Particle Acceleration and Injection Problem in Shocks

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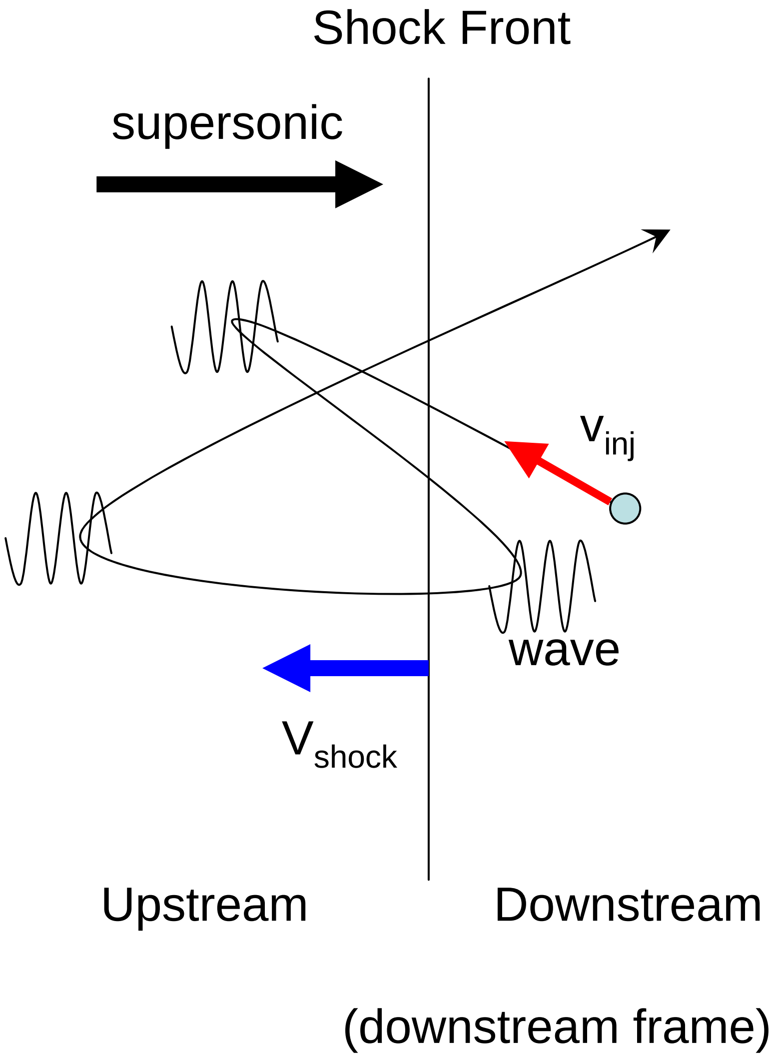
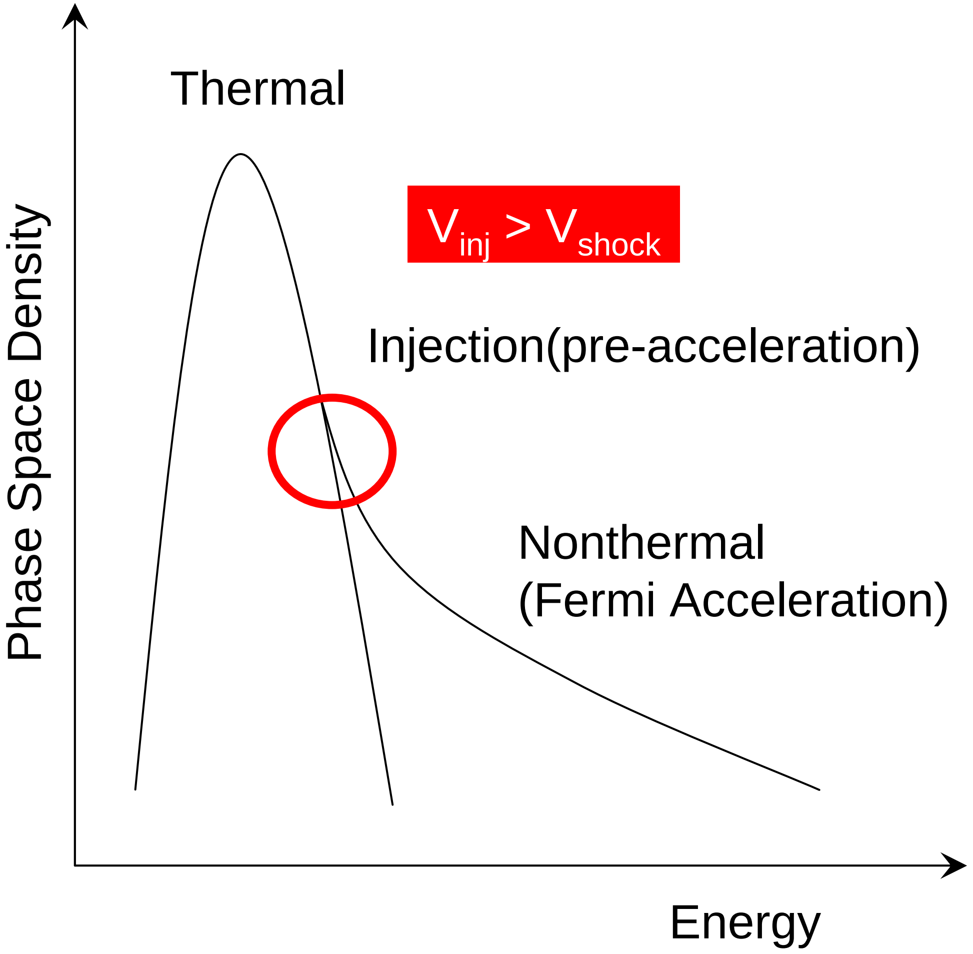
A. Amano, Y. Kuramitsu, T. Kato, T. Ebisuzaki, …

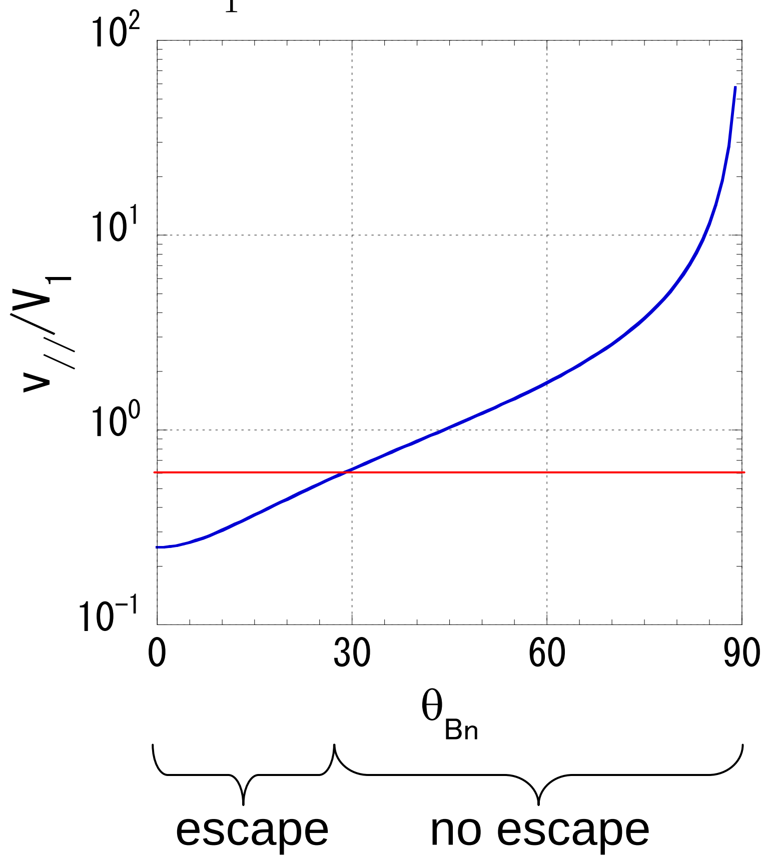
Injection Problem in Fermi Acceleration



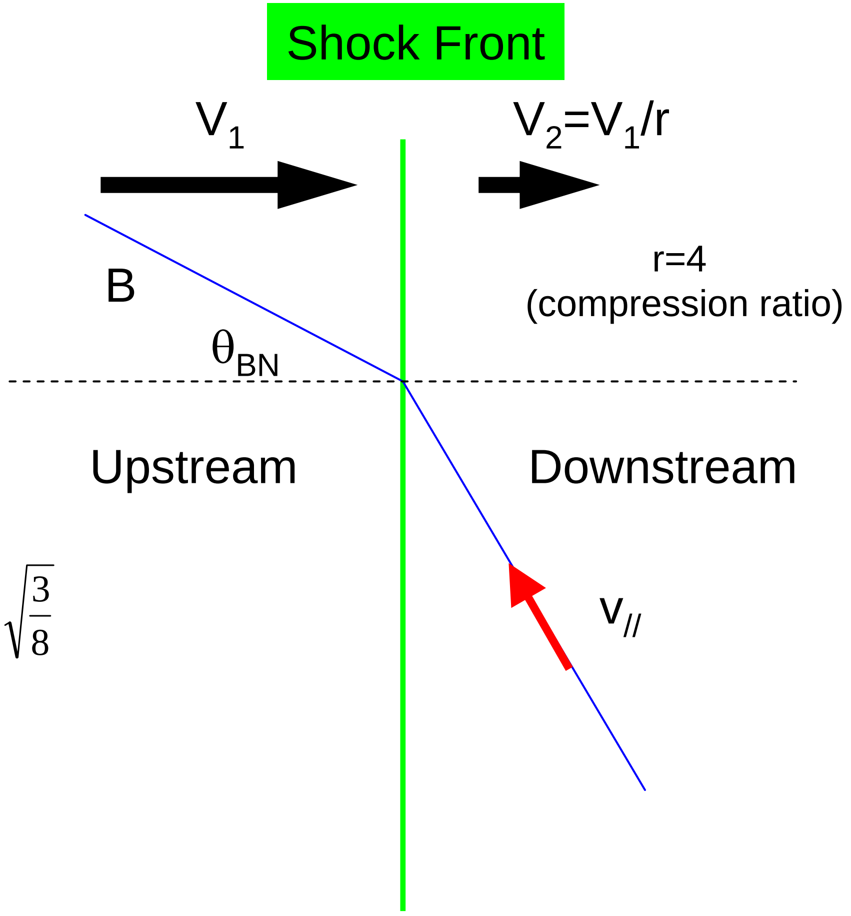


Ion Injection Problem under Magnetic Field

$$\frac{v_{//}}{V_1} > \frac{1}{r}\sqrt{r^2 \tan^2 \theta_{Bn} + 1}$$



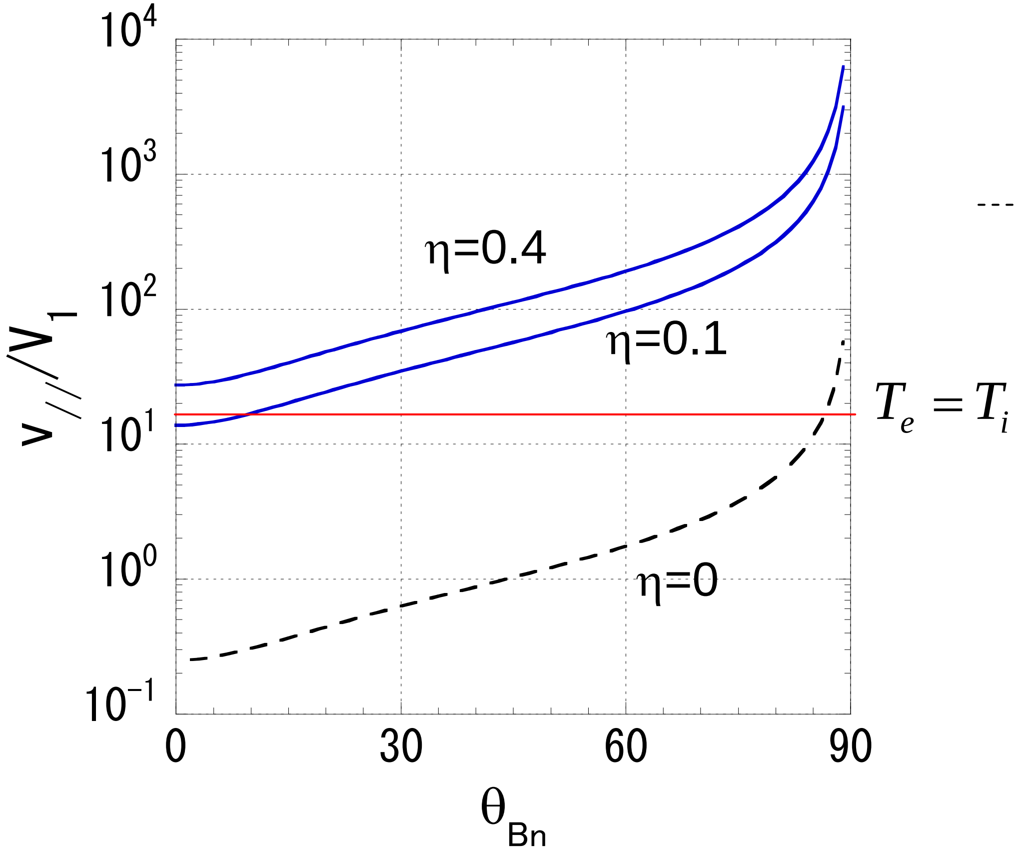
$$v_{th,2}/V_1 = \sqrt{\frac{3}{8}}$$

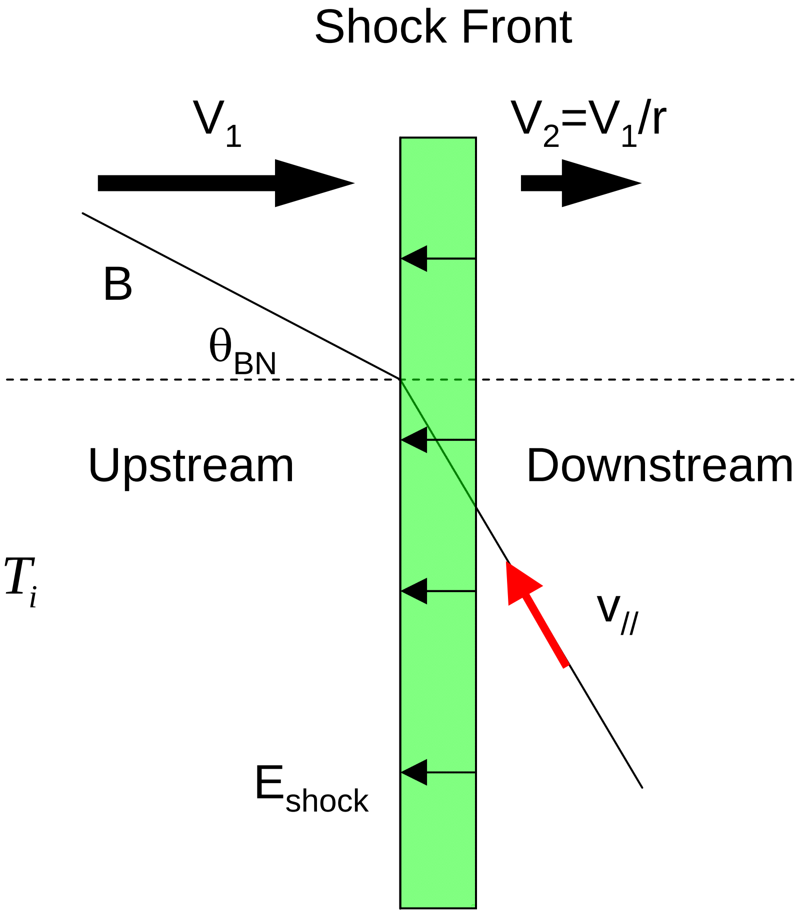


θ_{BN} < 30 → Injection can be explained by thermal plasma,
θ_{BN} > 30 → Additional heating/acceleration is needed.

Electron Injection Problem

$$\frac{v_{//}}{V_1} > \left(\frac{1}{r} + \sqrt{\eta \frac{m_{ion}}{m_{ele}}}\right)\sqrt{r^2 \tan^2 \theta_{Bn} + 1}$$





Electron Injection is Very Difficult

Ambipolar Electric Field (E_{shock})

$$\eta \equiv \frac{2e\phi_{shock}}{m_{ion}V_1^2} \approx 0.1-0.4$$

Pre-Acceleration Process in Shock

- Non-relativistic Shock
  - Shock Drift Acceleration
  - Surfing Acceleration
  - Shock Surface Rippling
  - Turbulence,…..

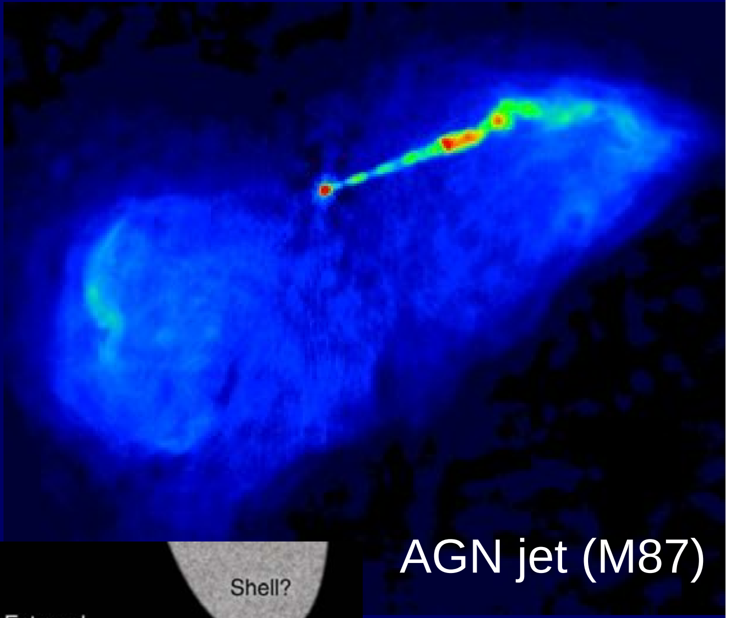
Next Talk
by Amano

- Relativistic Shock
  - Same Processes Above
  - Precursor Wave Acceleration (Wakefield Acceleration)

This Talk

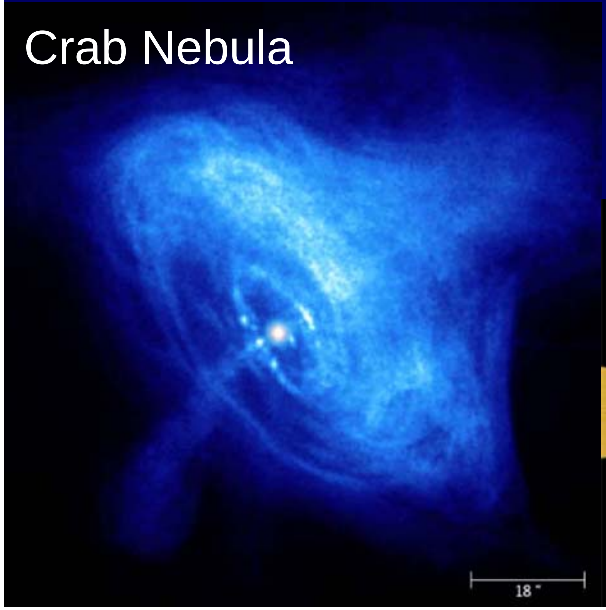
Relativistic Shock

- Extragalactic radio sources (γ ~ 10)
- Gamma ray bursts (γ > 100)
- Pulsars & Winds ($\gamma \sim 10^{6\text{-}7}$)

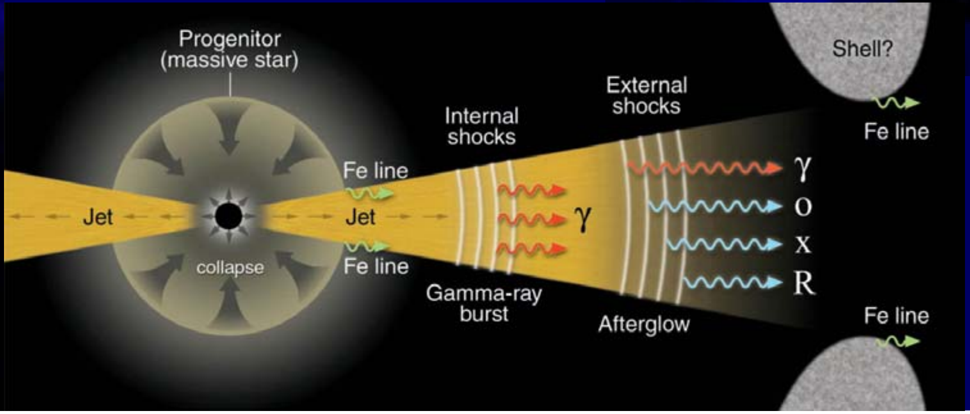


AGN jet (M87)

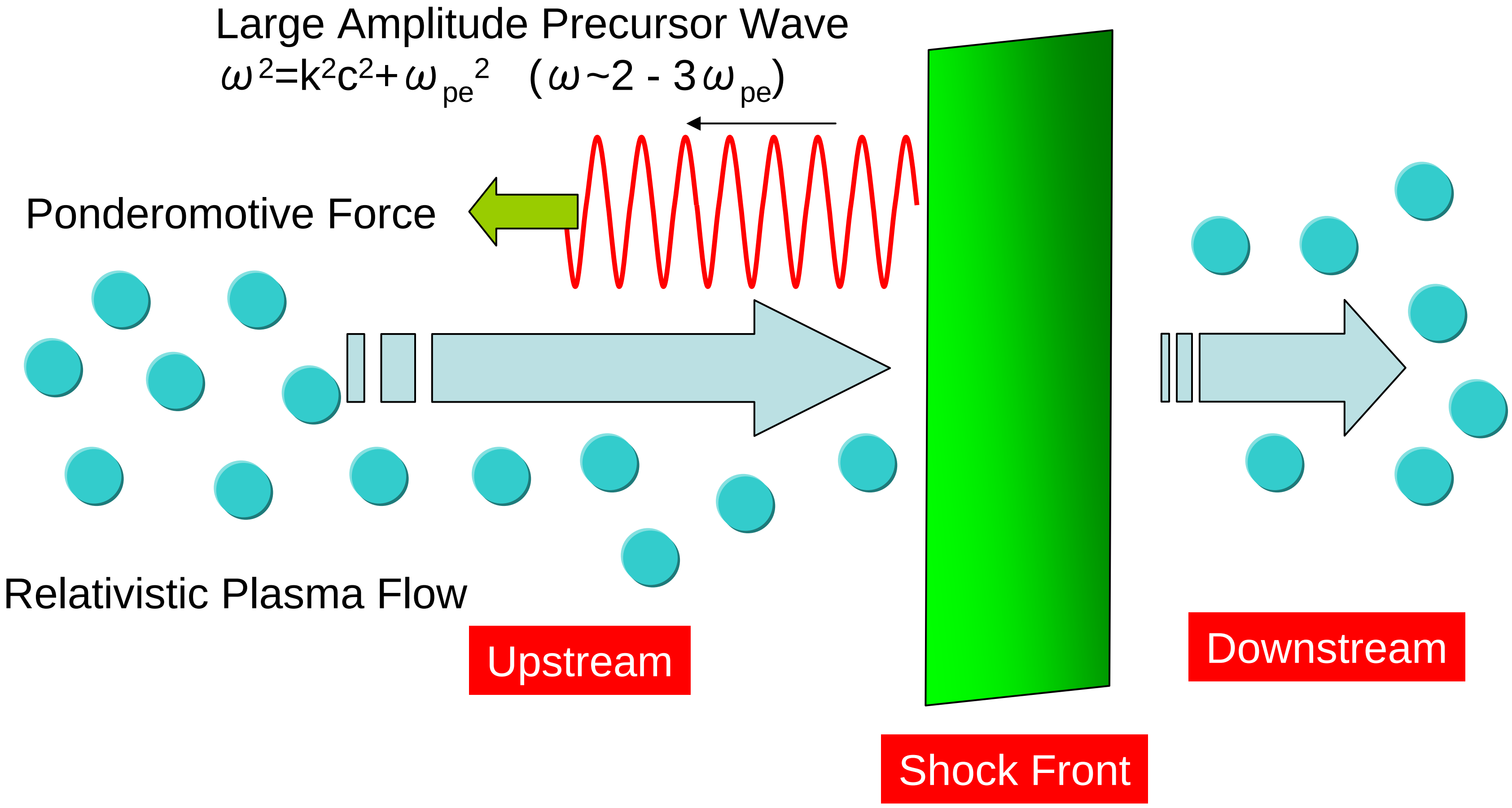
Crab Nebula



GRB model



"Large-Amplitude Precursor Wave" in Relativistic Shock



Large Amplitude Precursor Wave

$\omega^2 = k^2c^2 + \omega_{pe}^2 \quad (\omega \sim 2 - 3\omega_{pe})$

Ponderomotive Force

Relativistic Plasma Flow

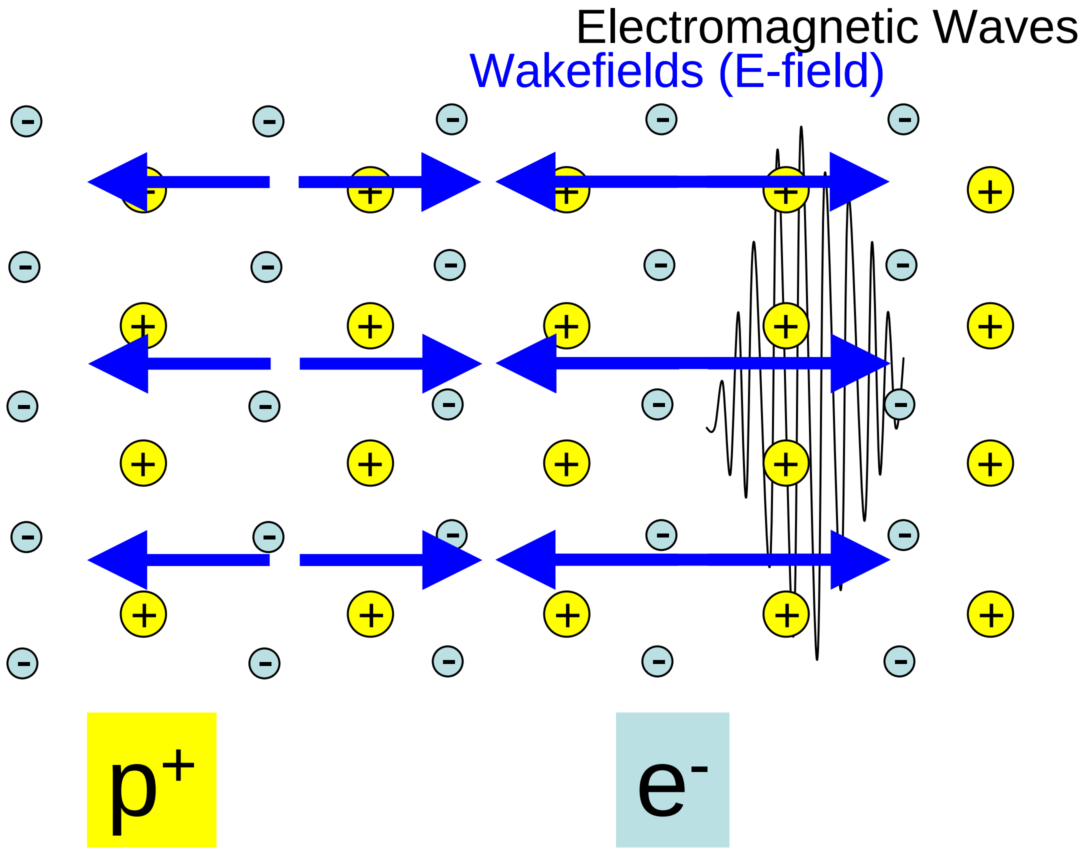
Upstream

Shock Front

Downstream

Langdon et al. PRL (1988), Gallant et al. ApJ(1992), MH et al. ApJ(1992) ….

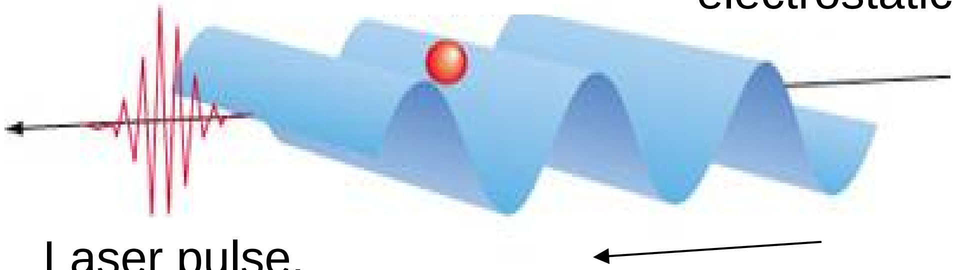
Ponderomotive Force in Precursor Wave



Electromagnetic Waves

Wakefields (E-field)

Wakefield Acceleration in Laboratory Laser Plasma



Electron

Wakefield,
electrostatic

Laser pulse,
electromagnetic

$V_{ph} \sim c$

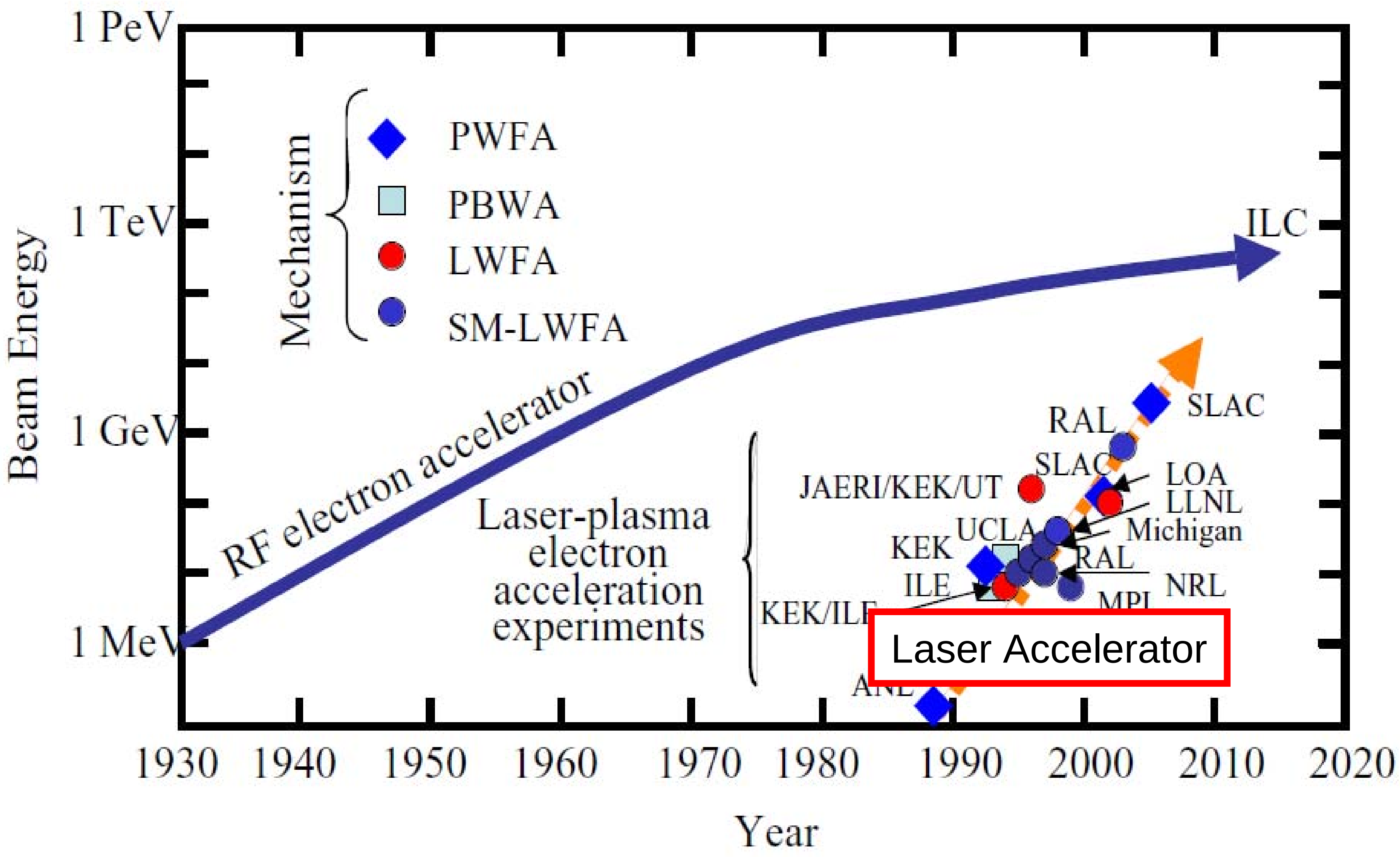
Tajima & Dawson, 1979

2002

Wakefield Acceleration in Relativistic Shock

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

Livingston Chart



Laser Accelerator

Particle (PIC) Simulation of Relativistic Shock

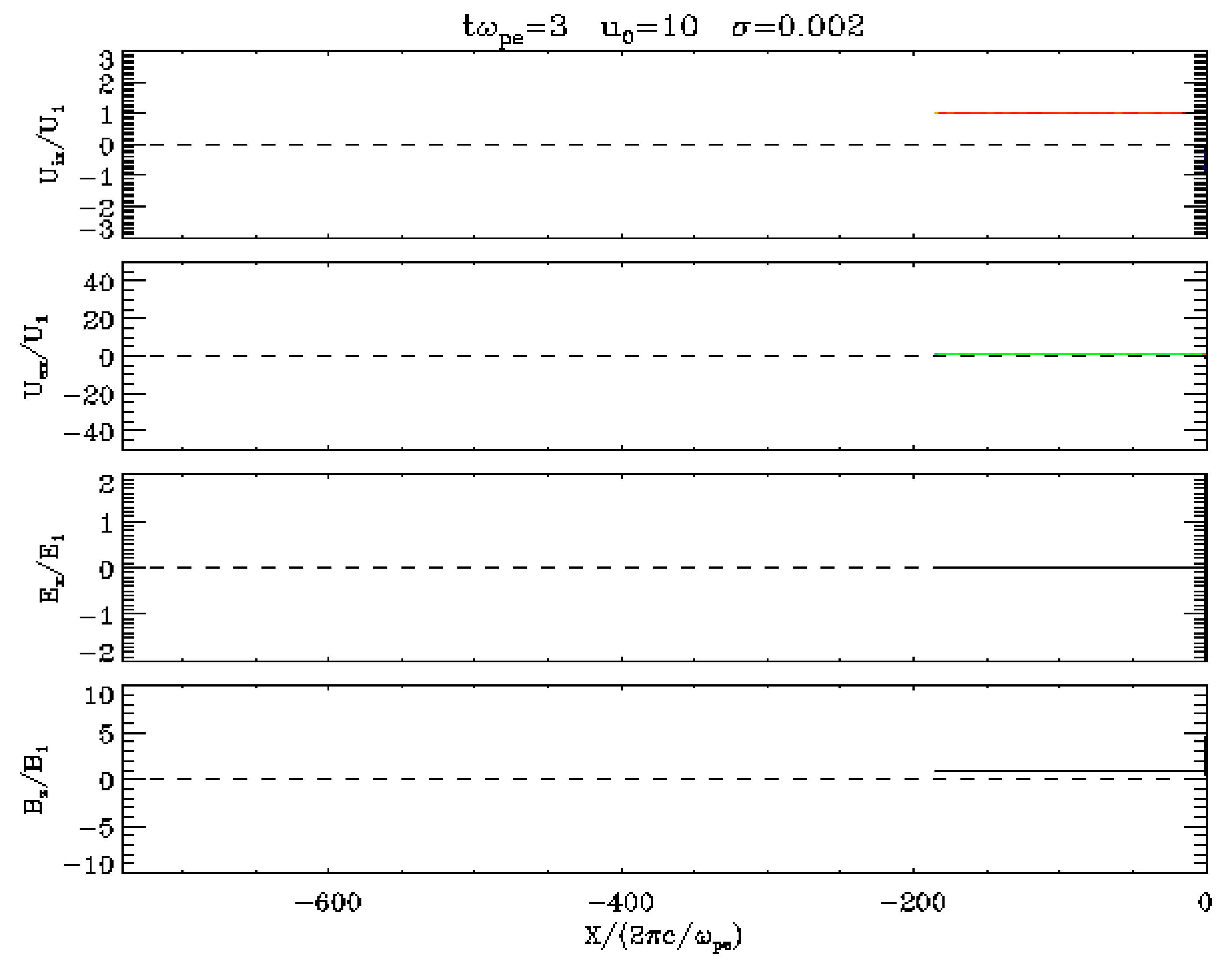
upstream (supersonic flow) downstream (sub-sonic)

$U_{x,ion}$

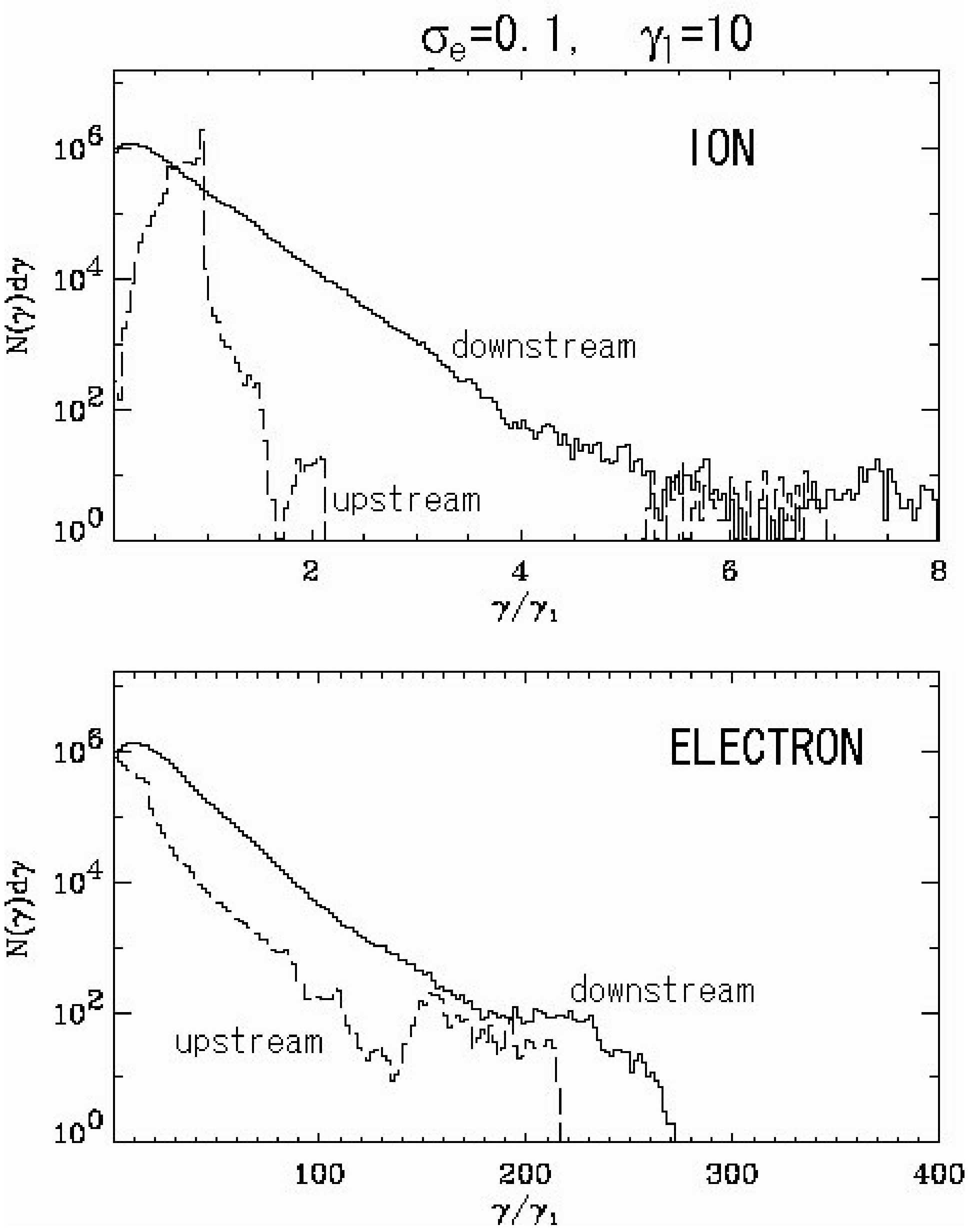
$U_{x,ele}$

E_x
(ES,plasmon)

B_z
(EM,photon)



Energy Spectra in 1D Shock



$\varepsilon_{max}/\varepsilon_0 > M_i/m_e$ (=50)

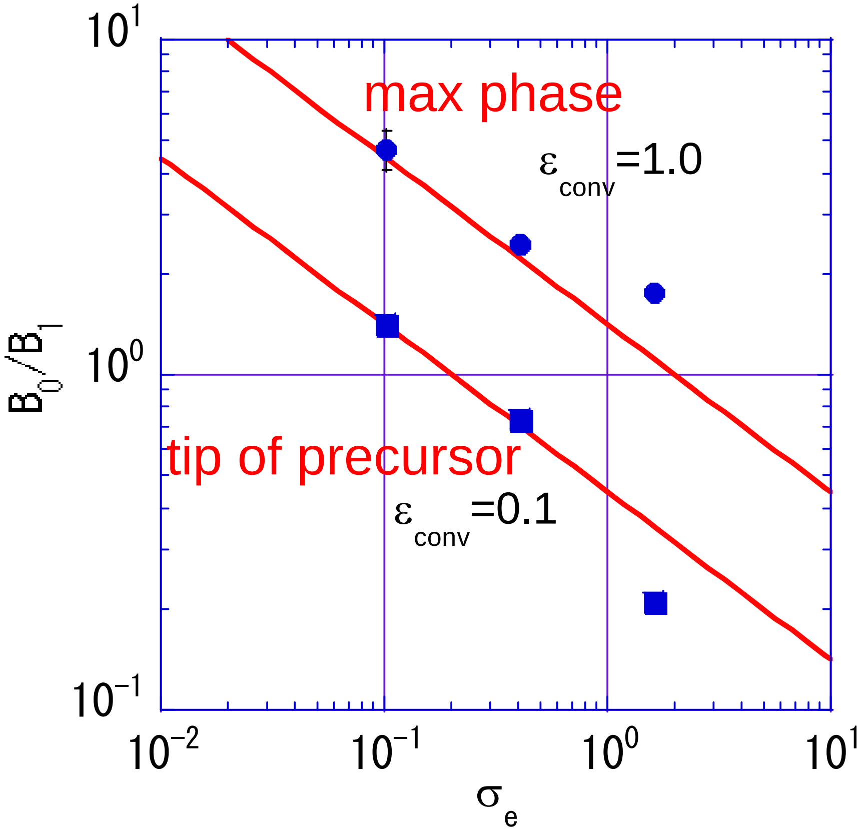
1) $\gamma_i m_i c^2 \approx \gamma_e m_e c^2$

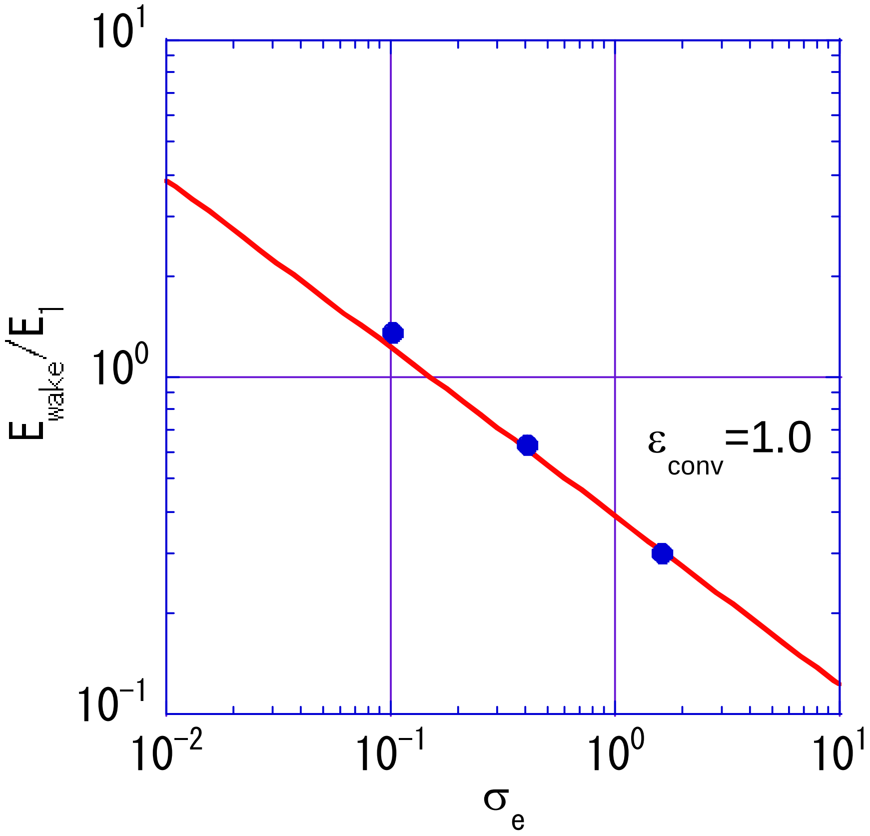
2) $\gamma_e m_e c^2 >> \gamma_1 m_i c^2$

Accelerated electron energy is more than upstream ion bulk flow energy

Amplitudes of $B_{precursor}$ and E_{wake}

Pair Plasma Shock ε_{conv} = 10 % (tip of precursor wave)
Ion-Electron Plasma Shock ε_{conv} = 100 %

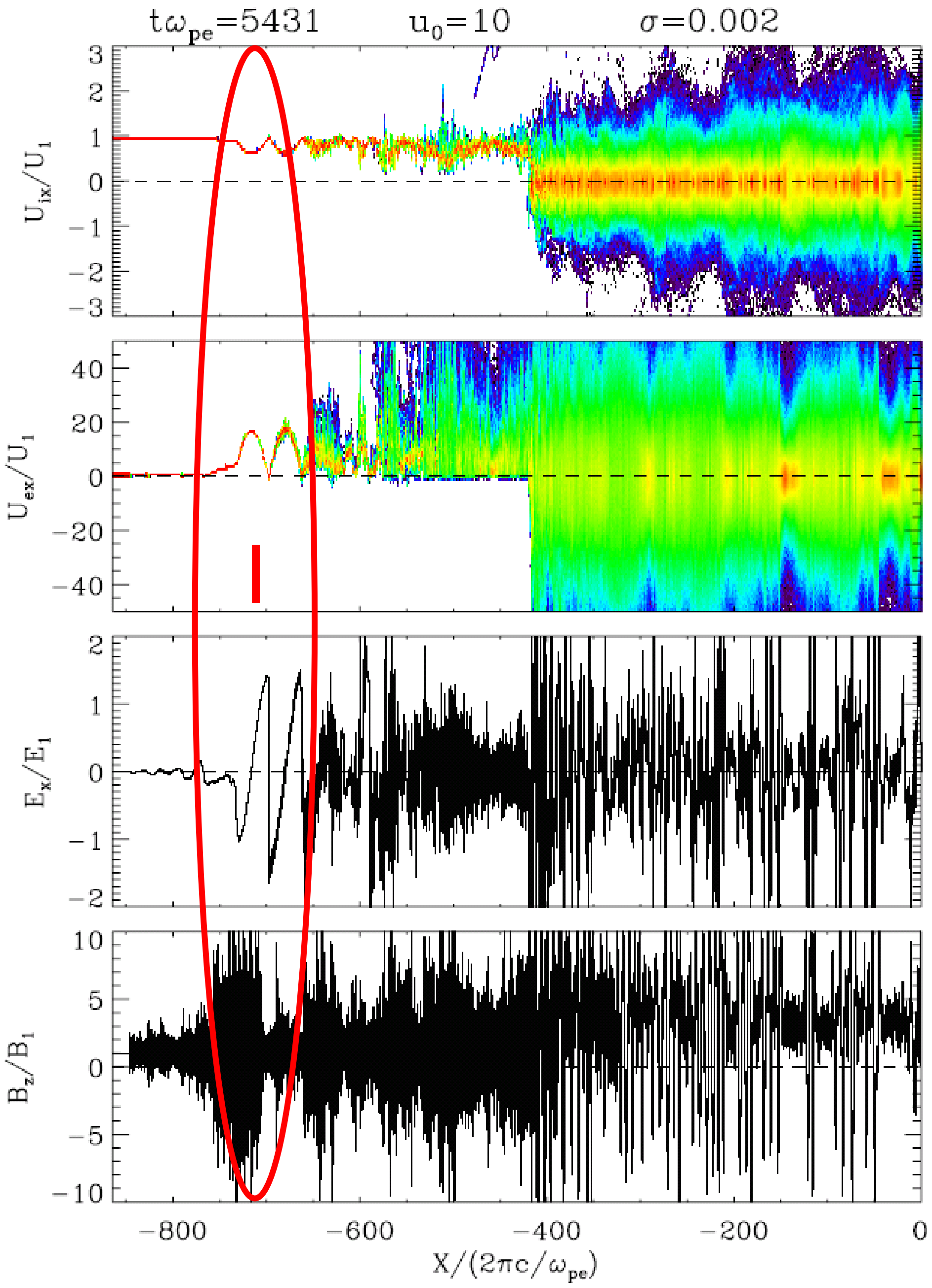




$$\sigma_e = \frac{\text{Poynting Flux}}{\text{Particle Flux}} = \frac{B_1^2}{4\pi N_1 \gamma_1 m_e c^2} = \frac{1}{M_A^2}$$

$$E_{es} = -\nabla \phi_{pond} ,$$

$$\phi_{pond} \equiv m_e c^2 \sqrt{1 + a_0^2} , \ a_0 \equiv eE_0 / m_e c \omega_0$$



ION

ELECTRON

Electrostatic Waves (Ex)

Electromagnetic Waves (Bz)

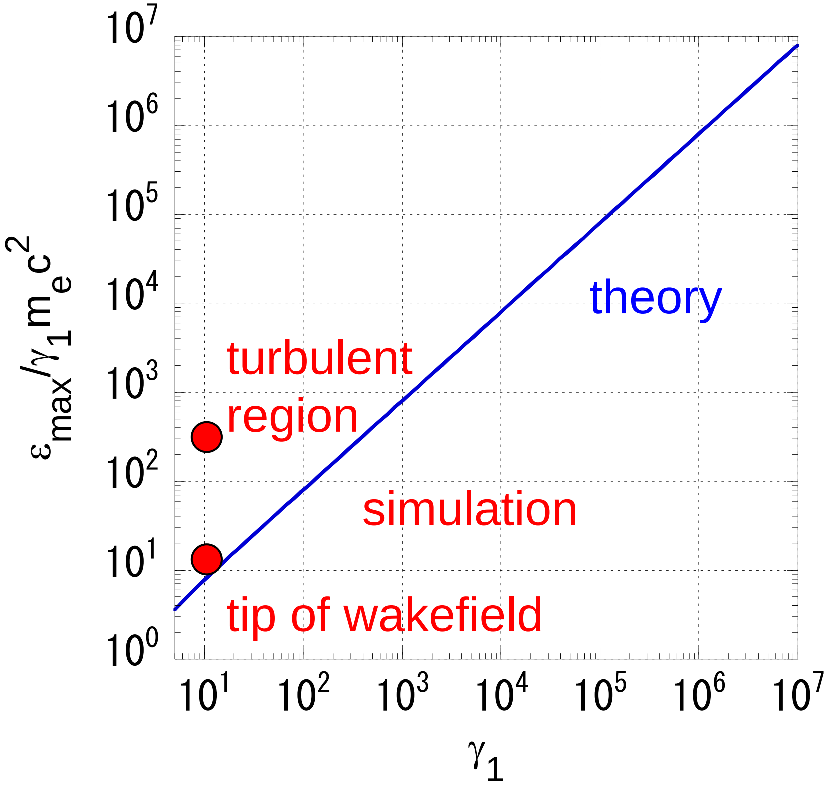
Maximum Energy in Simulation

- Wakefield Acceleration (non-resonant)

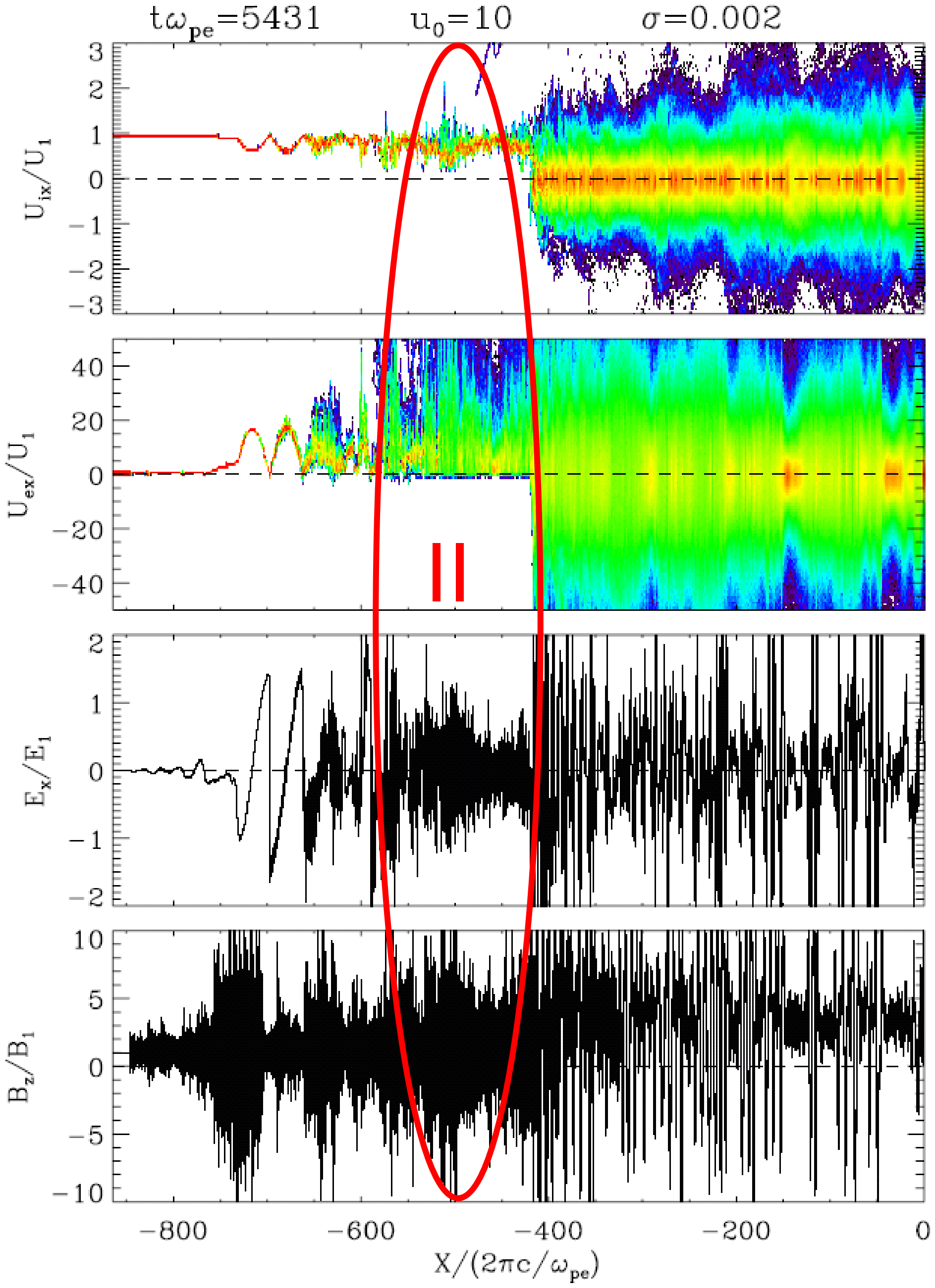
$$\frac{\varepsilon_{\mathrm{max}}}{\gamma_1 m_e c^2} = \frac{eE_{es}L}{\gamma_1 m_e c^2}$$

$$\approx \frac{2\eta a_0^2}{\sqrt{1+\eta a_0^2}} = \gamma_1 \varepsilon_{\mathrm{conv}}^{1/2}$$

→Strong Acceleration
(if $\gamma_1 = 10^7$, $\varepsilon_{\mathrm{max}} = 10^{20}$eV)



(Lorentz Factor of Upstream Flow)



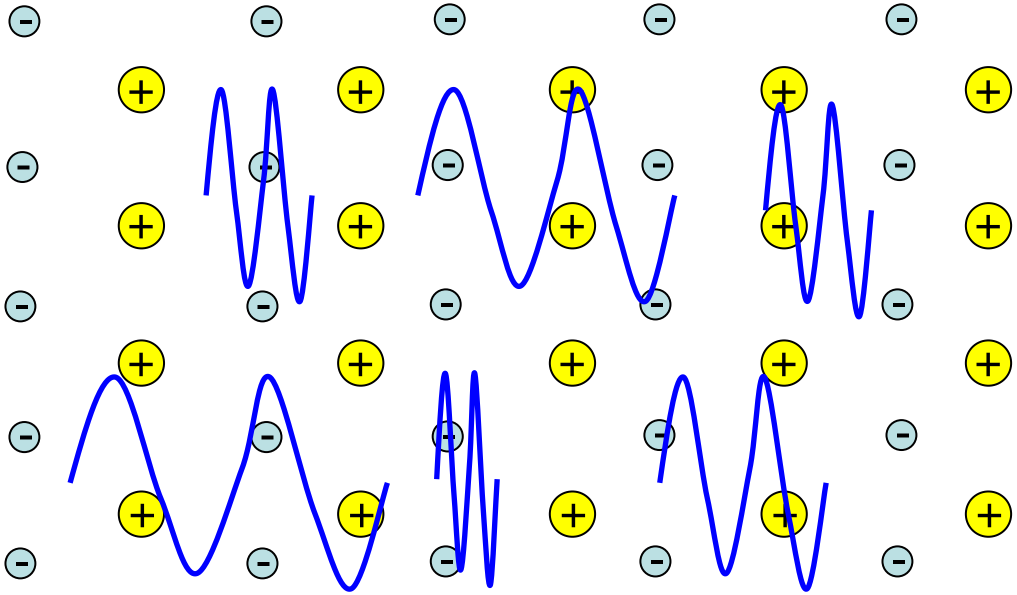
ION

ELECTRON

Electrostatic Waves (Ex)

Electromagnetic Waves (Bz)

Turbulence in Wakefield

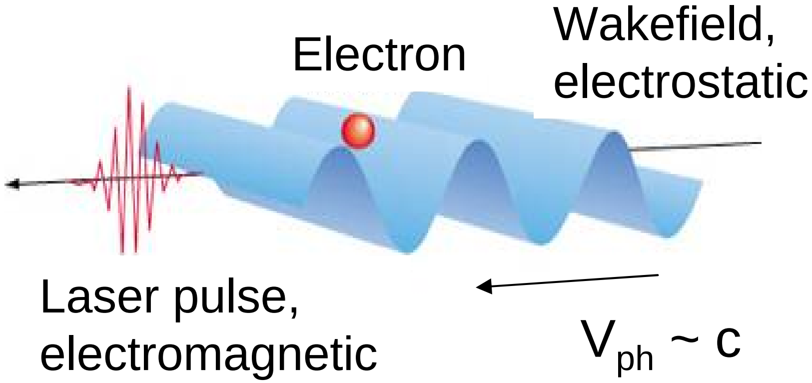


wave phase speed ~ c,
particles can be in resonance with waves,
stochastic acceleration

Resonant Wakefield Acceleration

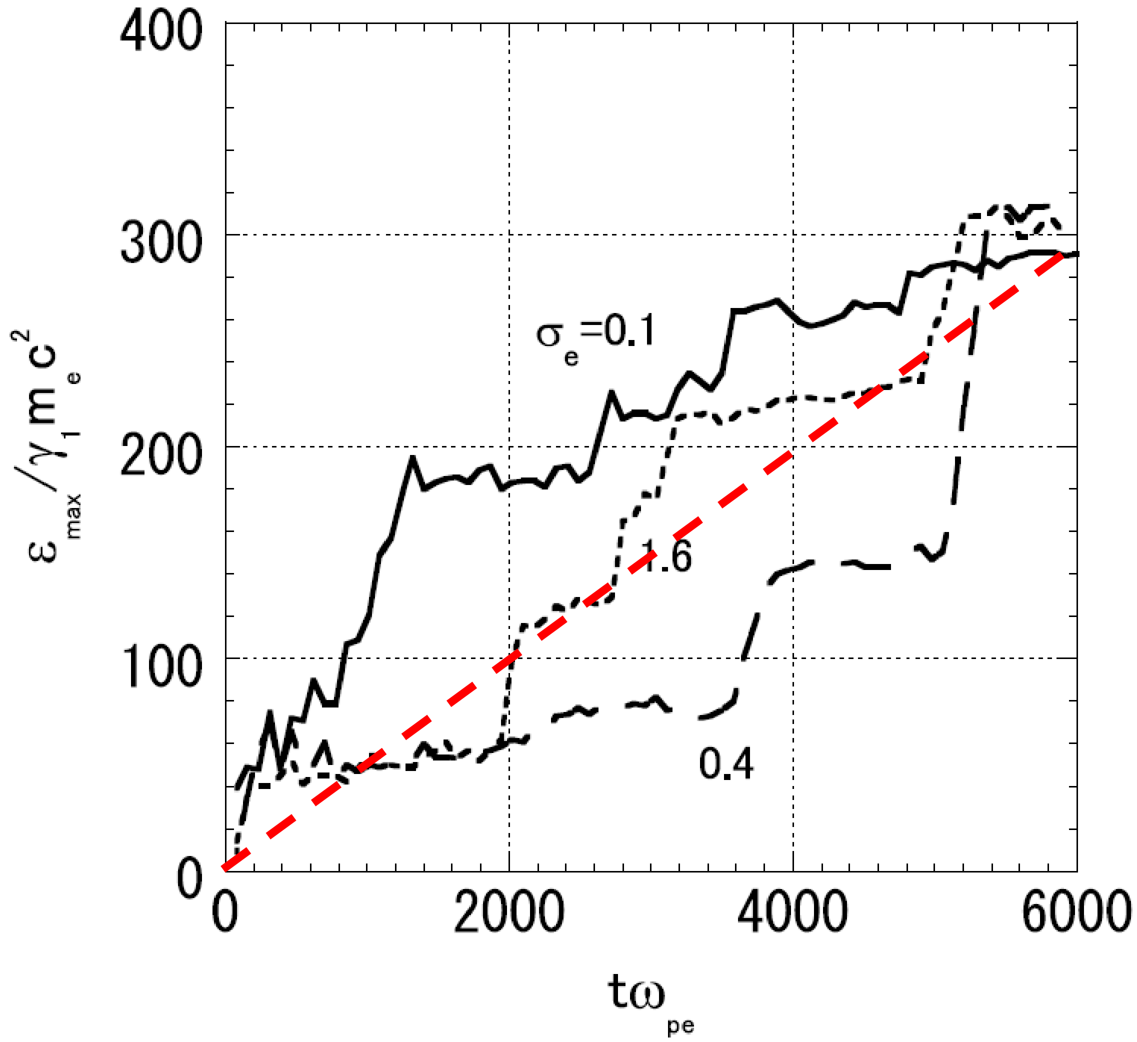
$$\varepsilon_{\max} \approx eE_{es}L\frac{c}{c - v_{ph}}$$

v_{ph} : propagation velocity of wakefield



Tajima & Dawson, 1979

Time Evolution of Maximum Energy



$$\frac{\varepsilon_{\max}}{\gamma m_e c^2} \approx \frac{1}{20} t\omega_{pe}$$

Wakefield region increases with increasing time

$$L_{sys} \approx ct(1-\sqrt{\Gamma-1})$$

$$\frac{\varepsilon_{\max}}{\gamma m_e c^2} \approx L_{sys}\frac{\omega_{pe}}{c}\beta_{eff}$$

$$\left(\beta_{eff} \approx \frac{1}{6} \sim \frac{1}{3}\right)$$

Application to AGN jet

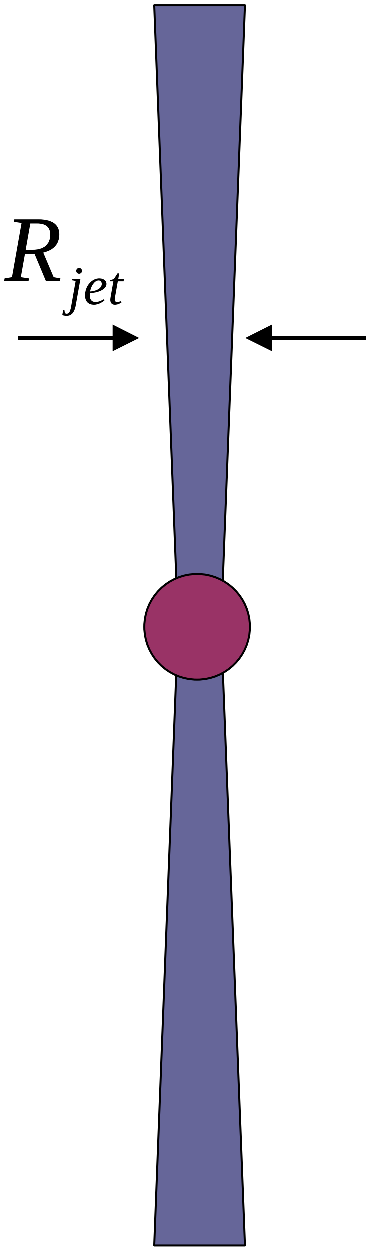
$$\frac{\varepsilon_{\max}}{m_e c^2} \approx \gamma L_{sys} \frac{\omega_{pe}}{c}$$

$$L_{sys} \approx R_{jet},$$

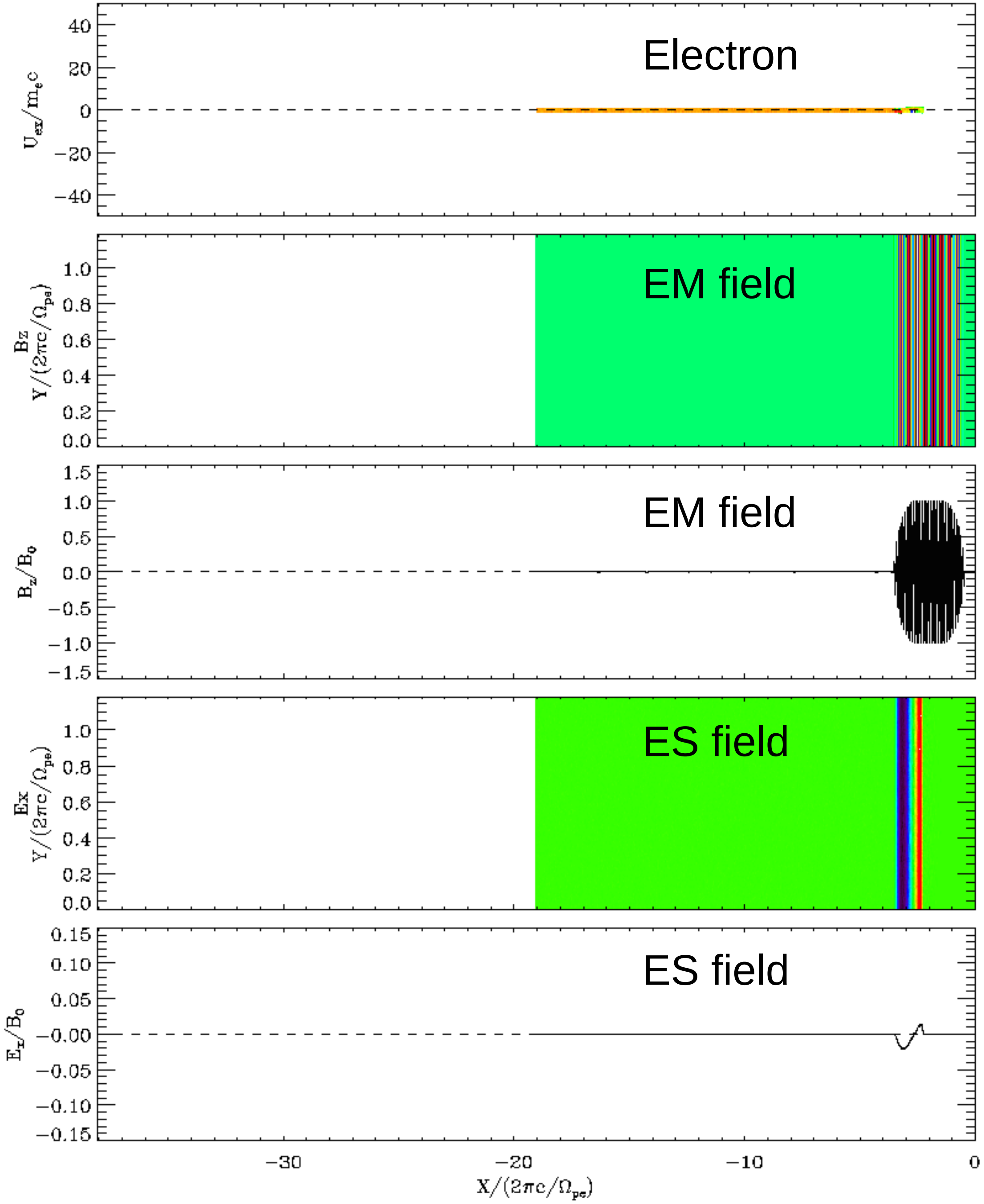
$$L_{jet} \approx \pi R_{jet}^2 \gamma m_p n_p c^3,$$

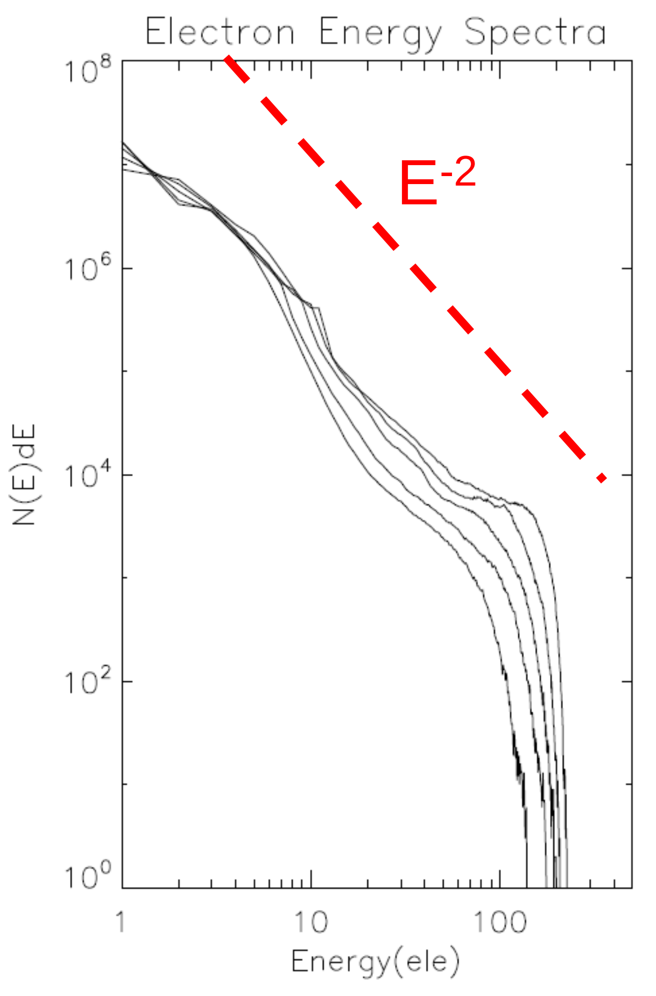
$$n_p = \alpha n_e, \quad (n_p < n_e, \ \alpha < 1)$$

$$\frac{\varepsilon_{\max}}{m_e c^2} \approx 5\times 10^{12}\left(\frac{1}{\alpha}\right)^{1/2}\left(\frac{L_{jet}}{10^{45}\ \mathrm{erg/s}}\right)^{1/2}$$

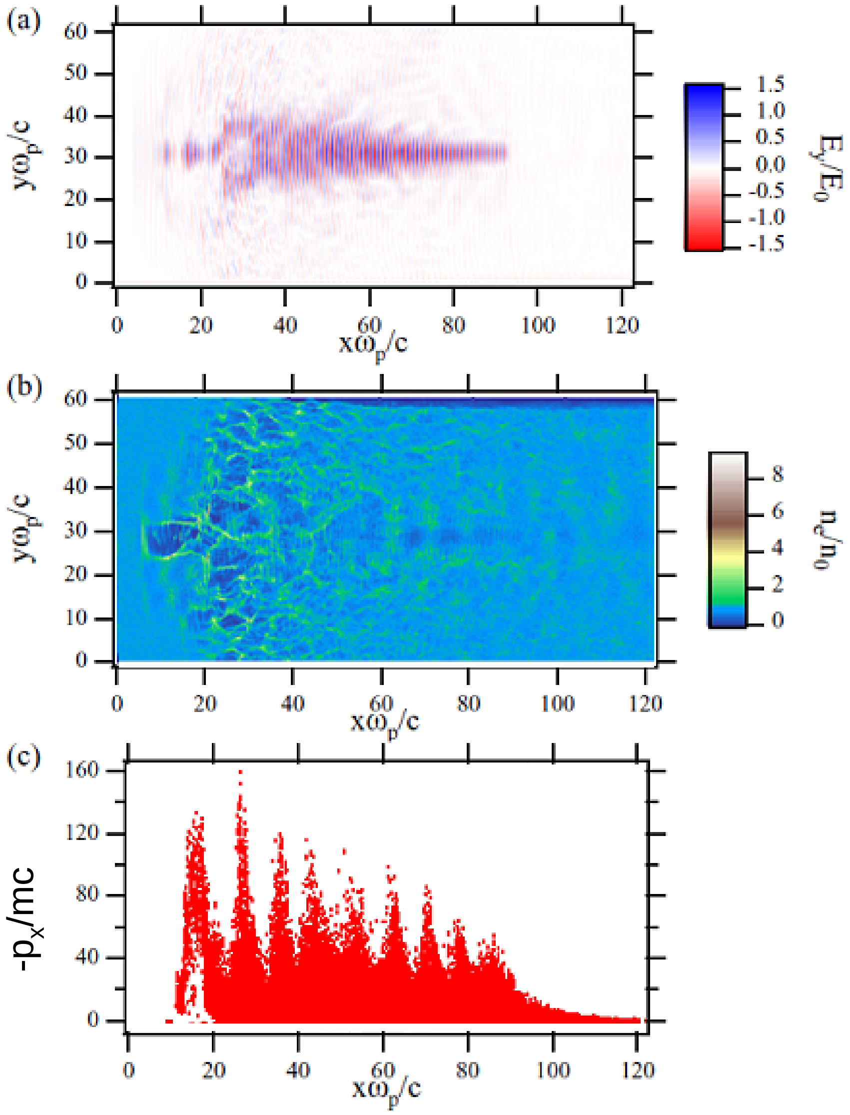


Energy Spectrum in 2D PIC

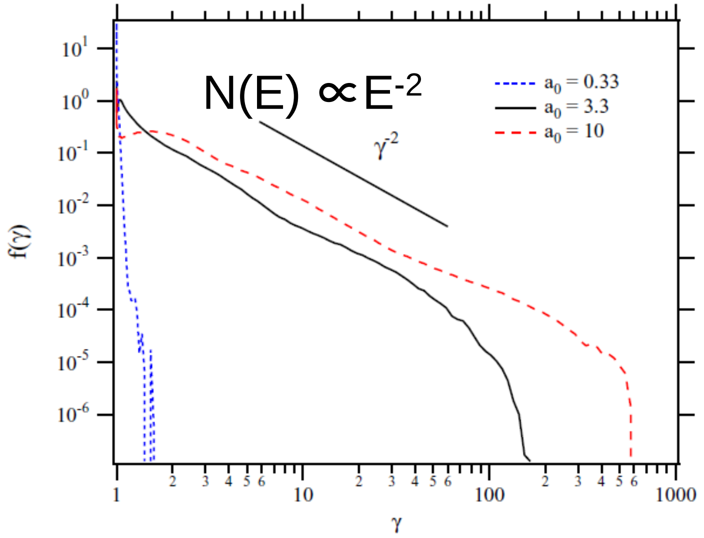


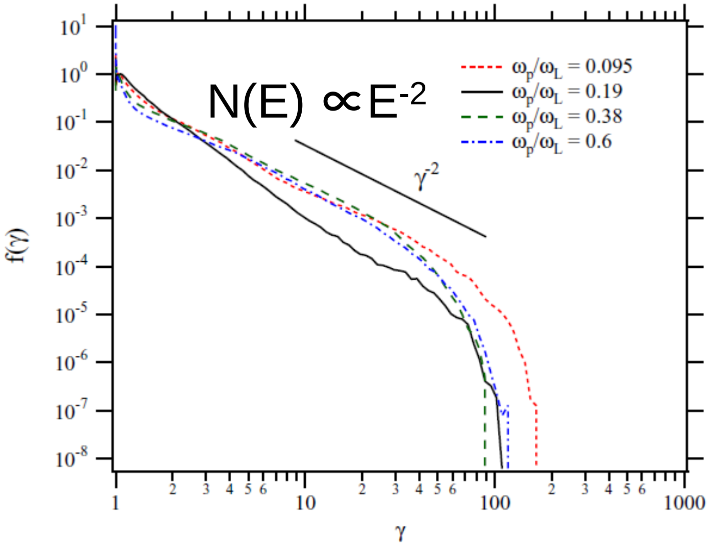


Energy Spectra in 2D Wakefield



Kuramitsu et al., ApJ (2008)





Summary

- Wakefield Acceleration in Relativistic Shock
  - Large Amplitude EM Precursor Wave
  - Large Amplitude ES Wave (Wakefield)
  - Particle Acceleration by Wakefield
    - Turbulence (forward/backward Raman scattering),

- Towards Understanding Ultra-High-Energy Cosmic Ray