What Does a Theorist Want?

Gordon Emslie, OSU

What Do We Tell The Theorists?

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RHESSI Science Objectives

- “RHESSI's hard X-ray imaging spectroscopy provides spectral resolution of ~1 keV, spatial resolution down to ~2 arcsec, and temporal resolution as short as tens of milliseconds. These parameters are, for the first time, commensurate with physically relevant scales for energy loss and transport of the >~10 keV electrons that are believed to contain much of the energy released in the flare.”

RHESSI Science Objectives

- “With RHESSI's high energy resolution, the photon spectrum in each spatial and temporal element can be directly inverted to obtain N(E,**r**,t), the X-ray producing electron number density, as a function of energy (E), position (**r**), and time (t). N(E,**r**,t), together with information on ambient density, magnetic field strength and topology, will allow the electron loss processes to be directly evaluated.”

Determination of Electron Flux

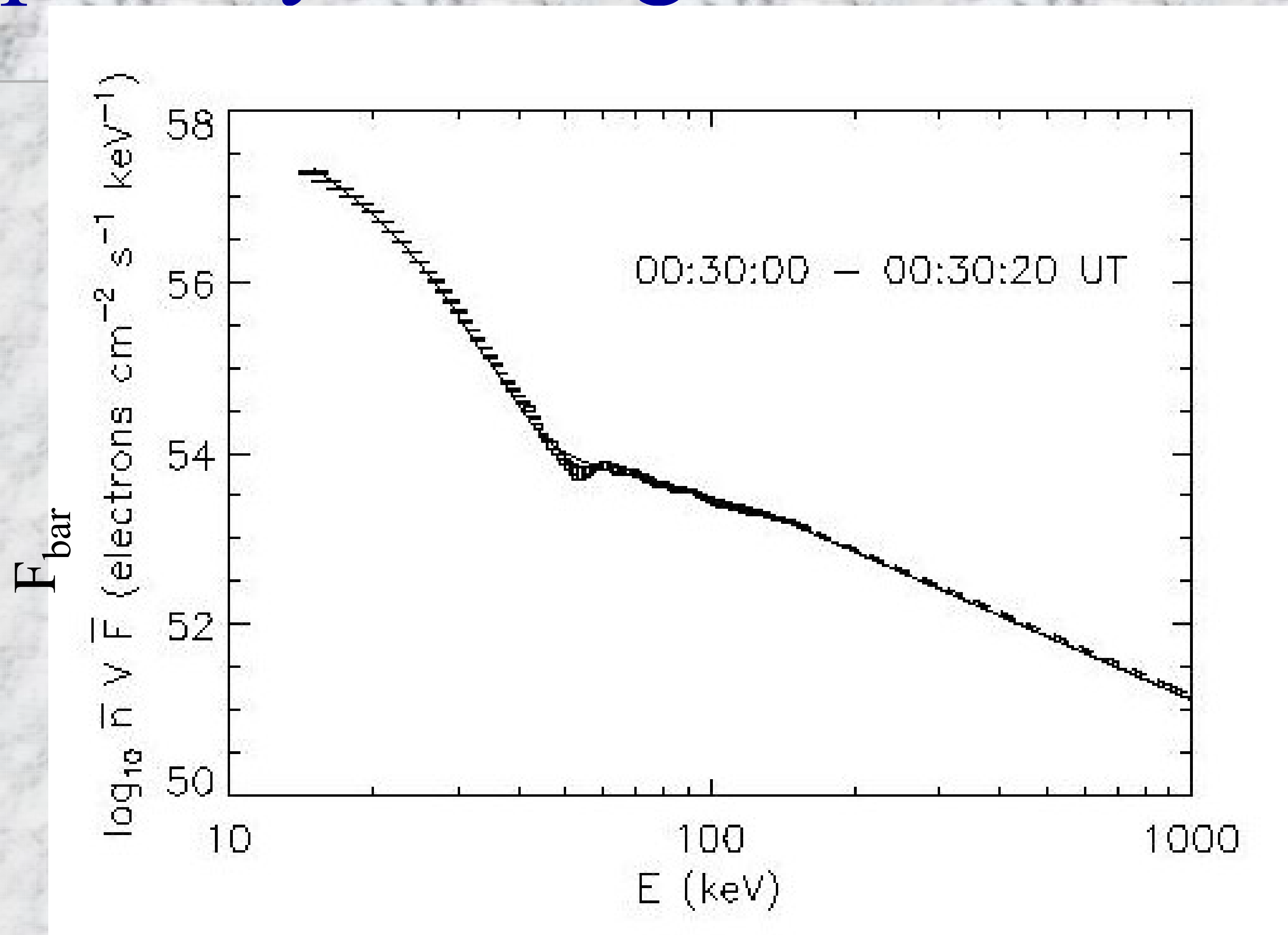
- Hard X-ray flux =
- Local Electron flux $F(E) \times$ (cross-section $\sigma(\varepsilon,E)$ for hard X-ray emission)
- more accurately:

$$I(\varepsilon) = \int F(E)\, \sigma(\varepsilon,E)\, dE$$

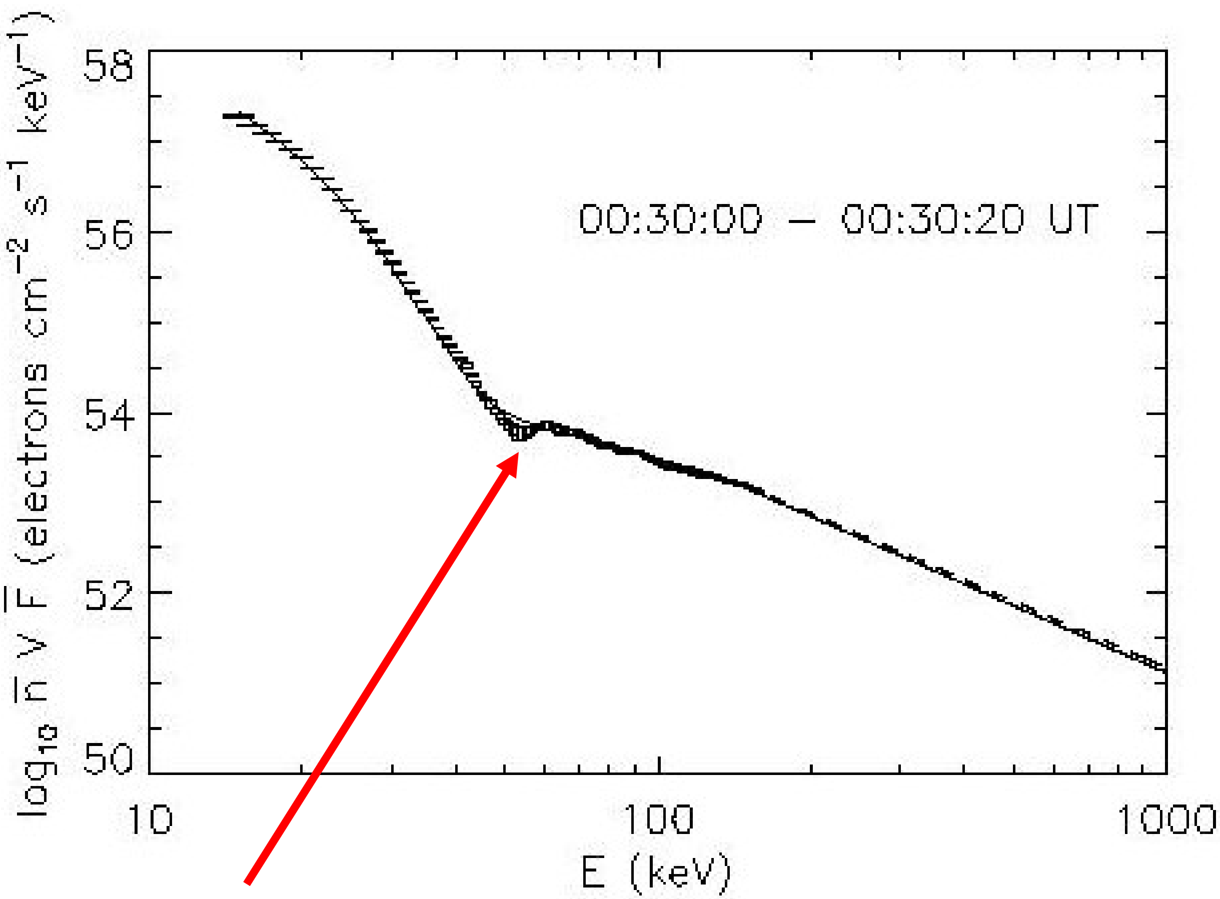
  - an integral equation for $F(E)$ given $I(\varepsilon)$
- $F(E)$ represents *average* over spatial 'pixel"
- For spatially integrated $I(\varepsilon)$,

$$I(\varepsilon) = \int F_{bar}(E)\, \sigma(\varepsilon,E)\, dE$$

Spatially Averaged Electron Flux

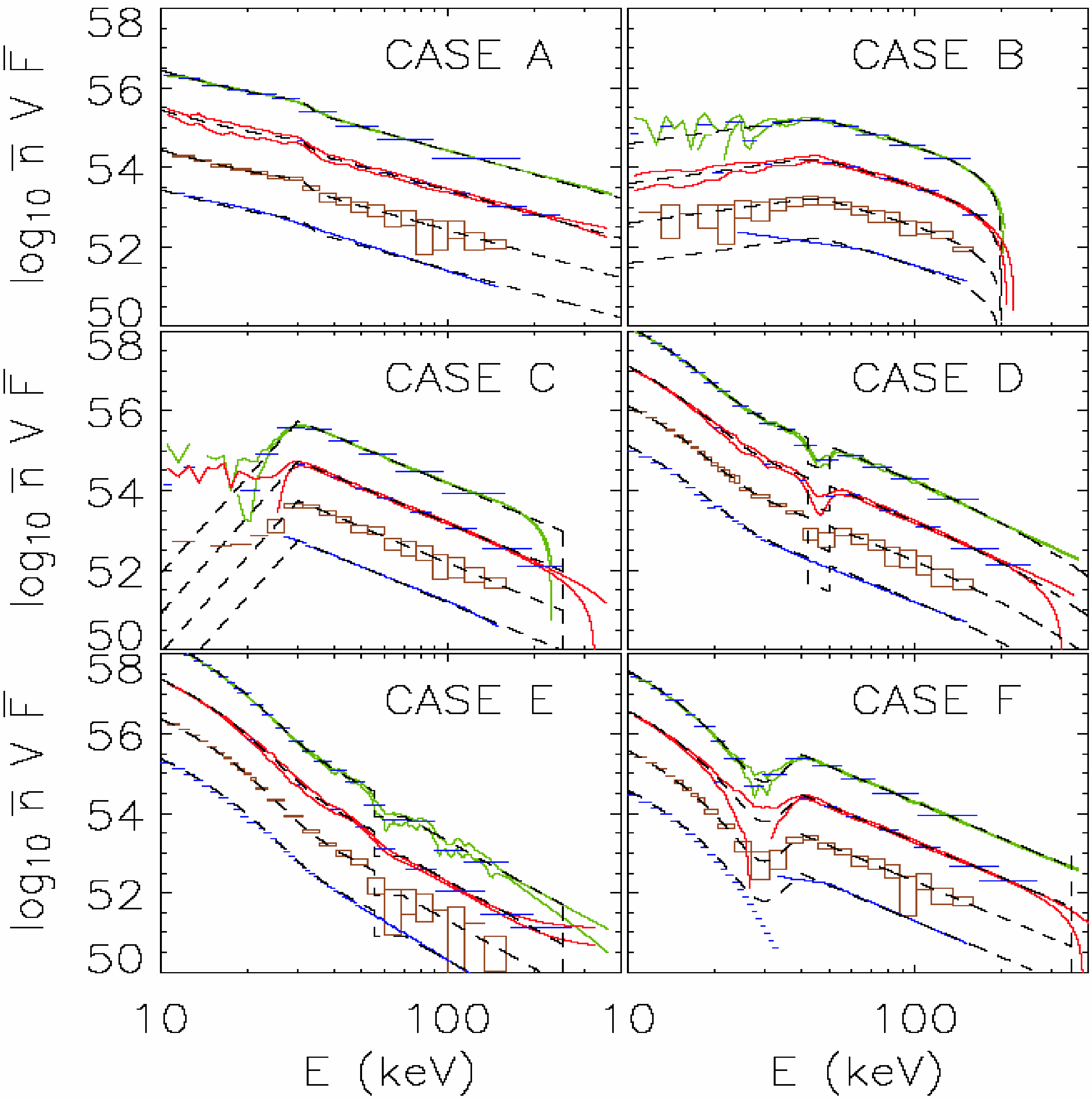


Spatially Averaged Electron Flux



F_{bar}

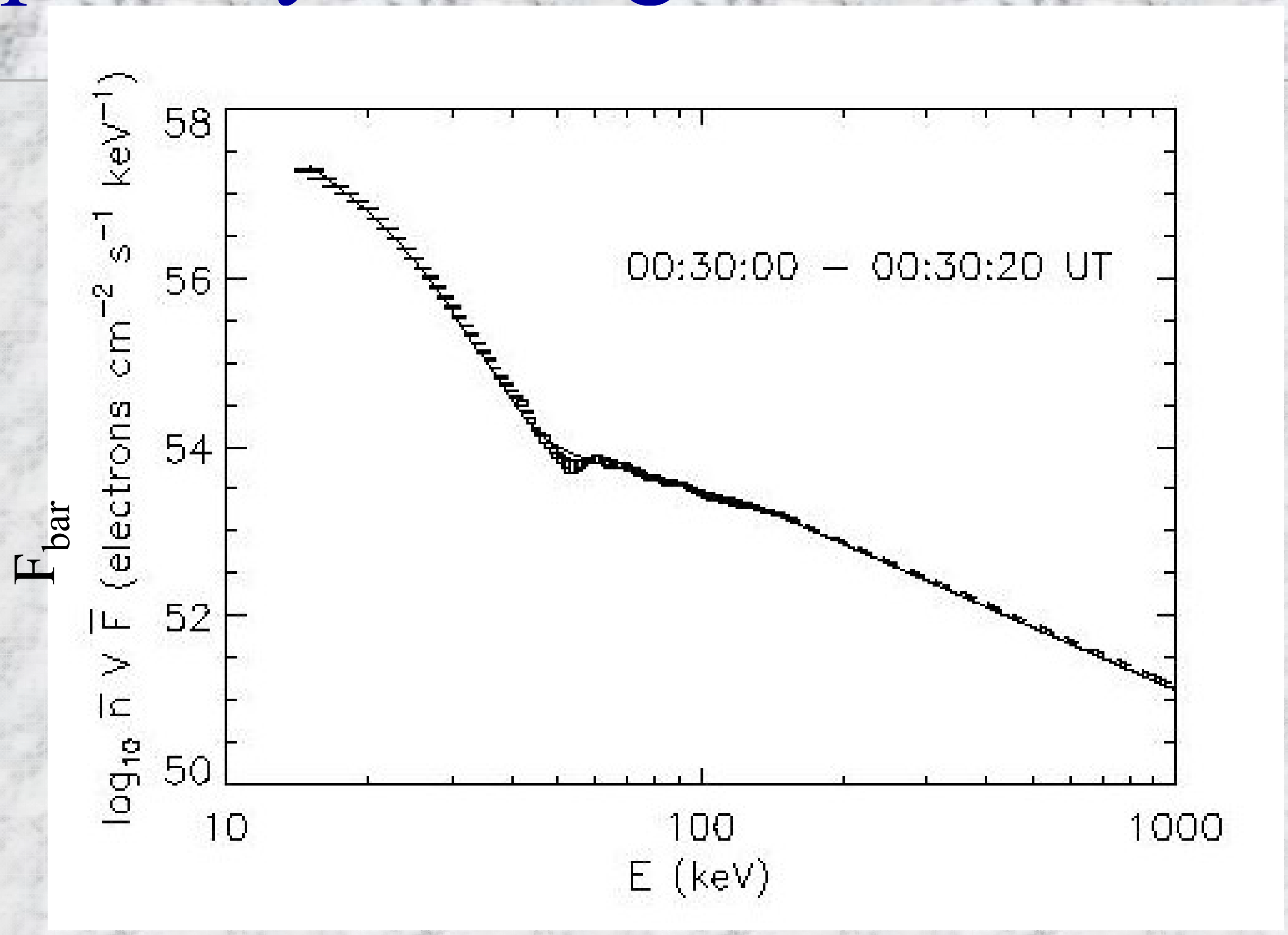
Real feature or not?


CASE A
CASE B
CASE C
CASE D
CASE E
CASE F
$\log_{10} \bar{n} V \bar{F}$
E (keV)

What do we Tell the Theorists? (1)

- We *can* infer subtle and/or significant features in the exciting emitting electron spectrum from hard X-ray observations
- The general absence of such features in recovered mean source electron spectra from actual avents implies that they do not exist
- *Mean source* electron spectra have generally simple forms

Spatially Averaged Electron Flux



But what does F(E) look like at different positions in the source?

Using Spatially Resolved Hard X-ray Data to Infer Physical Processes

- Electron continuity equation:

$$\partial F(E,N)/\partial N + \partial/\partial E\,[F(E,N)\,\mathbf{dE/dN}] = 0$$

- Solve for dE/dN:

$$\mathbf{dE/dN} = -\,[1/F(E,N)] \int [\partial F(E,N)/\partial N]\,dE$$

- So observation of F(E,N) gives ***direct*** empirical information on physical processes (**dE/dN**) at work

Parametric Study

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Suppose

$dE/dN \sim E^{-\alpha}$

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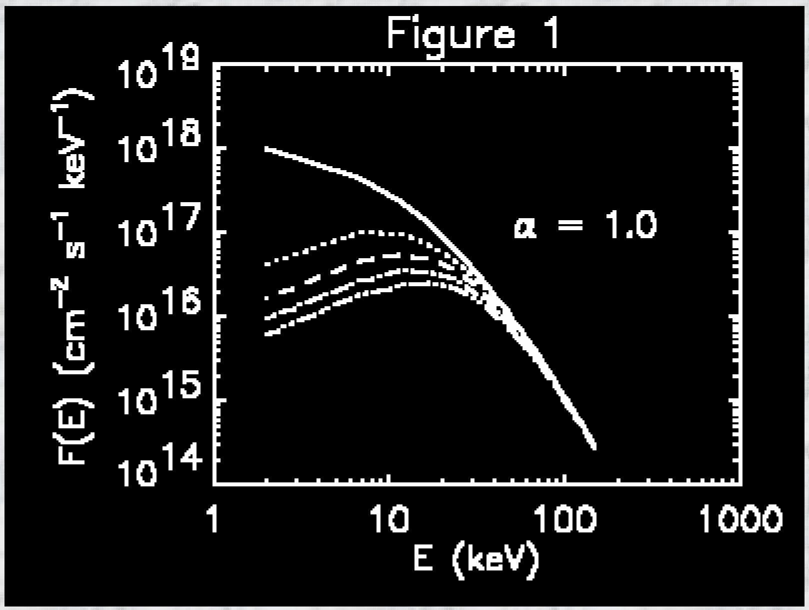
- Then variation of F(E) with depth is as shown



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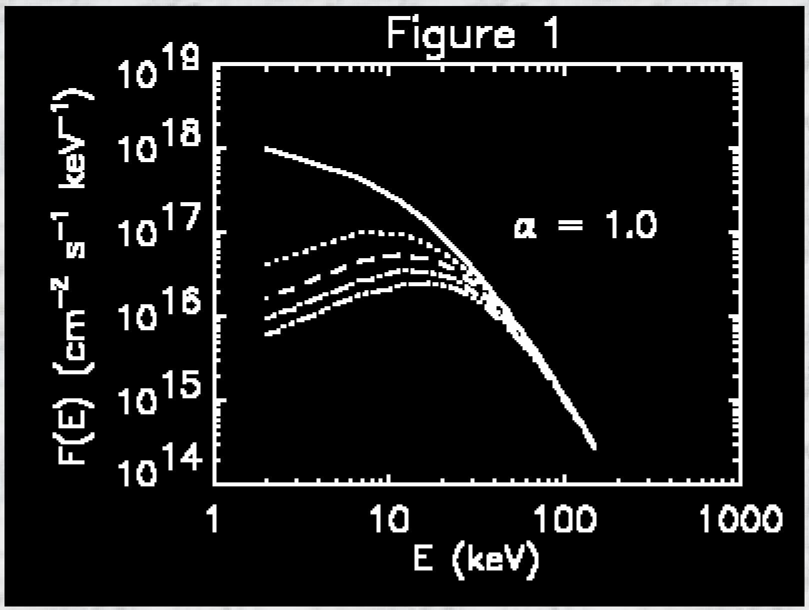

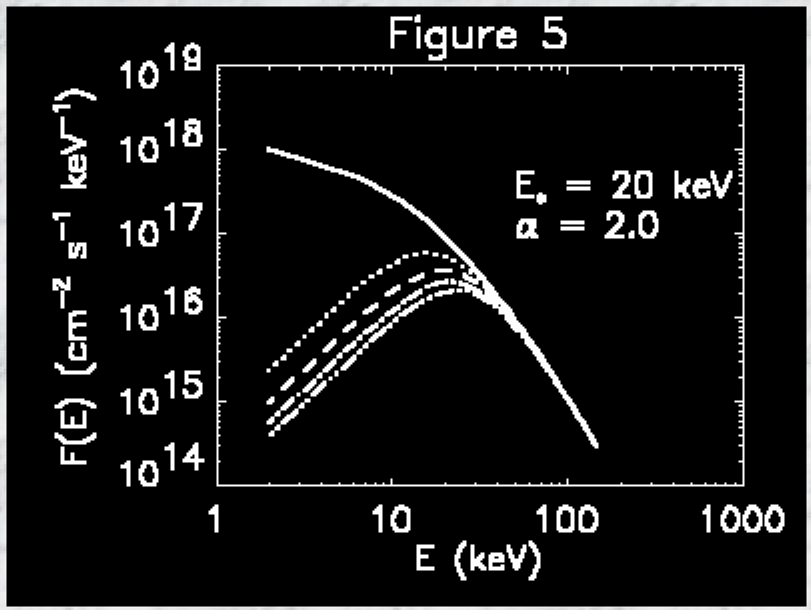

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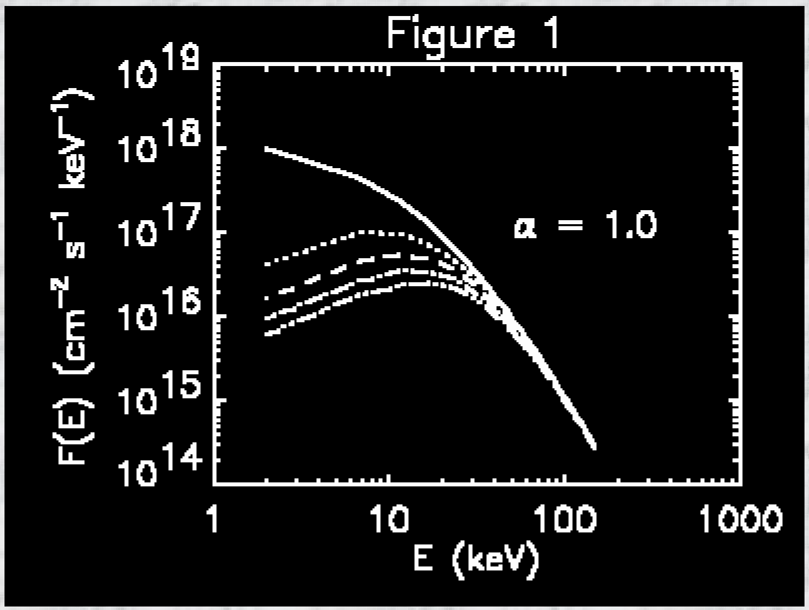
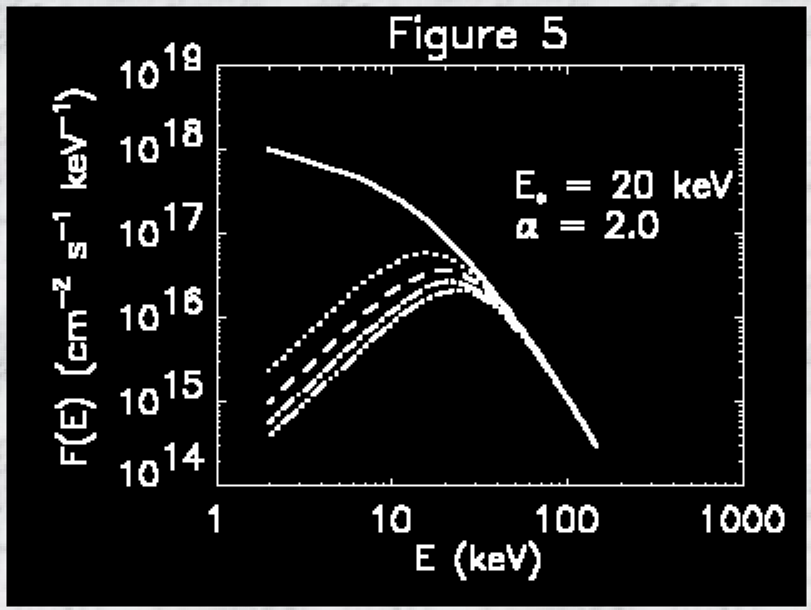




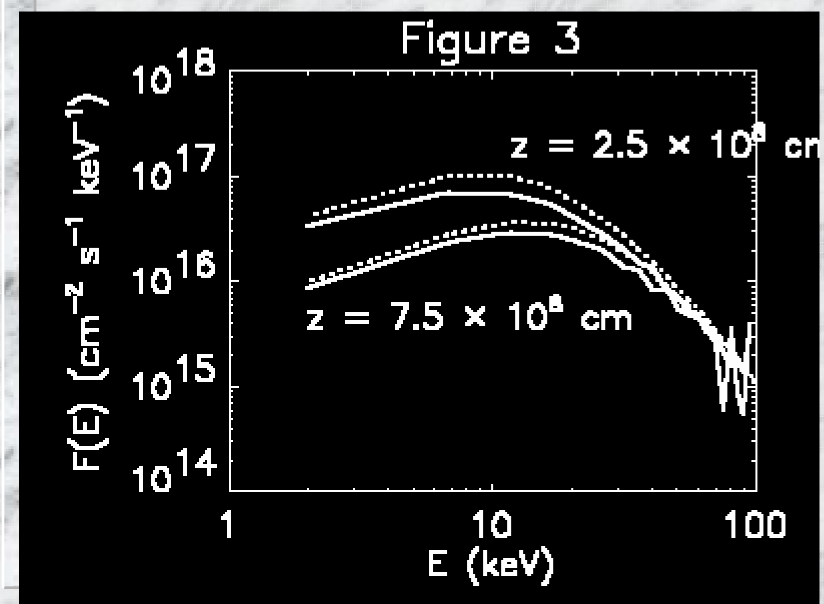
Can we recover the value of α from observations?

Parametric Study

- Construct local hard X-ray spectra from F(E)

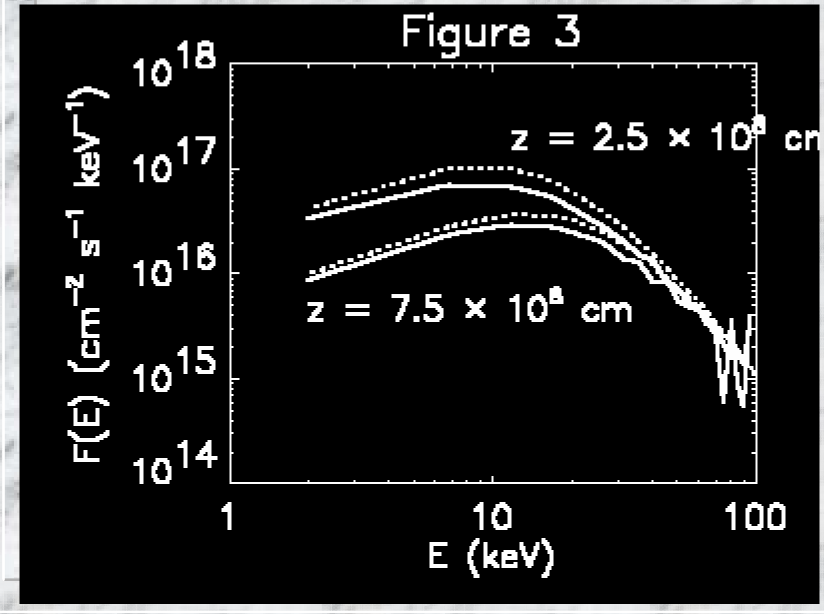
Parametric Study

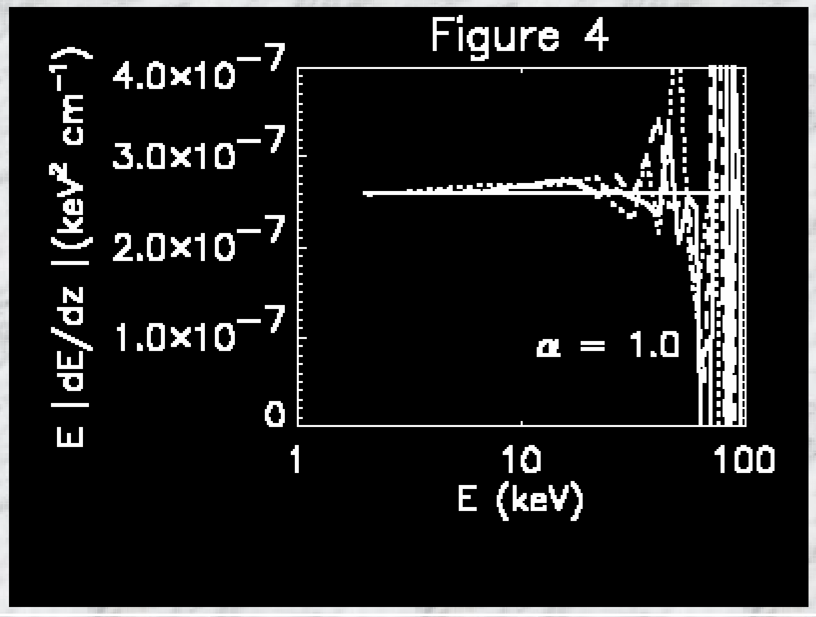
- Construct local hard X-ray spectra from F(E)
- Then add reasonable level of noise and invert



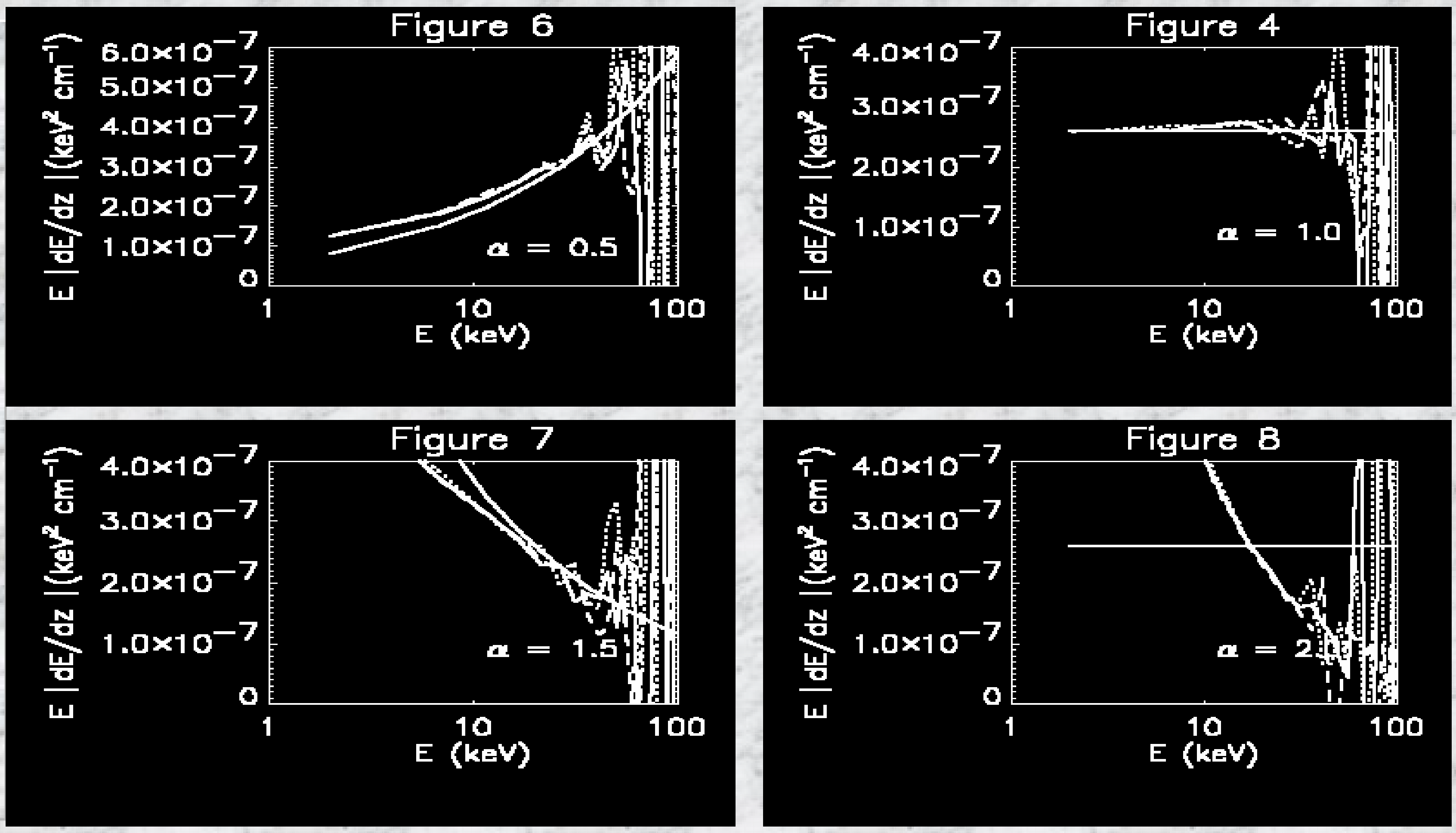
Parametric Study

- Construct local hard X-ray spectra from F(E)
- Then add reasonable level of noise and invert
- Then form energy loss rate from continuity equation

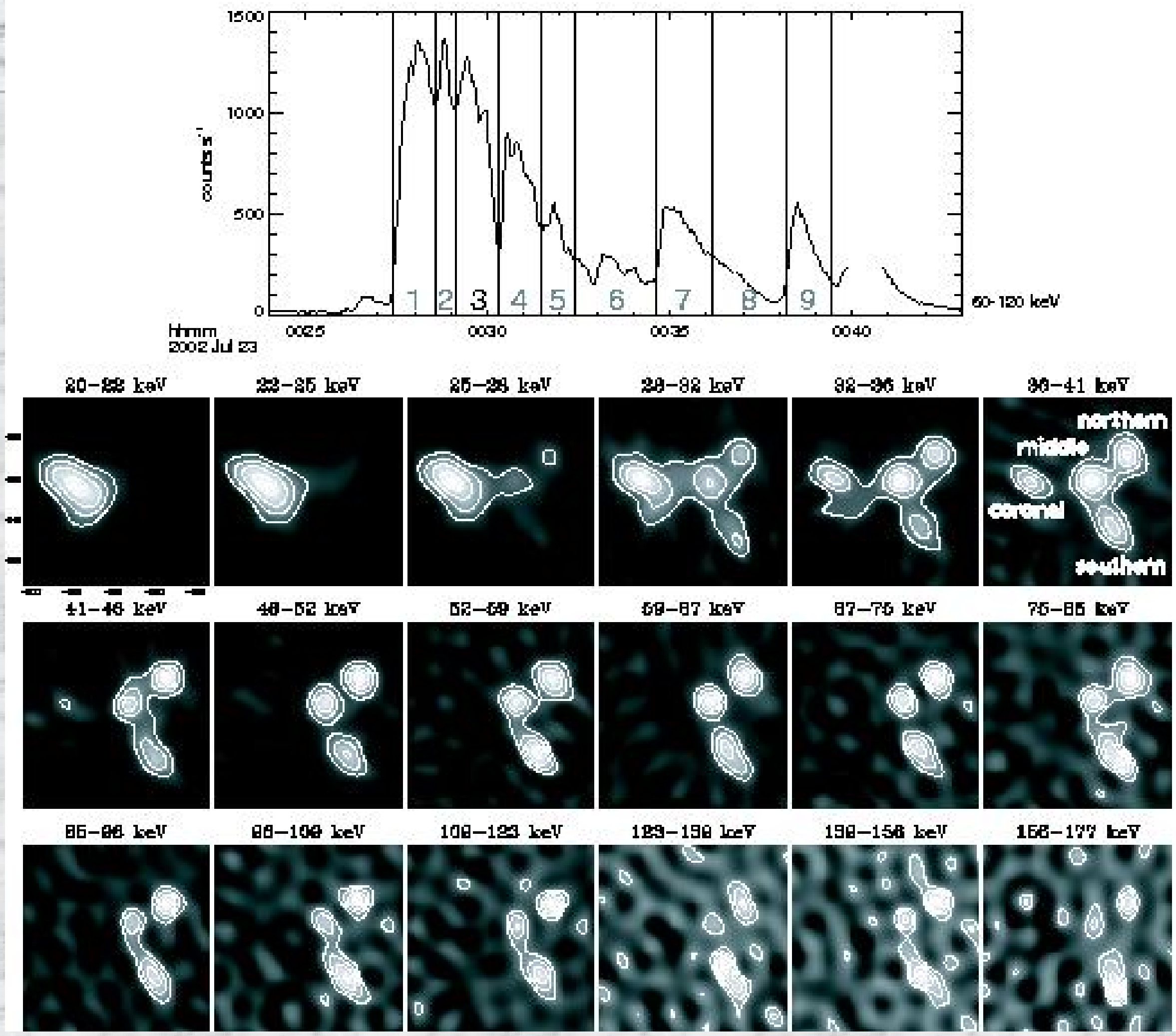




Results for various α



July 23 Imaging Spectroscopy



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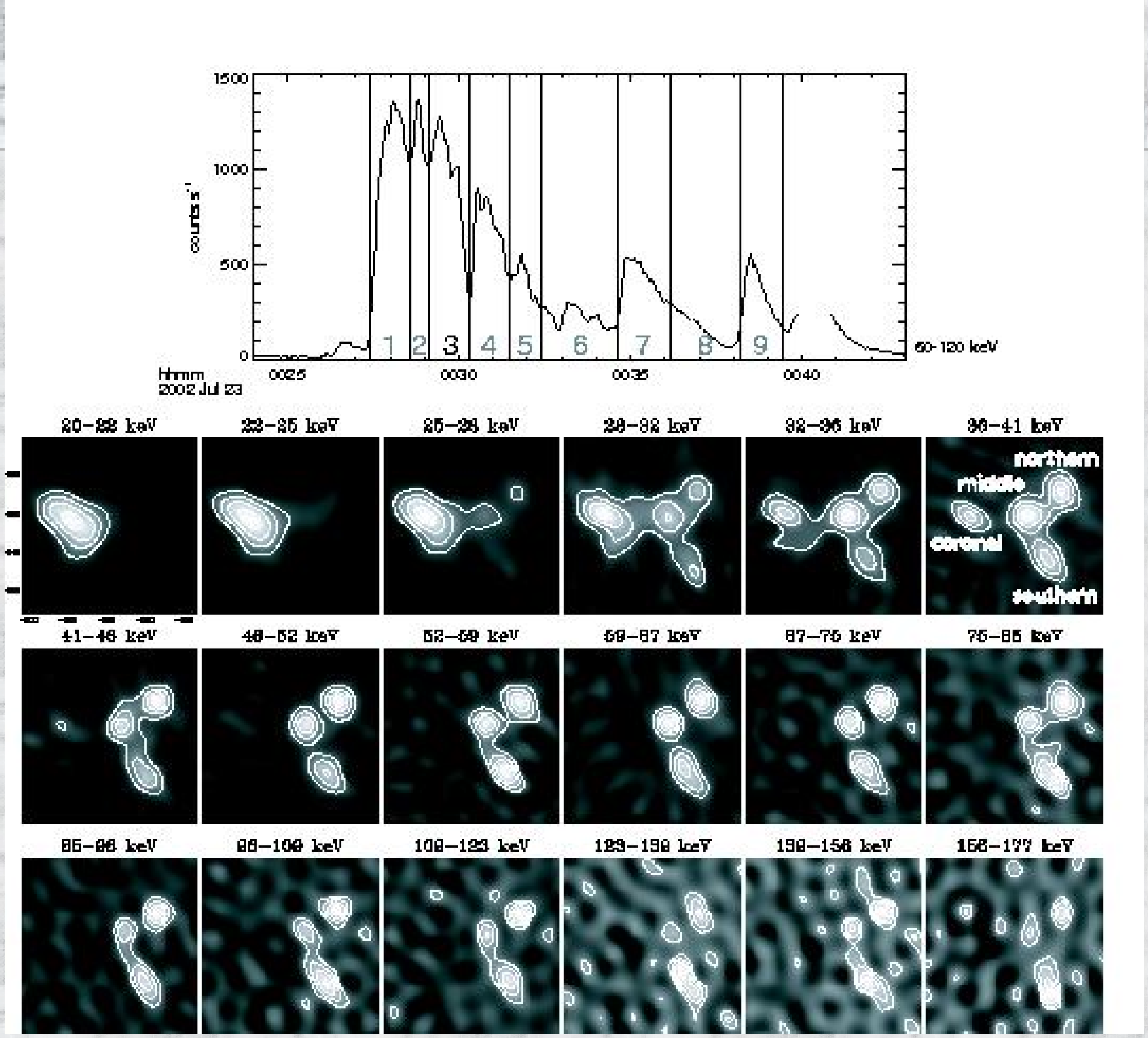
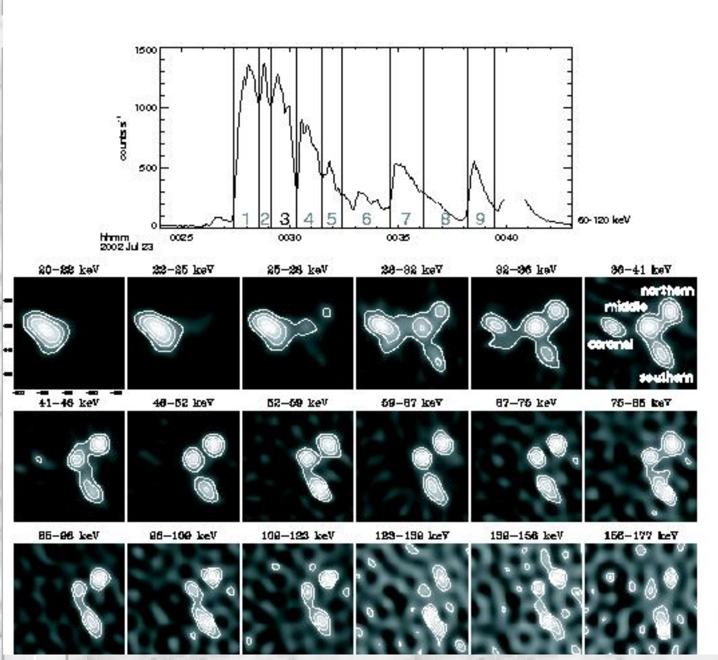
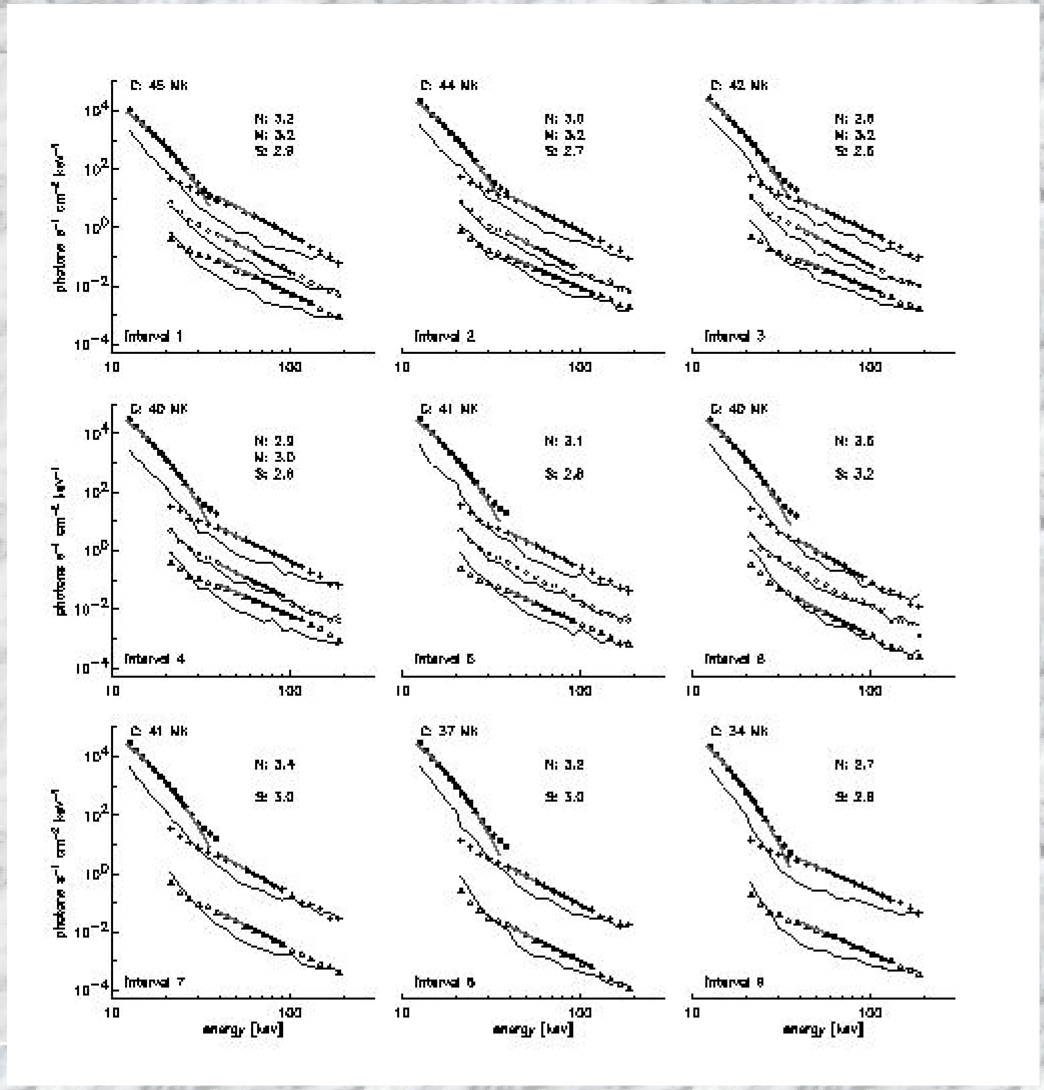


Concerned mostly with different spectra in discrete features

Feature Spectra





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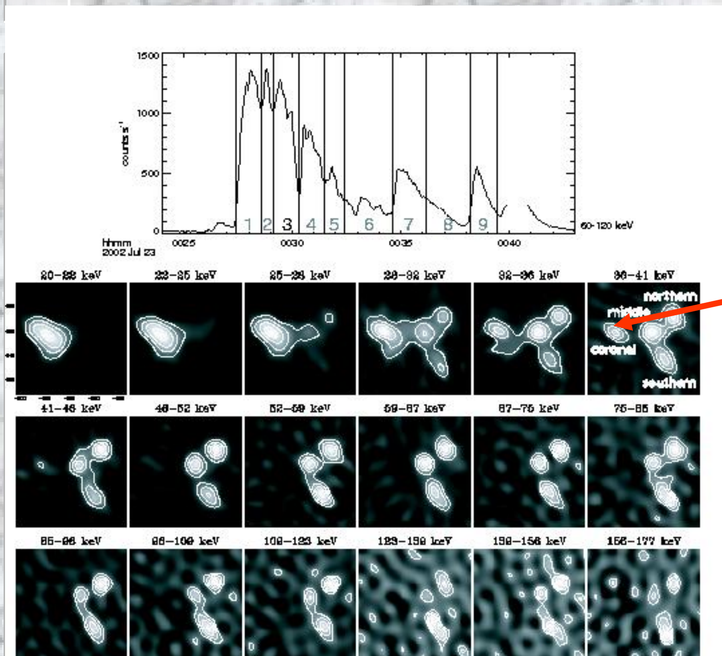

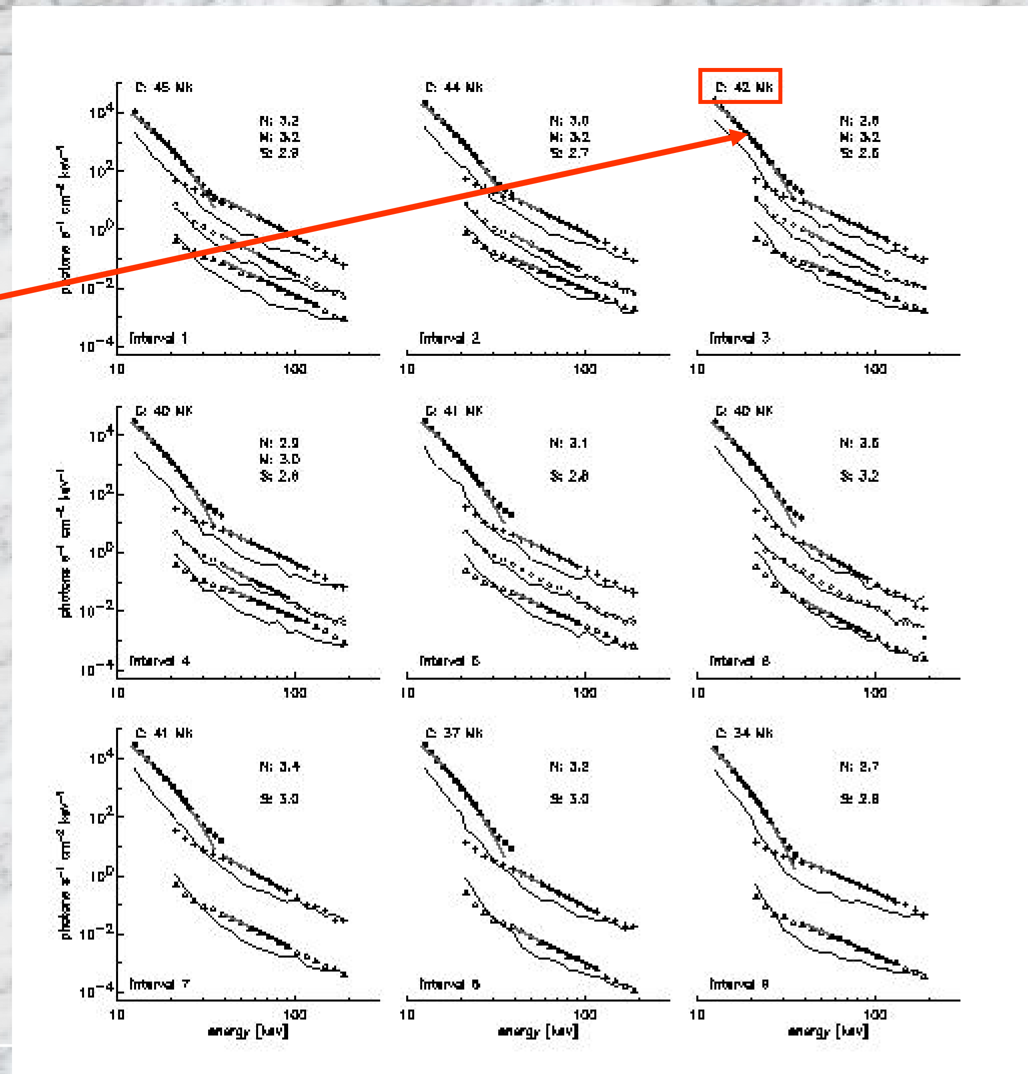

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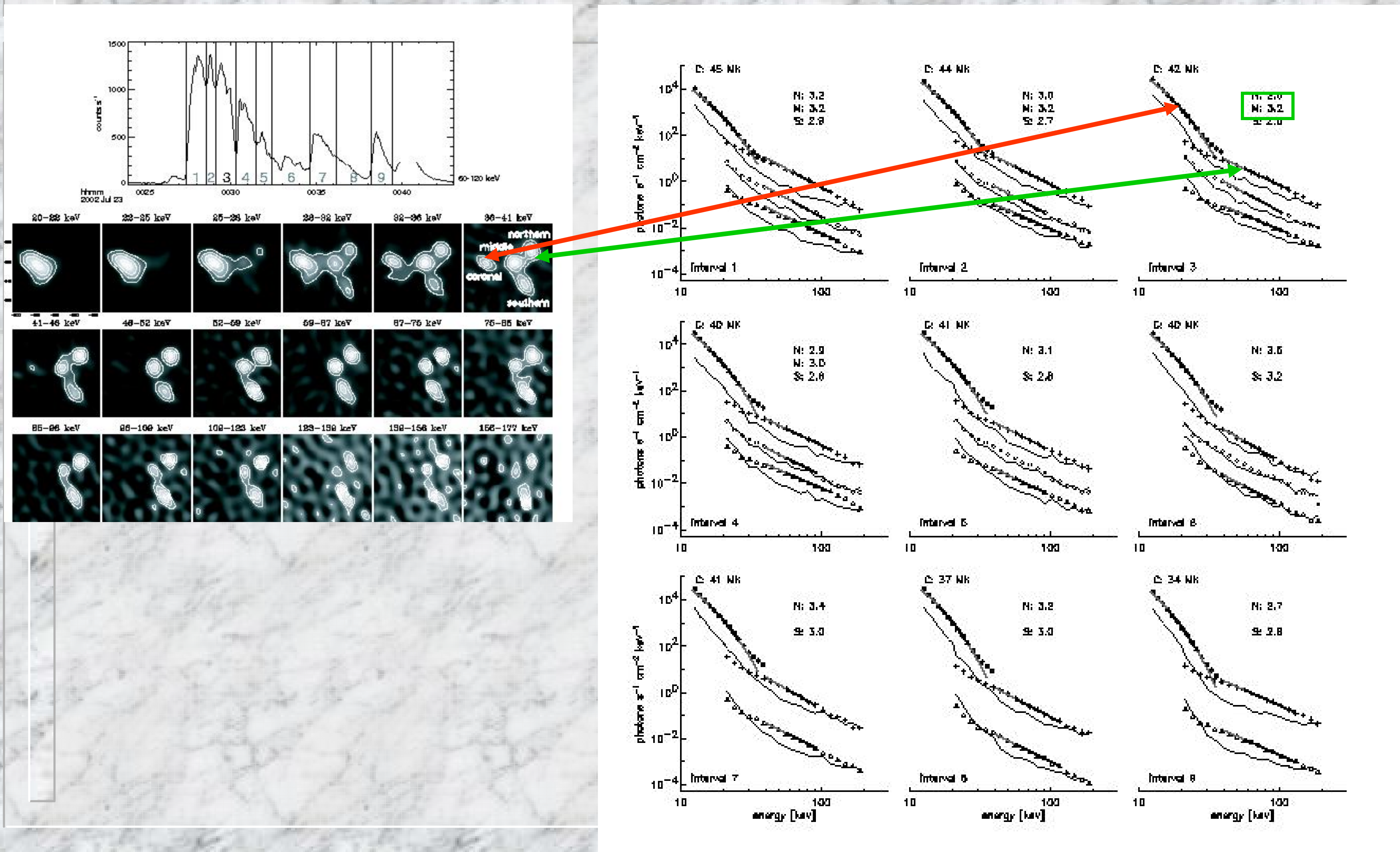

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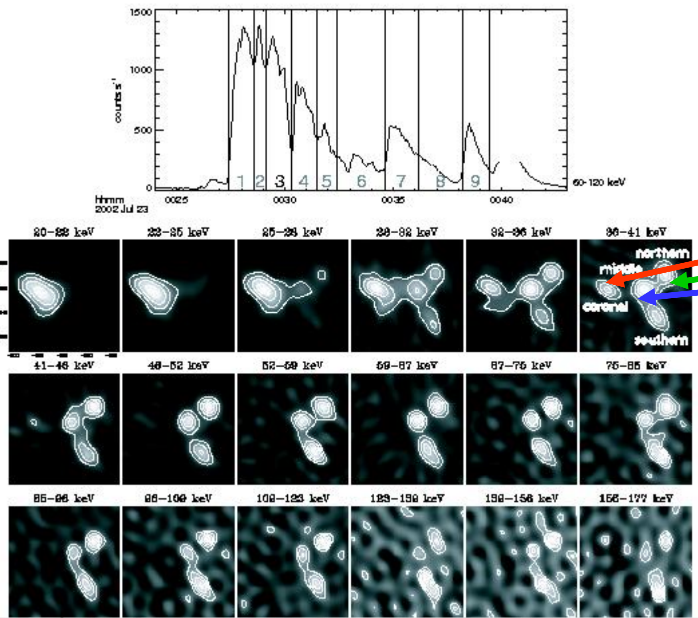

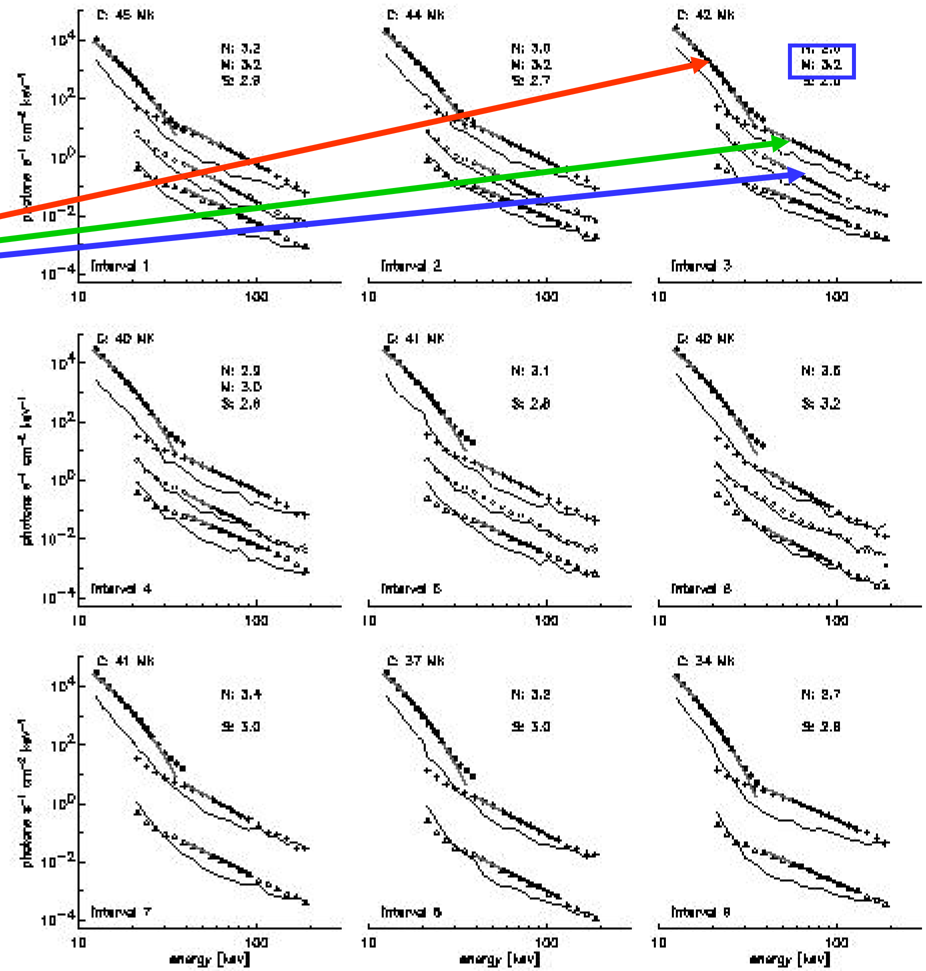

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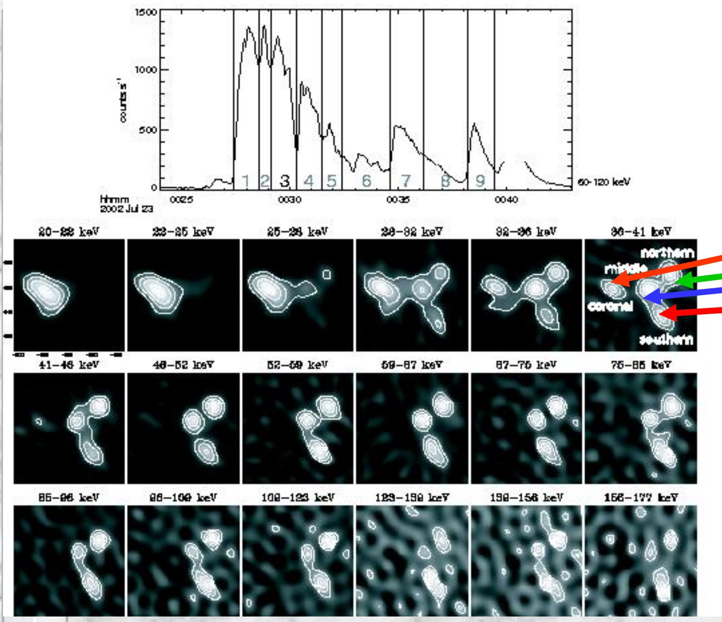
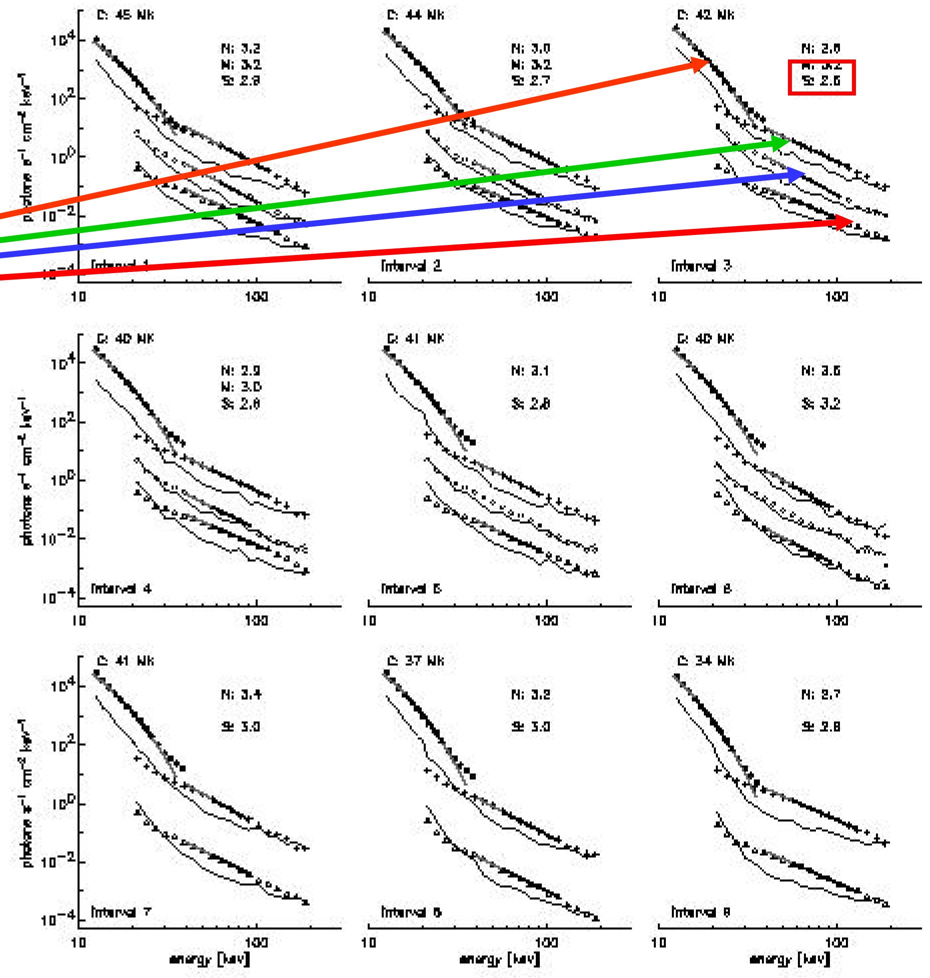
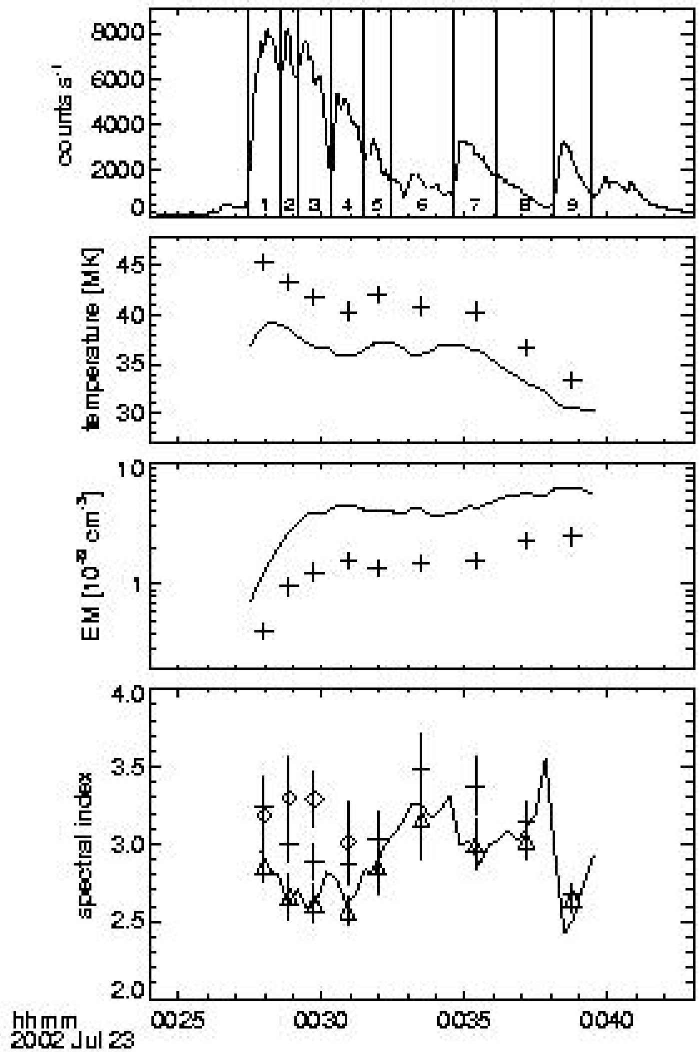




Temporal Trends



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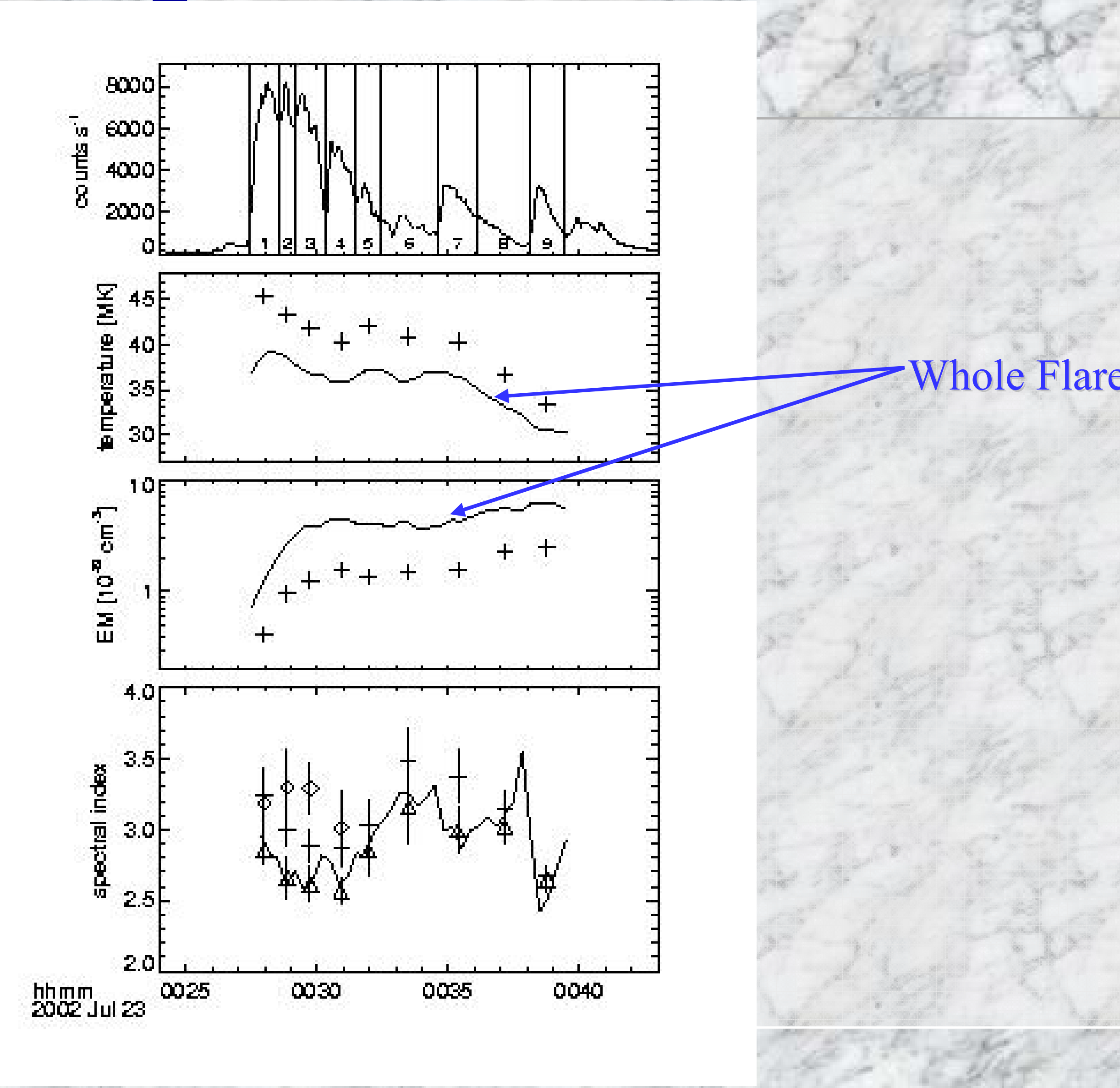
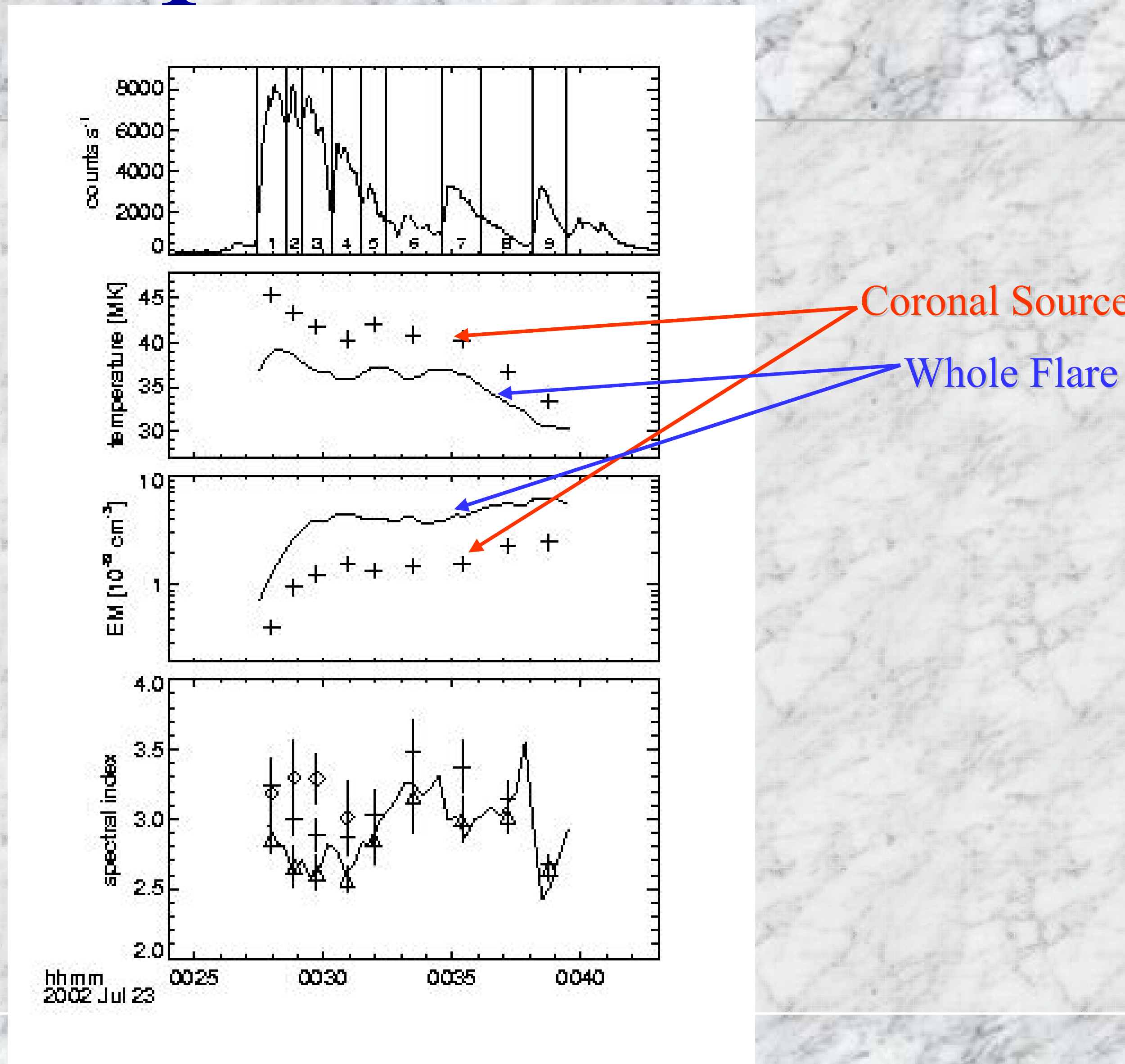
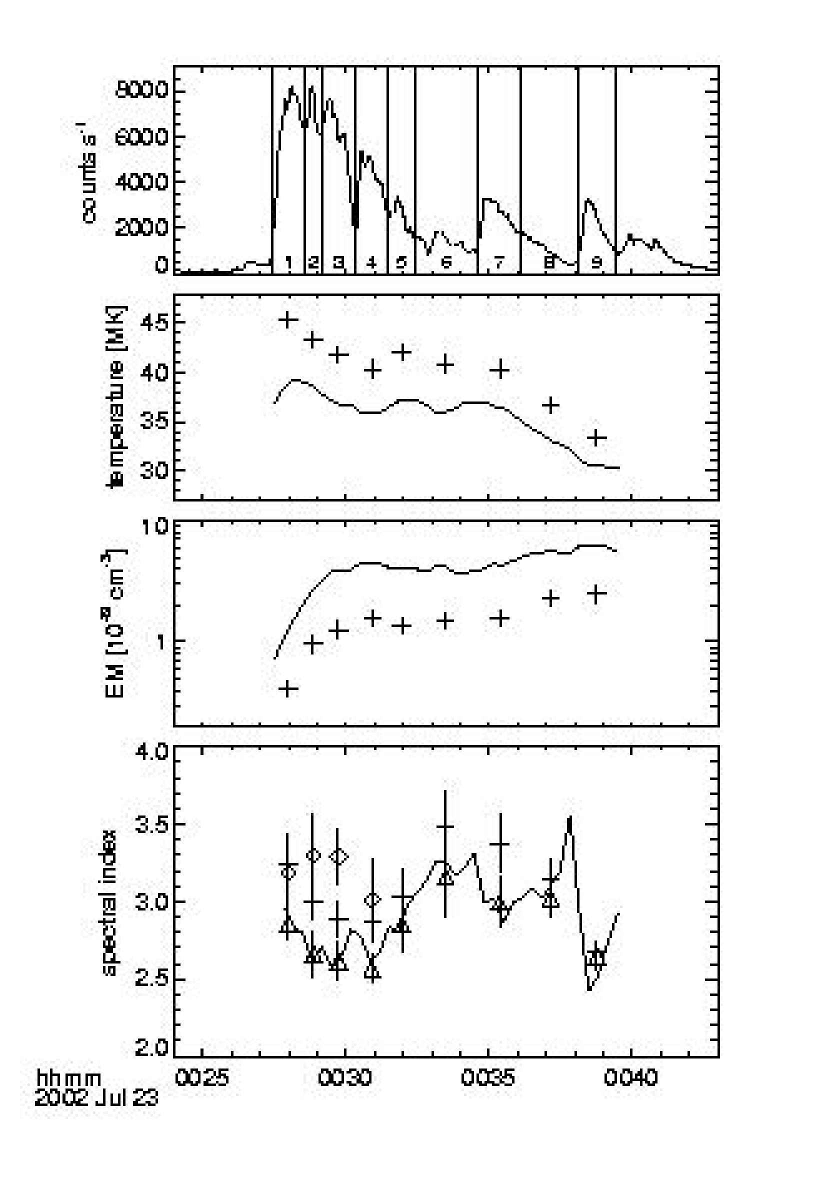


Temporal Trends



Temporal Trends



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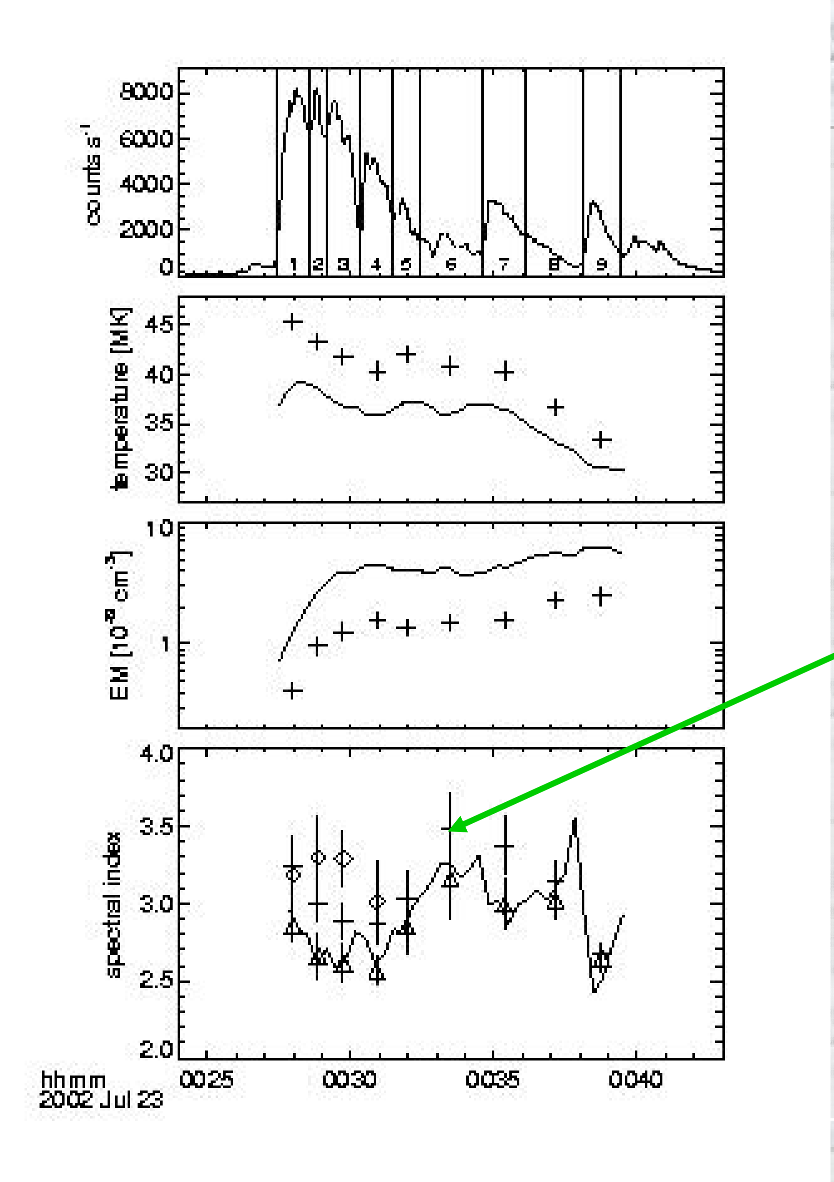

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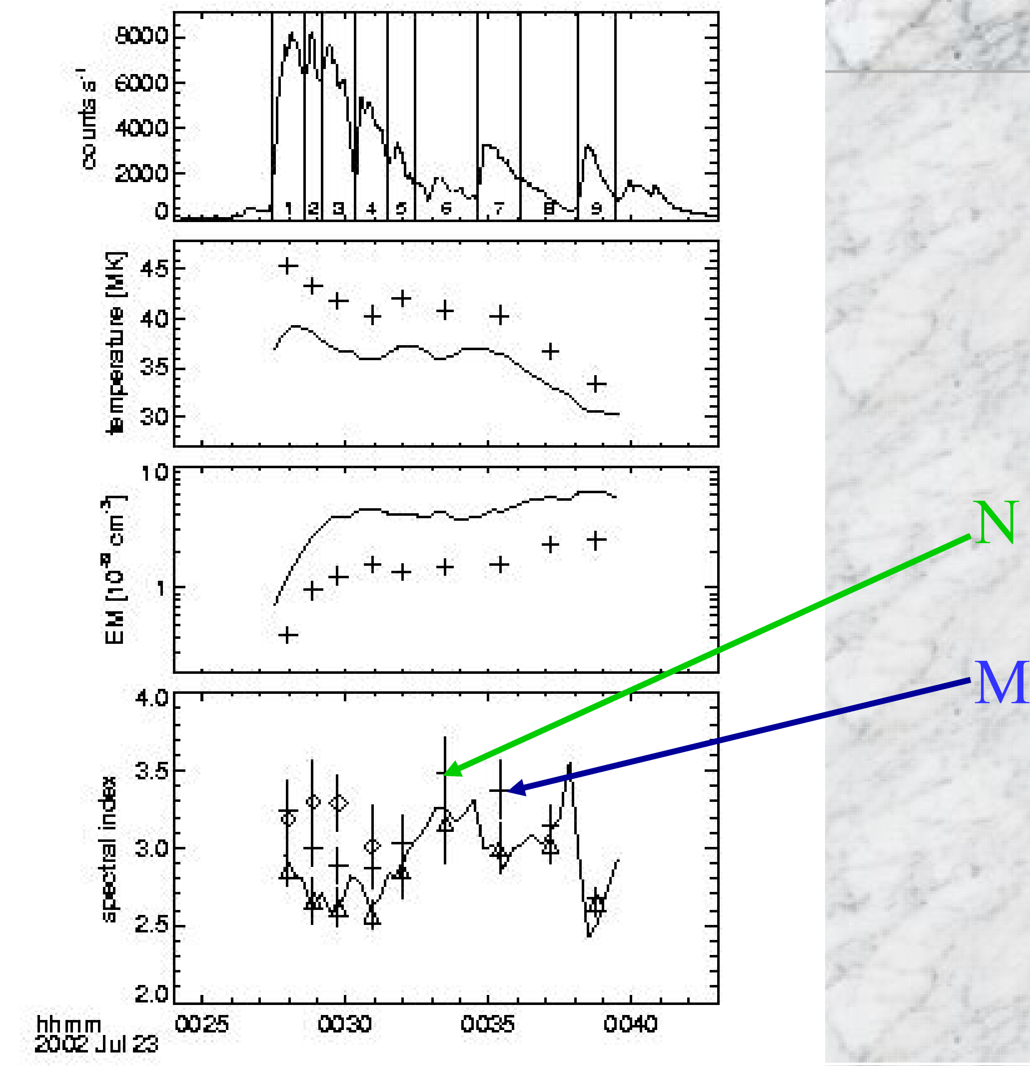

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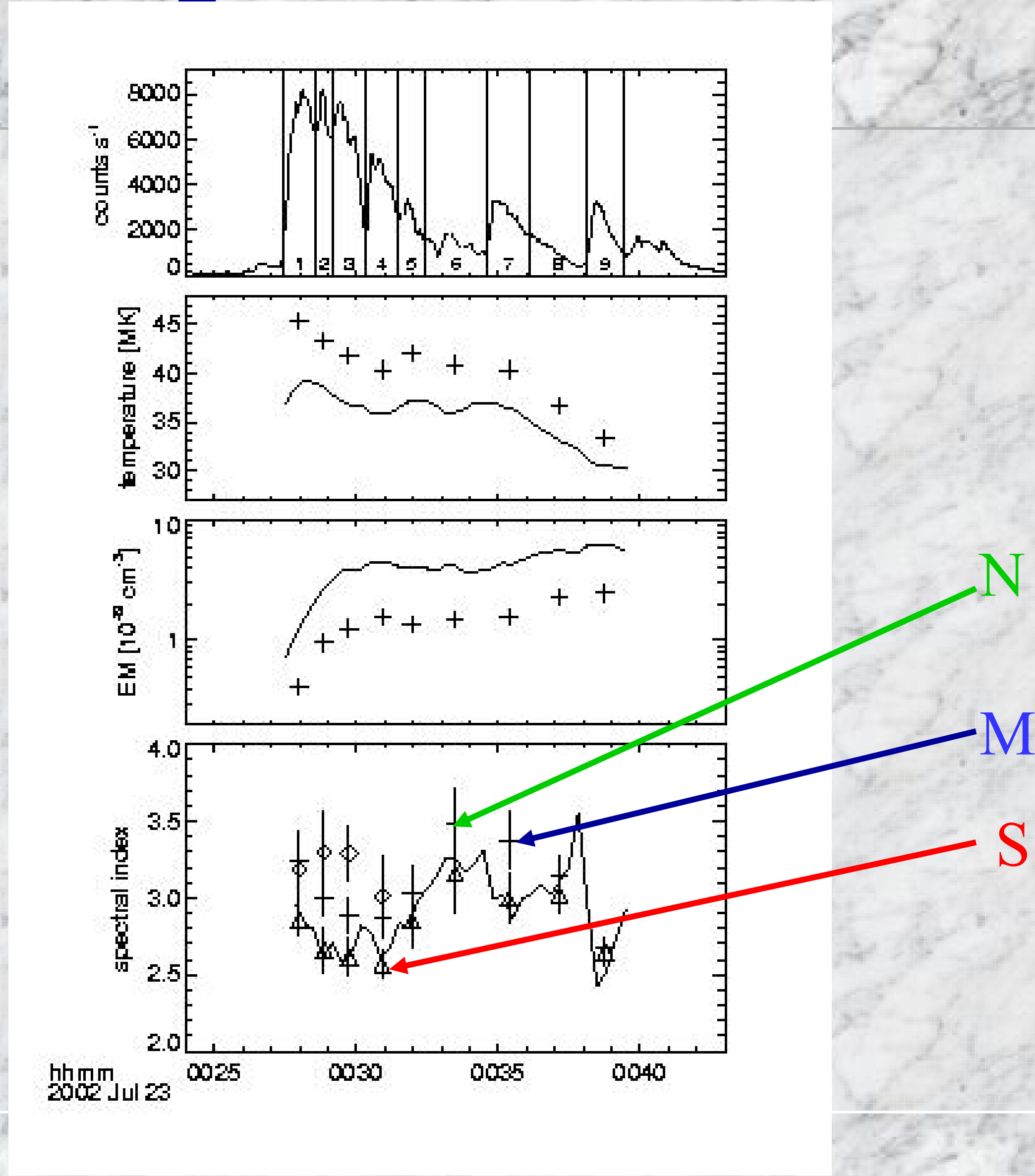


What do we Tell the Theorists? (2)

- Different discrete features in the same flare have manifestly different hard X-ray spectral forms and hence exciting electron spectra
- Spatially averaged measurements, while useful, do not reveal the whole picture – spatial and temporal variations are a key part of a model's predictive power
- Spectra of discrete features can be correlated, implying a connectivity

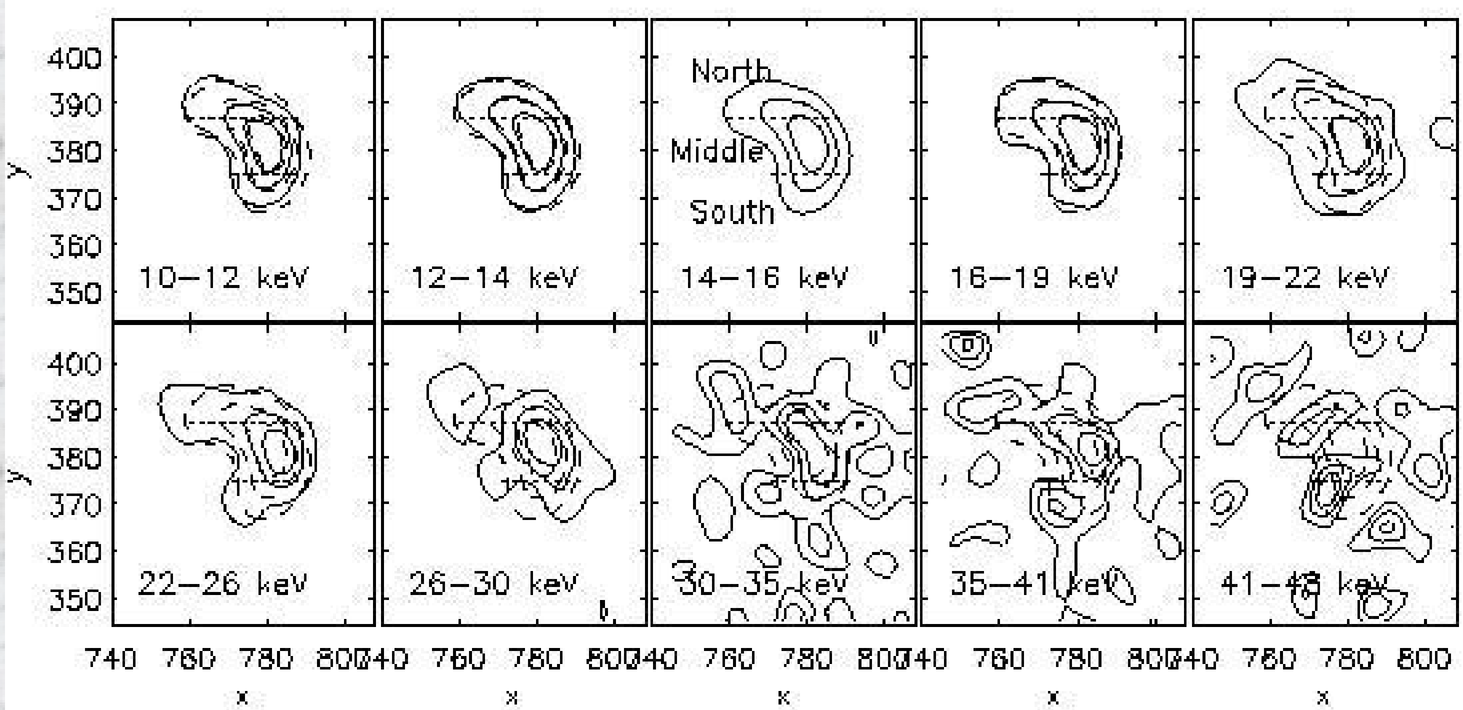
Generalization to Extended Sources

- Can we look for “smoother” variations of spectral parameters with position?

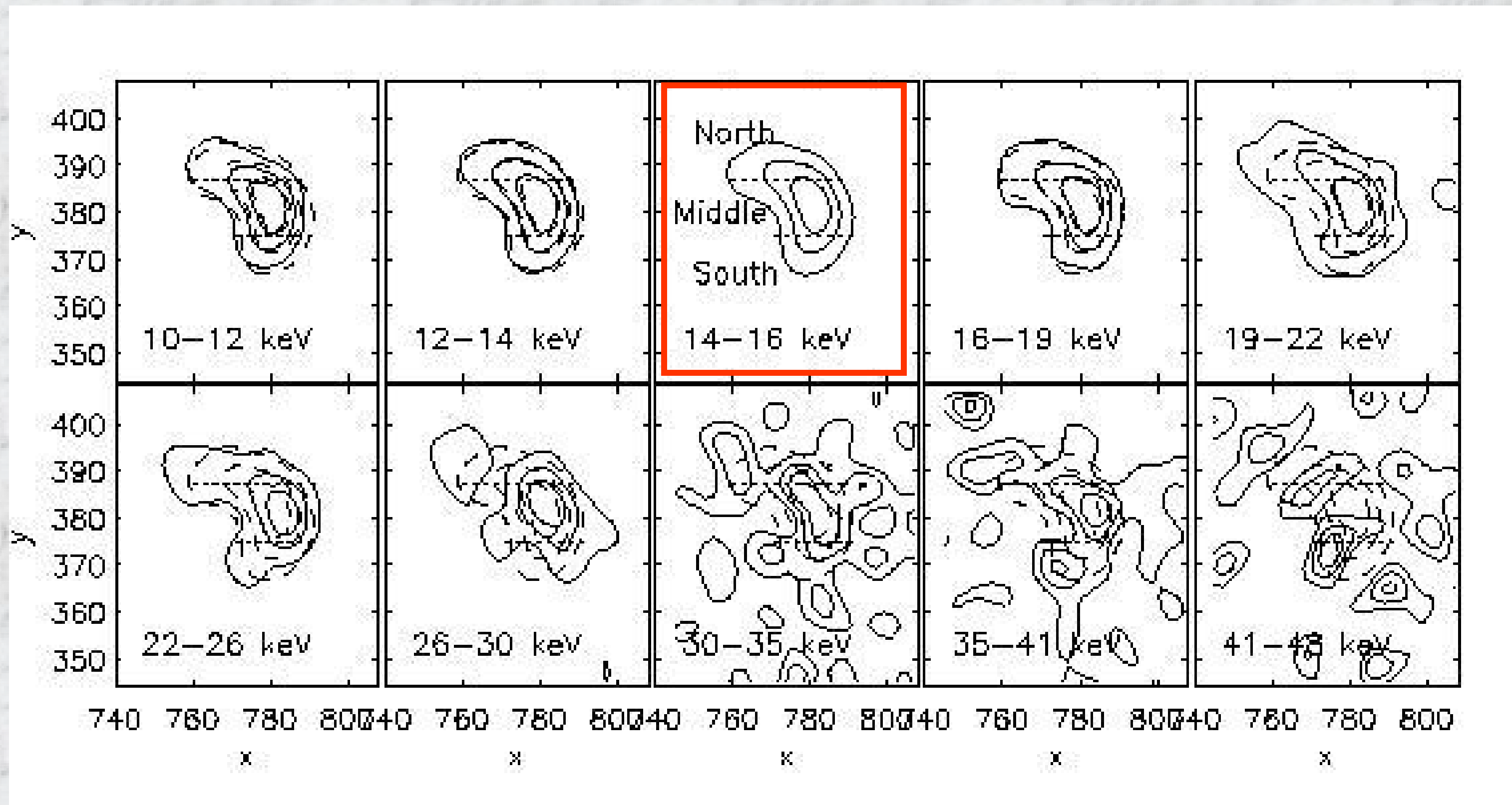
Generalization to Extended Sources

- Can we look for “smoother” variations of spectral parameters with position?
- Try dividing source up into subsources
- Obtain photon spectra and invert to get ‘local’ electron spectra

April 15, 2002 event



April 15, 2002 event



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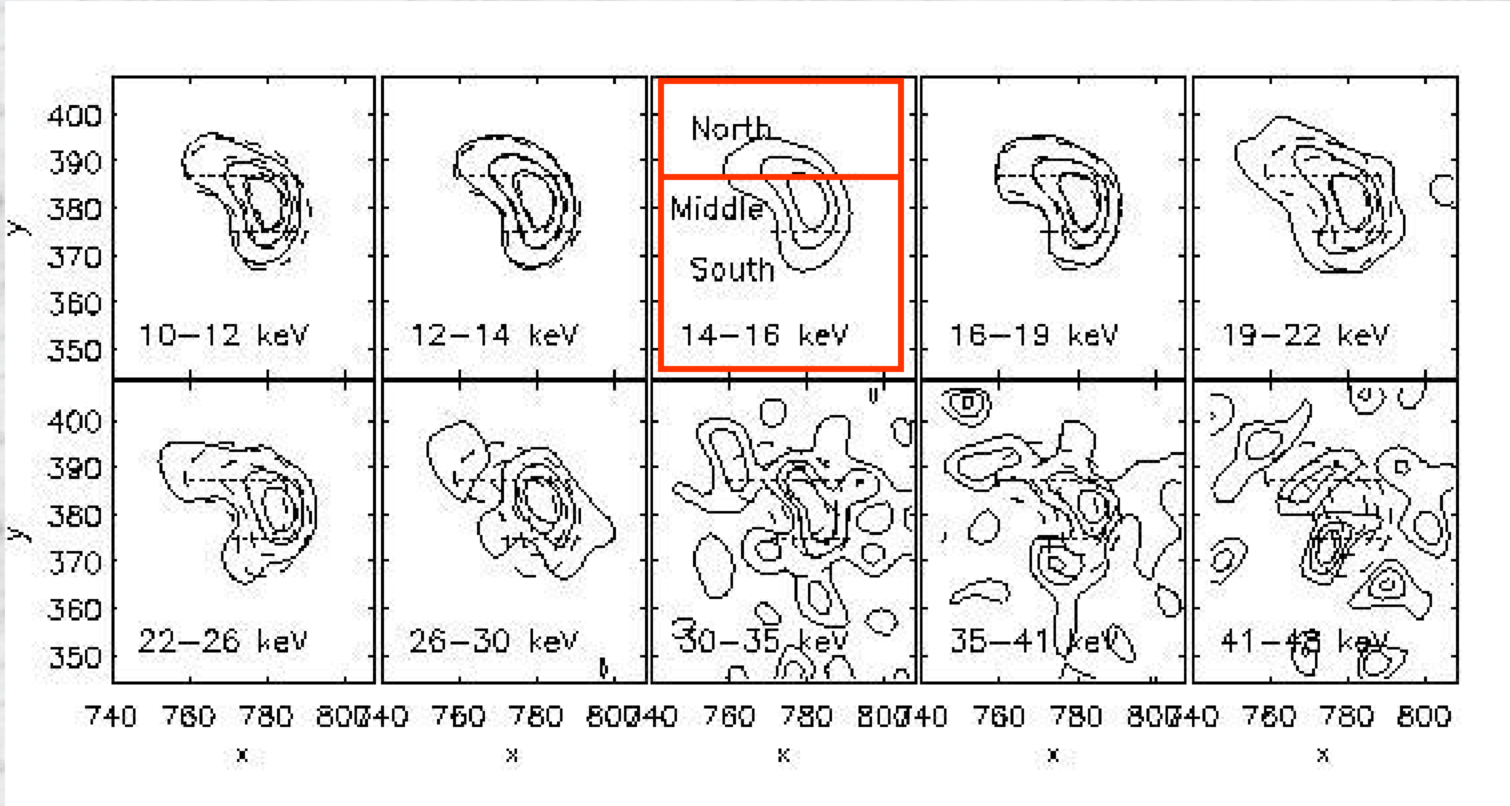

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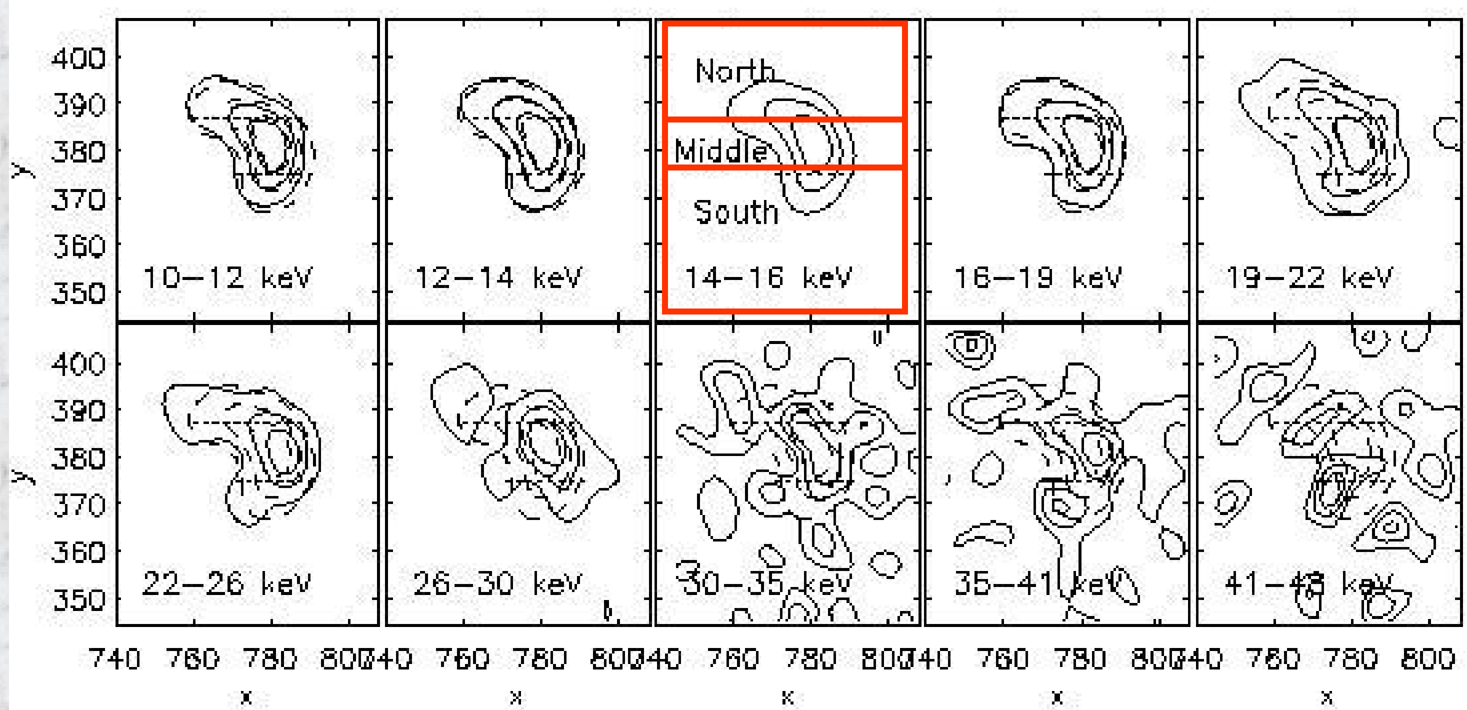
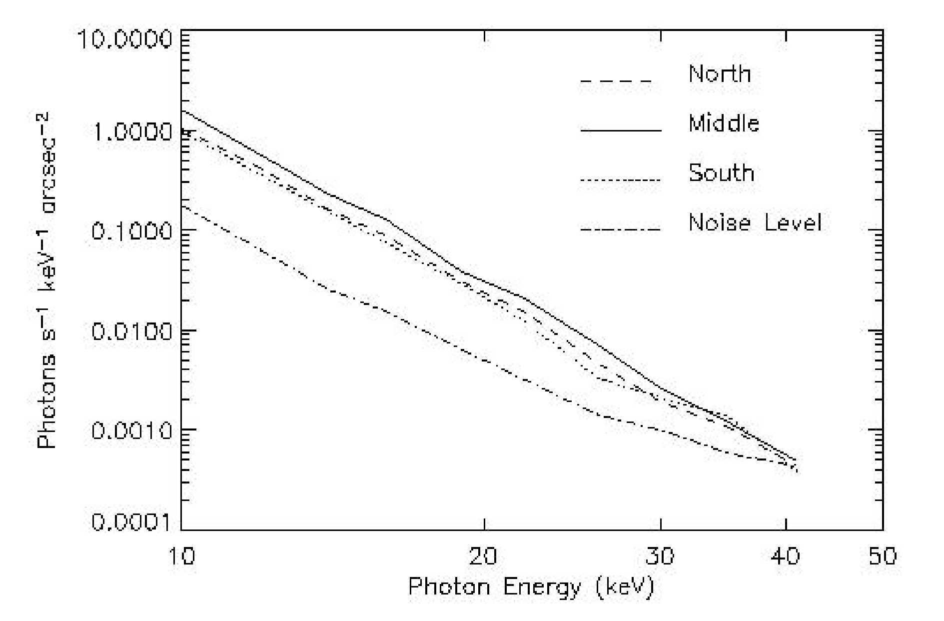
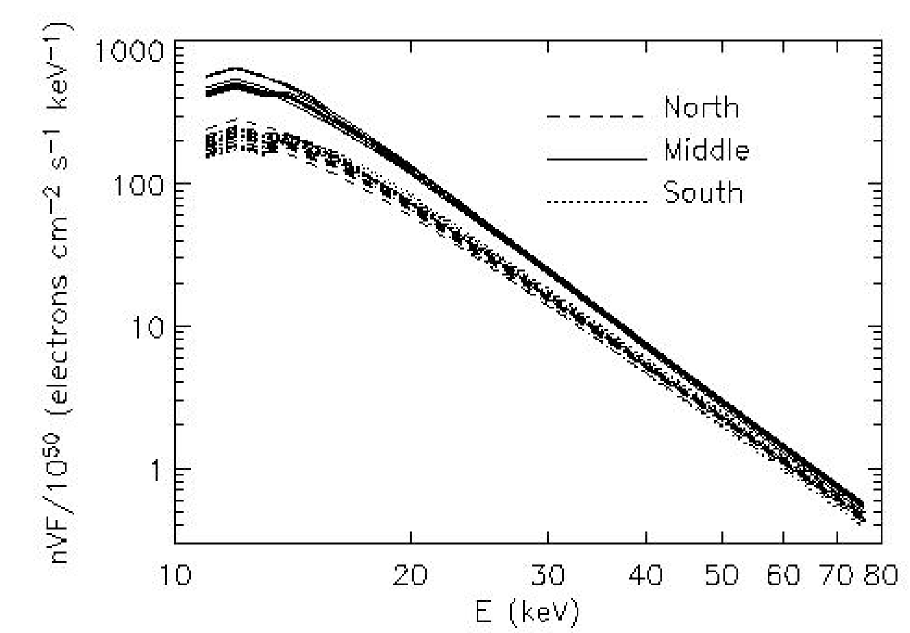
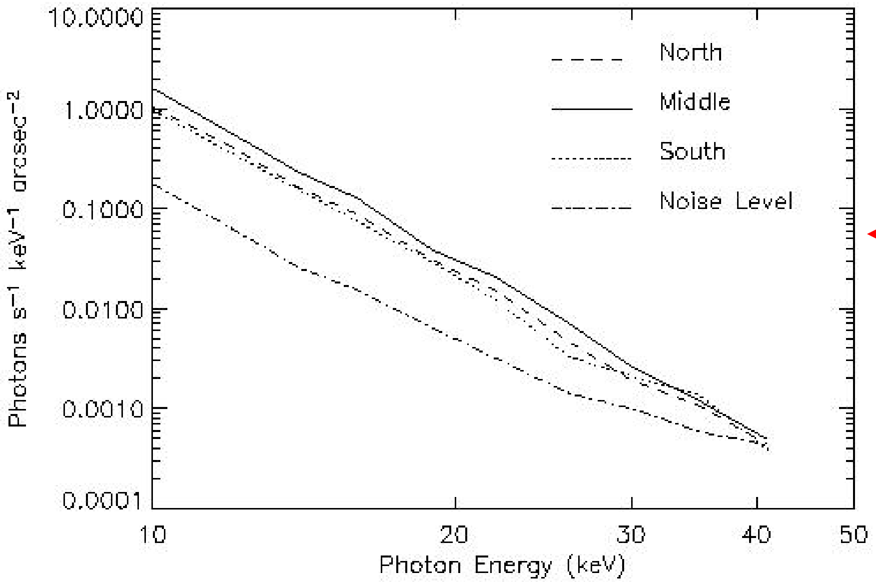


Subsource Spectra

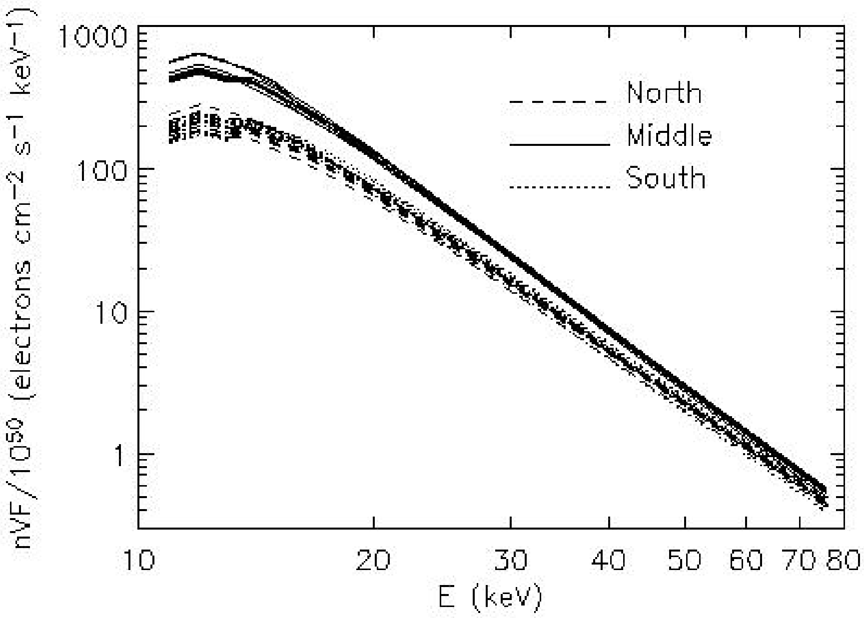




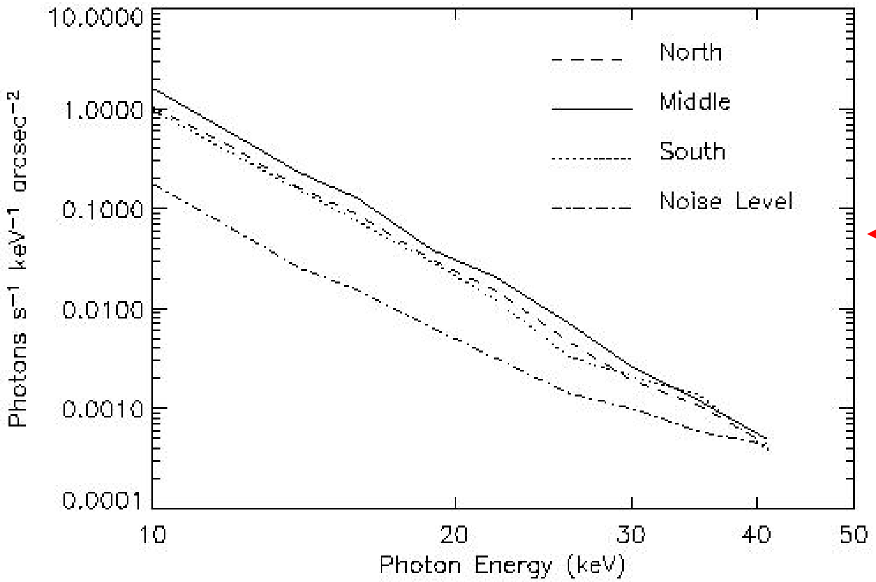
Subsource Spectra



Photon

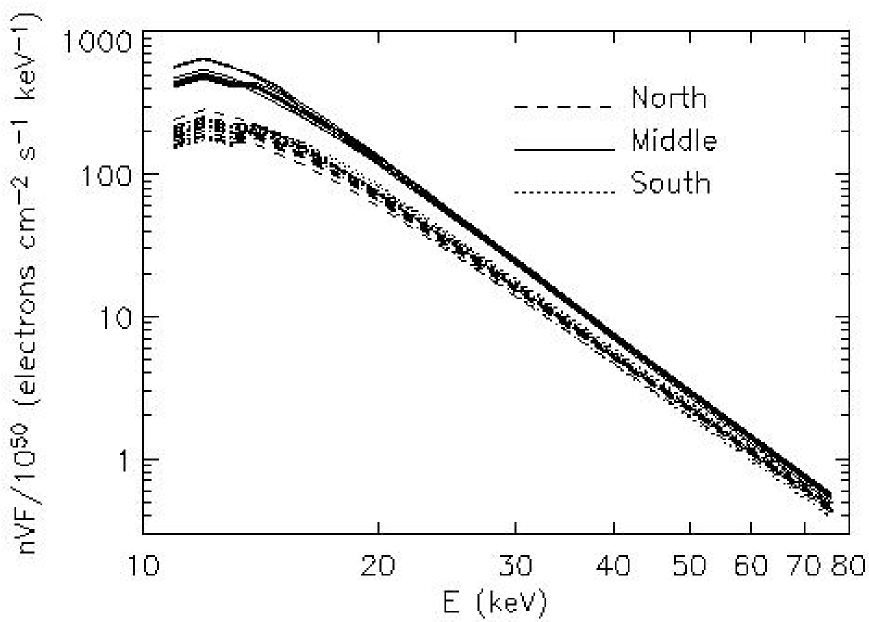


Subsource Spectra

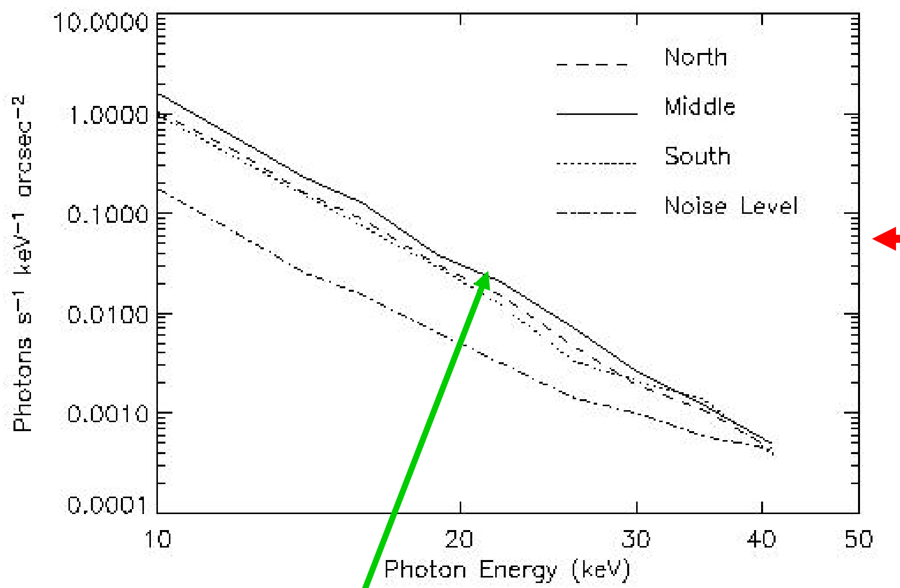


Photon

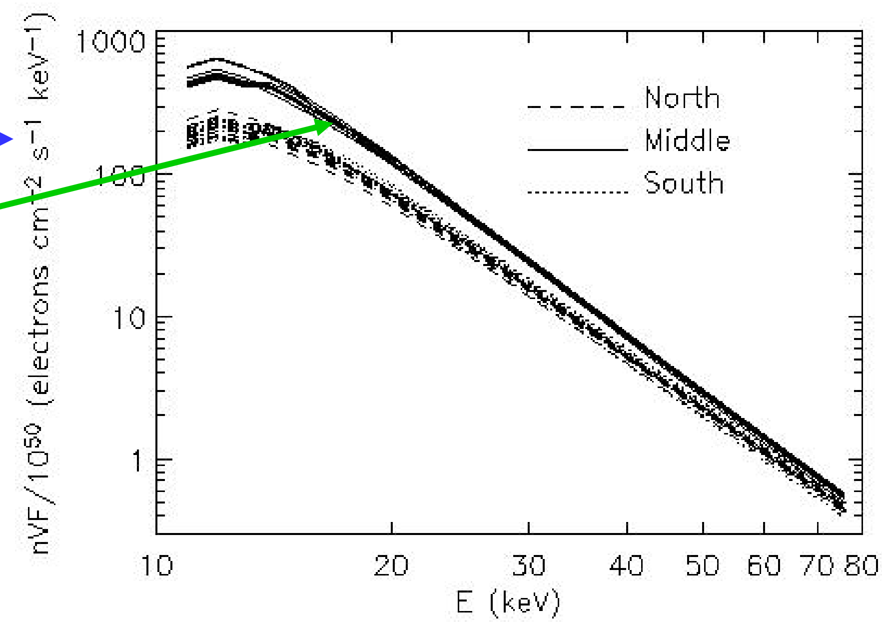
Electron



Subsource Spectra



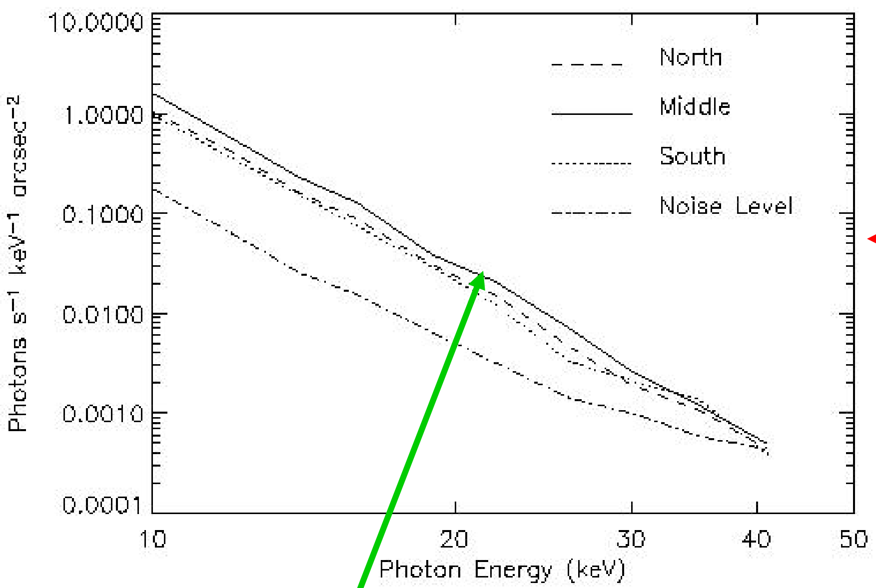
Photon



Electron

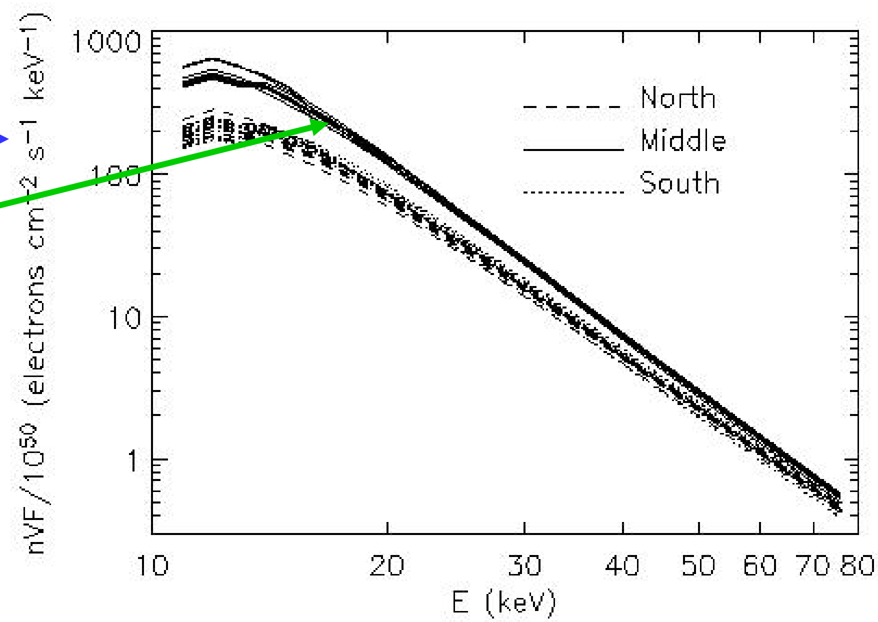
'Middle' region spectrum is softer

Subsource Spectra



Photon

Electron



‘Middle’ region spectrum is softer

But

$dE/dN = -[1/F(E,N)] \int [\partial F(E,N)/\partial N]\, dE$?

What do we Tell the Theorists? (3)

- Observations are not yet capable of defining the variation of electron spectrum with position in the source to the extent necessary to infer transport processes empirically

Can a Forward-Fit Method Yield α?

- Do parametric fits to images in different energy bands
- Study variation of parameters with energy
- Collisions: $dE/ds \sim -n/E \rightarrow L \sim \varepsilon^2$

In general, L *increases* with ε

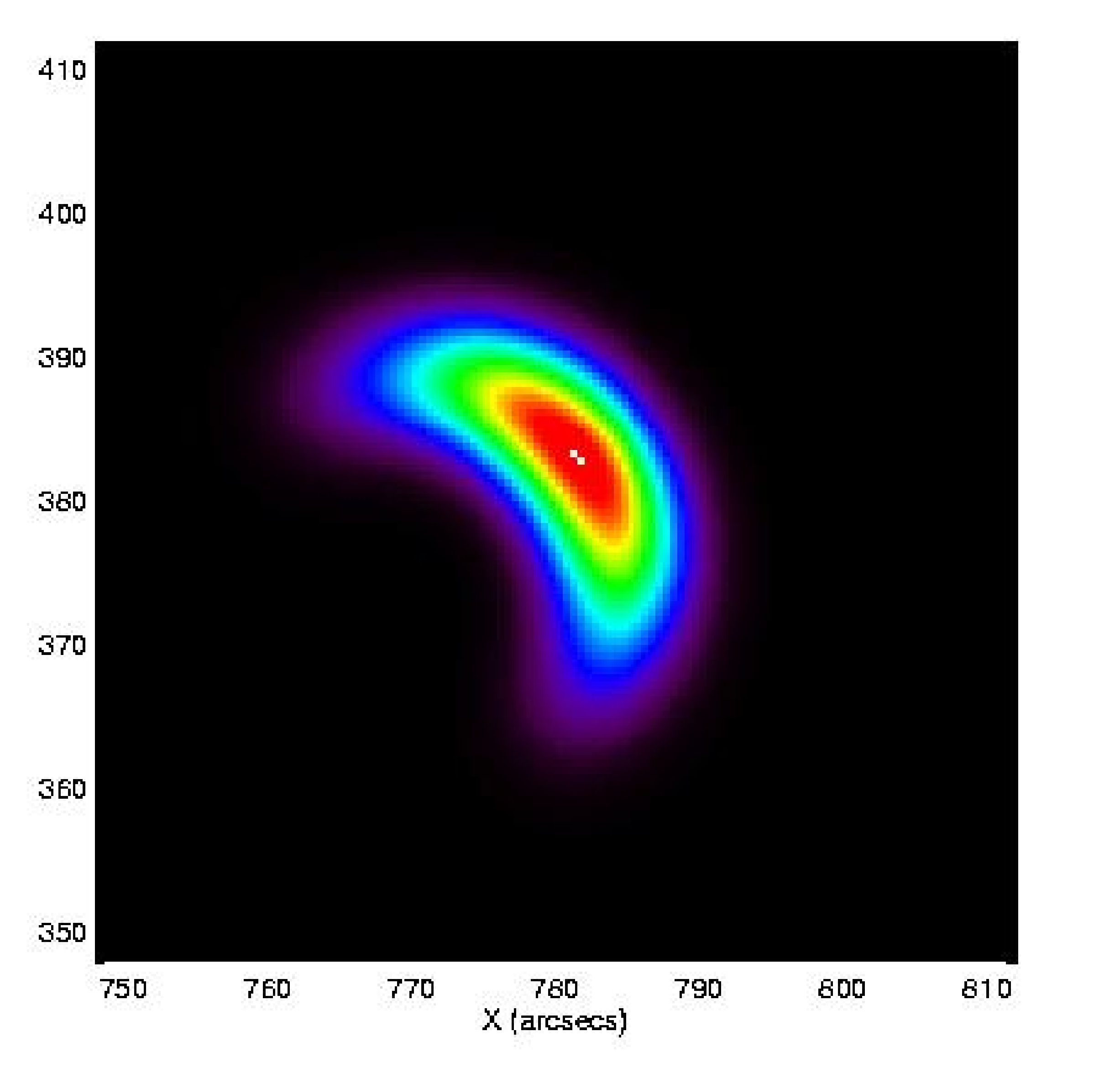
(increased penetration of higher energy electrons)

- General: $dE/ds \sim -n/E^\alpha \rightarrow L \sim \varepsilon^{1+\alpha}$
- Thermal: $T \sim T_o \exp(-s^2/2\sigma^2) \rightarrow L(\varepsilon, T_o, \sigma)$

In general, L *decreases* with ε

(highest-energy emission near temperature peak)

10 – 12 keV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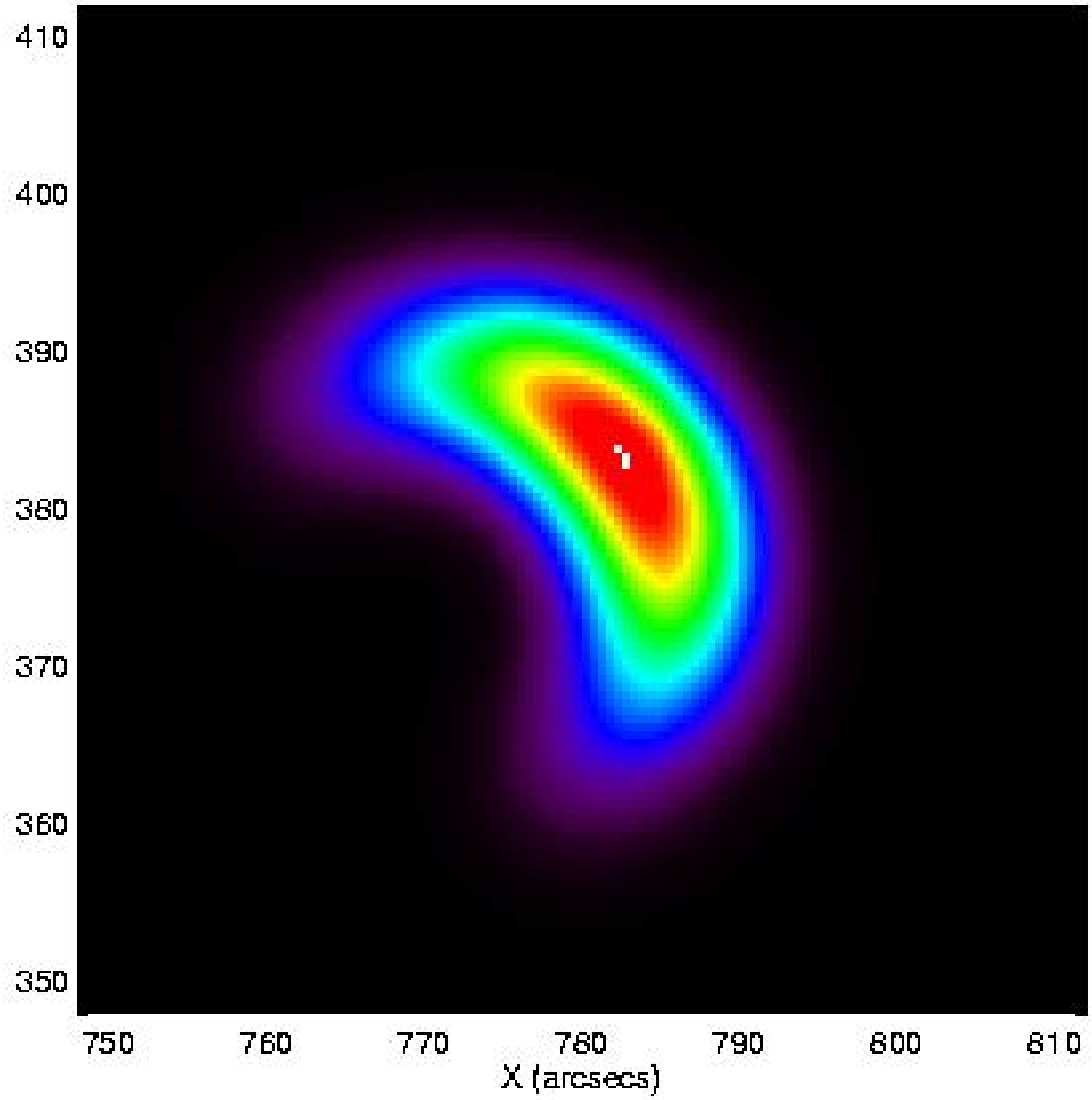
360
350
750
760
770
780
790
800
810
X (arcsecs)

14 – 16 keV



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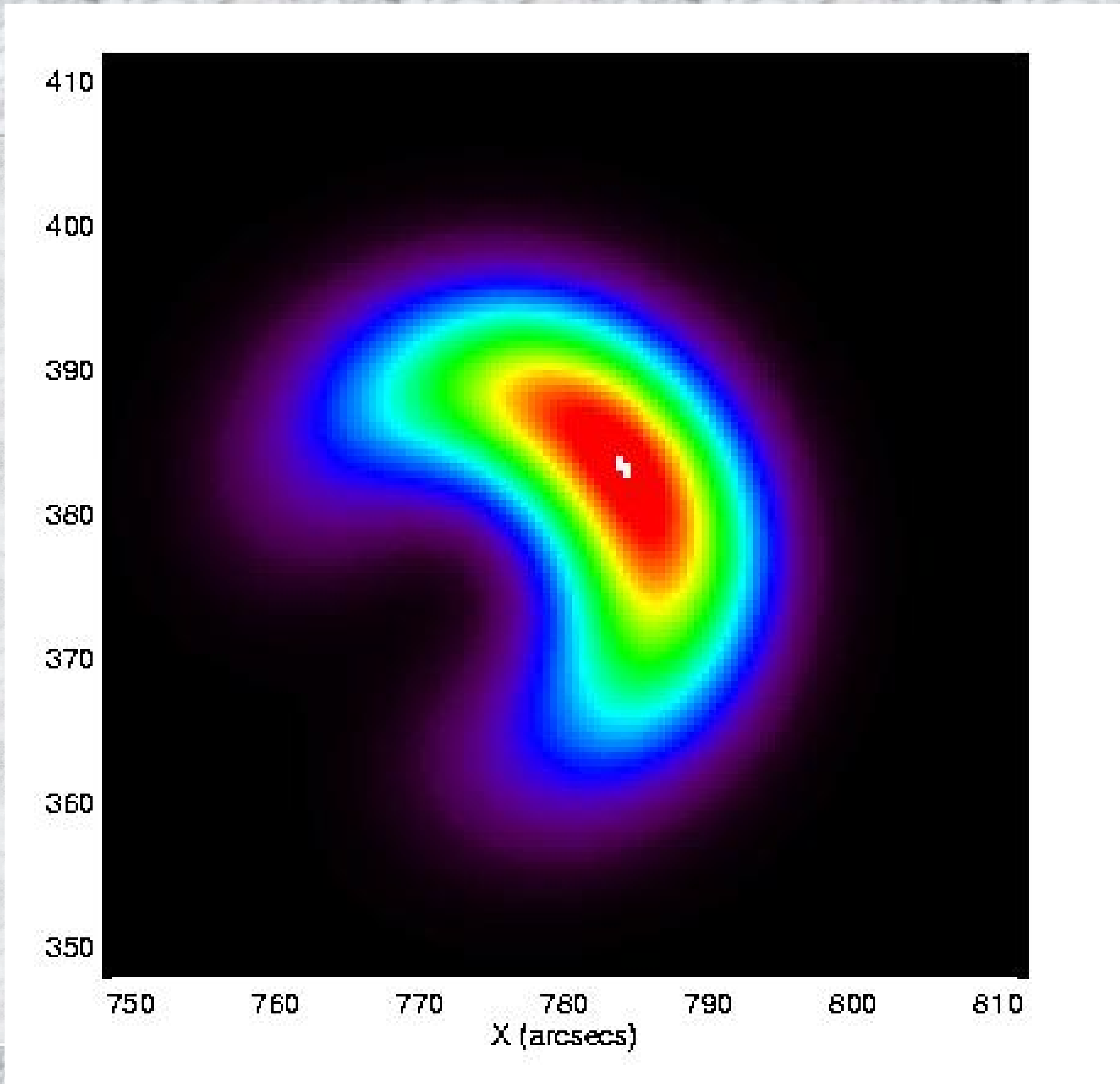
19 – 22 keV



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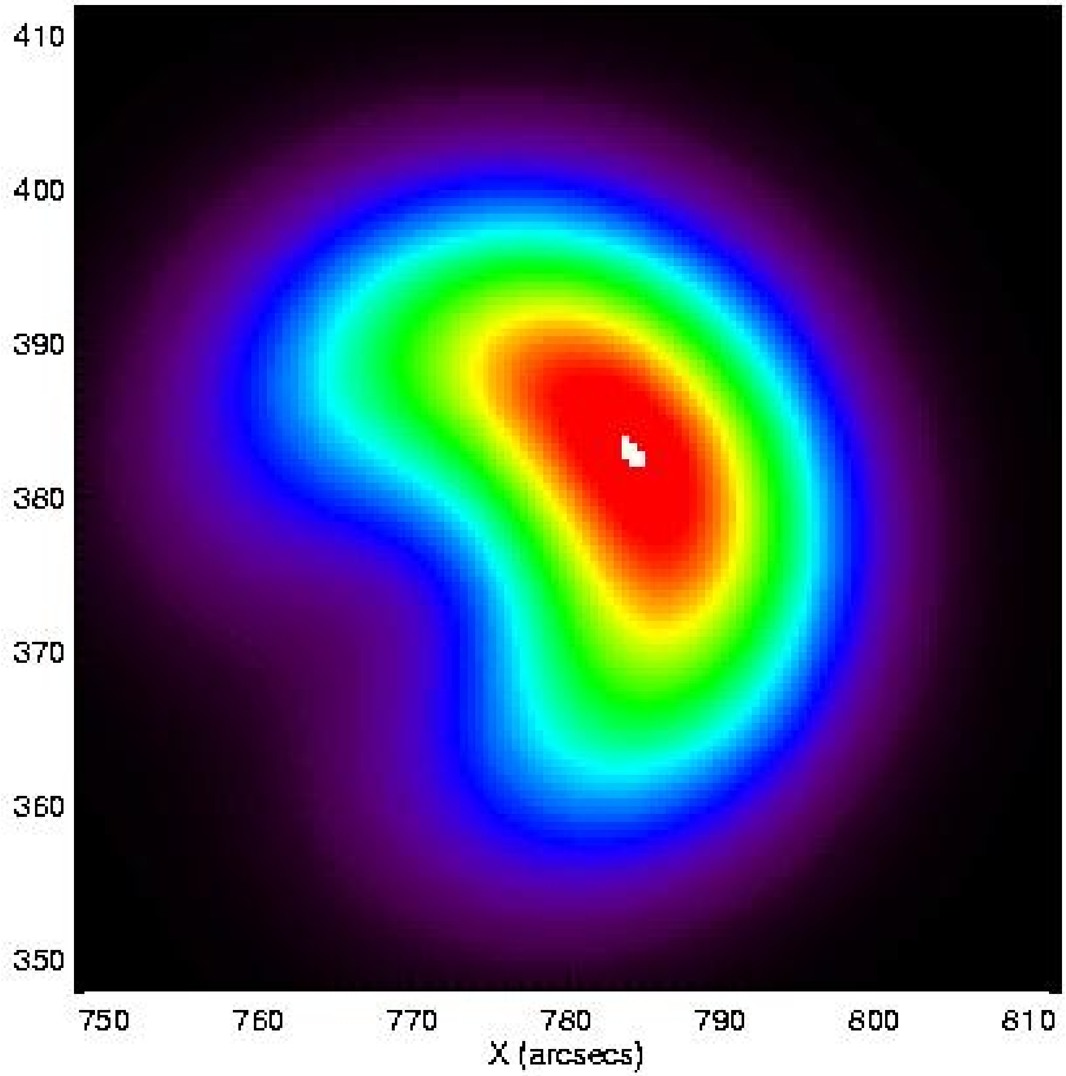
X (arcsecs)

26 – 30 keV



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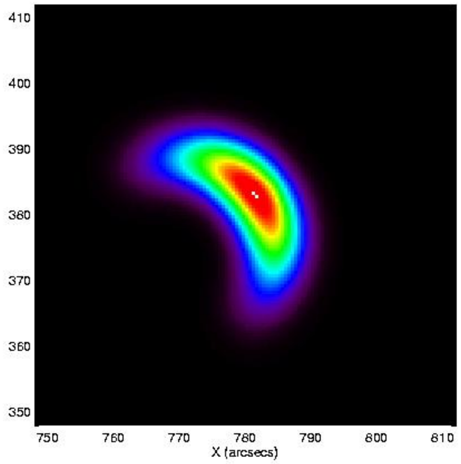

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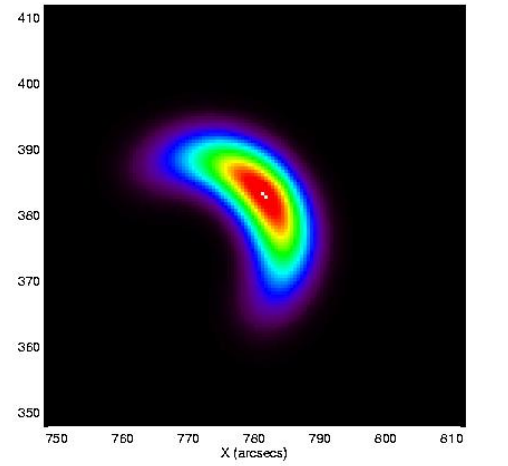

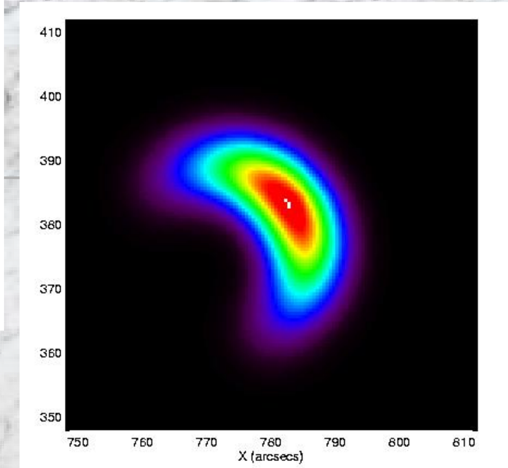

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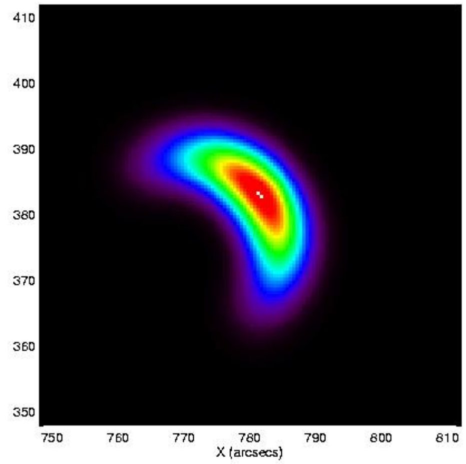

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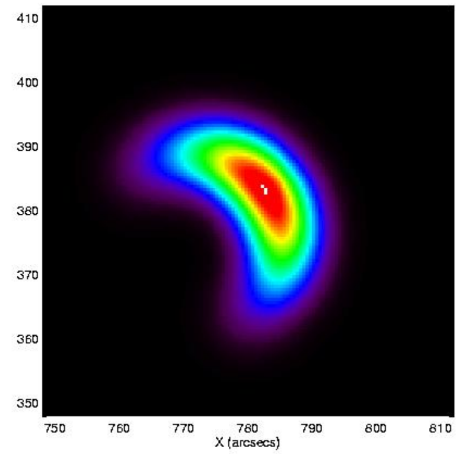

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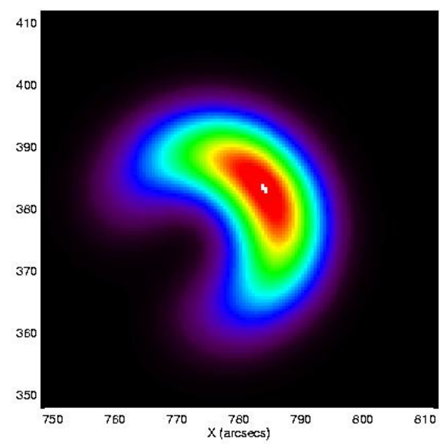

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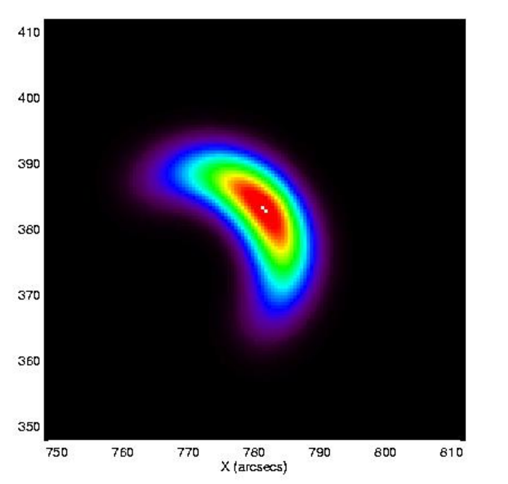

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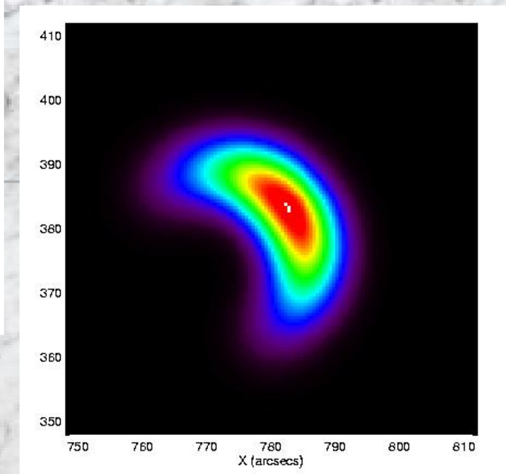

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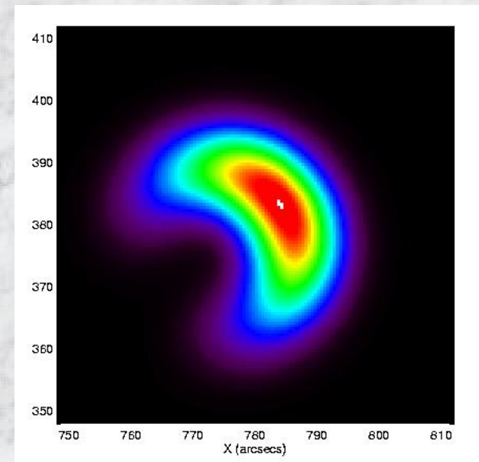

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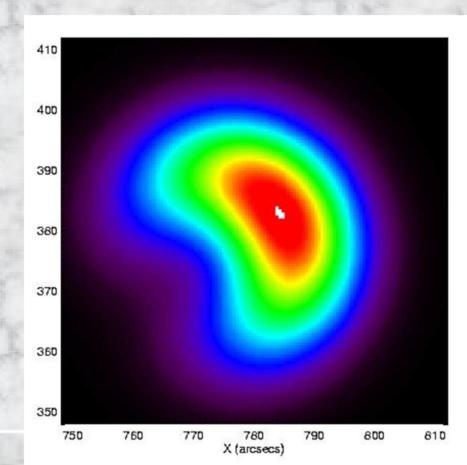
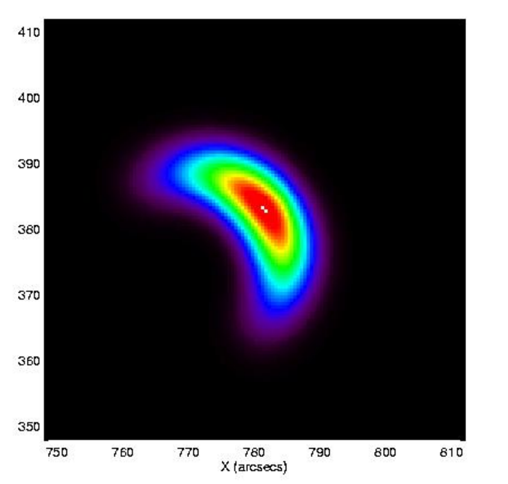
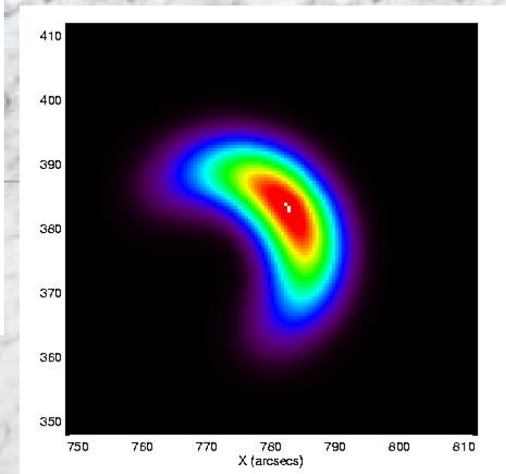
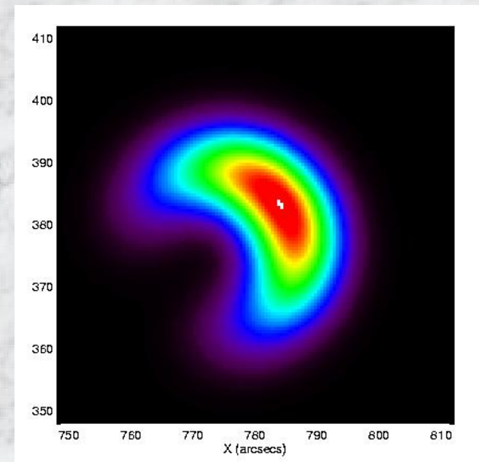




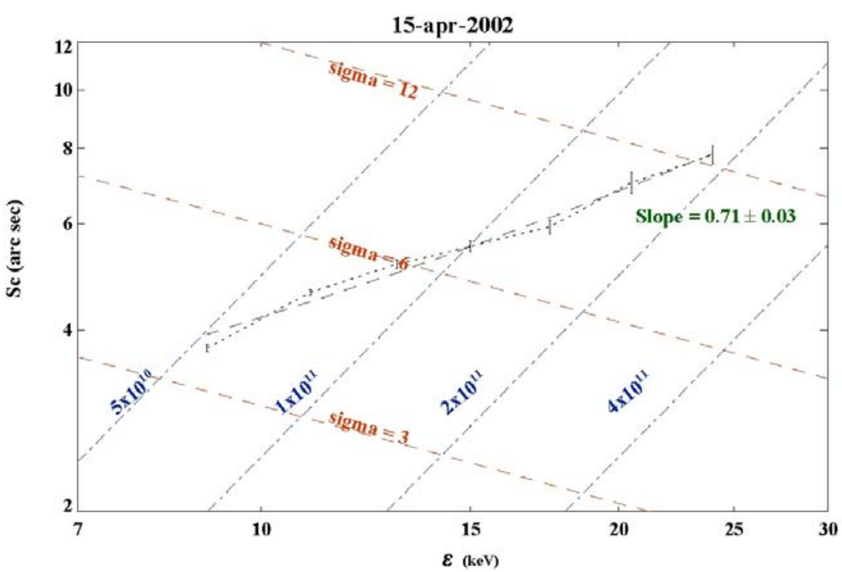
10 - 12 keV

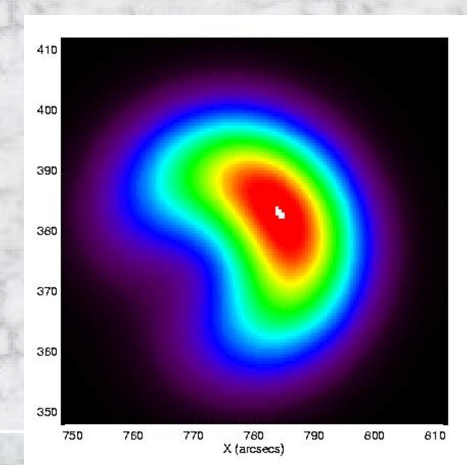


14 - 16 keV



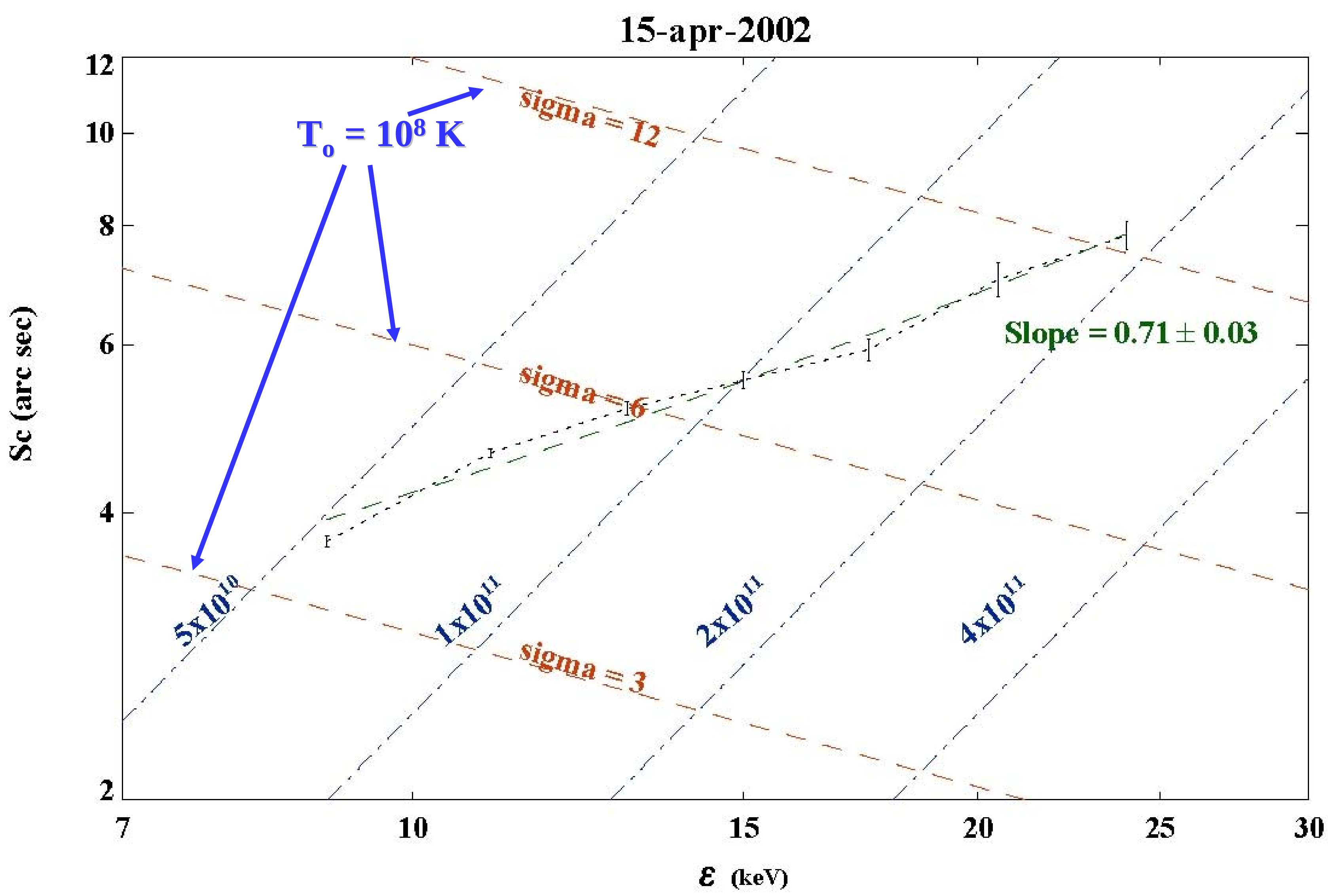
19 - 22 keV





26 – 30 keV

Source Size vs Energy



Can collisions be compatible?

- Yes, if the density is not uniform

$$dE/ds \sim -n/E \xrightarrow{\sim} d\varepsilon/ds \sim -n/\varepsilon$$

$$\boxed{n \sim -\varepsilon \, d\varepsilon/ds}$$

Previous Application of this Technique – Aschwanden, Brown, & Kontar 2002

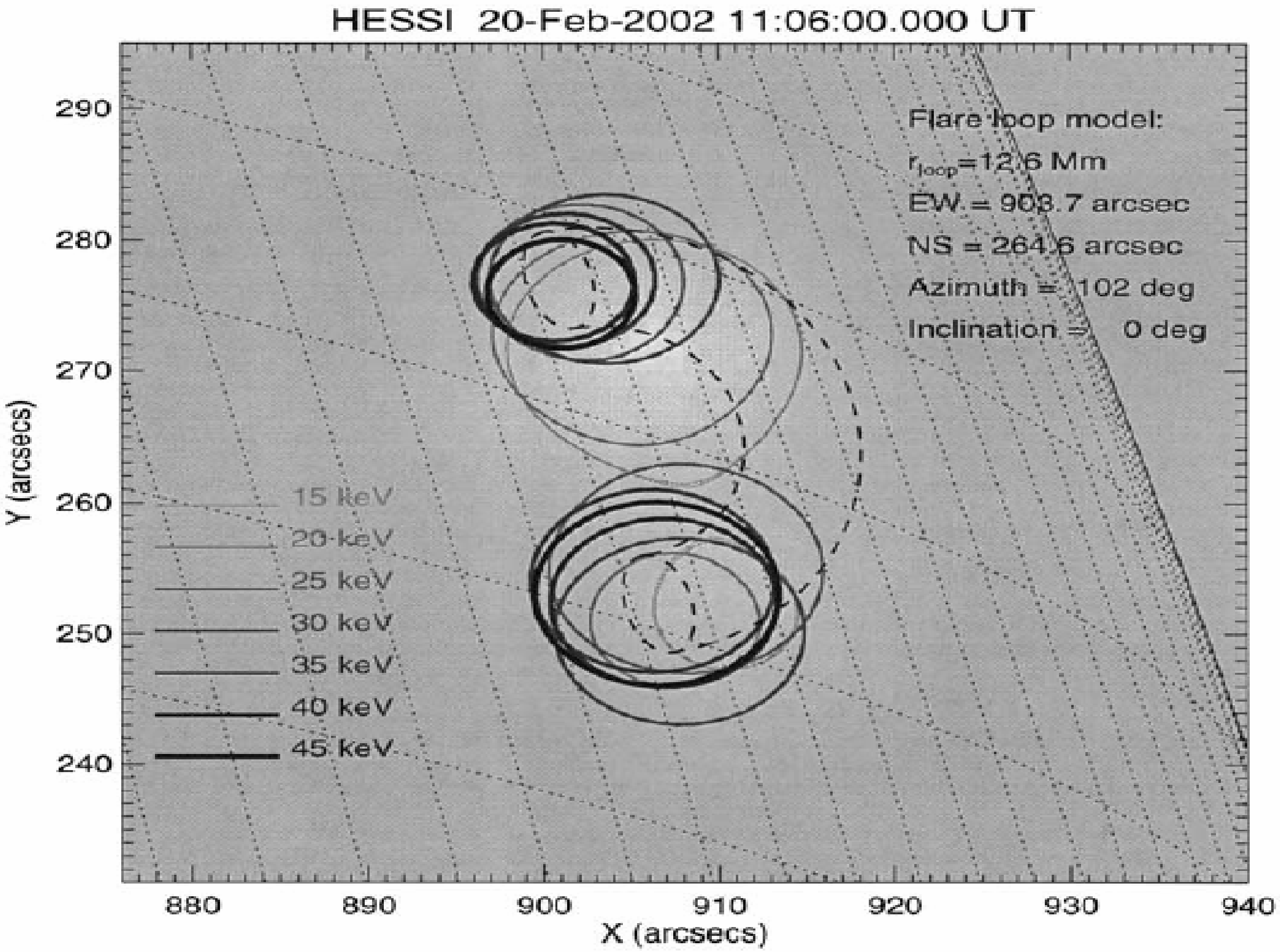


Figure 3. FWHM contours of forward-fit maps overlaid at different energies (15, 20, . . . , 45 keV). The greyscale map represents the 15 keV map. A heliographic grid with 1° spacing is overlaid. The *dashed lines* demarcate a flare loop with semi-circular geometry and vertical loop plane. Note that the centroids of the hard X-ray sources systematically increase in altitude with lower energies.

Previous Application of this Technique – Aschwanden, Brown, & Kontar 2002

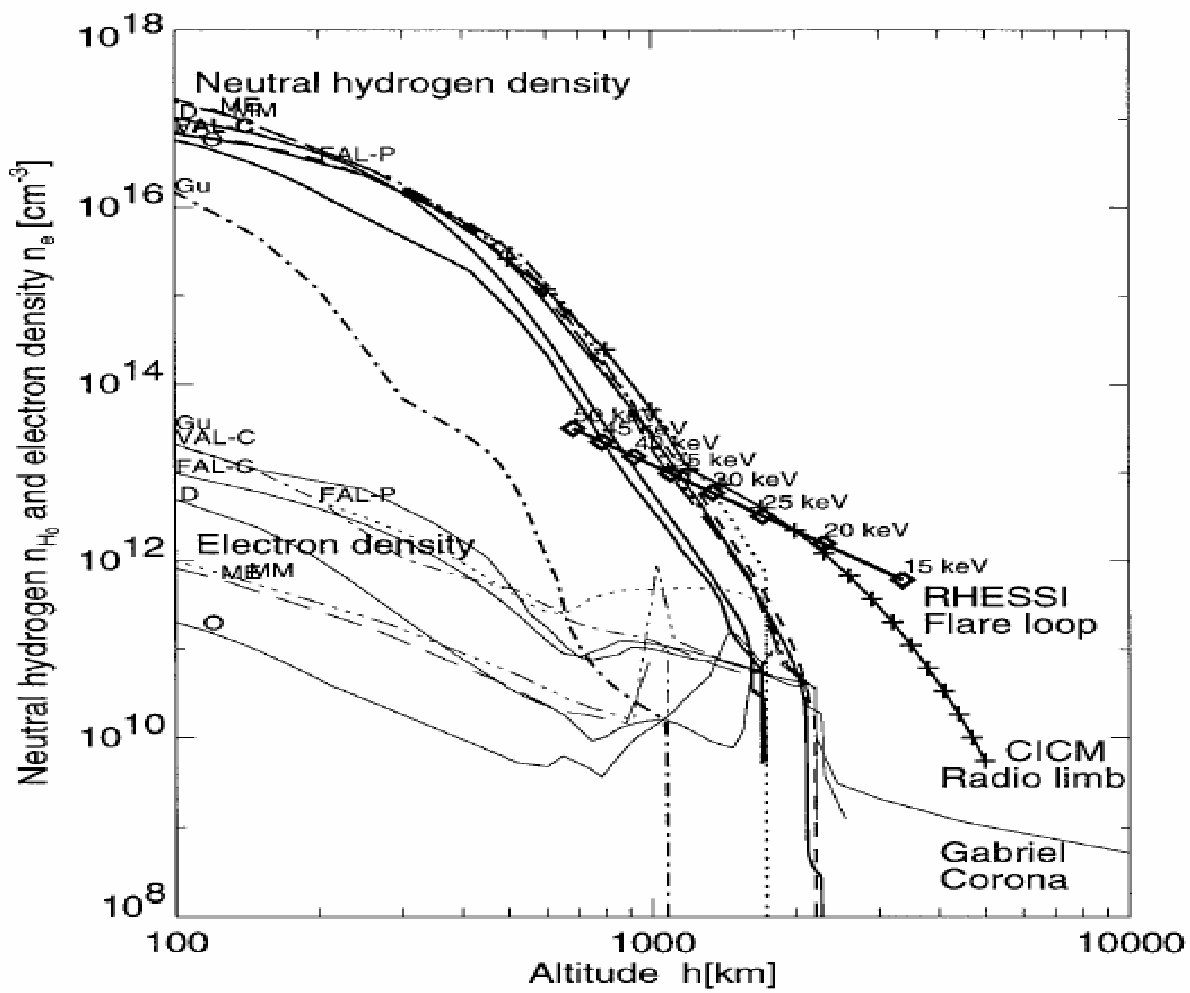
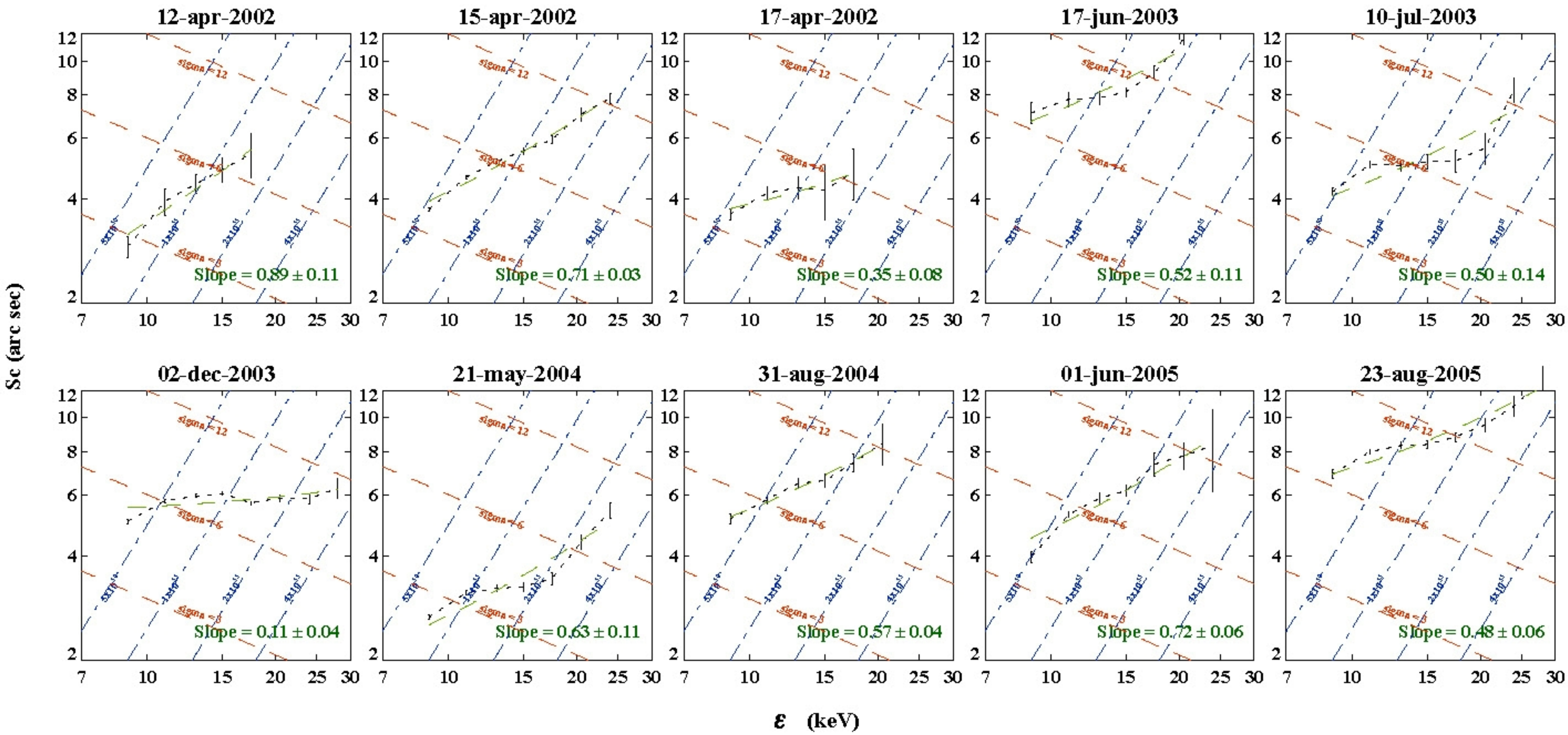
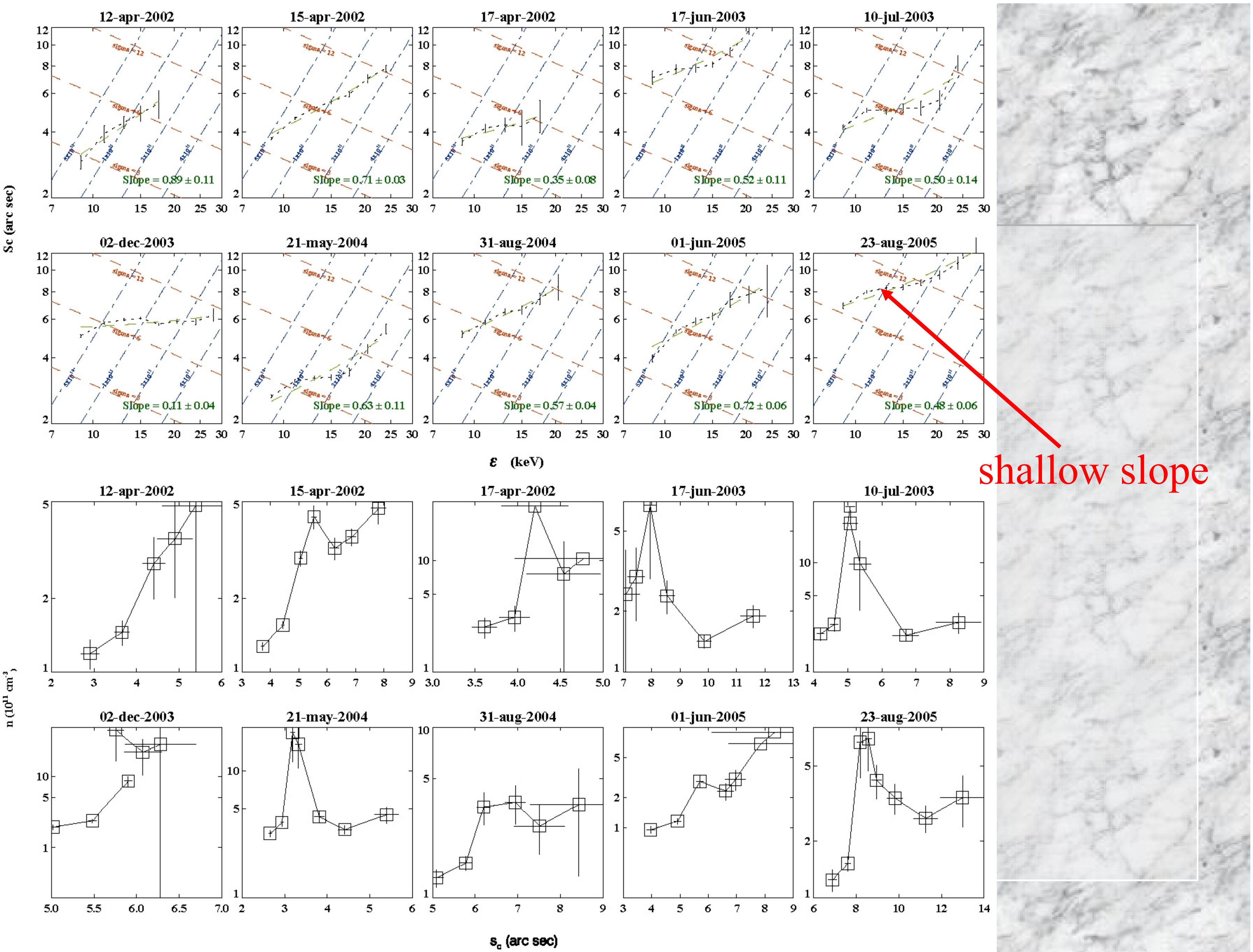


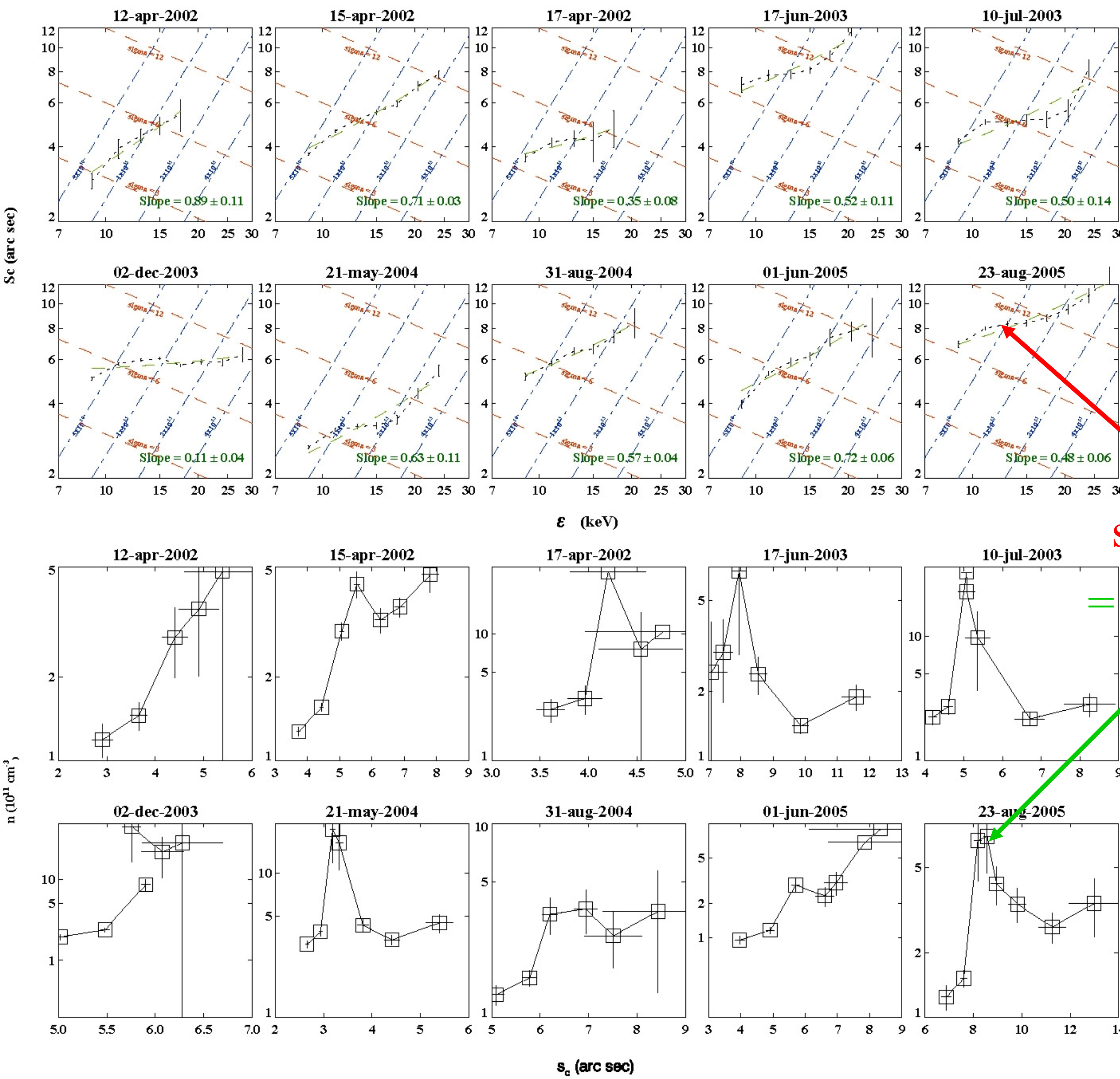
Figure 10. A compilation of chromospheric and coronal density models: VAL-C = Vernazza, Avrett, and Loeser (1981), model C; FAL-C = Fontenla, Avrett, and Loeser (1990), model C; FAL-P = Fontenla, Avrett, and Loeser (1990), model P; Gu = Gu *et al.* (1997); MM = Maltby *et al.*, 1986), model M; ME = Maltby *et al.* (1986), model E; D = Ding and Fang (1989); O = Obridko and Staude (1988); Gabriel = Gabriel (1976), coronal model; CICM = Caltech Irreference Chromospheric Model, radio sub-millimeter limb observations (Ewell *et al.*, 1993), RHESSI flare loop (this work).

Slopes for ensemble of events





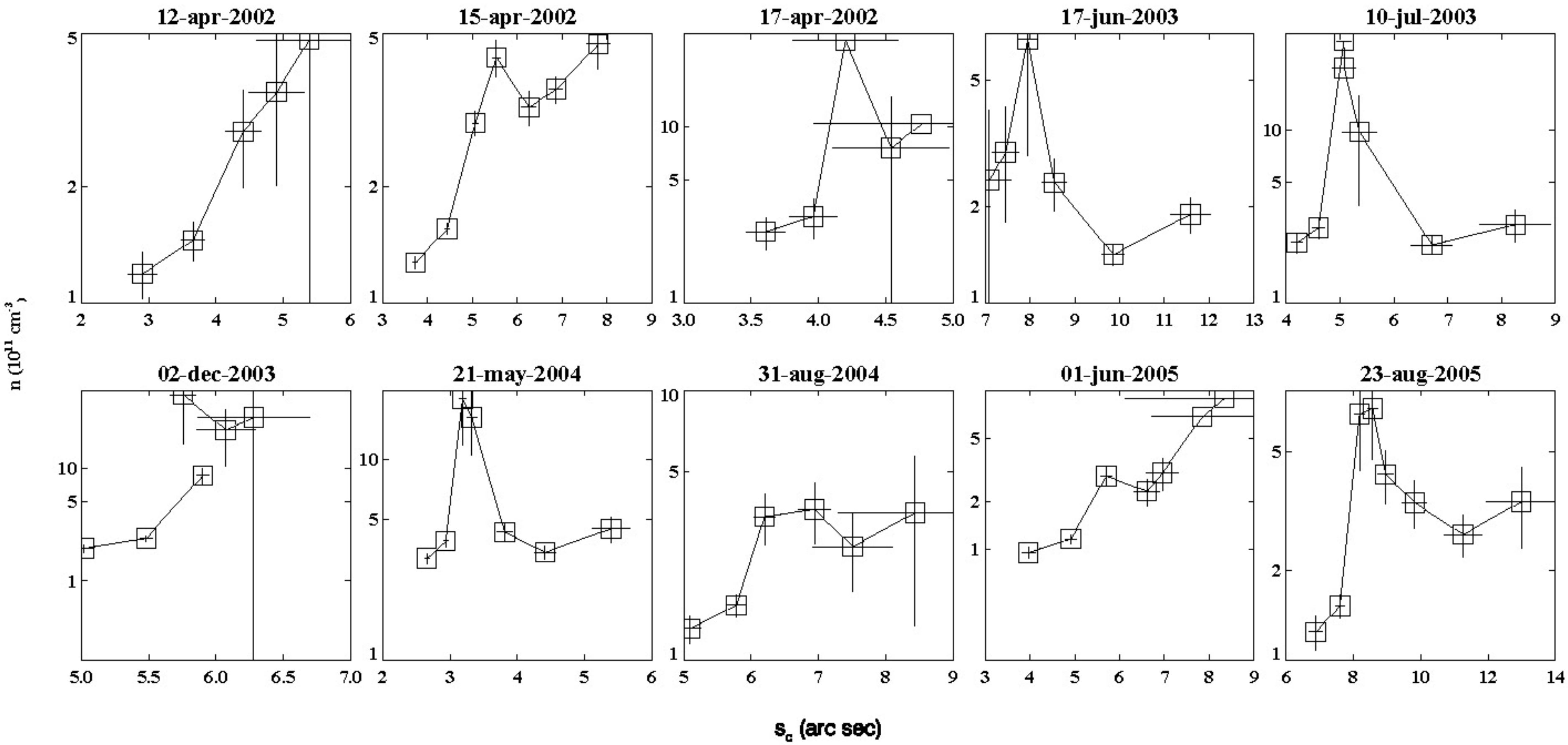
12-apr-2002
15-apr-2002
17-apr-2002
17-jun-2003
10-jul-2003
Slope = 0.89 ± 0.11
Slope = 0.71 ± 0.03
Slope = 0.35 ± 0.08
Slope = 0.52 ± 0.11
Slope = 0.50 ± 0.14
02-dec-2003
21-may-2004
31-aug-2004
01-jun-2005
23-aug-2005
Slope = 0.11 ± 0.04
Slope = 0.63 ± 0.11
Slope = 0.57 ± 0.04
Slope = 0.72 ± 0.06
Slope = 0.48 ± 0.06
Sc (arc sec)
ε (keV)
shallow slope
n (10^{11} cm^{-3})
s_c (arc sec)



shallow slope

= high density

Required density profiles



Collisional or not?

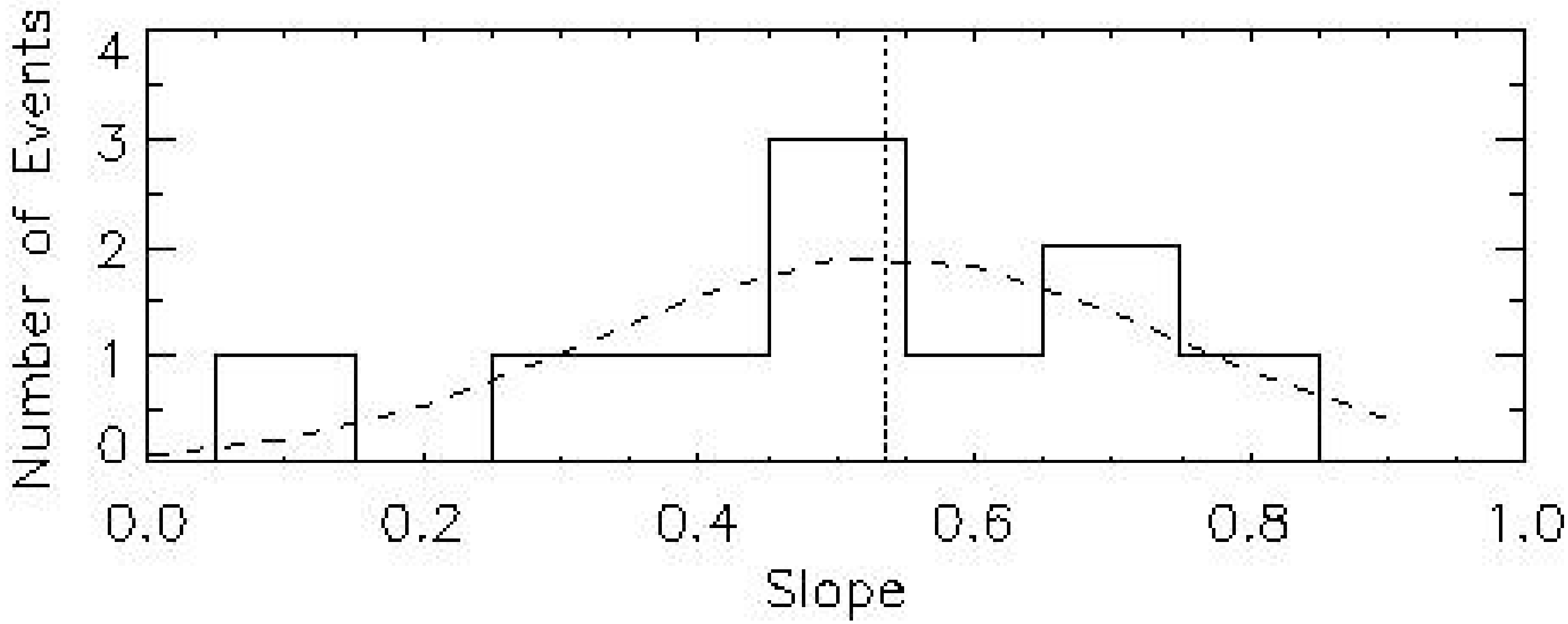
Implausible density profiles

Collisional or not?

Implausible density profiles

Alternative is non-collisional interpretation – slope $\neq 2$

Histogram of Slopes



NOT compatible with slope of 2!

Significance of Observed Slope

- Collisions

  $dE/ds \sim - n/E^{\alpha}$, $\alpha=1$, slope $= 1 + \alpha = 2$

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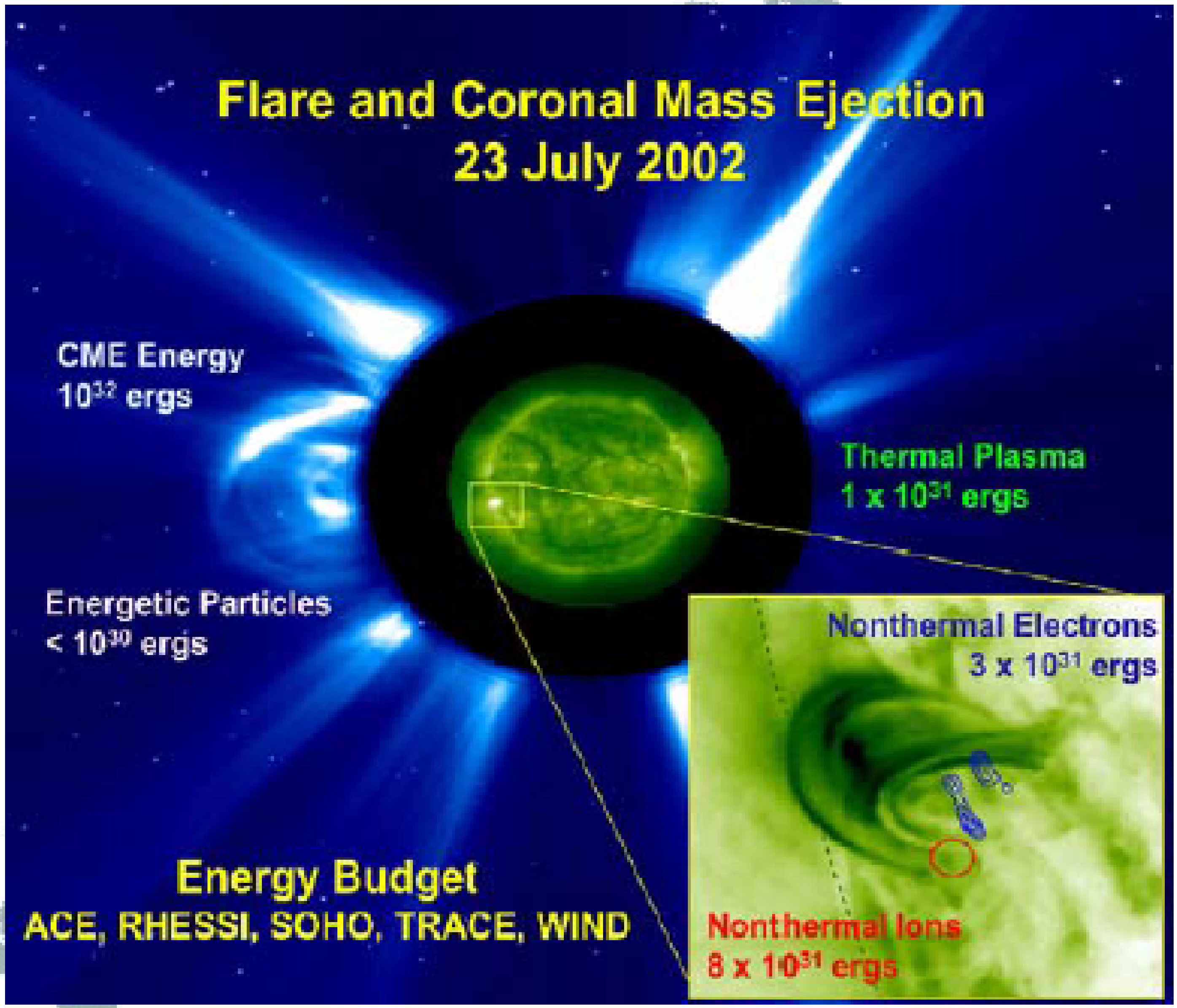
  $\alpha \sim -0.5$

  $\rightarrow dE/ds \sim -\, nE^{0.5} \sim -nv$ (??)

What do we Tell the Theorists? (4)

- There is considerable evidence that collisional modification to accelerated electrons in a uniform plasma is *not* the dominant mechanism driving energy loss processes in bremsstrahlung-producing electrons
- Either
  - (a) considerable ***inhomogeneity*** in the transport region is required; and/or
  - (b) ***non-collisional losses are important***
- Observations *can* define the empirical form of the energy loss process

Overall Energetics



What do we Tell the Theorists? (5)

- The CME and optical continua represent the bulk of the released energy in flares
- The energy in the thermal plasma and in accelerated particles are comparable
- One must be careful not to “double-count” in energetic partition studies, e.g.
  - energy in accelerated electrons and the EUV/HXR thermal plasma
  - energy in accelerated protons and optical plasma
- Shock acceleration of SEPs is ~10% efficient