Relativistic Ion Energization in Simulations of Collisionless Shocks

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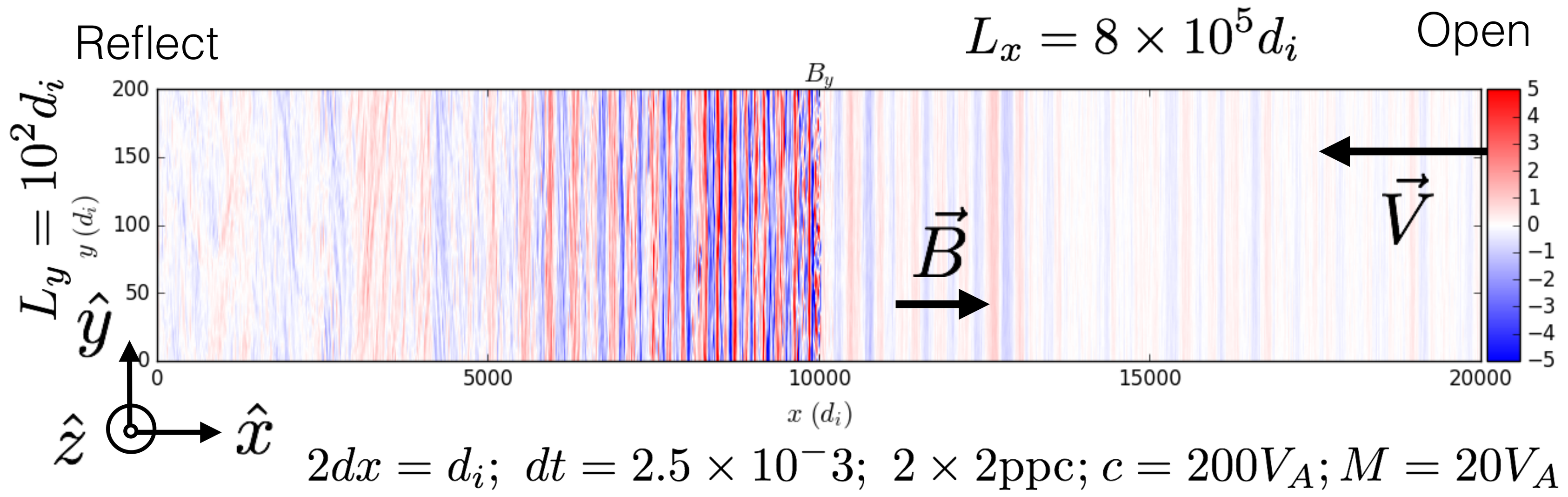
ABSTRACT

We present the first results from collisionless shock simulations using a kinetic ion/massless charge-neutralizing fluid electron hybrid code which retains relativistic ion dynamics (*dHybridR*). The development and structure of the non-thermal ion populations (cosmic rays or CR in this work) is characterized as it transitions to relativistic momenta/energy. The momentum distribution develops an extended power law tail with an index of -4 ($f(p) \propto p^{-4}$), consistent with diffusive shock acceleration (DSA) theory. However, the energy distribution's slope becomes steeper for energies larger than the ion rest mass ($E(p) \propto E^{-1.5} \rightarrow E^{-2}$). The slope of the growth rate of the maximum energy is shown to decrease by an approximate factor of 2 as the energy surpasses the ion rest mass energy. The injection efficiency is shown to saturate at about 10%. Lastly, we examine the effect of CRs slowing down the shock precursor and the resultant non-adiabatic heating.

SIMULATIONS



$2dx = d_i;\ dt = 2.5 \times 10^-3;\ 2 \times 2\text{ppc};\ c = 200V_A;\ M = 20V_A$

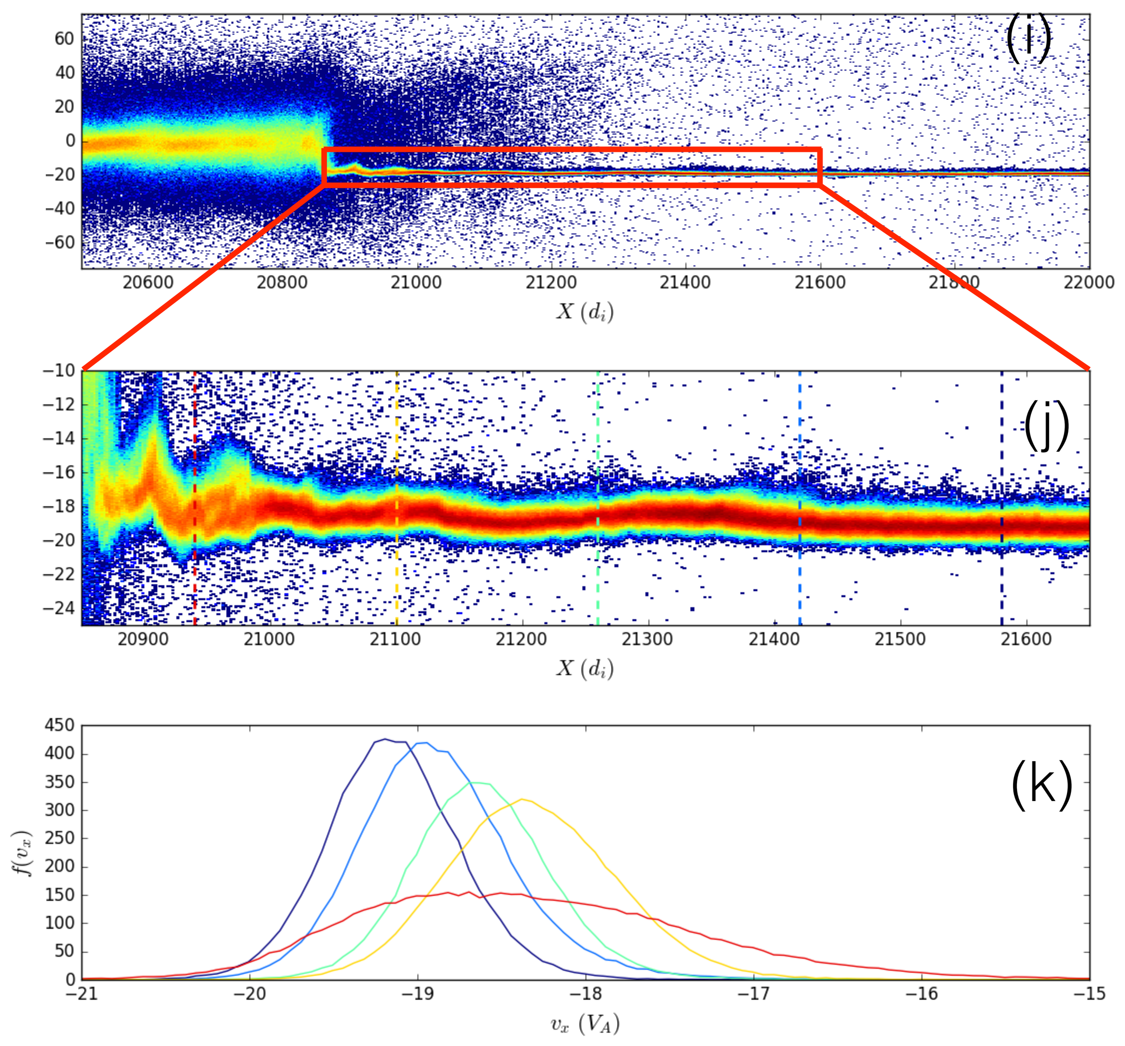
dHybridR is a kinetic ion/massless charge-neutralizing fluid electron hybrid simulation code [1] that implements the relativistic Lorentz force law for the evolution of the kinetic macro particles.

Ions: $\frac{d}{dt} m_s \gamma \mathbf{v} = q_s \mathbf{E} + q_s \frac{\mathbf{v}}{c} \times \mathbf{B}$

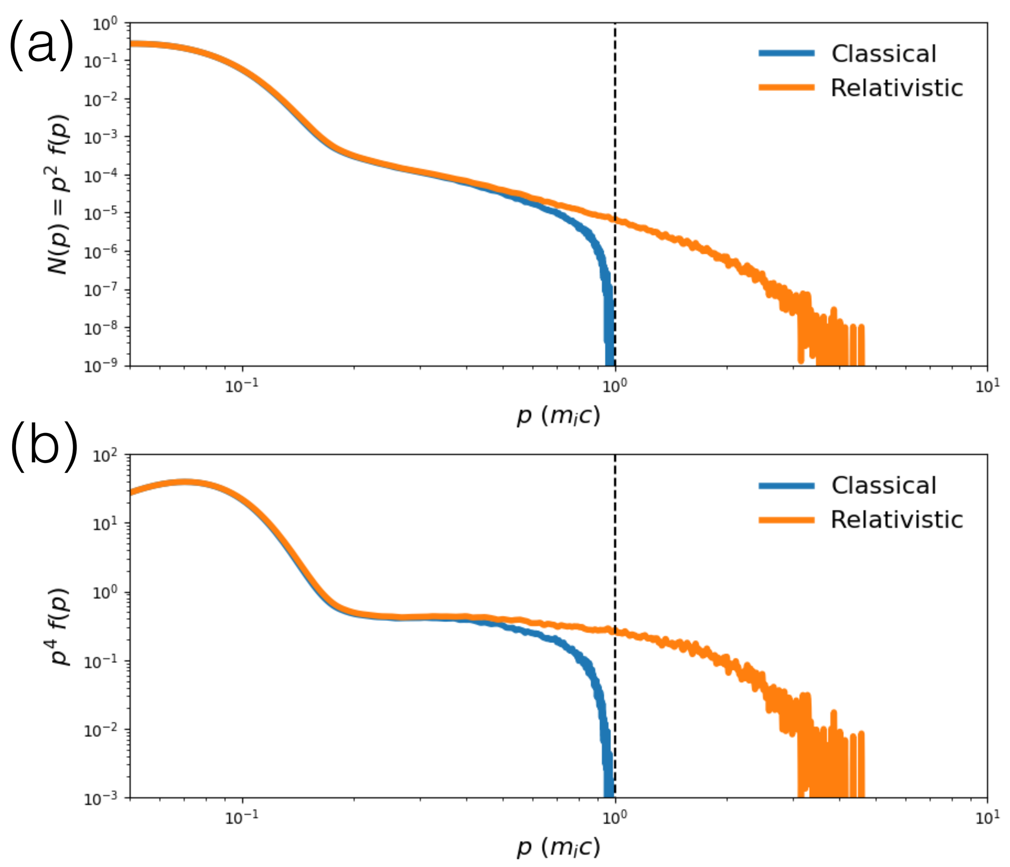
Using the hybrid approach allows the study of much larger length/time scales than in fully kinetic PIC simulations. We perform and analyze a parallel collisionless shock with a 8E5 x 1E2 di simulations run for over 4000 cyclotron times with the parameters listed above. This allows DSA to accelerate CRs to relativistic energies.

SHOCK PRECURSOR HEATING

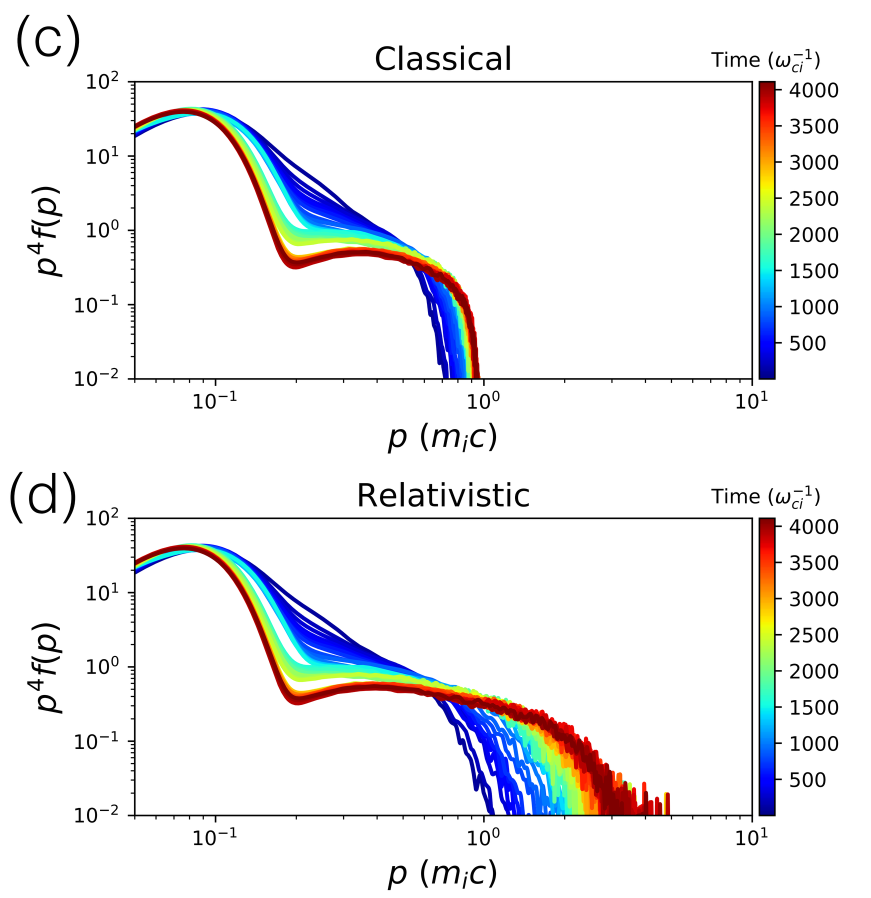
As the CR pressure just upstream of the shock grows, it affects the inflowing plasma in the precursors. Figure (j) shows a close up of the precursor in (i) and the dashed colored lines indicate cuts of the distribution displayed in (k). Successive cuts closer to the shock boundary show that the inflowing plasma is being slowed down and heated by the outflow CRs.

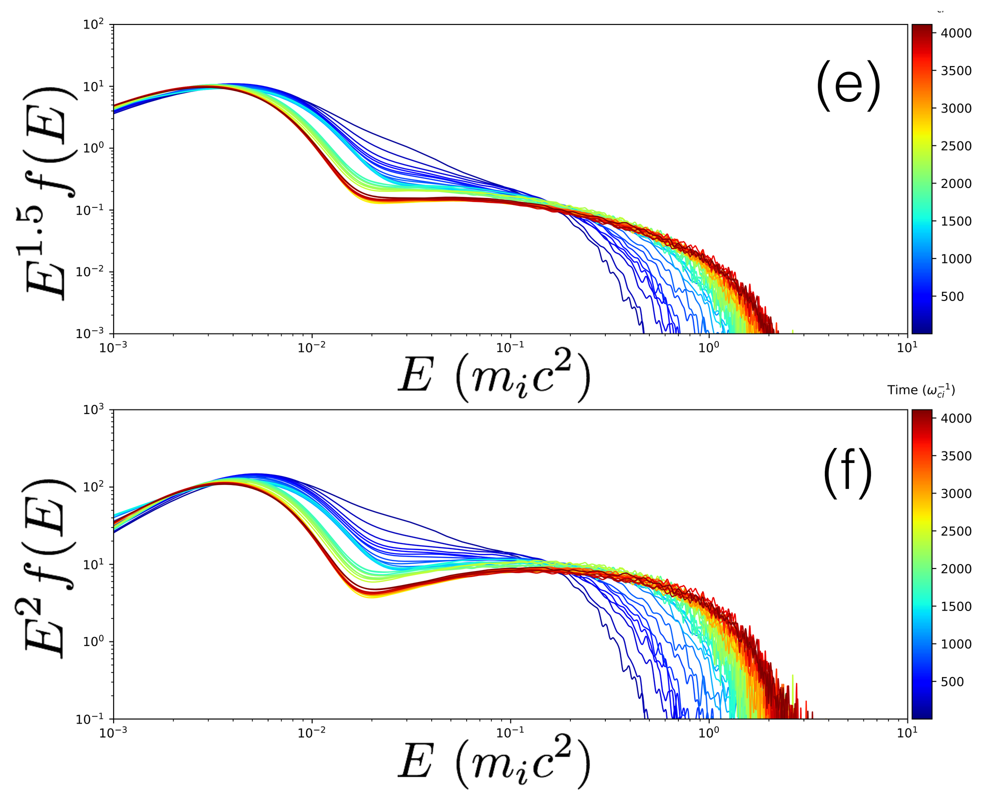


MOMENTUM & ENERGY SPECTRUM



To examine the development of the non-thermal tail generated from DSA in the shock, we calculate the distribution downstream of the shock. The number of particles as a function of classical (blue *mv*) and relativistic (orange *γmv*) total momentum spectra are plotted in (a). The spectra are in clear agreement for sub-relativistic values, however the classical momentum is limited to *mc* while the relativistic momentum continues with approx. the same slope. (b) shows the distribution multiplied by a factor of p^{-4} to emphasize the slope. The p^{-4} power law continues for relativistic values. In figure (c) and (d) the down stream distribution is plotted in time and shows how the tail develops. In the classical case the spectra the edge continues to approach *mc* and in the relativistic case the maximum momentum continues to grow with an index of -4. The energy spectrum plotted in (e) and (f) are multiplied by two different factors, $E^{1.5}$ and E^2, which correspond to a p^{-4} slope for $E \sim p^2$ and $E \sim p$ respectively. For energies << mc^2 in (e) the slope of the spectrum is flat, and in figure (f) the spectrum becomes flat for energies ~> mc^2 which is consistent with power law scaling of observed galactic cosmic rays.



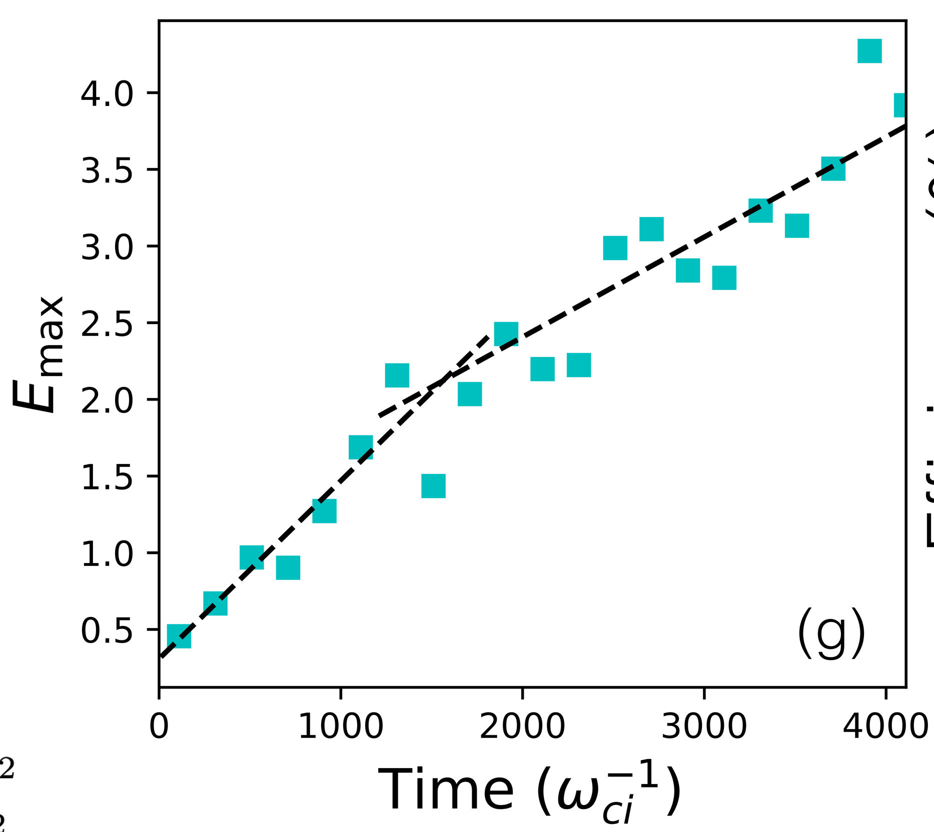


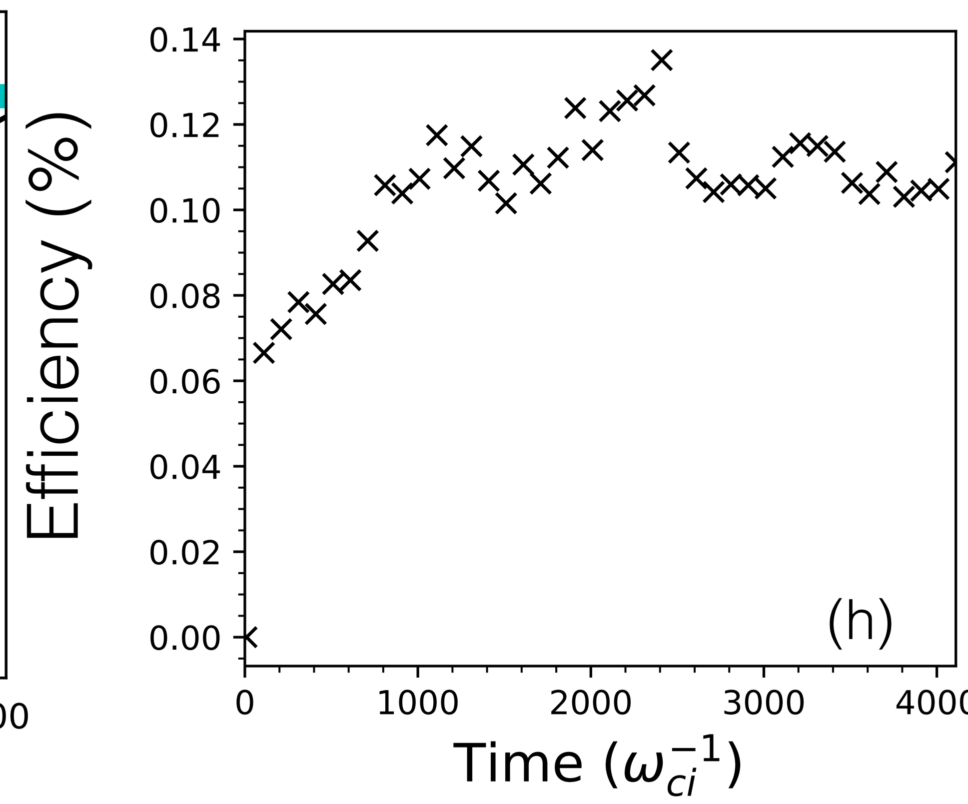
PARTICLE INJECTION & RATE OF INCREASE

As the shock continues to expand, the energy of the most accelerated particles continues to increase. Fig. (g) shows this increase as a function of time. As a significant fraction of particles are energized beyond the ion rest mass (around 1500 ω_c^{-1}), there is a break in the maximum energy increase rate:

$\Delta E_{max}/\Delta t \approx 1.15 \times 10^{-3} \omega_{ci} m_i c^2$ to $\approx 6.46 \times 10^{-4} \omega_{ci} m_i c^2$

differing by a factor of 2, which may be linked to the CRs' maximum speed being limited by the speed of light.





The acceleration efficiency is shown as a function of time in (h). The efficiency is defined as the fractional energy density in particles with $E > 10\ E_{sh}$ downstream of the shock. The acceleration efficiency increases dramatically in the first 100 ω_c^{-1} and then saturates to about 10% - 12% after 1000 ω_c^{-1}.

CONCLUSIONS

- ✦ This works presents results from the first relativistic ion hybrid code. The simulation reproduces results consistent in the classical regime and shows that relativistic results agree with theory.
- ✦ p^{-4} spectrum predicted from DSA continues for relativistic energies
- ✦ Rate of increase of maximum energy decreases in relativistic limit, and acceleration efficiency saturates to same approximate value as classical

Citations: [1] Lipotov, 2002, The Hybrid Multiscale Simulation Technology; [2] Gargaté, L., Bingham, R., Fonseca, R., & Silva, L. 2007, *Comput. Phys. Commun.*: [3] Bell, A. R. 1978a, MNRAS, 182, 147 : [4] Blandford, R. D., & Ostriker, J. P. 1978, ApJL, 221, L29: [5], [6], [7] Caprioli, D., & Spitkovsky, A. 2014a-c, ApJ, 783, 91
[8] Bai, X. N. 2015, ApJ, 809, 55