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SOLAR FLARE ENERGETIC PARTICLES

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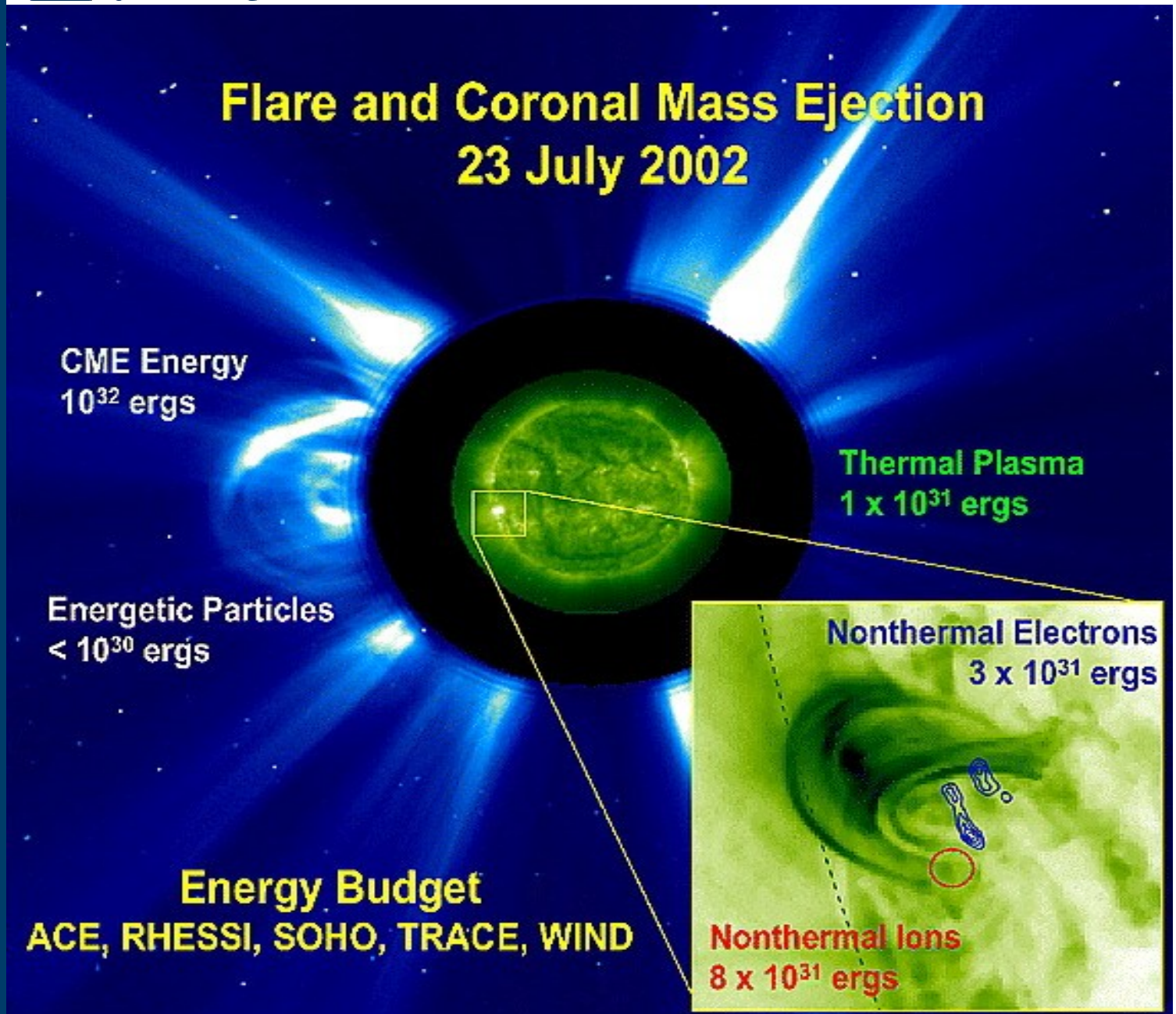
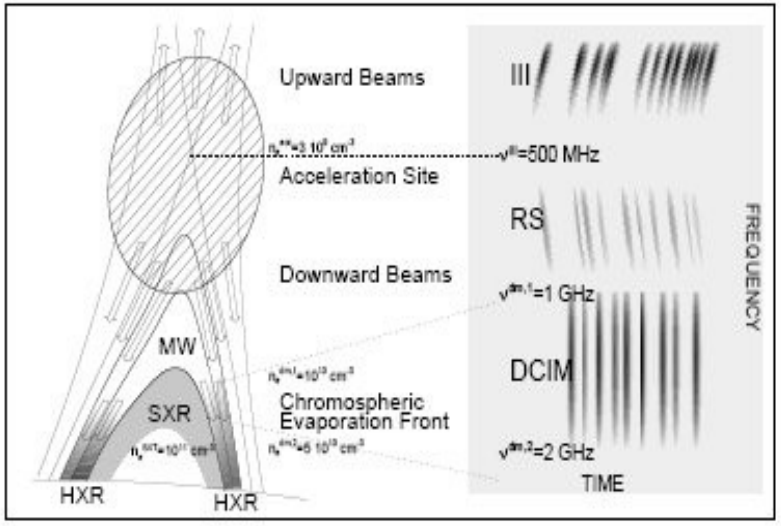
Solar flares and accelerated particles



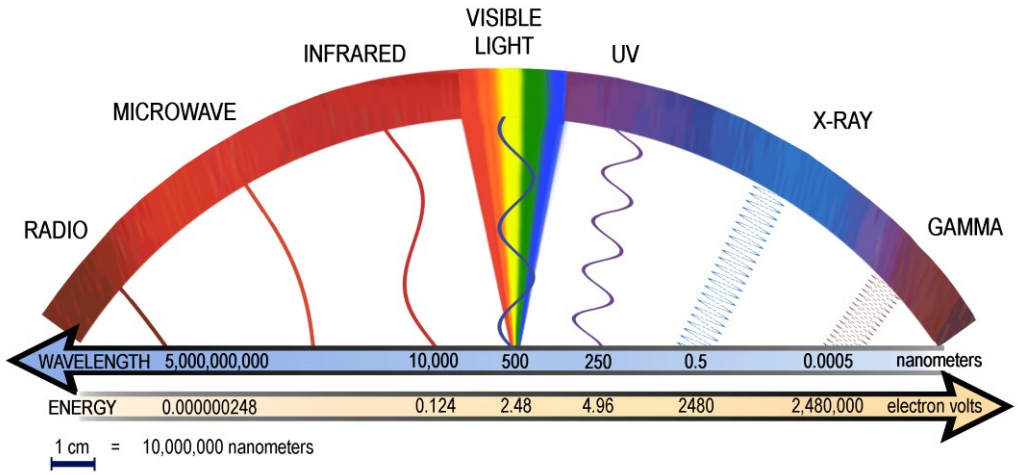
From Emslie et al., 2004

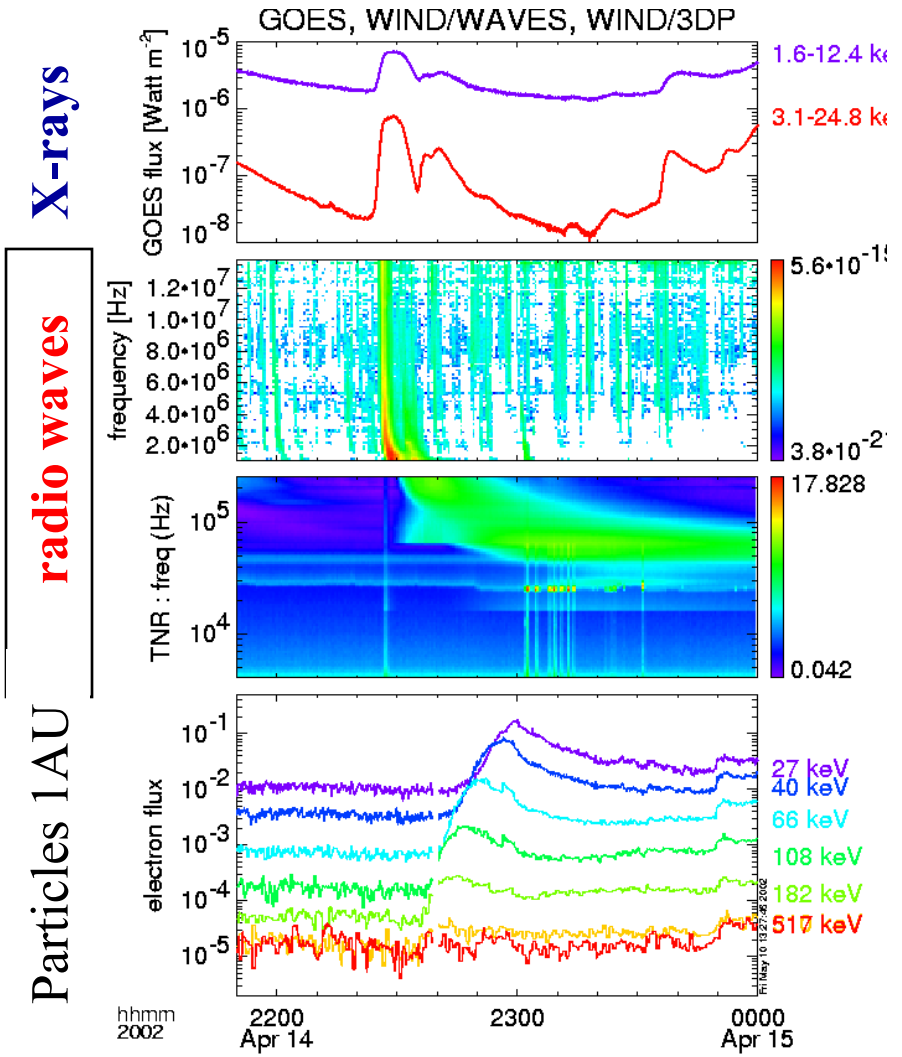
Free magnetic energy
~2 10^{32} ergs

Observations of energetic particles



Aschwanden and Benz, 1997

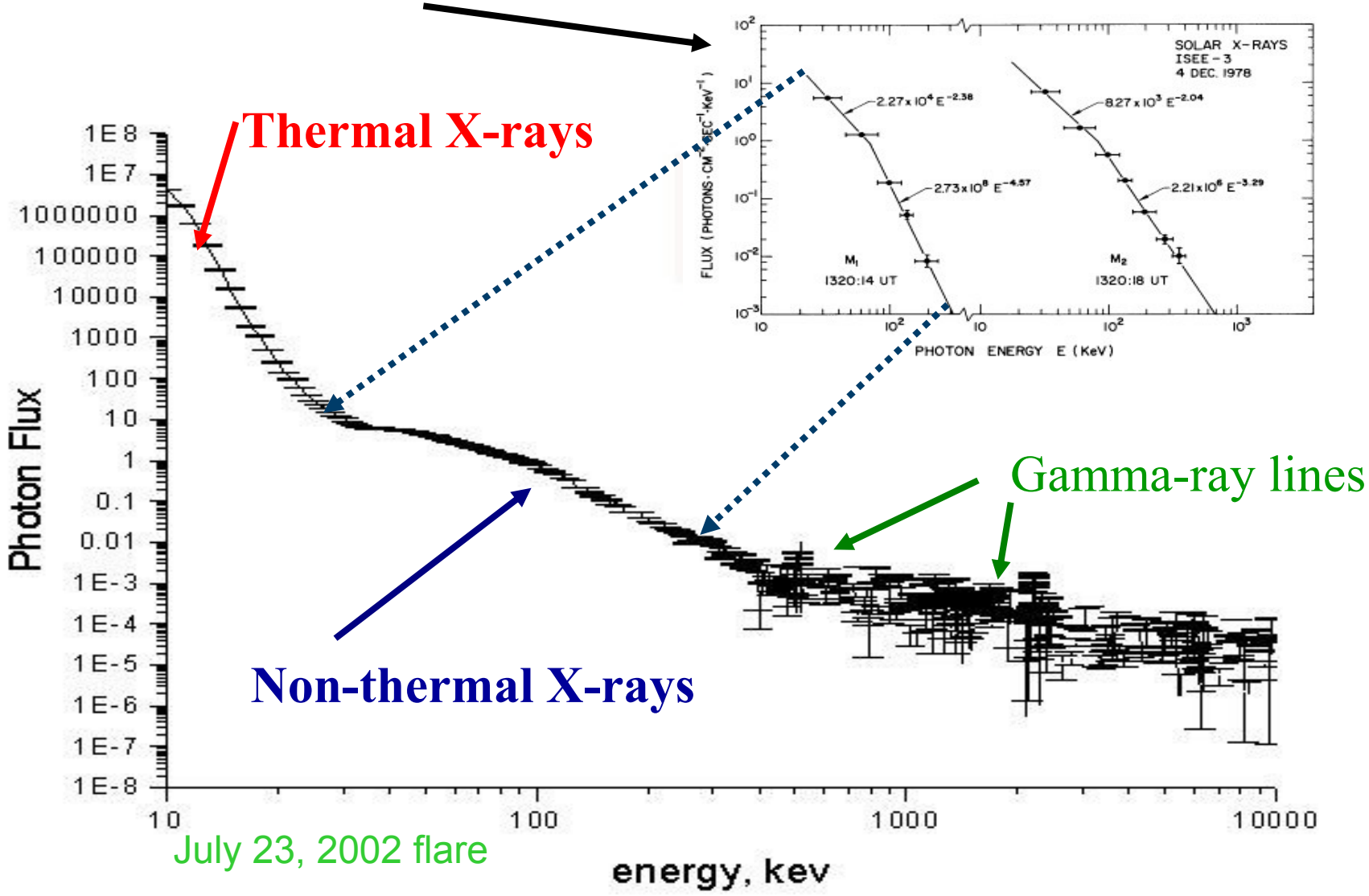




Krucker et al, 2001

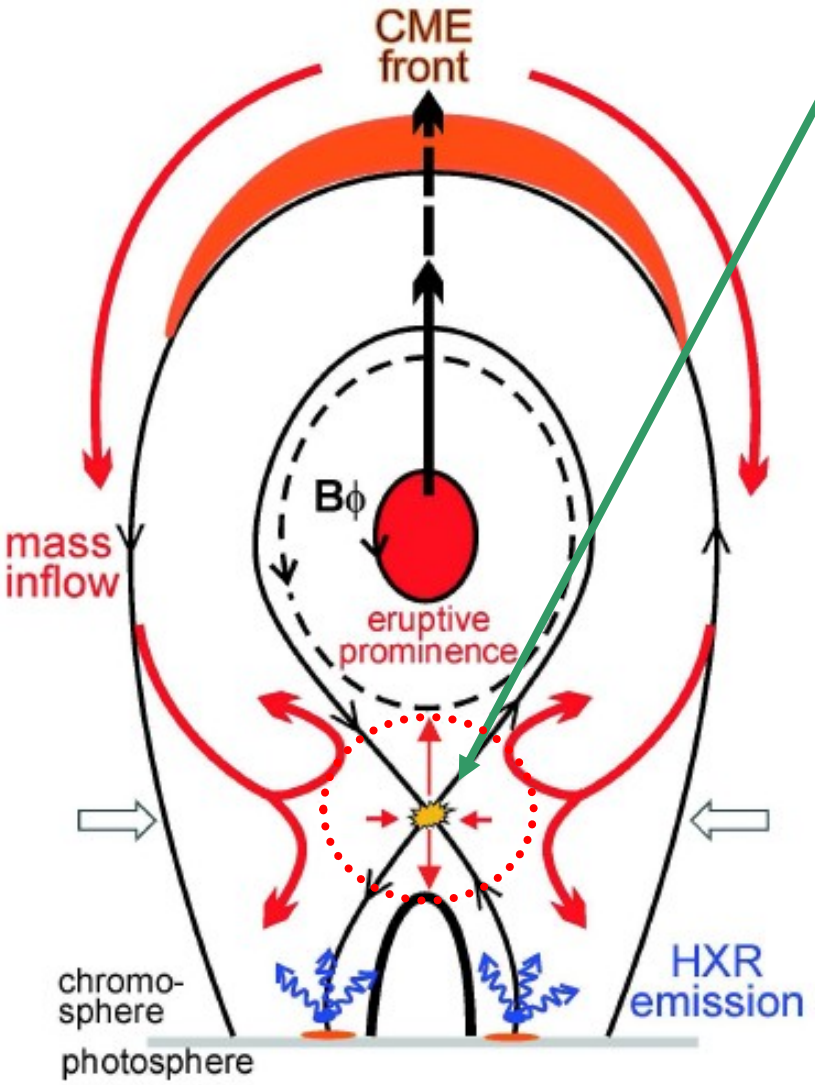
X-ray spectrum of solar flares

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



Ramaty High Energy Solar Spectroscopic Imager (RHESSI) spectrum

"Standard" model of a solar flare/CME



Temmer et al, 2009

Energy release/acceleration

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

Flaring region T ~ 4x10^7 K => 3 keV per particle

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

Plasma density 10^{10} cm^{-3}

Photons up to > 100 MeV

Number of energetic electrons 10^{36} per second

Electron energies >10 MeV

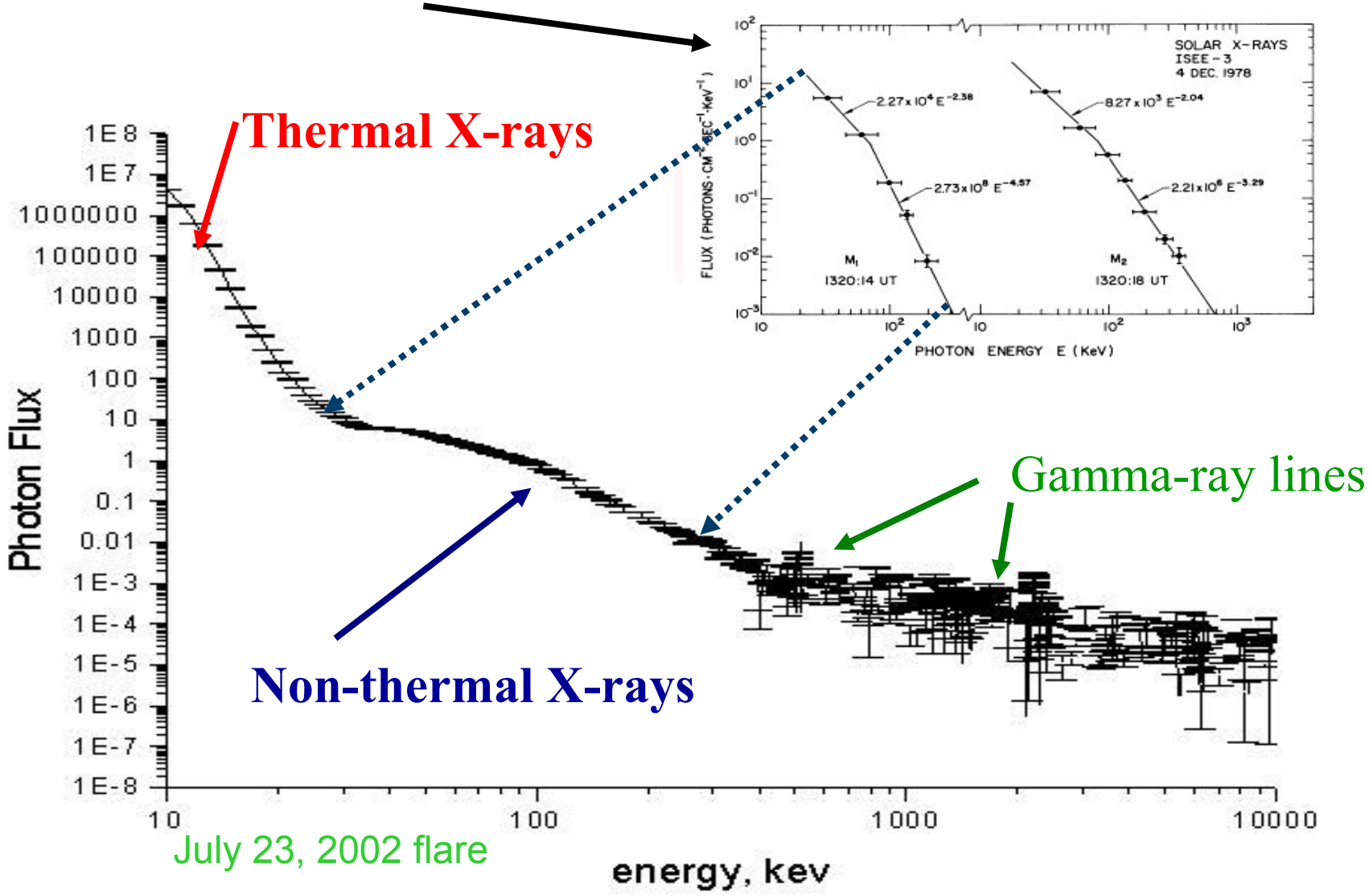
Proton energies >100 MeV

Large solar flare releases about 10^{32} ergs (about half energy in energetic electrons)

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

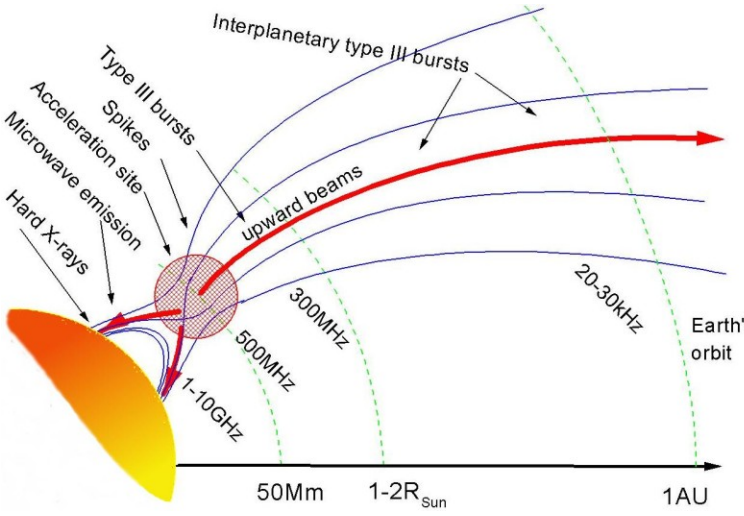
X-ray spectrum of solar flares

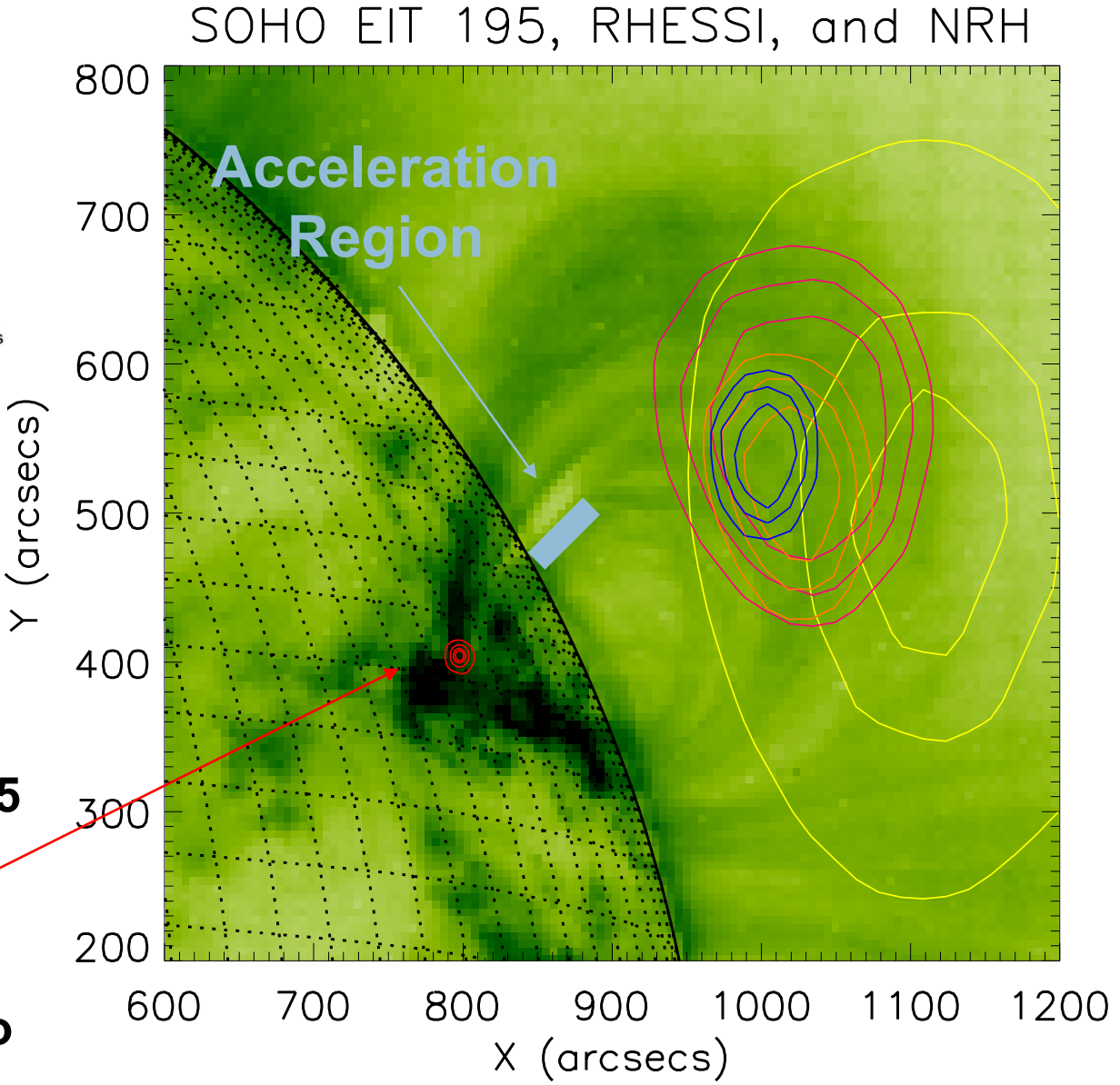
pre-RHESSI X-ray spectra (Kane et al, 1982)



Ramaty High Energy Solar Spectroscopic Imager (RHESSI) spectrum

X-rays and radio





April 15th 2002 Solar Flare.

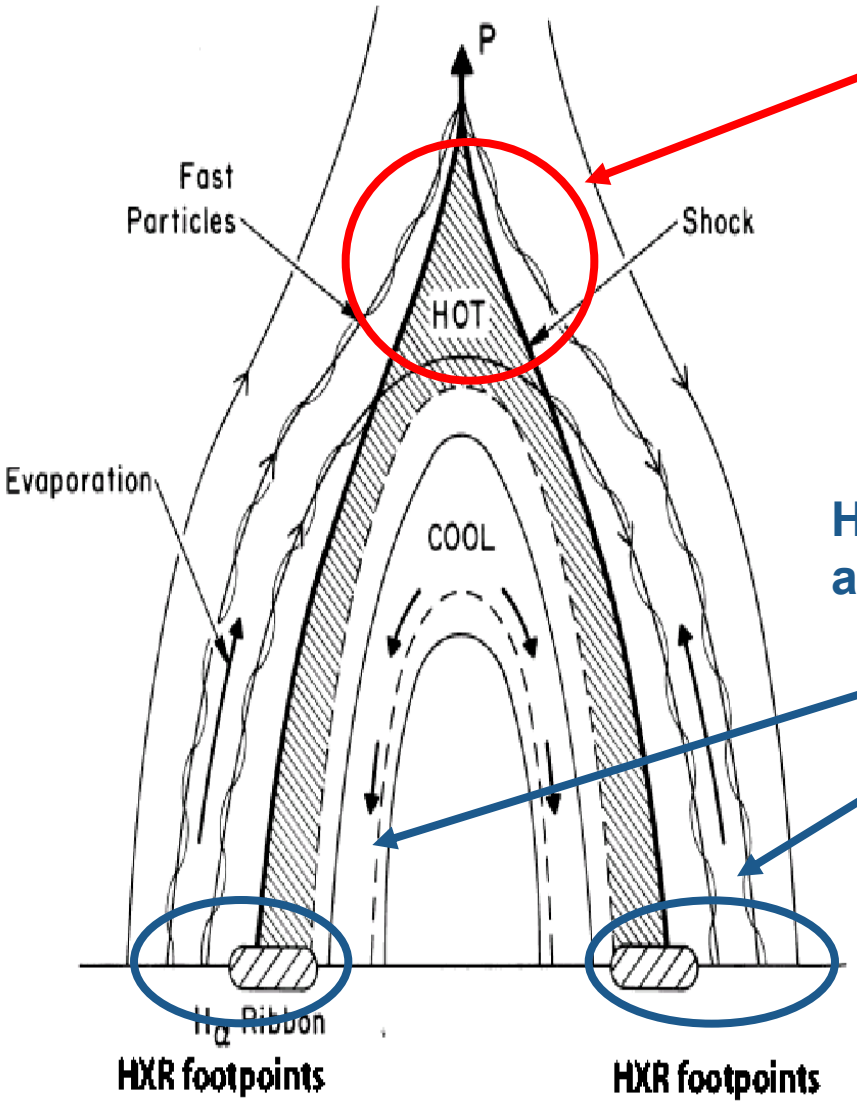
Background is SOHO/EIT 195

Small Red contours are RHESSI 15-30 kev

Coloured Contours are radio (NRH) 432 MHz Blue to 164 MHz Yellow

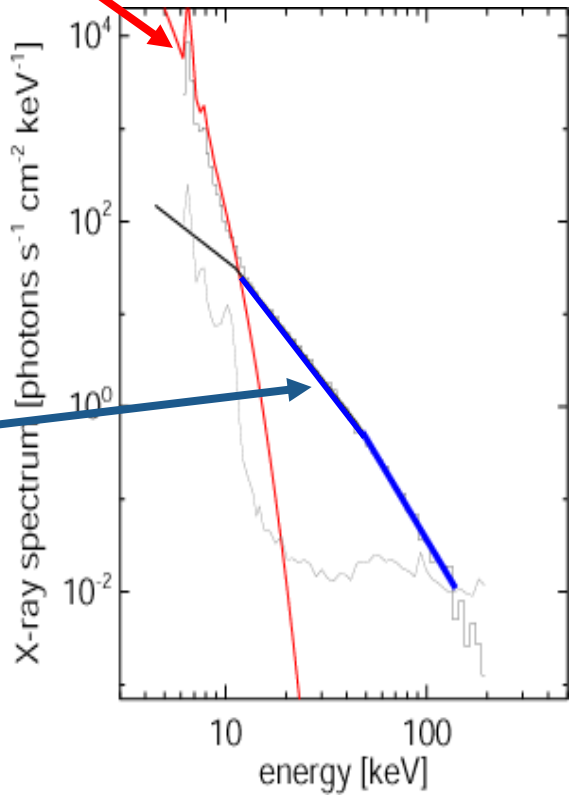
Reid, Vilmer, Kontar, 2011

Standard fare geometry



Soft X-ray emission up to ~10 - 20 keV

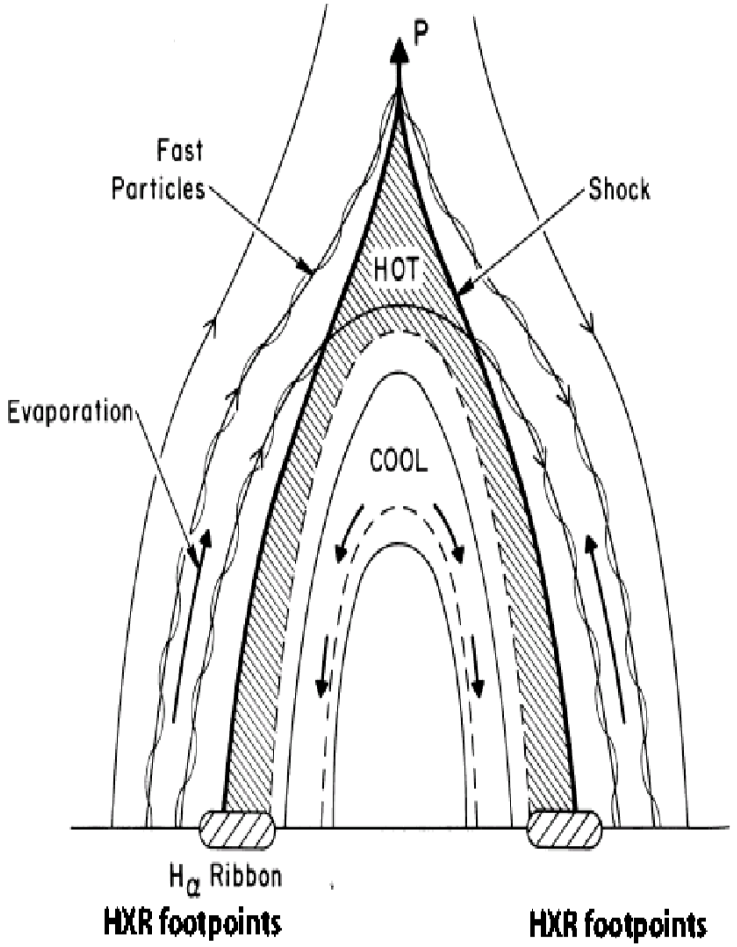
Hard X-ray sources above ~20 keV



RHESSI spectrum

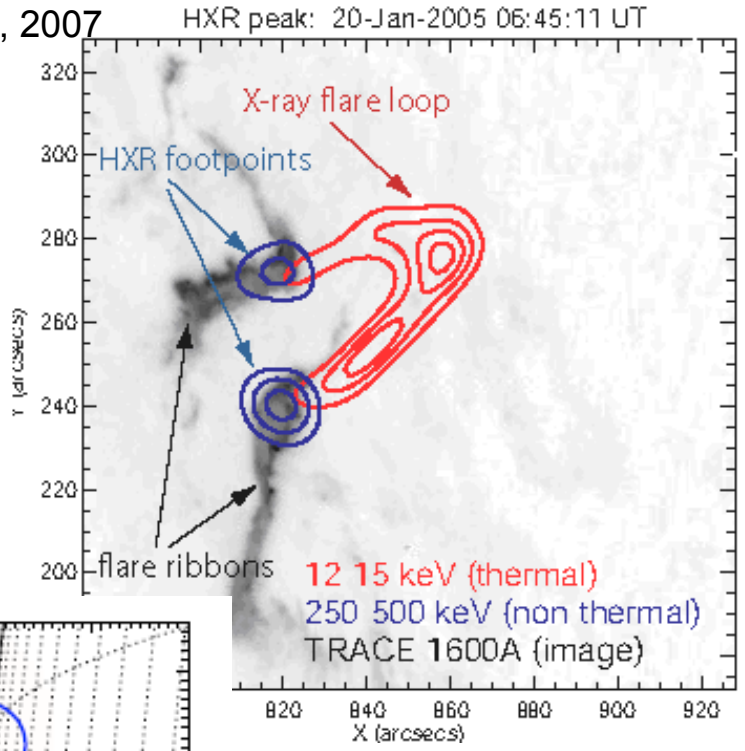
'Standard' flare model picture in 2D (Shibata, 1996)

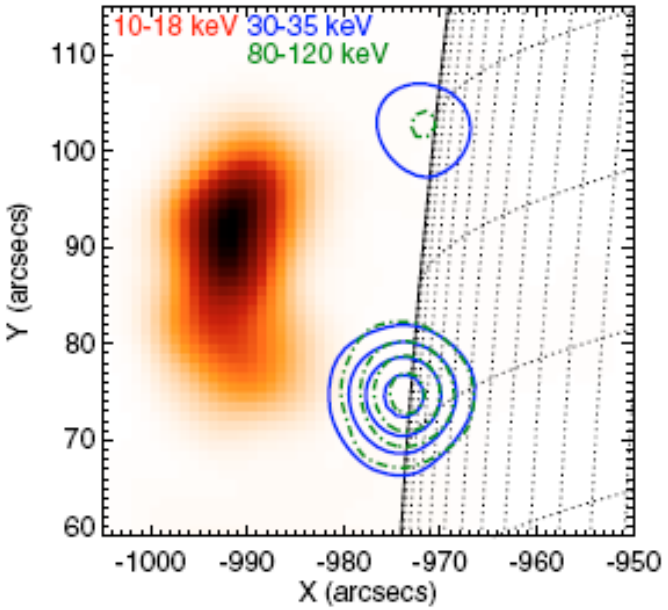
What do we see in RHESSI?



Standard flare model picture (Shibata, 1996)

Krucker et al, 2007

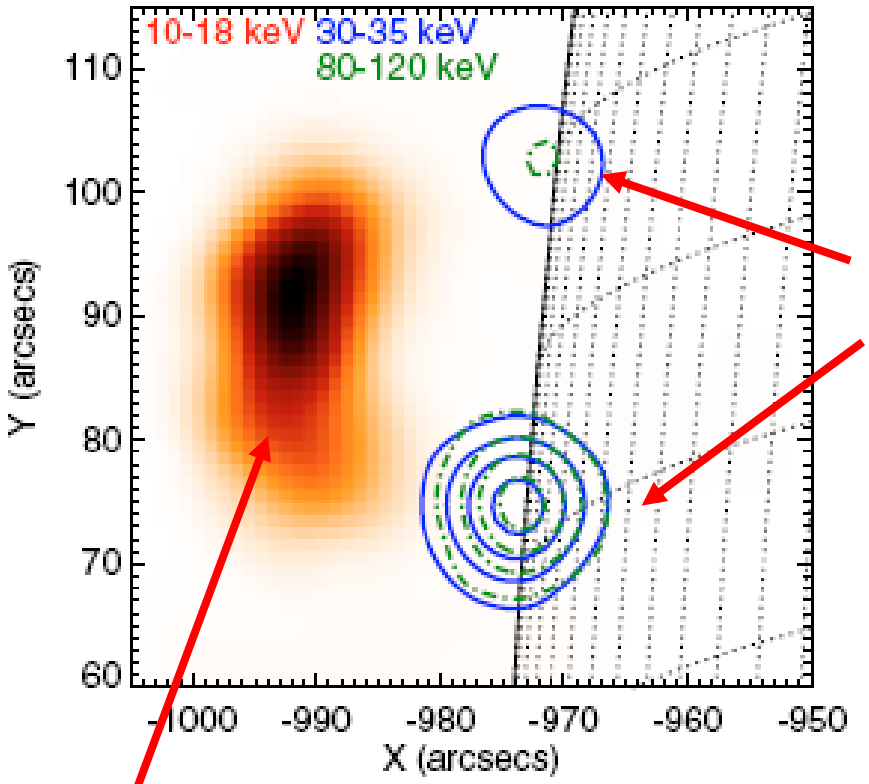




Kontar et al 2008

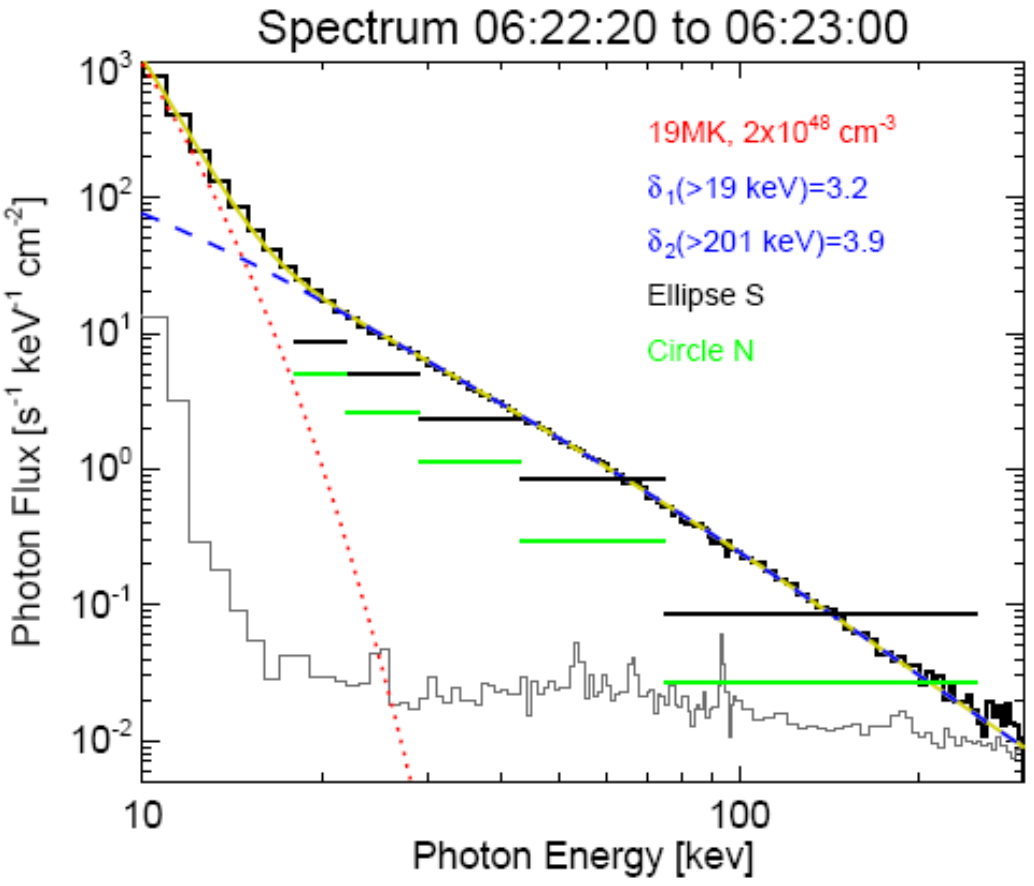
X-ray emission from limb flares

Limb flare event 6 January 2004

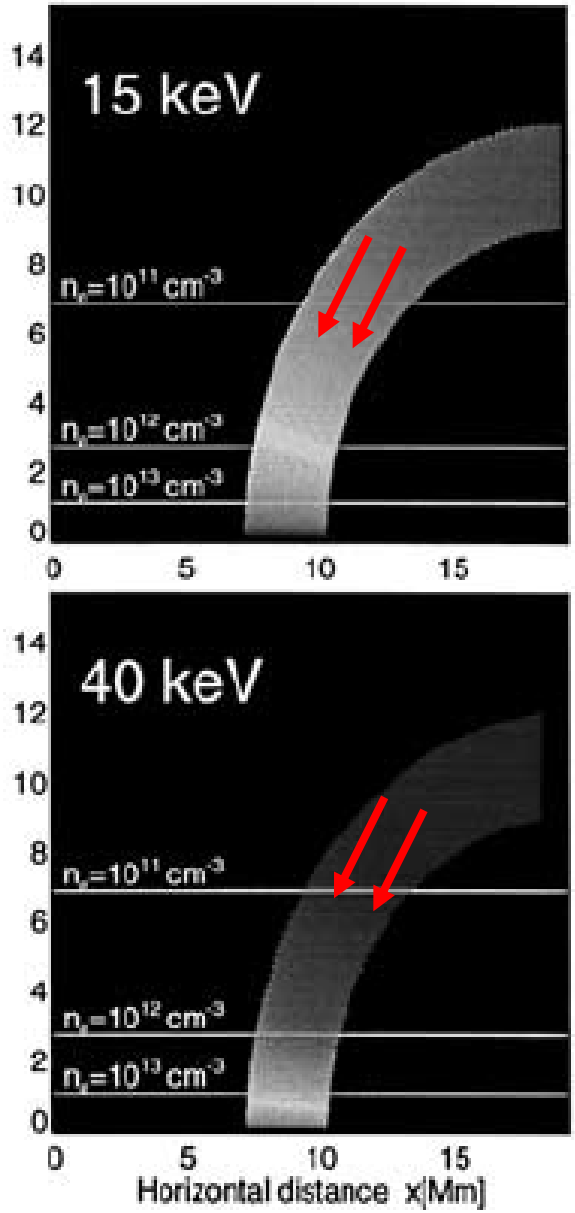


Footpoints

Coronal Source

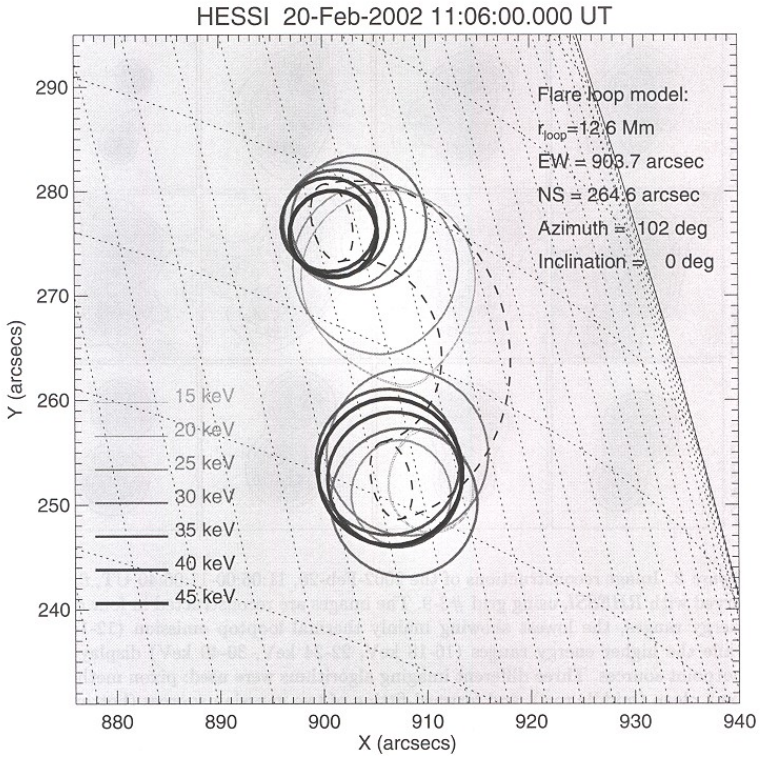


Downward propagation

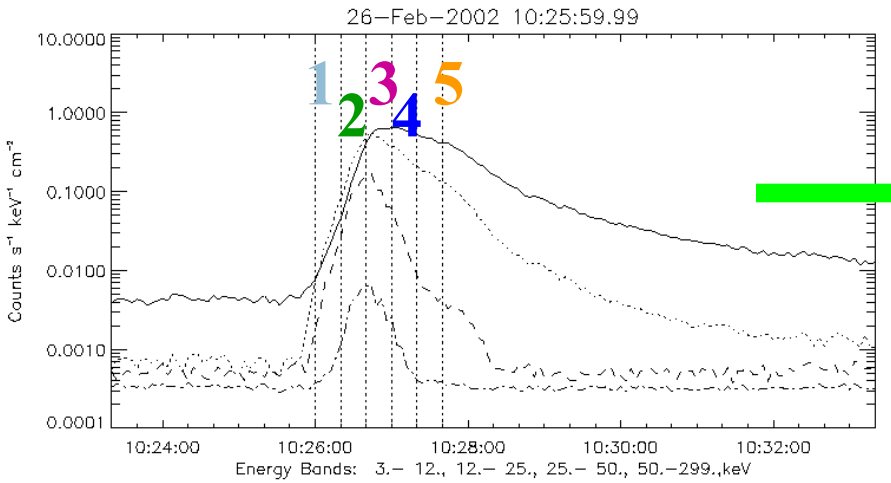


Aschwanden et al, 2002

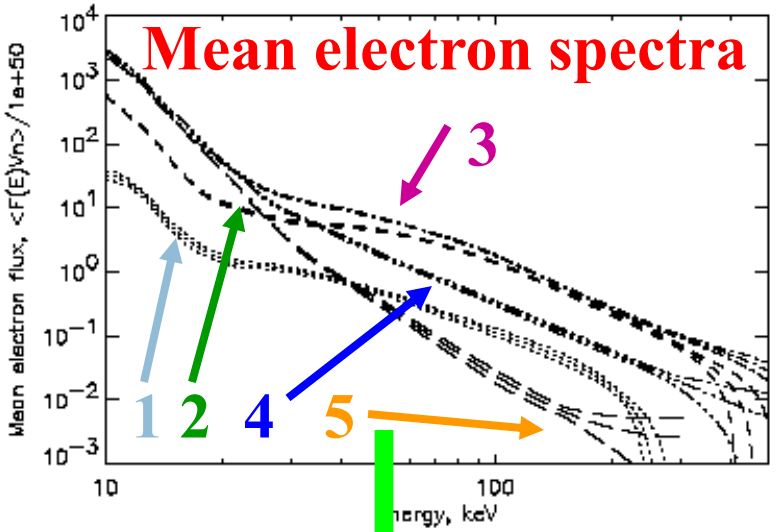
Higher energy sources appear lower in the chromosphere (consistent with simple collisional transport)



From X-rays to electrons

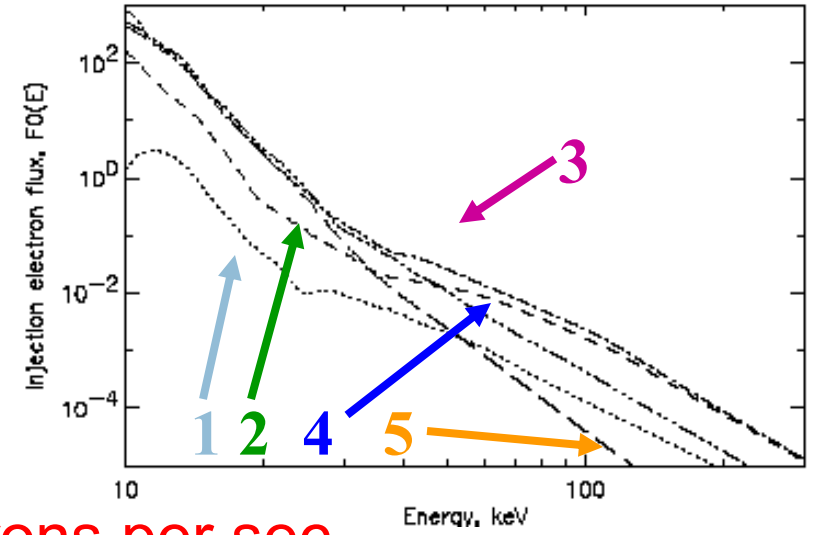


(Model independent)



(Model dependent)

Accelerated (injected) spectra

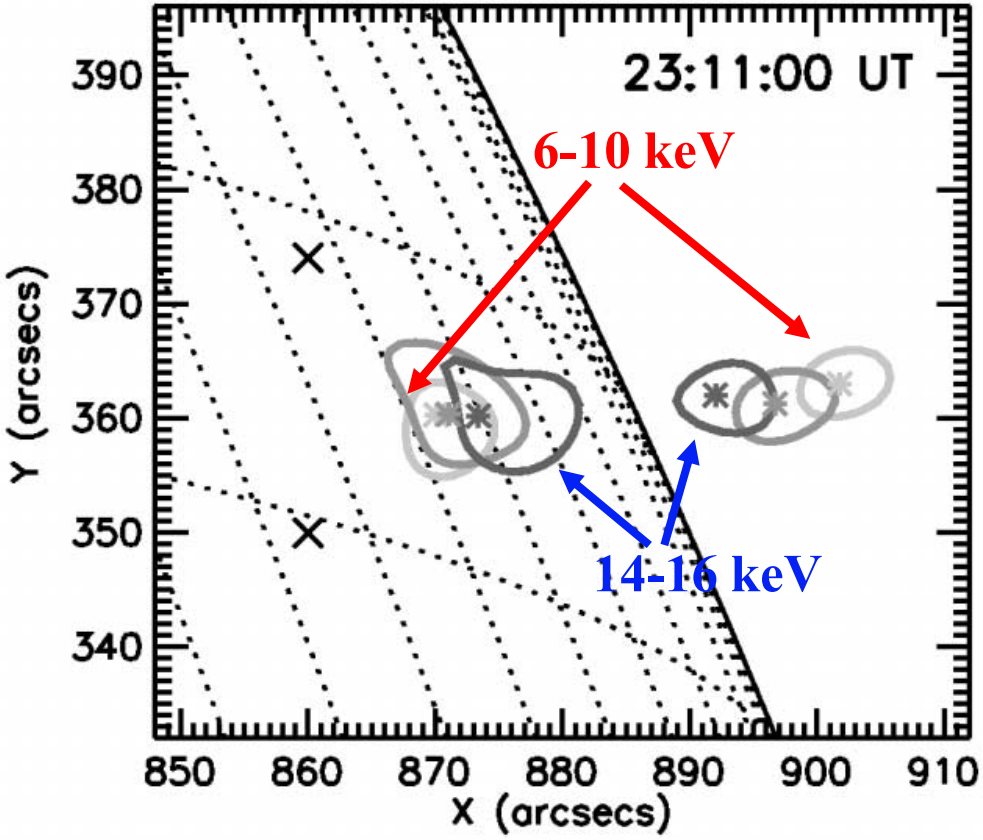


We measure density weighted electron flux spectrum quite accurately;

Injected rate is model dependent /particle transport is coupled/

=> accelerated rate is ~10^{36} electrons per sec

Location of energy release



Sui et al, 2004

Do we observe magnetic reconnection?

Plasma density 10^{10} cm^{-3}

Flare volume 10^{27} cm3 $(10^4$ km$)^3$

=> Number of electrons:10^{37}

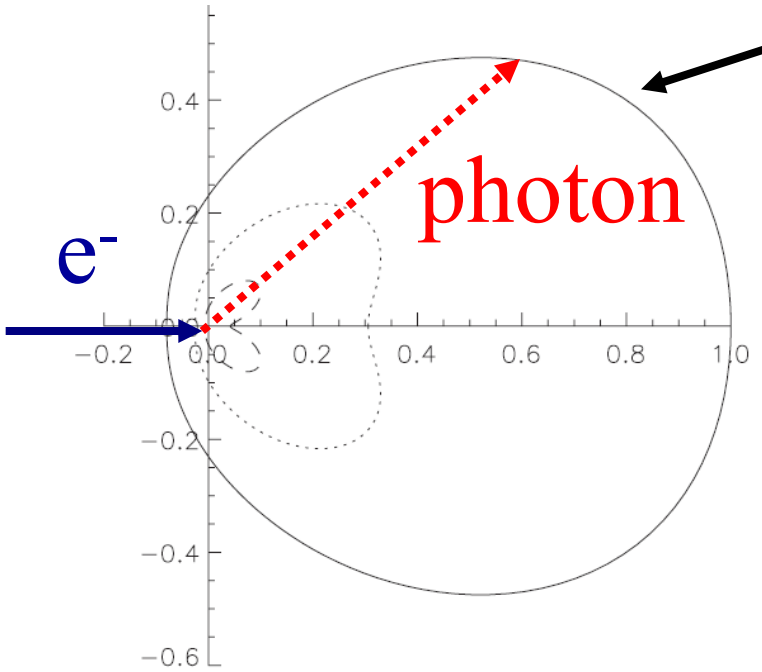
For acceleration rate **10^{36} per second**

=> All electrons will be evacuated from the volume within 10 seconds!

X-ray/electron angular distributions

The observed photon flux spectrum at the Earth:

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

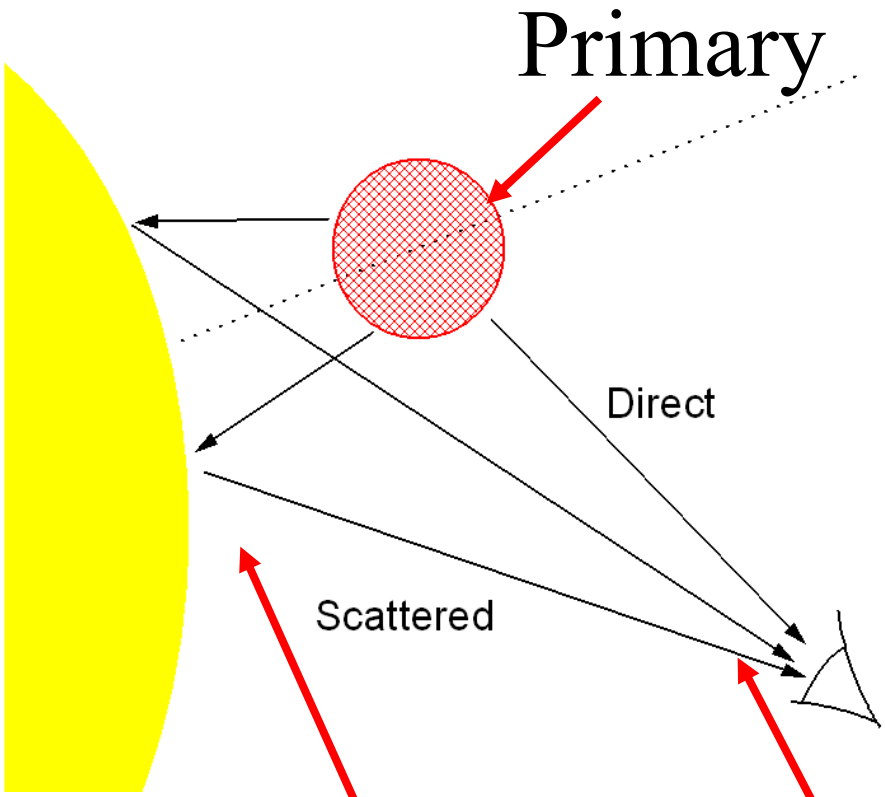


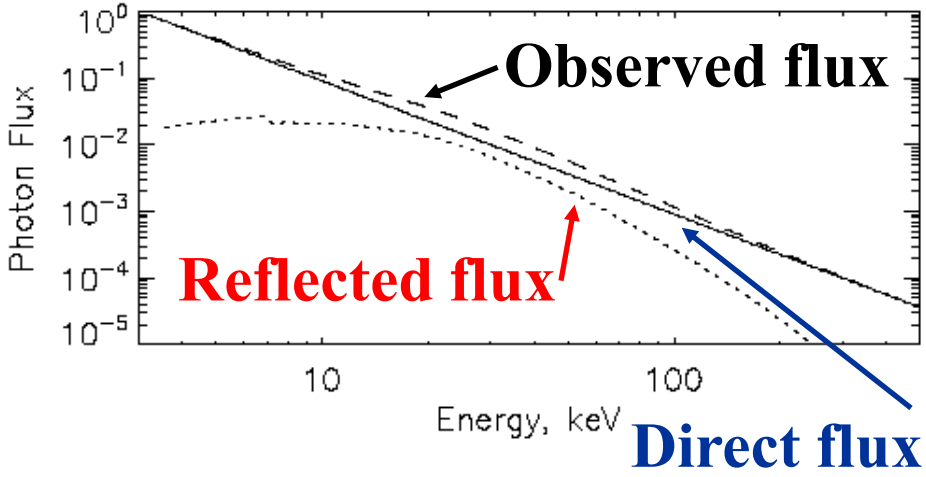
Because we observe 1D photon spectrum 3D character of electron distribution is often ignored and ***F(E,Ω)*** is assumed **isotropic**

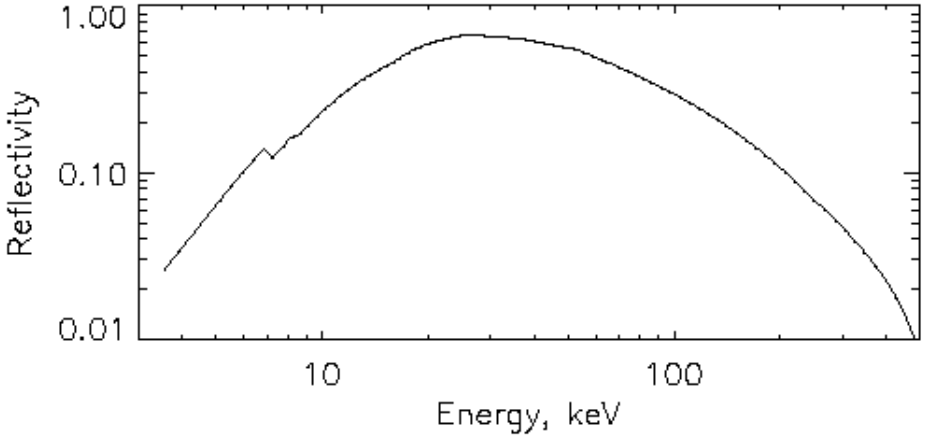
How to measure electron anisotropy?

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, Battaglia et al, this meeting*)

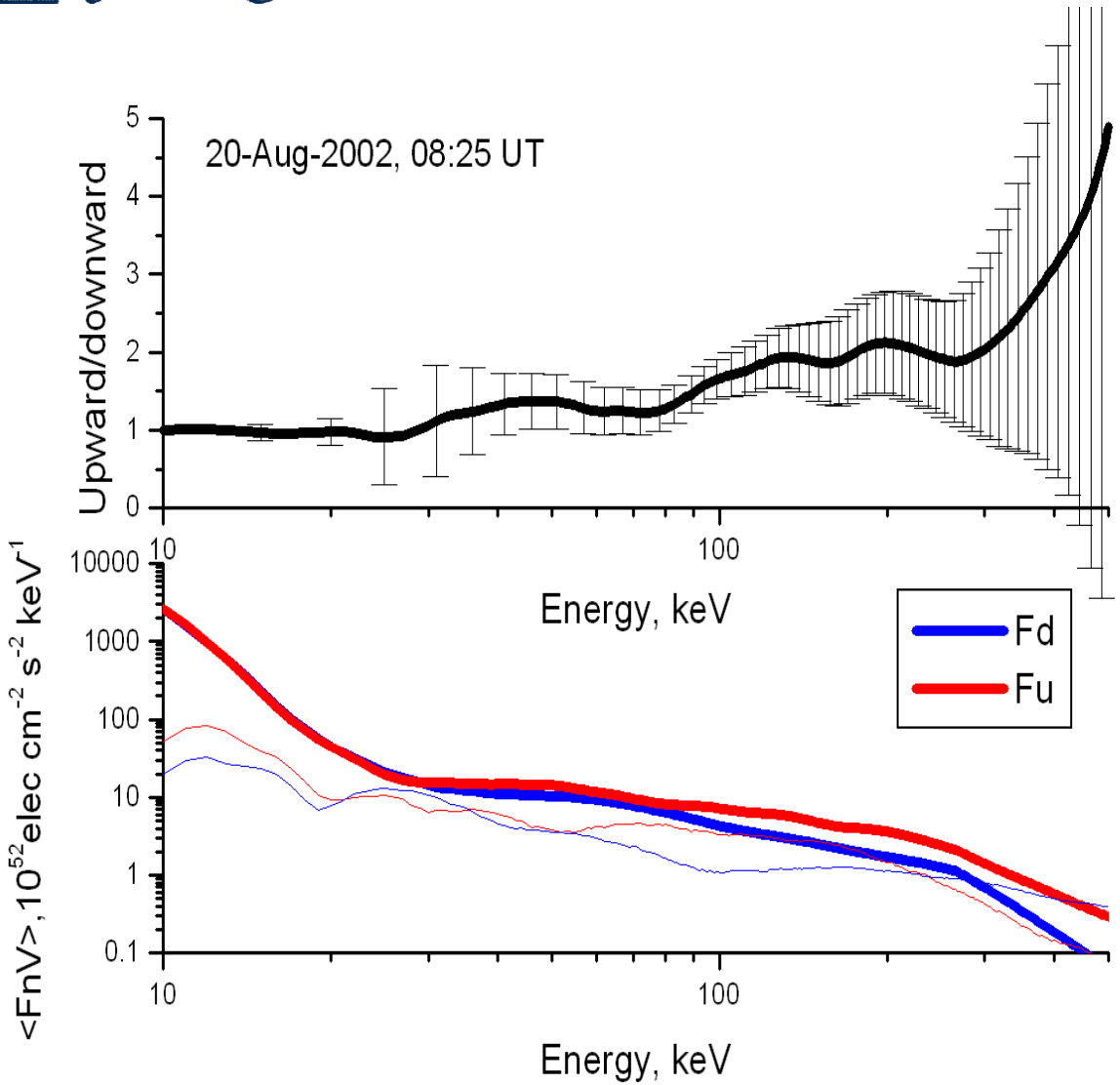
Compton scattering in pictures

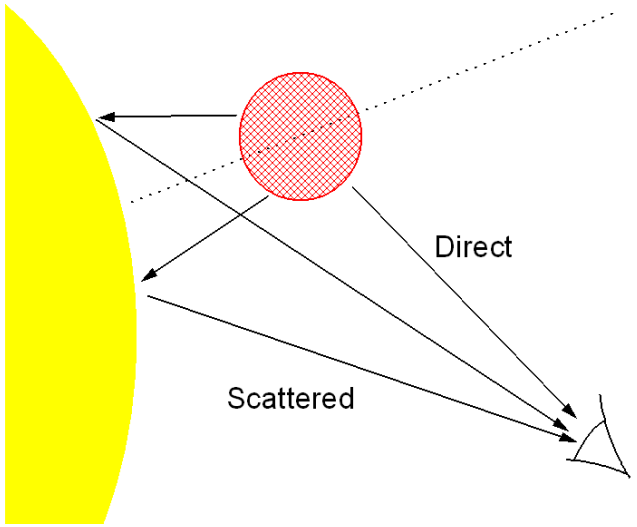






Electron anisotropy: individual events





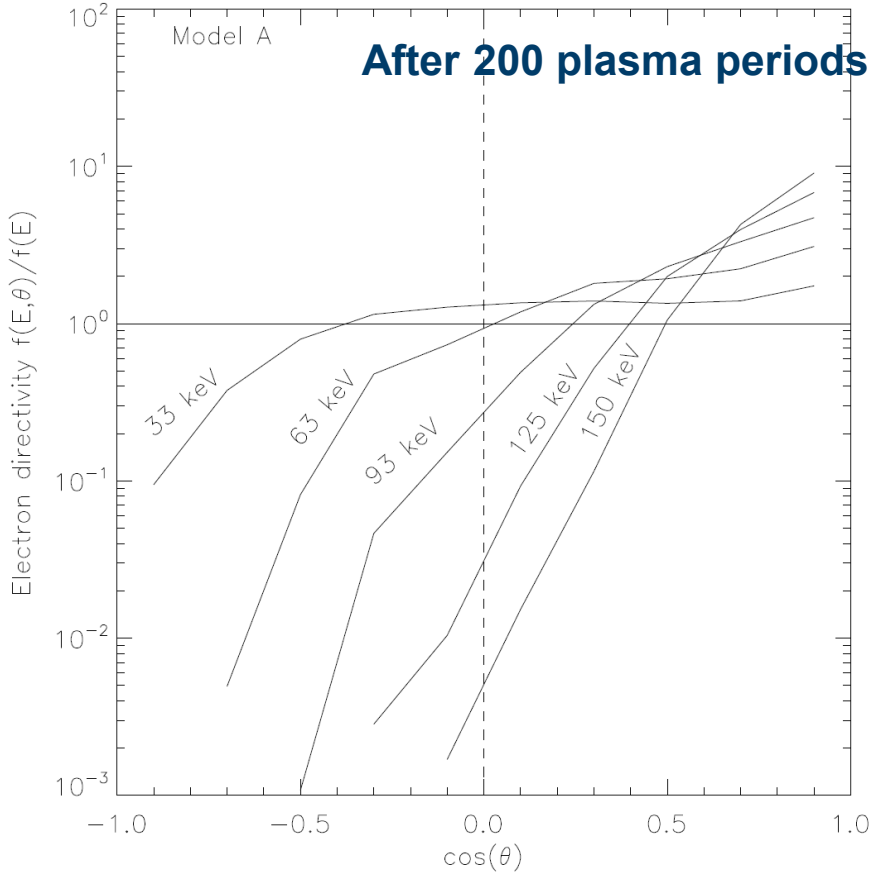
Albedo mirror suggest close to isotropic distribution (e.g. Kontar&Brown, 2006)

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

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

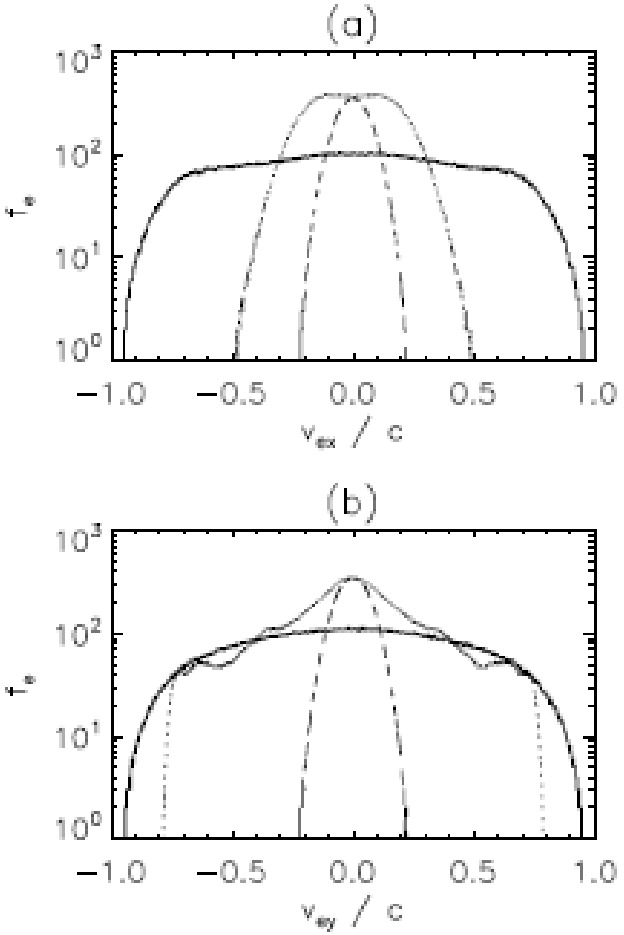
Electron anisotropy in flares

Collective effects of beam-plasma interaction?



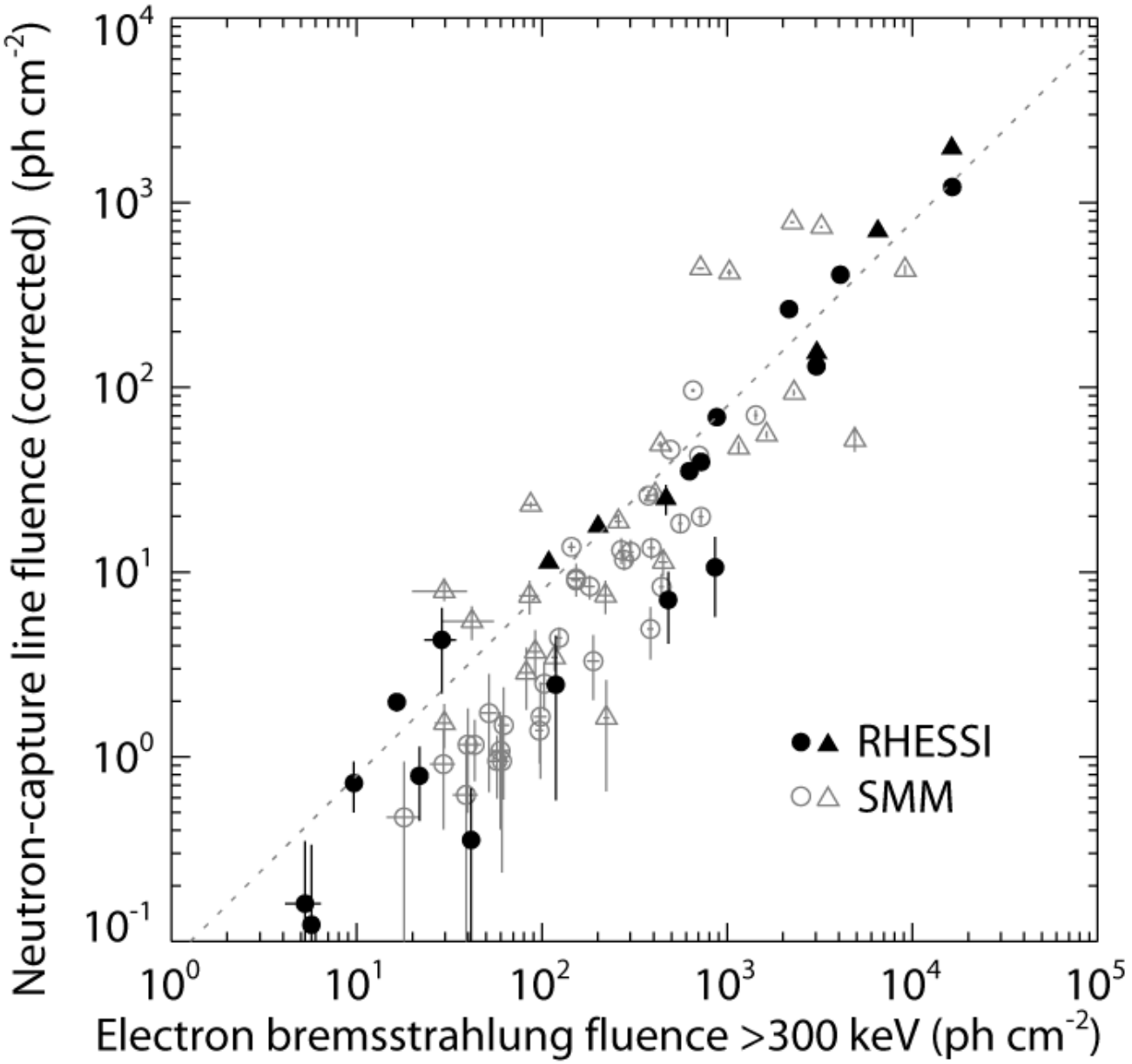
PIC simulations of electron transport (Karlicky & Kasparova, 2009)

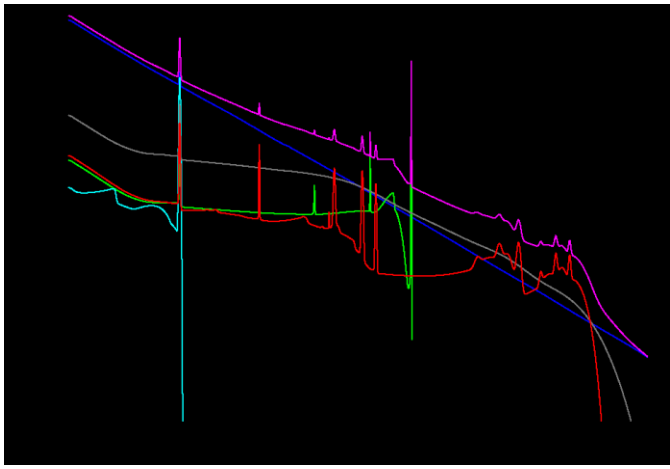
Related to the properties of accelerated electrons?



X-point collapse was studied using kinetic, 2.5-dimensional, PIC code (Tsiklauri and Haruki, 2008)

Electron vs ion acceleration



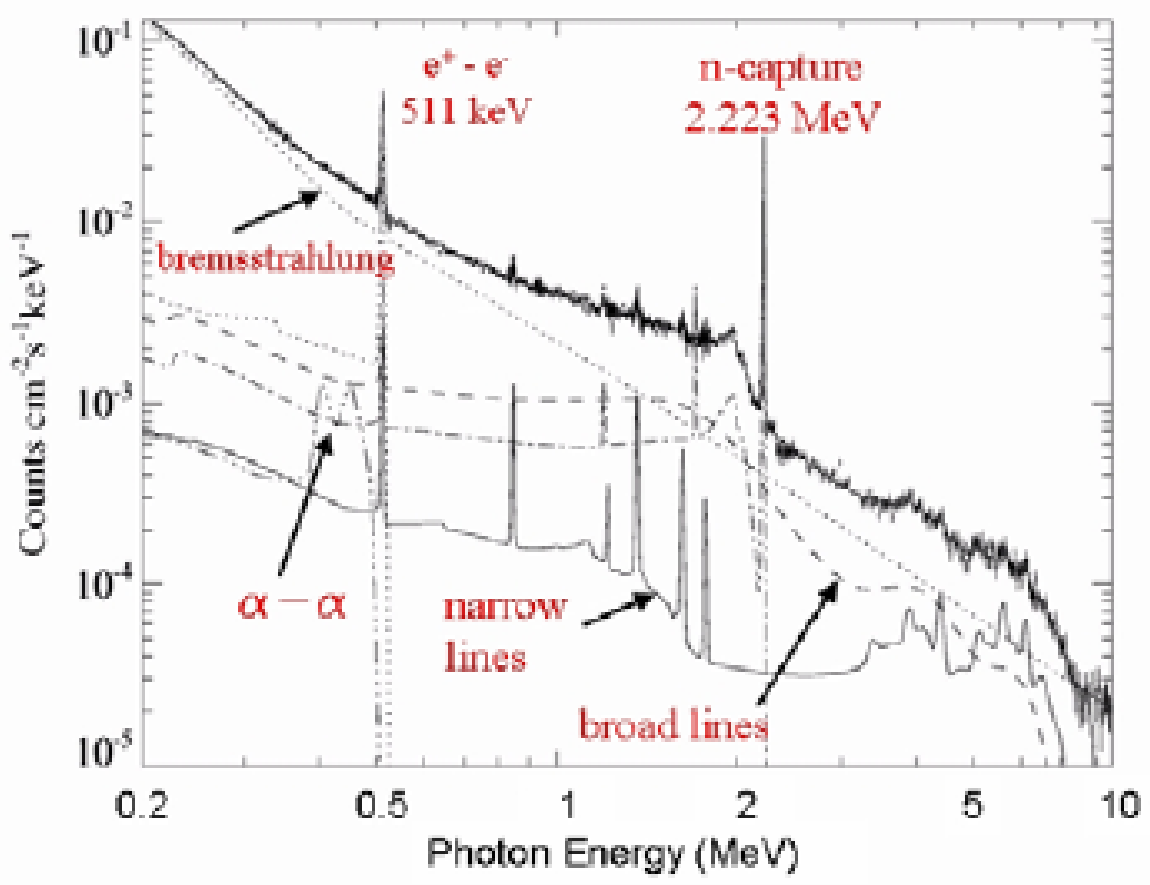


Ion acceleration >30 MeV is correlated with relativistic electron acceleration >300 keV

Ion acceleration >30 MeV is poorly correlated with electron acceleration >50 keV, with the possibility of two separate classes of flares
(Shih et al, 2009)

gamma-ray emission processes

From Murphy and Share, 2004



a) narrow-gamma lines

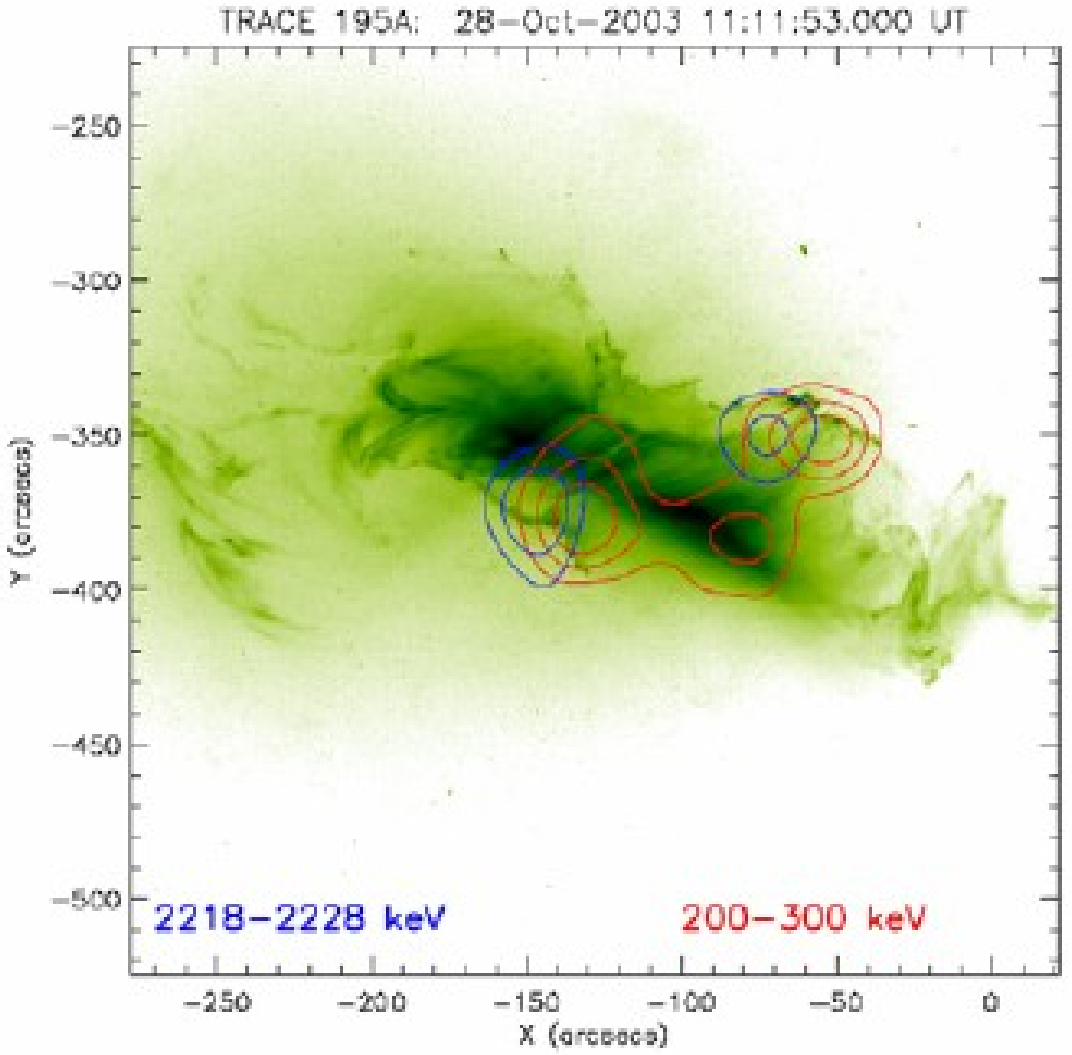
Accelerated protons and alpha particles

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

Accelerated heavy ions and unresolved lines and Compton scatttering

From X-rays to electrons

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. (Hurford et al, 2006)



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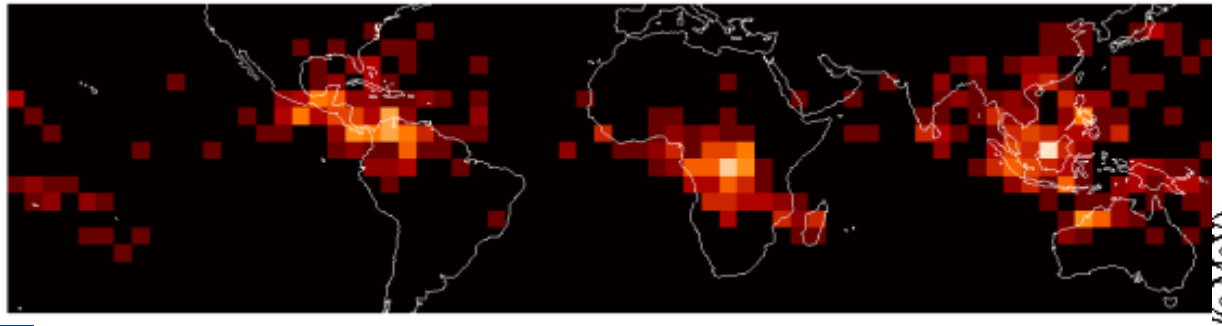
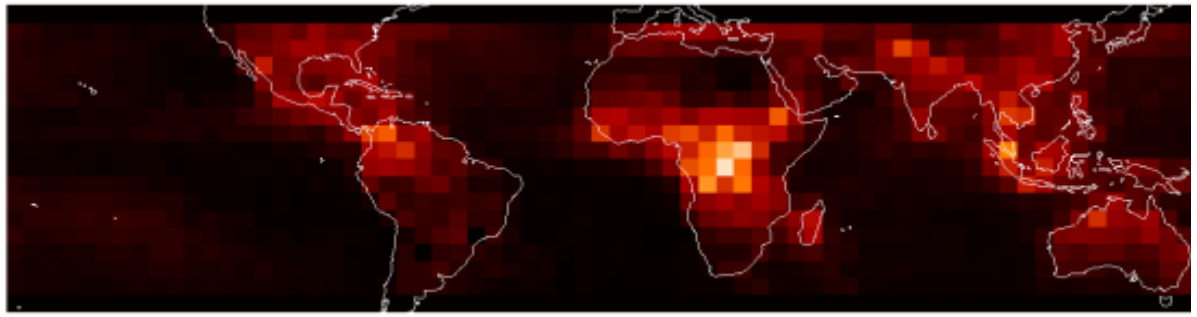
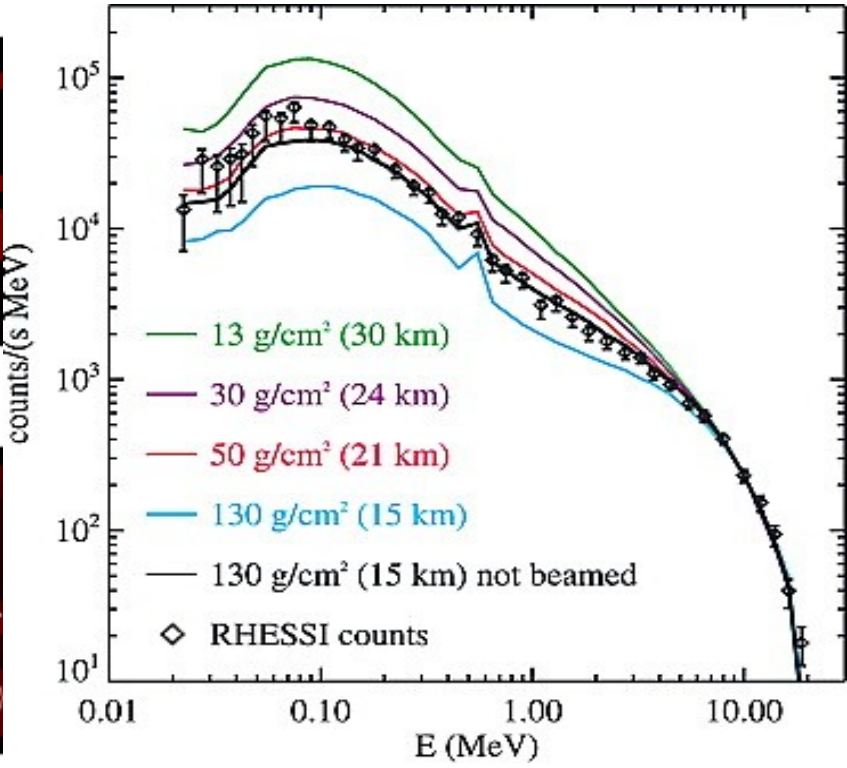
Instead of conclusions…

RHESSI Terrestrial Gamma-ray Flashes Positions



Visible Lightning Positions





Terrestrial gamma-ray flashes (TGFs) are very brief bursts of gamma radiation (typically around 1 millisecond long) coming upwards from the Earth's atmosphere from somewhere in the vicinity of a thunderstorm (Smith et al, 2005)