Solar flare energetics and X-ray diagnostics

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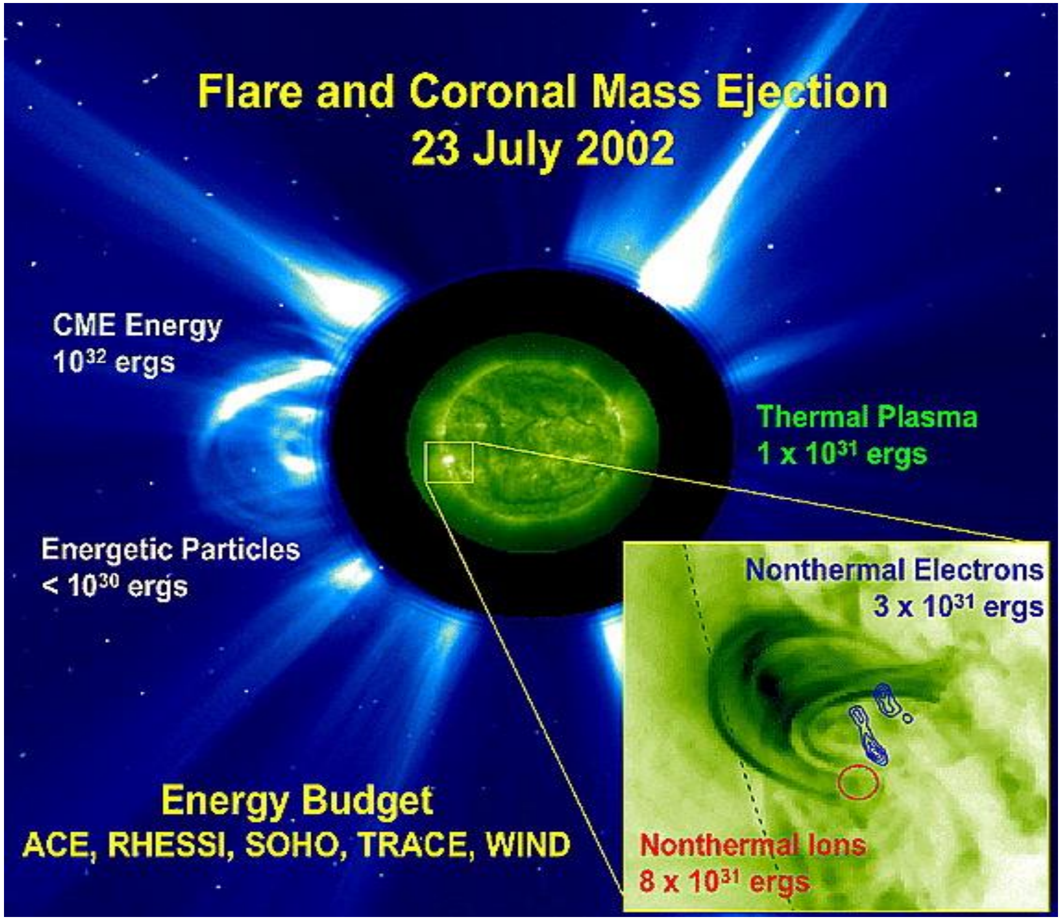
Solar webinar *July 11, 2018*

Solar eruptions and energetic particles



Solar corona T ~ 10^6 K => 0.1 keV per particle

Flaring region T ~ 4×10^7 K => 3 keV per particle

Flare volume 10^{27} cm^3 => (10^4 km)^3

Plasma density 10^{10} cm^{-3}

Photons up to > 100 MeV

Number of energetic electrons 10^{36} per second

Electron energies >10 MeV

Proton energies >100 MeV

Large solar flare releases about 10^{32} ergs

(about half energy in energetic electrons)

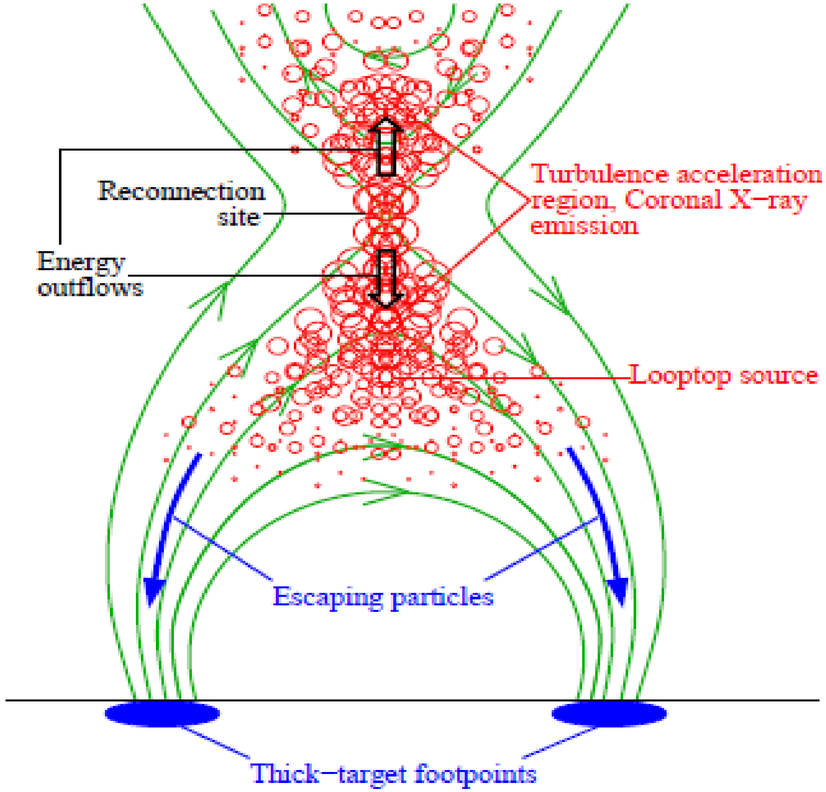
Energy ~2 10^{32} ergs

From Emslie et al, 2004, 2005

Sun et al, 2012, Aschwanden et al, 2016

But there is an order of magnitude uncertainties..

Standard model energetics



Cartoon from Petrosian (2012)

Magnetic Energy

↓

Turbulence/Fluctuating E field

↓

Acceleration/Heating

↓

Electrons/Ions

↓

Energy Deposition/Evaporation

↓

Radiation

Plasma turbulence plays an important role in virtually all key elements of standard solar flare model

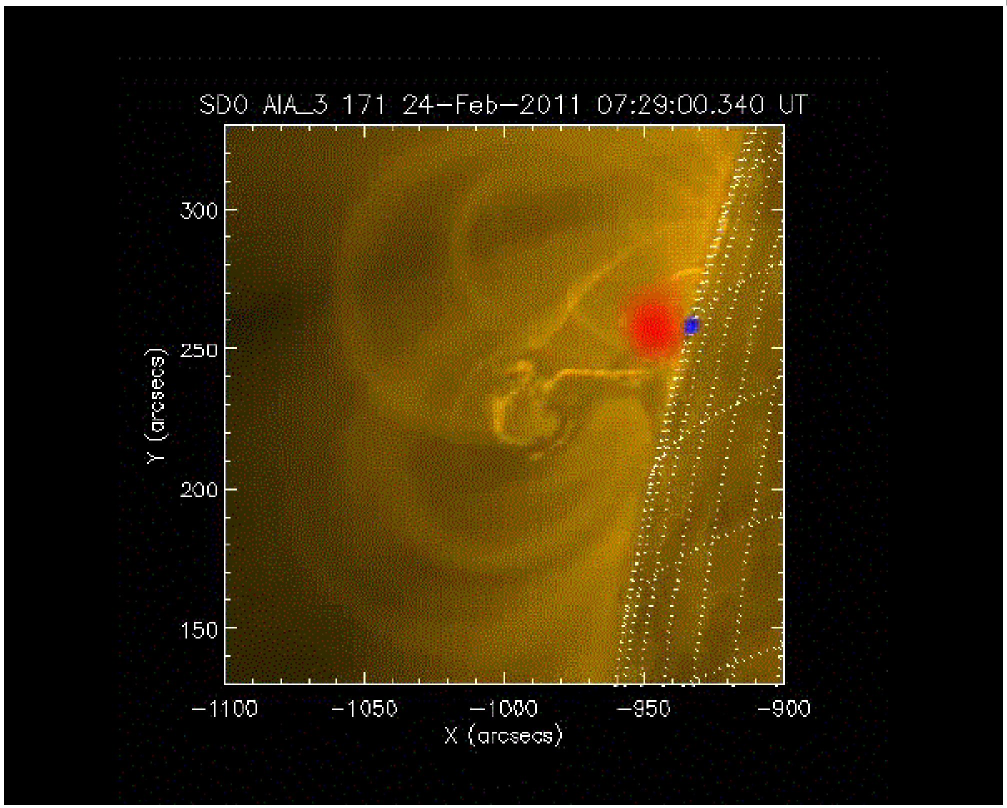
X-rays and flare accelerated electrons

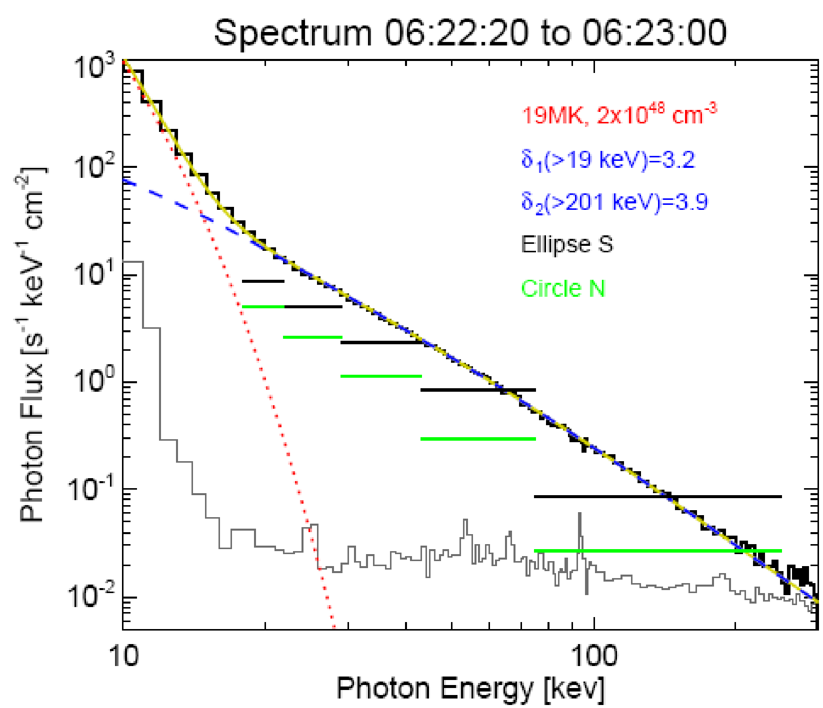
Observed X-rays — Unknown electron distribution — Emission cross-sections

$$I(\epsilon,\boldsymbol{\Omega},t)=\int_{\ell}\int_{\Omega'}\int_{\epsilon}^{\infty} n(\mathbf{r})\bar{F}(E,\boldsymbol{\Omega}',\mathbf{r},t)Q(\boldsymbol{\Omega},\boldsymbol{\Omega}',\epsilon,E)\,\mathrm{d}E\,\mathrm{d}\boldsymbol{\Omega}'\,\mathrm{d}\ell,$$

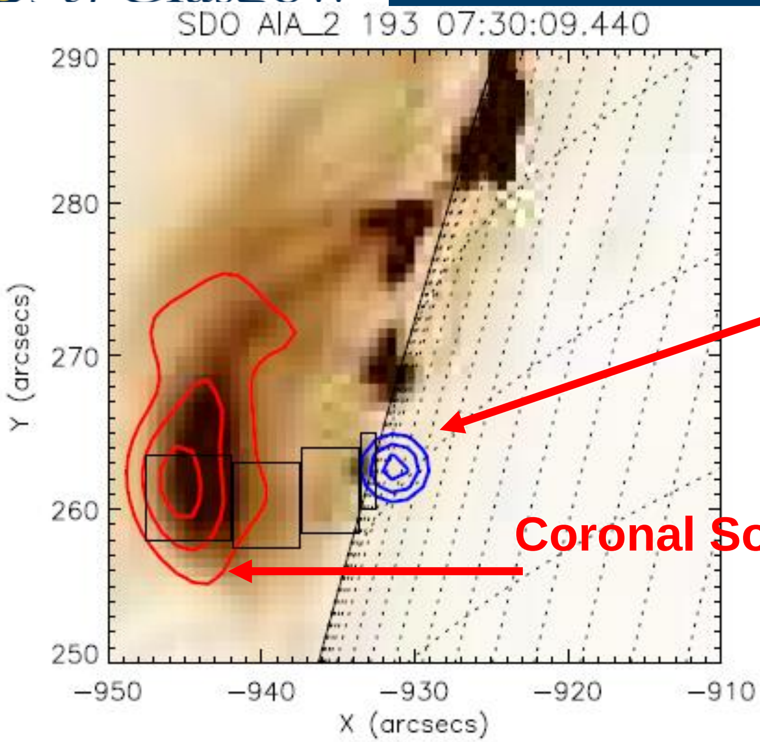
Thin-target case: For the electron spectrum **$F(E)\sim E^{-\delta}$**,

bremsstrahlung (free-free, free-bound)





Motivation1:X-ray emission from typical flares

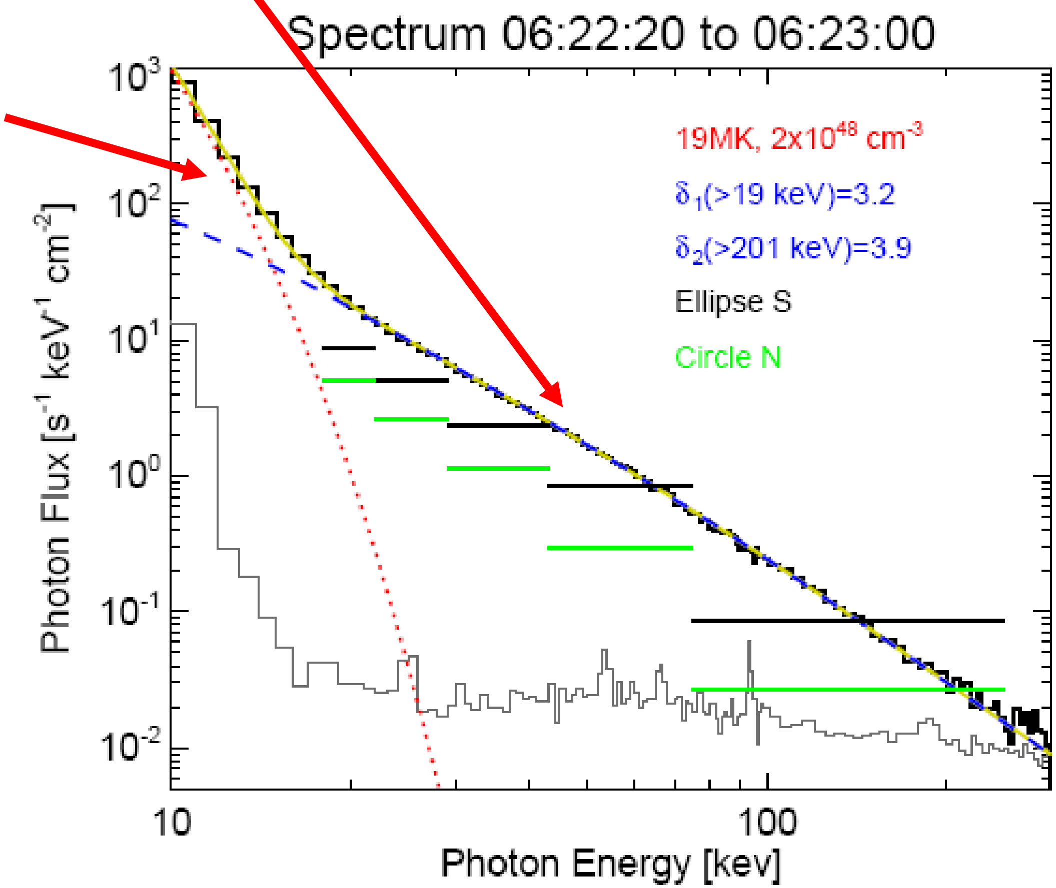


Battaglia & Kontar 2012

Soft X-ray coronal source
HXR chromospheric footpoints

Footpoints

Coronal Source



Flaring region
T ~ 1-3x10^7 K
=> 1-3 keV per particle

How do we estimate electron energetics?

Assuming isotropic electron distribution:

$$I(\epsilon) = \frac{1}{4\pi R^2} \int_{\epsilon}^{\infty} \sigma(\epsilon, E) \langle nVF \rangle (E) dE$$

Photon flux spectrum

Mean electron flux spectrum

Normally collisional thick-target is used to estimate the mean electron flux spectrum:

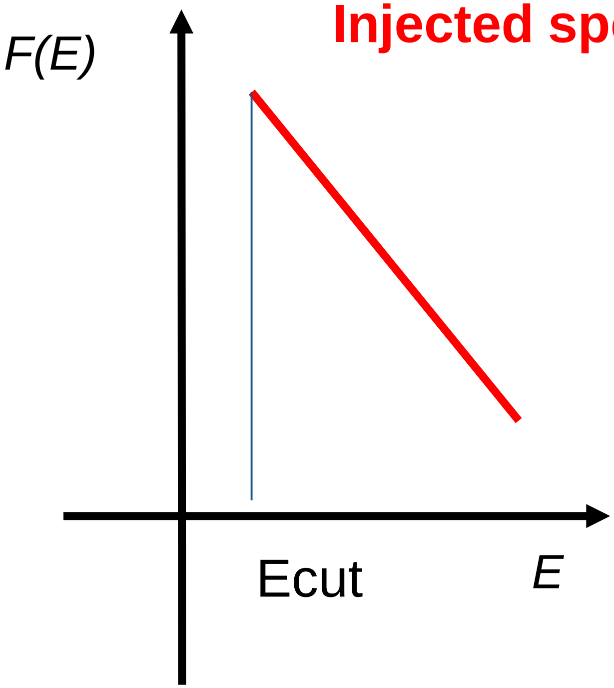
$$\langle nVF \rangle (E) = \frac{E}{2K} \int_{E}^{\infty} A F_0(E_0) dE_0 \ .$$

Injected or accelerated electron spectrum

Brown, 1971,
Brown et al 2003

Low-energy cut-off

Injected spectrum:

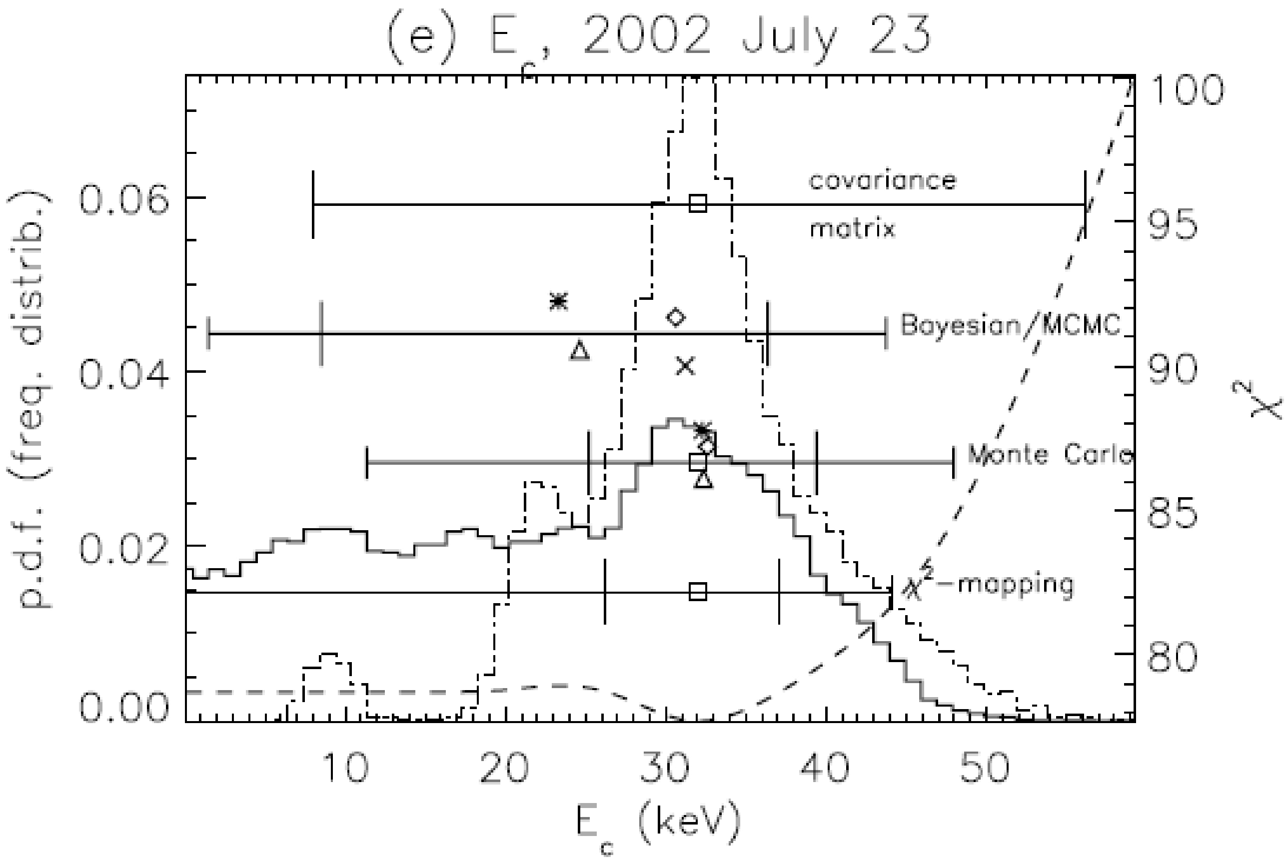


$F(E) \sim E^{-\delta}$

Using spectroscopy (or imaging spectroscopy) we normally infer electron power or/and total rate above some energy or lower limit.
We do not know the upper limit.

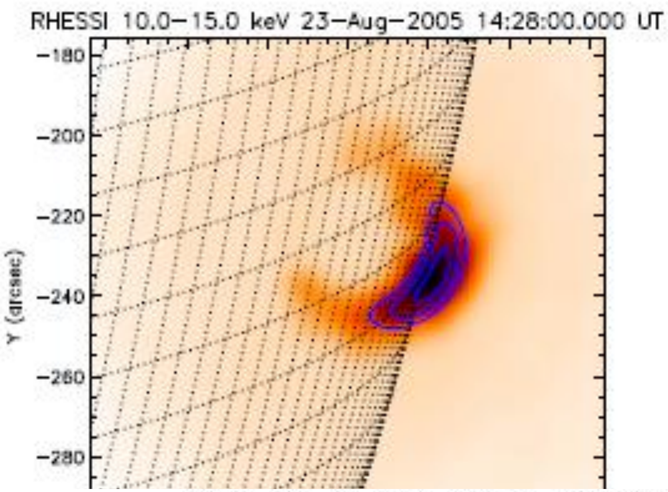
Can we better determine the lower energy cut-off and upper limits on power and injection rate?

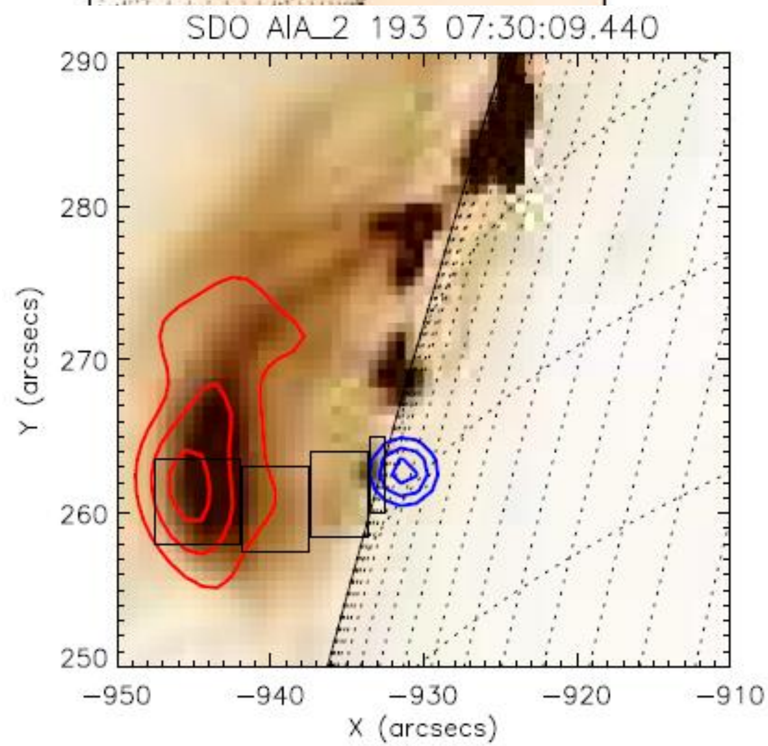
Low-energy cut-off problem



Four uncertainty analysis methods from Ireland et al ApJ 2013

Warm and cold target models

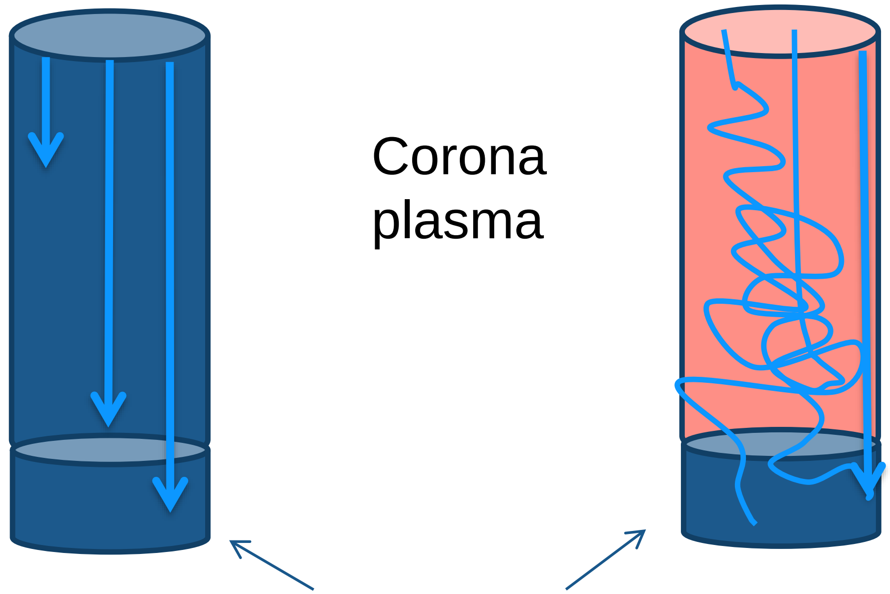




‘Cold’
Plasma Model

Our ‘Warm-cold’
Plasma Model

Electrons accelerated/injected

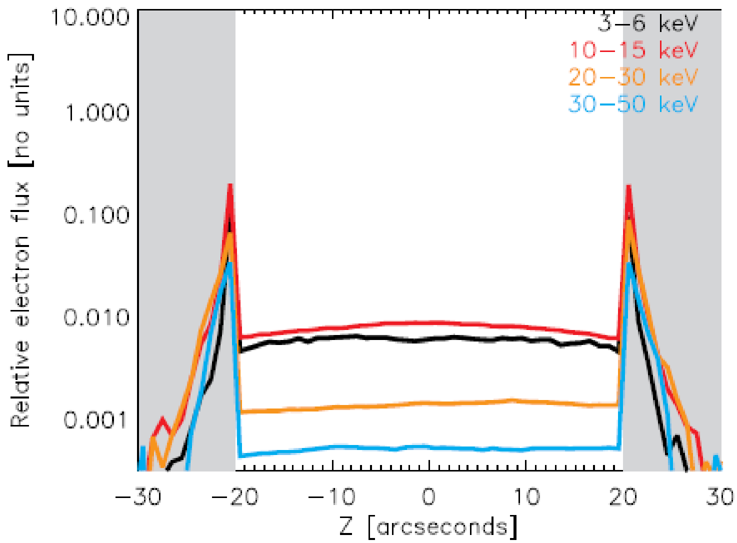


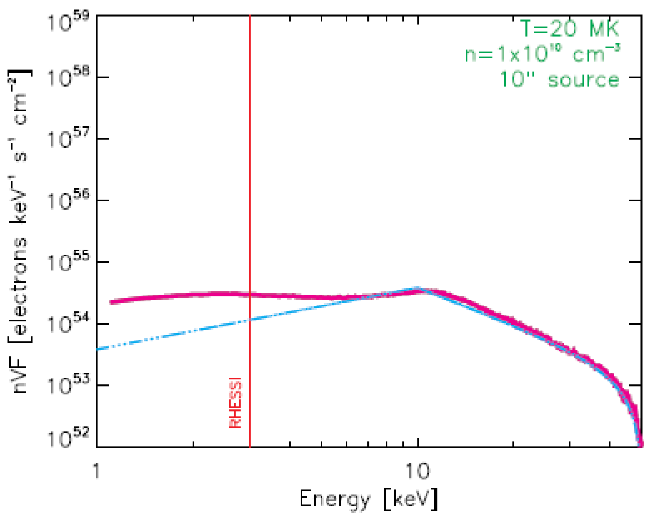
‘Cold’
Chromosphere plasma

See Kontar et al 2015 for details

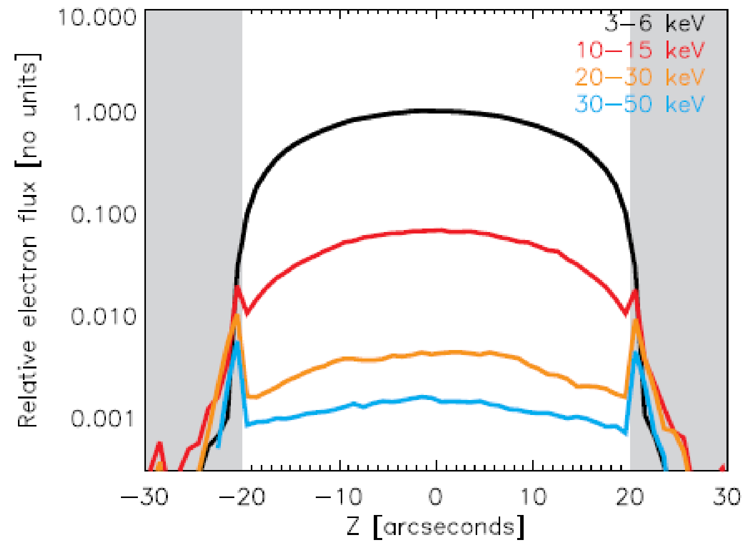
The model from simulations

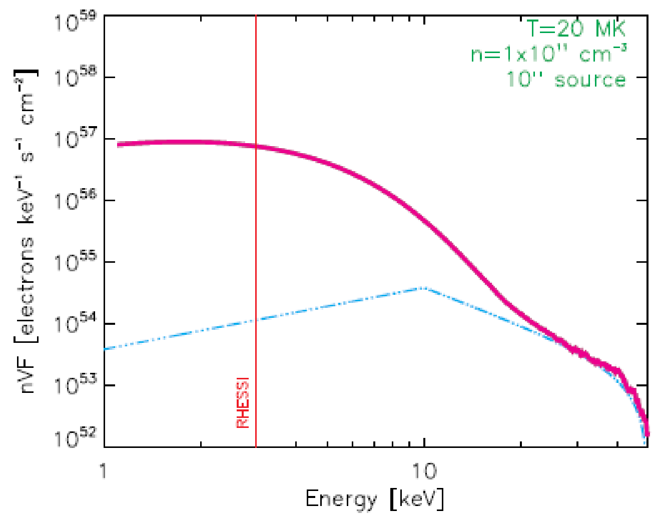
Hot, low density corona





Hot, high density corona





See Jeffrey et al ApJ 2015

Warm plasma collisional transport - Equations

To describe warm plasma environment we can use Fokker-Planck equation:

Collisional drag

Collisional diffusion

$$\mu \frac{\partial F}{\partial z} = 2Kn \left\{ \frac{\partial}{\partial E} \left[G\left(\sqrt{\frac{E}{k_B T}}\right) \frac{\partial F}{\partial E} + \frac{1}{E}\left(\frac{E}{k_B T} - 1\right) G\left(\sqrt{\frac{E}{k_B T}}\right) F \right] + \right.$$

$$\left. + \frac{1}{8E^2} \frac{\partial}{\partial \mu} \left[(1-\mu^2) \left(\mathrm{erf}\left(\sqrt{\frac{E}{k_B T}}\right) - G\left(\sqrt{\frac{E}{k_B T}}\right)\right) \frac{\partial F}{\partial \mu} \right] \right\} + F_0(E)\delta(z) \; .$$

Collisional scattering of electrons

Source of particles (injected spectrum)

Finite temperature effects: e.g. Emslie, 2003,Galloway et al 2005,Jeffrey et al, 2014

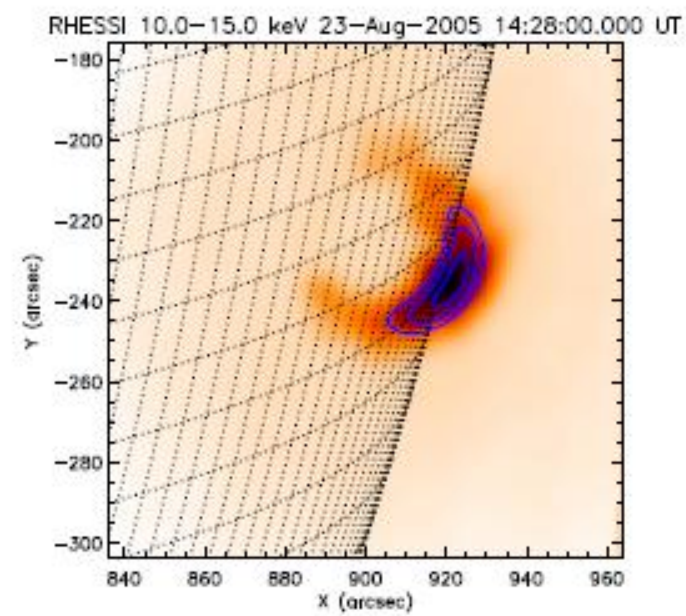
Integrating (twice) the kinetic equation one finds:

$$\langle nVF\rangle(E) = \frac{1}{2K} E\, e^{-E/kT} \int_{E_{\min}}^{E} \frac{e^{E'/kT}\, dE'}{E'\, G\left(\sqrt{\frac{E'}{kT}}\right)} \int_{E'}^{\infty} A\, F_0(E_0)\, dE_0 \;.$$

To find Emin we consider warm plasma loop and cold chromosphere.

In a stationary state the number of electrons in the target is balanced between injection and diffusive escape of thermalized electrons:

$$\frac{3\sqrt{\pi}}{2K}\sqrt{\frac{kT}{E_{min}}}\,\dot{N} = \sqrt{\frac{8}{\pi m_e}}\,\frac{nN}{(kT)^{3/2}}$$



Mean electron flux

Integrating, one obtains the mean electron flux

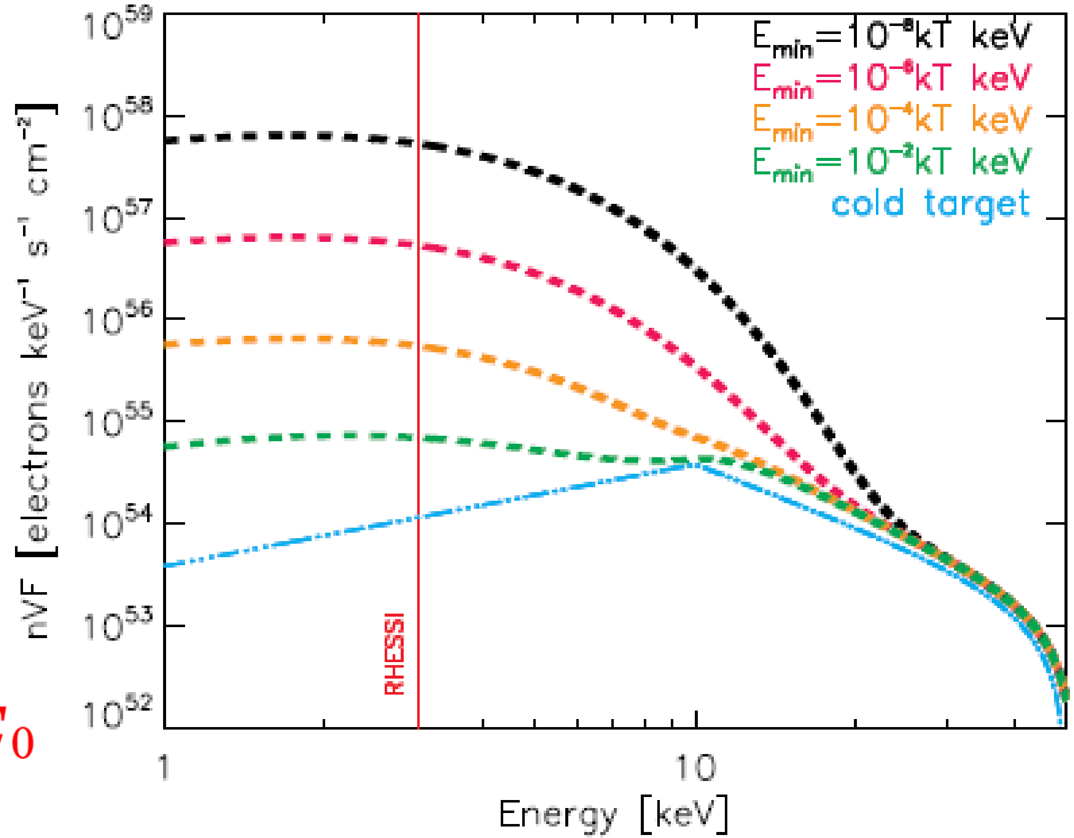
$$\langle nVF\rangle(E) = \frac{1}{2K} E\, e^{-E/kT} \int_{E_{\min}}^{E} \frac{e^{E'/kT}\, dE'}{E'\, G\left(\sqrt{\frac{E'}{kT}}\right)} \int_{E'}^{\infty} A F_0(E_0)\, dE_0 \ ,$$

$$\frac{E_{\min}}{kT} \simeq 3 \left(\frac{5\lambda}{L}\right)^4 \ ,$$

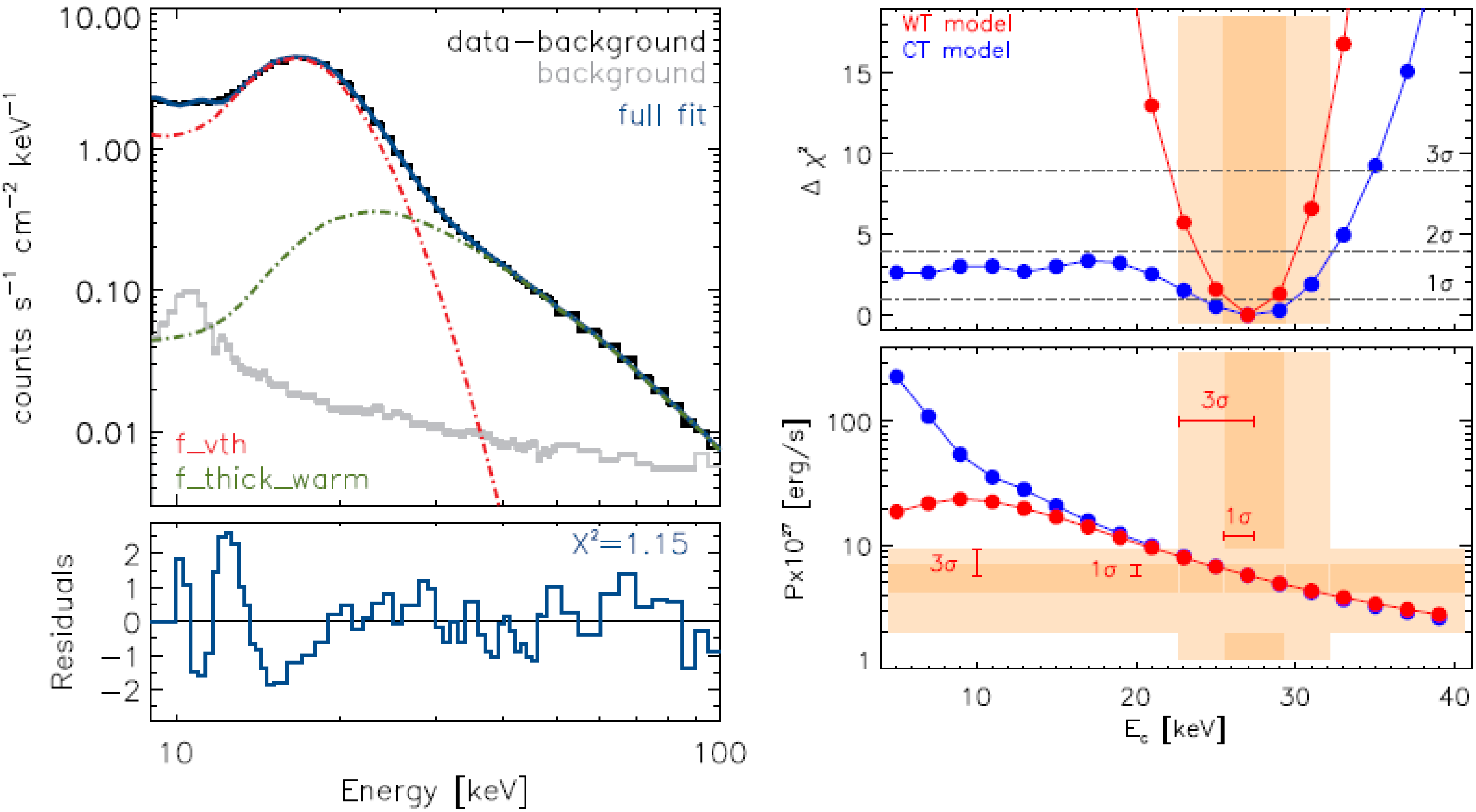
$$\lambda = (kT)^2/2Kn$$

c.f. cold target result:

$$\langle nVF\rangle(E) = \frac{1}{2K} E \int_{E}^{\infty} A F_0(E_0)\, dE_0$$

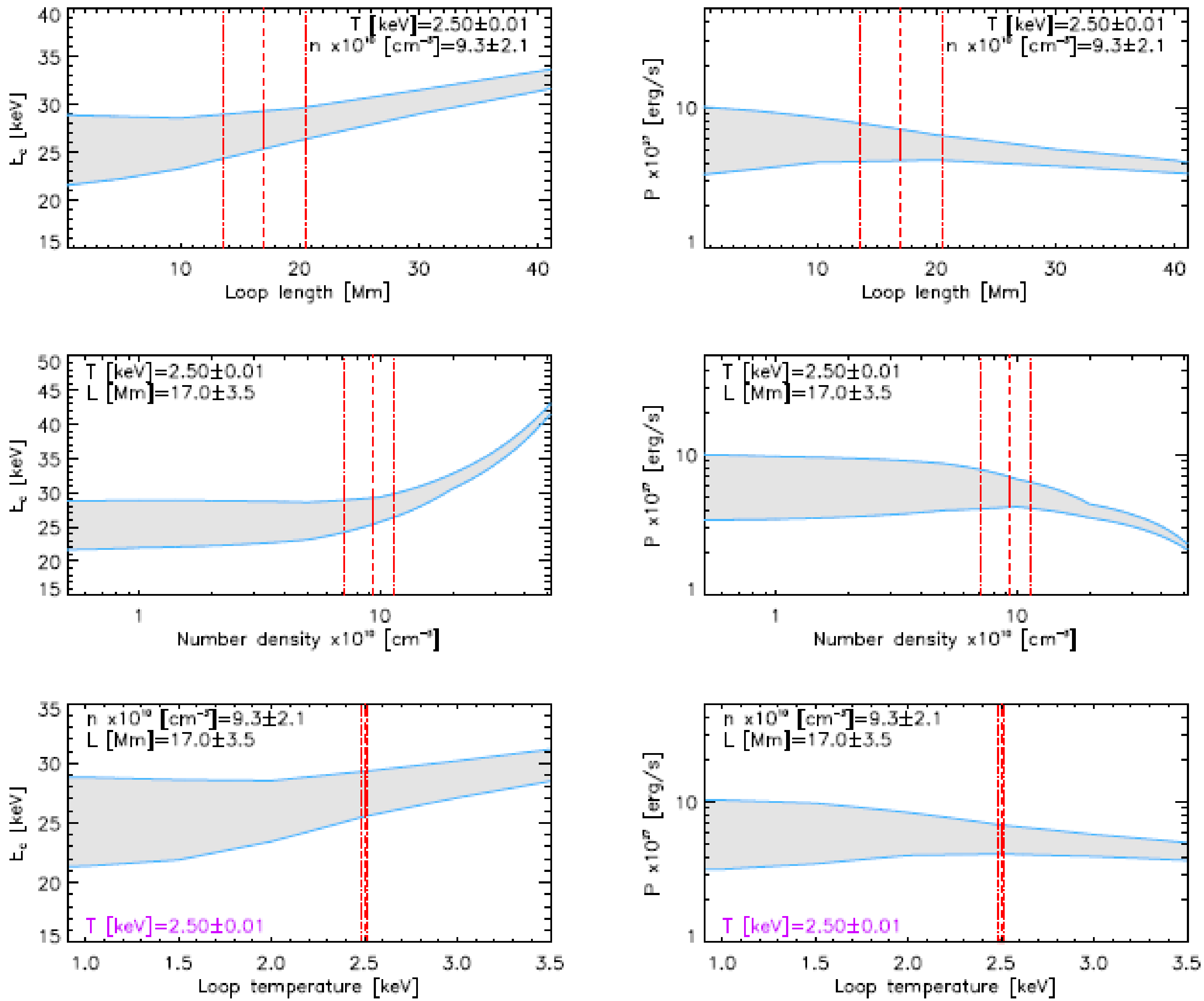


WT fit and errors

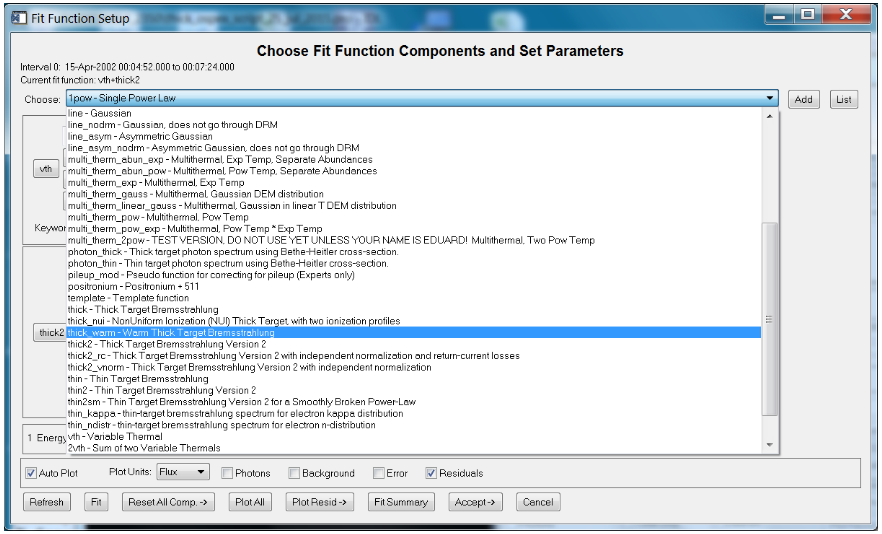


From Kontar et al, submitted to ApJ 2018

Warm thick target and loop parameters

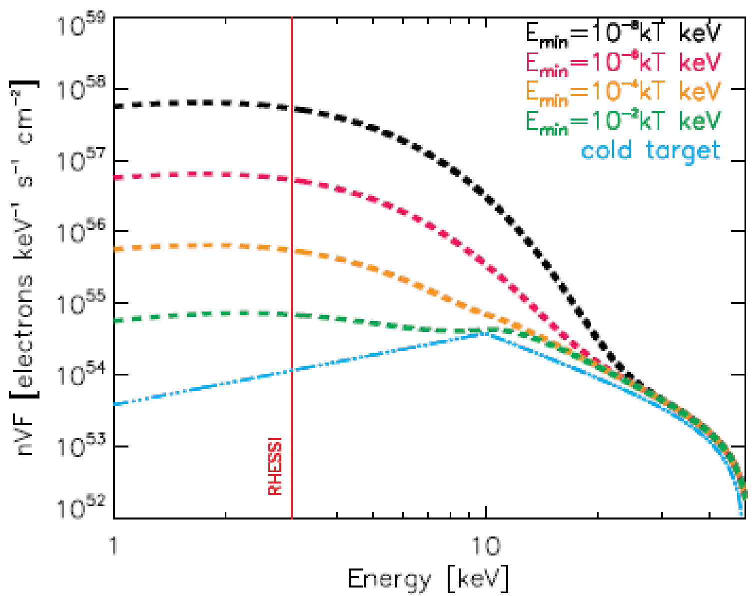


Conclusions



Warm target effects play important role for solar flares.

Warm target model determines the low energy cut-off (~14% for the flare considered)



Provides the total number or injected electrons or the total injected power.

=> The energy partitioning can be studied

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Extra slides….