Powerful astrophysical objects such as gamma-ray bursts, blazars, and supernovae provide ideal environments for efficient particle acceleration. These bursts of high-energy particles result from an efficient conversion of kinetic or Poynting flux in nonthermal distributions through collective plasma processes. Astrophysical shock waves are one of the most outstanding and extensively studied representatives of such complex many-body phenomena. They cover a large variety of physical conditions in magnetization, velocity, and composition, and are intrinsically nonlinear across very disparate scales. The study of these systems is a key challenge to unveiling the physics underlying observed multimessenger spectra. This nonlinear problem is tackled using large-scale kinetic simulations in combination with linear and nonlinear analytical models. In this context, my research focuses on exploring the physics of shock waves in three different regimes.

The afterglow emission of gamma-ray burst is interpreted as a synchrotron self-Compton (SSC) emission from electrons accelerated on a forward relativistic blast wave. The shock propagates at the interface between the interstellar medium and the relativistic ejecta. Their dynamics are led by the formation of kinetic scale magnetic structures, coherent over hundreds of kilometers, which compress and heat the ambient plasma in the shock upstream. These structures then cross the shock front and scatter nonthermal particles to sustain a Fermi-type acceleration and SSC emission. Some current issues in this regard are the nonlinear evolution of these electromagnetic instabilities in the shock upstream, their decay rate in the shock downstream, and the effect of pair creation on the shock dynamics.

Subrelativistic shocks of high alfvénic Mach numbers are particularly relevant to supernovae remnants. While their overall dynamics bear similarities to the aforementioned relativistic shocks, the nature of the instabilities may differ. One of the outstanding questions emerges from the difference in inertia between electrons and ions of the interstellar medium. While the mean kinetic energy pool is dominated by the ions in the far upstream, a substantial fraction is transferred to the electrons as they cross the shock. Modeling this energy transfer is a key challenge to understand the observed downstream temperature ratio. Another problem of interest is of course the mechanism at the origin of electron injection of particles from the thermal bulk to the nonthermal distribution of accelerated particles in these shock waves.

The first light detected from almost explosive stellar objects is shaped by its propagation in an optically thick environment. The shock wave propagating in such an opaque plasma is said to be radiation mediated and the transition from the optically thick to the interstellar medium is called the shock breakout. In other words, while compression and heating of the background plasma result from coherent electromagnetic structures in the above-stated shocks, radiation-mediated shocks result from the compression by a photon beam through Compton scattering and pair production. A priori subdominant and often neglected, plasma instabilities are present and may impact the shock dynamics. An important problem is thus to model the feedback of plasma instabilities on the spectra at shock breakout.

Modeling these phenomena requires understanding the micro-physics of collisionless shocks, where particles are accelerated through their interaction with turbulent electromagnetic fields that are themselves generated by micro-instabilities. We study these kinetic processes using large-scale Particle-In-Cell (PIC)simulations. The PIC method solves self-consistently the evolution of the particle distribution coupled to Maxwell's equations and consists of advancing a collection of particles through a grid on which the electromagnetic fields are discretized. In our studies, we use the state-of-the-art PIC massively parallelized code Tristan-MP [1] and Osiris [2] to include QED and radiation effects. We also develop reduced Monte Carlo-Poisson solvers to study the dynamics of multispecies plasma with microturbulence.

[1] https://ntoles.github.io/tristan-wiki
[2] http://epp.tecnico.ulisboa.pt/osiris/