Transport of Charged Particles in 3D Turbulent Solar Corona

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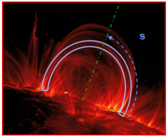
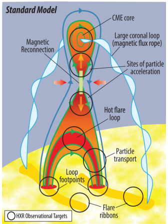
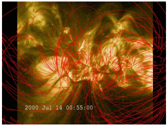
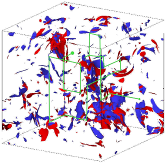
The main question

Is the physics of the acceleration of particles, the pre-flare and impulsive plasma heating and the transport of charged particles similar in a simple magnetic loop, isolated Reconnecting Current Sheet and a complex data driven confined or eruptive magnetic topology? If not, how we will proceed to approach the second?









The normal transport equation

Let us start with the "normal" transport equation: The Fokker-Planck equation in its simplest form

$$\frac{df(E,t)}{dt} + \frac{\partial}{\partial E}\left[F(E)f(E,t) - \frac{\partial}{\partial E}\left(D(E)f(E,t)\right)\right] = -\frac{f(E,t)}{t_{esc}(E,t)} \quad (1)$$

Critical parameters for a random walk process inside a turbulent enviroment

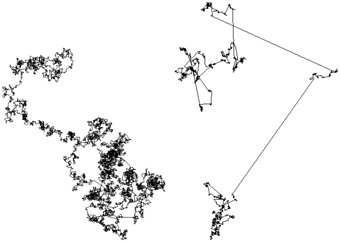
- $q(\Delta E, E)$= the probability of the energy change
- $F(E) =< E > /\Delta t = \int(\Delta E)q(\Delta E, E)d(\Delta E)/\Delta t$
- $D(E) =< (\Delta E)^2 > /\Delta t$= diffusion equation
- $t_{esc}(E,t)$= the spacial transport inside a finite acceleration volume

Limitations of the the FP equation

- $q(\Delta E, E)$ a sharply picked symmetric (mean value zero) distribution e.g. a Gaussian distribution
- The FP is the first term of a Taylor expansion
- The t_{esc} is not a simple function and represents the spatial transport inside the energy release volume.

Normal and Anomalous transport

Particle transport in Energy and Space in a simple magnetic topology (e.g. a simple solar loop) or in a simple loop with a weak magnetic disturbance $\delta B(r) << B_0(r)$ following a Gaussian probability obey the well known FP transport equation and the transport coefficients are estimated with the use of the Quasilinear Theory. The question we pose in this talk is: What happen when the magnetic disturbances are strong $\delta B > B_0$ and $q(\Delta E, E)$ is a power law in the solar corona?



Transport in a turbulent solar corona

1. The turbulent photosphere drives the active region magnetic filed in the state of turbulent reconnection (MHD). From turbulence to current sheets and turbulent reconnection. We define as turbulent reconnection the plasma state were large amplitude magnetic fluctuations and Unstable Current Sheets (UCS) co-exist and are responsible for the coronal heating and confined flares.
2. Emerging magnetic flux interacting with the ambient magnetic field or los of stability of emerged large scale magnetic structures form large scale current sheets which spontaneously fragment and lead again to turbulent reconnection (MHD) From large scale current sheets to turbulence.
3. How particles are heated and accelerated inside a turbulent reconnecting environment (MHD+Kinetic) were large amplitude MHD waves and Unstable Current Sheets co-exist?

Spontaneous formation of Reconnecting Current Sheets in the turbulent corona driven by the turbulent photosphere

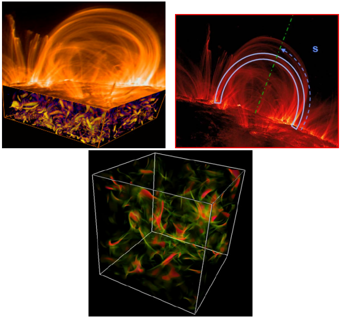


Figure: (a)Stressed from the turbulent convection zone magnetic fields form a turbulent reconnection environment in the Solar Active Regions ((b) Data driven 3D MHD simulations

Externally driven turbulent reconnection

Parker was the first to introduce the concept of driven **turbulent reconnection** in the solar corona. [Parker (1983), Parker (1988), Einaudi et al. (1996), Galsgaard and Nordlund (1996), Georgoulis et al. (1998), Rappazzo et al. (2010), Rappazzo et al. (2013), Dahlburg, et al. (2016)].

The random forcing of magnetic field lines at the photosphere develops spontaneously a turbulent reconnection environment in the corona. The initial magnetic topology is usually a single loop or dipole.

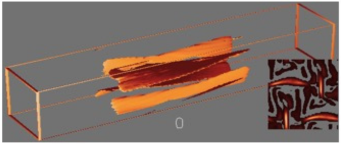
I have highlighted two aspects in our numerial experiments so far the the driver and the the initial magnetic topology

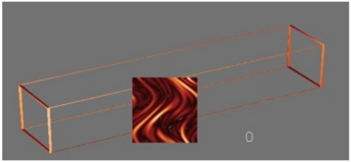
Externally driven turbulent reconnection

see details in [Galsgaard and Nordlund (1996)]

The stochastically driven loop model (Galsgaard)

- 3D MHD experiment of photospherically driven slender magnetic flux tubes
- Continued random driving of the foot points (incompressible sinusoidal large scale shear motions)
- Reconnection jets generate secondary perturbations in B
- Formation of stochastic current sheets





Externally driven turbulent reconnection

Rappazzo et al [Rappazzo et al. (2010)] initiate their simulation with uniform and strong magnetic field tracing the coronal loop between the photospheric planes. At the photosphere a velocity field in the form of a one-dimensional shear flow pattern is present.

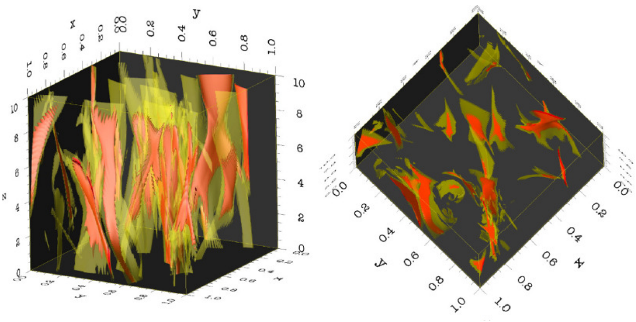


Figure: Isosurfaces corresponding to higher values of j^2. The current sheets filling factor value is small.

Statistical Properties of Unstable Current Sheets

Kanella and Gudiksen
[Kanella and Gudiksen (2017), Kanella and Gudiksen (2018)] use the magnetic filed derived from the potential extrapolation of a dipole magnetic filed and as a photospheric driver use again a continuous driver with random forcing again.

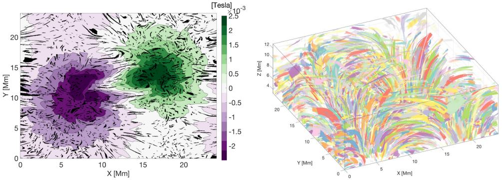


Figure: Left: Contours of the vertical component of the magnetic filed at the base of the corona (at t=1130sec) together with the bases of the identified heating events, Right: Identified features of coronal heating.

Statistical Properties of Unstable Current Sheets

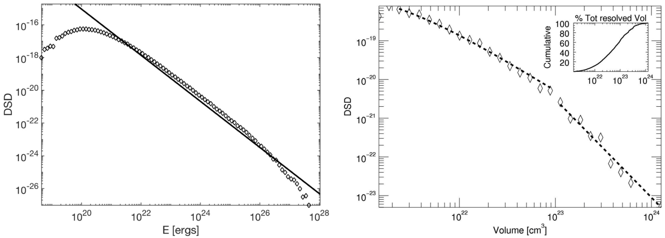
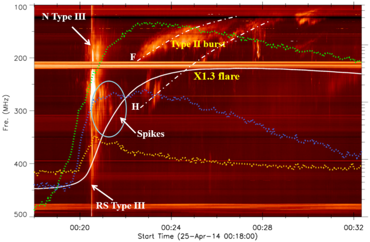


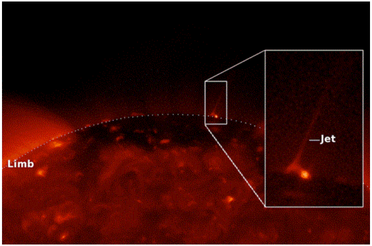
Figure: Left: Differential Size Distribution of the identified features' energy rate, the slope is 1.5, Right: DSD of the identified features, volume with slopes 1.53 and 2.53.

Level 1: From turbulence to turbulent reconnection

The photospheric turbulence spontaneously initiate large amplitude magnetic fluctuations and Unstable Current Sheets (UCS) with a relatively small filing factor the magnetic topology. The UCS interact with their jets or evolve and enhance the ambient turbulence in the corona [Galsgaard and Nordlund (1996), Pucci et al. (2018), Karimabadi et al. (2014)]. The statistical properties of the UCSs are almost universal when the Active Regions reach the state of turbulent reconnection. Coronal heating and confined flares are the result of these physical processes. More on how particles react on such strongly turbulent environment are published in a series of articles published recently [Vlahos et al. (2016), Pisokas et al. (2018), Li et al. (2018), Zhdankin et al. (2018), Comisso and Sironi (2018)]).

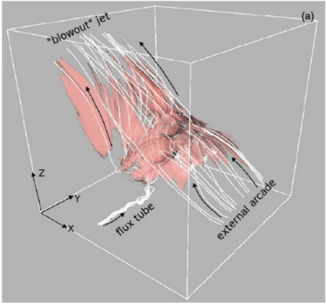
Formation of strong turbulence environment from magnetic flux emergence and jet formation





Formation of strong turbulence environment during explosive events on the Sun

The MHD simulations presented here were based on the article of Archontis and Hood (2013) [Archontis and Hood (2013)] and will plan to submit soon an article on "Particle acceleration and heating in regions of magnetic flux emergence" by Isliker, Archontis and Vlahos, ApJ, 882. 57, 2019.



Formation of strong turbulence environment from the fragmentation of large scale current sheet

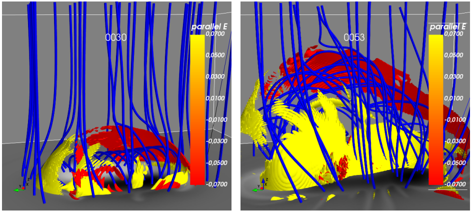
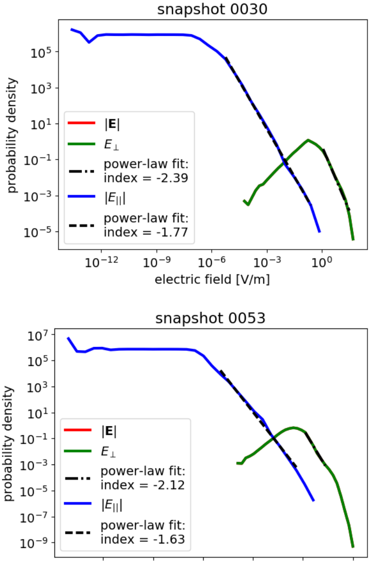


Figure: MHD simulations, snapshot 30, zoom into the coronal part: Magnetic field lines (blue tubes), together with an iso-contour plot of the electric field (red to yellow 3D-surfaces). At the bottom x-y-plane, the photo-spheric component B_z is shown as a 2D filled contour plot. The electric field is in physical units [V/m]. In the left panel, an iso-contour of the magnitude of the of the parallel electric field. Right: MHD simulations, snapshot 53, zoom into the coronal part: Magnetic field lines (blue tubes), together with an iso-contour plot of the parallel electric field (red to yellow 3D-surfaces, for the thresholds

Statistical analysis of the parallel electric filed



Summary of my second point

From large scale current sheets to turbulent reconnection

We claim that the statistical properties of the fragmented large scale current sheet, reported above can reach universal power laws, have fractal spatial distribution around 2, is confined along a 2D surface in this particular numerical experiment. Unfortunately, very few MHD studies have analyze the statistical properties of the current fragmentation in well developed strongly turbulent plasmas so far. The key differences here from the results reported in my previous point are (1) the fact that the they have higher filing factor of the fragmented currents and the prompt initiation of the fragmentation of the large scale current sheet. Both these factors help the explosive events to become more efficient on particle heating and acceleration. I have left out from my discussion here the other large scale non linear structure appearing in the explosive events, which is the shock which lead to turbulent reconnection.

Level 3 (MHD+kinetic): Test particle evolution inside the MHD fields

The relativistic guiding center equations (without collisions) are for the evolution of the position r and the parallel component $u_{||}$ of the relativistic 4-velocity of the particles,

$$\frac{d\mathbf{r}}{dt} = \frac{1}{B^*_{||}}\left[\frac{u_{||}}{\gamma}\mathbf{B}^* + \hat{\mathbf{b}} \times \left(\frac{\mu}{q\gamma}\nabla B - \mathbf{E}^*\right)\right] \qquad (2)$$

$$\frac{du_{||}}{dt} = -\frac{q}{m_0 B^*_{||}}\mathbf{B}^* \cdot \left(\frac{\mu}{q\gamma}\nabla B - \mathbf{E}^*\right) \qquad (3)$$

where $\mathbf{B}^* = \mathbf{B} + \frac{m_0}{q} u_{||} \nabla \times \hat{\mathbf{b}}$, $\mathbf{E}^* = \mathbf{E} - \frac{m_0}{q} u_{||} \frac{\partial \hat{\mathbf{b}}}{\partial t}$, $\mu = \frac{m_0 u_\perp^2}{2B}$ is the magnetic moment, $\gamma = \sqrt{1 + \frac{u^2}{c^2}}$, $B = |\mathbf{B}|$, $\hat{\mathbf{b}} = \mathbf{B}/B$, $u_\perp$ is the perpendicular component of the relativistic 4-velocity, and q, m_0 are the particle charge and rest-mass, respectively.

Initiating the particles

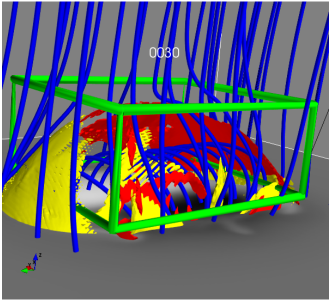
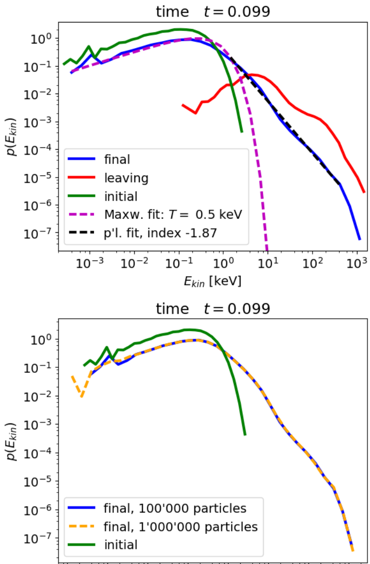
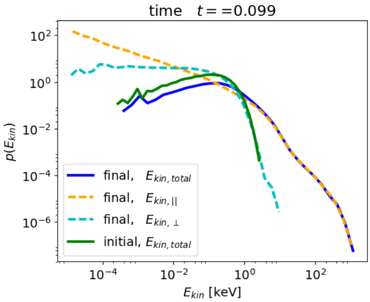


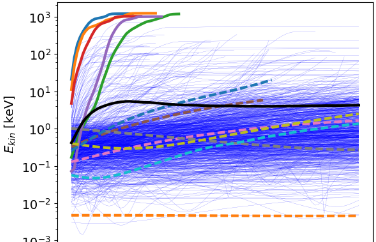
Figure: MHD simulations, snapshot 30, zoom into the coronal part: Magnetic field lines (blue tubes), together with an iso-contour plot of the parallel electric field (red to yellow 3D-surfaces), for the 2 thresholds discussed earlier the photo-spheric component B_z is shown as a 2D filled contour plot. The region in which the spatial initial conditions are chosen is out-lined by a green cube.

Particle energy distributions

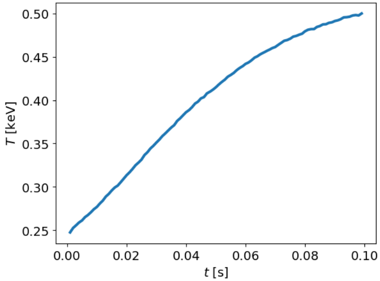


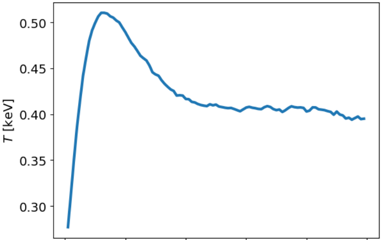
Particle energy distributions



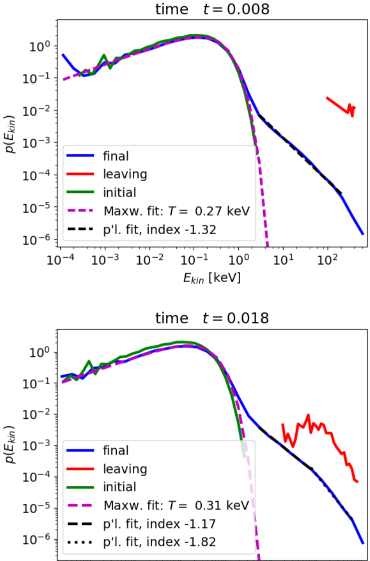


Heating


0.50
0.45
0.40
0.35
0.30
0.25
T [keV]
0.00
0.02
0.04
0.06
0.08
0.10
t [s]


0.50
0.45
0.40
0.35
0.30
T [keV]

Evolution of the distribution for “short” and “long” times



The blowout jet

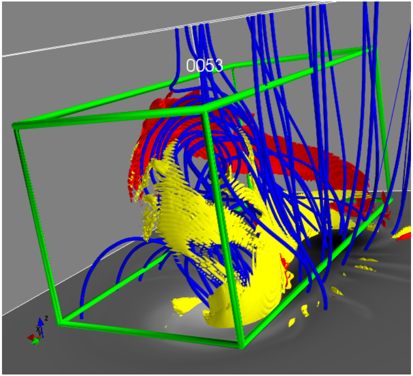


Figure: MHD simulations, snapshot 53, zoom into the coronal part: Magnetic field lines (blue tubes), together with an iso-contour plot of the parallel electric field (red to yellow 3D-surfaces), for the 2 thresholds discussed above. The green cube outlines the region from which the initial conditions are chosen.

Particle dynamics in the blowout jet

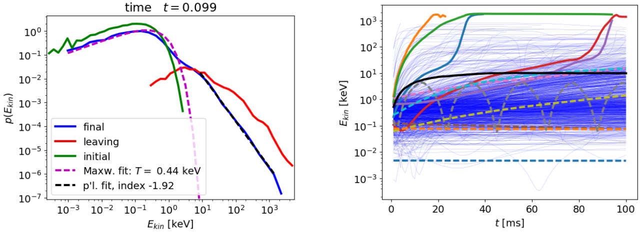


Figure: Snapshot 53: Kinetic energy distribution of electrons after 0.1 sec, without collisions, together with a fit at the low-energy, Maxwellian part and the high energy, power-law part, the initial distribution, and the distribution of the leaving particles (for every particle at the time it leaves) (left). Kinetic energy as a function of time for the test-particles (thin lines), with a few high energy (solid) and low energy (dashed) particles marked with colors, together with the evolution of the mean value (solid black).

Observations

Several RHESSI observations from the base of coronal jets are associated with Hard-X Ray (HXR) emission [Bain and Fletcher (2009), Glesener et al. (2012)]. Frequently during coronal jets the temporal profile of the associated HXRs matches the associated type III radio bursts [Chen et al. (2013)]. Impulsive solar energetic particle events are also related with the jets (see review by [Raouafi et al. (2016)]). It is then obvious that jets act as an efficient mechanism for the heating and acceleration of particles, mainly due to the reconnecting current sheets in the boundary between the emerging magnetic flux and the ambient magnetic field in the solar atmosphere.

Transport in fragmented current sheets: Energy transport

How we will estimate the transport coefficients using the wealth of data collected from the orbits analysed above?
A first and classical candidate for a statistical transport model is the Fokker-Planck equation, which in energy space writes as

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial E}\left[\frac{\partial (Df)}{\partial E} - Ff\right] - \frac{f}{\tau_{esc}} \tag{4}$$

with D the diffusion and F the convection coefficient, and τ_{esc} the escape time. In this approach, the basic step is the determination of the two transport coefficients, D and F, which we derive here from the test-particle simulation data.

Energy transport

An estimate of the energy-dependence of the transport coefficients, for a given time t_k, is made by first prescribing bins along the E_{kin}-axis, with mid-points E_i $(i = 1, ..., n)$, and then considering $E_{kin,j}(t_{k+h}) - E_{kin,j}(t_k)$ a function of E_i if $E_{kin,j}(t_k)$ lies in the bin i. The functional form of the transport coefficients, defined as

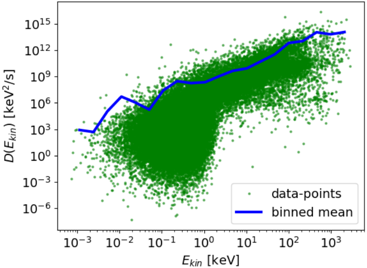
$$D\left(t_k, E_i\right) = \frac{1}{2(t_{k+h} - t_k)} \left\langle \left(E_{kin,j}(t_{k+h}) - E_{kin,j}(t_k)\right)^2 \right\rangle_j \left(t_k, E_i\right) \quad (5)$$

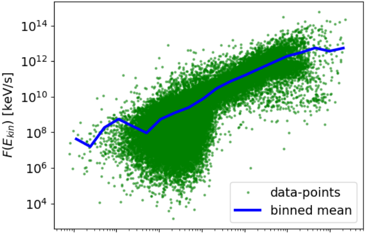
and

$$F\left(t_k, E_i\right) = \frac{1}{(t_{k+h} - t_k)} \left\langle E_{kin,j}(t_{k+h}) - E_{kin,j}(t_k) \right\rangle_j \left(t_k, E_i\right) \quad (6)$$

can then be determined by applying binned statistics, i.e. by calculating the mean values for each bin separately at a given time instance t_k.

Energy transport





Is the Fokker-Planck equation a valid approximation for particle acceleration in strongly turbulent plasmas?

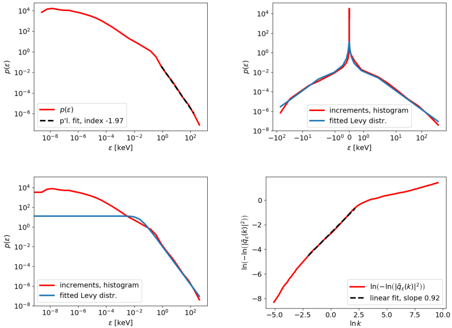


Figure: Snapshot 53, $t \approx 0.1\,$s: (a) Distribution of energy increments. (b) Two-sided distribution of energy increments, together with fitted stable Levy distribution. (c) One-sided distribution of energy increments, together with fitted stable Levy distribution. (d) Characteristic function estimate.

Is the Fokker-Planck equation a valid approximation for particle acceleration in strongly turbulent plasmas?

We show in the previous slides that the histogram $p(\epsilon)$ of the energy increments ϵ_j, which follows a double power-law distribution, with index -1.97 at the highest energies. It then follows that the drift coefficient F, as a mean values of the increments, is not representative for the scale-free data, and the diffusion coefficient D, as a variance of the increments, is ill-defined. This result, namely that the Fokker-Planck formalism breaks down, has been found also for the cases of strong turbulence [Isliker et al. (2017)] and of turbulent reconnection [Isliker et al. (2017)].

Is the Fokker-Planck equation a valid approximation for particle acceleration in strongly turbulent plasmas?

The power-law tail of the distribution of energy increments implies that the particle dynamics is anomalous, with occasionally large energy steps being made, the particles perform Levy-flights in energy space. In [Isliker et al. (2017)], we have introduced a formalism for a fractional transport equation (FTE) that is able to cope with this kind of non-classical dynamics.

Fractional Transport Equation

The FTE has the form [Isliker et al. (2017)]

$$\frac{\partial f}{\partial t} = \frac{a}{\Delta} D^{\alpha}_{|E|} f - \frac{f}{\tau_{esc}} \tag{7}$$

with $D^{\alpha}_{|E|}$ the symmetric Riesz fractional derivative of order α (defined in Fourier space as $\mathcal{F}(D^{\alpha}_{|E|} f) = -|k|^{\alpha} \hat{f}$), a the constant of the Levy stable distribution that is related to the width of the distribution of increments, and Δ the applied time-step in monitoring the particles' energies.

Solution of the Fractional Transport Equation

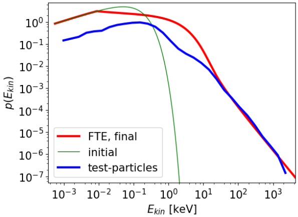


Figure: Snapshot 53: Kinetic energy distribution at initial ($t \approx 0.1$ s) and final time, together with solution of the FTE at final time.

Summary of my third point

Test particle dynamics is useful tool for analysing the particle heating and acceleration in Strongly Turbulent plasmas

- The statistical properties of the electric fields on the fragments of the current sheets and the overall topology play a crucial role for the heating and acceleration of particles.
- The transport of the particles in space and energy do not obey the Fokker-Planck equation, since their interaction with the strong turbulent fields is anomalous. Particles execute Levy flights in space and energy.
- The need for a Fractional Transport Equations is obvious from the particle dynamics.

Building a "satellite" for theory and modellimg

Theorists and modellers are not prepared to deal with the complexity of the magnetic fields in the solar atmosphere. My proposal for the coming years is to form expand the existing consortia to work on the synergy of the following systems

- Observations of the photospheric motions and magnetic flux emergence
- Non Linear Force Free extrapolation of magnetic fielsd
- 3D MHD codes
- Search for the CSs formation along the complex magnetic structures
- Statistical properties of the CSs and the electric fields
- test particle simulation and transport properties of the particles
- Radiation codes and prediction multi wavelength emission

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