Prospects for ultra-high-energy particle acceleration at relativistic shocks

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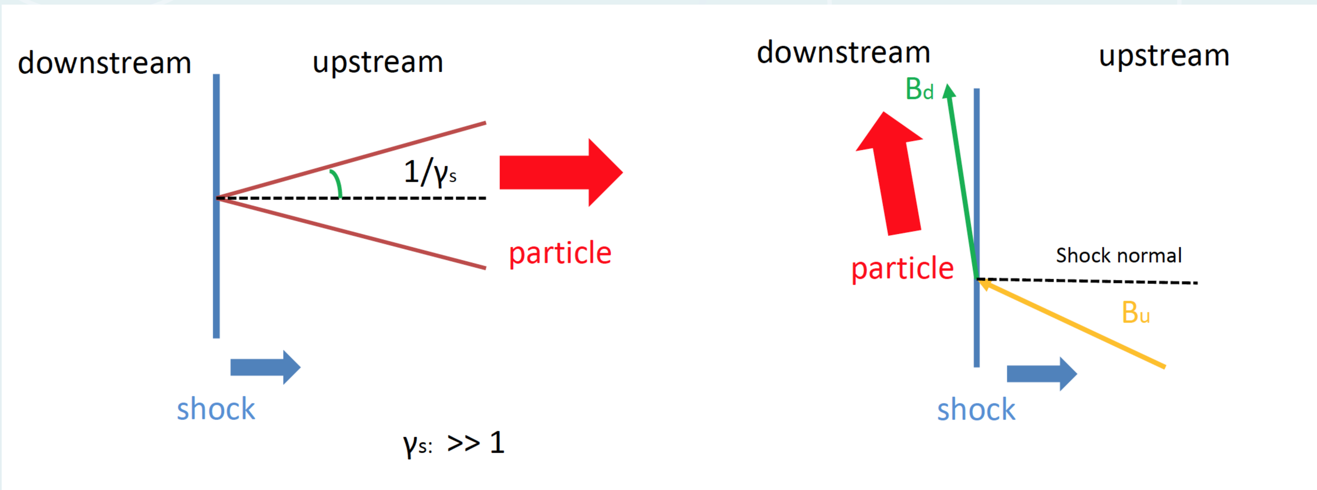
Abstract

Using test-particle Monte-Carlo simulations, we revisit the particle acceleration at ultra-relativistic shocks. We find two feasible mechanisms that could increase the maximum accelerated energy beyond the widely-held downstream magnetized limit. The produced particle spectra are studied on the conditions of two regular field configurations: (i) uniform upstream field perpendicular to the shock normal, and (ii) upstream field with a cylindrical geometry. For uniform field configurations, particles could keep being accelerated until becoming magnetized on either side of the shock, which contradicts the widely-held belief that the maximum energy is constrained by the *downstream magnetized limit*. The corresponding steady-state particle distribution satisfies $dN/d\gamma \propto \gamma^{-2.2}$, similar to that predicted for the parallel shock case. For the cylindrical field configuration, the acceleration efficiency depends on the charge of the particles. Particles with a favorable charge will experience a curvature drift motion parallel to the shock velocity and hence increases the probability of downstream particles to cross the shock. Considering the non-resonant scattering model, these particles can only escape when reaching the confinement limit of the system size, and the accelerated spectrum could become even harder.

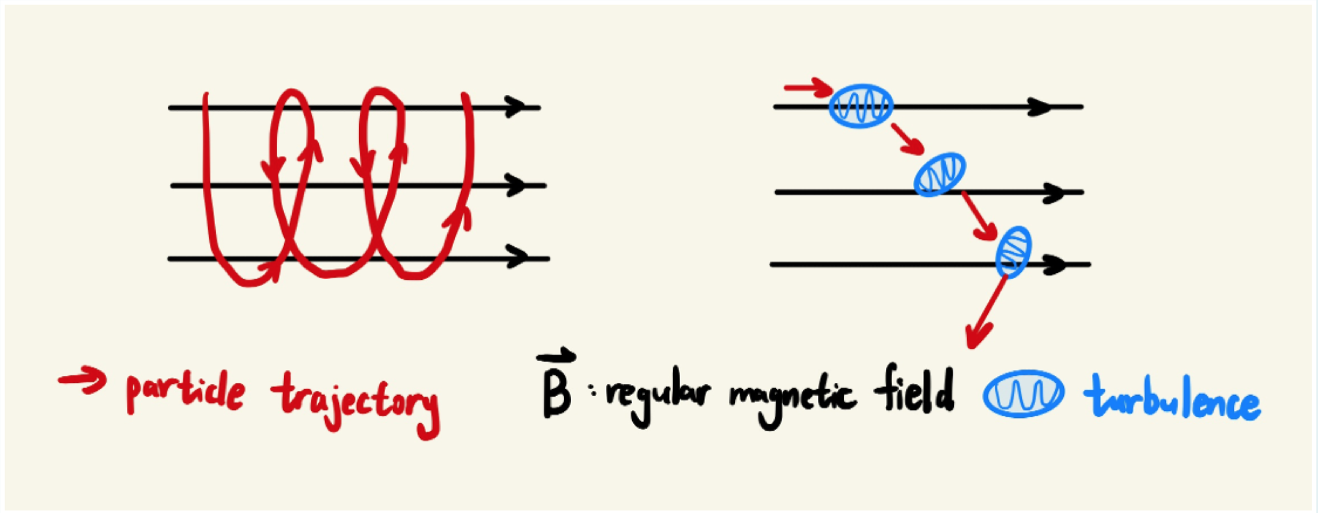
Relativistic shock

At a relativistic shock, the shock velocity becomes comparable with particle velocities. Particles can gain energy by finishing a crossing cycle from upstream to downstream and back. Particles in the downstream have to chase the relativistic shock. As a result, particles that can return back to the upstream are confined in a cone with a half opening angle $1/\gamma_s$, an effect of relativistic beaming. However, particles in this cone run faster than the shock and cannot return back to the downstream and be accelerated again. Therefore, these particles should change their motion directions to leave this cone. After that, particles would be swept up by the shock again immediately.
When crossing the shock, the component of the regular magnetic field that parallel to the shock front would greatly boost in the downstream. Hence the regular magnetic field in the downstream are almost perpendicular to the shock normal. The motion of particles in the downstream are constrained along the magnetic field. To return back to the upstream, these particles should be scattered through an angle of roughly 90°.



Magnetized limit

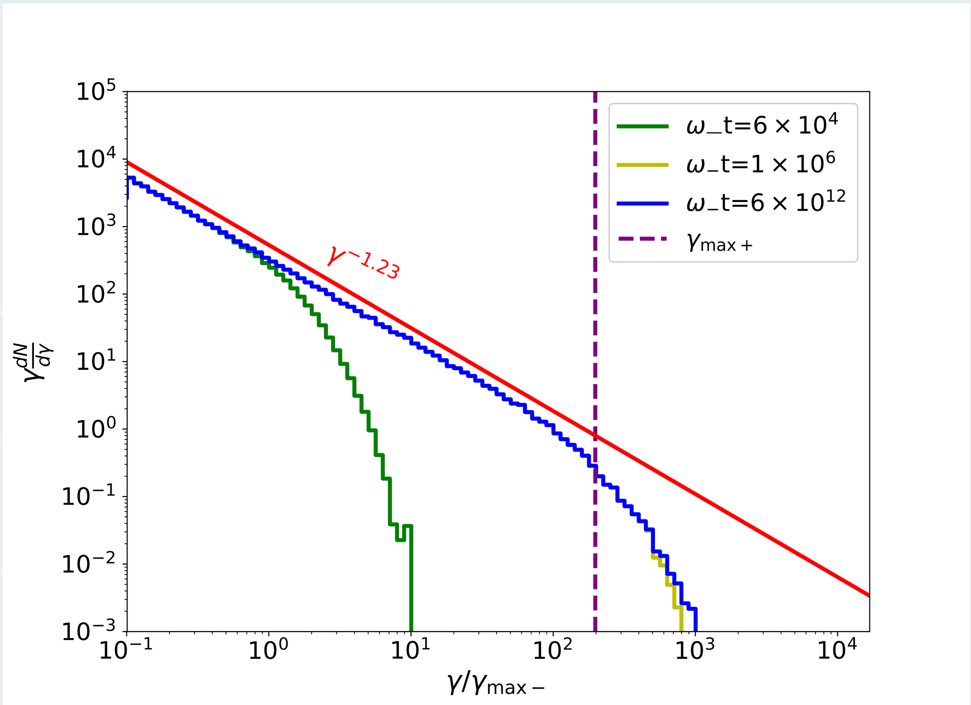
Due to the existence of the regular magnetic field, particles would rotate along the magnetic line and do gyro-motion, or what we call regular deflection. Besides, there also exist small-scale magnetic turbulence. Particles can collide with turbulence and be scattered by a small angel while doing ballistic motion between each scattering. Balancing the corresponding scattering timescale and deflection timescale in the upstream/downstream frame, we can obtain a limit known as the upstream/downstream **magnetized limit**.



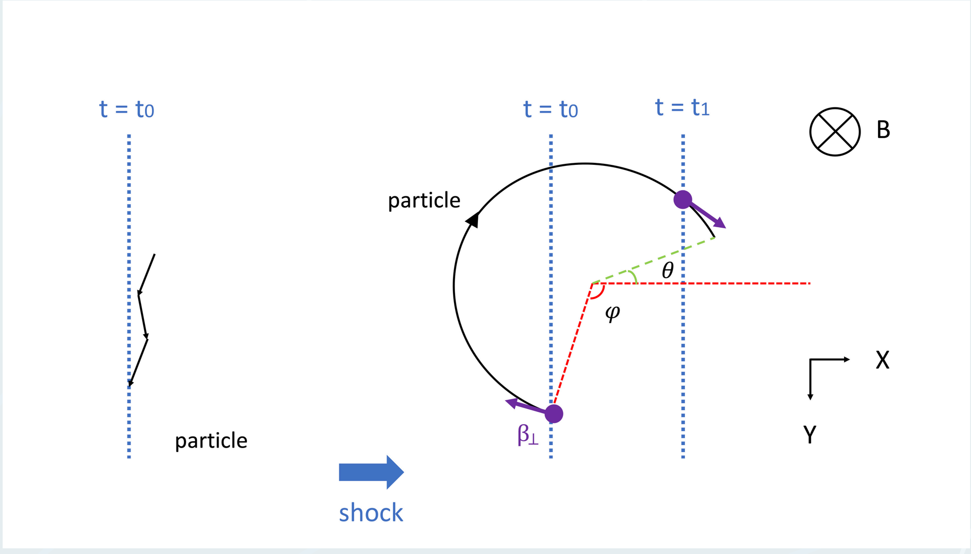
A widely-held belief is that, if a downstream particle is magnetized, it would be constrained to move along the magnetic line, washed away far downstream, and cannot be accelerated anymore. Hence the maximum accelerated energy is considered not to exceed the **downstream magnetized limit**.

Uniform perpendicular magnetic field

First we consider the case where a uniform upstream magnetic field is perpendicular to the shock normal. This is a generic configuration for relativistic shocks. The strength of the downstream field would be greatly compressed because of the jump conditions. When the upstream scattering rate is quite strong (i.e., the upstream magnetized limit is much larger than the downstream one), the accelerated spectrum could extend to much higher energy than previous predictions [1].



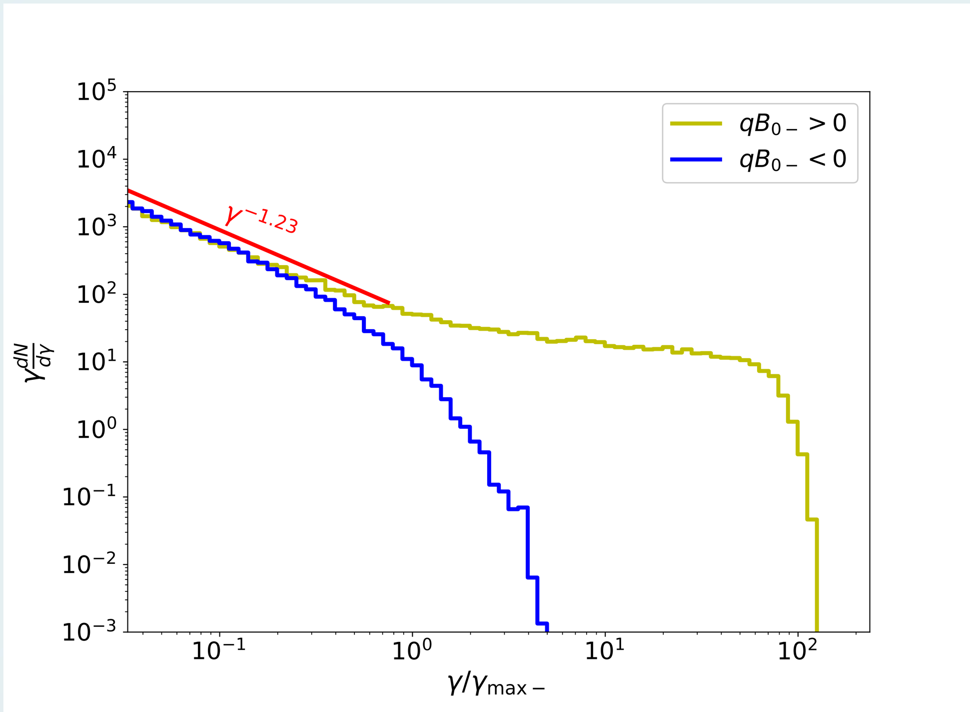
The following schematic picture illustrate the trajectory of a particle with energy much higher than the downstream magnetized limit.



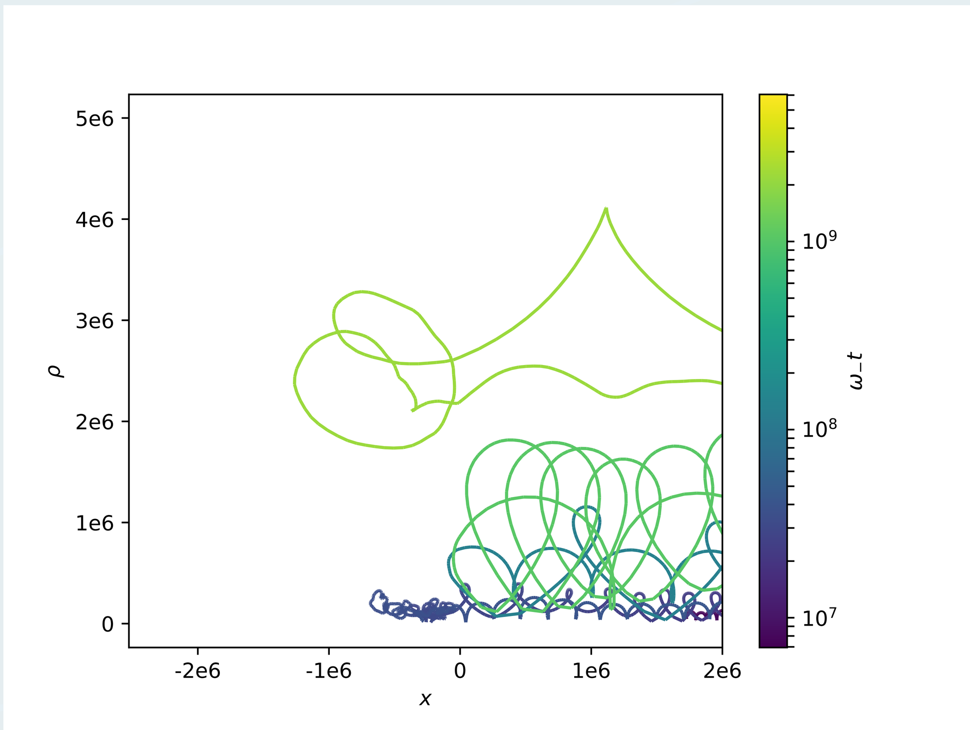
In a companion paper [2], an analytical approximation method is also used and get consistent conclusions with our numerical results.

Magnetic field with cylindrical symmetry

Next we consider a magnetic field with simple cylindrical symmetry where only azimuthal field components exist in cylindrical coordinates, and here shows the corresponding results [1].



Due to the curvature of the regular field, there would be a drift motion. For positively-charged particles in our case, the drift motion would be along the shock velocity, which makes particles much easier to catch the shock and hence increase the acceleration efficiency.



References

[1] Huang, Z.-Q., Reville, B., Kirk, J. G., & Giacinti, G. 2023, MNRAS, 522, 4955
[2] Kirk, J. G., Reville, B., & Huang, Z.-Q. 2023, MNRAS, 519, 1022