RHESSI Microflare Statistics, Hinode Microflares & RHESSI Quiet Sun Study

Iain G. Hannah

Department of Physics & Astronomy

University of Glasgow, Scotland, UK

S. Christe, H. S. Hudson, G. J. Hurford, S. Krucker, R. P. Lin

SSL, University of California, Berkeley, USA

Email: iain@astro.gla.ac.uk

Overview

- **RHESSI Microflare statistics** ***(Steve Christe also talking....)***
  - Over 25,000 A,B-Class AR flares over Mar-2002 to Mar-2007
  - Peak thermal image and photon spectra analysed
  - Many characteristics -> Thermal & Non-thermal Energy
- **Microflares with RHESSI & Hinode**
  - Mostly XRT (+TRACE,Radio) on individual events
  - Like to do statistics (some suitable data already)
- **RHESSI Quiet Sun Observations**
  - Difficult measurement -> RHESSI for flares not QS
  - Spatially averaged spectrum integrate over long time
  - Get upper limits spectrum
    - Constrain HXR nanoflare properties

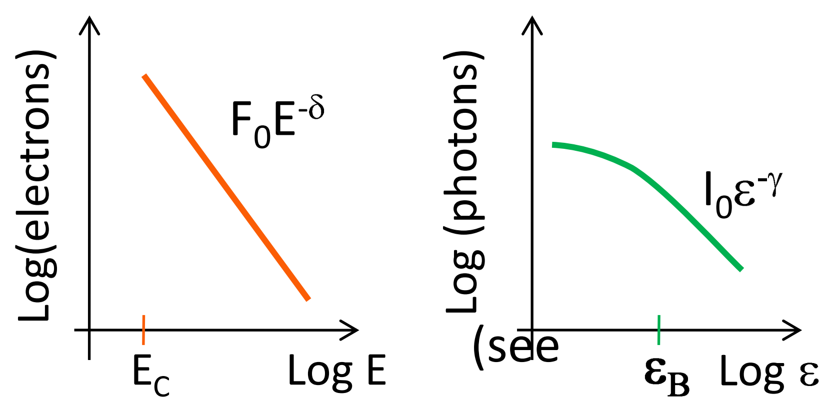
RHESSI Microflare Statistics

- **What are the properties of hard x-ray microflares observed with RHESSI ?**
  - Spatial and temporal properties
  - Thermal and non-thermal characteristics and energies
  - Impact on coronal heating.
- **RHESSI microflares were found by searching for sharp bursts in the 6-12 keV lightcurve during times of shutter out mode**
  - Found 25,705 events from March 2002 to March 2007
  - The microflares are low GOES C-class to below A-class events (background subtracted)
- **All results shown are for 16 seconds at the time of peak emission in 6-12 keV for each event.**
  - *Christe et al. 2008 ApJ & Hannah et al. 2008 ApJ*

Energy Calculation

- **Thermal Energy:** $$W_\mathrm{T} = 3\sqrt{EM \cdot V} k_\mathrm{B} T$$
  - Volume of thermal emission from imaging
  - Temperature & Emission Measure from spectral fitting

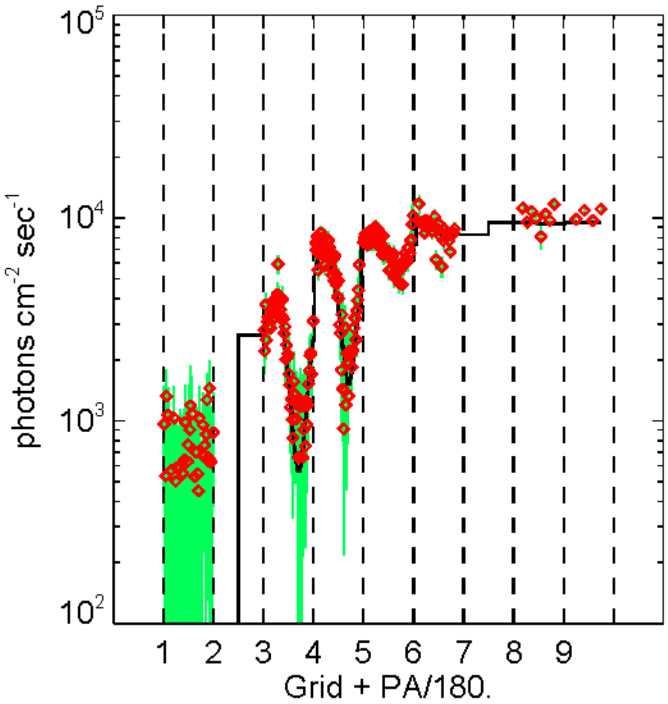
- **Non-thermal Power:**
$$P_\mathrm{N}(\geq E_\mathrm{C}) = 9.5 \times 10^{24} \gamma^2 (\gamma - 1) \times \beta\left(\gamma - \tfrac{1}{2}, \tfrac{3}{2}\right) I_0 E_\mathrm{C}^{(1-\gamma)}$$
  - Assumes high energy component of spectrum is due to a power-law of accelerated electrons (Brown 1971)
  - Fitting broken power-law to photon spectrum provides $I_0\ \gamma$
  - flattens at low energies but no analytic expression for ε_B to E_C
    - Find empirical relation (see Hannah et al. 2008)

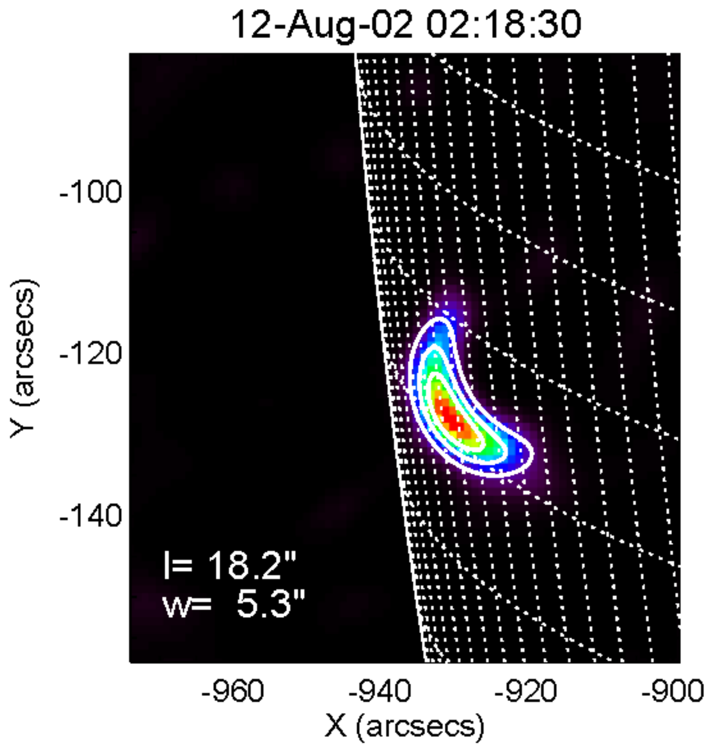


See Hannah et al. 2008 ApJ

"Imaging" Thermal Source

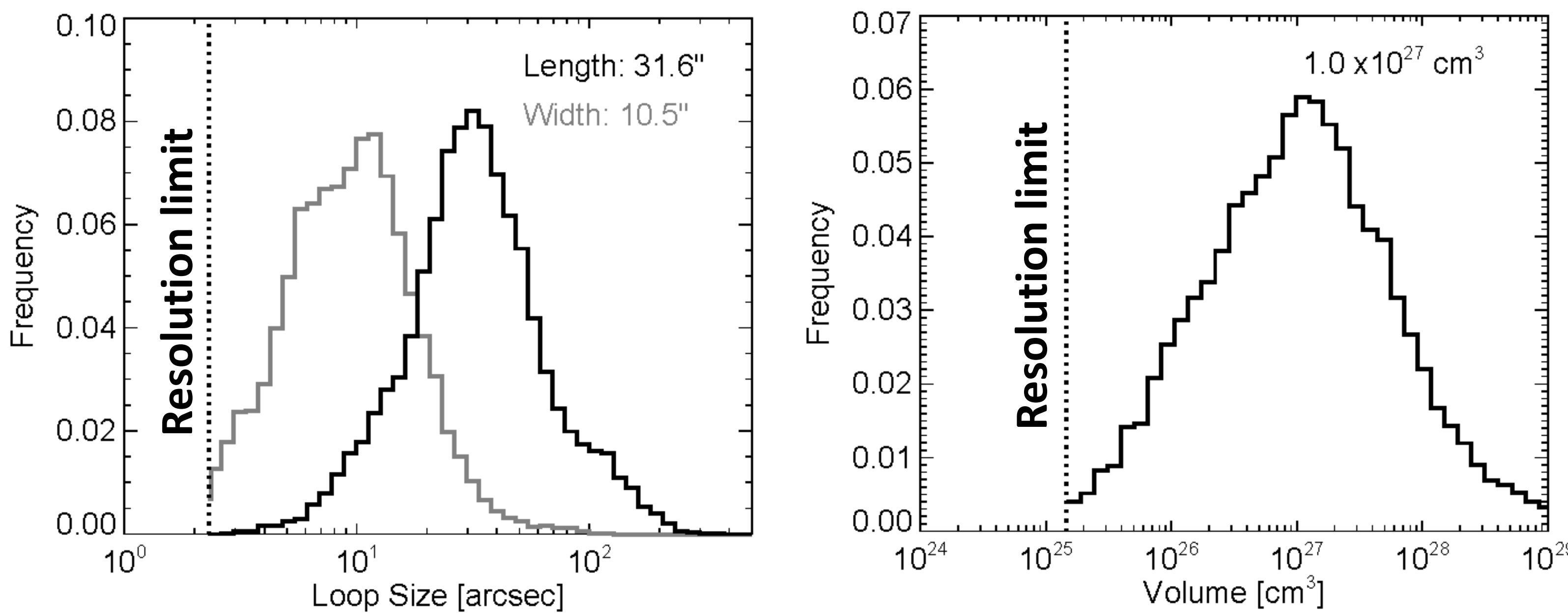
- **Forward Fit shape to RHESSI 4-8 keV data about peak time in each microflare converted to complex visibilities**
  - Not fitting the image but the visibilities
  - Fast and provides objective measure to quality of fit





Thermal Loop Size & Volume

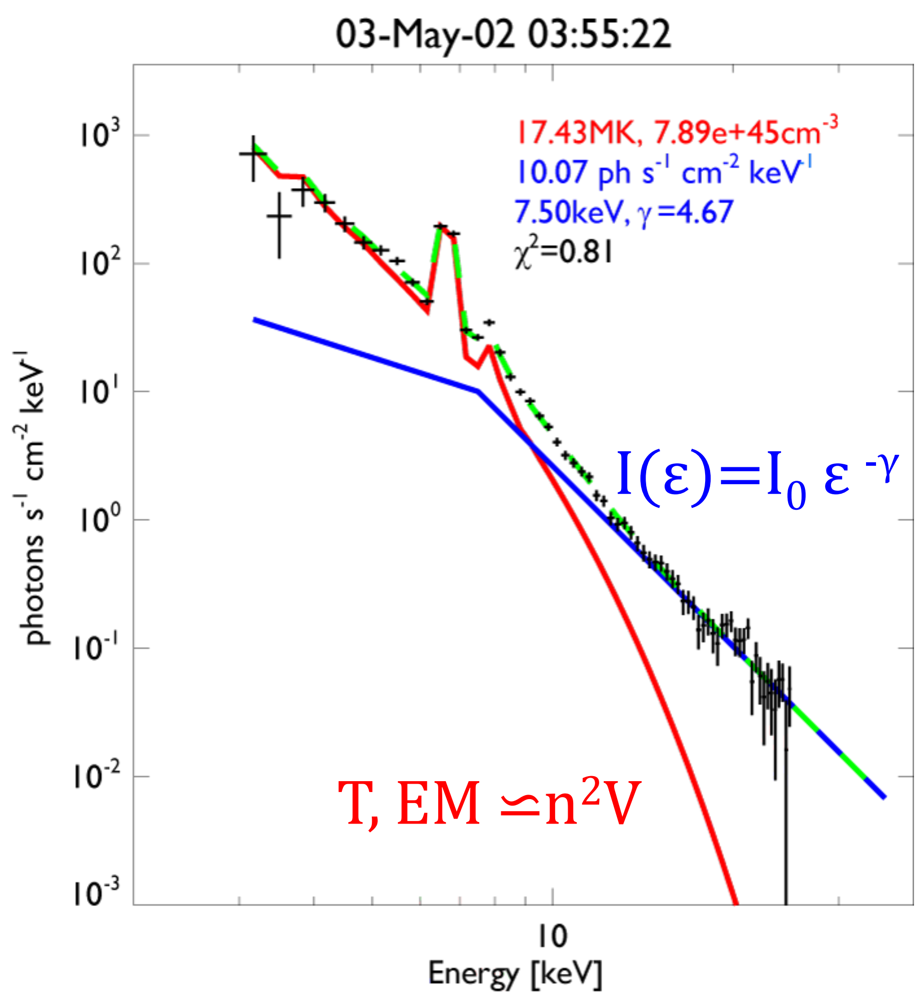
- **Fit curved 2D elliptical Gaussian to data**
  - Successfully fitted 18,656 out of 25,075 events
- **Assume cylindrical geometry, so width ~ depth** $V \approx lw^2$



- **No correlation between magnitude of flare (GOES class, flux) and loop size**

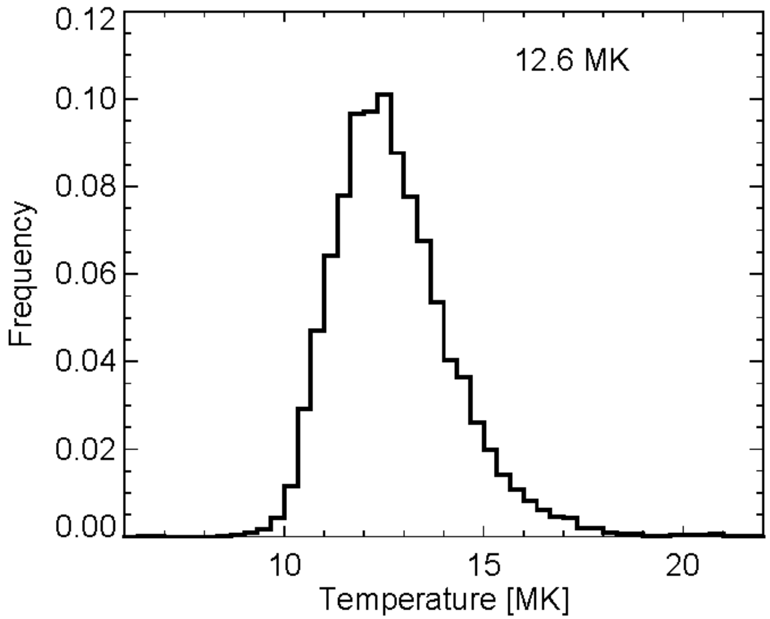
Spectrum Forward Fitting

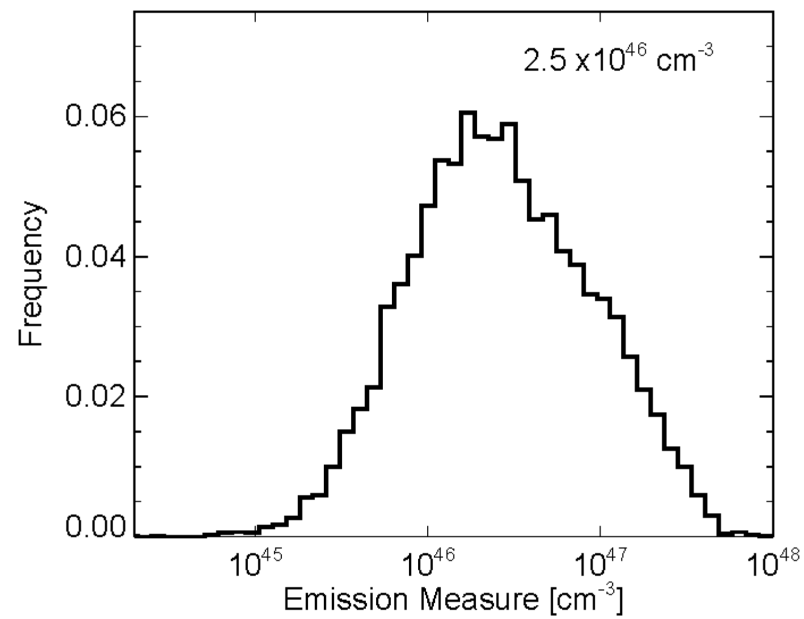
- **Fit thermal component plus non-thermal component**
- **Thermal is continuum and line features (CHIANTI)**
  - Temperature and Emission Measure~n^2V
  - Fe K-shell feature about 7 keV
- **Non-thermal is approximated with a broken power-law, with fixed index of -1.5 below break**
- **All analysis done for 16 sec about time of peak emission in 6-12 keV**



Thermal Parameters

- **Median T~ 13MK, EM~10^{46} cm^{-3}**
  - Large flares typically T~ 30+MK, EM~10^{49} cm^{-3}

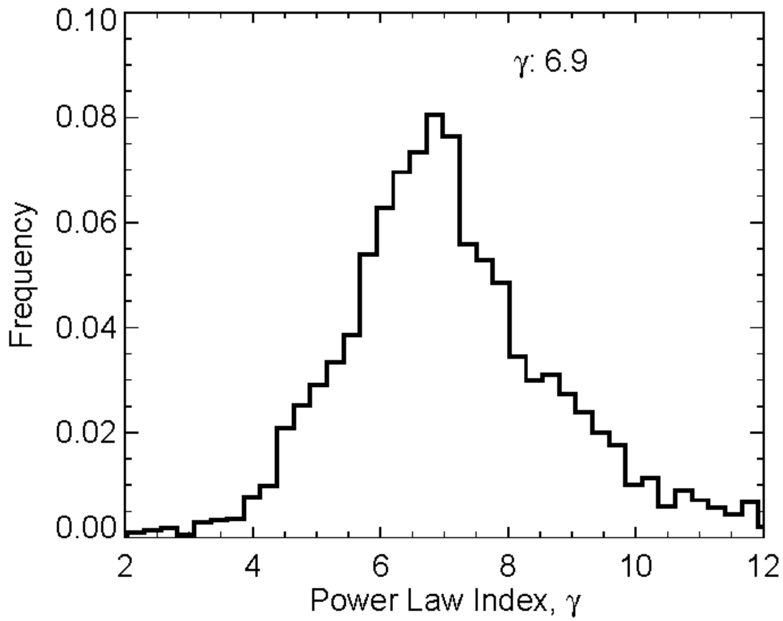


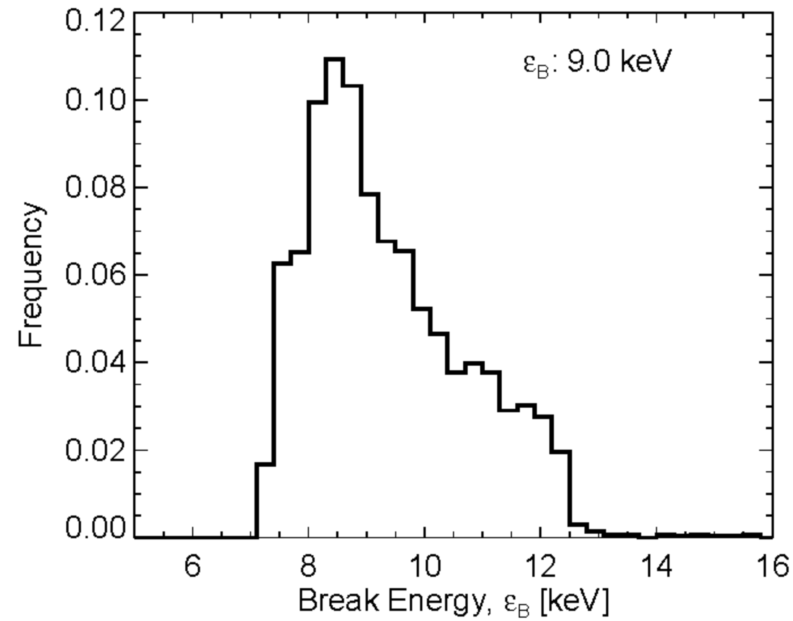


- **Successful visibility and thermal spectrum fit: 9,161 events**
  - Only about 12,000 of 25,705 events have flare to background>3

Non-thermal Parameters

- **Median values γ~7, ε_B~ 9 keV**
  - Large flare typically γ~5 (flatter & harder), ε_B >20 keV

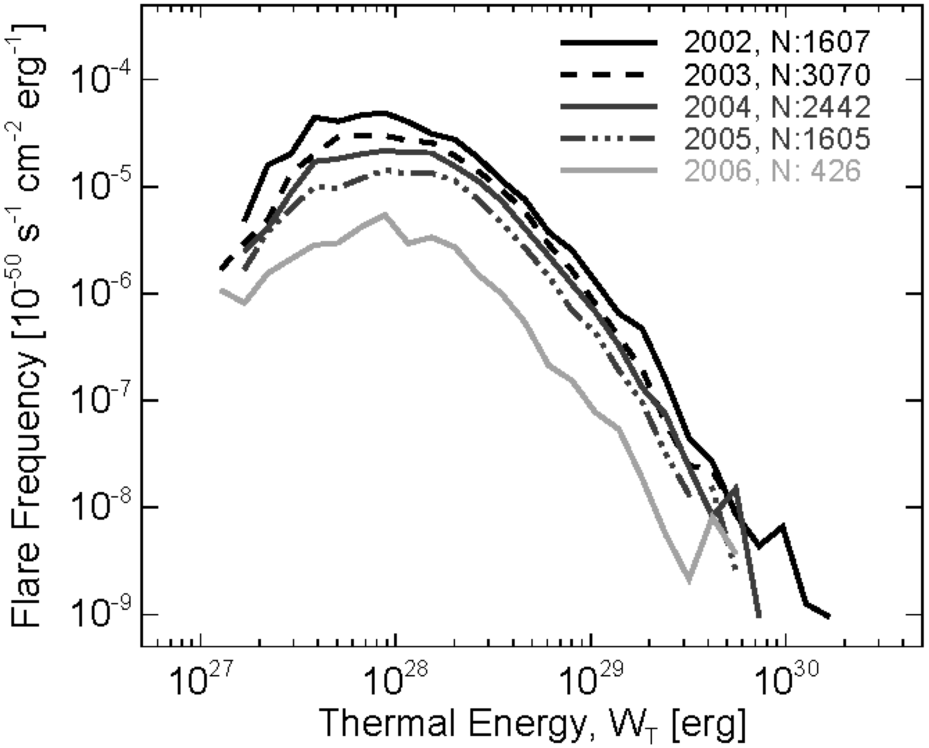




- **Successful visibility, thermal+non-thermal spectrum fit: 4,236**
  - Due steep spectra at low energies being difficult to distinguish from thermal component and line feature

Thermal Energy Distribution per Year

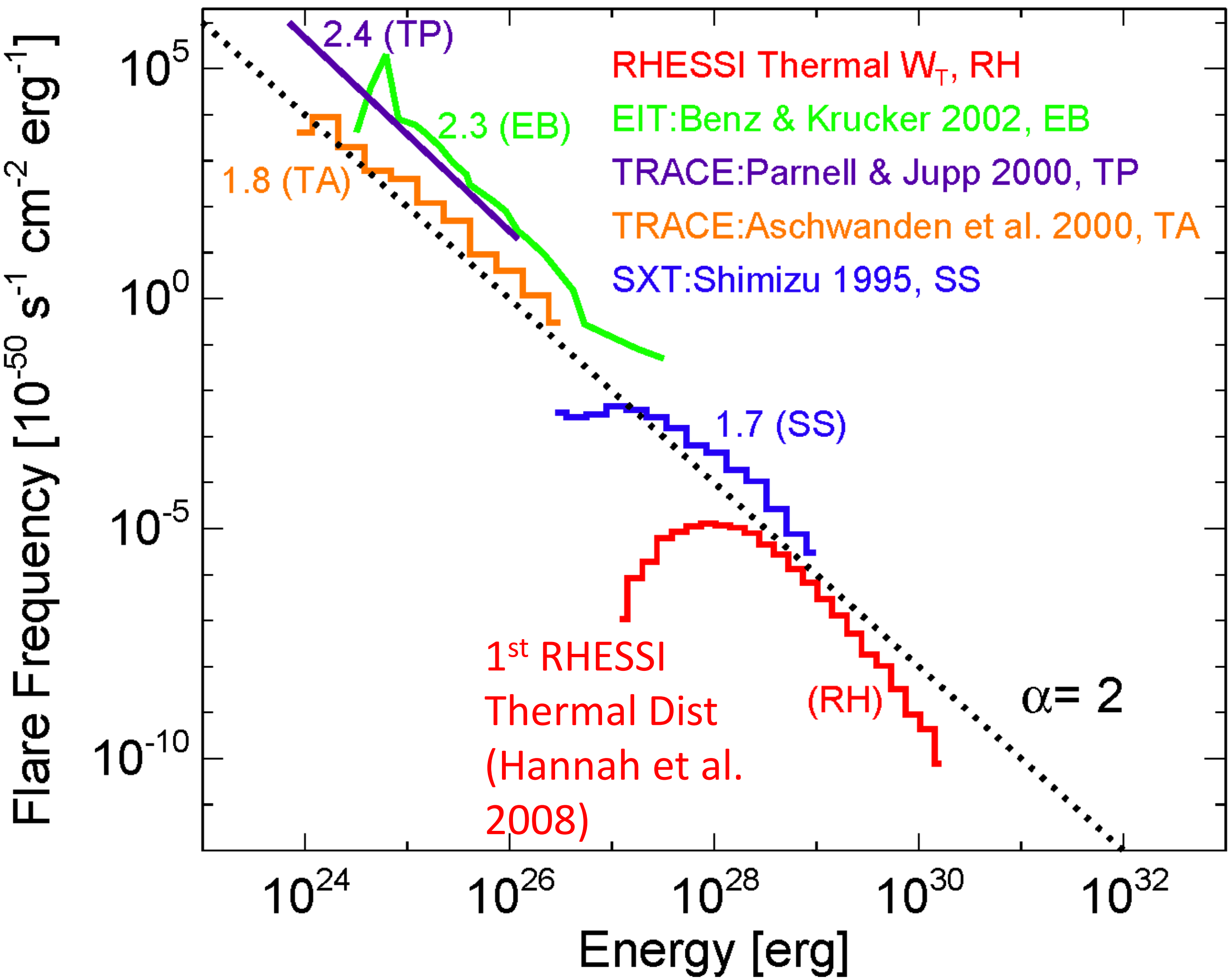
- **Normalisation decreases as approach solar minimum**
- **Slope shape and steepness roughly the same**
- **Deviates from power-law at low and high energies due to events missing from flare list or unsuccessful analysis**



- **Missing smallest**
  - Hidden by big flares or background
  - Not enough counts to analyse
- Missing largest
  - Shutters come in and not a microflare
  - Poor detector livetime

Comparison of Thermal Distributions

- **Do not trust this comparison, or others like it**

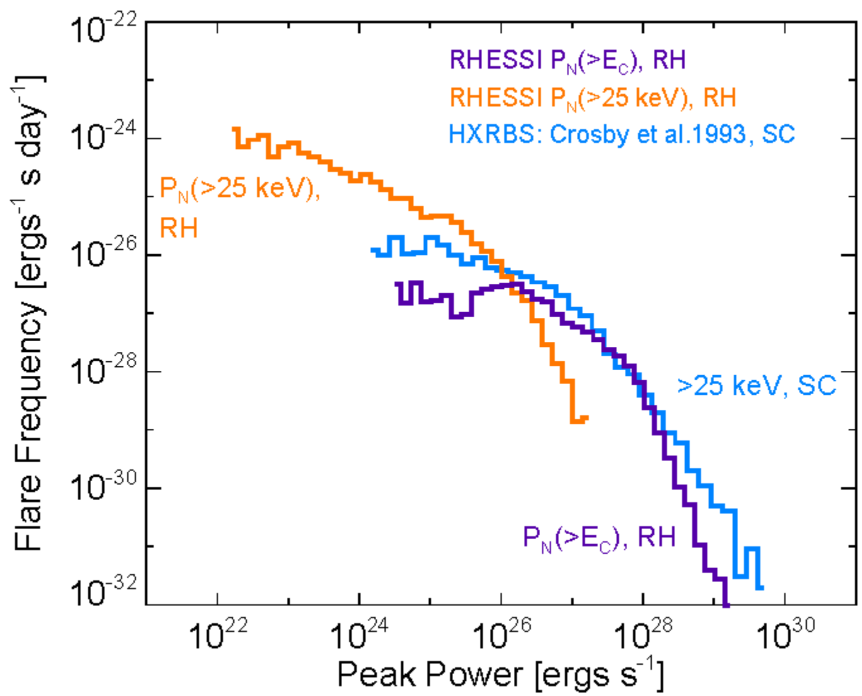


Comparison of Thermal Distributions

- **RHESSI distribution deviates from power-law at low/high energies**
  - cannot tell if power-law index is the magic α>2
- **Cannot tell if distribution extends to lower energies**
  - Instrumental, not physical, cut-off
- **Seems to be a extension of other distributions to higher energies................ ...**
- **But comparing very different events, using various instruments for different periods of solar cycle**
  - SXT: 291 ARTB from one active region over 5 days in Aug-1992
  - EUV: 1 hour of data from 12-Jul-1996, 17-Feb-1998, 16-Jun-1998
  - RHESSI: 5 years of microflares 2002 to 2007

Non-thermal Power Distribution

- **Compared to previous study of large flares (Crosby et al. 1993) using the same fixed E_C=25**
- **Using estimated E_C find considerable power in electrons accelerated to low energies**
- **Can we trust this ?**
  - Small uncertainties in steep spectra to low energies results in large uncertainty in non-thermal power
  - Although power deposited for shorter time than in larger flares so energy content is still smaller



Distributions badly affected by uncertainties in parameters and the same selection effects (missing events) seen in the thermal distribution

Microflares Summary

- **RHESSI for the first time allows statistical analysis of the thermal and non-thermal energy in microflares**
- **Energy distributions deviate from power-laws, primarily due to instrumental selection bias**
  - Selection effects and biases to be further investigated
- **Maybe considerable power in accelerated electrons even in small microflares but large uncertainties**

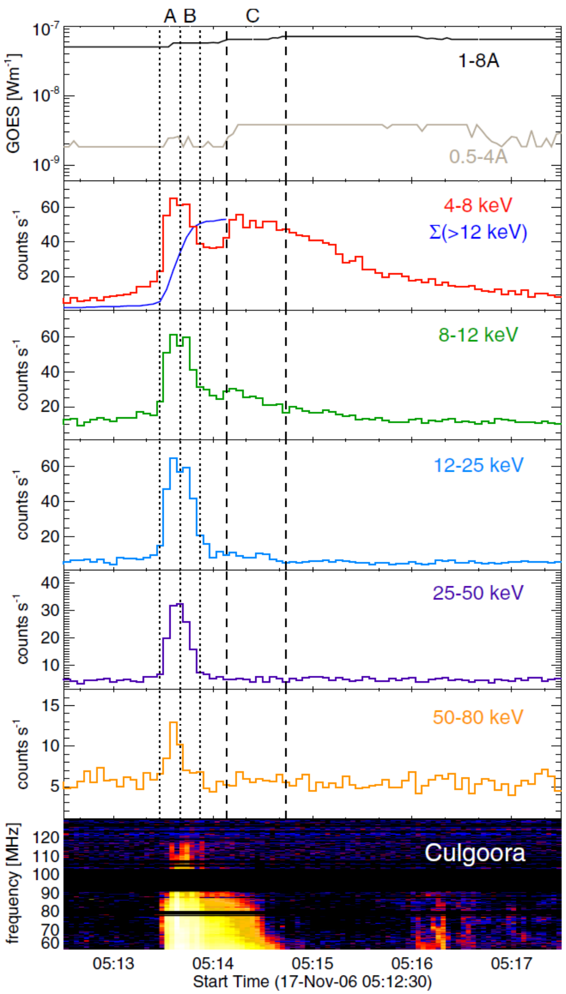
RHESSI Microflare Parameter		Typical Value
Temperature	T	13 MK
Emission Measure	EM	10^{46} cm^{-3}
Thermal Volume	V	10^{27} cm^{3}
Density	n_e	6×10^{9} cm^{-3}
Power-law Index	g	7
Break Energy	e_B	9 keV
Low Energy Cut-off	E_C	12 keV
Thermal Energy	W_T	10^{28} ergs
Non-Thermal Power	$P(>E_c)$	10^{26} ergs s^{-1}
	$P(>25)$	10^{24} ergs s^{-1}

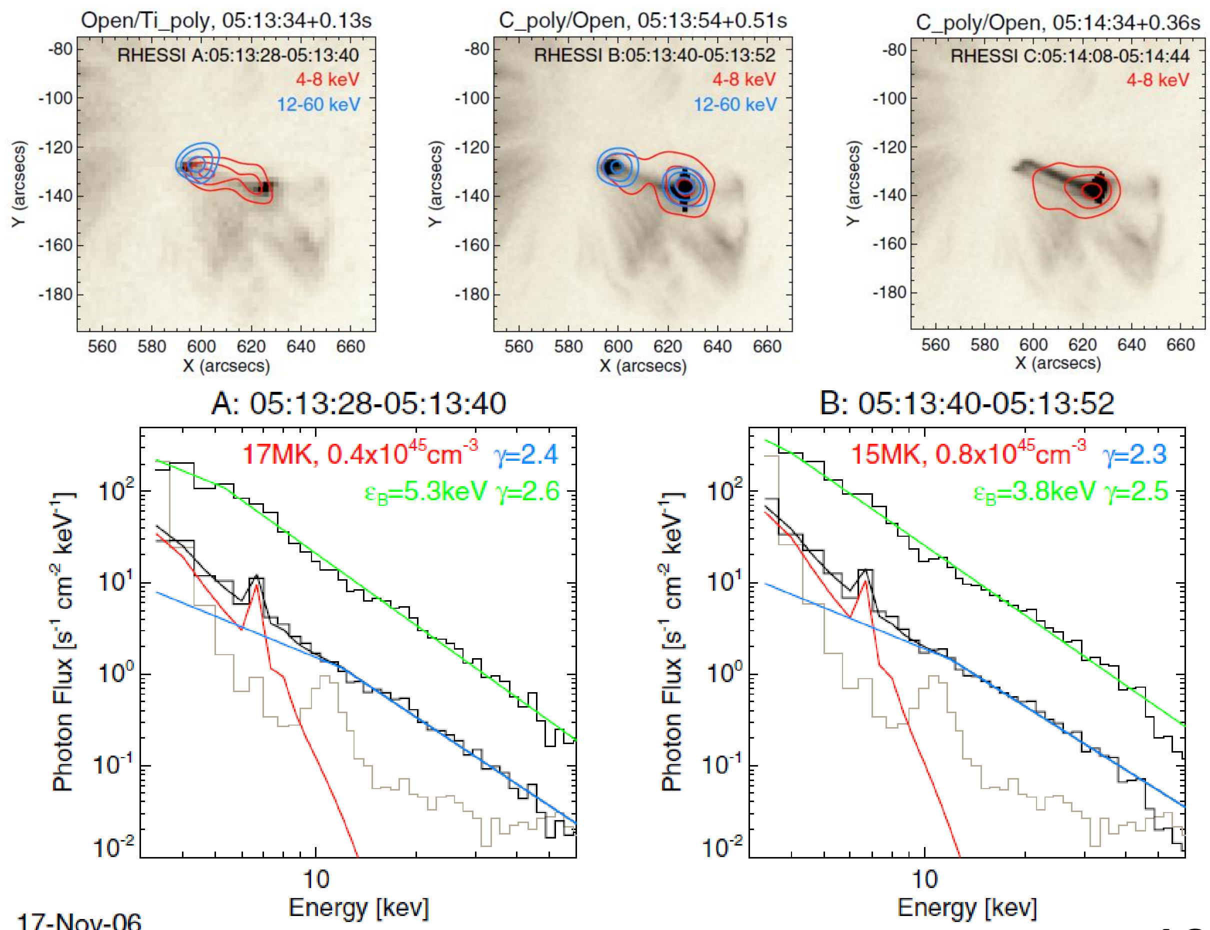
RHESSI & Hinode Microflares

- **Not enough has been done jointly with RHESSI & Hinode**
  - Hinode has not been focused/optimised for flare obs
  - RHESSI anneal issue (bad pre Nov’07)
  - Not enough flares (few 100 microflares jointly)
- **Should change for Cycle 24 (hopefully!)**
- **Microflare Observation pre-anneal**
  - November 2006, AR 10923
- **New RHESSI & Hinode microflare observations post anneal**
  - AR10978, December 2007
  - Many microflares with good RHESSI coverage and sometimes multiple filter observations with Hinode/XRT , slot mode with EIS

RHESSI & Hinode Microflare

- **Hannah et al. 2008 (A&A 481)**
  - Unusual microflare with hard spectrum to high >50 keV and possibly low 4 keV energies. Clear HXR footpoints matching XRT, TRACE & violation of Neupert Effect

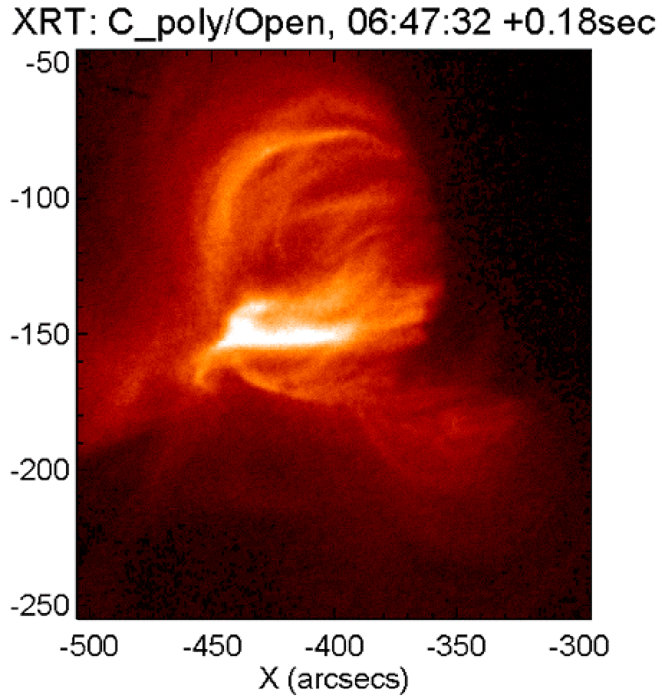


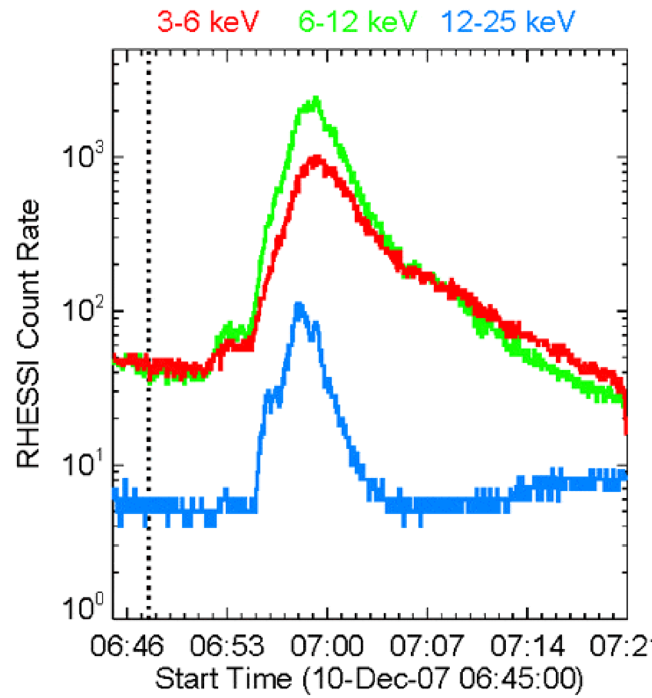


Newer Event: 10-Dec-2007 07:00, B7

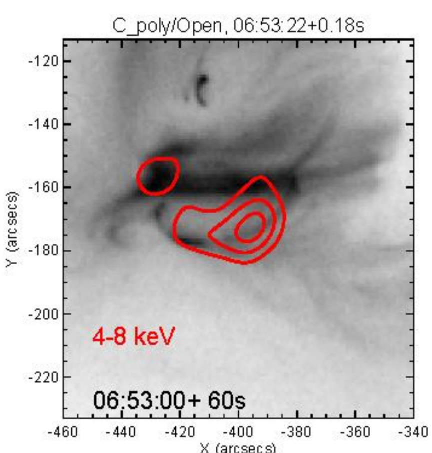
- **Heating in nearby/flaring loop before impulsive phase?**

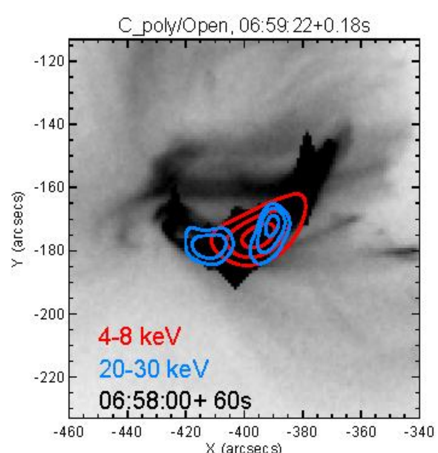
XRT MOVIE

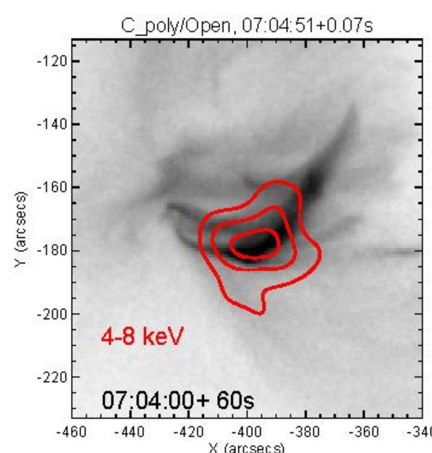




RHESSI Lightcurve







XRT IMAGES

x,y shift to match RHESSI

RHESSI 4-8keV

RHESSI 12-20keV

RHESSI/Hinode Conclusions

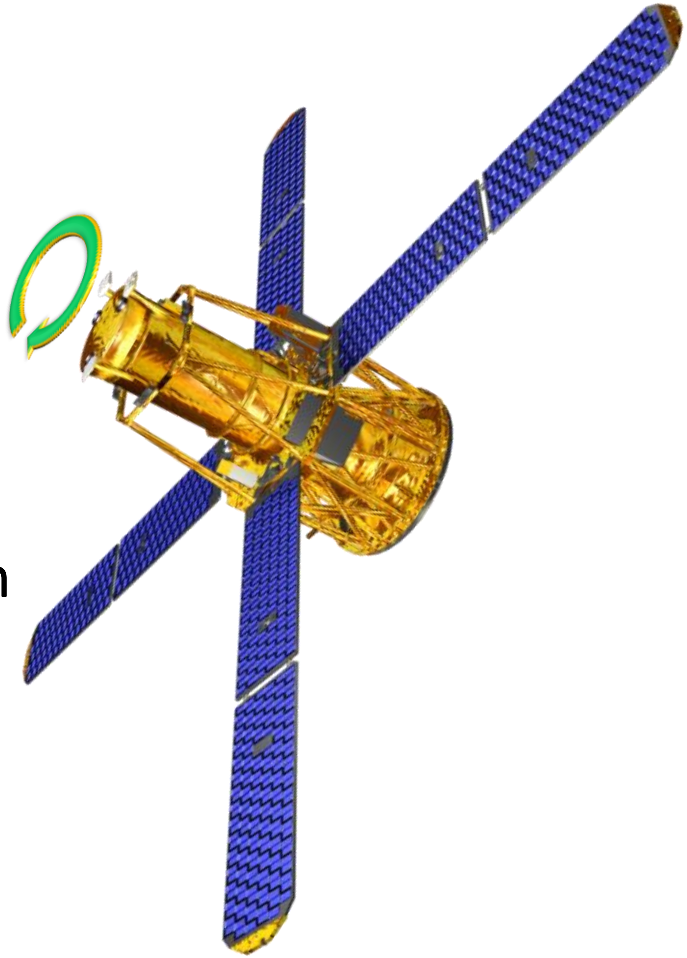
- **RHESSI and Hinode observations provide interesting insights that challenge the standard flare model, i.e.**
  - Why is the coronal energy release heating or acceleration dominated in some events

- **Ideally need to do statistical survey of detailed SXR and HXR microflare properties**
  - Easier post-anneal (Nov'07) but not many events
  - Many events pre-anneal but analysis challenges

- **New opportunities with (hopefully) forth coming events from Cycle 24 and new missions like SDO.**

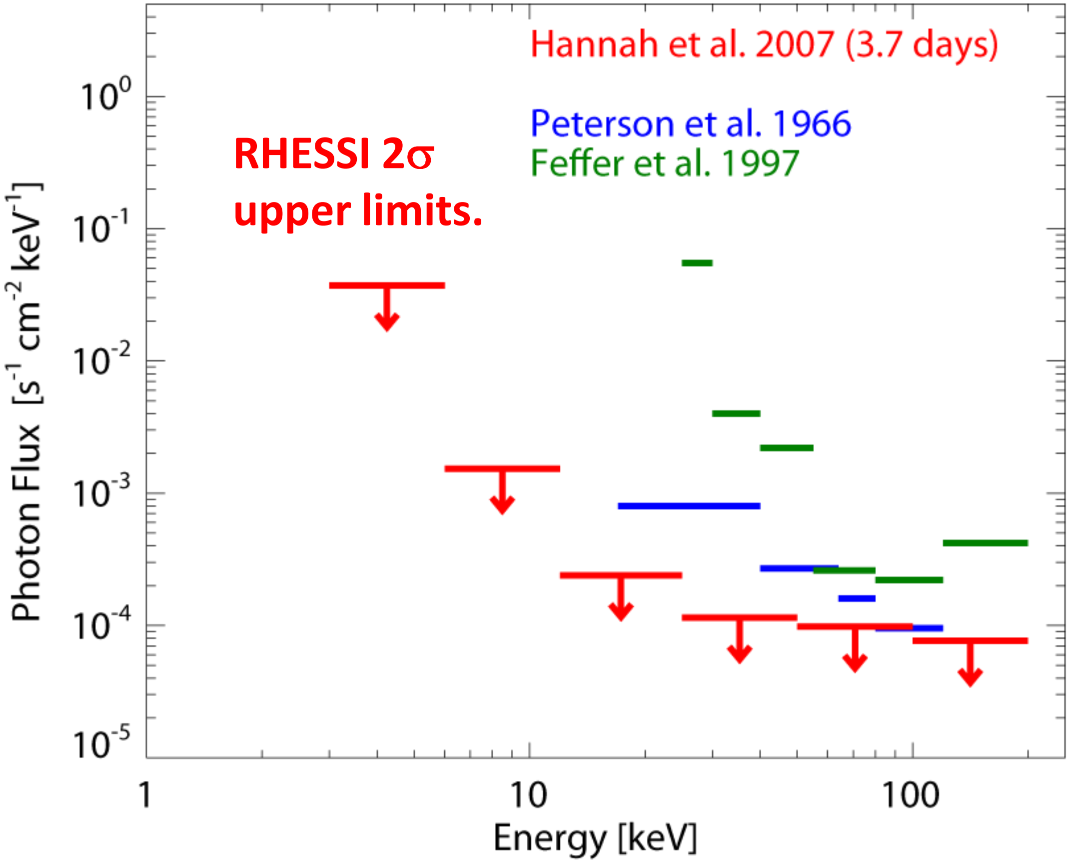
RHESSI Quiet Sun Overview

- **RHESSI imaging spectrometer uses 9 Rotating Modulation Collimators (RMCs) & has high sensitivity >3 keV**
- **However it is designed for bright compact flares not a well-dispersed population of faint "nanoflares"**
- **Solution is Fan Beam Modulation (Hannah et al. 2007)**
  - point the spacecraft slightly away from the Sun, "chopping" the solar disk's signal
  - Integrating over many offpointing periods do we get a statistically significant signal or are we noise limited?



RHESSI Quiet Sun Spectrum

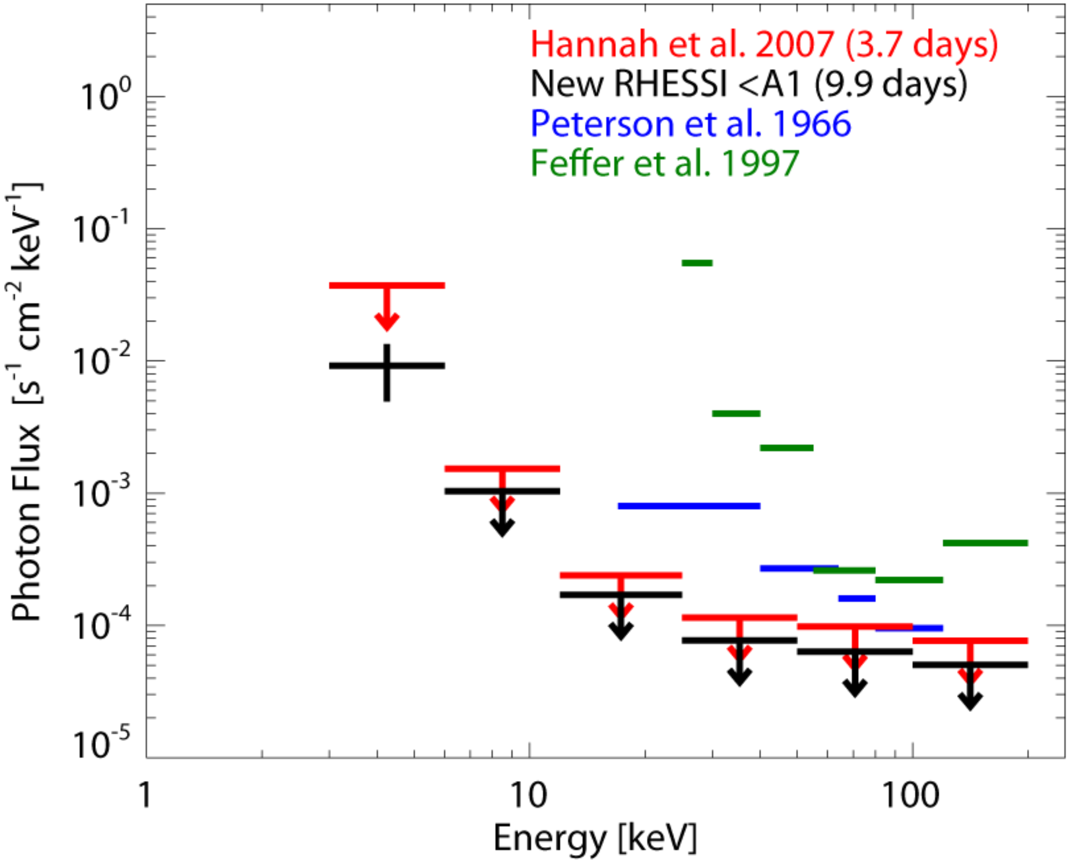
- **Previous work and first analysis of RHESSI QS data between October 2005 and October 2006, when GOES <A1.**



RHESSI Quiet Sun Spectrum

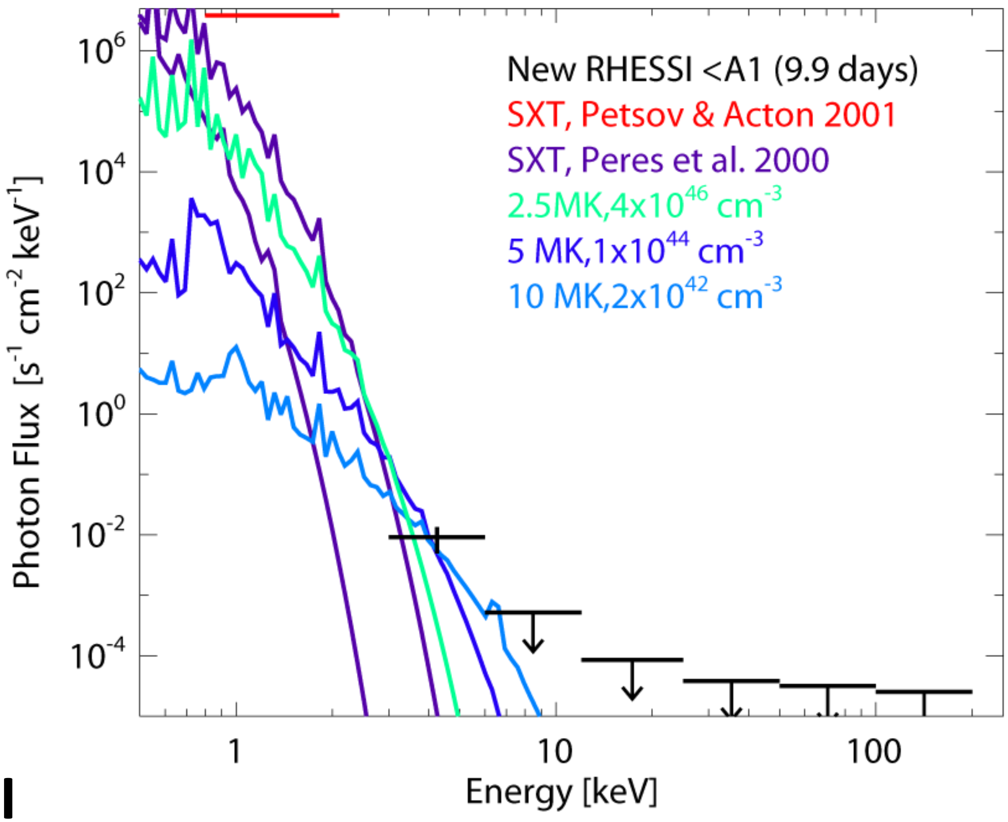
- Previous work and first analysis of RHESSI QS data between October 2005 and October 2006, when GOES <A1.

- New RHESSI QS analysis covers all useful offpointing data from Oct 2005 to Oct 2008, with GOES<A1.
- 3-6 keV now >3σ, not upper limits.
- What thermal or non-thermal emission is consistent with these limits?



Quiet Sun Thermal Emission

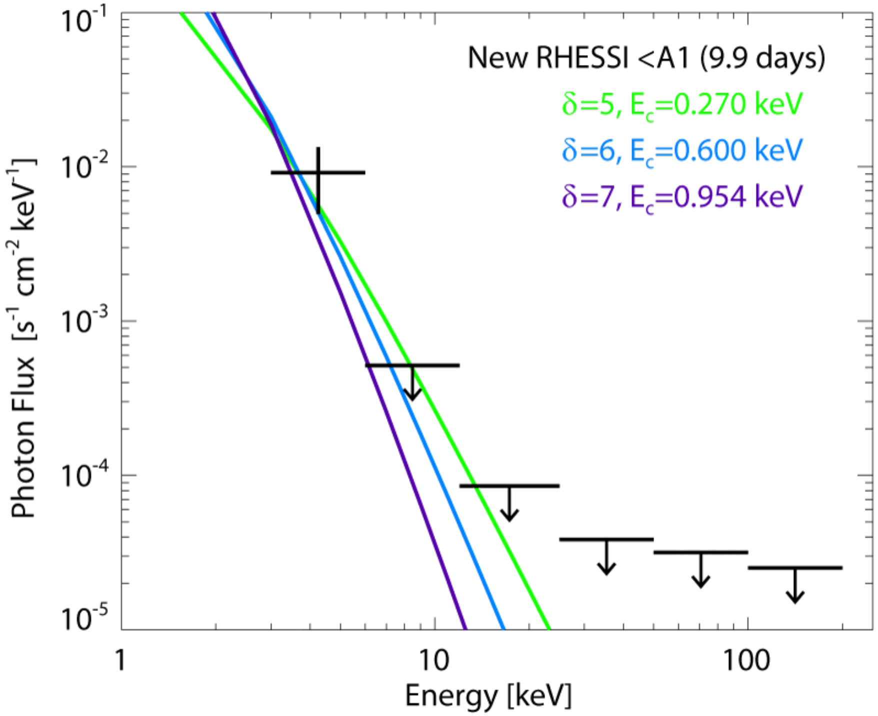
- Pevtsov & Action 2001 Yohkoh/SXT solar min AlMg 5×10^{6} ph/cm^2/s
- Peres et al. 2000 thermal fit to SXT solar min 0.97MK 1.3×10^{49} cm^{-3} and 1.78MK, 2.8×10^{48} cm^{-3}
- Find considerably lower EM than DEM(T) of Peres et al. 2000
- Other isothermal fits with higher T, lower EM fit RHESSI 3-6 keV but do not match SXT values.

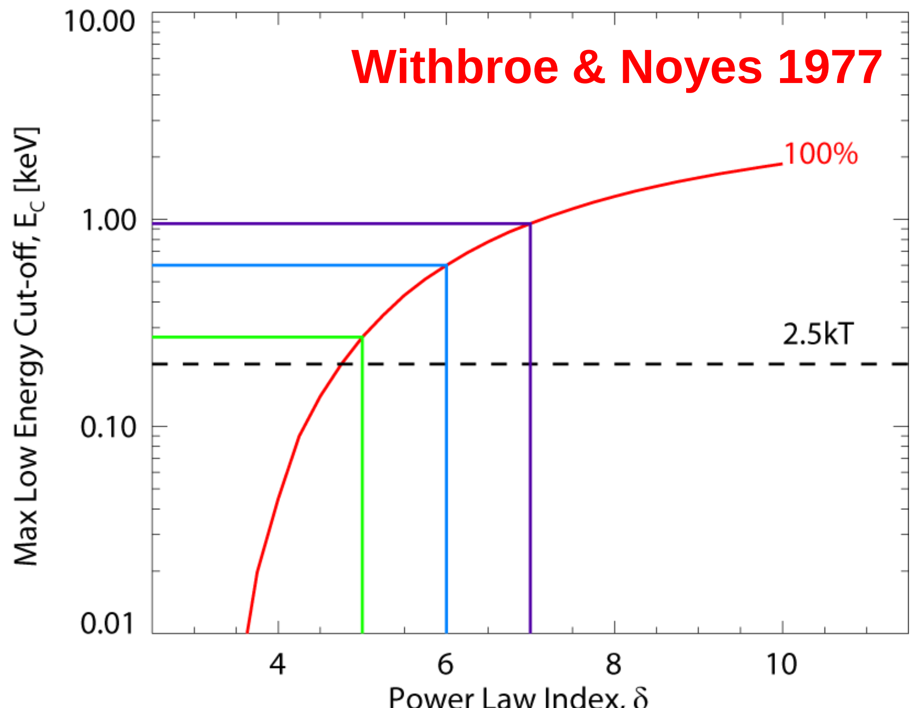


Not isothermal? Two Maxwellians?

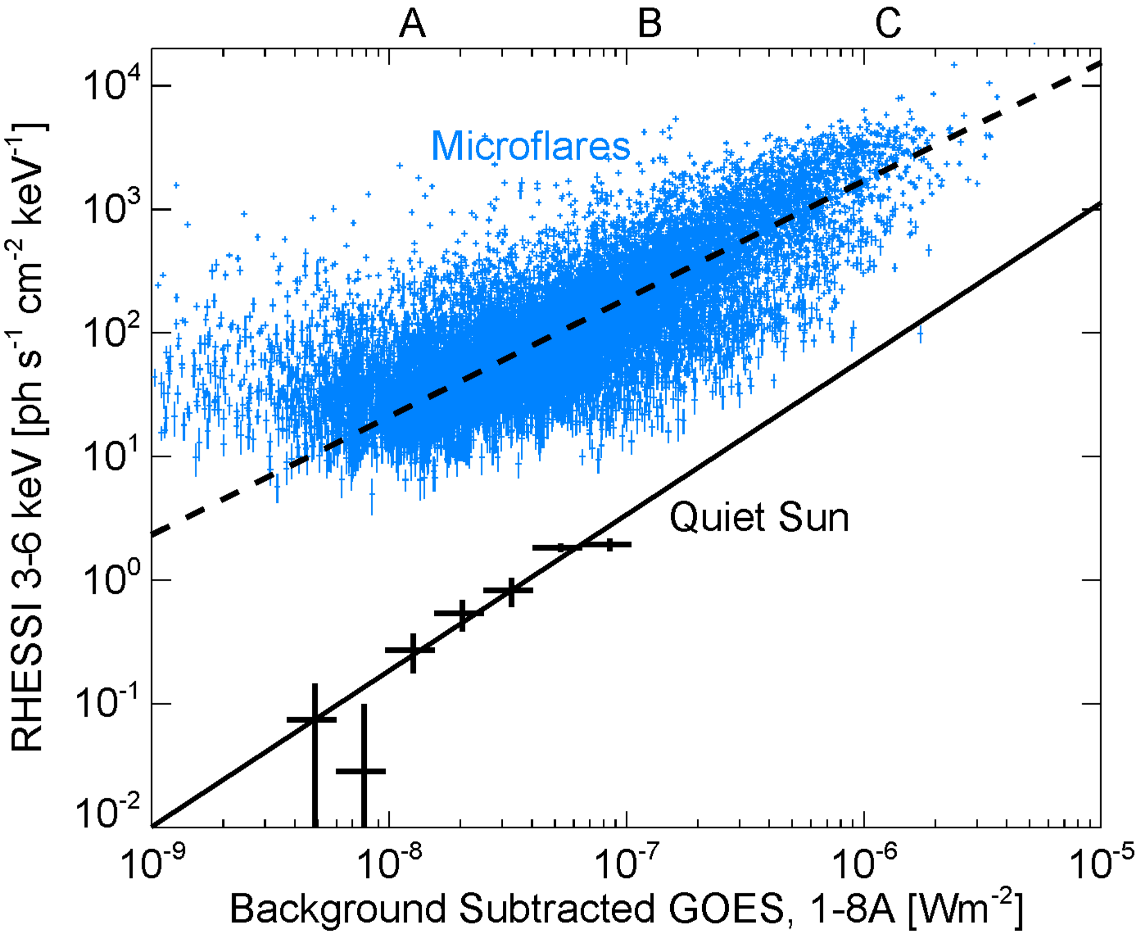
Quiet Sun Non-thermal Emission

- **What thick-target X-ray spectrum would be consistent with the RHESSI QS limits and the Coronal Heating Requirement ?**
  - Assume power-law of accelerated electrons, index δ above E_C
- **$I(\varepsilon)$ related to E_C ,δ ,$F(E>E_C)$ (Brown '71) and $I(\varepsilon)$ < RHESSI QS limits**
- **Power $P(E> E_C)=F(E> E_C)\, E_C\, (\delta-1)/(\delta-2)=$ 9×10^{27} erg/s**





RHESSI Microflares vs QS



- **Similar or different type of event?**
  - RHESSI vs GOES for microflare and QS

RHESSI QS Conclusions

- **RHESSI continues to provide new insights into the HXR QS**
- **In terms of a possible large scale temporally and spatially averaged "nanoflare" population :**
  - Find EM considerably lower than Peres et al. 2000
  - Assuming non-thermal emission then need steep spectrum (δ>5) down to limit of cold target assumption (E_C=2.5kT)
  - Need $F(E>E_C) \approx 10^{37}$ e^-/s accelerated to heat corona.
  - Makes coronal heating from hard X-ray "nanoflares" unlikely?
    - Including thermal component constrains the non-thermal parameters even further
- **Investigate results in terms of a distribution of "nanoflares"**
  - Found power-laws from SXR events or HXR microflares