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Exploring the gamma ray sky above 30 TeV with LHAASO

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The gamma ray sky at energies above a few tens of TeV is almost completely unexplored. Sources of photons above 30 TeV must however exist because cosmic rays are accelerated in the Milky Way at least up to the knee energy. Photon emission in this energy range, with a high degree of confidence, has an hadronic origin and traces the proton and nuclei acceleration sites. Gamma ray astronomy above 30 TeV is therefore of fundamental importance for the identification of cosmic ray sources.

LHAASO is a project of a multi-component air shower detector, to be built in Sichuan, China, at 4410 m of altitude. One element of the detector, the KM2 array, a grid of scintillators and muon detectors distributed over an area of $\sim$1 Km^2 will be able to monitor in one year the northern sky at 100 TeV with a sensitivity of 1% of the Crab Nebula flux.

In this paper the capabilities of LHAASO in gamma ray astronomy above 30 TeV are reviewed, and the scientific potential in identifying or constraining galactic and extragalactic cosmic ray sources is discussed.

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1. Gamma Ray Astronomy with LHAASO

The remarkable achievements in gamma ray astronomy during the last two decades, both with space borne instruments and ground based detectors have produced extraordinary advances in high energy astrophysics, with the detection of more than 3000 sources, about 150 of them emitting up to TeV energies. These sources belong to different classes of objects, both galactic (like pulsars, Pulsar Wind Nebulae (PWN), Supernova Remnants (SNR), compact binary systems, etc.) and extragalactic (like Active Galactic Nuclei and Gamma Ray Bursts), in which the emission of high energy photons can be produced by different mechanisms. The field is very dynamic: the observations continuously provide new results, often unexpected and surprising, while the theory makes efforts to clarify the structure of the sources and the mechanisms operating in the acceleration regions. In this rapidly evolving scenario a strong interest is addressed to the development of new instruments capable of more precise observations, with a better sensitivity and working in a more extended energy range.

So far, gamma ray observations at energies above 30 TeV are very scarce. Only six sources have been observed to emit above 30 TeV, and the spectral shape is measured with only large uncertainties. Even the most luminous TeV source, the Crab Nebula, is well studied only up to about 20 TeV.

The interest of gamma ray astronomy at energies above 30 TeV is related to the solution of one of the important open problems of high energy astrophysics: the identification of the astrophysical sites where most of the galactic cosmic rays are accelerated. Presently there is a general consensus that cosmic rays with energy up to the so called “knee” of the spectrum (2-4 PeV) are accelerated inside our Galaxy. Galactic sources could be the dominant source of the cosmic rays up to the “ankle” (at an energy of 3000 PeV). Supernova Remnants have been proposed as the most likely sources of the galactic cosmic rays, but this hypothesis is still lacking a clear experimental evidence. In fact, it is now known that SNRs can accelerate particles because gamma ray emission, in the GeV and TeV energy ranges, has been observed by several objects. The observations of AGILE and Fermi of two young SNRs (W44 and IC443) show the characteristic spectral feature around 1 GeV (the so called “π^0 bump”) present when the photon emission is dominated by the contribution of π^0 decay, indicating the presence of relativistic protons or nuclei in the sources [1]. What is not yet clearly established is if the acceleration of hadrons extends up to the knee, and if SNRs can provide the required CR injection power. Observations in the energy range $E \gtrsim 30$ TeV can play a crucial role in addressing these questions. The gamma ray emission should in fact extend to an energy approaching (10–30 times smaller than) the maximum energy of the particles accelerated in the source. Emission in this energy range should be dominated by the hadronic (π^0 decay) mechanism, because Inverse Compton scattering of electrons is strongly suppressed by the Klein-Nishina effect at these energies. Gamma ray astronomy above 30 TeV could threfore unambiguously detect the long sought “Pevatrons”.

Recently ICECUBE reported a first evidence of neutrinos of astrophysics origin of energy 0.4 - 1 PeV [2]. The nature of such a flux has been object of intense discussions and different hypothesis have been expressed about the galactic or extragalactic origin of the signal. If neutrinos were extragalactic the gamma rays generated by the same processes would be absorbed by the Cosmic Microwave Background (CMB) through pair production and would not be observable at

Earth (see the discussion ahead), but in case of a Galactic origin it would be important to detect a photon signal of comparable energy.

Most results of TeV gamma ray astronomy has been obtained with Cherenkov telescopes, directional instruments with a field of view limited to a few square degrees, that can make observations only in clear and moonless nights. These are obvious limitations in a field of research aimed to discover unknown sources, and where most of objects have variable emissions. Air shower detectors do not have these limitations, since they can continuously observe the whole overhead sky.

The multi-component LHAASO air shower array, to be built in Sichuan (China) at the altitude of 4400 m a.s.l, has been designed to detect with high sensitivity primary gamma rays of energies from $\sim$300 GeV to 1 PeV, and at the same time to study the cosmic ray spectrum, composition and anisotropy in a wide energy range ($\sim$1-10^5 TeV). Fig.1 shows the expected integral sensitivity to gamma rays in one year of measurement. The curve is the combination of two components, the first relative to the water Cherenkov detector (WCDA), operating in the energy range $\sim$0.3 - 10 TeV, the second relative to the KM2A array, sensitive to energies above 10 TeV [3].

The WCDA detector (a water Cherenkov detector of 300 $\times$300 $\times$5 m^3) uses the distribution of the Cherenkov light inside the pool to identify and reject cosmic ray showers. The KM2A array (a grid of 5635 scintillator detectors and 1221 underground muon detectors, distributed over an area of 1 km^2) use the muon data to reject cosmic rays events. Above 10 TeV the detection of muons allows a very efficient rejection of cosmic ray showers. According to simulations, above 10 (30) TeV the fraction of cosmic rays surviving the discrimination is only 0.01 (0.004)%. Above $\sim$ 80 TeV the fraction of surviving cosmic ray is less than 0.001%, and for observations as long as one year or less the measurement is background free, i.e. no CR events are selected as photons after the rejection procedure. In this energy range the efficiency to detect photons is close to 100%.

As a reference flux, the Crab Nebula spectrum is also shown in the same figure (arbitrarily extrapolated with a single power law up to 1 PeV), together with two spectra corresponding to 10% and 1% of the Crab flux. According to simulations, the minimum detectable gamma ray flux is lower than 1% Crab flux in the energy ranges $\sim$1-8 TeV and $\sim$30-150 TeV. The minimum flux has been evaluated requiring a statistical significance of 5 standard deviations for energies below 80 TeV, while in the background free regime, the sensitivity has been calculated requiring the detection of at least 10 events. This makes the integral sensitivity to be almost constant above 80 TeV. Note that the sensitivity scales with the square root of the observation time at low energy, but the dependence becomes linear when the measurement is background free.

In Fig.1 the sensitivity curves of other detectors [4, 5, 6, 7] (some in operation, some already switched off, and some in project) are also reported. LHAASO, thanks to the large area and the high capability of background rejection, can reach a sensitivity at energies above 30 TeV that is about 100 times higher than that of current instruments, offering the possibility to monitor the gamma ray sky up to PeV energies with an unprecedented sensitivity. According to Fig.1 the LHAASO sensitivity is $\sim$ 5 (30) times higher than that of CTA above 30 (80) TeV.

Following an often used convention, in Fig. 1 the sensitivity of air shower detectors is reported for one year of operation, while for Cherenkov telescopes the sensitivity is relative to 50 hours of “on source” measurement. It is in fact not straightforward to compare the scientific potential of observatories that use different detection methods. EAS arrays observe every day all the sources

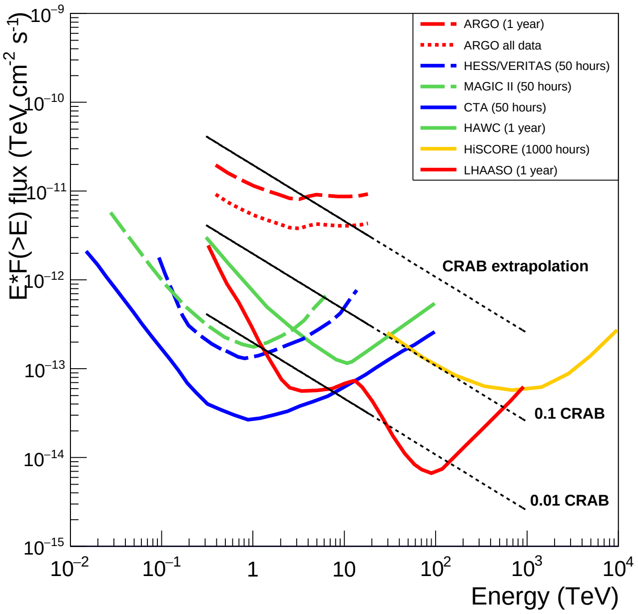

Figure 1: Sensitivity of LHAASO to a Crab-like point gamma ray source compared to other experiments. The Crab spectrum measured by ARGO-YBJ [8] from 300 GeV to 20 TeV extrapolated to 1 PeV is used as a reference flux.

that transit in the field of view for a certain time interval (in general from 3 to 7 hours, depending on the source declination), while Cherenkov telescopes observe only one source at the time, and only in the season of the year when the source culminates during night time. To evaluate the effective performance of different instruments, one must first determine the type of the observation to be done (sky survey, single source follow-up, observation of a flare/burst, etc.). For example, in the observation of the flare of one source lasting a few hours, one must consider the sensitivity curves for *that* particular observation time. The shape of a sensitivity curve is determined by the observation time, taking into account that in some energy regions the signal has to separated from the background, while in other regions the measurement could be background free.

In fact the two techniques – Cherenkov Telescopes and EAS arrays – are complementary, each of them exploring different aspects of the gamma ray emission. Below 10 TeV, observing a single source, a Cherenkov telescope array as CTA has a higher sensitivity compared to EAS arrays like HAWC and LHAASO. Thanks to the better angular and energy resolution, a Cherenkov telescope can study more in detail the source morphology and spectral features. EAS arrays however make more efficently a sky survey and have the possibility to monitor a source all days of the year, that in case of AGNs or variable sources in general, it's a clear advantage. Moreover, thanks to the large field of view, they have a much bigger chance to catch unpredictable transient events like flares.

1.1 LHAASO and galactic sources

To give a more quantitative idea of the LHAASO performance, we can compare the detector sensitivity with the fluxes of the known TeV sources. As said before, the number of known

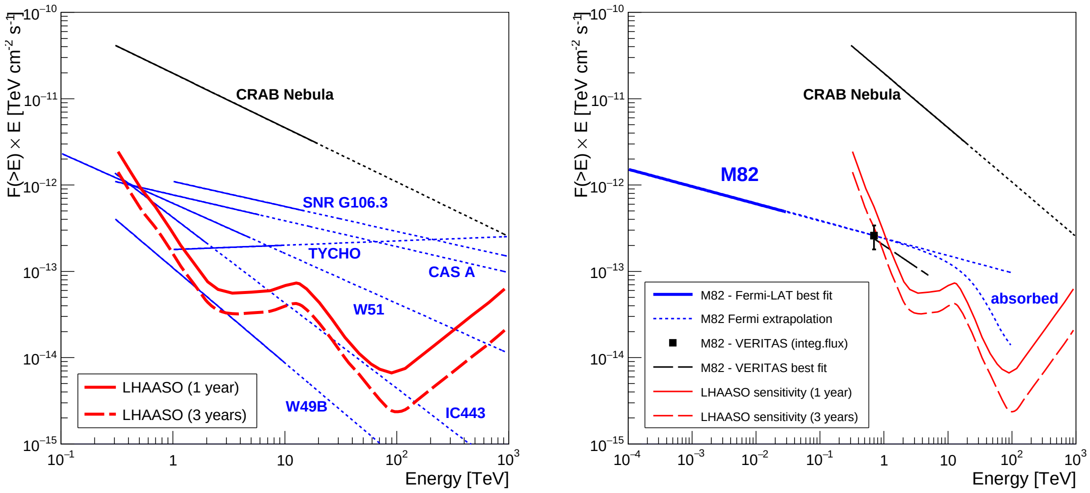

Figure 2: Left panel: integral spectra of the six SNRs in the LHAASO field of view extrapolated to 1 PeV. The solid lines represent the measured spectra, while the extrapolations are shown by dotted lines. Right panel: M82 integral flux measured by Fermi-LAT and VERITAS. The Fermi spectrum extrapolated to 100 TeV is shown, with and without taking into acount the EBL absorption. In both panels the LHAASO sensitivity in one year (solid line) and 3 years (dashed line) is shown. The Crab nebula spectrum measured by ARGO-YBJ [8] extrapolated to 1 PeV is plotted as a reference flux.

TeV gamma ray sources is about 150 [9]. Among them, 60% belong to our Galaxy and 40% are extragalactic (mostly Active Galactic Nuclei of Blazar type). About 1/3 of galactic sources are still unidentified, 1/3 are Pulsar Wind Nebulae (PWN) like the Crab Nebula, and the remaining are Supernova Remnants (SNR), compact binary systems and massive star clusters. The six sources for which data above 30 TeV exist are all galactic and are among the most luminous objects of the TeV sky: the Supernova Remnant RX J1713.7-3946, the Crab Nebula and Vela-X, (two Pulsar Wind Nebulae) and three MILAGRO extended sources, MGROJ2031+41, MGROJ2019+37, MGROJ1908+06, likely also PWNs.

Out of 150, 71 sources are in the LHAASO field of view (i.e. culminating with a zenith angle less than 40°), 31 of them galactic and 40 extragalactic. Extrapolating their spectra up to 100 TeV, more than 90% of sources would have a flux above the LHAASO sensitivity at this energy. Obviously most of spectra will not reach 100 TeV, but LHAASO could provide a unique information by studying the spectral steepening or cutoff.

High energy data on the Crab Nebula, for example, would be very useful for the understanding of phenomena related to the pulsar environments. Since long considered the "standard candle" for gamma ray astronomy, the Crab Nebula has unexpectedly shown a variable behaviour in the energy range 100 MeV-1 GeV. Strong flares lasting a few days and rate variations on time scales of months, are still waiting for a generally accepted interpretation [10]. The possible detection of Inverse Compton radiation above 10 TeV, correlated with the lower energy activity, will give important information on the flares origin.

As discussed before, Supernova Remnants are probably the most interesting sources to be studied at high energy, because the detection of an emission above 100 TeV could be the footprint of hadronic acceleration. In general, from an emission of hadronic origin, one expects a spectrum with the “π^0 bump” followed by a power law with a slope consistent with the cosmic ray spectrum slope up to 50-100 TeV, or even more. A leptonic emission (Inverse Compton) would produce a flatter power law spectrum, with a steepening around 10 TeV due to the Klein-Nishina effect. In general, one could expect a combination of the two emission types, with different weights depending on many parameters, as the density of target material for hadronic interaction, the magnetic field strength, the age on the Supernova, etc.

So far, only one remnant (SNR RX J1713.7-3946) has data above 30 TeV (actually, the spectrum reaches almost 100 TeV). In this case the spectrum steepens above a few TeV and does not show the “π^0 bump”, being more consistent with a leptonic emission.

In the LHAASO field of view there are 6 SNRs (Thyco [11], CAS A [12], W51 [13], IC443 [14], W49B [15] and SNR G106.3+2.7 [16]). The measured spectra show a power law behaviour without any cutoff up to the maximum energy reached by the current instruments, that ranges from $\sim$2 to 15 TeV for the sources considered. Fig.2a shows the measured spectra and their extrapolation to 1 PeV. Four out of six SNRs (Tycho, CasA, SNR G106.3+2.7 and W51) have fluxes much higher than the LHAASO one-year sensitivity. W49B flux is probably too low to be ever detected, but IC443 could be probably detectable in more than one year of measurement.

Given the LHAASO capabilities in sky survey, new supernova remnants will likely be discovered, since objects with fluxes at 1 TeV below the current instruments sensitivity but with hard spectra (like Tycho SNR, for example) can be detectable by LHAASO above $\sim$10 TeV.

1.2 Extragalactic sources and gamma ray absorption

Gamma rays can interact with radiation fields in the interstellar and intergalactic space with the process $\gamma\gamma \rightarrow e^+e^-$, and the flux is attenuated by a factor $e^{-\tau}$. The optical depth τ is a function of the gamma ray energy and is determined by the density and energy distribution of the target photons along the line of sight from the source to the Earth.

The spectral energy distribution of target photons, both in interstellar and intergalactic space shows three broad peaks: the first one centered in the optical band ($\lambda \sim 1$ μm), mostly due to stellar light, the second one in the infrared band ($\lambda \sim$100-200 μm), due to stellar light absorbed and re-radiated by dust, and the third one due to the Cosmic Microwave Background.

The cross section is maximum when E_γ(TeV) × E_{ph}(eV) = 1.07/(1-cosθ), where θ is the angle between the two photons. This means that gamma rays of $\sim$1 TeV mostly interact with photons of $\sim$1 eV (starlight), gamma rays of $\sim$100 TeV interact with IR photons, and gamma rays of $\sim$1 PeV with CMB. The three radiation components generate different absorption features in the source spectra, observable as changes in the spectrum slope. The precise evaluation of these spectrum features depends on the exact knowledge of the low energy radiation intensity. CMB is precisely measured, while the intensity of optical and infrared photons has large uncertainties. For this the evaluation of the opacity parameter is mostly indirect, based on assumptions and models, especially in the extragalactic case.

Concerning Galactic sources, the absorption depends on the relative position of the source and the Sun inside the Galaxy, that determine the amount of target photons along the gamma ray path. According to [17], up to $\sim$10 TeV the gamma ray attenuation would be less than a few percent for every source position. At $\sim$100 TeV the flux of a source close to the Galactic center would be reduced by 20%. The reduction is smaller for a source located in more peripheral regions, unless the source is beyond the Galactic center, for which the absorption can reach almost 50%. Above ∼200 TeV the CMB becomes effective and the absorption depends on the distance rather than on the position in the Galaxy: at ∼2 PeV, about 70% of the flux of a source at the distance of the Galactic center (8.5 kpc) is absorbed, while at 20 kpc the absorbed flux is 95% . From these calculations it is evident that the absorption is not an obstacle up to a few hundred TeV, while at higher energies it can seriously hamper the observations of sources even inside our Galaxy.

The situation is more problematic for extragalactic astronomy. The absorption of gamma rays from ∼1 TeV to ∼200 TeV is mostly due to the Extragalactic Background Light (EBL), that includes light from stars/AGNs and dust emission, and whose intensity is related to the whole Universe history. The absorption above 200 TeV is mostly due to CMB. The optical depth τ is generally expressed as a function of the gamma ray energy and the source redshift z. The evaluation of τ requires the modelling of the EBL spectrum at different redshifts. According to the model of Franceschini et al. [18], gamma rays above 30 TeV from a source at z=0.01 are 90% absorbed. At z=0.03 (that is the redshift of the *closest* blazars observed at TeV energies) the flux above ∼20 TeV is 95% absorbed. Increasing the energy or the redshift, the absorption becomes stronger and can seriously limit the study of most extragalactic sources.

In the LHAASO field of view, there are four known TeV extragalactic sources with a redshift smaller than 0.03. They are: M82 (starburst galaxy with z=0.00073), M87 (radio galaxy with z=0.0044), NGC 1275 (radio galaxy with z=0.019), and IC310 (blazar with z=0.019). The last three sources are variable, with a flux reaching 10–15% Crab units during flares in the case of M87 and IC310. The possibility to detect them above 20-30 TeV by LHAASO depends on the duration and intensity of their flaring activity.

The situation of the starburst galaxy M82 is different. So far only two starburst galaxies have been observed at TeV energy: M82 [19] and NGC 253 [20]. Starburst galaxies contain regions with a high star formation rate. If SNRs are the cosmic ray accelerators, one could expect in starburst galaxies a cosmic ray flux significantly higher than that observed in normal galaxies like the Milky Way, due to the higher supernova rate. In this case, the gamma ray emission should be due to the interactions of cosmic rays with the interstellar matter. So far it is not proved the hadronic origin of the observed TeV radiation, and the detection of 100 TeV gamma rays would strongly support it and would be an indirect proof that cosmic rays of PeV energies are accelerated by Supernova Remnants.

Assuming the M82 spectrum observed by Fermi-LAT [21] as the intrinsic source spectrum, we extrapolated it to higher energies taking into account the EBL absorption. Fig.2b shows the extrapolated spectrum using the absortpion model by [18]. According to these evaluations, M82 should be observable by LHAASO in one year of measurement. The integral flux measured by Veritas at 0.7 TeV energies is consistent with the Fermi extrapolation (see Fig.2b), even if the best fit spectrum is steeper (but consistent within the errors), suggesting a possible cutoff. LHAASO can explore the high energy part of the M82 spectrum and provide useful data to understand the mechanisms responsible to the gamma ray emission.

Finally, the study of the spectral features due to the EBL absorption in nearby objects can give information on the EBL itself, whose intensity is presently known with large uncertainties. Making reasonable assumptions on the intrinsic source spectra, from the observation of the position and shape of the spectral break of gamma ray sources at different z, one could infer the spectrum of EBL. As an example, the measurement of the spectra of 150 blazars at different redshifts by Fermi-LAT at energies above 1 GeV allowed the measurement of the EBL intensity in the UV band [22]. Similarly, the measurement by HESS of almost 20 blazar spectra at energies above $\sim$100 GeV, provided the spectrum of the EBL at energies of the optical "bump" [23]. The study of the energy spectra above 10 TeV of nearby objects could give spectral information on the EBL infrared spectrum "bump", whose region of $\lambda \sim$10-70 μm) is particularly difficult to measure because of the foreground light due to the interplanetary dust (zodiacal light). LHAASO, moreover, given its sky survey capability could increase the sample of these nearby objects and study their spectral features to probe the EBL in the IR region.

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