Non-thermal particle acceleration at highly oblique non-relativistic shocks

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Motivation

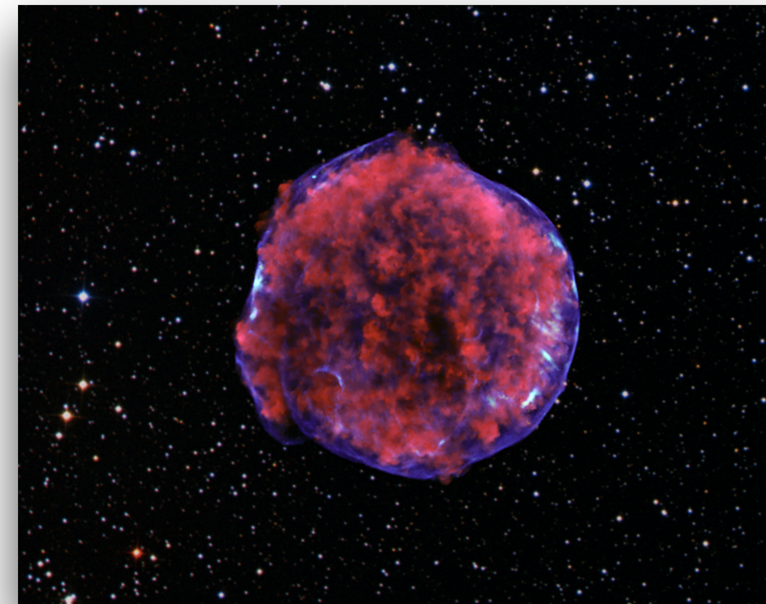
- In general, an uncorrelated magnetic field implies half of the shocks will have a quasi-perpendicular orientation; oblique shocks are efficient accelerators.

A. R. Bell, Brazilian Journal of Physics, 44, 415 (2014)

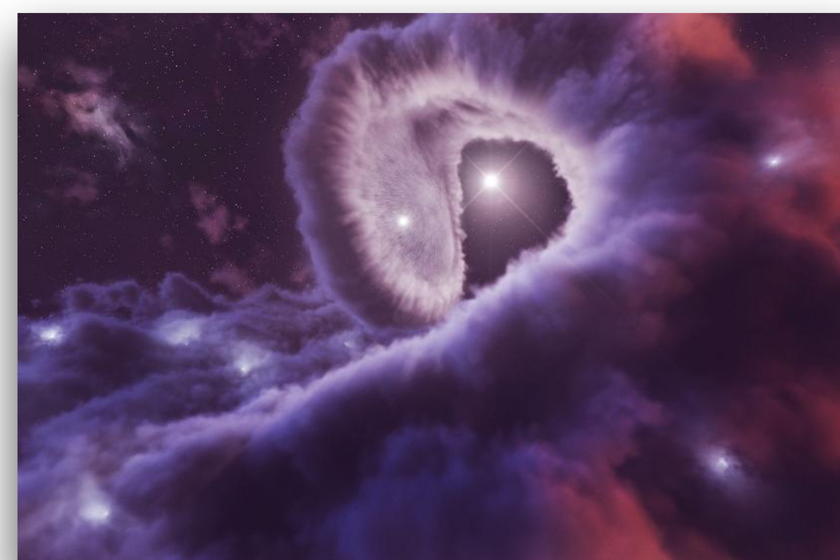
$$\frac{\langle \mathbf{B} \cdot \hat{n} \rangle}{|B|} = 0.5$$

- To understand the non-thermal x-ray observation of young SNRs, gamma rays from hadronic interactions. η-Carinae provide evidence of strong electron and ion acceleration at oblique shocks

Patnaude and Fesen, ApJ, 789, 138(2014), Eriksen et. al., ApJ, 728, L28 (2011), White et al, A&A, 635 (2020)



Tycho: credit NASA



η-Carinae: Science Comm. Lab, DESY

Recent studies

The Astrophysical Journal Letters, 897:L41 (6pp), 2020 July 10 — Xu, Spitkovsky, & Caprioli

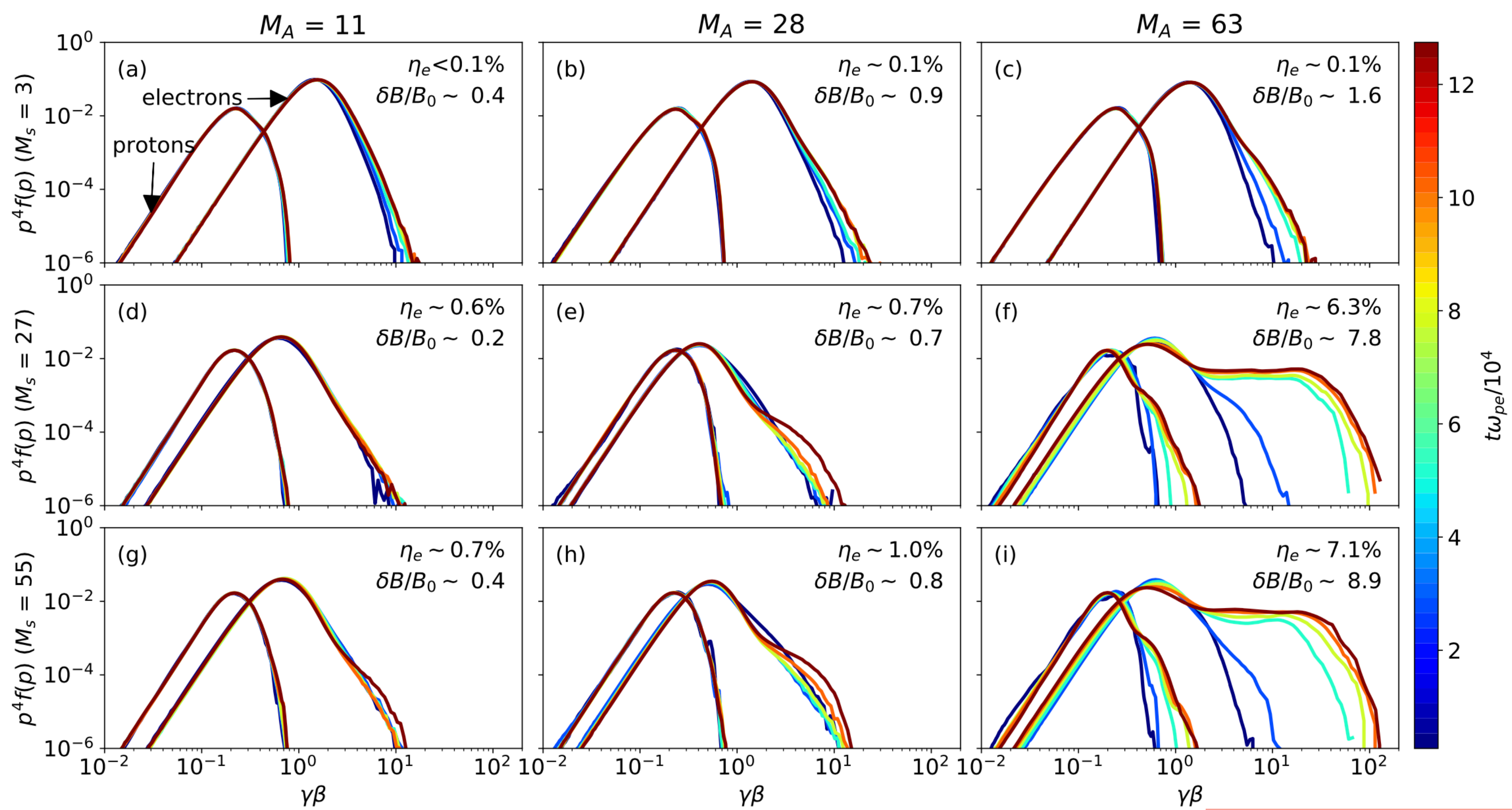
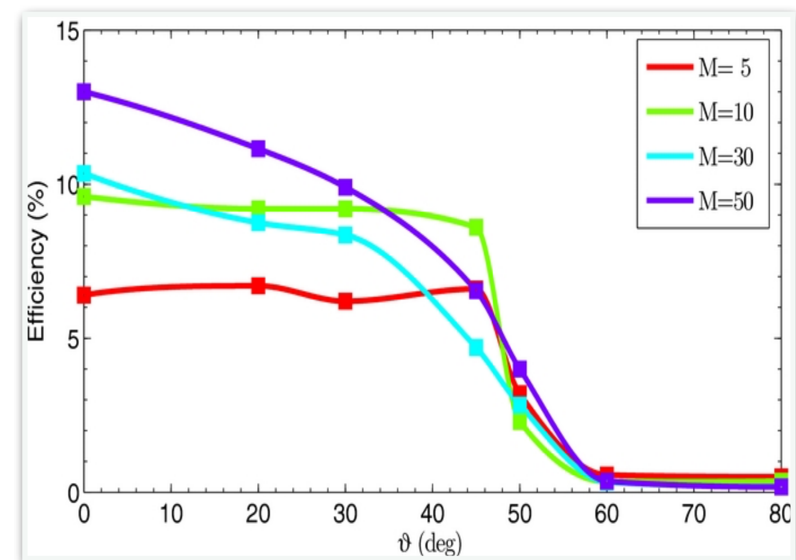


Figure 4. Downstream electron and proton spectra as a function of time for different M_s and M_A for quasi-perpendicular shocks with angle $\theta = 63°$ and $m_i/m_e = 100$. The spectrum is multiplied by p^4 to emphasize the scaling law expected in DSA. The color lines indicate time, as in the legend. The number fraction of nonthermal electrons η_e at the end of the simulations, and the level of upstream magnetic fluctuations $\delta B/B_0$ are shown at the top right corner of each panel. Only shocks with $M \gg 1$ are able to produce large amplitude fluctuations with $\delta B/B_0 > 1$, and in these cases electrons are injected into DSA after multiple cycles of SDA and scattering of upstream waves.

Interesting features in ion spectra. Electrons still have smaller gyro radii compared to ions.



Caprioli & Spitkovsky, ApJ, **783** 91 (2014)

An important result of this study is the existence of shocks that preferentially accelerate electrons and not ions. This helps

Are these hybrid simulation results in agreement with PIC simulations?

Large-scale 1D PIC simulations

Shock normal frame (SNF)

Kumar & Reville, ApJLett. (accepted)
arXiv:2110.09939

$$\mathbf{B} = B_x \hat{x} + Bz\hat{z}, \quad \theta = 75^\circ$$

$$\mathbf{u} = u_{\rm sh}\hat{x}, \; v_{sh} = 0.15c$$

$$M_A, M_S \geq 60$$

High Mach number shocks

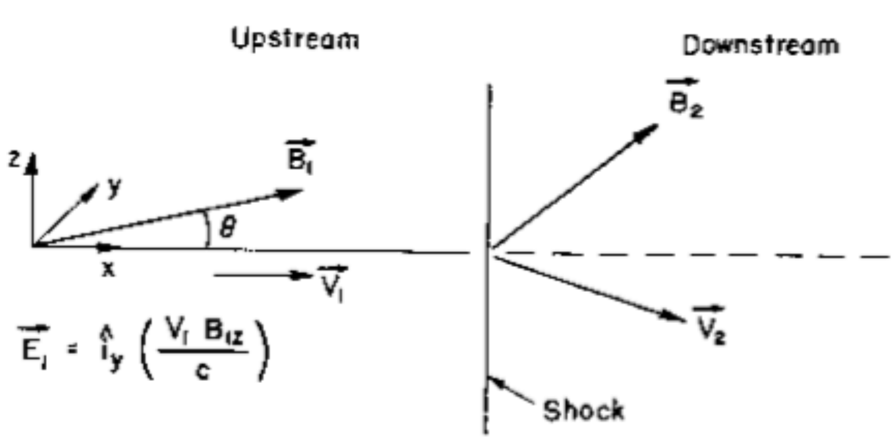


Fig. 1.4. Field and velocity vectors on the two sides of a shock transition in the rest frame of the shock.

Tidman and Krall 1971

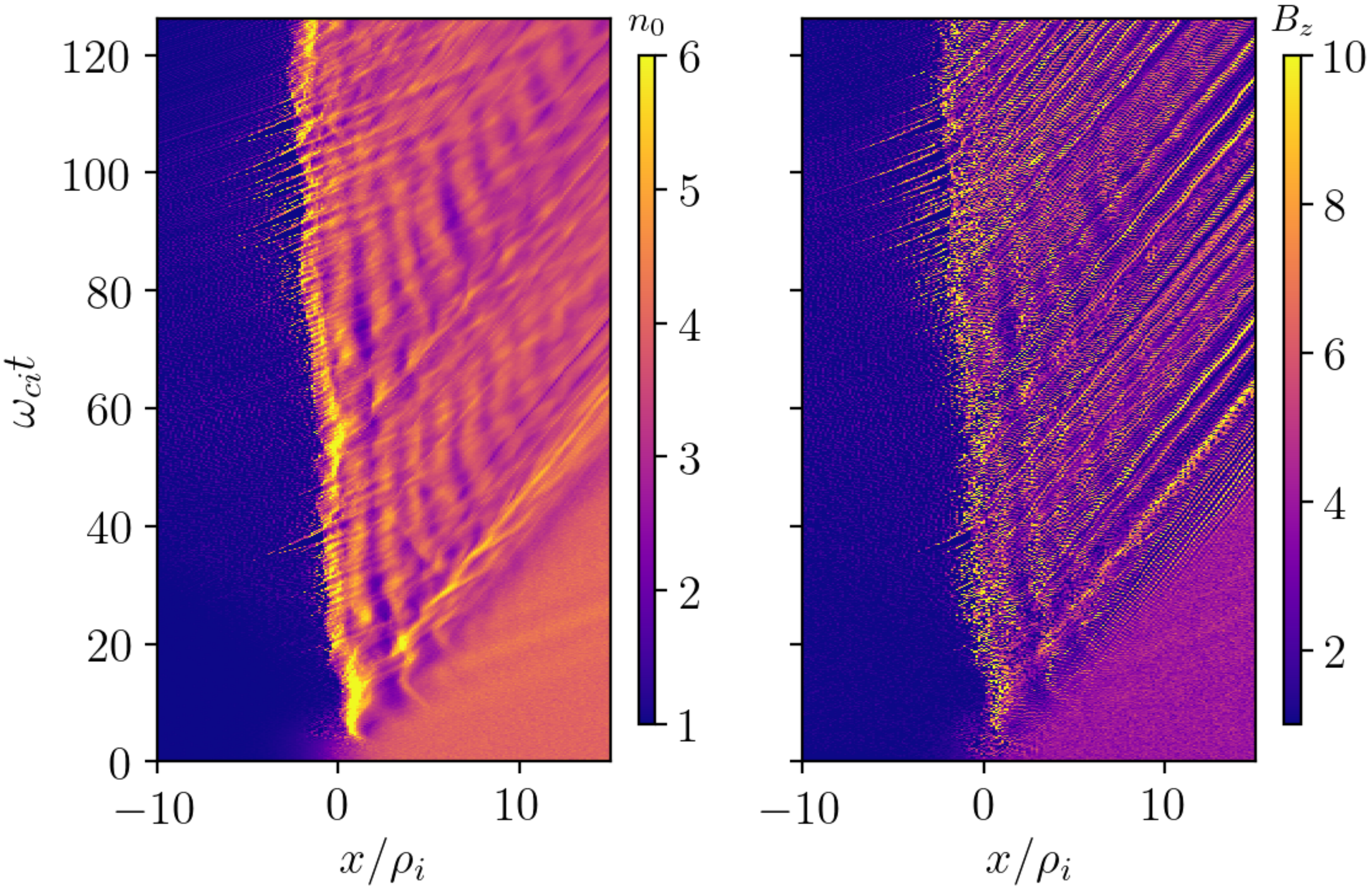
dHT (de Hoffmann and Teller) frame simulations

Kumar & Reville, PoS, 485, ICRC 2021

We use SMILEI PIC code; simulation domain is $\geq 500\,\rho_i$ (ion gyro radius); large number of total particles per cell (≥ 1000 ppc); no field and current filtering, proton mass is varied.

Simulations are run on Max-Planck supercomputers Raven and Cobra in Munich. Need more than ~ 40000 CPU hours for one run

Plasma density and the magnetic field



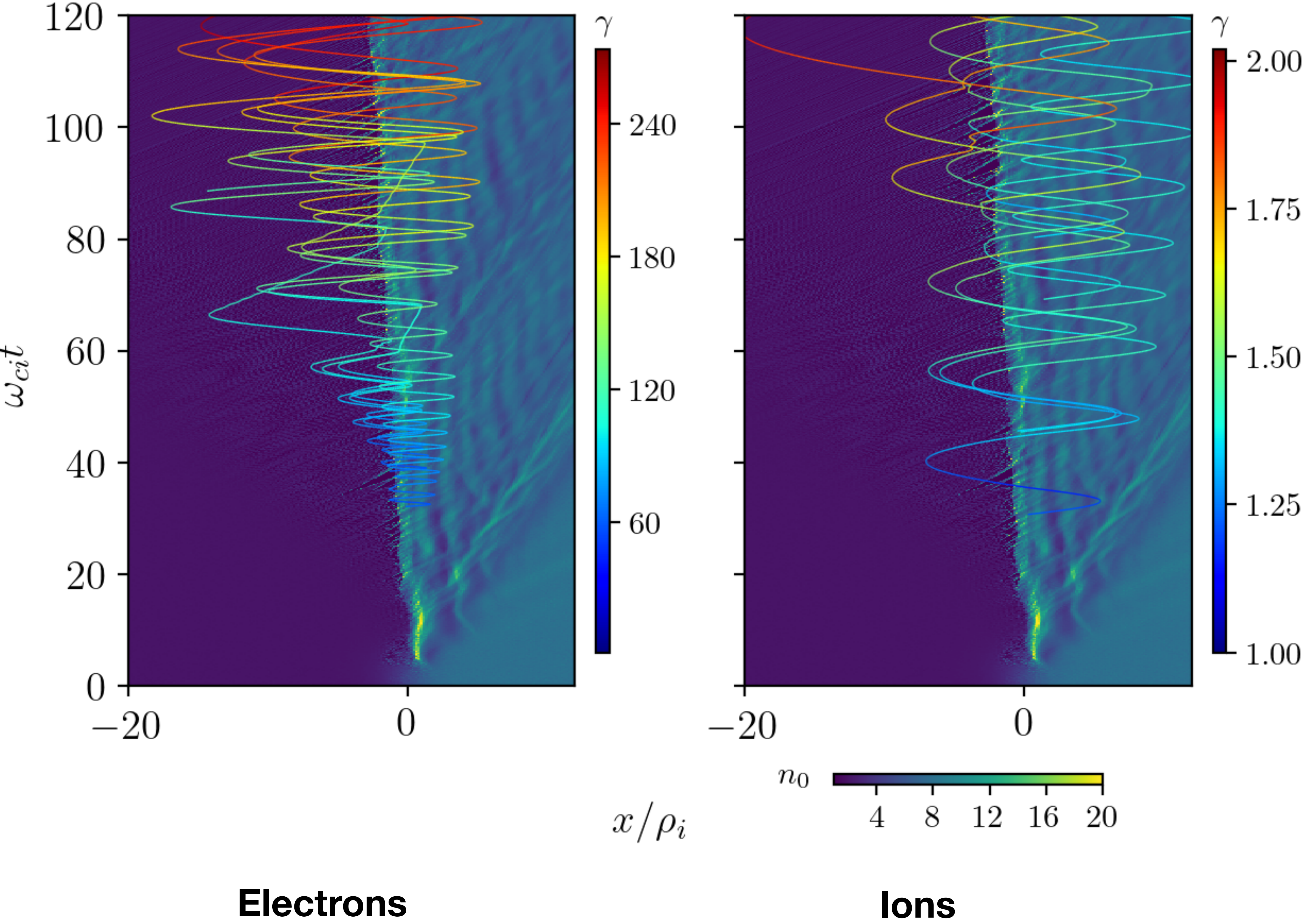
Mass ratio $= 256$

Parameters are similar to Xu et al, ApJ, 897, L41 (2020)

Periodic self-reformation of the shock

Leroy et al. (1981), Lembege (1990), Umeda et. al. (2014)

Trajectories of 5 most energetic particles

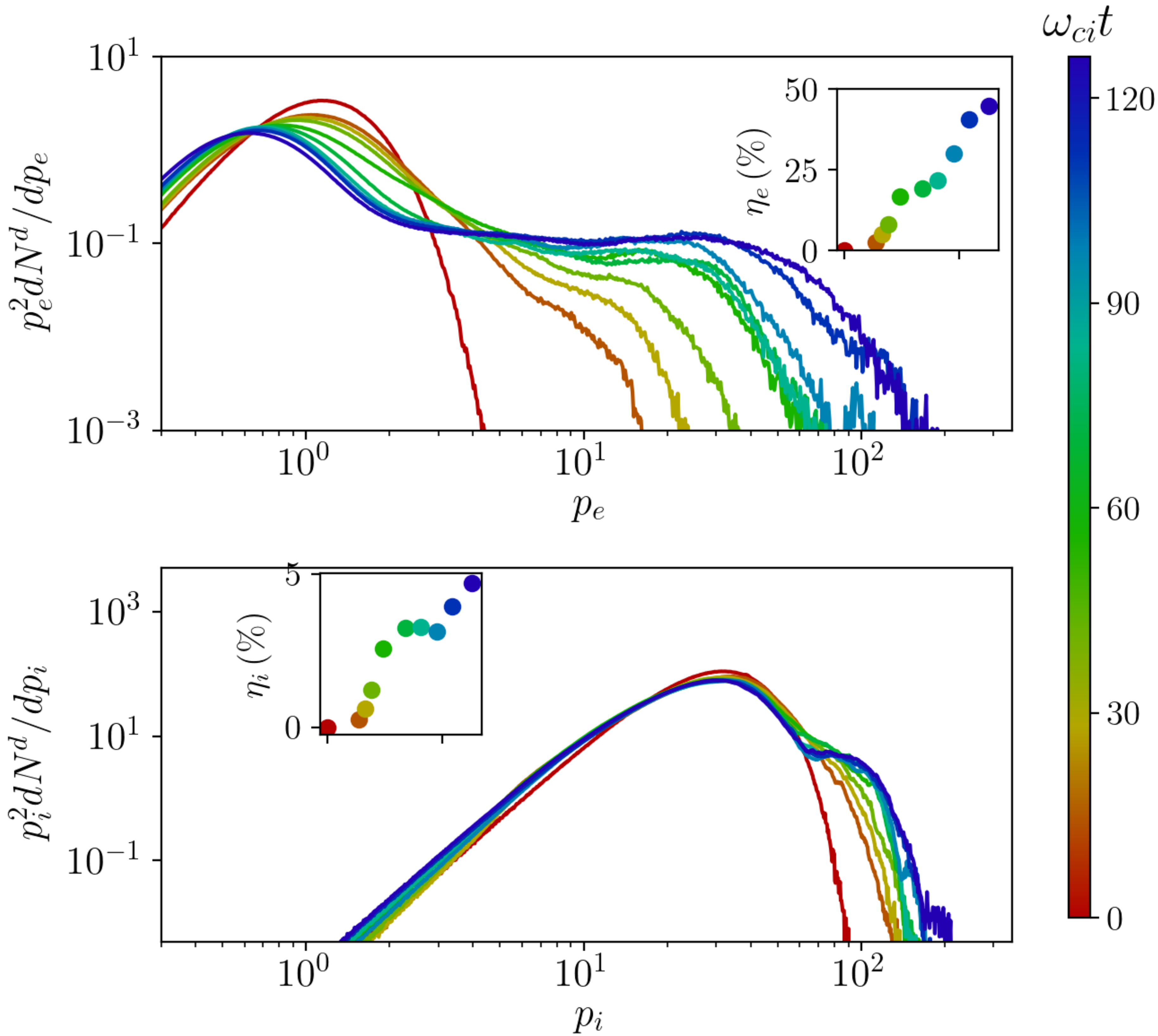


Particles satisfying a threshold condition on momenta

$p_e = 20\, m_e c$

$p_i = 0.3\, m_i c$

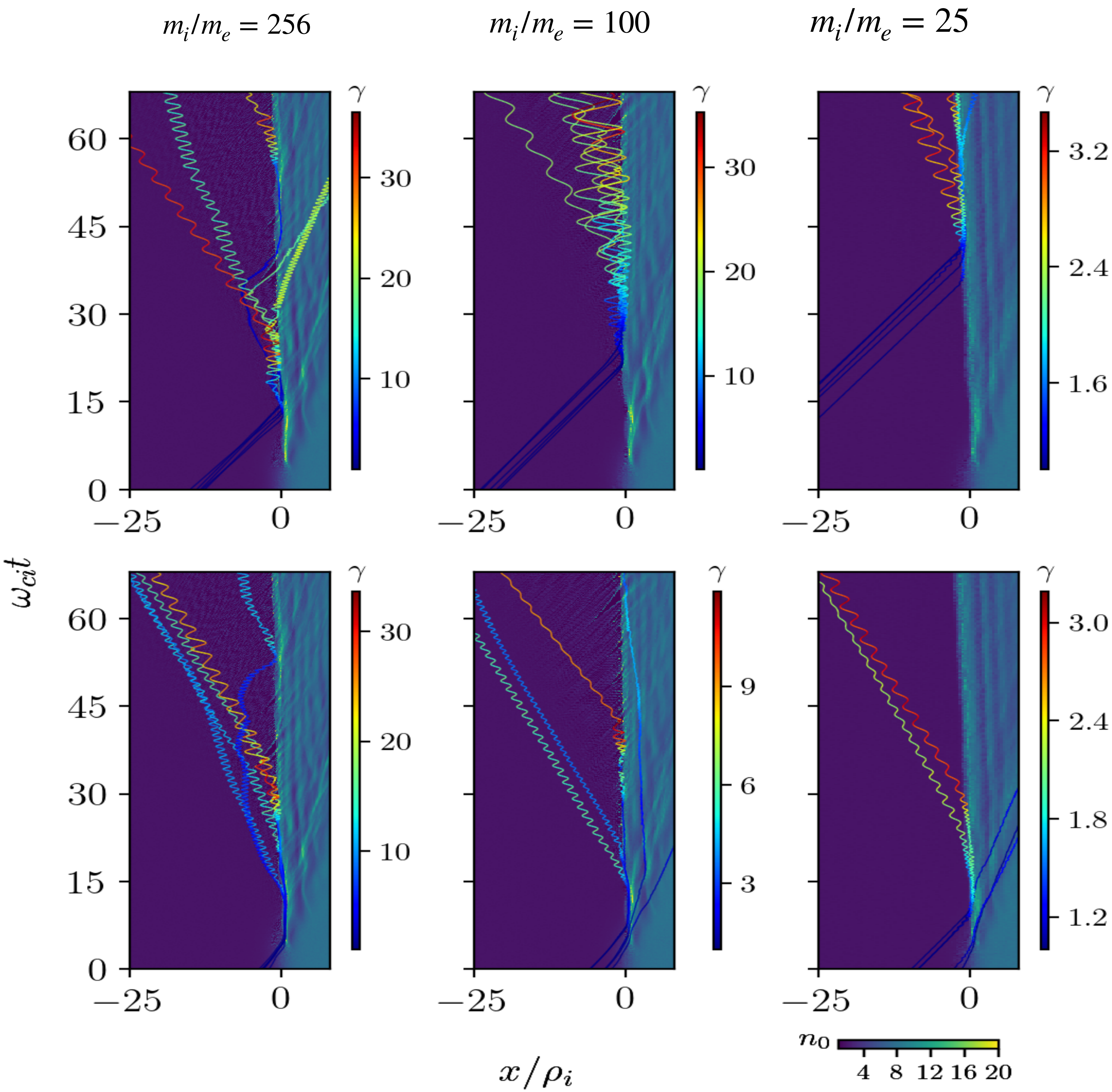
Particle spectra



Energy fractions into non-thermal particles are not saturated at the end of the simulation!

Strong correlation between electron and ion acceleration! Electron acceleration linked with the inertial effects

Electron acceleration (SNF)

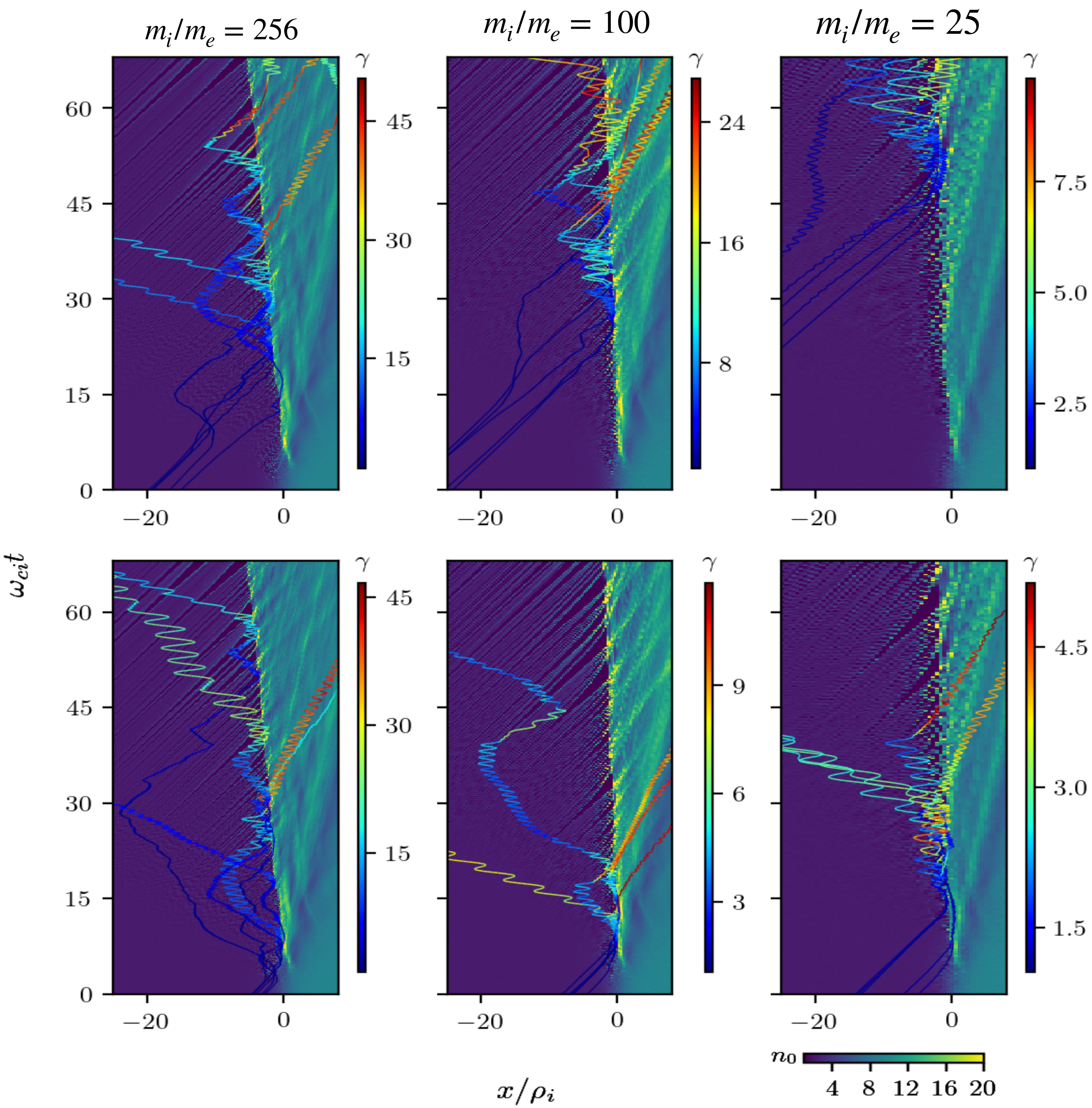


Test electrons acceleration for different mass ratios
$m_i/m_e = 256, 100, 25$

Electron acceleration is linked with the space-charge effects. Several plasma instabilities are also at play

Absence of strong electron acceleration for lower mass ratio
$m_i/m_e = 25$

Electron acceleration (dHT)



Similar behavior in dHT frame simulations. Though the properties of the wave generated are slightly different

Conclusions

- We see acceleration of electrons and ions at angle $\theta > 60°$. The energy fraction gone into ions is not saturated at the end of the simulation. To be consistent with η-Carinae observations, one needs about $10\,\%$ energy fraction into ions.

- Generation of high-frequency waves in the upstream region; heating of plasma electrons to facilitate their injection into the DSA process. The physics of the interaction is rather complicated but rich in content.

- 2D simulations are needed (currently underway).

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Thank you for your attention.