DEPARTMENT OF SPACE SCIENCE
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

# Electron Acceleration and the Development of Power-Law Energy Spectra in Magnetic Reconnection With A Force-free Current Sheet

(ApJ, 2020, 2021)

Haihong Che

University of Alabama in Huntsville, Alabama

RHESSI-20 virtual Workshop, 6-9 June, 2021

# Collaborators

- G. P. Zank (UAH)
- A. O. Benz (FHNW & ETH Zürich)
- B.  Tang (Postdoc, graduated 2020, UAH)
- C. Crawford (3rd year Graduate Student)

FHNW: University of Applied Sciences and Arts Northwestern Switzerland

# Characteristics of Solar Electron Acceleration

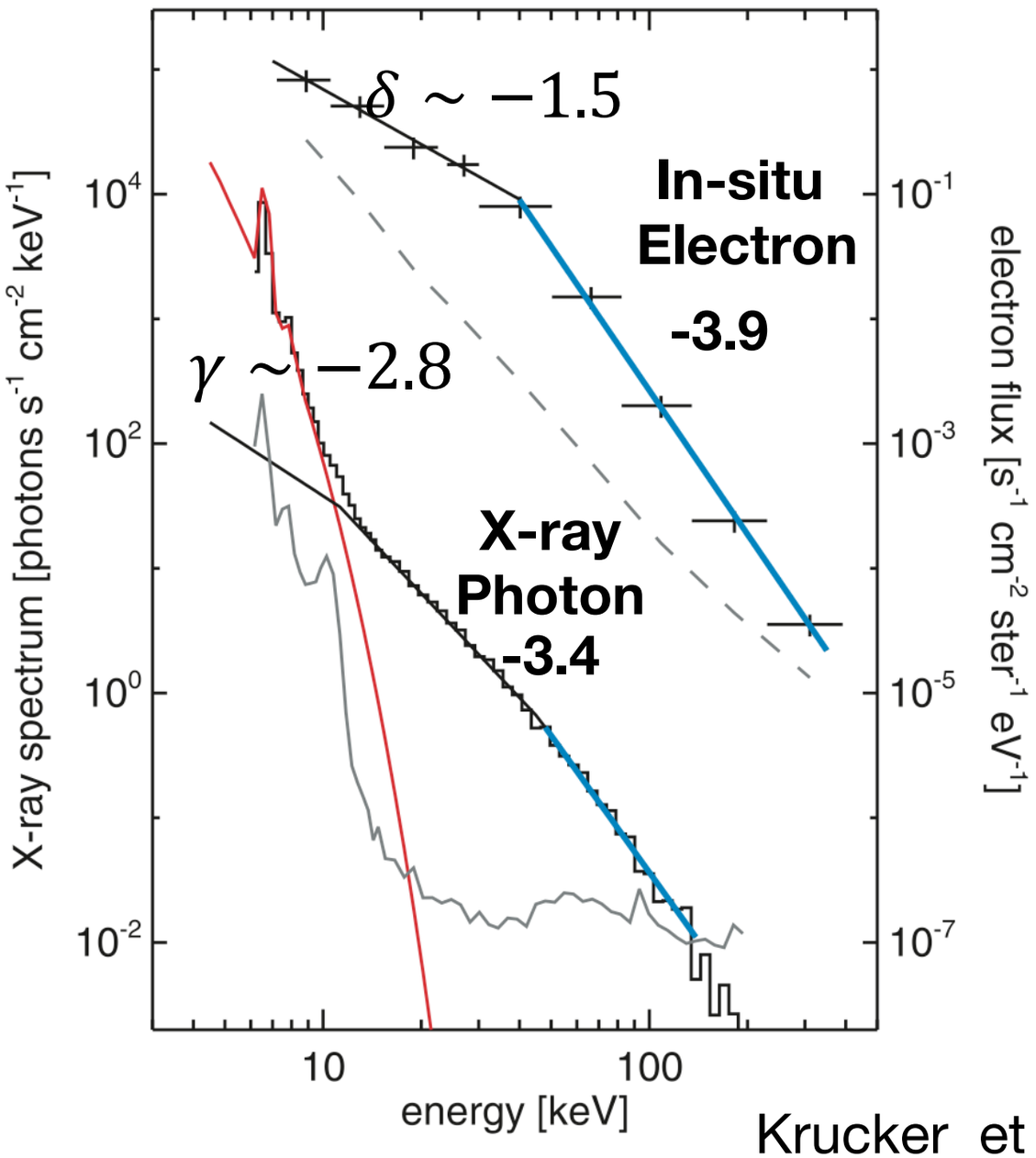
## 1. Energy of Electrons: very mild-relativistic

- Typical energetic electrons in solar flares : 20keV - MeV.
- Nanoflares: keV- hundrands keV

- The rest mass energy of electron is 511keV, MeV gives the Lorentz factor $\gamma \sim 2$.

# Characteristics of Solar Electron Acceleration

## 2. Power-Law Energy Distribution of Energetic Electrons




Krucker et al, 2007, ApJ

Power-law energy distribution implies

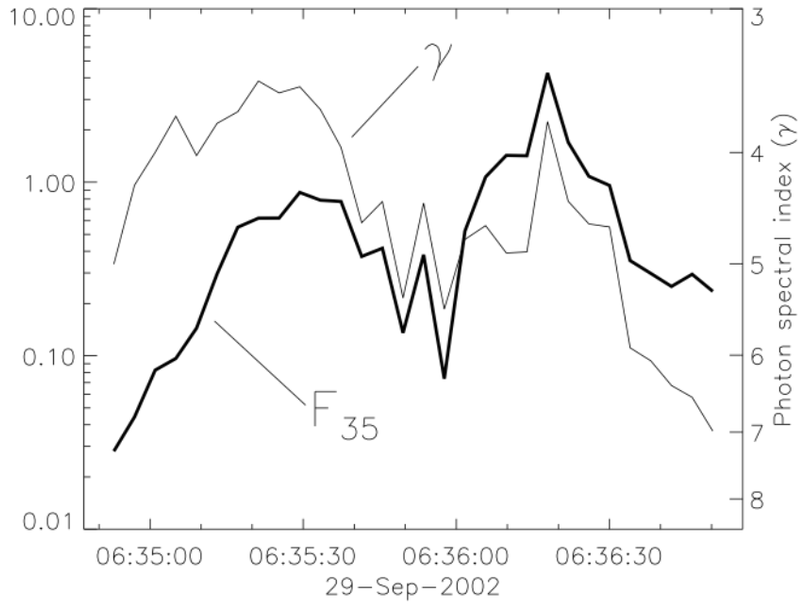
the acceleration is a **random** process-

Fermi-acceleration process in

reconnection.

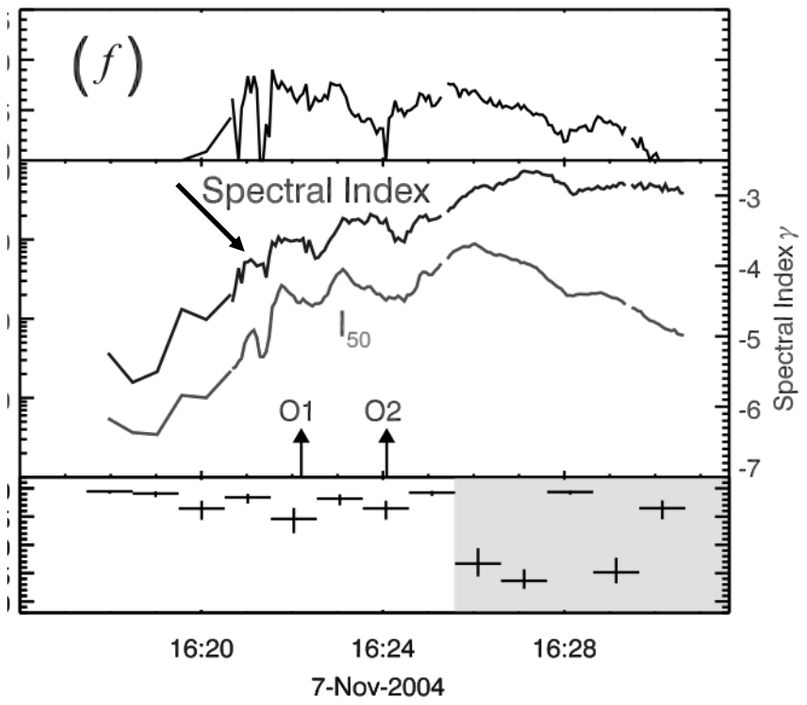
$$f(E) \propto E^{-\delta}$$

# Characteristics of Electron Acceleration
# 3. Two-Stage Evolution of  Electron Energy Spectra




**Soft-Hard-Soft evolution**

Grigis & Benz, 2004, ApJ




**Soft-Hard-harder**

Grigis & Benz, 2008, ApJ, Garyson et al, 2009, ApJ

# Characteristics of Electron Acceleration

## 4. Acceleration Time Scale <1s

(Benz, LRSP, 2017)

The acceleration of a particle to an energy $E_{kin}$ must occur faster than the collision time $\tau_{coll}(E_{kin})$ for energy loss. The energy loss time for an electron with velocity v is

$$\tau_{coll}(E_{kin}) = 3.1\times10^{-20}\frac{v^3}{n_e} = 0.31(\frac{v}{10^{10}cms^{-1}})^3(\frac{10^{11}cm^{-3}}{n_e})[s] < 0.1s$$

**Maximum time scale estimation:** $v = 0.03c = 3\times10^8 cm/s$ and $n_e = 10^{10}/cm^3, \tau_{coll}(E_{kin}) \sim 1s$**.**

Recent observations discovered that acceleration time can be shorter than 50 ms (Alexander T. Altyntsev et al., 2019)

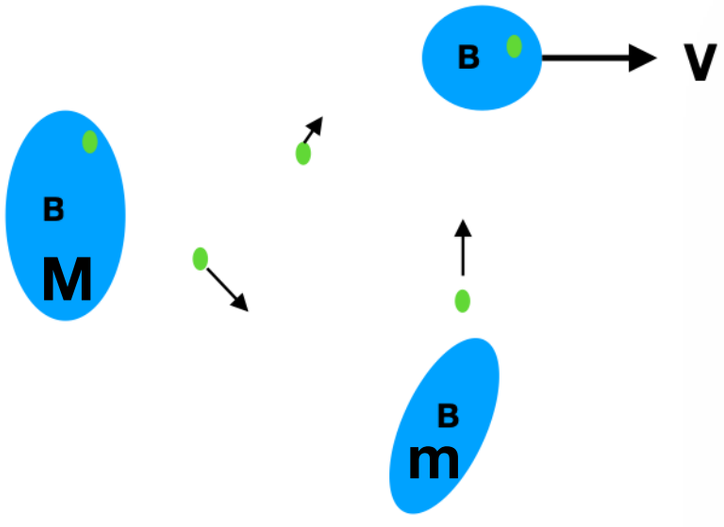
**The time scale is comparable to l/$V_A$ , where l is the acceleration region spatial scale and $V_A$ is the Alfven wave speed. Flare time scale: L/$V_A$. L is the active region spatial scale. l/$V_A$ << L/$V_A$.**

# Previous Models and “Injection Problem”

# Why Is Solar Energetic Particle Acceleration the long-standing“injection problem”?

# “Injection Problem” in Fermi Acceleration Model

(E. Fermi, 1949, Physical Review)




2nd order Fermi-acceleration. Cosmic rays are accelerated by random moving magnetic clouds.

The collision between the clouds and particles are elastic.

## Relativistic case

Assuming v~c, M>>m, energy and momentum conservation give

$$mc^2 + Mu^2/2 = m_1c^2 + Mu_1/2$$

$$mv + Mu = m_1v_1 + Mu_1$$

$$m = m_0/(1 - v^2/c^2)^{(1/2)}, \quad m_1 = m_0/(1 - v_1^2/c^2)^{(1/2)}$$

Give $\Delta E/E = 2u^2/c^2$, $\Delta E = m_1c^2 - mc^2$

## Non-relativistic case

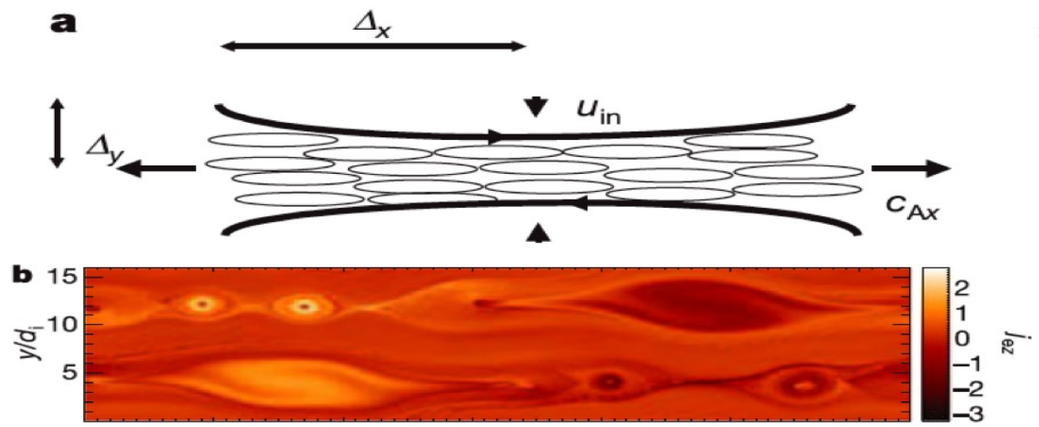
Assuming M>>m, energy and momentum conservation give

$$\Delta v = v + 2U$$

**Unable to produce power-law energy distribution.**

**Fermi-acceleration mechanism can not produce a power-law energy distribution for Non-relativistic particles and it requires energetic particles are injected into the system. “injection problem” was first realized by Fermi himself in his 1949 paper.**

# Previous Model: Multi-islands Acceleration Is Not Efficient




c Tearing instability produces multi-island. Tearing is driven by magnetic shear. Thus tearing instability is intrinsic to reconnection, But it is not an efficient acceleration mechanism.

The first adiabatic invariant $\mu = m_e v_\perp^2/2B = constant$ and the conservation of magnetic flux $\psi \sim Bl$ describe the electron acceleration in the perpendicular direction:

$$\frac{dv_\perp^2}{dt} = \frac{v_\perp^2}{B}\frac{dB}{dt}, \qquad \frac{dB}{dt} = -B\frac{dl}{dt}. \tag{3}$$

second adiabatic invariant $J = m_e \oint v_\parallel ds \sim m_e v_\parallel l$ implies

$$\frac{dv_\parallel}{dt} = -v_\parallel \frac{1}{l}\frac{dl}{dt}.$$

$$\Rightarrow \quad \frac{dW}{dt} \propto \frac{V_l}{c}\frac{1}{\tau_c}W,$$

Condition for the validity of adiabatic invariants: dl/dt <<1 and dv/dt<<dl/dt

**Acceleration time scale $\gtrsim$ reconnection (flare) time scale.**

# A New Fermi-Acceleration Mechanism

## Electron Acceleration in Magnetic Reconnection with a Force-free Current Sheet

(Che & Zank, ApJ, 2020
Che et al., 2021)

# Velocity Shear in Force-free Current Sheet

In force-free current sheet, both the guide field and velocity shear are required. Velocity shear can trigger Kevin-Helmholtz instability (KHI). Thus, KHI is intrinsic to force-free.

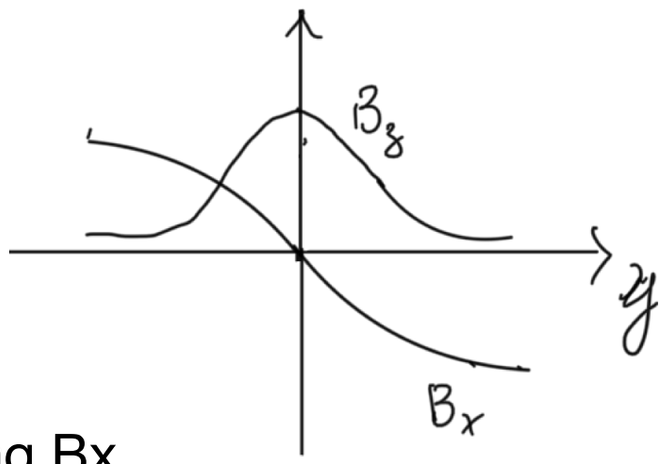
**On electron dynamic scale, the dominant shear is stored in the electron velocity which can trigger electron Kevin-Helmholtz instability.**

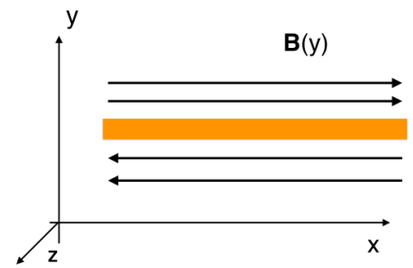
$$\mathbf{j}\times\mathbf{B} = 0$$

$$j_x B_z = j_z B_x \rightarrow B_x^2 + B_z^2 = C$$

$B_z \neq 0$ at y=0

$j_x = j_z B_x / Bz \neq 0$ Anti-parallel following Bx



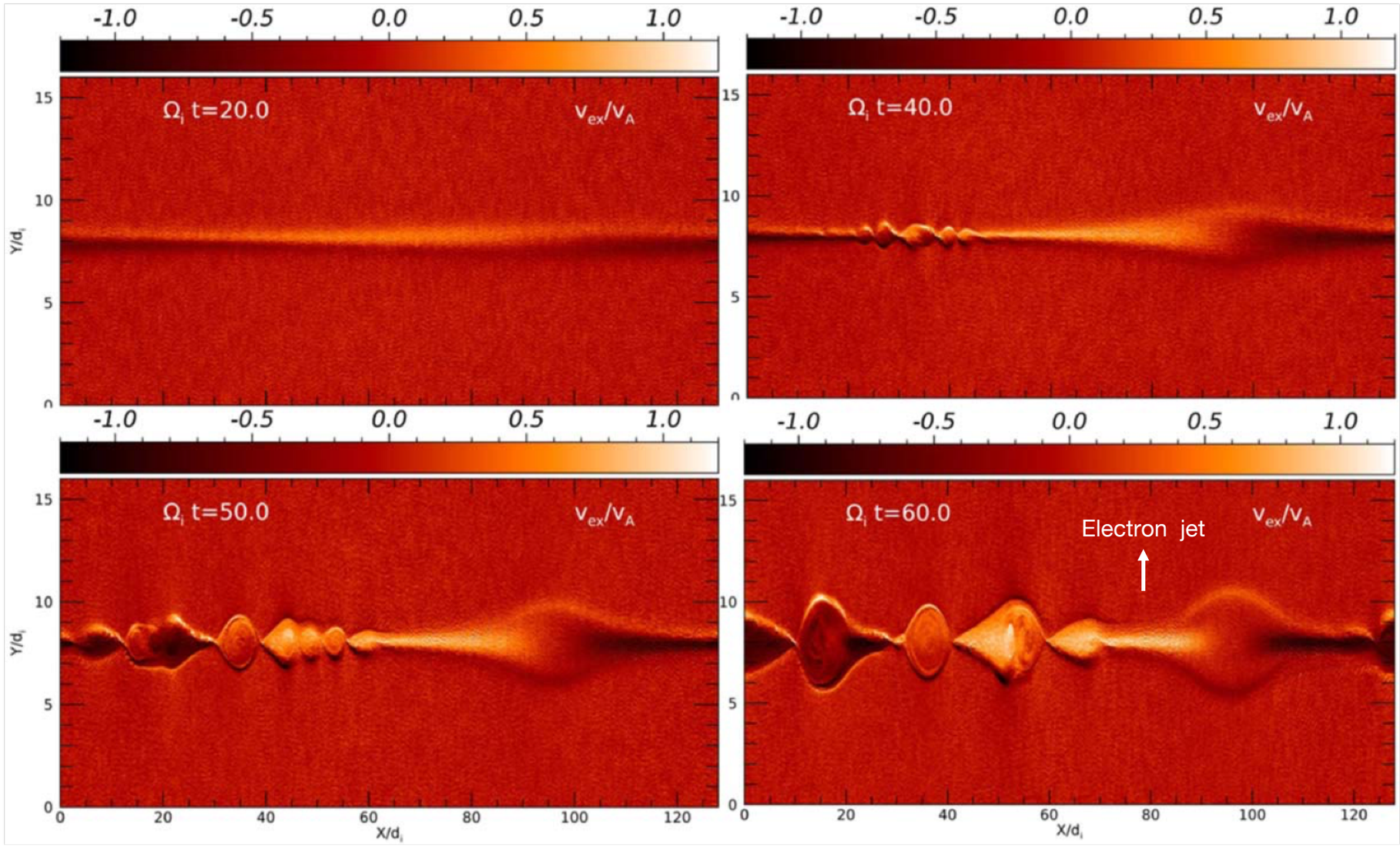
# PIC Simulation Results

- Electron Kevin-Helmholtz instability (EKHI) is triggered when the width of current sheet stinks to be around the electron inertial length.

- Magnetic vortices are generated along the currents and quickly expands with a growth rate of electron gyro-frequency $\Omega_{ce}$ —> leads to the fast magnetic energy release and electron acceleration.

- Electrons are accelerated to a power-law in about 20 ion gyro-periods (less than **1ms** in the solar corona).

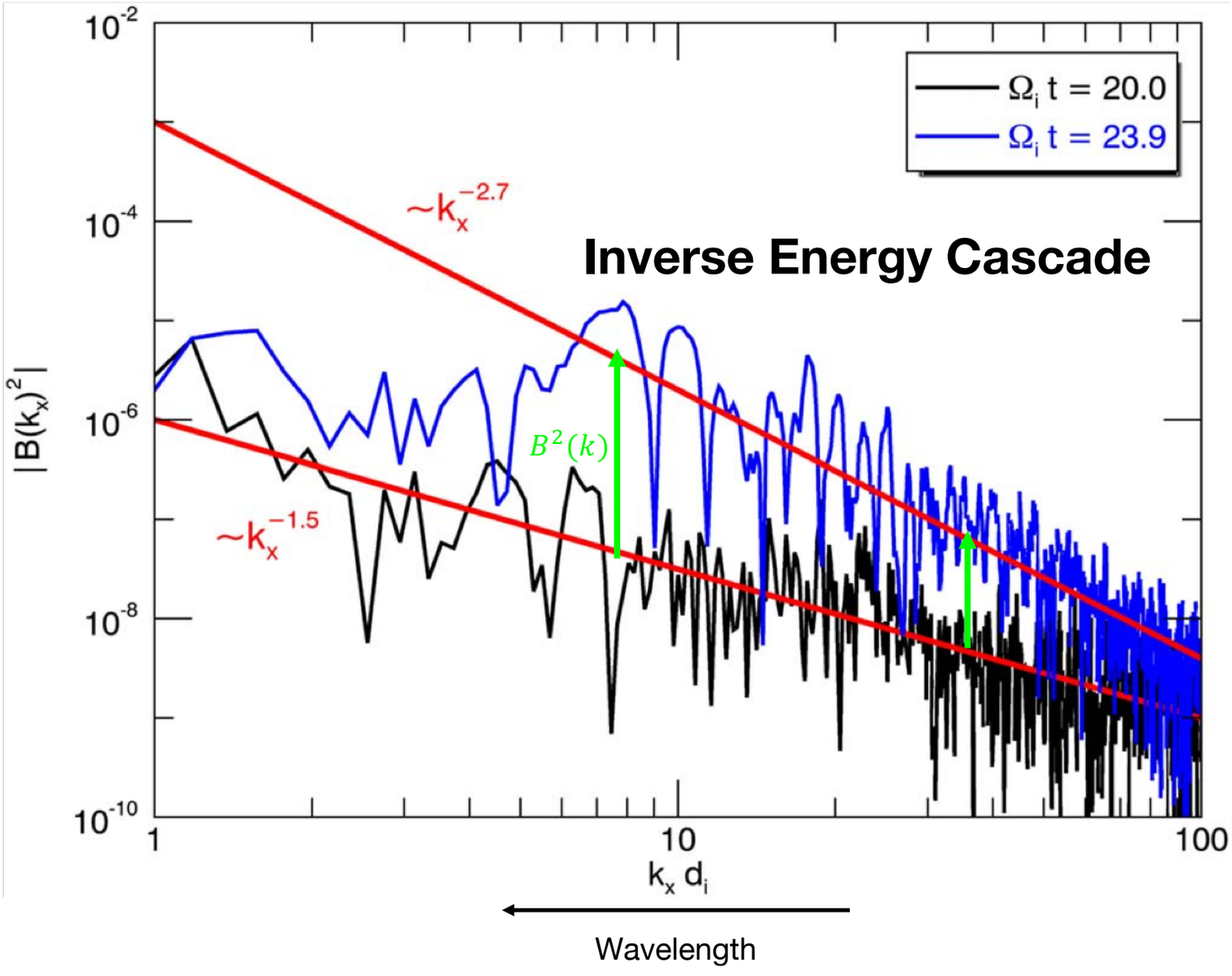
# Anti-parallel Velocity Shear Accumulated During Magnetic Reconnection and EKHI is triggered



# Two-stage Magnetic Turbulence

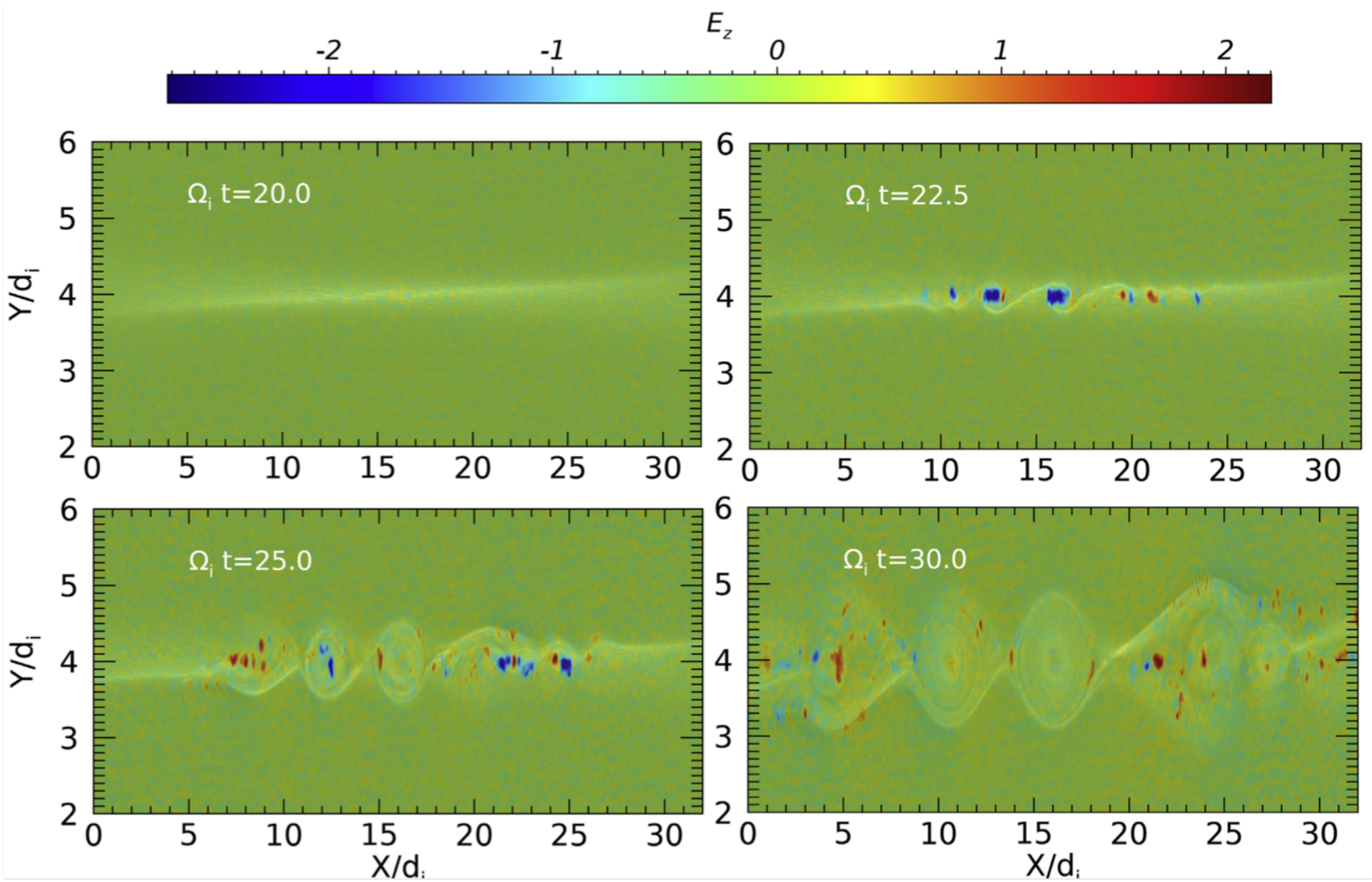
## 1st stage: linear stage, before $\Omega_i t = 20$

## 2nd stage: nonlinear stage, after $\Omega_i t = 20$




More magnetic energy move to longer wavelength at late time

# Stochastic Inductive Electric Fields Generated by Two-Stage Magnetic Turbulence




$$\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

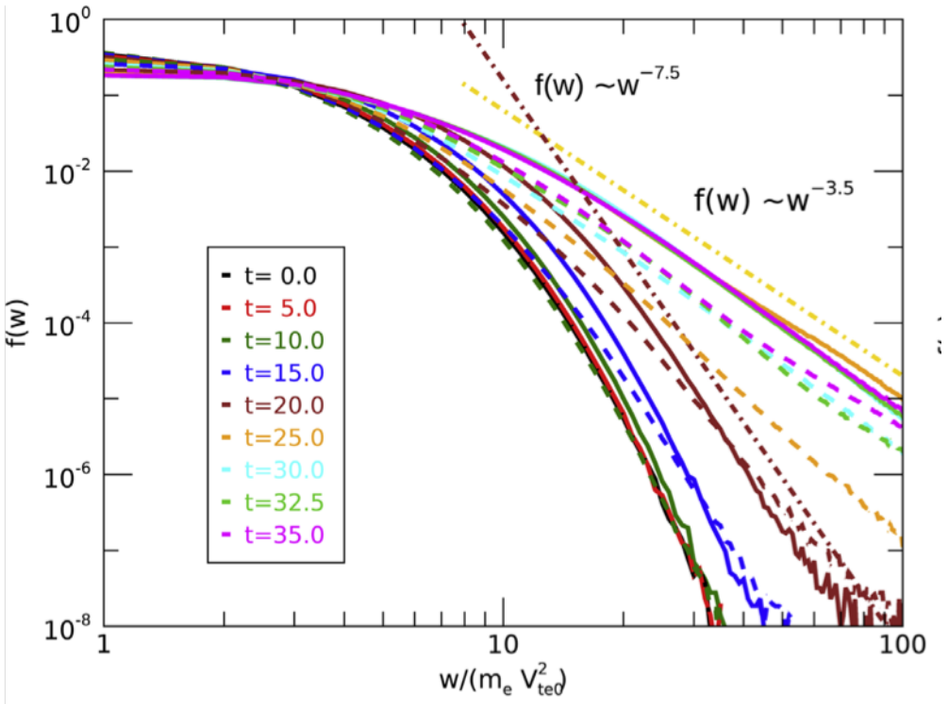
$$\mathbf{B} = B_x\hat{x} + B_y\hat{y}$$

$$\mathbf{E} = E_z\hat{z}$$

**We show that stochastic electric field acceleration is a 2nd-order Fermi-acceleration**

$$\frac{\delta v_z}{\delta t} = \frac{\cos^2\theta}{2\tau_g} v_z = \frac{F_z}{m_e},$$

# Two-Stage Soft-Hard-Harder Evolution Fermi-Acceleration—Consistent with Flare Observations




1st stage from: linear stage. Producing a power-law energy distribution with index -7.5

2nd stage from: nonlinear stage. Producing a power-law energy distribution with index -3.5

The acceleration time is on the order of tens ion gyro-frequency $\Omega_{ci} \sim 10^{-5} s^{-1}$, < 0.01 seconds.

We show that the index is determined by the turbulence structures, i.e. the ratio of the spatial scales of stochastic electric fields D and the magnetic vortices R and the guide field. The indices are consistent with the simulations and the observations.

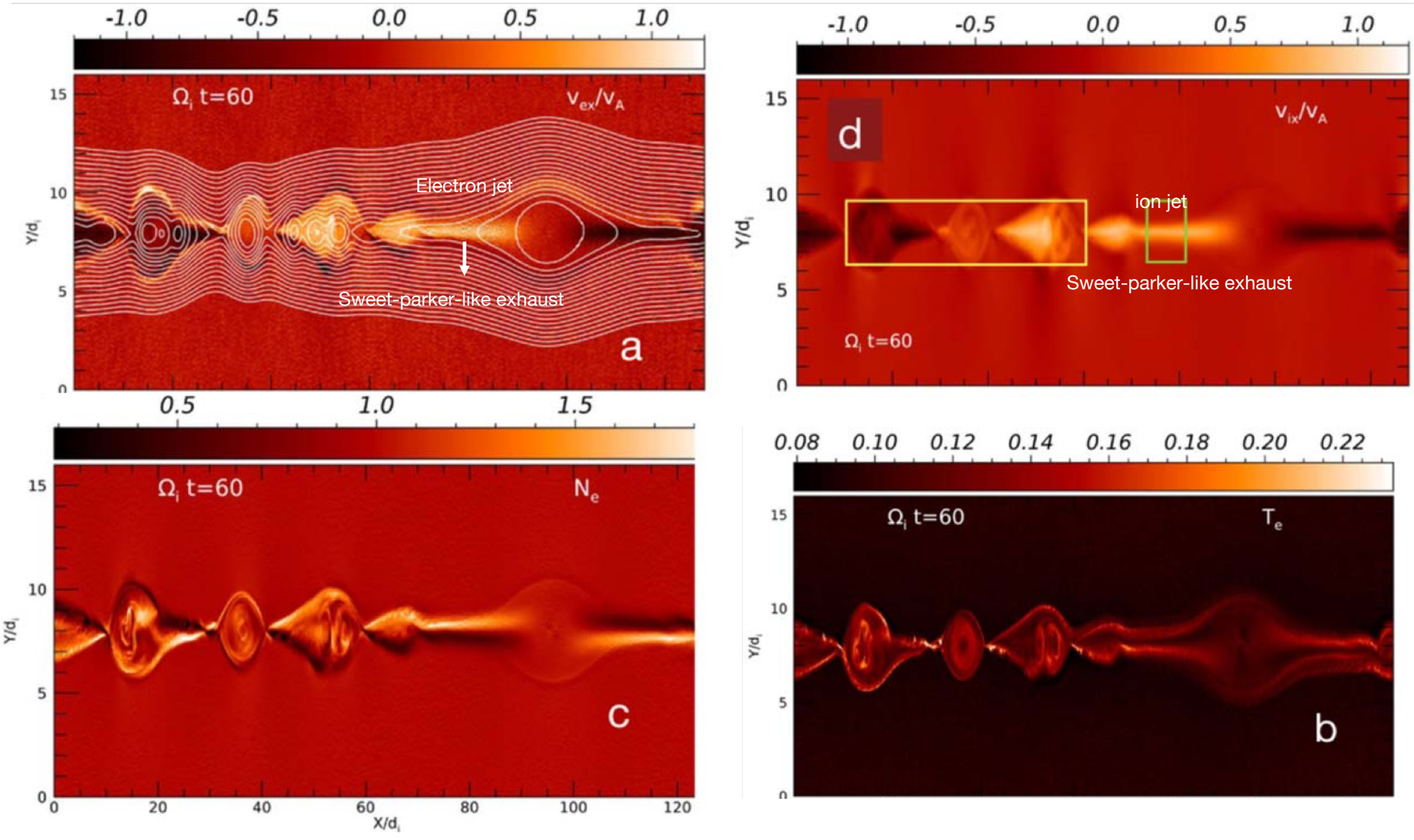
$$\bar{f}_z(W_z) \propto W_z^{-\left(1+4a^2\frac{D}{R}\right)/2}. \qquad a = B_g/B_0$$

$$\bar{f}_z(v_z) \propto v_z^{-7}; \bar{f}_z(w_z) \propto W_z^{-3.5},$$

# Outflow Jets and Properties

## Turbulence surpasses Hall effect and generate Sweet-parker-like outflow jets

## sweet-parker




**The density of electron jet is highly asymmetric—> asymmetric x-ray emission.**

# What are the “News” in Our Model?

- For the first time, we demonstrates a self-consistent PIC simulation from the generation of turbulence to the acceleration of the power-law electron energy spectra in a sufficiently short time scale required for solar flare acceleration.

- For the first time, we analytically proved that the stochastic electric field acceleration is a second-order non-relativistic Fermi-acceleration and related the index to the spatial scales of the turbulence. A viable solution for “injection problem”.

- For the first time, we demonstrate a two-stage spectral evolution that is observed in the solar flare acceleration.

- For the first time, we discover that turbulence can overcome the hall-effect and generate a elongated sweet-parker-like electron jet which is x-ray observable.

- **This mechanism can accelerate ions too (paper submitted)**

*Thank You !*