Turbulence and standard model of solar flares

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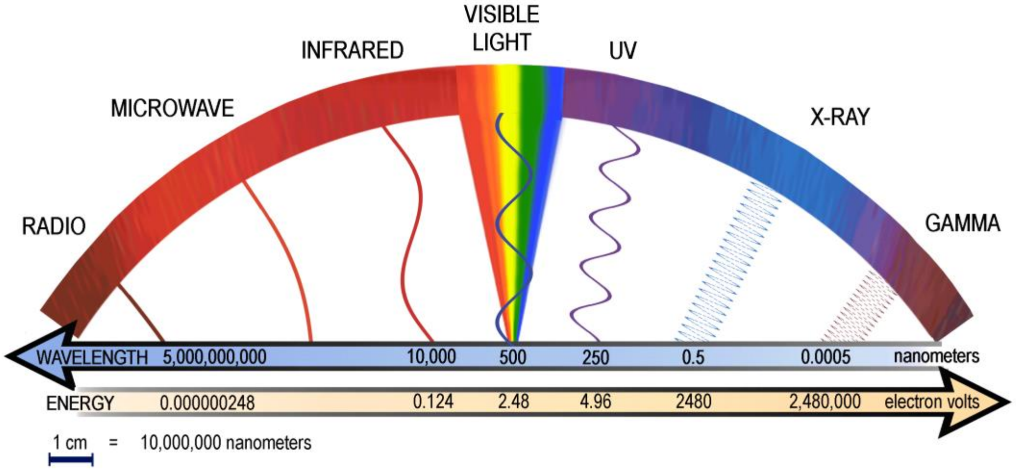
Solar flares: basics

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



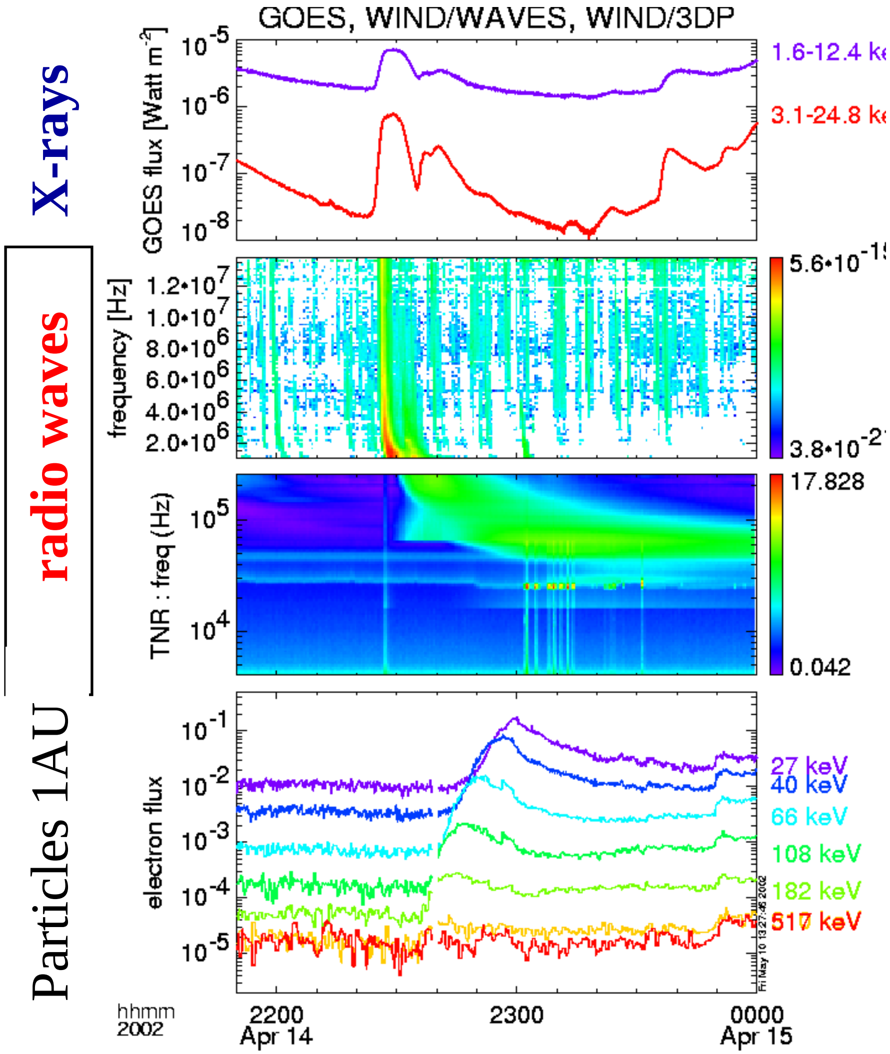
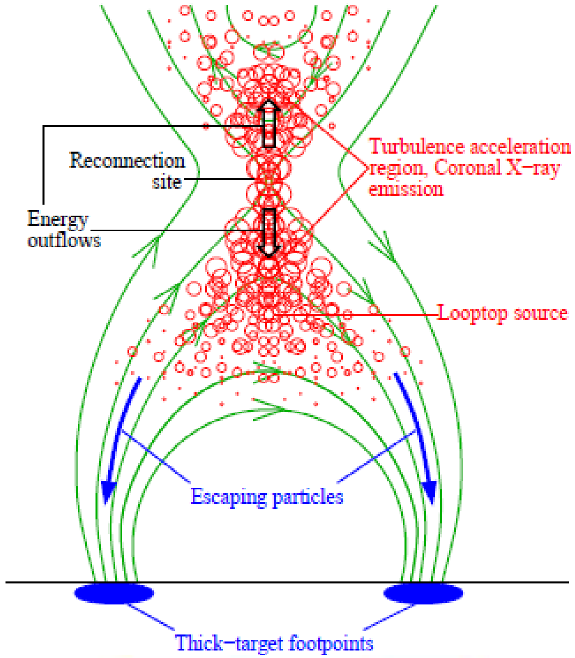
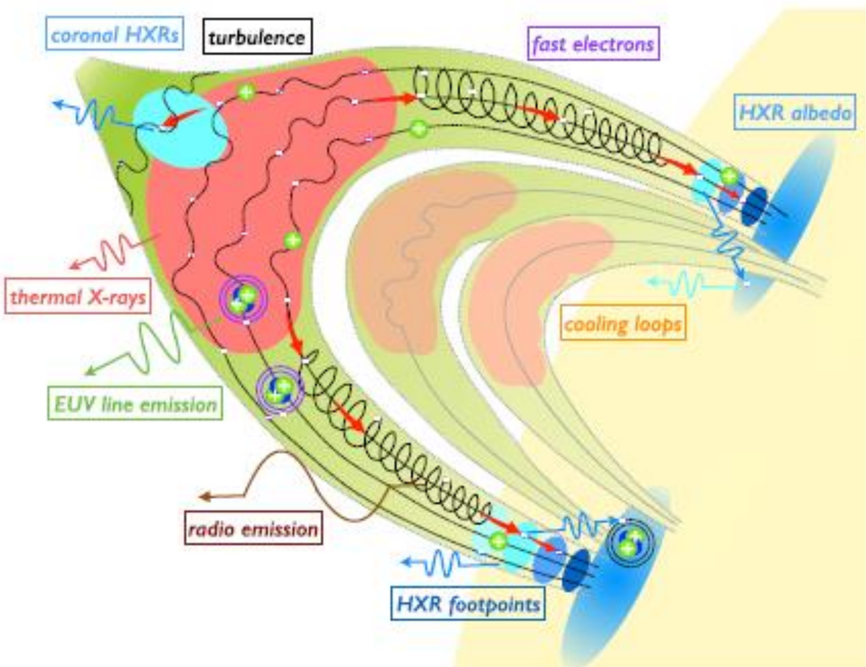


Figure from Krucker et al, 2007

Standard model energetics

Petrosian (2012) cartoon





Magnetic Energy

↓

Turbulence/Fluctuating E field

↓

Acceleration/Heating

↓

Electrons/Ions

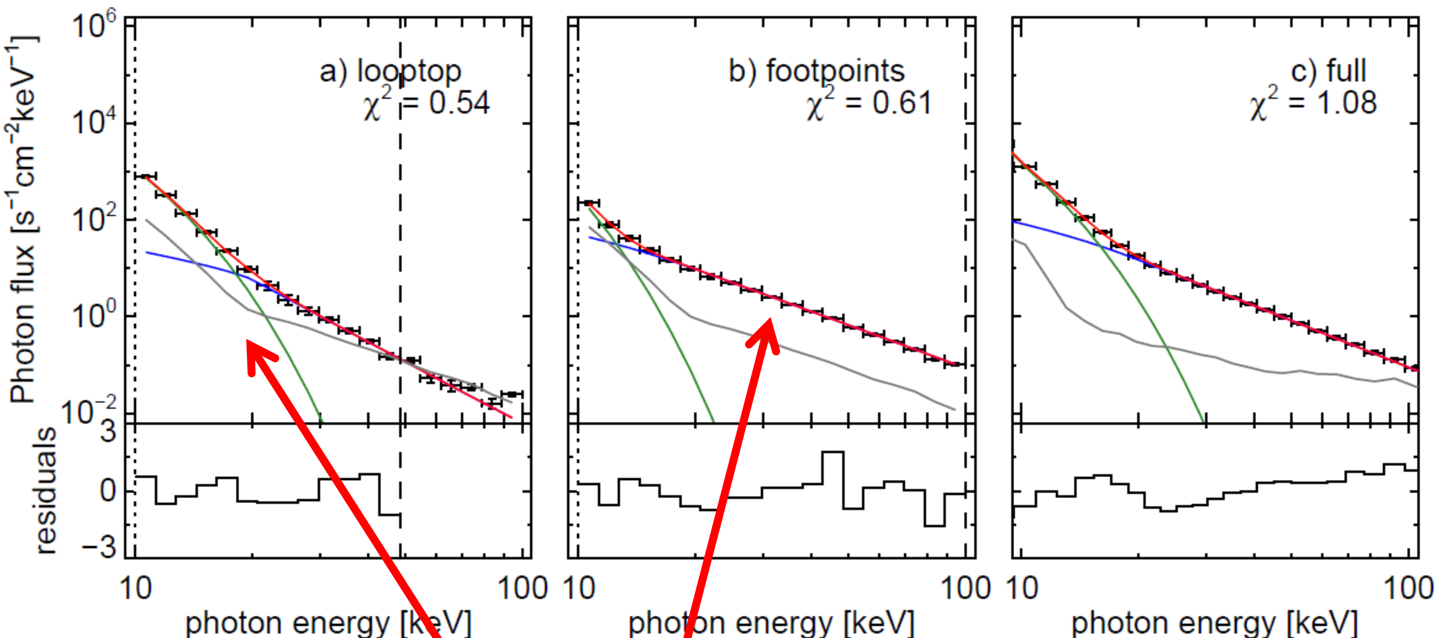
↓

Energy Deposition/Evaporation

↓

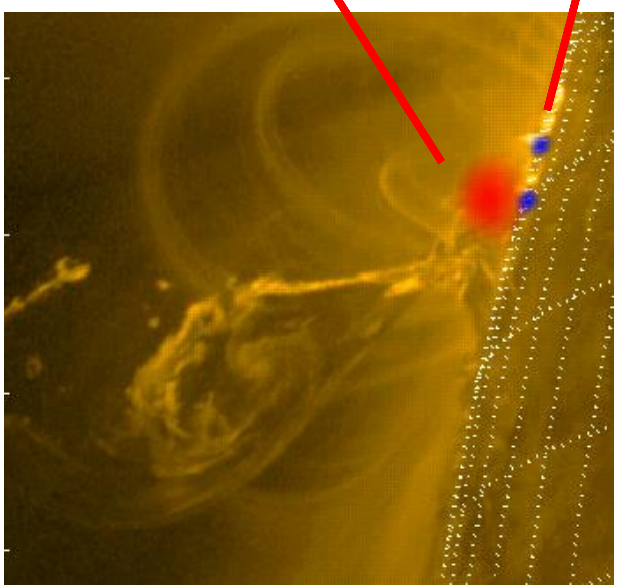
Radiation

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?*

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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⇒ Simoes & Kontar 2013, Kontar et al, 2014)

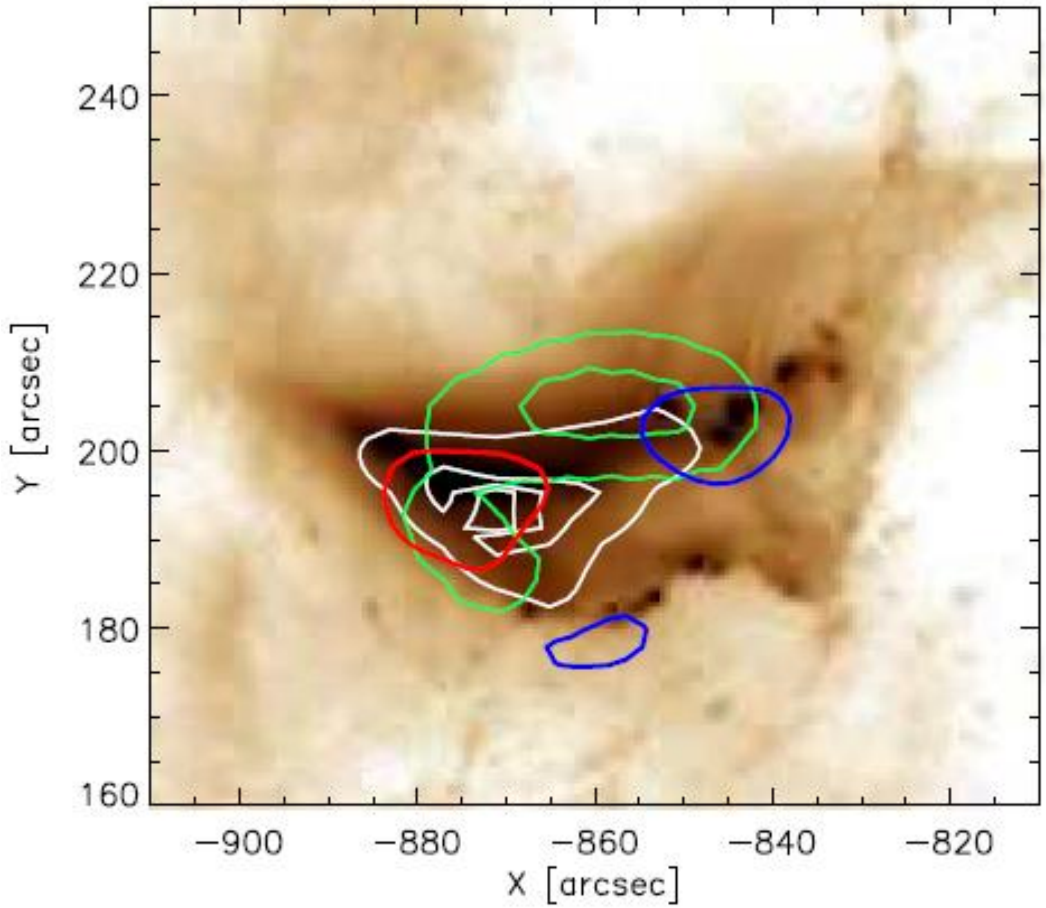
Reconnection models

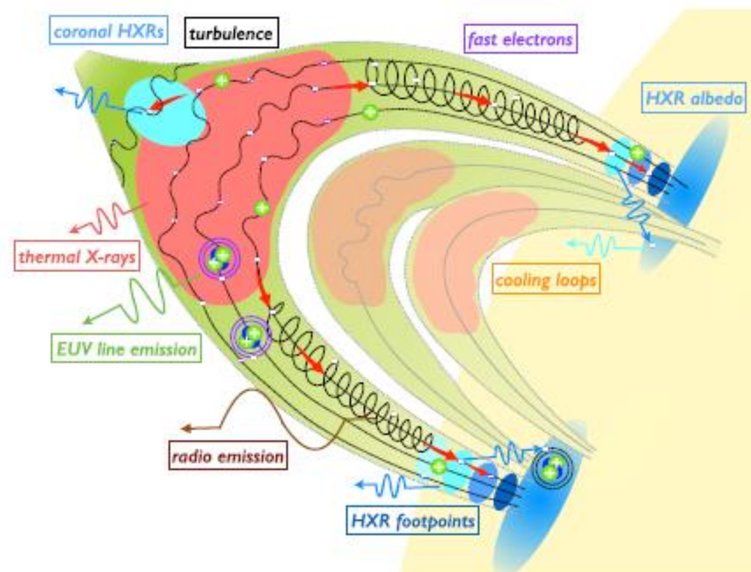
Anomalous resistivity is often required to make fast reconnection and strong parallel electric fields

see e.g. Lazarian et al, 1999, Raymond et al, 2012, Gordovskyy et al,2016

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

May 2013 Flare





SDO/Atmospheric Imaging Assembly (AIA) 193 Å image (background); RHESSI x-ray contours at 50% of peak value for 6–15 (red) and 25–50 keV (blue) energy ranges, EIS Fe XXIV (255 Å) intensity map (white contours at 30% and 75% of peak value), and Nobeyama 34 GHz radio emission (green contours at 30% and 75% of peak value).

From Kontar et al, PRL, 2017

Measurements for flare energetics

SDO/HMI - Magnetic field reconstruction and radio emission

Spatially resolved velocity fluctuations from EIS

SDO/AIA – thermal plasma

RHESSI and "warm target" electrons energetics

Magnetic Energy

Turbulence/Fluctuating E fields

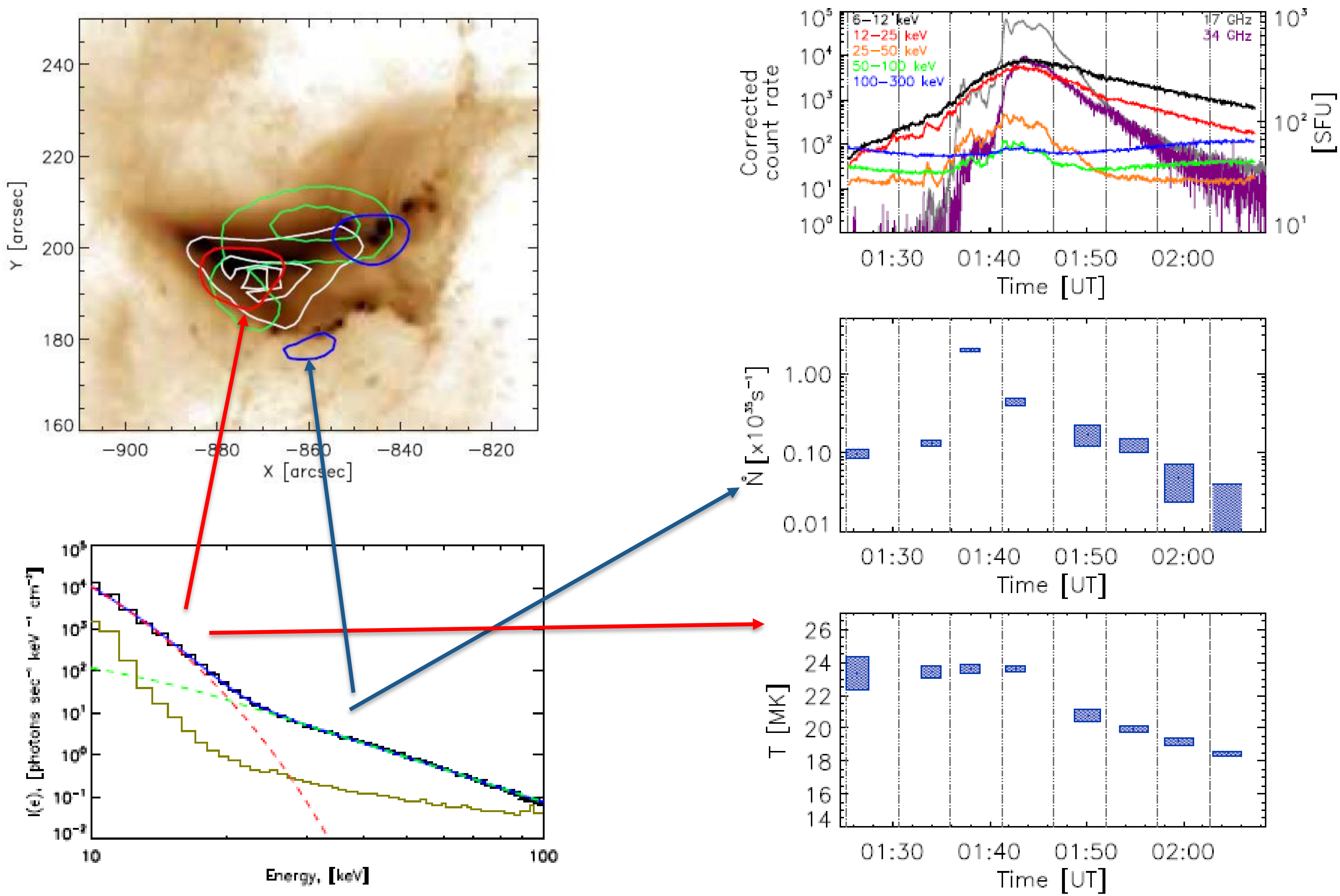
Acceleration/Heating

Electrons/Ions

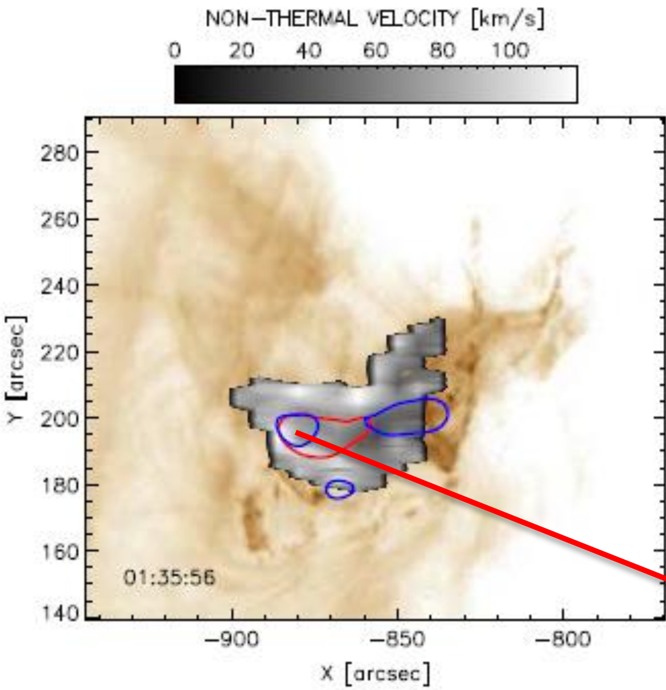
Energy Deposition/Evaporation

Radiation

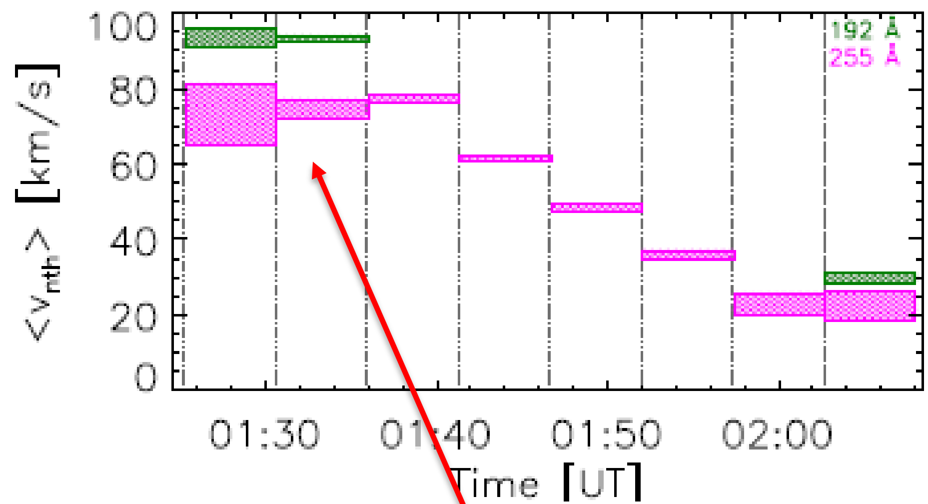
Electron energetics



Non-thermal line broadening



EIS Line width (Fe XXIV) => plasma velocity variance

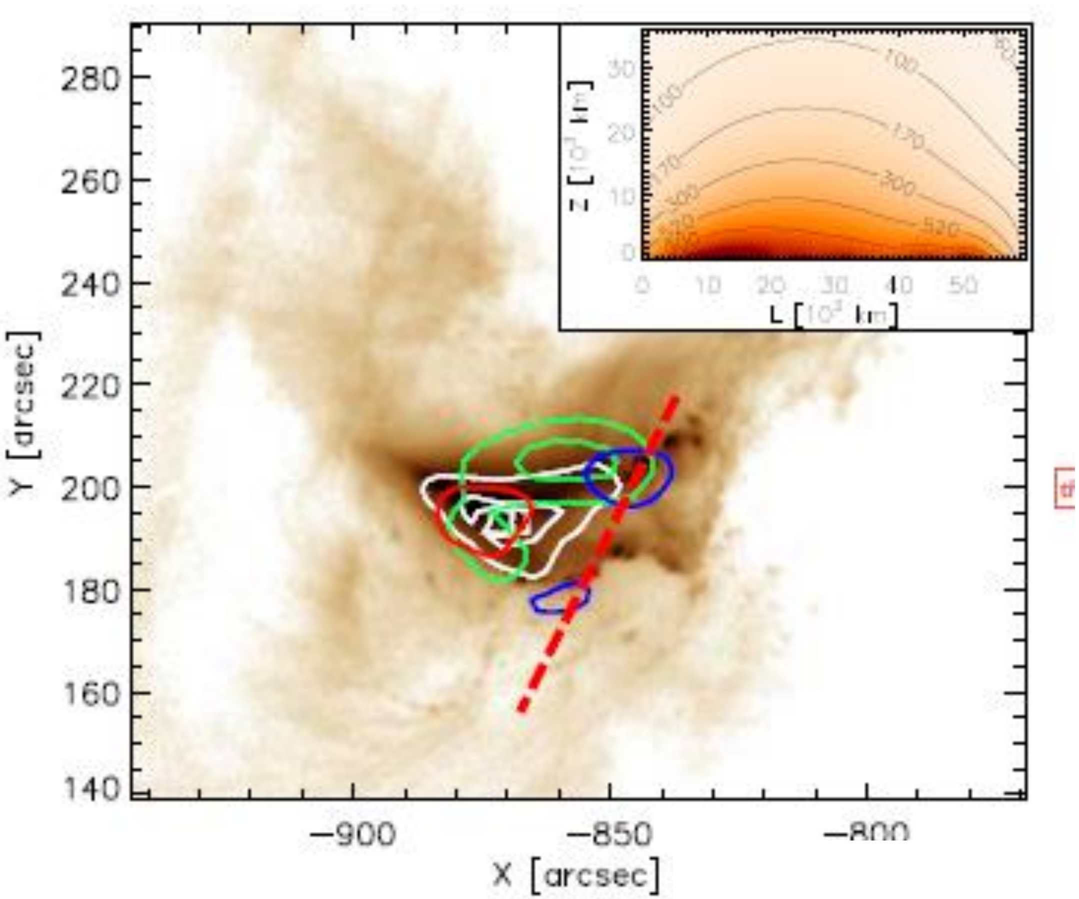


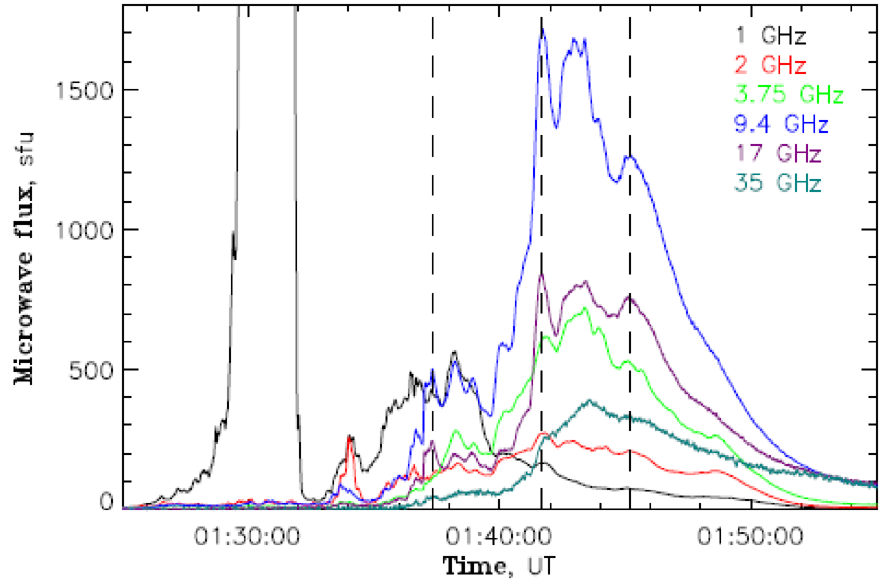
See Harra et al 2013 for details

$$\mathrm{FWHM}^2 = (\mathrm{instr}_{\mathrm{fwhm}})^2 + 4\ln(2)(\lambda/c)^2\left(v_t^2 + (v_{\mathrm{nt}})^2\right)$$

e.g. non-thermal line broadening observed in flares, normally spatially unresolved, but now with Hinode/EIS – spatially resolved

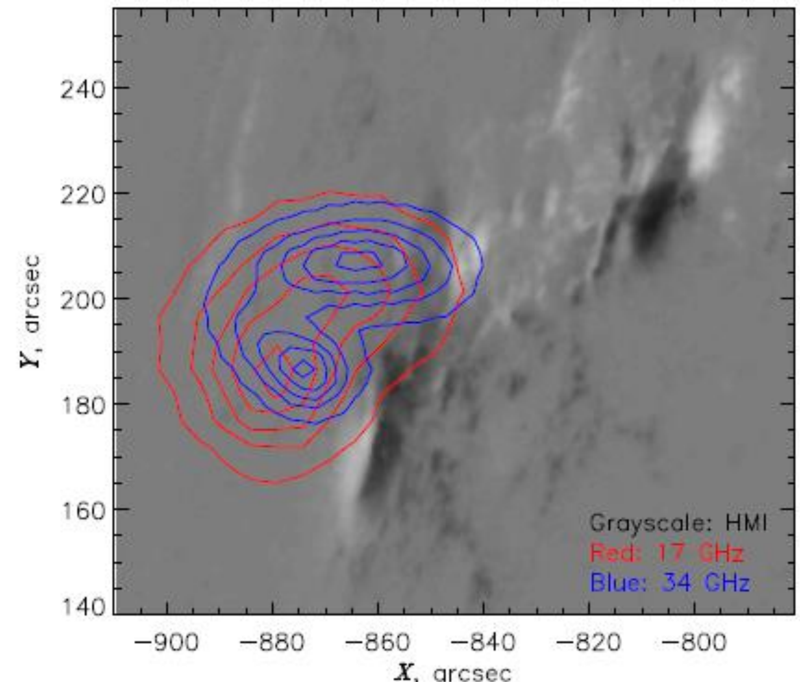
Magnetic field



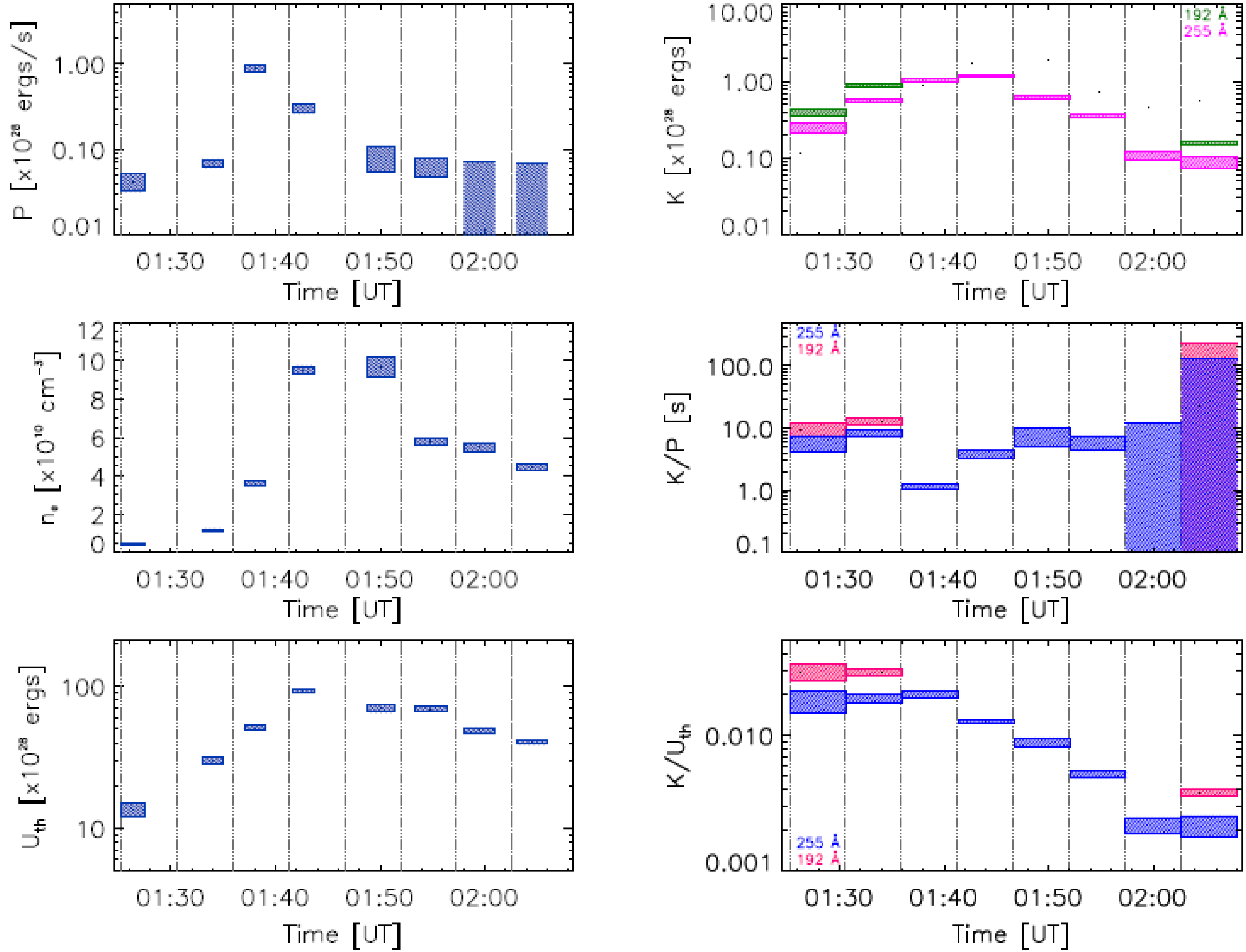


SDO HMI extrapolations

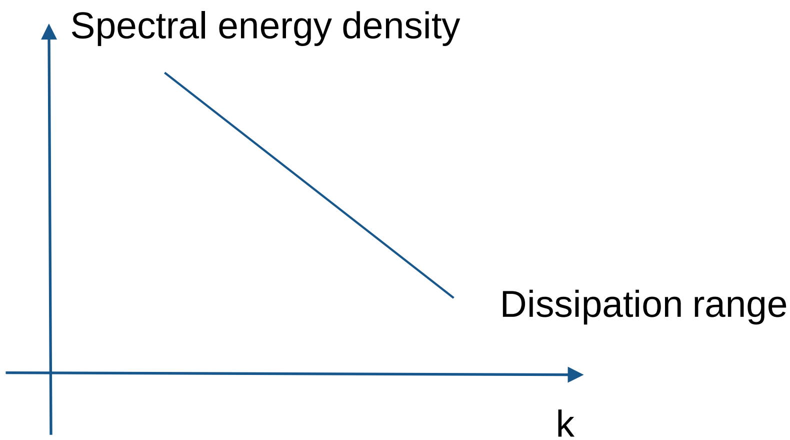
$$U_{\mathrm{m}} = \frac{B^2 L^3}{8\pi}$$

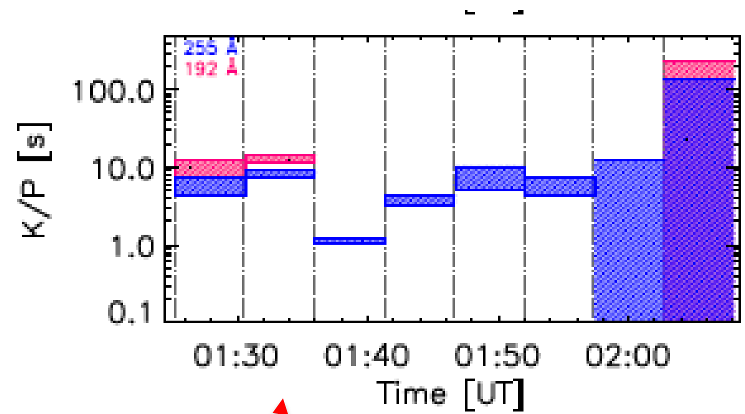


Flare energetics



Turbulence energy deposition



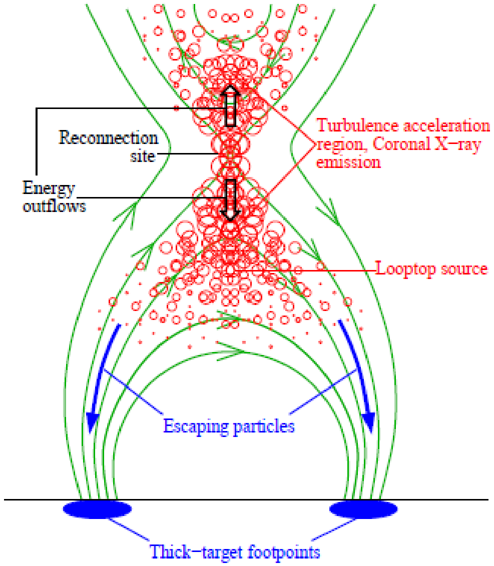


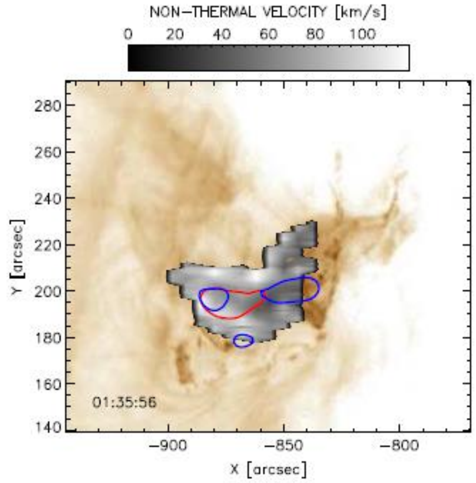
Turbulence dissipation timescale $\sim L_\perp / v_{nth}$.

P. Goldreich and S. Sridhar, 1995

The energy density associated with a turbulence-perturbed magnetic field δB is $U_B \simeq (\delta B)^2/8\pi$. Equating this to the turbulent energy content (Alfvenic MHD turbulence) $K = (1/2) n\, m \langle v^2_{nth} \rangle$, we obtain $\langle v^2_{nth} \rangle \simeq (\delta B)^2 / 4\pi n\, m$. Since the Alfvén speed $V_A = \sqrt{B^2/4\pi n\, m}$, it follows that $\langle v_{nth} \rangle / V_A \simeq \delta B / B \simeq L_\perp / L_\parallel$, where $L_\parallel$ is the longitudinal extent of the turbulence region. Thus the dissipation timescale $L_\perp / \langle v_{nth} \rangle$ is approximately the same as the Alfven crossing time $L_\parallel / V_A$, a quantity that is readily ascertainable from observations. Using the values found in the observations, the dissipation of turbulent energy occurs on a time scale $\sim 1 - 10$ seconds.

Standard model energetics





Magnetic Energy $\sim 10^{31}$ ergs

↓

Turbulence $\sim 10^{28}$ ergs

↓

Electron Acceleration $\sim 10^{28}$ erg/sec

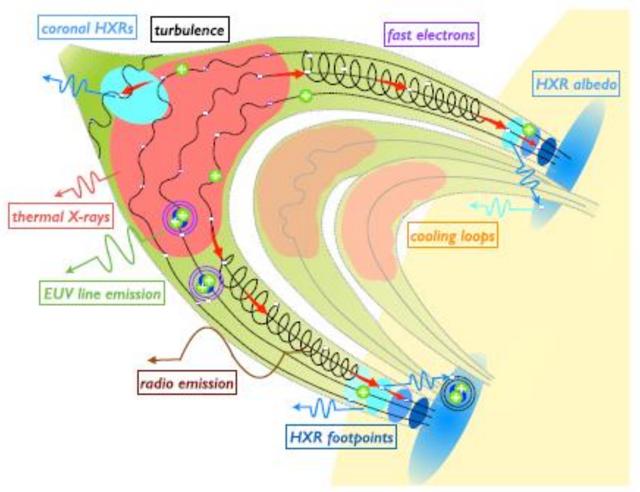
↓

Thermal energy $\sim 10^{30}$ ergs

↓

Radiation

Summary



The new multiwavelength observations provide persuasive evidence that plasma turbulence plays a key role in the energy transfer in solar flares, thus directly supporting the stochastic acceleration model.

The turbulent kinetic energy (instanteneous) comprises only a small part of the total flare energy budget (~0.2-1%). Nevertheless, provided that its energization and dissipation processes are rapid enough (with the timescales of ~1-10 s),

The energy dissipation rate and the power in accelerated nonthermal particles observed in the flare are consistent with the dissipation of anisotropic Alfvén MHD turbulence.

The observations could be used to test various acceleration models.