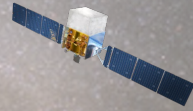


Gamma-Ray Constraints on Heavy Axion-Like-Particle Decays from Fermi-LAT and H.E.S.S. Blazar Spectra



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On behalf of the Fermi-LAT and H.E.S.S. Collaborations
in particular Sara Porras Bedmar and Manuel Meyer

Image Credits: The H.E.S.S. Collaboration

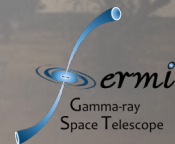
<https://arxiv.org/abs/2606.11923>



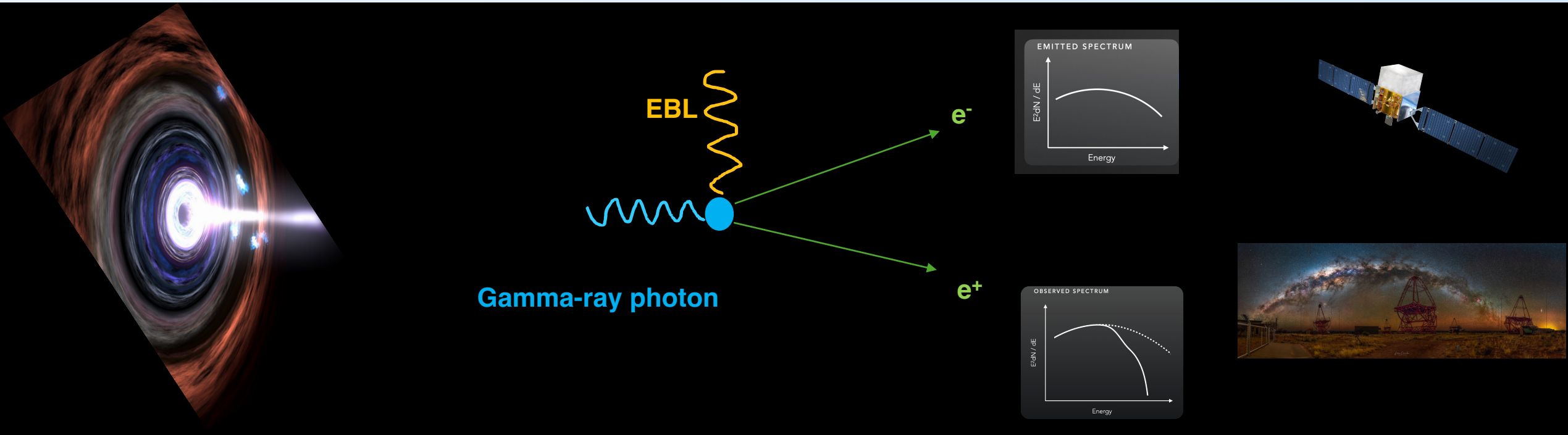
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Attenuation of VHE gamma rays from extragalactic sources

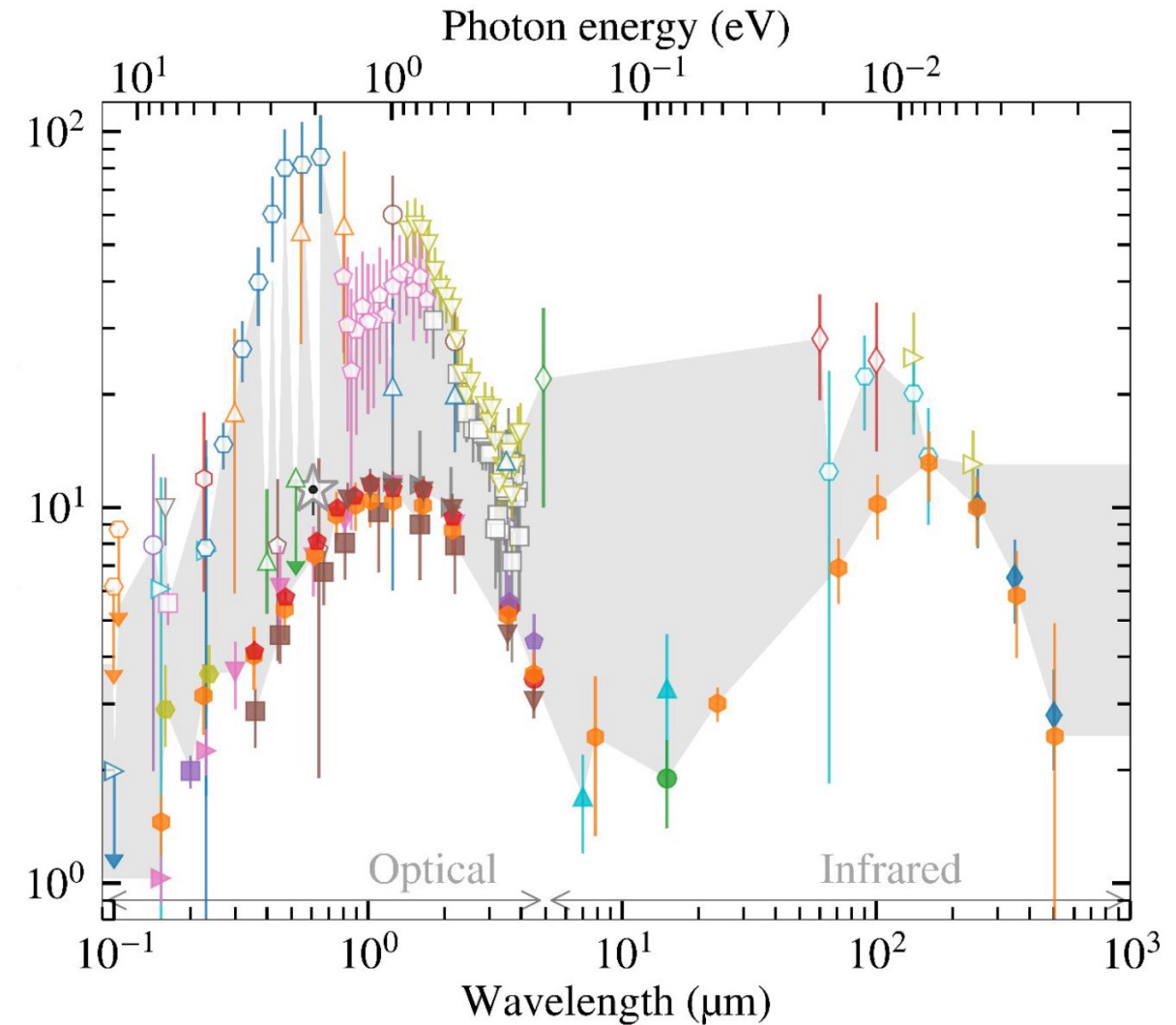


- Very-high-energy (VHE; $E_\gamma > 100\text{GeV}$) gamma rays from extragalactic sources are attenuated through electron-positron pair production on the extragalactic background light (EBL)
- The resulting attenuation increases with energy and redshift

Image Credits: NASA/Goddard Space Flight Center Conceptual Image Lab, The H.E.S.S. Collaboration, Manuel Meyer and Sara Porras Bedmar

Extragalactic Background Light (EBL)

- The EBL is the diffuse optical–infrared background produced by galaxies
- Direct measurements are challenging due to foreground contamination
- Gamma-ray studies therefore rely on physically motivated EBL models

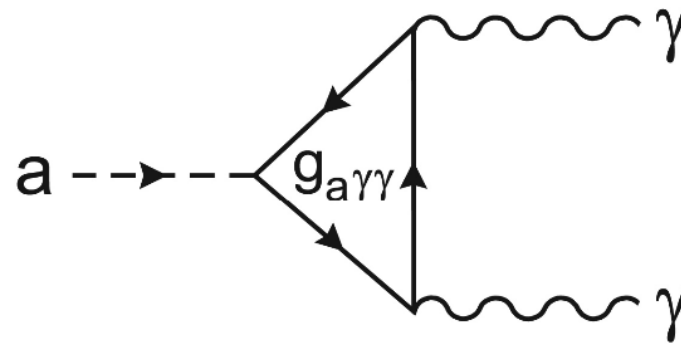


Data from: Hill et al. (2018), Biteau (2025), Postman et al. (2024)

Plot credit: Sara Porras Bedmar

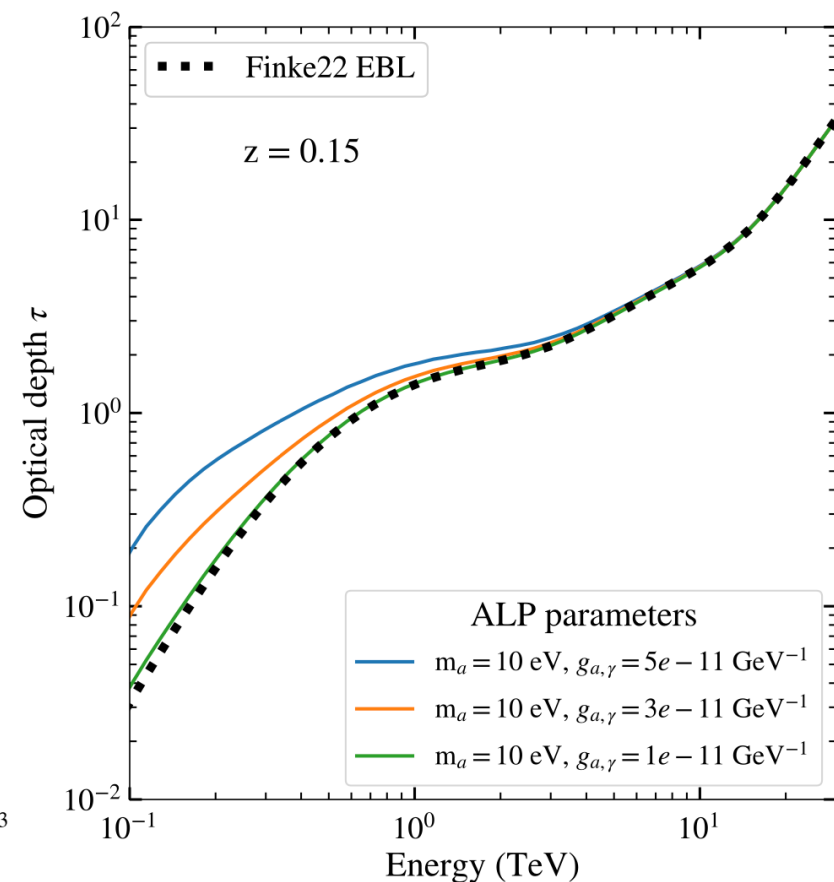
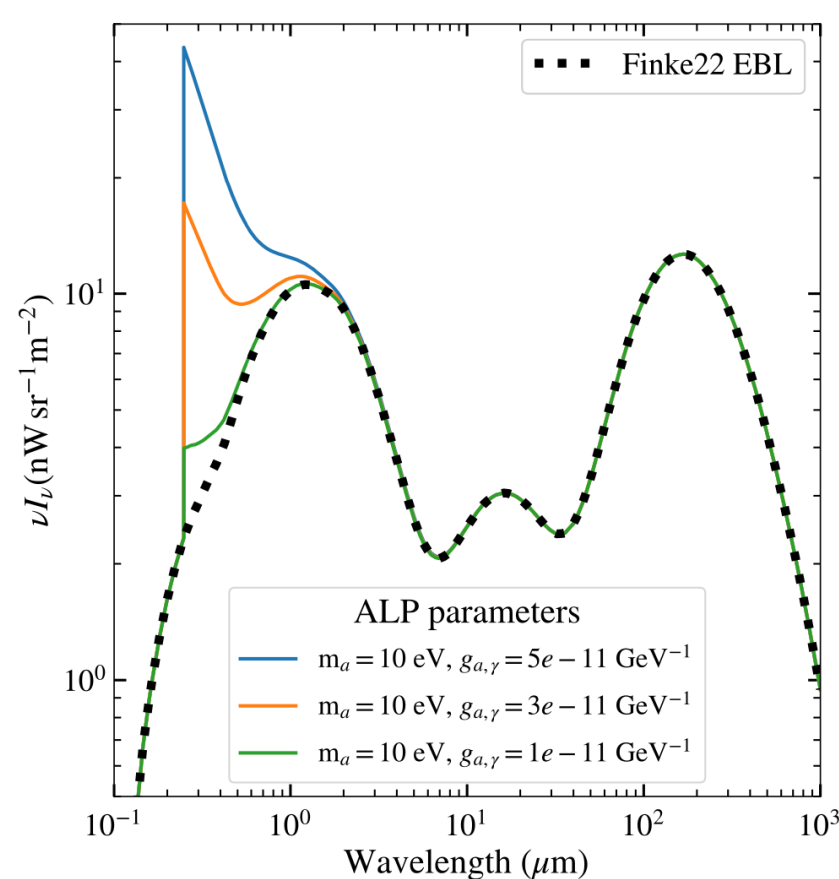
Axion-like particles (ALPs)

- Axion-like particles (ALPs) are well-motivated dark-matter candidates arising in extensions of the Standard Model
- ALPs couple to photons through the photon–ALP interaction
- If ALPs constitute the dark matter, their cosmological decay contributes additional photons to the EBL
- This additional EBL increases the opacity to VHE gamma rays
- Here, we test for this decay contribution



Inclusion of ALP decay in the EBL

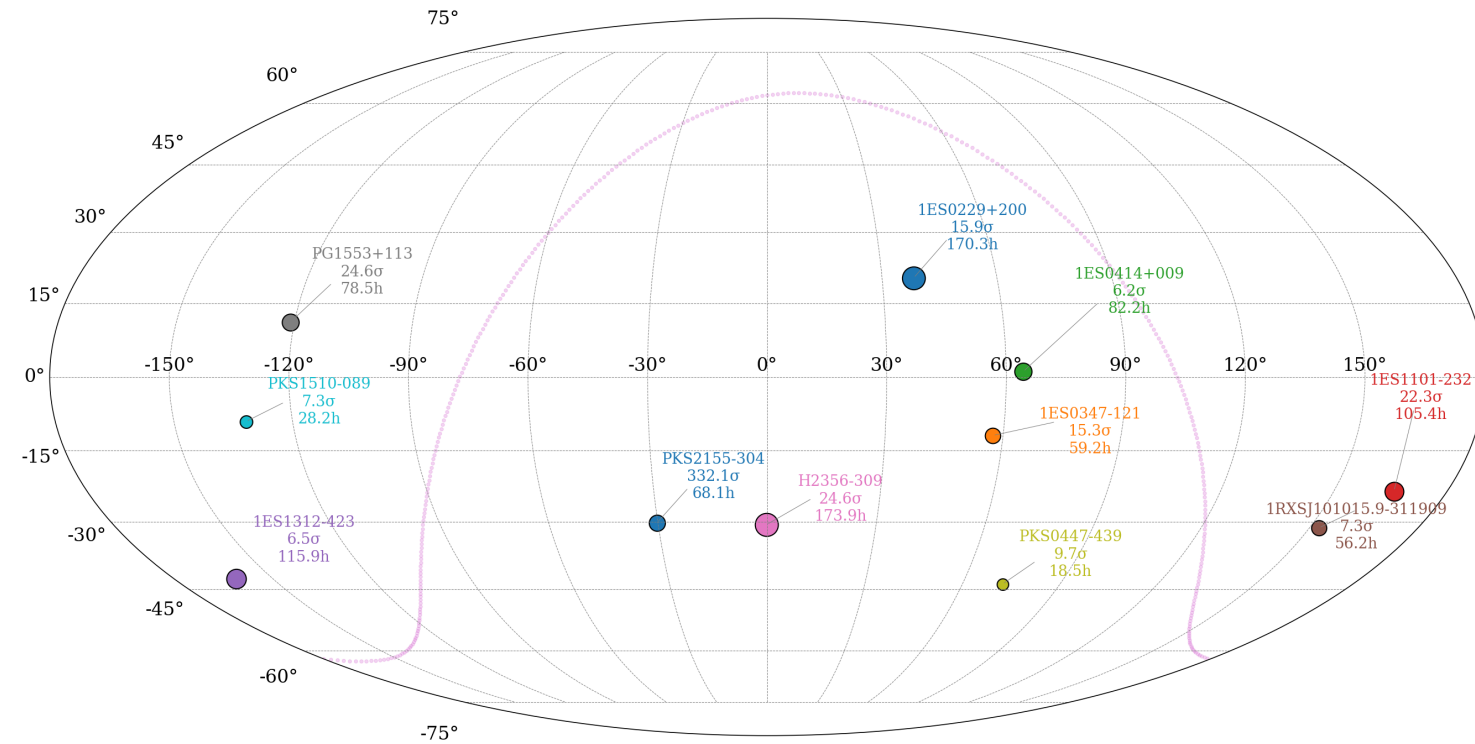
- Including the ALP contribution increases the optical depth, depending on the mass (m_a) and coupling constant ($g_{a\gamma}$)
- Fitting observed spectra with EBL models that include ALP decay allows us to constrain the ALP parameter space



References: [Porras-Bedmar, Meyer, and Horns\(2024\)](#), [Bernal et al.\(2023\)](#), [Korochkin et al.\(2020\)](#)

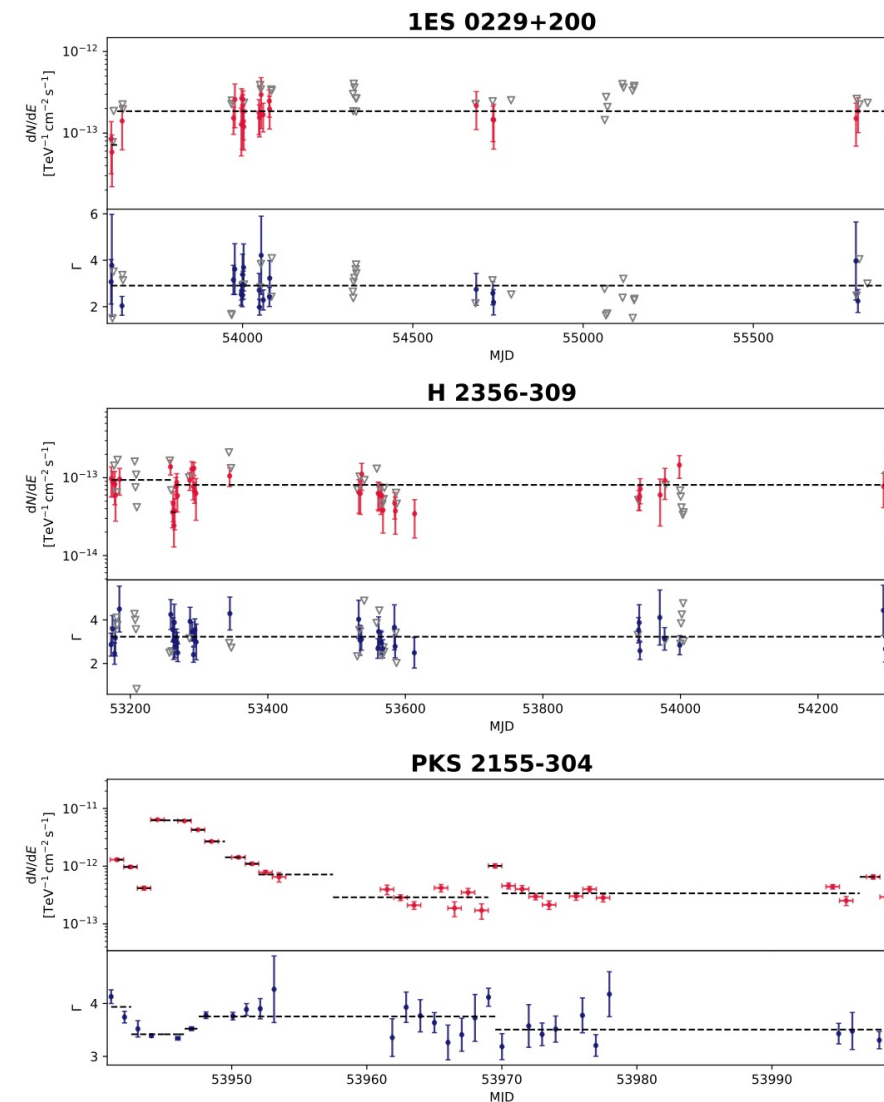
Source Selection

- Sample selection is driven by photon statistics, ensuring well-measured spectra for ALP/EBL studies
- Focus on the optically thick regime ($\tau > 2$) to maximise sensitivity to deviations from standard gamma-ray absorption
- Blazar sample selected from published H.E.S.S. observations probing $\tau > 2$, prioritising high energies and redshifts
- Final sample: 11 blazars satisfying the selection criteria ($\tau > 2$, $\theta_z < 60^\circ$)



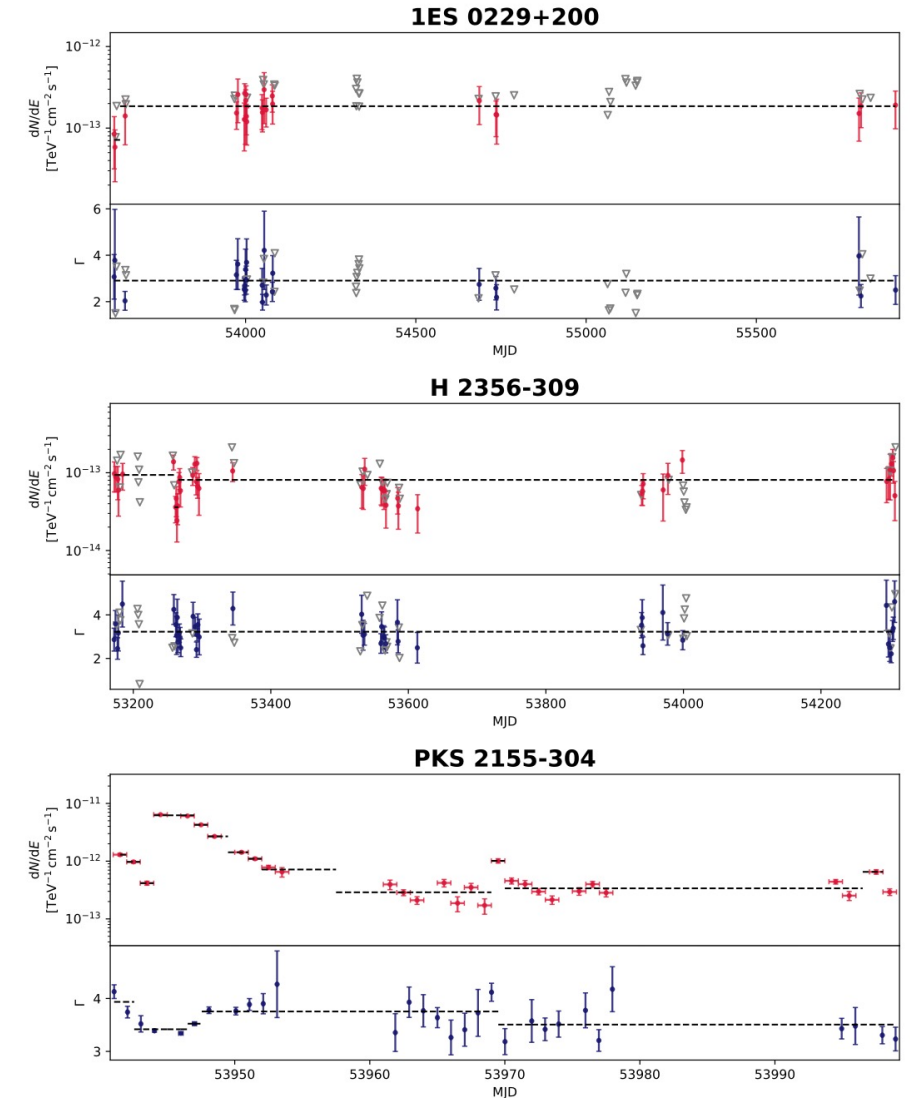
H.E.S.S.: Observations and Analysis

- Use homogeneous CT1–4 data only, excluding CT5, to avoid configuration-dependent systematics
- Event reconstruction with ImPACT using standard cuts, wobble-mode observations, and reflected-region background estimation
- Energy-scale systematics treated as a profiled nuisance parameter ($E \rightarrow E(1 + s)$) with a 10–15% Gaussian prior



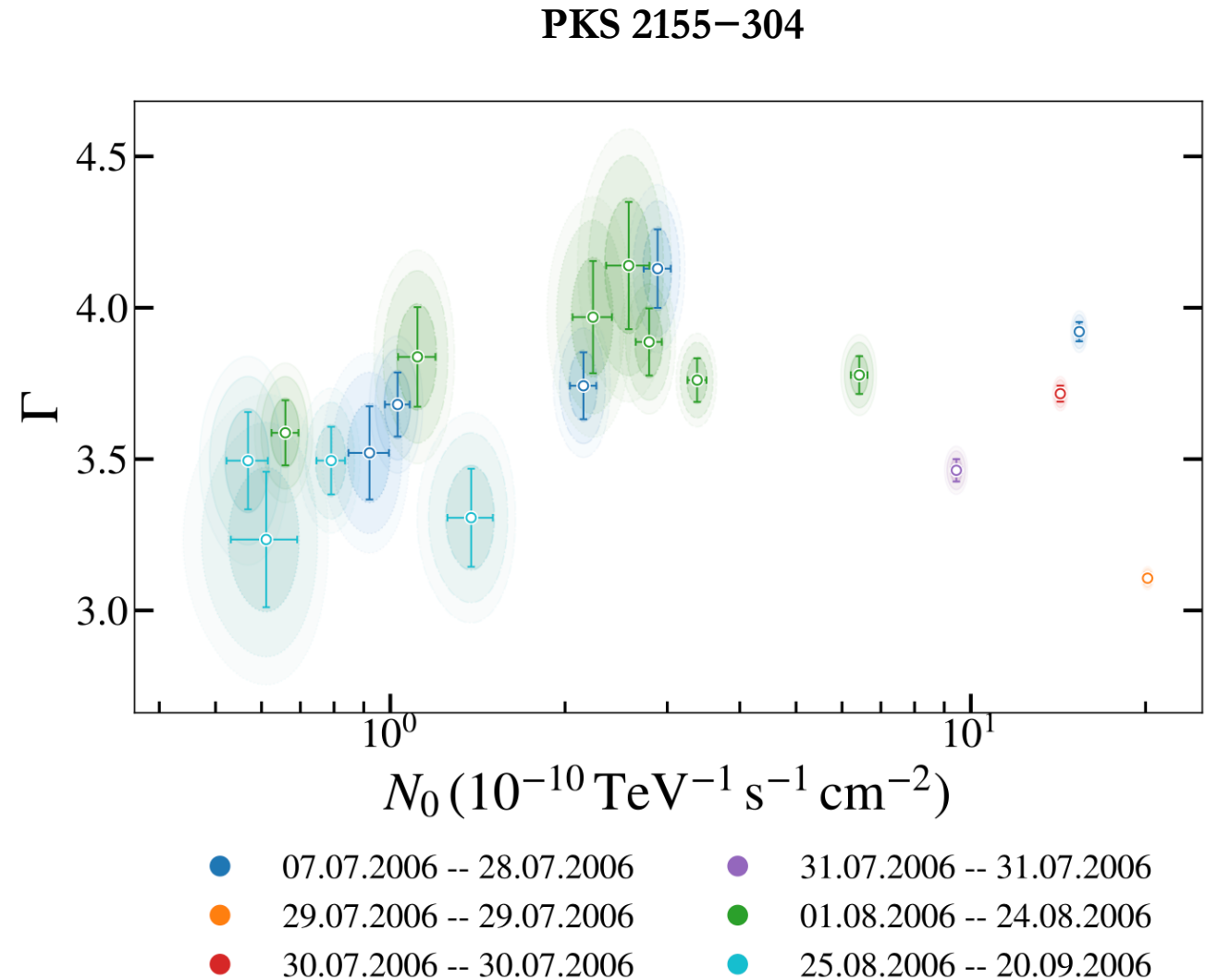
H.E.S.S.: Observations and Analysis

- Reduced event lists are converted into FITS for compatibility with Gammapy, enabling spectral fitting and nightly VHE light curves
- Temporal segmentation is applied to identify variability in the light curves
- Bayesian Blocks are used to identify significant flux changes
- Non-variable sources yield a single block, while variable sources are divided into multiple flux states



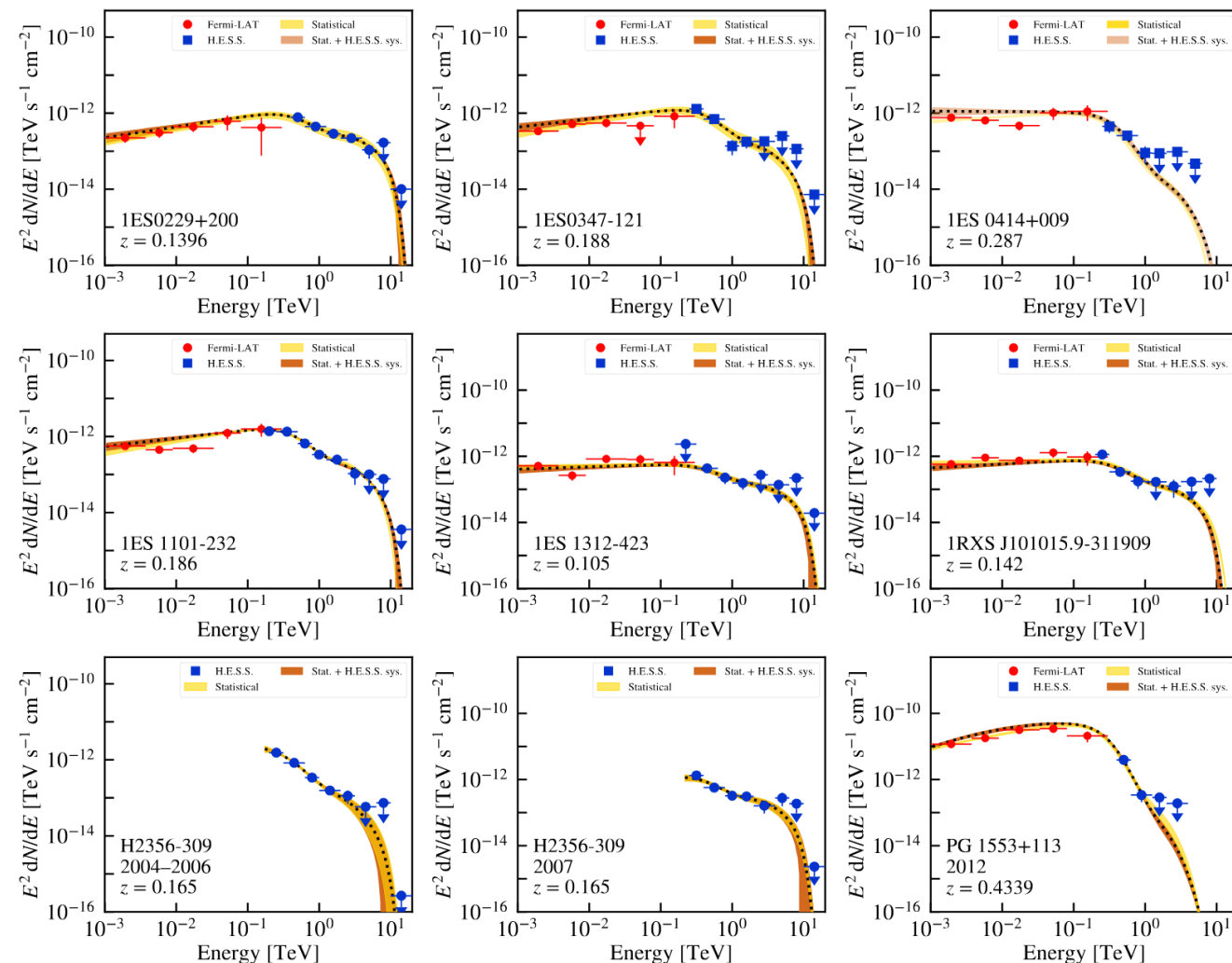
Final Segmentation

- Each block is independently fit with a power-law model to test for spectral evolution beyond what Bayesian blocks alone can detect
- Photon index (Γ) and flux normalization (N_0) are compared between adjacent blocks; spectral changes $> 2\sigma$ motivate keeping them separate
- Blocks with no significant spectral differences are merged, reducing spectral-averaging biases (illustrated for PKS 2155–304)



Fermi-LAT Observations and Data Analysis

- Extend spectra to 1–300 GeV using Fermi-LAT data
- Use 14-year averaged LAT data for non-variable sources, and contemporaneous segment-wise data for variable sources
- Pre-Fermi H.E.S.S. flares are analysed using H.E.S.S. data only
- Fermi-LAT analysis is performed with Gammapy and cross-checked using the Fermi Science Tools and Fermipy
- Fermi-LAT binned likelihood analysis (10° ROI; 4FGL-DR4 source model)
- Standard Galactic and isotropic diffuse emission models (free normalisations)



Joint Analysis

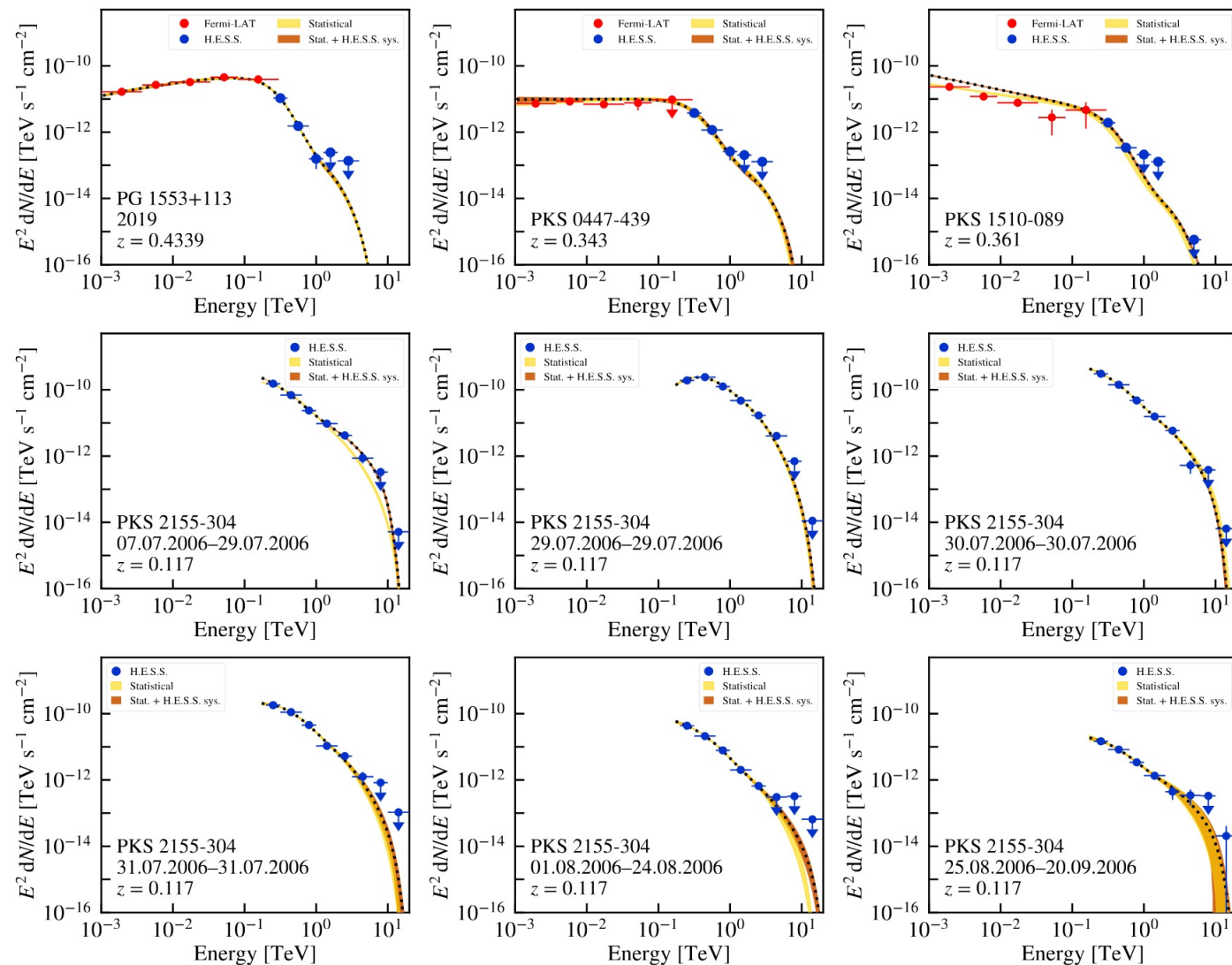
- Joint Fermi-LAT + H.E.S.S. analysis performed with Gammapy
- Spectra obtained by maximising the joint Poisson likelihood

Power Law

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0} \right)^{-\gamma}$$

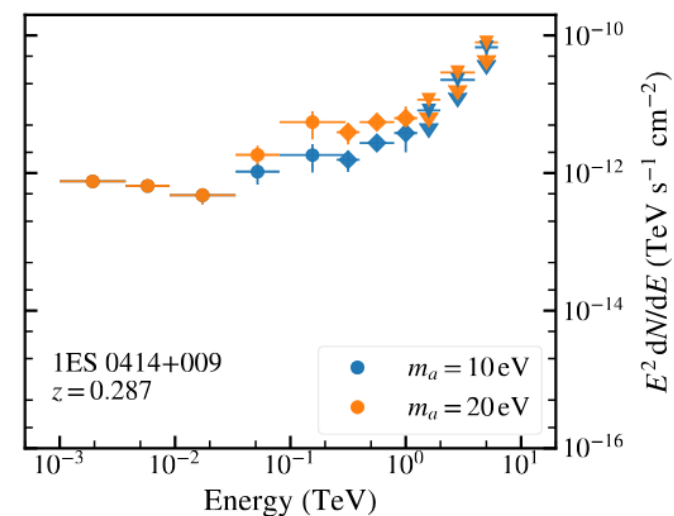
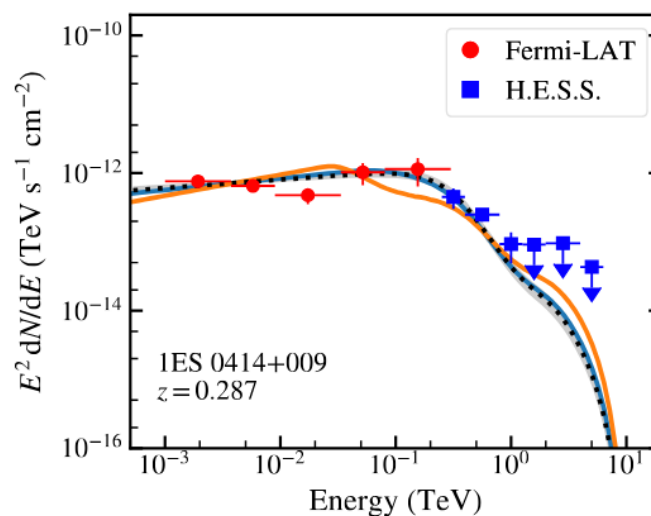
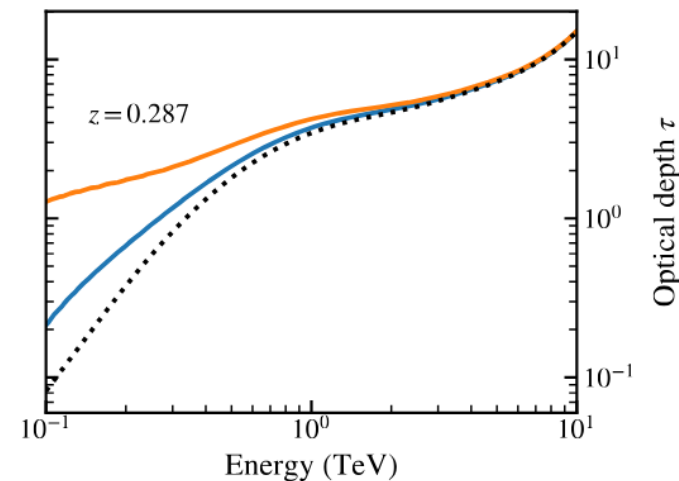
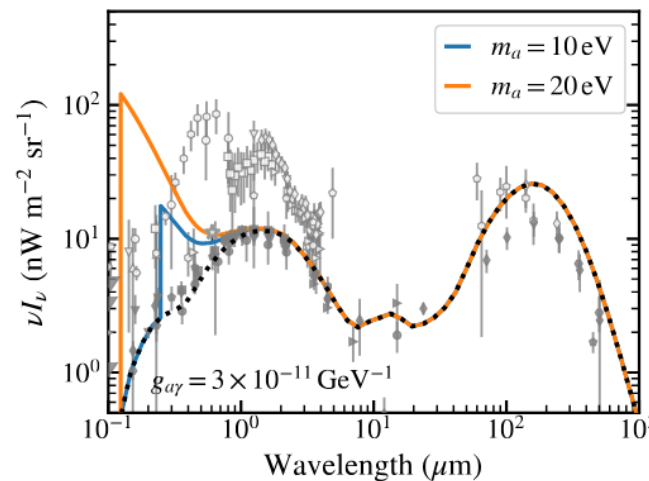
Log Parabola

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0} \right)^{-\alpha - \beta \ln \left(\frac{E}{E_0} \right)}$$



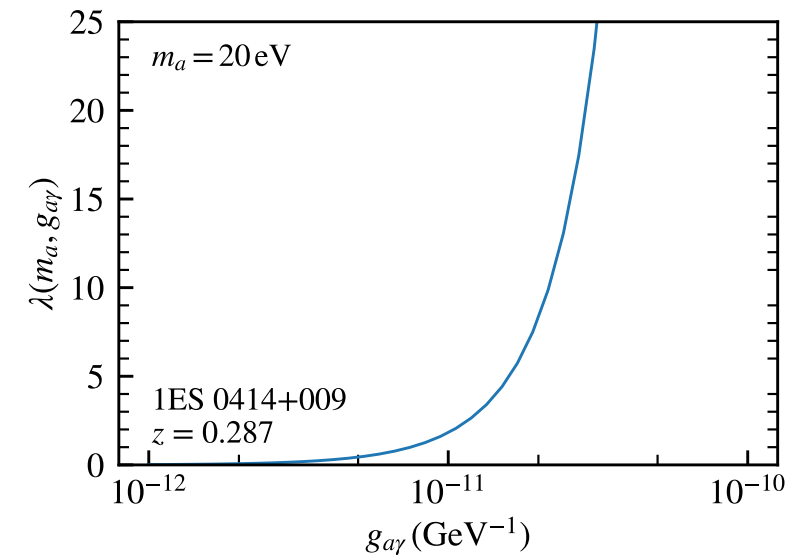
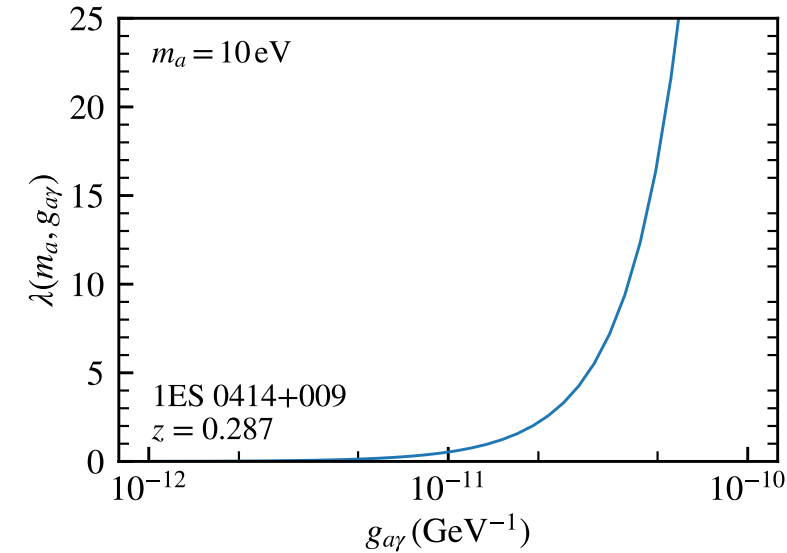
Computing the opacity and Spectral fits

- Total optical depth, $\tau(E, z)$, is computed from the standard EBL plus the ALP-induced contribution
- ALP decay increases the EBL intensity, leading to greater γ -ray opacity
- Joint Fermi-LAT + H.E.S.S. spectral fits use the full likelihood in Gammapy, rather than flux points alone



How do we test for ALP-induced opacity?

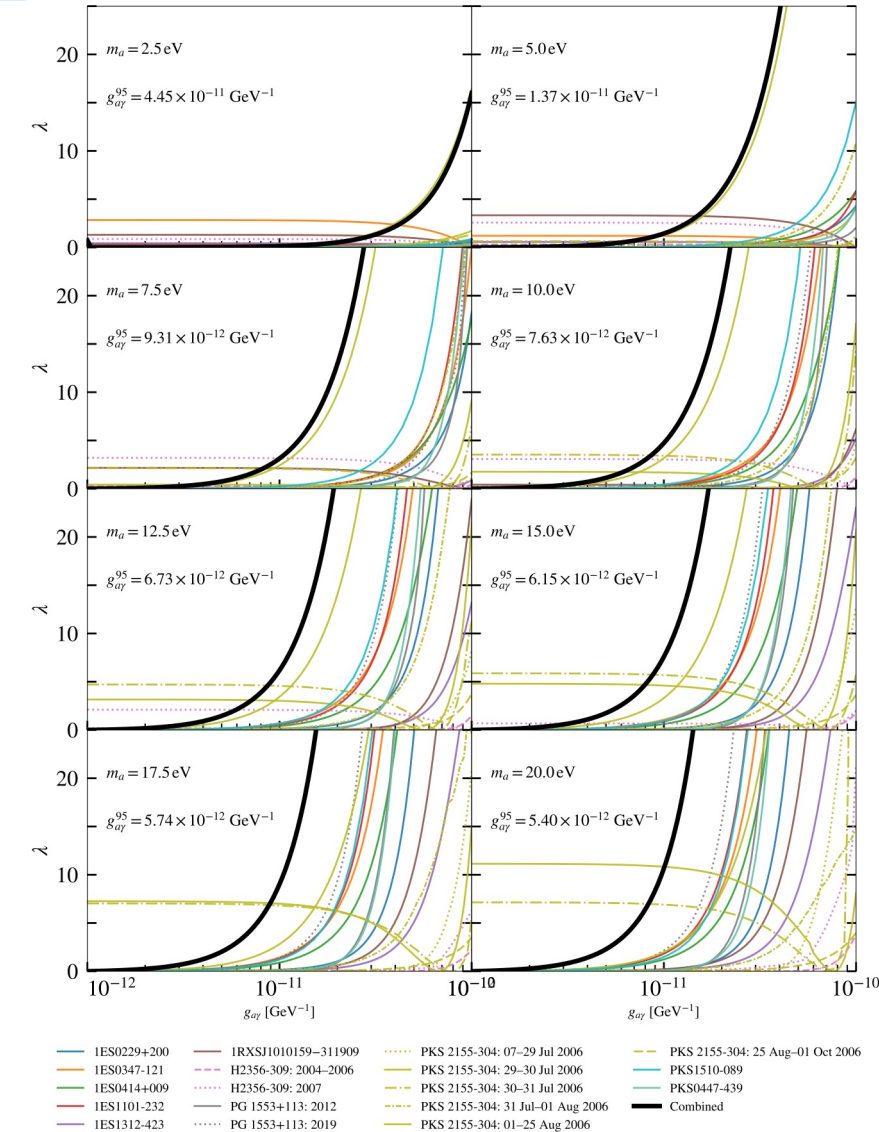
- Combine Fermi–LAT and H.E.S.S. spectra for each blazar and time interval
- Fit all spectra assuming no ALPs to obtain the reference model
- Add the predicted ALP-induced EBL contribution for different m_a and $g_{a\gamma}$
- Refit the spectra for each $(m_a, g_{a\gamma})$ and compare with the reference model
- Use the change in likelihood (λ) to determine whether ALPs improve the fit or are excluded
- Larger λ values indicate that the data disfavour a given ALP coupling.



Note: These plots show results for the Domínguez et al. 2011 EBL model

How we test for ALPs?

- For each ALP mass (m_a), combine the log-likelihood contributions from all blazars and time intervals
- Construct the profile statistic λ by comparing each coupling to the best-fitting value
- The 95% CL upper limit is defined by $\lambda = 2.71$
- The strongest constraint obtained is $g_{a\gamma}^{95} \simeq 6 \times 10^{-12} \text{ GeV}^{-1}$ at $m_a = 20 \text{ eV}$
- No significant preference for an ALP contribution is found



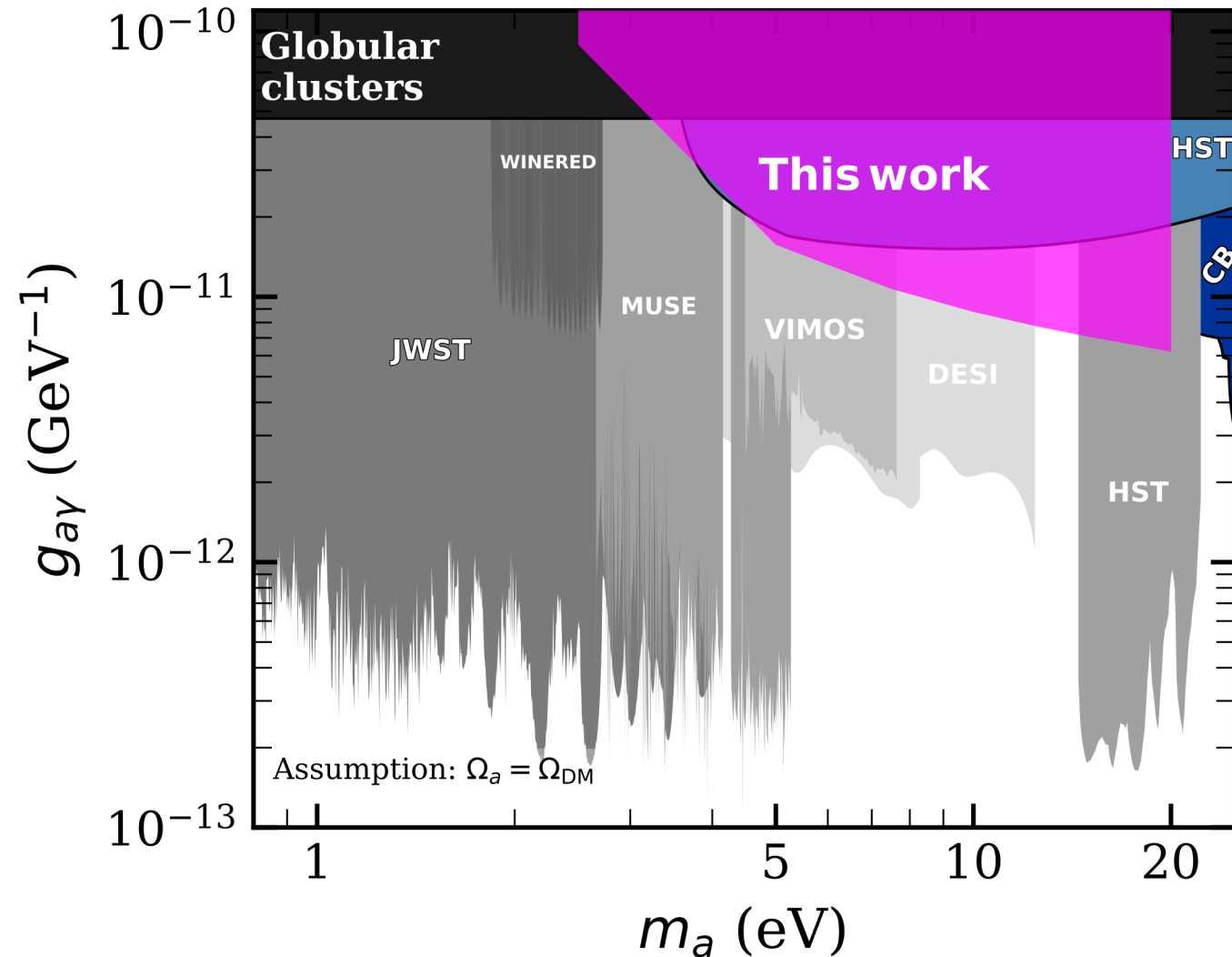
Note: These plots show results for the Domínguez et al. 2011 EBL model

The constraints on ALP parameter space

- Our joint Fermi–LAT + H.E.S.S. likelihood analysis finds no evidence for an ALP contribution
- This complementary approach, based on the integrated ALP-induced EBL, provides the tightest constraints to date around $m_a \sim 15$ eV

See also Lucas Gréaux's excellent poster, "Future Prospects for Gamma-Ray Cosmology."

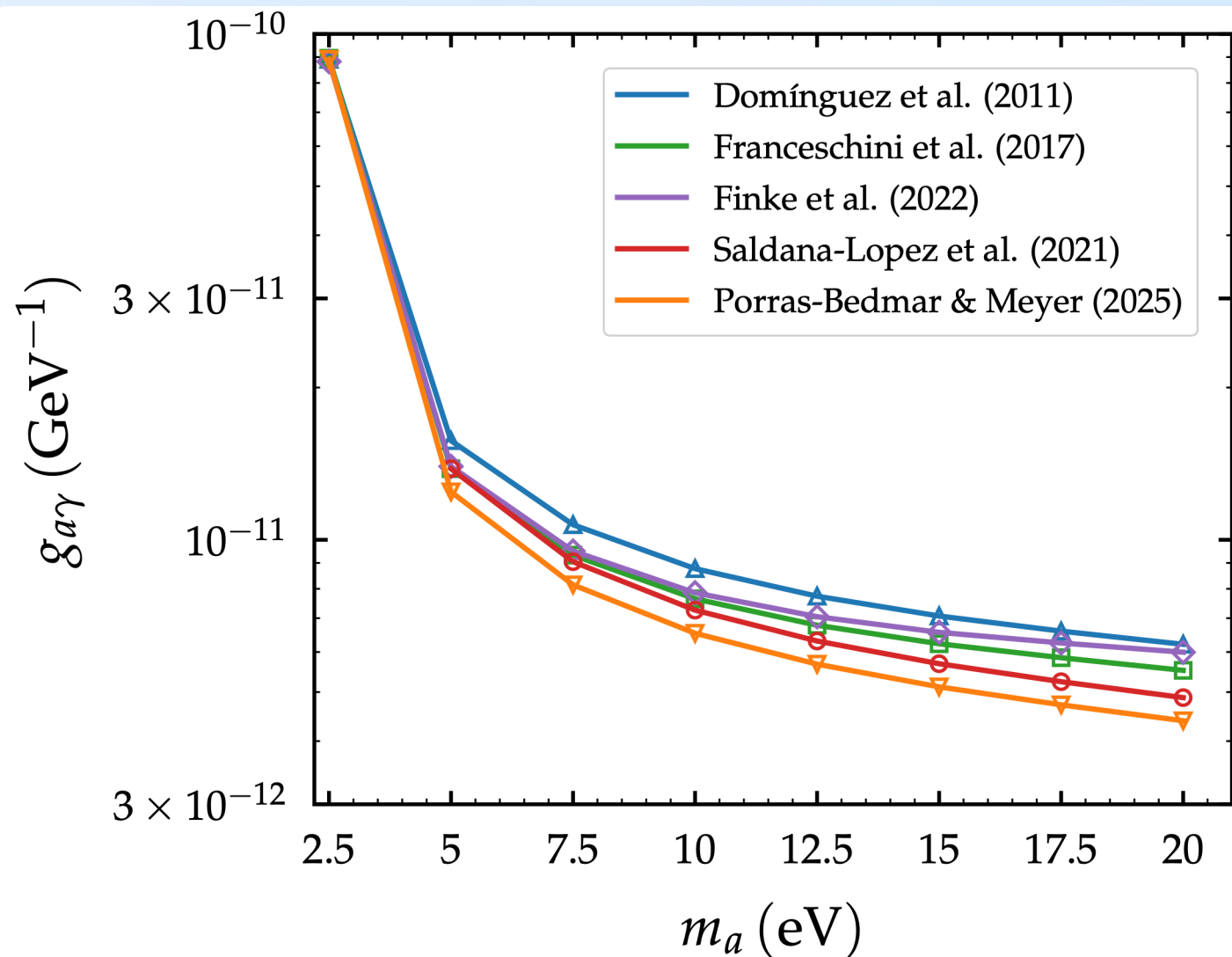
Comparison limits obtained from AxionLimits (Ciaran O'Hare):
<https://cajohare.github.io/AxionLimits/>



Note: These plots show results for the Domínguez et al. 2011 EBL model

EBL model systematics

- Repeat the full analysis using five state-of-the-art EBL models to assess EBL-related systematic uncertainties
- All models give very similar constraints; differences mainly reflect their predicted optical–infrared EBL intensity
- The spread is modest ($\lesssim 1.5$), demonstrating that the results are robust to current EBL-model uncertainties
- The Domínguez et al. model is shown in the final results as the most conservative case



Conclusions

We present the first joint Fermi–LAT + H.E.S.S. likelihood analysis constraining heavy ALP decay through its contribution to the EBL

By jointly fitting the Fermi–LAT and H.E.S.S. spectra with and without an ALP-modified EBL, we explored a wide grid in m_a and $g_{a\gamma}$, constructing a profile likelihood $\lambda(m_a, g_{a\gamma})$

No evidence for an ALP decay contribution is found, leading to new 95% C.L. exclusion limits in the $(m_a, g_{a\gamma})$ parameter space

Joint Fermi–LAT + H.E.S.S. analyses provide a powerful probe of new physics, with CTAO set to further improve sensitivity to heavy ALP dark matter

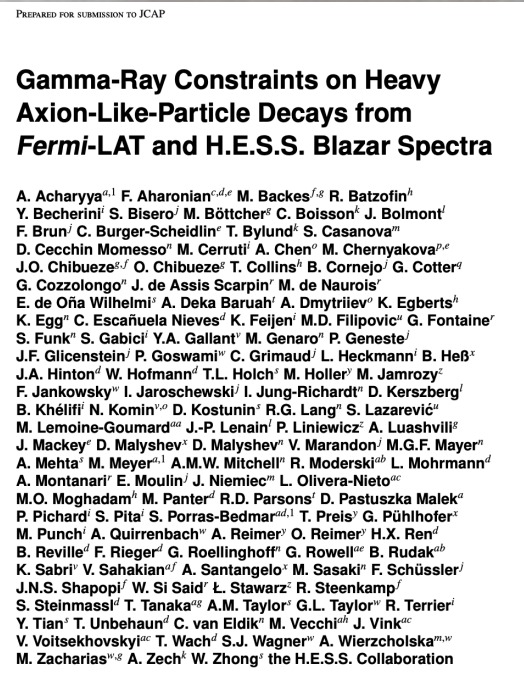
The resulting limits are complementary to laboratory and spectroscopic searches, and robust against current EBL modelling uncertainties

The strongest constraints are obtained around $m_a \sim 15 - 20 \text{ eV}$, providing the tightest limits to date in this mass range

Acknowledgements

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- Referee recommends publication after minor revisions



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In the meantime,
Rocco says,
“Thank you for
listening!”

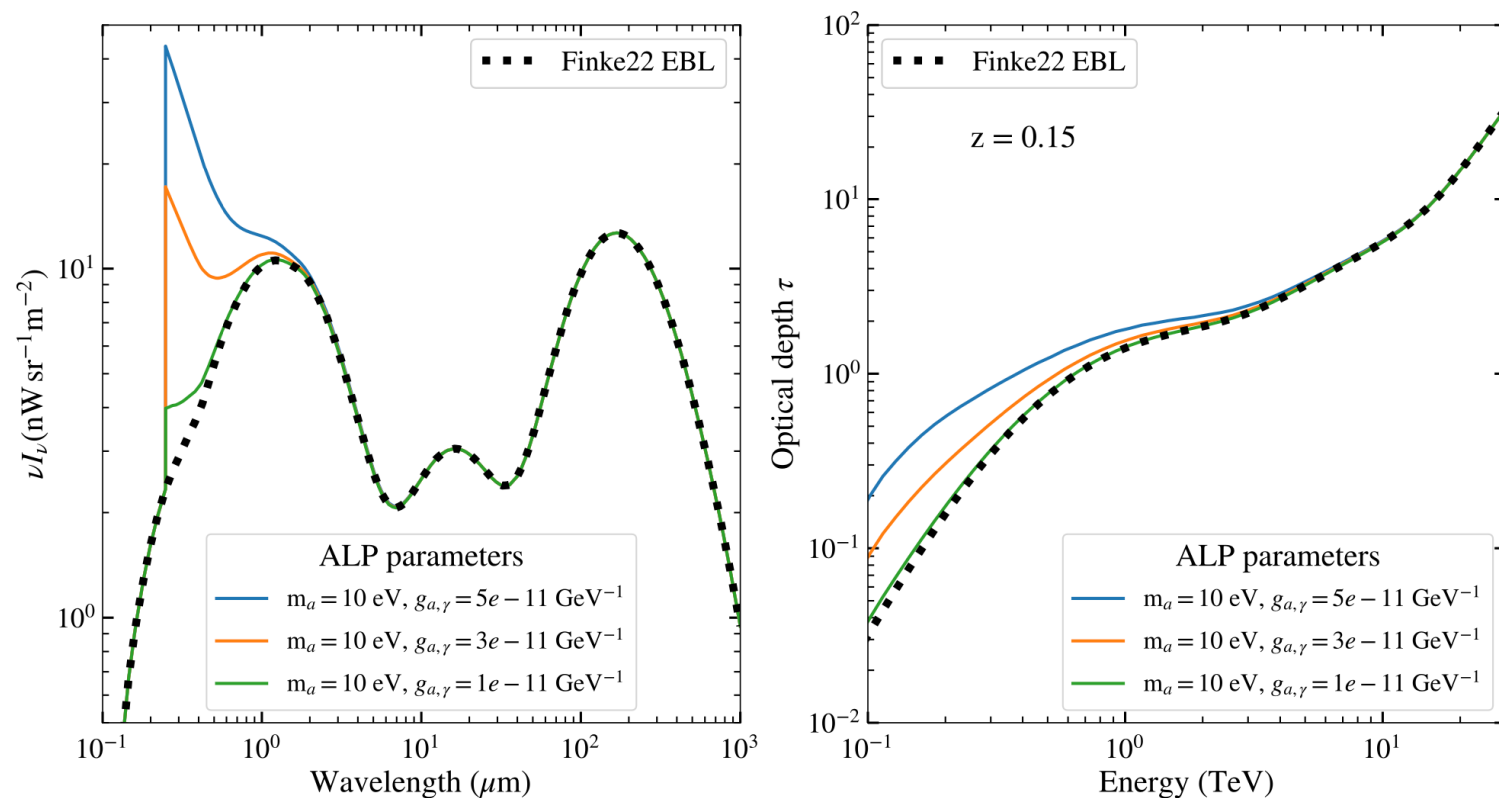


A composite image showing the H.E.S.S. (High Energy Stereoscopic System) observatory in a desert landscape under a starry night sky. The Milky Way galaxy is prominently visible, arching across the upper half of the frame. Several large, red, steel-frame radio telescopes are scattered across the horizon. The foreground is a dry, grassy field. The text "Back-up Slides" is centered in the middle of the image.

Back-up Slides

Mass range and Physical motivation

- Focus on ALP masses 2.5–20 eV, producing decay photons in the optical/UV band where EBL absorption of TeV gamma rays is strongest:
 - $m_a < 5$ eV: decay photons lie in the near-IR, contributing little to TeV opacity within the Fermi-LAT and H.E.S.S. regime
 - $m_a > 20$ eV: decay photons move to far-UV/soft X-ray, where absorption is dominated by neutral H and does not affect γ - γ opacity



Thus, 5–20 eV is the observationally most relevant range for modifying TeV gamma-ray transparency

Summary Table

Source Name	Observation Range [DD.MM.YYYY]	Redshift z	N_0 [$\times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$]	α	β	E_0 [GeV]	$s_{\text{H.E.S.S.}}$
1ES 0229+200	11.09.2004 – 07.01.2019	0.14	2.92 ± 0.45	1.71 ± 0.06	–	3.9	-0.091 ± 0.109
1ES 0347-121	26.08.2006 – 03.12.2013	0.19	3.19 ± 0.33	1.78 ± 0.06	–	3.6	-0.161 ± 0.071
1ES 0414+009	03.10.2005 – 10.09.2010	0.29	5.85 ± 0.49	2.01 ± 0.06	–	3.5	-0.160 ± 0.067
1ES 1101-232	15.04.2004 – 29.05.2019	0.19	1.84 ± 0.16	1.78 ± 0.05	–	5.7	-0.144 ± 0.073
1ES 1312-423	15.04.2004 – 09.07.2010	0.11	1.43 ± 0.14	1.93 ± 0.05	–	6.0	0.067 ± 0.101
1RXS J101015.9-311909	21.12.2006 – 16.04.2010	0.14	2.07 ± 0.16	1.89 ± 0.04	–	5.9	0.163 ± 0.092
H2356-309	16.06.2004 – 26.09.2006	0.17	160 ± 312	1.82 ± 0.60	0.03 ± 0.05	1.2	0.047 ± 0.137
H2356-309	14.07.2007 – 27.07.2007	0.17	17.75 ± 19.31	1.65 ± 0.16	–	1.16	0.023 ± 0.174
PG 1553+113	26.04.2012 – 28.04.2012	0.43	3.28 ± 0.21	1.40 ± 0.07	0.08 ± 0.02	1.8	-0.163 ± 0.062
PG 1553+113	08.04.2019 – 07.07.2019	0.43	4.83 ± 0.23	1.59 ± 0.05	0.03 ± 0.01	1.8	0.010 ± 0.046
PKS 0447-439	09.11.2009 – 07.12.2010	0.34	3.32 ± 0.16	1.99 ± 0.06	–	1.6	-0.128 ± 0.065
PKS 1510-089	22.03.2009 – 27.07.2016	0.36	39.4 ± 2.2	2.51 ± 0.04	–	0.9	-0.233 ± 0.052
PKS 2155-304	07.07.2006 – 28.07.2006	0.12	$(6.6 \pm 1.0) \times 10^3$	2.32 ± 0.04	0.05 ± 0.01	5.5	0.122 ± 0.047
PKS 2155-304	29.07.2006 – 29.07.2006	0.12	$(2.6 \pm 0.2) \times 10^3$	1.34 ± 0.03	0.15 ± 0.01	5.5	0.063 ± 0.039
PKS 2155-304	30.07.2006 – 30.07.2006	0.12	99.8 ± 8.5	1.22 ± 0.36	0.18 ± 0.03	5.5	0.085 ± 0.098
PKS 2155-304	31.07.2006 – 31.07.2006	0.12	2.73 ± 0.72	1.13 ± 0.15	0.29 ± 0.02	5.5	-0.161 ± 0.040
PKS 2155-304	01.08.2006 – 24.08.2006	0.12	3.38 ± 1.13	1.34 ± 0.58	0.19 ± 0.07	5.5	0.130 ± 0.026
PKS 2155-304	25.08.2006 – 20.09.2006	0.12	2.71 ± 6.33	1.64 ± 0.10	0.11 ± 0.01	5.5	-0.050 ± 0.156

Table 1: Summary of the blazar sample analysed in this work. For each source and observation period, we list the redshift and best-fit spectral parameters obtained under the no-ALP hypothesis. Each spectrum was fitted with both a power-law and a log-parabola model, and the model providing the better fit (based on likelihood comparison) is reported. The parameters N_0 , α , β , and E_0 denote the spectral normalization (in units of $10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$), photon index, curvature parameter, and pivot energy, respectively. A dash in the β column indicates that the spectrum is consistent with a simple power-law form. All fits assume the EBL model in [9], used as a baseline.

ALP decay contribution to the EBL

- EBL intensity due to a cosmological population of decaying ALPs:

Present-day ALP energy density =

fractional ALP density x critical density of the Universe today

$$\nu I_\nu(\lambda, z) = \frac{\Omega_a \rho_{\text{crit},0} c^4}{64\pi} \frac{(m_a c^2)^2 g_{a\gamma}^2}{\lambda H(z_*)} \Theta\left(\lambda - \frac{2hc}{m_a c^2}\right)$$

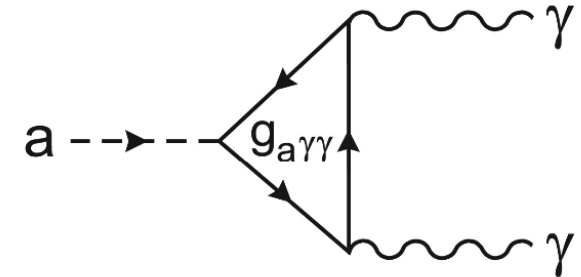
c = speed of light
 h = Planck's constant
 m_a = ALP mass
 $g_{a\gamma}$ = ALP photon coupling

where the redshift z_* at which ALP decay contributes photons of observed wavelength λ at redshift z

$$z_* = \frac{m_a c^2}{2} \frac{\lambda}{hc} (1 + z) - 1$$

- Heaviside cutoff, Θ , ensures only photons with $\lambda > 2hc/(m_a c^2)$ contribute
- The redshift-dependent Hubble parameter is

$$H(z) = H_0 \sqrt{\Omega_m (1 + z)^3 + \Omega_\Lambda}$$



$$\Omega_m = 0.315, \Omega_\Lambda = 0.685, \text{ and } H_0 = 67.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

Likelihood definitions

- Joint likelihood = Fermi-LAT + H.E.S.S. Poisson terms over all energy bins
- H.E.S.S. likelihood uses On/Off counts with exposure ratio α
- Profile likelihood: maximise over nuisance parameters at fixed g_{ay}
- Compare to the global maximum to form $\lambda(m_a, g_{\text{ay}})$

A joint spectral analysis of the combined *Fermi*–LAT and H.E.S.S. data is performed for each source and time interval to test for potential ALP-induced modifications to the EBL attenuation. The null (no-ALP) fits serve as the reference model for each segment (Figures 3a and 3b). We then introduce the ALP-decay contribution described in Eq. (3.1) and repeat the spectral fits over a grid of ALP masses m_a and photon–ALP coupling constants g_{ay} . For fixed values of m_a and g_{ay} and each spectrum i with data D_i this corresponds to maximizing the joint *Fermi*–LAT and H.E.S.S. log-likelihood in terms of nuisance parameters θ_i (spectral and background parameters),

$$\ln \mathcal{L}(m_a, g_{\text{ay}}, \theta_i, s_i | D_i) = \sum_j \ln \mathcal{L}(m_a, g_{\text{ay}}, \theta_i | D_{\text{Fermi},ij}) + \sum_j \ln \mathcal{L}(m_a, g_{\text{ay}}, \theta_i, s_i | D_{\text{H.E.S.S.},ij}) - \frac{s_i^2}{2\sigma_s^2}, \quad (4.1)$$

where the sum over j runs over the energy bins for both *Fermi* LAT and H.E.S.S., s_i denotes the nuisance parameter describing a coherent H.E.S.S. energy-scale shift, constrained by a Gaussian prior of width σ_s , and both likelihoods follow Poissonian statistics. The likelihood for the H.E.S.S. observations takes into account both the On region containing the source as well as Off regions to estimate the background, and is given by

$$\ln \mathcal{L}(m_a, g_{\text{ay}}, \theta_i, s_i | D_{\text{H.E.S.S.},ij}) = N_{\text{On},ij} \ln(\mu_{ij}(s_i) + b_{ij}) + N_{\text{Off},ij} \ln(b_{ij}/\alpha) - \mu_{ij}(s_i) - \left(1 + \frac{1}{\alpha}\right) b_{ij}, \quad (4.2)$$

where N_{On} and N_{Off} are the counts in the On and Off regions, respectively, $\mu_{ij}(s_i)$ are the expected number of counts from the source computed after rescaling the reconstructed H.E.S.S. energies as $E \rightarrow E(1 + s_i)$, depending on the spectral and ALP parameters as well as the EBL density, and b_{ij} are the expected counts from the background.

Likelihood definitions

- Joint likelihood = Fermi-LAT + H.E.S.S. Poisson terms over all energy bins
- H.E.S.S. likelihood uses On/Off counts with exposure ratio α
- Profile likelihood: maximise over nuisance parameters at fixed $g_{a\gamma}$
- Compare to the global maximum to form $\lambda(m_a, g_{a\gamma})$

For a fixed ALP mass, we then construct the profile log-likelihood ratio as a sum over all spectra,

$$\lambda(m_a, g_{a\gamma}) = -2 \sum_i \ln \left(\frac{\ln \mathcal{L}(m_a, g_{a\gamma}, \hat{\theta}_i | D_i)}{\ln \mathcal{L}(m_a, \hat{g}_{a\gamma}, \hat{\theta}_i | D_i)} \right), \quad (4.3)$$

where $\hat{\theta}$ denotes the spectral and background parameters maximizing the likelihood for a fixed ALP coupling strength, whereas $\hat{\theta}$ and $\hat{g}_{a\gamma}$ are the parameters that maximize $\mathcal{L}$ unconditionally.

By construction, $\lambda = 0$ at the best-fit value of $g_{a\gamma}$, and larger values of λ indicate increasingly disfavoured couplings. Since our goal is to set exclusion limits, we follow the dark matter search convention and use the profile likelihood λ [Eq. (4.3)] to construct confidence intervals. We adopt the criterion $\lambda = 2.71$, corresponding to a 95% confidence level (C.L.; one-sided, one parameter of interest). For each ALP mass, we extract the coupling where $\lambda = 2.71$; we denote this by $g_{a\gamma}^{95}(m_a) \equiv \{g_{a\gamma} : \lambda(m_a, g_{a\gamma}) = 2.71\}$, and use these points to construct the 95% C.L. exclusion contour. Figure 4 displays the resulting likelihood profiles $\lambda(m_a, g_{a\gamma})$ for several representative values of m_a . The resulting one-sided 95% C.L. upper limits on the photon–ALP coupling $g_{a\gamma}$ are shown in Figure 5. The strongest constraints are obtained at the highest ALP masses probed in our scan, where the much shorter decay lifetime (see Eq. 3.4) leads to a larger ALP-induced photon emissivity and hence a stronger impact on the gamma-ray optical depth. In our analysis, this yields the most stringent limit of $g_{a\gamma}^{95} \simeq 5.3 \times 10^{-12} \text{ GeV}^{-1}$ at $m_a = 20 \text{ eV}$.

PKS 2155-304

For PKS 2155-304, the absence of contemporaneous Fermi-LAT coverage implies that all available data are subject to EBL and ALP-induced attenuation, preventing a robust determination of the intrinsic spectral shape

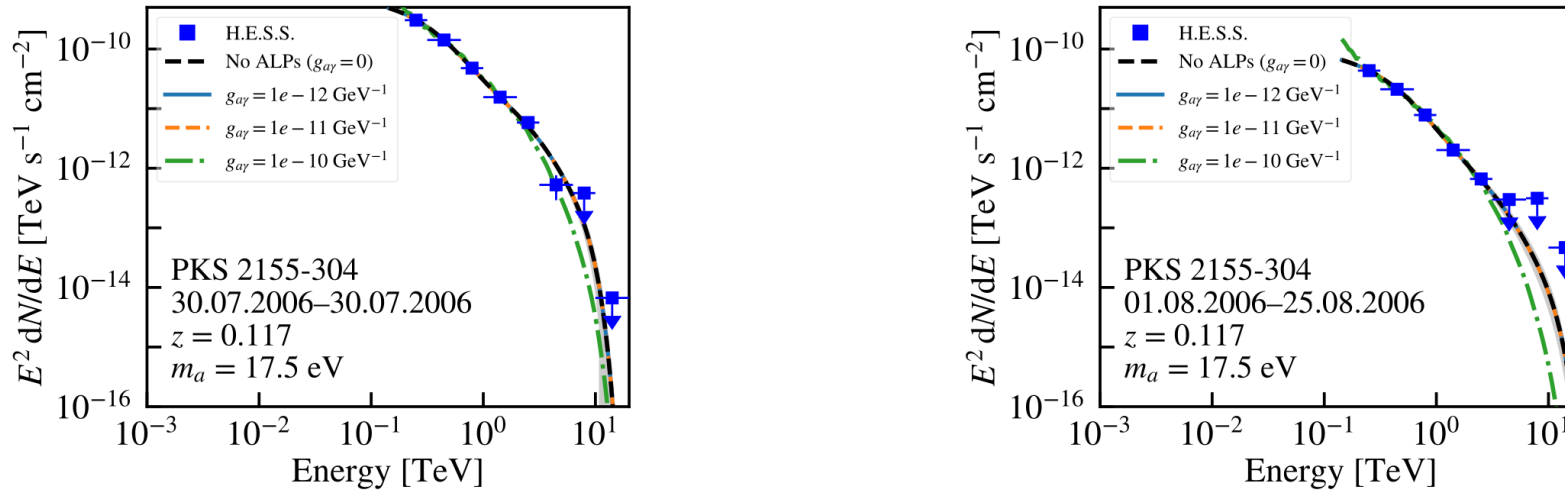


Figure A3: Spectral energy distributions (SEDs) of PKS 2155–304 for the two flare episodes corresponding to the strongest local preference for an ALP contribution in our sample. H.E.S.S. flux points (squares) are shown together with the best-fit no-ALP scenario and ALP models for representative photon–axion couplings ($g_{a\gamma} = 10^{-12}, 10^{-11}, 10^{-10} \text{ GeV}^{-1}$). In both panels, the ALP mass is fixed to $m_a = 17.5 \text{ eV}$. The best-fit spectral models overlap for the no-ALP scenario and the two lowest photon–axion couplings ($g_{a\gamma} = 10^{-12}, 10^{-11} \text{ GeV}^{-1}$).

Note: These plots show results for the Domínguez et al. 2011 EBL model