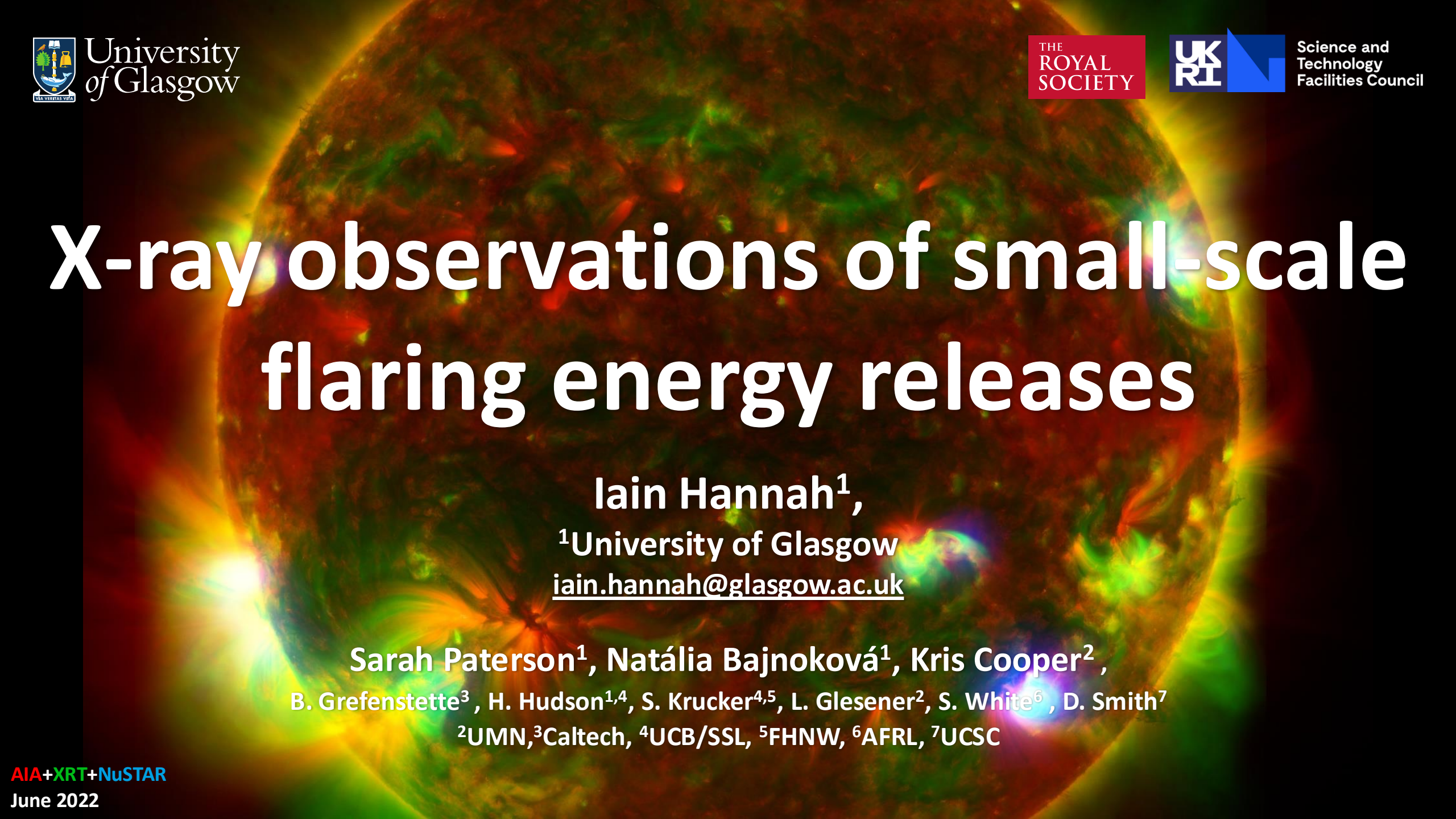

X-ray observations of small-scale flaring energy releases

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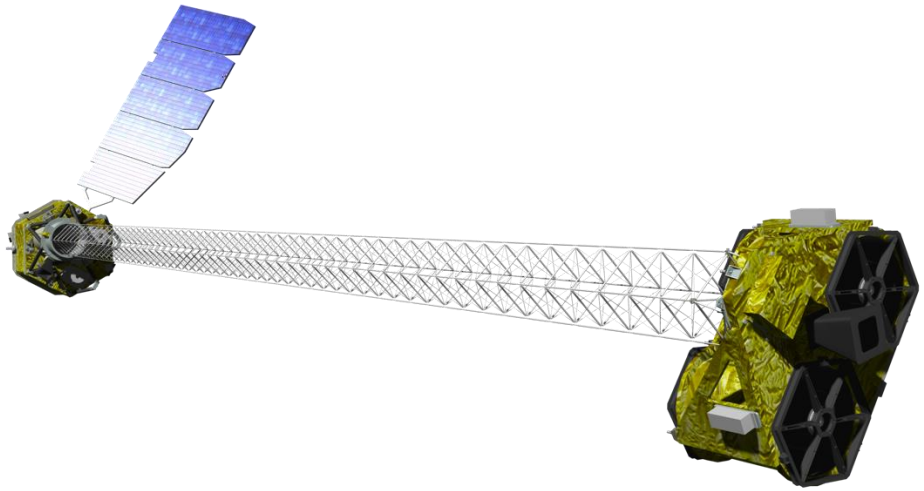
AIA+XRT+NuSTAR

June 2022

Motivation

- Energy rapidly released in large active region flares to accelerate particles and heat material
  - Seen in HXR via thermal and non-thermal bremsstrahlung
- Small active region microflares (A, B GOES) still show these processes but down to what scale?
  - Smallest HXR microflares?
- Do flares/transients outwith active regions (quiet Sun) still release energy in the same way?
  - Extensive work in EUV/SXR mostly showing heating to about 1 MK but what about HXR?
- Need a very sensitive HXR imaging spectrometer to detect hotter or non-thermal emission……
  - NuSTAR: Nuclear Spectroscopic Telescope Array (Harrison+ 2013)



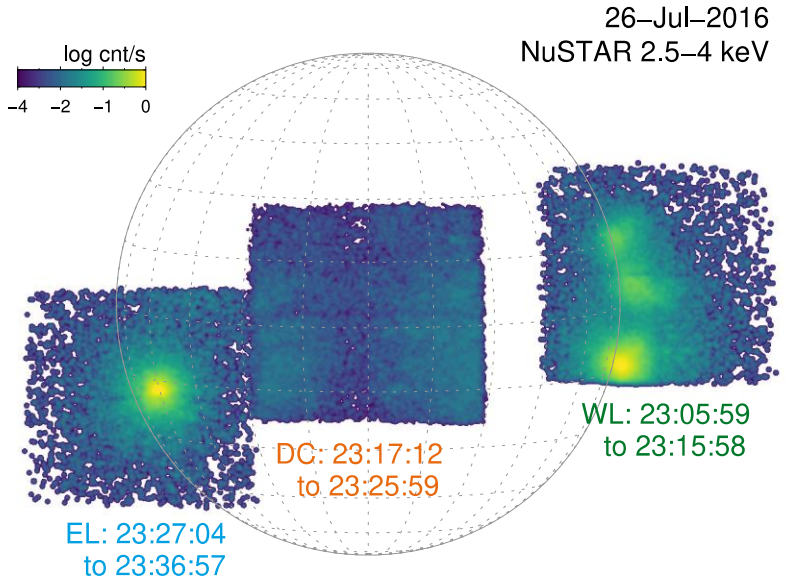
NuSTAR Solar Observations

- **NuSTAR astrophysics HXR direct focusing imaging spectrometer**
  - **Two telescopes (FPMA, FPMB)**
  - **>2keV, 12'x12' FoV**
  - **Output is event list: E,t,x,y per X-ray (+ "Grade" info)**

- **37 campaigns so far: Nov 2014 to Jul 2024**
  - **Co-ord with Hinode, IRIS, PSP, SO/STIX, XSM etc**
  - **QS, microflares, occulted flares etc**

- **Capable but not optimised for solar (Grefenstette+ 2016)**
  - **Low detector throughput: limits spectral dynamic range; cannot handle ≳ B5 microflares; pile-up & gain issues for A/B microflares**
  - **"Ghost-rays": weakly see things outside FoV**
  - **Mostly targets rest of the universe….**

Overview of NuSTAR solar obs
http://ianan.github.io/nsovr/



Hannah+ 2019

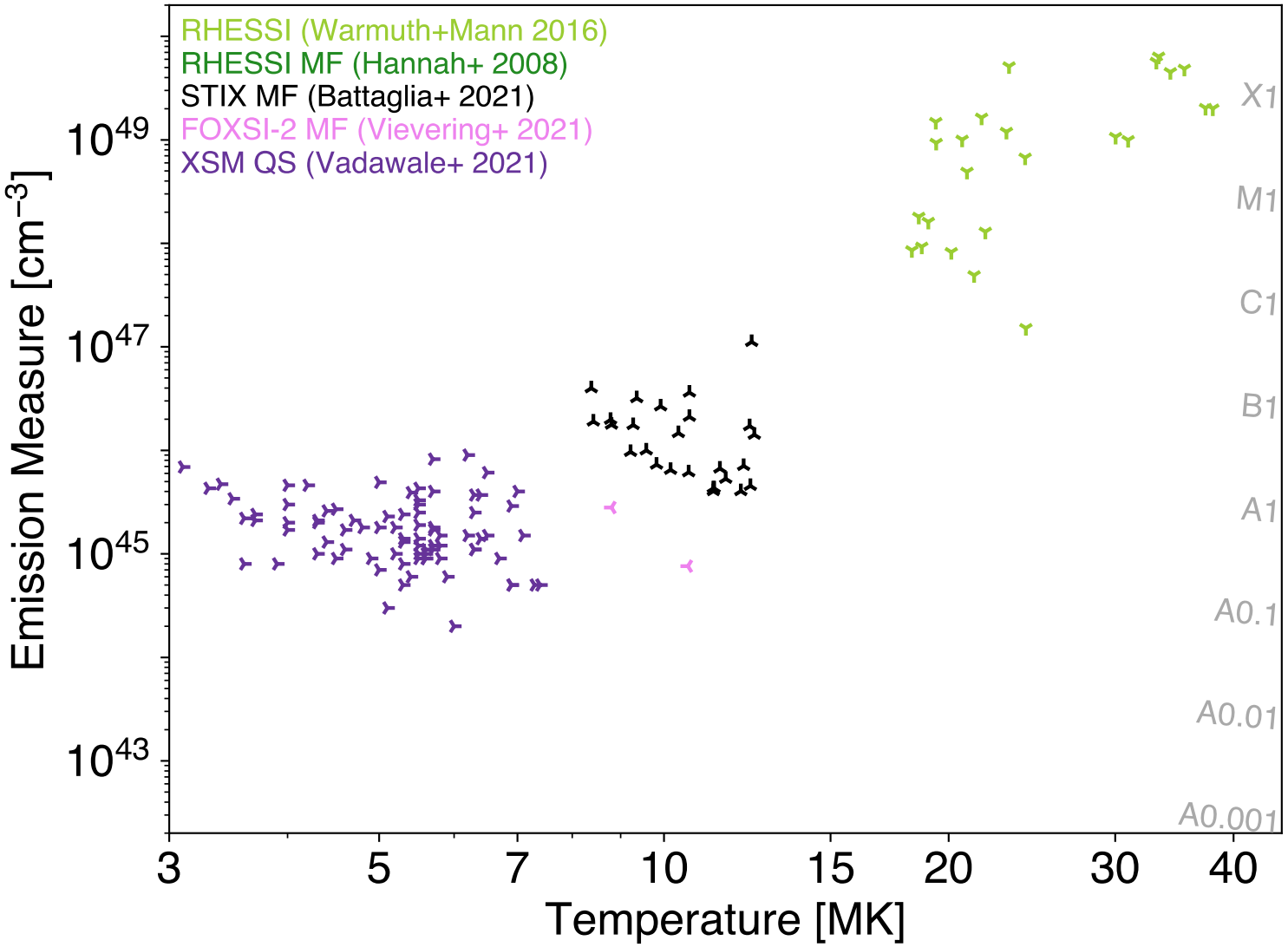
Scales of Flaring Energy Release: EM vs T

- **Not an exhaustive list of active regions and quiet sun flares**
- **Very approx. scaling:**

$$EM \propto 10^{cT}$$

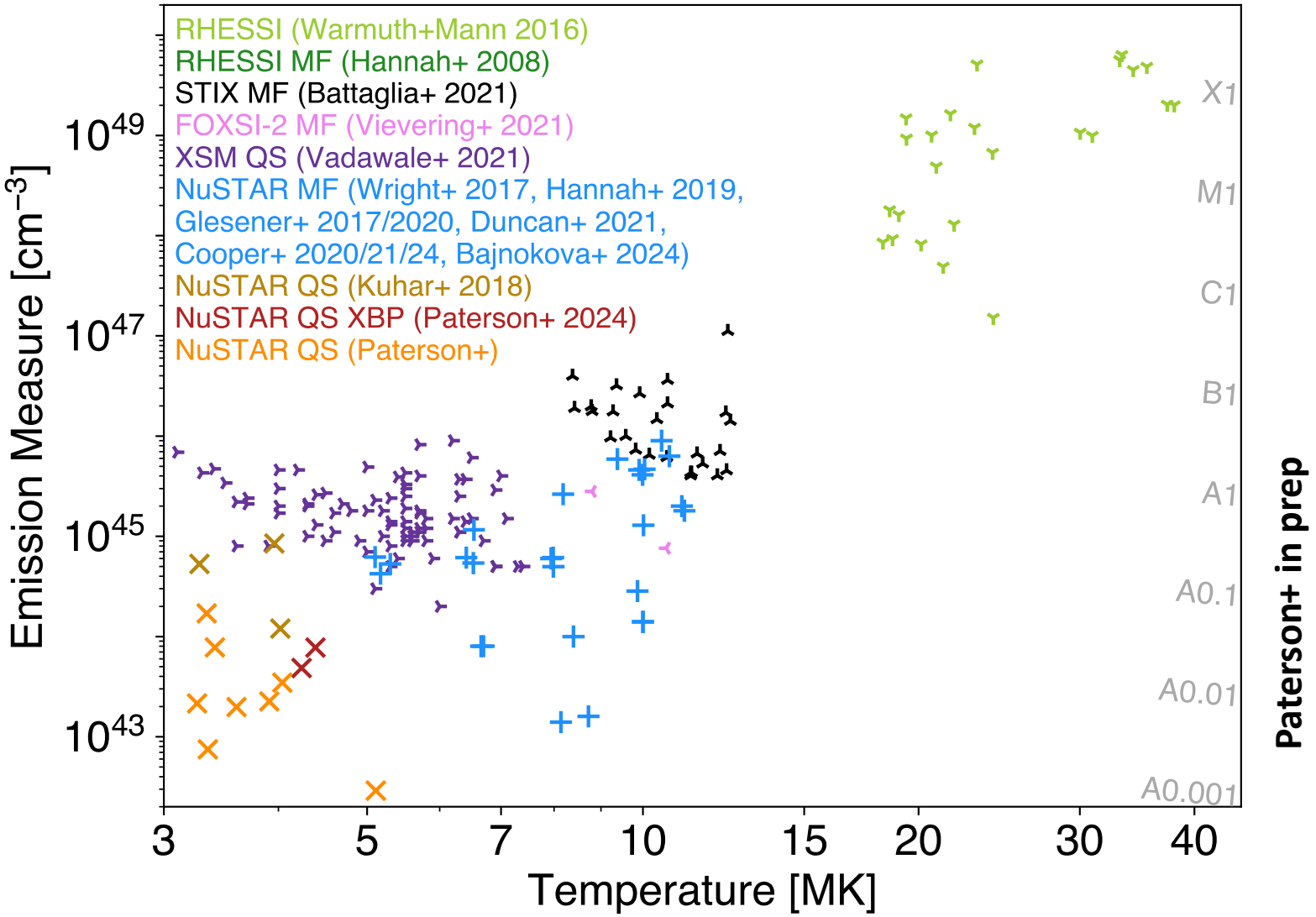
Feldman+ 1996

- **Warning: comparing different instruments, with different sensitivity, and different analysis approaches**
  - **Whole flare vs peak; thermal vs thermal + non-thermal model; etc**



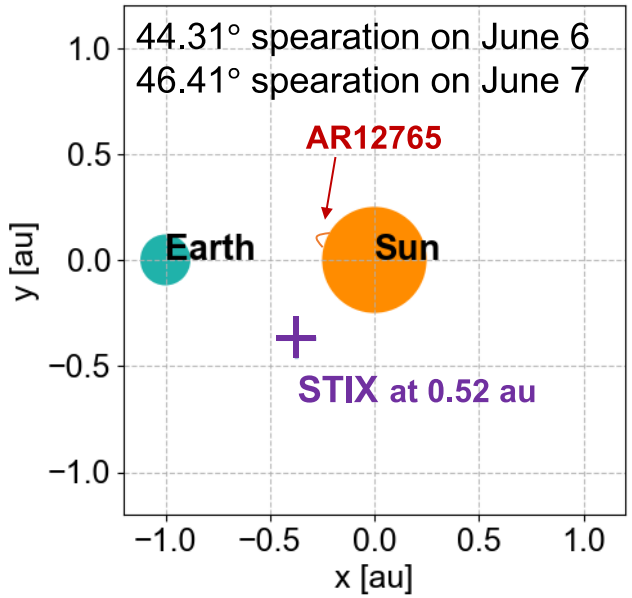
Scales of Flaring Energy Release: EM vs T + NuSTAR

- **NuSTAR microflare and quiet Sun studies greatly extends parameter space**
- **AR Microflares:**
  - **Thermal and non-thermal emission to orders of magnitude smaller**
- **QS "Flares":**
  - **Thermal emission to orders of magnitude smaller, non-thermal upper limits**

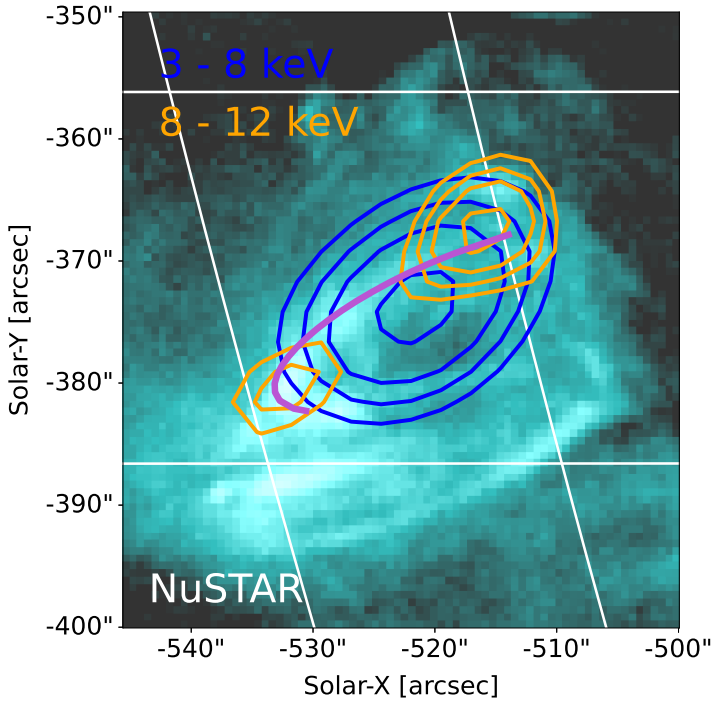


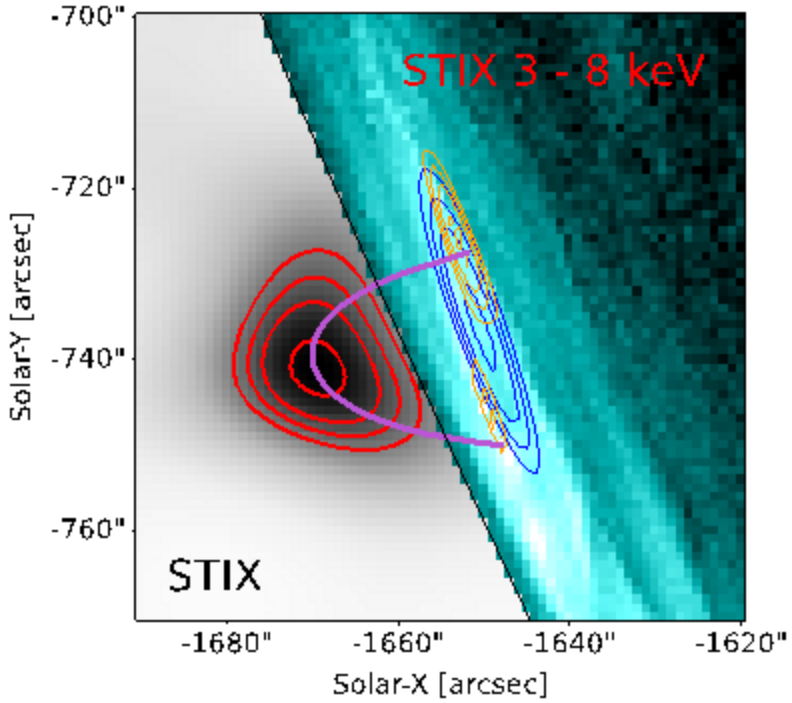
Microflares: NuSTAR + STIX

- **GOES B1 microflare: 06 June 2020 19:48**
- **Tricky as at limit of NuSTAR & STIX's sensitivity**
  - **Bright for NuSTAR but faint for STIX**
- **Location of thermal emission source matches**



Bajnoková+ 2024



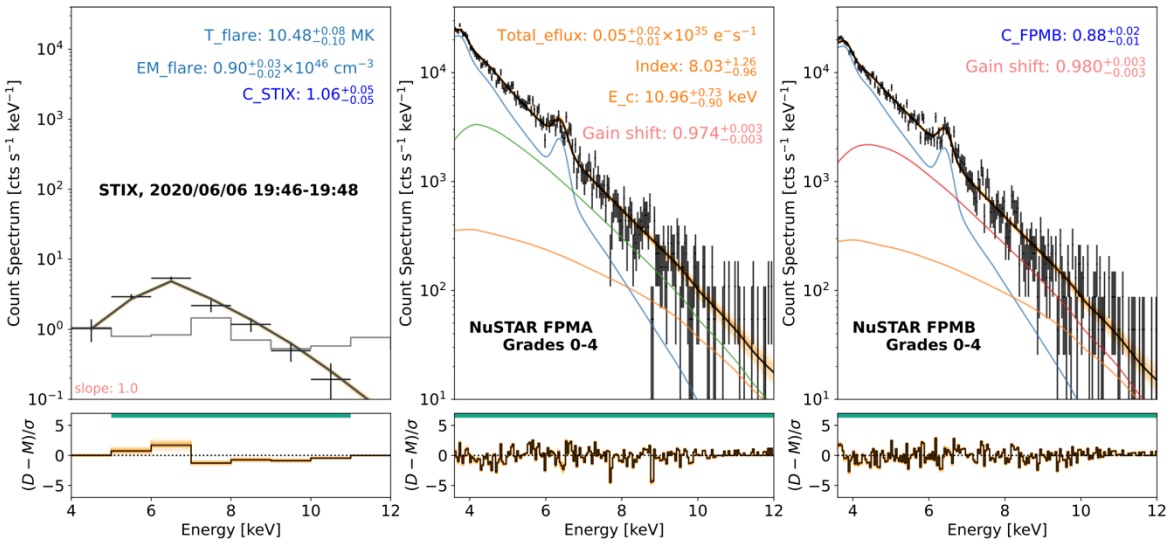


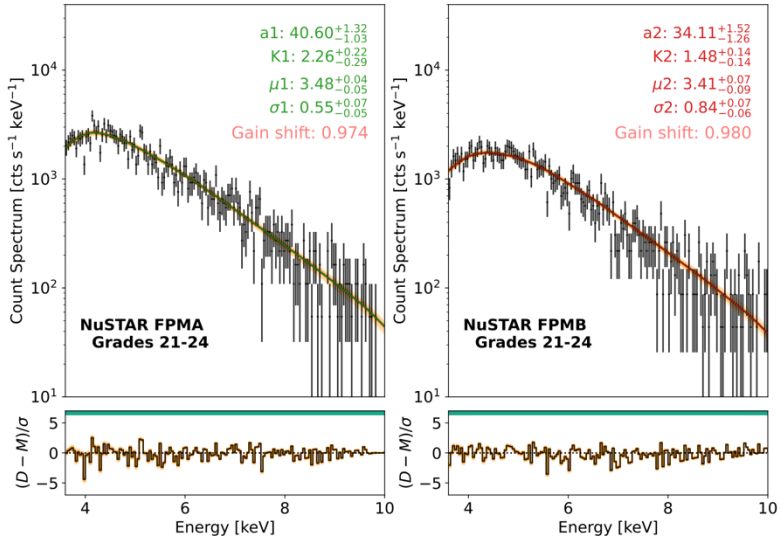
Microflares: NuSTAR + STIX

- **NuSTAR high count rate needs pile-up and gain correction**
  - **Pile-up: empirical model simultaneously fitted pile to Grade 21-24 (2 photon)**
- **Simultaneous fit to STIX and NuSTAR**
  - **FPMA & FPMB for NuSTAR**
- **Using Python package sunkit-spex**
  - **https://github.com/sunpy/sunkit-spex**
- **Both well fit with 10.5 MK, 9x10^{45} cm^{-3}, E_C=11 keV, δ =8, P_N=10^{25} erg s^{-1}**
- 5 joint spectra successfully fitted
  - More joint microflares under study

STIX spectra

NuSTAR Grade 0-4 spectra





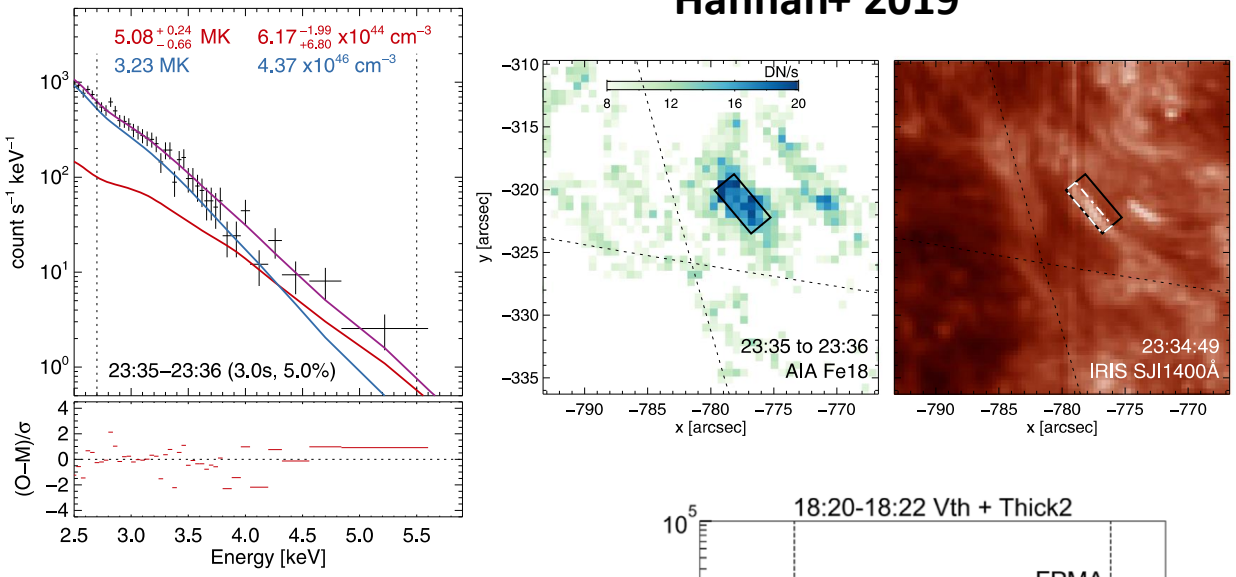
Bajnoková+ 2024

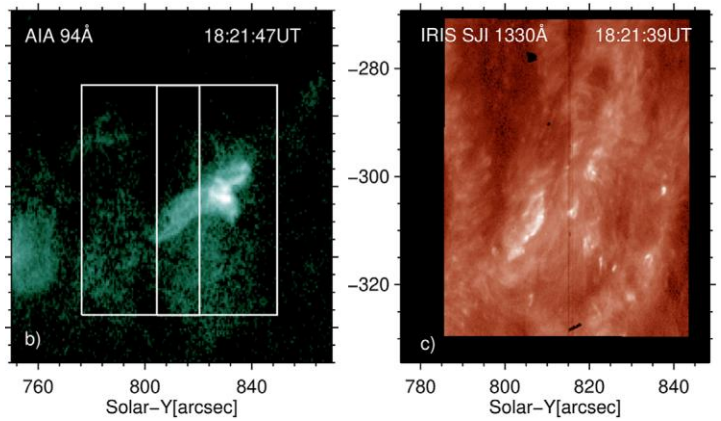
NuSTAR Grade 21-24 spectra (Pile-up)

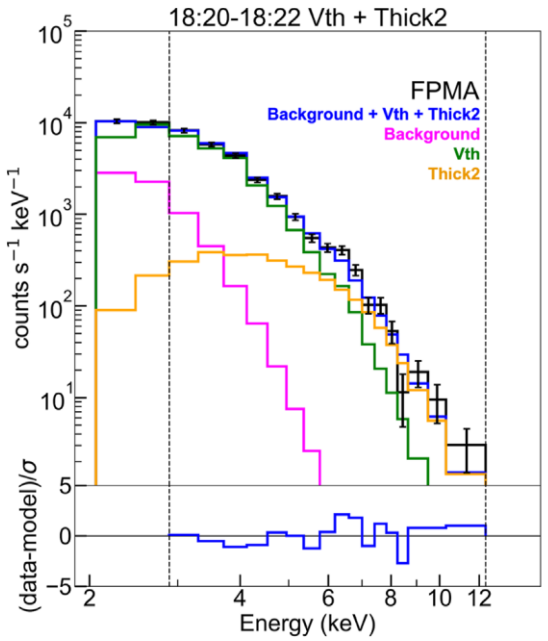
Microflares: NuSTAR + IRIS + RADYN

- RADYN simulation work shows blueshift in UV lines due to non-thermal electrons
  - Testa+ 2014, Polito+ 2018
- NuSTAR A1 microflare showed heating to 6 MK, no non-thermal, and IRIS redshift in Si IV and O IV
  - Hannah+ 2019
- NuSTAR B-class microflare showed non-thermal emission and IRIS blue shifted lines
  - Polito+ 2023

Hannah+ 2019



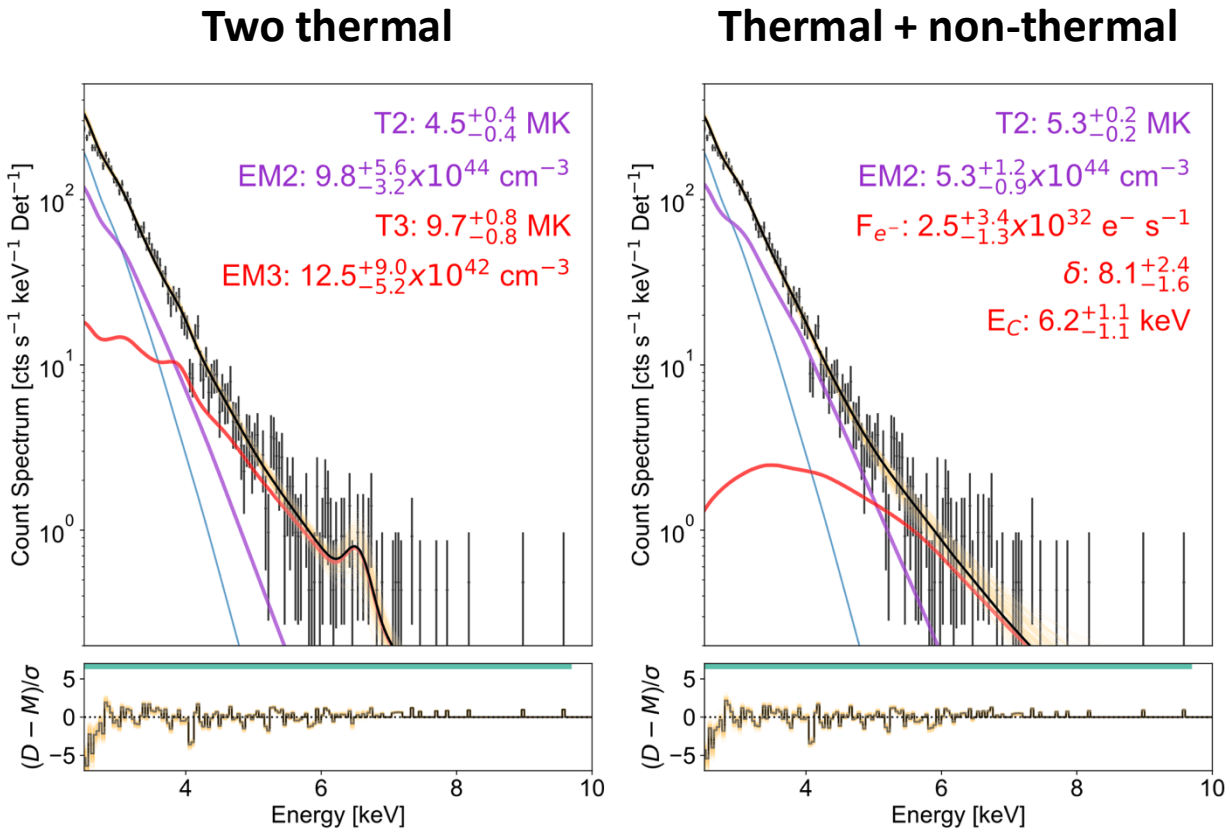




Polito+ 2023

Microflares: NuSTAR + Nested Sampling

- Very small AR microflare (A0.02) but unclear if two thermal or thermal + non-thermal model is a better fit
- No (clear) signatures at other wavelengths to help determine if weak high temperature (10 MK) or non-thermal
- Fit models using nested sampling
  - Via sunkit-spex and nestle packages
  - Evaluates Bayesian evidence
  - More efficient way of sampling parameter space, MCMC like results
- Stronger evidence for thermal + non-thermal in this A0.02 microflare
  - Thermal: ~10^{26} erg, Non-thermal: ~10^{24} erg s^{-1}

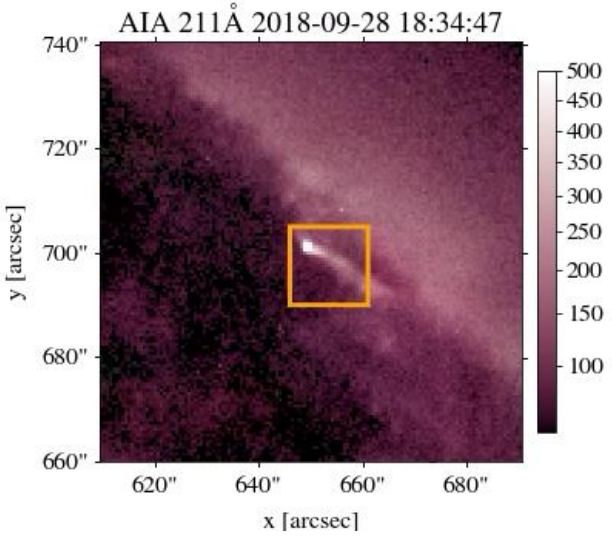


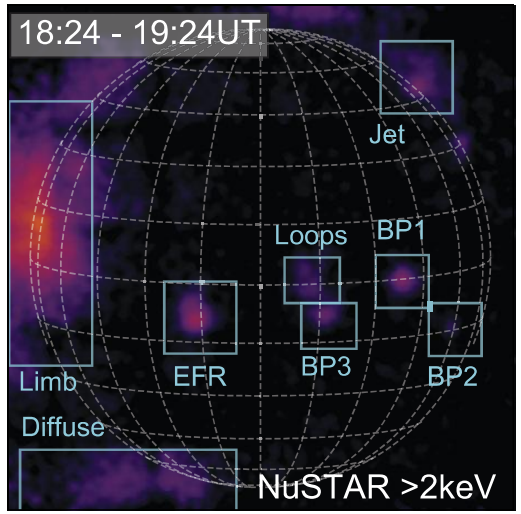
17 Nov 2021 21:24

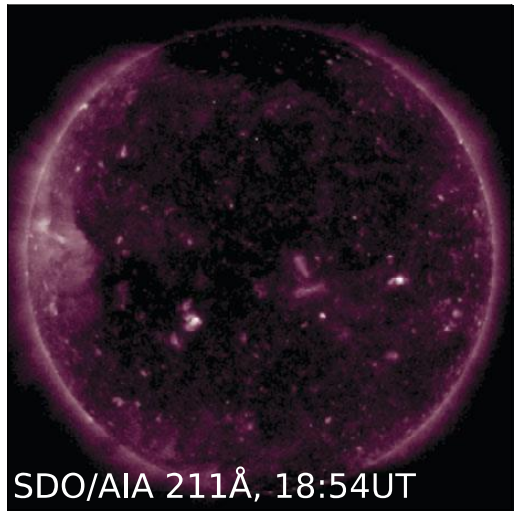
Cooper+ 2024

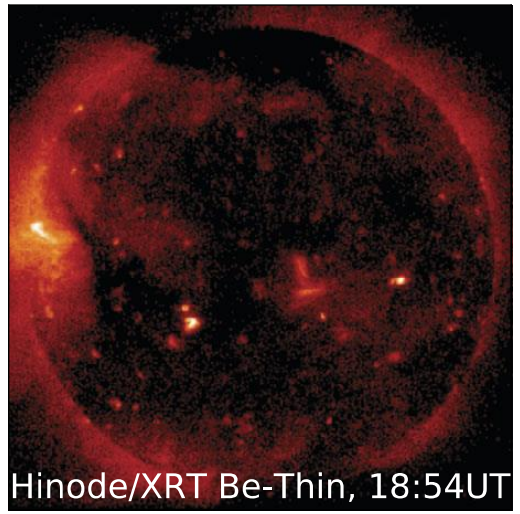
Quiet Sun: Overview

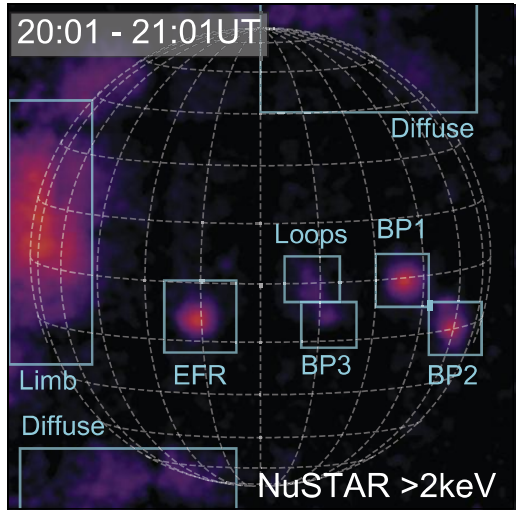
- **QS mosaic: multiple pointing changes to capture full disk**
- **Mostly steady sources**
  - **HXR spectra 2-3.2 MK**
- **Did catch a small jet**
  - **2.6 MK, no non-thermal**

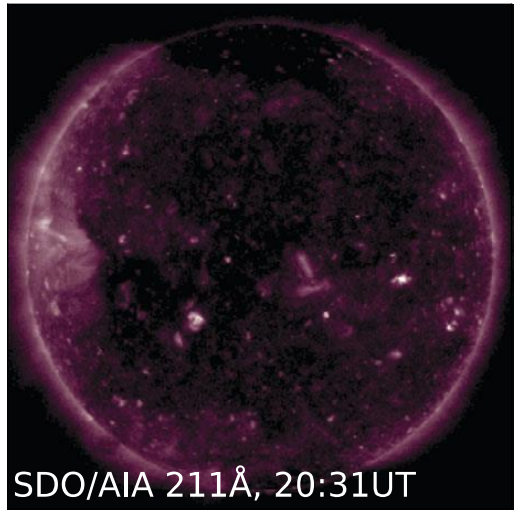


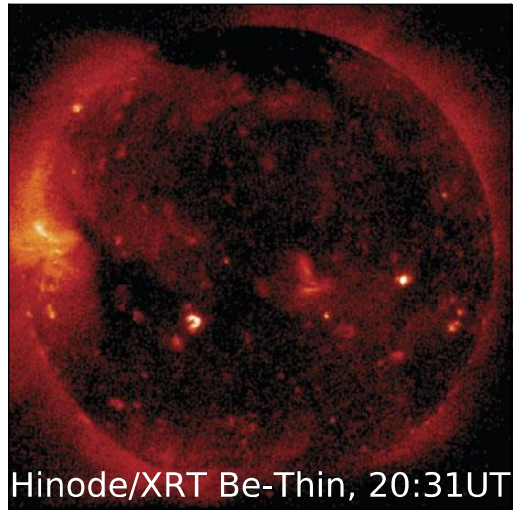








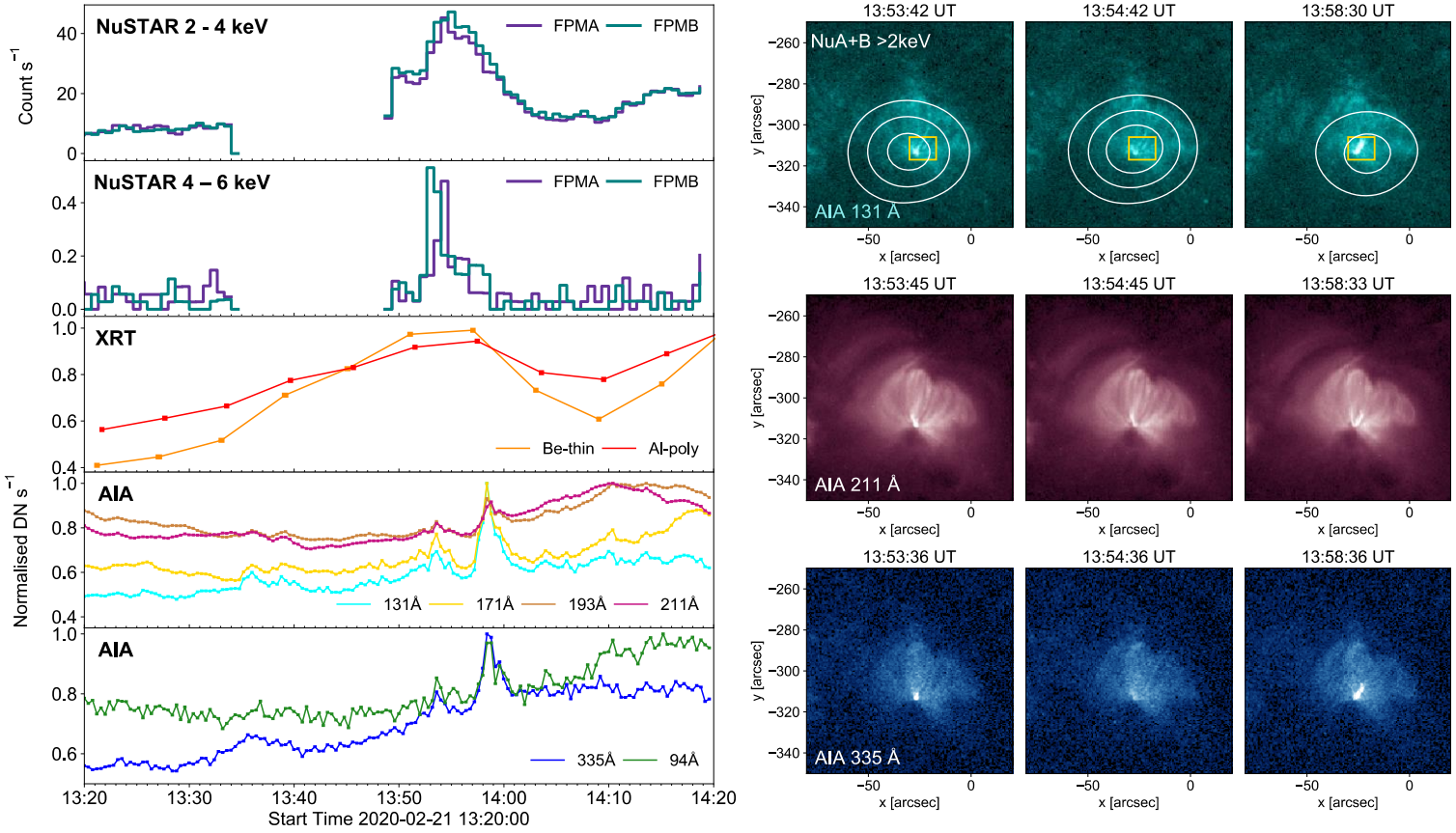




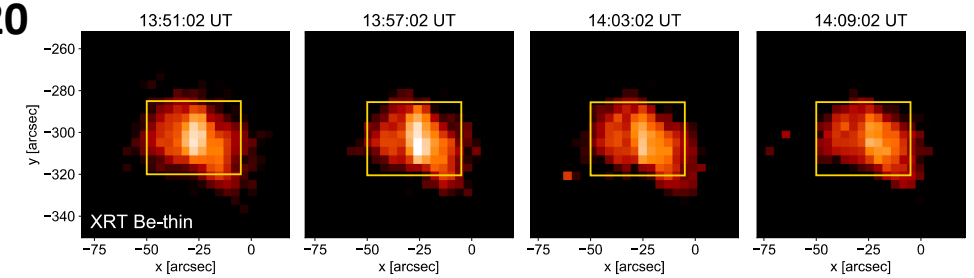
Paterson+ 2023

Quiet Sun: Flaring XBPs

- Dwells on XBPs caught them flaring
  - Solar minimum
  - 21 Feb & 12-13 Sep 2020
- Time profiles of XBPs flares match in NuSTAR + XRT but not in AIA
  - Due to different temperature sensitivities
- NuSTAR spectra give 3.2 MK, needs extra component > 4 MK during flare



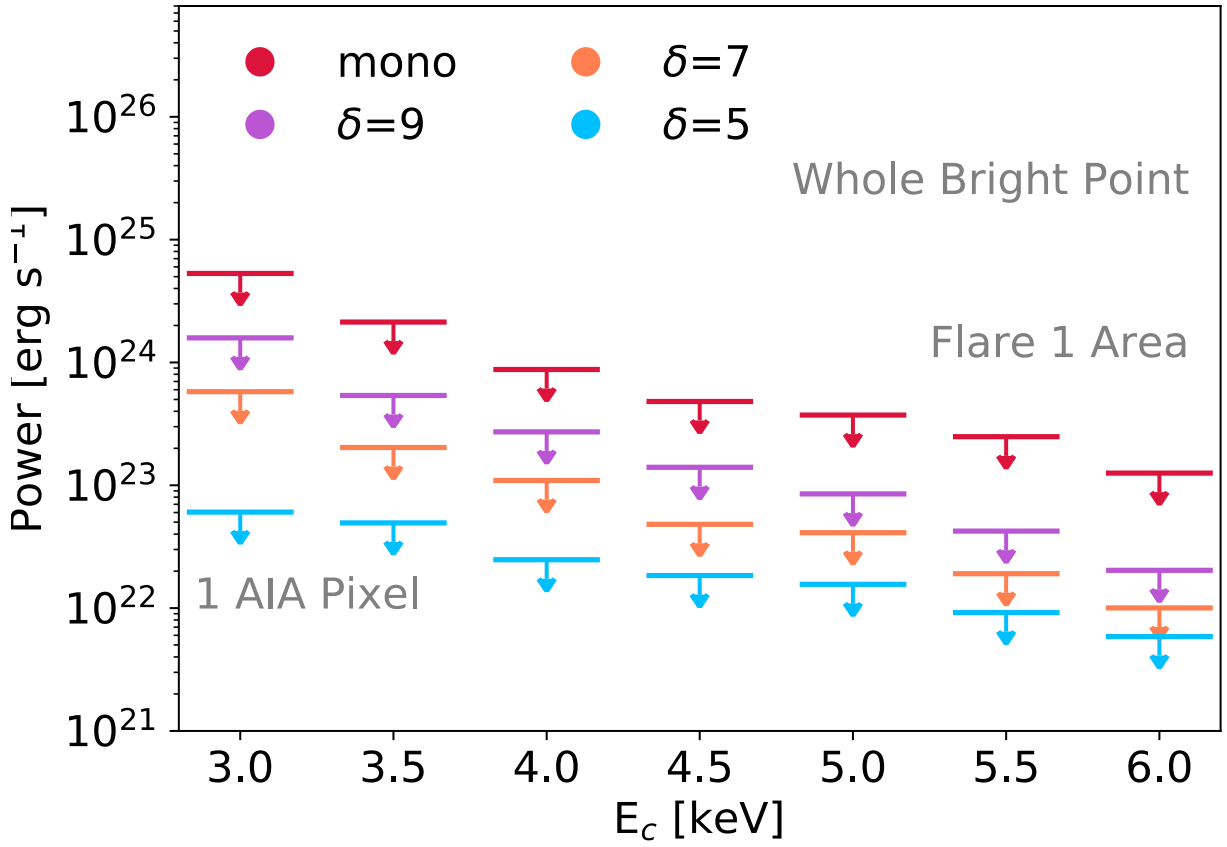
21 Feb 2020



Paterson+ 2024

Quiet Sun: Flaring XBPs

- No non-thermal detected
- Model non-thermal bremsstrahlung consistent with powering observed thermal but produce a null detection in NuSTAR
  - But uncertainty over thermal energy/heating power due to volume and filling factor
- Max thermal => only very steep electron beam at low energies consistent
- Lower heating requirement easier to power by non-thermal electrons

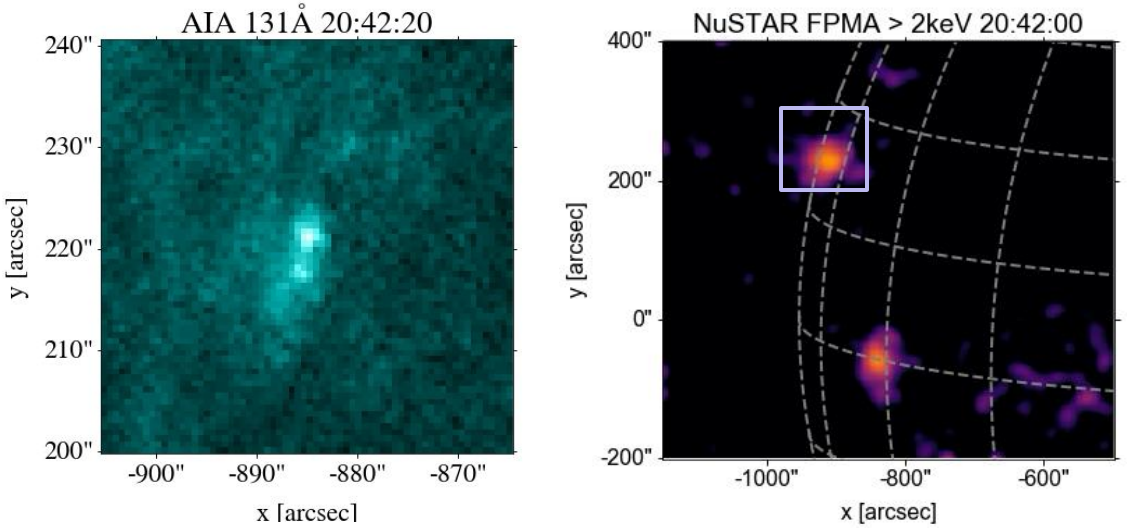


Paterson+ 2024

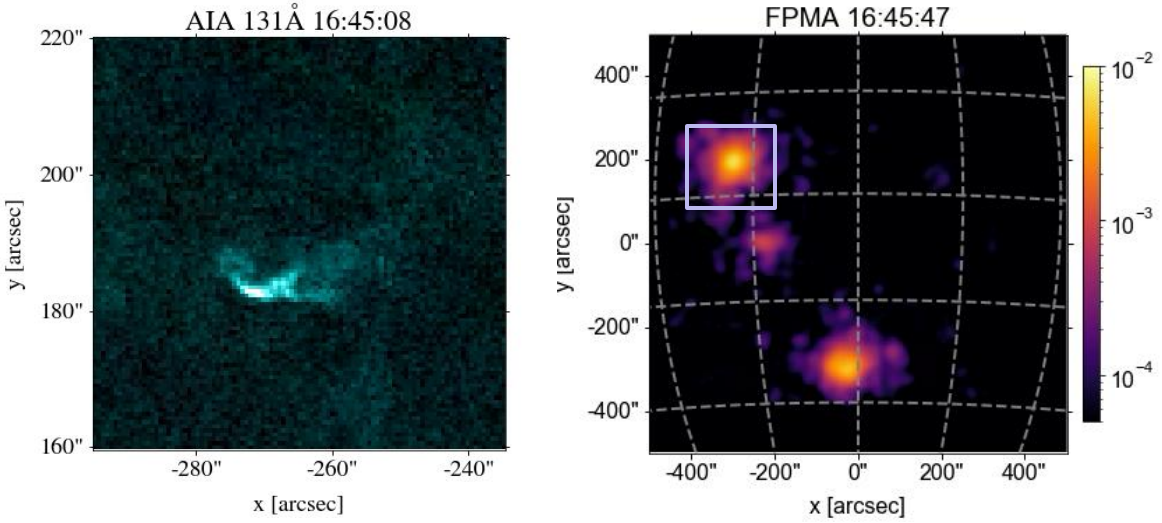
Quiet Sun: Flares/Transients

- QS Dwells also several caught flares/transients
  - Brightening smalls loops, occasional mini-filament eruption
- NuSTAR HXR spectra 3-4 MK, 10^{26} erg max thermal energy
  - Mini-filament ~ 5MK
- Hotter than EUV brightenings
  - NuSTAR sensitive to >2MK
- Again, no non-thermal but can model non-thermal emission to power heating + give null detection

12 Sep 2020 Small loops brightening



21 Feb 2020 Mini-filament Eruption

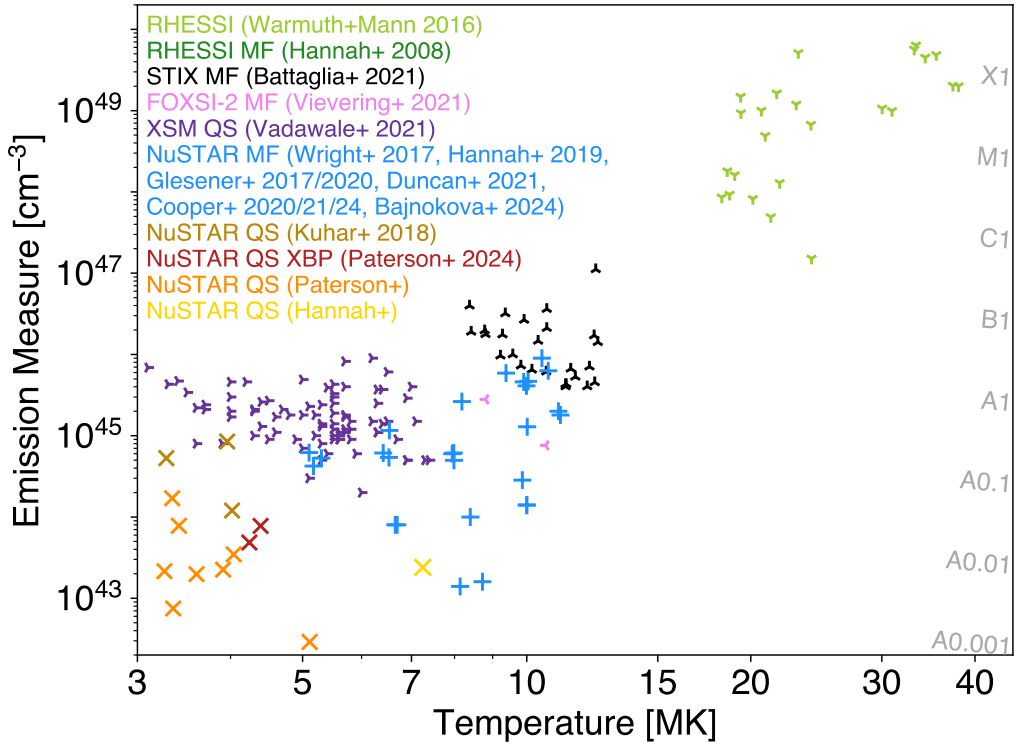


Paterson+ in prep

Summary

- **Orders of magnitude smaller HXR flares observed with NuSTAR**
- **Finding AR microflares down to <<A Class with heating 5-10 MK and non-thermal emission**
- **In QS finding steady sources 2-3 MK, with flares/transients mostly 3-4 MK**
  - **Upper limits on non-thermal emission to power the observed max heating would be steep to at low energies**
  - **Lower heating requirement flatter non-thermal**
- **NuSTAR continuing to target the Sun**
  - **Though challenging if >B5 in FoV….**

Bajnoková+ MNRAS 553, 2024
Cooper+ MNRAS 529, 2024
Paterson+ Sol Phys 298, 2023
Paterson+ MNRAS 528, 2024
Paterson+ MNRAS in prep



Paterson+ in prep

NuSTAR Solar: http://ianan.github.io/nsovr/
sunkit-spex: https://github.com/sunpy/sunkit-spex