Hale COLLAGE 2017 Lecture 23

Flare Impulsive Phase: Radio and HXR imaging spectroscopy II

Bin Chen (New Jersey Institute of Technology)

Outline

- Radiation from energetic particles
  - Bremsstrahlung → Lecture 20
  - Gyromagnetic radiation ("magnetobremsstrahlung") → Lecture 21
  - Other radiative processes → Lecture 22
    - Inverse Compton, coherent radiation
- Diagnosing flare energetic particles using hard X-ray and radio spectroscopy and imaging
  - **Where?** → previous lecture
  - What? → this lecture
- Suggested reading: Ch. 13 of Aschwanden's book for hard X-rays and Ch. 15 for radio

Diagnosing energetic electrons

- Each mechanism provides a method to probe the thermal plasma and/or energetic electrons

  → **Acceleration: Where? When? What?**

- HXR:
  - Thermal bremsstrahlung → n_e, T_e
  - Nonthermal thin-target and thick-target bremsstrahlung → $f(E)$
  - Inverse Compton → mostly corrections to $f(E)$
- Radio:
  - Thermal bremsstrahlung → n_e, T_e
  - Gyrosynchrotron → $f(E), n_e, T_e, B, \theta$
  - Coherent radiation → n_e (possibly $f(E)$, B, model dependent)

A note on electron energies

- For an electron
  - Total energy $\varepsilon_{total} = \gamma m_e c^2$
  - kinetic energy $\varepsilon = (\gamma - 1)\, m_e\, c^2$, where $\gamma = 1/\sqrt{1-\beta^2}$
- Thermal electron in the corona: T ~ 1 MK, $\beta \sim 0.018$, or $\varepsilon \approx 0.086$ keV → nonrelativistic
- Type-III-burst-emitting electron $\beta \approx$0.1-0.3 or ε ≈ 5-50 keV → 5~20 x thermal speed → bump-on-tail instability → nonrelativistic to mildly relativistic
- HXR-emitting electron ε ≈ 20-200 keV → $\beta \approx$0.2-0.5 → mildly relativistic
- Gyrosynchrotron-emitting electron $\gamma \approx 2-6$ → $\beta \approx$0.6-0.9 or ε ≈ 0.5-3 MeV → (upper-end of) mildly relativistic

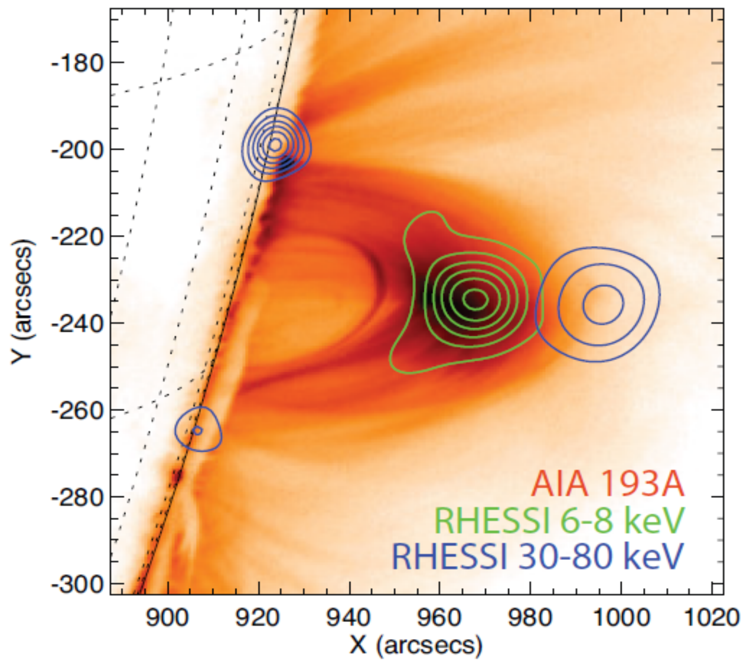
Each emission probes a different part of the electron energy spectrum!

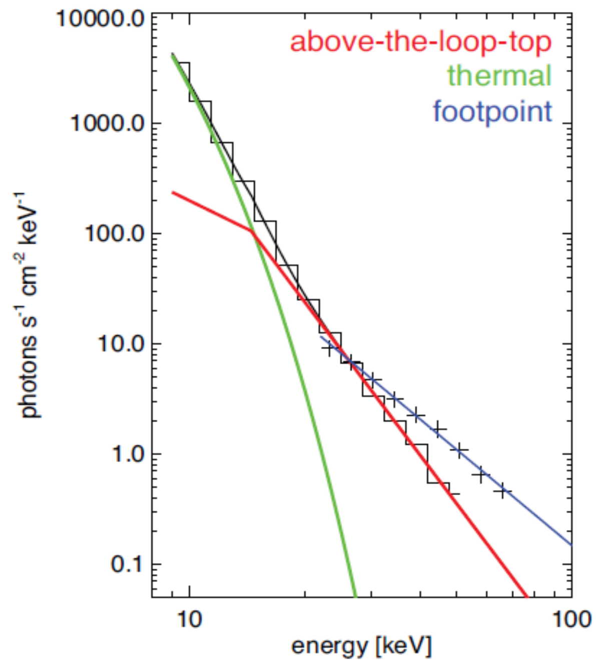
HXR spectral analysis

- Currently the most straightforward method to derive the distribution function of the accelerated electrons $f_{nt}(E)$. Also capable of obtaining $f_{nt}(E)$ of >~20 MK flare plasma
- Number density ratio n_{nt}/n_{th} (previous lecture)
- Energy density ratio $\varepsilon_{nt}/\varepsilon_{th}$
- Details of $f_{nt}(E)$ and its spatiotemporal evolution provide diagnostics for acceleration and transport processes

From HXR spectra to electron distribution

- Forward fitting with parameterized model(s): Thermal + power-law? Thermal + superhot? Thermal + kappa? Thin-target? Thick-target? …
- Regularized inversion





Forward fitting HXR spectra

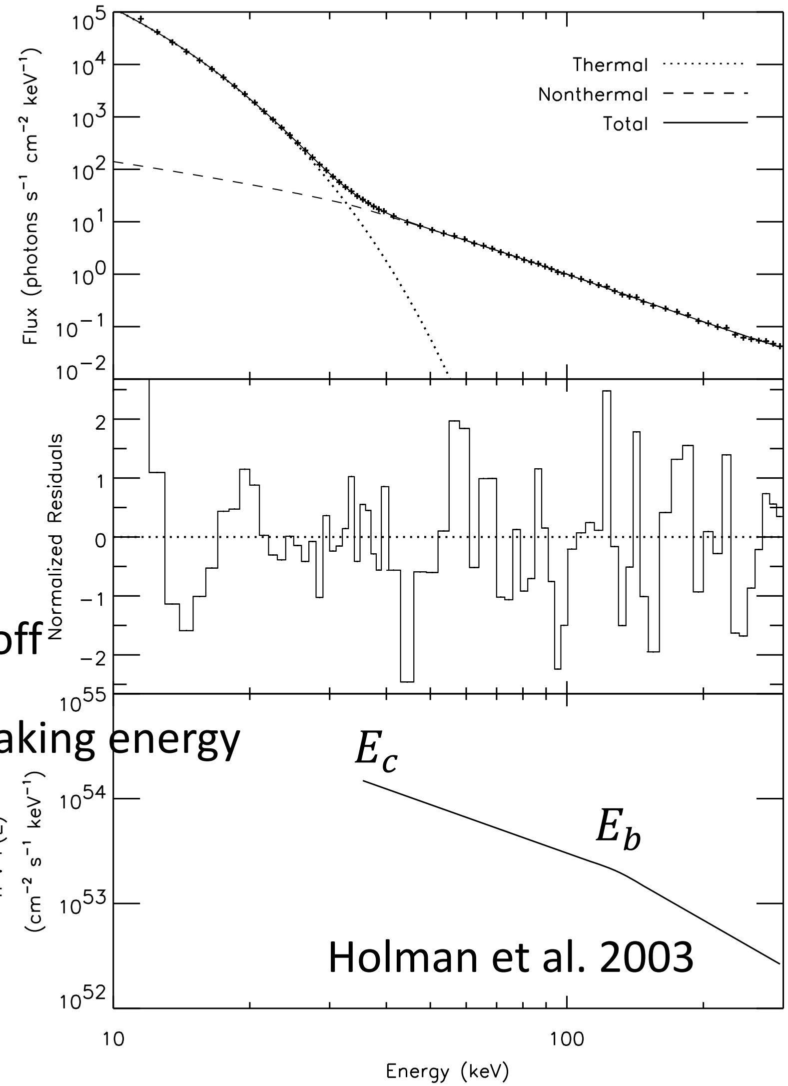
- People often use a two-component model electron energy spectrum to fit the HXR spectrum
  - Isothermal Mexwellian
  - Broken power-law with low-energy cutoff

Low-energy cutoff

Breaking energy

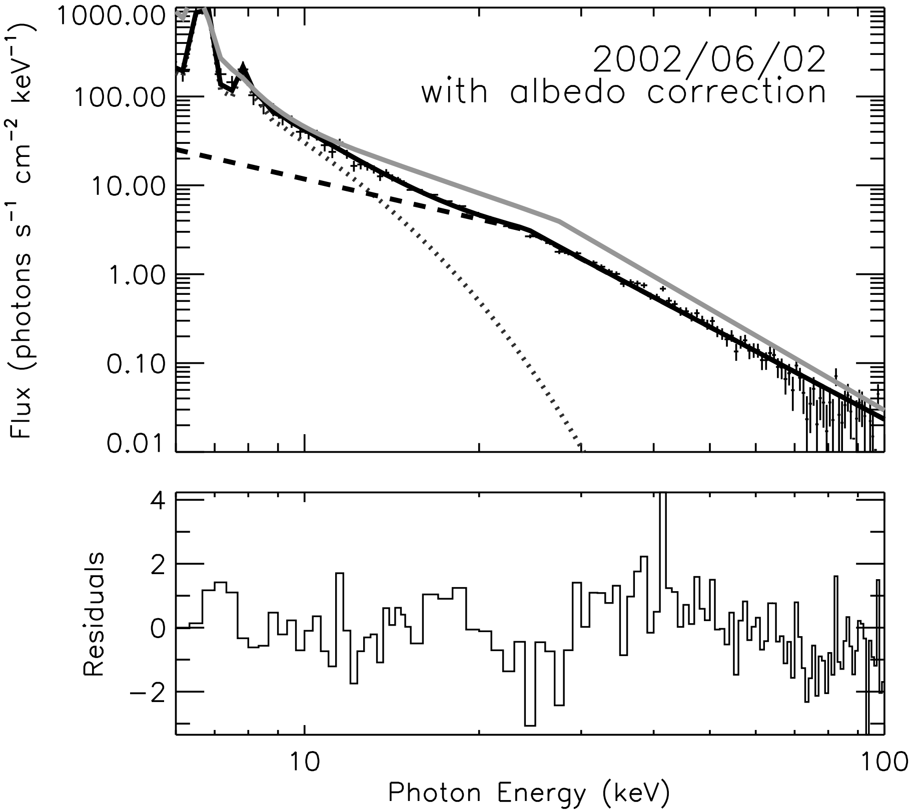
$$\overline{F}(E) = \begin{cases} 0; & E < E_c \\ A E^{-\delta_1}; & E_c < E < E_b \\ A E_b^{\delta_2 - \delta_1} E^{-\delta_2}; & E_b < E \end{cases}$$

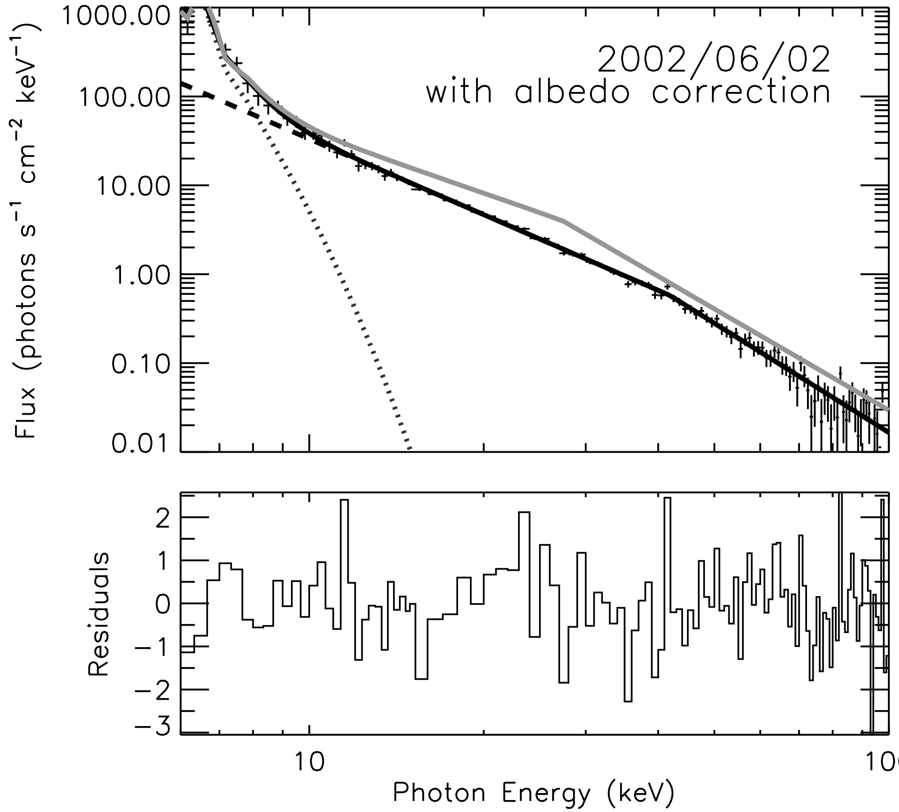
Mean electron flux (electrons cm^{-2} s^{-1} keV^{-1}, different from $f(E)$ -- c.f. Lecture 17)



Spot the difference…

After Sui et al. 2007





What is the difference in the model? Which forward fit result is better?

Low-energy cutoff plays a key role

- Let's assuming a single power-law with a low-energy cutoff: $\bar{F}(E) = AE^{-\delta}\ (E > E_c)$
- Nonthermal electron flux (electrons cm^{-2} s^{-1}):

$$\int_{E_c}^{\infty} AE^{-\delta} dE = \frac{A}{\delta-1} E_c^{-\delta+1} \text{ (if } \delta > 1)$$

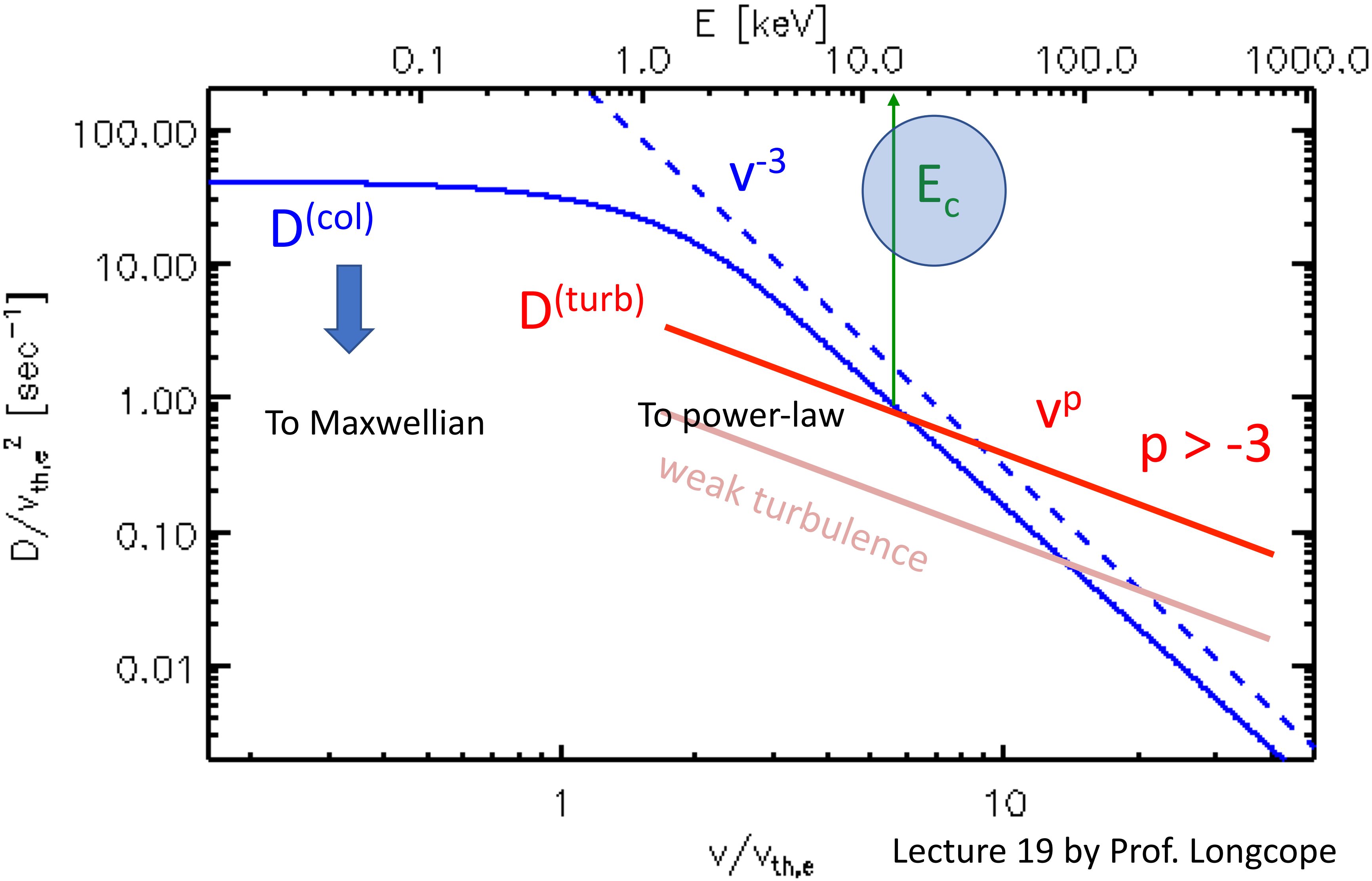
- Nonthermal electron energy flux (erg cm^{-2} s^{-1}):

$$\int_{E_c}^{\infty} AE^{-\delta+1} dE = \frac{A}{\delta-2} E_c^{-\delta+2} \text{ (if } \delta > 2)$$

- Both are very sensitive to E_c
  - e.g., for $\delta = 4$ ("typical" in a flare peak), a factor of 2 error in E_c means a factor of 4 error in energy flux!
- Both are very important observables to examine particle acceleration mechanisms

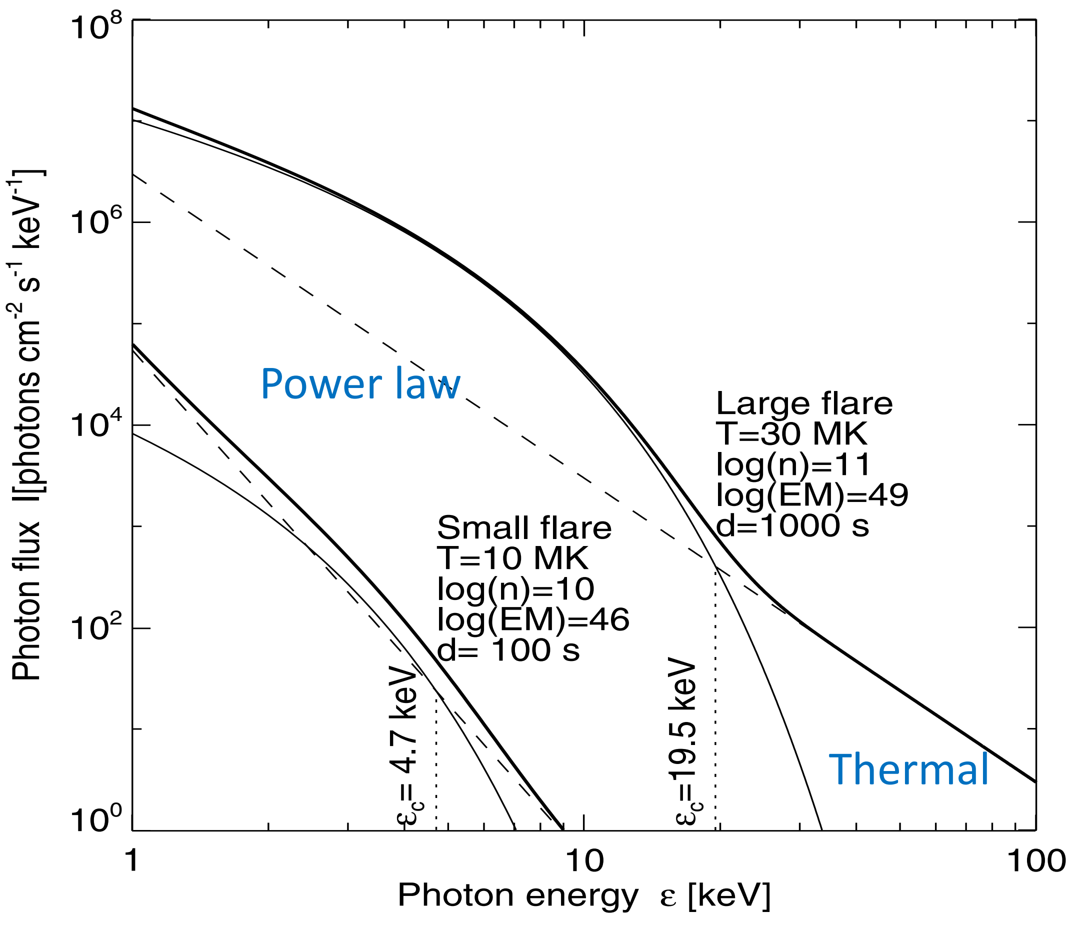
  → e.g., a smaller low-energy cutoff would require a much more efficient acceleration mechanism

Low energy cutoff plays a key role

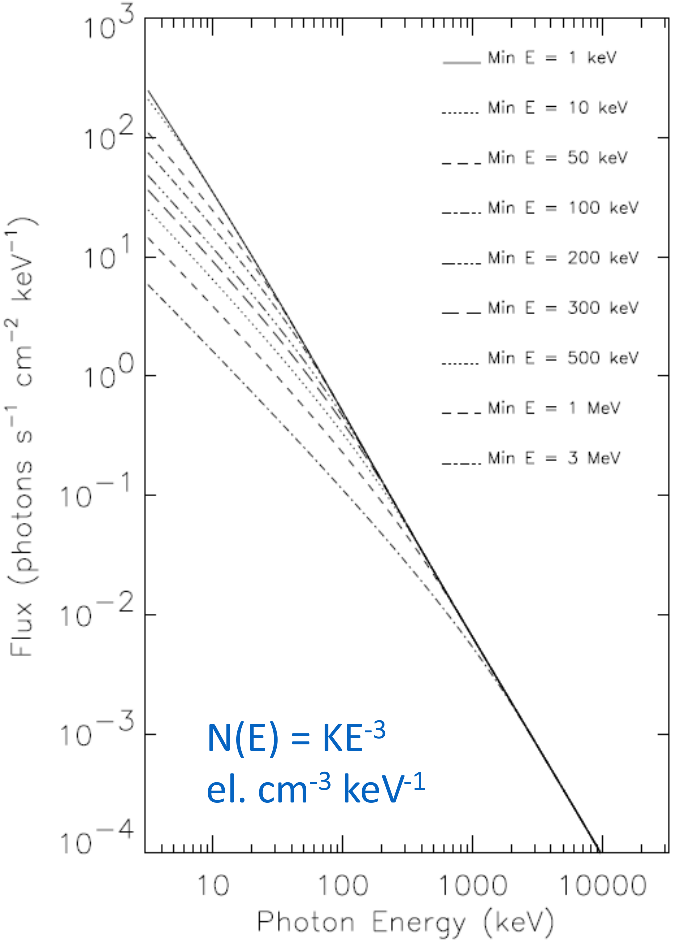


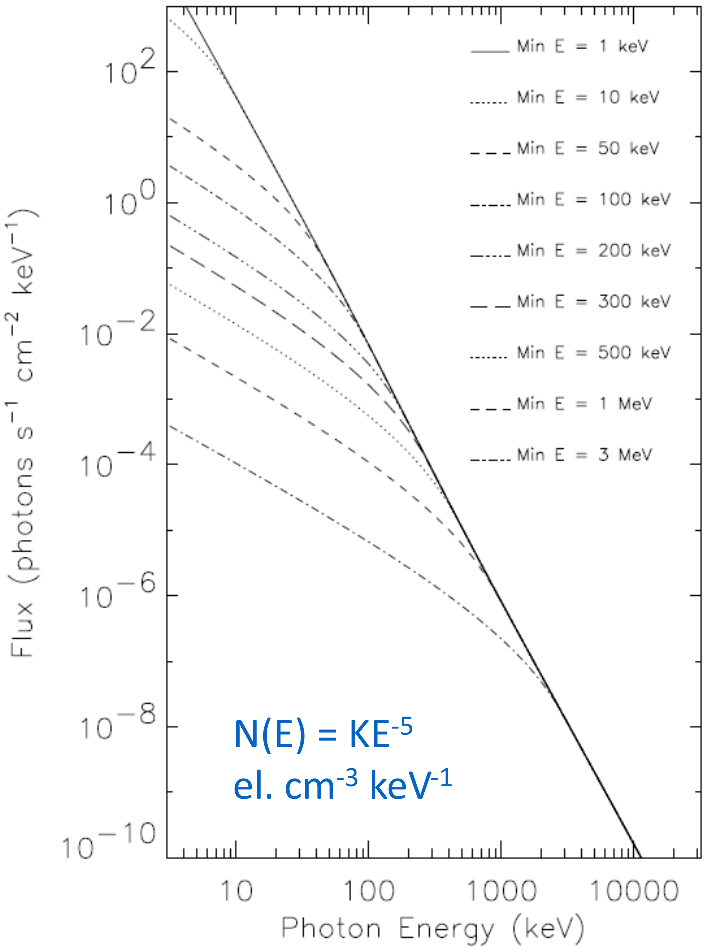
Lecture 19 by Prof. Longcope

Low-energy cutoff: Can we determine it from HXR spectral analysis?



HXR spectra: low-energy cutoffs



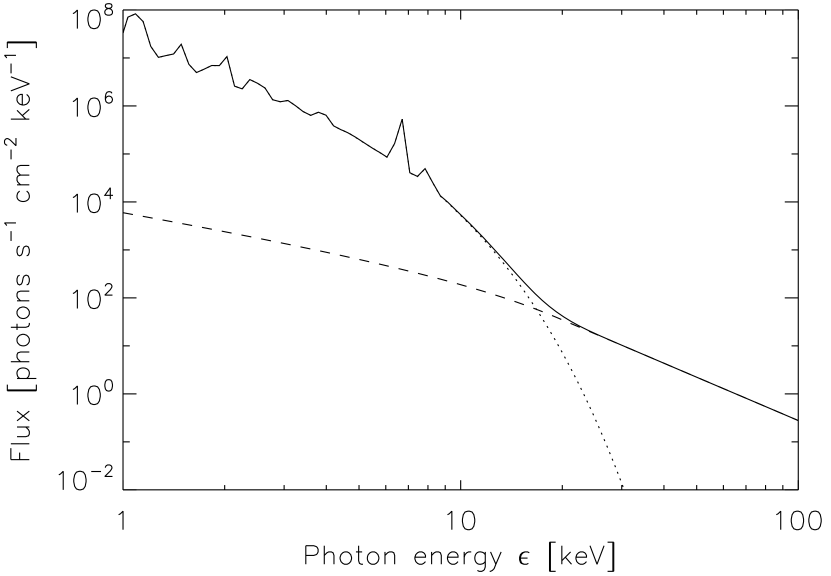


Holman 2003

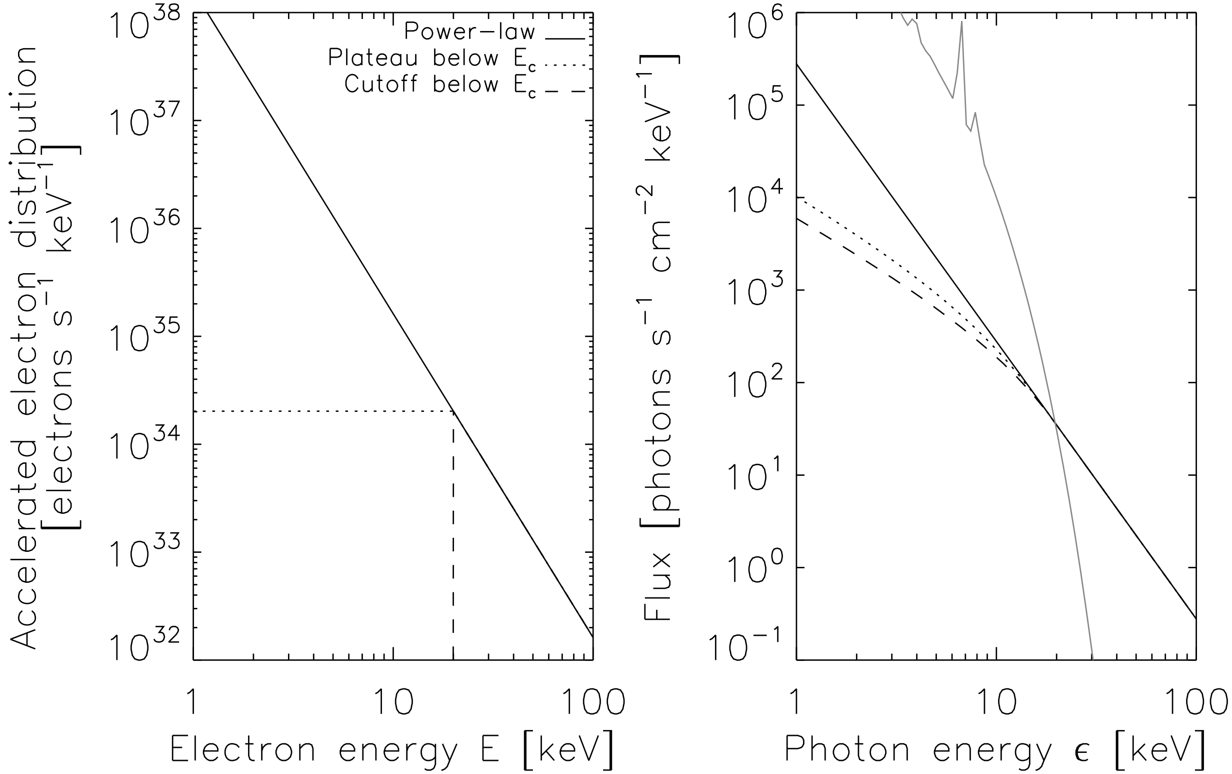
Low energy cutoff *flattens* the HXR spectra at lower energies

Low-energy cutoff

- Results in a flattening of HXR spectrum below E_c
- But usually masked by the thermal component!
- For a typical flare with distinctive thermal + nonthermal component:
  - Well constrained at the high-energy side
  - Poorly constrained at the low-energy side
- Low-energy cutoff is usually really the "*highest value* of E_c that still fits the data", which gives a *lower limit* of the total nonthermal energy

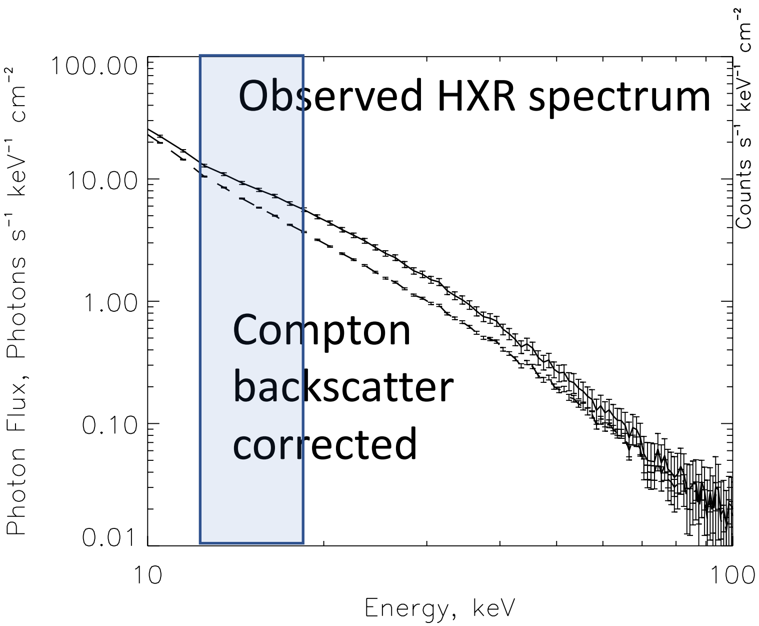


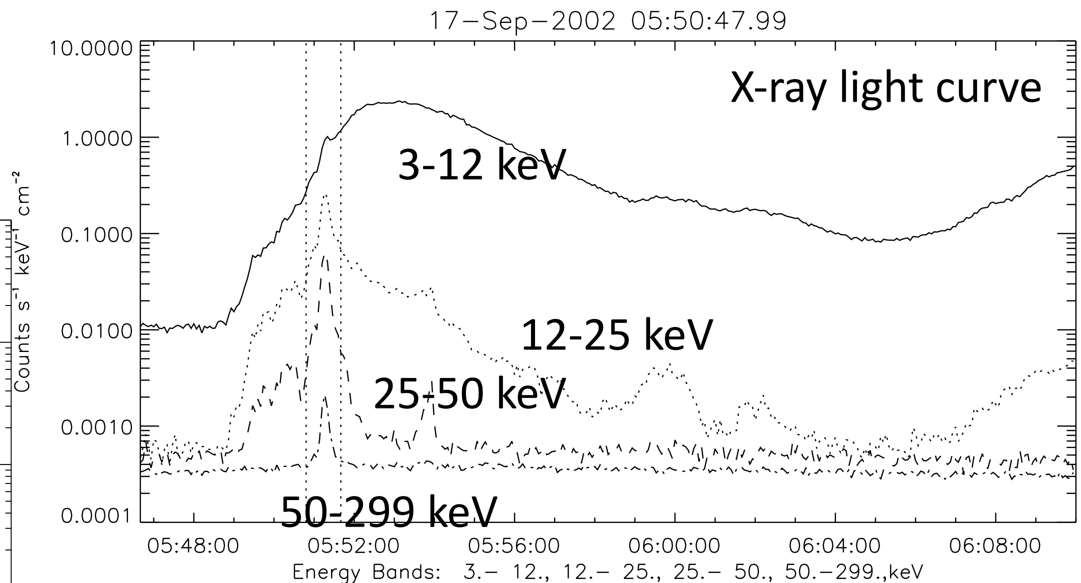
Different forms of low-energy cutoff



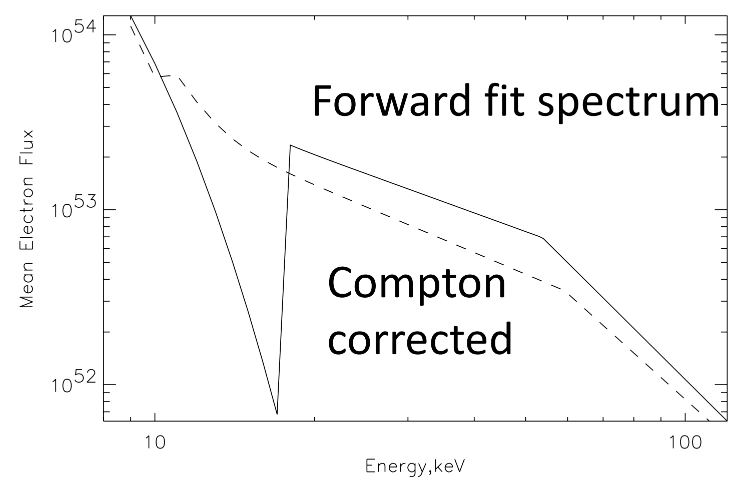
- Different forms of low-energy cutoff lead to subtle difference in the observed X-ray spectra → difficult to determine
- Luckily, the exact shape of low-energy cutoff is not dramatically important in terms of energetics

Low-energy cutoff: An example



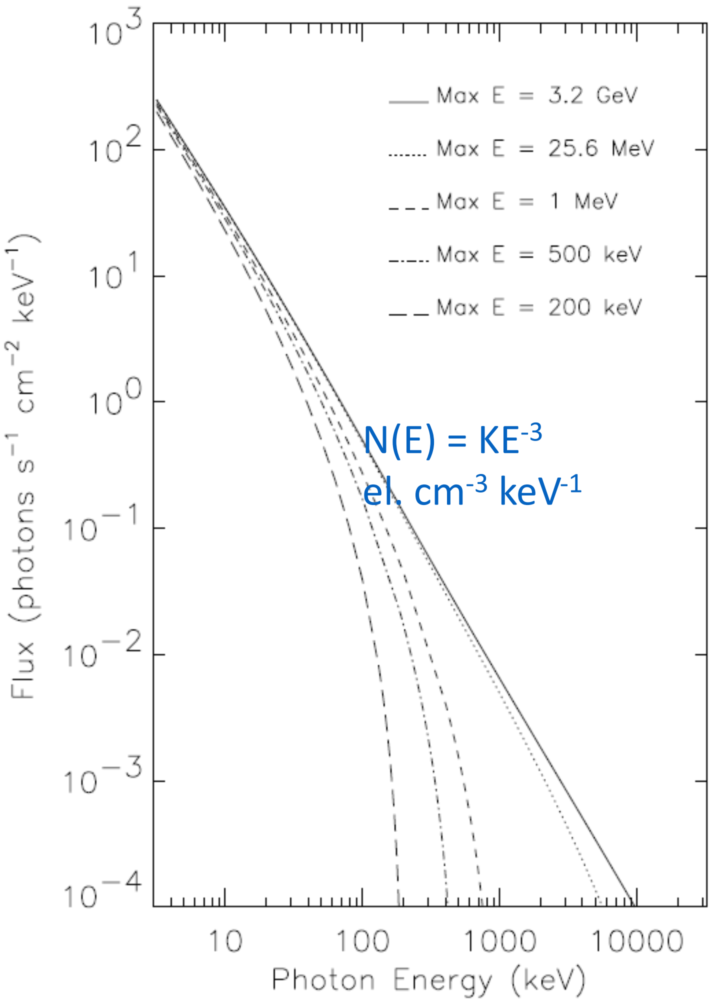


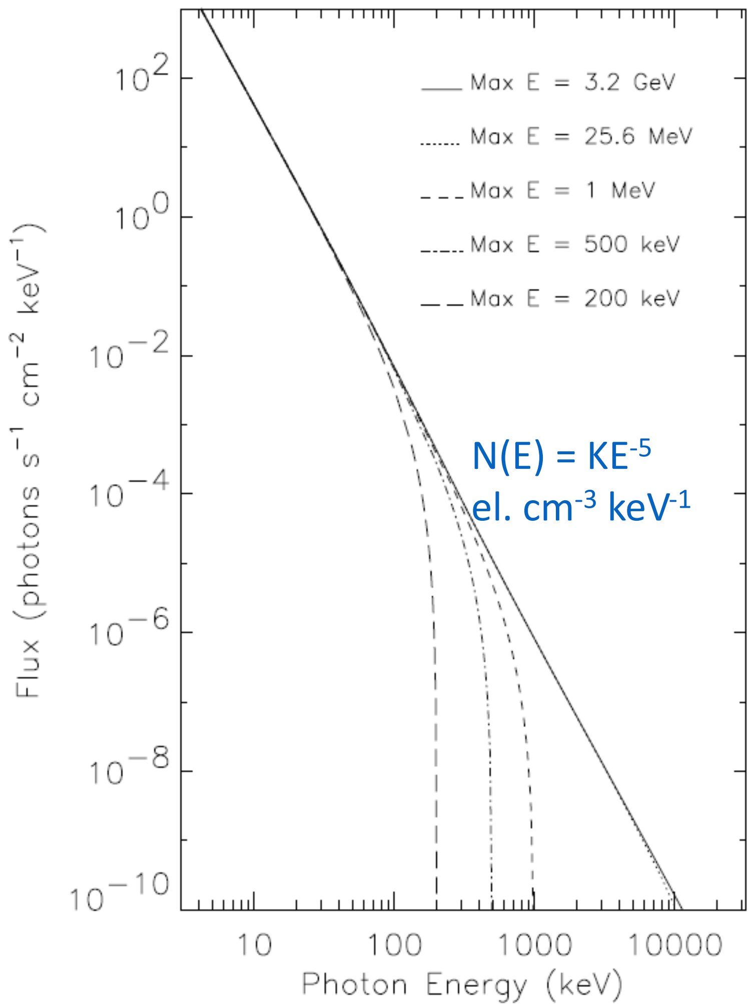
Can you identify the possible location of E_c and E_b?



Kontar et al. 2006

HXR spectra: high-energy cutoffs

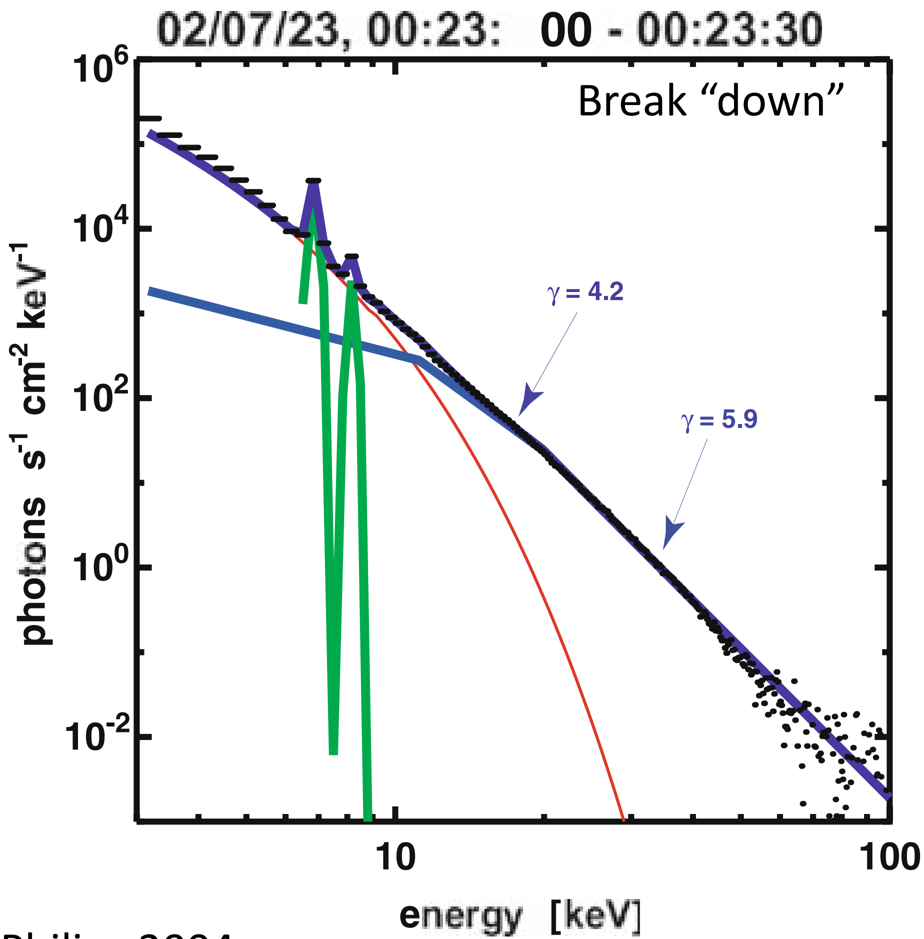




Holman 2003

High energy cutoff leads to a *steepening* of the HXR spectra at high energies

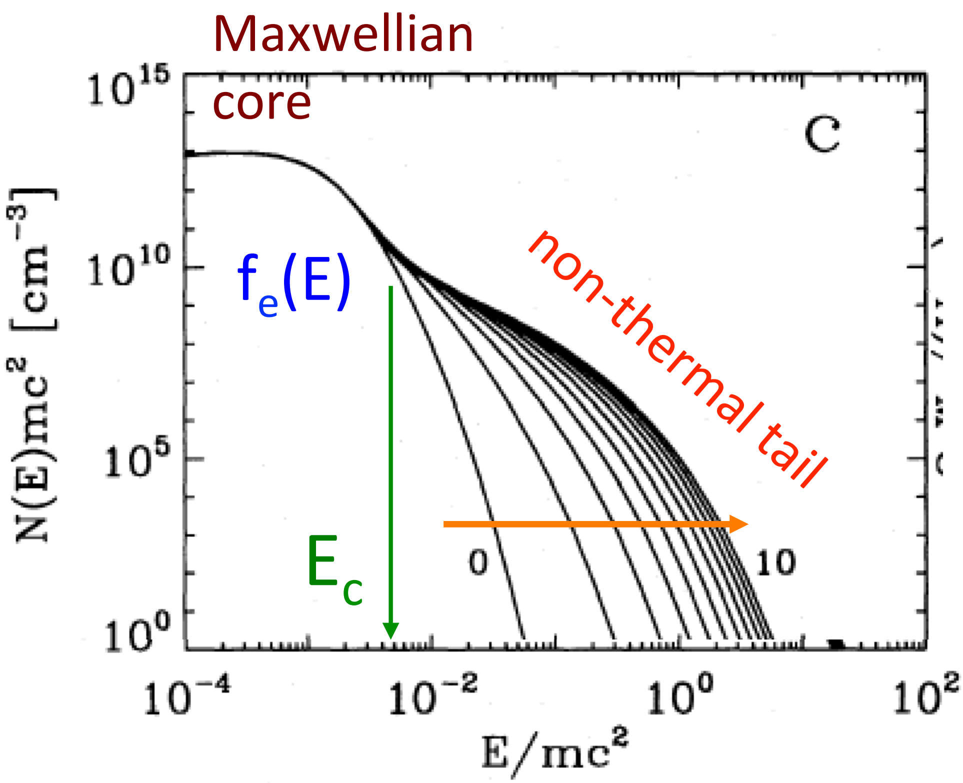
HXR Spectral breaks



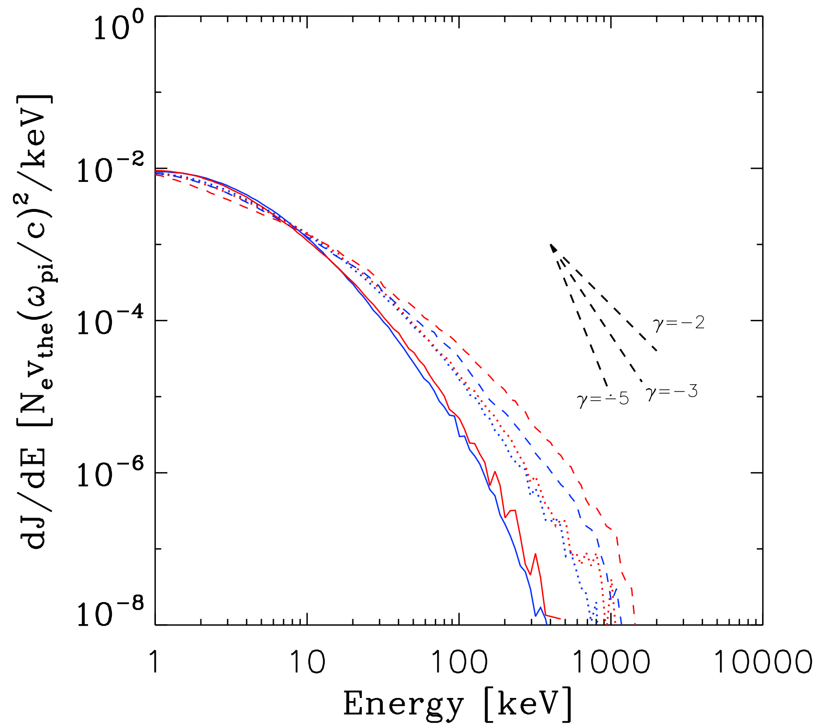
Philips 2004

- HXR spectral fit results usually show a spectral break at ~30-60 keV
- Flatter at lower energies, and steeper at higher energies

Possibility 1: less e⁻ at higher energies



Stochastic acceleration (Miller et al. 1996, see also Lecture 19 by Prof. Longcope)



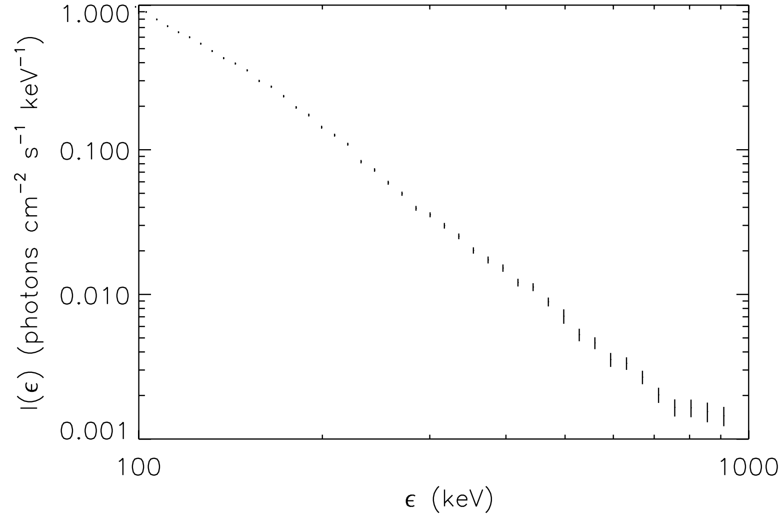
Acceleration by termination shock (Guo & Giacalone 2012)

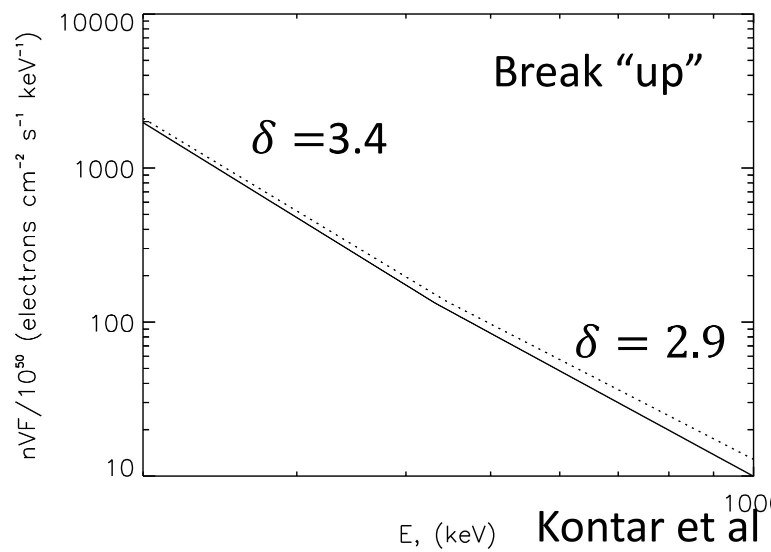
Possibility 2: loss of low energy e^-

- Return current: large number of electrons precipitating to the footpoint → "returning" ambient electrons to re-establish neutral charge → self-induced "return current"
- Return current generates an electric field (Ohm's law) along the loop
- Lower energy electrons lose a larger *fraction* of energy than their higher energy counterparts → flattening of the HXR spectrum at lower energies

Spectral breaks at higher energy

- At higher energies, the HXR/γ-ray spectrum break "up" again
- Contribution from the e-e bremsstrahlung
- Acceleration mechanism?

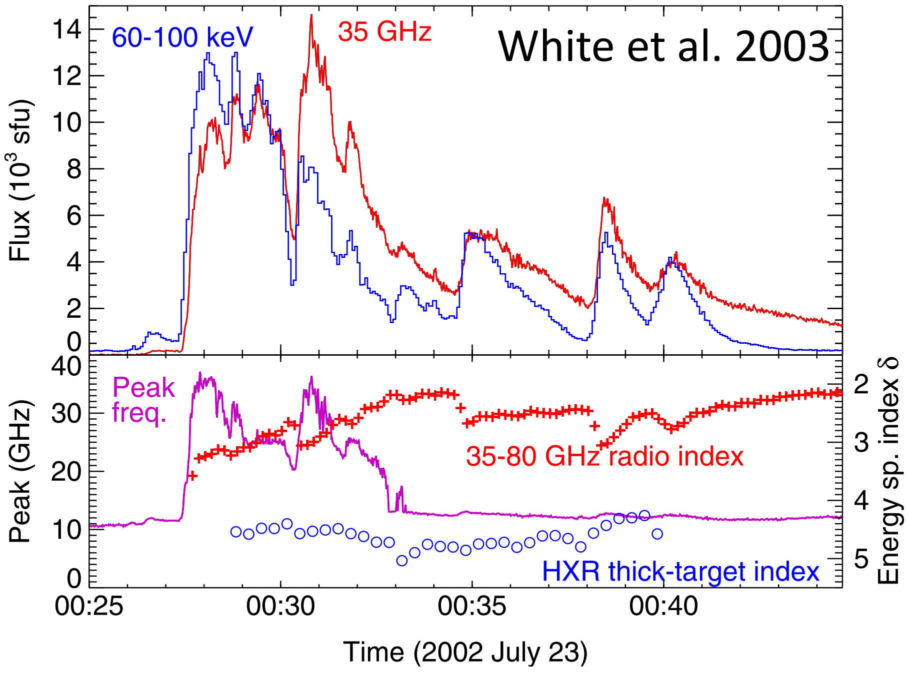




Kontar et al 2007

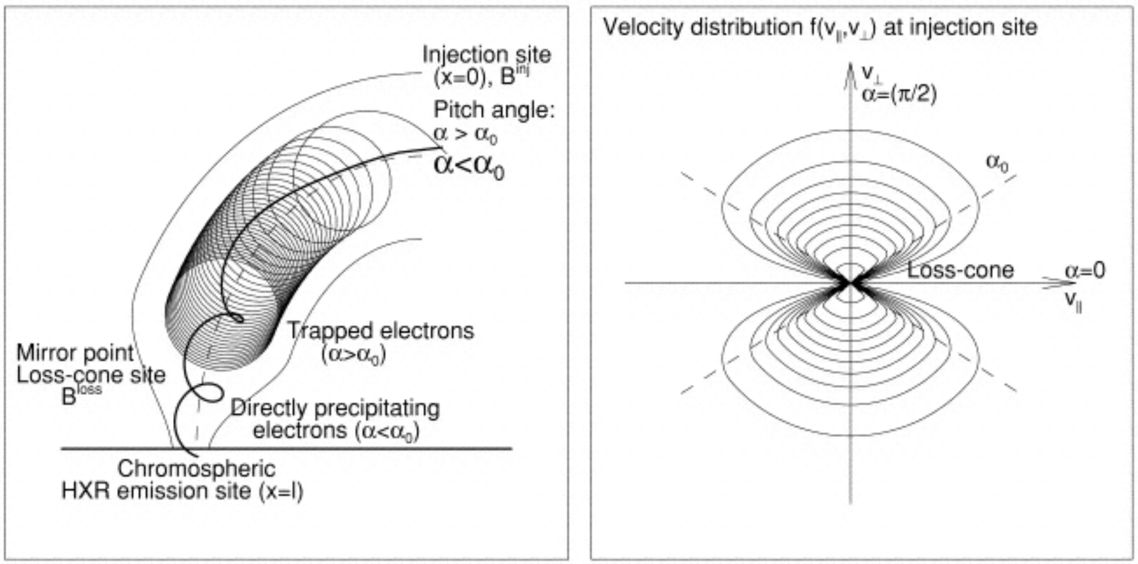
Microwave gyrosynchrotron spectra

- HXR photons with energy ε come from electrons with $\sim\varepsilon$ via bremsstrahlung → 10s to 100s keV
- Microwave gyrosynchrotron probes electrons with higher energies (>300 keV)
- Can one electron distribution fits all?



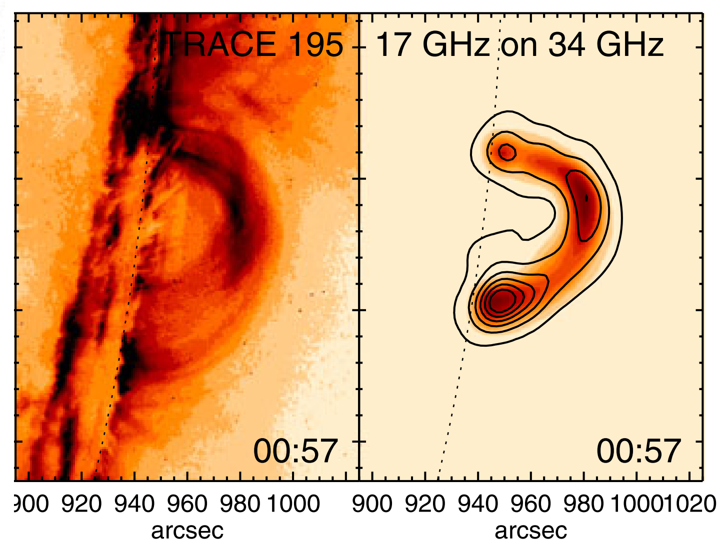
Large discrepancy usually found between HXR and microwave!

HXR and microwave discrepancy: What's wrong?



- HXR emission is dominated by the *precipitated* electrons at the chromosphere

White et al. 2011



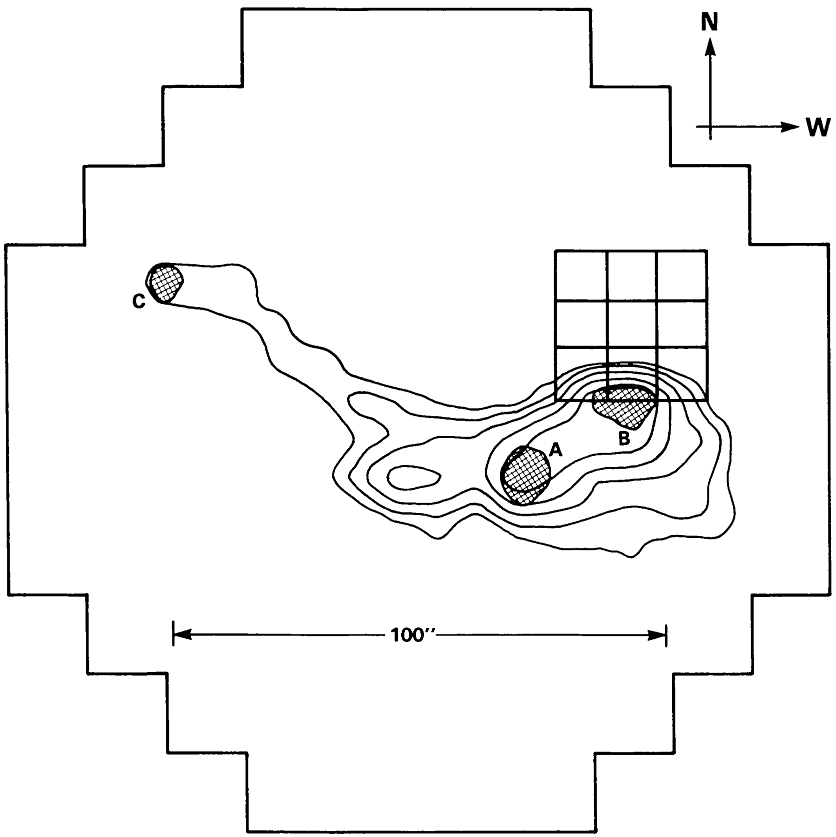
- Gyrosynchrotron emission is mainly from the *trapped* electrons in the flare loop
- Trapping may resulting in hardening
- *Anisotropy* of electron distribution also contributes to spectral hardening. How?

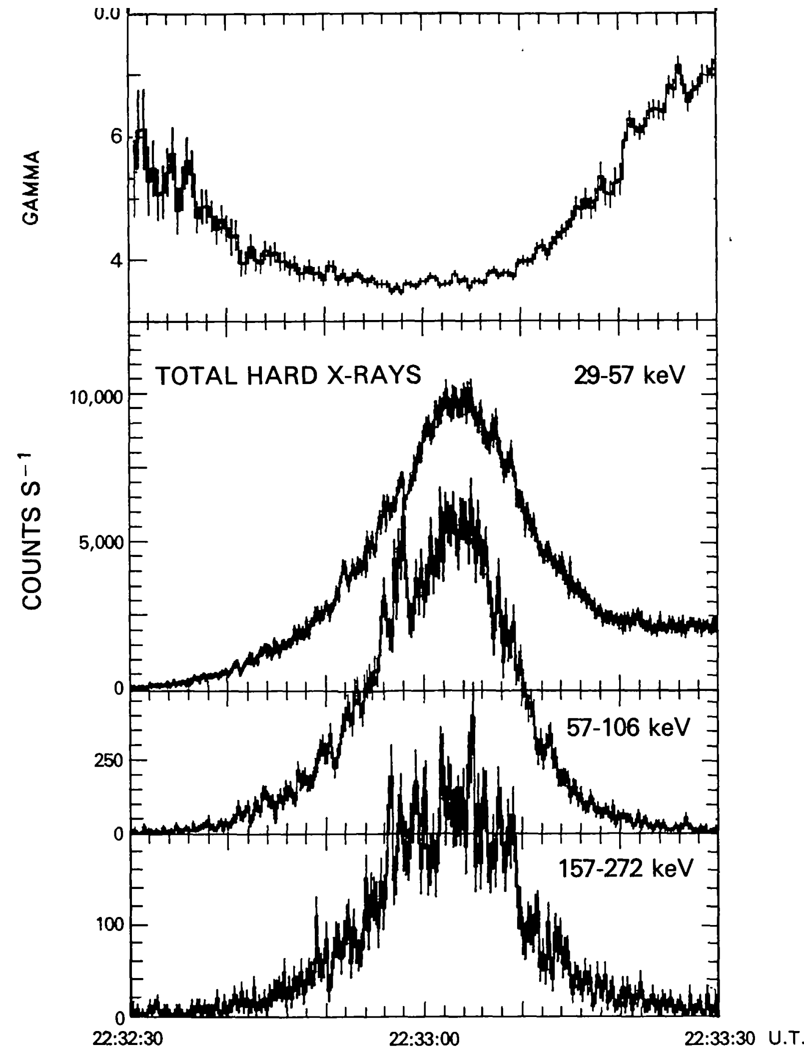
The HXR/microwave discrepancy is still largely unexplained

HXR/microwave spectra evolution

- Events showing impulsive HXR/microwave peaks usually have a harder spectral index during the peaks, and softer both in the rise and decay phase, known as a ***soft-hard-soft (SHS)*** spectral evolution
- In some events, the spectra stay hard or even gets harder, known as a ***soft-hard-harder (SHH)*** spectral evolution

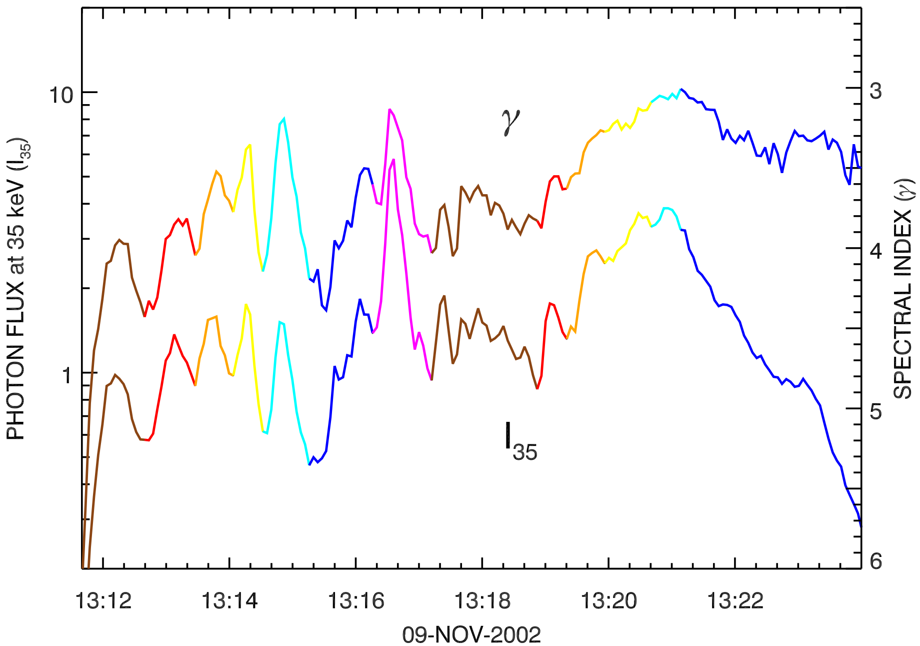
SHS HXR spectral evolution



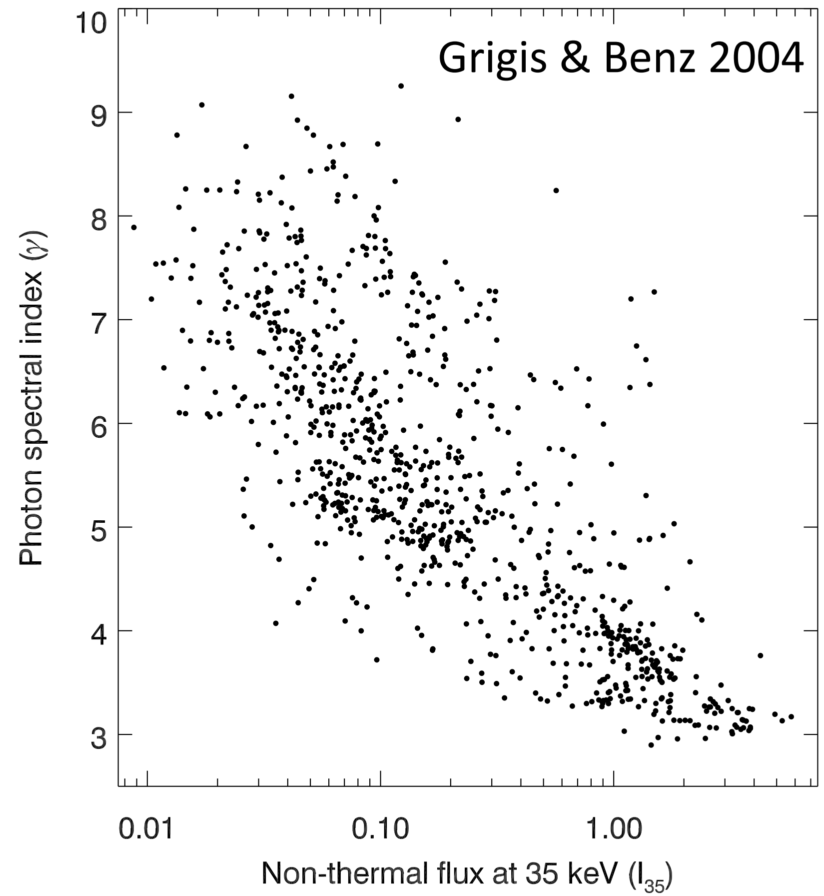


Dennis 1985

SHS feature at every HXR peak



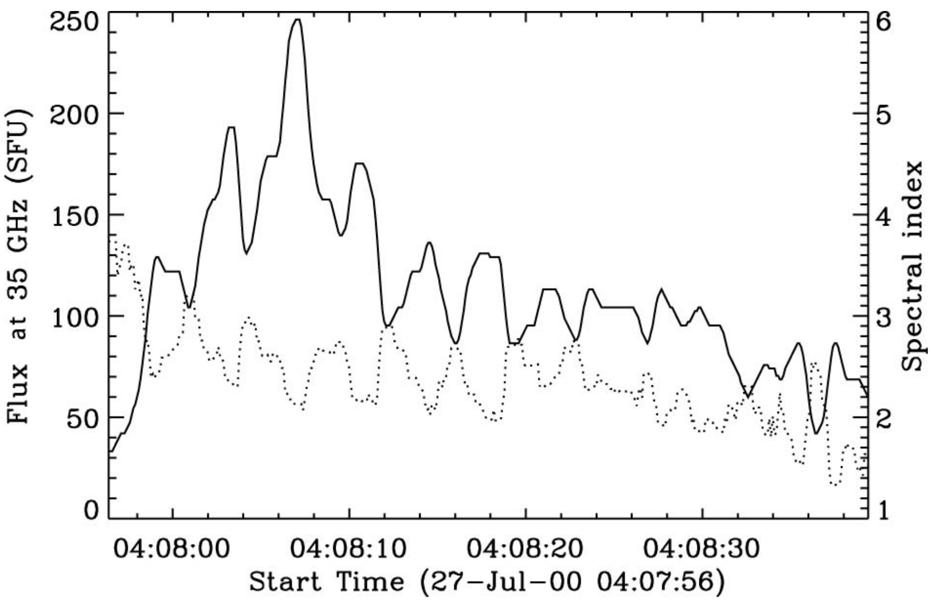
Flux and spectral index evolution



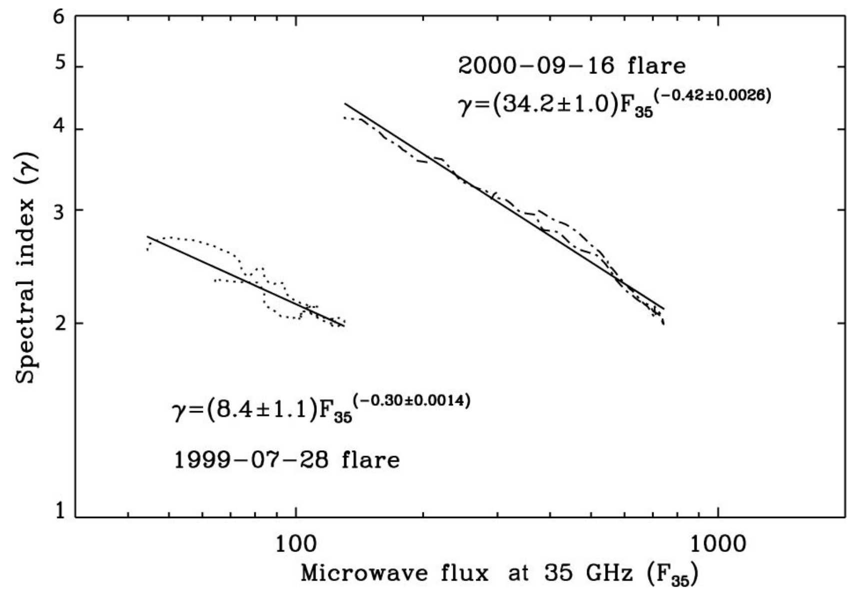
Flux vs. spectral index

SHS spectral evolution in microwave

Ning & Ding 2007

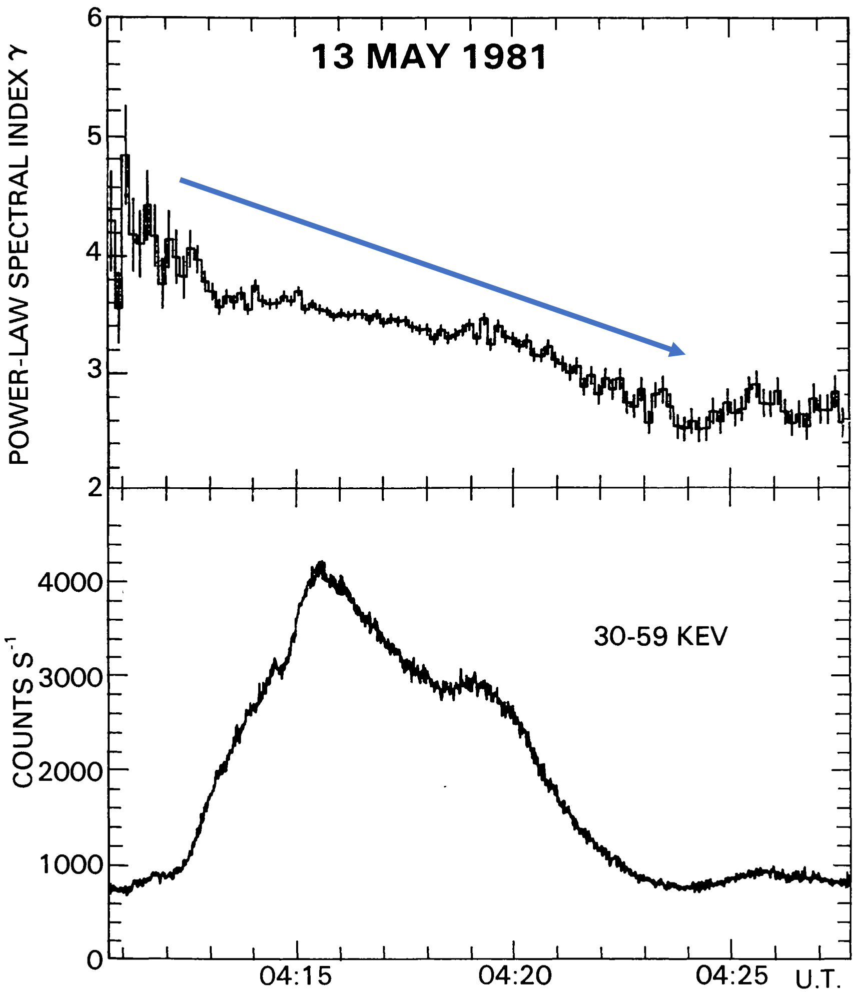


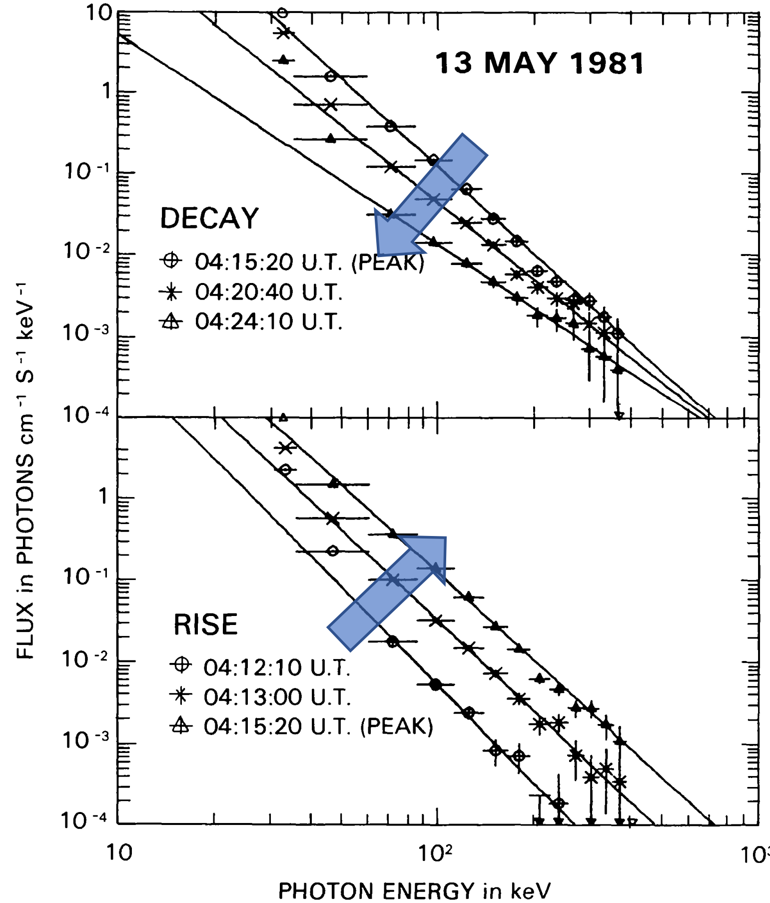
Flux and spectral index evolution



Flux vs. spectral index

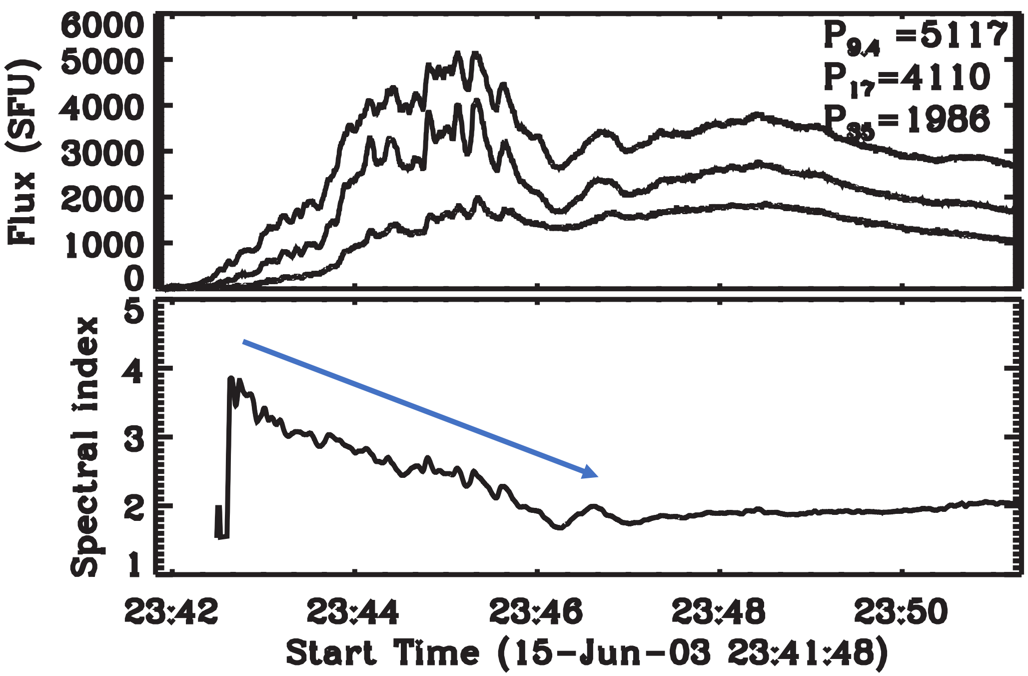
SHH HXR spectral evolution

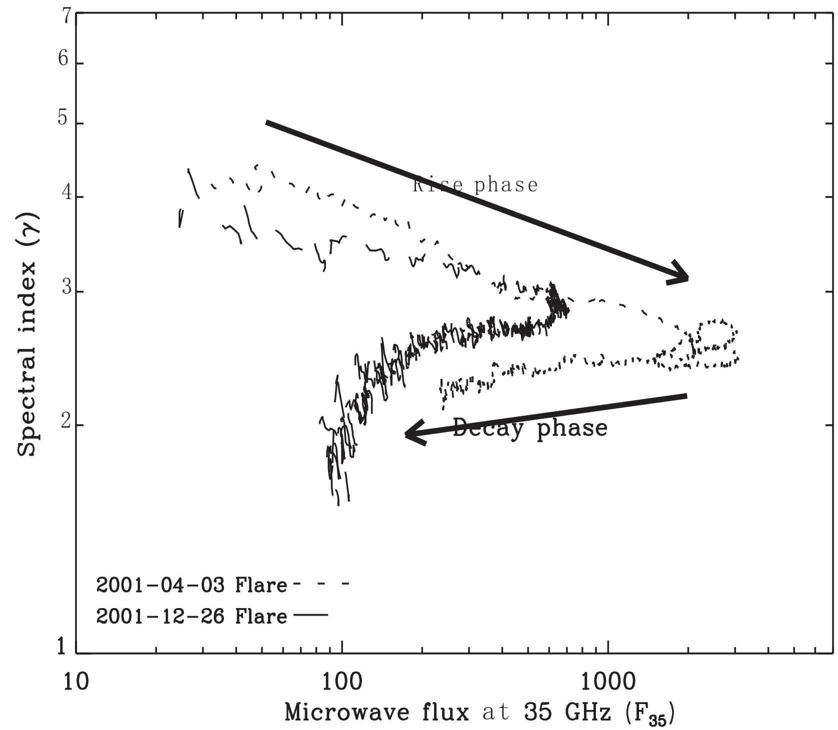




Dennis 1985

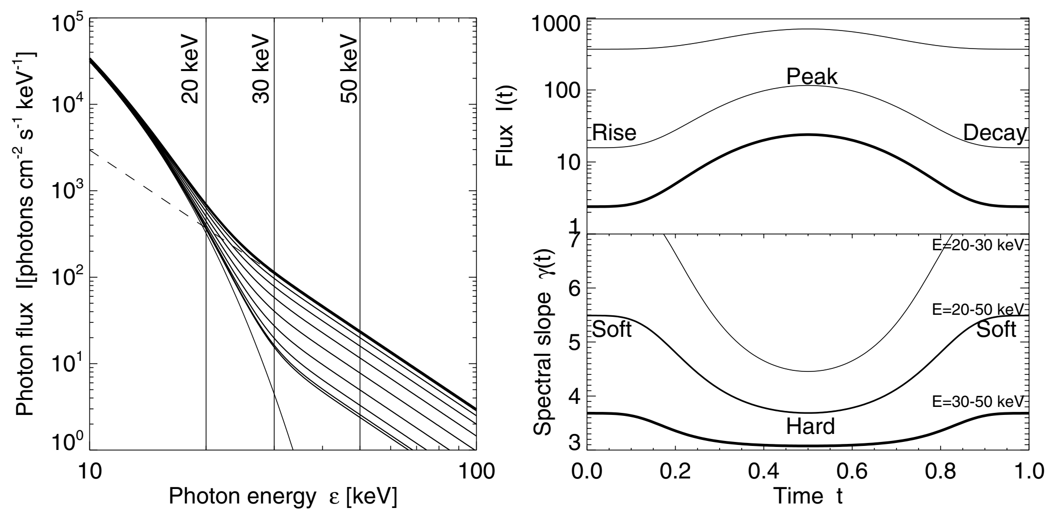
SHH microwave spectral evolution





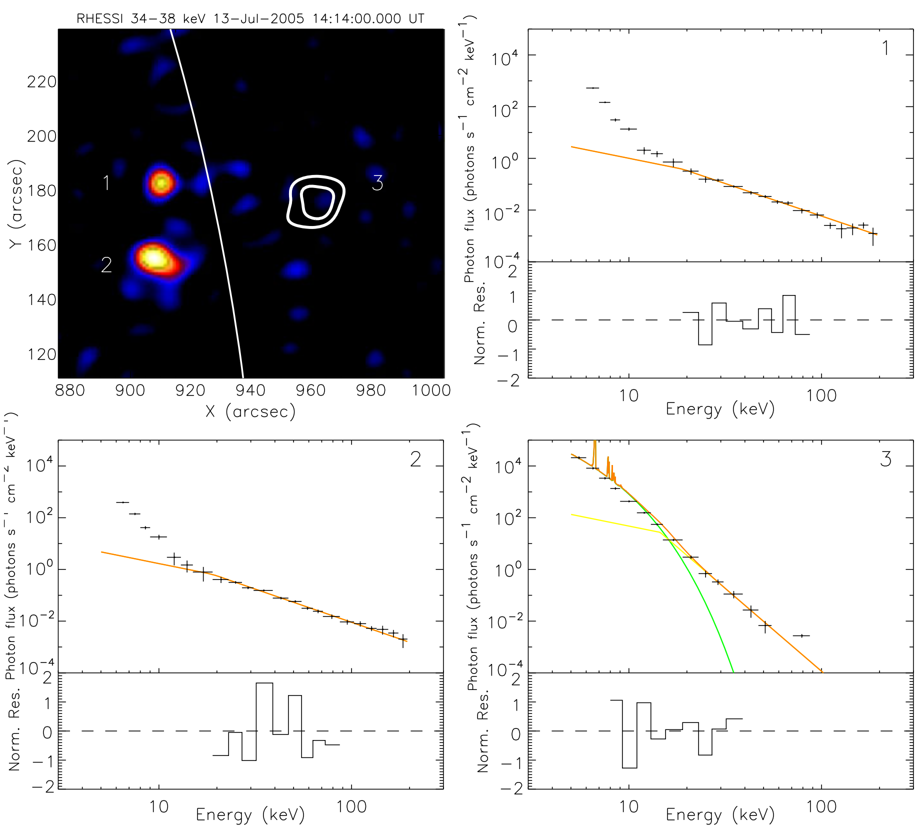
HXR spectral evolution: Why?

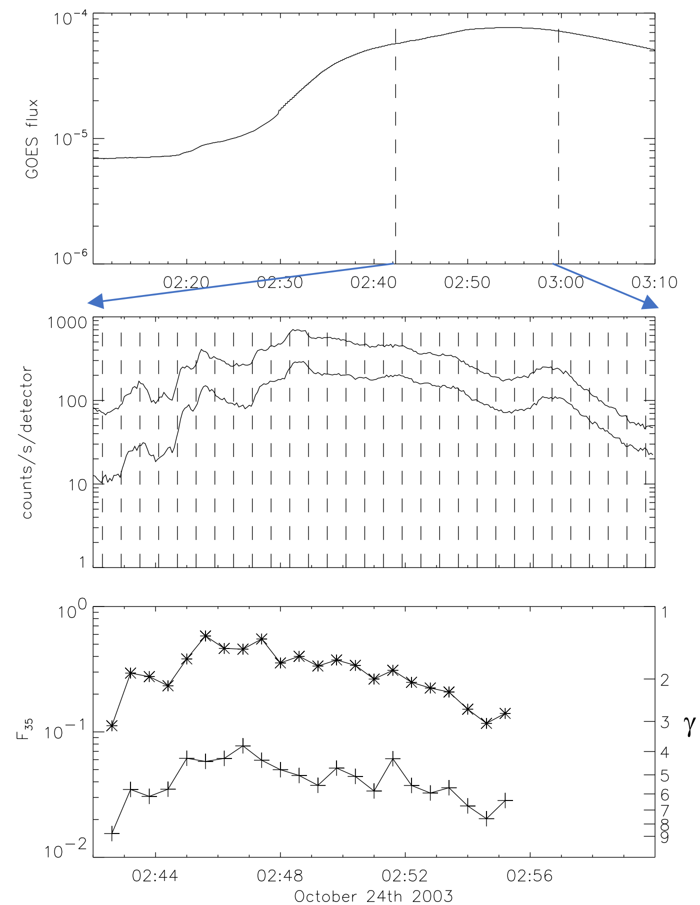
- Variation of thermal and non-thermal contribution in the X-ray energy range where spectral index is obtained
- Transport: Longer transport time → more loss in low-energy electrons → harder spectrum
- Particle acceleration mechanism itself



SHS also in coronal HXR sources

- Coronal HXR sources are at least closer to the acceleration site → probably from the acceleration mechanism?





Battaglia & Benz 2006

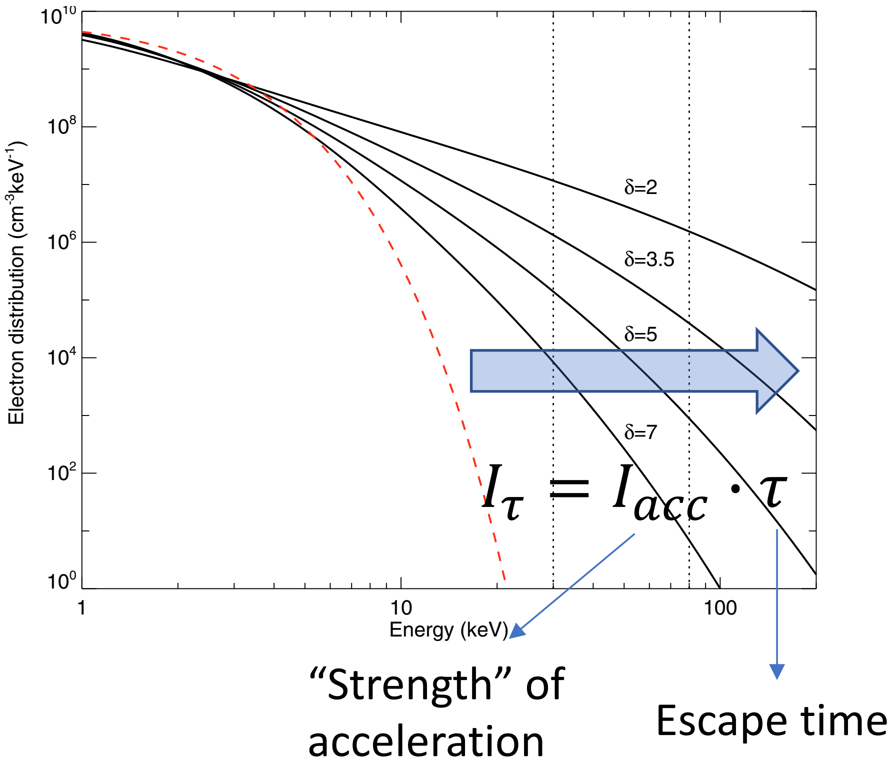
What causes HXR spectral hardening?

- Stochastic acceleration model by turbulent fast-mode waves (c.f. Lecture 19 by Prof. Longcope)

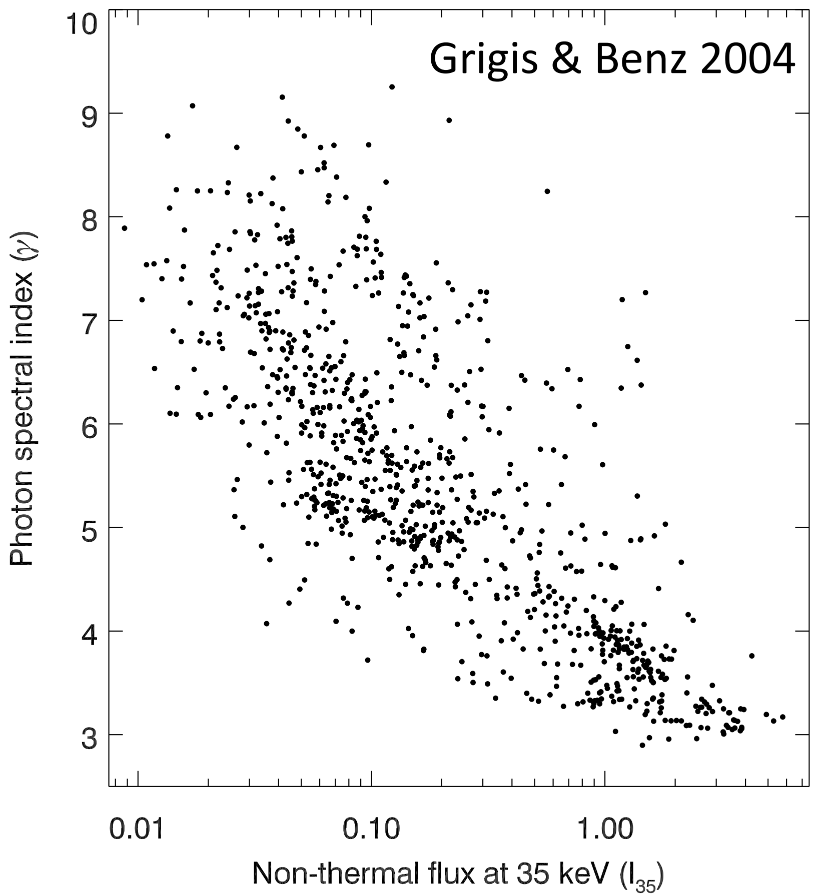
$$f(\mathbf{v}) \propto |\mathbf{v}|^{-\xi} \qquad \xi = \frac{e^2 n \Lambda \bar{k}}{\pi \varepsilon_{\mathrm{turb}}}$$

  - Stronger turbulence → harder spectrum
  - Longer trapping time τ → harder spectrum

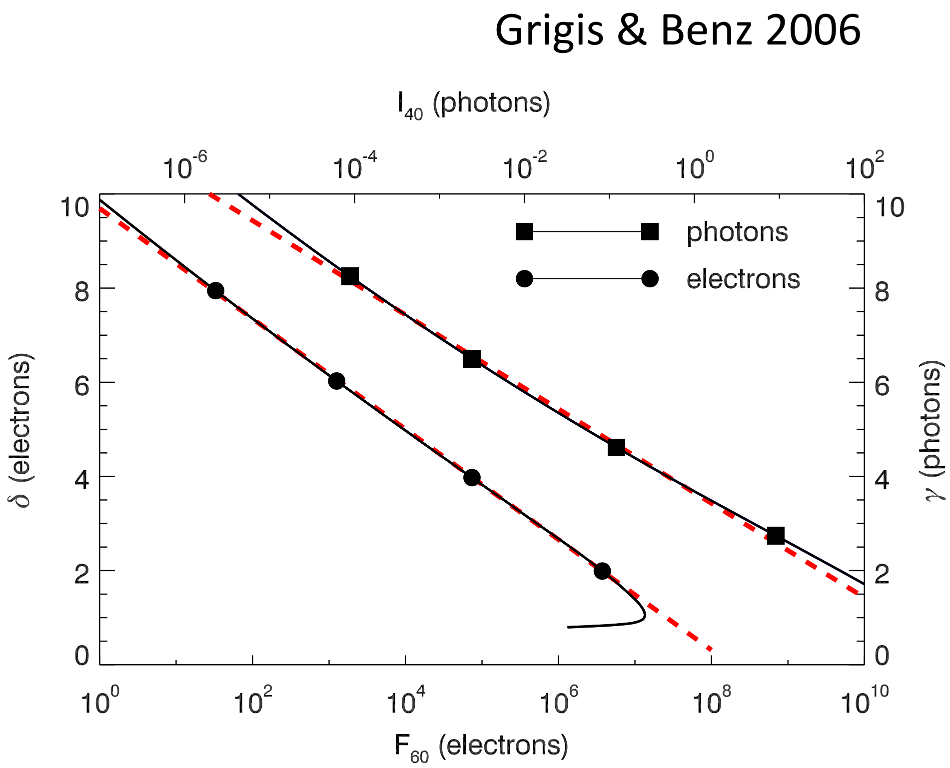
Grigis & Benz 2006



Modeling HXR flux vs. spectral index

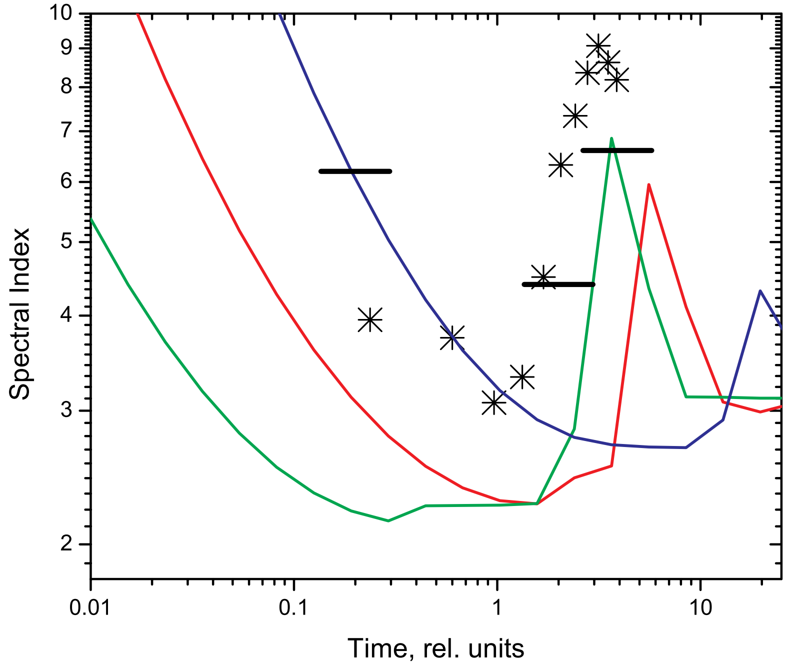


Flux vs. spectral index



So what causes the SHS behavior?

- Stochastic acceleration example: variation of the level of turbulence during the particle acceleration process
  - Energy release → strong turbulence
  - Efficient particle acceleration → harder spectrum
  - Turbulence exhausted
  - Less efficient particle acceleration → softer spectrum
- Shock? DC electric field?
- How about SHH?



Bykov & Fleishman 2009

Summary

- HXR and microwave observations provide critical diagnostics for particle acceleration mechanisms
  - Low-energy cutoff → number, energetics
  - Spectral breaks
  - Spectral evolution
- Some success in interpreting the observed phenomena
- But more are unexplained
- What can be improved?
  - More advanced instrumentation: HXR/microwave imaging spectroscopy with high spatial, spectral, and temporal resolution
  - Data-driven, self-consistent particle acceleration modeling