Probing γ-ray Propagation With H.E.S.S.

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Volatile Monster At Heart Of Messier 87

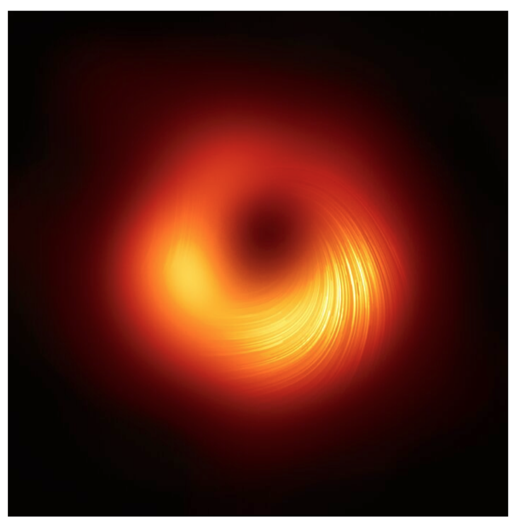

Fig.1. Image of the accretion disk surrounding the super massive black hole at the center of M87. Credit: ESO

Messier 87 or M87 for short, is also known as Virgo A and NGC4486 is a super-giant elliptical galaxy located at the center of the Virgo galaxy cluster. It hosts an active galactic nucleus, which spews collimated jets of energetic plasma which extend beyond 1,500 pc. It is located at a redshift of ~0.0042 and has been detected in flaring states in 2005, 2010 and 2018 with the H.E.S.S telescope array. During these states, we have seen γ-rays up to a few 10s of TeV.

Cosmic Showers Over The Namibian Desert

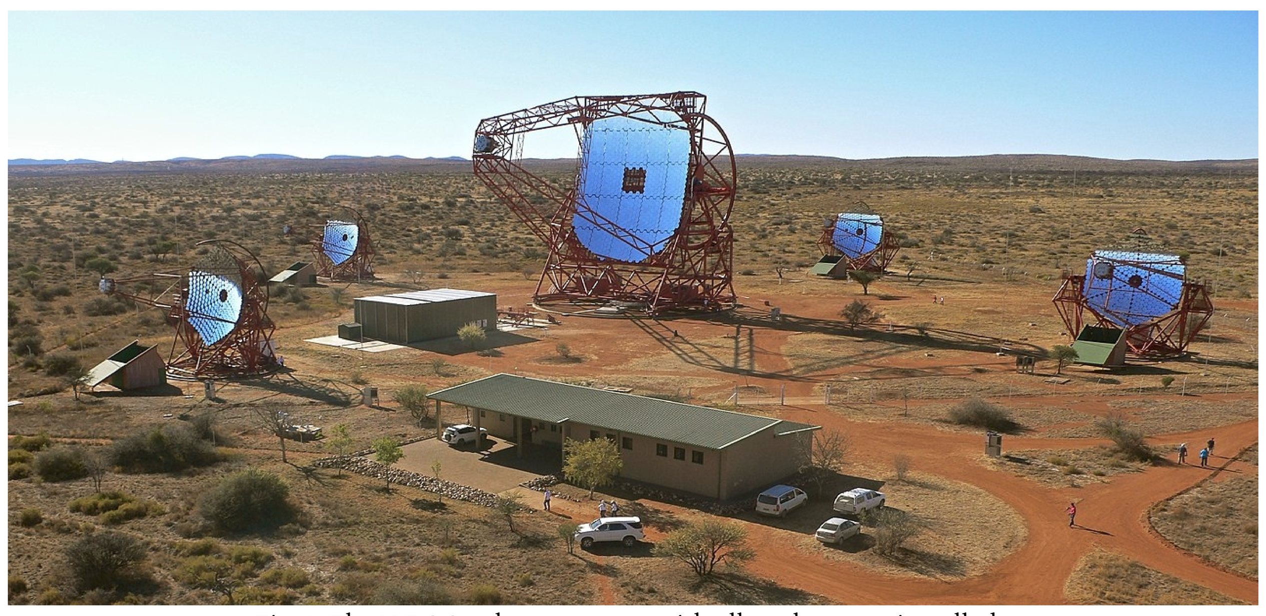

Fig. 2. The H.E.S.S. telescope array with all 5 telescopes installed. Credit: H.E.S.S. Collaboration

The **H**igh **E**nergy **S**tereoscopic **S**ystem, or H.E.S.S. is an array of 5 Imaging Air Cherenkov Telescopes located in the Khomas highlands of Namibia. The array consists of 4 small telescopes CT1-4 of 12 m diameter and one large central telescope CT5 with 28 m. H.E.S.S. is capable of detecting γ-rays within an energy range of 50 GeV – 100 TeV. It began operation with CT1-4 in 2004, CT5 being added in 2012 as an upgrade.

EBL Proves Troublesome For VHE γ-rays

The **E**xtra-galactic **B**ackground **L**ight, or EBL is a diffuse photon background that is present across the Universe. Its primary components are photons emitted from star formation throughout cosmic history, by re-emission from cosmic dust, and from AGNs. The EBL consists of photons between ultraviolet and far-infrared wavelengths, and depending on their energy have a chance of interacting with γ-rays traversing through this photon field. The higher the γ-ray's energy, the more readily it interacts with and scatters off the EBL. In VHE sources, this attenuation leads to a visible cut-off which becomes more significant with growing distances [3].

Elusive Axions/ALPs Could Be Dark Matter

These pseudo-scalar Nambu-Goldstone bosons came into the limelight when predicted by Weinberg and Wilczek [8,9] independently, in 1978. They predicted that spontaneous symmetry breaking in the Peccei-Quinn symmetry, which was originally introduced to solve the strong CP problem, would lead to the appearance of a particle Wilczek named the "Axion", referring to a soap brand because this particle "cleaned up" the strong CP problem. **A**xion **L**ike **P**articles are theoretical counterparts to the QCD axion, but we treat their mass and coupling to the photon field as independent parameters. These particles, would make for very good Dark Matter candidates.

Fig. 3. Axion dish liquid. Credit: Colgate-Palmolive

Axions/ALPs Have Identity Crisis

Axions and ALPs are weakly coupled to the Standard Model. Its coupling to the electromagnetic field predicts a very interesting phenomena: photon-ALP oscillations [7] inside a magnetic field. This provides an exploitable mechanism to search for these elusive particles. The interaction between photon and axion/ALP in the presence of a magnetic field is represented by the Feynman diagram shown in Fig. 4.

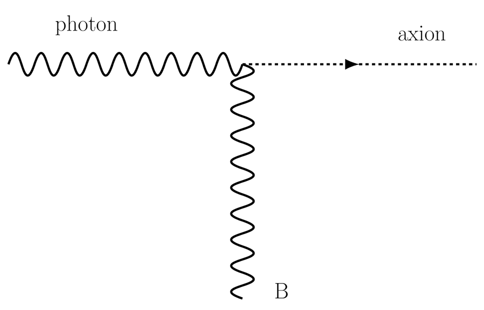

Fig. 4. Feynman diagram illustrating photon-axion oscillation.

Photon-ALP oscillations can be modeled using the gammaALPs package [5] by providing a magnetic field model, mass and coupling $g_{a\gamma}$. The models are characterized by their signature "wiggles"which appear in the spectrum of the observed VHE γ-ray sources. Other experiments which attempt to detect these oscillations are also being performed in ground based detectors.

Power Laws Can't Model Everything?

Data required for the study was obtained from the H.E.S.S. archival database by specifically limiting the data to observations made during flaring/high states of M87. Only observations with high count rates, specifically those exceeding a rate of 0.2 excess counts per minute were used for the analysis. The data was reduced within an energy range of 300 GeV - 31.6 TeV and the respective spectra were extracted. Furthermore, all the spectra were stacked for the analysis.

To establish the intrinsic shape of the spectrum, fits were performed on the spectrum with a power law and a log parabola. The results showed a preference for the curved log parabola over the straight power law, with a significance of ~5.4σ. The curvature was further tested by repeating the fits within a limited energy range of 300 GeV – 10 TeV, excluding the EBL contribution which is expected to dominate above ~10 TeV at this redshift. This further confirmed a preference for a curved intrinsic spectral model. This result proves quite interesting since significant curvature has not been observed in the spectrum of M87 in the high energy γ-rays previously. Follow-up on this result might prove interesting in the scope of other scientific studies.

Comic Of The Day

Credit & Rights: Tom Gauld for New Scientist

New Investigation Into Untamed Wilderness Of The EBL

The far-infrared region of the **E**xtra-galactic **B**ackground **L**ight is still largely unconstrained. Constraints are placed in this region of the photon background using the statistics obtained from M87 during its high states. The spectrum of M87 is fit against a log parabola with EBL attenuation. The EBL attenuation follows the equation:

$$\exp(-\alpha \times \tau(E, z))$$

Here, τ is the optical depth of the EBL, α is the normalization and E and z are energy and redshift respectively. We use the Dominguez et. al. 2011 [2] EBL model here. After performing fits, an upper limit is placed at $\alpha \leq 2.82$ with 95% confidence.

Chaos In The Virgo Cluster: Turbulent Magnetic Fields

In an attempt to search for photon-ALP oscillation signatures in the VHE γ-ray spectrum of M87, the spectrum is modeled and fit against pseudo-random spectral models containing their signature: wiggles. The specific shape and position of these wiggles depends on the external magnetic field, the ALP mass **m** and the coupling to the photon field $\mathbf{g_{a\gamma}}$. The magnetic field of the Virgo cluster is simulated as a divergence free, homogeneous and isotropic Gaussian turbulent magnetic field with zero mean and variance B^2 [6]. It is assumed that the power spectrum of the turbulence follows a power law with wave numbers, $M(k) \propto k^q$ between $k_L \leq k \leq k_H$ and otherwise zero [4]. The central magnetic field is constrained to 34.2 μG after modeling the magnetic field as having an inner and outer region and comparing Faraday rotation measures of from M87 and M84. The simulations are performed using gammaALPs (v0.3.0) [5], the process of which has been described in depth in a previous publication [1].

Is The γ-ray Spectrum of Messier 87 Wiggling?

Utilizing 1000 pseudo-randomly simulated realizations of the Virgo magnetic field, expected photon-ALP wiggles are simulated over a log parabola intrinsic spectrum. These models are simulated repeatedly for individual points in a 5x5 grid along the mass-coupling parameter space. The axes span a range of m = 3.162 neV – 316.2 neV and coupling $g_{a\gamma} = 4.6 \times 10^{-12} - 10^{-10}$ GeV^{-1}, with each axis being split into 5 log-spaced bins. Each of the 1000 models obtained for each individual pixel is fitted against the M87 spectrum by varying the intrinsic spectrum parameters.

The likelihood ($C = -2 \ln \mathcal{L}$) of each pixel is considered to be statistically represented by the 95[th] percentile value of the distribution of likelihoods for said pixel as illustrated in Fig. 5. . This 95[th] percentile value is used in each pixel to make a comparison against the no ALPs case, which in this case is a log parabola with EBL attenuation. A comparison of models is shown in Fig. 6. while the comparison of likelihoods is shown in Fig. 7. The fits show no significant preference for the ALPs model. Even in our best case, only a likelihood difference of 2.84 is observed, implying a preference for the ALPs model < 2σ. This result proves inconclusive and the wiggles cannot be separated from statistical fluctuations.

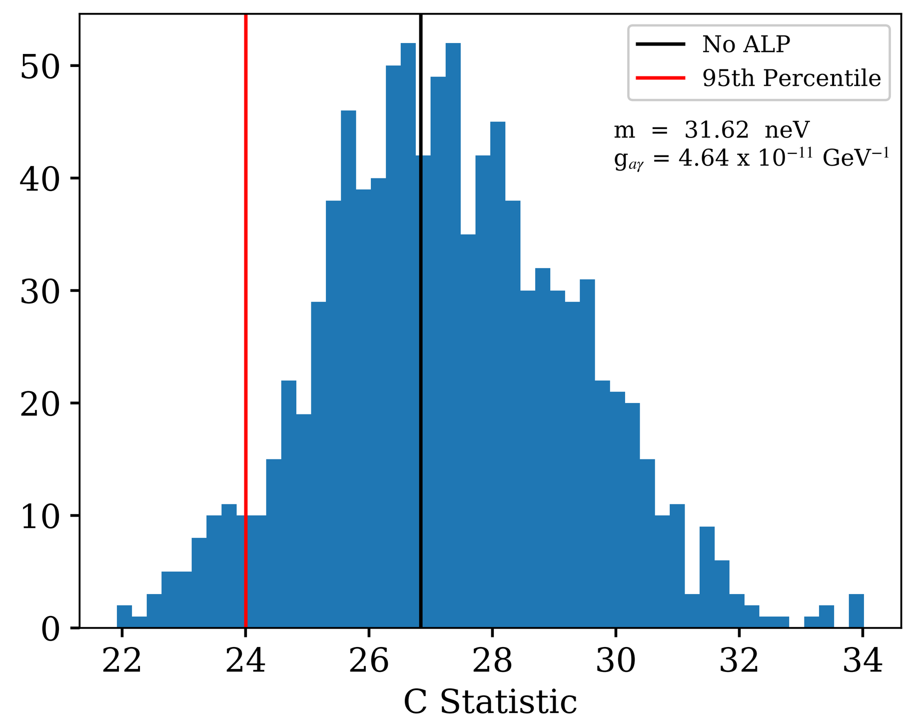

Fig. 5. The Likelihood of the No ALP fit shown against the distribution and 95[th] percentile of the most likely pixel in the parameter space.

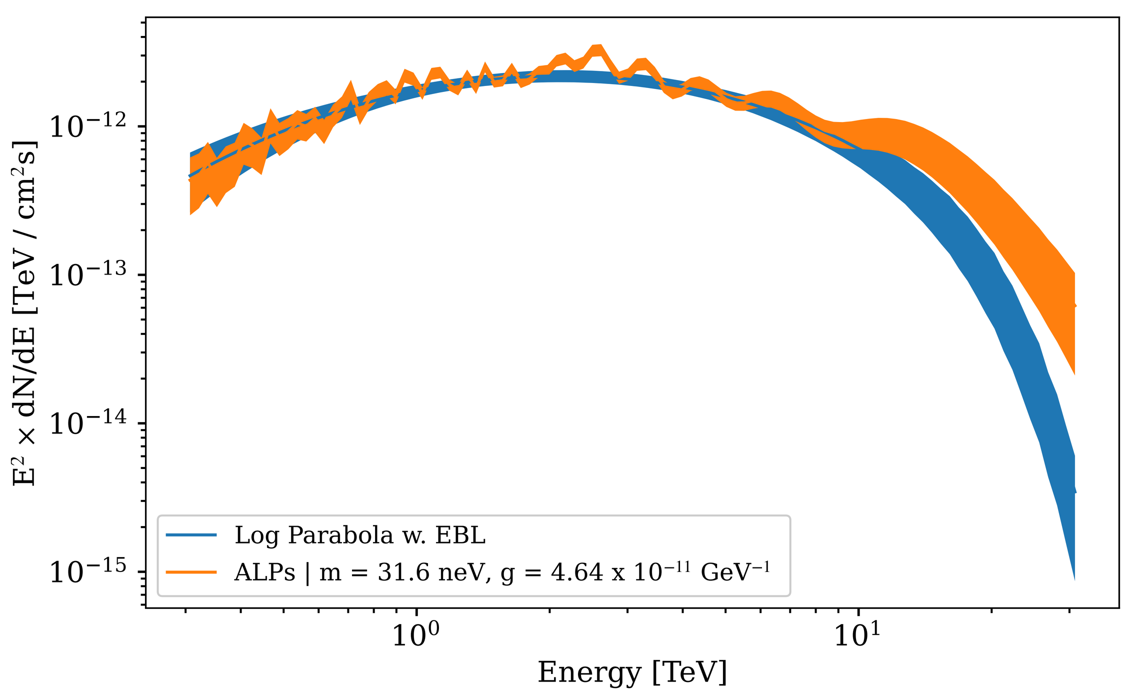

Fig. 6. The No ALPs model of a log parabola with EBL attenuation (norm at upper limit 2.82) plotted against the 95[th] percentile ALP model for the most preferred pixel in our parameter space.

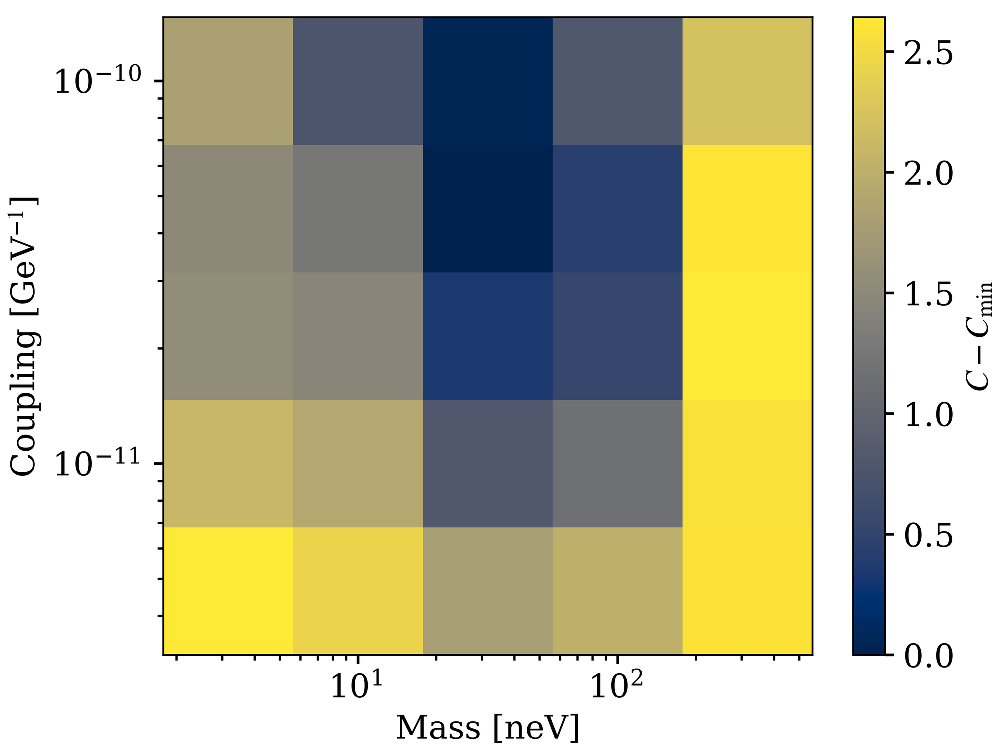

Fig. 7. The Likelihood difference between the most preferred pixel and the deviation of the other pixels from this value.

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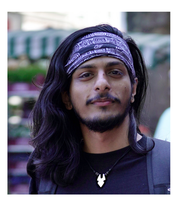

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