THE UNIVERSITY OF TOKYO

Nonlinear waves and particle acceleration in relativistic shocks: Possibility of "wakefield acceleration" for ultra-high-energy cosmic ray

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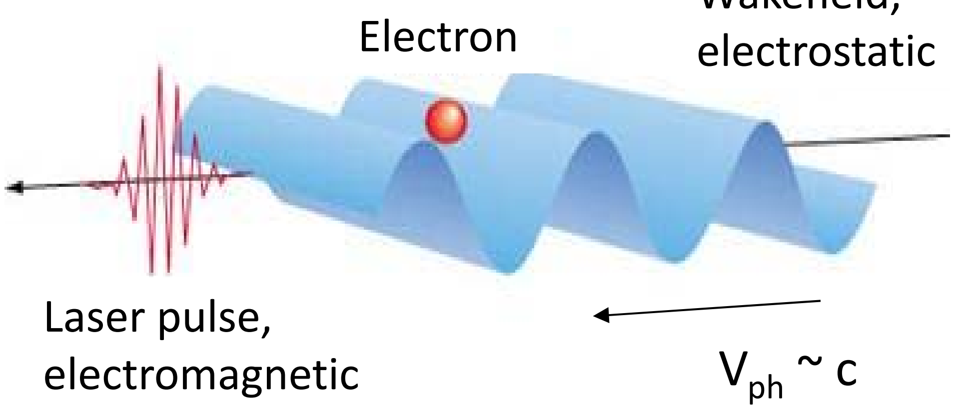
Wakefield Acceleration in Laser Plasma

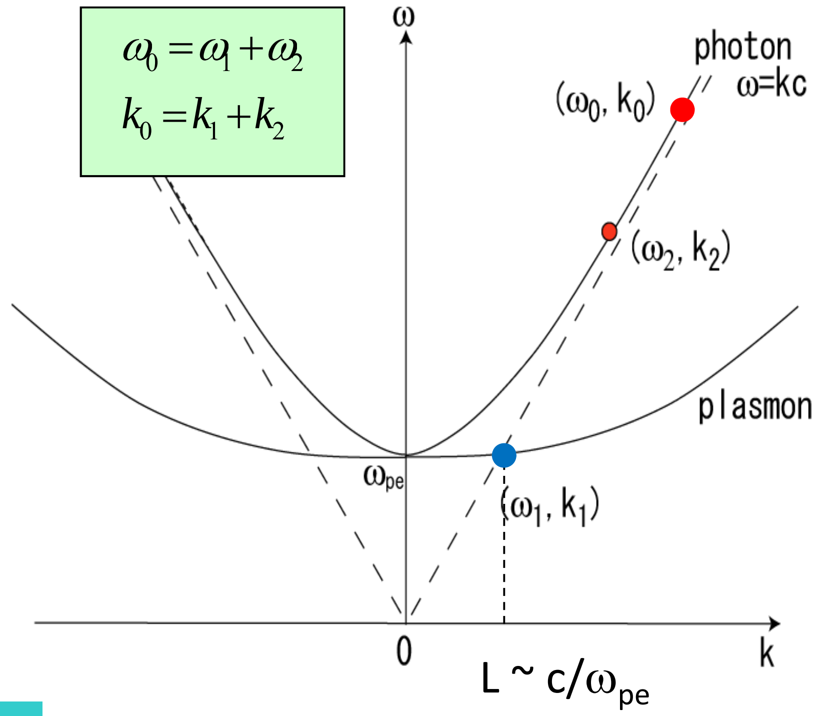
Tajima & Dawson, 1979



$$\varepsilon_{max} \approx eE_{es}L\frac{c}{c - v_{ph}}$$

v_{ph} : propagation velocity of wakefield

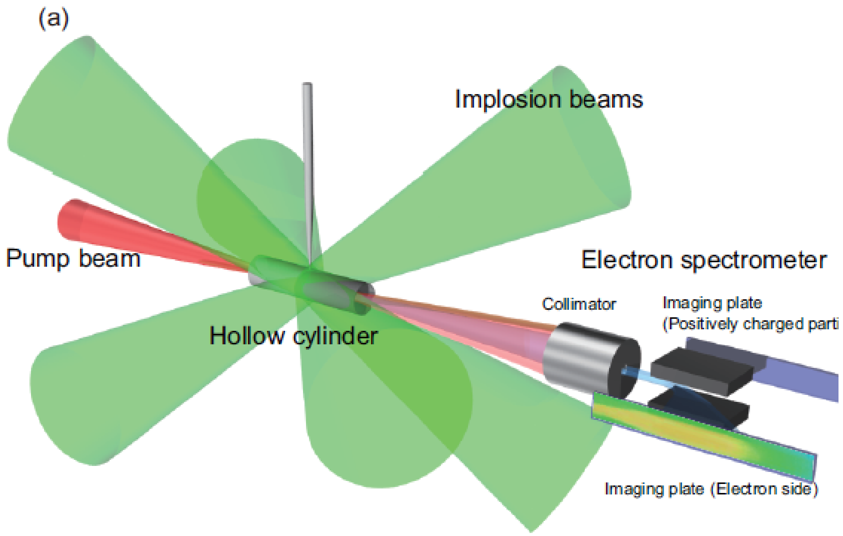
Forward Raman Scattering



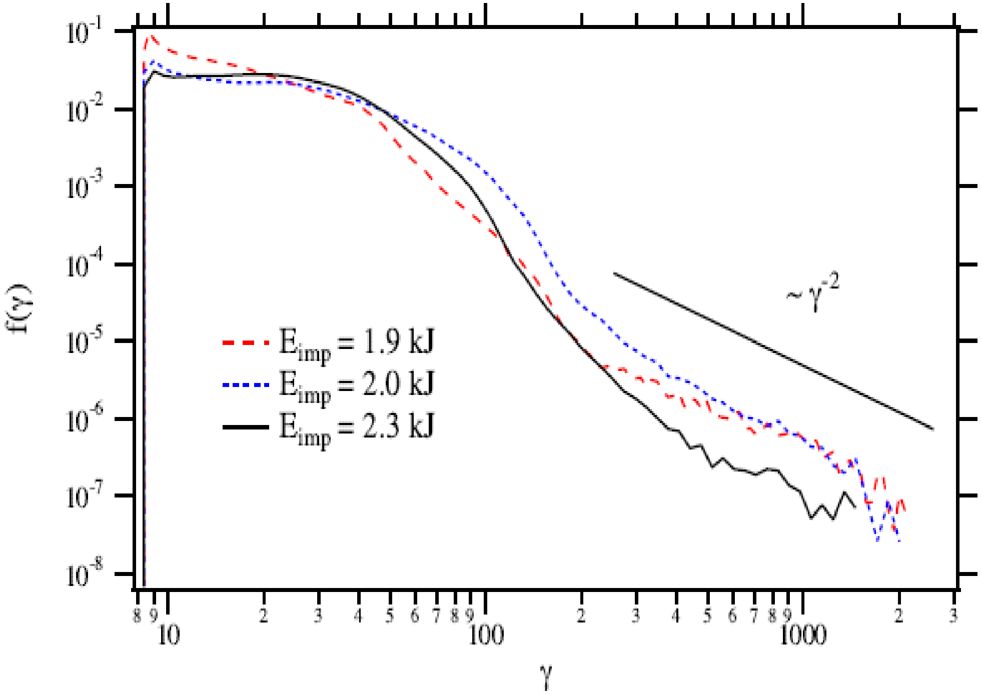
Wakefield Acceleration in Astrophysical Settings

Chen et al. PRL 2003, Lyubursky ApJ 2007, MH ApJ 2008,….

Laboratory Experiment: Incoherent Wakefield Acceleration



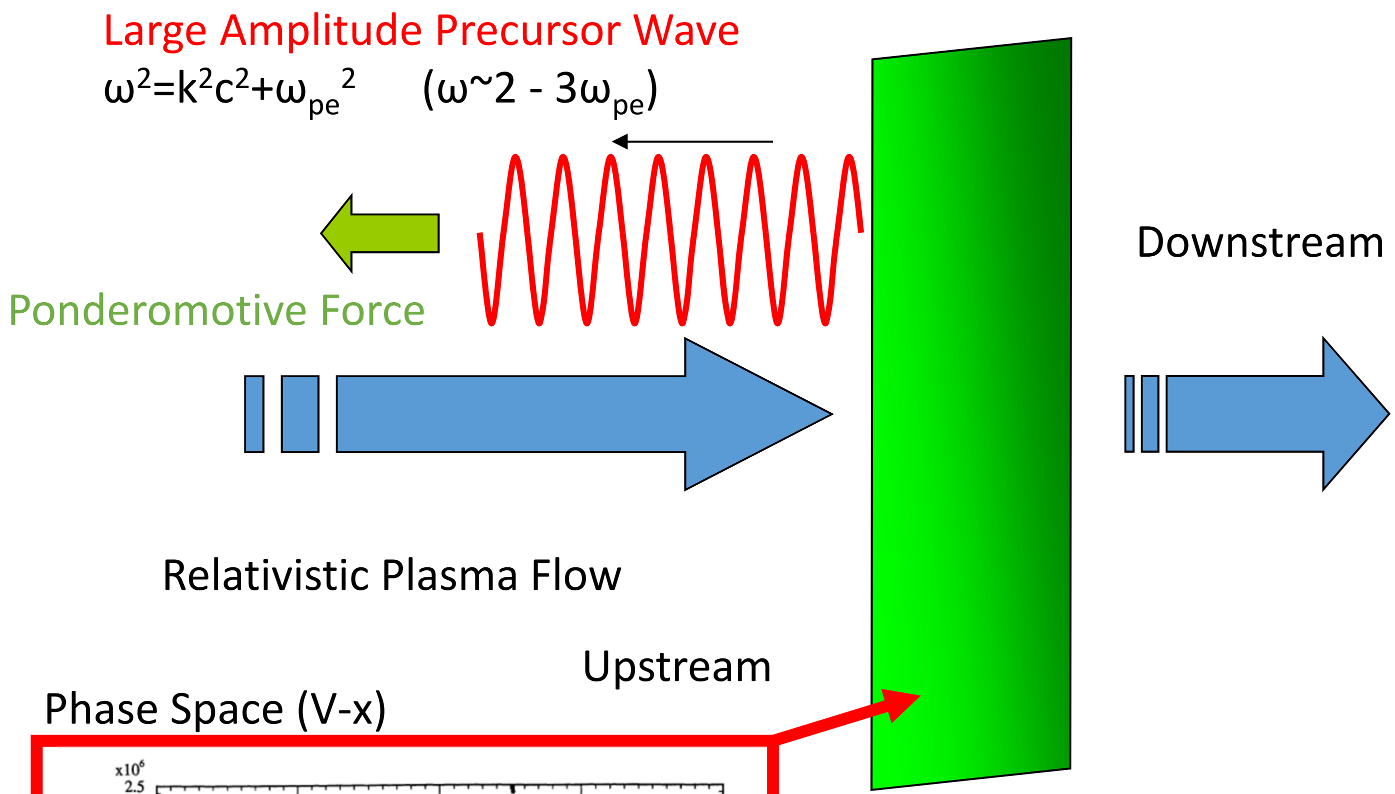
Energy Spectra



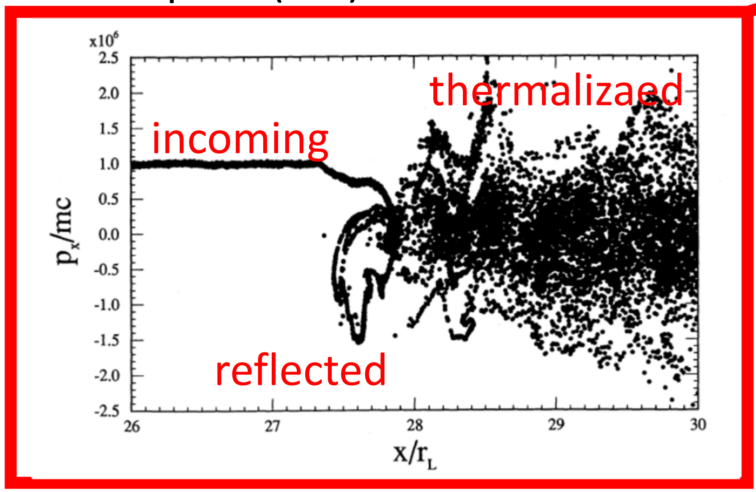
GEKKO XII Laser Plasma Experiment

Kuramitsu et al. PoP (2011)

Precursor Waves in Relativistic Shock



Phase Space (V-x)



"ring distribution" in velocity space,
synchrotron maser instability

Langdon+ PRL 1988; Gallant+ ApJ 1992;
MH+ ApJ 1992

Relativistic Shock: Wakefield Acceleration

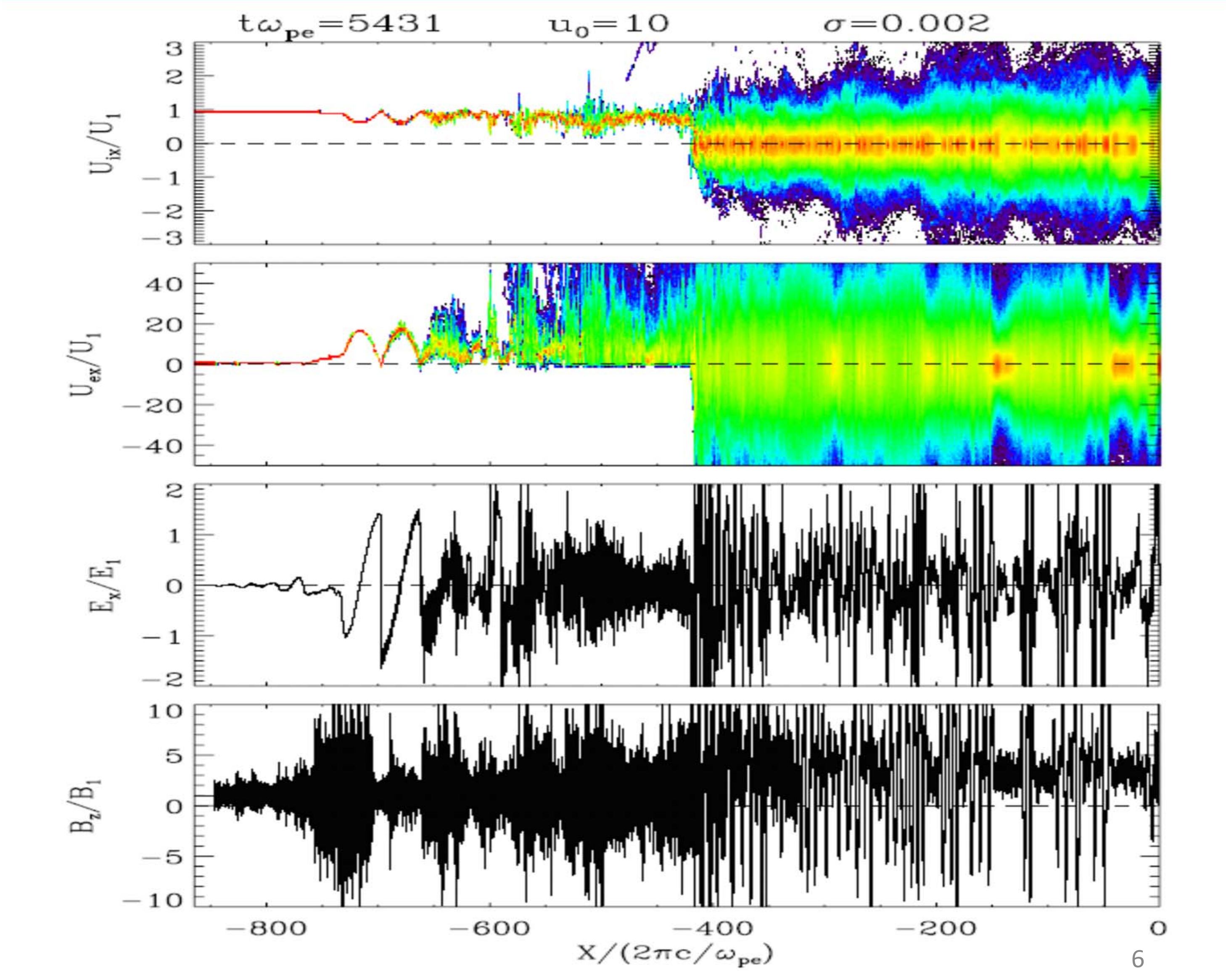
upstream （supersonic flow） downstream （sub-sonic）

$U_{x,ion}$

$U_{x,ele}$

E_x
(ES,plasmon)

B_z
(EM,photon)

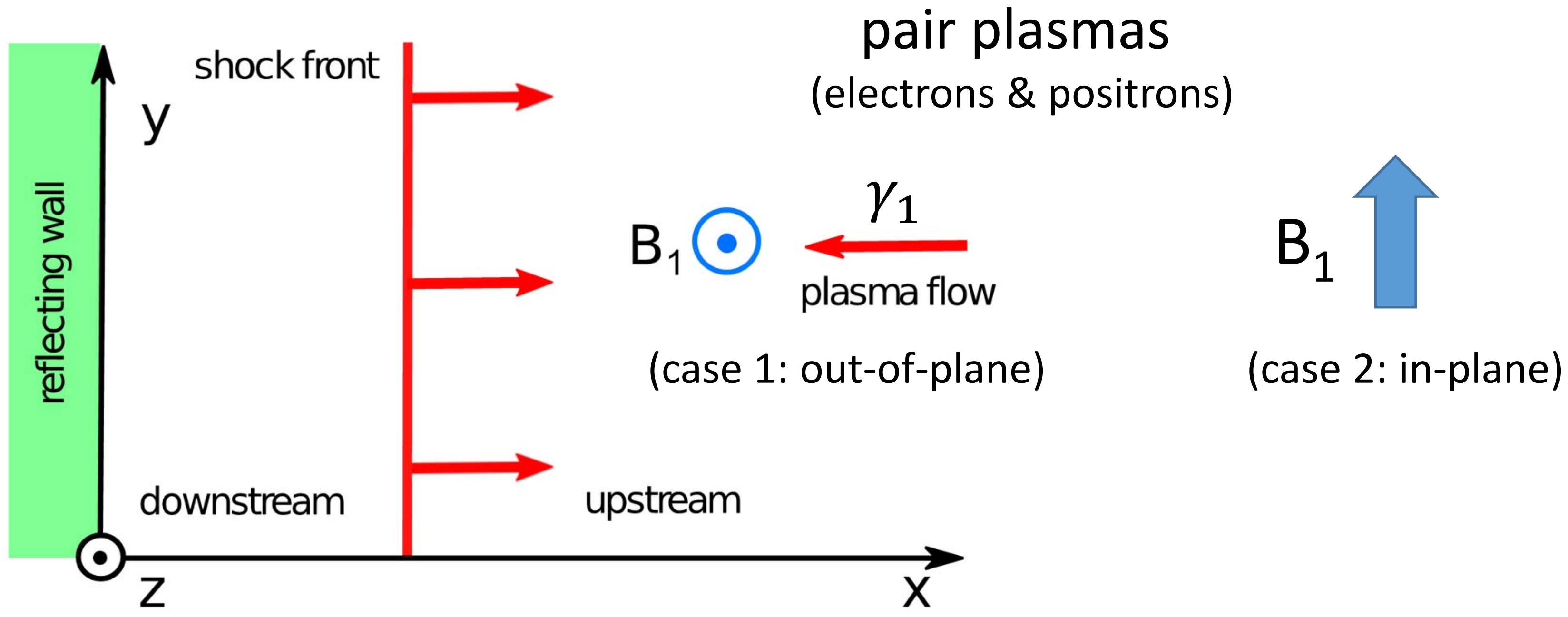


MH ApJ 2008

Open questions after WFA in 1d shock

- Do precursor waves exist in multi-dimensional system?
- Shock front is probably turbulent due to several plasma instabilities such as Weibel instability

Precursor waves in 2d relativistic shocks



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

✓ $\gamma_1 = 40$

✓ $N_x \times N_y = 16384 \times 1680$

✓ $N_1 \Delta x^2 = 64$

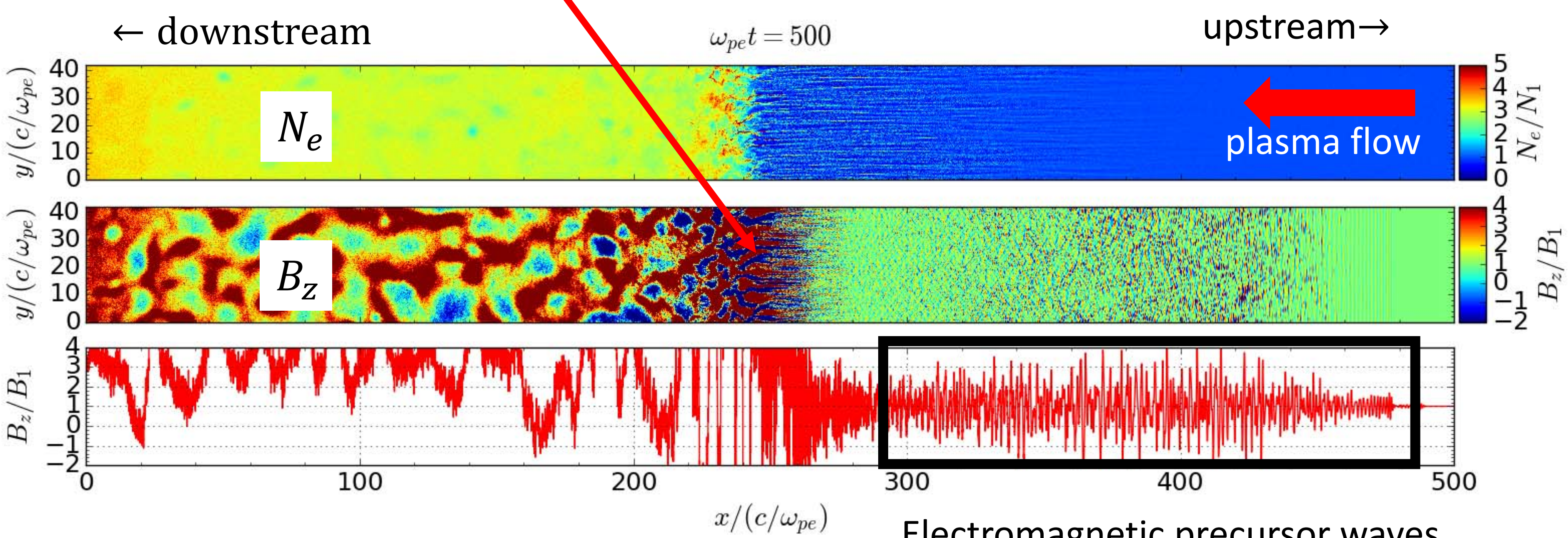
$$\sigma \equiv \frac{\text{Poynting flux}}{\text{kinetic energy flux}} = \frac{B_1^2}{4\pi\gamma_1 N_1 m_e c^2} = \frac{1}{M_A^2}$$

M_A: Alfvén Mach Number

Iwamato+, ApJ 2017 & ApJ 2018

Precursor wave are persistent !

Weibel Instability due to incoming & reflected ions (temperature anisotropy)

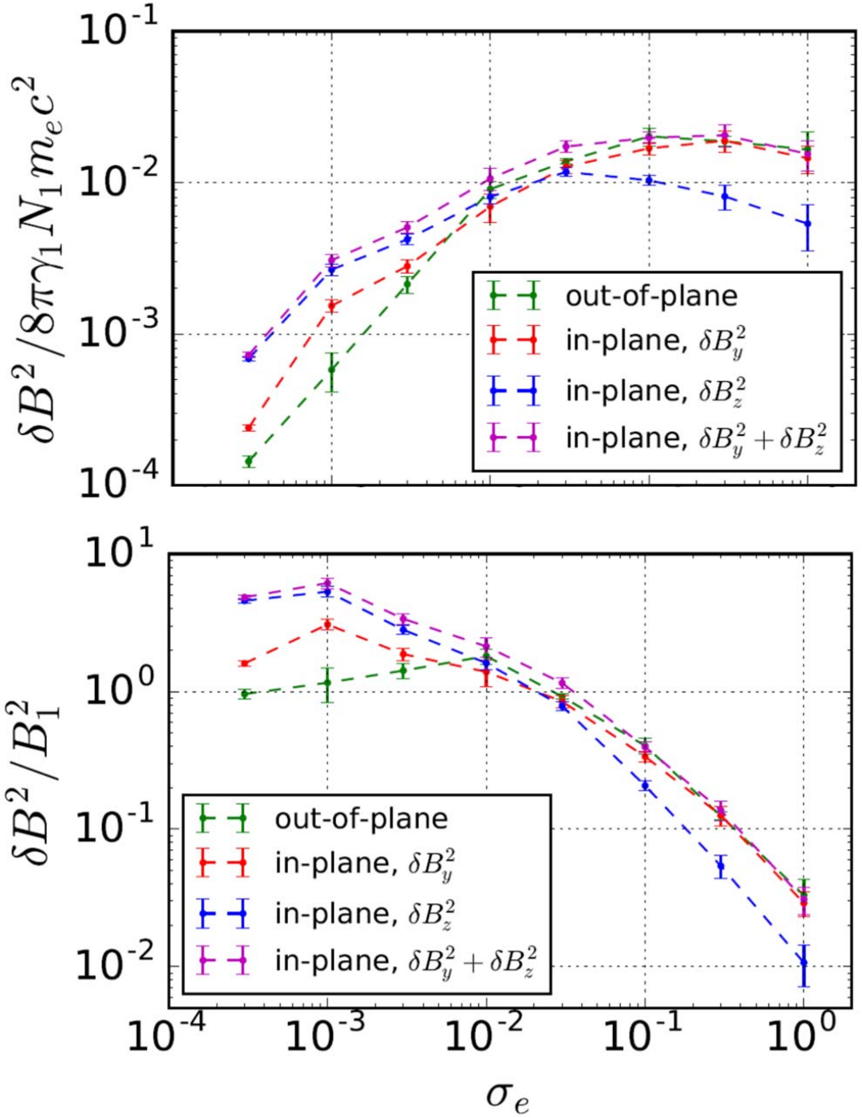


Electromagnetic precursor waves by synchrotron maser instability

$$\sigma = \frac{B_1^2}{4\pi\gamma_1 N_1 m_e c^2} = \left(\frac{\Omega_c}{\Omega_p}\right)^2$$
$$= 3 \times 10^{-3}$$

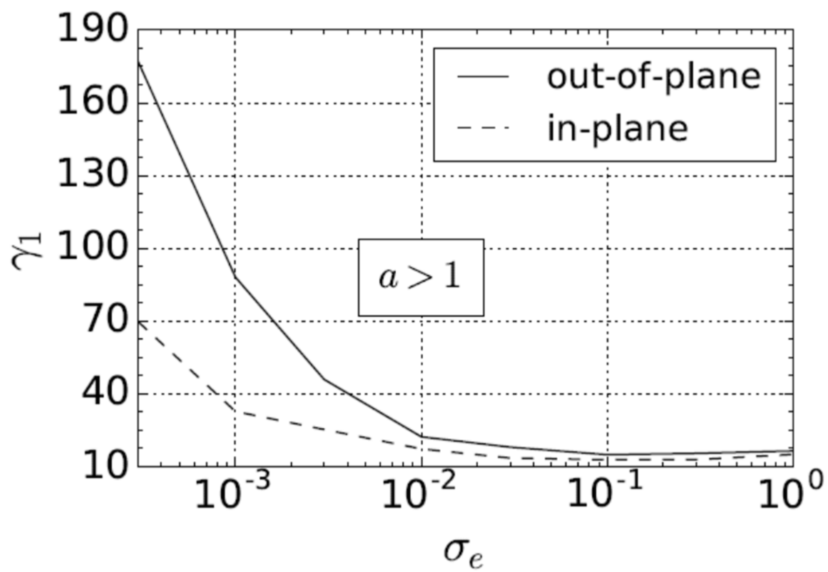
✓ Surprisingly, large-amplitude precursor waves can be generated in two-dimensional shocks

σ dependence of precursor waves: both in-plane & out-of-plane cases



Strength Parameter:

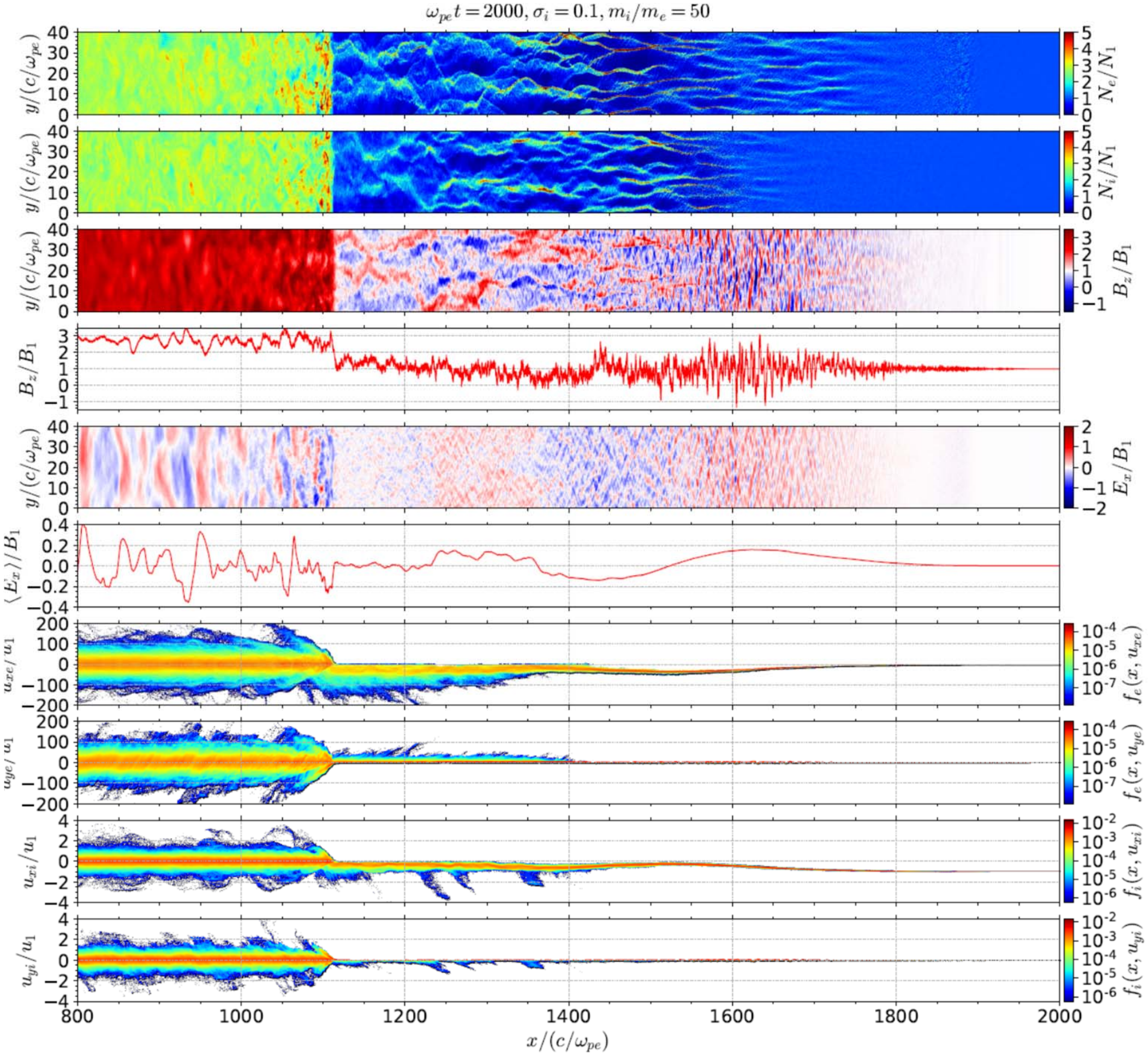
$$a = eE_w/m_e c\omega \approx \gamma_1\sqrt{\varepsilon_{conv}}$$



Iwamato+, ApJ 2018

WFA in 2d p^+-e^- shock (preliminary)

$\sigma_i = 0.1$, $m_i/m_e=10$, $\gamma=40$



e^- density

p^+ density

B_z

B_z (y=20)

E_x

<E_x>

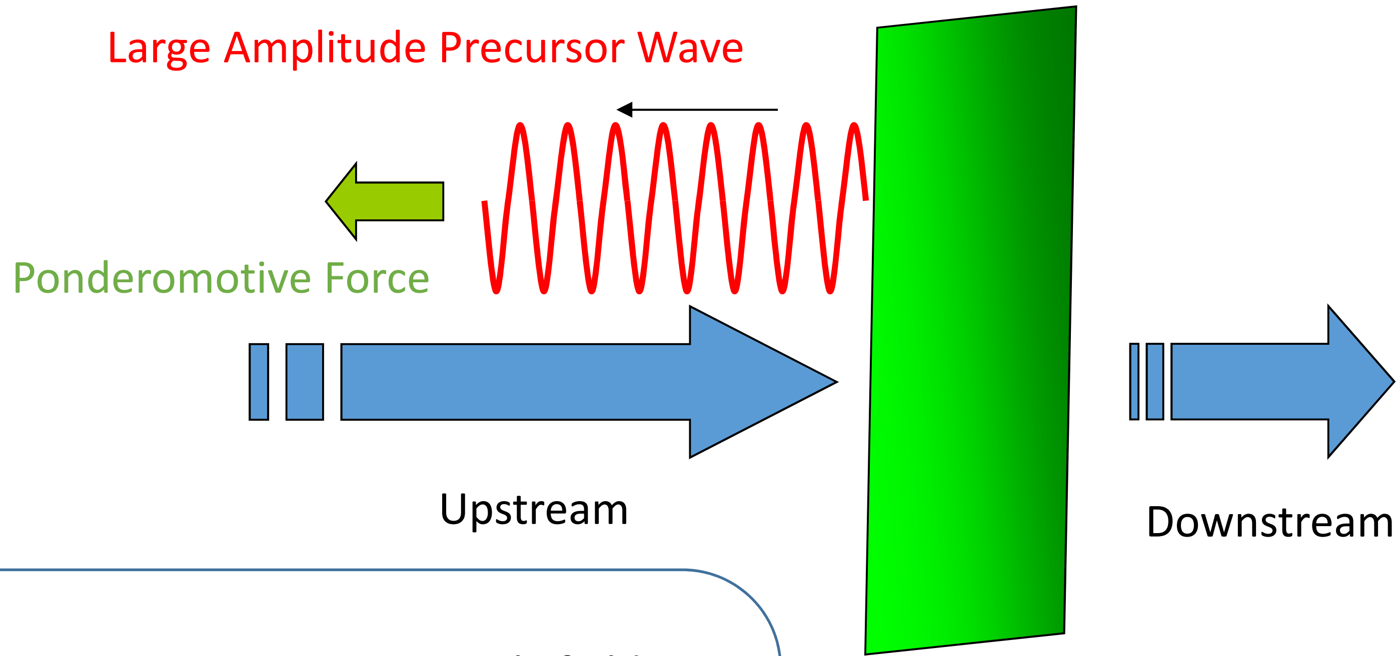
U_x for e^-

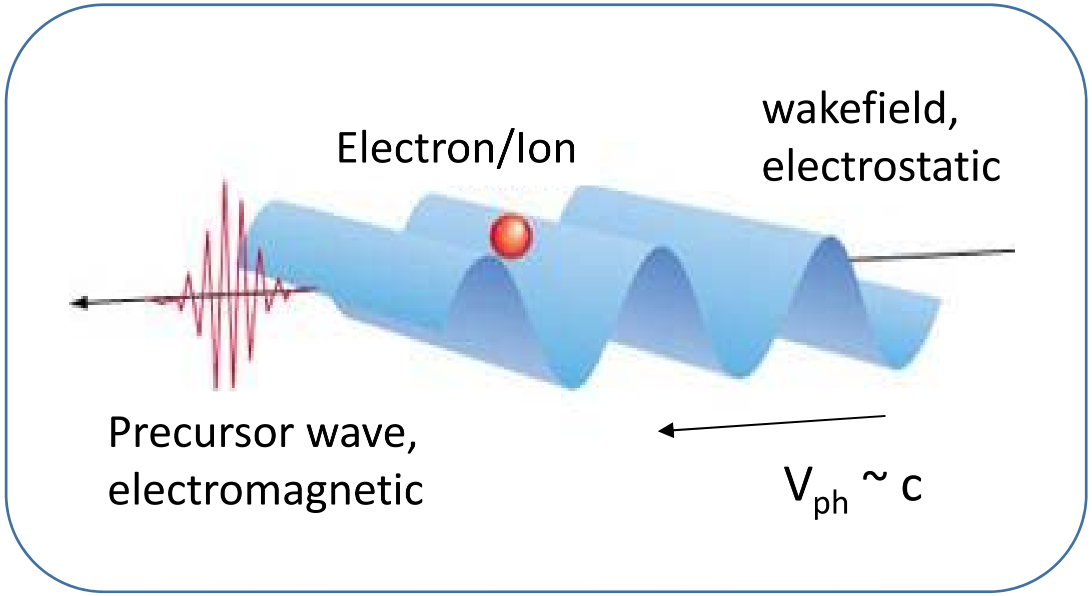
U_y for e^-

U_x for p^+

U_y for p^+

Possibility of Ion Acceleration ?

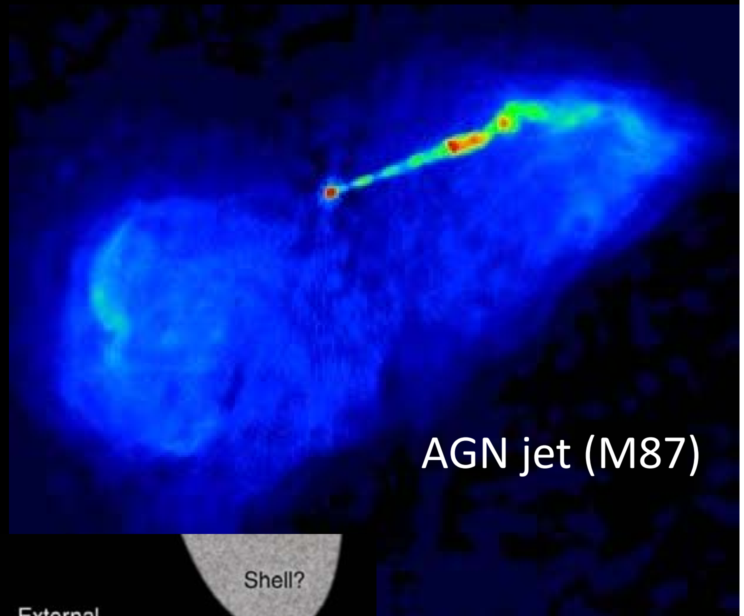




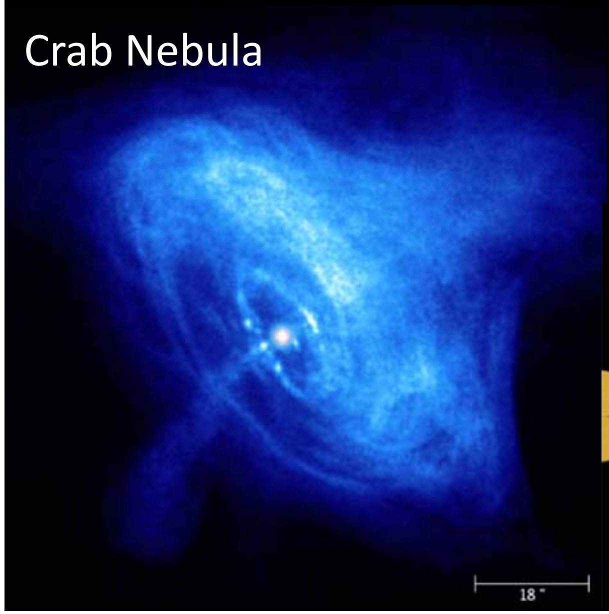
Our proposal:
If GeV protons were injected into upstream, the protons could be accelerated as well …

Summary

- Precursor waves are persistently excited in 2d relativistic shocks
- Electron acceleration can be confirmed in incoherent wakefield
- Possibility of ion acceleration


AGN jet (M87)

Crab Nebula



GRB model