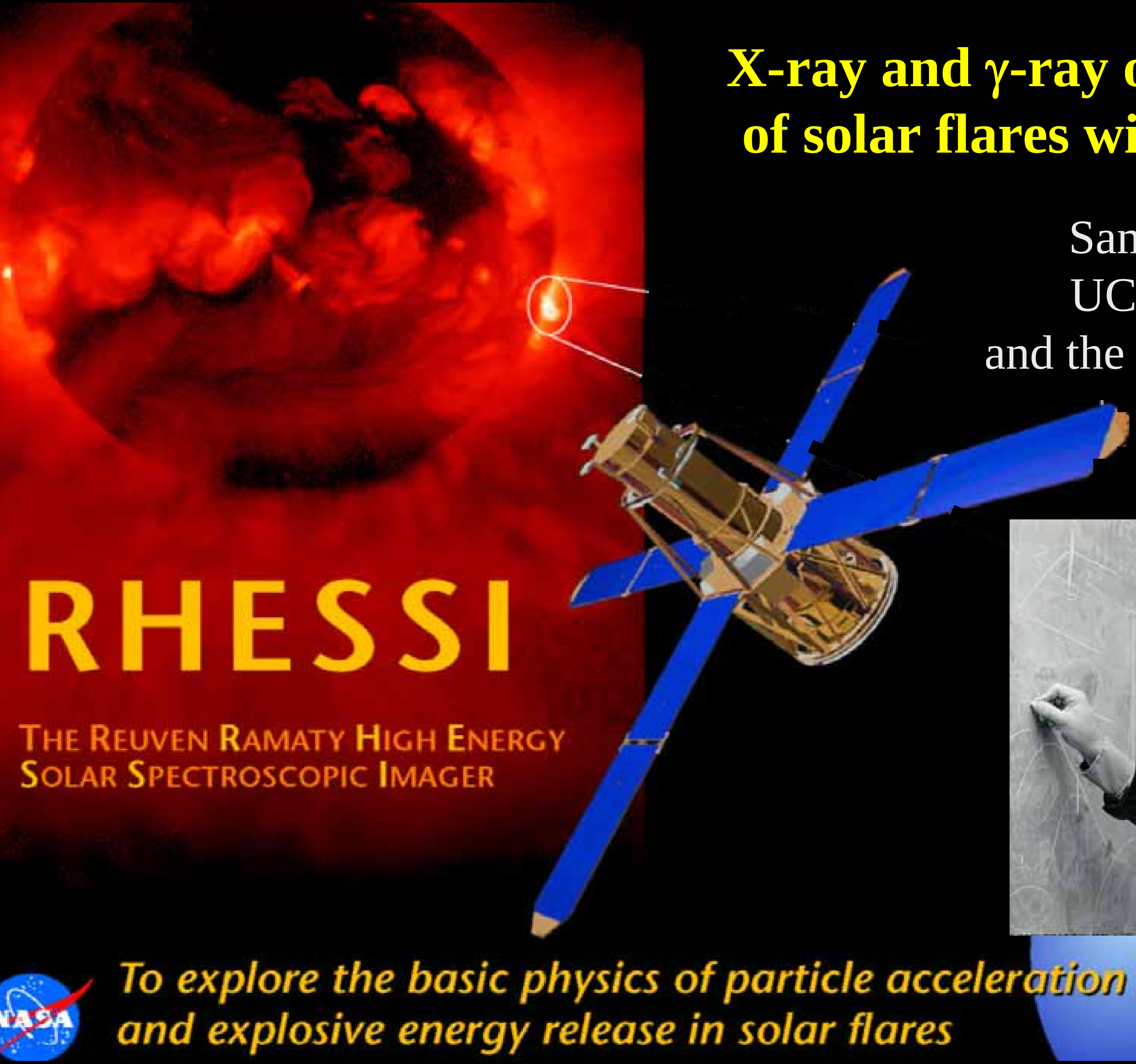
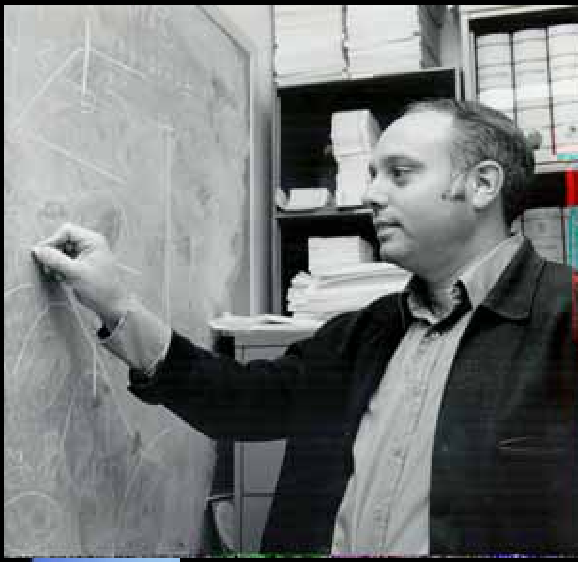
X-ray and γ-ray observations of solar flares with RHESSI

Sam Krucker
UC Berkeley
and the RHESSI team





Reuven Ramaty
1937 – 2001

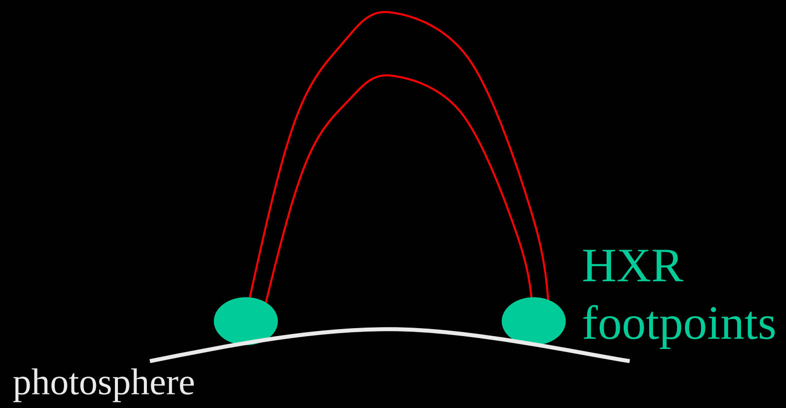
Solar X-ray emissions

- energetic electrons in plasma

  → non-thermal bremsstrahlung (collisions)

  more emission in high density plasma

  → emission from footpoints (thick target)



Solar X-ray emissions

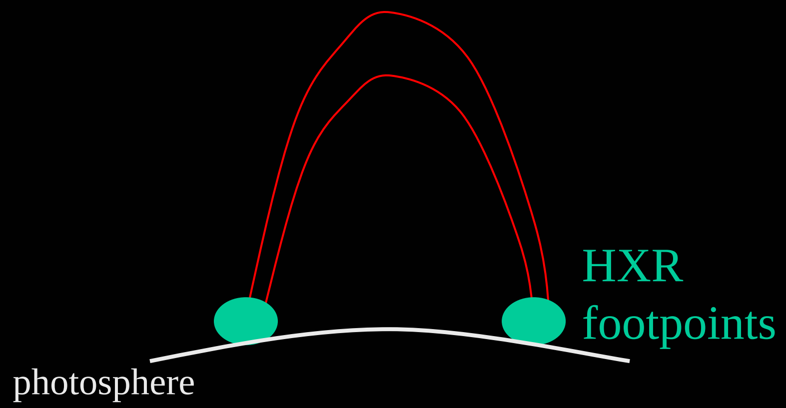
- energetic electrons in plasma

  → non-thermal bremsstrahlung (collisions)

  more emission in high density plasma

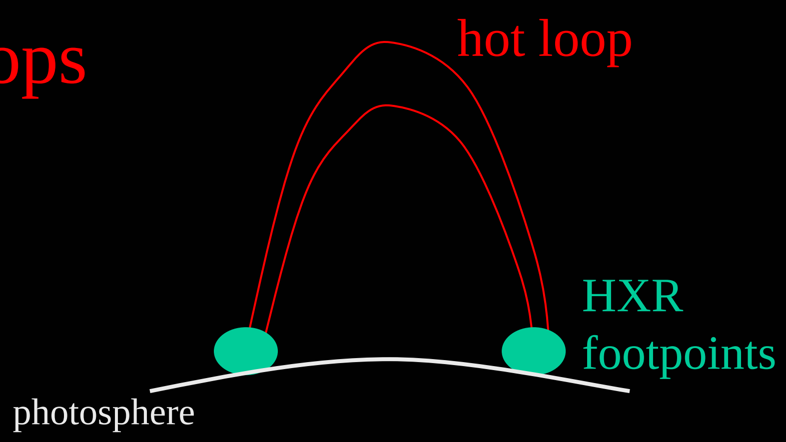
  → emission from footpoints (thick target)

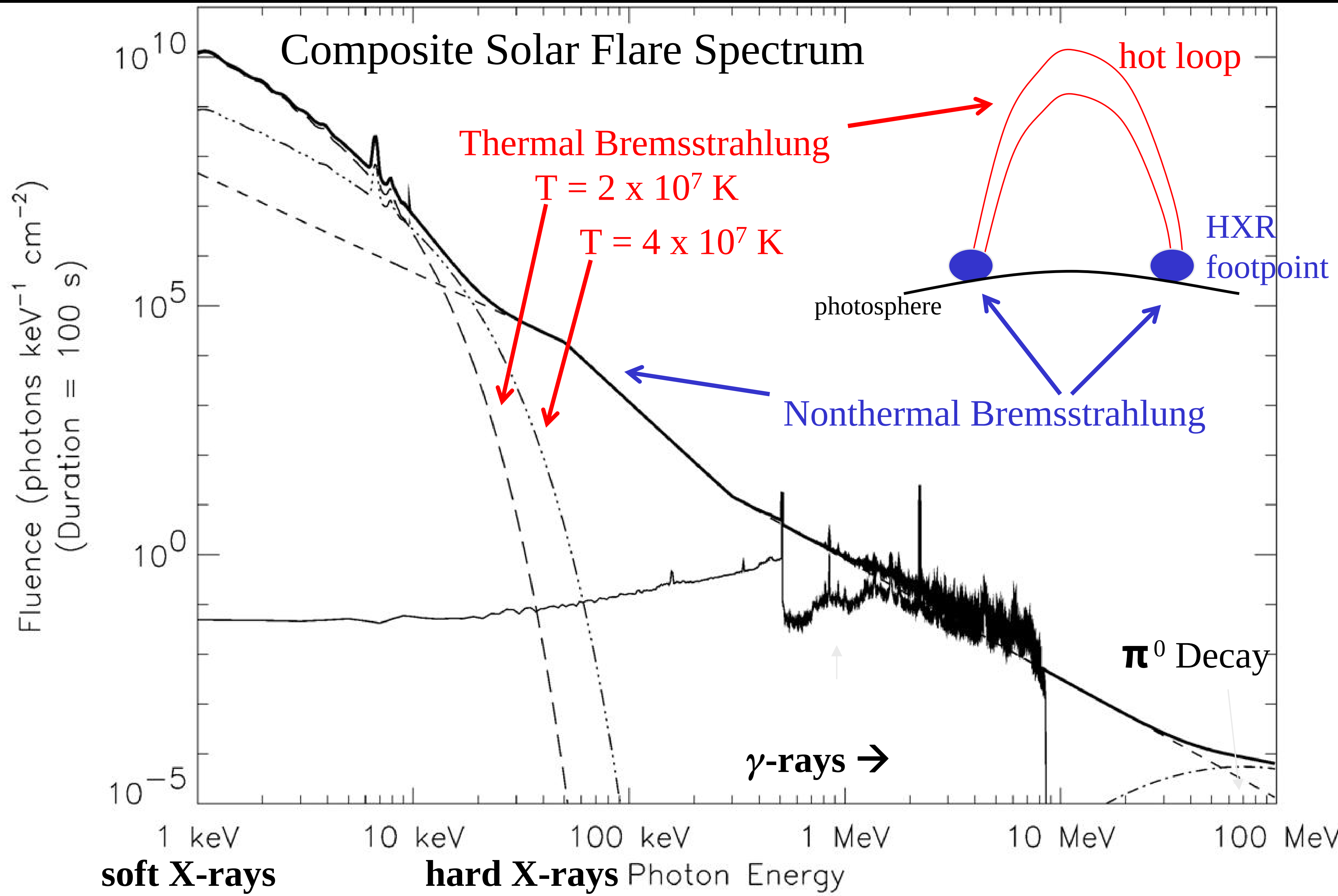
  → non-thermal emission from loop much weaker (thin target), most often too weak to be seen



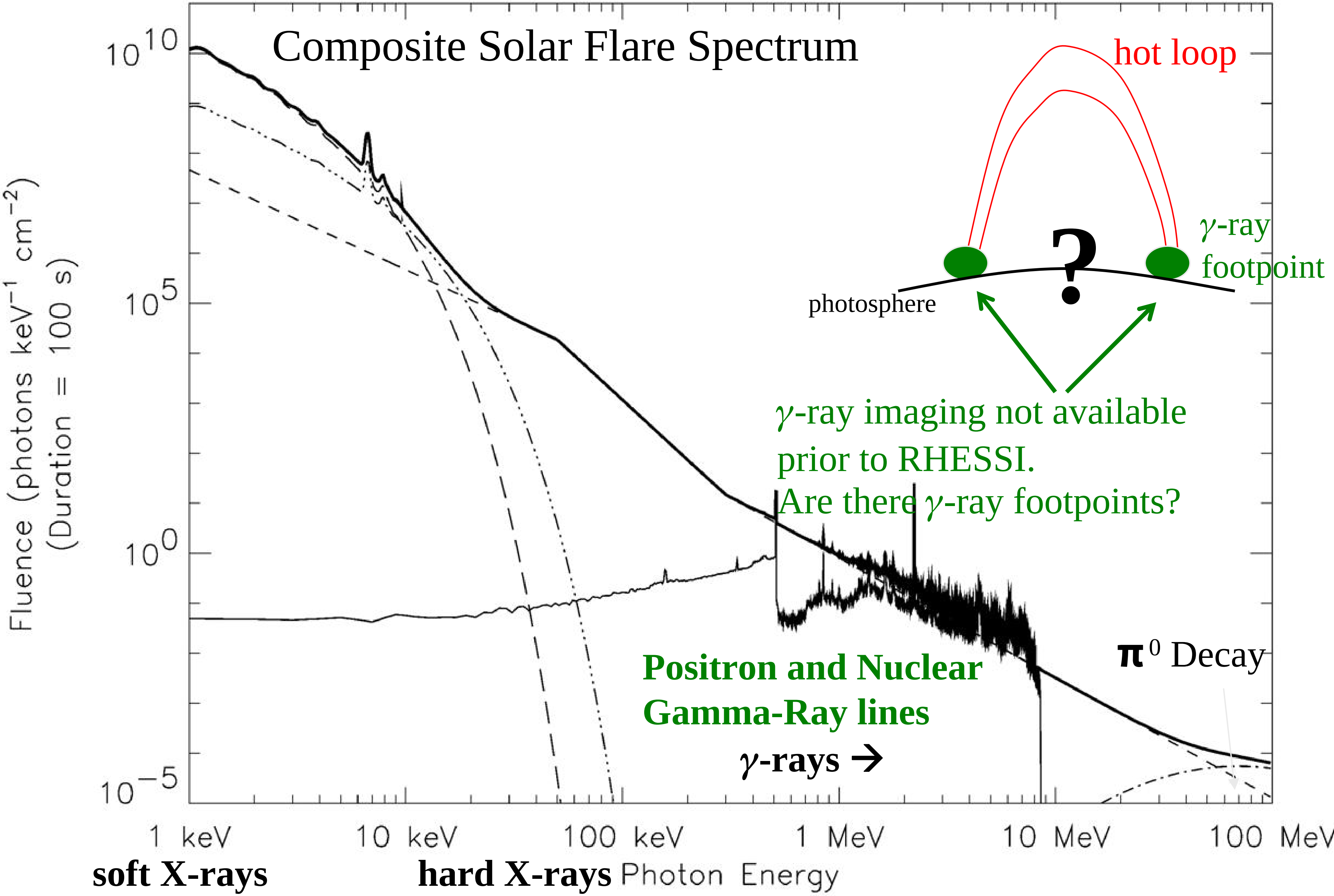
Solar X-ray emissions

- energetic electrons in plasma
  → non-thermal bremsstrahlung (collisions)
  more emission in high density plasma
  → emission from footpoints
- if temperature is high enough (~MK and above)
  → thermal bremsstrahlung in X-ray range
  hot, dense plasma in loops





Composite Solar Flare Spectrum
hot loop
Thermal Bremsstrahlung
T = 2 x 10^7 K
T = 4 x 10^7 K
HXR
footpoint
photosphere
Nonthermal Bremsstrahlung
π^0 Decay
γ-rays →
Fluence (photons keV^-1 cm^-2)
(Duration = 100 s)
10^10
10^5
10^0
10^-5
1 keV
10 keV
100 keV
1 MeV
10 MeV
100 MeV
soft X-rays
hard X-rays
Photon Energy

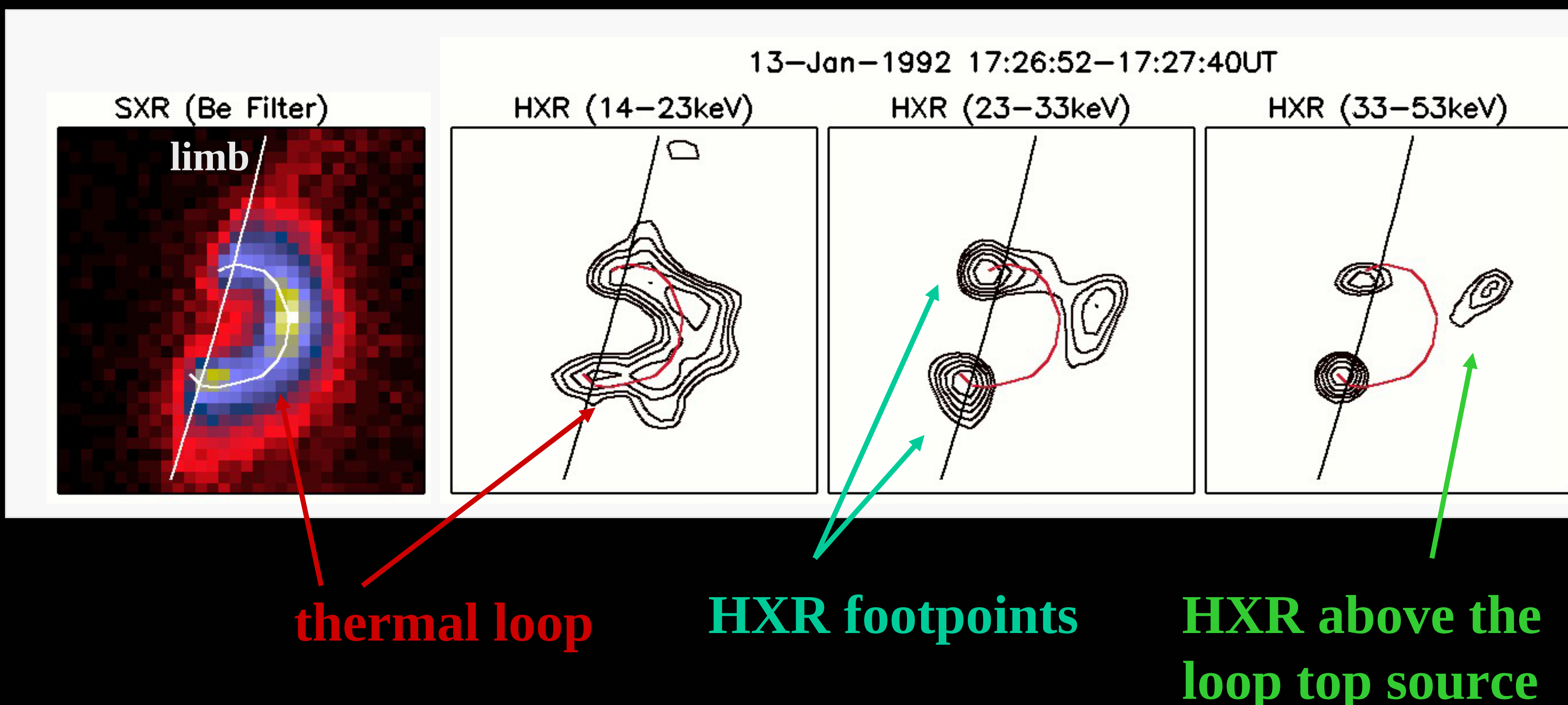


Composite Solar Flare Spectrum
hot loop
γ-ray
footpoint
?
photosphere
γ-ray imaging not available
prior to RHESSI.
Are there γ-ray footpoints?
Positron and Nuclear
Gamma-Ray lines
γ-rays →
π⁰ Decay
Fluence (photons keV⁻¹ cm⁻²)
(Duration = 100 s)
10¹⁰
10⁵
10⁰
10⁻⁵
1 keV
10 keV
100 keV
1 MeV
10 MeV
100 MeV
soft X-rays
hard X-rays
Photon Energy

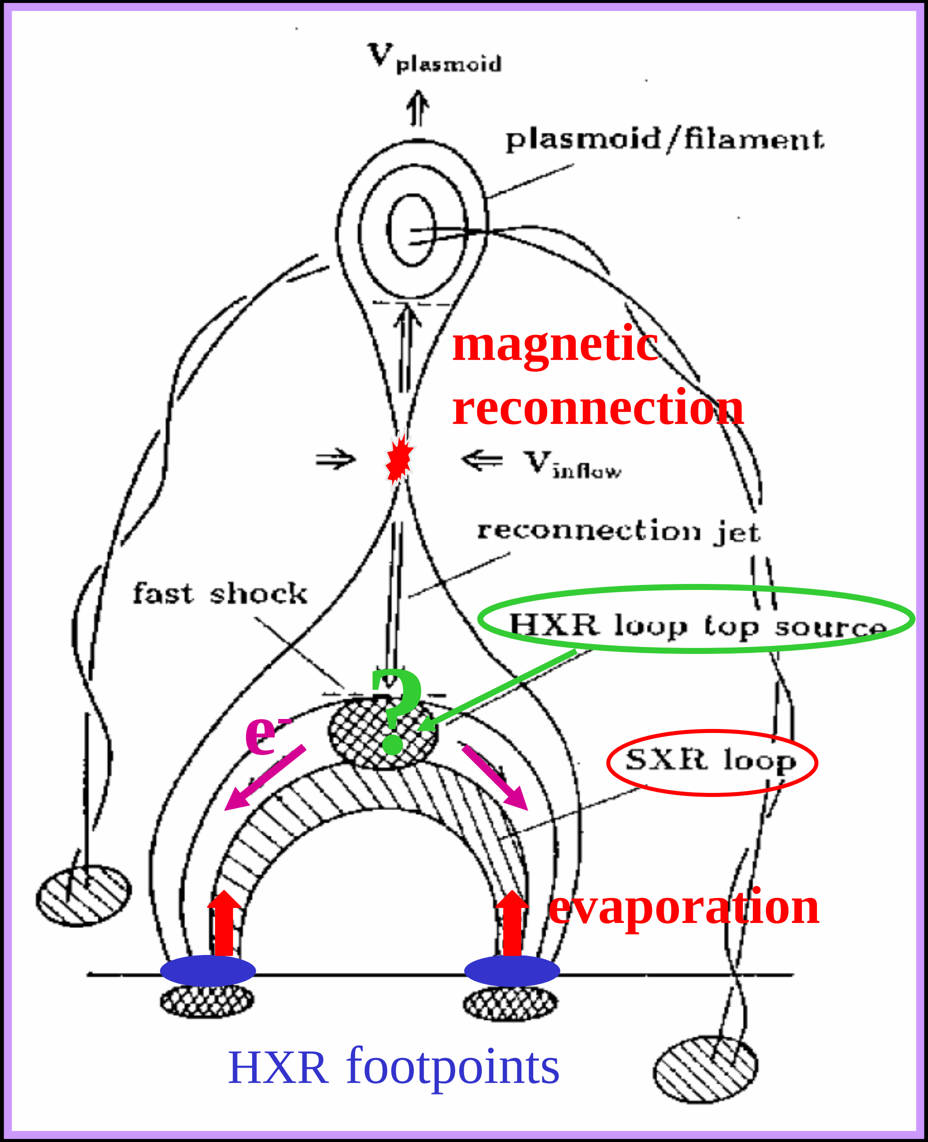
Above the loop to HXR source

YOHKOH HXT observations:

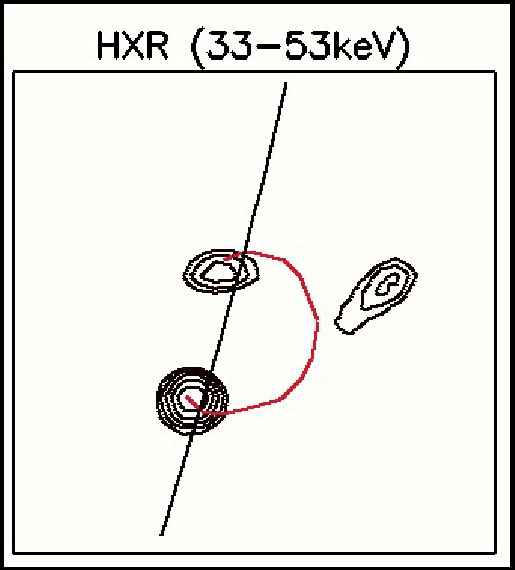
Only very rarely seen! 6 good events in 10 years.
The most famous one is the so-called Masuda flare (Masuda et al. 1994)



Magnetic reconnection model

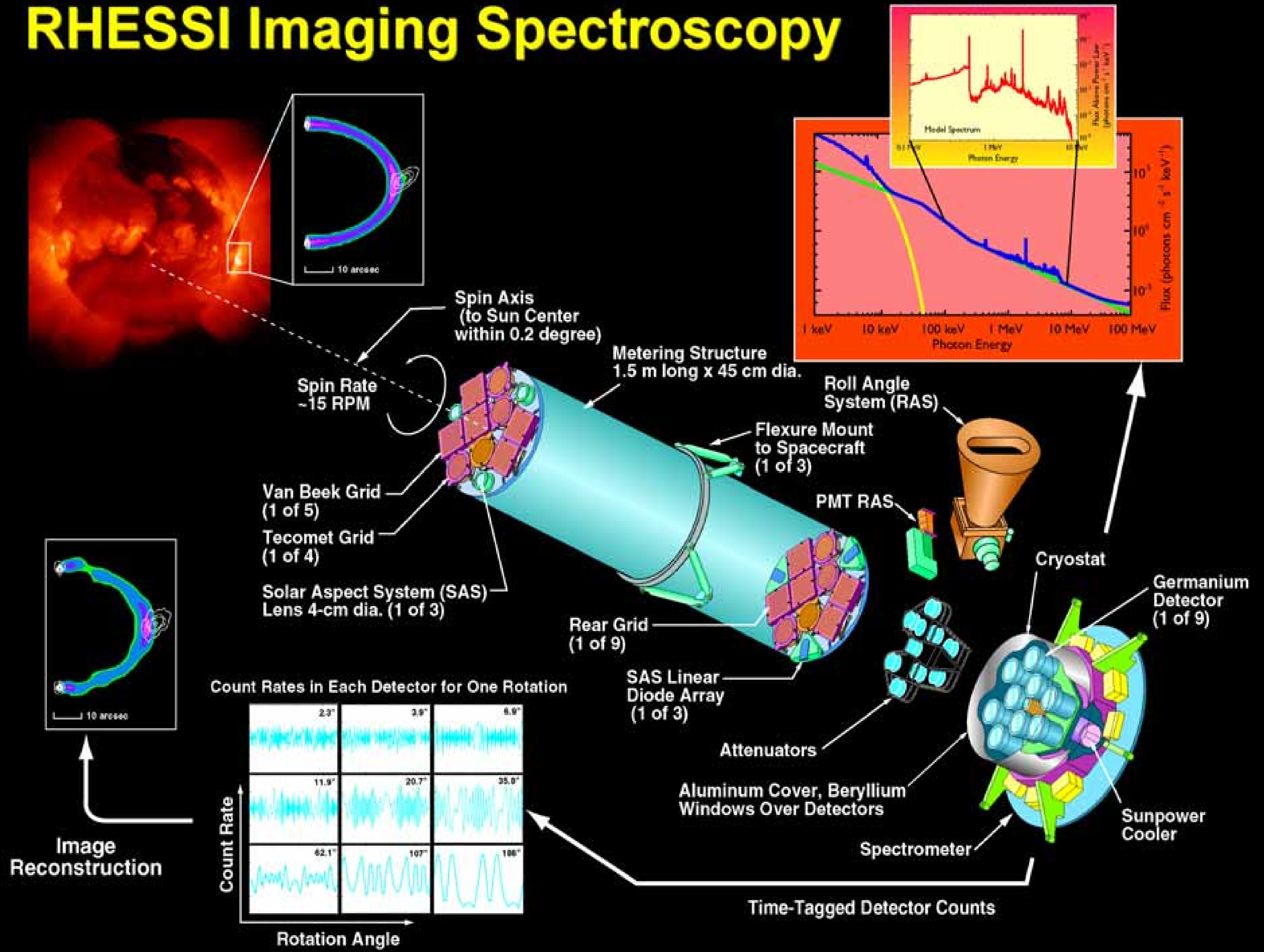


1) Release of magnetic energy
2) Accelerated electrons produce HXRs and heat loop
3) Above loop top source not understood
4) Ion acceleration even less understood. RHESSI provides first imaging.



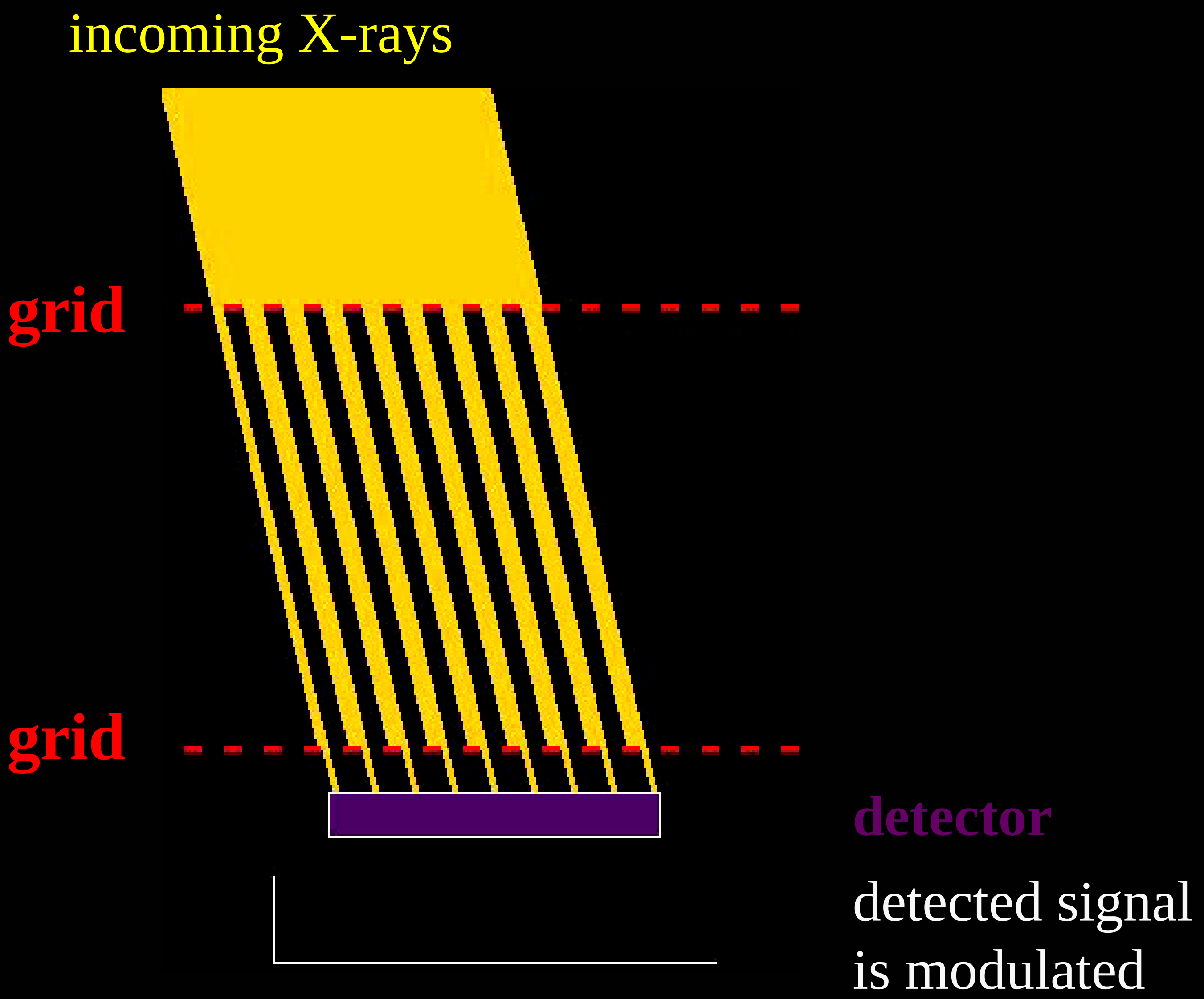
from Shibata

RHESSI Imaging Spectroscopy



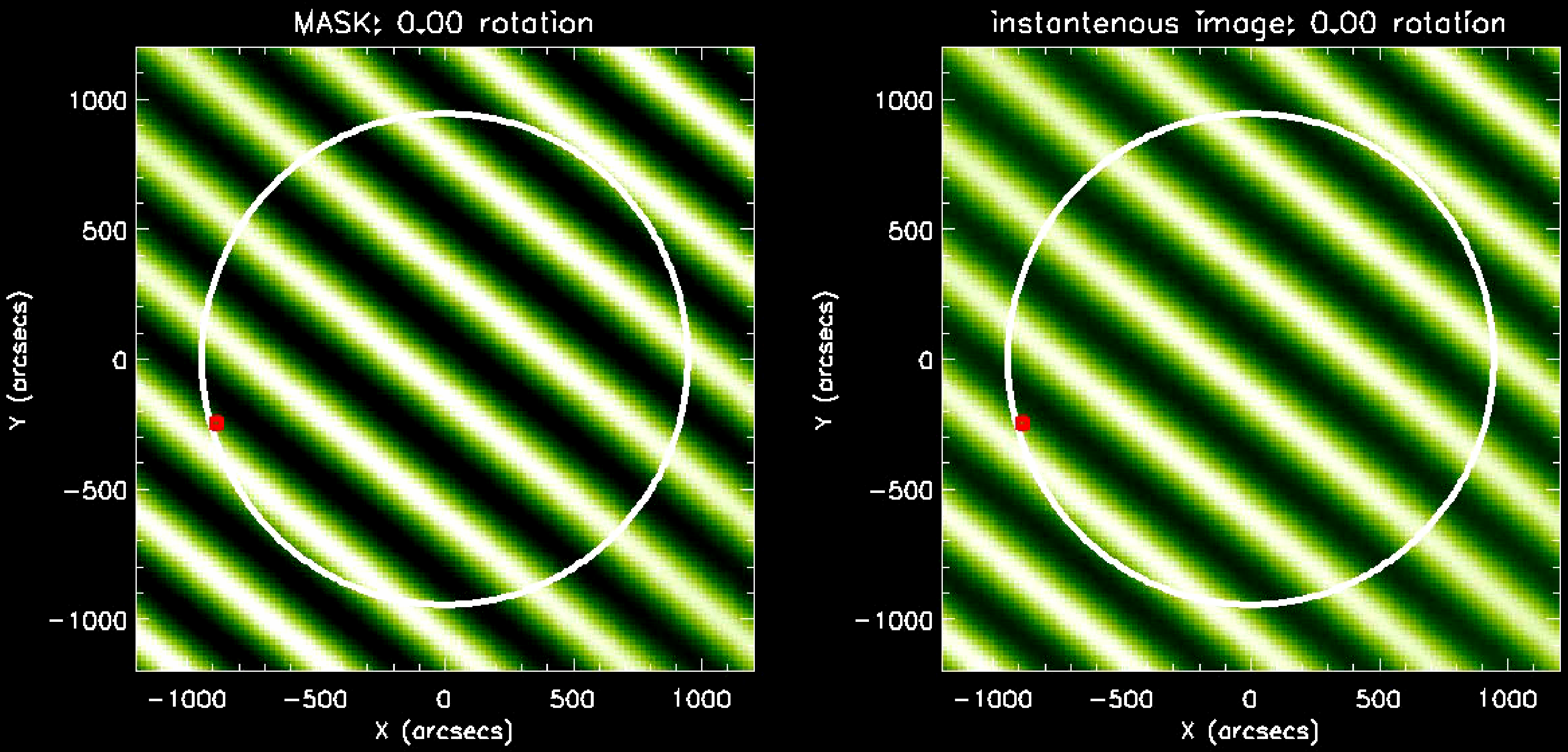
F1309_18.ai

RHESSI imaging



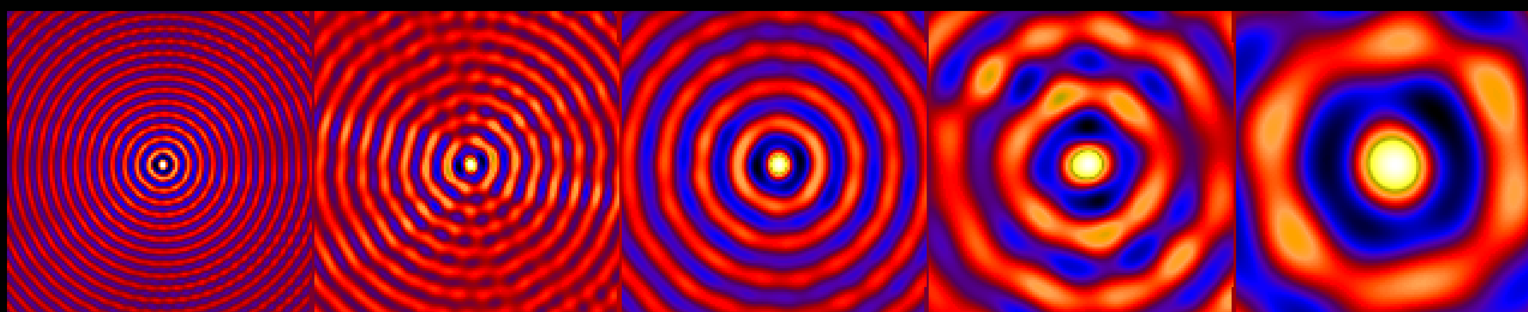
RHESSI imaging:
rotating modulation collimators (RMCs)

9 grids with different spacing → 9 images at different resolution



RHSI point spread function PSF

grid 5 grid 6 grid 7 grid 8 grid 9



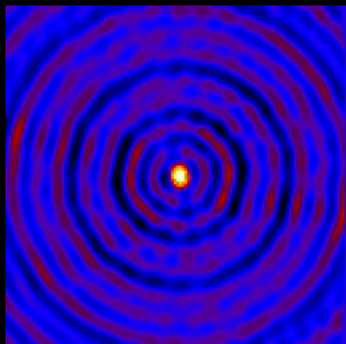
FWHM 20” FWHM 60” FWHM 180”

PSF is slightly different for different locations in image

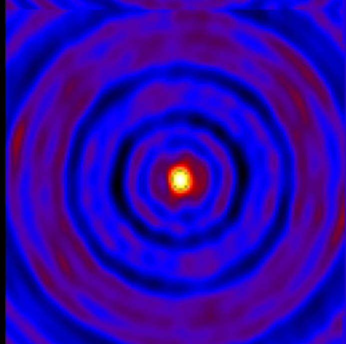
psf = o → getdata(class_name=‘hsi_psf’, xy_pixel=xy)
psf = hsi_annsec2xy(psf, o)

Summing individual PSF gives PSF of reconstructed image

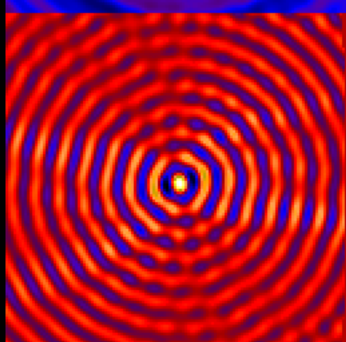
FWHM for grid 3-9



UNIFORM weighting
more weight to finer grids
→ FWHM smaller — 9.8”



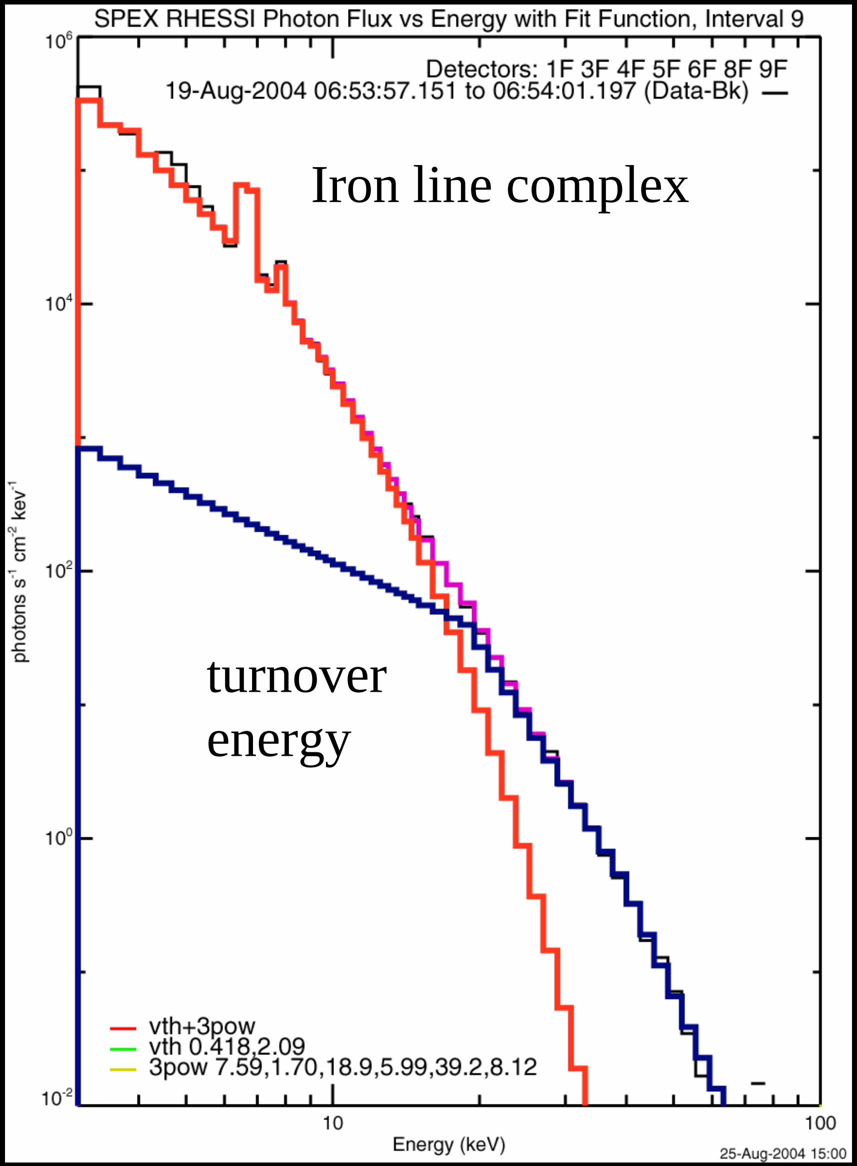
NATURAL weighting
same weight for all grids
→ FWHM larger — 15.5”



for comparison:
finest single grid — 7.1”

i.e. using grid 3 through 9 in BACKPROJECTION and CLEAN gives a net resolution larger than for grid 3 alone.

RHESSI spectrum: ~ 1 keV



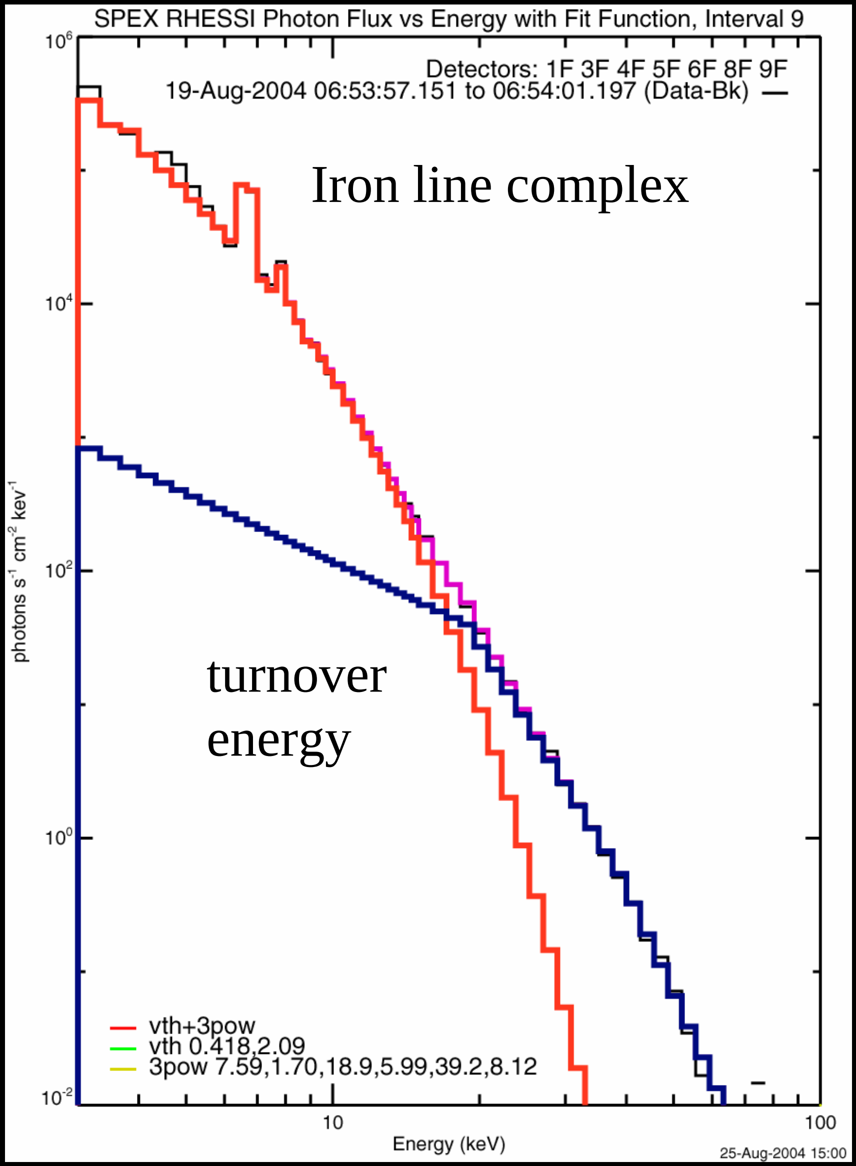
Photon spectrum

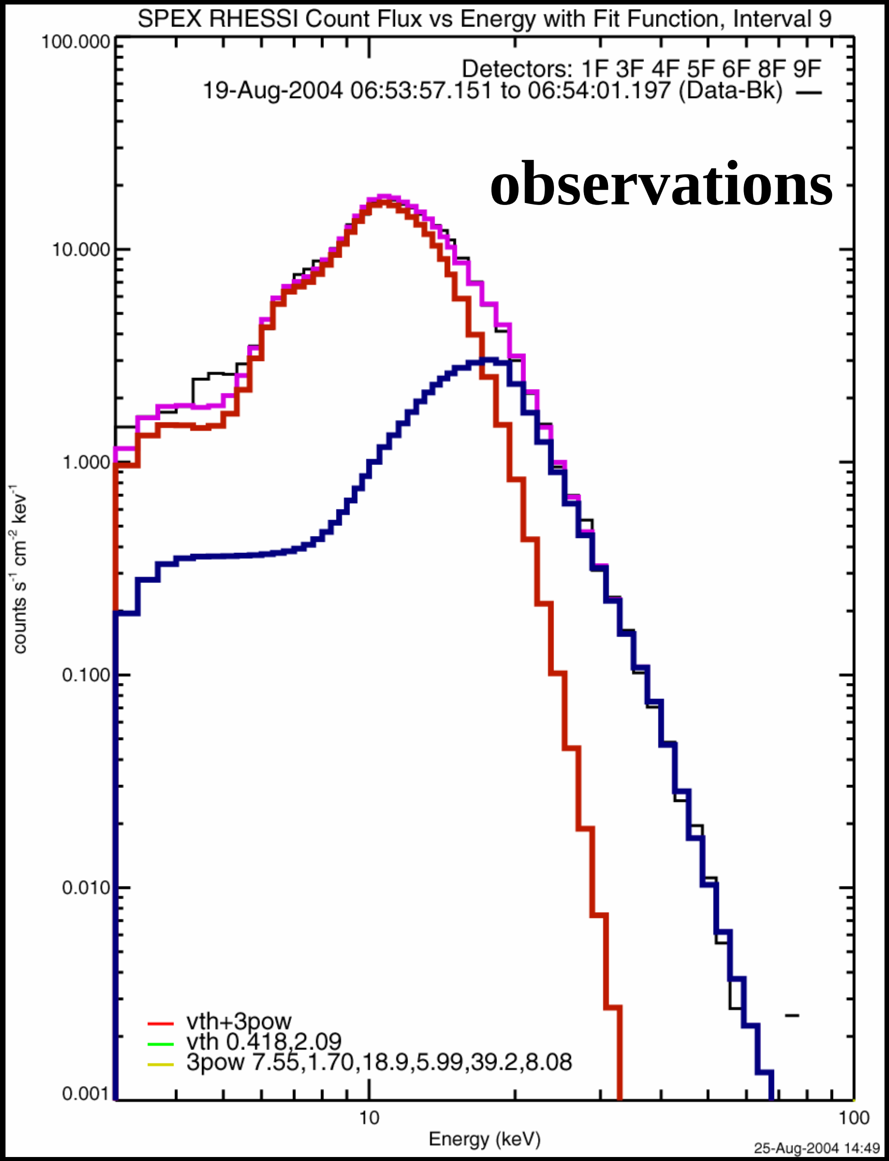
Thermal fit in red.

Non-thermal in blue.
(broken power law).

photon spectrum

count spectrum





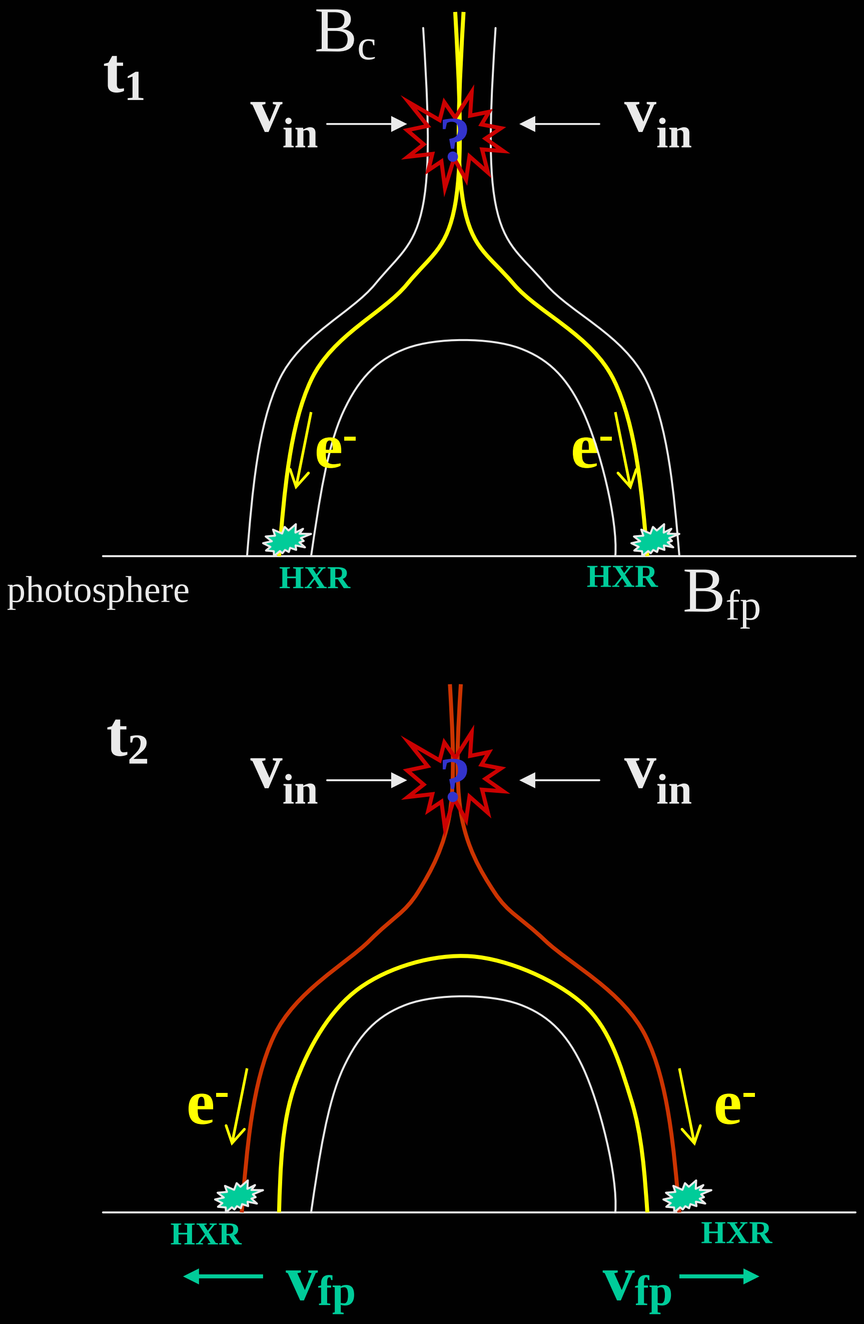
RHESSI
IMAGING SPECTROSCOPY

- Imaging down to ~3 keV with 2.3” resolution, less at higher energies, e.g. 35” at 2.2 MeV
- ~1 keV resolution, ~5 keV at higher energies

Selected RHESSI results

- HXR footpoints and their motions
- Coronal X-ray sources
- Imaging in γ-rays: location of protons

HXR source motions in magnetic reconnection models



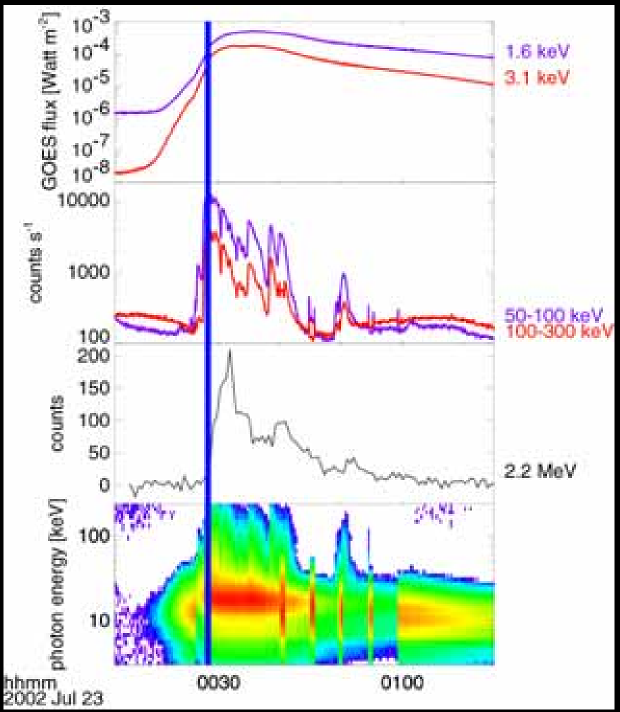
Yohkoh observations:
Sakao et al. 1994, 1995

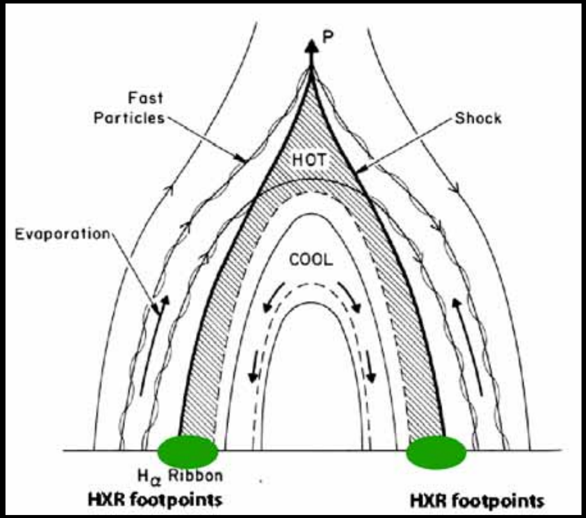
Simple motion in 2 dimensions;
in 3 dimensions motion is likely more complex.

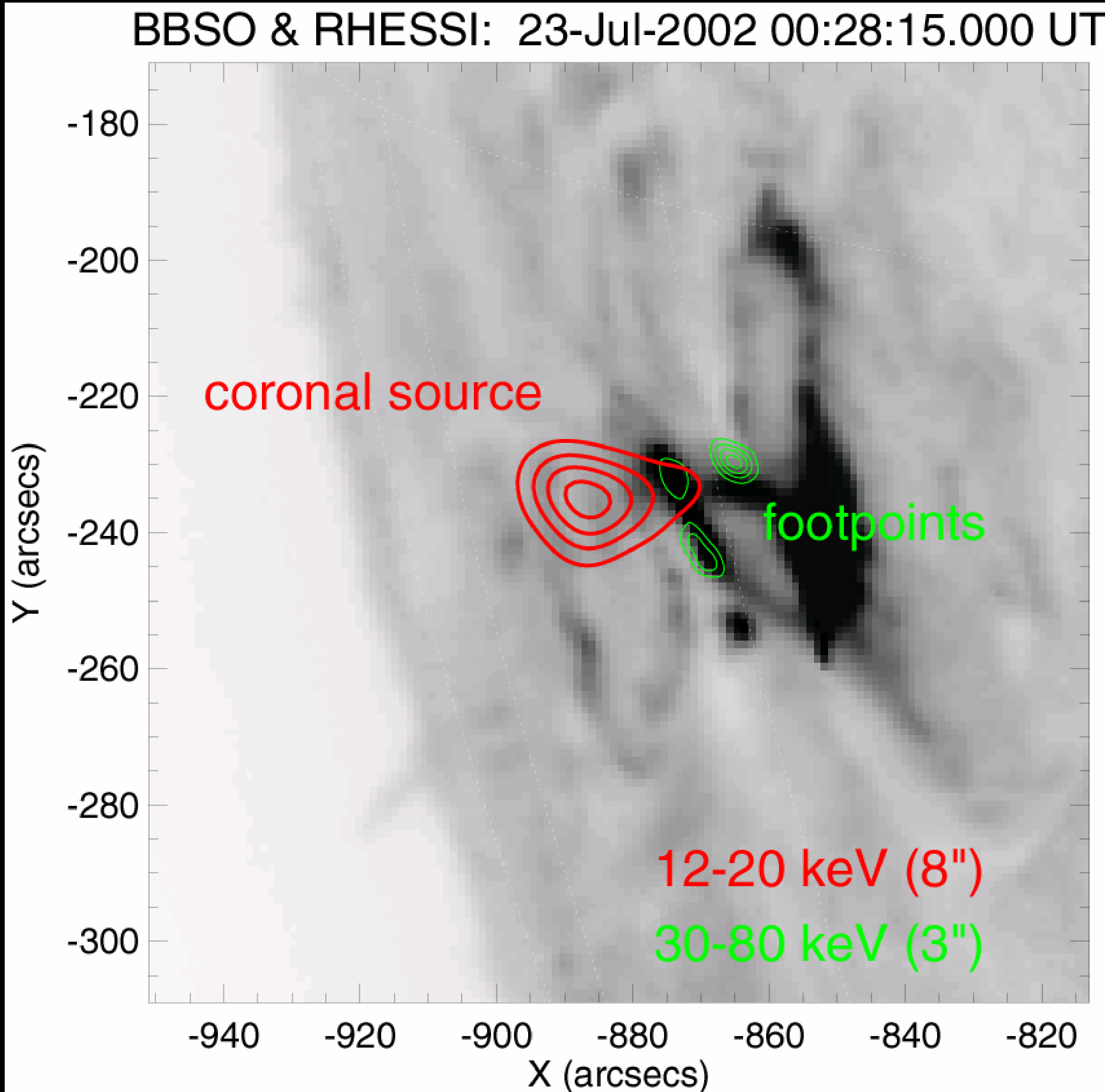
v_{in} and B_c are difficult to observe;
Easier to observed are v_{fp} and B_{fp}

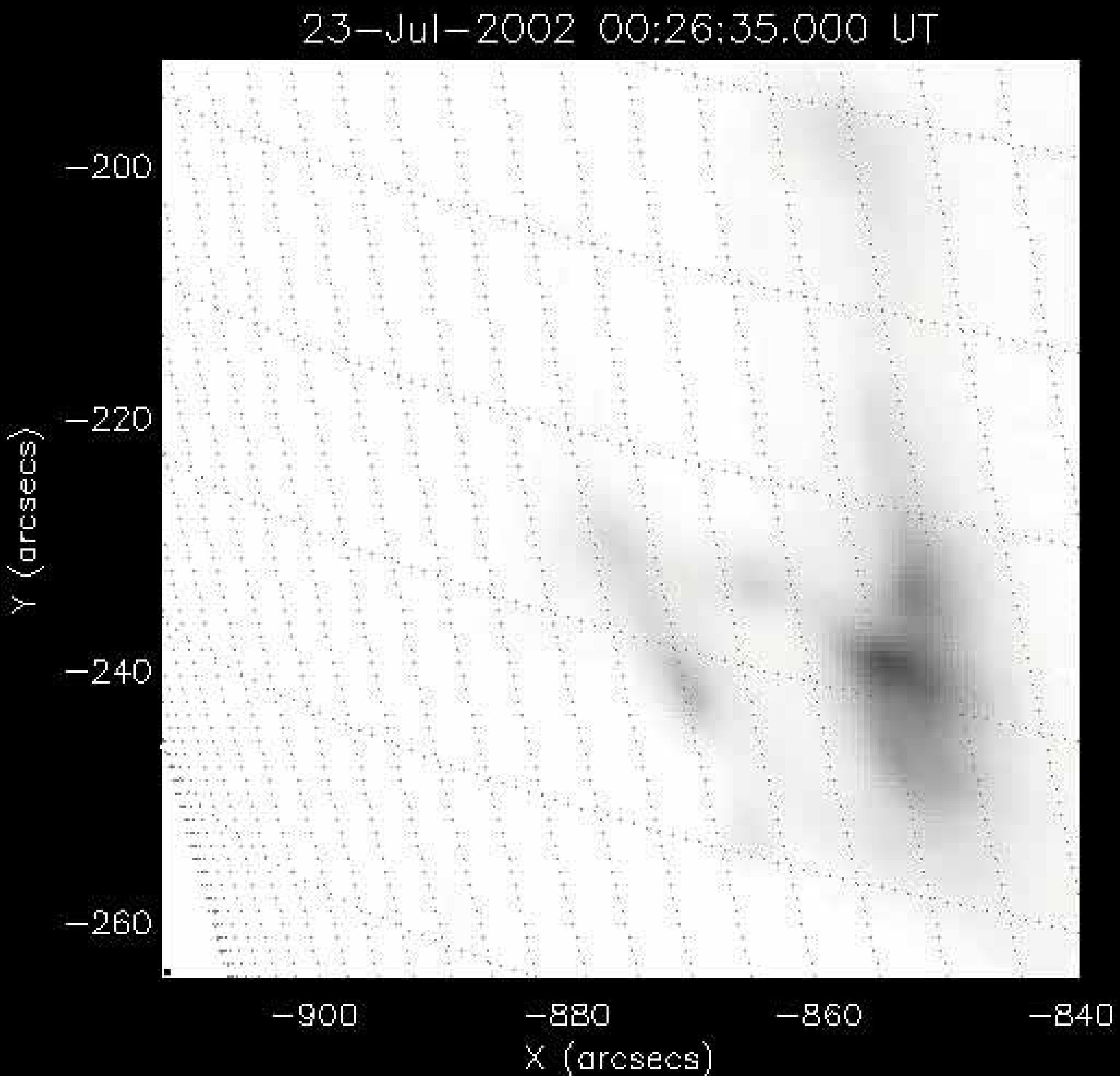
v_{in} = coronal inflow velocity
v_{fp} = footpoint velocity
B_c = coronal magnetic field strength
B_{fp} = magnetic field strength in HXR source
~ photospheric value

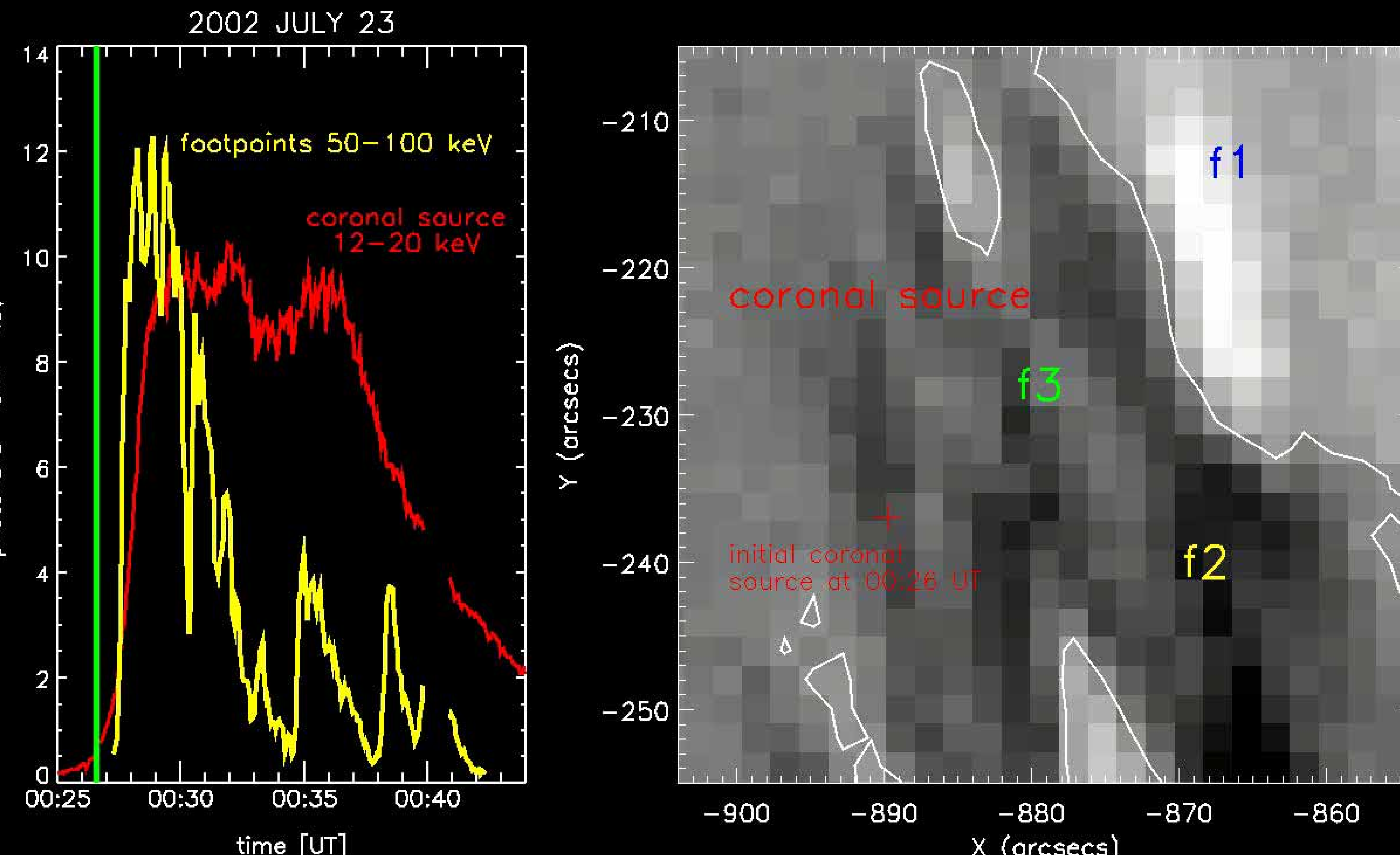
Main phase (Hα image)



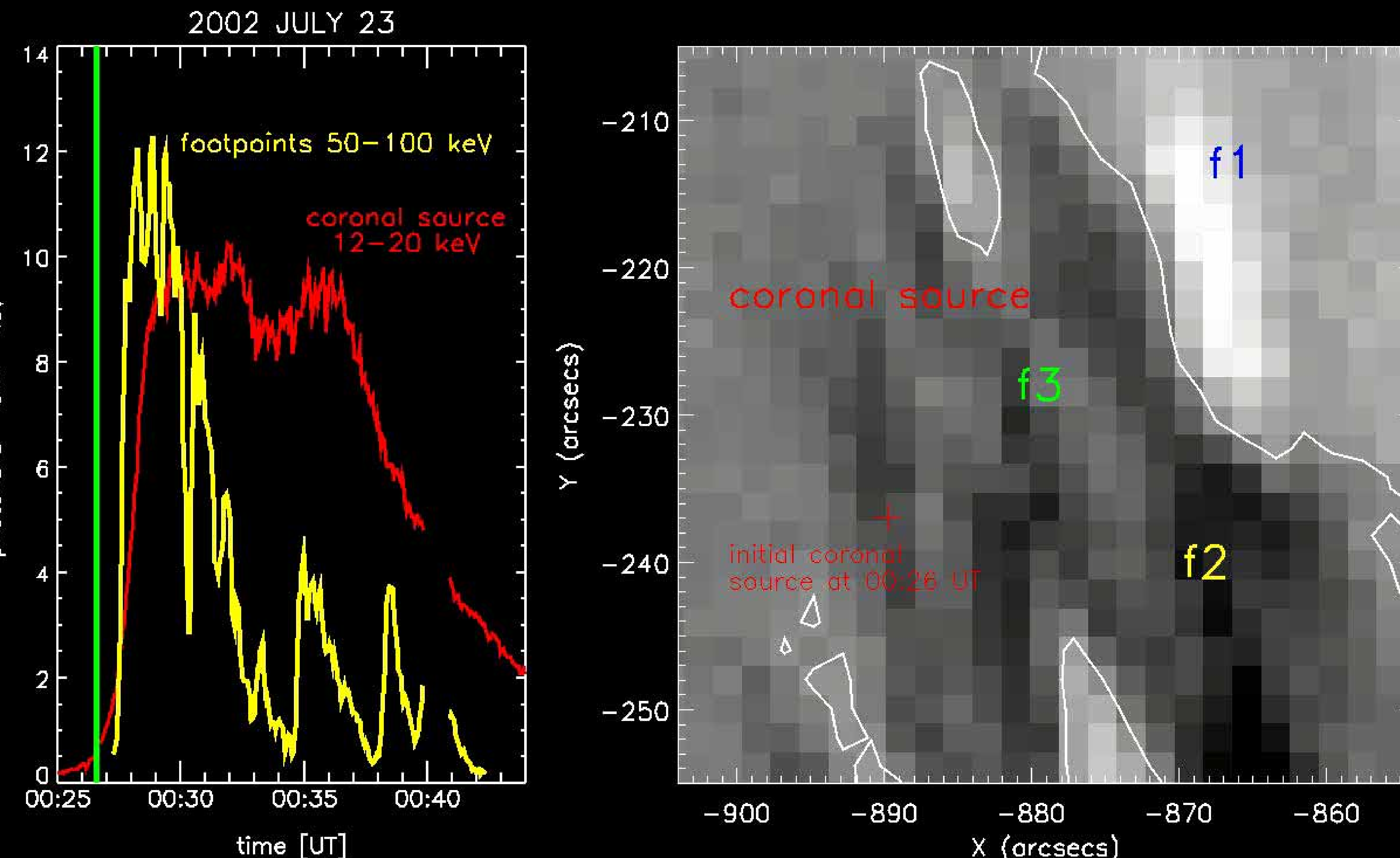





23-Jul-2002 00:26:35.000 UT
Y (arcsecs)
-200
-220
-240
-260
-900
-880
-860
-840
X (arcsecs)

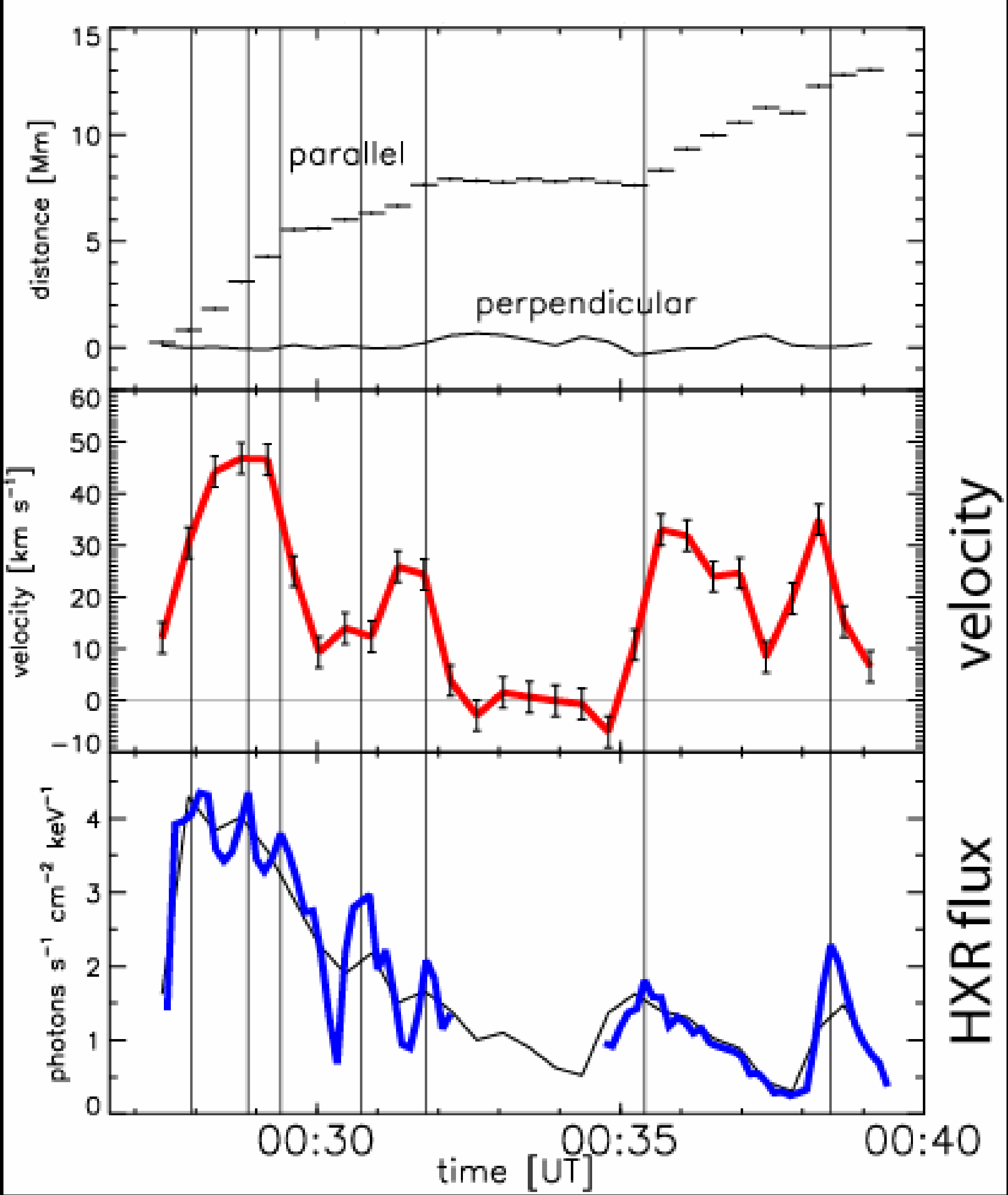


2002 JULY 23
footpoints 50-100 keV
coronal source
12-20 keV
time [UT]
00:25
00:30
00:35
00:40
coronal source
f1
f3
f2
initial coronal
source at 00:26 UT
Y (arcsecs)
X (arcsecs)



2002 JULY 23
footpoints 50−100 keV
coronal source
12−20 keV
14
12
10
8
6
4
2
0
00:25
00:30
00:35
00:40
time [UT]
coronal source
f1
f3
f2
initial coronal
source at 00:26 UT
−210
−220
−230
−240
−250
Y (arcsecs)
−900
−890
−880
−870
−860
X (arcsecs)

Velocity-HXR flux correlation



Rough correlation between v and HXR flux

$d\Phi = B\ v\ a\ dt$

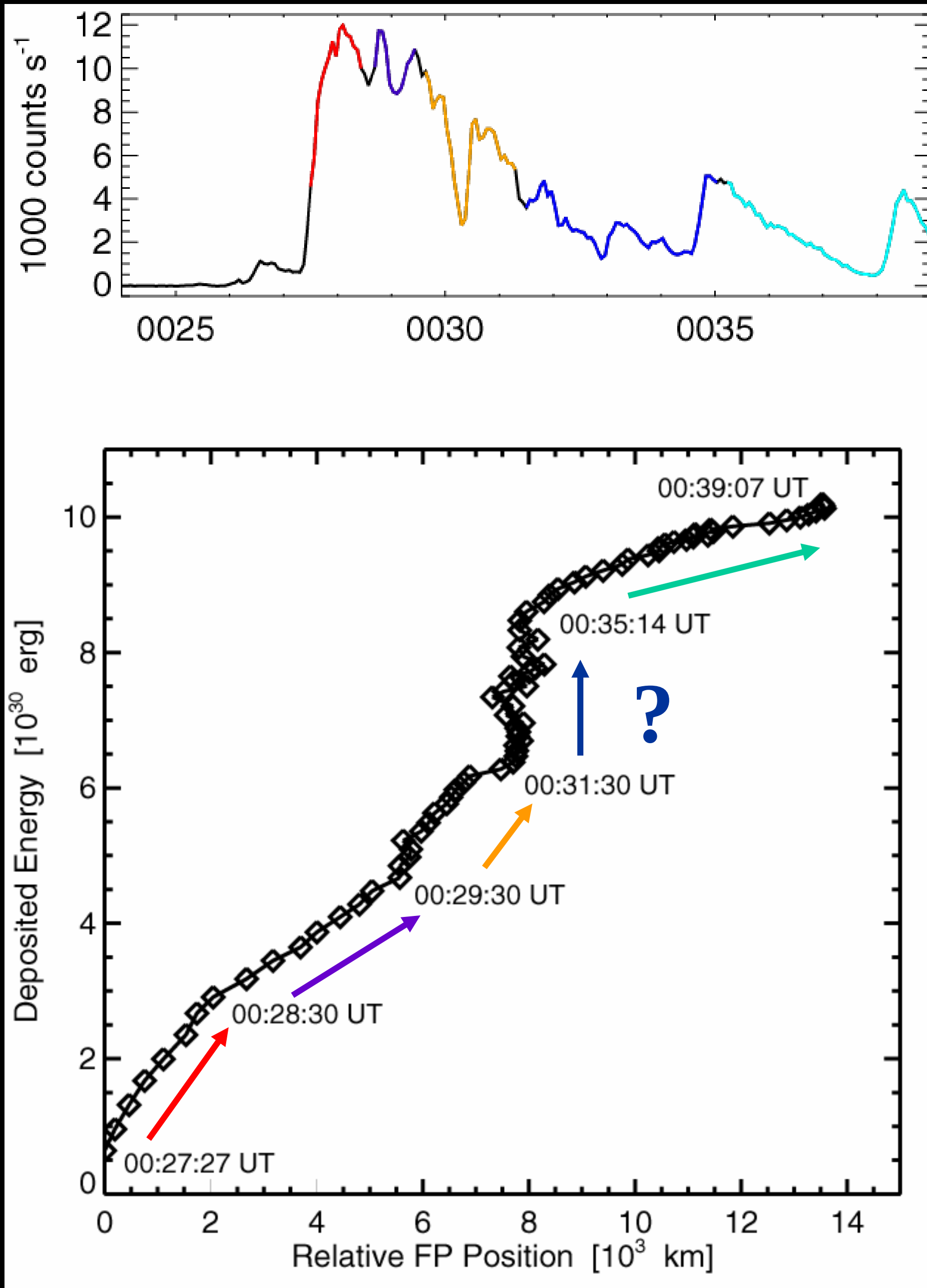
Reconnection rate

$d\Phi/dt = B\ v\ a$

v= velocity
B= magnetic field strength
a=footpoint diameter

B hard to observe for near flare
B~1000 G;   a~2000km

→ $d\Phi/dt$ ~ 2e18 Mx/s
→ E ~ 5 kV/m



Motion is correlated with energy release

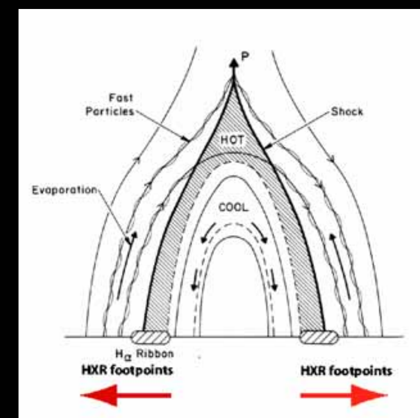
Reconnection rate

$d\Phi/dt = B\ v\ a$

v= velocity

B= magnetic field strength

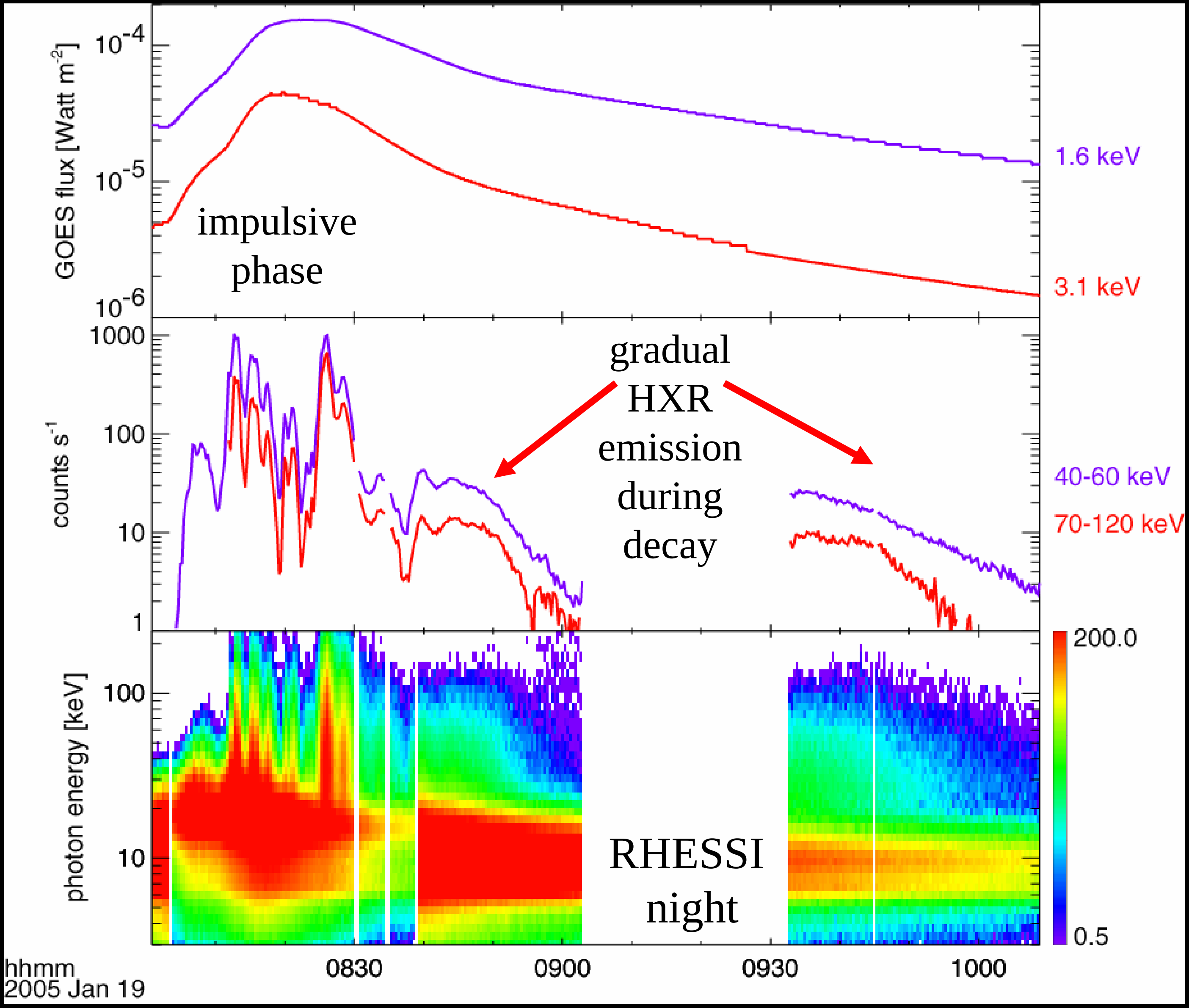
a=footpoint diameter



Magnetic field strength variations not known!

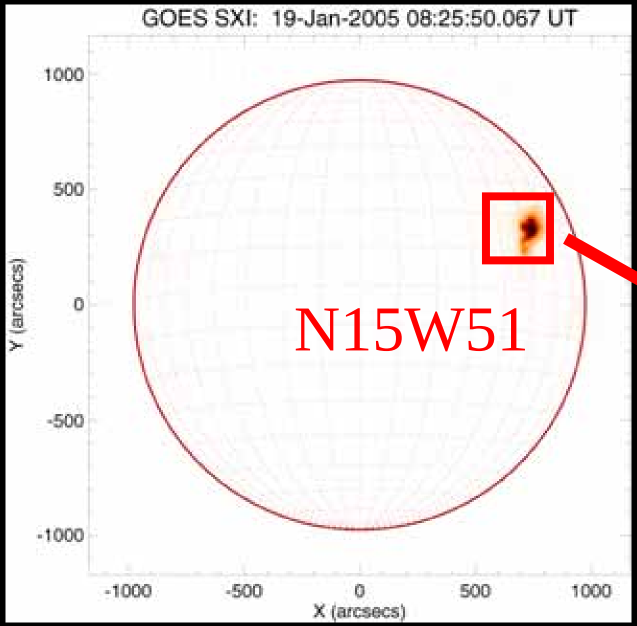
Middle phase without motion, but still with HXR emission. Does not fit in simple picture

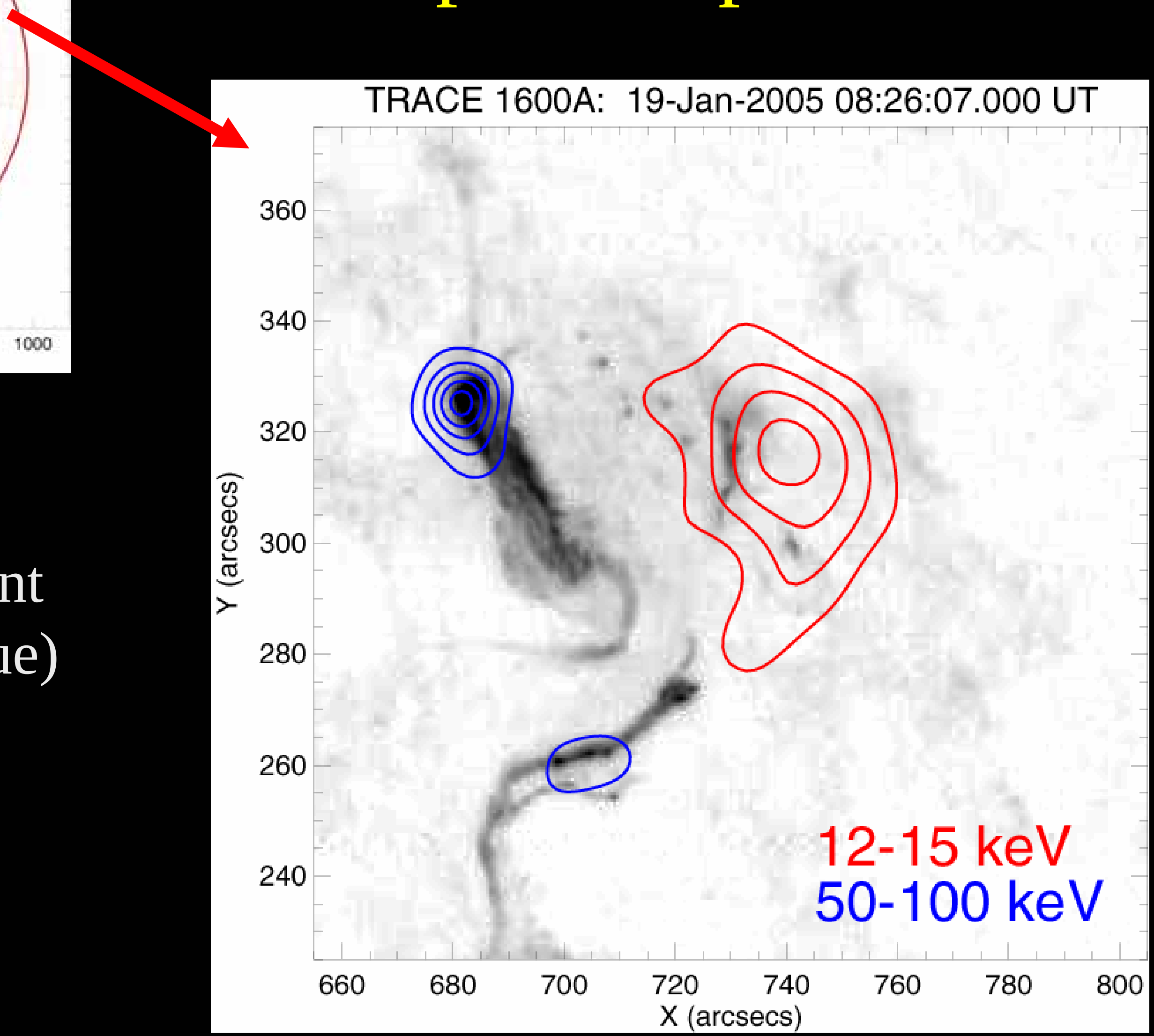
GOES X1.5 flare on Jan 19, 2005



RHESSI

X-ray imaging: impulsive phase



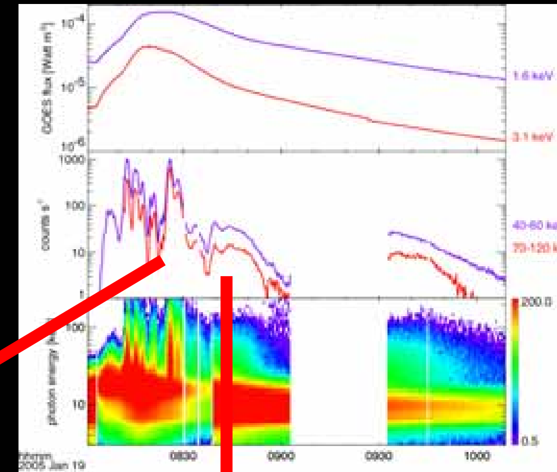


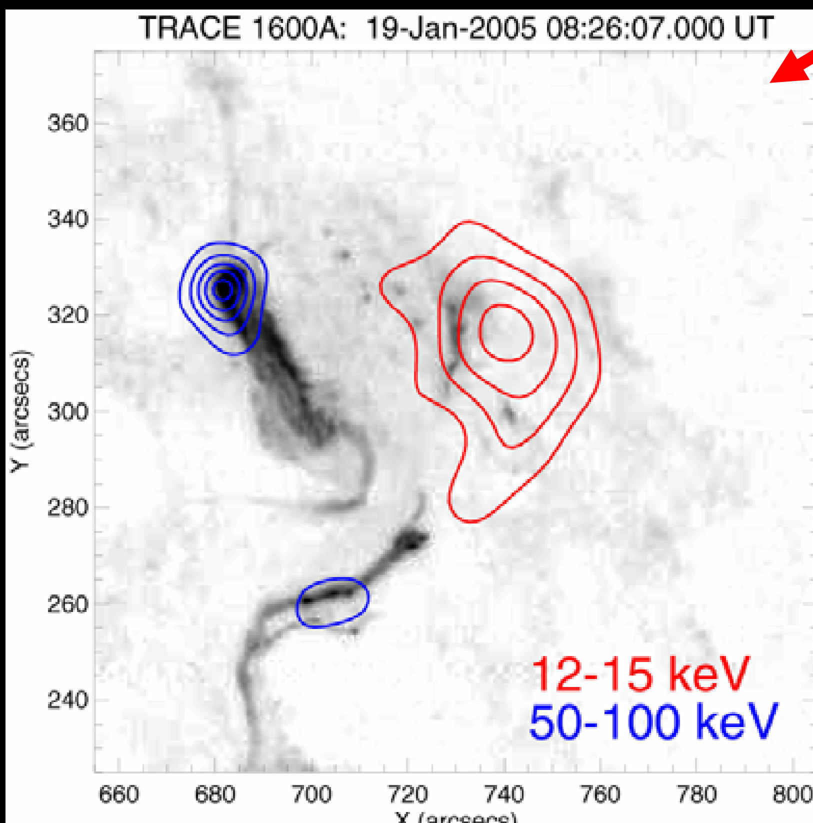
- two ribbon flare
- one HXR footpoint on each ribbon (blue)
- thermal source in corona between ribbons (red)

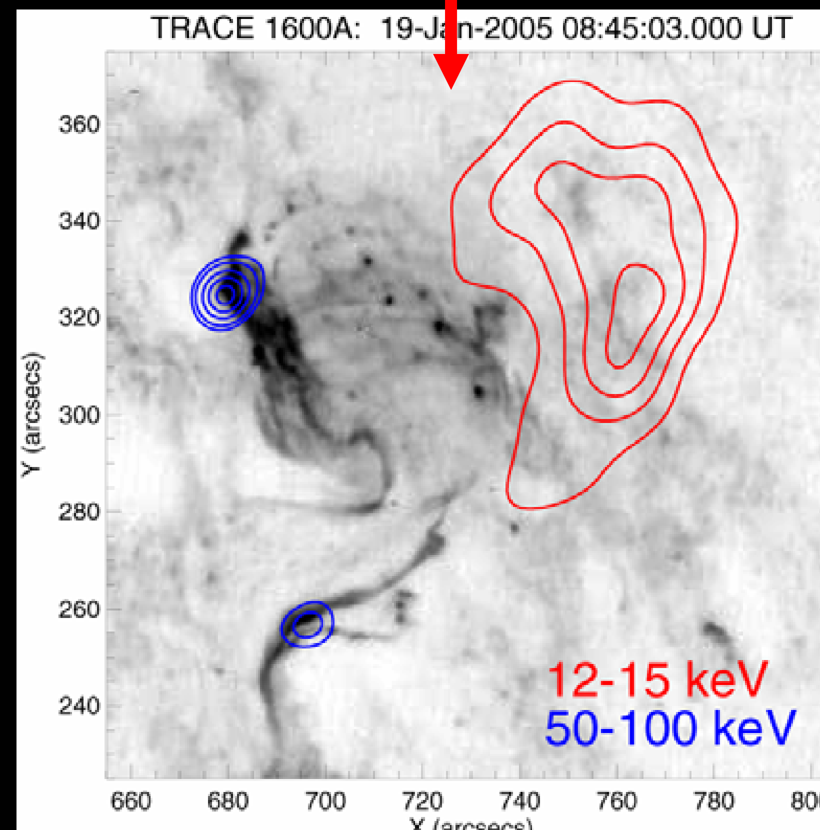
similar source geometry observed during gradual HXR emission:

Gradual HXR emission is coming from footpoints (THICK target model)

(Qui, Wang, Gary 2004, Kundu et al. 2004)



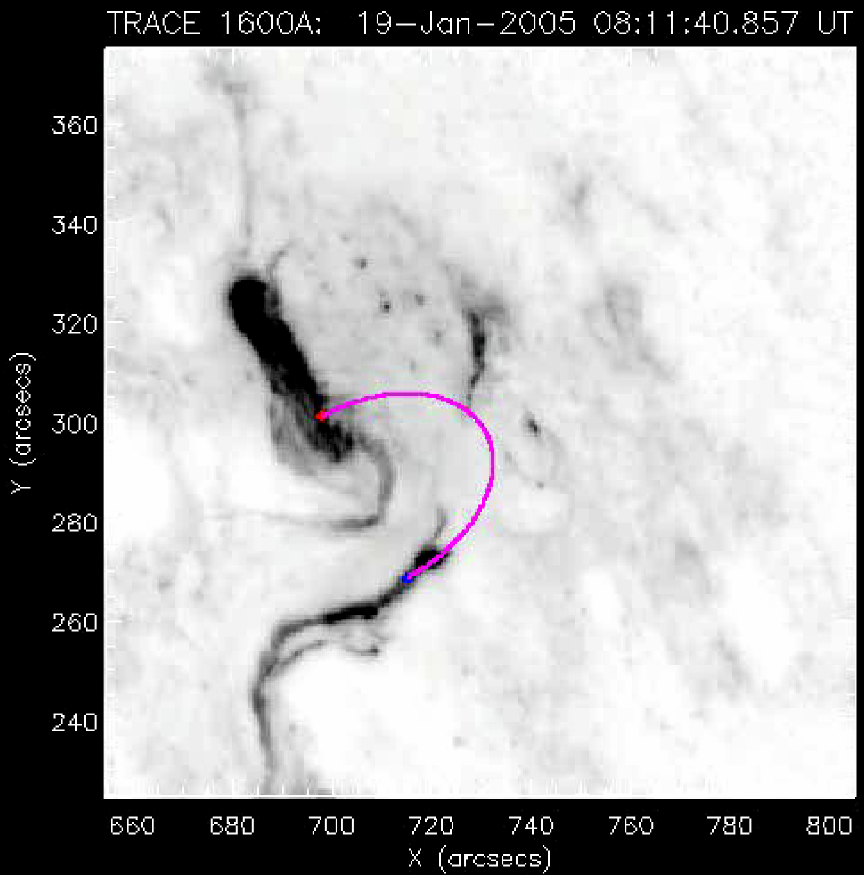


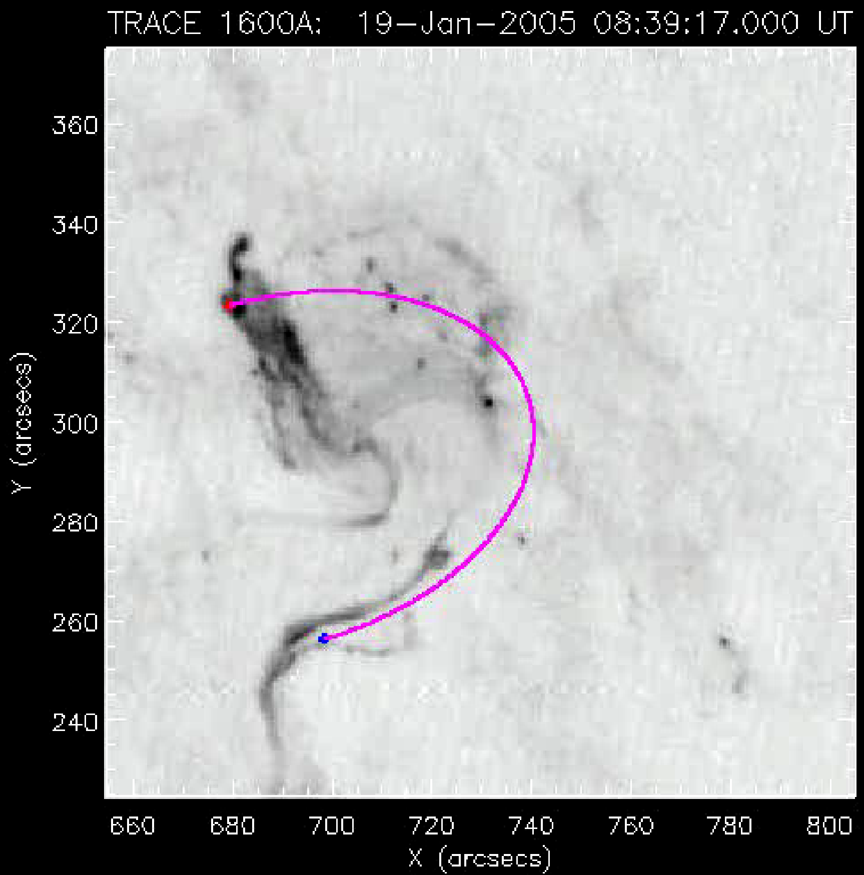


Footpoint motion

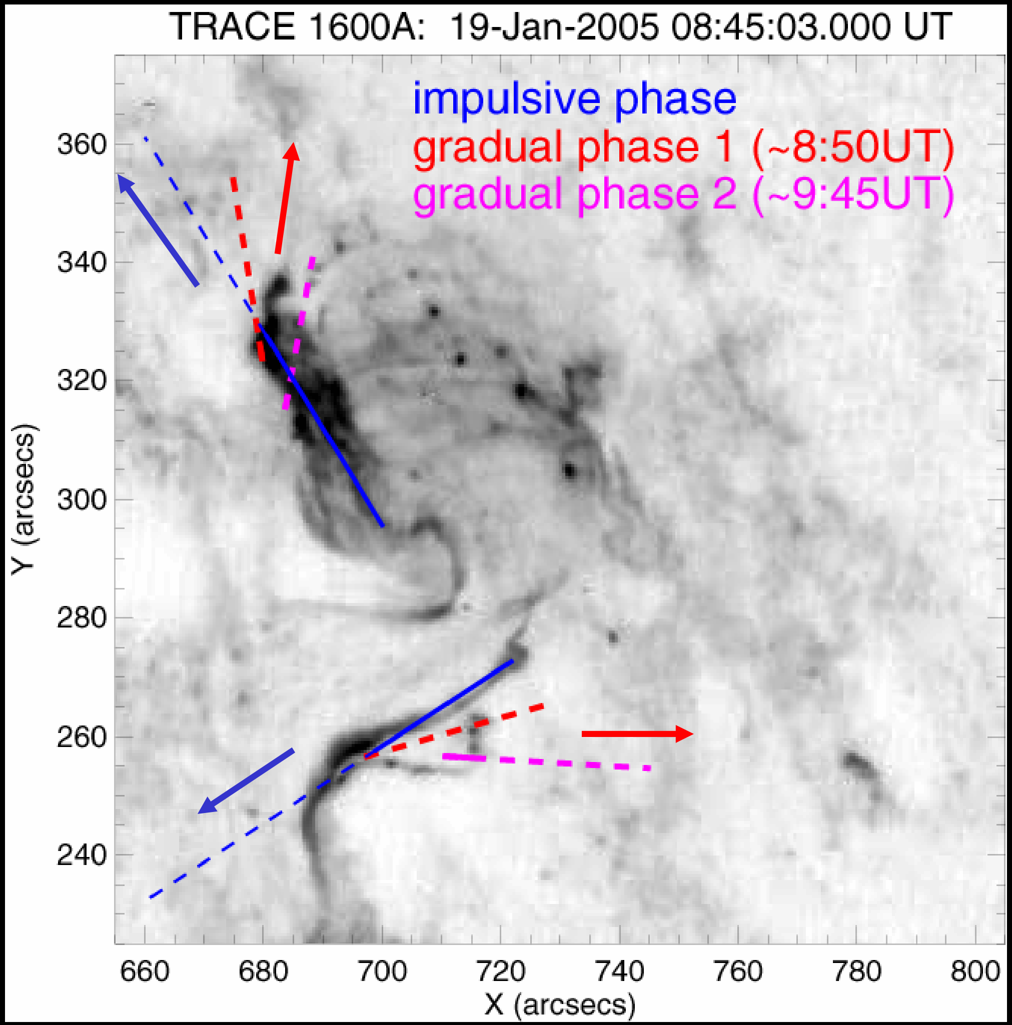
Impulsive phase:
Motion rather along the ribbon
Northern footpoint: 20-50 km/s
Southern footpoint: complex

Later phase:
Slow motion
Northern footpoint: ~2.5 km/s
Southern footpoint: ?





Different directions of motion in impulsive phase and gradual phase



Dashed lines give main direction of motion.

Impulsive phase:
Fast motion along ribbon

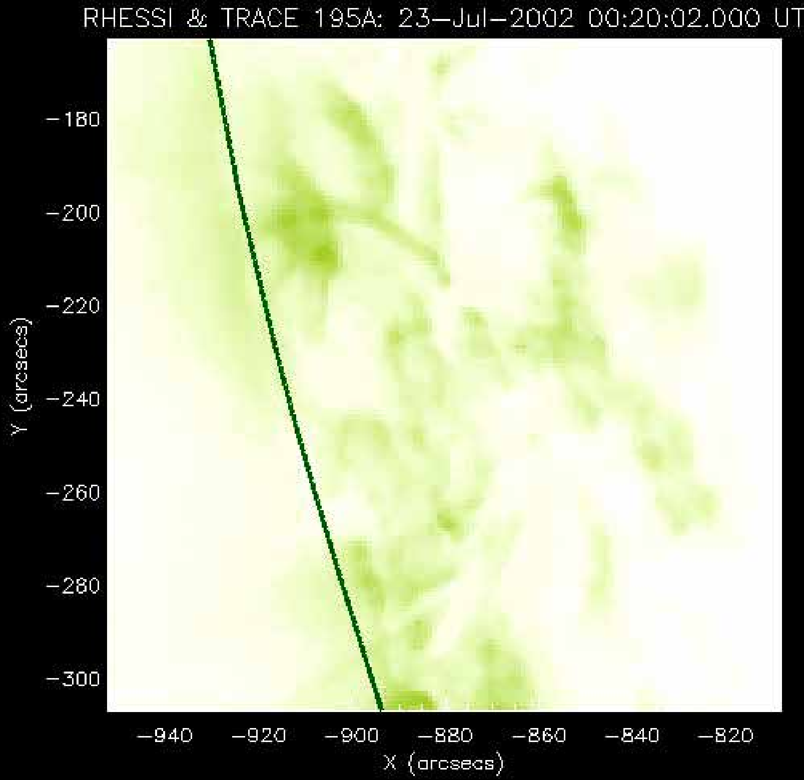
Gradual phase:
Slow motion rather perpendicular to ribbon

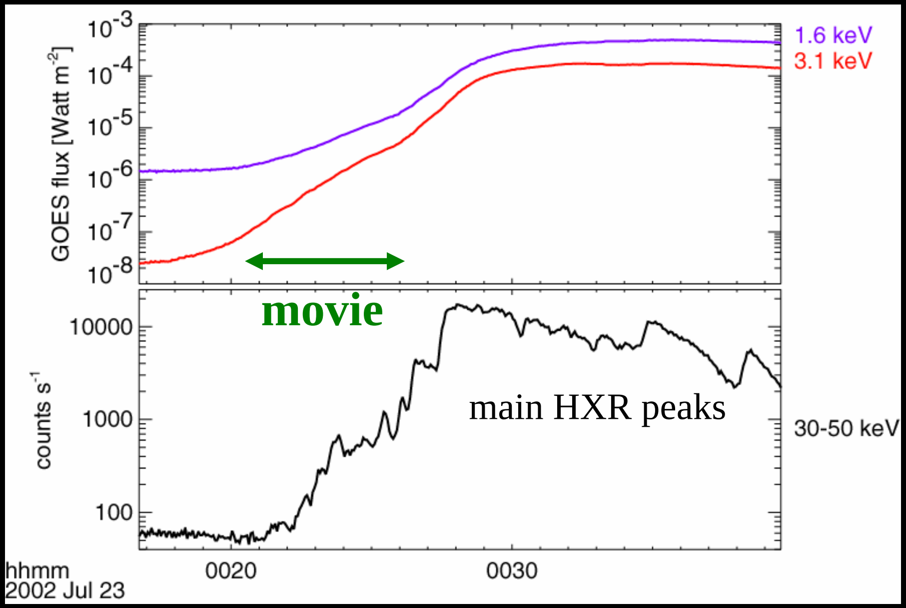
2002 november 9 flare:
Grigis&Benz 2005
Apj 625, L143

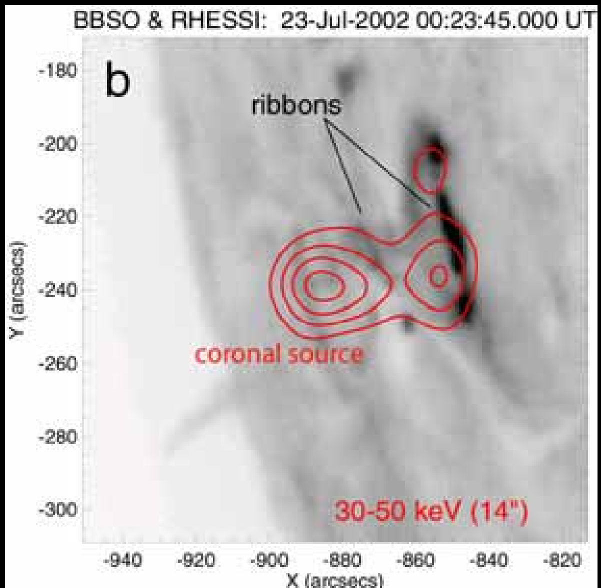
Summary footpoint motion

- Clear motion observed, but often along the ribbons
- Often complex source geometry & motions
- Sometimes motion correlated with energy release

Coronal sources in initial phase





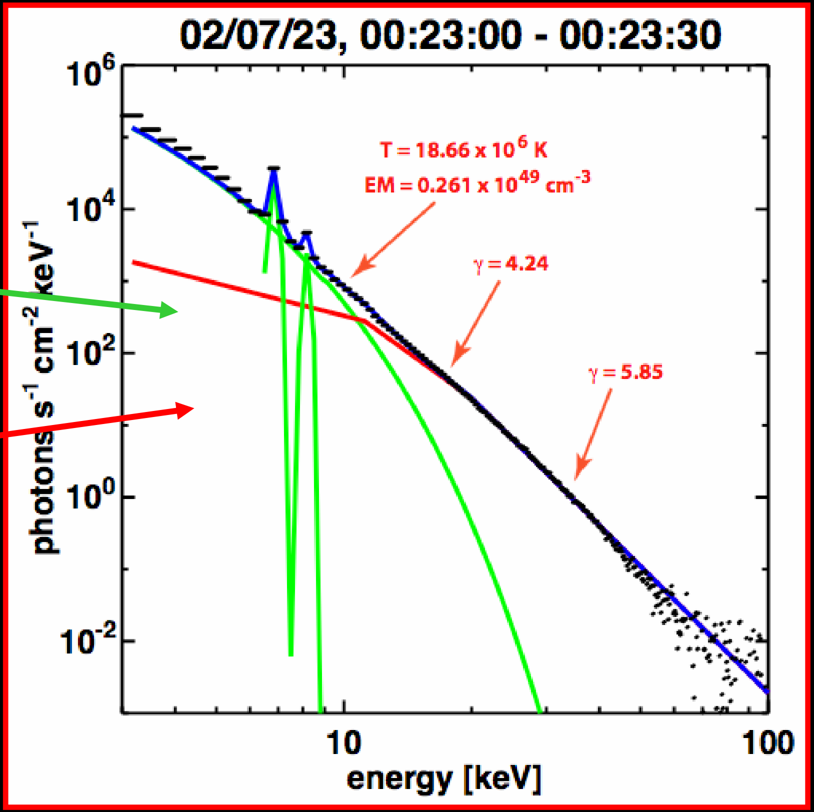


Spectrum is soft (power law index ~ 5), thermal fit does not work.

Initial phase: Thermal and broken power law fit (Holman et al. 2003, Caspi et al. 2005)

thermal fit
Fe&Fe/Ni
line ratio

power law

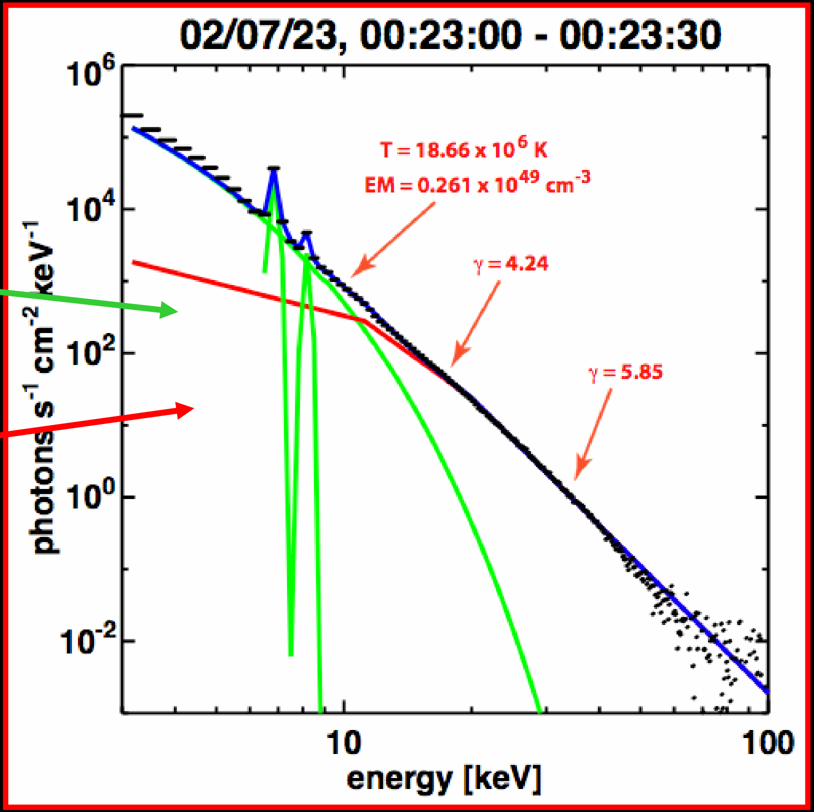


from Caspi

Initial phase: Thermal and broken power law fit (Holman et al. 2003, Caspi et al. 2005)

thermal fit
Fe&Fe/Ni
line ratio

power law

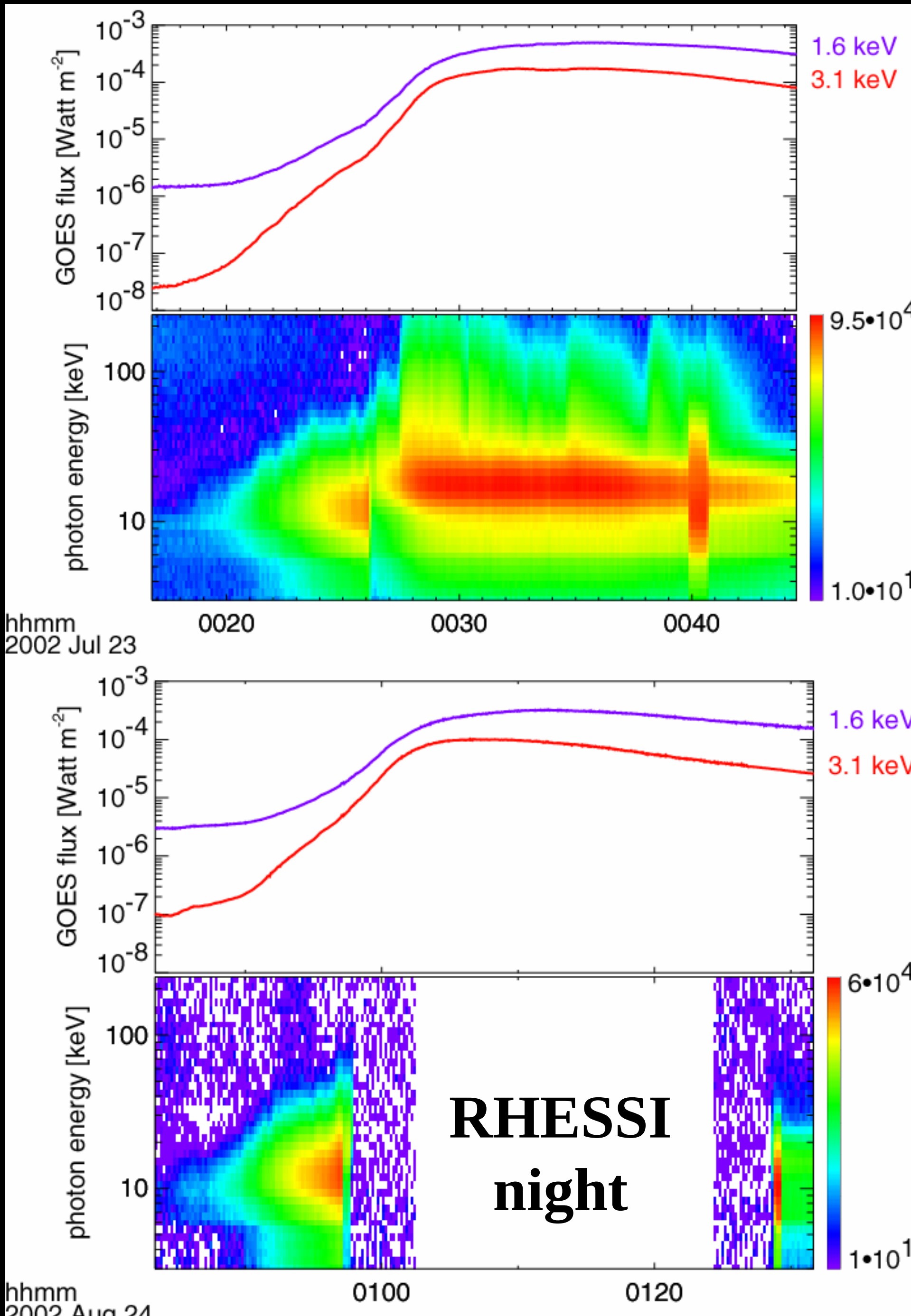


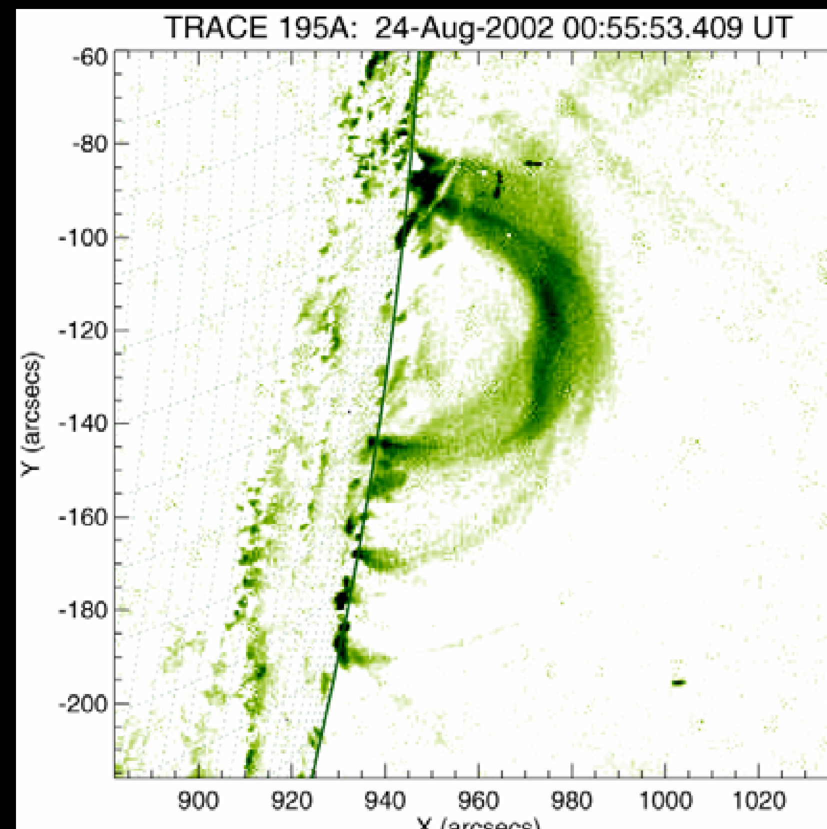
from Caspi

Nobeyama observations (White et al. 2003):
Spectrum too steep for thermal emission → non-thermal emission

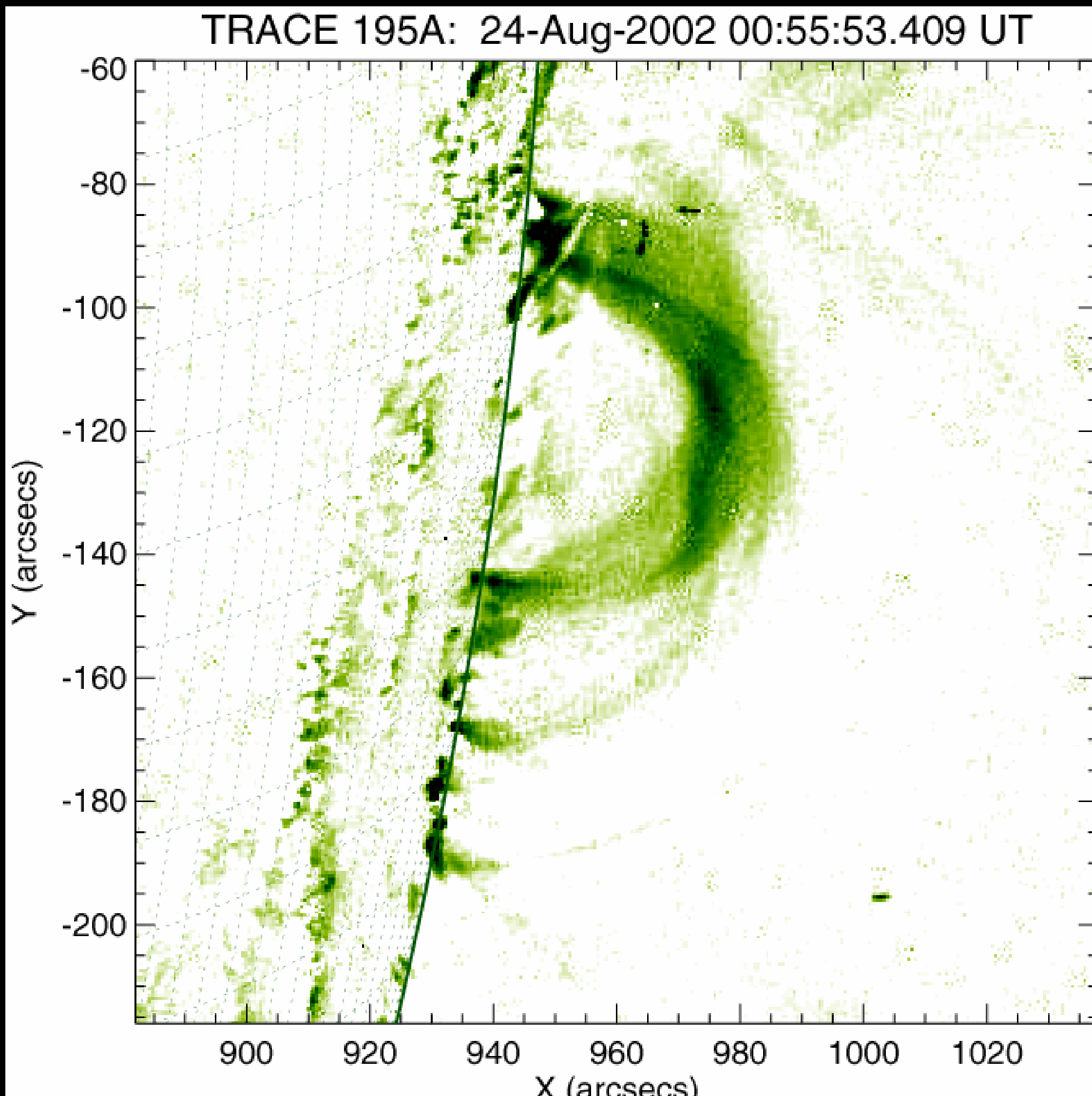
Very similar flare: 2002 August 24

Limb flare!
Nobeyama observations!



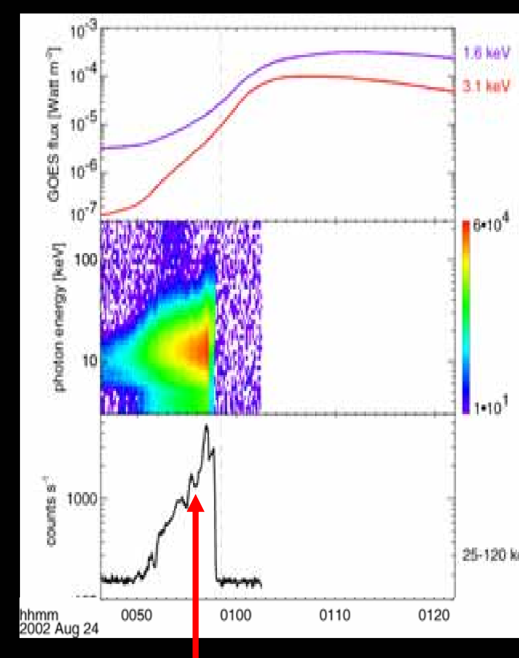


TRACE & RHESSI

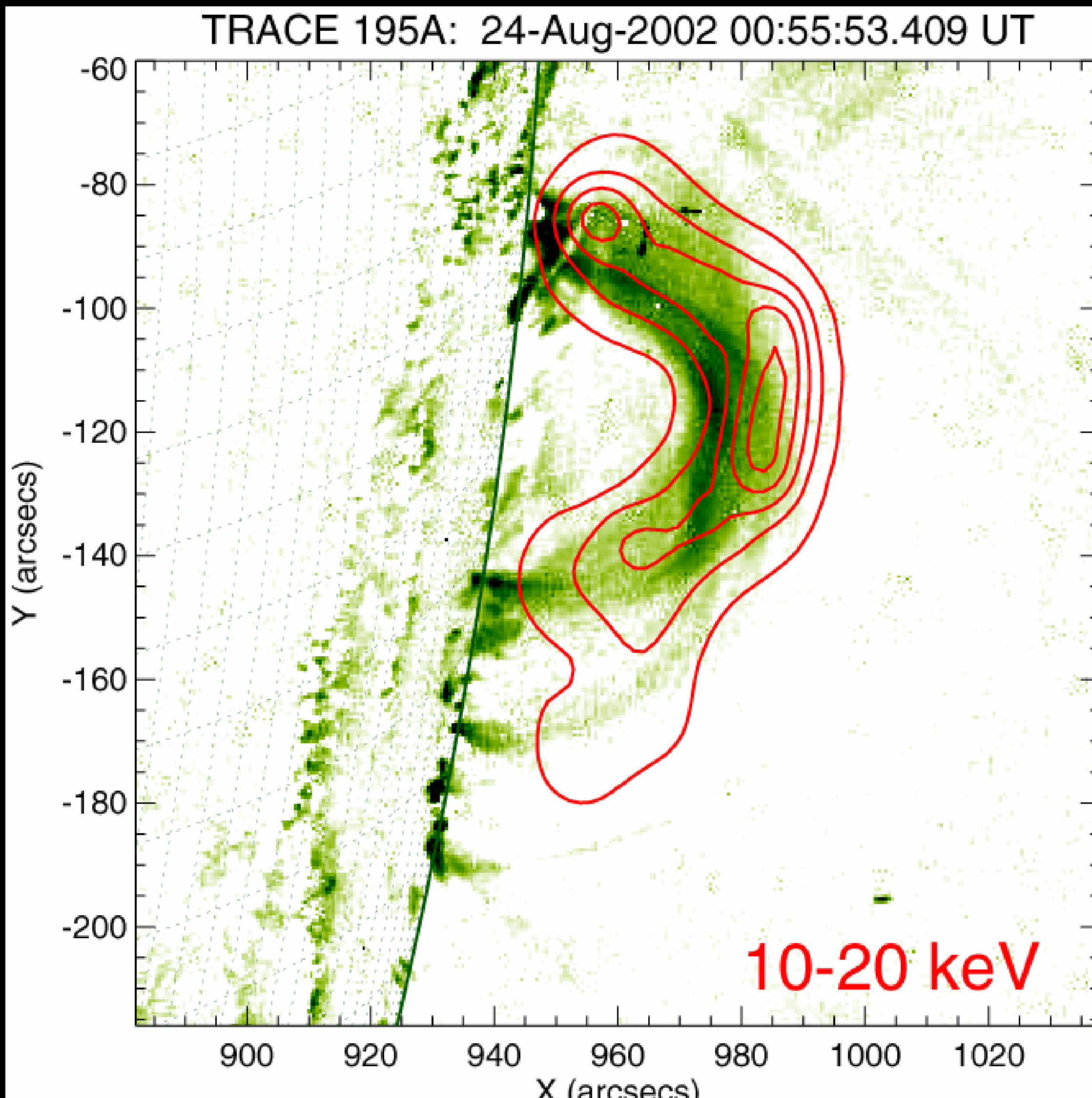


Limb flare, likely partly occulted.

EUV emission shows loop, possibly high temperature response.



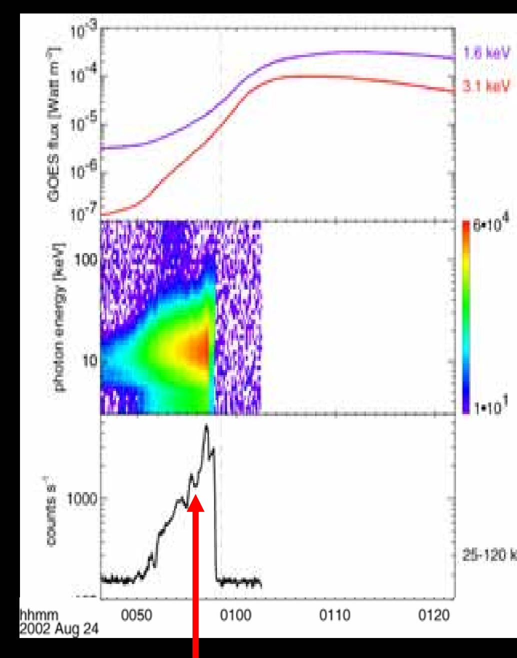
TRACE & RHESSI



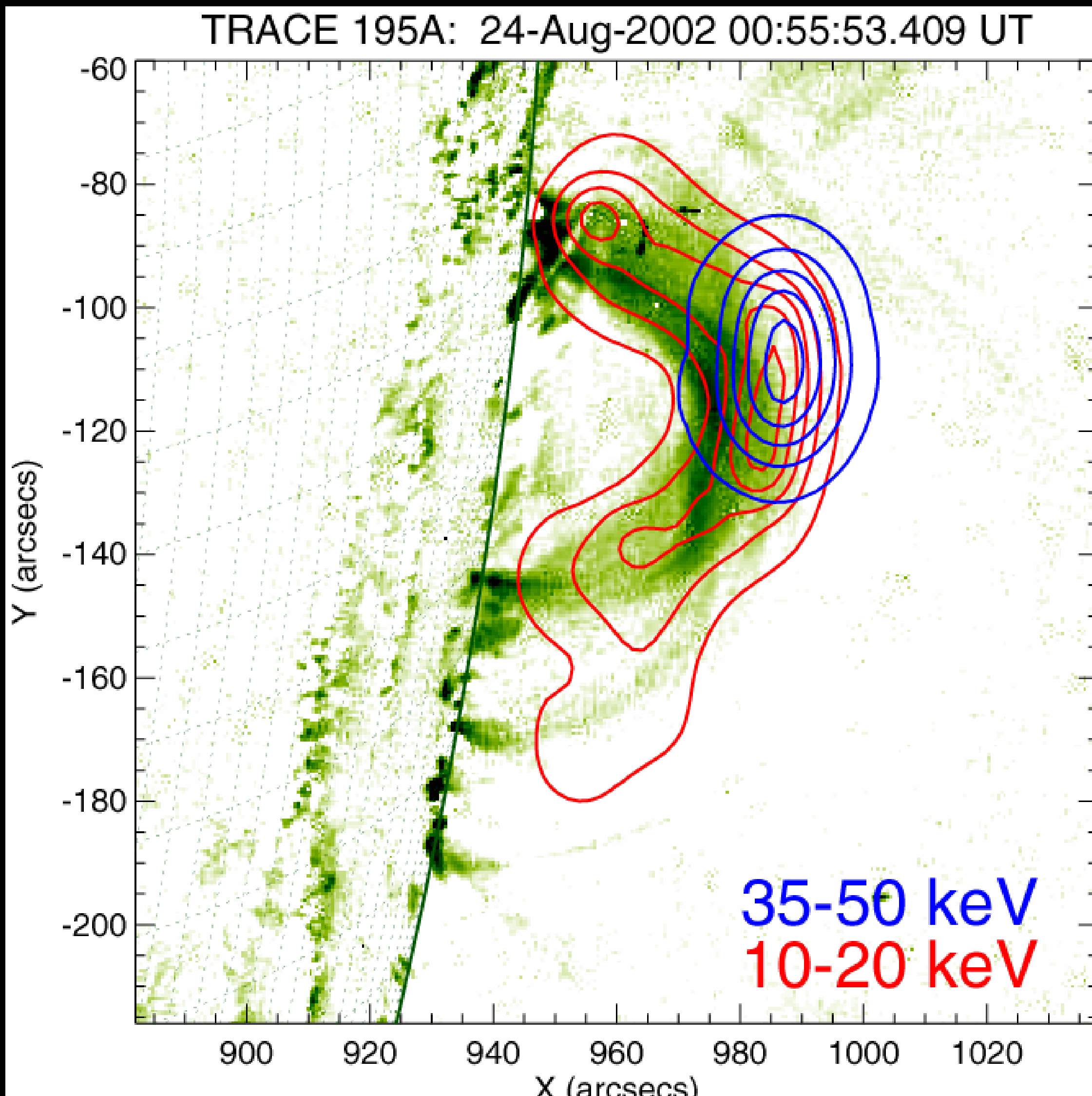
Limb flare, likely partly occulted.

Pixon image, g4-7:

10 keV emission from loops.



TRACE & RHESSI

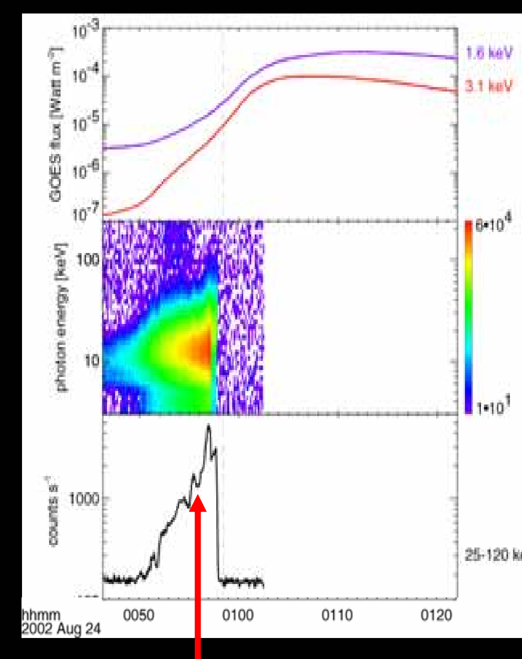


Limb flare, likely partly occulted.

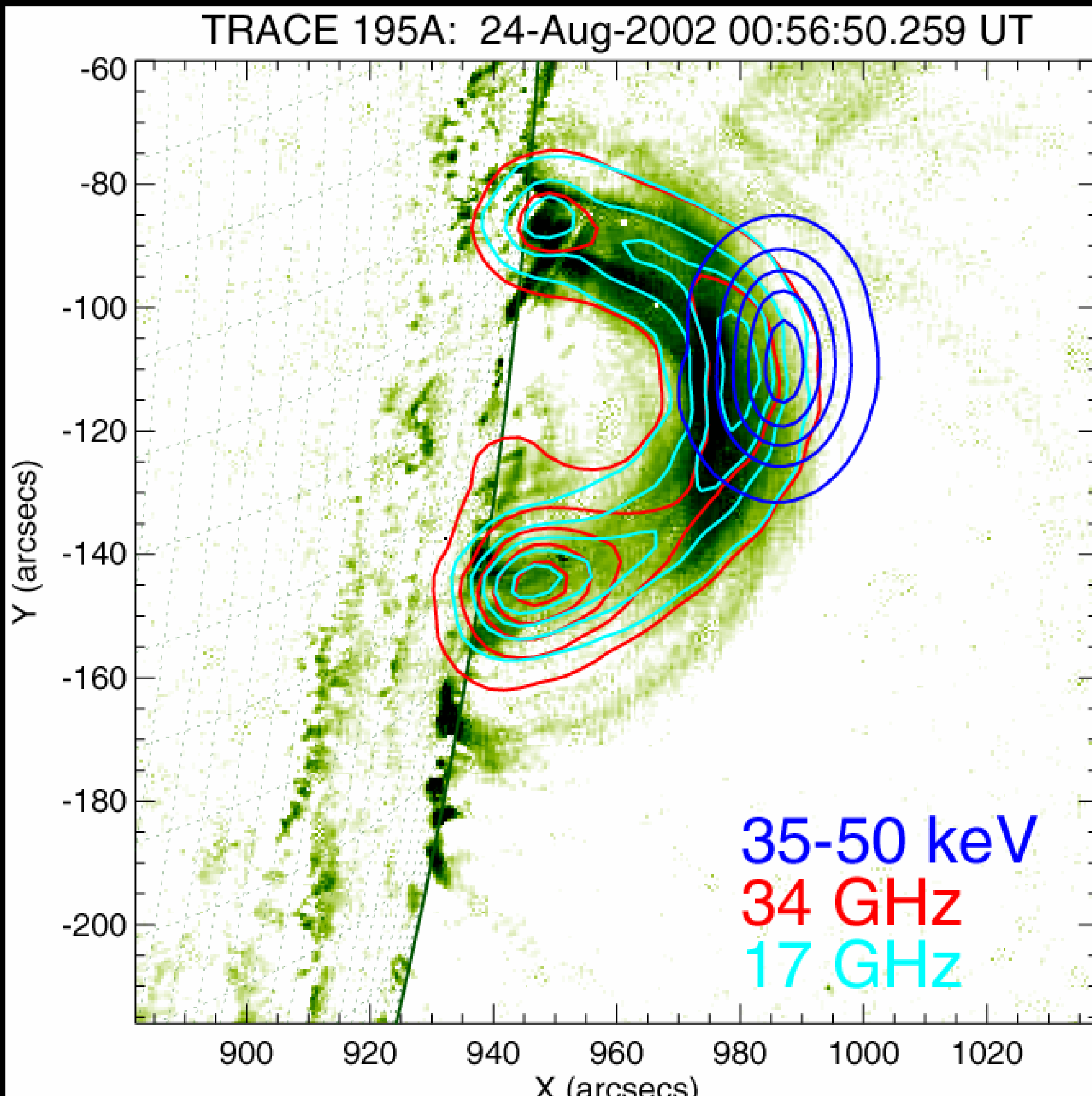
Pixon image, g4-7:

10 keV emission from loops.

35 keV emission from corona.



Nobeyama observations



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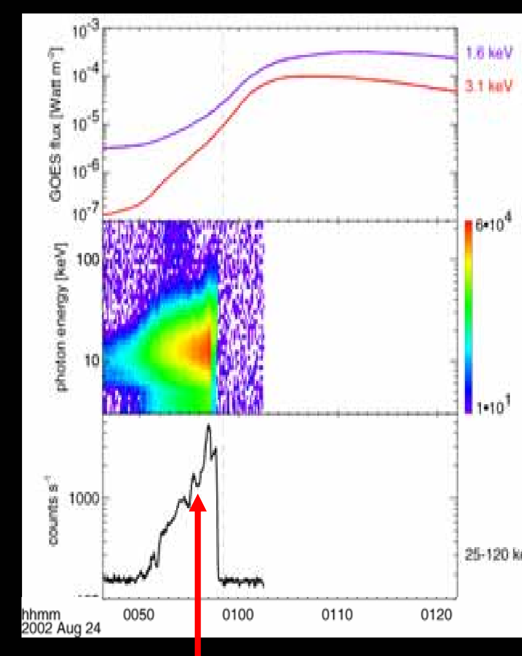
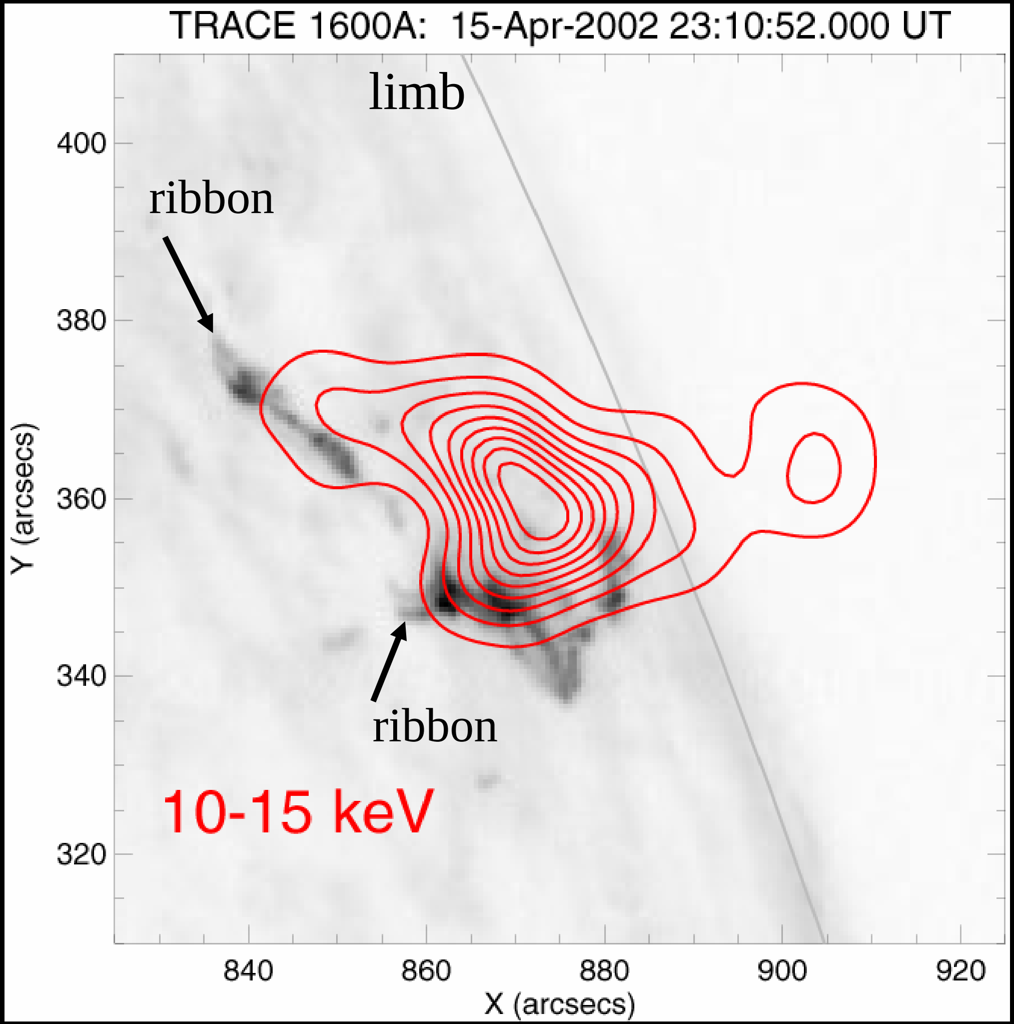
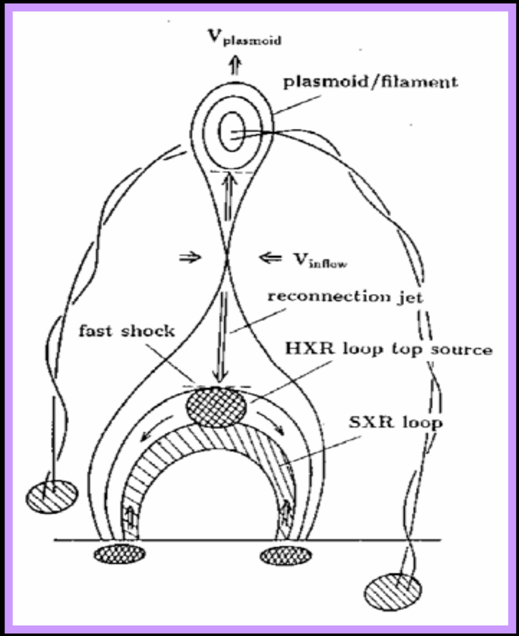


Evidence for the Formation of Large-Scale, Reconnecting Current Sheet

Linhui Sui, Gordon D. Holman



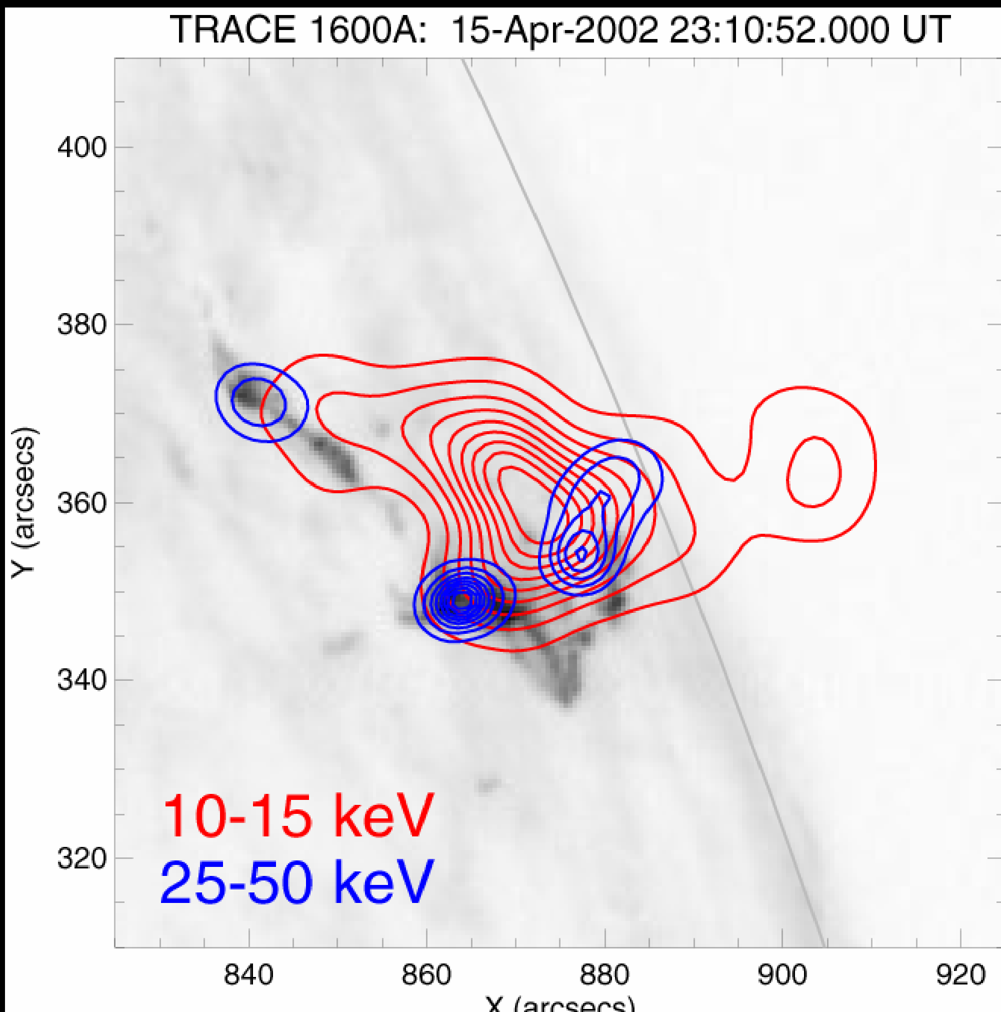
Cusp-shaped loop;
Possible formation
of current sheet?



From Shibata

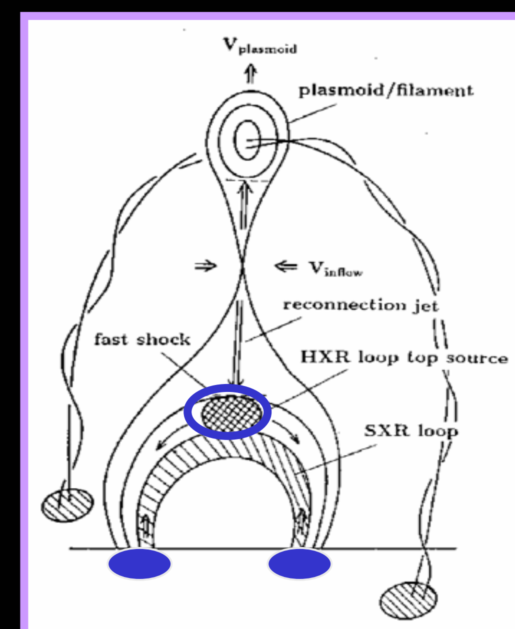
Evidence for the Formation of Large-Scale, Reconnecting Current Sheets

Linhui Sui, Gordon D. Holman

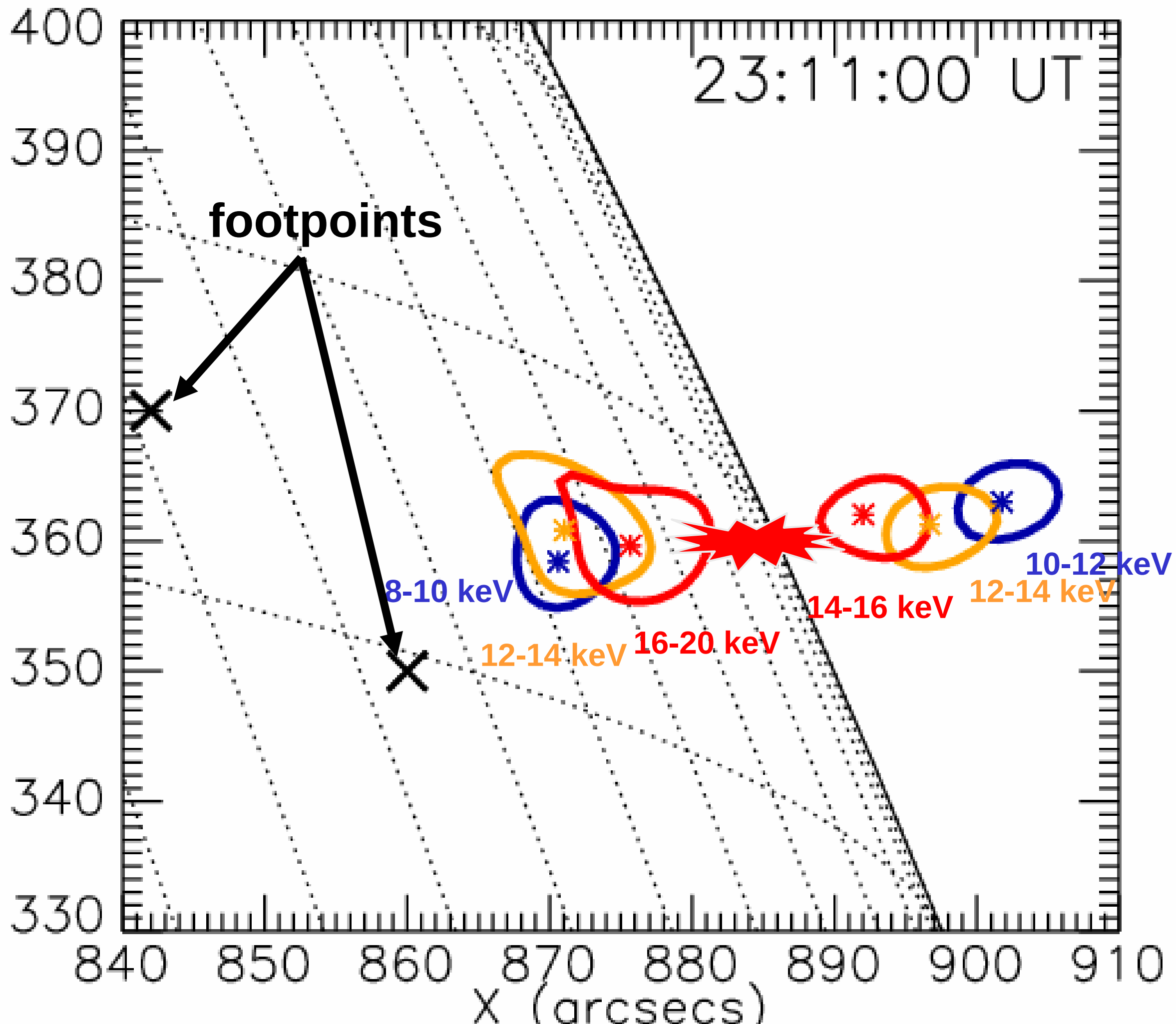


HXR emissions from

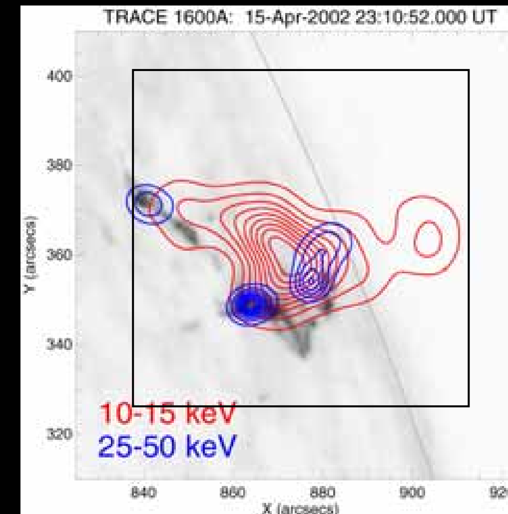
1) footpoints
2) source in corona? or projection effect?

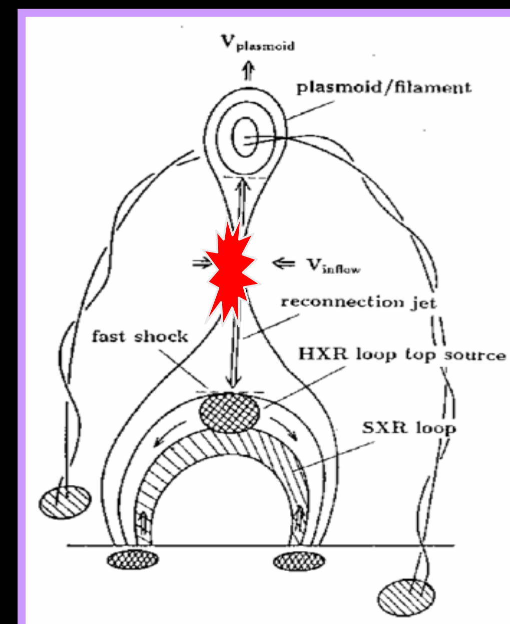


Temperature gradient is observed

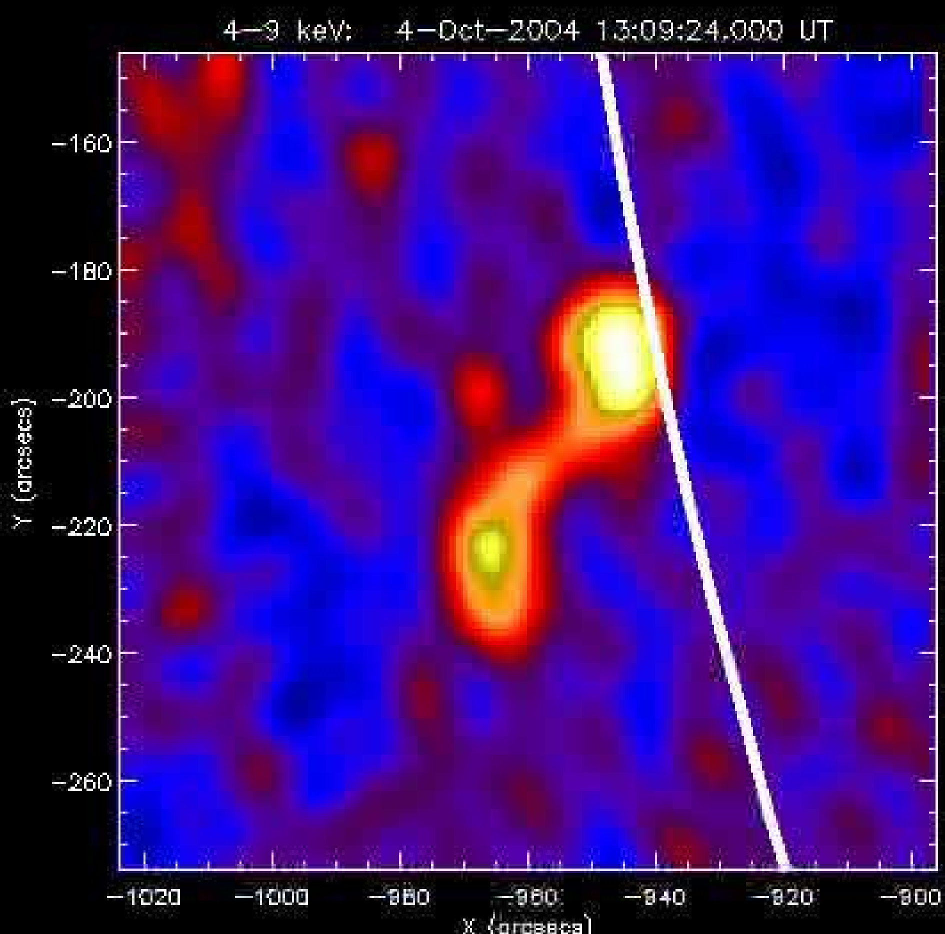


(Sui & Holman 2003)

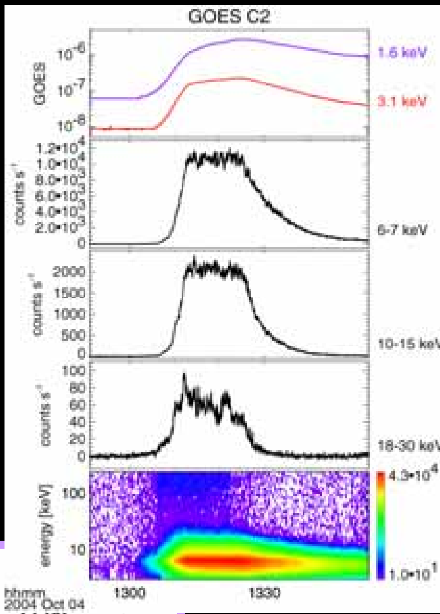


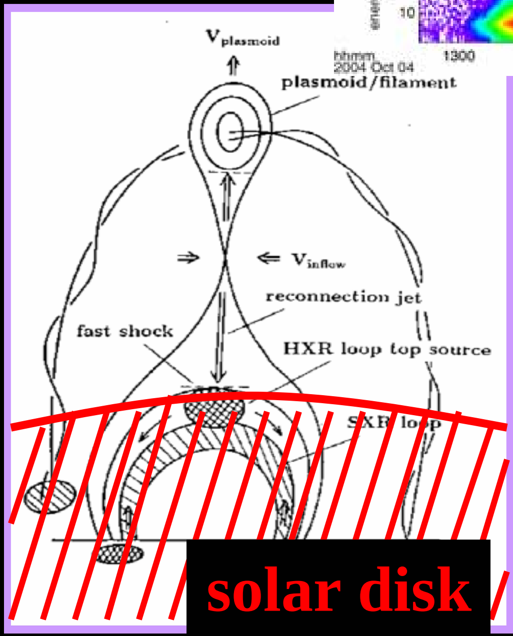


Coronal X-rays emission in a partially occulted flare



Occultation of intense source can reveal presence of weaker sources



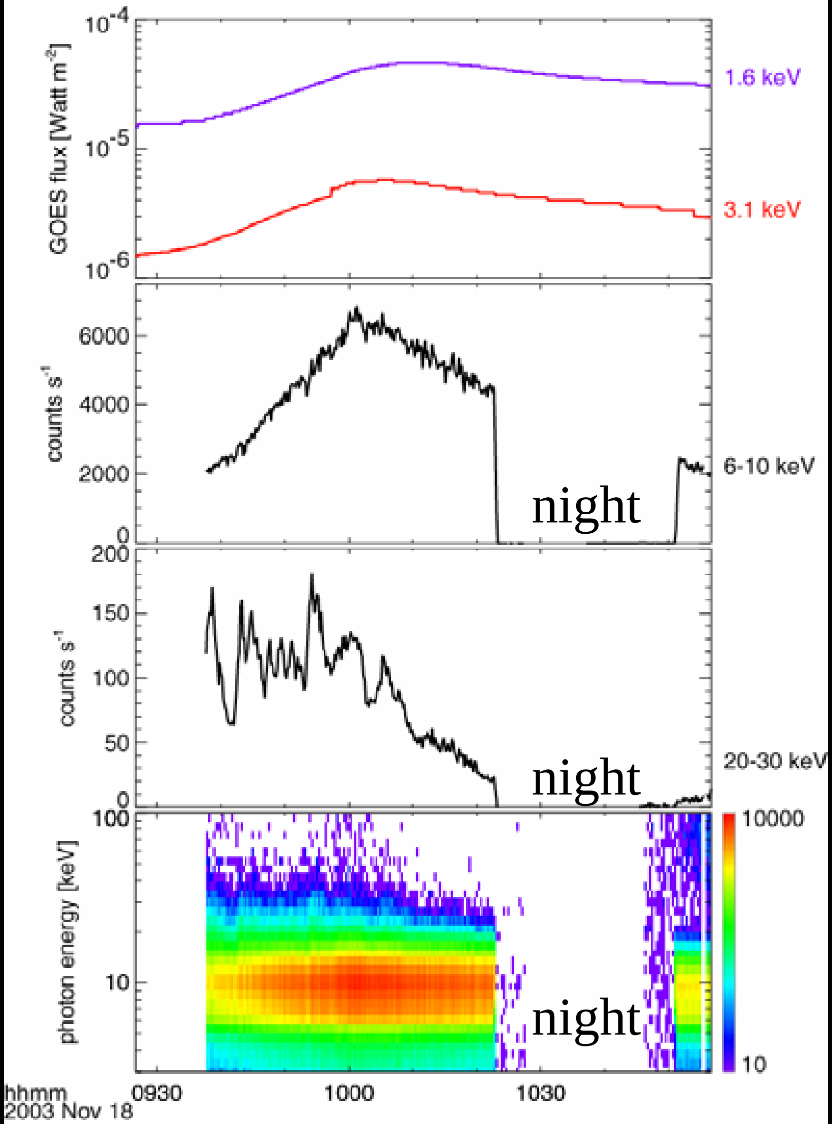


HXR footpoints are behind the limb; Not seen by RHESSI

Paula Balciunaite; Sa"m Krucker

Flare with occulted footpoints

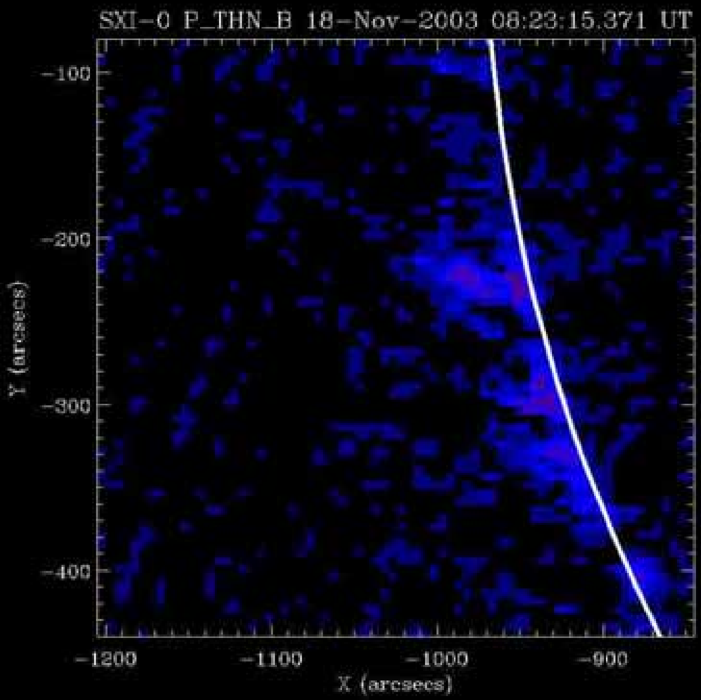
Nov 18, 2003: GOES M4



HXR emission from corona

Gradual variation below 10 keV

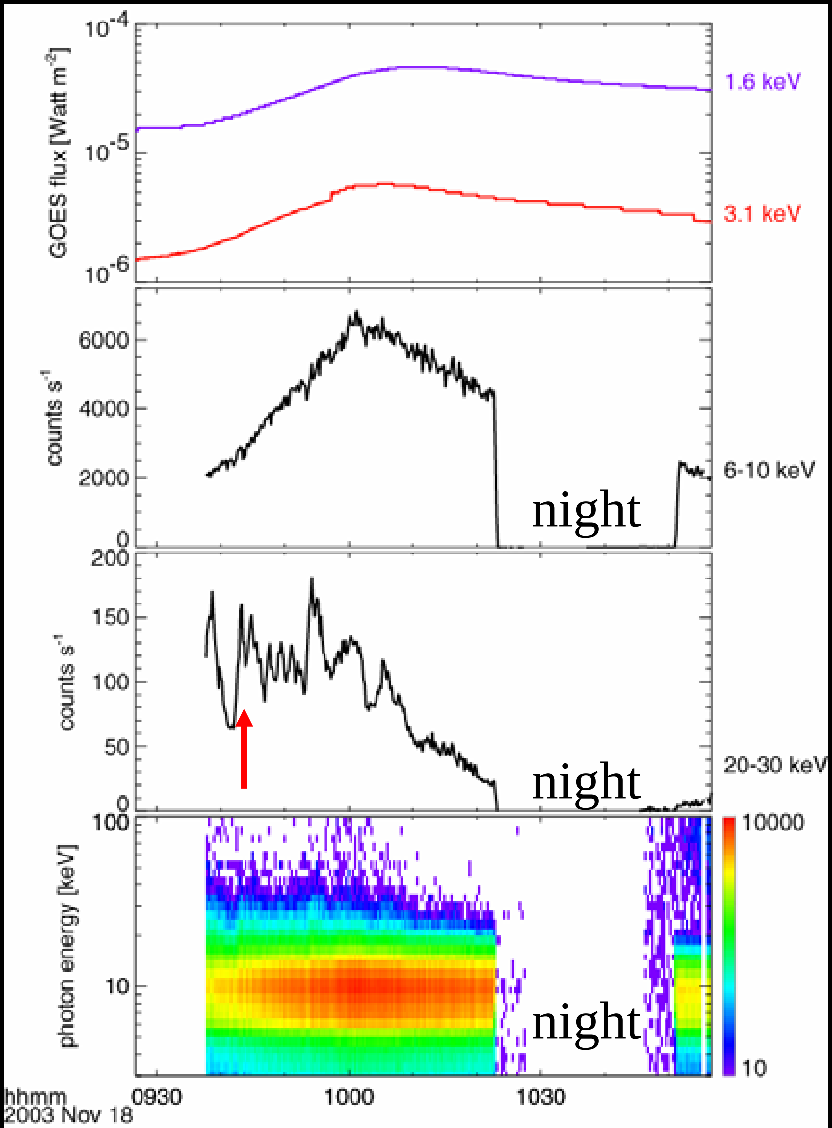
fast time variations in HXRs



SXR movie (GOES SXT)

Flare with occulted footpoints

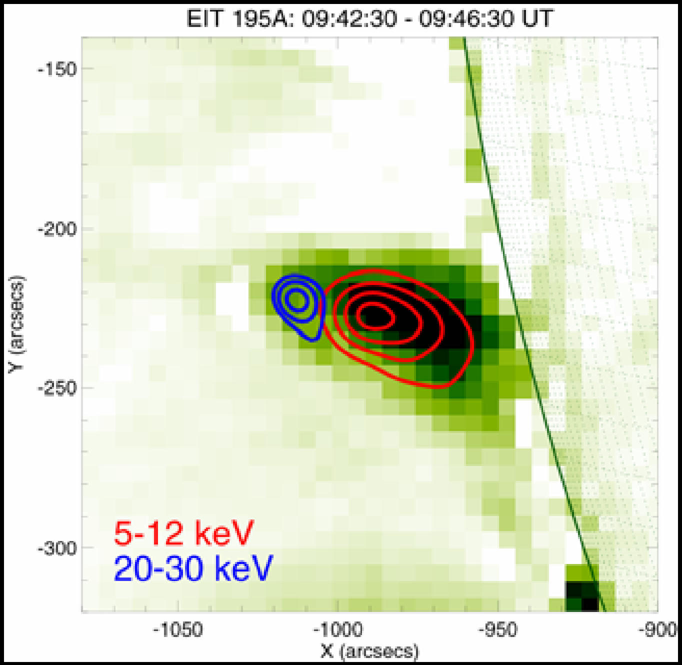
Nov 18, 2003: GOES M4

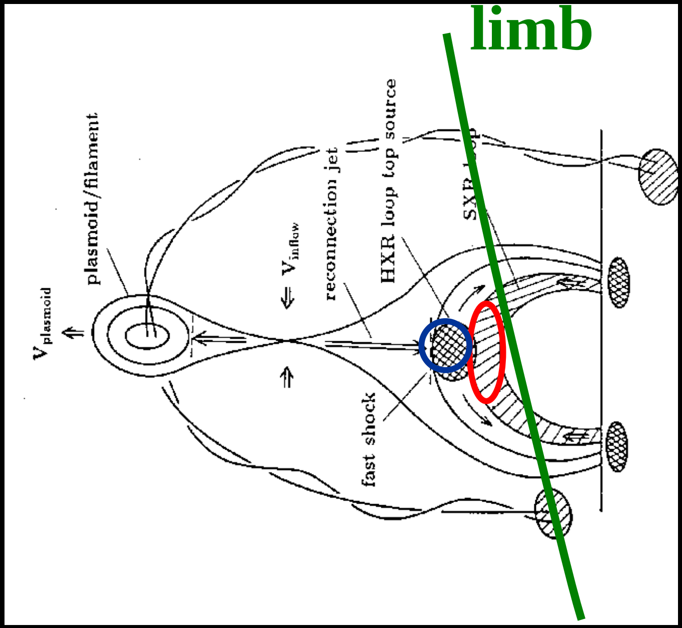


HXR emission from corona

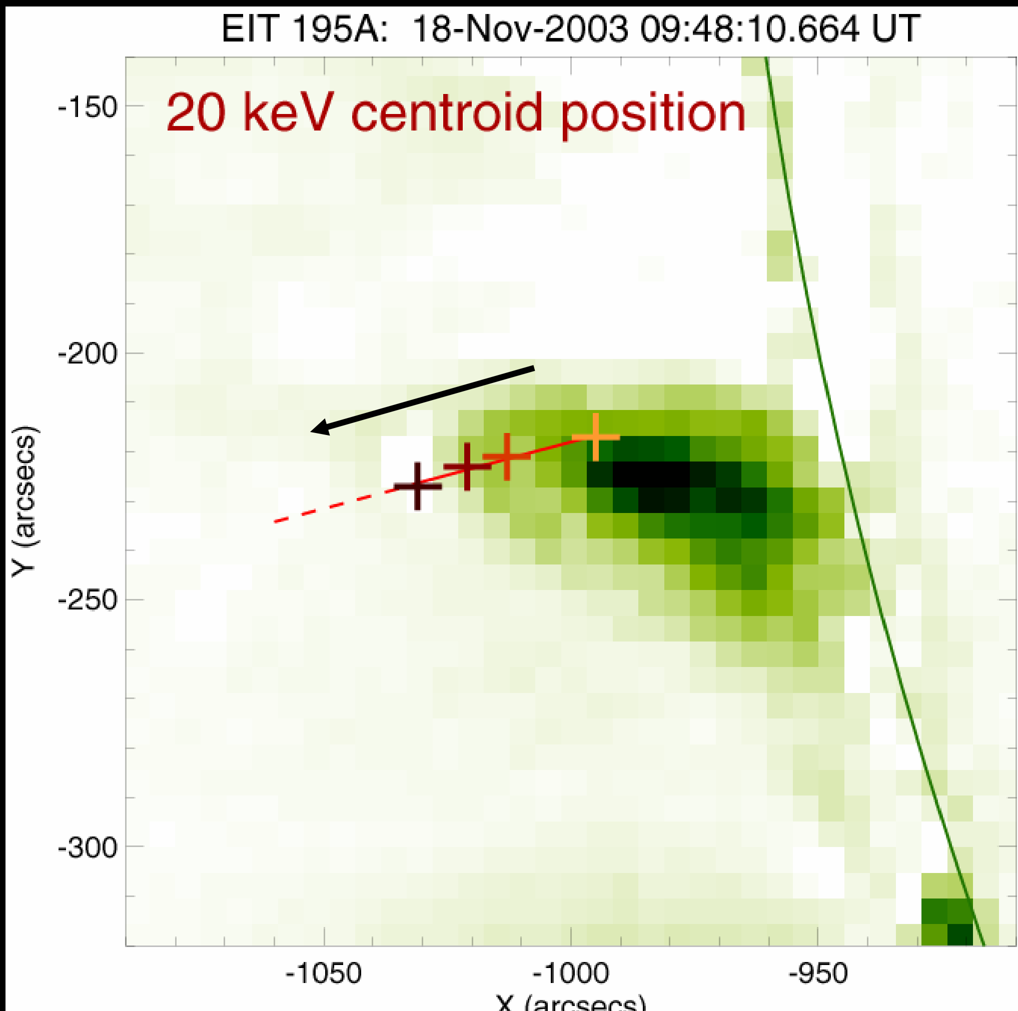
Gradual variation below 10 keV

fast time variations in HXRs

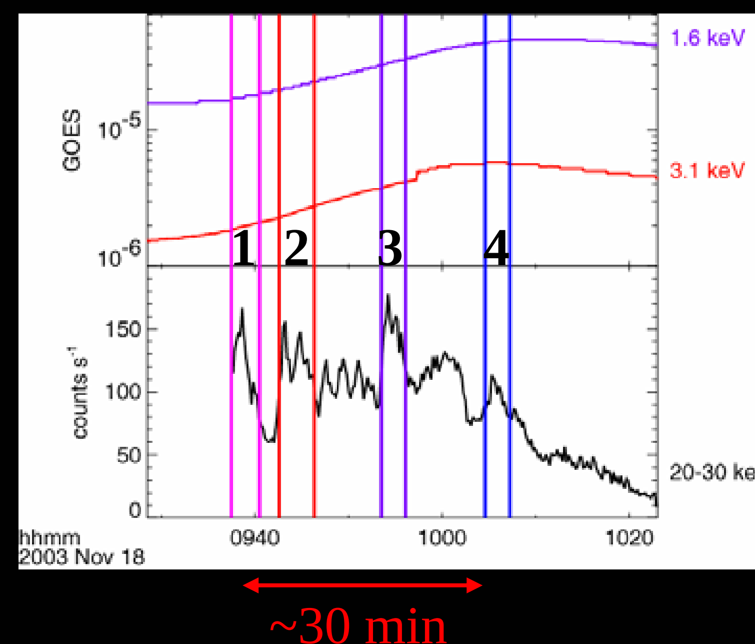




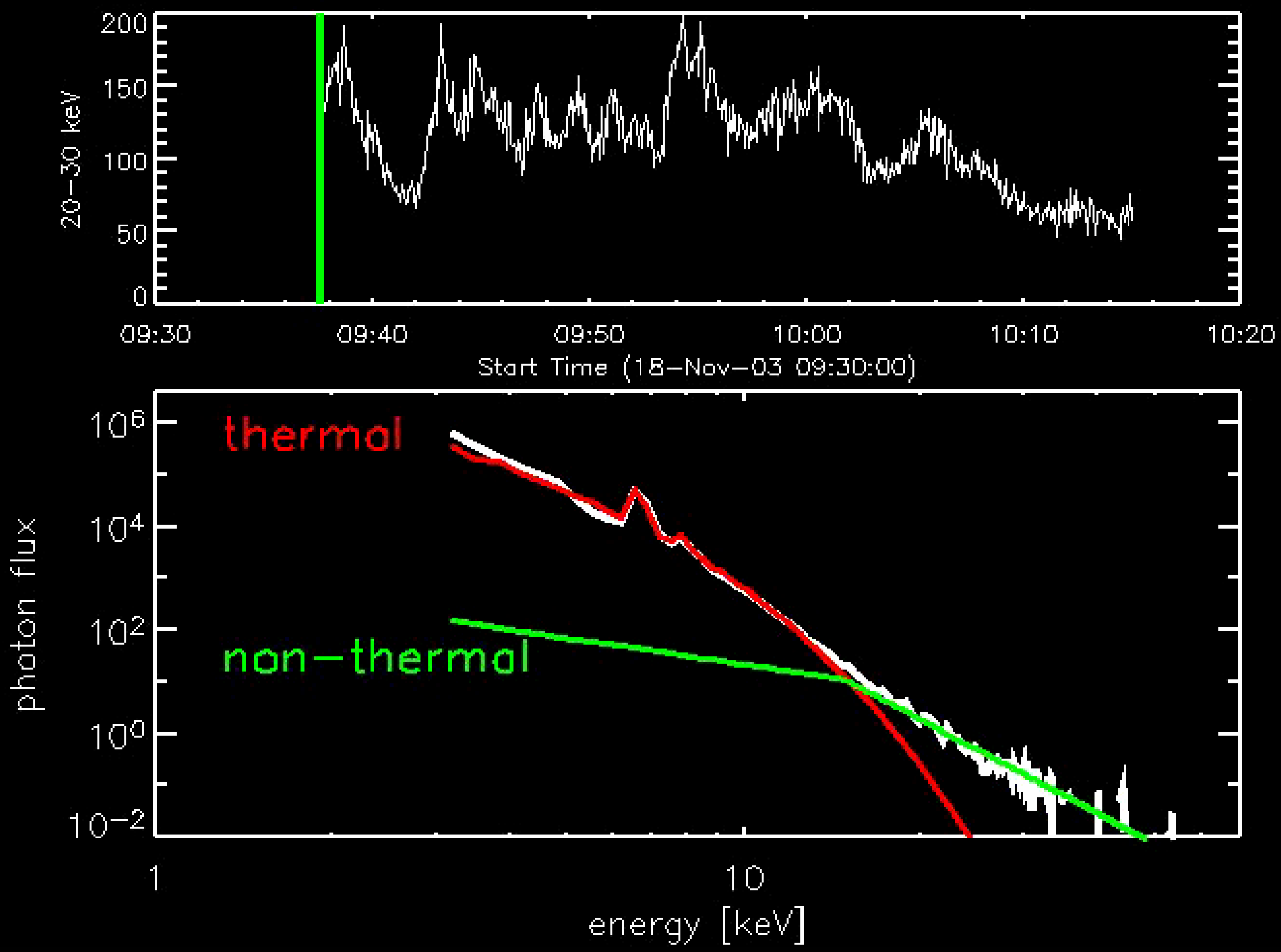
Above loop top source moves upwards in time



Velocities between 5-40 km/s.
Similar velocities as generally observed for footpoint motions



Spectral evolution



Thermal emission dominates below ~15 keV

soft spectrum (γ~6) at higher energies

Energy deposition in coronal source

Assuming **THICK** target model

integrated: close to 1e31erg!

→ a lot of heating in non-thermal source

Observed thermal source (GOES/RHESSI) contains ~1e30 erg

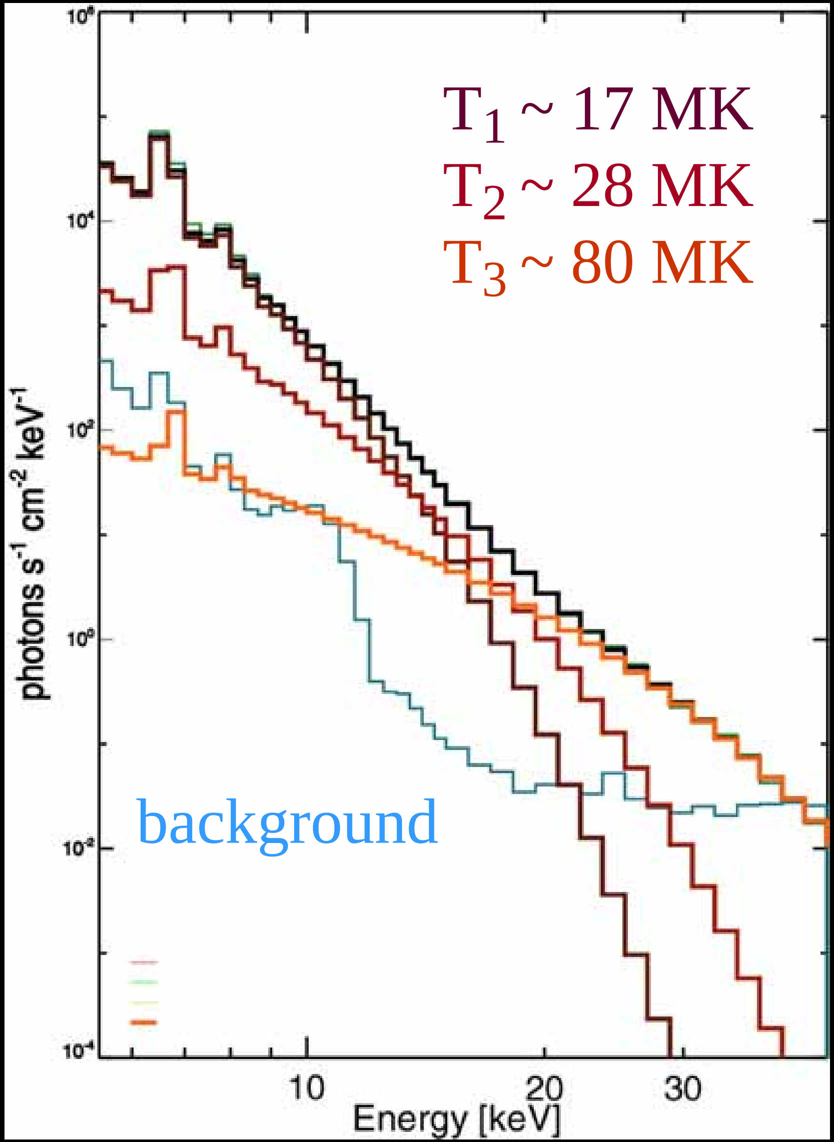
Assuming THIN target model

integrated: still ~1e30erg

→ significant heating is expected

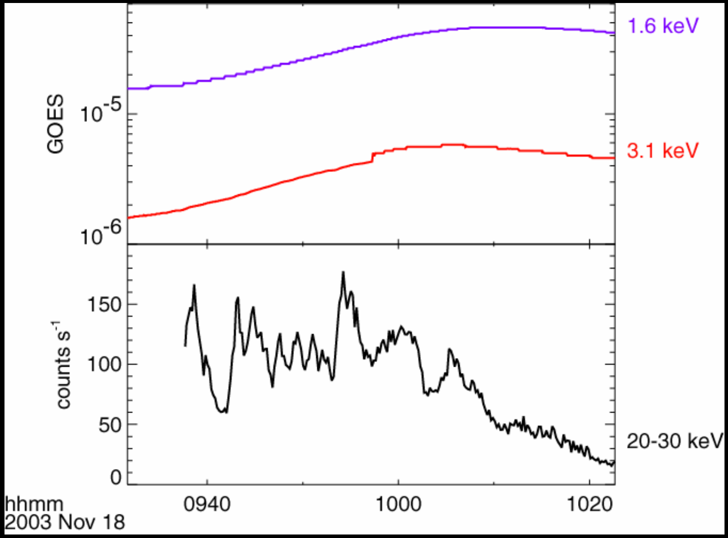
Is 20 keV source is a combination of thermal and nonthermal emission?

Multi-thermal fit?



3 thermal components fit spectra as well as a power law. Very hot temperatures needed, small EM (1e45 cm^{-3})

How can fast variations be explained?
Adiabatic compression?



Thermal or non-thermal emission?

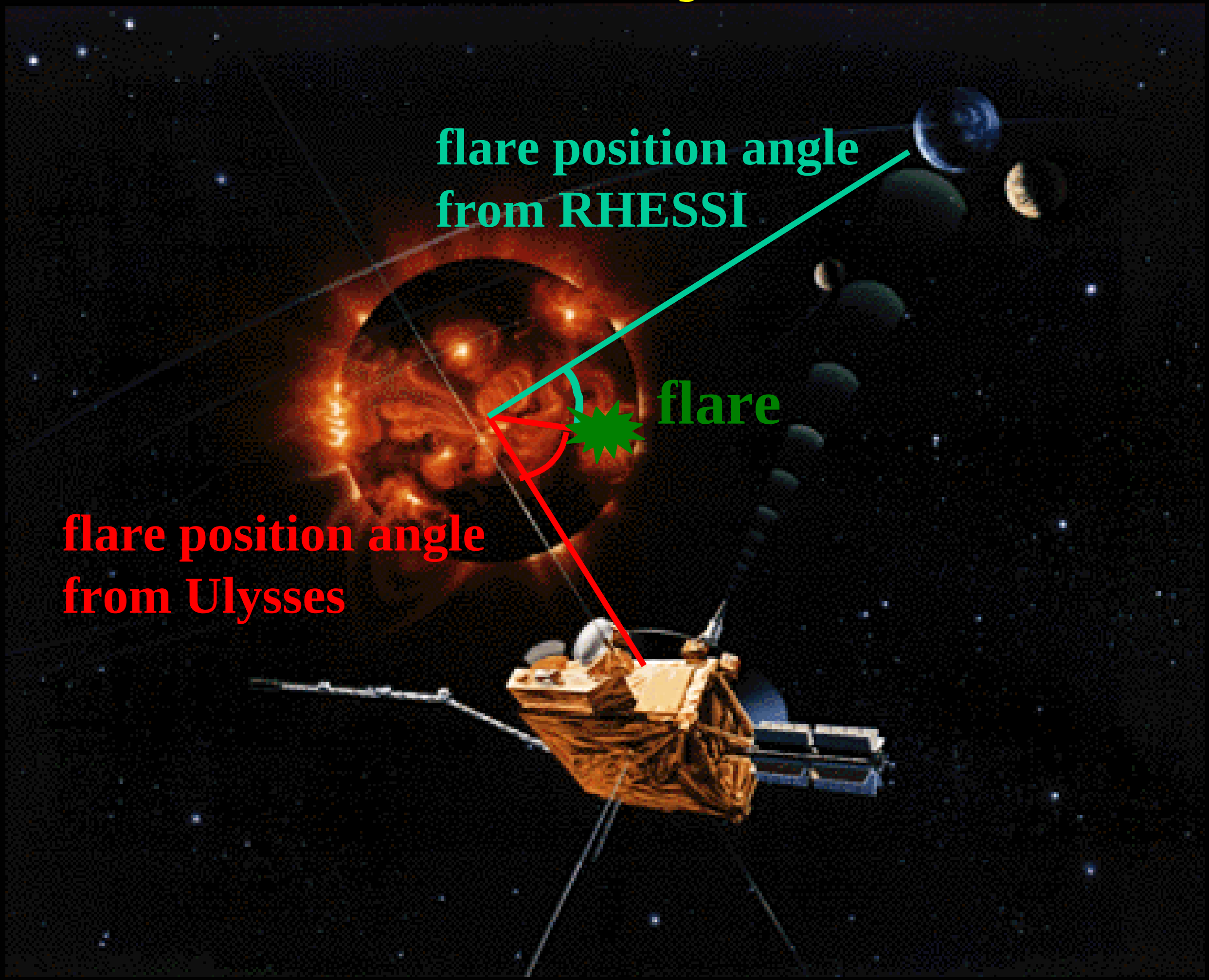
Problems with non-thermal interpretation

- is density high enough? Trapping?
- a lot of energy is deposited in corona → heating

Problems with thermal interpretation

- short time variations
- very high temperatures

RHESSI (>3keV) – Ulysses (>25 keV) solar X-ray flare observations



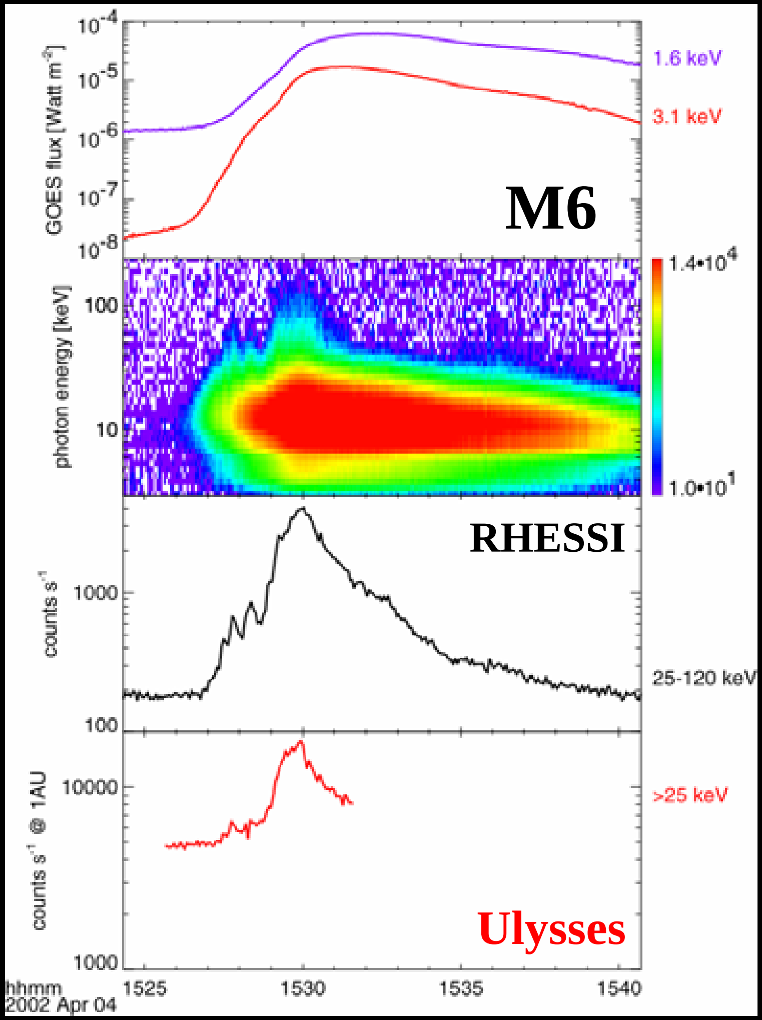
Partly occulted flae for one spacecraft

→ allows to study coronal HXR emission

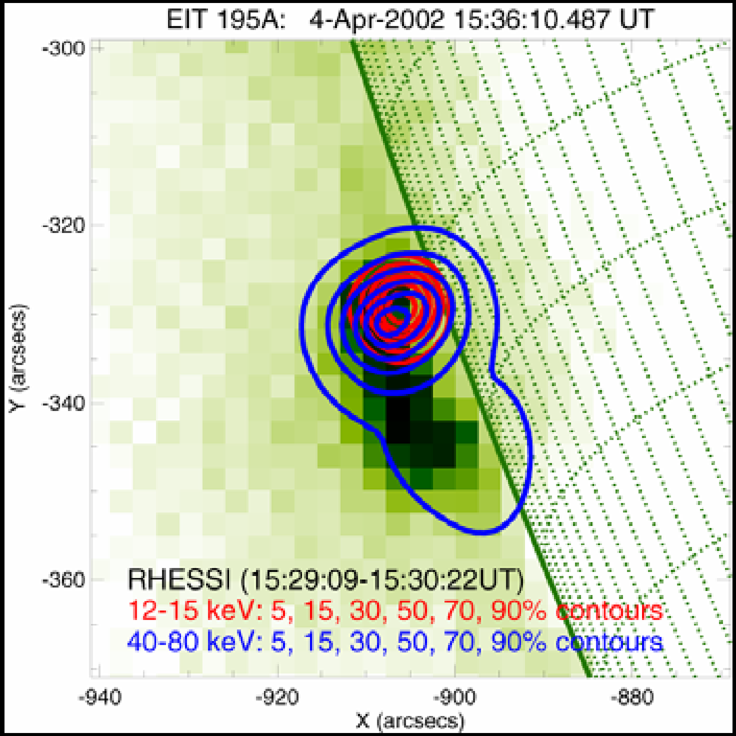
2002 April 04

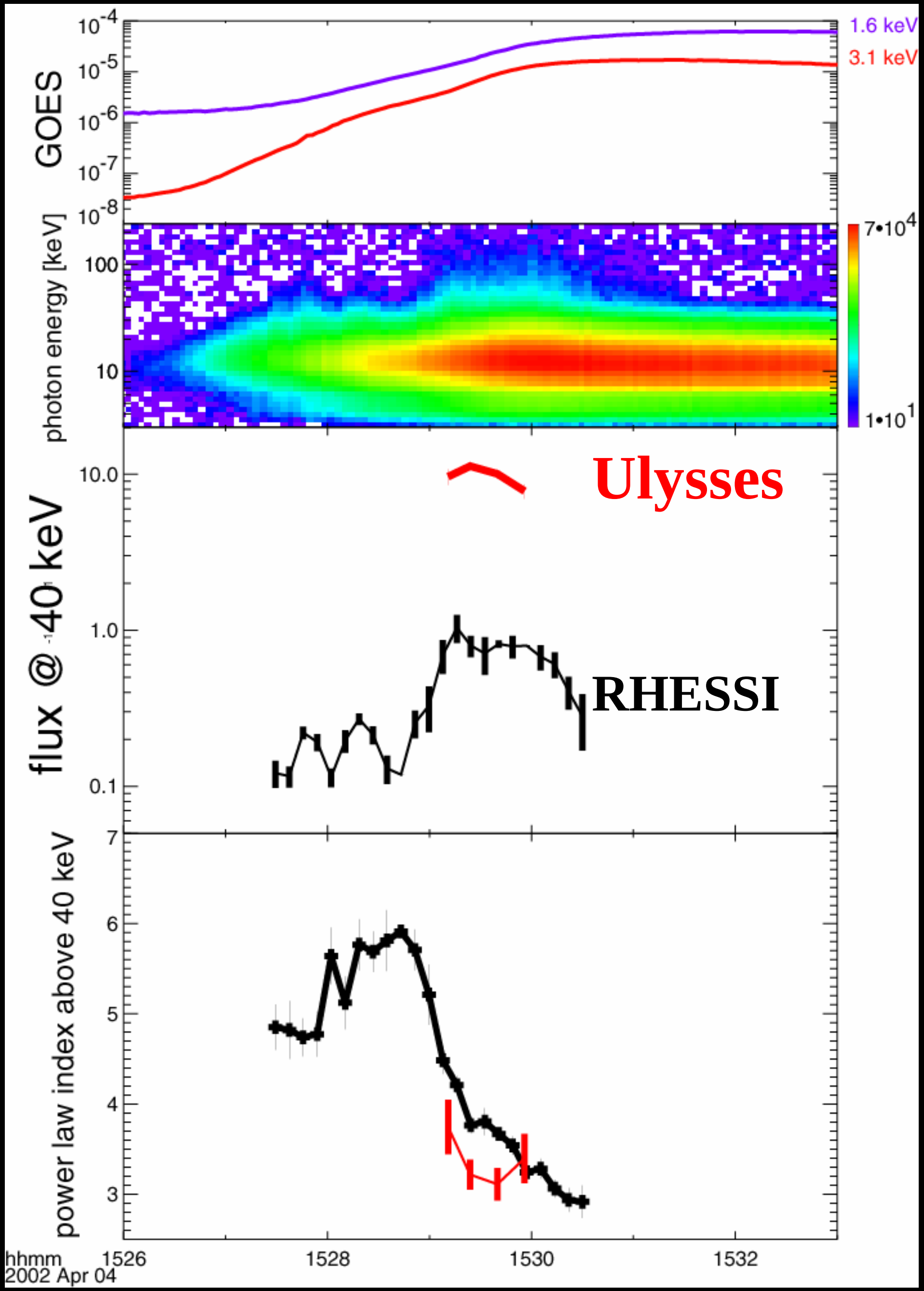
RHESSI: east limb, 93-102 degrees)

Ulysses: 74-78 degrees



EIT & RHESSI (pixon)





Power law fits above 40 keV

At 40 keV, RHESSI sees **~10 %** of the flux seen by ULYSSES (corrected to 1 AU).

ULYSSES (red):
Power law index around 3

RHESSI (black):
Spectral hardening during peak.

Difference in power law indices smaller than 2 (thin-thick target difference)

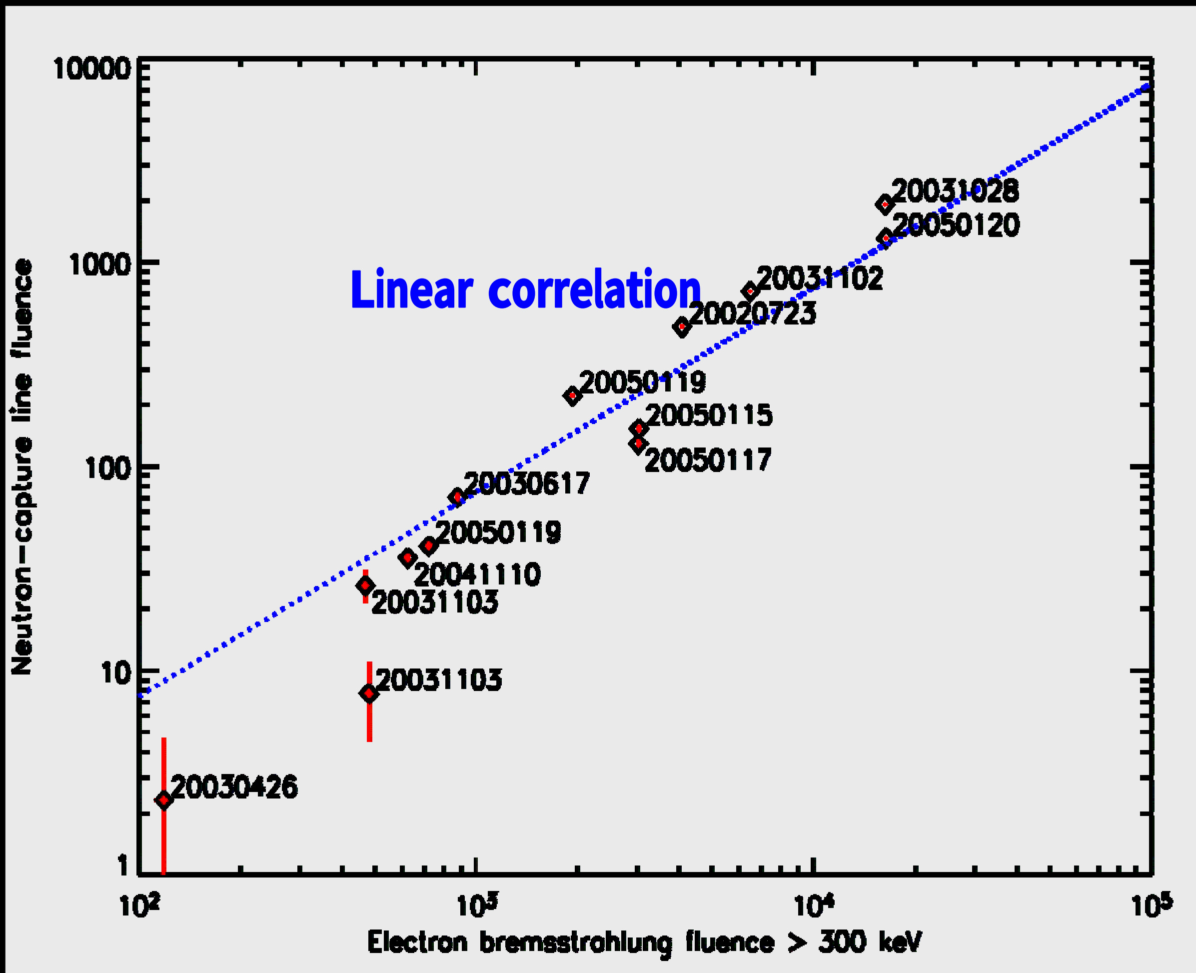
RHESSI γ-ray flares

Date	**GOES Class**
2002 July 23	X4.8
2003 June 17	M6.9
2003 October 28	X17
2003 October 29	X10
2003 November 2	X8.3
2003 November 3	X3.9
2004 November 10	X2.5
2005 January 15	X2.6
2005 January 17	X3.8
2005 January 19	X1.3
2005 January 20	X7.1

plus at least 6 flares with high-energy electron bremsstrahlung emission

Electrons vs Protons (Shih et al. 2005)

2223 keV fluence (PROTONS)

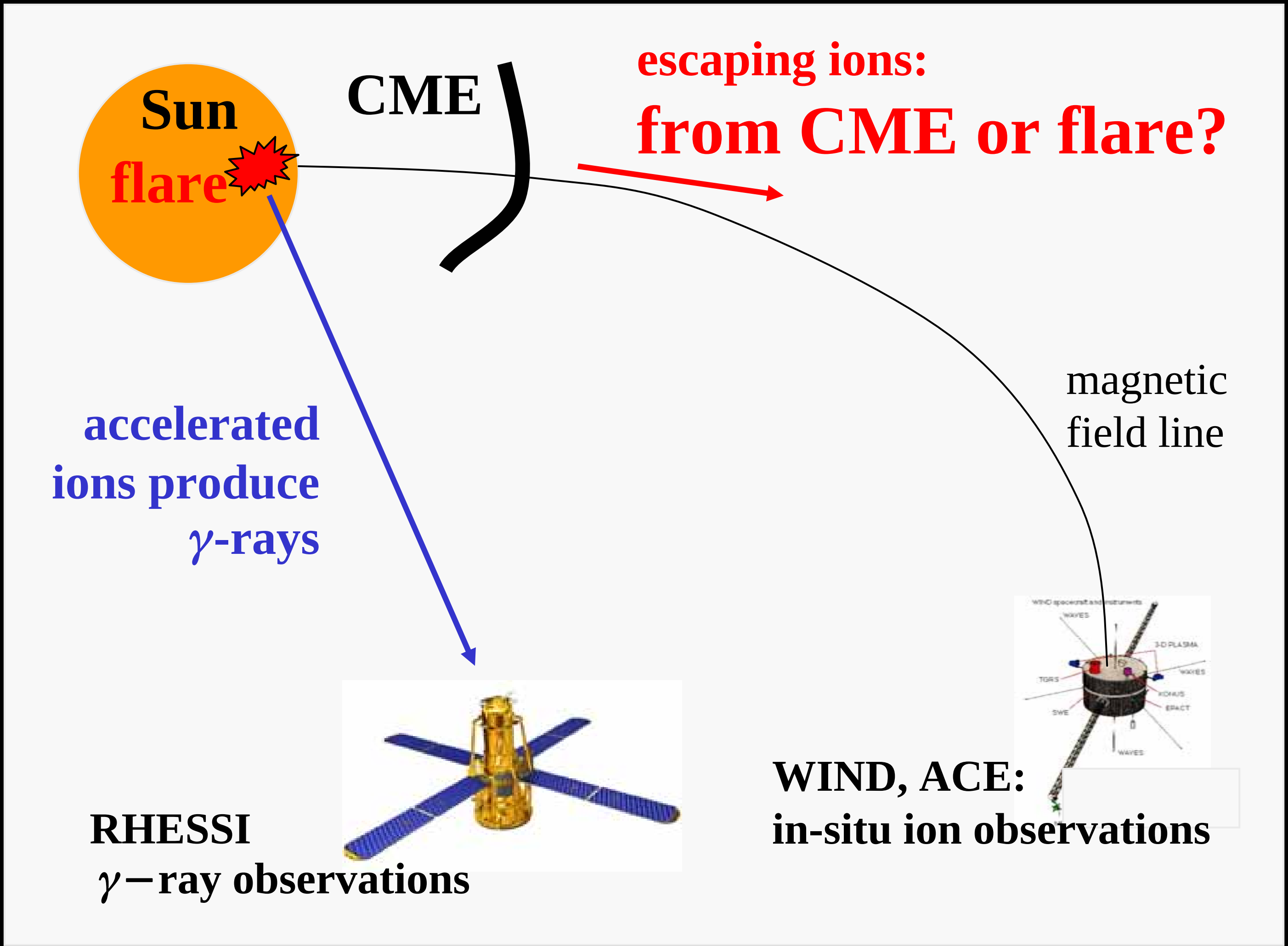


>300 keV fluence (ELECTRONS)

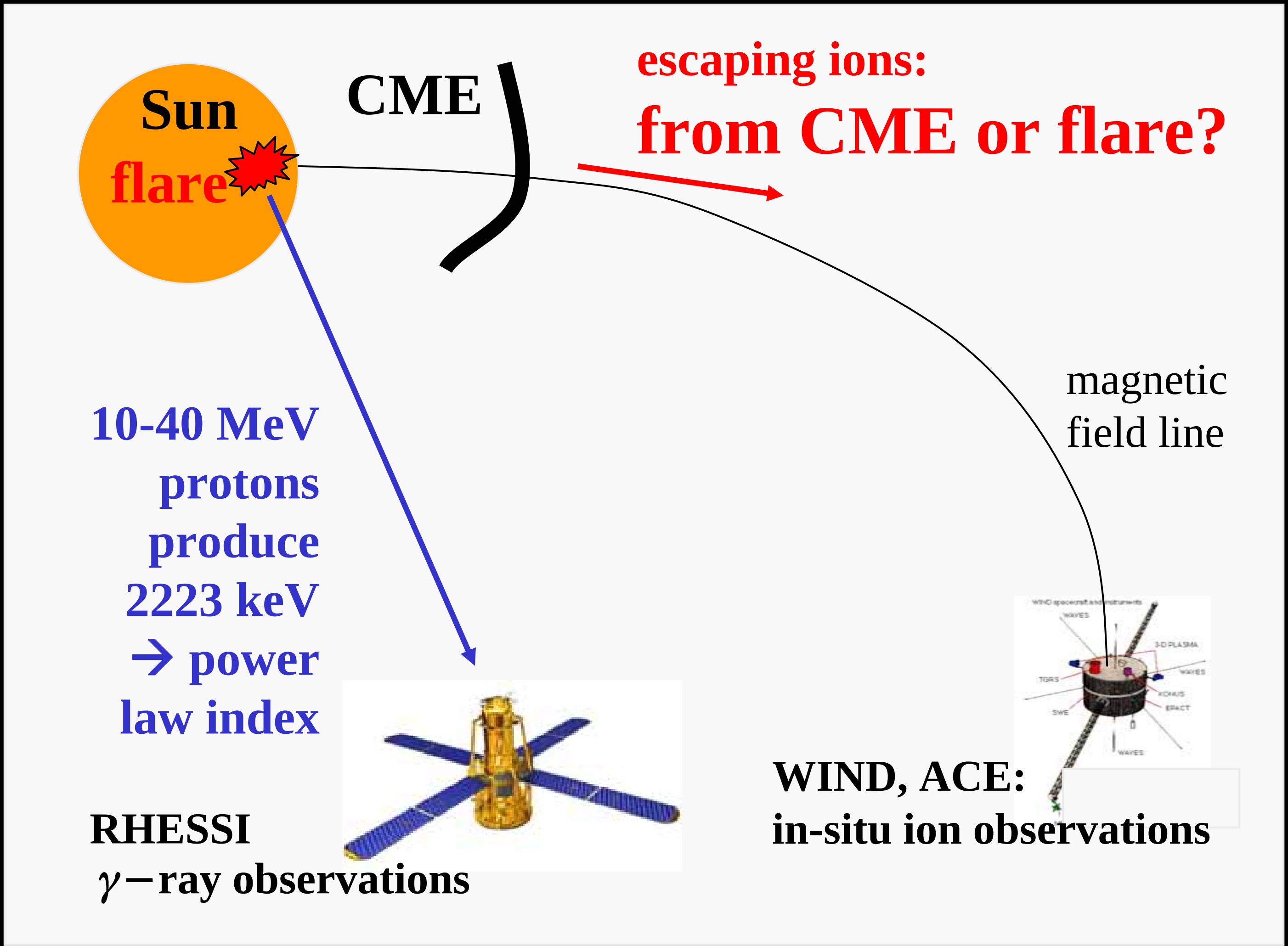
Rough linear correlation.

Electron and proton production is correlated.

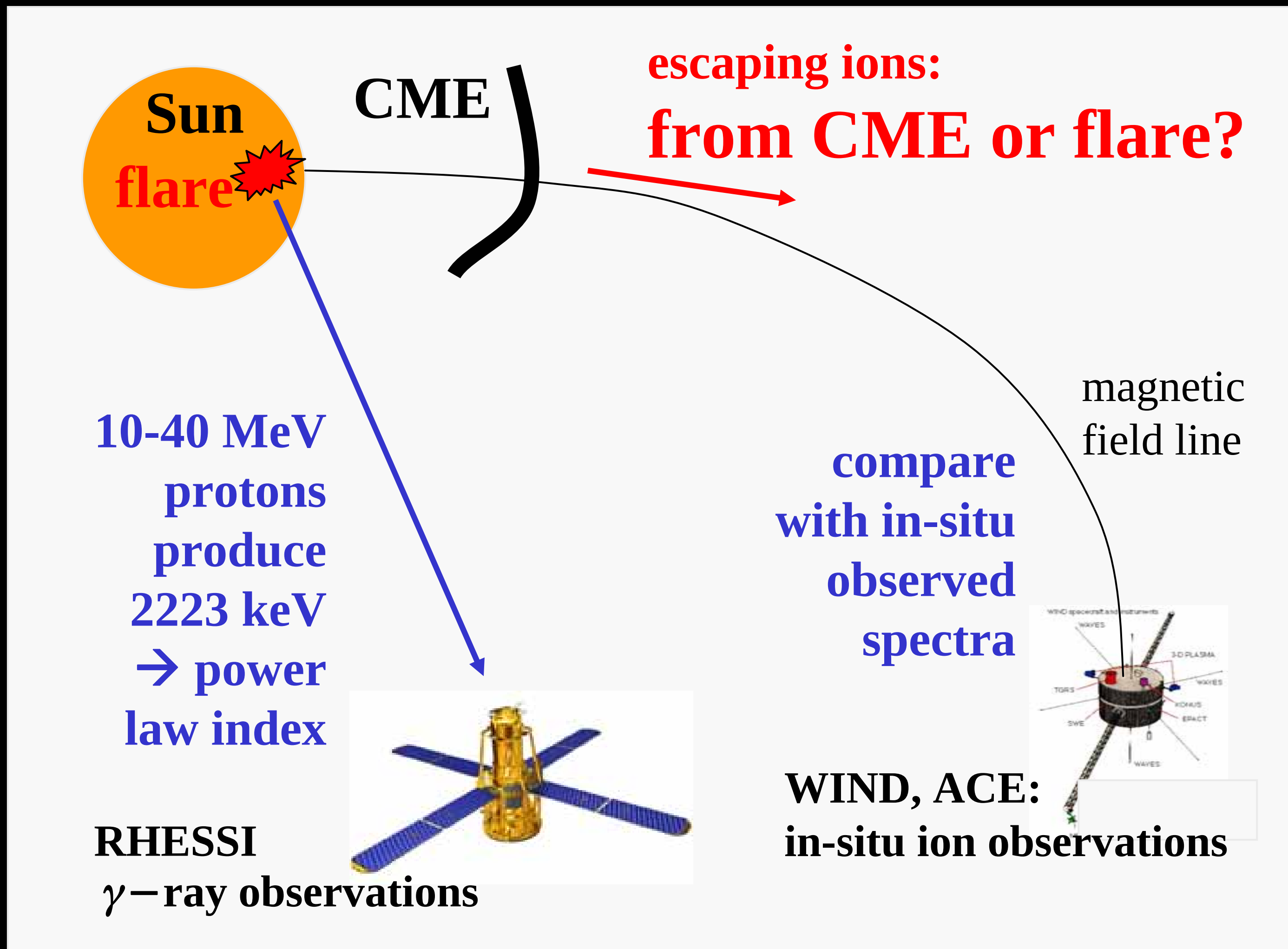
γ-rays and SEPs



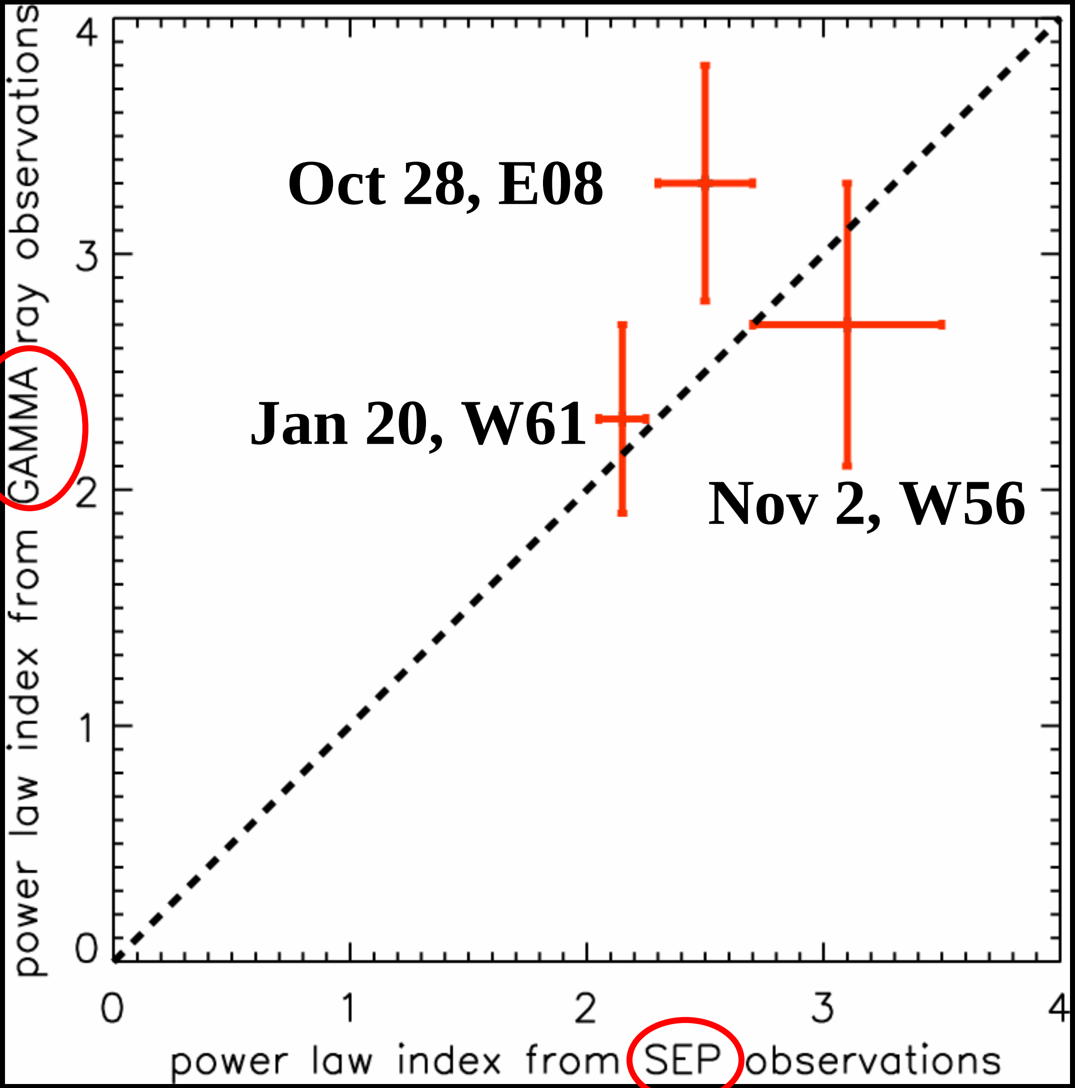
γ-rays and SEPs



γ-rays and SEPs



Comparing ion spectra: flare & SEP

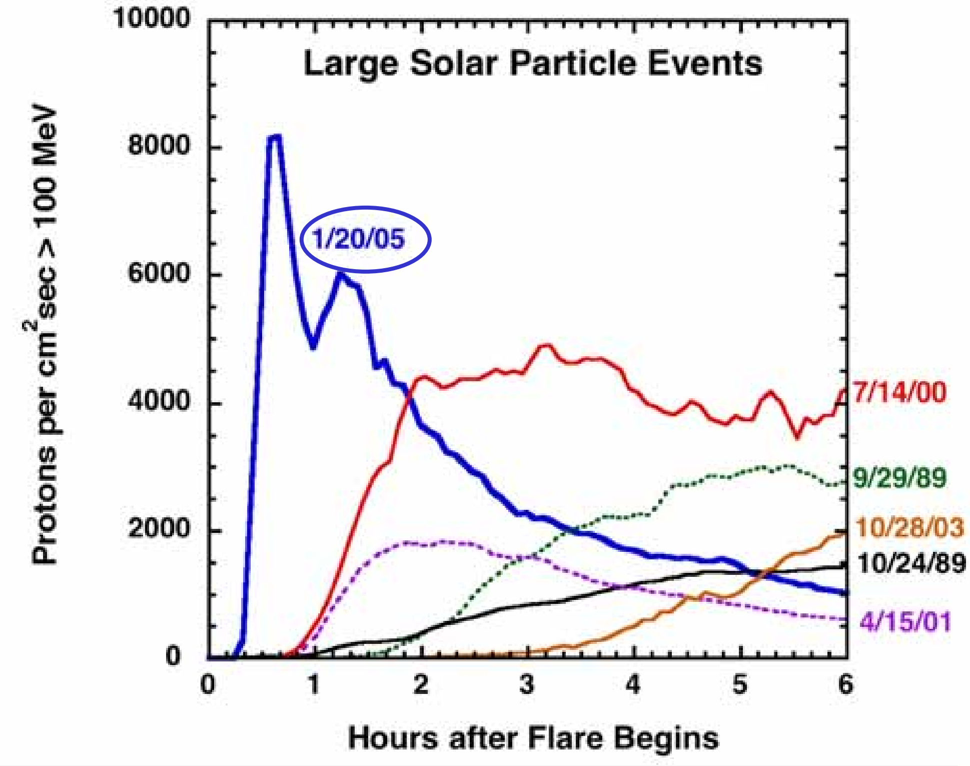


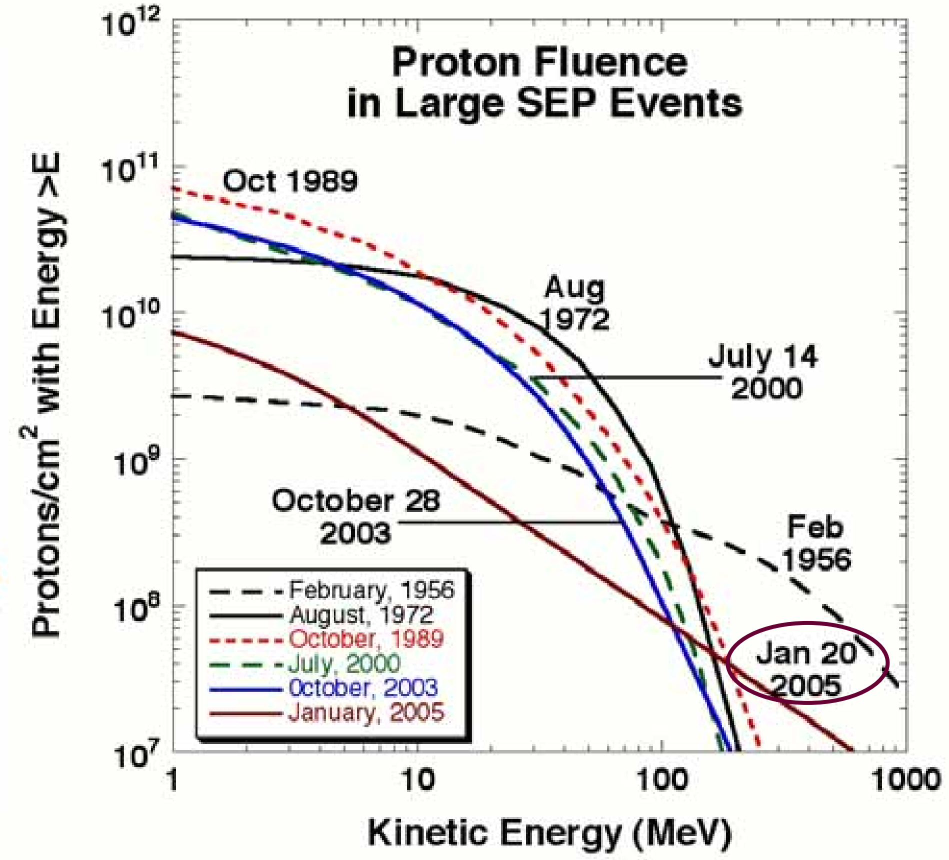
Comparing spectrum around 10-40 MeV.

Oct 28: somewhat off
Nov 2: large errors, but agrees
Jan 20: agrees

Well connected events agree → ions we see at 1AU could be from flare!

January 20, 2005 SEP event





Very short time to maximum intensity (30 min)

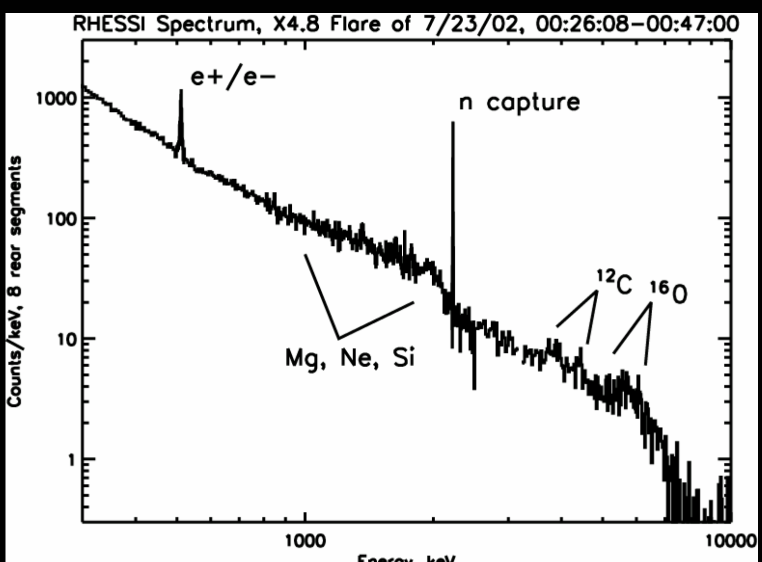
Very hard spectrum

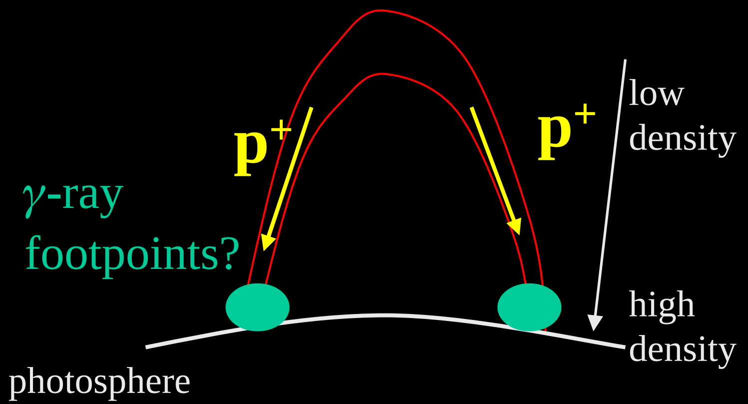
from Mewaldt et al.

γ-ray imaging with RHESSI

Gordon Hurford et al. 2003, 2005

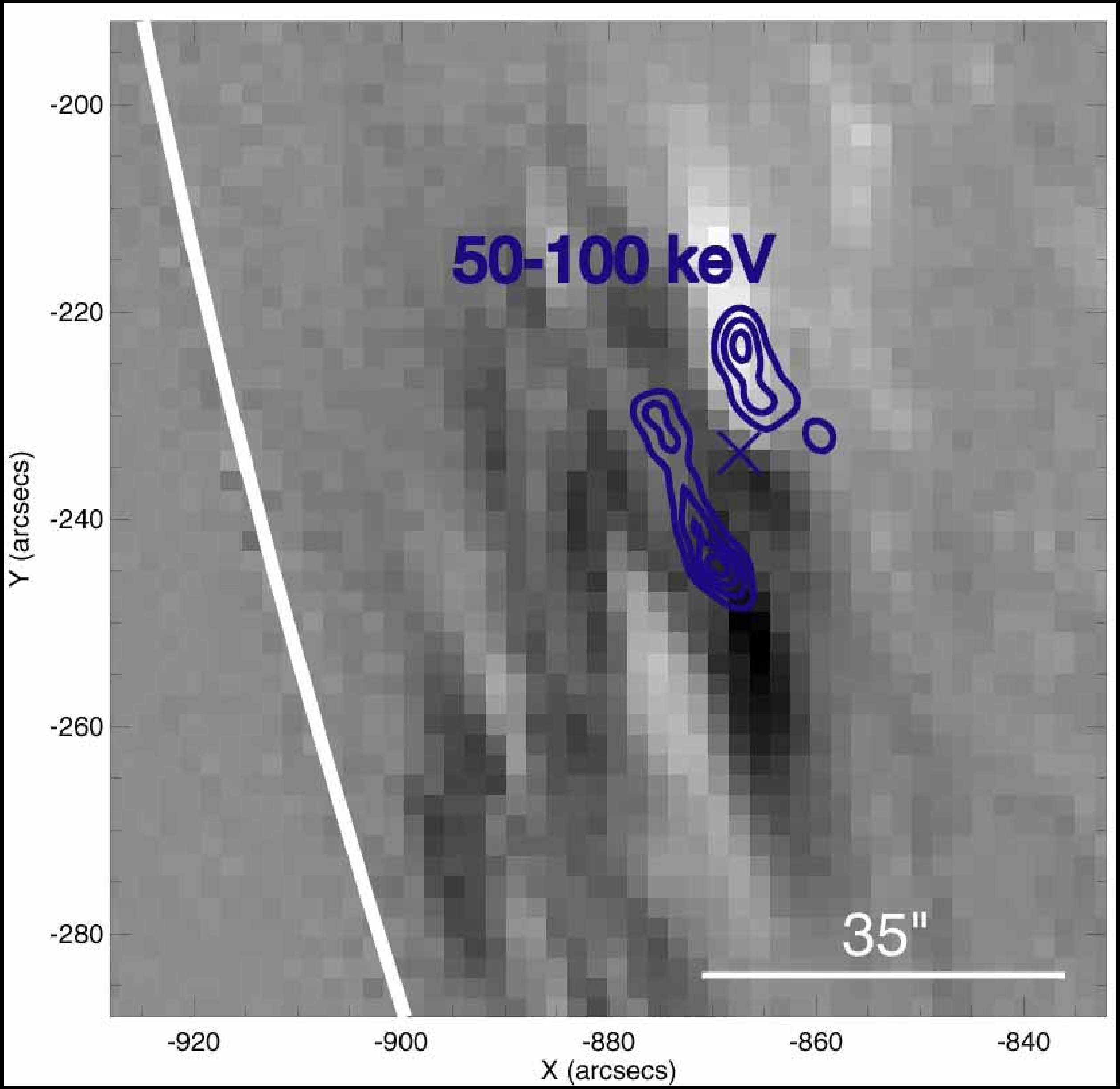
- Before RHESSI, no imaging in the γ-ray range available
- RHESSI γ-ray imaging at 35” and 180” resolution (compared to 2” for HXRs, i.e. electrons)
- Low photon statistics: integration over total flare duration needed
- 2.2MeV line is best candidate





Where are the γ-ray footpoints relative to the HXR footpoints?

July 23: electrons



Integrated image over main HXR peaks ~ 8 minutes

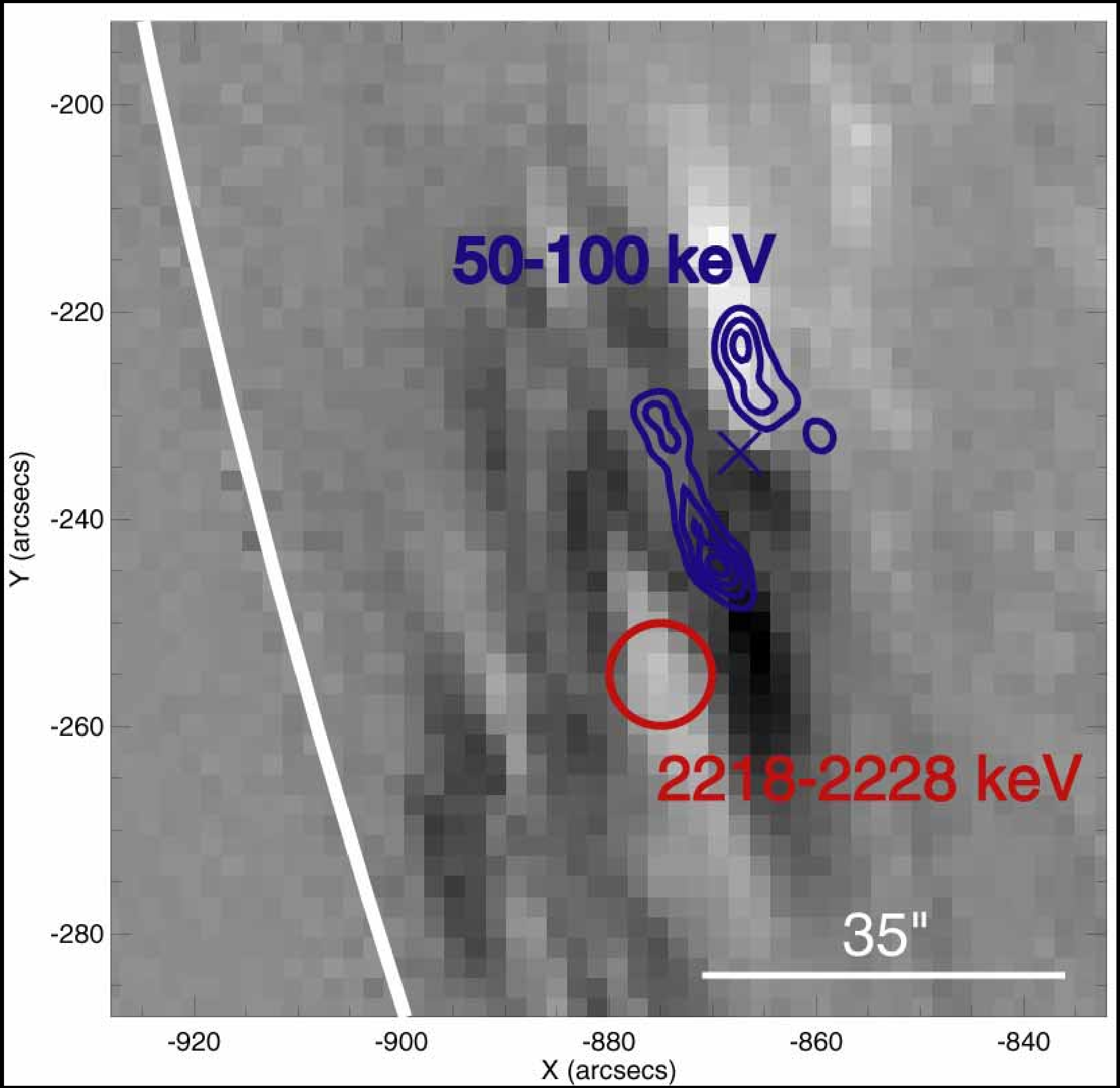
Contours:
3” resolution image

Cross marks centroid location when only grid 6 and 9 are used

HXR sources are on EUV ribbons

MDI magnetogram

July 23: electrons-ions

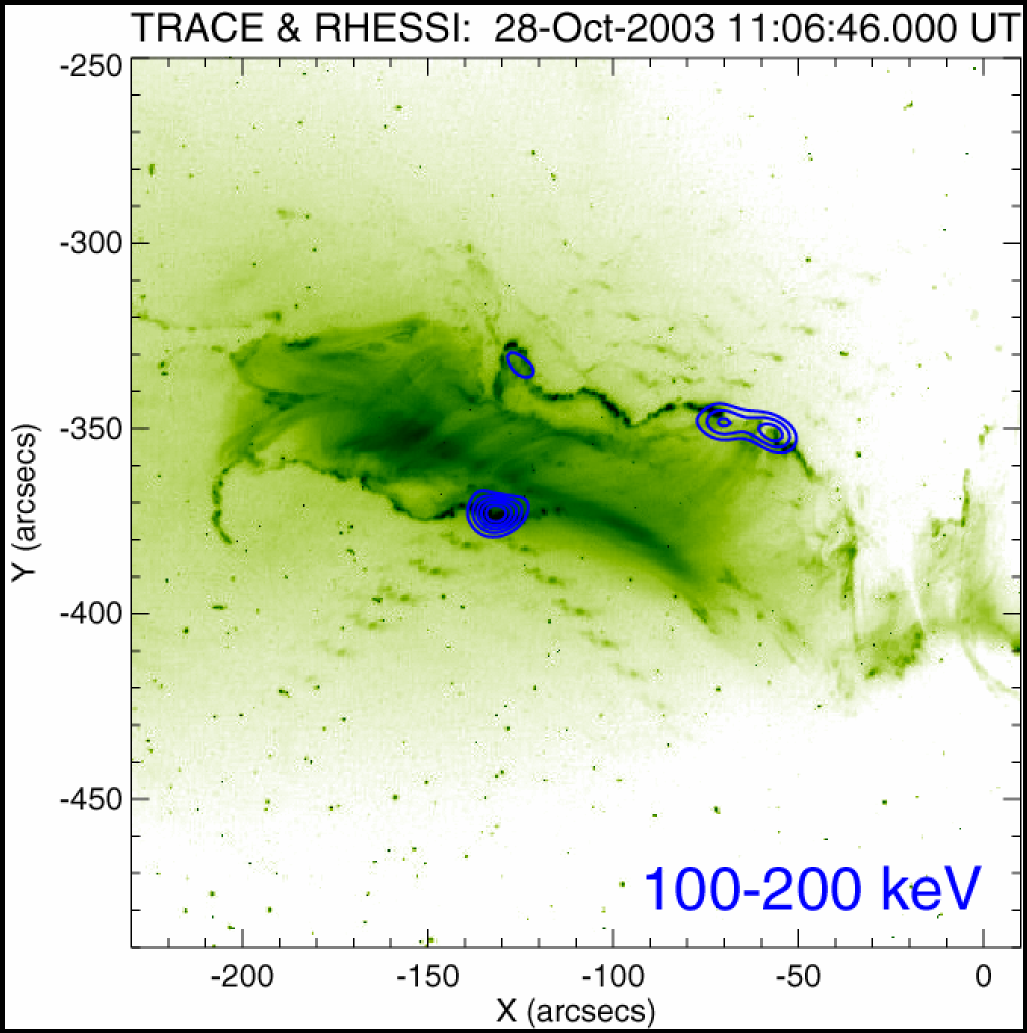


2.2 MeV centroid
(e.g. PROTONS)
displaced from
50 keV centroid
(i.e. ELECTRONS)
by ~ 20 arcsec
(~5 sigma result)

No Halpha, EUV,
X-ray enhancement
at 2.2 MeV centroid
location

from Hurford et al. 2003

October 28: electrons



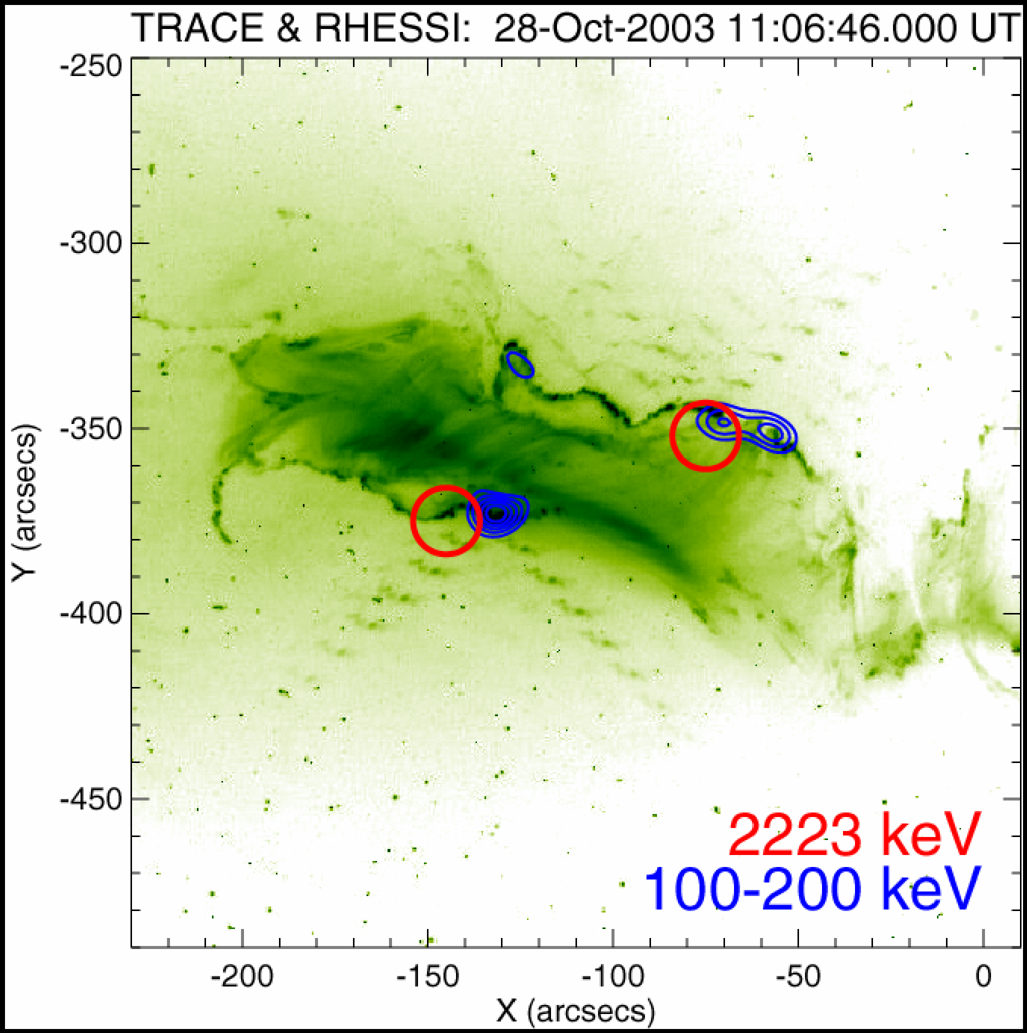
HXR image (electrons)
is snapshot at 11:06:46 UT

HXR ribbons are moving
2.2 MeV is produced ~100 s delayed
→ comparison not trivial

Also:
2.2 MeV image (protons)
is averaged over 15 minutes

different spatial resolution
Electrons ~2 arcsec
2223 keV: ~30 arcsec

October 28: electrons vs protons



HXR image (electrons)
is snapshot at 11:06:46 UT

2.2 MeV image (protons)
is averaged over 15 minutes

CONCLUSIONS:

1) Electrons and protons both close to ribbons
2) difference <15arcsec (~1e4 km)
3) e and p are accelerated in loops of similar size

SUMMARY

1) HXR footpoint motion: often motion along ribbons; correlated with energy release; often complex motions
2) Gradual HXR emission from footpoints
3) Temperature gradient possibly outlining reconnection region
4) coronal HXR emission have soft spectra with short time variations. HXRs above thermal loops
5) γ-ray footpoints: protons and electrons do not lose their energy at the same location

http://hessi.ssl.berkeley.edu

X-ray focusing optics

Advantage:

Large effective area, tiny detectors

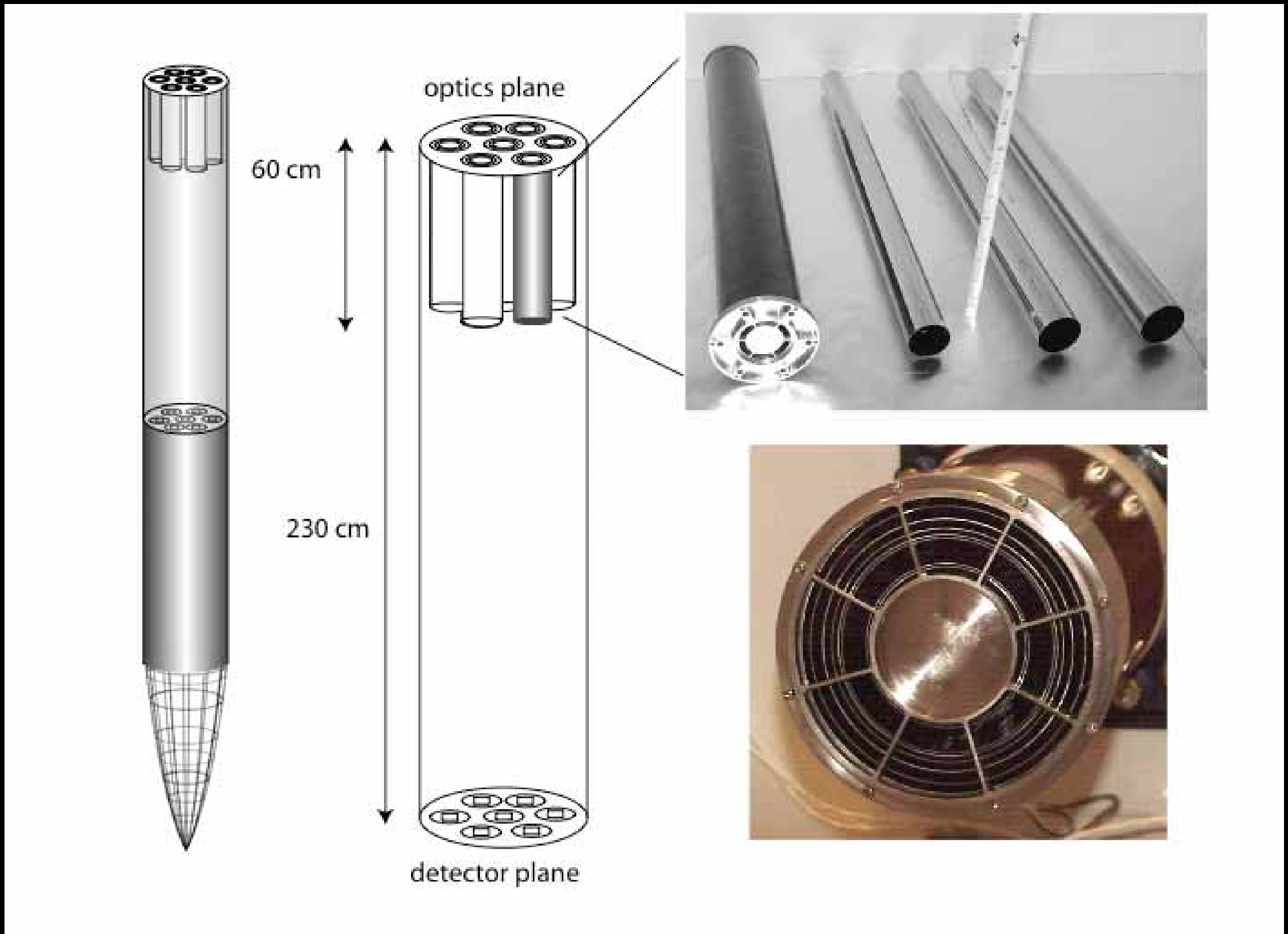
→ ~1000 times more sensitive than RHESSI

Better dynamic range

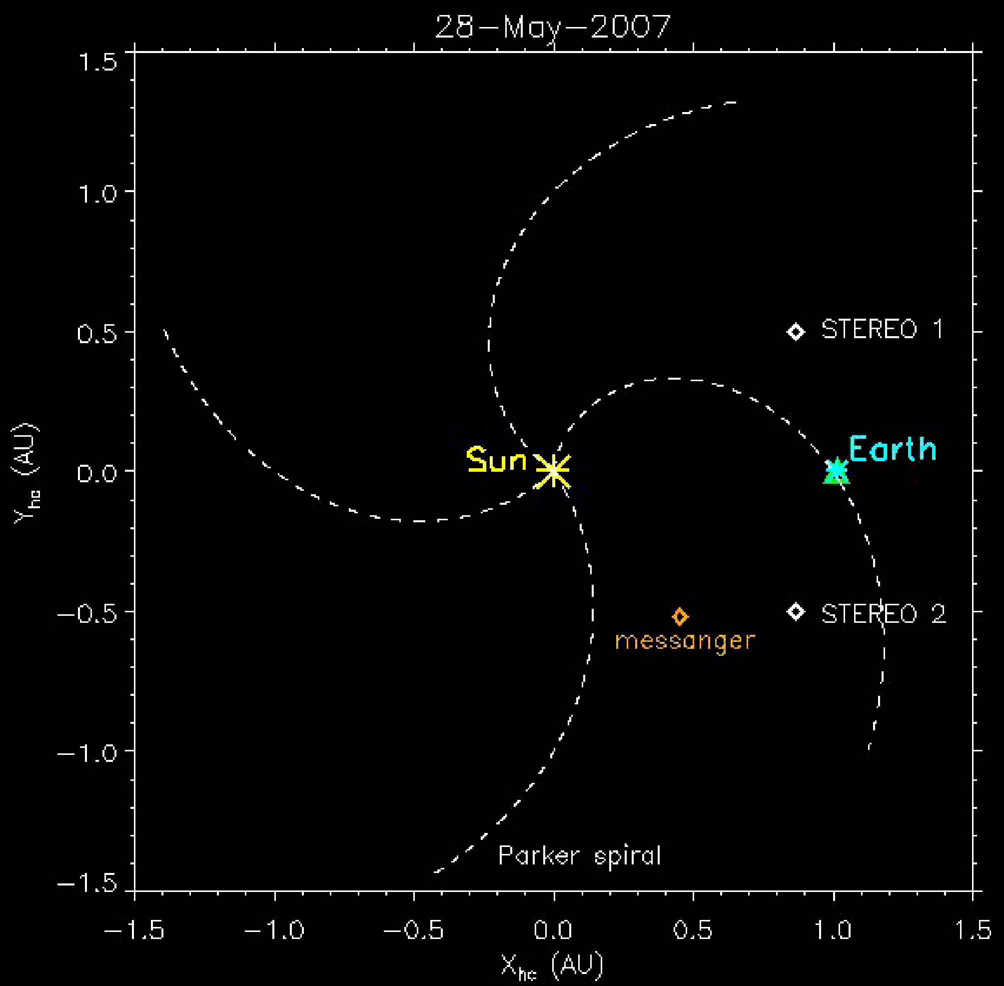
Disadvantage (2005):

works only up to ten’s of keV

resolution > 20 arcsec



Multi-spacecraft inner-heliosphere mission

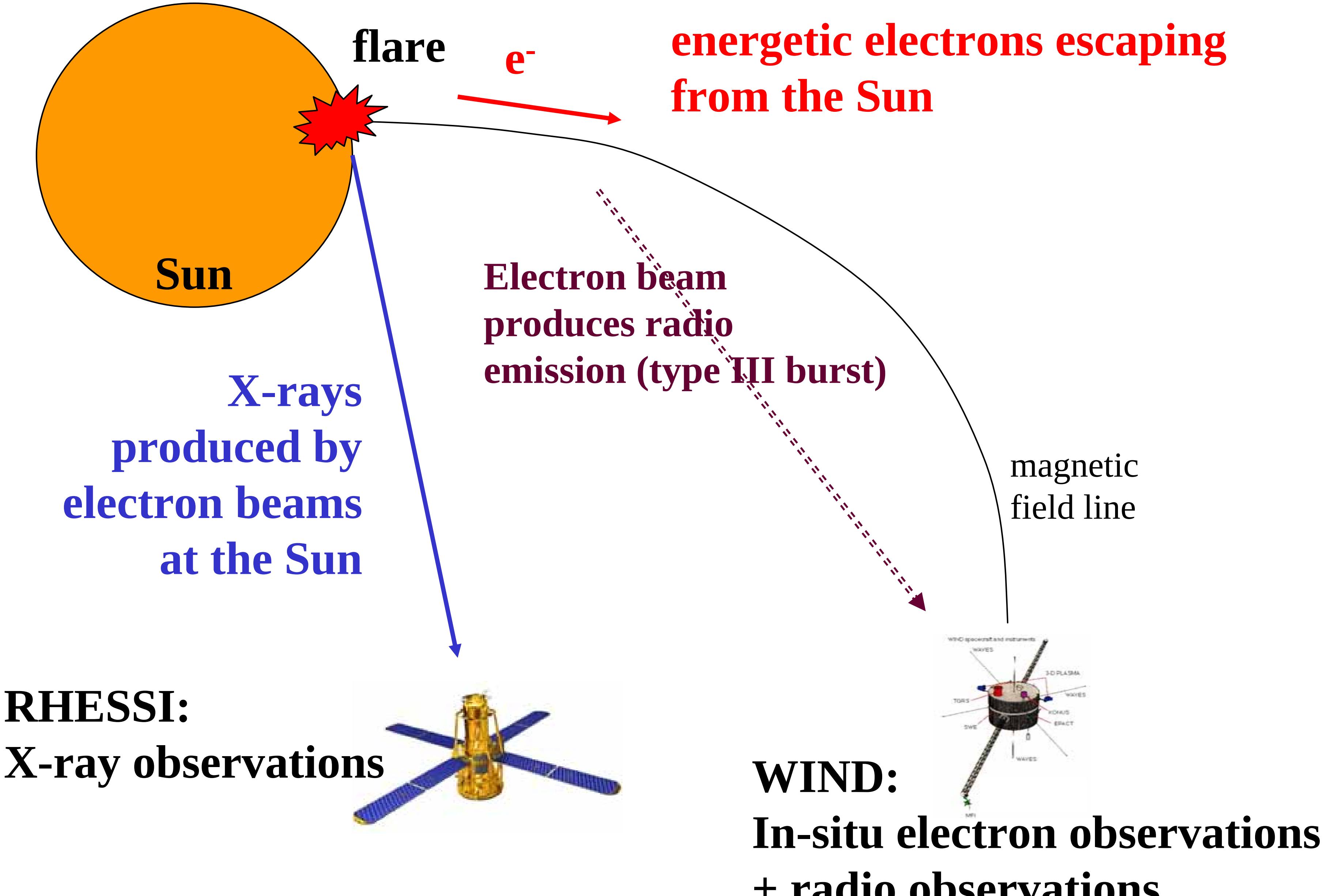


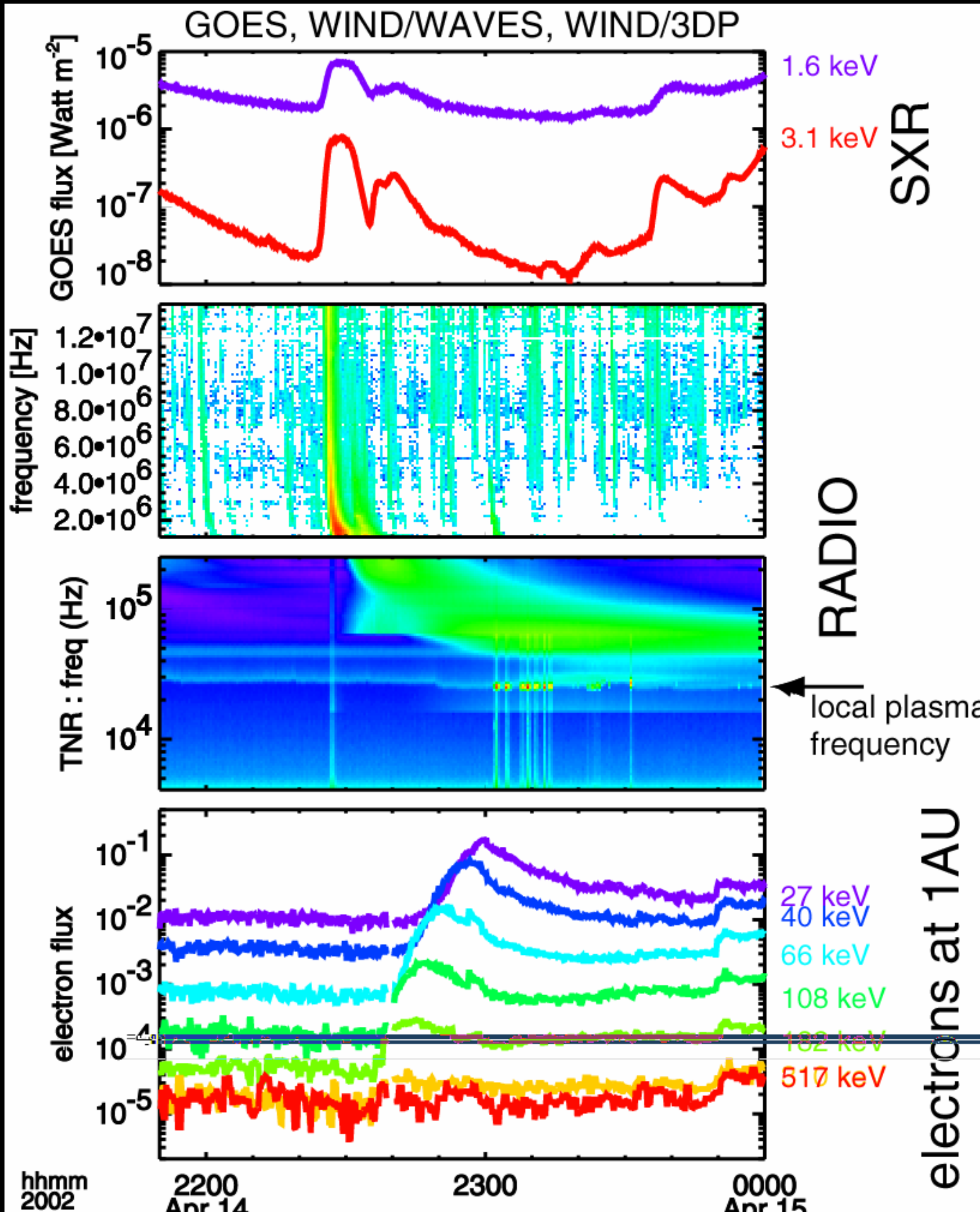
Combining remote sensing and in-situ observations.

e.g. X-ray imaging
in-situ electron

On NASA roadmap.

Movie shows possible orbits


flare
e-
energetic electrons escaping
from the Sun
Sun
Electron beam
produces radio
emission (type III burst)
X-rays
produced by
electron beams
at the Sun
magnetic
field line
RHESSI:
X-ray observations
WIND:
In-situ electron observations
+ radio observations



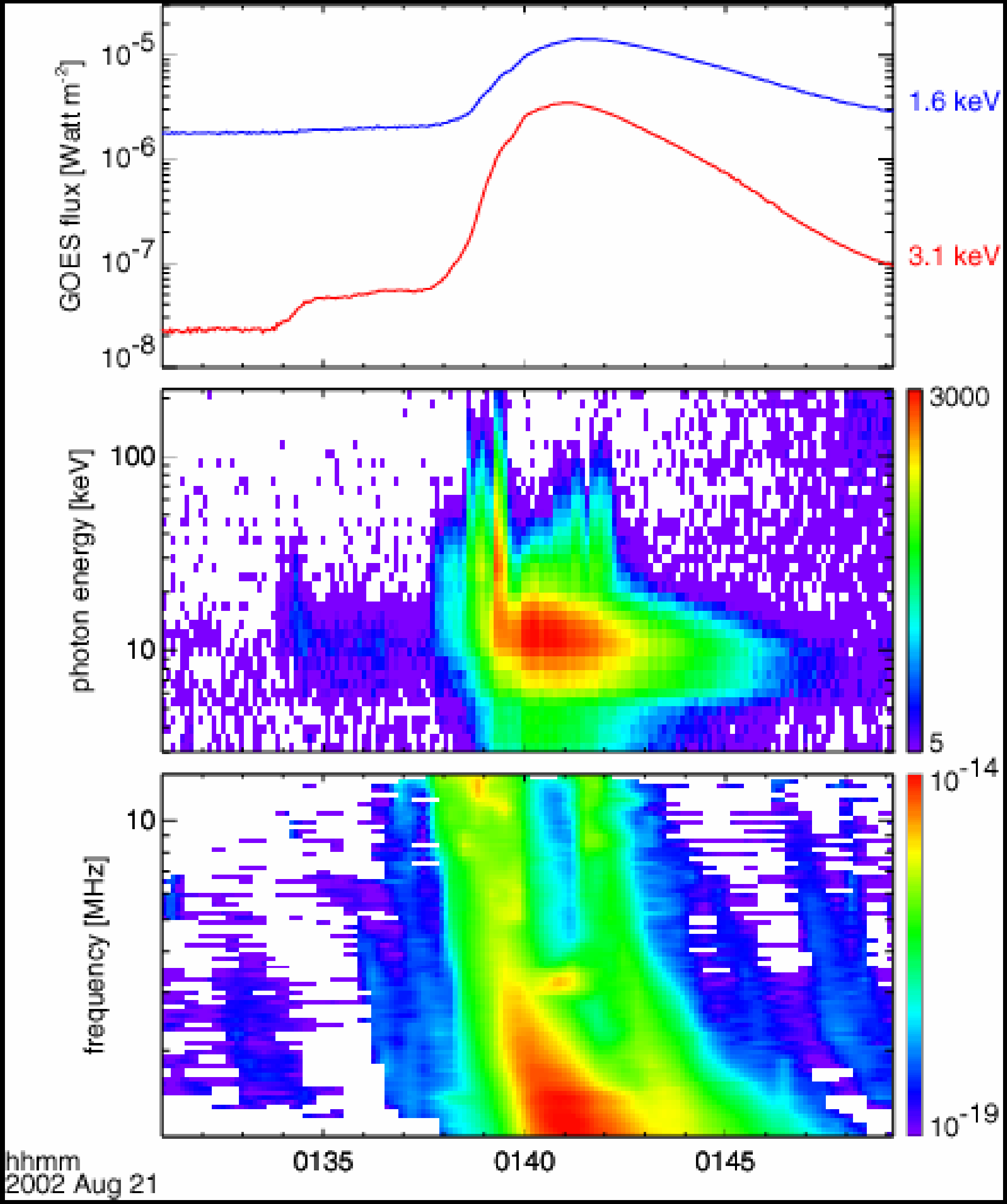
Escaping electrons

SXR flare emission (heating)

Radio type III burst (electron beam leaving Sun) plasma frequency around spacecraft shows Langmuir waves ~1-15 keV electrons produce Langmuir waves

electron event at 1 AU

GOES/RHESSI/Waves observations

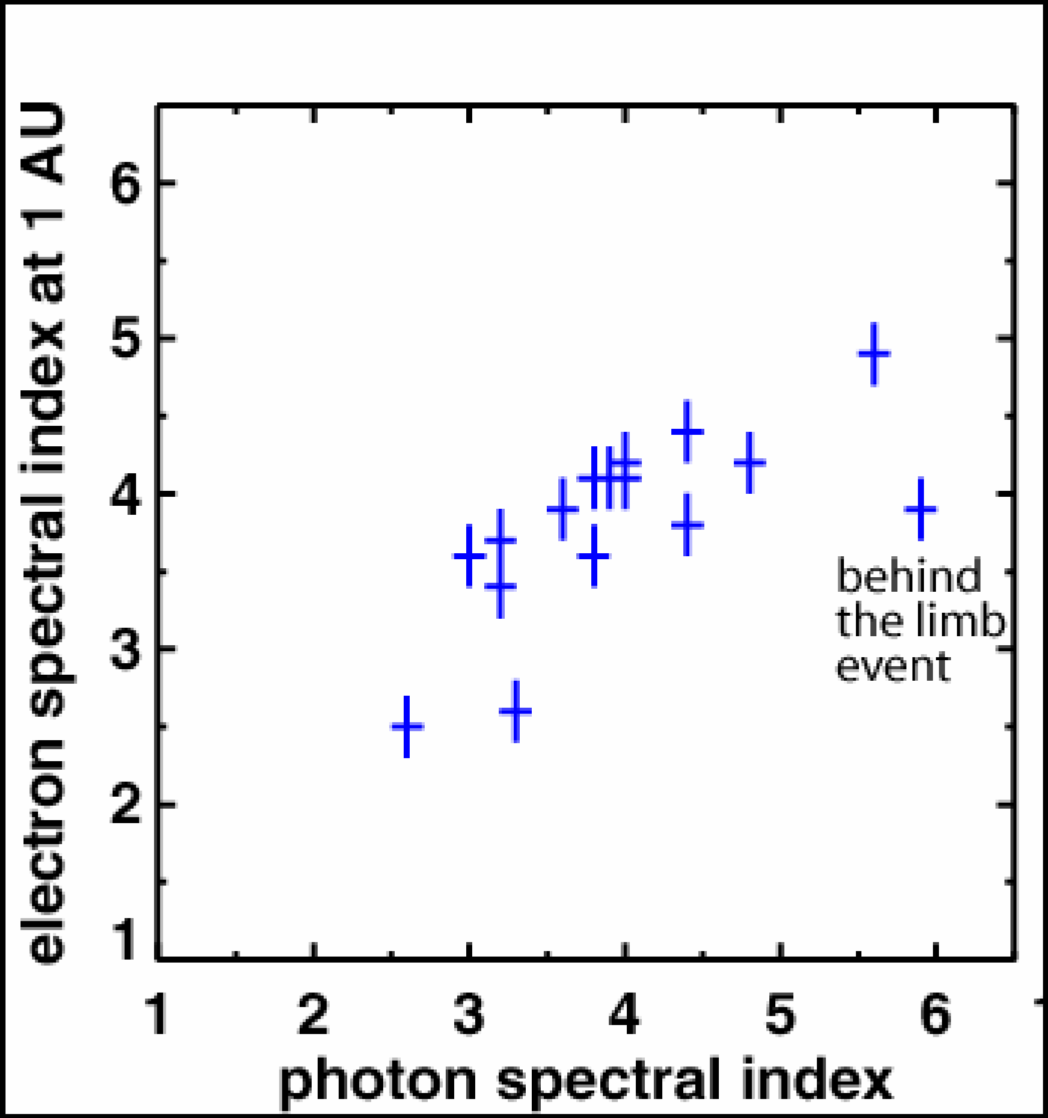


GOES M1 flare

RHESSI spectrogram

WIND/WAVES 1-14 MHz

Comparing spectra

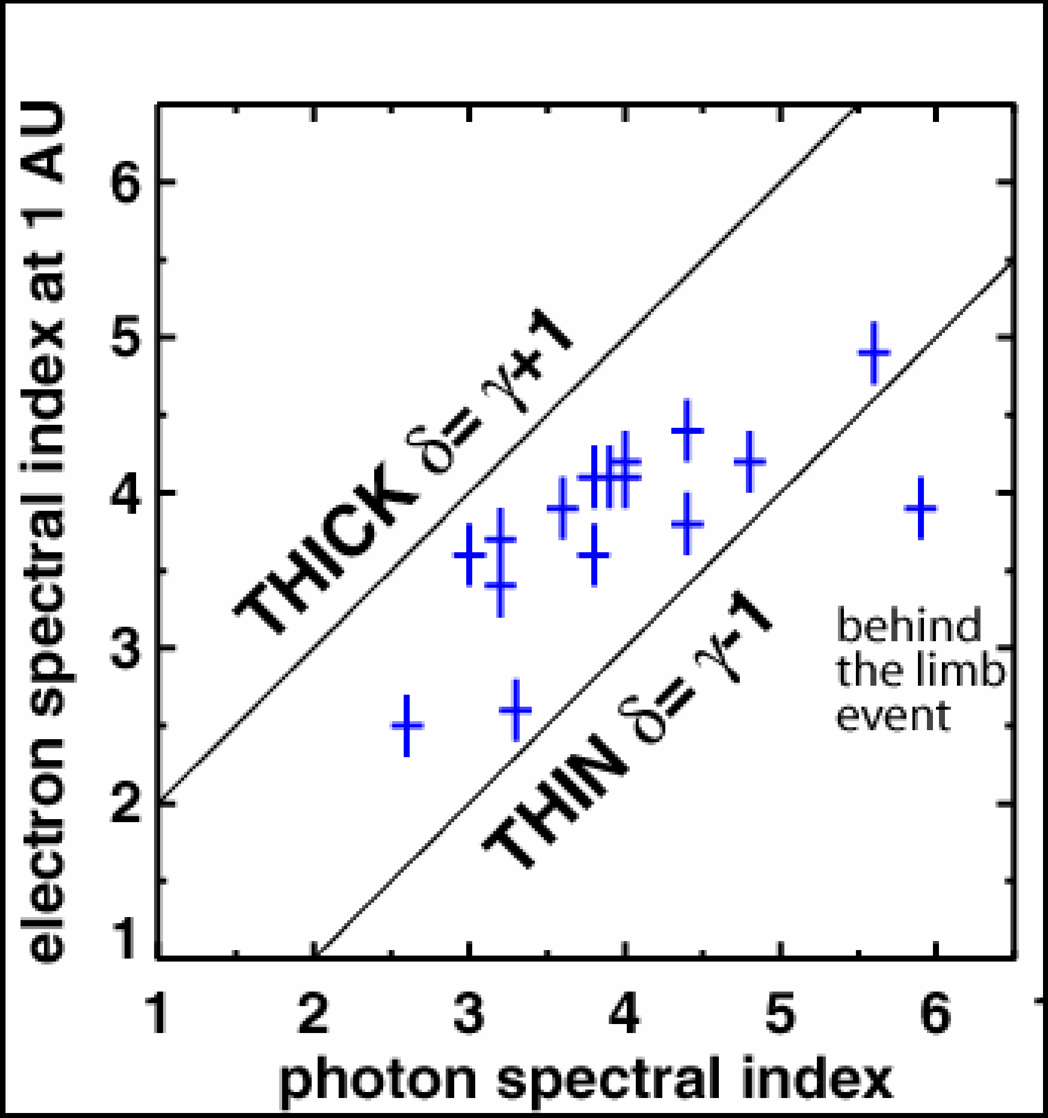


PHOTON SPECTRA:
Power law fit to HXR spectra averaged over peak

ELECTRON SPECTRA:
Power law fit to peak flux

→ rough correlation

Comparing spectra



PHOTON SPECTRA:
Power law fit to HXR spectra averaged over peak

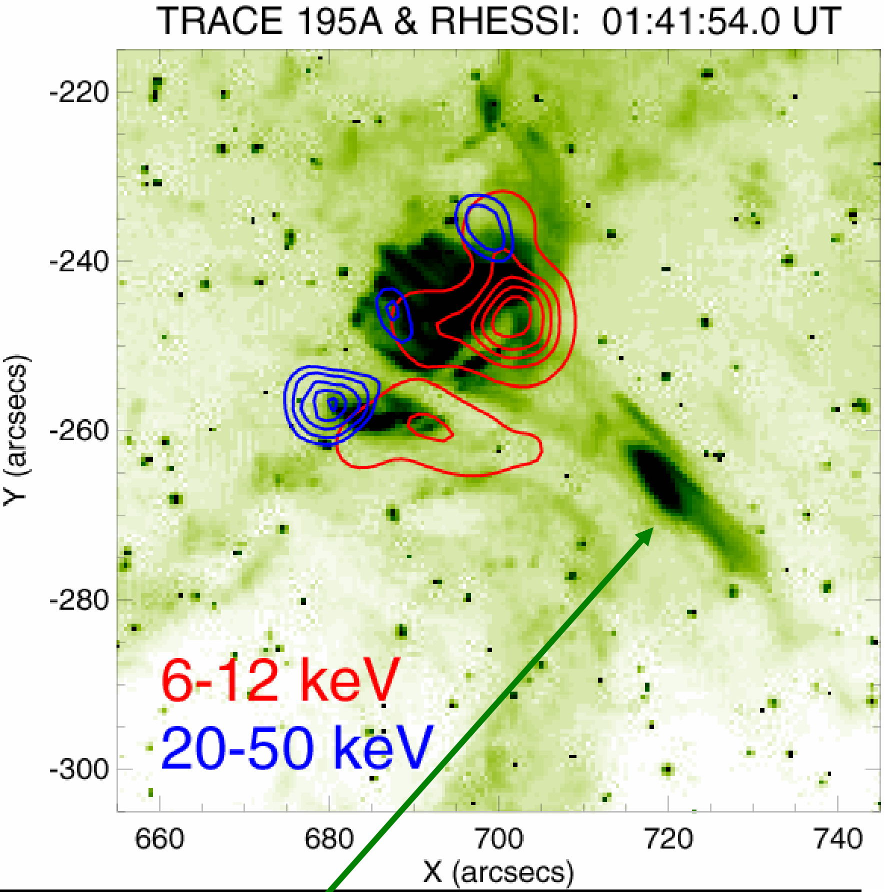
ELECTRON SPECTRA:
Power law fit to peak flux

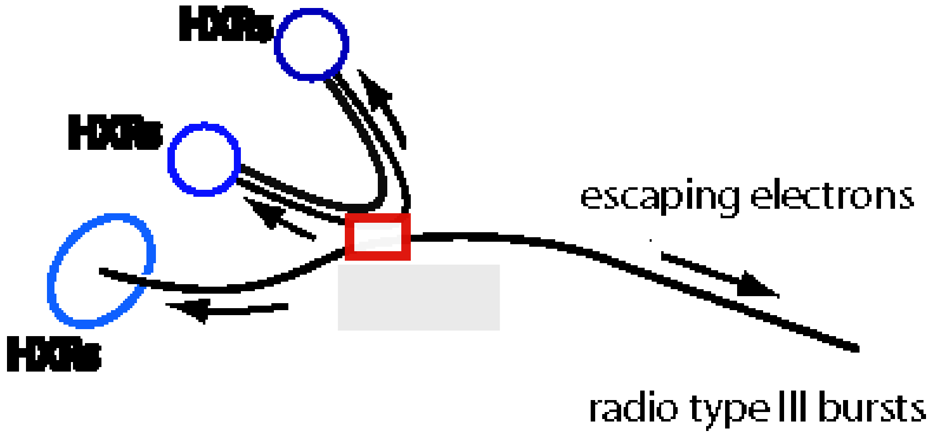
Assuming power spectra:

THIN: $\delta = \gamma - 1$
THICK: $\delta = \gamma + 1$

RESULTS:
1) correlation seen
2) values are between

Solar source region in HXRs & EUV

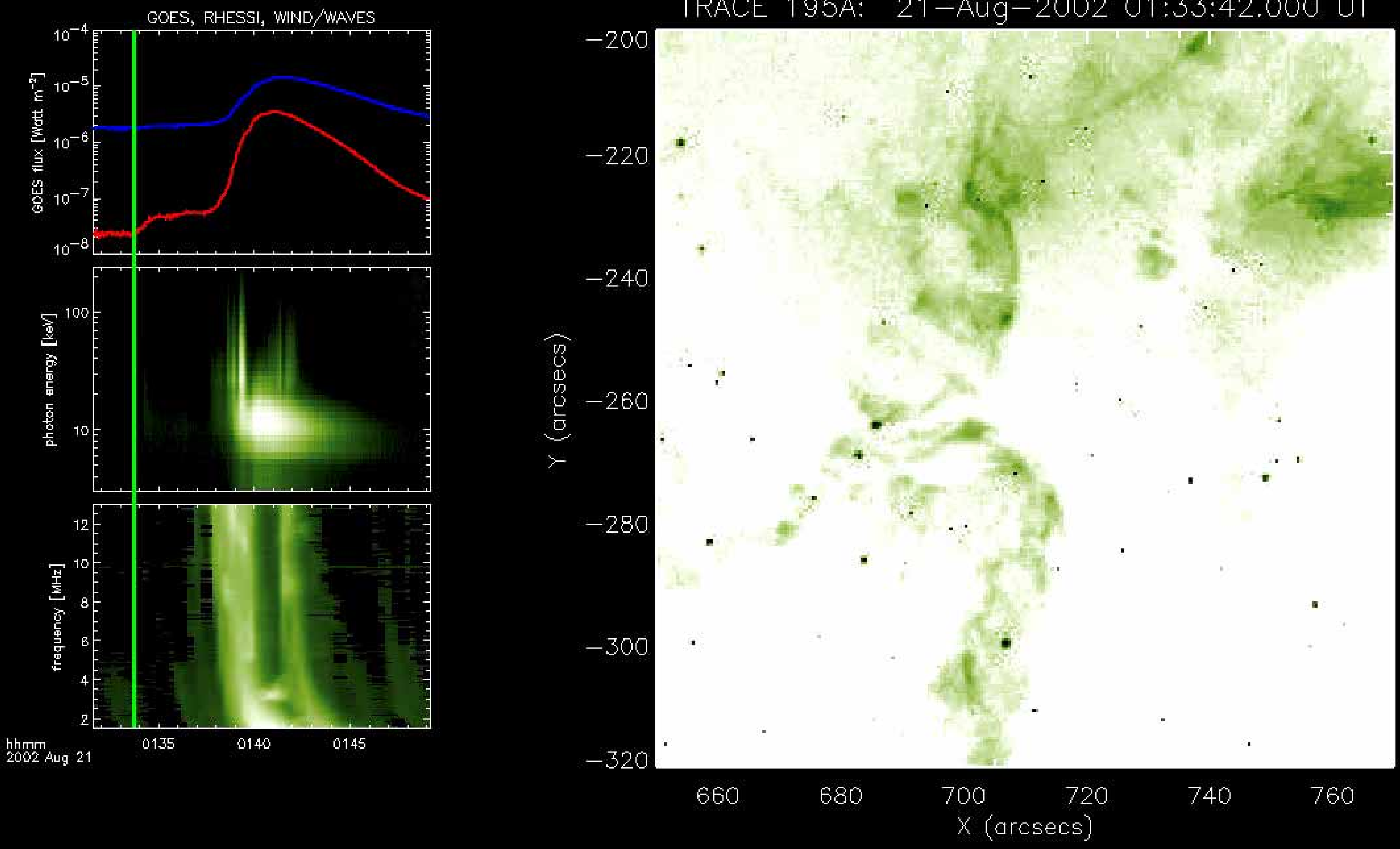




Red box could mark:

1) Escape region of flare-accelerated electrons
2) Reconnection site (interchange reconnection)
3) ?

EUV jet suggests existence of open field lines.



GOES, RHESSI, WIND/WAVES
GOES flux [Watt m^-2]
photon energy [keV]
frequency [MHz]
hhmm
2002 Aug 21
0135
0140
0145
TRACE 195A: 21-Aug-2002 01:33:42.000 UT
Y (arcsecs)
X (arcsecs)