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A concept for a wide-angle Cherenkov gamma-ray instrument with minimal imaging: ASGaRD

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We suggest a concept for a novel wide-angle imaging detector for gamma-rays with energies in the largely unexplored range between 10 TeV and several PeV. The energy range above 100 TeV is of central importance for high-energy astrophysics. PeV accelerators are expected to produce also copious photons of about a decade less in energy. Thus registering gamma-rays with energies above 100 TeV will pinpoint the galactic sources able to accelerate particles up to PeV energies (so-called PeVatrons). The All-Sky Gamma-Ray Detector (ASGaRD) is an array of optical modules with wide ($\approx 50°$) field of view and a low cost imaging, allowing affordable coverage of large areas for high energies. The ASGaRD optical modules comprise a Fresnel lens with a multi-pixel SiPM camera, read out by a novel dead-time-free data acquisition system based on FPGAs. ASGaRD is designed for simultaneous observation of large portions of the sky and for reaching energies of about 10 PeV. We study the capability of ASGaRD to yield a better gamma-ray sensitivity (for $E > 100$ TeV) than CTA and HAWC, at a fraction of the cost. We address also the ability of ASGaRD to complement wide-field non-imaging and narrow-field imaging gamma-ray experiments for energies beyond 10 TeV by studying the performance of hybrid ASGaRD/IACTs arrays.

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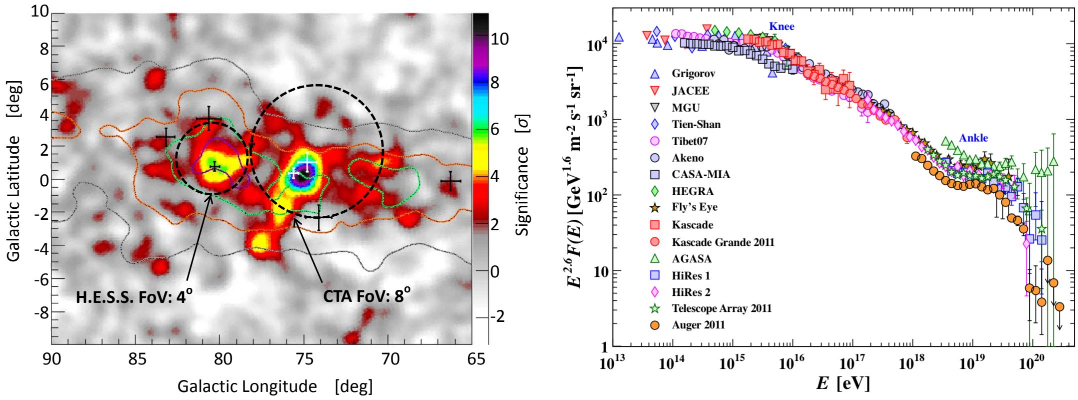

Figure 1: *Left:* TeV gamma-ray image of the Cygnus region of the Galaxy, obtained by Milagro (adopted from [1]). The FoVs of H.E.S.S. and of the future CTA are shown for reference. *Right:* All-particle cosmic ray energy spectrum as measured by different air-shower experiments (adopted from [2]).

1. Introduction

The flux of very-high-energy (VHE, $E > 100$ GeV) gamma-rays rapidly decreases with energy, roughly following a power law $E^{-\Gamma}$ with index $\Gamma \geq 2$. The limited sizes of space-borne experiments (EGRET, Fermi-LAT) make the detection of multi-TeV gamma-ray emission by satellites impossible. TeV-astronomy is the domain of ground-based air-shower facilities with unprecedentedly large collection areas. Nonetheless, for the majority of gamma-ray sources current instrument designs do not allow for sufficient statistics to measure spectral features or even to claim the detection at gamma-ray energies around $10-20$ TeV. Gamma-ray facilities like HAWC [3], based on the water-Cherenkov technique, and the future Cherenkov Telescope Array (CTA) [4], based on Imaging Atmospheric Cherenkov Telescopes (IACTs), will still provide limited all-sky sensitivity above 100 TeV. The excellent sensitivity of IACTs at lower energies (at 1 TeV) comes at the price of a rather narrow field of view (FoV) ($\sim 4^\circ$ for H.E.S.S. [5]). Currently, this drastically limits the analysis of sources with angular sizes $> 2^\circ$. Extended sources can occupy a significant part of the FoV, leaving no room for background level estimation (see the left panel of Fig. 1). A dominant fraction of the observations with IACTs are of pointing/follow-up type, meaning that the observational targets are a-priori determined (or instantly alerted) from the detection of their counterparts in other wavelengths (radio, X-ray). All-sky blind surveys have never been performed by IACTs. We aim to develop a unique instrument for an all-sky gamma-ray astronomy that possesses a wide FoV and covers the energy range from 10 TeV to a few PeV. The motivation for such an instrument is discussed in Section 2, the design concept is described in Section 3, and sensitivity estimates are presented in Section 4.

2. Wide-field multi-TeV astronomy

Measurements in the intriguing gamma-ray energy range beyond 10 TeV might reveal spectral features that originate from the acceleration mechanisms of leptons and hadrons, but this energy range is still barely covered by the current ground-based instruments. A wide-field instrument with

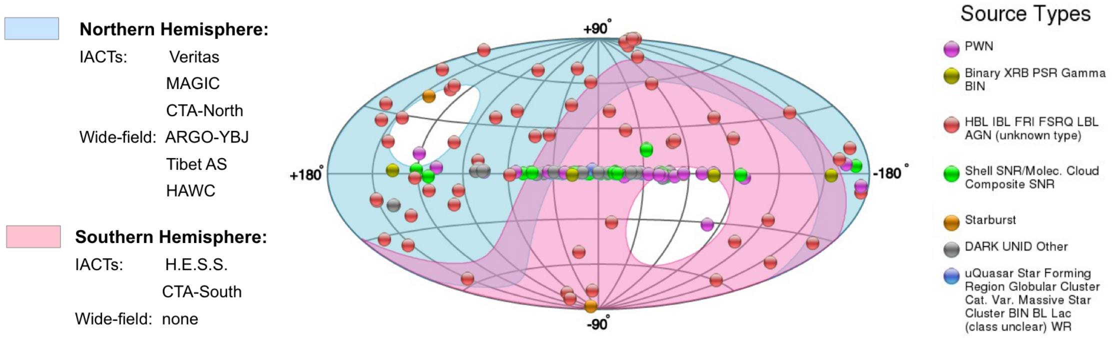

Figure 2: The sky (in Galactic coordinates) accessible for ground-based observatories located in the northern hemisphere (blue shaded area) and the southern hemisphere (red shaded area) along with known VHE sources from TeVCat catalog. The white areas correspond to observations with zenith angles $> 50°$.

sensitivity in the multi-TeV band will allow for unbiassed Galactic surveys and the detection of extended VHE gamma-ray emission, as well as for a systematic search of PeVatrons, i.e. sources capable to accelerate cosmic rays beyond PeV energies. Hunting such PeVatrons is a task of central interest for ground-based gamma-ray astronomy. We focus here on the potential for VHE gamma-ray observations and keep cosmic-ray (CR) studies like the CR directional anisotropy [6] out of the scope of this paper.

2.1 Surveys

Surveys of the Galactic plane have proven to be very fruitful due to the dense population of the gamma-ray emitters of various types. Observatories located in the southern hemisphere (like the H.E.S.S. experiment) have a prominent view of the central part of the Galactic plane (see Fig. 2). The Galactic Plane Survey of H.E.S.S. resulted in the detection of $\sim$70 sources [7]. Besides numerous known VHE gamma-ray sources (like supernova remnants (SNRs), pulsar wind nebulae (PWNe) and molecular clouds) the survey revealed a large number of still unidentified TeV emitters, and allowed first population studies for the new VHE sources [8]. A large fraction of the found energy spectra is well described by a simple power law $E^{-\Gamma}$, $2.0 < \Gamma < 2.6$, (see [9]) and shows *no evidence of spectral cut-offs* up to energies of 10 TeV. Due to the narrow ($\sim 4°$) field of view (FoV) of IACTs the average source exposure time was only several hours. Thus, the energy spectra for the majority of sources *beyond* $\sim$ *10 TeV remain uncovered*. However, the multi-TeV data provide essential input for the theoretical broad-band modelling of sources (see, e.g., [10] for the case of young PWNe). The future Cherenkov Telescope Array (CTA) observatory will comprise two facilities: one in the northern (CTA-North) and one in southern (CTA-South) hemisphere (see Fig. 2). It will possess a ten times better sensitivity compared to H.E.S.S. and will enrich the TeV gamma-ray data, but its survey abilities will still be constrained by the limited field of view of $\sim 8°$ (see the left panel of Fig. 1). The survey of the entire northern sky performed by the wide-field Milagro experiment revealed eight source candidates at energies around 20 TeV. Five of these candidates are concentrated in the Cygnus region [11]. Milagro's successor, the recently inaugurated HAWC experiment, will have a $\sim$ 10 times better sensitivity and improved angular resolution. It will, however, cover only an area of $\sim 0.02\,\text{km}^2$, so despite the nearly 100% duty cycle HAWC's sensitivity will deteriorate for energies beyond tens of TeV.

2.2 Galactic PeVatrons

The gamma-ray energy range $> 100\,\text{TeV}$ is beyond the reach of current experiments located just below the knee (at 3 PeV) of the cosmic-ray energy spectrum (Fig. 1), which is widely believed to signify the acceleration limit of galactic PeVatrons. PeV accelerators are expected to produce also copious photons of about a decade less in energy. Thus, with the discovery of gamma sources at $> 100\,\text{TeV}$ Galactic PeVatrons could be identified and their energy limits be explored. Energy-wise, the most suitable candidates for PeVatrons are supernova remnants (see [12] and references therein). With the help of diffusive shock acceleration (DSA) [13] SNRs could accelerate particles up to PeV energies if the magnetic field (MF) at the shock is amplified with respect to the interstellar MF. Stronger magnetic fields confine particles longer close to the shock and allow thus for more acceleration cycles. According to the DSA theory, the MF is generated by the escaping CRs [14]. MFs exceeding interstellar values many times were indeed found by X-ray observations [15]. The reported values are well sufficient to accelerate CRs up to PeV energies. However, subsequent gamma-ray observations of SNRs with amplified MF did not reveal any emission at several TeV or cut-offs due to the insufficient sensitivity of current instruments, thus leaving the PeVatron question open. Observations in the energy band above 10 TeV offer a promising way to clearly identify PeVatrons. Since severe radiation losses in an amplified MF limit the maximum energies of leptons it is expected that the PeVatron emission is mostly hadronic in origin (cf. Fig. 1). The same loss mechanisms prevent VHE leptons from diffusing far from the SNR while hadrons are not similarly restricted. If PeV hadrons escape and impact on nearby dense material, one expects VHE gamma-rays from an extended region around an SNR. Moreover, the morphology of the emission zone must be energy-dependent: regions emitting at VHE should be placed farther away from the SNR. There are several SNRs found to be illuminating nearby molecular clouds ([16, 17]). The measured spectra are, however, too soft and the SNRs are likely too old to be acting as PeVatrons. If they were PeVatrons in the past, the 100 TeV-emission would be located farther away than the TeV-emission and would be rather faint due to spatial dilution. The association of SNRs with nearby $> 100\,\text{TeV}$ sources would serve as a strong evidence that SNRs are the sought PeVatrons. For detection of sources in this scenario a sensitive wide field ($> 10^\circ$) instrument is required.

3. The ASGaRD concept

The physics cases discussed above demonstrate that TeV astronomy lacks a ground-breaking instrument to explore the sky beyond several tens of TeV. We also note that there is no wide-field gamma-ray observatory in the southern hemisphere (see Fig. 2). To improve this situation we propose the concept of a novel wide-field (50°) instrument called ASGaRD (**A**ll-**S**ky **Ga**mma-**R**ay **D**etector) to complement both the wide-field non-imaging and the narrow-field IACT experiments for energies beyond 10 TeV and to extend the accessible gamma-ray energy range to a few PeV. Deployed in the southern hemisphere ASGaRD would complete the sky coverage of wide-angle facilities (see Fig. 2).

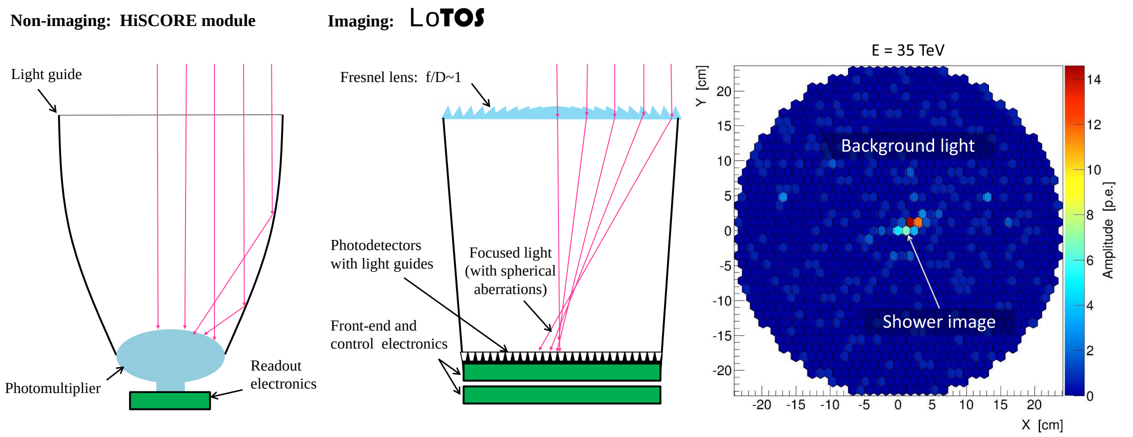

Figure 3: *Left:* Scheme of a non-imaging module. *Center:* The imaging LoTOS module. *Right:* Simulated LoTOS image with the response to a 35 TeV gamma-ray and with background signals induced by diffuse NSB light.

The air-Cherenkov instrumentation has been previously revised by the AIROBICC experiment and recently by the HiSCORE concept [19] - a large-area array of optical detectors, arranged on a grid with a pitch of ~ 150 m. The proposed ASGaRD instrument has a similar array layout, but a very different optical detector design (see the left and the central panels of Fig. 3). The *non-imaging* HiSCORE detector comprises a large photomultiplier coupled to a light guide with $\sim 30^\circ$ half-cone angular acceptance. In such a scheme, the night sky background (NSB) light is integrated over the entire field of view which raises the trigger threshold of the detector. However, the Cherenkov light from air-showers has a very limited angular spread $< 5^\circ$ and the integration over a wide angular range is therefore unnecessary. As an alternative to conventional wide-field non-imaging optical detectors we suggest for the ASGaRD array a novel imaging unit – the so-called **Lo**w **T**hreshold **O**ptical **S**tation (LoTOS) (see the central panel of Fig. 3).

The design of the module utilizes an acrylic spherical Fresnel lens ($f/D = 1$) with ~ 0.3 m radius and a multi-channel photosensitive camera, equipped with ~ 2000 Silicon Photomultipliers (SiPM) coupled to light guides. The feasibility of a design based on Fresnel lenses was proven by evaluation of the fluorescence light detector FAMOUS [20]. The applicability and particular robustness of SiPM photosensors for Cherenkov telescopes was demonstrated by the FACT telescope [21]. The LoTOS scheme provides a wide 50° field of view and implements the concept of *minimal imaging*. It has the following advantages over designs with non-imaging modules:

- The design greatly reduces the instrument's energy threshold. The focused shower light occupies only a small fraction of the focal surface, while the diffuse background light illuminates it uniformly. Restricting the shower signal region only to the bright "image" area excludes the unnecessary background light and thus optimizes the signal-to-noise ratio.

- Each LoTOS module has a directional sensitivity. The initial direction of the Cherenkov light bunch can be reconstructed by measuring the image center of gravity. This additional information may improve the overall angular resolution of the instrument.

- The design also provides a potential for background reduction. The Fresnel lens has large aberrations of $\sim 1^\circ$ (compared to $\sim 0.1^\circ$ for reflectors of IACTs), but they are nearly constant over the whole field of view. The angular spread of the Cherenkov light from multi-TeV showers can exceed these aberrations and can give a hint of the shower image shapes (see the right panel of Fig. 3).

The latter point is of particular interest. We plan to investigate this issue in great detail keeping in mind more complex optical designs with reduced aberrations. Such wide-field designs have been revised by the ASHRA experiment [22] based on the modified Baker-Nunn optics that provides a point spread function (PSF) of $\sim 0.02^\circ$ over the whole 50° FoV. This allows catching the features of Cherenkov images intrinsic to gammas and cosmic rays and to exploit the full power of the imaging Cherenkov technique. An optical module combining the ASHRA-like optical design and a high-resolution (with O(10^4) pixels) LoTOS imaging camera is the ultimate option for the ASGaRD unit that will possess both a wide FoV and a background rejection power comparable to IACTs.

A possible constraint for the LoTOS design is the high cost of the imaging camera which requires a complex data acquisition (DAQ) system. We overcome this issue with a novel approach - the **L**ong (i) **B**uffer **R**ead**O**ut **S**ystem (LiBROS). It comprises a trigger, based on Field-Programmable-Gate-Arrays (FPGAs), and a readout system based on Flash Analog-To-Digital Converters (FADCs) (see details in [23]). In LiBROS, following common approaches, the SiPM signal is split into two branches: a trigger branch and a data branch. The signals in the trigger branch are fed to discriminators which produce time-over-threshold (TOT) logic signals. We suggest to digitize these signals with only 1-bit resolution but 1 GHz rate directly inside the FPGAs exploiting the Serializer/Deserializer (SerDes) feature. In this manner the start and the stop time of the TOT signal is tagged and estimates the arrival time of the initial SiPM signal with a precision of ≤ 1 ns. Having the time *reconstructed by the trigger system* the data branch can have a limited bandwidth and, therefore, reduced FADC sampling rate. This suppressed FADC data-stream can be piped directly to the FPGA memory in *serial mode*, using only *one data-stream per FPGA input pin*. This allows one FPGA chip to serve O(100) readout channels which simplifies the design and reduces costs by a factor of ~ 5, compared to the current DAQ approaches used for IACTs. Moreover, due to the large FPGA memory and the suppressed data volume, this DAQ approach will possess an extremely long data buffer of $> 50\,\mu$s (see [23]). This allows the design of a simple central trigger system for arrays covering an area of several km^2.

4. Discussion

The proposed ASGaRD concept with minimal imaging stations deployed in an area of several km^2 offers a large room for new developments in the instrumentation for ground-based gamma-ray astronomy. The ASGaRD array can be composed of LoTOS units of different sizes. Optimization of such arrays by means of Monte-Carlo simulations should lead to improved sensitivity in a broader energy range compared to arrays that are equipped with units of just one size. Hybrid arrays, comprising wide-field LoTOS modules and narrow-field IACTs with excellent background reduction abilities, are of particular interest (see the right panel of Fig. 4). The optimization of layouts, observation strategies, and analysis techniques for such hybrid arrays is an important task.

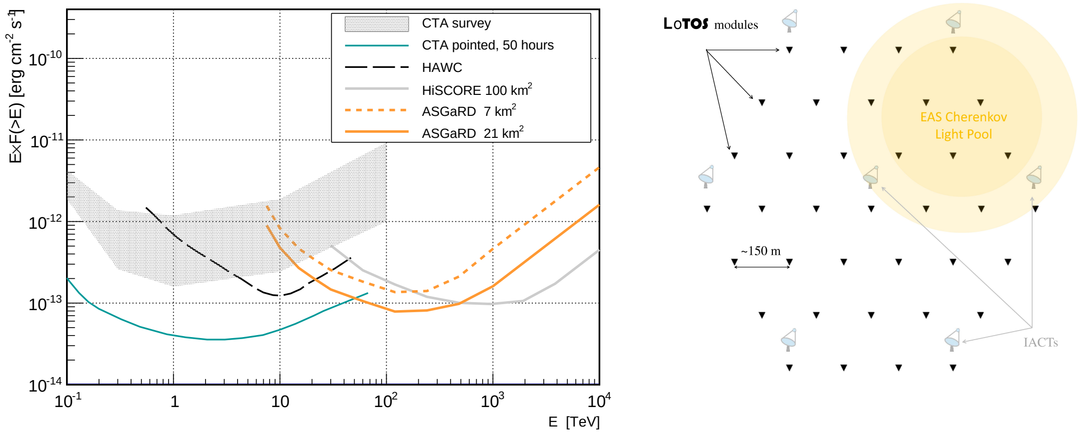

Figure 4: *Right:* ASGaRD point source sensitivity compared to other future facilities for 5 years of observations and π-sr sky coverage, requiring a detection significance of 5 standard deviations and a minimum of 50 registered gamma-rays. The upper and lower bounds of the CTA survey (shaded area) define sensitivities for a survey of π-sr of the sky and for a survey of the Galactic plane, respectively. The CTA sensitivity for 50 h of pointed observations is given for reference. *Left:* Plan of an ASGaRD array that covers $\sim 0.5\,\mathrm{km}^2$ with an optional sparse array of IACTs.

Currently, extensive Monte-Carlo simulations are ongoing within the CTA consortium to optimize observation strategies in terms of best wide-field sensitivity. A promising approach is the divergent telescope pointing where telescopes in a CTA sub-array point to neighboring regions of the sky [25]. In hybrid arrays, the wide-field LoTOS module would complement the stereo view of air-showers for several IACTs simultaneously. Thus, the extension of CTA with ASGaRD will lead to significant improvements of the CTA survey sensitivity, especially for divergent pointing strategies.

A conservative estimate of the ASGaRD sensitivity equipped only with LoTOS modules is shown in the left panel of Fig. 4. Two ASGaRD arrays are shown: a $7\,\mathrm{km}^2$ array (for the price of $\sim$ €10M) and a $21\,\mathrm{km}^2$ array. The price estimate for a $7\,\mathrm{km}^2$ ASGaRD array based on LoTOS modules shows that such an array will cost only about 5% of CTA (both sites). Another future experiment with a price comparable to CTA is the LHAASO [26] experiment. It can cover gamma-ray energies of 100 TeV, but it will be deployed in the northern hemisphere, leaving the southern hemisphere without wide-angle instruments. For all-sky observations beyond several tens of TeV the ASGaRD sensitivity surpasses all currently operating ground-based gamma-ray facilities as well as HAWC and the future CTA observatory.

5. Conclusions

Proposing this concept we suggest to revisit the domain of the ground-based wide-field instrumentation and send a message that already with current technologies the cost-effective non-imaging approach can be replaced by minimal imaging techniques delivering better performance at comparable costs. Deployed in the southern hemisphere ASGaRD would complement the current and future VHE gamma-ray instruments in both energy range and sky coverage. The highly integrated ASGaRD data acquisition system is a simple and low-cost solution that lends itself to application for any air-Cherenkov facility with a large number of readout channels. Moreover, the ASGaRD concept offers a large room for new developments in the field of gamma-ray data analysis. The evaluation of hybrid ASGaRD/IACT arrays as well as studies on the potential of an ultimate ASGaRD array equipped with high-performance optical modules are in progress. Both options will lead to new observation strategies for IACTs, novel data analysis methods and will significantly improve the instrumental sensitivities at the highest energies.

References

[1] Abdo, A. A., et. al, arxiv.orgpdfastro-ph0611691

[2] Particle Data Group, "Cosmic Rays", *http://pdg.lbl.gov/2011/reviews/rpp2011-rev-cosmic-rays.pdf*

[3] *http://www.hawc-observatory.org/*

[4] *https://www.cta-observatory.org/*

[5] *http://www.mpi-hd.mpg.de/hfm/HESS/*

[6] HAWC collaboration, arXiv:1408.4805

[7] Carrigan, S., et. al. for the H.E.S.S. collaboration, arXiv:1307.4690

[8] Aharonian, F., et. al., Science, 25 March 2005, Vol. 307 no.5717 pp. 1938-1942

[9] Aharonian, F., et al., 2006, ApJ, 636, 777

[10] Torres, D. F., Cillis, A., Martin, J., de Oña Wilhelmi, E., arXiv:1402.5485

[11] Abdo, A. A., et. al.,arXiv:0705.0707

[12] Reynolds, S. P., DOI: 10.1146/annurev.astro.46.060407.145237

[13] Blandford, R., Eichler, D., DOI: 10.1016/0370-1573(87)90134-7

[14] Bell, A. R., DOI: 10.1111/j.1365-2966.2004.08097.x

[15] Voelk, H. J., Berezhko, E. G., Ksenofontov, L. T., DOI: 10.1051/0004-6361:20042015

[16] H.E.S.S. collaboration, arXiv:0801.3555

[17] MAGIC collaboration, arXiv:0705.3119

[18] Vernetto, S., et. al., *http://dx.doi.org/10.1016/j.nima.2013.11.043*

[19] Tlyczykont, M. et. al., DOI: 10.1016/j.astropartphys.2014.03.004

[20] Niggemann, T., et. al., doi: 10.111712.925305

[21] Bretz, T., et. al., arXiv:1308.1512

[22] Sasaki, M. Kusaka, A., Asaoka, Y., arXiv: astro-ph/0203348

[23] Shayduk, M., et. al., A long buffer readout system for large-area gamma-ray facilities, these proc.

[24] *http://www.xilinx.com/support/documentation/application_notes/xapp1064.pdf*

[25] Gerard, L. and Maier, M., Divergent pointing with the Cherenkov Telescope Array for surveys and beyond, these proceedings

[26] http://english.ihep.cas.cn/ic/ip/LHAASO/

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