PROCEEDINGS OF SCIENCE

From present generation TeV observatories to CTA

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In the last decades Imaging Atmospheric Cherenkov Telescopes (IACTs) have opened up a new astronomical window at photon energies exceeding tens of GeV. The technique is based on the detection of Cherenkov light produced by electromagnetic showers in the Earth's atmosphere using telescope mirrors with diameters of a few to tens of meters. A world-wide community is behind the design and construction of the next generation Cherenkov Telescope Array (CTA), consisting of two arrays of IACTs at the northern and southern hemispheres. The first CTA telescope at an official CTA site, the first Large Size Telescope, is under construction at the ORM in La Palma.

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1. Imaging Atmospheric Cherenkov Telescopes

Since the times of Pierre Auger we know that cosmic and Very High Energy (VHE) gamma rays produce showers of particles in our atmosphere. Patrick Blackett realized in 1948 that air showers must produce Cherenkov light. By the end of WWII plenty of cheap searchlights and electronics were available and they were used to assemble primitive Cherenkov telescopes. Cherenkov light from showers was first detected by Galbraith and Jelley with a 2-inch photomultiplier (PMT) and a 25 cm diameter searchlight in 1953[1]. Cherenkov pulses were found to be faster than 1 ms.

Unfortunately showers produced by cosmic rays produce similar shower images at the telescope's focal plane and they are much more numerous that γ-rays. Rejecting the cosmic ray background soon became key to advance the Cherenkov telescope technique. Only after long analytical calculations by A. Chudakov and demanding computer MC simulations by A. M. Hillas was it realized that gamma ray images are roughly elliptical and they are not centred on the gamma ray incident direction but rather point to it, so one has a handle to discriminate γ-rays from cosmic rays and to estimate the arrival direction.

Jelley also realized already in the 1960s that having several telescopes would increase the efficiency of Cherenkov telescopes, because the shower produces images pointing in different directions at the different telescopes. Fitting the images to ellipses and intersecting the major axes allows a simple and more precise source position reconstruction, i.e. a better discrimination from the background of cosmic rays and an improved angular resolution. More images result in a better estimation of the shower shape and also in a better background rejection.

A γ-ray shower illuminates a circle of about 120 m radius at ground level. Since a telescope at any place inside that "light pool" is sensitive to the primary γ-ray, the collection area of the telescope easily exceeds $10^4\ m^2$. From the beginning it was clear that such a collection area is significantly larger than that of any spaced-based detector that detects the primary γ-ray.

Telescopes employing these detection principles are referred to as Imaging Atmospheric Cherenkov telescopes (IACTs).

2. Pioneers and the current generation of IACTs

Even if the key concepts were already there IACTs have not detected any source of γ-rays by the end of the 1960s. It soon became clear that there was a need for larger mirrors to reduce the energy threshold below 1 TeV, mirrors with better optical quality, more PMTs to resolve the shower shapes, faster electronics to reject light from the night sky and more accurate MC simulations to optimize hadron discrimination.

The 10m diameter telescope at Fred Lawrence Whipple Observatory on Mt. Hopkins, Arizona, was meant to address these needs. Whipple started operation in 1968 und detected the first TeV gamma ray source, the Crab Nebula, in 1989[2]. It was equipped with a reflector of 75 m^2 employing an improved Davies-Cotton optical design. The camera was instrumented with an array of 37 PMTs when the Crab Nebula was discovered. MC simulations were key to develop the so-called Hillas γ-hadron discrimination method.

The discovery of the first VHE γ-ray source prompted the construction of the HEGRA array of six 3m diameter telescopes in La Palma in the 1990s. Fig. 1 shows two of the telescopes. HEGRA

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Figure 1: Two of the telescopes of the HEGRA array at the Roque de los Muchachos observatory in the first years of the 21st century. HEGRA pioneered the stereoscopic technique in IACTs with an array of six 3m diameter telescopes at inter-telescope distances of about 100 m. The array reached a thereshold energy of $\sim$500 GeV.

finally proved that stereo allowed to boost sensitivity and angular resolution[3] and made the first survey of the northern galactic plane.

By the turn of the century the IACT technique was fully mature. Stereo allowed to achieve better gamma/hadron discrimination, angular and spectral resolution. Mirror diameter >10m allowed to achieve an energy threshold $\sim$100 GeV, a pixel diameter $\sim$0.1 deg is key to resolve the shower images and sampling of Cherenkov pulses with $\sim$1 GSps helps to eliminate light of night sky. Three major instruments were built following these requirements:

- H.E.S.S.: 4$\times$10m diameter telescopes plus 1 28m telescope in Namibia (with an optimal view of the galactic center)
- MAGIC: 2$\times$17m diameter telescopes in La Palma, Spain (at the old HEGRA site)
- VERITAS: 4$\times$10m diameter telescopes in Arizona, US (at the old Whipple site)

These instruments are still in regular operation and reach the following performance:

- Operation duty cycle 10-13%.
- Angular resolution somewhat better than 0.1°.
- Energy resolution of $\sim$10%
- Field of View of a few deg diameter

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- Energy range of ∼60 GeV to 10 TeV
- Sensitivity: <1% of the flux of the Crab Nebula in 50 hours for the range 100 GeV to 1 TeV. Fig. 2 shows the energy-dependent sensitivity of the three instruments.

3. A few scientific highlights

More than 200 sources are included in what we may consider the reference VHE source catalogue: TeVCat (http://tevcat.uchicago.edu/). Scientifically more significant is the fact that several populations of VHE sources are now established. It is also worth to mention that the field has produced a large number of high impact publications (more than 20 articles in Nature, Science and PRL) since 2004.

Roughly 25% of the sources are unidentified, although they are probably galactic because they lie in the galactic plane and some of them are extended. About 2/3 of the identified sources are galactic (mainly Pulsar Wind Nebulae and SNR), whereas extragalactic sources are mainly “blazars” (i.e. BL Lacs and Flat-Spectrum Radio Quasars).

In what regards galactic sources several shell-type SuperNova Remnants (SNR) have been detected. Some of them are as large as 1-2 deg and we can resolve their morphology. *Agile* and *Fermi-LAT* have found evidence for hadronic acceleration in SNR, so the case for their constituting the source of the galactic cosmic rays has got stronger, but IACTs have not found any SNR that accelerates cosmic rays up to the Knee of the cosmic ray spectrum (a so-called “PeVatron”). For instance an obvious candidate, the young SNR Cas A, shows a distinct spectral cutoff below 10 TeV[4].

Nebulae surrounding pulsars (Pulsar Wind Nebulae), like the Crab Nebula, have turned out to be very bright VHE sources. In fact they constitute the largest galactic population. γ-rays are produced via Inverse Compton by electrons and positrons injected by the pulsar and reaccelerated at the shock between the pulsar wind and the interstellar medium. Interest in these objects have increased in the last years because they may explain the excess of positrons observed by cosmic rays detectors aboard satellites at 100 GeV - 1 TeV.

IACTs have unveiled a population of gamma ray binaries[5, 6]. The name stems from the fact that these binary systems actually radiate most of their energy in the gamma ray range. Particle acceleration is probably produced at the shock between the pulsar wind and the wind of the companion star, but acceleration in shocks of a jet launched at the accretion disk remains a possibility.

The H.E.S.S. galactic survey represents a major breakthrough in galactic studies. In its latest incarnation[7], after 10 years and 3000 hours of observations, it comprises 78 sources. Comparing with restricted survey of Cygnus by VERITAS it has become clear that the VHE source density grows towards the galactic center. Numerous multiwavelength observations aim at characterizing this collection of VHE sources and identiflying the unassociated ones.

H.E.S.S. has also claimed the possible presence of a PeVatron at the Galactic Center[8]. The VHE emission region extends out to ∼200 pc from the Galactic center and is probably of hadronic origin. The spectrum goes up to tens of TeV, which points to the presence of primary cosmic rays up to ∼1 PeV.

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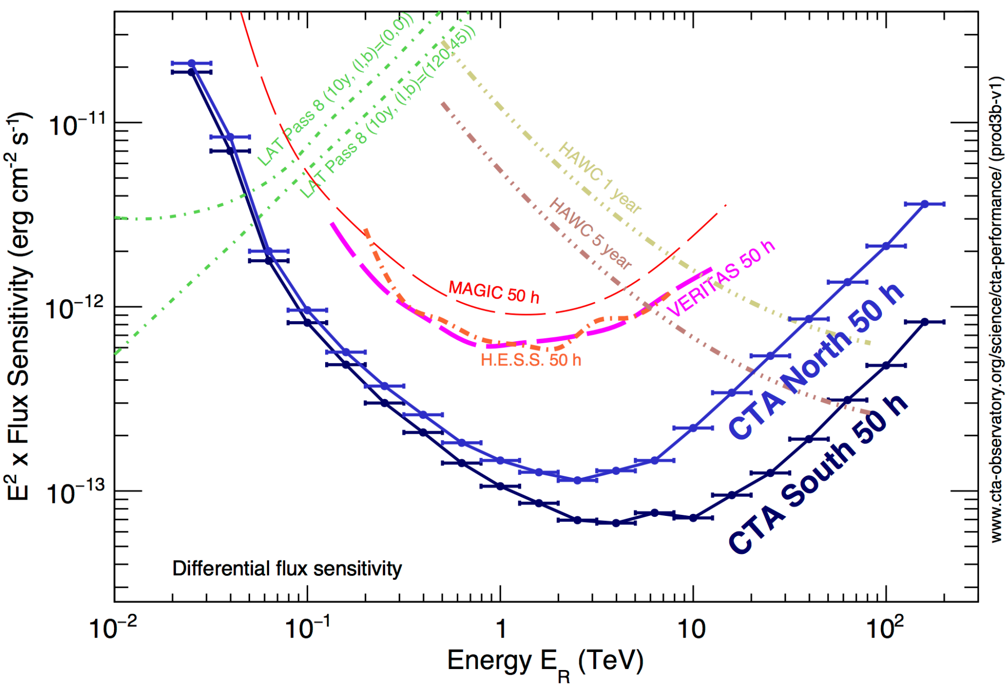

Figure 2: Comparison of the sensitivity of the CTA-North and CTA-South arrays with selected existing gamma-ray instruments. The differential flux sensitivity is calculated for five independent 5σ detections per decade in energy. Additional criteria applied are to require at least ten detected gamma-rays per energy bin and a signal/noise ratio of at least 20.

We have found evidence for a VHE component in the spectrum of two pulsars. MAGIC detected VHE emission from the Crab pulsar[9] , concluding that gamma rays must be produced at the outer gap in the pulsar magnetosphere. VERITAS extended the spectrum to 400 GeV and lately MAGIC detected pulsed γ-rays up to >1 TeV[10] (see Fig. 3). This energy turns out to be too high for synchrotron-curvature emission and probably points to Inverse Compton as the emission mechanism. H.E.S.S. has reported pulsed emission from the Vela pulsar, with evidence for a second component probably of Inverse Compton origin as well.

Around 70 extragalactic VHE sources have been detected. Except for two starburst galaxies, extragalactic VHE gamma rays come from AGNs. Models have been proposed to explain acceleration in jets either by magnetic reconnection or by internal shocks. A typical energy spectrum of a VHE AGNs shows two bumps: a low energy bump that corresponds to synchrotron radiation from relativistic electrons in the jet. In the leptonic production scenario, the second high energy bump corresponds to inverse Compton scattering by the same electron population. In the hadronic scenario primary protons produce VHE γ-rays via π^0 decay. The majority of the VHE AGNs are blazars (BL Lacs or Flat-Spectrum Radio Quasars) where the jet is pointing to us and the emission is relativistically beamed. There are a few nearby radiogalaxies emitting at VHE which jets point away from us.

Especially relevant in VHE extragalactic sources is their fast variability. Observations of Mrk 501 and PKS 2155-304 show flux doubling time scales as short as $\sim$2 min[12]. This is due to rela-

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tivistic beaming. Such short variability time scales allow to place limits on the Lorentz Invariance violation, i.e. on changes of the speed of light with energy. It also allows to study the physics of the object. In radiogalaxies, which suffer less beaming, fast variability on time scales of $<$10 min may point for instance to acceleration in gaps of the black hole magnetosphere "a la pulsar"[13].

4. Recent news: γ-rays and neutrinos

The origin of the highest energy cosmic rays, those with energies above the Knee and sometimes exceeding 10^{18} eV, remains a mystery. High energy neutrino observations can provide insights into this problem. As cosmic ray protons and nuclei are accelerated, they interact with gas and background light to produce secondary particles that in turn emit neutrinos with energies proportional to the energies of the primary protons. These neutrinos can be detected on Earth in large underground or underwater detectors such as Icecube, Antares and KM3net[14] and indeed Icecube has found evidence for extraterrestrial neutrinos above 30 TeV.

At energies above 100 TeV neutrinos detected by Icecube are probably of astrophysical and not atmospheric origin[15]. At the same time the neutrino arrival direction can be determined with relatively high accuracy (0.1-1 deg). Follow-up campaigns are organized so that, when Icecube detects one such neutrino, other instruments search for its electromagnetic counterpart.

On September 22nd 2017 Icecube sent an alert on 20:55:13 UT reporting a $\sim$300 TeV neutrino triggering 43 seconds earlier, with location accuracy of 15 arcmin radius (combined statistical and systematic errors, 50% containment). Data in the *Fermi-LAT* detector showed that a well-known γ-ray blazar called TXS 0506+056 was brightening in the GeV band. In fact its spectrum was hard, pointing to emission at even higher energies, which in turn triggered further VHE observations.

MAGIC had failed to detect the source at the time of the Icecube alert but a prolongued observation of 13 hours during the following days resulted in a $>5\sigma$ detection. The VHE spectrum reached energies up to 400 GeV, strenghtening the connection to the Icecube neutrino.

A chance coincidence of the neutrino with the flare of TXS 0506+056 is disfavored at the 3σ level. The energies of the γ-rays and the neutrino indicate that blazar jets may accelerate cosmic rays to at least several PeV[16]. The observed association during a period of enhanced γ-ray emission suggests that blazars may indeed be one of the sources of cosmic rays above the Knee.

5. What's coming now

A world-wide community is behind the design and construction of the next generation IACT: the Cherenkov Telescope Array (CTA, [17]).

An essential feature of CTA is that, contrary to previous IACTs, it will be the first ground-based gamma-ray open observatory, meaning that CTA will work essentially on the basis of the submission of observation proposals and data will be opened to the entire astronomical community. Another relevant characteristic of the instrument is the fact that it will consist of two sites, one in the Northern Hemisphere (CTA-North) and one in the South (CTA-South), so as to provide full sky coverage.

CTA aims at enhancing the flux sensitivity of current IACTs by as much as a factor 10 in the core energy domain (approaching the 1 mCrab level for 50 hour integration), achieving an angular

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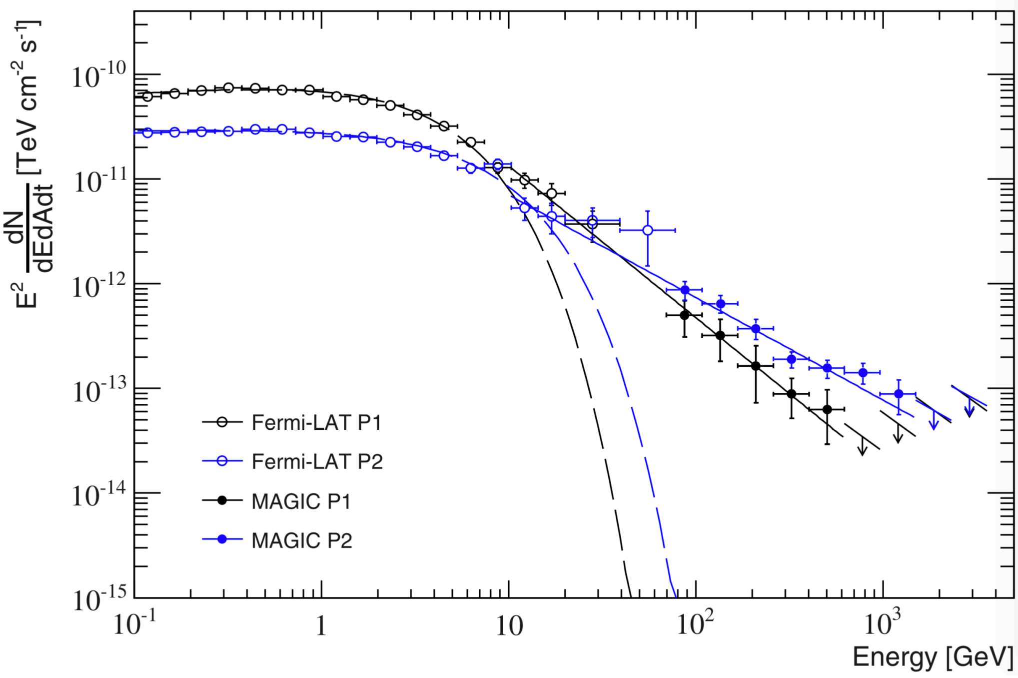

Figure 3: Phase-folded spectra of the Crab pulsar P1 (black circles) and P2 (blue circles) peaks at high energy and VHE (open and filled circles). The results of the power law with exponential cutoff fits to the *Fermi-LAT* points are shown by dashed lines, whereas the joint *Fermi-LAT*/MAGIC fits to power-law functions above 10 GeV are shown by solid lines. A second power law component is clearly visible above a few tens of GeV. From [11].

resolution as low as 0.1°-0.05° between 0.1-1 TeV) and extending the energy coverage to the range from 20 GeV to at least 300 TeV.

In doing so CTA needs to combine telescopes of different mirror sizes and build up to hundred of them. The very wide energy range covered by CTA-South necessitates the use of at least three different telescope types: 23m diameter Large Size Telescopes (LSTs), 12m diameter Medium Size Telescopes (MSTs) and ∼3m diameter Small Size Telescopes (SSTs). In CTA-North, the scientific focus will be on extragalactic science and hence (due to gamma-gamma absorption on Mpc scales) only a limited sensitivity is required much beyond 10 TeV. CTA-North can therefore be implemented with only LSTs and MSTs. See Fig. 2 for the expected sensitivity of the two arrays.

The CTA consortium has recently published the Science Case of the instrument[19]. In a nutshell it can be summarized with the following themes:

- Theme 1: Understanding the Origin and Role of Relativistic Cosmic Particles
  - What are the sites of high-energy particle acceleration in the universe?
  - What are the mechanisms for cosmic particle acceleration?
  - What role do accelerated particles play in feedback on star formation and galaxy evolution?

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- Theme 2: Probing Extreme Environments
  - What physical processes are at work close to neutron stars and black holes?
  - What are the characteristics of relativistic jets, winds and explosions?
  - How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?
- Theme 3: Exploring Frontiers in Physics
  - What is the nature of Dark Matter? How is it distributed?
  - Are there quantum gravitational effects on photon propagation?
  - Do axion-like particles exist?

6. LST prototype: first complete CTA telescope on site

The LST subarrays[18] allow to extend the energy range of CTA to the lowest energies down to 20 GeV. Currently the CTA baseline arrays feature 8 LSTs, 4 at CTA-North and 4 more at CTA-South.

Each LST is equipped with a primary tessellated mirror dish of 23 m diameter, supported by a structure made mainly of carbon fibre reinforced plastic tubes and aluminum joints. This solution guarantees light weight (around 100 tons), essential for a fast repositioning to any position in the sky in less than $\sim$20 seconds.

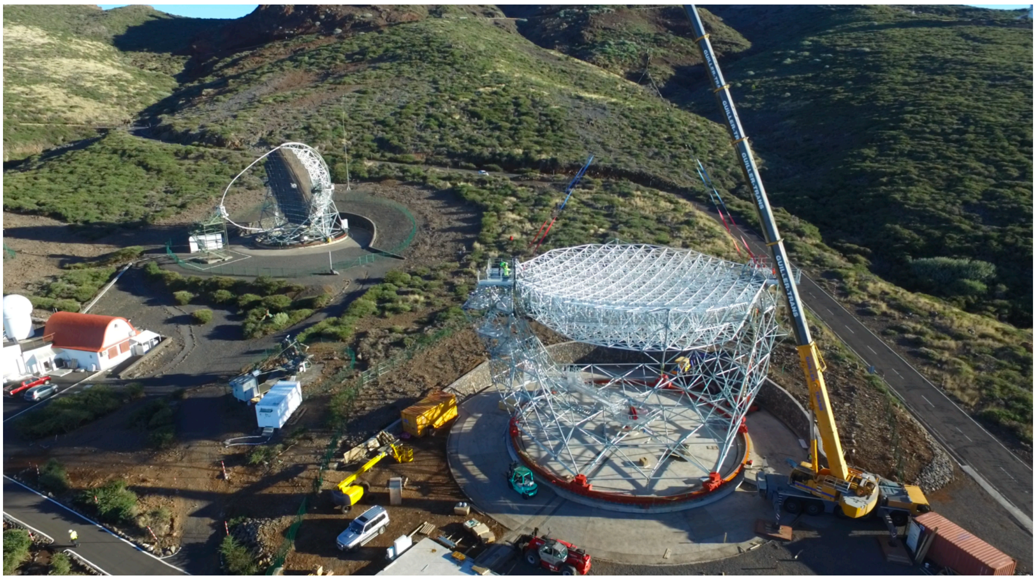

Figure 4: Installation of the mirror support structure on top of the lower mechanical structure of the LST prototype at the CTA-North site in December 2017. The mirror support structure is a space frame mainly made of carbon fiber tubes and weighs only 18 tonnes. One of the MAGIC telescopes and the mechanical support of one of the former HEGRA telescopes (now refurbished as FACT) are also visible on the left.

The camera of the LST shares many elements with the NectarCam proposed for use in the MSTs. With a weight of less than 2 tonnes the camera is comprised of 265 PMT modules that

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are easy to access and maintain. Each module has 7 channels, providing the camera with a total of 1855 channels. Hamamatsu photomultiplier tubes with a peak quantum efficiency of 42% (R11920-100) are used as photosensors. All control, readout based on the DRS4 chip (Domino Ring Sampler version 4, 8 channel/chip, 1024 sample buffer, 11-12 bit dynamic range) and custom trigger electronics are embedded in the camera.

The first LST is about to finish installation at the CTA-North site and will become the first CTA telescope at an official site. Fig. 4 shows the installation of the mirror support structure on top of the lower structure at the end of 2017. Commissioning should start in October 2018 and finish in one year. The goal is to produce all the four LSTs in CTA-North over the next four years, ending with the commissioning of the last LST in 2022.

7. Conclusions

Imaging Air Cherenkov Telescopes have become the reference technique to study VHE γ-rays. Building on pioneering efforts in the 1960-2000 the currently operational IACT arrays H.E.S.S., MAGIC and VERITAS have indeed opened a new astronomical window at energies above 50 GeV. VHE observations offer crucial insights into the physics of compact objects, cosmic rays and fundamental physics. CTA, the next generation IACT observatory, is well on track. It will represent a major improvement in sensitivity, sky and energy coverage, angular and spectral resolutions. The first CTA telescope on site, one of the 23m LSTs, is about to finish installation at the Roque de los Muchachos observatory, La Palma.

8. Questions of the audience

Daniel Fargion: when VHE tau neutrinos are skimming the Earth you may have a PeV-EeV tau escaping the ground, decaying in flight and having a bright air shower shining at MAGIC telescope looking at the sea. The Japanese experiment Ashra and the array Auger put upper limits. My best suggestion is to follow AGNs while at MAGIC horizons. See arXiv:0711.2326 “Reflecting on Cherenkov Reflections”, arXiv:0710.3805 “Cherenkov flashes”, arXiv:0305128 “Upwards tau air showers from the Earth”, ApJ 570 (2002) 909 “Discovering VHE by tau”.

Answer: MAGIC is about to publish a paper with results of tau neutrino observations[20]. MAGIC can point to the sea in a restricted right ascension range. About 30 hours were taken and UL to a diffuse flux of tau neutrinos were obtained in the energy range between 1 PeV and 3 EeV. The UL is not competitive with other experiments like IceCube or Auger. However this is the first time such an UL has been placed using this method with a realistic background measurement. One can obtain competitive ULS to the diffuse flux only by observing for more than 300 hours, probably in the bulkpark of 3000 hours, and that is unfeasible. Observing specific AGNs is challenging because the range of RAs is limited.

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