Connecting neutrino Astrophysics to Multi-TeV to PeV gamma-ray astronomy with TAIGA

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Recent evidence for neutrinos in the PeV energy range from IceCube provides additional motivation for the search for the most energetic Galactic accelerators. Gamma-ray astronomy is a sound strategy to reach this goal, providing the energy range beyond 10 TeV can be covered at a sufficient sensitivity level. The energy spectra of most known gamma-ray emitters only reach up to few 10s of TeV. The HEGRA IACT installation reported evidence for gamma-ray energies from the Crab Nebula as high as 80 TeV. Uncovering their spectral shape up to few 100s of TeV could answer the question whether some of these objects are cosmic ray Pevatrons, i.e. Galactic PeV accelerators. Extending observations beyond this energy range requires very large effective detector areas, as planned by the TAIGA collaboration.

1 Introduction

Ground based gamma-ray astronomy has rapidly evolved in the past decade, significantly affecting our knowledge of the non-thermal universe. Imaging atmospheric Cherenkov telescopes (IACT) led to a break-through with the first significant detection of gamma-rays in the TeV energy range from the direction of the Crab Nebula [1]. Further innovations such as fast high-resolution PMT cameras (CAT) and the stereoscopic detection technique (HEGRA) led to currently existing instruments (H.E.S.S., MAGIC, and VERITAS). Today, more than 150 sources of very high energy (VHE, $E>100\,\mathrm{GeV}$) gamma-rays are known [2].

Above 100 GeV, the stereoscopic imaging technique is the method of choice. Existing and planned instruments, such as the Cherenkov Telescope Array CTA [3], are relying on the IACT technique. Their optimal operation regime is typically located in the TeV energy range. The total energy coverage spans from few 10s of TeV to 100 TeV. Beyond these energies, at multi-TeV to PeV energies, the gamma-ray universe is so far only poorly explored. Due to the powerlaw shape of source spectra, the observable flux drops quickly with increasing energy. Much larger sensitive areas than the ones from existing instruments are required for detection here.

While imaging air Cherenkov telescopes have proven to be the instruments of choice in the GeV to TeV energy range, large detector areas are more easily accessed with the (non-imaging) shower-front timing technique which also naturally provides large viewing angles. The poor gamma-hadron separation power of shower front timing arrays can be compensated by a combination with small imaging air Cherenkov telescopes. Such a new hybrid detector concept is currently being implemented by the TAIGA collaboration in the Tunka-valley in Siberia.

In the next section, the astrophysical motivation for multi-TeV to PeV astronomy is adressed. Subsequently, the strategy pursued by the TAIGA collaboration to access this energy range is described.

2 Astrophysics with ultra-high energy gamma-rays and neutrinos

Observations in the multi-TeV energy range have a potential for discovery of new sources, and are particularly important to measure the spectral shape of known gamma-ray sources in the cutoff regime, where the objects reach their maximum acceleration energy. The accelerators of cosmic rays up to the knee region of the cosmic ray spectrum, the Pevatrons, are especially in the focus of observations in the multi-TeV to PeV range. The paradigm of charged Galactic cosmic ray production is the scenario of acceleration in shock fronts at the boundaries of expanding shells of supernova remnants (SNR). Nuclear scattering of the accelerated nuclei off the ambient medium produce neutral and charged pions which subsequently decay into gamma-rays and neutrinos at energies of about a factor 10 less than the primary cosmic ray particles (due to the typical inelasticity of the hadronic interaction). A Pevatron accelerating charged cosmic ray particles up to cutoff energies of 3 PeV would produce hard gamma-ray and neutrino spectra up to cutoff energies of roughly 300 TeV.

While neutrinos from an astrophysical source are an unambiguous smoking-gun signature for hadronic processes, this is not necessarily the case for gamma-rays. From few 10s of GeV up to about 10 TeV, the origin of a gamma-ray signal is difficult to identify. Gamma-rays can also be produced in leptonic scenarios, in which electrons scatter off low energy seed photons, boosting the photons up to TeV energies (Inverse Compton scattering). Above few 10s of TeV, the inverse Compton effect becomes less efficient because of Klein-Nishina suppression, resulting in soft spectra. As opposed to that, nucleonic gamma-ray production increases efficiency because of increasing inelastic cross-sections, resulting in harder spectra. Therefore, the observation of hard gamma-ray spectra in this energy regime would resolve the leptonic/hadronic ambiguity and represent a smoking-gun signature of cosmic ray acceleration. The difference in leptonic and hadronic spectra is illustrated qualitatively in Figure 1. Observations of the Galactic center by H.E.S.S. [4], and recent evidence for astrophysical neutrinos from IceCube [5, 6] are further motivation for a search for multi-TeV to PeV gamma-rays.

As reported in [6], the IceCube neutrinos were detected in the energy range from 100 TeV to about 1 PeV. The data are reported to be in favour of an astrophysical interpretation. Among the 37 neutrino events detected by IceCube, 5 were speculated to be associated with extreme Blazars by other authors [7]. Based on this tentative association, [8] have presented model calculations for gamma-ray fluxes expected in a hadronic emission scenario and using the neutrino events as flux constraints. The predicted fluxes (see Figure 1) are reaching their maximum between 1 and 10 PeV, a region so far not accessed by gamma-ray experiments.

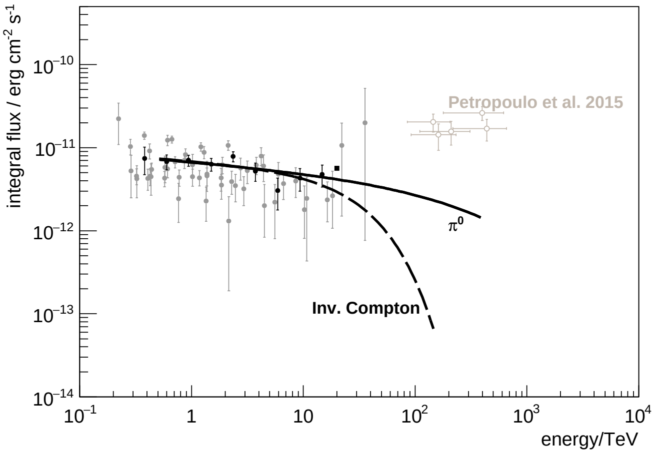

Figure 1: Extrapolations to the multi-TeV regime: π^0-decay spectrum (solid curve, powerlaw with exponential cut-off, no attenuation), inverse Compton spectrum (dashed curve, double exponential cutoff). Curves are scaled to data from the H.E.S.S. Galactic plane survey [9] (grey circles) and the Milagro source MGRO J1908+06 (black square: Milagro [10], black circles: H.E.S.S. [9]). Open circles: hypothetical gamma-ray fluxes from Blazars possibly associated with ν events [8].

While gamma-rays and neutrinos must both be produced in the same astrophysical environments, their detection requires slightly different approaches on considerably different scales. Gamma-rays from GeV to PeV energies can be detected on the ground via extended air shower (EAS) detectors, which measure either the particles (scintillators, water Cherenkov detectors) produced in electromagnetic interactions in the EAS, or their secondary Cherenkov light emission (IACTs, timing arrays). Neutrinos can be detected in large volume detectors via their neutral current or charged current interaction with the ambient medium. While for both particle types the detection methods mostly rely on the measurement of Cherenkov light emission from secondary particles resulting from the interaction in the atmosphere or the detector medium, the scale of the required instrumentation is much larger for neutrino detection due to the low cross section of the weak interaction.

The much higher cross section of the electromagnetic interaction makes the detection of gamma-rays possible on smaller scales. On the other hand and for the same reason, gamma-ray fluxes can be strongly attenuated in astrophysical environments and during their propagation to Earth. Gamma-rays can interact with photons from low energy photon fields and produce electron-positron pairs, therewith reducing the observable flux at Earth as compared to the source intrinsic flux. The attenuation effect depends on the gamma-ray energy, the energy of the low energy photon, and the distance travelled. The absorption of TeV gamma-rays from Active Galactic Nuclei (AGN) has been extensively studied by Fermi-LAT and the current generation of IACT experiments, providing limits on the density of the extragalactic background light (EBL) in the wavelength range from $0.1\,\mu$m to $5\,\mu$m. Spectroscopy of nearby AGN in the energy range from 5 TeV to 50 TeV would access the wavelength band from $5\,\mu$m to $50\,\mu$m. It was shown by [11] that gamma-rays in this energy range from nearby AGN might undergo less absorption by pair production than expected. Possible explanations for this effect could be mixing of photons with light pseudoscalars or effects of breaking of Lorentz-invariance [12], which would lead to a reduction in the effective cross-section for electron positron pair production due to a modification of the kinematics of the interaction (see e.g. [13]).

In the ultra-high energy regime, the absorption effect is strong enough to be relevant also for Galactic sources. [14] have shown that the dominant photon fields are the interstellar radiation field (ISRF), and the cosmic microwave background (CMB). The strength of absorption by pair production on the ISRF reaches a maximum at about 100 TeV, and can vary from few percent for nearby sources up to 50% for faraway sources (i.e. located inside the Galactic disk at a distance of 20 kpc beyond the Galactic center). The absorption caused by the CMB is maximal at about 3 PeV, where more than 90% of the gamma-ray flux from a faraway Galactic source is absorbed. Beyond 3 PeV, the Galaxy becomes transparent to gamma-rays again. A measurement of gamma-ray spectra modified by the absorption effect can provide an estimate of the ISRF density. Since the CMB density is very well known, such a measurement up to PeV energies could provide a new method to measure the distance of Galactic sources from their spectral shape in the gamma-ray energy range.

3 Accessing the ultra-high energy gamma-ray regime

3.1 Detection techniques

The questions described above can be adressed by accessing the ultra-high energy gamma-ray regime, i.e. energies beyond 10 TeV and up to the PeV regime. While it is in principle possible to reach energies beyond 100 TeV with IACTs, the existing and planned instruments are limited by their instrumented area, the large number of required channels per km^2, and their dynamical range. Even CTA will only be able to do spectroscopy beyond 100 TeV by investing a significant fraction of its available observation time. Considering a flux of only few photons per km^2 per hour even from the strongest gamma-ray sources, a very large intrumented area is obviously the key to making spectroscopic studies at these energies.

Ground-based non-imaging EAS detectors measure the arrival-time distribution and density of particles or photons on the ground. A high reconstruction quality (and thus sensitivity) can be achieved using the density and arrival-time distribution of particles or photons on the ground. While Milagro, HAWC [15], and LHAASO [16] mainly use charged particle detectors to access the multi-TeV regime, the timing of the air shower front is best measured using the Cherenkov photons emitted by the secondary air shower particles. Air Cherenkov timing-arrays can provide an angular resolution of the order of 0.1° and relative energy resolution of better than 15 % (see, e.g. [17]), as compared to 1° and 100% for particle shower front sampling techniques. However, the rejection of the predominant hadronic background is difficult using the timing-array technique alone. This is better achieved by IACTs, using the image shape for hadron rejection.

3.2 HiSCORE

One concept to access the multi-TeV energy range with a very large area wide angle instrument is the HiSCORE experiment [18]. HiSCORE consists of an array of timing stations, measuring the air Cherenkov photon front emitted by the secondary particles in the EAS. A HiSCORE detector station consists of four 8 inch photomultipliers (PMTs), each equipped with a 40 cm Winston cone light concentrator, built from flexible segments of reflective foil sheets. The light collection area per station is 0.5 m^2 and the solid angle covered is 0.6 sr. A picture of a HiSCORE station is shown on the left side of Figure 2. The analog signals from the anodes and the next to last dynode are digitized in the GHz regime using a custom developed readout board based on the DRS 4 chip. Before readout, an analog summator board is dividing the analog signals, and summing the anodes. The analog sum is used for triggering. The stations can be manually tilted along the N-S axis in order to access different parts of the sky. A relative time synchronization at sub-ns level is required over the full scale of the array. Two independent time-calibration methods were successfully employed, reaching the required accuracy [19].

A first implementation of the HiSCORE concept was realized by the Tunka-HiSCORE group. Today, the HiSCORE detector is operated as part of the TAIGA collaboration and consists of 28 HiSCORE timing stations distributed over an area of 0.25 km^2 in the Tunka valley in Siberia. The layout of the 28 station array is shown in Figure 2. An extension to a 0.6 km^2 array and a combination with an IACT is planned between 2016 and 2017. This combination is described in the next section. First results from the HiSCORE timing array were presented recently and will be the subject of proceedings publications [20].

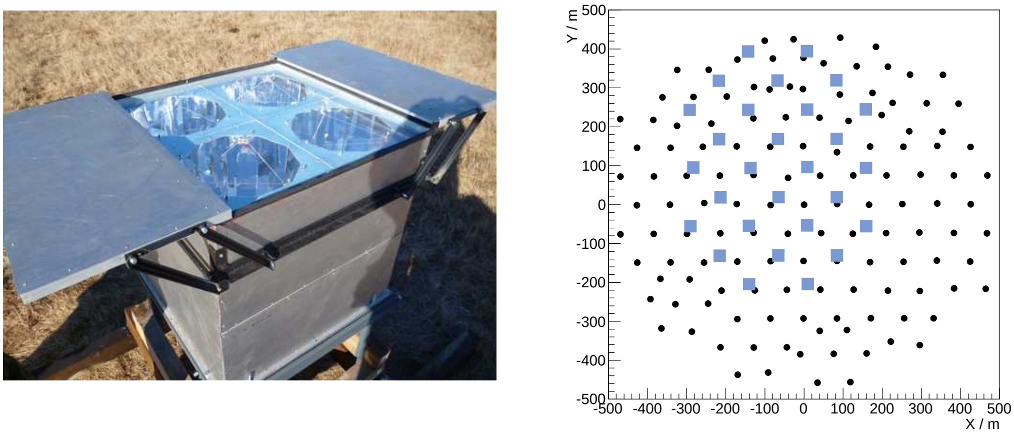

Figure 2: *Left:* Picture of a HiSCORE timing station. *Right:* Layout of the 28 HiSCORE stations (Filled squares). The optical stations of Tunka-133 are shown as filled circles.

3.3 TAIGA: combining imaging and timing

TAIGA [21, 22] stands for Tunka Advanced Instrument for cosmic ray and Gamma ray Astronomy. The TAIGA experiment is planning to combine the HiSCORE timing array with 10 small sized imaging air Cherenkov telescopes. A first IACT is currently under construction on the Tunka site.

A TAIGA IACT consists of a Davies-Cotton mirror dish with 34 mirror facets of a diameter of 60 cm each. The mirror dish diameter will be 4.3 m. A PMT camera is mounted at a focal distance of 4.75 m. The camera consists of 547 PMTs with a 0.36 ° field of view (foV) per pixel, resulting in a total field of view of 9.72 ° in diameter. The PMTs will be arranged with a 30 mm center-to-center distance in 11 hexagonal rings around the central pixel. The expected energy threshold for monoscopic events is 500 GeV. Near the threshold and up to few 10s of TeV, the IACTs will operate in stand alone mode, using the classical imaging technique, performing monitoring observations of transient sources. Above few 10s of TeV and in the overlapping part of the IACT foV with the larger foV of the HiSCORE timing array, the IACTs will operate together with the timing array in a new promising hybrid operation mode. The timing stations will trigger independently from the individual IACTs, and data will be merged using synchronized (sub-ns) event time-stamps.

The basic idea for a combination of the imaging and timing techniques is to use the timing array as estimator of the air shower core position and direction of the primary particle and to provide these parameters to the IACT for improvement of the monoscopic image analysis. Since a large instrumented area is the key aspect for reaching the multi-TeV range, the telescopes will be placed at a distance of roughly 600 m from each other. In this configuration all telescopes will operate in monoscopic mode for zenith angles up to 60°. Since the direction of the air shower is not unambiguously known to a monoscopic IACT, the timing array will provide this information, therewith allowing to reject a large fraction of isotropic hadronic background events. Furthermore, the knowledge of the core impact position from the timing array will allow to introduce the hybrid scaled width parameter, similarly to the classical stereoscopic mean scaled width parameter used in standard imaging analyses based on the Hillas parameters. This concept was previously described in [23, 24] and was also presented at this conference [25]. Using the hybrid scaled width and further gamma-hadron separation parameters based on the IACT image analysis as well as the timing array, we expect to reach a gamma-hadron separation quality factor of the order of 3-5. The hybrid imaging-timing point-source sensitivity of a $0.6\,\mathrm{km}^2$ TAIGA detector is estimated to reach a sensitivity of $5 \cdot 10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ at 100 TeV after 200 h of observation time. The integral sensitivities to point sources for this, and a $5\,\mathrm{km}^2$ detector stage (after 1000 h) are shown in Figure 3 and compared to the sensitivities from other experiments. Already the upcoming $0.6\,\mathrm{km}^2$ array will significantly extend the spectra of known sources into the multi-TeV regime.

4 Summary

While the field of gamma-ray astronomy has made tremendous progress over the past decades, the observation window in the multi-TeV to PeV regime needs yet to be covered by sensitive instruments. This energy range is the key to different astrophysical questions, aforemost the question of the origin of cosmic rays and the localization of the highest energy Galactic accelerators. Recent observations from H.E.S.S. and the IceCube neutrino events are further motivating this search.

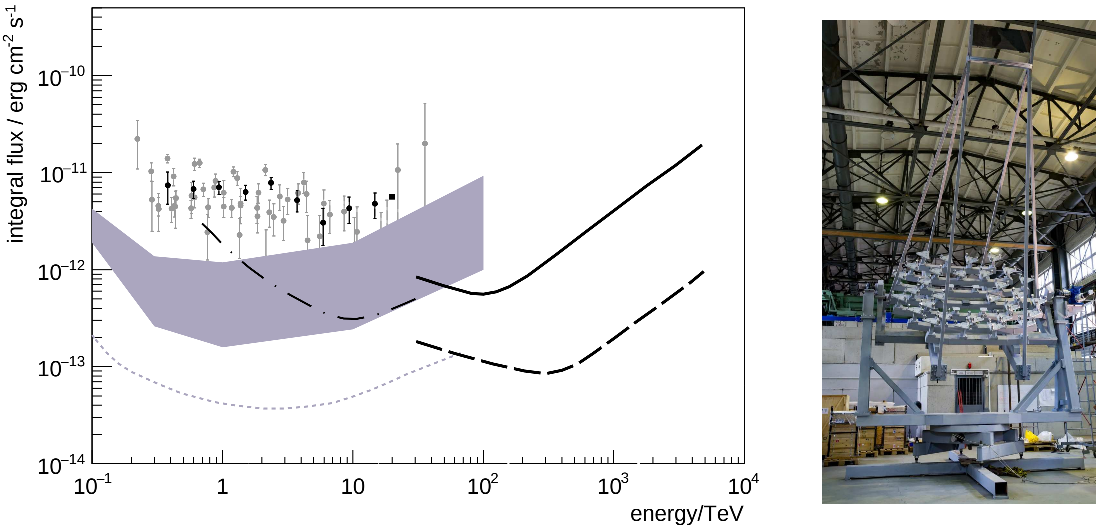

Figure 3: *Left:* Integral flux survey sensitivities of TAIGA, combining timing array stations with IACTs, for a 0.6 km^2 array after 200 h of observation time (solid red line, requiring 5 σ and at least 10 gamma-rays) and a 5 km^2 array after 1000 h of observation time (dashed red line). For comparison, further sensitivities are shown: CTA survey (grey area [26]), HAWC ([15] dash-dotted line), CTA pointed observations (large exposure on specific sources, dashed grey). Data points as in Fig. 1. *Right:* Photograph of the first TAIGA IACT, shortly before transportation to the Tunka valley.

The TAIGA collaboration is aiming at this goal, using a novel hybrid approach, combining the air Cherenkov timing technique with the imaging technique. The upcoming 0.6 km^2 stage of TAIGA will for the first time allow to probe the ultra high energy gamma-ray regime at a sensitivity level comparable to the sensitivity of existing instruments at lower energies.

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