Determination of Stochastic Acceleration Model Parameters for RHESSI Flares

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Outline

Stochastic Acceleration (SA) Model

Determination of Model Parameters
Based on RHESSI Observations

Electron Flux Spectral Images

Spatially Resolved HXR Spectra
Spatially Integrated HXR Spectra

Solar Flare HXR Observations

✓Solar Flares:
– energy release and particle acceleration in the corona

✓Nonthermal electrons manifested in HXR bremsstrahlung

➔Commonly seen loop footpoints (FP) sources
– Collisional Thick Target emission by an electron beam

➔Discovery of coronal looptop (LT) source Masuda et al. 1994
– Requires enhanced scattering of electrons at LT
– Turbulence can scatter/accelerate electrons simultaneously

Stochastic acceleration by turbulence is the most widely accepted acceleration mechanism for solar flares.

Basic Model:
Stochastic Acceleration

Accelerated electron number spectrum $N(E)$ in the LT (n, L) can be described by the Fokker-Planck equation

$$\frac{\partial N}{\partial t} = \frac{\partial^2}{\partial E^2}\left[D_{\rm EE}N\right] - \frac{\partial}{\partial E}\left[\left(A(E) - \dot{E}_{\rm L}(E)\right)N\right] - \frac{N}{T_{\rm esc}(E)} + \dot{Q}(E)$$

SA by turbulence $$A(E) = \frac{{\rm d}D_{\rm EE}}{{\rm d}E} + \frac{D_{\rm EE}}{E}\frac{(2\gamma^2-1)}{(\gamma^2+1)}$$

Energy loss $$\dot{E}_{\rm L} = \dot{E}_{\rm Coul} = 4\pi r_0^2 m_{\rm e} c^3 n_{\rm LT} \ln\Lambda/\beta$$

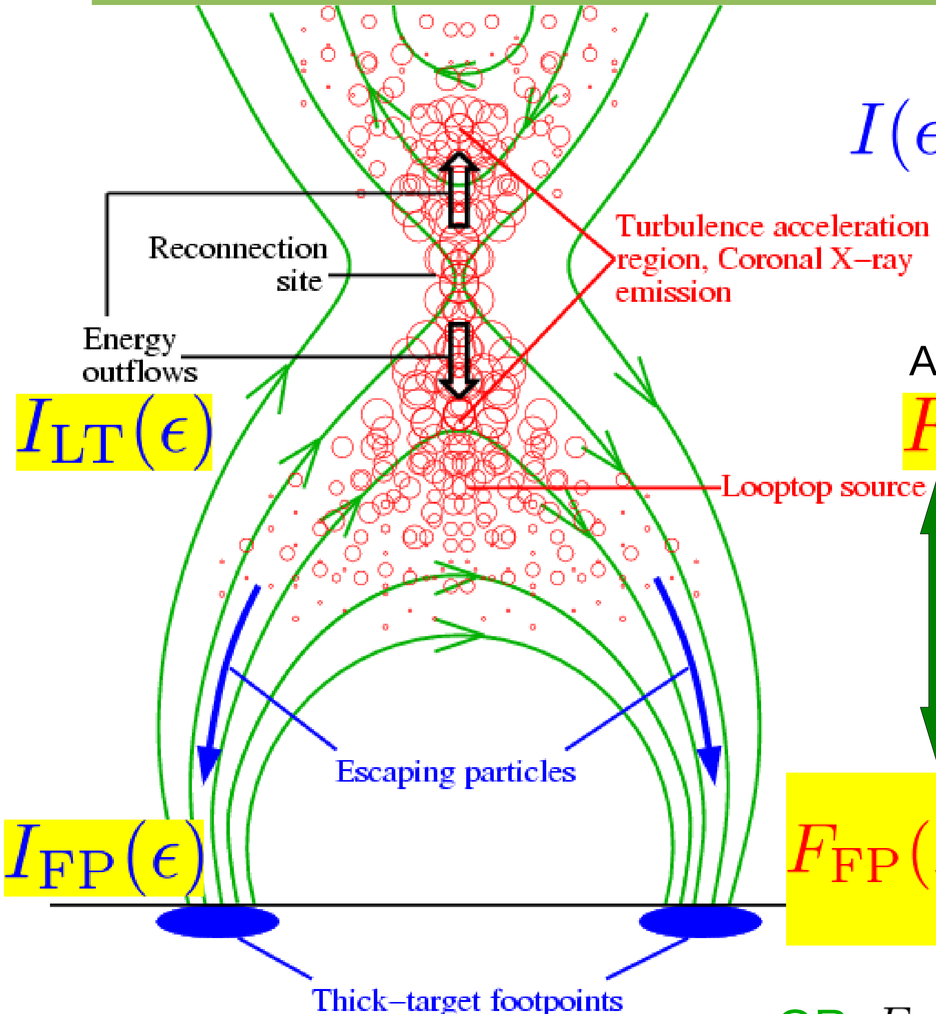
Escape time $$T_{\rm esc}(E) \simeq \tau_{\rm cross}\left(1 + \tau_{\rm cross}/\tau_{\rm scat}\right) \qquad \tau_{\rm cross} = L/v$$

Scattering time $$\tau_{\rm scat}(E) = \frac{1}{8}\int_{-1}^{1}\frac{(1-\mu^2)^2}{D_{\mu\mu}^{\rm Coul}(\mu,E) + D_{\mu\mu}^{\rm turb}(\mu,E)}d\mu$$

Coulomb collisions $$D_{\mu\mu}^{\rm Coul} = \frac{2(1-\mu^2)}{\gamma+1}\frac{\dot{E}_{\rm Coul}}{E}$$

Petrosian & Liu 2004

Basic Model:
Radiating Electrons and Photons



$$I(\epsilon) = \frac{nV}{4\pi R^2}\int_\epsilon^\infty F(E)\sigma(\epsilon, E)dE$$

Accelerated electron flux spectrum at LT

$$F_{\rm LT}(E) = v(E)N(E)$$

Injected electron flux spectrum to the loop legs

$$F_0(E) = F_{\rm LT}(E)(\tau_{\rm cross}/T_{\rm esc})$$

Effective radiating electron flux spectrum at FPs

$$F_{\rm FP}(E) = vN_{\rm FP} = \frac{v(E)}{\dot{E}_{\rm L}(n)}\int_E^\infty \frac{N(E')}{T_{\rm esc}(E')}dE'$$

OR $F_{\rm FP}(E) = \frac{\frac{1}{2}m_{\rm e}vv}{E_{\rm cr}^2}\int_E^\infty F_0(E')dE'$, where $E_{\rm cr}^2 \propto nL$

Determining Model Parameters
Based on Electron Flux Spectral Images

Piana et al. (2007): $F(x, y, E)$ for RHESSI flares,
the radiating electron flux spectral images

count visibility spectrum => electron flux visibility spectrum => electron flux images

(1) LT region gives the accelerated electron spectrum $F_{\rm LT}(E) = v(E)N(E)$

(2) FP regions give the effective radiating spectrum $F_{\rm FP}(E) = \frac{v(E)}{\dot{E}_{\rm L}(n)} \int_E^\infty \frac{N(E')}{T_{\rm esc}(E')} dE'$

From these LT and FP spectra we derive the escape time

$$T_{\rm esc}(E) = \frac{\tau_{\rm L}(E)(F_{\rm LT}/F_{\rm FP})}{\delta_{\rm FP}(E) + 2/(\gamma+\gamma^2)}, \text{ with } \tau_{\rm L}(E) = \frac{E}{\dot{E}_{\rm L}} \propto \frac{E\beta}{n}$$

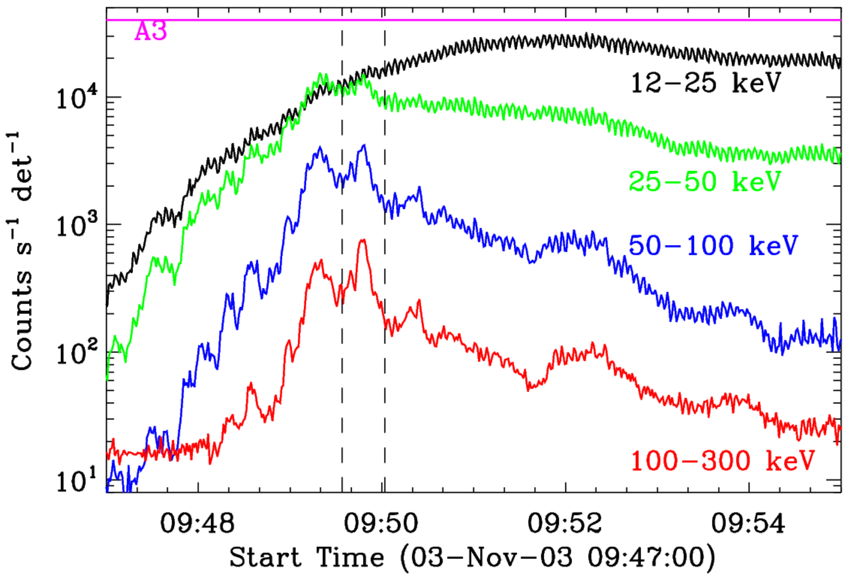
and determine the mean and turbulence scattering times

$$\tau_{\rm scat}(E) \simeq \tau_{\rm cross}^2/(T_{\rm esc} - \tau_{\rm cross}) \quad \text{for } T_{\rm esc} > \tau_{\rm cross}$$

$$\tau_{\rm scat}^{\rm turb}(E) \simeq \tau_{\rm scat}(1 + \tau_{\rm scat}/\tau_{\rm scat}^{\rm Coul}) \quad \text{when turbulence dominates}$$

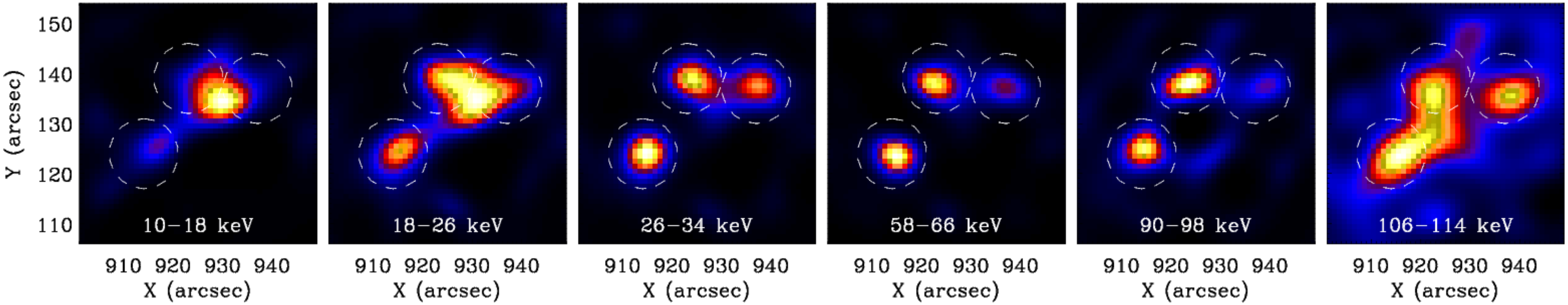
See Petrosian & Chen, 2010, ApJL, 712, 131

2003 Nov 3 Flare (X3.9 class)

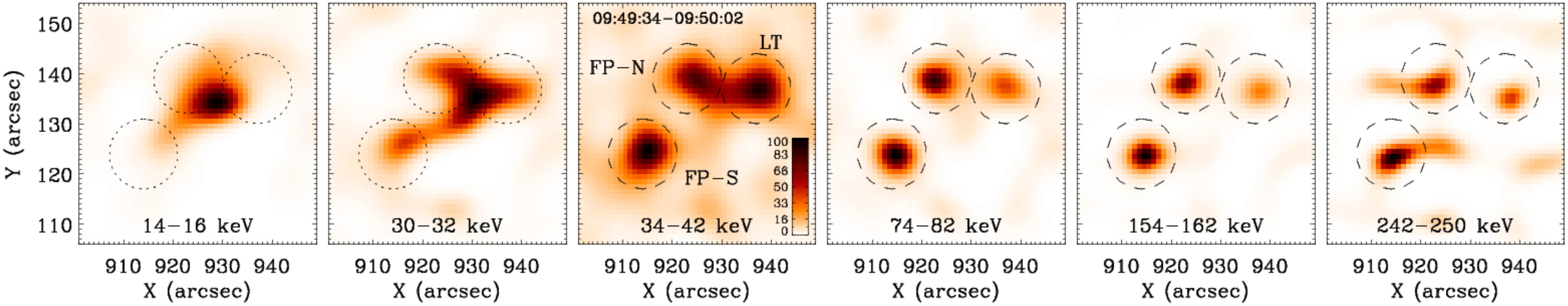


LT source detected up to 100-150 keV
(Chen & Petrosian, in preparation)

HXR images by MEM_NJIT

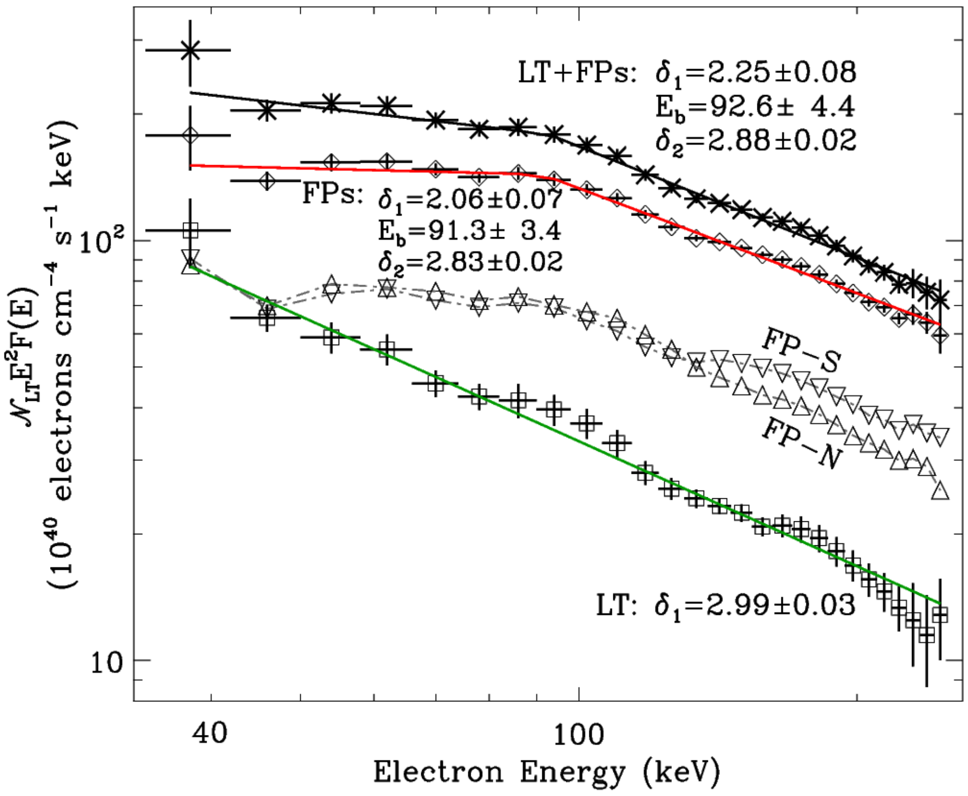


Electron images by MEM_NJIT

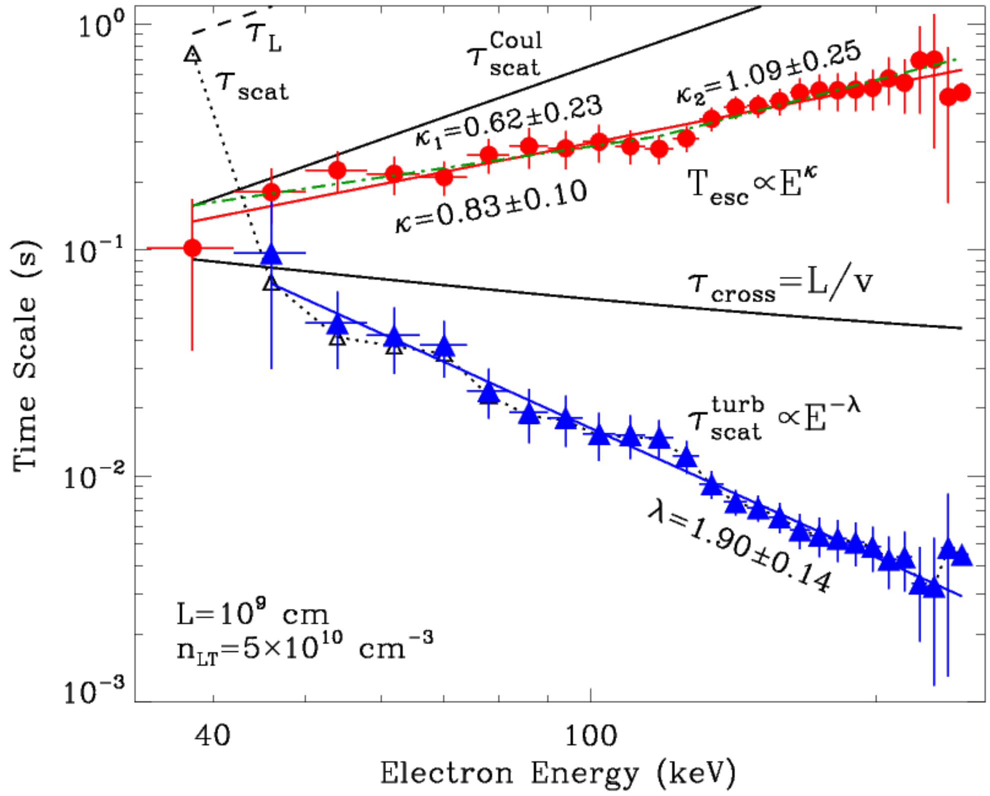


2003 Nov 3 Flare: Model Parameters

Electron flux spectra



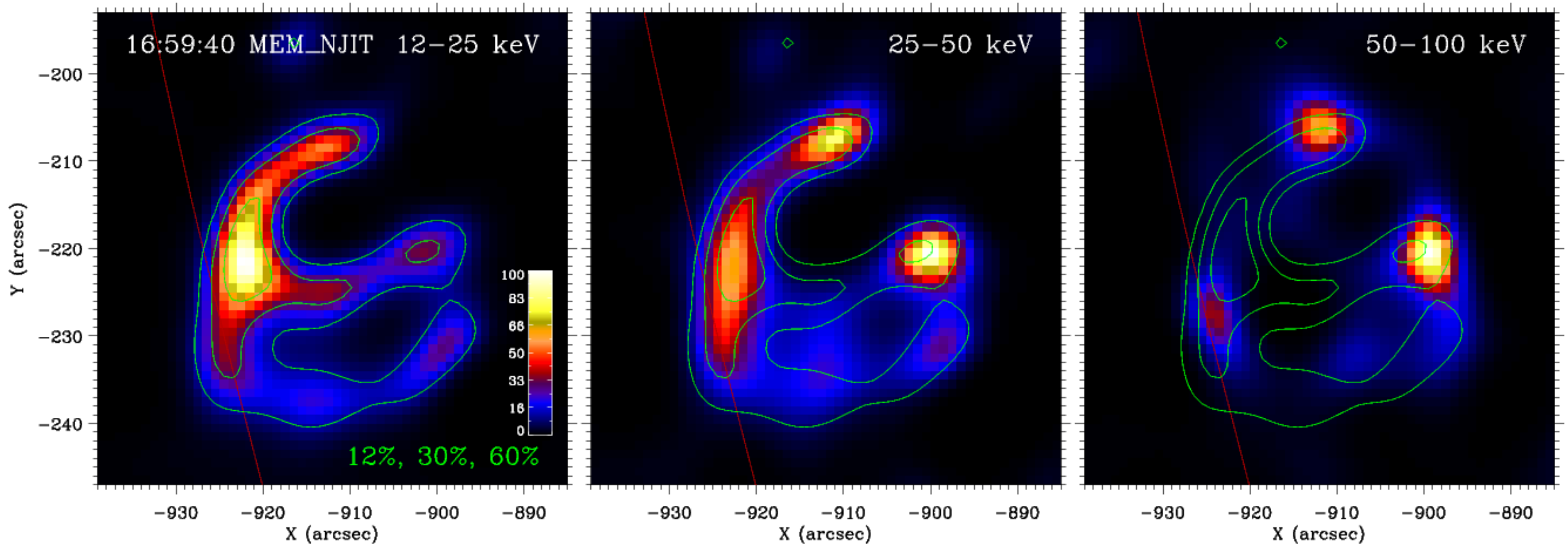
Time scales



Escape time increases with electron energy!

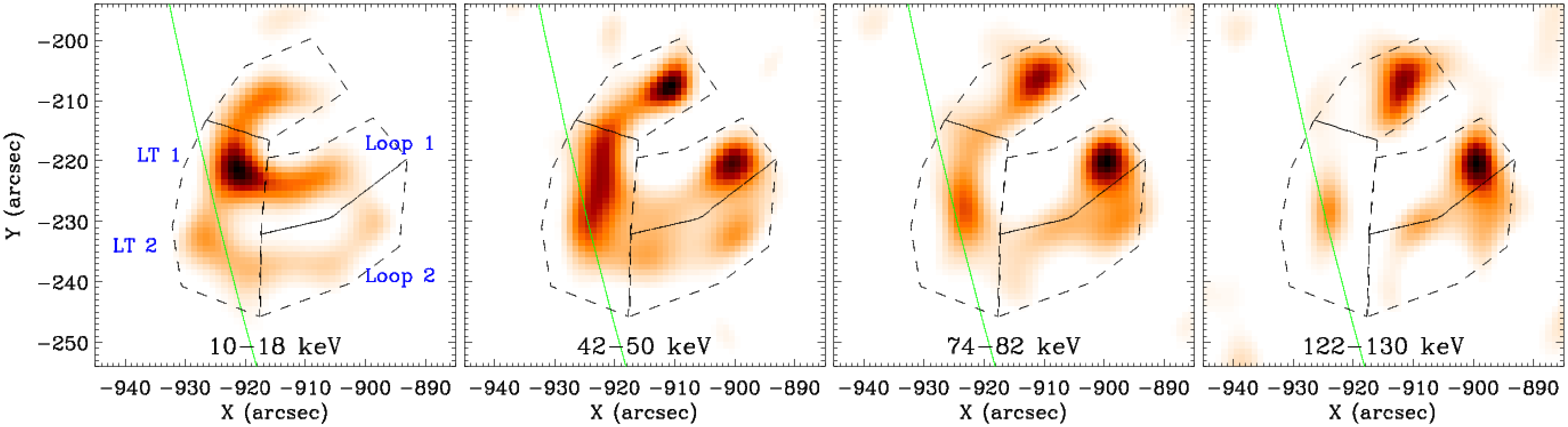
Scattering time ~ 10 ms at 100 keV.

2005 Sep 8 Flare (M2.1): Images



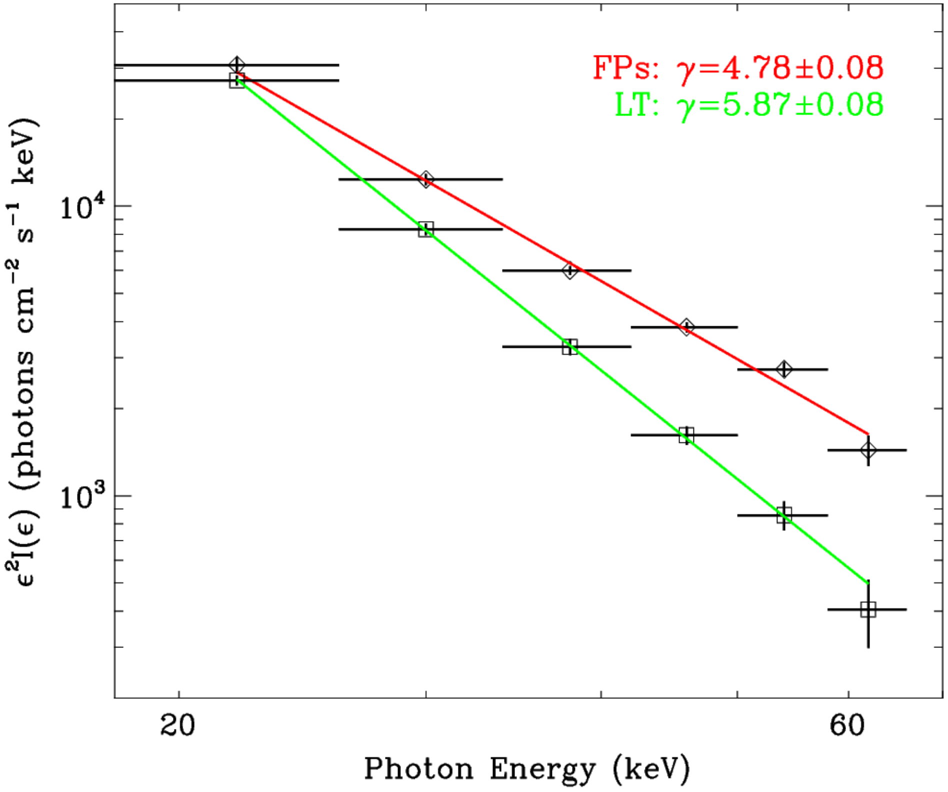
HXR:
2 loops

Electron

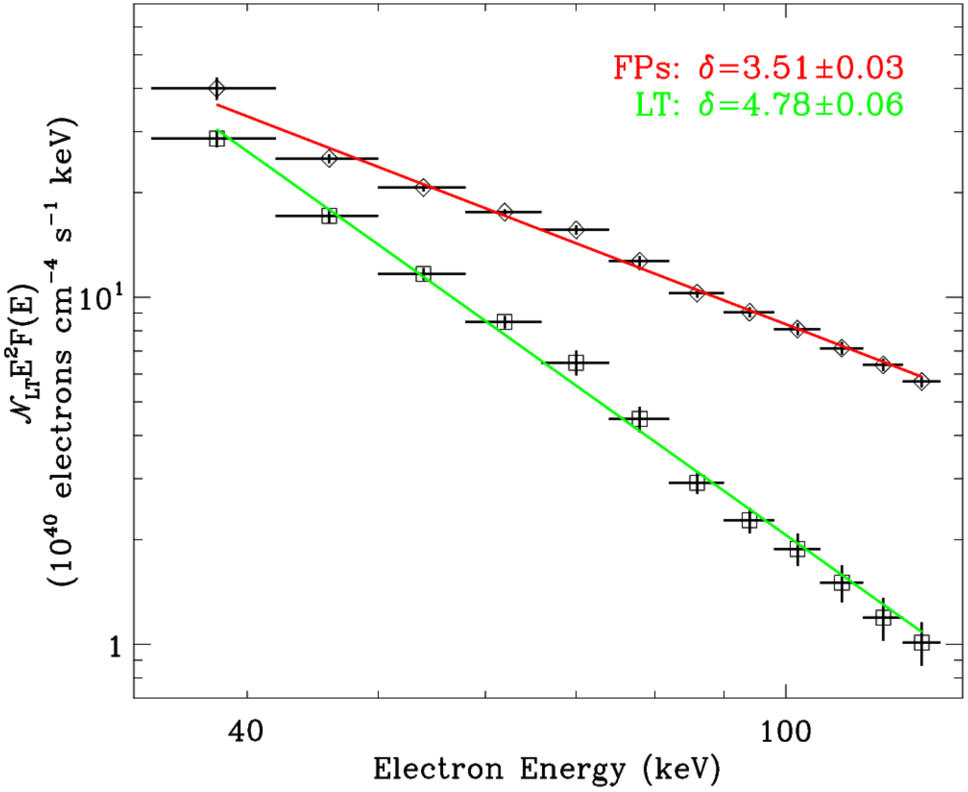


2005 Sep 8 Flare: Spectra

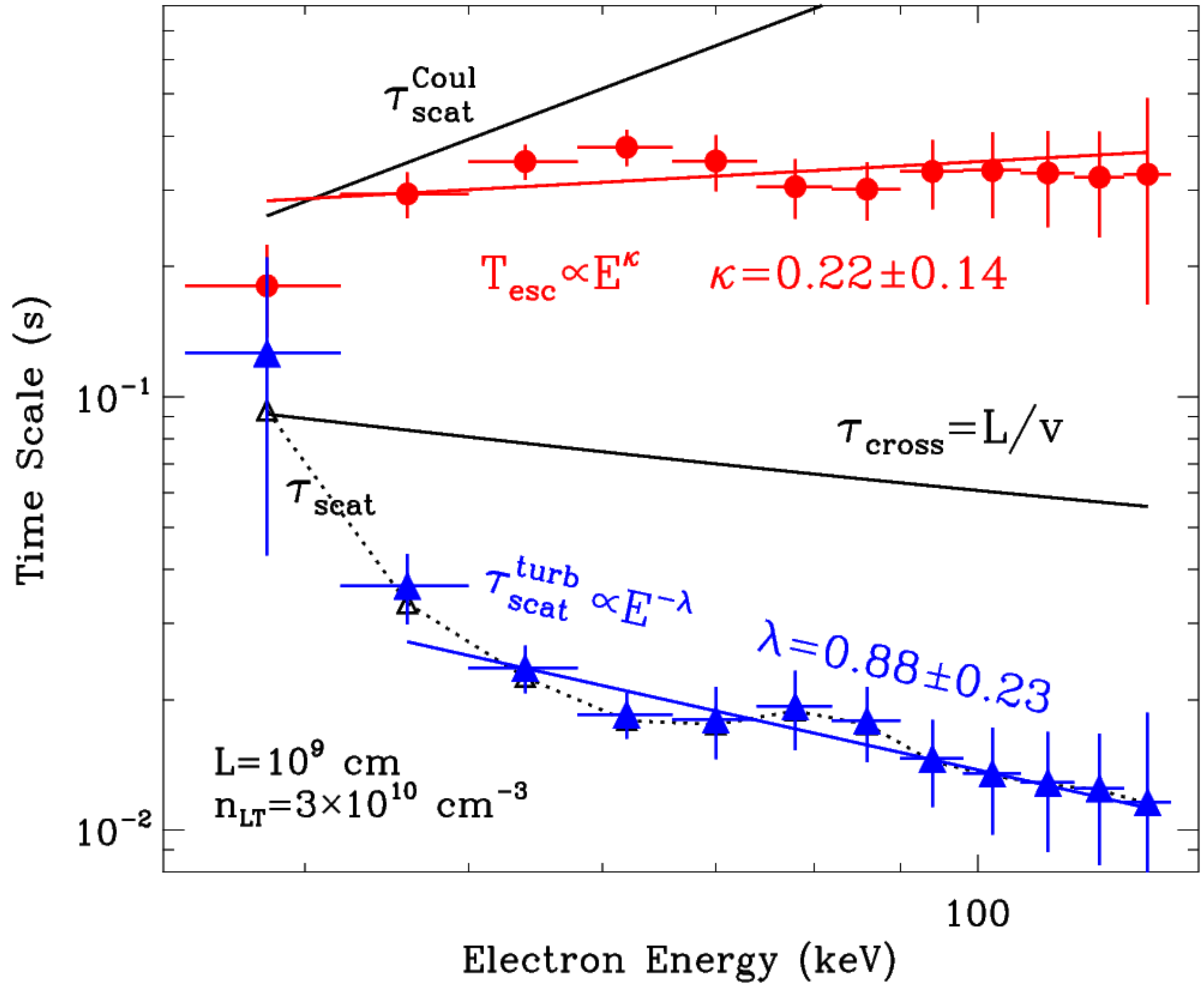
HXR photon spectra



Electron flux spectra



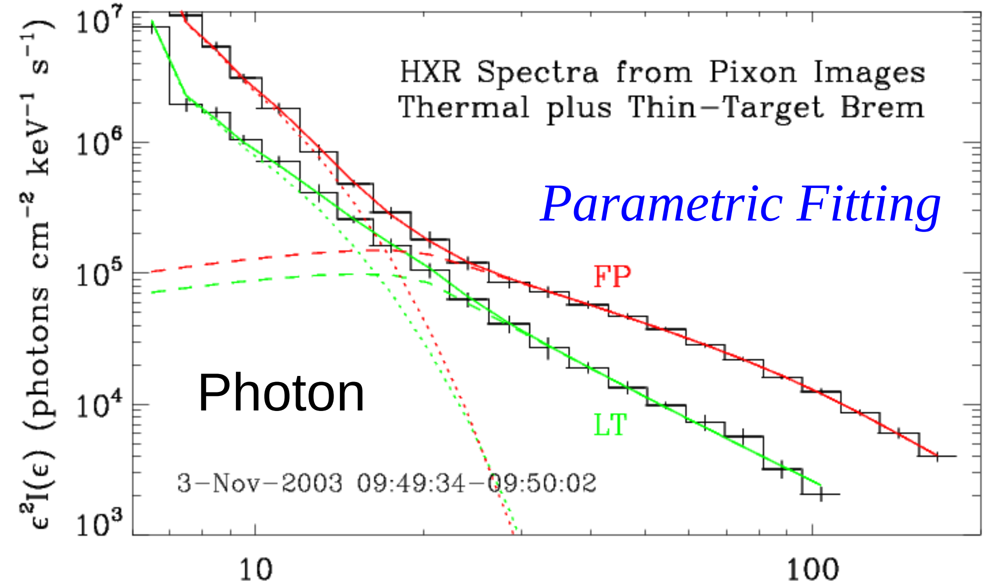
2005 Sep 8 Flare: Time Scales

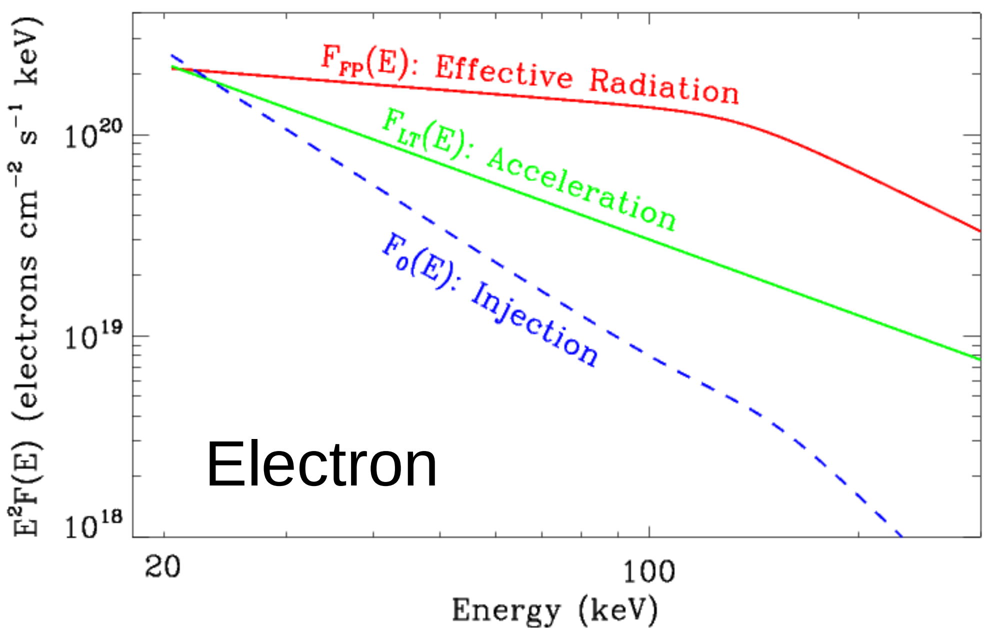


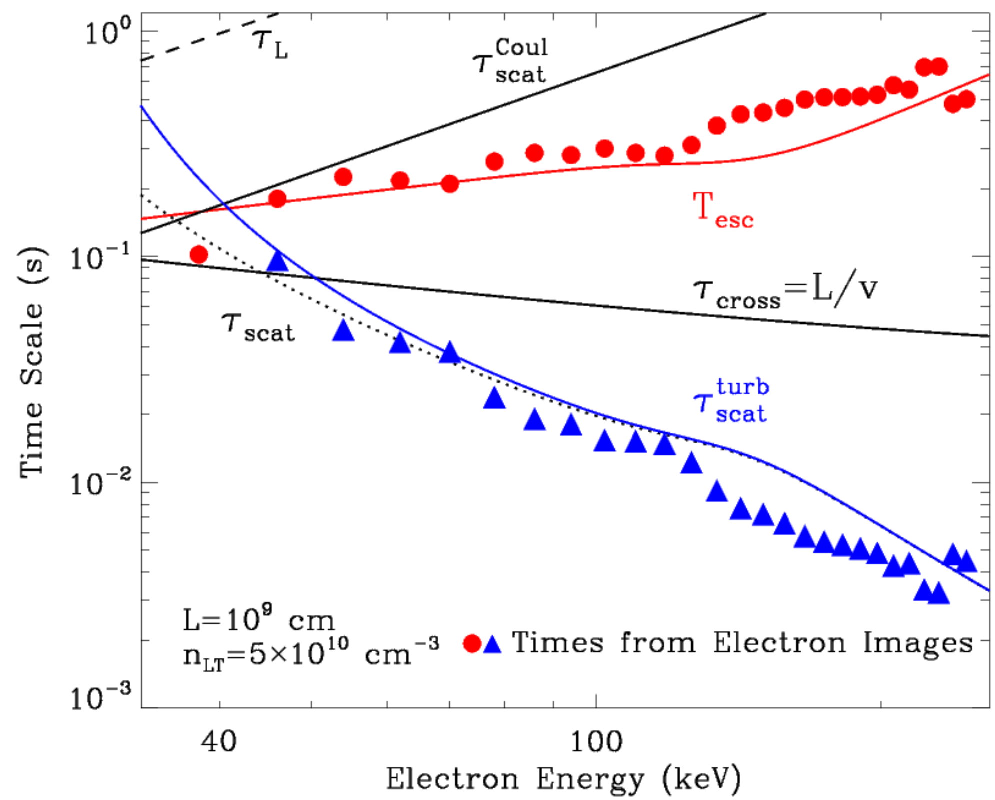
Determining Model Parameters
Based on LT & FP HXR Spectra

$$I(\epsilon) = \frac{nV}{4\pi R^2}\int_\epsilon^\infty F(E)\sigma(\epsilon,E)dE$$

$$T_{\rm esc}(E) = \frac{\tau_{\rm L}(E)(F_{\rm LT}/F_{\rm FP})}{\delta_{\rm FP}(E)+2/(\gamma+\gamma^2)}$$







Compared to Page 8

Determining Model Parameters
Based on LT & FP HXR Spectra

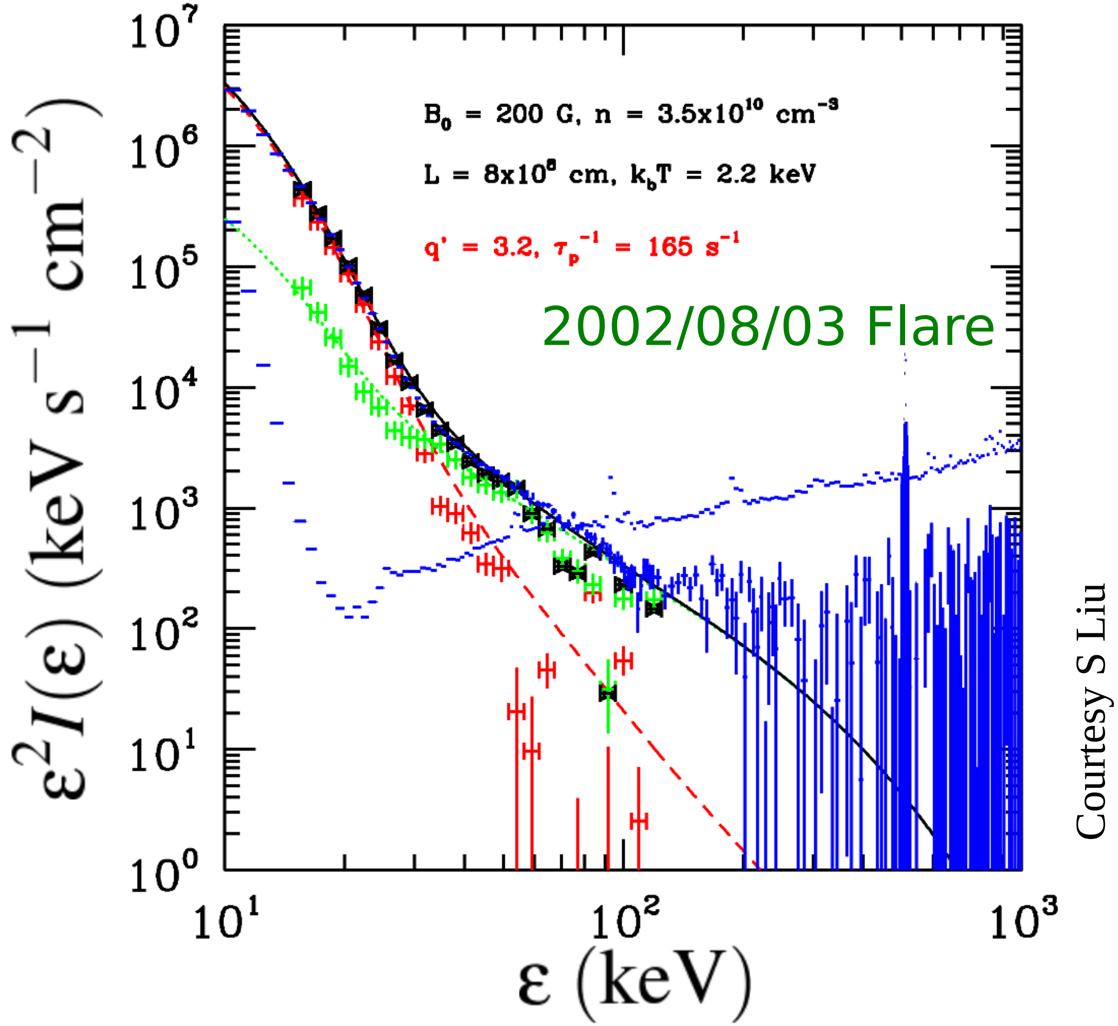
1. Assume parameters of plasma and turbulence, and calculate coefficients

$D_{\rm EE}, A(E),$ and $T_{\rm esc}(E)$

2. Evaluate spectra

$N(E)$ and $I(\epsilon)$

3. Then forward fit to the HXR spectra



Determining Model Parameters
Based on Total Radiating Electron Spectrum

Regularized inversion of the spatially integrated HXR spectrum:
e.g. Piana et al. 2003, Kontar et al. 2005

Assuming all HXR emission comes from the closed loop

$$I_{\rm Tot} = I_{\rm LT} + I_{\rm FP} = \frac{nV}{4\pi R^2}\int_{\epsilon}^{\infty} v N_{\rm eff}(E)\sigma(\epsilon, E){\rm d}E$$

➡ The *total effective radiating* electron spectrum $N{\rm eff}(E)$

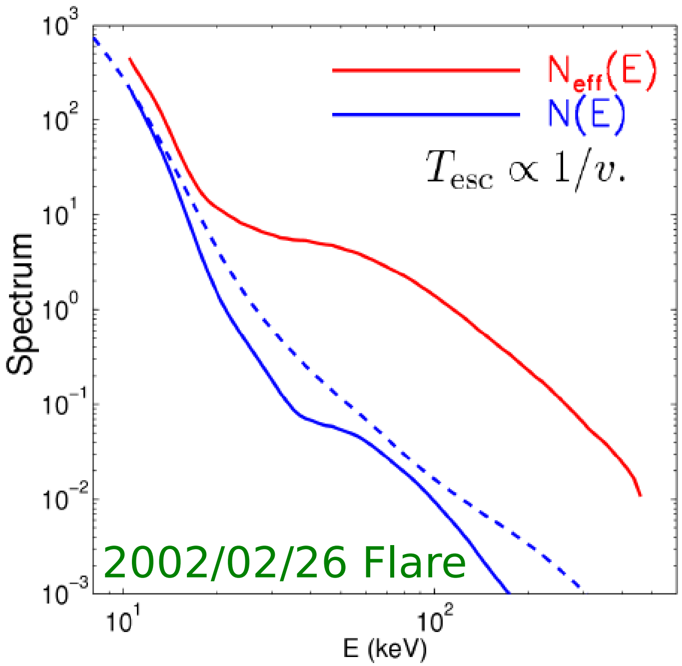
$$N_{\rm eff}(E) = N(E) + \frac{1}{\dot{E}_{\rm L}}\int_{E}^{\infty}\frac{N(E')}{T_{\rm esc}(E')}dE', \text{ or } \frac{{\rm d}(N/v)}{{\rm d}E} - \frac{N/v}{\dot{E}_{\rm L}T_{\rm esc}} = \frac{{\rm d}(N_{\rm eff}/v)}{{\rm d}E}$$

➡ The *accelerated electron* spectrum

$$N(E) = N_{\rm eff}(E) - v(E)\int_{\eta(E)}^{\infty}\frac{N_{\rm eff}(E)}{v(E)}e^{\eta-\eta'}d\eta'$$

$$\text{with } d\eta = \frac{dE}{\dot{E}_{\rm L}T_{\rm esc}}$$

But requires a knowledge of escape time!



Courtesy YW Jiang

Summary & Discussion

We demonstrate that the spatially resolved or integrated (HXR or electron) spectra from RHESSI flares can be used to determine some acceleration parameters.

We obtain electron flux images and spectra for two relatively strong flares with LT and FP sources detected above 50 keV/HXR, and determine the accelerated electron spectrum $N(E)$ and the escape time and scattering times in the acceleration region.

The inferred acceleration model characteristics are mainly dependent on the spectral difference between the LT and FP sources.
The results imply very steep turbulence energy spectrum for the two flares.
Also, given $N(E)$ and $T_{esc}(E)$, one may in principle determine the only unknown quantity $A(E)$ in the steady-state Fokker-Planck equation.

Next step, go beyond these “phenomenological” results?