Hard X-ray observations of non-flaring active regions & coronal loops

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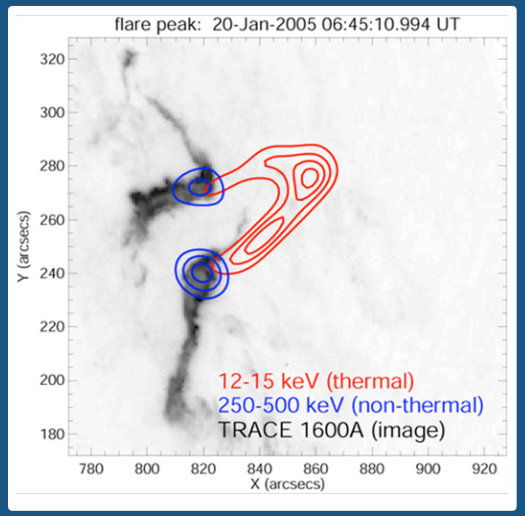
Overview

- Importance of energetic particles
  - (Direct ?) product of the flaring energy release
  - Non-thermal particles heat the solar atmosphere in flares
- Why hard X-rays (HXRs: > few-tens keV)
  - Direct signature of accelerated electrons
    - Radio and EUV also provide diagnostics of non-thermal
  - Range also cover hot SXRs

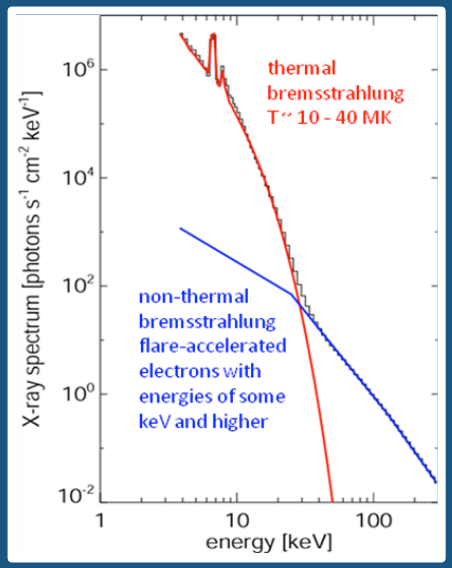
- Recent observations
  - Mostly limits as optimized for flare observations
- Future observations
  - Need higher sensitivity & better dynamic range

"Typical" Big Flare

- Magnetic reconnection facilitates the liberation of stored energy
- A sizeable fraction goes into accelerating particles
  - Sun is a prolific particle accelerator
- When theses particles stop and thermalize in chromosphere get:
  - Bright HXR footpoints (10+ keV)
  - Heats material ➔ expands forming hot coronal loops (SXR, EUV)
  - Neupert Effect



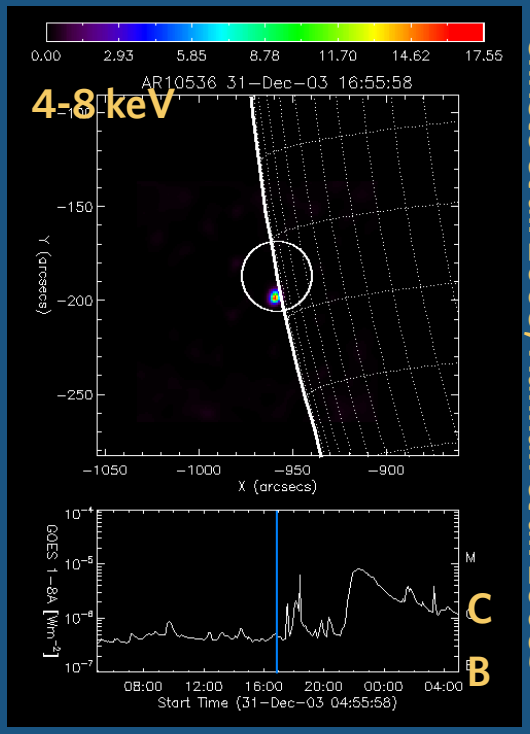
Krucker et al. 2008



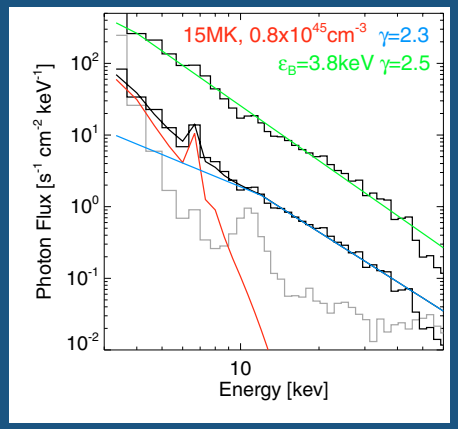
$$I(\epsilon) \propto \int_{\epsilon}^{\infty} \langle nVF(E) \rangle \, Q(\epsilon, E) dE$$

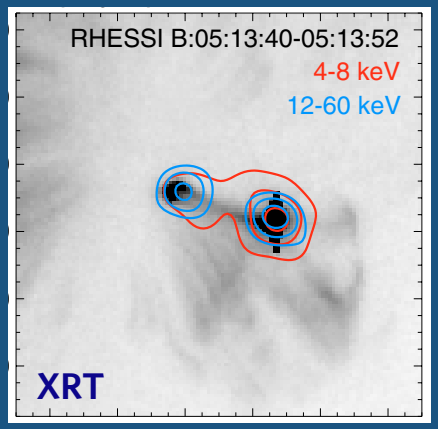
Microflares

- Similar picture for microflares
  - A, B class/RHESSI attenuators out
  - Non-thermal HXR (>6 keV)
  - Heating (>10MK)
  - More frequent than large flares
- All RHESSI microflares in AR
  - Over 24,000 (2002-2007)

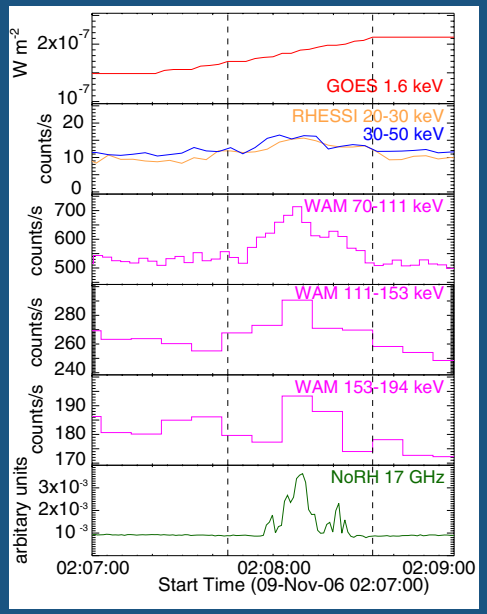


RHESSI MF Statistics: Christe et al. 2008, Hannah et al. 2008b





Hannah et al. 2008a

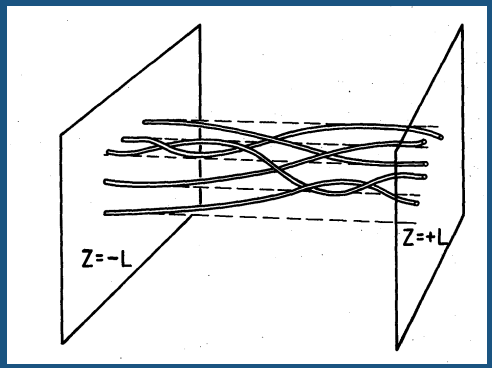


Ishikawa et al. 2013

Nanoflares ?

- Variety of thermal signatures (see rest of meeting)
  - Hot non-flaring active regions/coronal loops
  - Brightpoints/bursts/"nanoflares" in Quiet Sun
  - Consistently hot corona

- Parker's nanoflare to explain myriad of heated phenomena
  - Energy released via reconnection of braided fields
  - Ensemble/storm/cacophony to power non-flaring features
    - Accelerated electrons would quickly thermalize so hard to directly see?
  - Larger ensemble powering larger flares ?
    - *But mostly done with MHD (no particle) models.....*

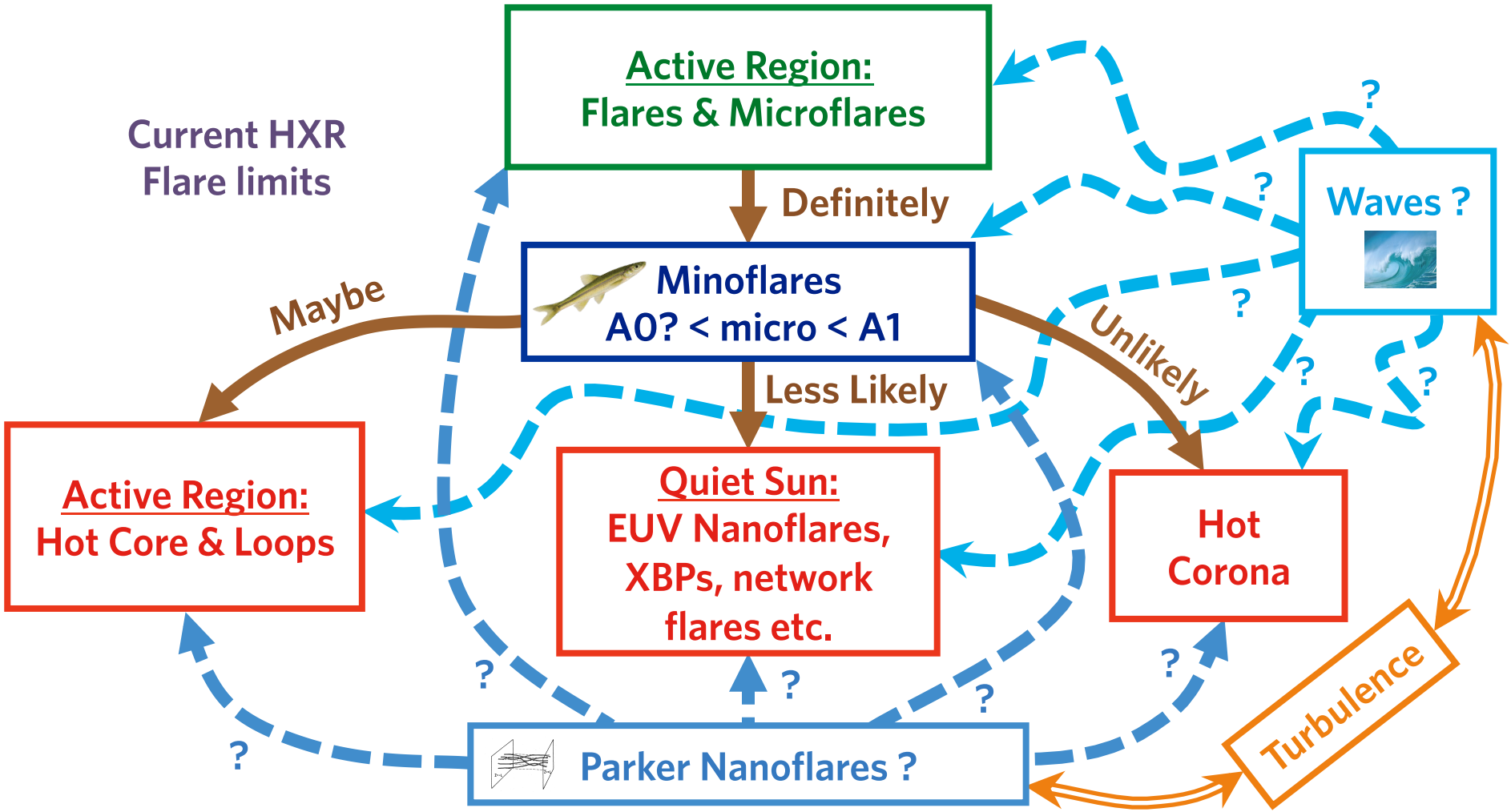


Parker 1972

Observed Events	Features	Relationship
"Regular" Flares (SEE) (GOES C,M,X)	Particle acceleration & heating	Same physics: micro are wee SEE
Microflares (GOES A,B)	Particle acceleration & heating	
Active regions/ coronal loops	Heating Only (?)	Powered by microflare or nanoflares*? Are nano small micro?
Quiet Sun bright points/ network flares/ coronal loops/ nanoflares†	Heating Only (?)	Similar physics to hot active regions?

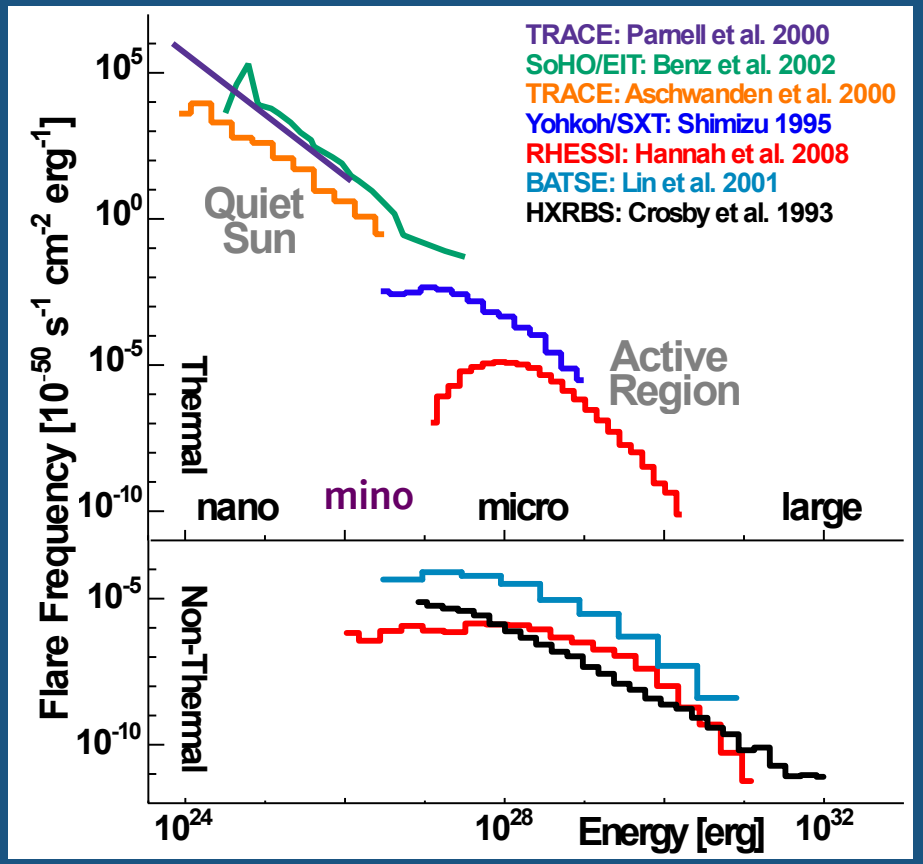
*Theoretical nanoflares: Parker impulsive energy release

†Observed nanoflares: Small EUV brightens energy about 10^{24}-10^{27} erg


Current HXR
Flare limits
Active Region:
Flares & Microflares
Definitely
Minoflares
A0? < micro < A1
Maybe
Unlikely
Less Likely
Active Region:
Hot Core & Loops
Quiet Sun:
EUV Nanoflares,
XBPs, network
flares etc.
Hot
Corona
Waves ?
Parker Nanoflares ?
Turbulence
?

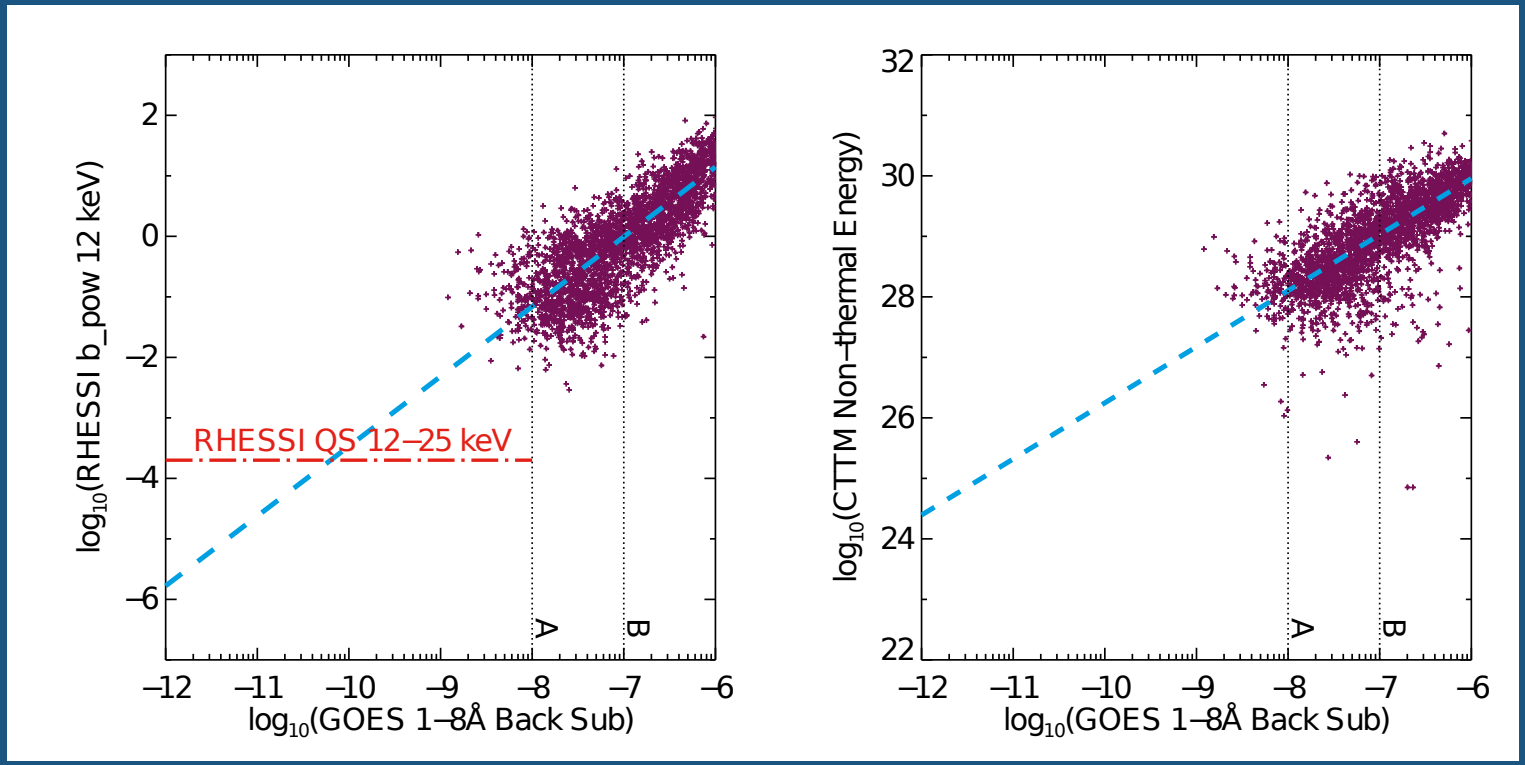
Flare Frequency Distributions

- More frequent to smaller
- Tricky comparison
  - Different phenomena
  - Different data sets/analysis
- Power-law index α=2?
  - Hudson 1991
  - Low energy cut-off to each population more important?
- Need high sensitivity observations to cover:
  - AR micro to mino (to nano?)
  - AR micro to QS "nano"



Hannah et al. 2011

HXR Microflares to Mino/Nanoflares?

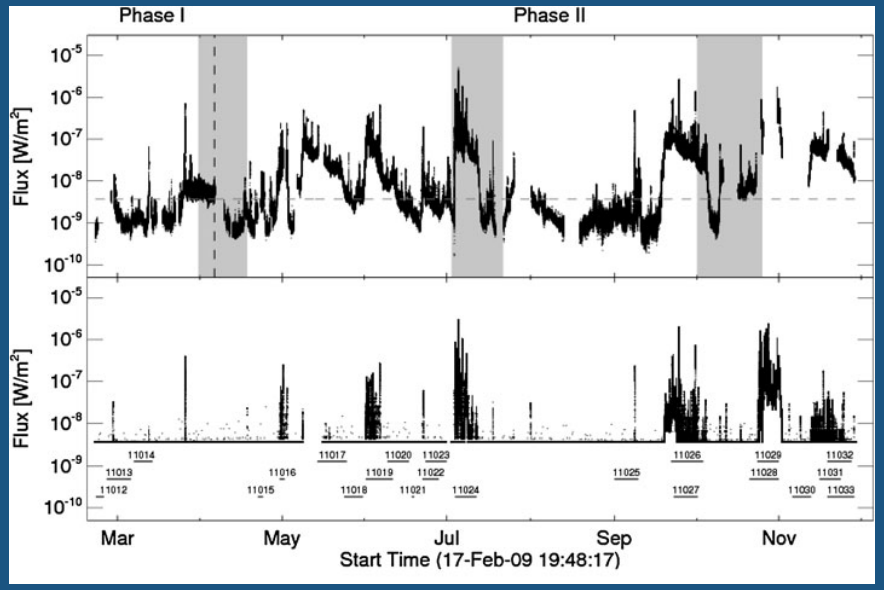


- Non-thermal to thermal properties below current limits
  - GOES 1-8Å to RHESSI non-thermal flux (12keV) & peak energy
  - Caveats: Flux via fitted power-law model & CTTM energy

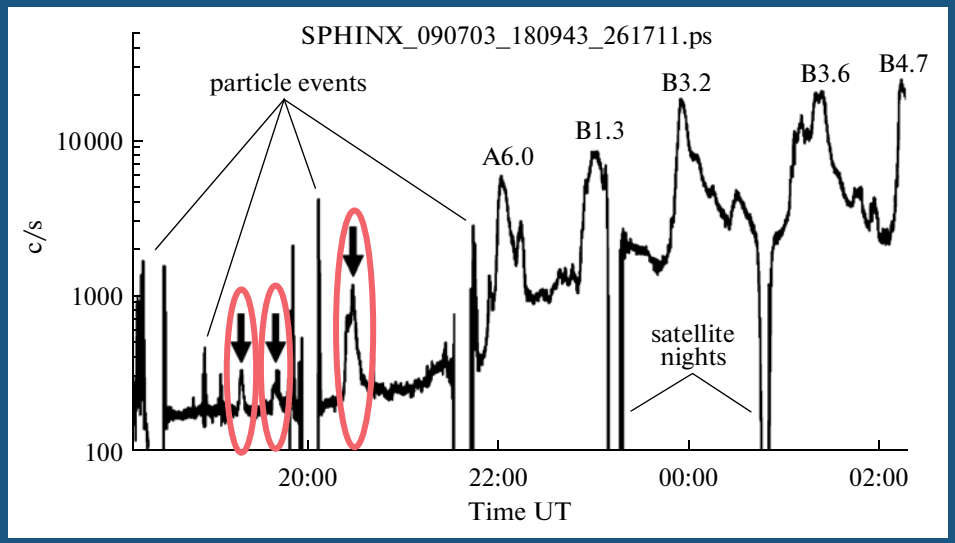
Recent SXR/HXR observations

Coronas-Photon/SphinX

- SXR Spectrophotometer
  - 20-Feb to 28-Nov 2009
  - 1 – 15 keV (0.4 keV)
- Solar Min/Quiet Sun
  - Thermal emission
    - 1.7MK, 4×10^{47} cm^{-3}
    - 1.9 MK, $1.1 \times 10^{48} cm^{-3}$
  - Sylwester et al. 2012
- Active region flares
  - Variability < A-level
    - S (small) and Q (quiet)
  - Gburek et al. 2011



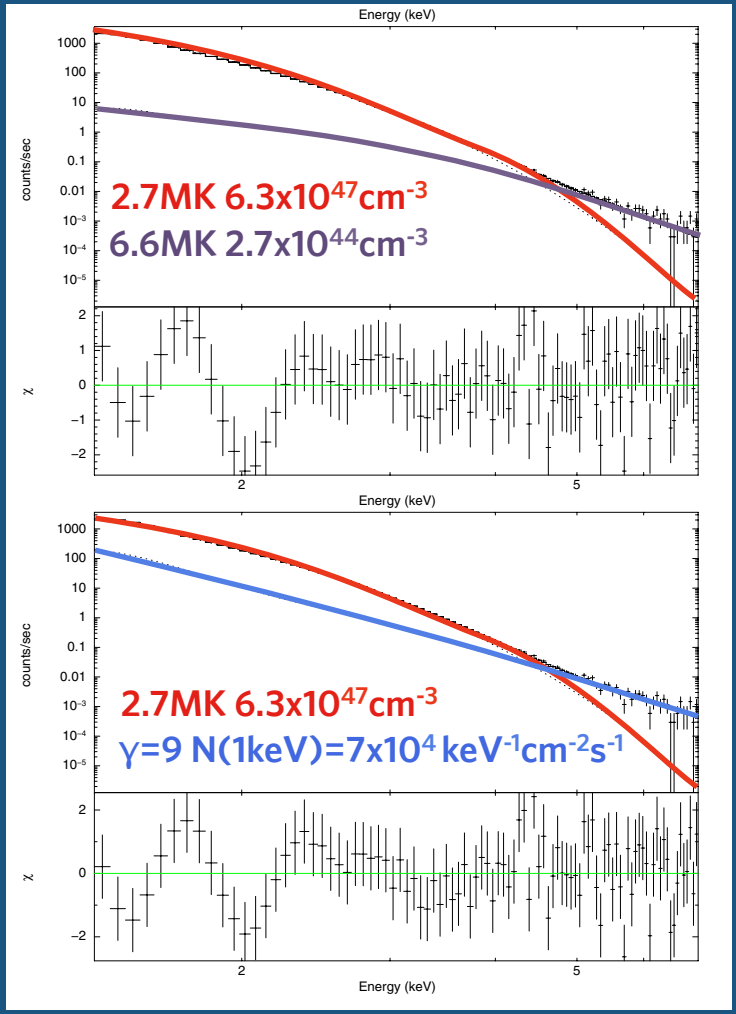
Gburek et al. 2013



Gburek et al. 2011

Coronas-Photon/SphinX AR Spectrum

- Integrated spectrum of non-flaring active regions
  - Miceli et al. 2012
- Thermal component and
  - Another thermal component?
  - Non-thermal component?
- Not clear evidence for nanoflares
  - Most likely micro/minoflare
  - Plus can be other HXR emission
    - More on this later

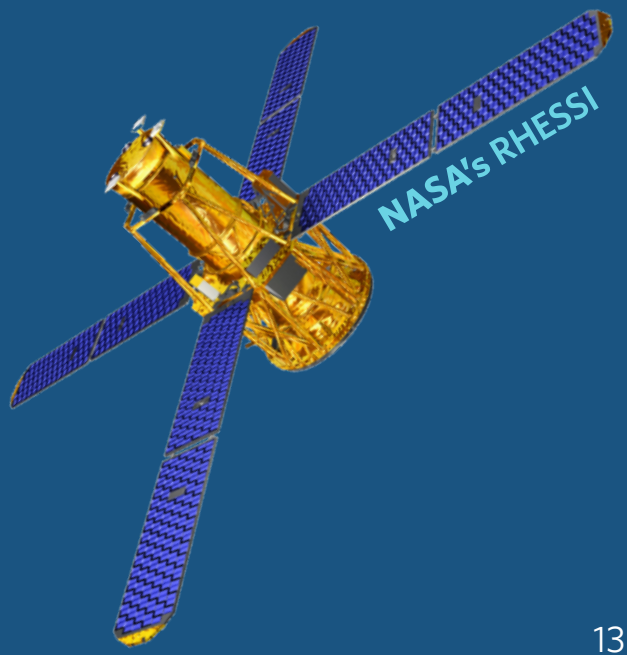


Miceli et al. 2012

RHESSI Non-Flaring Observations

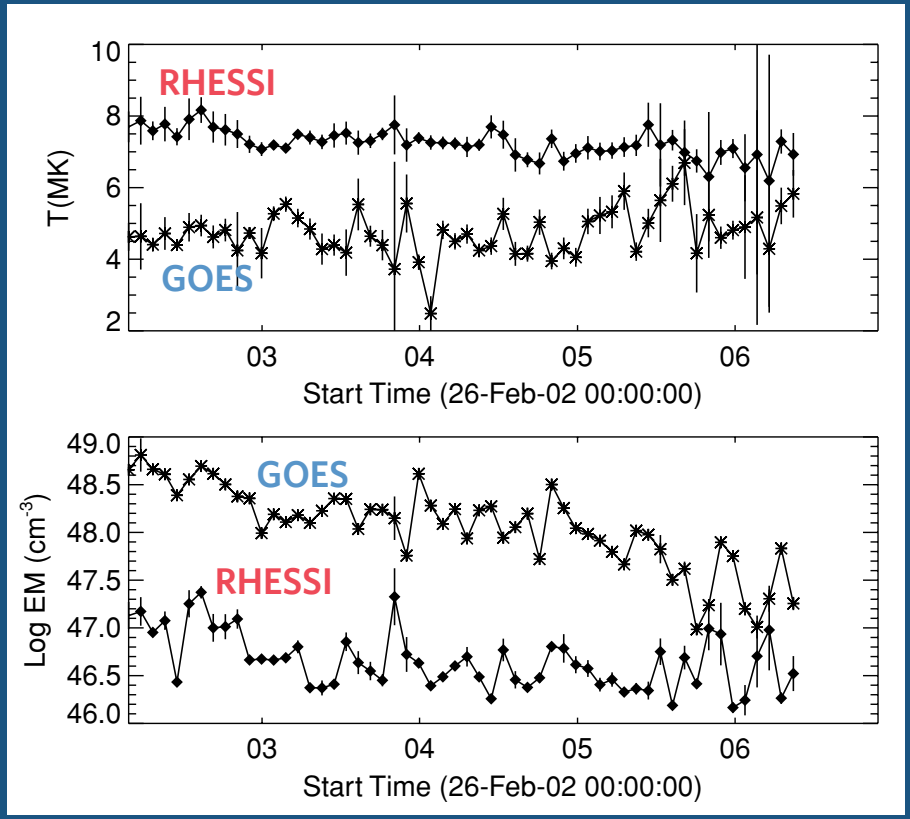
- RHESSI fantastic for flares X through to A-Class
  - But need different analysis techniques for fainter emission

- Long integrations & temporal chopping of solar "signal"
  - Day/Night terminator
    - Non-flaring active regions
    - McTiernan 2009
  - Off-pointing/Fan beam modulation
    - Quiet Sun & Non-flaring active regions
    - Hannah et al. (2007a,2007b, 2010)



RHESSI Non-flaring Active Regions

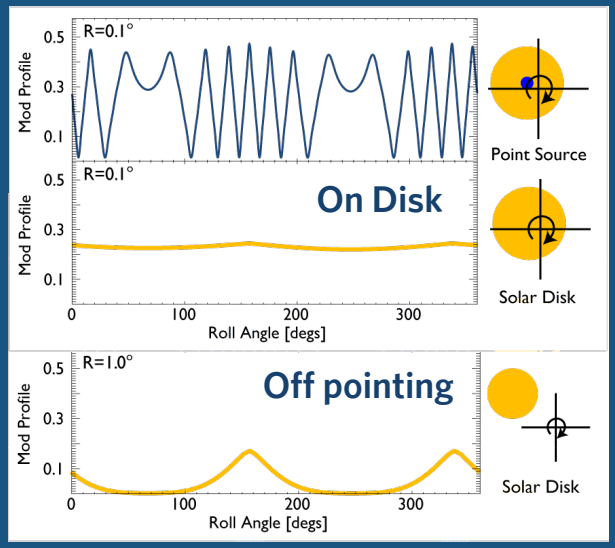
- Use the day/night terminator
  - ± 5 minutes
  - No flares/spikes
  - Isothermal fit to spectrum
    - Background subtracted
    - 3 to 30 keV (or max E 3σ)
- Showing 28 day average
  - 6-8 MK
  - 10^{46} – 10^{47} cm^{-3}
- Minoflares the likely source?

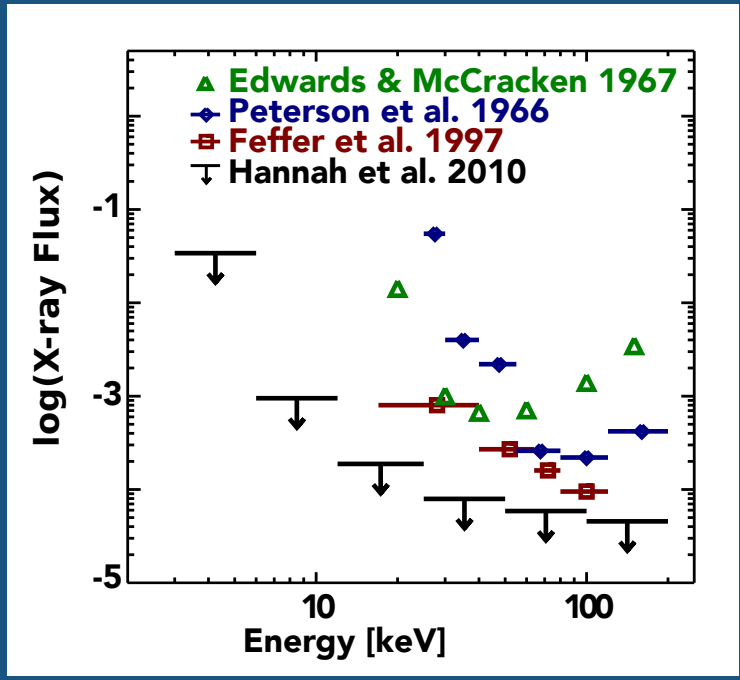


McTiernan 2009

RHESSI Quiet Sun Limits

- From times with no active regions & GOES < 10^{-8} Wm^{-2}
- Off-point from disk centre
  - Get strong time modulation
    - Peaks twice per rotation
  - Predictable location given pointing and source location
  - Max mod: offset 0.4° - 1°
- No signal
  - Accumulate many QS times to produce upper limits
    - July 2005 to Aug 2009

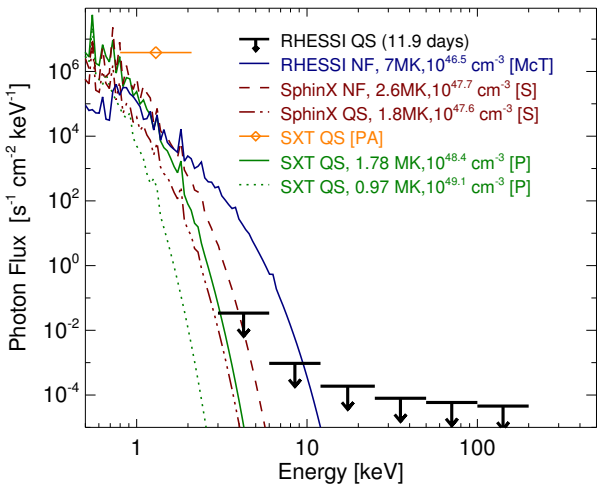


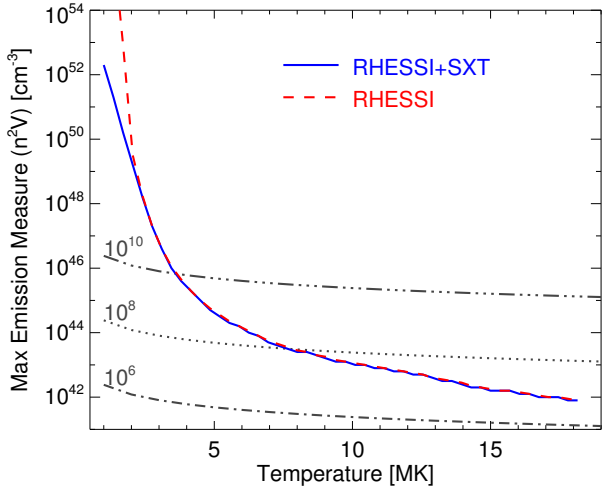


Hannah et al. 2010

Constrain Parameter Space

Hannah et al. 2010

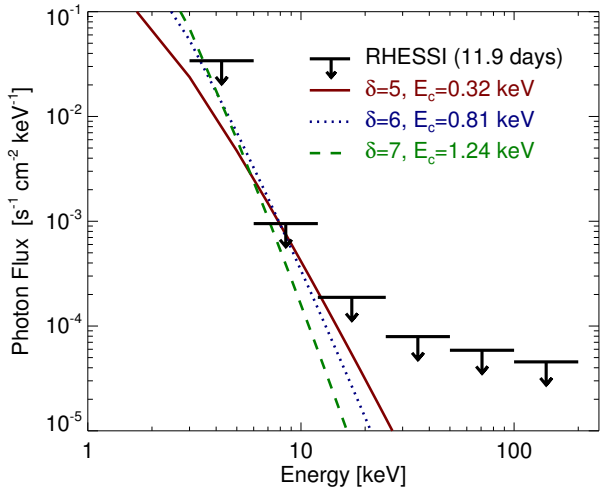


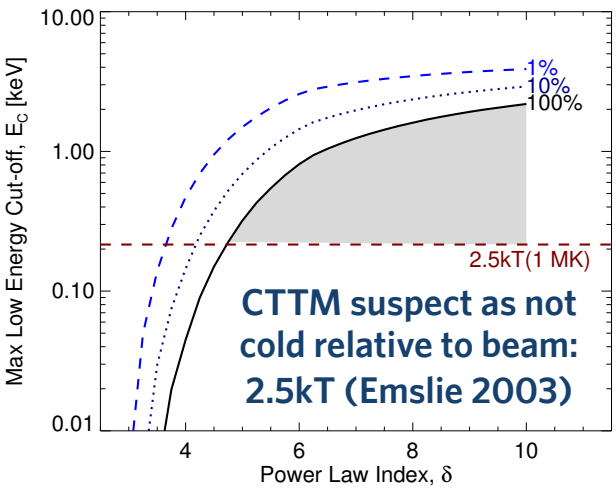


Thermal

- Max EM for each T_0 consistent with limits
- nkT=coronal heating

Hannah et al. 2010





Non-Thermal

- Max low energy cut-off for each δ consistent with limits
- CTTM=coronal heating

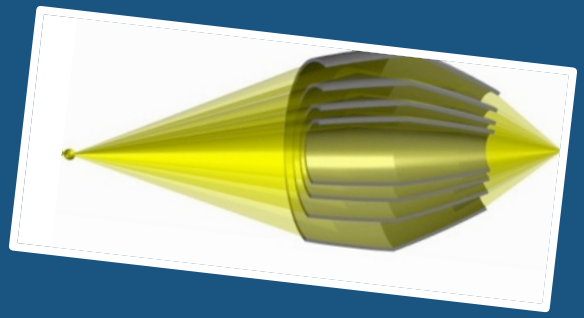
P=9x10^{27} erg s^{-1} (Withbroe and Noyes 1977)

Future HXR Observations

Future HXR Observations

- Need higher sensitivity imaging spectroscopy than RHESSI to detect the smaller events
  - Need imaging to pin point source
  - Need spectroscopy to determine thermal/non-thermal

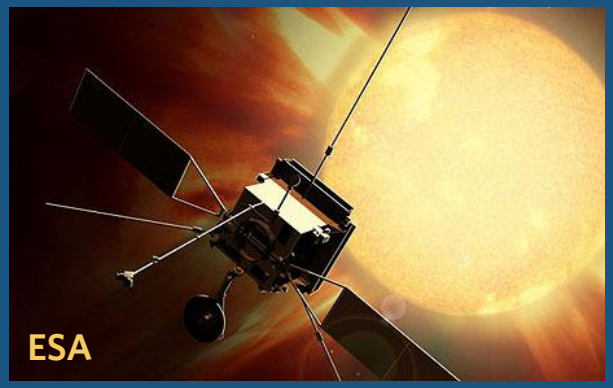
- Indirect imagers – Grids/collimators
  - Solar Orbiter/STIX
- Direct imagers – Focusing optics
    - Technology now practical/cost effective
  - FOXSI / HEROES / Super-HERO (2012 – 2014 +)
  - NuSTAR (solar 2014 +)

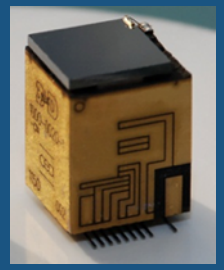


Wolter Mirrors

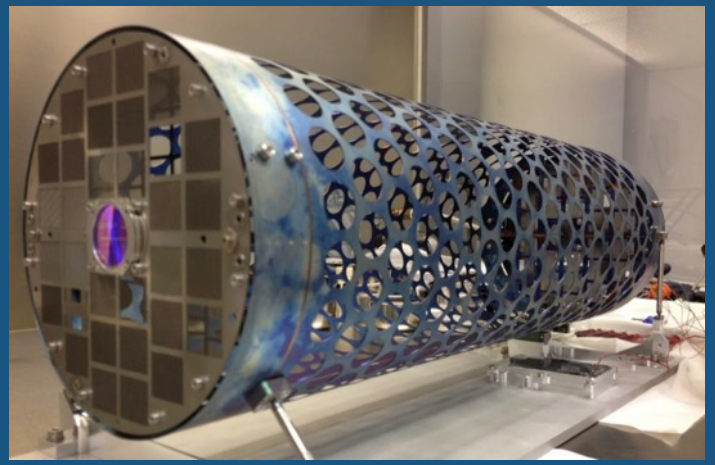
ESA's Solar Orbiter/STIX

- Spectrometer/Telescope for Imaging X-rays
  - Krucker (PI)
  - Provides crucial link between remote and in-situ instruments
- Although an indirect imager still more sensitive than RHESSI (x15)
  - Closer to Sun + Lower background
  - But still low dynamic range
- Specification
  - CZT: 4-150 keV (1-15 keV res)
  - Grids/Collimators: 7" of full Sun



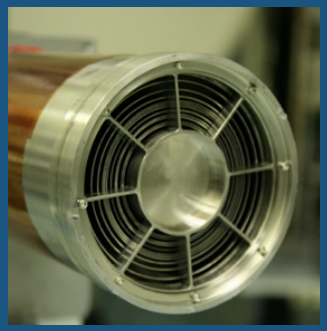


STIX CZT
Detector x 32

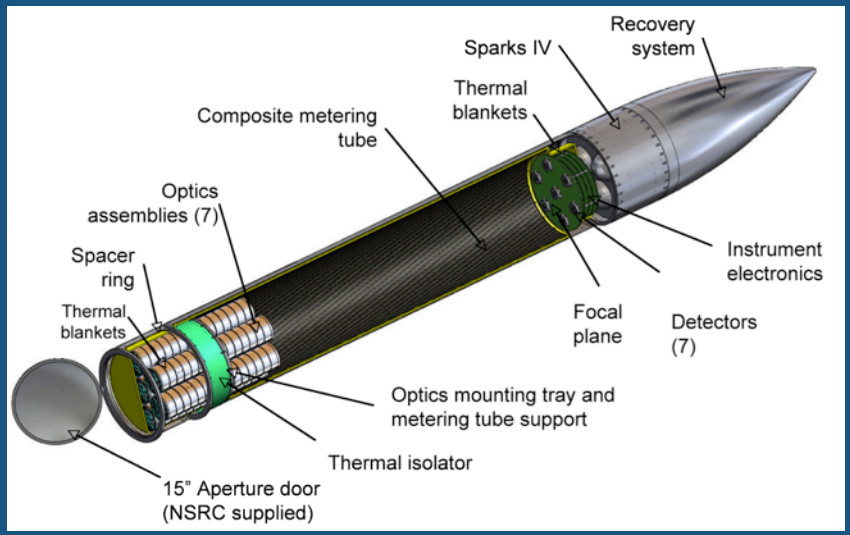


FOXSI Sounding Rocket

- Focusing Optics X-ray Solar Imager
  - Krucker (PI), Glesener [UCB] & Christe [GSFC]
  - Grazing-incident replicated optics
    - Flown on HERO Balloon, Ramsey et al. 2002 [MSFC]
  - Double-sided Si strip detectors
    - Developed for Astro-H, Takahashi [JAXA/ISAS]

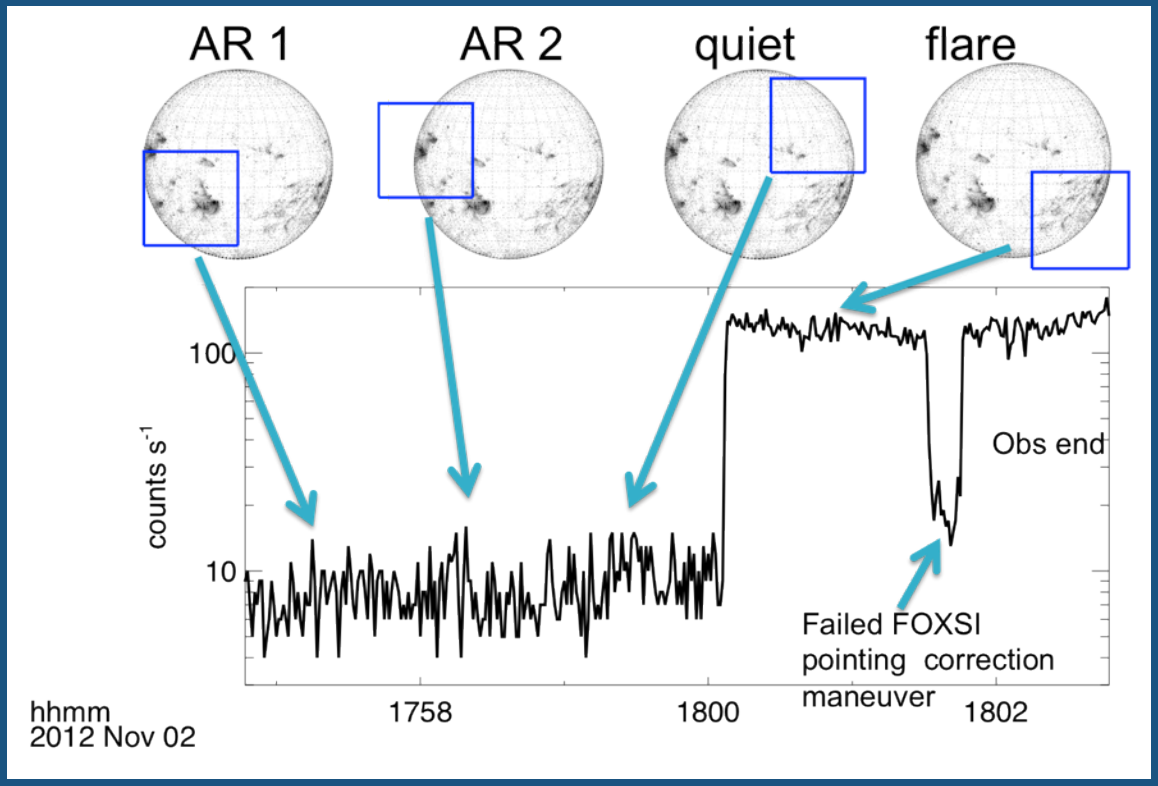


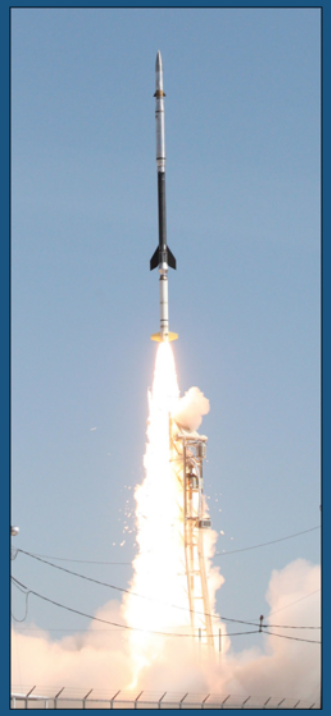
- Specifications:
  - Energy: 4-15 keV (0.5 keV)
  - Spatial: FOV 16'x16'
    - 10" FWHM
  - Effective Area: 3 x RHESSI
  - Dynamic Range: 10 x RHESSI



FOXSI Launch: 02-Nov-2012

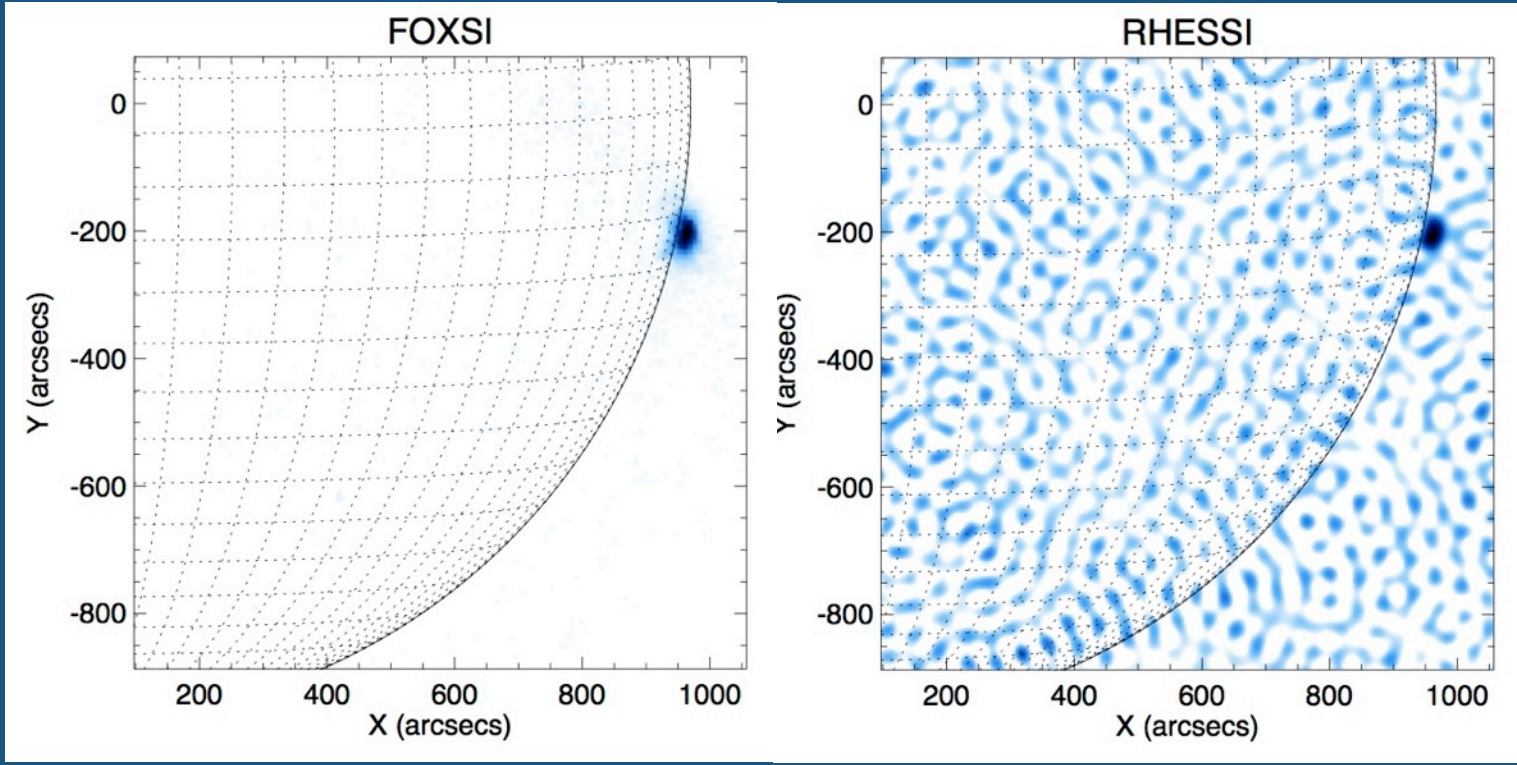
- 6.5 min observation interval





Courtesy of L. Glesener

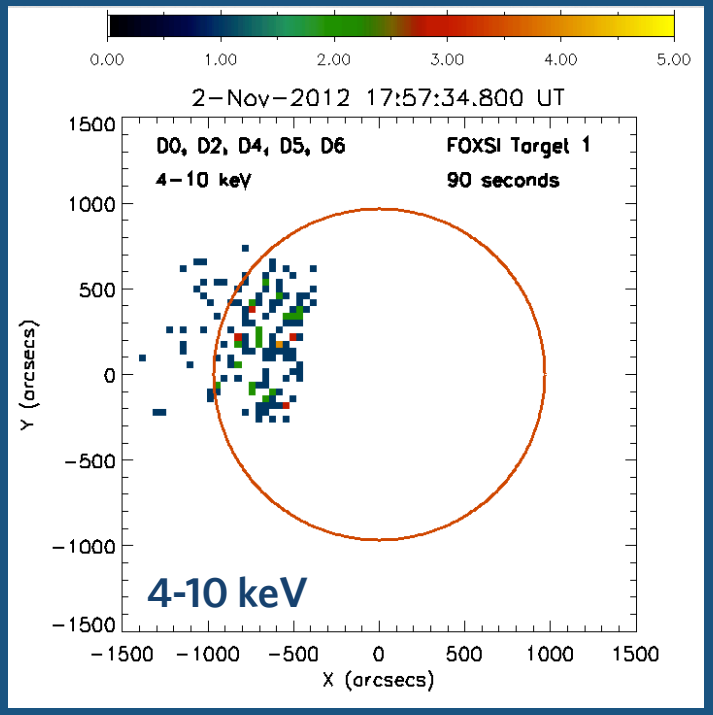
FOXSI Microflare: B4

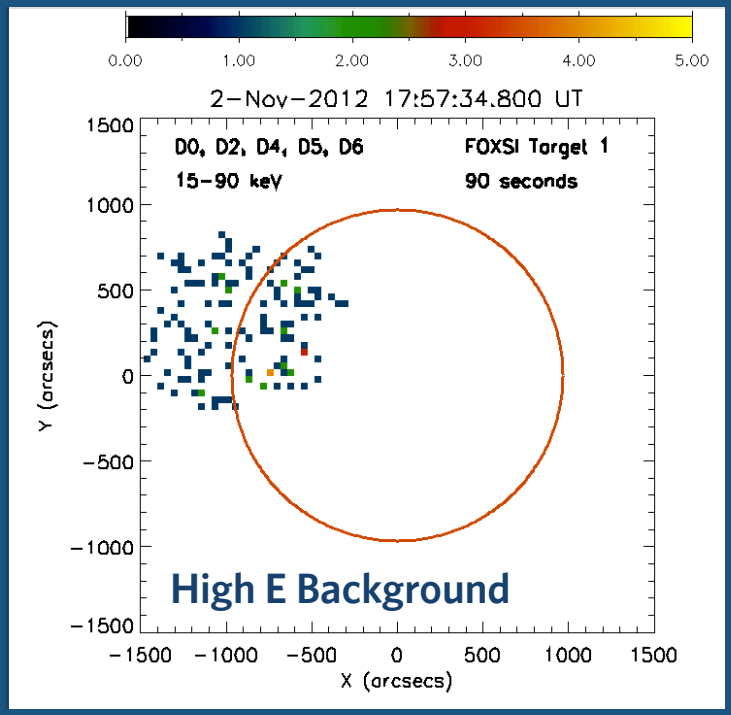


- FOXSI image free of RHESSI CLEAN artefacts

Courtesy of L. Glesener & S. Christe

FOXSI Non-flaring AR target



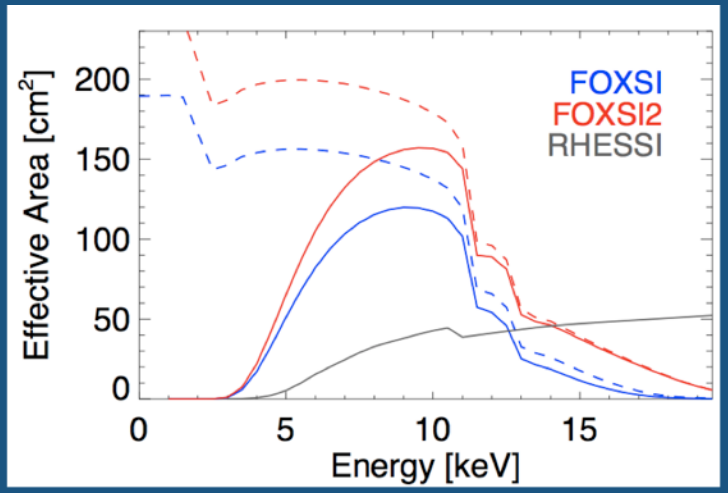


- 90s of data gives 4.6σ detection of HXR from the disk
- Under study: Not noise and not localized to AR
  - If real, difficult to say if thermal or non-thermal

Courtesy of L. Glesener

FOXSI Future

- FOXSI 2nd flight (late 2014)
  - Upgrade detectors (CdTe)
  - More inner optics
  - Improved high energy response



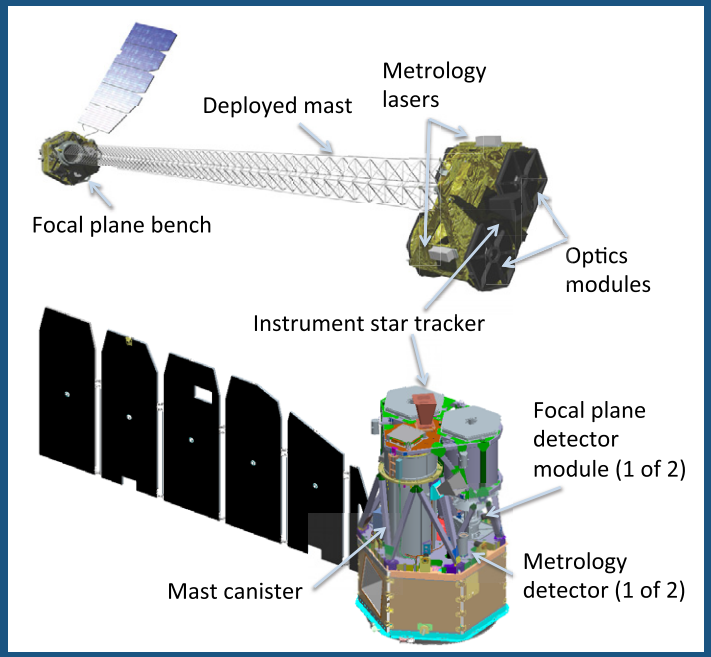
- HEROES Balloon (Sep 2013)
  - High Energy Replicated Optics to Explore the Sun
  - Gaskin (MSFC) & Christe (GSFC)
  - Similar optics but 6m focal length ➔ 60 keV

- Super-HERO Antartica Balloon (proposed)
  - Couple weeks of observations
  - Upgrade to CdTe HEXITEC detectors

Courtesy of S. Christe

NASA's NuSTAR

- Nuclear Spectroscopic Telescope Array
  - PI: Fiona Harrison (Caltech)
  - Launched June 13, 2012
  - 2 grazing incidence telescopes
  - Energy: 3-79 keV (0.4 -0.9V)
  - Spatial: 13′ x 13′ (FWHM: 18″)
  - 200x more sensitive than RHESSI
    - 10x FOXSI

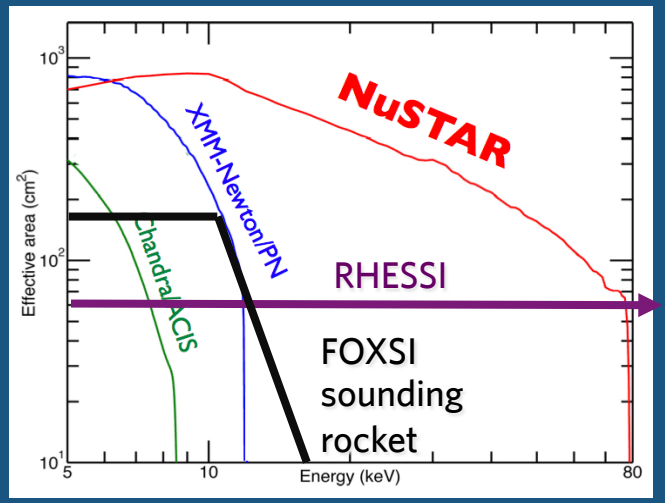


Harrison et al. 2013

- Astrophysics mission so main targets so far are non-solar

NuSTAR Solar Observations

- Solar observations part of the base line mission
  - Expecting 3 weeks in 2014
  - Minimum observable flare: about 0.01 A-Class (10^{-10} Wm^{-2})
  - Maximum observable flare: <B-Class
- Solar Working group chaired by David Smith (UCSC)
  - Grefenstette, Hudson, Glesener, Hurford, Krucker, Marsh, Mewaldt, Pivovaroff, Vogel, White, Hannah (Collaborator)
- Early target: HXR "nanoflares" signatures in AR & QS
  - Existence;
  - Relationship to microflares;
  - Extension of flare distribution etc.
- Testable model parameters?
  - Suggestions welcome……



Summary & Future

- Smallest HXR bursts are active region microflares
  - 10,000s of examples with RHESSI
- Relationship to smaller events in active regions unclear
  - Micro ➔ "Mino" ➔ "Nano" ?
  - Relationship AR to QS events more speculative ?
- HXR focusing optics observations within next 12/18 months
  - Targeting HXR emission from non-flaring AR and QS
- Dedicated solar mission (Super FOXSI ?)
  - 1-80 keV + <10" + x100 RHESSI sensitivity
  - Great for flares/CMEs/jets and "nanoflares"