# Acceleration of plasma ions via the Weibel instability and Buneman instability driven by high-energy lepton flows

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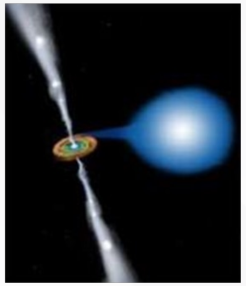
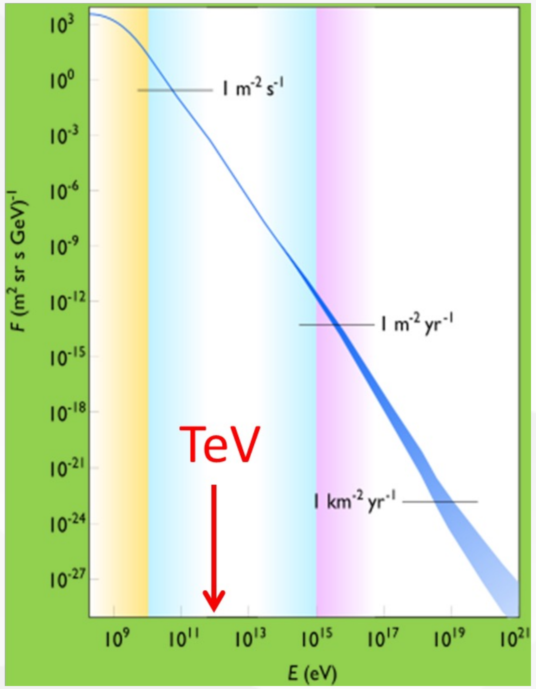
# Background --- electron positron jets in astrophysical environment

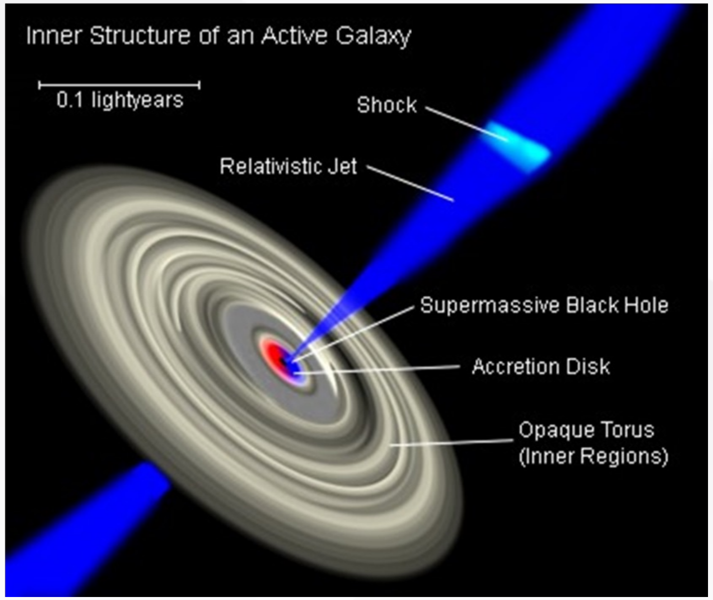
## Particle acceleration is pervasive in the universe




Are they relevant and how?

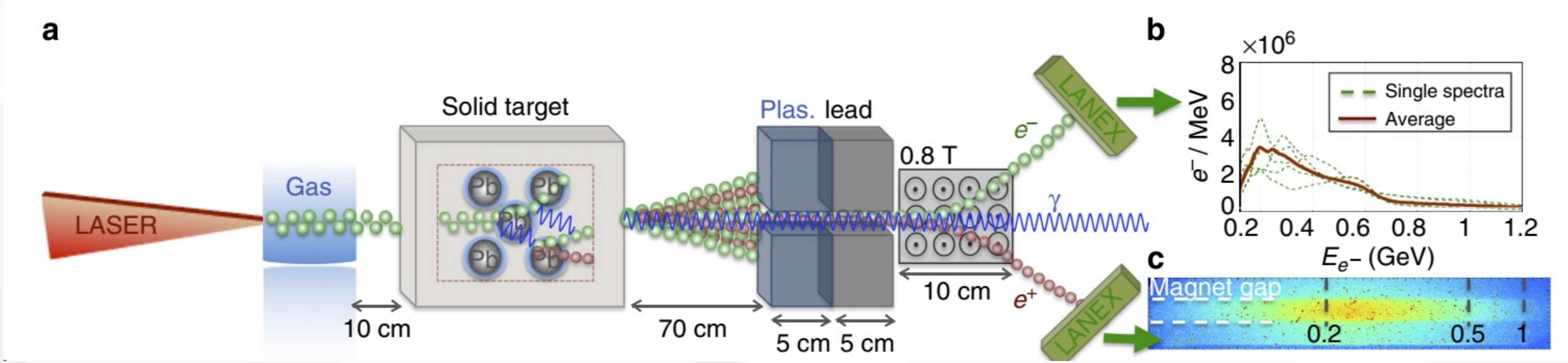
Electron-positron jets found widely in astrophysical environments such as quasars, black holes

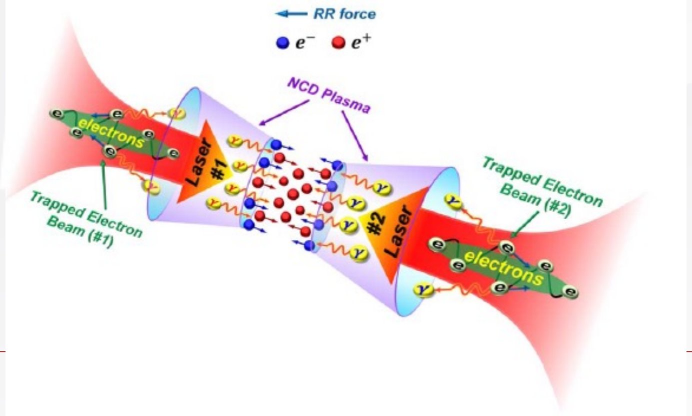

https://en.wikipedia.org/wiki/Quasar https://en.wikipedia.org/wiki/Astrophysical_jet

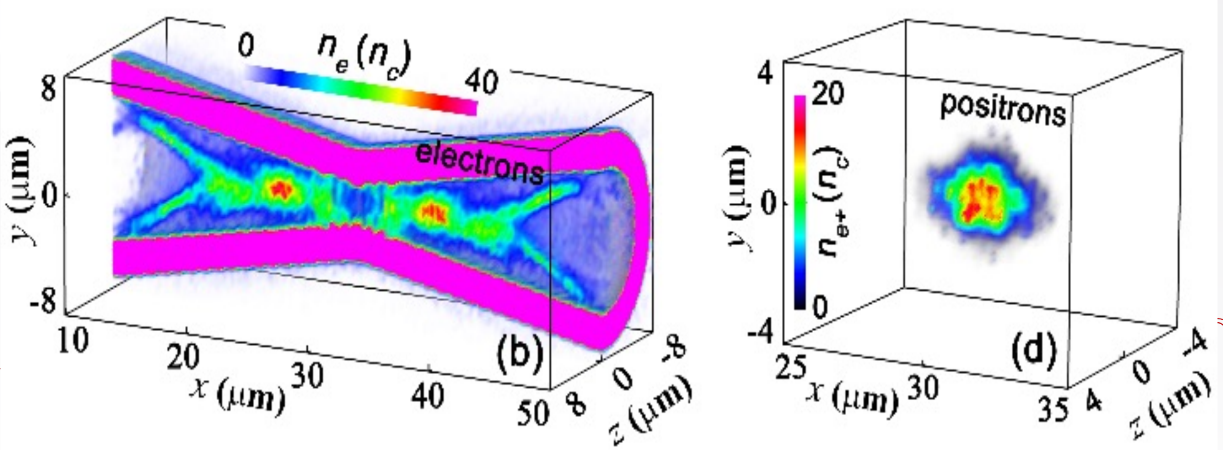
# Background --- electron-positron jets produced in laboratory with high power lasers

Pair production via the Bethe-Heitler process: G. Sarri et al., NATURE COMMUNICATIONS 6:6747 (2015)




Pair production via the Breit-Wheeler (BW) process: X. L. Zhu et al., NATURE COMMUNICATIONS 7, 13686 (2016).



# Interaction of lepton jets with plasma: Buneman instability

Electron-positron jet with density $n_j$ and $\gamma$

**Electron-proton ambient plasma at density $n_{am}$**

*J. Huang et al.,* Astrophys. J. 931:36 (2022)

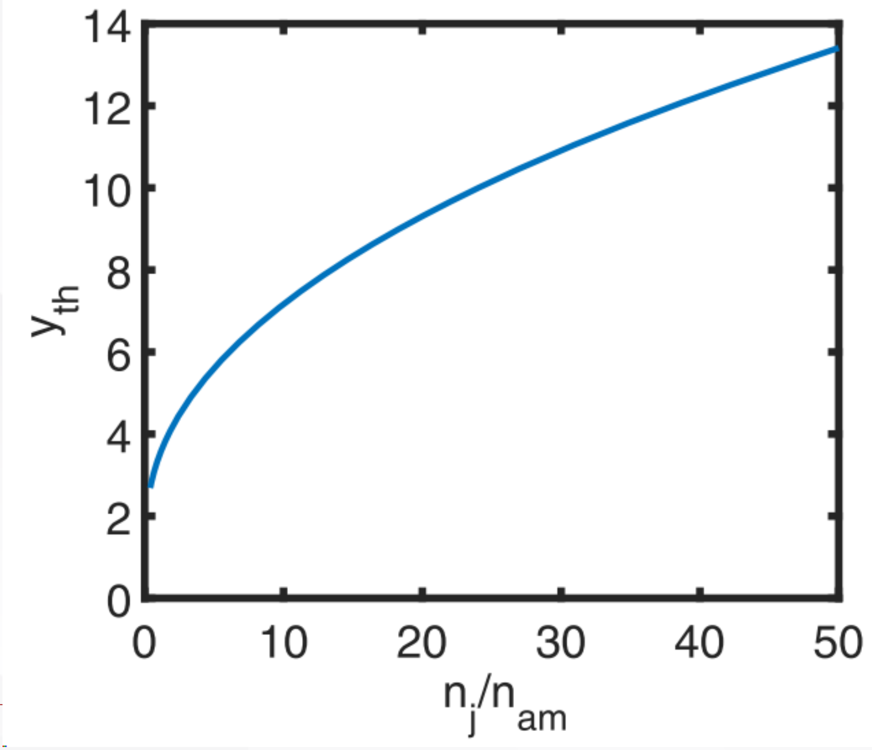
Buneman instability: Different particle species (ions, electrons, or positrons) have different drift velocities.

$$1 = \omega_p^2 \left[ \frac{2(n_j/n_{\rm am})}{(\omega - v_0 k)^2} + \frac{m_e/m_i}{\omega^2} + \frac{1}{\omega^2} \right]$$

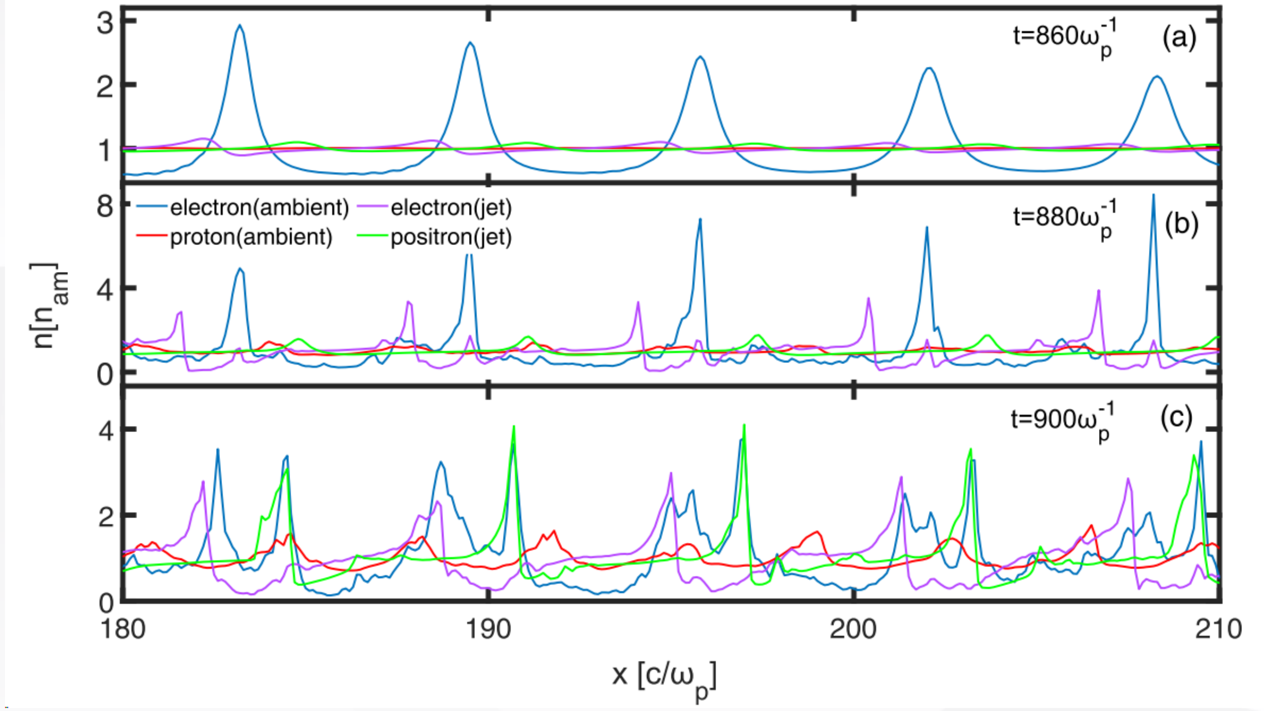
$$\frac{k_{th} v_0}{\omega_p} \equiv y_{th} = \beta^{1/2} \left[ 1 + \frac{2\alpha}{\beta} \right]^{3/2}$$

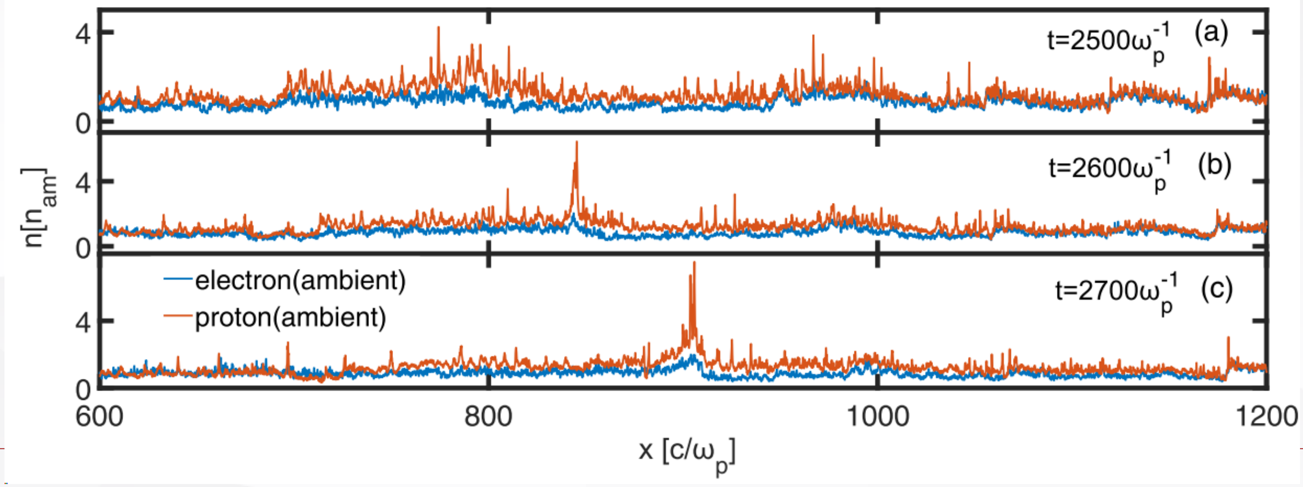
$\alpha = n_j/n_{\rm am}$ and $\beta = 1 + m_e/m_i$

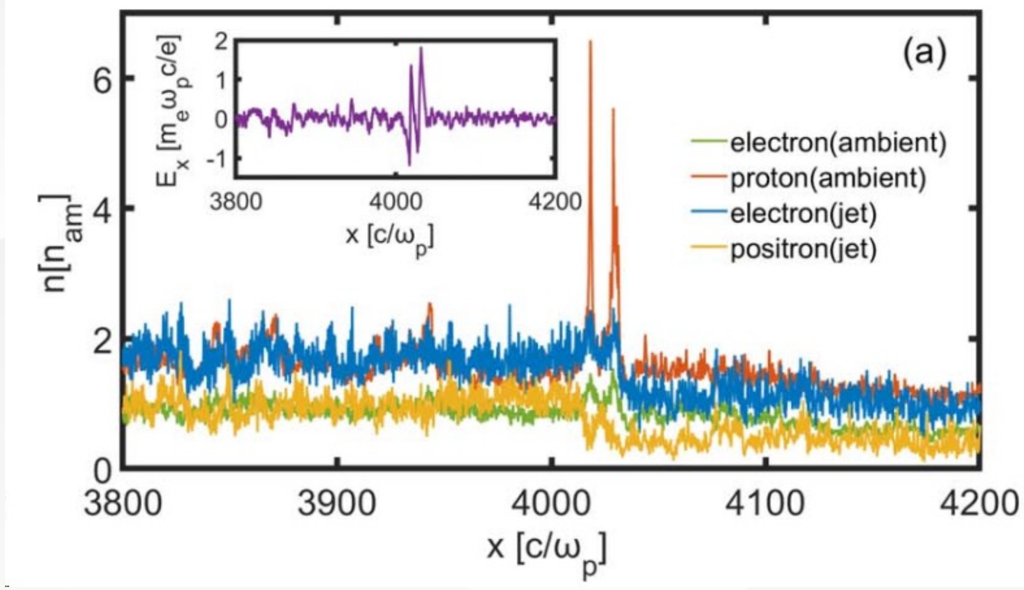
Buneman instability threshold

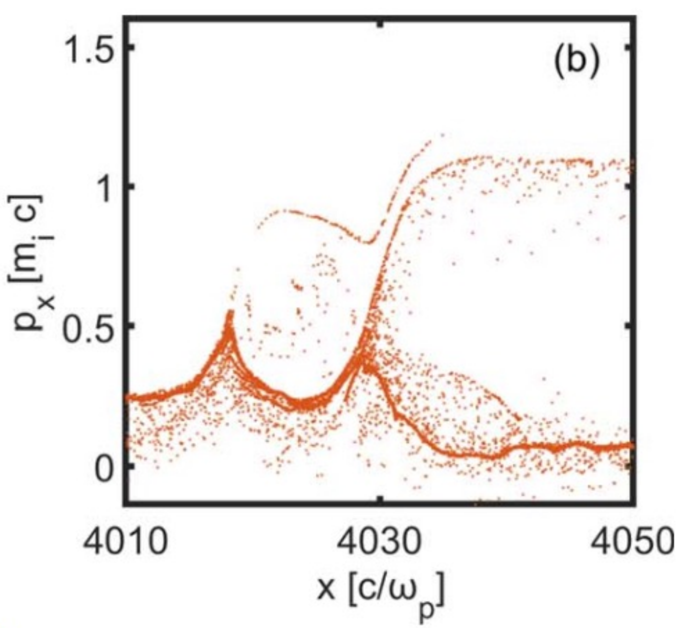


# Transition from ion acoustic waves to shock waves

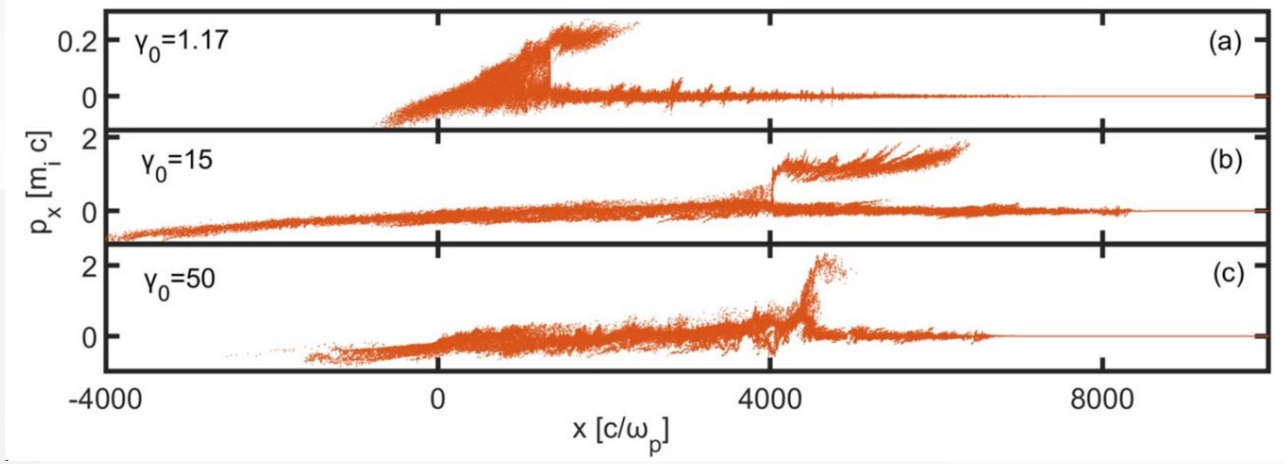


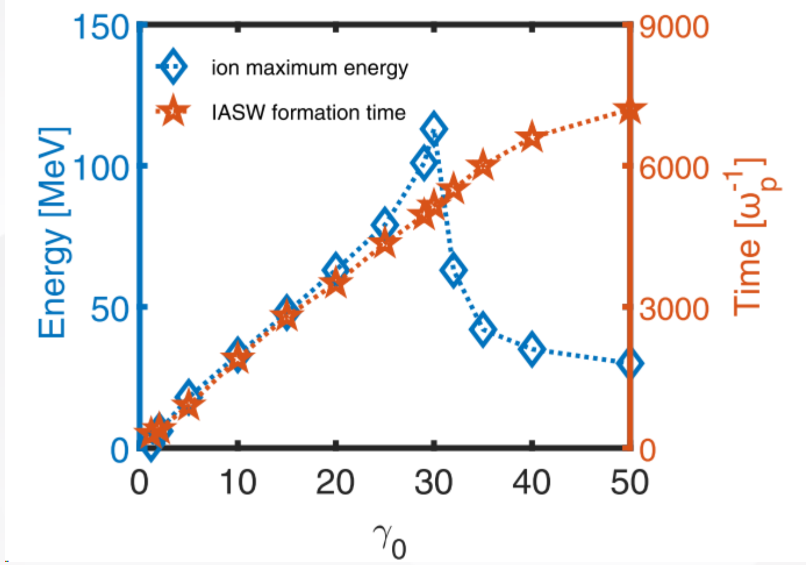



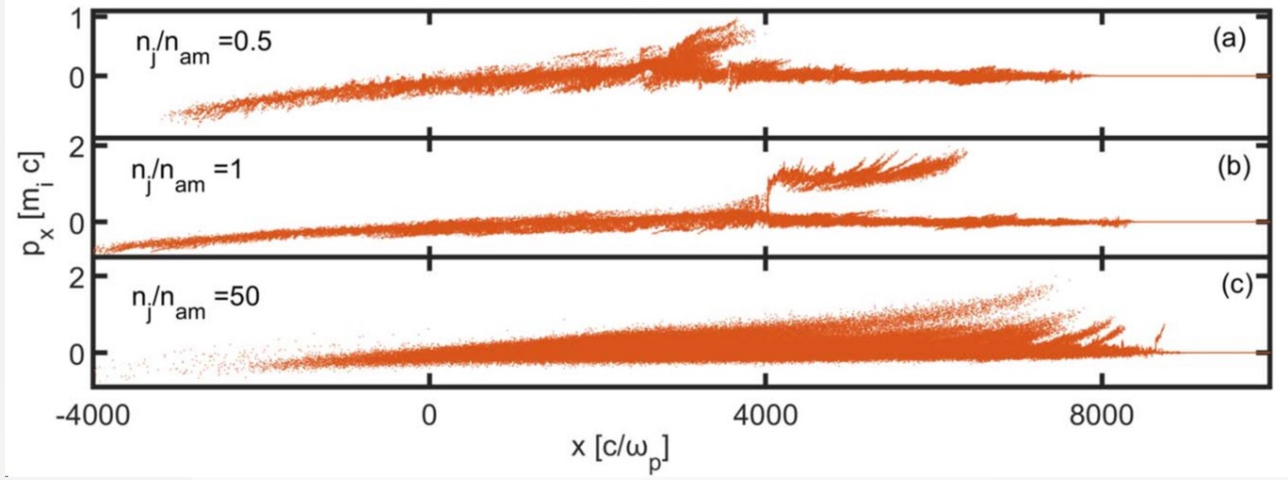



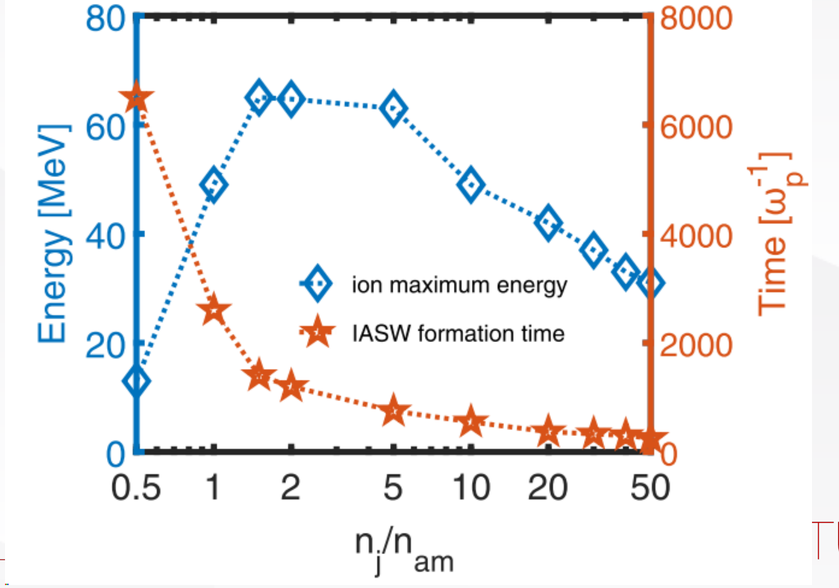



# Proton energy scaling with lepton parameters



# Interaction of lepton jets with plasma: Weibel instability

*D. Conor et al., J. Plasma Phys.* 88, 905880206 (2022)

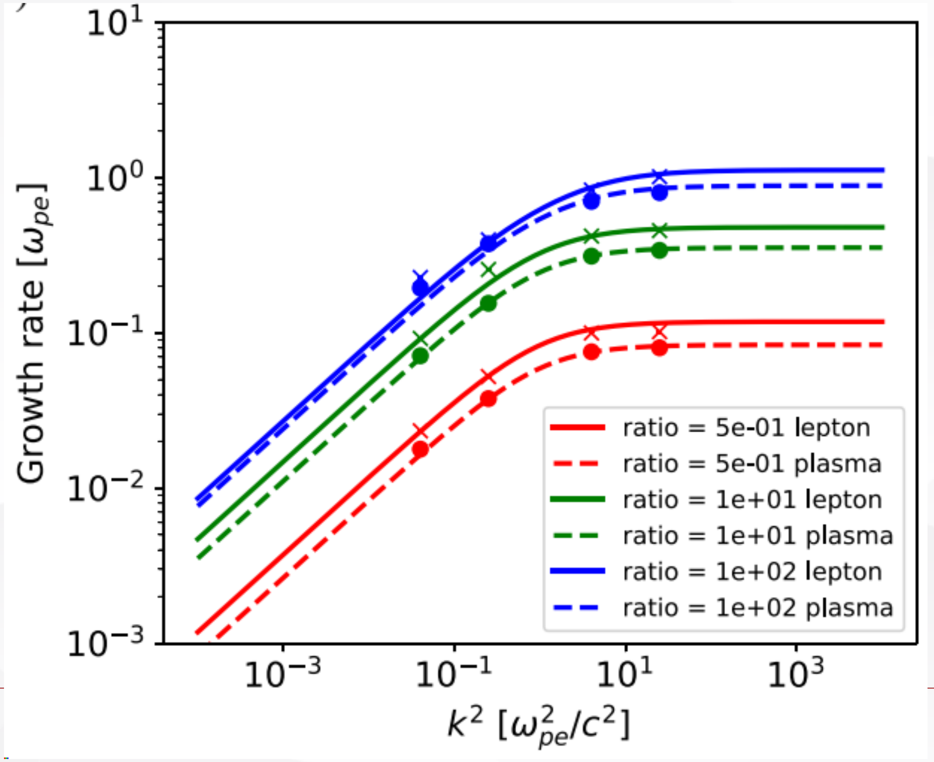
Electron-positron jet with density $n_j$ and $\gamma$

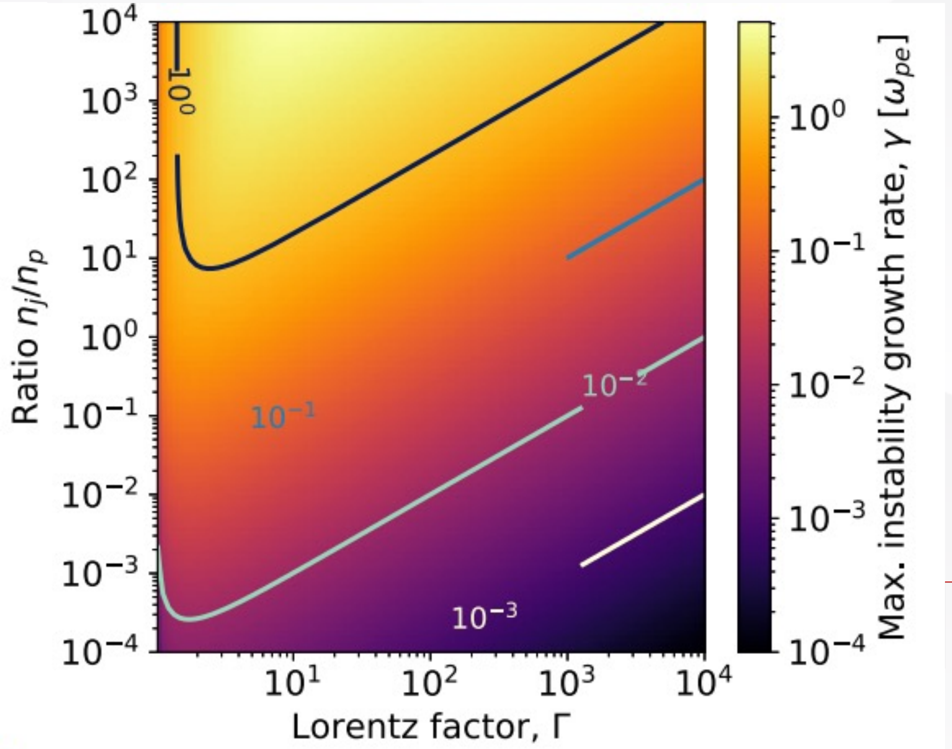
**Electron-proton plasma at density $n_p$**

$$(\omega^2-\Omega_a^2)[\omega^4-\omega^2(k^2c^2+\Omega_b^2)-k^2c^2\Omega_c^2]-k^2c^2\Omega_d^4=0$$

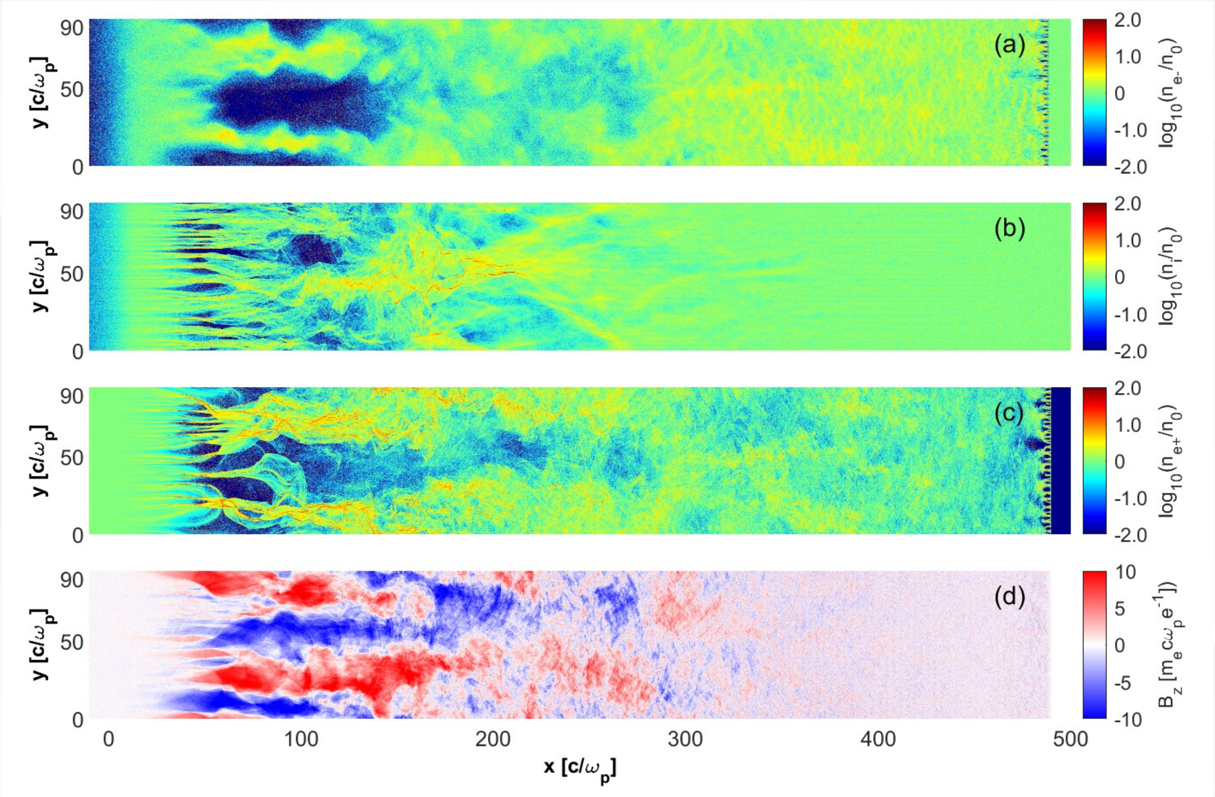
$$\Omega_a^2=\omega_{pe}^2\sum_\alpha \frac{n_{0\alpha}}{n_i\Gamma_\alpha},\qquad \Omega_b^2=\omega_{pe}^2\sum_\alpha \frac{n_{0\alpha}}{n_i\Gamma_\alpha^3},$$

$$\Omega_c^2=\omega_{pe}^2\sum_\alpha \frac{n_{0\alpha}v_{0x\alpha}^2}{n_i\Gamma_\alpha c^2},\qquad \Omega_d^2=\omega_{pe}^2\sum_\alpha \frac{n_{0\alpha}v_{0\alpha}}{n_i\Gamma_\alpha c}$$

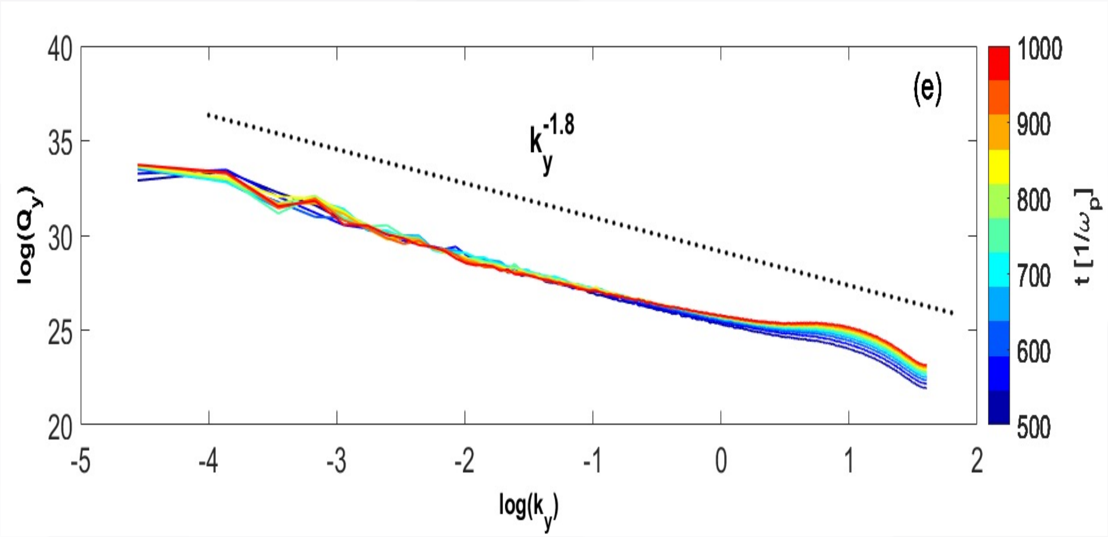


# Generation of turbulent fields

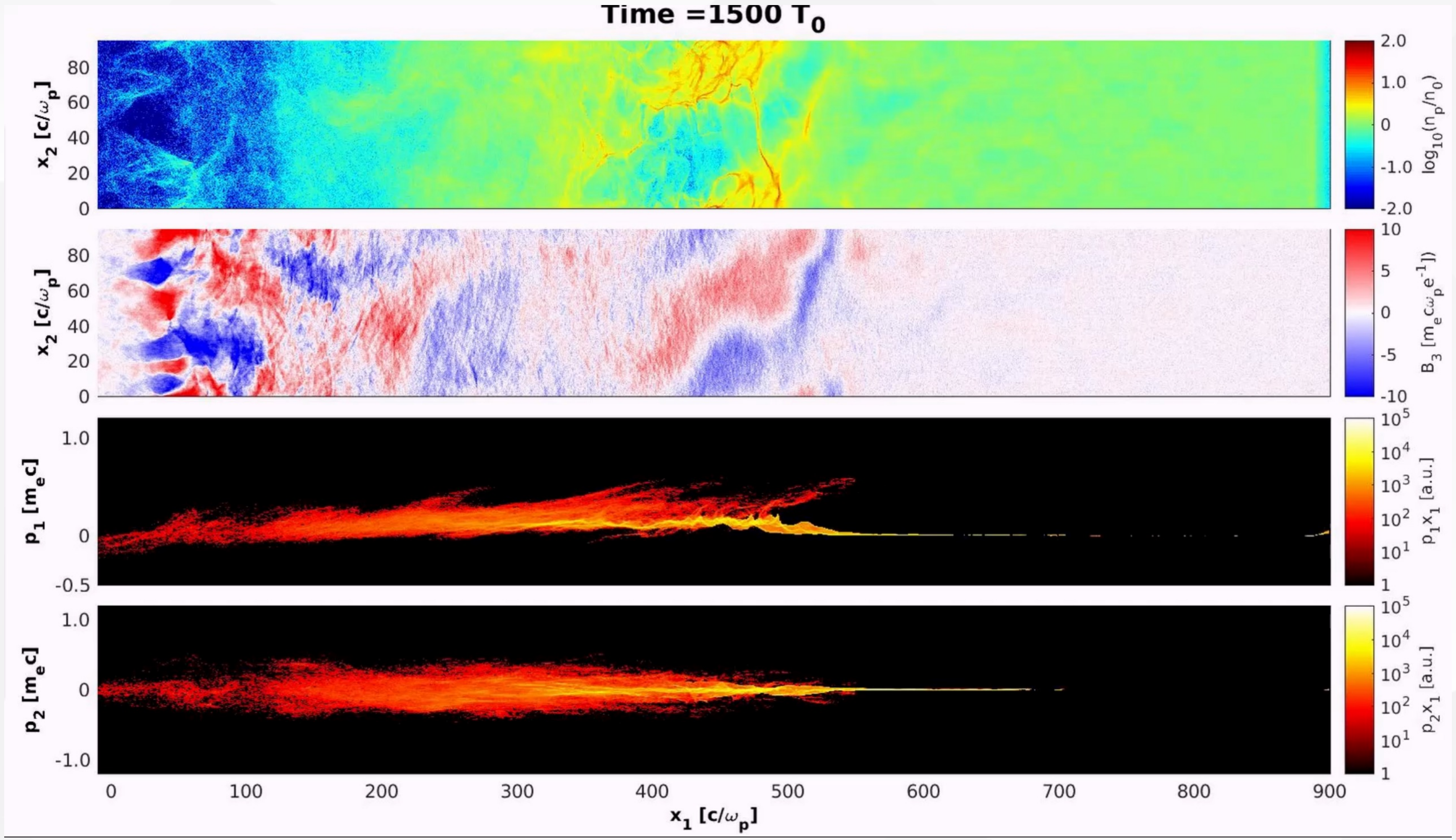



Snapshots of the spatial distributions of background plasma electron density (a), background plasma ion density (b), injected positrons (c), and the magnetic fields (d) at t=500/$\omega_p$.

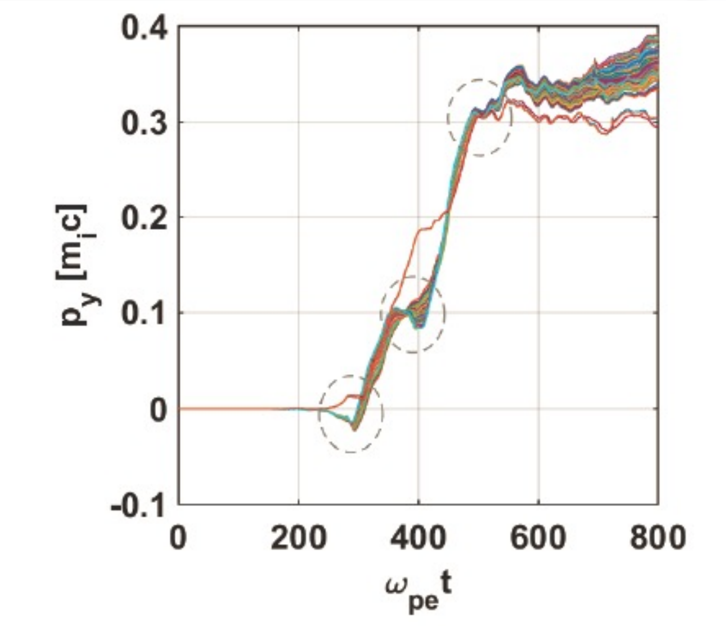



(e) Fourier spectrum of magnetic fields distributed between [0,400]c/$\omega_{pe}$ within time window t=500-1000/$\omega_p$ represented by color lines. The turbulent magnetic fields have a power law spectrum with a slope about-1.8.

# Acceleration of background protons in turbulent fields



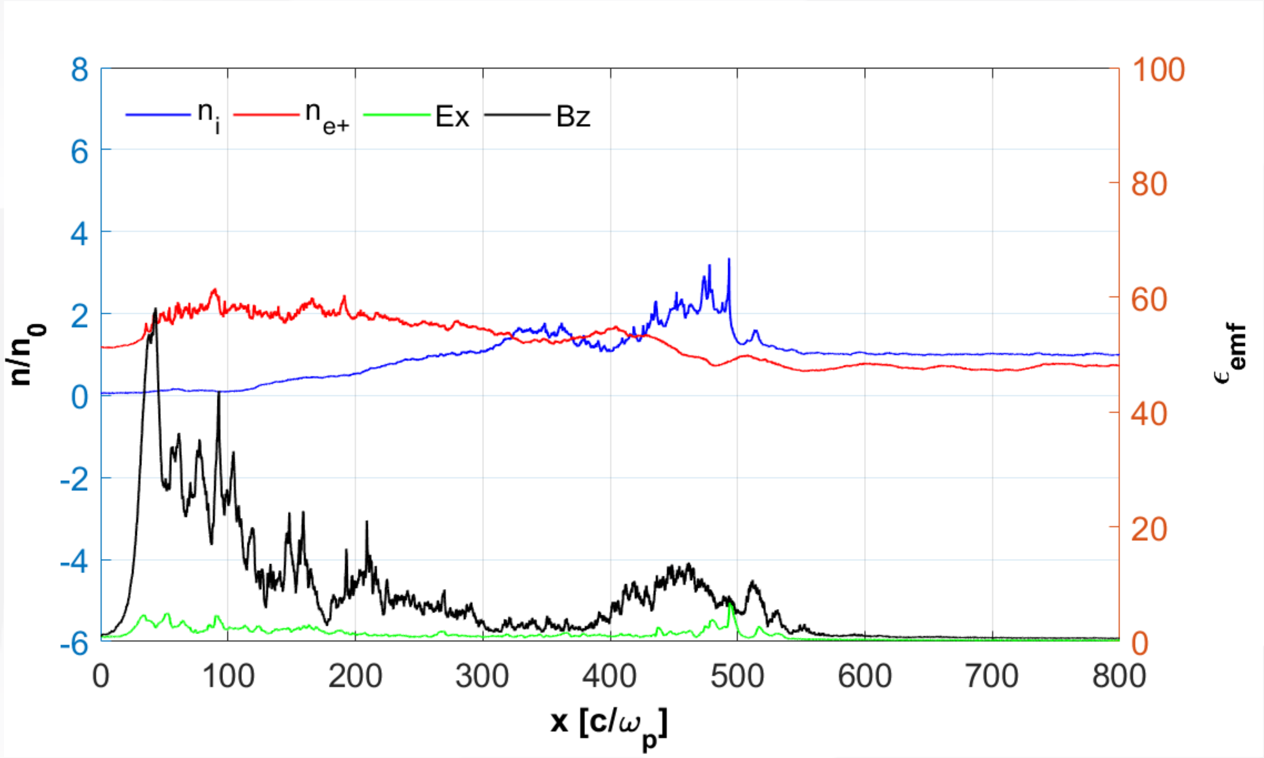

Y. Q. CUI, Z.M. SHENG, Q.M. LU, Y.T. LI & J. ZHANG, ***Sci China-Phys Mech Astron 58, 105201(2015).***

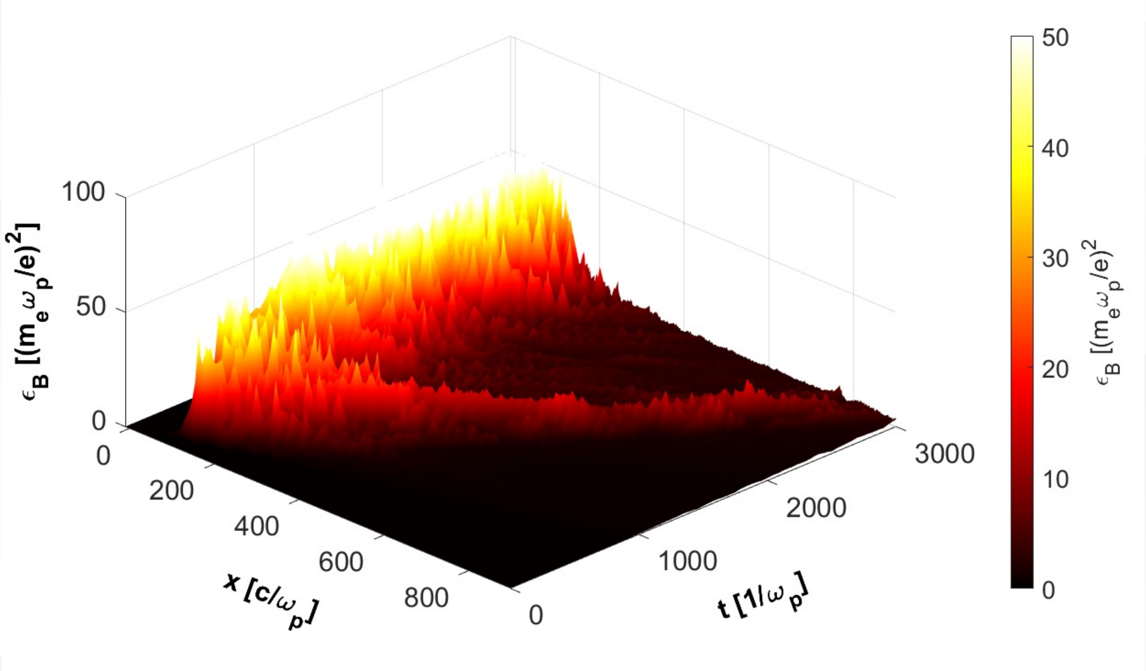



PIC code: Osiris

$\gamma = 100, n_{beam} = n_{plasma}$

# Generation of collisionless shock waves

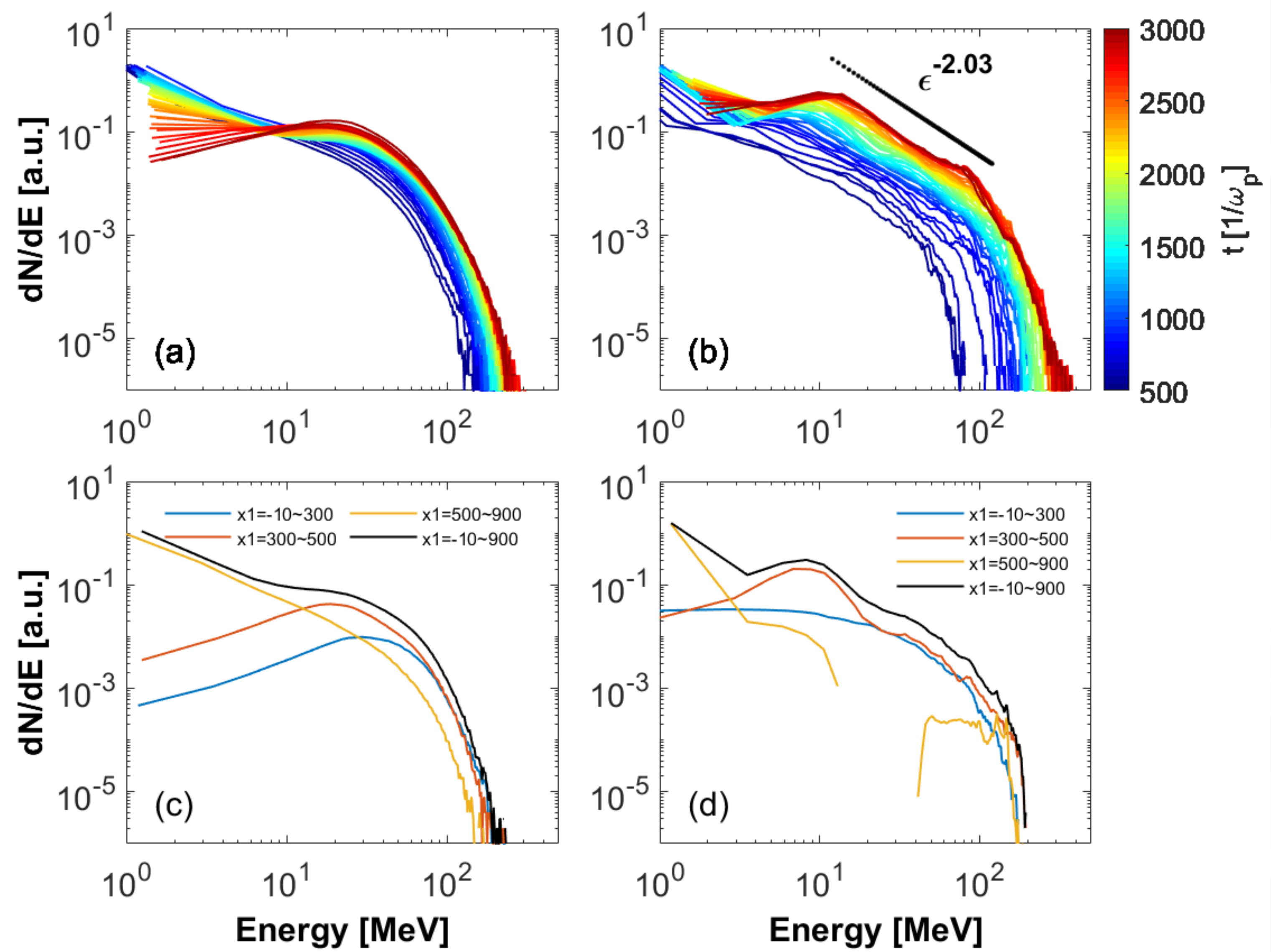



A sharp proton density front is built up at x=500 at the time T=1500 /$w_p$, which is associated the formation of the collisionless shock.

The variation of the magnetic field energy with time and space along the x-direction after averaging along the y direction.

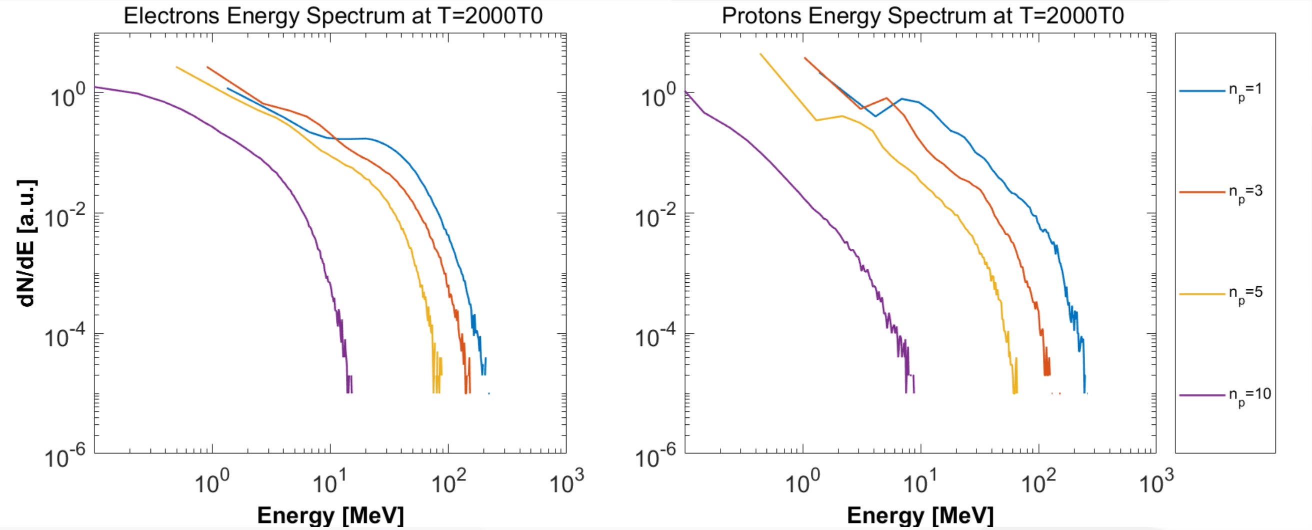
# Acceleration of background protons and electrons

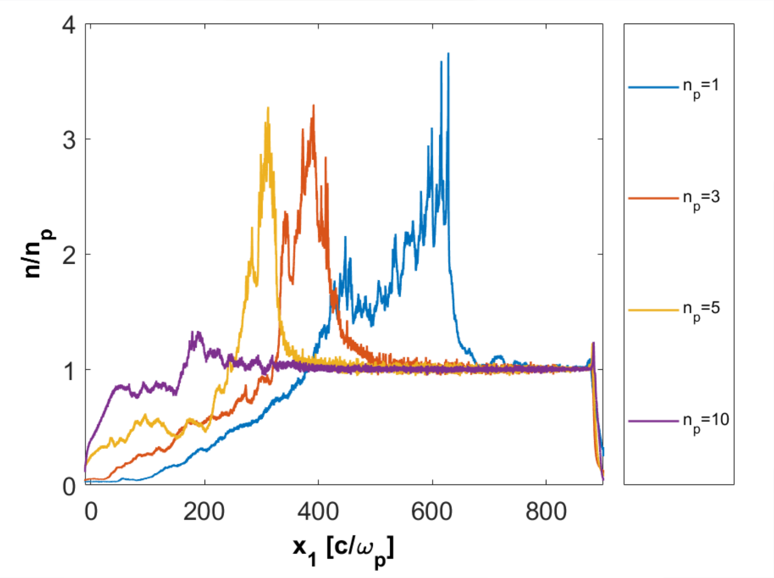



Evolution of the electron and ion spectra (a, b) during the time [500, 3000]/$\omega_p$; Background electron and ion spectra at different x positions at T=1500/wp .

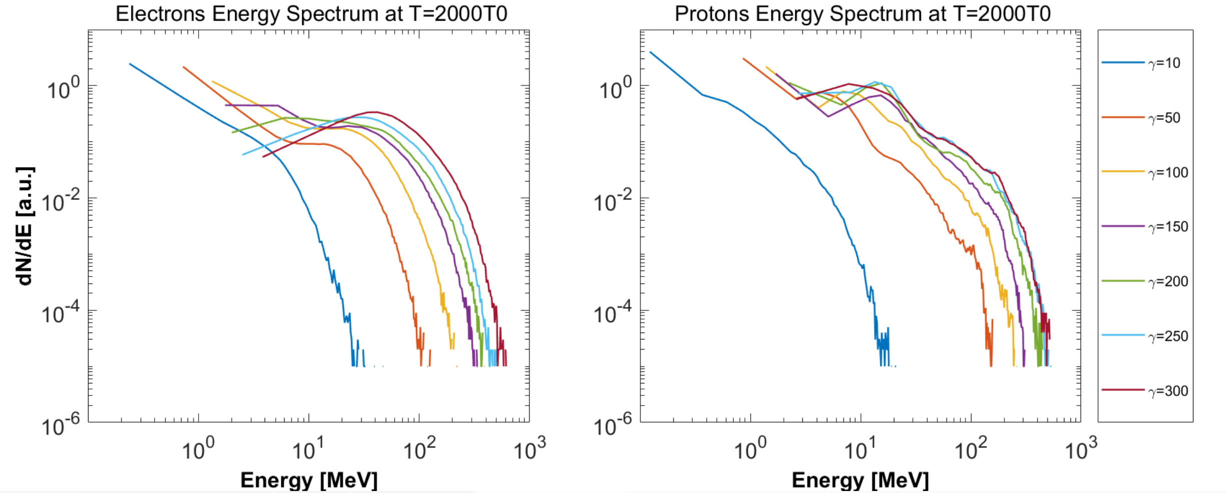
The maximum energy of electrons are accelerated to about 300 MeV and ions are accelerated to above 400 MeV. These are much higher than the injected lepton flow at 50 MeV.

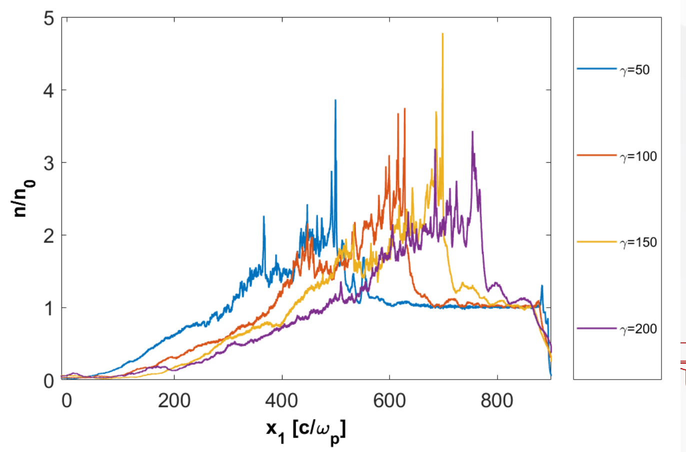
- **Effect of density ratio between jet and plasma: As the background plasma density increases, the energy of electrons and ions decreases significantly.**




- **Effect of lepton energy: the velocity of the shock wave increases with lepton flow energy.**



# Summary

- Electron and positron pairs injected into background plasma will excite both the Buneman instability and the Weibel instability.

- In the case with Buneman instability, ion acoustic waves will be excited first. During the interaction, the amplitude of the IAW increases and its waveform is steepened. Subsequently collisionless shocks are formed. This leads to ion acceleration.

- In the case with the Weibel instability,  turbulent fields are excited first, which accelerates background electrons and ions. Later collisionless shocks are driven, which can trap some preaccelerated ions to higher energy.

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# THANK YOU

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