Electron accelerations at high Mach number collisionless shocks : 2D Particle-in-Cell simulations on massively parallel supercomputer systems

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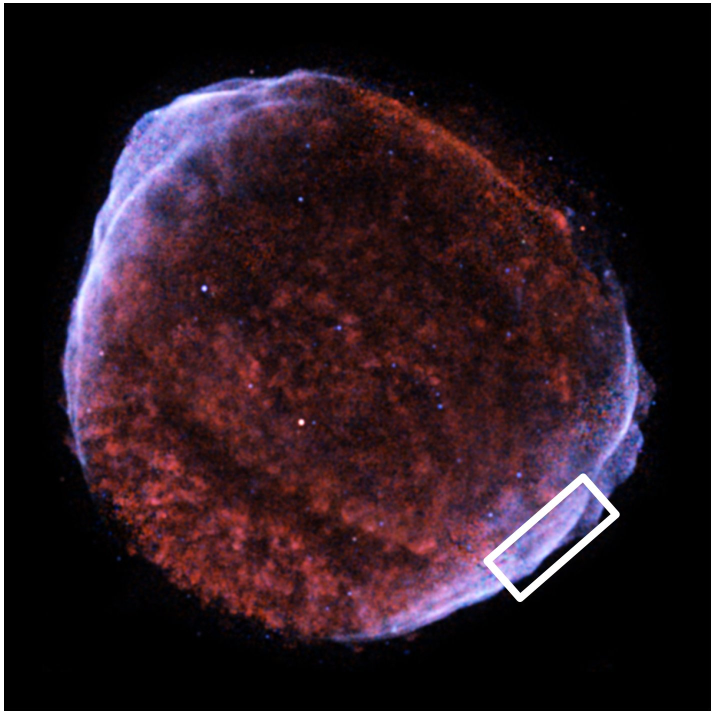
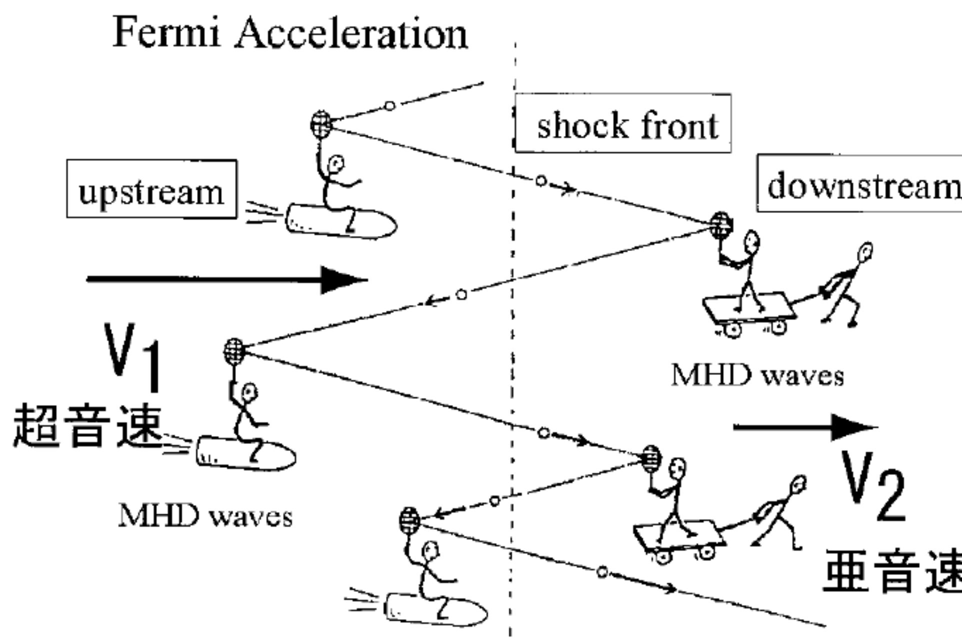
Electron accelerations at SNR shocks





electron ●

For diffusive shock acceleration to work on electrons

$$\frac{mc\gamma v}{qB} = \frac{McV_0}{qB} \rightarrow \gamma = \sqrt{1 + \left(\frac{M}{m}\frac{V_0}{c}\right)^2} \sim O(10)$$

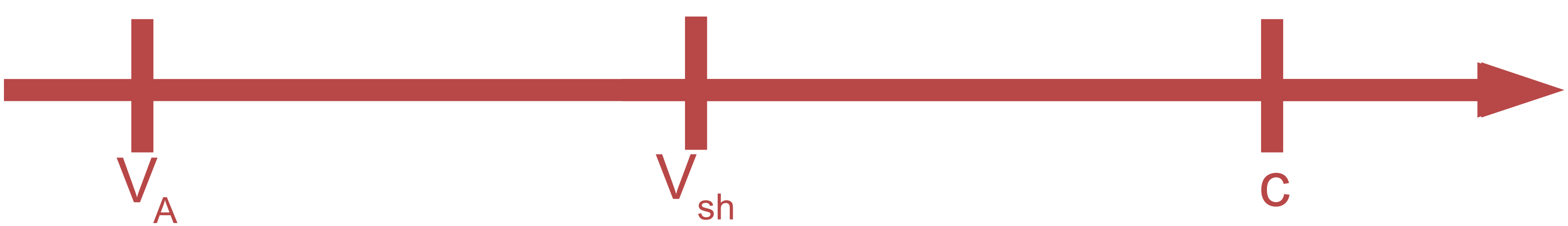
electron gyro radius

shock scale

for SNR shocks

Parameters of SNR shocks

- Shock speeds
  - V_{sh} = 1000 – 10000 km/s
  - non-relativistic shocks
- Magnetic field
  - a few μG : Alfven speed V_A ~ 10 km/s (n~0.1 /cc)
  - (Alfven) Mach number M > 100 !
- Dynamic ranges
  - shock scale : MHD ($L >> r_{gi} >> r_{ge}$)
  - Ion to Electron mass ratio M/m=1836
  - relativistic electrons : v~c ($>>V_{sh} > V_A$)



Electromagnetic Particle-in-Cell simulation

Particles

$$\frac{d\boldsymbol{x}_p}{dt} = \frac{\boldsymbol{u}_p}{\gamma_p}$$

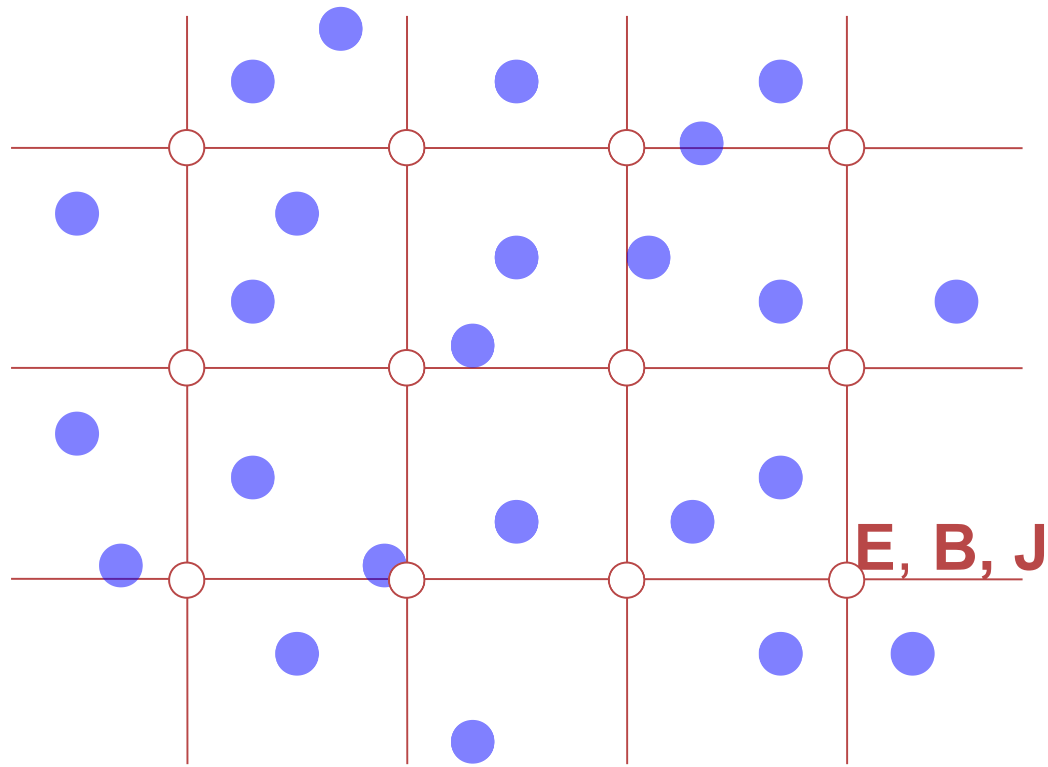
$$\frac{d\boldsymbol{u}_p}{dt} = \frac{q}{m}\left(\boldsymbol{E} + \frac{\boldsymbol{u}_p}{c\gamma_p} \times \boldsymbol{B}\right)$$

$$\boldsymbol{J} = \sum_p q_p \frac{\boldsymbol{u}_p}{\gamma_p}$$

Maxwell equation

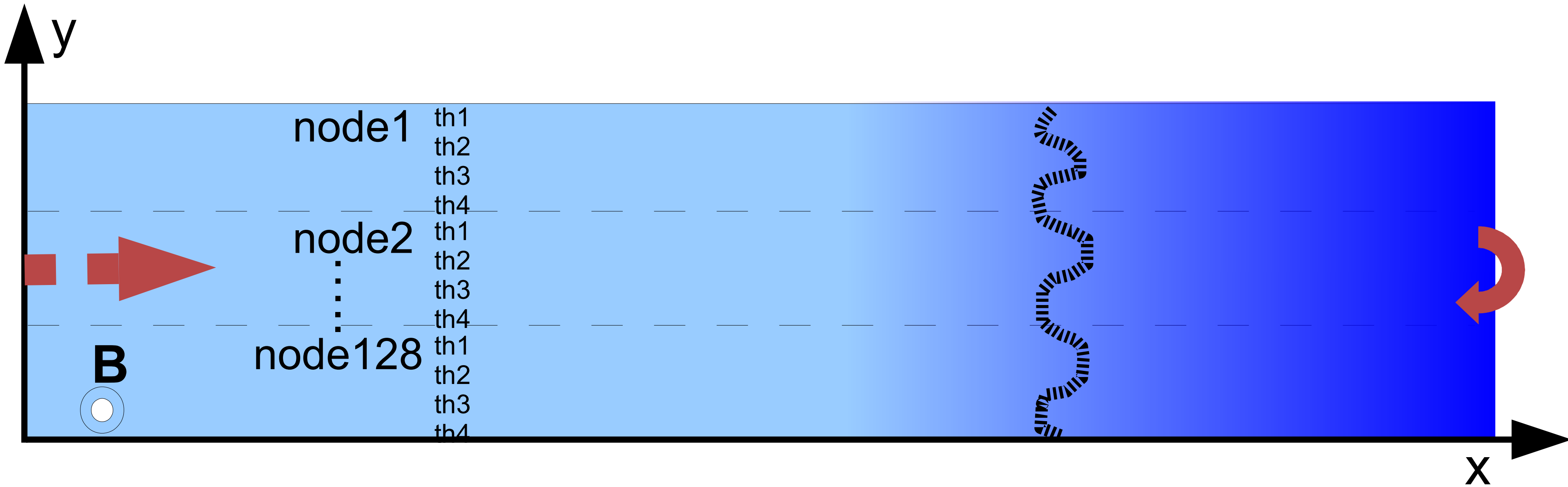
$$\frac{\partial \boldsymbol{B}}{\partial t} = -c\nabla \times \boldsymbol{E}$$

$$\frac{\partial \boldsymbol{E}}{\partial t} = c\nabla \times \boldsymbol{B} - 4\pi \boldsymbol{J}$$

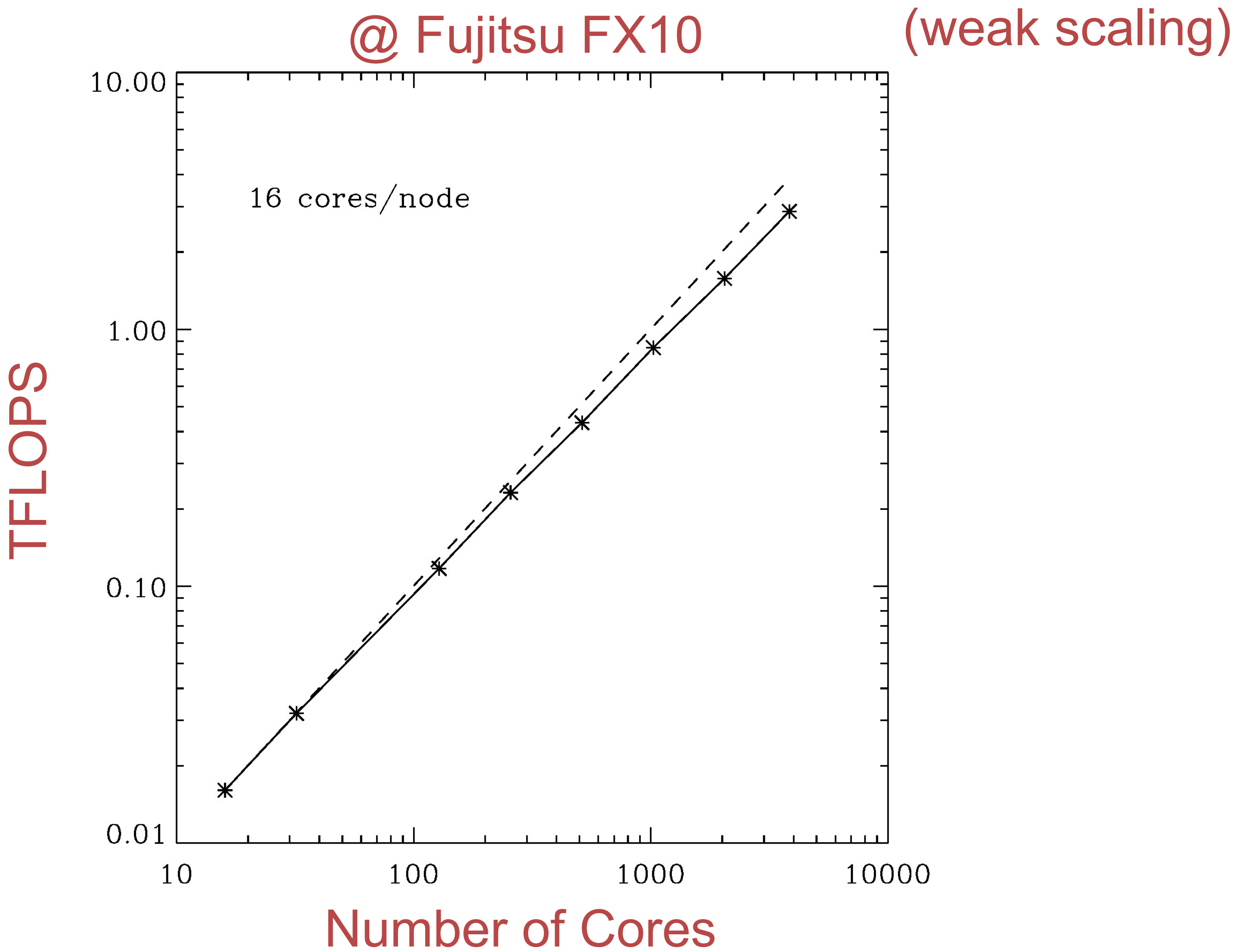


2D EM-PIC simulation of high M_A shocks

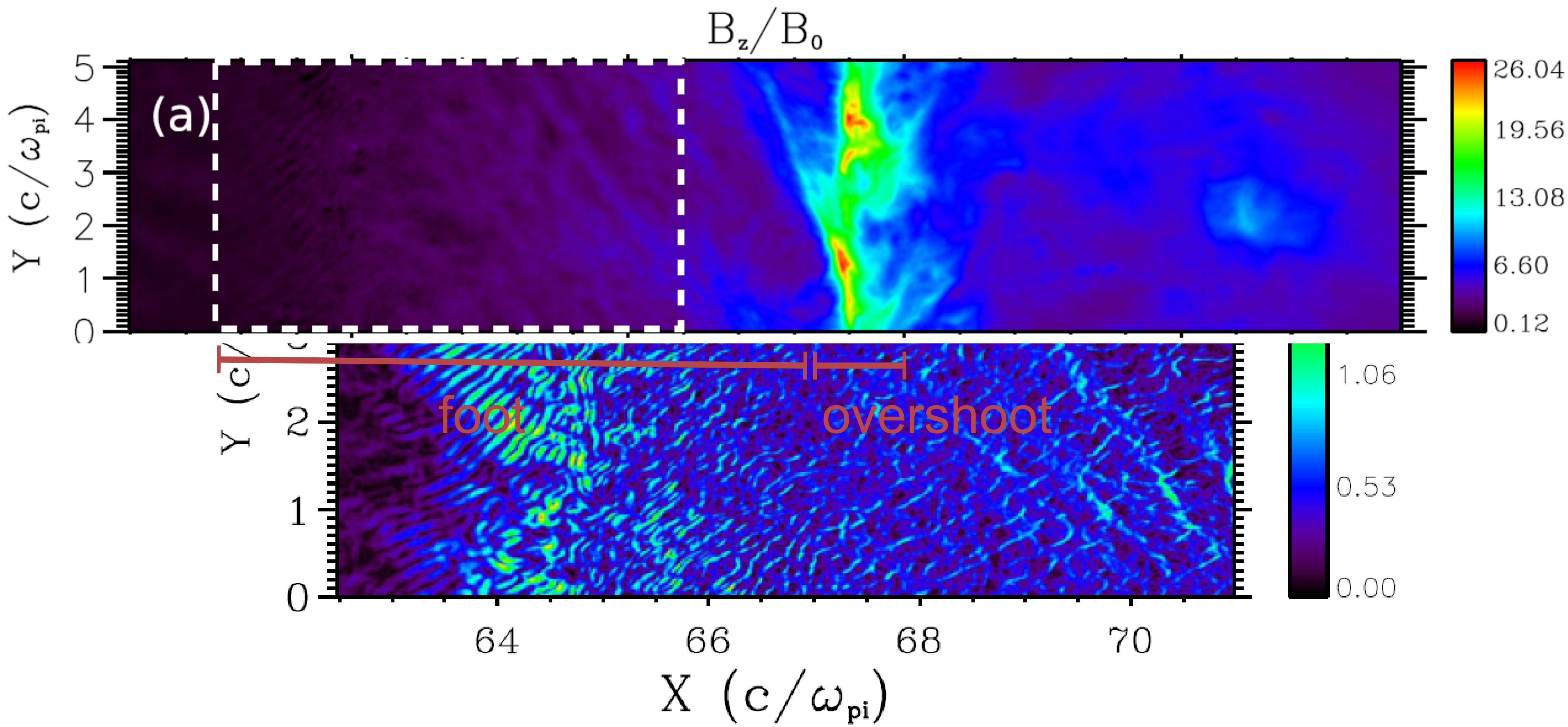
- M/m=25, 100
- $M_A=V_0/V_A$~15 - 30
- N~10^{10} particles
- 2D perpendicular shocks （out-of-plane）
- Injection method (downstream rest frame)
- 512 cores on FX1@JAXA



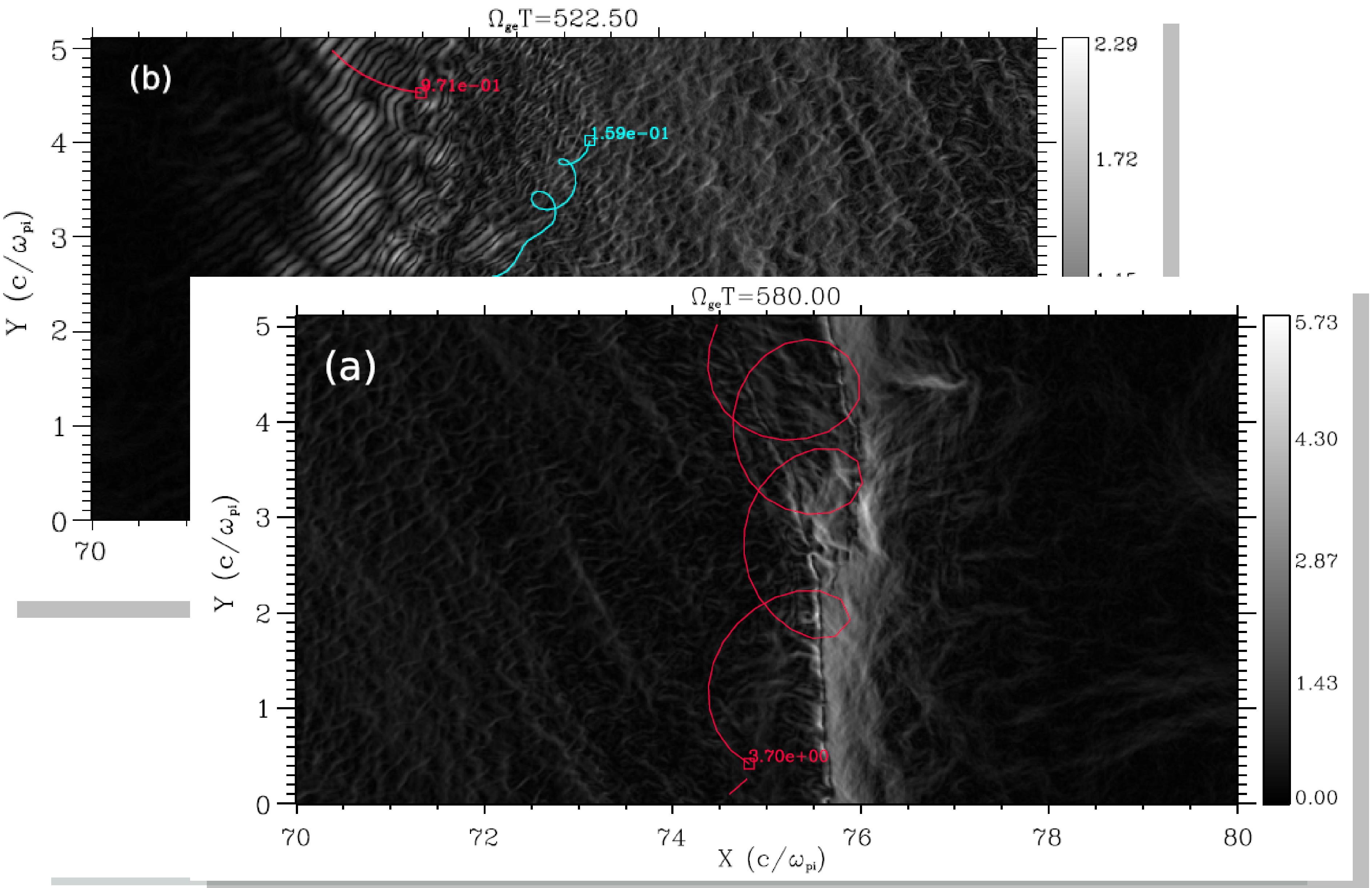
Scalability of 2D EM-PIC code



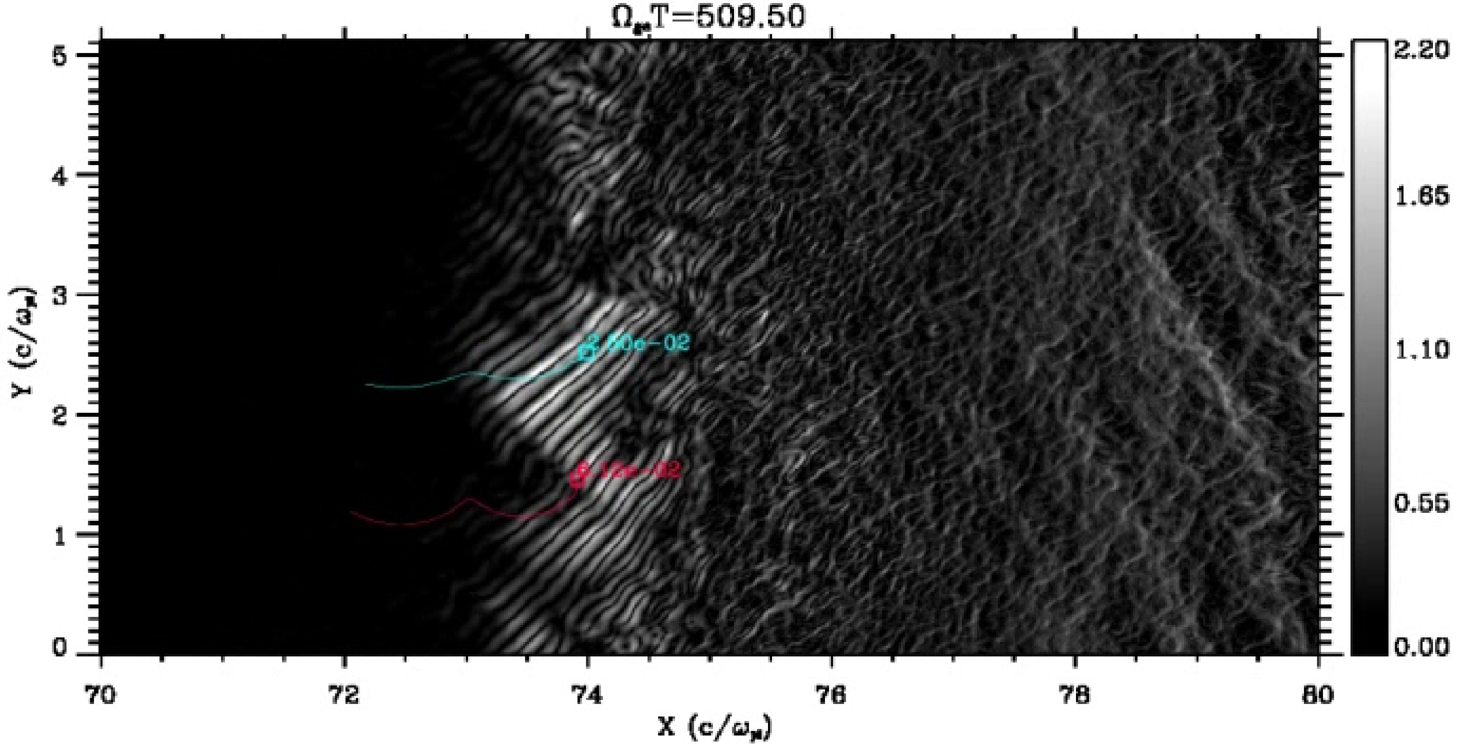
Overview (M/m=100, M_A~30)



Overview - Electron orbit

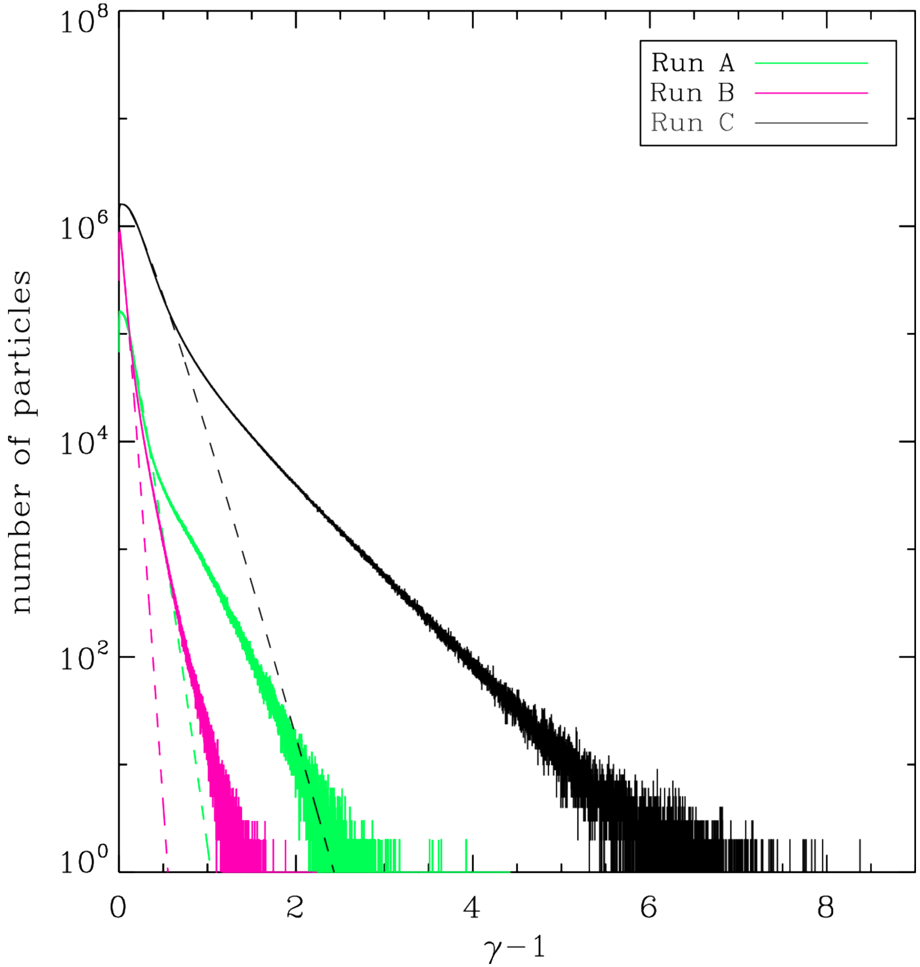


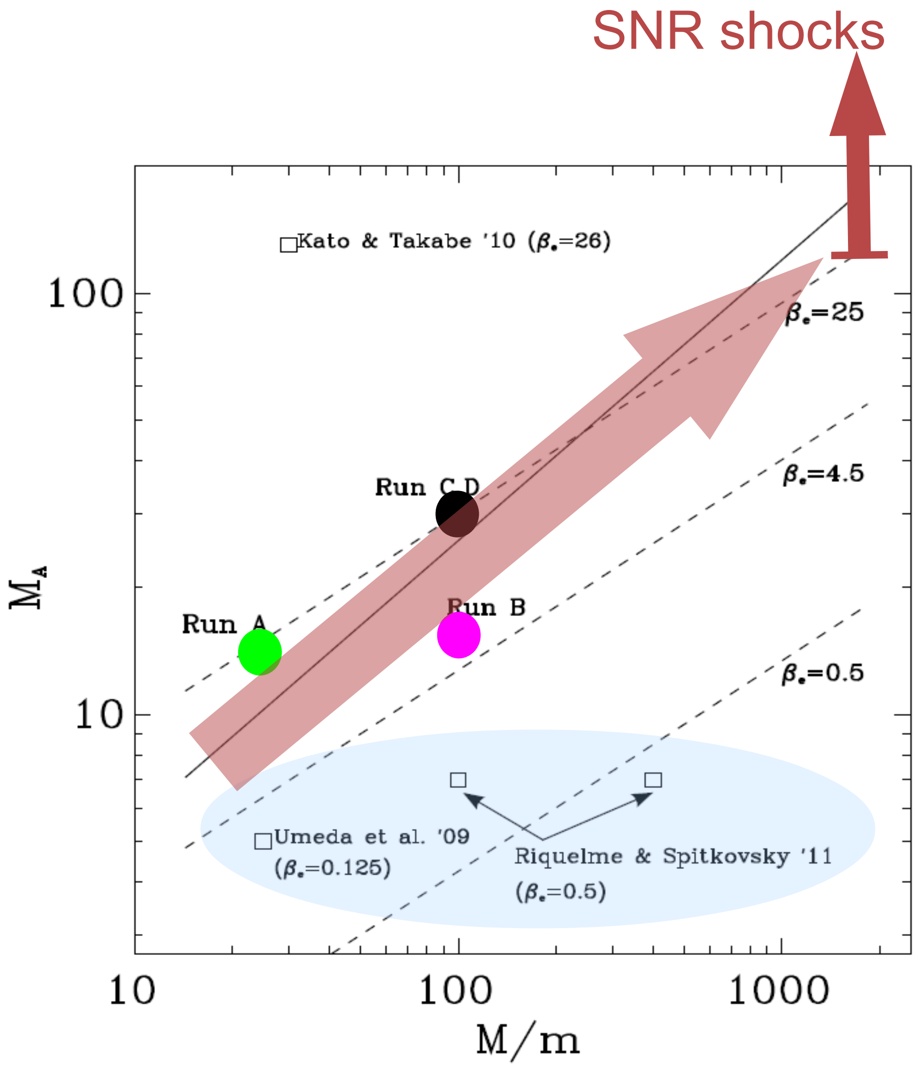
V_0



Matsumoto et al., *ApJ*, 2012 Animation courtesy of 4D2U, NAOJ

Electron energy spectra





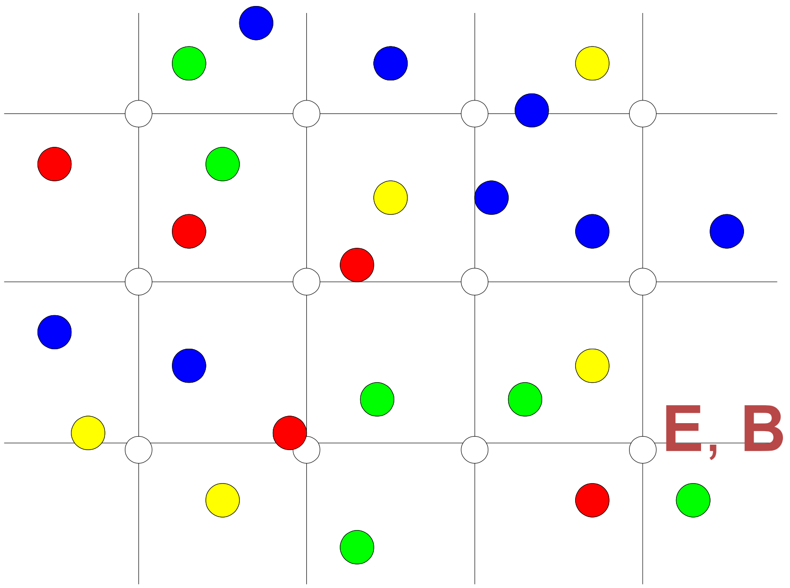
Summary

- High Mach number non-relativistic shock simulations require huge computational costs
- EM PIC simulation code is now hybrid-parallelized for K-computer type systems.
- Scalable up to 4000 cores (1D domain decomposition)
- Large scale 2D PIC simulations indicated efficient electron accelerations to occur at SNR shocks (M_A>100)

- 3D PIC simulations of high Mach number shocks to be reported

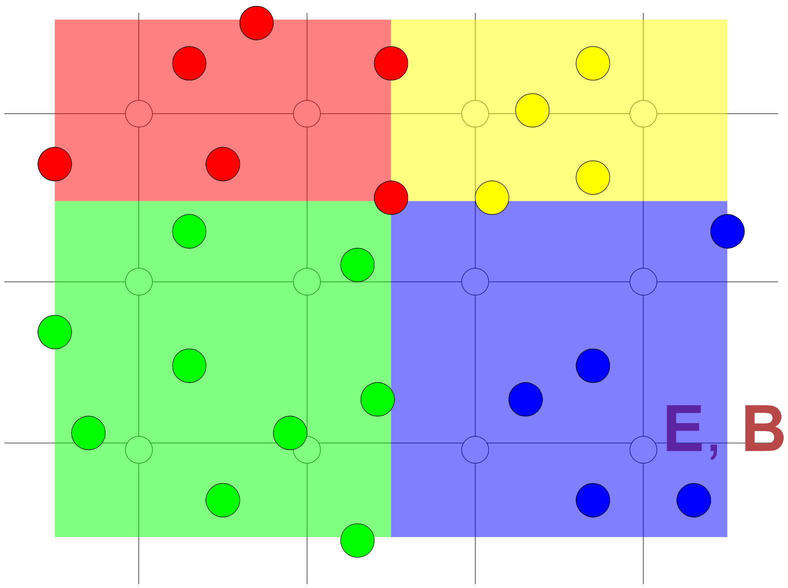
Parallelization of PIC code

particle decomposition



- legacy PIC codes
- easy to implement
- reduction
- cache inefficient
- scalable up to 100 cores

domain decoposition



- scalable > 1000 cores
- efficient cache usage
- implementation is somewhat complex
- load inbalance

Code description

- semi-implicit (explicit for particles' motion)

$$\frac{\boldsymbol{B}^{t+\Delta t}-\boldsymbol{B}^{t}}{\Delta t}=-c\nabla\times\left(\theta\,\boldsymbol{E}^{t+\Delta t}+(1-\theta)\,\boldsymbol{E}^{t}\right)$$

$$\frac{\boldsymbol{E}^{t+\Delta t}-\boldsymbol{E}^{t}}{\Delta t}=c\nabla\times\left(\theta\,\boldsymbol{B}^{t+\Delta t}+(1-\theta)\,\boldsymbol{B}^{t}\right)-4\pi\,\boldsymbol{J}^{t+\Delta/2}$$

⬇

$$\left(I-(\theta c\Delta t)^2\nabla^2\right)\delta\boldsymbol{B}=\theta(c\Delta)^2\left(\nabla^2\boldsymbol{B}^t+\frac{4\pi}{c}\nabla\times J^{t+\Delta t/2}\right)$$

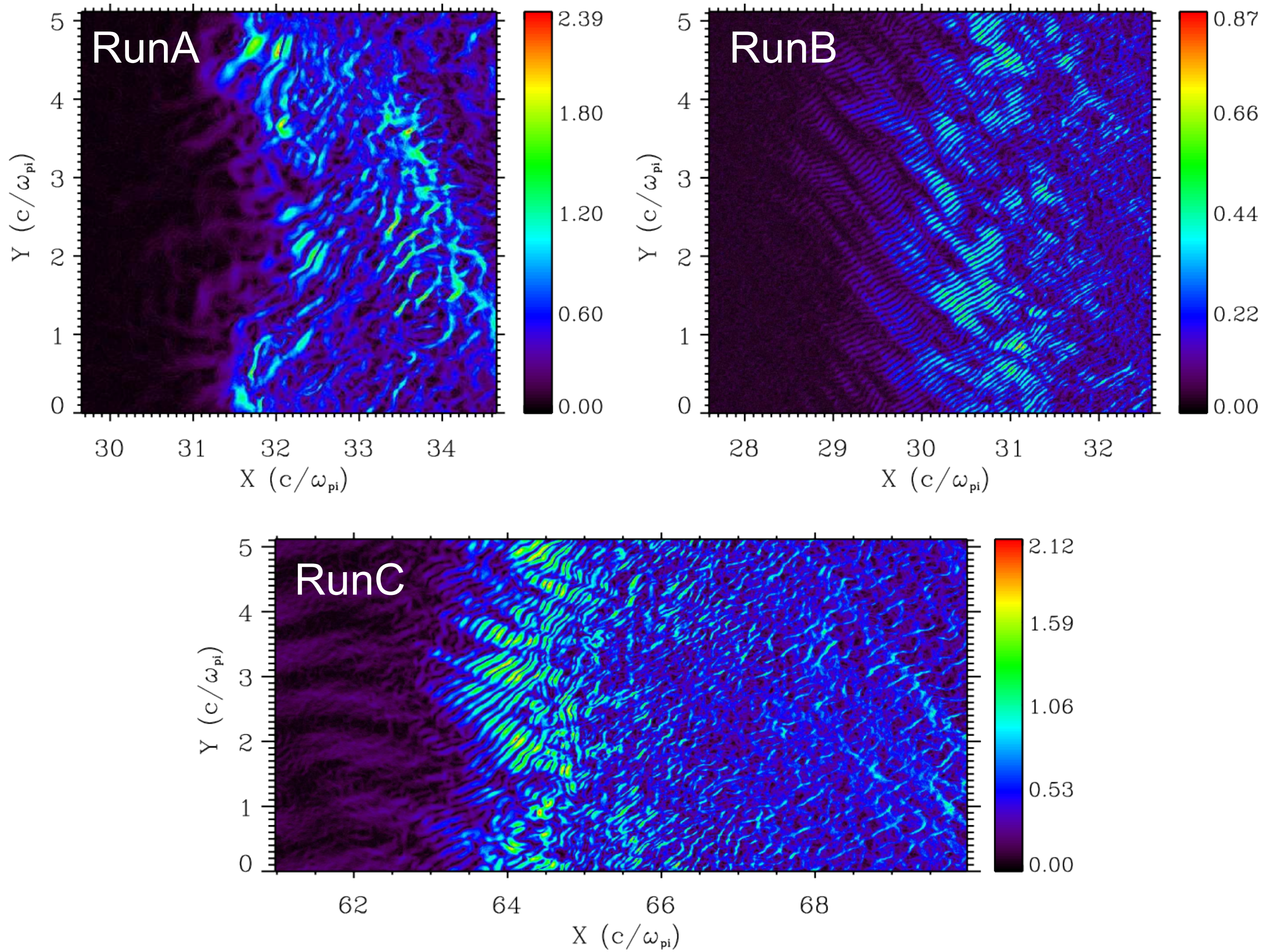
$$\theta=0.501\sim0.505$$

- charge conservation

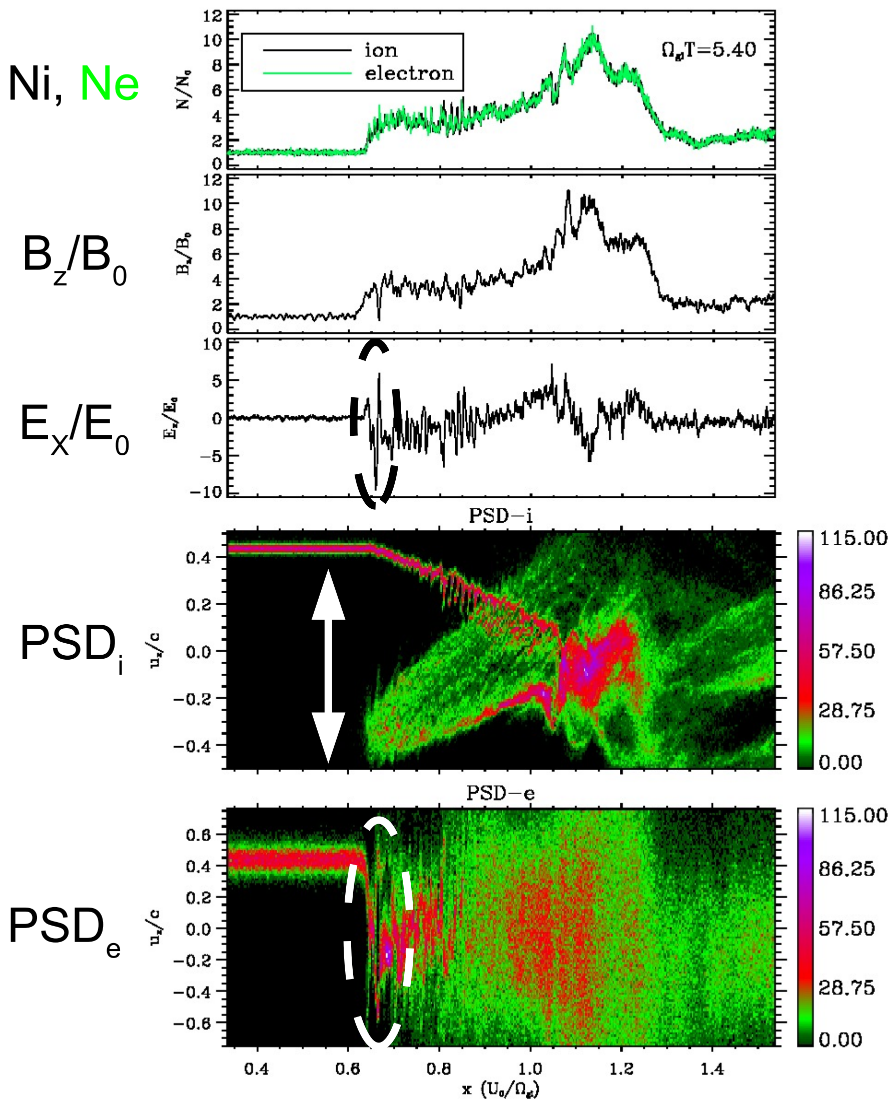
$$\frac{\partial\rho_e}{\partial t}+\nabla\cdot\boldsymbol{J}=0$$

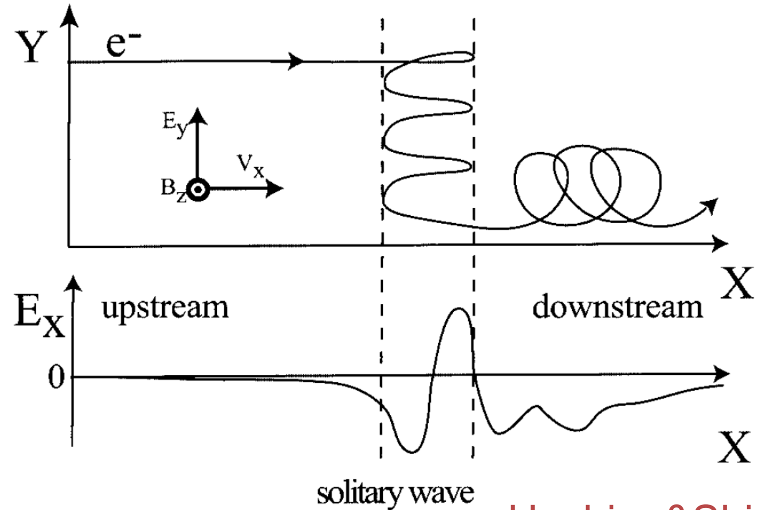
  - Zigzag scheme (1st order shape function, Umeda+ 03)
  - Density decomposition (Esirkepov 01) for higher order shape functions

Comparison of leading edge



Electron shock surfing acceleration





Hoshino&Shimada 02

Unstable condition

$$M_A > \sqrt{\frac{M}{m}}\sqrt{\beta_e} \sim 40$$

Trapping condition

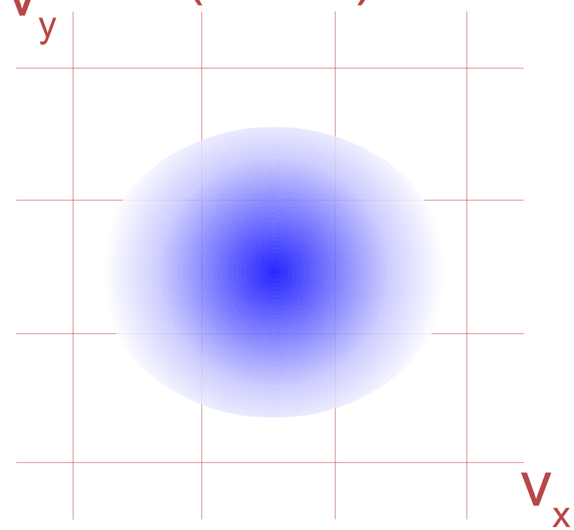
$$M_A > \left(\frac{M}{m}\right)^{2/3} \sim 100$$

Boltzmann equation for collisionless plasma

$$\frac{\partial f_s}{\partial t} + \boldsymbol{v}\cdot\nabla f_s + \frac{q_s}{m_s}\left(\boldsymbol{E}+\frac{\boldsymbol{v}}{c}\times\boldsymbol{B}\right)\cdot\nabla_v f_s = 0$$

physical (3D) + velocity space (3D) = 6D

Vlasov (Euler)



Particle-in-Cell (Lagrangian)