Searches for spectral upturns due to photon to Axion-like particle (ALP) conversions

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GAMMA RAY PROPAGATION AND AXION-LIKE PARTICLES

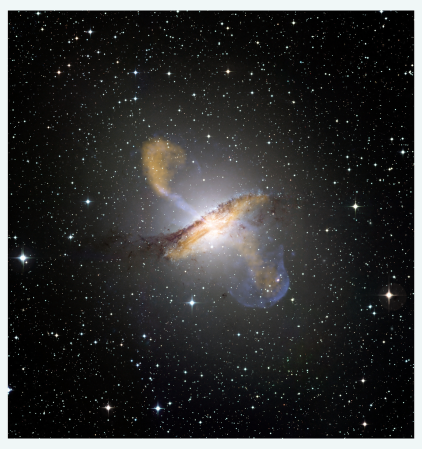
Gamma rays emitted by distant sources attenuated at highest energies ($E_\gamma > 100$ GeV) due to **extragalactic background light** (EBL).

Axions / Axion-like particles (ALPs): beyond Standard Model particles originally introduced as solution to the strong CP problem, possible dark matter candidates. [1-3]

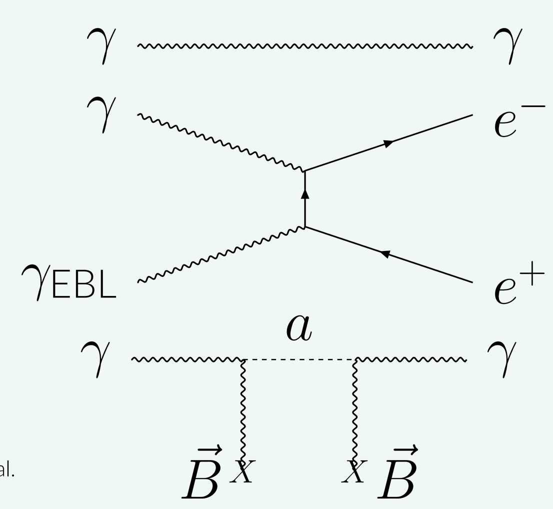
Described by their mass m_a and coupling to the electromagnetic field $g_{a\gamma}$, associated interaction Lagrangian term allows for **photon-ALP conversions**:

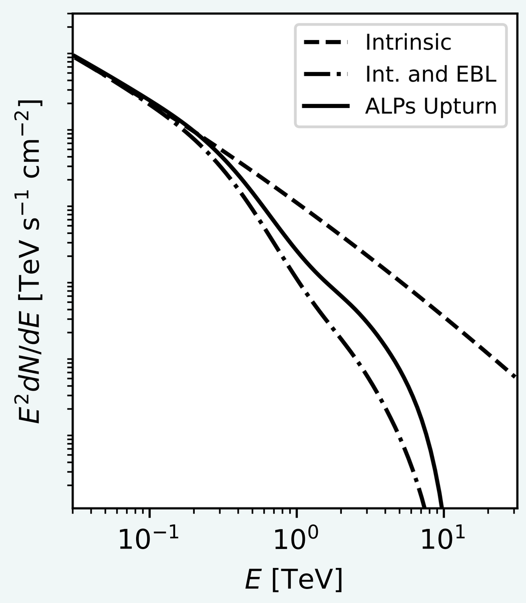
$$\mathcal{L}_{a\gamma} \sim -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a \qquad (1)$$

Could partially alleviate EBL attenuation, producing characteristic **spectral upturns**. [4-6]



Credits: ESO/WFI (Opt.); MPIfR/ESO/APEX/A.Weiss et al. (Sub-mm); NASA/CXC/CfA/R.Kraft et al. (X-ray).

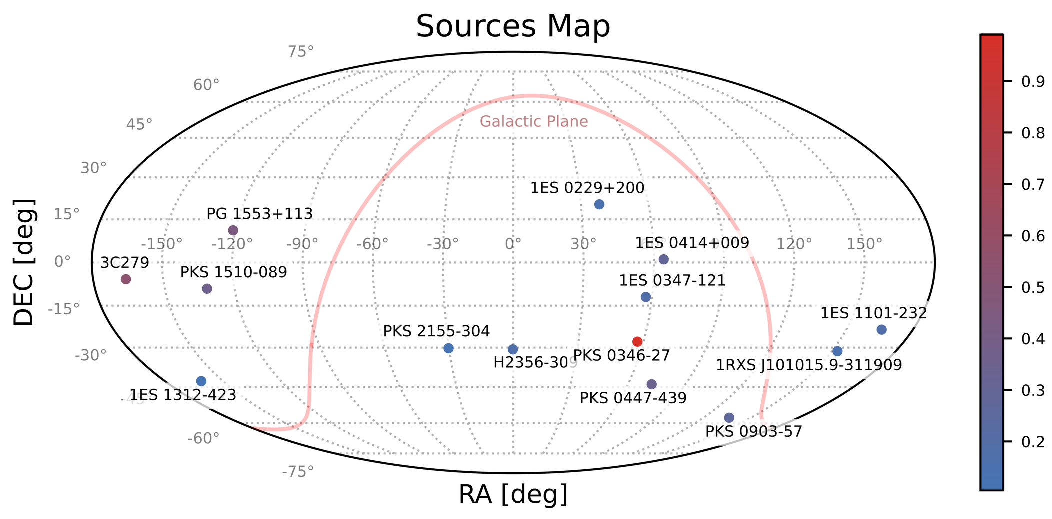




SOURCE SELECTION AND OBSERVATION TIMES

Dataset of 14 active galactic nuclei **(AGN) Blazar sources** with high-energy emission in optically thick regime ($\tau > 2$), with redshifts $z \in [0.1, 1.0]$.

Main selection from **H.E.S.S.** observations (long-term campaigns and flaring periods) with ***Fermi*-LAT** data to constrain the lower-energy range of spectra.



INTRINSIC SPECTRAL ENERGY DISTRIBUTION MODELING

Time variability analysis using nightly-binned light curves and **Bayesian block** method, [7] **spectral evolution analysis** separating blocks by statistically-significant physical variability.

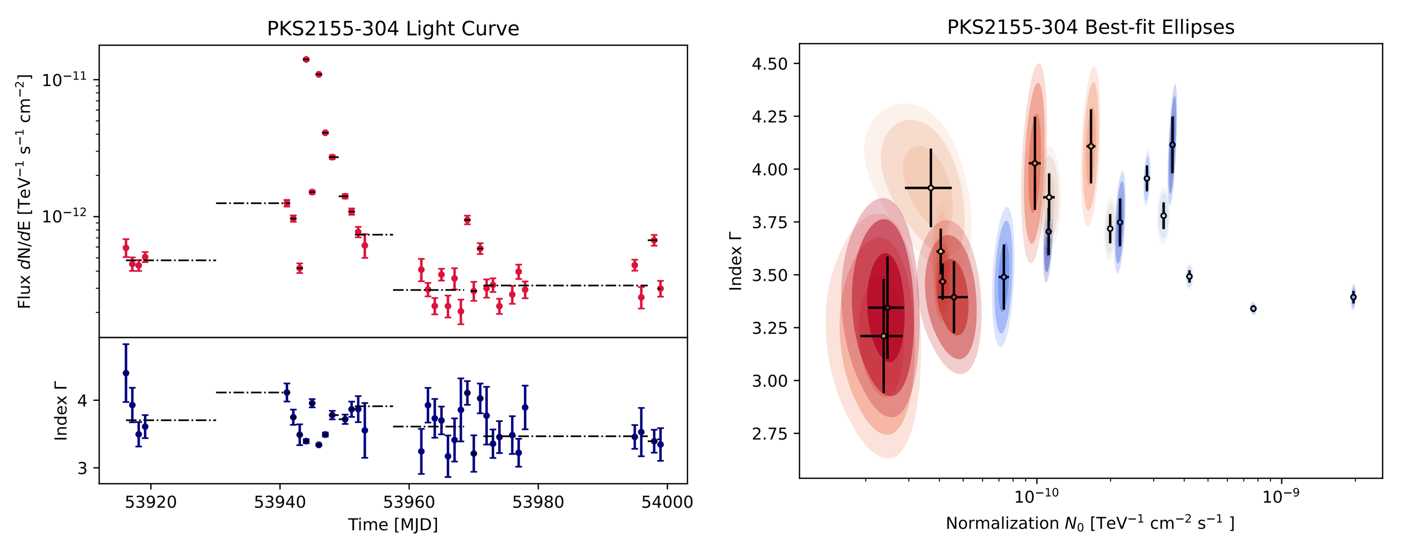


Figure 1. Bayesian-blocked light curve across flux and spectral index, spectral variability best-fit ellipses.

Binned Poisson likelihood-based **intrinsic spectral modeling** with EBL attenuation:

$$\phi_{\text{int}}(E;\theta_{\text{int}} = \{\Gamma,\beta,N_0,E_0\}) \cdot \phi_{\text{EBL}}(E;z) = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma-\beta\log(E/E_0)} \cdot e^{-\tau(E,z)} \qquad (2)$$

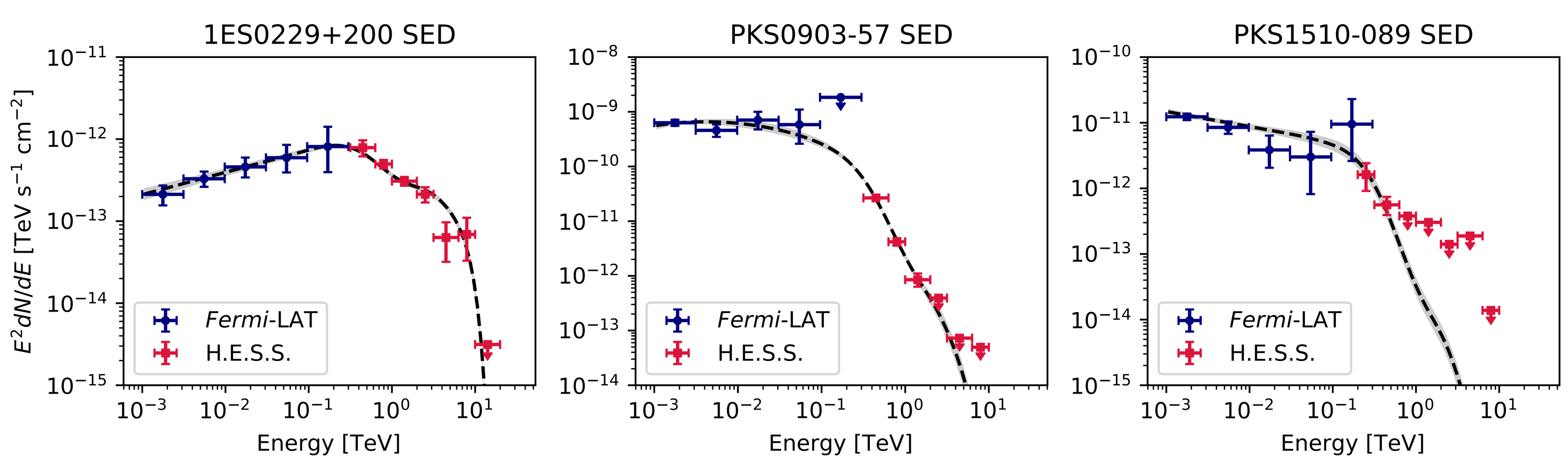


Figure 2. Intrinsic spectral energy distribution (SED) with baseline Domínguez et al. (2011) EBL model. [9]

SPECTRAL UPTURN MODELING

Model **spectral upturns** by introducing a "smooth break" factor:

$$\phi_{\text{int, EBL}}(E;\theta_{\text{int}},z) \cdot \phi_{\text{brk}}(E;\Delta\Gamma,E_{\text{brk}},\beta_{\text{brk}}) = \phi_{\text{int, EBL}}(E;\theta_{\text{int}},z) \cdot \left[1 + \left(\frac{E}{E_{\text{brk}}}\right)^{\Delta\Gamma/\beta_{\text{brk}}}\right]^{-\beta_{\text{brk}}} \qquad (3)$$

where we impose an upturn by $\Delta\Gamma = \Gamma_{\text{brk}} - \Gamma_{\text{int}} < 0$ and $\beta_{\text{brk}} = 1$.

Perform grid search over break parameters to obtain **upturn likelihood** (ΔC-stat):

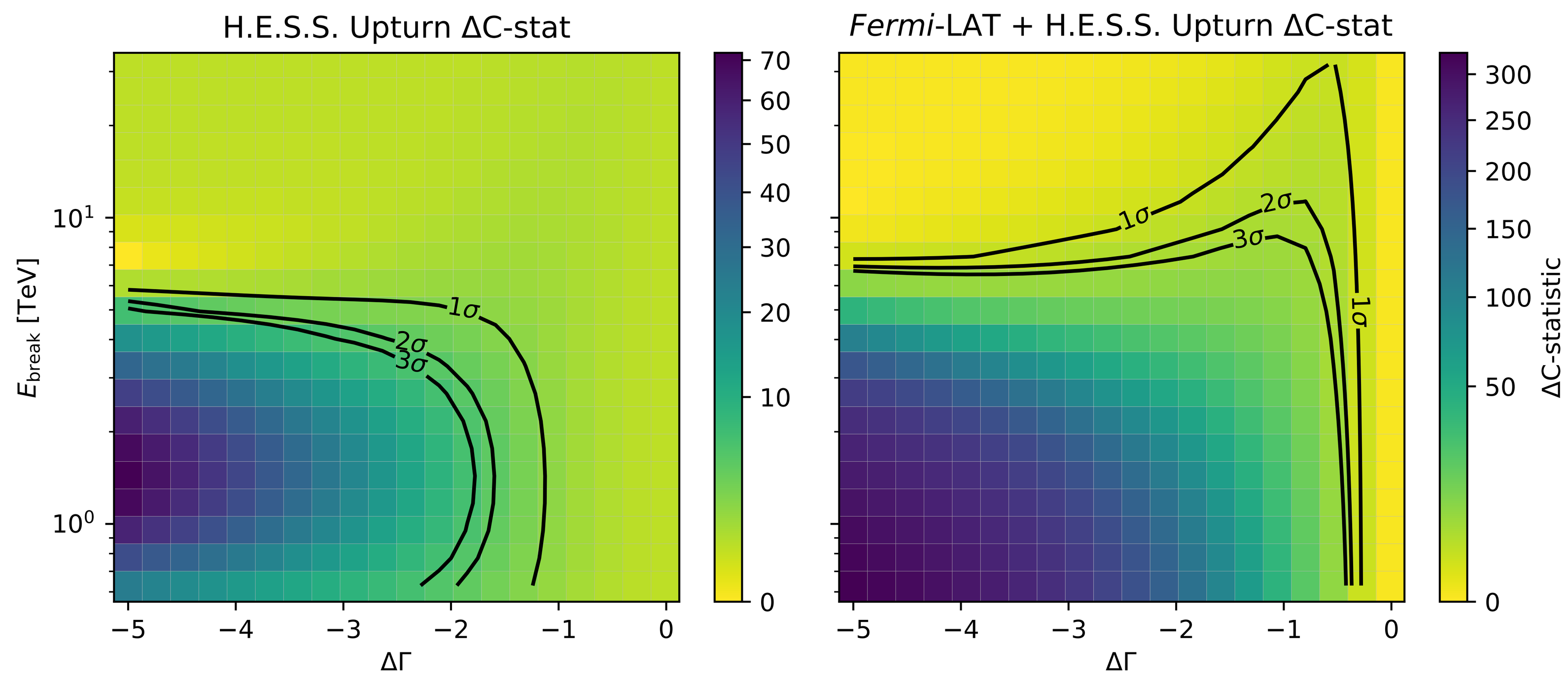


Figure 3. Upturn likelihood grid (Source: 1ES 0229+200).

SIMULATIONS OF PHOTON-ALP CONVERSION UPTURNS

Compute **photon survival probability** $P_{\gamma\gamma}$ numerically (via transfer matrix approach) [8] of photon-ALP beam propagating across astrophysical environments:

- Conversion $\gamma \to$ ALP in **Intergalactic Magnetic Field** (IGMF) $\sim$ Random domains
- Re-conversion ALP $\to \gamma$ in **Galactic Magnetic Field** $\sim$ Jansson-Farrar (2012) model [9]

Considering very light ALPs ($m_a \sim 10^{-3}$ neV) in **strong mixing regime** ($g_{a\gamma} \sim 10^{-11}$ GeV^{-1}).

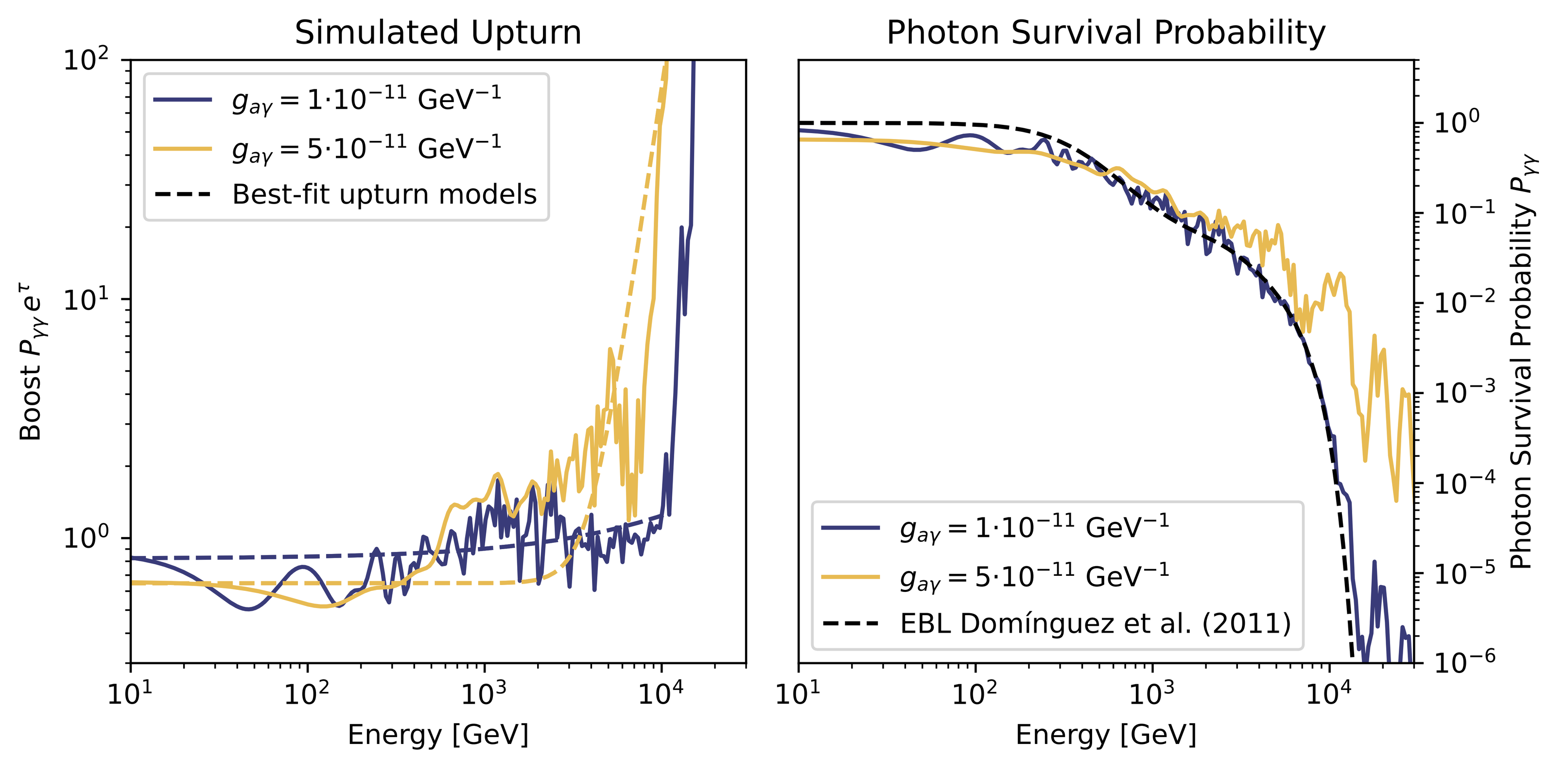


Figure 4. Simulated photon survival probability $P_{\gamma\gamma}$ and expected spectral upturn with photon-ALP conversions (Source: 1ES 0347-121).

Fit expected upturn with a "smooth break" model $N_{\text{brk}} \cdot \phi_{\text{brk}}(E;\theta_{\text{brk}})$ as previously, obtaining the best-fit parameters $\theta_{\text{ALP}} = \{\Delta\Gamma_{\text{ALP}}, E_{\text{brk, ALP}}\}$

LIKELIHOOD ANALYSIS OF SPECTRAL UPTURNS DUE TO PHOTON-ALP CONVERSIONS

Interpolate best-fit parameters of simulated ALP upturns parameters θ_{ALP} onto ΔC-stat grids obtained from upturn modeling $\to$ Estimated **likelihood for ALP-induced upturn**.

Compute likelihood across all sources and time blocks and sum all contributions.

Study across different EBL models: {Domínguez et al (2011), [10] Finke et al. (2022), [11] Franceschini et al. (2008), [12] Saldana-López et al. (2021), [13]}.

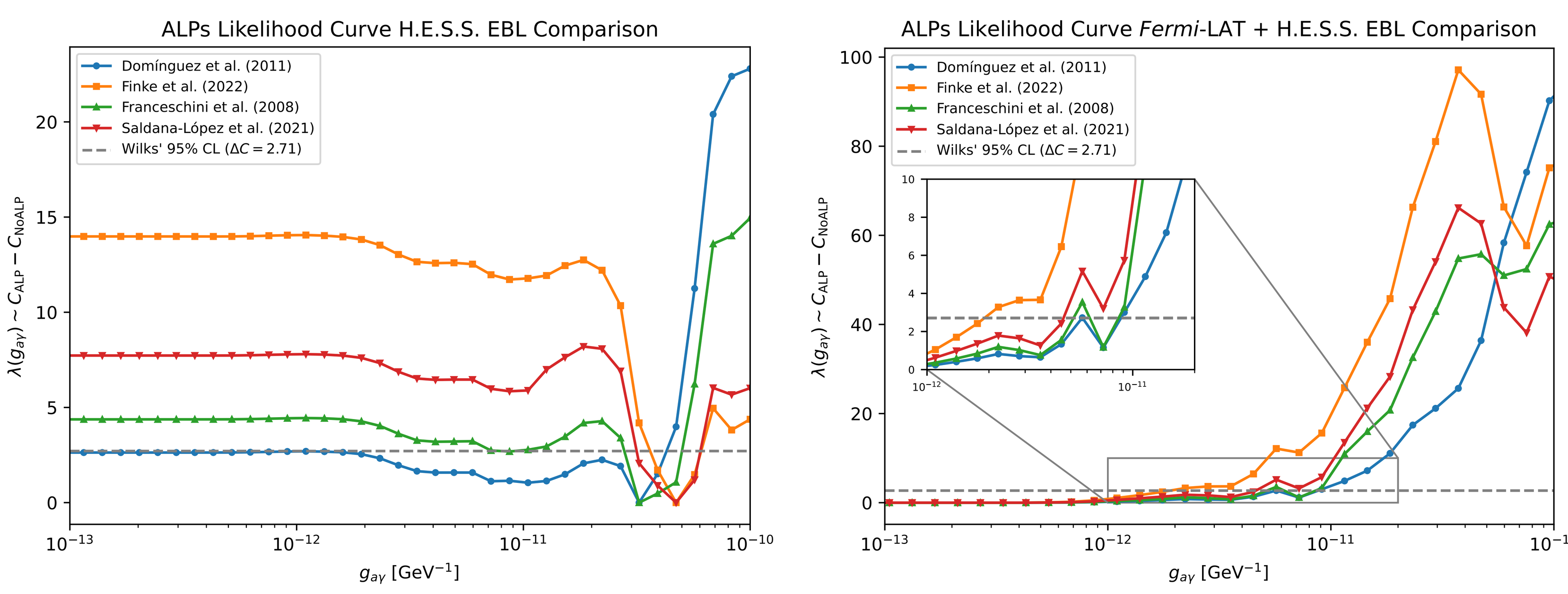


Figure 5. Likelihood curves for upturns due to photon-ALP conversions.

Slight preference for ALP-induced spectral upturns for H.E.S.S.-only data at coupling values of $g_{a\gamma} \sim 4 \cdot 10^{-11}$ GeV^{-1}.

Possible **constraints** for ALP couplings $g_{a\gamma} \sim [10^{-12}, 10^{-11}]$ GeV^{-1} for joint *Fermi-LAT* and H.E.S.S. dataset considering preliminary statistical thresholds.

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