Electron heating in coronal loops by Kinetic Alfvén Wave turbulence

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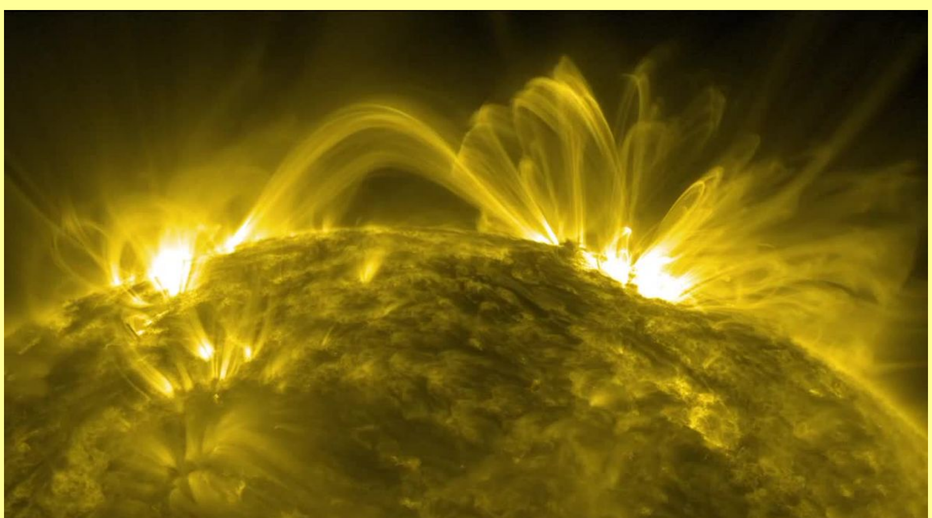

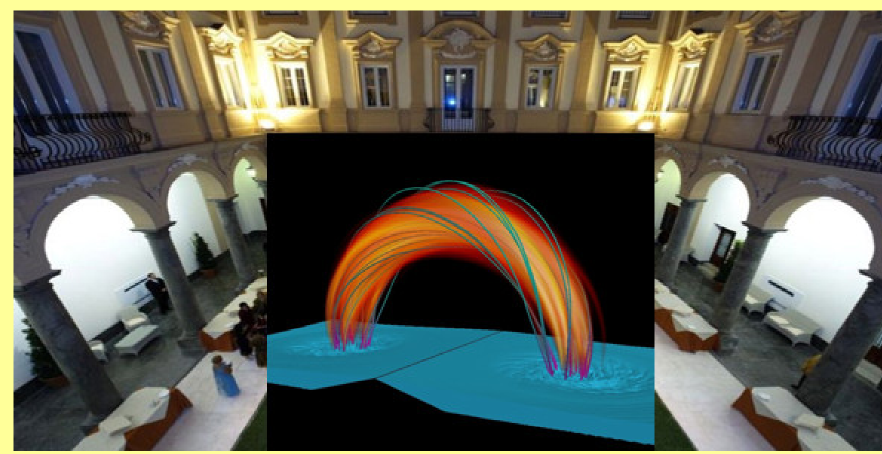

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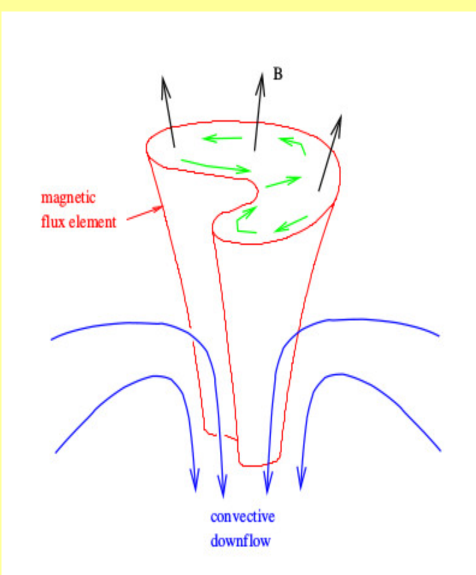
1. Motivation

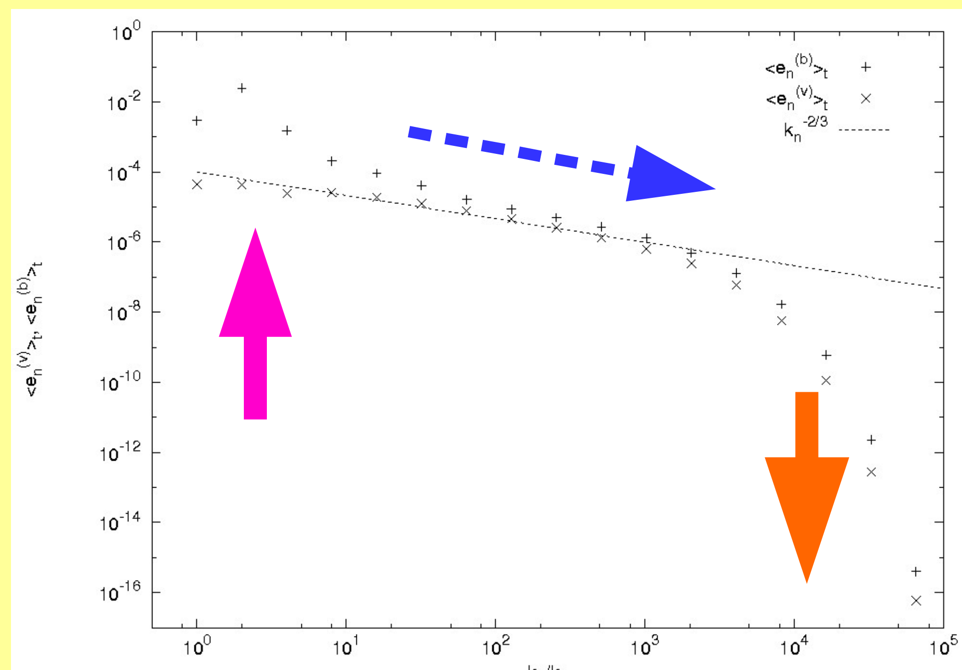
Several models of **turbulence in coronal loops** have been formulated (*e.g., Nigro et al., 2004; Rappazzo et al., 2008; Malara et al. 2010; van Ballegooijen et al., 2011;...*)

In a turbulence:

- energy is **injected at large scales** (*motions at the loop bases*);
- nonlinear effects move energy to smaller scales (***cascade***), generating a **spectrum of fluctuations**;
- at dissipative scales fluctuation energy is **converted into heat**.



(*van Ballegooijen et al., 2011*)

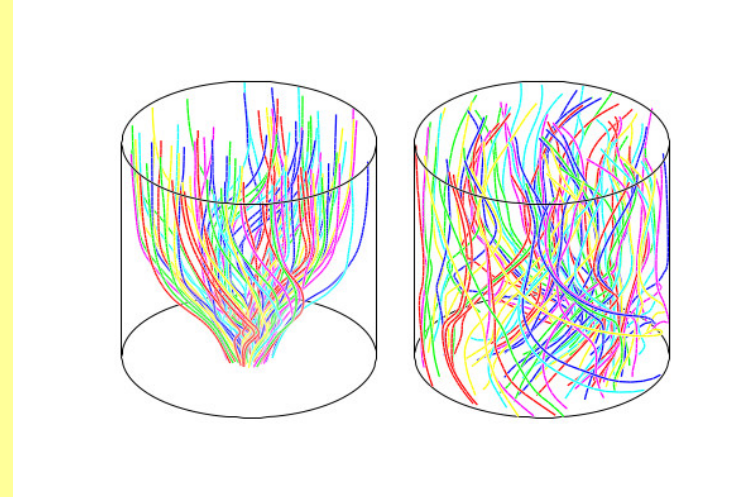


(*Nigro et al., 2008*)

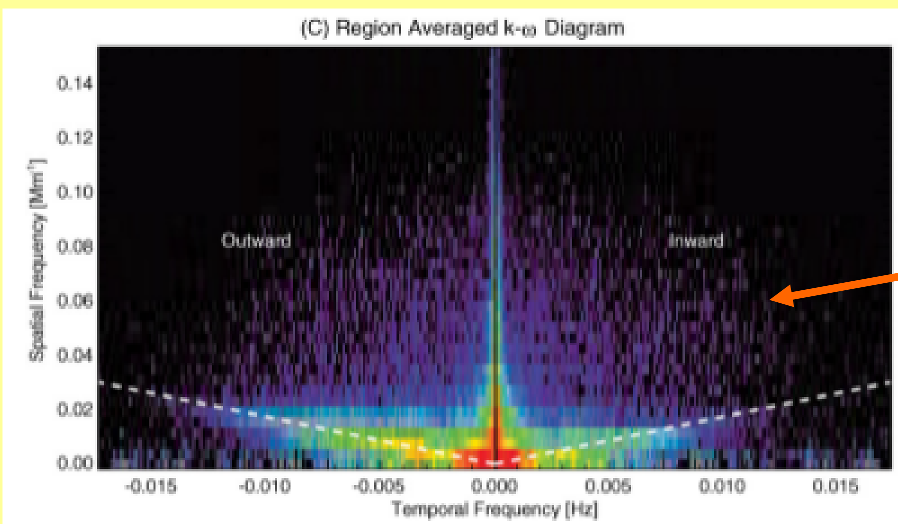
Strong axial magnetic field in a loop
► **Reduced MHD** is often employed:

► **Alfvénic fluctuations** which propagate along **B**, while interacting.

► **Heating rates** compatible with those necessary to heat a loop *(e.g., van Ballegooijen et al., 2011*)



(van Ballegooijen et al., 2011)

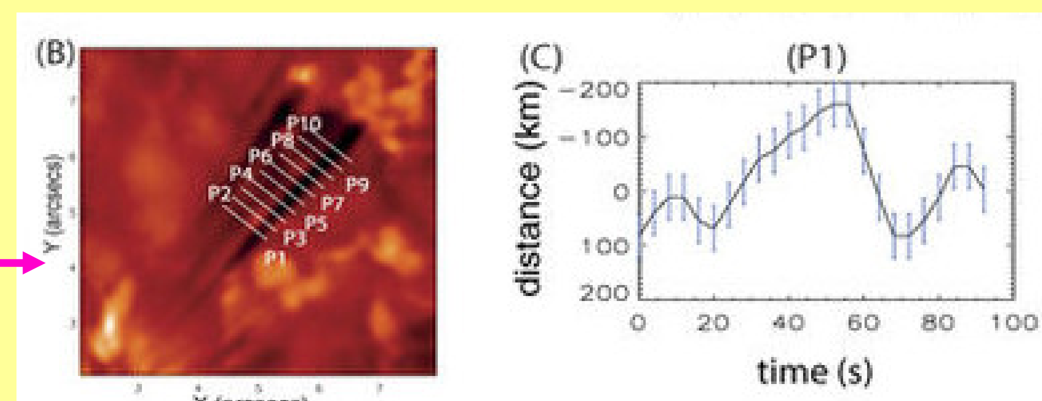


(Tomczyk & McIntosh, 2009)

Alfvénic fluctuations somehow **supported by observations**:

- Velocity fluctuations propagating in coronal flux tubes (*Tomczyk & McIntosh, 2009*);

- torsional motions in the Chromosphere (Srivastava et al. 2017).



(Srivastava et al. 2017)

► *Here, we focus on **the smallest spatial scales**, where turbulent energy is transferred to particles (**dissipation**).*

the **collisional dissipative scale** $l_D \sim c^{3/2}\left(\frac{\eta}{4\pi\delta v_0}\right)^{3/4} l_{\perp 0}^{1/4} \sim 1\ \text{cm}$

is smaller than the **proton Larmor radius** $\rho_P \approx 10 - 100$ cm

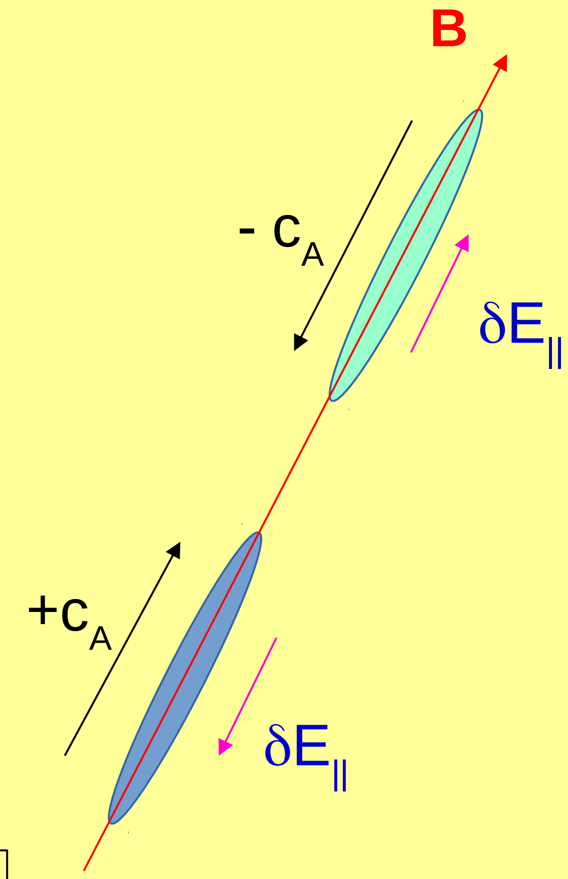
► ***kinetic effects can play an important role in energy dissipation.***

- *Our purpose is to study a **kinetic mechanism** which could be able **to heat electrons** in a coronal loop.*
- *Such a mechanism is related to **parallel electric field fluctuations** which should be present at scales comparable with the proton Larmor radius.*

2. The model: physical properties

- The turbulent cascade takes preferentially place **perpedicularly to the background magnetic field B_0** *(e.g. Oughton et al., 1994)*:

► small-scale perturbations are structures **elongated along B_0**, filling up the whole space.



- Perturbations move along **B** at the Alfvén speed $\pm c_A$.

- At scales $l_\perp \approx \rho_p$, Alfvénic perturbations become **Kinetic Alfvén Waves (KAWs)**.

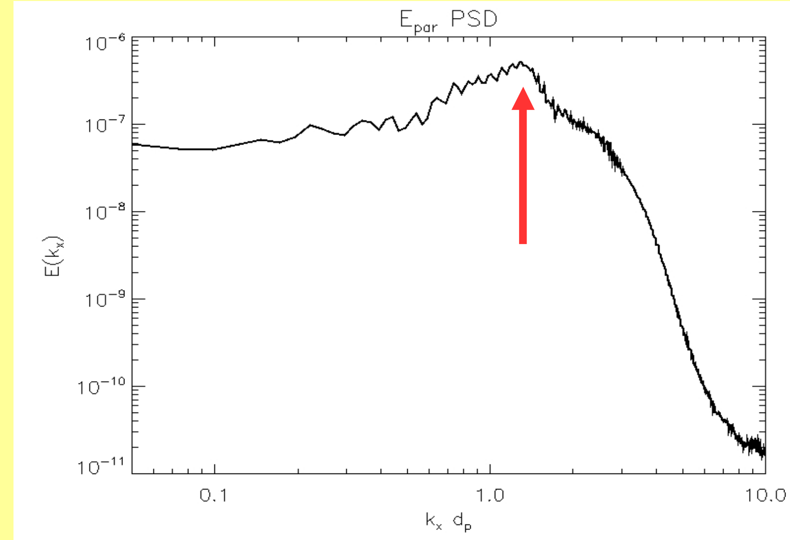
- **A (weak) parallel electric field** $\delta E_{||}$ is <u>associated with KAWs</u> (*e.g., Hollweg, 1999; Voitenko & Goossens, 2004; Tsiklauri et al., 2004*).

Question:

Can weak $E_{||}$ of <u>a large number</u> of fluctuating structures **energize electrons**, compatibly with coronal temperatures?

Fluctuation properties

a) we consider **fluctuations at ion scales** $l_\perp \approx 2\pi\rho_p$, where $\delta E_{||}$ is maximum
(e.g,, turbulence at ion scales, *Pezzi et al., 2017*)

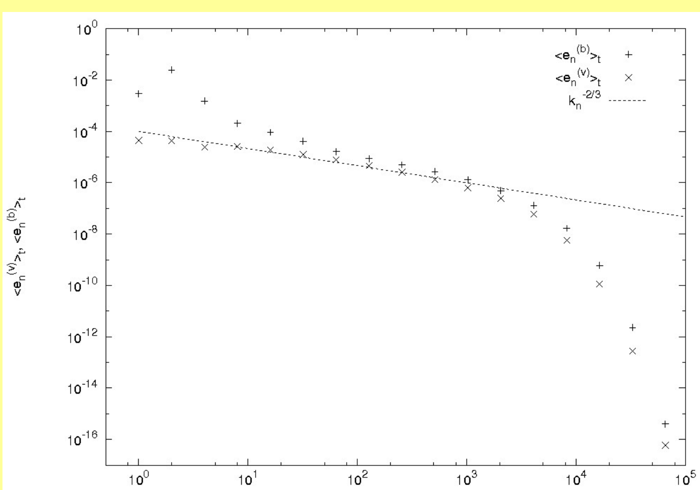


(Pezzi et al., 2017)

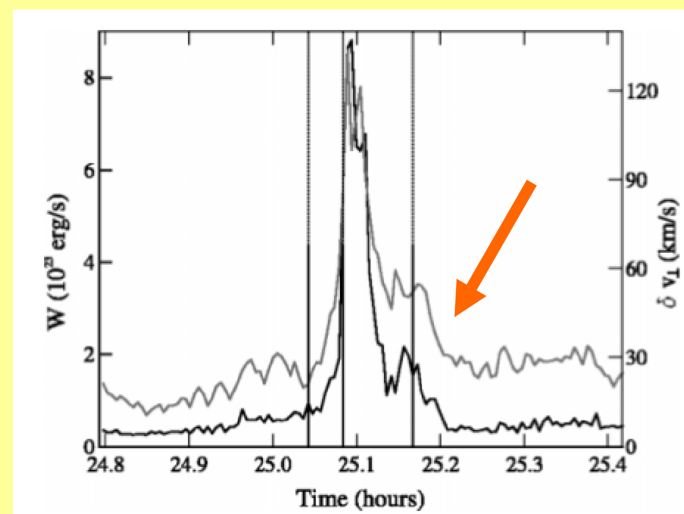
b) we assume $\delta v_\perp$ to follow a **Kolmogorov spectrum**:

$$\delta v_\perp(l_\perp) = \delta v_{\perp 0} \left(\frac{l_\perp}{l_{\perp 0}}\right)^{1/3}$$

with $\delta v_{\perp_0}$ = 40 - 100 km/s



(Nigro et al., 2008)



(Nigro et al., 2005)

c) the typical **lifetime of structures** is the *eddy-turnover time:*

$$\tau_{life} \sim \frac{l_\perp}{\delta v_\perp(l_\perp)} \sim \frac{l_{\perp 0}^{1/3}\, l_\perp^{2/3}}{\delta v_{\perp 0}} \simeq (2-5)\times 10^{-3}\,\mathrm{s}$$

d) parallel length $l_{||}$ determined by the **“critical balance”** condition *(Goldreich & Sridhar, 1995):*

$$l_{||} \sim \frac{c_A}{\delta v_{\perp 0}}\, l_{\perp 0}^{1/3}\, l_\perp^{2/3}$$

e) the associated **parallel electric field** (*Voitenko & Goossens, 2004*):

$$\delta E_{||} \simeq \frac{4\pi c_A}{c} \frac{\rho_p^2}{\sqrt{1+4\pi\rho_p/l_\perp}} \frac{\delta B_\perp(l_\perp)}{l_{||} l_\perp} \sim \frac{(2\pi)^{2/3}}{\sqrt{3}} \frac{\delta v_{\perp 0}^2}{c\, c_A} \left(\frac{\rho_p}{l_{\perp 0}}\right)^{2/3} B_0$$

Electron dynamics:

- Small electron Larmor radius $\rho_e \ll \rho_p \sim l_\perp$ ► **drift approximation**

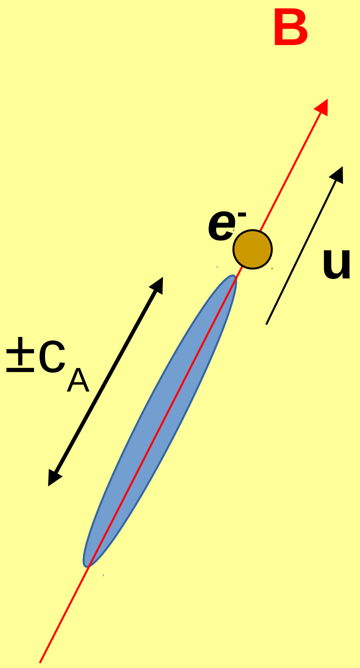
transverse drift velocity $u_\perp \approx \delta v_{\perp 0} \approx$ tens of km/s

longitudinal velocity $u_{||} \approx u_{th} \approx 5000$ km/s

► **electrons mainly move parallel to B**

- Crossing a structure, electrons experience an **energy variation:**

$$\Delta E_{kin} = \pm \Delta W \sim \pm e\,\delta E_{||}\,\Delta l_{int}$$



- the **interaction length** Δl_{int}:
  a) is limited by the lifetime τ_{life} of the structure;
  b) is influenced by the propagation of the structure at speed $\pm c_A$

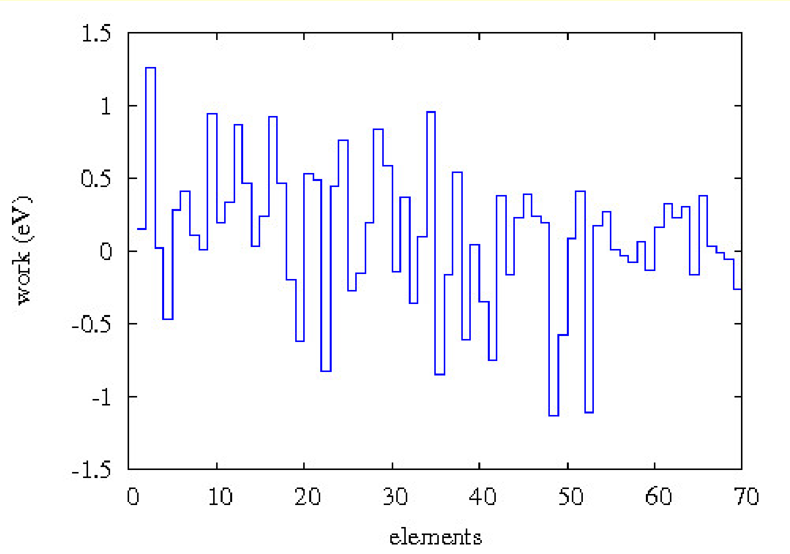
$$\Delta l_{int} = \min \left\{ u_{||}\tau_{life}\,,\ \frac{l_{||}u_{||}}{u_{||} \mp c_A} \right\}$$

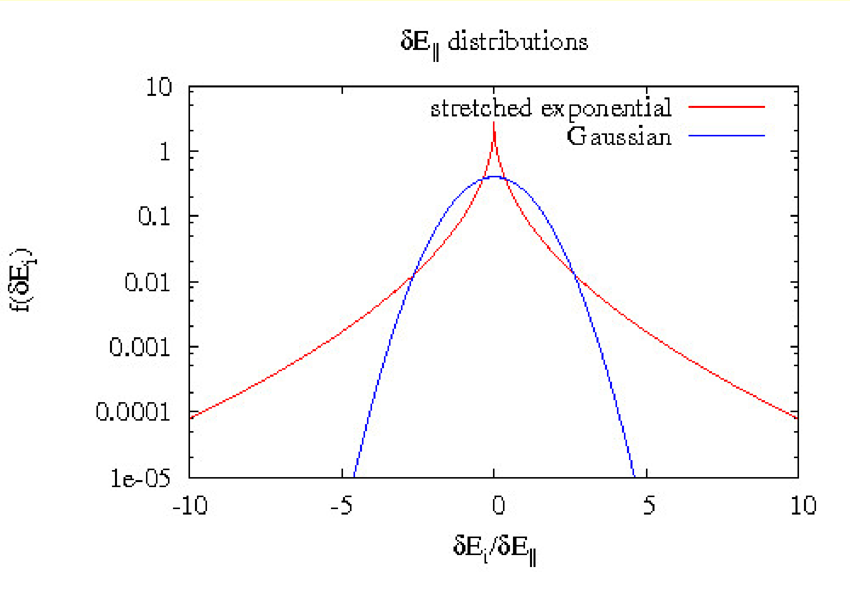
Note:
The energy variation ΔE_{kin} <u>increases with the velocity</u> $u_{||}$ ***(nonlinearity)***

3. The model: implementation

We performed **test-particle simulations** to study the time evolution of the energy in an electron population.

- ***work done on electrons*** is modeled by a **step function:** at each step, E_{kin} **increases or decreases** by $W_i = e\, \delta E_i\, \Delta l_{int,i}$





- Distribution of electric field fluctuations δE_i

a) Gaussian

b) stretched-exponential (to simulate intermittency)

with <u>the same</u> $(\delta E_i)_{RMS} = \delta E_{||}$

- the **interaction length** determined by: $\Delta l_{int,i} = l_{||} \min\left\{ \frac{u_{||i}}{c_A}, \frac{u_{||i}}{u_{||i} - \sigma_i c_A} \right\}$

- The **propagation sense** σ_i of fluctuations is randomly chosen

- if at one step E_{kin} drops under zero, the particle is **reflected back**: $u_{||} \rightarrow -u_{||}$

- the current time calculated by: $t_i = \sqrt{\frac{3m_e}{2}} \sum_{k=1}^{i} \frac{\Delta l_{int,k}}{\sqrt{E_{kin,k}}}$

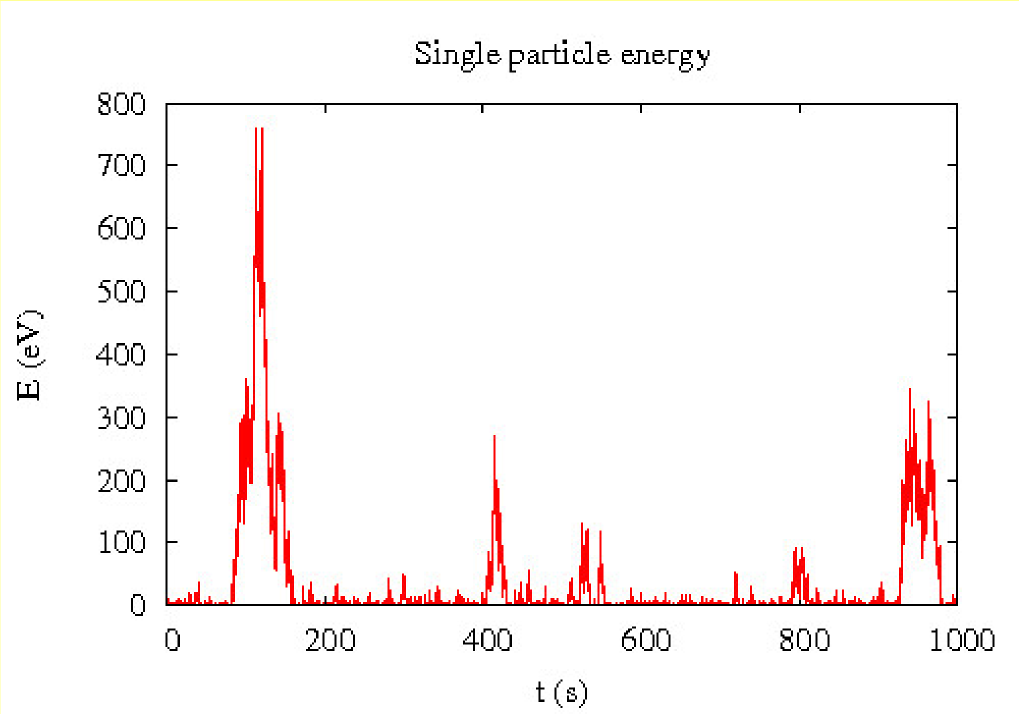
Statistics is calculated by following the evolution of a large number of test particles.

4. Results

Parameters:

- perp. energy injection scale: $l_\perp$ = 3000 km
- electron density: $n = 10^9$ cm^{-3}
- background magnetic field $B_0 = 10^2$ G
- velocity perturb. $\delta v_{\perp 0}$ = 40 – 100 km/s
- ***particle initial energy*** $E_{kin}(t=0)$ *= 10 eV << typical* E_{th}

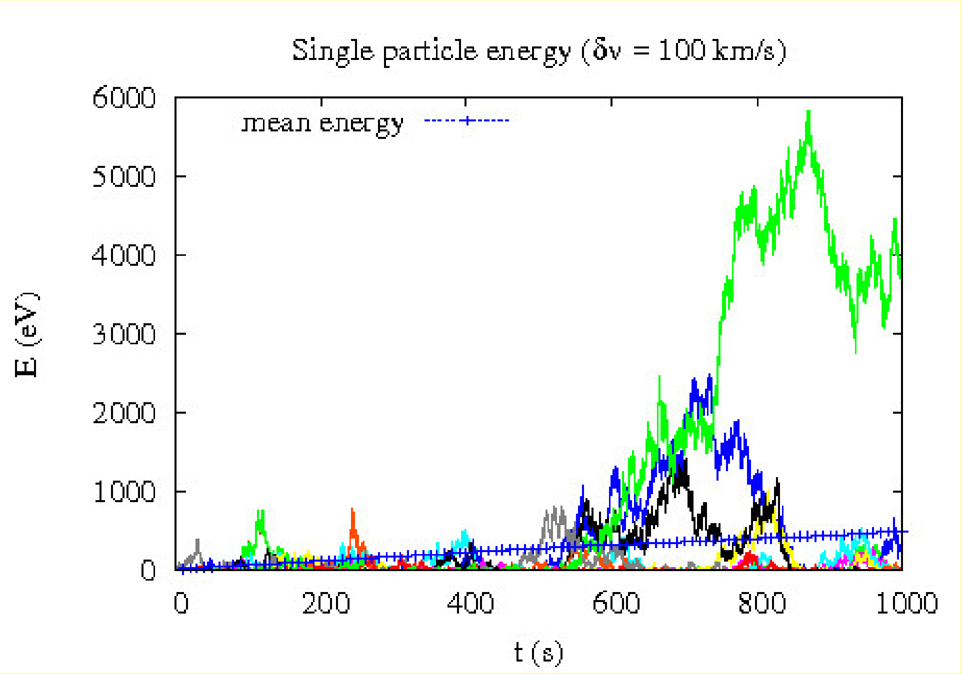
Energy evolution of a single particle

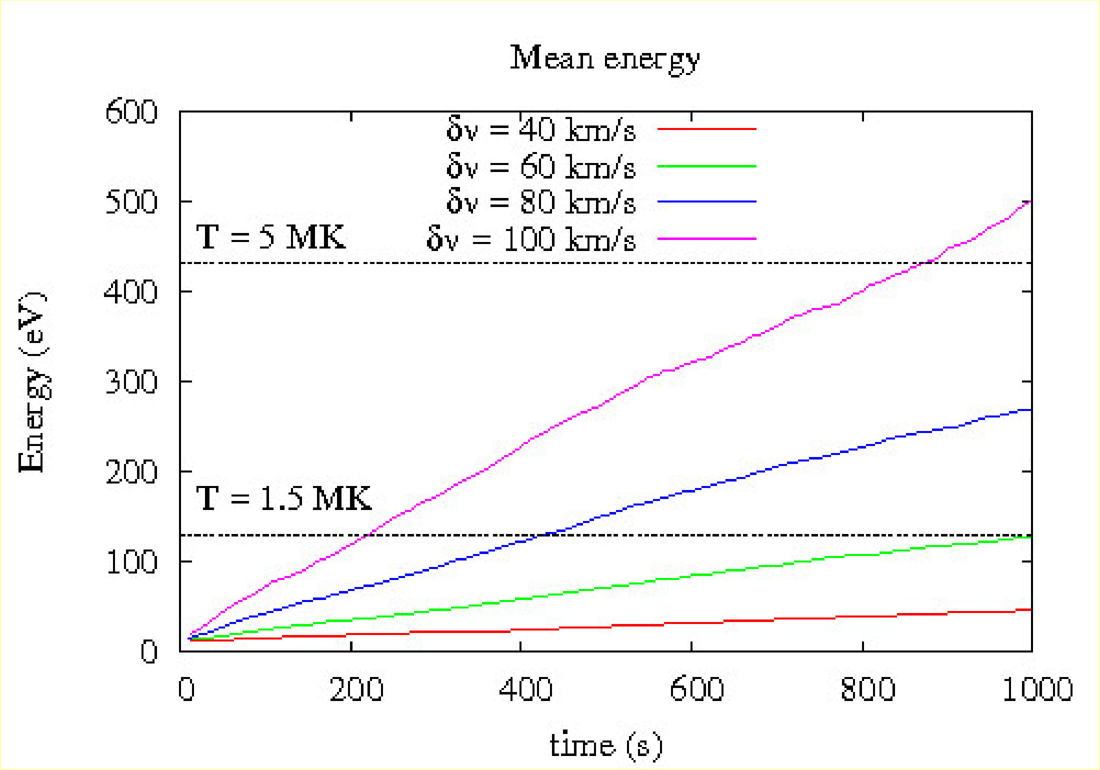


A "bursty" behaviour:

- E_{kin} occasionally attains ***high energies****;*
- Due to ***nonlinearities***: work done on particles <u>increases with velocity.</u>

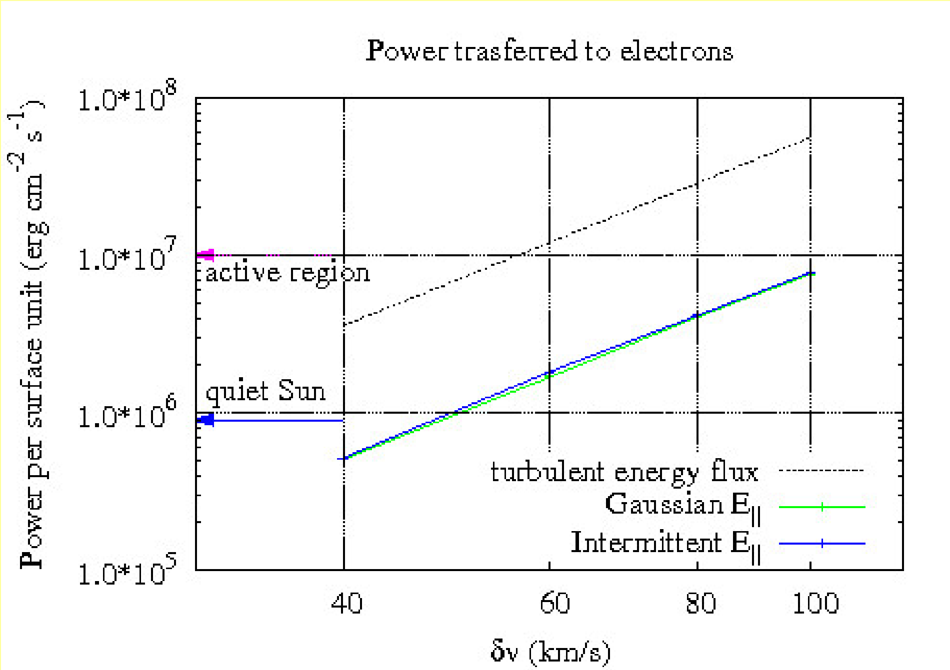
However, the ***mean energy*** of whole distribution **increases** (almost) linearly in time.





- **Coronal temperatures** attained in few minutes.
- Faster for larger $\delta v_{\perp 0}$

Note:
due to ***lack of energy losses***, E_{kin} increases with no limits



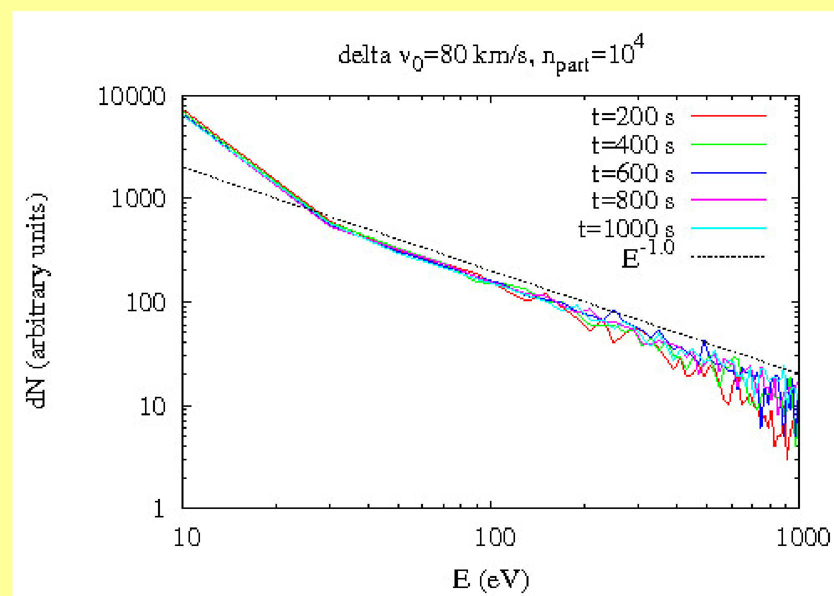
- **Power W** transferred to electrons is ***of the order or larger than that required to heat quiet-Sun Corona*** *(Rosner et al., 1978; Withbroe,1988)*

turbulent energy flux

$$\Phi_{turb} \sim m_p n \frac{\delta v_{\perp 0}^3}{l_{\perp 0}} L$$

- $\langle W \rangle_t$ is **proportional to** $(\delta v_{0\perp})^3$, as for the turbulent energy flux Φ_{turb}
- at any value of $\delta v_{0\perp}$, ***about 20% of*** $\boldsymbol{\Phi_{turb}}$ ***is transferred to electrons***.
- intermittency has <u>no effects</u>.

The ***energy distribution*** of electron population tends to a power law E^{-1} (lack of collisions!)



5. Conclusions

- ***We built up a model for turbulent heating of electrons in a coronal loop, based on parallel electric field of small-scale flucuations. Multiple crossings amplify the effects of many tiny electric potential jumps.***
- ***The power transferred from turbulence to electrons is of the order of that required to heat the quiet-Sun Corona, and is a constant fraction (≈ 20%) of the turbulent flux, regardless of turbulence level.***
- ***Electron mean energy reaches values compatible with coronal temperature within few tens of minutes.***
- ***Temperature increases in time, with no limits: inclusion of energy loss mechanisms needed (future work).***
- ***Work in progress: inclusion of collisions (thermal distributions expected); exploration of parameter space.***
- ***Other mechanisms could also contribute to energize electrons (e.g., reconnection…)***