# *3-D RPIC simulations of relativistic jets: Particle acceleration, magnetic field generation, and emission*

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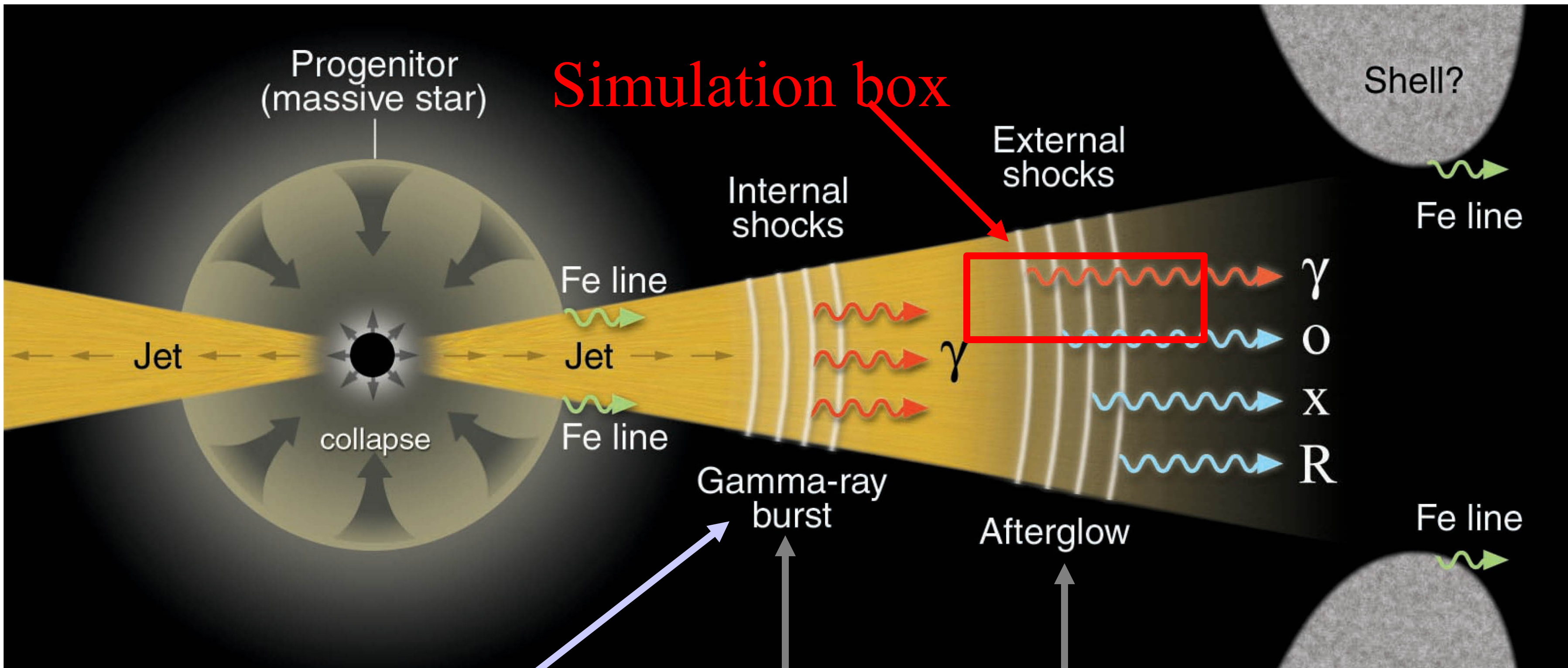
***CHALLENGES OF RELATIVISTIC JETS**, Cracow, Poland, June 25 – July 1, 2006*

# *Scientific objectives*

- **How do shocks in relativistic jets evolve in accelerating particles and emission?**
- **How do 3-D relativistic particle simulations reveal the dynamics of shock front and transition region?**
- **What is the main acceleration mechanism in relativistic jets, shock surfing, wakefield, Fermi models or stochastic processes?**
- **Understand observations from GLAST (GBM) based on simulation and theoretical studies**
- **Obtain spectra and time evolutions from simulations and compare with observations**

# *Schematic GRB from a massive stellar progenitor*

(Meszaros, Science 2001)




Prompt emission

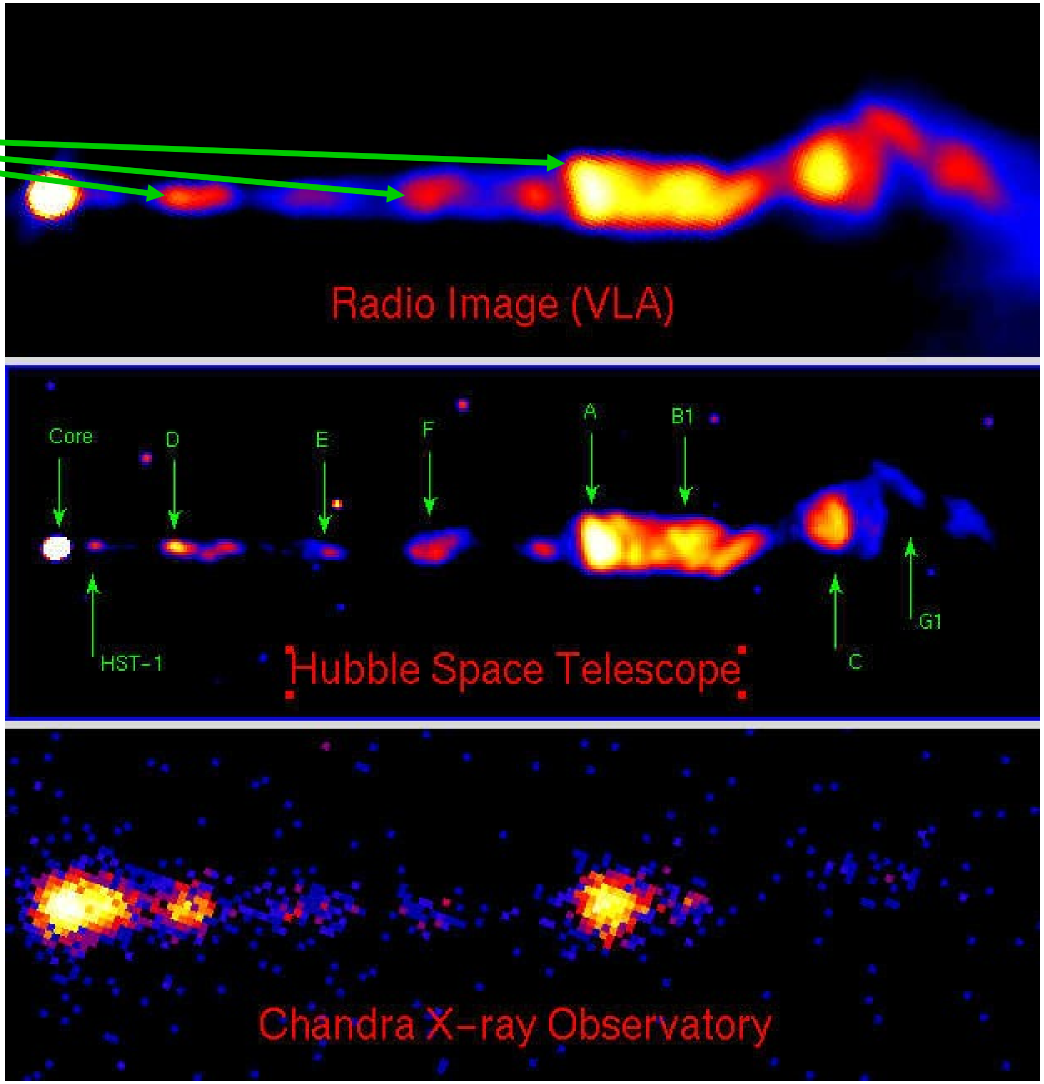
Polarization ?

Accelerated particles emit waves at shocks

# *Observations of M87*

**Shocks?**

**nonthermal electrons, enhanced magnetic field, jitter radiation (Medvedev 2000, 2006; Fleishman 2006)?**



# *Necessity of 3-D full particle simulation for particle acceleration*

- **MHD simulations provide global dynamics of relativistic jets including hot spots**
- **MHD simulations include heating due to shocks, however do not create high energy particles (MHD simulation + test particle (Tom Jones))**
- **In order to take account of acceleration, the kinetic effects need to be included**
- **Test particle (Monte Carlo) simulations can include kinetic effects, but not self-consistently**
- **Particle simulations provide particle acceleration (η) with ($\varepsilon_e$, $\varepsilon_B$) and emission self-consistently. However, due to the computational limitations, particle-in-cell (PIC) simulations covers only a small part of the full jet.**
- **Particle simulations can provide synchrotron and jitter radiation from ensemble of each particle (electron and positron) motion in electromagnetic fields.**

# *Weibel instability*

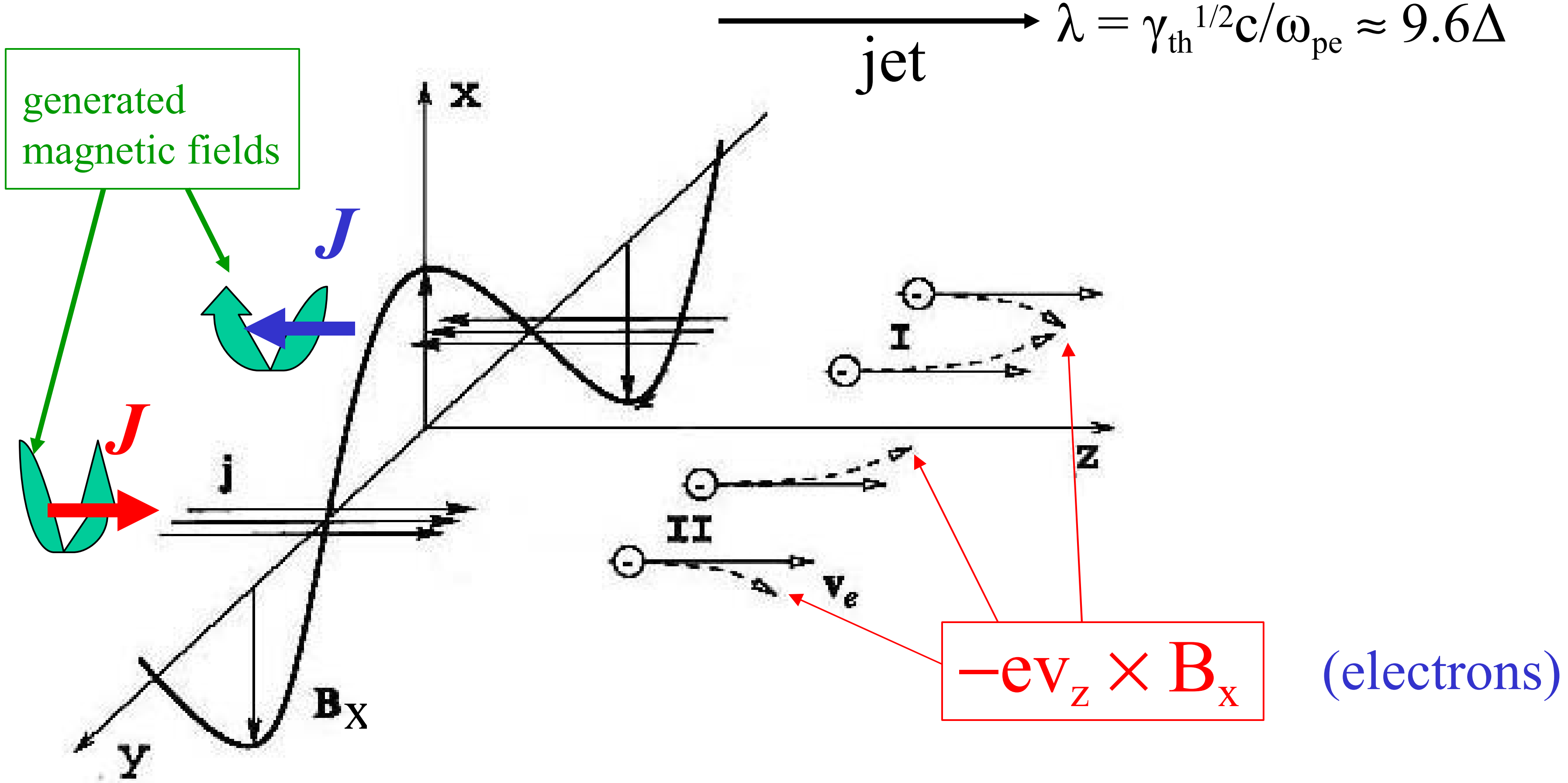
**current filamentation**

Growth time:

$\tau = \gamma_{sh}^{1/2}/\omega_{pe} \approx 21.5$

Length:

$\lambda = \gamma_{th}^{1/2}c/\omega_{pe} \approx 9.6\Delta$




(Medvedev & Loeb, 1999, ApJ)

# *Initial parallel velocity distributions of pair-created jets*

- A: $\gamma = (1-(v_j/c)^2)^{-1/2} = 5$
- B: $\gamma = (1-(v_j/c)^2)^{-1/2} = 15$
- C: $4 < \gamma < 100$ (distributed cold jet)

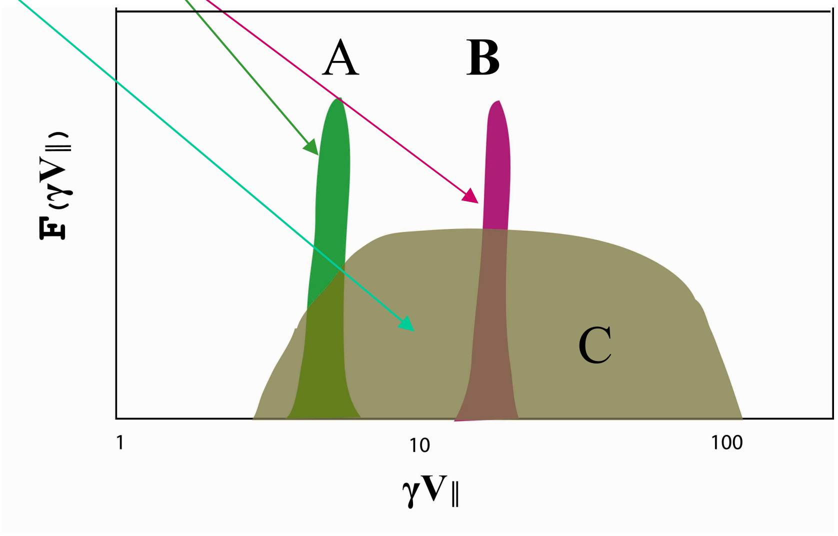
(pair jet created by photon annihilation, $\gamma+\gamma \rightarrow e^{\pm}$)

- A': $\gamma = 5$ (electron-ion)

Growth times of Weibel instability:

$\tau_A \ll \tau_{A'} \ll \tau_B \ll \tau_C$

Schematic initial parallel velocity distribution of jets



# *Snap shots at* $\omega_{pe}t$ =59.8

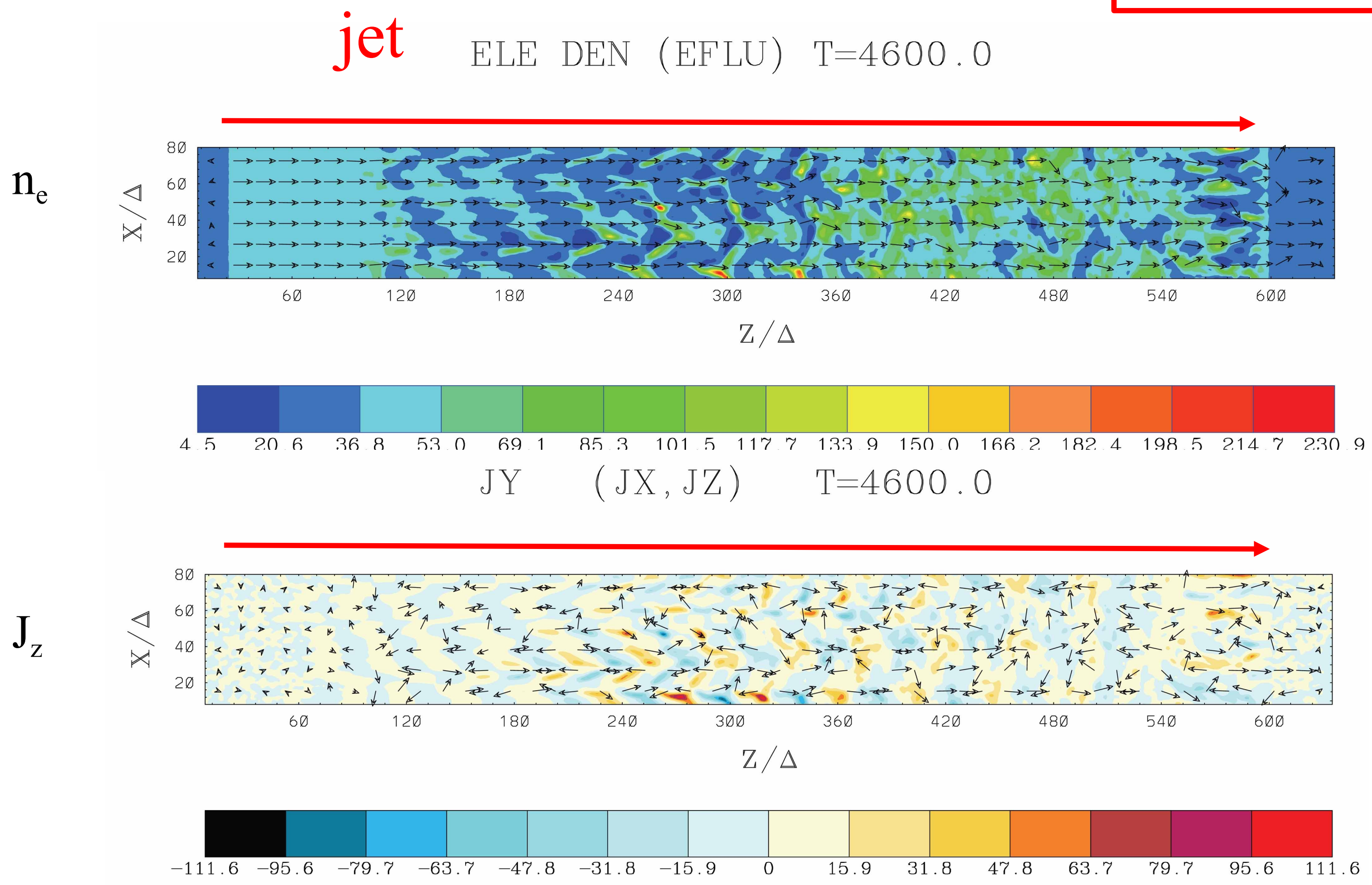
**electron-positron jet (γ= 15) (B)**

$n_{ISM} = 1/cm^3$

$\omega_{pe}^{-1} = 0.1msec$

$c/\omega_{pe} = 5.3$ km

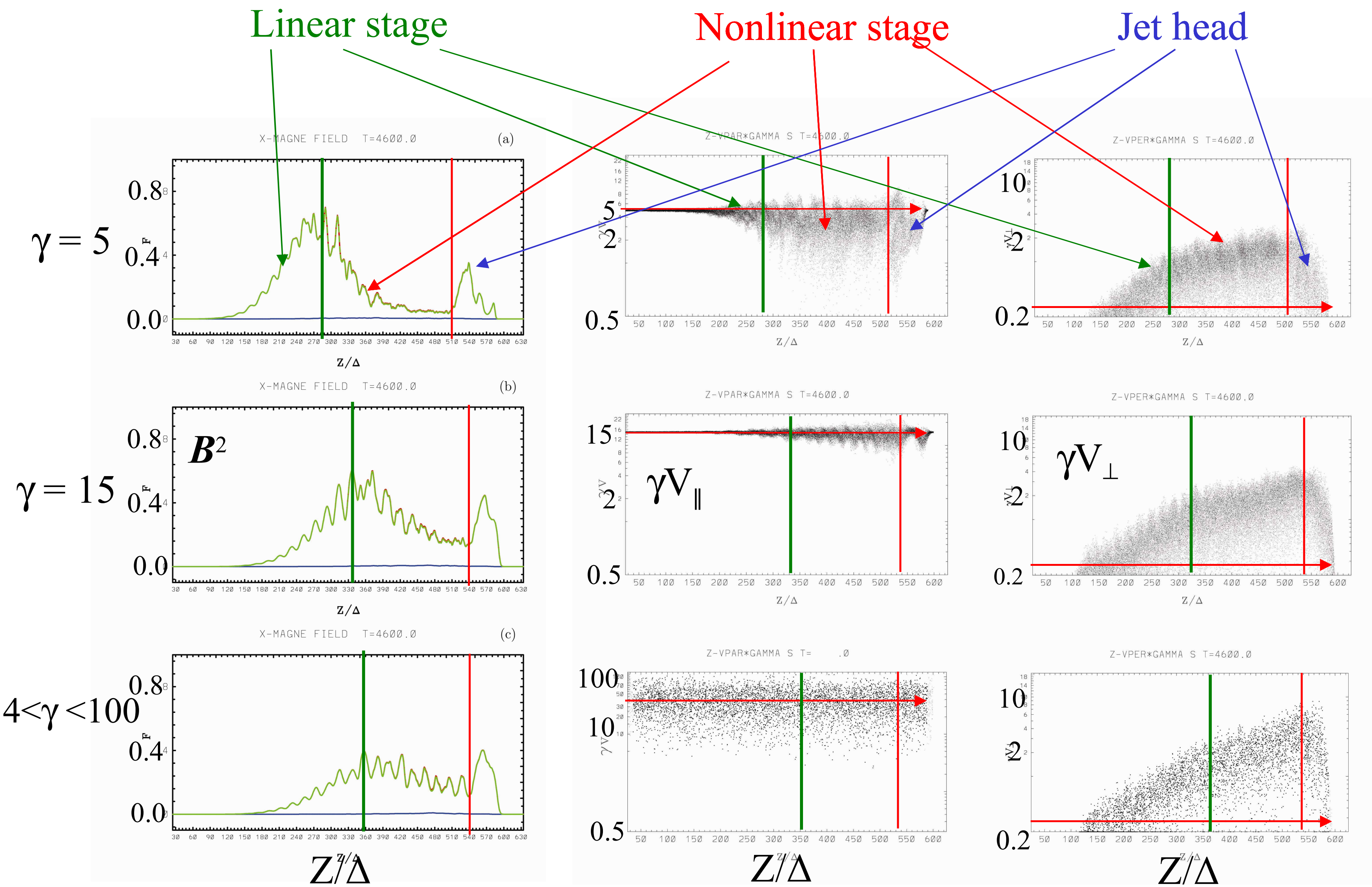
$L \approx 300$ km




(Nishikawa et al. 2005)

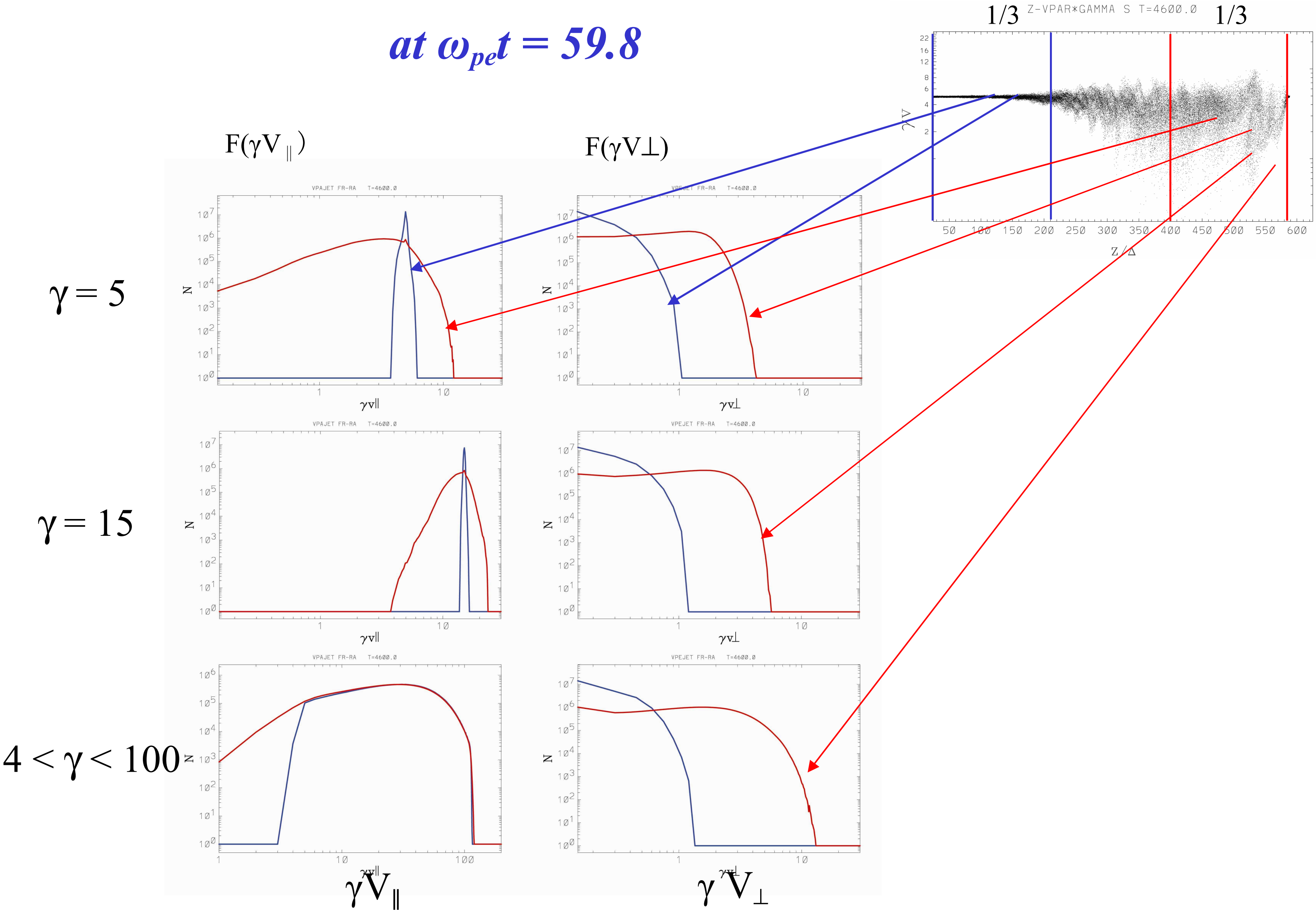
# Magnetic field energy and parallel and perpendicular velocity space along Z

$\omega_{pe}t = 59.8$



# *Parallel and perpendicular velocity distributions*

## *at $\omega_{pe}t = 59.8$*



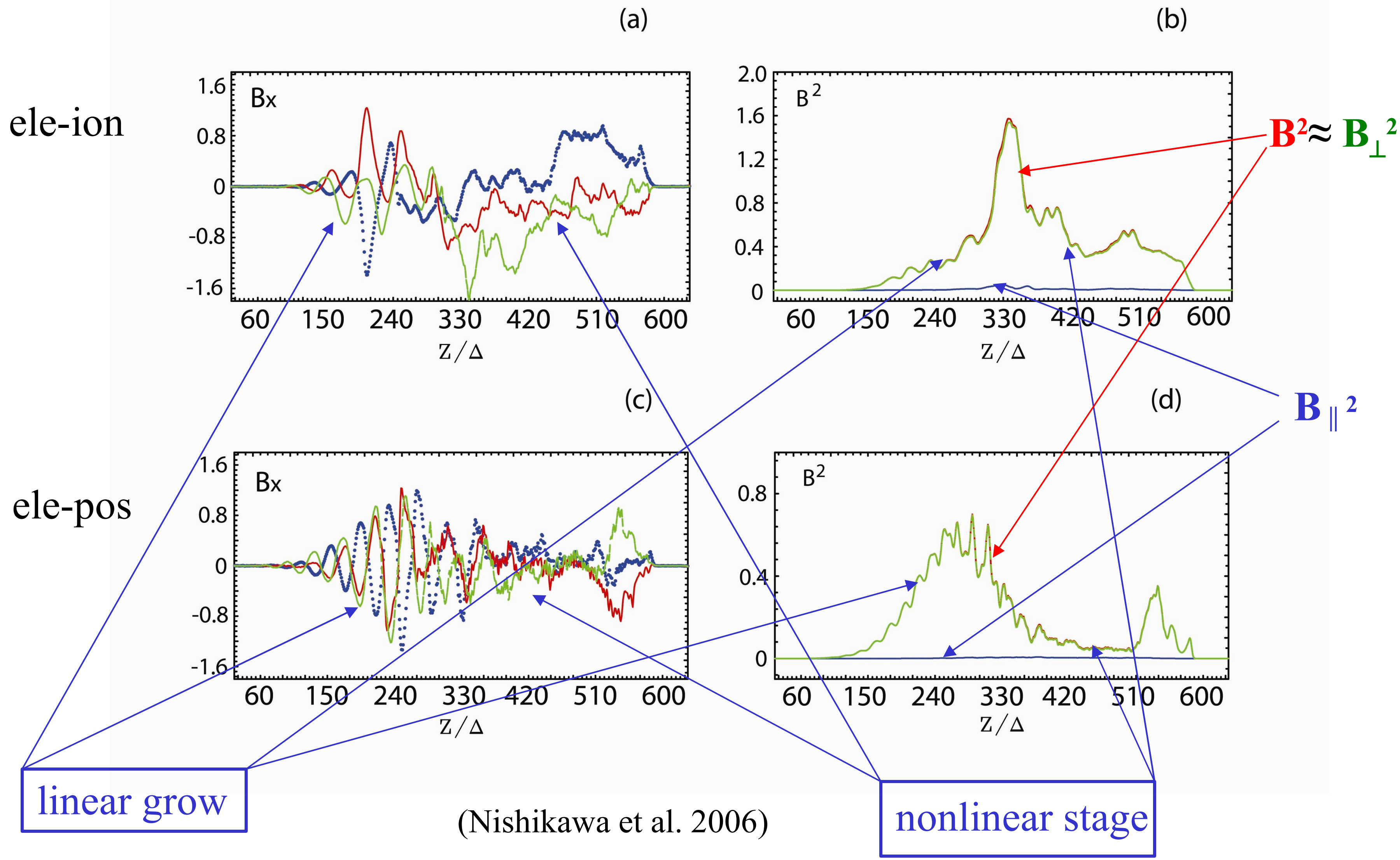
# *Evolutions of magnetic fields*

$\omega_{pe}\, t = 59.8$

$\gamma = 5$

*x/Δ* = 38

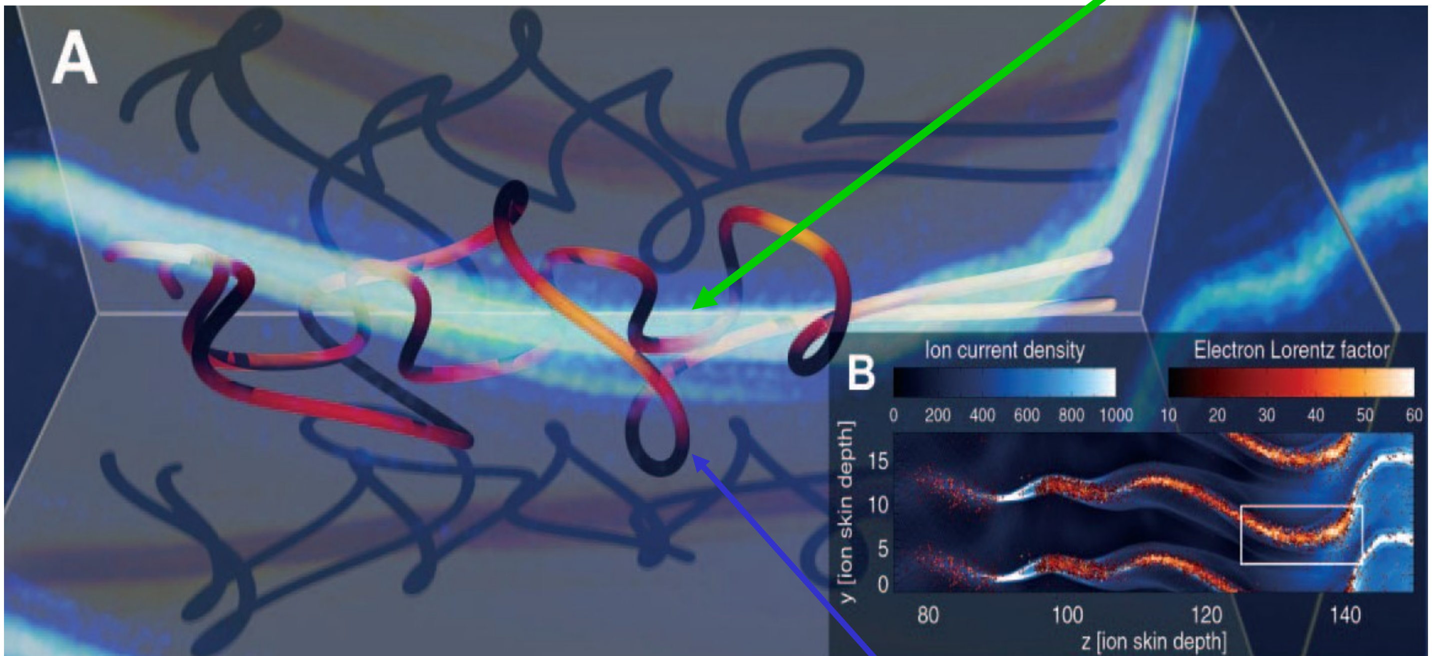
*y/Δ* = 33 (*blue*); 43 (*red*); 53 (*green*)

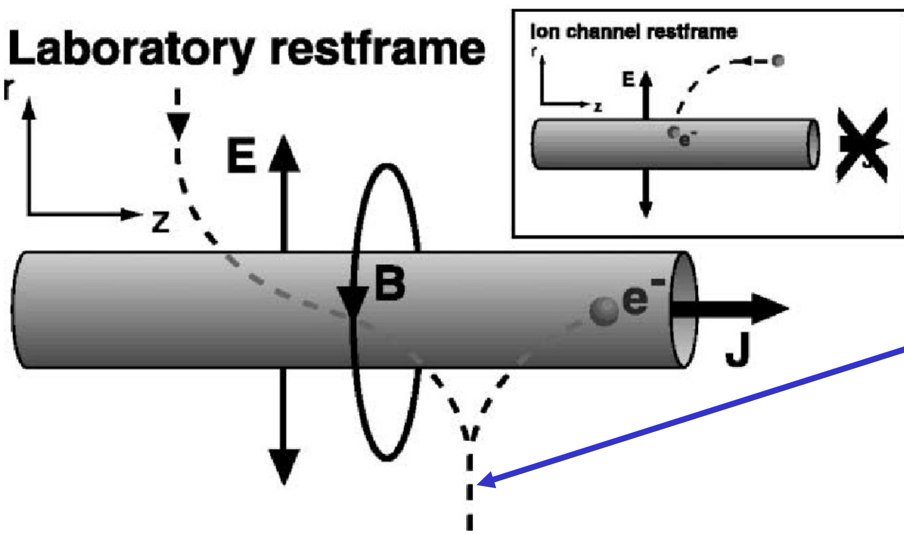



(Nishikawa et al. 2006)

# *Ion Weibel instability*

**ion current**




***E × B acceleration***

**electron trajectory**

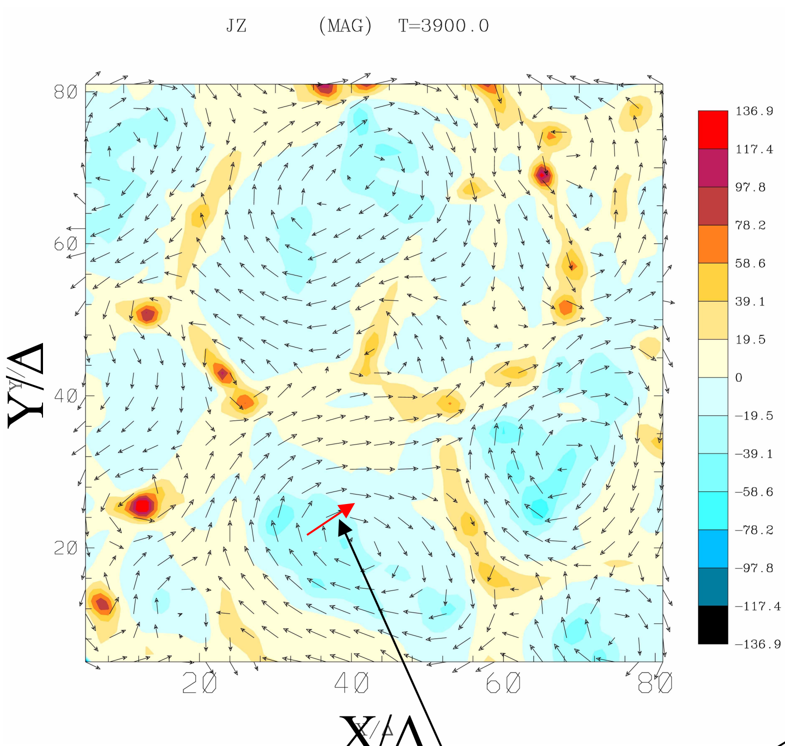
**(Hededal et al 2004)**

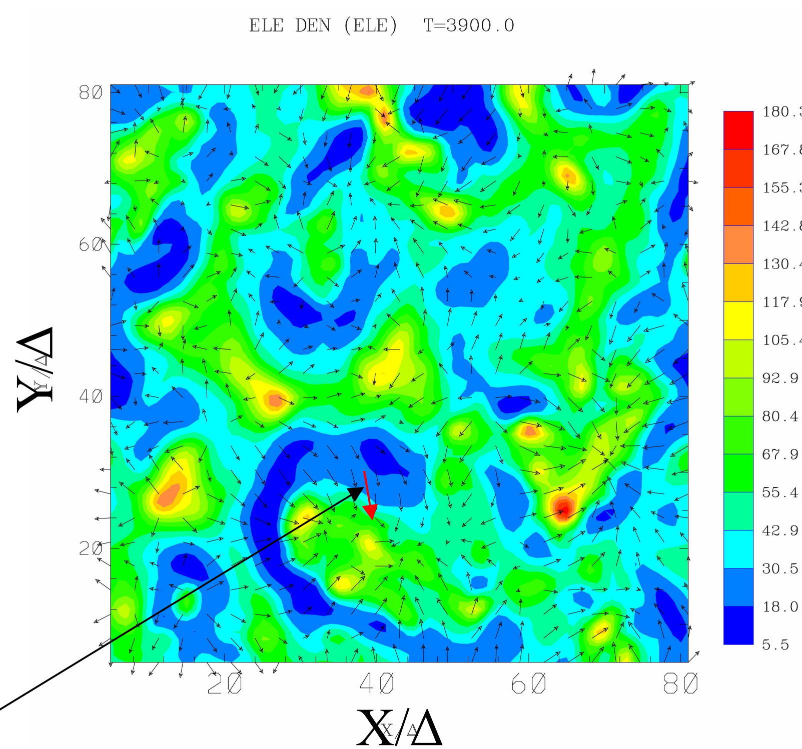
# *E×B acceleration due to the current channel* (Z/Δ= 430)

$t = 50.7\omega_{pe}$ ***electron-ion jet*** $\gamma = 5$

$J_z$ arrows: $B_x$, $B_y$

$n_e$ arrows: $E_x$, $E_y$



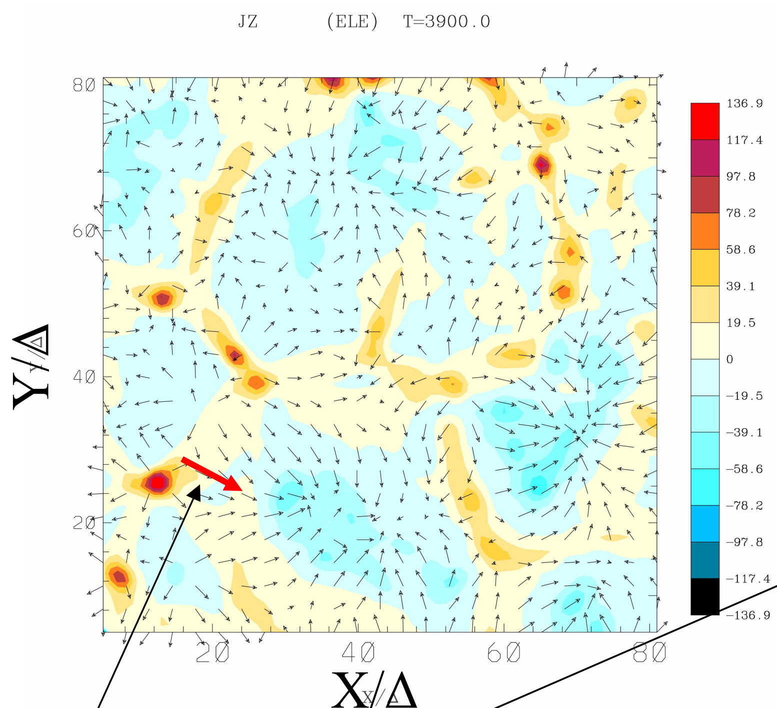



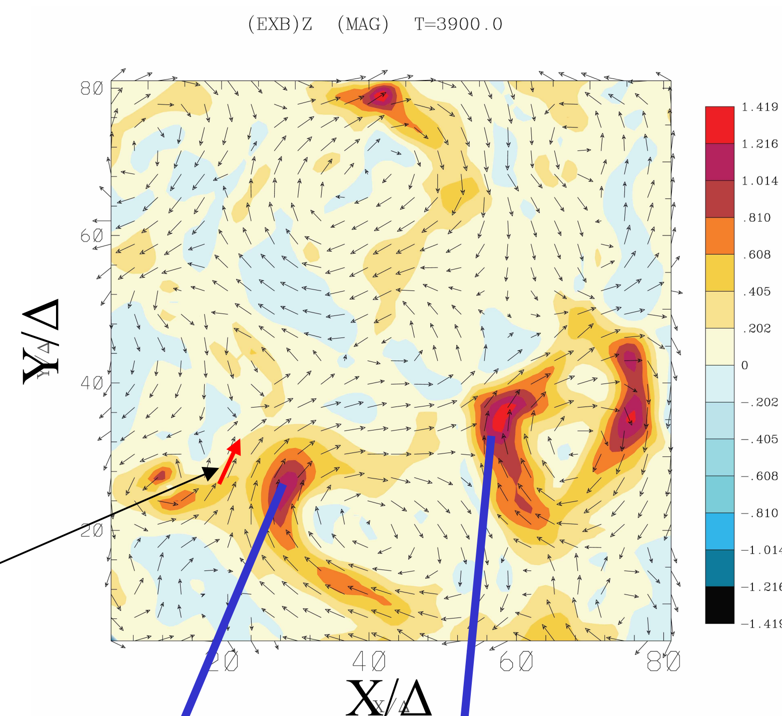

***B*** and ***E*** are nearly perpendicular

# *E×B acceleration and deceleration* (Z/Δ= 430)

t = 50.7$\omega_{pe}$ ***electron-ion jet*** $\gamma = 5$

$J_z$ arrows: $E_x$, $E_y$ $(E\times B)_z$ arrows: $B_x$, $B_y$

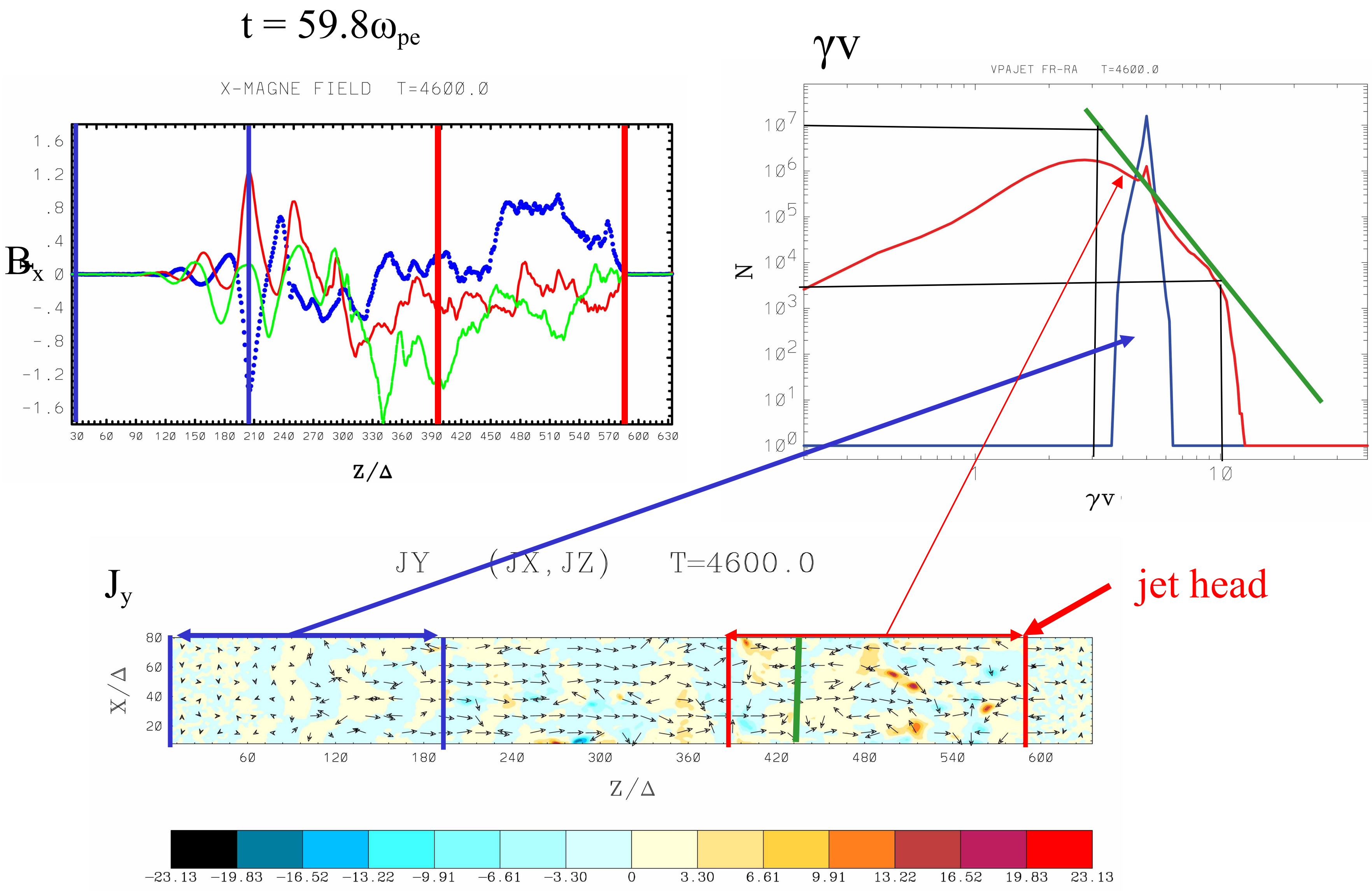



***E*** and ***B*** are nearly perpendicular

both electrons (and positrons) are accelerated in this region

# *Longer simulation of electron-ion jet injected into unmagnetized plasma*



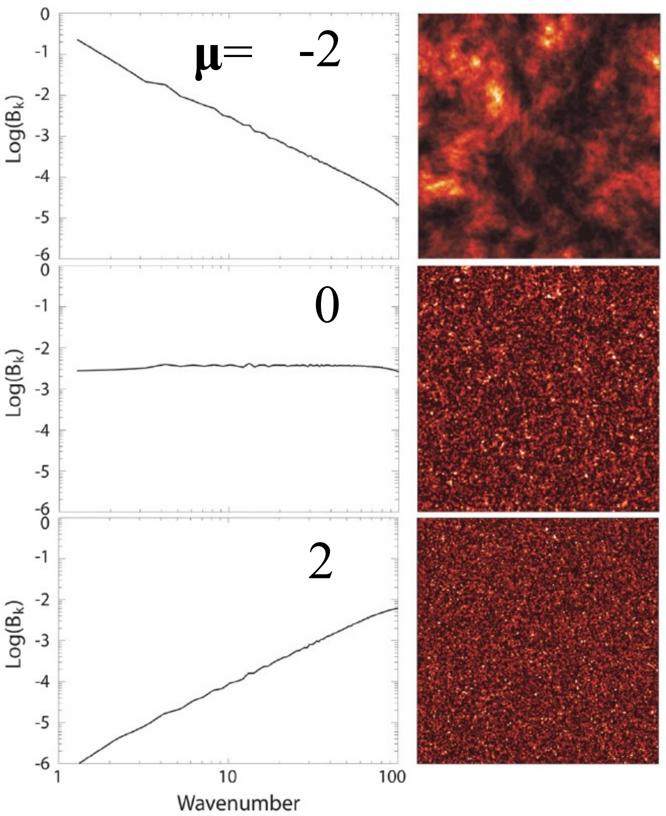

(Nishikawa et al, 2006)

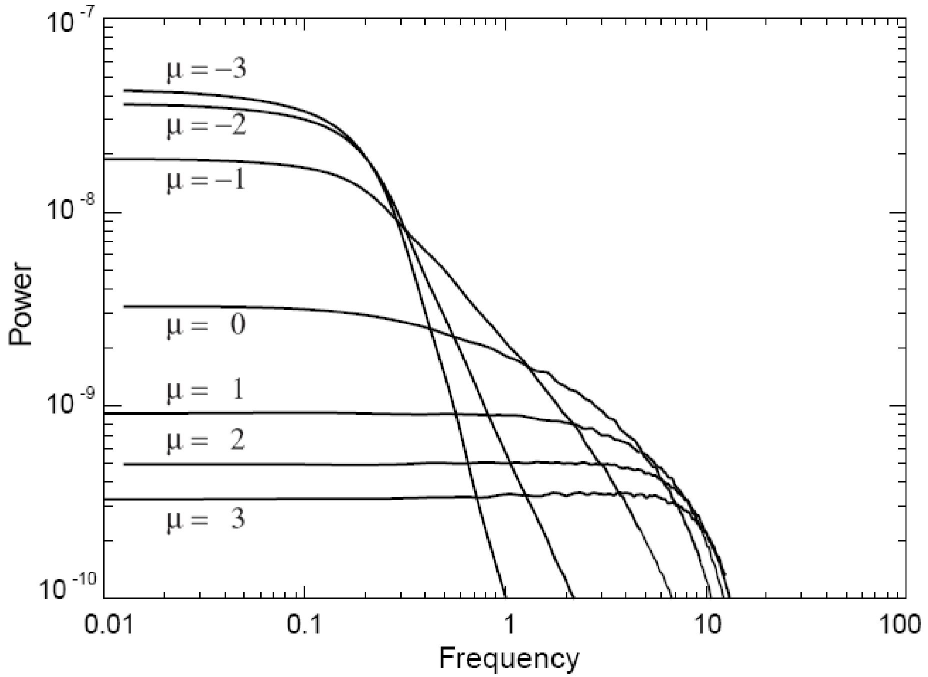
# *3D jitter radiation (diffusive synchrotron radiation) with a ensemble of mono-energetic electrons ($\gamma$= 3) in turbulent magnetic fields (Medvedev 2000; 2005, Fleishman 2005)*

$P_B(k) \propto k^{\mu}$

2d slice of magnetic filed

3D jitter radiation with $\gamma$ = 3 electrons

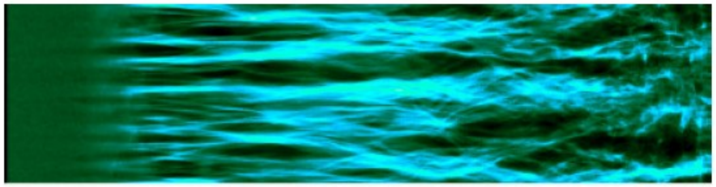



Hededal & Nordlund (astro-ph/0511662)

# *Radiation from collisionless shock*

Spectrum obtained directly from shock simulations



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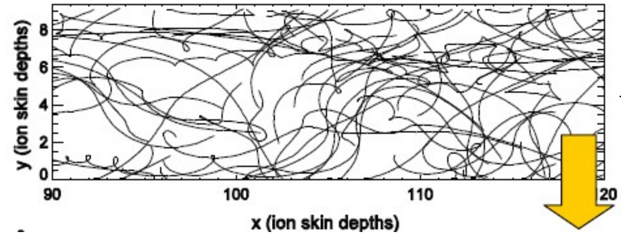
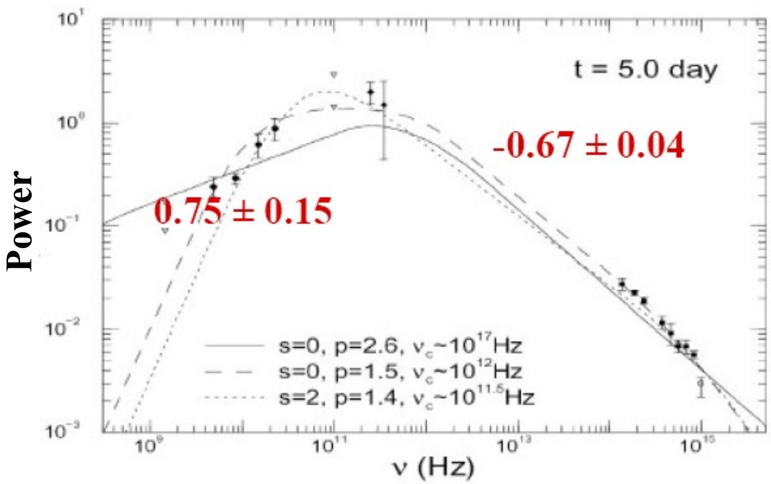
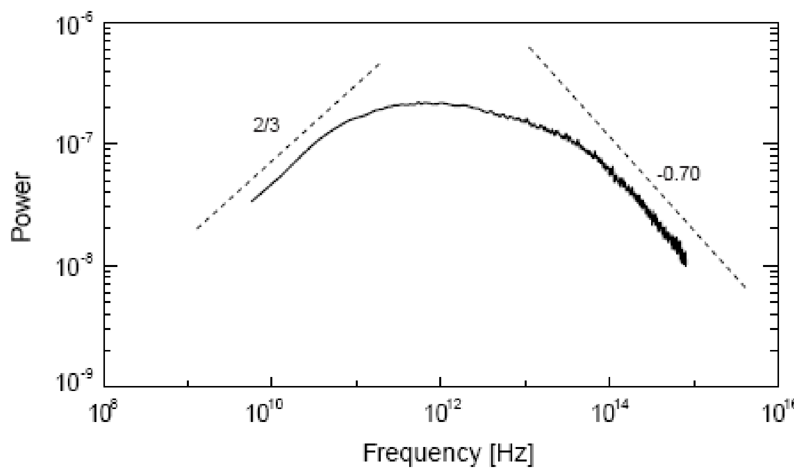



observer




GRB 000301c (Panaitescu 2001)

Shock simulations

Hededal Thesis: http://www.astro.ku.dk/~hededal

Hededal & Nordlund 2005 (preparation)

# *Summary*

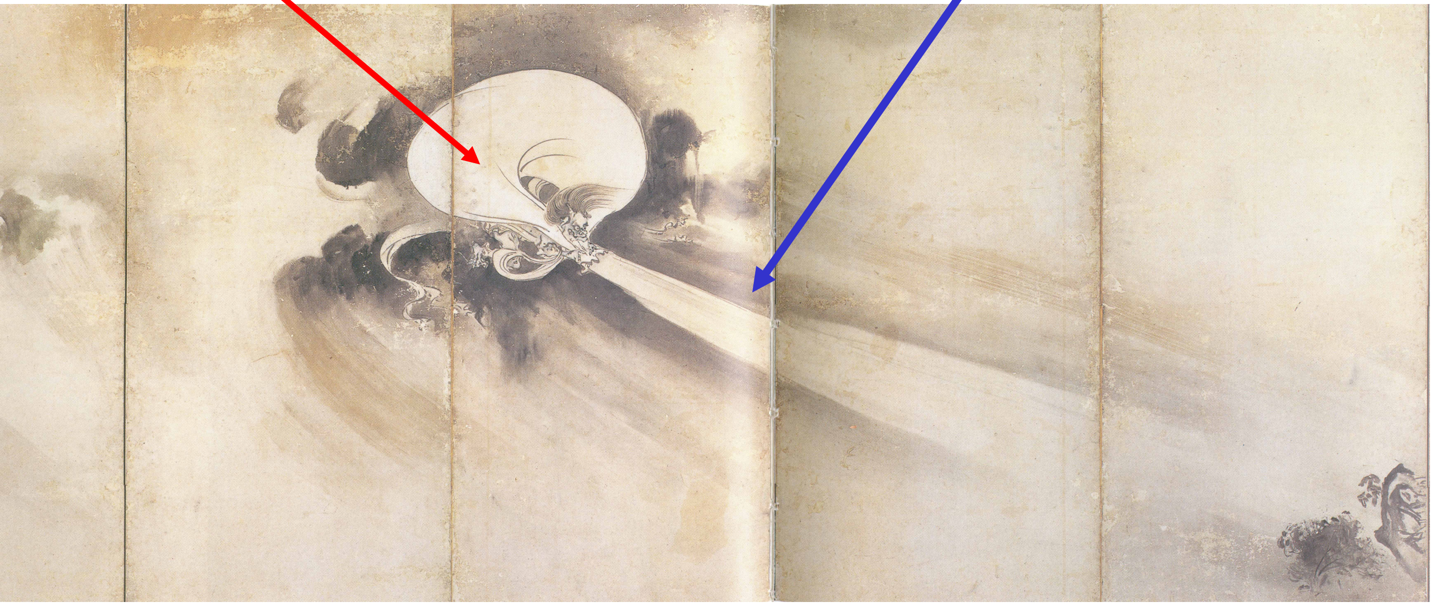
- **Simulation results show Weibel instability which creates filamented currents and density along the propagation of jets.**
- **Weibel instability may play a major role in particle acceleration in relativistic jets.**
- **The magnetic fields created by Weibel instability generate highly inhomogeneous magnetic fields, which is responsible for Jitter radiation (Medvedev, 2000, ApJ).**
- **For details see Nishikawa et al. ApJ, 2003, 2005, 2006, Hededal & Nishikawa ApJ, 2005 and proceeding papers (astro-ph/0503515, 0502331, 0410266, 0410193)**

# *Future plans for particle acceleration in relativistic jets*

- **Further simulations with a systematic parameter survey will be performed in order to understand shock dynamics**
- **In order to investigate shock dynamics further diagnostics will be developed**
- **In order to improve the performance of the code, High Performance Fortran (HPF) or Message Passing Interface (MPI) will be used**
- **Investigate synchrotron (jitter) emission, and/or polarity from the accelerated electrons and compare with observations (Blazars and gamma-ray burst emissions)**
- **Develop a new code implementing synchrotron loss and/or inverse Compton scattering**

*GRB progenitor*

*relativistic jet*

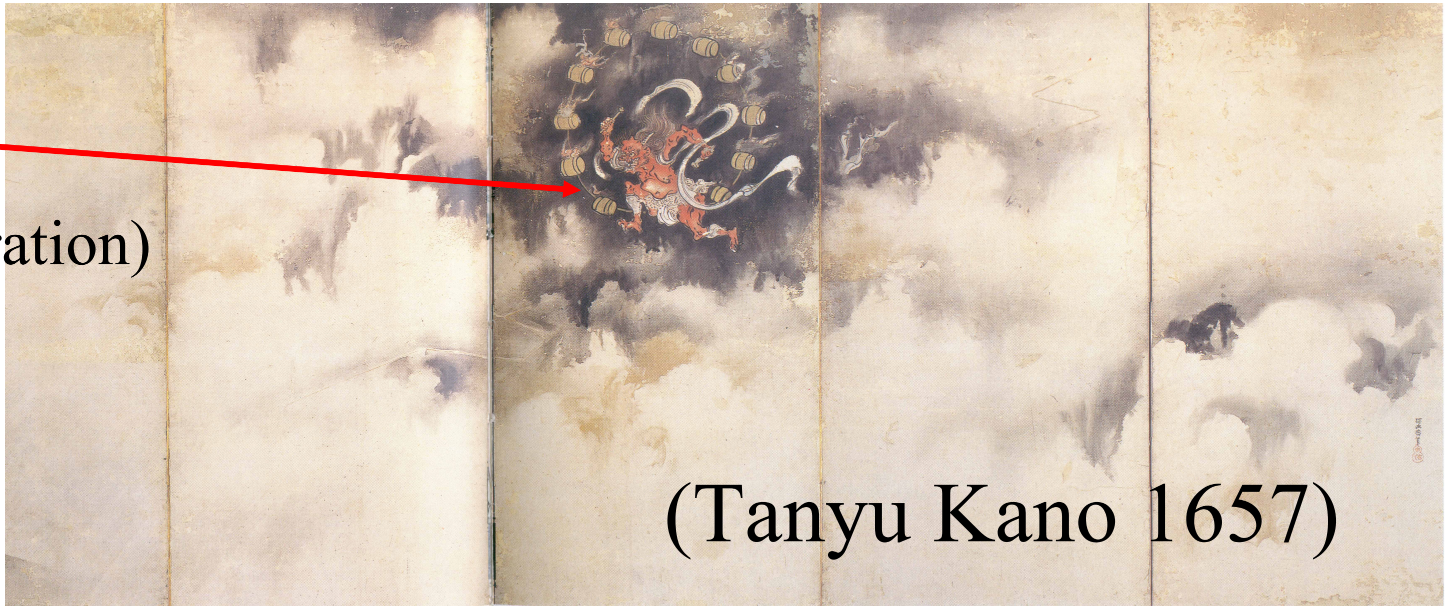


**Fushin**

(god of wind)

*emission*

(shocks, acceleration)



**Raishin**

(god of lightning)

(Tanyu Kano 1657)