# CTAO sensitivity to axion-like particles

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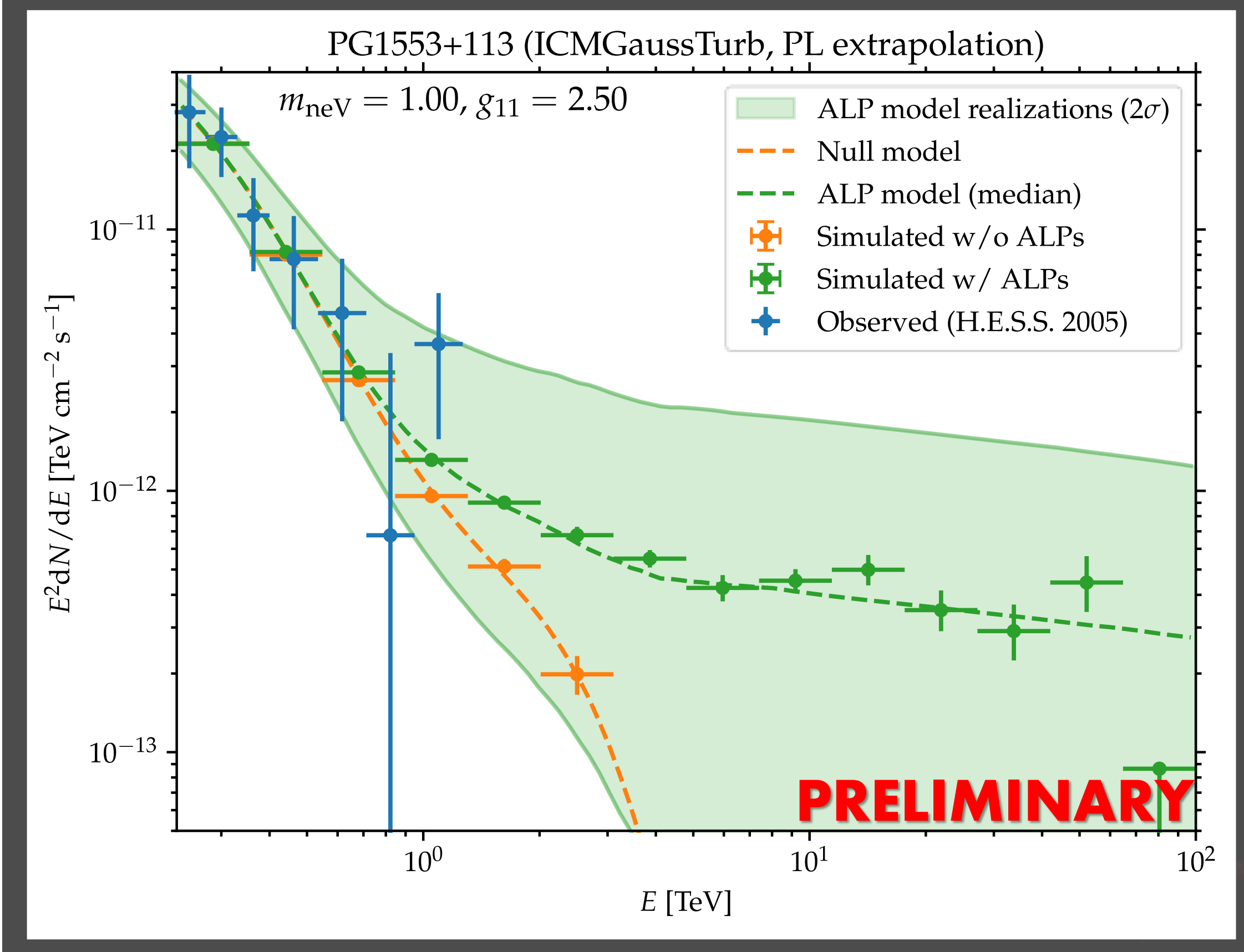
Axion-like particles (ALPs) are a common feature in several extensions of the Standard Model, arising, for example, as a solution to the strong CP problem in quantum chromodynamics, or as a prediction of string theories. A significant property for the experimental detection of ALPs is their coupling to photons, which enables ALP-photon conversions in ambient magnetic fields.
In particular, gamma-ray photons could convert into ALPs in the magnetic fields of distant objects and then reconvert in the Milky Way's magnetic field. By eluding absorption by the extragalactic background light (EBL), such a mechanism could produce a hardening in the gamma-ray spectra of these sources. We investigate the capability of the Cherenkov Telescope Array Observatory (CTAO) to detect signals of ALP-photon conversions in the very-high-energy spectra of known blazars at energies above 10 TeV, comparing different magnetic field scenarios.

## Axion-like particles in high-energy astrophysics

Distant astrophysical sources ($z \lesssim 1$) are difficult to observe in the very high energy (VHE) gamma rays due to scattering on the extragalactic background light (EBL), i.e. the integrated emission produced by stars over the course of their lifetimes, and the cosmic microwave background (CMB). Interaction between the VHE photons and the soft EBL photons leads to electron-positron pair production via the Breit-Wheeler process, making the Universe effectively opaque to VHE radiation. It has been proposed (Batković *et al*, 2021 for a review) that axion-like particles (ALPs) could reduce this opacity by ALP-photon oscillations in external magnetic fields. These oscillations essentially depend on the ALP mass $m_a$ and ALP-photon coupling $g_{a\gamma}$.



In the magnetic fields at the source, VHE photons could convert into ALPs, which would then traverse the EBL and reconvert to photons in the Milky Way's magnetic field. In this case, the resulting VHE spectra of distant sources would be harder than expected in the EBL-only case, providing a signature for ALP-photon interaction. The observed spectrum of a source with intrinsic spectrum $\phi_{\rm int}$ would be given by

$$\phi_{\rm obs} = P_{\gamma\gamma}\phi_{\rm int},$$

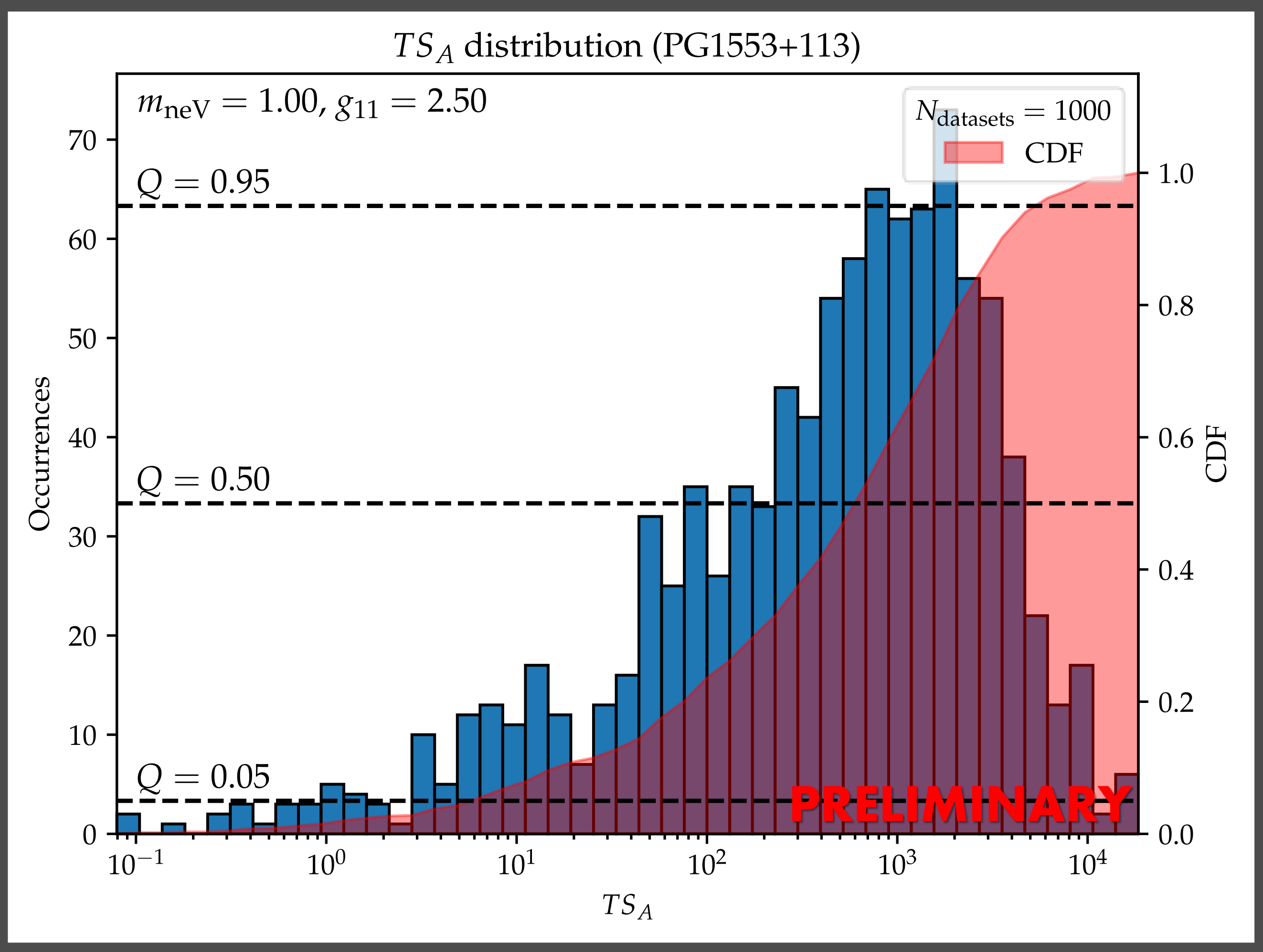
where $P_{\gamma\gamma}$ is the photon survival probability.
The figure on the left shows an example simulated spectrum of blazar PG 1553+113 both in the presence and absence of ALP-photon conversions. The intrinsic spectrum was extrapolated up to 100 TeV, and the highlighted band in the ALP case reflects different configurations of the turbulent magnetic field considered (see «Dataset simulation» for details).

## Dataset simulation

Choosing two known distant blazars, PG 1553+113 ($z \gtrsim 0.4$) and PKS 1424+240 ($z \gtrsim 0.6$), we simulated 50 h of observations for each source in Gammapy v1.0 using the CTAO Southern Array prod5 instrument response functions (IRFs). Following Meyer and Conrad, 2014, we considered two different source magnetic field scenarios, a turbulent intra-cluster magnetic field ($B \sim 1\ \mu$G over $\sim$ kpc scales) and a coherent jet magnetic field ($B \sim 10^{-2}$ G over $\sim$ pc scales) respectively.
Photon survival probabilities over the relevant ALP parameter space were computed using the GammaALPs software and intrinsic spectra were calculated by deabsorbing observed points by H.E.S.S. (2005) and VERITAS (2009) respectively. The simulated spectra were then computed between $0.1 - 100$ TeV assuming both a simple power law (PL) and a power law with exponential cutoff (ECPL) with cutoff energy 1 TeV as intrinsic spectral shapes. The assumed EBL model is the one by Domínguez *et al*, 2011.
A test statistic (TS) was used of the form

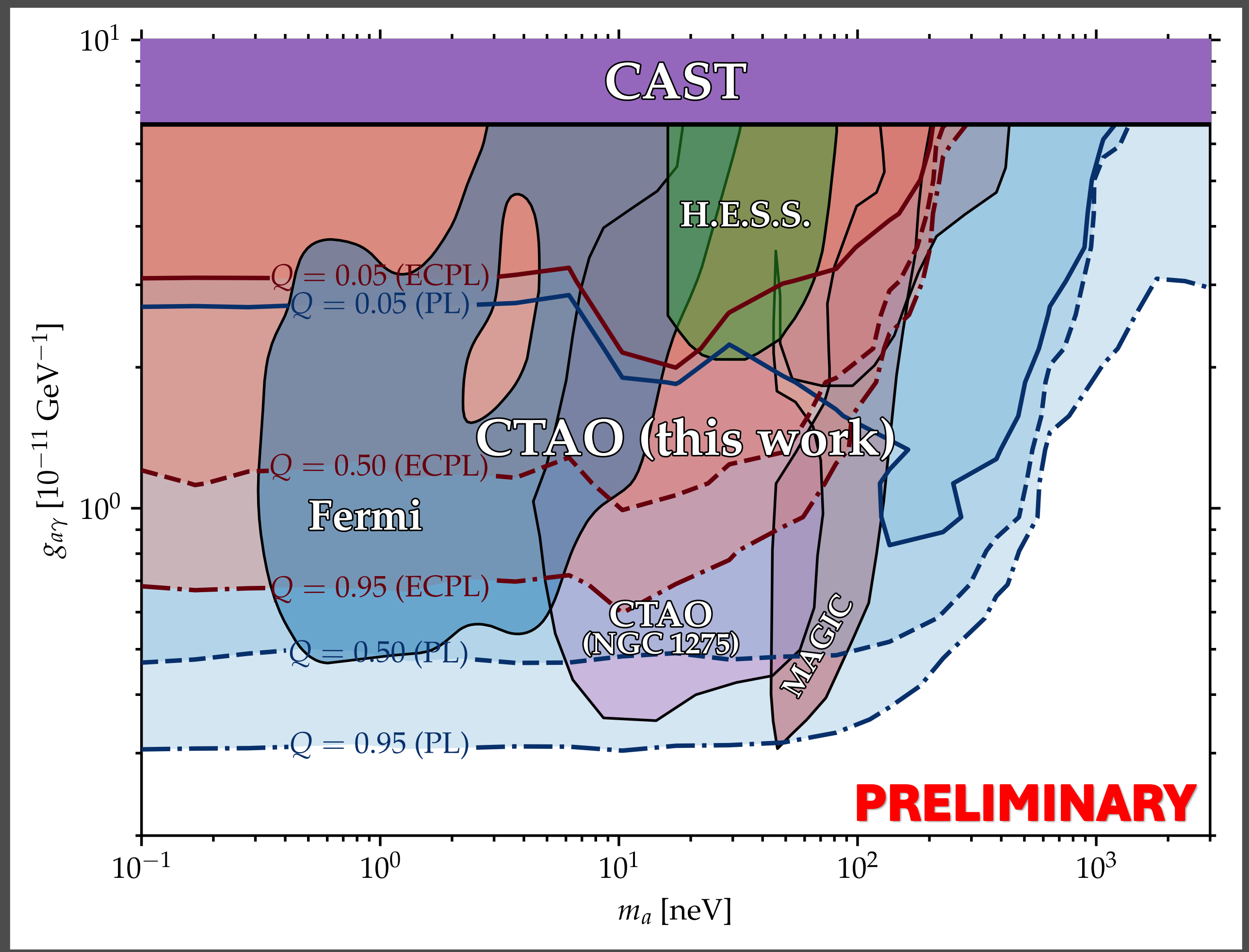
$$TS_A = -2\ln\frac{\mathcal{L}(g_{a\gamma}=0)}{\mathcal{L}(m_a, g_{a\gamma}, B)}.$$

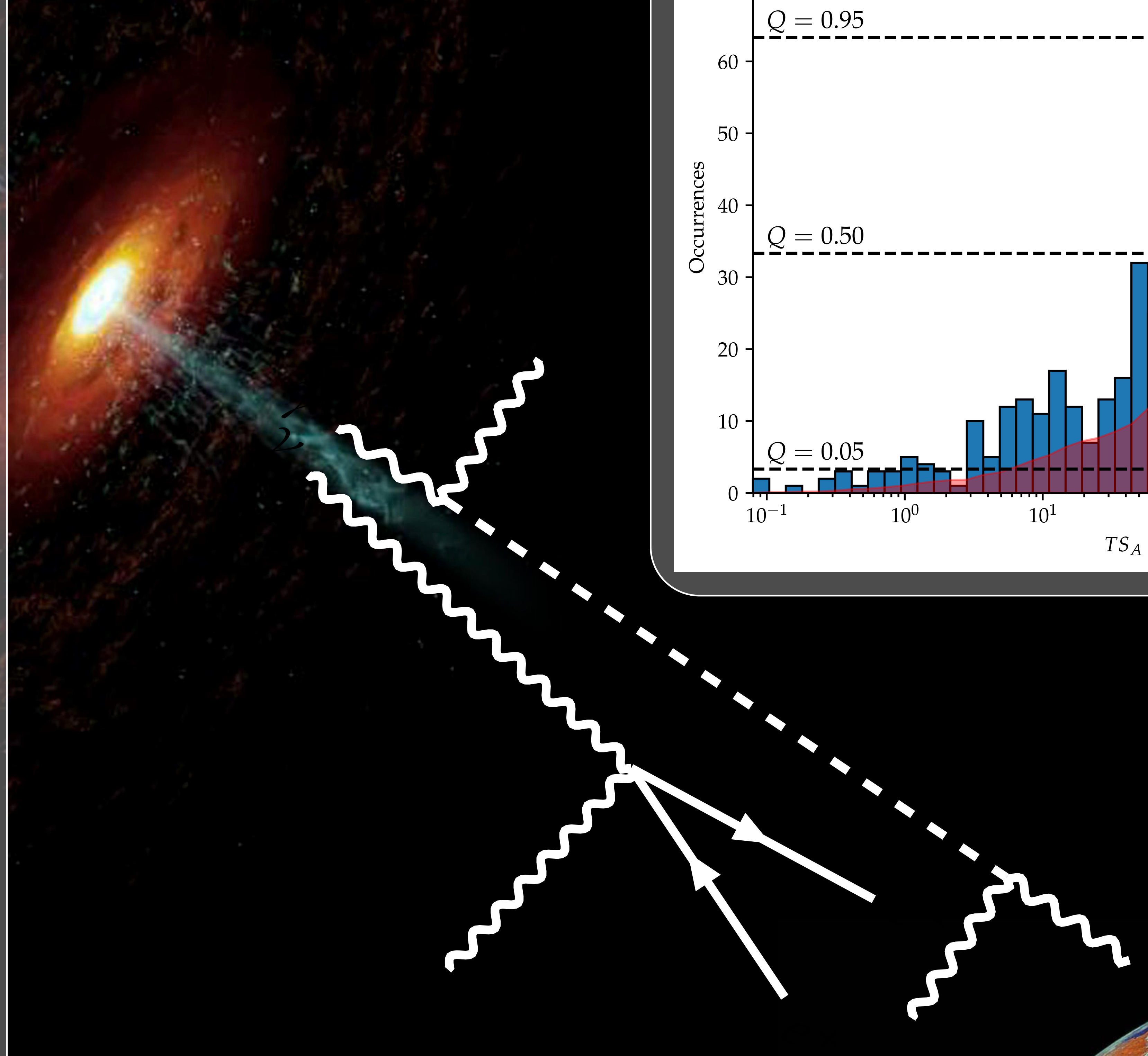
In the case of turbulent cluster fields, the same choice of parameters may lead to widely varying TS values depending on the specific field realization. Therefore a full TS distribution had to be determined for each ALP parameter set $(m_a, g_{a\gamma})$, as shown below.



## Results

The obtained TS for each simulated dataset was compared to the expected distribution in the null hypothesis (which we checked to be compatible with a $\chi^2$ distribution with 7 degrees of freedom) in order to obtain detection confidence levels for each point in the ALP parameter space.
Following Meyer and Conrad, 2014 we used «Asimov datasets», which allow us to regard the obtained significance as a median value. In the case of turbulent magnetic fields, however, the TS still depends on the specific field realization. The choice of different quantiles of the TS distribution for a certain ALP point thus reflects different degrees of optimism in detection significance.
Below we compare the combined $3\sigma$ sensitivity over the ALP parameter space from both considered blazars with known excluded regions by other gamma-ray observatories and with the CTAO projections from simulated observations of NGC 1275 (reported in Abdalla *et al*, 2021). We note that, in general, the regions of the parameter space that can be probed greatly depend upon the employed instruments and considered sources, so it is worthwhile to gather, simulate and combine data from different observations.
Work is currently in progress to improve these projections by using dedicated simulations carried out within the CTAO collaboration. Reduction of uncertainties will be possible as soon as more accurate magnetic field models will be available.





## References and acknowledgements

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We would like to thank the computing centers that provided resources for the IRF generation, listed at https://zenodo.org/records/5499840.
This project has made use of the software packages Gammapy v1.0.1 (https://zenodo.org/records/7311399) and GammaALPs v0.3.0 (https://github.com/me-manu/gammaALPs).
The H.E.S.S. and VERITAS data points used are available on the respective collaboration websites: https://www.mpi-hd.mpg.de/HESS/ and https://veritas.sao.arizona.edu/.
The ALP parameter space limits used for comparison are collected in https://github.com/cajohare/AxionLimits.

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