Shocks in astrophysics and laser-plasma interactions

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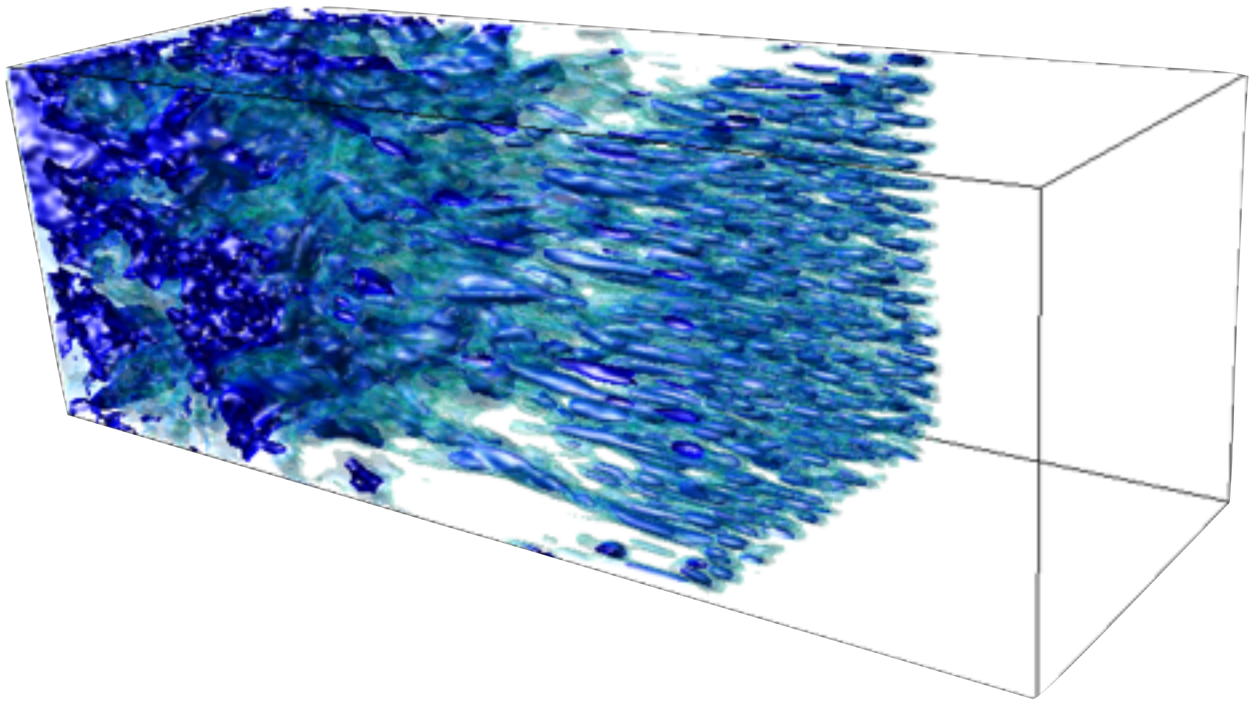

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Overview

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Key quantities

Electromagnetic shocks (EM)

Weibel instability and diffusive shock acceleration

e^-i^+ vs. e^-e^+ plasmas

Electrostatic shocks (ES)

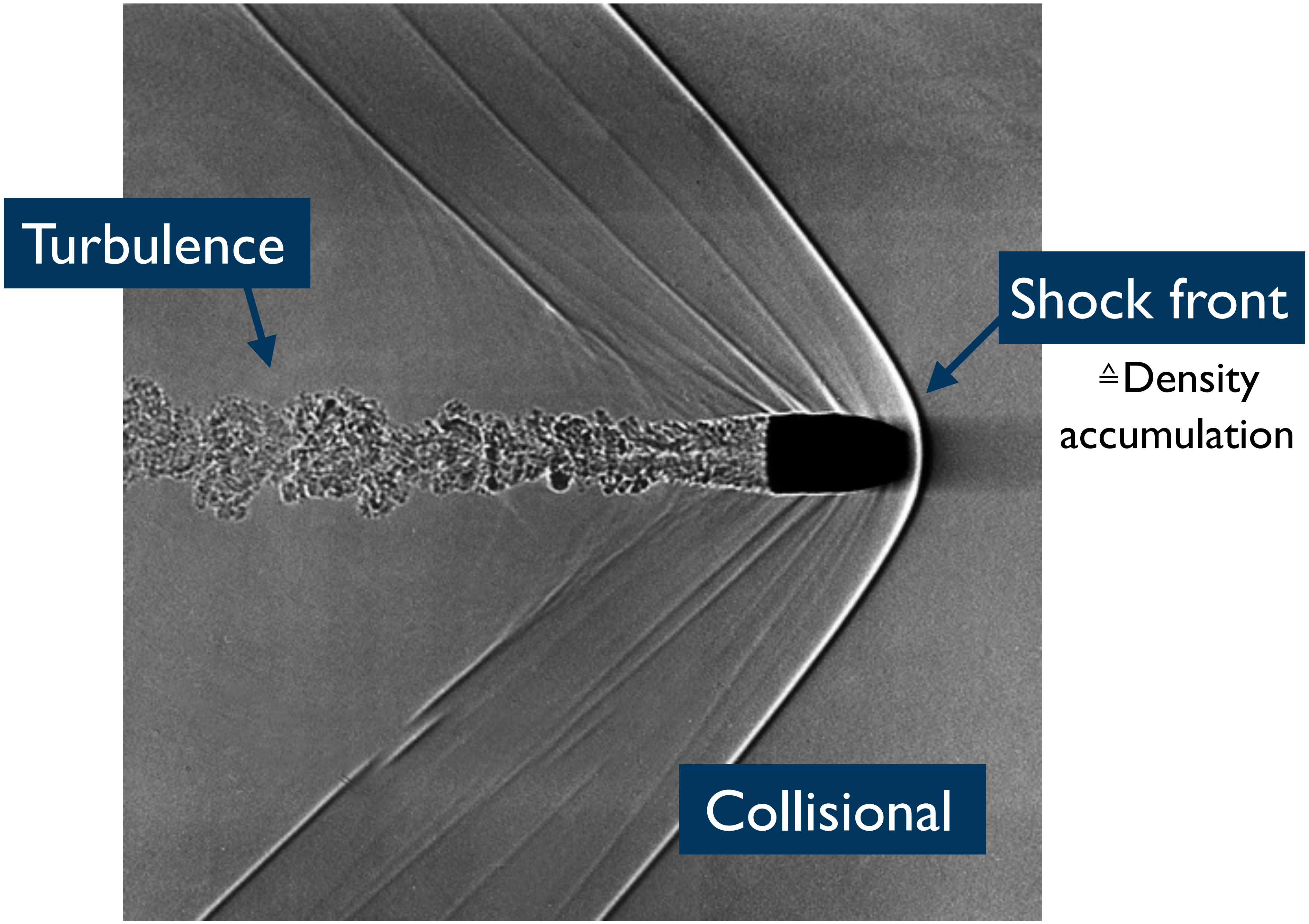
Shock reflection

Electromagnetic modes in ES

ES in the laboratory

Conclusions

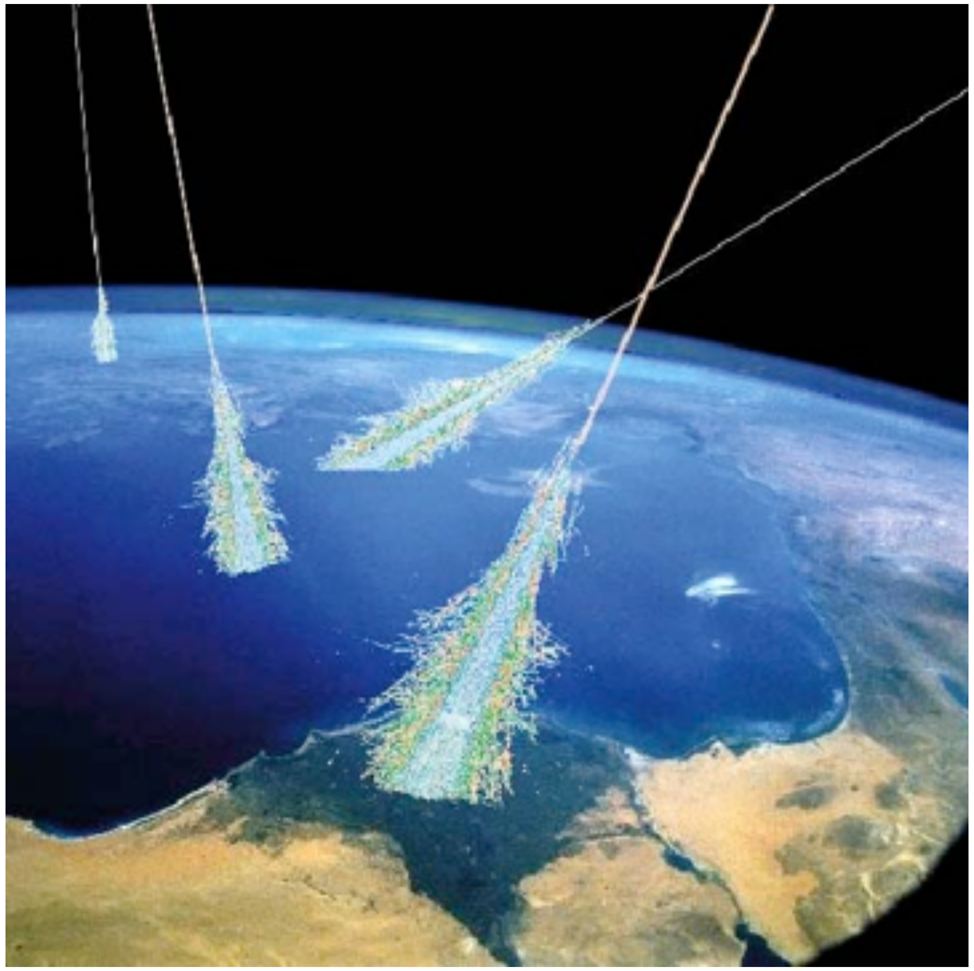
Bullet in water as example for a shock



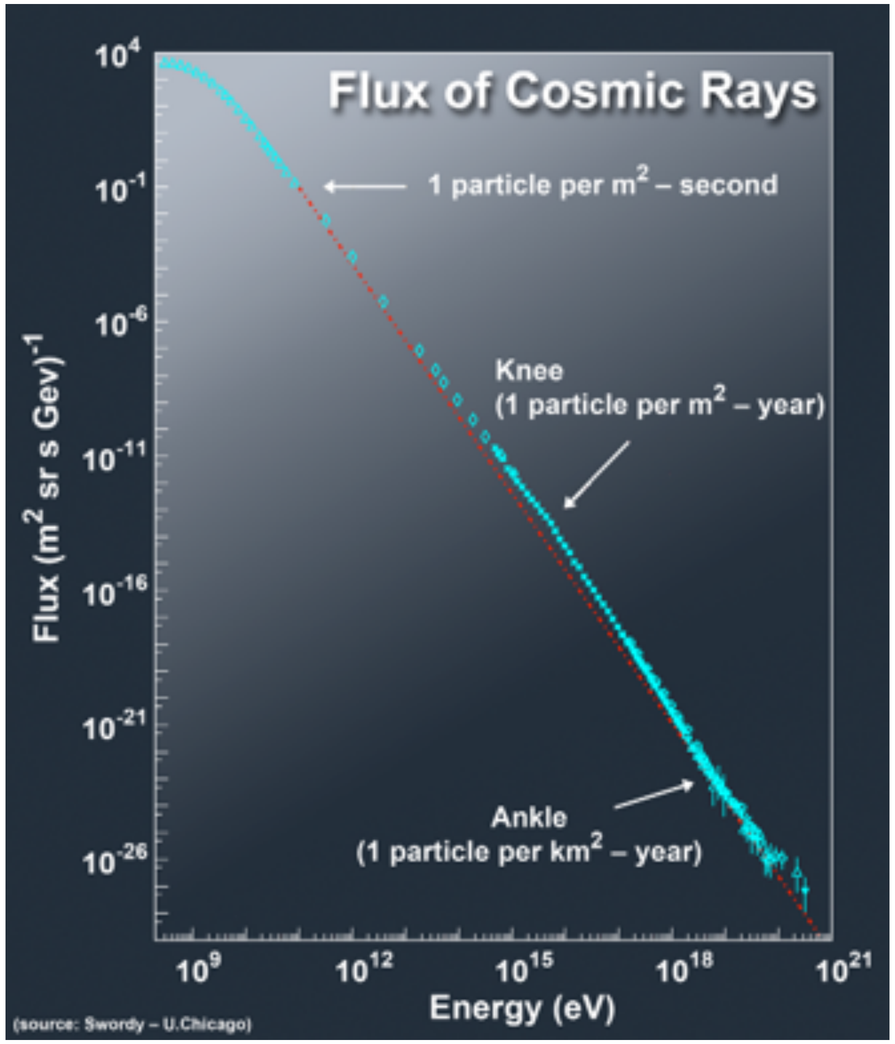
blogs.scientificamerican.com

Cosmic rays accelerated in shocks

Travel to the earth



Cosmic ray spectrum



Cosmic rays

- 90% protons (H^+)
- 9% alpha
- 1% heavier nuclei

Efficient particle acceleration in shocks!

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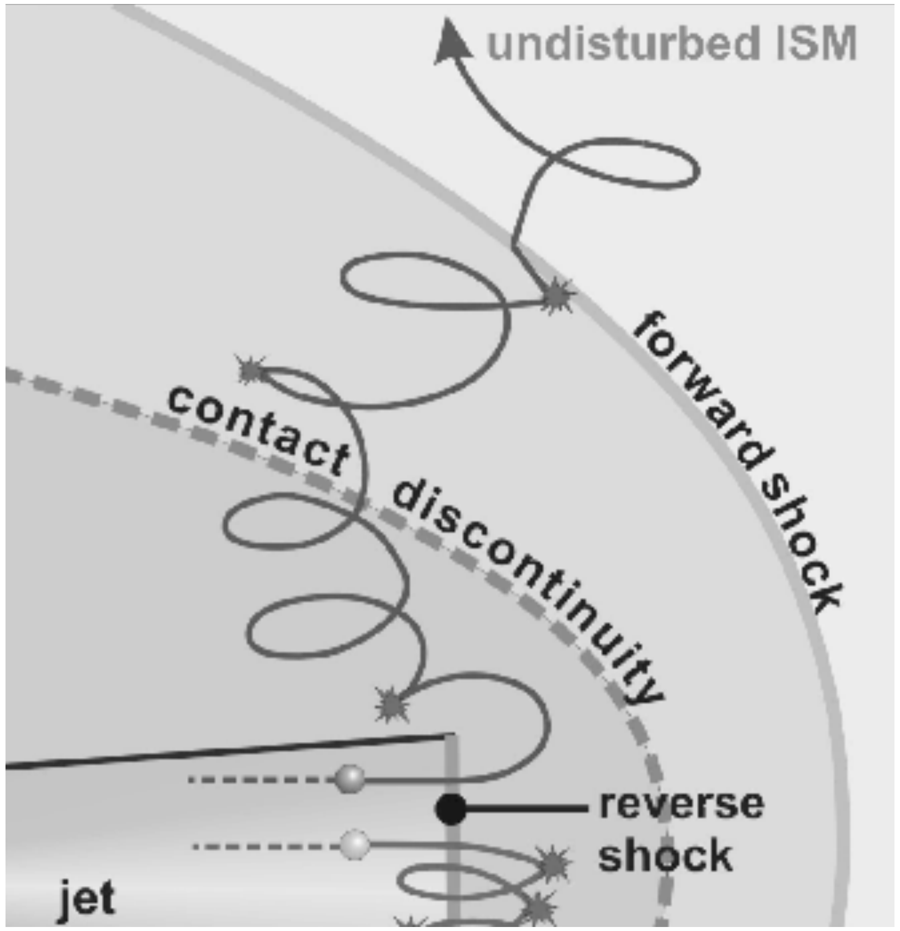
Scattering in the shock front



Diffusive shock acceleration

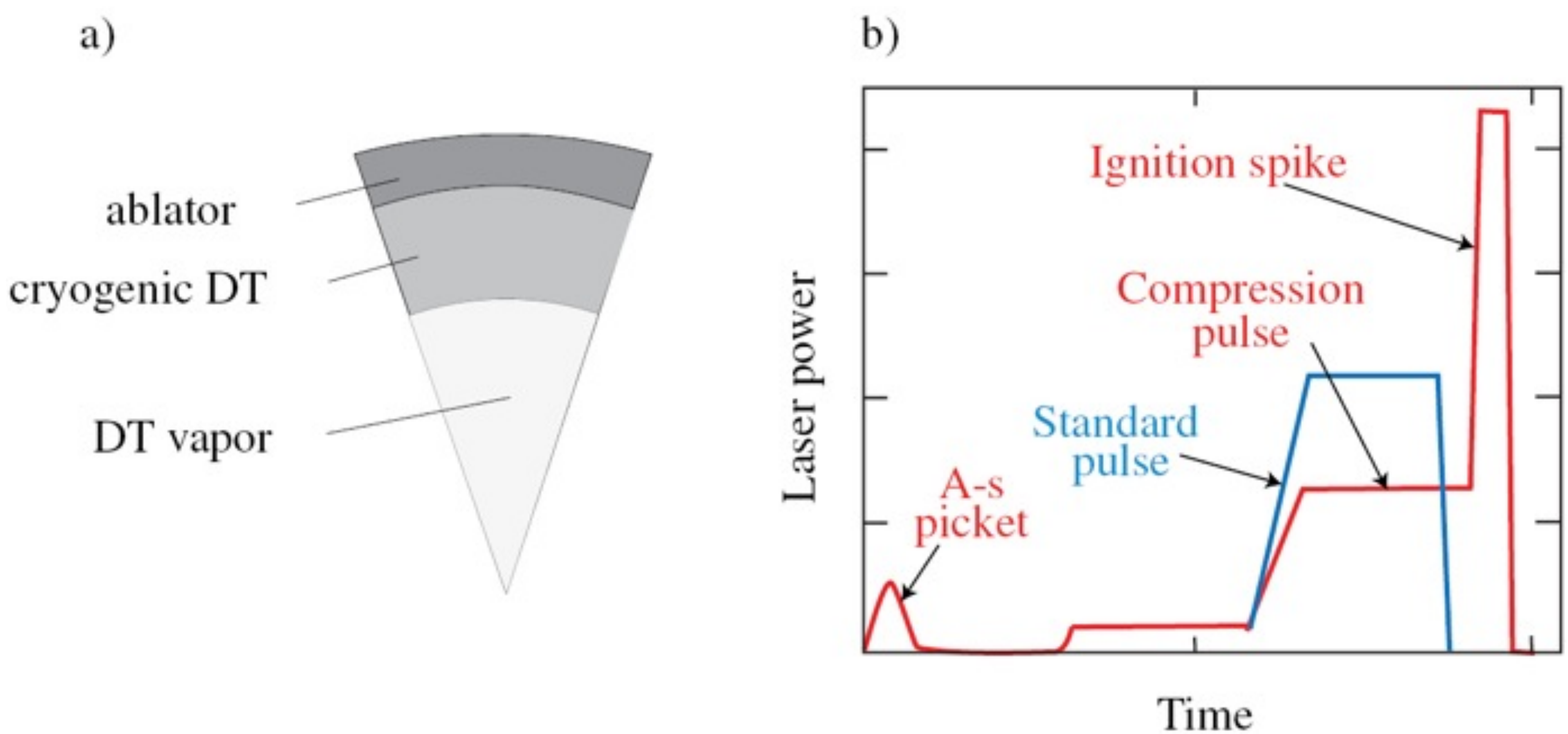
- Energy gain per crossing:

$$\frac{\Delta E}{E} \propto \frac{v}{c}$$

- Power-law distribution:

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

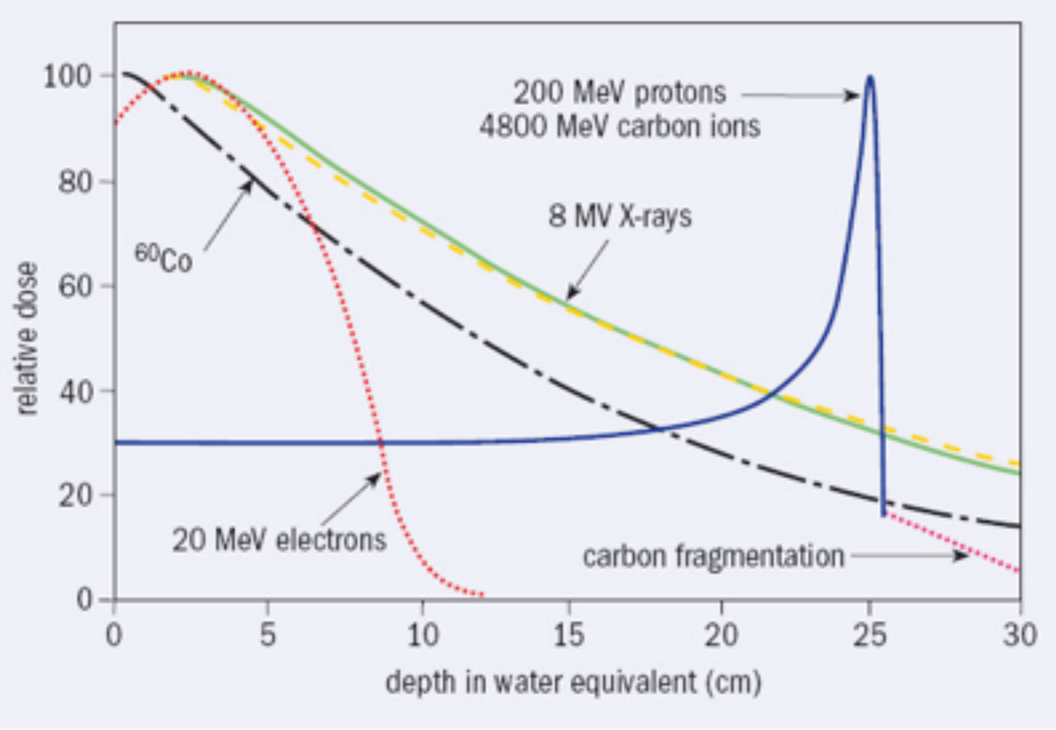
Shock ignition in inertial confinement fusion



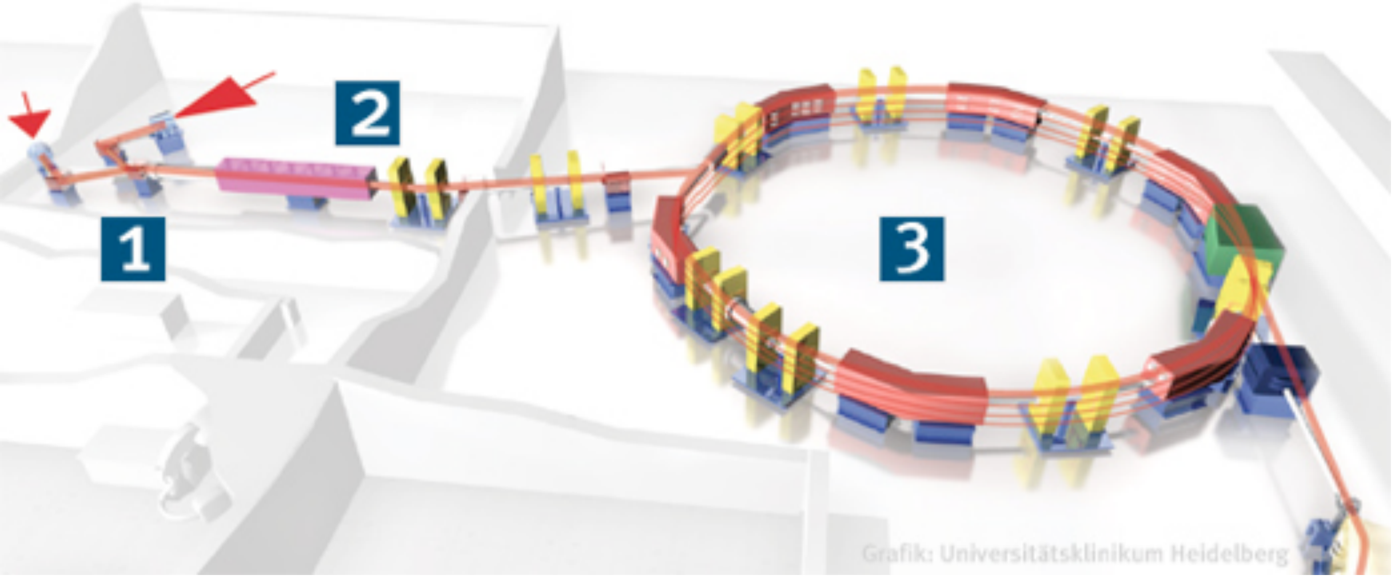
Compression and hot spot formation in separate stages
→ Better control over instabilities

Atzeni et al. (2015) PPCF **57** 014022

Fast ions for cancer therapy

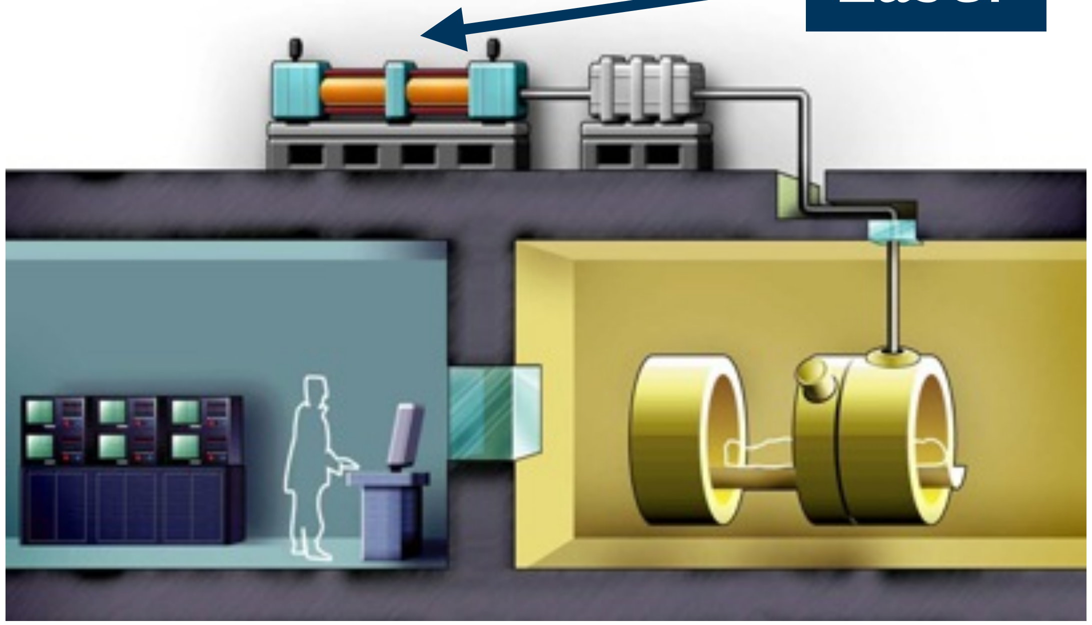


Synchrotron



www.klinikum.uni-heidelberg.de

Laser

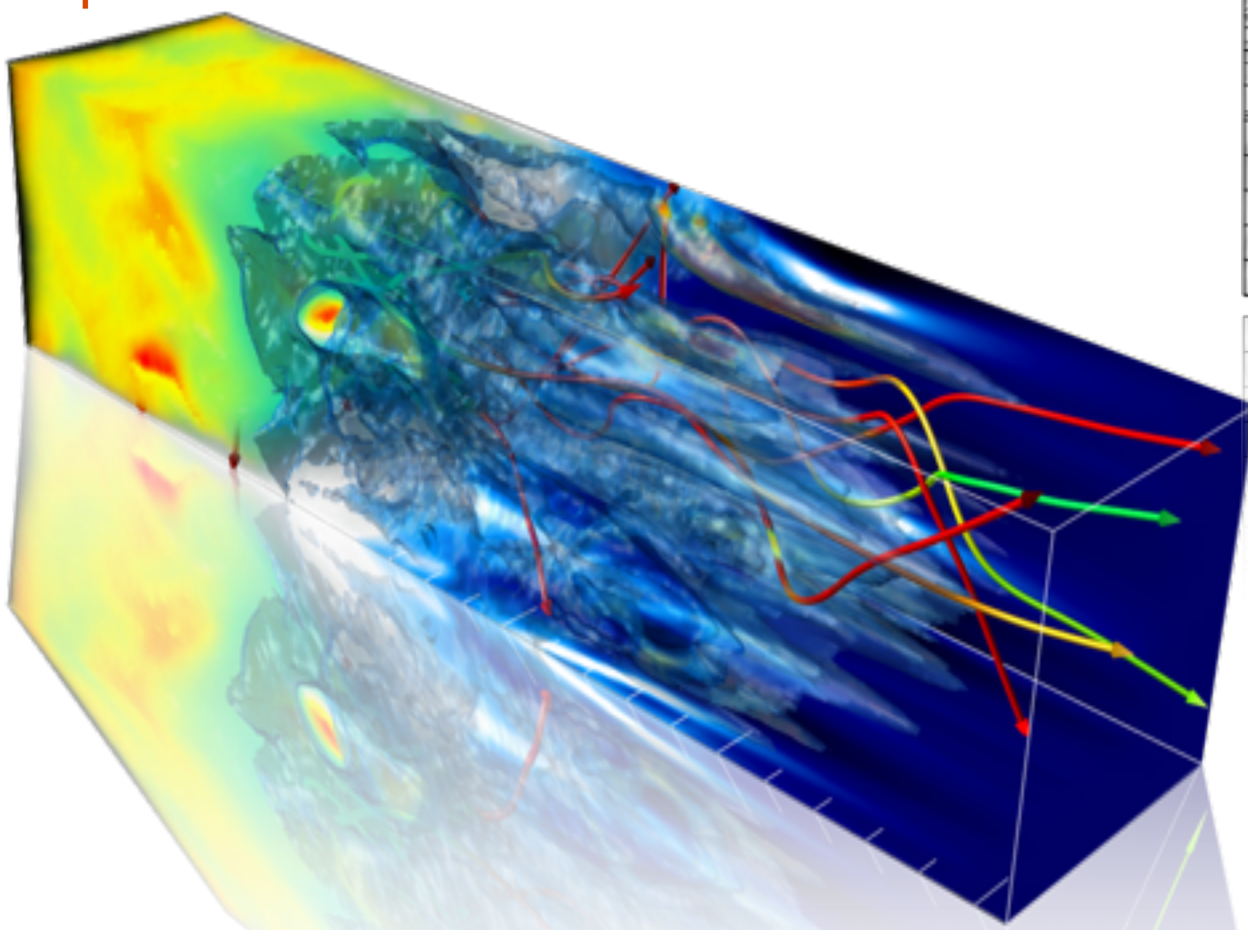


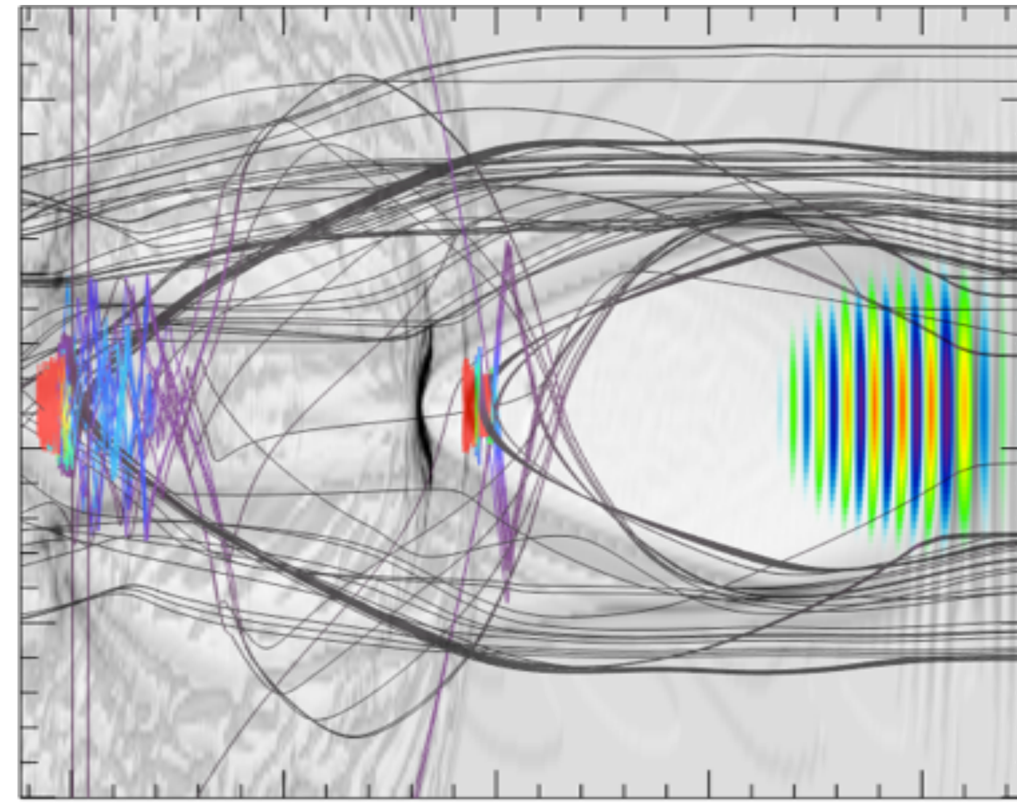
www.eli-beams.eu

OSIRIS 2.0

osiris framework

- Massively Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  - ⇒ UCLA + IST





New Features in v2.0

- Bessel Beams
- Binary Collision Module
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing
- PML absorbing BC
- Optimized higher order splines
- Parallel I/O (HDF5)
- Boosted frame in 1/2/3D

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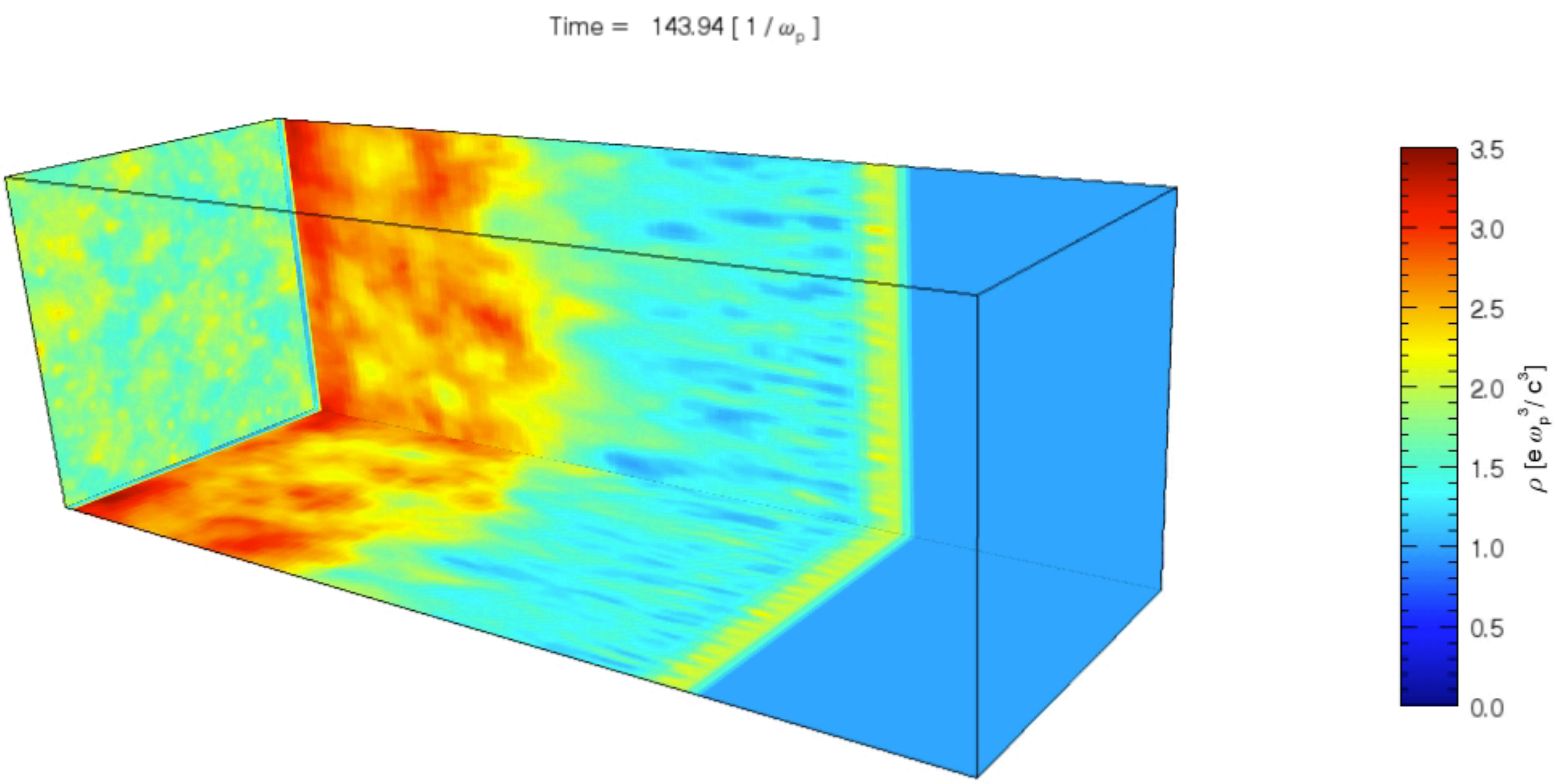
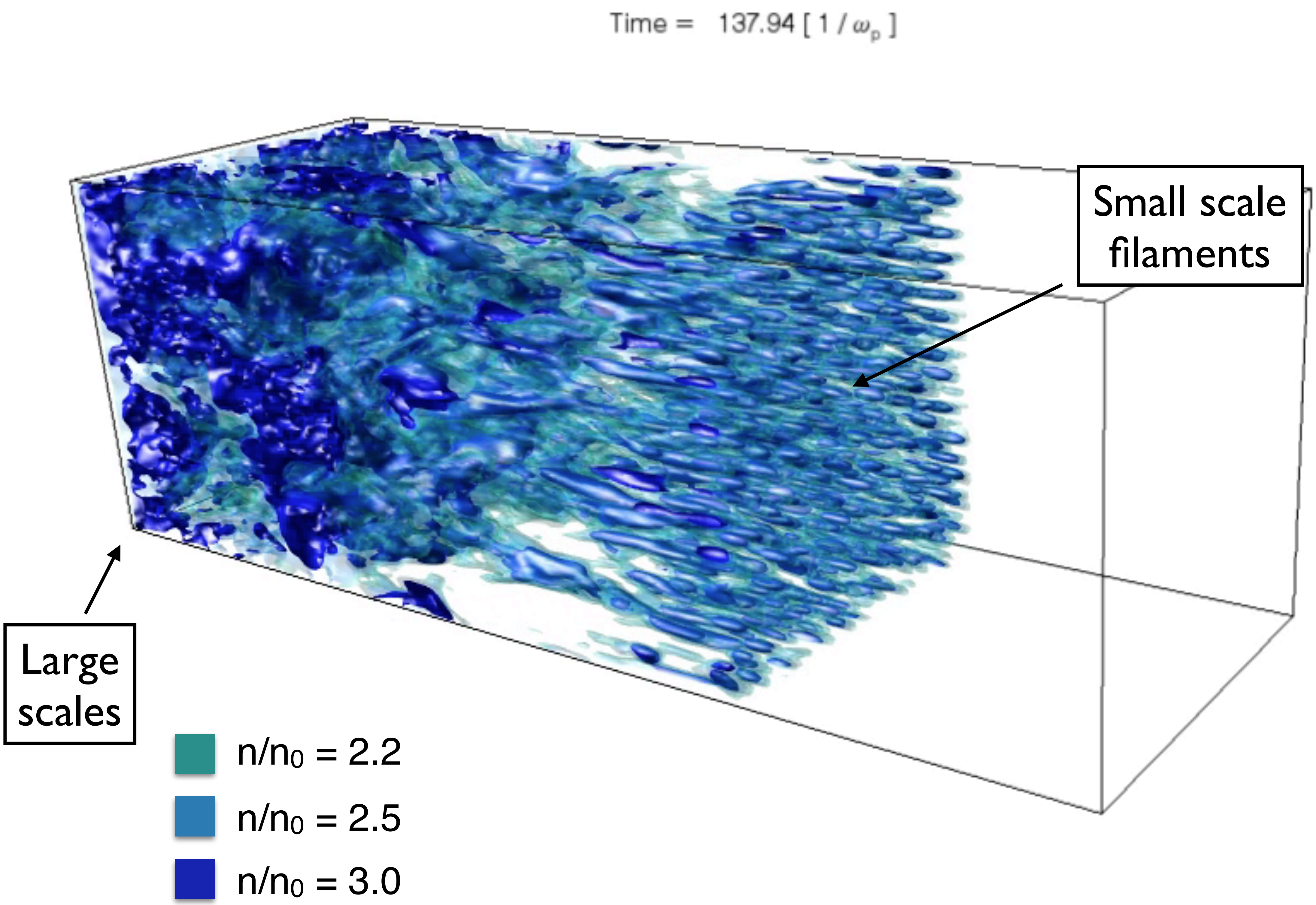
http://cfp.ist.utl.pt/golp/epp/
http://exodus.physics.ucla.edu/

Collisionless shocks



Collisionless shocks



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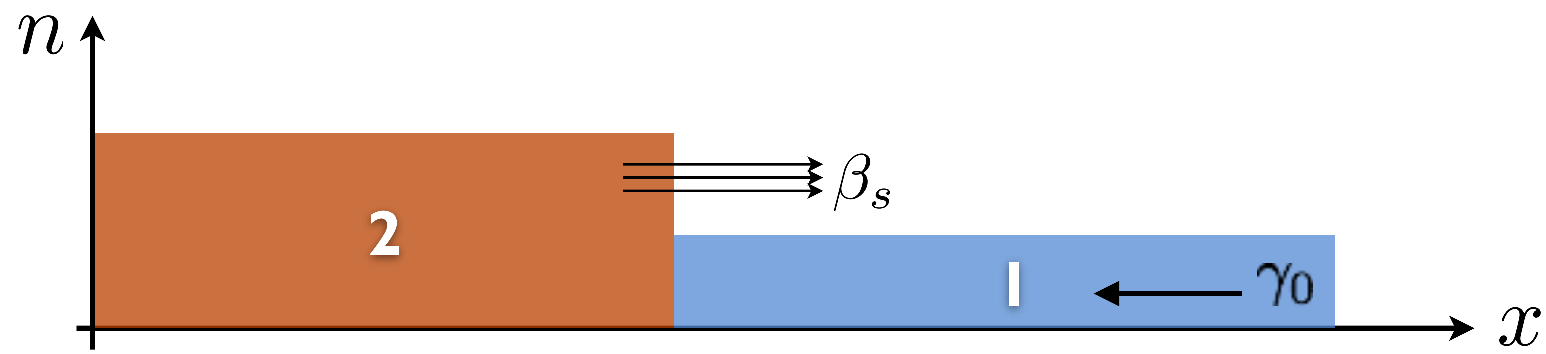
Hydrodynamic equations for steady state

Shock model



Continuity of main quantities

$$
\begin{aligned}
n_1 u_{1s} &= n_2 u_{2s} \\
\gamma_{1s}\mu_1 &= \gamma_{2s}\mu_2 \\
u_{1s}\mu_1 + \cancel{\frac{p_1}{n_1 u_{1s}}} &= u_{2s}\mu_2 + \frac{p_2}{n_2 u_{2s}}
\end{aligned}
$$

Strong shock approximation

$$p_2/n_2 \gg p_1/n_1$$

Pressure energy relation

$$p = (\Gamma_{ad} - 1)(e - \rho)$$

Jump conditions in simulation frame

$$\beta_s = (\Gamma_{ad} - 1)\sqrt{\frac{\gamma_0 - 1}{\gamma_0 + 1}}$$

$$\frac{n_2}{n_1} = \frac{\Gamma_{ad}}{\Gamma_{ad} - 1} + \frac{1}{\gamma_0(\Gamma_{ad} - 1)}$$

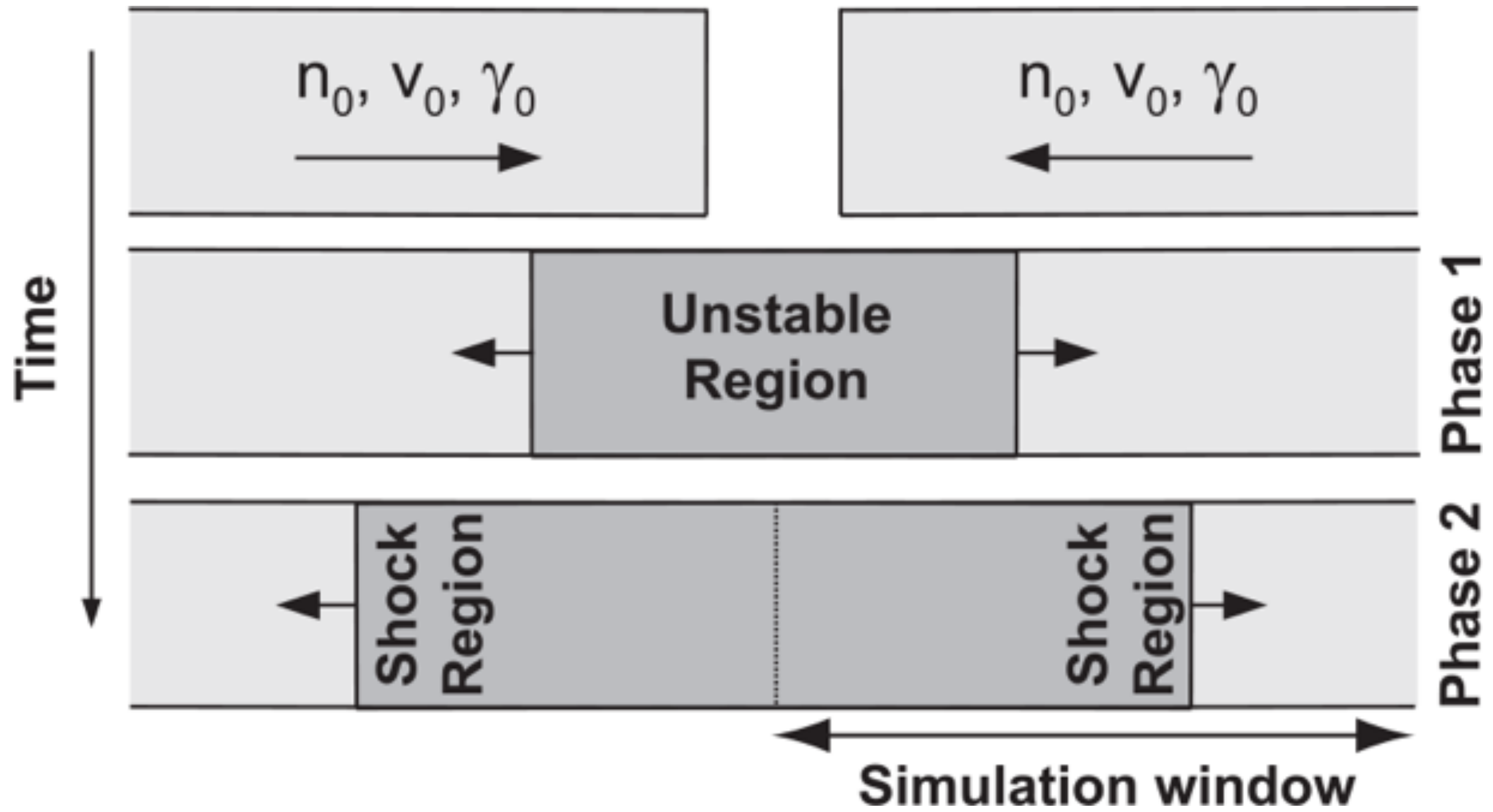
Blandford & McKee (1976)

Simulation setup for a collisionless shock

e^- and e^+, i^+: $m_i/m_e \geq 1$

Non-relativistic or relativistic beams: v_0, γ_0

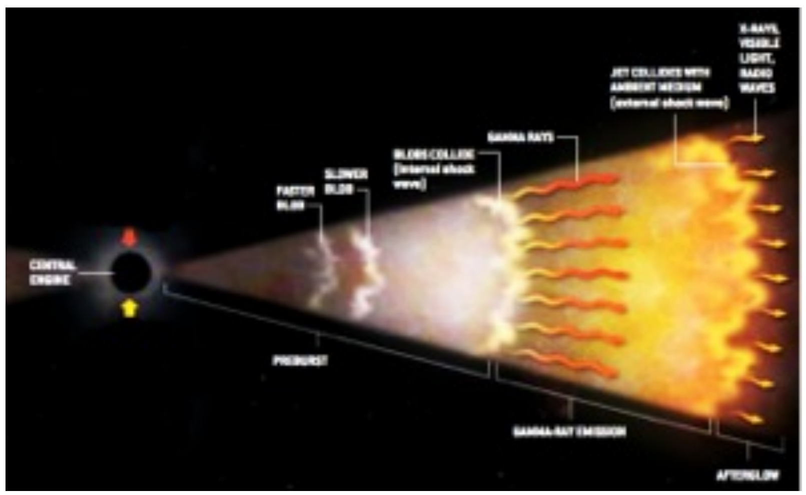
Hot or cold beams: $k_B T_e/m_e c^2$



Bret, Stockem et al., PoP (2013)

Electrostatic vs. electromagnetic

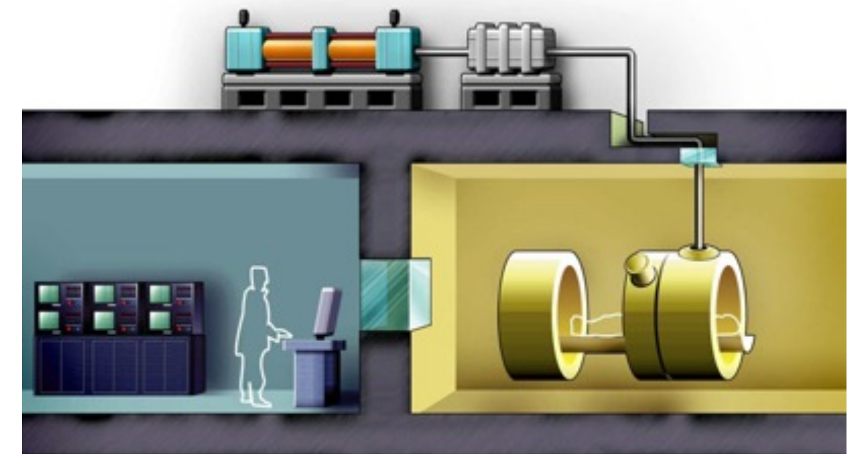
Electromagnetic shocks in lab and astro



Shock front transition mediated by (electro) **magnetic** field

Formation time scales on 100s ω_{pi}^{-1}

Electrostatic shocks in the laboratory



Shock front transition mediated by **electrostatic** field

Formation time scales on 10s ω_{pi}^{-1}

Different formation mechanisms in EM and ES

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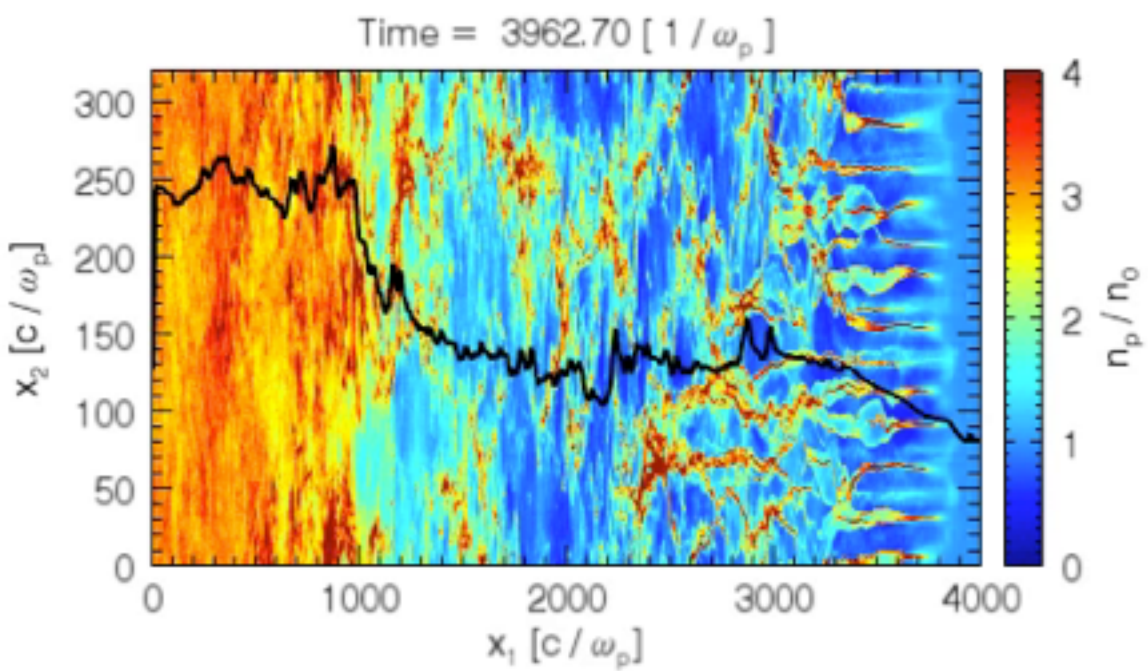
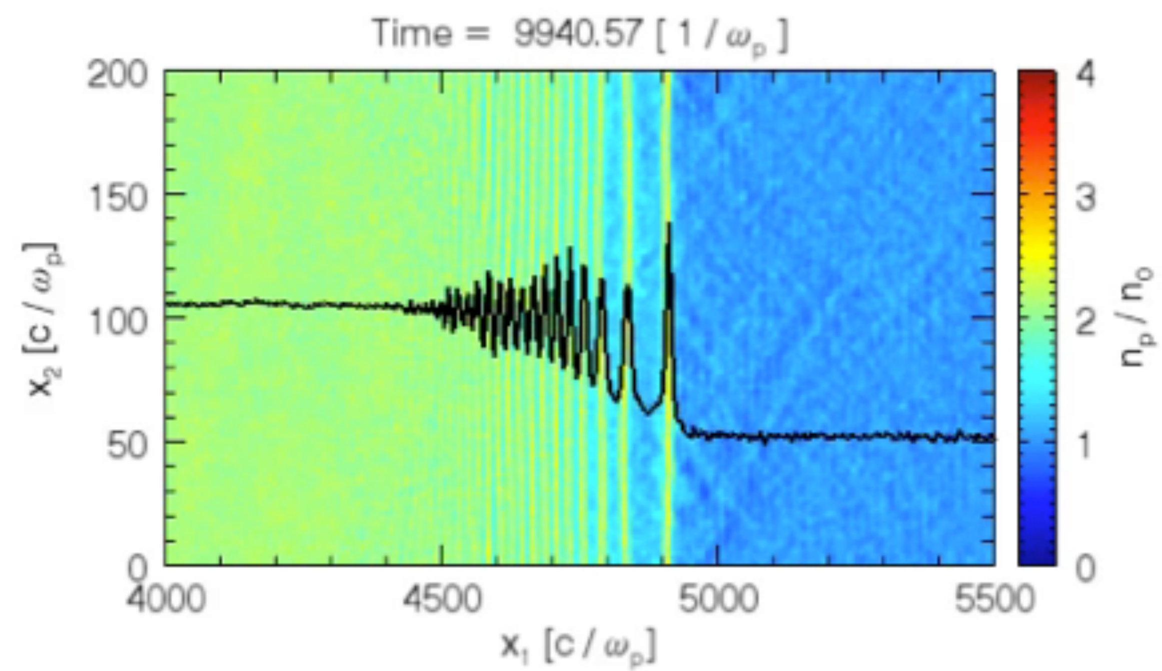
Electromagnetic shock (EM)



Electrostatic shock (ES)



- Density compression ~ 3
- Filaments
- Driven by Weibel/filamentation instability

- Density compression $\gtrsim$ 2
- Oscillatory structure
- Driven by longitudinal modes

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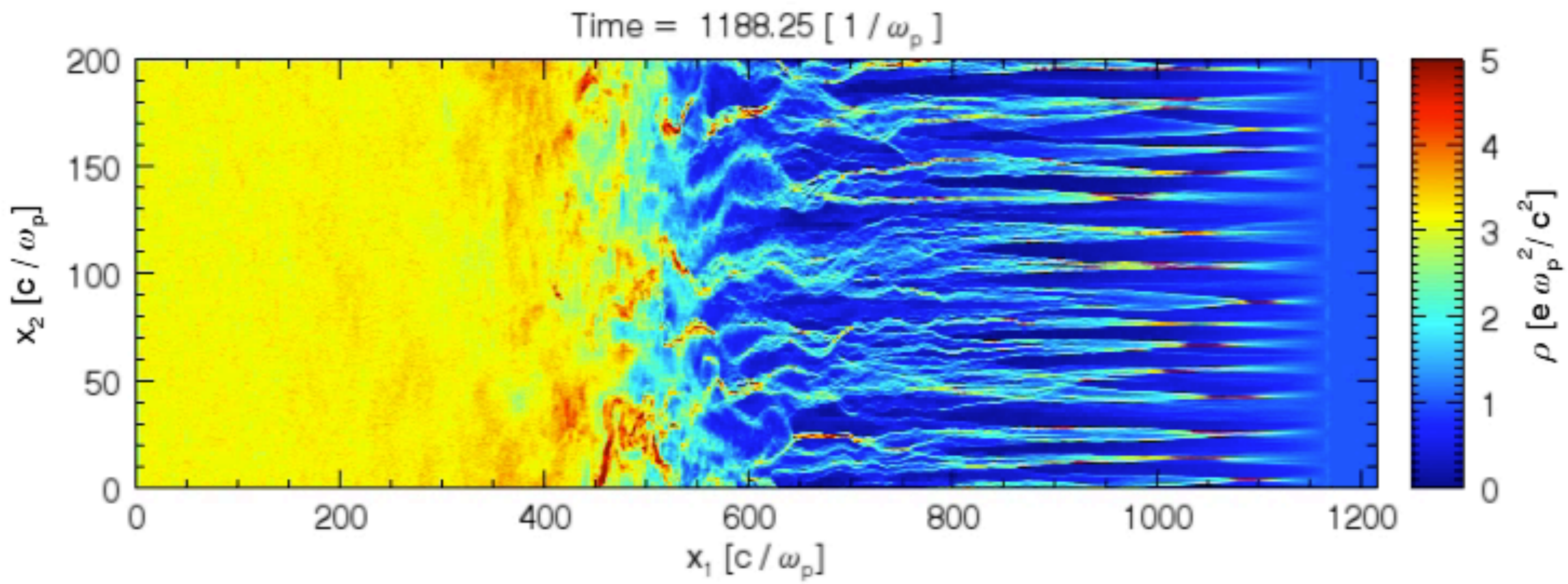
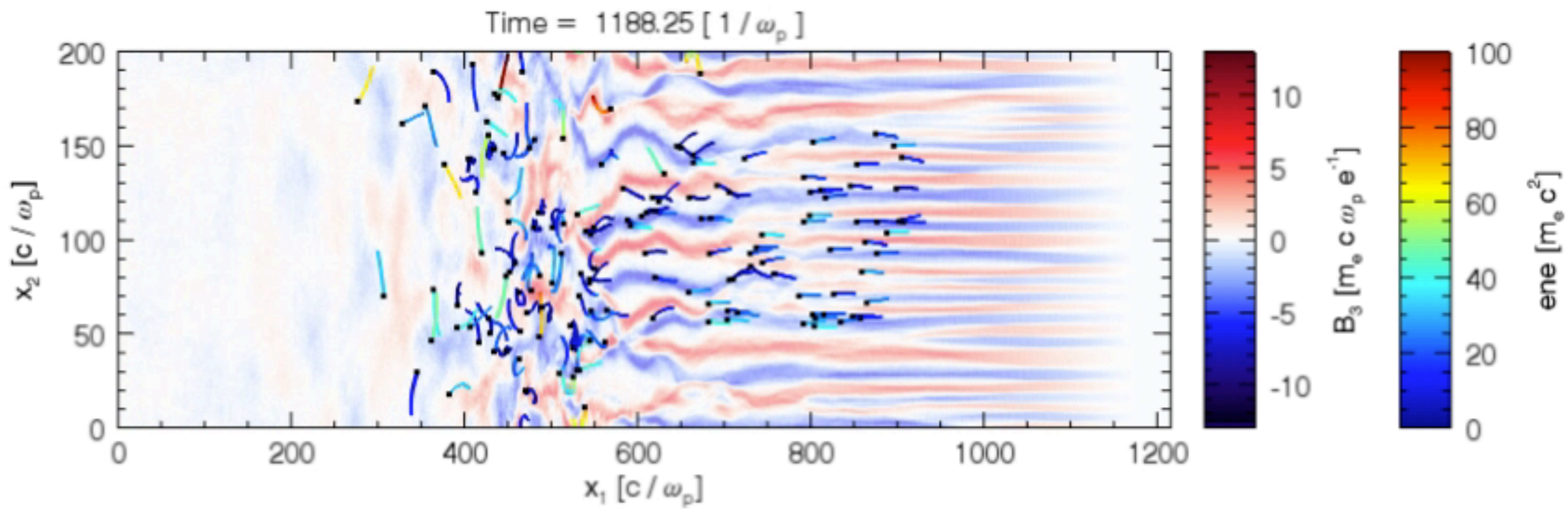
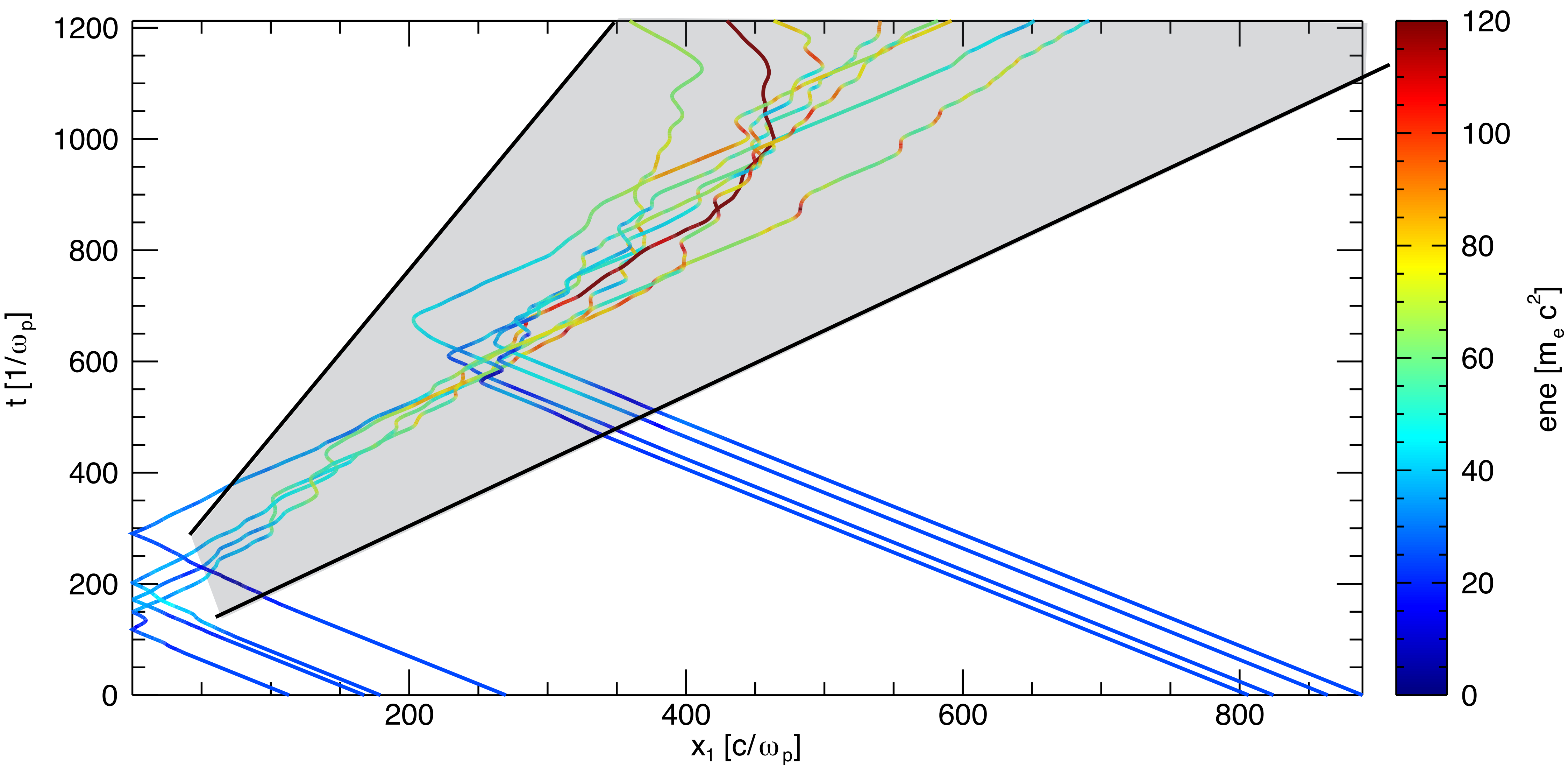
B3 is generated, density is accumulated





Turbulent scattering increases energy



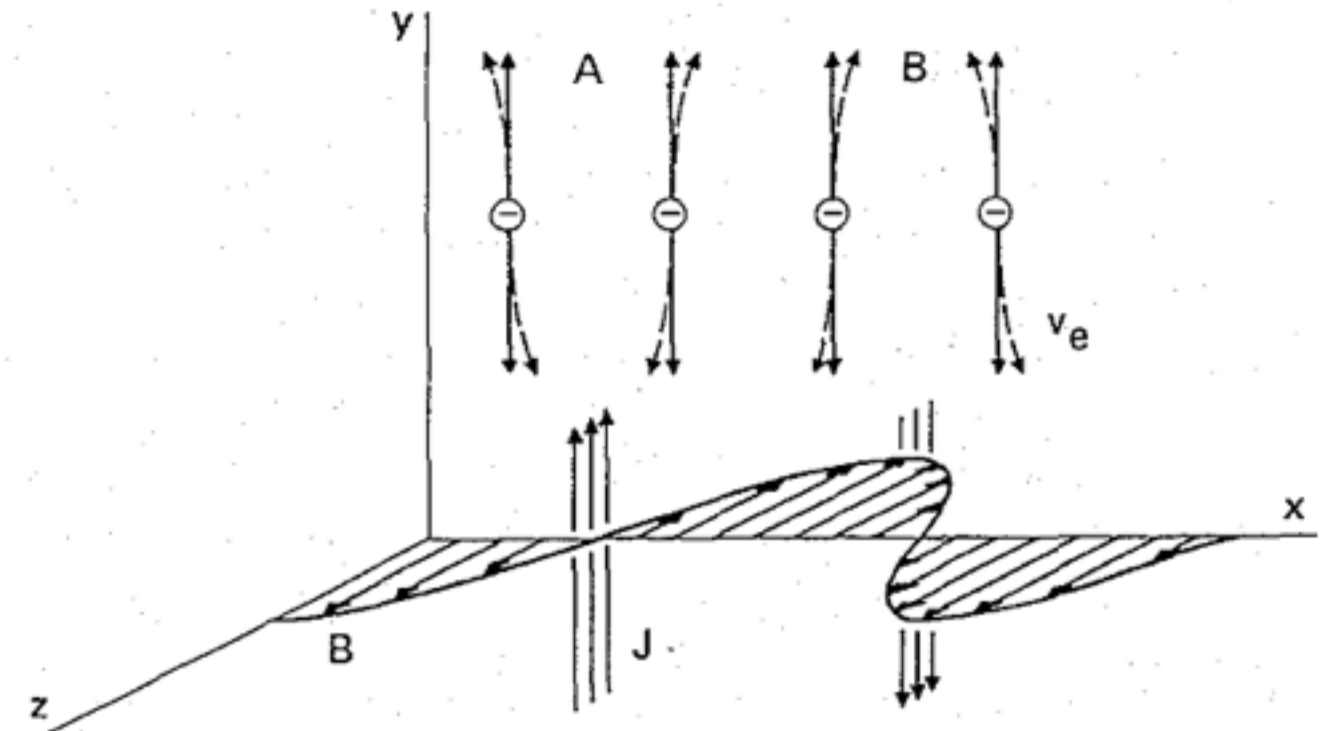
Filamentation instability generates B_3

Growth rate of cold filamentation

$$\frac{\delta}{\omega_p} = \sqrt{\frac{2}{\gamma_0}}\beta_0$$

Exponential field growth:

$$\tau_s = \frac{1}{2\delta}\ln\left[\frac{B_f^2}{B_i^2}\right]$$



Physical mechanism of the Weibel instability.

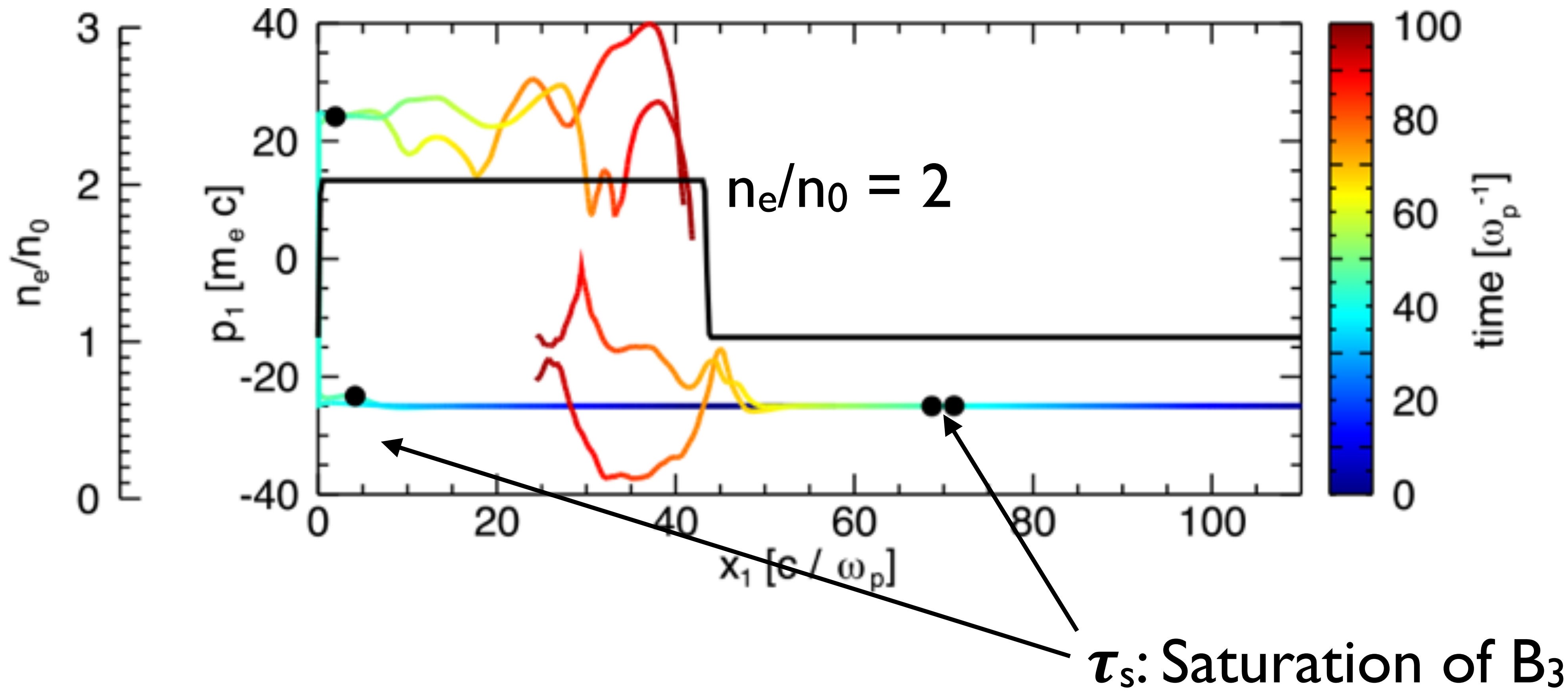
$$\tau_s\omega_p = \frac{\sqrt{\gamma_0}}{2\sqrt{2}}\ln\left[4\times 10^2\sqrt{\frac{\pi}{3}}\frac{\mu}{\gamma_0}N\right]$$

$$\mu = \frac{m_e c^2}{k_B T}$$

$\gamma_0 = 25$: $\tau_s\omega_{pe} = 40$

Bret, Stockem et al., PoP (2013)

Density is accumulated: a shock is formed



Quasi-steady shock: Density jump condition fulfilled

$$\frac{n_2}{n_1} = \frac{\Gamma_{ad}}{\Gamma_{ad}-1} + \frac{1}{\gamma_0(\Gamma_{ad}-1)}$$

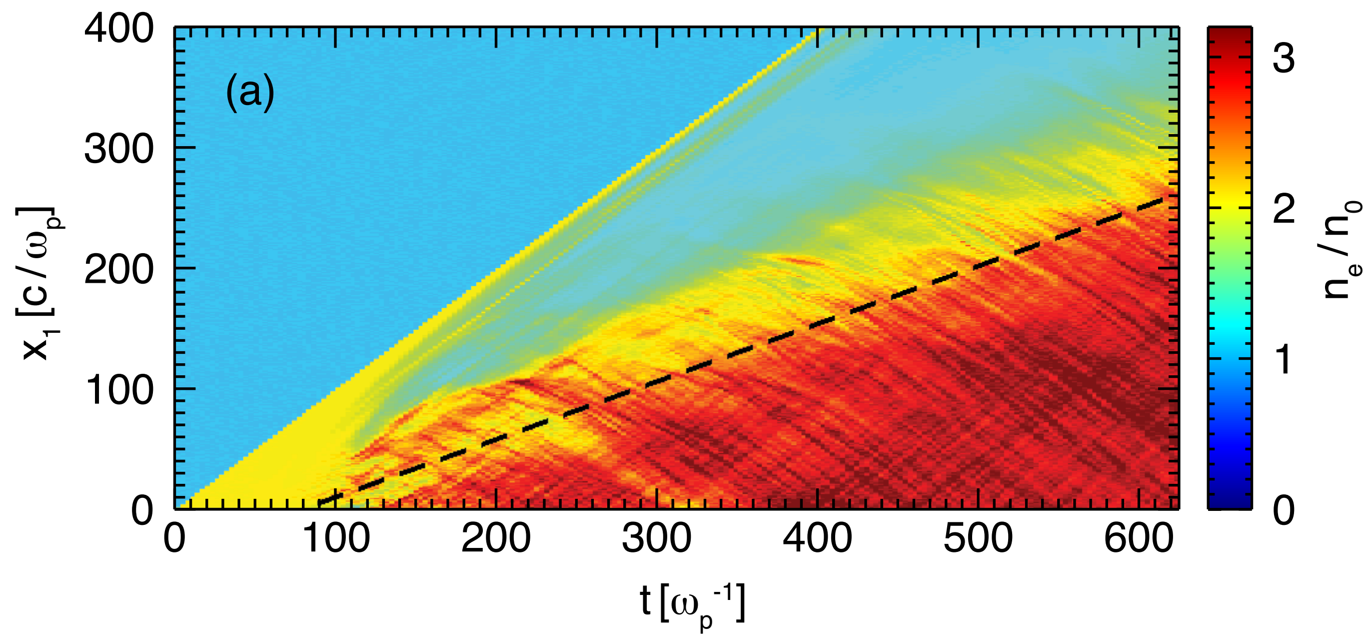
Shock formation time:

$$\tau_{sf} = \begin{cases} 2\tau_s & (2D) \\ 3\tau_s & (3D) \end{cases}$$

Bret, Stockem et al., PoP (2014)

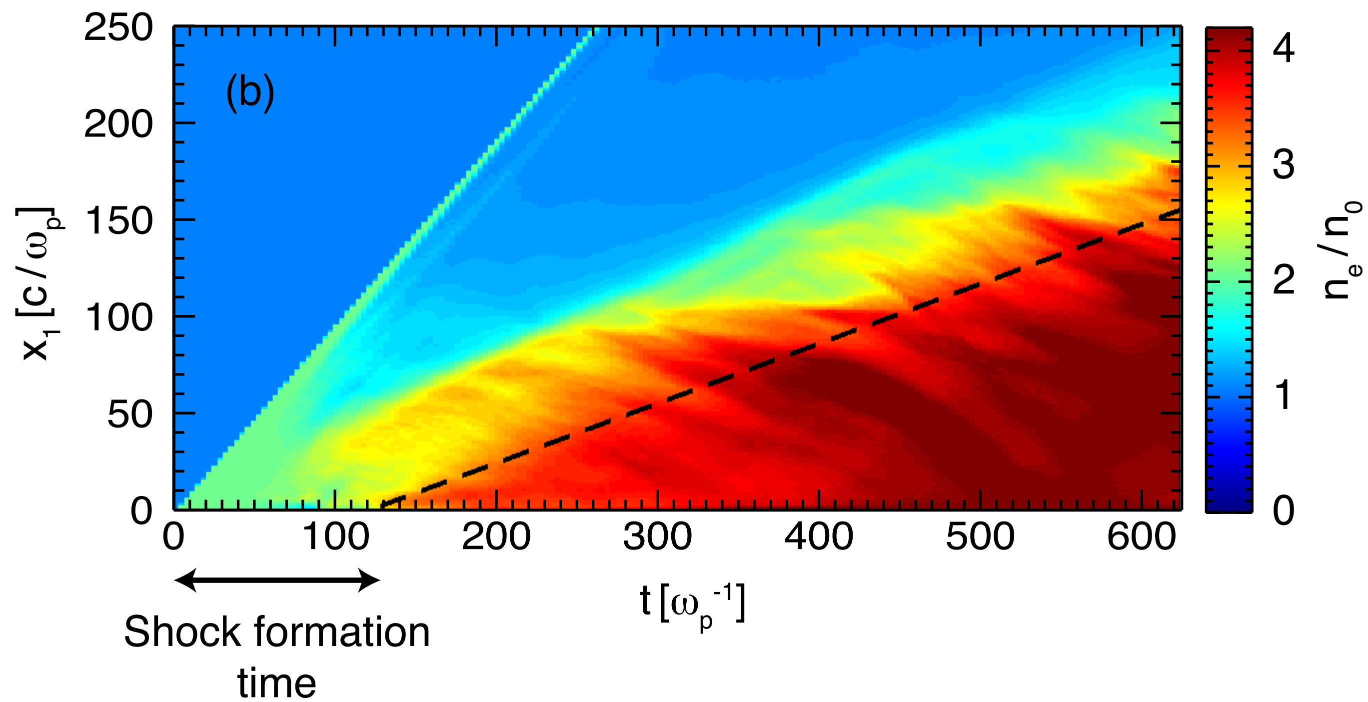
Formation of quasi-steady state

2D



$\tau_{sf} = 2\tau_s$

3D



$\tau_{sf} = 3\tau_s$

Bret, Stockem et al., PoP (2014)

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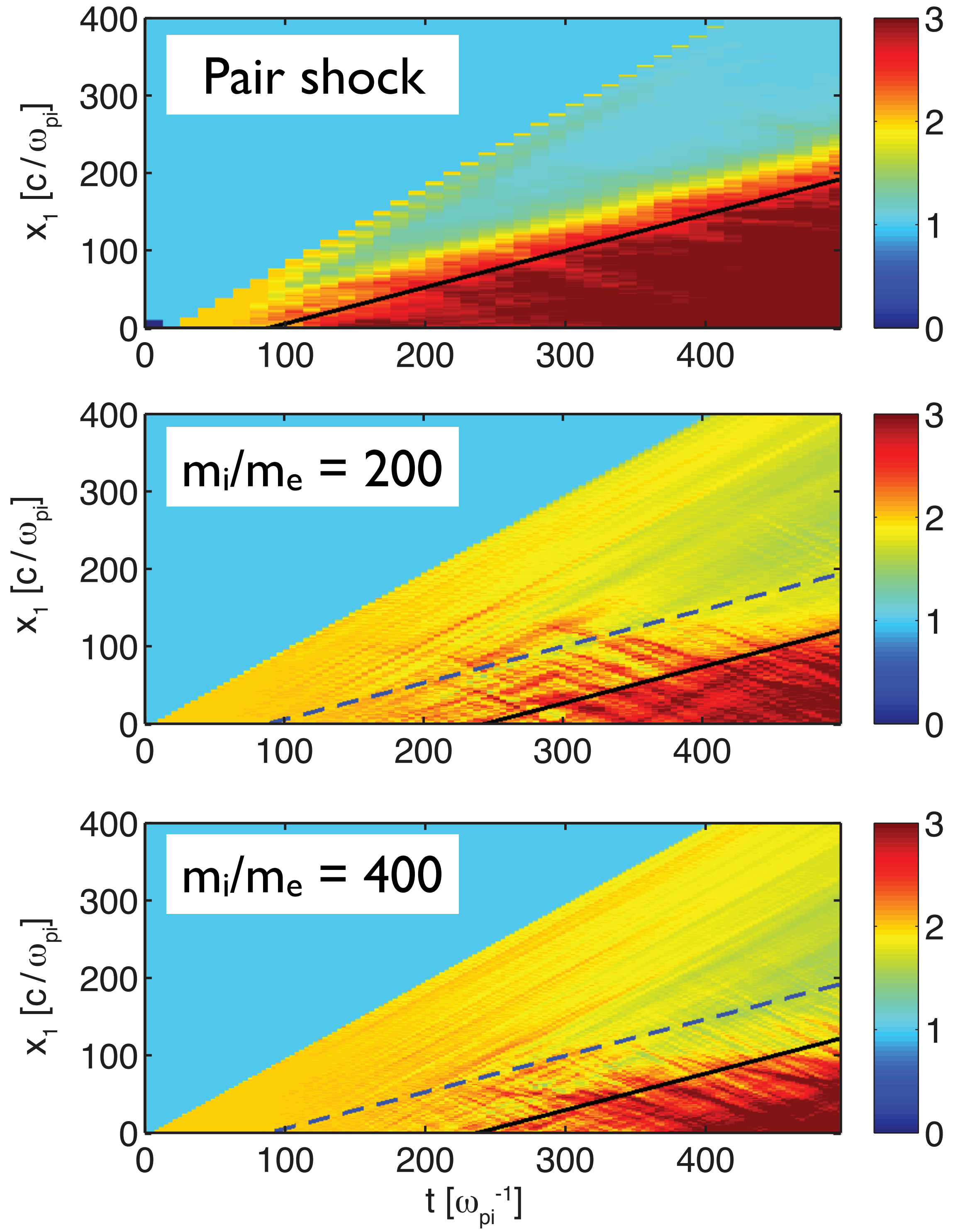
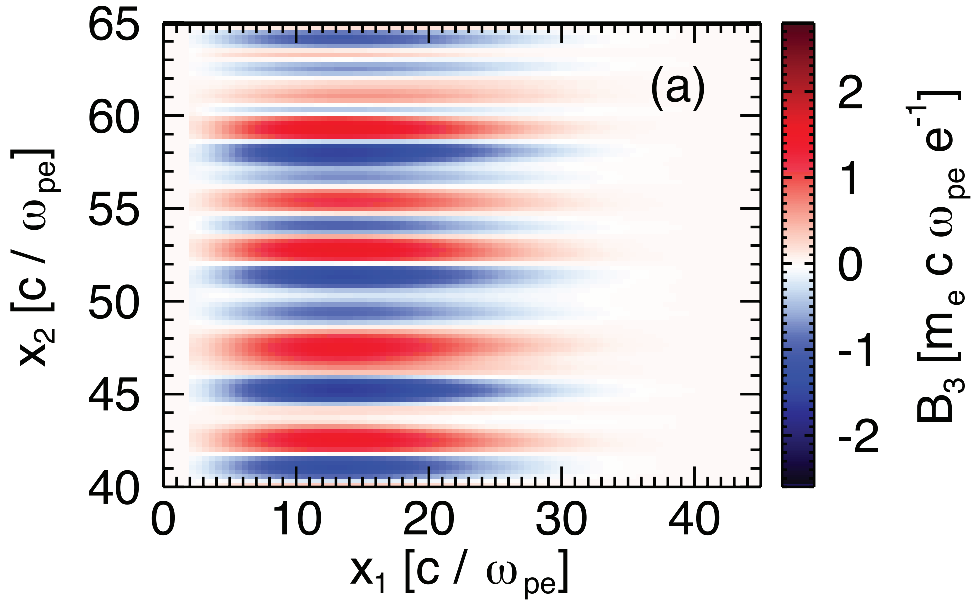
Quasi-steady shock formation takes longer



Smaller turbulence scales in e-i shocks

Pair shock

$t\omega_{pe} = \tau_{s,e}\omega_{pe} = 40$



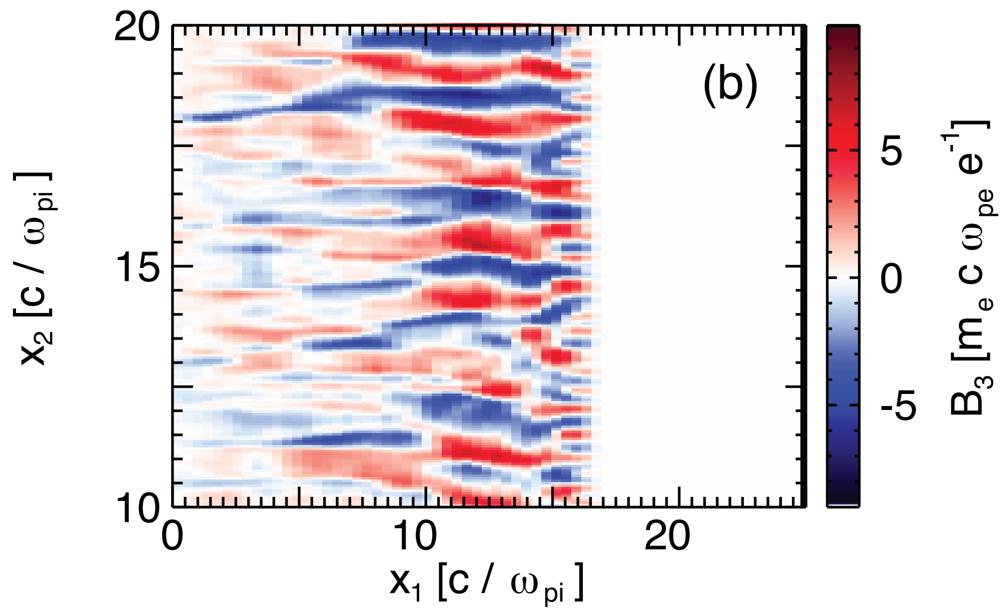
Electron-positron

$\Delta_{filament} > r_L$

For $\gamma \leq 12$

$m_i/m_e = 400$

$t\omega_{pi} = \tau_{s,i}\ \omega_{pi} = 18$



Electron-ion

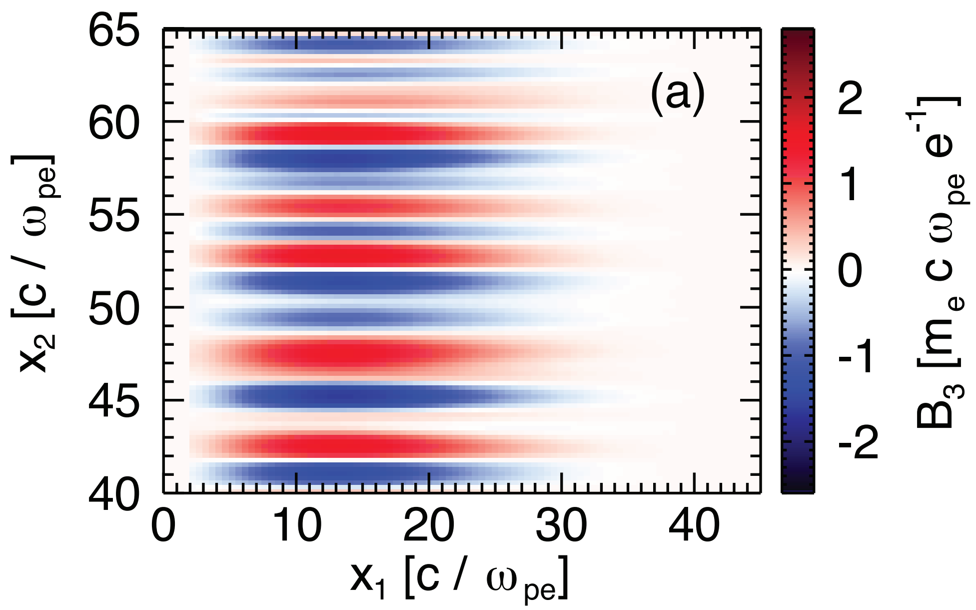
$\Delta_{filament} > r_L$

For $\gamma \approx 1$

Smaller turbulence scales in e-i shocks

Pair shock

$t\omega_{pe} = \tau_{s,e}\omega_{pe} = 40$



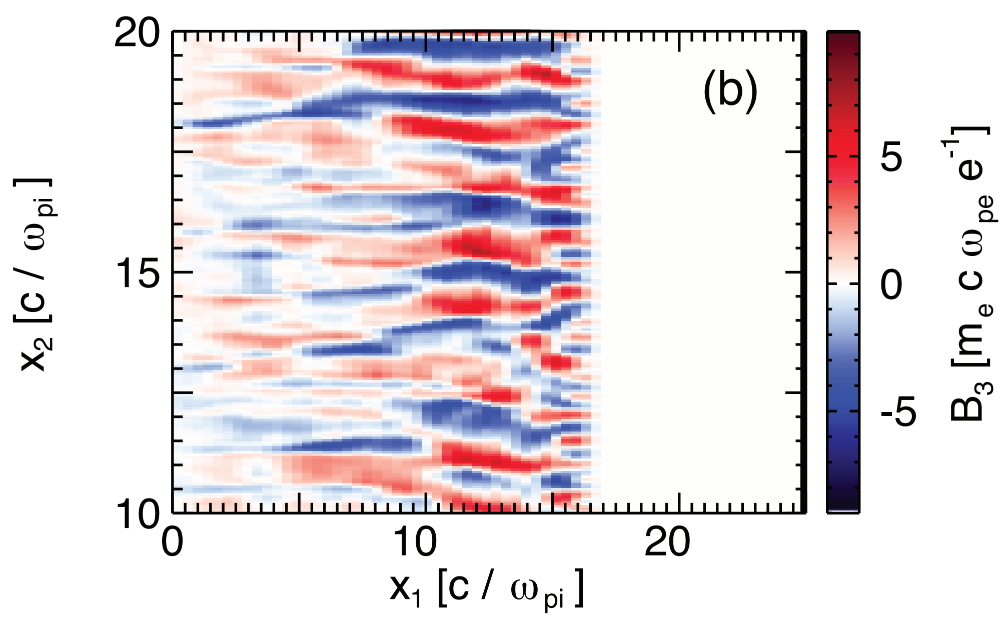
Extra merging time

$$\tau_m \omega_{pi} = \frac{2^{3/2}}{\ln 2} \gamma^{1/2} \ln\left(\frac{m_i}{m_e}\right)$$

$$\frac{\tau_{sf,i}}{\tau_{sf,e}} = \frac{6.2}{\Pi} \ln\left(\frac{m_i}{m_e}\right) \sqrt{\frac{m_i}{m_e}}$$

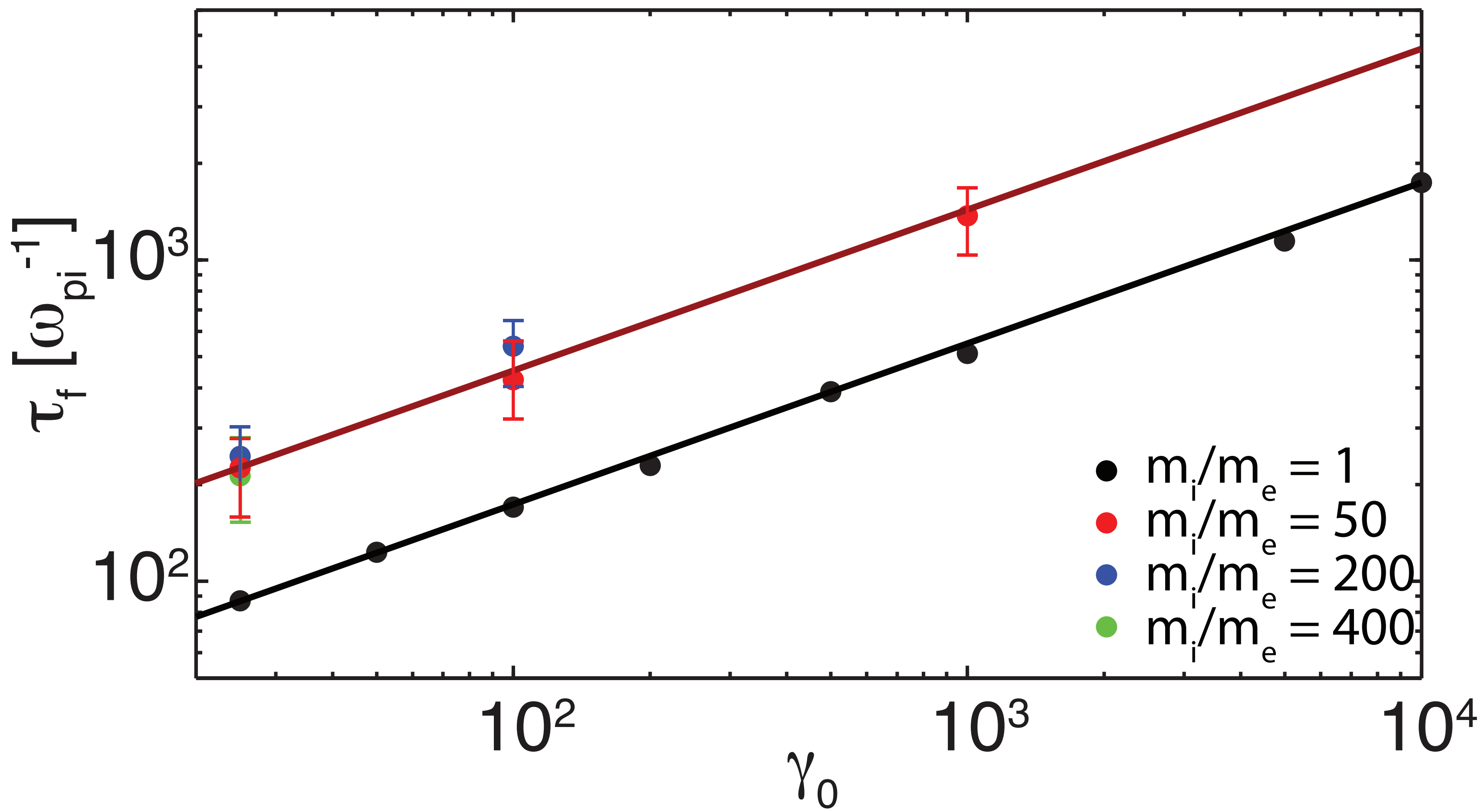
$m_i/m_e = 400$

$t\omega_{pi} = \tau_{s,i}\,\omega_{pi} = 18$



Stockem Novo et al., ApJL (2015)

Shock formation in e-i-plasmas takes longer



Shock formation time in electron-ion shocks is increased by **factor 3**

$$\tau_{sf,i} = 3\sqrt{m_i/m_e}\tau_{sf,e}$$

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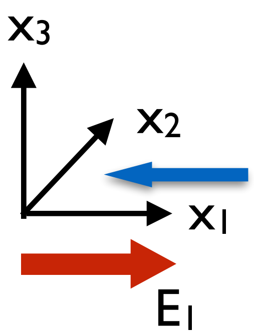
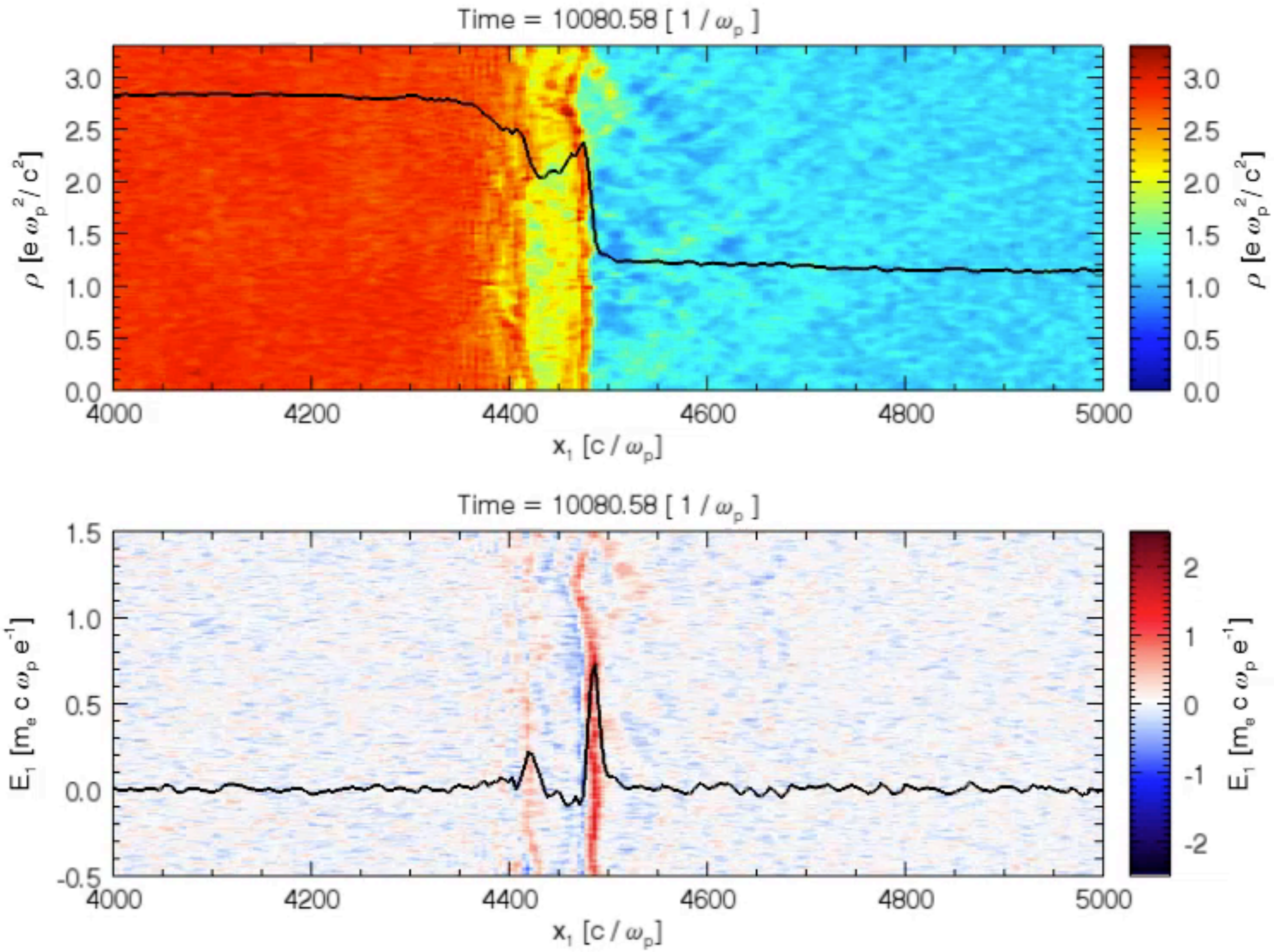
Electrostatic shock (ES) formation





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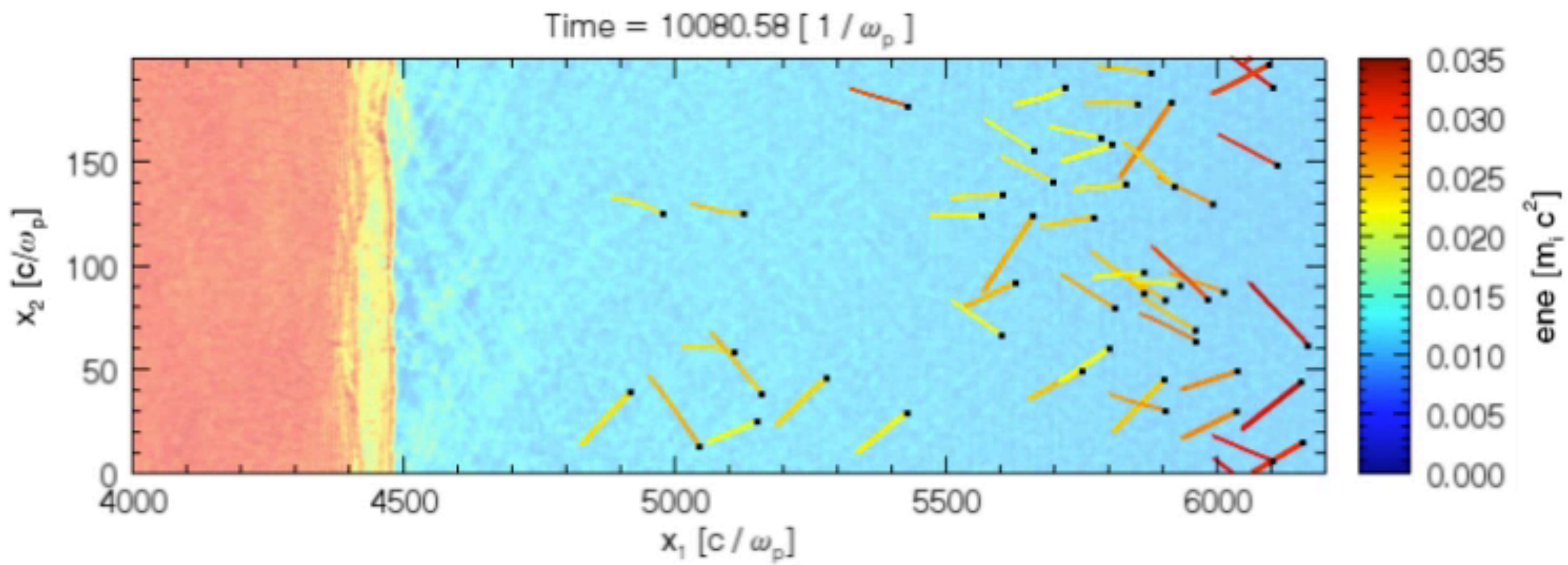
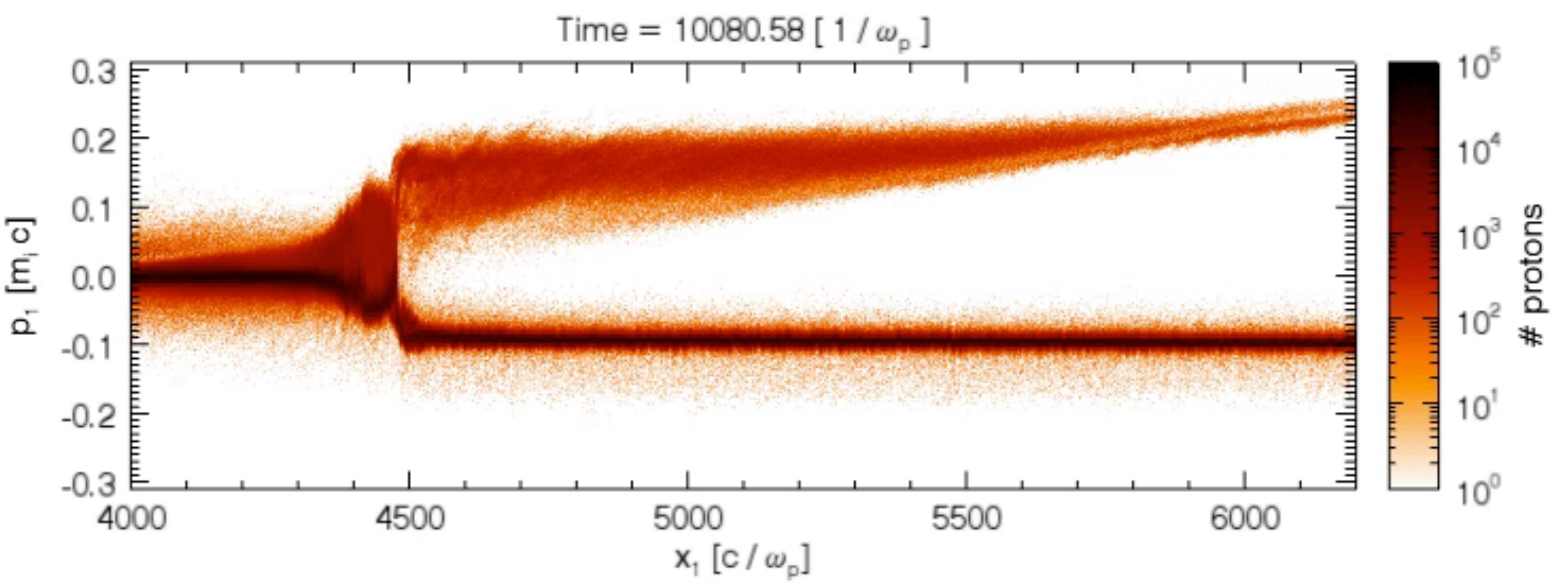
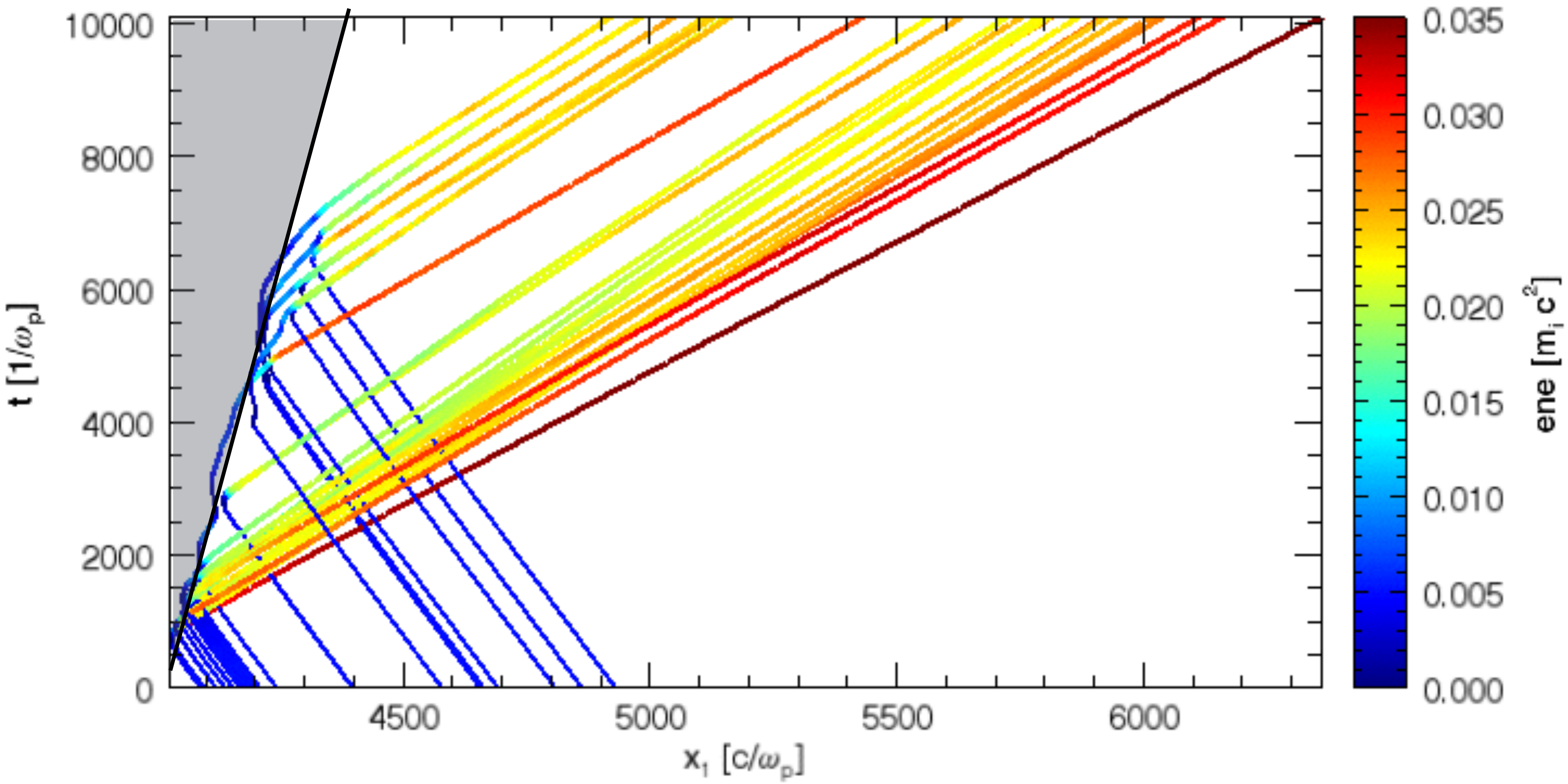




Ions are reflected at the shock front



Shock reflection:
Ion velocity in ion rest frame

$$v_i \approx 2v_{sh}$$

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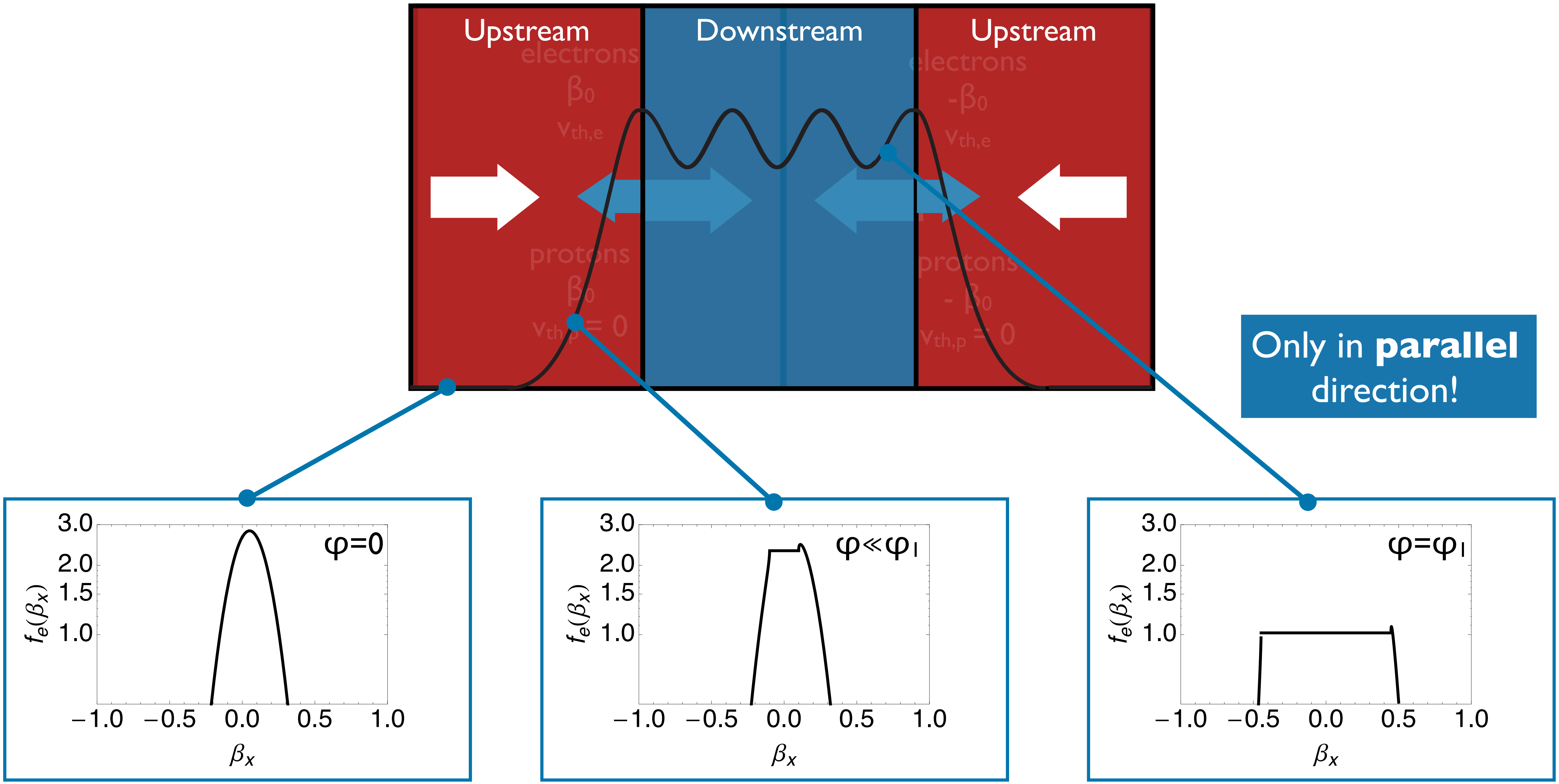
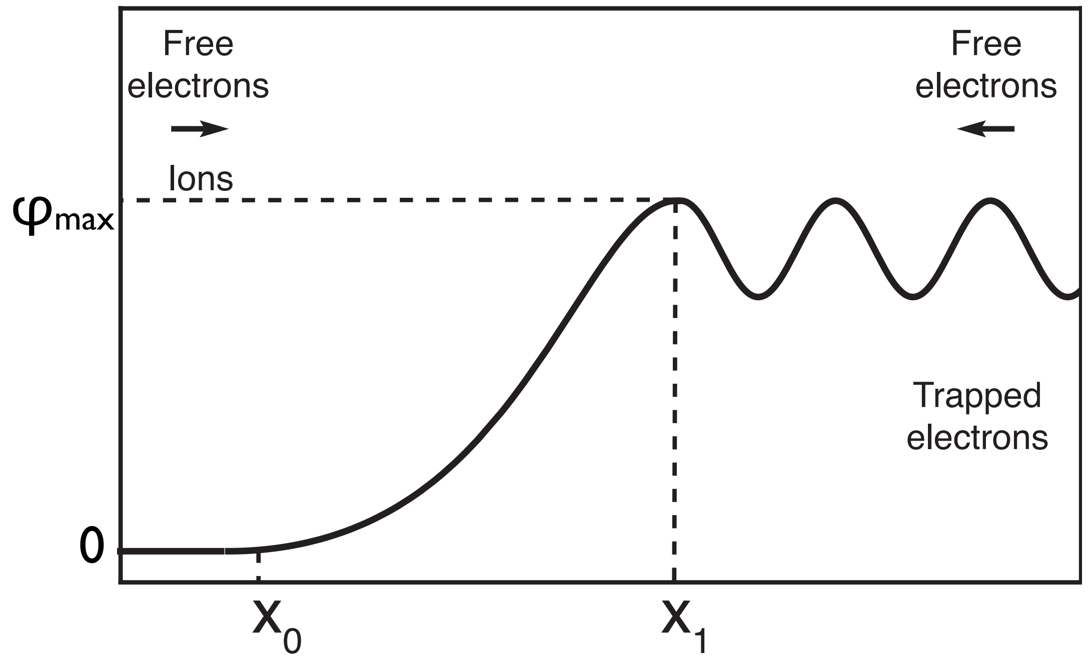
Electrostatic shocks in a symmetric setup



Does new distribution function go Weibel unstable?

→ **electromagnetic modes**

Electron distribution



Sagdeev (1966) model

Shock formation condition:

$$1 < M_{max} \lesssim 3.1$$

$$1 < v_0\sqrt{\frac{m_i c^2}{k_B T_e}} \lesssim 3.1$$

Electron distribution:
(e.g. Schamel, JPP 1972)

$$f_e = n_0 e^{-\frac{\mu}{2}(\beta_y^2+\beta_z^2)} \begin{cases} \exp\{-\frac{\mu}{2}(\sqrt{\beta_x^2 - 2\varphi} + \beta_0)^2\} & \beta_x < -\sqrt{2\varphi} \\ \exp\{-\frac{\mu}{2}\beta_0^2\} & |\beta_x| \leq \sqrt{2\varphi} \\ \exp\{-\frac{\mu}{2}(\sqrt{\beta_x^2 - 2\varphi} - \beta_0)^2\} & \beta_x > \sqrt{2\varphi} \end{cases}$$

Electromagnetic modes in ES shock

Dispersion relation of EM waves in plasma:

$$k^2c^2 - \omega^2 - \omega_{pe}^2(U+V) = 0$$

with

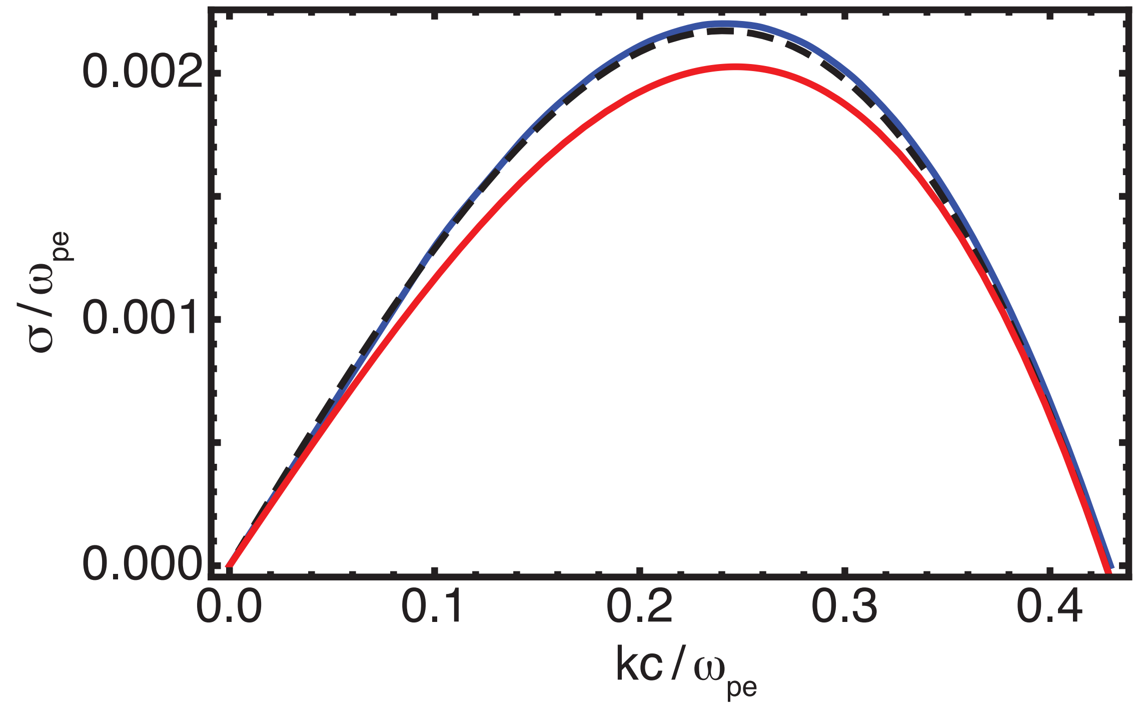
$$U = \int_{-\infty}^{\infty} d^3u \frac{u_x}{\gamma}\frac{\partial f_e}{\partial u_x}$$

$$V = \int_{-\infty}^{\infty} d^3u \frac{u_x^2}{\gamma\left(\gamma\frac{\omega}{kc} - u_z\right)}\frac{\partial f_e}{\partial u_z}$$

Electromagnetic modes in ES shock

Nonrelativistic approximation of the growth rate:

$$\sigma(k) \approx \sqrt{\frac{2}{\mu\pi}} kc \left[1 - \frac{k^2c^2 + \omega_{pe}^2}{\omega_{pe}^2 V(\varphi)} \right]$$



$\mu = \frac{m_e c^2}{k_B T_e}$

$$V(\varphi) = n_0 \left\{ e^{\mu\varphi} \mathrm{erfc}\sqrt{\mu\varphi} + 2\sqrt{\frac{\mu\varphi}{\pi}} + \frac{4}{3}\sqrt{\frac{\mu^3\varphi^3}{\pi}} e^{-\mu\beta_0^2/2} \right\}$$

Comparison of time scales

1) Inverse shock formation time scale:

$$\sigma_{ES,ii} = \frac{1}{2\gamma_0^{3/2}}\omega_{pi}$$

2) Electromagnetic ion-ion filamentation instability

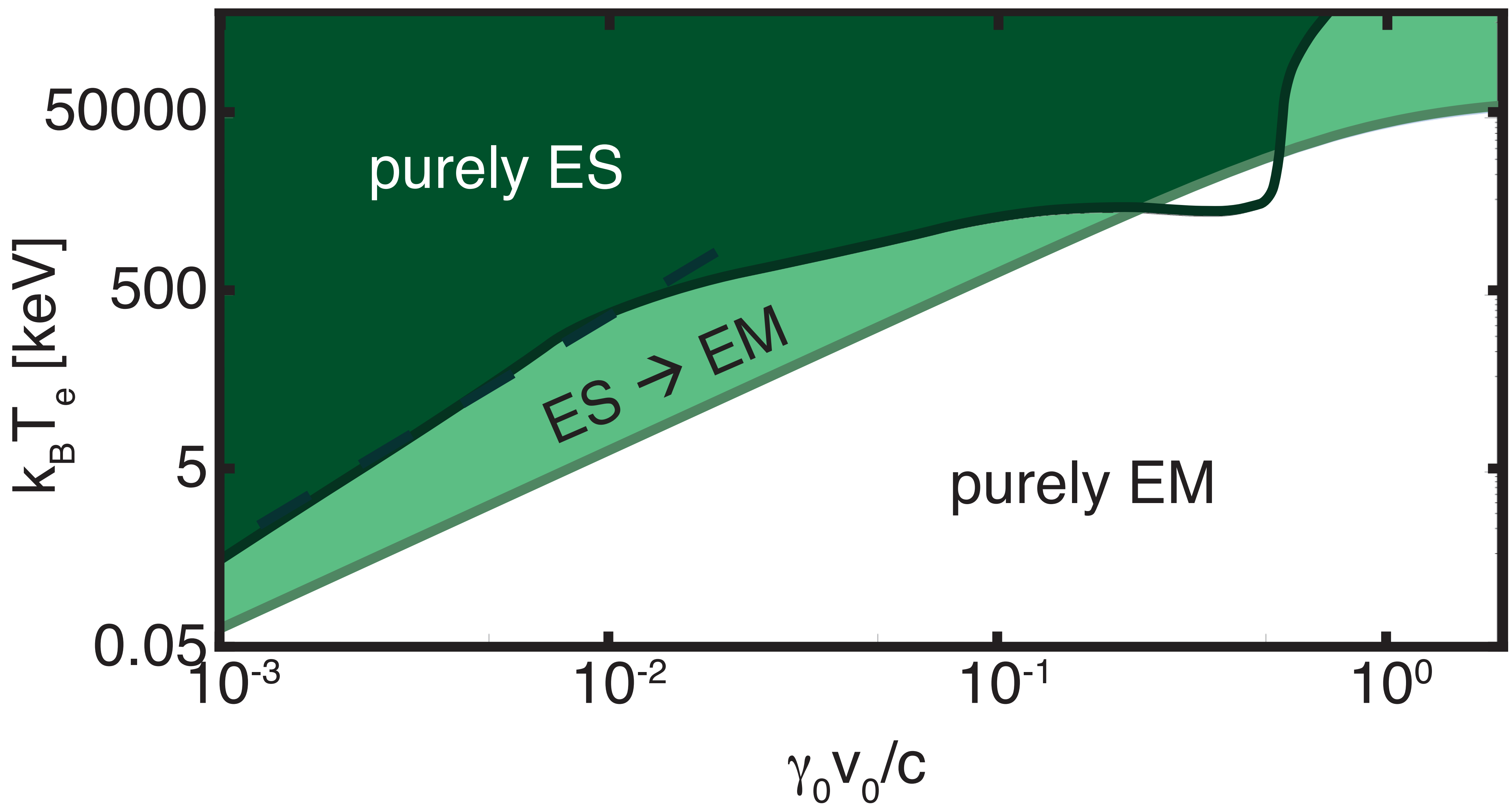
$$\sigma_{EM,ii} = \beta_0\sqrt{\frac{2}{\gamma_0}}\omega_{pi}$$

Not important for $v_0 < c/3$

3) Electromagnetic modes in electrostatic shock

$$\sigma_{EM,ee} \approx \sqrt{\frac{1}{\pi\mu}\frac{\omega_{pe}}{V(\varphi)}}\left(\frac{2}{3}(V(\varphi)-1)\right)^{3/2}$$

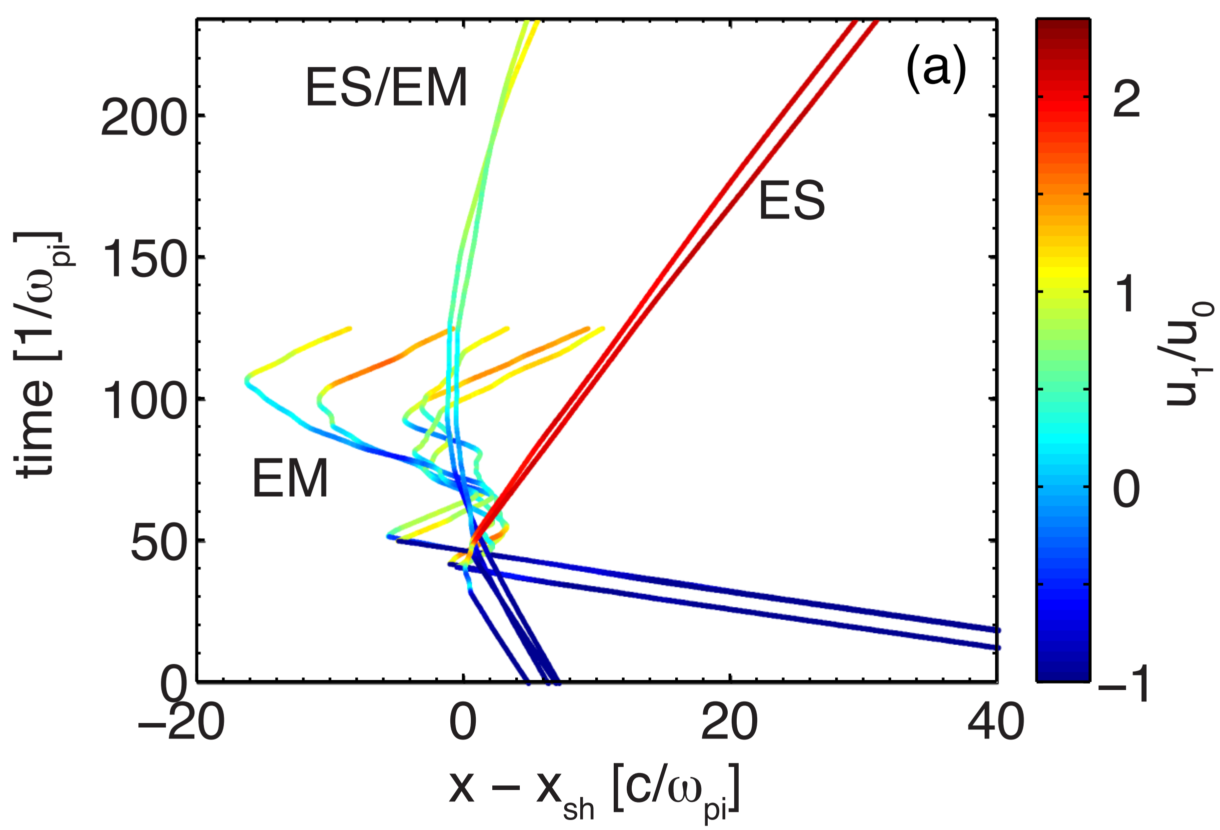
ES/EM dominated regimes can be defined



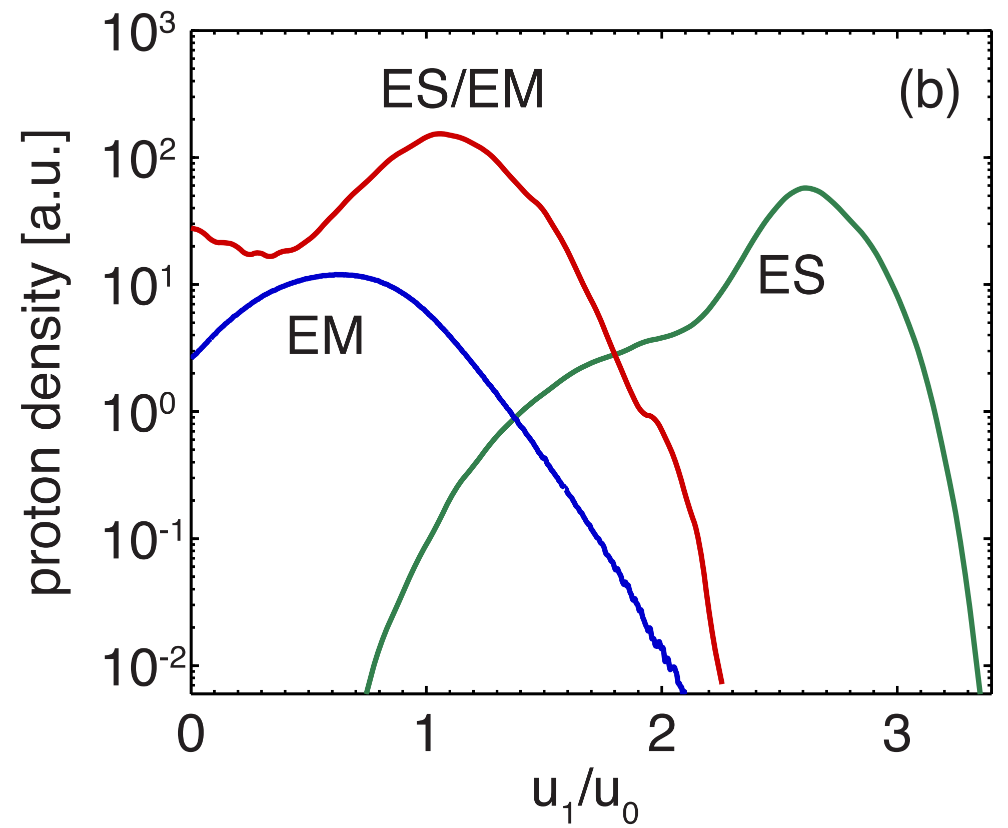
A. Stockem et al., Sci. Rep. 4, 3934 (2014)

Ion spectra are fundamentally different

Ion trajectories



Ion spectra



ES: Ions experience single reflection from shock front

EM: Multiple scatterings in shock front region

ES: Highest ion energies, narrower spectrum

EM: Wider spectrum, lowest energies

ES/EM: Transition between both cases

A. Stockem et al., Sci. Rep. 4, 3934 (2014)

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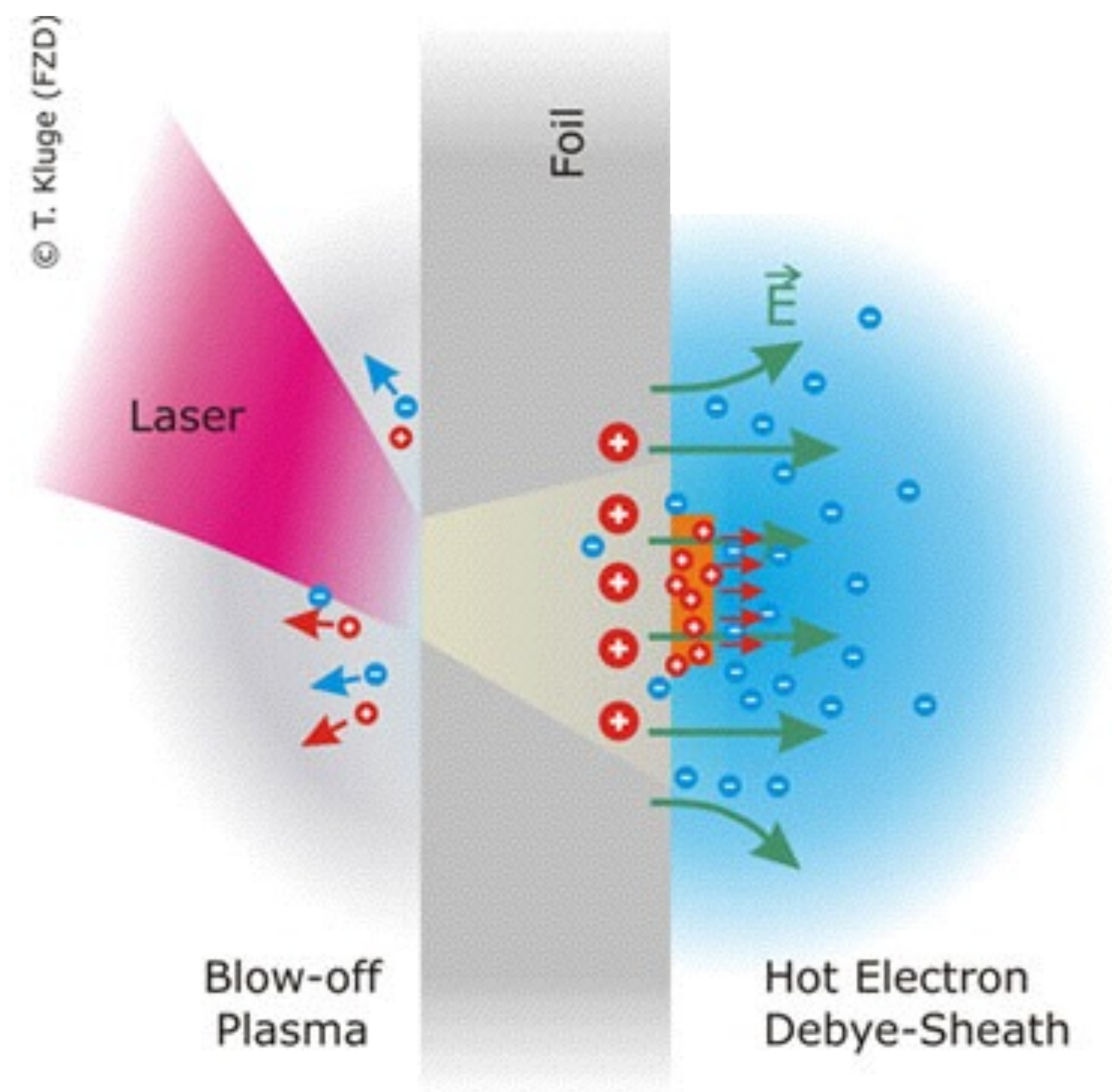
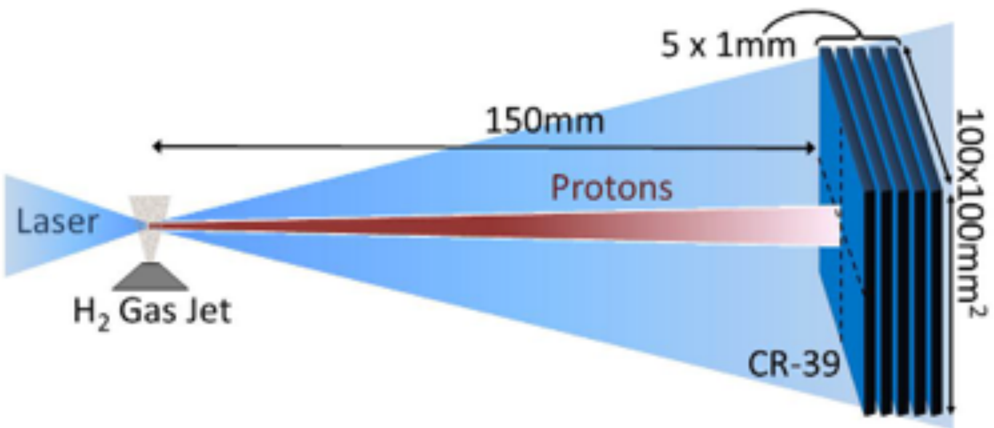
Target-normal-sheath acceleration



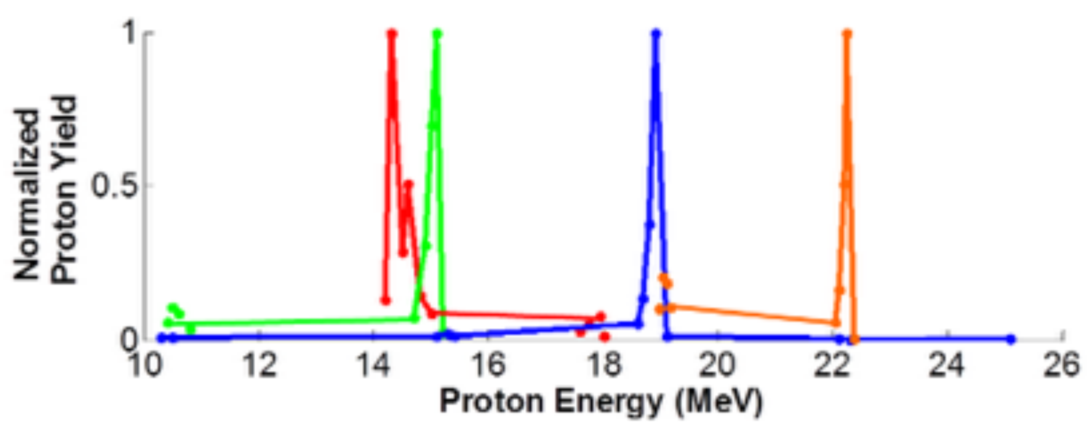
www.oncoray.de

Shock experiments in the laboratory

Collisionless shock acceleration:

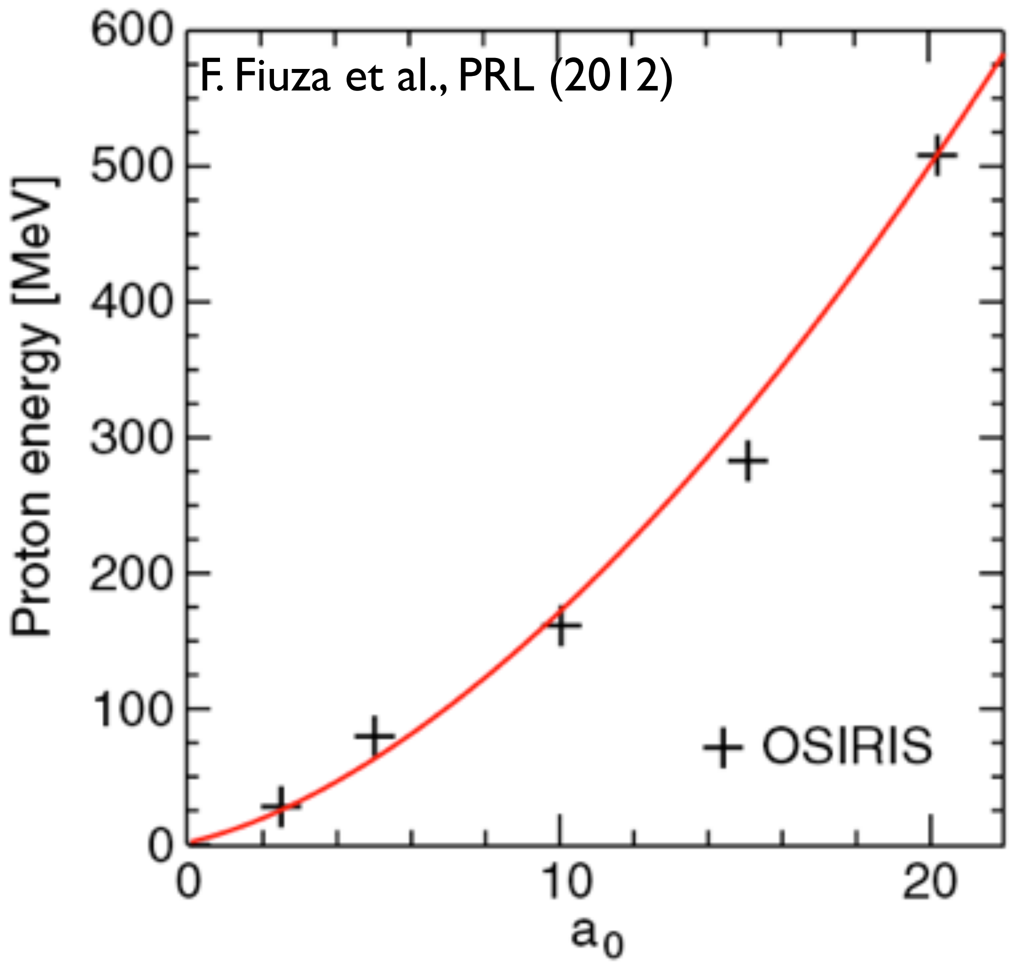


Mono-energetic ion beams:



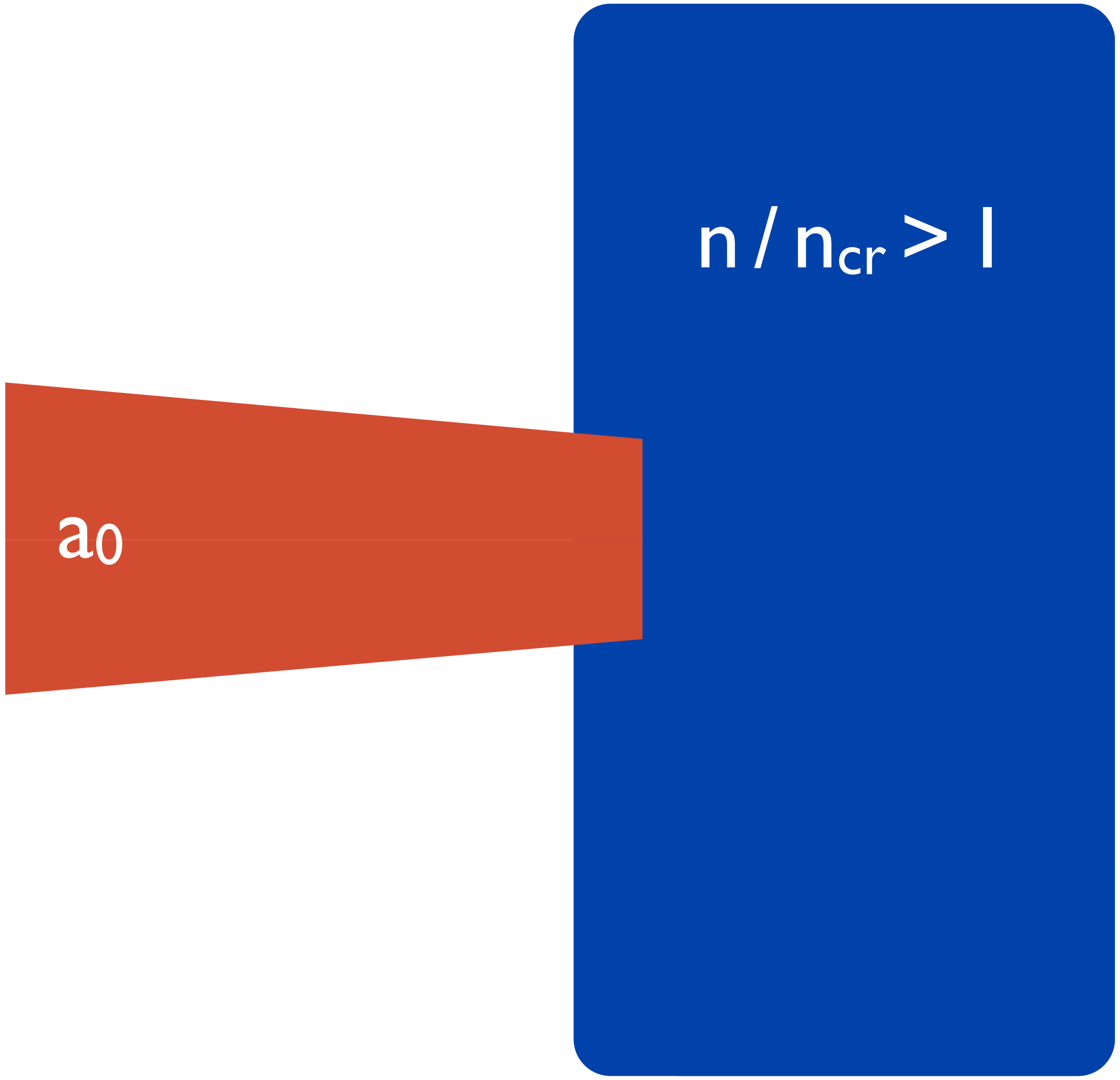
D. Haberberger et al., Nature (2012)

Laser intensity vs. proton energy:



200 MeV protons for $a_0 \approx 10$

Overdense plasma target



Dispersion relation of EM wave

$$\omega_0^2 = \omega_p^2 + c^2 k^2$$

Critical density

Wave propagation up to

$$n < n_{cr} = \omega_0^2 \frac{\gamma m_e}{4\pi e^2}$$

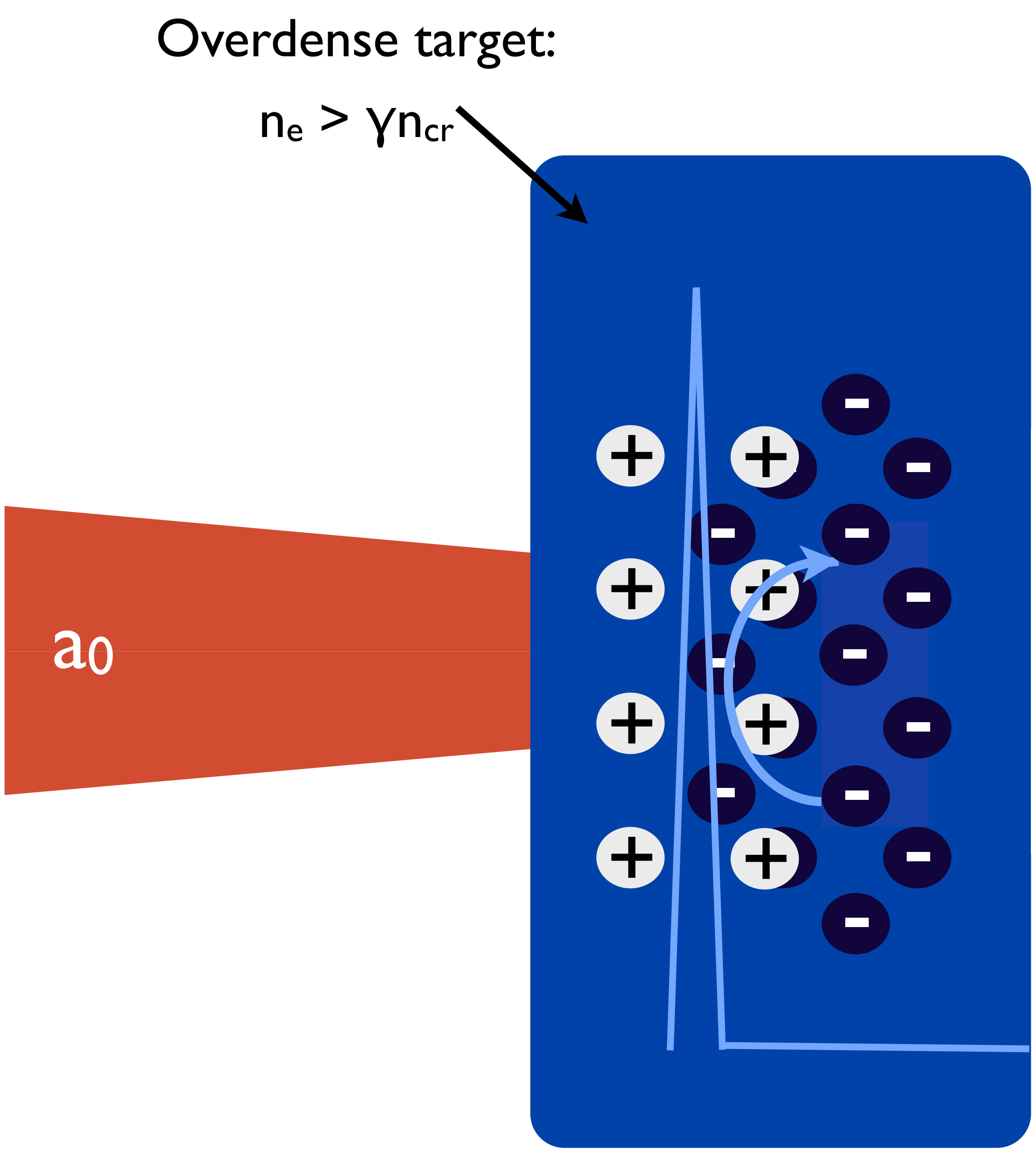
with relativistic factor

$$\gamma = \sqrt{1 + a_0^2}$$

and normalised laser intensity

$$a_0 = \frac{e A_0}{m_e c^2}$$

Hole boring



Hole boring velocity:

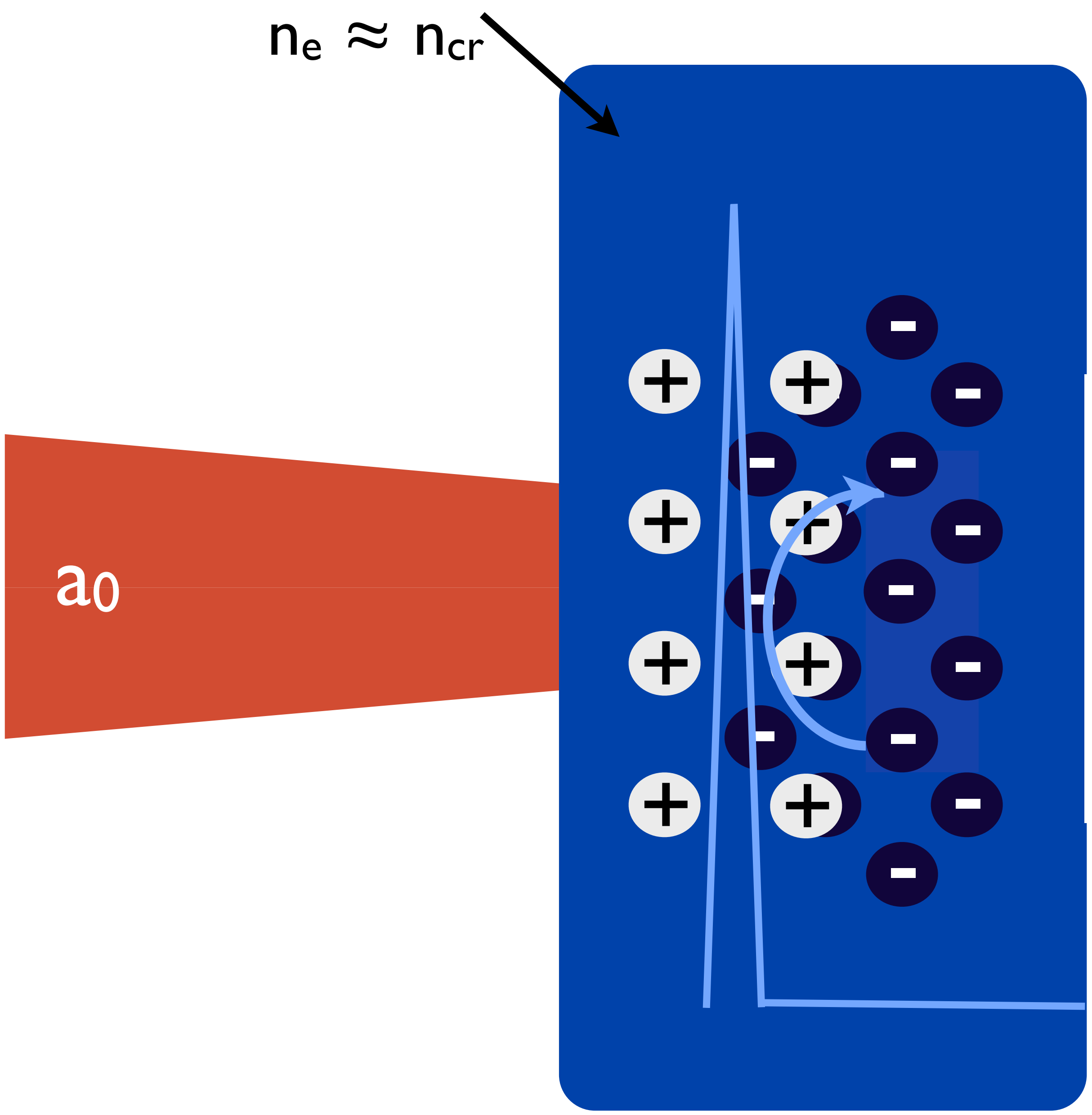
$$\frac{v_{hb}}{c} = a_0 \sqrt{\frac{n_{cr} m_e}{2 n_e m_p}}$$

Proton energy:

$$E_p \approx m_e c^2 a_0^2 \frac{n_{cr}}{n_e}$$

Collisionless shock acceleration

Near-critical density:



Shock condition:

$$v_e > c_s = \sqrt{\frac{k_B T_e}{m_i}}$$

Shock velocity:

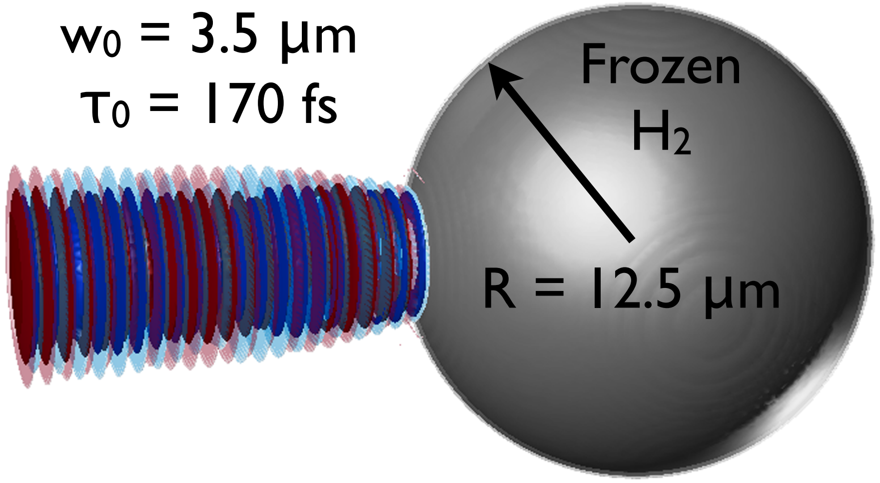
$$\frac{v_{sh}}{c} = a_0 \sqrt{\frac{m_e n_{cr}}{8 m_p n_e}} (1 + \Gamma_{ad})$$

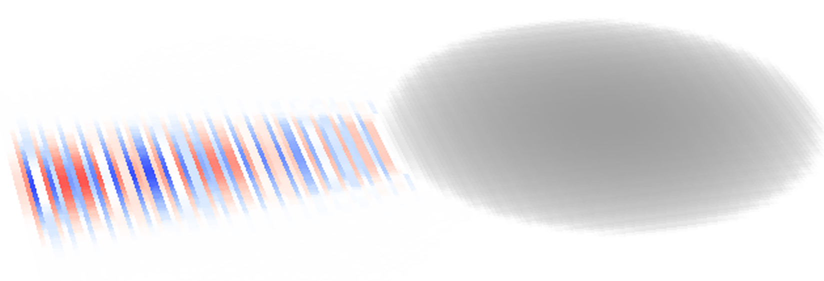
Proton energy:

$$E_{p,S} \approx 1.8\, m_e c^2 a_0^2 \frac{n_{cr}}{n_e} = 1.8\, a_0 \frac{n_{cr}}{n_e} E_{p,T}$$

3D simulation of a full experiment

$a_0 = 10$
$w_0 = 3.5\ \mu m$
$\tau_0 = 170$ fs





Target:

Frozen H_2

$n_e = 0.1\text{-}4 \times n_{crit}$

$d = 15\text{-}25\ \mu m$

$\rho = 0.086\ g/cm^3$

$n_{H2} = 2.6 \times 10^{22}\ cm^{-2}$

$N_p = 4.2 \times 10^{14}$

Laser parameters:

$\lambda_0 = 1.03\ \mu m$

$a_0 = 10\text{-}12$

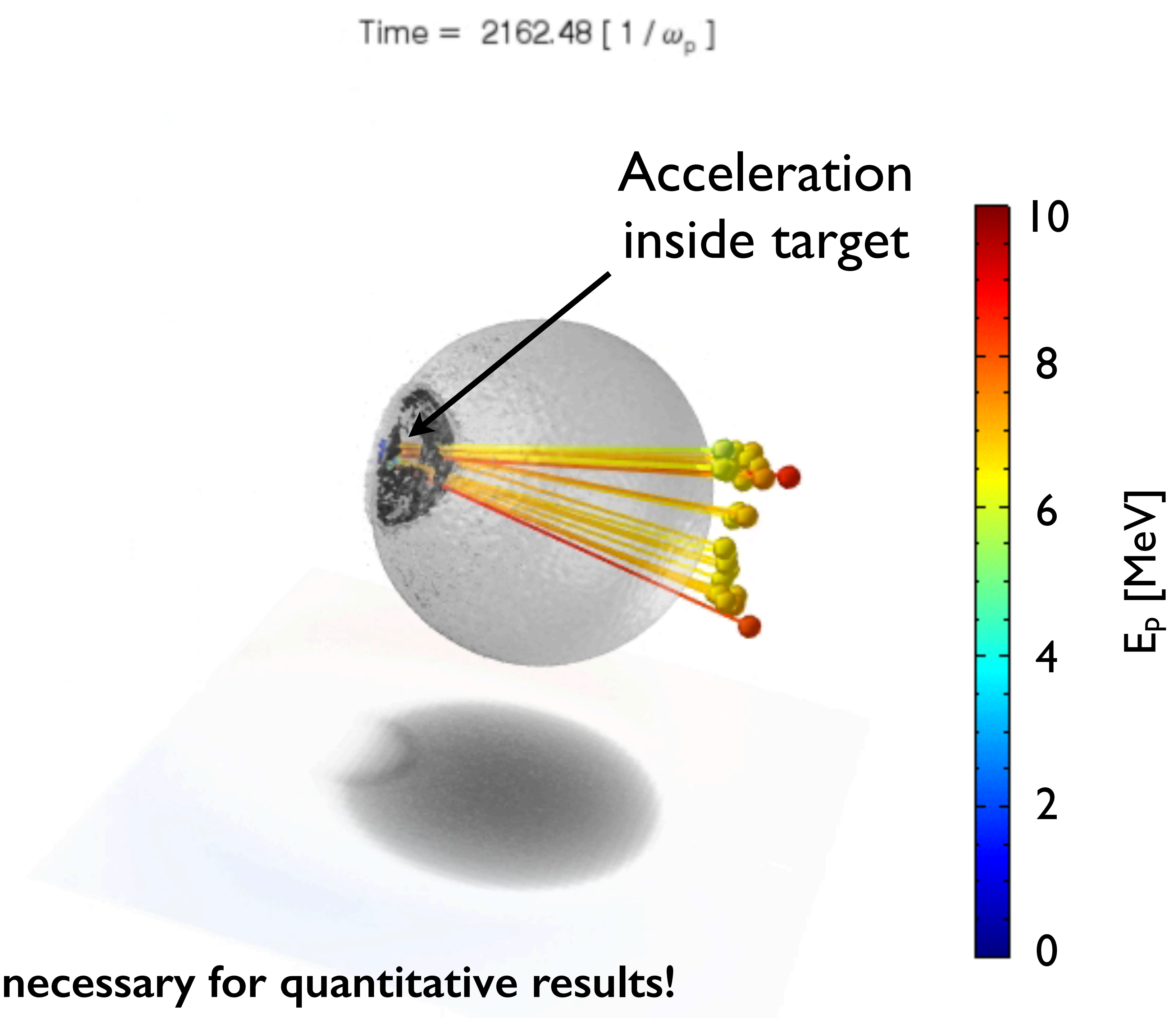
$F_0 = 8\text{-}9\ \mu m^2 \rightarrow w_0 = 3.5\ \mu m$

$\tau_0 = 150\text{-}170$ fs

$I_0 = 1.3 \times 10^{20}\ W/cm^2$

Protons are shock-accelerated to 10 MeV

$n_0 / n_{cr} = 1$



3D experiments necessary for quantitative results!

PW laser systems required for 200 MeV

Conclusions

EM/ES shock formation and particle acceleration show different features

ES shocks in the laboratory

- Increasing laser intensity: new regime of mixed modes
- Parameter choice critical for beam quality
- 3D simulations for quantitative analysis