Merger reconnection as an engine of electron acceleration

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teamed-up with
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Abstract.

In a thin elongated current sheet, it is likely that more than "*one X-type reconnection*" form and thus "*multiple magnetic islands*" are produced. The islands are then subject to merger. By numerically simulating such a case by two-dimensional full-particle code, we show that a merger produces the most energetic electron population in the system. By setting the lateral extent of the simulation size to be as large as ~100 ion inertial length, we introduce many small islands in the initial thin current sheet (~1 ion inertial length thickness). Merger of these islands proceeds to leave only two islands in the system. Then strong electron acceleration is seen upon the final merger that produces the single island in the large simulation box. Almost all the most energetic electrons in the system are accelerated at the merger line. **The merger line dominates in the electron acceleration because the reversed-reconnection facilitating the final merger is in such a strongly driven manner that the associated electric field is an order of magnitude larger than those available upon normal reconnection.** Combining the results from additional runs enable us to obtain a scaling law, which suggests a non-negligible role played by merger lines in the observed electron acceleration phenomena.

Electron acceleration at X-type reconnection site?

- Surfing acceleration due to bipolar electric field. (Hoshino2005)
- Direct acceleration due to reconnected electric field (Speiser1965)
- Shock-like acceleration due to steeping of magnetic gradient (Pritchett2008)

What if many X-type reconnection sites exist?

- Magnetospheric observations that suggest the linkage between energetic electrons and magnetic islands (*Chen et al.* 2008; *Retinò et al.*2008).
- Fermi-like acceleration due to contraction of magnetic island coalescence (Drake et al.2006)
- The resultant energy spectrum takes the form of power law with a spectral index that matches magnetospheric observations (*Øieroset et al.*2002).
- Previous talk showed that the electron energization depends on Nm (number of magnetic islands).

What do we want to perceive?

- While some X-lines disappear, other X-lines develop. These disappearing X-lines turn into O-lines.
- ➔ i.e. **"MERGER LINES"** formation.
- If an electron experiences many merger lines in a large scale current sheet, the guy should gain a relativistic energy.
- **HOW DO MERGER LINES APPEAR?**
- **DID ENERGETIC ELECTRONS TRULY EXPERIENCE THE MERGING ELECTRIC FIELDS?**

Our study: Numerical experiment assumption

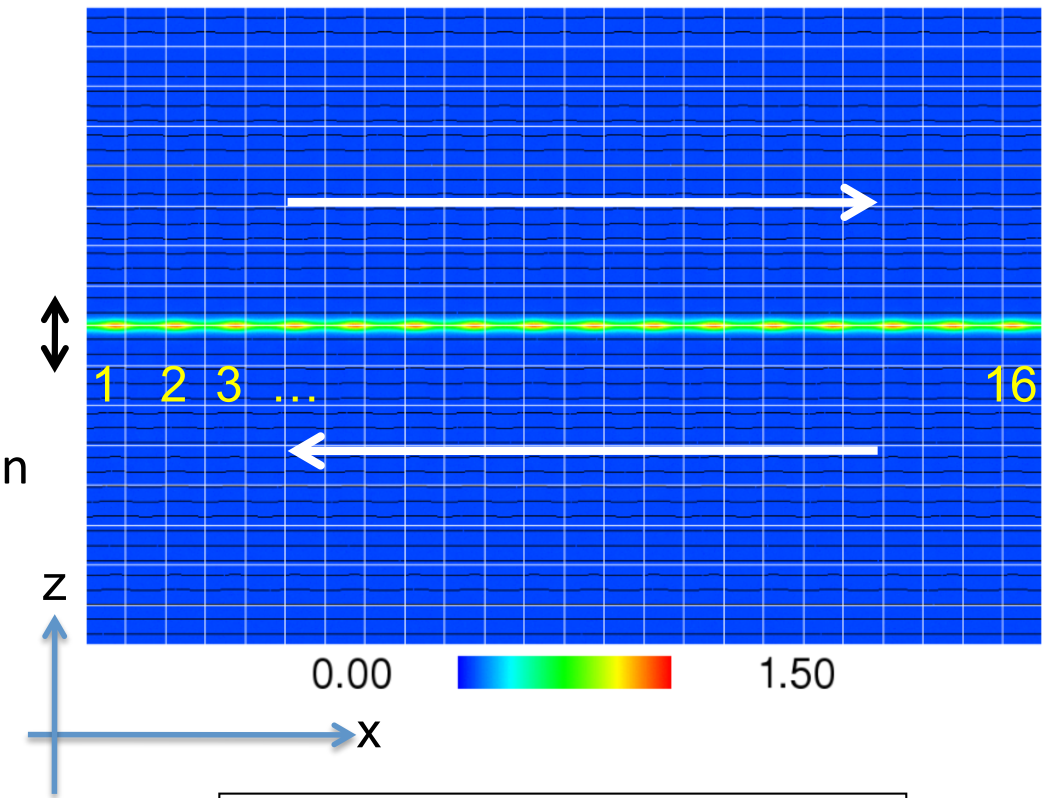
- Two-dimensional

- Harris sheet
- zero guide field
- Half-thickness D=0.5 λ_i
- N_{lobe}=0.1 N_{ps}

- Nm=16 small islands set initially in the current sheet
  (wavelength = 12D = 6λ_i)
- Lx=96 λ_i

- Periodic in the x-direction

- $M = M_{ion}/M_{ele} = M$
- $\tau^{-1} = \Omega_e/\omega_{pe} = V_{Ae}/c$



λ_i	ion inertial scale
V_{Ae}	electron Alfven velocity
V_{Ai}	ion Alfven velocity

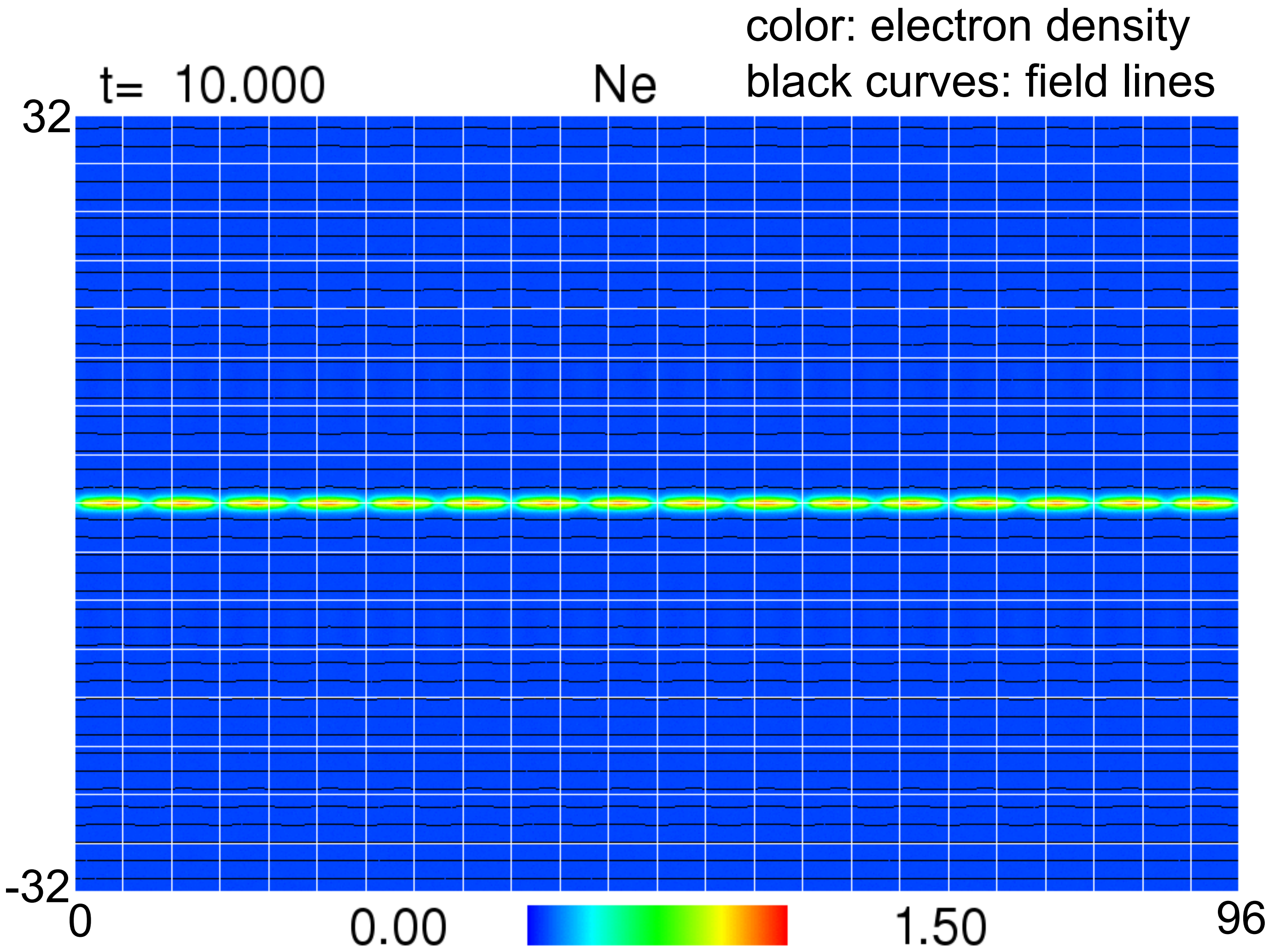
Definition

- t1, t2: start and end time of acceleration
  (determined by visual inspection with energy spectrum)
- t*: time when the merging electric field becomes largest.
- Ecr: Maximum energy at t=t1
  (determined by visual inspection with energy spectrum)
- εmax: Maximum energy at t=t2
  (determined by visual inspection with energy spectrum)
- ***How much energy do electrons gain within the interval Δt = t2 – t1 ?***

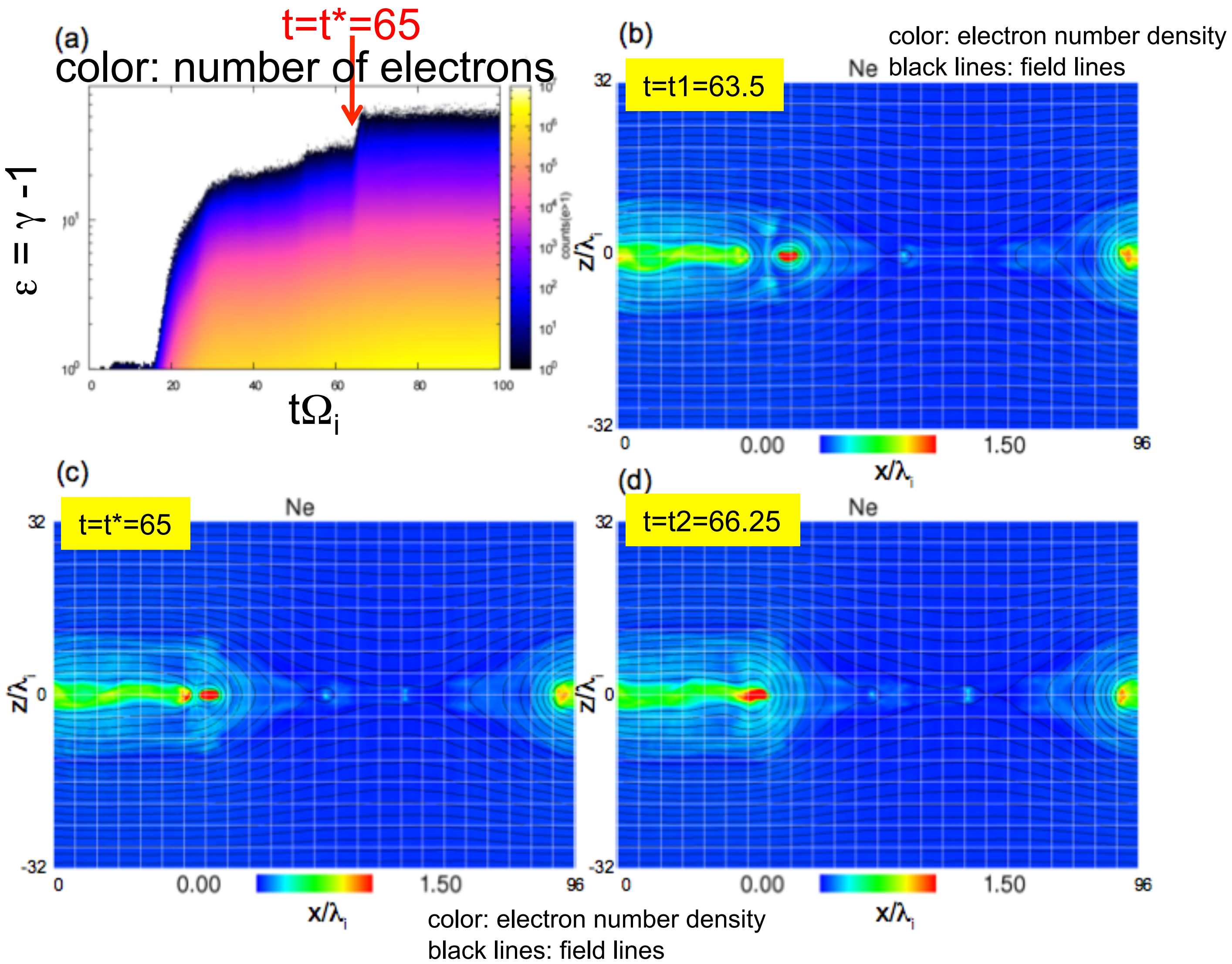
Experimental results

Start with Nm = 16 M = 100 τ = 1

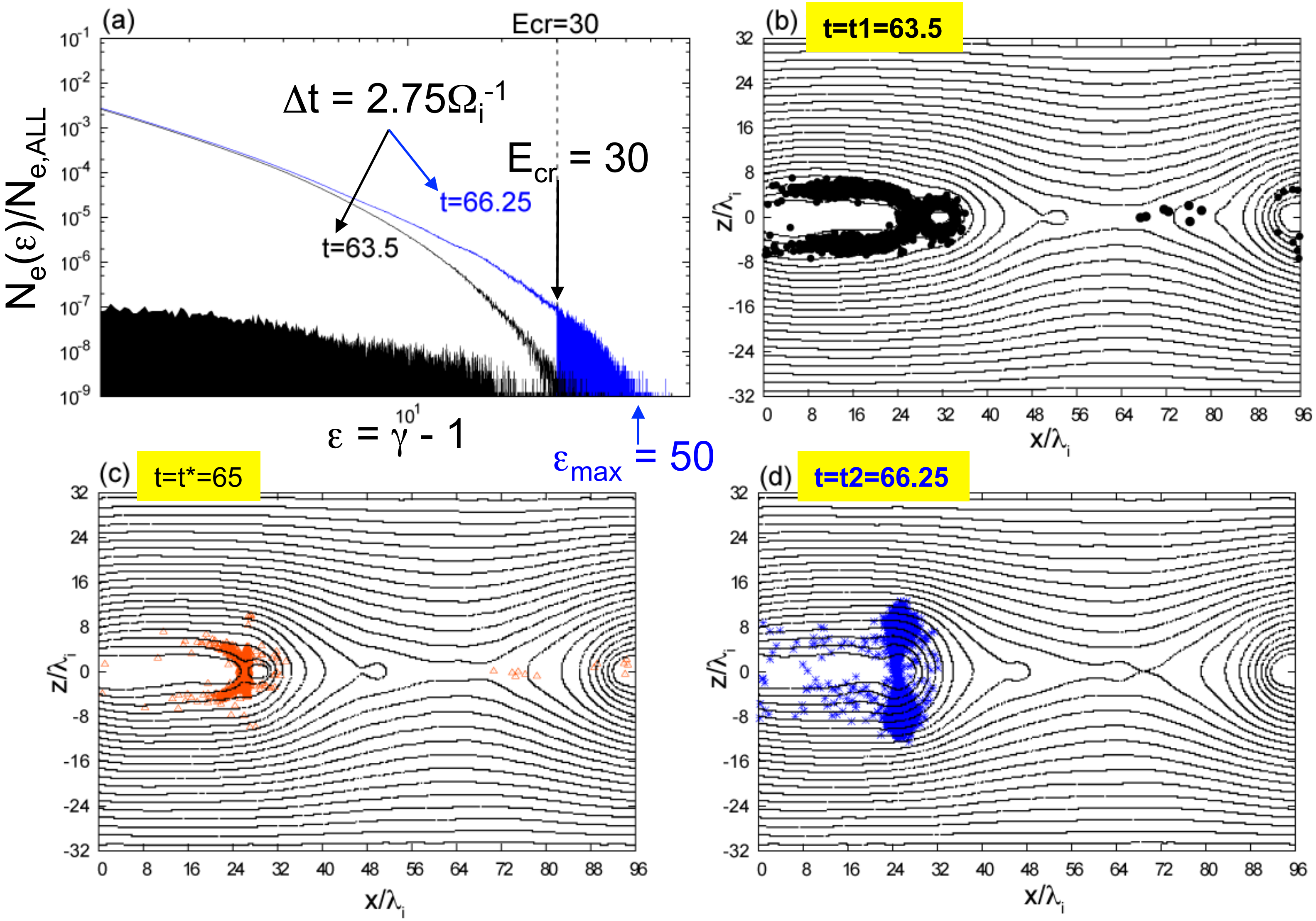
Watch what happens.

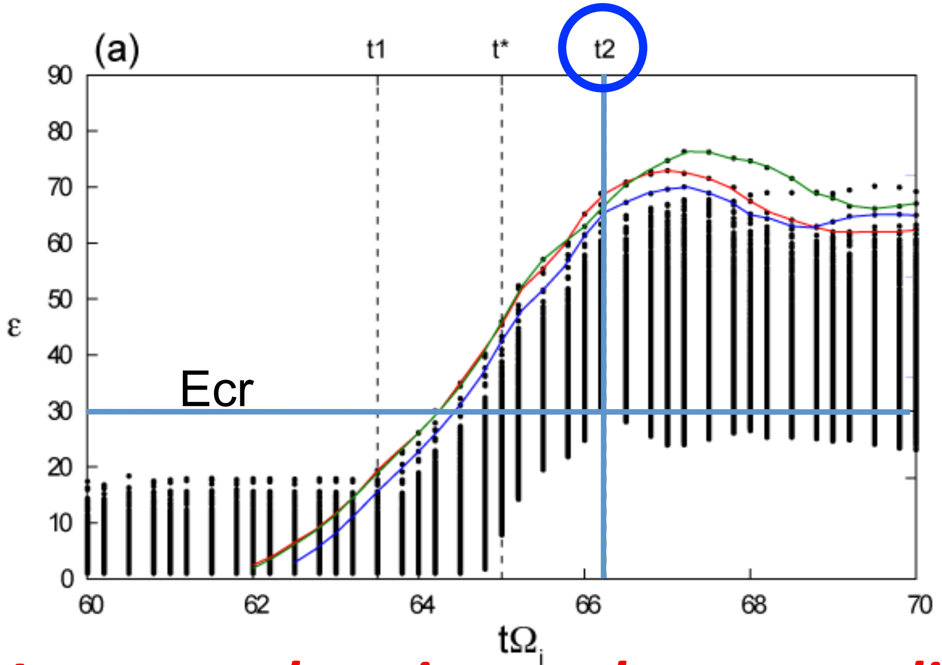


Merger of magnetic islands and the associated electron acceleration



Where and when electrons are accelerated?

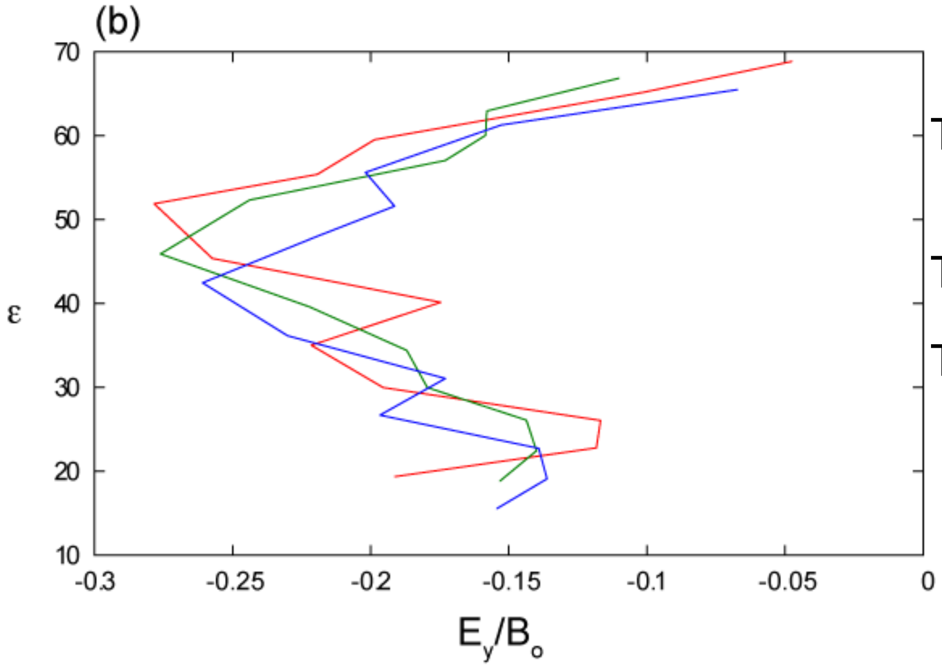




HOW TO MAKE THE FIGURE:

1. Select electrons with $\varepsilon > E_{cr}$ at t = t2.
2. Trace these guys (t=60~70, in this case).
3. Plot their energies with black dots.
4. For the top-three guys at t=t2 in energy, line plots are made (red, green, blue).

Jump acceleration at the merger line due to merging electric field

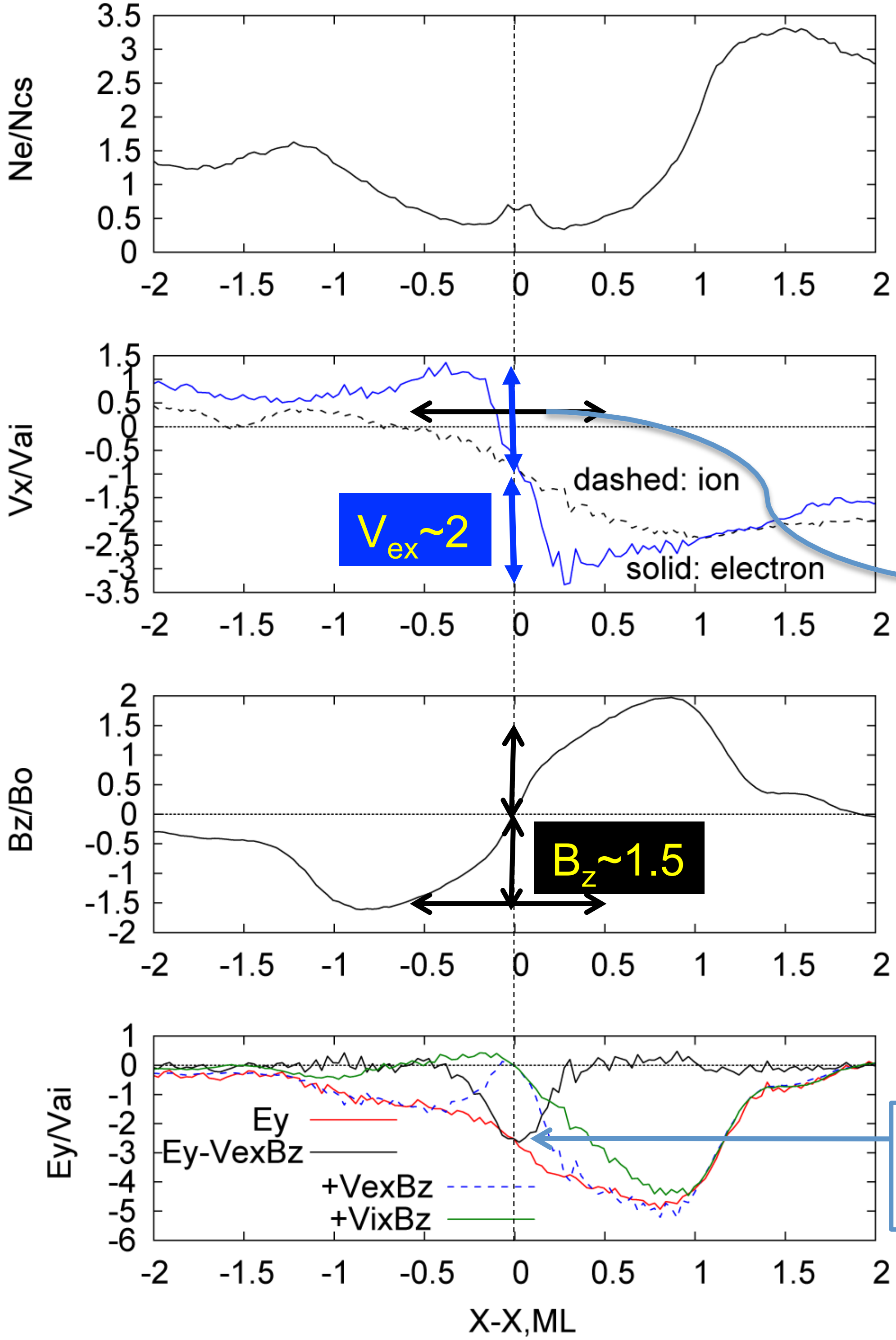


Temporal developments of the three guys' energy (t=t1~t2)

These guys feel strong negative electric field.

The merger line produced this electric field.

X-DIRECTIONAL CUT AT MERGER LINE AT t=t*



Jump acceleration at the merger line due to merging electric field

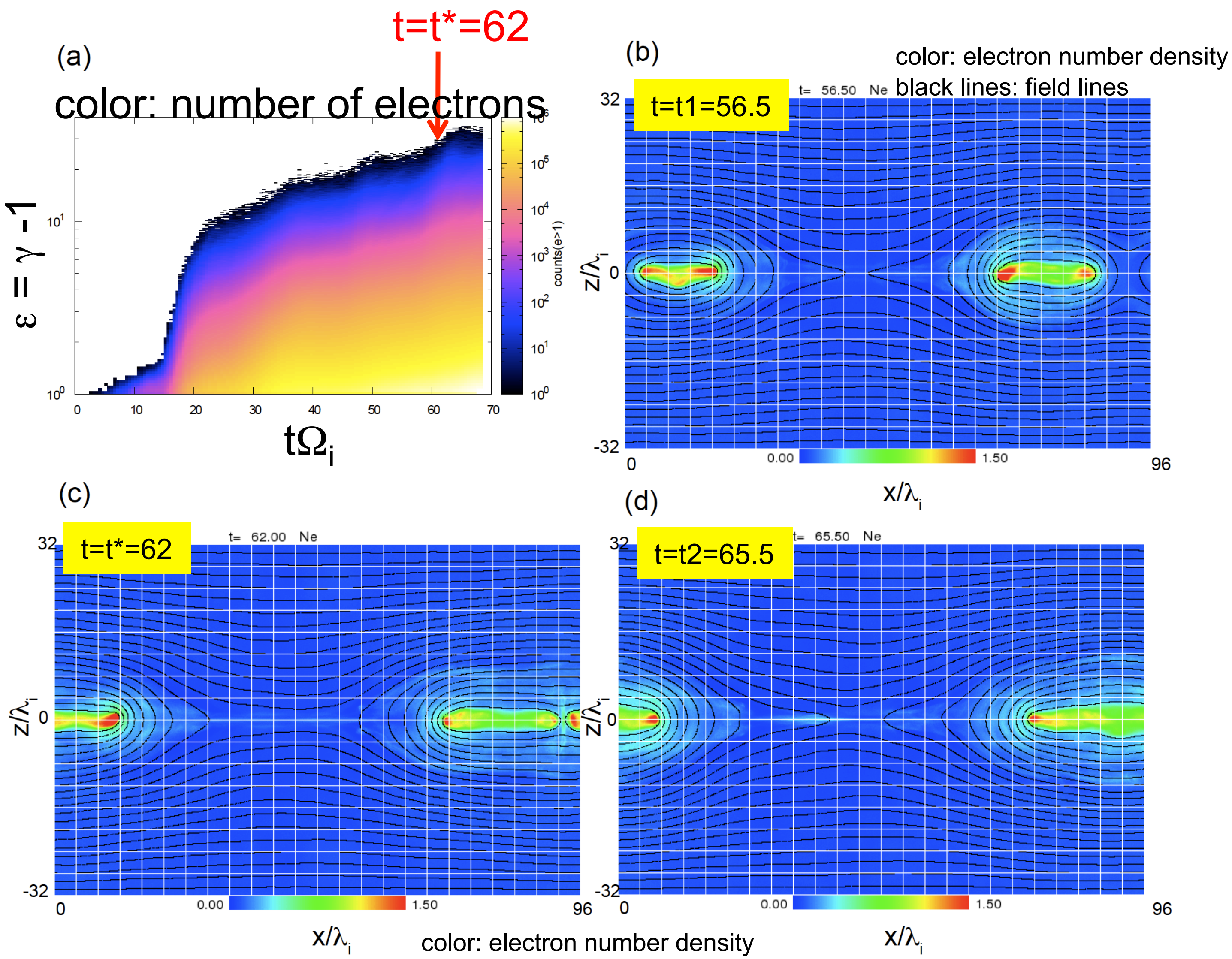
Convection electric field at the inflowing boundary in the V_{ex}-rest frame:

$E_y \sim V_{ex}B_z \sim -3V_{Ai}B_o$

Good agreement!

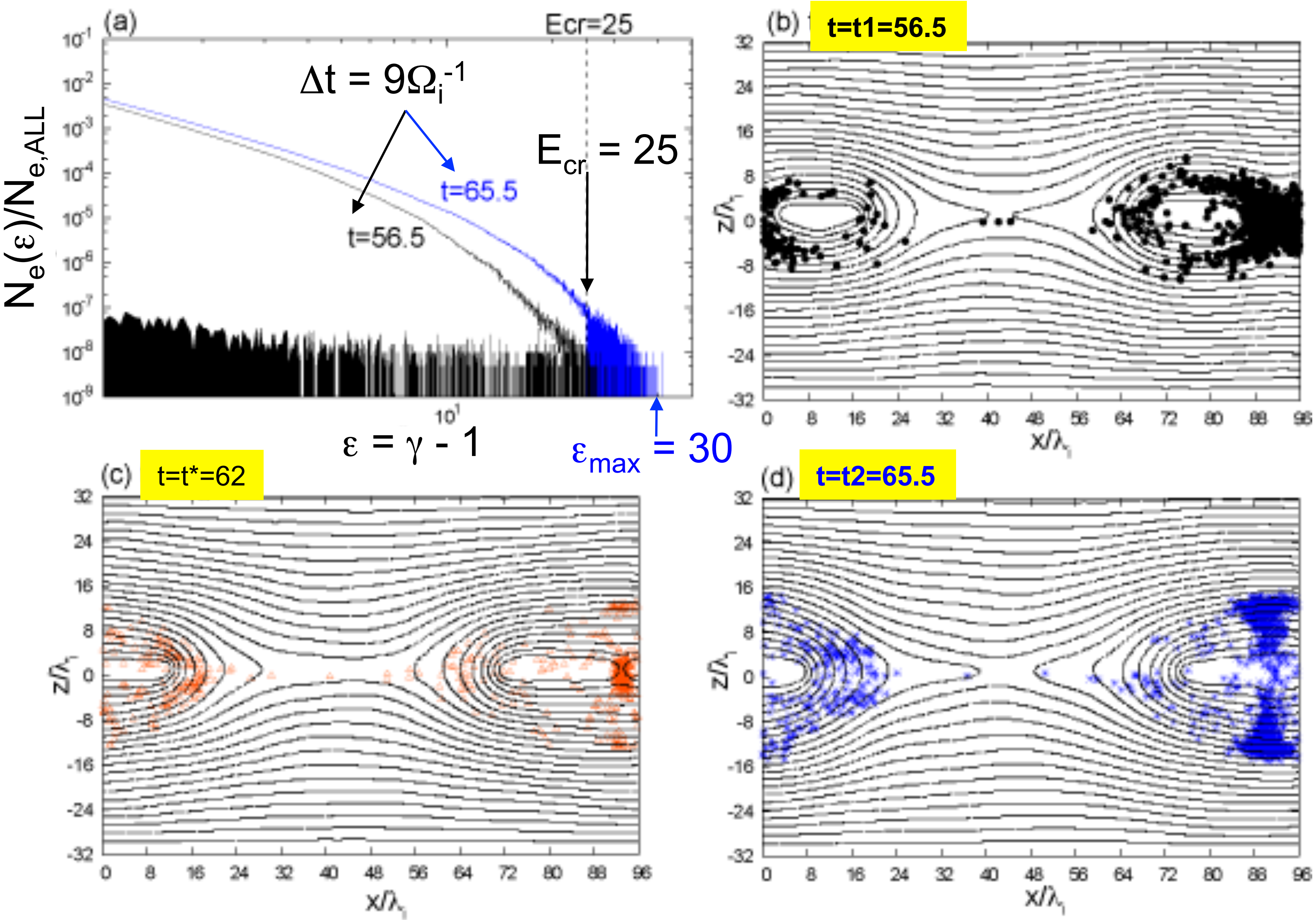
Merging electric field:
$E^*_y = E_y - V_{ex}B_z = -2.5V_{Ai}B_o$

Mass dependence ? [M=25]

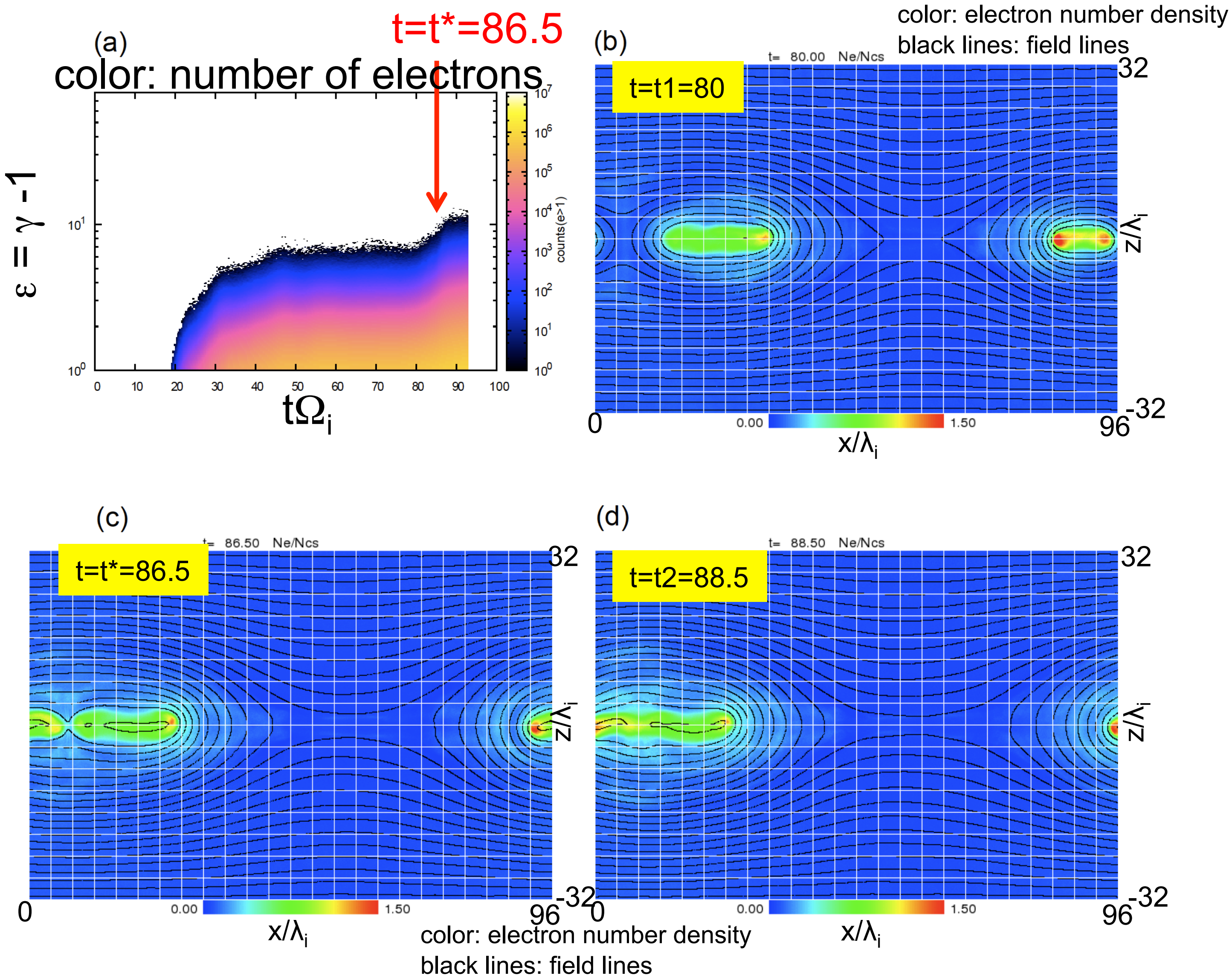


color: electron number density
black lines: field lines

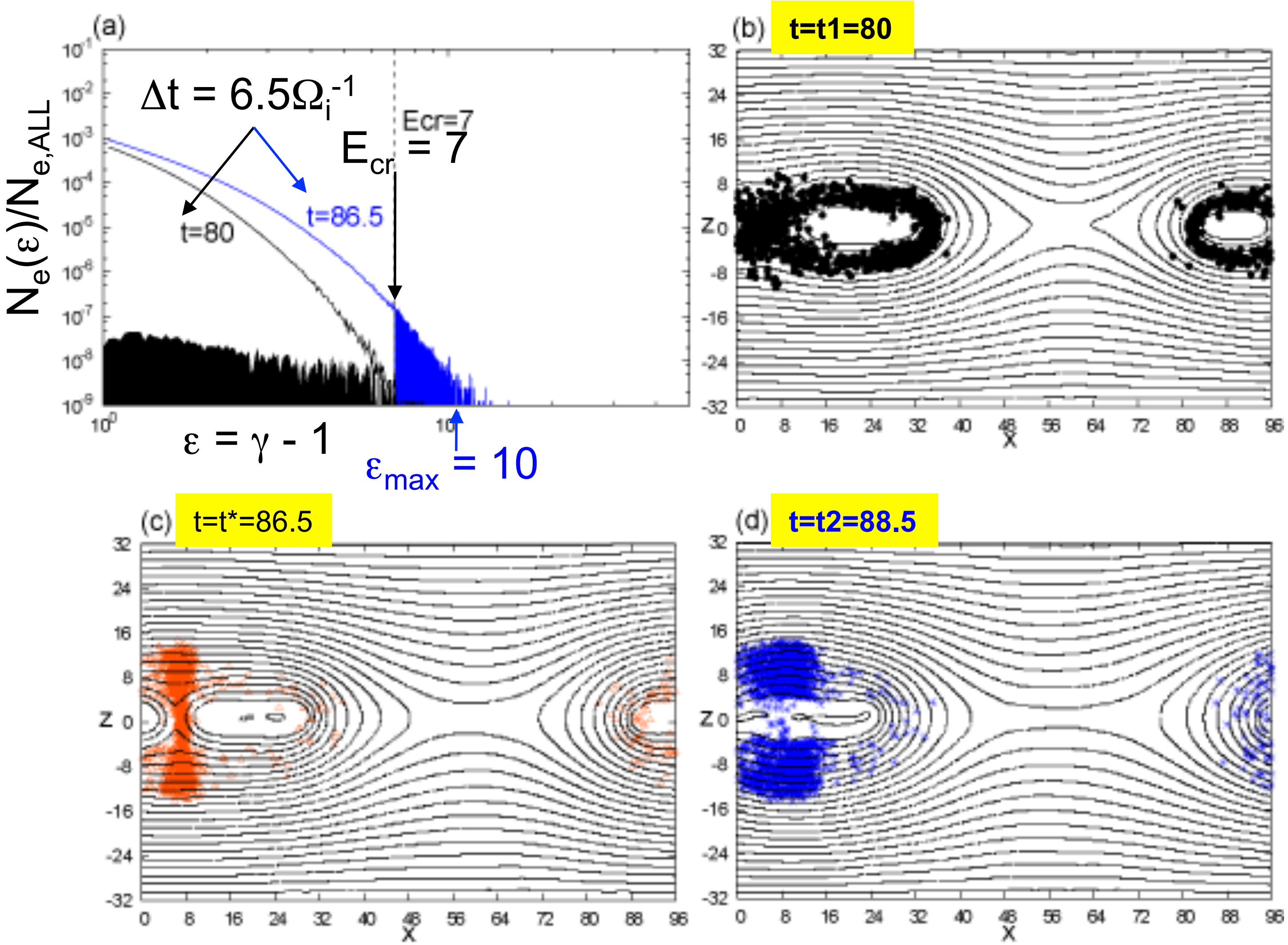
Mass dependence ? [M=25]



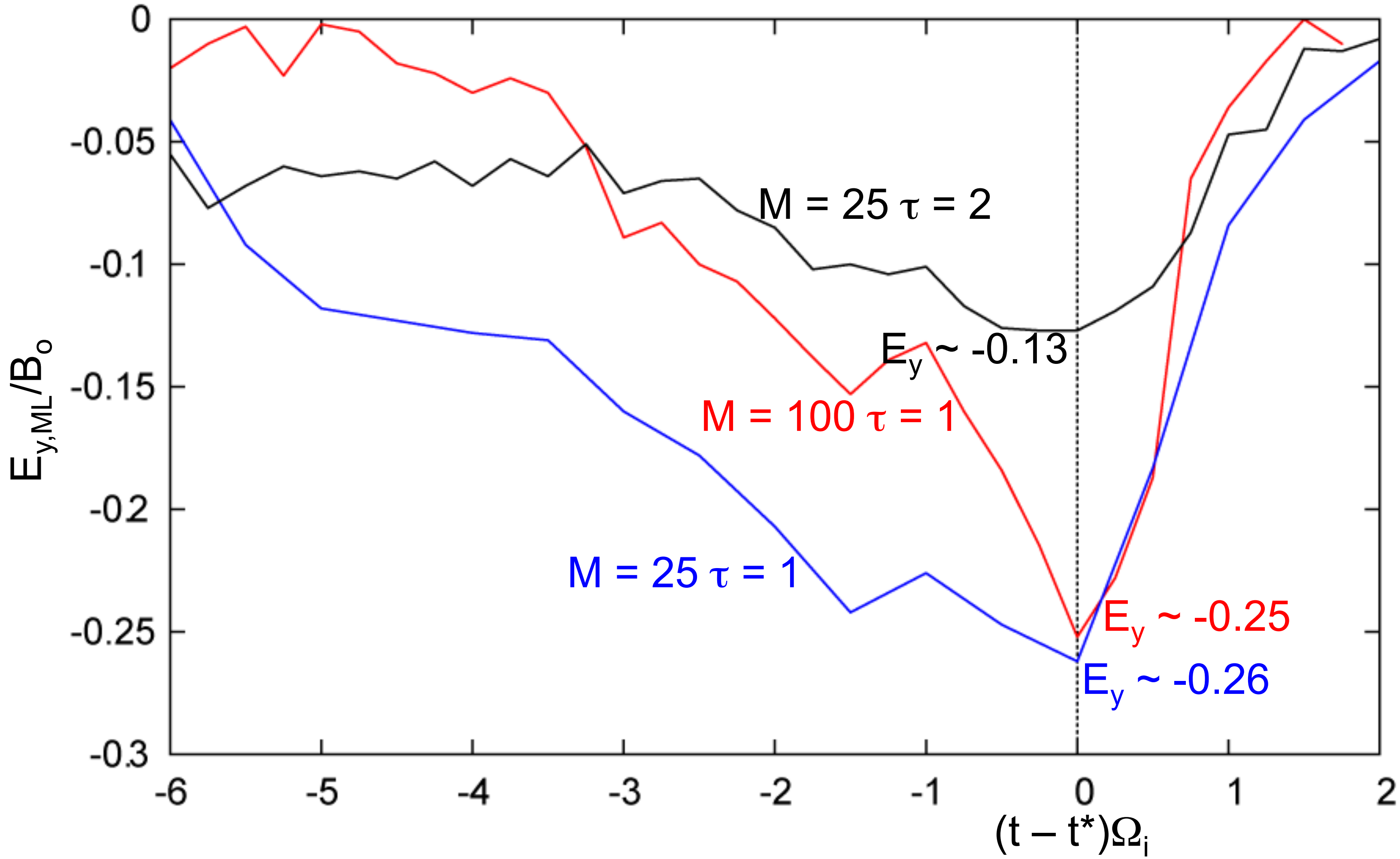
τ dependence ? [τ=2 M=25]



τ dependence ? [τ=2 M=25]



Parameter dependence on $E_{y,ML}$?



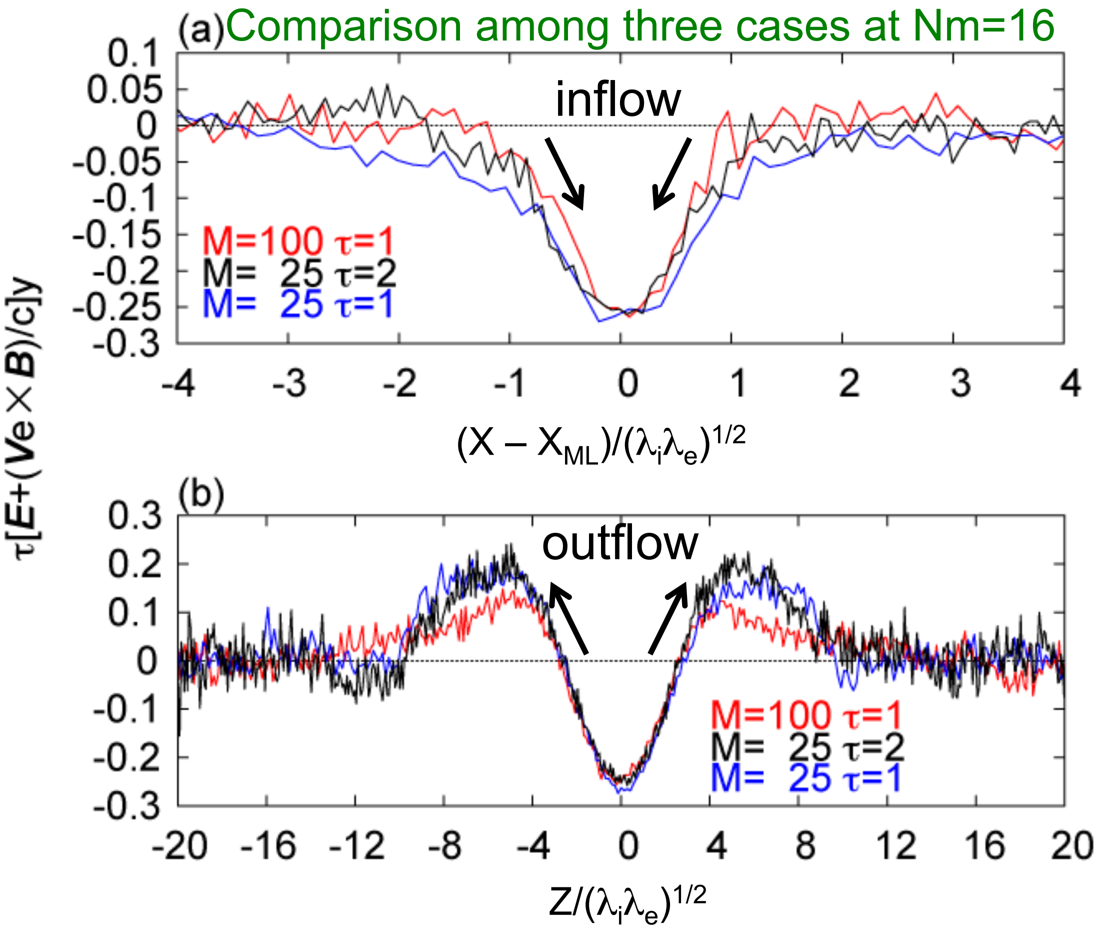
Discussion

Summary table

M	τ	t1	t*	t2	E_{cr}	ε_{max}	$E_{y,ML}/B_o$
100	1	63.5	65	66.25	30	50	-0.25
25	1	56.5	62	65.5	25	35	-0.26
25	2	80	86.5	88.5	7	10	-0.13

X and Z-directional profile of E_y at the merger line

Electric field is scaled as
$E_y \sim V_{Ae}B_o/c = B_o/\tau$



M=100
M=25
M=25 τ=2

Spatial length is scaled as ~ $(\lambda_i\lambda_e)^{1/2} = \lambda_i M^{-1/4}$
→ Meandering length determines the diffusion size

Scaling?

- ***ENERGY***:

$$\varepsilon_{max} \sim \Delta\gamma_{max} \leq eE_y c\Delta t/(m_e c^2)$$

- ***ELECTRIC FIELD***:

$$E_y \sim V_{Ae}B_o/c = B_o/\tau$$

- ***SPATIAL SCALE***:

$$l \sim \lambda_i M^{-1/4}$$

- ***ACCELERATION TIME***:

$$\Delta t \sim l/c \sim \lambda_i M^{-1/4}/c = (M^{1/4}/\tau)\Omega_e^{-1}$$

One gets maximum energy gain $\boldsymbol{\varepsilon_{max} \sim M^{1/4}/\tau^2}$

Useful results for astro-application. Substorm application?

- If you believe in the scaling law, MeV electrons are produced when islands of $4R_E$-size crash.
- The earthward boundary may be regarded as a hard wall that sets a favorable situation for the crash to be violent.