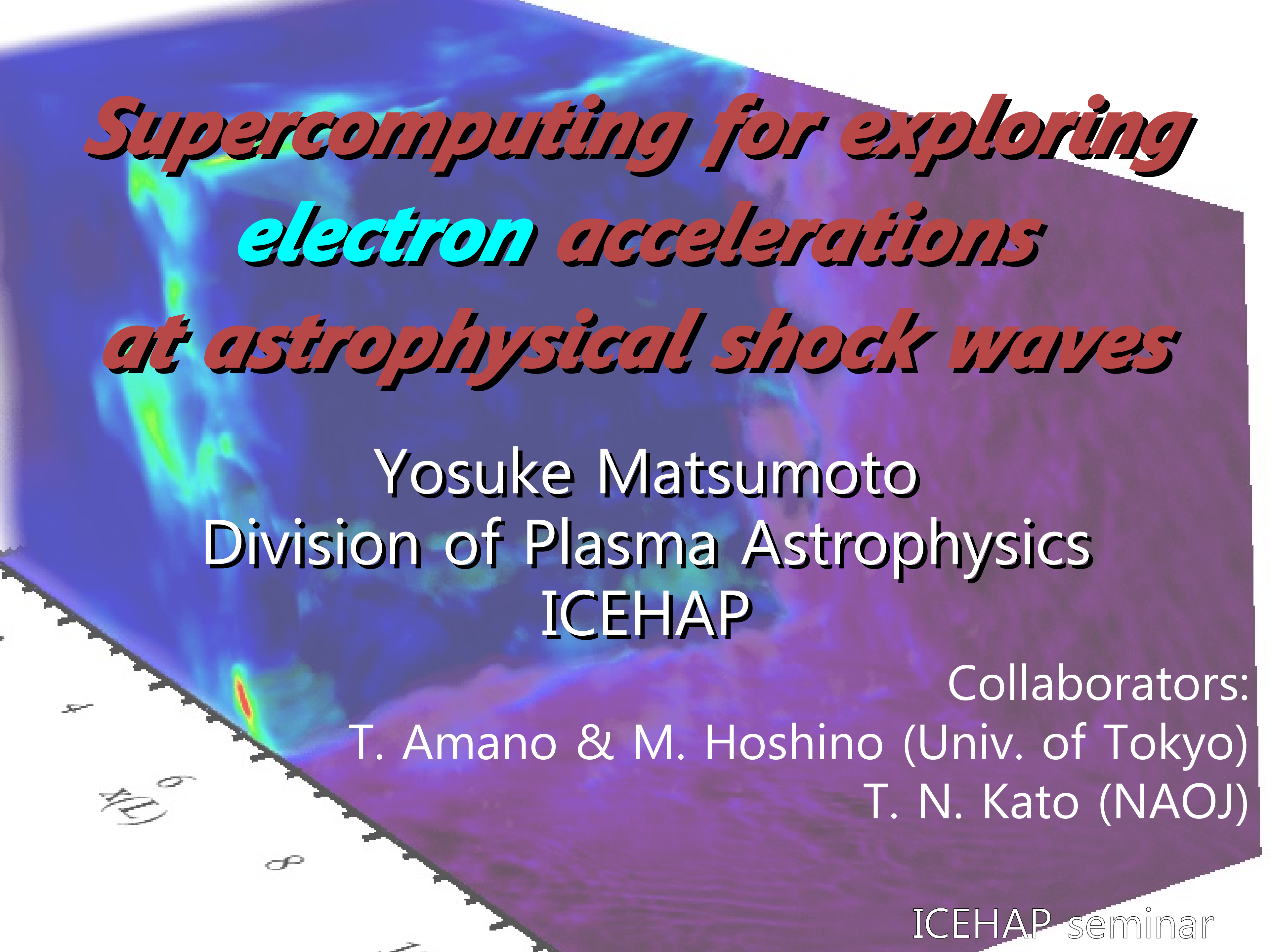


Supercomputing for exploring electron accelerations at astrophysical shock waves

Yosuke Matsumoto
Division of Plasma Astrophysics
ICEHAP

Collaborators:
T. Amano & M. Hoshino (Univ. of Tokyo)
T. N. Kato (NAOJ)

ICEHAP seminar

Outline

- Introduction
  - Collision-less shock
  - Fermi acceleration (Why ***e-*** acceleration?)
  - Magnetic reconnection
- Methods
  - Basic eqs.
  - Ab initio particle-in-cell simulation
  - Shock experiments on supercomputer systems
- Results
  - ***e-*** shock surfing acceleration (YM+ '13 *PRL*)
  - Stochastic ***e-*** acceleration (YM+ '15 *Science*)
- Summary

PERSPECTIVES

PLASMA PHYSICS

Understanding particle acceleration in astrophysical plasmas

Simulations reveal new scenarios to accelerate electrons to extremely high energies

By Hantao Ji[1,2] *and* Ellen Zweibel[3]

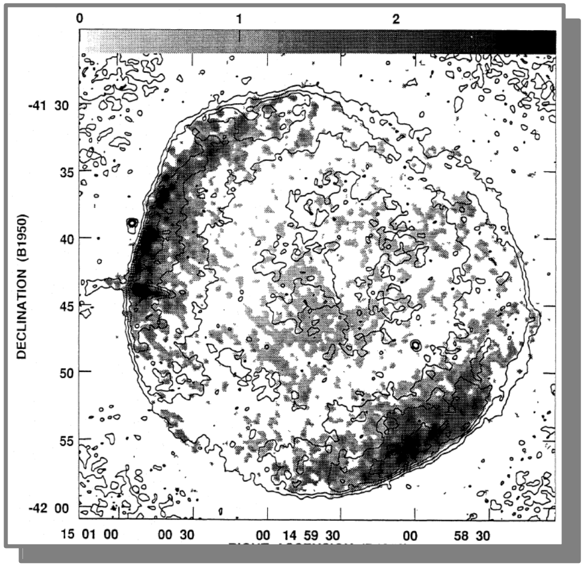
Energetic electrons are ubiquitous in astrophysical plasmas, as they are considered to be behind the surges of emission across the electromagnetic spectrum at wavelengths from radio to gamma rays. These dynamic phenomena include stellar flares, supernova explosions (see the figure) (*1*), gamma ray bursts, and extragalactic jets. Energetic electrons are also directly observed in situ during terrestrial substorms. Despite these rich observations and substantial progress in theory, numerical simulations, and laboratory experiments over the past few decades, however, the mechanisms by which the electrons obtain their energy still remain elusive. On page 974 of this issue, Matsumoto *et al.* (*2*) make progress toward resolving these issues.

Introduction

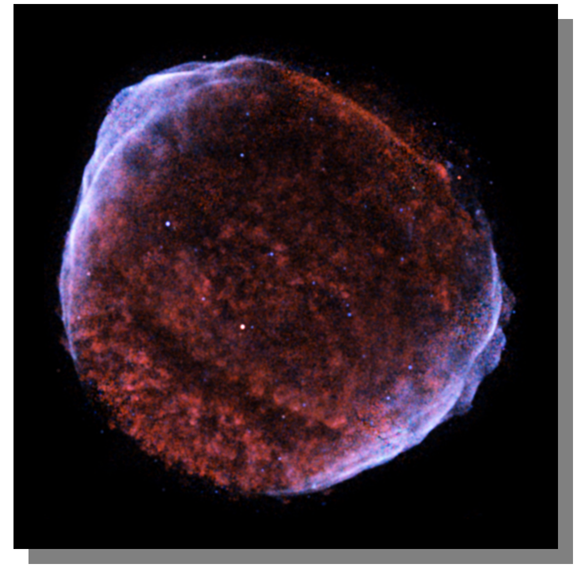
Shock, Shock, Shock! (radio, X, γ)

SNR shocks

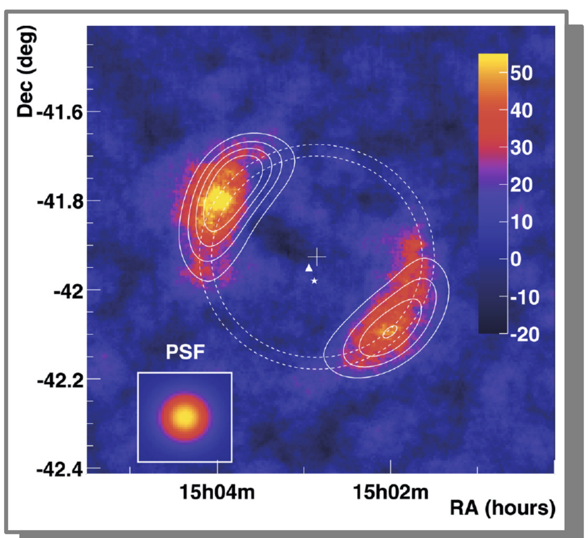
radio
(Reynolds+)



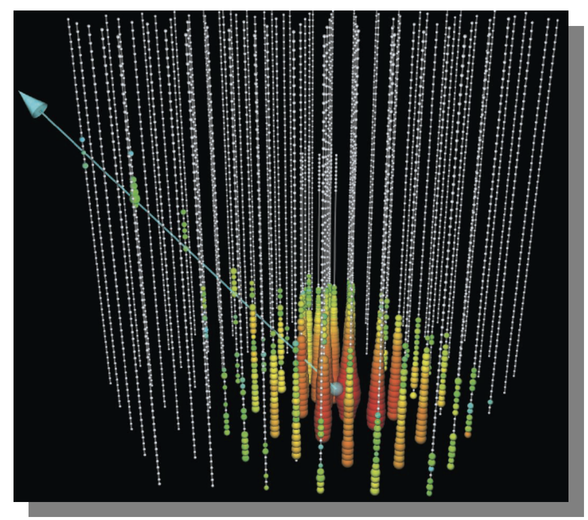
X-ray
Chandra



γ-ray
HESS

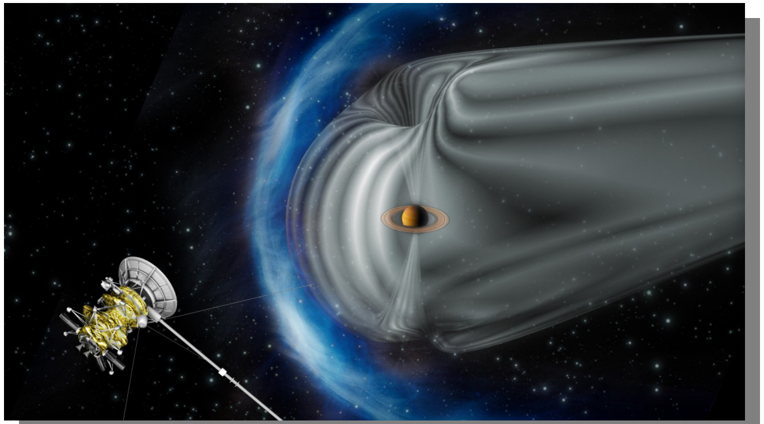


ν
IceCube
?

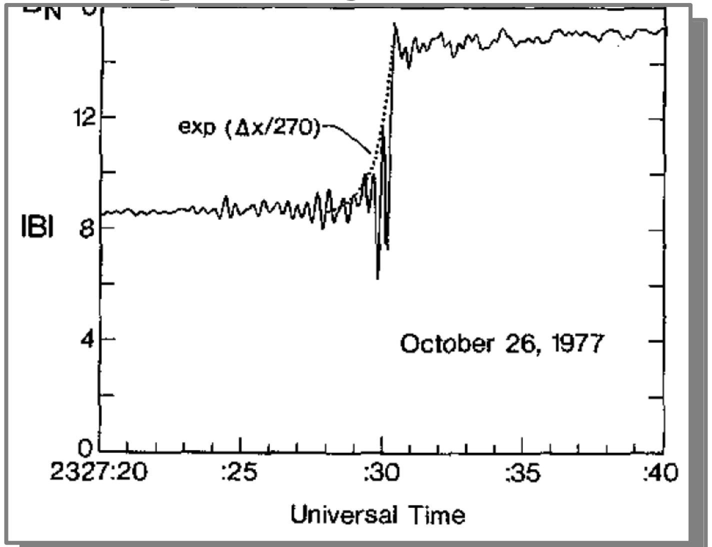


Shock, Shock, Shock! (in-situ)

Planetary shocks



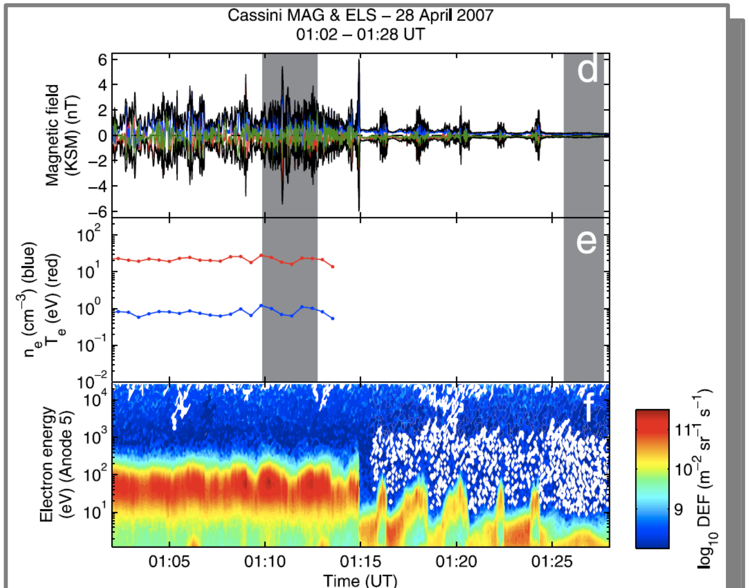
Interplanetary shock @ 1AU



Russel & Greenstadt '79

30 years later...

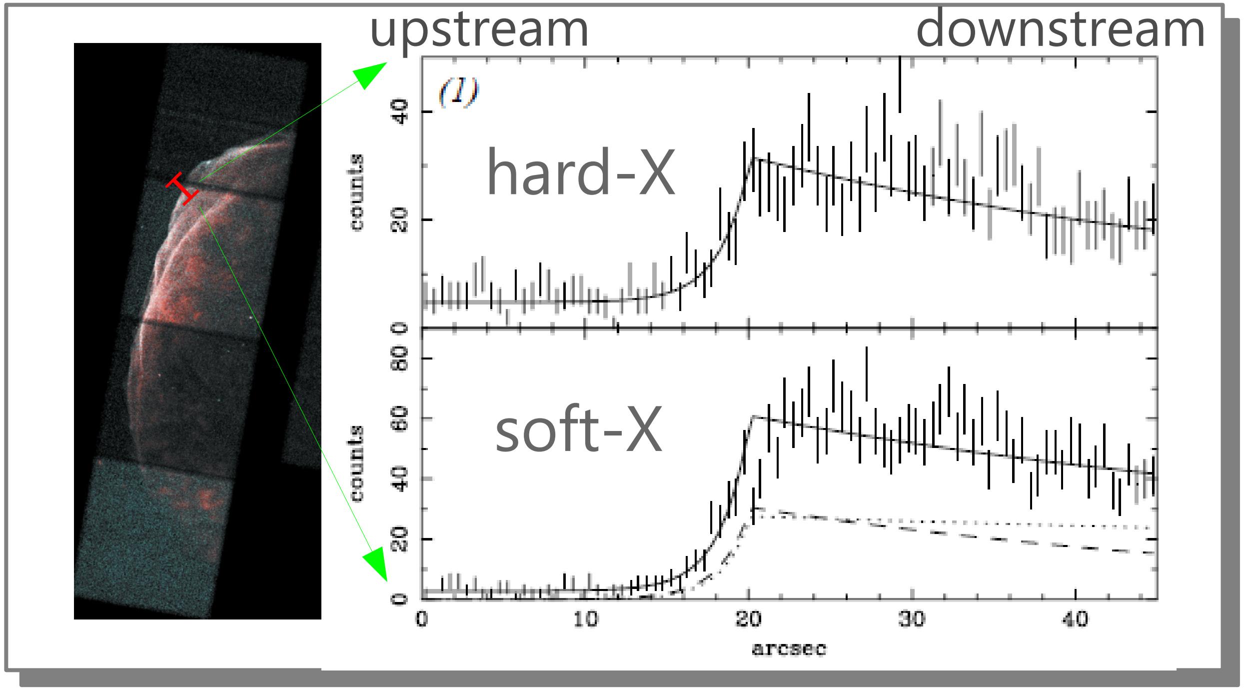
Bow shock @ Saturn



Masters+ '11,'13

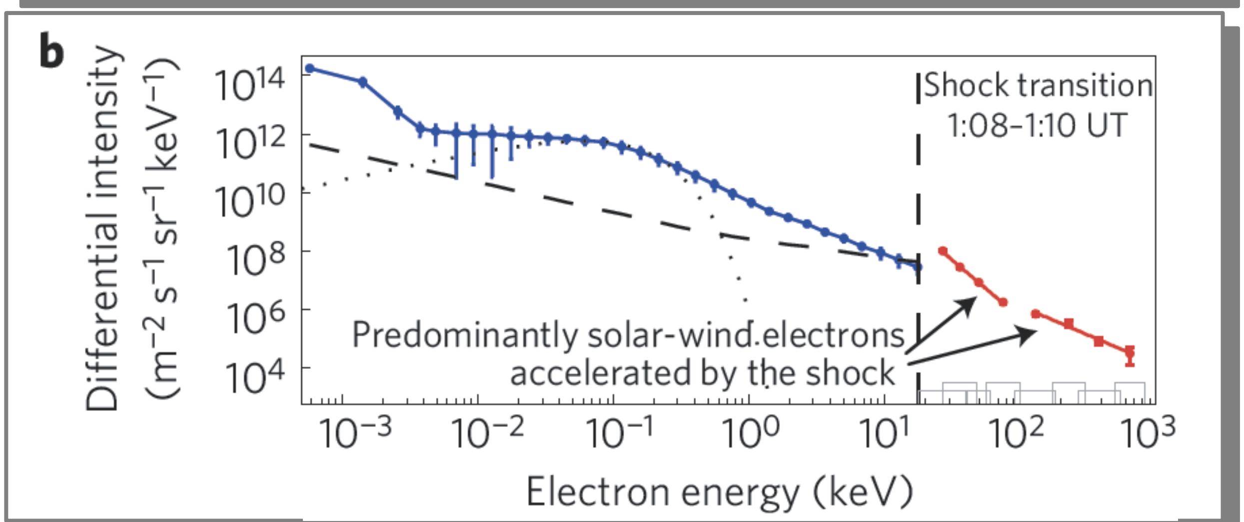
High-energy electrons at strong shock waves

SN1006



Bamba+ '03

Saturn's bow shock

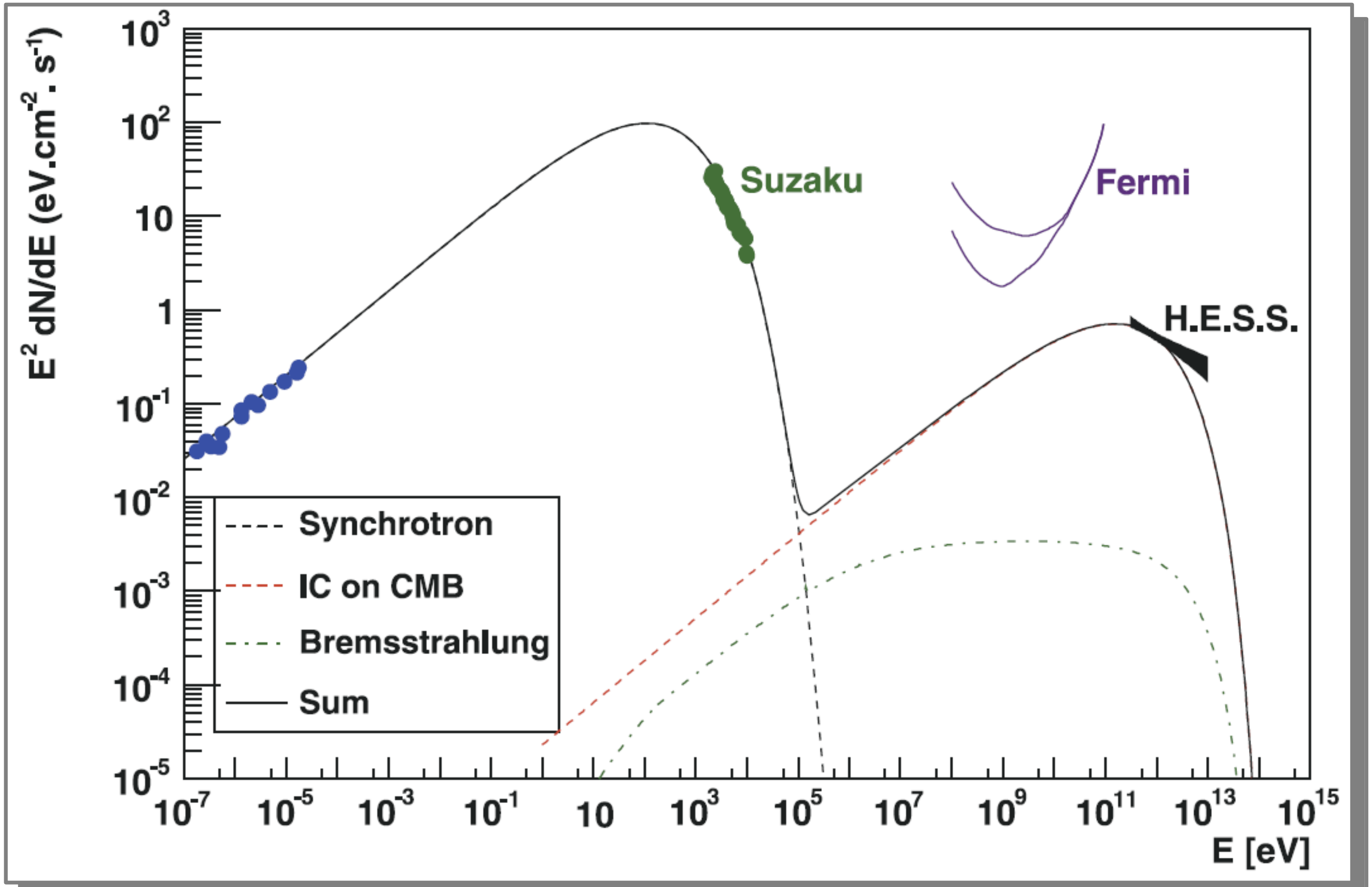


Masters+ '13

Why *electron*? (99% of CR are nuclei/protons...)

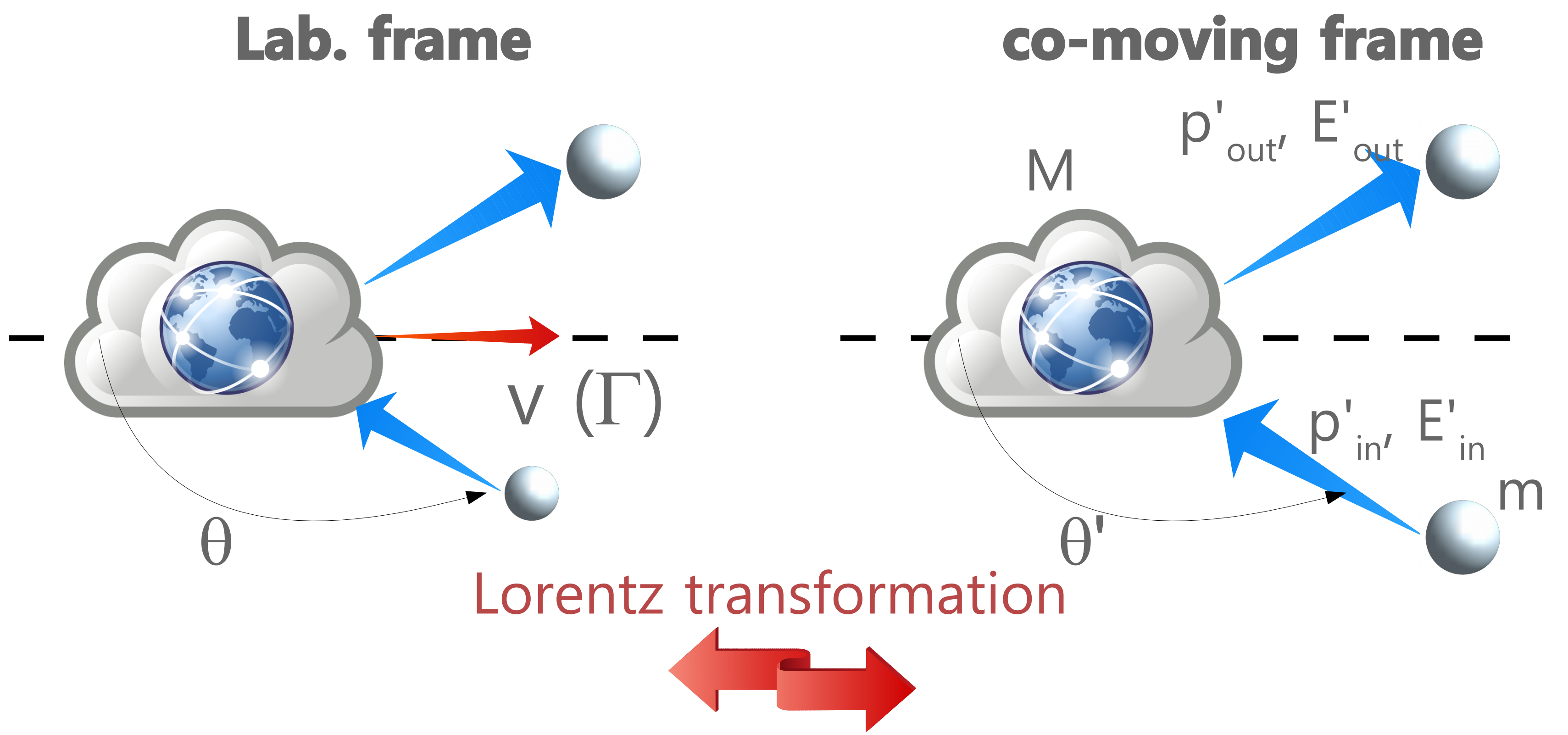
Observationally evident, theoretically puzzling.

(contrary to protons, viz. leptonic vs. hadronic for TeV γ)



HESS collaboration '10

Fermi acceleration (Fermi, '49)



- p_{in}
- E_{in}
- $E_{out} = \Gamma(E'_{out} - Vp'_{in}\cos(\theta'))$

$$=\Gamma^2 E_{in}(1+V/c^2-2vV\cos(\theta))$$

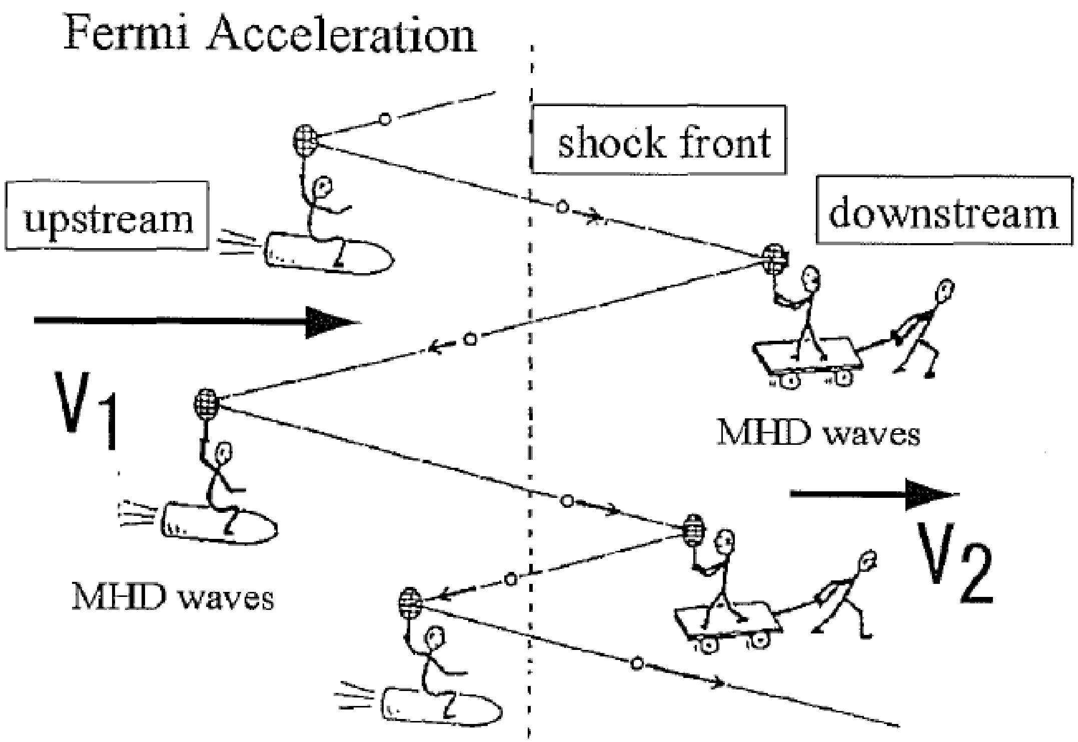
- $p'_{out}\cos(\theta') = -p'_{in}\cos(\theta')$
- $E'_{in} = \Gamma(E_{in} - Vp_{in}\cos(\theta))$
- $E'_{out} = E'_{in}$

1st & 2nd order Fermi accels. ($v \sim c$, $\Gamma \sim 1$)

$$\frac{E_{out} - E_{in}}{E_{in}} = \frac{\Delta E}{E} = -2\frac{V}{c}\cos\theta + \left(\frac{V}{c}\right)^2$$

- cos(θ)
  - θ = 0 → over taking : energy loss
  - θ = π → head-on : energy gain
- 2nd order
  - cos(θ) ~ -1 ~ +1
  - $(V/c)^2$ term remains
- 1st order if the head-on collisions dominate
  - <cos(θ)> ~ -1
  - the fist term (V/c) is the leading order

Diffusive shock acceleration (1st order Fermi)

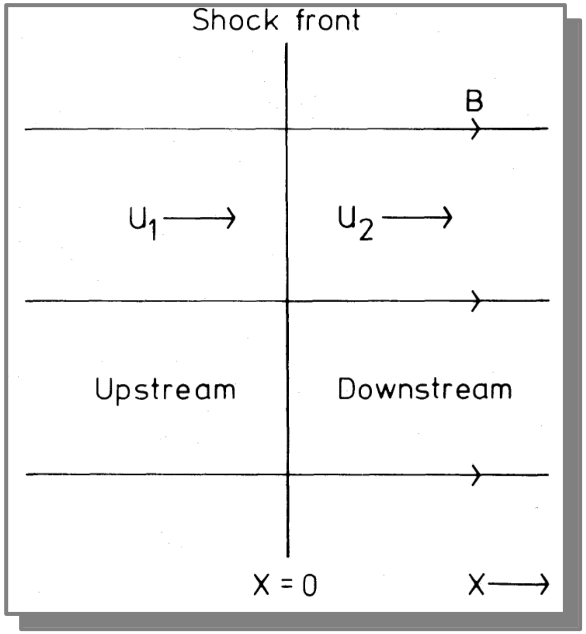


M. Scholer

- V_1-V_2 > 0 (div(V)<0) → head-on
- 1st order Fermi acceleration
- γ = r+2/r-1, where r is the compression ratio. γ=2 for strong shocks (r=4)

Theoretical issues

- **Injection**
  - Shock scale $L \sim \alpha\lambda_i >> r_{ge}$
  - Thermal electrons are strongly magnetized
  - $\gamma_e > \sim 10$ can be injected
  - Pre-accelerations for electrons are necessary

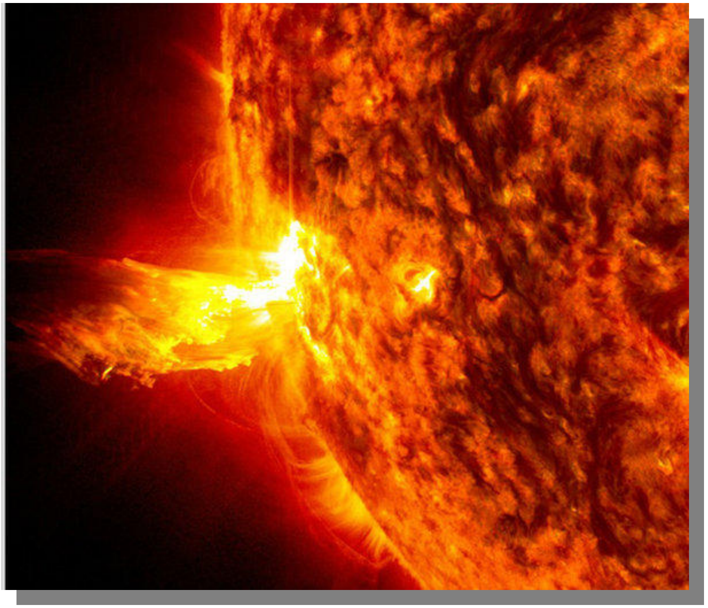


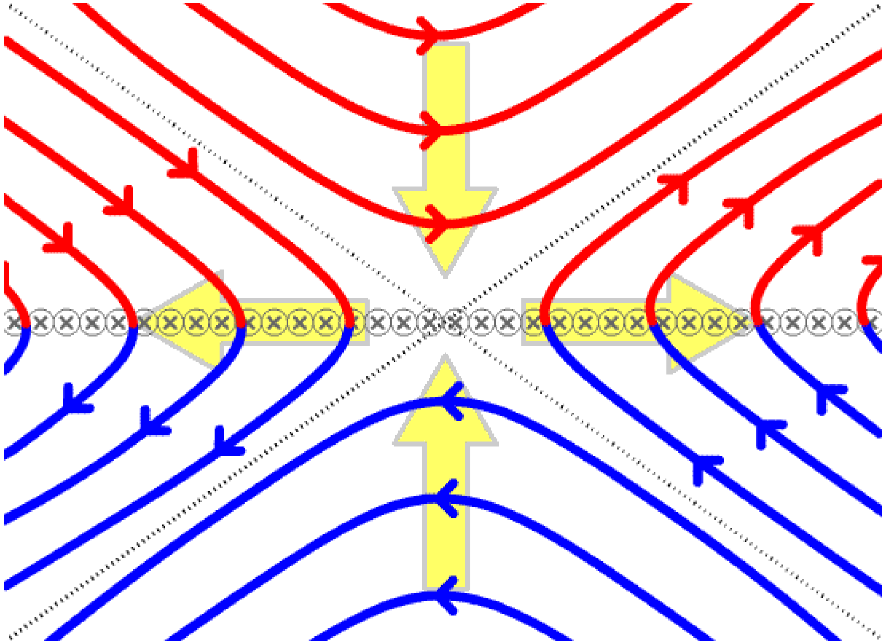
Bell, 1974

- **Scattering bodies**
  - Alfven waves – cannot scatter thermal electrons
  - magnetic clouds – found by YM+ '15 *Science*
  - magnetic field amplification (x ~100)

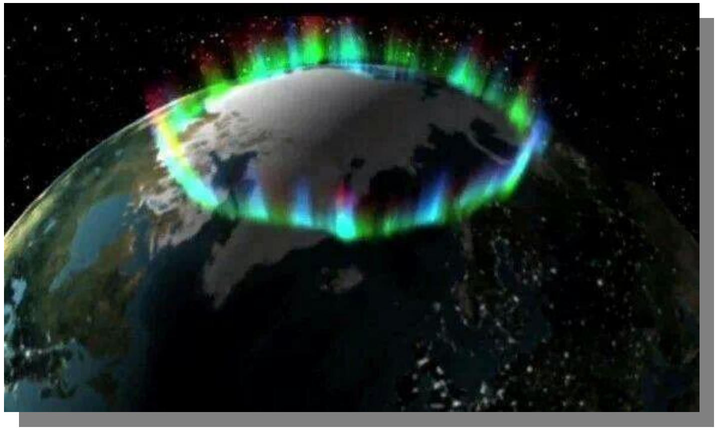
Magnetic reconnection

Solar flare





Aurora



- Topology change of anti-parallel magnetic field lines
- Conversion of magnetic energy to plasma kinetic energy
- Fundamental process in planetary and astrophysical phenomena

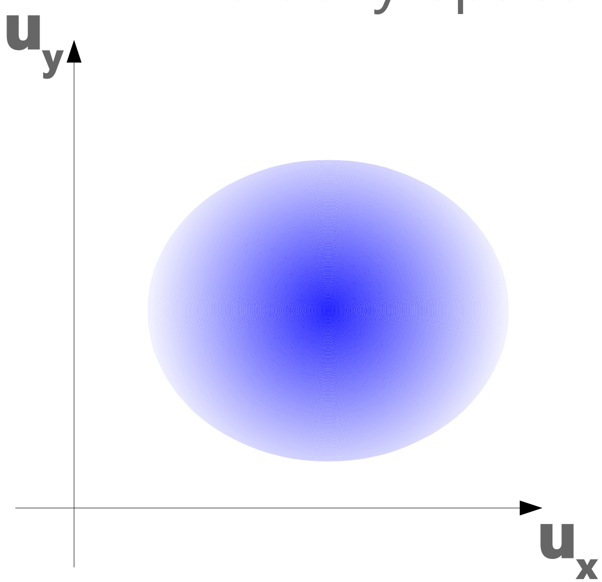
Methods

Vlasov equation

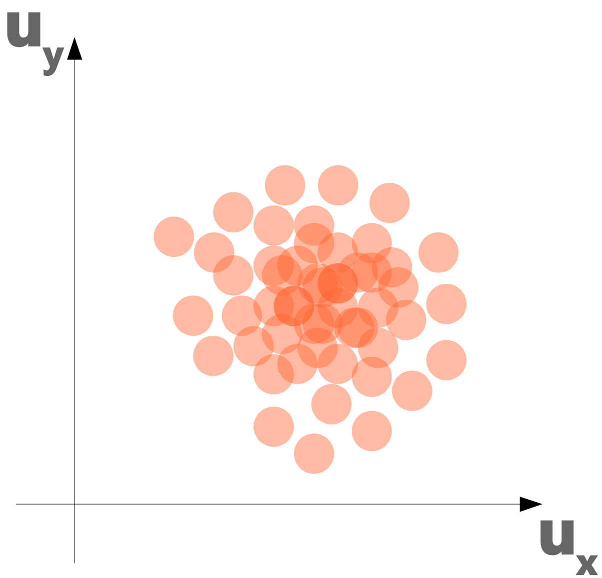
$$\frac{\partial f_s}{\partial t} + \boldsymbol{v} \cdot \nabla f_s + \frac{q_s}{m_s}\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B}\right) \cdot \nabla_u f_s = 0$$

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

distribution function in velocity space



particle-in-cell simulation

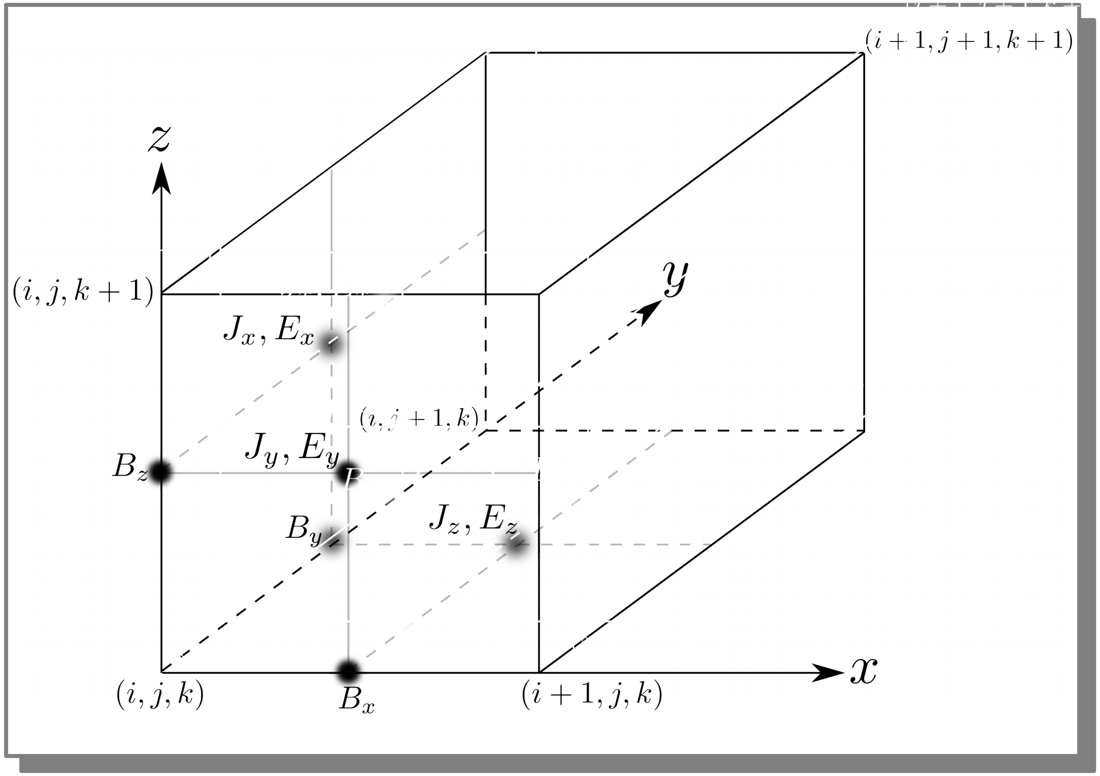


Maxwell equation

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

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

with $\nabla \cdot \boldsymbol{B} = 0$, $\nabla \cdot \boldsymbol{E} = 4\pi\rho_e$



Implicit FDTD method

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

θ: implicitness factor

solved within ~10 interations by the conjugate gradient method

particle-in-cell (PIC) simulation

Particle push

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

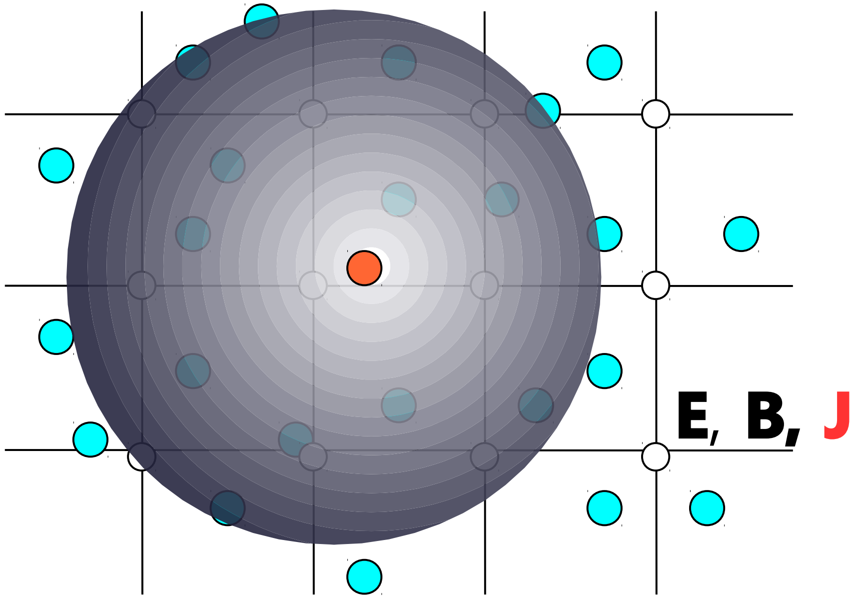
$$\frac{d\boldsymbol{u}_p}{dt} = \frac{q}{m}\left(\boldsymbol{E} + \frac{\boldsymbol{u}_p}{c\gamma_p} \times \boldsymbol{B}\right)$$

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

Maxwell equation

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

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



Characteristic scales in PIC simulations

- Δh ~ Debyle length λ_D:

$$\lambda_D[m] = 7.4\, T^{\frac{1}{2}}[eV]\left(\frac{1}{n[cm^{-3}]}\right)^{\frac{1}{2}}$$

- Δt ~ electron plasma frequency ω_{pe}^{-1}:

$$\omega_{pe}^{-1}[sec] = \frac{1}{9}\left(\frac{1}{n[cm^{-3}]}\right)^{\frac{1}{2}} 10^{-3}$$

- Proton-to-Electron mass ratio M/m:

$$M/m \sim O(10)\ (\leftrightarrow 1836)$$

parsec and $10^{3\text{-}6}$ yrs in astrophysics!

Characteristic scales of SNR shocks

Shock speed

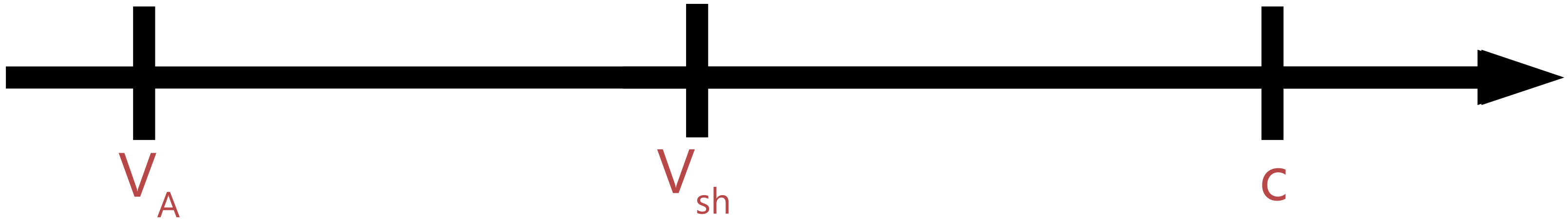
- V_{sh} = 1000 – 10000 km/s
- non-relativistic shocks

Magnetic field (upstream)

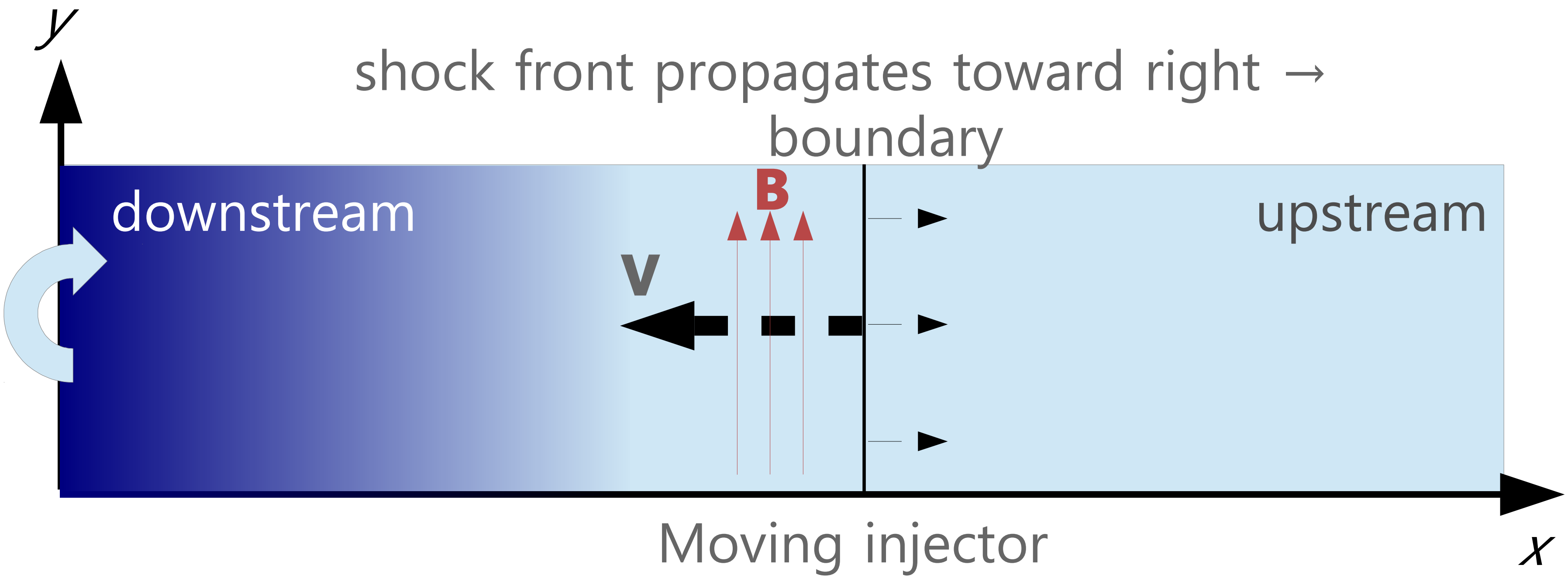
- a few μG : Alfven speed V_A ~ 10 km/s (n~0.1 /cc)
- (Alfven) Mach number M > 100 !

Dynamic ranges

- shock scale : MHD ($L >> r_{gi} >> r_{ge}$)
- Ion to Electron mass ratio M/m=1836
- relativistic electrons : v~c ($>>V_{sh} > V_A$)



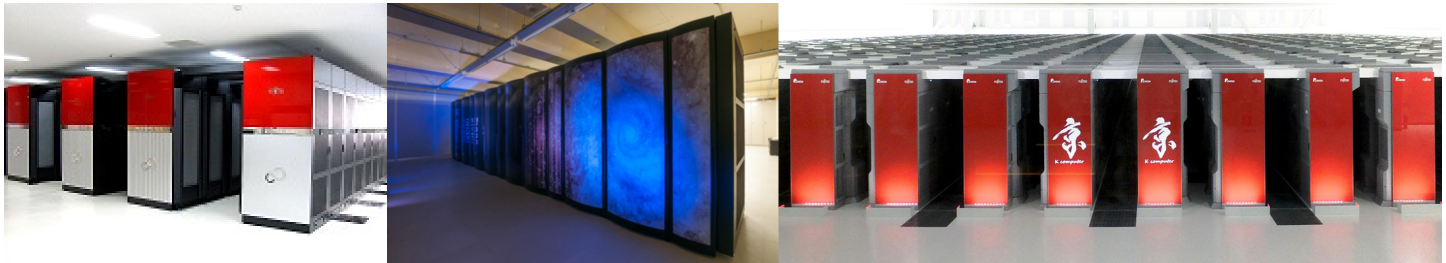
Shock creation - Injection method

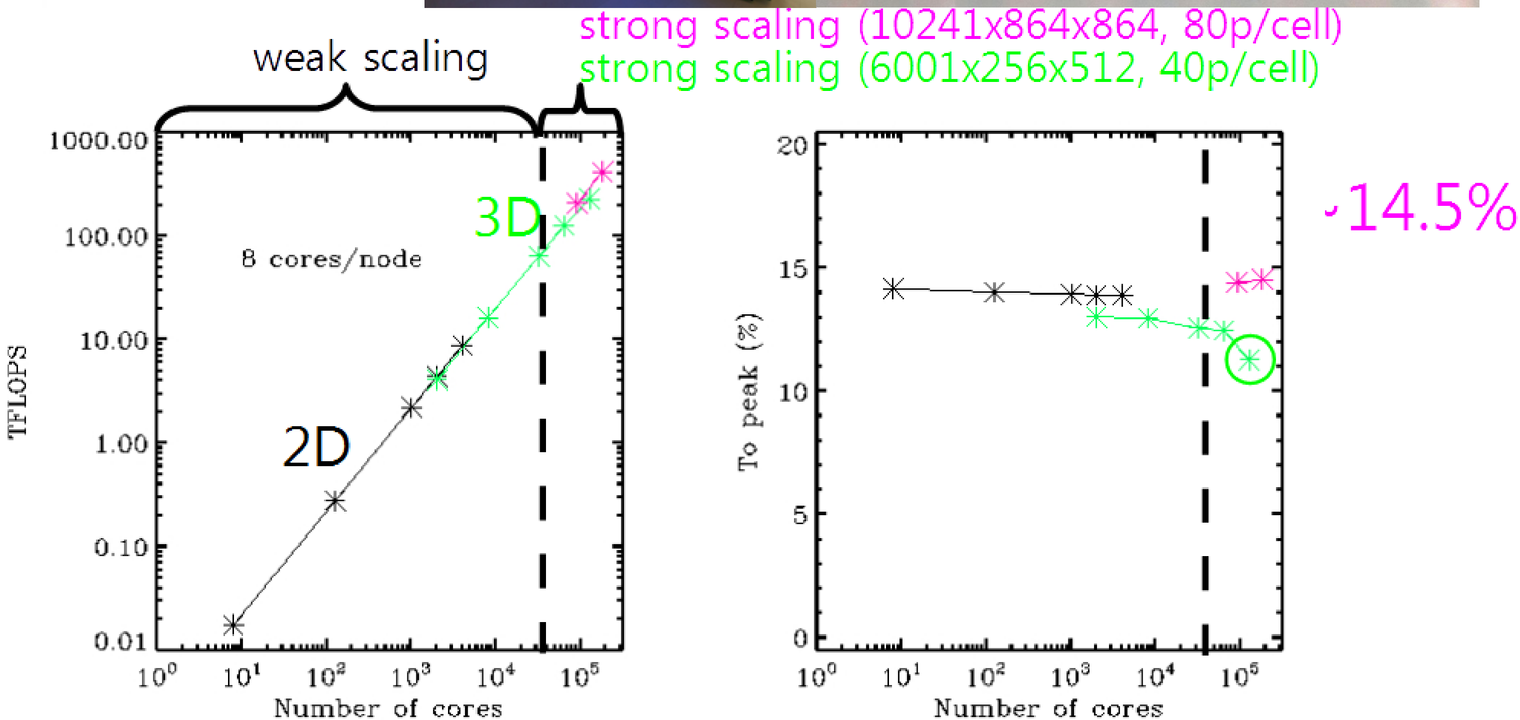


Moving injector
(Riquelme & Spitkovsky '11)

- 2D PIC simulations
- Perpendicular shocks (**B** ⊥ ***n***)
- Non-relativistic shock speeds ($V_{sh}/c \sim 0.3$)
- High Mach numbers (V_{sh}/C_s and V_{sh}/V_A) ~ 40
- M/m: O(100)

Shock experiments on supercomputer systems



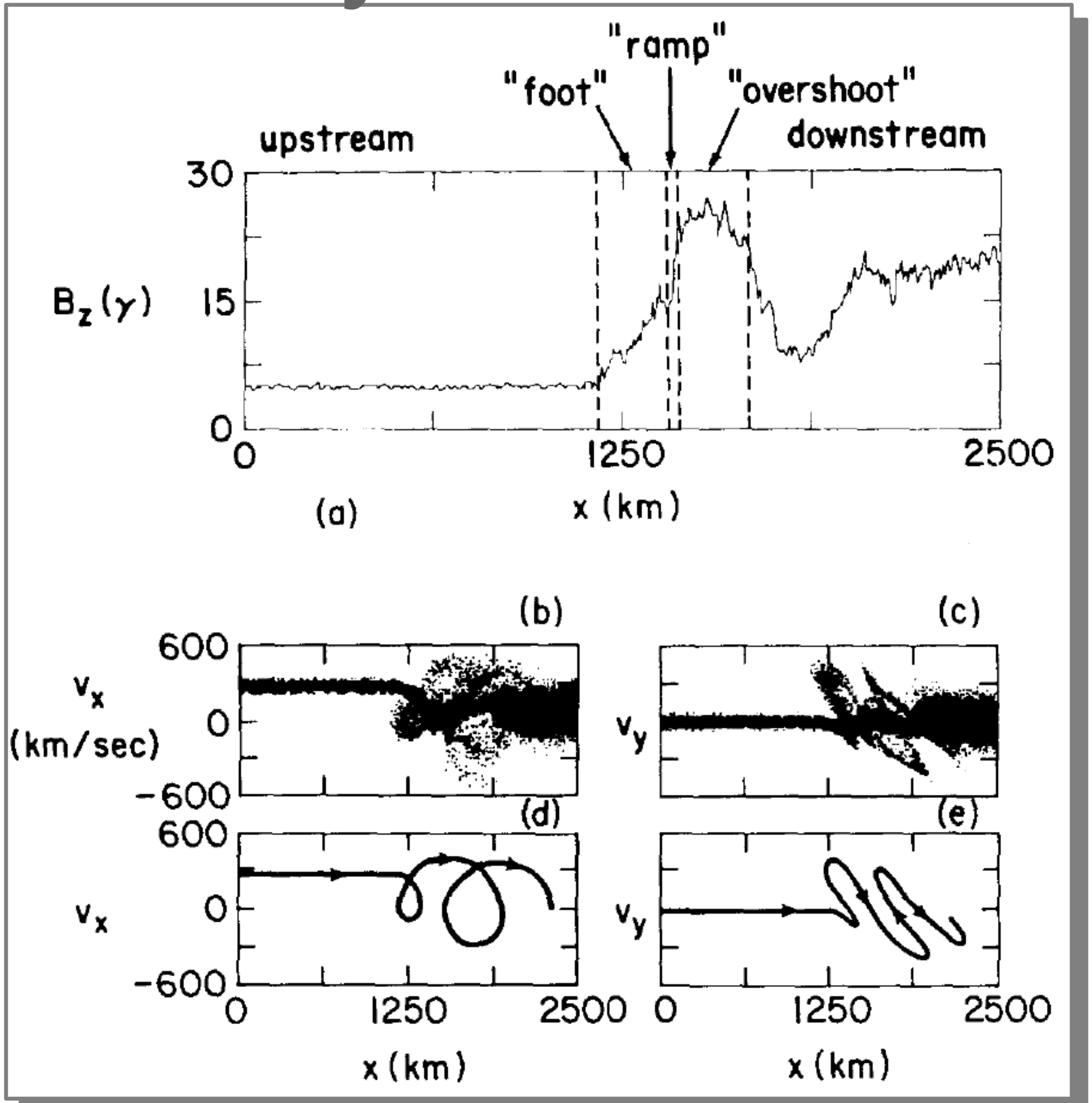


- Optimized on K computer at AICS, RIKEN
- MPI+OpenMP hybrid parallelization
- Scalable up to 10^5 cores

Collision-less shock simulations

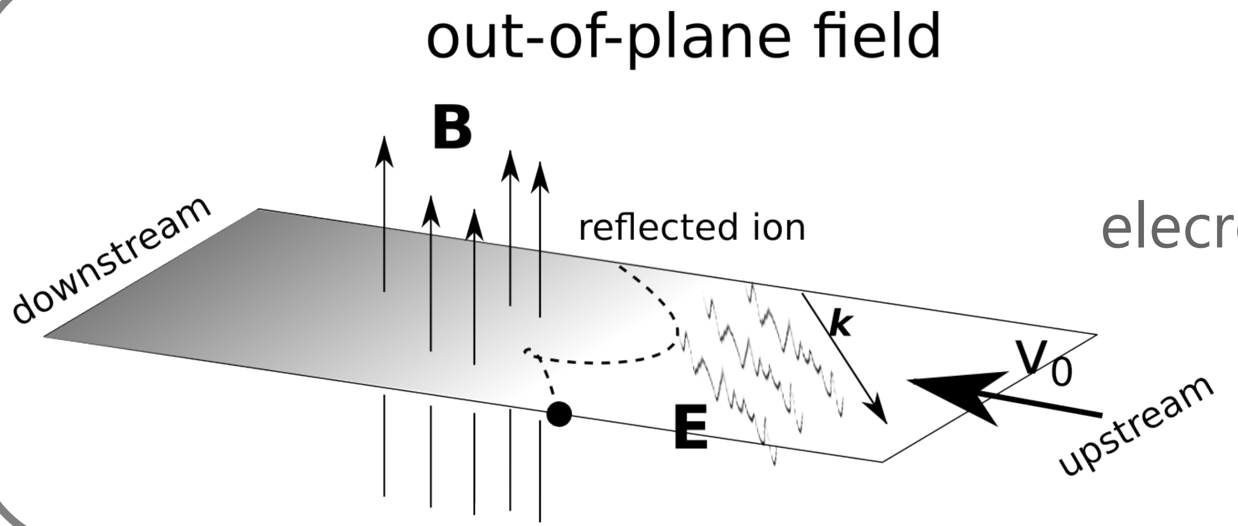
Super-critical (M_A> ~3) shock structures

key: Reflected ions



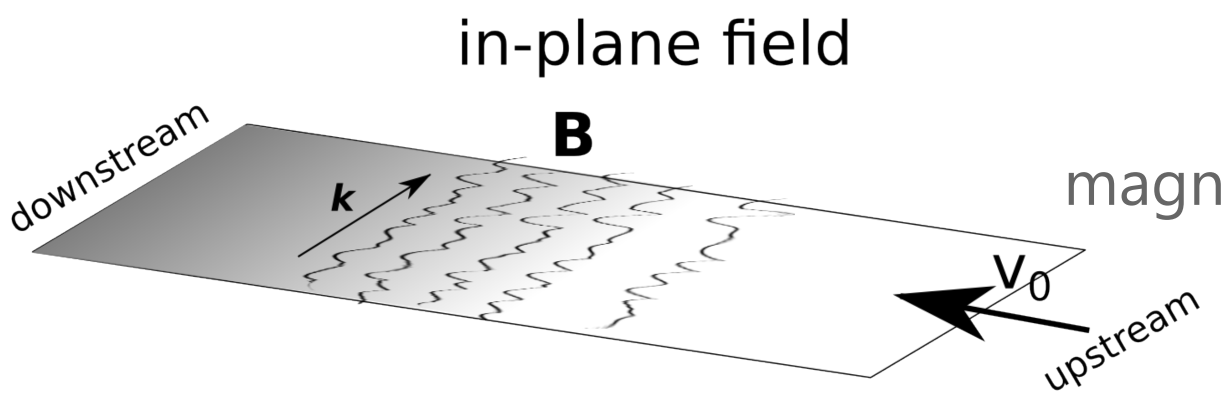
Leroy '82; Wu+ '84

Physics in high M_A shocks



$\boldsymbol{k} \perp \mathbf{B}_0$

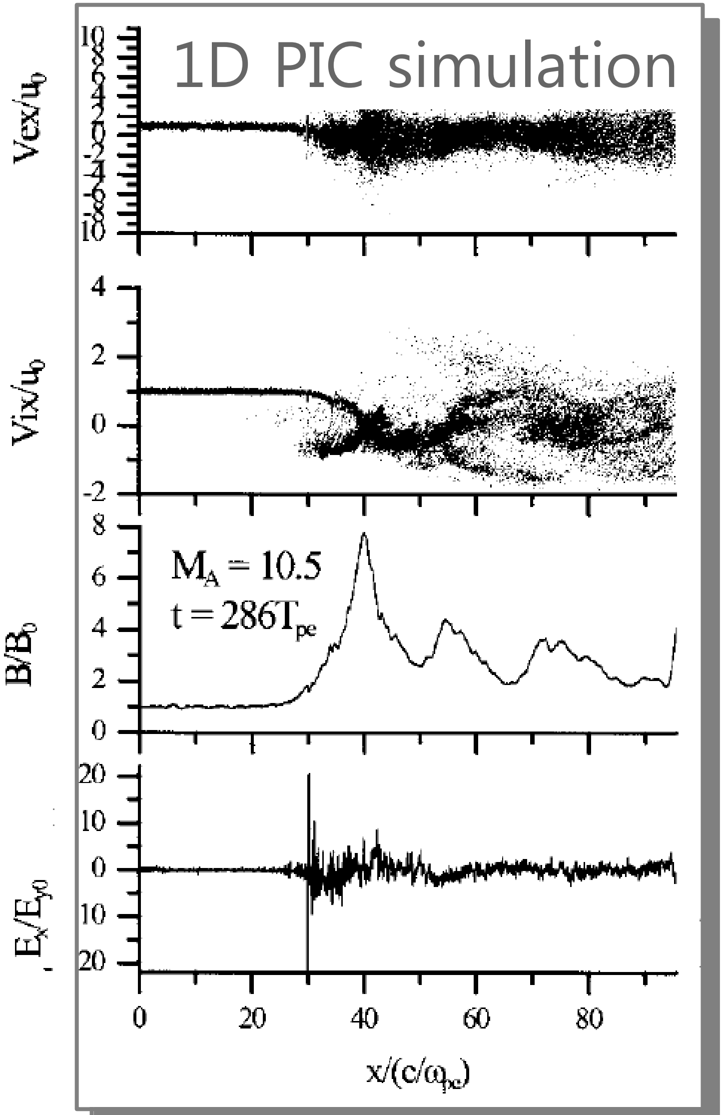
elecron pre-acceleration



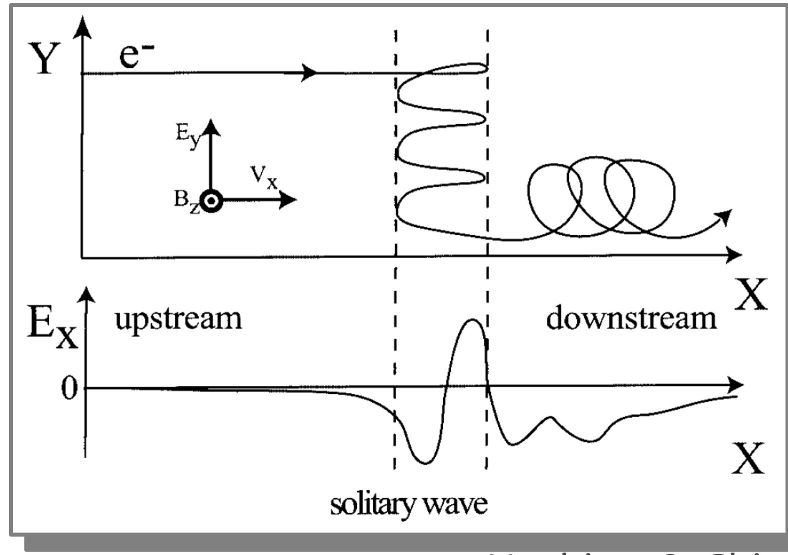
$\boldsymbol{k} \,//\, \mathbf{B}_0$

magnetic field turbulence

Electron shock surfing acceleration (eSSA)



Shimada & Hoshino '00
McClements+ '01



Hoshino & Shimada '02

Linear unstable condition

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

Trapping condition

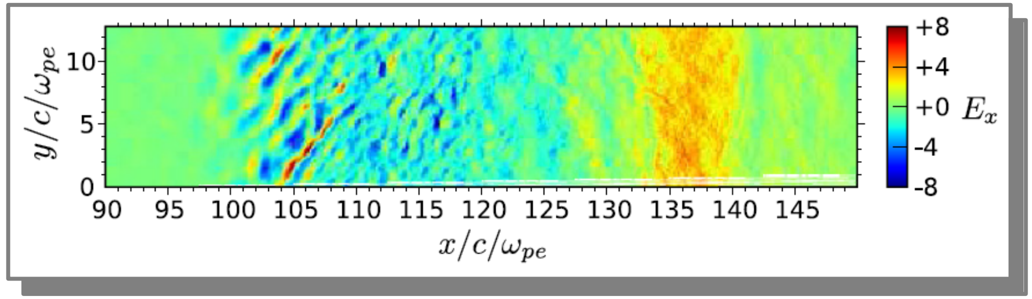
$$M_A > \left(\frac{M}{m} \right)^{2/3}$$

Matsumoto+ '12

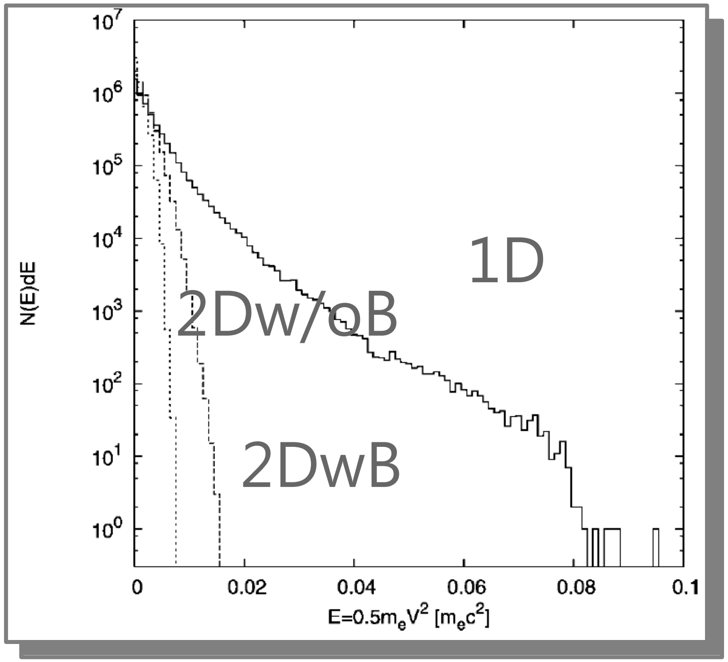
eSSA in multi dimensions ?

multi-dimensinonal effects

M/m=25, M_A~15



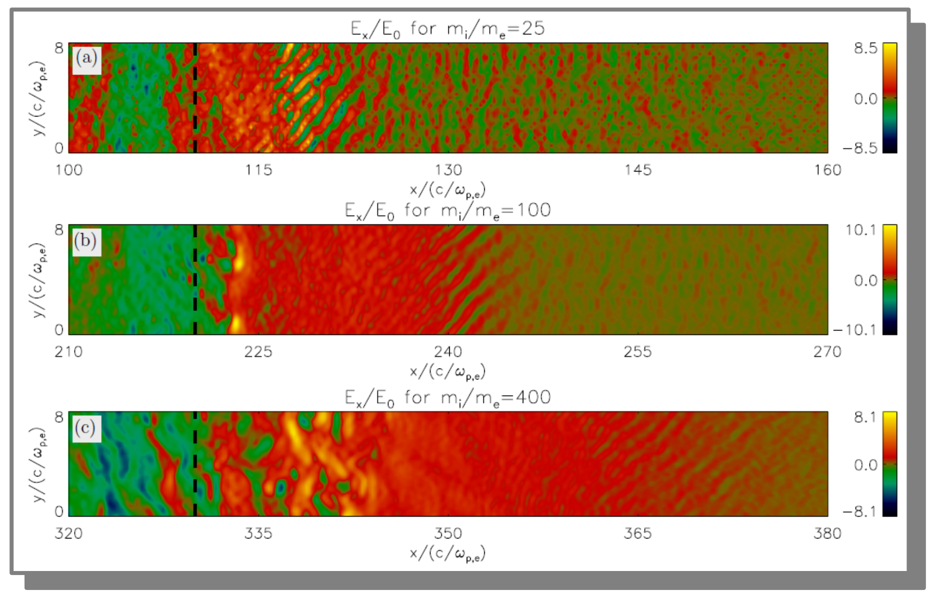
Amano & Hoshino '09



Ohira & Takahara '07

*periodic system modeling foot region

mass ratio dependence
(M/m=25, 100, 400)

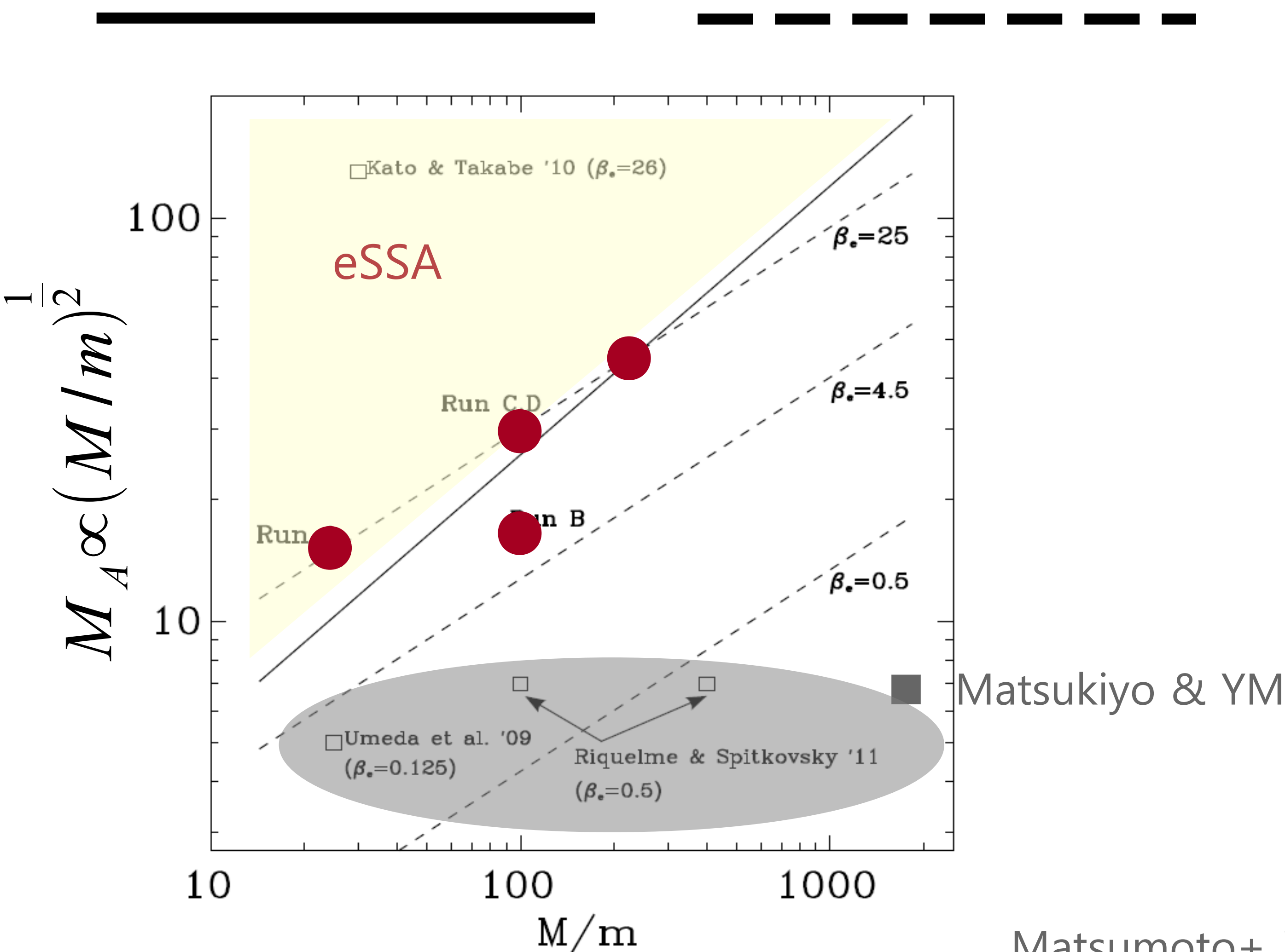


Riquelme & Spitkovsky '11

2D PIC simulations of perpendicular shocks

Trapping condition

Linear unstable condition



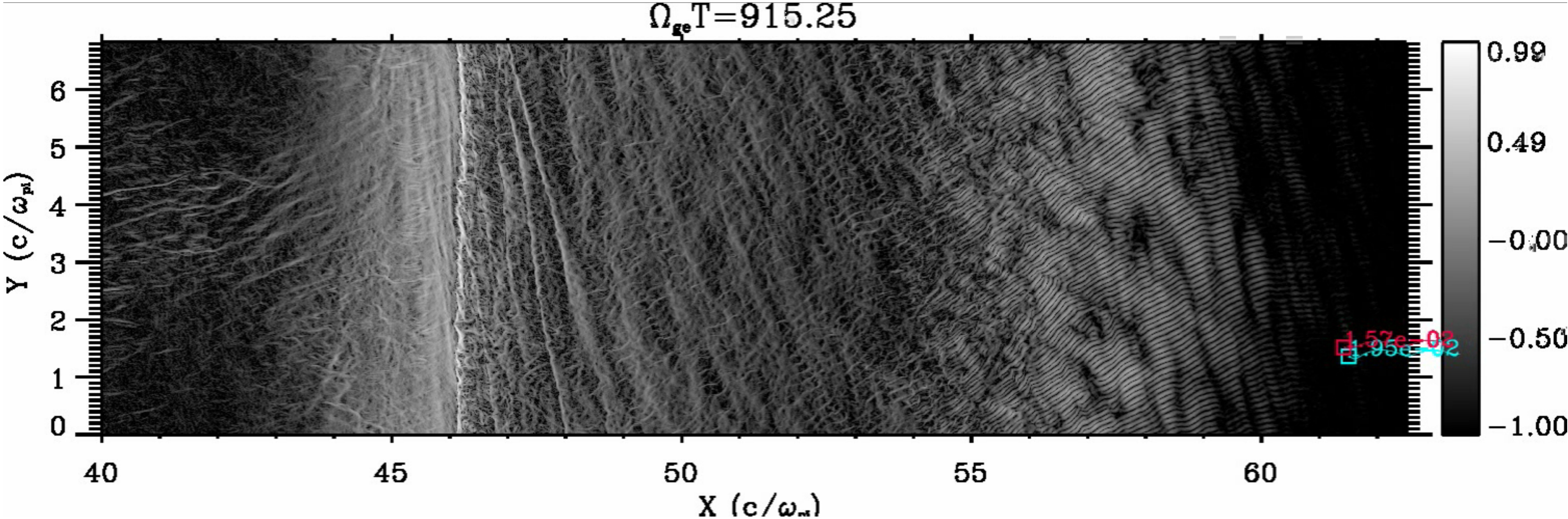
Matsumoto+ '12

e- acceleration at M/m=225, M_A~45 shock

$|E_{es}|/B_0$

downstream

upstream



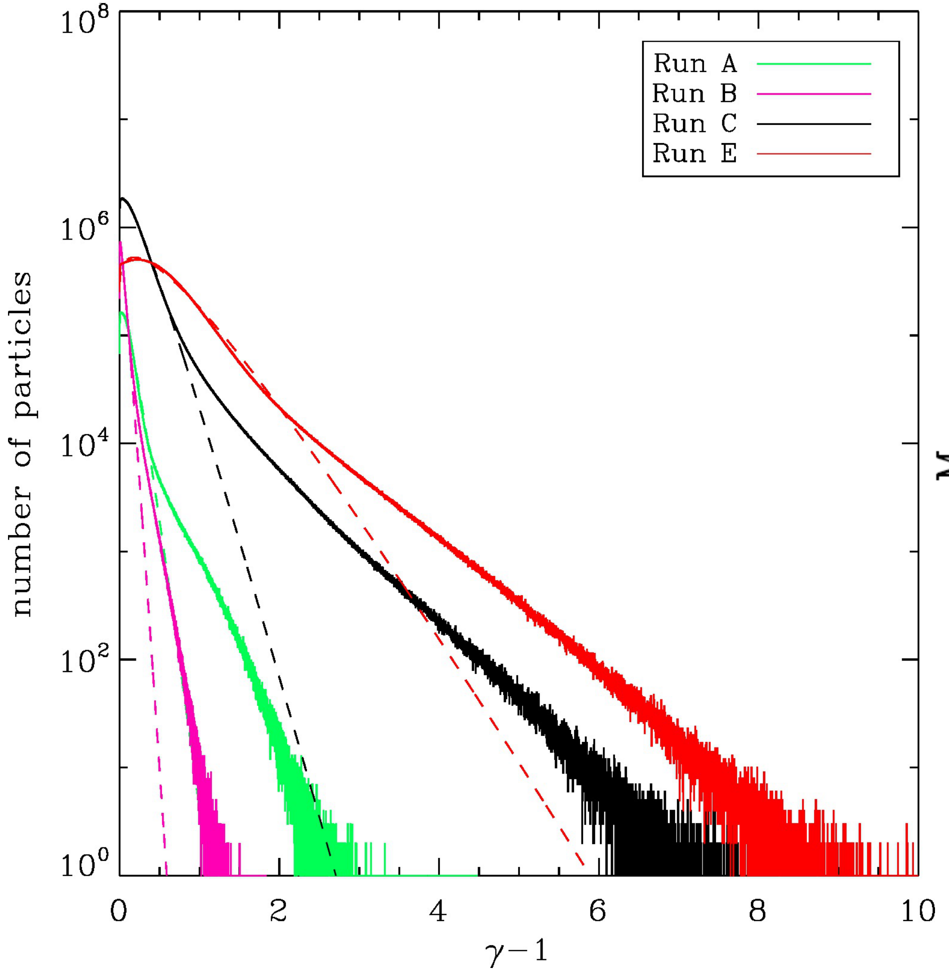
Matsumoto+ '13 *PRL*

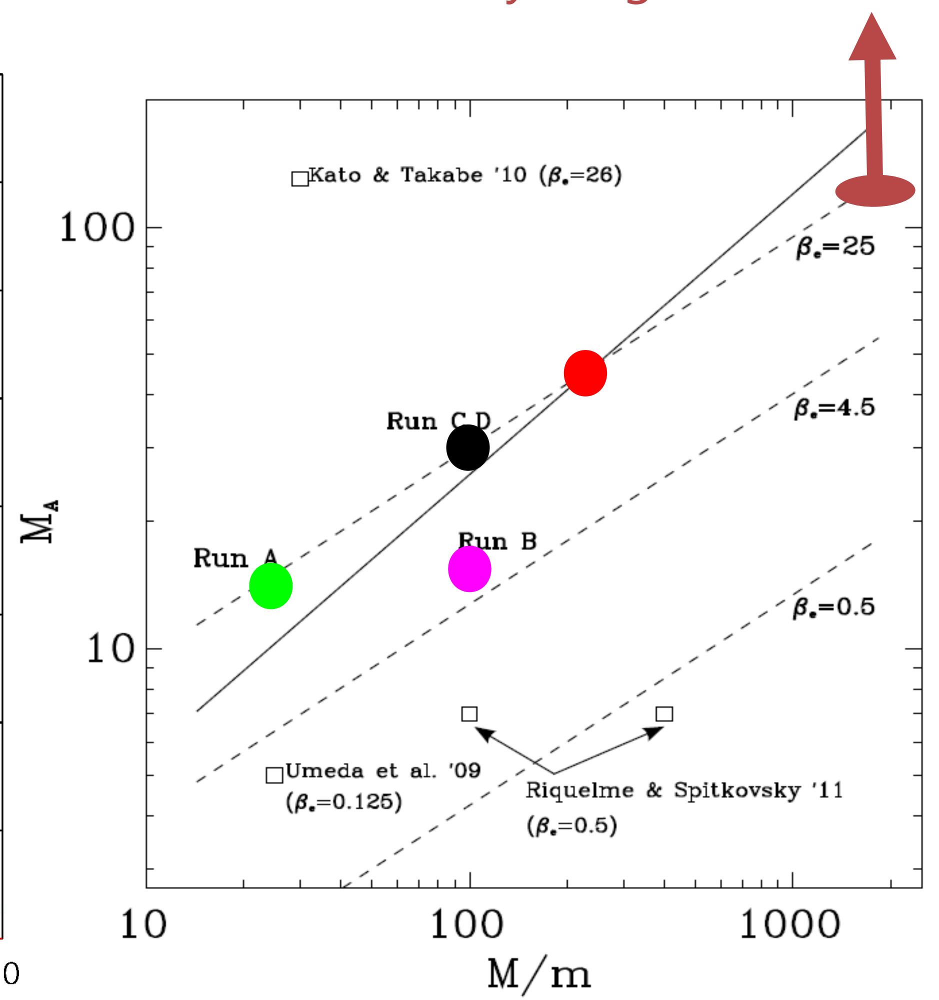
:accelerated

:thermal

Electron downstream energy spectra

young SNR shocks

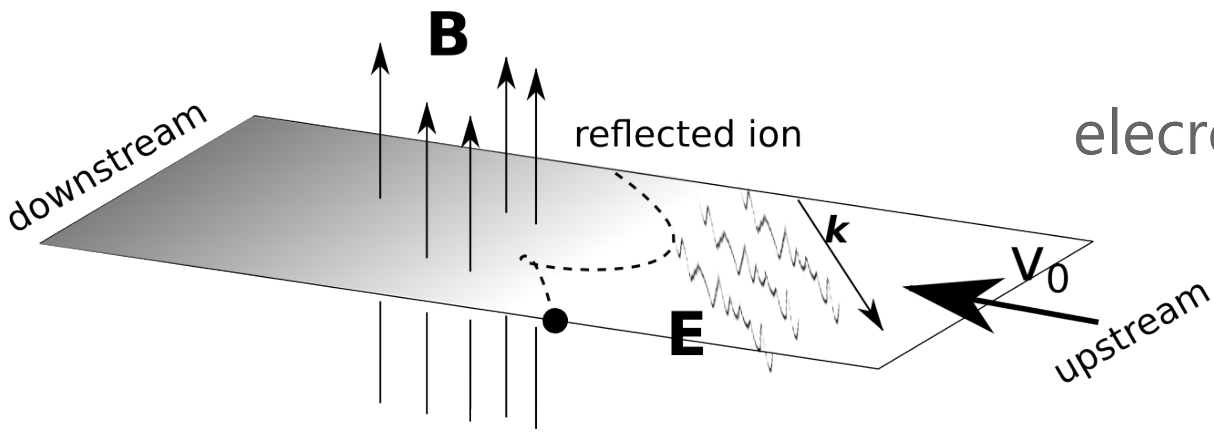




Matsumoto+ '12, '13

Physics in high M_A shocks

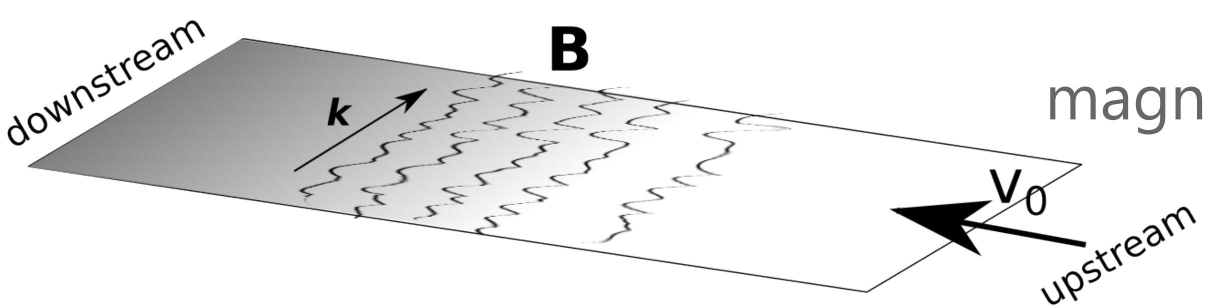
out-of-plane field



$\boldsymbol{k} \perp \mathbf{B_0}$

elecron pre-acceleration

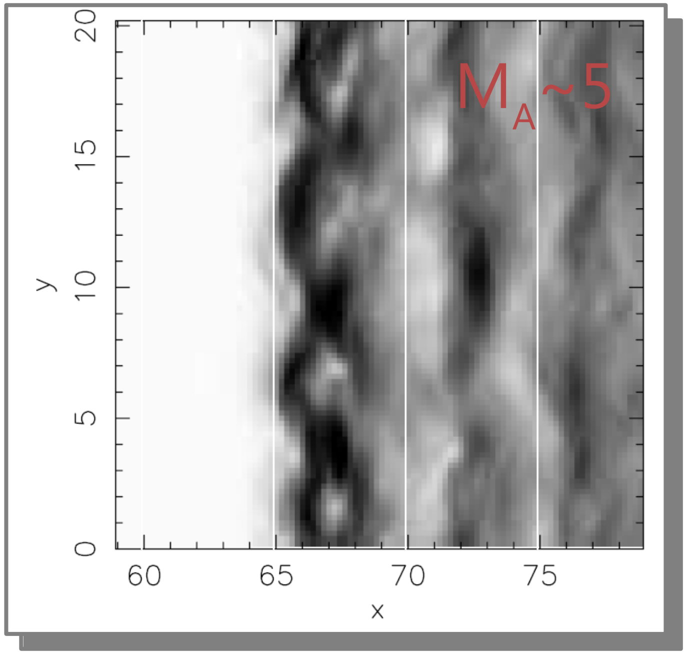
in-plane field



$\boldsymbol{k} \,//\, \mathbf{B_0}$

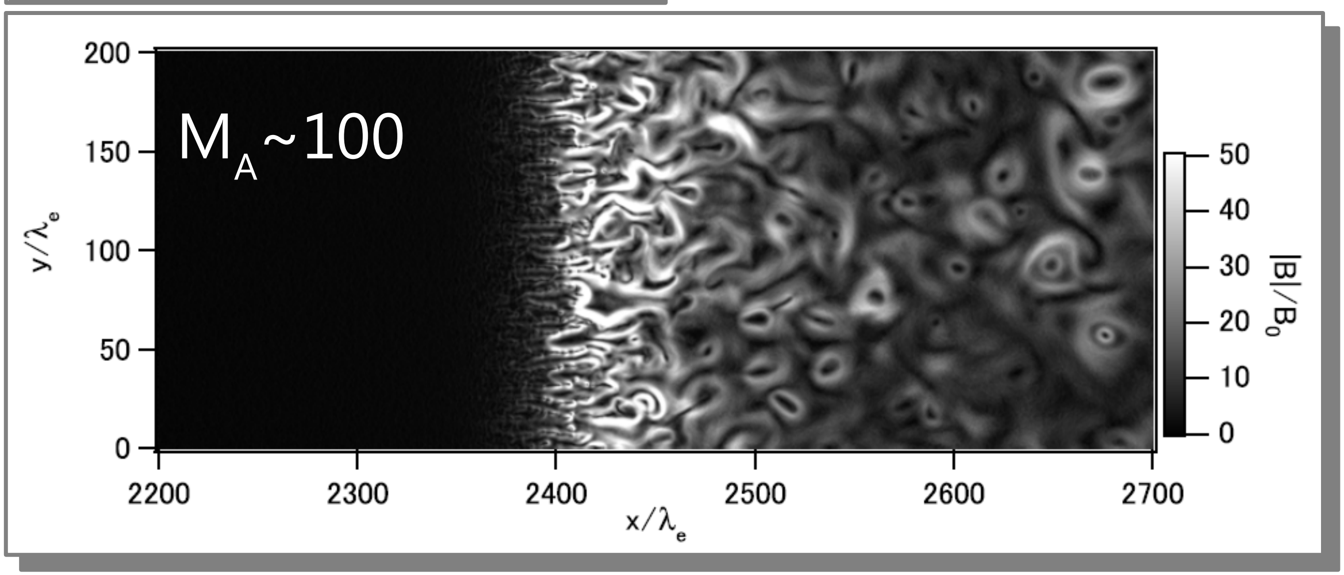
magnetic field turbulence

In-plane **B** field case



- Ion-scale ripples along the shock surface
- Ion cycrotron-instability
- Ion-beam Weibel instability
- Origin of ion-scale magnetic field turbulence

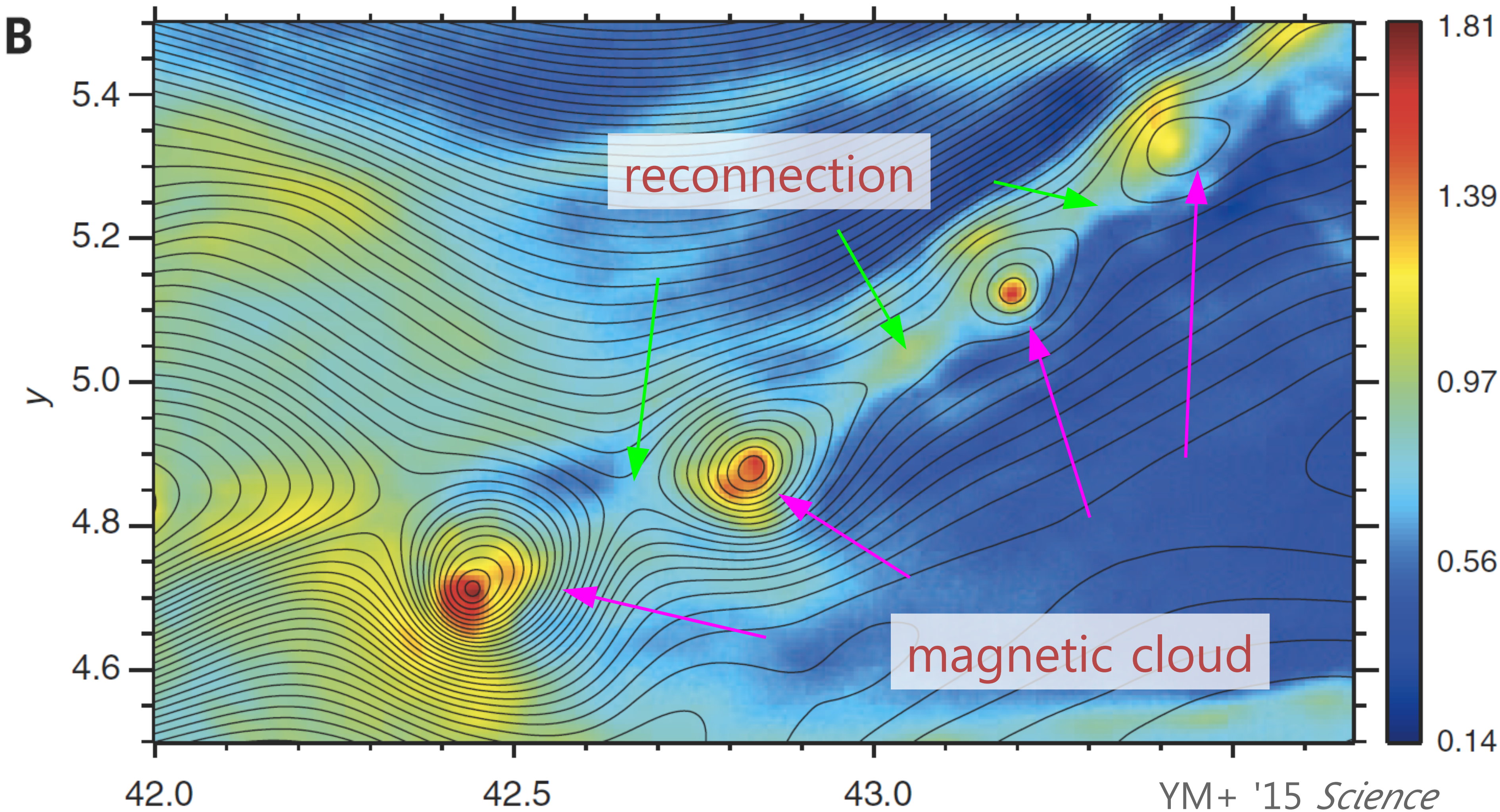
Burgess, '06



Kato & Takabe, '11

M/m=225, M_A~42 shock (in-plane **B** case)

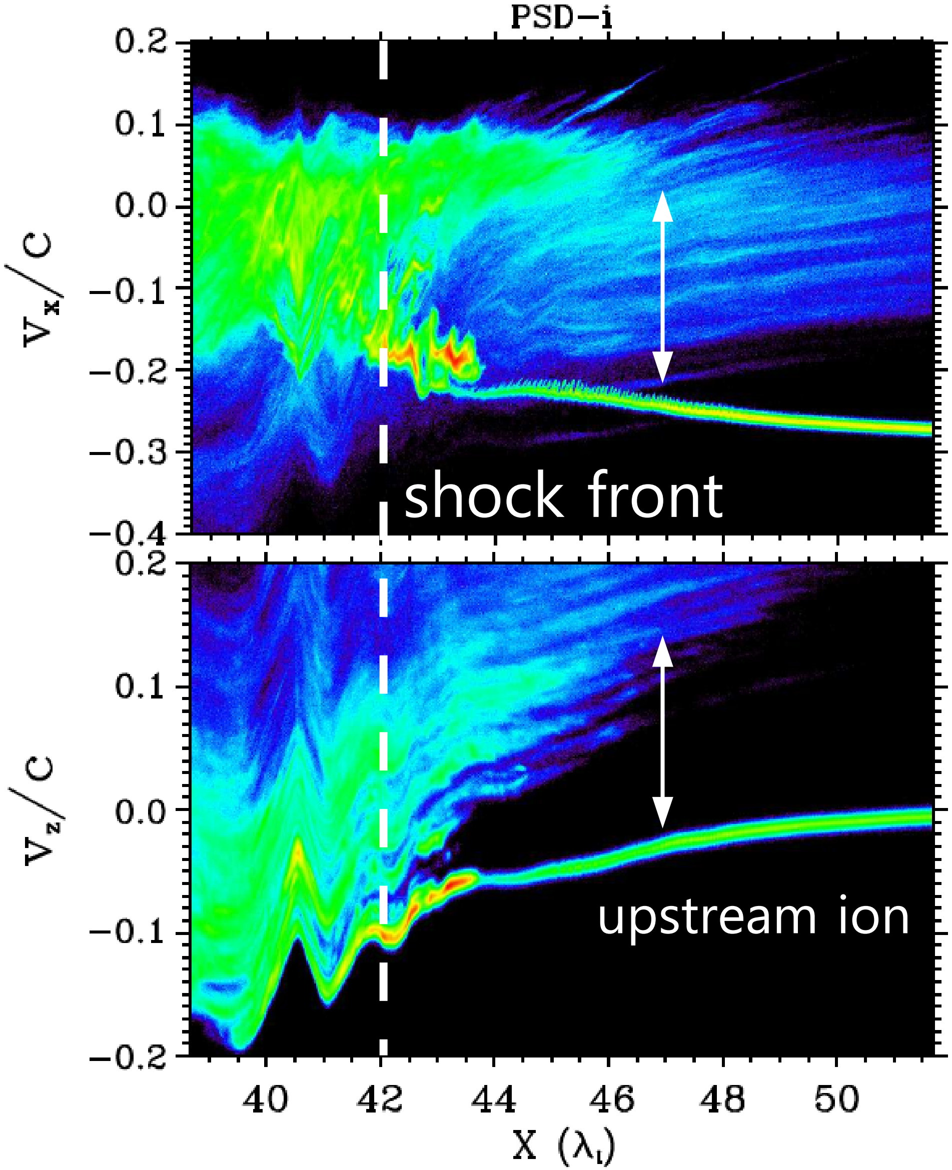
downstream $\log_{10}(N_e/N_0)$ upstream

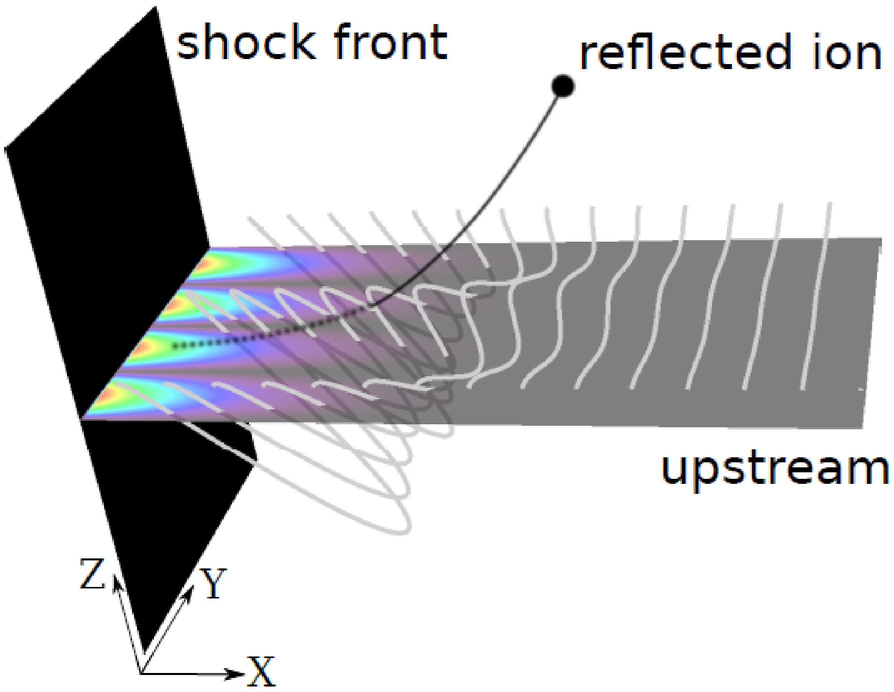


YM+ '15 *Science*

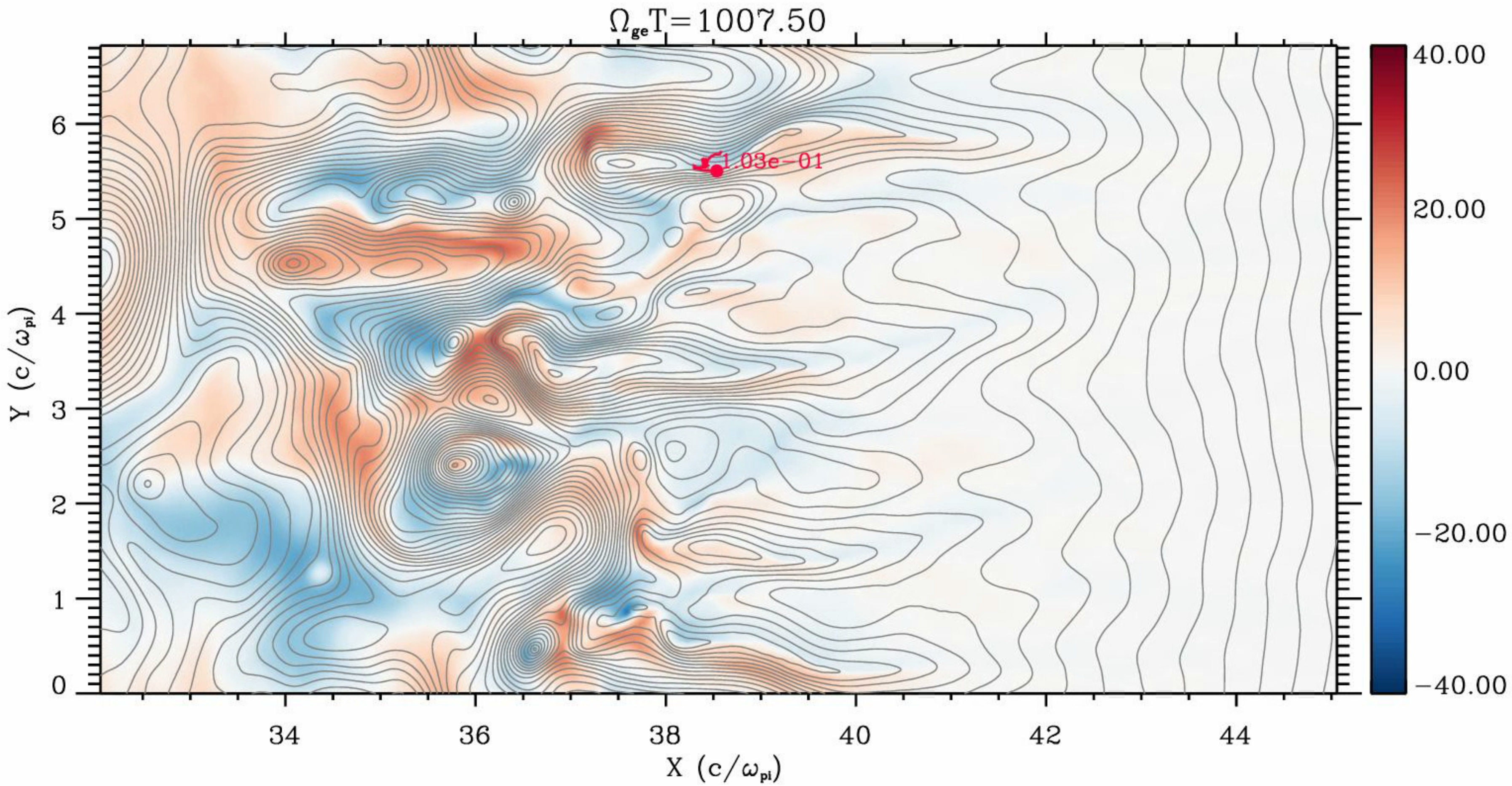
Current sheet formation via ion Weibel instability

cf. Kato & Takabe '08, '10



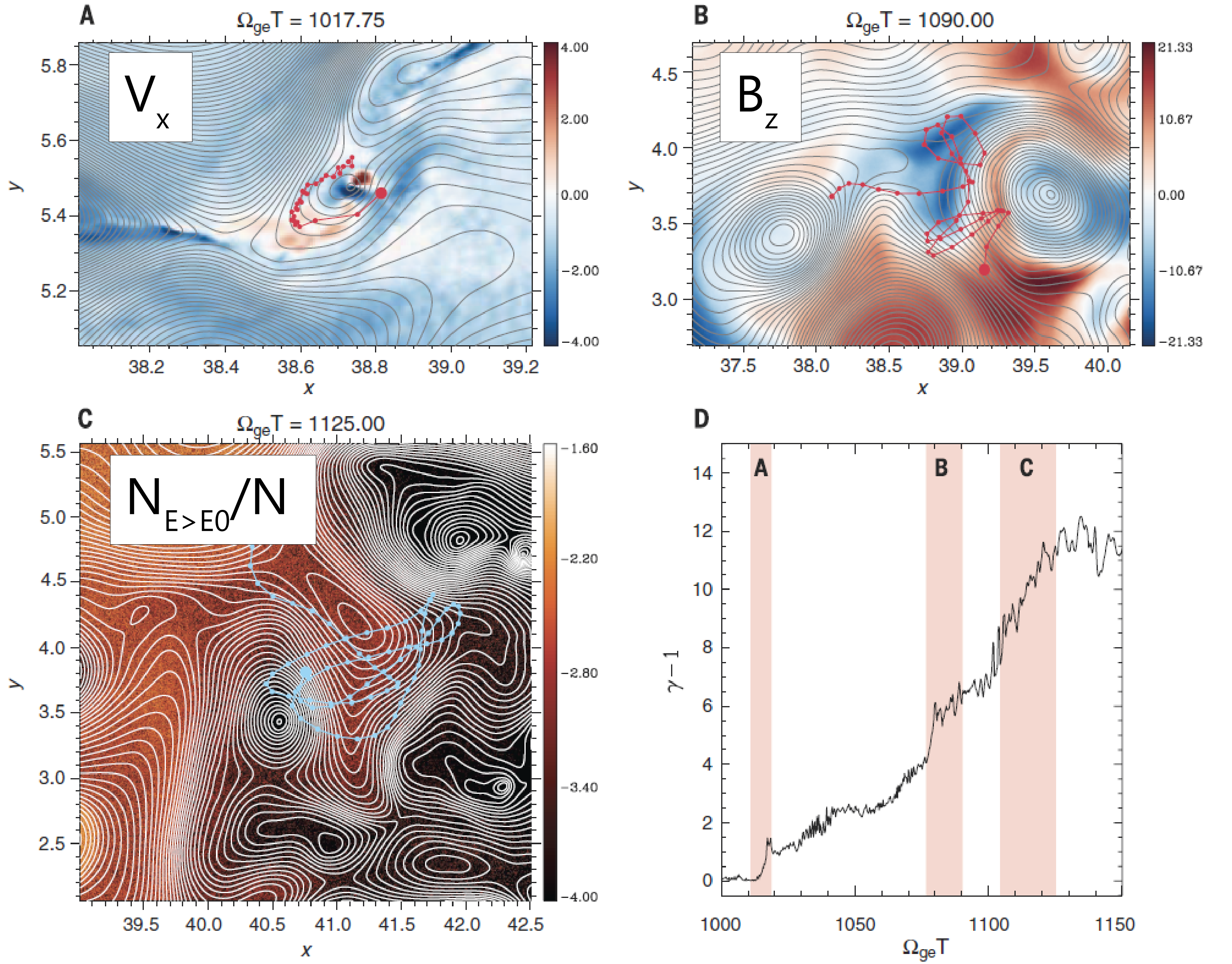


Stochastic *e* acceleration

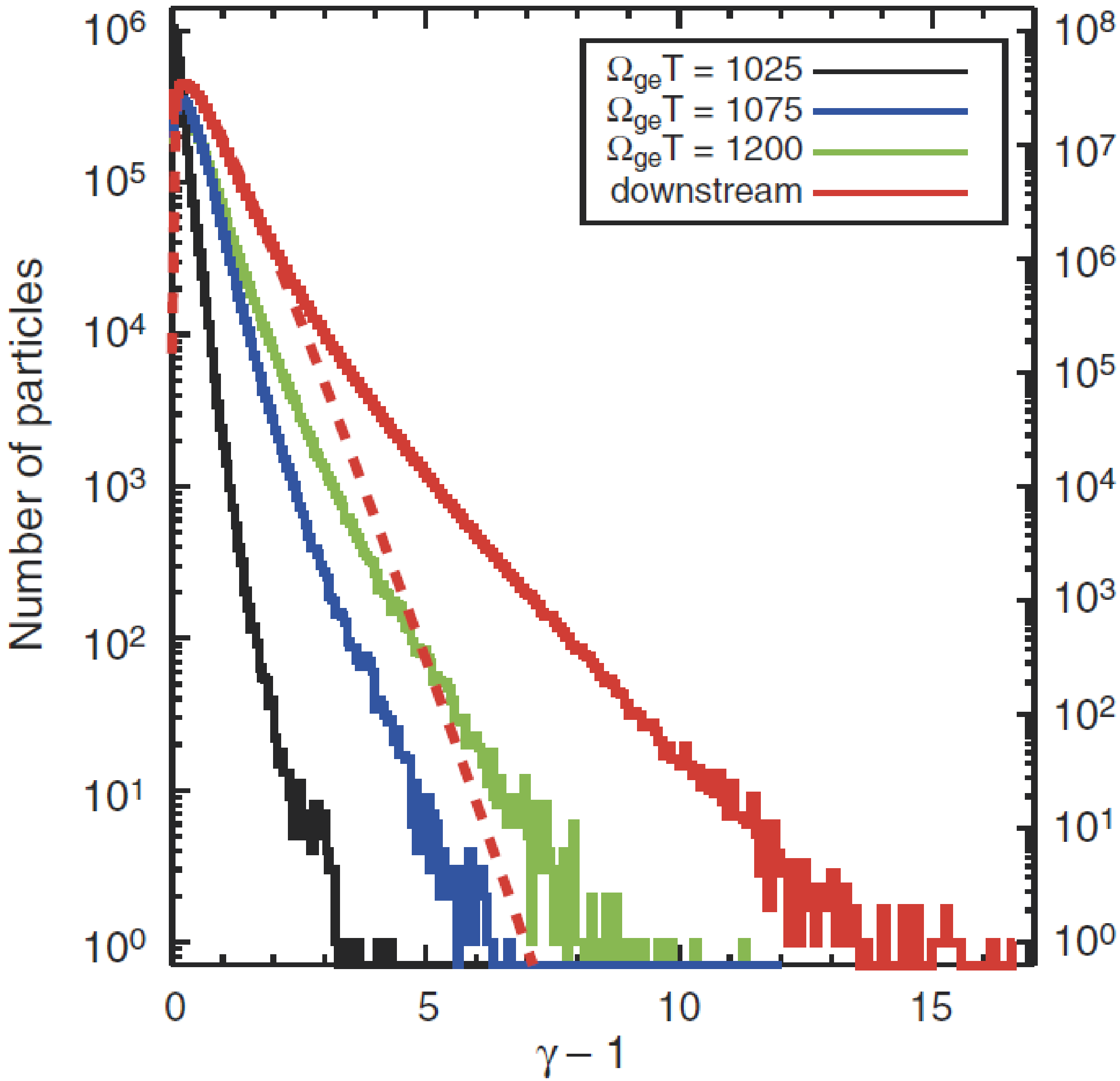


blue/red: B_z, gray: in-plane **B** field lines, circle: electron orbit

Stochastic *e* acceleration (contd.)

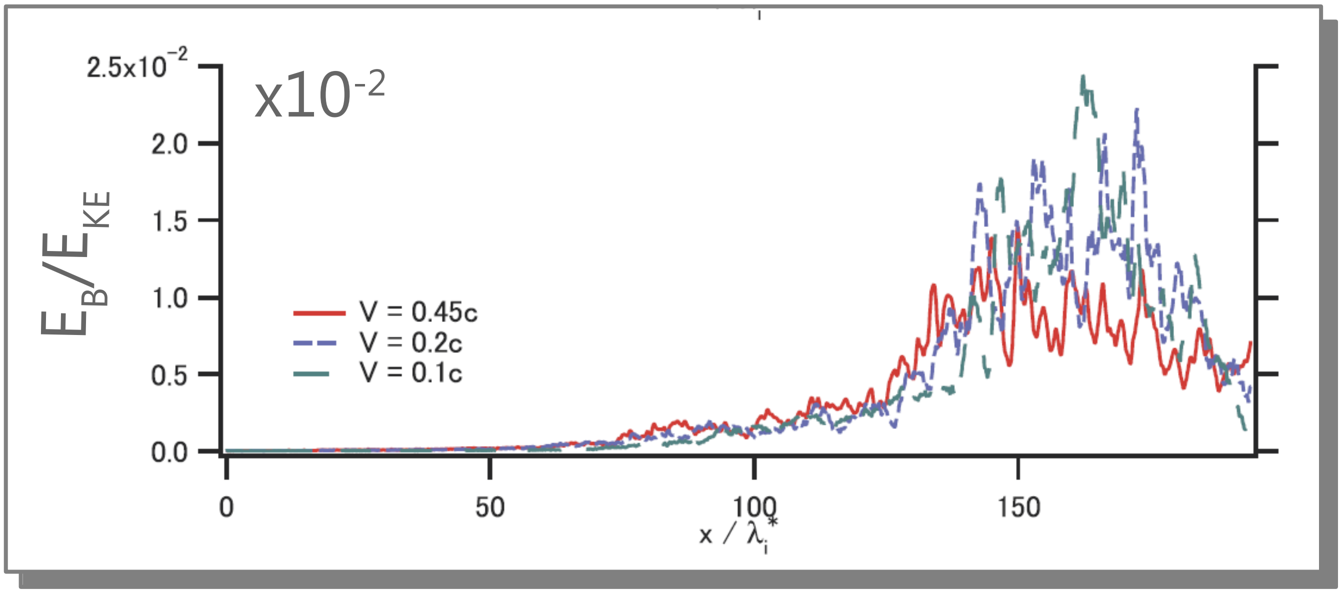


Time evolution of energy distribution



Condition for turbulent reconnection

- ion Weibel B_{iw} >> upstream B_0
- 1-2% of beam energy ($0.5\rho_0 V_0^2$) can be converted to the magnetic energy $B_{iw}/8\pi$

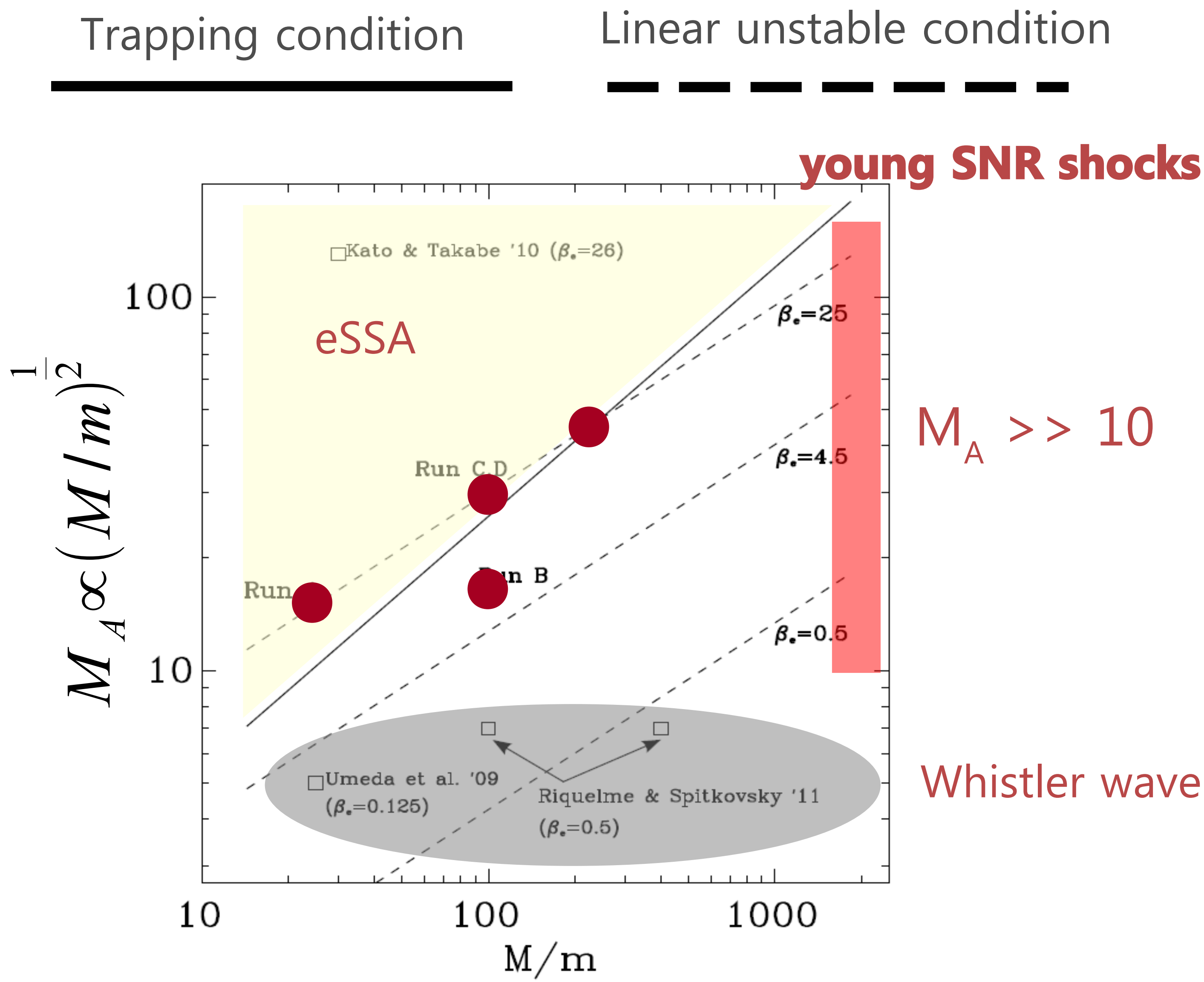


Kato & Takabe '08

$$B_{iw} \sim 0.1\sqrt{4\pi\rho_0 V_0^2} \gg B_0$$

$$M_A \gg 10$$

Electron accelerations in perp. shocks



Summary

- High-energy electrons are observationally evident, but puzzle in theory
- High performance computing helps to reveal generation of cosmic rays at astrophysical shock waves
- On-going 3D PIC simulations are promising!
- Hopefully, hadron/lepton accelerations to collaborate with IceCube