Particle Acceleration and X-Ray Emission During Flares

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Solar eruptions and energetic particles

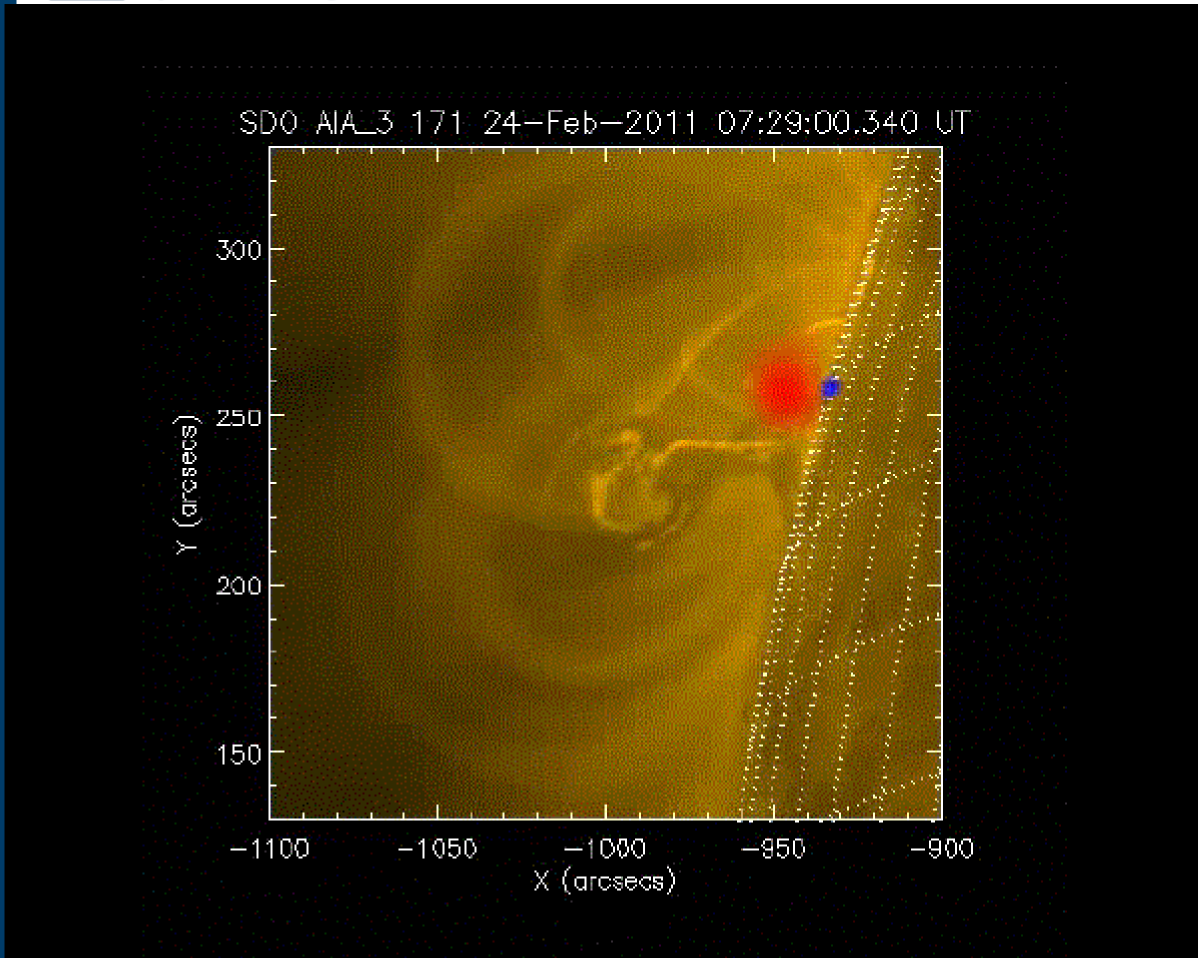


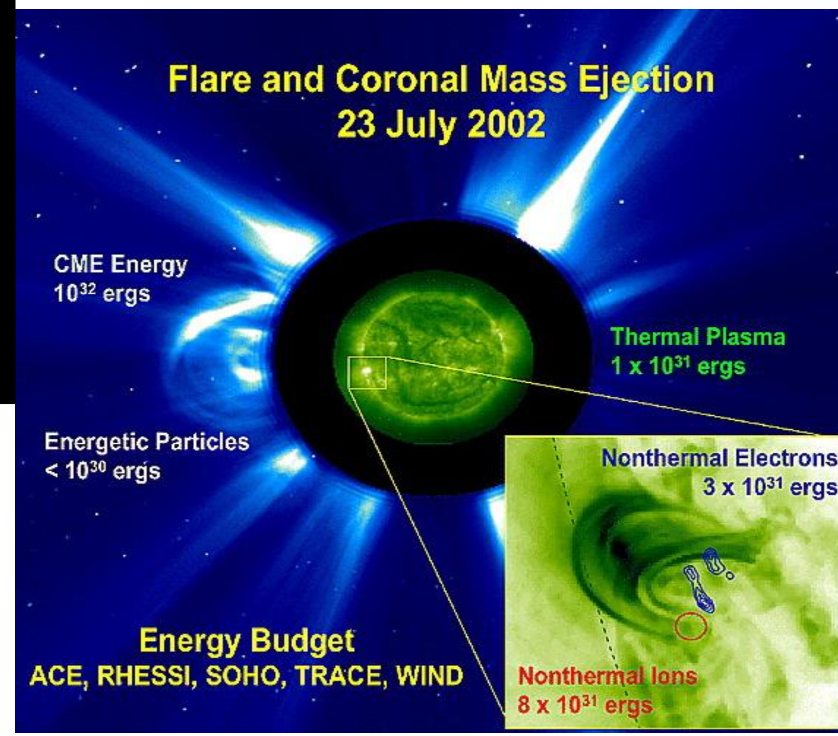
Figure from Battaglia & Kontar, 2011

Energy ~2 10^{32} ergs

But there is an order of magnitude uncertainties..

Sun et al, 2012

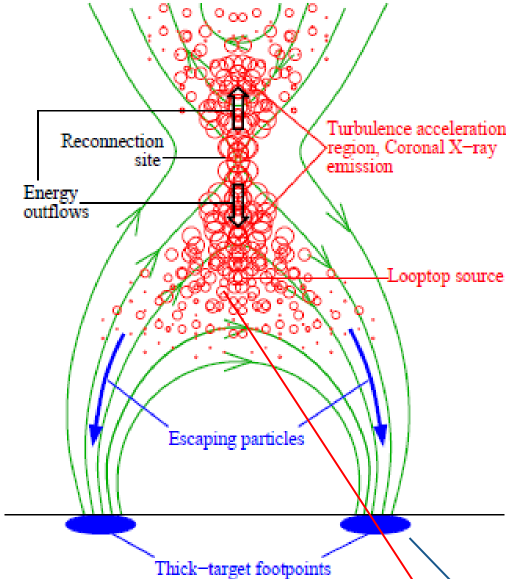
Around tens of % of energy released is in energetic particles (both electrons and ions)

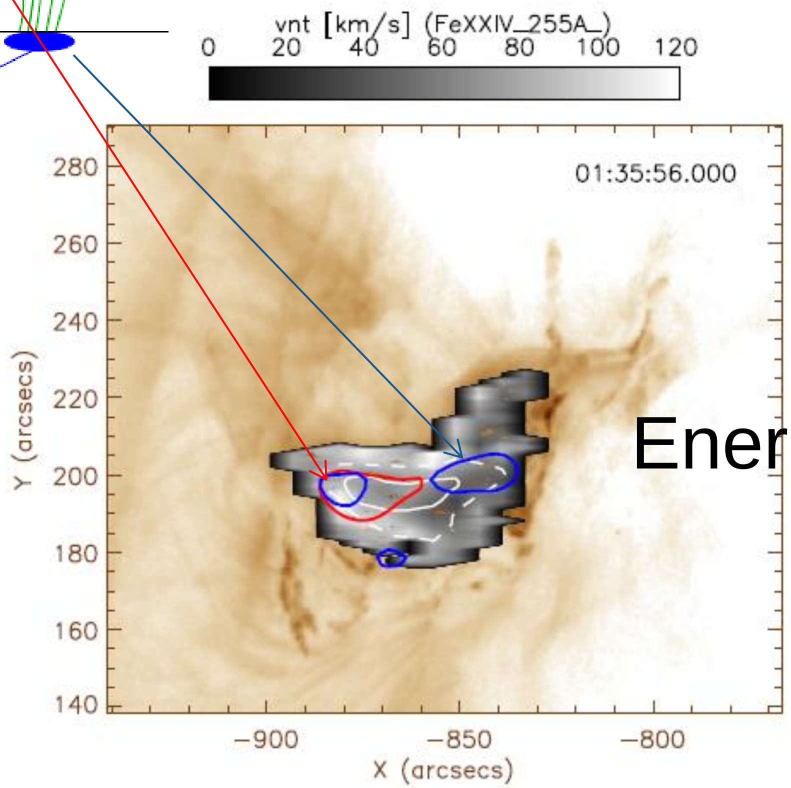


From Emslie et al, 2004, 2005

Electrons in flare energetics?

Petrosian (2012) cartoon





Enrique
Perez
results

Magnetic Energy

Turbulence/Fluctuating E fielc

Acceleration/Heating

Electrons/Ions

Energy Deposition/Evaporation

Radiation

Key aspects

Characteristics of electron acceleration site(s)

1) Time characteristics
2) Spatial scales
3) Spectral
4) Pitch angle characteristics

Particle transport

1) Physical processes controlling transport
2) Self-consistency

Escaping and trapped populations (of electrons)

1) What controls escape ?
2) Similarities and differences in these two populations

X-rays and flare accelerated electrons

Observed X-rays

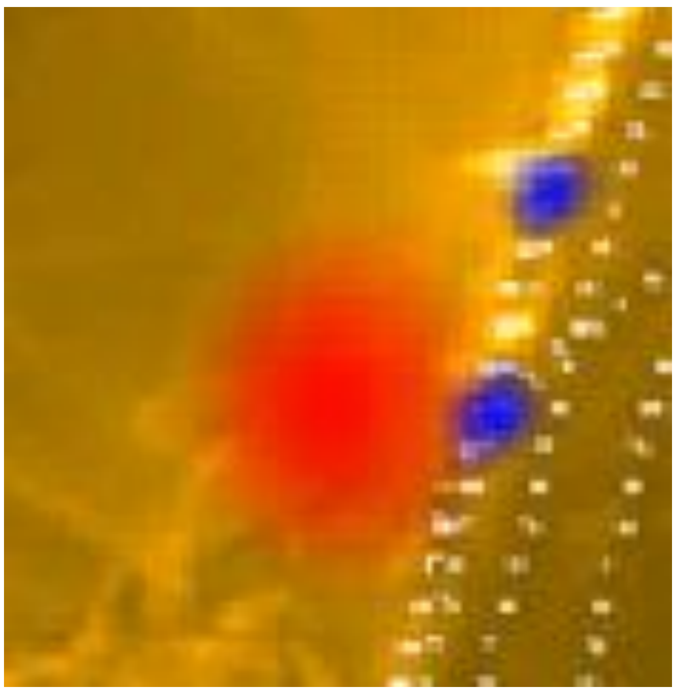
Unknown electron distribution

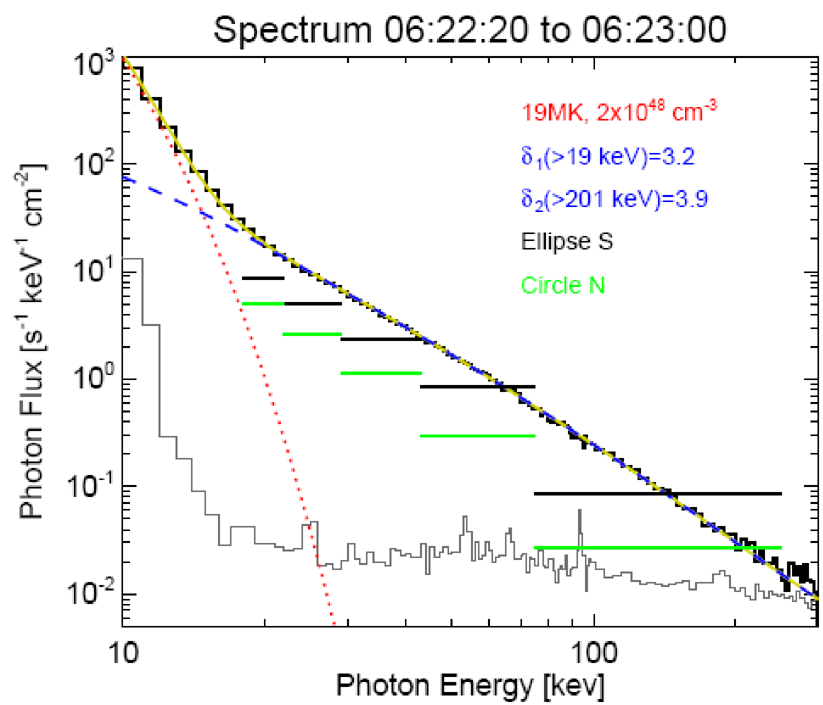
Emission cross-sections

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

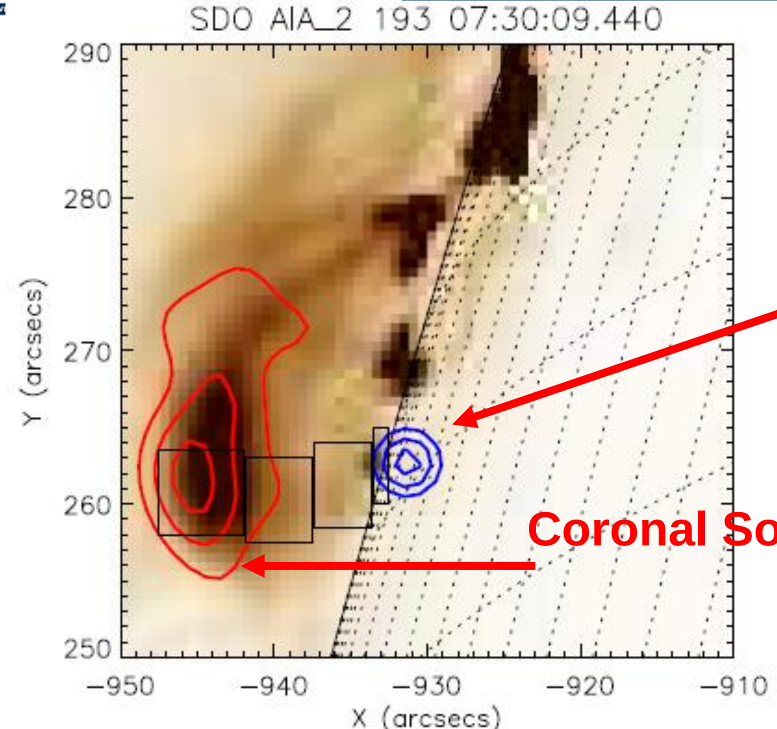
Thin-target case: For the electron spectrum **$F(E) \sim E^{-\delta}$** ,

bremsstrahlung (free-free emission)





X-ray emission from typical flares

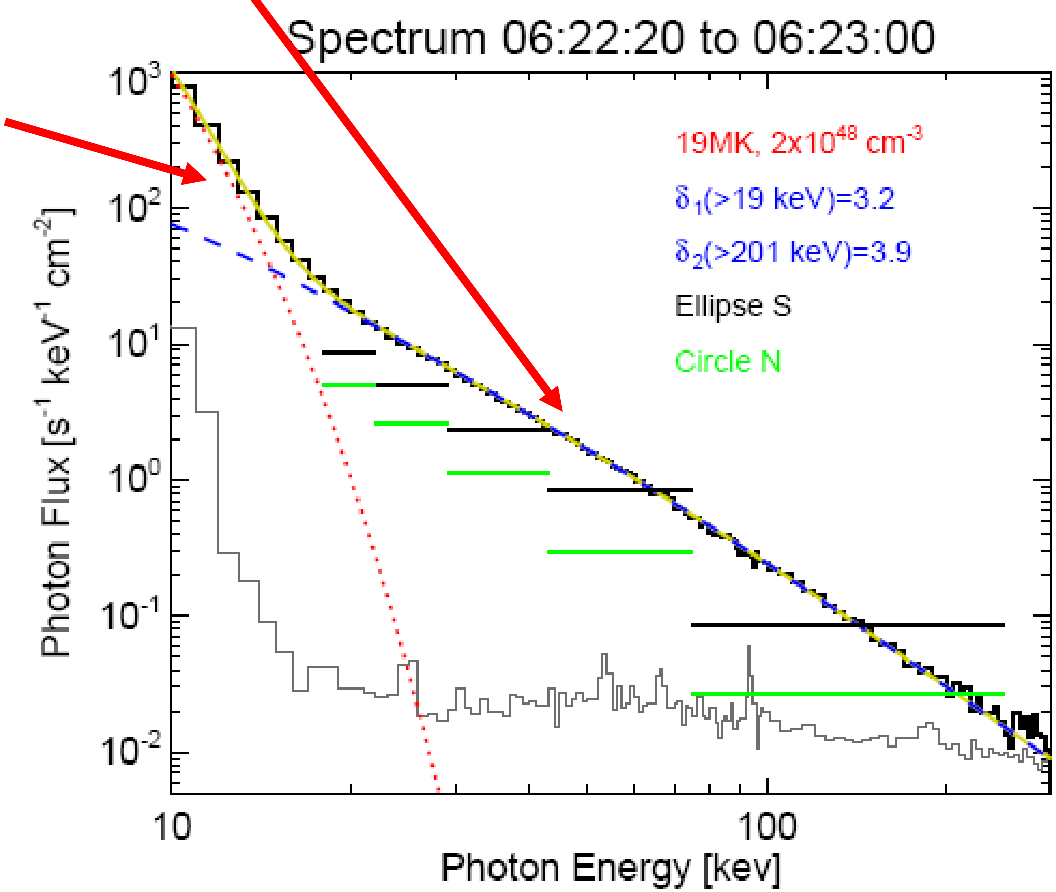


Battaglia & Kontar 2012

Soft X-ray coronal source
HXR chromospheric footpoints

Footpoints

Coronal Source



Solar corona $T \sim 10^6$ K => 0.1 keV per particle

Flaring region $T \sim 4\times10^7$ K => 3 keV per particle

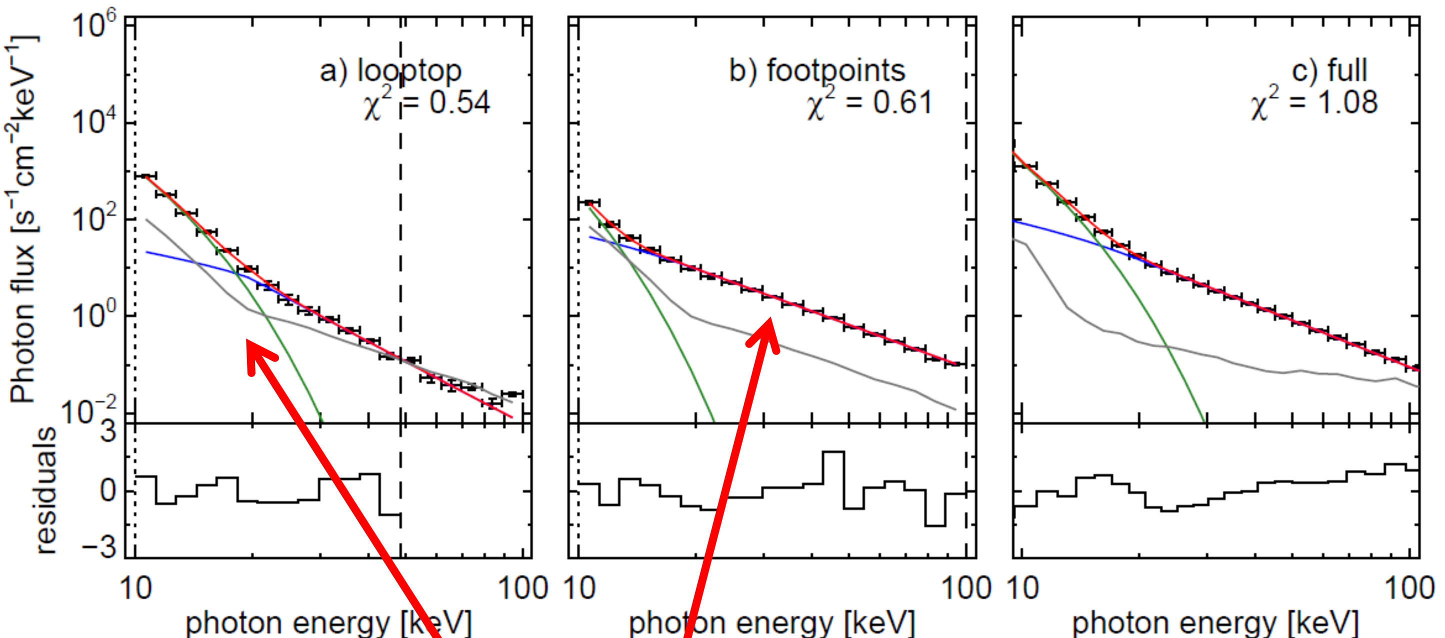
Flare volume 10^{27} cm^3 => $(10^4$ km$)^3$

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

Number of energetic electrons up to 10^{36} per second

Electron energies >10 MeV

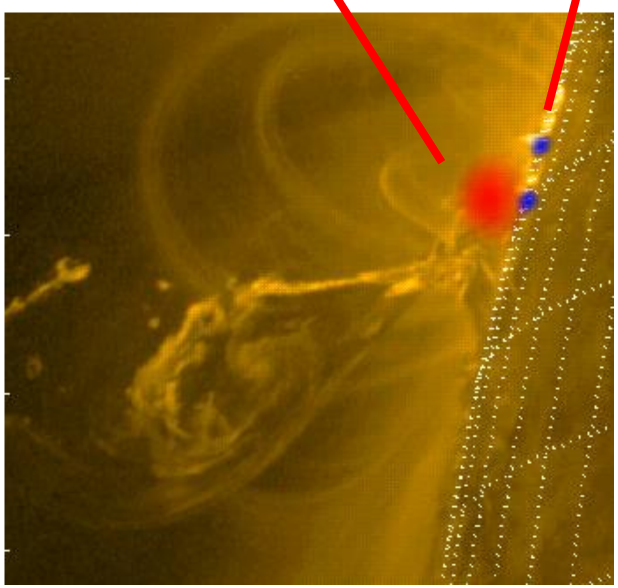
Typical solar flare: X-ray prospective



Loop-top: Soft X-ray plus non-thermal component

Footpoints: Hard X-ray non-thermal power-law

Figure from Simoes & Kontar, A&A, 2013



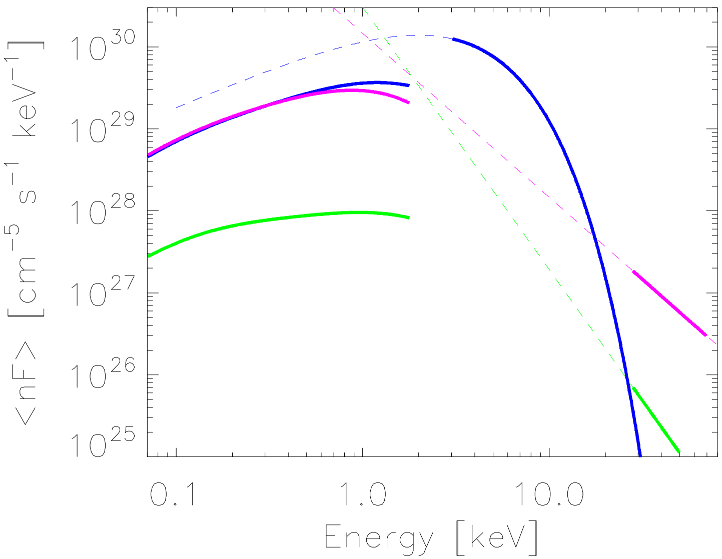
Similar results: Emslie et al 2003, Battaglia &Benz 2006 etc

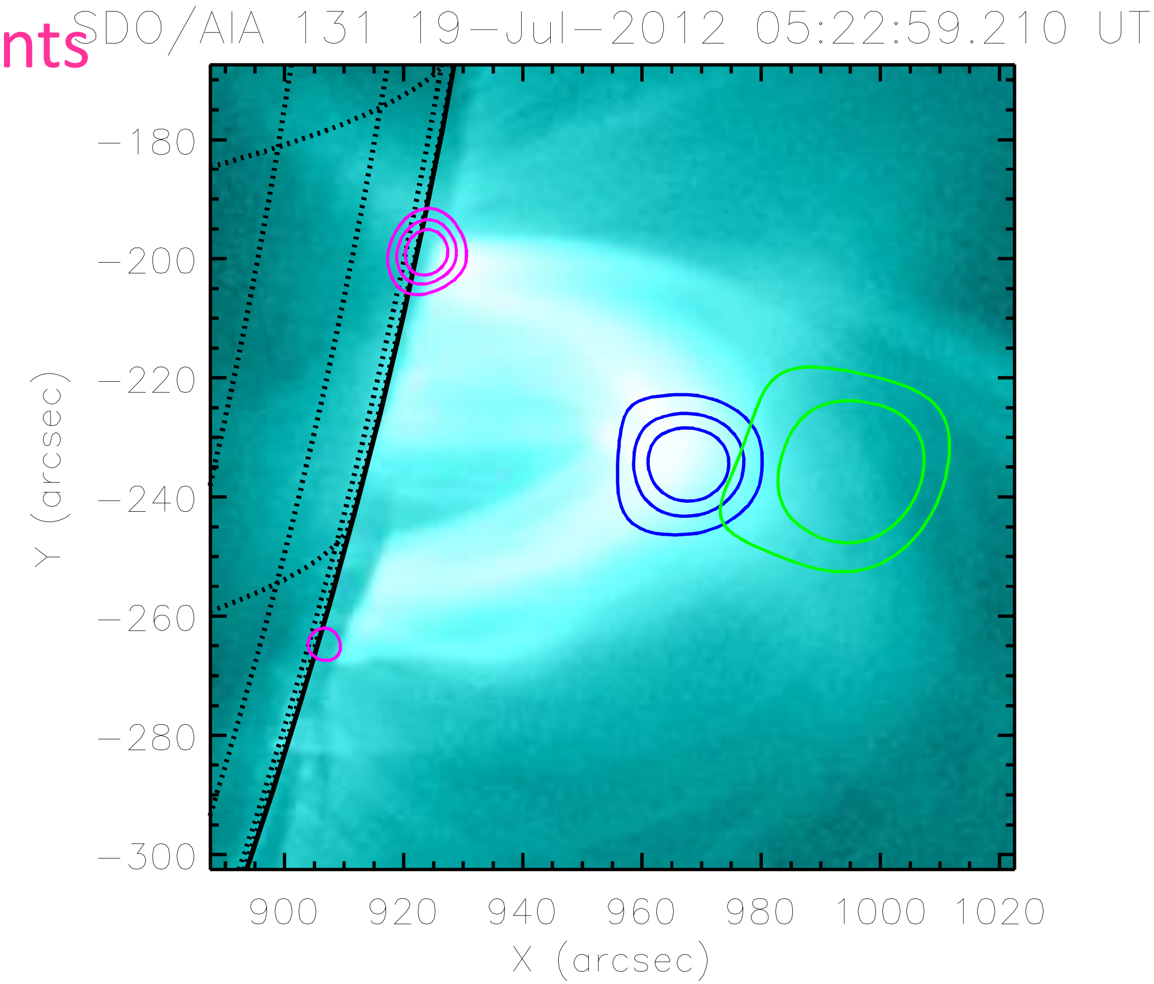
RHESSI imaging spectroscopy, we can infer spectra and numbers of energetic electrons both in coronal and foot-points sources.

Above 30 keV, we have normally a few times electrons more in the LT than in FP source. *Possible trapping by waves or mirror?*

July 19, 2002 flare

3 X-ray sources: coronal SXR source, above the loop-top HXR source, HXR footpoints

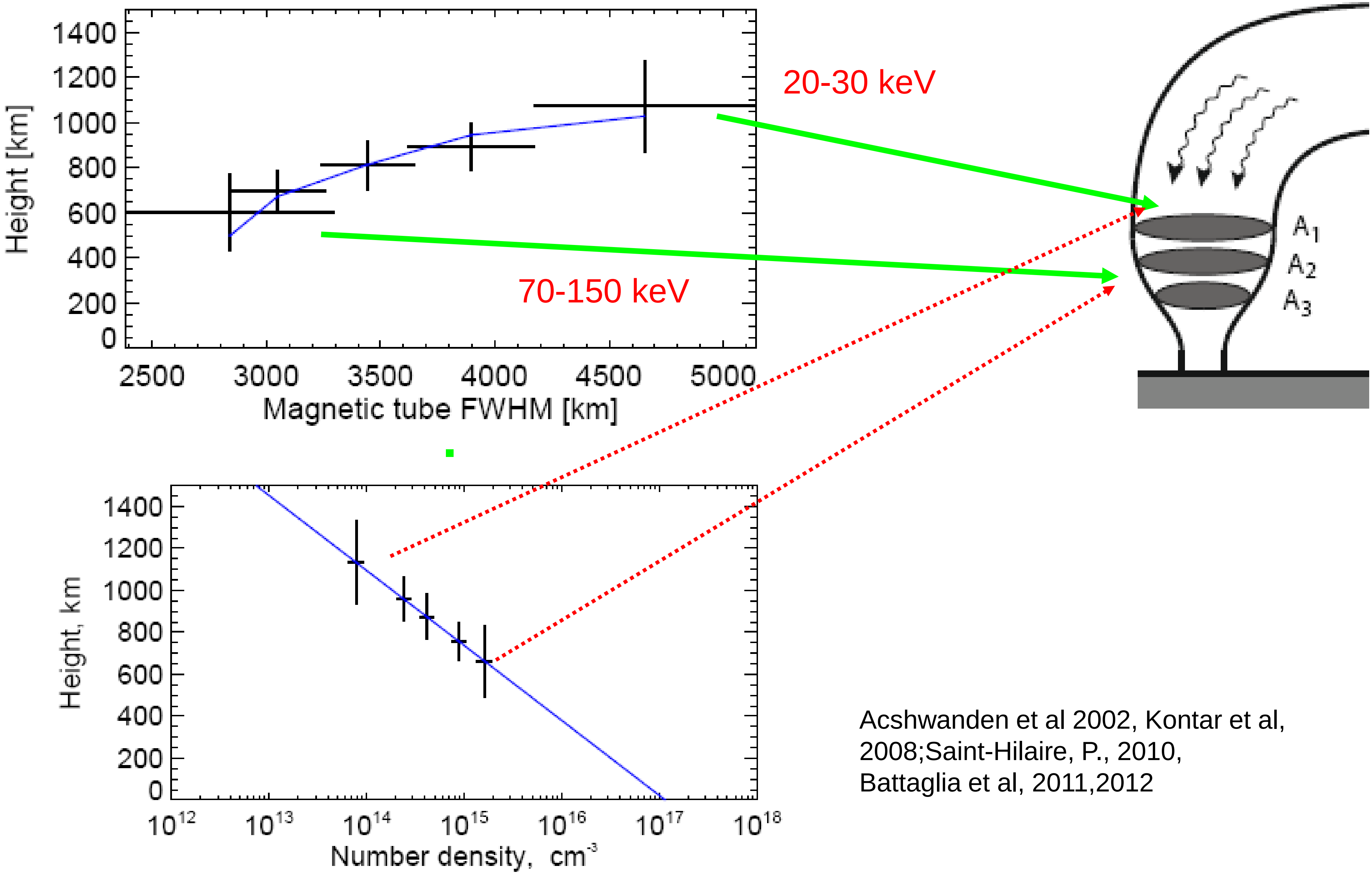




AIA 131 Å image overlaid with RHESSI 30%, 50 %, 70 % contours

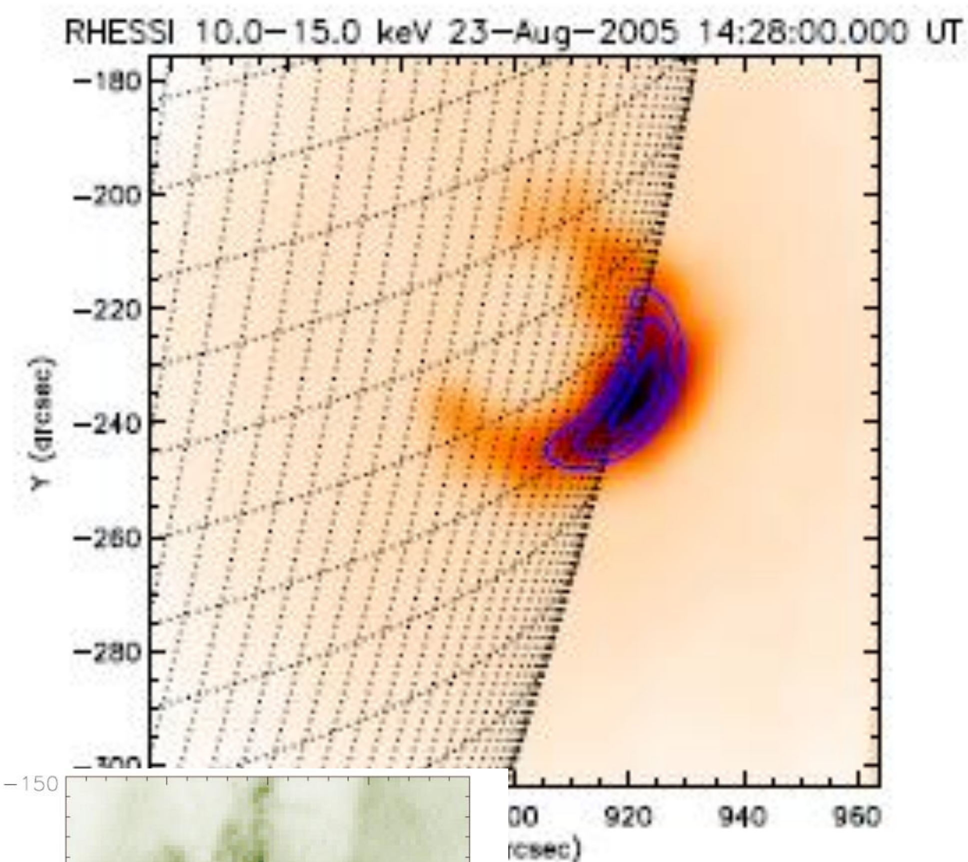
Battaglia & Kontar, ApJ, 2013

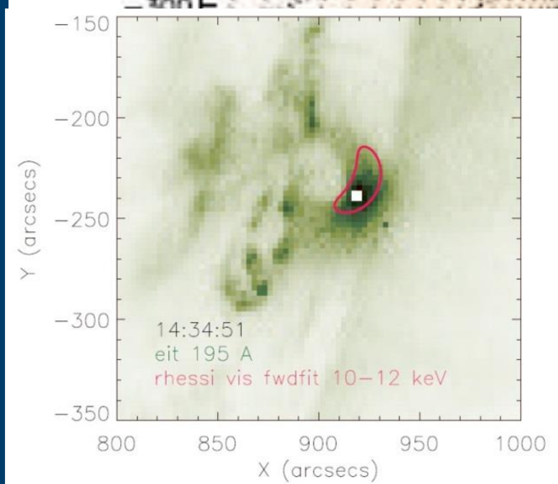
From X-ray to the structure of B field



Acshwanden et al 2002, Kontar et al, 2008;Saint-Hilaire, P., 2010, Battaglia et al, 2011,2012

HXR loops





Advantages:

Well-resolved magnetic geometry
Collisional mean free path of 20 keV electrons is short ~5-7 arcsec
Detailed study of acceleration and transport of electrons

Disadvantages:

Small number of suitable events

Xu et al 2008, Kontar et al 2011, Guo et al, 2013,2013; Jeffrey & Kontar 2012

Acceleration site characteristics

Spatial scales:

(larger number of electrons in the corona, flares with weak(or no) footpoints => Hard X-ray producing electrons are accelerated in the corona:

height $\sim 1-2\times10^{9}$ cm

size $\sim 0.5-2\times10^{9}$ cm

Characteristic time scales:

Shortest timescale ~0.1sec (e.g. Hoyong et al 1976, Kiplinger et al 1983)

Majority(?) of flares do not show such short timescales

=> Comparable to loop size/speed timescales

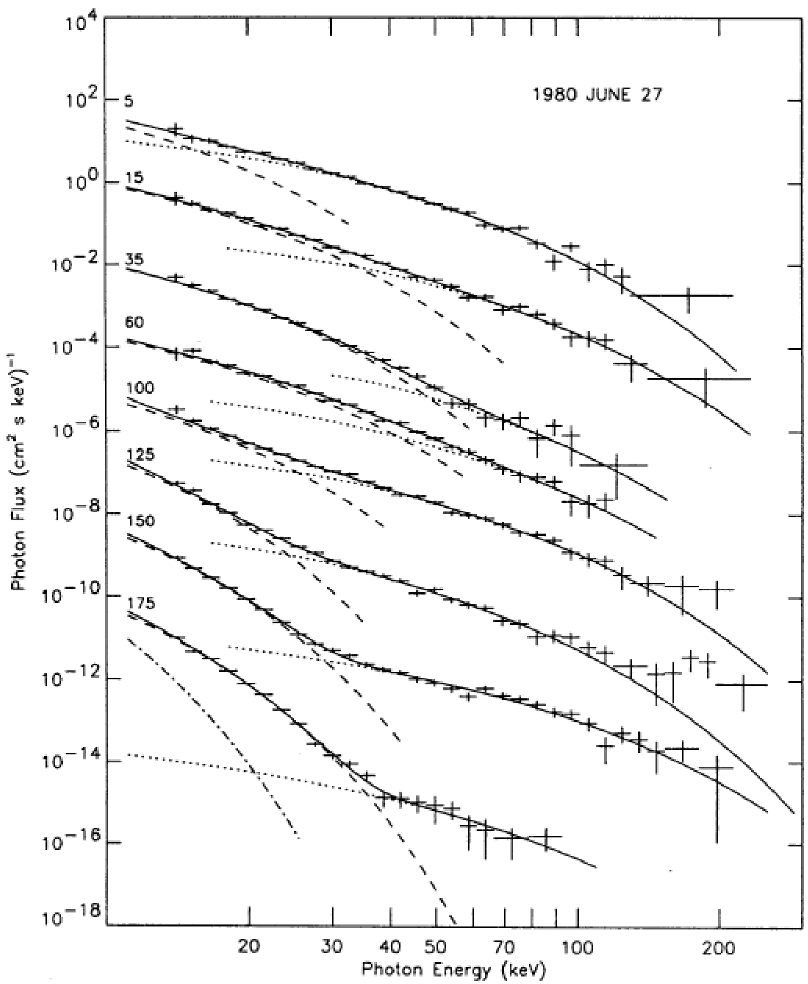
=> Much shorter than HXR burst duration ~ 1-10 minutes

Open question:

What is the electron spectrum at the scales < 0.1sec?

Electric field acceleration: sub-Dreicer field

Runaway acceleration in sub-Dreicer fields has been applied to solar flares by a number of authors (Kuijpers (1981), Heyvaerts (1981), Holman (1985), etc)



In principle, such models can partially explain observations, e.g. Benka and Holman (1994) demonstrate good spectral fits.

Open questions:

1) ***Stability of the involved DC currents***
2) ***Large scale fields e.g., the size of a loop 10^{10}cm***
3) ***Issues with return current***

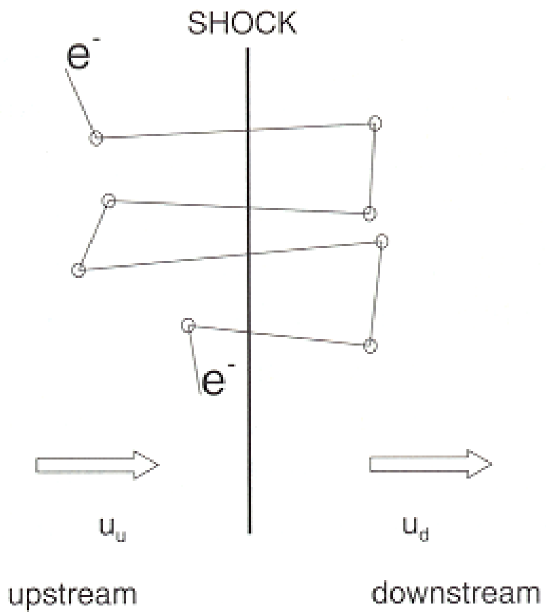
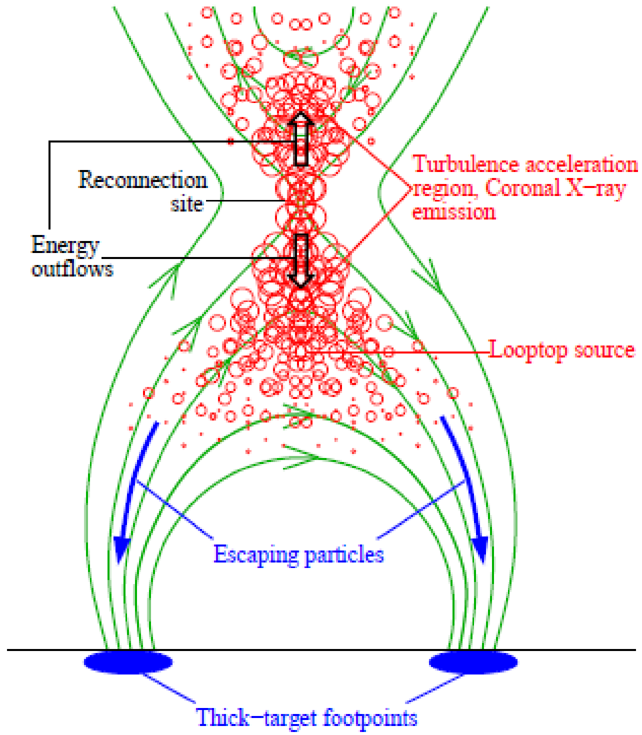


Fig from Aschwanden 2006

Diffusive shock acceleration



Liu et al 2008, Petrosian, 2012

Open questions:

1) Large areas required
2) Number of accelerated electrons
3) Observational evidence of shocks in the low atmosphere

Open questions:

1) The origin and properties of turbulence

Stochastic or 2nd order Fermi acceleration

Large number of interactions with small change of energy per interaction and <F>=0

Average force

$$\frac{\partial f}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D(p)\frac{\partial f}{\partial p}\right)$$

$$D(p) = < F^2 > \tau$$

Correlation Time = Length/speed

Assumptions:

1. Small change of energy/speed per interaction
2. Isotropic distribution => strong pitch angle scattering

Open question:

What is the dominant force F accelerating electrons and ions?

Back-reaction of large number of accelerated particles

What is the correlation time (transport in acceleration region)?

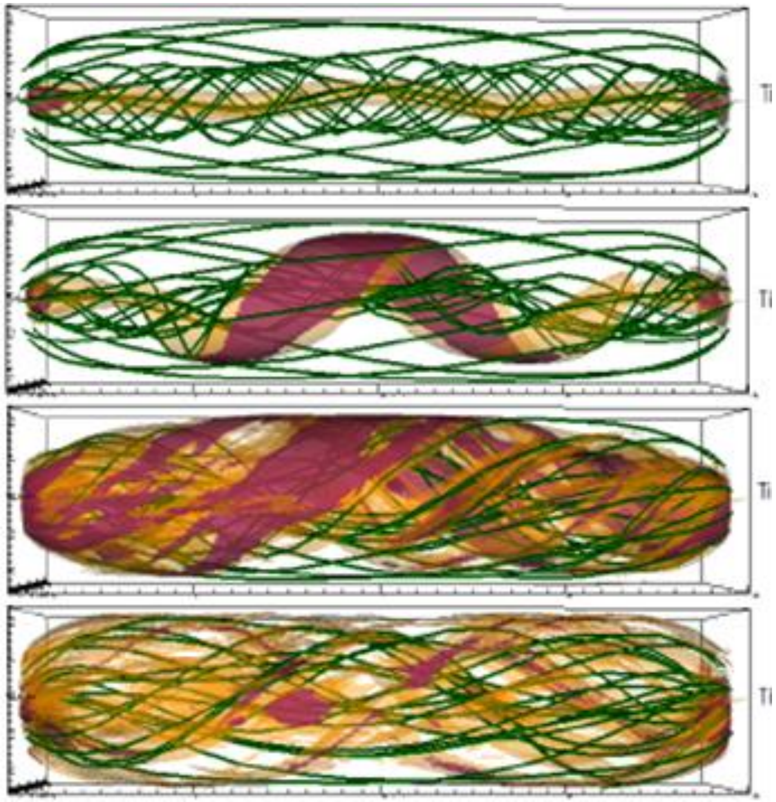
Possible models of stochastic acceleration:

Resonant acceleration by low frequency MHD waves
e.g. Melrose, 1968, Ramaty 1978, Miller et al 1992, Petrosian 2013

Strong turbulence
(e.g. Byukov & Fleishman 2009)

Stochastic acceleration electric fields
(e.g. Bian et al 2014)

Multiple current sheets
(e.g. Vlahos et al 1998, Turkmani et al, 2005, Hood et al, 2008, Browning et al 2008, Gordovskyy et al, 2012, 2014)



Gordovskyy et al 2012

Importance of transport

$$D(p) = < F^2 > \tau$$

Lagrangian correlation time

Correlation length

Assume *F=eE, E* is the electric field

Depends on transport

Pitch angle scattering of particles is important for efficient stochastic acceleration reduced thermal conductivity, electron transport e.g. artificial injection of electrons often involved to explain strong radio sources at the loop-tops (e.g. Melnikov et al 2001, Lee et al, 2002)

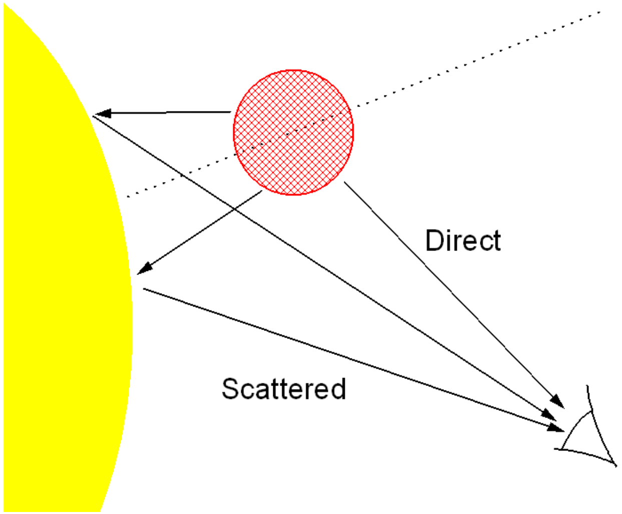
Electron anisotropy

1. Statistical centre-to-limb variation of X-ray spectrum parameters

2. Stereoscopic observation for a few flares

3. Albedo diagnostics of anisotropy

4. Polarisation measurements (large uncertanties)



Observations suggest rather low anisotropy, distribution of electrons is probably close to isotropic
Better constraints?

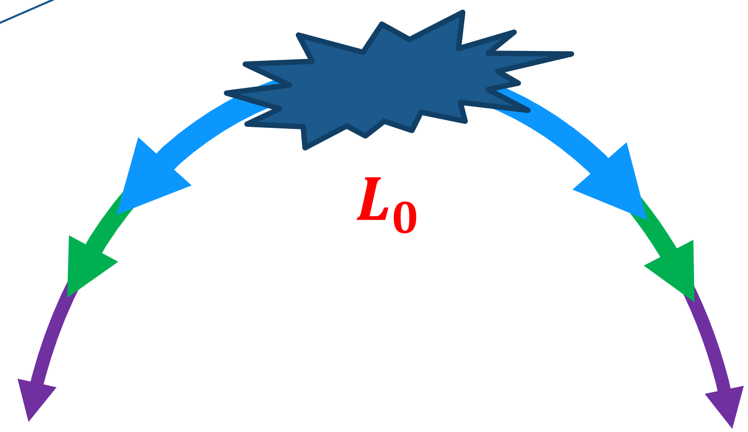
Pitch angle scattering and transport

$$\frac{\partial f}{\partial t} + \mu\, v\, \frac{\partial f}{\partial z} = \frac{2Kn(z)}{m_e^2}\,\frac{\partial}{\partial v}\left(\frac{f}{v^2}\right) + \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\,\frac{\partial f}{\partial \mu}\right) + S(v,\mu,x,t)$$

Energy loss via binary collisions

Pitch angle scattering

Source of electrons



$$\mu v\,\frac{\partial f}{\partial z} \to D_{zz}\,\frac{\partial^2 f}{\partial z^2}$$

$$D_{zz} = \frac{v^2}{8}\int_{-1}^{1}\frac{(1-\mu^2)^2}{D_{\mu\mu}^{(T)}}\,d\mu = \frac{\lambda v}{3}$$

Diffusive transport (strong scattering) with one parameter (mean free path):

Pitch angle scattering and transport

Scatter-free transport:

$$\frac{\partial F(E,z)}{\partial z} - \frac{\partial}{\partial E}\left(\frac{Kn(z)}{E} F(E,z)\right) = F_0(E)\, S(z)$$

Strong scattering: Ballistic transport becomes (on average) a spatial diffusion parallel to the guiding field:

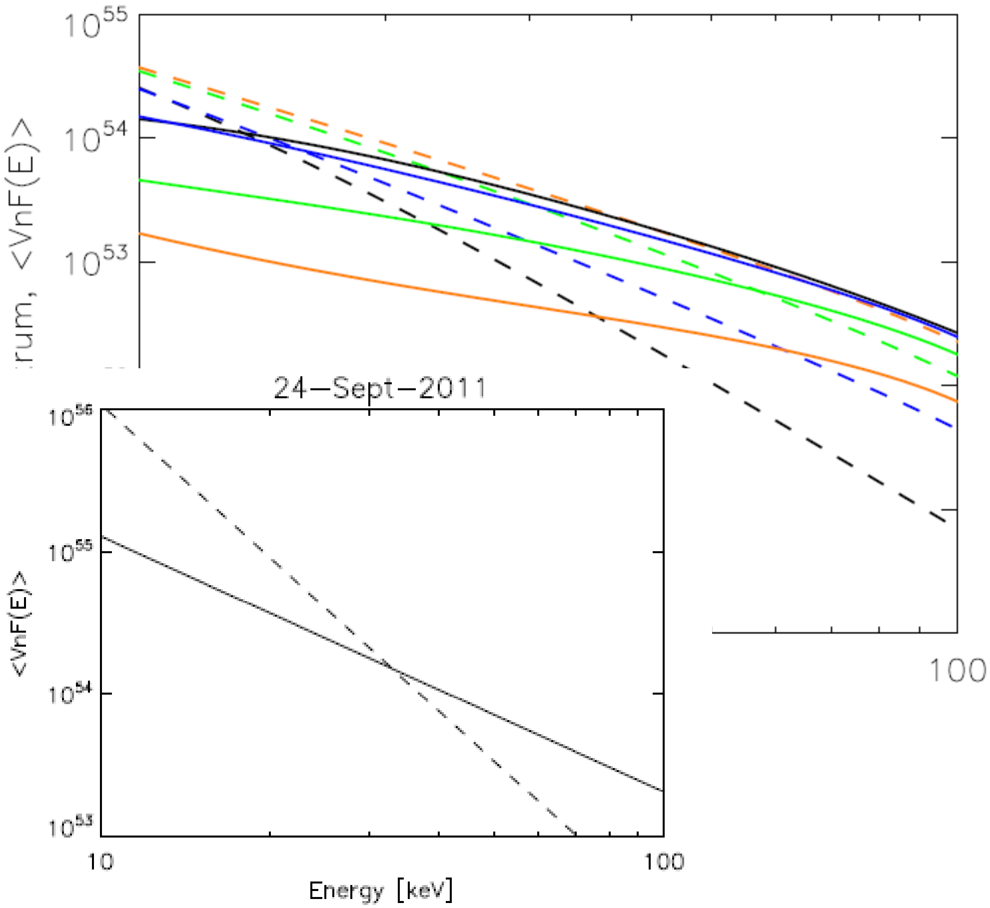
$$\mu v \frac{\partial f}{\partial z} \rightarrow D_{zz} \frac{\partial^2 f}{\partial z^2}$$

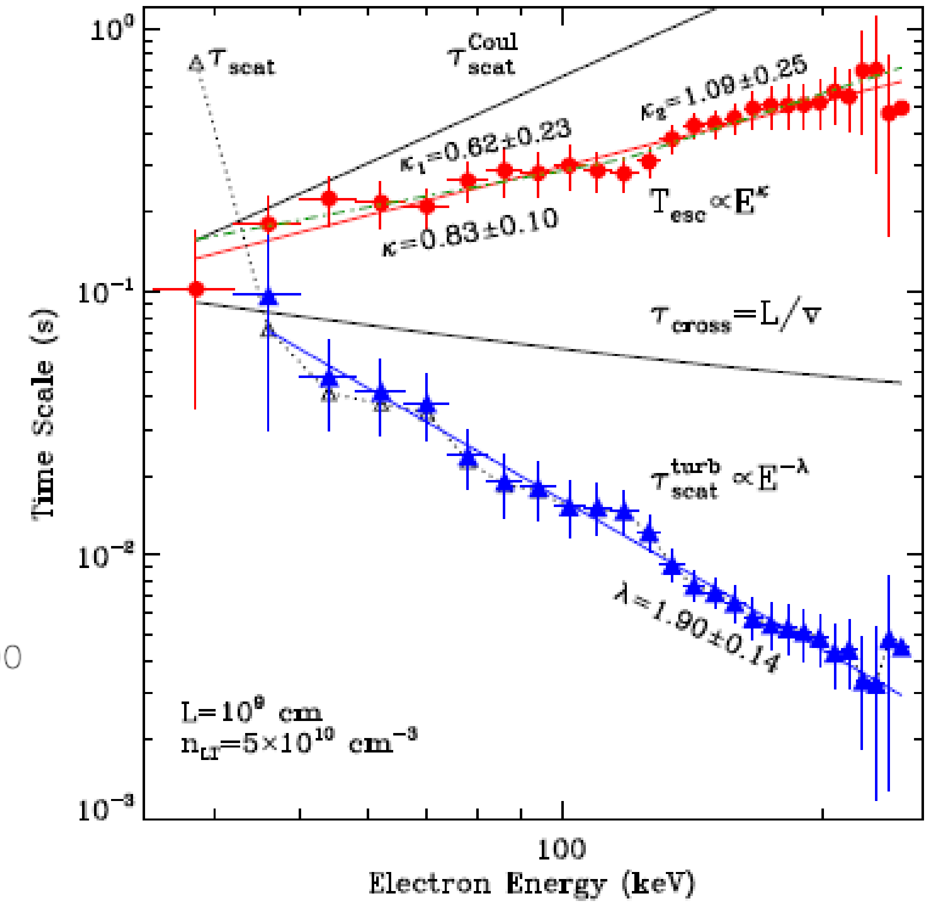
$$D_{zz} = \frac{v^2}{8}\int_{-1}^{1} \frac{(1-\mu^2)^2}{D_{\mu\mu}^{(T)}}\, d\mu = \frac{\lambda v}{3}$$

Diffusive transport with one parameter (mean free path):

$$\frac{1}{v}\frac{\partial}{\partial z}\left(D_{zz}^{(T)} \frac{\partial F}{\partial z}\right) = \frac{\partial}{\partial E}\left(\frac{Kn(z)}{E} F\right) + F_0(E)\, S(z)$$

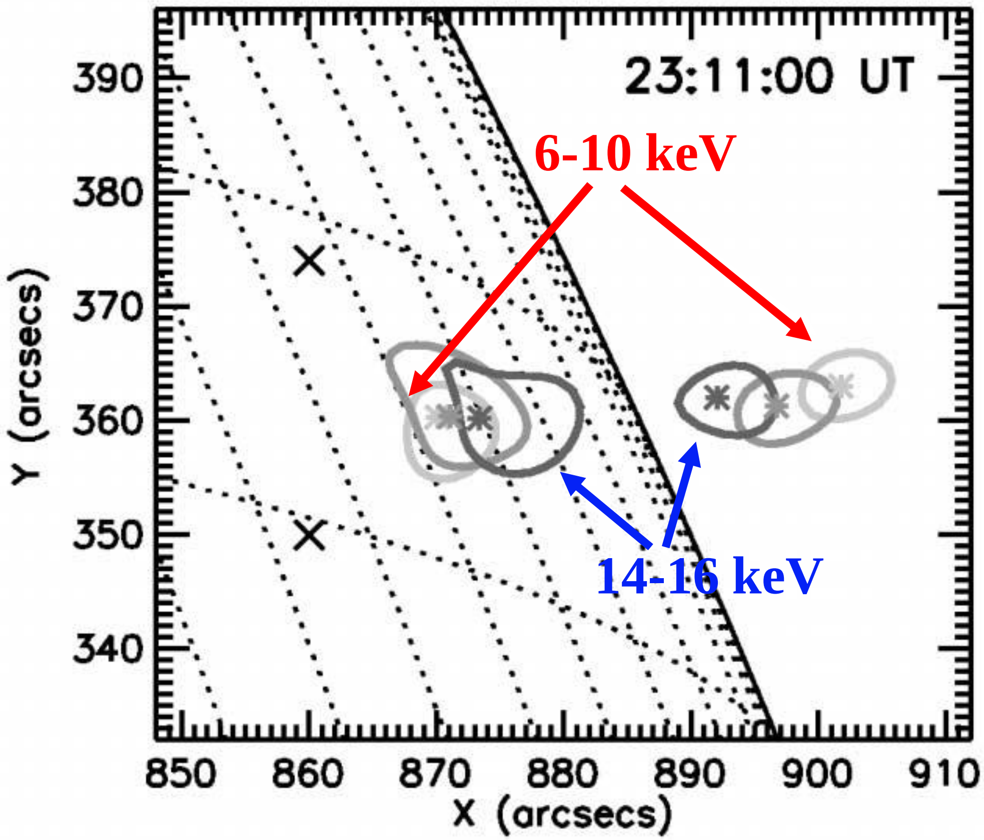
Non-collisional pitch angle scattering





Mean free path around 5e8cm
Kontar et al, ApJ 2014

Particle transport



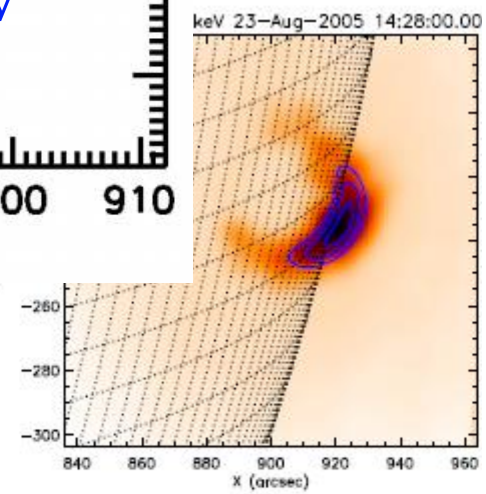
Sui et al, 2004

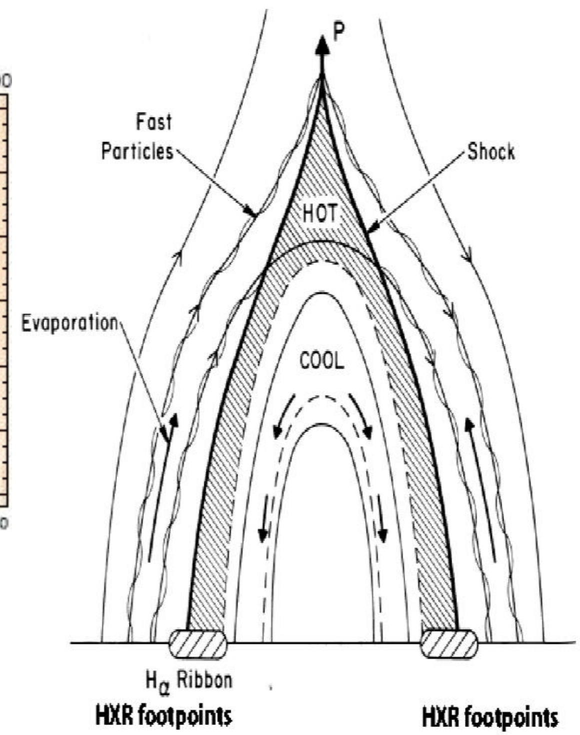
Plasma density 10^{10} cm^{-3}

Flare volume 10^{27} cm3 $(10^4 \text{ km})^3$

=> Number of electrons:10^{37}

=> All electrons will be evacuated from the volume within 1 second!



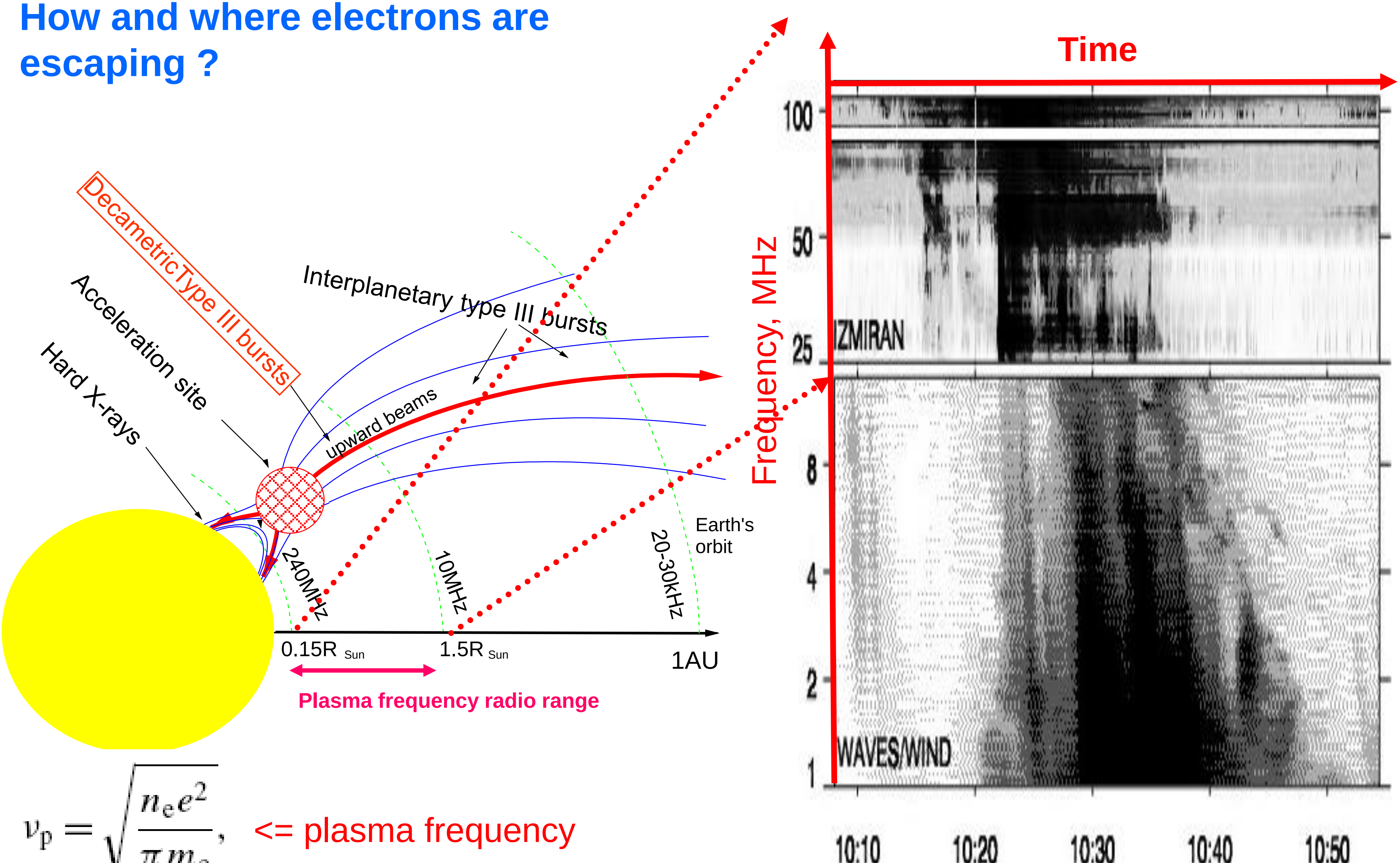


Standard flare model picture (Shibata, 1996)

Large flux of particles => self-consistent treatment required.

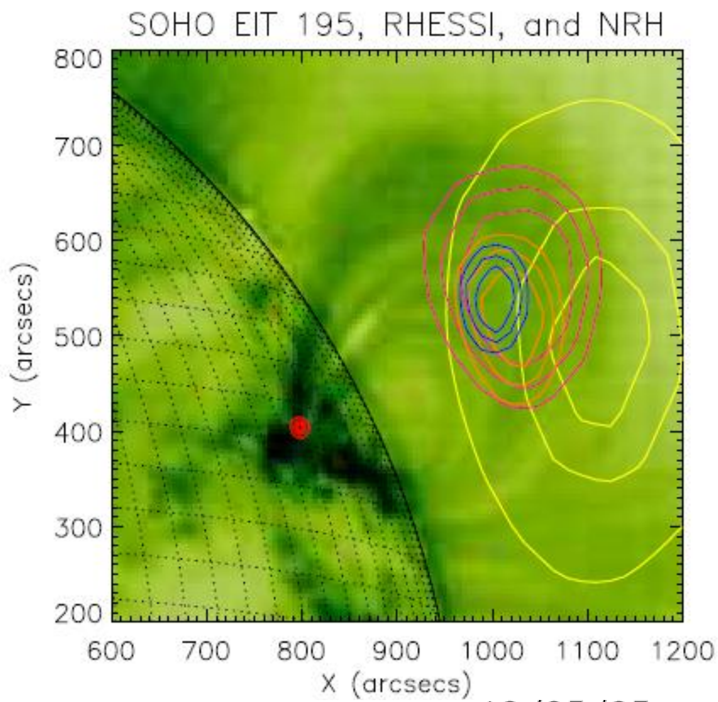
Flares and accelerated particles

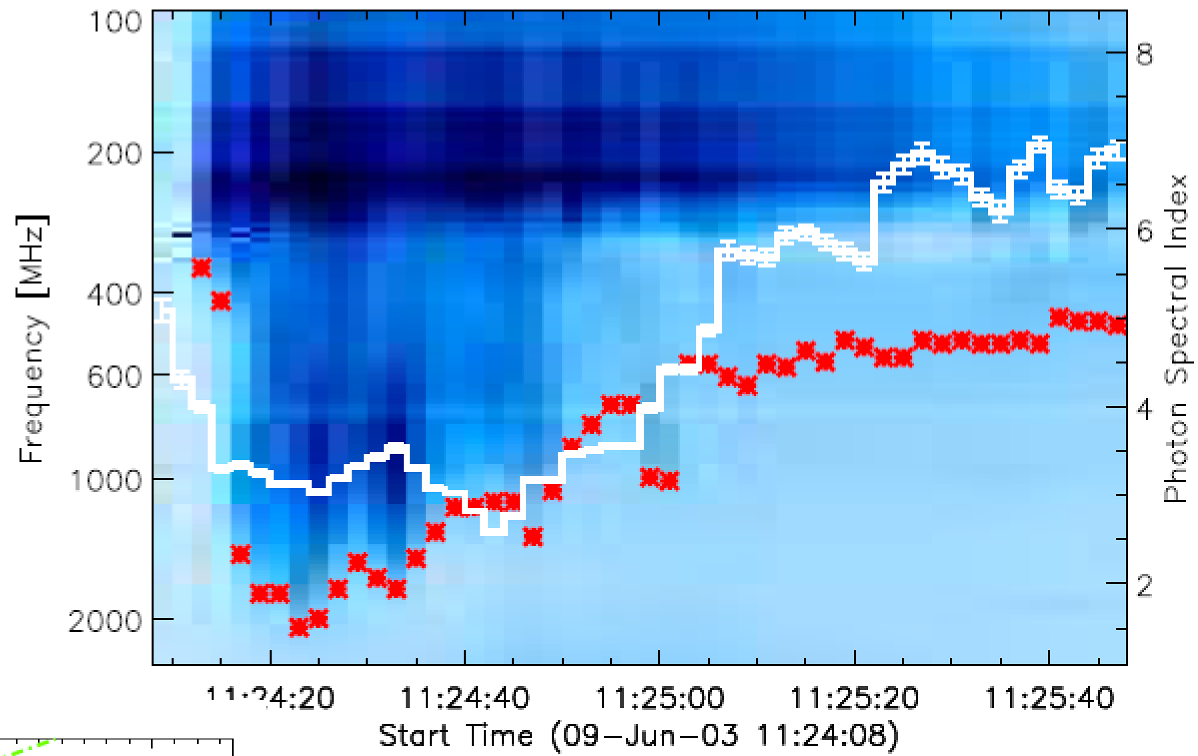
How and where electrons are escaping ?

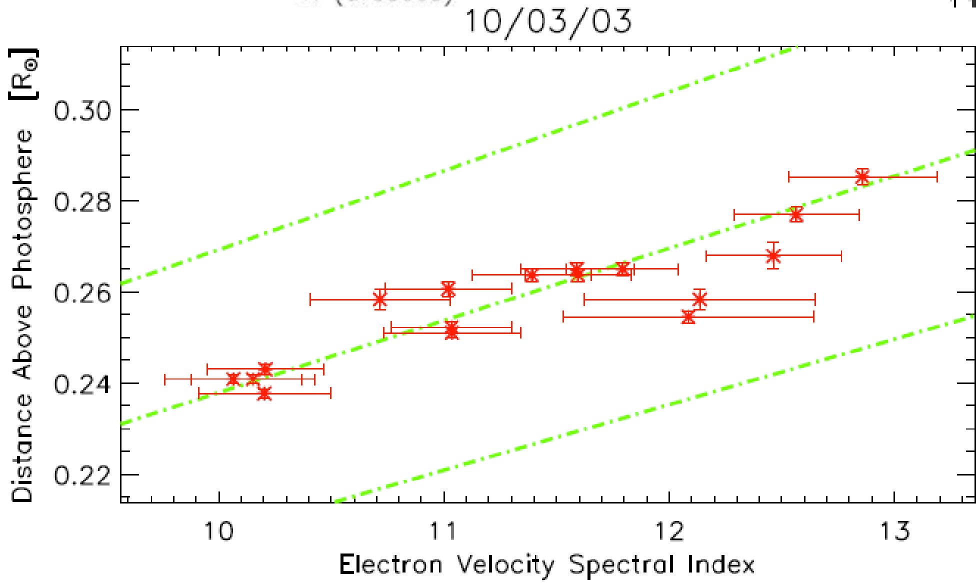


$$\nu_p = \sqrt{\frac{n_e e^2}{\pi m_e}},$$ <= plasma frequency

Observations of energetic particles



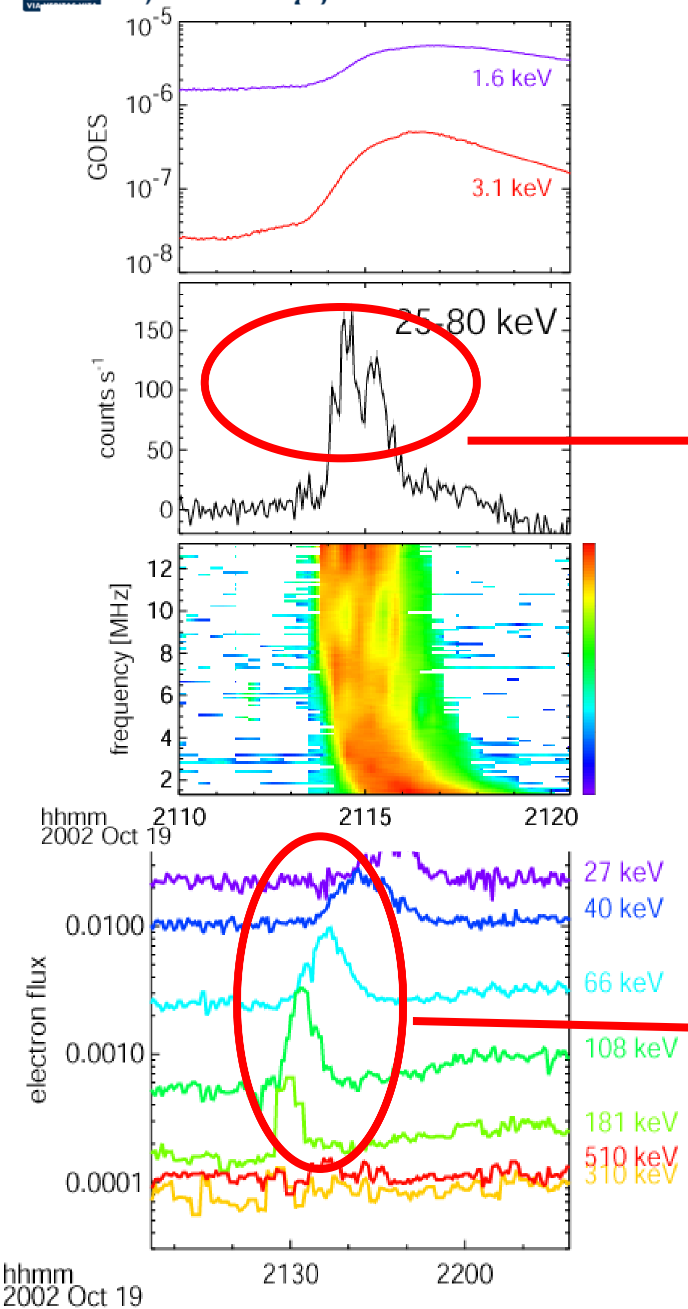




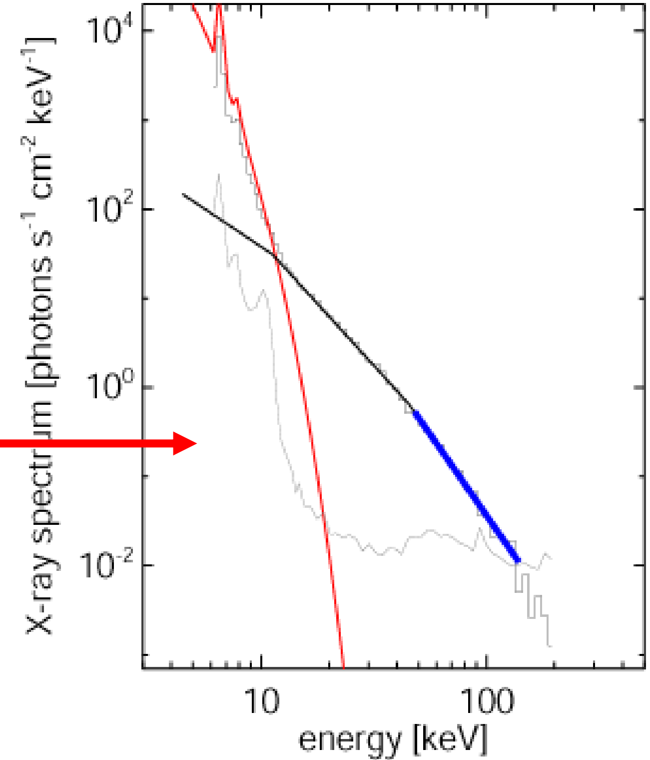
Reid et al, A&A, 2011,2014

> 50 % of the selected events show correlation between the starting frequencies of the groups of type III bursts and the hard X-ray spectral indices – see a low-high-low trend

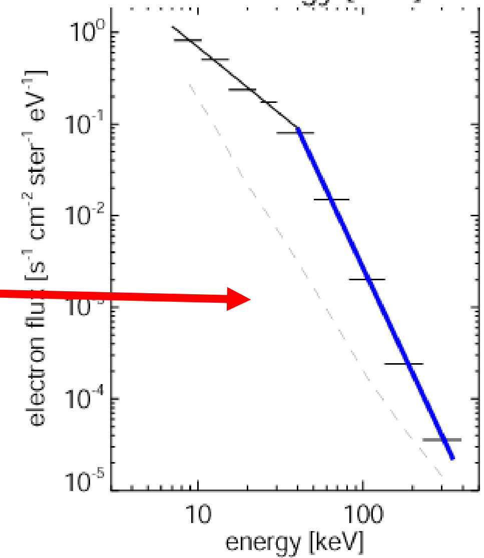
From X-rays to electrons



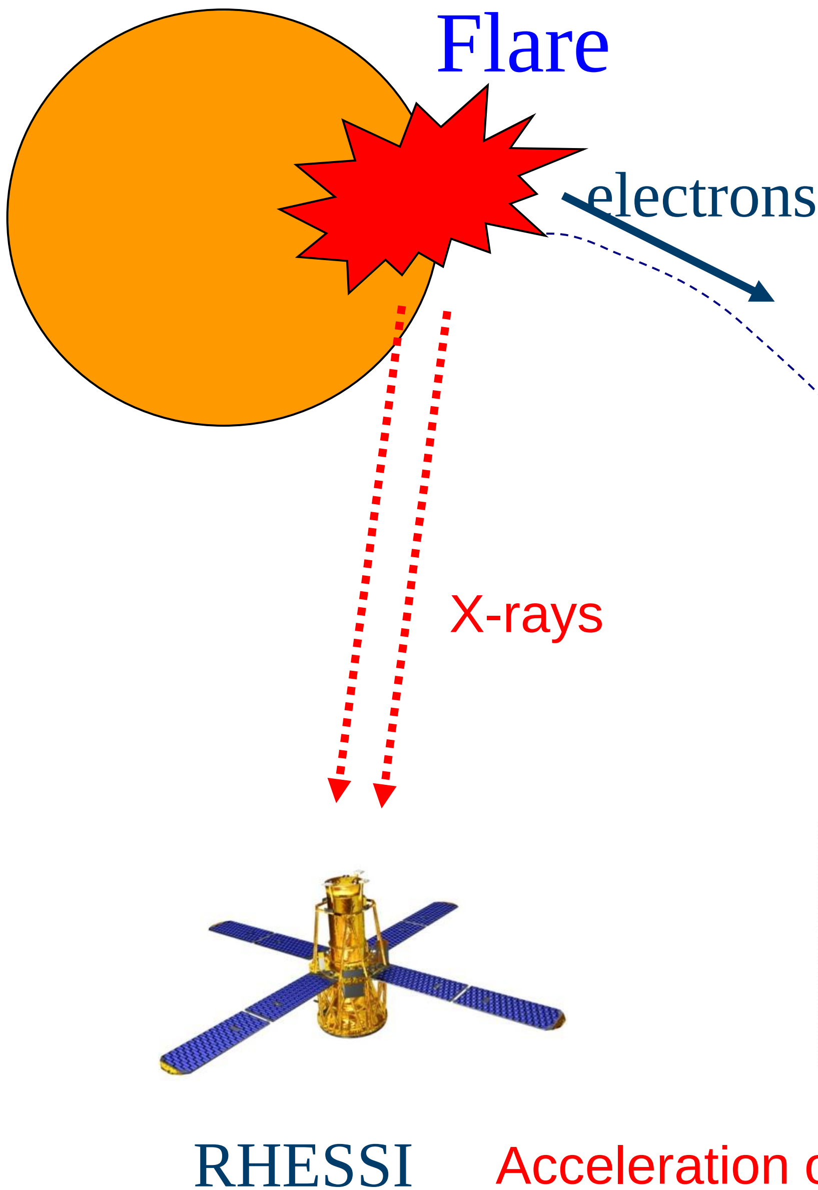
X-ray spectra from RHESSI

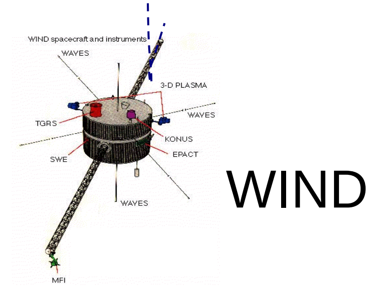


Electron peak spectra at 1AU from WIND

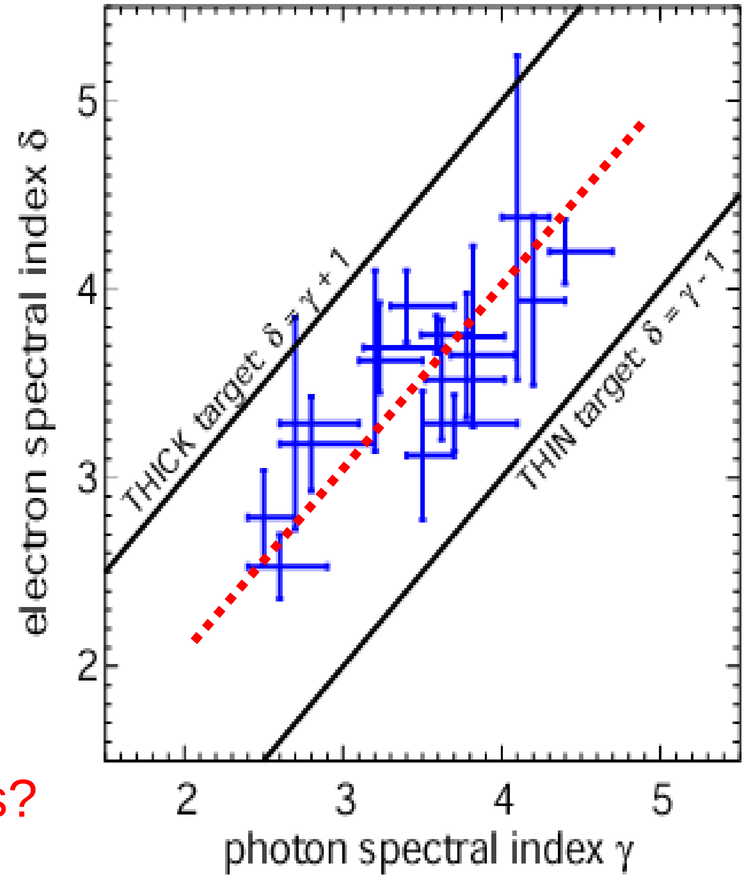


From X-rays to electrons





From the analysis of 16 “scatter-free” events (Lin, 1985; Krucker et al, 2007) :
Although there is correlation between the total number of electrons at the Sun (thick-target model estimate) the spectral indices do not match either thick-target or thin-target models.



Acceleration or transport effects?

Summary and open questions

The combination of X-ray spectroscopy and imaging capabilities brings the most insightful results.

The models tend to consider multiple scatters for individual particles (stochastic acceleration is the RHESSI-era model?) (e.g. waves, multiple current sheets)
The observations suggest rather little scattering in the acceleration region (?); Can we better constrain anisotropy?

Strong drawback of the current models is the lack of self-consistency. **Imaging/spectroscopy at the scales 0.1 sec?**

What and how controls the scape – better and simultaneous X-ray and radio observations ?