Non-thermal heating of plasma particles due to relativistic nonlinearity of lasers

= Modeling cosmic-ray acceleration in laboratory =

Hideaki Takabe, NTU, Taiwan

1. Laser acceleration by wake-field induced by ponderomotive force
2. An experiment shows no mono but power-law heating (Pinch to Chance)
3. Stochasticity of the particle motion by filamentation and reflection of laser
4. Power law spectrum by nonlocal diffusion in p-space. (FFPE)
5. Generation of waves and cosmic-rays in relativistic collisionless shocks in Universe
6. Proposal to NIFS

核融合科学研究所ユニット構築会議への提案として用意した。ZOOM会議。2021年7月5日

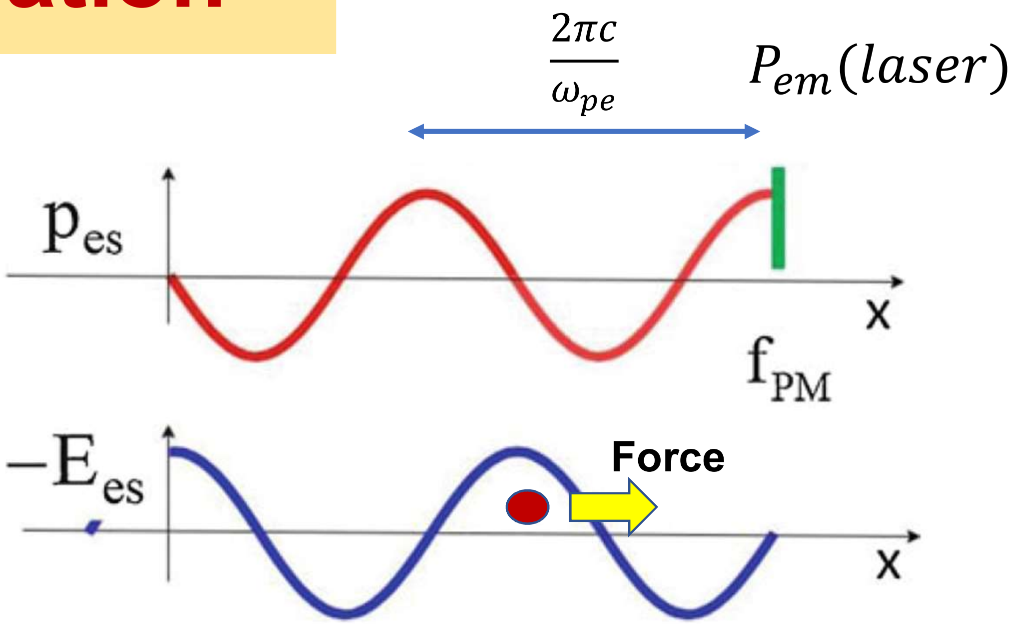
Main reference: HT book-1; https://www.springer.com/gp/book/9783030496128

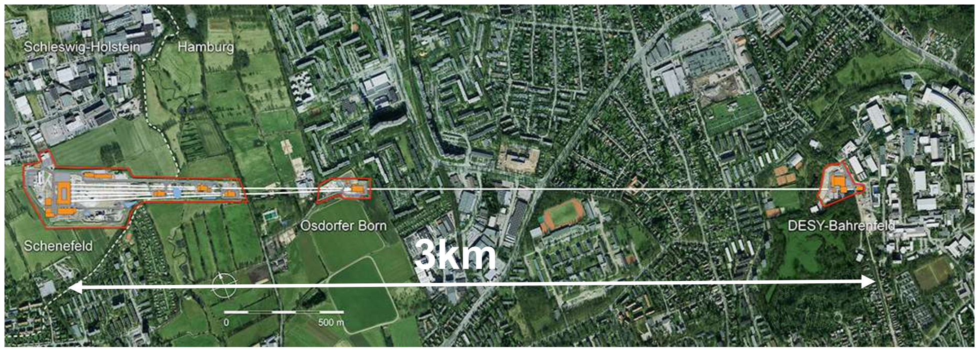
Laser wake-field acceleration

$$\frac{d^2 p_{es}}{dt^2} = -\frac{\omega_{p0}{}^2}{\gamma} p_{es} + p_{em}\delta(t - x_0/c)$$

$$E = \frac{e}{\varepsilon_0} n_e \frac{c}{\omega_{pe}} \sim 100 \text{ [GV/m]}$$

$$E = 10 \text{ [MV/m]} \quad \text{(LINAC)}$$

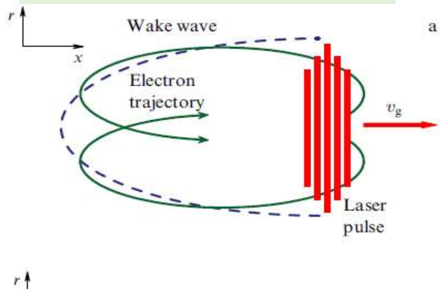


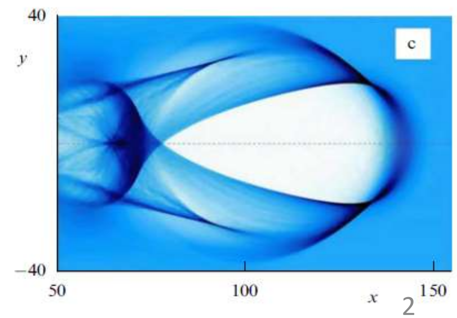


XFEL, DESY, Hamburg (17GeV/1.7km)

HT book-1 p. 206

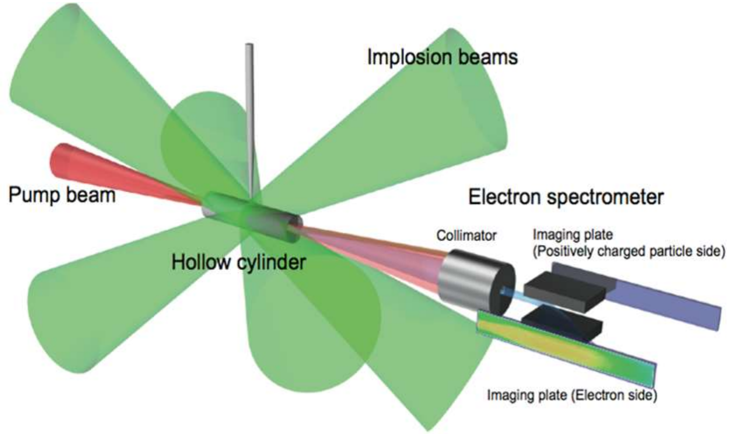
Electrons in 2-D 3-D

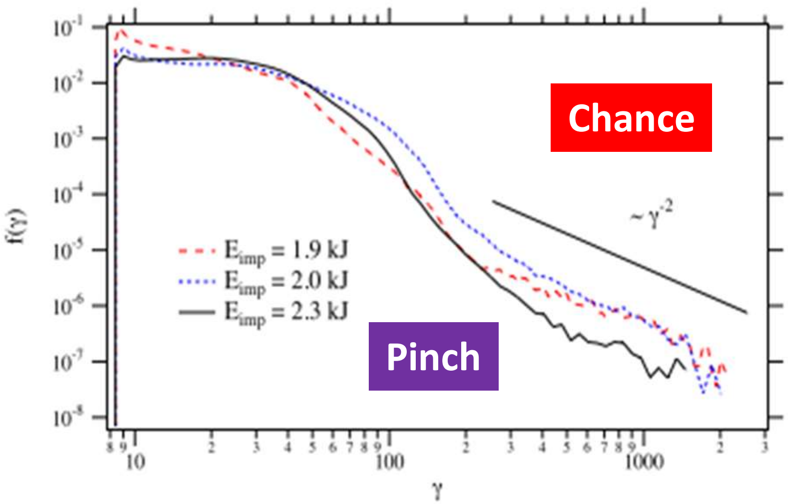


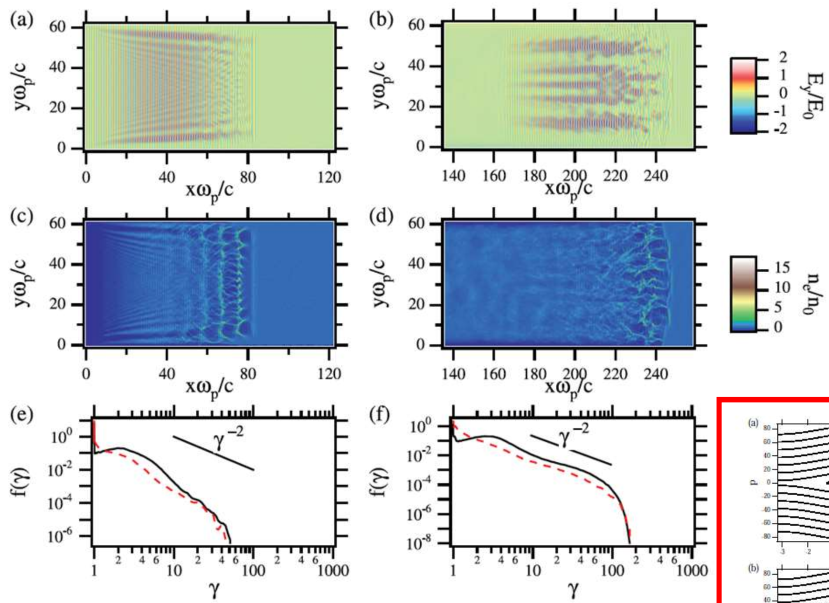


LFEX experiment at ILE

蔵満（阪大）







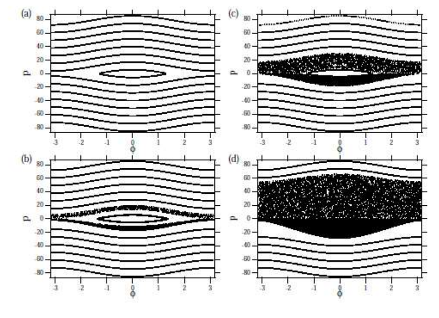
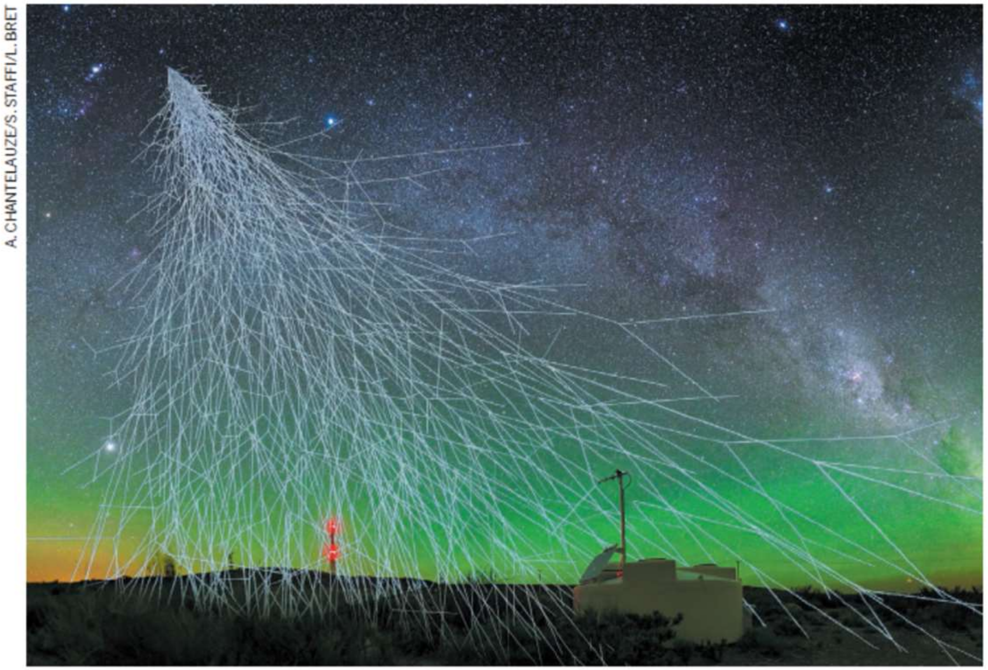


FIG. 3: Poincaré maps on $p-\phi$ plane with (a) $e_2 = 0$, (b) $e_2 = 0.1$, (c) $e_2 = 0.3$, and (d) $e_2 = 1$.

Y. Kuramitsu, *Model Experiment of Cosmic Ray Acceleration due to an Incoherent Wakefield Induced by an Intensive Laser Pulse*", Physics of Plasmas (Letter), **18**, 010201 (4 pages), (2011),

Y. Kuramitsu et al, *NONTHERMAL ACCELERATION OF CHARGED PARTICLES DUE TO AN INCOHERENT WAKEFIELD INDUCED BY A LARGE-AMPLITUDE LIGHT PULSE*, The Astrophysical Journal, 682: L113 (2008)

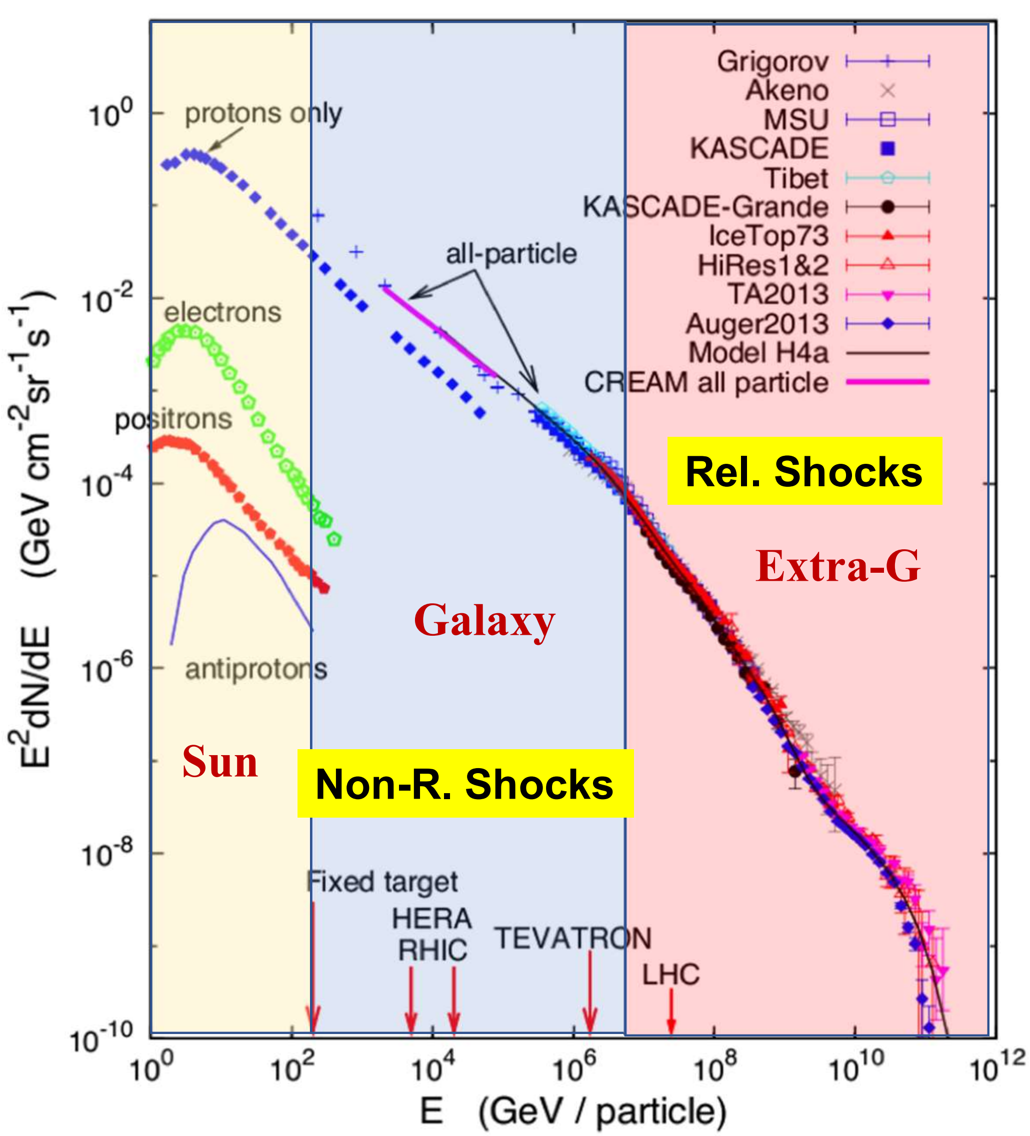
Cosmic-rays and observation fact



An artist's impression shows how a high-energy cosmic ray creates a broad spray of particles.

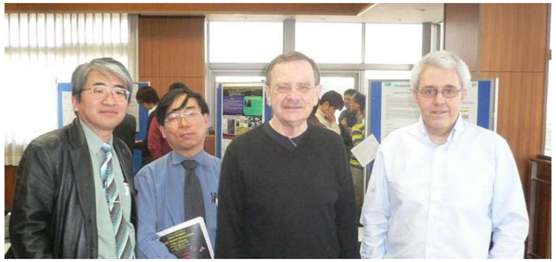
Artistic view of the avalanche of created many particle in the air triggered by an injection of one high-energy cosmic-ray to the air. Molecules in the air decays short-life particles to create also another particles like chain reaction.

D. Castelvecchi, Nature **549**, 440 (2017).



T. Gaisser, arXiv:1704.00788v1, astro-ph.HE (2017)

Standard model of accelerating cosmic-rays (DSA)
=Non-relativistic shocks=



A. R. Bell

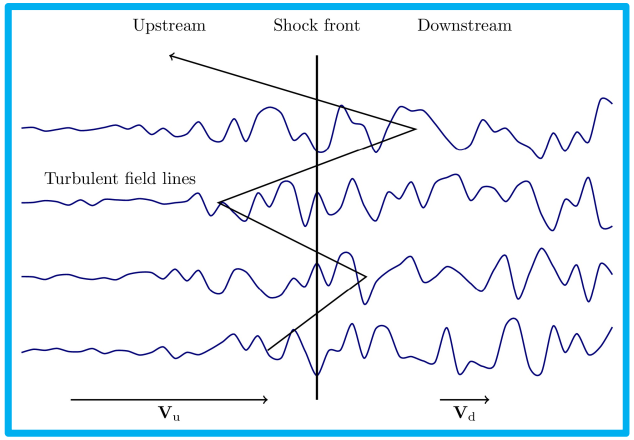
Tokyo I T, Feb. 22, 2007

40 years old

E. Fermi, Astrophys. J. **119**, 1 (1954).
A. R. Bell, Mon. Not. R. Astro. Soc. 182, 147 (1978).
R. D. Blandford & J. P. Ostriker, Astrophysical J., 221, L29 (1978)

Power law for non-thermal particles

Collisionless shock



$$E_n = E_0 (1+\varepsilon)^n$$

$$N(E) \propto N_0 (1-P)^n$$

$$\varepsilon = \Delta E / E$$

$$\frac{dN(E)}{dE} \propto E^{-\alpha}$$

$$\alpha = 1 - \ln(1-P)/\ln(1+\varepsilon) \approx 1 + P/\varepsilon$$

$$\alpha = 1 + P/\varepsilon = 1 + \frac{3}{R-1}$$

$N(E) \sim E^{-2}$ for R=4

Relativistic shocks?

X-ray image of SN1006 and DSA

1. **Relativistic Synchrotron Emission**

$$h\nu = 2keV\left(\frac{B}{10\mu G}\right)\left(\frac{E_e}{10^{14}eV}\right)^2$$

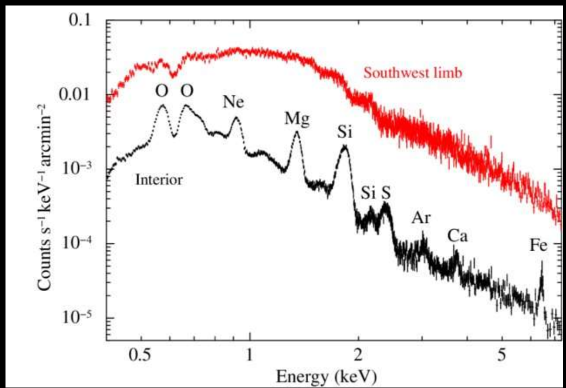
2. **Shock Thickness (Observation)**

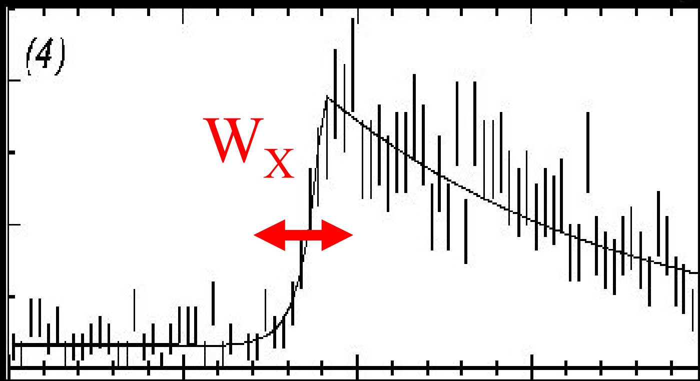
$$W_X = 1 \times 10^{17}\ \text{cm}\ (=1/400\ l_{mfp})$$

SN1006

u_0= 4330km/s

diameter = 60 ly





Chandra X-ray Satellite

G. Casssam-Chenai et al., Astrophys. J. **680**, 1180 (2008)
A. Bamba et al., Astrophys. J. **621**, 793 (2005).

We have demonstrated non-relativistic collisionless shock formation in experiment with NIF laser

John Dawson Award for Excellence in Plasma Physics Research

American Physical Society, 2020 Awardee

https://www.aps.org/programs/honors/prizes/dawson.cfm

Nonlinear Physics of Magnetic Turbulence, Shock Formation, and Particle Acceleration via Weibel Instability in Laser Astrophysics

= Theory, PIC Simulation and Laser Experiment =

Presented at Prof. Yoshida’s final seminar, March 7-8, 2021 by ZOOM

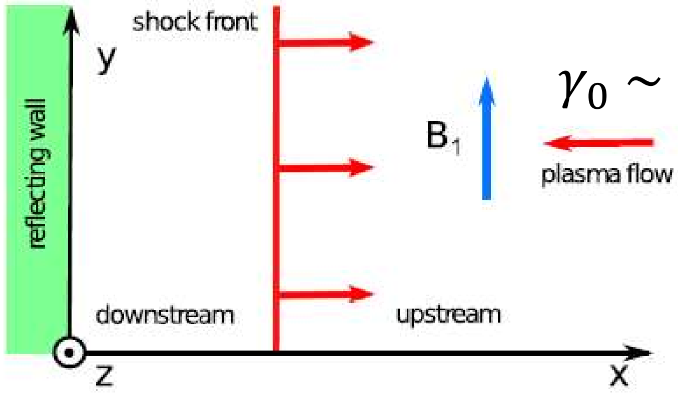
(Video of my talk)

http://www.ppl.k.u-tokyo.ac.jp/takabe.mp4

Next is relativistic shocks and cosmic-ray acceleration physics

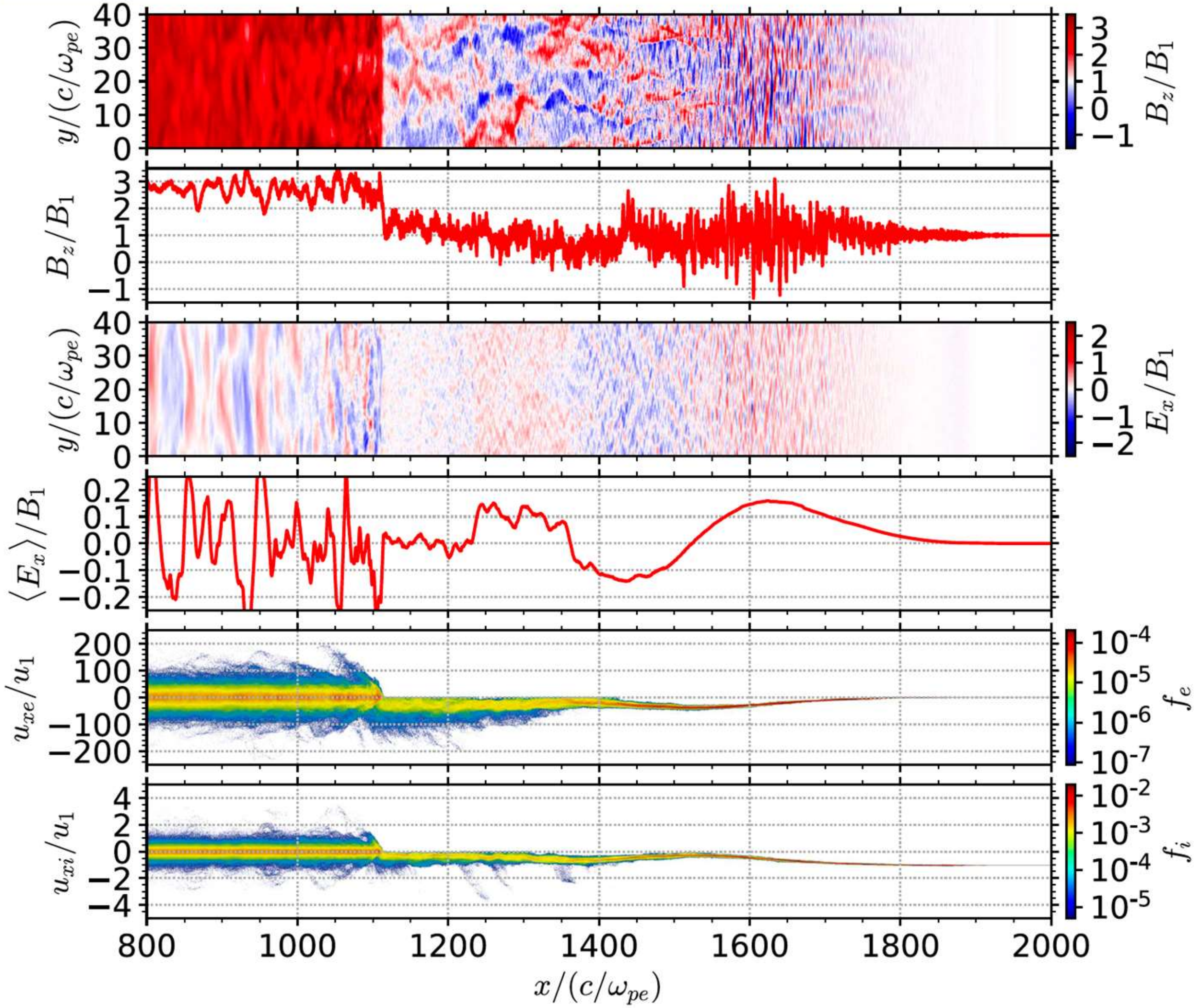
Global Structure of 2D ion-e^- relativistic shocks

Previous one-dimensional (1D) particle-in-cell (PIC) simulations showed that **synchrotron maser instability (SMI)** is the significant dissipation mechanism for relativistic magnetized shocks (e.g., Langdon et al. 1988; Gallant et al. 1992; Hoshino et al. 1992; Amato & Arons 2006).

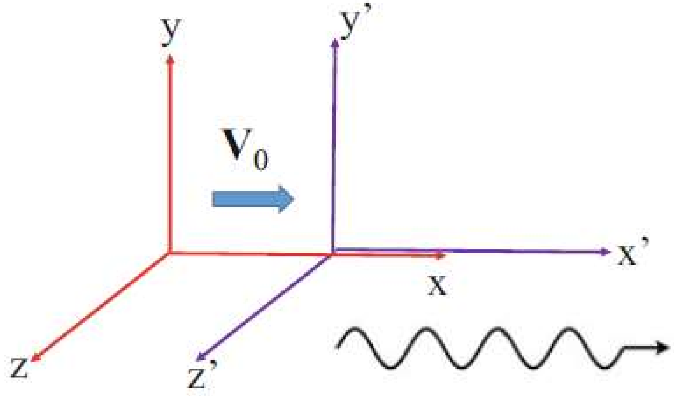


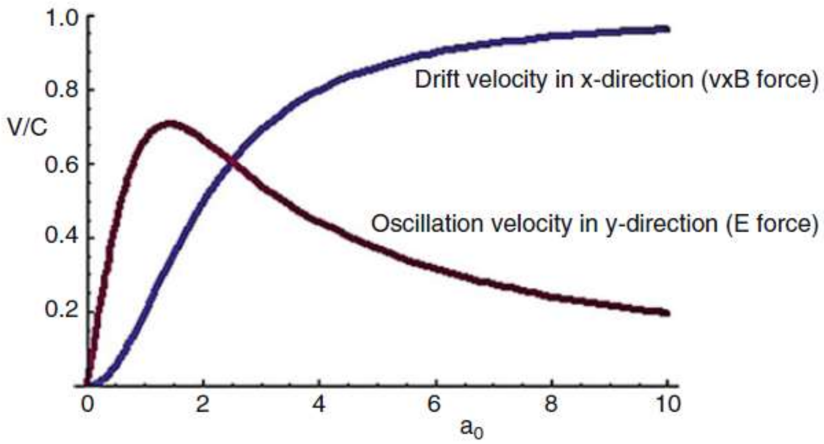
$\gamma_0 \sim 40$

M. Iwamoto et al., *Precursor Wave Amplification by Ion–Electron Coupling through Wakefield in Relativistic Shocks,* The Astrophysical Journal Letters, 883:L35, (2019).



Relativistic EM waves (Lasers)
= Relativistic shocks =





$$\boldsymbol{E}'_\perp = \boldsymbol{E}_\parallel + \gamma_0(\boldsymbol{E}_\perp + \boldsymbol{V}_0 \times \boldsymbol{B}_\perp)$$

$$E'_\perp = \gamma_0(1-\beta_0)E_\perp \qquad \gamma_0(1-\beta_0) = \sqrt{\frac{1-\beta_0}{1+\beta_0}}$$

$$(\omega', k') = \sqrt{\frac{1-\beta_0}{1+\beta_0}}(\omega, k)$$

$$A = A_0 \cos(kx - \omega t)$$

$$a_0 = \frac{eA_0}{mc} = \frac{eE_0}{mc\omega} = \frac{v_{os}}{c}$$

Strength parameter

Lorentz invariant

$$a_0 = 0.85\sqrt{I_{18}\lambda_{\mu m}^2}$$

HT book-1, Chapter 5

An electron motion in relativistic laser (Nonlinear)

$$\frac{dp_x}{dt} = -ev_y B_z - eE_x$$

$$\frac{dp_y}{dt} = -eE_y + ev_x B_z$$

$$mc^2 \frac{d\gamma}{dt} = -ev_y E_y - ev_x E_x$$

$$E_y = -\frac{\partial A}{\partial t} \qquad A = A_0 \cos(\xi)$$

$$B_z = \frac{\partial A}{\partial z} \qquad \xi = \omega(t - x/c) + \xi_0$$

$$\frac{dp_x}{dt} = -\beta_y \frac{\partial a}{\partial x} \qquad \frac{dp_y}{dt} = \frac{da}{dt}$$

$$\frac{d\gamma}{dt} = \beta_y \frac{\partial a}{\partial t}$$

$$p_y - a = \beta \qquad \gamma - p_x = \alpha$$

$$p_x = \frac{1}{2\alpha} p_y^2 + \frac{1 - \alpha^2}{2\alpha}$$

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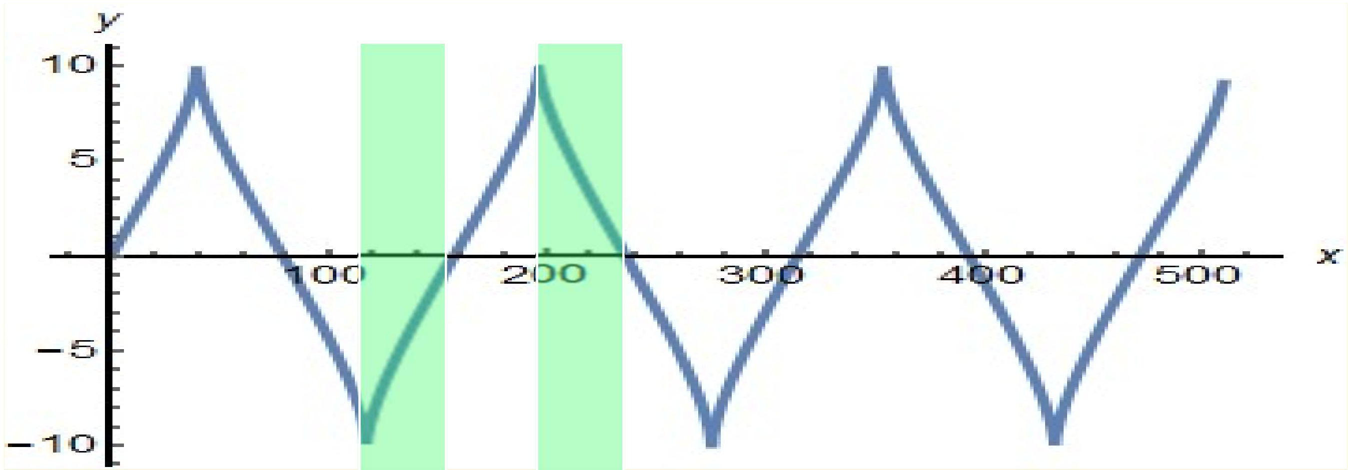
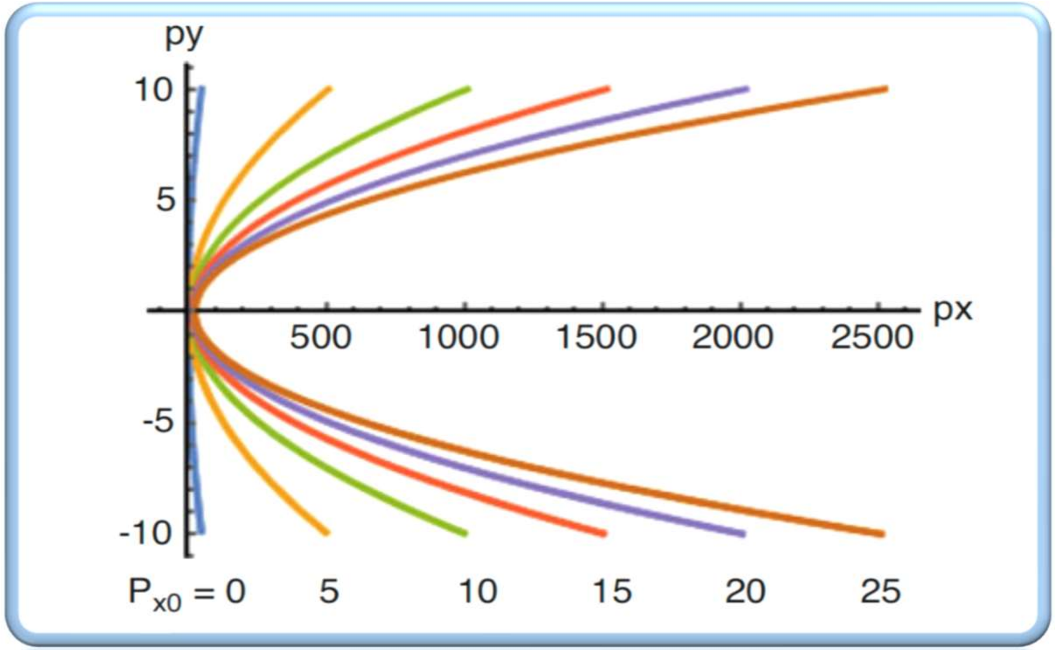
Solution of an electron motion

Incident laser

acceleration phase



Non-linear oscillation



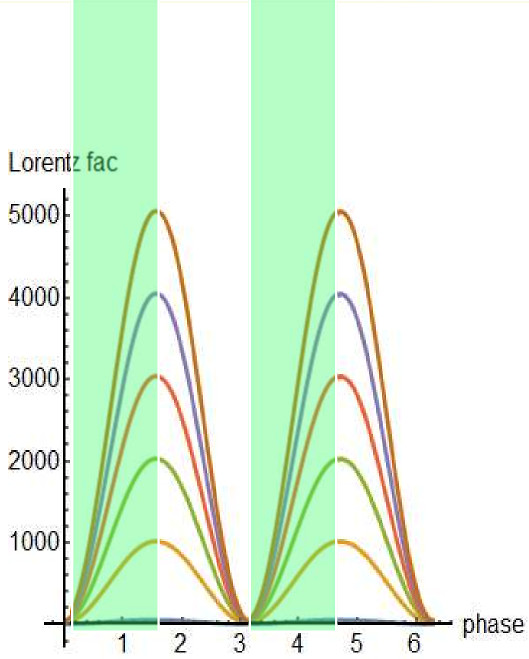
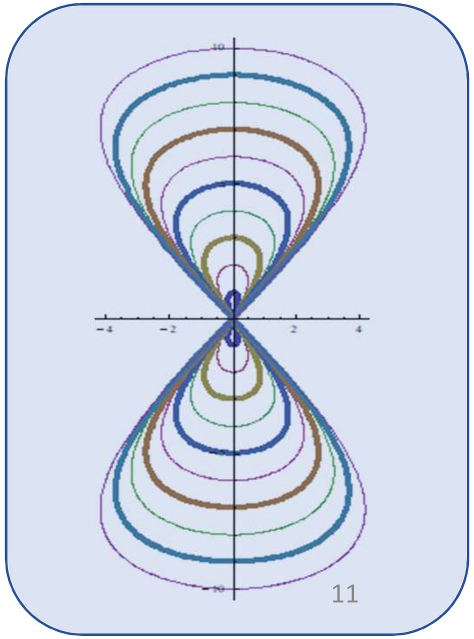


Figure of 8 motion



Motion is chaotic due to reflected laser and filamentation

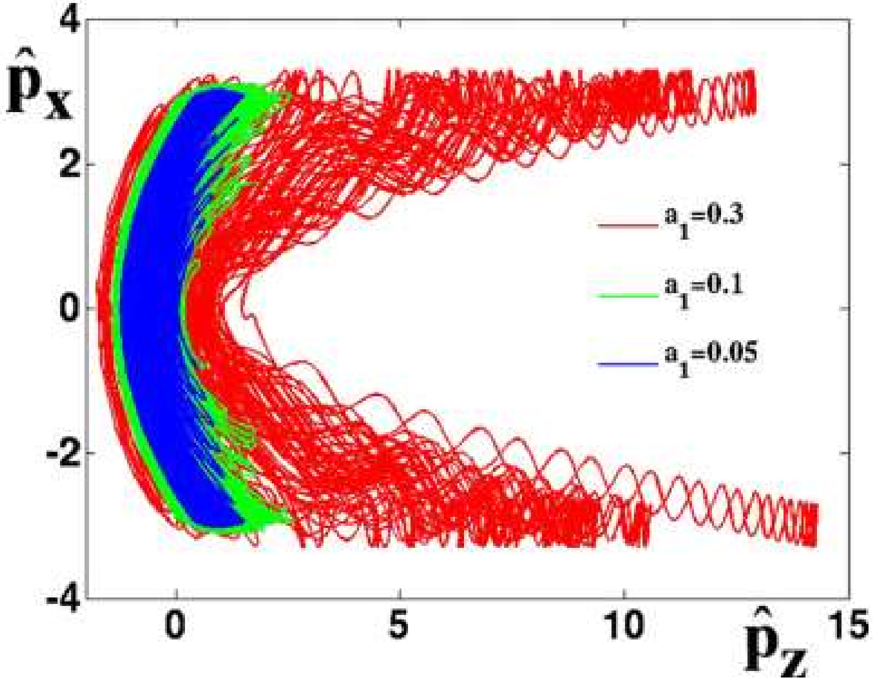
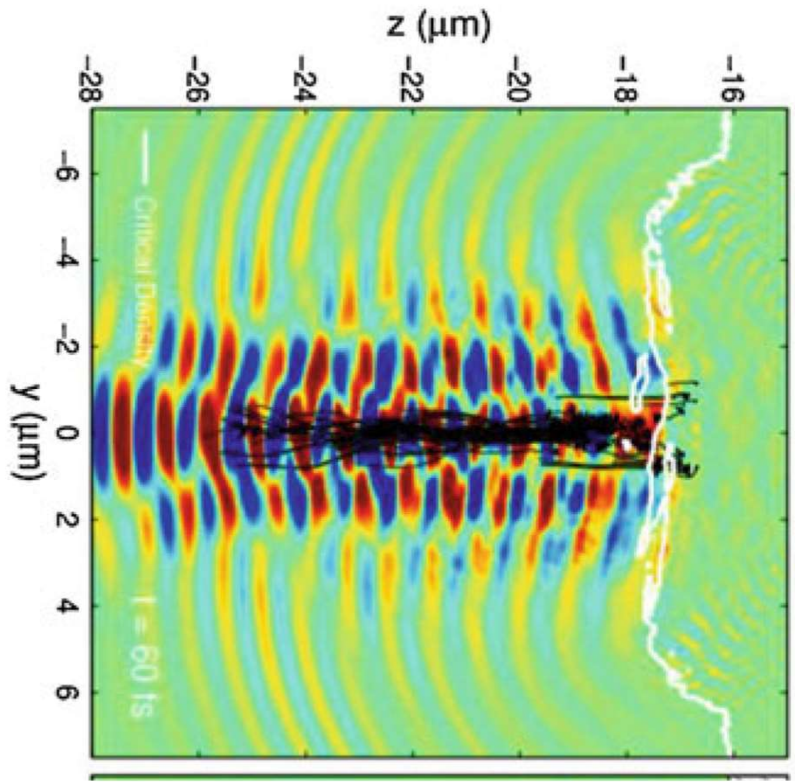


FIG. 6. a = 3, $P_\perp = 0$, $\gamma_0 = \sqrt{1+a^2}$ (initial value of γ). Coordinates of the mechanical momentum of a single charged particle for three values of a_1.



S. Rassou, A. Bourdier, and M. Drouin, Phys. Plasmas 21, 083101(2014)

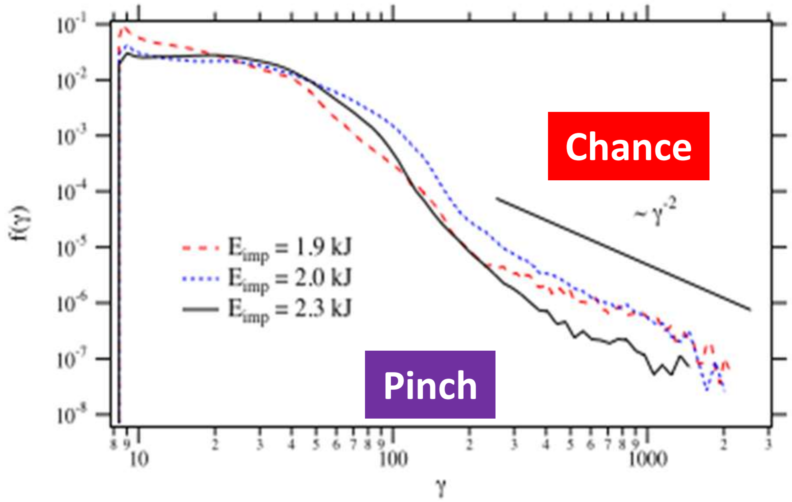
HT book-1, Chapter 9

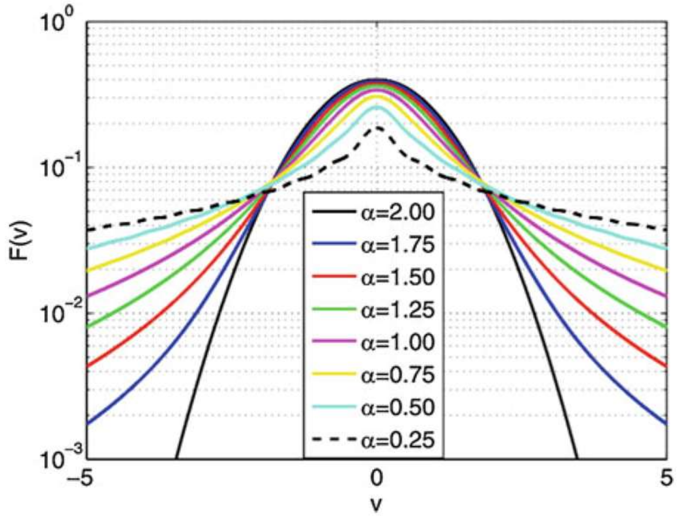
Levy's nonlocal transport (FFPE) can explain the non-thermal components

$$\frac{\partial}{\partial t} f(p,t) = D \frac{\partial^2}{\partial p^2} f(p,t), \qquad D = \left\langle \frac{(\Delta p)^2}{2\Delta t} \right\rangle$$

$$\frac{\partial^\alpha}{\partial |p|^\alpha} \equiv \frac{1}{2\pi} \int_{-\infty}^{\infty} |k|^\alpha e^{-ikp} dk \qquad -k^2 \quad \Rightarrow \quad -|k|^\alpha$$

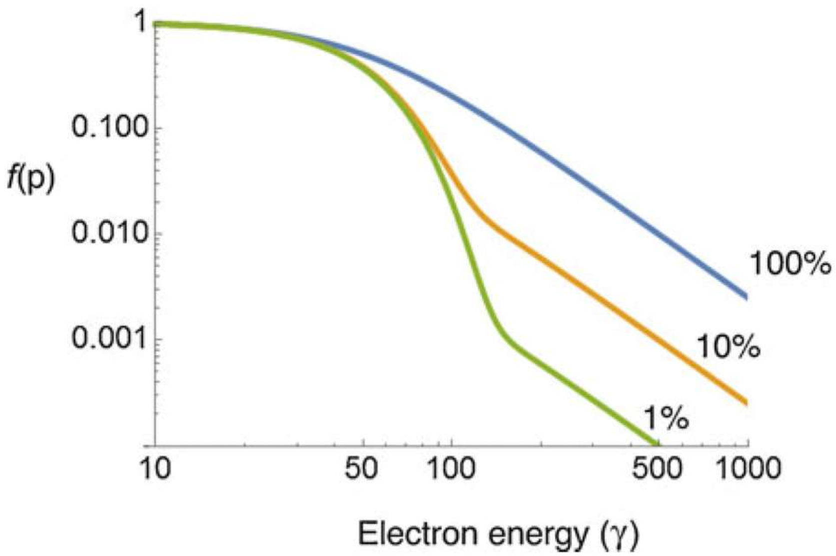
$$\frac{\partial}{\partial t} f = D \frac{\partial^\alpha}{\partial |p|^\alpha} f \qquad f^\alpha(p,t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \exp\left(-Dt|k|^\alpha + ikp\right) dk$$





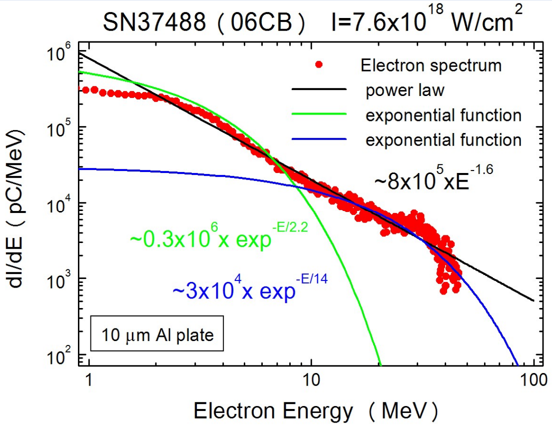
C. Tsallis et al., Phys. Rev. Lett. 75, 3589 (1995)

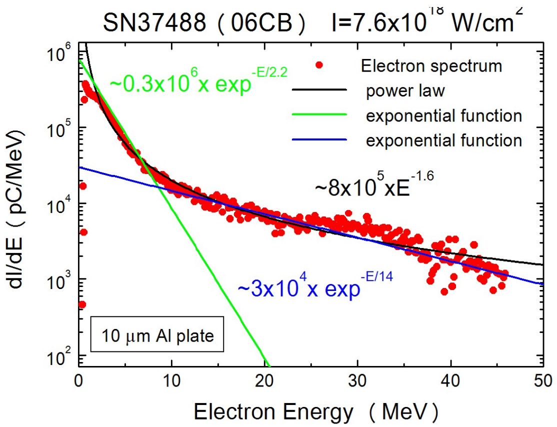
HT book-1, Chapter 9

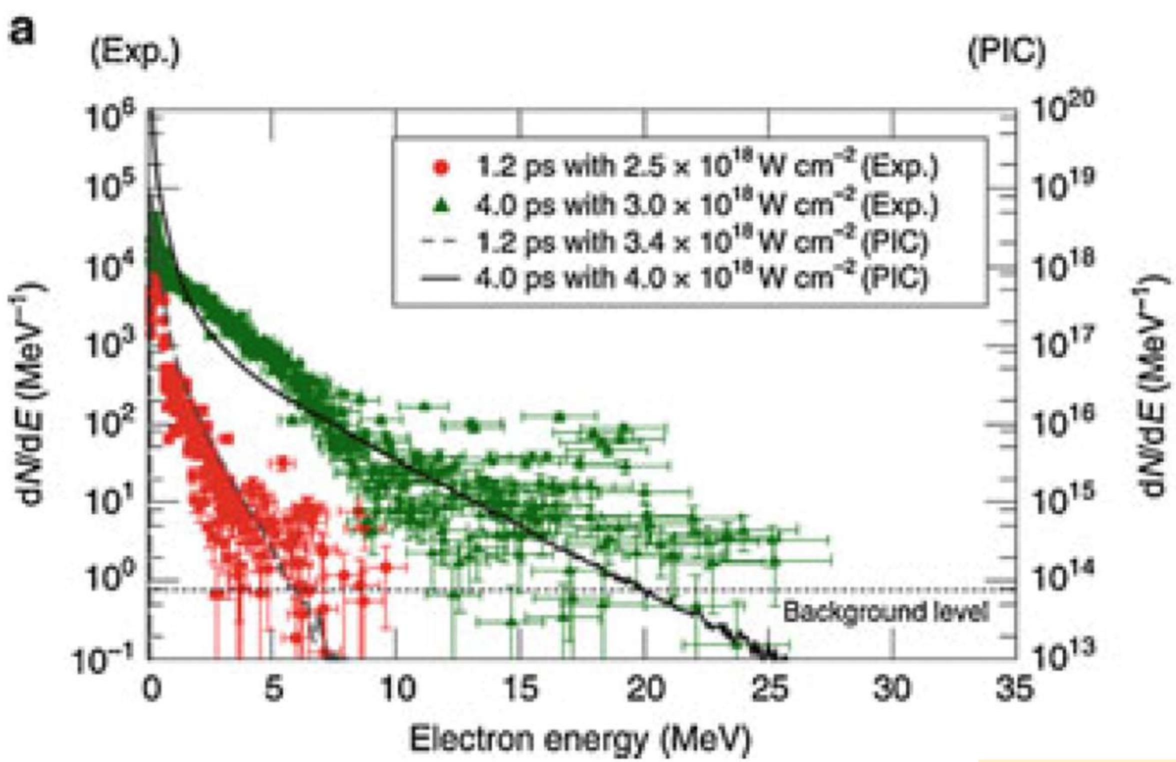


J. Anderson et al., Phys. Plasmas 21, 122109 (2014)

LFEX experiment (ILE) can be explained by chaotic heating with relativistic intensity lasers







HT book-1, p. 353

S. Kojima, *et al. Electromagnetic field growth triggering super-ponderomotive electron acceleration during multi-picosecond laser-plasma interaction. Commun Phys* **2,** 99 (2019).

EM waves induced by collisionless shocks in Space

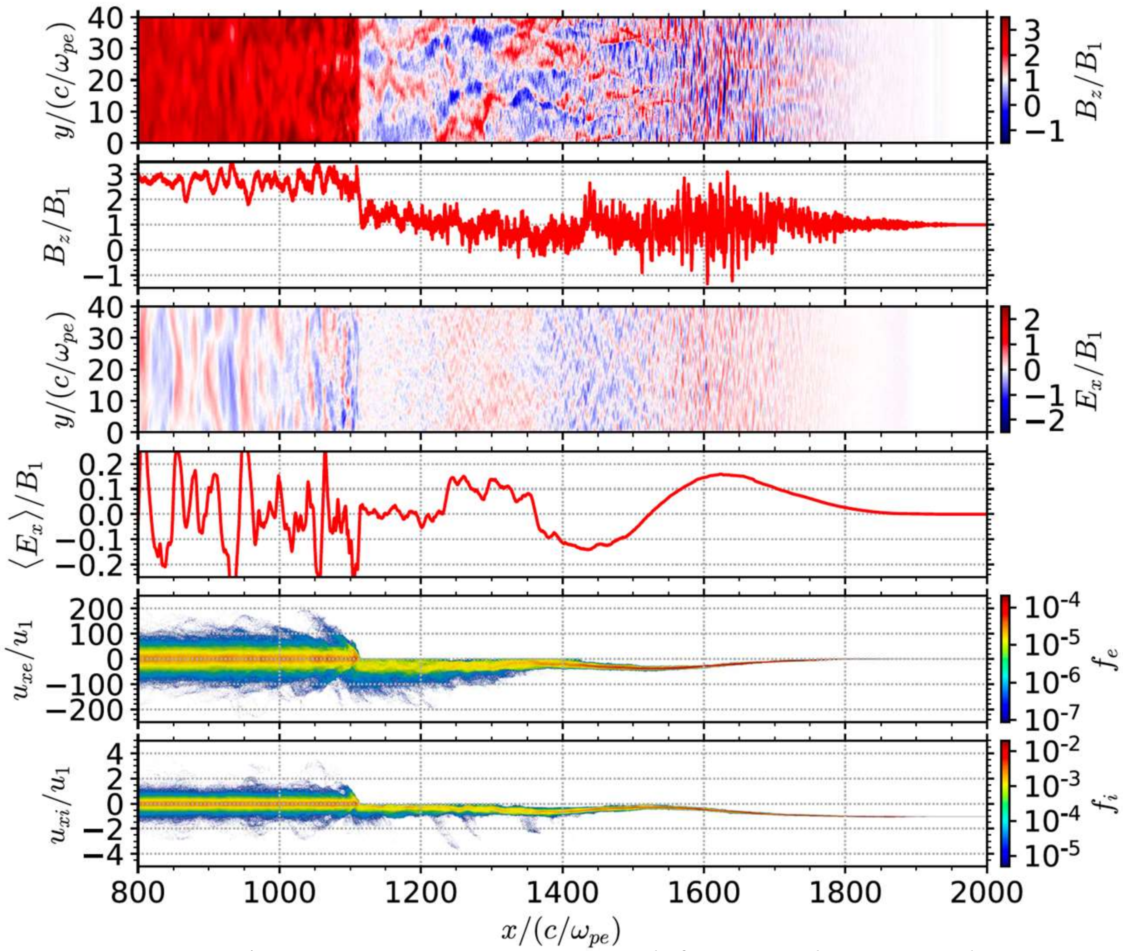


Figure 1. Shock structure for σe = 5 at ωpet = 2000. The out-of-plane magnetic field Bz, the 1D profile of Bz, the longitudinal electric field Ex, the y-averaged electric field Ex, and the phase space plots in the x–uxs plane for electrons and ions are shown.

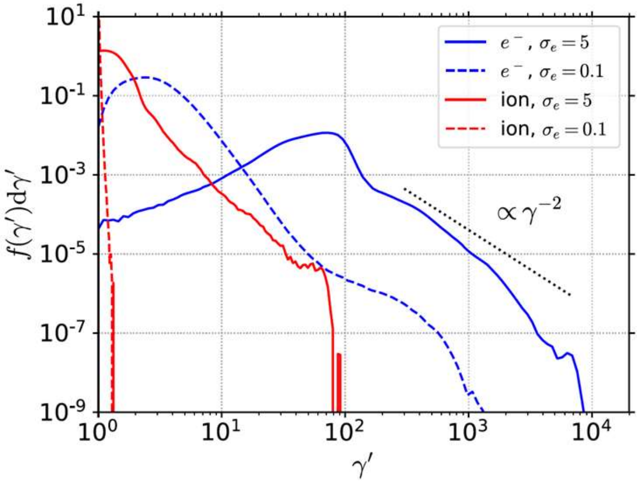


Figure 4. Near-upstream energy spectra of electrons (blue) and ions (red) for $\sigma_e = 5$ (solid lines) and $\sigma_e = 0.1$ (dashed lines) measured in the proper frame.

M. Iwamoto et al., *Precursor Wave Amplification by Ion–Electron Coupling through Wakefield in Relativistic Shocks,* The Astrophysical Journal Letters, 883:L35, (2019).

HT book-1, p. 354

Proposal to the NIFS unit

- Study the theory of chaotic acceleration of electrons by relativistic EM waves
- Relate the theory to the physical mechanism of cosmic-ray acceleration in relativistic regime ($E > 10^{15}$ eV)
- Carry out big computing to visualize the physical mechanism
- Design a verification experiment with reasonable facility parameters
- Perform the experiment with any of international facilities like ELIs in EU.
- Challenge to propose a new theoretical mode and experimental proof to the big community of the cosmic-ray research.