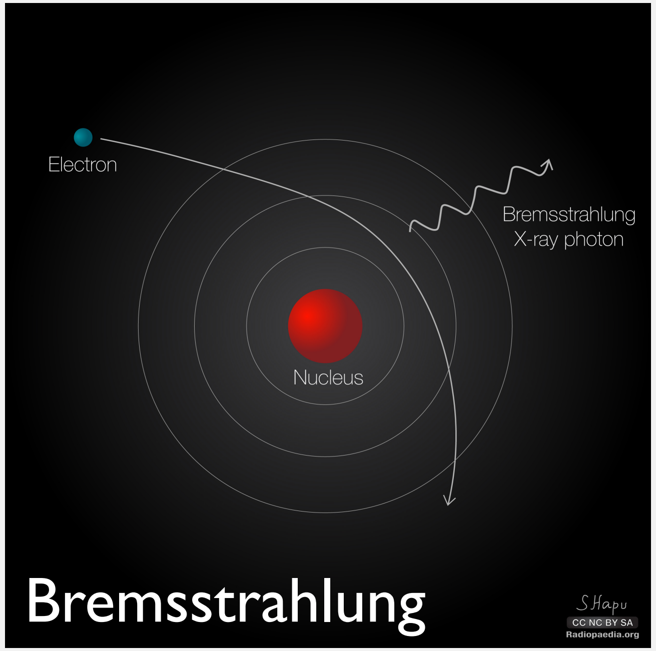
- Awesome physics result!

Hard X-ray instrument that made the observation



Nonthermal

Thermal



Dr Sachintha Hapugoda, Radiopaedia.org

ENERGY RELEASE IN LARGE FLARES

GOES Class: C5-X9

ENERGY BUDGETING FOR *LARGE ERUPTIVE EVENTS*

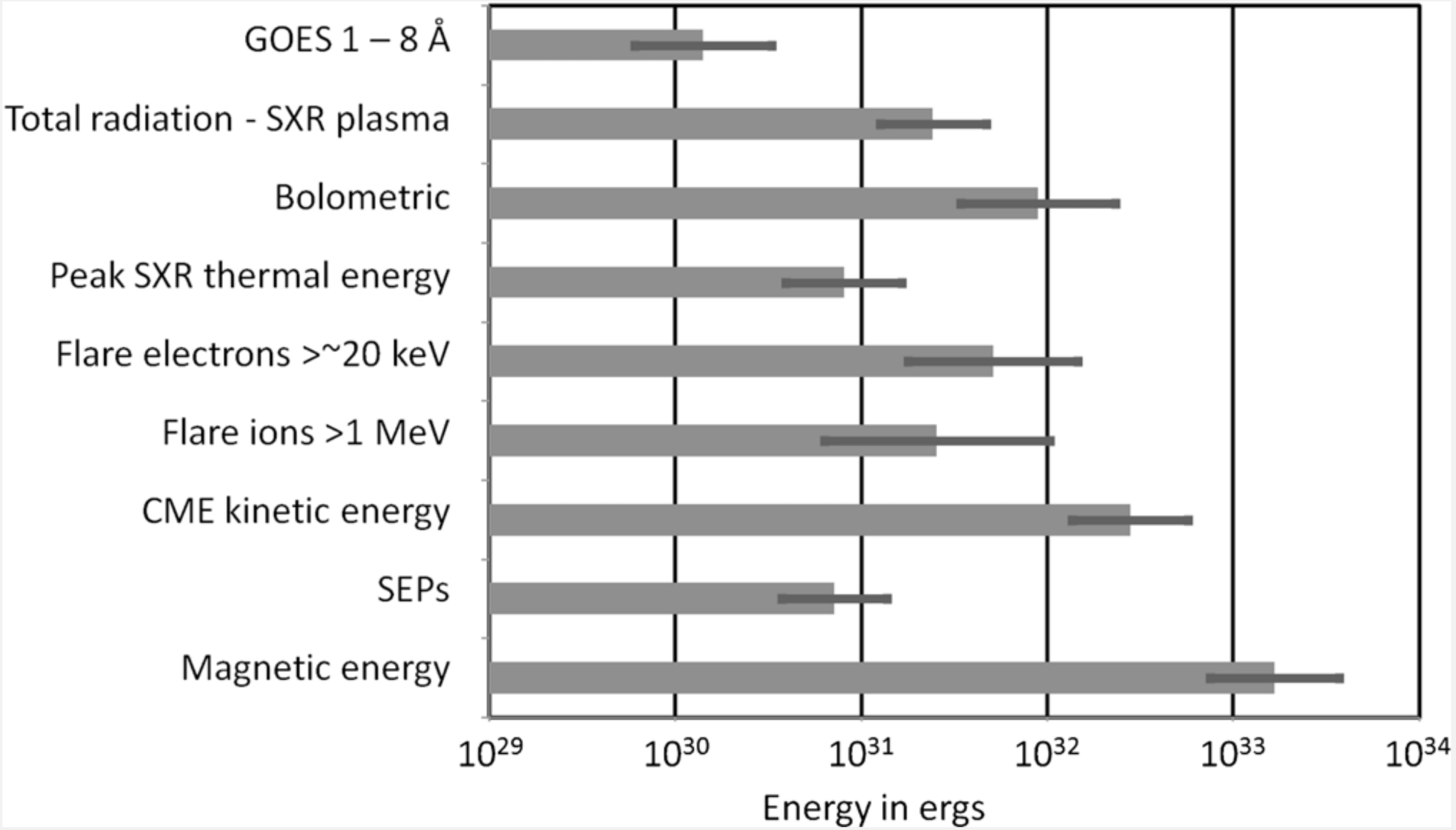


Figure 4. Bar chart showing the (logarithmic) average energies of the different components for the six events for which values were obtained for all components—Events 13, 14, 20, 23, 25, and 38. The short thin bars show the $\pm 1\sigma$ logarithmic scatter of the energies of the six events.

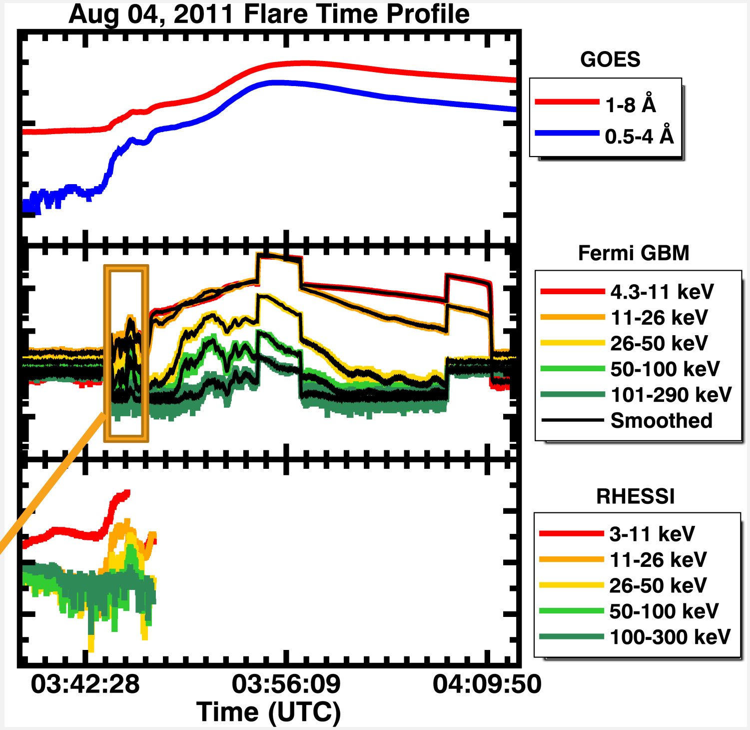
Emslie et al. (2012)

GOES
Class: M9

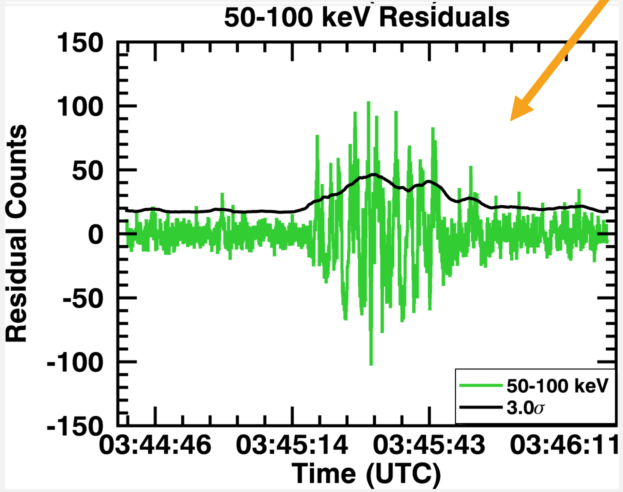
LARGE FLARES ARE ALSO THOSE MOST LIKELY TO SHOW **SUBSECOND VARIATIONS**.

Fermi/GBM

- Fermi data show a **myriad of fast spikes** in hard X-ray flux during two M9 class flares.
- This topic was also studied by Kiplinger (using SMM), Aschwanden (using BATSE), Qiu & Cheng (by demodulating RHESSI), and Glesener & Fleishman (Fermi and Konus-WIND).



These spikes result from acceleration timescales convolved with propagation effects
→ potentially a powerful diagnostic of acceleration mechanisms.



Knuth & Glesener (ApJ, in revision)
GOES M.9 flare
Average HXR spike duration **0.7 s**

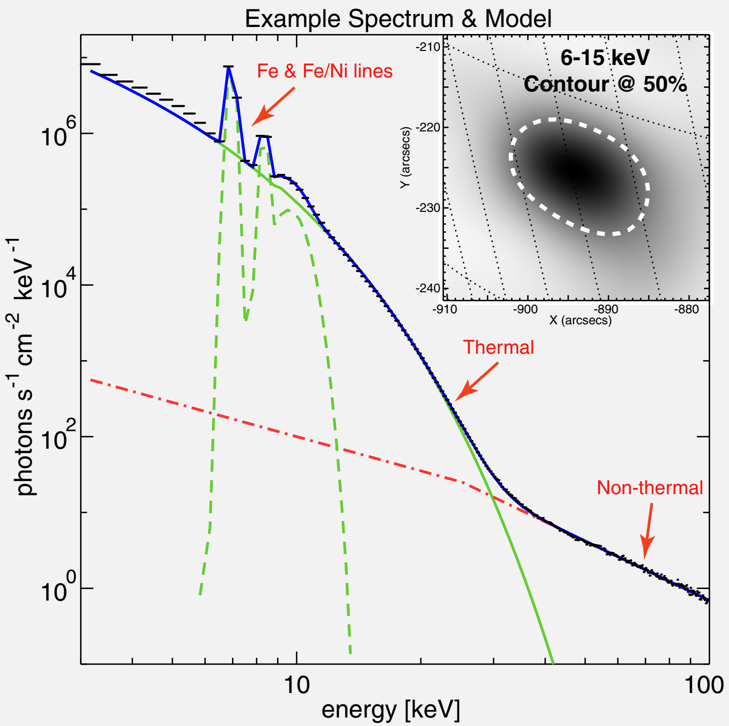
GOES Class: M-X

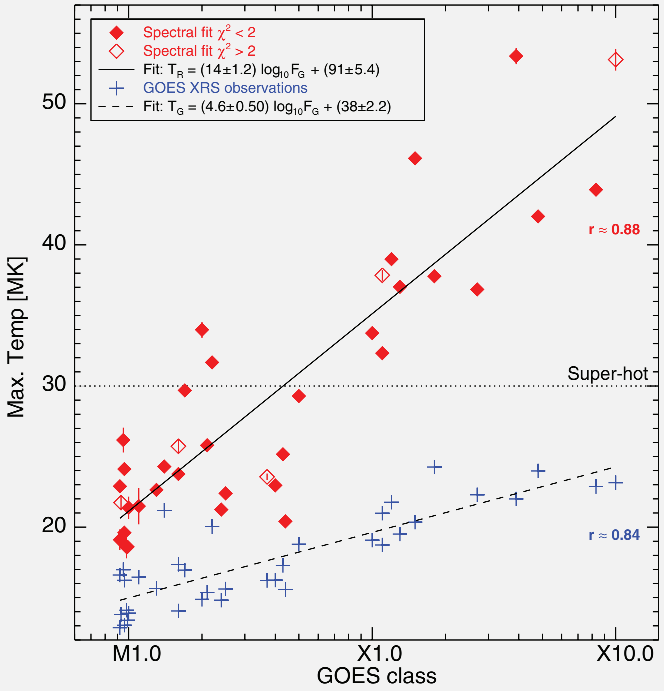
THE HOTTEST FLARE PLASMA IS FOUND IN THE LARGEST FLARES → **SUPERHOT FLARES**

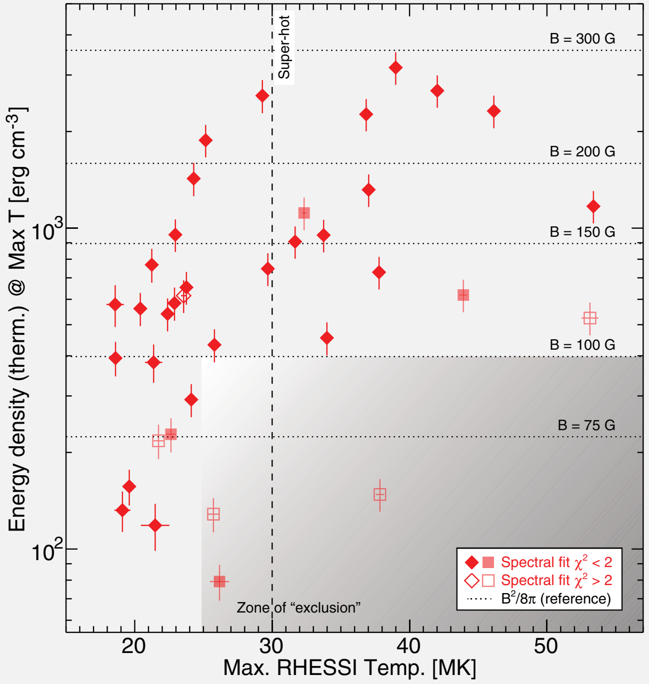
RHESSI

- Caspi & Lin (2010); **Caspi, Krucker, & Lin (2014)** - statistical study of 37 M, X RHESSI flares
- "Superhot" defined as temperature >30 MK
- Temperature scales with GOES class; most superhot flares are X flares.

- Most superhot flares have high densities, greater total energies, and require magnetic fields of >100 G.
- There are clues, but not confirmation, that superhot plasma arises from **direct heating**.





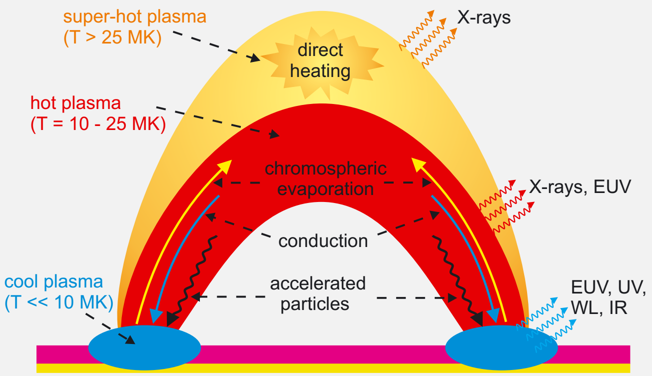


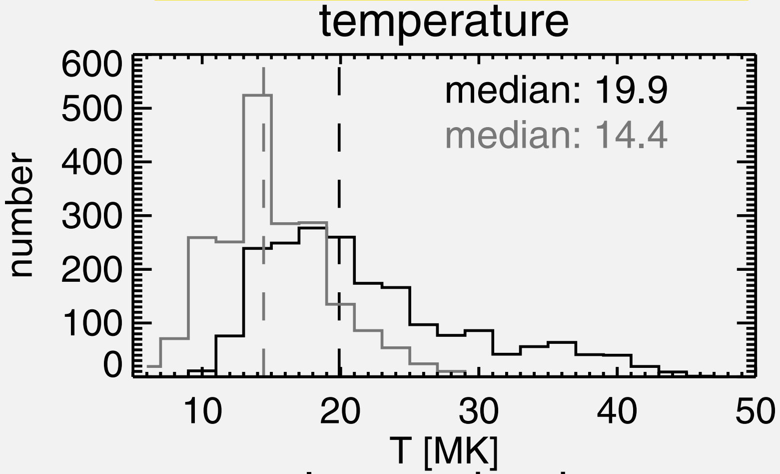
GOES Class: C3-X17

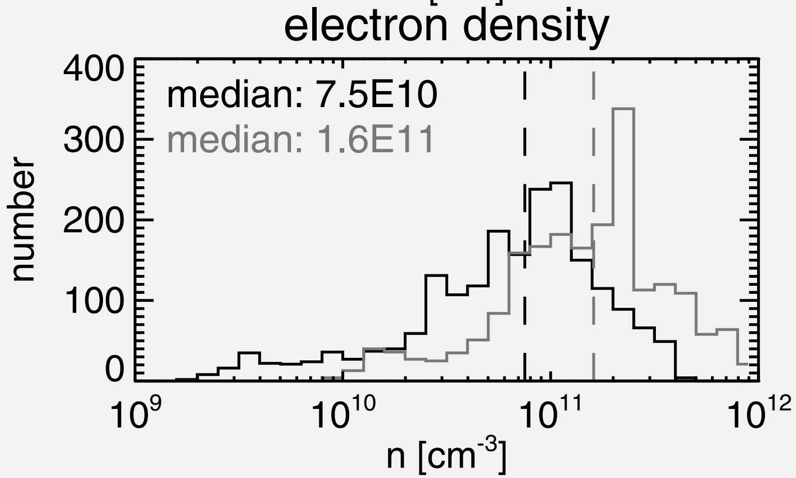
RHESSI

HOW DO THESE PARAMETERS SCALE?

- **Warmuth & Mann (2016; Papers I and II)**
- 24 flares, C3-X17 were studied using an isothermal approximation.
- Higher emission measures with higher GOES class result both from a larger source volume and a higher density.
- Chromospheric evaporation vs direct heating
  - $T_{RHESSI} > T_{GOES}$ consistently → multithermal plasma
  - Especially true early in flare, high coronal sources
  - Both RHESSI and GOES see chromospheric evaporation, but RHESSI sees direct, in situ heating in addition.



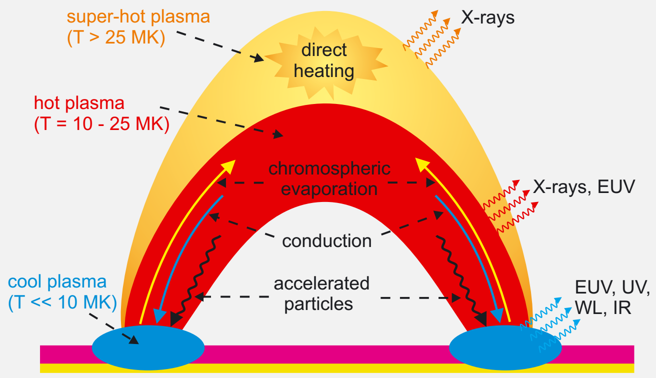




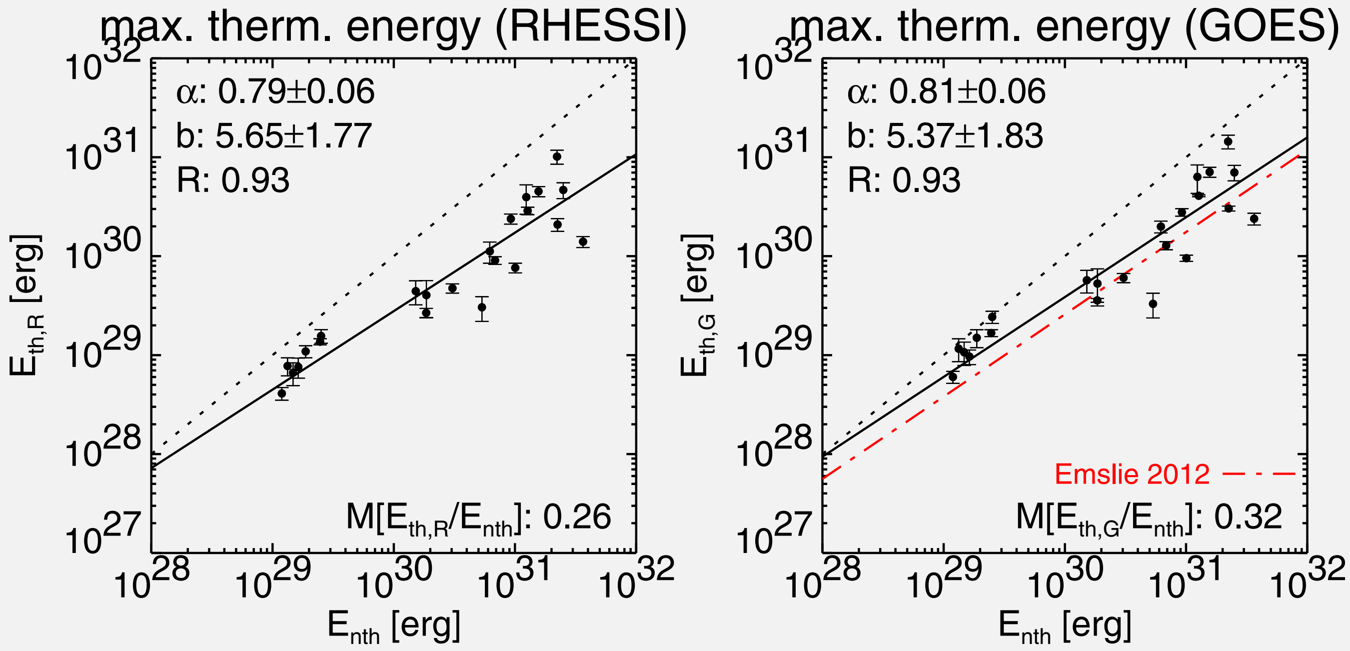
GOES Class: C3-X17

HOW DOES THE ***NONTHERMAL ENERGY*** SCALE?

RHESSI



- From past studies, smaller flares have a higher fraction of thermal to nonthermal energy (relatively ***lower acceleration efficiency***)
- But it is unknown what causes this trend, whether it continues to smaller energies, and whether there are selection effects!



Warmuth & Mann (2016)

See also…
Battaglia & Benz 2005
Aschwanden et al. 2016, 2017

ENERGY RELEASE IN SMALL FLARES

GOES Class:
Sub A to low C

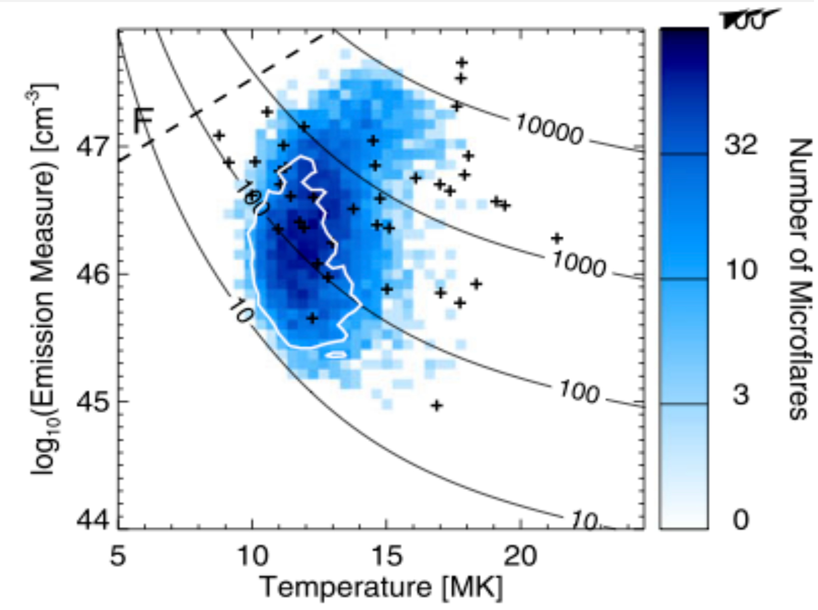
SMALL X-RAY FLARES STUDIED INDIVIDUALLY WITH *RHESSI*

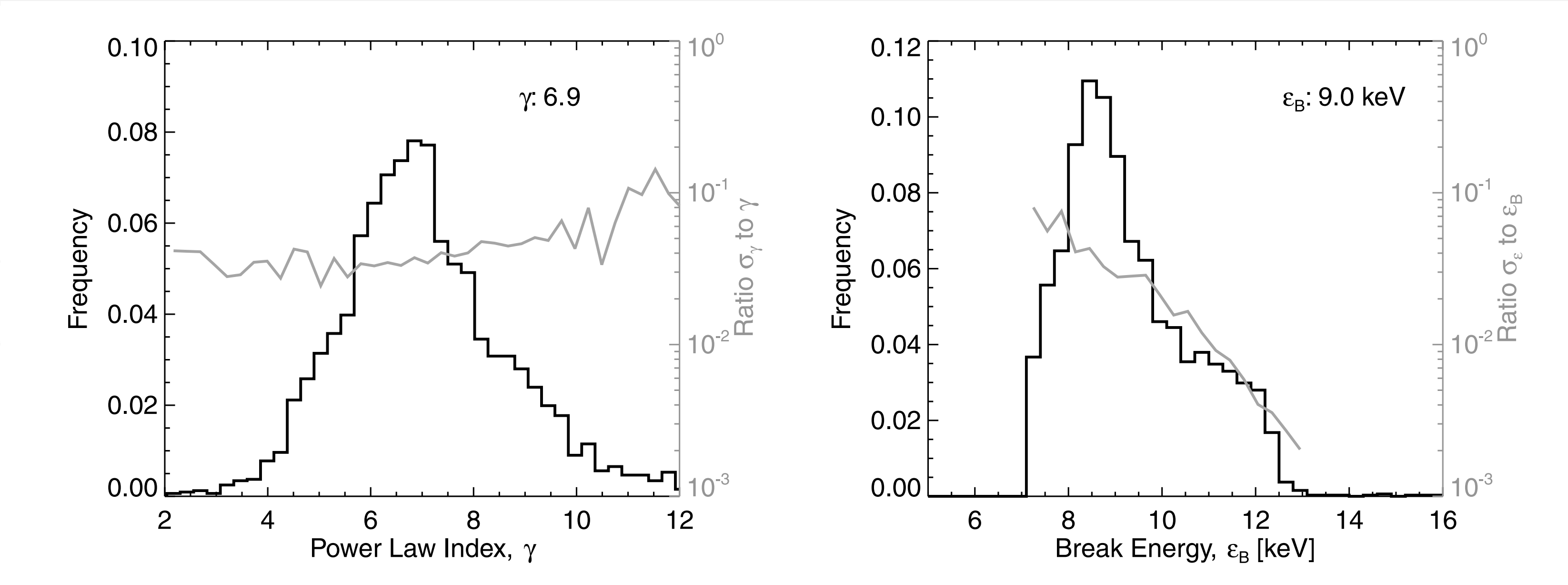
RHESSI

Hannah & Christe analyzed thermal and nonthermal properties of >25,000 microflares!

The ***RHESSI*** microflares…

- are only found in active regions.
- do not explain coronal heating.
- have steeper nonthermal distributions and lower break energies than larger flares do.





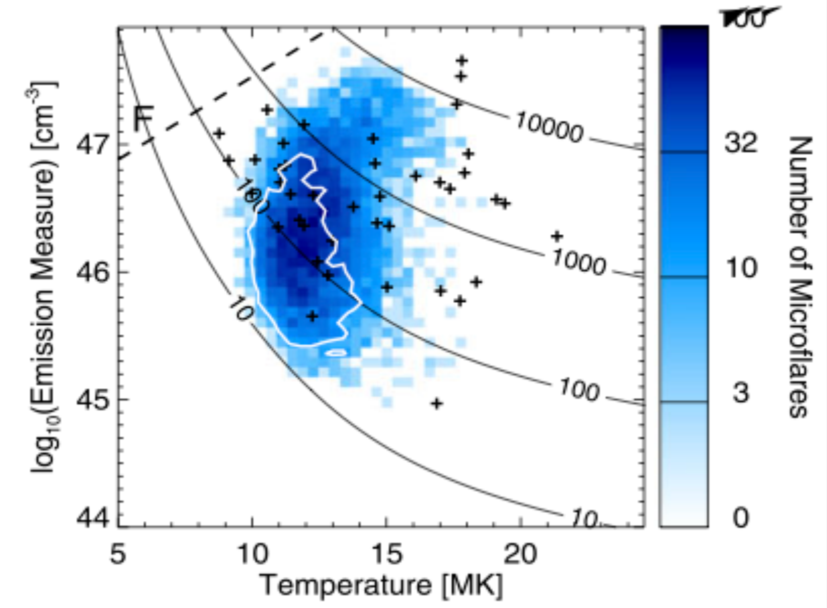
Hannah et al. (2008), Christe et al. (2008), Hannah et al. (2011)

GOES Class: Sub A to low C

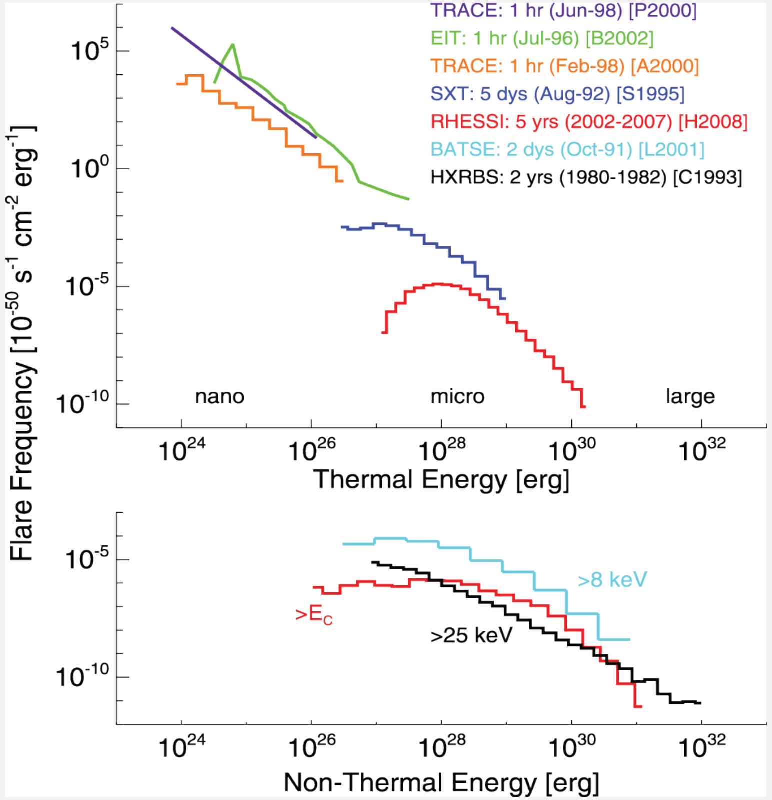
SMALL X-RAY FLARES STUDIED INDIVIDUALLY WITH *RHESSI*

RHESSI

Hannah & Christe analyzed thermal and nonthermal properties of >25,000 microflares!



Flare frequency distribution



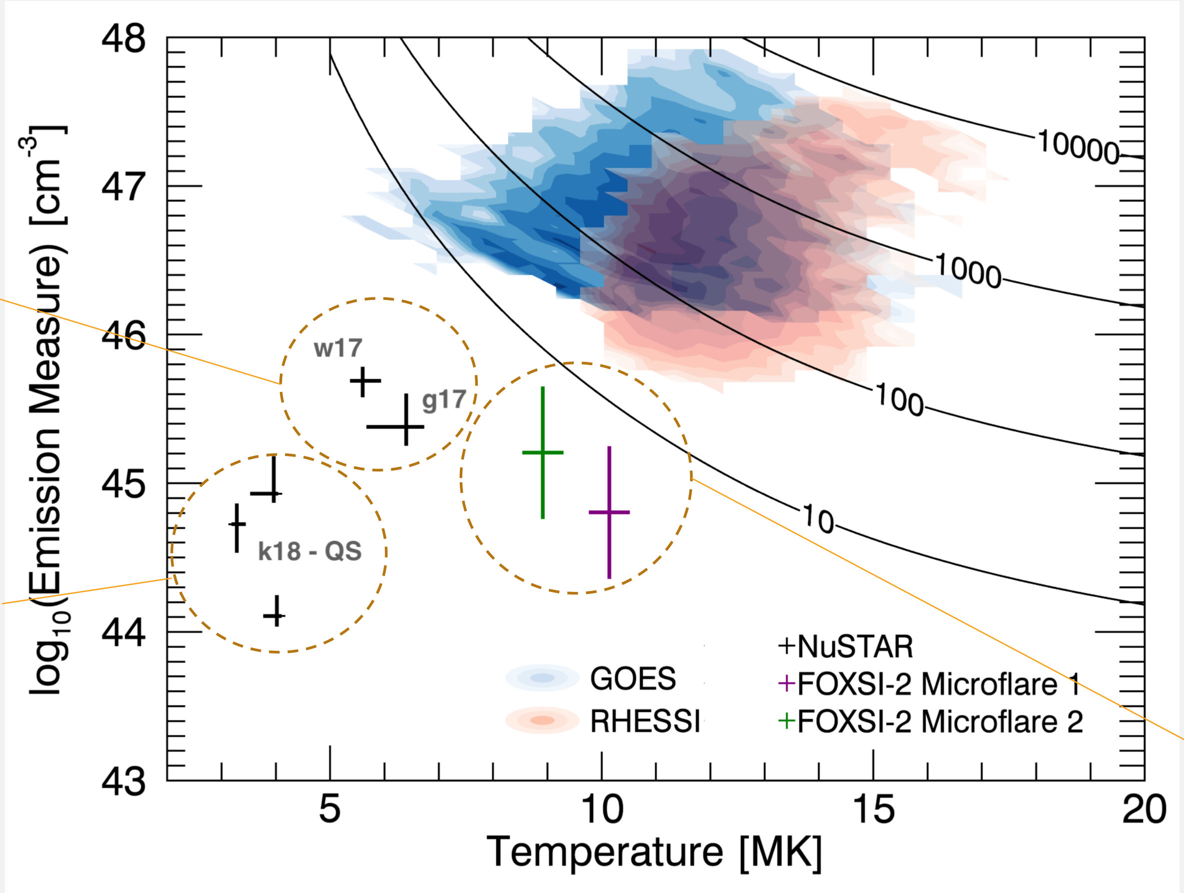
RHESSI data filled in important gaps in the flare frequency distribution, but sensitivity limitations did not permit the measurement of a distribution slope directly from the RHESSI data.

Hannah et al. (2008), Christe et al. (2008), Hannah et al. (2011)

SMALL X-RAY FLARES, MEASURED INDIVIDUALLY WITH **FOXSI** AND **NUSTAR**

Hard X-ray microflares are now being observed to two orders of magnitude smaller in brightness than previous observations.

Wright+ (2017)
Glesener+ (2017)
Kuhar+ (2018)
Hannah+ (2019)
Athiray+(2020)
Glesener+(2020)
Cooper+(2020)
Vievering+(in prep)



NuSTAR microflares

NuSTAR quiet Sun transient brightenings (Kuhar et al. 2018)

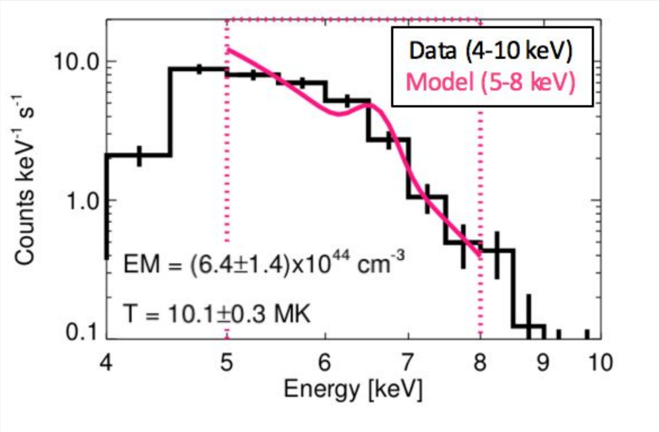
FOXSI-2 microflares

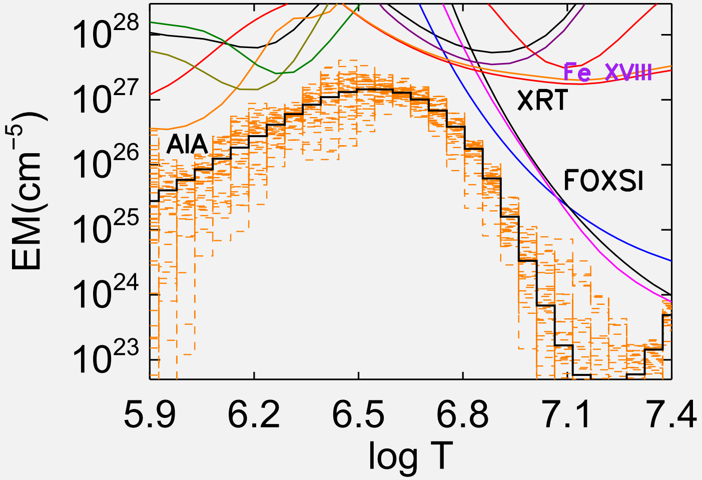
J. Vievering dissertation, 2019

GOES Class: Sub A

SMALL MICROFLARES SHOW COMPLEXITY AND BROAD DEMS

FOXSI-2



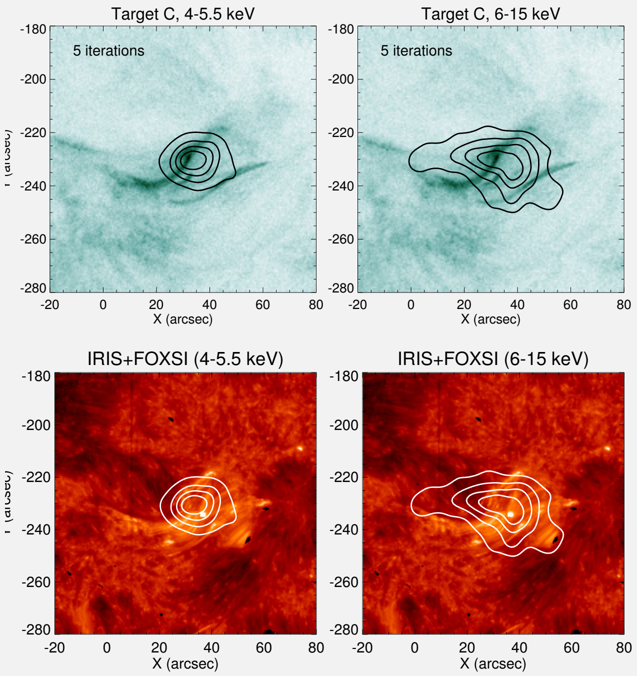


Athiray et al. (2020)

- FOXSI-2 microflares are made up of multiple loop brightenings within single events.
- 3-4x more thermal energy is found for a broad DEM as compared with an isothermal fit.

Table 2
Thermal Energy Estimates of Microflares Observed during *FOXSI-2* Using the Multi-thermal DEM Analysis

Flare	Targets	Start (UT)	End (UT)	Multi-thermal DEM $E_{th} \times (10^{28}$ erg)	Isothermal E_{th} $(\times 10^{28}$ erg)
1	A	19:12:42	19:13:14	$5.1^{+0.7}_{-0.2}$	$1.4^{+0.2}_{-0.2}$
1	B	19:13:18	19:13:42	$4.9^{+0.4}_{-0.4}$	$1.5^{+0.2}_{-0.2}$
1	C	19:13:47	19:14:25	$5.1^{+0.6}_{-0.6}$	$1.2^{+0.1}_{-0.1}$
2	J	19:18:51	19:19:23	$1.6^{+0.6}_{-0.7}$	$1.0^{+0.1}_{-0.1}$



There are hints of a high-energy excess, but no nonthermal component directly detected.

Vievering et al. (in prep)

GOES Class: A0.1

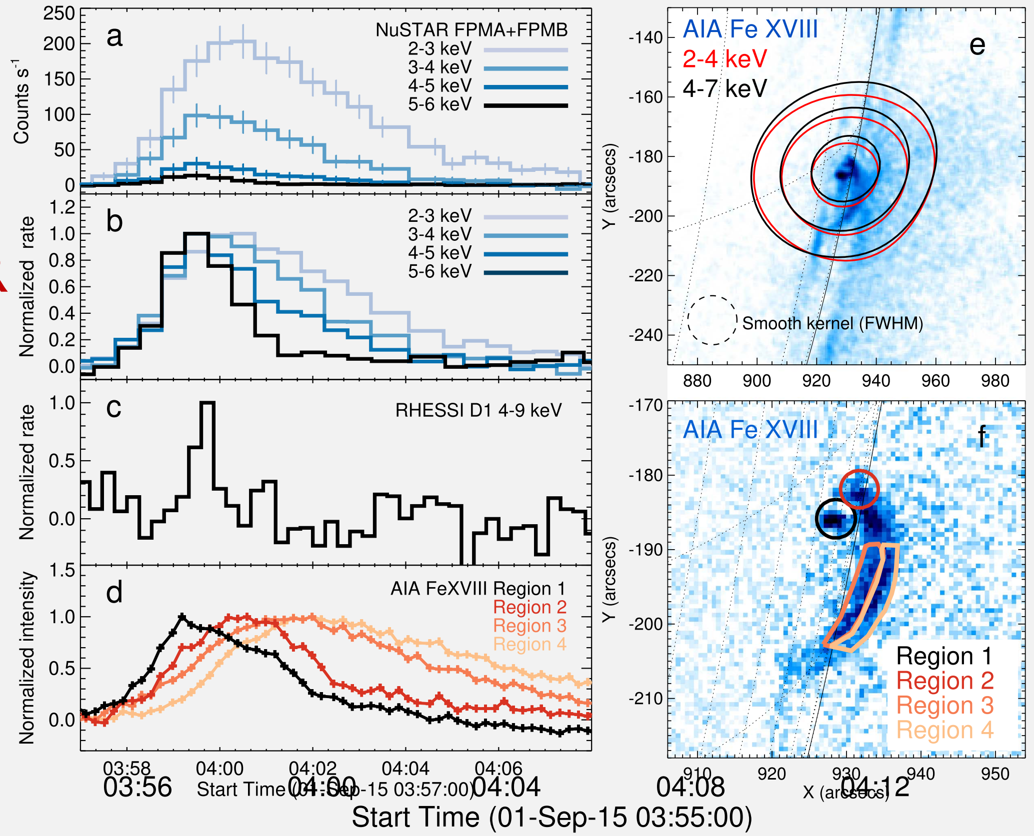
SMALL MICROFLARES SHOW SIMILAR TIME PROFILES TO BIGGER FLARES.

NuSTAR

NuSTAR

RHESSI

AIA



Glesener et al. (2017)

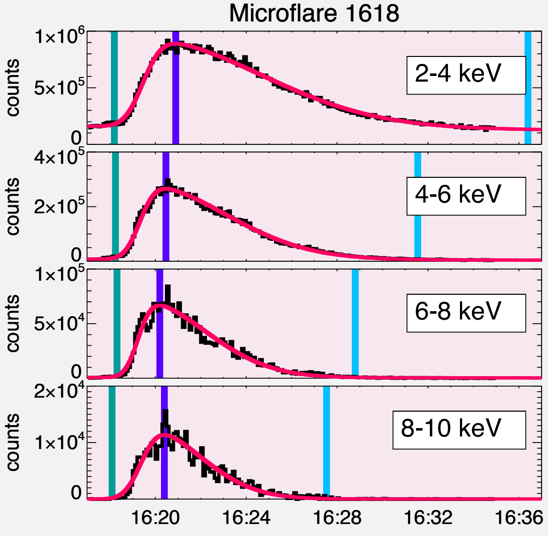
HXR emission quickly rises and slowly decays.

Differing regions, even in a small flare, have different temporal evolutions.

GOES Class: A and sub A

SMALL MICROFLARES SHOW SIMILAR TIME PROFILES TO BIGGER FLARES.

NuSTAR



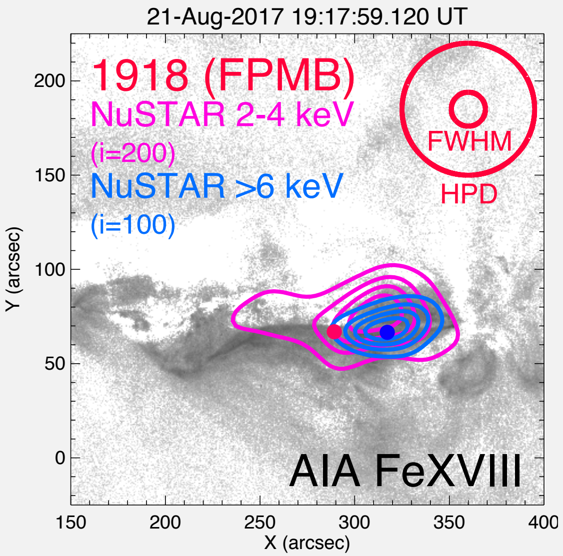
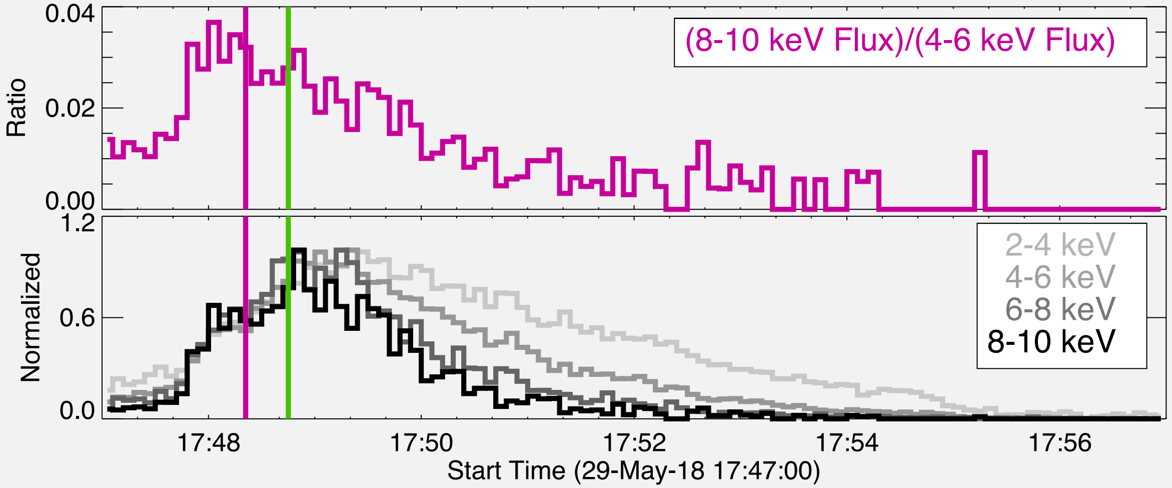


Table 1. Event Asymmetries (A_{ev})

Event	2-4 keV	4-6 keV	6-8 keV	8-10 keV
1850	0.00±0.07	0.57±0.03	0.57±0.07	0.31±0.24
1918	0.55±0.02	0.59±0.02	0.78±0.02	0.79±0.10
1618	0.70±0.01	0.67±0.01	0.64±0.04	0.51±0.10
1900	0.43±0.02	0.28±0.03	0.35±0.04	0.66±0.09
1747	0.48±0.02	0.46±0.02	0.37±0.10	0.31±0.22
1909	0.69±0.10	0.38±0.75	0.90±4.6	0.54±0.63
1736	0.23±0.03	0.07±0.07	-0.02±0.17	-0.68±0.06
1940	0.46±0.03	0.36±0.03	0.32±0.06	0.22±0.36
1646	0.69±0.04	0.63±0.04	0.46±0.14	0.70±0.29
1606	0.62±0.05	0.64±0.03	0.80±0.09	0.95±0.85
1917	0.86±0.01	0.56± 0.07	0.28±0.28	X
	Color Key:	Impulsive ($A_{ev}>0$)	Consistent With Either	Non-Impulsive ($A_{ev}<0$)

Duncan et al. (in prep)

11 events: NuSTAR microflares are almost always impulsive and rapidly reach their highest temperatures, followed by a gradual cooling. All events showed a high-energy excess over an isothermal model.



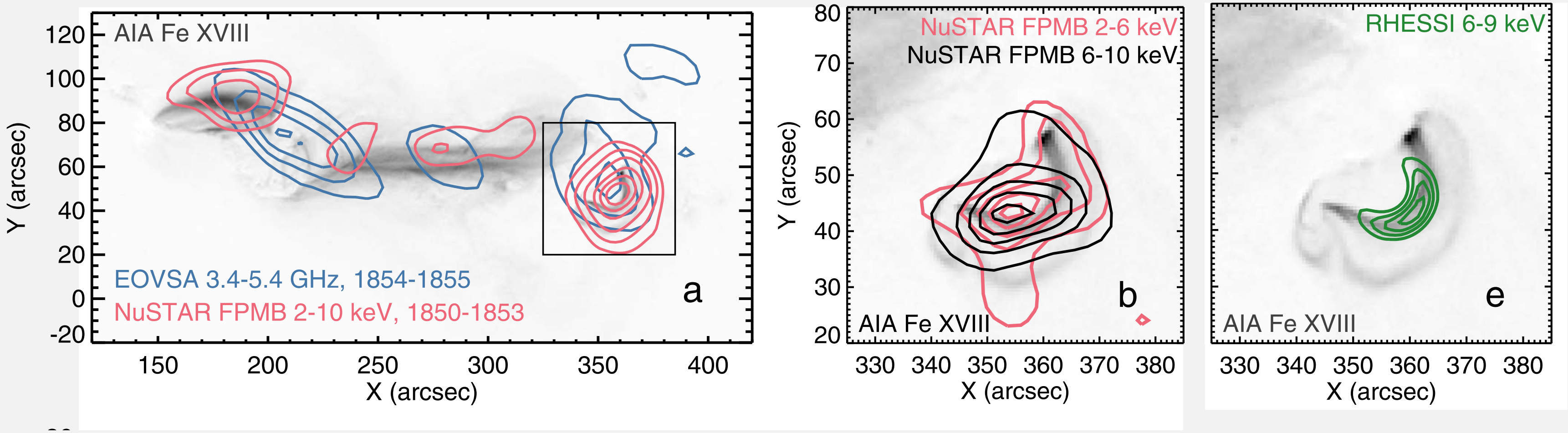
ARE THESE FLARES HIDING SOMETHING?

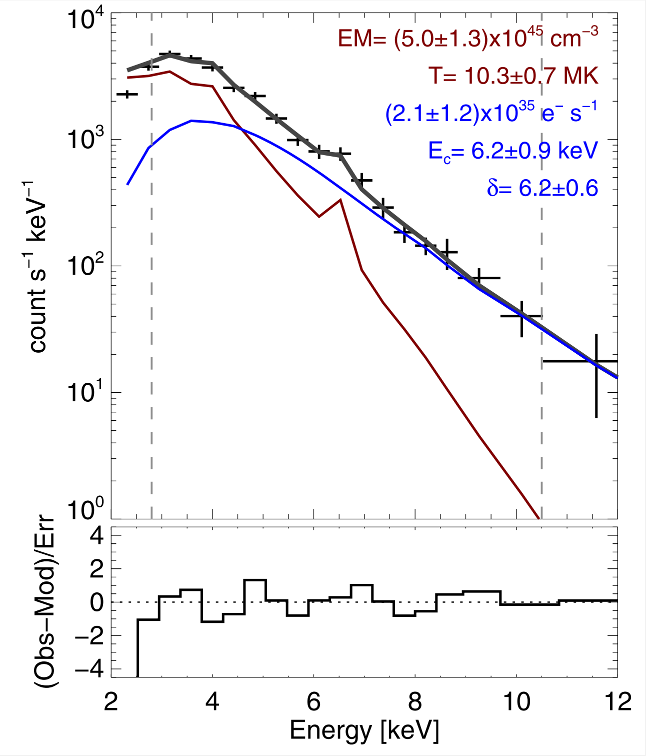
[Like hidden banks of nonthermal energy?]

GOES Class: A6

SMALL MICROFLARES ***CAN*** HAVE ACCELERATED ELECTRONS.

NuSTAR



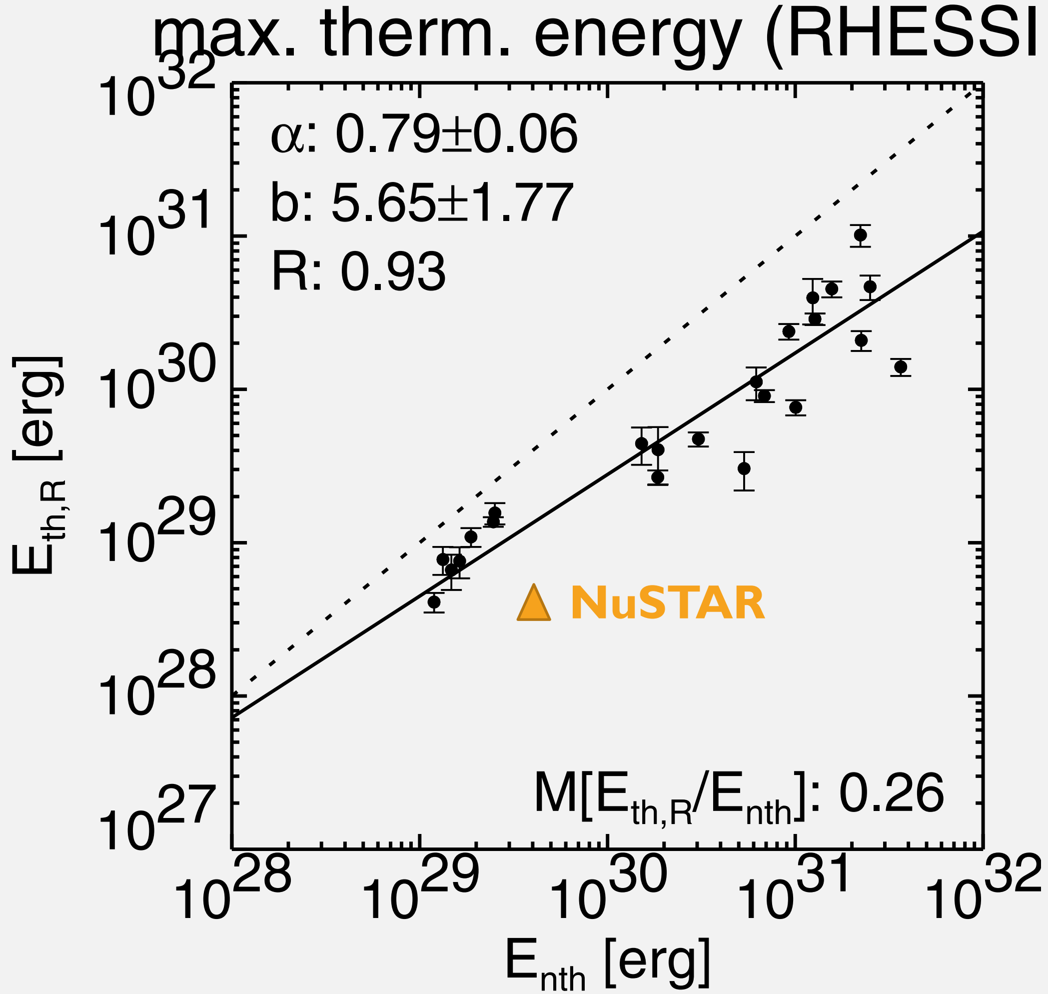


Glesener et al. (2020)

- We have one clear observation of a nonthermal electron distribution in a NuSTAR microflare.
- The distribution extends down to **~6 keV** and contains a large amount of energy (4 x 10^{29} erg, about 10x the estimated thermal energy).
- Electrons thermalize *mostly in the corona*.

HOW DOES THIS COMPARE WITH LARGER FLARES?

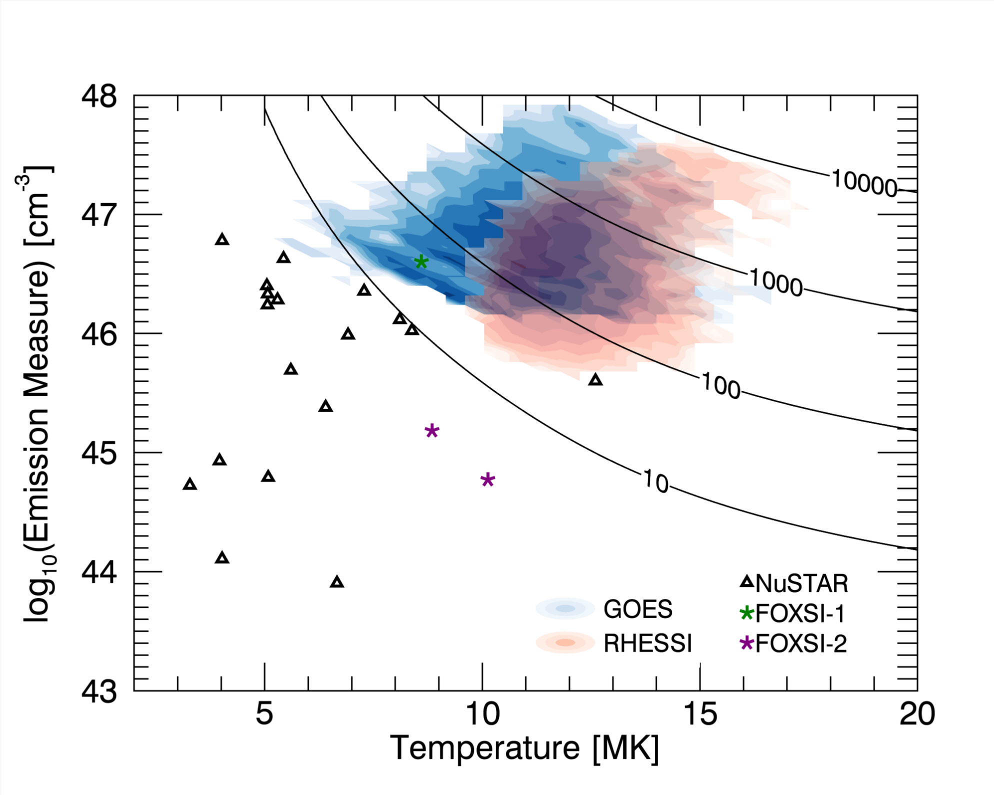
- The energy ratio of this flare is not very different from the energy ratios of larger flares.
- This doesn't follow the same trend as RHESSI studies, but sensitivities of those analyses could be responsible.
- This flare ***does*** fit the trend of ***steeper*** distributions at small energies. ($\delta \approx 6$)

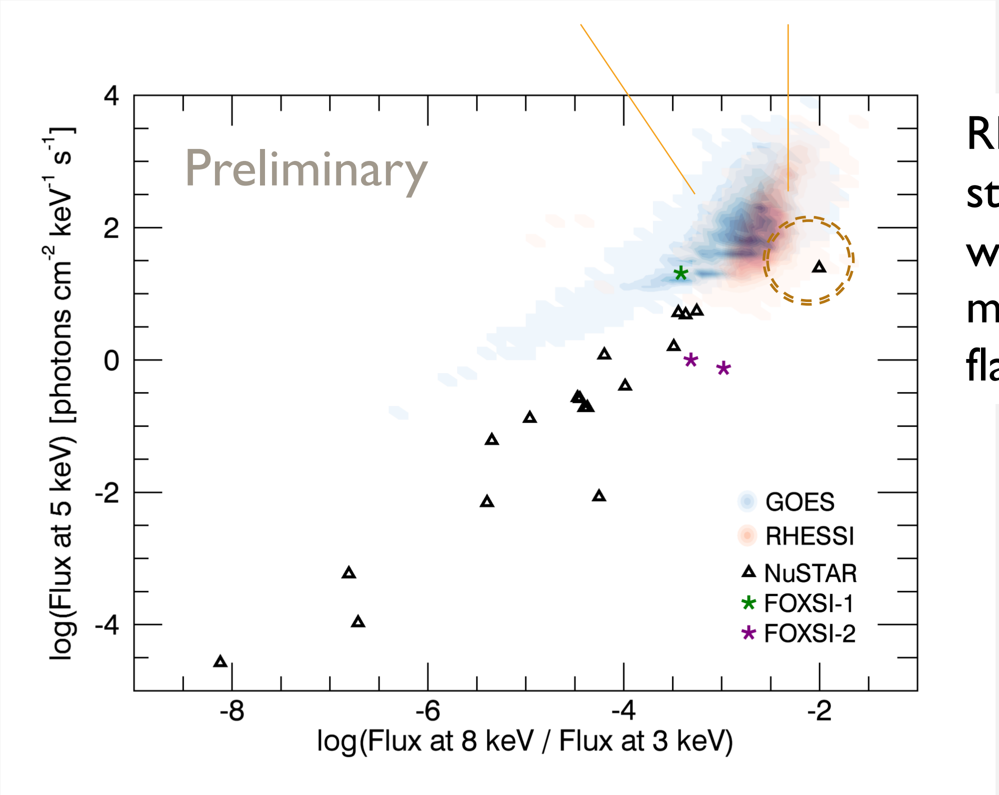


Edited from Warmuth & Mann (2016)

HOW DOES THE ***SPECTRAL SHAPE*** SCALE?

GOES and RHESSI points are from isothermal approximations. (Do not compare directly with others.)





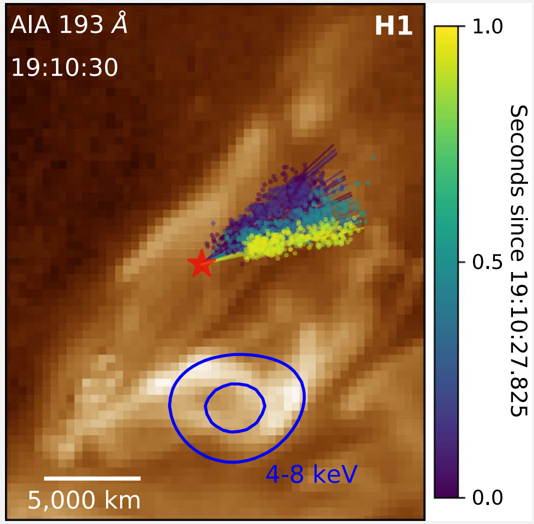
RHESSI studies would have missed flares here.

See **Vievering et al. (in prep; FOXSI-2)** and **Duncan et al. (in prep; NuSTAR)**

Scaling of the spectral shape ***includes the nonthermal flare***.

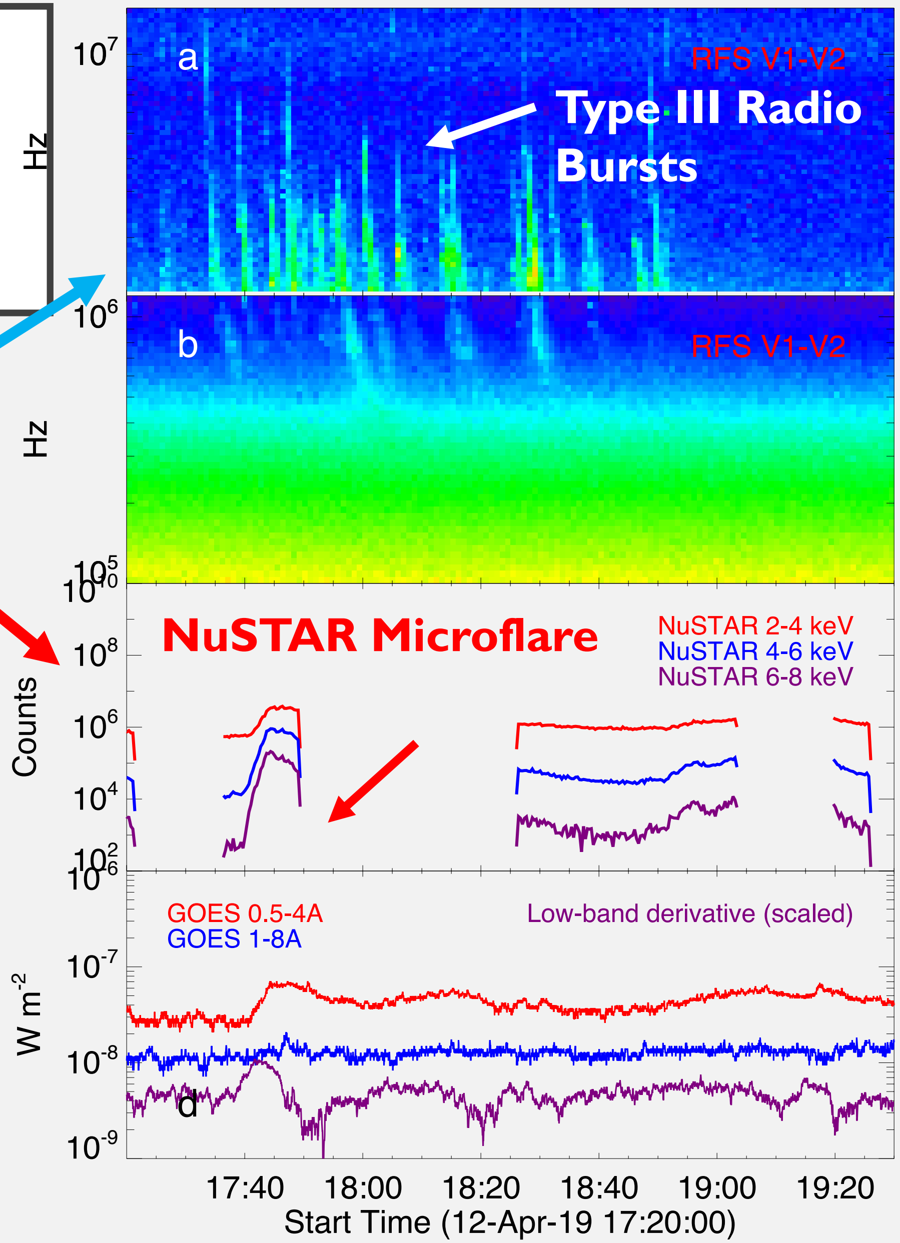
PLUS…*WE KNOW FROM RADIO MEASUREMENTS* THAT THERE ARE NONTHERMAL ELECTRONS!

Example: *NuSTAR and GOES* X-ray lightcurves reveal a small microflare at the same time as the FIELDS instrument on ***Parker Solar Probe*** detects a flurry of Type III radio bursts (escaping electrons)



Another example: The ***VLA*** identifies Type III bursts in an A2 flare with no evident nonthermal X-ray emission.

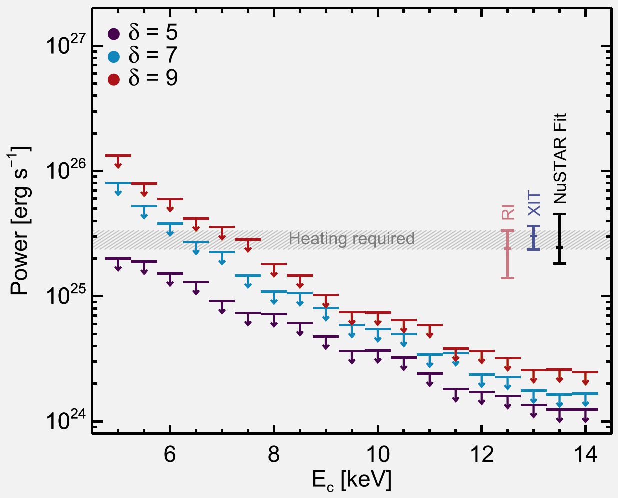
Chen et al. (2018)



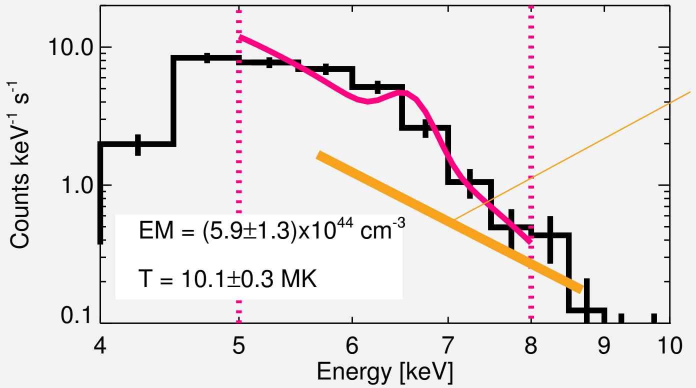
Cattell et al. (in prep)

COULD SIGNIFICANT NONTHERMAL ENERGY BE HIDING?

Several studies examine whether a steep nonthermal spectrum **hidden beneath the thermal emission** could power the flare via the thick-target model. The answer is yes.



Wright et al. (2017) found a reasonable range of allowed parameters for a hidden nonthermal distribution.



Vievering et al. (in prep) found similar results for one of the FOXSI microflares (though not for the other).

Cooper et al. (2020) studied a 10^{26} erg flare and found that the nonthermal energy could equal the thermal energy and still be unobserved.

CLOSING THOUGHTS

- Energetic properties of large flares are fairly well characterized. Correlations with flare energetic size are observed in temperatures, emission measures, and most nonthermal parameters. Most cross-scale studies find that smaller flares tend to be less efficient particle accelerators.
- However, new studies of the smallest observable hard X-ray microflares imply that there may be more nonthermal energy than was apparent to previous instruments. One nonthermal flare has been observed with NuSTAR to have a large nonthermal energy. Other flares do not exhibit clear nonthermal behavior but could easily be hiding abundant nonthermal energy.
- A solar-optimized direct-focusing hard X-ray telescope supported by high-resolution EUV imaging is necessary in order to settle these questions!

EXTRA SLIDES

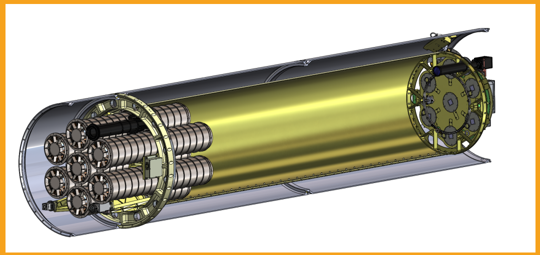
DIRECT-FOCUSING HARD X-RAY INSTRUMENTS

FOCUSING OPTICS X-RAY SOLAR IMAGER SOUNDING ROCKET

- Solar sounding rocket experiment flown for 6-minute flights in 2012, 2014, and 2018.
- Uses direct-focusing telescopes as opposed to indirect imagers like RHESSI → orders of magnitude greater sensitivity.

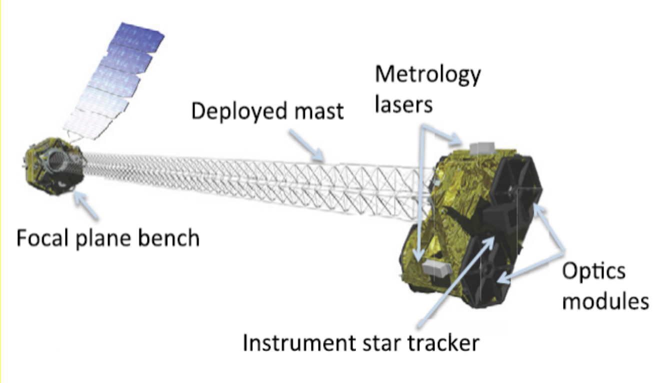
Goals:

- Demonstrate focusing HXR optics optimized for **the Sun**.
- Look for indicators of nanoflares in active regions and the quiet Sun

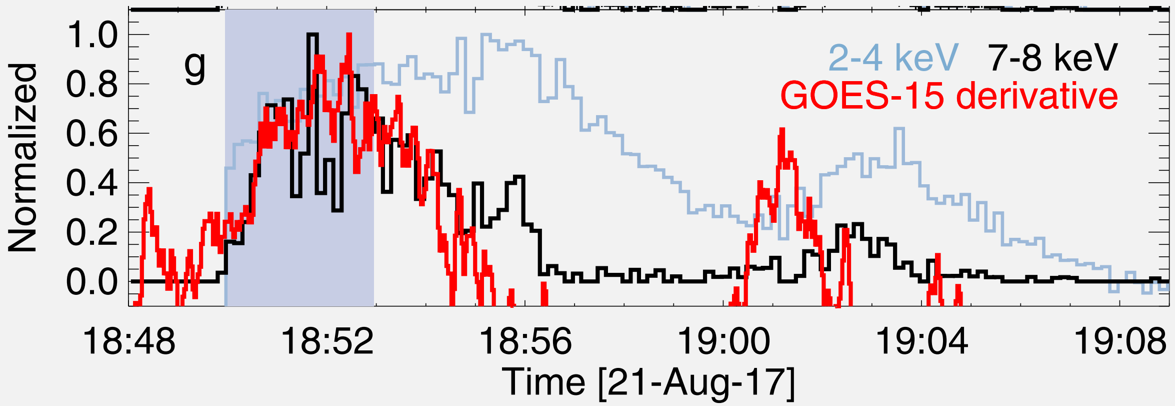


THE NUCLEAR SPECTROSCOPIC TELESCOPE ARRAY (NUSTAR)

- ***Astrophysics*** spacecraft not optimized for solar pointing
- Best conditions: targets $\lesssim$GOES B5
- Observations are planned 3-4 days in advance (minimum) or as planned coordinations with other spacecraft observing campaigns (better).



NONTHERMAL EMISSION IN THE 2017 AUGUST 21 NUSTAR MICROFLARE



The Neupert effect is observed between the high-energy NuSTAR emission and the GOES SXR derivative. This is usually interpreted as a signature of nonthermal emission.

No purely thermal models were found to fit the data well. Double thermal models required unphysically high temperatures and still exhibited clear mismatches to the data.

Glesener et al. (2020)

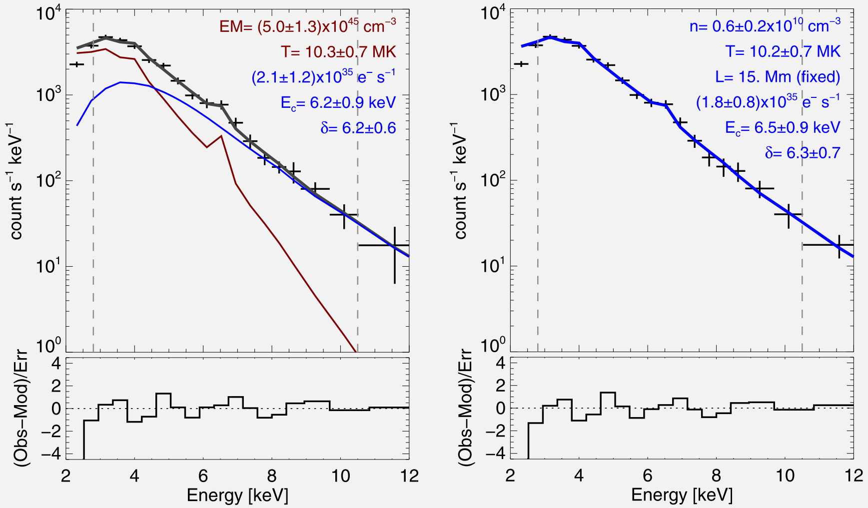
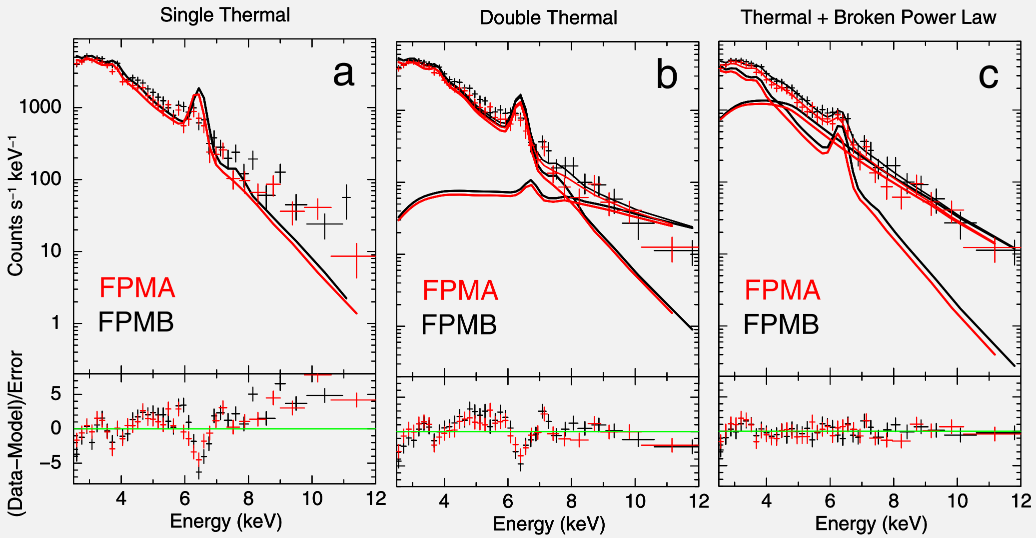


Figure 4. Results of thick-target spectral fitting in OSPEX using models (left) `thick2` and (right) `thick_warm`, which model an accelerated electron distribution propagating in a cold or warm plasma target, respectively. Fits were performed to FPMB data only. The warm-target model fits the data well with no additional thermal component needed, indicating that the thermal plasma arises from energetic electron thermalization within the loop. For the warm-target model, the loop half-length was fixed to 15 Mm from AIA images and both temperature and density were allowed to vary.

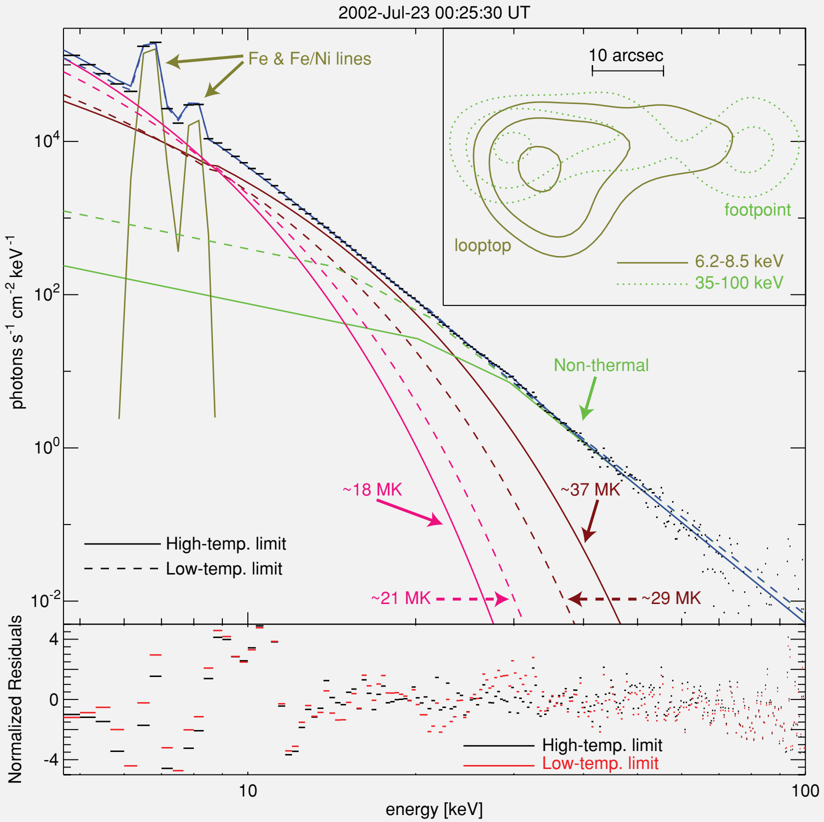


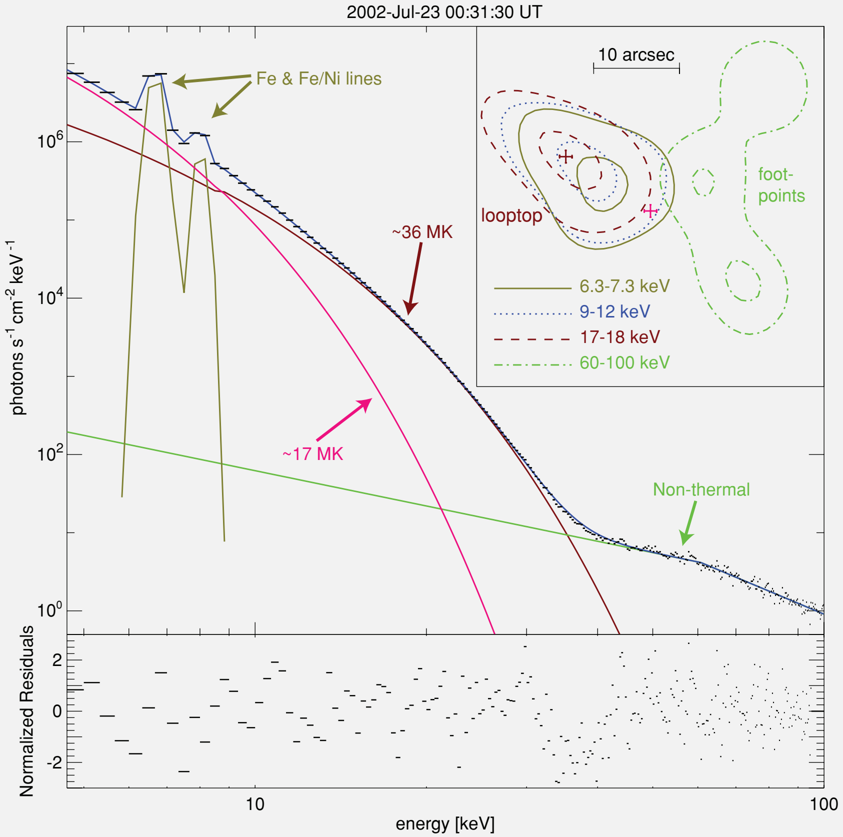
GOES Class: X5

A SPECIFIC **SUPERHOT** EXAMPLE **(CASPI & LIN 2010)**

- The **2002 July 23 RHESSI flare** showed multiple thermal components. The hottest (~30-35 MK) was located relatively higher in the corona. It lasted through the flare peak but can be seen prominently in the pre-impulsive phase, when footpoints are almost nonexistent.
- Caspi & Lin attributed the superhot plasma to direct heating.

Pre-impulsive phase





Flare peak