# Energetic particles and their radiative and neutrino yields in astrophysical environments

## Project Description

Acceleration of particles to ultra-relativistic energies is known to occur in many different astrophysical environments, as testified by the direct detection of Cosmic Rays (CR) at Earth, and by the detection of a variety of sub-products, i.e., high-energy neutrinos and non-thermal radiation (e.g., $\gamma$-rays from neutral pion decay, and radio synchrotron radiation from charged-pion-decay secondary electrons) from a variety of cosmic sources, both Galactic and extragalactic. These different messengers testify of a ubiquitous processes accelerating protons (and electrons and heavy nuclei as well) to very large energies (from GeV to $\gtrsim 10^2$ EeV). In spite of the apparent wealth of information and availability of different investigation channels, our understanding of the processes responsible for particle acceleration is still quite poor. Moreover, the role of magnetic fields and the effects of the environment in modifying and shaping the detected particle and radiation spectra have not been clarified yet.

Many are the open questions related to CRs and their sources.

For Galactic CRs, we still lack the ultimate proof of SuperNova Remnant (SNR) shocks being the main acceleration site. Additional related open questions include the level of neutrino production and their detectability with present and future facilities, the leptonic/hadronic origin of $\gamma$-ray radiation, and CR propagation in the surrounding medium and in the Galaxy. CR propagation plays indeed a fundamental role in shaping the CR spectra at Earth and also in shaping the $\gamma$-ray emission detected from Molecular Clouds (MC) illuminated by CR escaping a nearby acceleration site. The properties of particle propagation (both close to the acceleration site and on a Galactic scale) and the interplay between propagating CRs and background magnetic fields are still uncertain. Furthermore, little is known about the capability of SNR shocks in accelerating particles up to PeV energies: in view of the upcoming progresses in multi-TeV detectors, this issue is very relevant as it bears on our ability to finally identify PeV-particle sources (i.e., PeVatrons) in our Galaxy.

Extragalactic sources of high-energy emission (radiation and neutrinos) pose, in many cases, pressing questions about their own nature. Related issues concern the origin of the TeV/PeV-neutrino and $\gamma$-ray backgrounds (and their link, through the respective emission mechanisms occurring in the sources), as well as the sites of ultra-high-energy cosmic-ray (UHECR) production. Most promising sources are AGNs, starburst galaxies (SBG), and GRBs; among SBG, the two local sources M82 and NGC253 have been positively identified as sources of hadronic $\gamma$-rays. The respective contributions of these source classes to the neutrino and $\gamma$-ray backgrounds and to UHECR flux detected at Earth are not firmly quantified yet. A class of sources to be studied in more detail are radio galaxy lobes. These are the interface of relativistic jets with the environment. If located in clusters, radio lobes can be primary sources of relativistic particles into the intra-clusters medium.

Recent observational progresses and new facilities that will become available in the near future make the subject very interesting and timely. The knowledge of the $\gamma$-ray sky in the GeV-TeV range largely rests on the space-borne *Fermi* Large Area Telescope (LAT) and on several ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs), i.e., HESS, MAGIC, VERITAS – to be soon superseded by the upcoming Cherenkov Telescope Array (CTA). The increasing number of SNR and SNR-MC systems detected in $\gamma$-rays allows deeper studies about the origin of Galactic CRs and their propagation. Their number is expected to substantially increase with CTA, one of whose three Key Science projects is concerned with particle acceleration and the identification of PeVatrons. *IceCube* has recently discovered an isotropic flux of high-energy neutrinos of (presumably) extragalactic origin. Data taking and analysis are ongoing, and progressively more *IceCube* events are expected in the near future. While their astrophysical sources have not been clearly identified yet, blazars and SBG have been suggested as likely sources. In particular, the ability of blazars in producing high-energy neutrinos has recently gained support by the recent detection of a $\sim 0.3\,\mathrm{PeV}$ neutrino coincident in direction and time with a flare detected in $\gamma$-rays from the Blazar TXS 0506+056.

The proposed line or research focuses on three main general questions, that apply to different classes of source: i) the nature (leptonic vs. hadronic) of their $\gamma$-ray emission; ii) their production level of neutrinos, and their contribution to *IceCube* neutrinos; and iii) their efficiency in accelerating CRs and the properties of the latter's spectra. These investigations, involving different sources & messengers, aim to solve some fundamental tightly-coupled issues: acceleration sites, acceleration process(es), CR acceleration efficiency & maximal energy, role of magnetic fields, on-site particle spectrum.

To reach this goal, we consider different sources, that share similar physical processes and similar open questions. The investigation will require a full modeling of several physical processes, such as: i) hadronic and leptonic processes, emission mechanisms, and emitted radiation (in the GeV-TeV band); ii) particle propagation & interaction with ambient matter, radiation, and magnetic field; and iii) neutrino production, and contribution to the neutrino background. These investigations are linked to one other: besides implying different $\gamma$-ray spectral signatures, different relative amounts of leptonic and hadronic yields also imply different neutrino spectra and fluxes.

The acquired solid understanding of particle acceleration and propagation will also be instrumental in deriving robust gamma-ray spectra of cosmic sources that – contrasted with the recorded ones – can be exploited to asses the absorption suffered by high-energy photons interacting with the IR-optical cosmic background and to highlight possible *anomalies* related to Lorentz Invariance Violation effects or the conversion of photons into axion-like particles.