無衝突衝撃波における電子加速の
最先端PICシミュレーション
State-of-the-arts PIC simulations of electron accelerations at collision-less shocks

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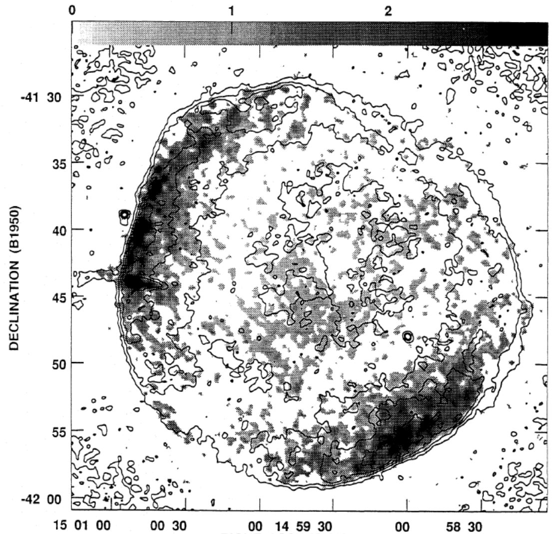
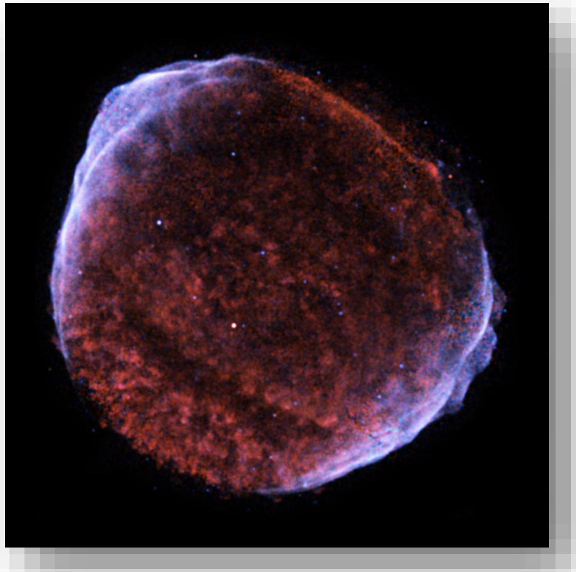
Shock waves in the universe

radio

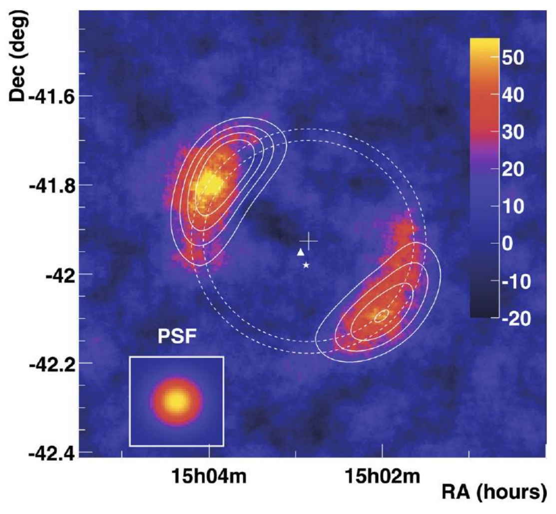


Reynolds+ 93

Chandra
X-ray



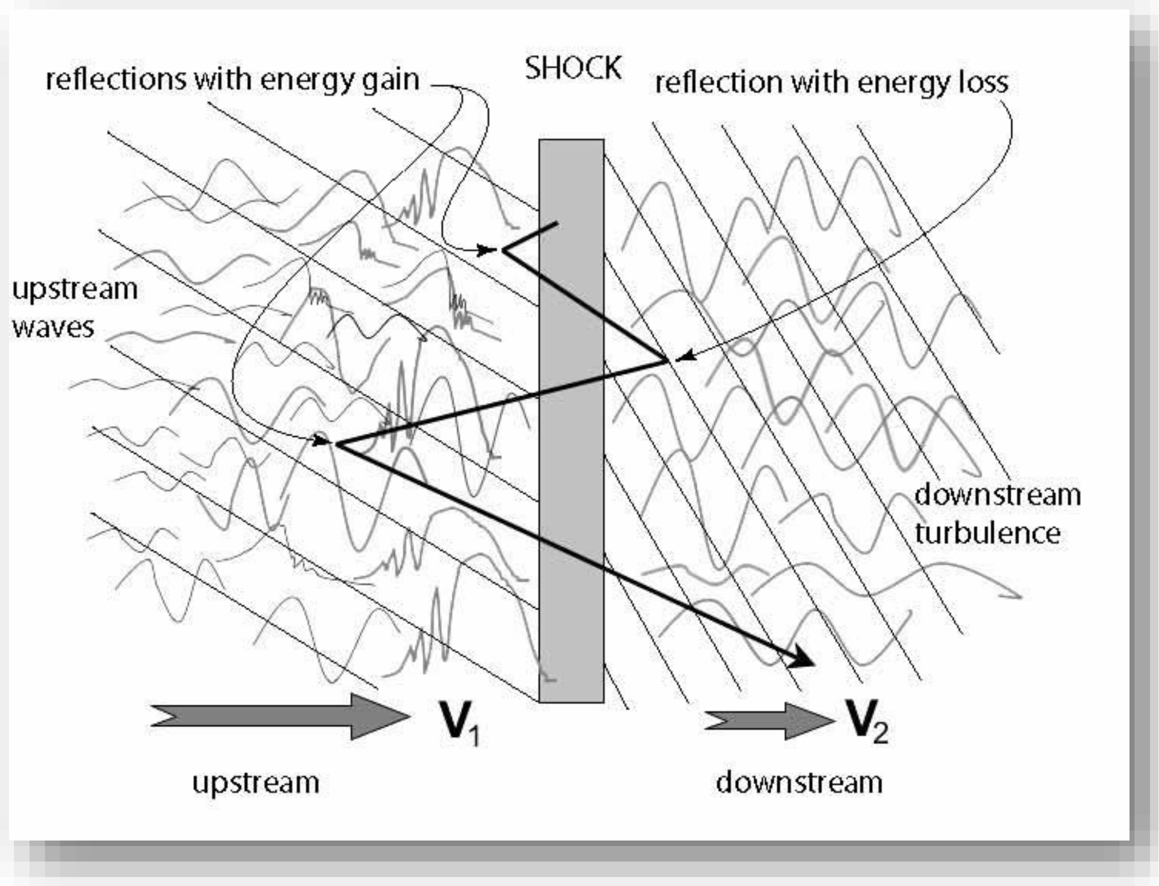
γ-ray



HESS collaboration 10

Evidences for relativistic electrons up to TeV energies at SNR shocks

Diffusive Shock Acceleration (DSA)



Treumann & Jaroschek 08

- ☐ Electron injection problem
  - ✓ No scattering bodies for thermal electrons
  - ✓ Alfven waves : only for protons
  - ✓ Whistler waves? (Amano & Hoshino ’10; Riquelme & Spitkovsky '11)
  - ✓ Thermal electrons are strongly magnetized
  - ✓ Shock scale $L \sim \alpha\lambda_i >> r_{ge}$
  - ✓ Pre-accelerations for electrons are necessary
- ☐ We try to resolve this issue from the first principle of collision-less plasmas

Particle-in-Cell simulation

Vlasov eq. as particle motions

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

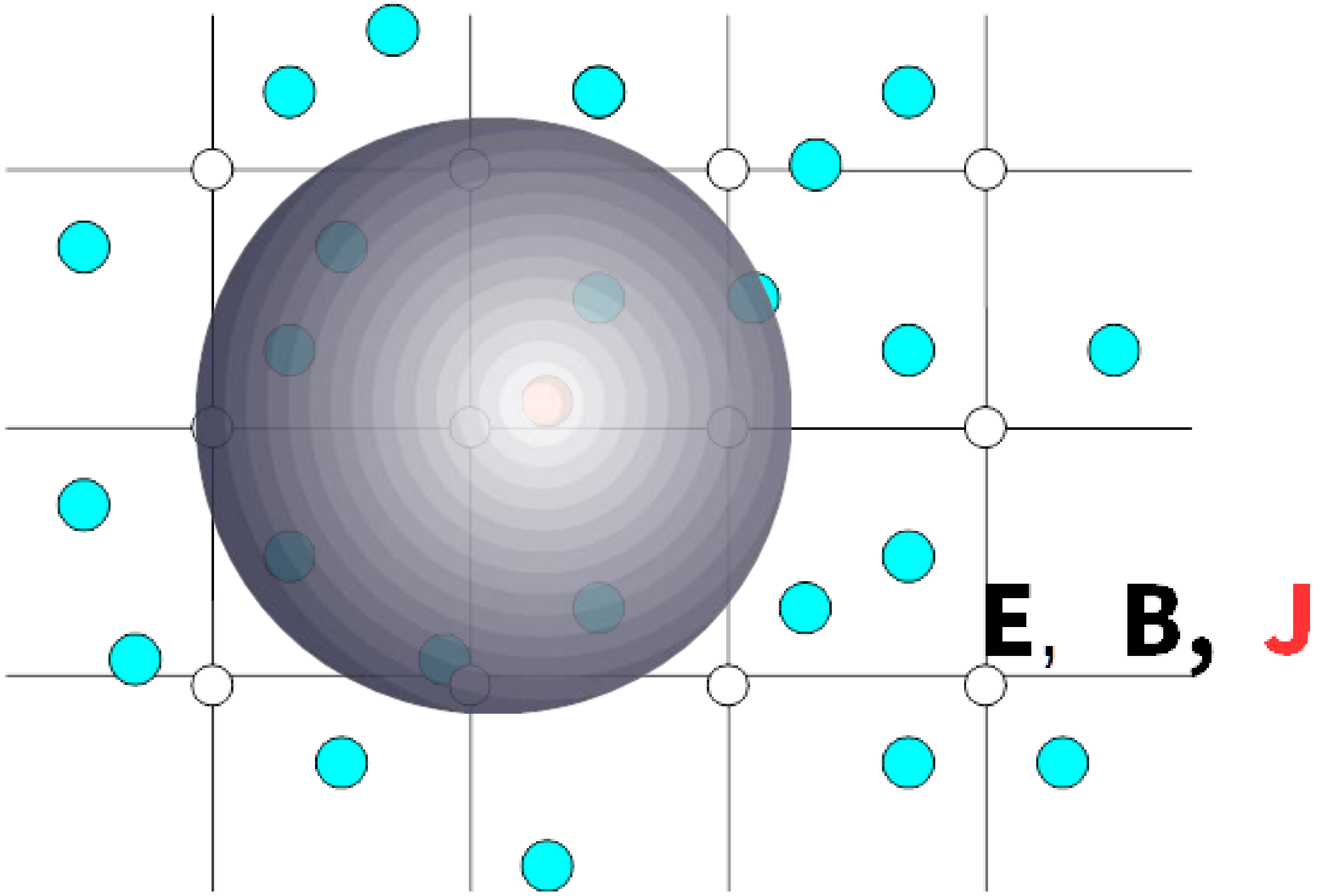
$$\frac{d\boldsymbol{u}_p}{dt}=\frac{q}{m}\left(\boldsymbol{E}+\frac{\boldsymbol{u}_p}{c\,\gamma_p}\times\boldsymbol{B}\right)$$

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

Maxwell eqs. on grid points

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

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



Characteristic scales in PIC simulations

- Δh ~ Debye 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 $\omega_{pe}{}^{-1}$

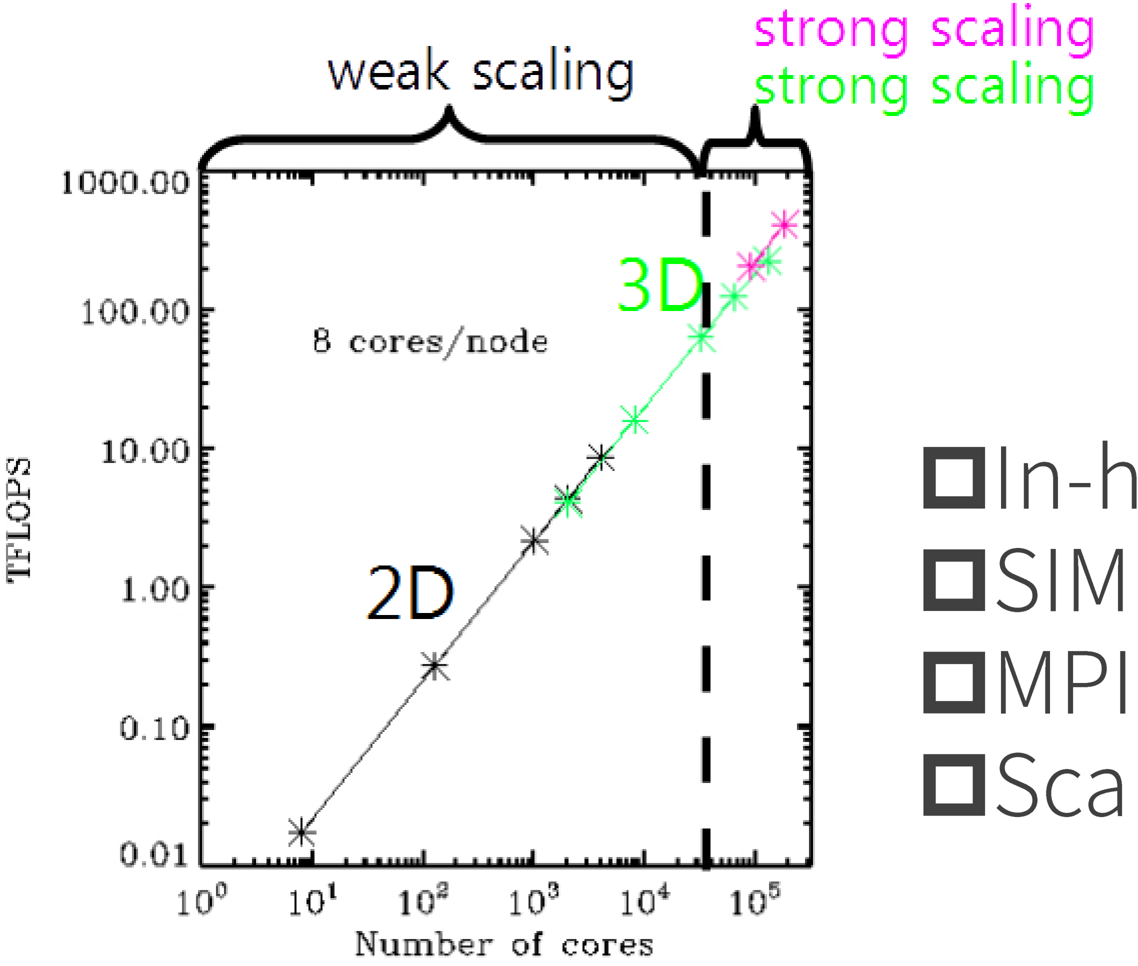
$$\omega_{pe}^{-1}[sec]=\frac{1}{9}\left(\frac{1}{n[cm^{-3}]}\right)^{\frac{1}{2}}10^{-3}$$

- Proton-to-Electron mass ratio M/m

M/m = O(100) <-> 1836

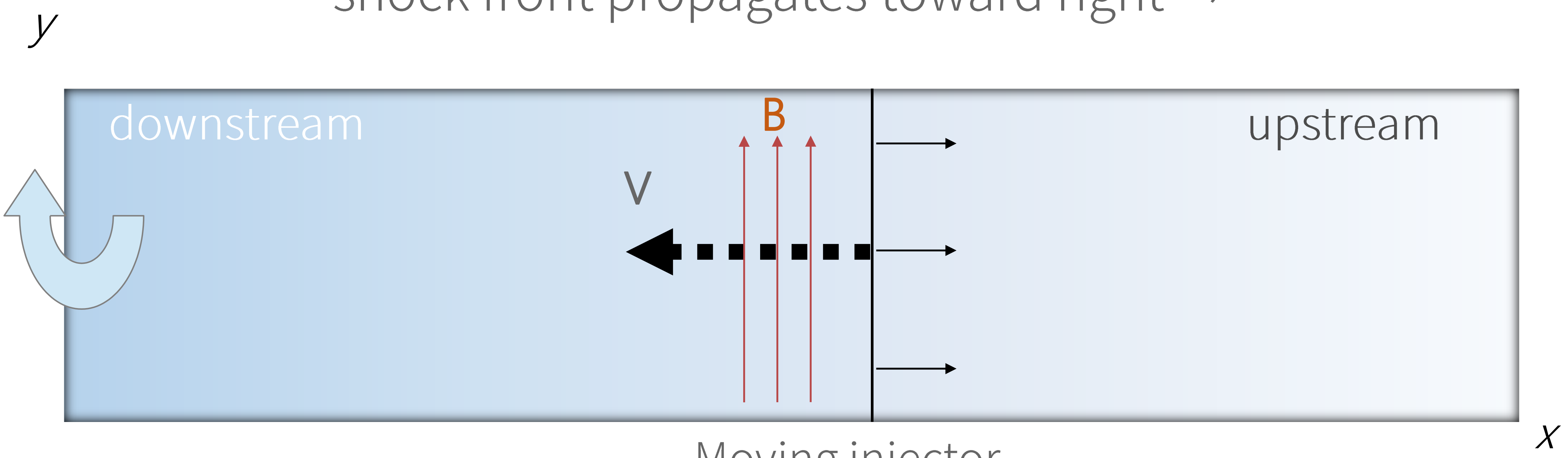
parsec and $10^{2\text{-}6}$ yrs in astrophysics! 😭

Shock experiments on supercomputer systems



☐In-house 2D/3D particle-in-cell code
☐SIMD-optimization
☐MPI+OpenMP hybrid parallelization
☐Scalable to ~10^5 cores

Shock creation - Injection method



Moving injector
(Sironi & Spitkovsky '09)

TRISTAN-PIC vs. others

Computational resources

$\sigma = M_A^{-2}$

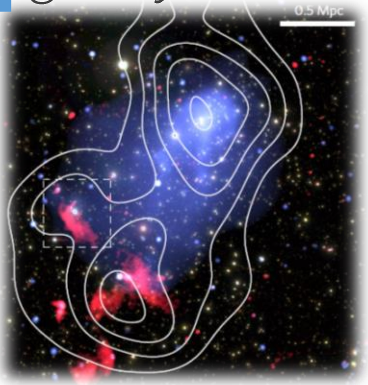
1

weak shock

strong shock

0

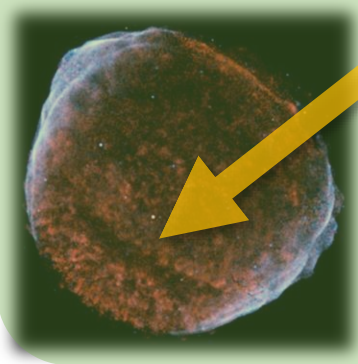
galaxy cluster



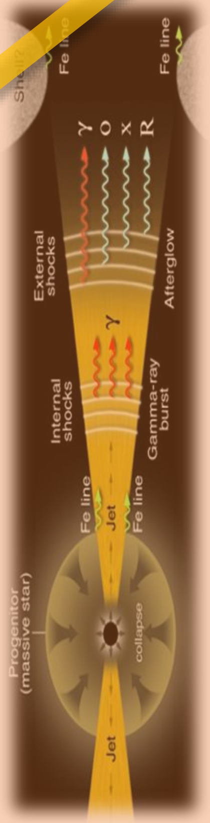
Weeren+ 2017

Matsukiyo+ 2011
Riquelme & Spitkovsky 2011
Guo+ 2014a,b
Matsukiyo & YM 2015
(and many more in solar-terrestrial physics)

SNR shock



Kato+ 2010; 2015
YM+ 2012; 2013;2015; 2017
Niemiec+ 2012; 2013
Park+ 2015
Wieland+ 2016



Meszaros 2001

relativistic shock

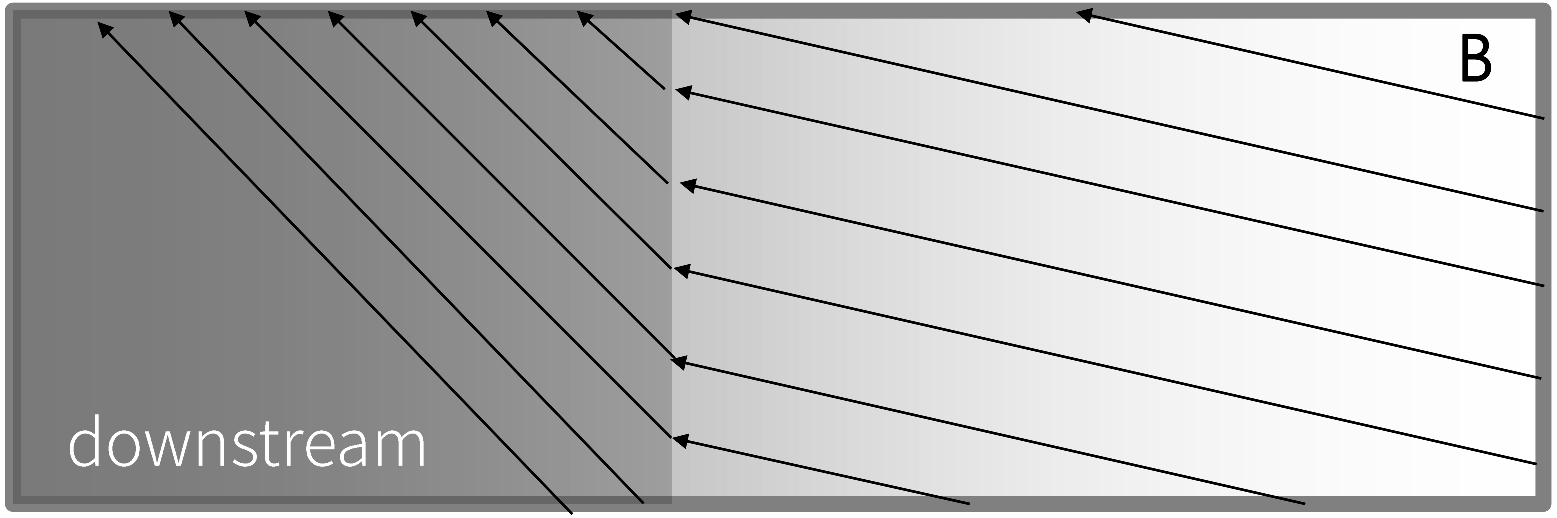
Kato 2007
Spitkovsky 2008
Hoshino 2008
Sironi+ 2009; 2011; 2013
Ikeya & YM 2015
Ardaneh+ 2016
Tomita & Ohira 2016
Iwamoto+ 2017

Non-relativistic ← - - - - - - - - - → relativistic 1

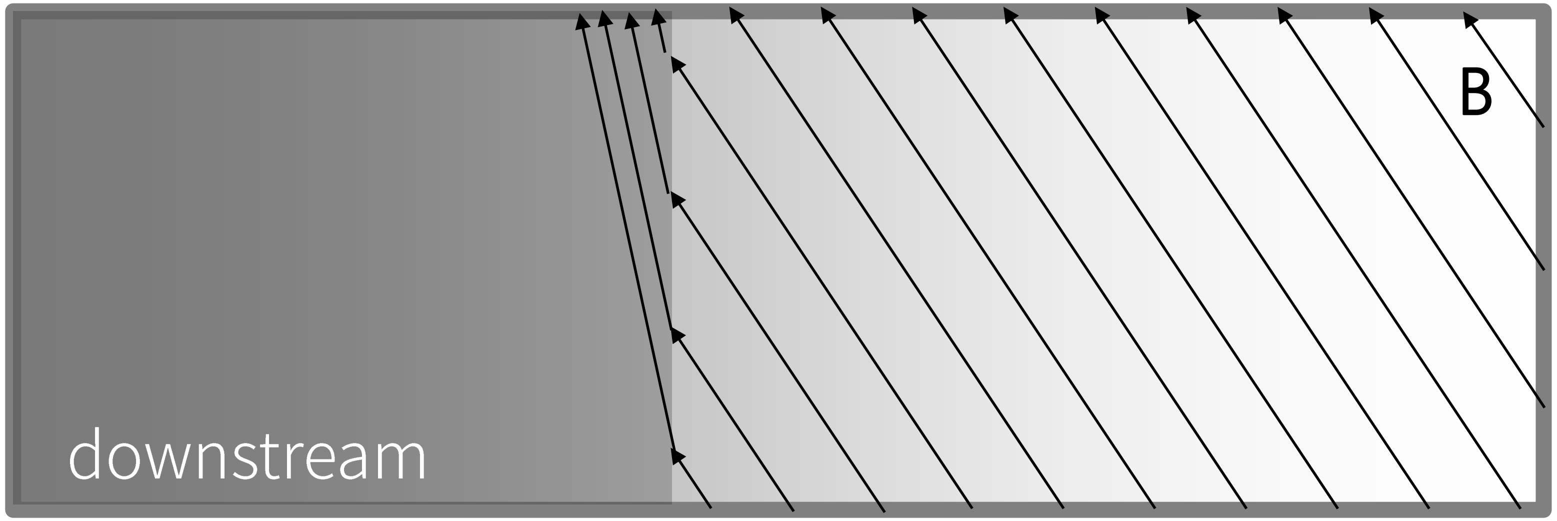
V_{shock}/c

Parallel / Perpendicular shocks

Parallel shock (Θ_{Bn} < 45 deg.)

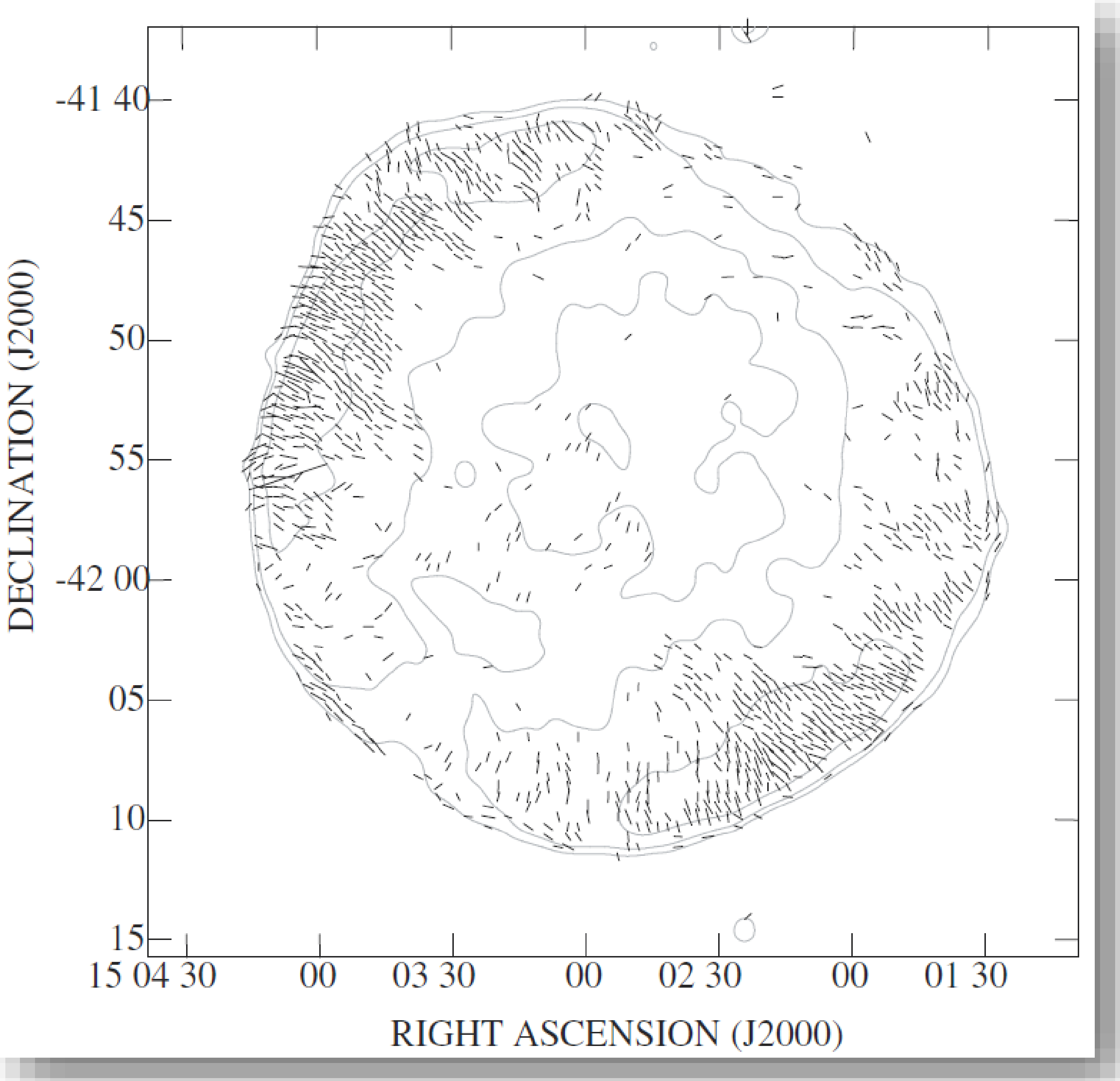


Perpendicular shock (Θ_{Bn} > 45 deg.)



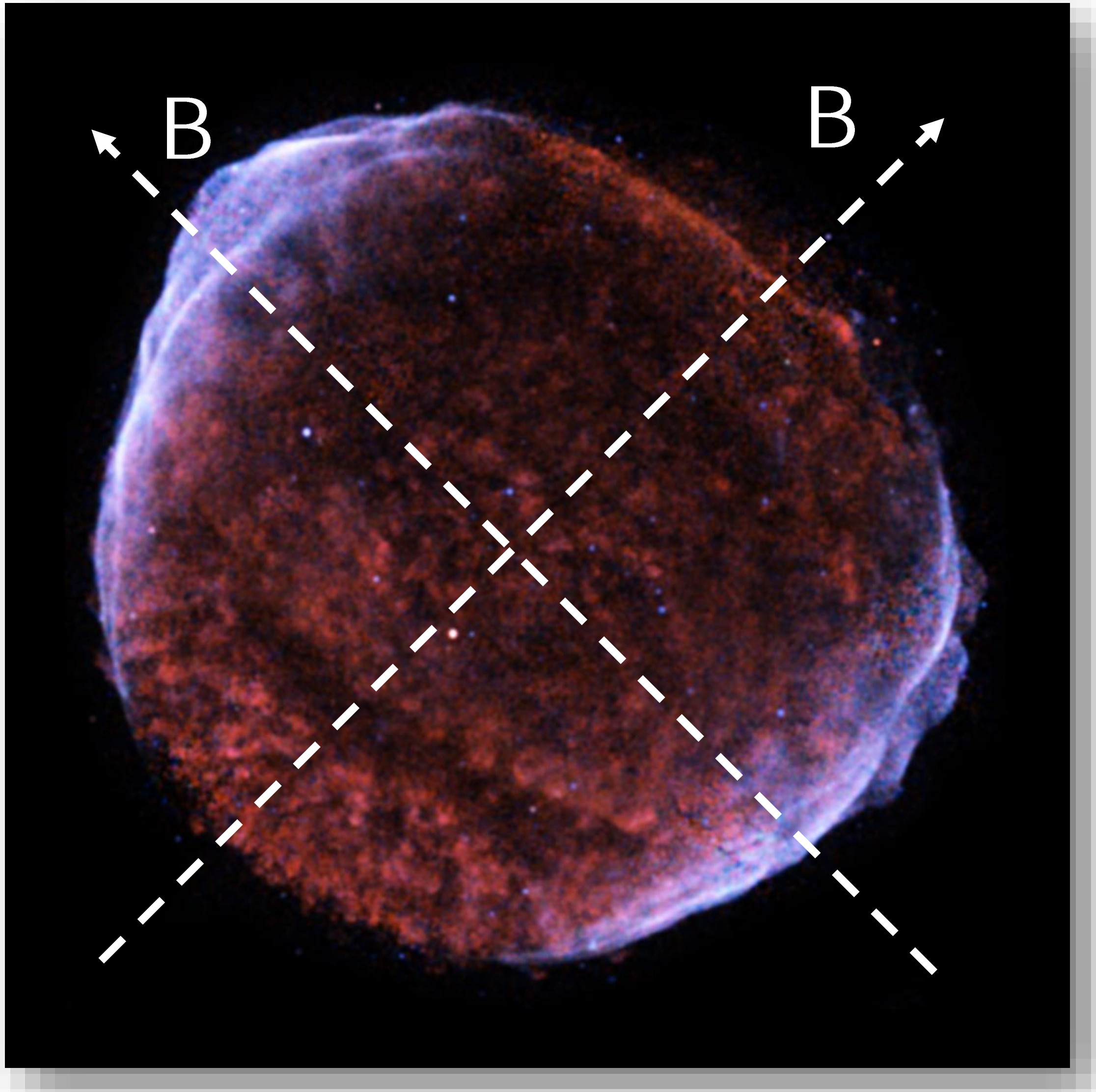
// or ⊥ shock?

Radio polarization observation (magnetic field)



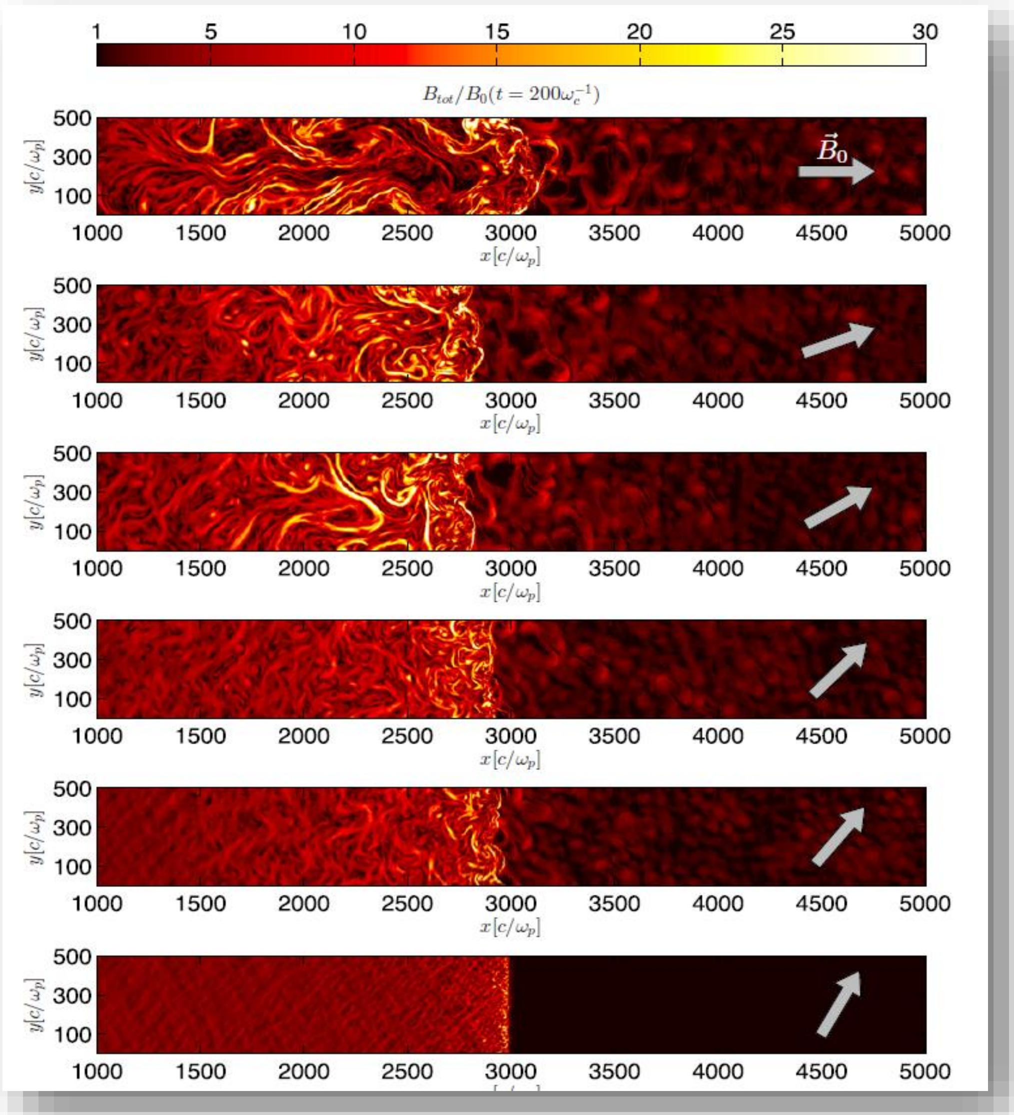
Reynoso+ '13

X-ray observation (relativistic electrons)

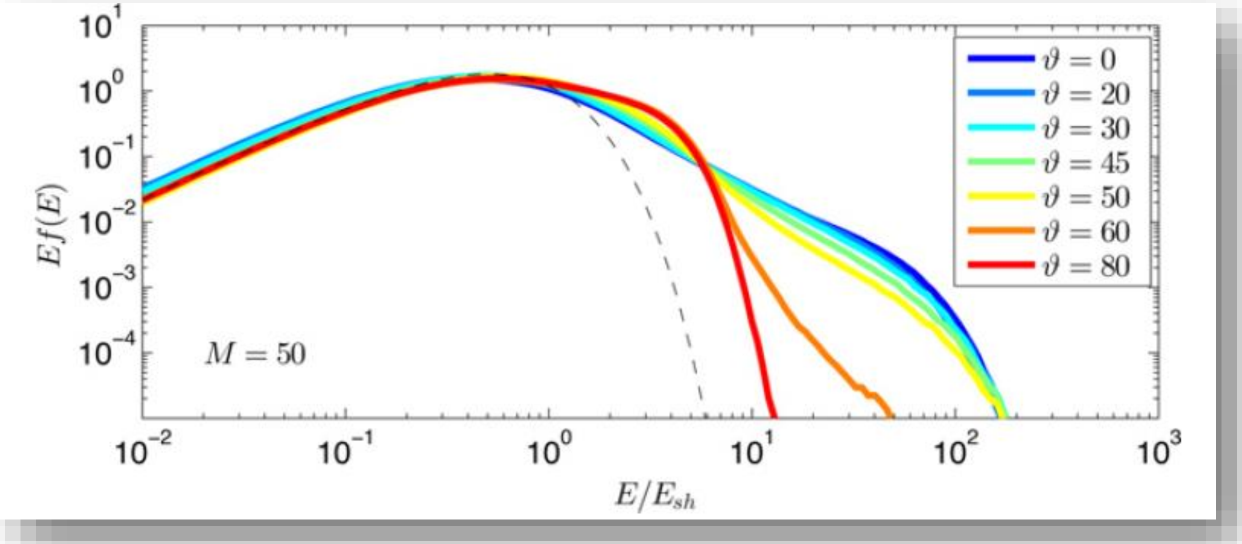


Chandra X-ray observation

p^+ accelerations in // shocks

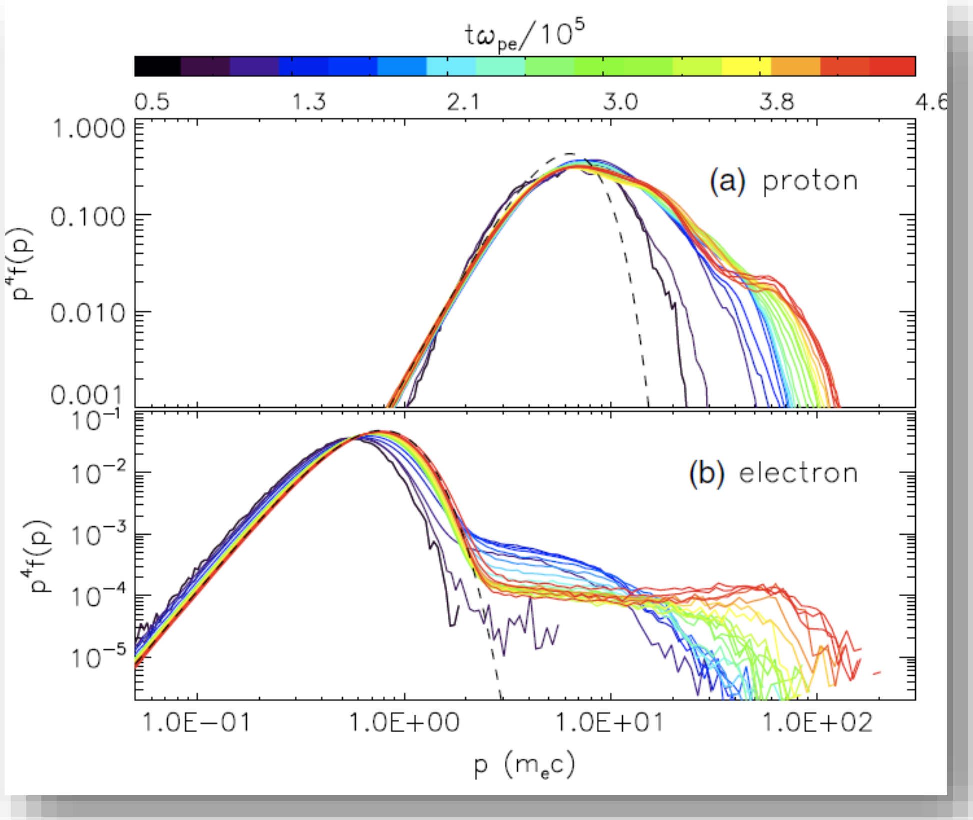


Capriori & Spitkovsky 14

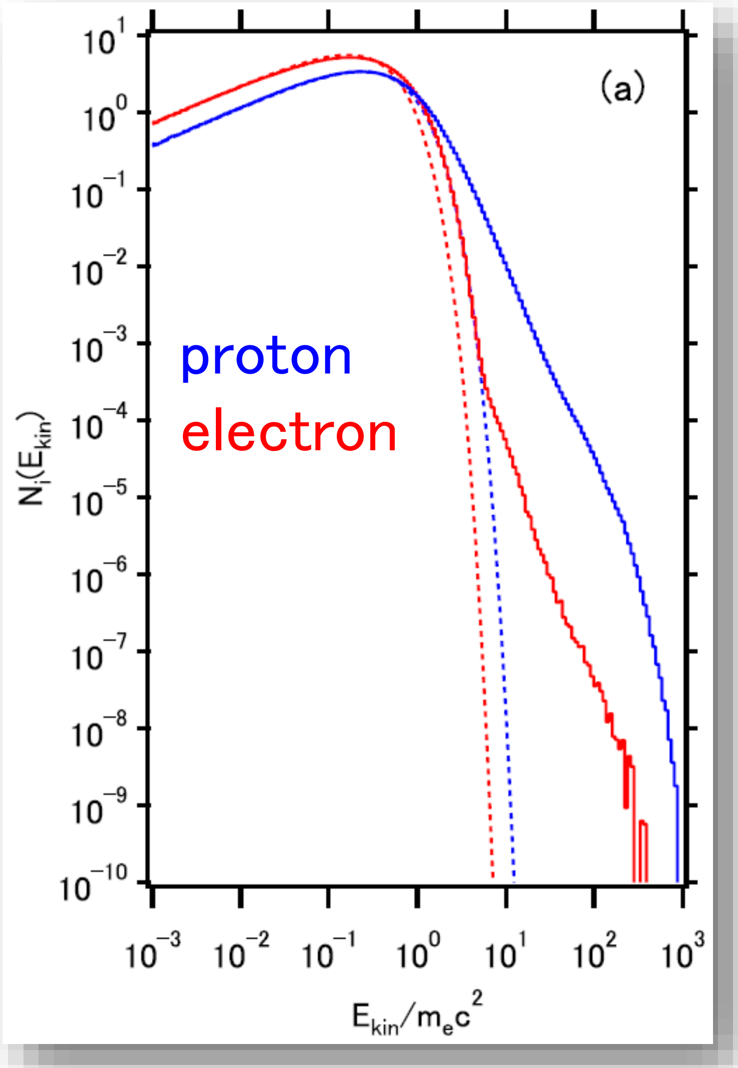


- ☐ 2D hybrid simulation (particle ions & mass-less electron fluid)
- ☐ DSA works well for quasi-parallel shocks
- ☐ Spectral index followed DSA theory ($f(p) \sim p^{-4}$)

e^- accelerations in // shocks



Park+ 15 PRL



Kato 15 ApJ

☐ 1D PIC simulations
☐ Both p^+ & e^- accelerations
☐ Electron injection: SDA
☐ Shown only recently

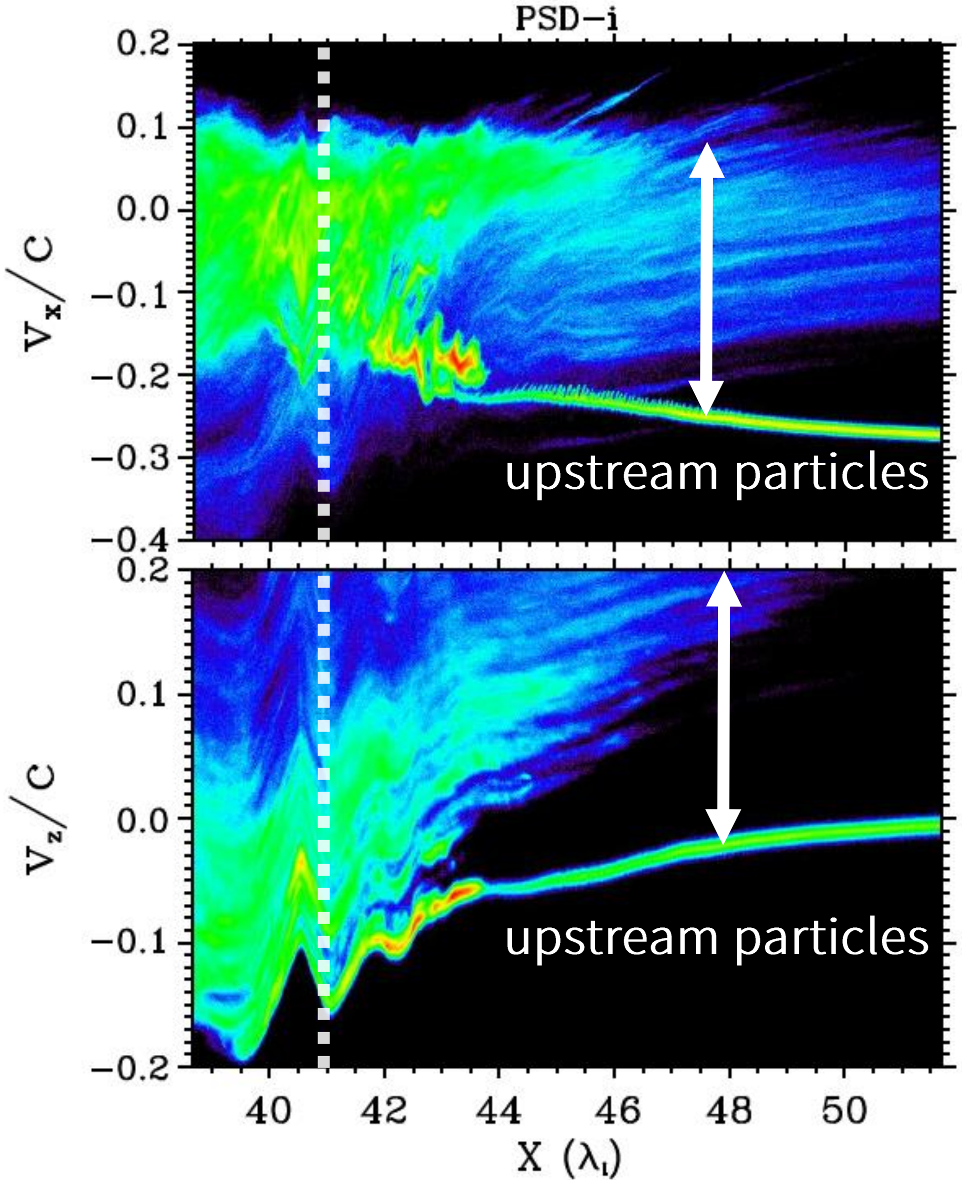
Current understanding of shock accelerations from PIC simulations

	Parallel shocks	Perpendicular shocks
p^+	Yes 1D PIC simulations & 2D-3D hybrid simulations	NO From hybrid simulations (Yes, if charge exchange effects were included, cf. Ohira 13; 16)
e^-	May be possible but still controversial Only from 1D PIC simulations in 2015	Today's talk

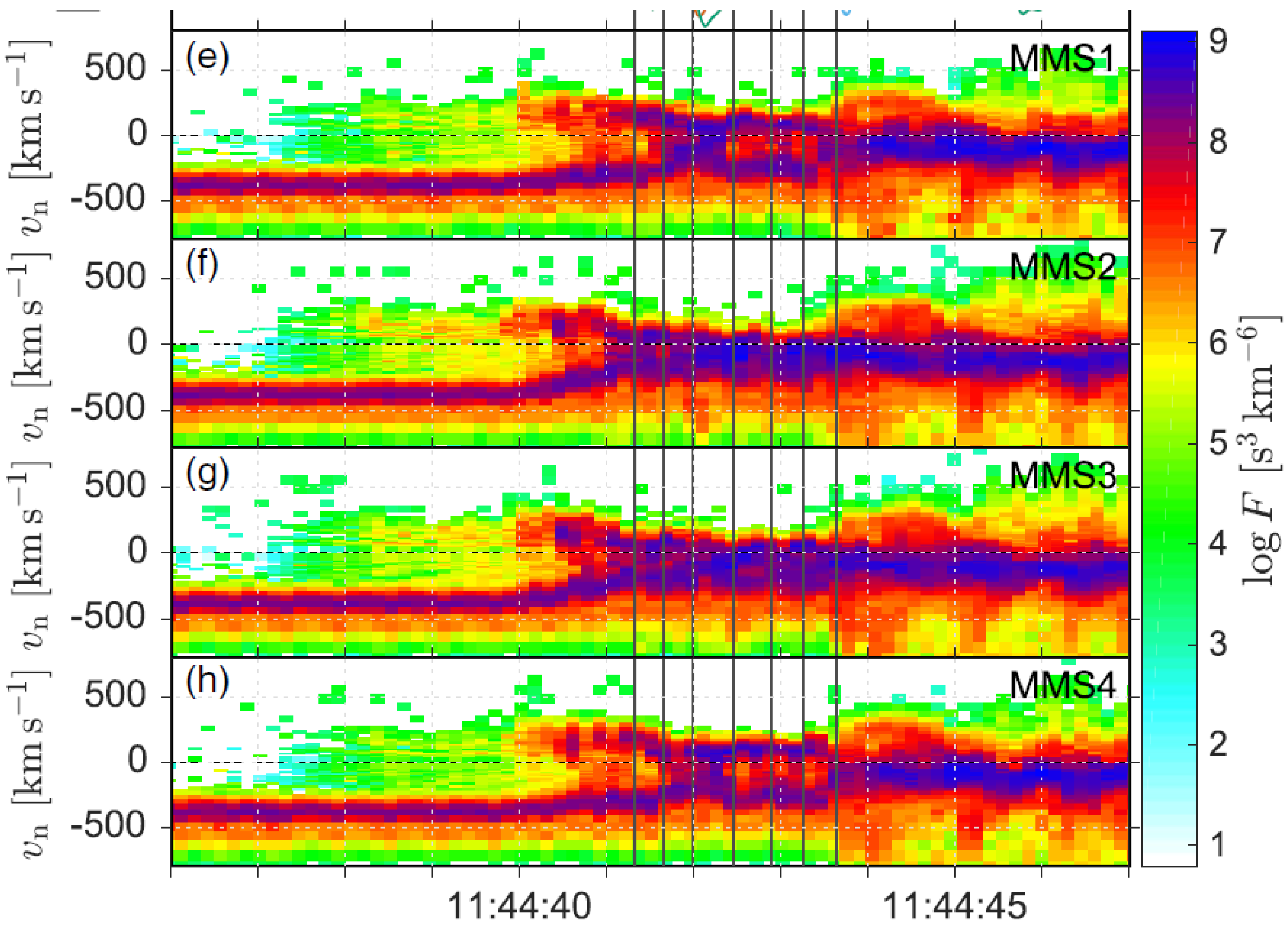
Today's talk concerns

- ☐ High Mach number shocks
  - ✓ applications to SNR shocks
- ☐ Electron accelerations
  - ✓ implications to synchrotron radio & X-ray, TeV γ-ray emissions
- ☐ Perpendicular shocks
  - ✓ no theory for electron DSA so far

Energy dissipation in the shock transtion

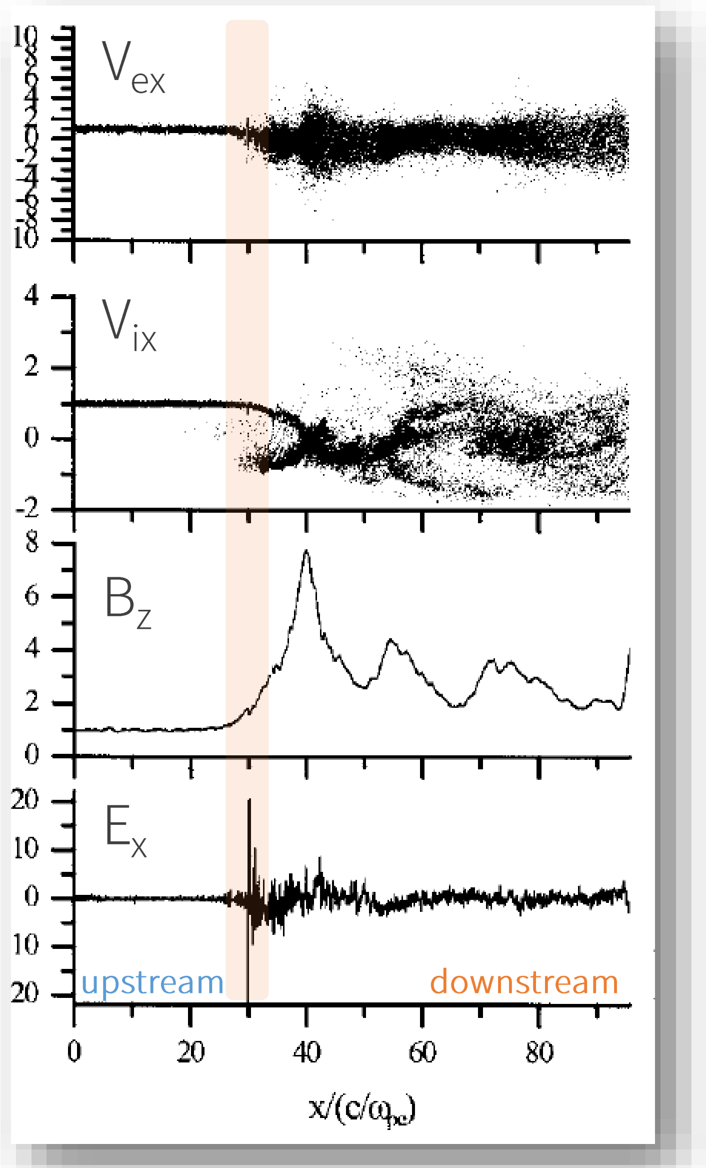


In-situ observations of the bow shock

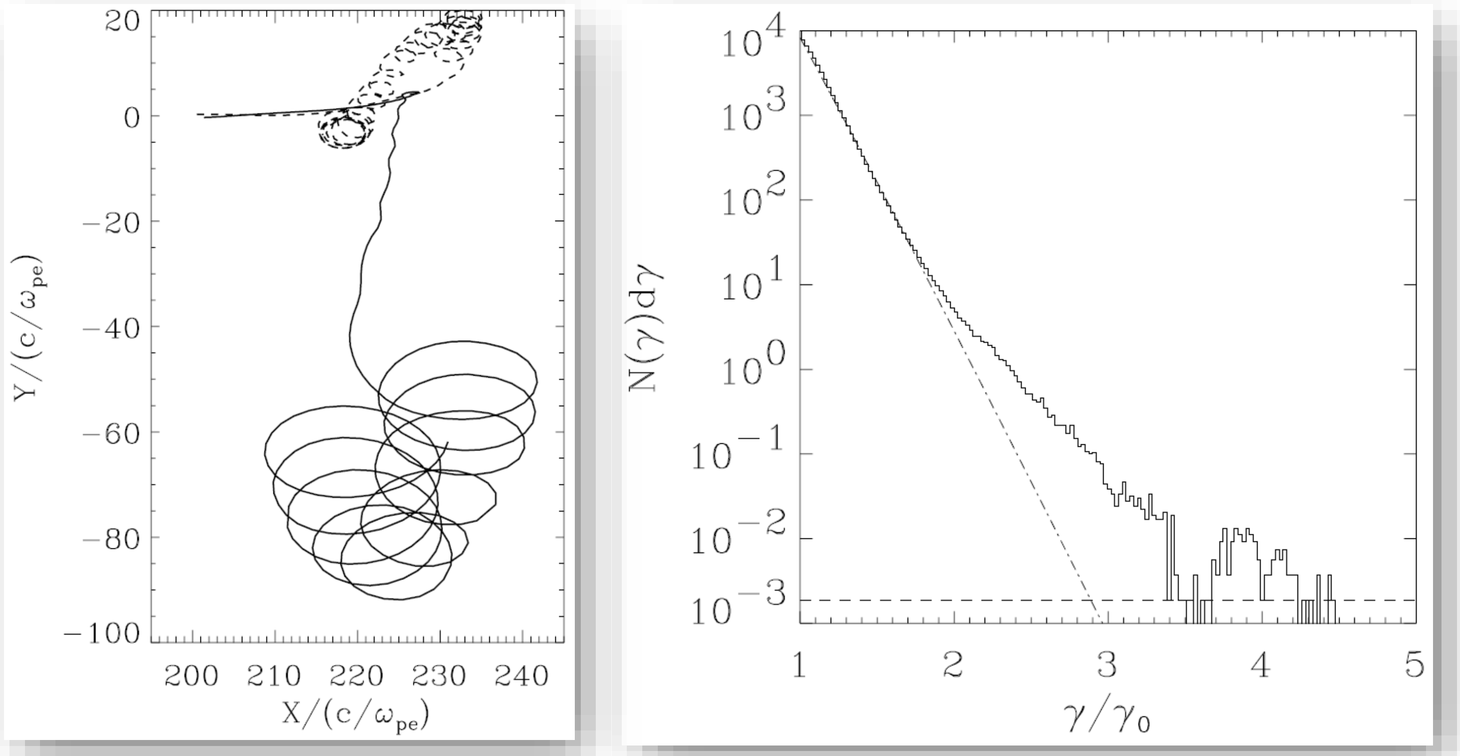


Johlander+16 PRL

Electron SSA



Shimada & Hoshino 00



Hoshino & Shimada 02

Linear unstable condition of BI

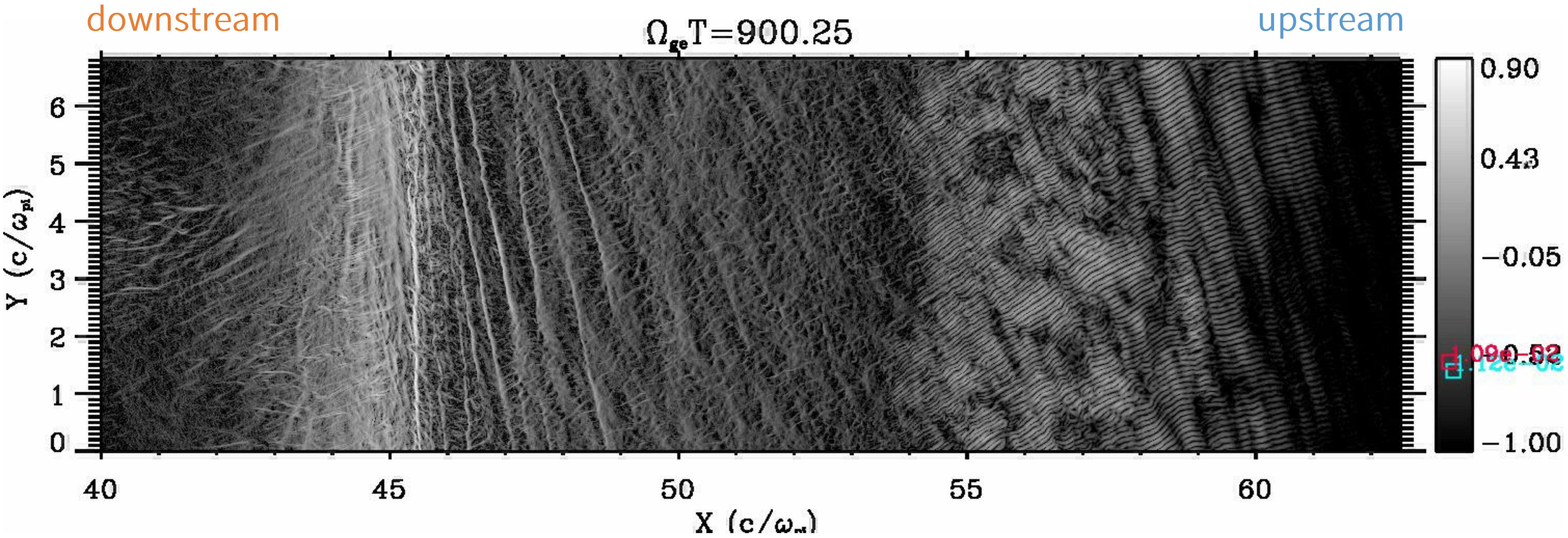
$$M_A > \sqrt{\beta_e}\sqrt{\frac{M}{m}} \sim 43$$

Trapping condition for relativistic particles

$$M_A > \left(\frac{M}{m}\right)^{\frac{2}{3}} \sim 150$$

Matsumoto+ 12

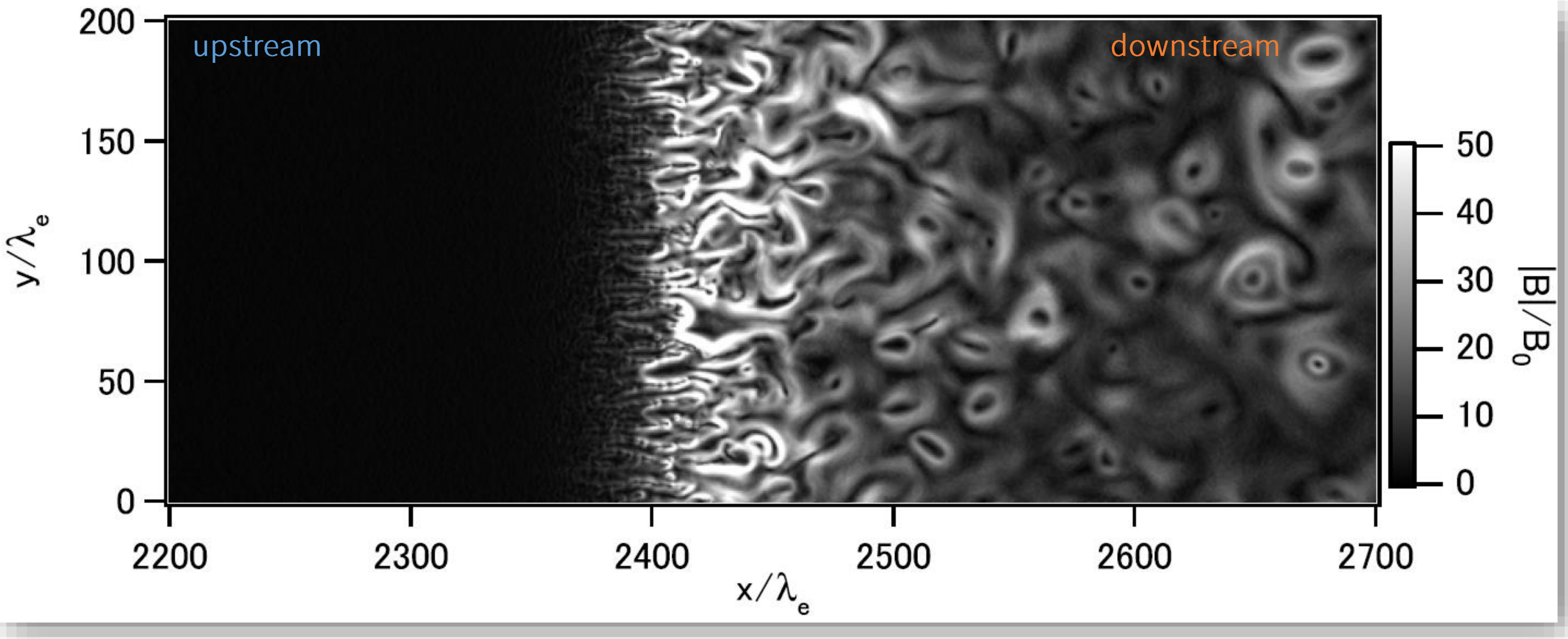
eSSA in two dimensions with M/m=225, M_A~44



Matsumoto+ 13 PRL
See also Amano & Hoshino 09

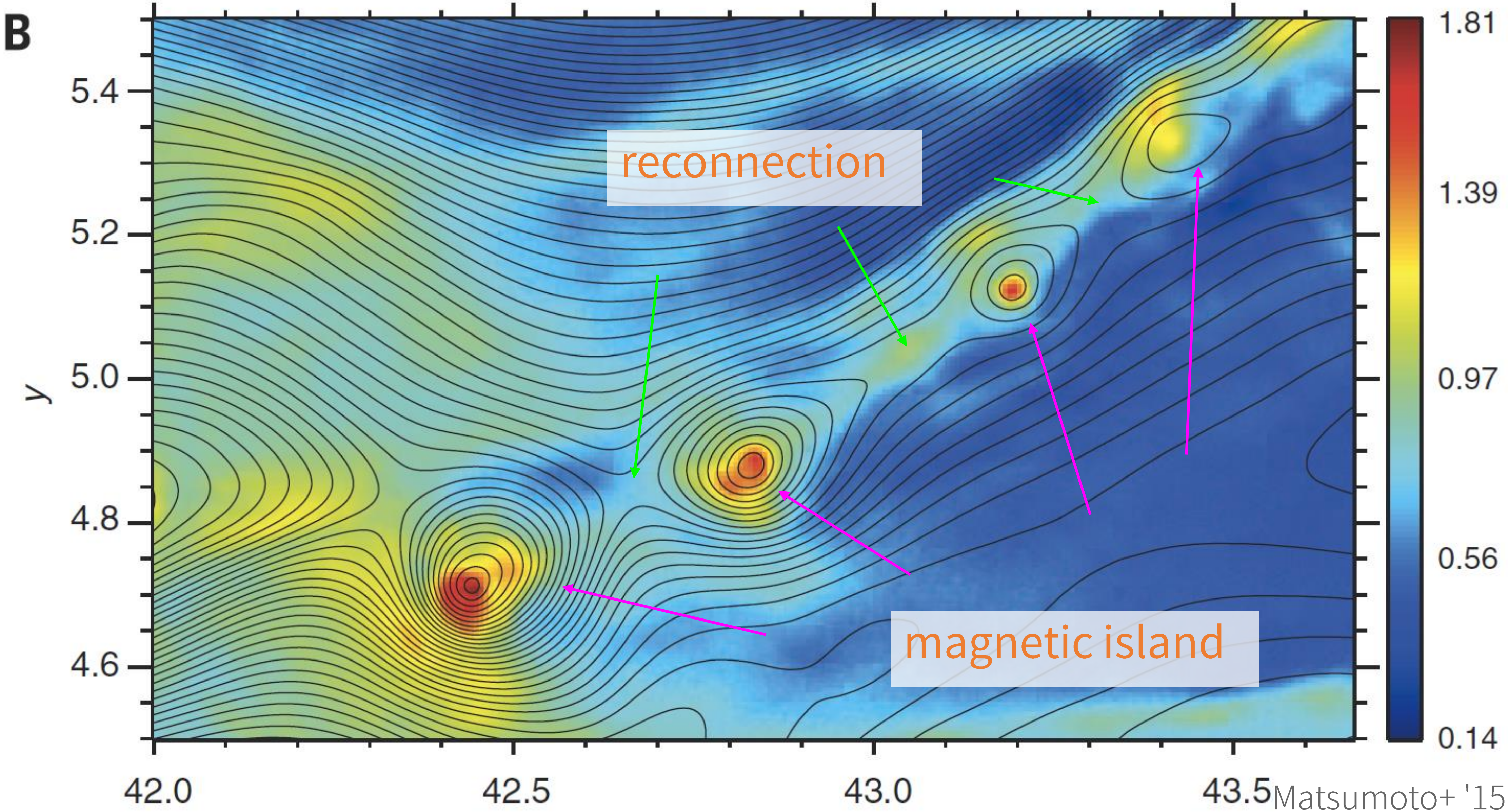
gray: electrostatic field strength , squares: electron orbits

Ion Weibel instability in the shock transition region



Kato & Takabe 10

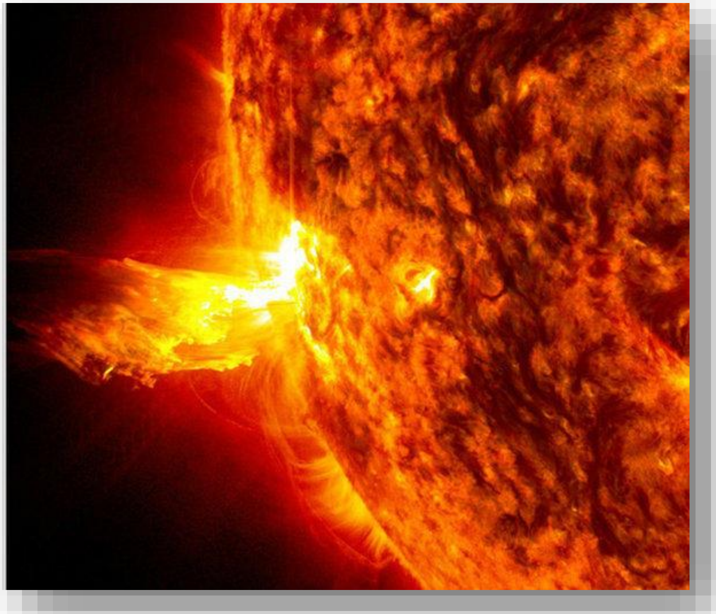
Ion Weibel Shock revisited with $M/m=225$, $M_A \sim 42$



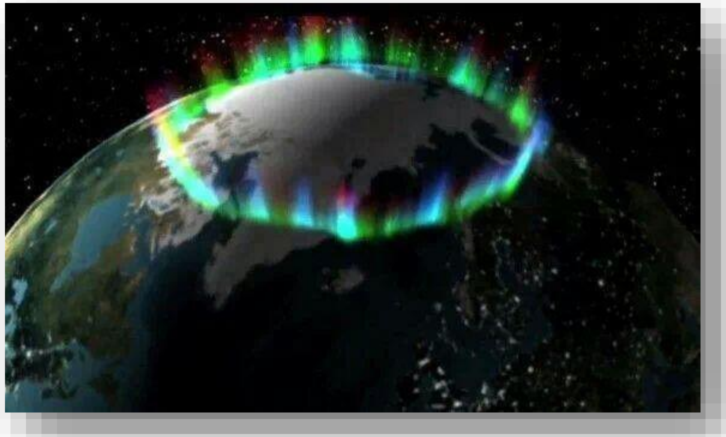
Matsumoto+ '15 *Science*

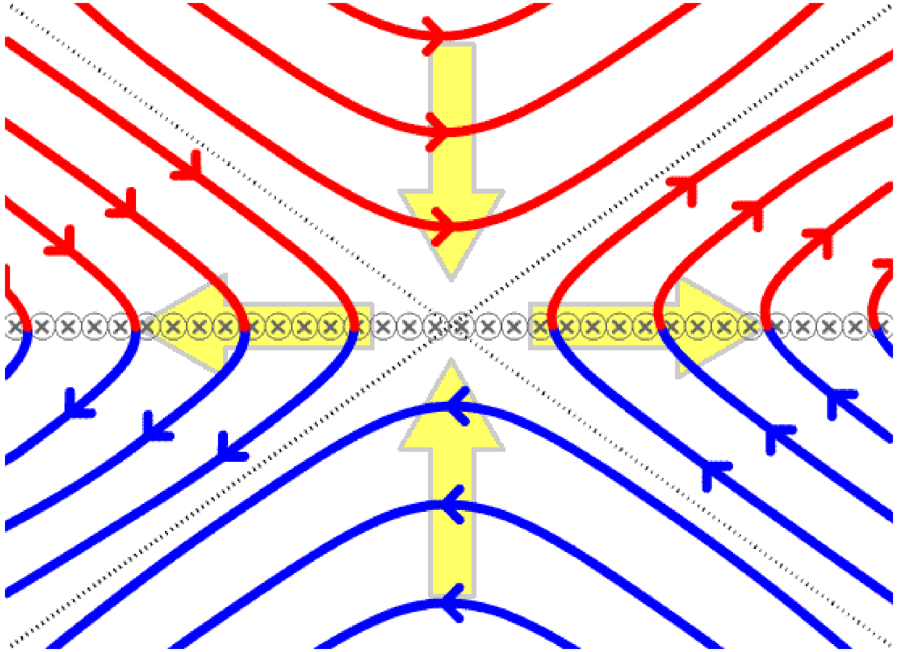
Magnetic reconnection

Solar Flare



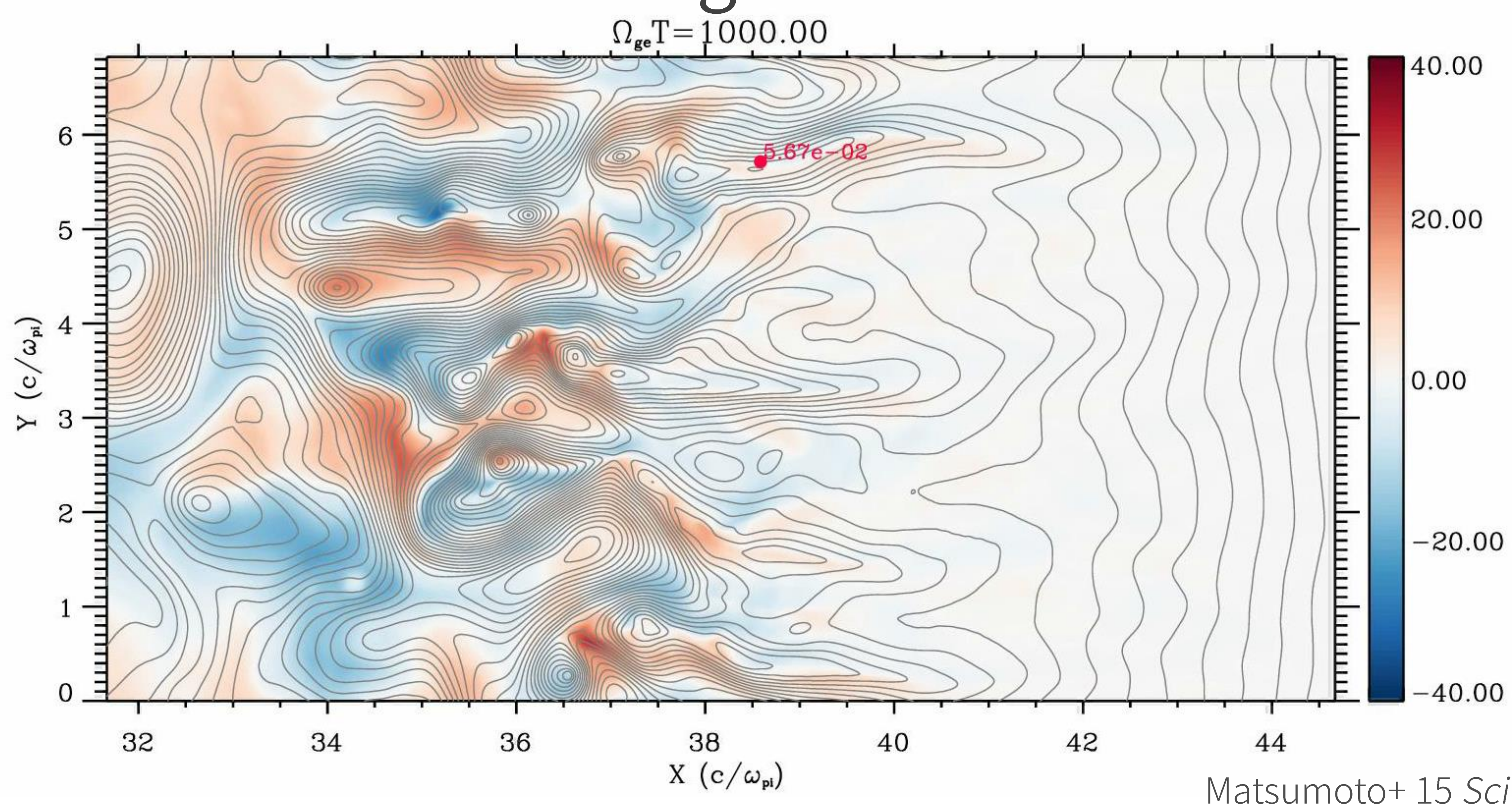
Aurora





- ☐ Topology change of anti-parallel magnetic field lines
- ☐ Conversion of magnetic energy to plasma kinetic energy
- ☐ Fundamental process in planetary and astrophysical phenomena
- ☐ New role of MR as a fundamental process in shock physics

e^- acceleration during turbulent reconnection

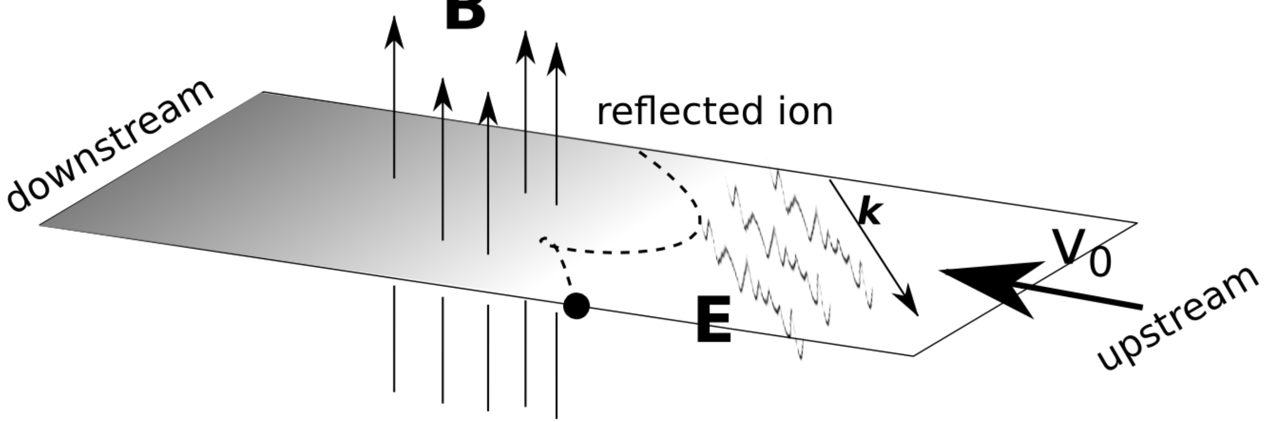


Matsumoto+ 15 *Science*

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

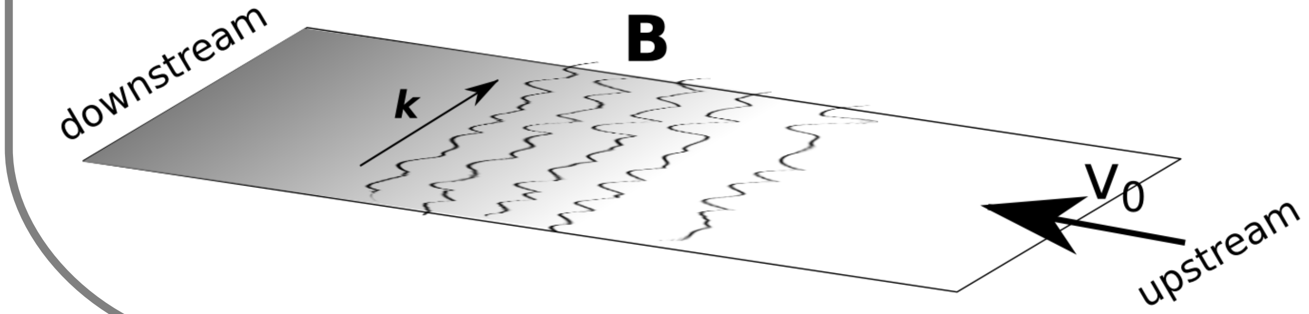
e^- accelerations in high M_A shocks

out-of-plane field



$k \perp B_0$
electron-scale
Buneman instability
surfing acceleration

in-plane field



$k \mathbin{/\!/} B_0$
B field turbulence via
ion Weibel instability
stochastic acceleration

Trillion-particle simulations on K computer

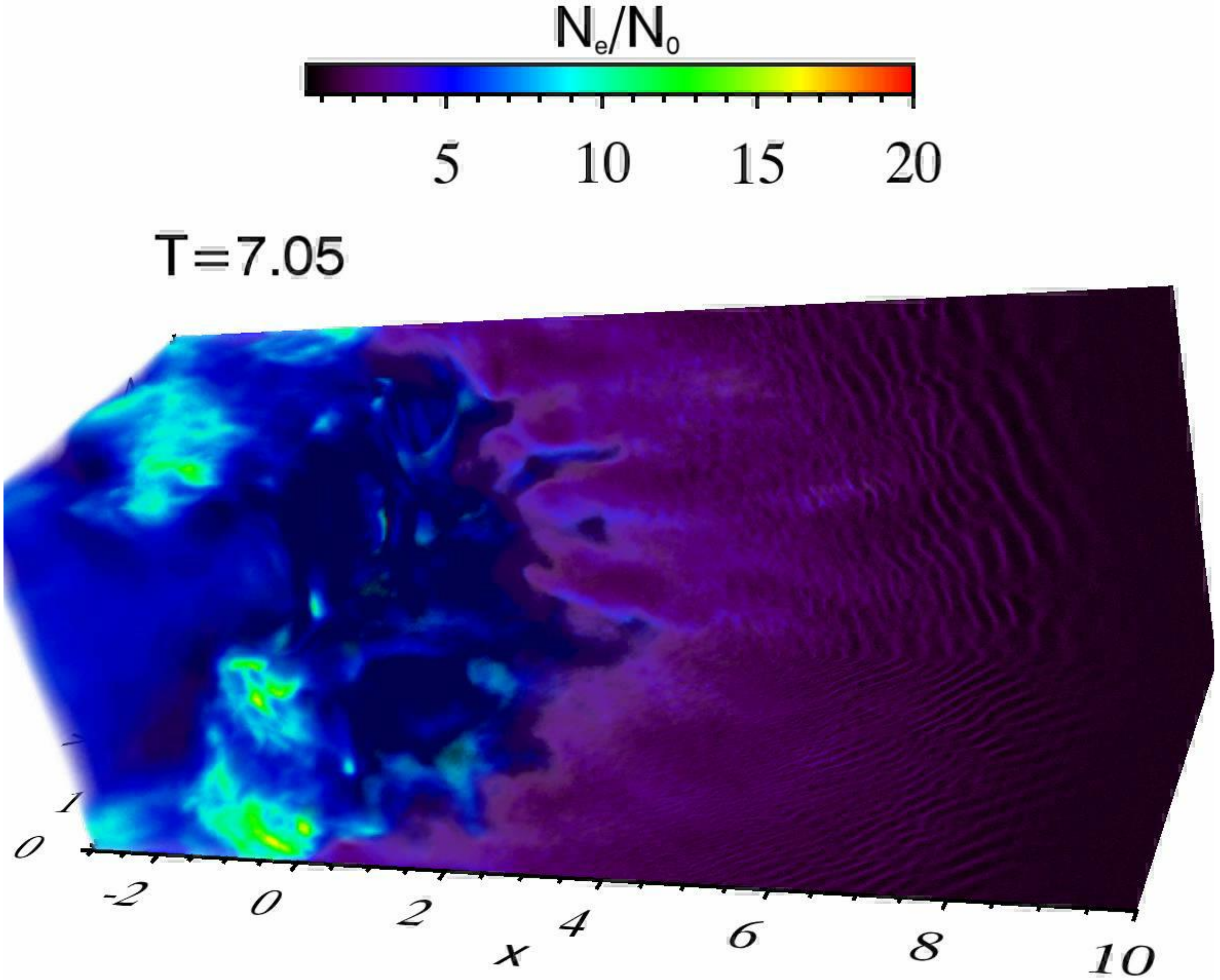
- ☐ 3D PIC simulations of quasi-perpendicular shocks
- ☐ $(N_x, N_y, N_z) = (8801, 768, 768)$
- ☐ ~10^{12} particles (~ 100 /cell)
- ☐ On 9216 nodes (73,728 cores)
- ☐ 1 PB of data in total for analysis

Simulation setup

	M/m	V_{sh}/c	M_A	Θ_{Bn}	$\beta_i=\beta_e$	N_0	L_y, L_z
Run1 trans-luminal	64	0.26	~20.8	74.3	0.5	20 /cell	4.8 c/ω_{pi}
Run2 super-luminal	64	0.27	~21.6	84.0	0.5	20 /cell	4.8 c/ω_{pi}
Run3 sub-luminal	64	0.26	~20.8	70.0	0.5	20 /cell	4.8 c/ω_{pi}

☐ Normalizations: Ω_{gi}^{-1}, c/ω_{pi}

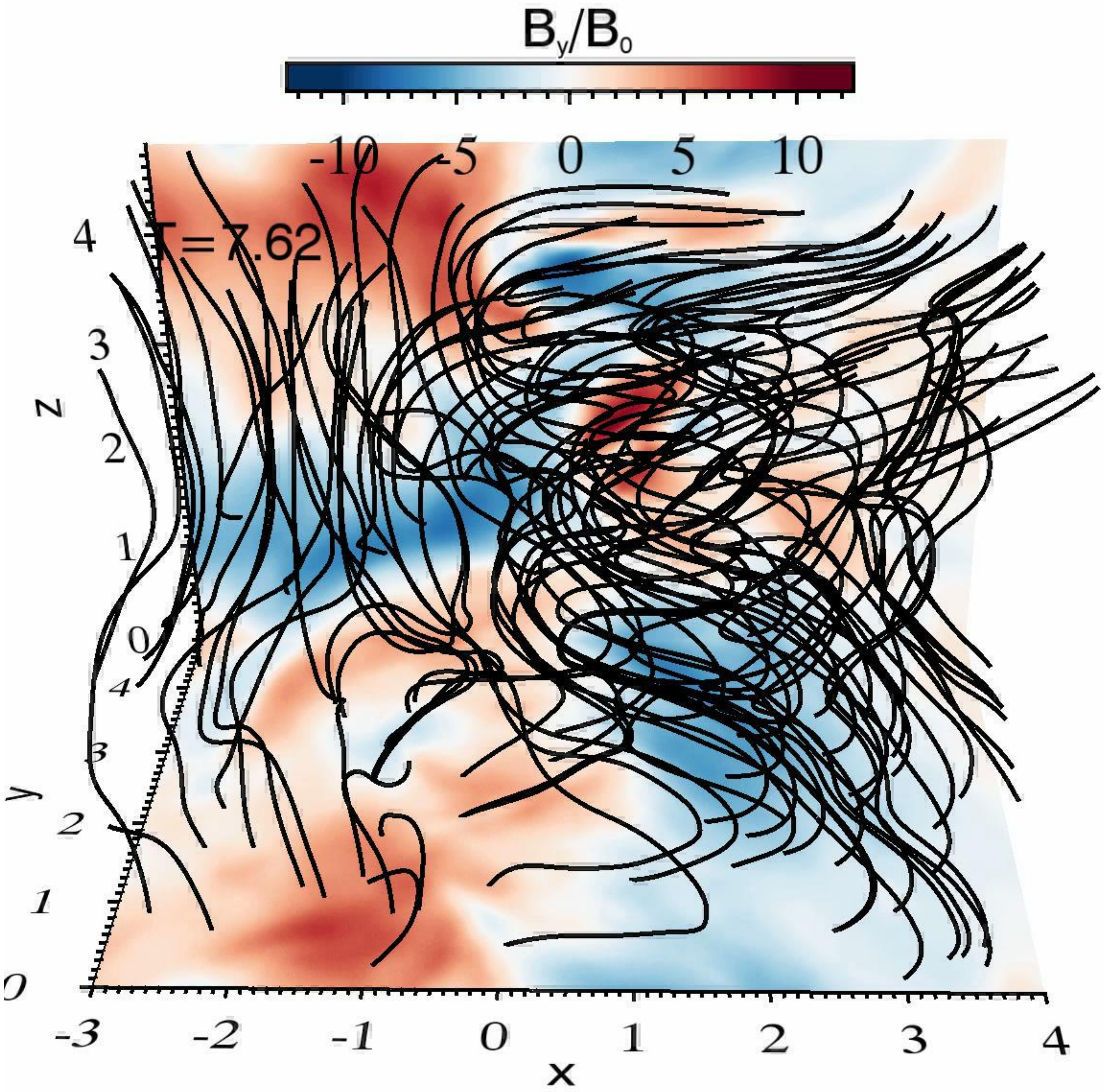
☐ Following results base on Run1



downstream

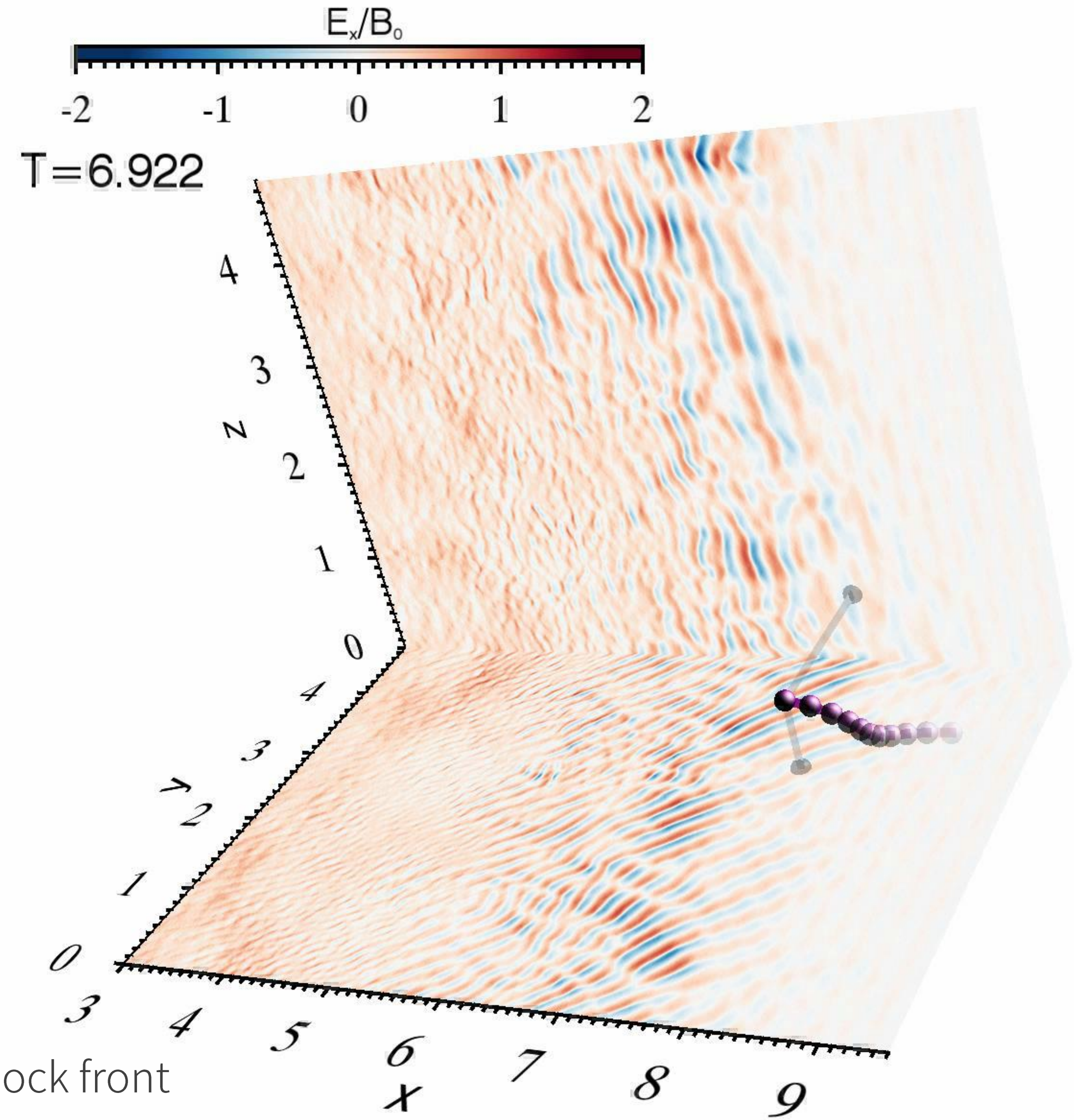
upstream

downstream



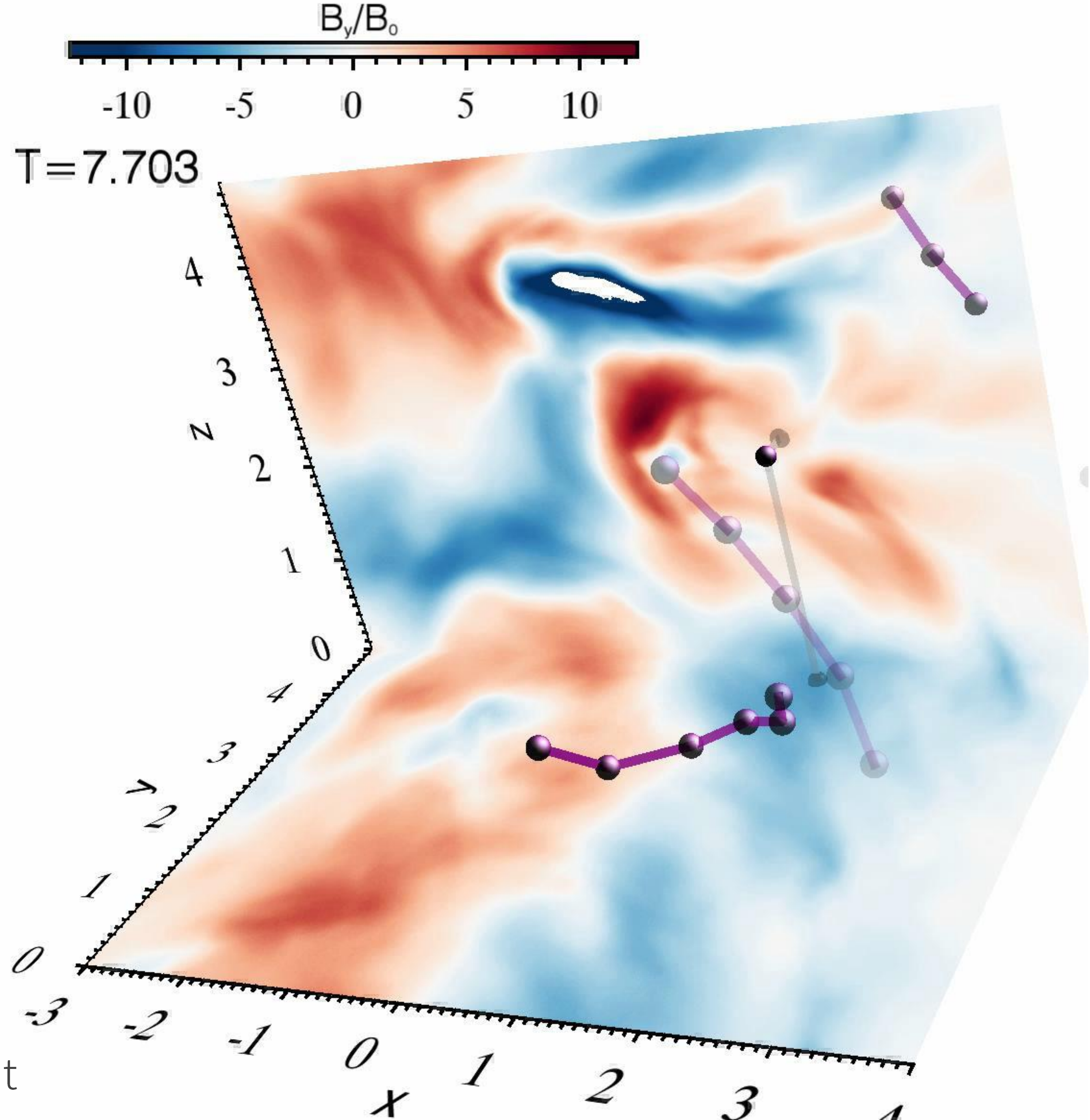
upstream

eSSA
(leading dge)



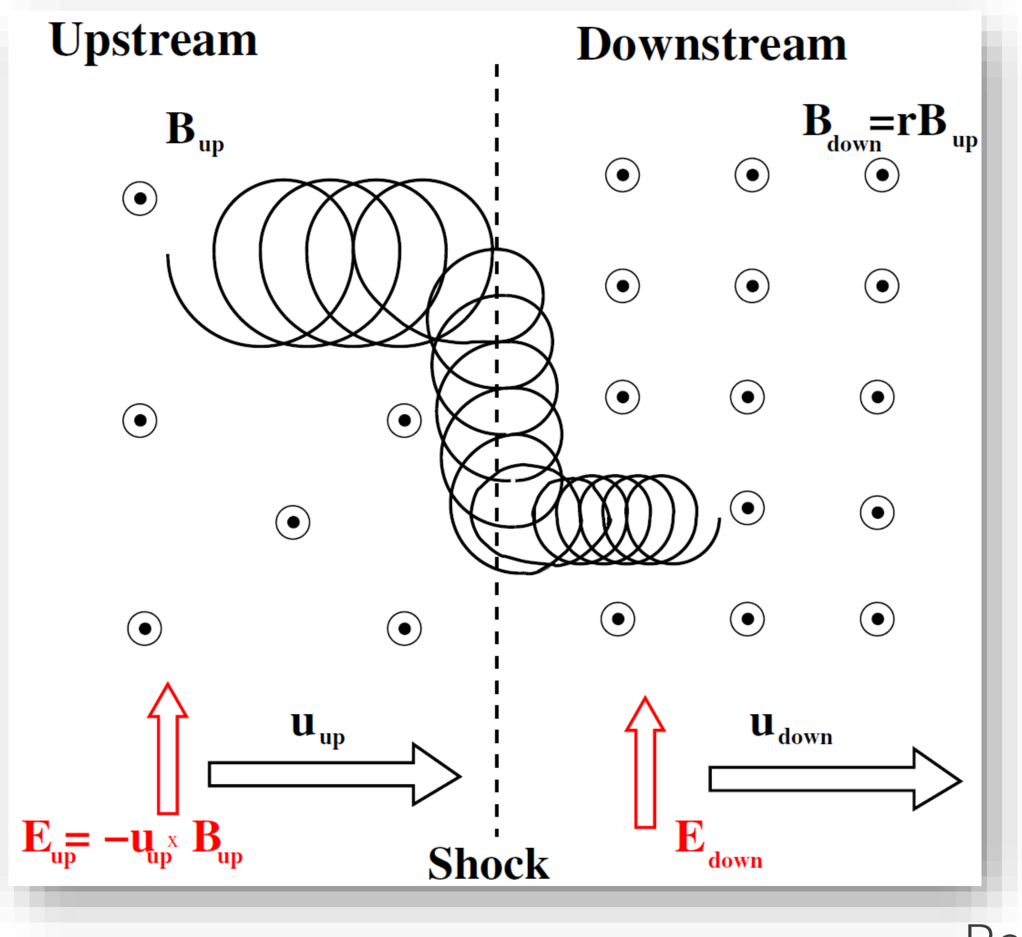
distance from the shock front

Drift + scattering (around shock front)



distance from the shock front

Shock Drift Acceleration (SDA)

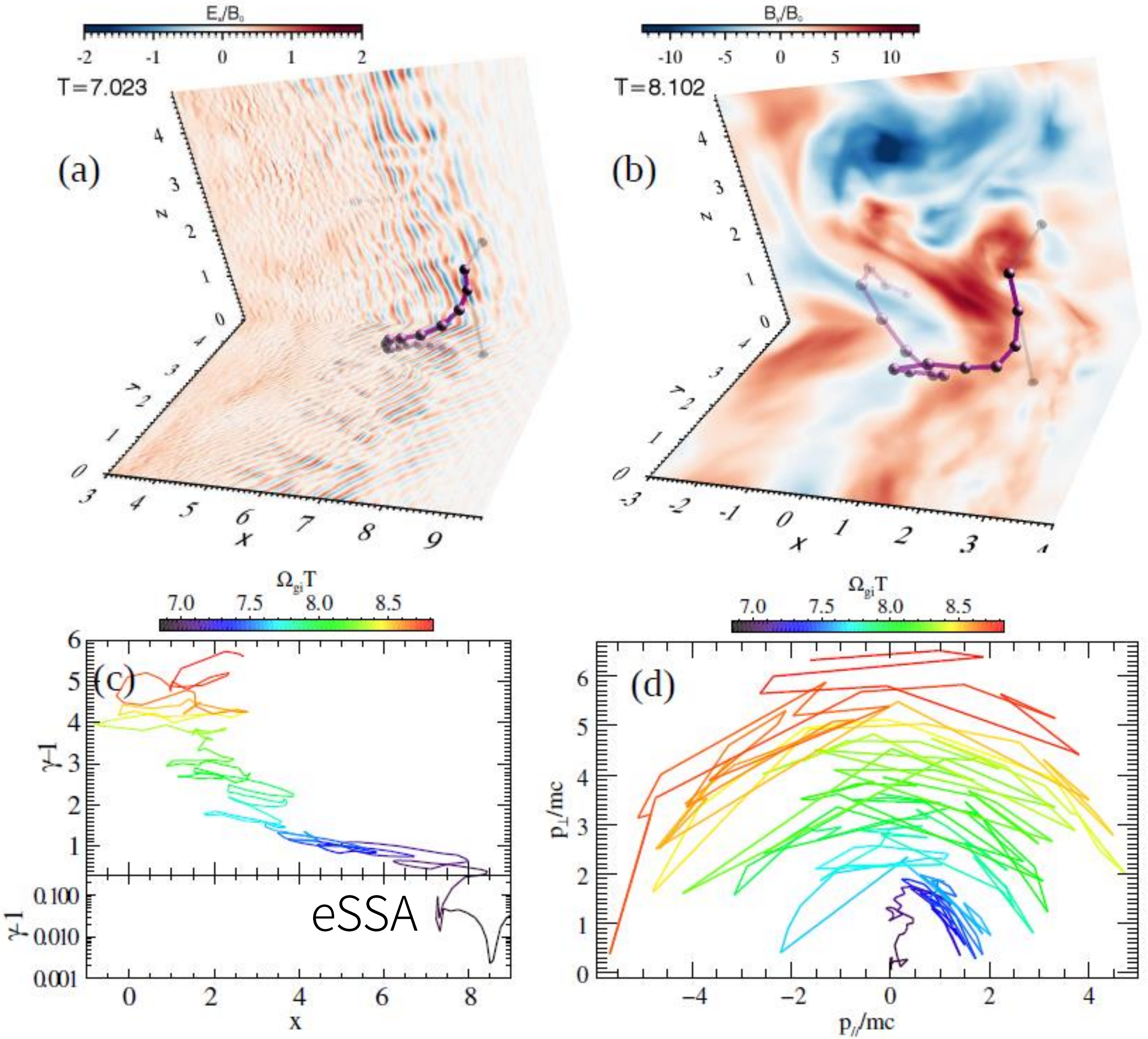


Reville+ 13

- ☐ B field jump at the shock front
- ☐ Grad B drift along the motional E field -> acceleration

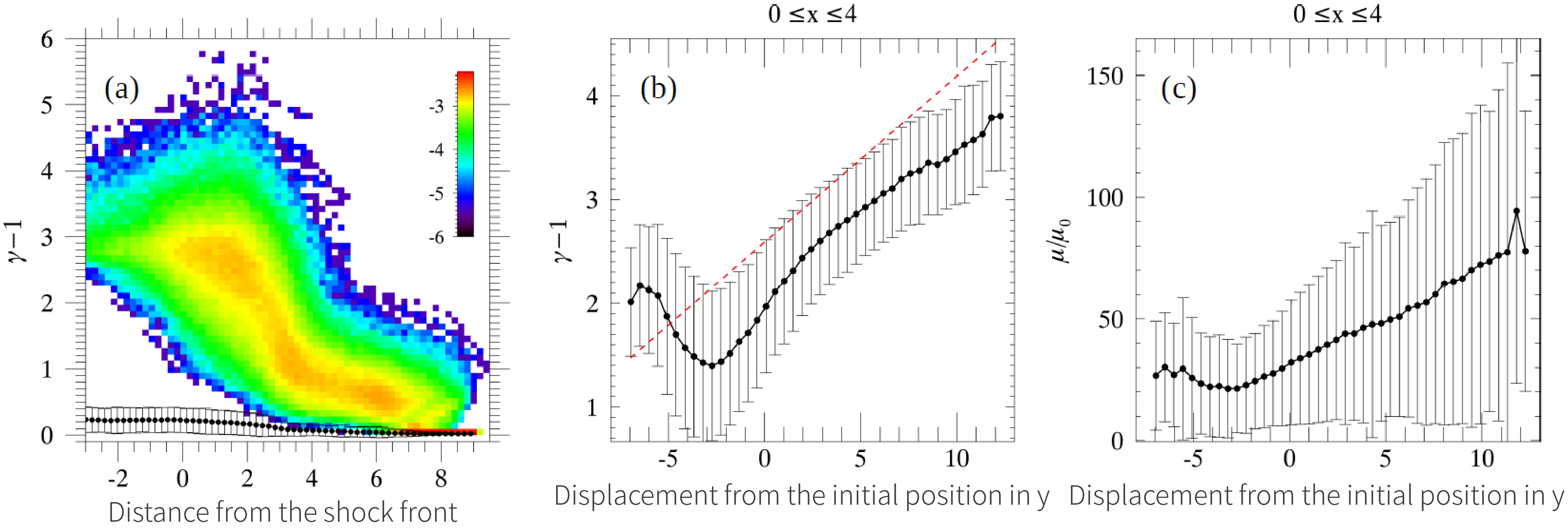
eSSA

drift + scattering



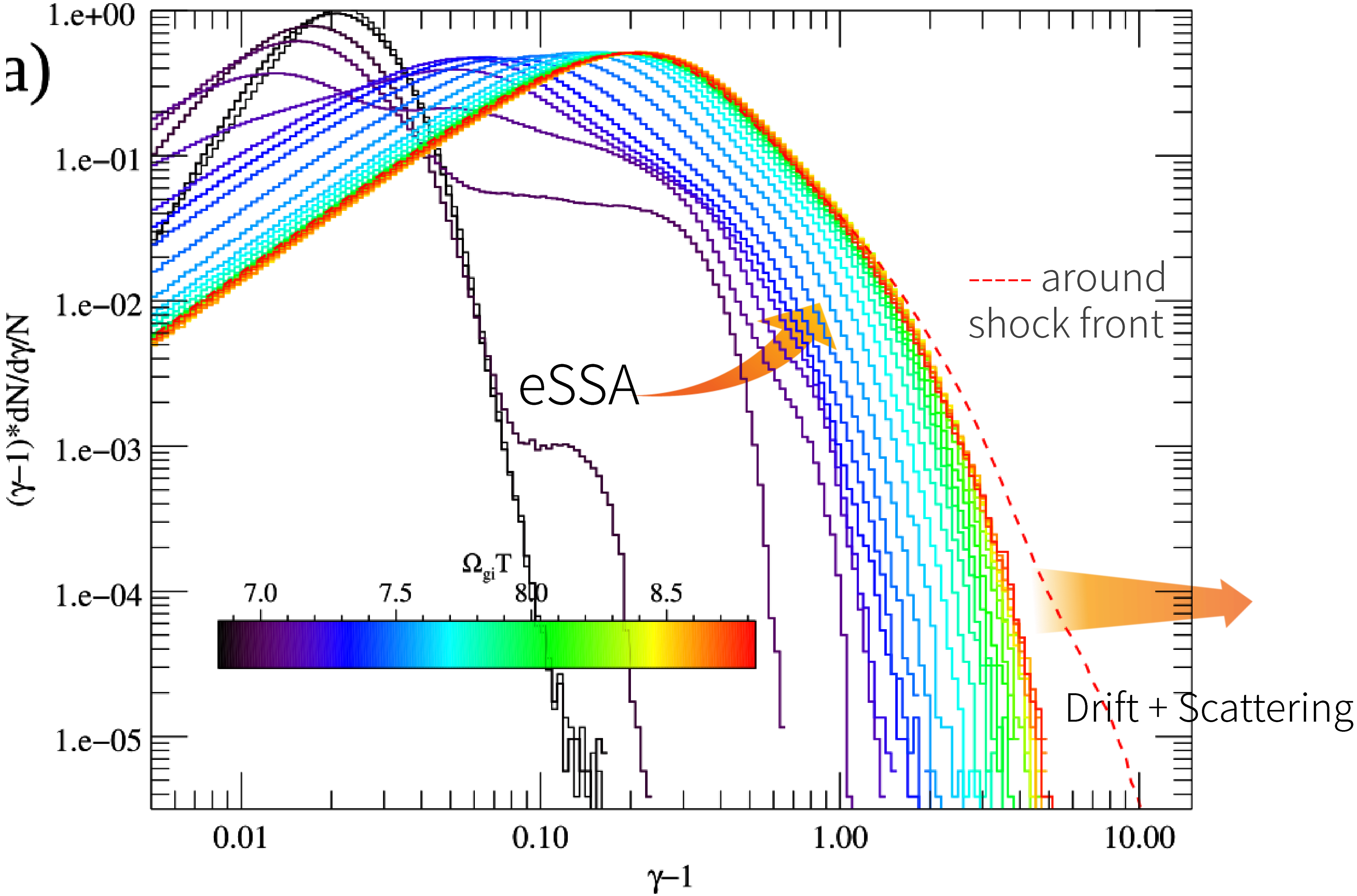
eSSA

Transport of high-energy electrons



- Tracking 10^7 particles from the upstream region for $\sim 2\Omega_{\mathrm{gi}}^{-1}$
- Sort for TOP1000 most energetic particles at the final tracking time
- The most energetic particles experienced SSA and stochastic SDA
- Strong scattering by the ion Weibel turbulence -> non-adiabatic acceleration

Evolutions of tracer particles

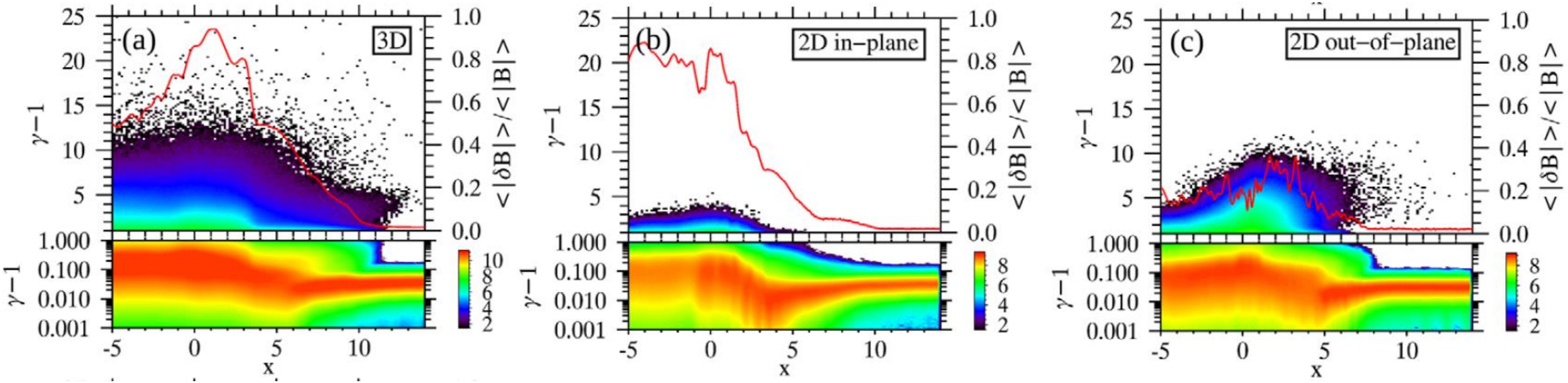


eSSA

around shock front

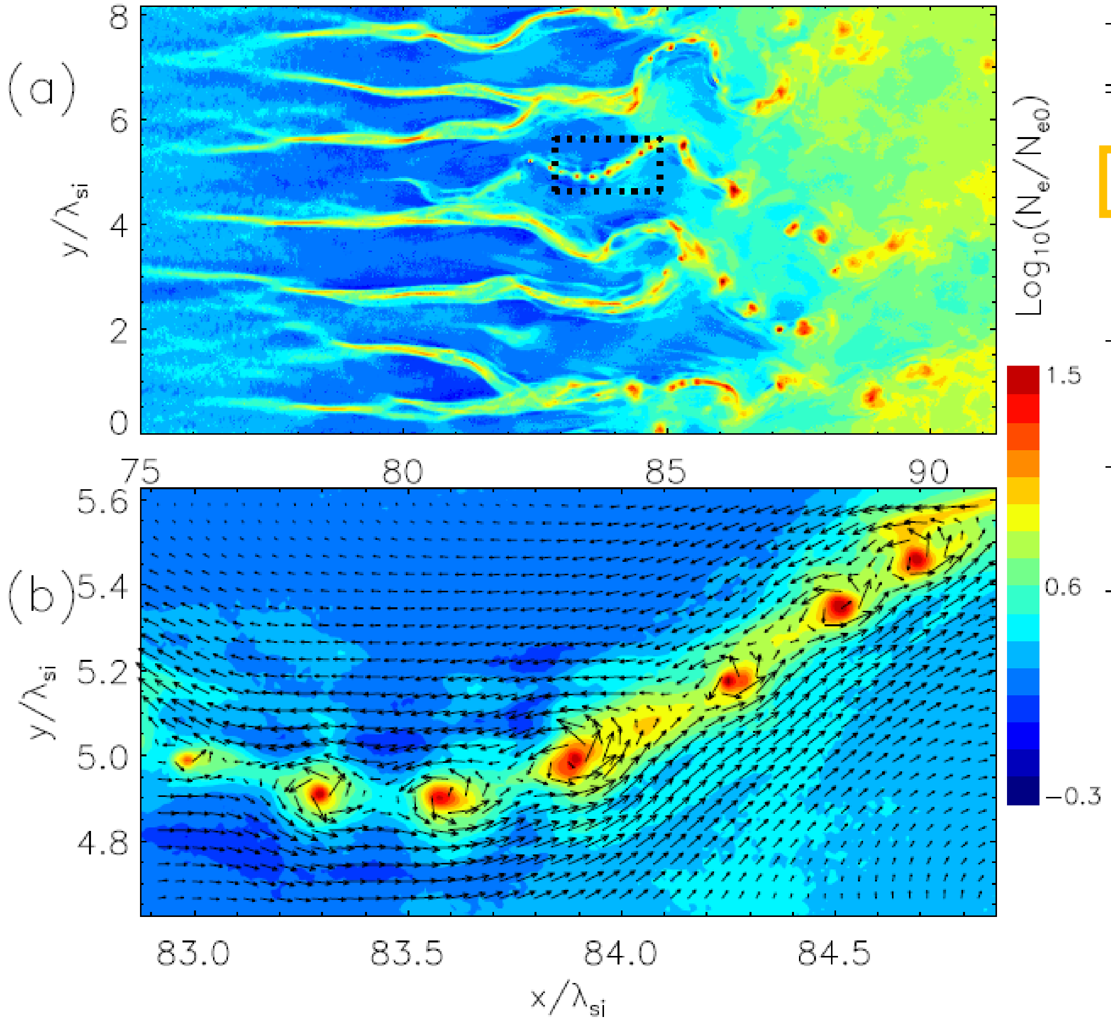
Drift + Scattering

3D vs. 2D

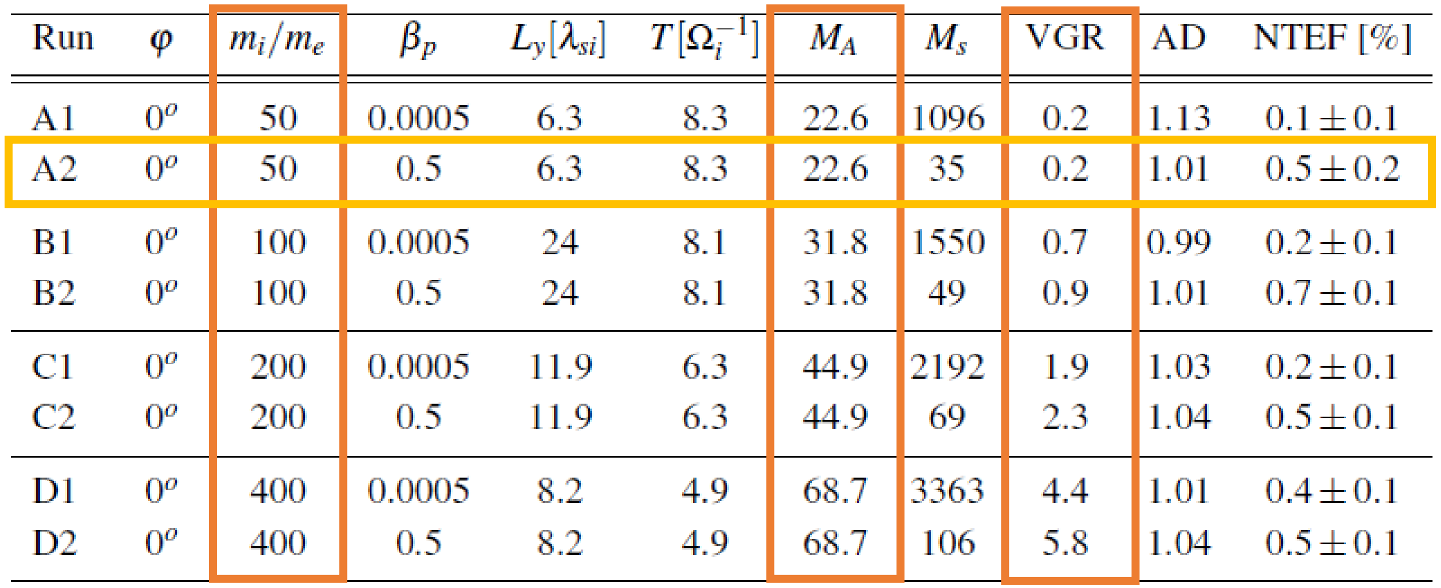


- 2D in-plane: Buneman mode is weakly destabilized -> in-efficient SSA
- 2D out-of-plane: Weak magnetic turbulence -> Energy gain by SDA is limited

What about turbulent reconnection?



Bohdan+, ICRC2017



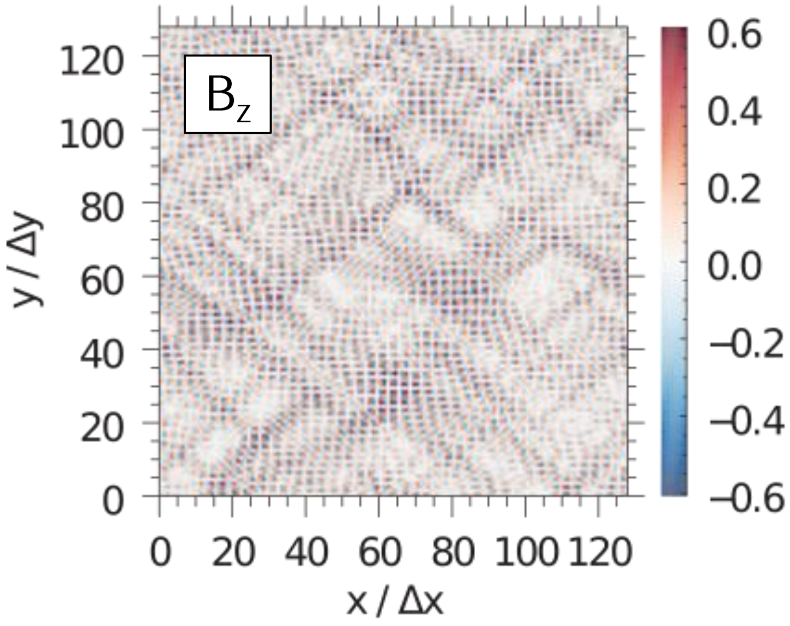
Run	φ	m_i/m_e	β_p	$L_y[\lambda_{si}]$	$T[\Omega_i^{-1}]$	M_A	M_s	VGR	AD	NTEF [%]
A1	0^o	50	0.0005	6.3	8.3	22.6	1096	0.2	1.13	0.1 ± 0.1
A2	0^o	50	0.5	6.3	8.3	22.6	35	0.2	1.01	0.5 ± 0.2
B1	0^o	100	0.0005	24	8.1	31.8	1550	0.7	0.99	0.2 ± 0.1
B2	0^o	100	0.5	24	8.1	31.8	49	0.9	1.01	0.7 ± 0.1
C1	0^o	200	0.0005	11.9	6.3	44.9	2192	1.9	1.03	0.2 ± 0.1
C2	0^o	200	0.5	11.9	6.3	44.9	69	2.3	1.04	0.5 ± 0.1
D1	0^o	400	0.0005	8.2	4.9	68.7	3363	4.4	1.01	0.4 ± 0.1
D2	0^o	400	0.5	8.2	4.9	68.7	106	5.8	1.04	0.5 ± 0.1

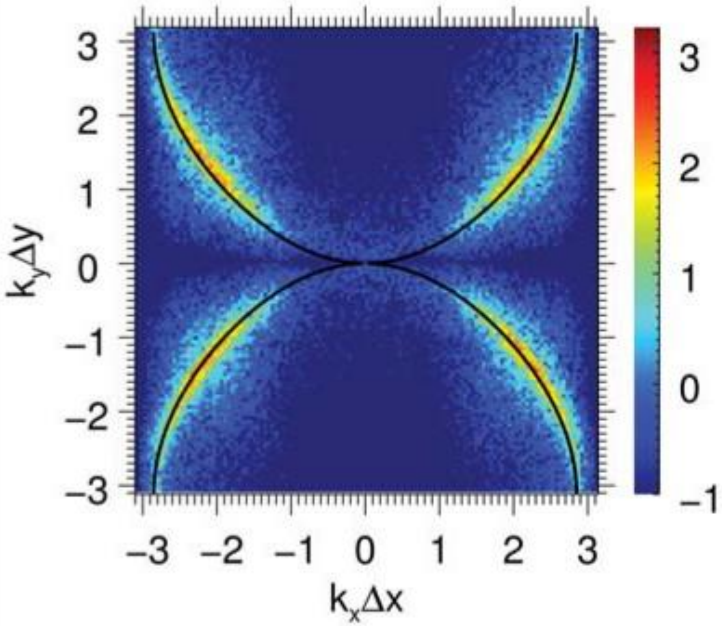
- We could not find significant accelerations by turbulent reconnection in the present 2D/3D cases
- Probably due to using small M/m or M_A
- Bohdan+ found high occurrence rate with larger M/m and M_A shocks

2D relativistic shock simulations mitigating the numerical Cherenkov instability

Numerical Cherenkov Instability (NCI)

- ✓ Periodic boundary conditions
- ✓ 10 ptcl/cell
- ✓ $\Gamma = 100$ in x direction



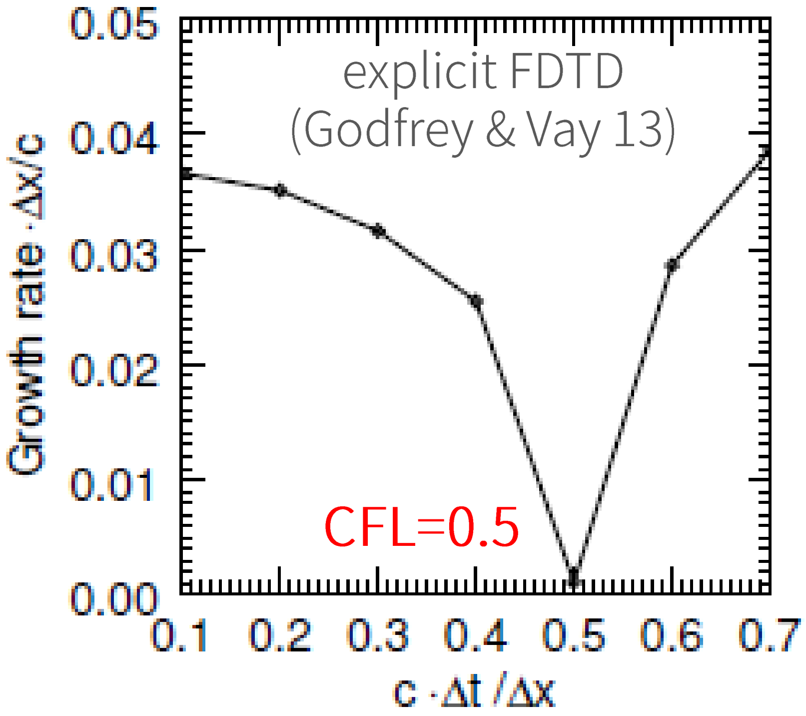


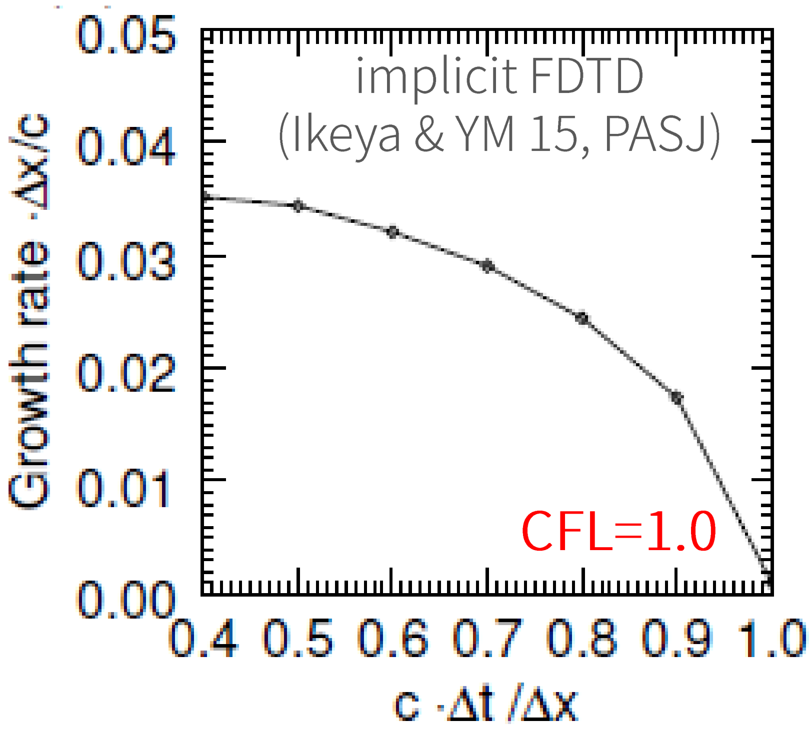
- ✓ Excited at specific locations in k_x-k_y space
- ✓ Related to the numerical dispersion relation of the light wave

<u>Recipes</u>

- ☐ Spectral methods (Kato 07; Yu+ 14)
  - ✓ Solved in Fourier space
  - ✓ Need of global communications for FFT in massive-parallel computations
- ☐ FDTD (finite difference method)
  - ✓ Digital filtering (smoothing) to **J, E, B** (Vay+ 11)
  - ✓ + 4th order FDTD (Greenwood+ 04; Sironi & Spitkovsky 09; Tomita & Ohira 16)

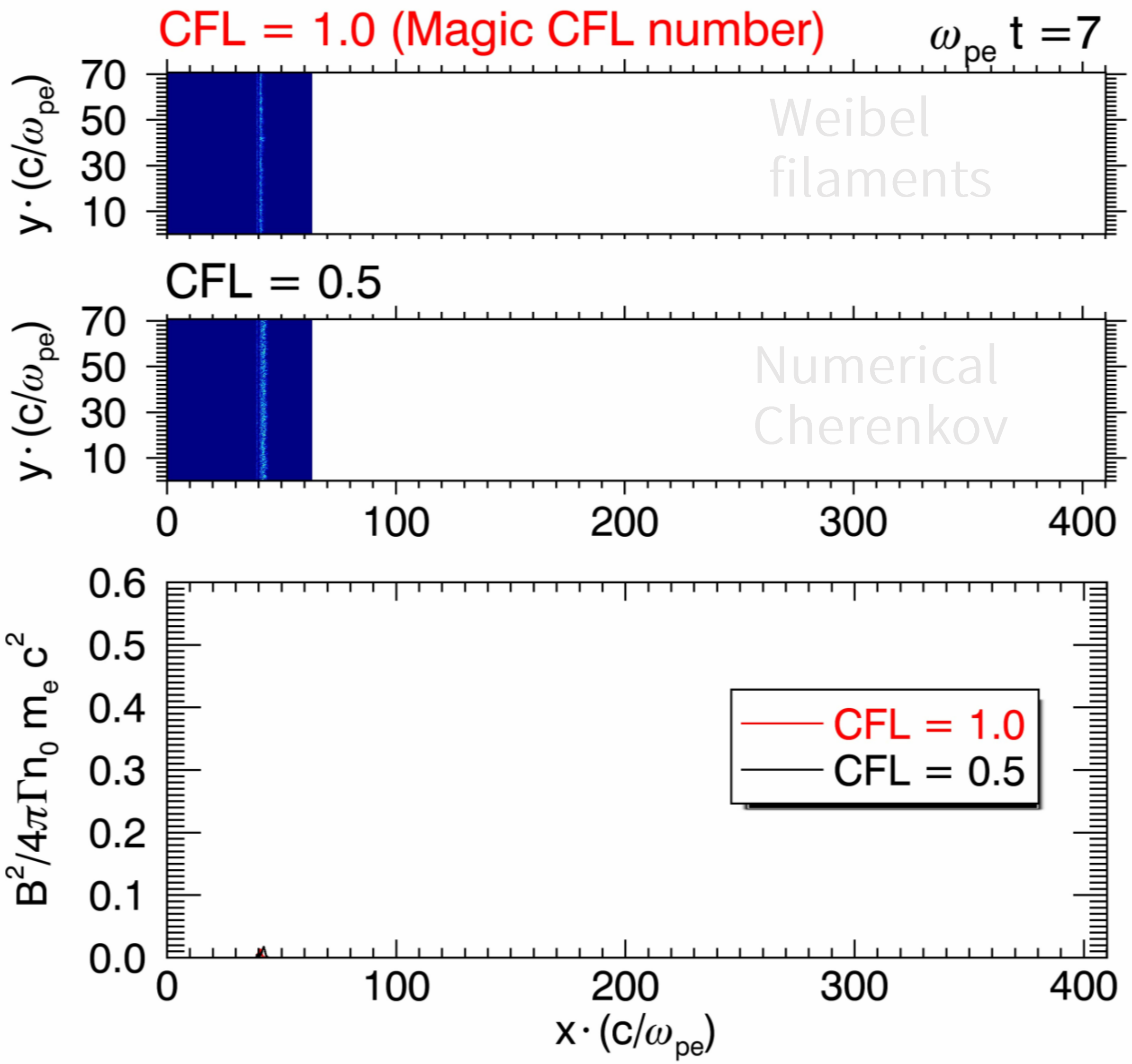
Magic CFL number





- ☐ Growth rate of the NCI drops at a particular CFL number ($c\Delta t/\Delta x$) (Vay+ 11)
- ☐ Specific to PIC algorithms
  - ✓ Esirkepov's current deposit algorithm (Esirkepov 00)
  - ✓ Field solvers - explicit (Godfrey & Vay 13) & implicit (Ikeya & YM 15) FDTD
  - ✓ field interpolations

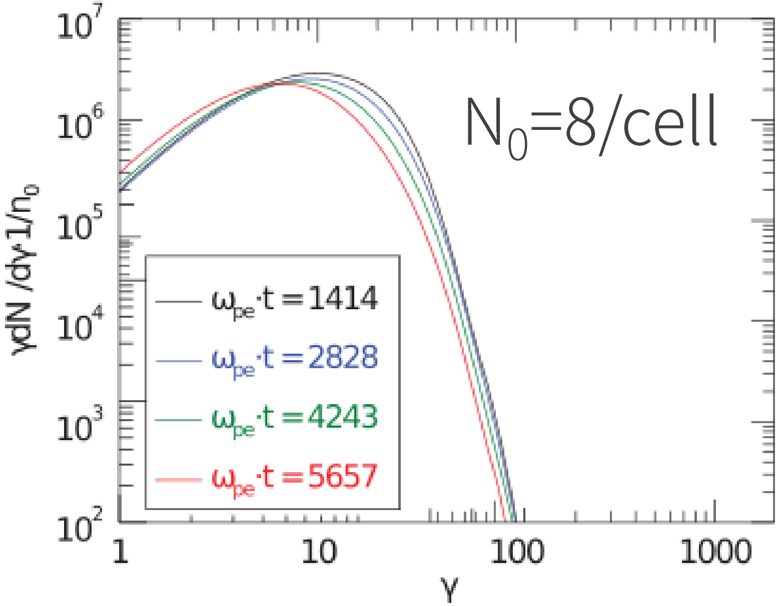
PIC simulations of relativistic shocks in pair plasmas (Γ=100) w/o NCI



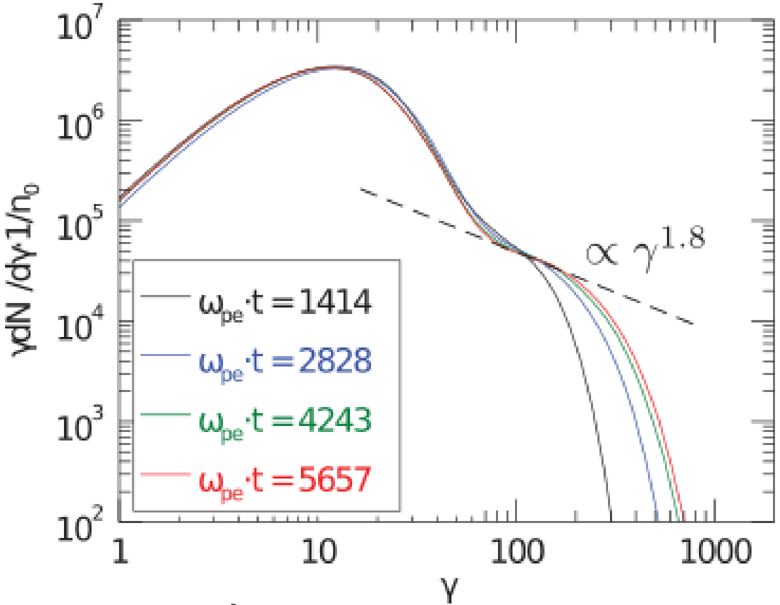
Ikeya & YM 15, PASJ

Time evolutions of downstream energy spectrum

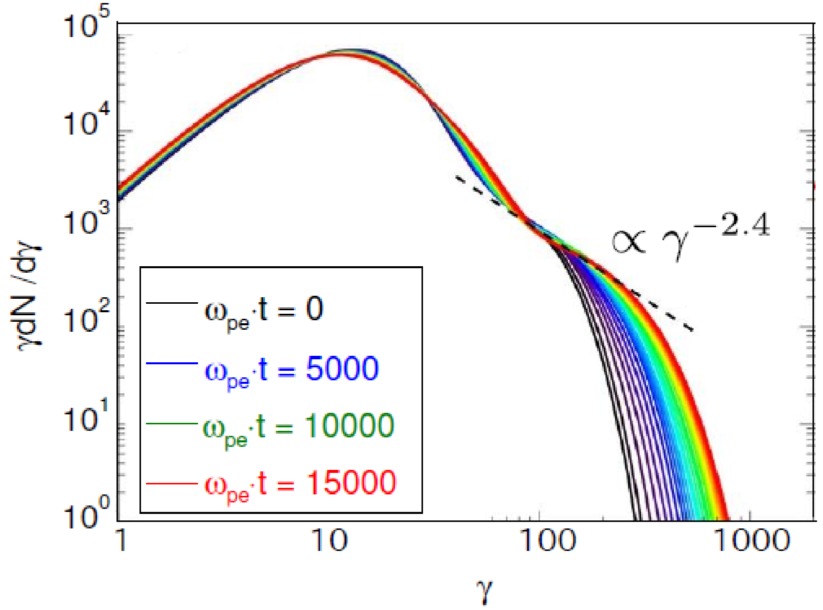
CFL=0.5 (Non-magic)



N_0=50/cell, CFL=1.0



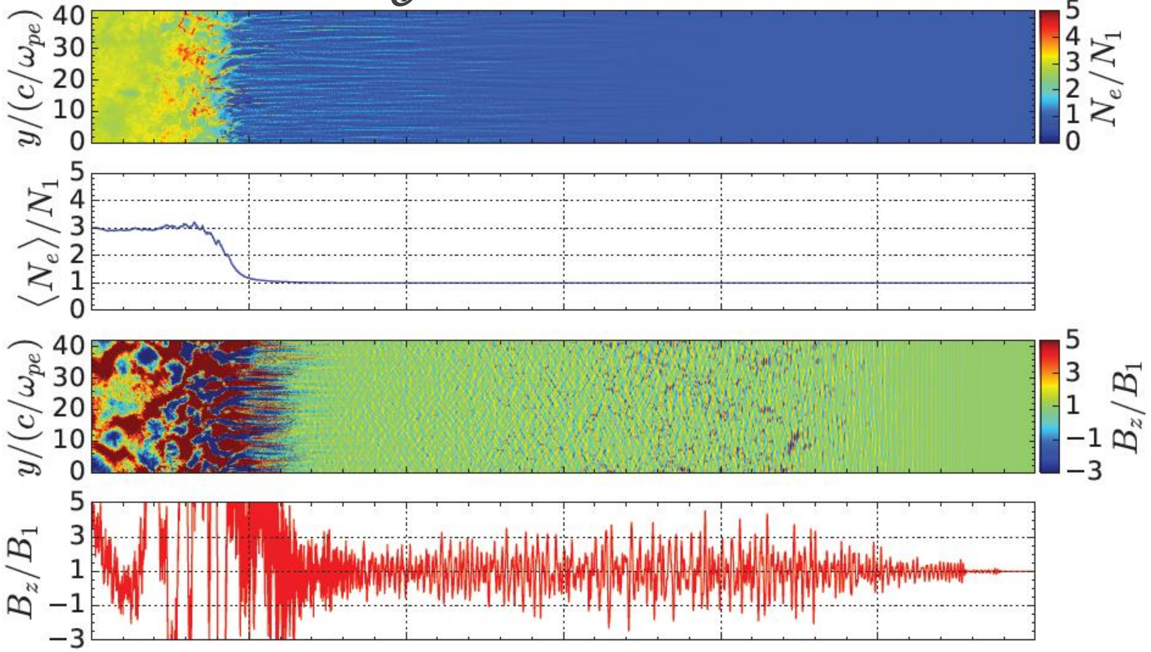
Sironi+13



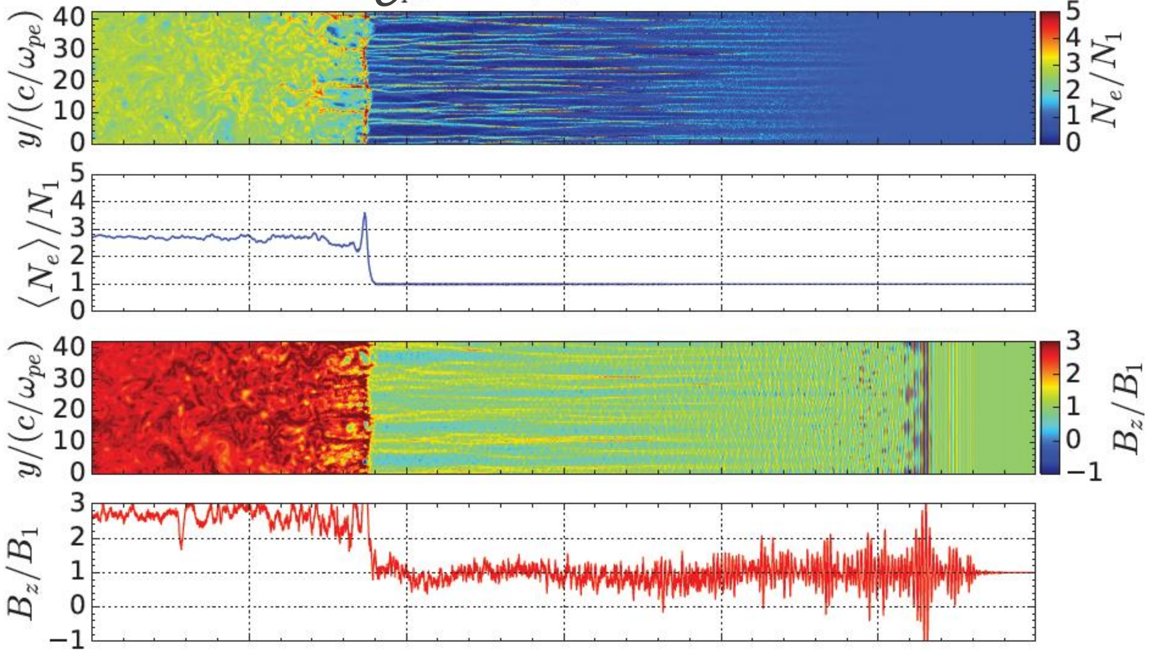
- Direct comparison with Sironi+ 13
- No efficient acceleration with NCI
- Efficient accelerations were obtained by using Magic CFL number method
- Spectral index -1.8 vs. -2.4

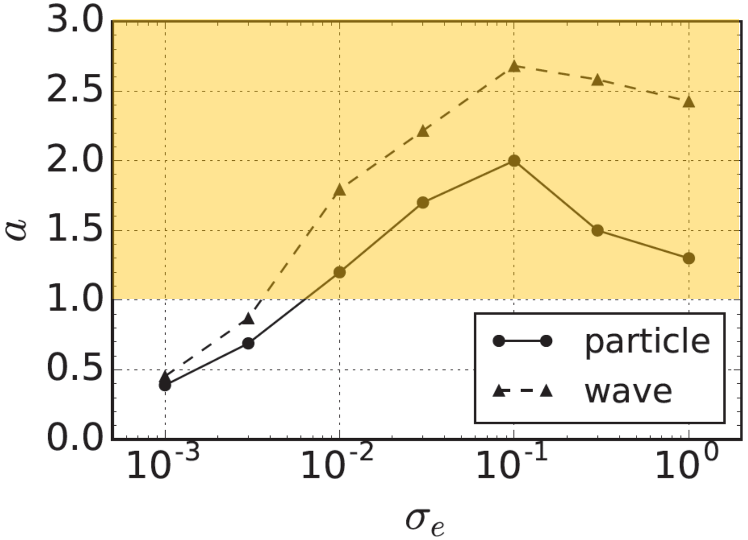
Iwamoto+, ApJ, 2017

$\sigma_e = 3 \times 10^{-3}$



$\sigma_e = 3 \times 10^{-1}$





- ☐ Precusor waves still survives in Weibel-dominated shocks
- ☐ Self-focusing of light waves (2D effect)
- ☐ Large amplitudes of precursor waves under wide σ_e implying for WFA.

Summary

- ☐3D PIC simulations of a high-M_A shock for the first time
- ☐Electron shock surfing & drift accelerations under strong Weibel turbulence can generate relativistic particles efficiently
- ☐Spatial diffusion of energetic particles into the upstream region suggests a possibility of self-generation of MHD waves and successful participation into DSA

Matsumoto, Amano, Kato, & Hoshino, *Phys. Rev. Lett.*, in press.

- ☐We have developed a numerical technique to mitigate the numerical Cherenkov instability problematic in relativistic plasma flows
- ☐Opening a new era of investigating relativistic shocks in multi dimensions (See also Tomita & Ohira, Iwamoto+ in this workshop)