University of Glasgow

From X-ray observations of solar flare energetic electrons, to new models of particle acceleration and transport

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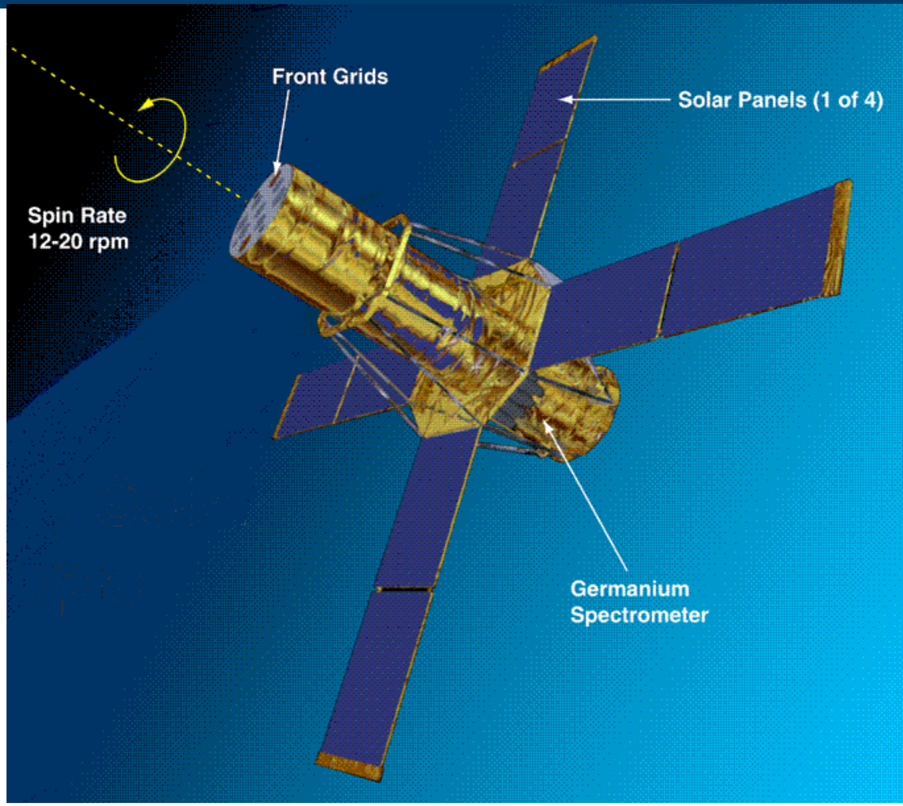
What is RHESSI?

Ramaty
High
Energy
Solar
Spectroscopic
Imager



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

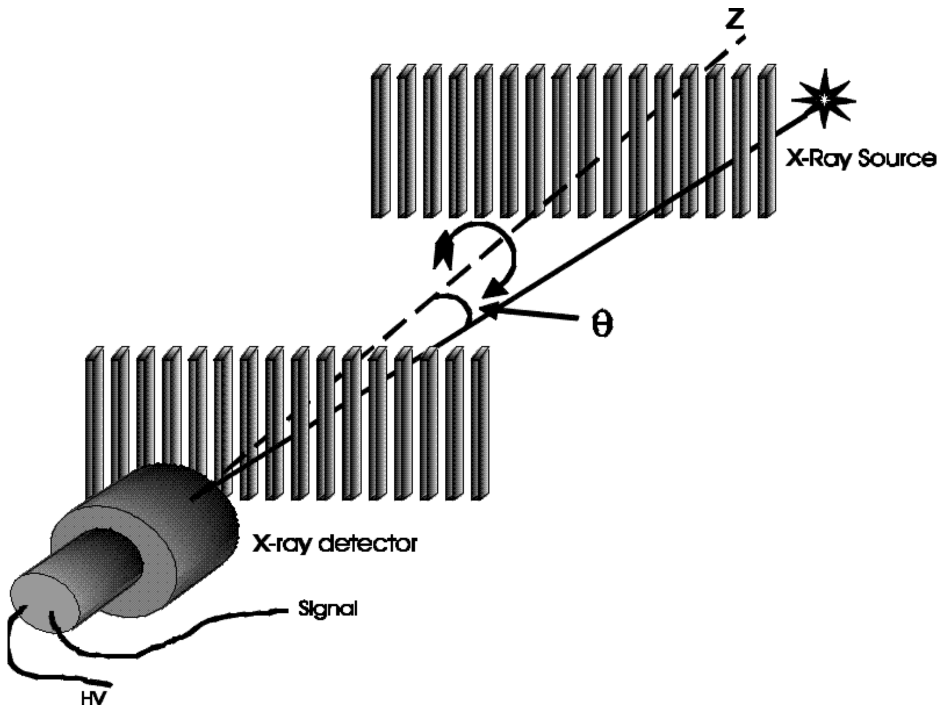
RHESSI is designed to investigate particle acceleration and energy release in solar flares through imaging and spectroscopy of hard X-ray and gamma-rays in the range from 3 keV up to 17 MeV (Lin et al 2002).

What is RHESSI?

Spectroscopy: 9 Ge detectors with energy resolution around 1 keV;

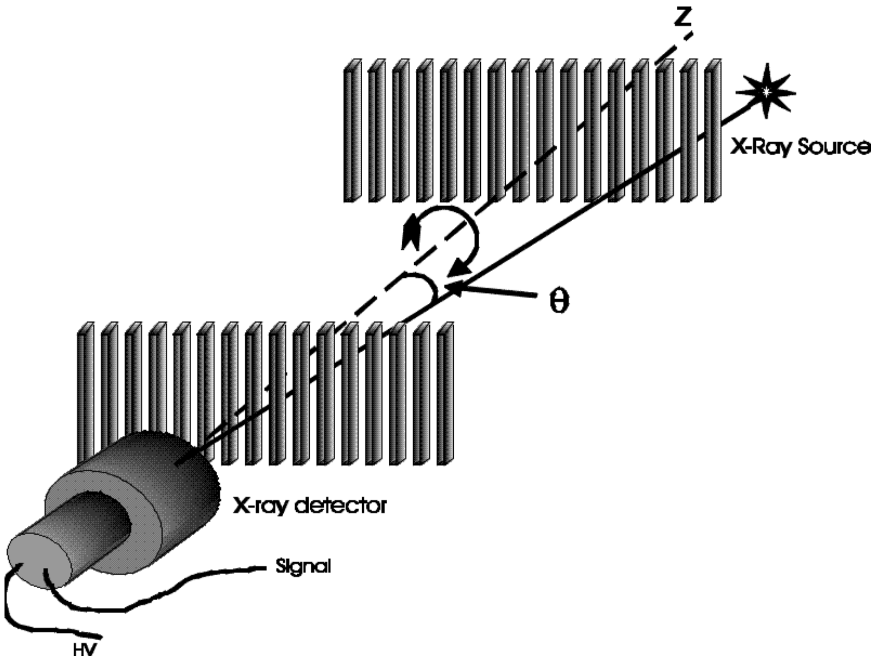
Imaging: rotating modulating collimators allowing angular resolution down to 2.3 arcsec;

Imaging spectroscopy: spectral information in various locations



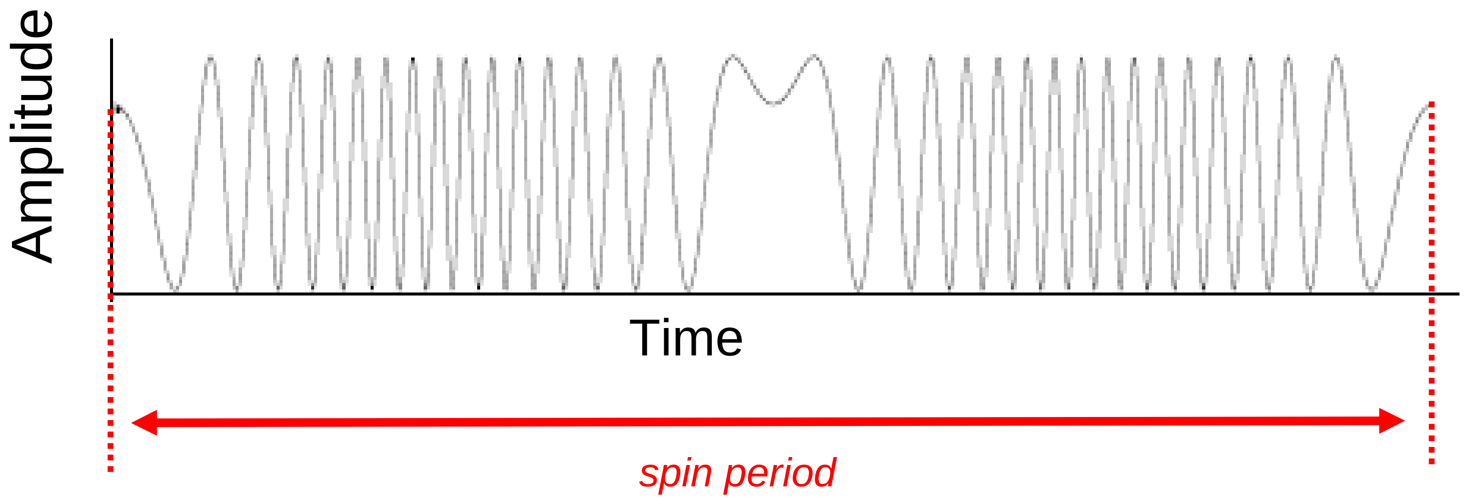
Incoming X-ray flux is modulated by a pair of grids – modulated lightcurves are used later to recover spatial information

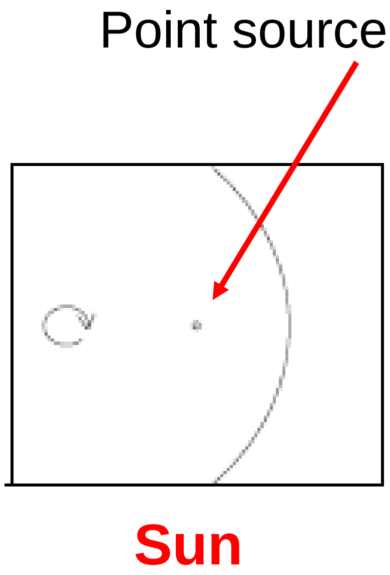
Rotating Modulating Collimators



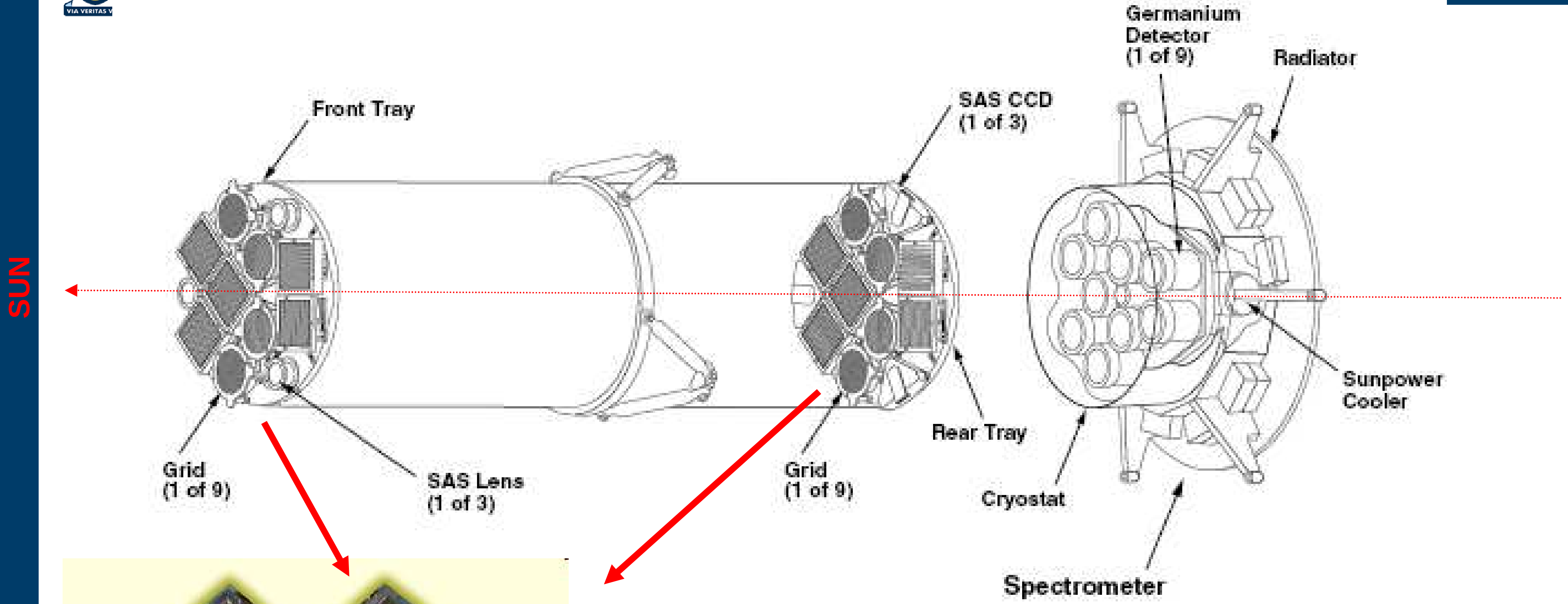
RHESSI detectors look at the source through a pair of grids called **Rotating Modulating Collimator** (RMC)

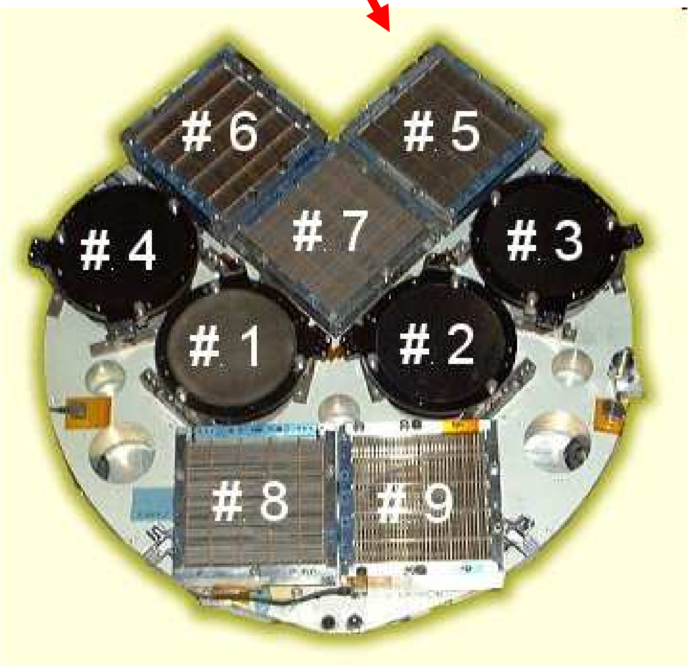
Spacecraft spins about once every ~4 sec => ***artificial modulation of incoming X-ray flux***





RHESSI imaging

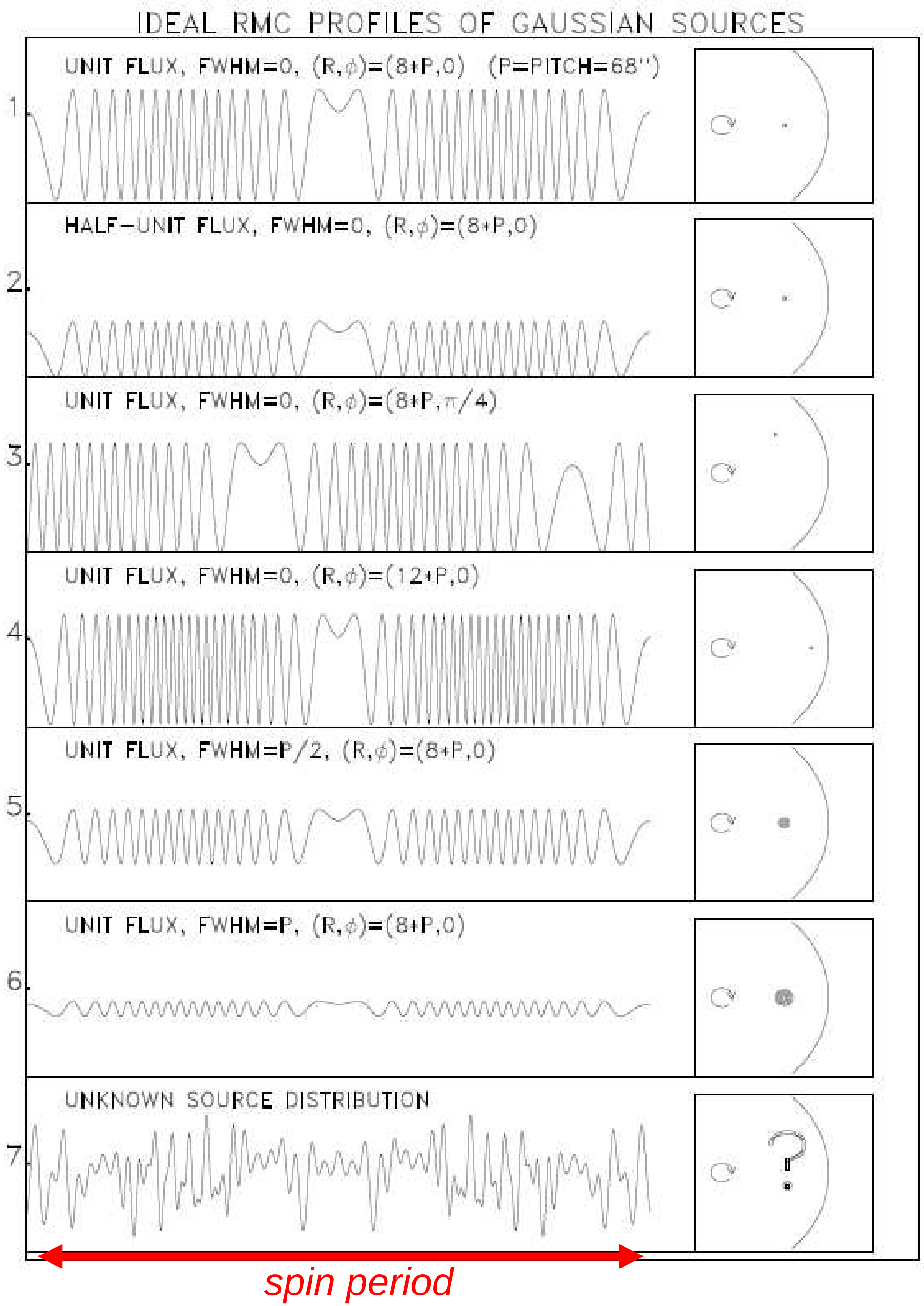




RHESSI has 9 RMCs for 9 detectors

Slats/Slits spacing growing with detector (RMC) number
⇒ angular resolution from ~2.3'' (RMC #1) to 180'' (RMC #9)

RHESSI: ideal modulated lightcurves



Modulation profiles for various ideal sources for a grid of pitch ***P*** with equal slits and slats

Point source

Half flux from the point source => note half amplitude

45 degrees angle => note change of phase

Source further from the axis => note change of modulation frequency

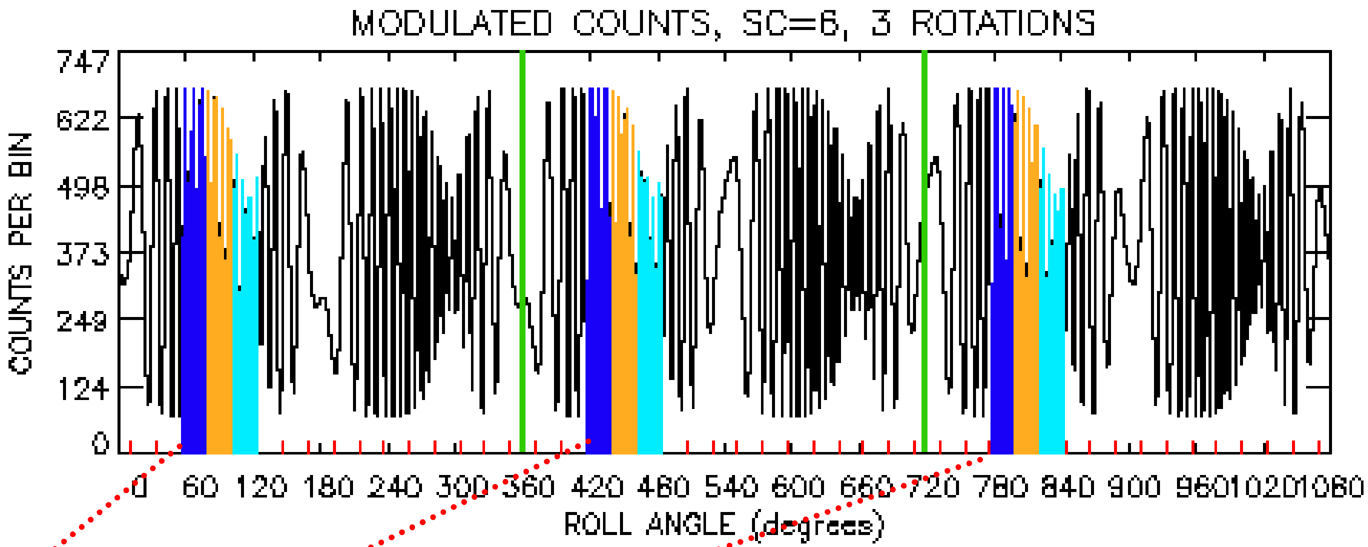
Source size=P/2 => note change of the amplitude

Source size=P => note change of modulation depth (no modulation for source size >> P)

Modulation encodes spatial source information:
Phase of the modulation => position angle
Distance from the centre => modulation frequency
Amplitude => source size

RHESSI imaging

X-ray visibilities



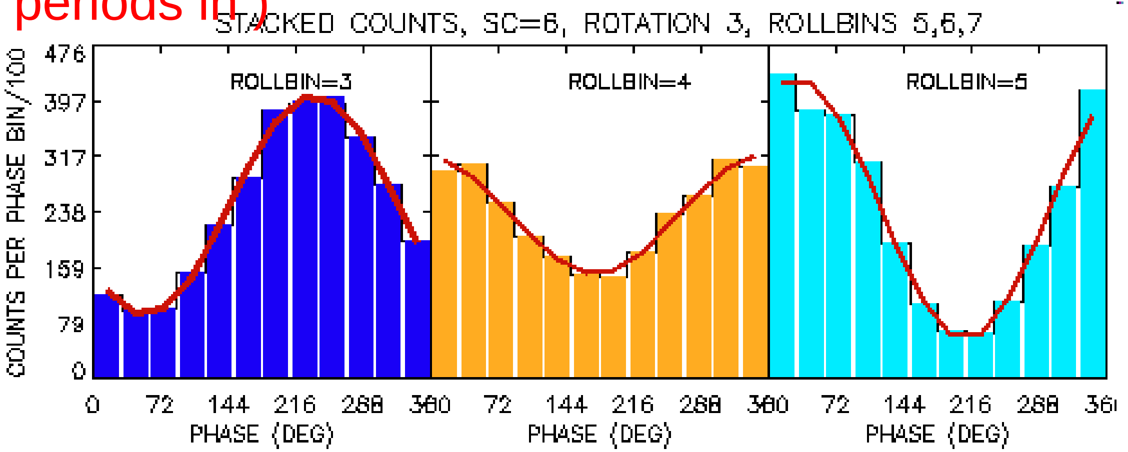
Fourier, Joseph, Baron
(***From Britannica.com***)

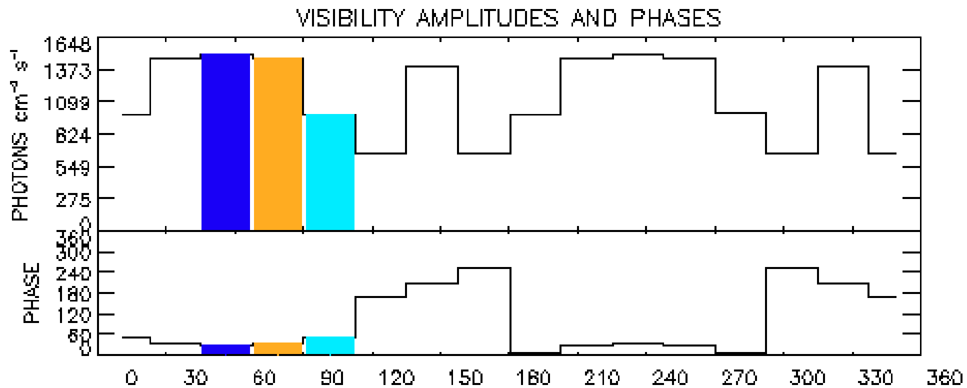
RHESSI Modulation profile over three periods from (*Schmahl and Hurford*)
(http://sprg.ssl.berkeley.edu/~tohban/nuggets/?page=article&article_id=39)

Stacking
(sum one roll bin over a few periods in.)

Each period is split into **roll bins** (here it is 16)

Stacking increasing signal-to-noise ratio and helps to calculate **mean amplitude and phase**
=> **X-ray Visibilities!**



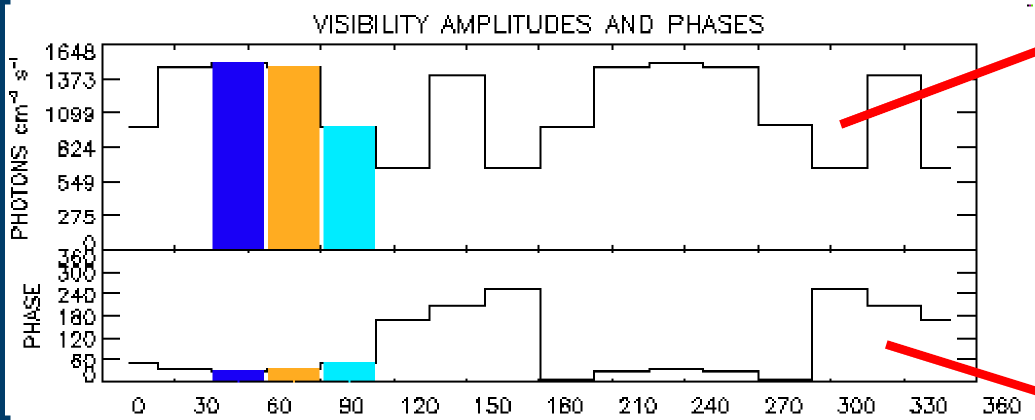


X-ray visibilities

X-ray Visibilities are two dimensional spatial Fourier components of X-ray source

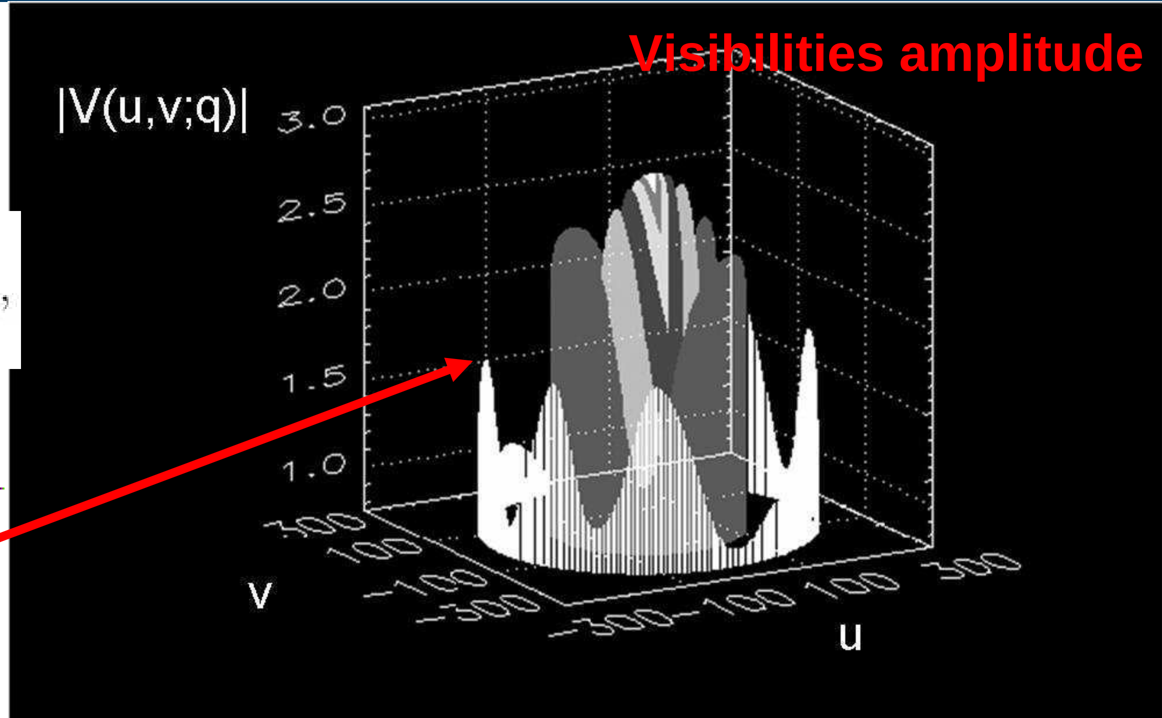
$$V(u,v;q)dq = \int_x \int_y \int_{\epsilon=q}^{\infty} D(q,\epsilon) I(x,y;\epsilon) e^{2\pi i(ux+vy)} d\epsilon dx dy \quad ,$$

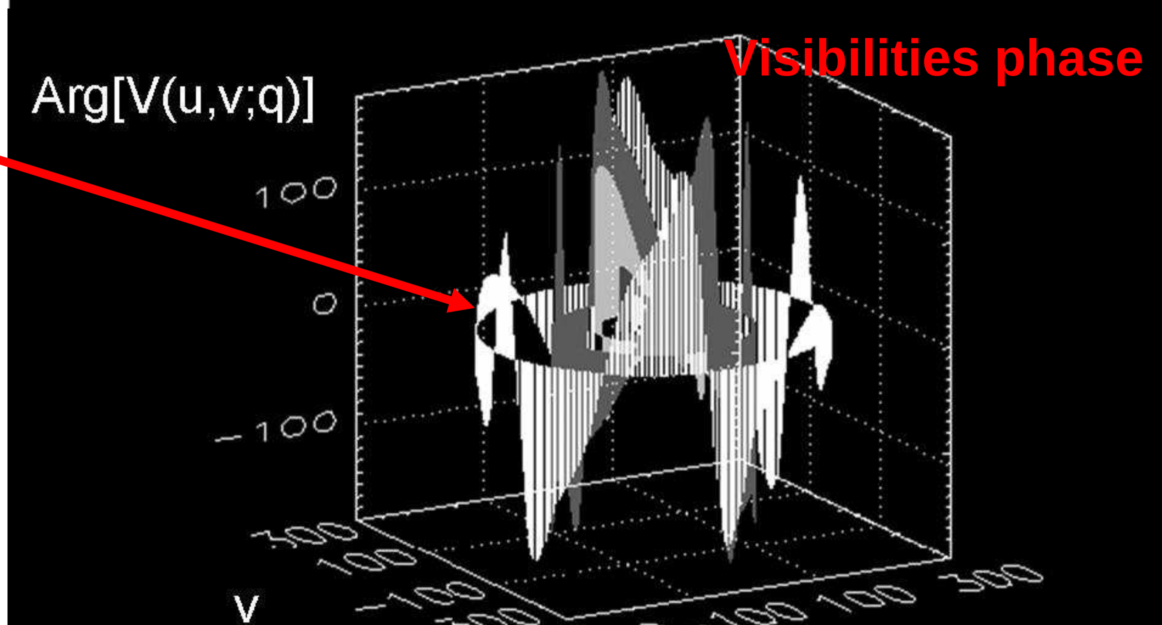
Visibilities amplitude



Visibilities phase

Note 9 circles (nine RMCs) in U,V (spatial frequencies) plane

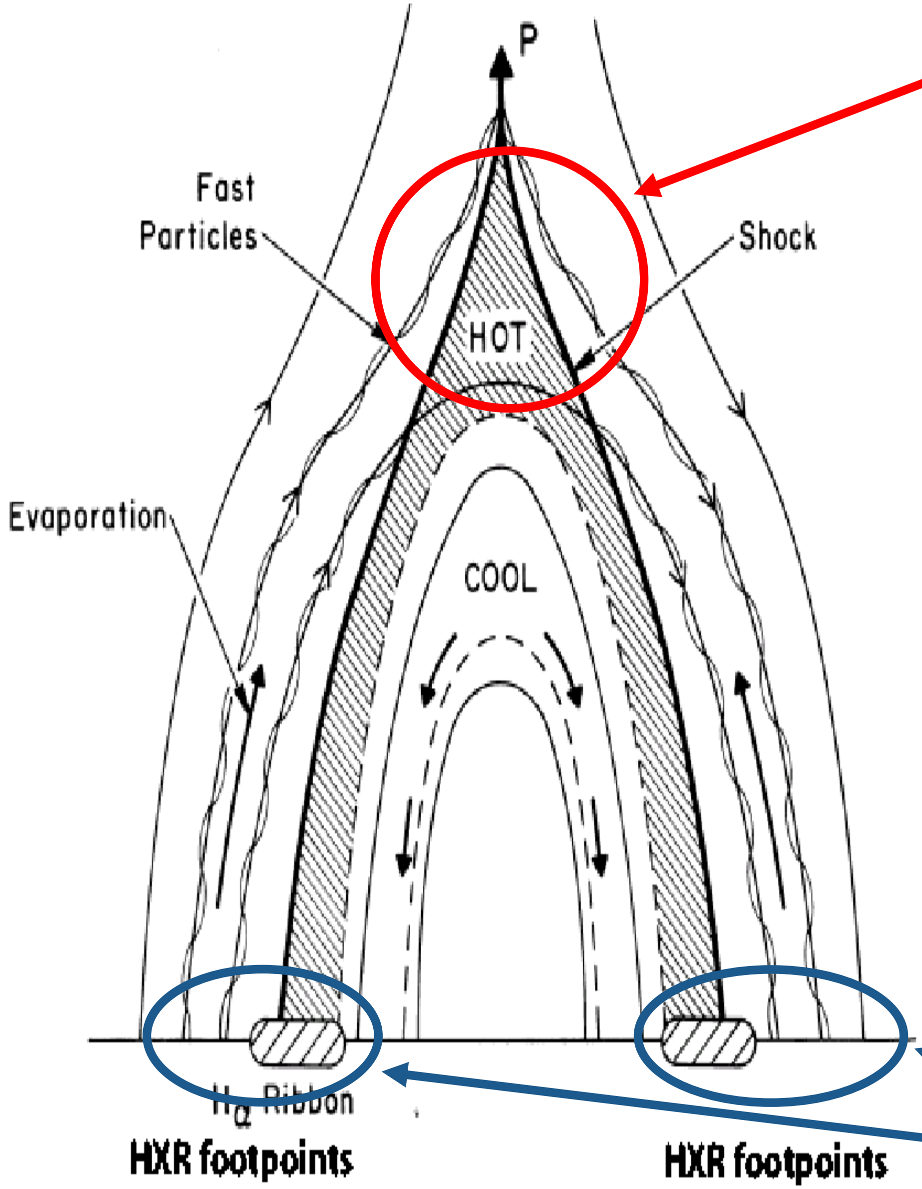




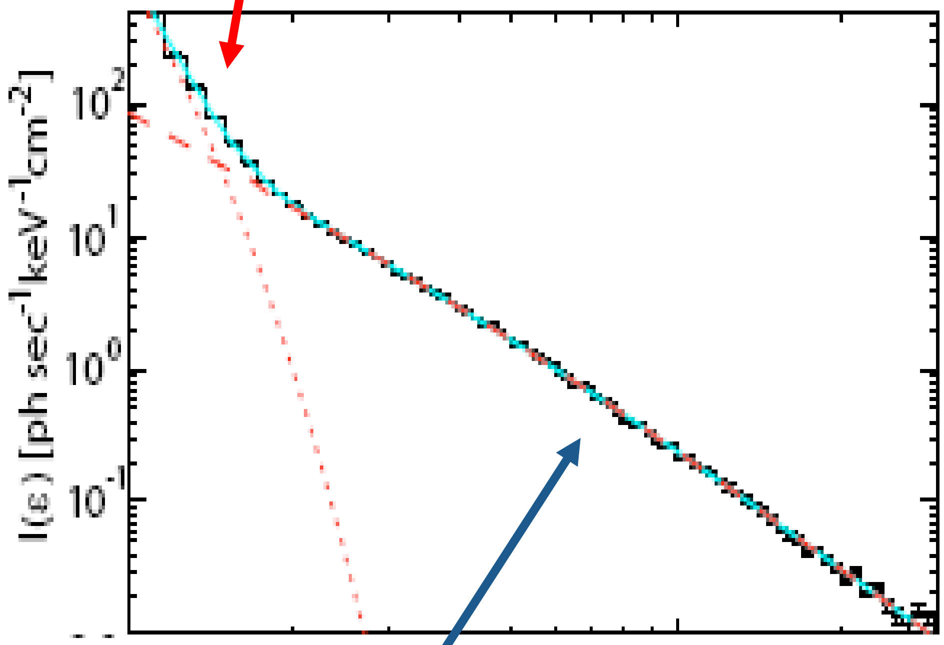
Prato et al, 2008

Standard fare geometry

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



RHESSI spectrum

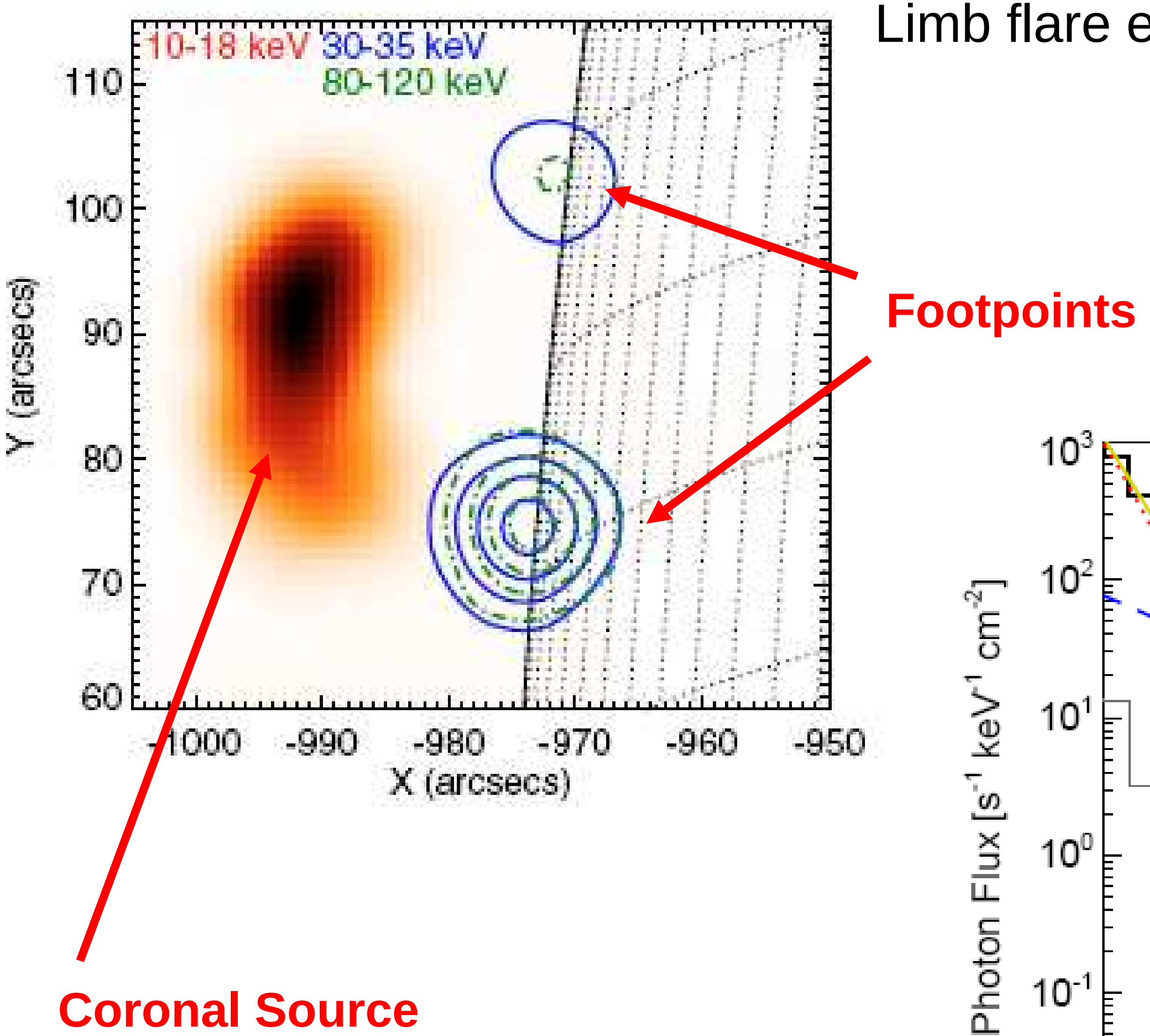


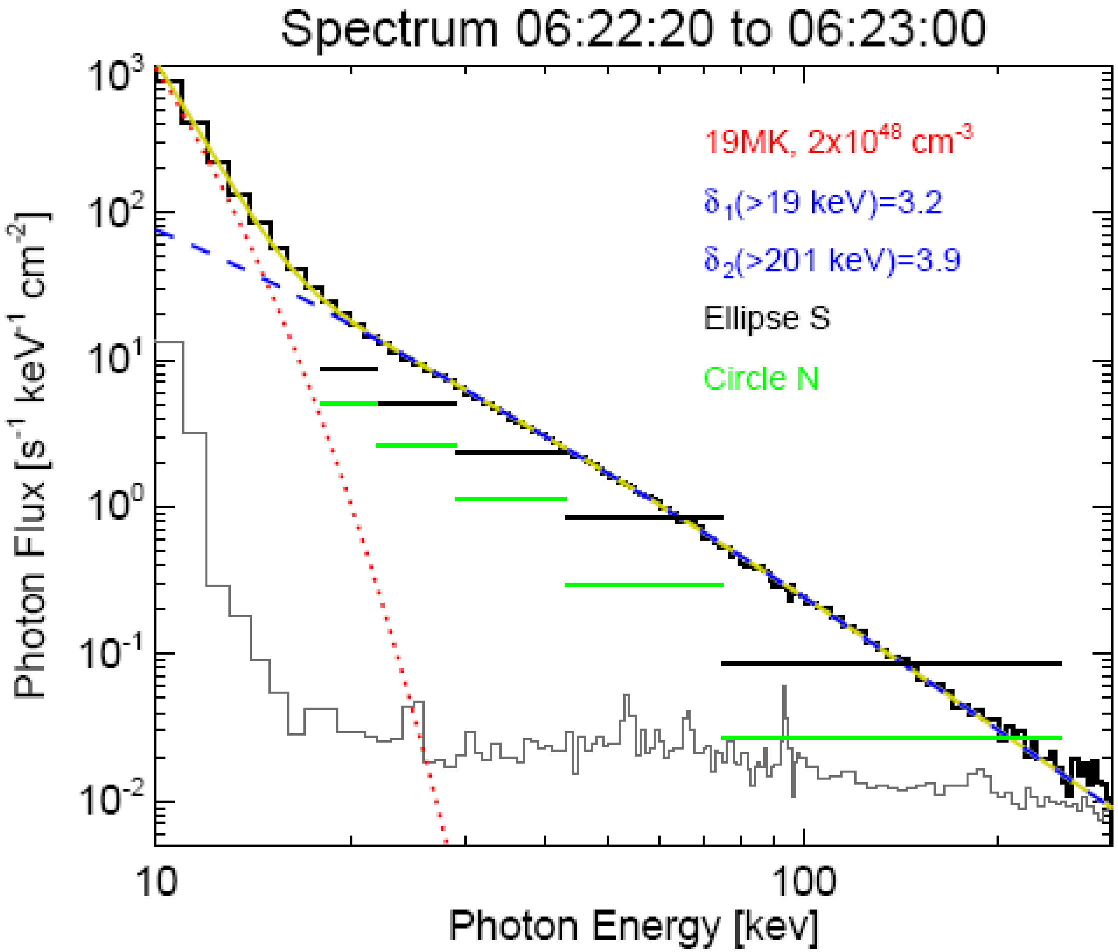
Hard X-ray sources above ~20 keV

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

X-ray emission from limb flares

Limb flare event 6 January 2004

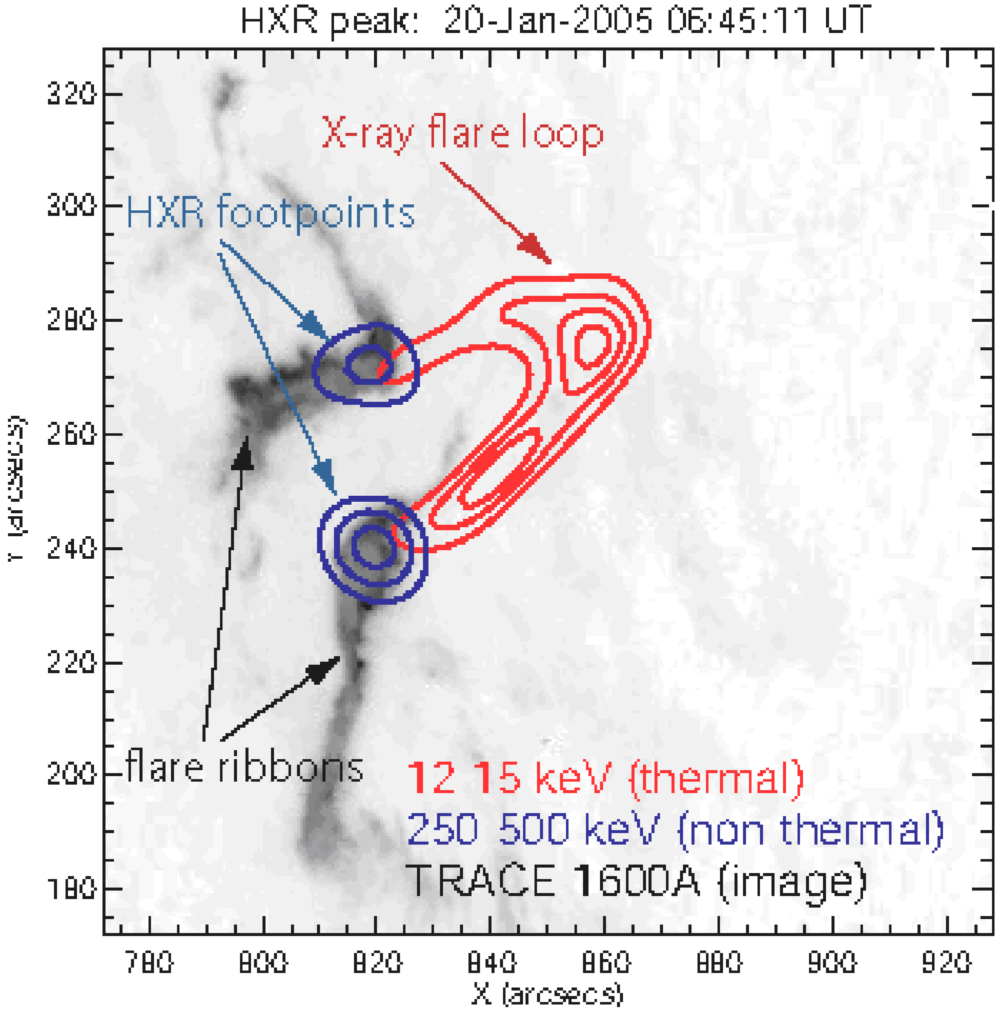




X-rays and flare accelerated electrons

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

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



*F(E,**Ω**,**r**)=???*

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

2) What is the ***angular*** distribution, *F(E,**Ω**)*?

3) What is ***spatial*** distribution, *F(E,**r**)*?

From Krucker et al, 2007

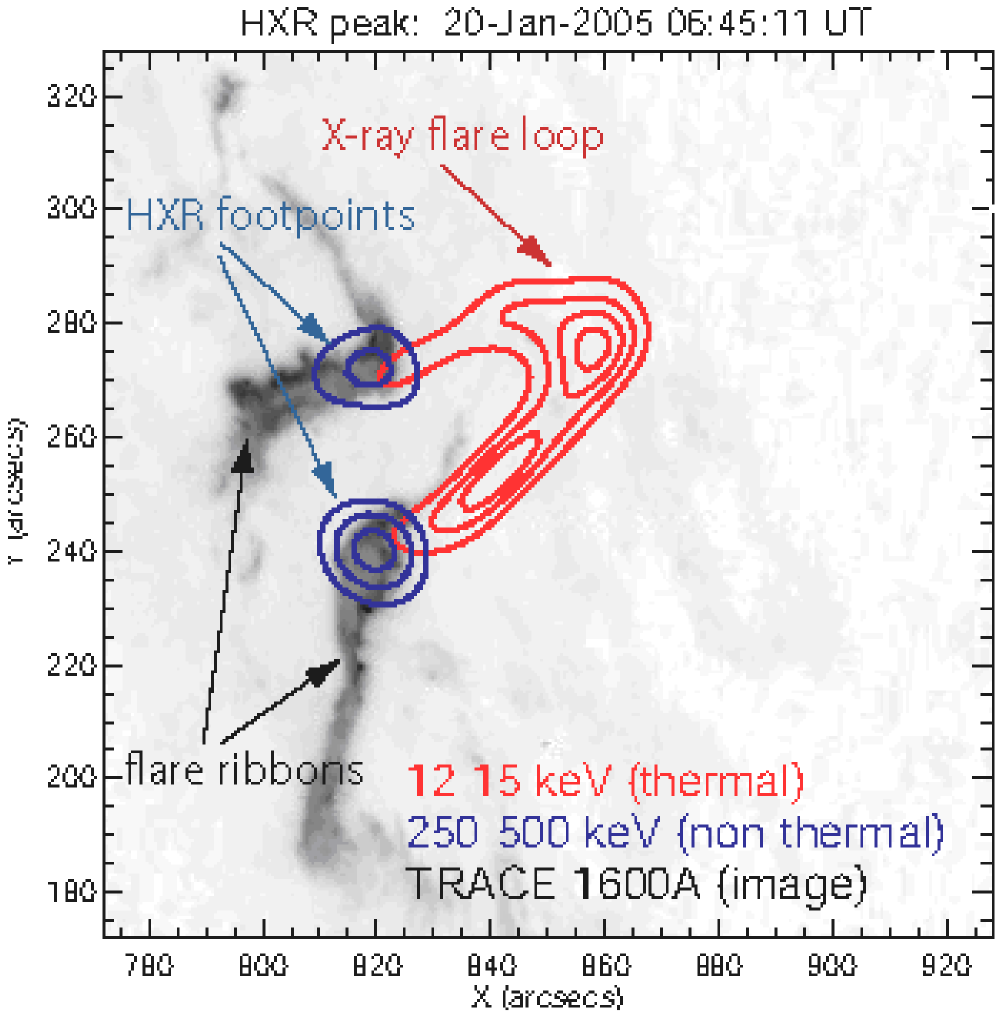
X-rays and flare accelerated electrons

Observed X-rays

Unknown electron distribution

Emission cross-sections

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



Resolution is > 2.3''

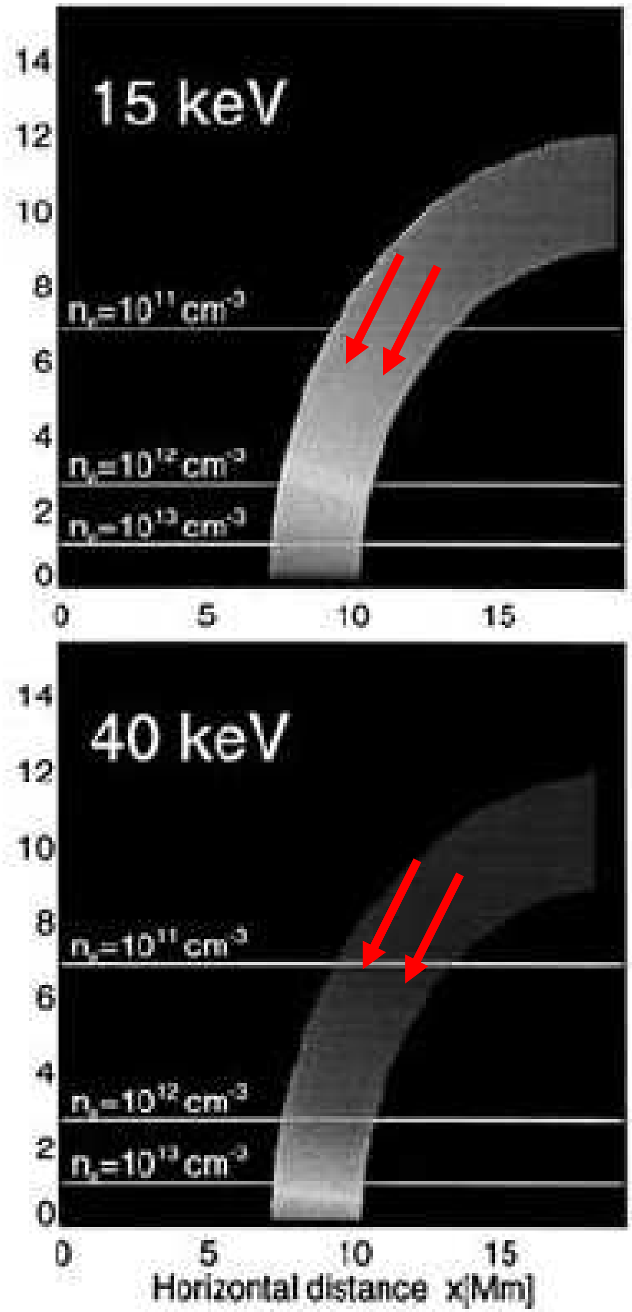
However, we can accurately measure moments of distribution:

1st moment – position

2nd moment - size

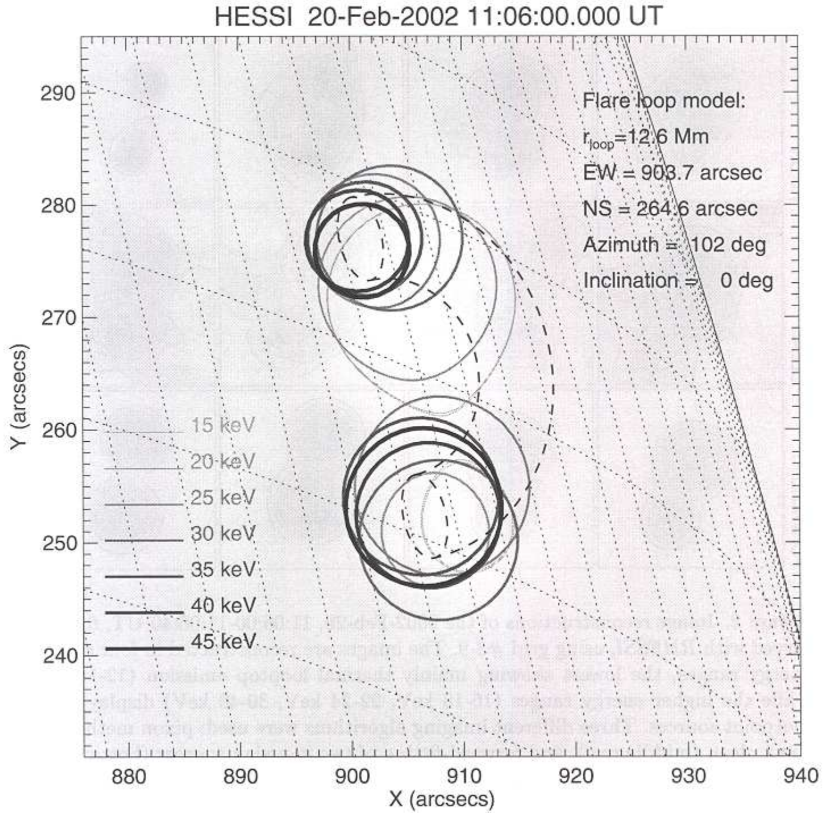
From Krucker et al, 2007

First measurements using fit to the light curves



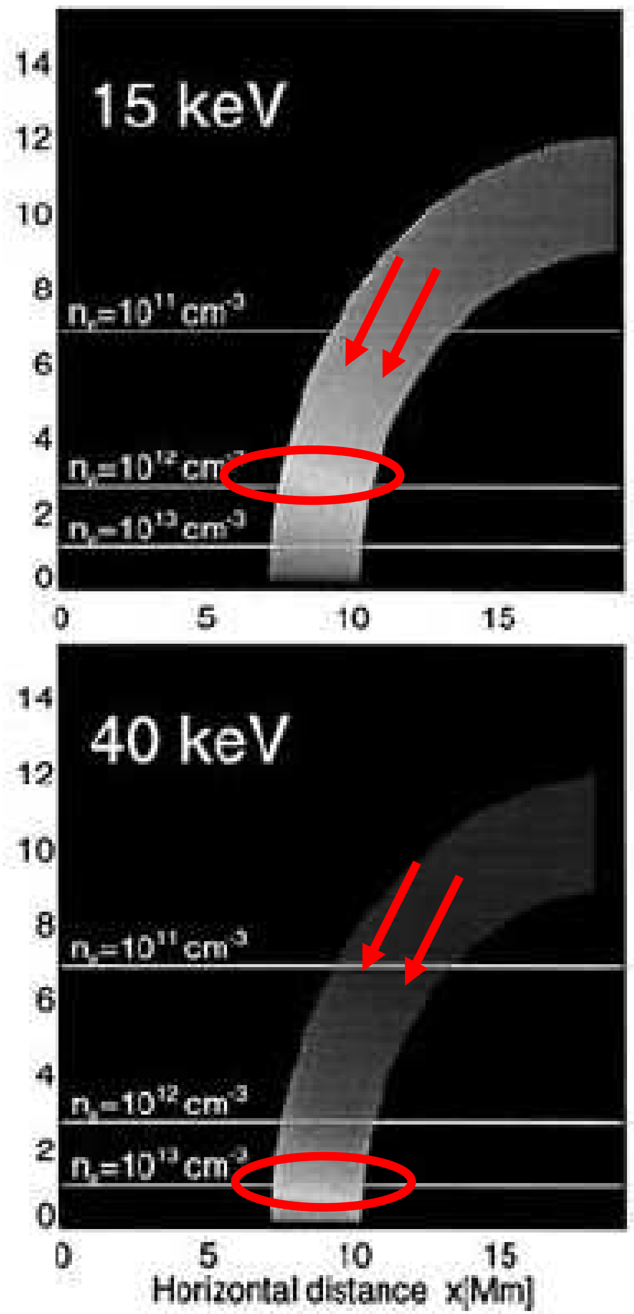
Aschwanden et al, 2002

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



=> Max position with 1'' accuracy

Electron transport: theory



If we assume collisional transport:

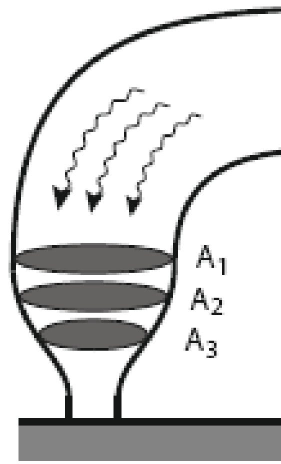
$$F(E,z) = F_{\rm IN} E \left(\sqrt{E^2 + 2KN(z)} \right)^{-\delta-1},$$

X-ray emission at various energies should appear at different heights (Brown et al, 2002):

$$I(\epsilon, z) = \frac{n(z)}{4\pi R^2} \int_{\epsilon}^{\infty} F(E,z)\sigma(\epsilon, E)\mathrm{d}E$$

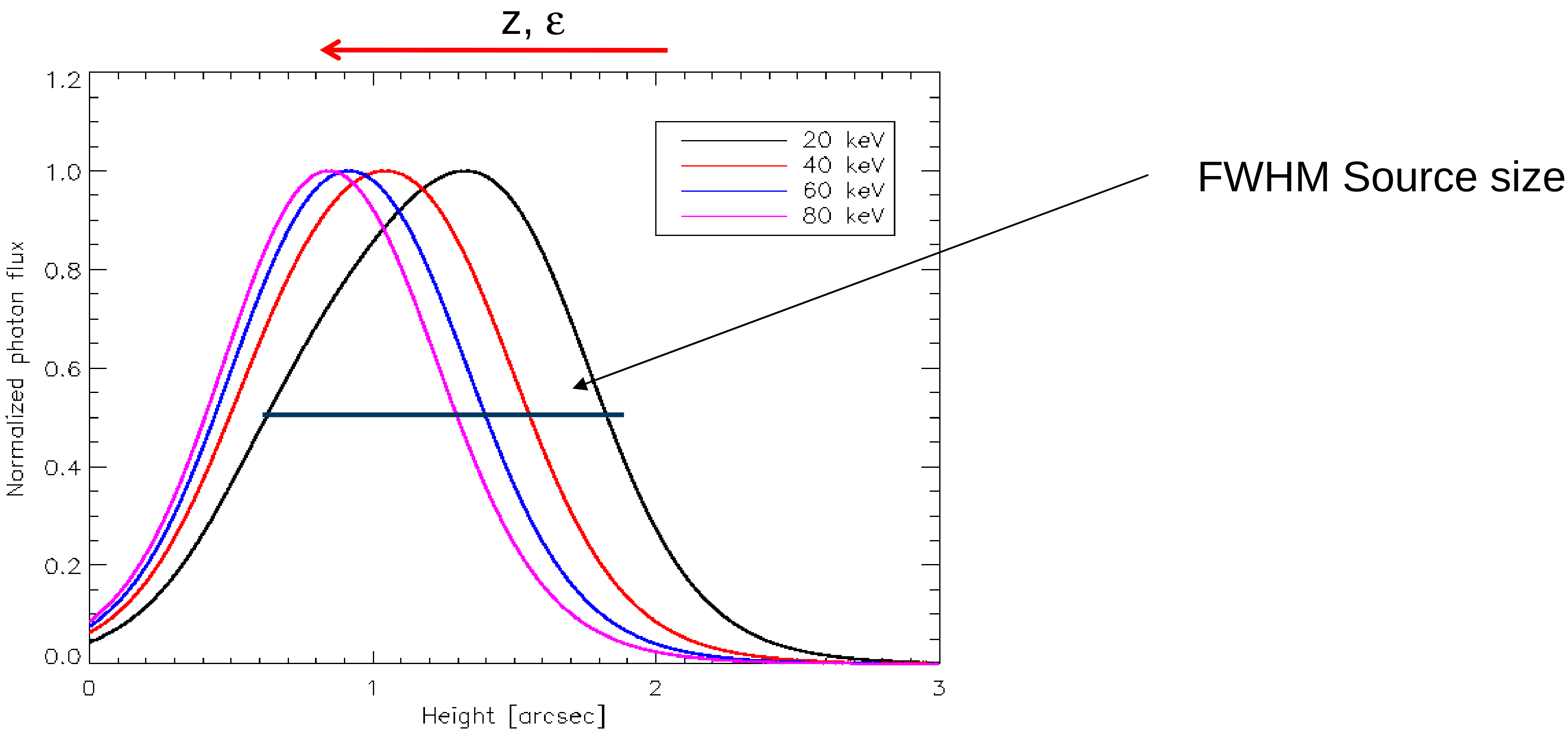
Indeed, higher energy sources appear lower in the chromosphere (consistent with simple collisional transport) Aschwanden et al, 2002

If we can we measure not only the positions but the sizes of X-ray sources we can learn about the transport of the electrons in the chromosphere



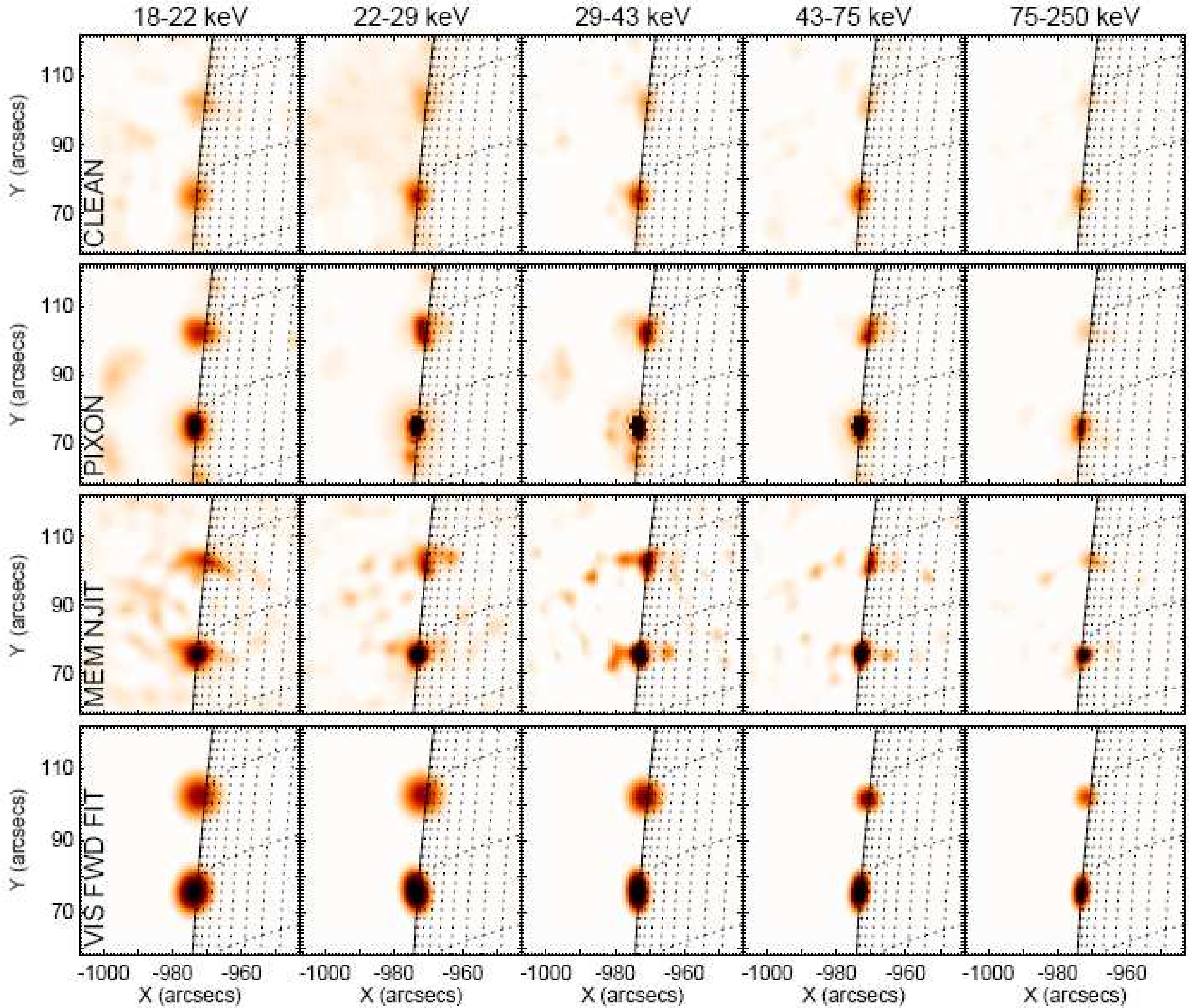
X-ray flux at different energies: theory

$$I(\epsilon, z) = \frac{n(z)}{4\pi R^2} \int_{\epsilon}^{\infty} F(E, z)\sigma(\epsilon, E)\mathrm{d}E$$

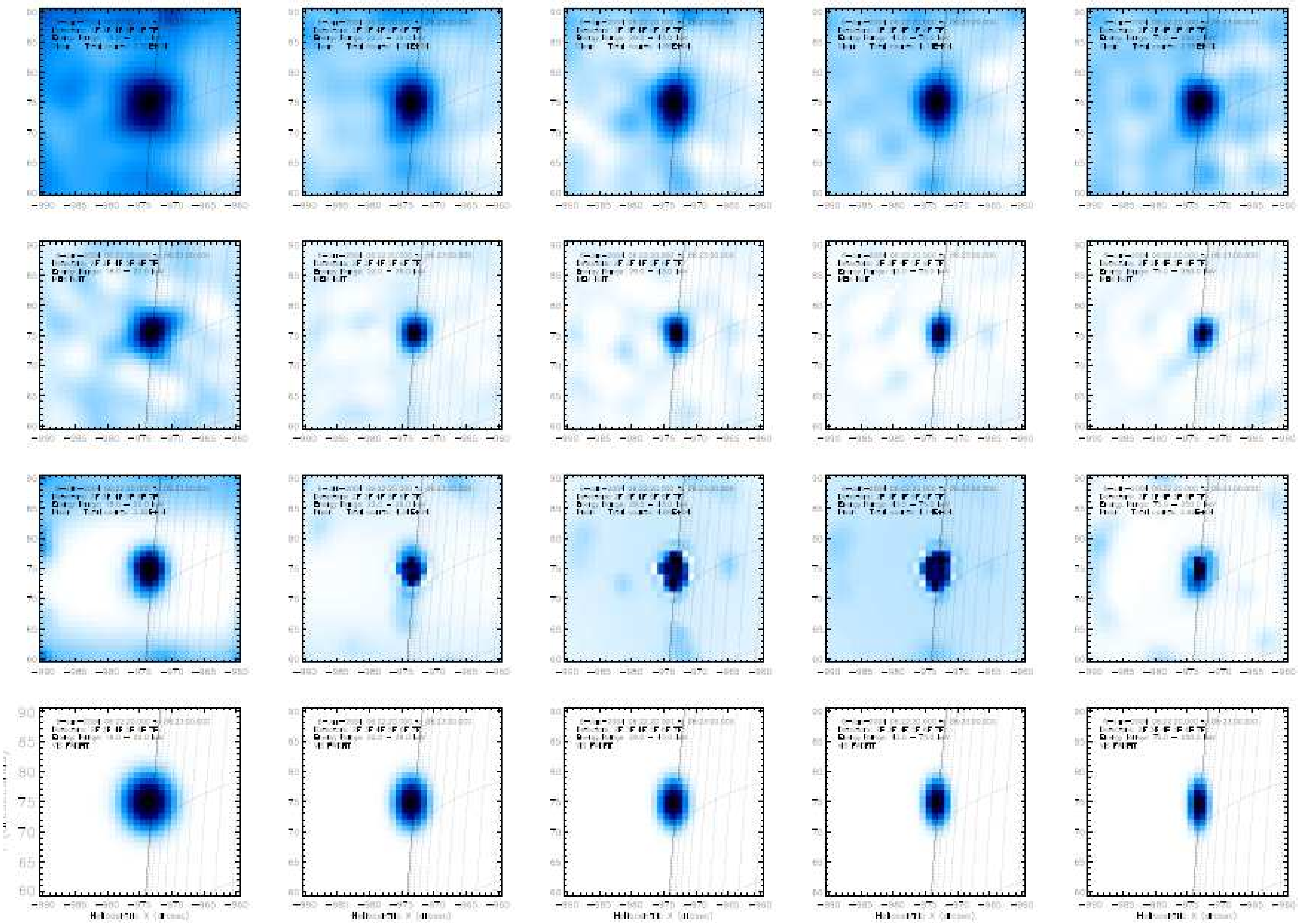


Photosphere → Corona

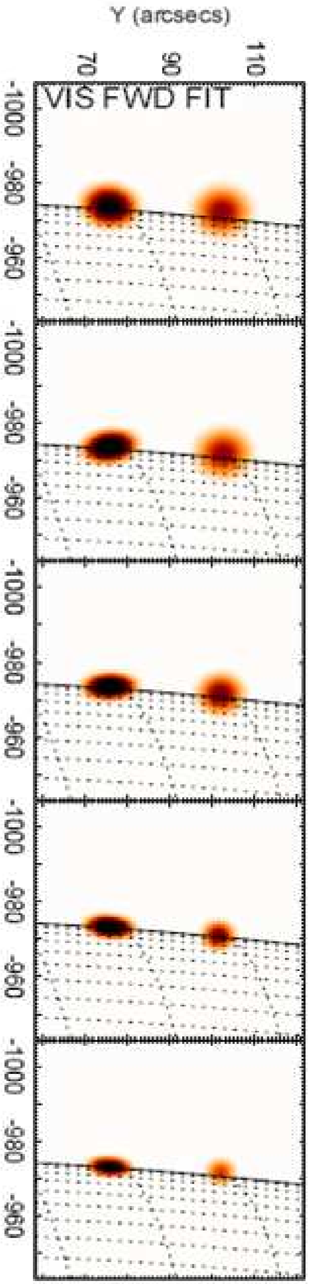
Hard X-ray images

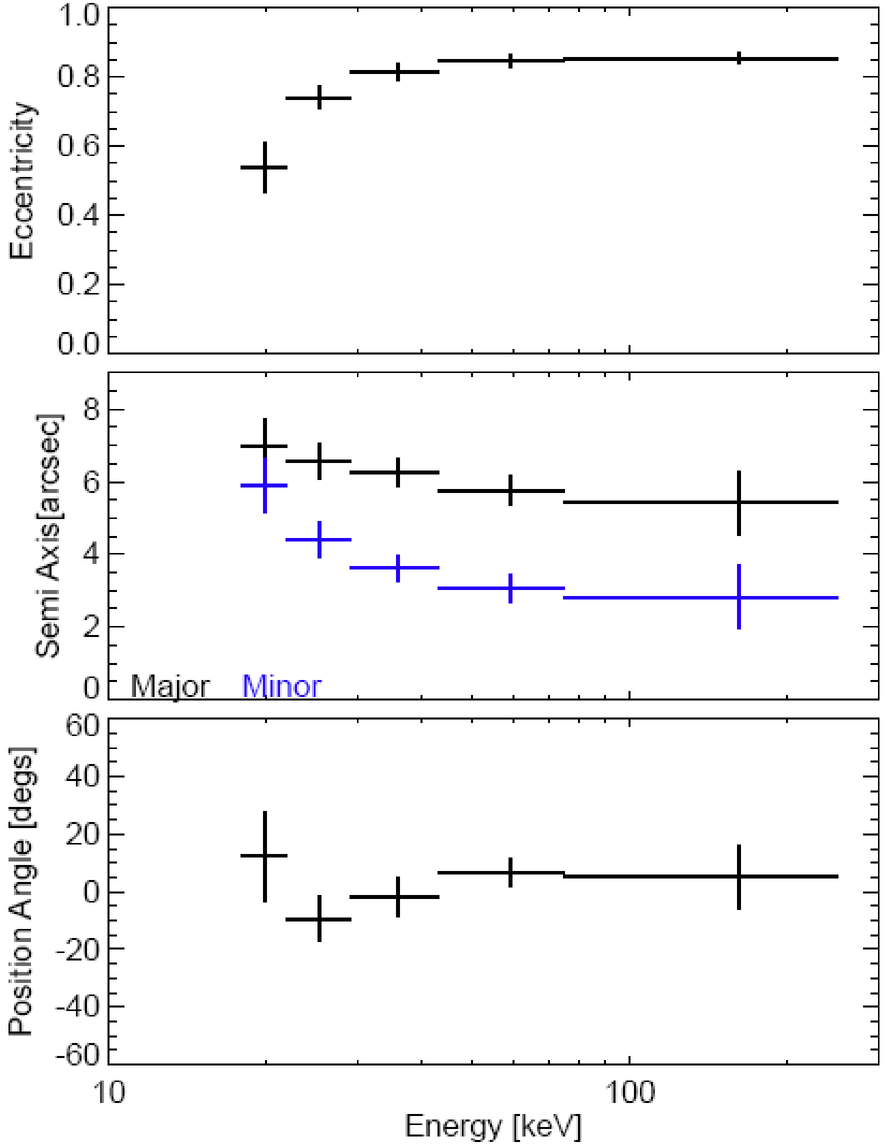


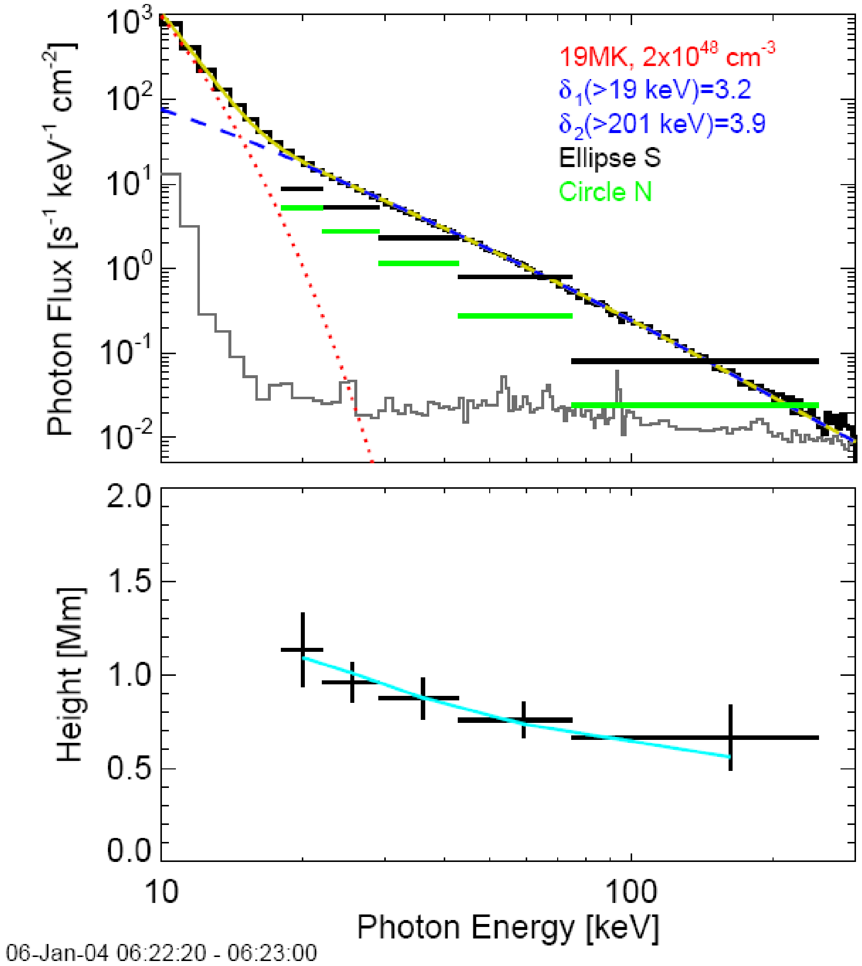
X-rays images: ”southern” footpoint



Energy dependent positions



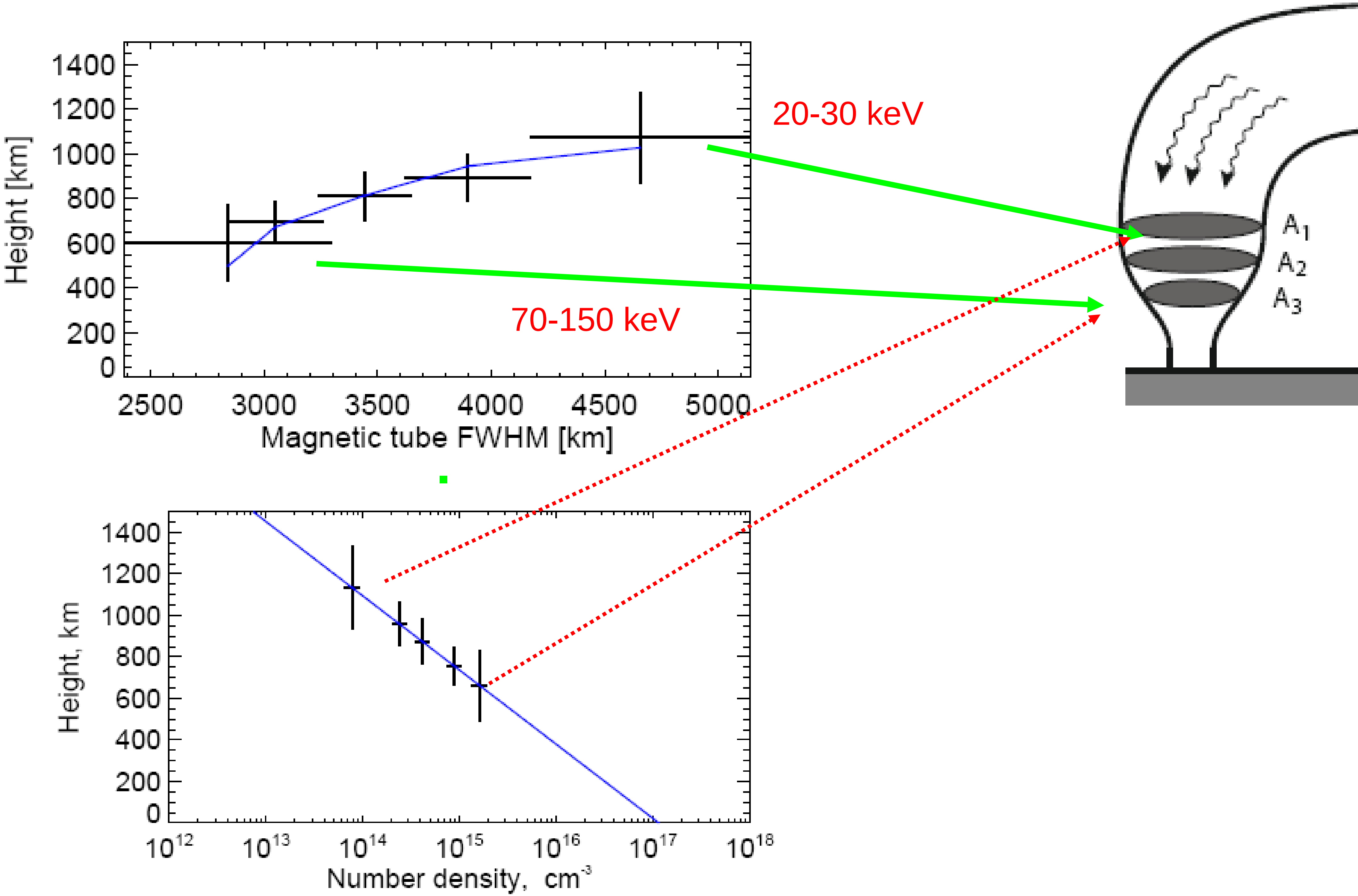




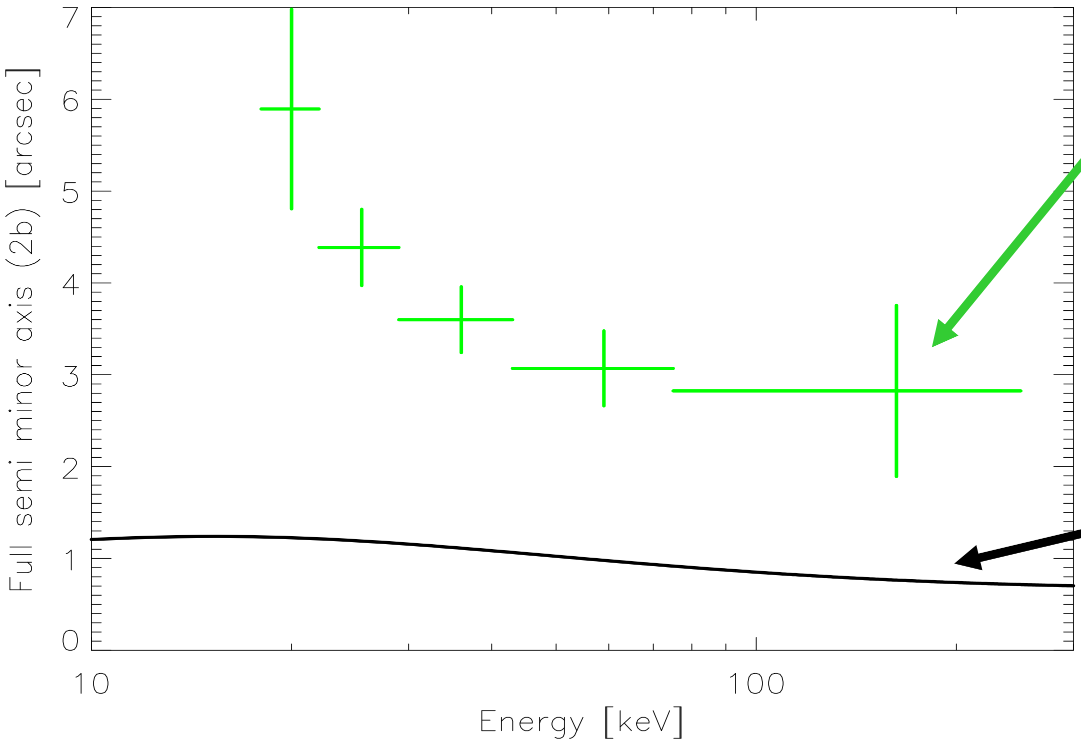
$$n(h = r - r_0) = n_0 \exp\left(\frac{-(r - r_0)}{h_0}\right),$$

Fixed at photospheric density

Chromospheric field structure measurements



The simple thick target case is inaccurate



Vertical size of the footpoint measured in 6th January event

Vertical size of the footpoint, expected from collisional transport

Possible explanations

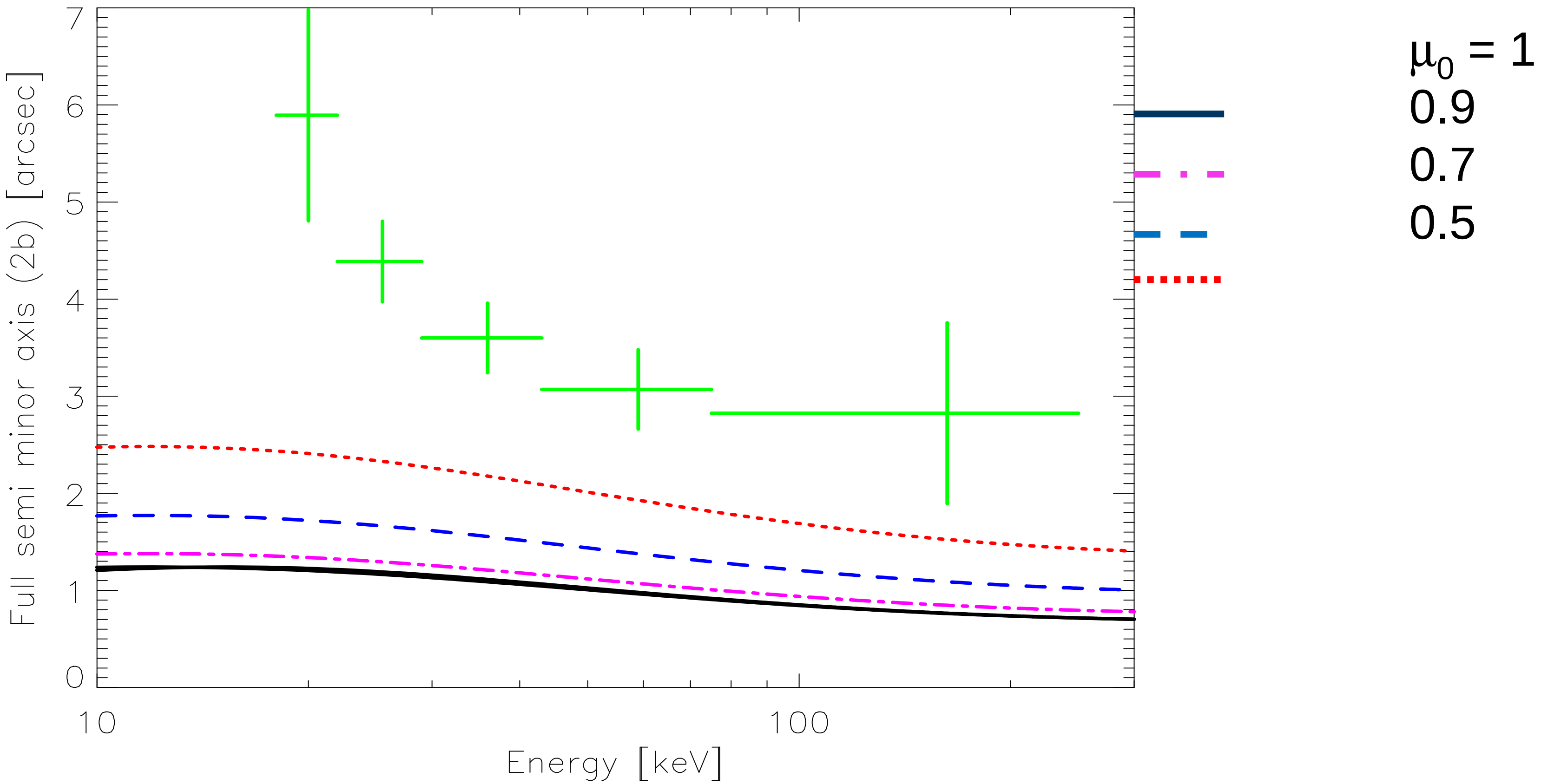
- Non-uniform magnetic field

- Strongly inhomogeneous chromosphere

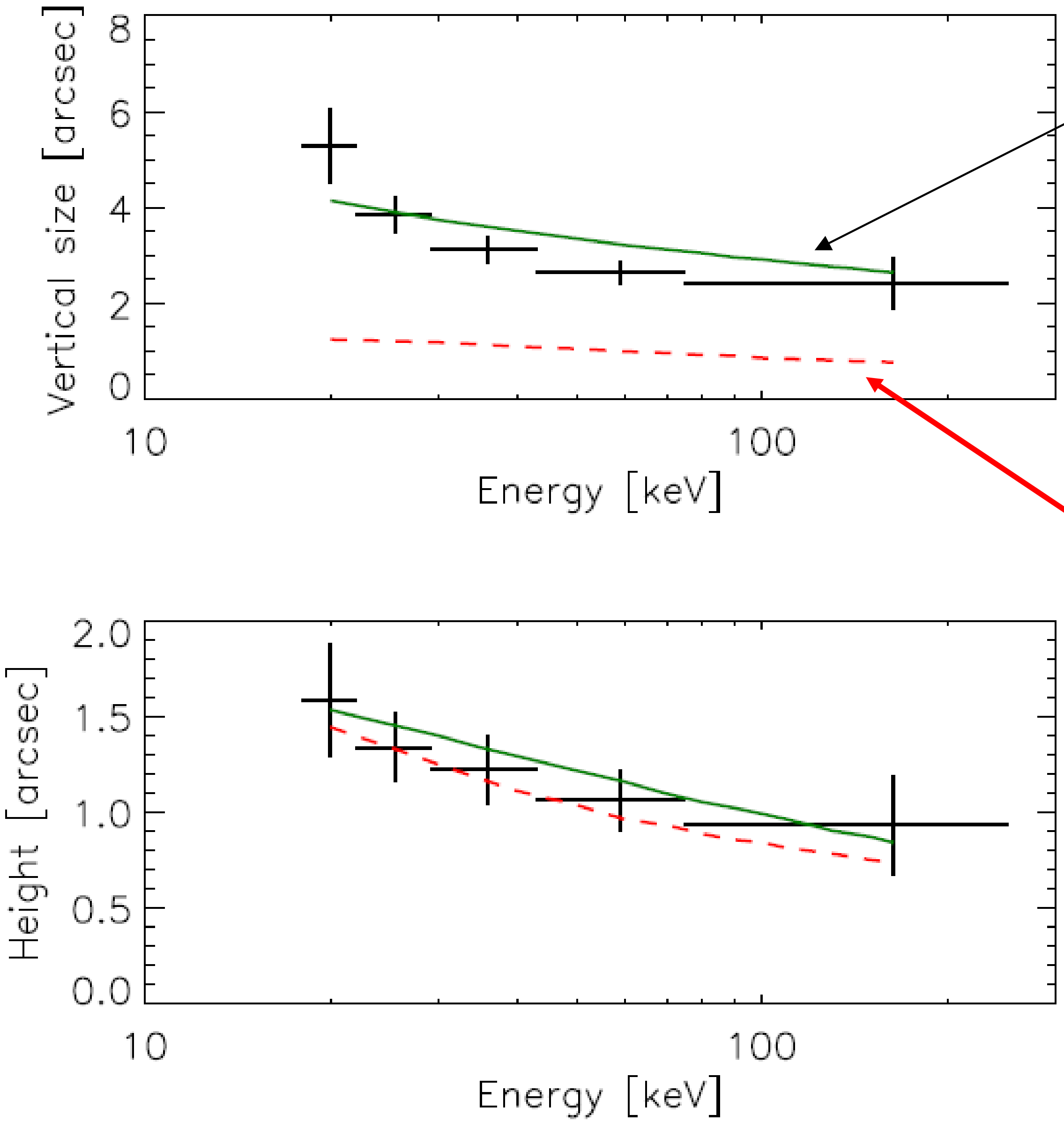
- Strong pitch angle scattering (simple collisions do not work)

Constant pitch angle in the simple thick target

$$F(E,N) = F_{norm} E \sqrt{E^2 + 2KN/\mu_0}^{(-\delta-1)}$$



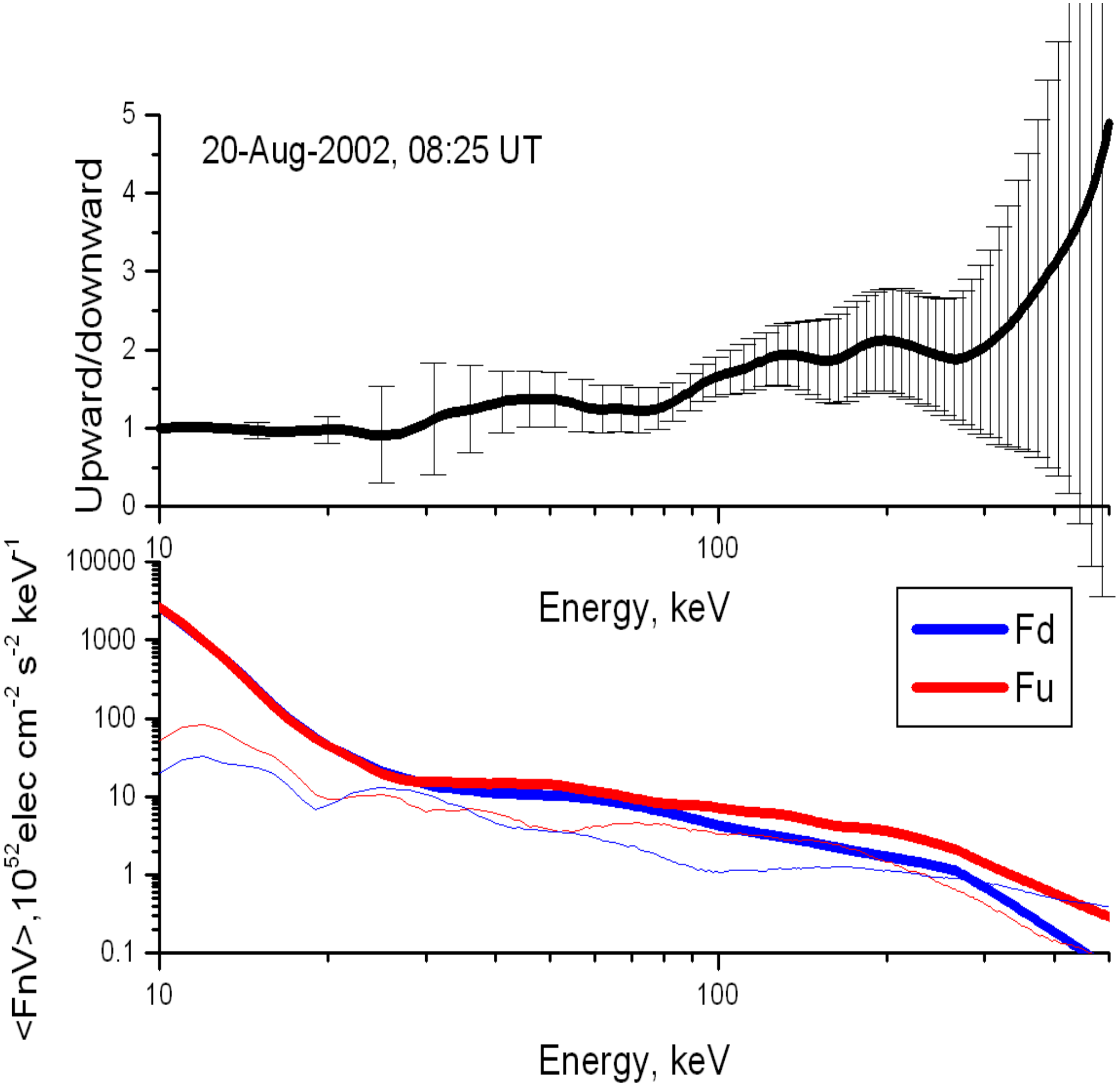
Strongly non-uniform atmosphere

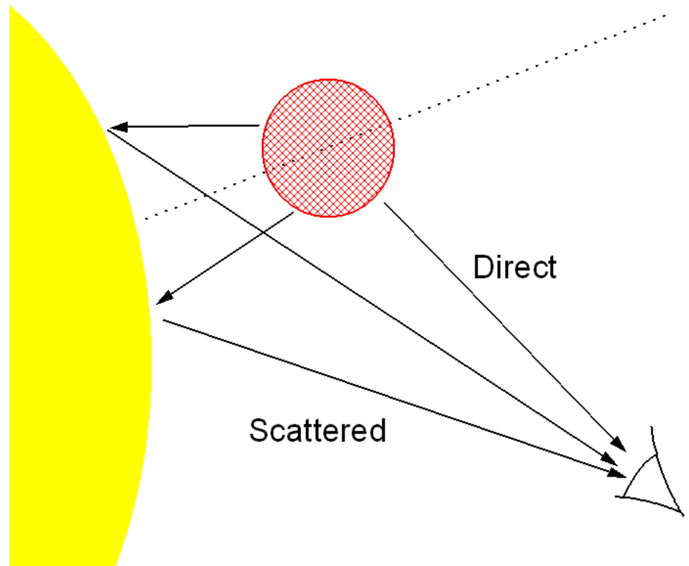


If we assume that electrons propagate along the different paths with different density profiles we can increase the vertical size of X-ray footpoint.

Vertical size of the footpoint, expected
from collisional transport

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**

Conclusions

RHESSI X-ray imaging allows to infer the shape and the source positions with sub-arcsecond precision.

The characteristic **vertical and horizontal sizes of X-ray sources at various** energies.

The **size of footpoints decrease with energy** suggesting expansion of the magnetic flux tube with height and the presence of strong horizontal fields at ~900km.

The vertical variations of the magnetic field can be measured at ~0.2” scale although, but requires reference height.

The electron transport can be collisional but strong pitch angle scattering or multiple density profiles within the loop is needed