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Tuesday 16:30-17:00

Particle Acceleration and Energy Release in RHESSI Era

Kontar, E.
University of Glasgow

Since high energy emission (X-rays and gamma-rays) represents optically-thin radiation from energetic particles, it is a relatively straightforward, and hence extremely valuable, tool in the diagnostic study of flare-accelerated electrons and ions at the Sun. The observed X-ray/gamma-ray flux is fundamentally a convolution of the cross-section for the emission process(es) in question with the distribution function(s) of accelerated particles, which are in turn functions of energy, direction, spatial location and time. To address the key problems of particle acceleration, propagation as well as energy release one needs to infer as much information as possible on the particle distribution function, through a de-convolution of this fundamental relationship.

This review presents recent observational progress toward the understanding of energy release and particle acceleration using spectroscopic, imaging and polarization measurements, primarily from the Ramaty High Energy Solar Spectroscopic Imager (RHESSI). Previous conclusions regarding the energy, angular (pitch angle) and spatial distributions of energetic electrons and ions in solar flares are critically reviewed. The diagnostics of radiation processes, particle transport, and acceleration, using both spectroscopic and imaging techniques will be discussed. The unprecedented quality of the RHESSI data in combination with novel data analysis techniques have revealed previously unknown details of energetic particle distributions and imposed new challenging constraints on the particle acceleration.

PARTICLE ACCELERATION AND ENERGY RELEASE IN RHESSI ERA

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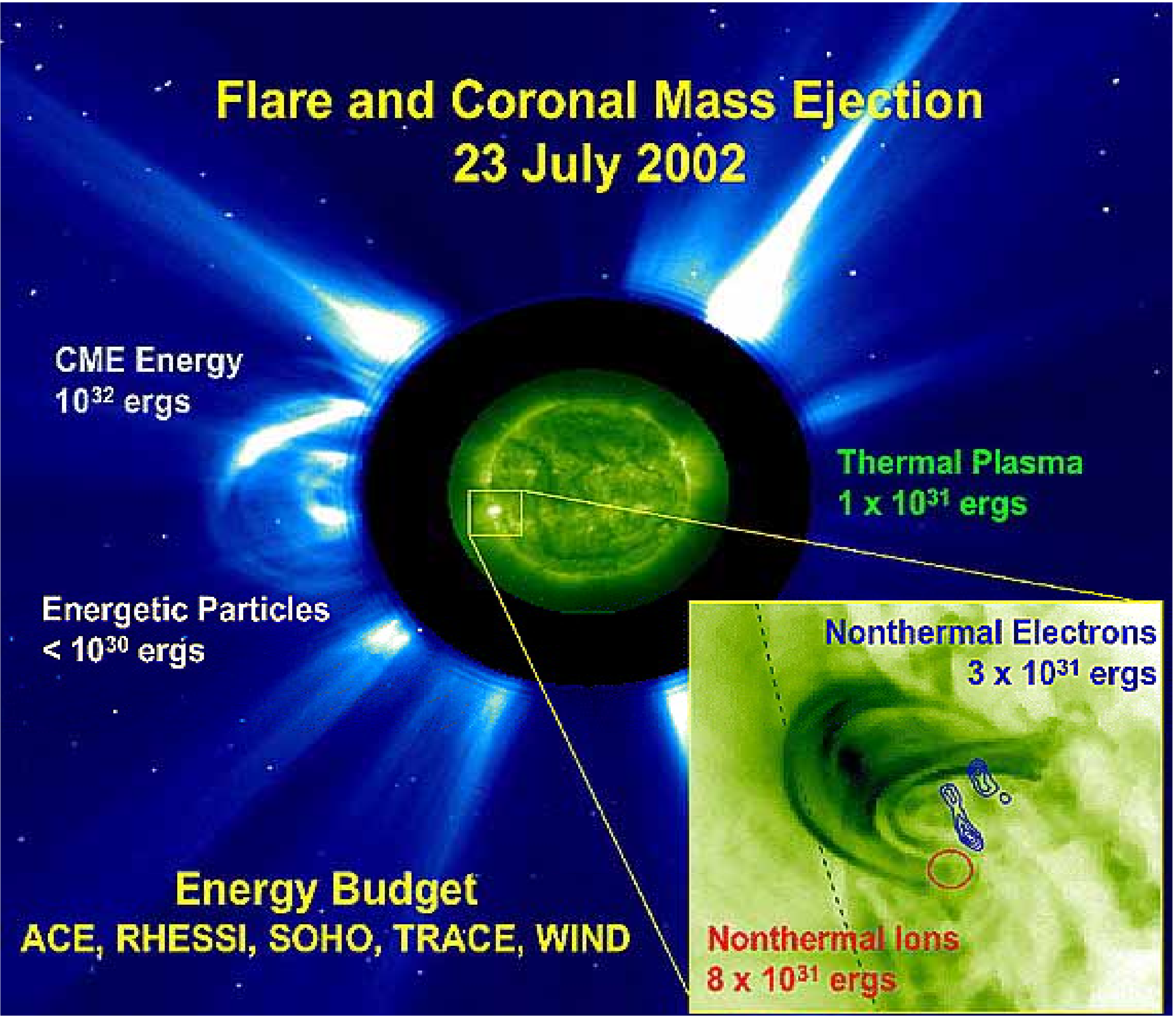
12th European Solar Physics Meeting, Freiburg, Germany

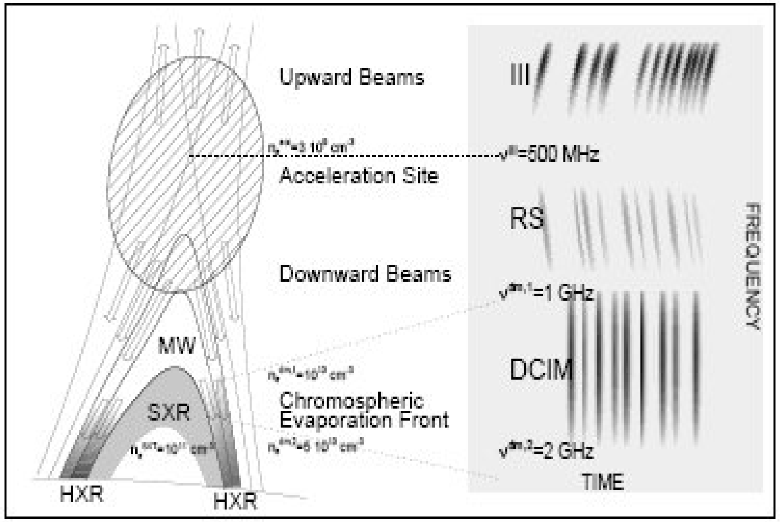
Solar flares and accelerated particles



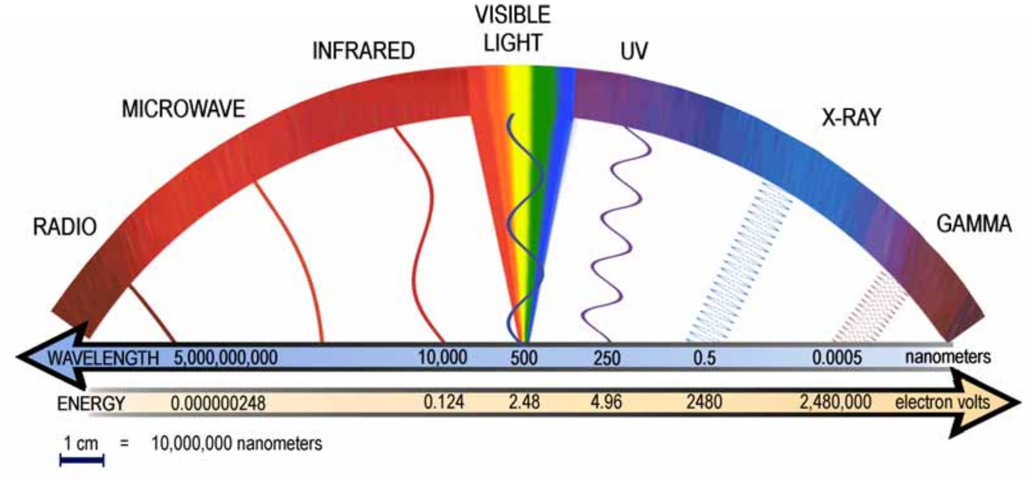
From Emslie et al., 2004

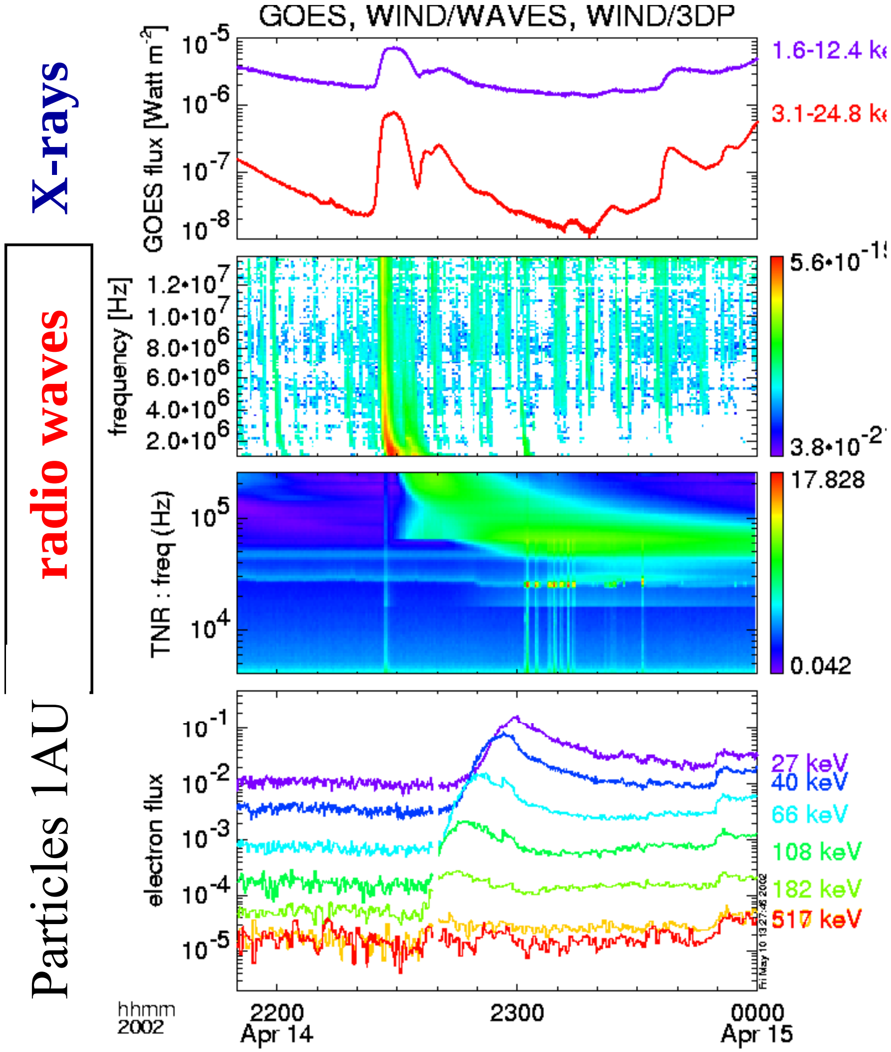
Free magnetic energy ~2 10^{32} ergs

Observations of energetic particles



Aschwanden and Benz, 1997





Krucker et al, 2001

Observations of energetic particles

Solar corona T ~ 10^6 K => 0.1 keV per particle

Flaring region T ~ 4×10^7 K => 3 keV per particle

Flare volume 10^{27} cm^3 => $(10^4\ \mathrm{km})^3$

Plasma density $10^{10}\ \mathrm{cm}^{-3}$

Photons up to > 100 MeV

Electron energies >10 MeV

Proton energies >100 MeV

Number of energetic electrons 10^{36} per second

Typical timescale < 0.1 sec

Particle spectrum is a power-law (or combination of a few)

Anti-correlation between spectral index and particle flux

Enhanced abundances of ions

Acceleration of ions/electron in different locations?

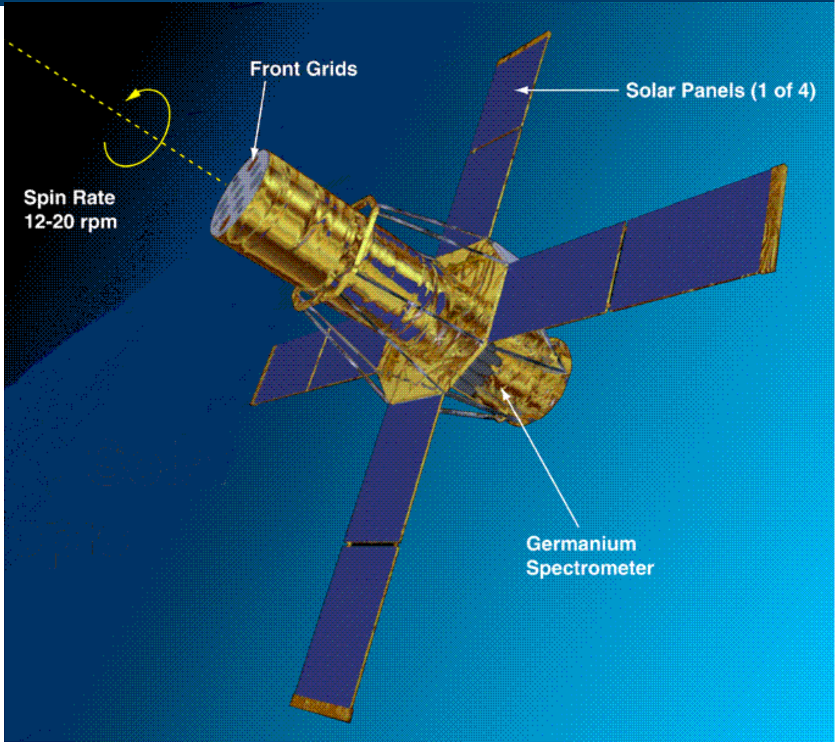
Large solar flare releases about 10^{29} ergs/s

(about half energy in energetic electrons)

1 megaton of TNT is equal to about 4×10^{22} ergs.

What is RHESSI?

Ramaty
High
Energy
Solar
Spectroscopic
Imager



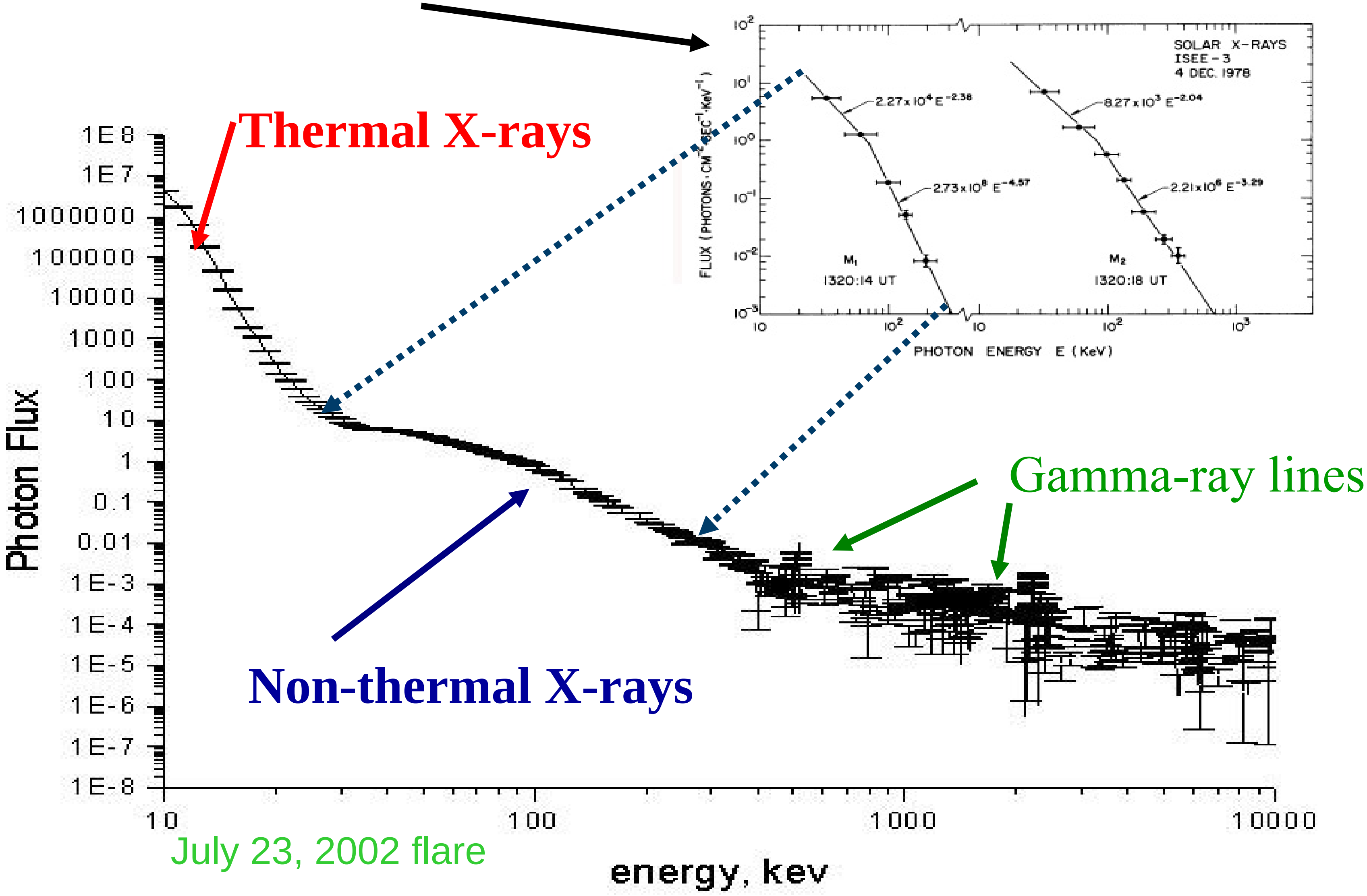
is a NASA-led mission launched in ***February 2002***

RHESSI is designed to investigate particle acceleration and energy release in solar flares through imaging and spectroscopy of hard X-ray and gamma-rays in the range from 3 keV up to 17 MeV (Lin et al 2002).

Spectroscopy: 9 Ge detectors with energy resolution around 1 keV; **Imaging:** rotating modulating collimators allowing angular resolution down to 2.3 arcsec; **Imaging spectroscopy**

X-ray spectrum of solar flares

pre-RHESSI X-ray spectra (Kane et al, 1982)



Thermal X-rays

Gamma-ray lines

Non-thermal X-rays

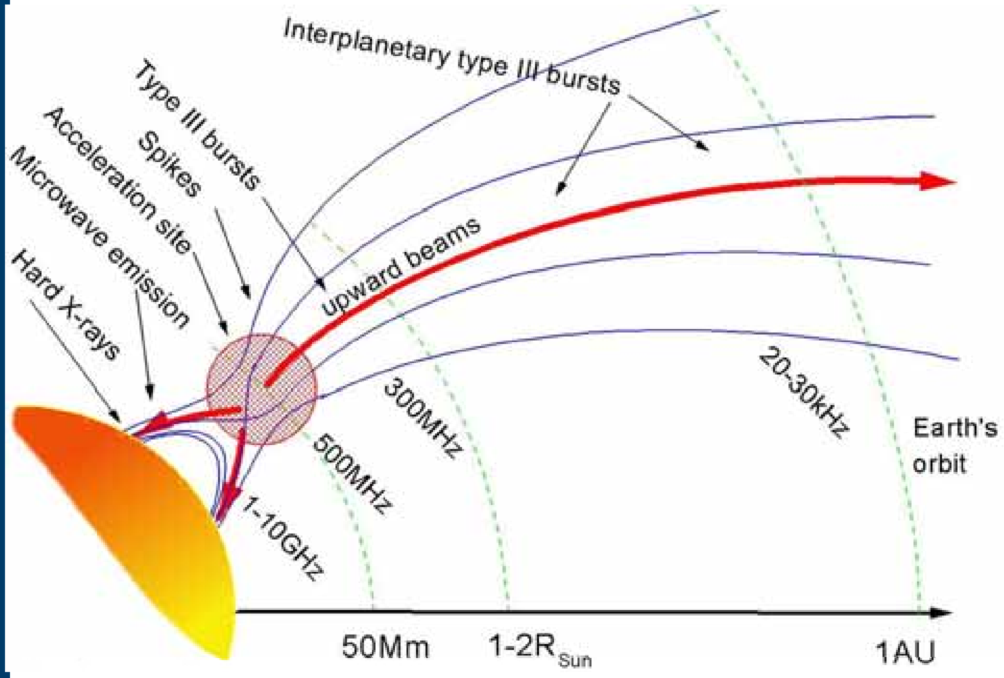
July 23, 2002 flare

Ramaty **H**igh **E**nergy **S**olar **S**pectroscopic **I**mager (**RHESSI**) spectrum

X-rays and flare accelerated electrons

Observed X-rays | Unknown electron distribution | Emission cross-sections

$$I(\epsilon,\mathbf{\Omega},t)=\int_{\ell}\int_{\Omega'}\int_{\epsilon}^{\infty} n(\mathbf{r})\bar{F}(E,\mathbf{\Omega}',\mathbf{r},t)Q(\mathbf{\Omega},\mathbf{\Omega}',\epsilon,E)\,\mathrm{d}E\,\mathrm{d}\mathbf{\Omega}'\,\mathrm{d}\ell,$$



$F(E,\mathbf{\Omega},\mathbf{r})=???$

1) What is the ***energy*** distribution, $F(E)$?

2) What is the ***angular*** distribution, $F(E,\mathbf{\Omega})$?

3) What is ***spatial*** distribution, $F(E,\mathbf{r})$?

X-ray emission processes

For spatially integrated spectrum:
$$I(\epsilon) = \frac{1}{4\pi R^2}\,\overline{n}V \int_{\epsilon}^{\infty} \overline{F}(E)\,Q(\epsilon, E)\,dE,$$

Thin-target case: For the electron spectrum **$F(E) \sim E^{-\delta}$** ,

a) Electron-ion bremsstrahlung (free-free emission)

Dominant process for energies ~10 – 400 keV

the photon spectrum is **$I(\varepsilon) \sim \varepsilon^{-\delta-1}$**

In the simplest form Kramers’ approximation:
$$Q(\epsilon, E) = Z^2 \frac{\sigma_o}{\epsilon E},$$

b) Electron-electron bremsstrahlung (free-free emission)

Dominant process for energies above 400 keV

the photon spectrum is **$I(\varepsilon) \sim \varepsilon^{-\delta}$**

c) Recombination emission (free-bound emission)

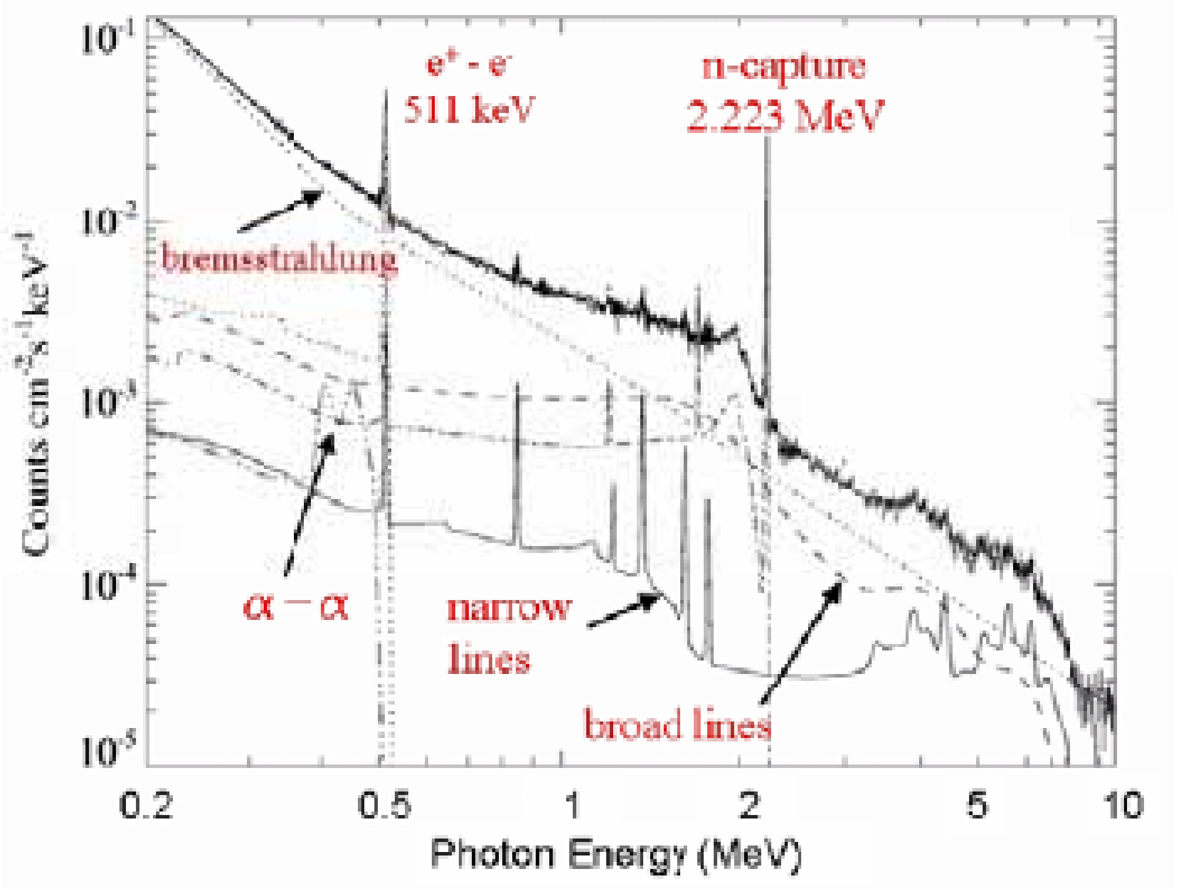
Could be dominant process for energies up to 20 keV

the photon spectrum is **shifted by ionisation potential** and **$I(\varepsilon) \sim \varepsilon^{-\delta-2}$**

(The process requires high temperatures and detailed ionisation calculations)

gamma-ray emission processes

From Murphy and Share, 2004



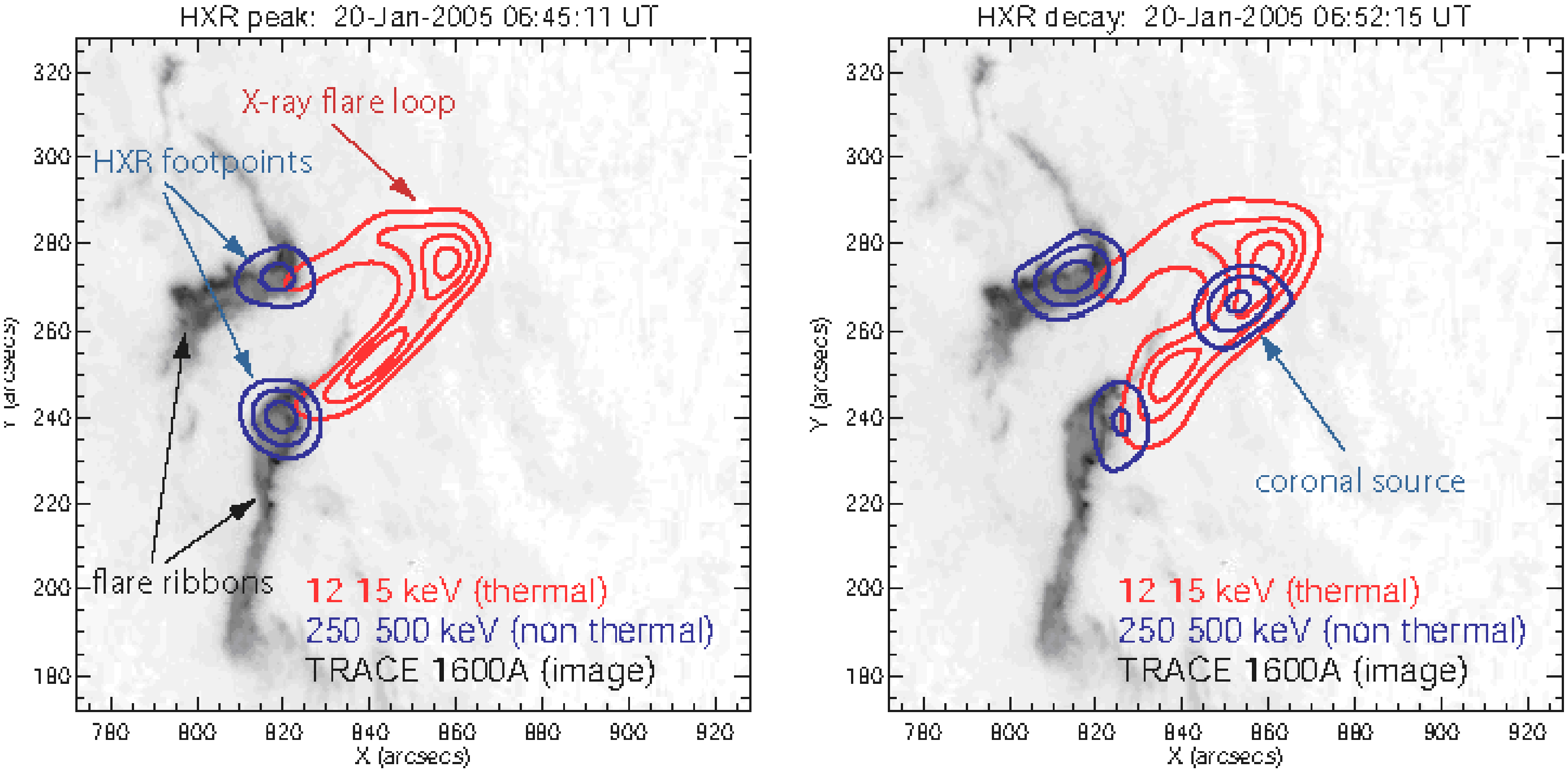
a) narrow-gamma lines

Accelerated protons and alpha particles

b) broad-gamma lines and gamma-ray-continuum

Accelerated heavy ions and unresolved lines and Compton scattering

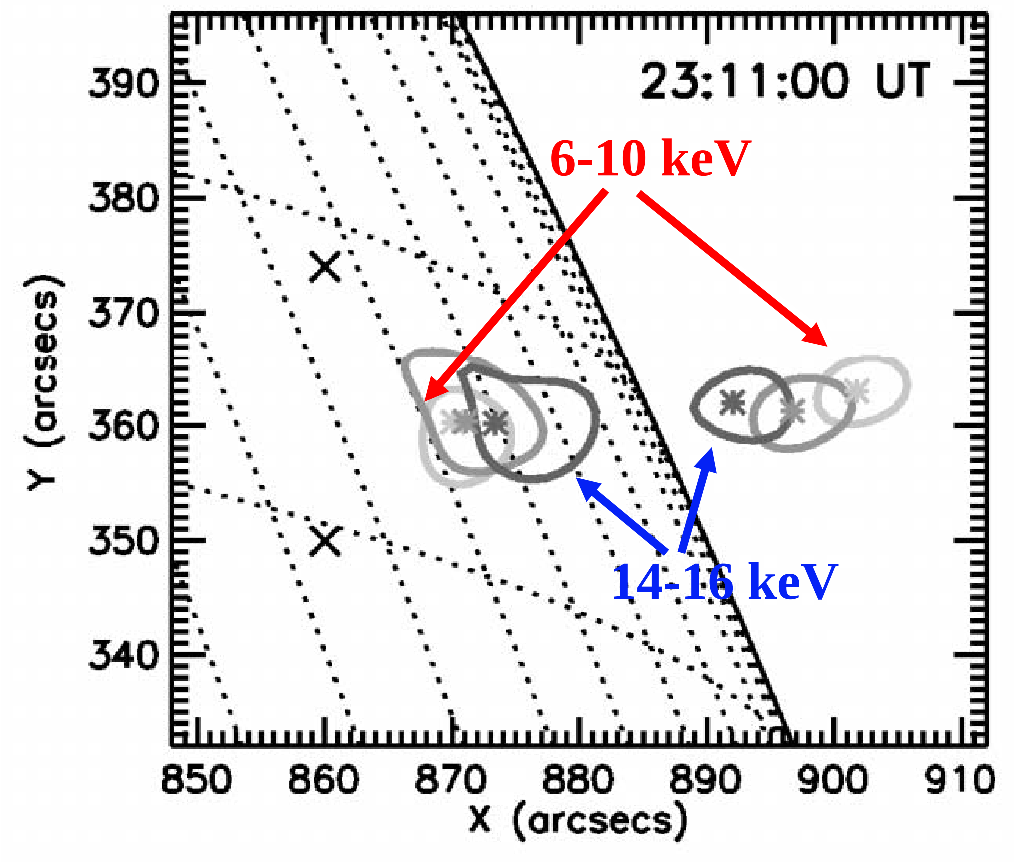
Location of X-ray sources



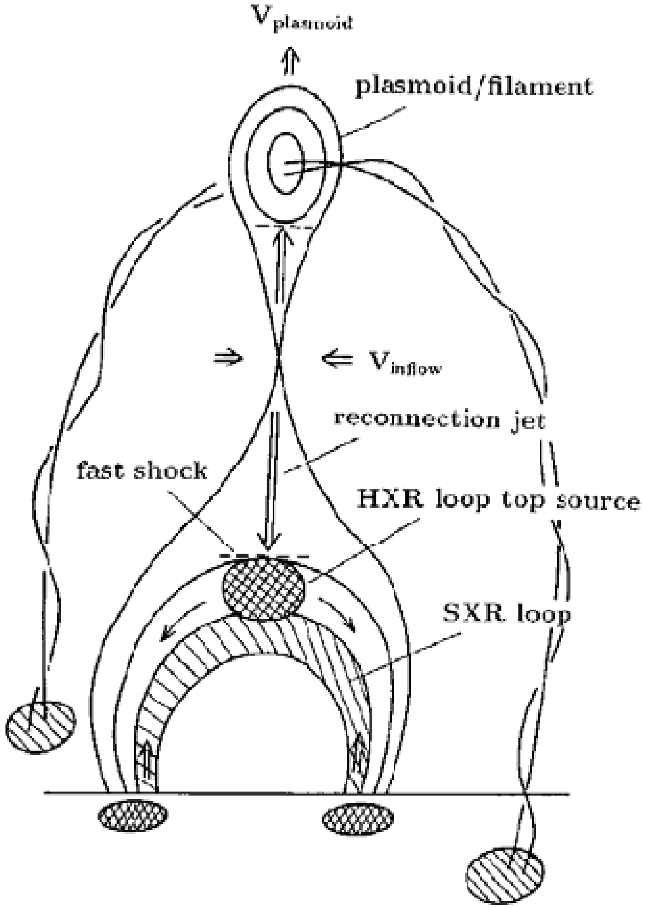
Krucker et al, 2007

Solar flare geometry in X-rays:
Soft loop-top source and hard X-ray footpoints (Krucker & Lin 2002; Emslie et al, 2003)
What is the origin of nonthermal coronal X-ray sources?

Location of energy release



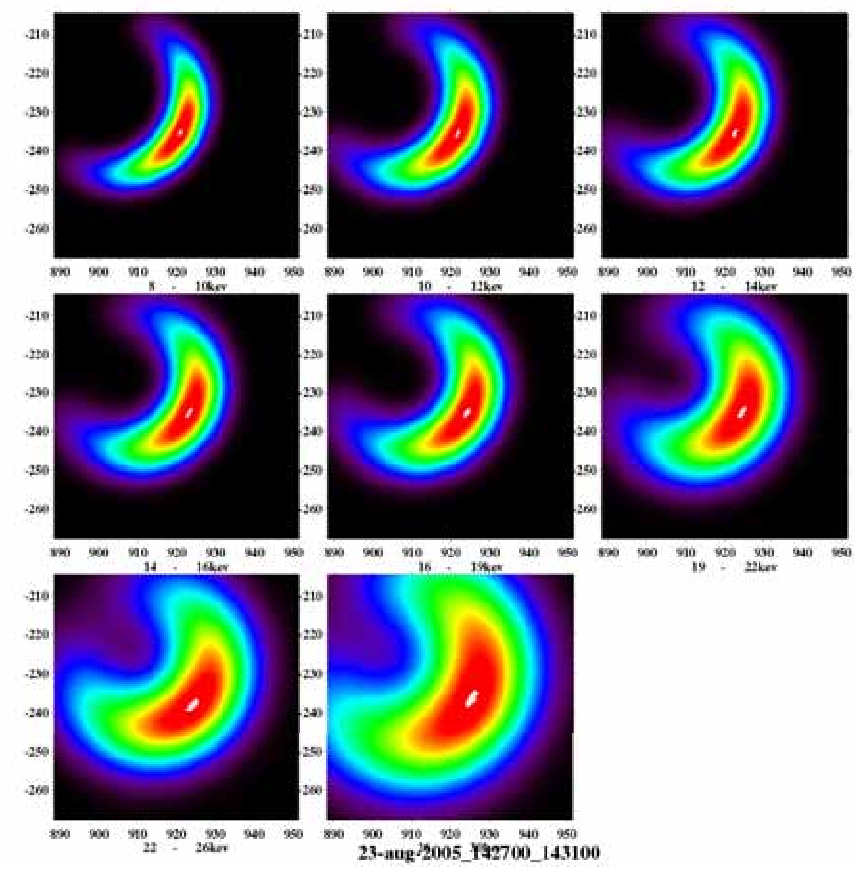
Liu et al, 2004



Shibata, 1996

Do we observe magnetic reconnection?

Location of energy release



From Xu et al, 2007, Emslie et al, 2008

Number **of particles in acceleration region**

$$N = n\,A\,(2L)$$

Hard X-ray intensity I(ε) is proportional to the *rate of injection* of electrons at energy $E_o > \varepsilon$:

$$dN/dt\,(> \varepsilon) \sim 10^{34}\, I(\varepsilon)$$

Specific acceleration rate

$\gamma = (1/N)\, dN/dt$ (***particles*** s^{-1} ***per particle***)

Acceleration rate

$$E_D = \frac{e^3 n_e \ln \Lambda}{6\pi \varepsilon_0^2 kT}$$

Dreicer field
(Dreicer, 1959)

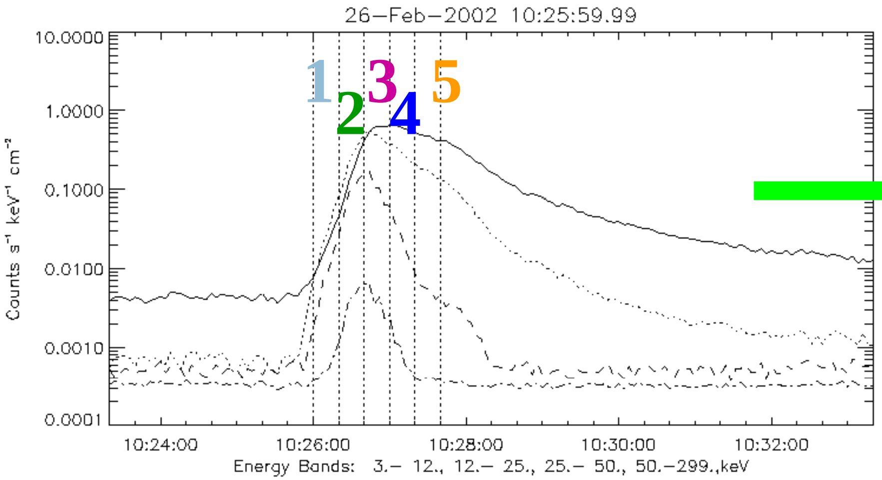
The size and density of the acceleration region, plus the hard X-ray brightness, can be used to determine the specific acceleration rate (particles s^{-1} $particle^{-1}$) – values are ~ (0.1 – 5) × 10^{-3}

Consistency with sub-Dreicer models (e.g. Kuijpers (1981), Heyvaerts (1981), Holman (1985), etc) require a very narrow range of accelerating electric fields

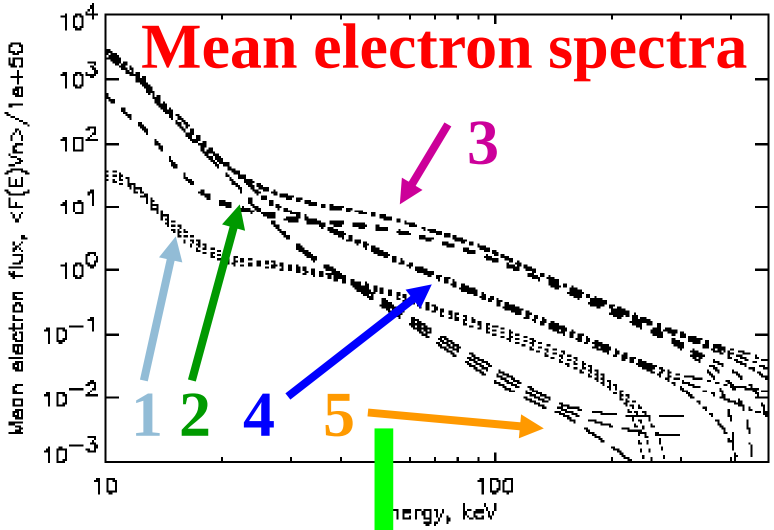
For super-Dreicer current sheet acceleration (e.g. Martens (1998), Litvinenko (1996, 2003), Fletcher & Petkaki, 1997, Mori et al, 1998, Browning & Dalla, 2007), the specific acceleration rate is determined by the aspect ratio of the current sheet.

For stochastic acceleration models (e.g. Miller 1991 etc), values for the specific acceleration rate are generally consistent with the data, but more simulations are needed.

From X-rays to electrons

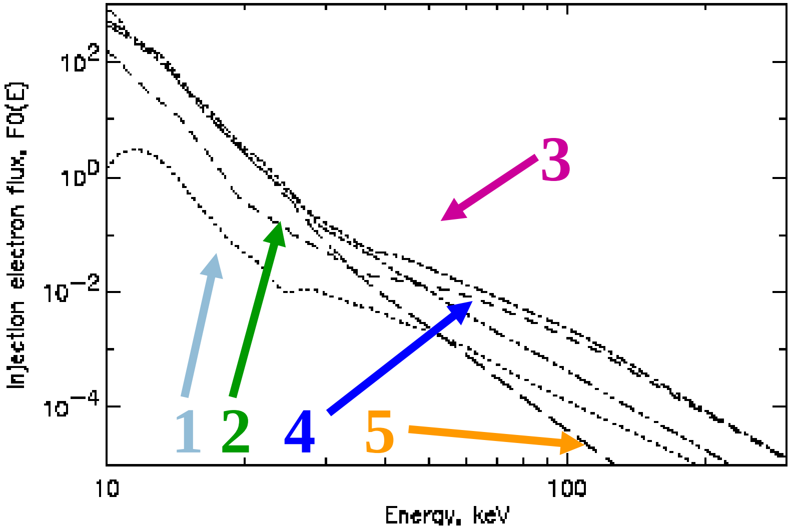


(Model independent)


Mean electron spectra

(Model dependent)

Accelerated (injected) spectra



-Deviations from power-laws; Spectral features inconsistent with simple models

- High/low energy cutoffs in the electron spectra

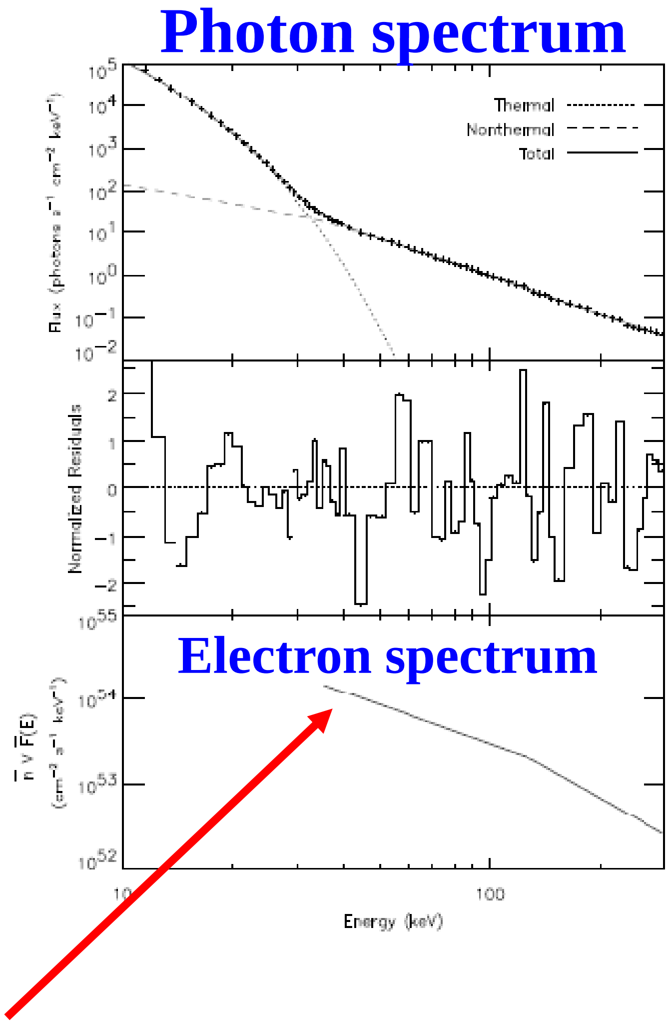
-Possibility to study acceleration and propagation effects on non-uniform plasma ionisations, return currents, etc

Low energy cutoffs

- Requiring that the assumed thermal emission dominates over non-thermal emissions, Sui *et al.* (2005) and that a low energy cutoff of > 24 keV should be present.

- Assuming "theoretical Neupert effect" to be satisfied, Veronig *et al.* (2005) conclude that the low-energy cutoffs should be between 10 keV and 30 keV for four flares analysed in their paper.

- Hannah *et al.* (2008) have used an empirical relation between the observed parameters of the photon power-law and the low-energy cutoff of the electron distribution, and have found that the low-energy cutoffs in 25000 microflare events could range from 9 to 16 keV with the median being around 12 keV.

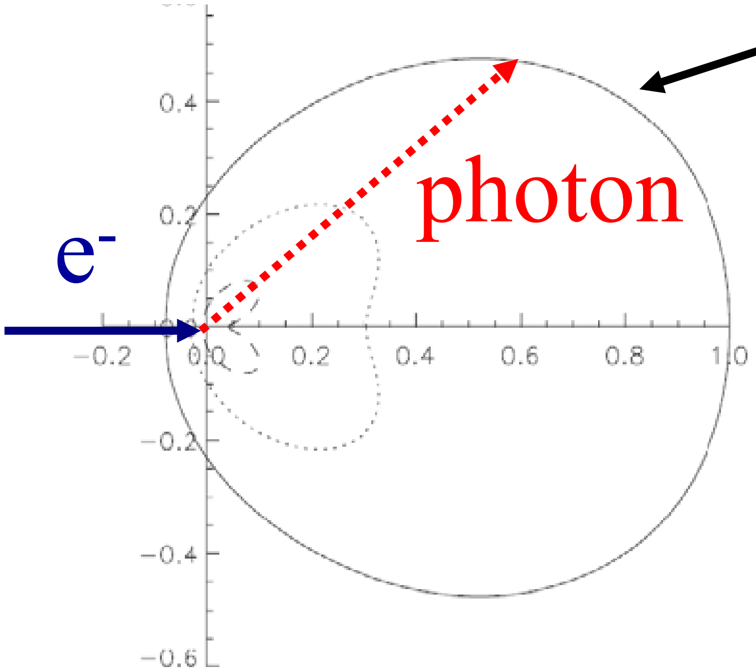


Low-energy cutoff in nonthermal electron spectrum

X-ray/electron angular distributions

The observed photon flux spectrum at the Earth:

$$I(\epsilon) = \frac{\bar{n}V}{4\pi R^2} \int_{\Omega'} \int_{\epsilon}^{\infty} \bar{F}(E, \Omega')Q(\Omega, \Omega', \epsilon, E)dE\, d\Omega',$$

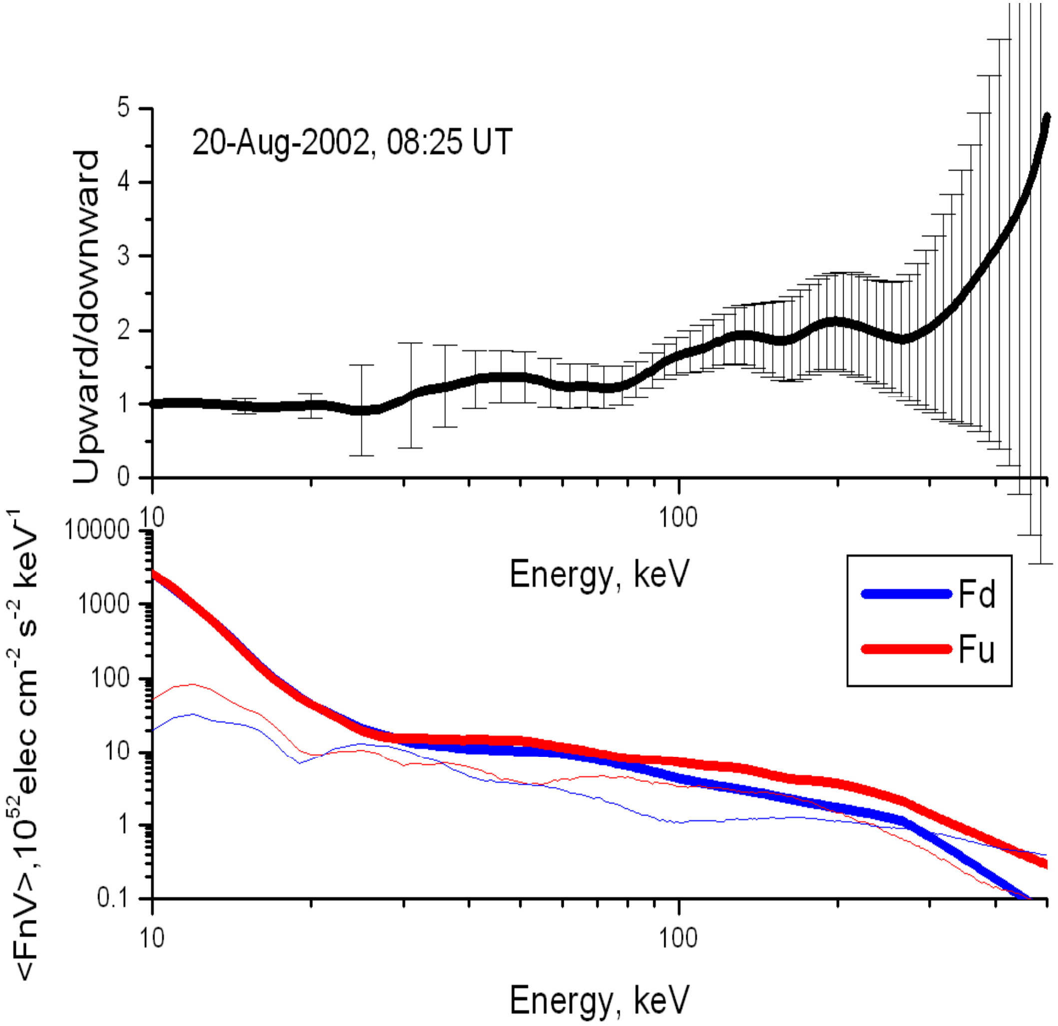


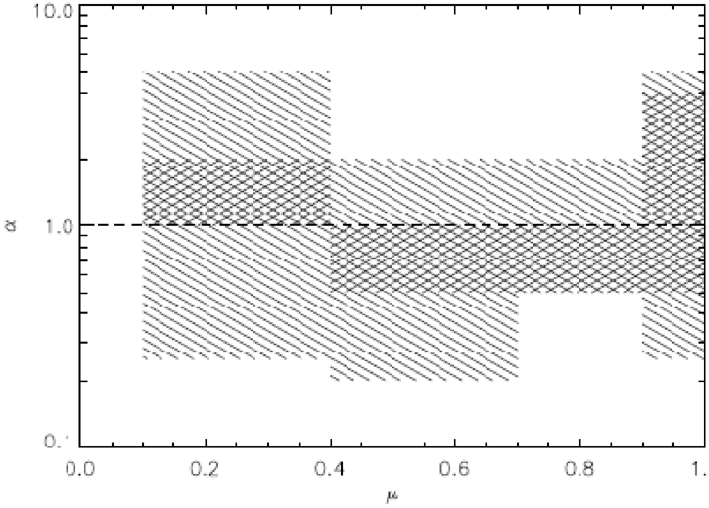
Because we observe 1D photon spectrum 3D character of electron distribution is often ignored and ***F(E,Ω)*** is assumed **isotropic**

How to measure electron anisotropy?

1)Stereoscopic X-ray observations (*Kane et al, 1982 etc*)
2) X-ray polarization (e.g. *McConnell et al (2003);*)
3) Centre-to-limb variations in solar flares (*Ohki (1969), Pinter (1969) at 10 keV, Datlowe et al. (1977) etc)*
4) Albedo as a probe of electron angular distribution (*Kontar& Brown 2006; Kasparova et al 2007*)

Electron anisotropy: individual events



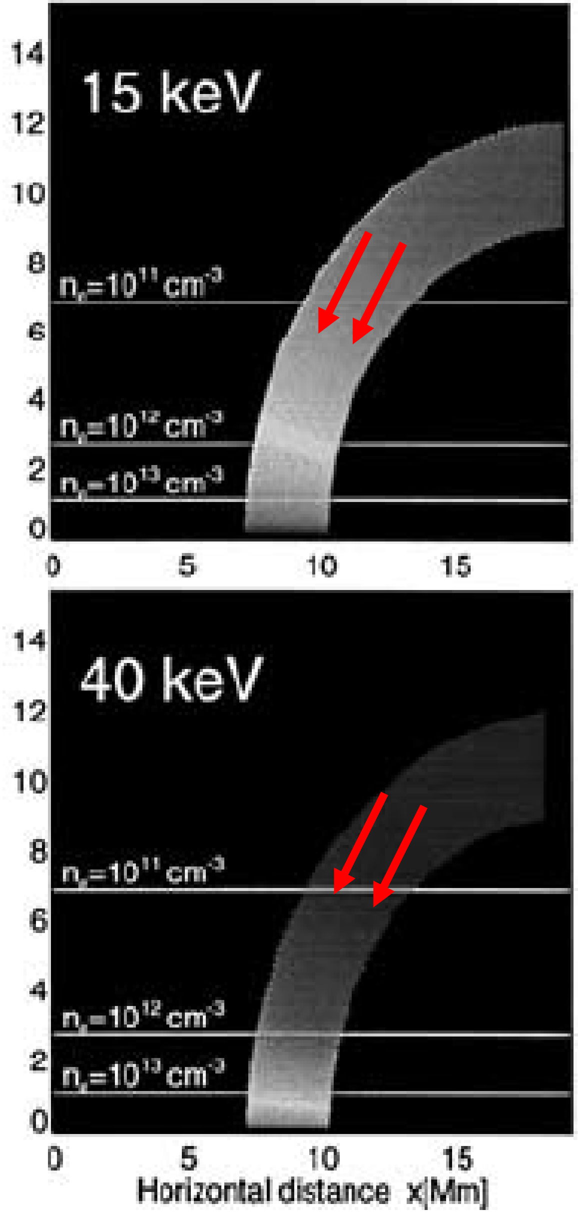


Consistent with isotropic distribution (e.g. Kane et al, 1988; Kontar&Brown, 2006, Kasparova et al, 2007)

Collisional scattering and return current effects cannot explain the isotropy of electron distribution

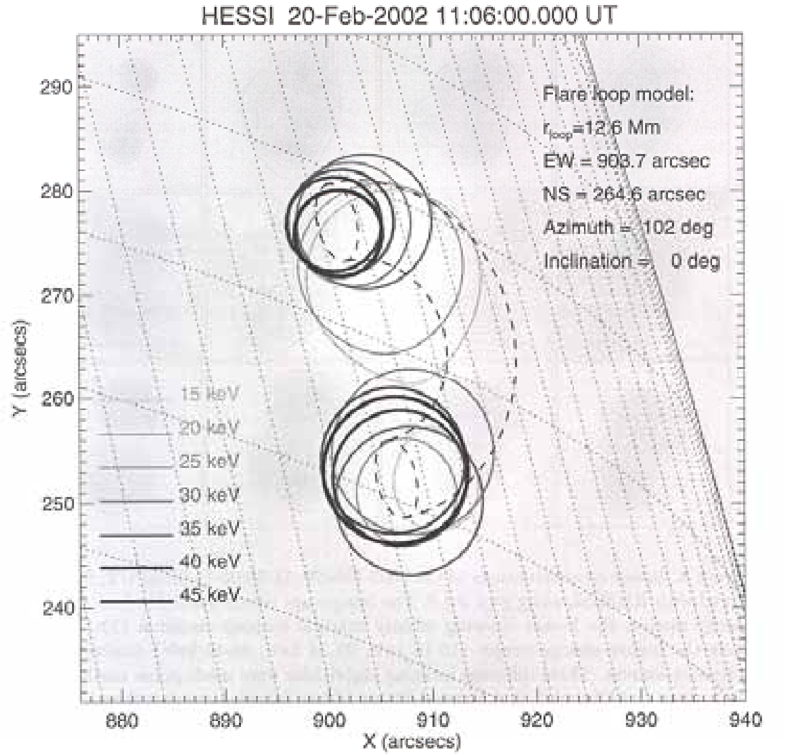
=> The angular distribution found is **inconsistent with downward beamed distributions**

Downward beaming



Aschwanden et al, 2002

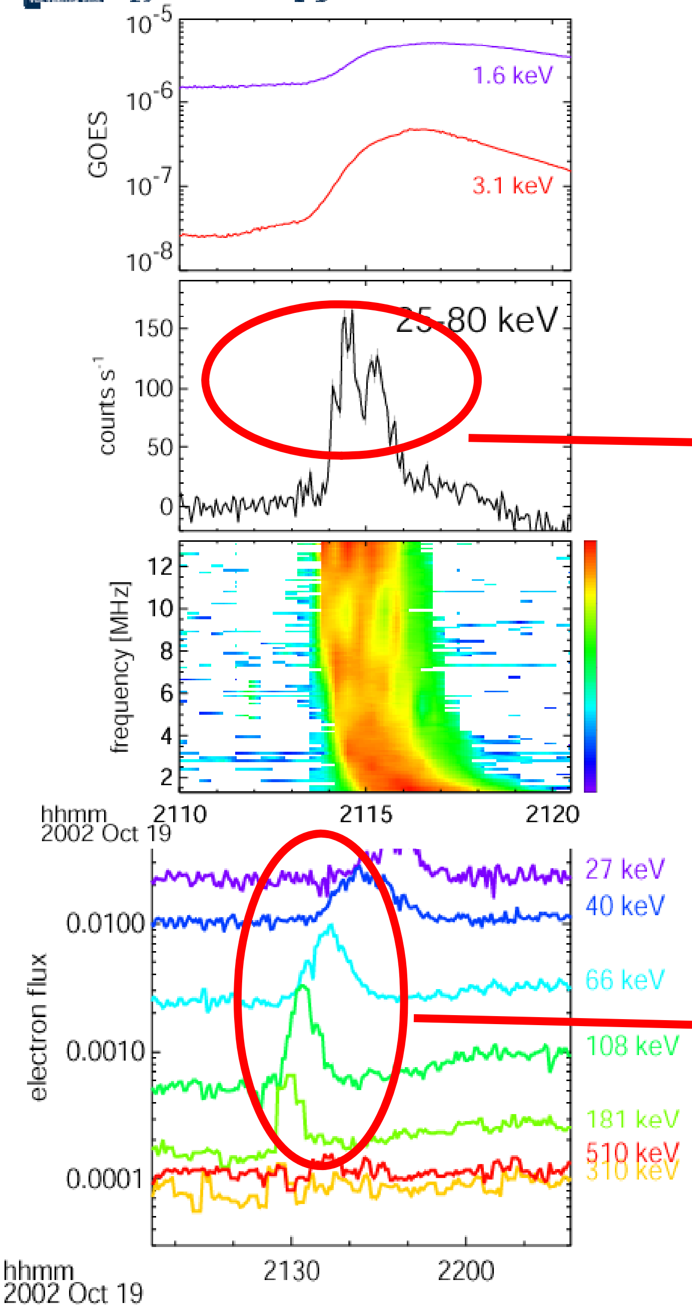
Higher energy sources appear lower in the chromosphere (consistent with simple collisional transport)
=> downward electron beaming



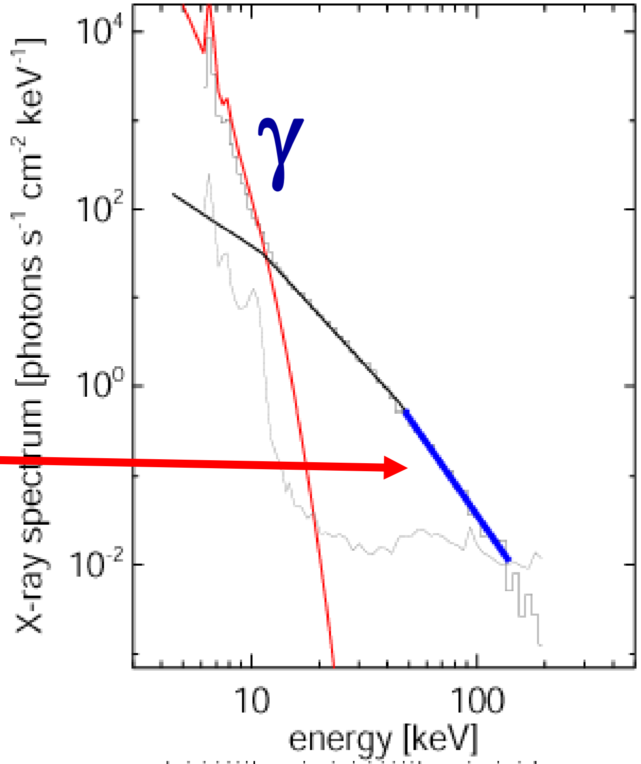
Timing analysis (e.g. Aschwanden et al, 1995) also suggests the beaming of electrons

= > electrons beam downwards as in a classical scenario?

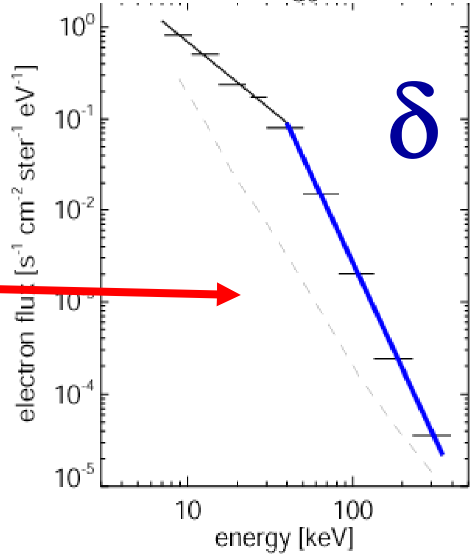
From X-rays to electrons



X-ray spectra from RHESSI



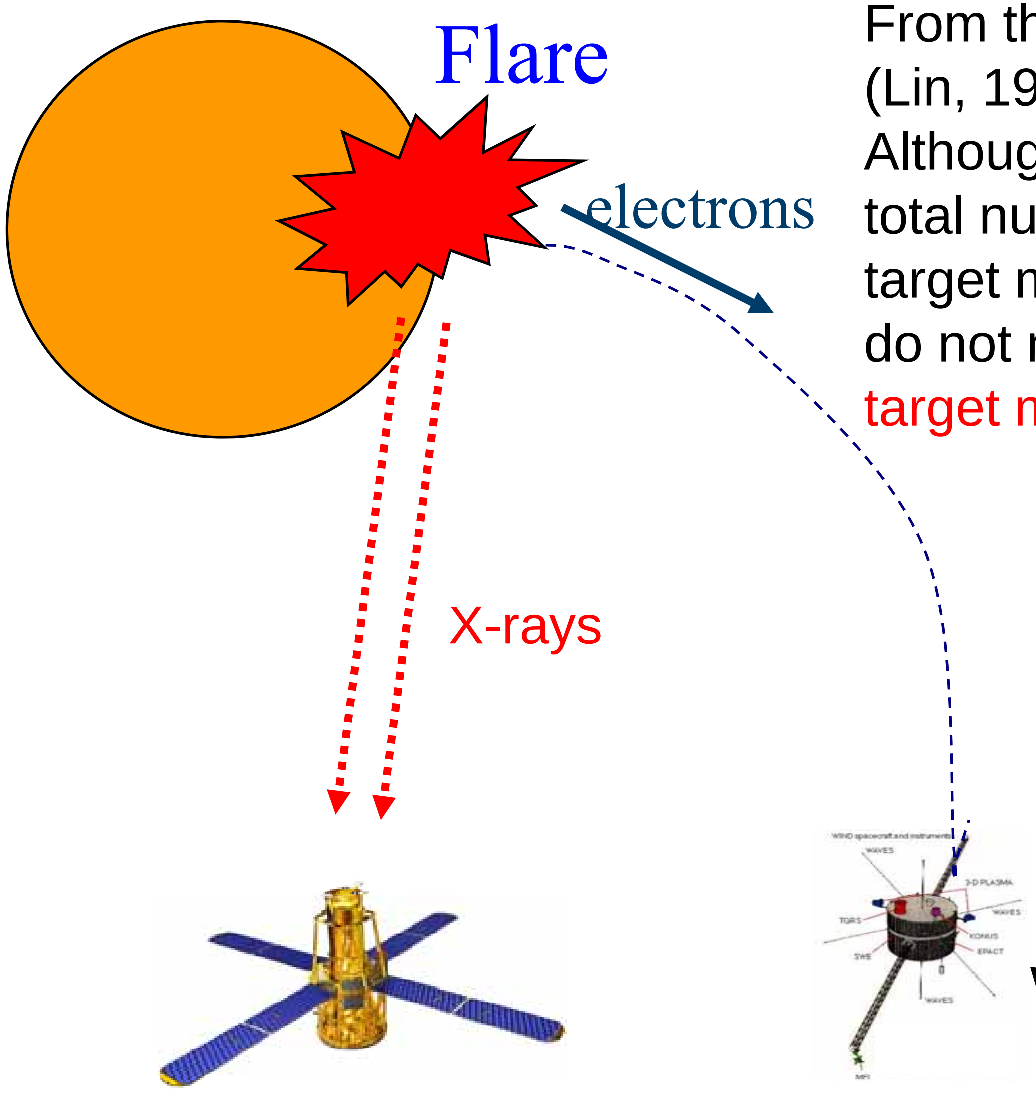
Electron spectra at 1AU from WIND

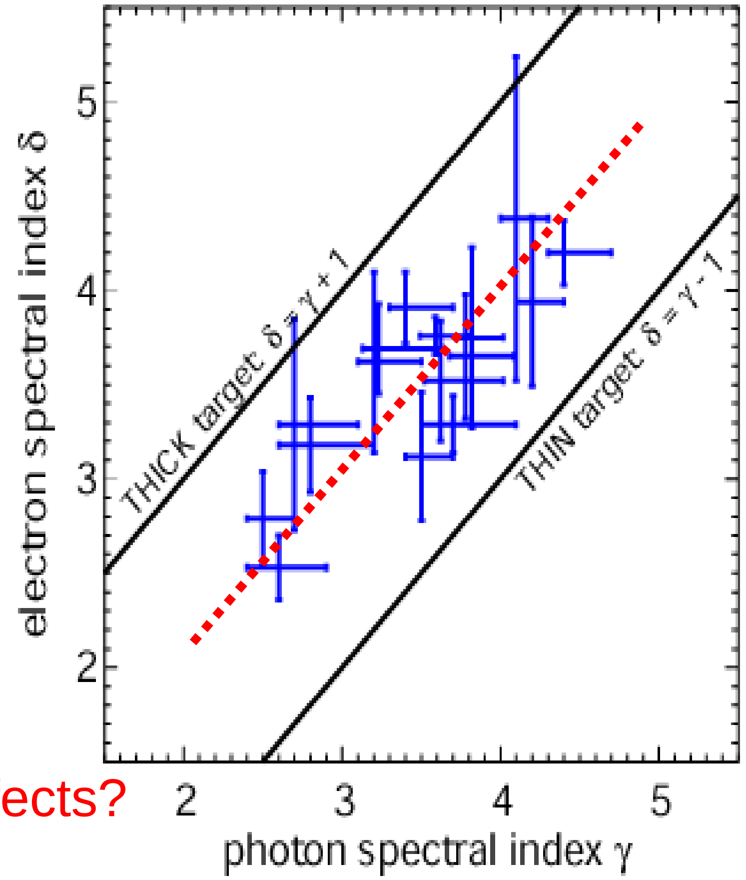


From Krucker et al 2007

From X-rays to electrons

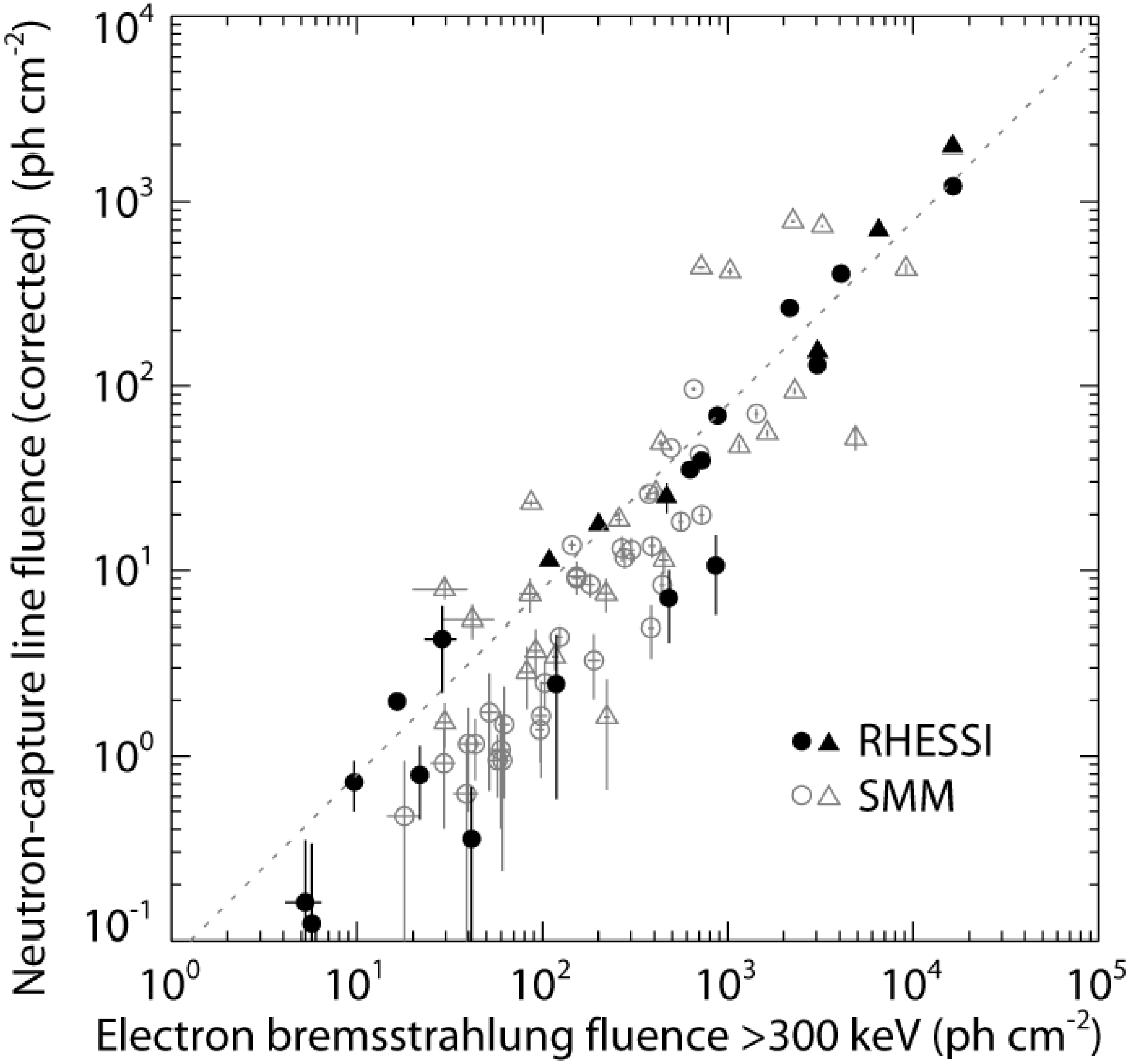
From the analysis of 16 “scatter-free” events (Lin, 1985; Krucker et al, 2007) : Although there is correlation between the total number of electrons at the Sun (thick-target model estimate) the spectral indices do not match either thick-target or thin-target models.

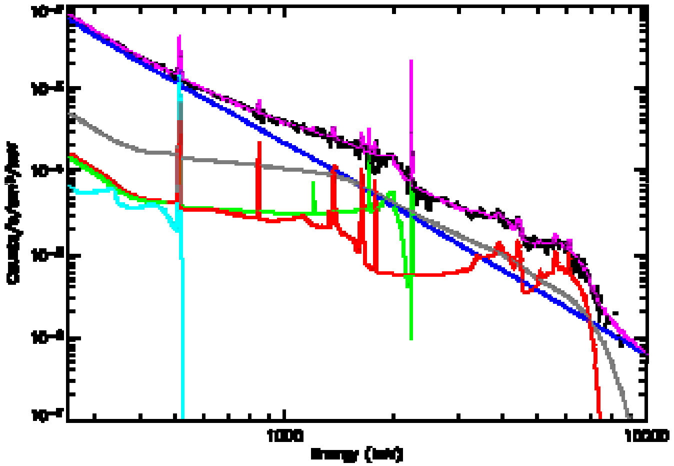




Acceleration or transport effects?

Electron vs ion acceleration

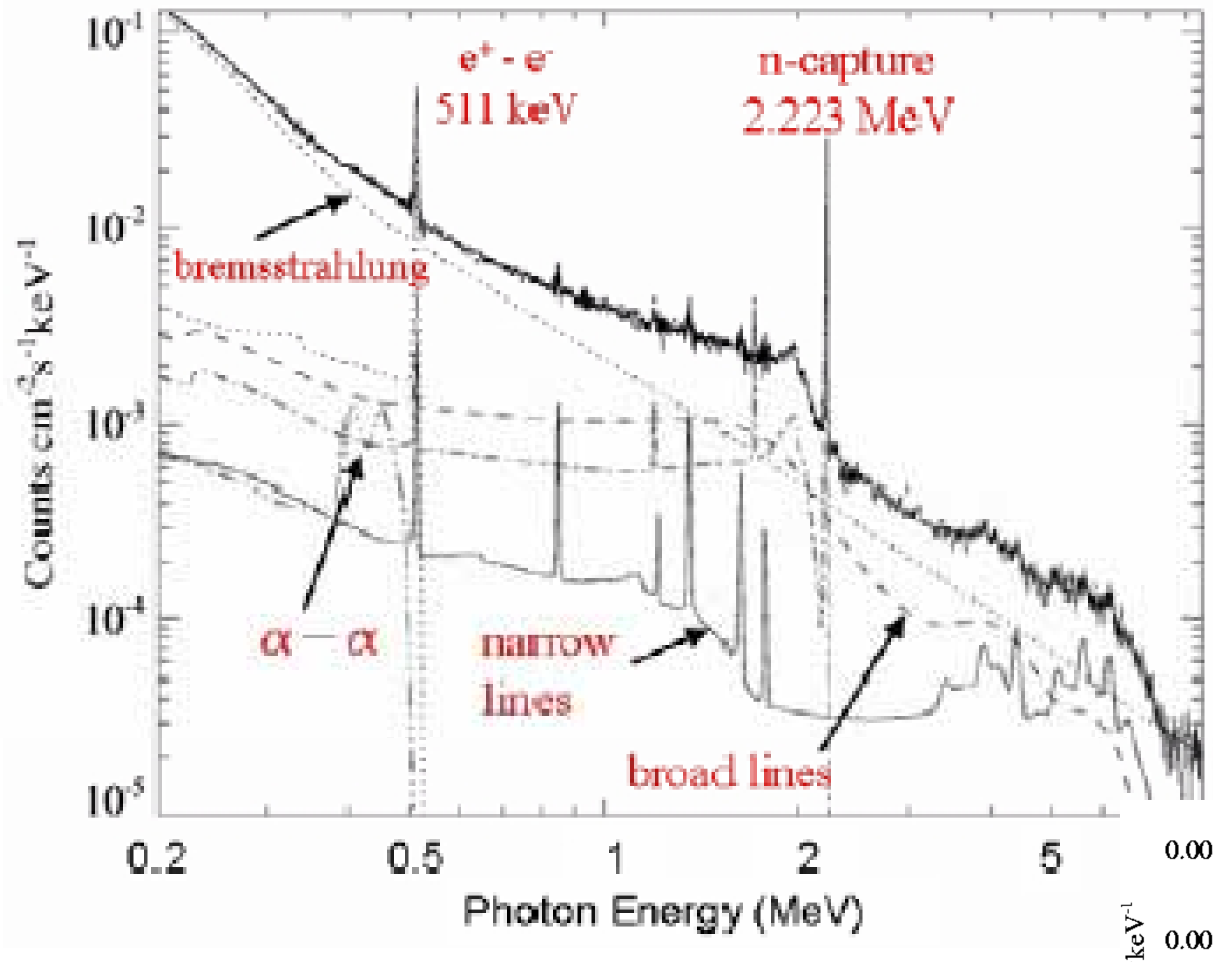




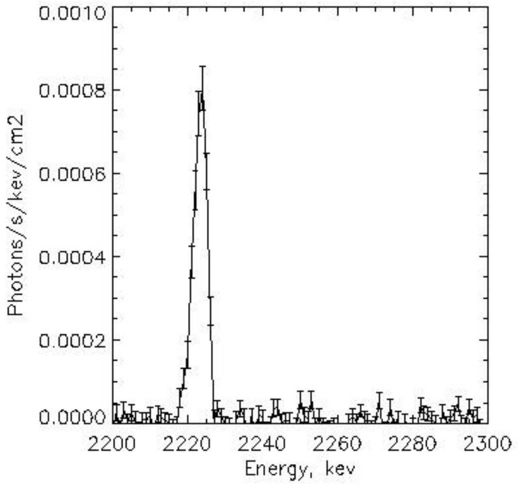
Ion acceleration >30 MeV is correlated with relativistic electron acceleration >300 keV

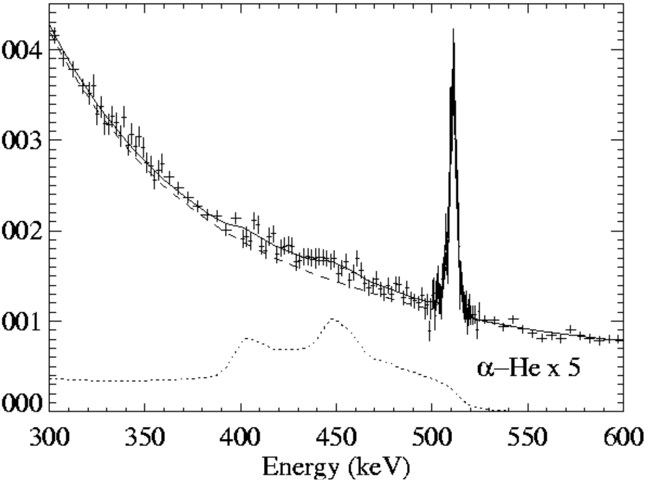
Ion acceleration >30 MeV is poorly correlated with electron acceleration >50 keV, with the possibility of two separate classes of flares
(Shih et al, 2007)

Gamma-ray spectroscopy



October 28, 2003 X-class flare
(Share et al, 2004)
spectrum

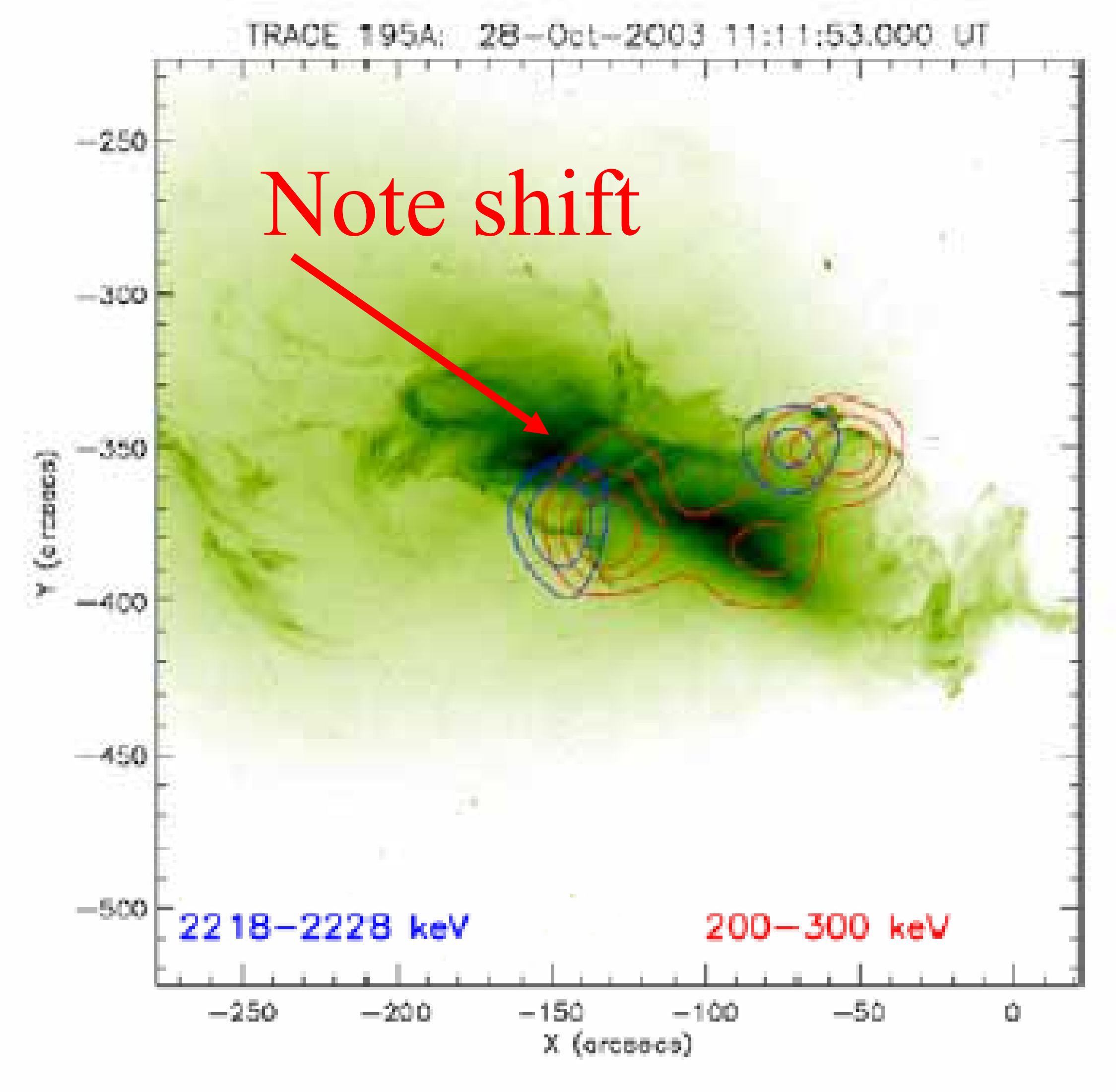




Alpha-alpha lines favours forward **isotropic distribution**
Proton & Alpha power law index is 3.75
2.2MeV line shows ~100 s delay

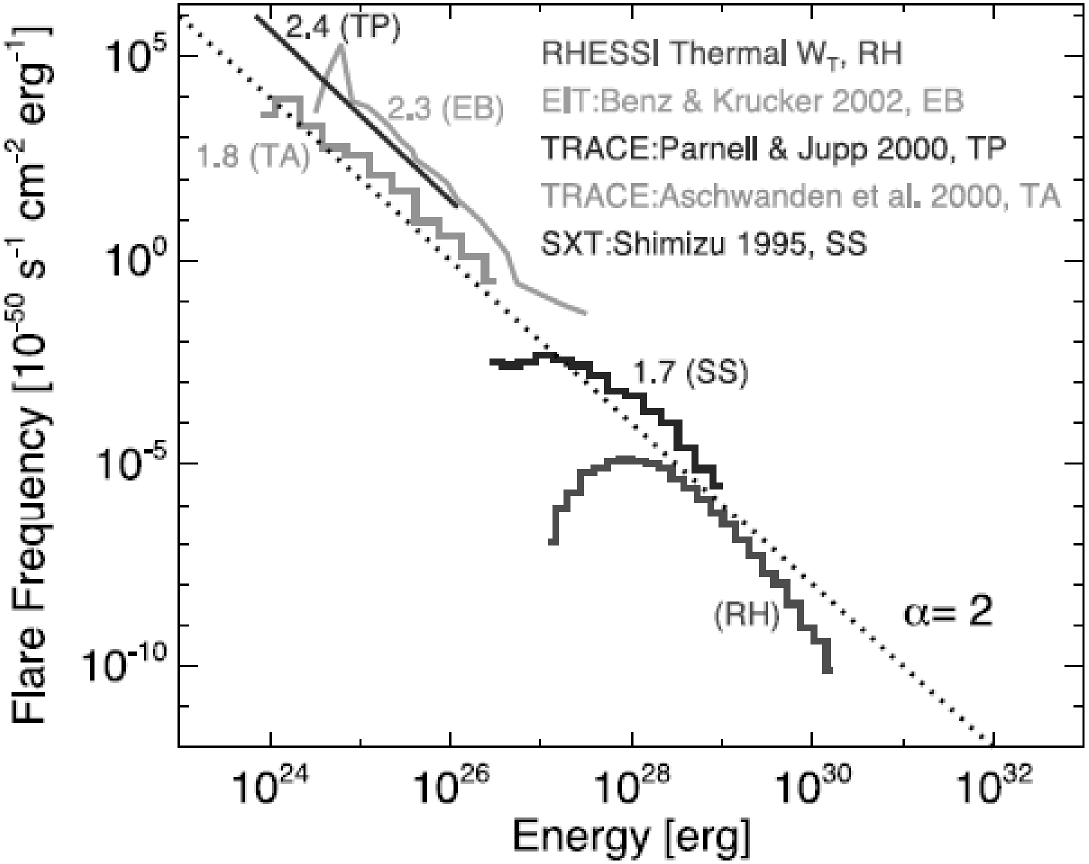
Gamma-ray images

Hurford et al, 2006: Imaging of the 2.223 MeV neutroncapture line (blue contours) and the HXR electron bremsstrahlung (red contours) of the flare on October 28, 2003. The underlying image is from TRACE at 195 Å. The X-ray and γ-ray imaging shown here used exactly the same selection of detector arrays and imaging procedure. Note the apparent loop-top source in the hard X-ray contours.

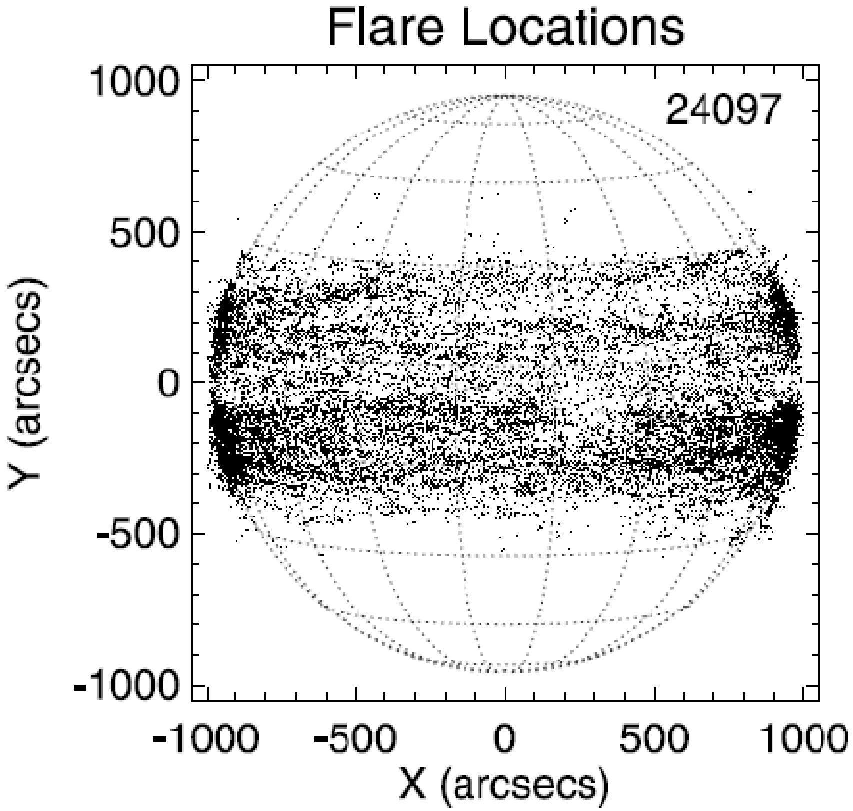


Why do electrons and ions emit in different locations?

Microflares



Hunnah et al, 2008



Christe et al, 2008

Do the observations rule out microflare/nanoflare heating scenario?

Conclusions and questions

RHESSI X-ray spectroscopic data allow to scrutinise current electron acceleration/propagation models.

Spatially resolved electron spectra help to understand the physics of electron transport/acceleration -Do we understand particle transport?

Non-thermal hard X-ray emission from coronal sources: Electron trapping or the signature of acceleration?

If the electron distribution has a lower value low-energy cutoff (<12 keV), do we systematically underestimate the total number of accelerated electrons ?

Anisotropy of electrons: How do the electrons propagate downward but have close to isotropic electron distribution ? Propagation effects or electron acceleration is extended ?

2.2MeV line sources are displaced with respect to X-ray sources for 2 events. Are the electrons and ions are accelerated in different regions?