Non-thermal electron rate at loop-top and foot-point sources of solar flares: implications for electron acceleration

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Introduction

X-ray flare images: Yohkoh and RHESSI

Thermal coronal source: E < ~10keV
Non-thermal chromospheric sources (foot-points): E > 20keV
Non-thermal coronal source E > ~20keV

Many authors investigated the photons intensity and/or spectral index of loop-top and foot-point sources.
Some examples:
Petrosian et al. (2002): 18 Yohkoh events
Battaglia & Benz (2006): 5 RHESSI events
Tomczak & Ciborski (2007): 117 Yohkok events

Differences and evolution of photons counts and spectral index of the sources

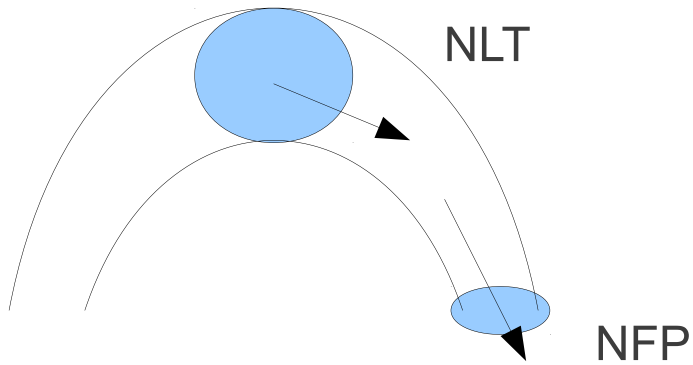
So far, no estimative of the **number** of electrons at the non-thermal loop-top source were attempted.

Introduction

Ideally, one could infer the electron rate the the loop-top and foot-points and verify how these values change over time.

With RHESSI, we can try to estimate the electron rate integrating over a long time (entire impulsive phase): counts needed.

Assuming that the acceleration region is small (point):
Electron rate at LT is due to trapped + precipitating population
Electron rate at FP is due to precipitating population



R = NLT / NFP

R=1 traditional thick-target model (beam streaming down towards foot-points)
R>1 partial trapping (magnetic trap, pitch-angle scattering)
R<1 “then we have a problem” (Marina Battaglia, last week)

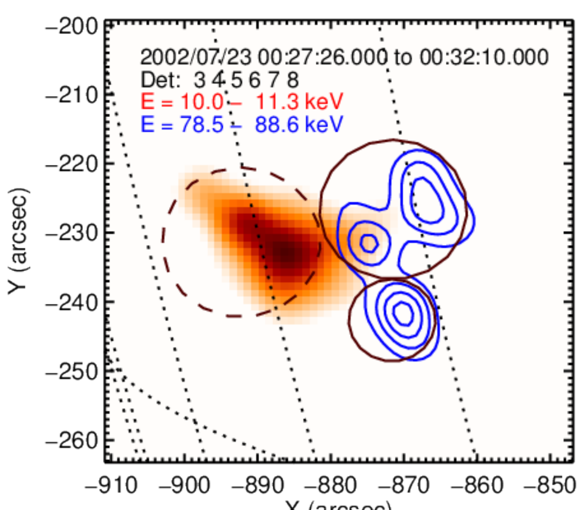
Outline

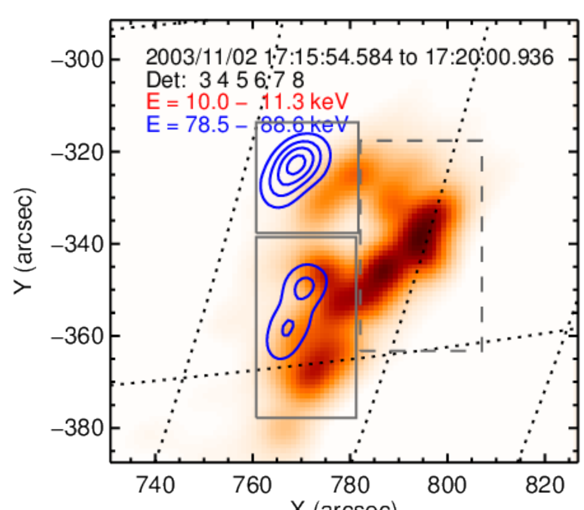
1. Select flares with a spatially resolved non-thermal loop-top source
2. Imaging spectroscopy: modeling thin (LT) and thick-target (FP) sources
3. Measure source sizes
4. Calculate the electron rate
5. Discuss the implications of the results

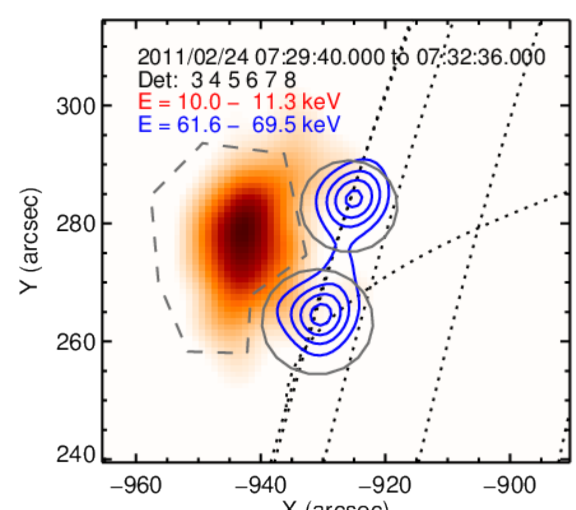
Flare Selection

Events with resolved loop structure (loop-top and foot-point sources)
No overlapping of the sources
Strong events: enough counts for imaging spectroscopy
Non-thermal loop-top source resolved.

Flare	A	B	C	D
Date	2002-07-23	2003-11-02	2011-02-24	2011-09-24
Time	00:27:26	17:15:54	07:29:40	09:35:53
Δt [s]	284	246	176	82
GOES	X8.3	X4.8	M3.5	~X1.9







Methodology

CLEAN images
- detectors 3 to 8
- 19 energy bins 10-100keV (log-spaced)

clean_beam_width: visibility forward-fitting of foot-points

Imaging spectroscopy:
Foot-points: thermal + thick-target
Loop-top: thermal + thin-target

Non-thermal models set as single power-law with fixed energy range (Emin=20keV)

Results:
Thick-target
Electron spectral index and integrated electron rate (NFP electrons/s)

Thin-target
Electron spectral index and the product <nVF> (electrons /cm^2/s)

Calculate electron rate at looptop (need plasma density *n* and source size *L*)

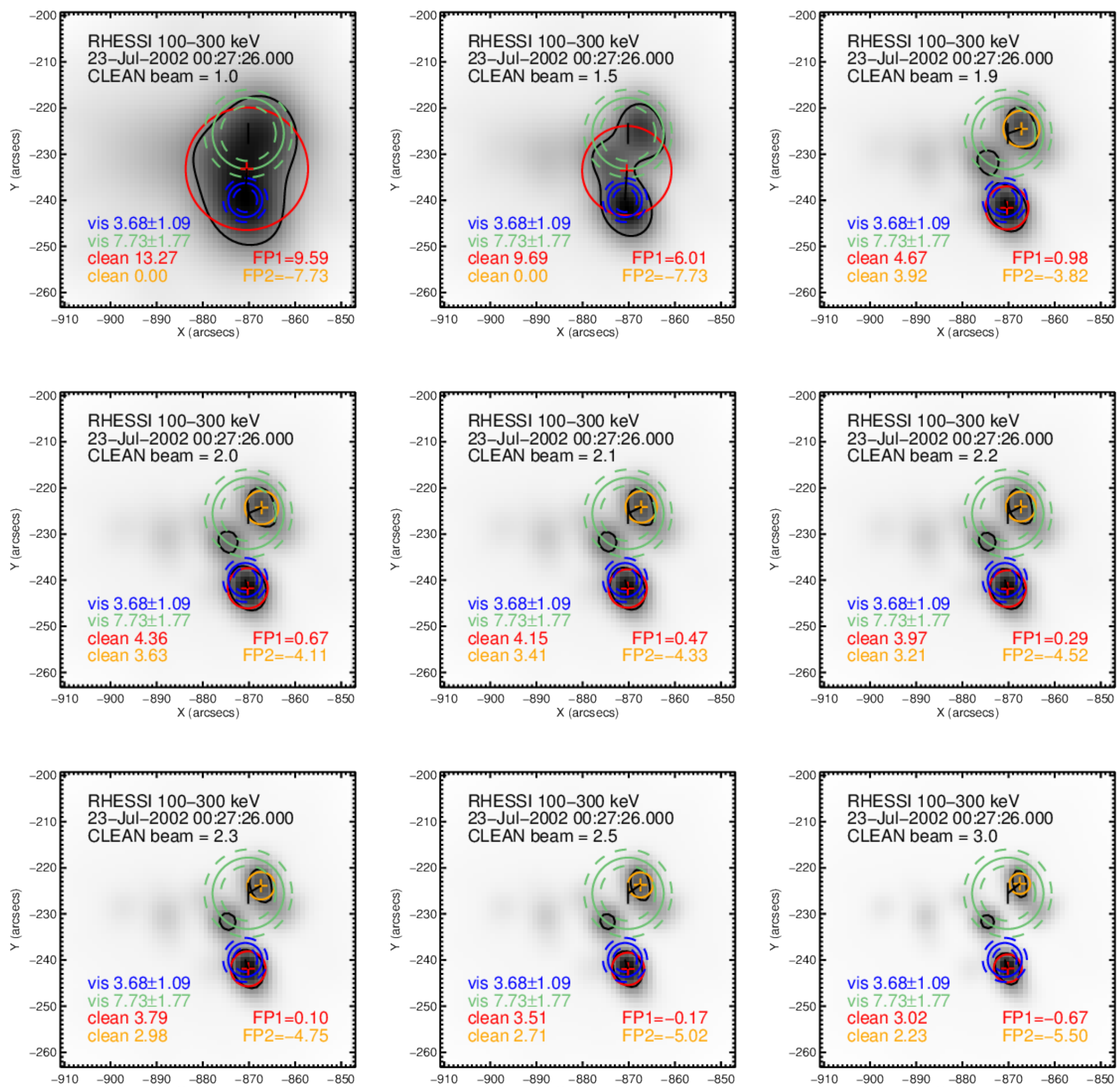
$$\dot{N}_{LT} = \frac{< nV\bar{F} >}{nV} S = \frac{< nV\bar{F} >}{nL},$$

Finding CLEAN beam width factor

Comparing CLEAN and visibility forward fitting: footpoint size

2002 July 23

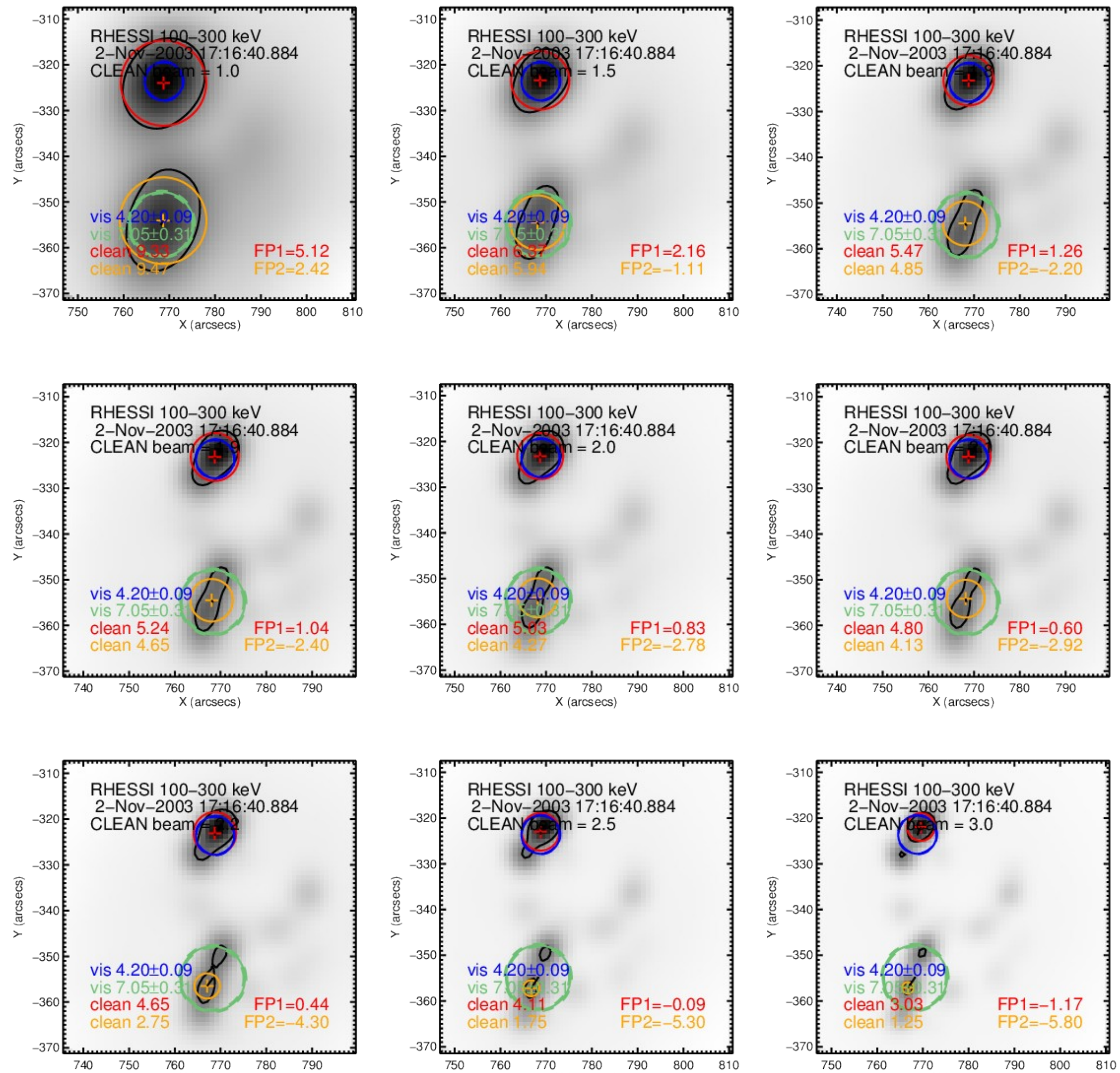
Beam width factor = 2.3



Finding CLEAN beam width factor

2003 November 02

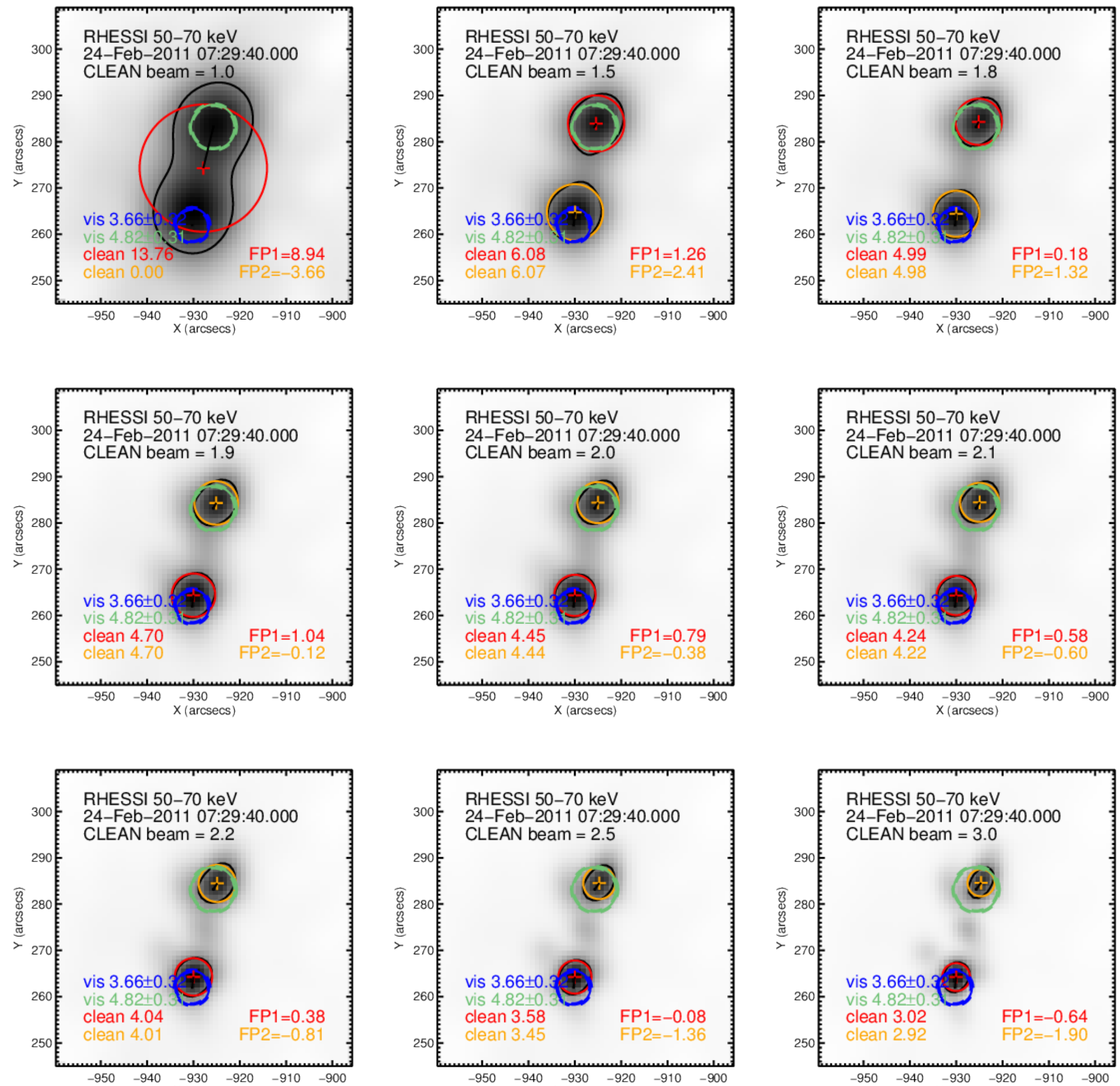
Beam width factor = 2.0



Finding CLEAN beam width factor

2011 February 24

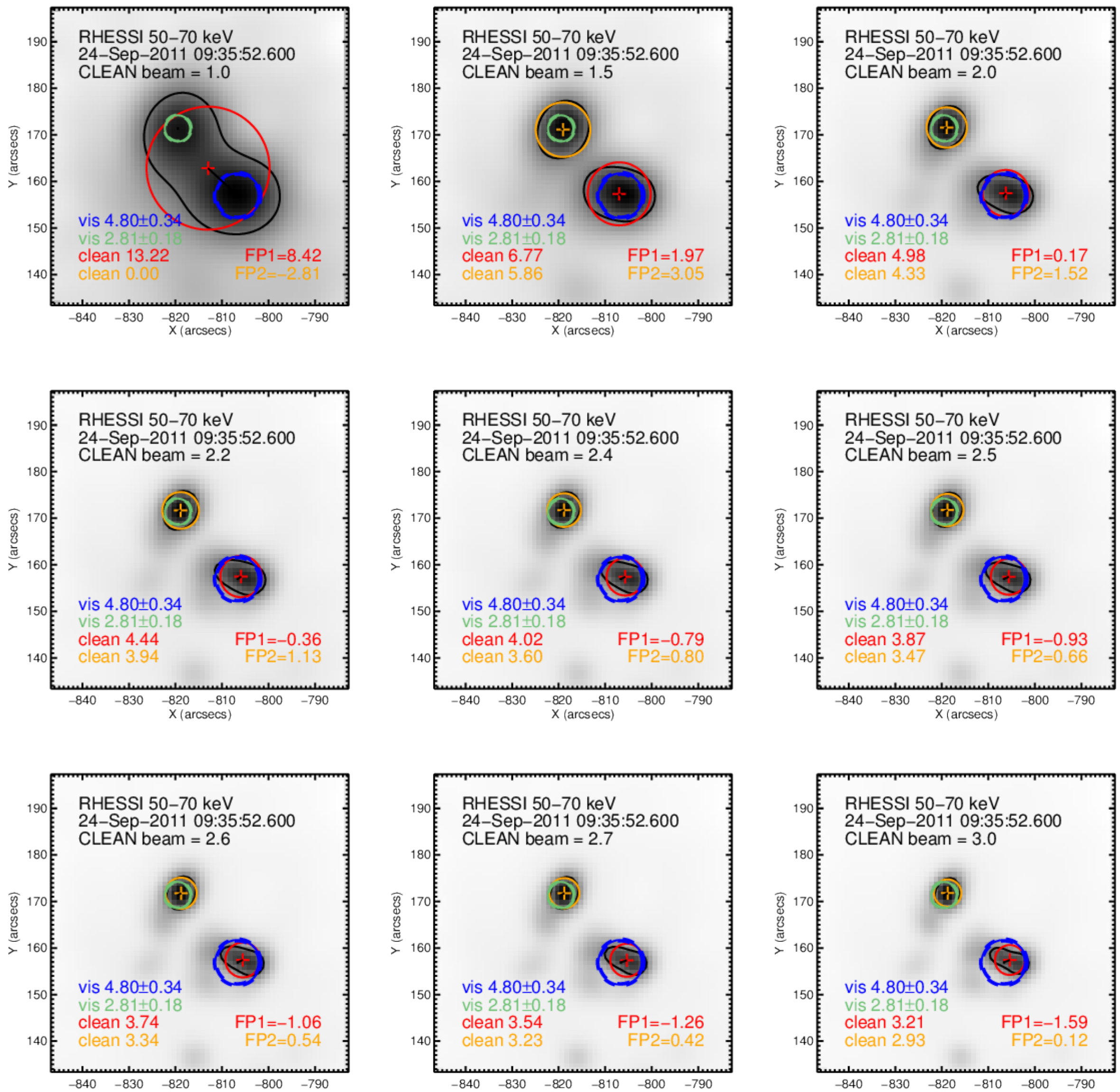
Beam width factor = 1.9



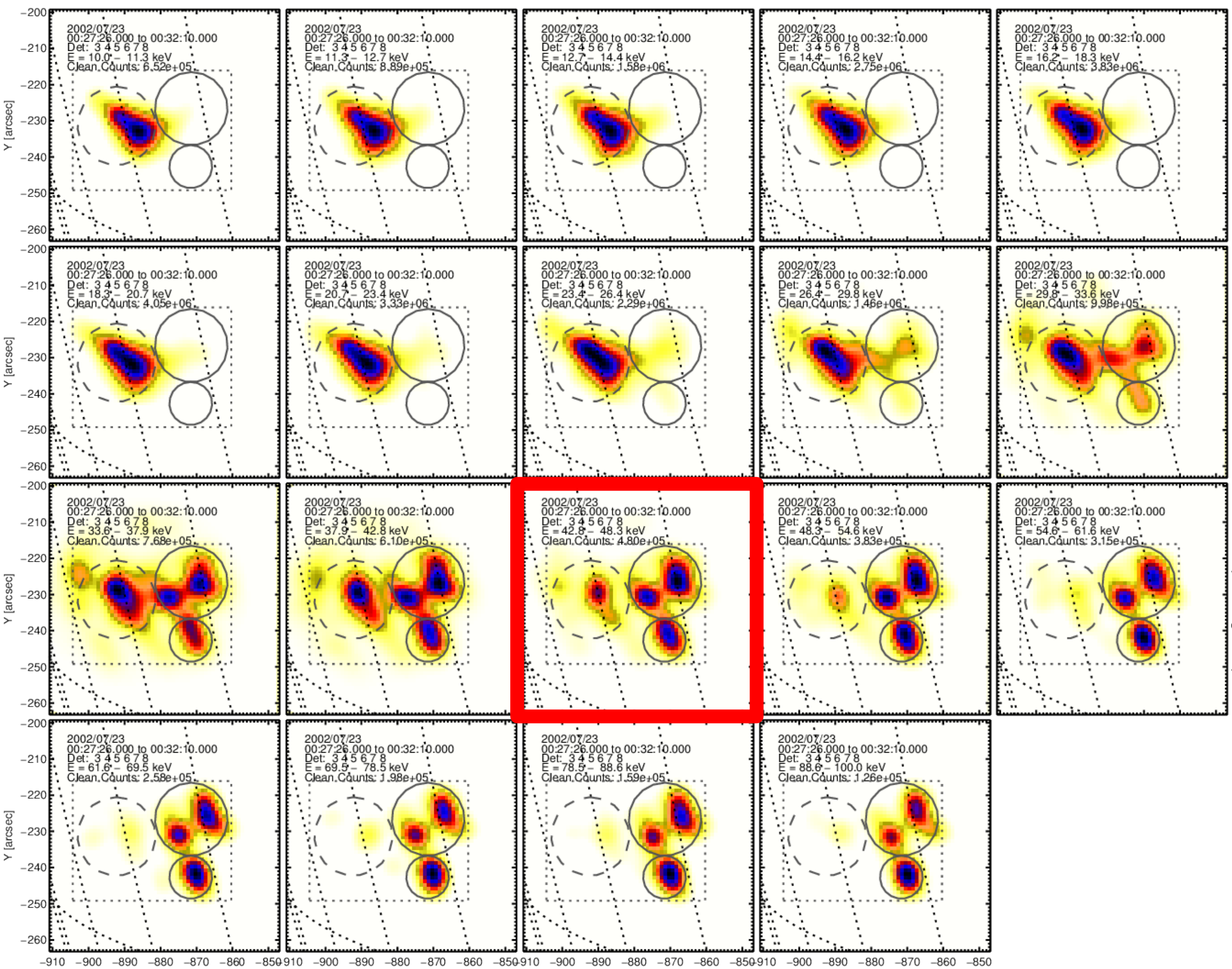
Finding CLEAN beam width factor

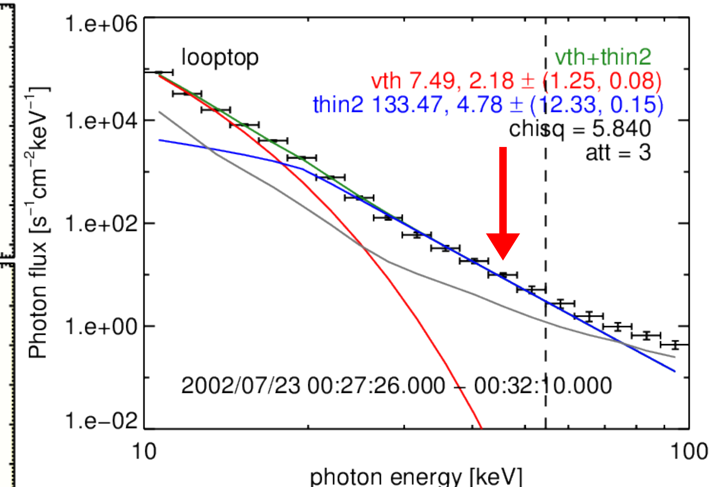
2011 September 24

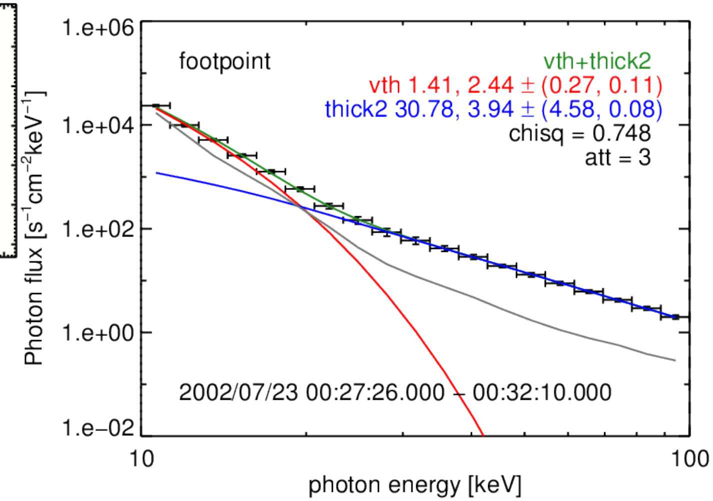
Beam width factor = 2.4



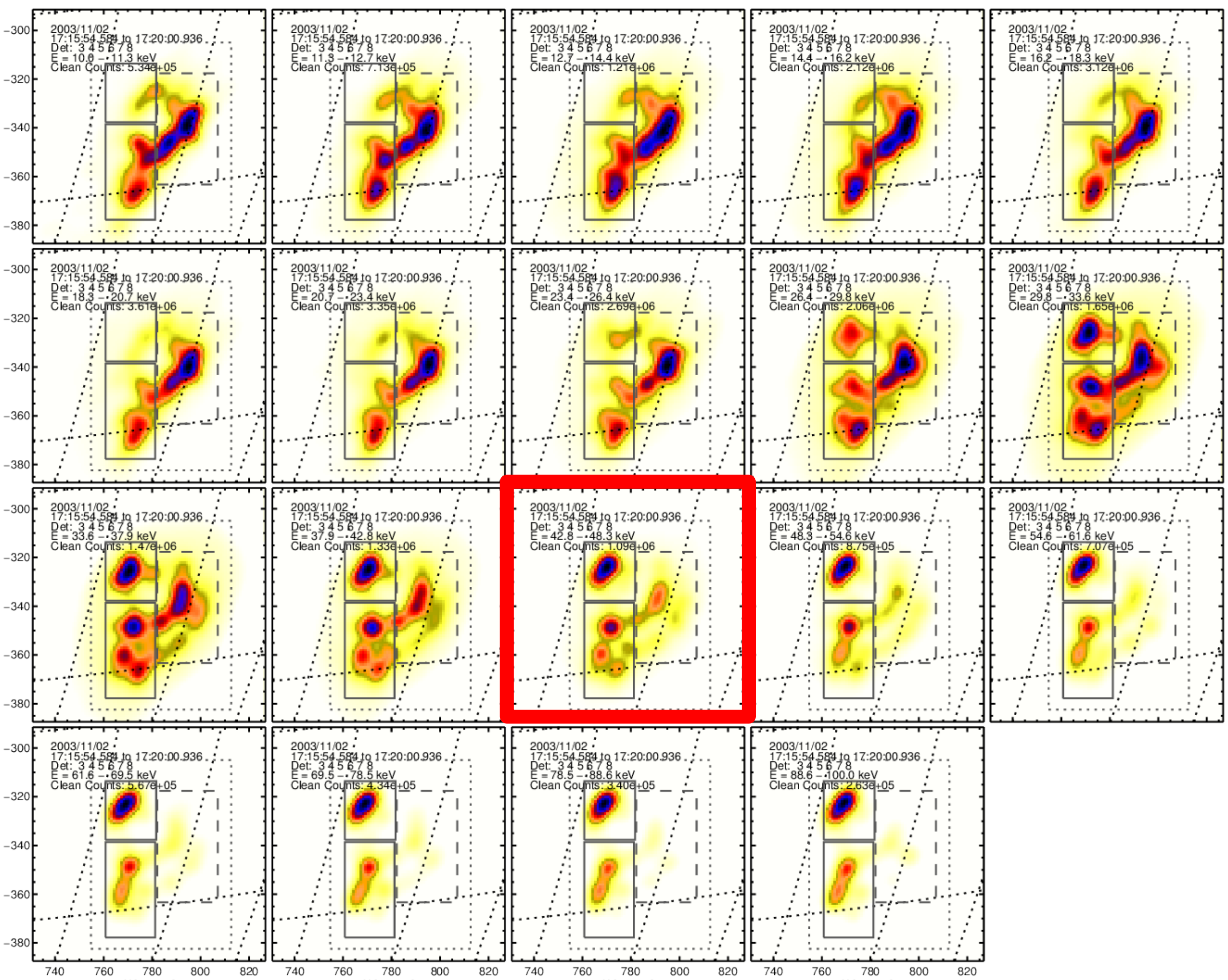
Maps and spectroscopy: 2002-07-23

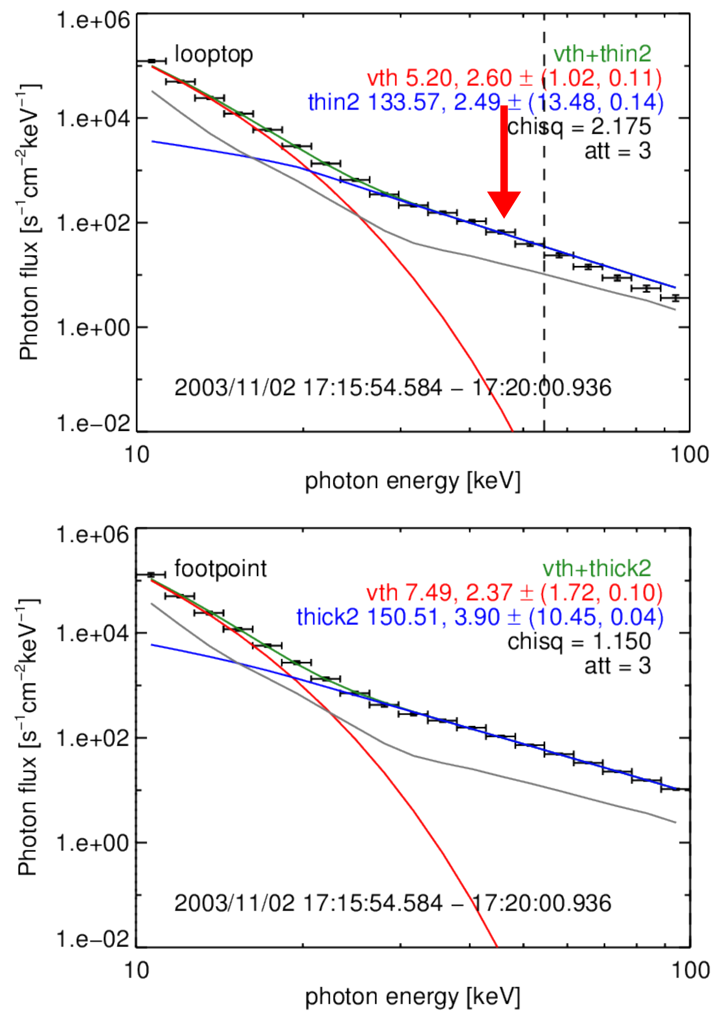




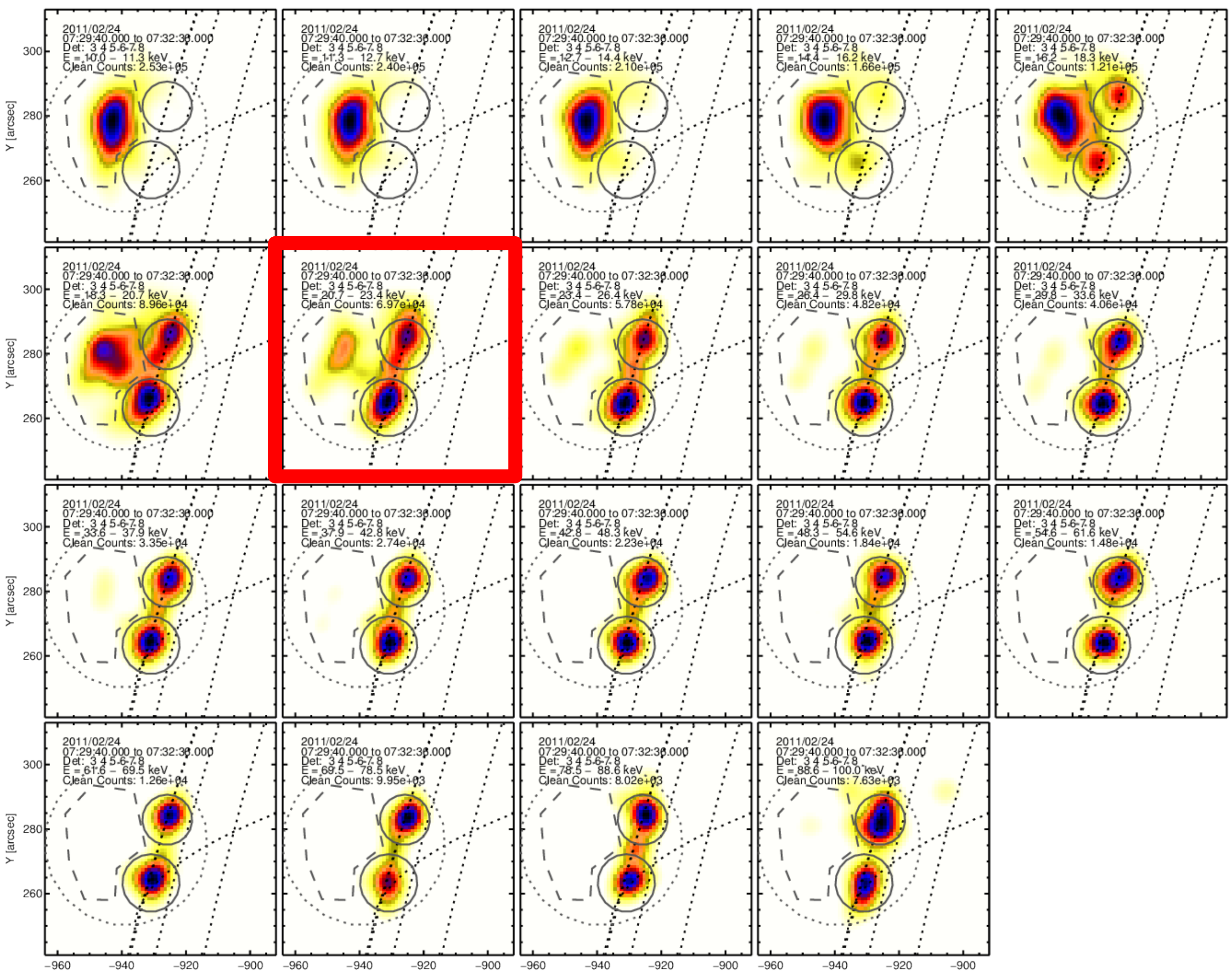


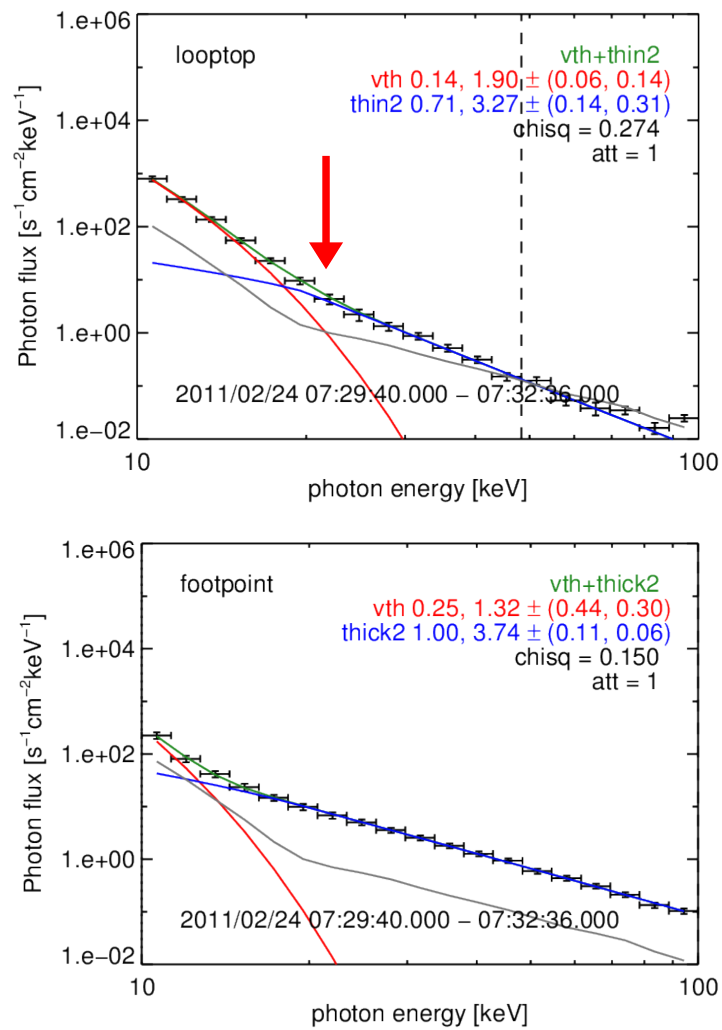
Maps and spectroscopy: 2003-11-02



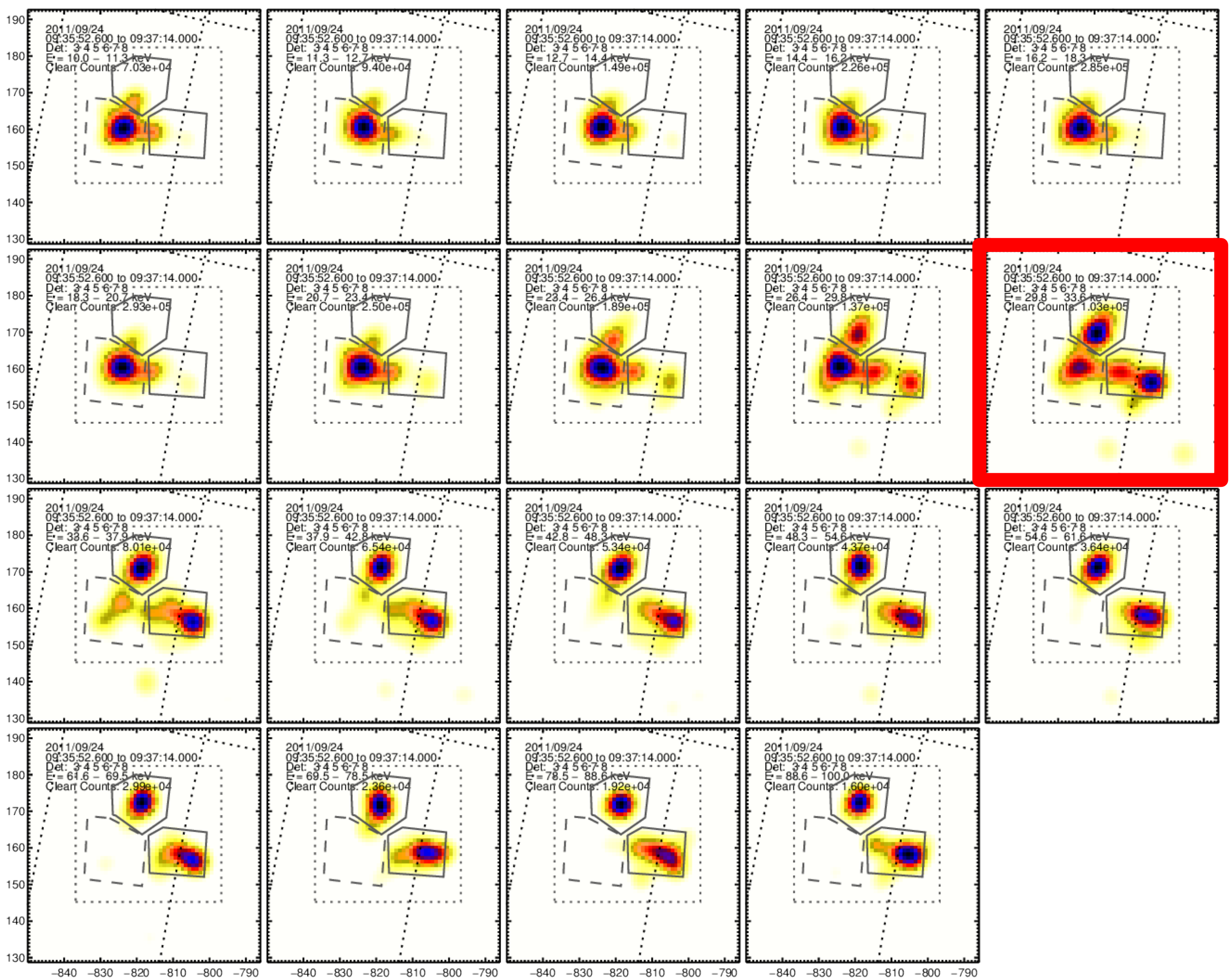


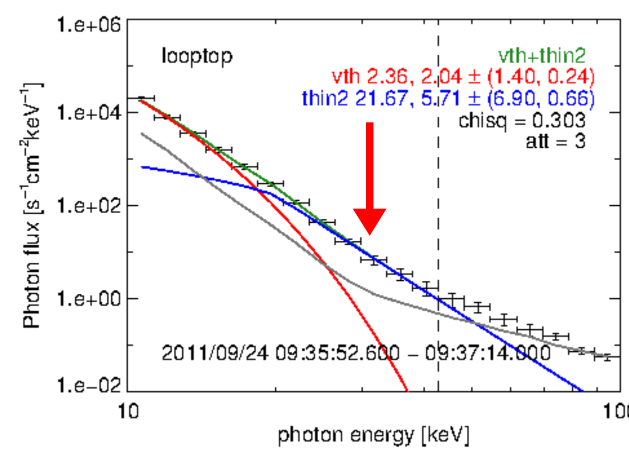
Maps and spectroscopy: 2011-02-24

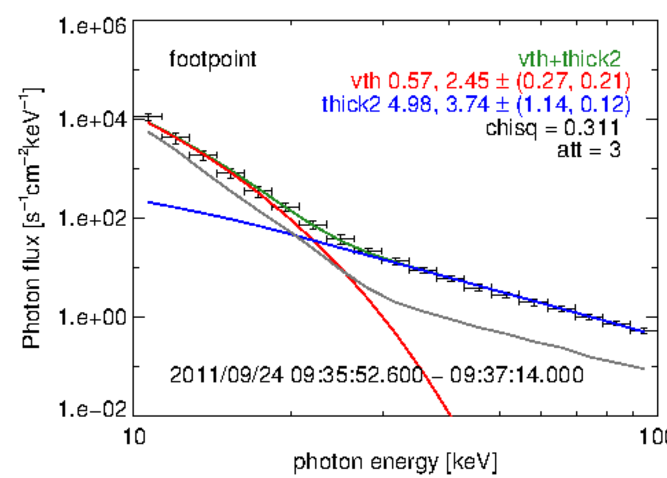




Maps and spectroscopy: 2011-09-24





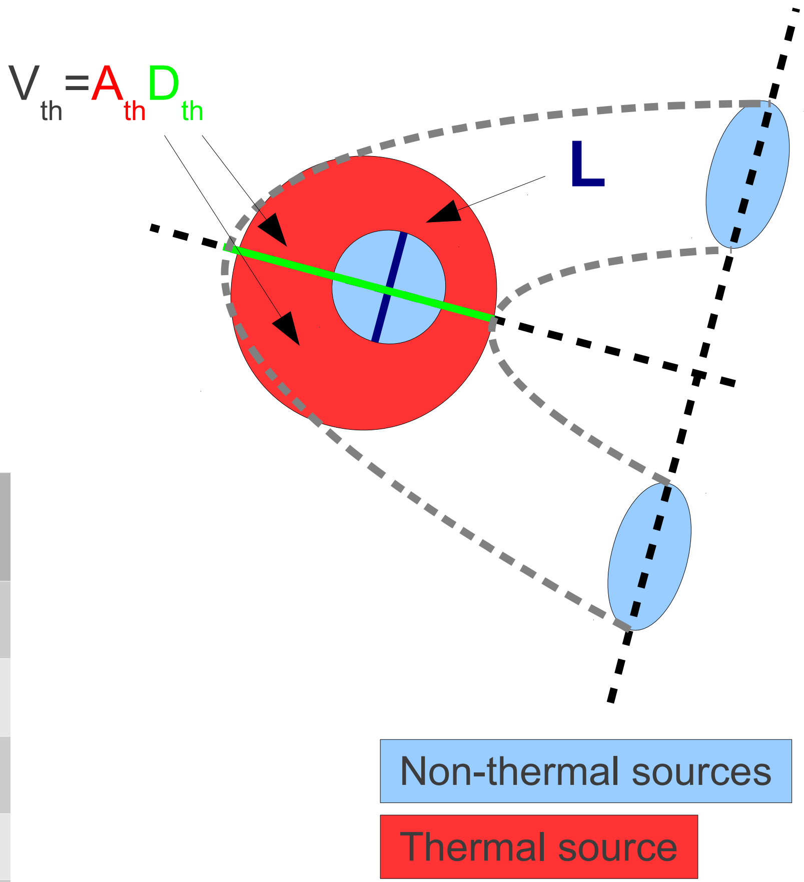


Source geometry

$$\dot{N}_{LT} = \frac{< nV\bar{F} >}{nV} S = \frac{< nV\bar{F} >}{nL},$$

Plasma density

$$EM = n^2 V_{th},$$
$$V_{th} = A_{th} D_{th},$$



	Flare	2002-07-23	2003-11-02	2011-02-24	2011-09-24
A_{th}	10^{18}cm^{-2}	0.57	2.24	0.91	0.34
D_{th}	10^{8}cm	9.7	11.5	8.5	6.0
V_{th}	10^{27}cm^{3}	0.55	2.57	0.78	0.20
L	10^{8}cm	5.18	4.26	8.30	4.7
n	10^{10}cm^{-3}	26	13	6	24

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Results

Flare	2002-07-23	2003-11-02	2011-02-24	2011-09-24
NLT	99.3 ± 14.4	248.2 ± 47.0	1.6 ± 0.4	19.2 ± 6.8
NFP	30.8 ± 4.6	150.5 ± 10.5	1.0 ± 0.1	5.0 ± 1.1
R	**3.2 ± 0.7**	**1.6 ± 0.3**	**1.5 ± 0.4**	**3.8 ± 1.6**
Uncert.	22%	19%	27%	42%

NLT, NFP in electrons/s

R > 1
Partial trapping of electrons:
magnetic trapping, pitch-angle scattering (collisions and/or waves)
Note:

- size of acceleration region unknown;
- pitch-angle distribution unknown;
- magnetic mirror ratio unknown.

R=1
~~Traditional thick-target model~~

R<1
~~“we have a problem”~~

Magnetic trapping

Collisionless magnetic trapping

$$\begin{aligned} I &= T + P \\ T &= \xi I \\ P &= (1-\xi) I \end{aligned}$$

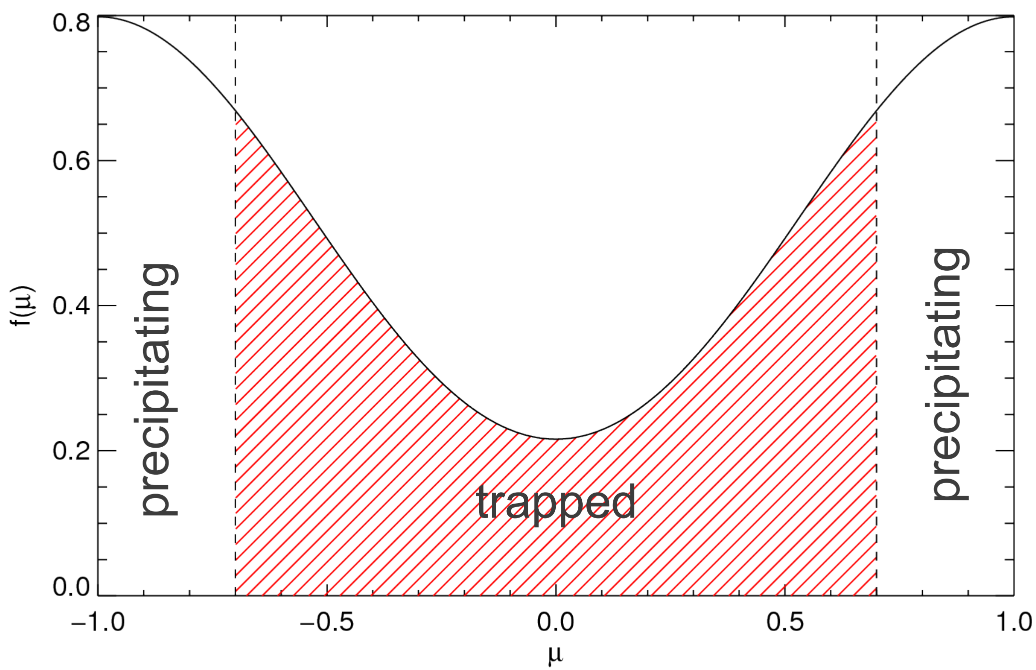
$$\begin{aligned} \dot{N}_{FP} &= P \\ \dot{N}_{LT} &= P + T \end{aligned}$$

$$R = \frac{\dot{N}_{LT}}{\dot{N}_{FP}} = \frac{1}{1-\xi}$$

$$\xi = 1 - \frac{1}{R}$$

$$\frac{T}{I} = \xi = \frac{\int_{-\mu_0}^{\mu_0} f(\mu)d\mu}{\int_{-1}^{1} f(\mu)d\mu}$$

$$\frac{P}{I} = 1 - \xi = \frac{\int_{-1}^{-\mu_0} f(\mu)d\mu + \int_{\mu_0}^{1} f(\mu)d\mu}{\int_{-1}^{1} f(\mu)d\mu}$$



Flare	2002-07-23	2003-11-02	2011-02-24
ξ	0.69	0.38	0.33
σ (iso)	1.9	1.2	1.1
σ (beam)	25	11	10

2 pitch-angle distributions:
Isotropic
Narrow beam along magnetic field

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Pileup

Pileup:

2 photons at E arriving at the same time are counted as one event with 2*E.

Spatially integrated spectra:
correcting pileup gives a difference of 24%, 15% and 1.6% in NFP, for the 3 flares, respectively.
2 X-class flares, 1 M-class flare.

No pileup correction for images.

In our analysis, other uncertainties reach ~20% - 27%, and still R > 1.