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Future neutrino + Extensive Air Shower challenges

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"Multimessenger" astrophysics, connecting traditional astronomy with cosmic ray (CR), γ-ray and neutrino observations, is a new branch of physics connecting particle physics, astrophysics and cosmology. It is made possible by the availability of experimental techniques and detectors developed for high-energy physics. These have allowed the realization of sensible detectors in space (for the measurement of the primary CR flux, search for primary antimatter, astrophysical studies of γ-ray sources up to hundreds of GeV), on the Earth surface (arrays of detectors for the study of the high energy component of CRs, the identification and characterizations of γ-ray sources up to hundreds of TeV), deep underground detectors (for studies of neutrino oscillations, measurement of solar neutrinos, searches for neutrinos from gravitational core-collapse of massive stars) and under kilometers of water or ice (detection of high-energy neutrinos emitted from astrophysical accelerators). The experimental identification of the engines (or *class* of engines) able to accelerate protons to energies orders of magnitude larger than in the LHC is one of major open problems in multimessenger astrophysics. In additions, almost all experiments enter in the game for the indirect searches for dark matter candidates.

All the involved detectors are characterized by long term measurement campaigns in hostile or inaccessible environments, requiring stable, robust, low cost and low-power electronics detectors. Here, we present a brief outlook and perspectives for the multimessenger studies, with particular attentions to cosmic neutrinos and ground-based observatories of air shower.

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1. Introduction

Multimessenger astrophysics is a recent experimental strategy, connecting traditional astrophysics observations with the new observational windows opened by charged particles, γ-ray and ν detectors. In the near future, likely also gravitational wave observatories will be part of the game.

The availability of experimental techniques and detectors used in high-energy (HE) physics have allowed the construction and operation of experiments in space, on the Earth ground and under-ground (-water, -ice). Space-based experiments are particularly suited for studies of cosmic matter and antimatter, and the detection of HE γ-rays with good pointing capabilities. At ground, Extensive Air-Showers (EAS) arrays are composed of a collection of detectors distributed over a large area to measure primary CRs from $\sim 10^{15}$ eV up to more than $\sim 10^{20}$ eV. Scintillators or water-Cherenkov counters are typically used to detect charged particles reaching the ground, §2. Other methods include the fluorescence detectors, which observe the fluorescence light emitted by atmospheric Nitrogen excited by the shower particles, and the Cherenkov telescopes, which detect the Cherenkov light emitted by the shower. The Cherenkov imaging technique is particularly suited for primary γ-rays, §3. Underground laboratories, created to test particle physics beyond the Standard Model, offer an ideal low-background environment for neutrino physics and astrophysics. Deep underwater/ice neutrino telescopes (§4) have started to provide information on cosmic accelerators while at the same time allowing tests of several physical properties of neutrinos.

In the following, we briefly summarize (refer to [1] for an extended description of the status of multimessenger astrophysics) the experimental techniques used in this field, and the detection challenges for future experiments.

2. The CRs, γ-rays and neutrino connection

The nature of cosmic accelerators able to transfer energy to protons and nuclei up to 10^{20} eV, is one of the major unsolved astrophysical problems. The bulk of CRs is believed to be of galactic origin. Supernova remnants are the likely sites where the galactic CR acceleration occurs. Models exist which foresee that a fraction (up to $\sim$10%) of the kinetic energy released in the supernova explosions is used to accelerate protons, heavier nuclei and electrons.

Direct measurements on balloons, satellites [2] and (recently) on the International Space Station allow a study of the CRs impinging on the top of the atmosphere before their first interaction with Earth matter. When entering the Earth's atmosphere, CRs collide with nucleons of atmospheric nuclei and produce a cascade of secondary particles, the so-called air shower [3]. The thickness of the atmosphere at ground level is ~ 1000 g cm^{-2}, which corresponds to 28 radiation lengths (or ~ 1.5 m of iron). The measurement of the secondary particles with ground-based detectors (indirect measurements) allows the knowledge of the CR flux up to the highest energies. Details on large area detectors used for detection of secondary CRs on ground are given in [4].

It is plausible that the feature in the CR spectrum at $\sim 10^{15}$ eV, known as the *knee* (see Fig. 1, right), represents a transition between different classes of galactic CR accelerators [5]. Below the knee, about 80% of the primary nucleons are free protons and about 70% of the rest are nucleons bound in helium nuclei. Above ~ 1 GeV, the flux of electrons corresponds to less than 1% of that of protons at the same energy. This does not correspond to a charge-asymmetry in CR sources: due

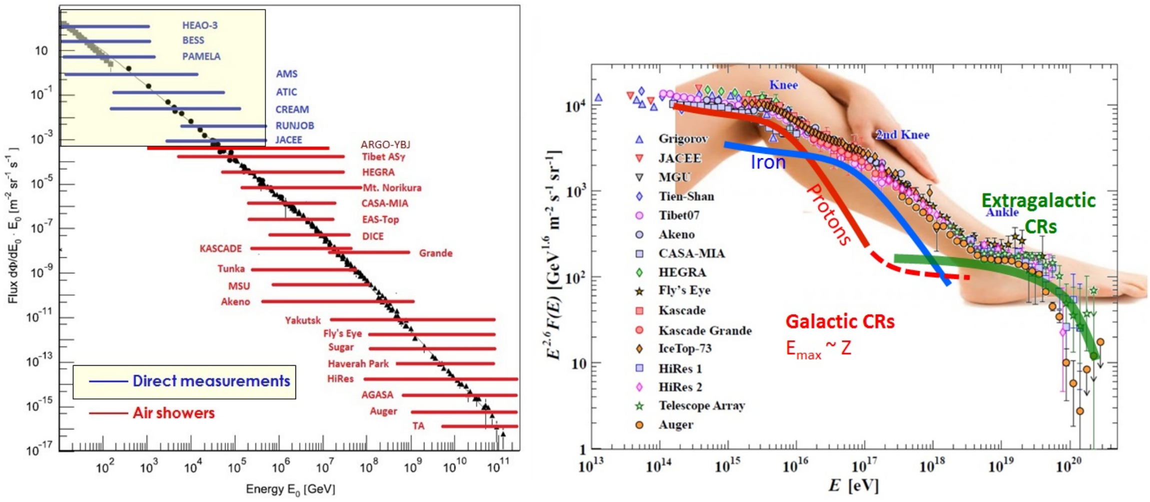

Figure 1: (Left) Flux of CRs vs. energy. The energy range of the CR flux measured by some direct experiments is shown as a blue line and that measured by some indirect experiments as a red line. (Right) CR flux multiplied by $E^{2.6}$. The structures (in particular, the knee and ankle) are more evident. One possible interpretation in terms of galactic and extragalactic sources is also shown.

to magnetic fields, electrons suffer larger energy losses in proximity of sources and produce most of the electromagnetic radiation observed on Earth by astronomers from radio waves to X-rays.

Multiple detection methods will be employed by the next generation ground-based experiment LHAASO in China, able of acting simultaneously as a CR detector and a γ-ray telescope. LHAASO plans to install a 1 km^2 array that includes $\sim$5600 scintillation detectors with 15 m spacing for detection of the electromagnetic component; an overlapping 1 km^2 array of 1221, 36 m^2 underground water Cherenkov tanks, with 30 m spacing, for muon detection (total sensitive area 40,000 m^2); a close-packed, surface water Cherenkov detector facility with a total area of 90,000 m^2; 24 wide field-of-view air Cherenkov telescopes; 452 close-packed burst detectors, located near the centre of the array, for detection of HE secondary particles in the shower core region.

Huge detector arrays are needed to measure the Ultra High Energy Cosmic Rays (UHECRs) [6] with energies exceeding 10^{18} eV, where a second feature in the CR spectrum is observed (the ankle, Fig. 1, right). UHECRs are probably of extragalactic origin [7] because the arrival directions are no longer significantly affected by galactic magnetic fields and no anisotropies from the galactic plane are observed. The arrival directions of UHECRs could provide information about the location of sources. At $E \sim 10^{20}$ eV, the flux is only about one particle per square kilometer per century and experiments covering huge surfaces are needed to collect a reasonable number of events. The largest active array is the Pierre Auger Observatory (PAO), a hybrid system of two detectors, the fluorescence detector (FD) and the surface detector (SD). The SD consists of 1600 water Cherenkov stations separated by 1.5 km in a triangle grid over an area of 3000 km^2. Photo-sensors are used in both FD and SD detectors. An extension of the PAO project is foreseen, as well as studies for a next generation ground-based UHECR experiment [8]. SiPMs are considered a very good alternative to the classical PMT for the SD. The experimental challenge is the measurement, in addition to the primary CR energy, of its nuclear charge/mass. This information is necessary to understand which kind of galactic or extragalactic engines are at work in the acceleration process.

For CR energies below $\sim 10^{19}$ eV, the presence of galactic magnetic fields makes it impossible to localize CR sources using charged particles. The only way to have information about their acceleration sites is by observing the neutral particles (γ-rays and neutrinos) generated by their interactions during acceleration.

3. Detecting γ-rays

Gamma-rays are produced by a large variety of energetic astrophysical phenomena, including supernova remnants, pulsars, and quasars. Unlike the sky at visible wavelengths, the γ-ray sky is dominated by a diffuse radiation originating in our Galaxy, due to the propagation of CRs in the interstellar medium. In most cases, sources appear as point-like objects, i.e. with angular dimensions much smaller than the resolution of the detectors, over the diffuse γ-ray background

The development of compact space experiments (like AGILE and *Fermi*-LAT) has been made possible by the availability of new detectors coming from technologies of experimental particle physics, see [9]. Space experiments cover a very broad γ-ray energy region, extending from a few MeV to tens of GeV. Beyond few hundreds of GeV the γ-ray fluxes are extremely small: the brightest sources, such as the Crab Nebula, exhibit a flux of $\sim 10^{-7}$ photons m^{-2} s^{-1}. Thus, collecting area at ground of the order of 10^4 m^2 are needed to provide adequate statistics.

Arriving on Earth, the γ-ray starts a shower with e^+e^- pair creation at an altitude of ~ 20 km. The depth of the shower maximum, X_{max}, depends logarithmically on the energy of the incoming particle. For 1 TeV γ-ray, it corresponds to an altitude of 10 km above sea level. The rate of showers induced by charged CRs (background for these studies) is up to 10^4 larger than γ-rays.

Some experiment as Milagro, ARGO-YBJ (not anymore in operation) and the new HAWC directly detect secondary charged particles. They are located at high altitudes, can operate continuously with and energy threshold of ~ 100 GeV and with large field of view (FoV, about 2.5π sr), but their angular resolution is not very accurate. These detectors are suited to perform sky surveys and to study transient phenomena. The HAWC detector consists of 300 steel tanks, each 5 m high and 7.3 m in diameter, holding 188 tons of water each. The detector (as the former Milagro) operates on the principle of detecting the Cherenkov light from the shower particles in the water tanks. Four PMTs with high QE are located in the bottom of each tank. HAWC uses the difference in arrival times of the light at different tanks to measure the direction of the primary particle.

A second experimental technique is that employed in imaging atmospheric Cherenkov telescopes (IACTs). For these, the main technical breakthrough involved the use of a camera with 1000-2000 pixels to exploit the difference in shape of the atmospheric shower between γ-rays and protons, and the use of stereoscopy. The camera typically cover a FoV of $\sim 5^\circ$ of diameter ($\sim 10^{-2}\pi$ sr). Because of the use of these techniques in H.E.S.S., MAGIC and VERITAS IACTs, TeV astronomy rapidly evolved from an underdeveloped branch of CR studies to a truly astronomical discipline. For historical reviews, details on current experiments, presentation of results and perspectives, see [10].

IACTs collect the Cherenkov light of the air showers with mirrors onto a fast camera in the focal plane of the mirrors. The total amount of light is linearly dependent on the total track length

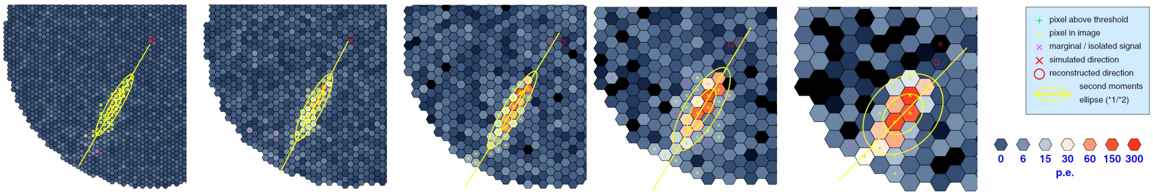

Figure 2: Part of the FoV of $\sim 6^\circ$ of cameras with different pixel sizes (0.07, 0.10, 0.14, 0.20, and 0.28°), viewing the same shower (460 GeV γ-ray at 190 m core distance) with a 420 m^2 telescope. Low-energy showers would be difficult to register, both with very small pixels (signal not contiguous in adjacent pixels) and with very large pixels (not enough pixels triggered above the increased thresholds). Adapted from [11].

of all the particles in the shower. This, in turn, is proportional to the energy of the primary particle. The light front is in the plane perpendicular to the incoming γ-ray direction and its thickness is about 1 m wide, i.e. the arrival time has typical width of few ns. Showers induced by γ-rays are seen on the camera with an elliptical shape (Fig. 2), whose typical RMS projection in the sky of width and length of 0.1° and 0.3°, respectively. With 1000-2000 pixels in the camera, the angular resolution reach $\sim 0.1^\circ$. Typically, about 100 Cherenkov photons m^{-2} TeV^{-1} of primary energy arrives in a ring on the ground with a radius of $\sim$ 120 m at an altitude of 2000 m. At sea level, this number is reduced by an order of magnitude. The spacing of the telescopes should thus be $\mathcal{O}(100)$ m. Closer spacing allows for an improvement in low-energy performance at the expense of collection area at higher energies (and vice versa).

The background at dark sites during moonless nights is typically 10^{12} photons m^{-2} s^{-1} sr^{-1}, i.e. nine orders of magnitude smaller than the daytime sky background. For these reasons, IACTs take data during dark nights and with extremely short exposures (a few ns) in order to detect the faint Cherenkov light from the shower over the night-sky background, with duty cycle of $\sim$ 10%. With the quantum efficiency of typical photo sensors in the pixeled camera (including a $\sim$ 10% mirror losses), the mirror area must be $\sim$ 100 m^2 to trigger a telescope with 100 p.e. for a 100 GeV shower. Correspondingly, the night sky background corresponds to a rate of $\sim$ 100 MHz.

The next-generation of ground-based instruments is the Cherenkov Telescope Array (CTA), which is expected to start operation in 2017 with a partially completed array. CTA will provide sensitive observations of the γ-ray sky over the energy range from a $\sim$ 50 GeV to hundreds of TeV. To achieve the optimal sensitivity over that wide a range in energy, the array will employ three different-sized telescopes: Large Size (LST, 23 m diameter), Medium Size (MST, 10-12 m) and Small Size (SST, 4-6 m) Telescopes. The design goal is a point-source sensitivity that is at least an order of magnitude better than the operating instruments, with an important improvement in the angular resolution, from 0.1° at 100 GeV to 0.03° above 1 TeV [11].

Photon sensors most commonly used in IACTs are PMTs with bialkali type photo-cathodes that provide the highest QE. They are sensitive in the wavelength range of 300-600 nm, well matching the spectrum of Cherenkov light. This well-established technology is subject to continuous development and improvement. The relatively high peak QE currently available (up to 30%), low noise and and high gains (up to 10^6), allow the reliable measurement even of single p.e. and with a dynamic range reaching $\sim 5 \times 10^3$ p.e. Pulses must be usually amplified in order to match the sensitivity of the DAQ electronics. New photon detectors are under study and the CTA cameras must be optimized to allow their integration if their performance and cost provide significant advantages over PMTs [11].

4. High-energy neutrino detectors

Neutrino astronomy shares with γ-ray astronomy the objective of understanding the sources and mechanisms of CR acceleration and indirect searches for DM candidates [12]. While γ-rays can be produced both by hadronic (through π^0 decay) or leptonic processes (inverse Compton, bremsstrahlung), neutrinos can only be produced by hadronic processes ($\pi^\pm$ decay). The small neutrino interaction cross-section allows them to come from far away. Moreover, neutrinos, being neutral, are not deflected by magnetic fields. Despite the substantial progress of space and ground γ-ray observations, finding a convincing case of γ-rays due to π^0-decay remains extremely difficult, in particular in the PeV region. Only the detection of neutrinos could unambiguously solve the problem of the origin of the highest energy hadrons in CRs and neutrino telescopes are expected to be decisive in the quest of CR sources.

The idea of a large volume experiment for cosmic neutrinos based on the detection of the secondary particles produced in neutrino interactions was first formulated in the 1960's by M. Markov. He proposed: *"to install detectors deep in a lake or in the sea and to determine the direction of the charged particles with the help of Cherenkov radiation"*. The challenge to detect galactic neutrinos is open for a multi kilometer-scale apparatus deployed in the Antarctic ice or in deep seawater. At present a km^3 detector (IceCube) is operating in the ice of the South Pole and another smaller underwater telescope (ANTARES) is running in the Mediterranean Sea, waiting for the Mediterranean km^3 telescope (KM3NeT). They all adopt the Markov idea using a grid of PMTs inside the so-called *instrumented volume*.

IceCube consists of 5,160 digital optical modules (DOMs), each with a 10" PMTs and associated electronics. The DOMs are attached to vertical strings with separation of 17 m and arrayed from 1,450 meters to 2,450 meters depth. The 86 strings, frozen into boreholes, are deployed on a hexagonal grid with 125 meters spacing and hold 60 DOMs each. IceCube provided in 2013 the first evidence for a cosmic neutrino flux up to PeV observing interactions within the detector. The discrimination over the background of atmospheric neutrinos was obtained through selection criteria in a restricted fiducial volume leading to the so-called High Energy Starting Events (HESE) [13]. The largest fraction of HESE are showers for which the angular determination is poor (10°-20°). The HESE flux is compatible with flavor ratios $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$, as expected from charged meson decays in CR accelerators and neutrino oscillation on their way to the Earth. Due to the poor angular resolution of HESE, no identification of sources has been possible so far. For the future, an extension of the detector is foreseen by the IceCube-Gen2 project, based upon the robust design of the current detector. It includes also a very dense core (PINGU) for the measurement on the neutrino mass hierarchy. Details for particle-physics neutrino studies in [14].

ANTARES is at present the largest neutrino telescope in the Northern hemisphere, operating since 2008 [15]. It is anchored to the seabed at a depth of 2.5 km, 40 km off the coast of Toulon (F), and consists of an array of 885 10" PMTs covering an instrumented volume of approximately 0.02 km^3. After the discovery of the cosmic neutrino diffuse flux by IceCube, the search for its

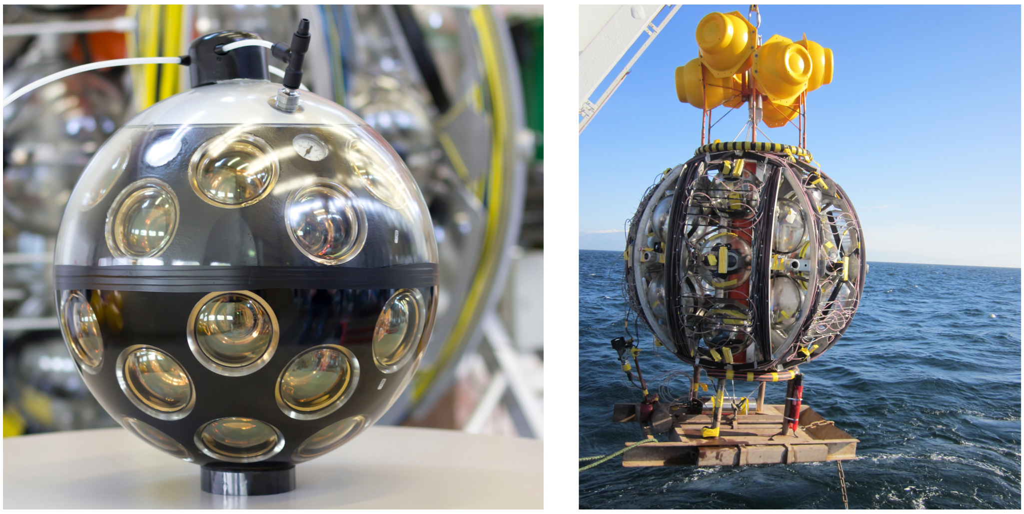

Figure 3: (Left) The KM3NeT-DOM. It is a 17” pressure resistant glass sphere holding 31 3” PMTs and the related electronics. (Right) The deployment of a string with the Launcher of Optical Modules (LOM). The LOM is a spherical frame with a diameter of 2.2 m, onto which a detection unit is rolled.

origin has become a key mission in HE astrophysics. ANTARES is large enough to constrain the origin of the IceCube excess from regions extended up to 0.2 sr if located in the Southern sky.

KM3NeT (www.km3net.org) is a multi-site deep-sea research infrastructure with two similar detectors optimized for different physics studies. ARCA (Astrophysical Research with Cosmics in the Abyss), for neutrino astrophysics, will be located in Sicily; ORCA (Oscillations Research with Cosmics in the Abyss), for studing neutrino oscillations parameters and resolve the neutrino mass hierarchy, will be located in France, close to the ANTARES site. The first KM3NeT string has been deployed in the ARCA site in December 2015.

ARCA, off-shore Capo Passero (Sicily) at a seafloor depth 3500 m, will consist of two detection blocks, each of 115 vertical detection units (DUs). A DU contains 18 DOMs with 31 PMTs per DOM (Fig. 3). The area of photocathodes in a single DOM is comparable to that of three 10” PMTs used in IceCube and ANTARES. Having many small co-located PMTs has several advantages: a large dynamic range; a better rejection of atmospheric μs; a much more uniform angular coverage; and the ability to calibrate on multi-fold coincidences from ^{40}K decays. ARCA ($\sim$ 30 DUs have been already funded) is planned to replace ANTARES in data taking starting in 2017.

5. Conclusions and Outlooks

This workshop took place in the INFN - *What Next* context and intended to be an opportunity to discuss strategies for future detectors, comparing different experimental needs. In the field of multimessenger astrophysics, the experiments for detection of charged CRs, γ-rays and neutrinos play a fundamental role. All the studied phenomena are characterized by low fluxes (for neutrino, also low cross-section); the experiments must consequently cover large areas/volumes and take data for $\mathscr{O}(10)$ year. After many decades of developments, most experiments obtain information on primary CRs, γ and ν (as presented in the previous sections) through photo sensors that measure secondary particles. EAS arrays make use of scintillator or water Cherenkov detectors, or exploit the fluorescence emission of Nitrogen in the atmosphere; IACTs observe the Cherenkov light emission of the electromagnetic shower in the atmosphere induced by TeV γ-rays; neutrino telescopes detect the Cherenkov light emission in water/ice by charged particles induced by ν interactions.

The new major projects on the ground (as LHAASO and the PAO upgrade for CRs; the CTA for TeV γ-ray astronomy) and the neutrino telescopes are huge apparata located in remote or almost inaccessible sites. The signal rate is usually low, or very low. The background on the contrary is huge (the night light in IACTs, the ^{40}K and the bioluminescence for neutrino telescopes in water) and computing issues for triggering, data reduction and reconstruction is a fundamental part of experiments. The present technical solution to convert photons in a signal is in all cases the use of PMTs. Different R&D are ongoing for the use of semiconductor devices. The general need is robust and cheap detectors (for instance, KM3NeT will use about 65,000 optical sensor for one block of 118 DUs), with low power dissipation (AUGER rely on solar cells for power supply), stable all over the detector lifetime. In most cases, pile-up is not an issue, as well as the radiation hardness and the needed time resolutions are $\mathcal{O}(1)$ ns.

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