HESPE: WP3 - Theory

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With contributions from:
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Objectives:

The objectives of this WP are: to capitalize on the improved techniques in X-ray and gamma-ray data analysis and diagnostics; to develop the background theory of particle acceleration; to improve the efficiency of X-ray diagnostics by integration with appropriate datasets.

Deliverables :

D3.1 Specification of models for particle acceleration mechanisms for selected events (Month 24)

D3. 2 Specification of models for energy release for selected events (Month 24)

D3.3 Specification of paradigms for simulation of synthetic data (Month 24)

D3.4 Specification of paradigms for multiwavelength interpretation (X-rays, EUV, radio) (Month 36)

D3.5 Part of the Project Report (first year) concerning the Theory Work Package (Month 12)

D3.6 Part of the Project Report (second year) concerning the Theory Work Package (Month 24)

D3.7 Part of the final Project Report concerning the Theory Work Package (Month 36)

WP3-Theory: Tasks

Task 1: Parameters of accelerated particles
Derivation of the characteristic parameters of the accelerated particle populations in solar flares and use X-ray and gamma-ray diagnostics to measure the electron angular distributions and X-ray source structures.

Task 2 Study of the energy release sites and particle acceleration mechanisms
Combination of X-rays and other wavelengths to derive the physical conditions of the energy release sites and to better understand particle acceleration mechanisms: with radio observations related to geo-effective factors (space weather); optical, SXR and EUV (SDO mission).

Task 3 Development of paradigms for generating synthetic data
Design of physical/geometric configurations for flaring events; formulation of simulation paradigms for producing calibrated event lists, hard X-ray visibilities, count spectra and images.

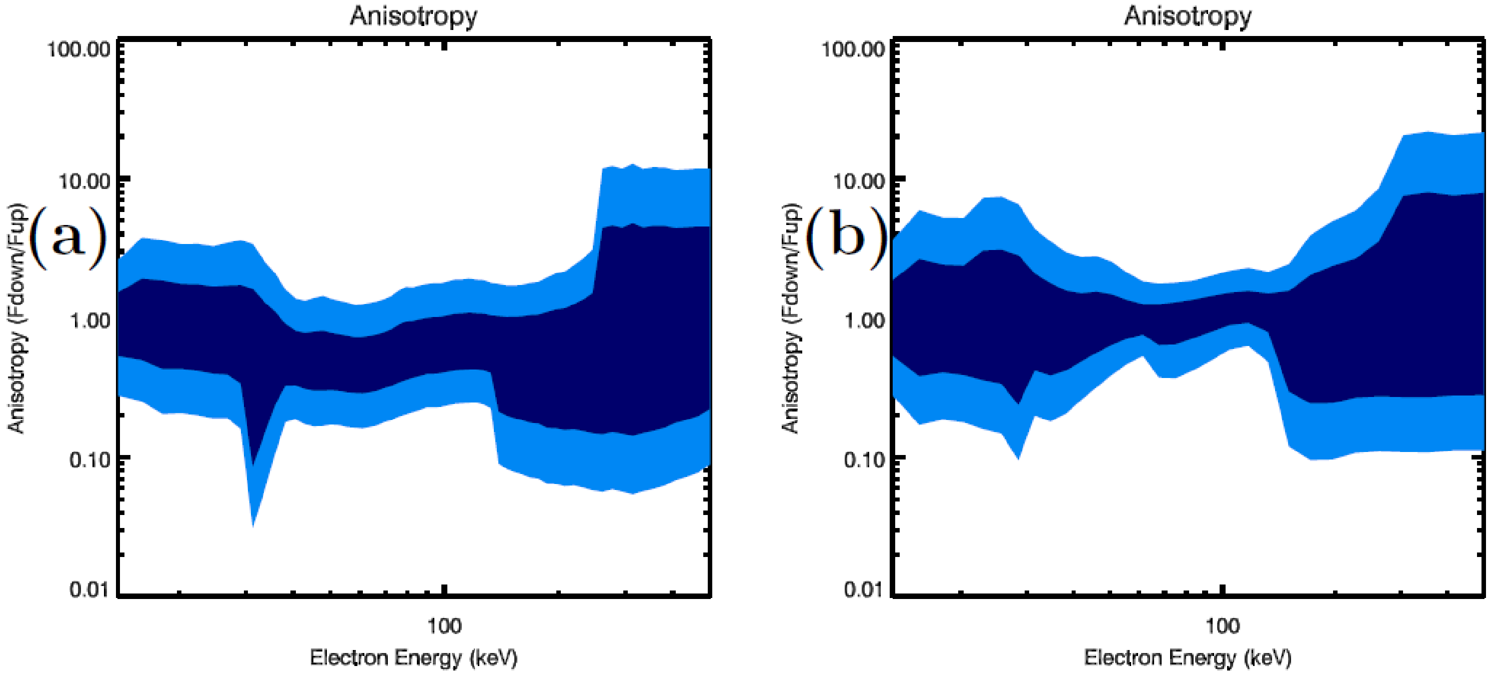
Task 4 Development of particle acceleration and propagation models
Based on the results obtained in tasks 2.1 and 2.2, we will undertake theoretical development of particle acceleration models, and particle propagation models.

Task 1: Parameters of accelerated particles

Derivation of the *characteristic parameters* of the accelerated particle populations in solar flares and use X-ray and gamma-ray diagnostics *to measure the electron angular distributions* and *X-ray source structures*. *Combination of the analysis of SEP events at the Earth and at the Sun using X-ray and gamma-ray data, to identify the propagation properties of energetic particles* in turbulent plasma media of the solar corona and interplanetary space.

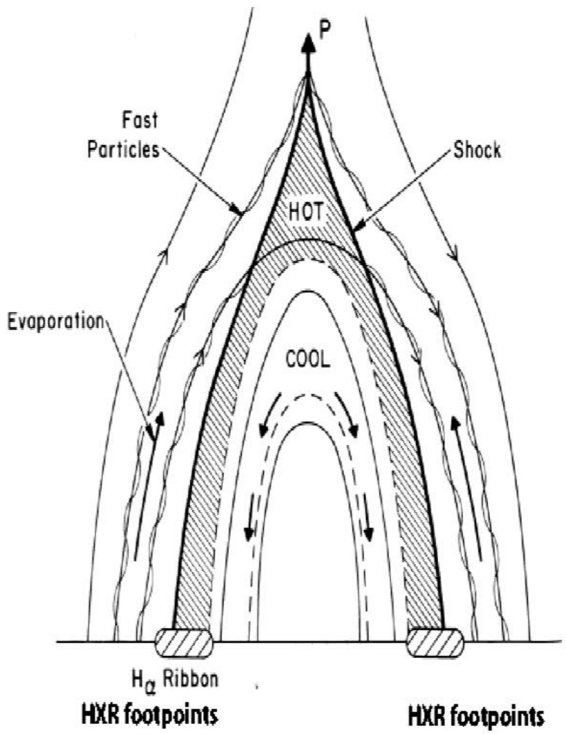
Task 1a: … *The electron angular distributions*

Dickson & Kontar, *Sol. Phys.*, 2013 *Measurements of Solar Flare Anisotropy Using albedo with RHESSI, 9 flares analysed.*

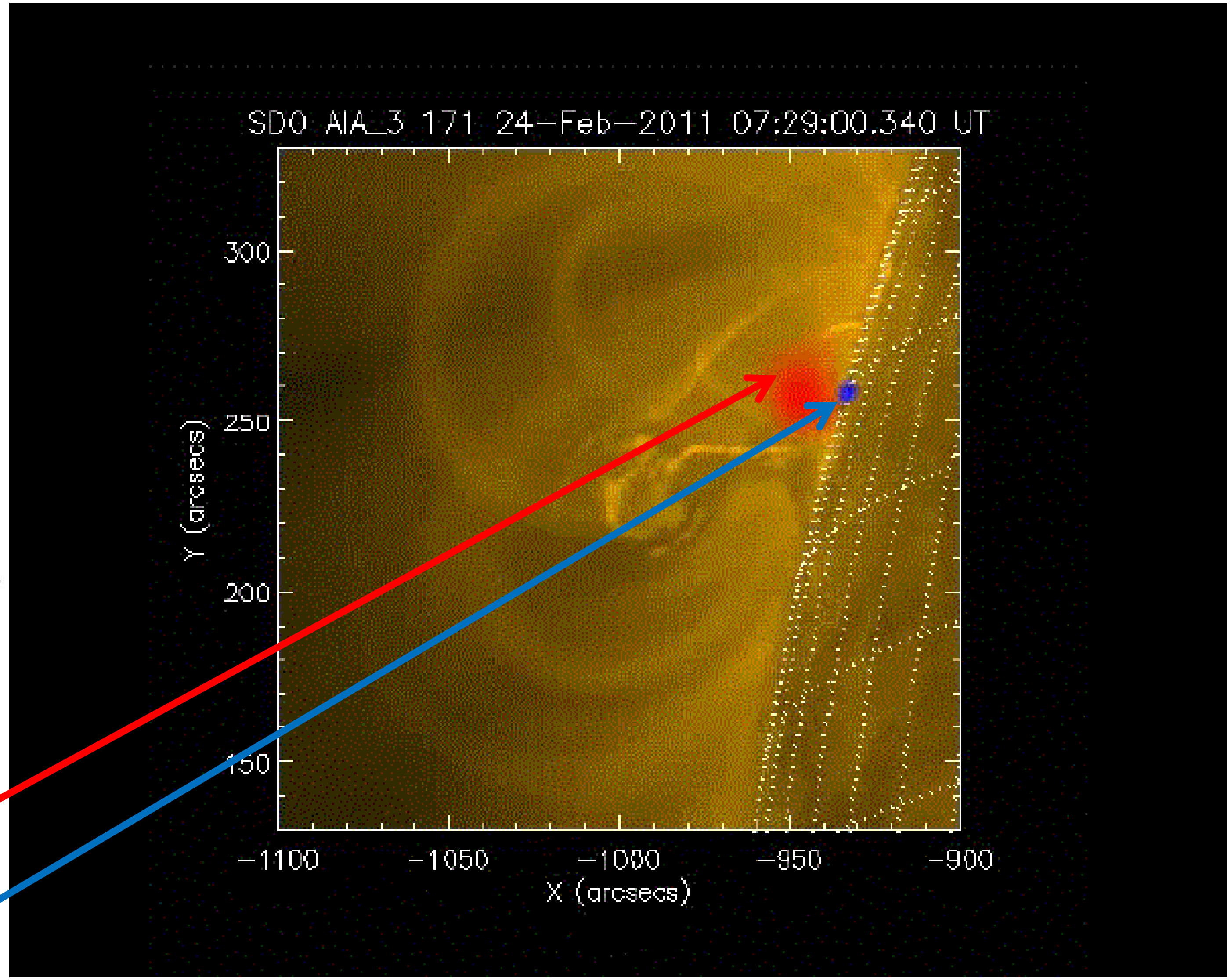


Diego Casadei – “Fully Bayesian method ”

Typical solar flare: X-ray prospective



Standard flare model picture (Shibata, 1996)

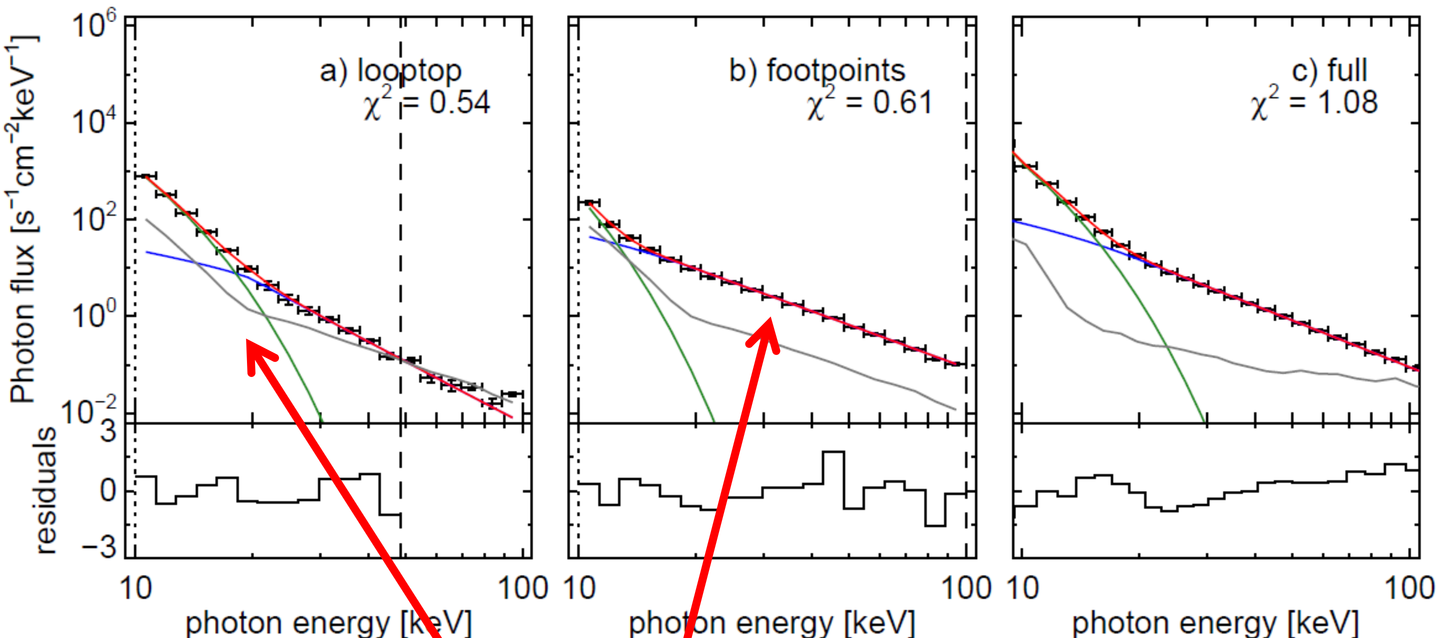


Loop-top: Soft X-ray plus non-thermal component

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

Animation from Battaglia & Kontar, 2011

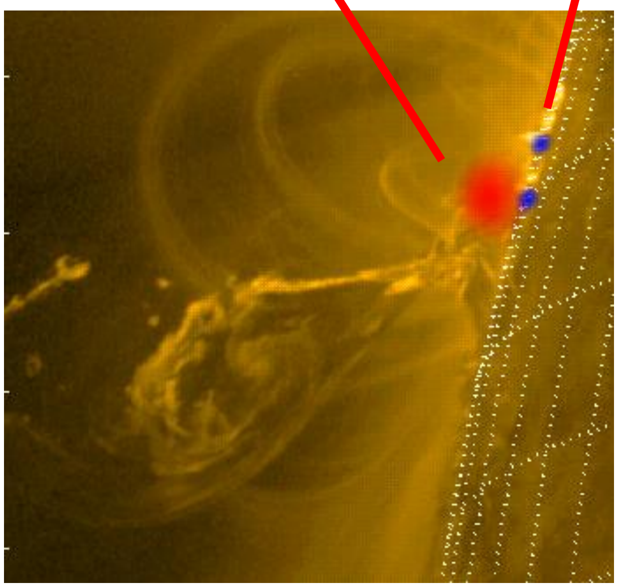
Motivation



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

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

Simoes & Kontar, A&A, 2013

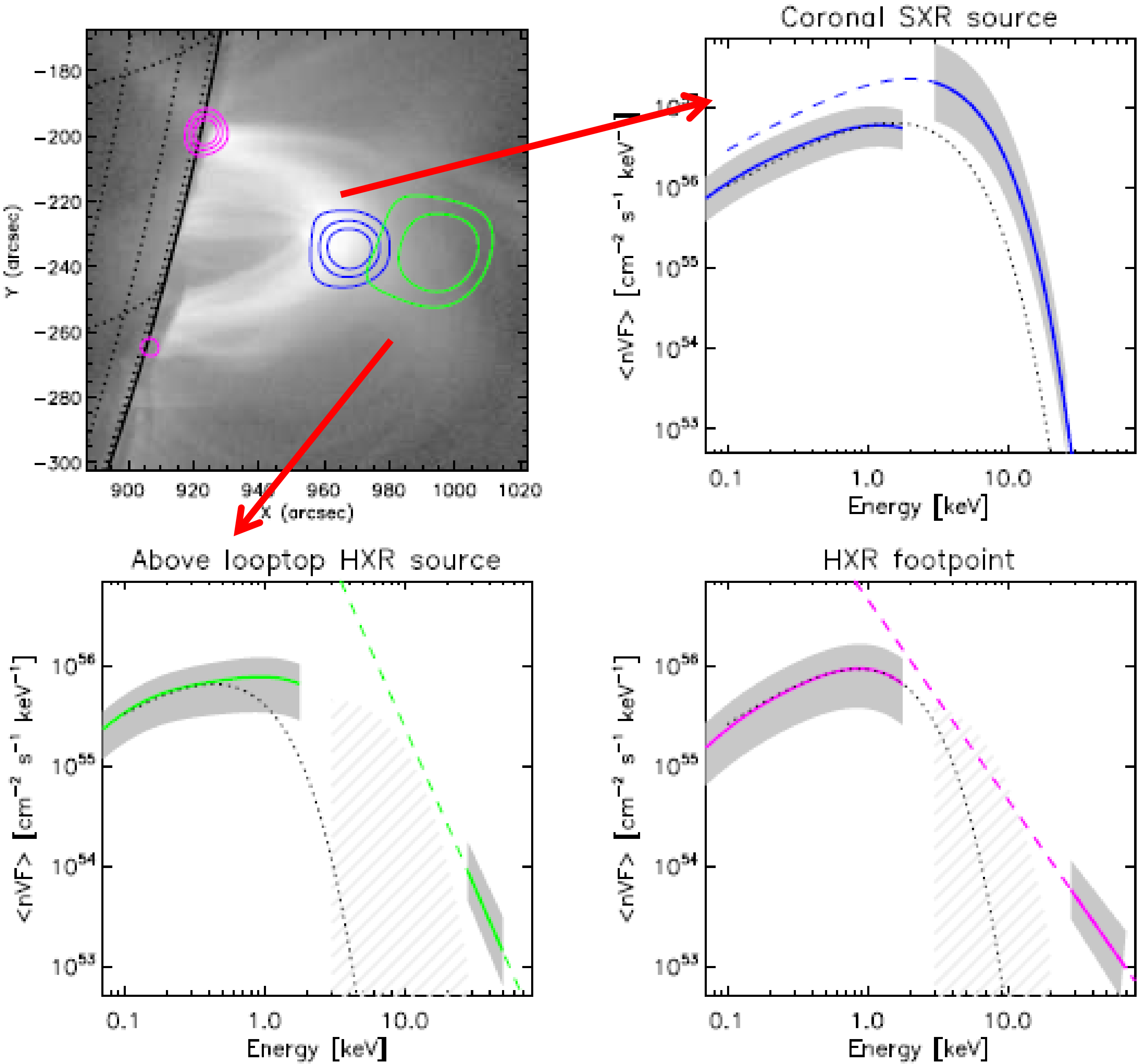


Using imaging spectroscopy, we can infer spectra and numbers of energetic electrons both in coronal and foot-points sources.

Above 30 keV, we have normally a few times (2-8) electrons more in the LT than in FP source.

Possible trapping by waves or magnetic mirroring….

Electron distributions from 0.1 to ~50 keV

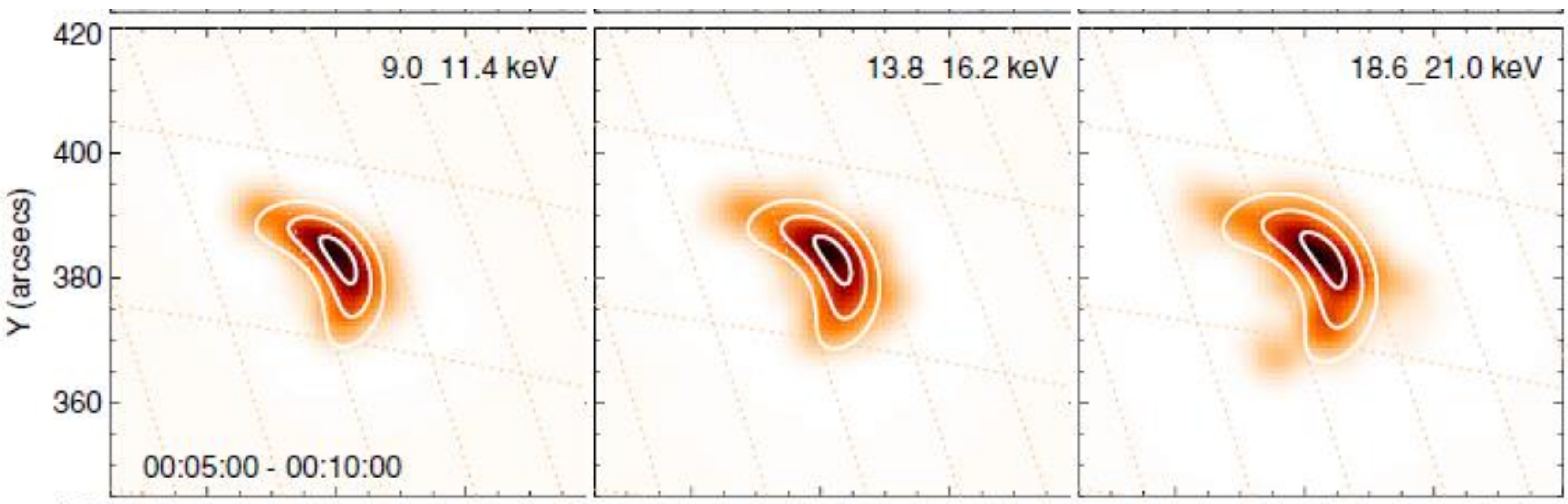


The combined analysis of RHESSI and AIA data allows to infer the electron distribution function over the broad energy range from 0.1 keV up to a few tens of keV.

Battaglia & Kontar, ApJ,2013

Task 1b: … *X-ray source structures in the corona*

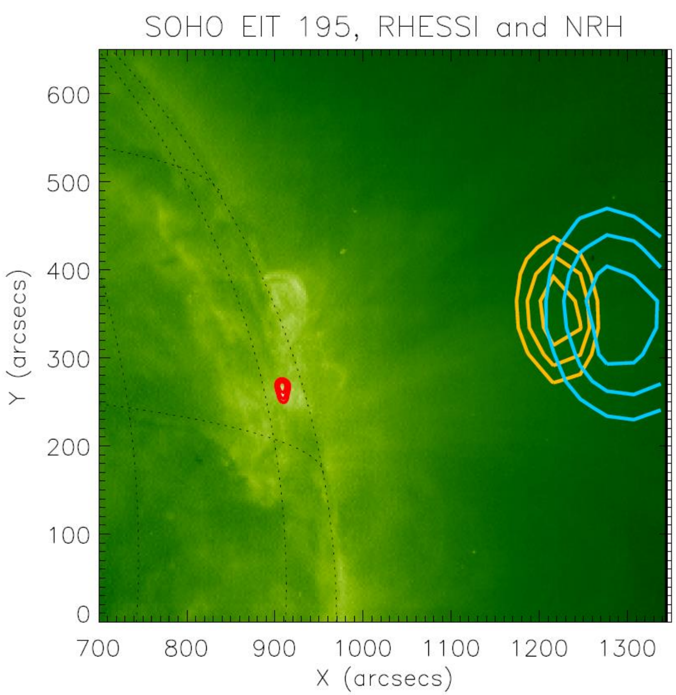
Acceleration region and particle transport diagnostics

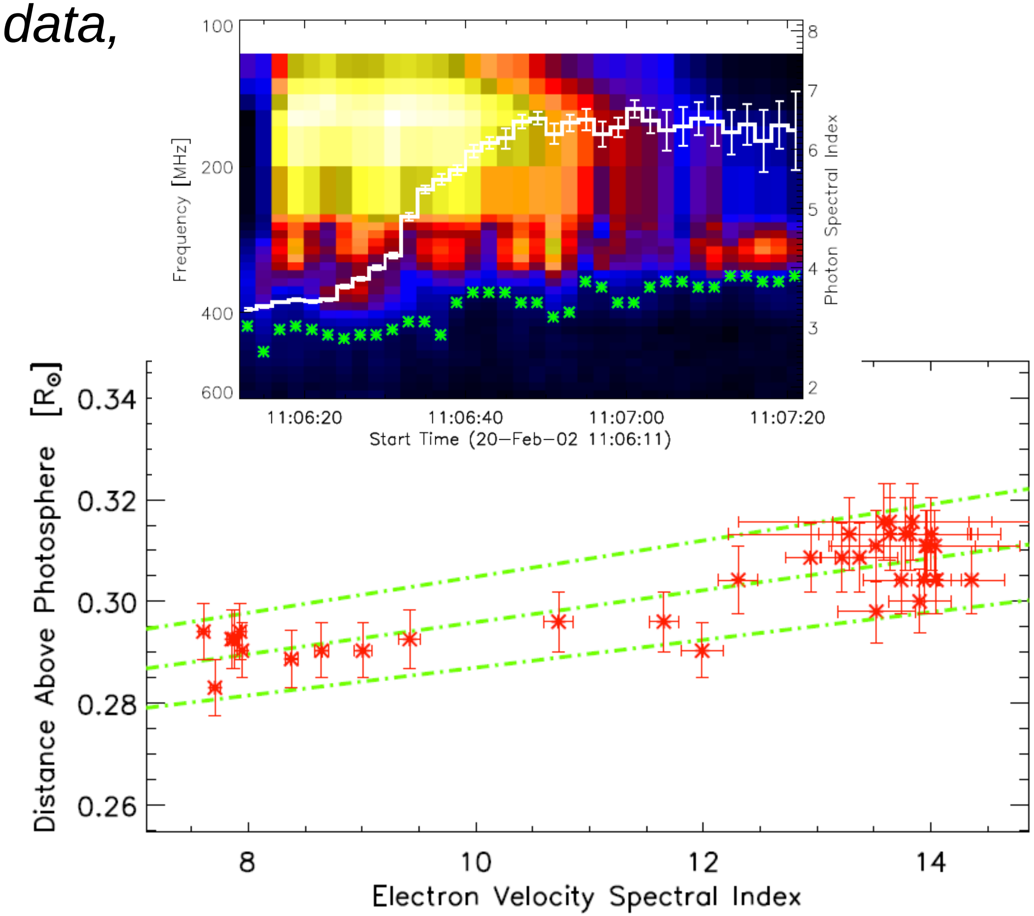


Unique diagnostic potential of acceleration size and magnetic fluctuations… Poses new questions – electron visibilities (Jingnan work) and finite temperature effects on transport (Michele work)

Task 1c: … combination of the analysis of SEP events at the Earth and at the Sun using X-ray … (in collaboration with Meudon)

Reid, Vilmer, and Kontar, *Analysis of escaping and HXR producing electrons using X-ray and radio data,*





Nicole's talk …

Task 2 Study of the energy release sites and particle acceleration mechanisms
Combination of X-rays and other wavelengths to derive the physical conditions of the energy release sites and to better understand particle acceleration mechanisms: with radio observations related to geo-effective factors (space weather); optical, SXR and EUV (SDO mission).

Task 2a: *… X-ray source structures -> parameters of acceleration site*

…better understanding of acceleration…

Nicolas Bian, A. Gordon Emslie & Eduard P. Kontar, *A Classification of Stochastic Acceleration Processes, ApJ, 2012*

Classification of stochastic acceleration models
for particle transport
a) free streaming
b) diffusion
c) free streaming + diffusion

$$\frac{\partial f(p,t)}{\partial t} = \frac{\partial}{\partial p}\left[D_0 p^\alpha \frac{\partial f(p,t)}{\partial p}\right]$$

for fields
a) general case
b) plasma modes [specific case with omega=omega(k)]
c) resonance broadened growth/damping of waves

.. better understanding of acceleration…

Nicolas Bian, A. Gordon Emslie & Eduard P. Kontar, *A Classification of Stochastic Acceleration Processes, ApJ, in preparation*

$$D(p) = \int_0^\infty dt \int_{-\infty}^\infty dx\, C(x,t)\, P(x,t)$$

$$D(p) = \int \int dk\, d\omega\, S(k,\omega)\, G(k,\omega) \quad ,$$

What is the amount of scattering required?

We assume that the trapping is due to pitch angle scattering inside the loop and quantify how strong the pitch-angle scattering should be to explain the observation?

Some background:
Efficient pitch angle scattering is rather common requirement for stochastic acceleration
during flares (e.g., Petrosian 2012; Bian et al. 2012, for recent reviews).

The presence of magnetic fluctuations in flaring loops is suggested by the increase of loop width with energy revealed by *RHESSI* observations (Kontar et al. 2011a; Bian et al. 2011).

The effects of turbulent pitch angle scattering, which may lead to diffusive transport in the limit of strong scattering, have been considered in the solar flare literature (e.g. Holman et al. 1982; Bespalov et al. 1991; Stepanov & Tsap 2002; Stepanov et al. 2007) and used in the interpretation of solar flare observations (e.g. Jakimiec et al. 1998; Fleishman et al. 2013)

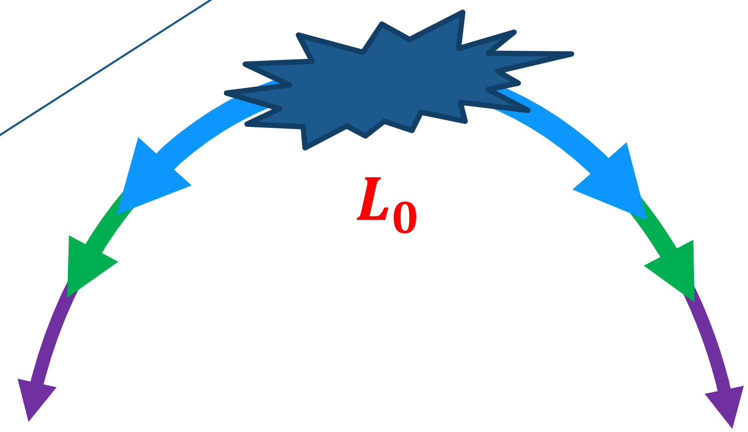
Pitch angle scattering and transport

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

Energy loss via binary collisions

Pitch angle scattering

Source of electrons



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 against collisions):

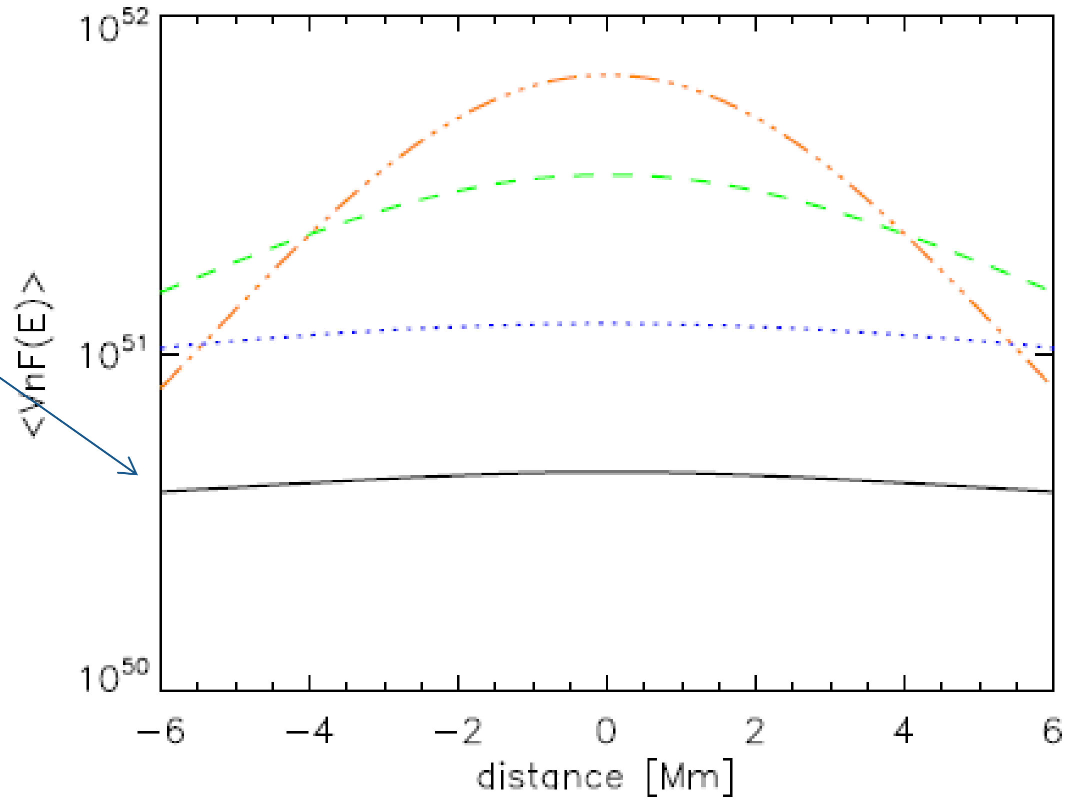
$$\frac{1}{v}\frac{\partial}{\partial z}\left(D_{zz}^{(T)}\frac{\partial F}{\partial z}\right) = \frac{\partial}{\partial E}\left(\frac{Kn(z)}{E}F\right) + F_0(E)\,S(z)$$

Non-collisional trapping

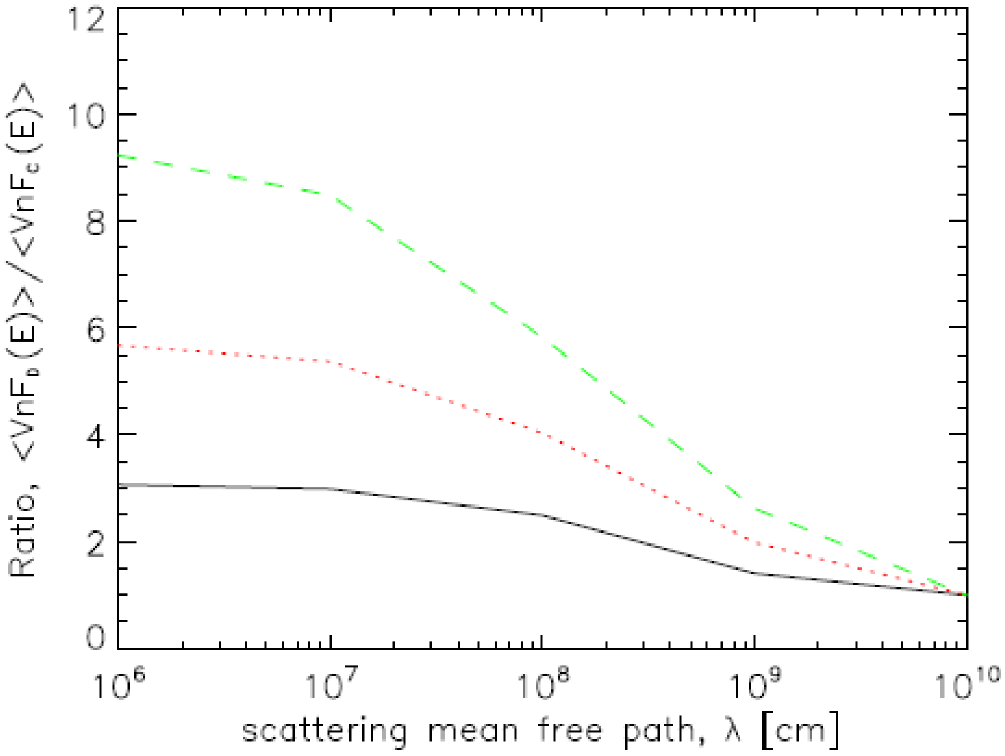
Spatial distribution of energetic electrons at 20 keV:

The standard (scatter-free) transport

the diffusive-collisional transport cases
for $\lambda = 10^9$ cm
(blue dotted line),
$\lambda = 10^8$ cm
(green dashed line), and
$\lambda = 10^7$ cm
(orange dot-dashed line).



Non-collisional trapping

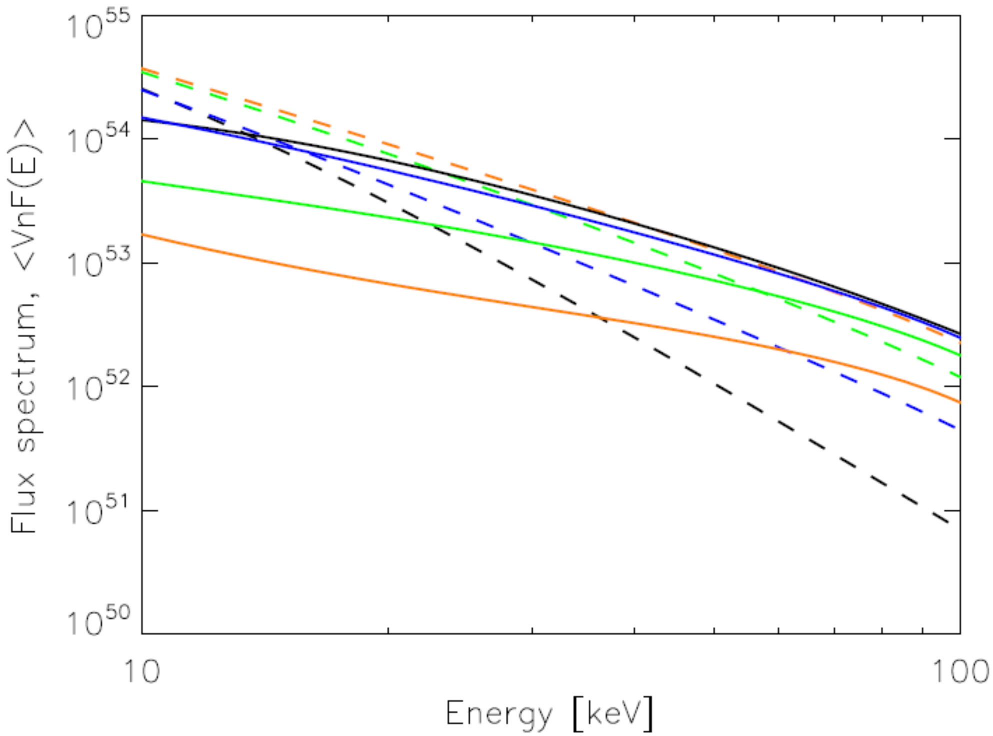


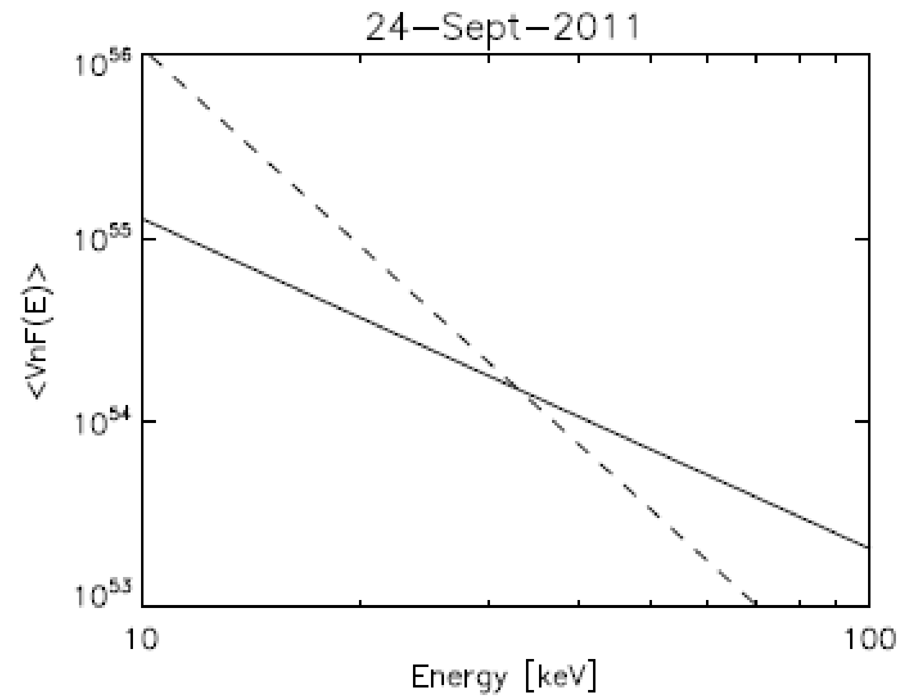
Ratio of the diffusive and scatter-free mean electron fluxes
in the coronal source for plasma densities: 5×10^{10} cm−3

Three characteristic energies:
20 keV (solid black line),
30 keV (red dotted line),
and 40 keV (green dashed line).

Non-collisional pitch angle scattering

Solid line – footpoint; dashed is the coronal



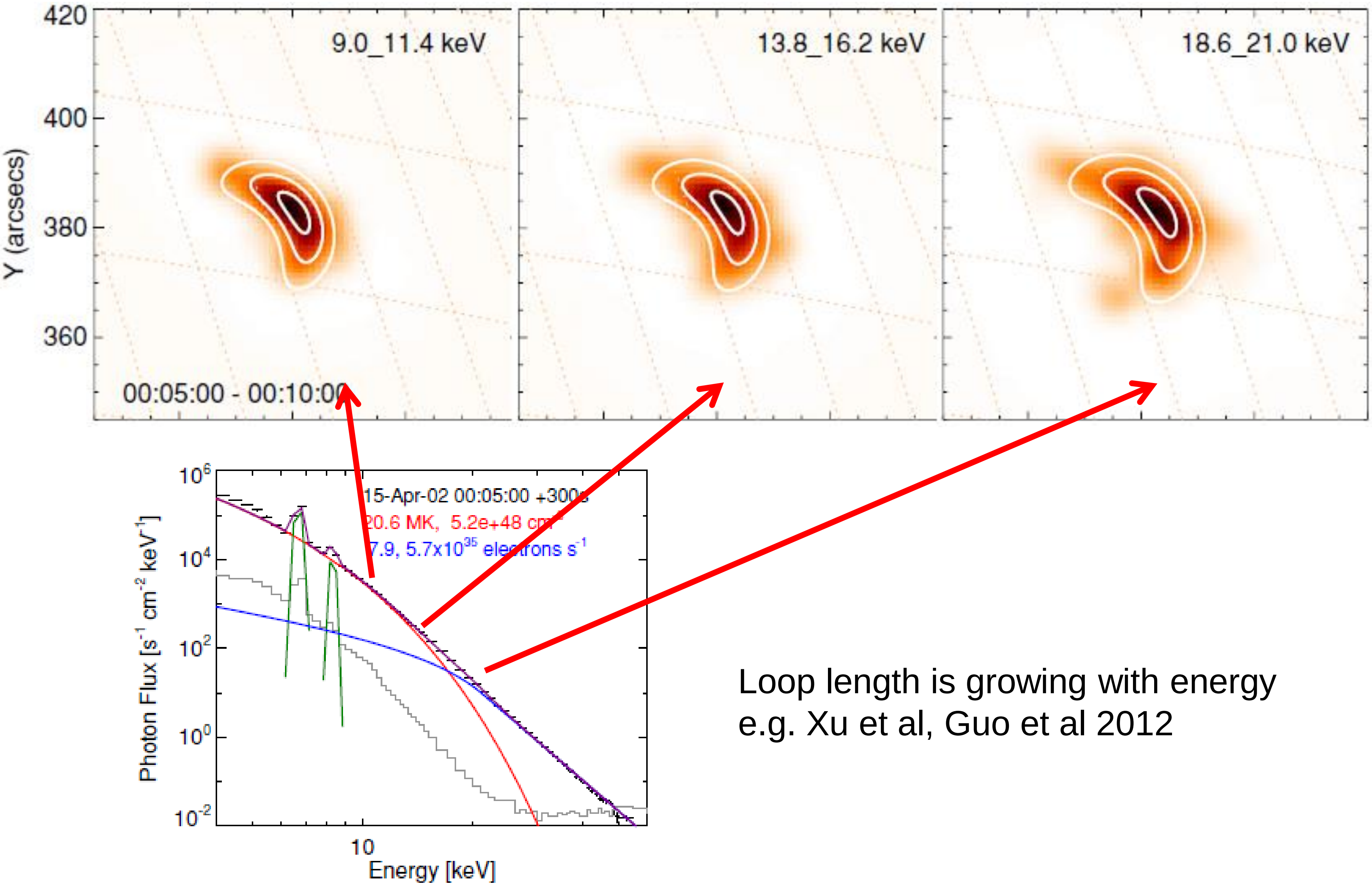


RHESSI Observations

Black – no scattering, non-collisional scattering with mean free path 10^9 cm (blue), 10^8 cm (green), 10^7 cm (orange)

Kontar et al, 2013 submitted to ApJ

HXR flaring loops (high density)

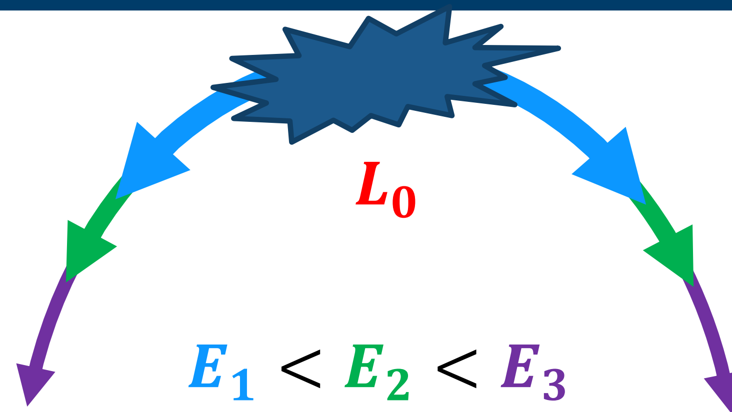


Loop length is growing with energy
e.g. Xu et al, Guo et al 2012

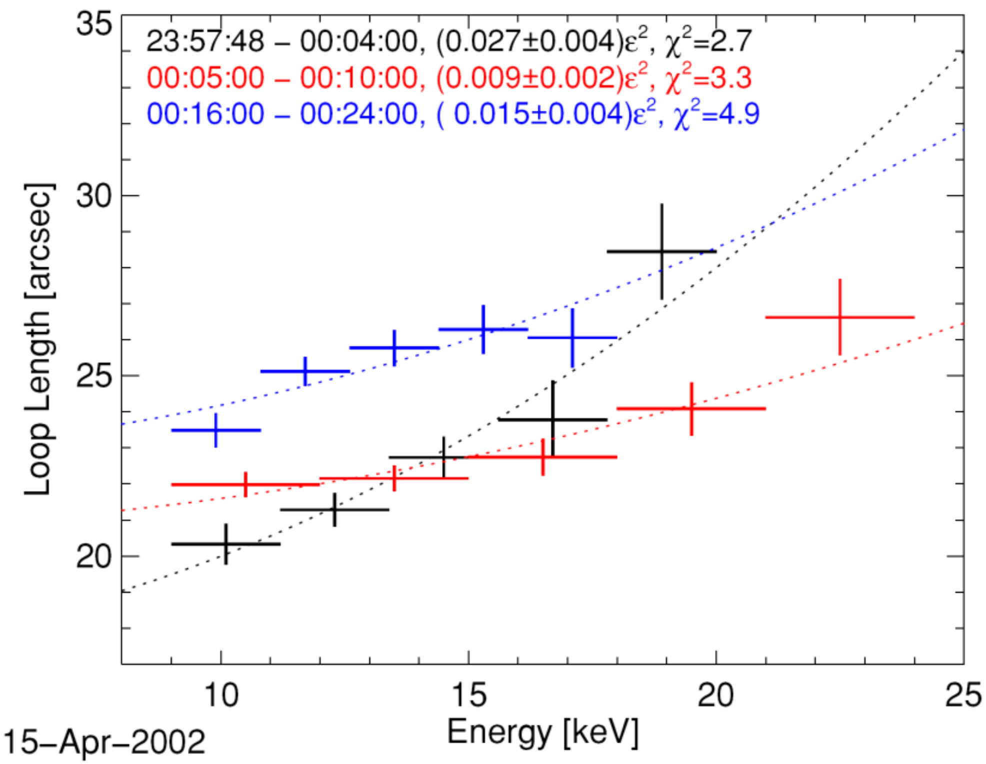
Basics of parallel particle transport

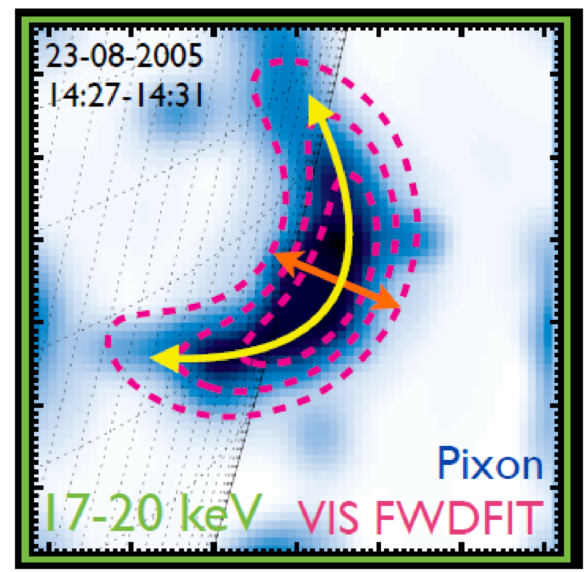
Parallel transport: collisional transport along the field lines of the loop

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

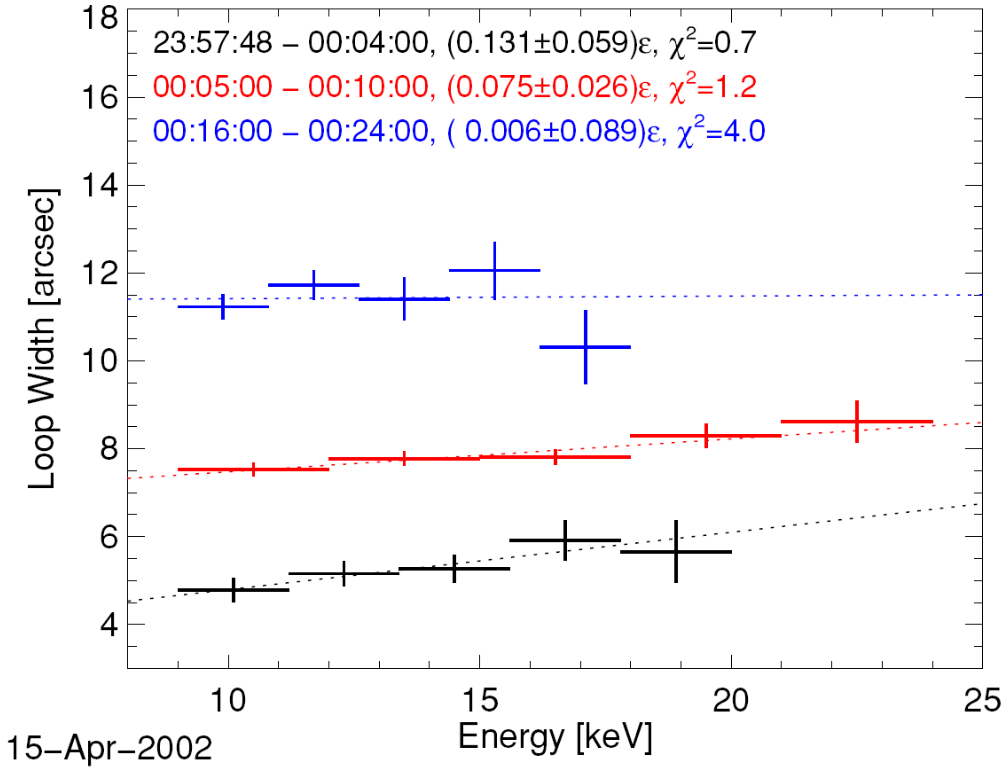


$$L(\epsilon) = L_0 + \alpha_{||}\epsilon^2$$





Width of the loop

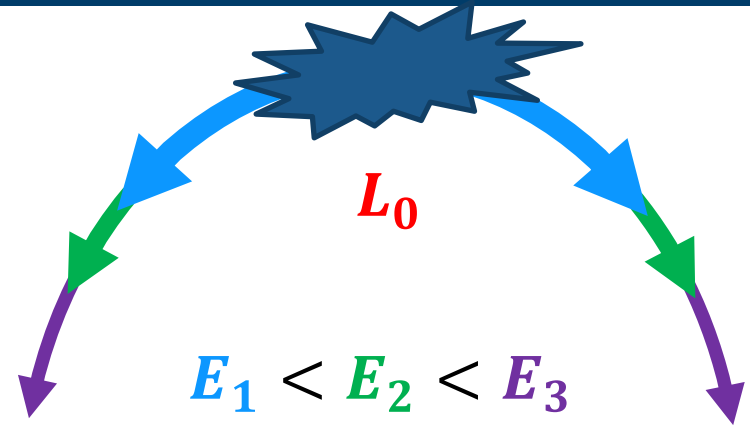


$$W(\epsilon) = W_0 + \alpha_\perp \epsilon$$

Loop width also grows with energy but slower

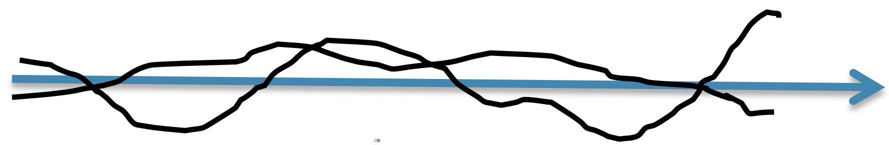
Kontar, Hannah,Bian 2011
Bian, Kontar, MacKinnon,2012

High density loops



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

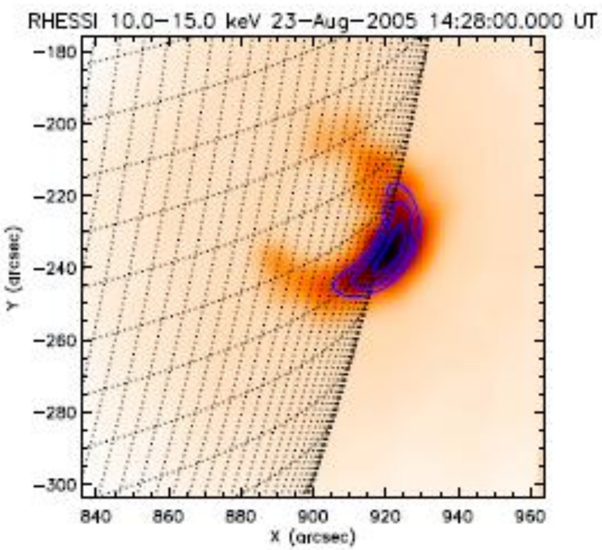
$$\frac{d\mathbf{r}_\perp}{dt} = v_z \frac{B_\perp}{B_0}.$$



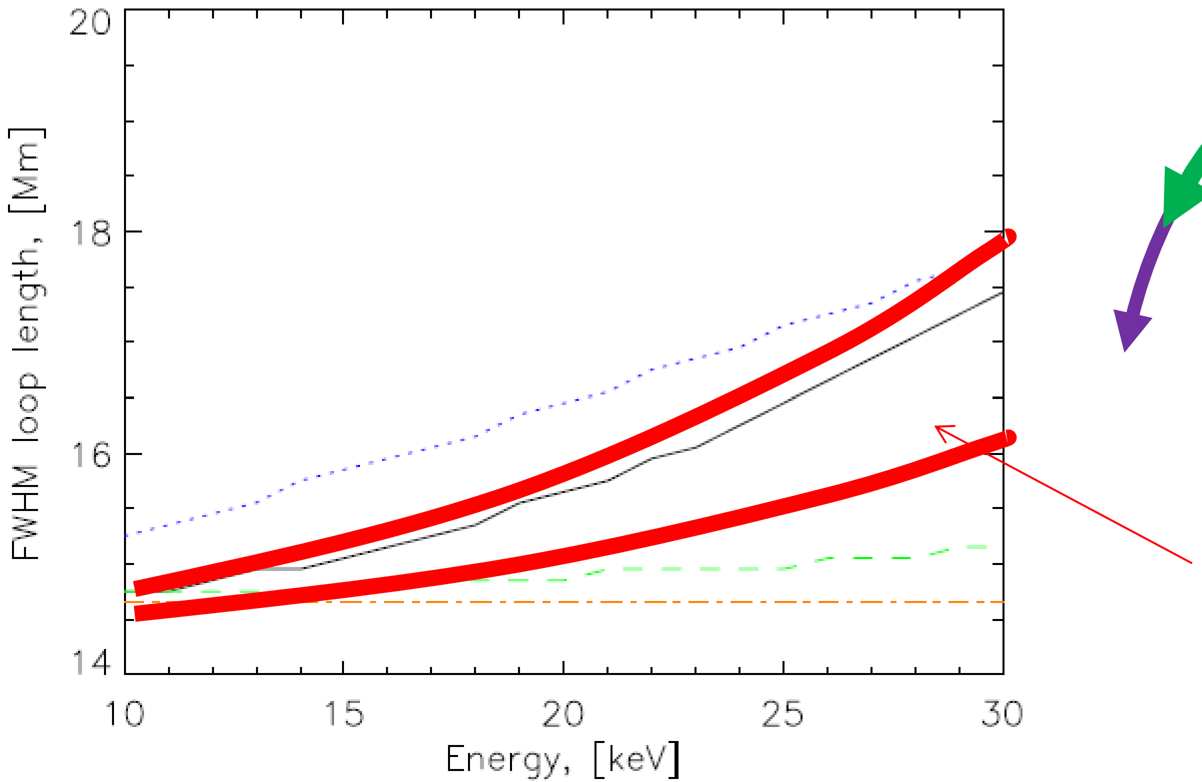
$$r_\perp = \sqrt{2 D_M r_\parallel}$$

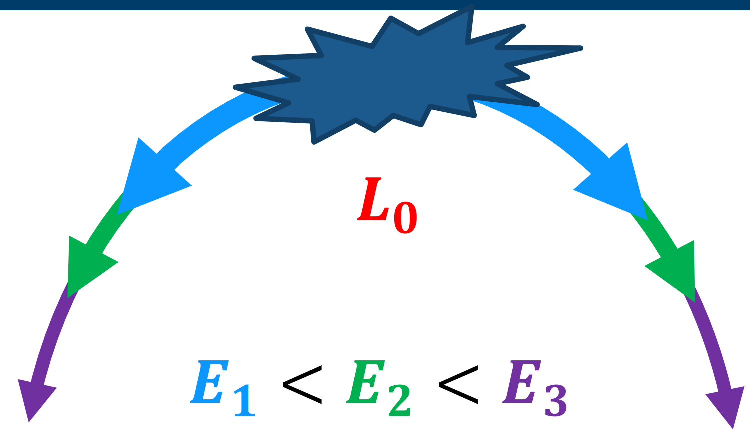
Perpendicular diffusion due to magnetic field fluctuations (wandering) (Jokipii & Parker 1969, Rochester and Rosenbluth, 1978).

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



High density loops

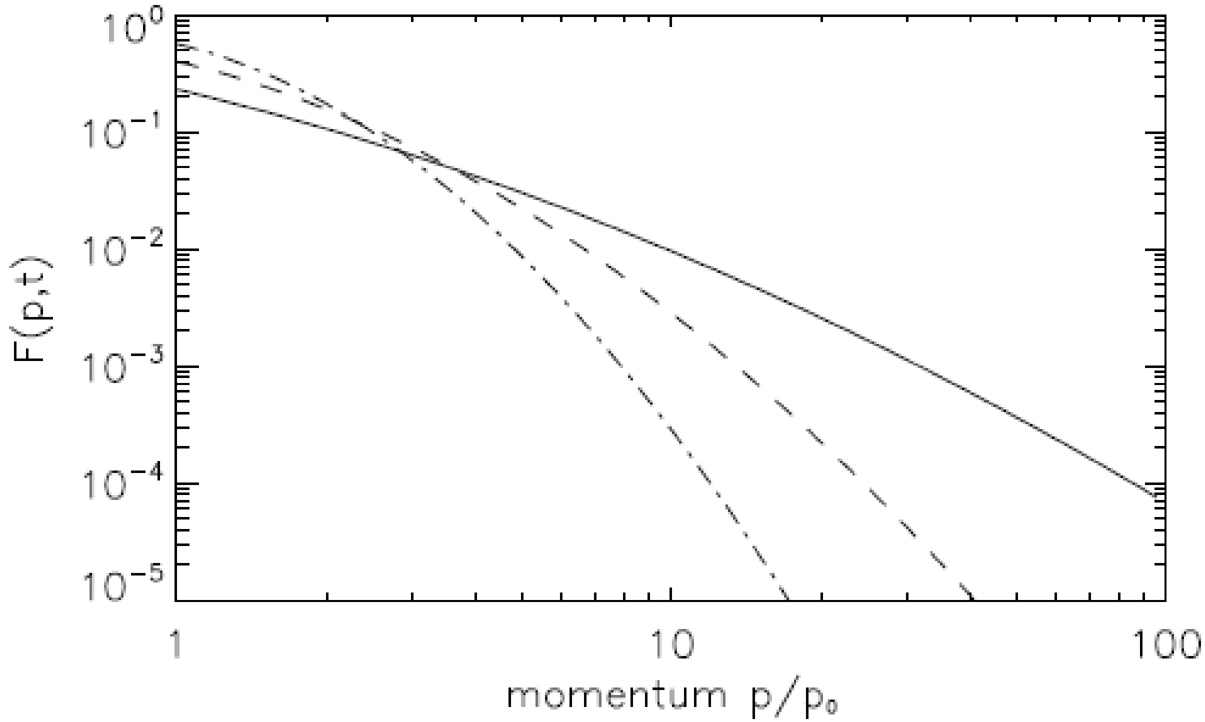




Full Width at Half Maximum (FWHM) length of the coronal source measured as a function of energy in a high density loop. The scatter-free transport is shown by the black solid line. Diffusive transport cases: $\lambda = 10^9$ cm (blue line), $\lambda = 10^8$ cm (green line), and $\lambda = 10^7$ cm (orange line).

Task 4 Development of particle acceleration and propagation models
Based on the results obtained in tasks 2.1 and 2.2, we will undertake theoretical development of particle acceleration models, and particle propagation models.

Stochastic acceleration by multi-island contraction during turbulent magnetic reconnection, **Bian and Kontar, PRL, 2013**



Task 4 …. propagation models …. see also Jingnan/Michele…

Reid and Kontar, Solar Physics, 2013,
Evolution of the solar are energetic electrons in the inhomogeneous turbulent inner heliosphere.