X-ray Imaging & Spectral Statistics of Small Solar Flares Observed with RHESSI

Iain G. Hannah

Steven Christe, Säm Krucker, Gordon Hurford, Hugh Hudson & Robert P. Lin

Space Sciences Laboratory, University of California, Berkeley

hannah@ssl.berkeley.edu

Motivation

- What are the properties of small (micro) solar flares?
  - Especially the characteristics of heating and particle acceleration in these low-level energy releases
- What is the flare frequency distribution?
  - Is there enough energy available to heat the solar corona?

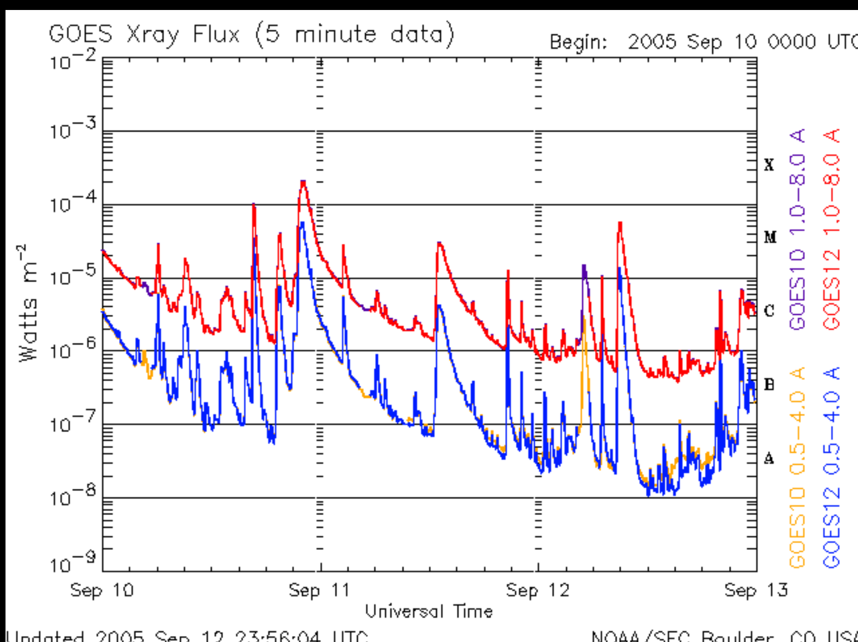
- RHESSI is uniquely sensitive to these events, providing imaging and spectroscopy >3 keV
  - Observes non-thermal emission to lower energies than before
    - Better estimate of Non-thermal energy
  - Observes and images high temperature thermal emission
    - Estimate of Thermal energy
- Automated analysis of nearly 25,000 flares

Outline

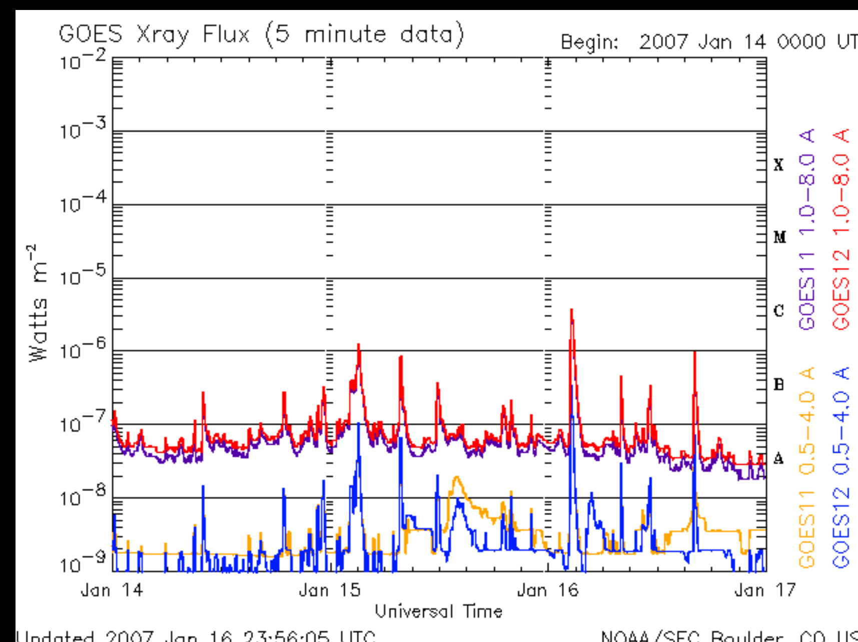
- X-ray emission from large and microflare
- Coronal Heating and Flare frequency Distributions
- Overview of RHESSI
- Finding RHESSI microflares
- Imaging with visibilities
  - Recover thermal volume information
- Spectroscopy
  - Recover Thermal and Non-thermal Parameters
- RHESSI flare frequency distribution
- Conclusions
- Trying to observe even smaller events with RHESSI

Microflares

- Miniature version of a large flare:
  - Flare is the observed multiwavelength atmospheric response to a rapid transient release of magnetic energy from the coronal fields
- Energy about 10^{-6} to 10^{-3} of large flare (~10^{26} - 10^{29} ergs)

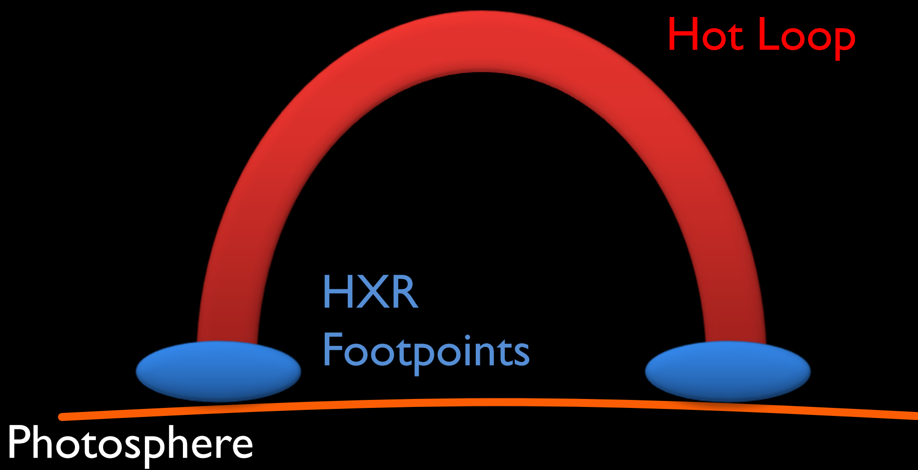


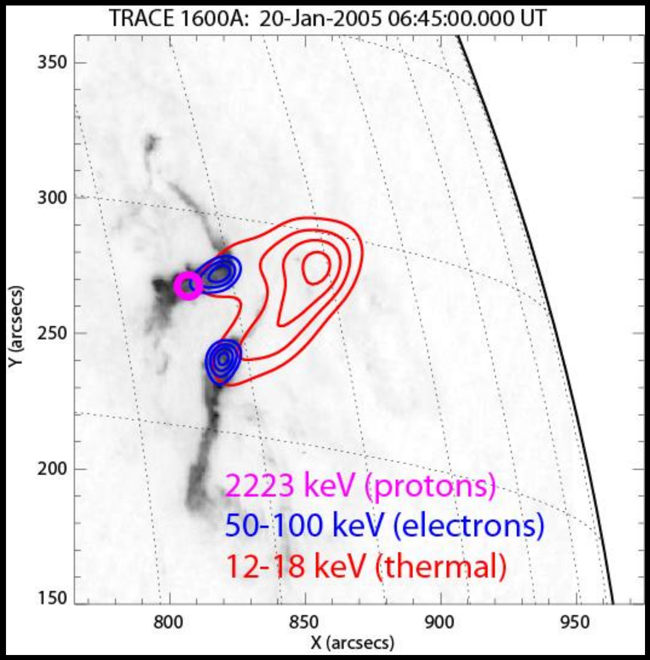
Dominated by large flares
C,M,X-Class



Just microflares
A,B, low C-Class

Flare X-ray Emission >3 keV



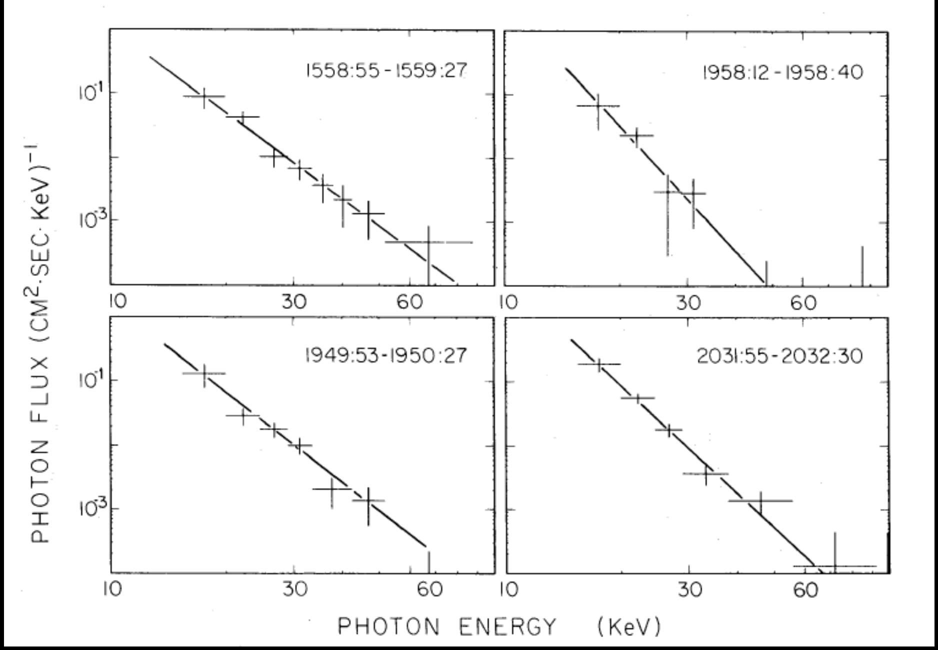


RHESSI Image, Krucker 2006

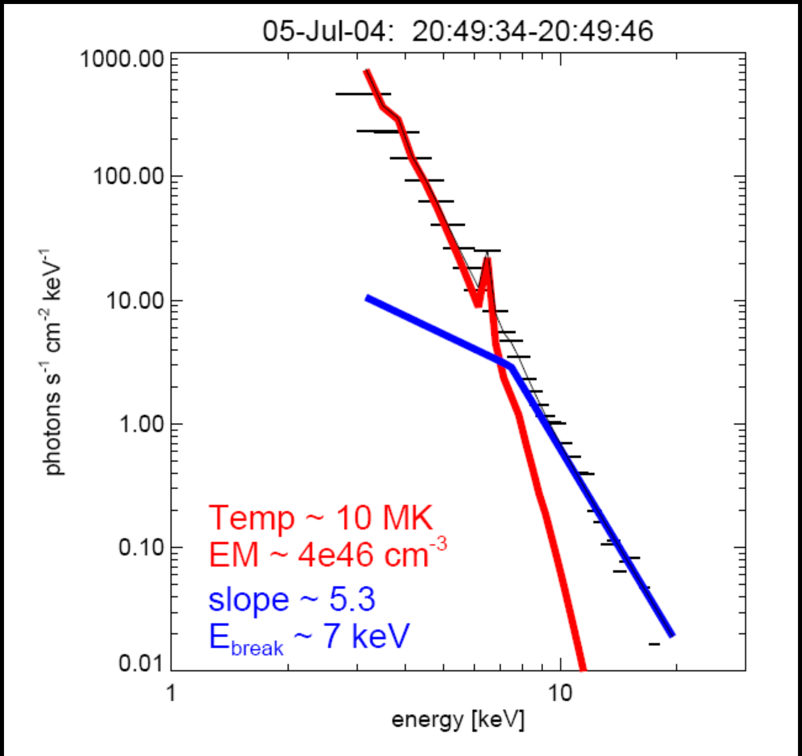
- Thermal (soft x-rays)
  - Electron bremsstrahlung continuum, (free-free and free-bound) and line features
  - 10s MK
  - Loop structures
- Non-thermal (hard x-rays)
  - accelerated out of the thermal distribution
  - thick target bremsstrahlung
  - Coulomb collisions in higher density plasma
  - footpoints (generally)
- Non-thermal dominates
  - > 7 keV RHESSI microflares
  - > 25 keV large flares

Microflare X-ray Spectrum

- RHESSI has better resolution and extends to lower energies than previous

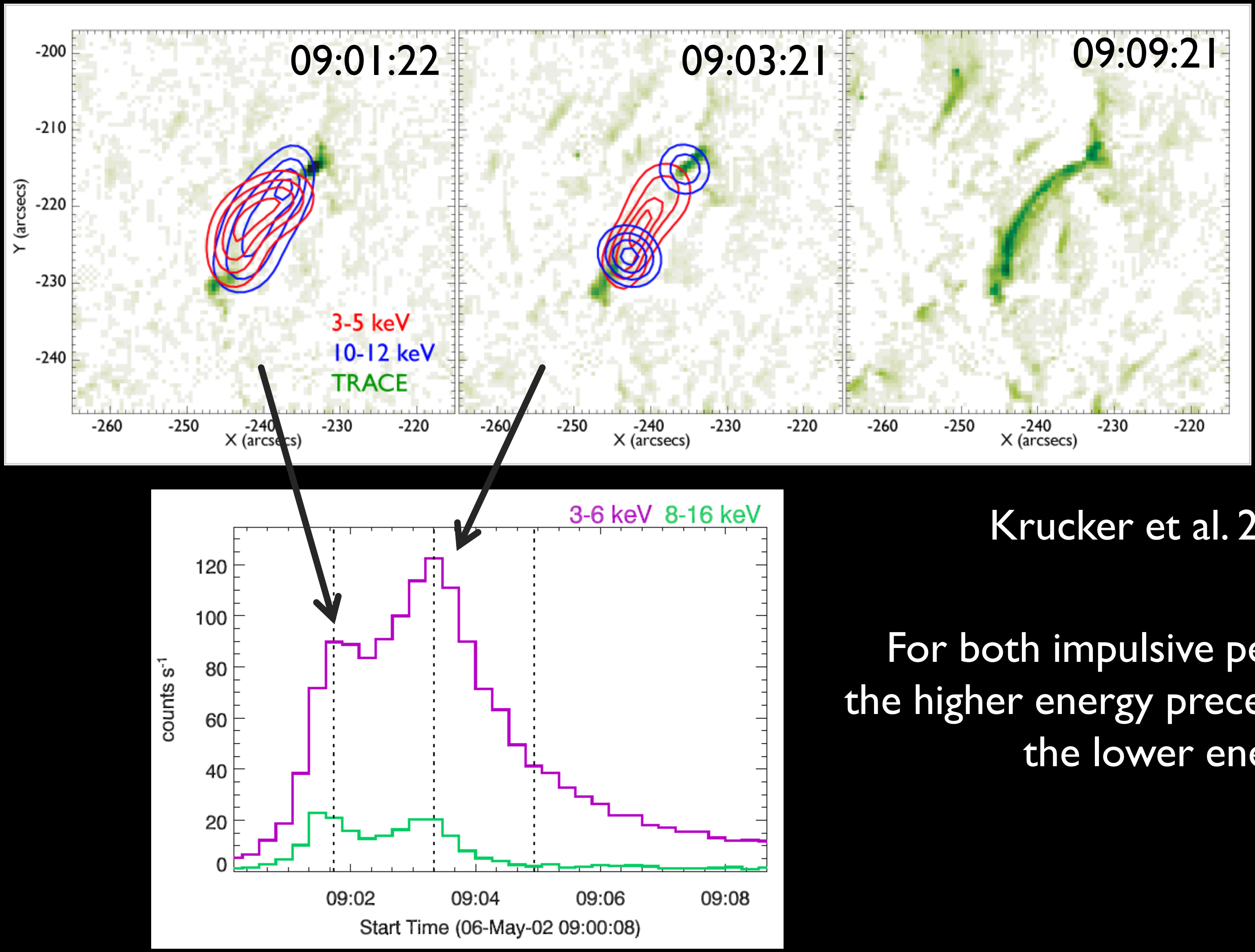


First hard x-ray microflares
Balloon-borne instrument,
Lin et al. 1984



RHESSI
Krucker & Hudson, 2004

Microflare X-ray RHESSI Images



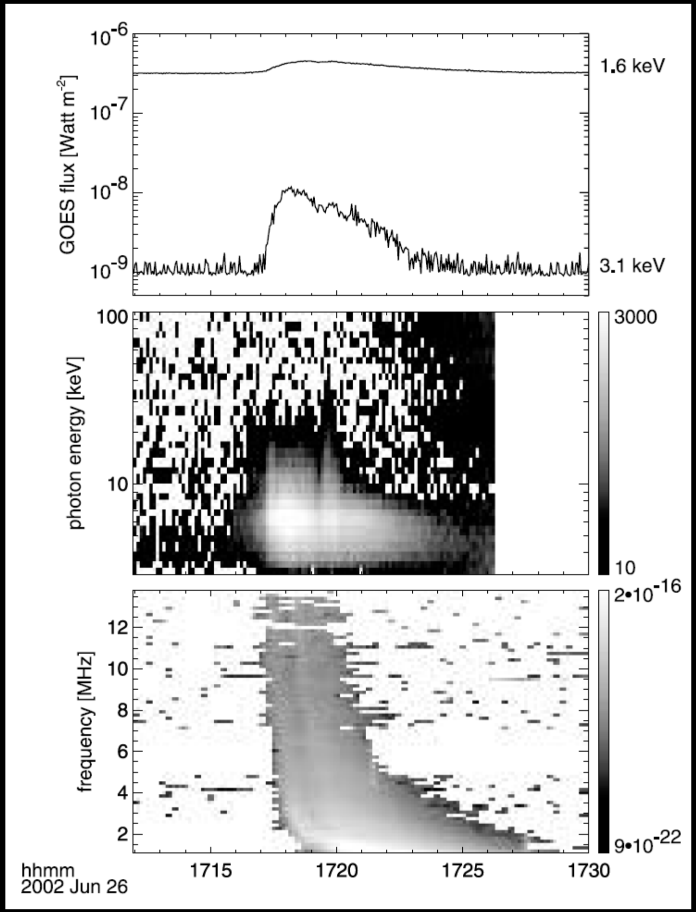
Krucker et al. 2002

For both impulsive peaks the higher energy precedes the lower energy

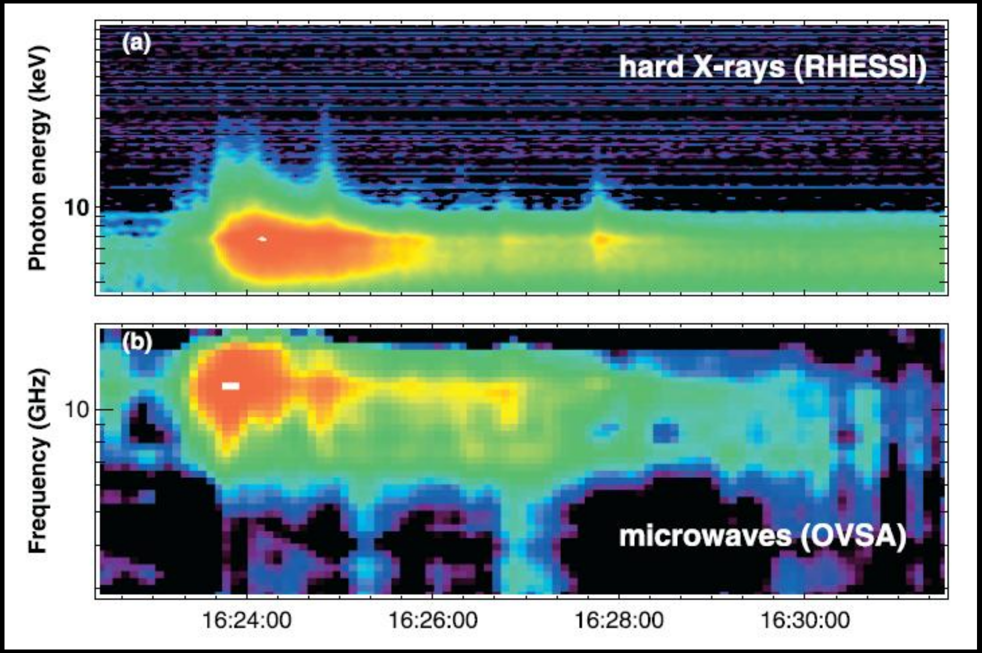
Non-thermal or Hotter Component ?

- Related radio & microwave observations to RHESSI microflares

GOES RHESSI WIND



Type III Radio Burst, Liu et al. 2004



14-July-2002
Qiu et al. 2004

Gyrosynchrotron emission from electron beams

Other Small Transient Events

1. X-ray Bright points – Soft X-ray
   - Non Active Region associated and possible non-thermal emission
     - Nitta et al. 1992, Kundu et al. 1994 Krucker et al. 1997
2. Active Region Transient Brightenings – Soft X-rays
   - Active region associated, possibly microflare related
   - Small hot loops (4-8 MK) seen with SXT on Yohkoh, Shimizu 1995+
   - Some show radio and hard x-ray signatures
     - Gopalswamy et al. 1997+, White et al. 1995, Gary et al. 1997
3. "Nano-flares" – EUV Transient Brightenings
   - about 10^{-9} to 10^{-6} of large flare (~10^{24} to 10^{27} ergs)
   - Temperature 1-2 MK
     - SOHO/EIT: Krucker & Benz 1998+
     - TRACE: Parnell & Jupp 2000, Aschwanden et al. 2000+, Aschwanden & Parnell 2002

Energy Calculation

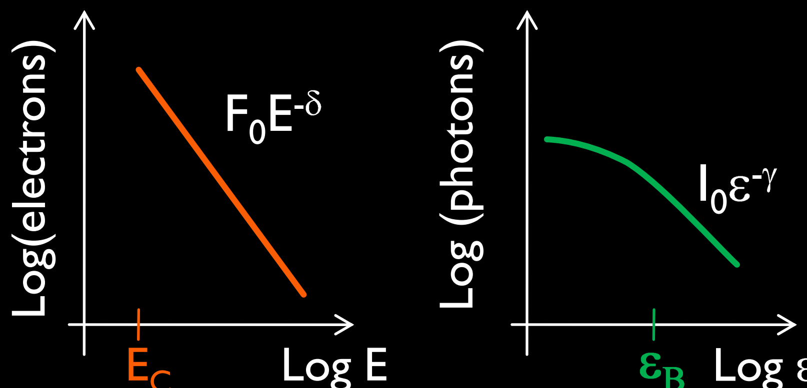
Thermal Energy $$W_{\mathrm{T}} = 3 n_{\mathrm{e}} k_{\mathrm{B}} V T$$

- Temperature, density and Volume (implied from area)

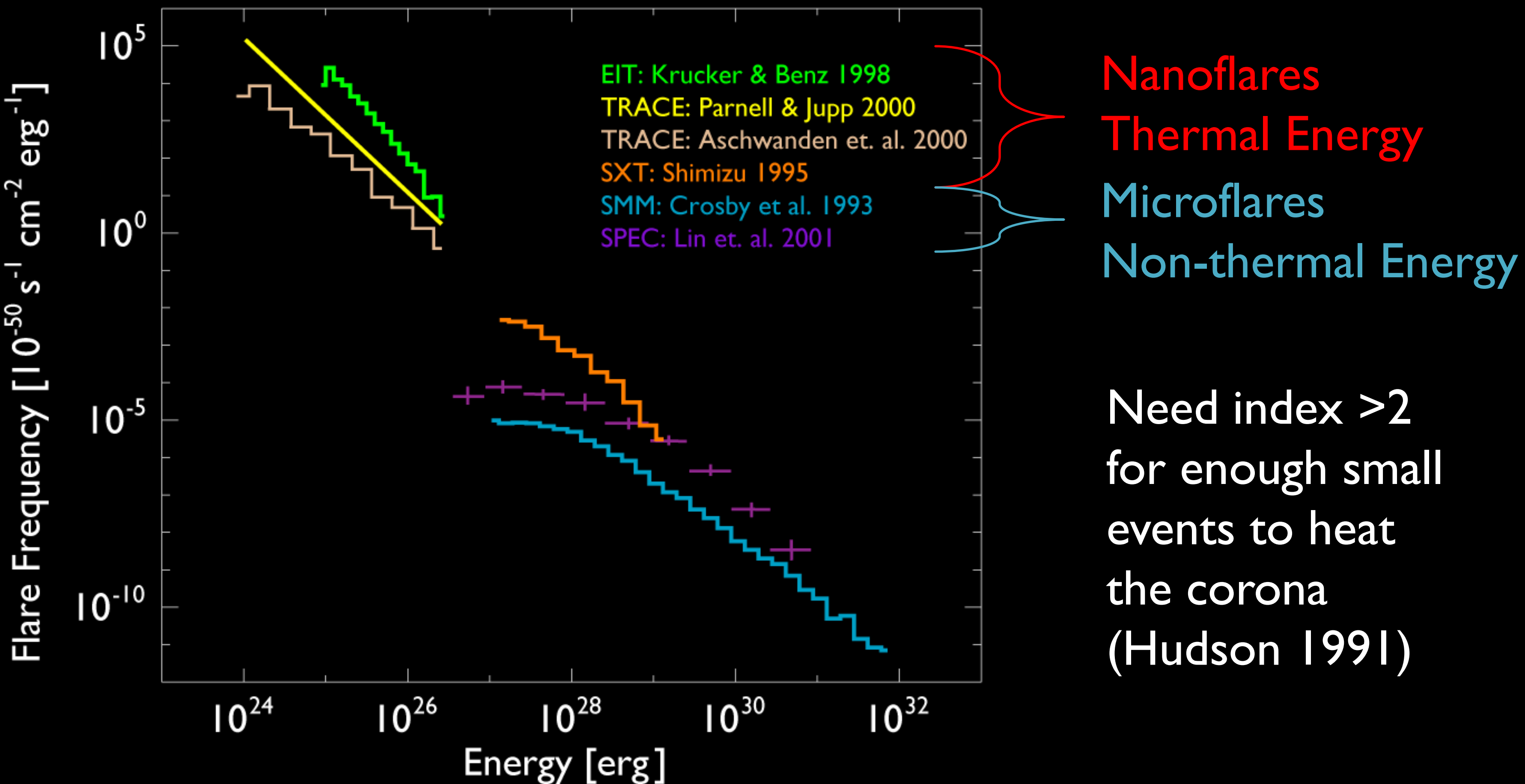
Non-thermal Energy

$$W_{\mathrm{N}}(> E_{\mathrm{C}}) = 9.5 \times 10^{24} \gamma^2 (\gamma - 1) \beta \left(\gamma - \frac{1}{2}, \frac{3}{2} \right) I_0 E_{\mathrm{C}}^{(1-\gamma)} \Delta t$$

- Assuming thick target: power-law electron spectrum analytically results in photon power-law spectrum, $\delta=\gamma+1$ (Brown 1971)
- Flattens at low energies but no analytic expression for ε_B to E_C
- Requires numerical integration
  - to investigate flattening
  - use more realistic cross-section
  - Holman 2003



Energy Distributions pre-RHESSI



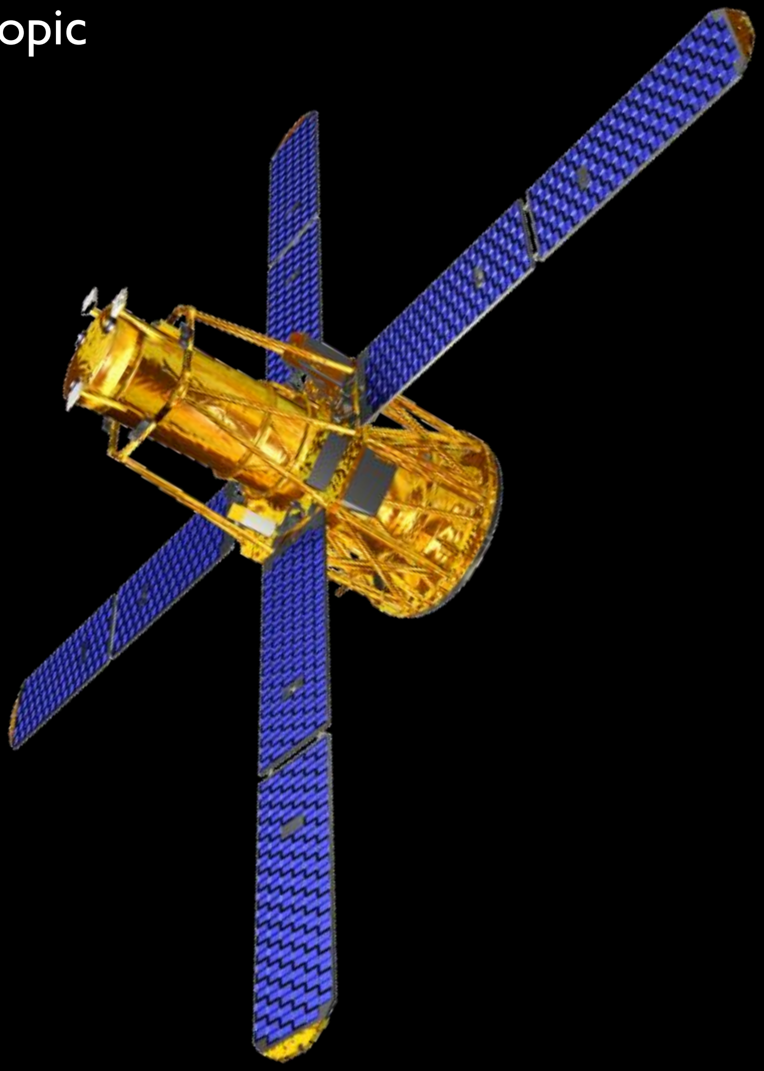
Need index >2 for enough small events to heat the corona (Hudson 1991)

Total Power in the distribution

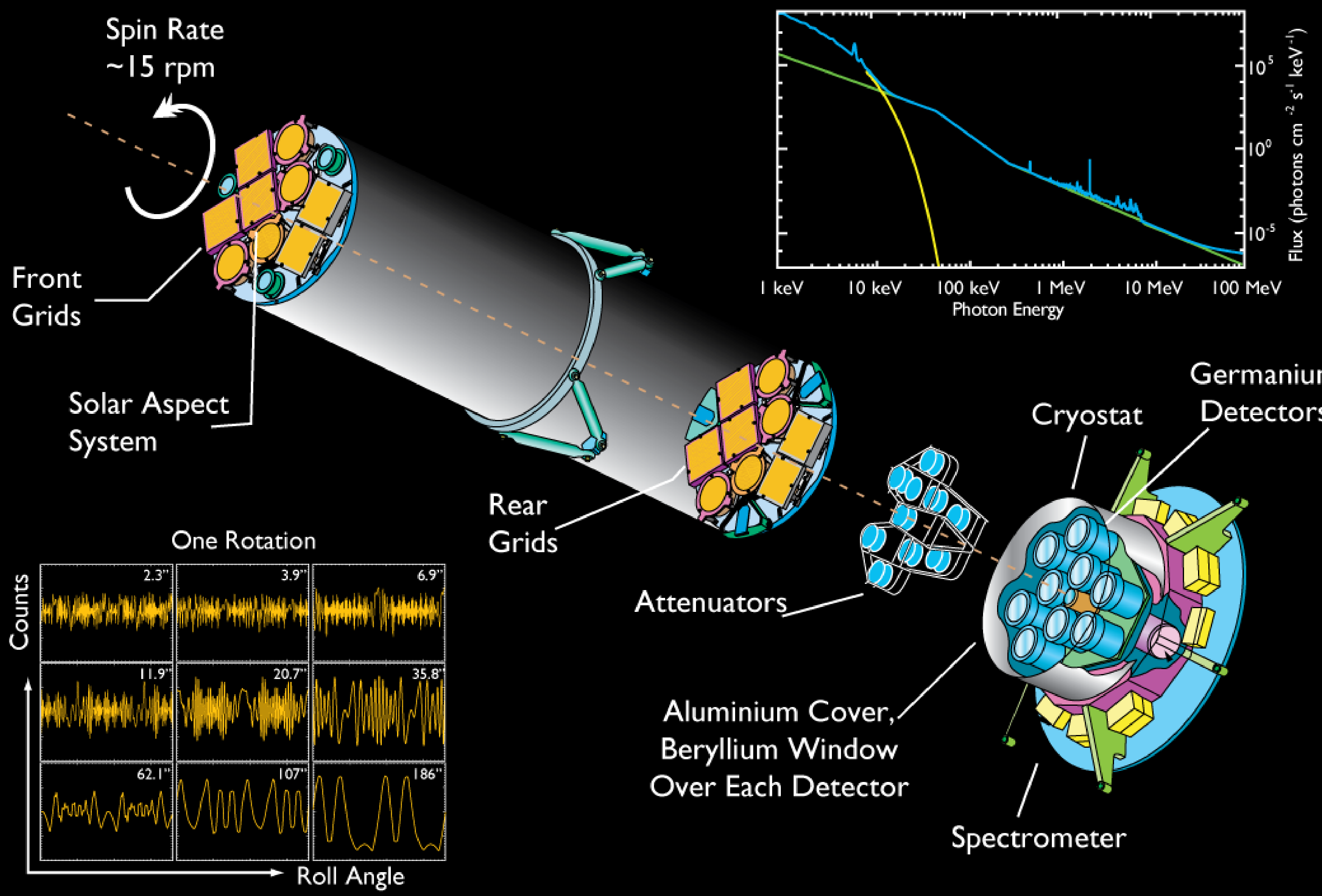
$$P = \int_{W_{min}}^{W_{max}} (\mathrm{d}n/\mathrm{d}W) W \, \mathrm{d}W = \frac{A}{-\alpha + 2} W^{-\alpha+2} \Big|_{W_{min}}^{W_{max}} .$$

RHESSI Overview

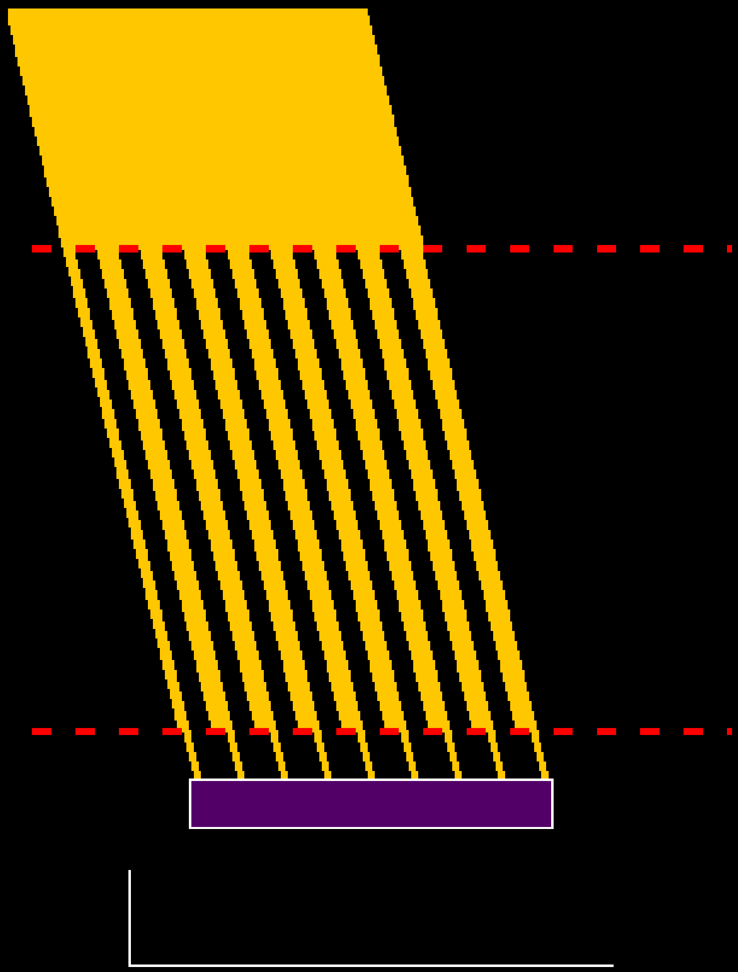
- Reuven Ramaty High Energy Solar Spectroscopic Imager,
  - launched Feb-2002 into LEO
  - 90 min orbit, ~60 min sunlight
- High spatial, energy and temporal resolution
  - 2.3”, ~1 keV, <<1sec (~2 sec imaging)
- Consists of 9 Germanium detectors behind 9 bigrid collimator pairs
  - Records energy & time of each photon
  - 3 keV to 17 MeV
- Entire spacecraft spins at ~15 rpm
  - Rotation Modulation Collimators (RMC)
- Provides spectroscopy, imaging & imaging spectroscopy information of solar flares



RHESSI Spectroscopy & Imaging



RHESSI Imaging

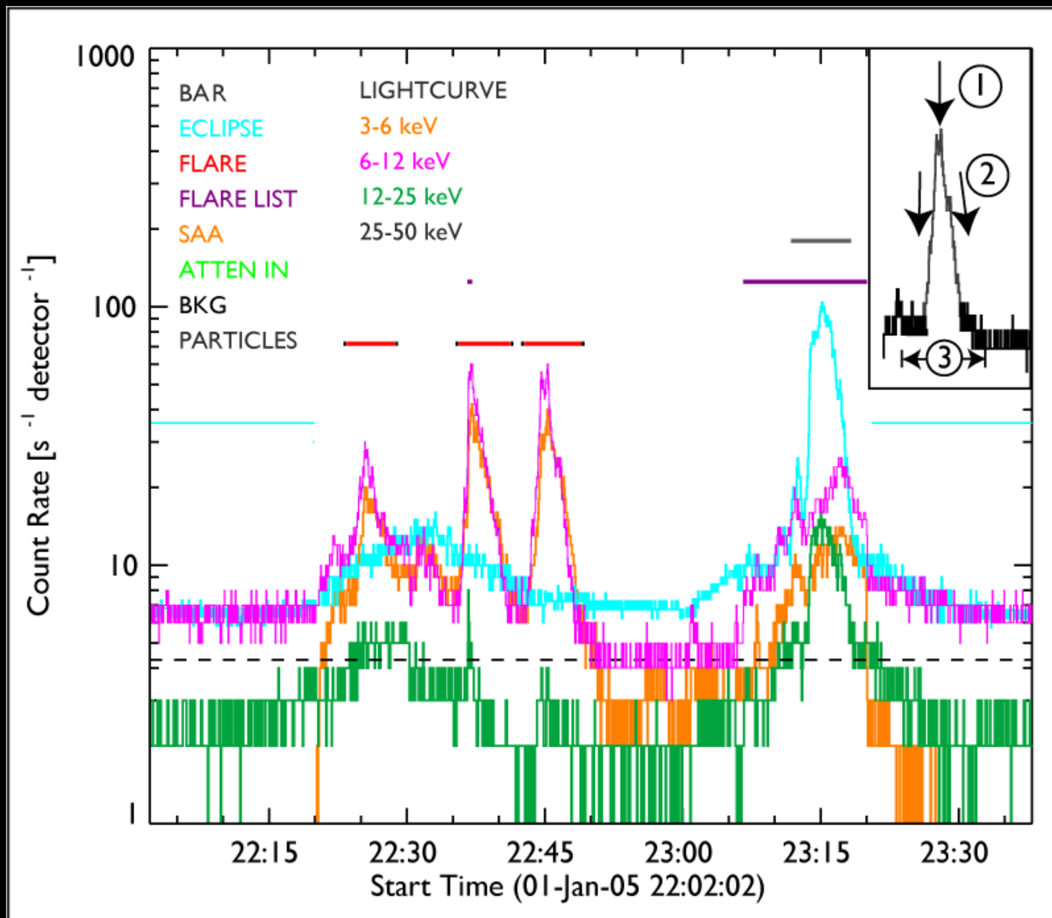


- Imaging achieved through a Fourier-based method using the RMC
- Each RMC time-modulates sources whose size scale is smaller than their resolution
- You choose time, energy and resolution (which grids)
- Reconstruct into an image via a technique such as back projection, equivalent to a 2D inverse Fourier transform
- Also CLEAN, PIXON
- New techniques use visibilities
  - Detailed later

Why RHESSI is good for Microflares

- Uniquely sensitive over 3-15 keV
  - 100 times more sensitive at 10 keV than HXIS on SMM
  - Previous telescopes used fixed attenuators in front of detectors to shield from excess low energy photons during flares.
- Investigate spectrum down to 3 keV
  - Determine thermal and non-thermal spectrum parameters
  - Estimate non-thermal Energy
- Image thermal emission to estimate thermal volume
  - Estimate thermal energy

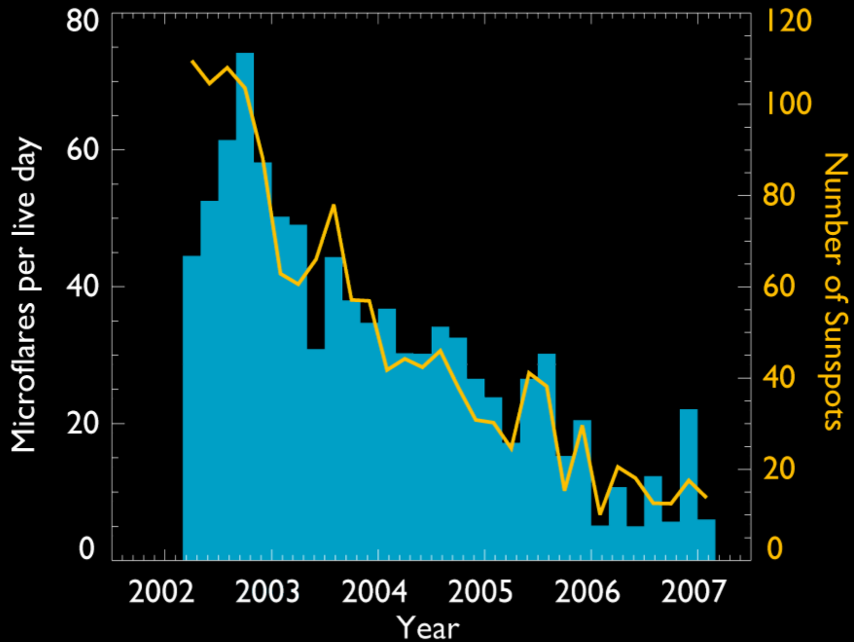
RHESSI Microflare Finding

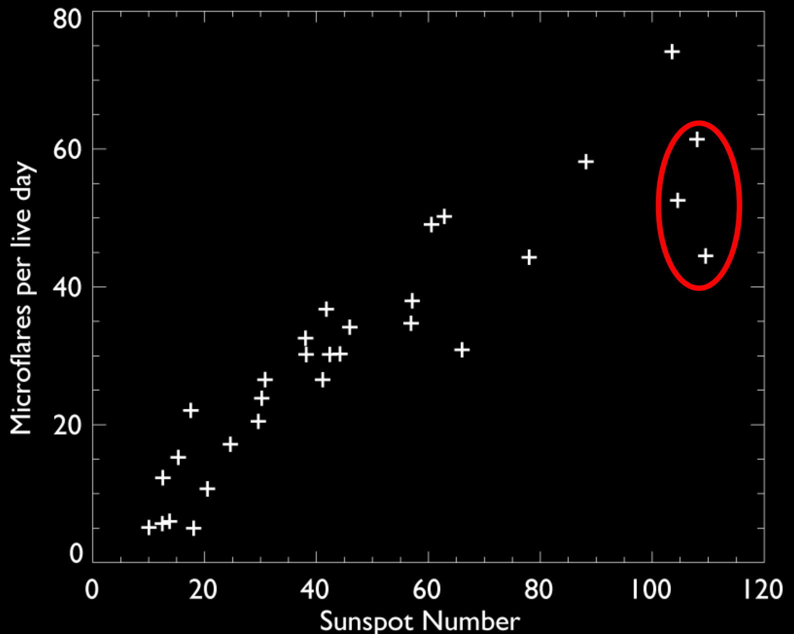


March 2002 to March 2007: ***24,799 events***

- Searched 6-12 keV
- Looks for maxima then follows derivative before and after until changes
- Attempts to find before and after background times
    - If not uses pre-flare night time
- Provides rough location from back projection image with coarse grids (7,8,9)
- More events and information than standard RHESSI flare list

Microflare Rate





Live day is corrected for night time and times of attenuators in, SAA or offpointing

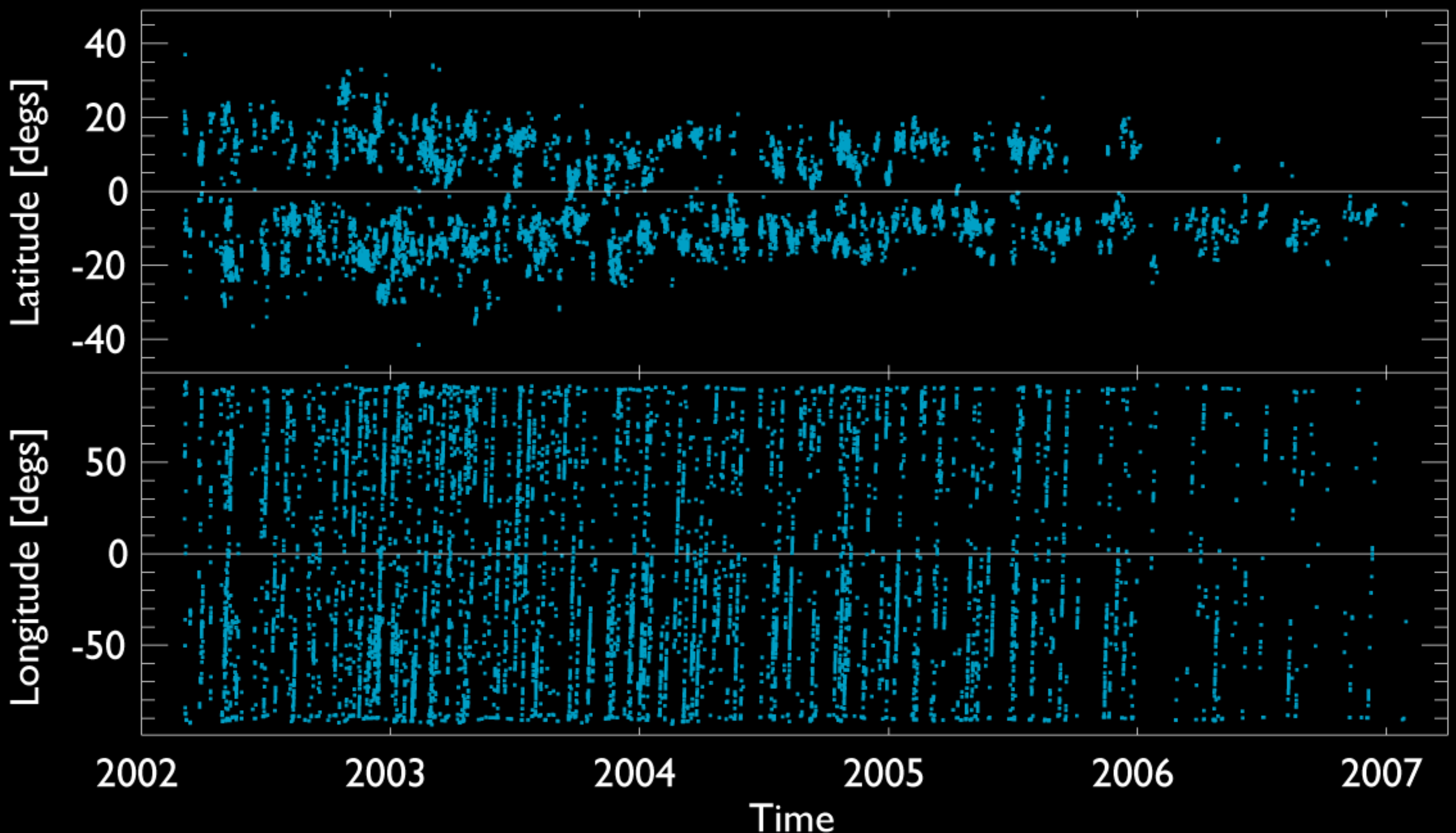
Correlation between Sunspot Number and RHESSI microflare rate

Max Rate: > 70 per live day

Min Rate: < 10 per live day

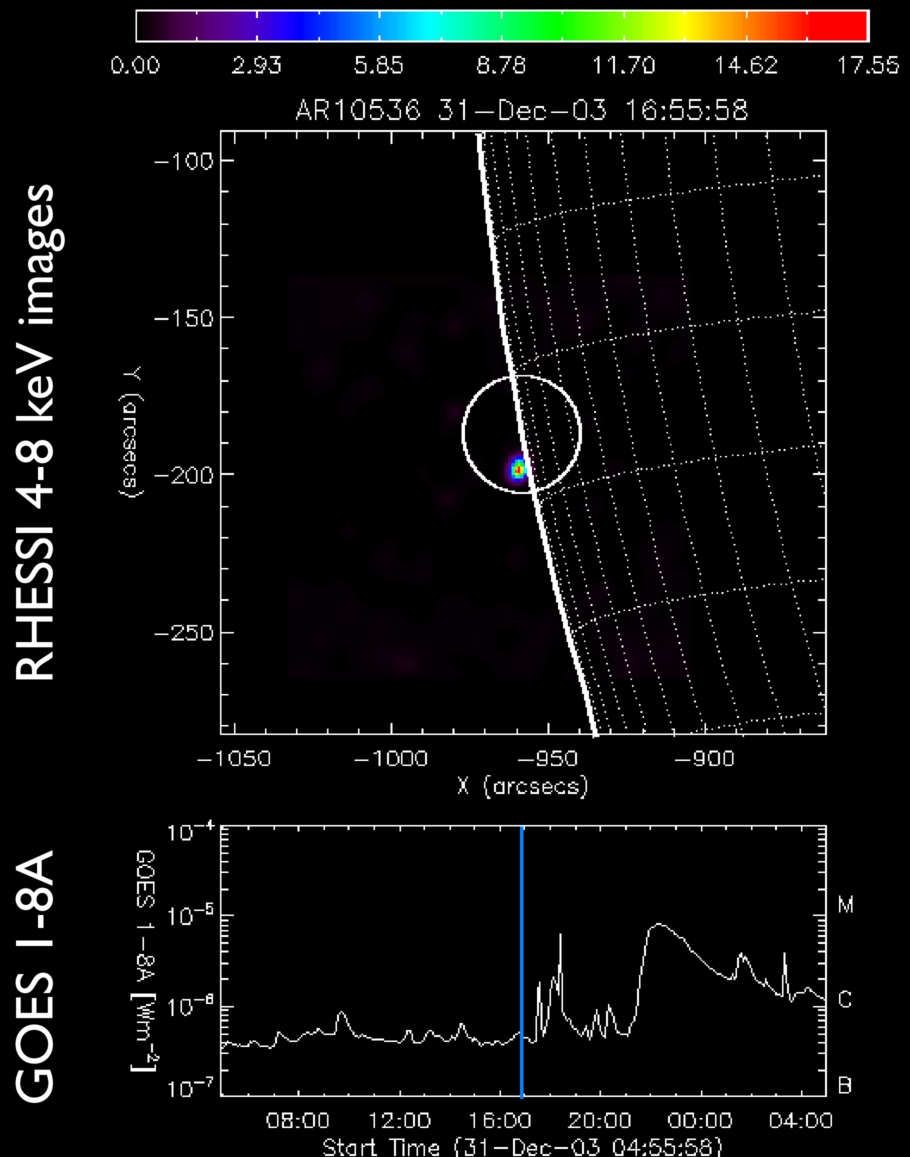
First 6 months (3 bins)

Microflare Locations



All RHESSI microflares are active region associated phenomena.

Microflares from AR10536



All the good imaged microflares from one active region as it moves across the disk.

Found using MEM_NJIT image of visibilities [Schmahl et al. 2007].

Colour scale changes => so nosier is smaller event

GOES events not shown either too big for microflare list, from other active region or RHESSI missed.

Analysis overview

- Analyse 16 seconds about peak time in 6-12 keV
- Image/Forward fit visibilities for 4-8 keV
  - Get estimate of thermal volume
- Fit spectrum with thermal + non-thermal model 3-30 keV
  - Get spectral parameters
- Fitting spatial scale and spectrum provides objective measures to the quality of fit
  - Can automatically discard events with not enough counts or instrumental issue not allowing detailed analysis
  - 9219 microflare image thermal and fit thermal spectrum
  - 5108 image thermal and fit thermal + non-thermal spectrum

Imaging with Visibilities

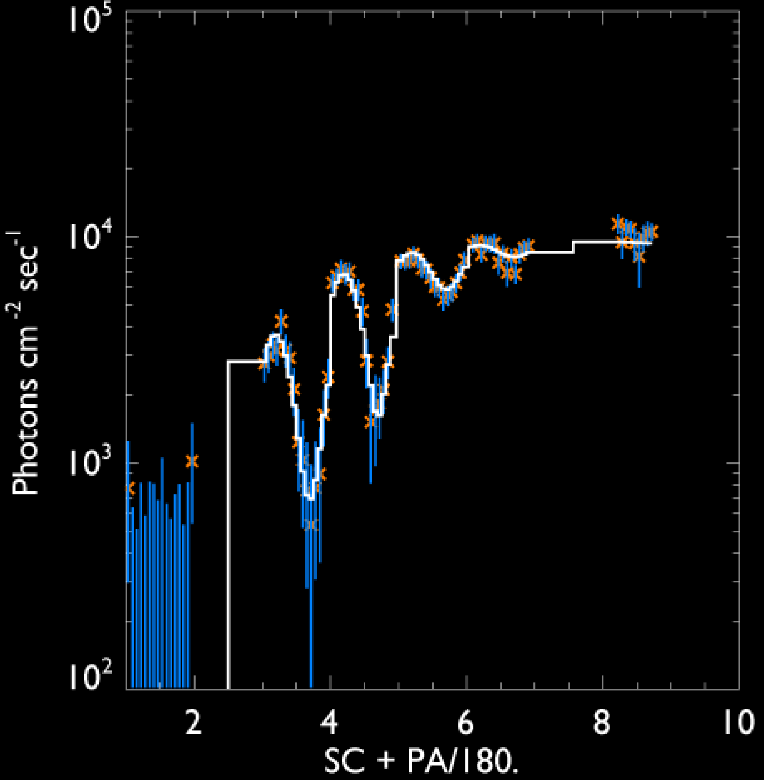
- Visibility
  - is a calibrated measurement of a single Fourier component of the source distribution measured at a specific spatial frequency for a chosen energy and time range
  - The resulting set of visibilities for all roll angles and RMCs is a calibrated and compact representation of the original time profile, with little loss of information.
  - Long heritage in radio astronomy

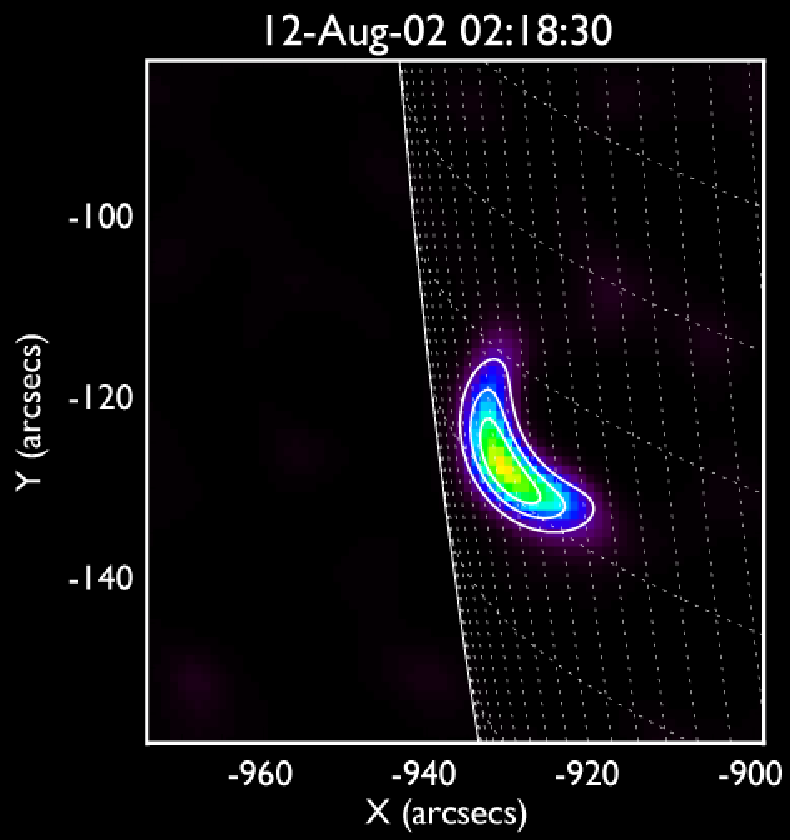
Advantages

- Faster than normal imaging
  - Processing compact set of visibilities instead of time profile
- Semi-calibrated data
  - Can combine visibilities from different time periods
  - Recover spatial information from visibililties without imaging
    - Forward Fitting , Hurford et al. 2007

Forward Fitting Example

Forward fitting a curved elliptical Gaussian to the visibilities

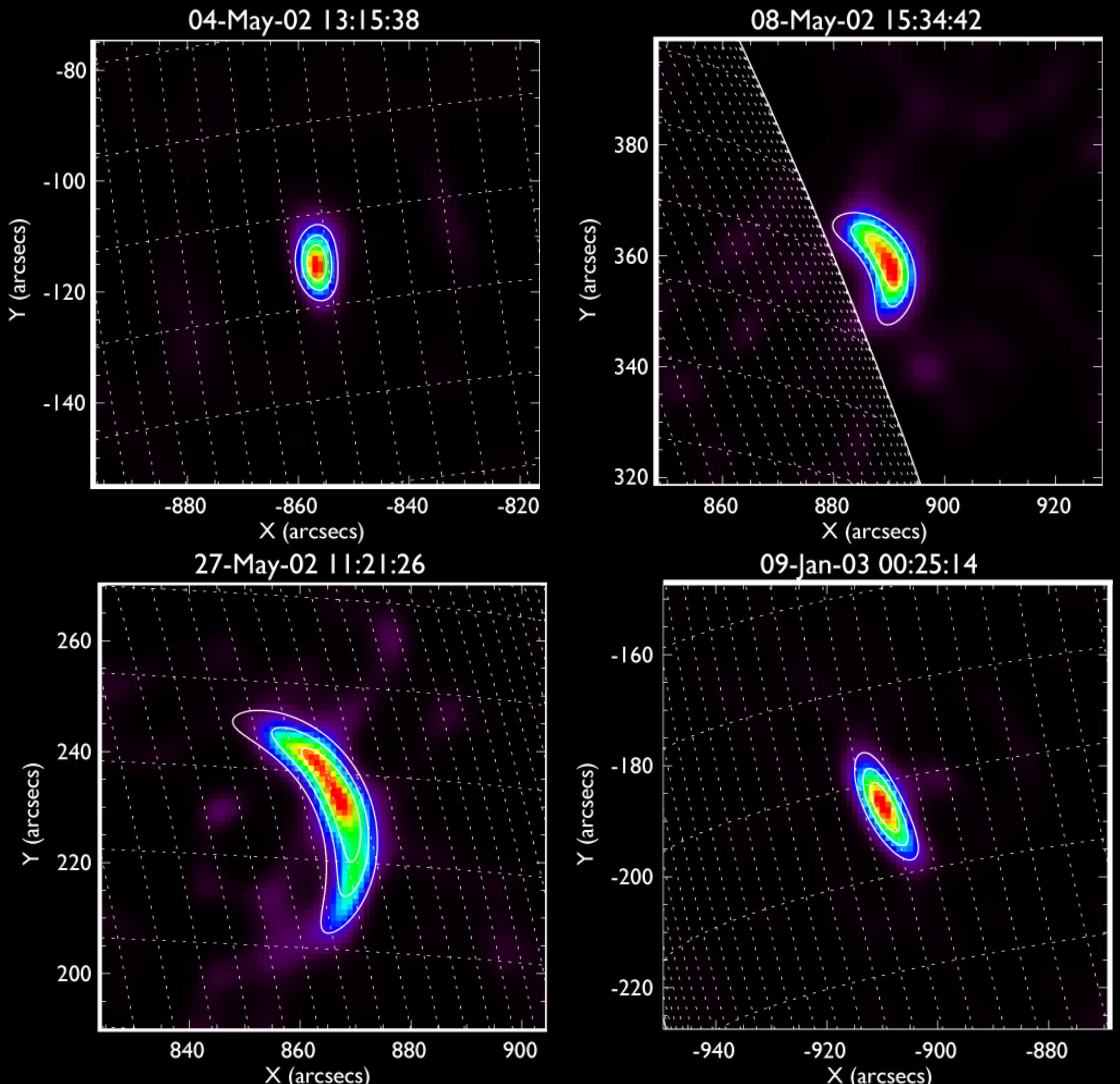




Visibilities (orange data points), with associated error, the fitted shape (the white line) for detectors 3,4,5,6,8

Image of visibilities using MEM_NJIT [Schmahl et al. 2007], overlaid with contours of forward fitted shape

Example 4-8 keV images



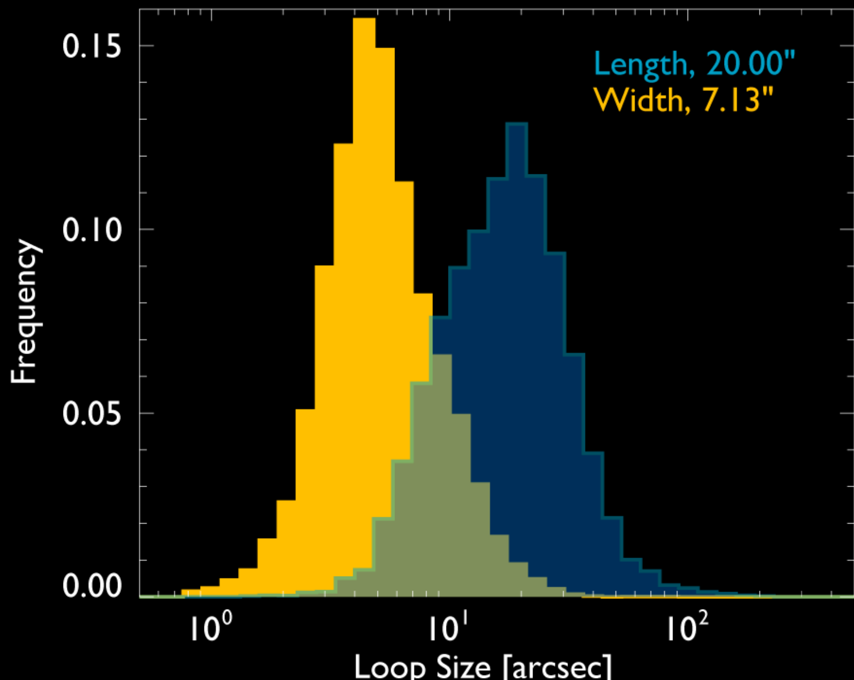
MEM_NJIT image [Schmahl et al. 2007]

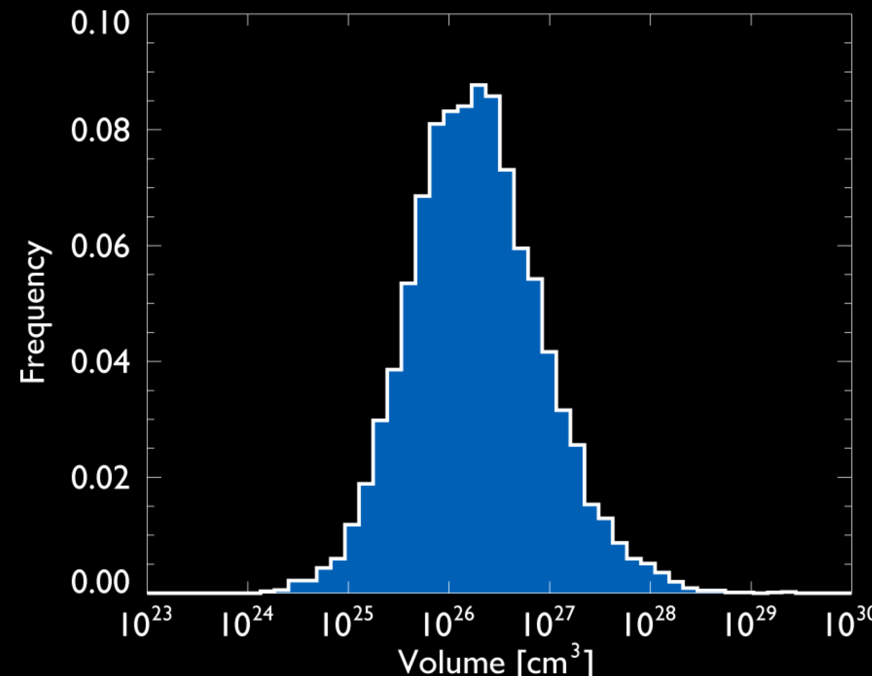
Forward Fit 25%, 50%, 75% contours

Fit parameters : x,y centroid position, FWHM flux, loop length and width, eccentricity, rotation angle, loop angle

For ellipse: loop length and width are major and minor axes, loop angle=0

Loop Length, Width & Volume





Average size:
Width ~7",
Length~20"

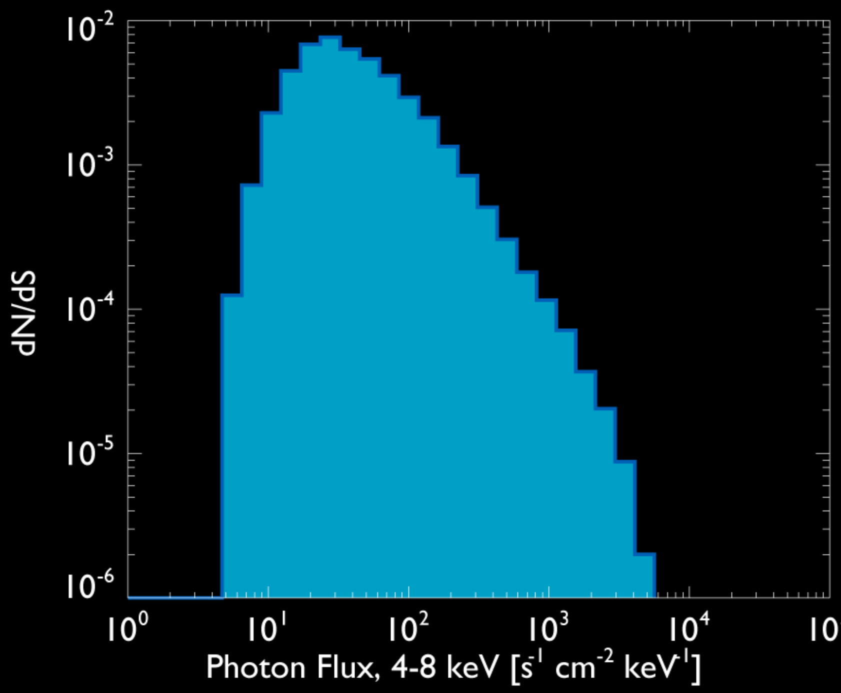
So Length ~3 x Width

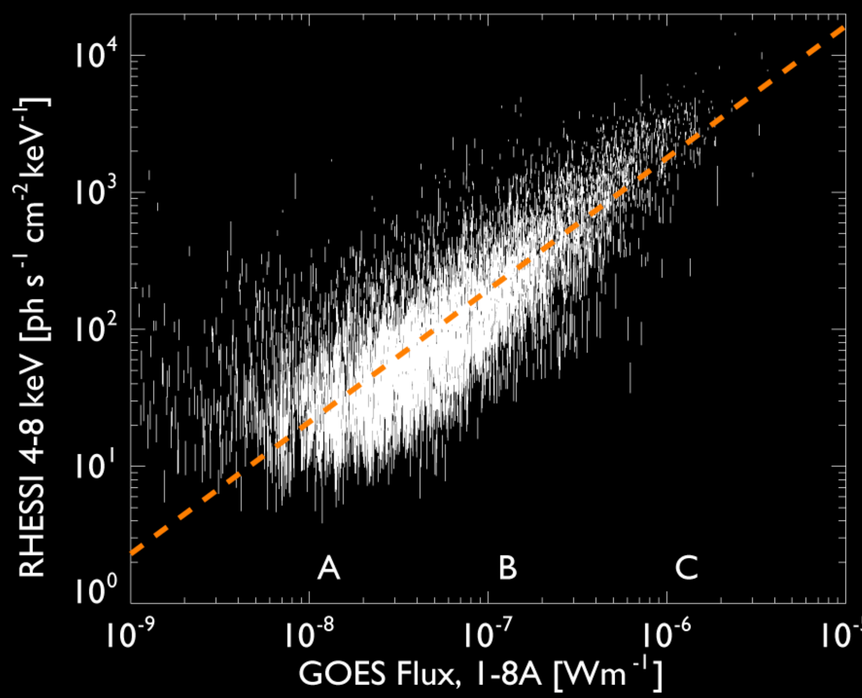
Assume width=depth , cylindrical volume

$$V \approx lw^2$$

Average volume=7.4×10^{26} cm^3

4-8 keV FWHM Flux

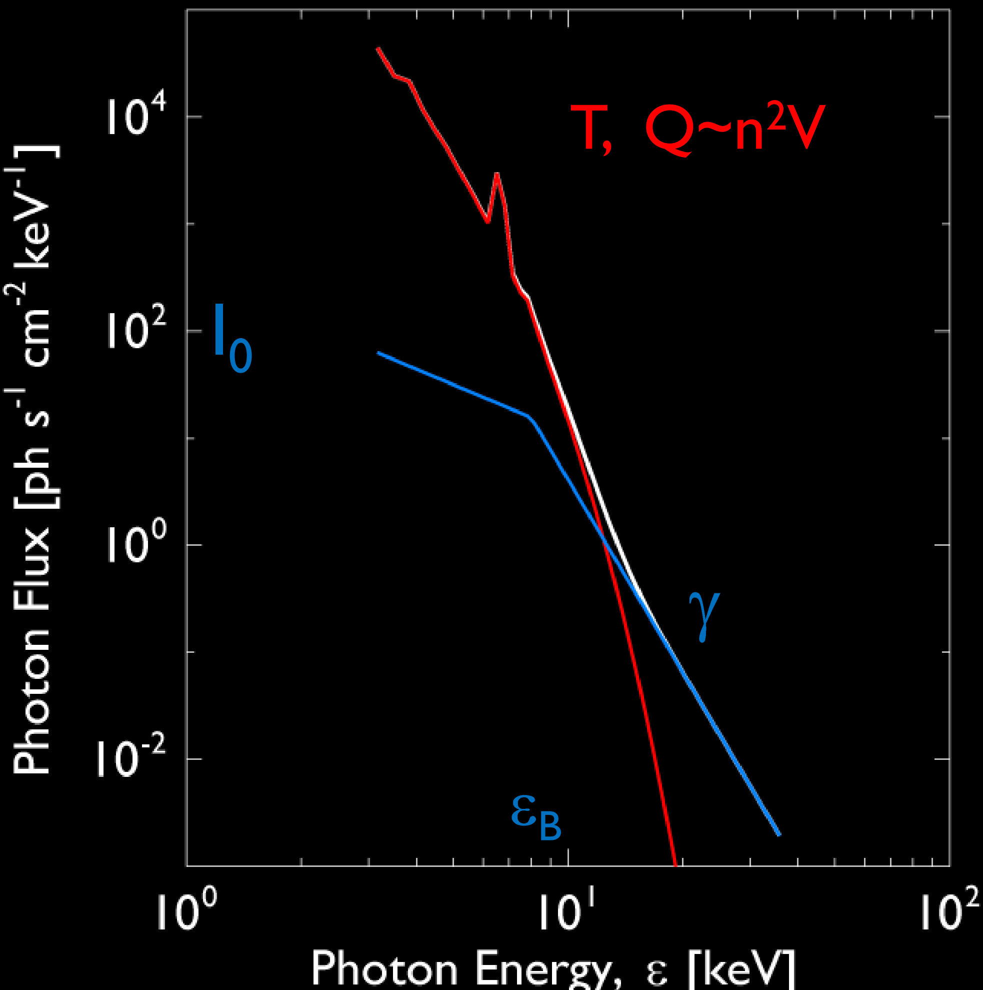




FWHM flux from Forward Fit is a power-law, similar behaviour to peak flux found in previous studies at higher energies (Crosby et al. 1993) Sensitivity range: about 5 to 5×10^3

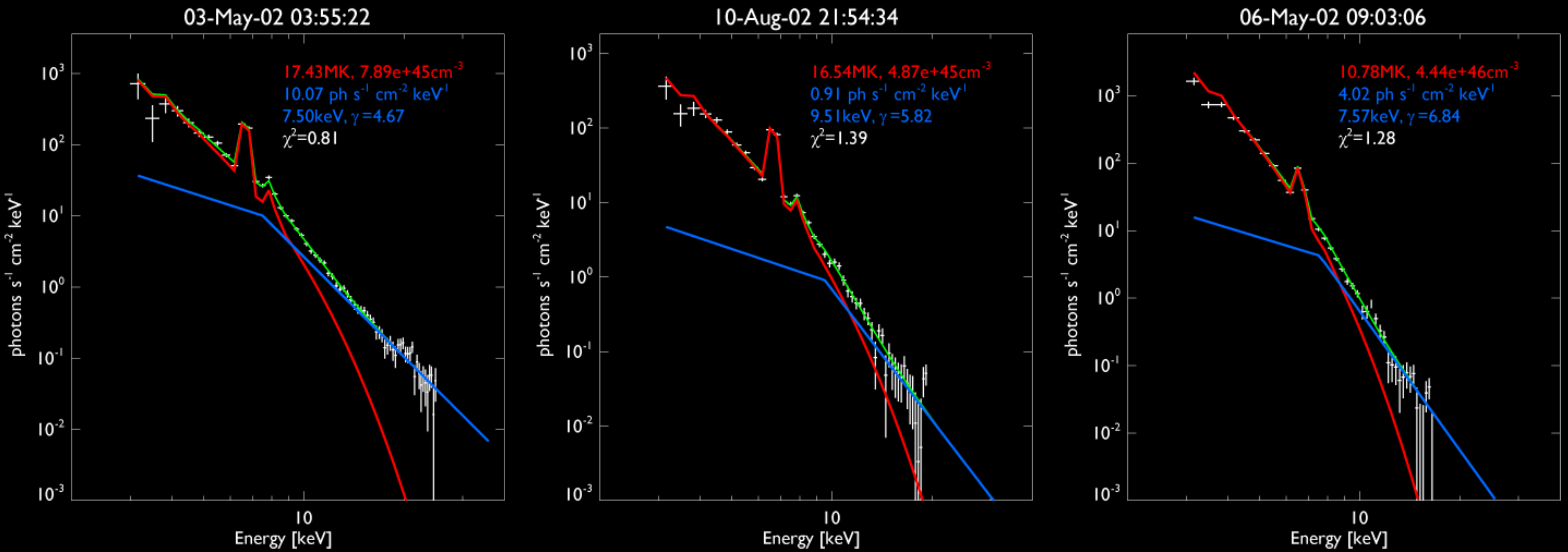
Correlation to background subtracted GOES flux 1-8A (softer x-rays) has power-law index~1

Spectrum fitting with OSPEX



- Fit thermal component plus non-thermal component
- Thermal is continuum and line features (CHIANTI)
  - Temperature and Emission Measure~n^2V
- Non-thermal is approximated with a broken power-law, with fixed index of -1.5 below break
  - Comparison to actual thick target spectrum later

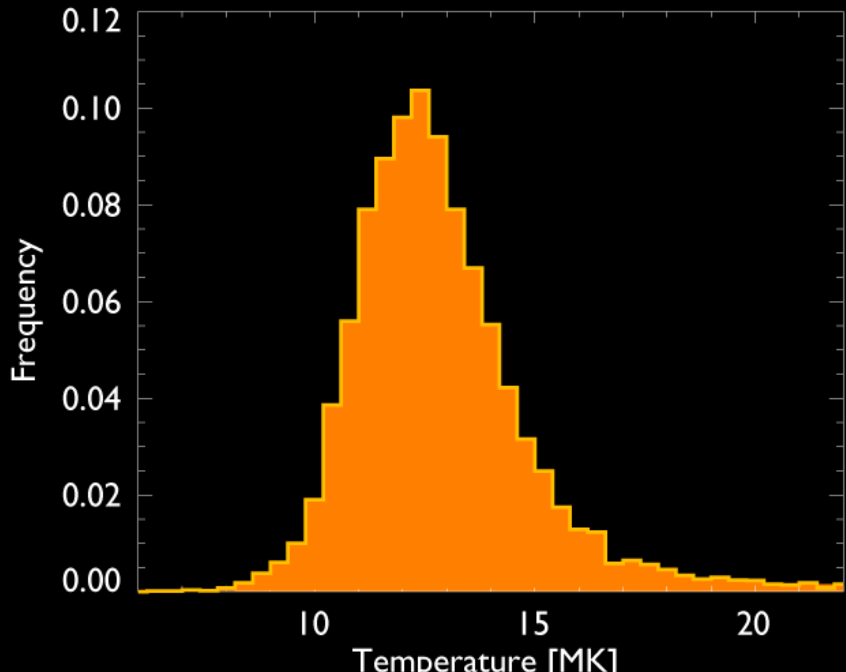
Example spectrum

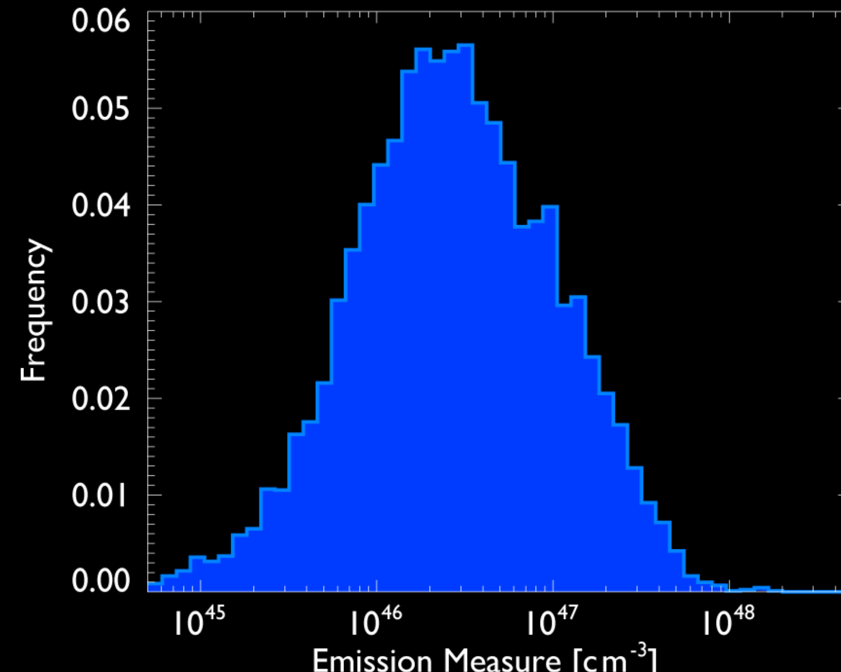


Get thermal >10 MK, presence of Fe K-shell about 7keV confirm >8MK

Steep non-thermal (steeper than large flares), with break down close to spectral features, making the fit tricky

Temperature & Emission Measure





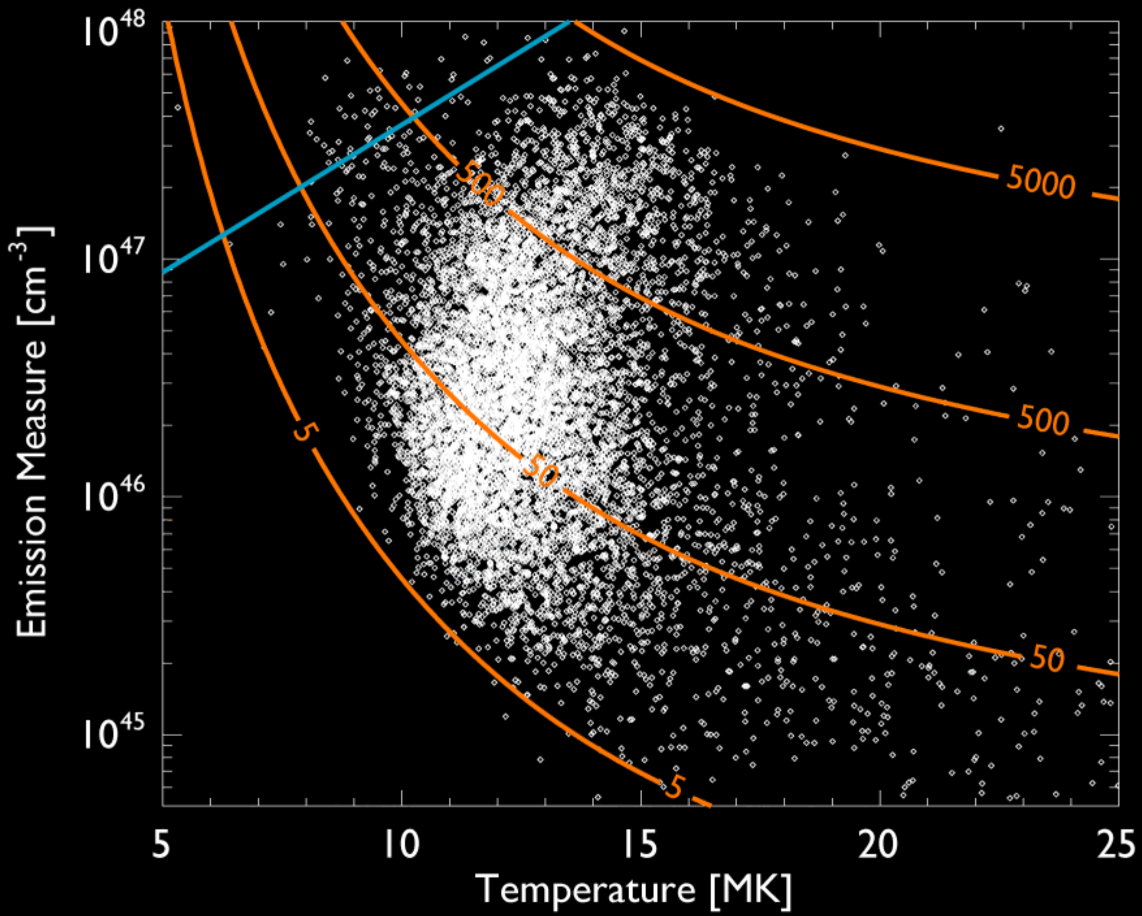
Average Temperature: 12.95 MK, majority between 10 to 16 MK

Average Emission Measure: 5.94×10^{46} cm^{-3}

Average Volume (7.4×10^{26} cm^{3}) implies electron density of 8.96×10^{9} cm^{-3}

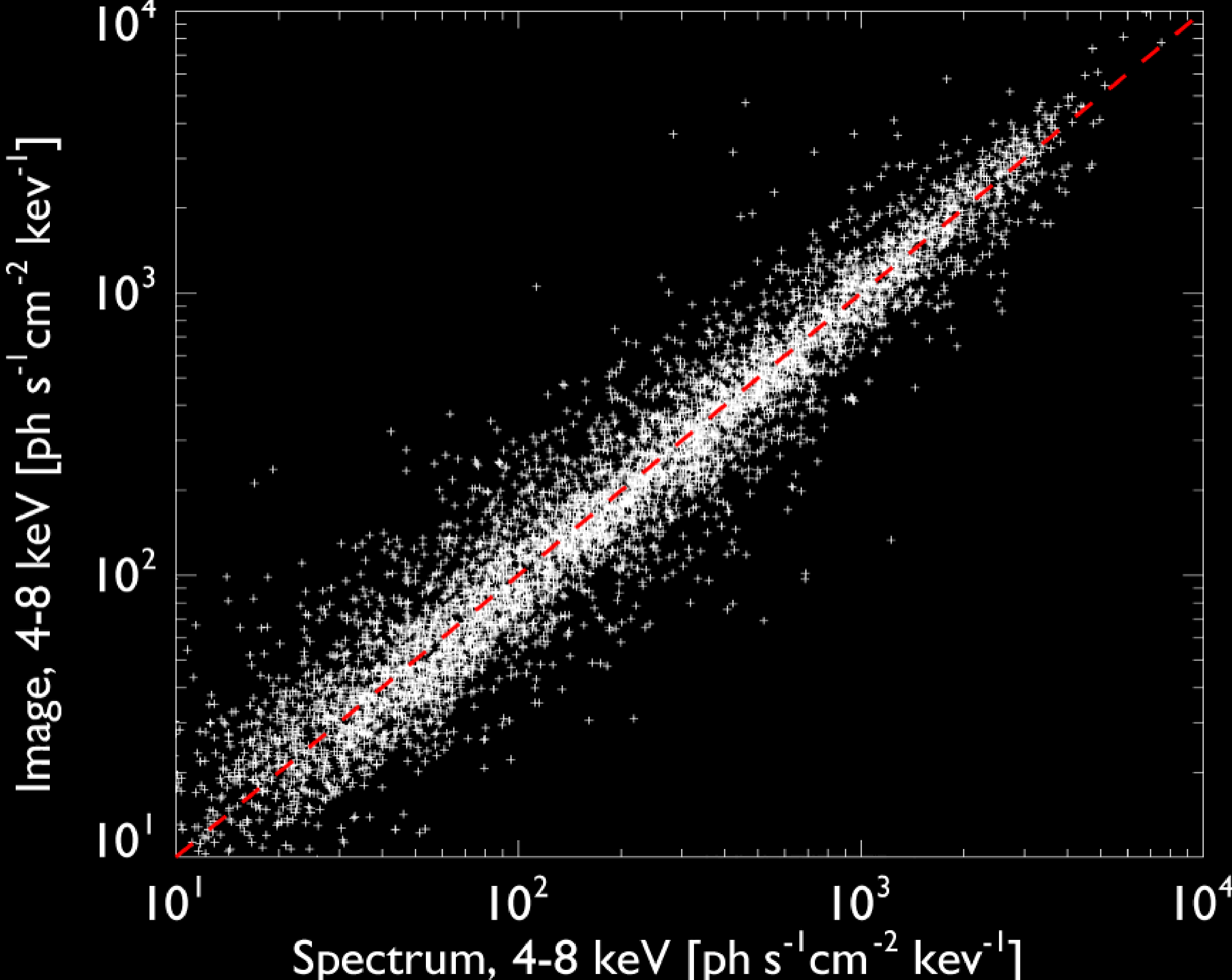
$$Q = \int n_{\mathrm{e}}^{2} \mathrm{d}V \approx n_{\mathrm{e}}^{2} V$$

Temperature vs Emission Measure

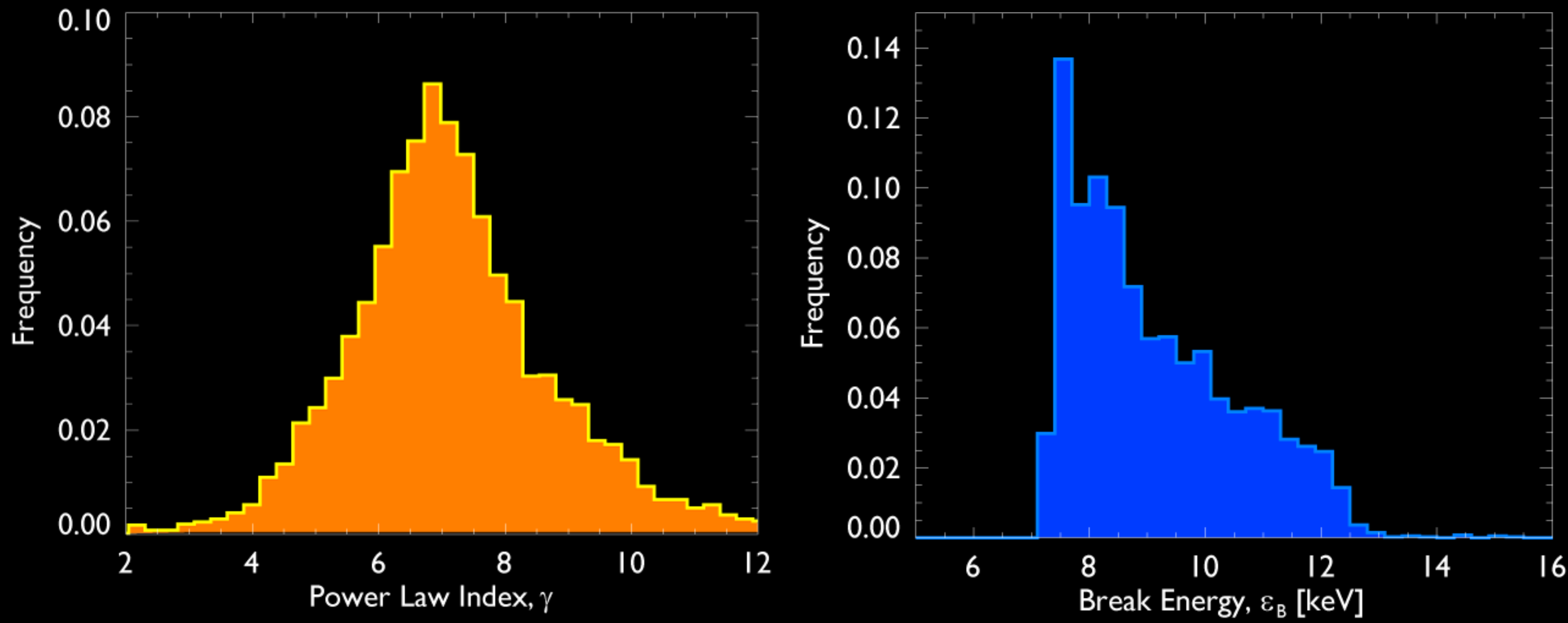


- No Correlation between Temperature and Emission Measure
- Feldman found the shown correlation using Yohkoh/BCS vs GOES (lower temperature/ energies)
- Overplotted contours for sensitivity range in 4-8 keV from imaging
  - Reasonable match

Important Consistency Check



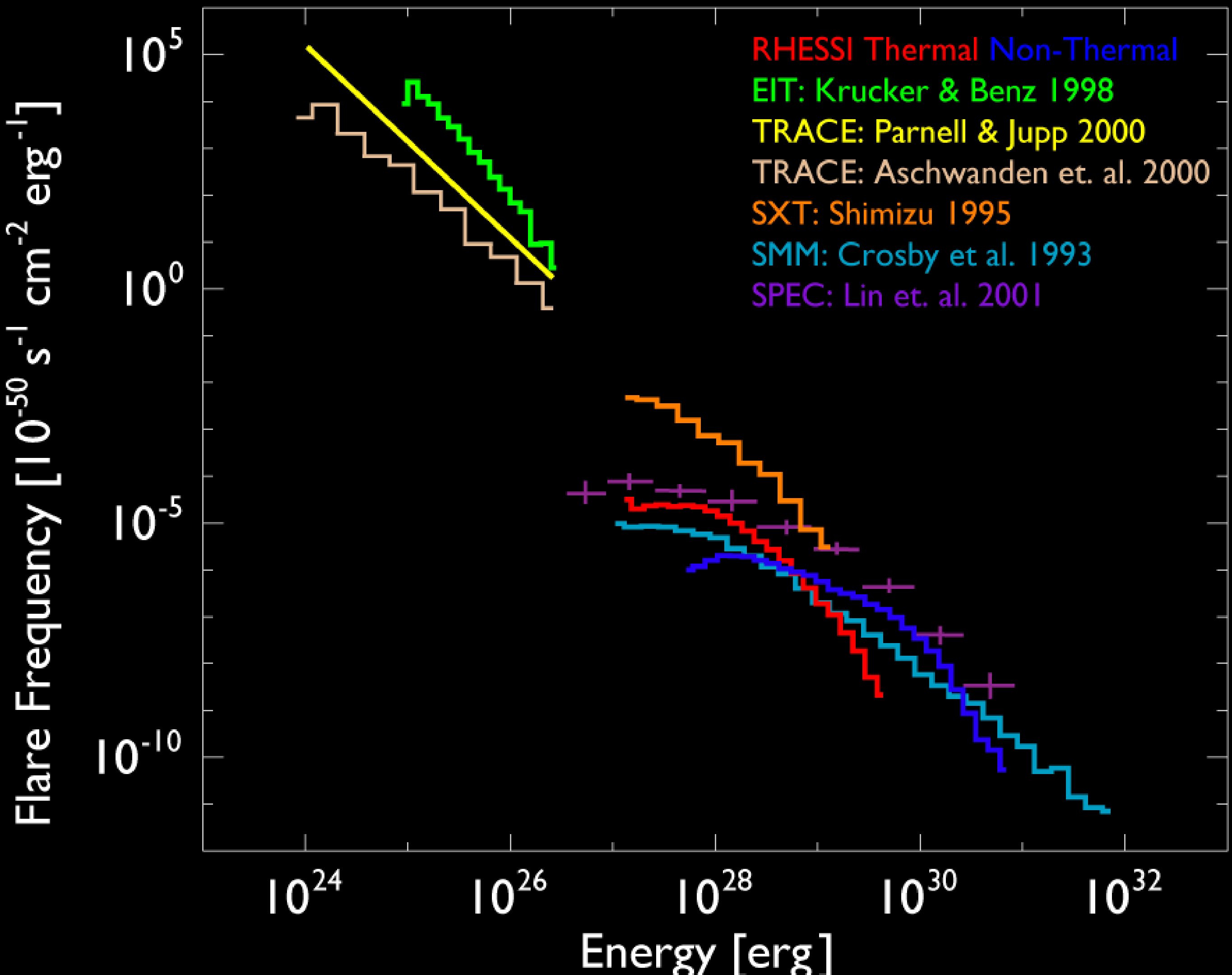
Power-law Index and Break



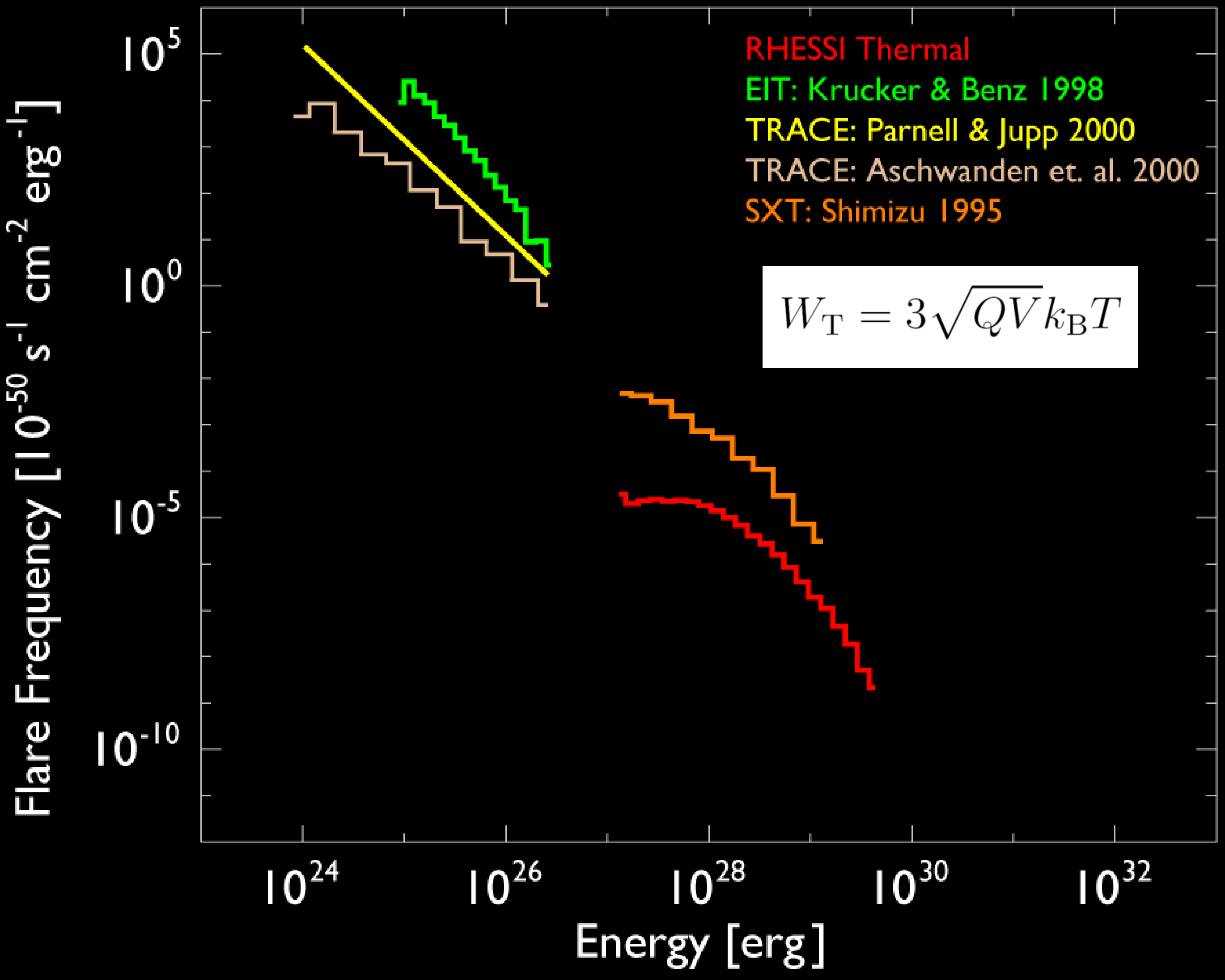
Average power-law index: 7.13, majority considerably steeper (bigger) than large flares

Average break energy: 8.74 keV, although peaking down towards 7 keV, where thermal + non-thermal harder to distinguish (not allowed to fit below 7 keV)

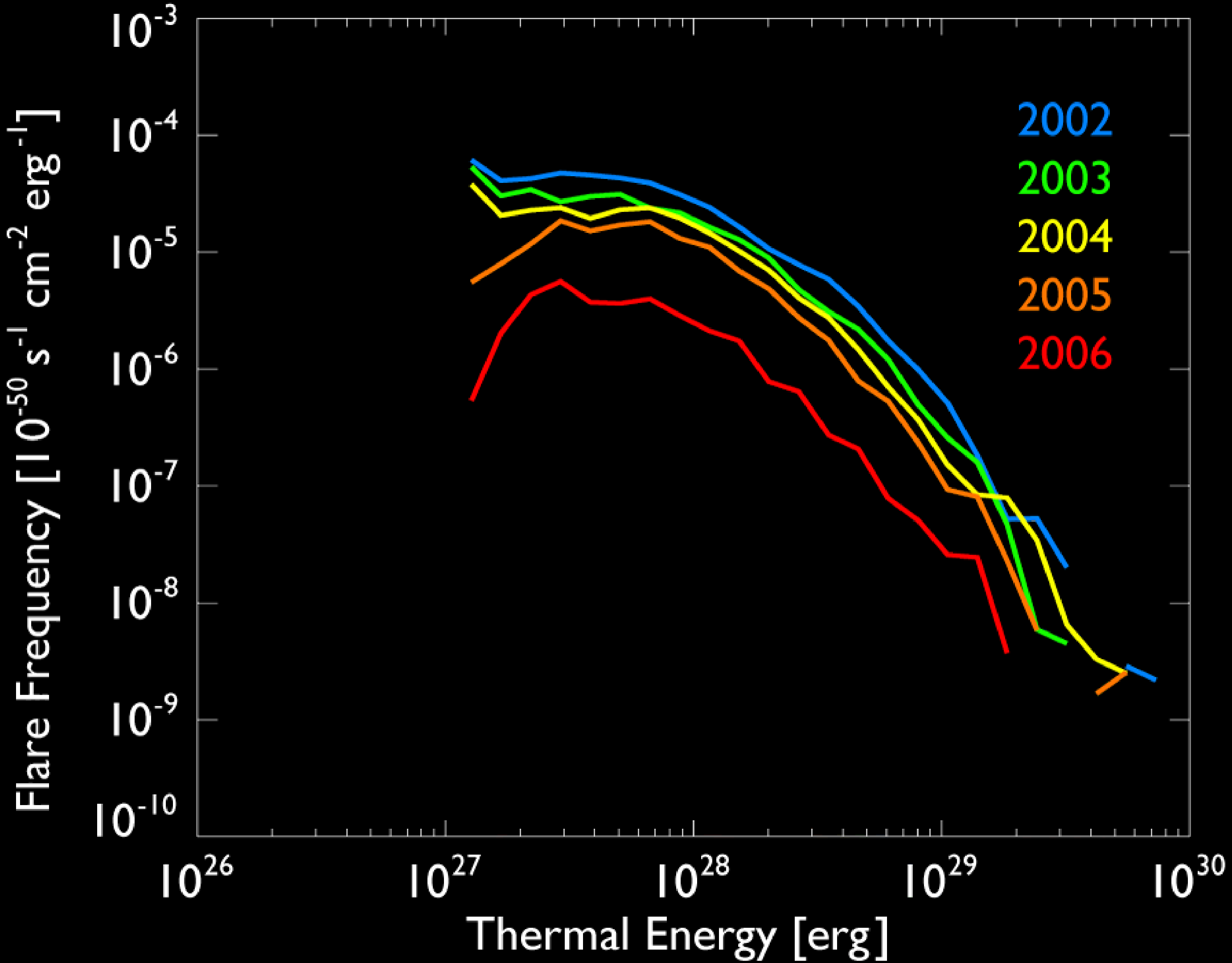
Flare Energy Distributions + RHESSI



Thermal Energy Distributions

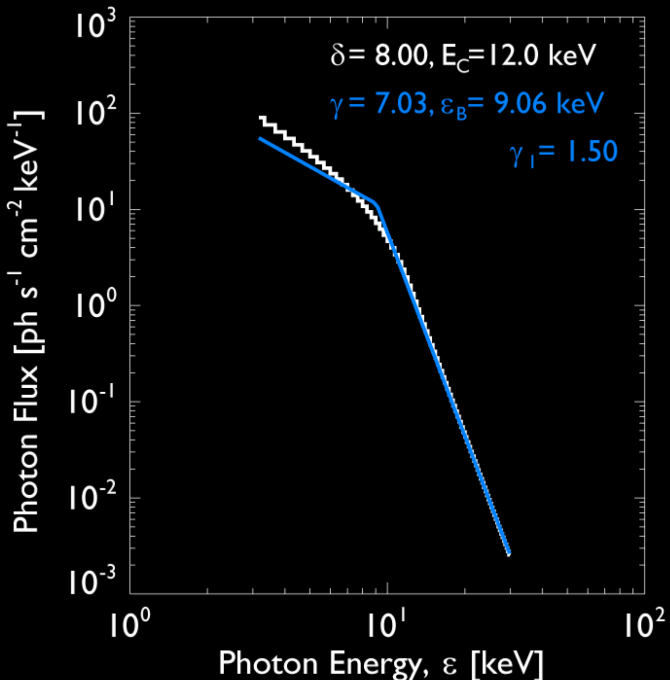


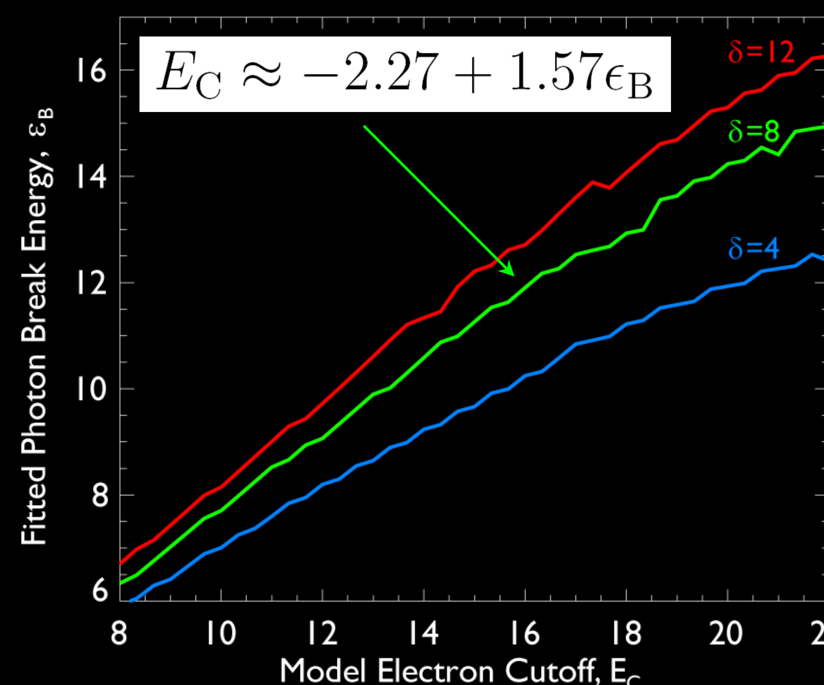
Thermal Distribution per Year



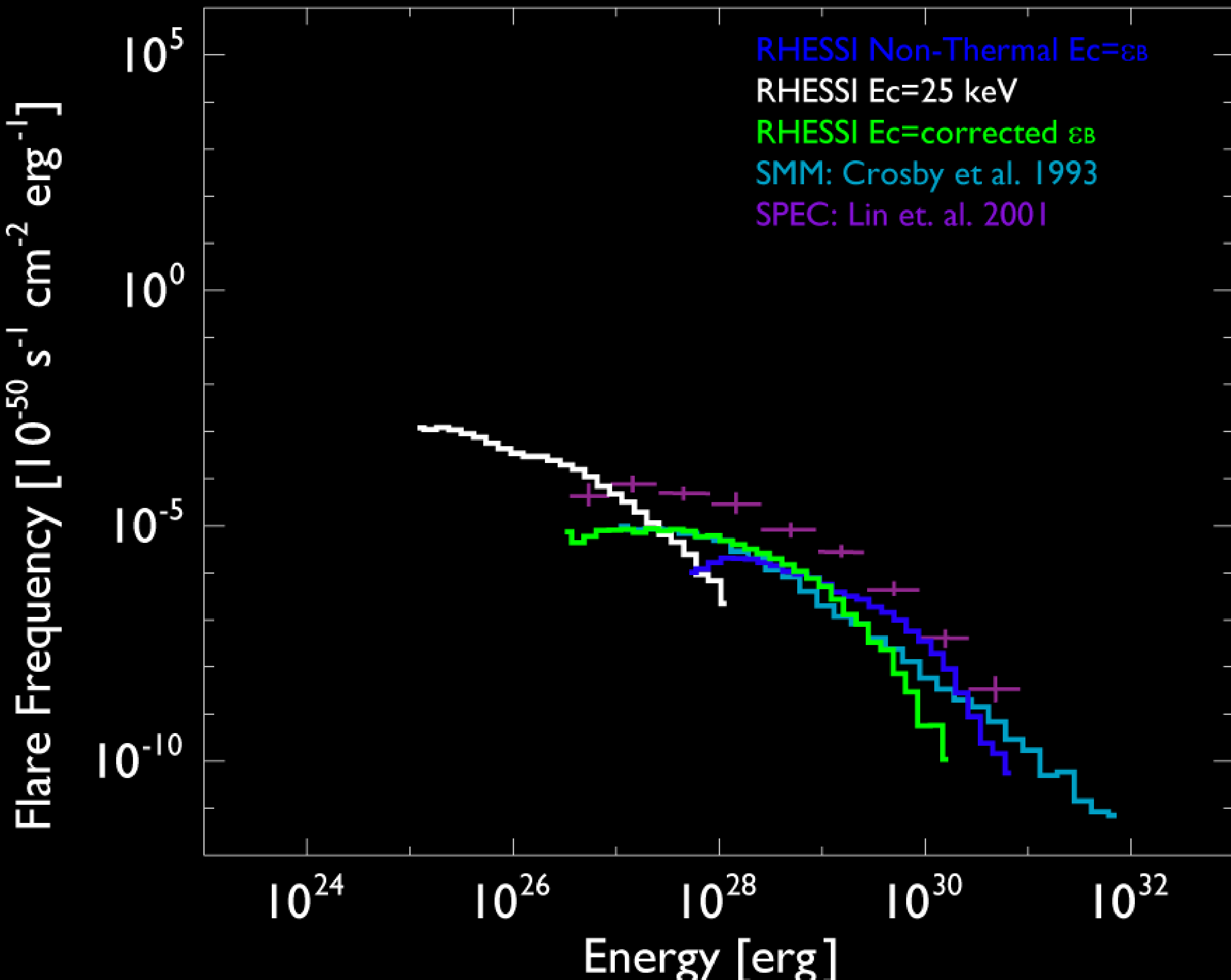
Fitting Power-law to Thick Target

- Taking $E_C = \varepsilon_B$ gives W_N upper limit as $\varepsilon_B > E_C$
- Previous instruments (Crosby et al. 1993) didn't observe down to ε_B so E_C (25 keV) was instrument limit
- Tested broken power-law fit to numerically found thick target as a function of E_C, δ

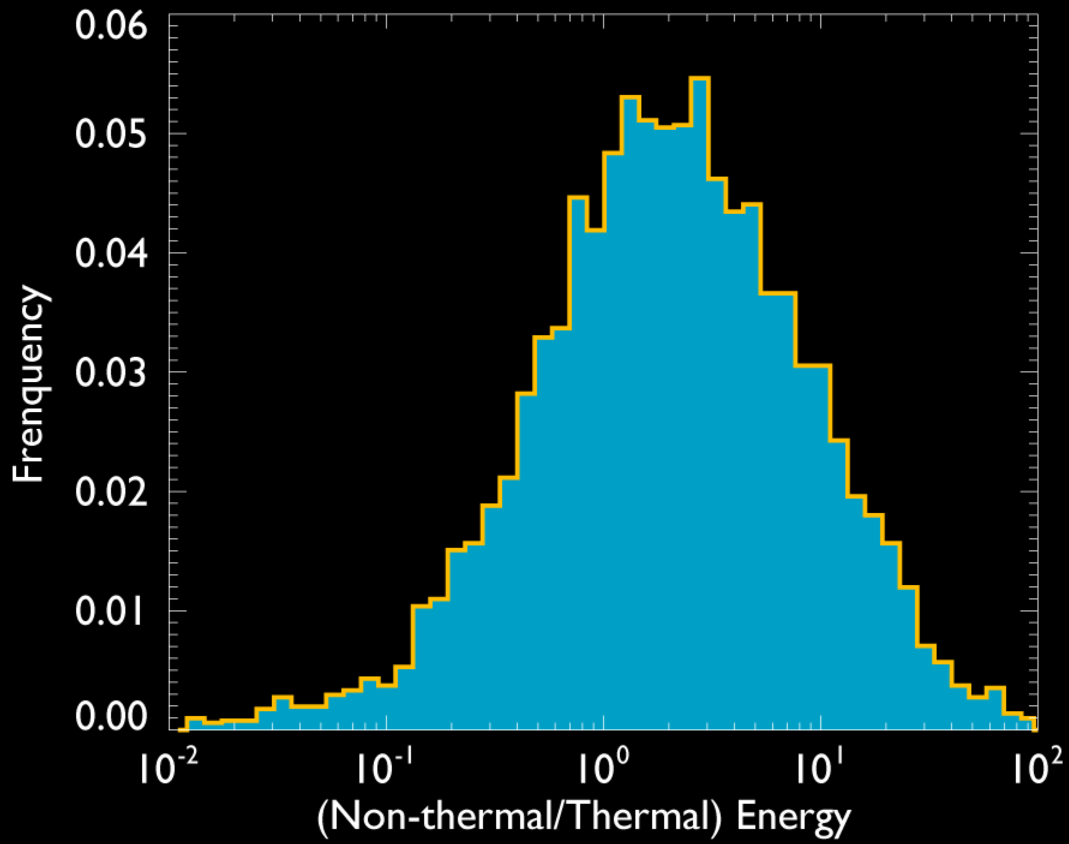




Non-thermal Energy Distributions



Ratio of Energies



- Microflares 6-12 keV peak time (% composition)
  - 50-80% Non-thermal
- Large flares
  - 10 % Non-thermal
    - Hudson & Ryan 1995
  - 10-50% Non-thermal
    - Lin & Hudson 1971, 1976
  - 50-66% Non-thermal
    - Saint-Hilaire & Benz 2005

Using W_N with $E_C=f(\varepsilon_B)$

Frequency Distribution Indices

- Fitted power-law to distributions using Parnell & Jupp (2000) Maximum Likelihood Method
- The "magic" numbers are:
  - W_T — 2.14 for > 1.19×10^{28} ergs
  - W_N ($E_C = \varepsilon_B$) — 2.24 for > 2.69×10^{29} ergs
  - W_N(E_C=25keV) — 1.96 for > 4.74×10^{26} ergs
  - W_N($E_C = f(\varepsilon_b)$) — 2.20 for > 4.48×10^{28} ergs

- Do we trust this ?
  - Not really clear power-laws
  - Low energy turn off due to missing events/sensitivity
  - High energy turn off due to missing event to detector dead-time/attenuators
  - Need to investigate the selection effect and fitting biases (future work)

Conclusions & Future Work

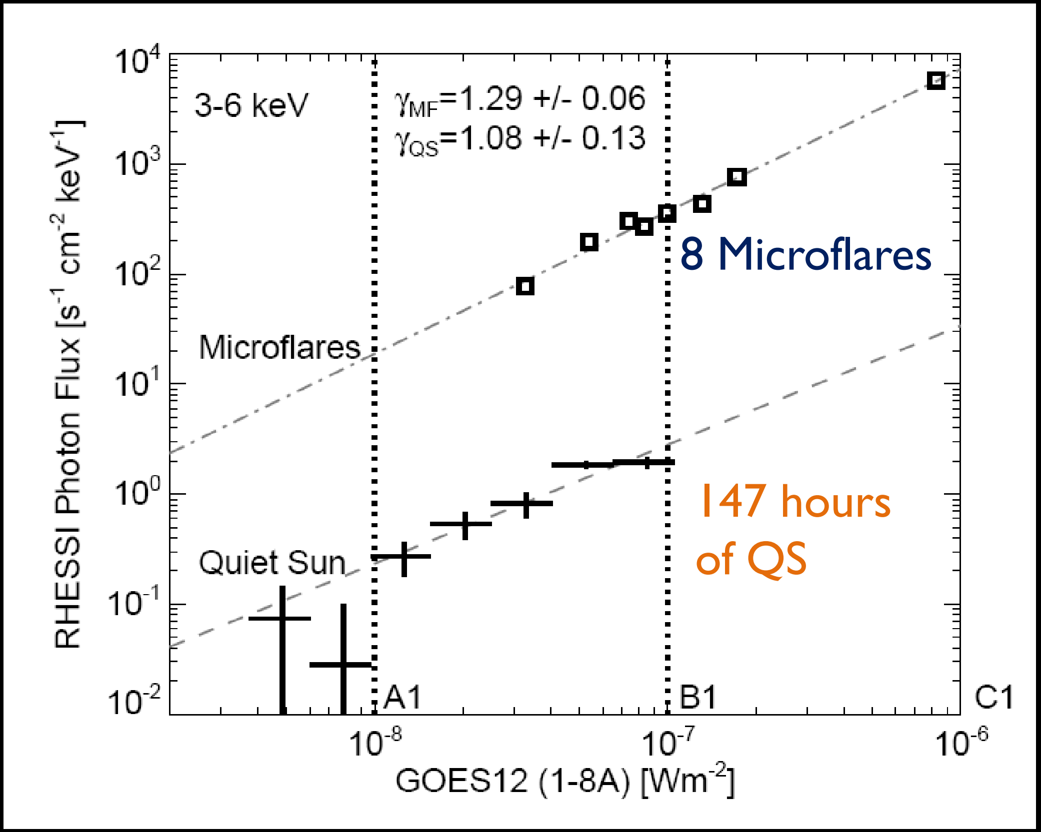
- RHESSI microflares are found as impulsive events in 6-12 keV, are C-Class and below and are Active Region phenomena.
  - Small in energy/flux but not necessarily spatial size
  - Non-thermal energy dominates
- Typical RHESSI Microflare:
  - Thermal Size (4-8 keV): 20" x 7", Volume 7.4×10^{26} cm^3
  - Temperature 12.95 MK, Emission Measure 5.94×10^{46} cm^{-3}
  - Power-law index 7.13, Break Energy 8.74 keV
  - Thermal energy 3.56×10^{28} ergs, Non-thermal energy 5.62×10^{28} ergs

- Investigate the selection effect and fitting biases
- Compare our microflare database to observations at other wavelengths: radio, euv, softer x-rays
  - SOHO, TRACE, STEREO & HINODE

penultimate slide

Observing smaller than micro

- Tricky as RHESSI designed for bright flares
  - Optimise analysis for small events only in 3-6 keV
  - Individual analysis instead of automation?
- Alternative: weak emission from full disk during quiet times
  - Fan-beam modulation technique (Hannah et al. 2007)
  - Correlation with GOES similar to microflares but 2 orders of magnitude smaller
  - Ensemble of XBPs/nanoflares ?



(Hannah et al. 2007)