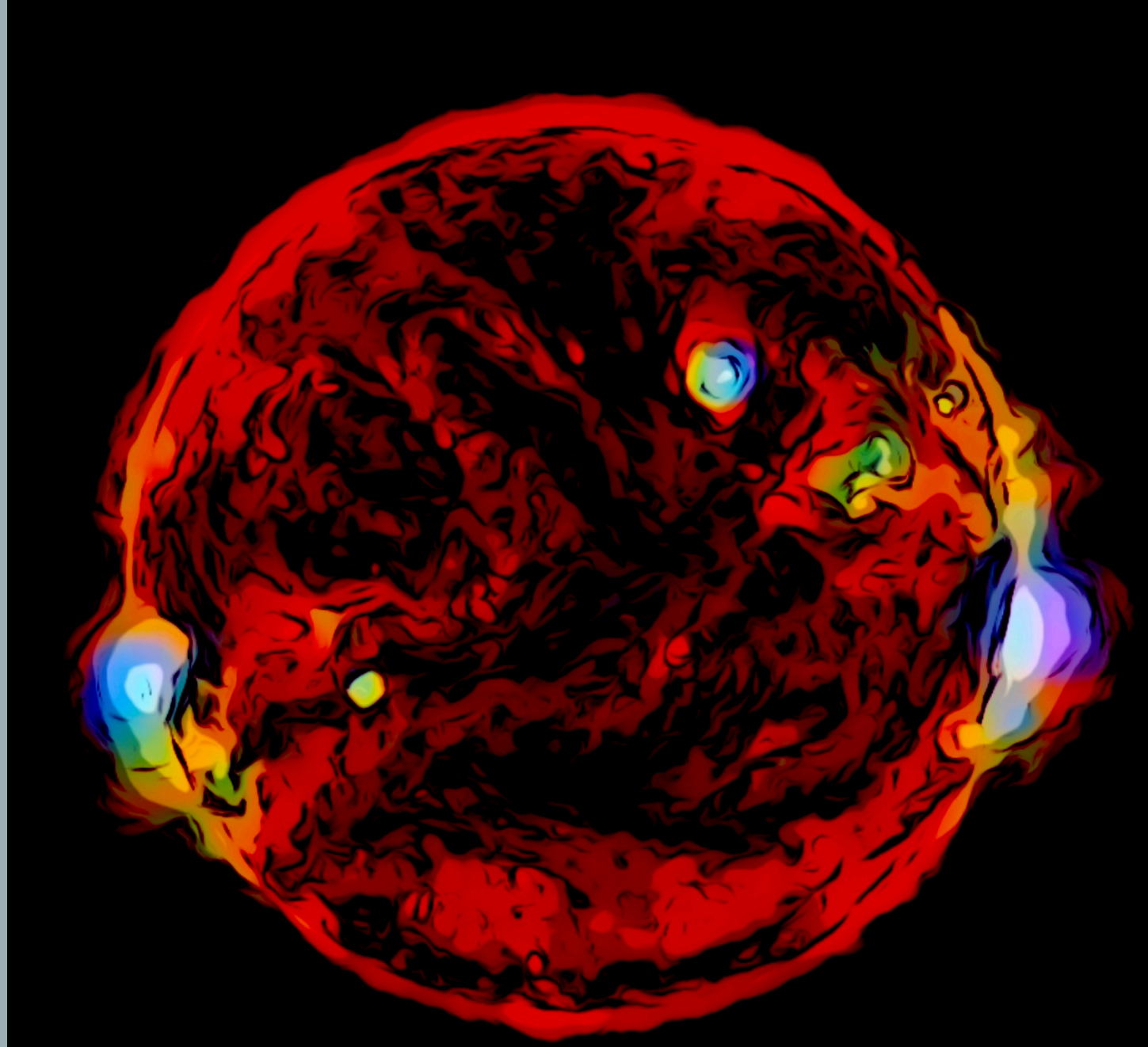
NUSTAR SOLAR OBSERVATIONS IN THE PARKER AND ORBITER ERA

Lindsay Glesener, on behalf of the NuSTAR Heliophysics Team plus *Parker*/FIELDS friends!

RHESSI WebEx Workshop

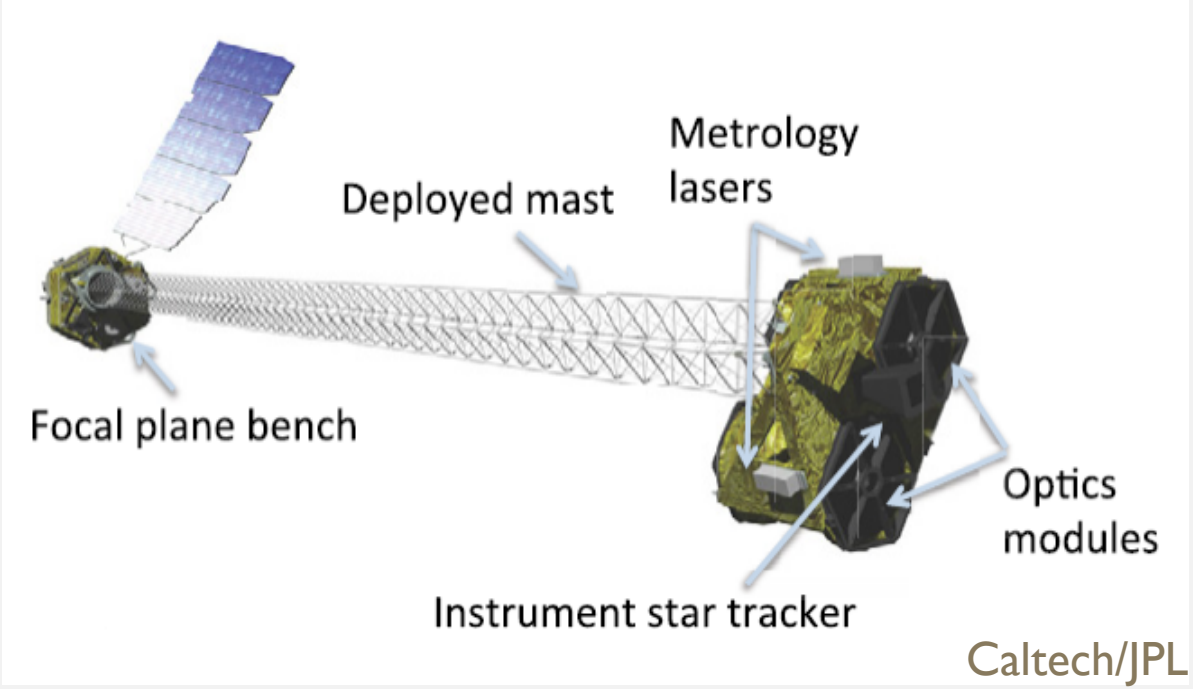
2020 July 8



I. Hannah render of SDO+Hinode+NuSTAR composite

THE NUCLEAR SPECTROSCOPIC TELESCOPE ARRAY (NUSTAR)

- ***Astrophysics*** spacecraft not optimized for solar pointing
- Best conditions: targets ≲GOES B5
- Observations are planned 3-4 days in advance (minimum) or as Guest Observer programs, including planned coordinations with other spacecraft.



The NuSTAR Heliophysics Team:

David Smith, Brian Grefenstette, Lindsay Glesener, Iain Hannah, Hugh Hudson, Säm Krucker, Matej Kuhar, Stephen White, Paul Wright, Amir Caspi, Bin Chen, Chris Moore, Kathy Reeves, Jaime Ruiz, Albert Shih, Julia Vogel

Graduate Students: Kris Cooper, Jessie Duncan, Sarah Paterson

TOPICS

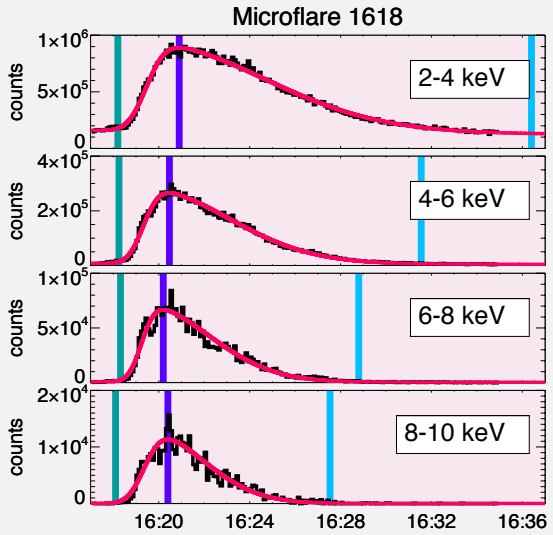
- **NuSTAR has recently made advances in measuring small-scale energy release** – some highlights will be shown here.

- **NuSTAR has coordinated with the Parker Solar Probe** for a few perihelia and will continue to do so. Some sample quicklooks and upcoming plans will be shown.

RECENT NUSTAR PROGRESS IN UNDERSTANDING SMALL-SCALE ENERGY RELEASE

GOES Class:
A and sub A

SMALL MICROFLARES SHOW SIMILAR TIME PROFILES TO BIGGER FLARES.



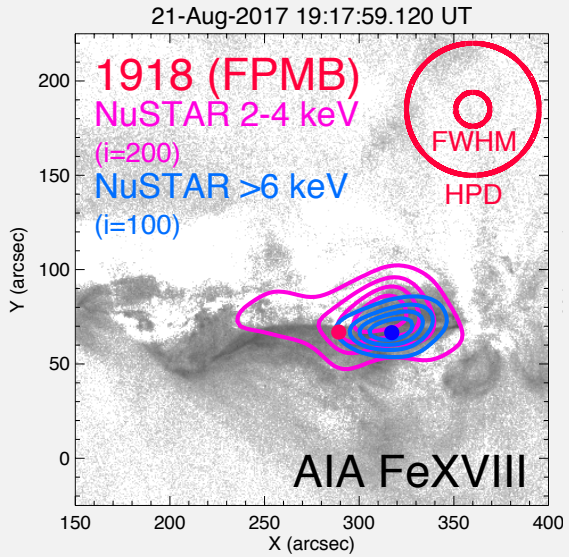
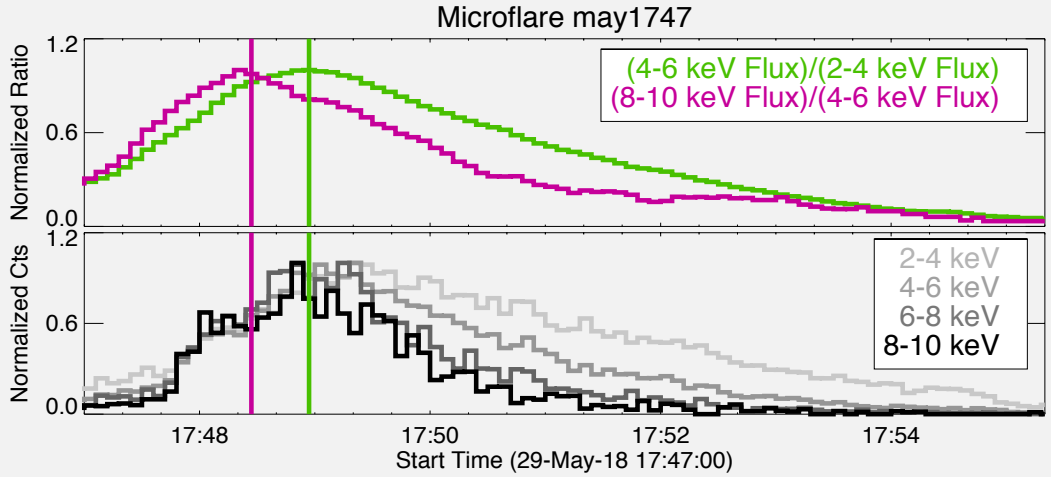


Table 1. Event Asymmetries (A_{ev})

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)

Eleven events: NuSTAR microflares are almost always impulsive and rapidly reach their highest temperatures, followed by a gradual cooling.

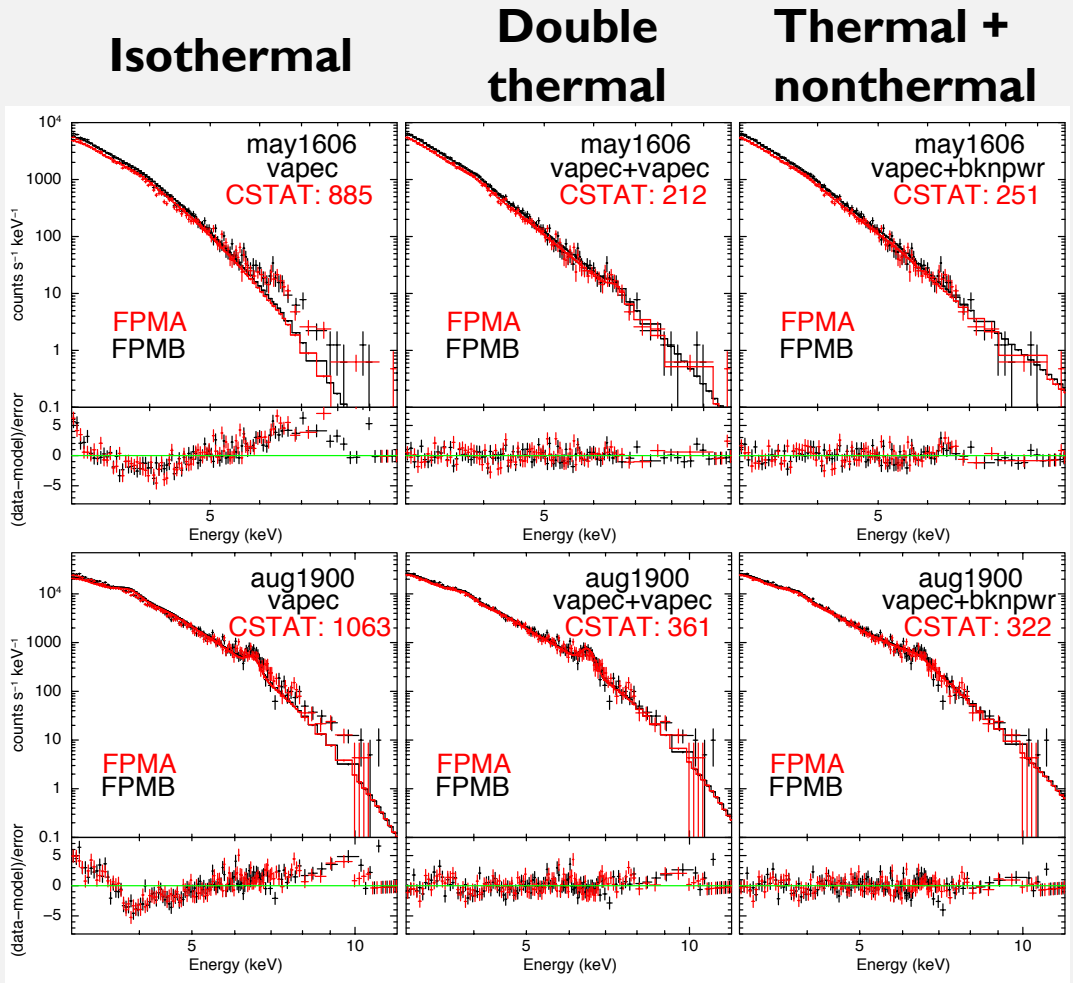


GOES Class: A and sub A

SMALL MICROFLARES ARE NOT WELL-FIT BY AN ISOTHERMAL MODEL.

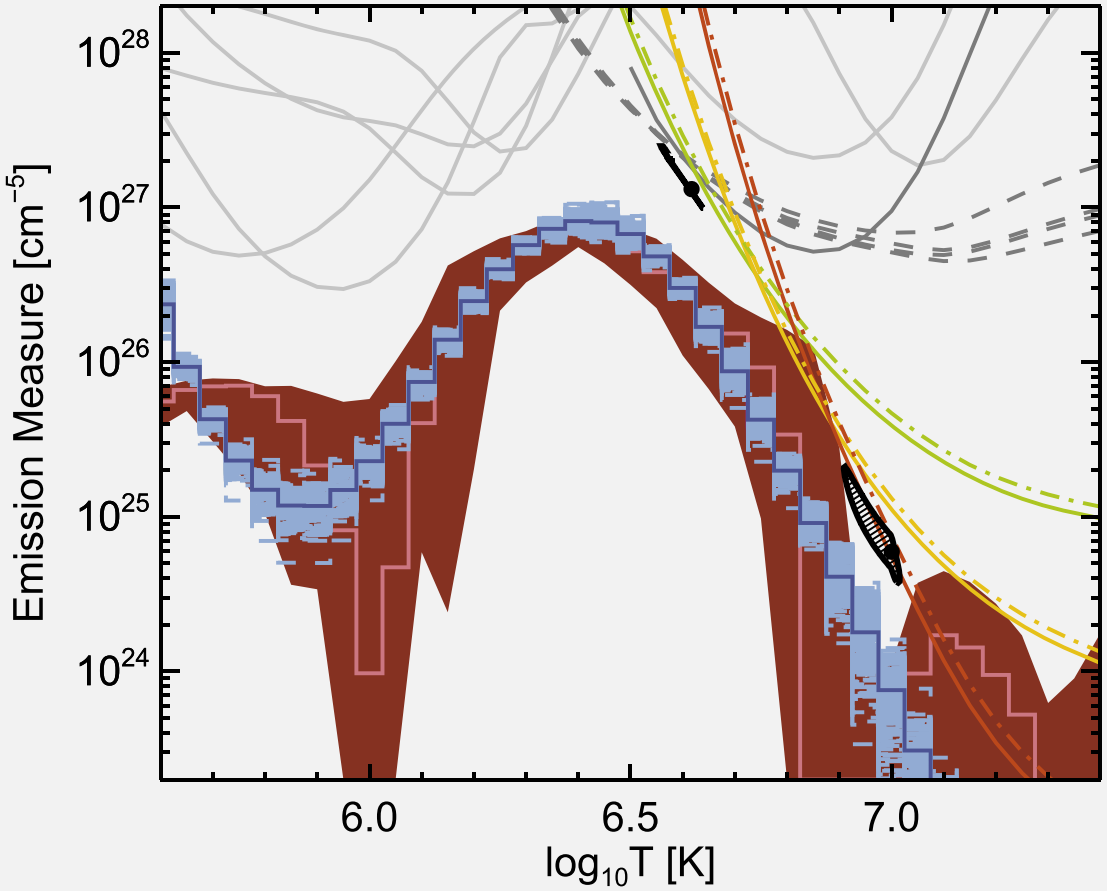
GOES Class: A 0.1

All eleven flares showed high-energy excess.



Duncan et al. (in prep)

Combining NuSTAR with Hinode/XRT reveals a broad DEM.

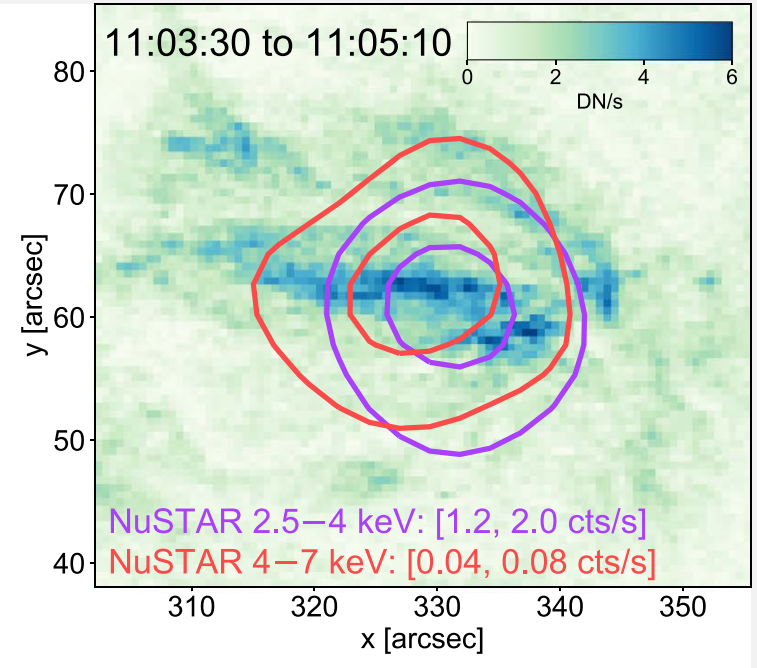


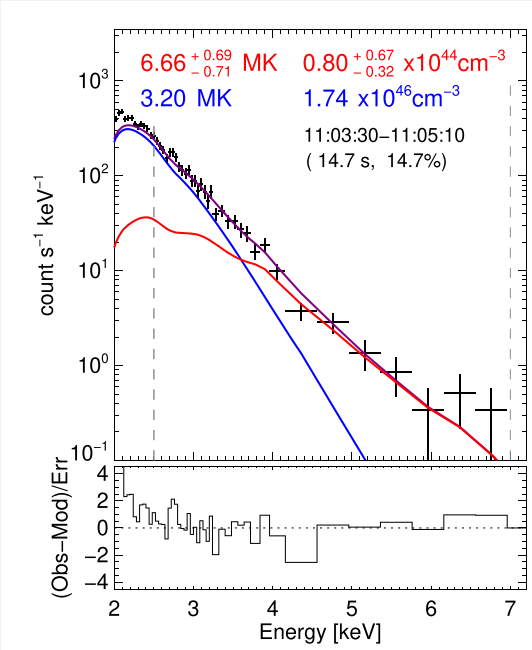
Wright et al. (2017)

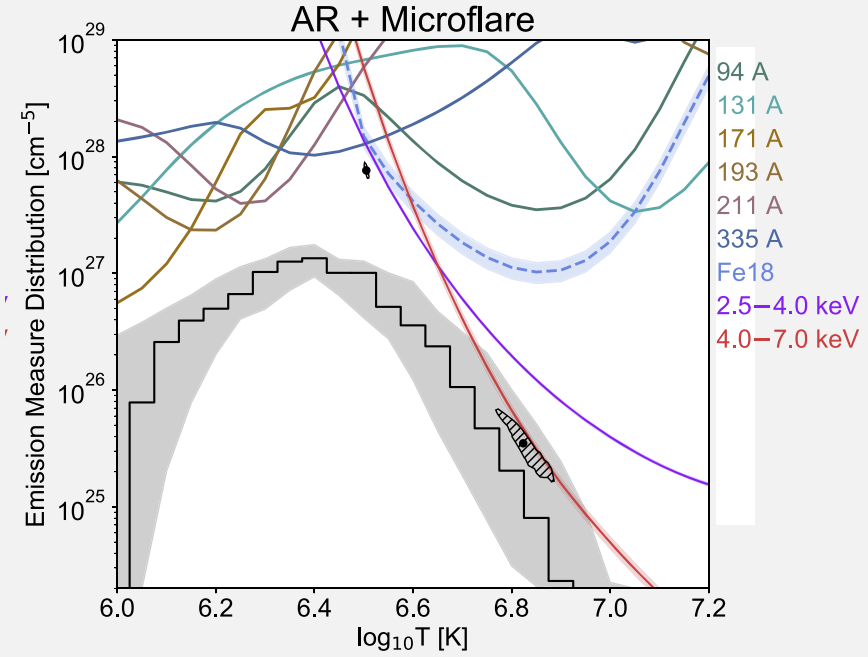
GOES Class:
teeny tiny

THIS IS TRUE EVEN FOR THE ***REALLY*** FAINT ONES!

A very faint microflare of energy ~10^{26} erg was found to have a DEM reaching up to T~6.7 MK (though note the difficult in separating a flare from the quiescent region at these small scales).



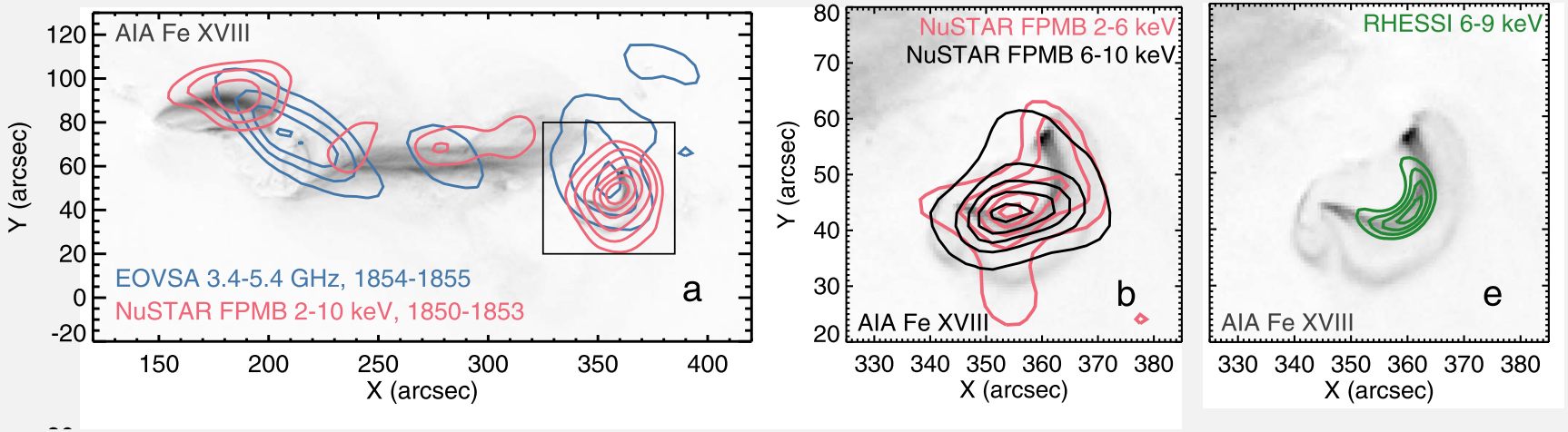


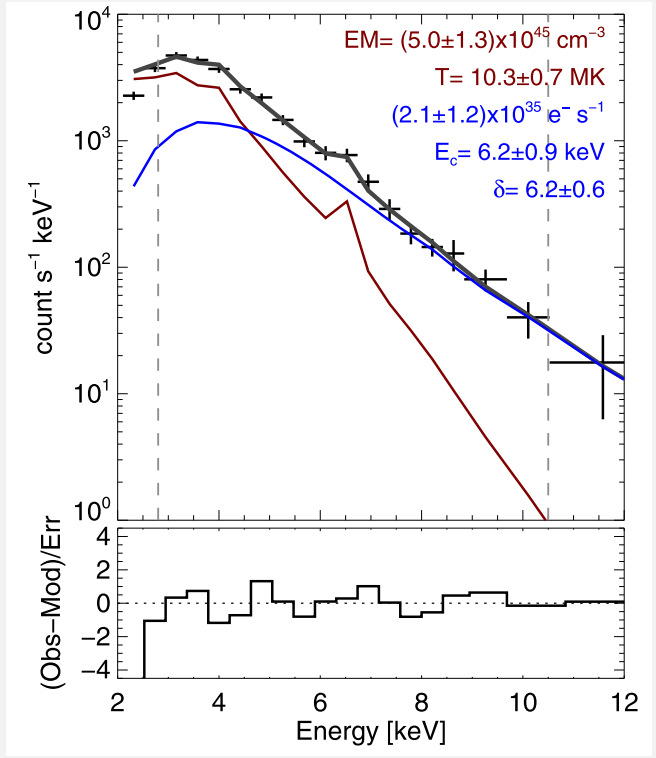


Cooper et al. (2020)

GOES Class: A6

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



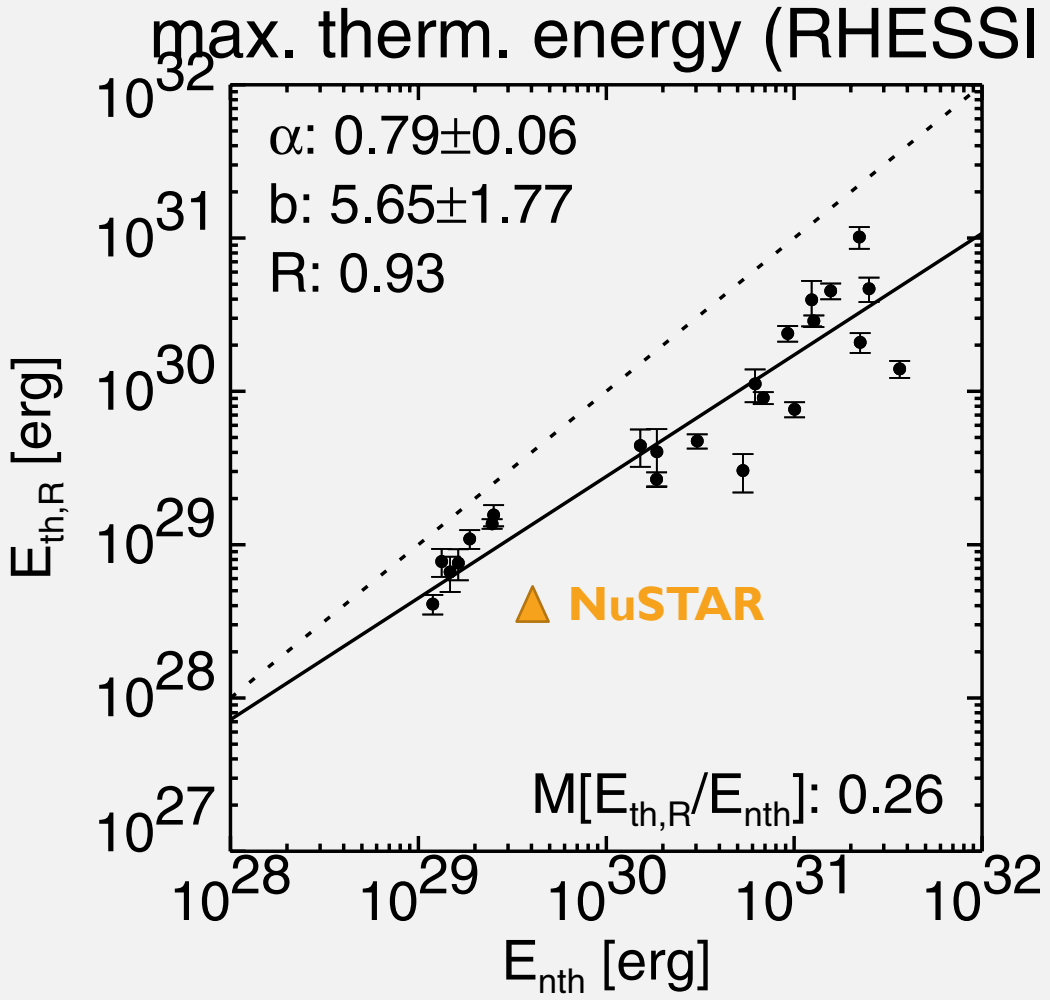


- We have one clear observation of a nonthermal electron distribution in a NuSTAR microflare.
- The distribution extends down to **~6 keV** and contains a large amount of energy (4 x 10^{29} erg, about 10x the estimated thermal energy).
- Electrons thermalize *mostly in the corona*.

Glesener et al. (2020)

HOW DOES THIS COMPARE WITH LARGER FLARES?

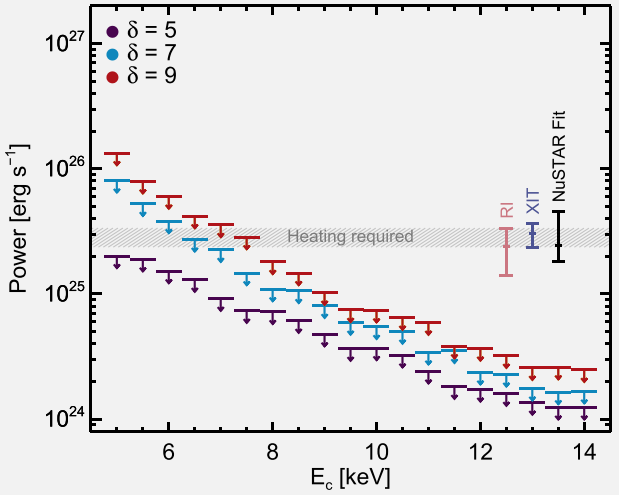
- The energy ratio of this flare is not very different from the energy ratios of larger flares.
- This doesn't follow the same trend as RHESSI studies, but sensitivities of those analyses could be responsible.
- This flare ***does*** fit the trend of ***steeper*** distributions at small energies. $(\delta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



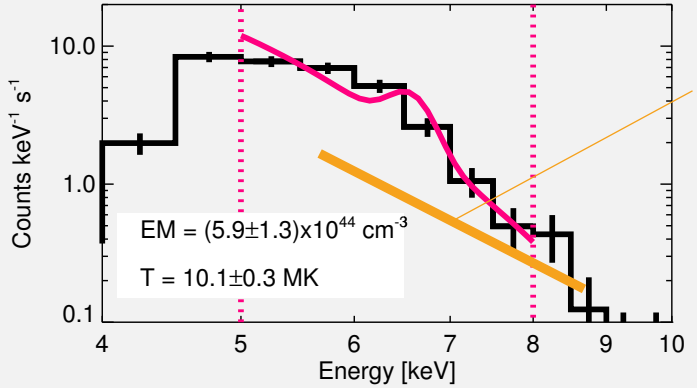
Edited from Warmuth & Mann (2016)

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.

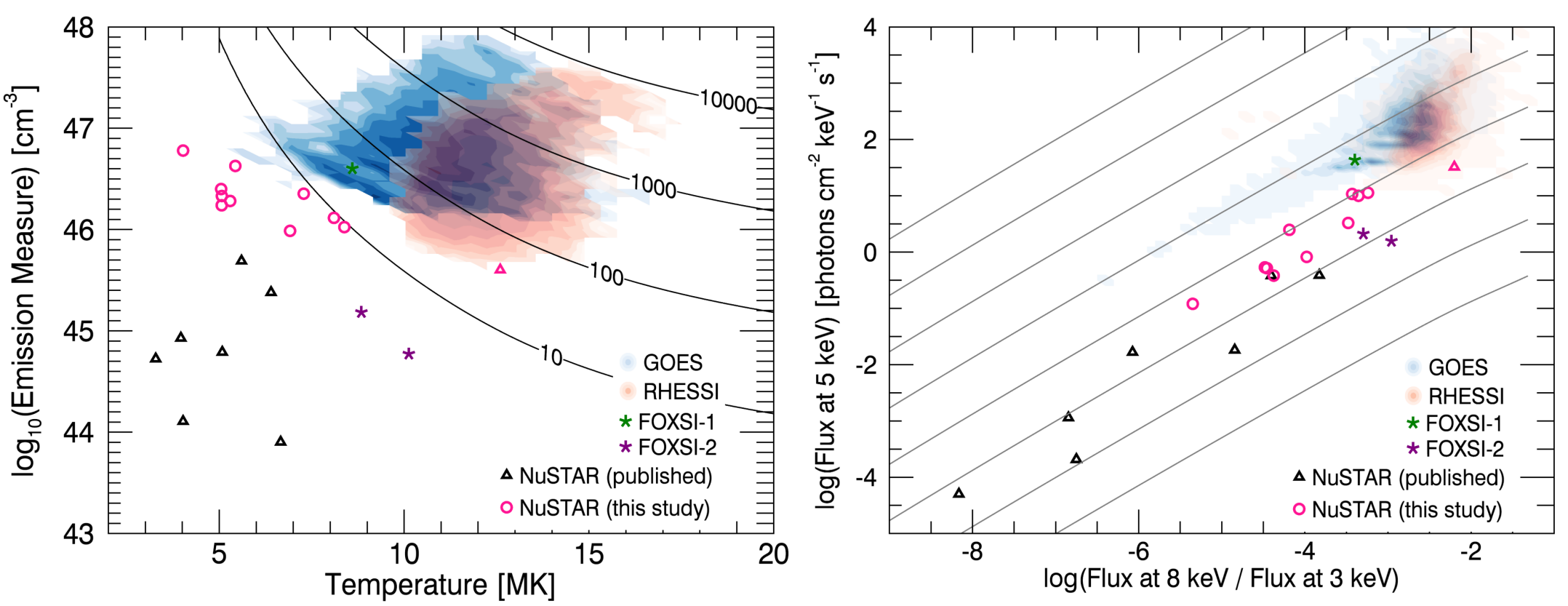


Hidden nonthermal component?

Vievering et al. (in prep) found similar results for one of the FOXSI microflares.

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.

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



Images courtesy of Julie Vievering and Jessie Duncan

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

NUSTAR COORDINATIONS WITH PARKER SOLAR PROBE

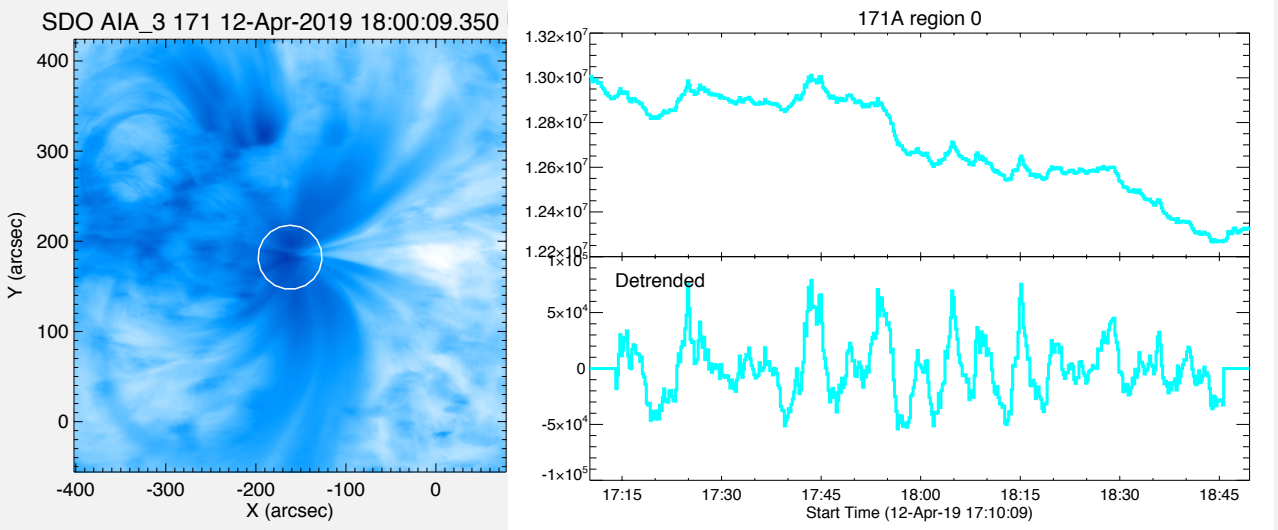
Made possible by:

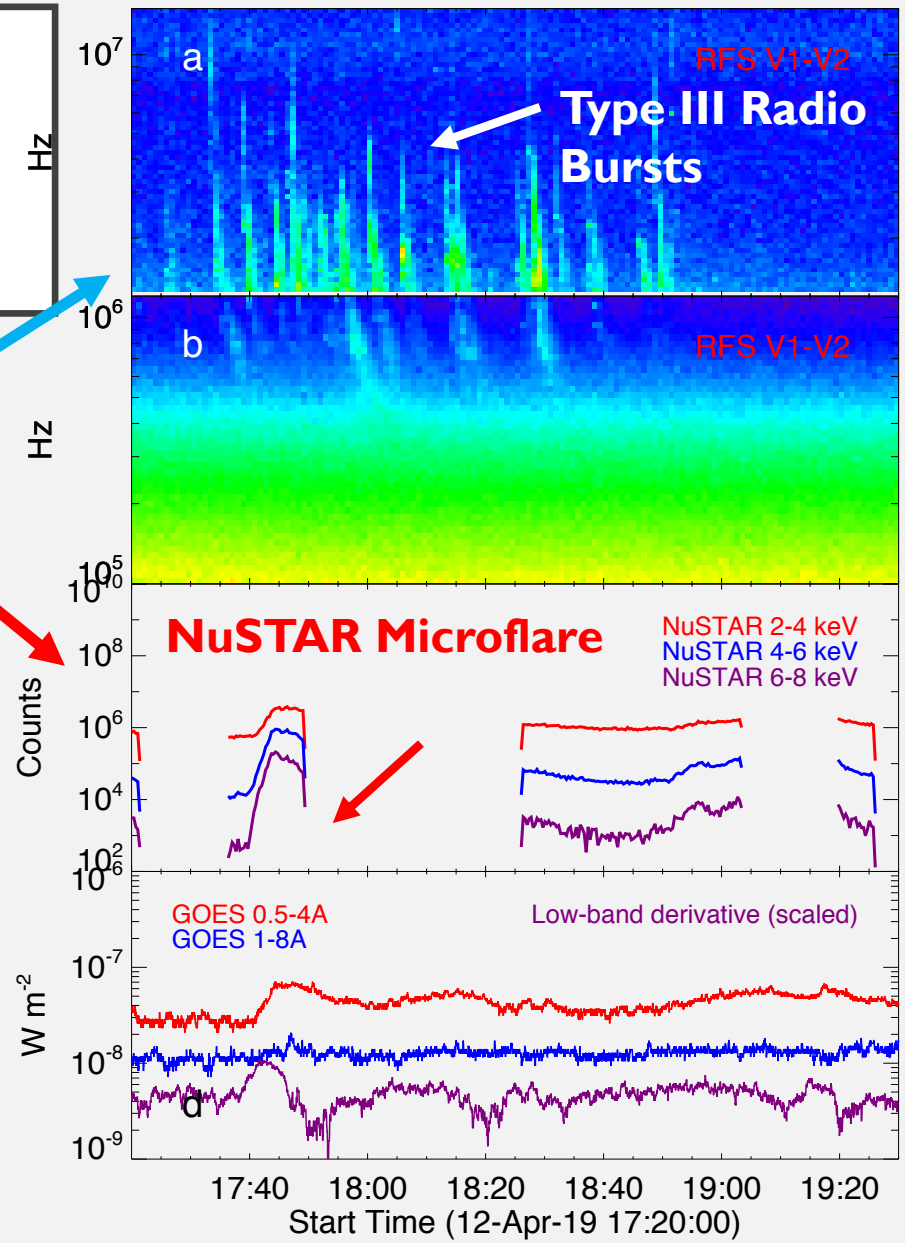
Cindy Cattell, Marc Pulupa, Keith Goetz

THE FIRST CO-OBSERVATION CAMPAIGN IN APRIL 2019

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)

AIA 171A



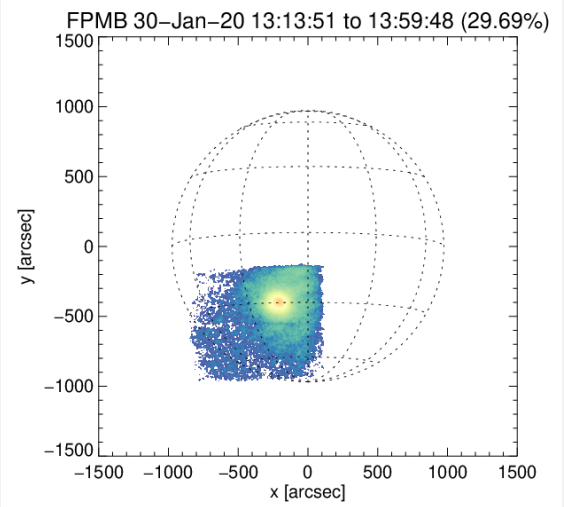


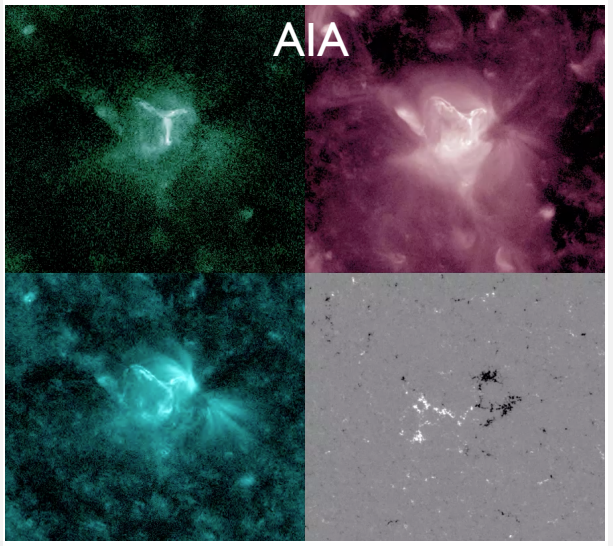
Cattell et al. (in prep)

4TH PSP PERIHELION, JANUARY 29, 2020

- Guest Observer Program #5181, led by Jessie Duncan
- NuSTAR observed intermittently on Jan. 29 and 30th.
- Targets: Both active regions + southern pole (at different times)
- At least one flare captured, probably more.

NuSTAR





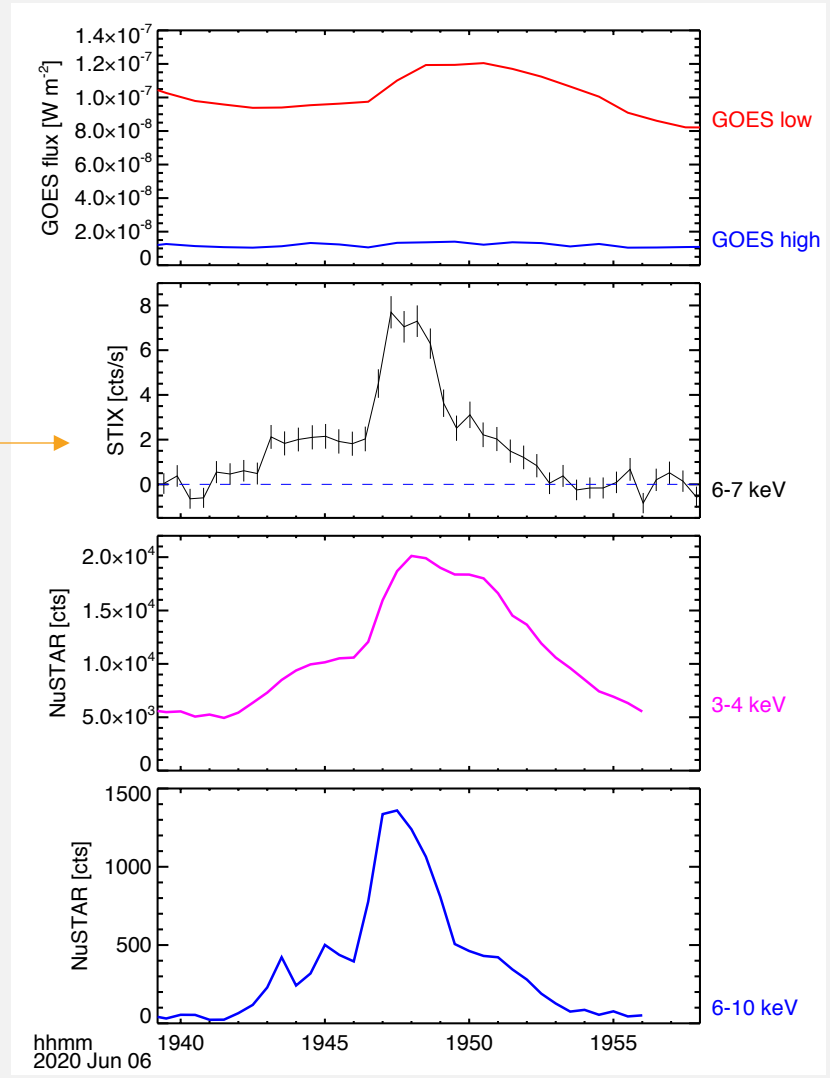
Plots by Iain Hannah

NUSTAR GUEST OBSERVER PROGRAM #6259

- Principal Investigator: Jessie Duncan
- Six co-observations with Parker over June 2020-2022.
- The first observation occurred June 6-10 2020.
- STIX crashed the party!

Table 1: Properties of Cycle 6 & 7 PSP Perihelia

Date	Distance	Location
June 7th, 2020	27.9 $R_\odot$	East Limb
Jan. 17th, 2021	20.4 $R_\odot$	Central Meridian
April 29th, 2021	16.0 $R_\odot$	East Limb
Nov. 21st, 2021	13.3 $R_\odot$	West Limb
Feb. 25th, 2022	13.3 $R_\odot$	Central Meridian
June 1st, 2022	13.3 $R_\odot$	East Limb



Plot by Säm Krucker

CLOSING THOUGHTS

- You can't measure a big flare (**on the Sun**) with NuSTAR. But the small flares are proving quite lucrative!
- New studies of the smallest observable hard X-ray microflares find similar behavior to larger flares. One observation implies that there may be more nonthermal energy than was apparent to previous instruments.
- NuSTAR is actively supporting Parker Solar Probe campaigns and will continue to do so for at least the next two years. Small microflares will be the best targets for these campaigns.
- A solar-optimized direct-focusing hard X-ray telescope supported by high-resolution EUV imaging and high-resolution soft X-ray spectroscopy is necessary for thorough investigation!

MORE BACKGROUND ON NUSTAR SOLAR OBSERVATIONS:

Papers published (microflare papers highlighted)

- Grefenstette+ (2016)
- Hannah+ (2016)
- Wright+ (2017)
- Glesener+ (2017)
- Marsh+ (2017)
- Kuhar+ (2017)
- Marsh+ (2018)
- Kuhar+ (2018)
- Hannah+ (2019)
- Glesener+ (2020)
- Cooper+ (2020)

Getting the data and the software:

- Quicklooks by Iain Hannah: http://ianan.github.io/nsigh_all/
- HEASARC data (all data are public): https://heasarc.gsfc.nasa.gov/docs/archive.html
- Some software tools (casual development by team):
  - https://github.com/ianan/nsigh_all
  - https://github.com/NuSTAR/nustar_pysolar

Fun fact!

NUSTAR FLARE OBSERVATIONS ARE **NOT** LIMITED TO THE SUN.

The Astrophysical Journal, 882:72 (8pp), 2019 September 1 https://doi.org/10.3847/1538-4357/ab2e0d

New Star Observations with *NuSTAR*: Flares from Young Stellar Objects in the ρ Ophiuchi Cloud Complex in Hard X-Rays

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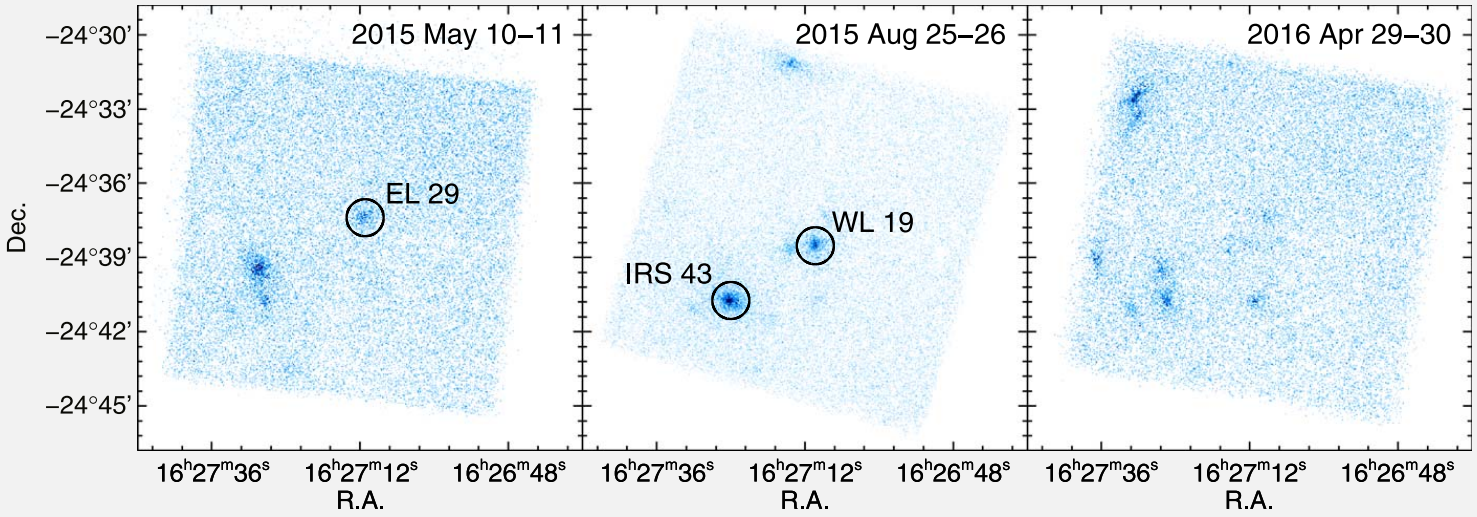

NuSTAR observations of giant flares on other stars exhibit some of the same properties observed in solar flares.

- Impulsivity, early high-energy emission, etc.