Nature of Power-law Particle Distributions

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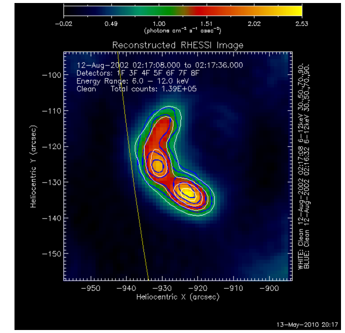
Outline

1: Spectroscopic Study of flaring loops



Five phase evolution: Heating + Evaporation(Evp); Acceleration + Evp; Heating; Equilibration; Cooling

Transport + Acceleration ⇒ **Power-law**

2: Power-law distributions: Classical

Individual Particles: Acceleration, Loss, Escape

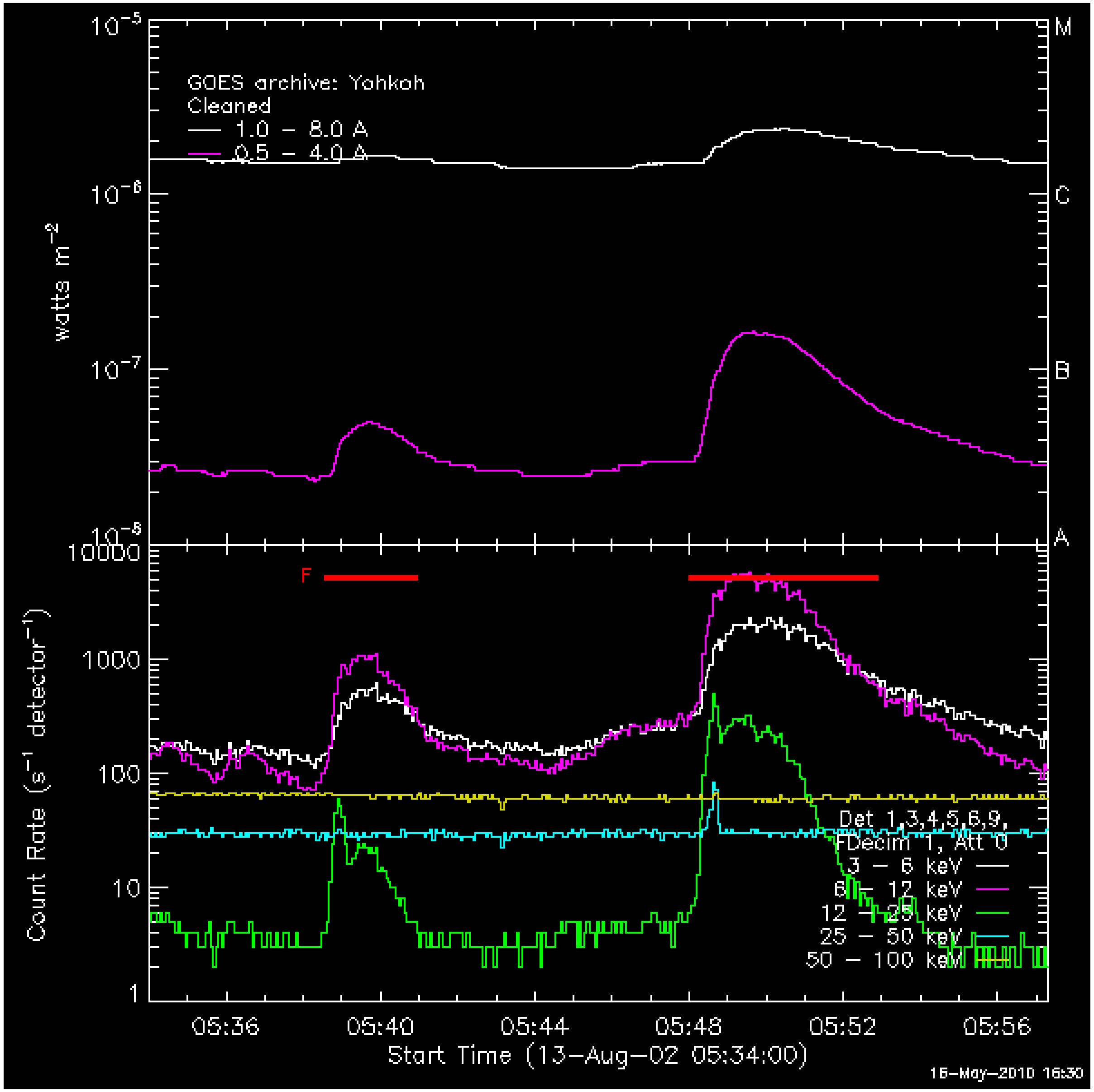
Systems: Stochastic leaky box, shock, electric fields

3: Power-law distributions: Contemporary

Turbulence: Fractal and Intermittency

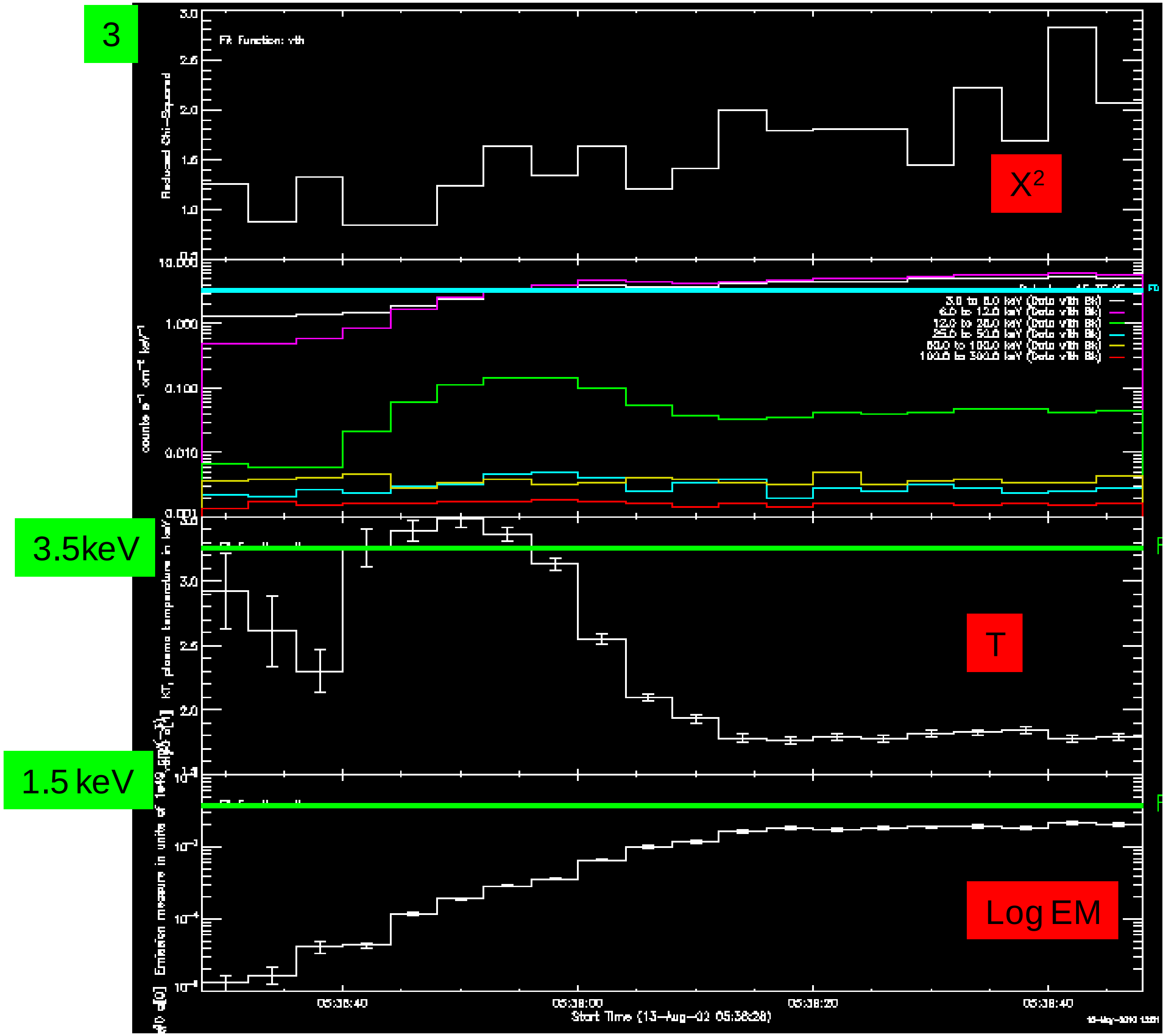
Statistics: Levy flights; Entropy; Phase space interdependence

Case Study: Two Simple Flares



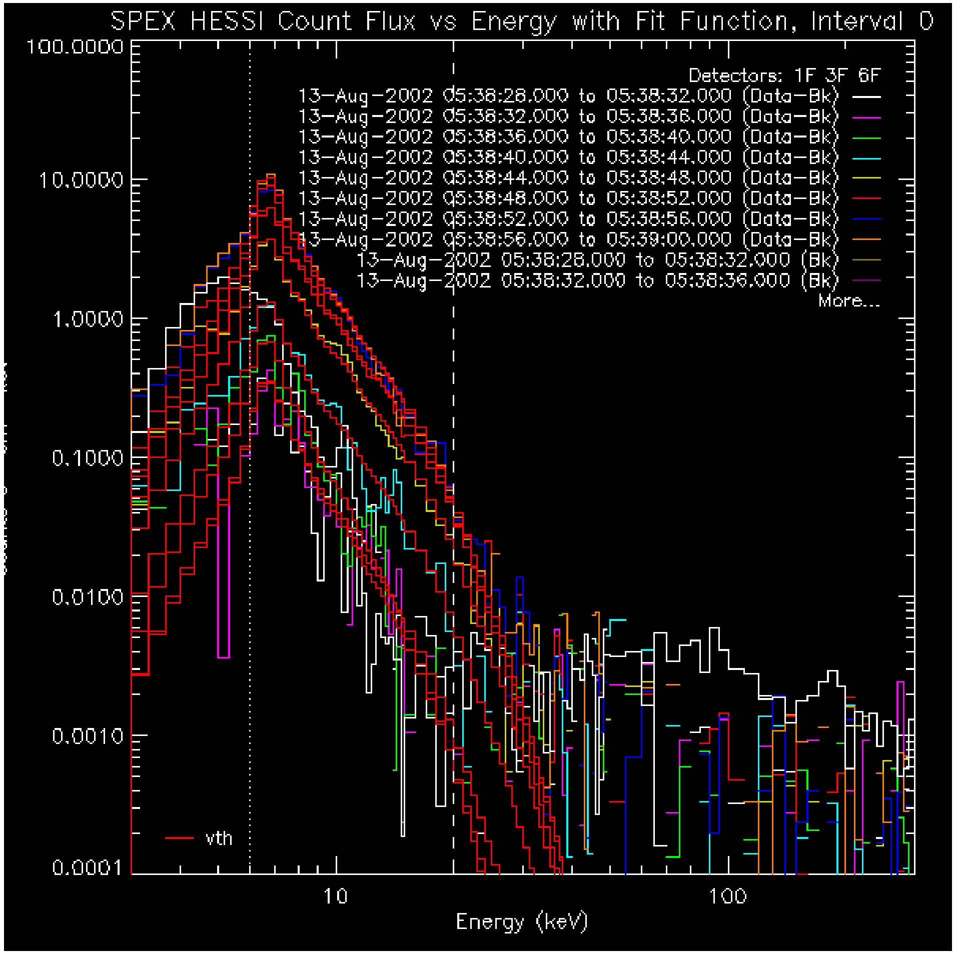
LIGHT CURVE:
Two simple classical flares with an impulsive hard X-ray pulse leading gradual evolution in soft X-rays

Case Study: A Thermal Flare

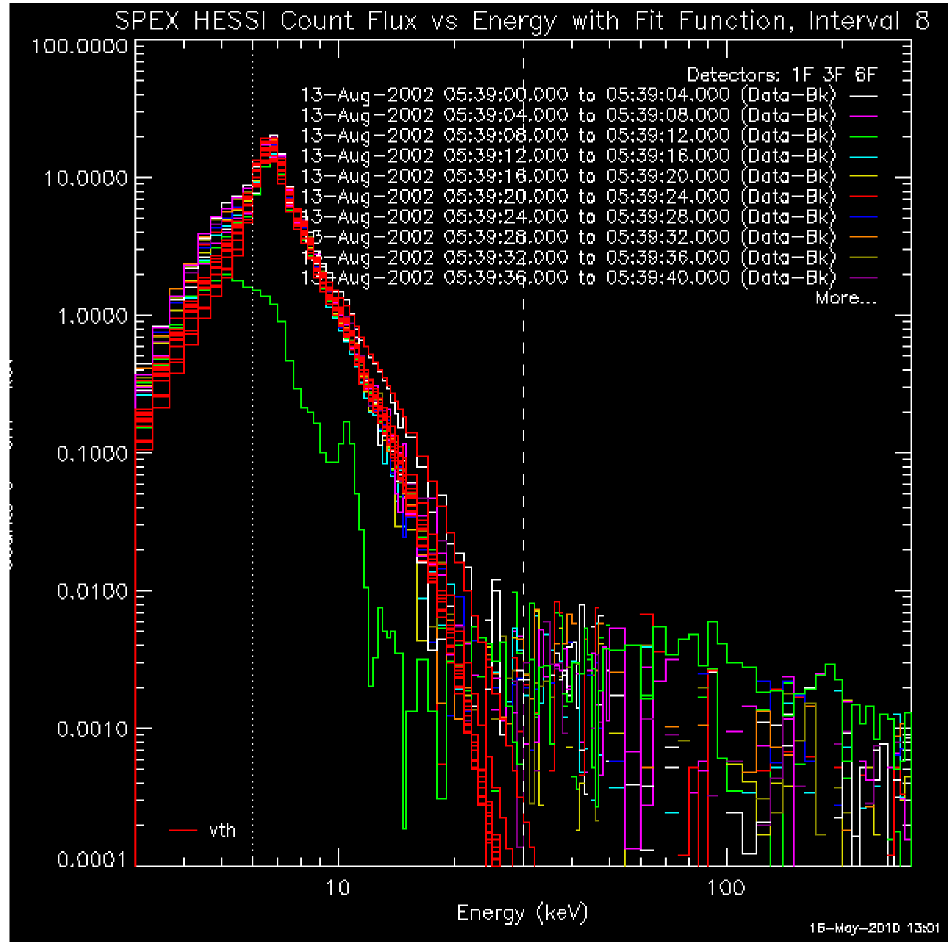


Case Study: A Thermal Flare

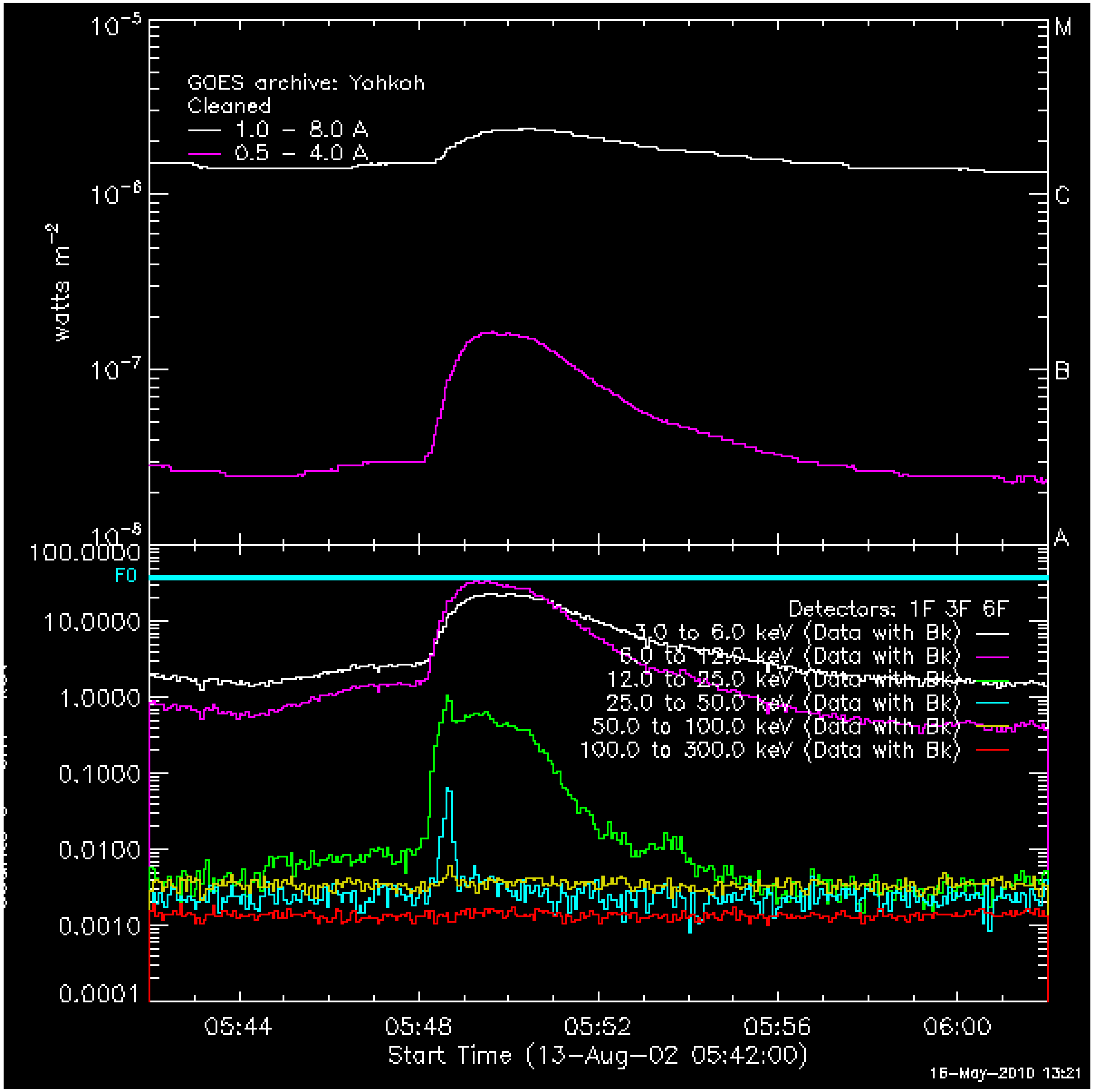
Thermal Rise



Thermal Decay

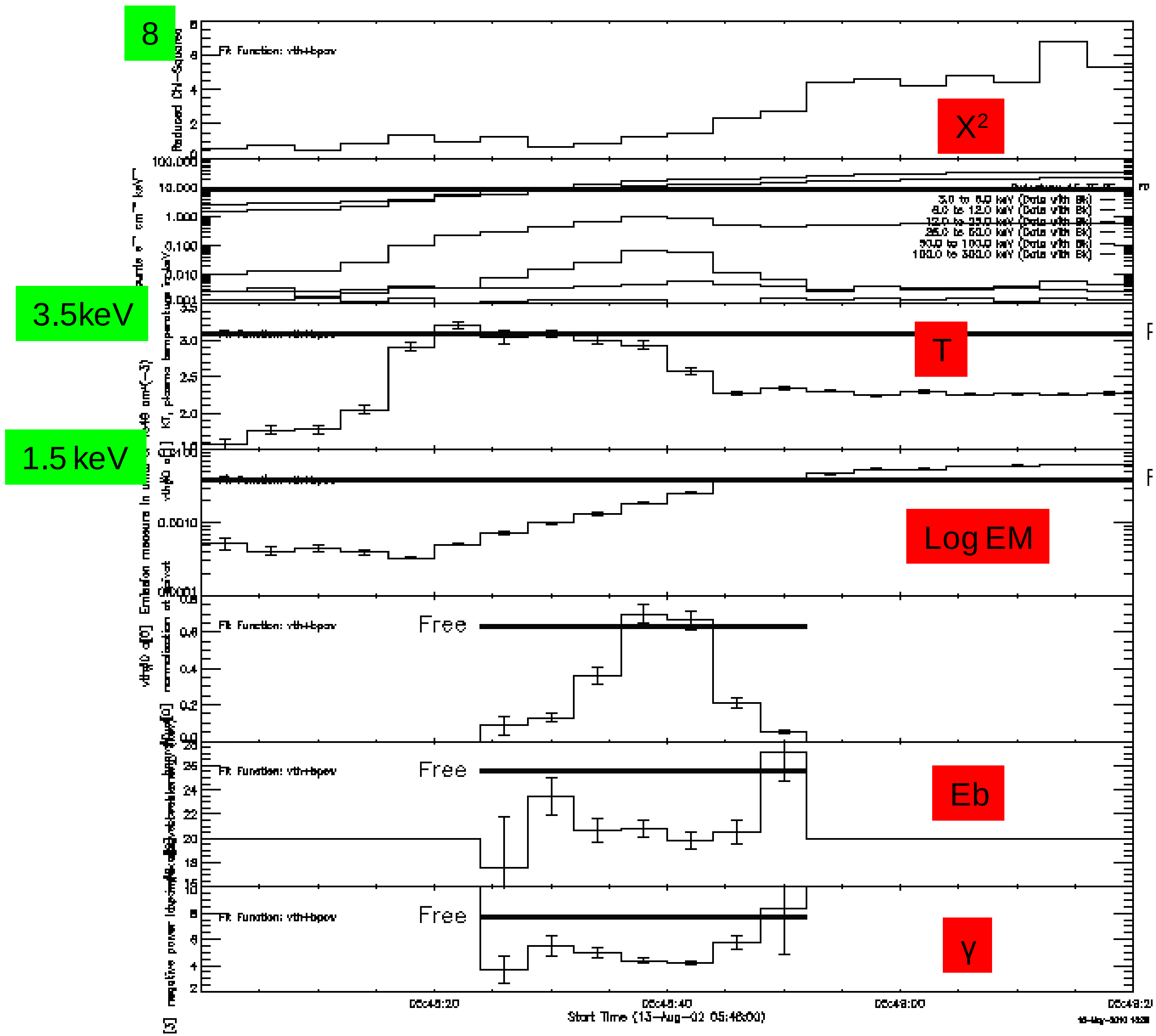


Case Study: The Bigger Flare



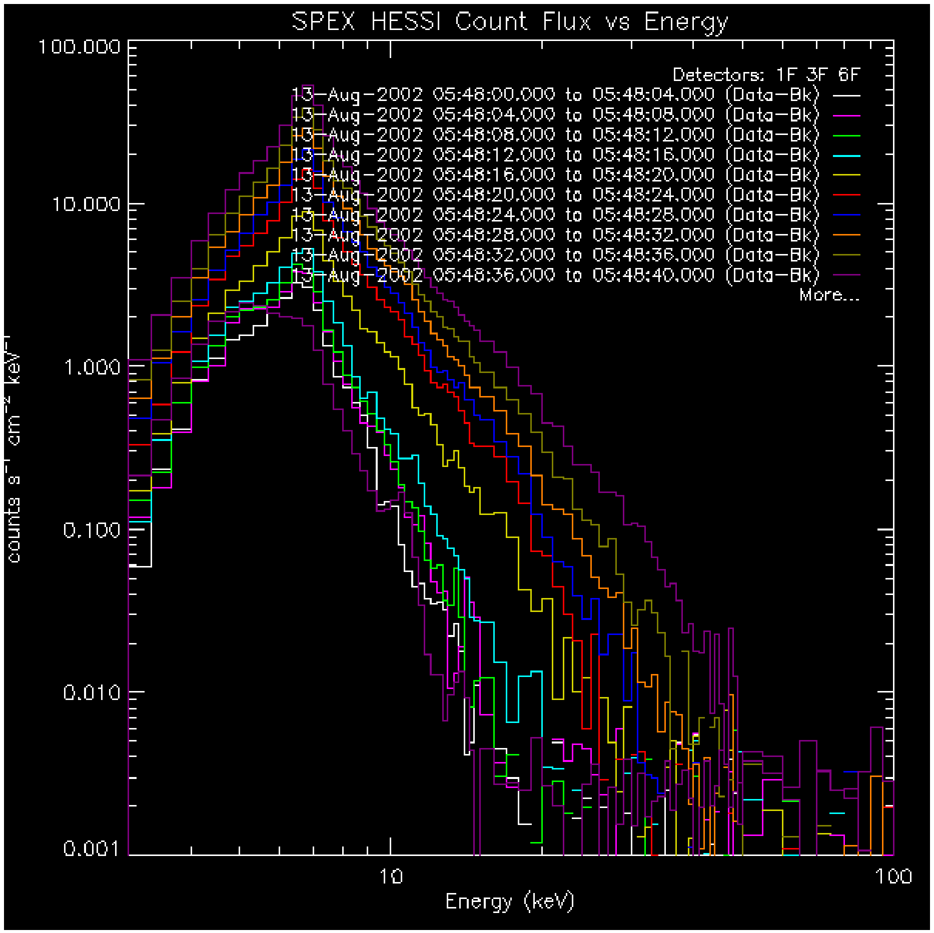
LIGHT CURVE:
A simple classical flare with an impulsive hard X-ray pulse leading gradual evolution in soft X-rays

Case Study: A Bigger Flare

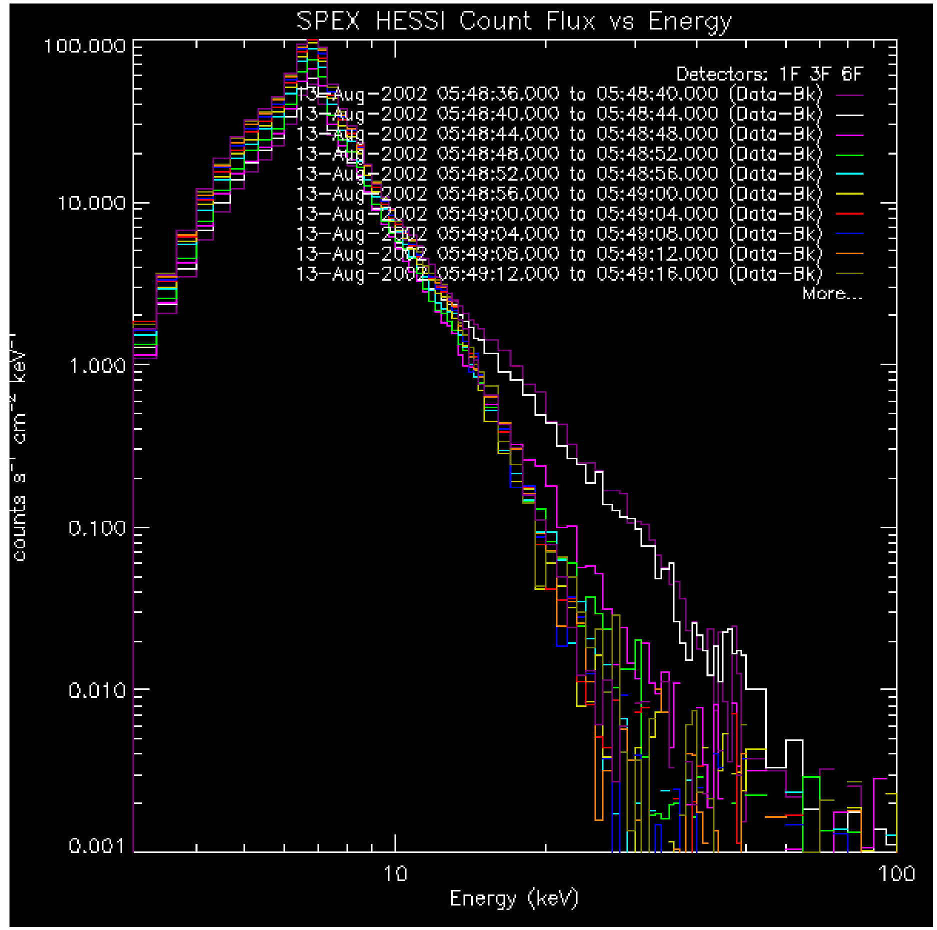


Case Study: A Bigger Flare

Rise

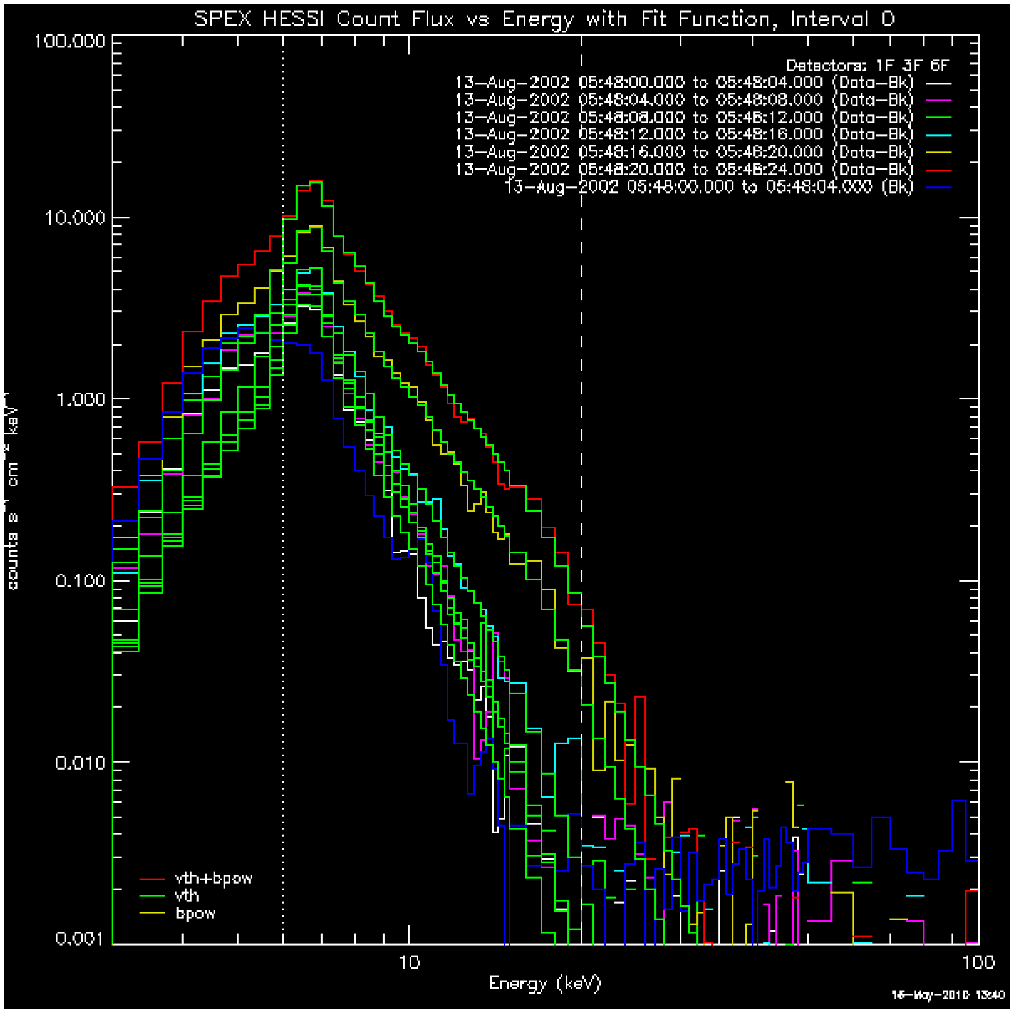


Decay

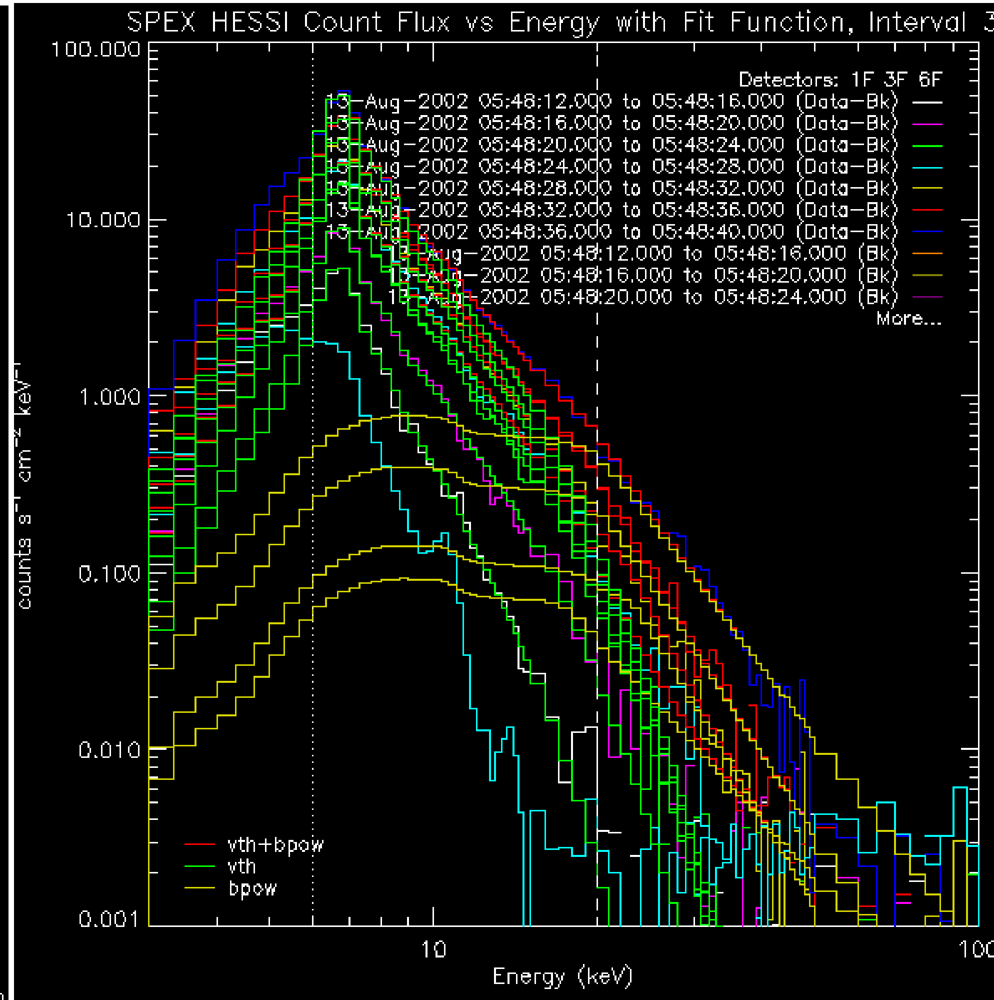


Case Study: A Bigger Flare

Thermal Rise



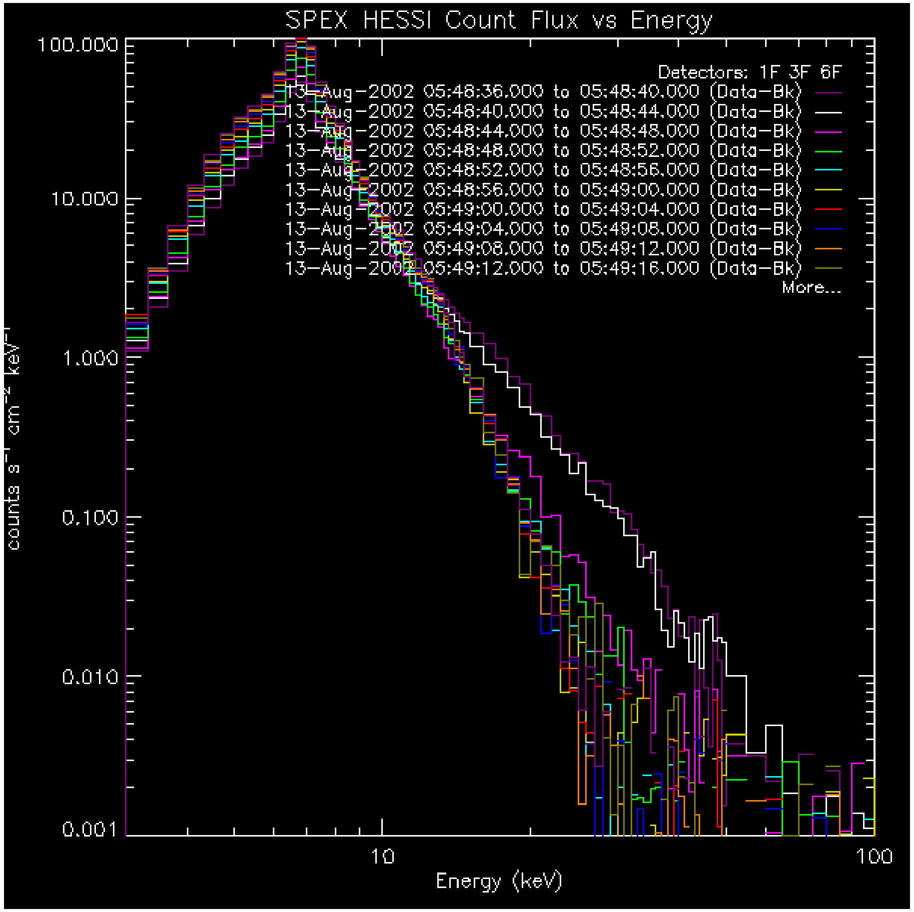
Rise

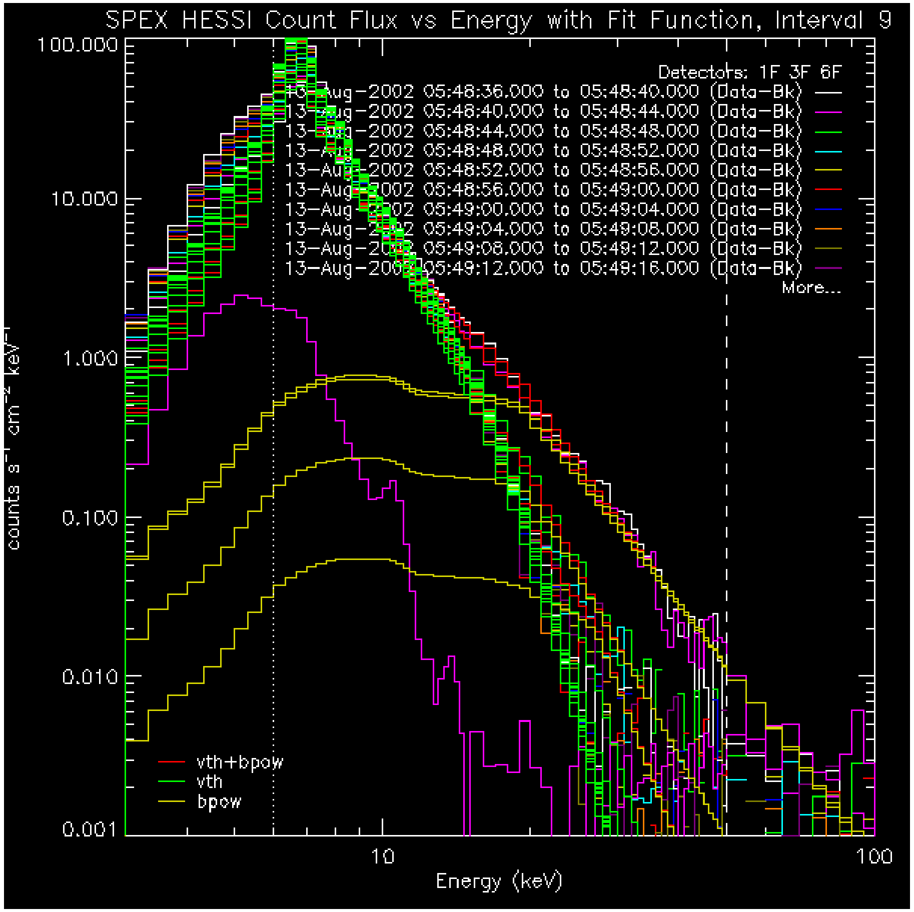


Case Study: A Bigger Flare

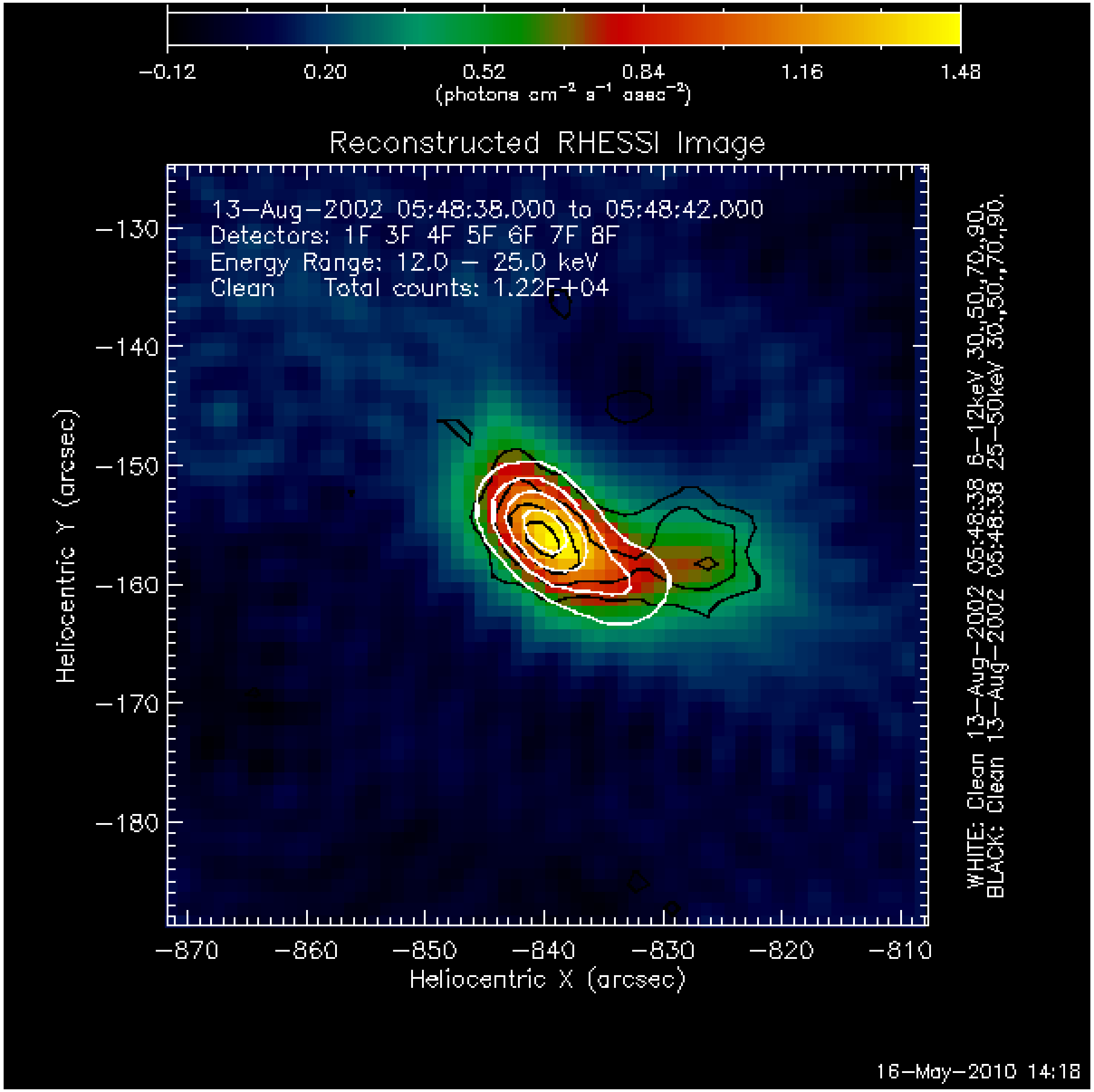
Decay

Decay



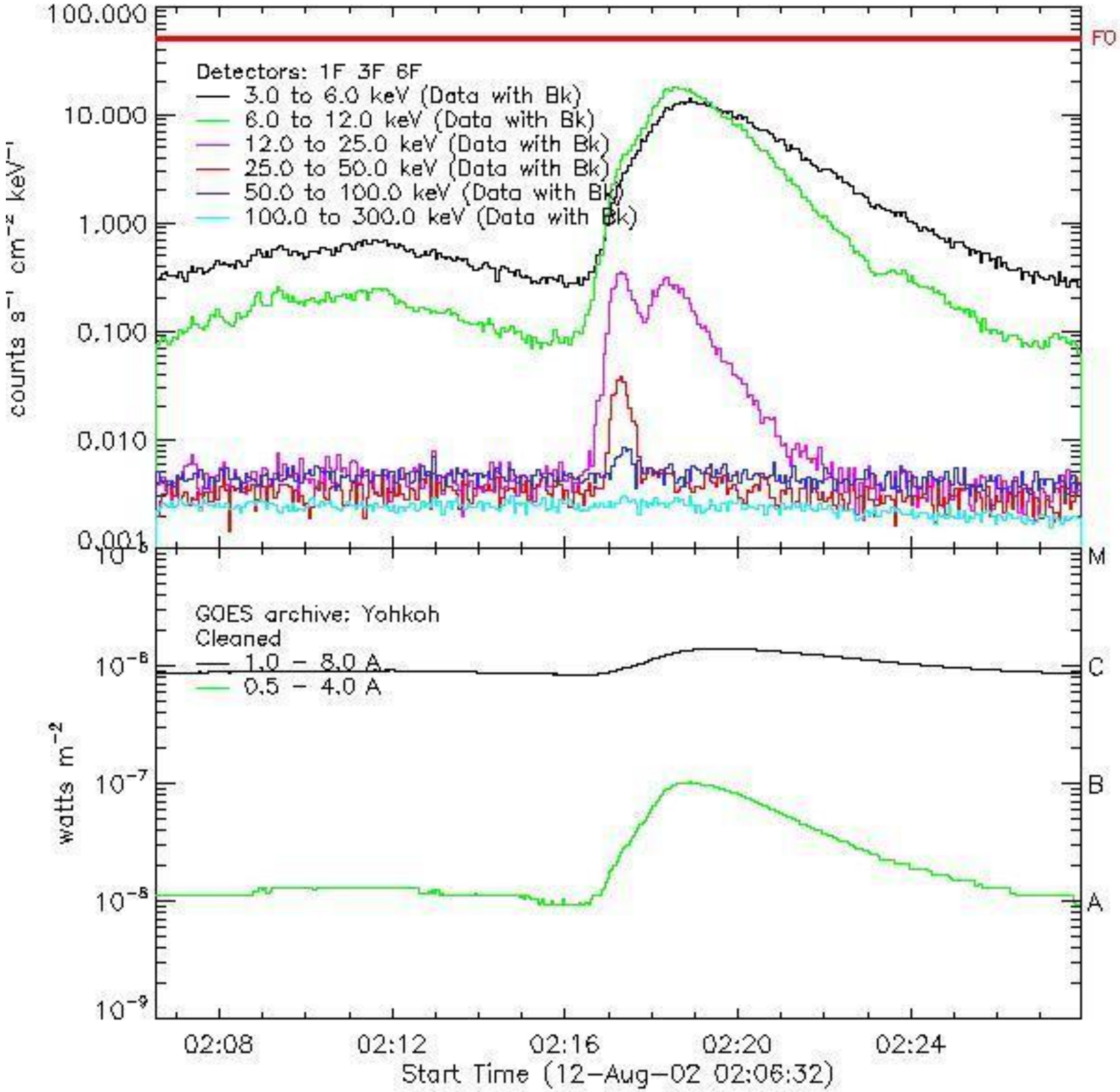


Case Study: Power-Law or Multi-Thermal?



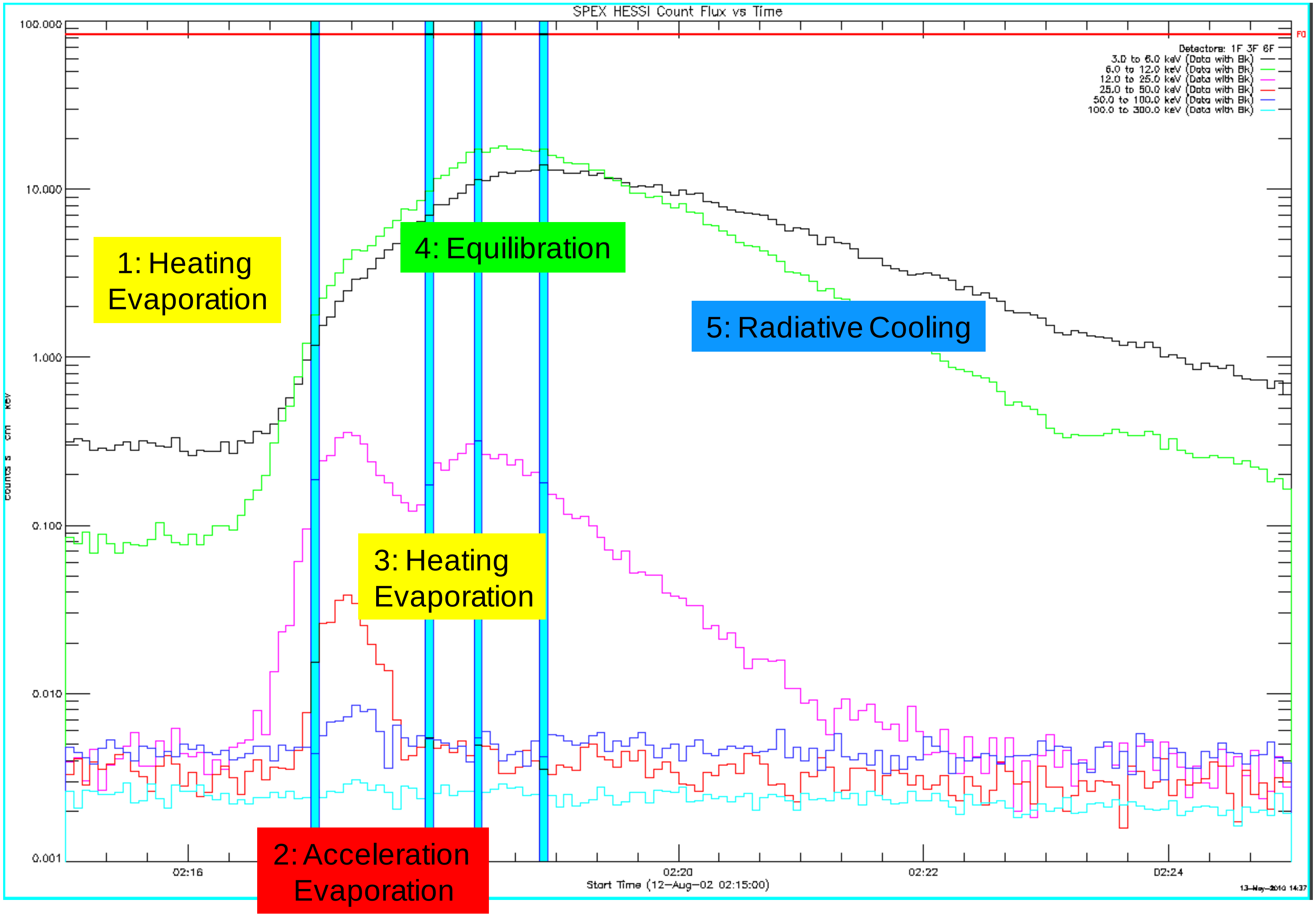
$$EM(T) = V(T)n^2(T)$$

A case study

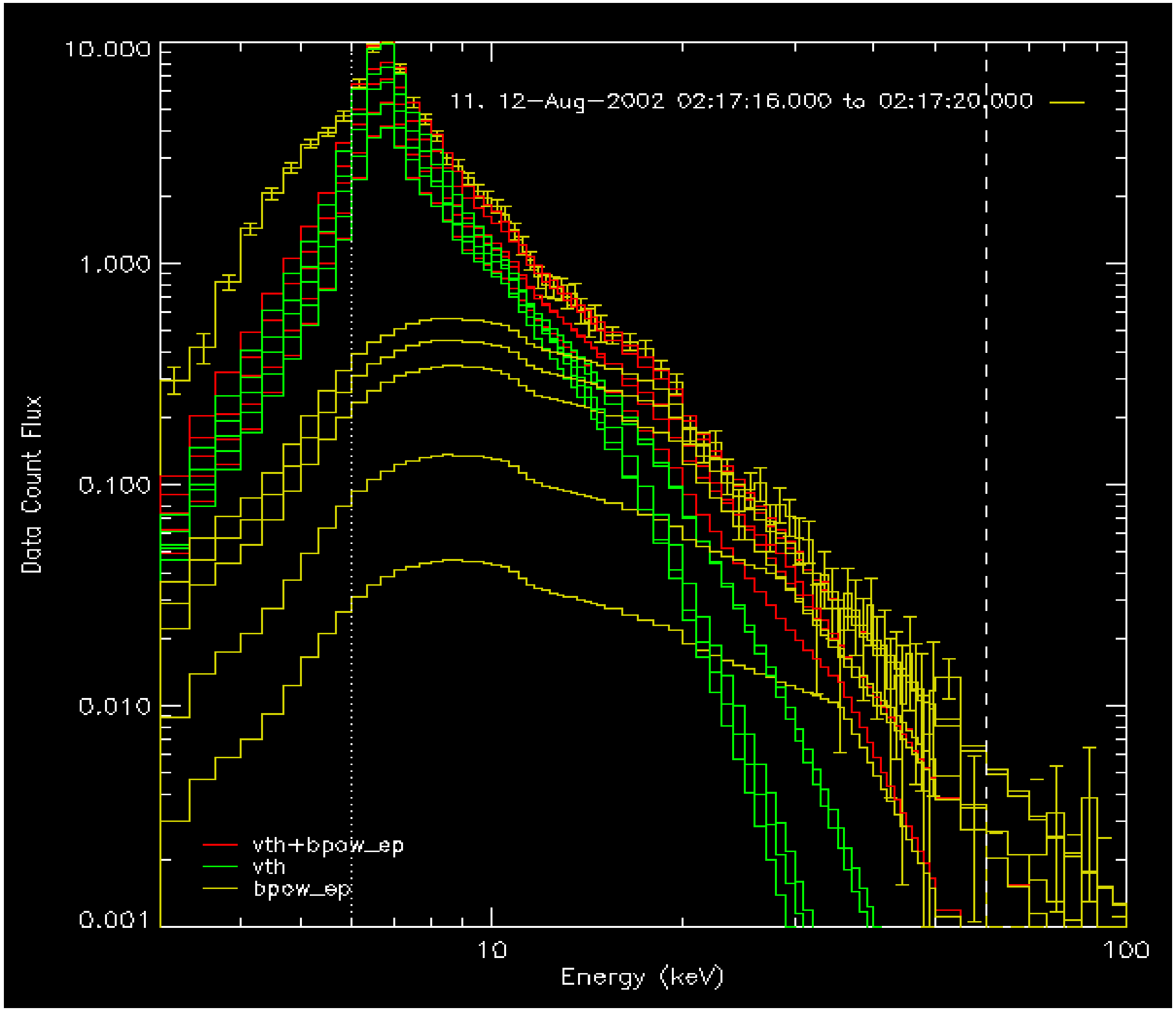


LIGHT CURVE:
A simple classical flare with an impulsive hard X-ray pulse leading gradual evolution in soft X-rays

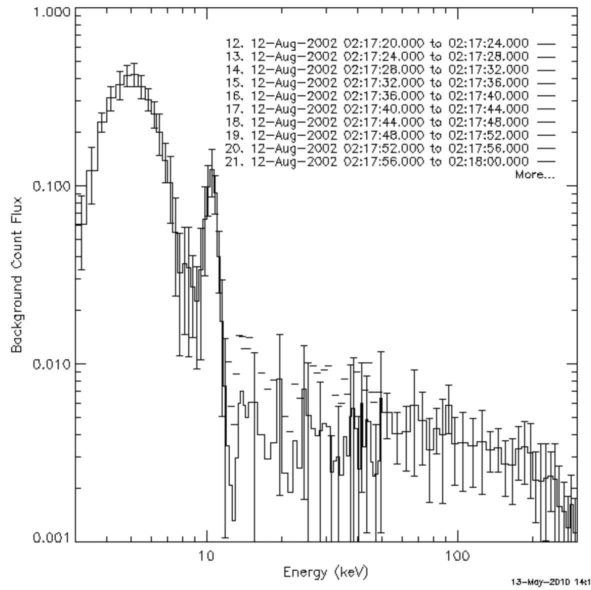
A case study: 5 Phases



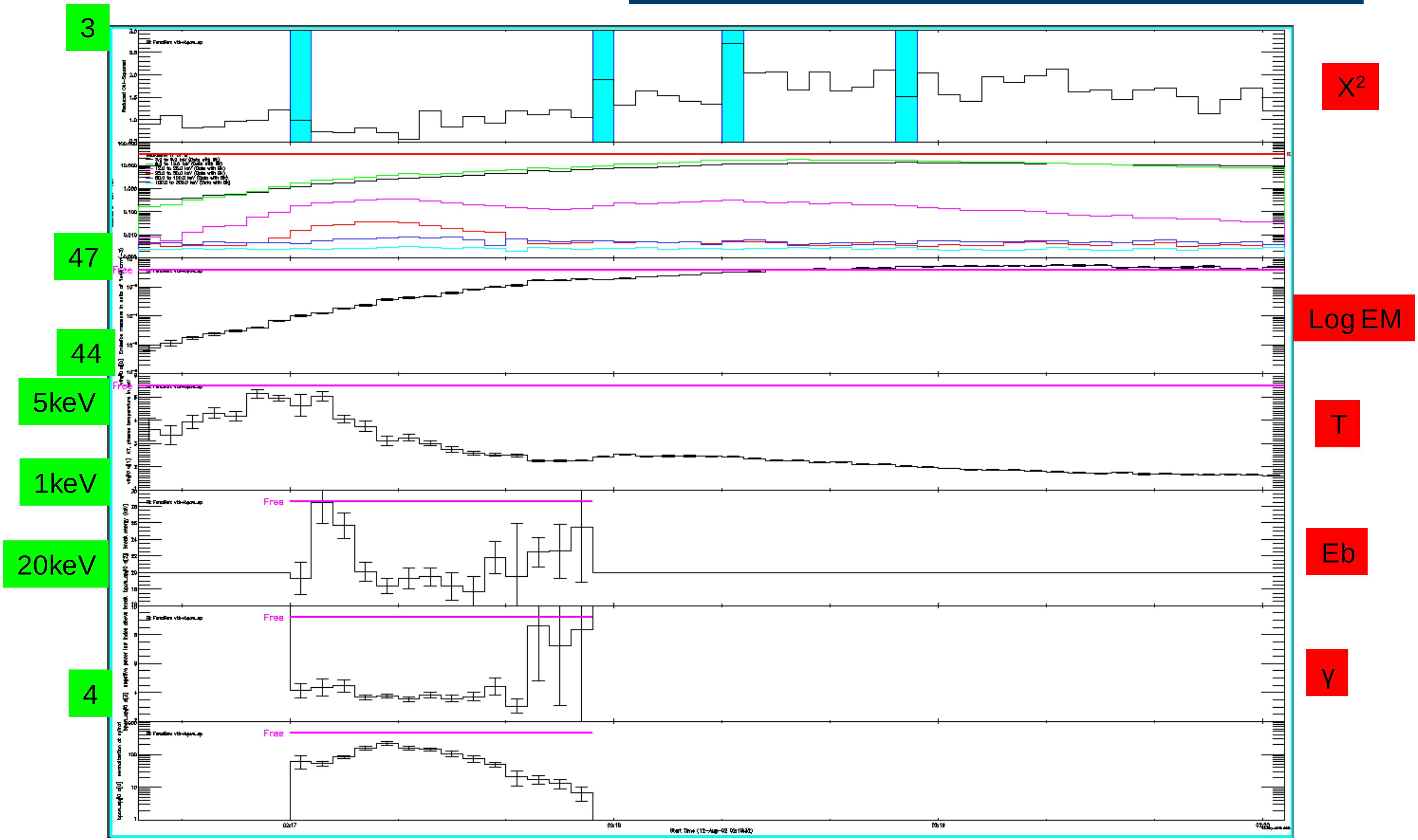
A case study: Thermal + Broken power-law



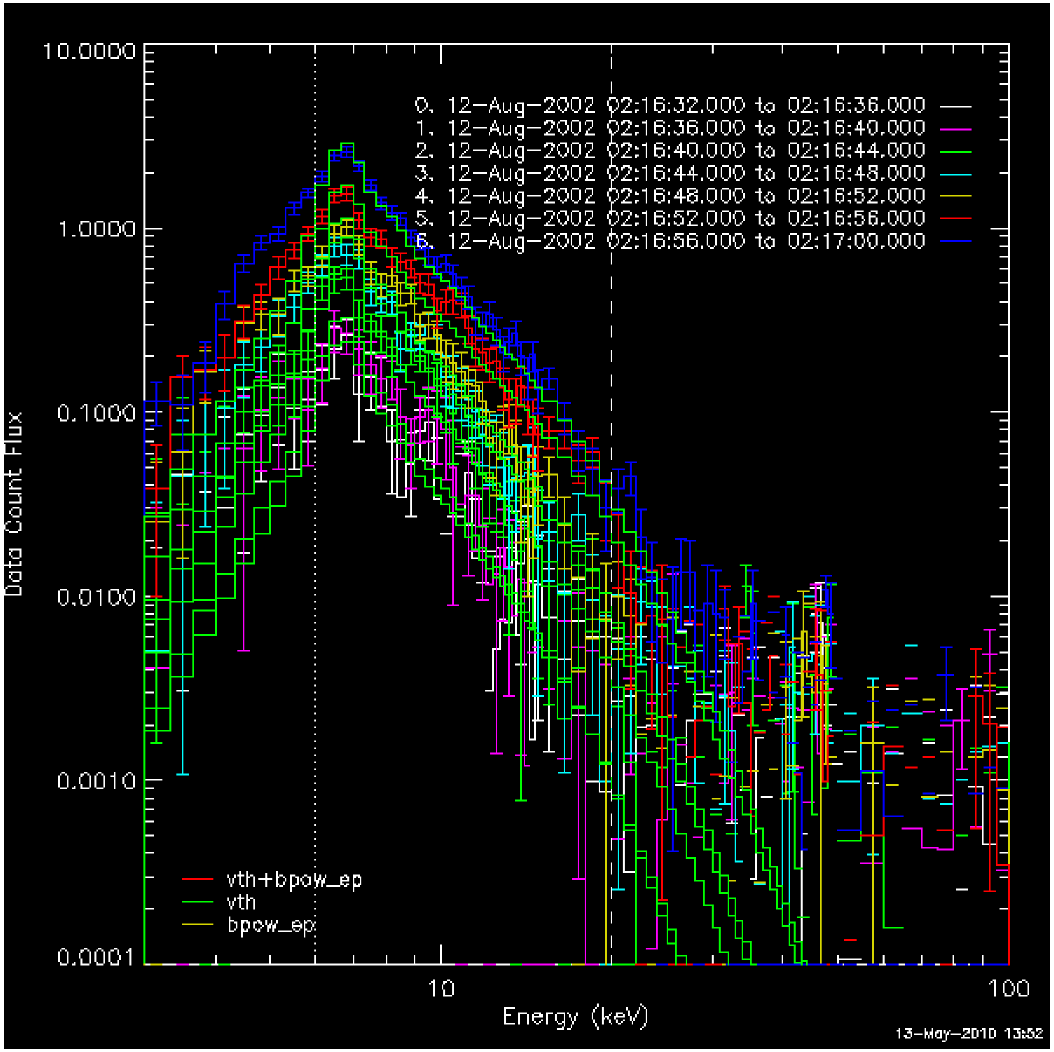
Background

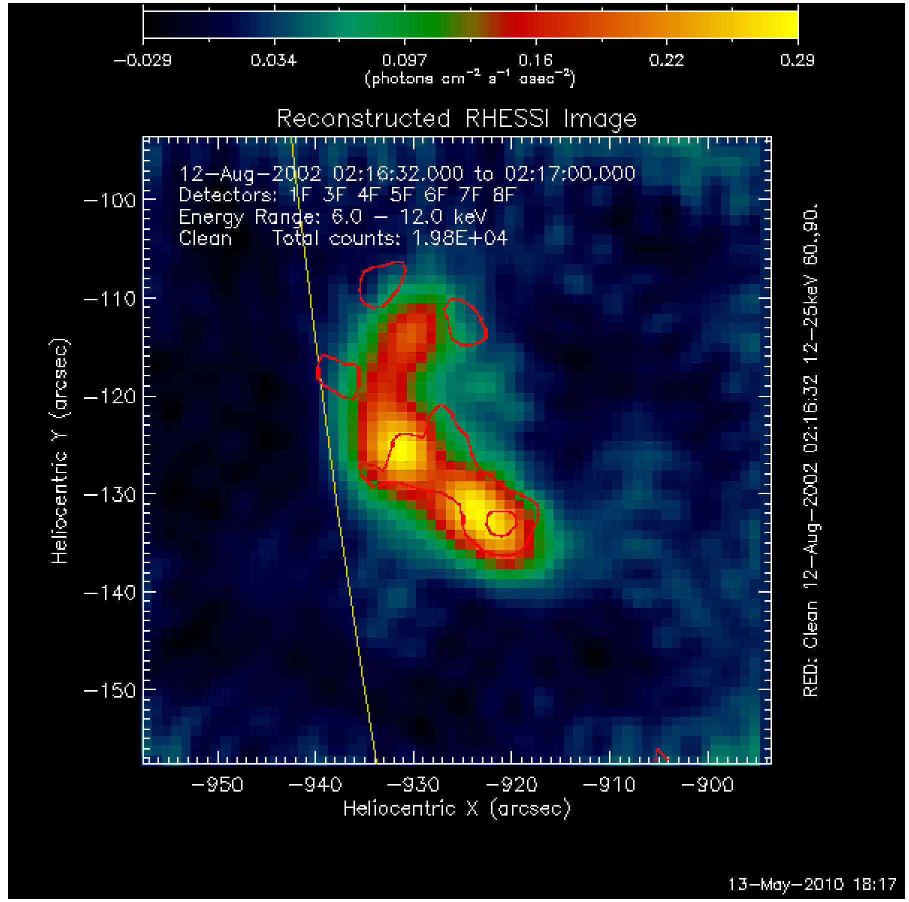


A case study: Parameters



A case study: Preheating
Phase 1 heating and evaporation





6-12 keV image 12-25 contours

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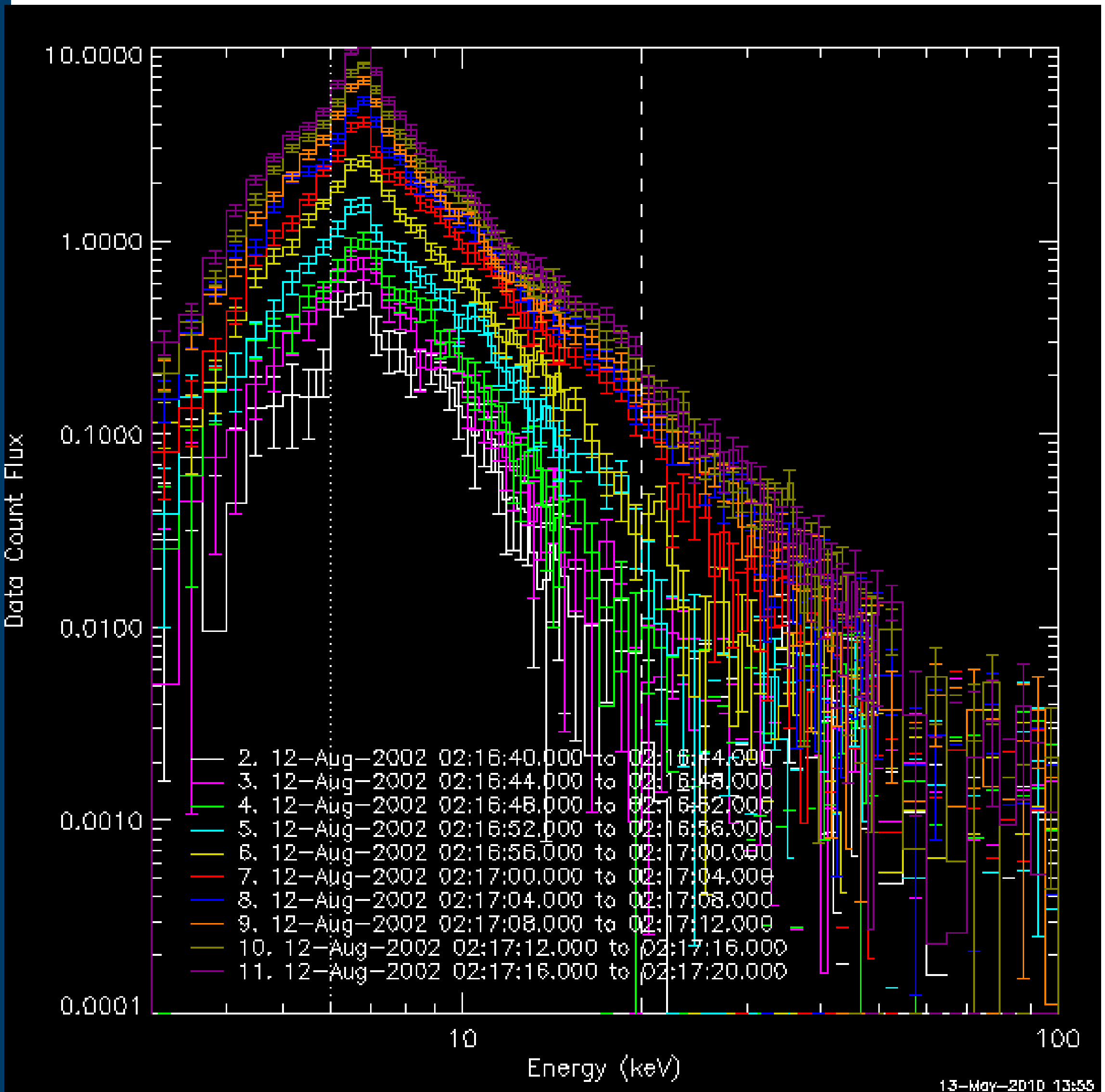
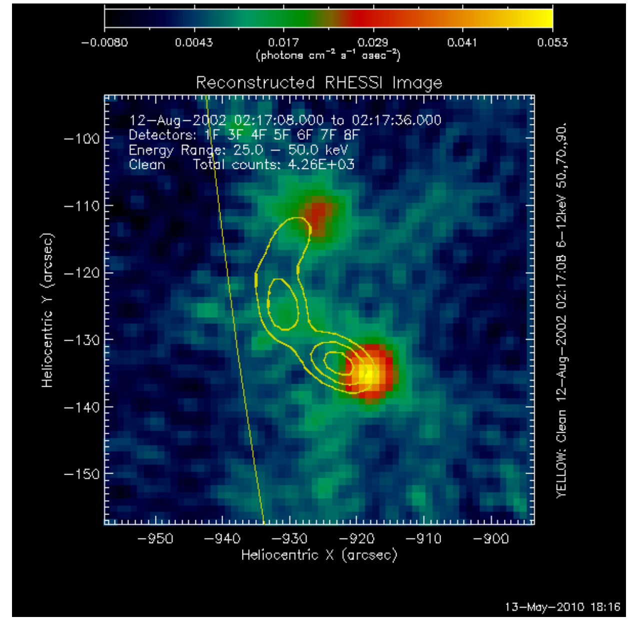
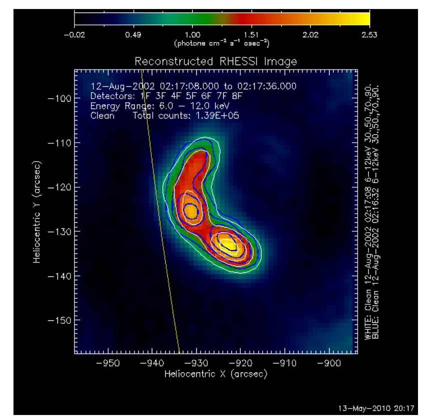
A case study: Phase 1 and Phase 2 Impulsive onset of particle acceleration?!





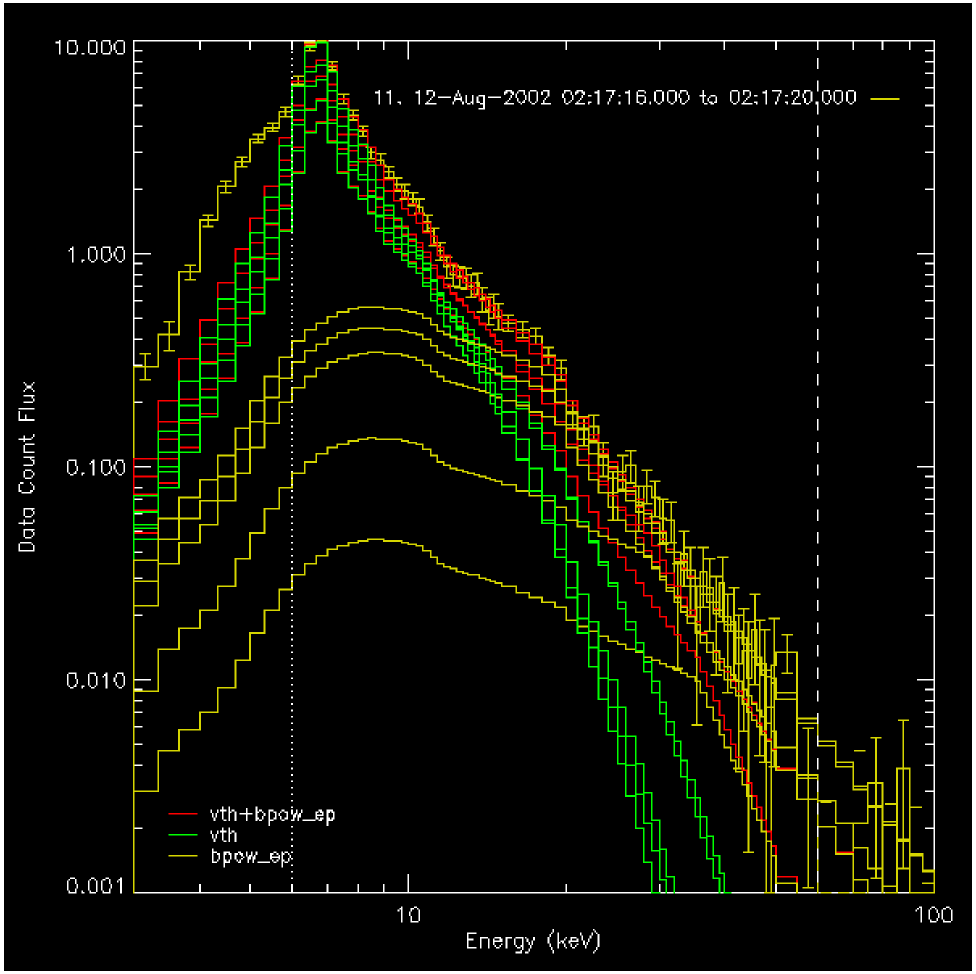
6-12 keV contours 25-50 image

6-12

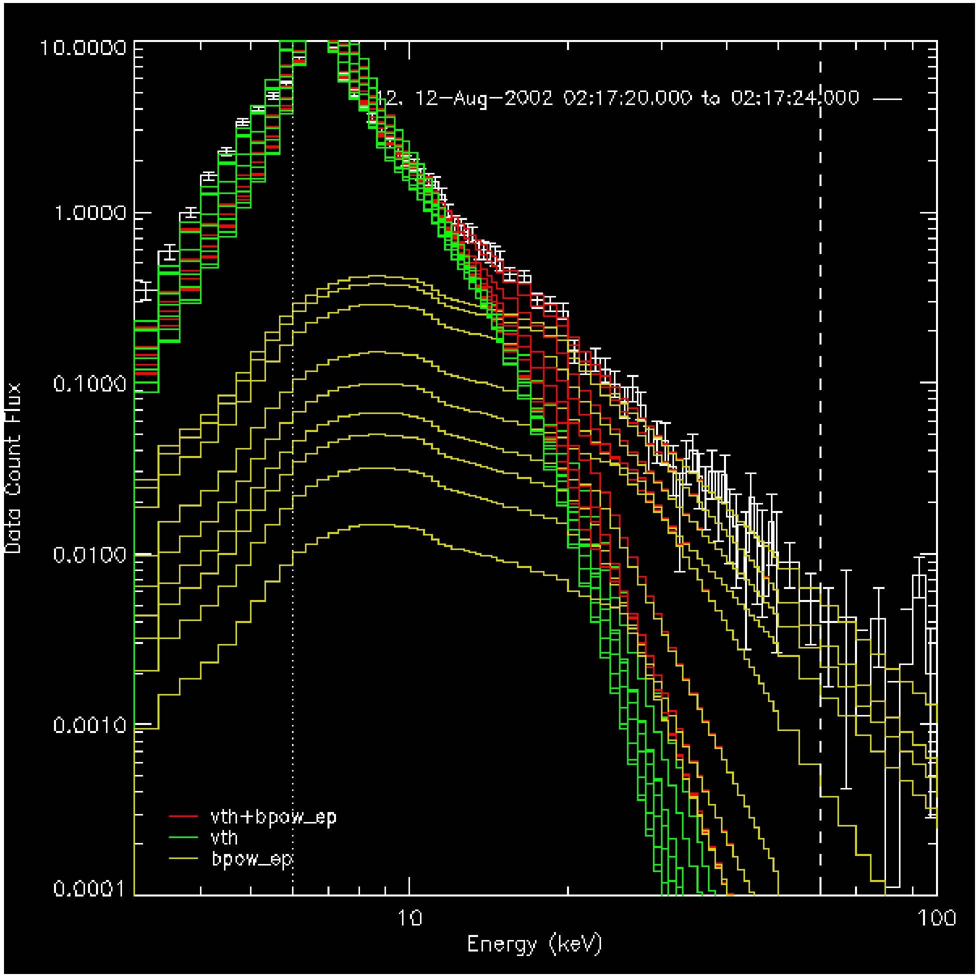


A case study: acceleration
Phase 2 acceleration and evaporation

Nonthermal Rise

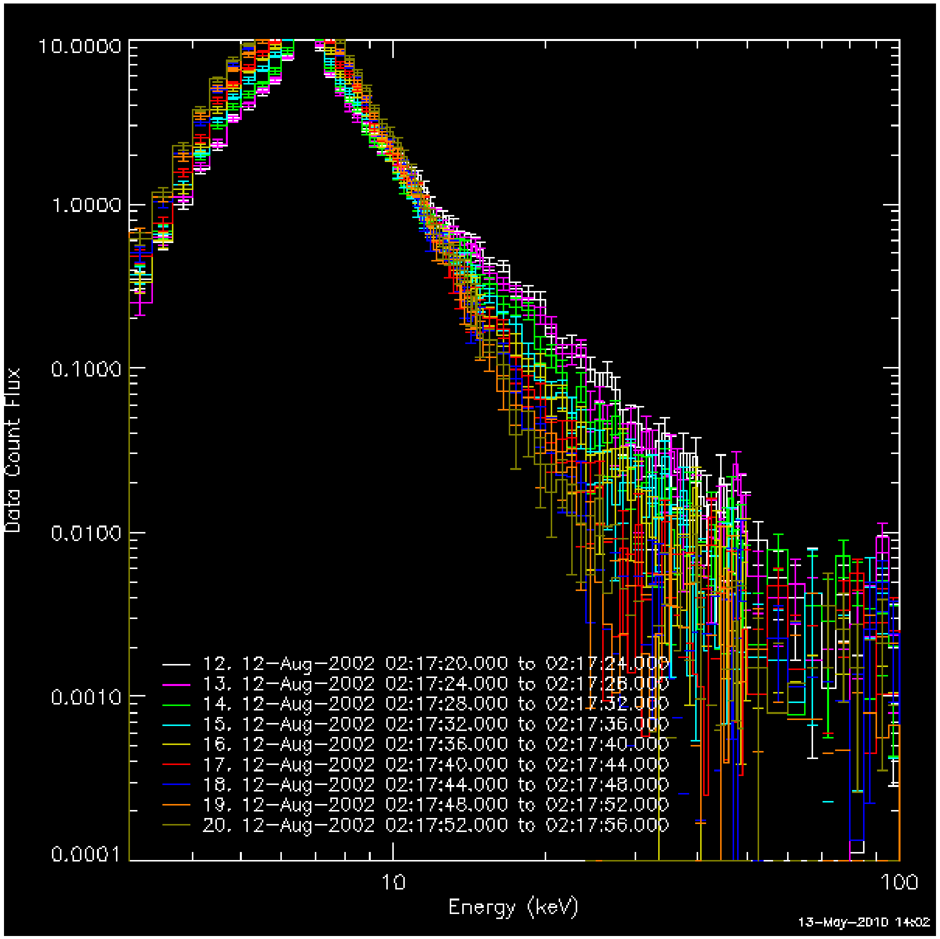


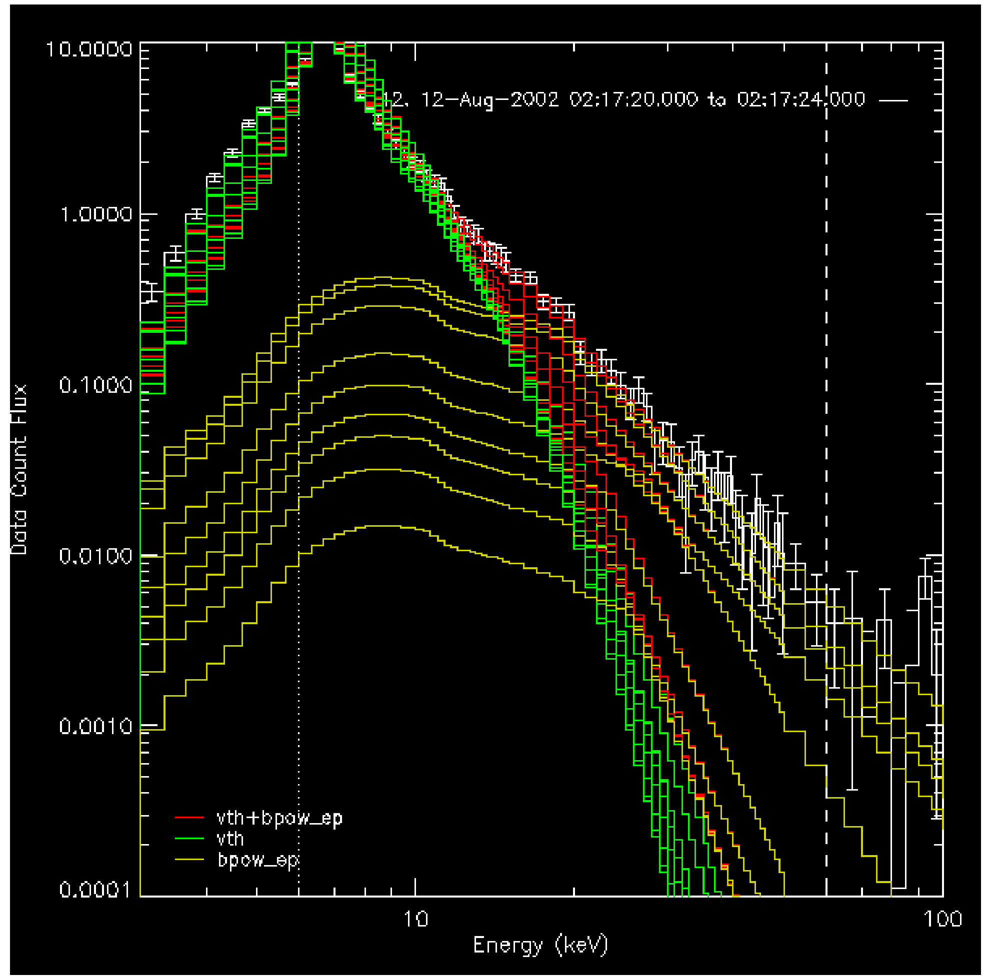
Nonthermal Decay



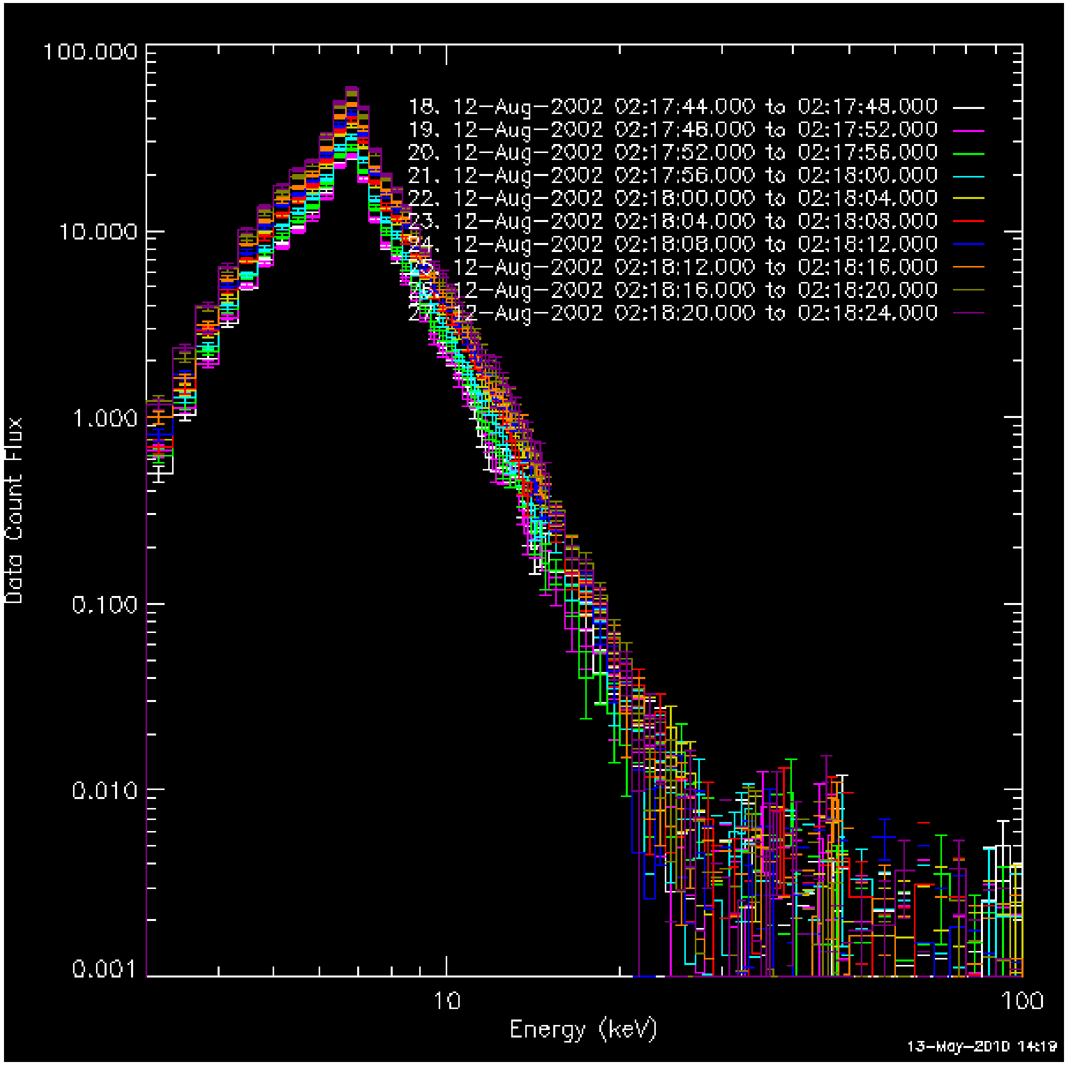
A case study: acceleration and evaporation nonthermal component vanishes smoothly!?

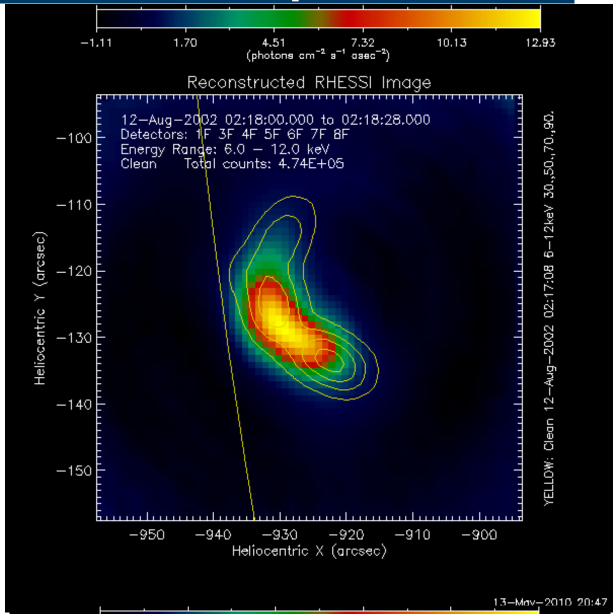
Nonthermal Decay

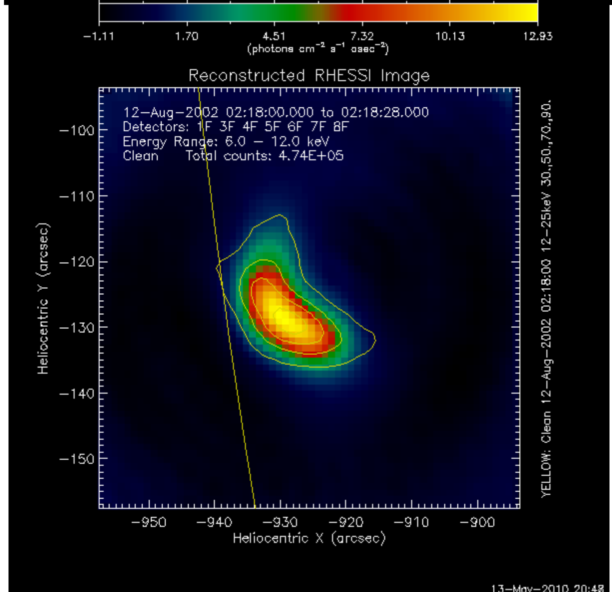




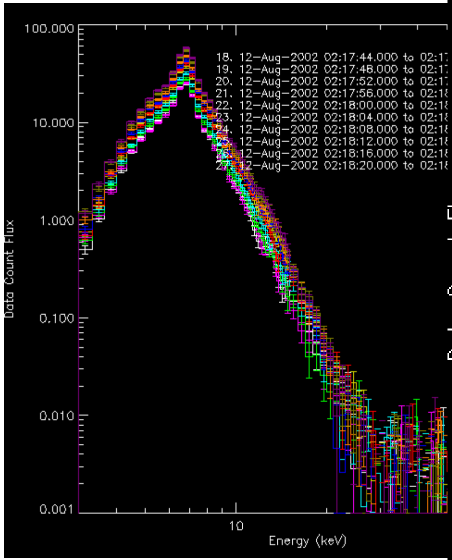
A case study: Heating
Phase 3 heating and evaporation

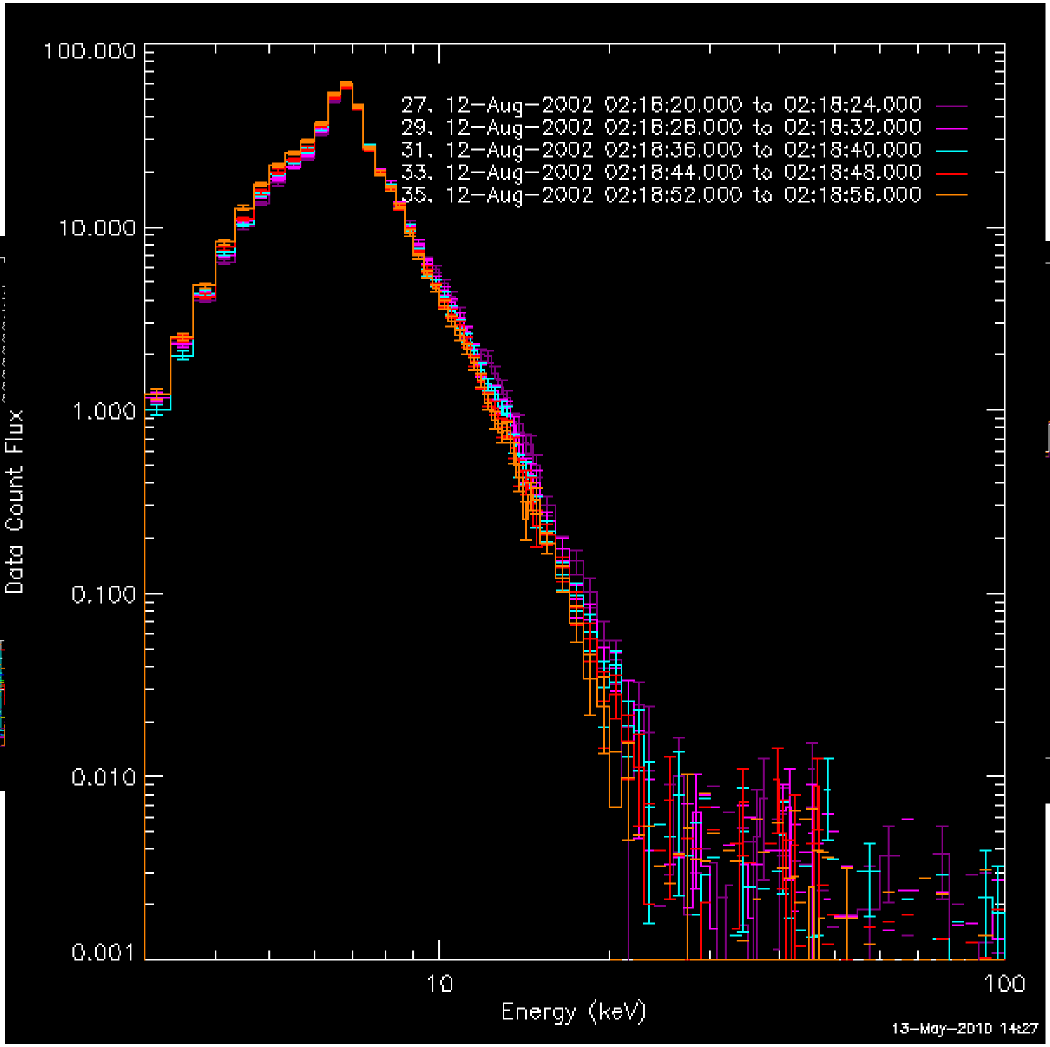


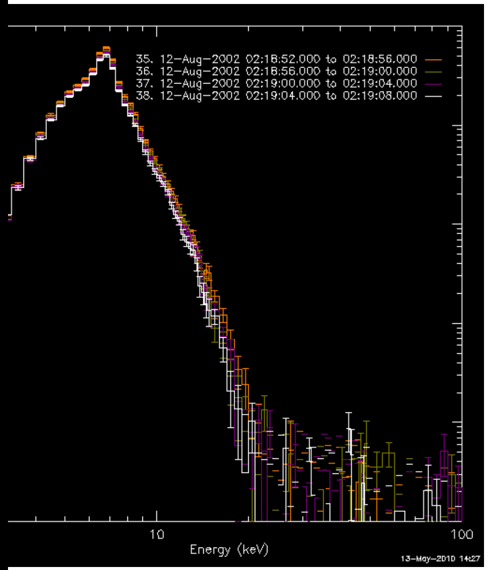




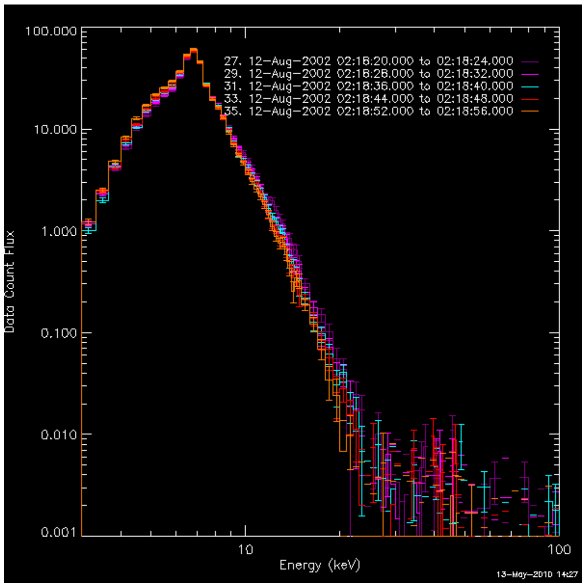
A case study: Phase 4 Equilibration

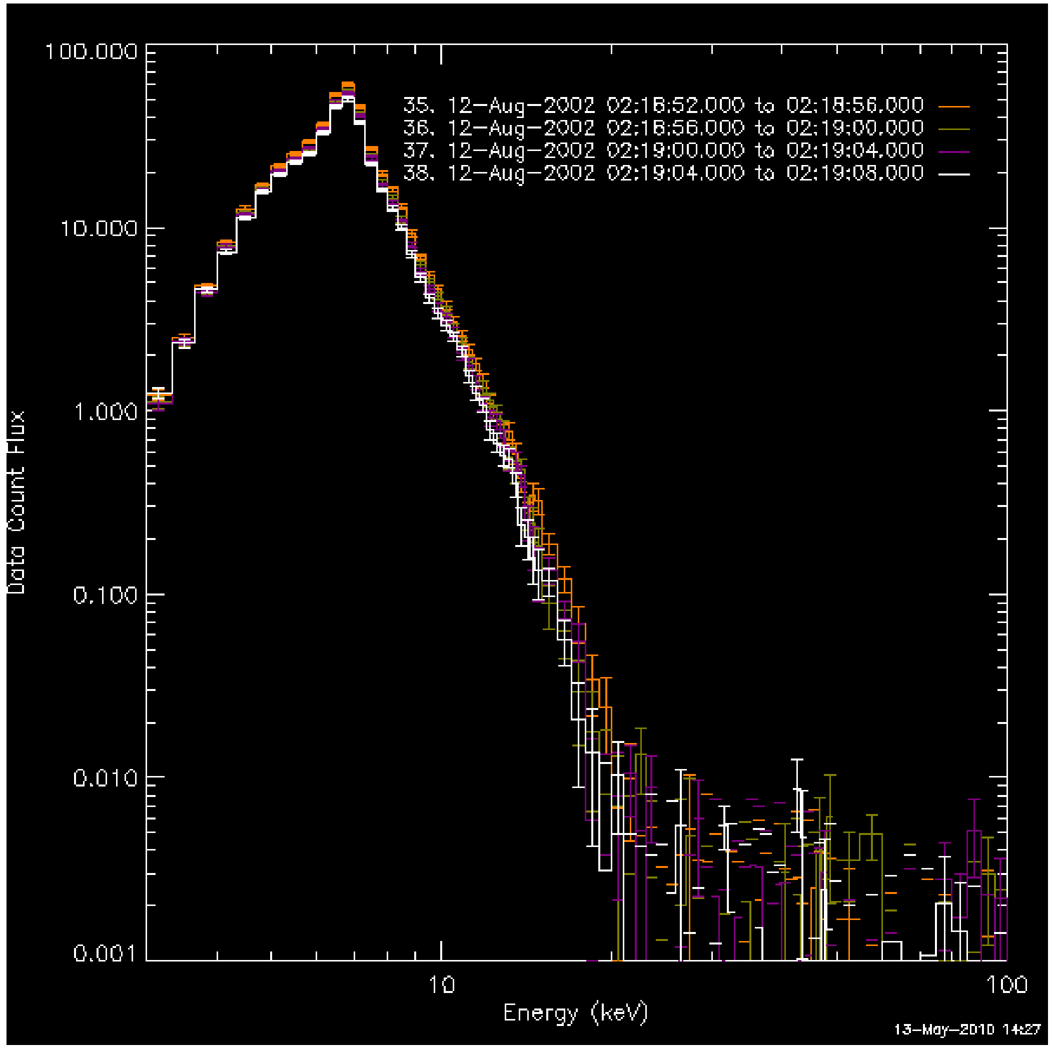




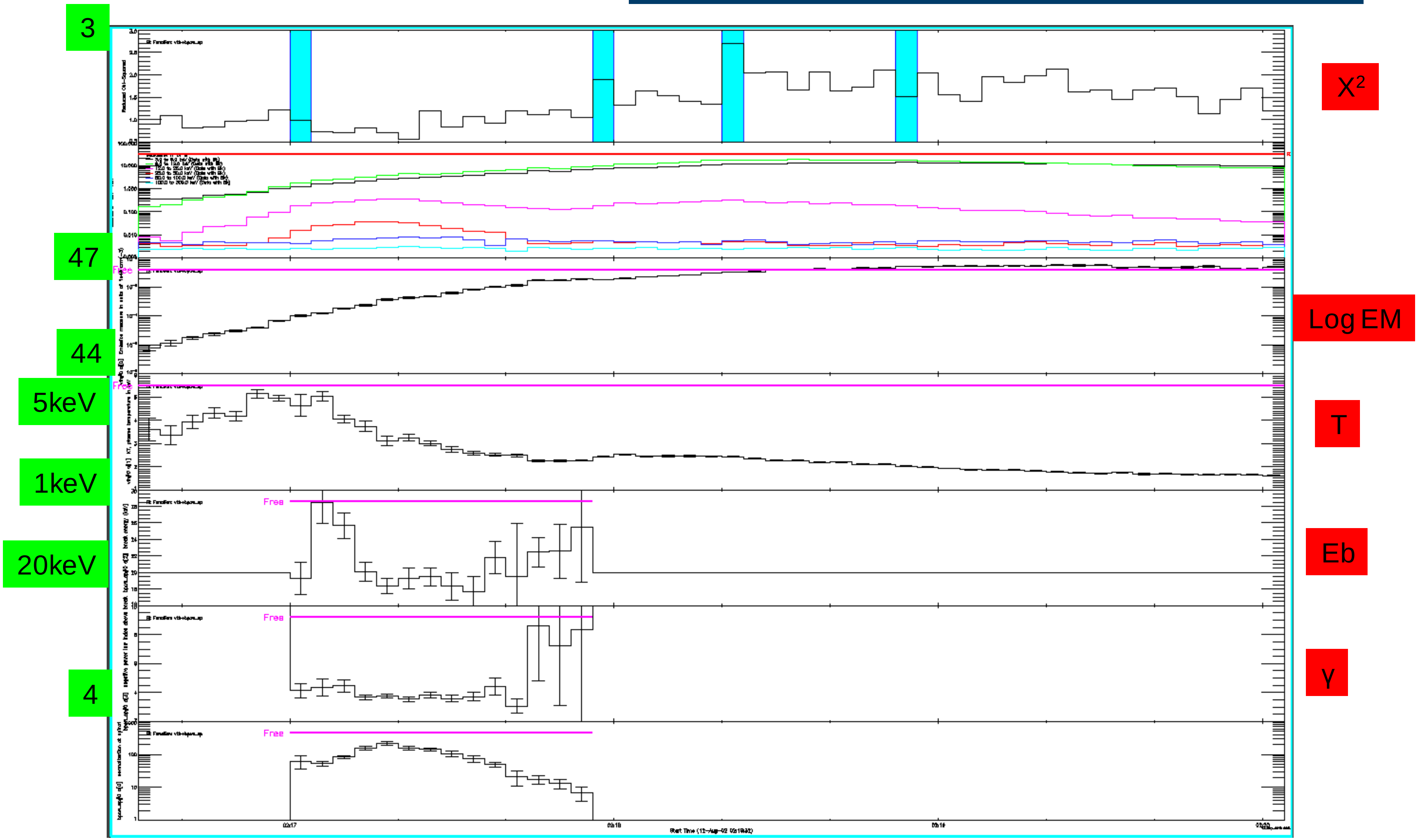


A case study: Phase 5 radiative cooling





Summary



Power-law Distributions: Classical

Cascade — Damping — Escape — Source

Waves
$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial k_i}\left[D_{ij}\frac{\partial}{\partial k_j}W\right] - \Gamma(\mathbf{k})W - \frac{W}{T^W_{\rm esc}(\mathbf{k})} + \dot{Q}^W,$$

Particles
$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial E}\left[D_{EE}\frac{\partial N}{\partial E} - (A - \dot{E}_L)N\right] - \frac{N}{T^p_{\rm esc}} + \dot{Q}^p,$$

Power-law Distributions: Classical

Gradual Energy Changes

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

Plasma Distribution Function in a Superthermal Radiation Field

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AT&T Bell Laboratories, Murray Hill, New Jersey 07974
and
Kunioki Mima
Institute of Laser Engineering, Osaka University, Osaka 565, Japan
and
Minh Duong-van
Lawrence Livermore National Laboratories, Livermore, California 94550
(Received 10 July 1984)

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial \mathbf{v}} \cdot \left[\frac{1}{2}\mathbf{D}(\mathbf{v}) \cdot \frac{\partial f}{\partial \mathbf{v}} - \mathbf{v}\gamma(\mathbf{v}) f\right],$$

where the diffusion tensor is given by

$$\mathbf{D} = D_{\parallel}\mathbf{I} + D_{\perp}(\mathbf{I} - \mathbf{vv}/v^2).$$

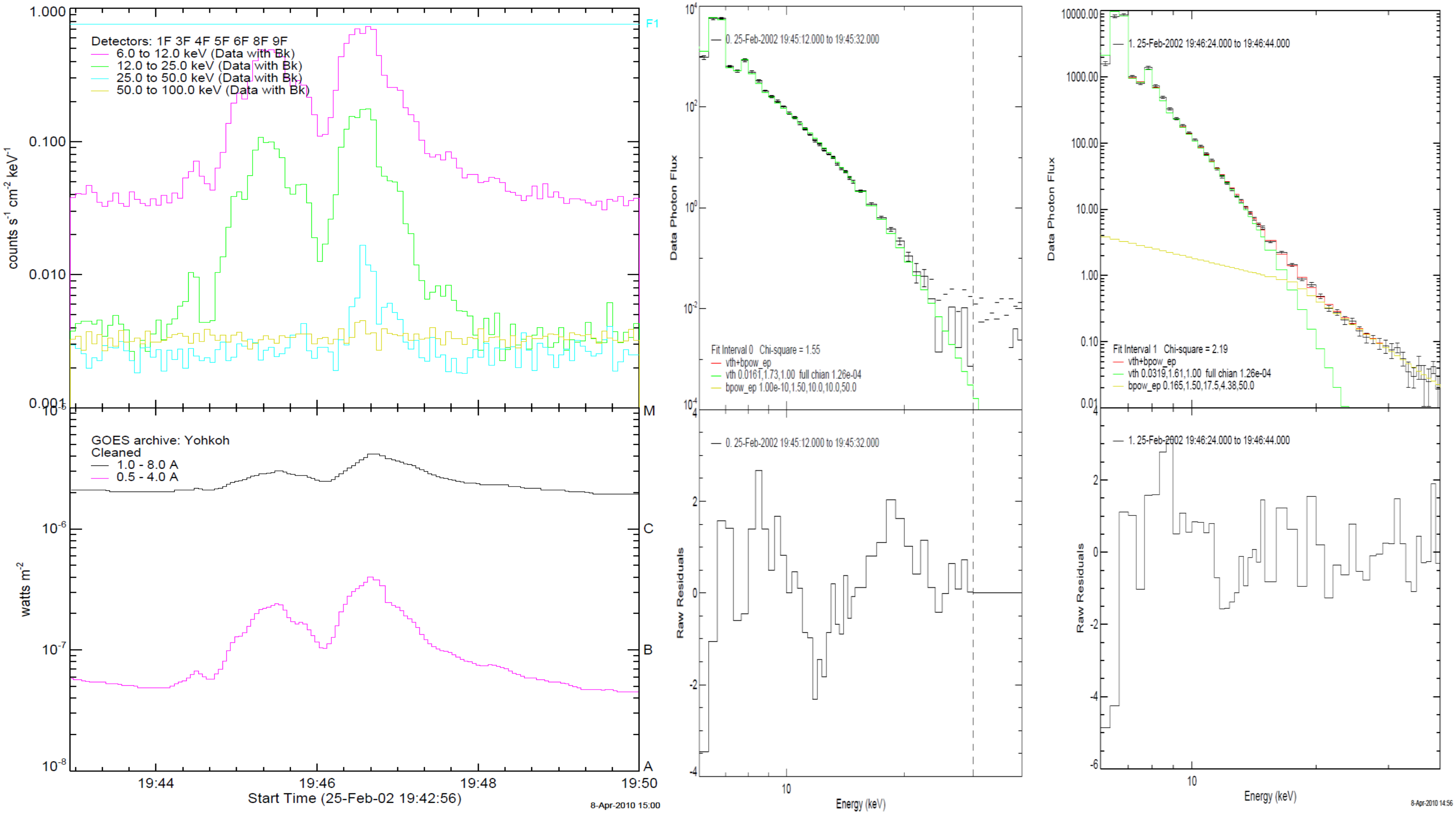
$$D_{\parallel}^{\rm eq}(v) = -2T\gamma(v)$$

$$D_{\parallel}^{{\rm NL}(e)} = \frac{k_{\rm D}^2 |r_0|^2}{6\pi} \frac{v_{Te}^3}{v} \omega_{pe} \frac{k_{\rm D}^3}{n_0} \frac{1}{|\epsilon(\omega_0, 0)|^2},$$

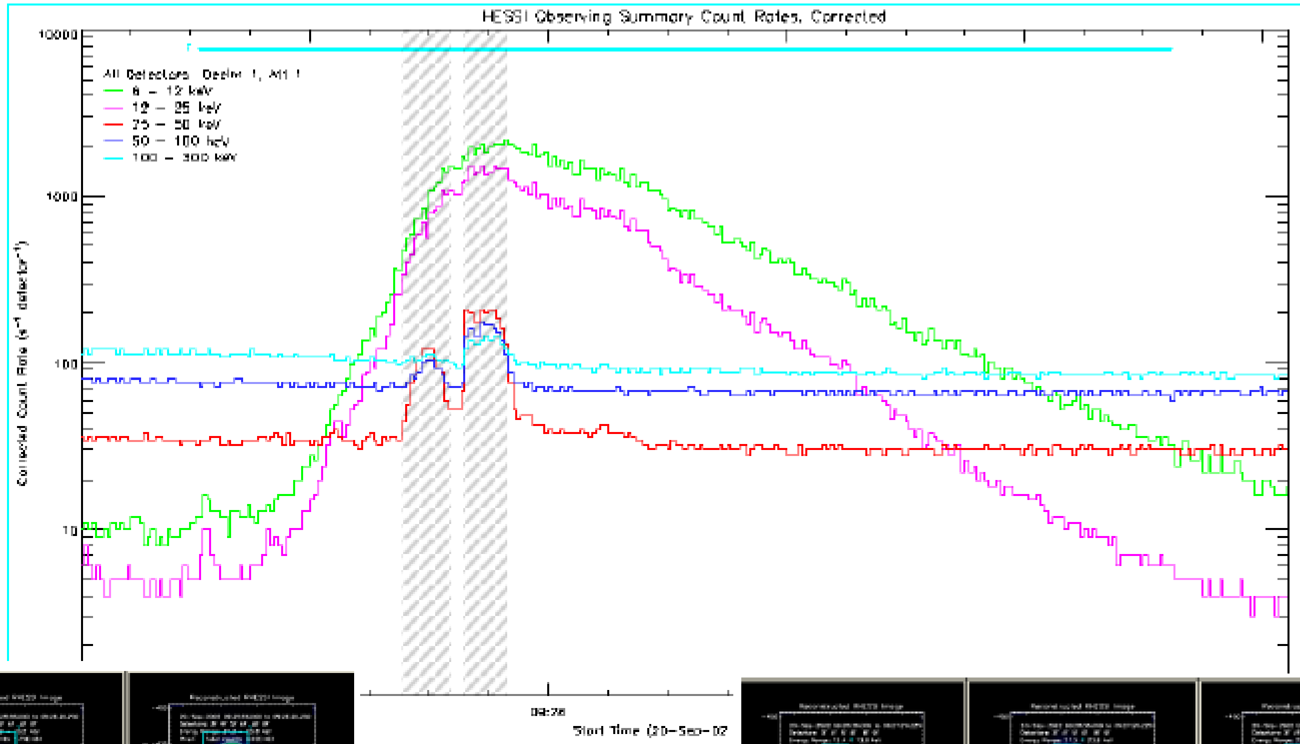
Intermittency

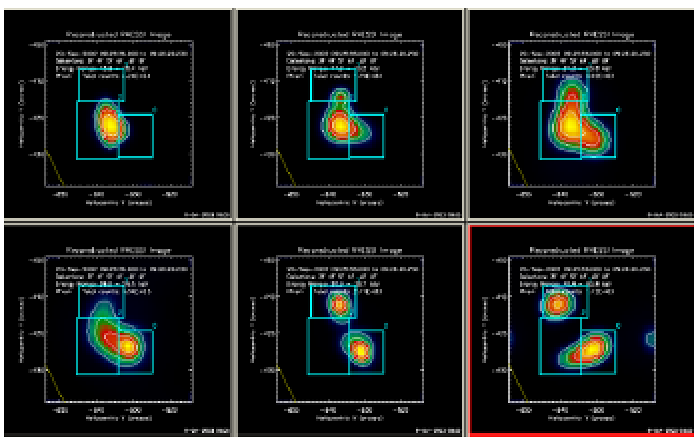
Fractal

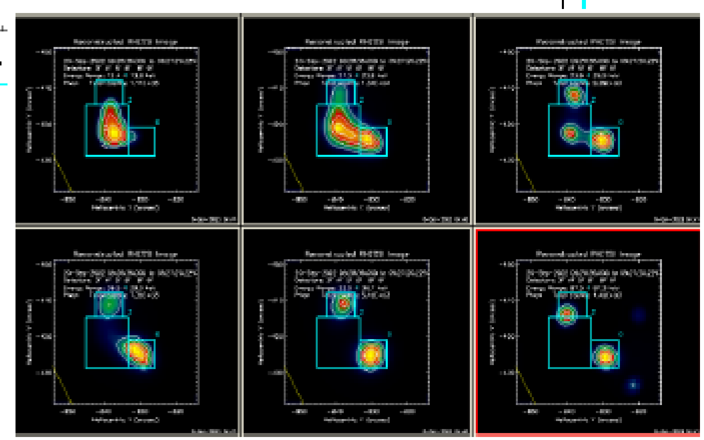
Observations of Intermittency
HXR behavior cannot be predicted from SXR



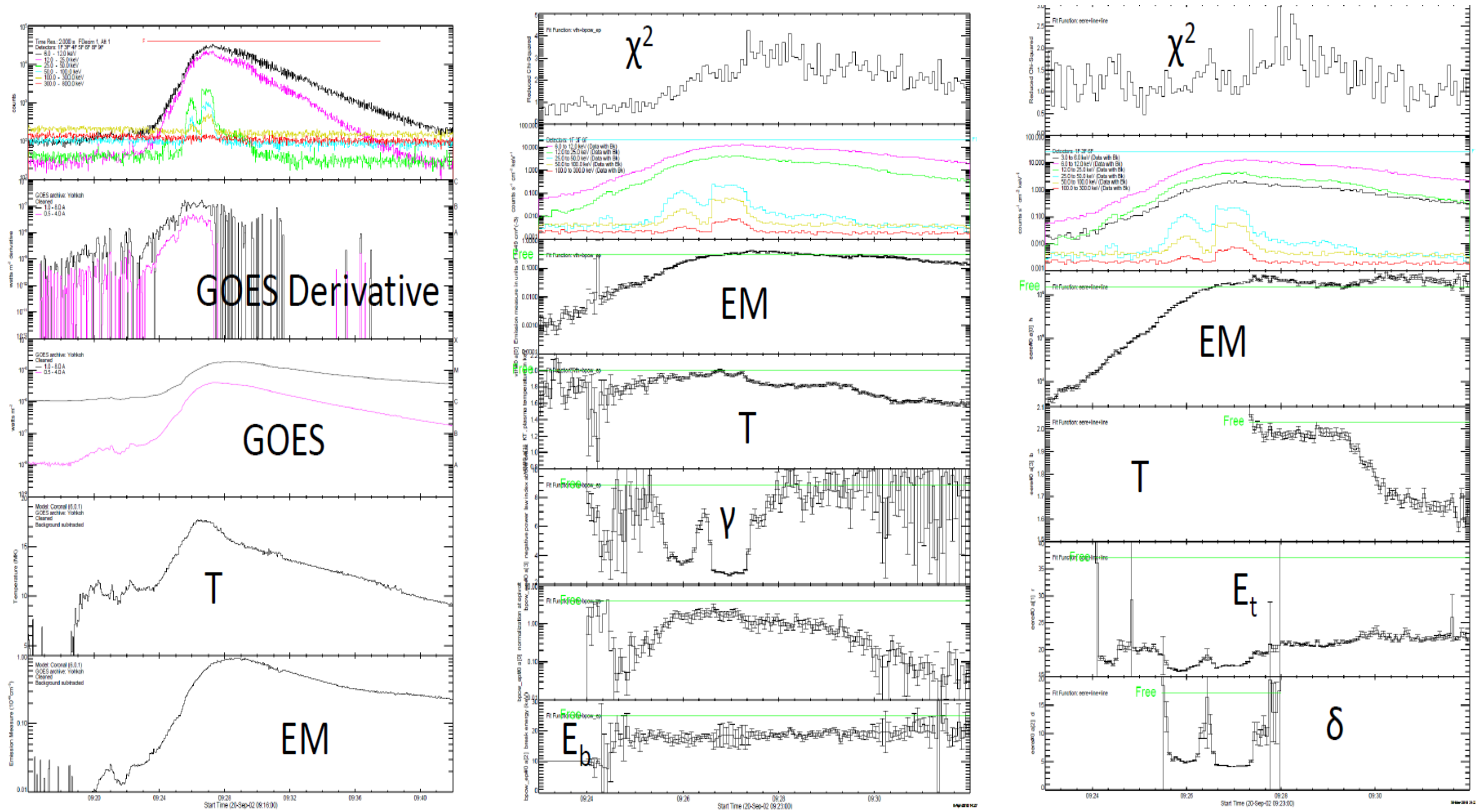
Observations of Intermittency
Energetically trivial intermittent HXRs





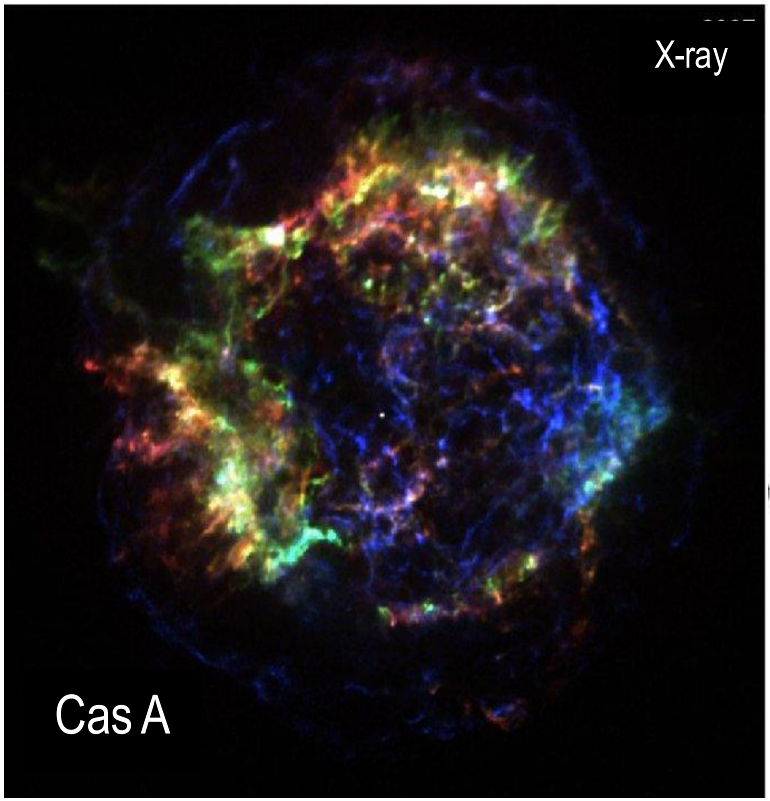


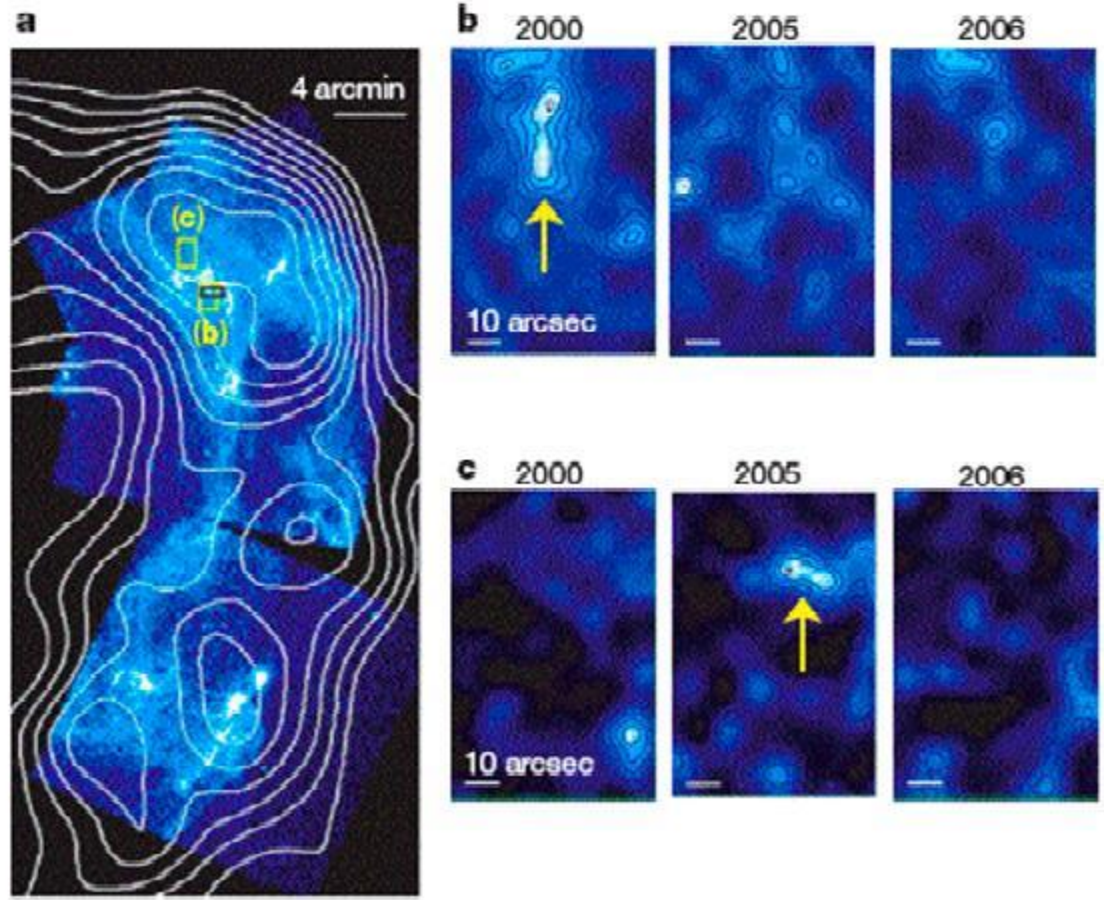
Observations of Intermittency
Energetically trivial intermittent HXRs



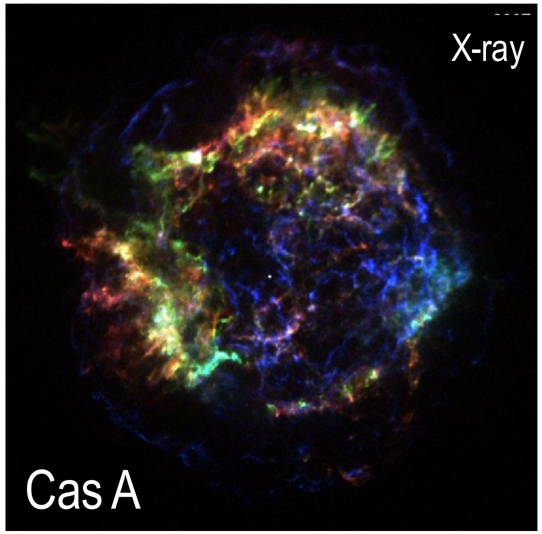
Observations of Intermittency
X-ray filaments in Supernova Remnants

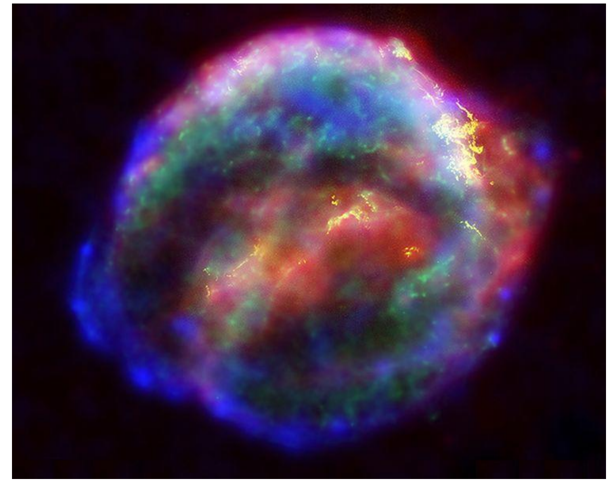
X-ray Variability

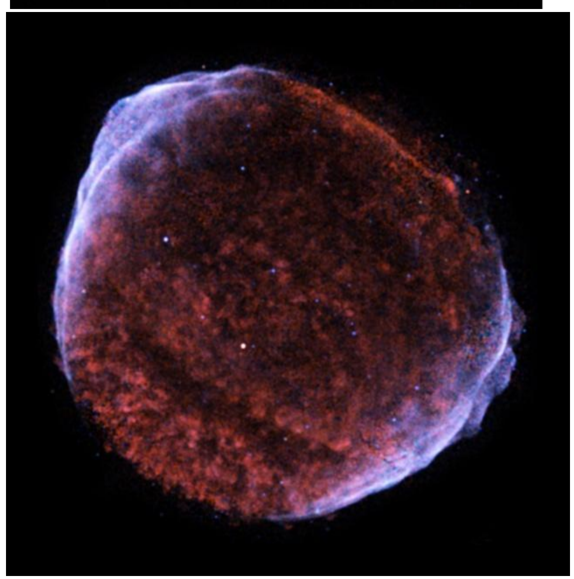




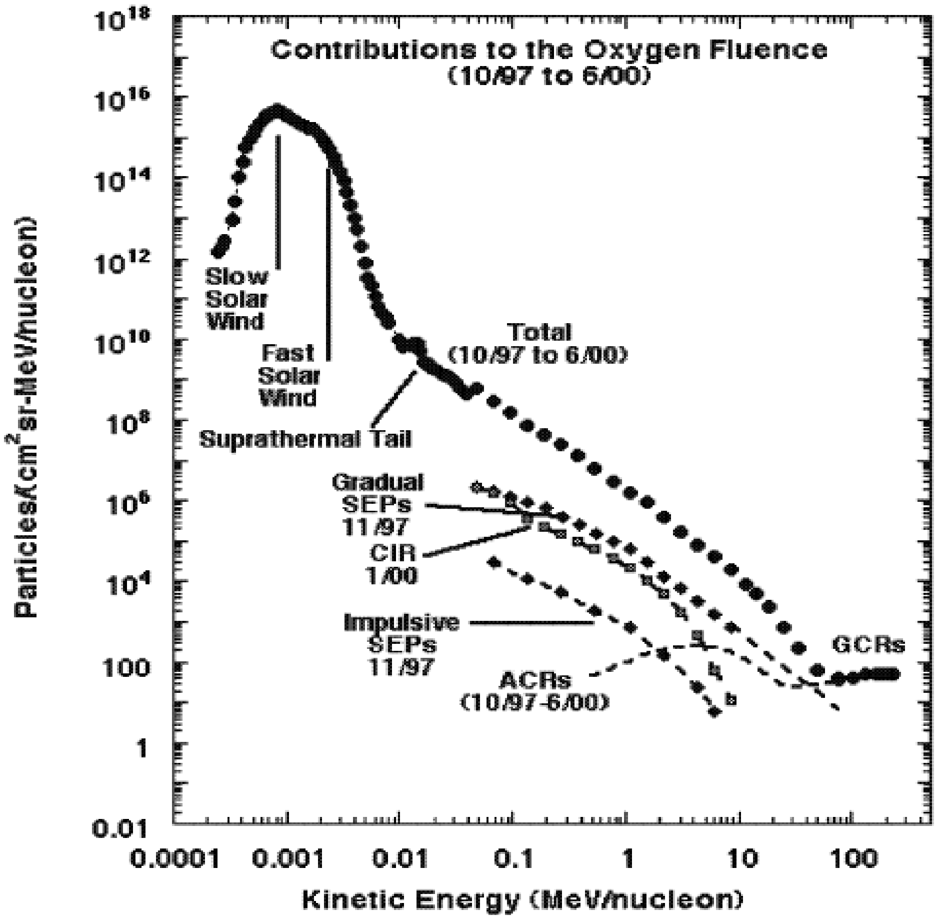
The Zoo of Shell-Type Supernova Remnants

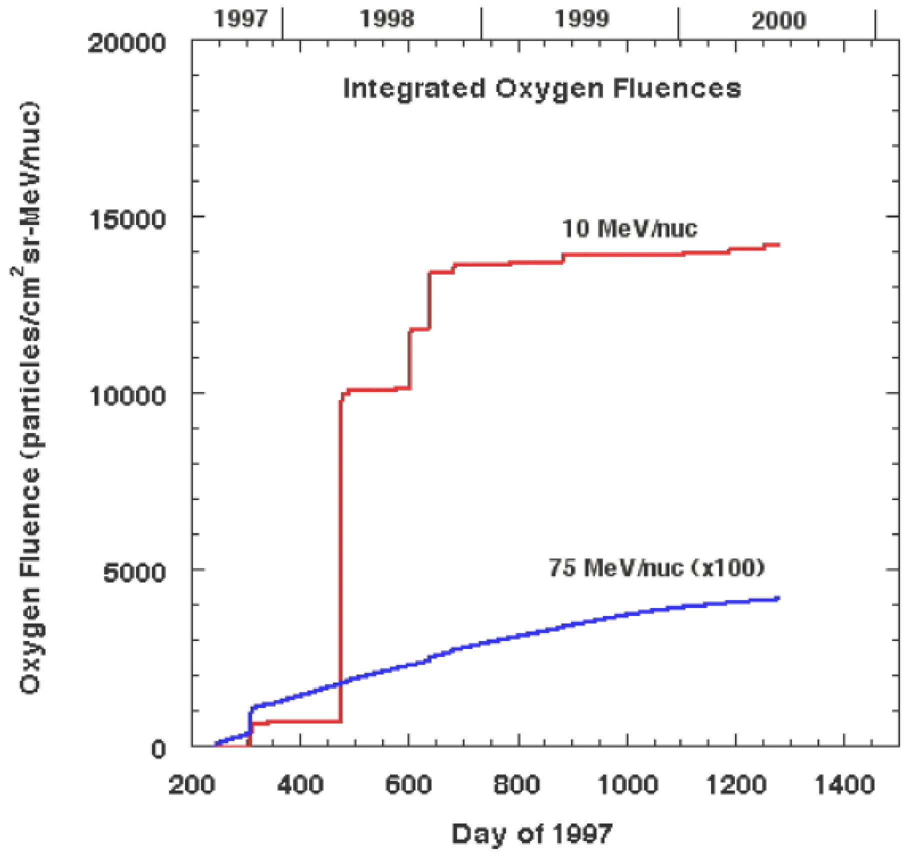




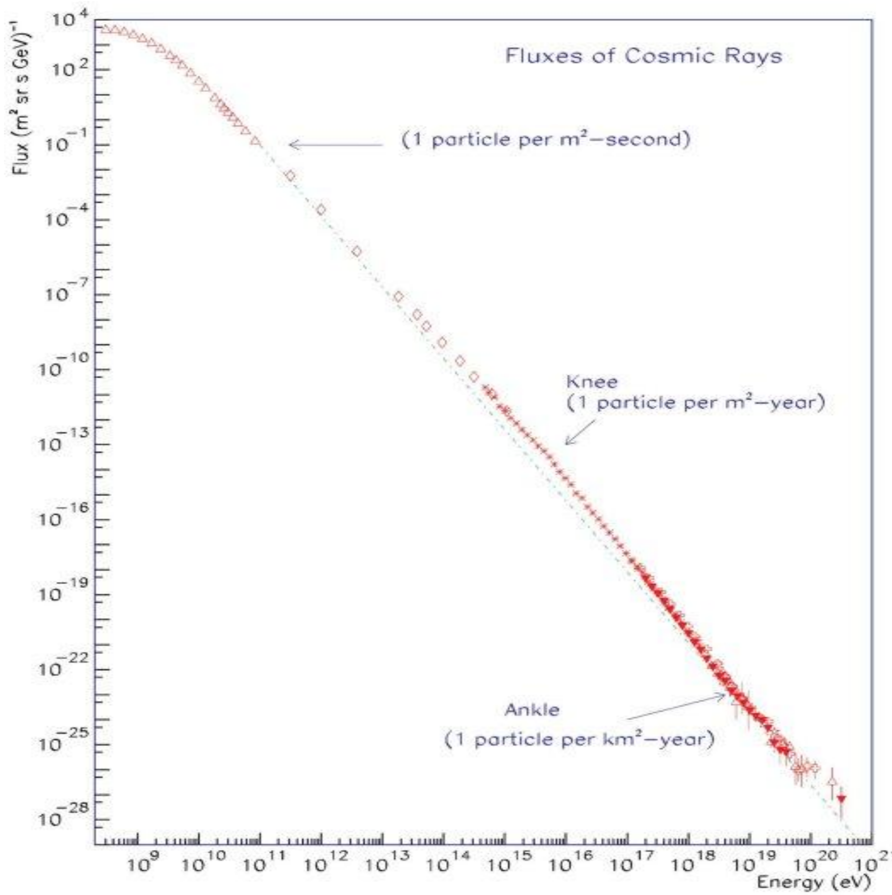


Observations of Intermittency
Nature of power-law SEP spectra

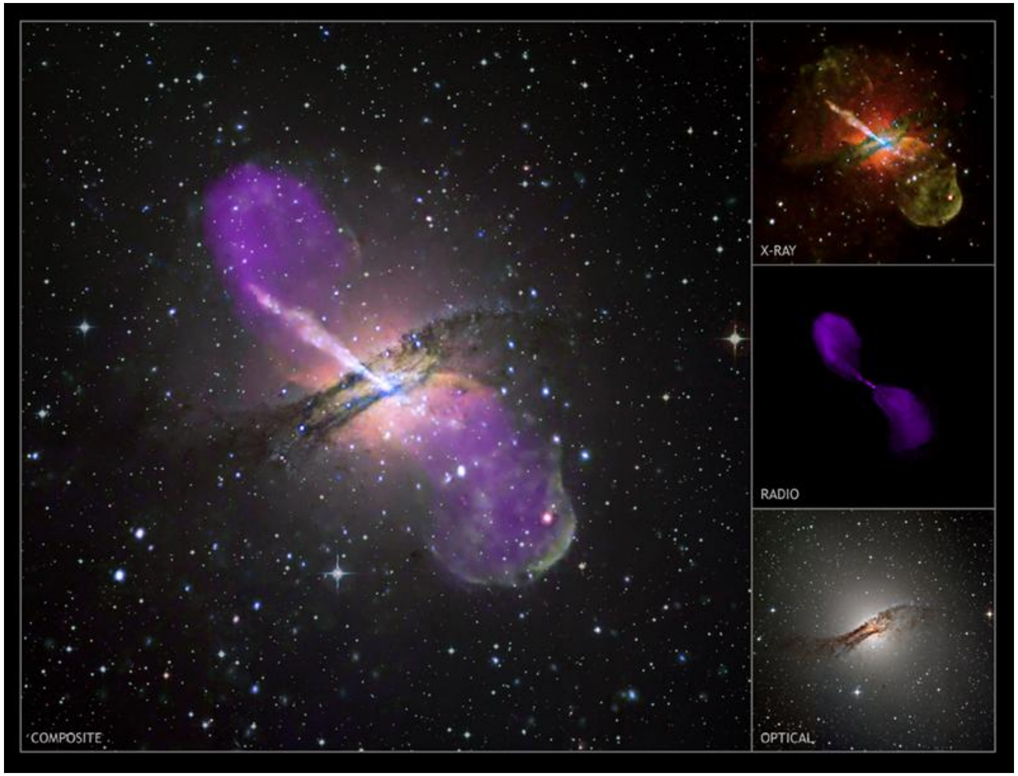




Nature of power-law Cosmic Ray spectrum



Nature of power-law distribution in Radio Galaxy



Hardcastle et al. 2007

Power-law Distributions: Contemporary Levy Flights

Impulsive Energy Changes

$$P(v)dv = \frac{\mu\epsilon^{\mu}dv}{v^{1+\mu}}$$

$$\frac{\partial f(v,t)}{\partial t} = \frac{1}{2}\mu\epsilon^{\mu}\left[\int_{-\infty}^{v-\epsilon}\frac{f(s,t)ds}{(v-s)^{1+\mu}} + \int_{v+\epsilon}^{\infty}\frac{f(s,t)ds}{(s-v)^{1+\mu}}\right] - f(v,t).$$

ON GENERATING KAPPA-LIKE DISTRIBUTION FUNCTIONS USING VELOCITY SPACE LÉVY FLIGHTS

Michael R. Collier

University of Glasgow

Power-law Distributions: Contemporary Statistics

Statistical Approaches: Entropy

$$S_1 \equiv \lim_{q \to 1} S_q = k \lim_{q \to 1} \frac{1 - \sum_{i=1}^{W} p_i \exp[(q-1)\ln p_i]}{q-1}$$

$$= -k \sum_{i=1}^{W} p_i \ln p_i$$

$$p_i = \frac{[1 - \beta(q-1)\varepsilon_i]^{1/(q-1)}}{Z_q} \qquad Z_q \equiv \sum_{l=1}^{W} [1 - \beta(q-1)\varepsilon_l]^{1/(q-1)}$$

Tsallis 1988

Phase space interdependence

$$\frac{d\Gamma'(\epsilon')}{d\epsilon'} = \frac{1}{\Delta\epsilon'}\left[S'_\kappa(E) - \frac{S'_\kappa(\epsilon')}{\kappa}\right]^{-(\kappa+1)}. \qquad w_{i,\kappa}(\epsilon_i) = A\left(1 + \frac{\epsilon_i}{\kappa T_\kappa}\right)^{-(\kappa+1)},$$

Treumann and Jaroschek 2008

Power-law Distributions: Contemporary Statistics

Temperature T	Power-law index
Mean energy of each degree of freedom	? (Energetic dissipation rate)
Physics is invisible in ideal thermal equilibrium system	Processes may not be separable in ideal power-law (scale free or no dominant scale)

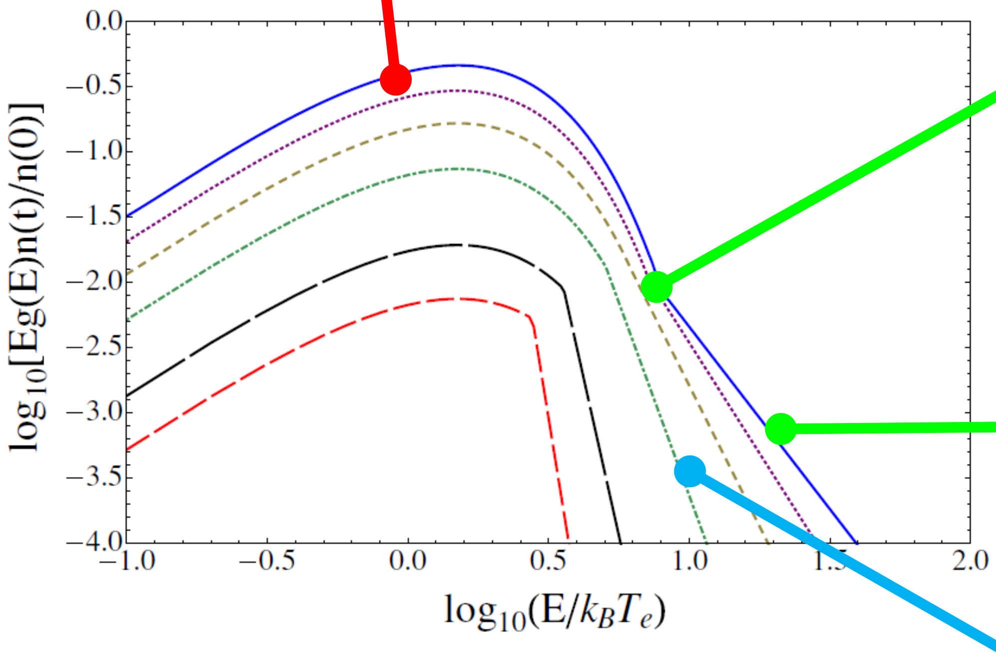
Energetic particles in nature likely result from complex dissipation processes in magnetized collisionless plasmas.

The wish is that collective plasma effects may be classified so that interactions of energetic particles with electromagnetic field fluctuations can be studied quantitatively.

Generic Particle Distribution in Turbulent Plasmas

Thermal Emission

Balance between Collision and Acceleration



Balance between Diffusive Acceleration and Escape

Samples of Particle Distribution Function

Emissions by Energetic Particles

Liu et al. 2009, 2010