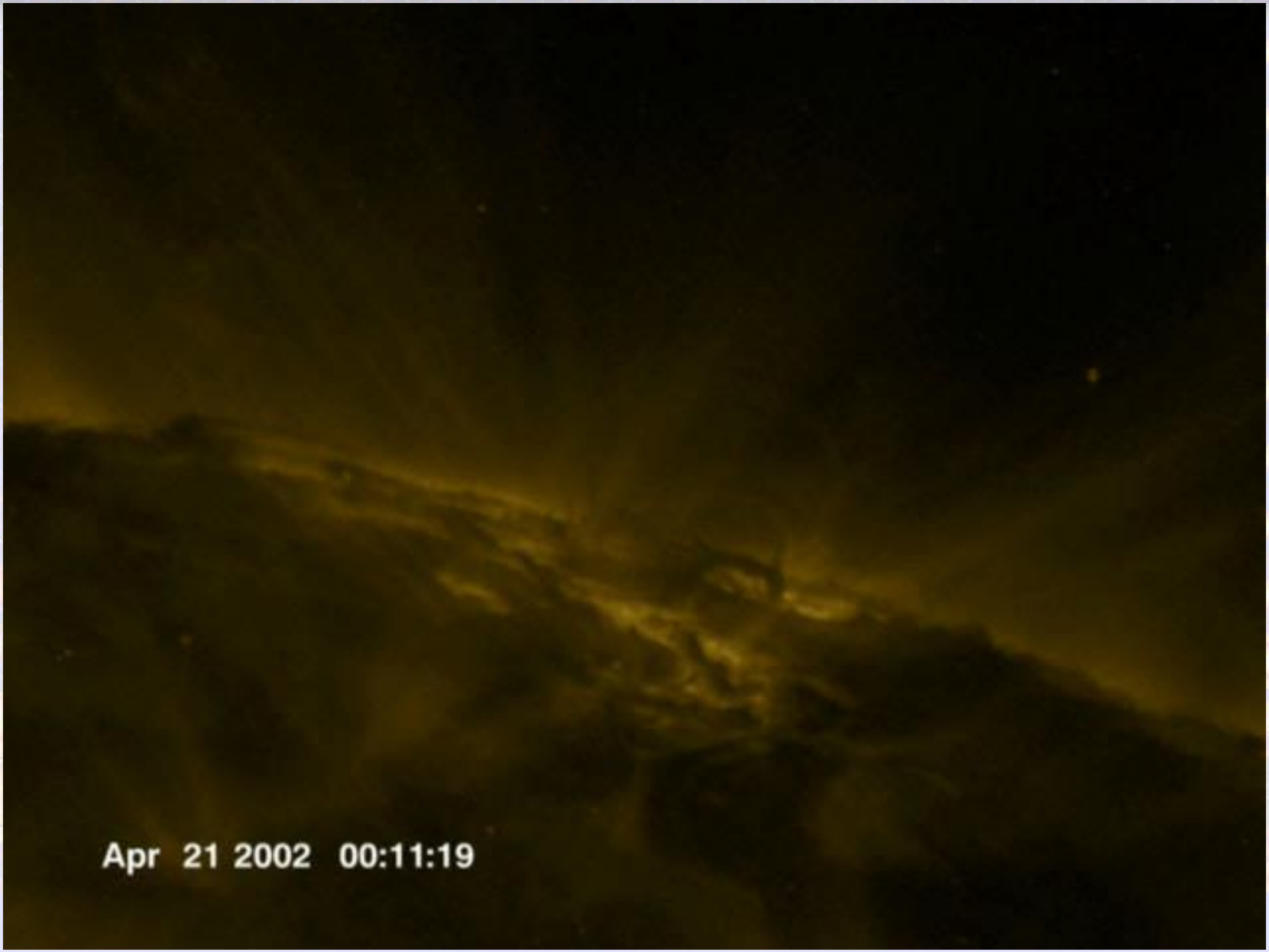
Investigation of plasma velocity field in solar flare footpoints from RHESSI observations

T. Mrozek[1,2], S. Kołomański[2], B. Sylwester[1], A. Kępa[1], J. Sylwester[1], S. Gburek[1], M. Siarkowski[1], M. Gryciuk[1], M. Stęślicki[1]

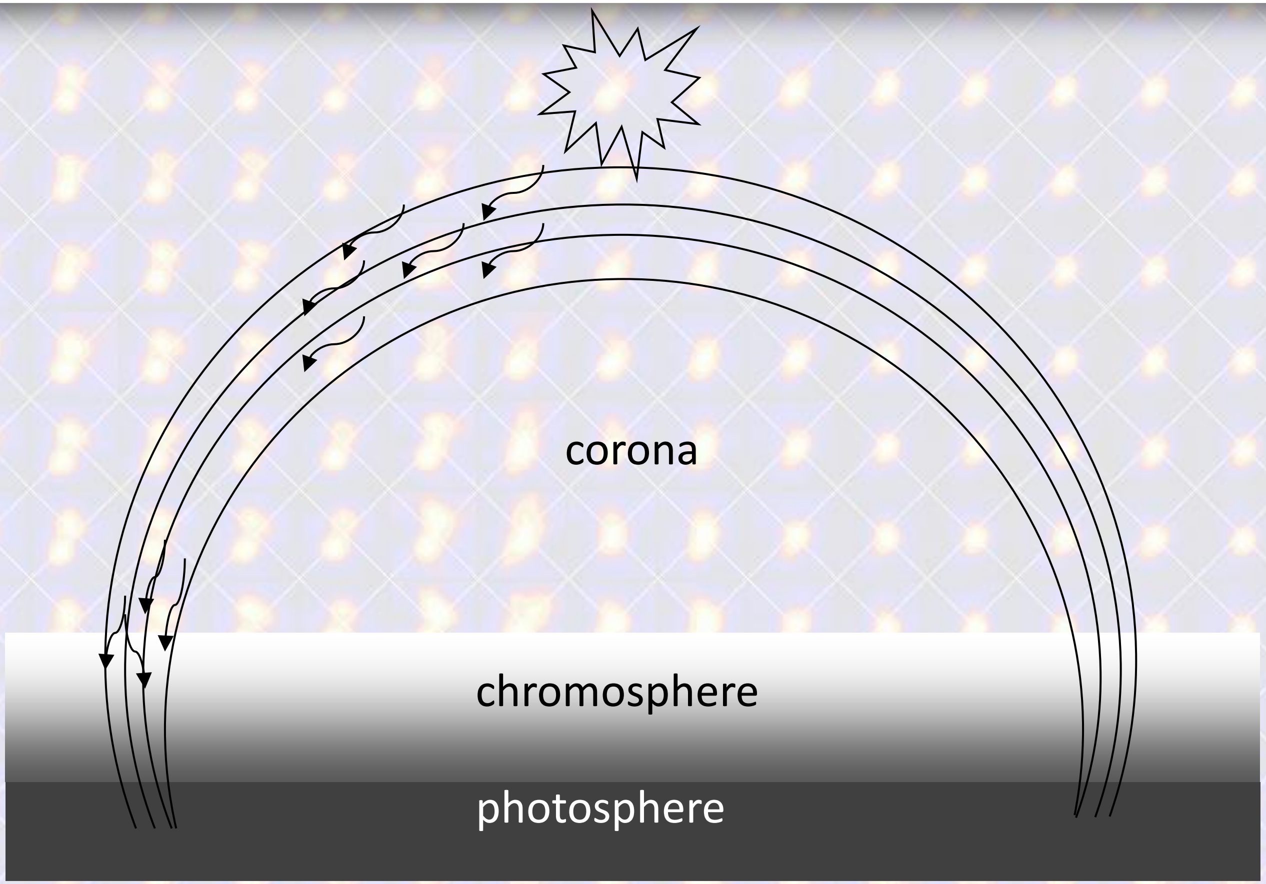
[1]Solar Physics Division, Space Research Centre PAS
[2]Astronomical Institute, University of Wrocław

NCN Grant 2011/01/M/ST9/06096

The Solar Flare - observations

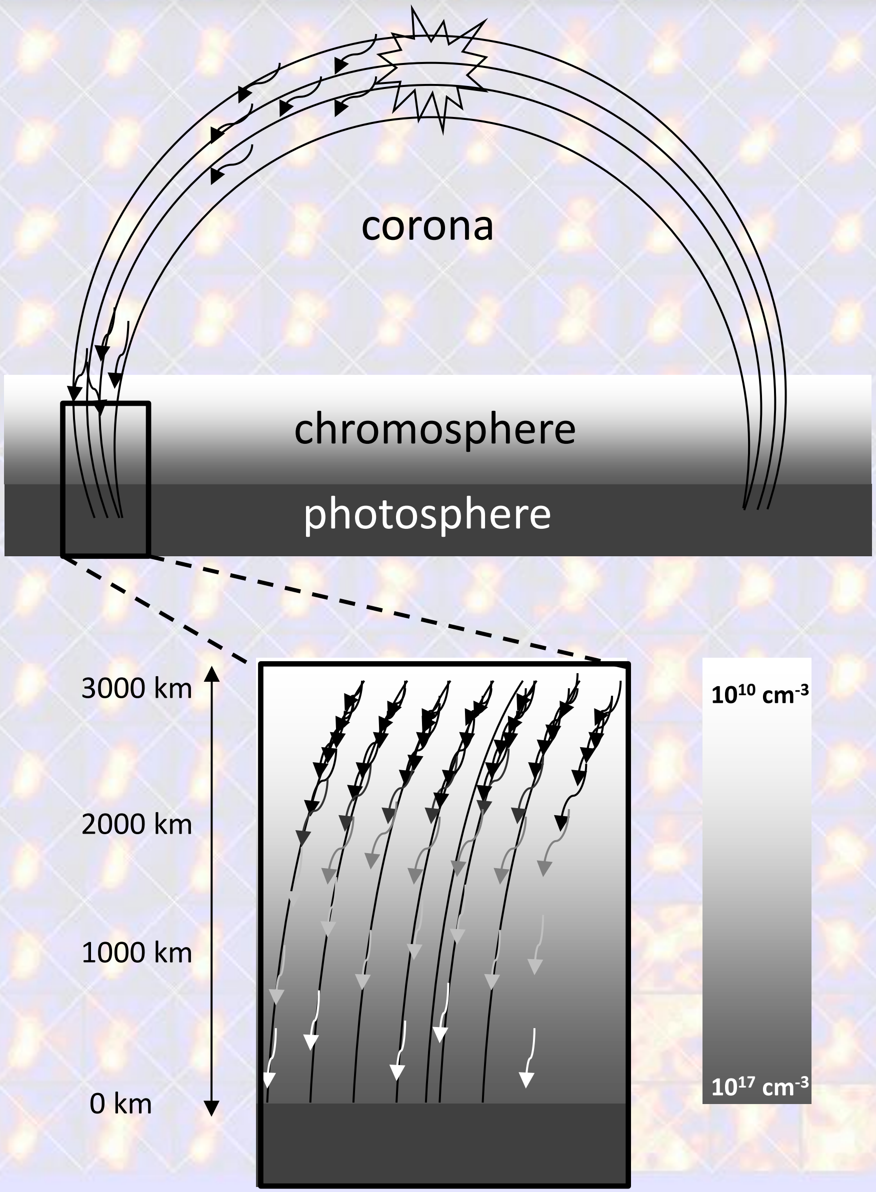


The Solar Flare - cartoon



- conversion of magnetic energy into other forms
- transport of energy via non-thermal particles
- the chromosphere is heated and „evaporates"
- hot plasma fills magnetic structures and cools down

Electron beam in the chromosphere



Brown,J., 1971, Sol. Phys., 18, 489

Brown, J. and McClymont,A.N. 1976, Sol. Phys., 49, 329

Brown, J et al., 2002, Sol. Phys., 210, 373

From collisional transport (simplified):

$$E(E_0, N) = \left(E_0^2 - 2KN\right)^{1/2}$$

Stopping depth for electron of energy E_0:

$$N_s(E_0) = \frac{E_0^2}{2K}$$

Relation between an altitude and energy of the source should be observed.

Observed relation gives opportunity for direct measurements of the density of a collision region

Altitudes of footpoint sources before RHESSI era

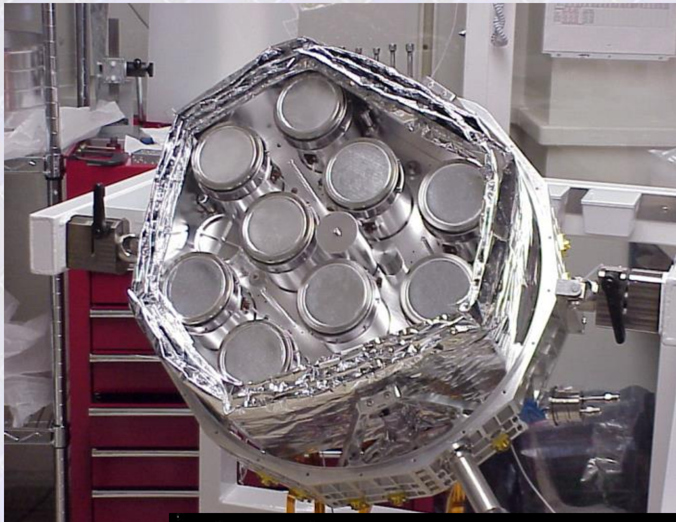
Takakura, K., Tanaka, K., Nitta, N., Kai, K., and Ohki, K., 1987, Sol. Phys. 107, 109

- **HINOTORI 20 - 40 keV**
- **$h = 7.0 \pm 3.5$ Mm**

Matsushita, K., Masuda, S., Kosugi, T., Inda, M., and Yaji, K., 1992, Publ. Astron. Soc. Japan 44, L89

- **YOHKOH**
- **$h_{14} = 9.7 \pm 2.0$ Mm (L)**
- **$h_{23} = 8.7 \pm 0.3$ Mm (M1)**
- **$h_{33} = 7.7 \pm 0.5$ Mm (M2)**
- **$h_{53} = 6.5 \pm 0.7$ Mm (H)**

RHESSI



- launched: February 2002

- 9 large germanium detectors

- energy resolution ~ 1 keV

- spatial resolution depends
  on detector selection:
  ~2.5'' (maximal)
  >7'' (in practice)

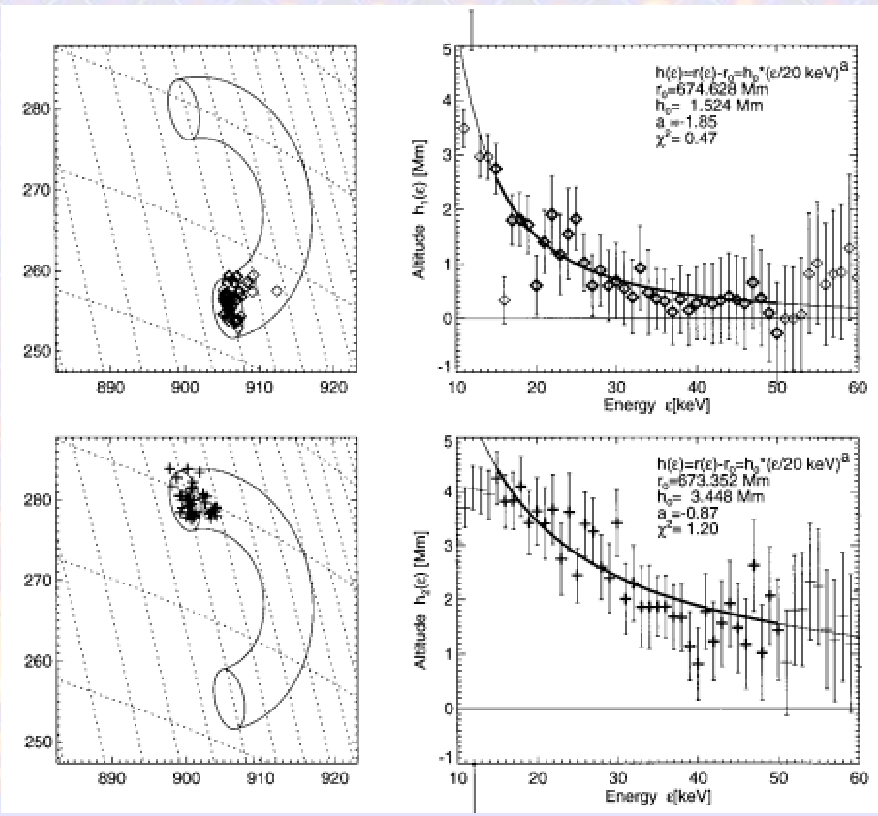
- temporal resolution for
  imaging depends on photon
  statistic, but must be equal
  at least ~2 s (half of the
  RHESSI rotation)

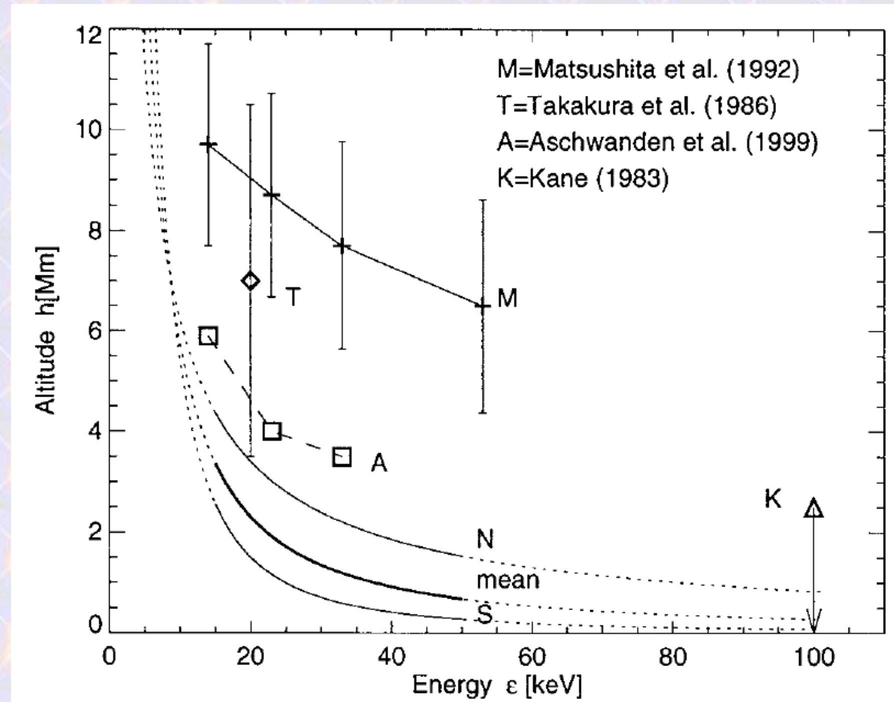
Altitudes of footpoint sources

Aschwanden, M.J., Brown, J.C. & Kontar, E.P., 2002, Sol. Phys., 210, 373

20 Feb 2002

Observations fitted with power-law function

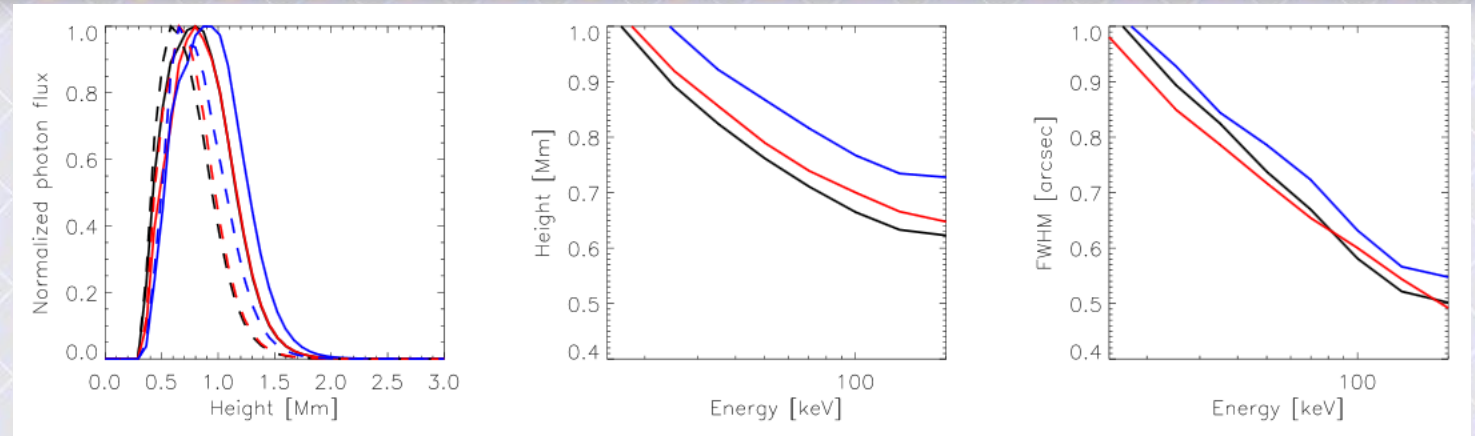


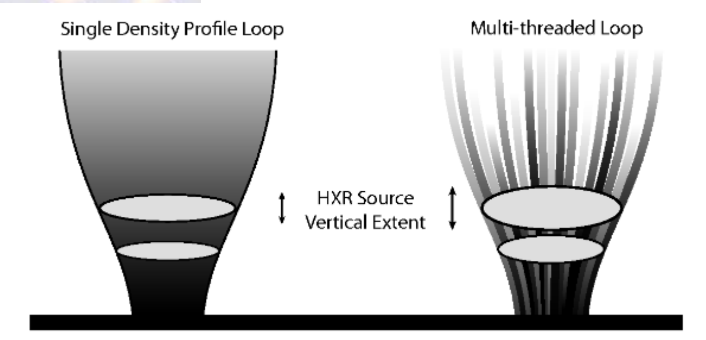


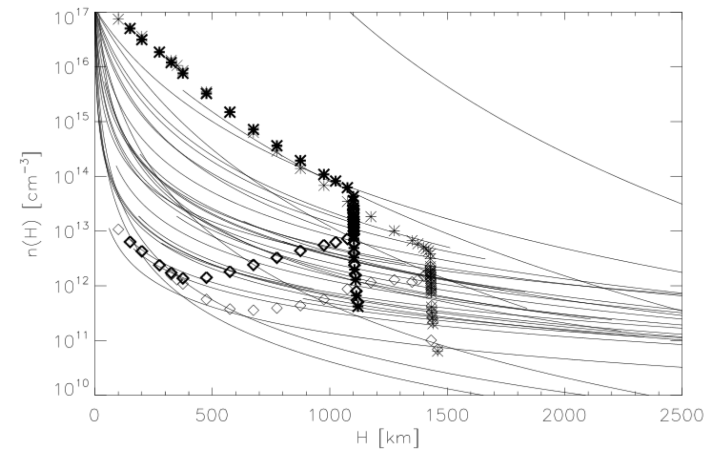
Energy: 15-50 keV, Heights: 4000-700 km

Well below previous measurements.

Altitudes of footpoint sources







Mrozek, T. 2006, Adv. in Space Res. 38, 962

Kontar, E. P. et al. 2010, ApJ 717, 250

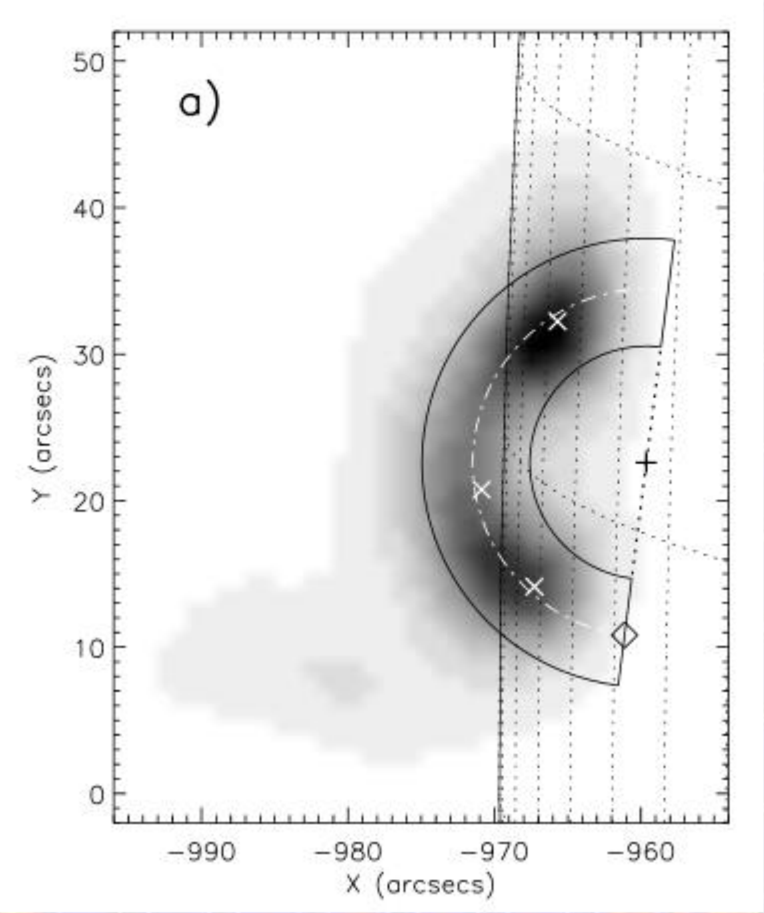
Mrozek, T. & Kowalczuk, J. 2010,
Centr. Eur. Astr. Bull. 34, 73

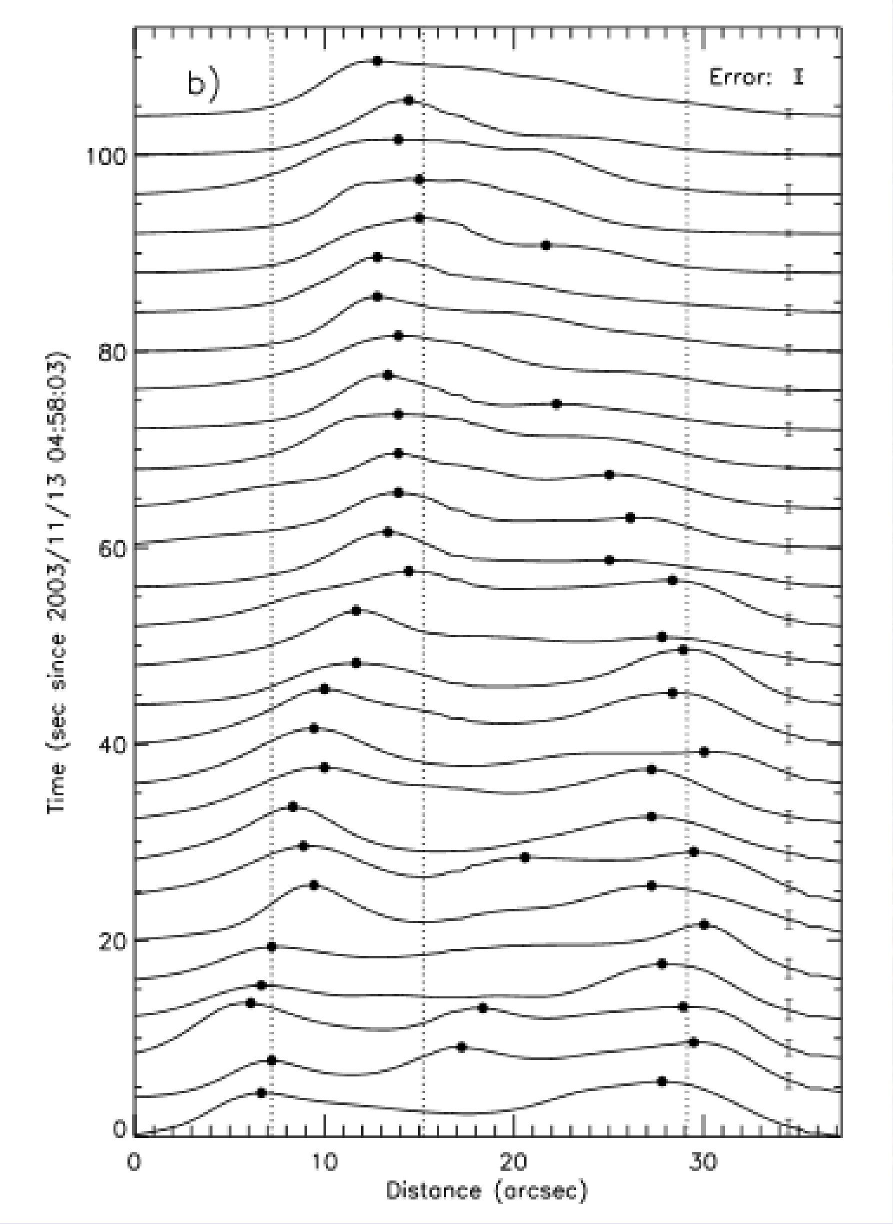
Battaglia, M. & Kontar, E.P. 2011, A&A 2011, 2B

Battaglia, M. & Kontar, E.P. 2011, ApJ 735, 42

Battaglia, M. et al. 2012, ApJ 752, 4B

Chromospheric evaporation in RHESSI images





Liu, W. et al. 2006, ApJL 649, 1124

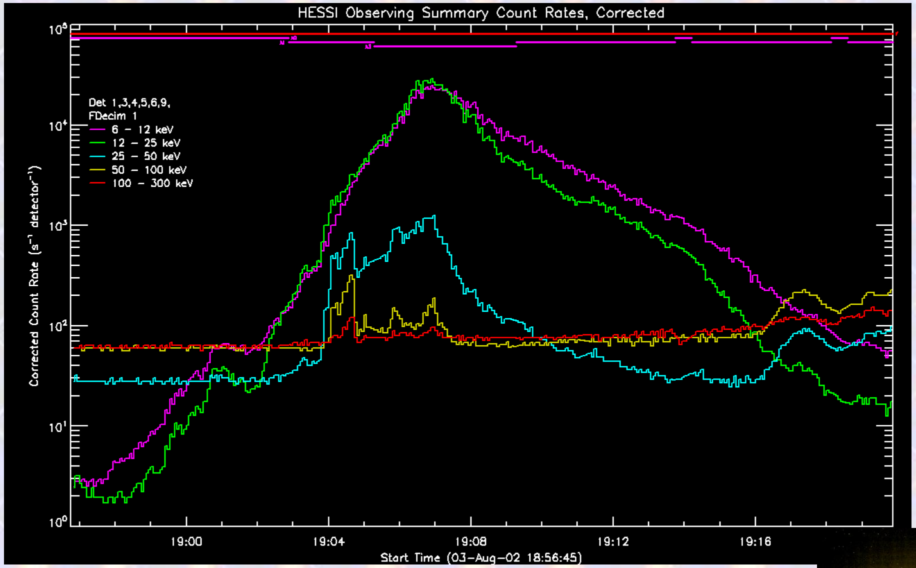
Case study: 3-Aug-2002

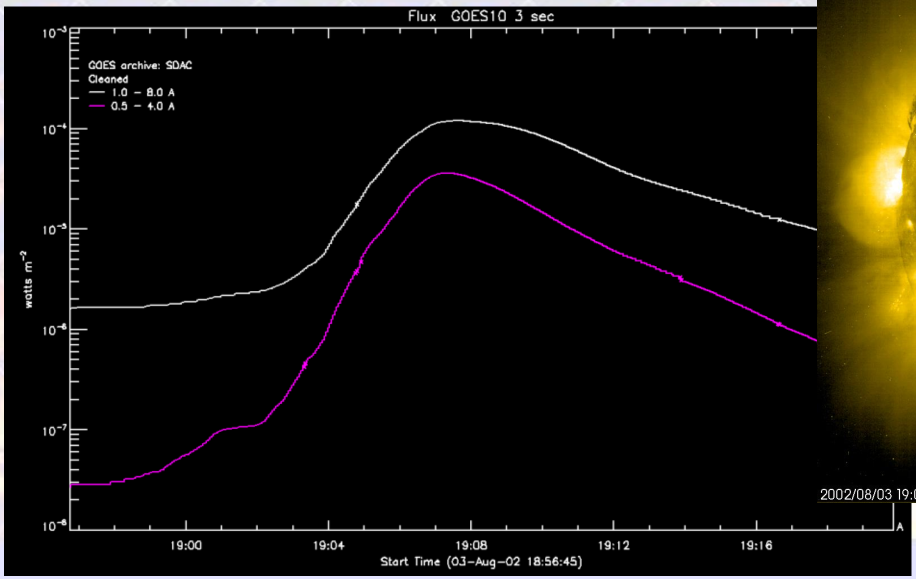
GOES class: X1.5

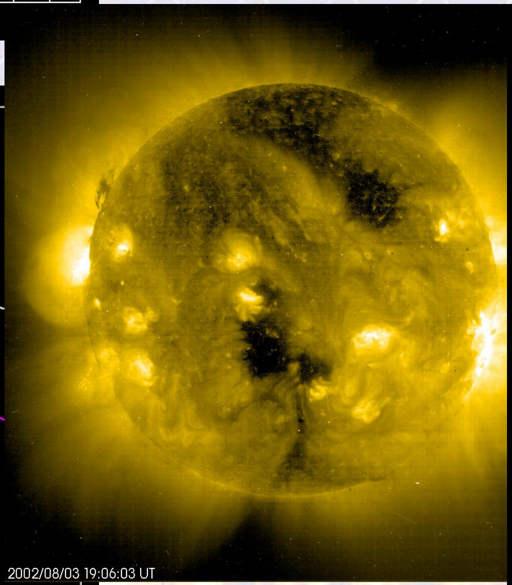
location: S15W70

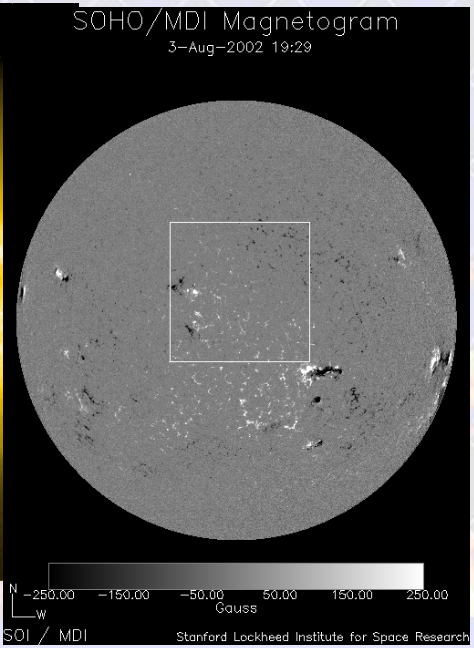
utilized observations:

- TRACE (171 Å, 30 s cadence)
- RESIK (2.05 – 3.65 keV)
- RHESSI (entire event)









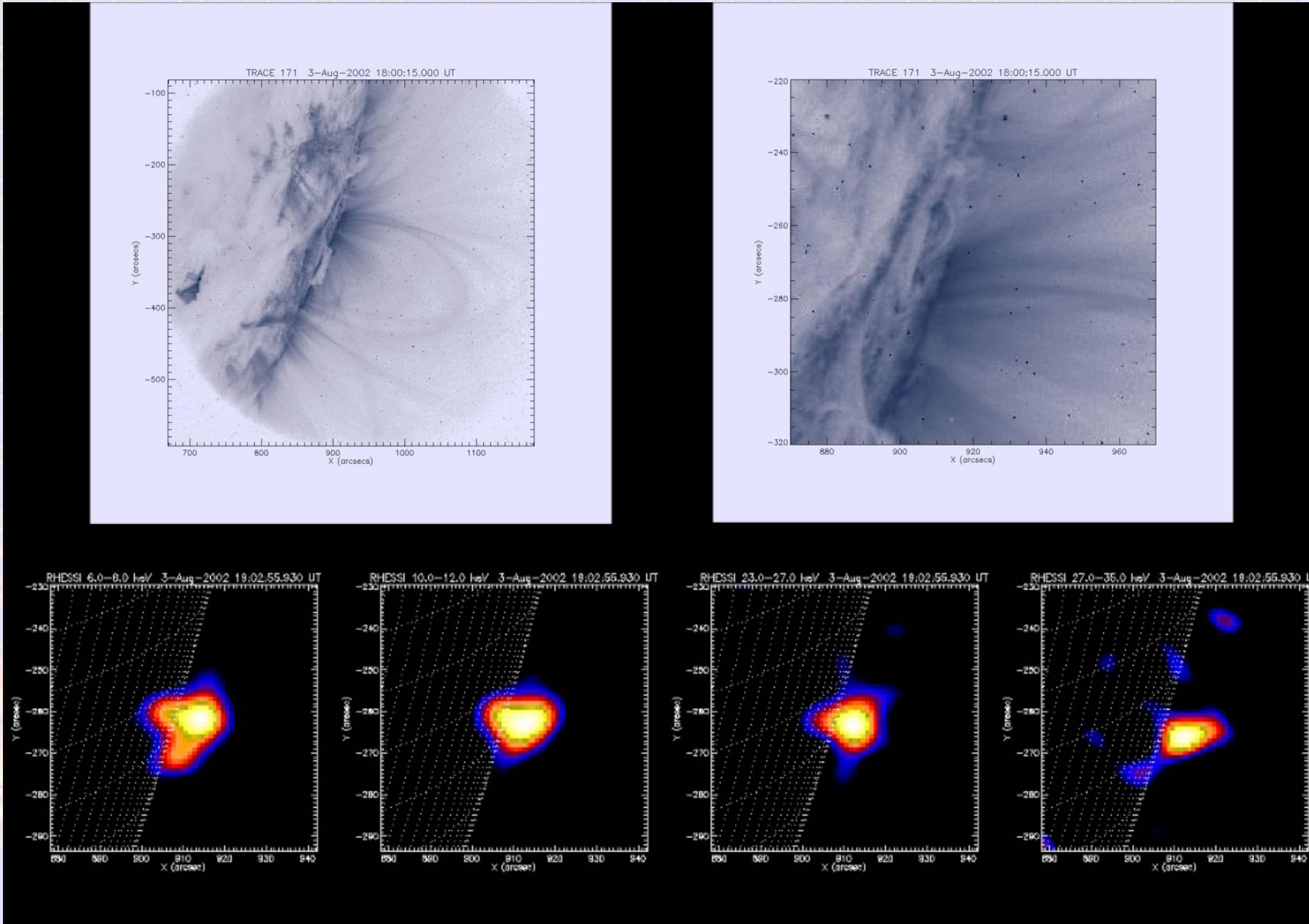
Instruments

RESIK: Bragg crystal spectrometer

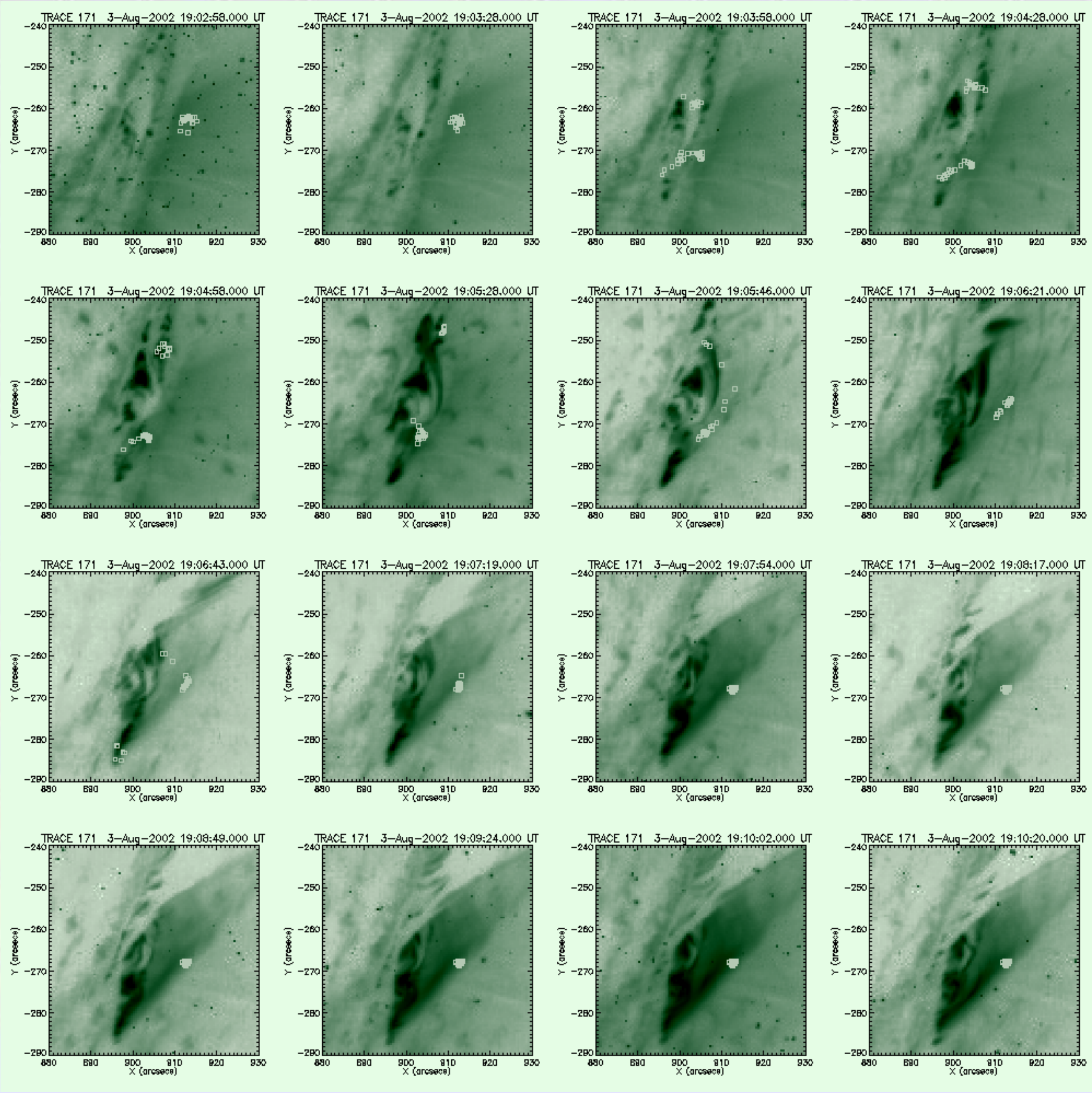
Four spectral bands: 3.37 - 3.88 Å, 3.82 - 4.33 Å, 4.31 - 4.89 Å and 4.96 - 6.09 Å

Data packets are available from October 2001 to April 2003:
http://www.cbk.pan.wroc.pl/experiments/resik/resik_catalogue.htm

Overall picture



Overall picture



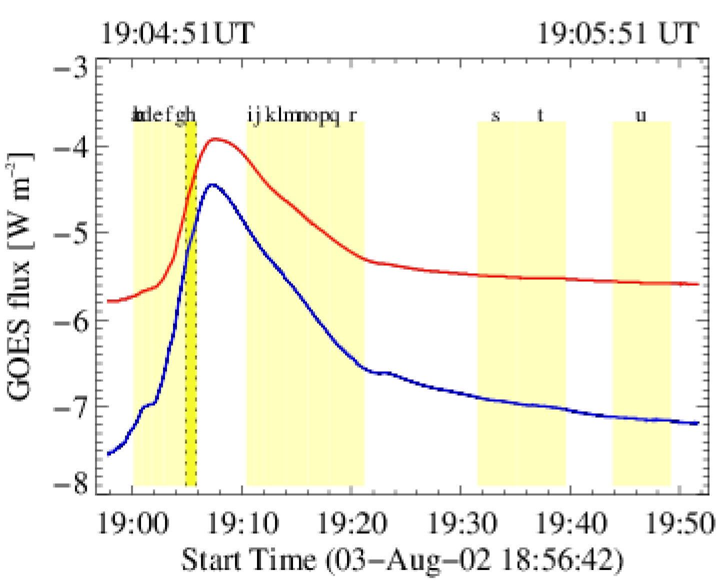
First minutes of flare evolution – coronal source

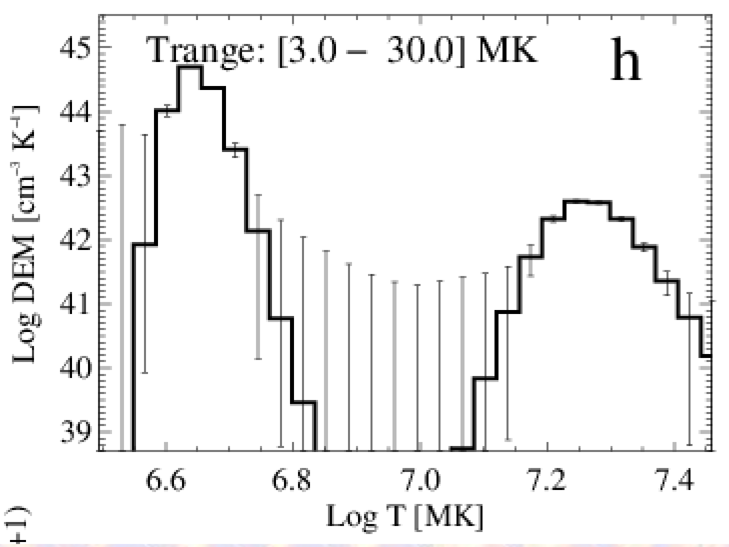
Footpoints are visible since ~19:04 UT

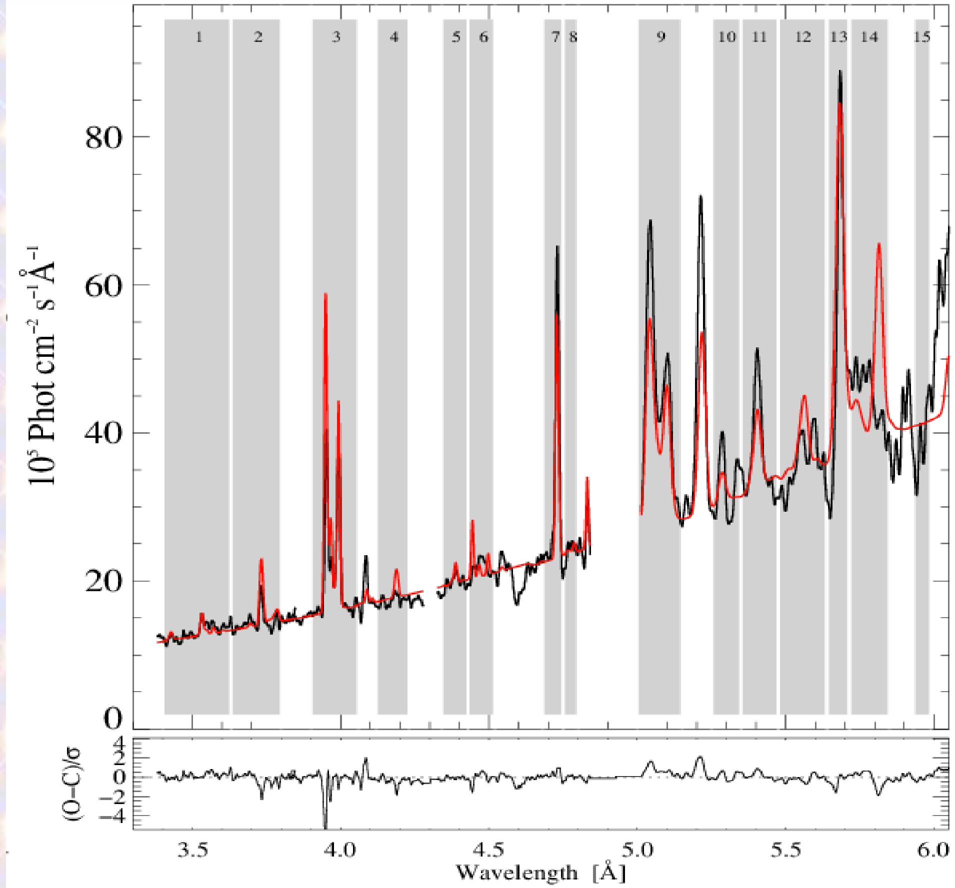
Correlation with EUV footpoints is visible

Starting from ~19:07 UT coronal source dominates again

RESIK observations

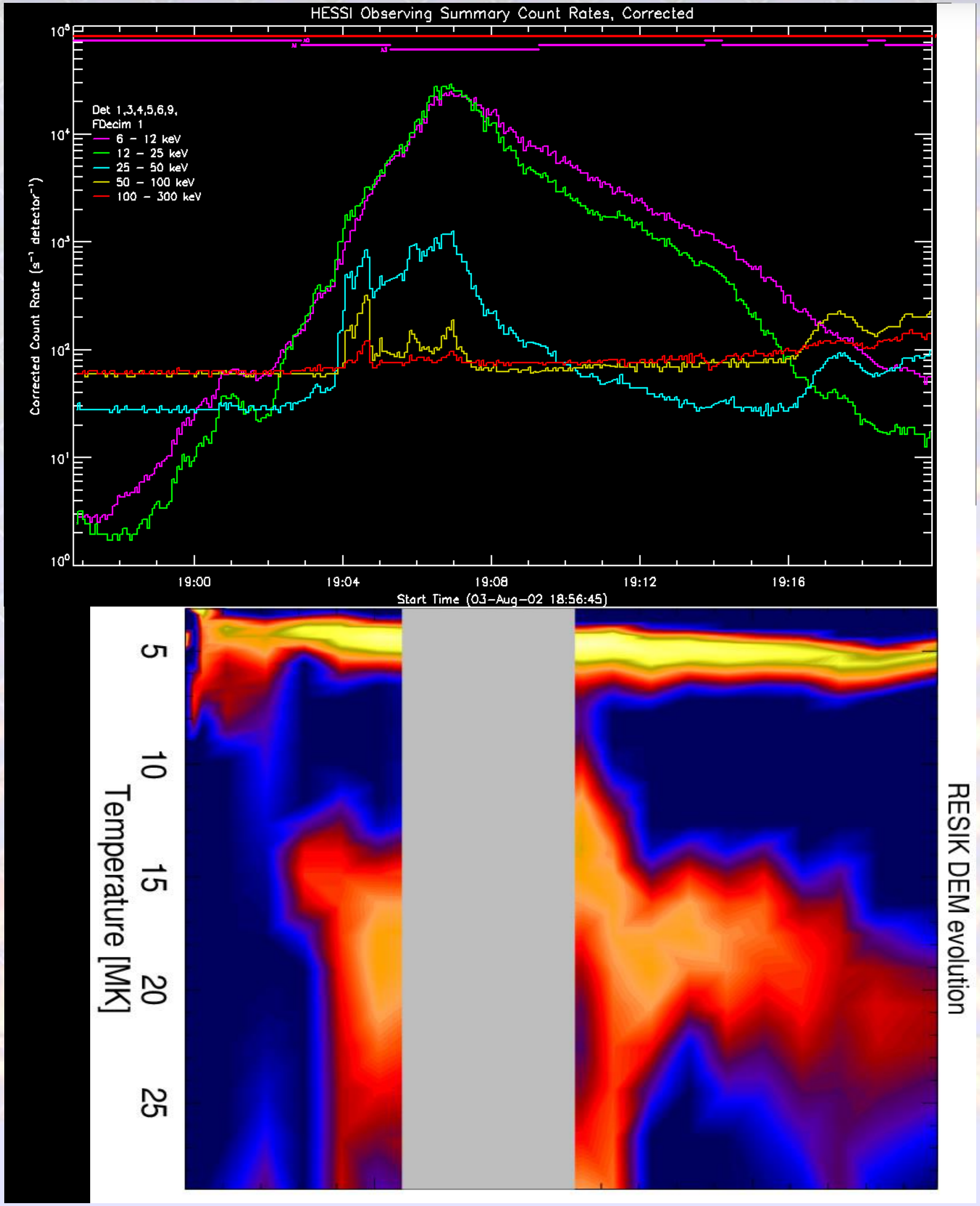






RESIK spectra were fitted with a use of Withbroe-Sylwester algorithm for a number of accumulated spectra

RESIK - RHESSI



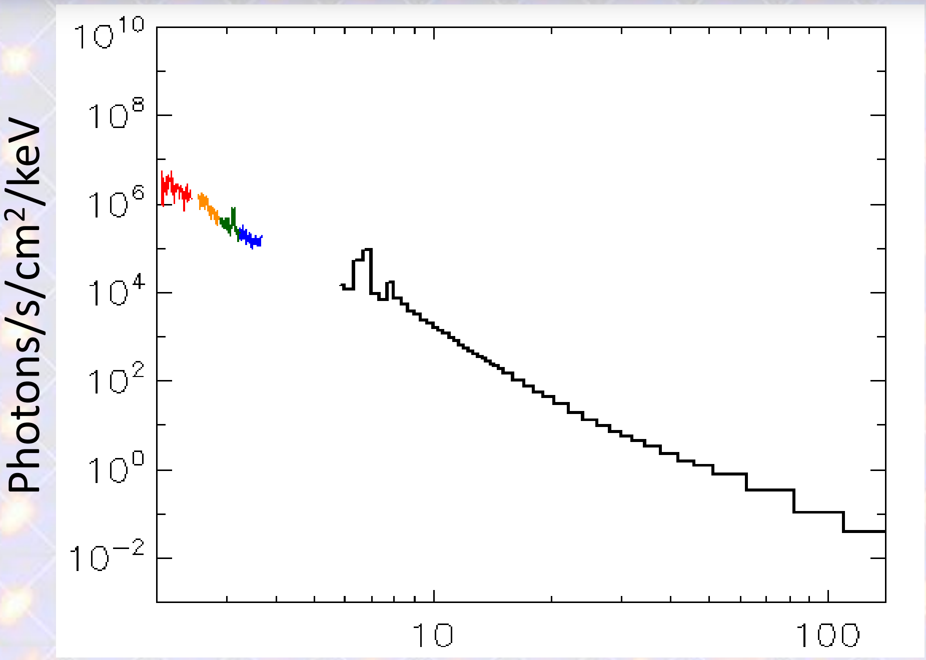
During the main phase RESIK detectors were saturated.

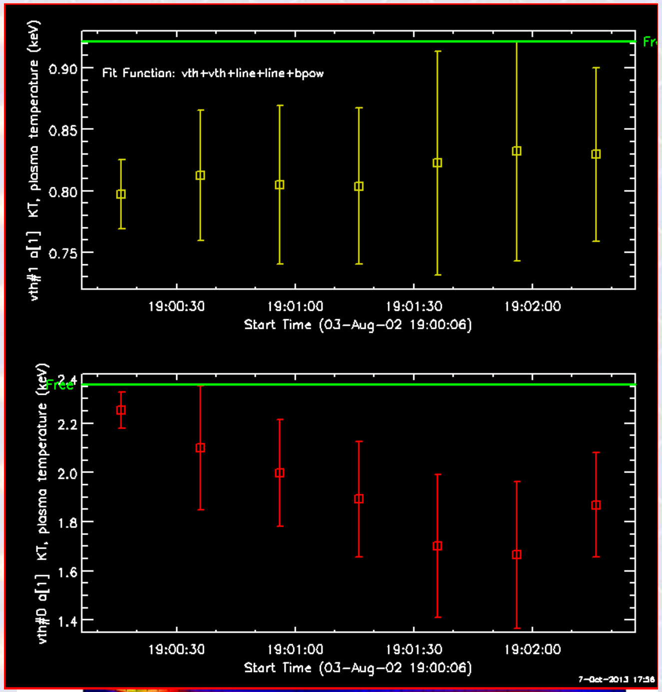
The hot component was visible since ~19:03 UT.

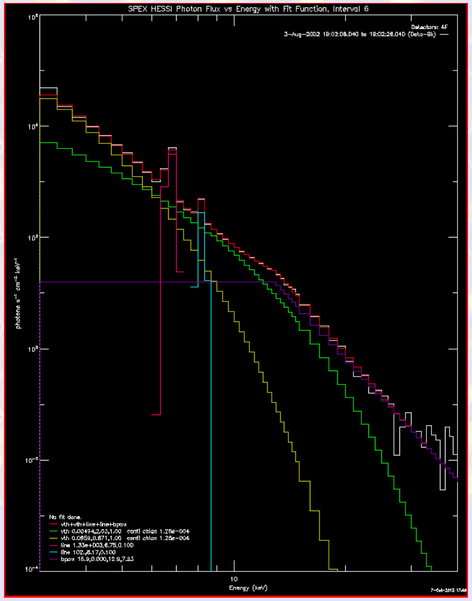
The warm component was present during entire event.

RHESSI data were not affected by attenuator before 19:03 UT which gave a chance for comparison data from both instruments.

RESIK - RHESSI

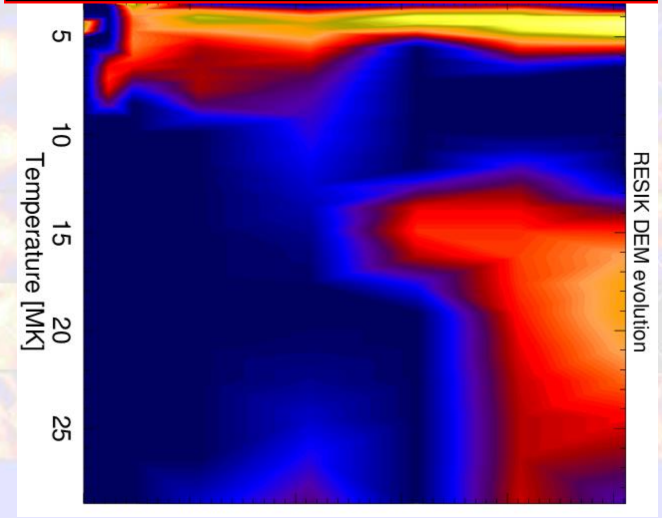




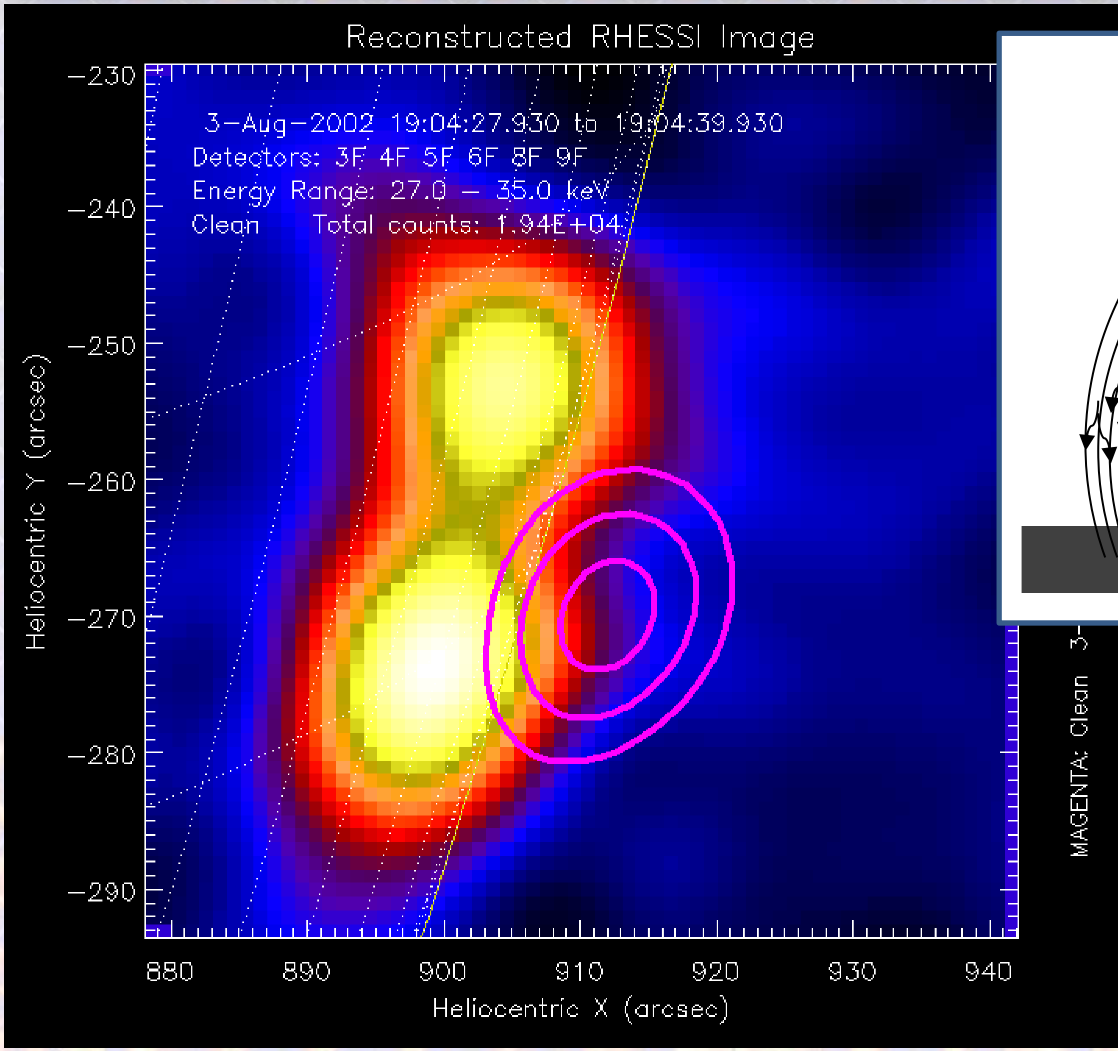


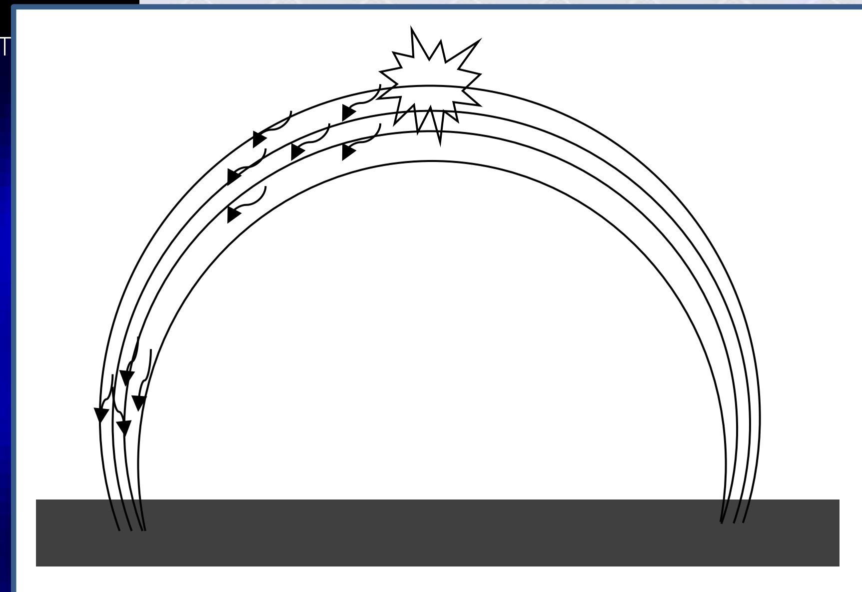
RHESSI spectra were fitted with two thermal components, two gaussians and broken power-law.

Temperatures from RHESSI are slightly above RESIK ones.



Flare morphology





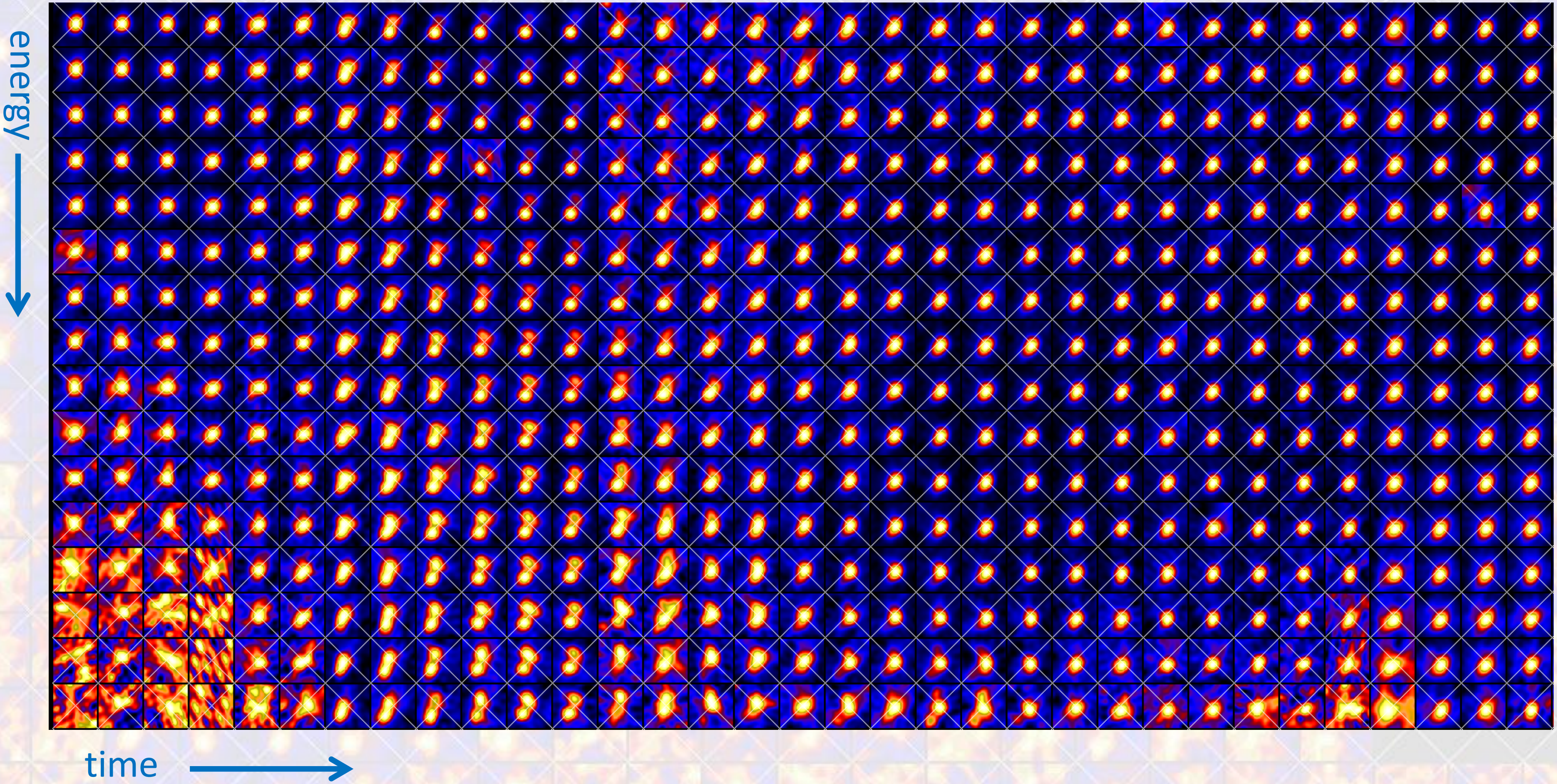
RHESSI image is consistent with our „intuition". We see two footpoints and coronal source, so we have single-loop flare.

image – 27-35 keV sources during impulsive phase
contours – 6-7 keV source during maximum

Are you sure?

Flare morphology

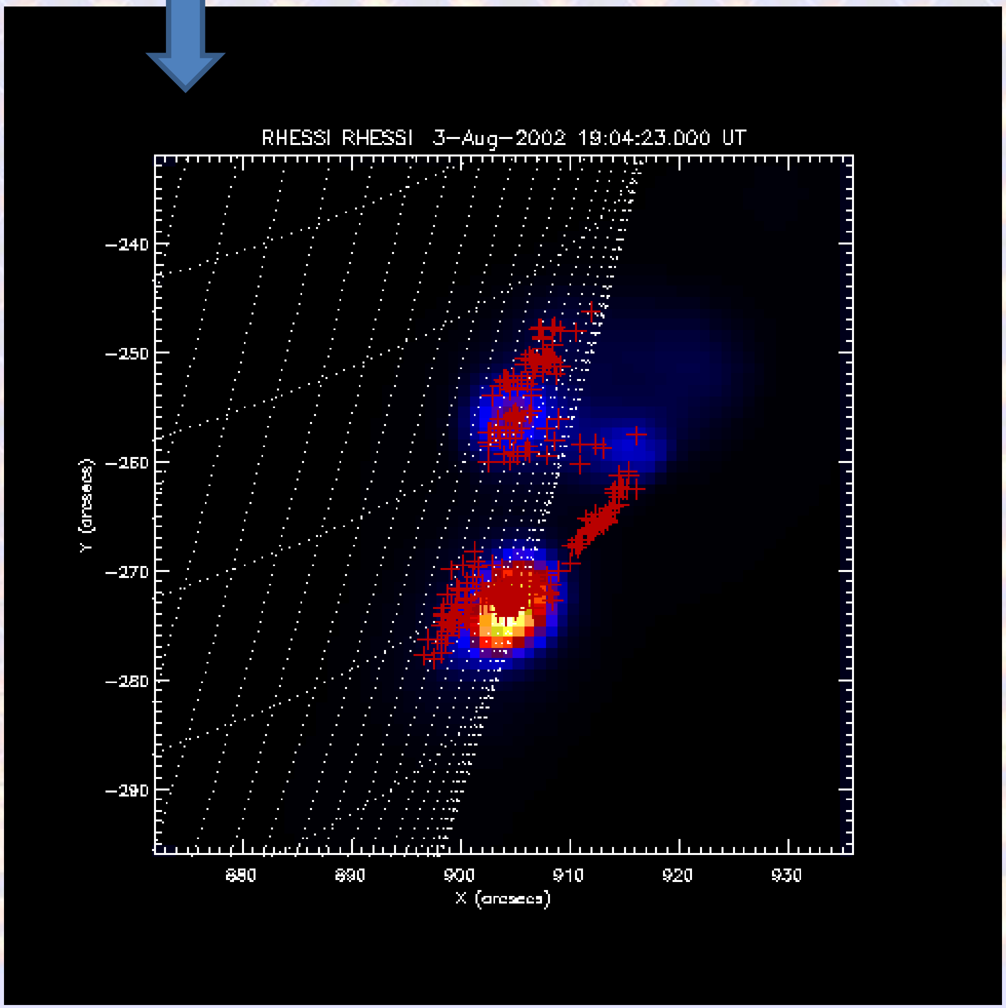
CLEAN, detectors: 3,4,5,6,8,9, narrow energy bands

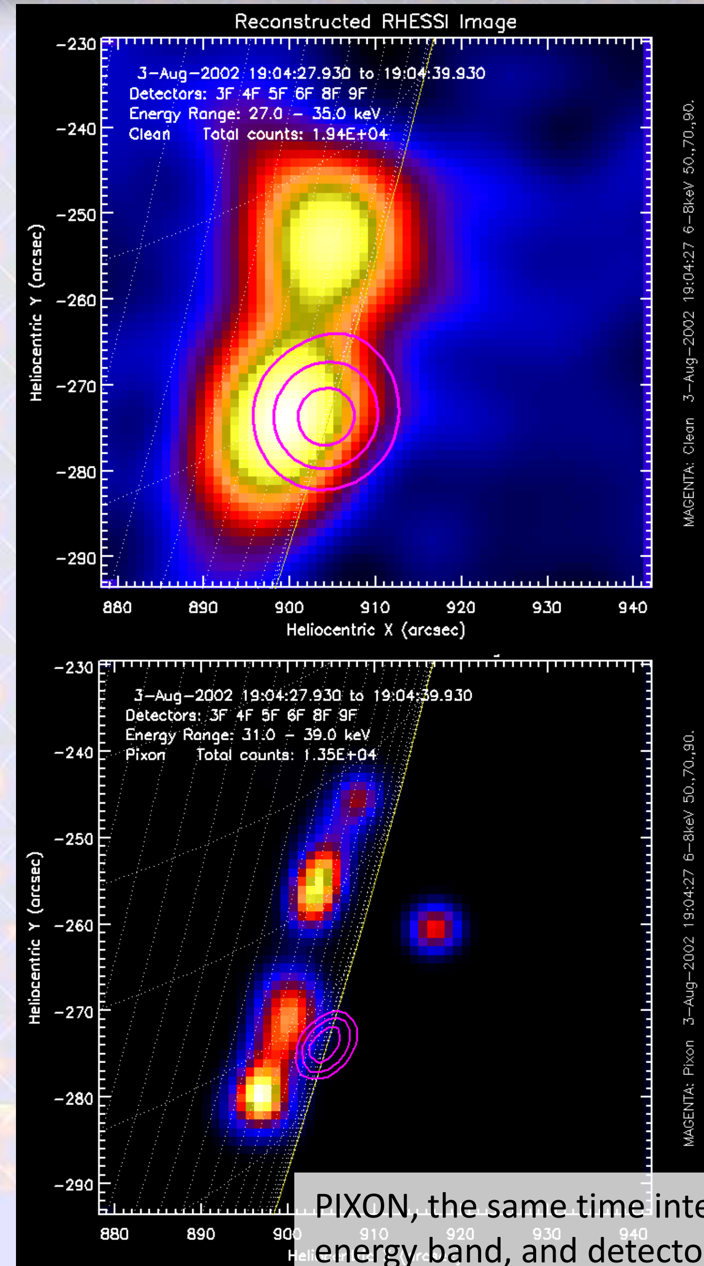


Flare morphology

Centroids for each reconstructed source

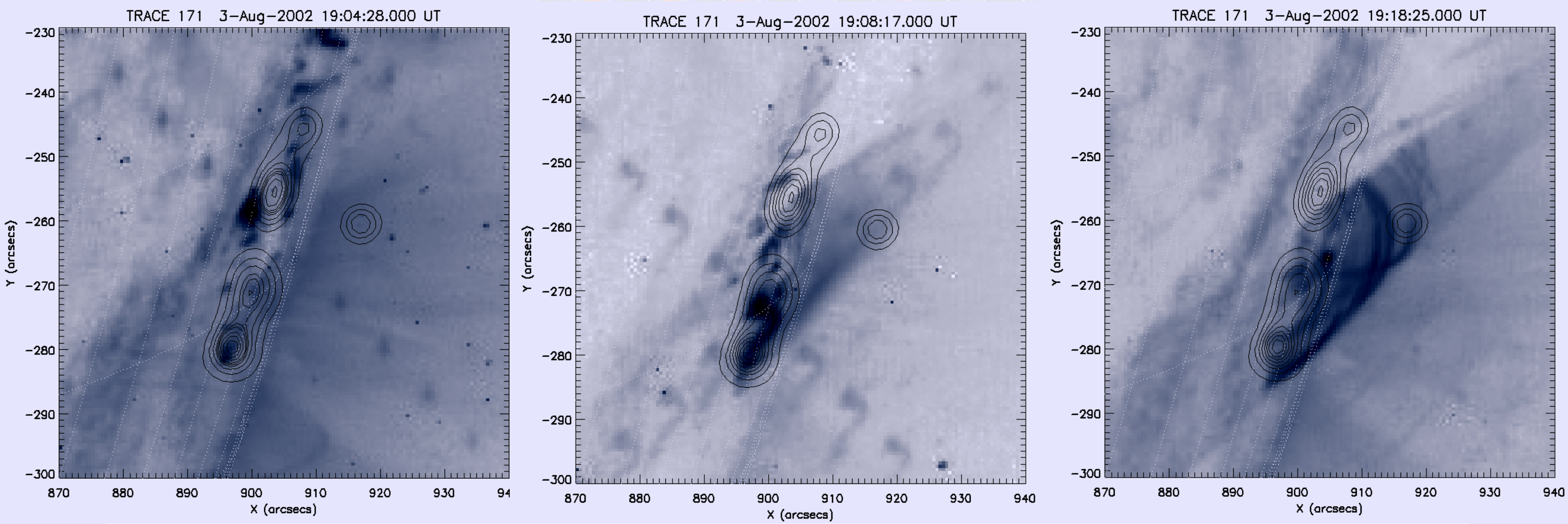
image: 27-35 keV
contours: 6-7 keV





PIXON, the same time interval, energy band, and detectors

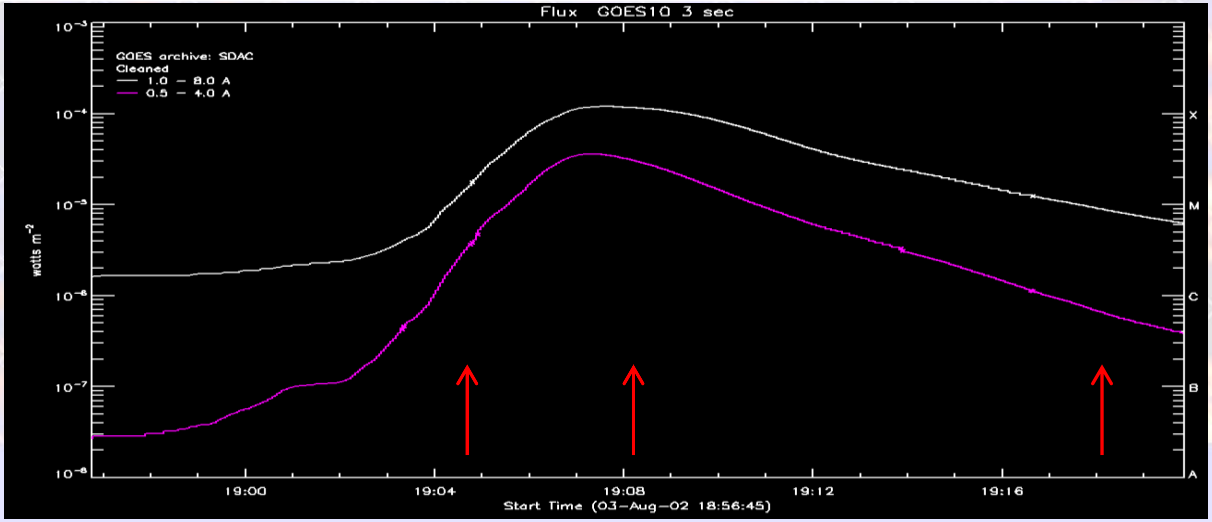
HXR sources



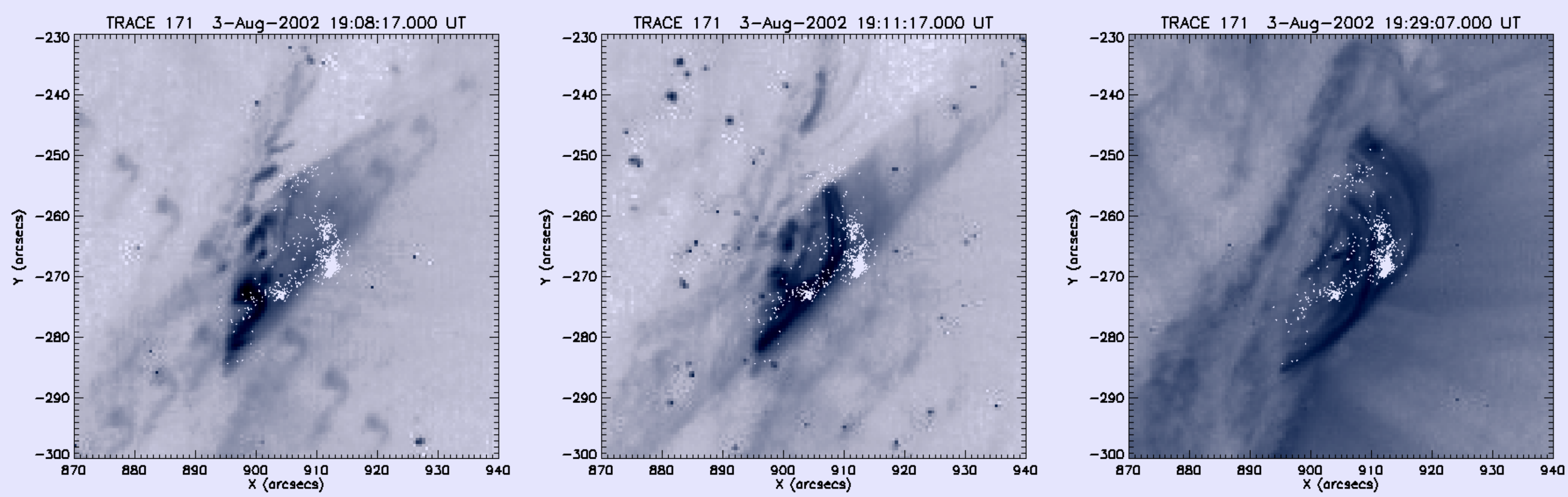
contours – 27-35 keV sources during impulsive phase (19:04:27 UT – 19:04:39 UT)

RHESSI PIXON image fits better to structures visible on EUV images.

Footpoints are cospatial with small loop as well as other system of visible loops.

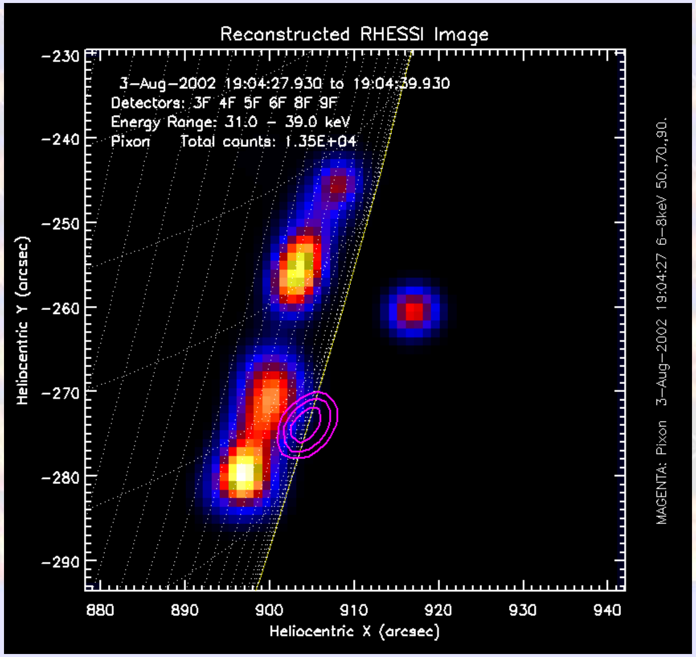


Flare morphology

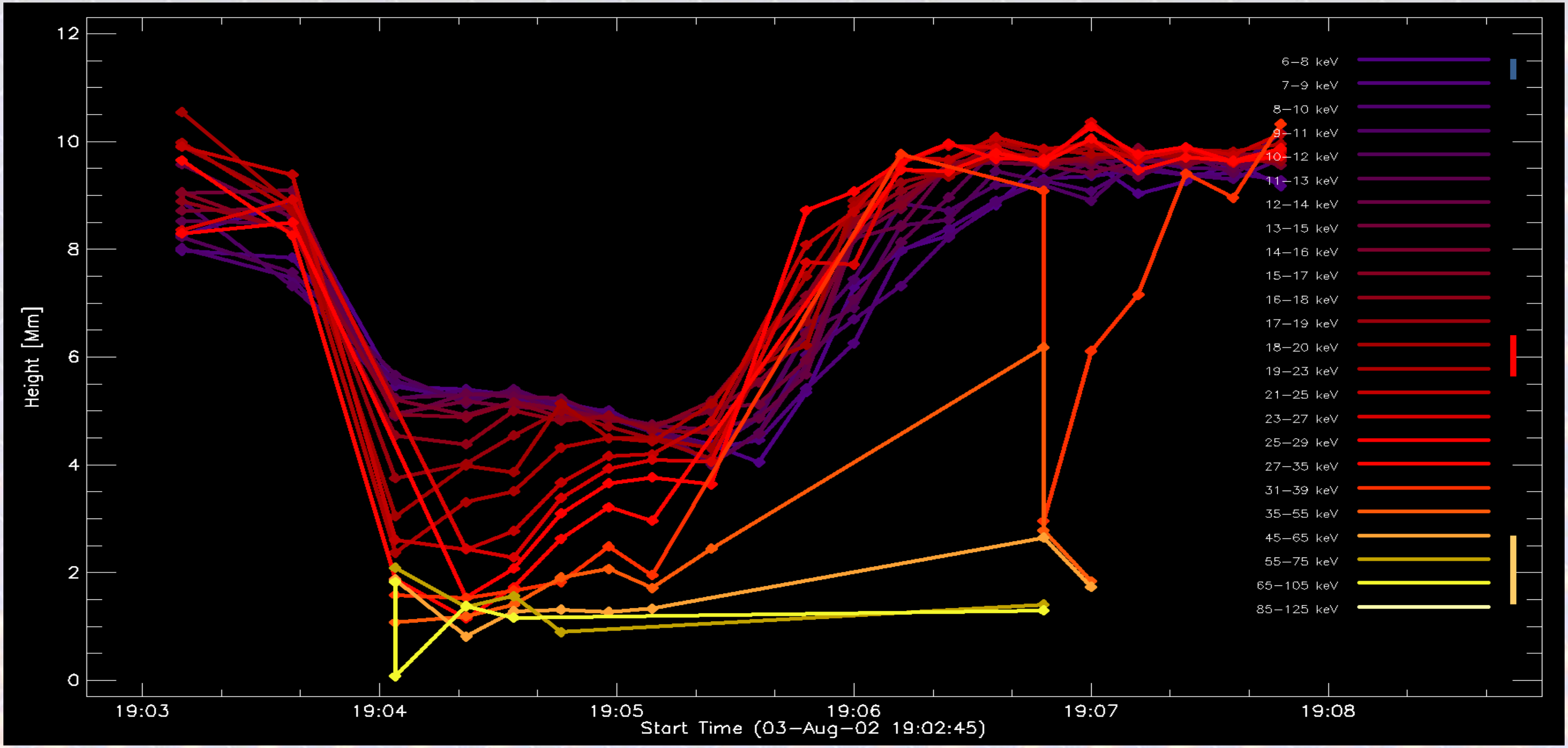


For small loop we are able to analyze energy-altitude relation.

The overall picture is rather complicated and misleading in terms of one-loop interpretation.



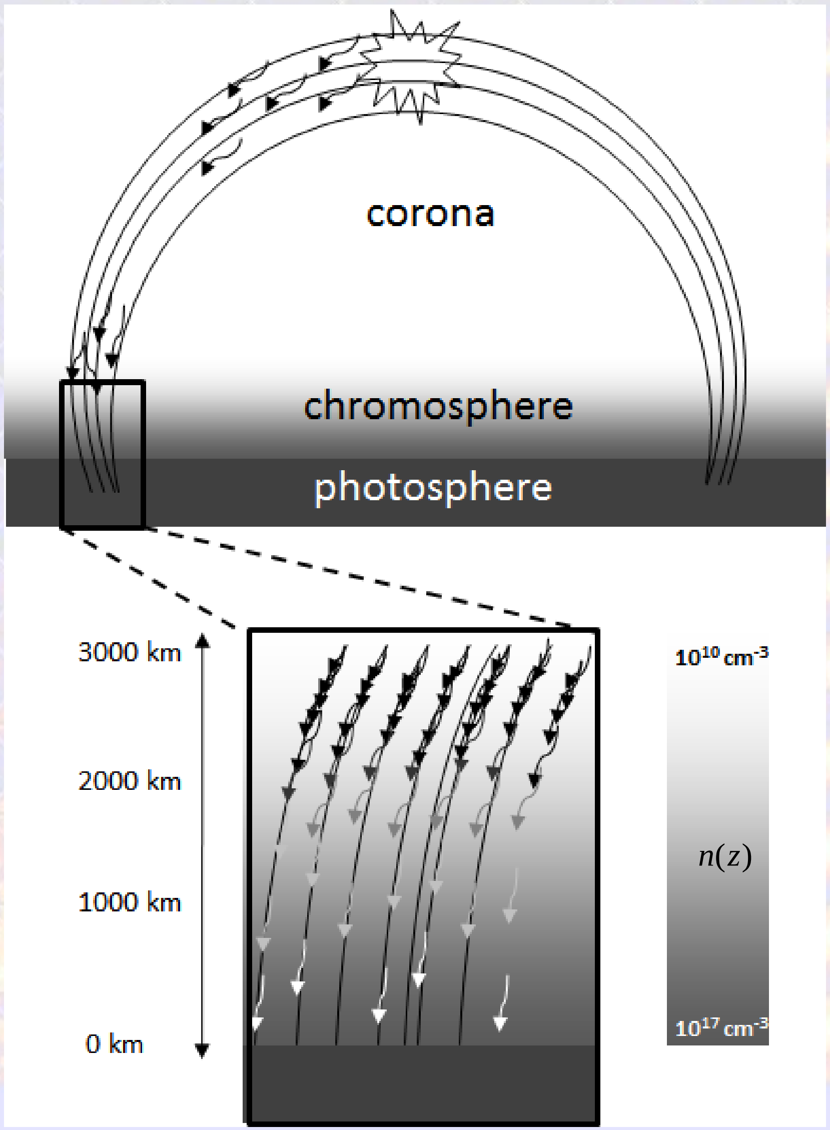
Time variation of HXR sources altitudes



Three phases:

1. Early phase - single source high in the corona
2. Impulsive phase - double-footpoint morphology in higher energies, dominated by southern source
3. Maximum&decay – single source in the corona

RHESSI: energy – altitude relation



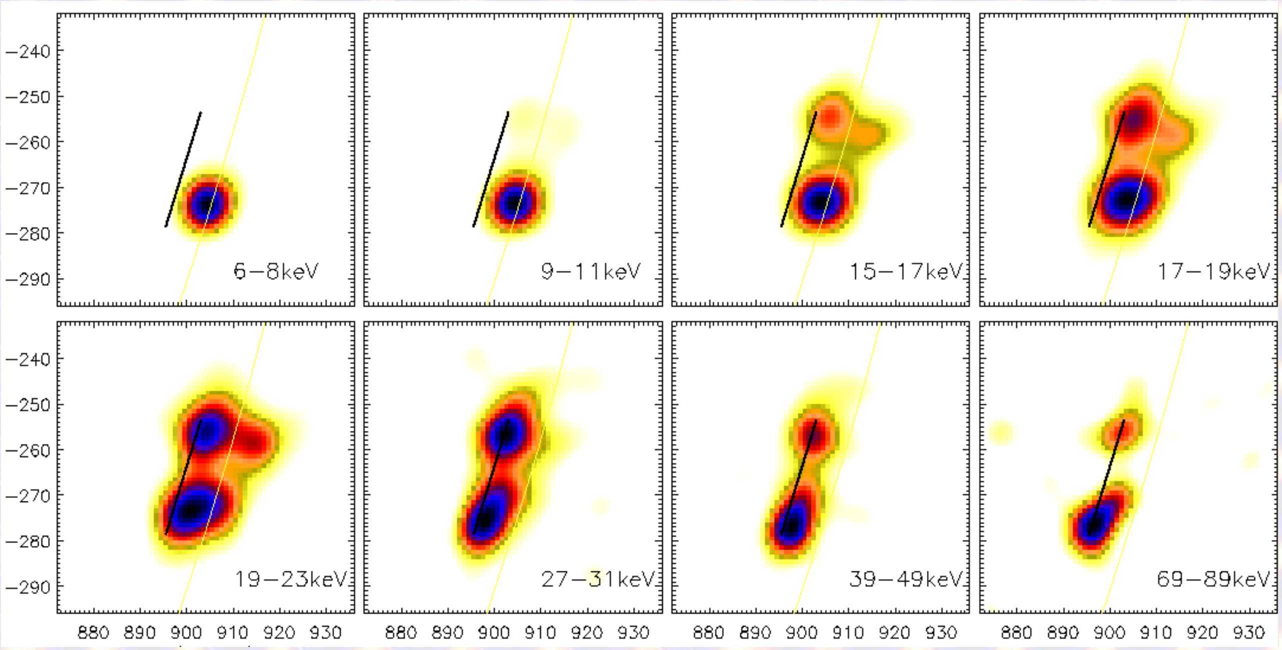
$$E(E_0, N) = \left(E_0^2 - 2KN\right)^{1/2}$$

$$N_s(E_0) = \frac{E_0^2}{2K} \qquad N_s(z) = \int_z^{z_{max}} n(z')dz'$$

$$n(z)$$

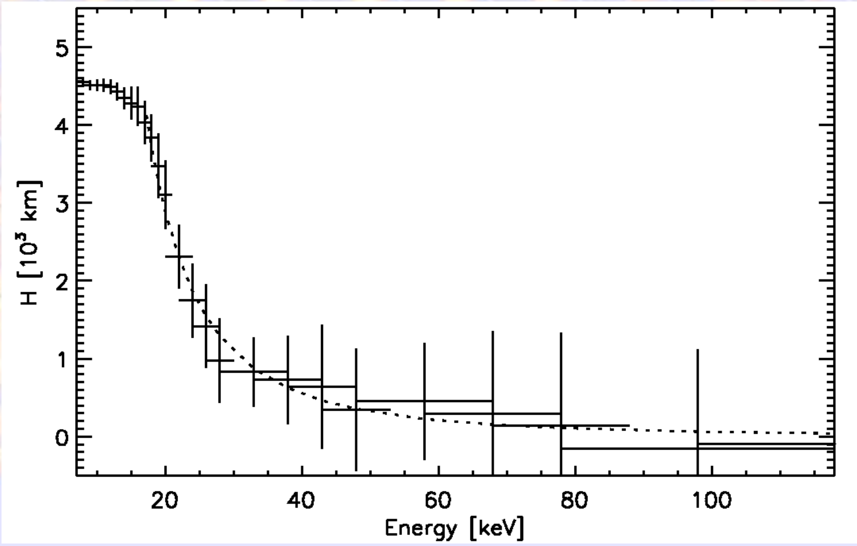
Having n(z) distribution we can localize the altitude of the 1.17×10^{17} cm^{-3} (upper photosphere) and use it as a reference level.

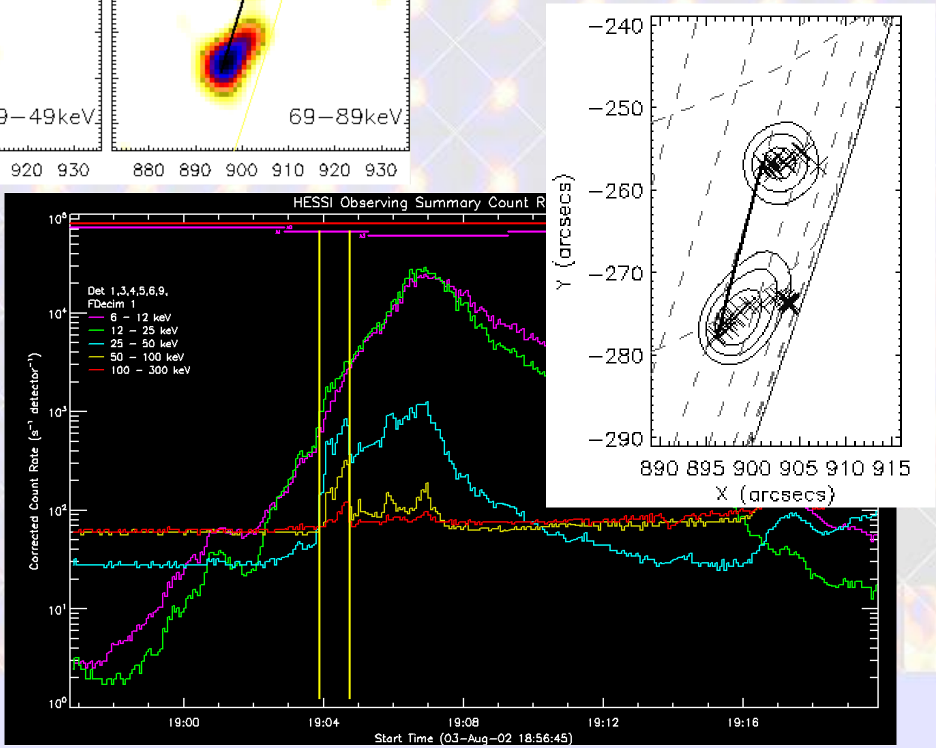
RHESSI: energy – altitude relation



Main HXR peak:
19:04 – 19:05 UT

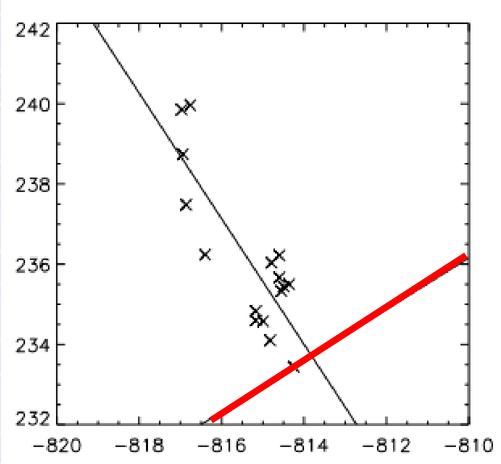
Reference level defined with highest-energy sources



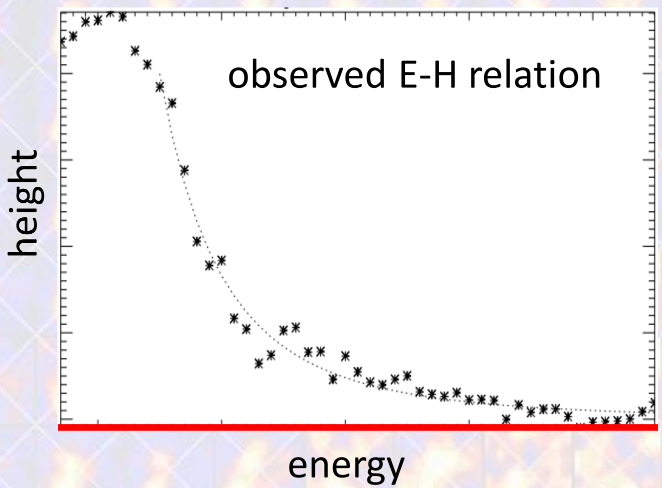


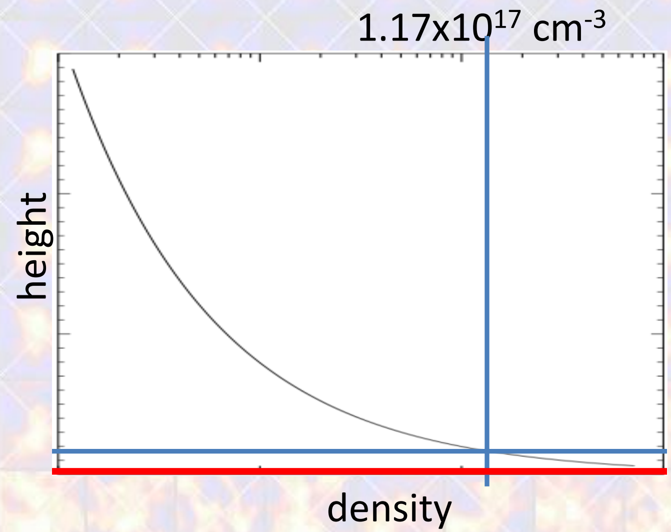
Absolute reference level

Centroids of HXR sources observed in several energy intervals



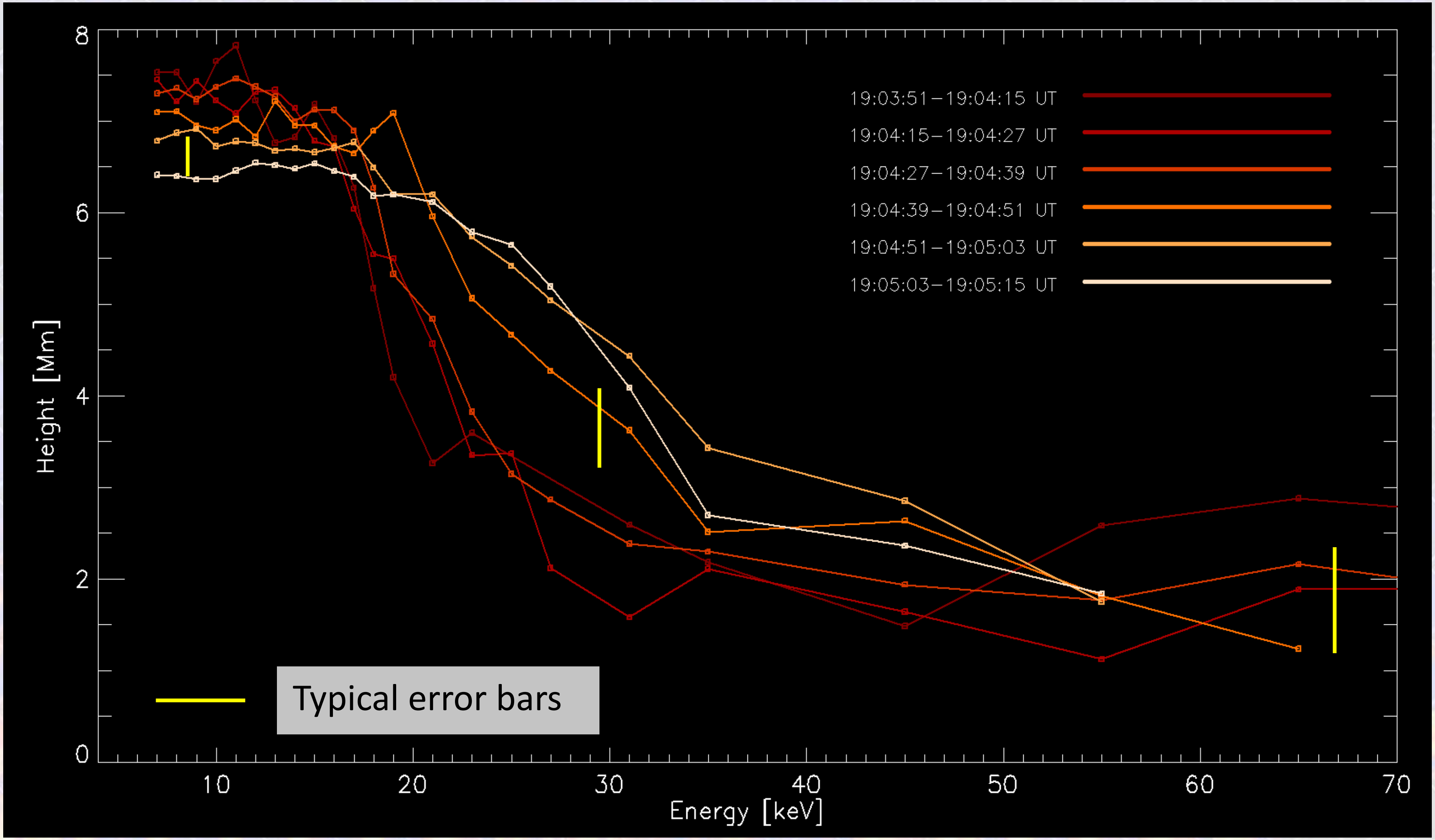
Location of the photosphere is calculated directly from the energy-altitude relation





correction factor

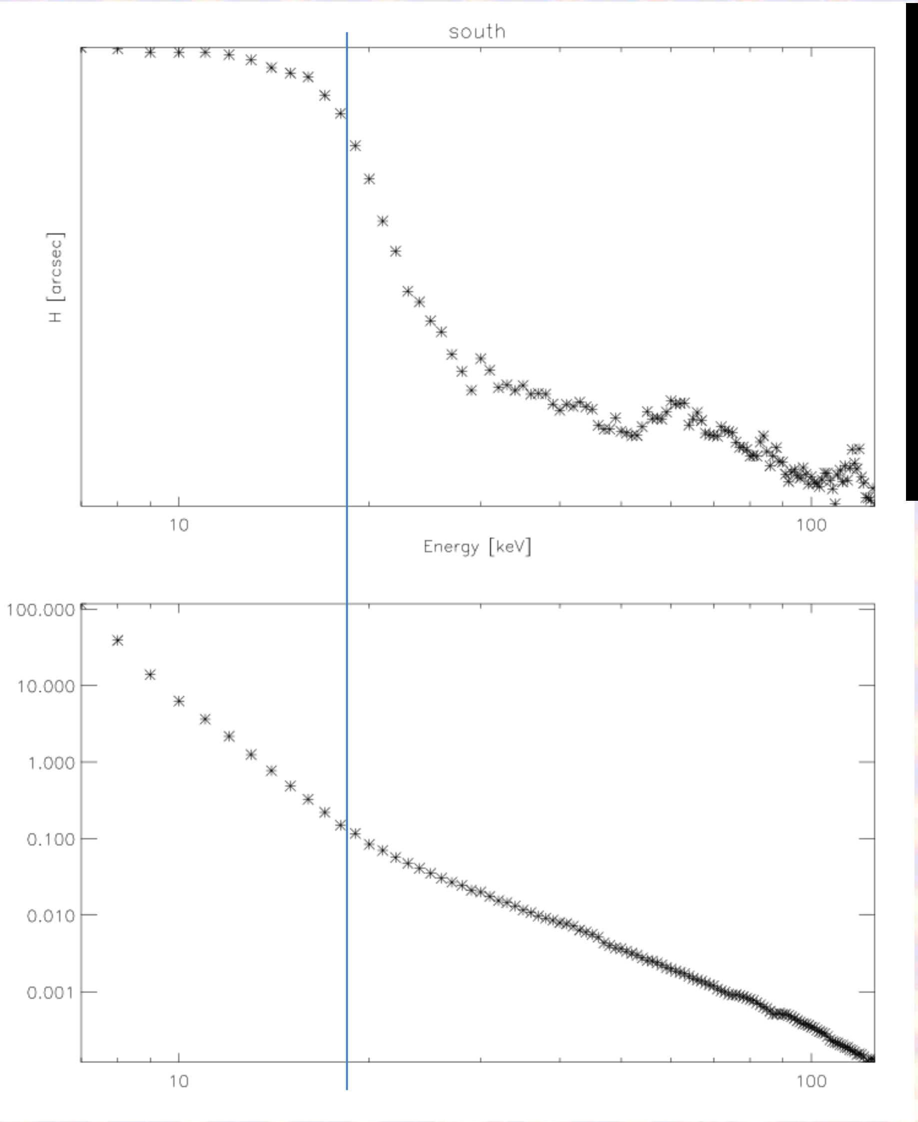
Time variation of E-H relation

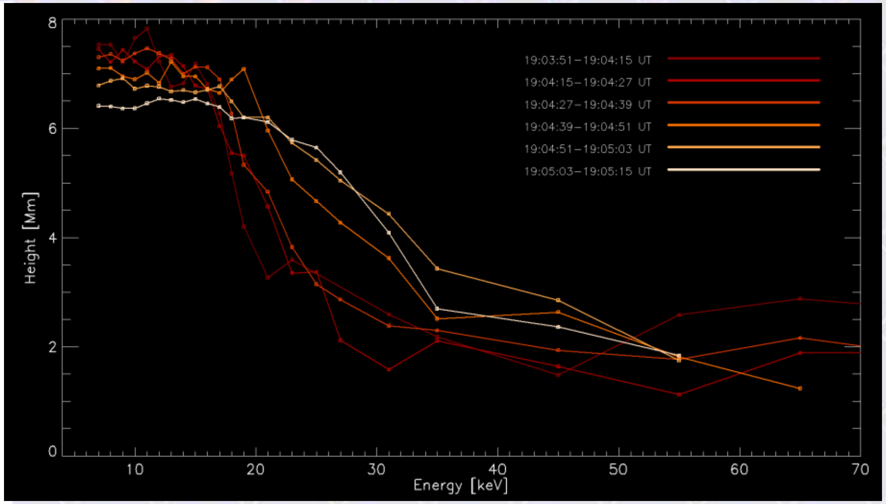


Six consecutive time intervals covering main HXRburst

Observed changes may be caused by changes of column density or electron spectrum index

Chromospheric dynamics



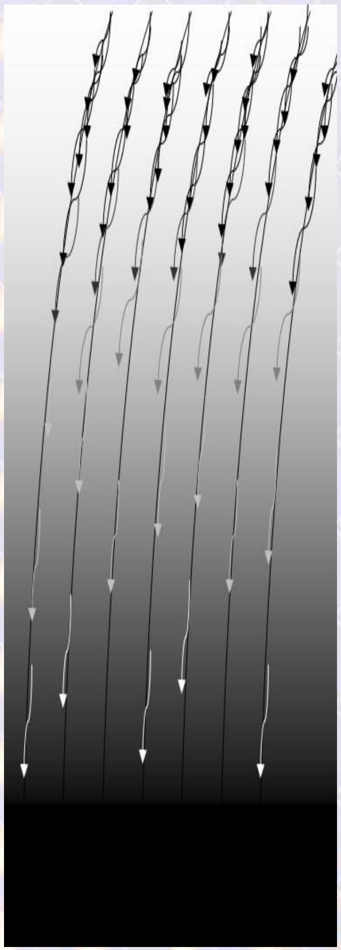


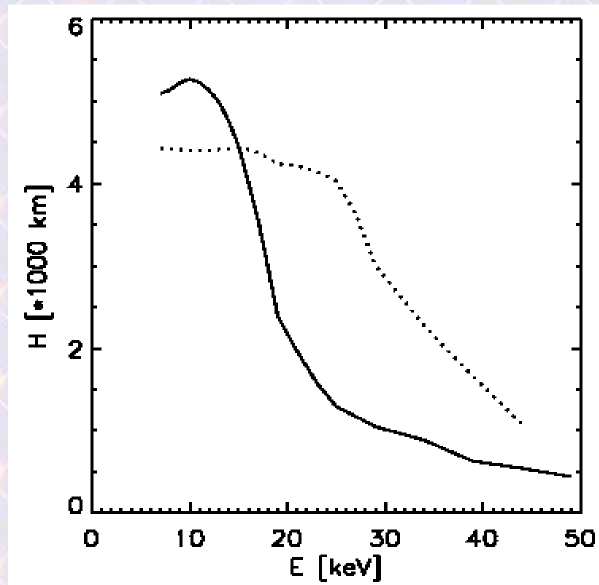
Low energy part of the curve is purely thermal – top of small loop

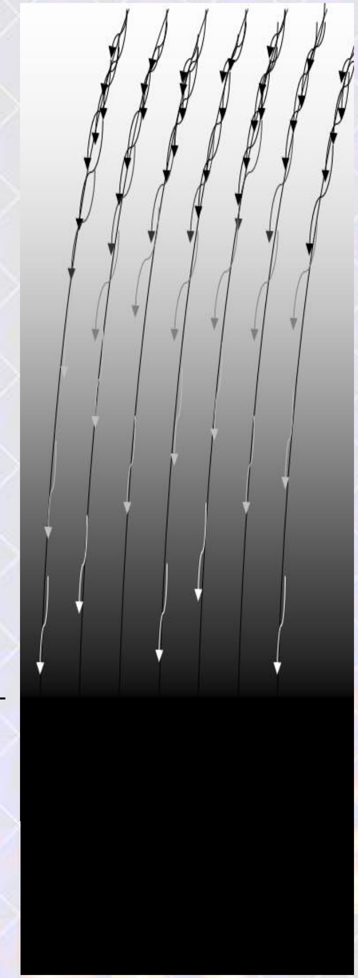
Non-thermal sources are visible above 20 keV, and theirs altitudes may be measured with good accuracy.

Assuming the relation depends on a column density we may trace the plasma dynamics in footpoints.

Chromospheric dynamics





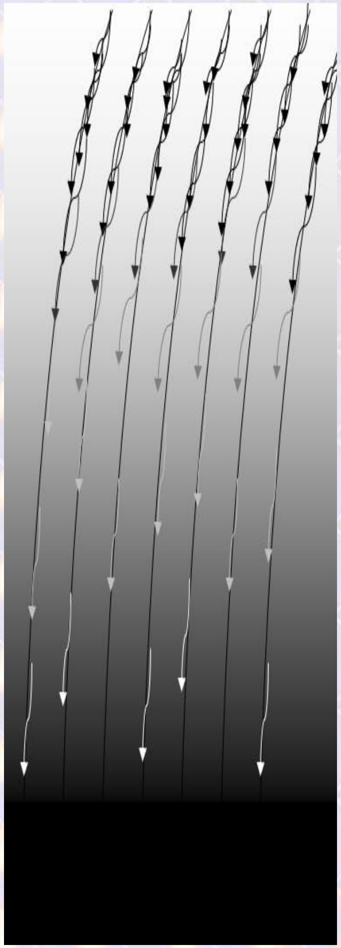


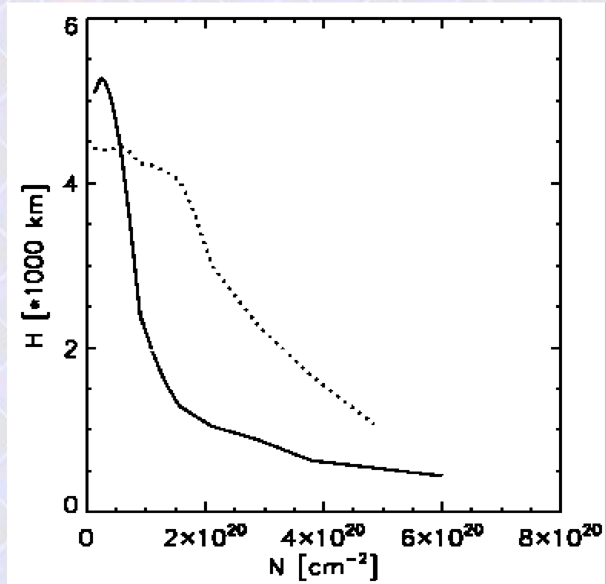
h_0, E_0, N_1 $\qquad$ h_0, E_0, N_0

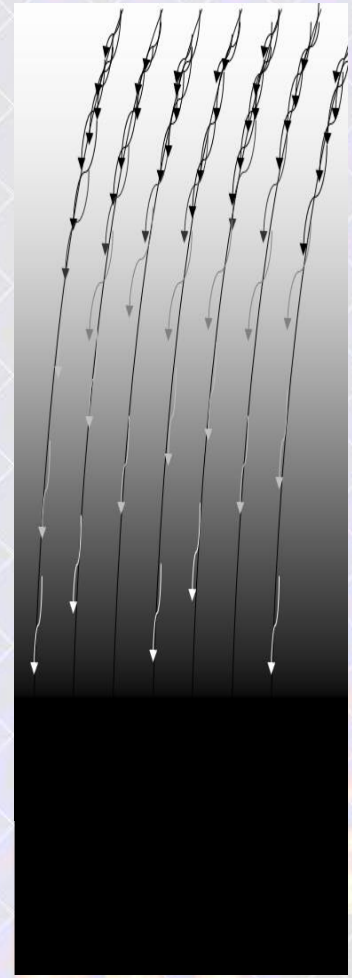
$$N_s(E_0) = \frac{E_0^2}{2K}$$

Energy-altitude relation may be transferred to energy-column density relation

Chromospheric dynamics





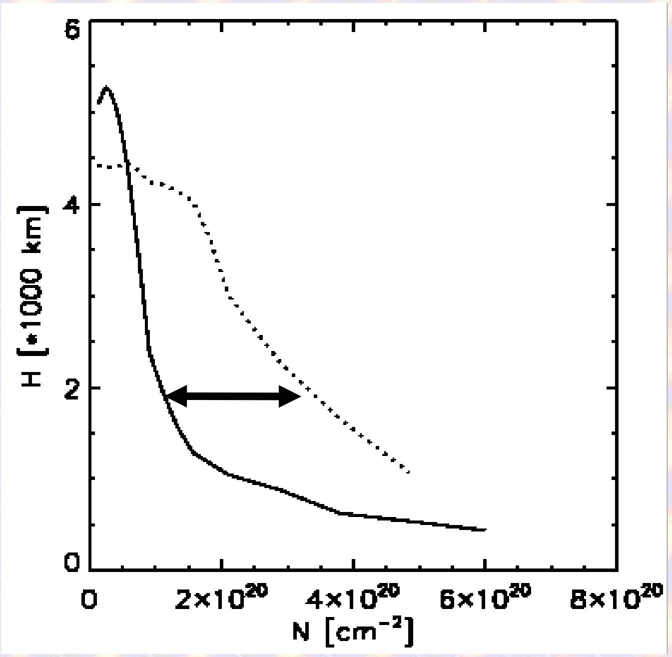


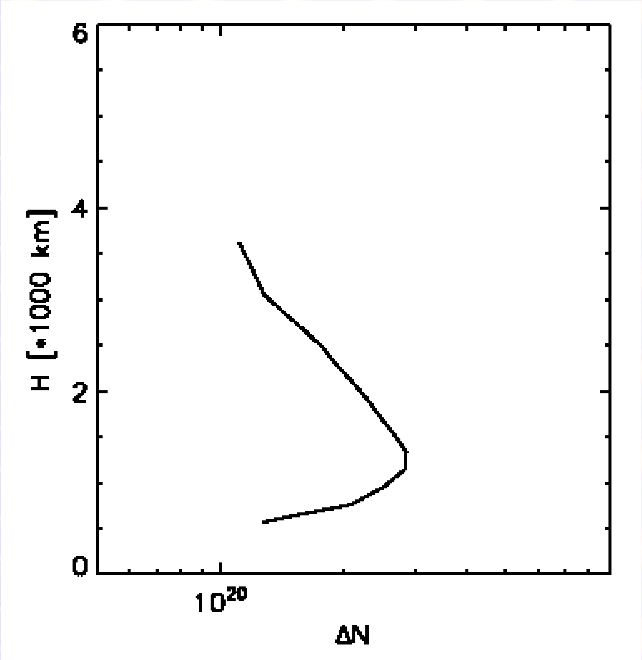
h_0, E_0, N_1 h_0, E_0, N_0

$$N_s\left(E_0\right) = \frac{E_0^2}{2K}$$

Difference between column densities calculated at several levels may be transferred to difference of masses

Chromospheric dynamics



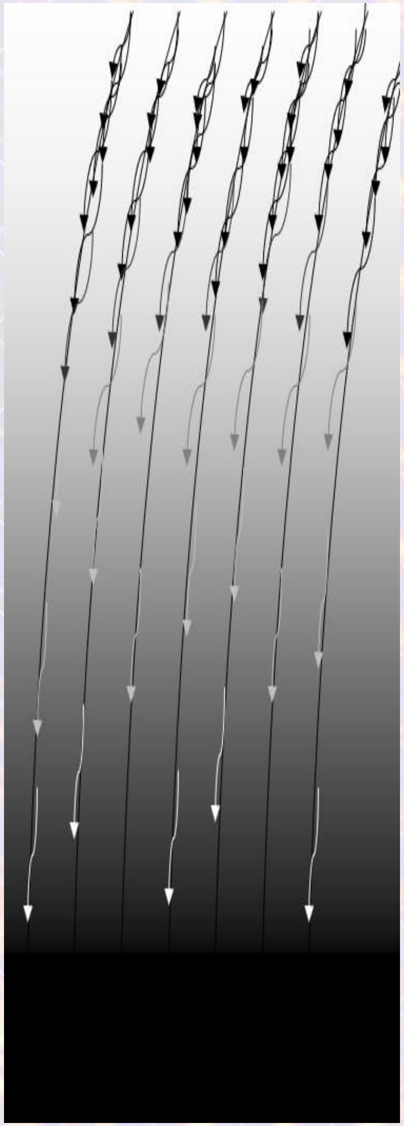


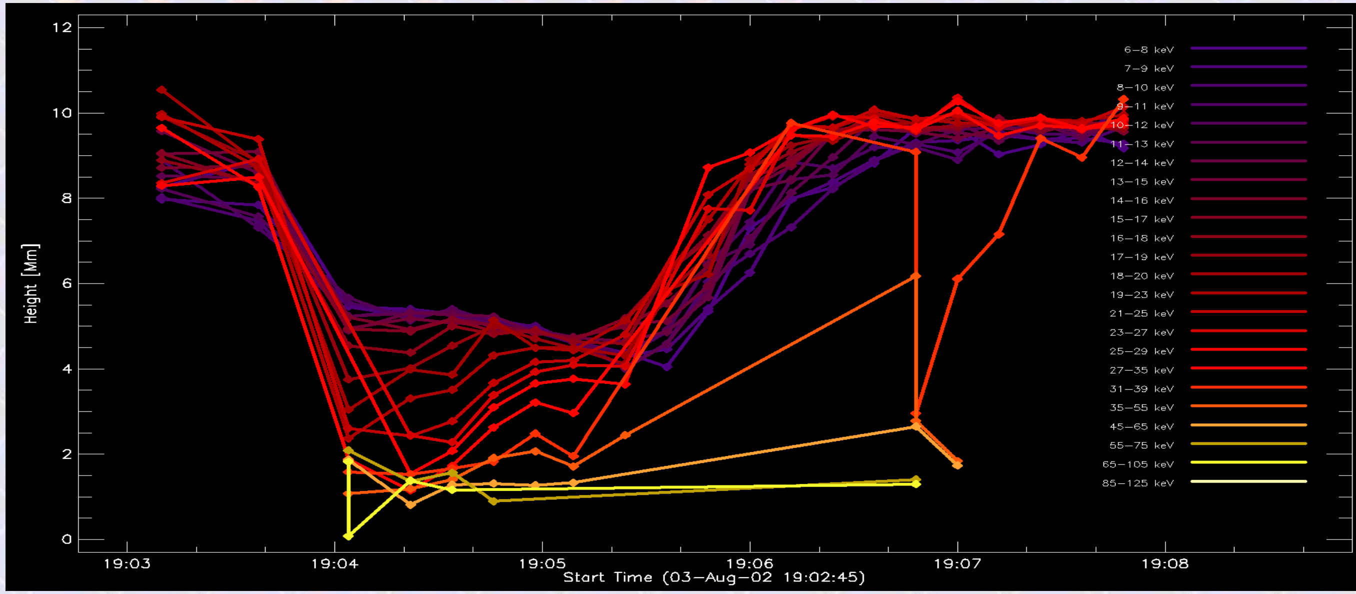
The „maximum" informs how much mass was moved between levels

Additional mass above 1000 km: 5×10^{13} g

ΔEM (EM at the maximum minus initial EM for loop top) : 8×10^{13} g

Chromospheric dynamics





Velocities estimated in footpoints are of 150-200 km/s

Non-thermal energy (main peak): 1.6×10^{30} ergs

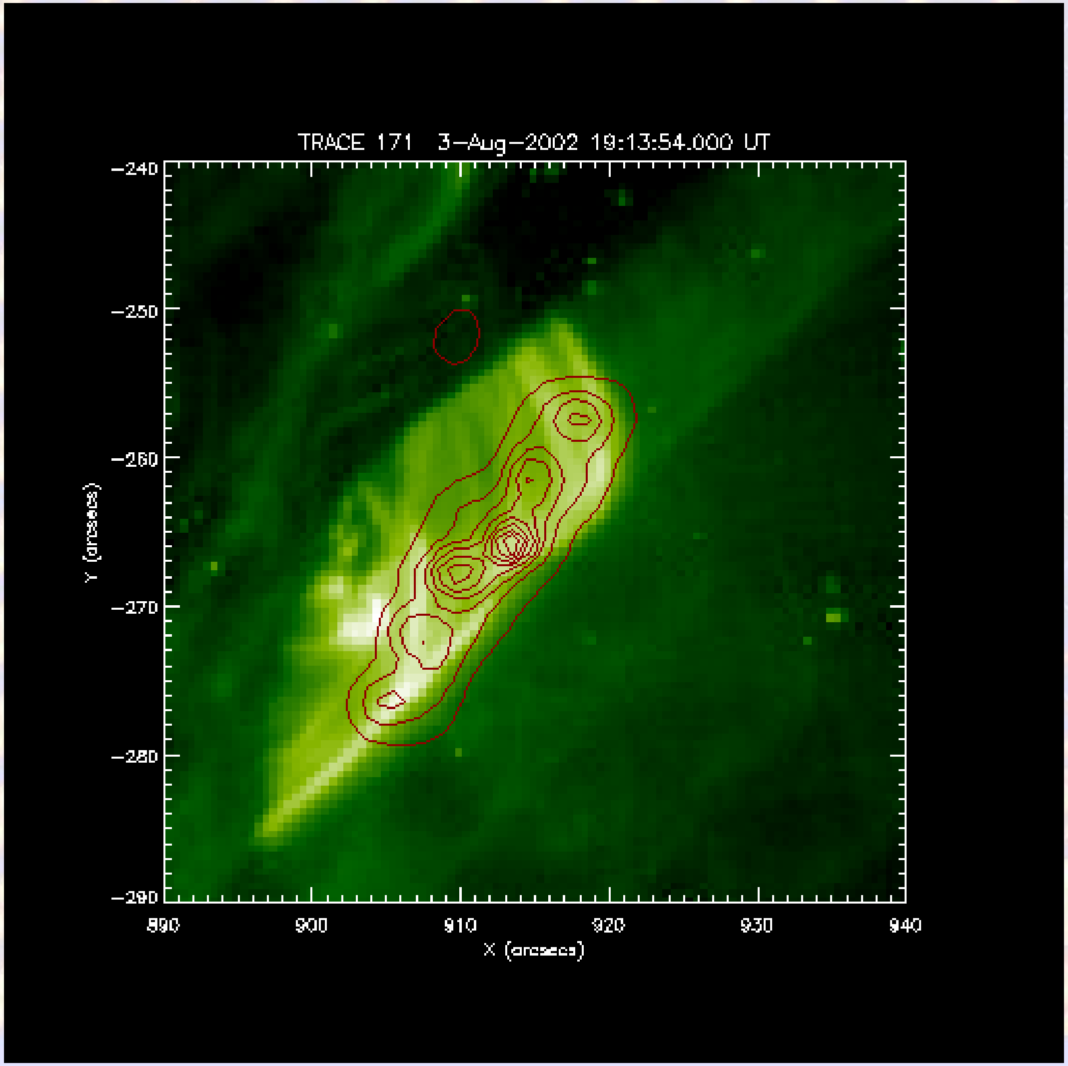
Kinetic energy (we estimated mass) of evaporated plasma: 10^{28} ergs

Summary

- The energy – altitude relation gives a chance for detailed investigation of electron beams propagating in chromosphere and the hydrodynamical response of heated plasma.
- Treating electrons as a tool that probes chromospheric density we are able to analyze chromospheric dynamics.
- The observed HXR sources has a great advantage – the physics of emission is simple and it is optically thin.
- Several observations suggest that we should forget ideas like „HXR sources are simple, large and without internal structure”.
- HXR images have a huge potential for analysing the energy deposition by non-thermal electrons, but we need better time and spatial (!) resolution.

Do we need high spatial resolution for hot plasma?

YES!



Thank you for your attention