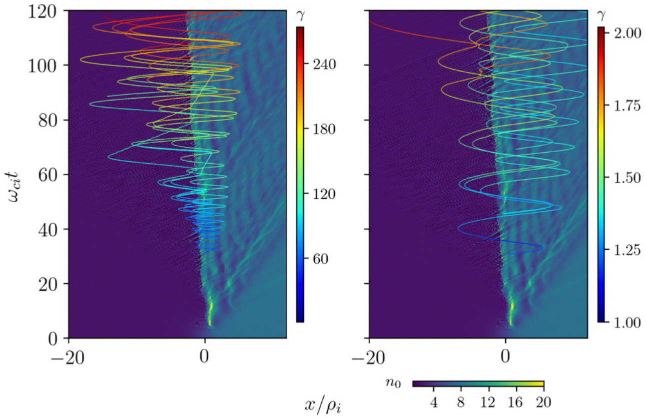
Advanced Plasma Simulation Techniques

Understanding how particles are accelerated in astrophysical systems requires different approaches. Numerical simulations play an increasingly important role in this effort. However, the relevant energy and length scales typically span several orders of magnitude, a separation that is not easy to capture in numerical simulations. The problem can be dissembled, by isolating the physical mechanisms of interest, or by making physically motivated, simplifying assumptions to construct new models. This often requires very specific tools and computational techniques. We both exploit existing open-source codes, and develop new numerical schemes to address previously unexplored physical regimes.



Results of 1D Particle-in-Cell simulations of a collisionless shocks using the SMILEI code. The evolution of the density profile around the shock is shown. Overlaid are selected trajectories of electrons (left) and ions (right) as they repeatedly cross the shock surface, coloured according to their increasing energy.

Front cover: Numerical simulation of a cloud of particles evolving in a uniform magnetic field. The code uses a novel spectral method to capture velocity space anisotropy, and transport is solved with a high-order discontinuous Galerkin scheme. The 2D surface plot shows the dipole anisotropy induced as the cloud expands, but rotates in an out-of-plane magnetic field.

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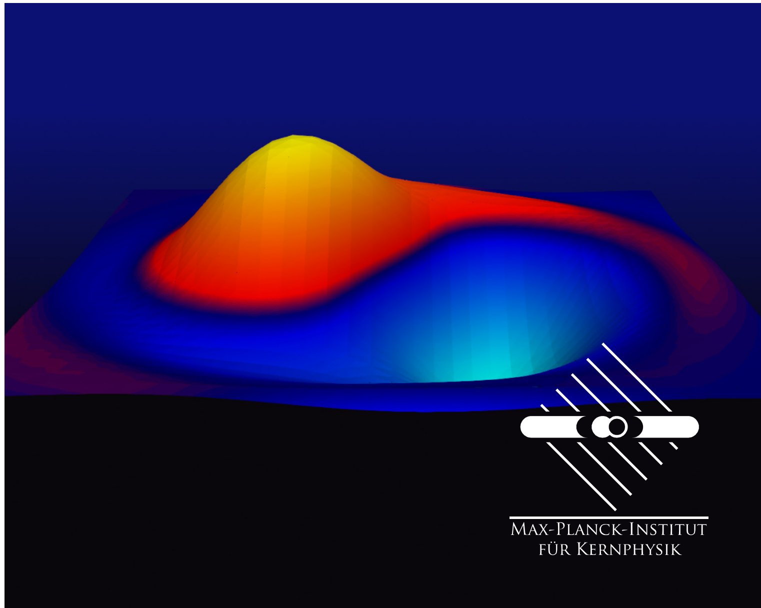
Astrophysical Plasma Theory

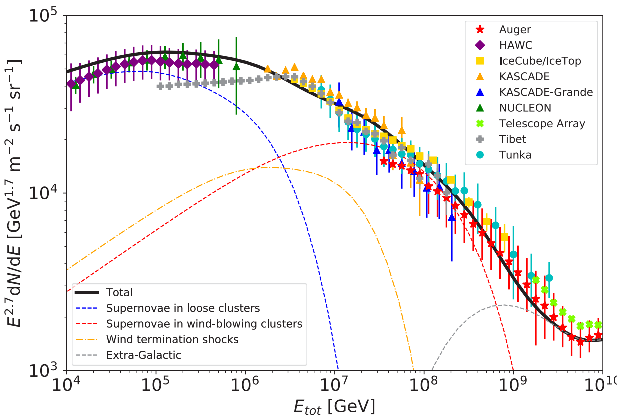


Astrophysical Plasma Theory

The Universe is filled with countless particle accelerators that efficiently energise electrons, protons and other nuclei to extreme values. The highest energy particles arriving at Earth for example, greatly exceed what is achievable in terrestrial experiments. Where and how does Nature produce such energetic particles? What role do they play in our Galaxy, and elsewhere? To answer such questions, it is necessary to develop reliable models of complex astrophysical systems, guided by theory, simulations, laboratory experiments and observations.

Our Galaxy is permeated by a population of energetic particles, known as cosmic rays, that continuously bombard our atmosphere. Since their existence was first discovered more than a century ago, dedicated experiments have accumulated a depth of knowledge about these cosmic rays, revealing crucial details on their energy spectrum and composition. And yet, the origins of cosmic rays, both within our Galaxy and elsewhere remains the subject of speculation.

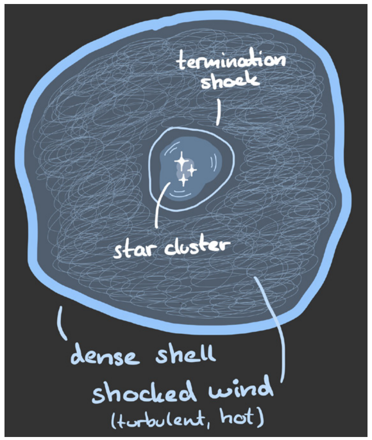
While conclusive evidence is lacking, most experts agree that cosmic rays are primarily accelerated at fast moving shocks, such as those produced in the explosions that mark the end of a star's life. In order to firmly establish such a connection, we study details of the acceleration process in different scenarios, the particle dynamics in and around their sources, the plasma physics underpinning these processes including feedback, and crucially the prospects for identification of radiative signatures.



Experimental data points showing measurements of the cosmic-ray flux, summed over all particle species, arriving at Earth. Theoretical curves derived from a scenario in which Galactic cosmic rays are accelerated primarily in Young Massive Stellar Clusters.

Supernova Remnants & Massive Stellar Clusters

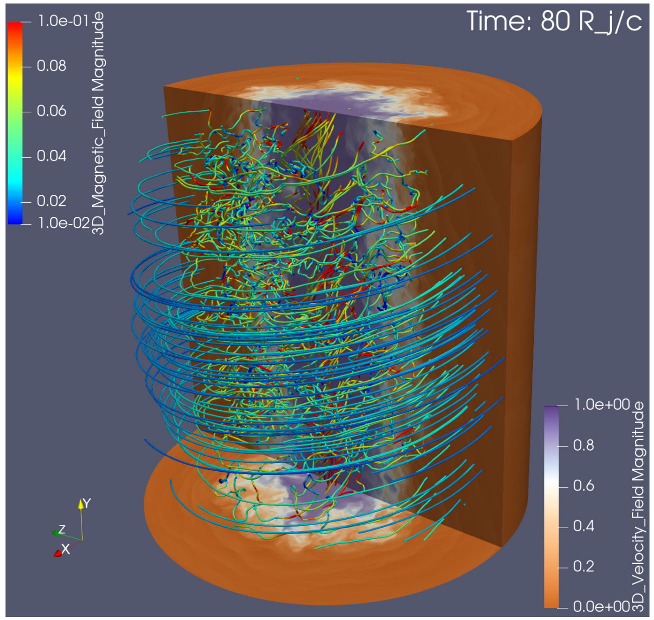
The standard model for galactic cosmic-ray production suggests they are primarily energised at the shocks that surround the remnants of supernova explosions. That these systems can account for all existing observations is not certain. It has been argued that the maximum energy a particle attains in this scenario is sensitive to the ambient conditions around the parent star, with very few stars meeting the necessary requirements to reproduce measured features in the local cosmic-ray spectrum. There is currently no clear candidate source for the highest energy galactic cosmic rays. A possible solution to this puzzle may be provided by young massive stellar clusters, the nurseries of massive stars. The unique conditions in cluster environments may be favourable for cosmic-ray acceleration to the most extreme values that can be achieved in our Galaxy. The next generation of gamma-ray observatories will probe many such systems in unprecedented detail which, supported by theoretical predictions, may finally answer the century-old problem of the origin of galactic cosmic rays.



Cartoon of a compact stellar cluster, a type of superbubble, showing the key global features. The stars in the core drive a collective supersonic wind, that terminates in a shock. The shock is located where the "ram" pressure of the wind reaches equilibrium with the confined, turbulent, shock-heated wind. A dense shell forms as the bubble sweeps up external material.

Extra-Galactic Jets & Gamma-Ray Bursts

The most energetic cosmic rays detected at Earth can not be confined in our own Galaxy, and hence are not produced within it. The most plausible candidates for their production are the relativistic jetted outflows emanating from the centres of certain active galaxies, or from the jets that power gamma-ray bursts. How particles succeed in tapping into the bulk energy of these flows remains uncertain. Shocks or instabilities in the jets provide possible routes to accelerate particles, though the maximum energies that can be reached remains a contentious issue. This is a multi-scale challenge, which must take into consideration both the microphysics that determine the individual particles' motion, and the global scales that establish the physical boundaries. We use a combination of numerical and analytic tools to address these problems, making predictions for the particle spectra, and resulting emission. We explore the physical processes that determine the maximum particle energies achievable in different sources.



Magneto-hydrodynamic (MHD) simulation of a cylindrical jet, revealing the turbulent structure at the jet boundary, where particles can be accelerated.