PROCEEDINGS OF SCIENCE

ICRC 2023 Rapporteur: Status of the Gamma-ray Astronomy field

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This document attempts to summarize the Gamma ray section of the 38th International Cosmic Ray Conference held in Nagoya. There were 387 contributions submitted to this section distributed in 22 parallel oral and three poster sessions, plus four related highlight or review talks. The information included in this contribution is a description of what was reported at the conference, that represent the state of the art of the field.

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1. Instrumentation

In the last couple of years there have been several instruments that kept producing scientific results and new ones that recently started operation and are opening new windows in the electromagnetic (EM) spectrum with unprecedented sensitivity. There are also projected instruments that have been approved or are proposed to either cover a given energy range with better sensitivity or to improve the capabilities of the detections with respect to previous instruments. This section covers all these instruments and it is divided into five different subsections with increasing energy. The techniques used to detect gamma rays in these different energy ranges are also diverse, the sub-GeV energy range being covered by balloons and satellites, the GeV to TeV accessible to Imaging Atmospheric Cherenkov Telescopes and finally the TeV to PeV dominated by Particle Detectors.

1.1 The keV energy range

This energy range (also sub-MeV) is where phenomena like the Cosmic X-ray Background (CXB) or Gamma Ray Bursts (GRBs) are monitored. There were presentation of balloons like CXBe, the flexible X-ray detector focused on the CXB studies [1], POLAR-2, the next generation of GRB polarization detector that will be located in the Chinese Space Station (CSS) after the successful results of POLAR [2], the MoonBEAM cislunar SmallSat design [3] or XL-Calibur, a proposal for a balloon-borne X-ray polarimeter [4].

1.2 The MeV energy range

In this energy range, phenomena like positron annihilation, nuclear lines and polarization are studied. The MeV gap is the region of the EM spectrum that has not been covered by any instrument with an improved sensitivity since the launch of COMPTEL several decades ago (see Fig. 1). To cover this gap, there are several proposals like the the COSI Compton small explorer satellite to be launched in 2027 [5]. There are also balloon prototypes of more ambitious projects like ComPair [6], that will be carrying some of the load proposed for AMEGO-X, the medium satellite explorer improving about two orders of magnitude the sensitivity in the MeV energy range [7] as it can be seen in Fig. 1.

This energy range will not only be covered by instruments focused on improving the sensitivity, but also on proposals to improve the angular reconstruction of the received photons, like GECCO, the Compton satellite with Coded Aperture Mask [8]. Other instruments proposed in this energy range are balloons like SMILE-2 [9], GRAMS [10], miniSGD [11], HEPD-02, a payload of CSES [12] and the XRPix detector [13].

1.3 The GeV energy range

This energy range was traditionally dominated by instruments that had been studying point-like sources as well as large scale emission for several years. We had reports from the CALET satellite at the ISS [14] and DAMPE [15] that have both been working for around 8 years. We also had studies of performance of polarimetry with *Fermi*-LAT [16] and the latest results from the GRAINE balloon whose last flight took place in 2023 [17]. Future proposals of satellites like HERD for the CSS [18], VLAST [19] or ADAPT, a balloon with a final goal of a super-Fermi satellite [20].

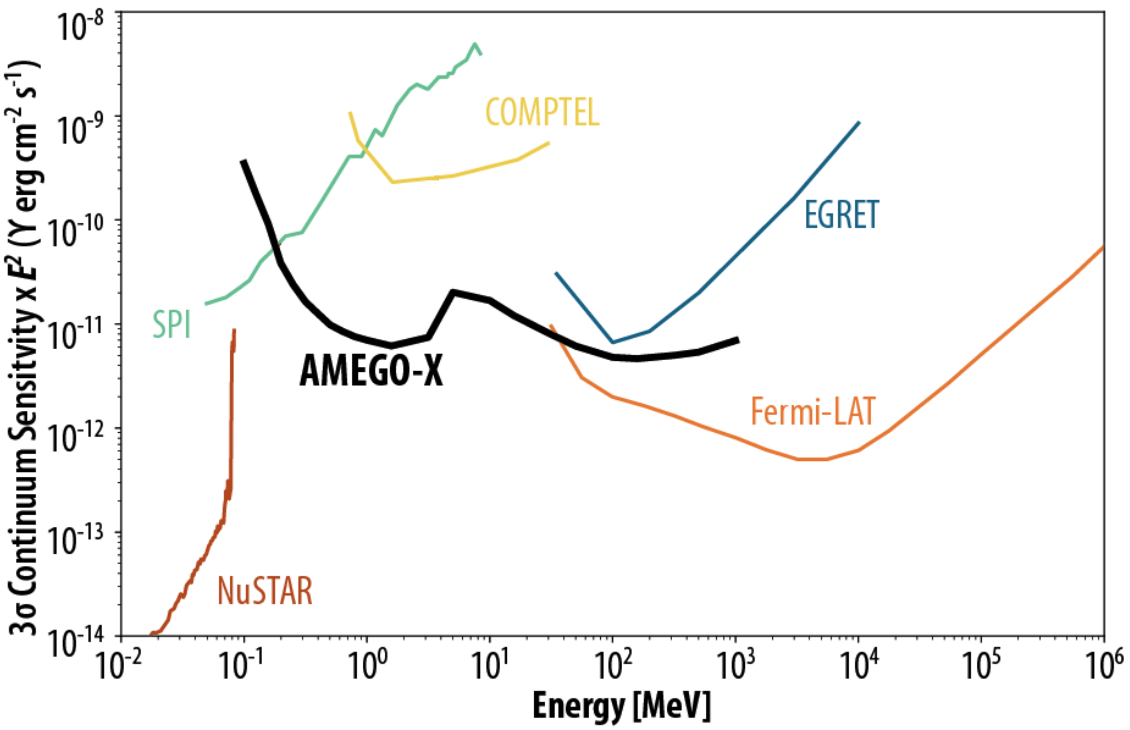

Figure 1: MeV gap and instruments proposed for the future AMEGO-X [7].

1.4 The TeV energy range

This energy range has usually been covered by imaging atmospheric Cherenkov telescopes (IACTs), instruments with excellent resolution that allows to study point sources, morphology and achieve a good spectral precision, systems like MAGIC [21] that have been operating during 20 years, presented their updates. We also had updates from instruments in construction like the ASTRI Mini-Array project [22]. The next generation of instruments working in this energy range, that will improve the sensitivity and resolution is the CTAO Observatory. CTAO will be composed of telescopes of different sizes, the Large-Sized Telescope will be the largest of the array and the prototype is already ready and is showing its first results [23], confirming an excellent performance [24] (see Fig. 2). The other telescopes of the array like the Medium-Sized Telescope [25], Schwarzschild-Couder Telescope [26] and Small-Sized Telescope [27] also showed their updates, as well as the extension of the observatory with the CTA+ project [28].

New developments in this energy range like the HADAR refracting atmospheric Cherenkov telescope [29], the MAGIC + LST-1 joint usage [30] and a proposal to connect them with a hardware trigger with the HaST system [31], the study of divergent pointing to increase IACTs field of view [32], LACT, an array of imaging atmospheric Cherenkov Telescopes for LHAASO [33] or the development of Silicon Photomultiplier cameras for LSTs [34]. Finally, the usage of VERITAS [35] and MAGIC [36] to perform stellar intensity interferometry measurements with very competitive performance was also shown at the conference.

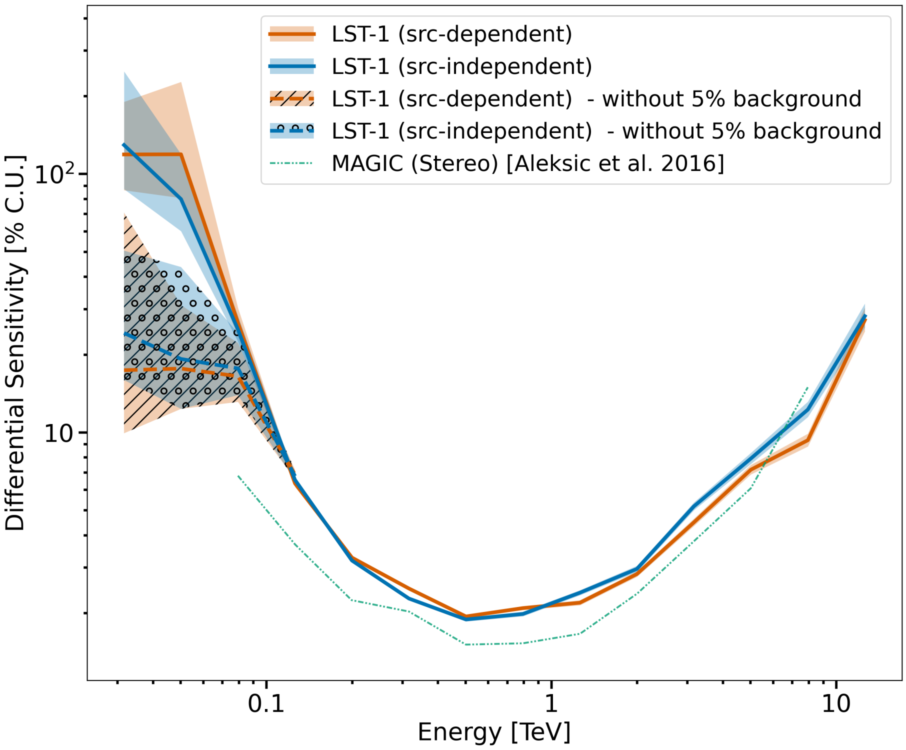

Figure 2: Differential sensitivity of the Large-Sized Telescope of CTAO [23].

1.5 The PeV energy range

This energy range, even though it was within reach since several years, it was only accessible to study several sources since less than a decade. It is worth highlighting the role that HAWC [37], working for more than eight years and LHAASO [38] have done extending the energy coverage. One cannot forget the role that other instruments working in the same energy range have been performing since several years ago like Tibet AS-γ [39], GRAPES-3 [40] and the TAIGA-IACT telescopes for Multi-Messenger observations [41]. It is worth mentioning that all the above instruments are working in the Northern hemisphere, and therefore a similar coverage in the Southern Hemisphere comes as a must, thus, the future is also very promising for instruments covering this energy range. In the Southern Hemisphere, there are arrays planned or being constructed with detectors based on scintillators like ALPACA [42] or its upgrade Mega-ALPACA [43]. The Southern Wide Field Gamma-ray Observatory (SWGO) [44], whose technology and location are still under study, has ambitious sensitivity and resolution goals to be able to investigate multi-TeV emitting sources. There are also proposals like PANOSETI, the Pulsed optical signal detector that can also be used for PeV Gamma-ray Astronomy [45].

2. Galactic science

One of the most important unanswered questions in astroparticle physics as of now is that of the sources accelerating hadronic CRs up to PeV energies, the so-called PeVatrons. It is widely agreed that these sources need to have Galactic origin, but there are a zoo of different sources modeled to

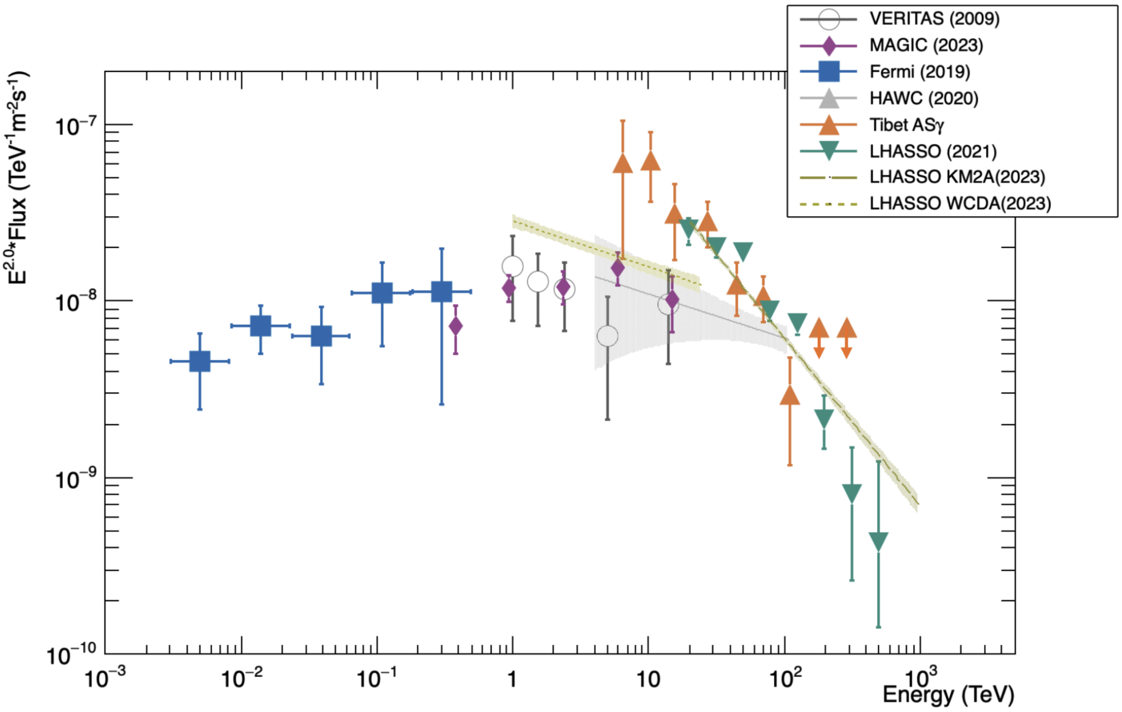

Figure 3: Boomerang spectrum including data from different experiments [50].

accelerate particles up to PeV [46], we will discuss some of the most important candidates as well as sources of leptonic CRs known to have the capabilities to produce PeV particles.

2.1 Supernova Remnants

The usual suspects are Supernova Remnants (SNRs) due to the fact that they provide in the Galaxy enough power to account for all galactic cosmic rays with only a fraction of their total energy budget. Some already known sources for which we had some updates are W51C, measured by LHAASO up to 300 TeV [47] for which still hadronic models (with an energy cut-off at 400 TeV) are favored to explain the emission. Updates on the measurement of another claimed PeVatron SNR G106.3+2.7 (Boomerang) were shown by HAWC [48], MAGIC [49] and also VERITAS [50], showing a spectrum that extends up to 500 TeV (see Fig. 3). The VHE observations of γ Cygni [49, 51] favor a hadronic origin for the emission although also reaching lower than PeV energies. New sources like LHAASO J2002+3238 is spatially associated with SNR G69.7+1.0 [52] but the origin of the VHE γ-ray emission is unclear whether it is leptonic or hadronic. SNR G150.3+4.5 observed by LHAASO [53] is a SNR with a pulsar at the center for which both leptonic and hadronic scenarios work. Unfortunately the TeV Morphology of the source is still under study and whenever settled, it may help distinguishing scenarios.

Other SNRs accelerating protons to lower energies are, for example, the HB9 delayed emission due to protons illuminating a nearby molecular cloud by *Fermi*-LAT [54] (see Fig. 4) or HB3 [55] and Puppis A [56, 57] detections by the same satellite. Finally, modeling of these sources is very

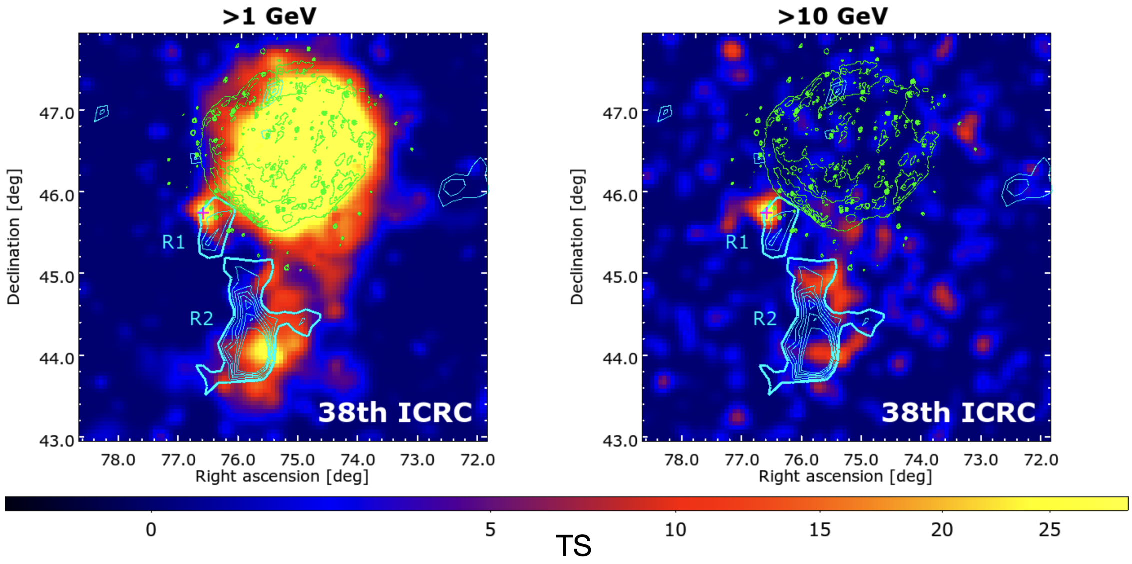

Figure 4: HB9 Skymap above 1 GeV (left panel) and 10 GeV (right panel). Radio continuum 1420 MHz are shown in green and ^{12}CO (J=1-0) in cyan [54].

important in order to reproduce their morphology and spectra as it wass shown for W28 [58] and RXJ1713.7-3946 [59]

2.2 Stellar Clusters

Since PeV proton acceleration is difficult to be achieved for SNRs, people started to look for other source types being able to reach PeV energies and with enough energy budget to be able to explain the energetics observed for the local CR spectrum. Stellar Clusters, with their strong winds due to the abundance of OB stars, were other obvious candidates. Since several years there has been an increase interest to investigate the origin of their VHE γ-ray emission through spectral and morphological studies. There are several models manage to get particles up to PeV energies [60, 61] and prospects to search for their signatures [62] not only in gamma rays, but also in neutrinos. For sources like the Cygnus Cocoon [63] it was shown that synchrotron emission limits the lepton contribution at the highest energies to be less than 25% emission beyond PeV in LHAASO data [64]. Westerlund 2, on the other hand, shows several components aligning with molecular structures [65]. For W43, the γ-ray emission is likely generated by massive stars accelerating CRs and interacting with gas [66].

2.3 The Galactic Center

The Galactic Center is a very complex region with several sources possibly contributing to the VHE γ-ray emission in the region. PeVatron acceleration was claimed in the past [67] by H.E.S.S. and in this conference we had a revisiting of the region with the usage of LST-1 and MAGIC [68]. The correlation of the gamma rays with gas tracers is very complicated in the region and actually any modelling needs to include 3D components to be able to properly reproduce the γ-ray emission [69]. Due to the mass quantity in the region, there is also the possibility of a non-negligible quantity of dark matter as it was searched for by VERITAS [70] or DAMPE [71]. Finally, structures like the Fermi Bubbles that have not been seen at higher energies up to now were also searched for by instruments like LHAASO [72].

2.4 Diffuse emission and Cosmic Rays

LHAASO recently reported the study of diffuse emission in the inner galactic plane using both the KM2A and the WCDA detectors [73, 74]. It was also also claimed that it was difficult to explain this emission using only standard CR propagation. Several works were presented in this respect in which they claimed that depending on the parameters of the propagation, the emission from the CR sea or with the contribution from sources may be the answer to explain this new data [75–81].

2.5 Pulsar Wind Nebulae

Even though most likely accelerating leptons, Pulsar Wind Nebulae (PWNe) like the Crab Nebula need to be accelerating electrons and positrons up to PeV energies to produce the broadband emission observed and polarized X-rays as seen by IXPE [82]. This acceleration can be explained by models like the one presented in [83], but there is also the possibility of a hadronic contribution to the VHE gamma-ray spectra [84]. Moreover, the Crab Nebula also shows flares at GeV energies as seen by *Fermi*-LAT and AGILE, and a very extensive study whose conclusion is that GeV flares mary not be driven by a single mechanism was also shown [85].

Another interesting PWN is HESS J1825-137 viewed by LHAASO [86] and HAWC [87]. They measured spectra ranging from a few TeV up to above 200 TeV showing an energy-dependent extended morphology that points towards the presence of electrons injected by the central source and being cooled down. For HAWC J2031+415, the HAWC morphological studies do not show any energy-dependence [88], but more data are needed to support the PWN scenario. Additionally, the magnetar wind nebula around Swift J1834.9-0846 [89] claimed to be the first magnetar wind nebula powered by the internal magnetar energy of the central source.

2.6 Halos

Halos are regions of slow propagation glowing in gamma rays powered by pulsars [90] in general dominated by diffusion [91] (although there are models that claim that the mechanism is in dispute [92]). Geminga and Monogem were the first confirmed sources of this type [93] and there were updates by HAWC [94] and H.E.S.S. [95] presented at the conference. Most importantly, there was a new measurement of the emission around Geminga, this time using LHAASO-KM2A [96] in which there are claims of asymmetric diffusion as it is shown in Fig. 5. This could be related to the alignment of the magnetic field in the region or that that the propagation is happening inside/outside of the SNR in different regions.

The extended emission surrounding PSR J1813-1749 (see Fig. 6) , despite the young age of the pulsar at the center, shows characteristics of a halo [97]. There are also other studies like the LHAASO measurement of the PWN tail of PSR J1740+1000 [98] that might point towards a halo origin, but pulsar offset and small extension may make the scenario not suitable. HAWC J0359+5414 was put forward as a halo candidate [99] with two powerful pulsars in the region may power it. Additionally, HAWC searches for halos around pulsars [100], millisecond pulsars [101]

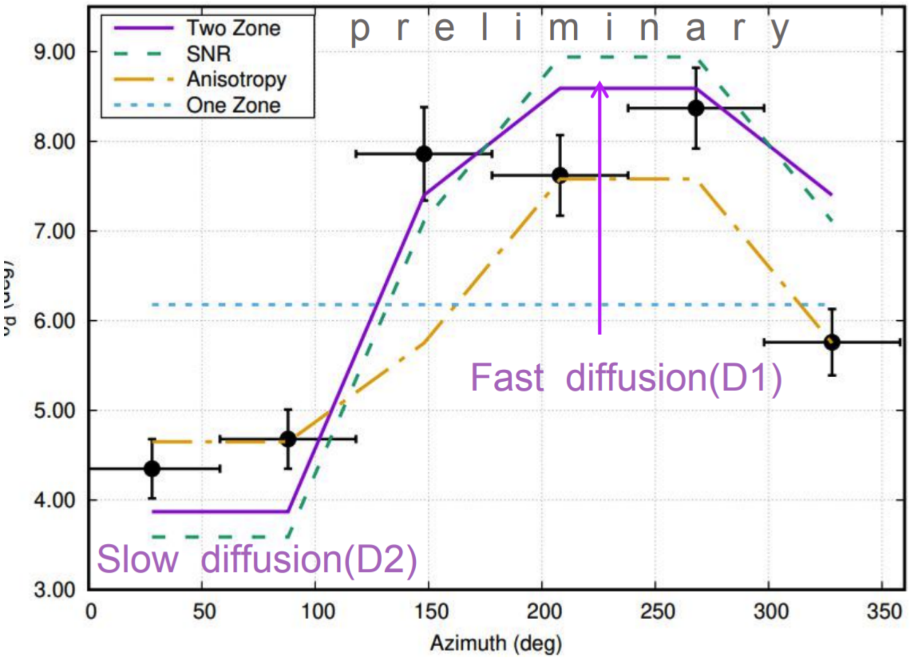

Figure 5: Geminga VHE γ-ray emission observed by LHAASO-KM2A [96].

and M31 [102] were also shown. Finally, we also had prospects for CTAO [103] and eROSITA [104].

2.7 Pulsars

There are three pulsars that have been detected in the VHE γ-ray band. Two of those (Geminga and Crab) have already been detected with the LST-1 [105]. Both peaks observed in the Crab and Geminga detected with a high significance as it can be seen in the phaseogram shown in Fig. 7. LHAASO observed gamma rays from the location of the millisecond pulsar J0218+4232 [106], but even though spatially coincident, it is difficult to associate it with the millisecond pulsar and MAGIC did not find any emission coming from the region [49]. Finally, a study of the X-ray and γ-ray emission of the variable γ-ray pulsar PSR J2021+4026 [107] observed in different wavelengths shows a gamma-to-X shift of 0.21 in phase related to mode change.

2.8 Binaries

The microquasar SS 433 was first detected by HAWC and deeply studied by H.E.S.S., that favors a leptonic origin of the emission [108]. The electrons propagate from the central source and cool down faster for higher energies as it is depicted in Fig. 8. HAWC also updated its original results with a well-measured spectrum [109] in contrast with the original report of only one flux point. Other results on the study of binary systems were the observation of the periastron passage of PSR B1259-63 [110], composed by a pulsar and a O9.5Ve-type star binary system with equatorial disk that the pulsar crosses twice. It showed X-ray-to-TeV correlation more strongly after second disc crossing, but no GeV-to-TeV correlation. The γ-ray binary LMC P3 showed the peak of emission after inferior conjunction as seen by H.E.S.S. [111]. We could also see the VHE

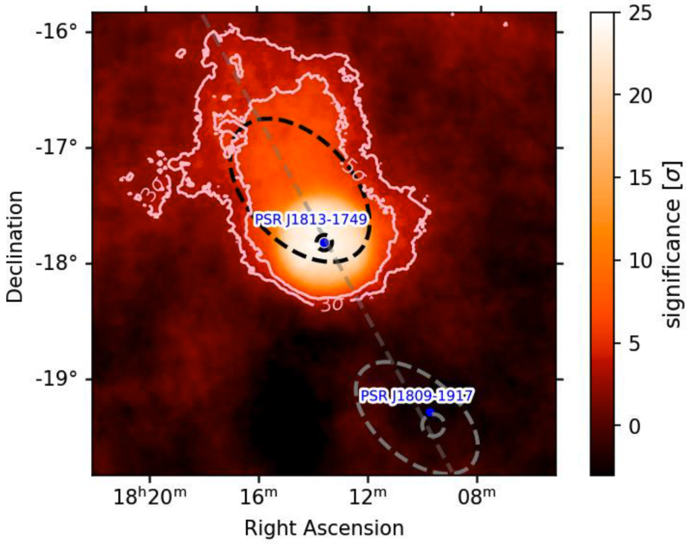

Figure 6: PSR J1813-1749 extended emission above 0.4 TeV seen by H.E.S.S..

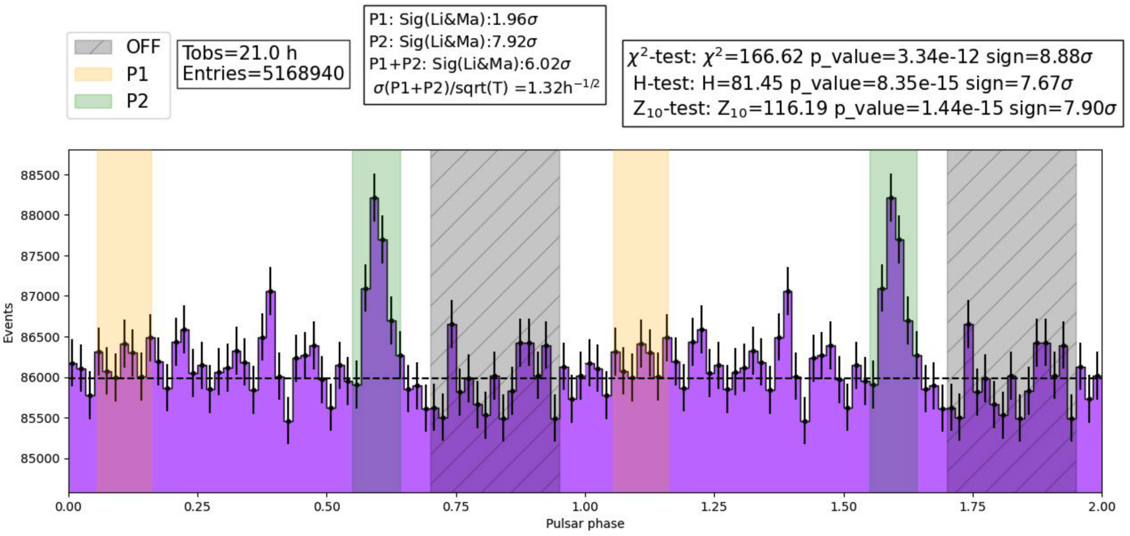

Figure 7: Geminga pulsar phaseogram.

gamma-ray observations [112] and modeling [113] of Eta Carina, the MAGIC observation of HESS J0632+057 and MAXI J1820+070 [49], the LS 5039 modulation and source coincident with V4641 Sgr detected by HAWC [114] and the observation of the Be/X-ray binary LS V +44 17 by VERITAS during outburst [115].

2.9 Novae

Although novae had been established as gamma-ray emitters several years ago, they had never been detected in the VHE γ-ray band until RS Ophiuchi, a symbiotic nova that erupted August 8th 2021 was detected by H.E.S.S., MAGIC and the LST-1 for several days after the eruption (see

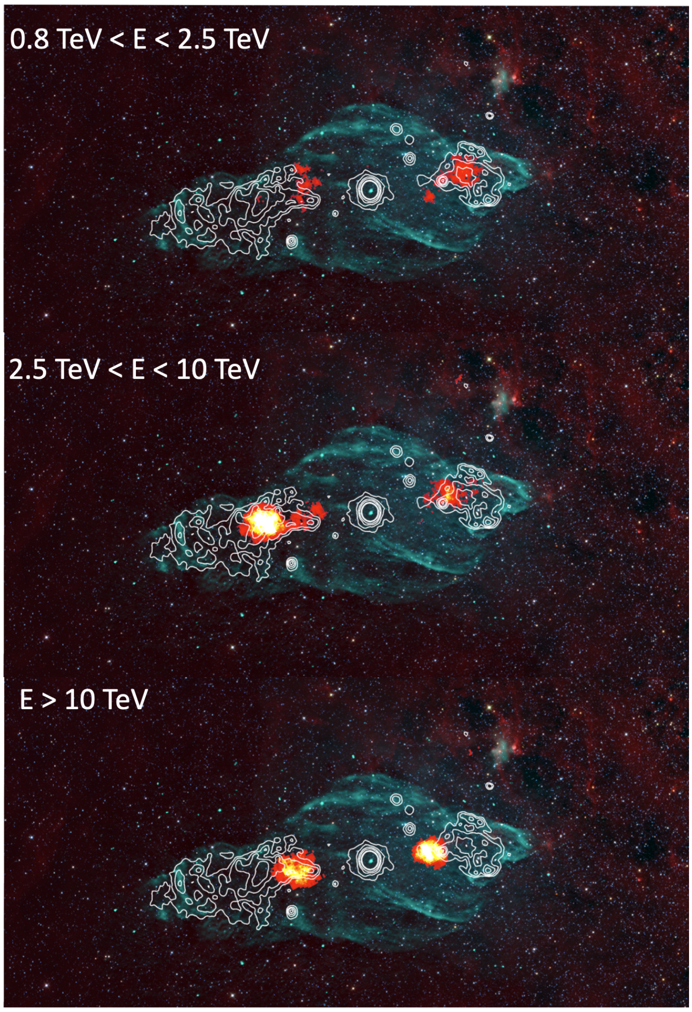

Figure 8: SS 433 Energy dependent morphology [108].

Fig. 9 for the evolution). Proton acceleration is strongly favored [116, 117] to explain the γ-ray emission and these accelerated protons will eventually escape nova shock and contribute to the sea of CRs. Although the previous works using simple modeling assume that the same particle population produce the GeV-to-TeV emission, there are other models that disfavor the single-shock scenario to explain it [118].

2.10 Galactic Transients

There are a plethora of source types that might produce transient γ-ray emission [119]. There are other candidates for PeV cosmic-ray acceleration like for example core-collapse supernovae in dense environments. Transitional millisecond pulsars whose origin of the gamma-ray emission during the intermediate accretion stage is unclear or magnetars and Fast Radio Bursts searches with VERITAS [120], H.E.S.S. [121], HAWC [122], *Swift* and *Fermi*-LAT [123].

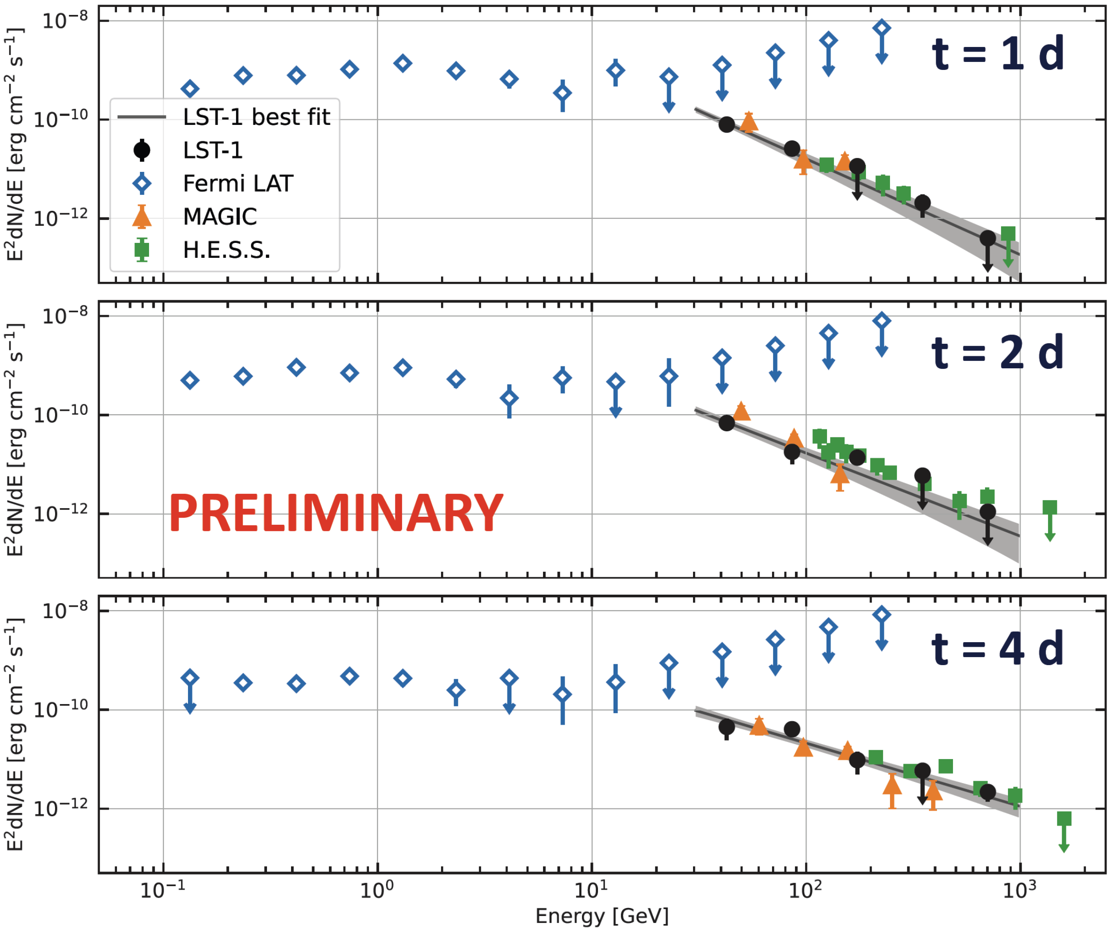

Figure 9: Daily RS Oph spectra [117].

2.11 Unidentified sources

There are still sources for which the nature of their emission is still unclear and they are therefore classified as unidentified. Below we can find a list of them with a few notes that may help to identify them in the future or understand the origin of their current classification.

- MGRO J1908+06. Leptonic model favor to explain the VHE gamma-ray emission observed by VERITAS [124].
- LHAASO J0341+525. Emission confirmed by HAWC [125]
- LHAASO J1959+2850. Powerful pulsars in the surroundings, therefore it is likely a PWN [126].
- LHAASO J1929+1745 region [127]. It shows a similar morphology than that in HAWC [37]
- LHAASO J2108+5157. Observed by LST-1 [128] and VERITAS+HAWC [129]. Molecular clouds in the surroundings [130] may point towards a hadronic origin of the emission, although modeling shows a compatibility between the origin being leptonic as well.

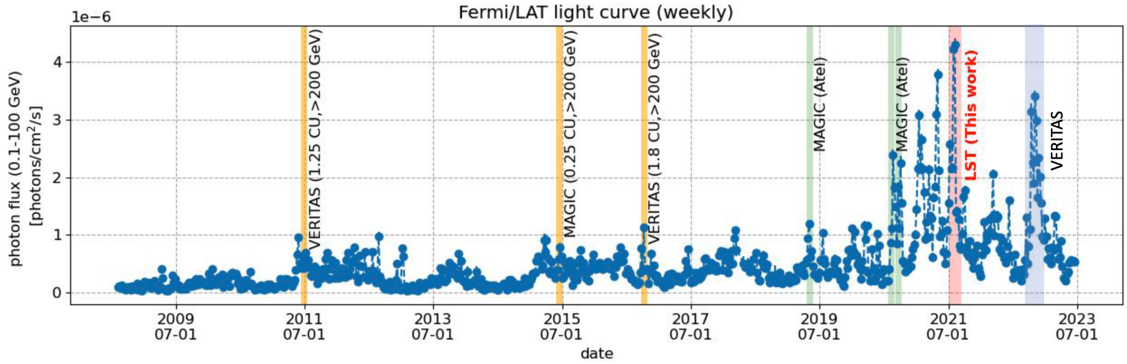

Figure 10: BL Lac *Fermi*-LAT long-term lightcurve evidencing the 2020, 2021 and 2022 flares together with other episodes[149].

- HAWC counterpart of LHAASO J1849-0003 [131]. There is a high spin-down power pulsar in the region, and therefore the origin is expected to be of a PWN.
- HESS J1809-193. Observed by HAWC [132], the lepto-hadronic scenario is favored by the modelling, but a halo could also be the origin as indicated by X-rays from Chandra [133].

3. Extragalactic science

3.1 Starburst Galaxies

Starburst Galaxies are factories of cosmic rays that glow in gamma rays. The origin of their emission is thought to be due to the strong winds from the stars contained in the galaxy. In this conference, we had an update on the M82 detection by VERITAS[134] and also the proposal of PWNe as the origin of the γ-ray emission and their non-negligible contribution to the Extragalactic Gamma-Ray Background [135]

3.2 Blazars

Active Galactic Nuclei (AGNs) present different features depending on the angle their ultrarelativistic jets form with the line of sight from the Earth. Blazar jets point directly towards the Earth. We had several presentations about the theory and prospects, like those studying the nature of TeV γ-ray variability in blazars [136, 137], SED modeling [138] and second-order effects [139].

The theory for the emission of low-luminosity AGNs is advancing with studies like the spine-sheath jet model [140] or that of the emission from their jets [141]. For the future we also had a novel method to identify blazar emission states using clustering algorithms [142] and prospects for CTAO with the study of bright flares [143], variability predictions [144] and redshift determination [145].

BL Lac is the prototypical blazar and it shows very frequent flares (see Fig. 10) as those observed by MAGIC in 2020 [146], LST-1 in 2021 [147] and VERITAS in 2022 [148], every one of them evidencing a different aspect of the emission.

Mrk 421 and 501 are some of the most monitored blazars in the VHE γ-ray sky. We had updates on the observations by HAWC [150] and LST-1 [149], added to the X-ray and TeV correlation study

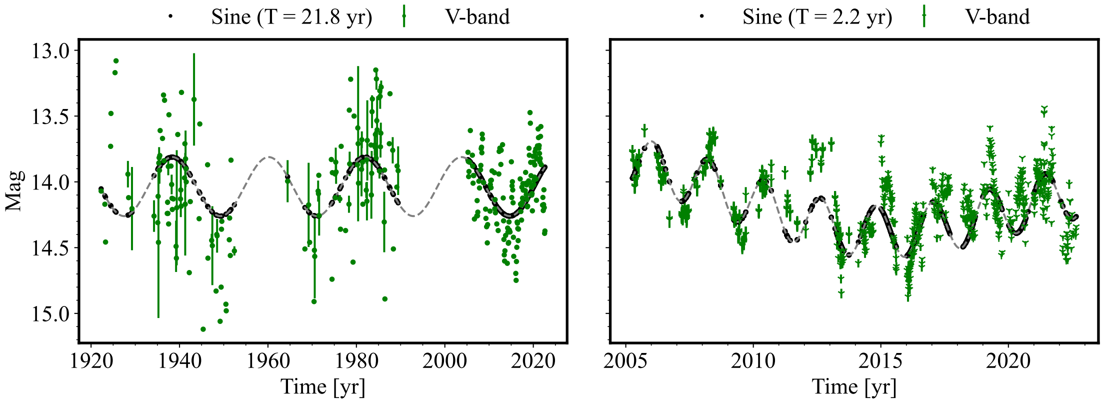

Figure 11: PG 1553+113 2.2 (right panel) and 21.8 year period (left panel) derived using optical data in the V-band [154].

from Mrk 421 by VERITAS [151] that favors leptonic models and the Lorentz Invariance Violation constraints using Mrk 421 as well [152]. Kinks may be present in the spectra of these sources, as it hinted in the past, which may point to structured jets [153].

PG 1553+113 has been claimed to contain a binary black hole at the center [154] because of the evidence for a 2.2 yr periodicity that can be seen in *Fermi*-LAT data. In this contribution, the hypothesis that was put forward was that the 2.2 yr periodicity of the γ-ray data can be part of a longer trend with a long-term period of ~22 yr that has a 3σ statistical significance when considering long-term optical data in the V-band (see Fig. 11). A lump scenario was put forward as the explanation for this additional periodicity.

Finally, there are monitoring programs of several AGNs, like that shown in the VERITAS AGN Highlights [155]: RBS 1366 [156] and S3 1227+25 [157], flaring Blazar ToOs with H.E.S.S. [158], HAWC detection of Mark 421, 501, M87 and 1ES 1215+303 [159], the Flat Spectrum Radio Quasars monitoring with MAGIC [160] or the MAGIC detection of GB6 J1058+2817 and B2 1811+31 [161].

3.3 Radio Galaxies

Radio Galaxies are AGNs whose jet subtends a larger angle than blazars with respect to the line of sight from the Earth. M87 is one of these long-known radio galaxies for which a long term monitoring by MAGIC, VERITAS and HAWC was shown [162]. There were additional studies of the VHE γ-ray Propagation [163] and morphology [164], for which the extension upper limits exclude the radio lobes as the origin of the VHE emission in the low state. Centaurus A is another of these sources for which the GeV gamma rays support a jet scenario, but hard X-rays are consistent with jet and corona models [165]. In general, for this type of sources, the comparison of the X-ray spectra of GeV-loud/quiet ones show that GeV-loud ones have a steeper spectrum and jets are less inclined [166].

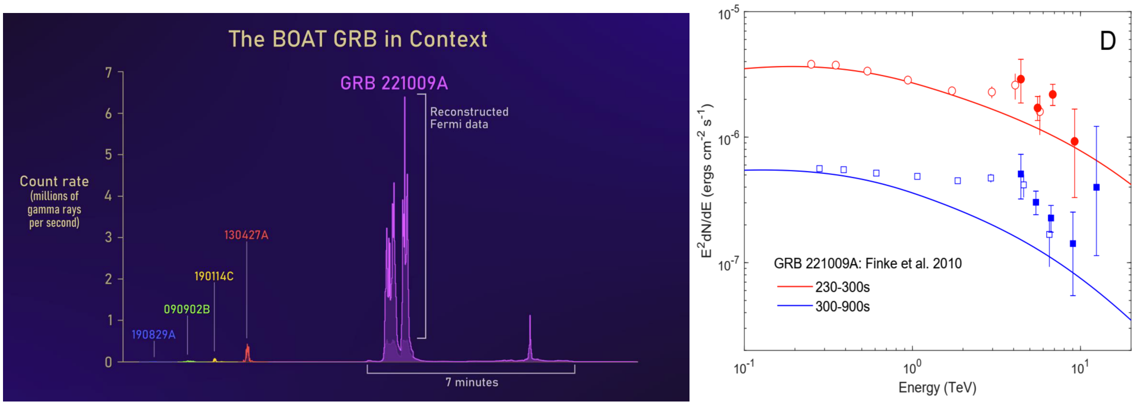

Figure 12: GRB 221009A count rate (left panel) and LHAASO spectra for different integration times after the burst (right panel).

3.4 Gamma Ray Bursts

The merging of two compact objects or a hypernova are the origin of the so-called Gamma Ray Bursts (GRBs). In this conference, we had the luck of being less than one year away from GRB 221009A, the brightest of all time (B.O.A.T.).

Several GRBs have been detected in the last few years at TeV energies while we were searching for them since many years ago. The possibility that this distribution has only a chance origin is discussed in [167]. The reality is that at the moment, five GRBs have been detected at VHE gamma rays: GRB 180720B (H.E.S.S.), GRB 190114C (MAGIC), GRB 190829A (H.E.S.S.), GRB 201216C (MAGIC), GRB 221009A (LHAASO), all of them are long duration GRBs (duration T90 > 2 sec) and what it has been detected is the afterglow emission very likely produced by Synchroton Self Compton (SSC) emission by relativistic electrons in the forward shock.

The B.O.A.T. mentioned above (GRB 221009A) showed no polarized emission as measured by IXPE [168], breaking records (see Fig. 12) in *Fermi*-GBM [169] and *Fermi*-LAT [170] being the one with the highest isotropic energy, the highest fluence, the highest peak flux and the 3rd highest isotropic intrinsic luminosity. No detection by IACTs [171] and a detection by LHAASO that puts a lot of constraints [172]. LHAASO detected photons up to 13 TeV from the afterglow [172] putting the most stringent limits on the prompt TeV emission (emission detected only 230 s after the alert) that could mean that either there is no SSC emission or the absorption is too high. LHAASO data above 3 TeV also hints to an additional component as it is seen on the right panel of Fig. 12. Due to the energies reached by this emission, it is difficult to explain ≥ 10 TeV leptonic emission due to SSC [173]. Thanks to these observations, there were constraints put on the emission of Ultra High Energy CRs from GRBs [174], limits derived on the Intergalactic Magnetic Field (IGMF) ($> 10^{-18}$ G [175] or 4×10^{-14} G [176], depending on the assumption) and even dark matter constraints [177].

We also had theory presentations like that of the study of the origin of afterglow plateaus with a promising interpretation coming from structured jet [178]. Models for the afterglow emission of GRBs based on GRB 190114C [179, 180], constraints on the IGMF [181] using GRB190114C data.

Finally, further GRB searches were presented like that from LHAASO-WCDA [182] for which only upper limits were derived so far except for GRB 221009A. There were also contributions about the monitoring of SDSS 1430+2303, the first candidate host for the merger of a Supermassive Black Hole Binary with H.E.S.S. [183] with no detection so far, the *Fermi*-LAT detection of the afterglow of GRB 211211A [184] or the CTAO prospects comparing different CTAO Medium-size telescopes array layouts performances for gamma-ray burst observations [185].

3.5 Cosmology

The Extragalactic Background Light (EBL) is the light emitted by galaxies after the reionization era. This EBL has been measured using results from HE and VHE gamma-ray observations from distant AGNs and computing the γ-ray attenuation of their spectra. In this conference we had a proposal for a new EBL measurement, this time using a Bayesian mathematical framework [186] that in general agrees with previous estimations except at low wavelengths. Using this EBL measurements, one can perform other cosmological estimations, such as for example to put upper limits on the redshift of galaxies [187] or the measurement of the Hubble constant [188]. Additionally, using the spectra from several AGNs, the first EBL skymap was built to study its anisotropies [189] for which no significant dipole is observed at the moment, but shows promising results for the time of the advent of CTAO when more precise measurements will be performed.

4. Surveys, Software and analysis methods

There were several surveys and catalogs covering a wide energy range that were presented in this conference. We could see the presentation of several results obtained using satellites like INTEGRAL, COMPTEL and *Fermi*-LAT [190], DAMPE with almost 250 sources in 7 years of data [191] or CALET with an improved γ-ray reconstruction [14]. We also saw the preparation for the second H.E.S.S. Galactic Plane Survey catalogue [192] and the second HAWC high energy catalog [193] apart from the presentation of LHAASO catalogs below [194] and above 25 TeV [195].

The software development is also essential for the advancement of Science, in particular in fields in which the analysis of Big Data is a must. There were several presentations about methods, simulations and analysis software like ctapipe [196], the low-level data processing pipeline software for CTAO, gammapy [197] the high level one, pyirf [198] the software to build the instrument response functions in CTAO, astripipe [199] the ASTRI pipeline, NectarChain [200] Nectar one or cosipy [201], the COSI pipeline or libraries to fit data (Bjet_MCMC) [202] or catalogs (STeVECat [203]). It is also worth noting the role that deep learning is starting to acquire, not only to improve the data processing, but also in any task related to population classification or regression of some quantity, for which we had more than ten contributions in the conference.

5. Final remarks

From the results shown at the conference, my personal take is that we currently are in a transitional period: we have been having a couple of decades of great data that have been surprising us and telling us in which direction to move forward with the models, theory and phenomenology, but we need to take a leap step to be able to disprove all these models that are now at hand. There are a some exceptions like a few instruments coming into operation that are already producing great results, and also transient events that are always surprising us. But we are lucky, the future is very bright, in the next few years there are projected experiments and observatories that will boost the covering of the γ-ray sky with an unprecedented sensitivity that will imply an expansion in the theories explaining all these new observations.

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