Nonthermal Hard X-Ray Radiation from Solar Flares: Observations and Models

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What do we mean by “hard X-rays and “nonthermal radiation”?

- **Hard X-rays**: 10 keV – 300 keV, between soft X-rays and gamma-rays

- **Nonthermal radiation**: radiation from an electron distribution that is *not locally Maxwellian*

First X-ray Observations

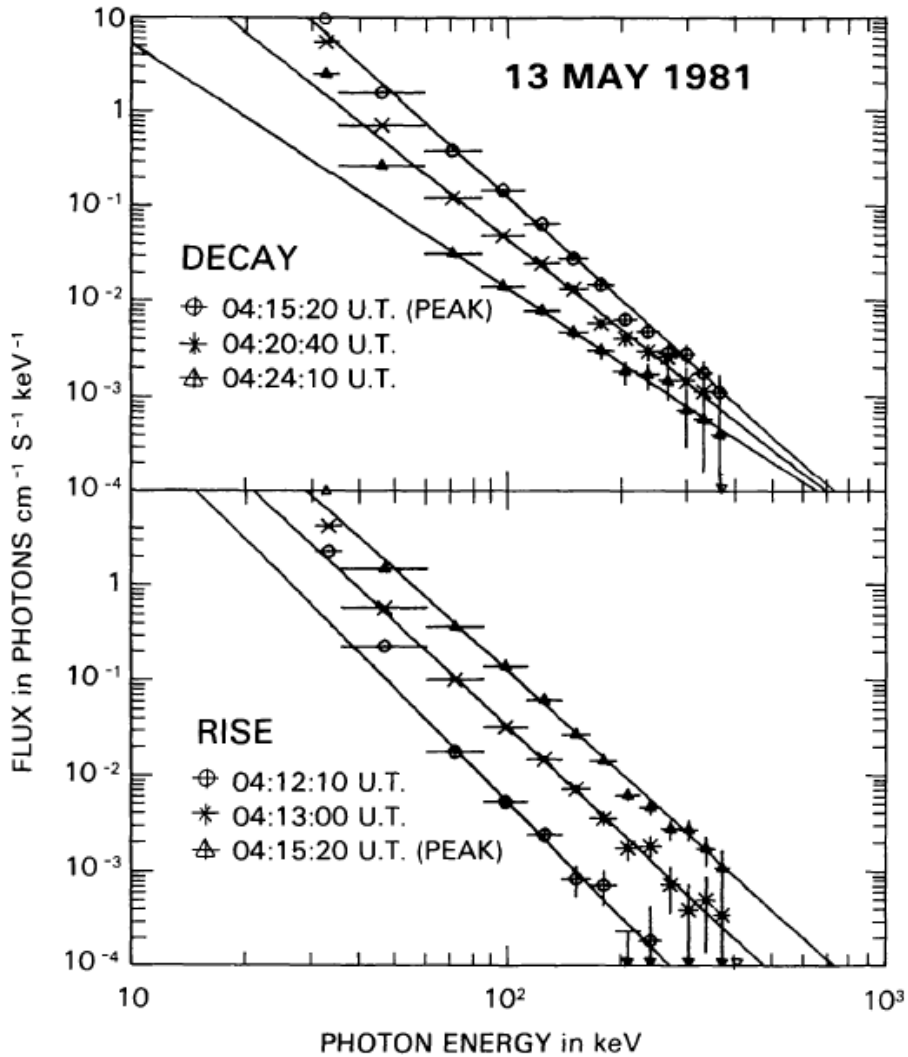
- X-rays first observed from the Sun by Friedman (Naval Research Lab.) with Geiger counters on a V-2 rocket in 1949
- First detection of a solar flare in hard X-rays/γ-rays: 1958 by Peterson & Winckler (Univ. of Minnesota) during a balloon flight from Cuba (1958 *Physical Review Letters*)

First Image of Hard X-ray Footpoints?

Solar Maximum Mission (SMM)
Hard X-ray Imaging Spectrometer (HXIS)

Hoyng et al., *The Astrophysical Journal Letters*, 1981

Spectra from the *Solar Maximum Mission* Hard X-Ray Burst Spectrometer



Dennis, *Solar Physics*, 1985

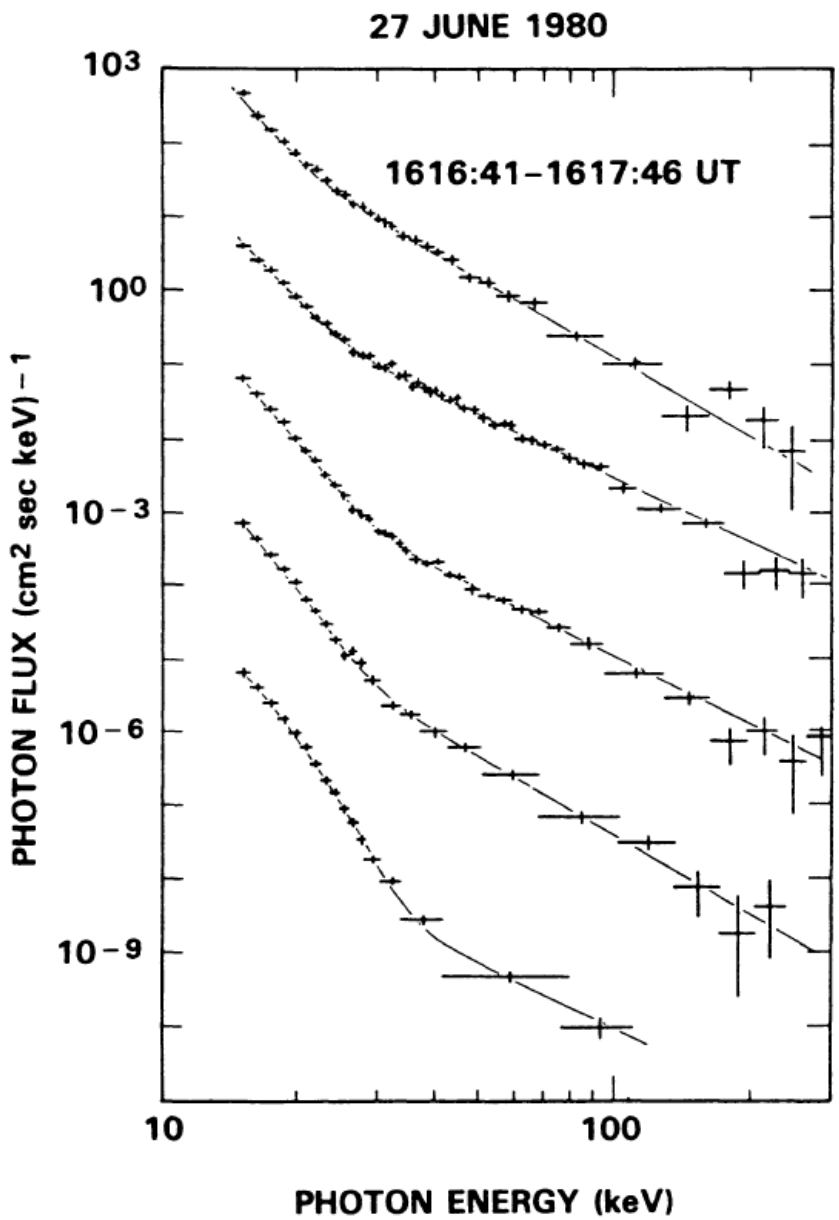
Flare Spectra Obtained with Cooled Germanium Detectors - 1980 Balloon Flight

34 MK “superhot” plasma

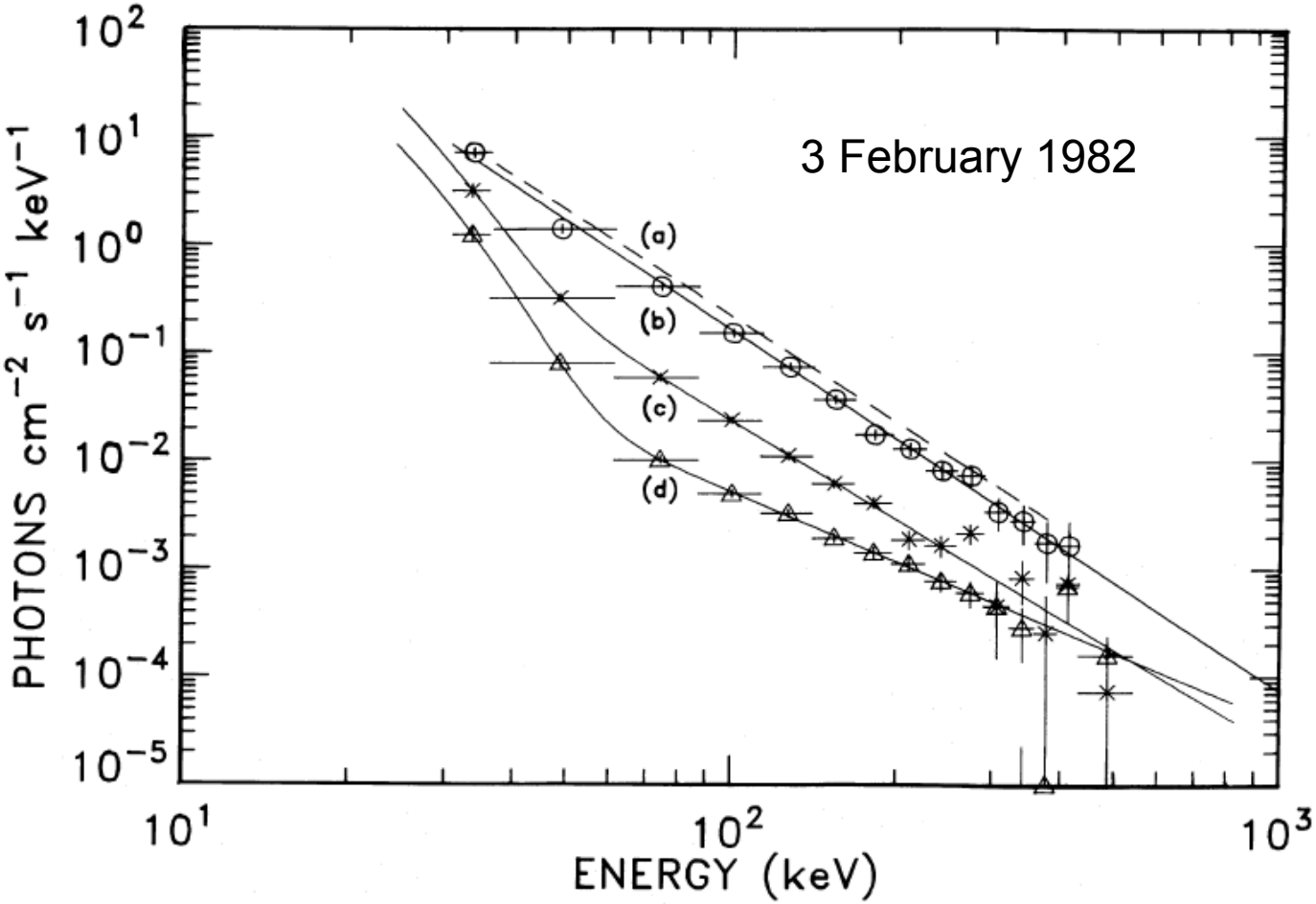
Lin et al., *The Astrophysical Journal Letters*, 1981

Double power-law spectra

Lin & Schwartz, *The Astrophysical Journal*, 1987

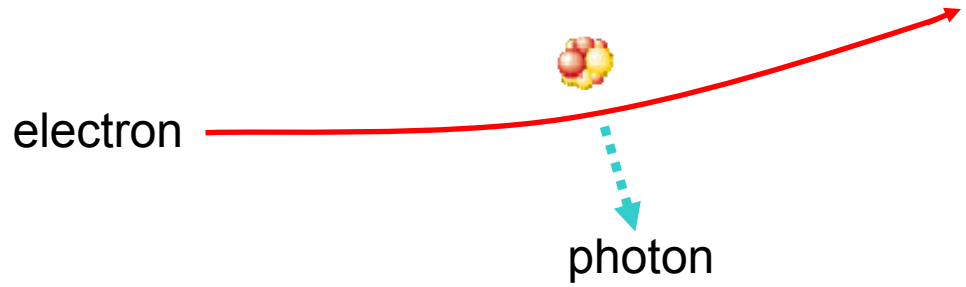


SMM HXRBS Spectra Indicating a Thermal Component at Low Energies



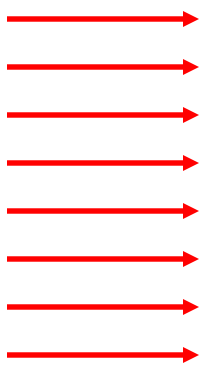
Kiplinger et al., *The Astrophysical Journal*, 1989

From Fast Electrons to Bremsstrahlung Photons



n
ions cm^{-3}

Nv
electrons cm^{-2} s^{-1}



Bremsstrahlung

Cross section
σ (cm^2)

$N_{ph} = nNv\sigma$

photons s^{-1} cm^{-3}

From an Electron Distribution Function to a Bremsstrahlung Spectrum

$$N_{ph}(\varepsilon, E) = nN(E)v\sigma(\varepsilon, E)$$

ε = photon energy

E = electron energy

Differential cross section

$$\sigma(\varepsilon, E) = d\sigma(\varepsilon, E)/d\varepsilon$$

Electron Flux Distribution Function

$$F(E) = N(E)v \quad \text{electrons cm}^{-2}\ \text{s}^{-1}\ \text{keV}^{-1}$$

$$N_{ph}(\varepsilon) = n \int_{\varepsilon}^{\infty} F(E)\sigma(\varepsilon, E)\, dE$$

photons s^{-1} cm^{-3} keV^{-1}

Photon Flux at Detector & Mean Electron Flux

$$I(\varepsilon) = (1/4\pi R^2) \int_V n(r) \int_\varepsilon^\infty F(E,r)\sigma(\varepsilon, E)\, dE\, dV$$

photons s^{-1} cm^{-2} keV^{-1}

$$R = 1\ AU$$

$$I(\varepsilon) = (1/4\pi R^2) \int_\varepsilon^\infty \left[\int_V n(r)F(E,r)\, dV\right] \sigma(\varepsilon, E)\, dE$$

$$I(\varepsilon) = (1/4\pi R^2) \langle n\rangle V \int_\varepsilon^\infty \langle F(E)\rangle\, \sigma(\varepsilon, E)\, dE$$

photons s^{-1} cm^{-2} keV^{-1}

Mean Electron Flux: $\langle F(E)\rangle = (1/\langle n\rangle V) \int_V n(r)F(E,r)\, dV$

Thick-Target Bremsstrahlung I

$$I(\varepsilon) = (1/4\pi R^2) \int_V \int_\varepsilon^\infty n(r)\, F(E,r)\, \sigma(\varepsilon, E)\, dE\, dV$$

$$I(\varepsilon) = (1/4\pi R^2) \int_x \int_\varepsilon^\infty n(x)\, F(E,x)\, \sigma(\varepsilon, E)\, dE\, dx$$

For a steady state and E = E(x), electron flux conservation gives

$$F(E,x)\, dE = F(E_0)\, dE_0$$

$$F(E,x)\, (dE/dx)\, dx = F(E_0)\, dE_0$$

$$F(E,x)\, dx = F(E_0)\, dE_0 / (dE/dx)$$

$$\boxed{\begin{gathered} I(\varepsilon) = (1/4\pi R^2) \cdot \\ \cdot \int_\varepsilon^\infty F(E_0) \int_{E_0}^{\varepsilon} [\, n(x)\, \sigma(\varepsilon, E) / (dE/dx)\,]\, dE\, dE_0 \end{gathered}}$$

Thick-Target Bremsstrahlung II

$$I(\varepsilon) = (1/4\pi R^2) \int_{\varepsilon}^{\infty} F(E_0) \int_{E_0}^{\varepsilon} [\, n(x)\, \sigma(\varepsilon, E) / (dE/dx) \,]\, dE\, dE_0$$

For collisional energy losses in a *fully ionized plasma*,

$$dE/dx = -\, K\, n / E$$

$$\boxed{I(\varepsilon) = (1/K4\pi R^2) \int_{\varepsilon}^{\infty} F(E_0) \left[\int_{\varepsilon}^{E_0} \sigma(\varepsilon, E)\, E\, dE \right] dE_0}$$

Independent of plasma density, n(x)!

Can deduce the injected electron flux distribution, $F(E_0)$ electrons s^{-1} keV^{-1}

Accelerated Electron Number Flux & Energy Flux

$$dN_{el}/dt = \int F(E_0)\, dE_0$$

electrons s^{-1}

$$dW_{el}/dt = \int E\, F(E_0)\, dE_0$$

erg s^{-1}

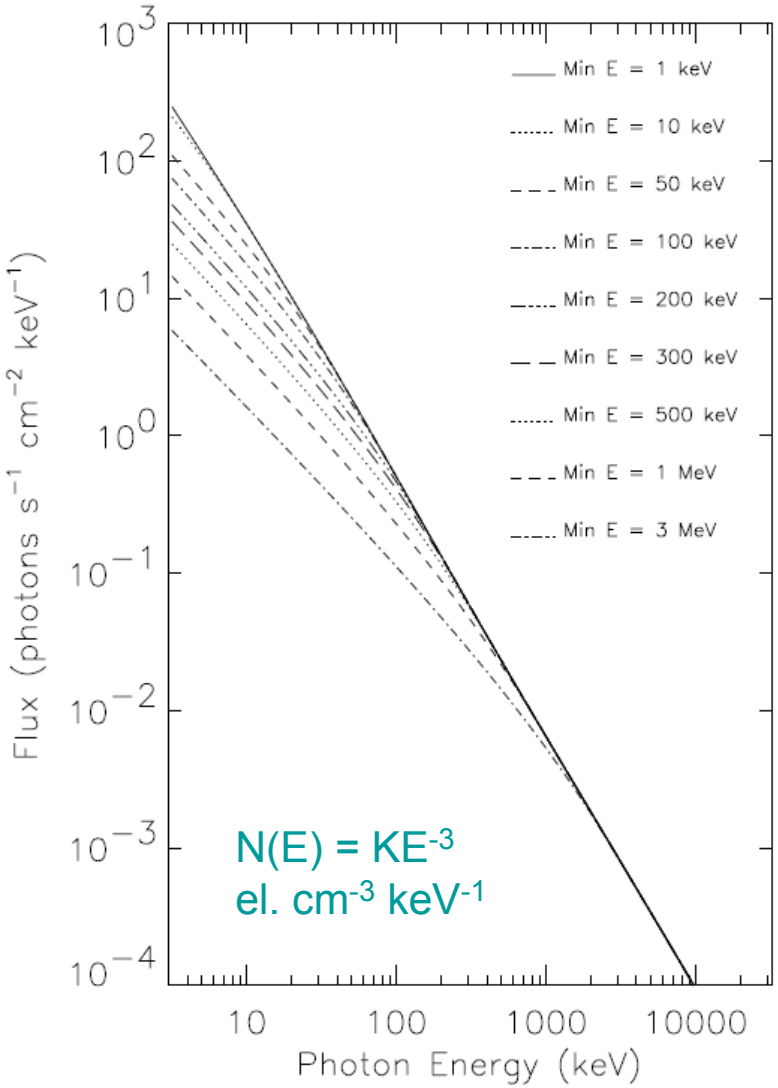
The Bremsstrahlung Cross Section

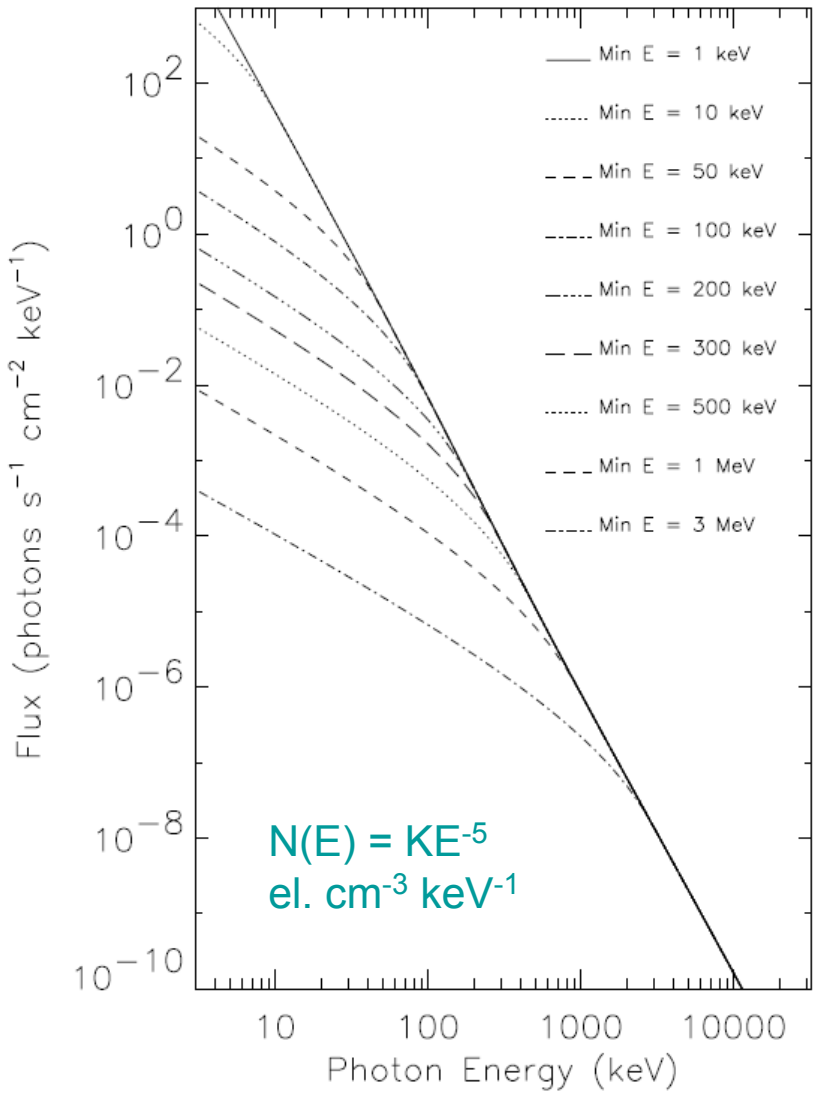
- Nonrelativistic approximations
  - Kramers: $\sigma(\varepsilon, E) = \sigma_0 / \varepsilon E$
  - Bethe-Heitler:
    $\sigma(\varepsilon, E) = (\sigma_0 / \varepsilon E) \ln[(E/\varepsilon)^{1/2} + (E/\varepsilon - 1)^{1/2}]$
- For relativistic, angle dependent, and polarization dependent cross sections, see Koch & Motz, *Reviews of Modern Physics*, 1959, and Haug, *Astronomy & Astro-physics*, 1997.

Approximate Results for Power-Law Electron Distributions (Brown, *Solar Physics*, 1971)

- Assume $I(E) \propto E^{-\delta}$ (photons s^{-1} cm^{-2} keV^{-1})
- Thin target: $F(E) \propto E^{-(\delta - 1)}$
  (electrons cm^{-2} s^{-1} keV^{-1})
- Thin target: $N(E) \propto E^{-(\delta - ½)}$
  (electrons cm^{-3} keV^{-1})
- Thick target: $F(E_0) \propto E_0^{-(\delta+1)}$
  (electrons s^{-1} keV^{-1})

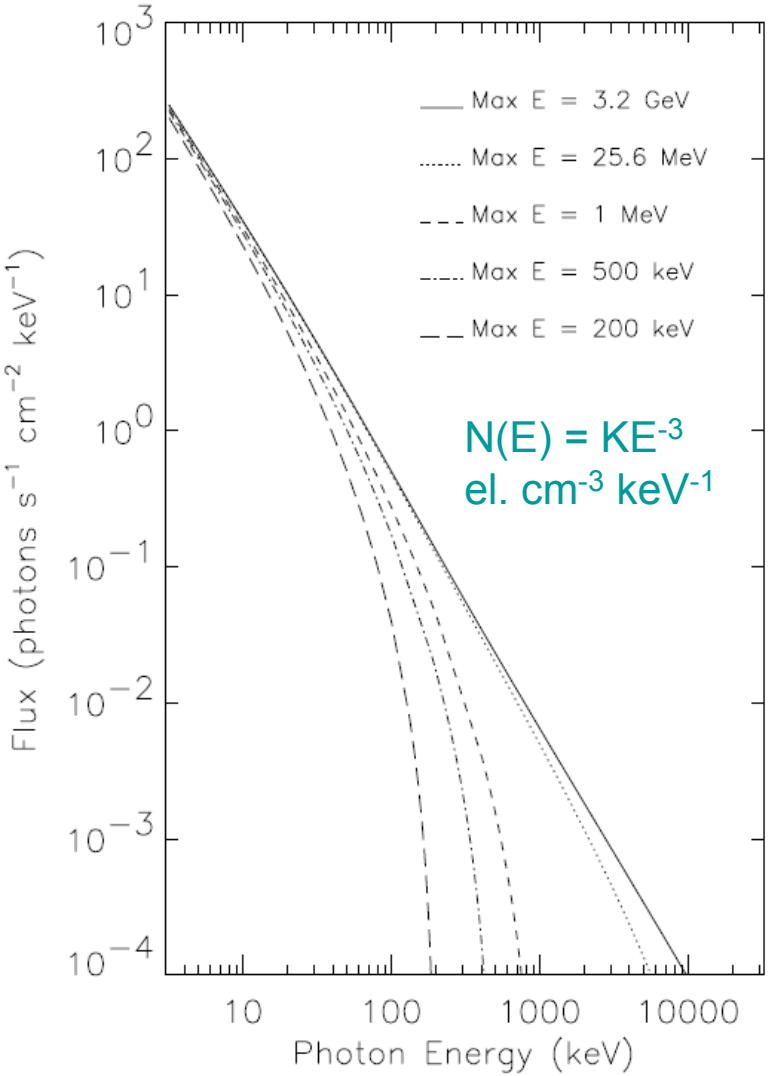
Spectra from Electron Distributions with a Low-Energy Cutoff

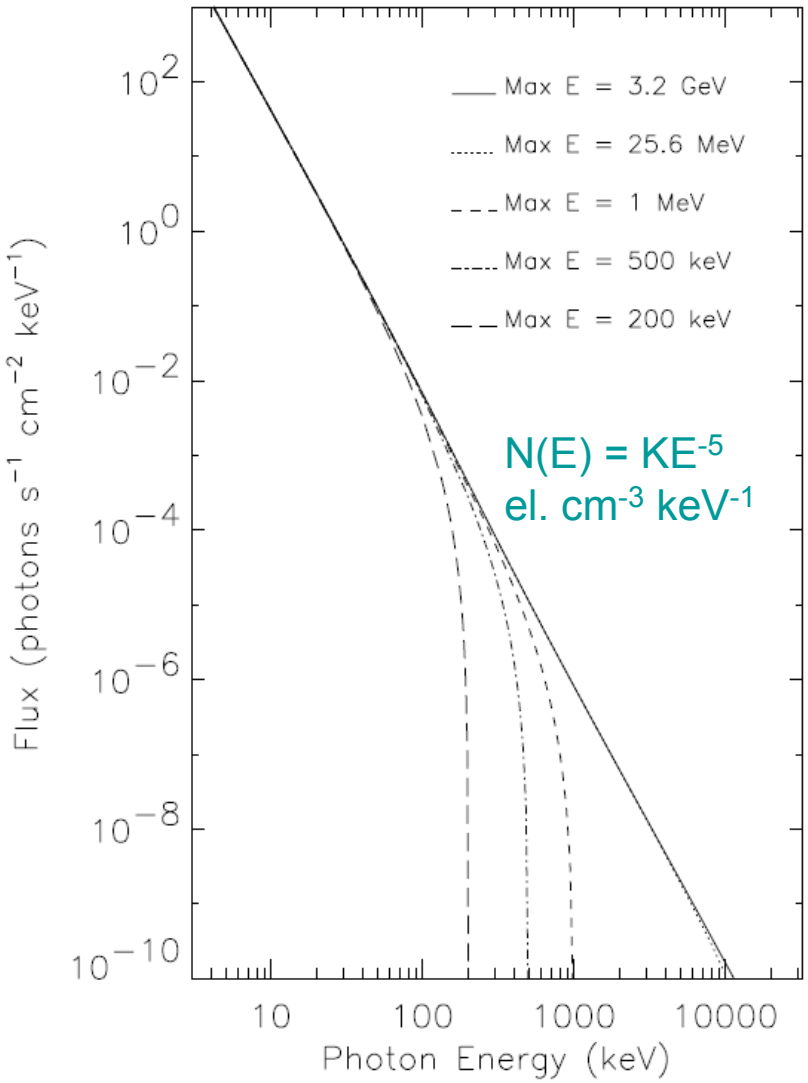




Holman, *The Astrophysical Journal*, 2003

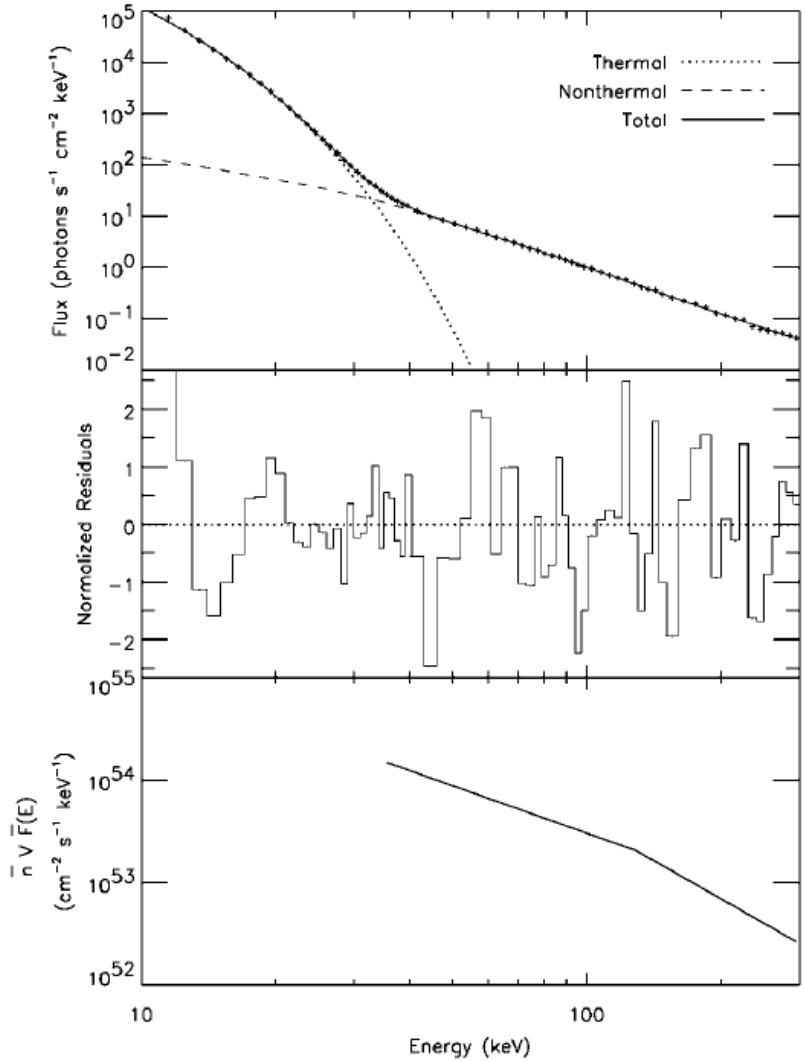
Spectra from Electron Distributions with a High-Energy Cutoff





Holman, *The Astrophysical Journal*, 2003

Forward Fit to a RHESSI Flare Spectrum



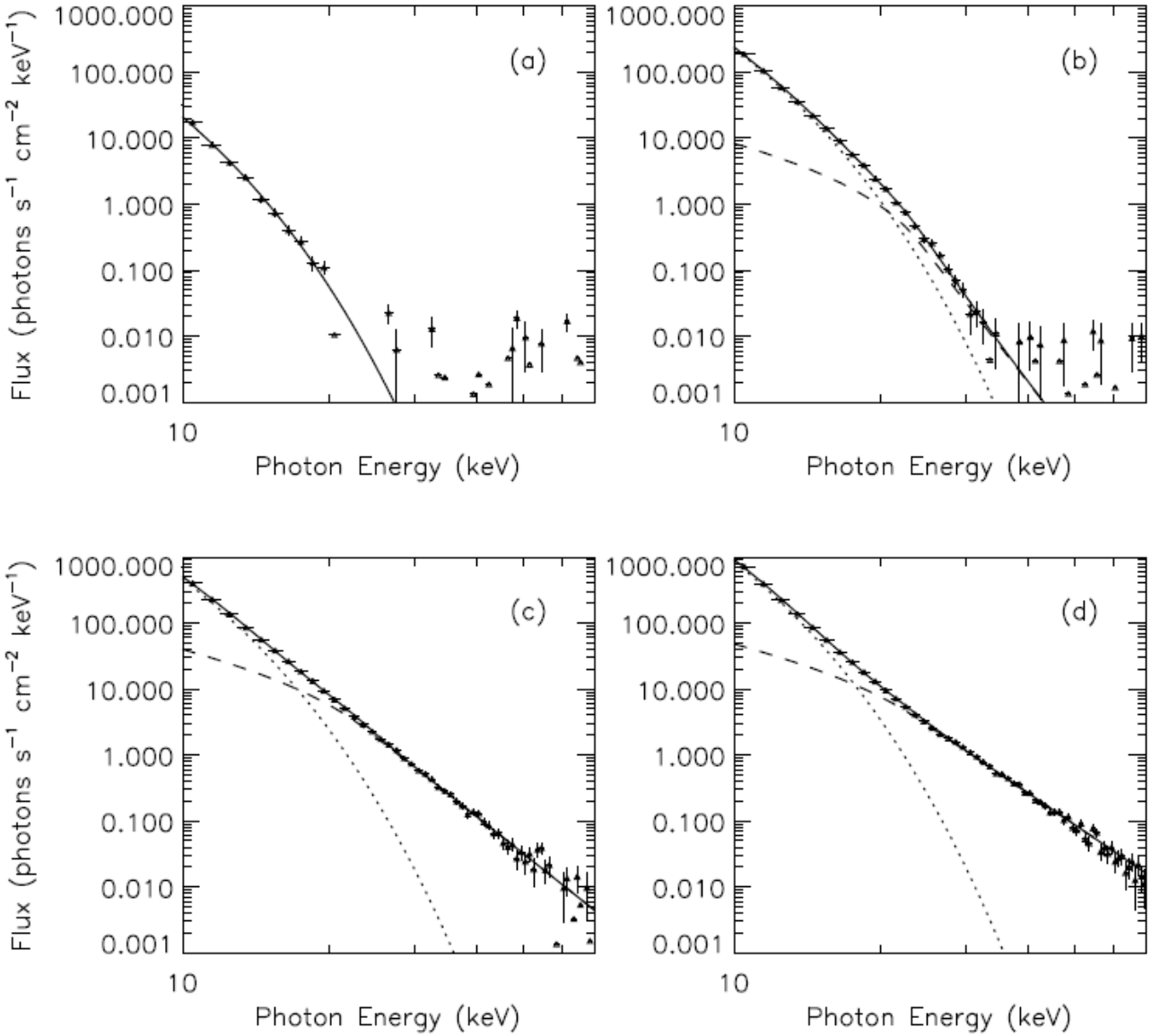
23 July 2002
00:30:00 – 00:30:20 UT

(Observed Flux – Model Flux) / σ

Best-Fit Model Mean Electron Flux Electron Distribution

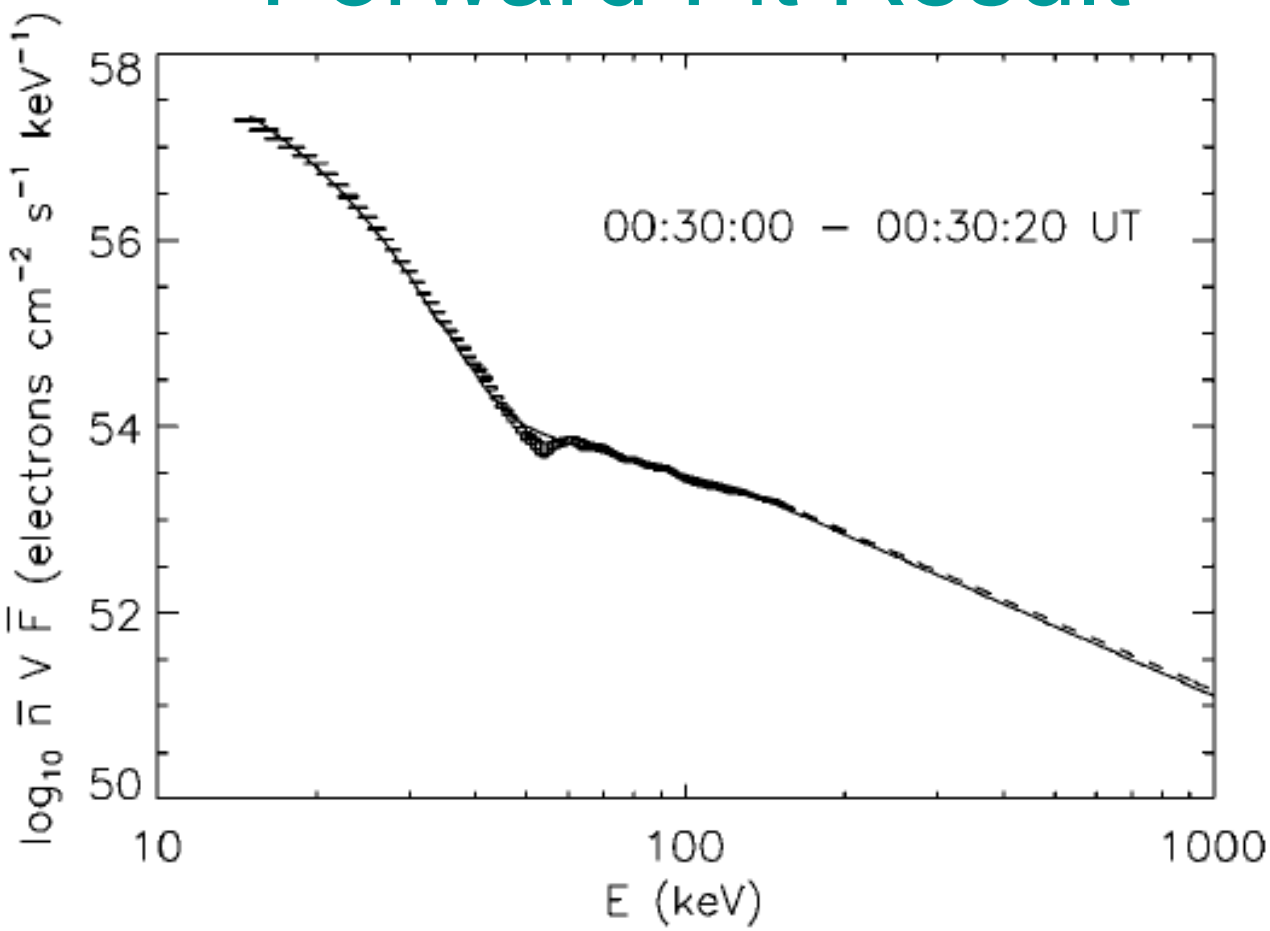
Holman et al., *The Astrophysical Journal Letters*, 2003

Spectral Fits to the 15 April 2002 Flare



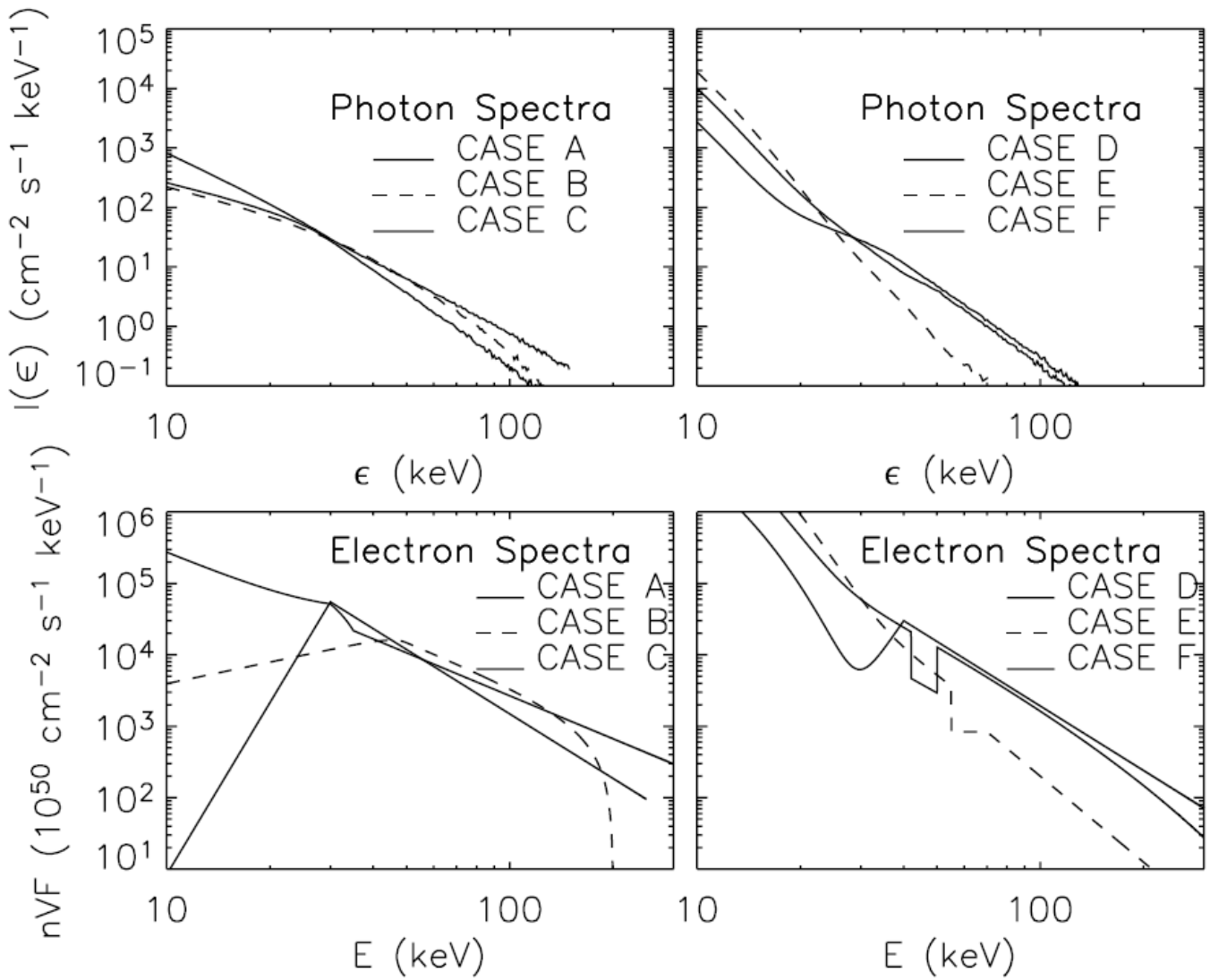
Sui et al., ApJ, 2005

Regularized Inversion of the July 23 Spectrum Compared with the Forward Fit Result



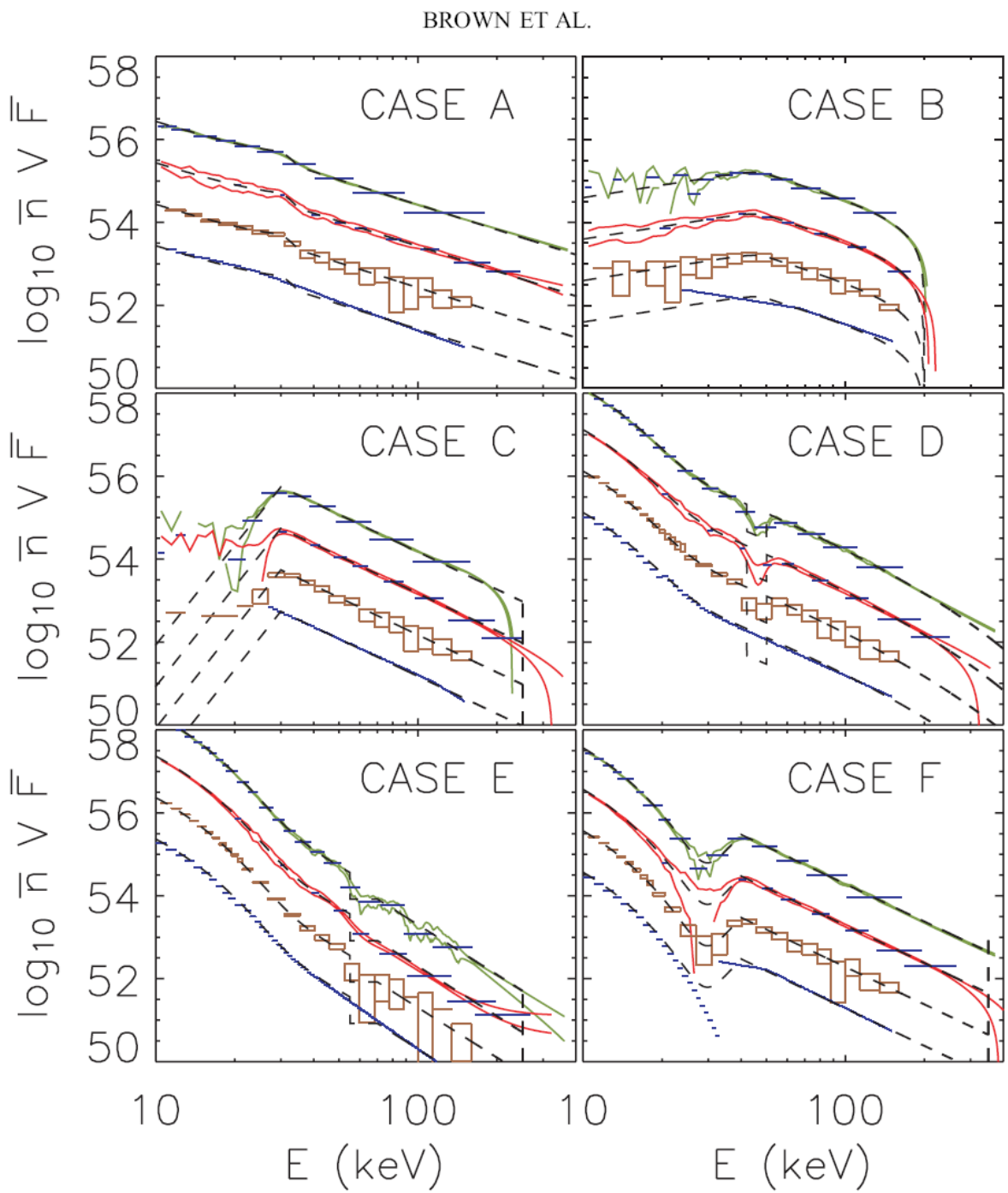
Piana et al., *The Astrophysical Journal Letters*, 2003

Photon Spectra from Theoretical Electron Distributions with “Interesting Features”



Brown et al., *The Astrophysical Journal*, 2006

Three Inversions and a Forward Fit to the Theoretical Photon Spectra

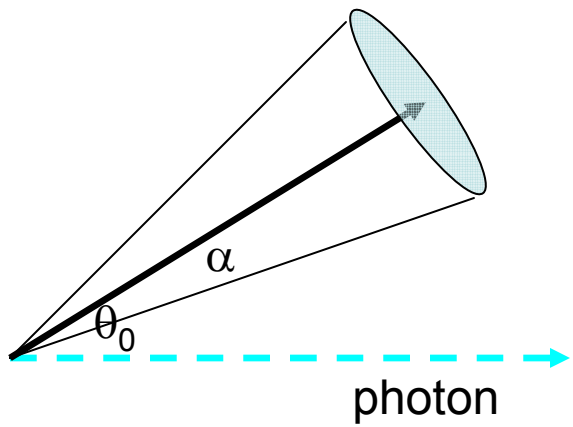


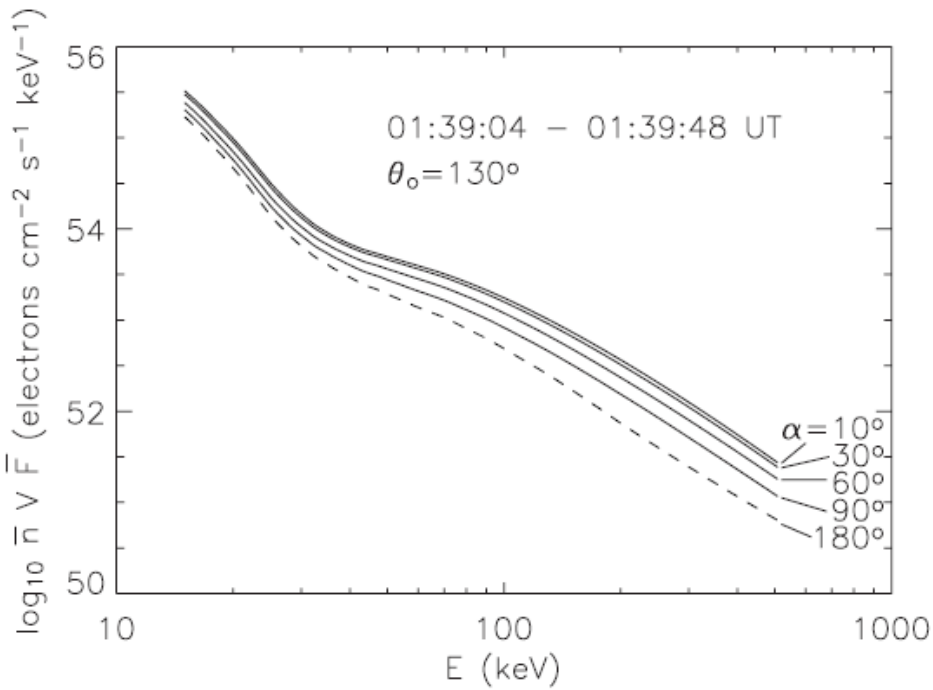
Alternative Emission Mechanisms

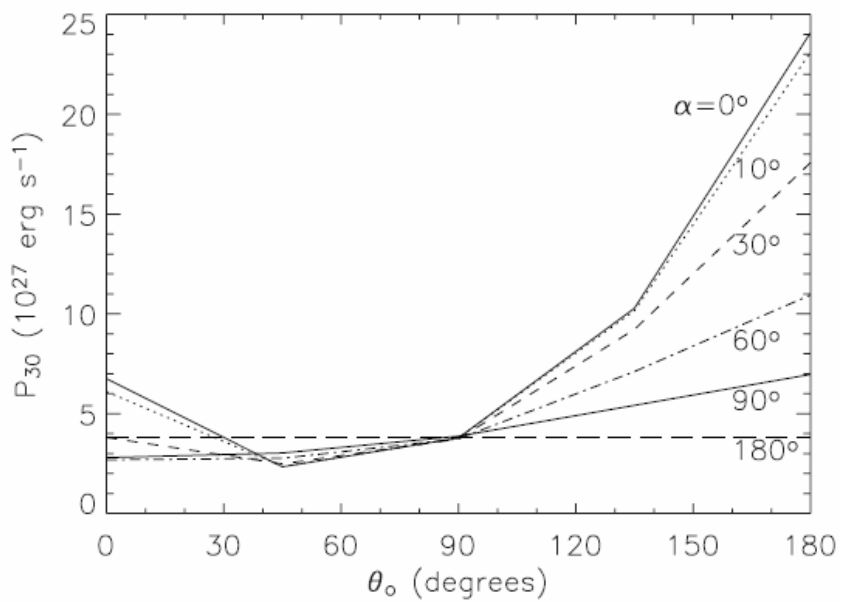
- Inverse Compton Radiation
- Synchrotron Radiation
- Inverse (proton-electron) bremsstrahlung

- Electron-electron bremsstrahlung – becomes significant at energies above ~100 keV

Anisotropic Electron Distribution

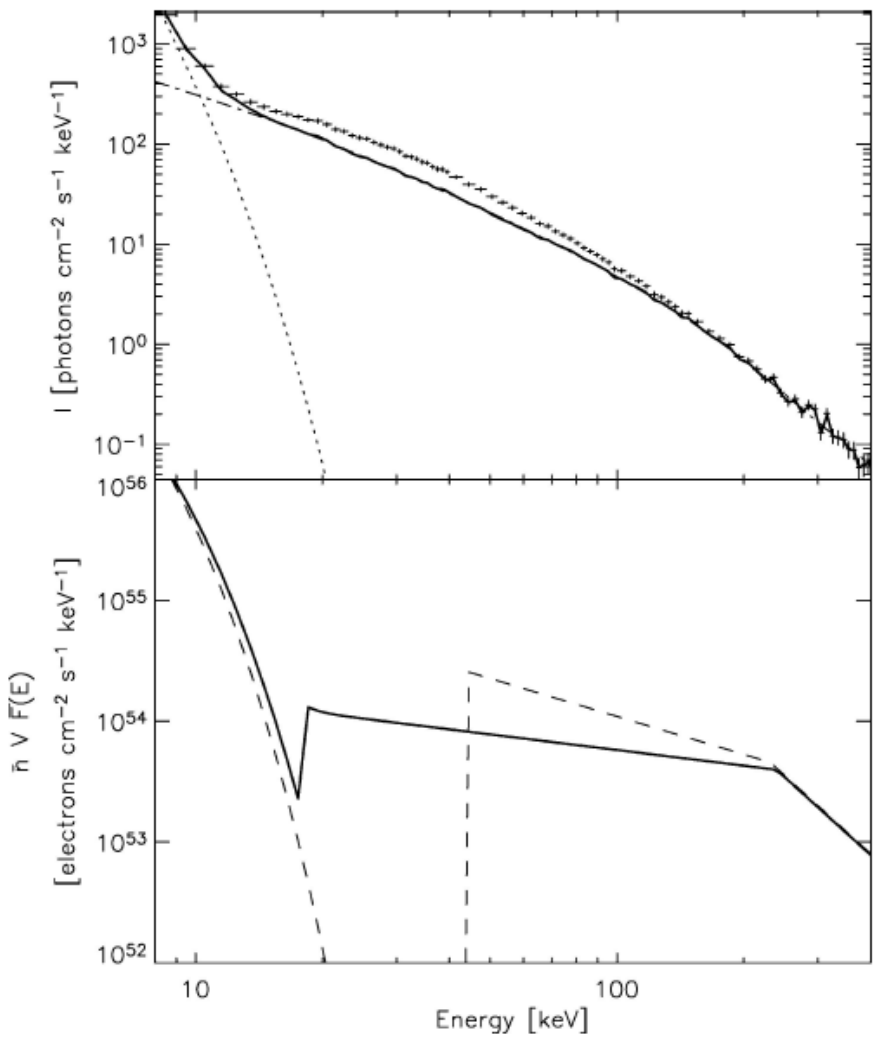






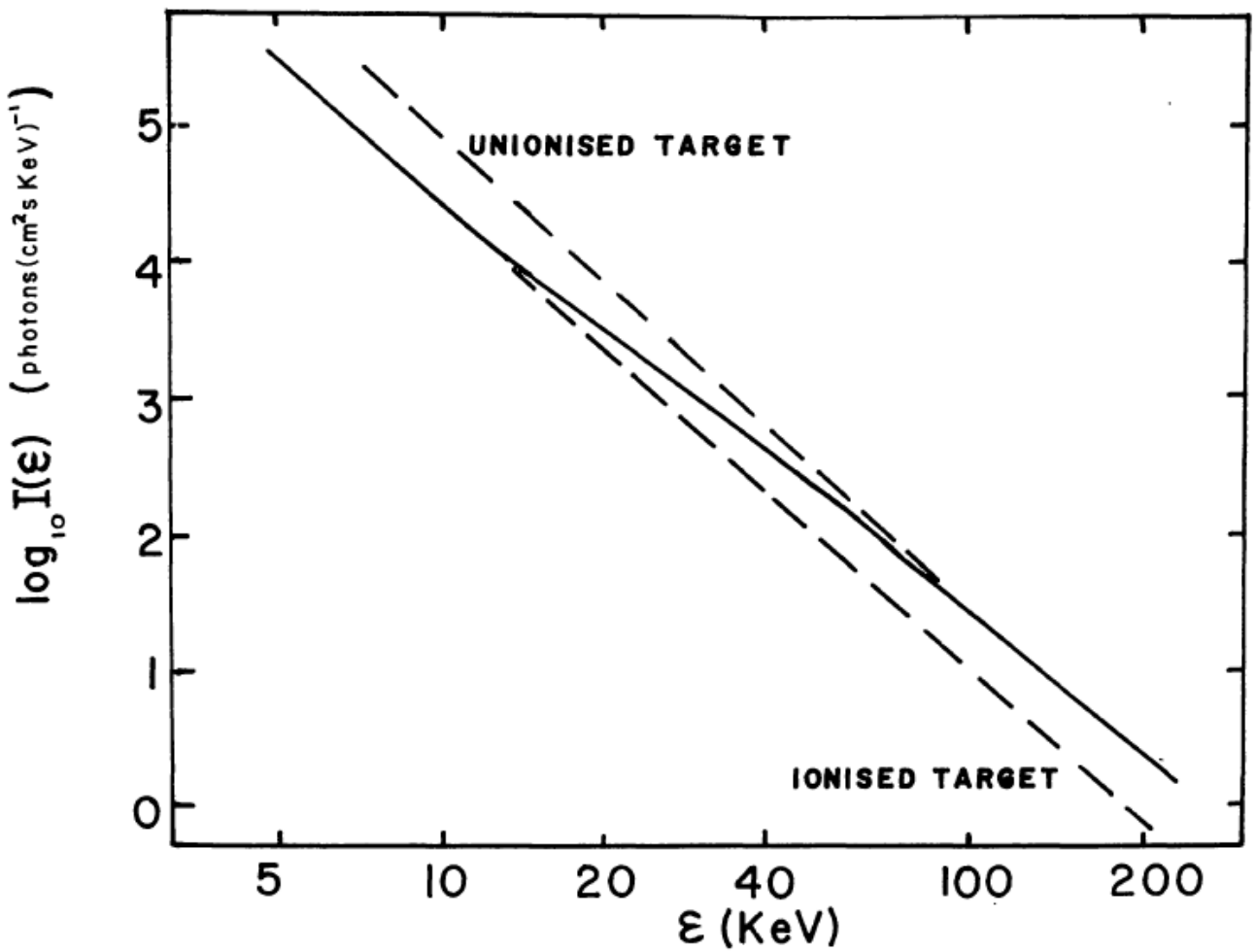
Massone et al., *The Astrophysical Journal*, 2004

Compton Backscattered Photons (Albedo)



Kasparova et al., *Solar Physics*, 2005

Partially Ionized Thick Target



Brown, *Solar Physics*, 1973

Time Delays & Electron Propagation

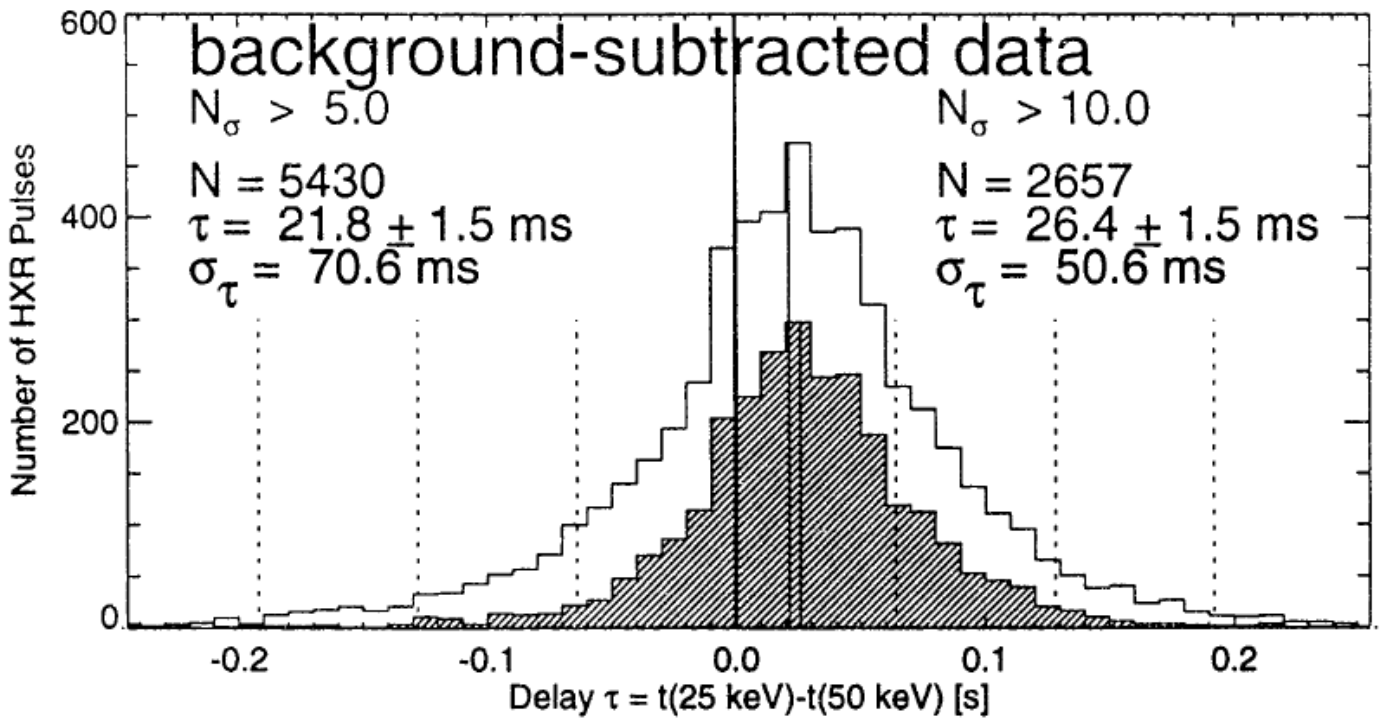
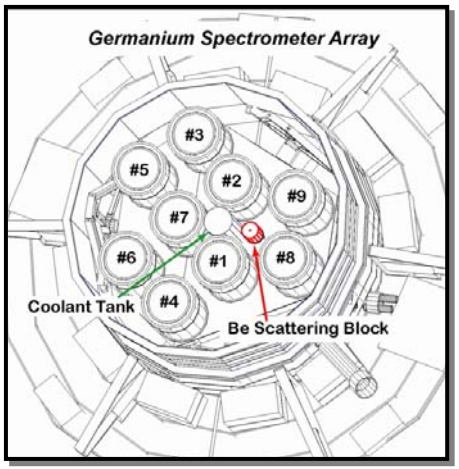


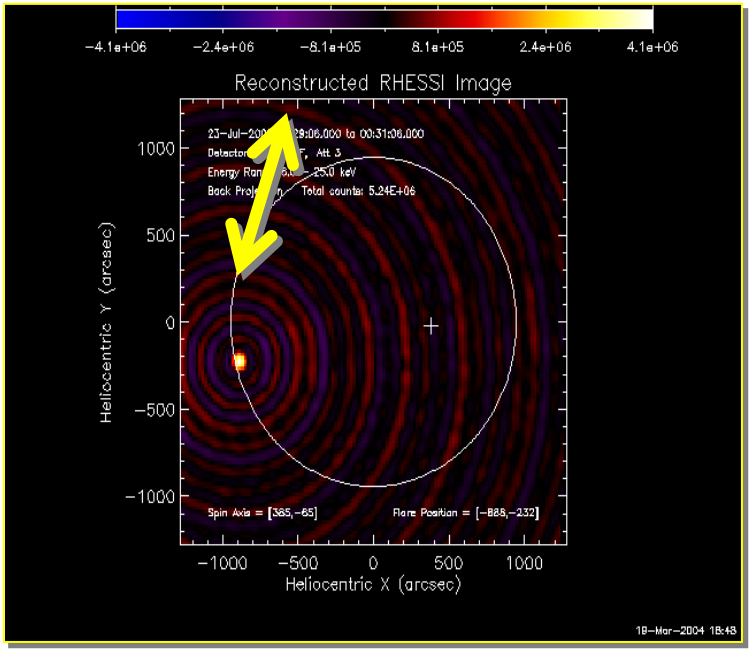
FIG. 7.—Distribution of measured time delays $\tau = t(25\ \text{keV}) - t(50\ \text{keV})$

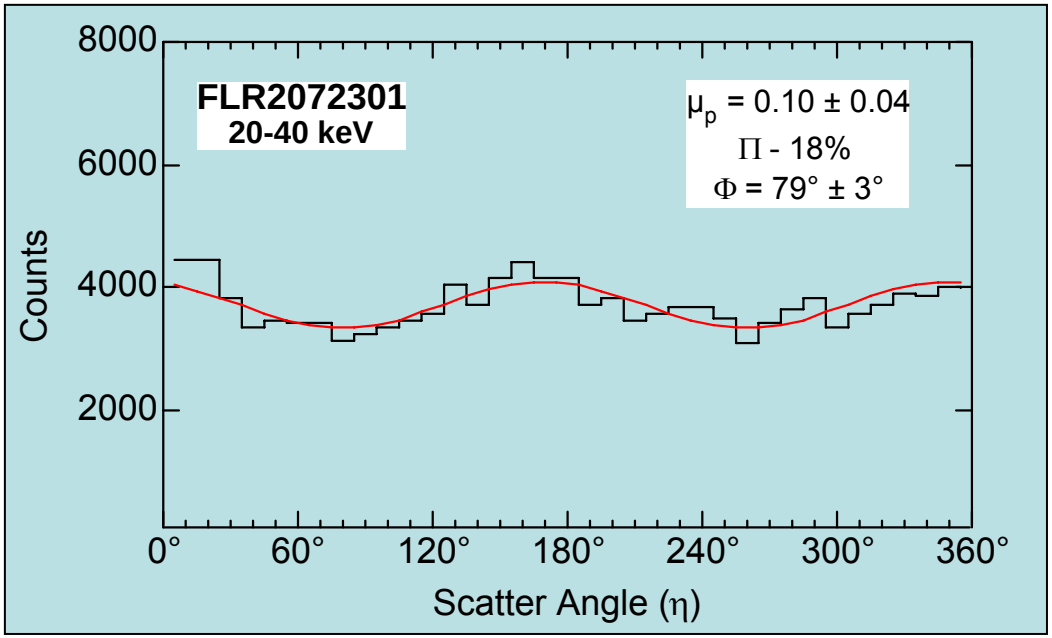
Aschwanden et al., *The Astrophysical Journal*, 1995

Hard X-Ray Polarimetry

X4.8 Flare of 23-July-2002



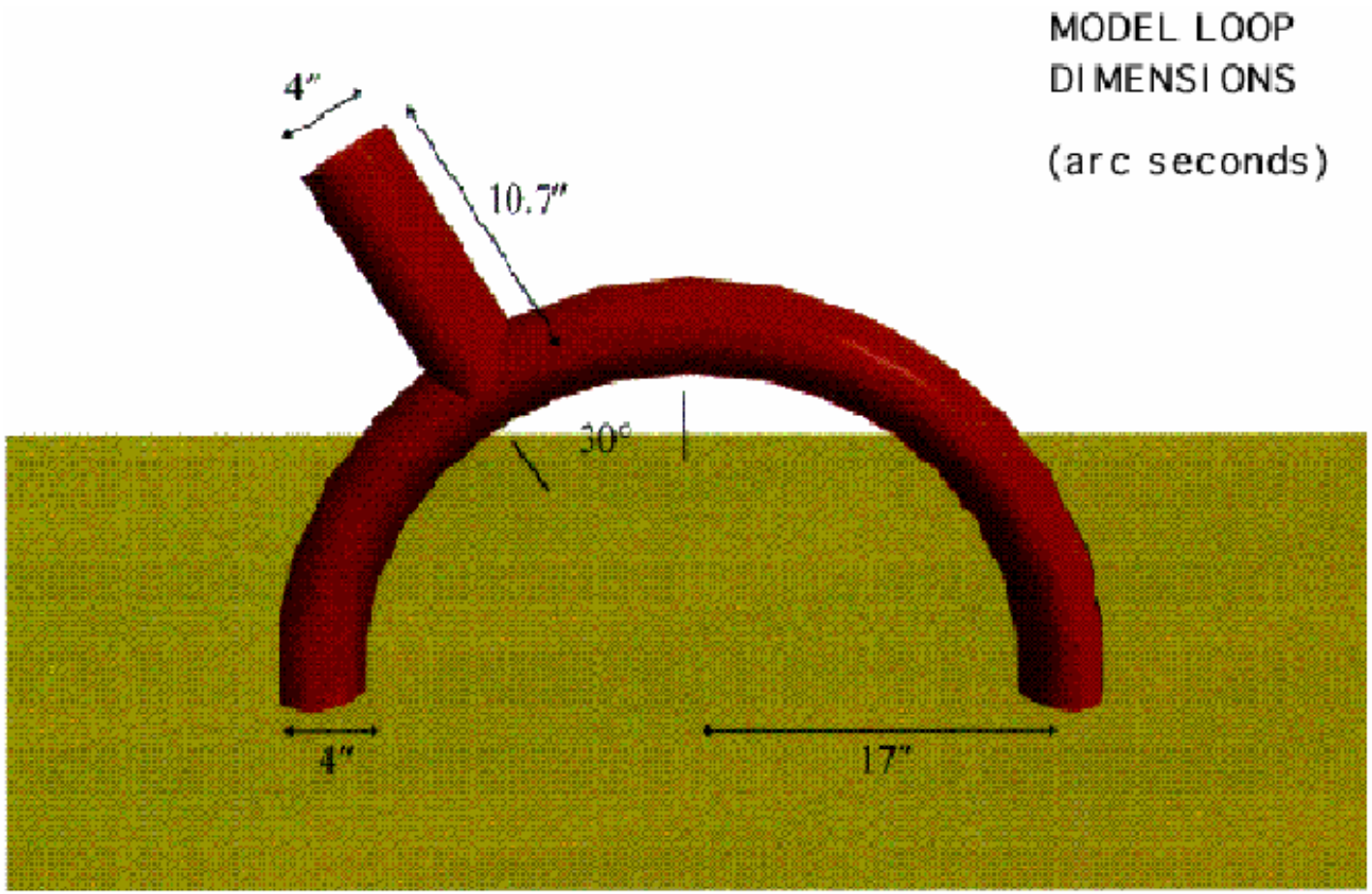




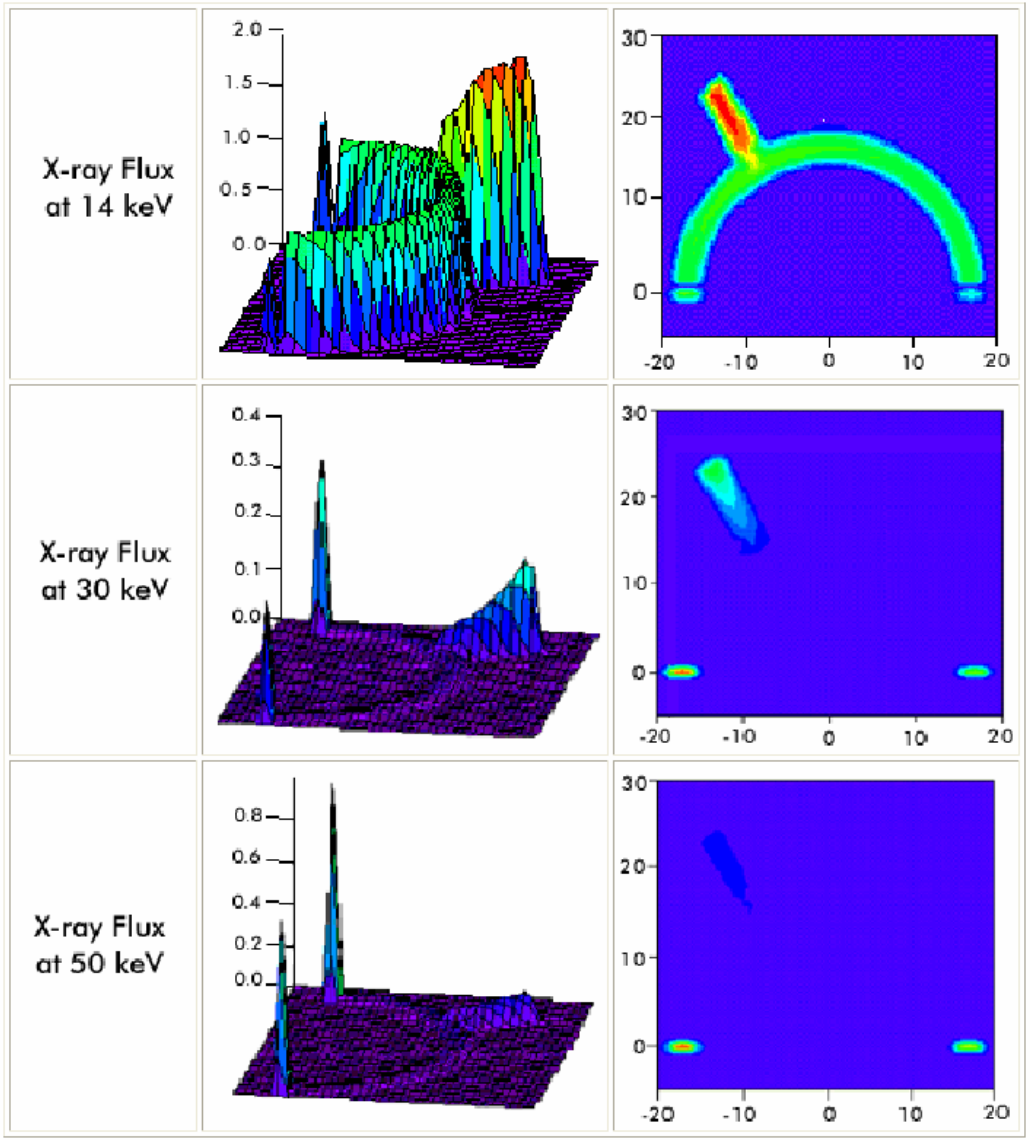
20 - 40 keV Polarization

Mark McConnell, UNH

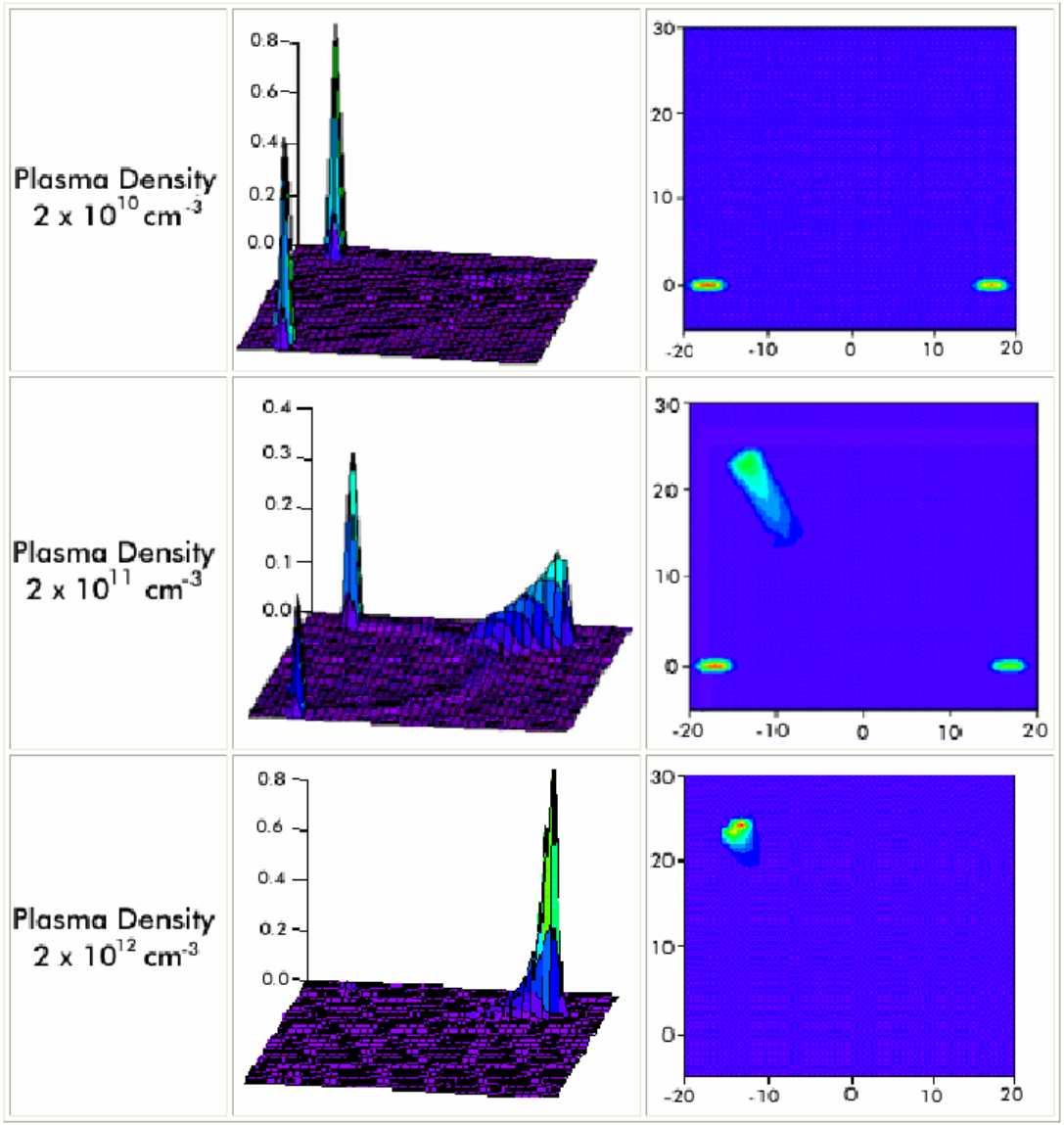
Model Flare Loop with Cusp



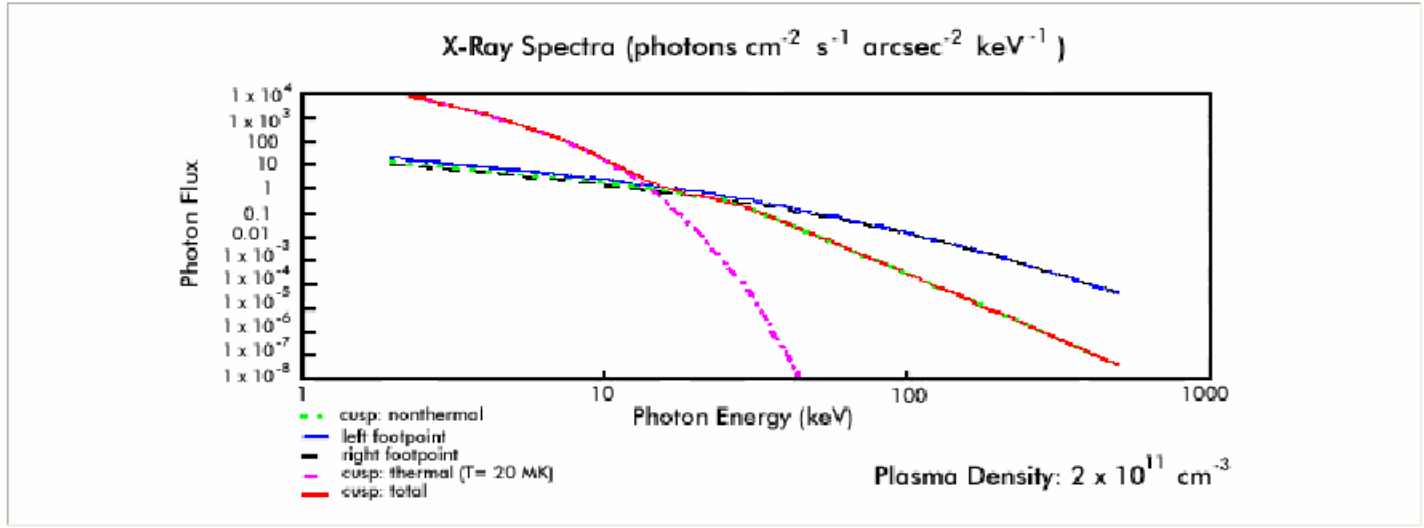
Model Loop in Hard X-Rays

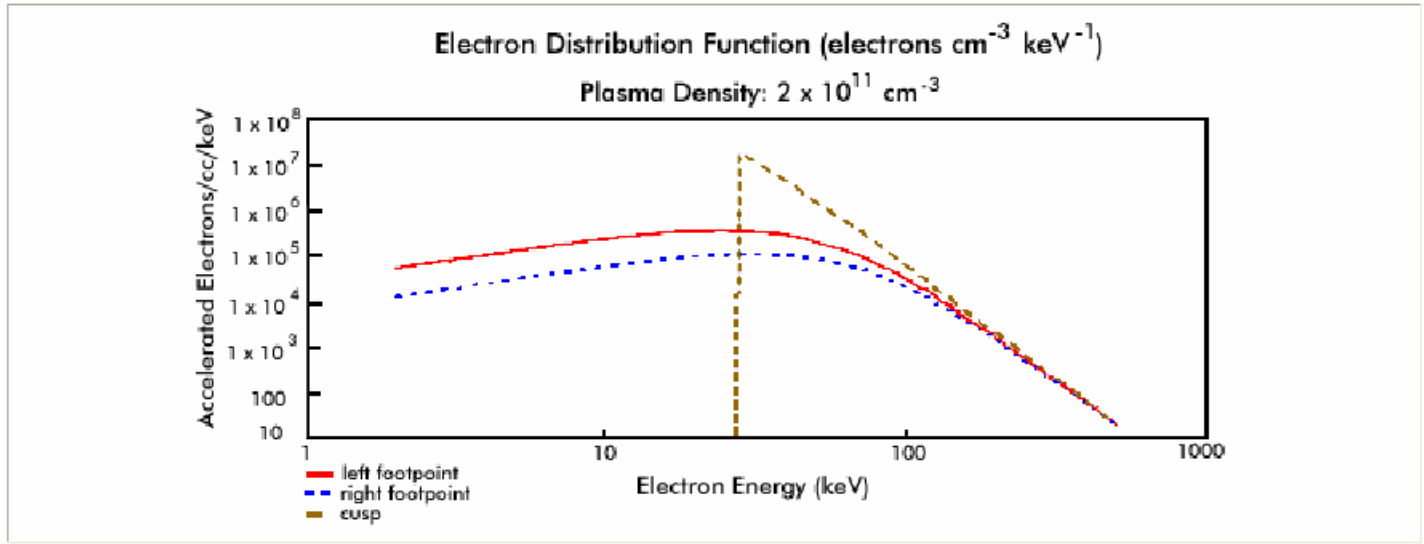


Change with Plasma Density in Loop

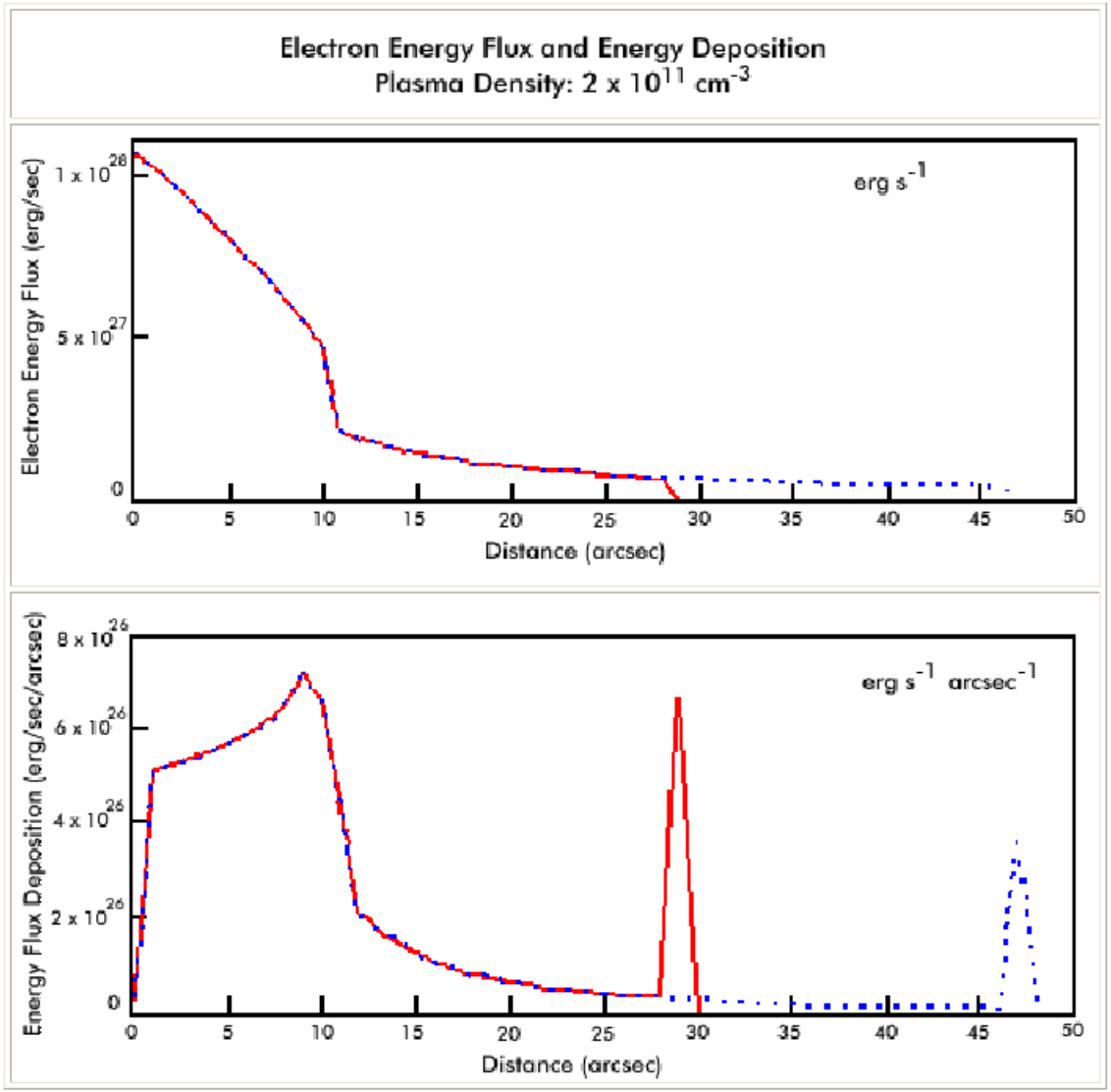


Computed Spectra





Energy Deposition



Presentations at the SPD Meeting

- Oral
  - 27.05, Wednesday June 28, 10:50 AM – 12:25 PM:
    Wei Lu
    X-ray Emission from Flaring Loops: Comparison Between RHESSI Observations and Hydrodynamic Simulations
  - 28.05, Wednesday June 28, 1:30 – 3:00 PM:
    Linhui Sui
    Motion of 3-6 keV Nonthermal Sources Along a Flare Loop
- Poster
  - 13.15: Gordon Holman
    Understanding X-Ray Source Motions in a Solar Flare Loop