Fundamental Physics with Imaging Atmospheric Cherenkov Telescopes

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Ground-based gamma-ray astronomy experienced a major boost with the advent of the present generation of Imaging Atmospheric Cherenkov Telescopes (IACTs) in the past decade. Photons of energies $\gtrsim 0.1$ TeV are a very useful tool in the study of several fundamental physics topics, which have become an important part of the research program of all major IACTs. A review of some recent results in the field is presented.

1 Introduction

Imaging Atmospheric Cherenkov Telescopes (IACTs) are currently the most sensitive instruments for the observation of the Universe in the Very High Energy band of the electromagnetic spectrum (VHE, $E_\gamma \sim 0.1$ - 100 TeV). There are now three major IACT arrays in operation: H.E.S.S. in Namibia, MAGIC in the Canary island of La Palma, and VERITAS in Arizona (see \cite{1} for a recent review of the field). Typical performance parameters of the current generation of IACTs are an energy threshold between $\simeq 20$ and 100 GeV, an angular resolution $\mathcal{O}(0.1^\circ)$, an energy resolution of $\simeq 15\%$ (both of them energy-dependent), and an integral flux sensitivity for point-like sources of about 1% of the Crab Nebula flux (or $\simeq 1.2 \times 10^{-12} \text{ cm}^{-2}\text{s}^{-1}$ above 300 GeV) in 25 hours of observation. The projected Cherenkov Telescope Array (CTA) is expected to provide, by the end of this decade, an order of magnitude improvement in sensitivity over existing facilities.

Several topics related to fundamental physics can be addressed with IACTs: here we review the results obtained in the past few years in three of these areas: tests of the invariance of the speed of light, the search for gamma rays from dark matter annihilation, and the search for signatures of the existence of axion-like particles. The fundamental physics prospects for CTA are presented elsewhere in these proceedings\cite{3}.

2 Testing the invariance of the speed of light

Some quantum gravity (QG) theories predict violation of Lorentz invariance (LIV) which, among other consequences, could result in an energy dependence of the speed of light\cite{4}. This effect would be suppressed by some large QG energy scale, of order of the Planck mass $m_P$ (or below, in some models), so that the speed of light as a function of energy would behave as $v(E) = c \left(1 \pm E/M_{QG1} \pm (E/M_{QG2})^2 \pm \ldots\right)$. The observations with IACTs of rapidly varying VHE emission from active galactic nuclei (with flux-doubling timescales down to few minutes) in a wide -O(TeV)- energy range, have not produced to date any convincing evidence for a small hint of energy-dependent time shift in the light curve of Mrk 501; it has to be noted that such delays, if confirmed, may also have less exotic explanations.

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this phenomenon\textsuperscript{6,7}, but have been used to set constraints on the values of $M_{QG1}$ and $M_{QG2}$, for the cases of dominating linear and quadratic term respectively. The best current limits, from H.E.S.S. observations of the blazar PKS 2155-304, are $M_{QG1} > 0.172 \, m_P$ and $M_{QG2} > 5.2 \times 10^{-9} \, m_P$. The latter, though far from the Planck scale, is the most constraining limit on the quadratic term obtained by any technique, thanks to the long \textit{lever arm} in energy provided by IACTs. For the linear term, the Fermi-LAT limits from the observation of Gamma-Ray Bursts (GRBs)\textsuperscript{8,9} are the most constraining ones ($M_{QG1} > 1.2 \, m_P$). Since the relevant observable is the \textit{accumulated} photon delay upon arrival on Earth, very distant sources are the best candidates for LIV tests; unfortunately, the \textit{horizon} for IACTs is limited by the non-perfect transparency of the Universe to VHE radiation (see §4.1). This, together with the limited field of view (FoV) of IACTs, makes the detection of GRBs in the VHE range a challenging task - yet to be accomplished. A promising alternative\textsuperscript{10} for LIV searches is the observation of pulsars, after the detection by VERITAS\textsuperscript{11} and MAGIC\textsuperscript{12} of a power-law tail in the VHE emission of the Crab pulsar. The smaller distance would be compensated by the fast variability ($\sim$ms), which allows a more precise measurement of possible delays, and by the possibility of accumulating long observation times (limited in all other cases by the duration of the flaring states).

\section{Indirect dark matter searches}

Weakly Interacting Massive Particles (WIMPs), with masses in the GeV - TeV range are promising dark matter (DM) candidates, on the grounds of the so-called WIMP miracle\textsuperscript{13}, i.e. the fact that, for a weak-scale annihilation cross-section, their present relic abundance could roughly account for the DM density inferred from cosmological observations. WIMPs are part of various extensions of the standard model (SM) of particle physics (e.g. supersymmetric models), and, upon annihilating into SM particles, are expected to produce gamma-rays mostly via $\pi^0$-decay and final state radiation. The resulting gamma-ray continuum spectrum would extend up to the DM particle mass, and hence can reach the IACT energy band for $m_{DM}$ in the order of hundreds of GeV or above. In this type of search, a drawback of IACTs with respect to the lower-energy, space-borne telescopes, is their limited FoV, which enforces the a-priori selection of few DM targets, and limits (through competition for observation time with other programs) the exposure that can be accumulated on them. In the case of annihilating DM, the most relevant parameter of a candidate source is the volume integral, along the line of sight, of the squared DM density over distance squared, often called \textit{astrophysical factor}, which enters linearly in the computation of the expected gamma-ray flux. Other desirable features are an angular extension well below the telescope FoV, to facilitate evaluation of the background due to cosmic-ray initiated air showers, and the lack of nearby conventional astrophysical gamma-ray sources.

\subsection{Limits from dwarf spheroidal galaxies}

The above wish list has made of dwarf spheroidal galaxies orbiting our own galaxy the most popular targets for indirect DM searches with IACTs. All three major IACT arrays have conducted observational campaigns on several of these objects, and no significant excess of gamma rays has been observed from any of them (for the most recent results, see refs.\textsuperscript{14,15,16}). Flux upper limits can be transformed into an upper limit in the velocity-averaged DM annihilation cross section, $\langle \sigma_{\text{ann}} v \rangle$, for a given energy-dependent gamma-ray yield per annihilation $dN_\gamma/dE(E)$. The latter is the result, in a specific particle physics model (e.g. a given realization of supersymmetry), of the sum of all possible annihilation channels. Alternatively, one can assume 100\% annihilation into a single channel, e.g. $xx \rightarrow b\bar{b}$, and hence obtain upper limits on $\langle \sigma_{\text{ann}} v \rangle$ for that specific channel. Even for the channels with highest gamma-ray yield in the VHE range, the current IACT limits from dwarf spheroidal observations are two to three orders of magnitude above the expected $\langle \sigma_{\text{ann}} v \rangle \lesssim 3 \times 10^{-26} \, \text{cm}^3\text{s}^{-1}$ for thermally produced DM (see left panel of fig. 1). It must be noted that the estimated \textit{astrophysical factors}, that are needed to translate observa-
Figure 1: Left pad: compilation by Conrad \textsuperscript{22} of various limits on $\langle \sigma_{\text{ann}} v \rangle$ by IACTs compared to the stacked analysis of 24 months of Fermi-LAT observations of 10 dwarf spheroidal galaxies \textsuperscript{19}. Pure $b\bar{b}$ or $b\bar{b}$-dominated annihilation channel is assumed. The squares show models of phenomenological Minimal Supersymmetry, red ones being those assuming thermal DM production and with relic density consistent with WMAP measurements\textsuperscript{20}. Right pad: Milky Way DM profiles used in the H.E.S.S. search for an annihilation signal from the galactic halo\textsuperscript{21}, and definition of the signal and background regions.

3.2 Limits from observations of the galactic halo

Flux-wise, the center of our own galaxy should be, for observers on Earth, the brightest source of gamma rays from DM annihilation. However, the presence of astrophysical gamma-ray backgrounds (diffuse emission from cosmic ray interactions and a strong source coincident with the position of the central black hole Sgr A*) makes this a challenging region in the search for DM annihilation. The situation improves as one gets away from the galactic center, but then IACTs face the problems associated to the determination of the background in the search for a faint diffuse gamma-ray excess which spans (and hardly varies across) the whole FoV of the telescopes. Instead of trying to set a limit on the absolute DM annihilation flux in this central part of the galactic halo, the H.E.S.S. collaboration \textsuperscript{21} looked for systematic differences between the diffuse background rates (after masking all known astrophysical sources) in two different ranges of galactocentric distance (see fig. 1, right), with a careful selection of the signal and background regions to ensure that they were completely equivalent in terms of instrumental gamma-ray acceptance. In 112 hours of live time, no significant excess was found in the signal region. Under the assumption that the galactic DM halo follows a Navarro-Frenk-White or an Einasto profile, the resulting limits (fig. 1, right) on $\langle \sigma_{\text{ann}} v \rangle$ are the best obtained by IACTs to date, and are just one order of magnitude away from constraining the relevant part of the WIMP parameter space. Note however that the 2-year Fermi-LAT observations of dwarf spheroidals \textsuperscript{19} provide the best constraints up to DM masses as high as 1 TeV (thanks to its large FoV and duty cycle, Fermi-LAT achieves much higher exposure than IACTs; besides, most of the annihilation photons would be emitted at energies well below the DM particle mass, within Fermi-LAT’s range). The H.E.S.S. galactic halo observations were also used recently \textsuperscript{23} to set limits on DM annihilation lines or other narrow spectral features in the energy range 0.5 - 25 TeV.

Clusters of galaxies have also been targeted by IACTs\textsuperscript{24,25,26}, but currently provide weaker DM constraints than either dwarf spheroidals or the galactic halo, with the additional complication of potential gamma-ray contamination from active galaxies in the cluster and from
cosmic-ray interactions.

4 Search for axion-like particles

Axion-Like Particles (ALPs) are hypothetical spin-0 bosons with a 2-photon interaction vertex. They are a generalization of the axion which would result from the spontaneous breaking of the Peccei-Quinn symmetry postulated to solve the strong CP problem [27]. ALPs can convert into photons and vice-versa in the presence of an electric or magnetic field (Primakoff effect), a process which could enable the direct detection of ALPs in experiments like CAST [28] and ADMX [29]. The existence of ALPs could also affect the propagation of photons over cosmological distances. They were once invoked as an alternative explanation for the dimming of type Ia supernovae without resorting to cosmological acceleration [30], as well as to account for the observation, by the AGASA experiment, of an excess of cosmic rays of energies above the GZK cutoff [31]. In the latter case, super-GZK events were assumed to be ultra-high energy photons which convert to ALPs through interaction with intergalactic magnetic fields, thus evade suppression via $e^+e^-$ pair-production against the extragalactic radio background, and finally convert back to photons in the vicinity of the Earth. However appealing, this solution was rendered unnecessary when newer data from HiRes [32] and the Pierre Auger Observatory [33] showed the presence of the expected GZK suppression in the cosmic ray spectrum. But the idea that ALPs could play an important role in photon propagation in the Universe would soon revive in the context of VHE astronomy.

4.1 VHE gamma-ray propagation

Propagation of VHE photons over intergalactic distances is hindered by the presence of the so-called Extragalactic Background Light (EBL), an ubiquitous radiation in the UV to IR wavelength range, which results from the thermal emission by stars and dust in galaxies throughout the history of the Universe. For center-of-momentum energies above 2 $m_e$, VHE and EBL photons can interact to produce $e^+e^-$ pairs, a process which induces an energy-dependent depletion of the VHE gamma-ray flux from distant sources. The flux suppression increases with the gamma-ray energy, and sets a limit to the size of the Universe observable in the VHE range, often referred to as the “gamma-ray horizon”.

Direct measurements of the EBL are challenging due to the strong foreground emission, mainly from zodiacal light. Robust lower limits have been derived by integrating the contribution of resolved galaxies in deep-field optical and infrared observations [34,35]. Upper limits to the EBL density were derived from IACT observations (see e.g. [36]), under the assumption that the intrinsic VHE spectra of BL Lac sources and other blazars should have shapes allowed by the gamma-ray emission models, e.g. should not be much harder than $dF/dE \propto E^{-1.5}$, and should become softer as energy increases. There were also claims [40,41,42] that some VHE spectra were violating these constraints (or at least in tension with them), even when the lowest possible EBL density was assumed in order to derive the intrinsic spectra from the observations. Axion-Like Particles were then proposed as a possible explanation of these anomalies (see §4.2).

The first actual indirect measurements (not upper limits) of the EBL density using gamma-ray observations were published independently by the Fermi-LAT [37] and H.E.S.S. [38] collaborations in 2012. In both cases, a number of gamma-ray spectra were combined, using certain assumptions on the intrinsic spectral shapes, to build a single likelihood which was maximized to obtain the most likely scaling factor for the optical depth $\tau(E,z)$, whose energy- and redshift dependence was taken from the Franceschini '08 EBL model [39] - FR08 in the following. These works concluded that, within uncertainties, the EBL density at UV - near IR frequencies was compatible with that of FR08 and other similar models, and less than $\simeq 50\%$ above the lower limits from galaxy counts.
4.2 Propagation anomalies and ALPs

There have been several works\textsuperscript{40,41,42} claiming that VHE observations of some sources indicate that the Universe is more transparent to gamma-rays than expected from “low EBL” models like FR08 and others, in a sort of revival of the $\text{TeV-IR crisis}$\textsuperscript{43} triggered by the 1997 observations of Markarian 501 by the HEGRA array of Cherenkov telescopes\textsuperscript{44,45}. The most recent of these claims, by Meyer et al\textsuperscript{46,47}, makes use of a sample of 50 VHE gamma-ray AGN spectra from the current and previous generation of IACTs, and studies how the spectral points in the optically-thick regime (i.e. those affected by significant absorption in the EBL) deviate from the fluxes expected under some reasonable assumptions on the EBL density and on the intrinsic spectral shape of the gamma-ray emission. The authors find that, using the best-fit EBL density from H.E.S.S.\textsuperscript{38} ($\tau \simeq 1.3 \times \tau_{\text{FR08}}$), the spectral points at $\tau > 2$ are in average above the expectation, i.e. they show a smaller flux suppression than anticipated (see fig. 2). This excess seems to be correlated with the optical depth $\tau(E,z)$, and not with the energy of the spectral points, hence suggesting the anomaly is a propagation effect, rather than being related to the intrinsic source spectra. The statistical significance of the anomaly is 3.5 standard deviations\textsuperscript{47}. They term this effect “pair production anomaly”, and speculate that it might be due to conversion of gamma rays into (EBL-immune) axion-like particles and vice versa in the magnetic fields traversed by the radiation.

Figure 2: Relative residuals of measured VHE fluxes with respect to the expectations for reasonable intrinsic spectra and for the EBL density favoured by H.E.S.S. observations (taken from\textsuperscript{47}). The horizontal axis indicates the optical depth for $\gamma\gamma \rightarrow e^+e^-$. Spectral points in the $\tau > 2$ regime lie in average above the expectations.

Under that assumption, they present in a separate paper\textsuperscript{48} lower limits to the photon - ALP coupling constant $g_{a\gamma}$ as a function of the ALP mass. Since the conversion of photons into ALPs depends on the magnetic fields in the space between the source and the observer, several different scenarios were considered for the source, its environment and the intergalactic magnetic field. Conversions in the galactic magnetic field were also included in the framework. For each of the B-field scenarios and scanned ALP masses, the minimum value of $g_{a\gamma}$ to reproduce the observed anomaly was computed (fig. 3). Although this is presented as a lower limit to $g_{a\gamma}$, this is certainly not a “limit” in the same sense as the upper limits from direct axion searches. The existence of ALPs with lower coupling constants, or even the non-existence of ALPs, is not forbidden by these observations. What fig. 3 really shows is the region of the parameter space in which ALPs would be a viable explanation for the pair production anomaly.

It must be remarked that the statistical significance of the pair production anomaly is just 3.5 $\sigma$, and besides, there are a number of possible systematic effects which may be contributing to it. For example, in steep spectra, there is a significant spill-over of events towards larger energies, given the limited energy resolution of the IACT technique ($\Delta E/E \simeq 15\%$). The correction of
this effect requires a good matching of the data and the Monte Carlo (MC) simulations used in the calculation of the instrument response (something difficult to achieve, given the crucial role of the atmosphere in the IACT technique). Since energy reconstruction is trained on MC, any mismatch will likely result in worse energy resolution in the real data as compared to the simulations, hence in larger event spill-over in the data, which will not be fully corrected by the simulation-based response function. Another problem comes from the fact that the highest-energy points of VHE spectra are naturally biased towards higher fluxes: for an average flux slightly below the instrument sensitivity, positive fluctuations, of the signal or of the background, will make the point to become part of the measured spectrum, and the estimated flux will then have a positive bias. The corresponding negative fluctuations, on the contrary, would not be present in the spectra. The authors of the first paper\(^\text{46}\) discuss these sources of systematics and conclude that in the worst case they would reduce the significance of the anomaly from 4.2 \(\sigma\) to 2.6 \(\sigma\).\(^b\)

On the other hand, in the 17 high-quality VHE spectra from 7 sources used by the H.E.S.S. collaboration in the measurement of the EBL density, there seems to be no hint of anomalies for any of the spectral points, even at large optical depths (see fig. 4). It might be argued, indeed, that the high-\(\tau\) points enter the fit which determines the EBL density, but the energy- and redshift dependence of \(\tau\) are fixed to those of the FR08 model, so anomalous high-\(\tau\) points could not possibly pull the fit without worsening the agreement at lower \(\tau\). As mentioned above, the best-fit normalization, within uncertainties, is perfectly compatible with the FR08 value. Since the hypothesized ALP-gamma mixing would depend on the magnetic field structure between source and observer\(^\text{49}\), it is just possible that for those particular sources, by chance, the net effect of the ALPs is negligible. A plausible alternative to reconcile both results without ALPs is to blame the anomaly fully on experimental systematics which may be absent in high-quality spectra like those used in the H.E.S.S. EBL measurement.

Another recent work in which ALPs are proposed as a solution for an observed anomaly in VHE data is the paper\(^\text{53}\) by Tavecchio \textit{et al}, which addresses the difficulties in modelling the observations by MAGIC\(^\text{54}\) of the quasar PKS 1222+216. The fast variability of this object indicates a compact emission region close to the central engine, i.e. in a very \(\gamma\)-ray opaque environment, due to photon-photon interaction in the dense UV fields originated in the broad

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\(^{b}\)In the 2012 paper by Horns and Meyer\(^\text{46}\) the so-called “minimal EBL model” was used, and the significance of the anomaly was 4.2 \(\sigma\). For the updated 3.5 \(\sigma\) result\(^\text{47}\), using the scaled FR08 EBL, the effect of systematics is not reported, but assuming it to be similar, it would bring the significance down to around 2 \(\sigma\).
Figure 4: Transmission factor vs. gamma-ray energy for the best joint likelihood fit of EBL density and intrinsic spectra of a sample of very high quality H.E.S.S. observations of bright blazars. Adapted from 38. Three ranges of redshift are shown separately. Even for optical depth $\tau > 3$ (transmission < 0.05) the data (points with error bars) do not seem to be systematically above the expectations (solid lines and shaded regions).

line region. While ALPs are, once again, a possible way to reduce the optical depth and hence explain the observations, alternative models exist (see discussion in 53) which do not require new physics.

4.3 Spectral irregularities as a signature of photon - ALP mixing

It has been noted 49,50,51 that, due to the turbulent nature of the intergalactic magnetic fields (IGMF), the effects of ALPs on gamma-ray propagation, and in particular, the possible reduction of the EBL-induced flux suppression, will depend on the detailed magnetic field structure along the beam path, and will be impossible to predict for a single source. Even under the assumption of a certain IGMF intensity (or spectrum of intensities) and coherence length, only the average effect on a large number of sources can be predicted for a given ALP scenario. Wouters et al 51 propose an alternative method which can be applied to individual VHE spectra, namely to look for spectral irregularities resulting for the strong energy dependence of the ALP → $\gamma$ conversion probability in the so-called weak mixing regime, at energies close to the threshold of the process. This method has already been applied by the H.E.S.S. collaboration, and results are presented elsewhere in these proceedings 52.

5 Conclusions

With the current generation of IACTs, astronomy in the VHE band has reached its maturity, and is providing a wealth of data which allow to address, besides the traditional topics of high-energy astrophysics, a number of questions in the field of Fundamental Physics. Despite some interesting hints, no evidence for new phenomena has been found to date. Nonetheless, IACTs are already providing competitive constraints which foster the hopes set in the next-generation ground-based gamma-ray telescope, CTA 55.

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