Comparison of transit-time damping electron stochastic acceleration models with RHESSI hard X-ray observations of solar flares.

Paolo Grigis and Arnold Benz

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Introduction

➔ Our goal is to quantitatively compare model predictions for the photon spectrum emitted by the electrons in the accelerator with looptop source spectra observed by RHESSI.

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➔ The imaging spectroscopy observational data are provided Battaglia and Benz (2006).

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Overview of Transit-Time Damping Acceleration

- Miller, LaRosa and Moore (1996) have presented a model of stochastic electron acceleration from thermal to ultrarelativistic energies, the transit-time damping (TTD) mechanism.

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➔ The TTD model can account for the observed total number and energy of the electrons accelerated above ~ 20 keV (these are well-known and strong constraints for acceleration models).

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- However, the model predicts very hard electron spectra.
- Reason: perfect trapping was assumed, no particle escape mechanism is present in the model.

➔ Rationale: the observed footpoint spectrum depend on both escape from the accelerator and transport effects on the way to the footpoints. We lack both observational and theoretical firm constraints on these effects.

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Overview of RHESSI observations

➔ Using RHESSI imaging spectroscopy we can observe the spectral evolution of both footpoint and looptop sources.

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➔ If we make the reasonable assumption that the particles are accelerated near the top of the loop, this means that the observed hard X-rays from the looptop source are emitted by the electron population which is in the process of being accelerated!

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➔ Comparison of these observations with acceleration models still needs to deal with the trapping/escape mechanism, but it is no longer necessary to account for further transport effects down to the footpoints.

Transit-Time Damping Acceleration

- Energy source: magnetic reconnection, which produces waves with large wavelengths.
- A turbulent cascading process takes place, transferring energy into waves with shorter wavelengths.
- The high-frequency waves exchange energy with the electrons resonantly by the transit-time damping process (which involves the interaction between the magnetic moment of the electron and the parallel gradient of the wave magnetic field).
- Resonance condition: $k_{||} v_{||} = \omega = k v_{\mathrm{A}}$
- Only electrons faster than the Alfvén speed can be accelerated.
- The acceleration only occurs in the parallel direction.
- Isotropization mechanism needed (e.g. firehose instability).

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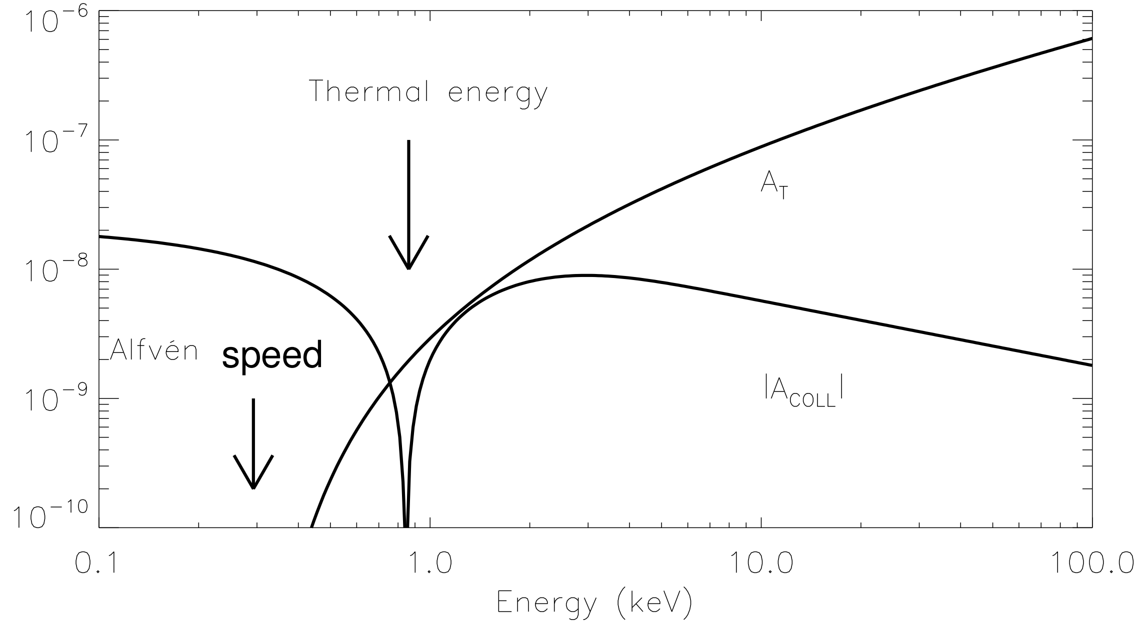
Evolution of the Electron Distribution

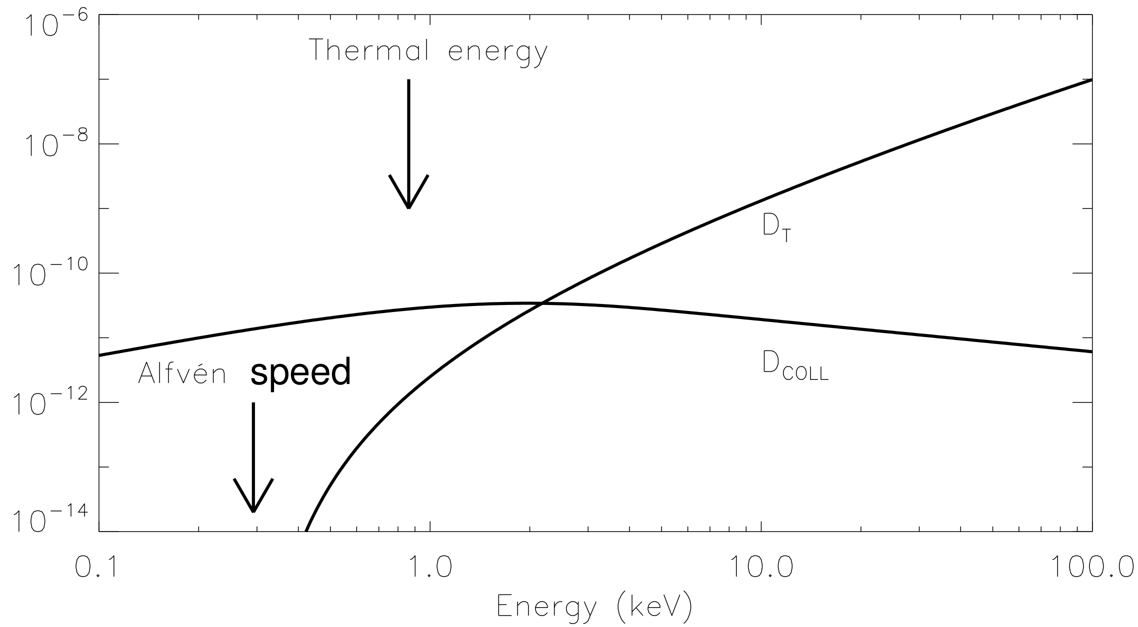
- Miller et al. have computed the diffusion (D_T) and convection (A_T) coefficients for the Fokker-Planck equation describing the transit-time damping energization of the electrons.

$$\frac{\partial N}{\partial t} = \frac{1}{2}\frac{\partial^2}{\partial E^2}\Big[(D_C + D_T)N\Big] - \frac{\partial}{\partial E}\Big[(A_C + A_T)N\Big]$$

- The equation also contains the contribution to the coefficients due to Coulomb scattering with the ambient plasma (D_C, A_C).



10^-6
10^-7
10^-8
10^-9
10^-10
Thermal energy
Alfvén speed
A_T
|A_COLL|
0.1
1.0
10.0
100.0
Energy (keV)



10^-6
10^-8
10^-10
10^-12
10^-14
Thermal energy
Alfvén speed
D_T
D_COLL
0.1
1.0
10.0
100.0
Energy (keV)

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- The equation also contains the contribution to the coefficients due to Coulomb scattering with the ambient plasma (D_C, A_C).

➔ The TTD coefficients are proportional to the acceleration parameter:

$$I_{ACC} = \frac{U_T}{U_B} \cdot \frac{c\langle k\rangle}{\Omega_H}$$

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Evolution of the Electron Distribution

- Miller e ... ection (A_T) coeffici ... he transit- time da ...

$$\frac{\partial N}{\partial t} = \quad \ldots \quad A_T)\, N \Big]$$

- The ec ... oefficients due to ... A_C).
- The T ... celeration parame ...

$$I_{ACC} = \frac{U_T}{U_B} \cdot \frac{c\langle k \rangle}{\Omega_H}$$

- U_T: Energy density of the turbulent waves
- $c\langle k \rangle$: Average wave-vector of the accelerating waves
- U_B: Energy density of the ambient B-field
- Ω_H: Proton gyrofrequency

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Escape/Trapping

- We add a sink and source term to the FP equation

$$\frac{\partial N}{\partial t} = \frac{1}{2}\frac{\partial^2}{\partial E^2}\Big[(D_\mathrm{C} + D_\mathrm{T})N\Big] - \frac{\partial}{\partial E}\Big[(A_\mathrm{C} + A_\mathrm{T})N\Big] - SN + Q$$

with

$$S(E) = \frac{T_\mathrm{H}\beta}{\tau(E)}$$

and

$$Q = n_0 \cdot N_\mathrm{MB}(E)$$

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with

$$S(E) = \frac{T_H \beta}{\tau(E)}$$

β → Electron speed

$\tau(E)$ → Escape Time

and

$$Q = n_0 \cdot N_{MB}(E)$$

$N_{MB}(E)$ → Maxwell-Boltzmann distribution with temperature *T*

n_0 → Number of lost particles $n_0 = \int S\,N\,dE$

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Evolution of the Electron Distribution 2

➔ The FP equation is integrated numerically (using a Crank-Nicholson finite differencing scheme) until the electron spectrum reaches its equilibrium state (see movie).

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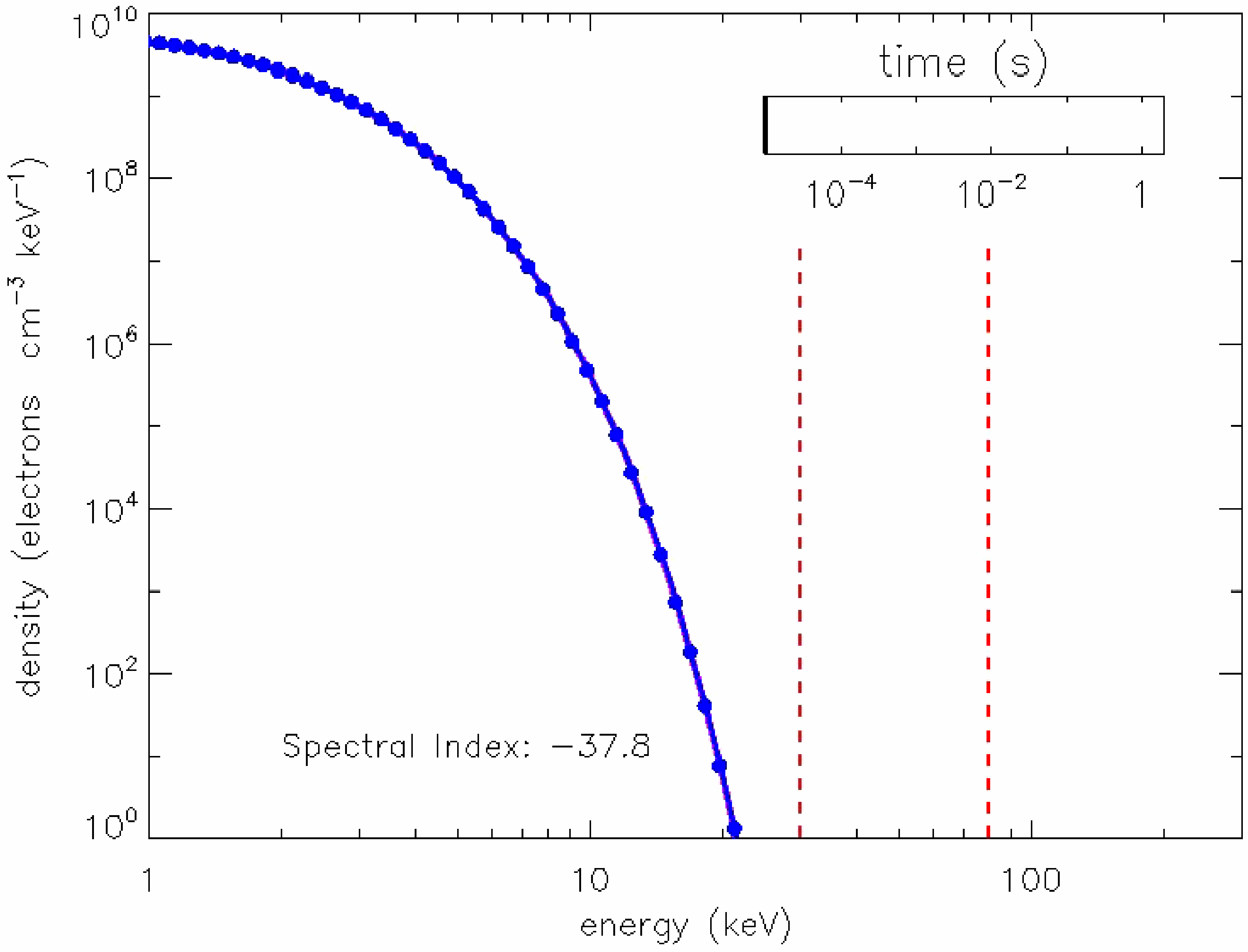
time (s)
10^{-4}
10^{-2}
1
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
density (electrons cm^{-3} keV^{-1})
Spectral Index: −37.8
1
10
100
energy (keV)

Evolution of the Electron Distribution 2

- The FP equation is integrated numerically (using a Crank-Nicholson finite differencing scheme) until the electron spectrum reaches its equilibrium state (see movie).

➔ The shape of the electron spectrum (for fixed values of the model parameters like T,n,B_0) depends on the escape time τ and the acceleration parameter I_{ACC}.

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Evolution of the Electron Distribution 2

- The FP equation is integrated numerically (using a Crank-Nicholson finite differencing scheme) until the electron spectrum reaches its equilibrium state (see movie).
- The shape of the electron spectrum (for fixed values of the model parameters like T, n, B_0) depends on the escape time τ and the acceleration parameter I_{ACC}.

➔ Furthermore, at energies higher than the thermal energy of the ambient plasma, and densities lower than a few times 10^{10} cm^{-3} the spectrum only depends on the product $\tau \cdot I_{ACC}$ (because in that regime, the TTD acceleration coefficients dominate the Coulomb collisional coefficients).

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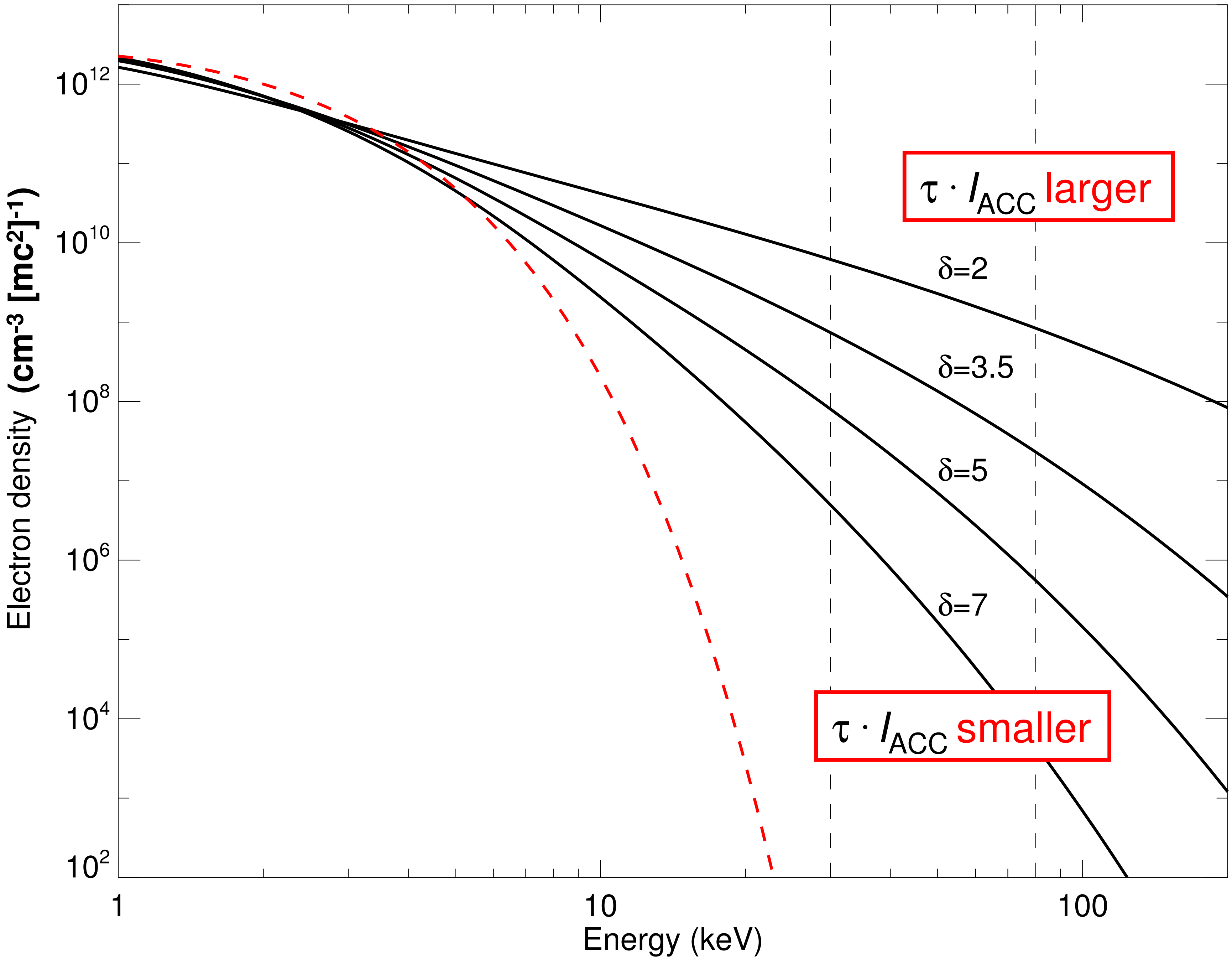

τ · I_ACC larger
δ=2
δ=3.5
δ=5
δ=7
τ · I_ACC smaller
Electron density (cm⁻³ [mc²]⁻¹)
Energy (keV)
10^12
10^10
10^8
10^6
10^4
10^2
1
10
100

Electrons → Photons

➔ We transform the electron spectrum into a photon spectrum by assuming thin-target bremsstrahlung emission from the equilibrium particle population in the accelerator. The relativistically correct form of the Bethe-Heitler cross section is used for the computation.

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Model Results: Soft-Hard-Soft Effect & Pivot Point

➔ The computation of the equilibrium electron and photon spectra for different values of $\tau \cdot I_{ACC}$ show the presence of soft-hard-soft spectral evolution.

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- The computation of the equilibrium electron and photon spectra for different values of $\tau \cdot I_{ACC}$ show the presence of soft-hard-soft spectral evolution.

➔ More precisely, a pivot point can be identified in the spectra.

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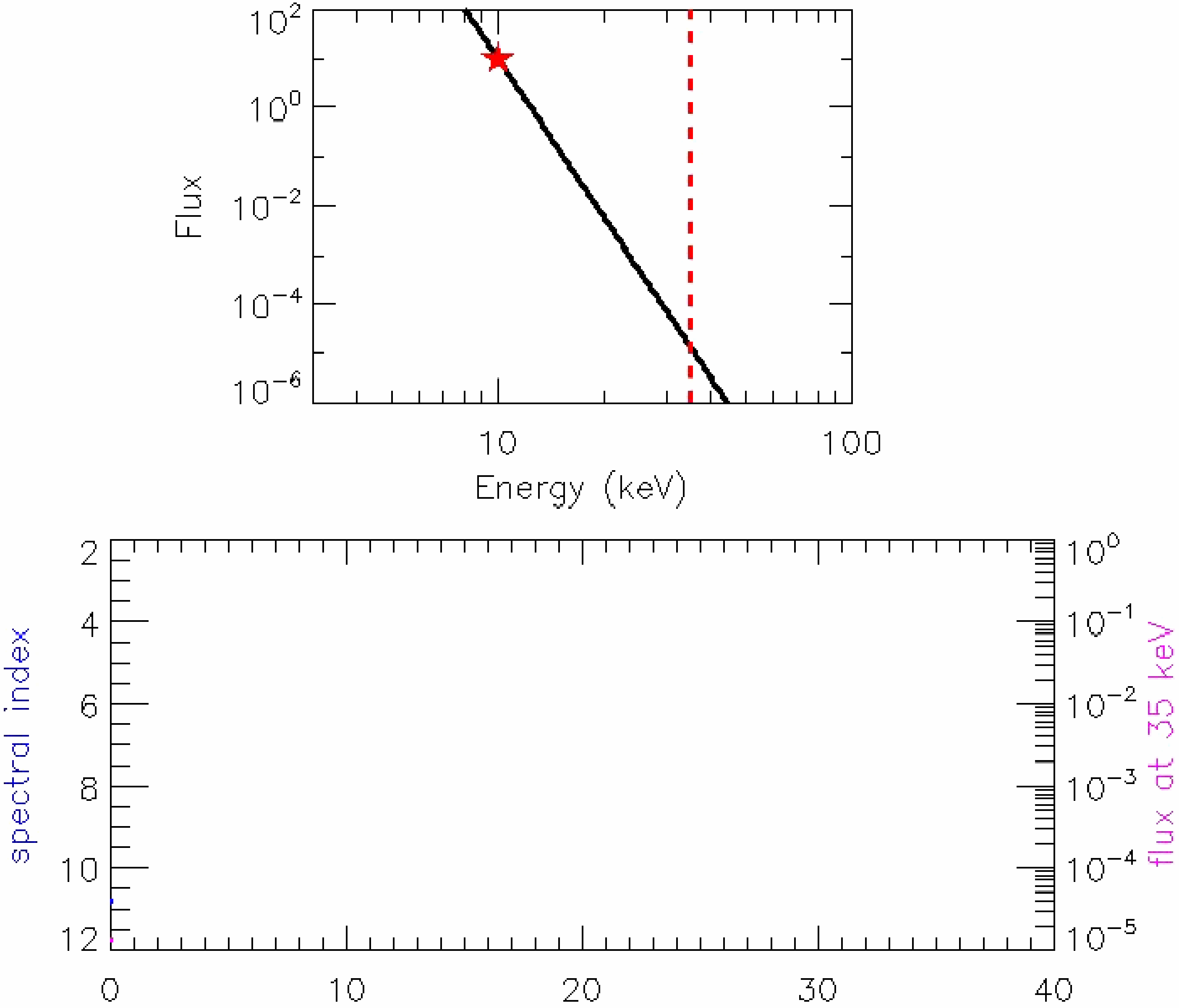
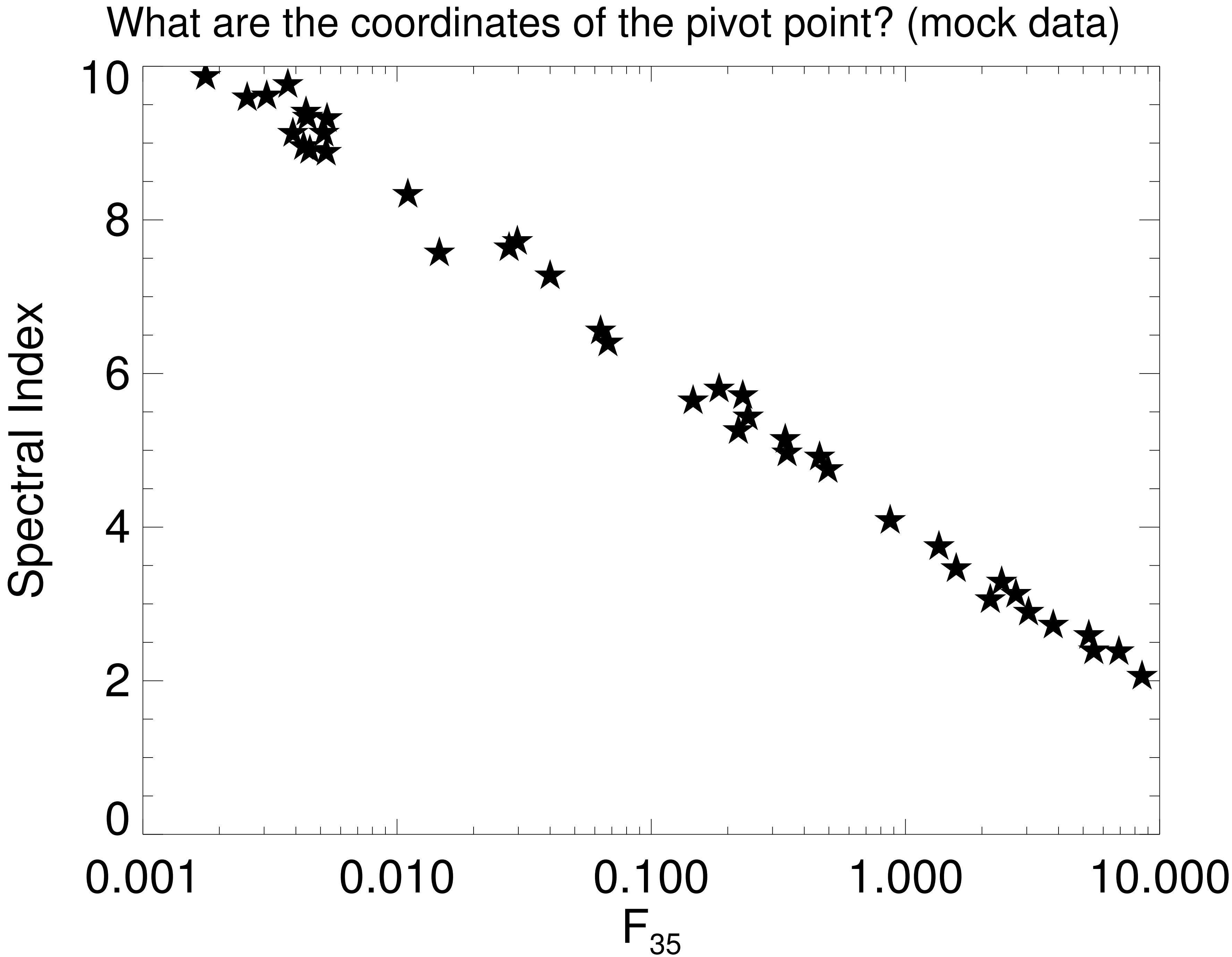
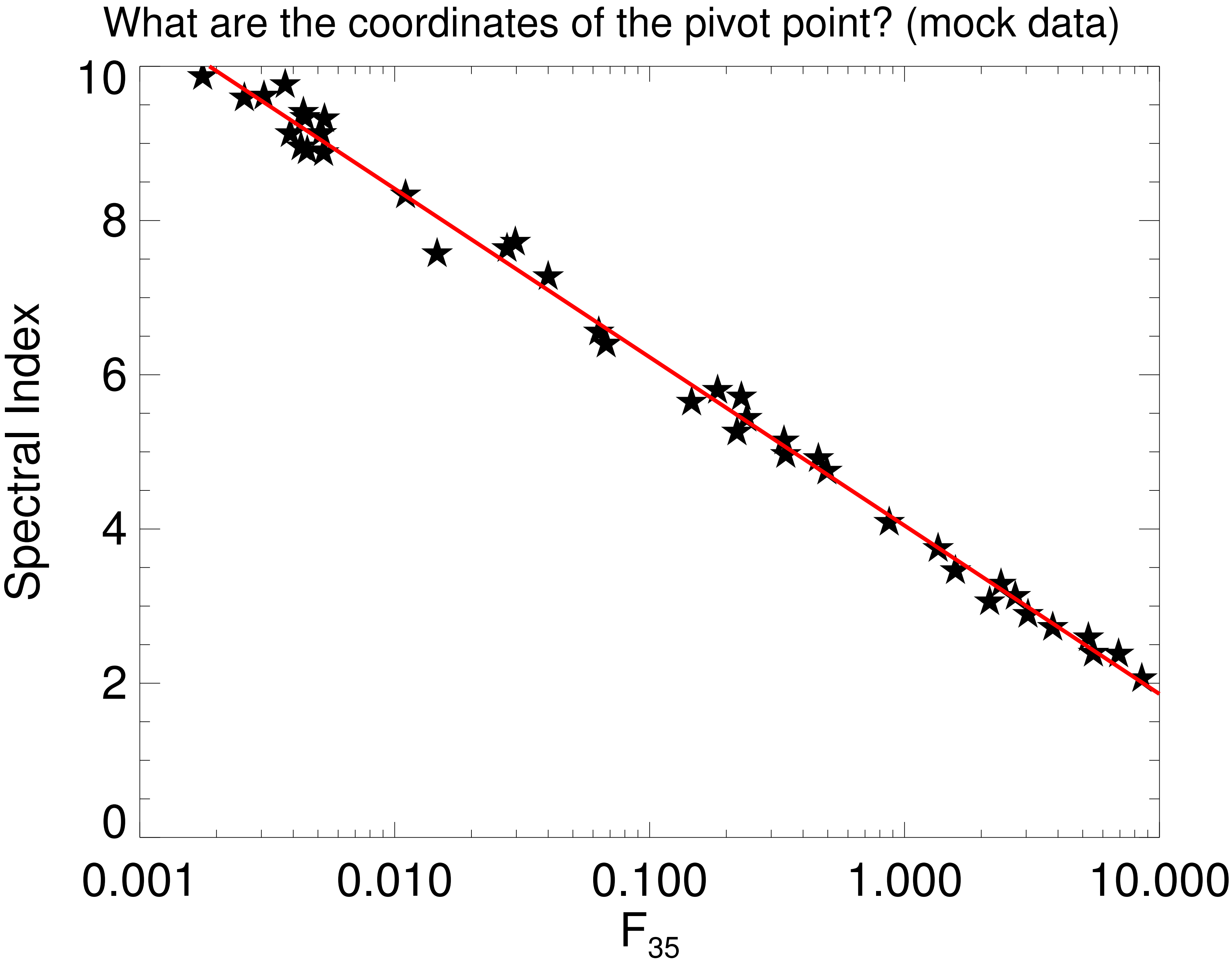
What is a pivot point? (mock data)




What are the coordinates of the pivot point? (mock data)
Spectral Index
F35
10
8
6
4
2
0
0.001
0.010
0.100
1.000
10.000



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1.000
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F35

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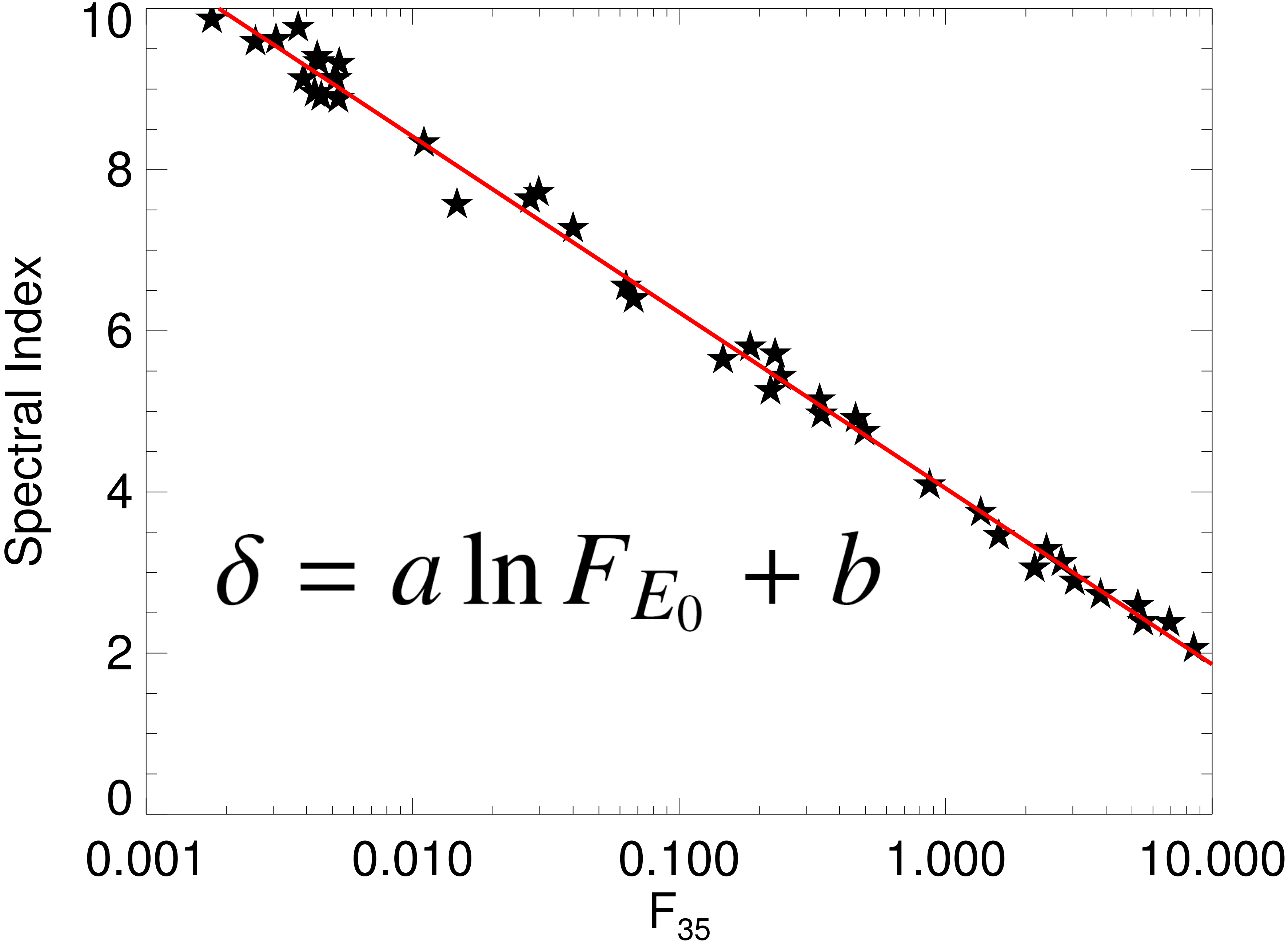
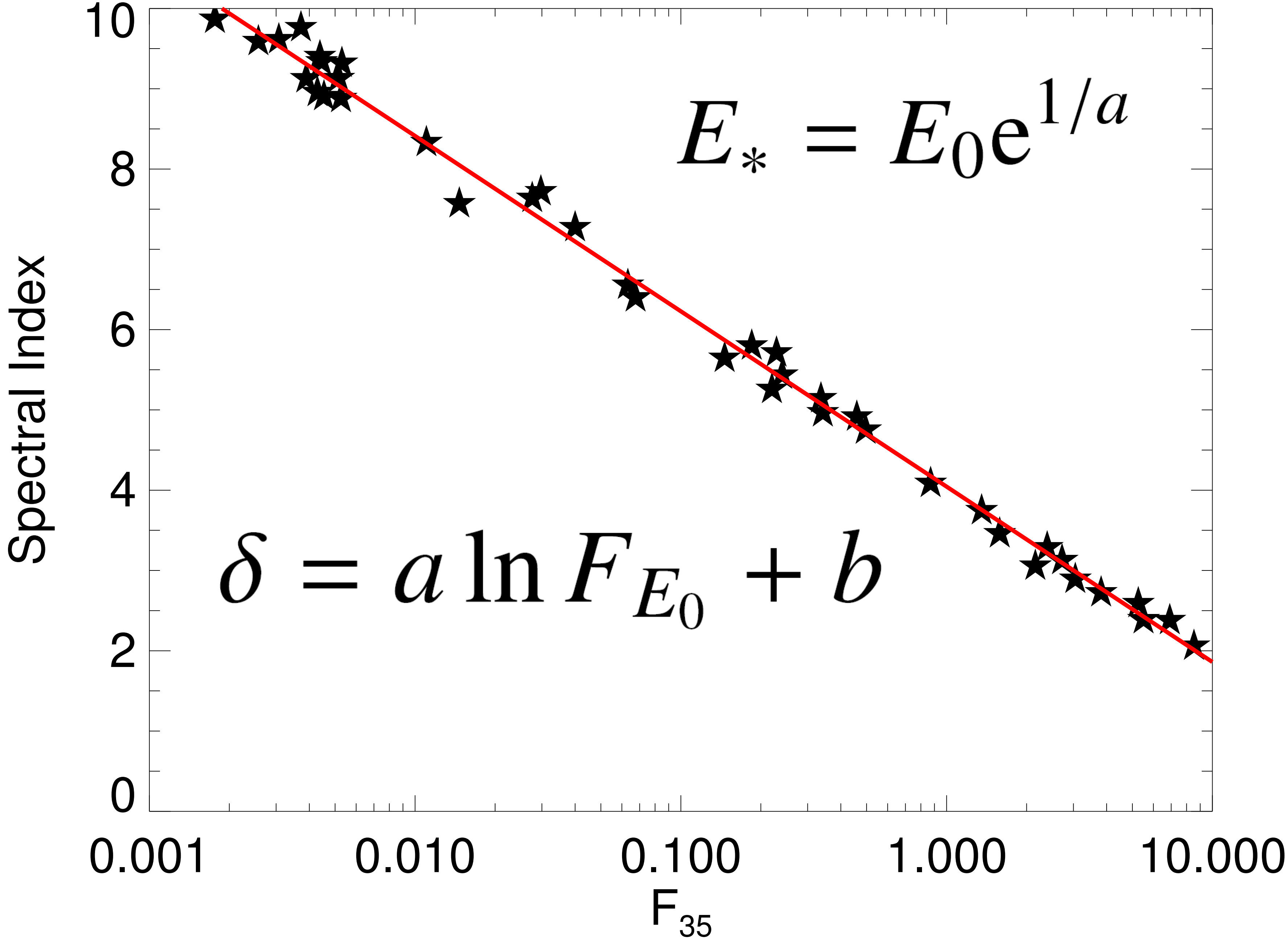


$$\delta = a \ln F_{E_0} + b$$

What are the coordinates of the pivot point? (mock data)



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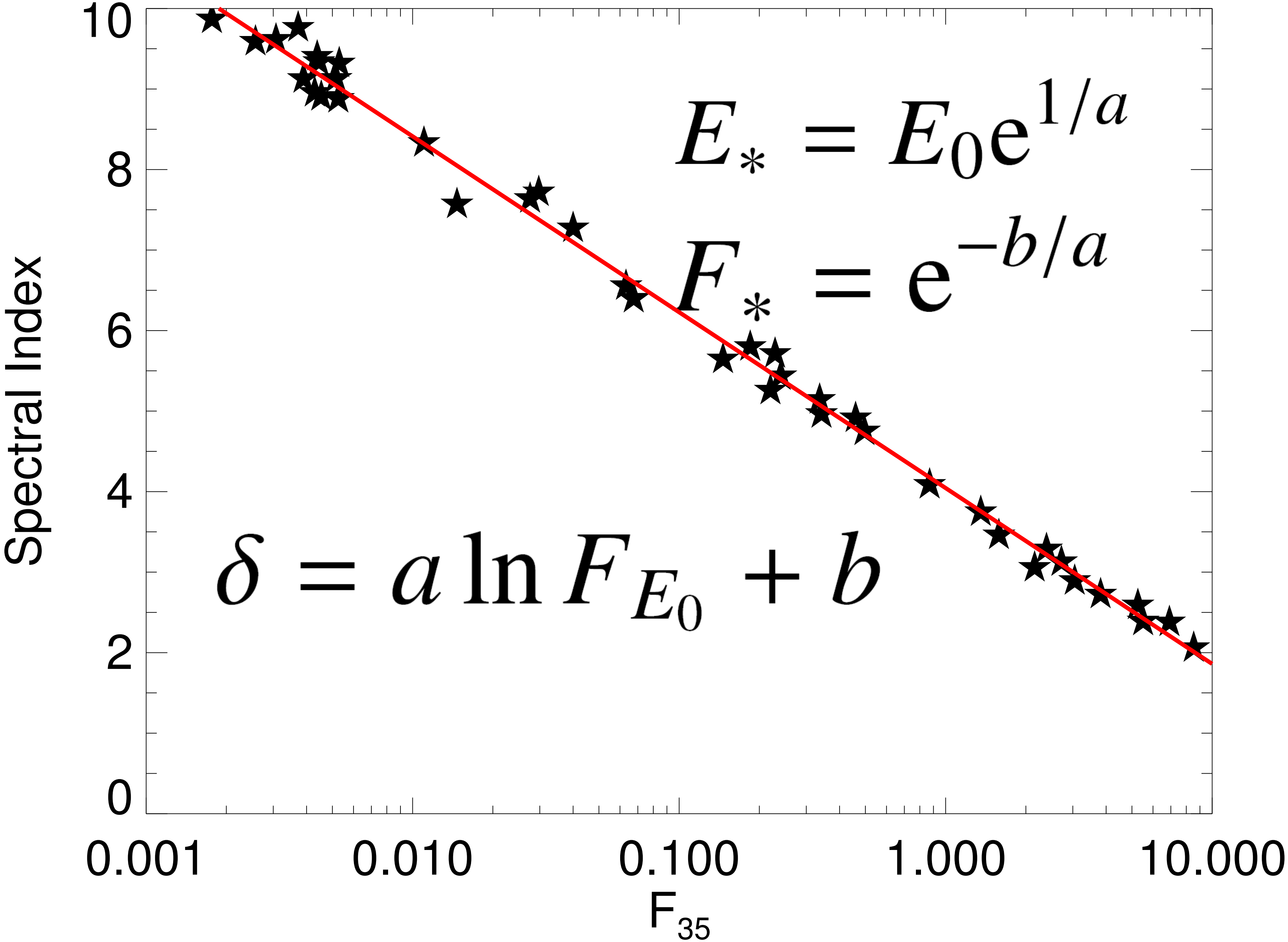

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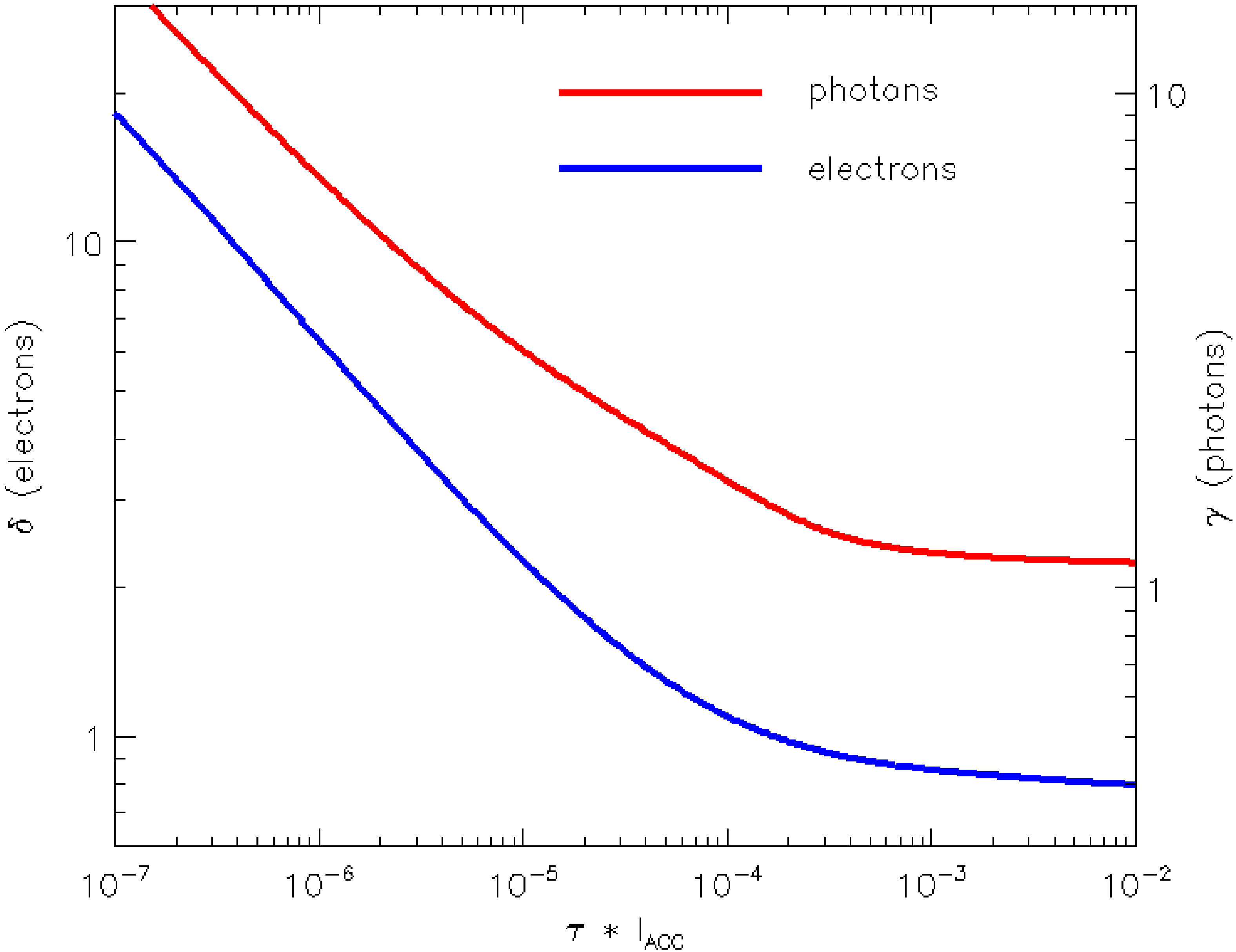

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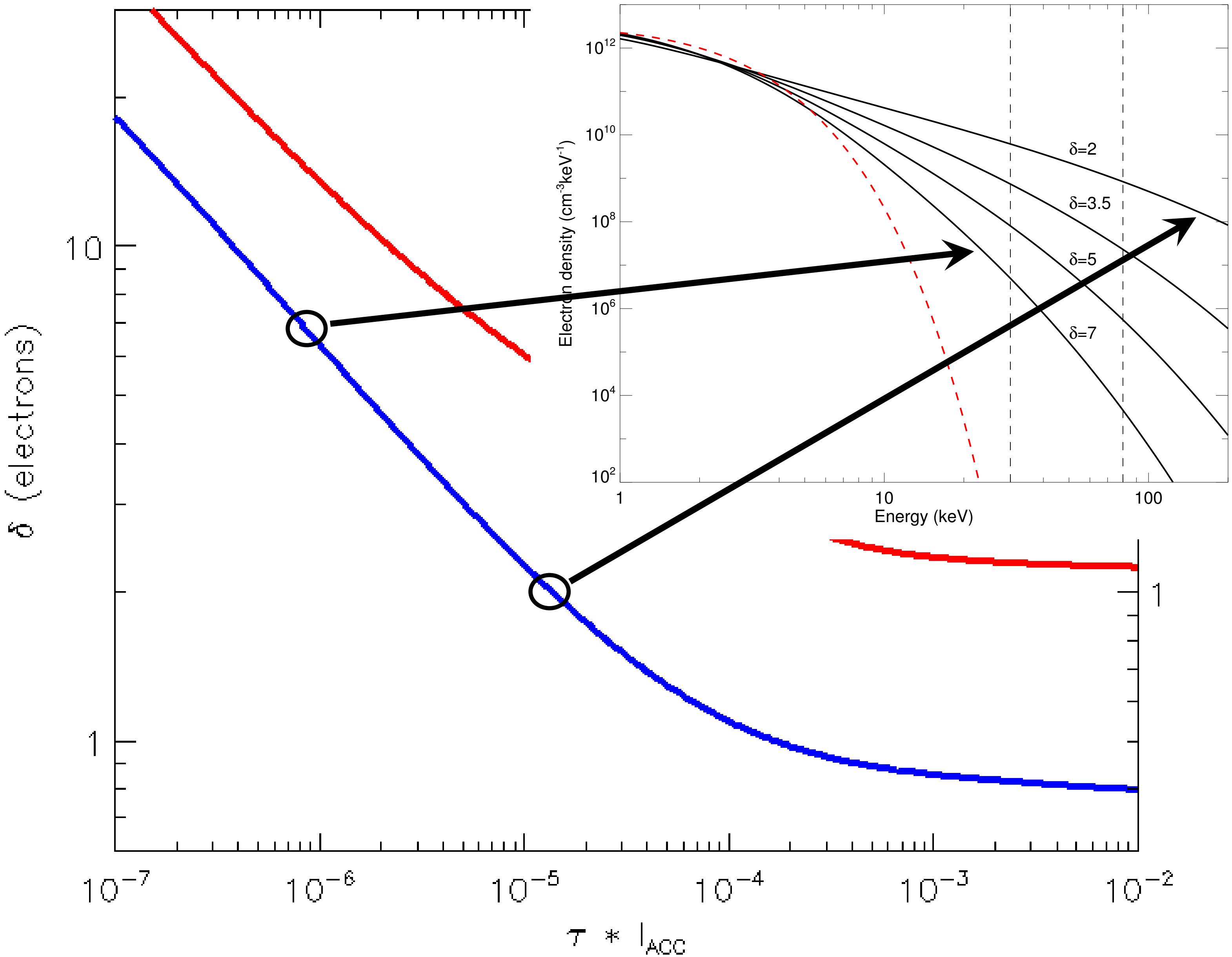

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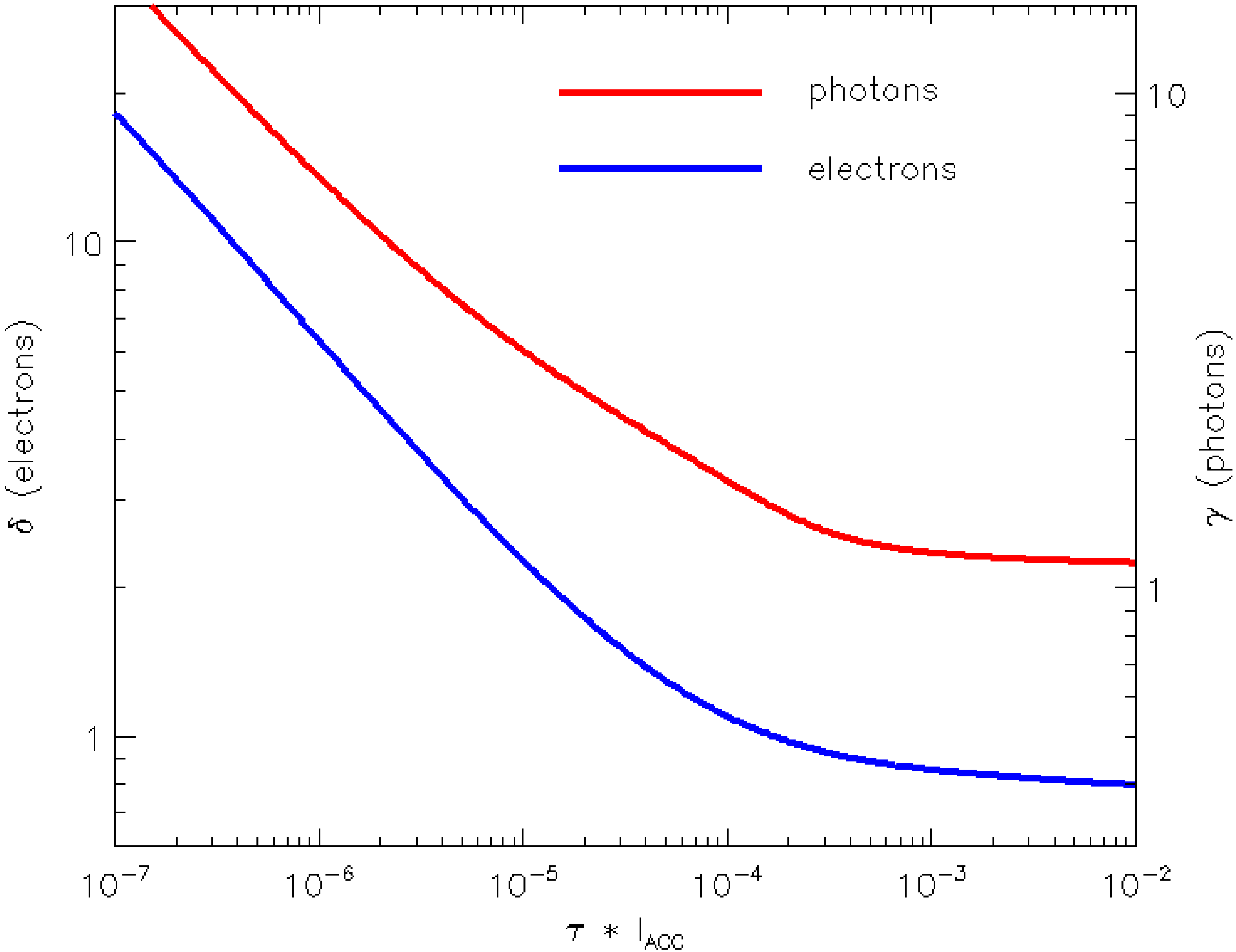

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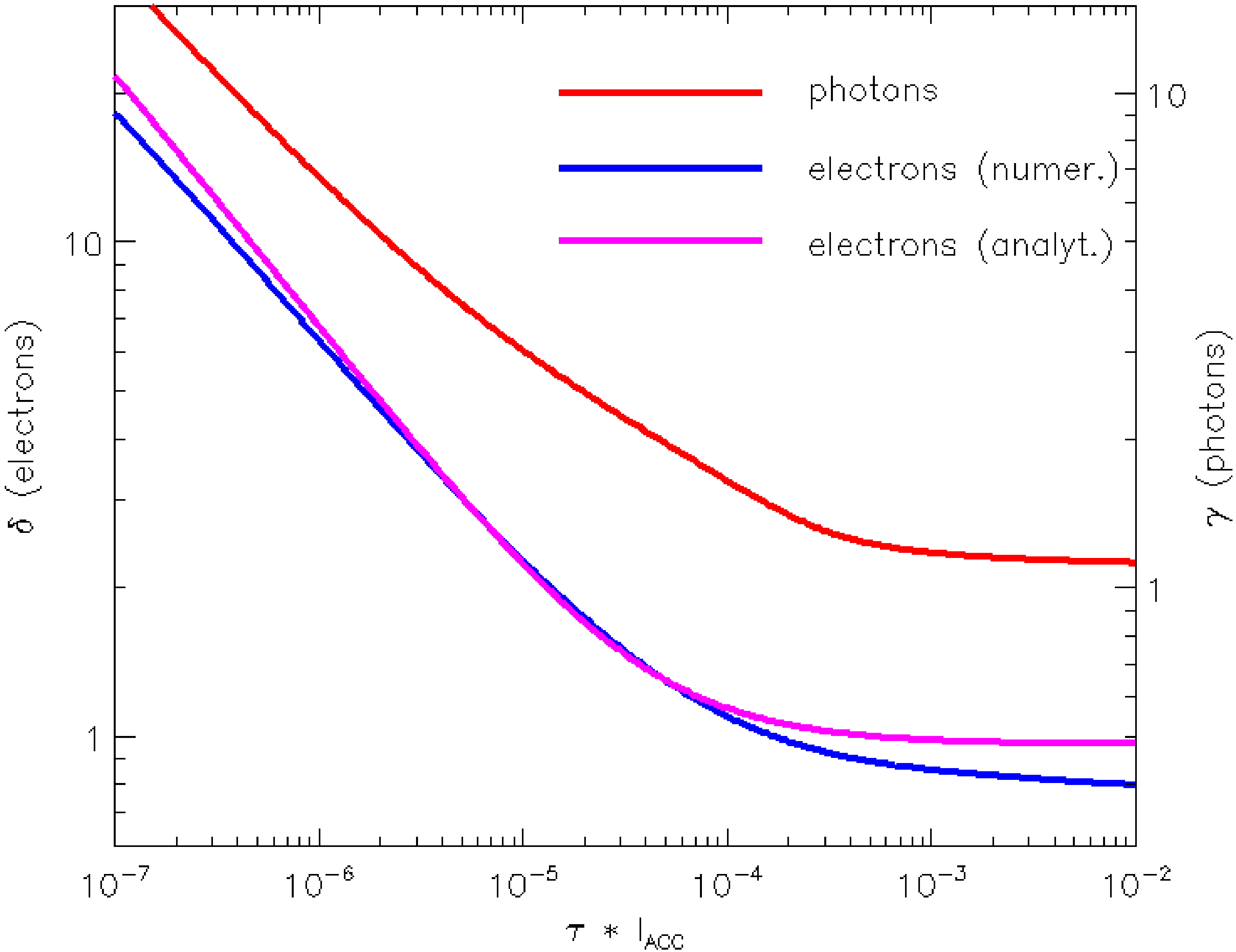

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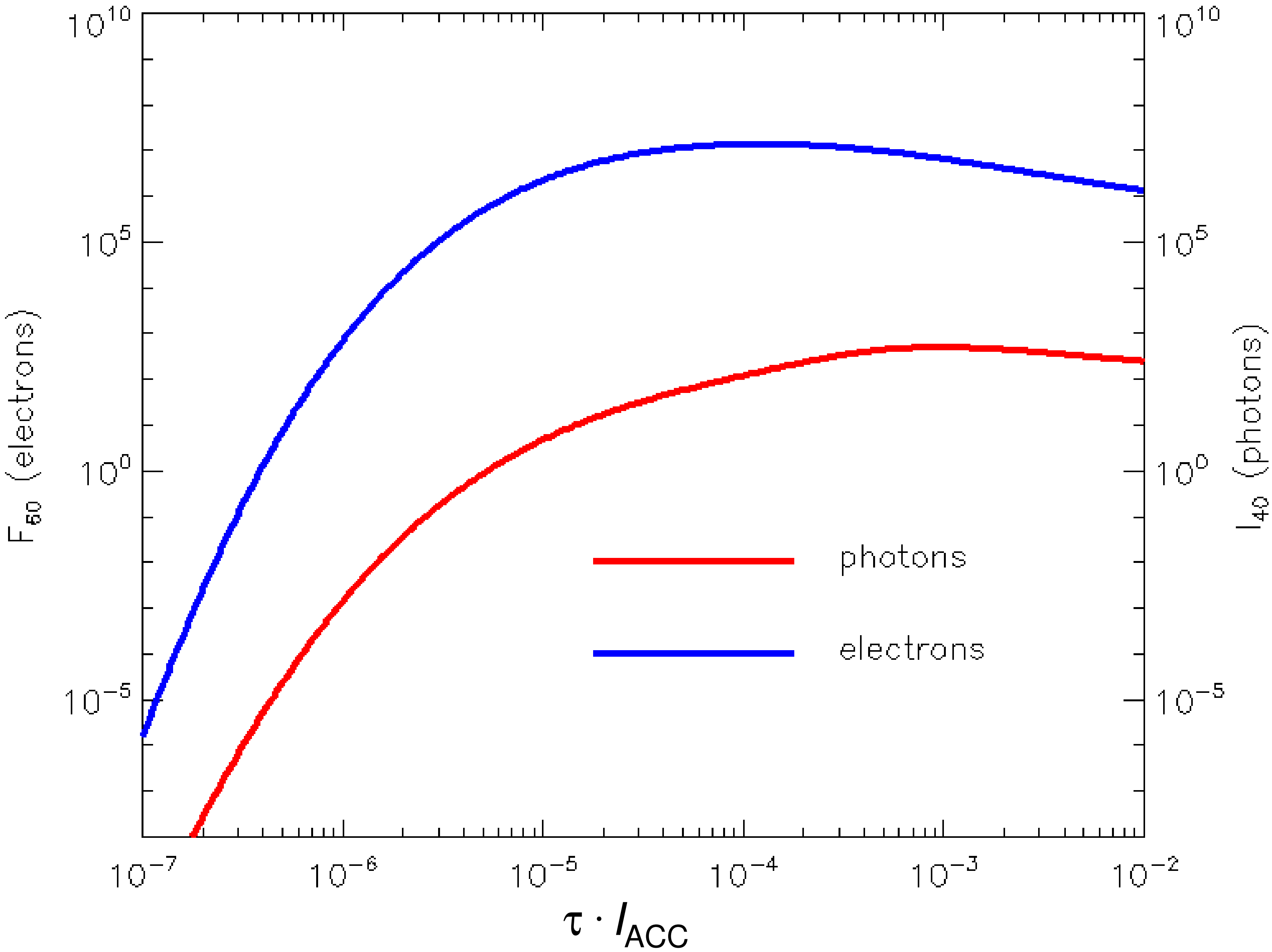

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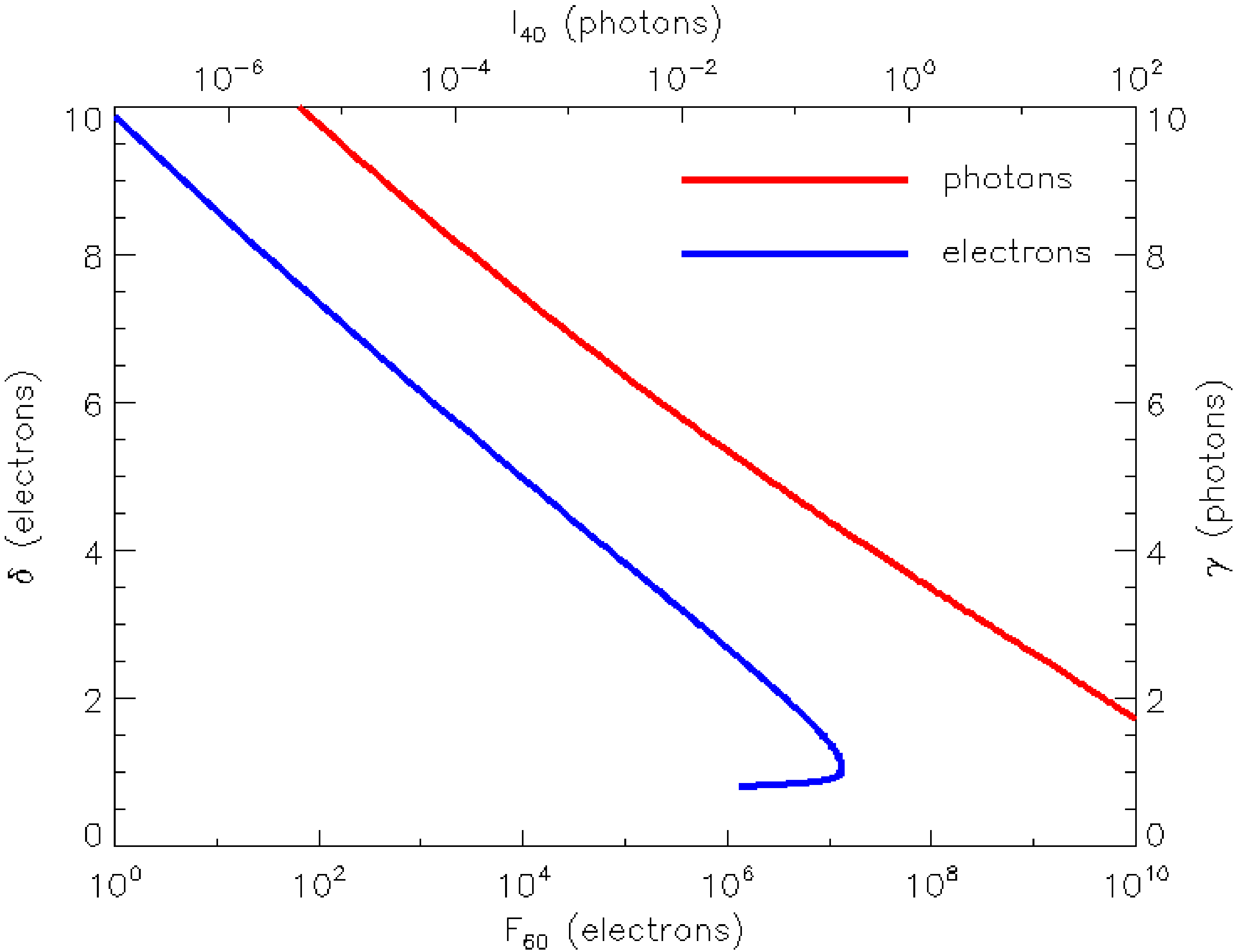

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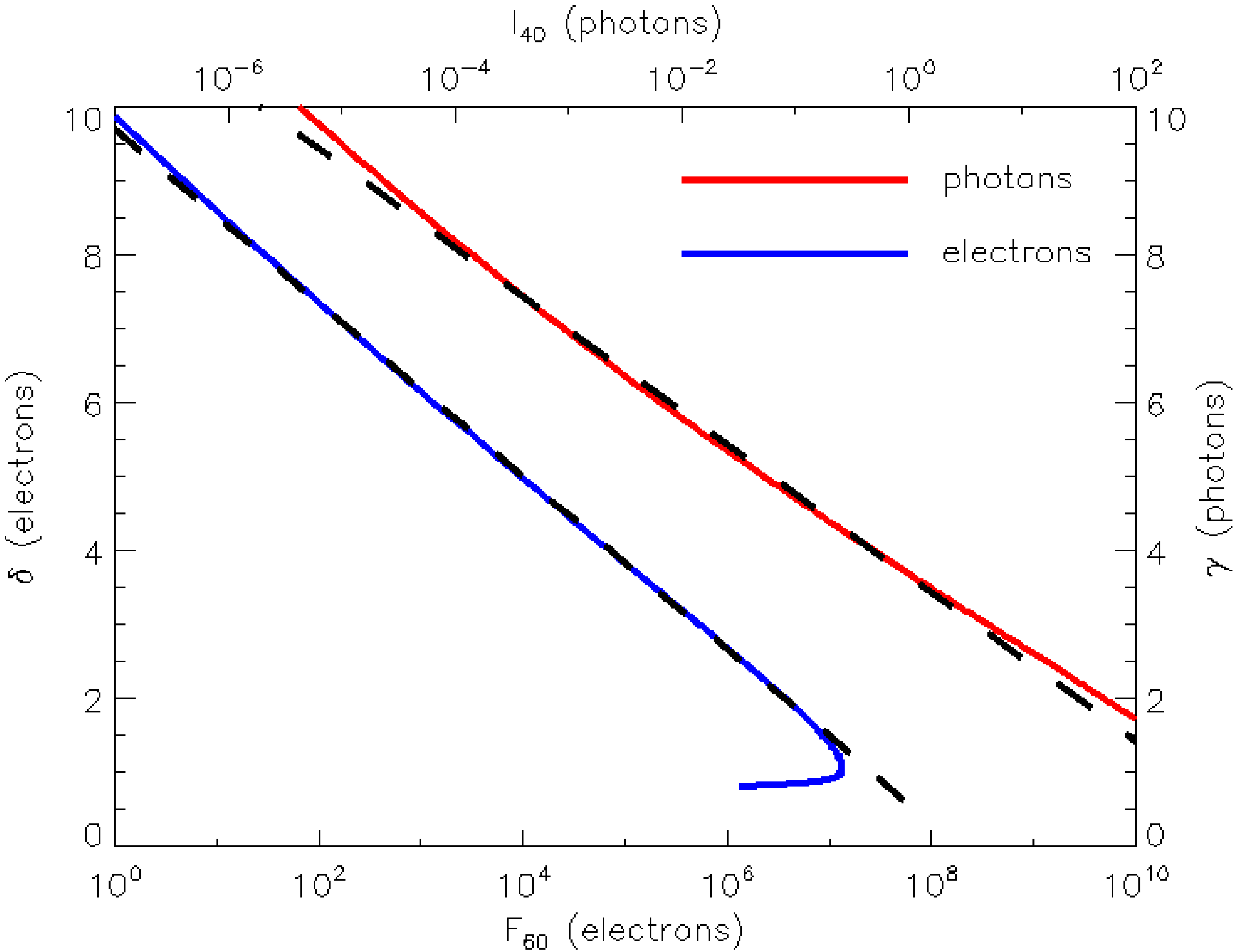

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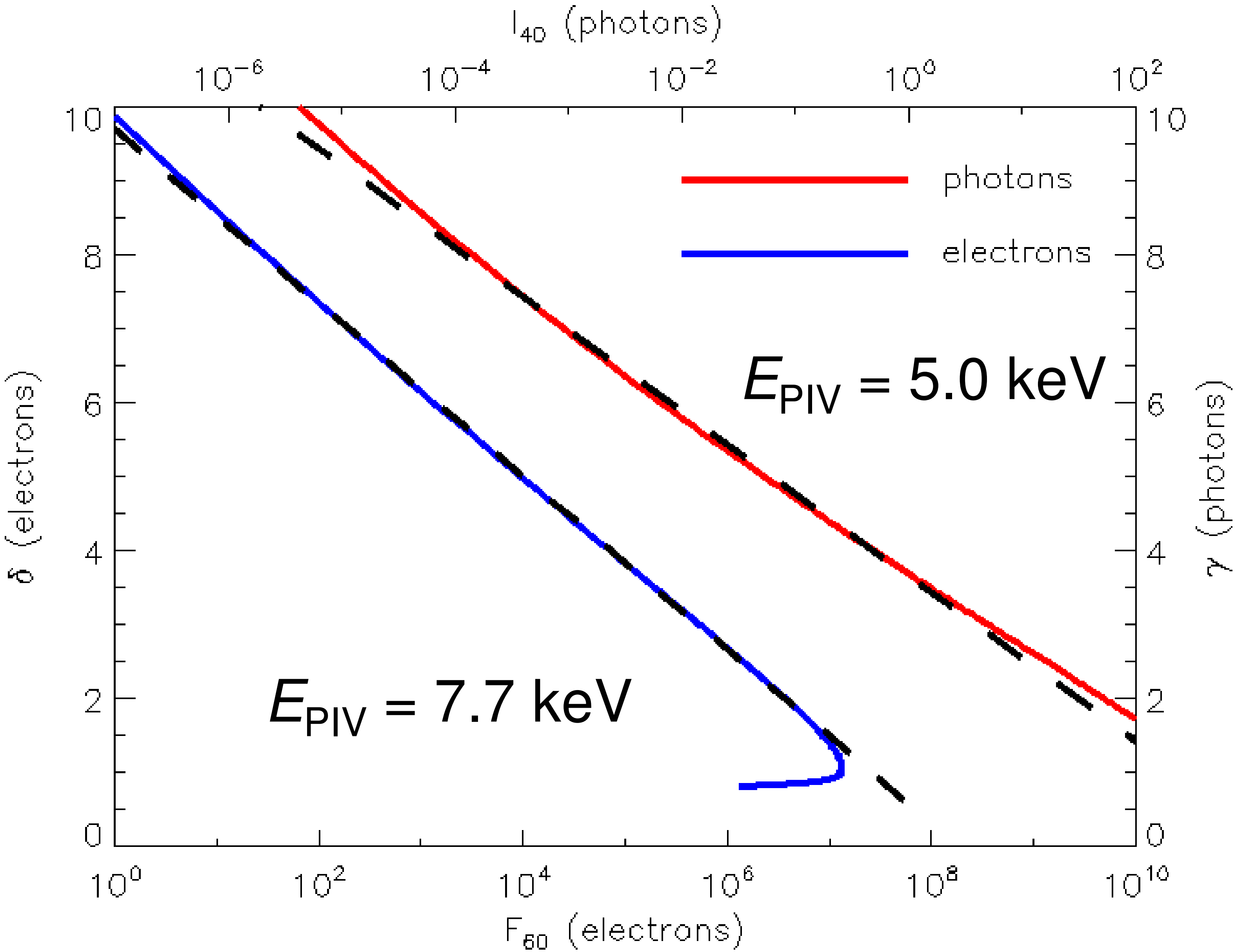

Model Results: Soft-Hard-Soft Effect & Pivot Point

- The computation of the equilibrium electron and photon spectra for different values of $\tau \cdot I_{ACC}$ show the presence of soft-hard-soft spectral evolution.
- More precisely, a pivot point can be identified in the spectra.

➔ For model parameters

Ambient temperature: T=10 MK

Ambient density: n=10^{10} cm^{-3}

we get values for the pivot-point energy around 8 keV for the electron spectra and around 5 keV for the photon spectra (difference due to the effects of the bremsstrahlung cross section on the energy distributions).

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Observation Results: SHS Effect & Pivot Point

➔ RHESSI imaging spectroscopy observations of looptop sources show the Soft-Hard-Soft effect.

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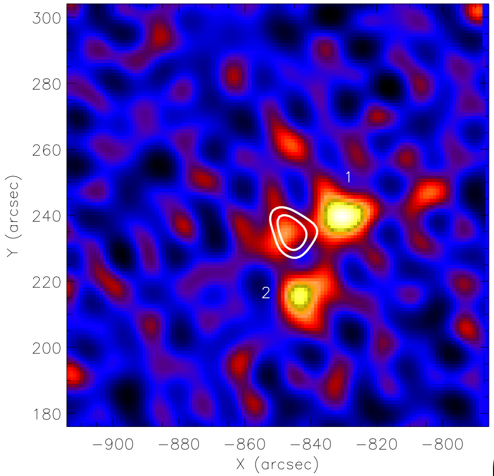
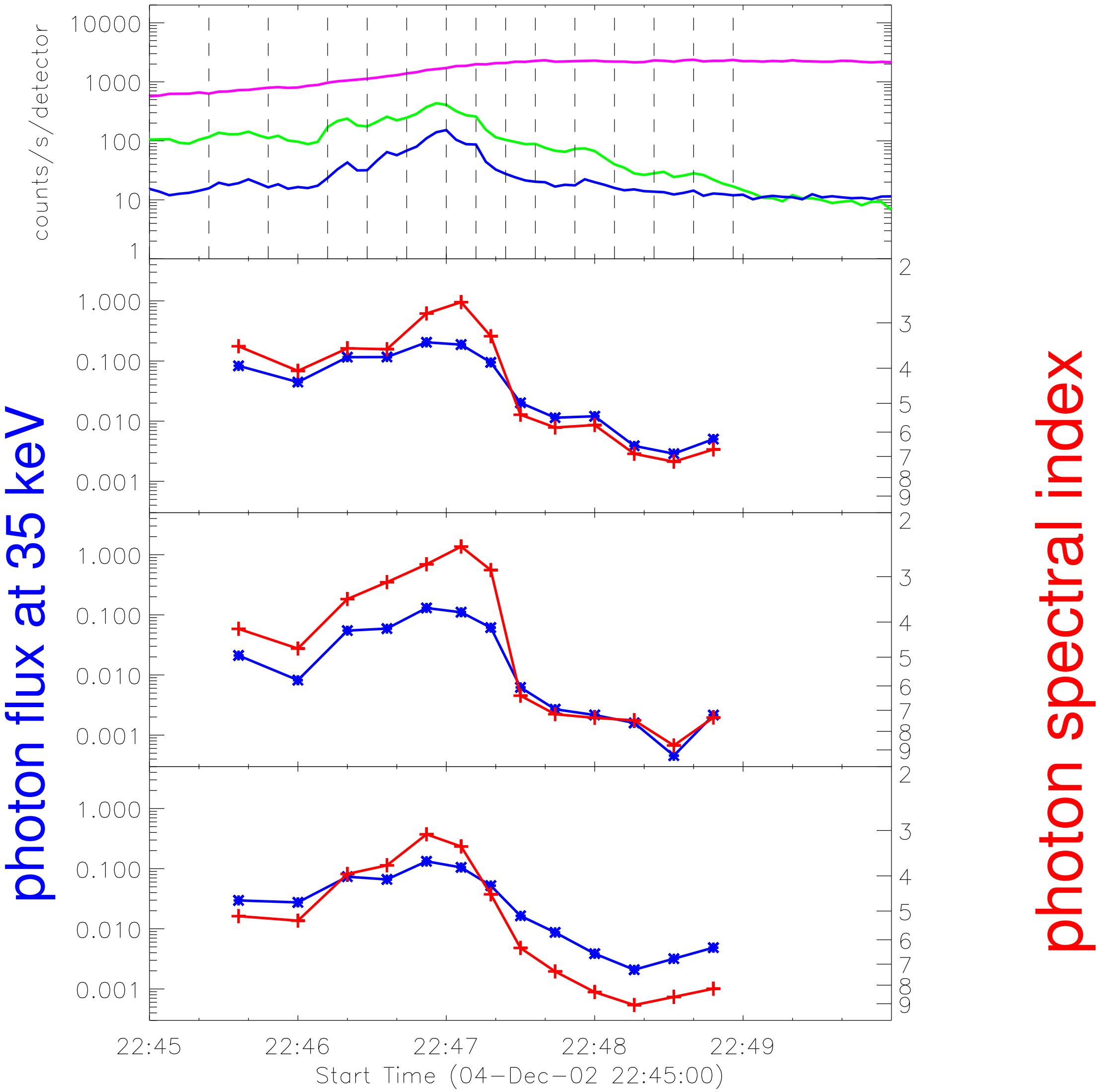
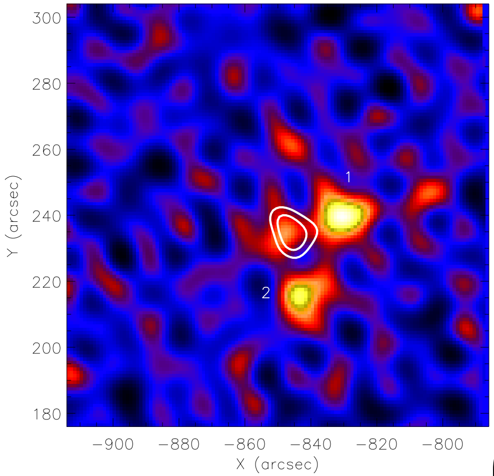


Footpoints:

Looptop source:

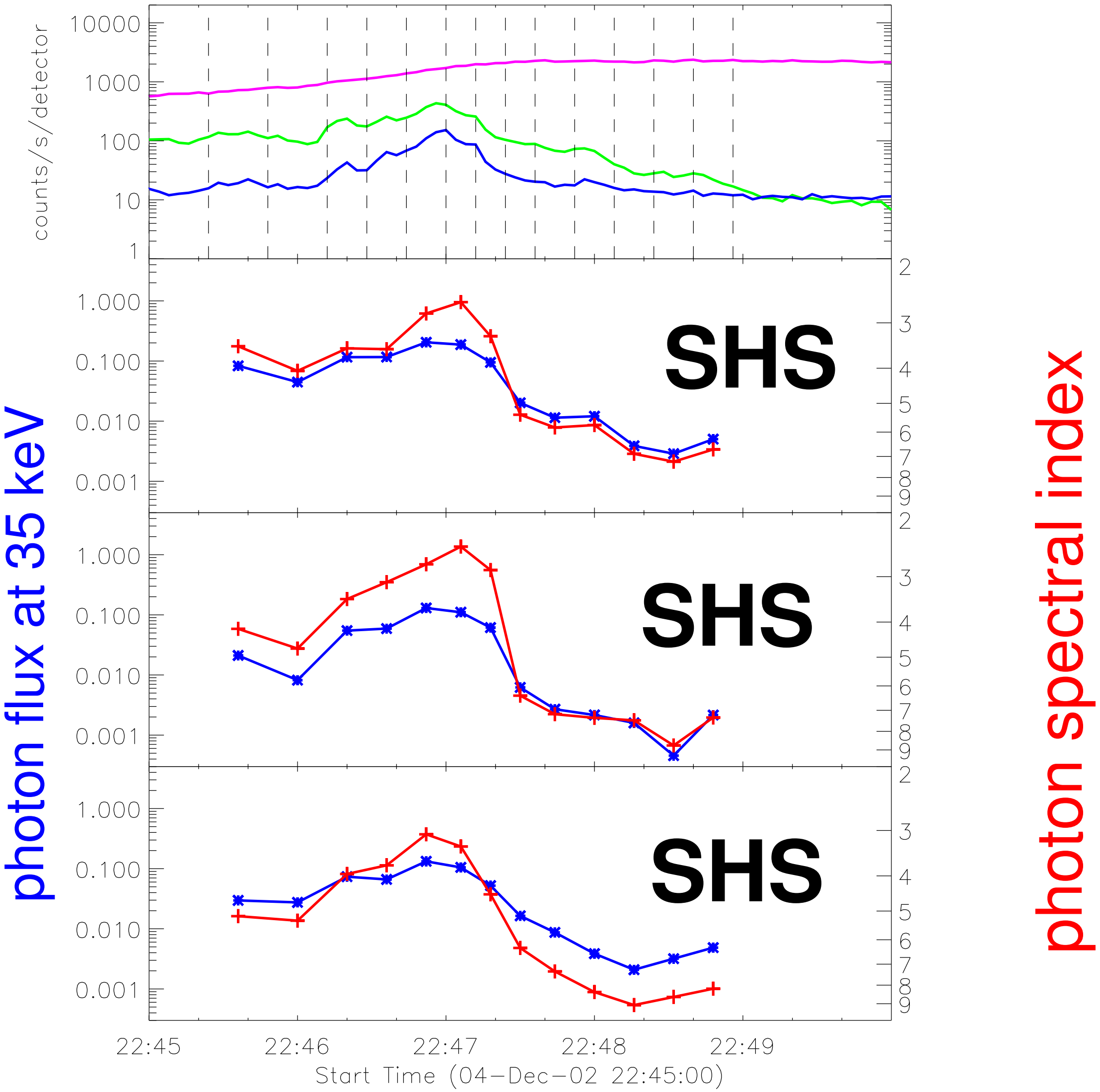


from Battaglia & Benz (2006)



Footpoints:

Looptop source:



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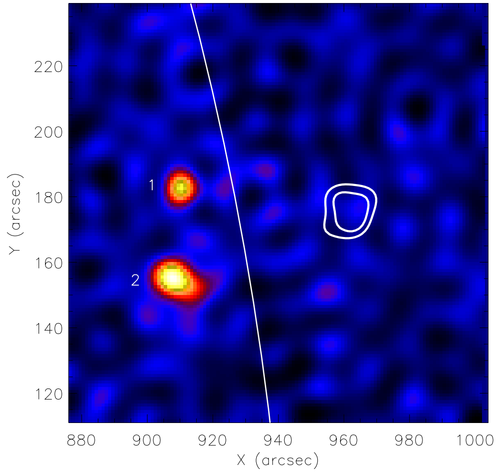
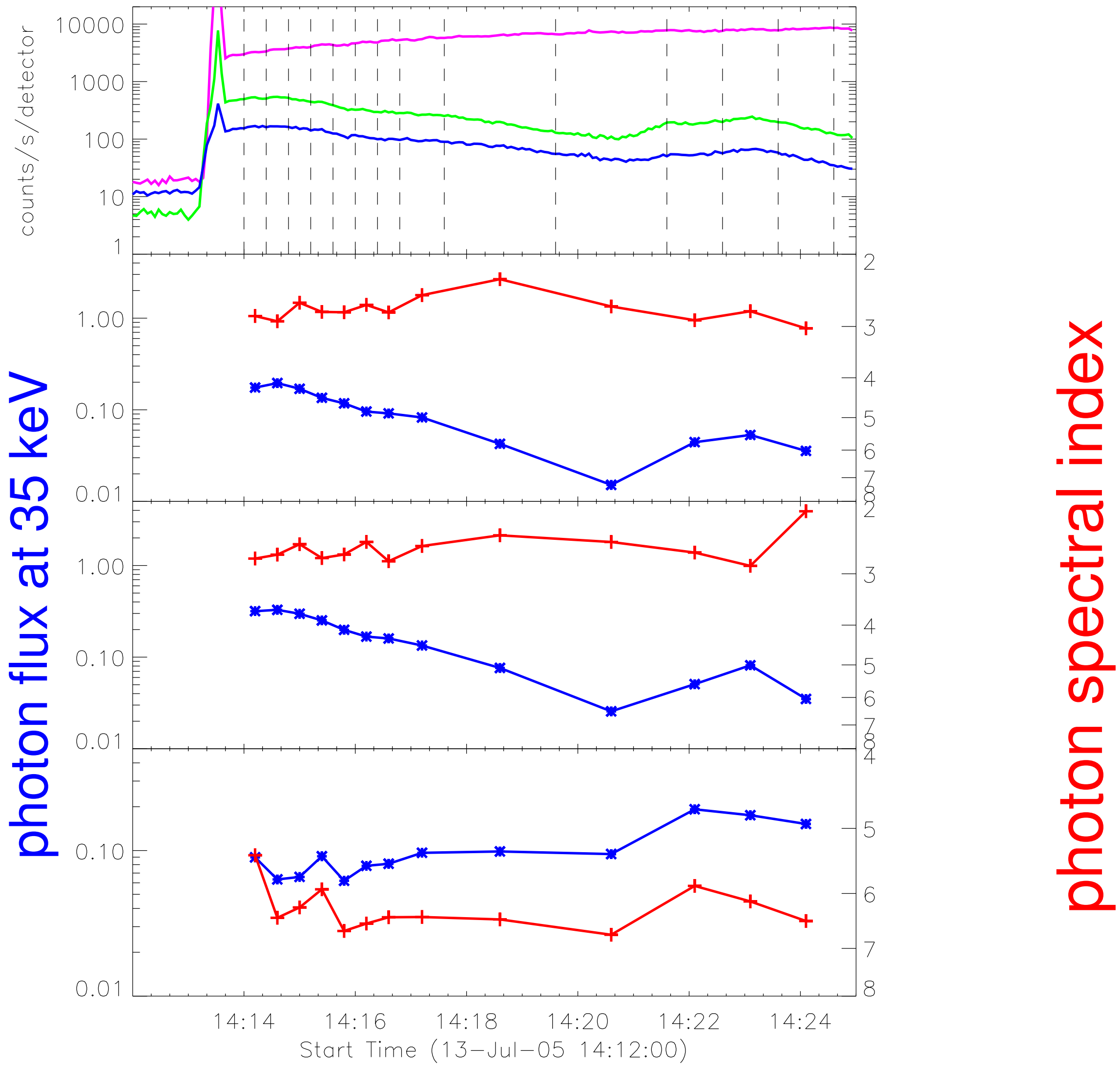


Footpoints:

Looptop source:



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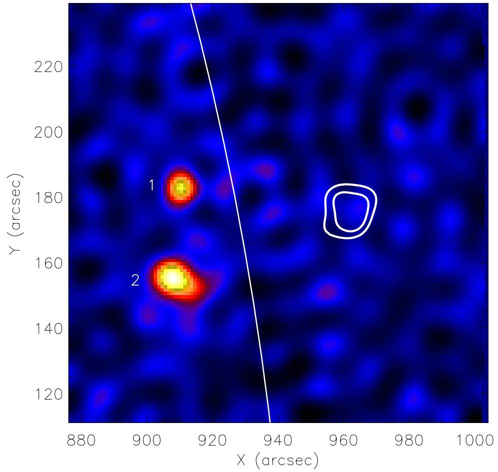
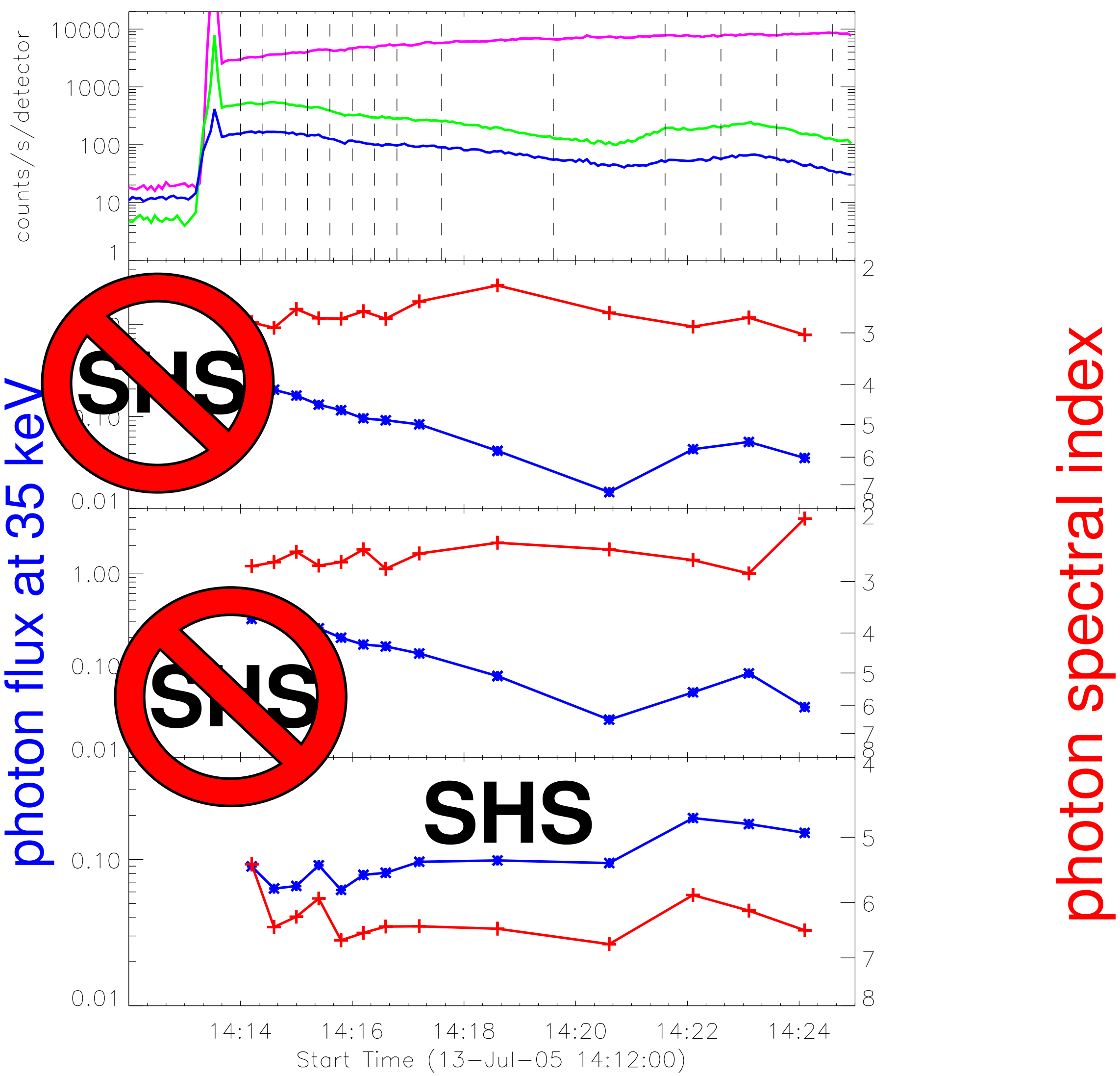


Footpoints:

Looptop source:



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Observation Results: SHS Effect & Pivot Point

- RHESSI imaging spectroscopy observations of looptop sources show the Soft-Hard-Soft effect.

➔ The pivot-point energy is rather large, around 20 keV.

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Table 1. Observational constraints for looptop sources (taken from Battaglia & Benz 2006).

Parameter Description	Average	Range
Pivot-point energy ε_*	20 keV	16–24 keV
Pivot-point flux[a] I_*	2	1–4
Temperature	22	18–25 MK
Nonthermal fitting range:		
Lower energy $\varepsilon_{\min}$	25 keV	20–30 keV
Upper energy $\varepsilon_{\max}$	60 keV	40–80 keV

[a] In units of photons cm^{-2} s^{-1} keV^{-1}.

Model vs. Observations

➔ The model successfully reproduces observed spectra and features the soft-hard-soft effect.

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- The model successfully reproduces observed spectra and features the soft-hard-soft effect.

➔ However, the pivot-point energy is too small.

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➔ How does the pivot-point energy E_* depends on the model parameters?

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Model vs. Observations

- The model successfully reproduces observed spectra and features the soft-hard-soft effect.
- However, the pivot-point energy is too small.
- How does the pivot-point energy E_* depends on the model parameters?

➔ Where does the approximation that the spectra depend only on the product $\tau \cdot l_{ACC}$ breaks down?

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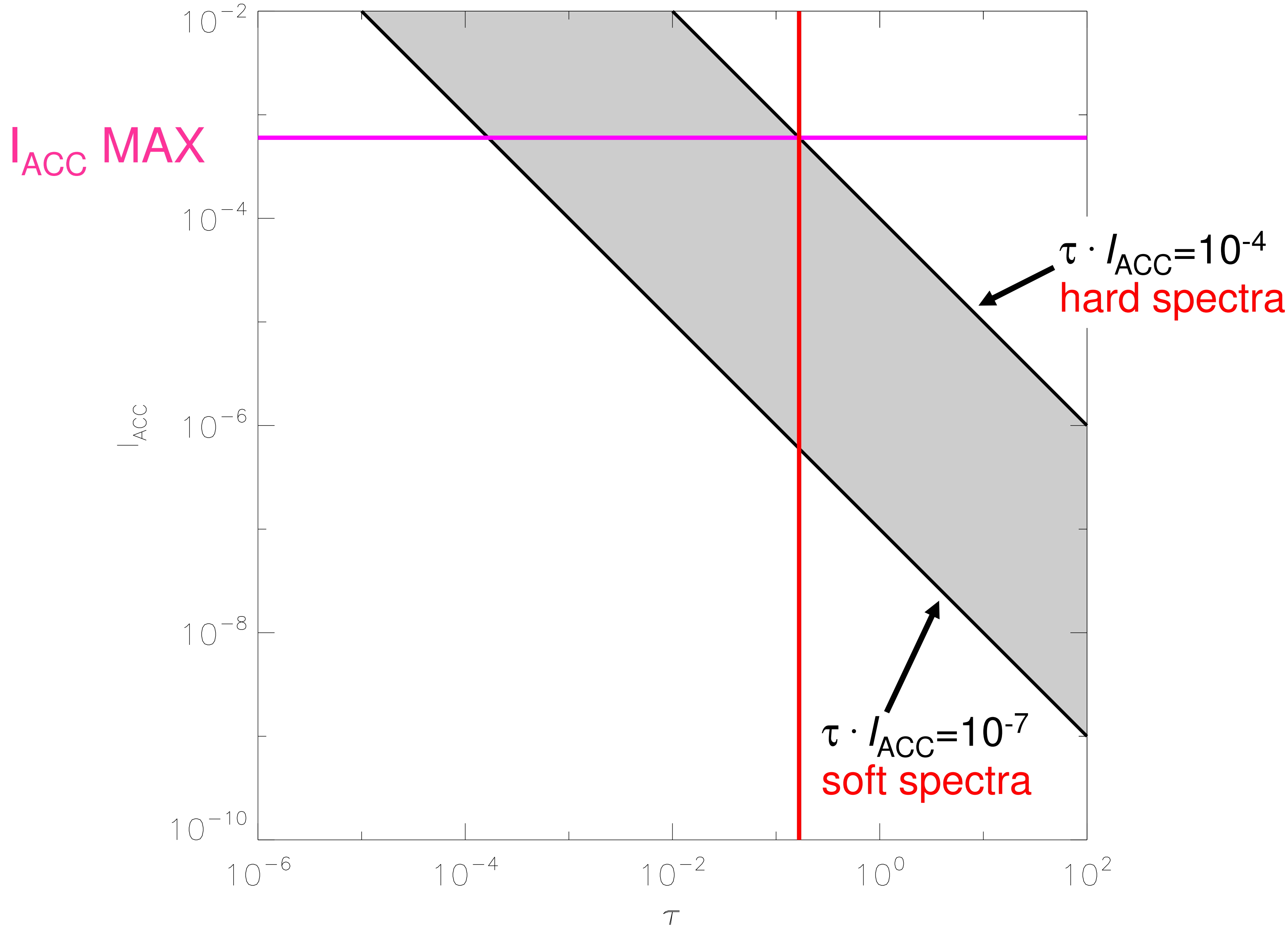
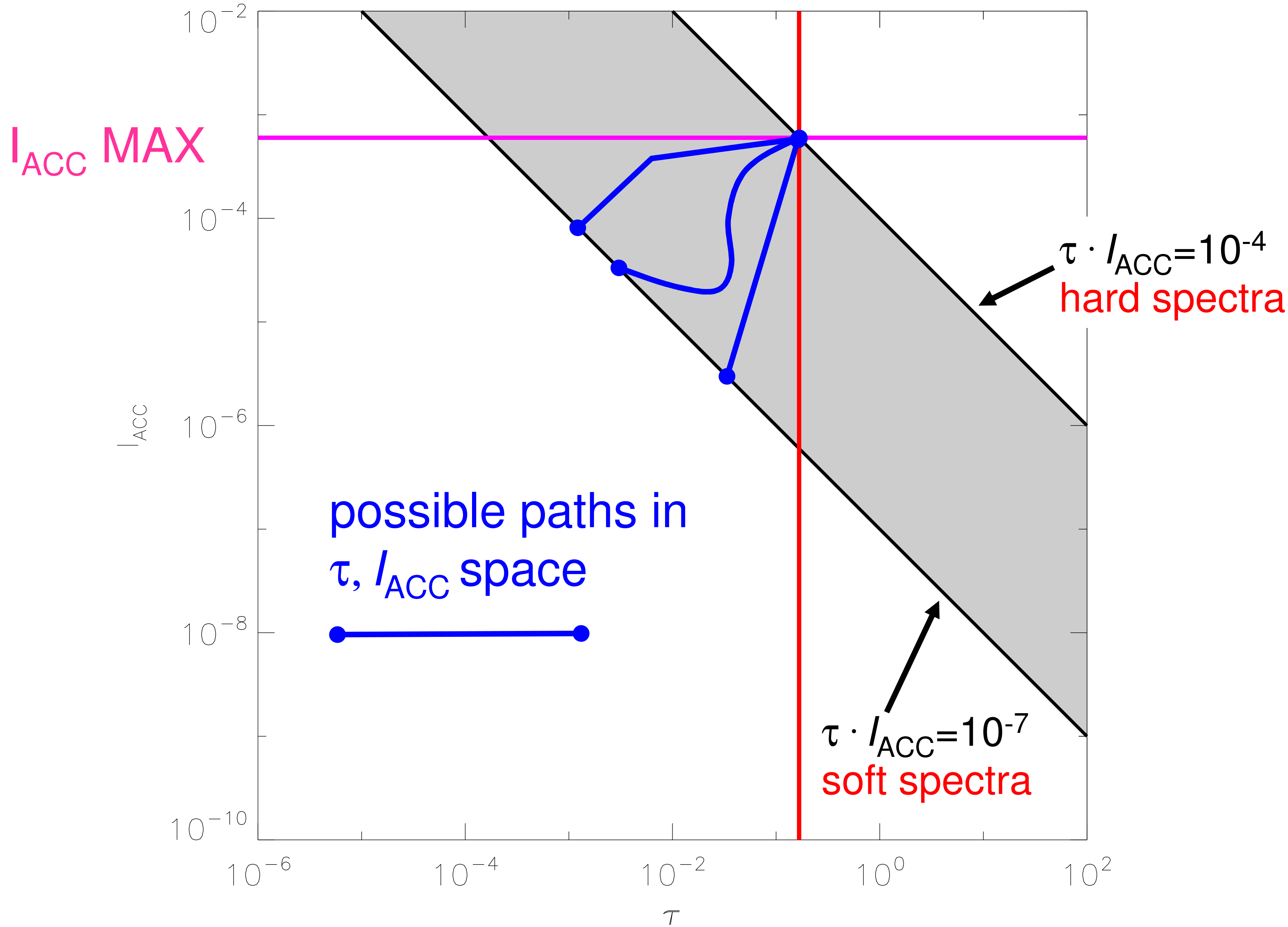
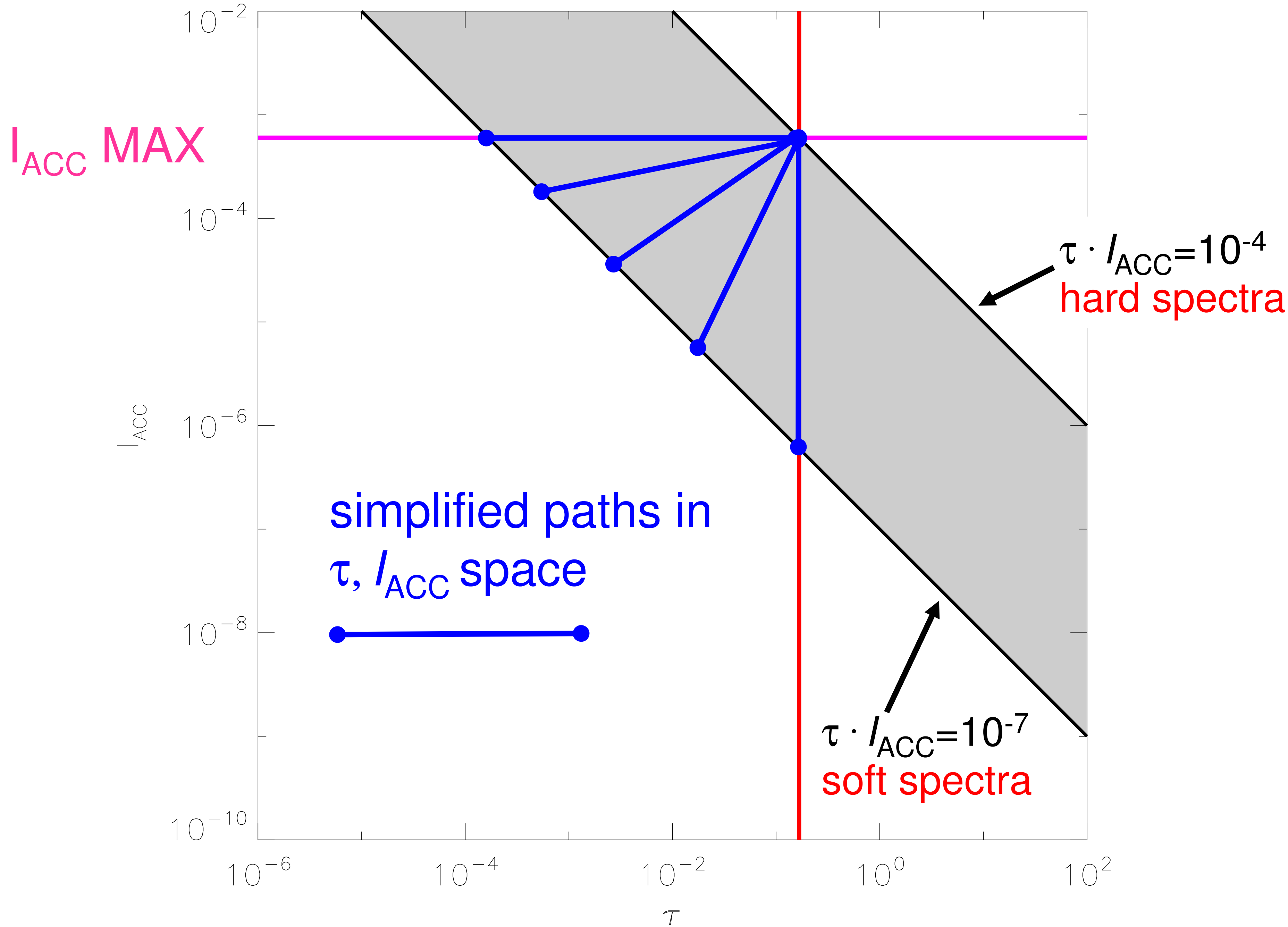


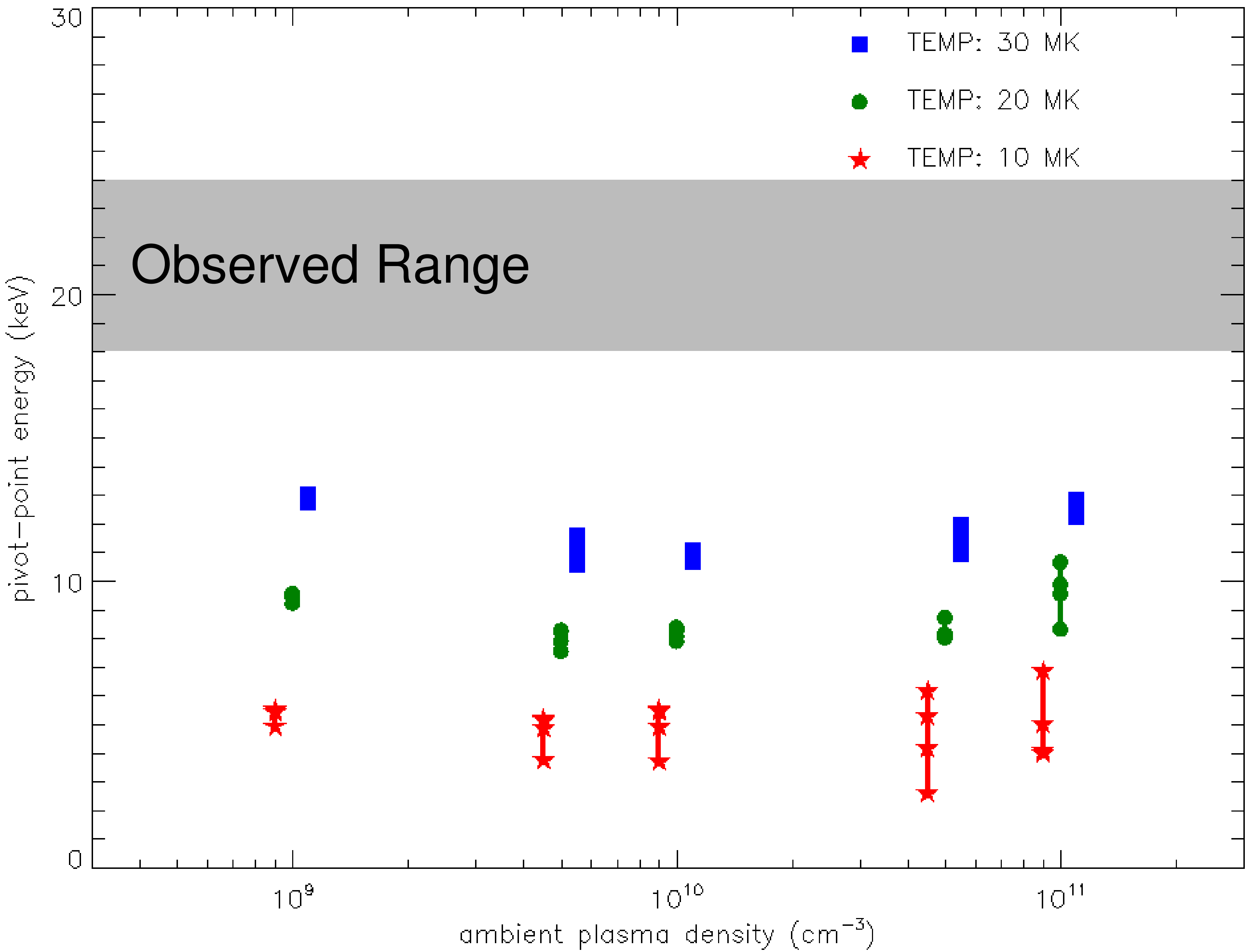
I_ACC MAX
τ · I_ACC=10^-4
hard spectra
τ · I_ACC=10^-7
soft spectra
I_ACC
τ
10^-2
10^-4
10^-6
10^-8
10^-10
10^-6
10^-4
10^-2
10^0
10^2

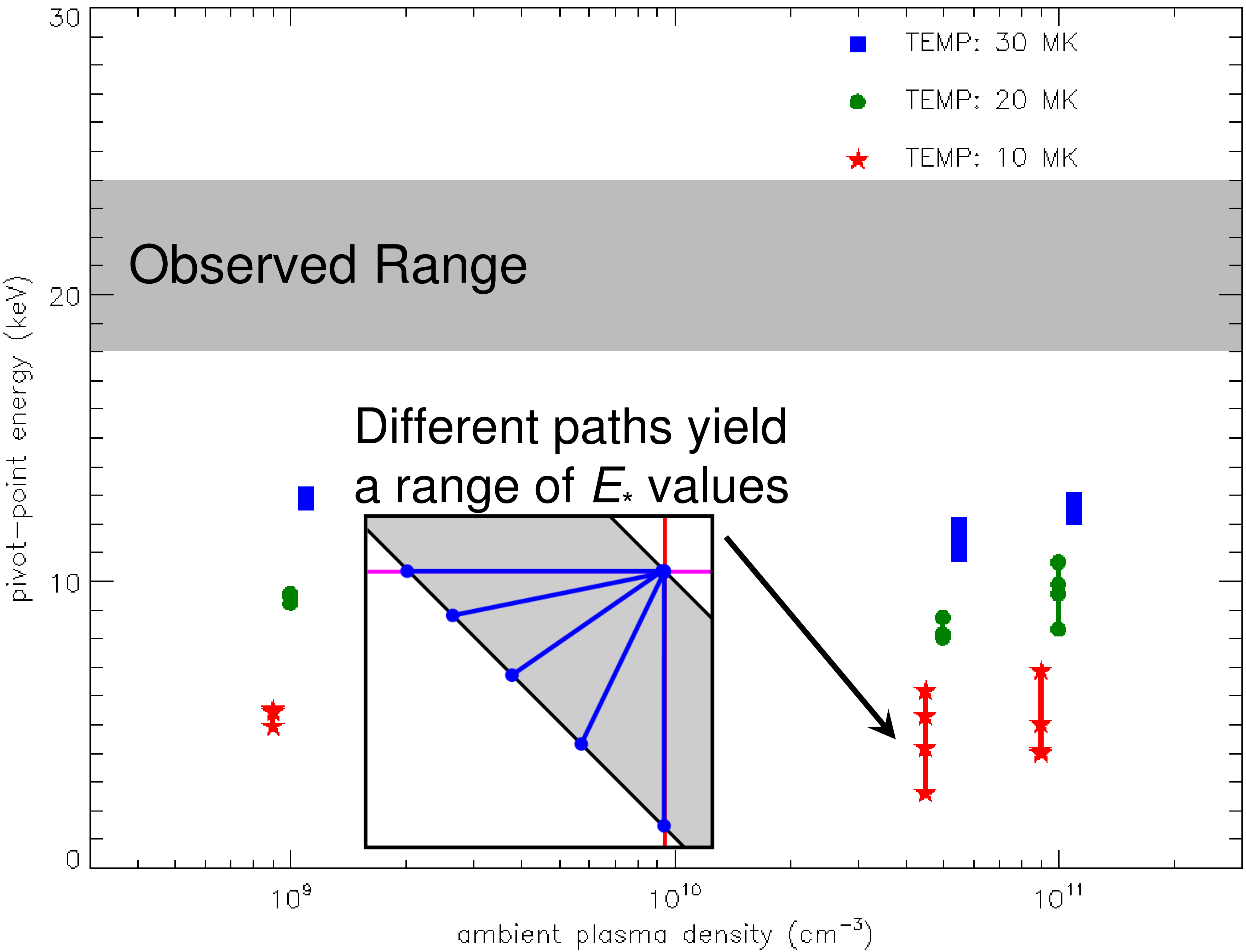


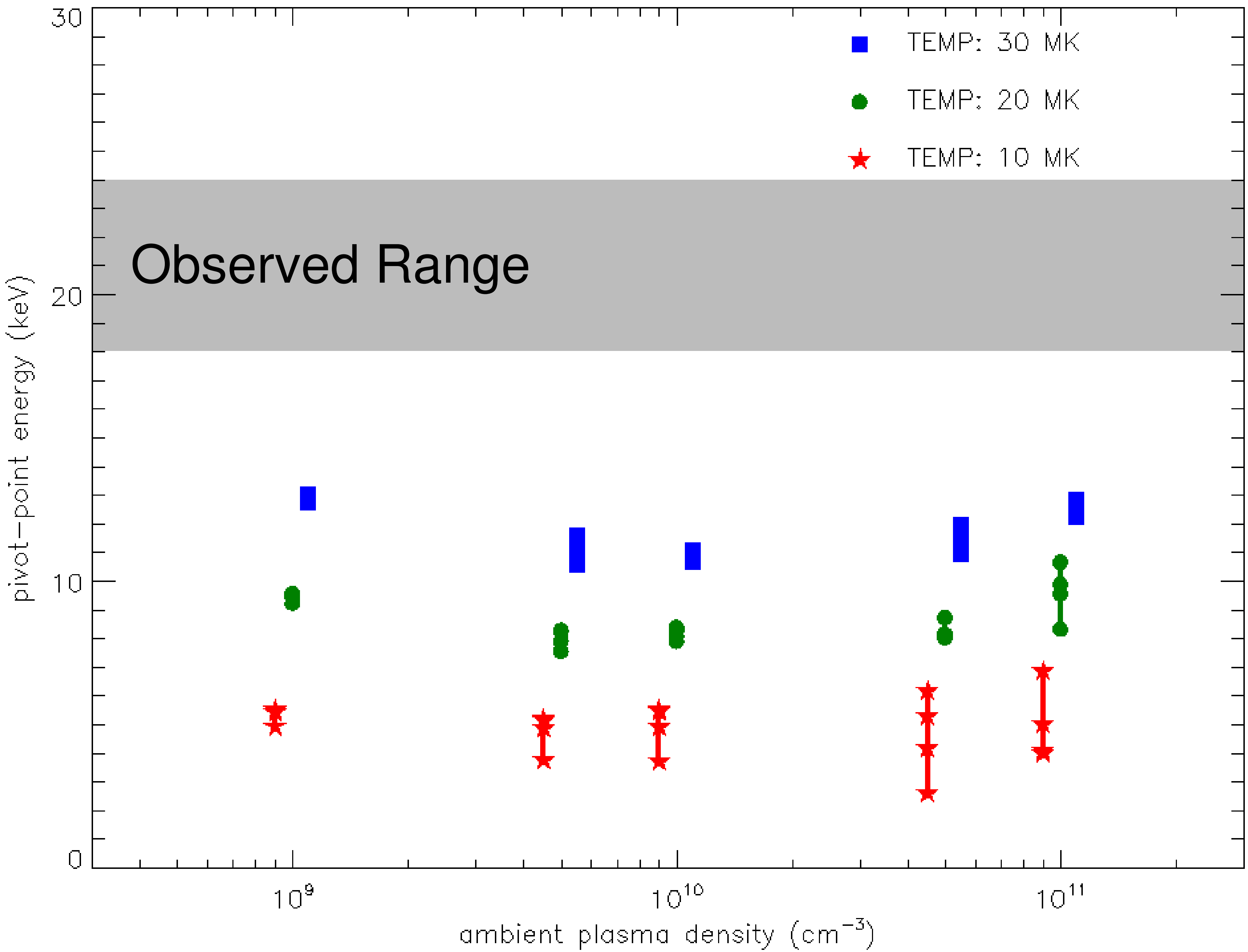
I_ACC MAX
10^-2
10^-4
10^-6
10^-8
10^-10
I_ACC
10^-6
10^-4
10^-2
10^0
10^2
τ
τ · I_ACC=10^-4
hard spectra
τ · I_ACC=10^-7
soft spectra
possible paths in
τ, I_ACC space



I_{ACC} MAX
$\tau \cdot l_{ACC}=10^{-4}$
hard spectra
$\tau \cdot l_{ACC}=10^{-7}$
soft spectra
simplified paths in
τ, l_{ACC} space
l_{ACC}
τ
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}


TEMP: 30 MK
TEMP: 20 MK
TEMP: 10 MK
Observed Range
30
20
10
0
pivot-point energy (keV)
10^9
10^{10}
10^{11}
ambient plasma density (cm^{-3})


TEMP: 30 MK
TEMP: 20 MK
TEMP: 10 MK
Observed Range
Different paths yield
a range of E_* values
pivot-point energy (keV)
0
10
20
30
10^9
10^{10}
10^{11}
ambient plasma density (cm^{-3})



TEMP: 30 MK
TEMP: 20 MK
TEMP: 10 MK
Observed Range
pivot-point energy (keV)
ambient plasma density (cm^{-3})
30
20
10
0
10^9
10^{10}
10^{11}

Model vs. Observations

- The model successfully reproduces observed spectra and features the soft-hard-soft effect.
- However, the pivot-point energy is too small.
- How does the pivot-point energy E_* depends on the model parameters?
  - ➔ Weak density dependence of E_* .
  - ➔ E_* increases with increasing temperature (still not enough).
- Where does the approximation of spectra dependent only on the product $\tau \cdot I_{ACC}$ break down?
  - ➔ No problems with that yet.

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Model vs. Observations: Alternative Escape

➔ What happens if we modify the escape model?

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Model vs. Observations: Alternative Escape

- What happens if we modify the escape model?

➔ Let's assume there is a potential barrier V between the accelerator and the footpoints (this is needed to drive a return current anyway).

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Model vs. Observations: Alternative Escape

- What happens if we modify the escape model?
- Let's assume there is a potential barrier V between the accelerator and the footpoints (this is needed to drive a return current anyway).

➔ All electrons with an energy lower than $E_{\text{Threshold}}=eV$ cannot escape and will come back into the accelerator.

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Model vs. Observations: Alternative Escape

- What happens if we modify the escape model?
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- All electrons with an energy lower than $E_{\text{Threshold}}=eV$ cannot escape and will come back into the accelerator.

➔ Therefore we compute spectra with escape suppressed below $E_{\text{Threshold}}$

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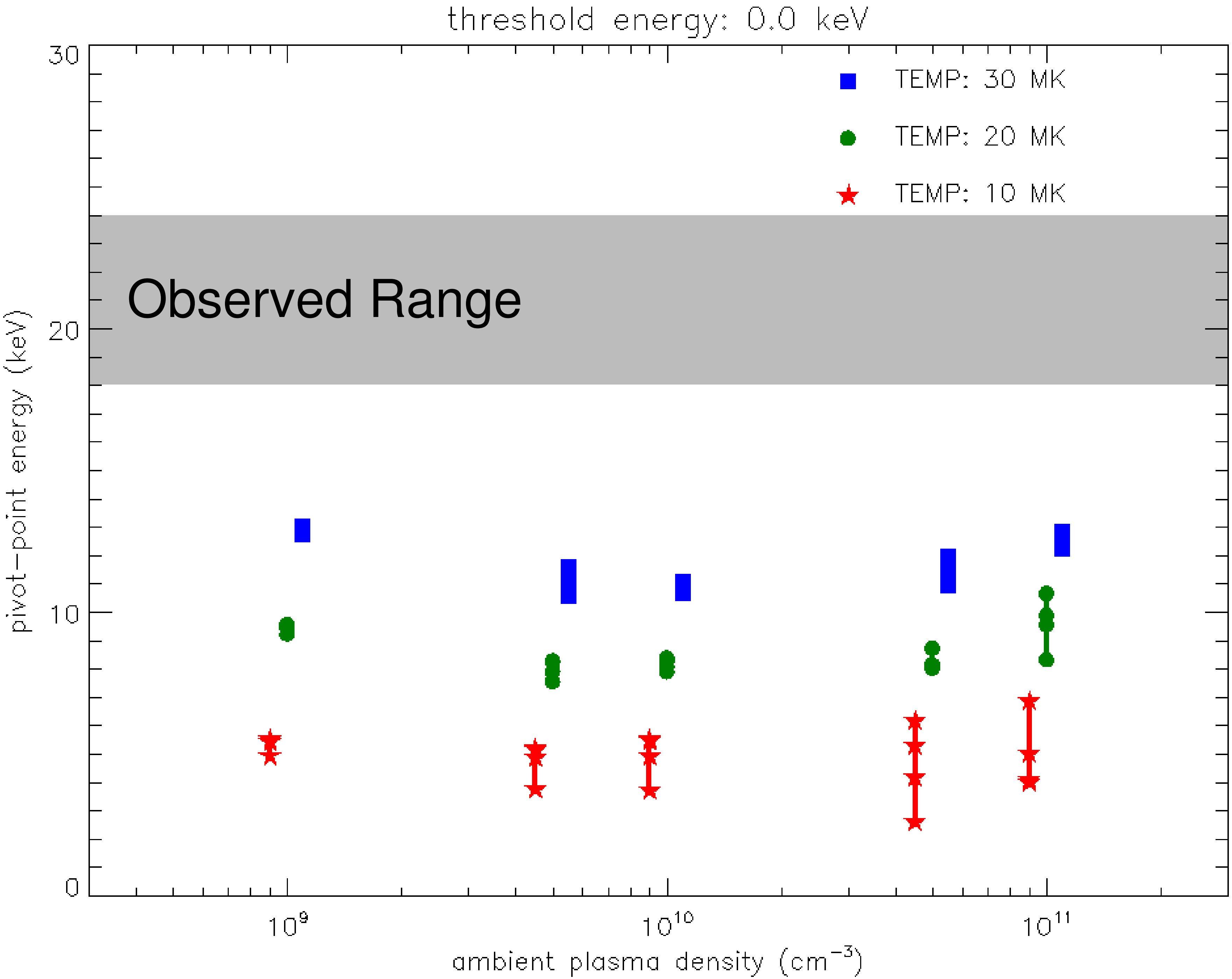
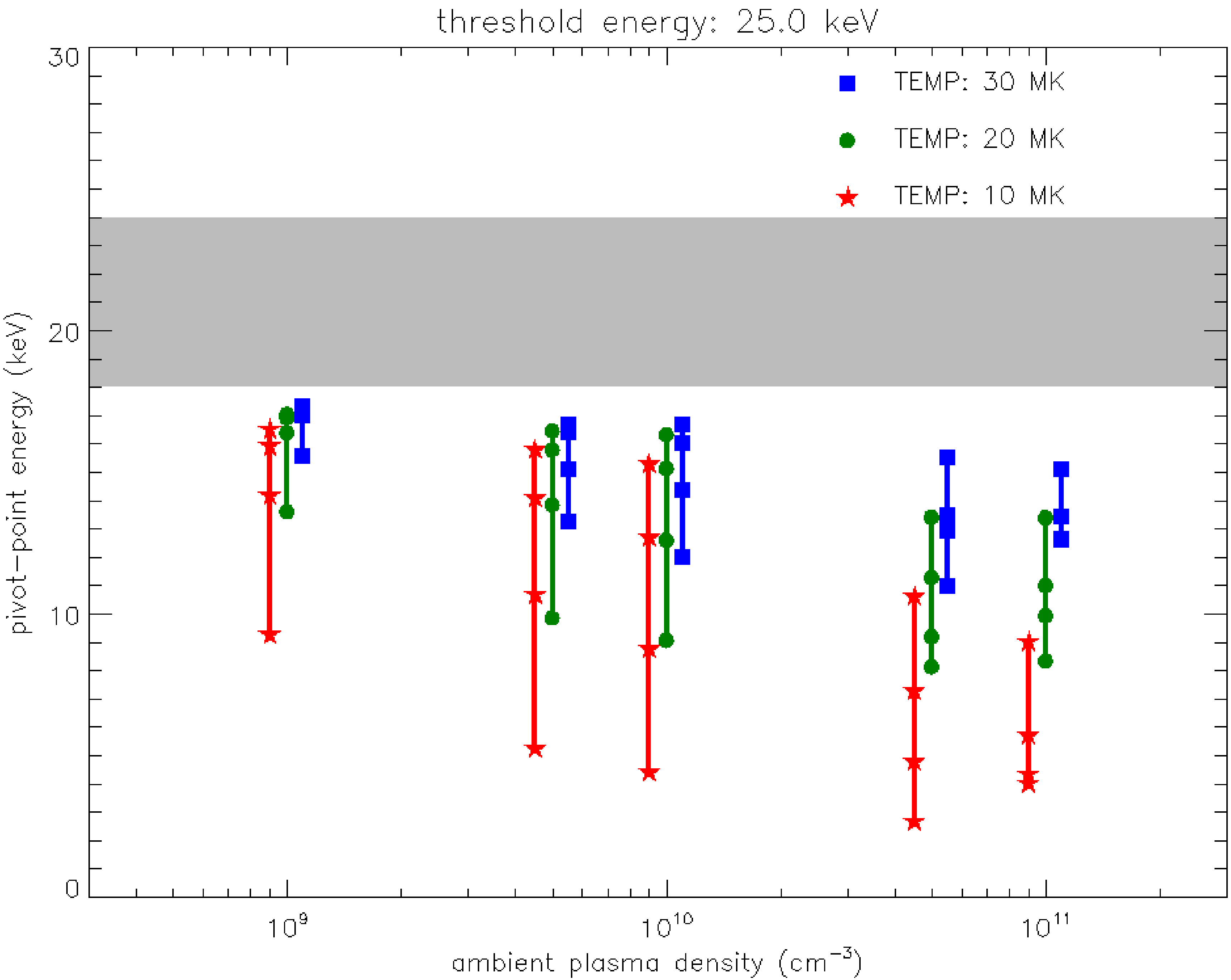
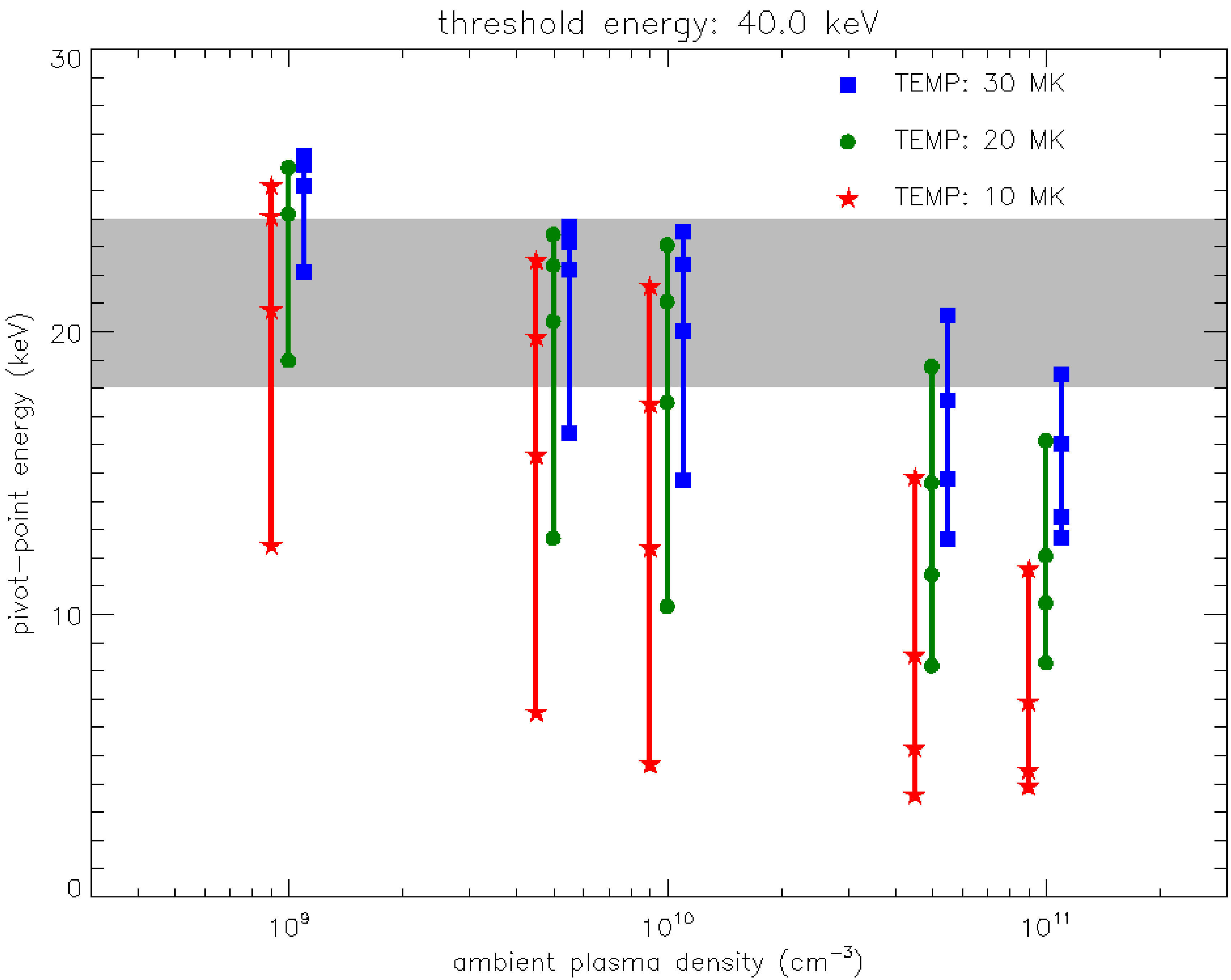


threshold energy: 0.0 keV
TEMP: 30 MK
TEMP: 20 MK
TEMP: 10 MK
Observed Range
pivot-point energy (keV)
ambient plasma density (cm^{-3})
0
10
20
30
10^9
10^{10}
10^{11}



threshold energy: 25.0 keV
TEMP: 30 MK
TEMP: 20 MK
TEMP: 10 MK
30
20
10
0
pivot-point energy (keV)
10^9
10^{10}
10^{11}
ambient plasma density (cm^{-3})


threshold energy: 40.0 keV
TEMP: 30 MK
TEMP: 20 MK
TEMP: 10 MK
pivot–point energy (keV)
30
20
10
0
10^9
10^{10}
10^{11}
ambient plasma density (cm^{-3})

Model vs. Observations: Alternative Escape

- What happens if we modify the escape model?
- Let's assume there is a potential barrier V between the accelerator and the footpoints (this is needed to drive a return current anyway).
- All electrons with an energy lower than $E_{\text{Threshold}}=eV$ won't be able to escape and will come back into the accelerator.
- Therefore we compute spectra with escape suppressed below $E_{\text{Threshold}}$.

➔ For $E_{\text{Threshold}}$ larger than about 30 keV and at low densities or high temperatures we can reach the observed values of the pivot-point energy.

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Model vs. Observations: Alternative Escape

- What happens if we modify the escape model?
- Let's assume there is a potential barrier V between the accelerator and the footpoints (this is needed to drive a return current anyway).
- All electrons with an energy lower than $E_{\mathrm{Threshold}}=eV$ won't be able to escape and will come back into the accelerator.
- Therefore we compute spectra with escape suppressed below $E_{\mathrm{Threshold}}$.
- For $E_{\mathrm{Threshold}}$ larger than about 30 keV and at low densities or high temperatures we can reach the observed values of the pivot-point energy.

➔ This spectra, however, become hard below $E_{\mathrm{Threshold}}$ because of the efficient trapping there.

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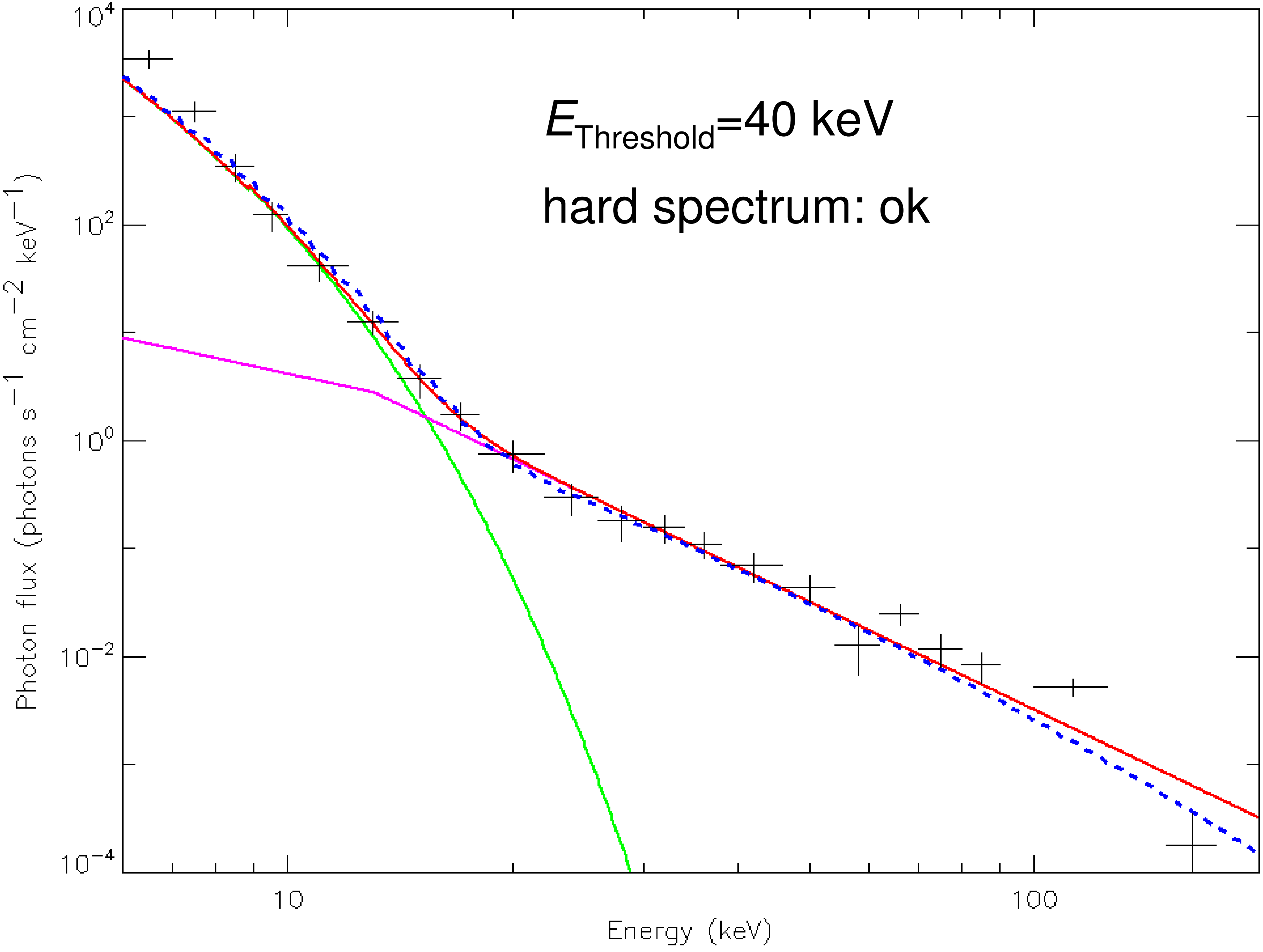
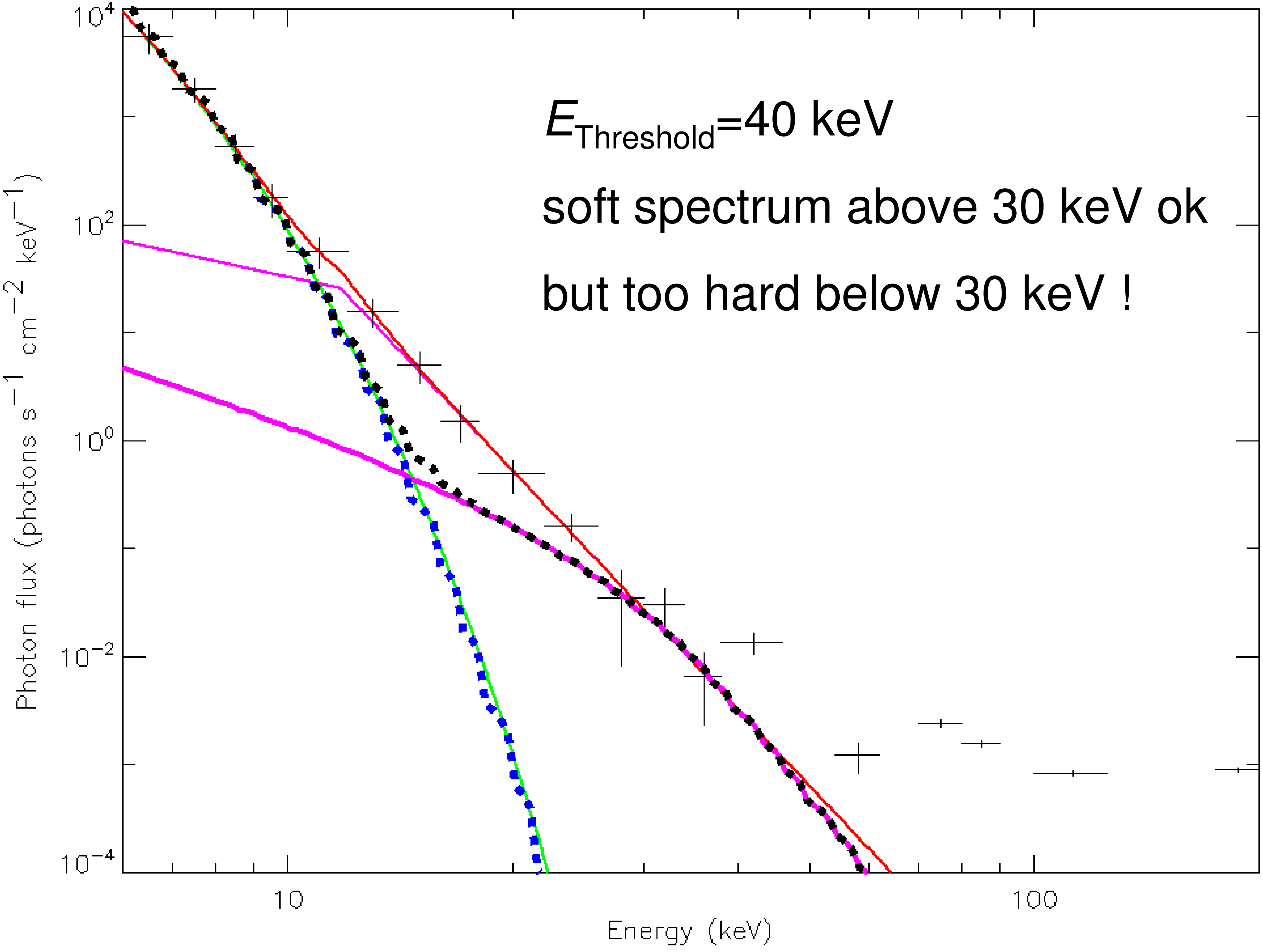

$E_{Threshold}$=40 keV
hard spectrum: ok
Photon flux (photons s^{-1} cm^{-2} keV^{-1})
Energy (keV)
10^4
10^2
10^0
10^{-2}
10^{-4}
10
100


$E_{Threshold}$=40 keV
soft spectrum above 30 keV ok
but too hard below 30 keV !
Photon flux (photons s^{-1} cm^{-2} keV^{-1})
Energy (keV)
10^4
10^2
10^0
10^{-2}
10^{-4}
10
100

Discussion

➔ Does it work for other stochastic acceleration mechanisms?

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Discussion

- Does it work for other stochastic acceleration mechanisms?
  ➔ It should as long as you have reasonably well behaved diffusion and convection coefficients.

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Discussion

- Does it work for other stochastic acceleration mechanisms?
  - It should as long as you have reasonably well behaved diffusion and convection coefficients.

➔ Is a pivot point really needed?

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Discussion

- Does it work for other stochastic acceleration mechanisms?
  - It should as long as you have reasonably well behaved diffusion and convection coefficients.
- Is a pivot point really needed?
  - ➔ The pivot-point energy is just a useful number, suggested by the observations, which characterizes the relative change in flux occurring when the spectral index varies.

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Conclusions

- The introduction of a simple escape term does soften the electron spectra in the accelerator produced by the TTD model.
  - hard spectra results from strong acceleration and strong trapping
  - soft spectra results from weak acceleration and weak trapping
- The Soft-Hard-Soft spectral evolution is approximately compatible with the presence of a pivot point at energies around 10 keV.
- Observations suggest a value near 20 keV: this can be accomplished by increasing the trapping efficiency below electron energy of ~30 keV, but this results in too hard spectra in the range 10-20 keV.

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