University of Glasgow

Electron acceleration and turbulence in solar flares

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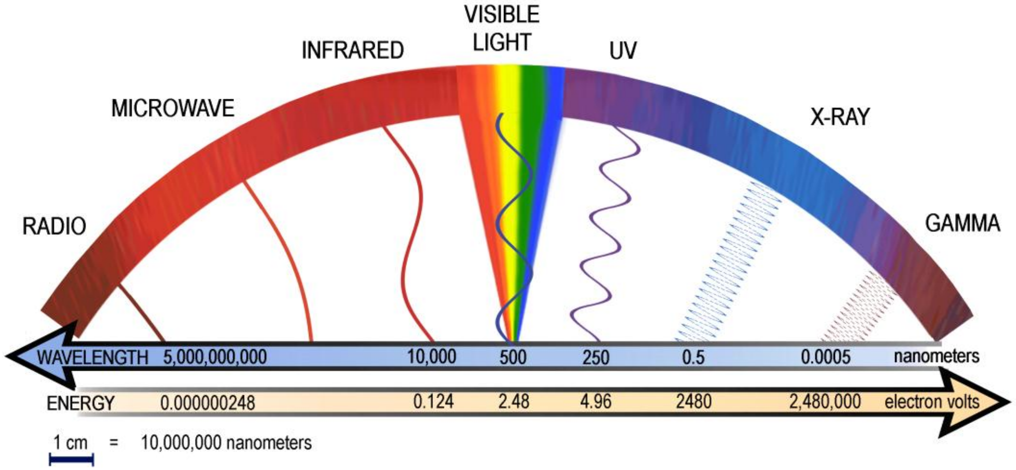
Solar flares: basics

Solar flares are rapid localised brightening in the lower atmosphere.

More prominent in X-rays, UV/EUV and radio…. but can be seen from radio to 100 MeV



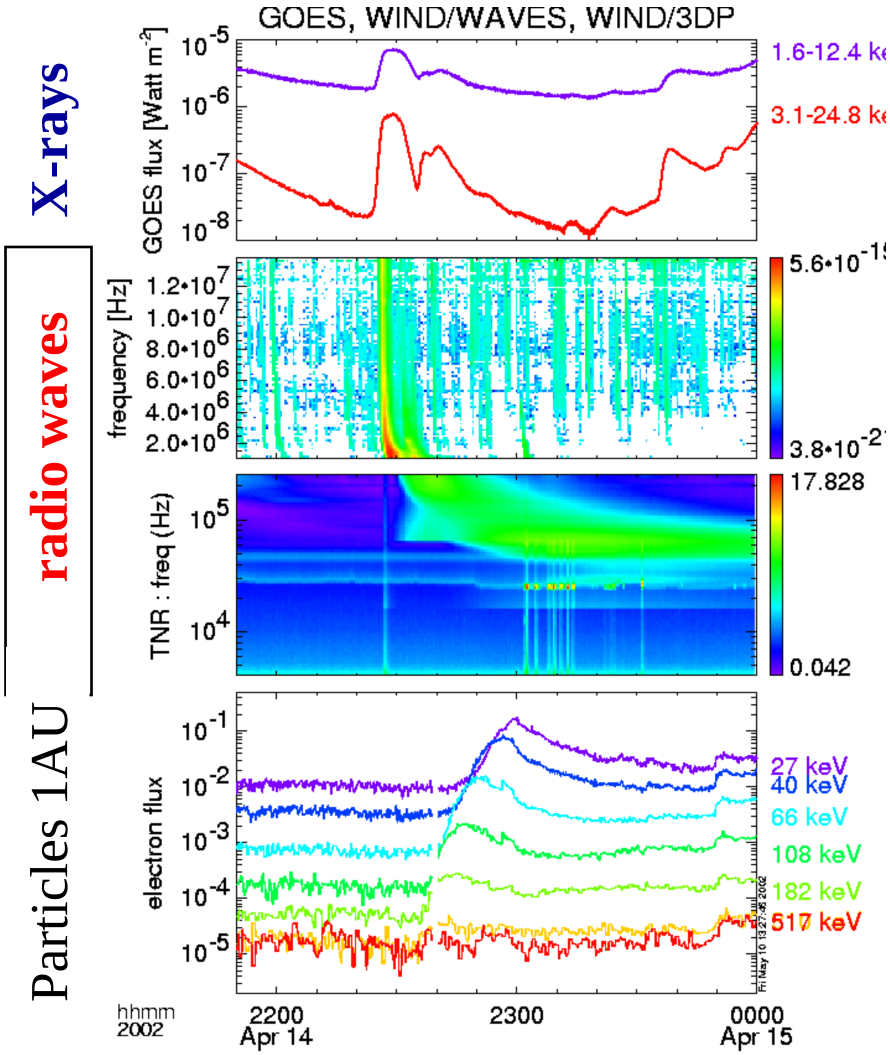
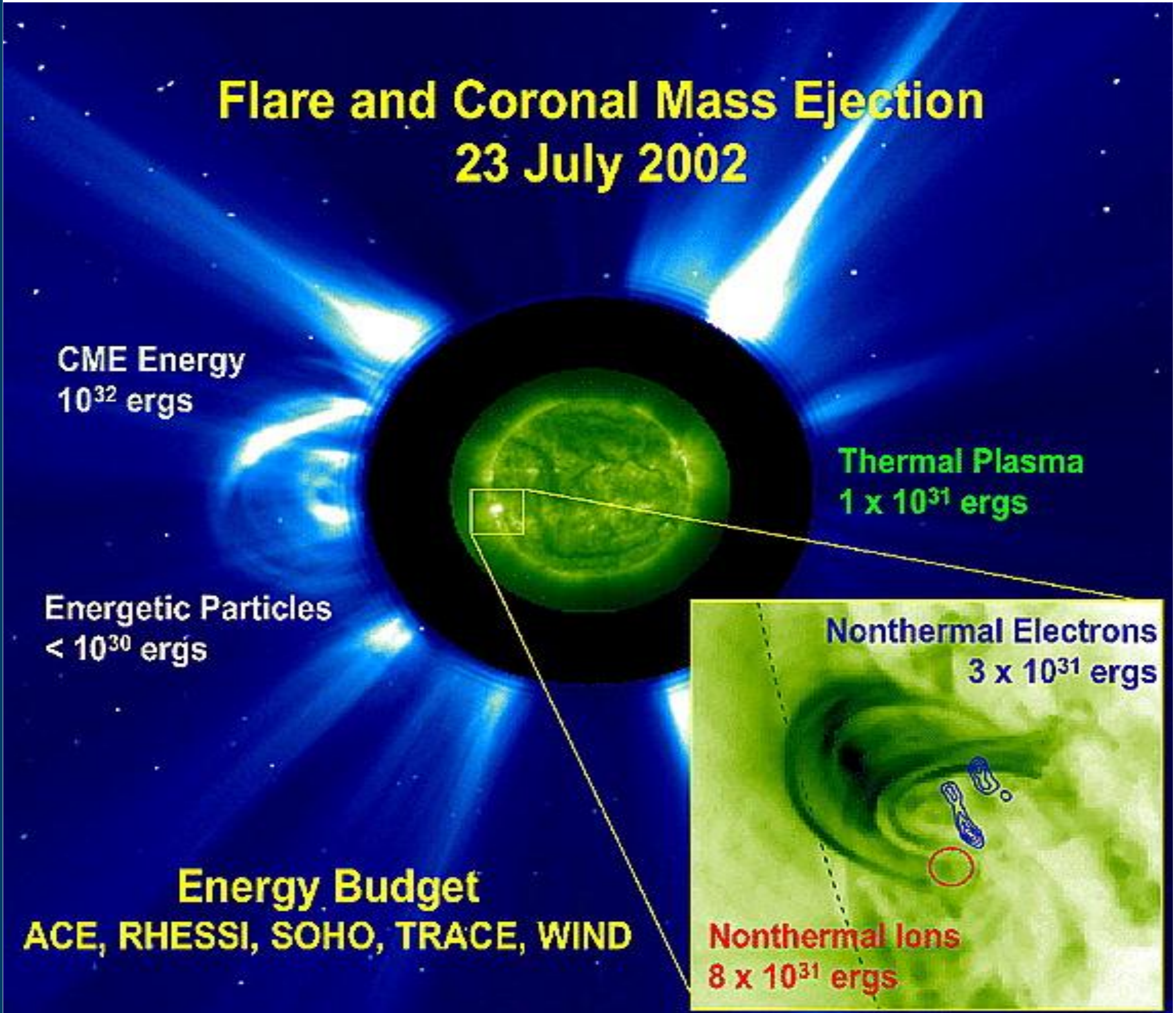


Figure from Krucker et al, 2007

Solar flares and accelerated particles



From Emslie et al., 2004, 2005

Free magnetic energy ~2 10^{32} ergs

"Standard" model of a solar flare/CME

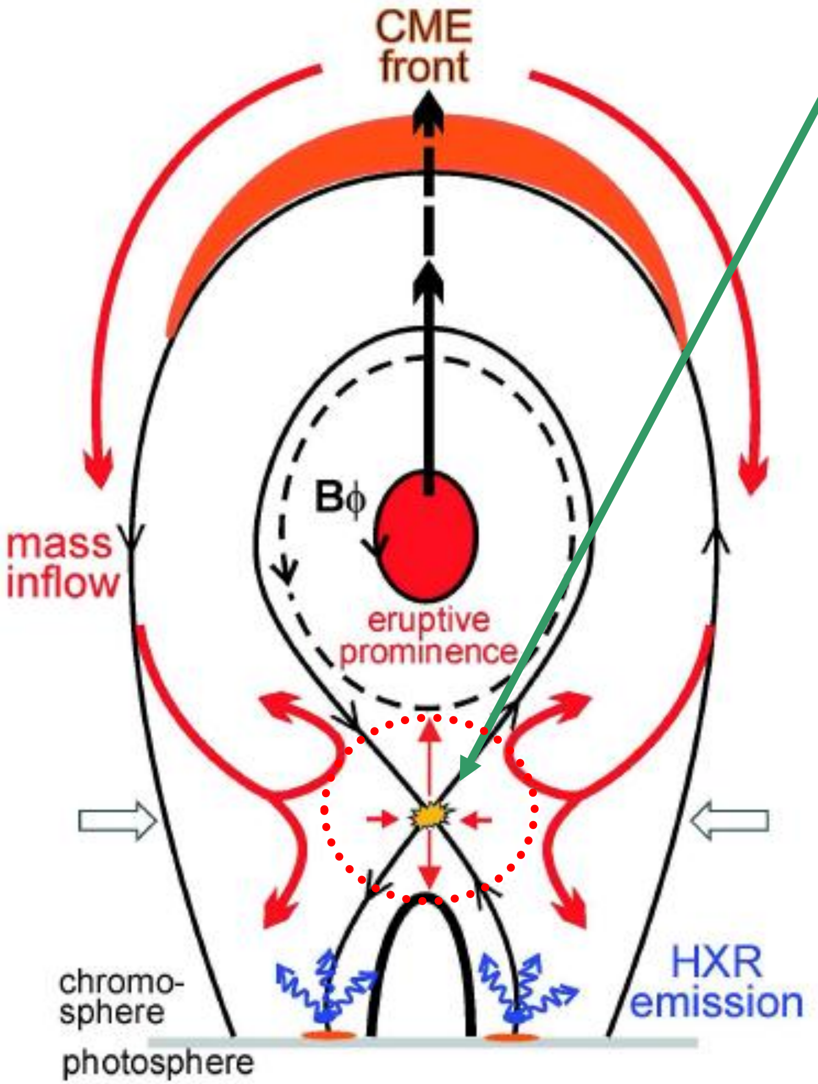


Figure from Temmer et al, 2009

Energy release/acceleration

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)

1 megaton of TNT is equal to about 4 x 10^{22} ergs.

Motivation

Stochastic particle acceleration

Vast literature exists e.g. Miller et al, 1997; Petrosian 2012; Bian et al, 2012 Cargill et al, 2012 as reviews

⇒ Generally efficient electron and proton acceleration, He3 enhancement, variety and variability of particle spectra

Particle and energy transport

Pitch angle scattering of particles, reduced thermal conductivity, etc

=> 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)

Reconnection models

Anomalous resistivity is often required to make fast reconnection and strong parallel electric fields

see e.g. Priest and Forbes, 2002, Zharkova et al, 2012, Raymond et al, 2012 as recent reviews

Plasma turbulence is characterised by chaotic and stochastic property changes, e.g. velocity, density, magnetic field in space and time.

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see e.g. Zharkova et al, 2012, Raymond

MODELS WANT TURBULENCE IN SOLAR FLARES !

Plasma turbulence is characterised by chaotic and stochastic property changes, e.g. velocity, density, magnetic field in space and time.

Observations

Density fluctuations

observed via scintillation techniques (power-law spectrum of density fluctuations), normally in the higher corona and not in flares

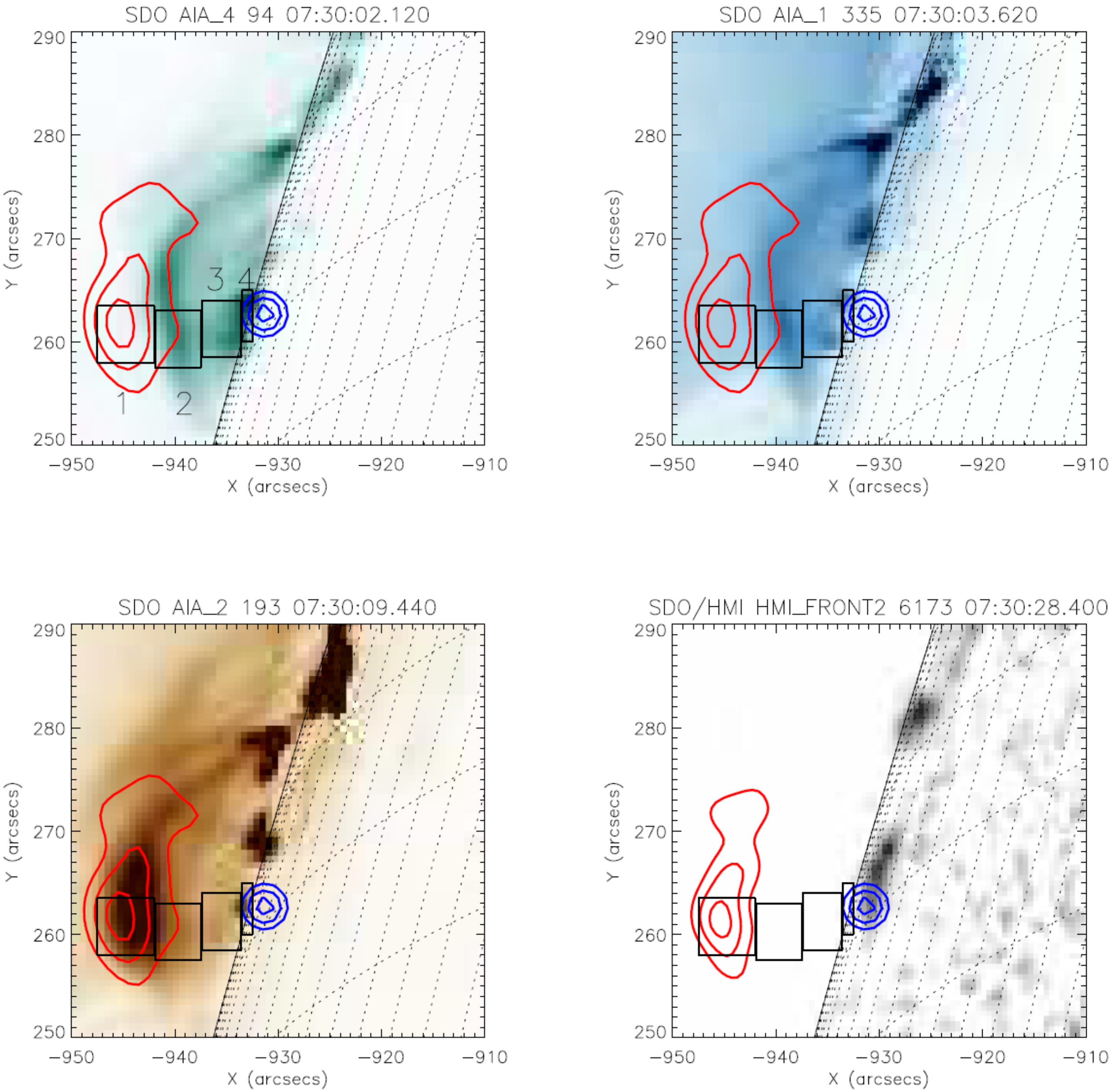
Velocity fluctuations

e.g. non-thermal line broadening observed in flares, normally spatially unresolved, but now with Hinode/EIS – spatially resolved Doschek et al, 1980, Harra et al, 2001…

Magnetic field fluctuations

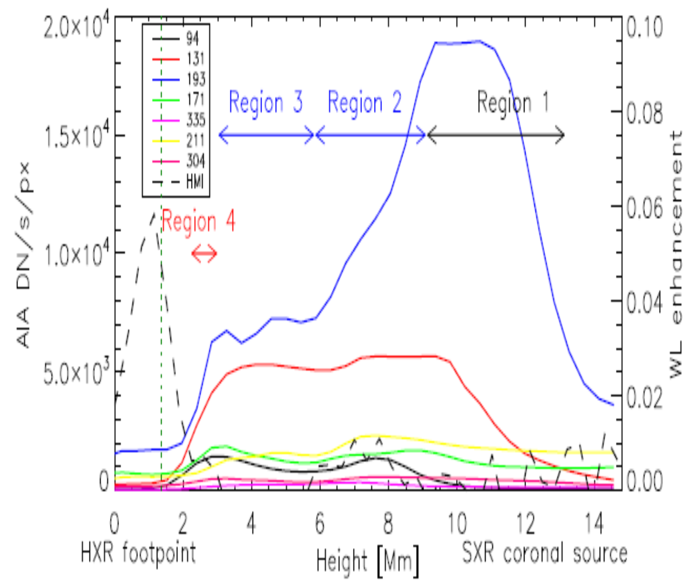
Normally magnetic fields are not measured in flares…
One exception is the radio measurements of gyrosynchrotron emission in flaring loops.
This talk…

Typical solar flare: X-ray prospective

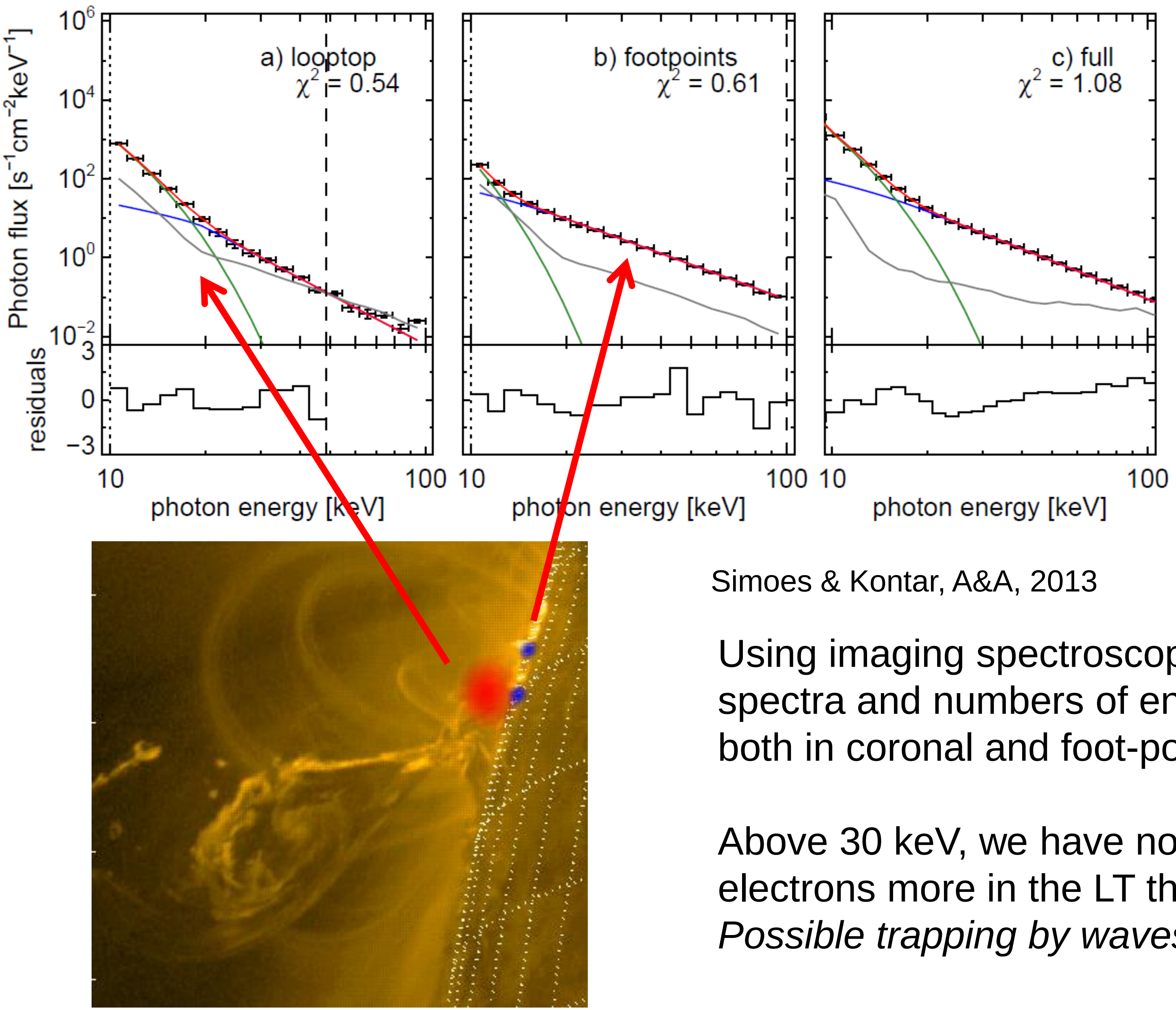


24 February,2011 flare
(Battaglia & Kontar 2012)

Well observed coronal Soft X-ray emission, clear foot-points and WL emission as a bonus.



Typical solar flare: X-ray prospective



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

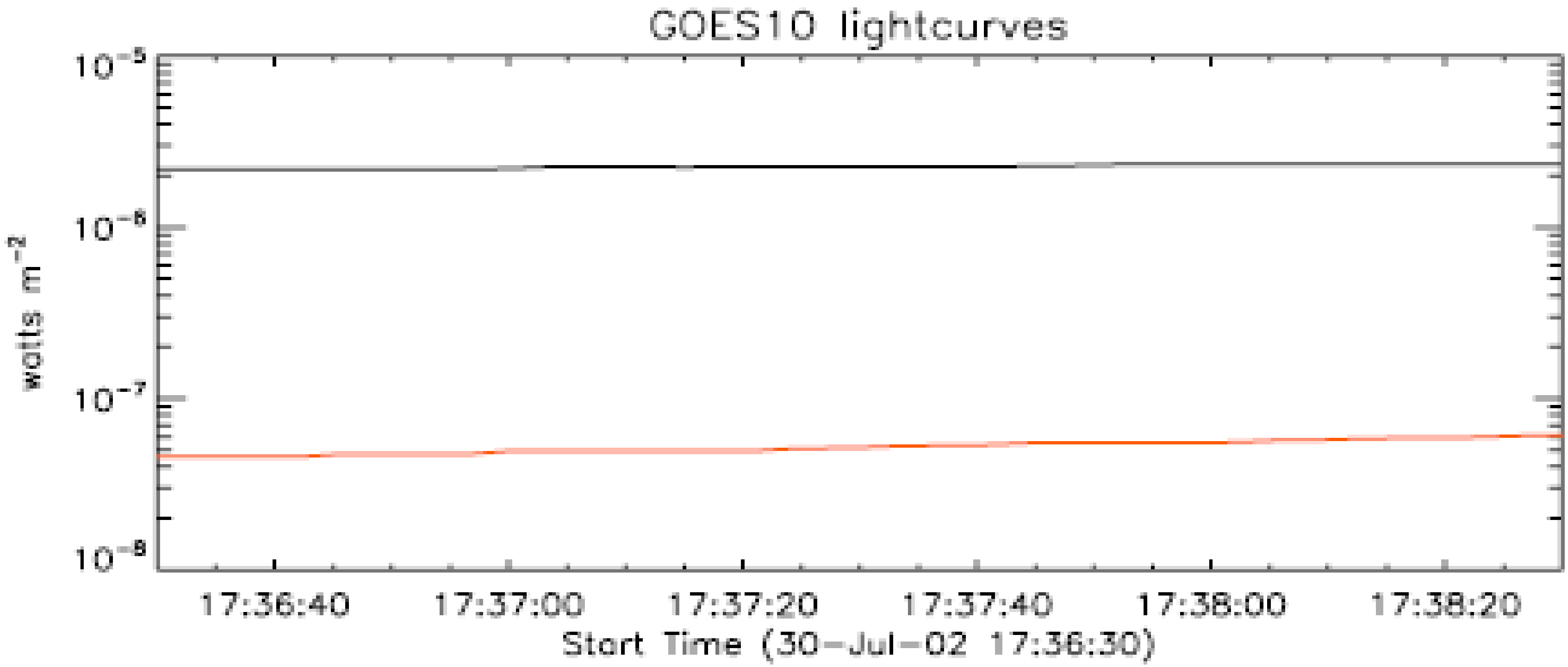
Footpoints: Hard X-ray non-thermal power-law

Simoes & Kontar, A&A, 2013

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

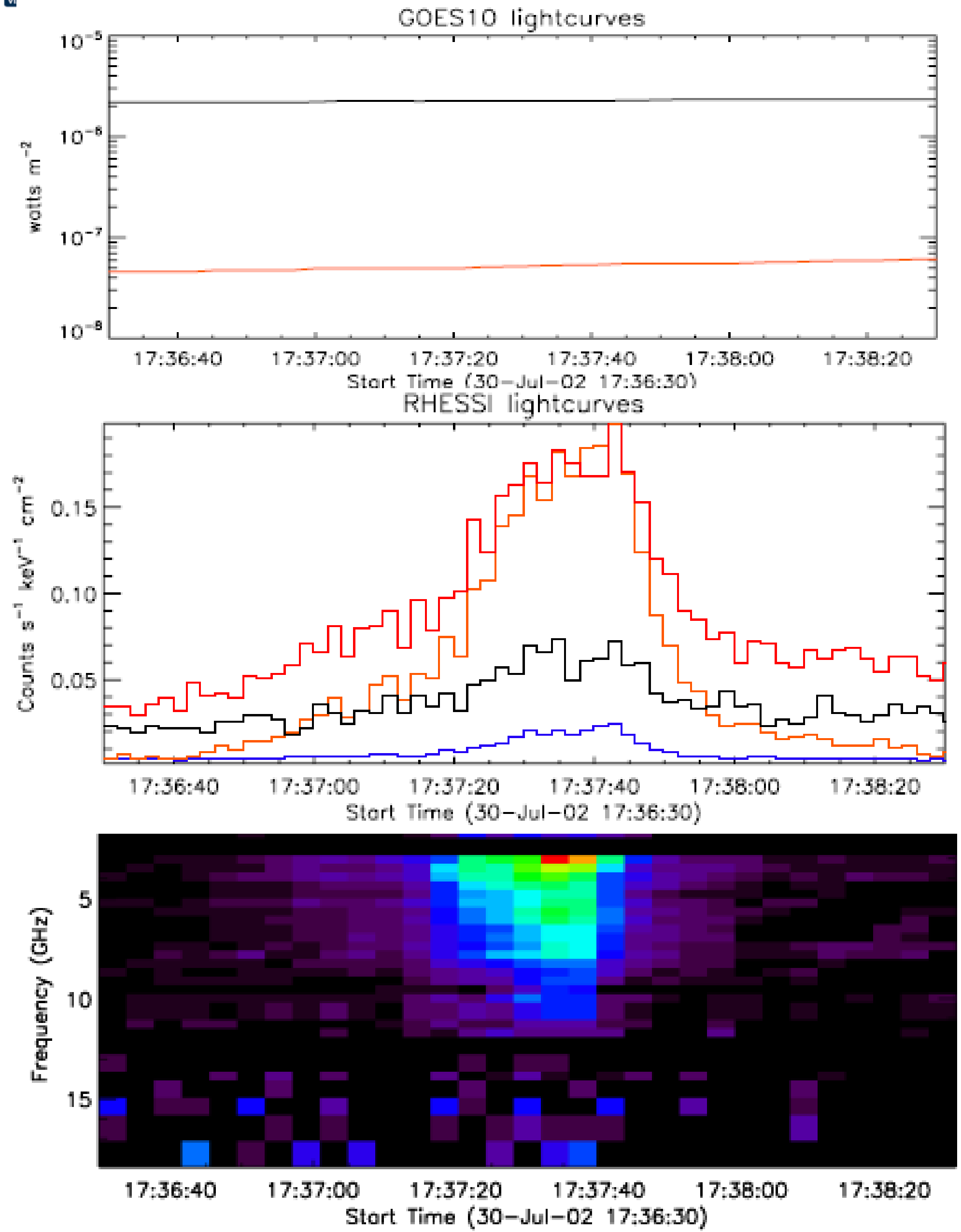
Above 30 keV, we have normally a few times electrons more in the LT than in FP source. *Possible trapping by waves or mirror?*

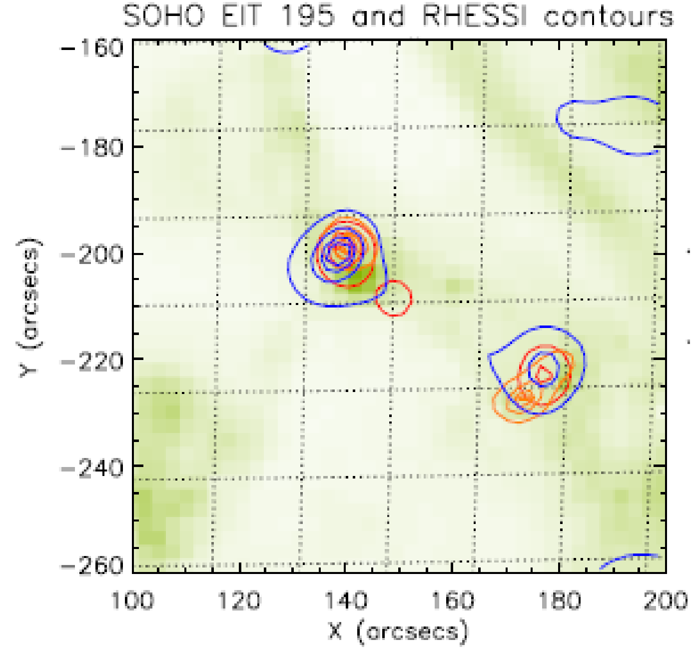
Atypical solar flares: “cold flare”

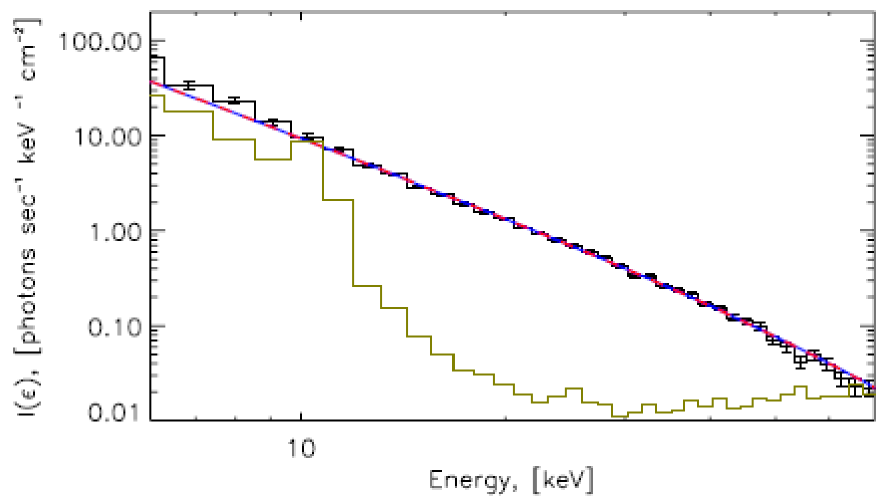


What is happening at the Sun ?

Atypical solar flares: “cold flare”

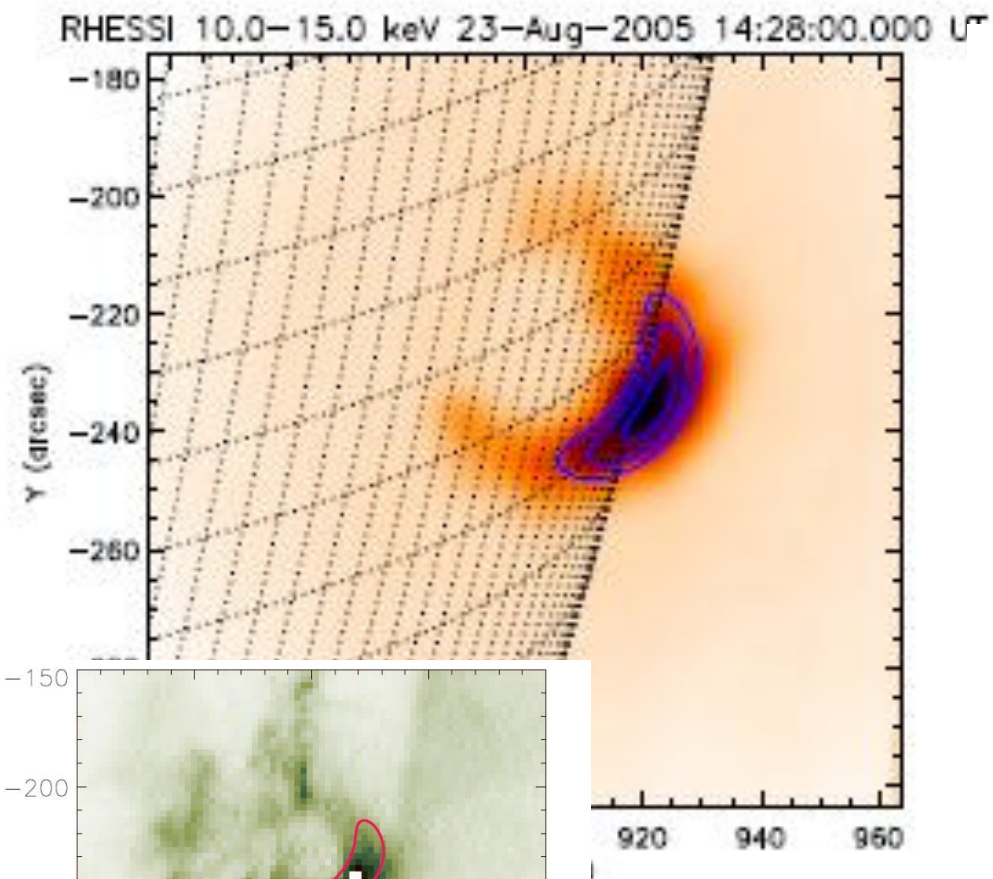


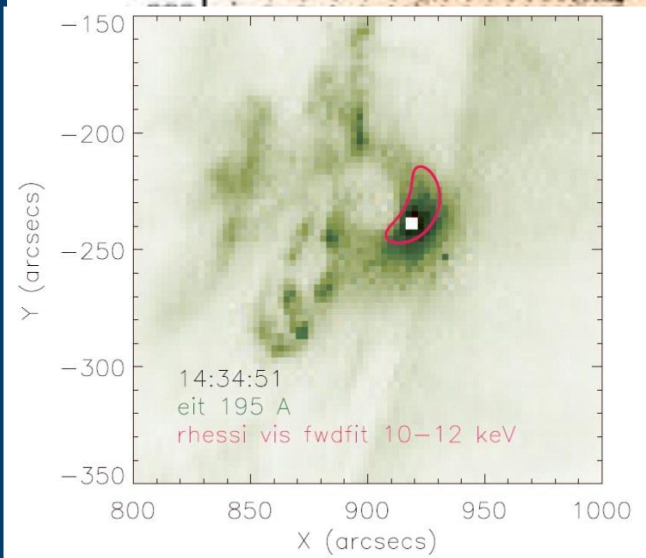


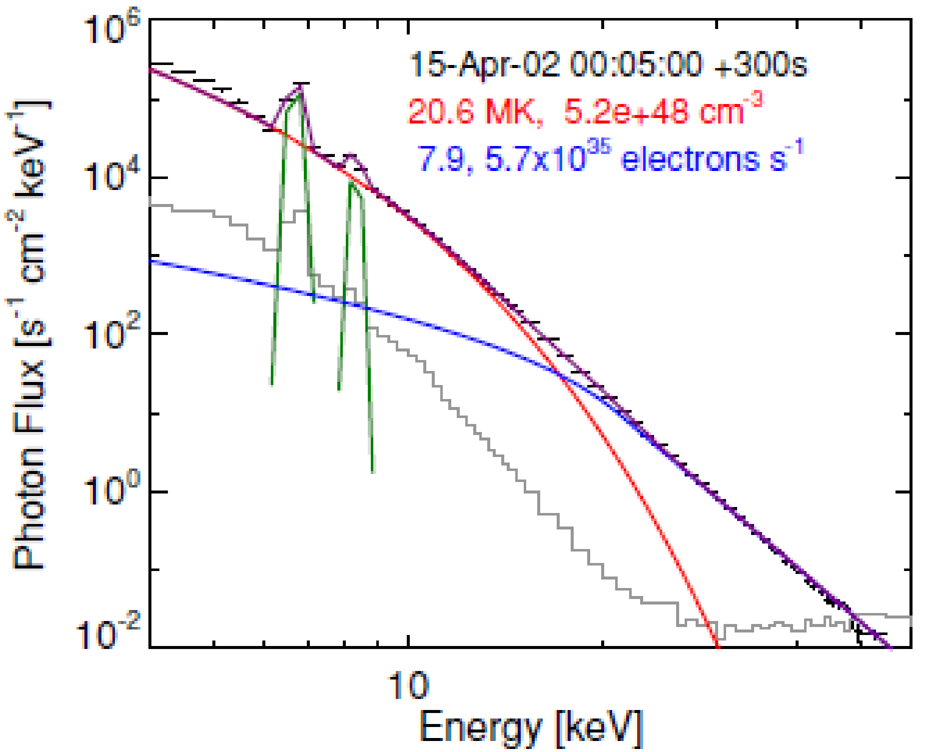


Fleishman et al 2011

HXR flaring loops (no clear footpoints)





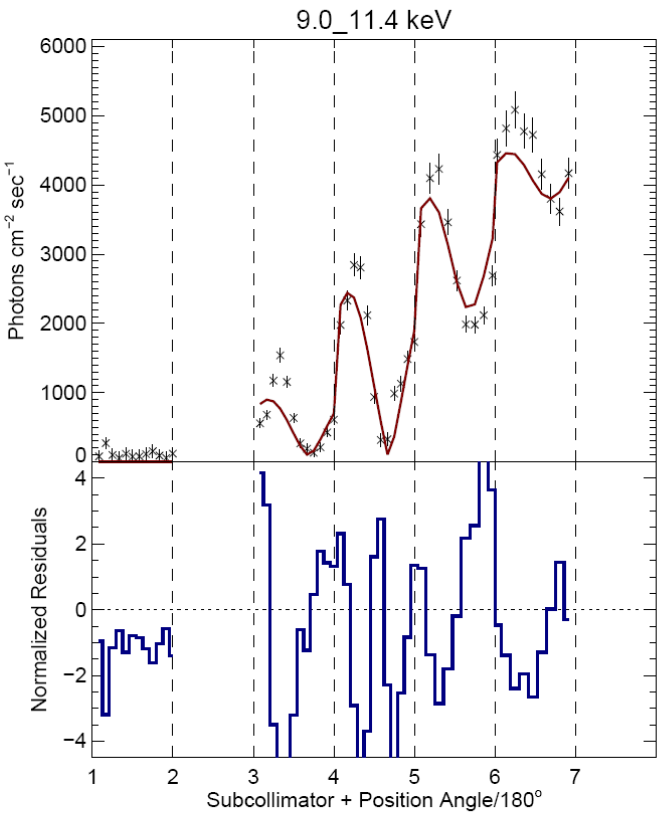


Jeffrey & Kontar, 2013

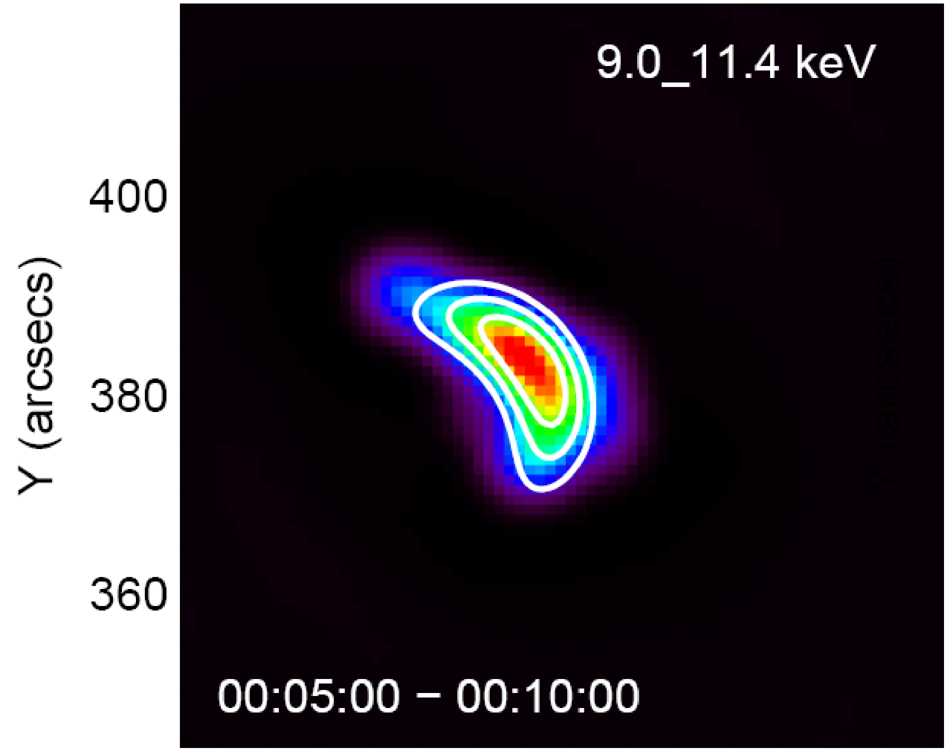
HXR loops sizes and visibilities

$$I(x, y; \epsilon) = I_0 \exp\left(-s^2/2\sigma^2\right) \exp\left(-t^2/2\tau^2\right),$$

$$V(u, v; \epsilon) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(x, y; \epsilon) \exp[2\pi i(ux + vy)]\, dx\, dy,$$



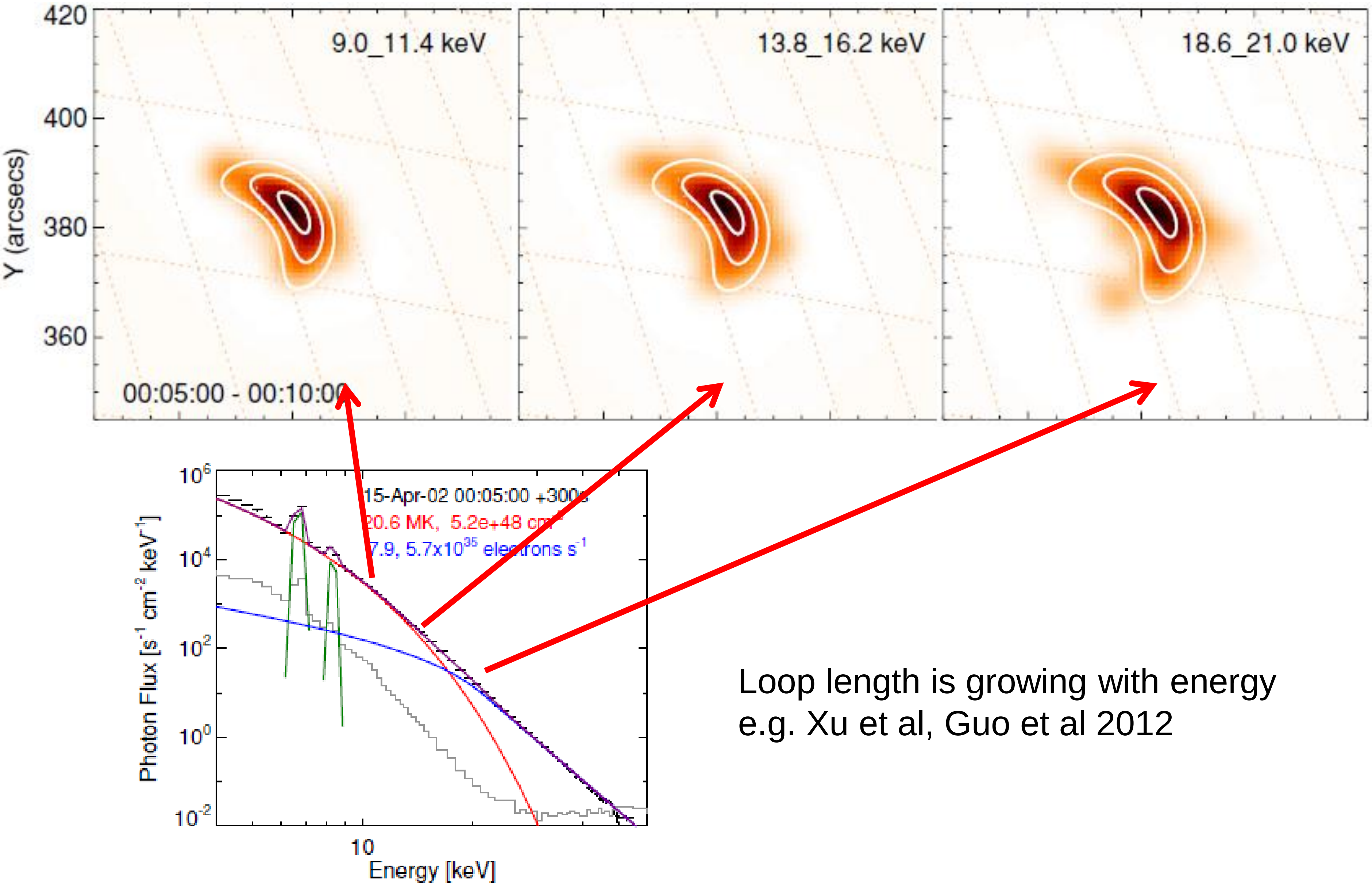
Kontar, Hannah, Bian 2011



Fitting curved ellipse to visibilities

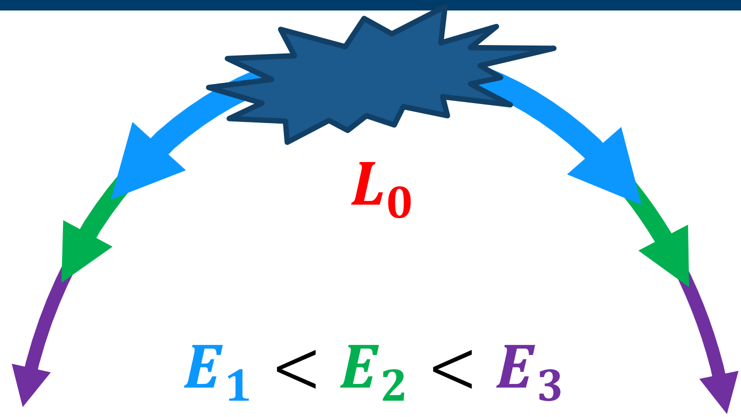
Xu et al, 2008

HXR flaring loops (no clear footpoints)



Loop length is growing with energy
e.g. Xu et al, Guo et al 2012

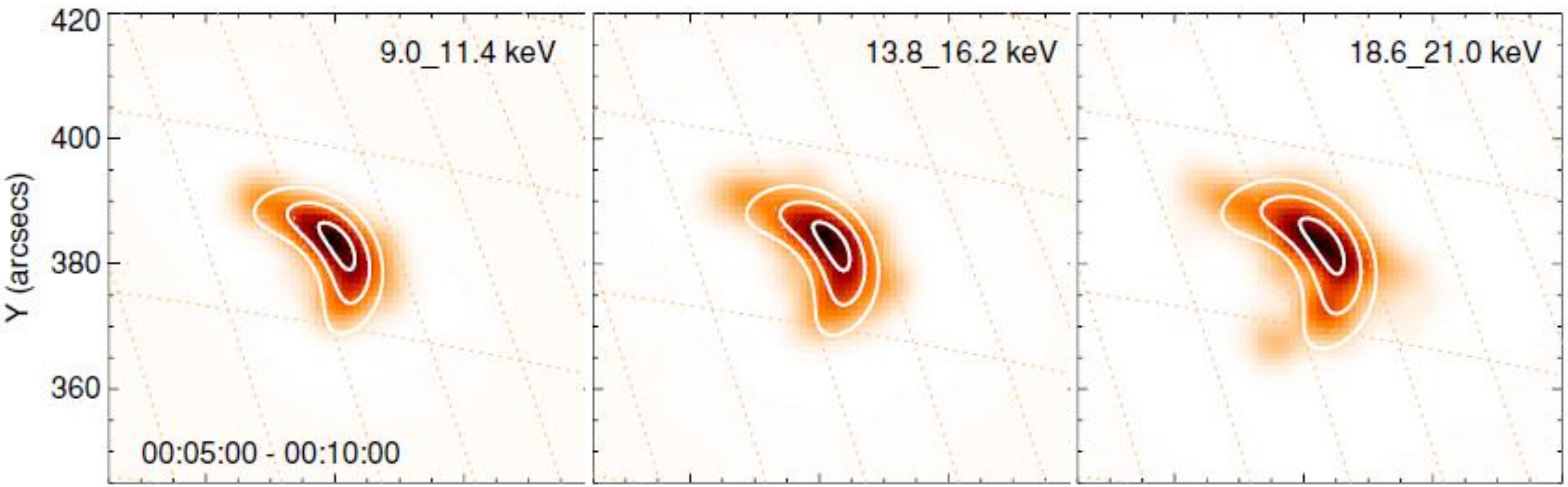
Basics of parallel particle transport



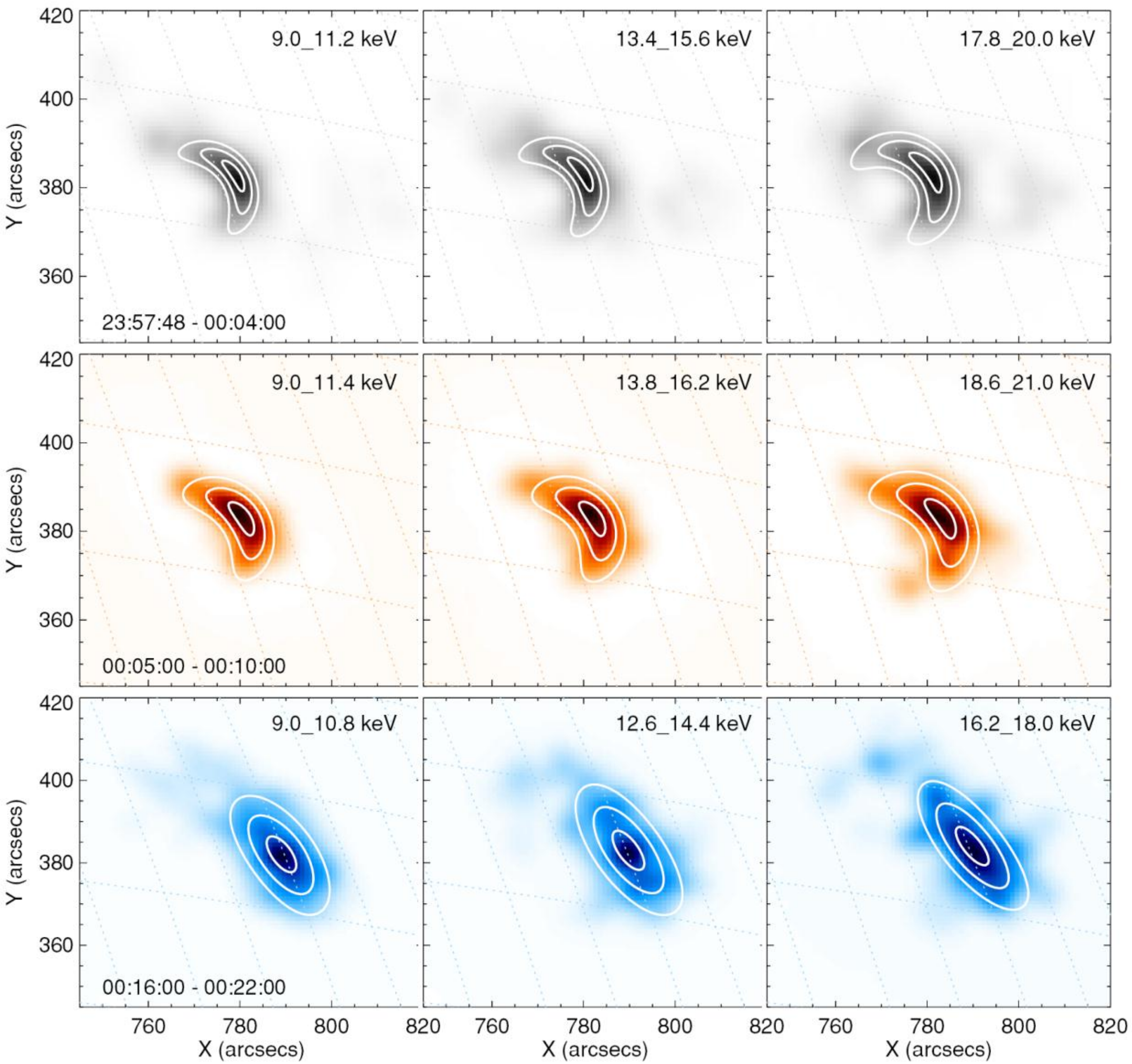
Parallel transport: collisional transport along the field lines of the loop

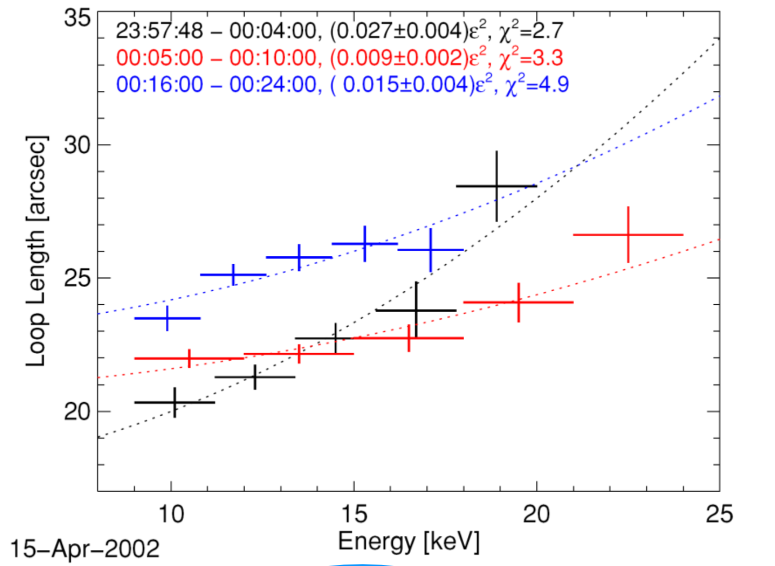
$$\frac{dE}{dz} = -\frac{K}{E} \qquad K = 2\pi e^4 n \ln \Lambda$$

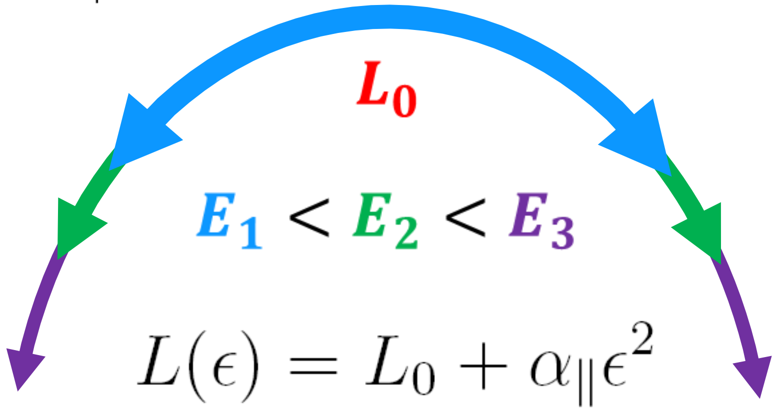
$$L(\epsilon) = L_0 + \alpha_{||}\epsilon^2$$



Energy release inside the loop?

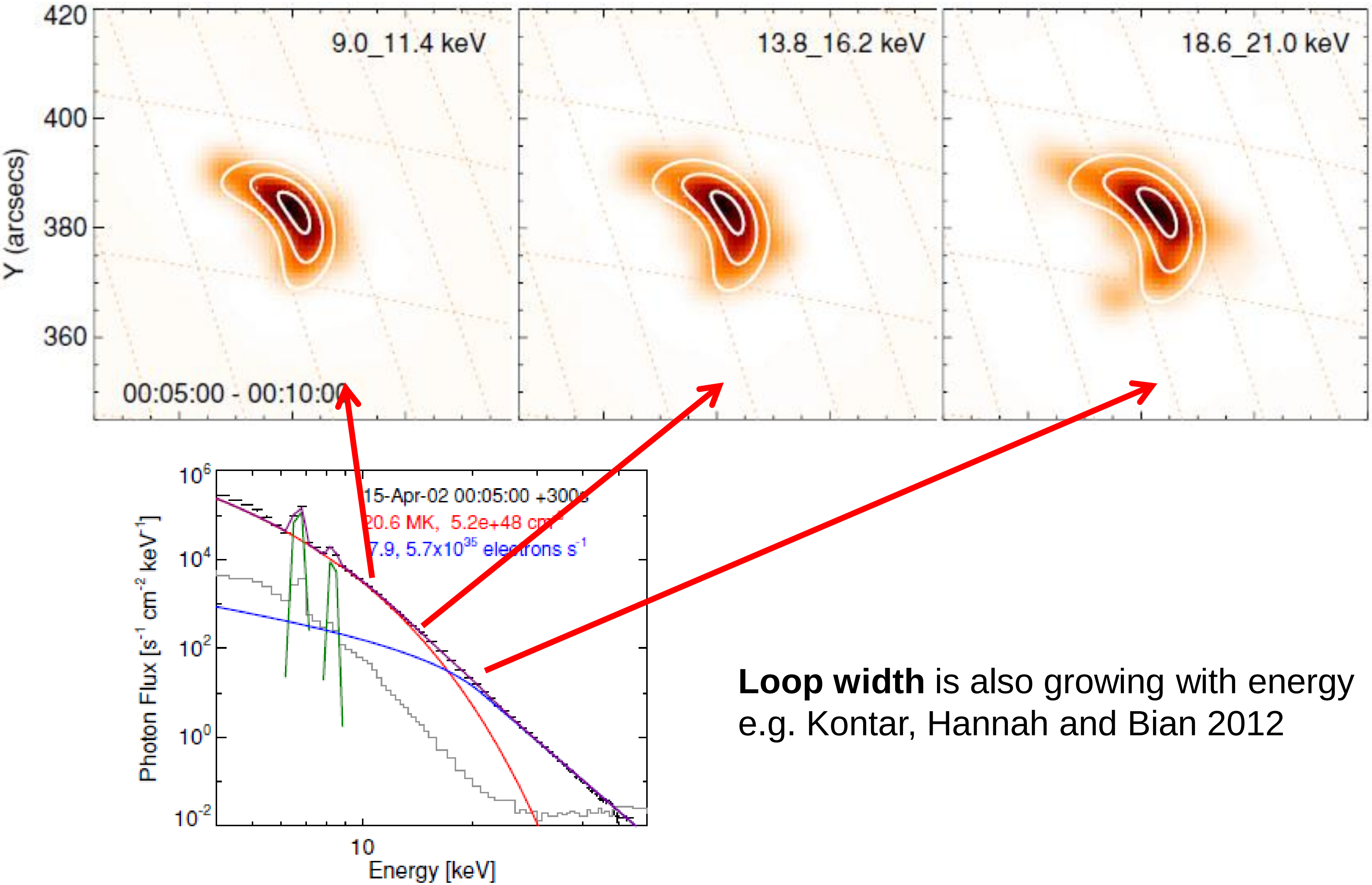






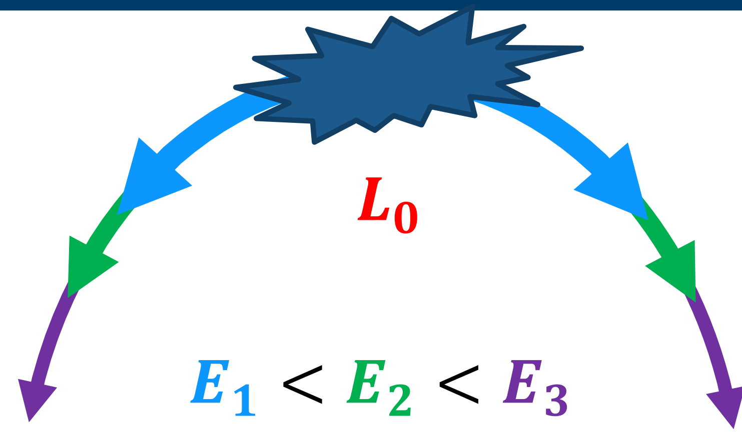
$$L(\epsilon) = L_0 + \alpha_{\|}\epsilon^2$$

HXR flaring loops (no clear footpoints)



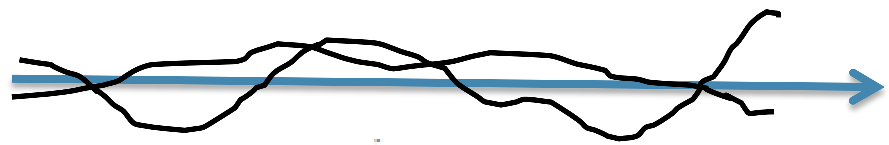
Loop width is also growing with energy e.g. Kontar, Hannah and Bian 2012

Basics of perpendicular particle transport

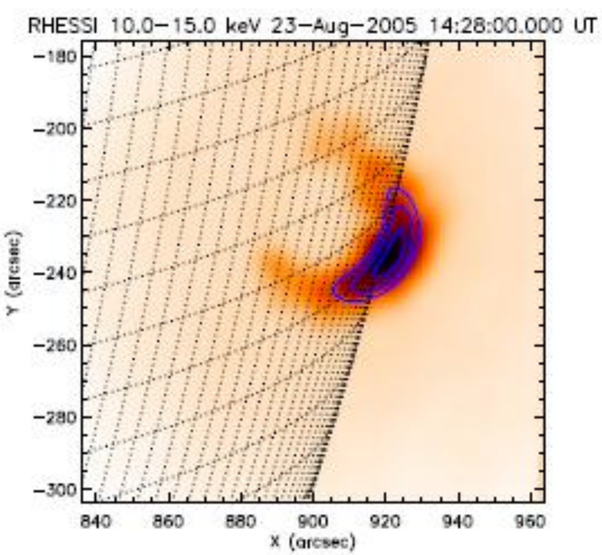


Perpendicular transport: In the guiding-center approximation, the perpendicular transport of particles (for small E × B drift) is described by

$$\frac{d\mathbf{r}_\perp}{dt} = v_z \frac{B_\perp}{B_0}.$$



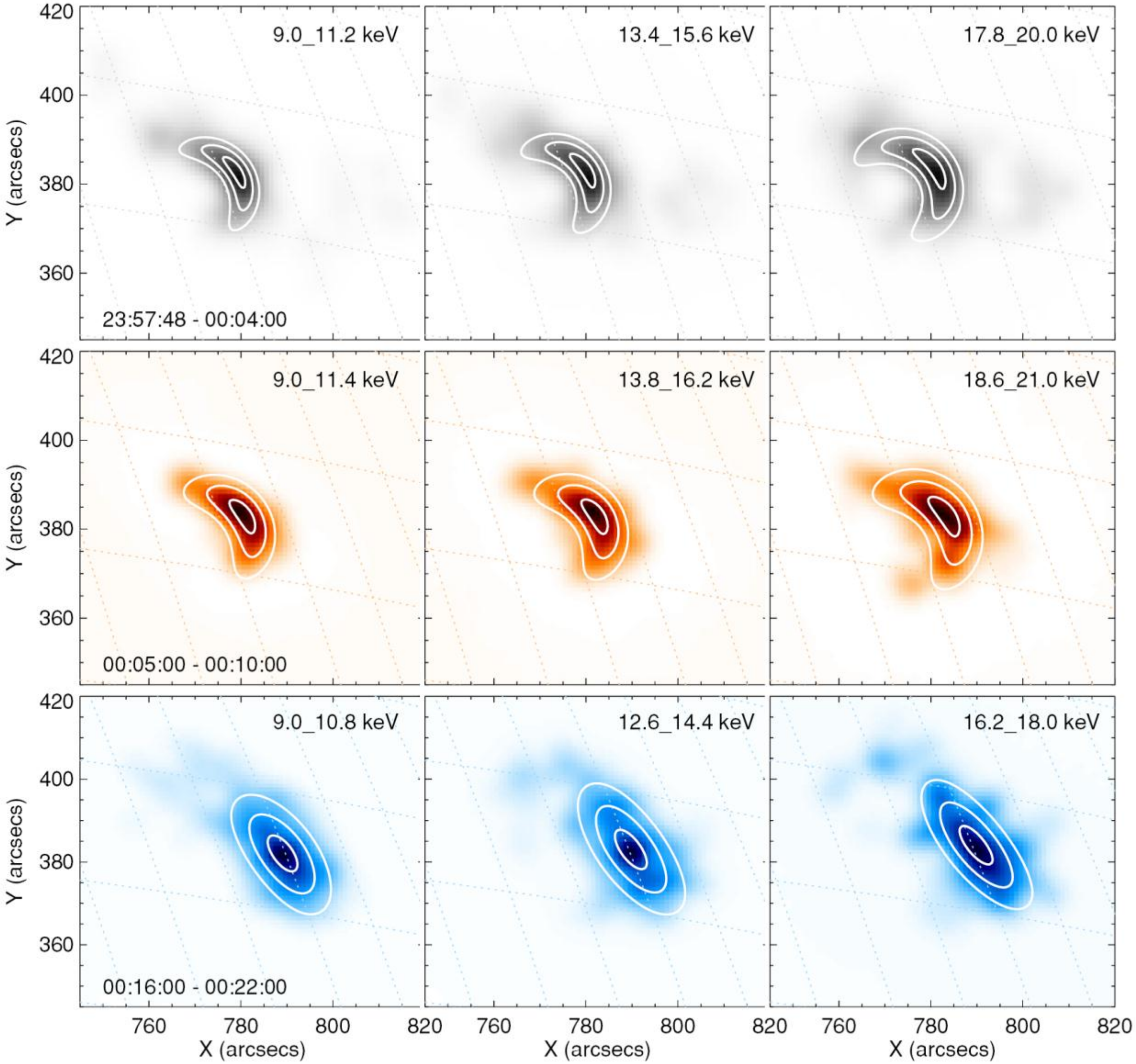
$$r_\perp = \sqrt{2 D_M r_\parallel}$$

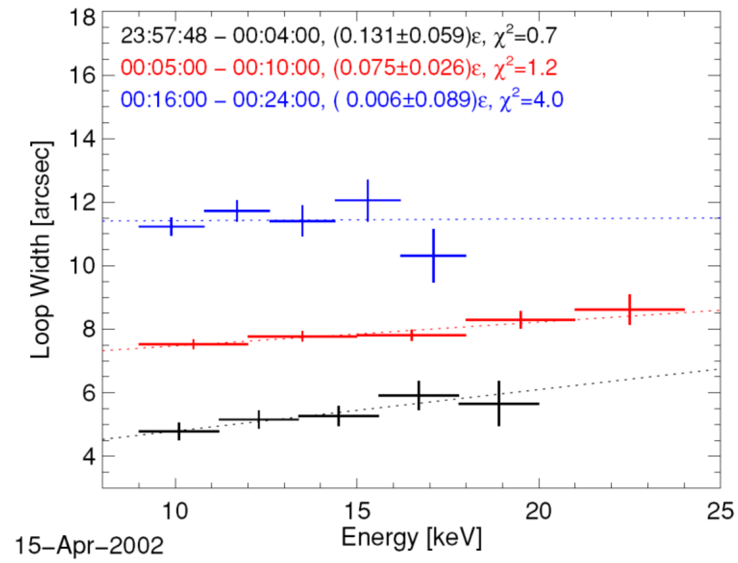


Perpendicular diffusion due to magnetic field fluctuations (wandering) (Jokipii & Parker 1969, Rochester and Rosenbluth, 1978).

$$D_M \simeq (B_\perp^2 / B_0^2)\lambda_\parallel$$

Width of the loop





$$W(\epsilon) = W_0 + \alpha_{\perp}\epsilon$$

Loop width also grows with energy but slower

(Kontar, Hannah,Bian 2011)

Width and length of the loop

$$L(\epsilon) = L_0 + \alpha_{\|}\epsilon^2$$

$$r_{\|} \simeq \epsilon^2/2Kn$$

=> Propagation of electrons **along the magnetic field** lines is consistent with collisional transport

$$W(\epsilon) = W_0 + \alpha_{\perp}\epsilon$$

=> Energy dependent width of the loop is consistent with **cross-field transport** due to the magnetic fluctuations

$$r_{\perp} = \sqrt{2D_M r_{\|}},$$

$$D_M \simeq (B_{\perp}^2/B_0^2)\lambda_{\|}$$

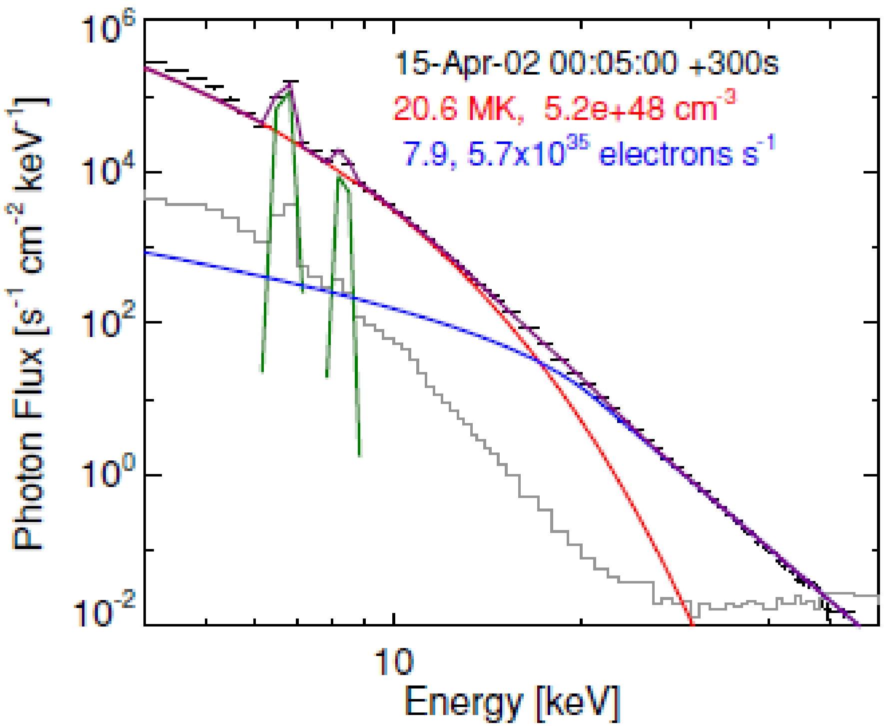
$\Rightarrow$ Hence we estimate the **magnetic fluctuations in the flaring loop where electrons are accelerated** from the source sizes

$$D_M = \lambda_{\|} B_{\perp}^2/B_0^2 = \alpha_{\perp}^2/(2\alpha_{\|})$$

=> From radio observations (Bone et al, 2007), magnetic field is ~150G, the absolute values of magnetic fluctuations can be estimated.

Turbulence energetics

The energy density of magnetic fluctuations in the loop is



$$B_\perp^2/8\pi \simeq (B_0^2/8\pi)D_M/\lambda_\parallel$$

The energy density (for max size 2x10^9 cm) ~ 10 erg/cm^3

$$B_\perp/B_0 \sim 0.1$$

=> From radio observations (Bone et al, 2007), magnetic field is ~150G, the absolute values of magnetic fluctuations can be estimated.

This energy is comparable to non-thermal energy of energetic electrons, but less than thermal for this lambda parallel.

Non-thermal velocities

If we assume that the magnetic field fluctuations are due to MHD waves, the fluctuation velocity and magnetic field fluctuations are related e.g. for linear Alfvenic modes

$$v \sim B_{\perp}/B_0 v_A$$

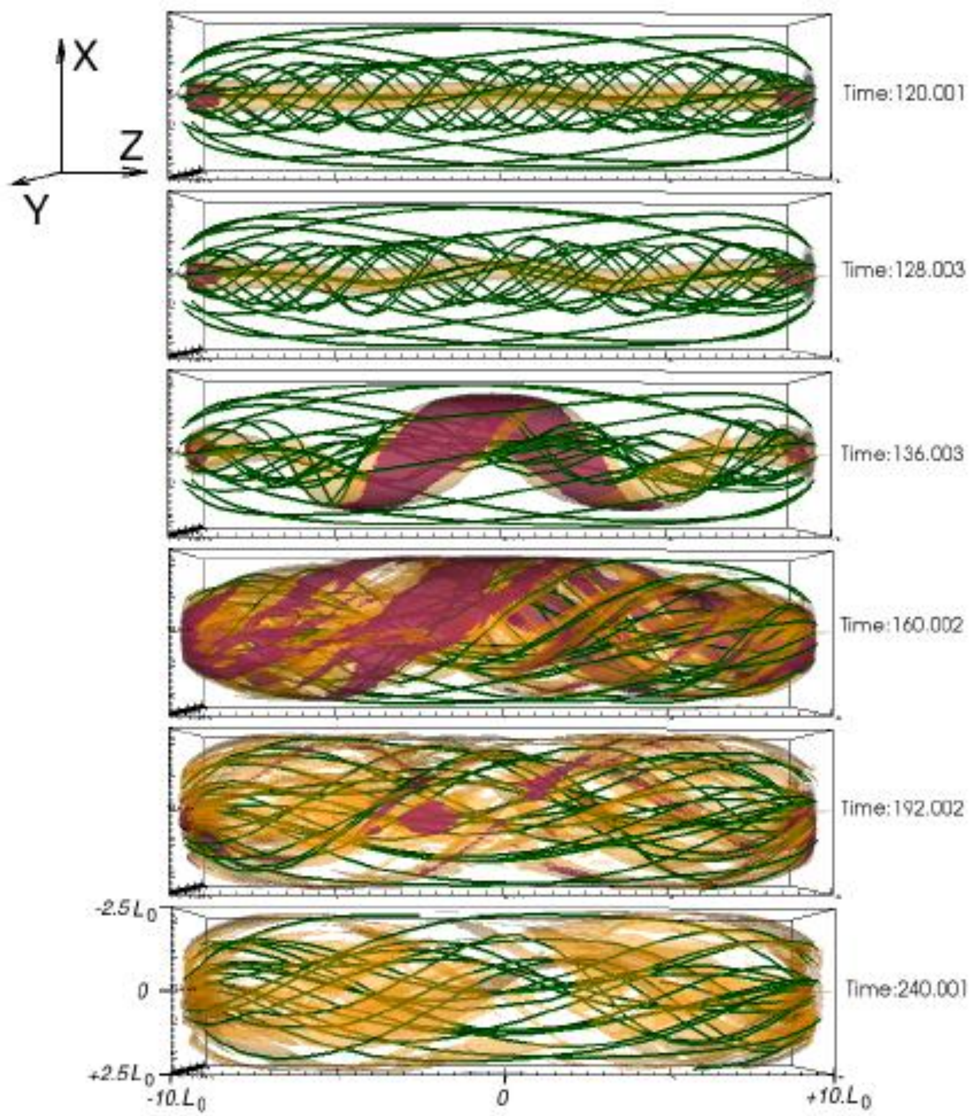
Radio measurements provide us with magnetic field and X-ray measurements with density

$$\text{for } v_A \simeq 1000 \text{ km s}^{-1}$$

$$B_{\perp}/B_0 \sim 0.1$$

Turbulent (non-thermal velocities) velocities
Vnt ~ 100 km/s

Extended acceleration scenario



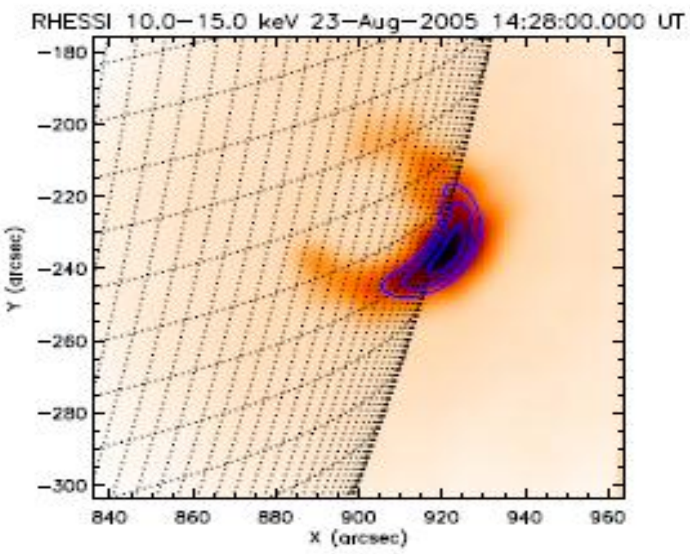
Simulations by Gordovskyy, et al 2012

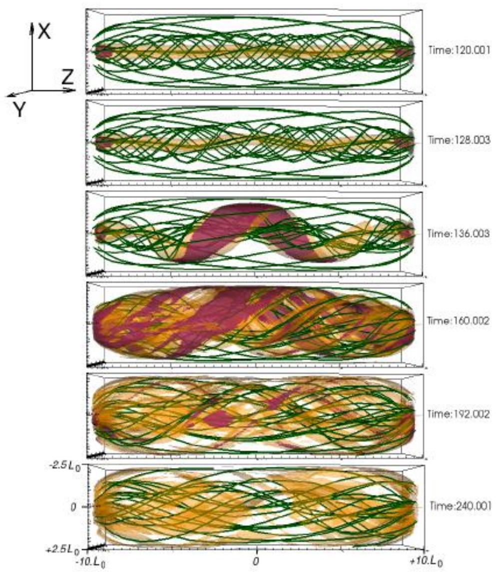
Are particles accelerated within the loop?

Multiple current sheets
Vlahos et al 1998, Turkmani et al, 2005, Hood et al, 2008, Browning et al 2008, Gordovskyy et al, 2012

Plasma turbulence acceleration
Sturrock, 1966, Melrose, 1968
Miller et al 1997, Petrosian et al, 1994; Bian et al, 2012

Summary





Dense HXR loops allow to observe and spatially distinguish acceleration and transport of energetic particles.

Propagation of electrons **along the magnetic field** lines is consistent with collisional transport

Energy dependent width of the loop is consistent with **cross-field transport** due to the magnetic fluctuations and implies line-of-sight non-thermal velocities of the order of 100 km/s.

Simultaneous observations of non-thermal line widths and loop-energy width can scrutinise these models and diagnose turbulence in flaring loops.