Axion-like particles constraints obtained by MAGIC observations of the Perseus cluster

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Fakultet za fiziku
Sveučilište u Rijeci

Image Credit: Urs Leutenegger (@urs.leutenegger)

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On behalf of the MAGIC collaboration

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Axion-like particles

CP violation in QCD

$$\mathcal{L}_{\theta_{QCD}} = \theta_{QCD} \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}_a^{\mu\nu}$$

Experimentally: no CP violation in QCD

$$\theta_{QCD} < 10^{-10}$$

Fine-tuning problem!

Solution:
Peccei–Quinn (PQ) mechanism

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Axion-like particles

CP violation in QCD

$$\mathcal{L}_{\theta_{QCD}} = \theta_{QCD} \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

Experimentally: no CP violation in QCD

$$\theta_{QCD} < 10^{-10}$$

Fine-tuning problem!

Solution:
Peccei–Quinn (PQ) mechanism

$$U(1)_{PQ}$$

$$m_a \simeq 6 \times 10^{-6}\ \text{eV} \left(\frac{10^{12}\ \text{GeV}}{f_a} \right)$$

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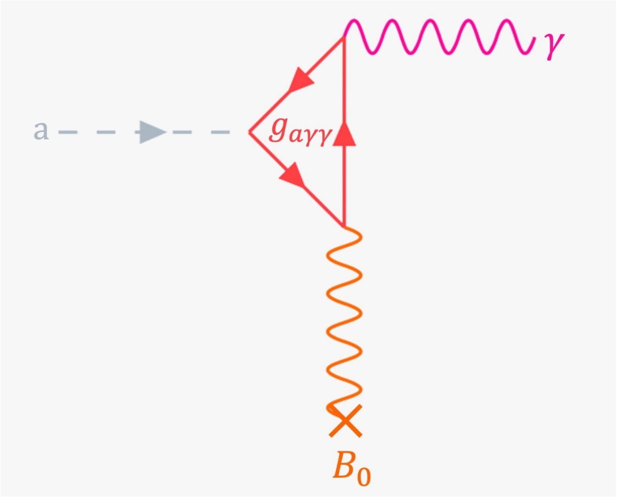
Axion-like particles

- After many unsuccessful searches for axions, the axion model was extended to a wider group of particles, called Axion-Like Particles (ALPs)
- The decay constant is no longer coupled with the axion mass
- ALPs are also often found in SM extensions



$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} F_{\mu\nu}\tilde{F}^{\mu\nu} a = g_{a\gamma\gamma} \vec{E} \cdot \vec{B} a$$

Axion field (a)

Electric field ($\vec{E}$)

External magnetic field ($\vec{B}$)

photon-ALP coupling ($g_{a\gamma\gamma}$)

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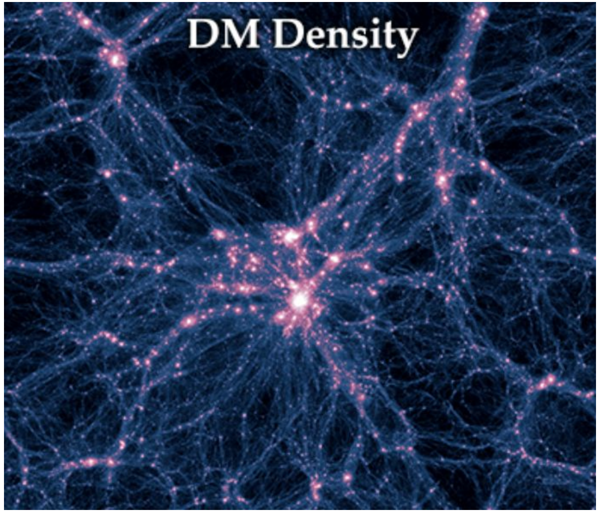
ALPs as Dark Matter candidates

- ALPs were also proposed as viable Dark Matter (DM) particle candidates
- They could have been produced in the early Universe via “misalignment” mechanisms
- According to Arias et al. [1] in order to explain the current amount of DM with ALPs

$$g_{a\gamma\gamma} < 10^{-12}\left[\frac{m_a}{1\ \mathrm{neV}}\right]^{1/2}\mathrm{GeV}^{-1}$$

Very Weakly Interacting Slim Particles (WISPs)



Illustris simulation

[1] Arias et al. , 2012 J. Cosmol. Astropart. Phys. 2012, 013

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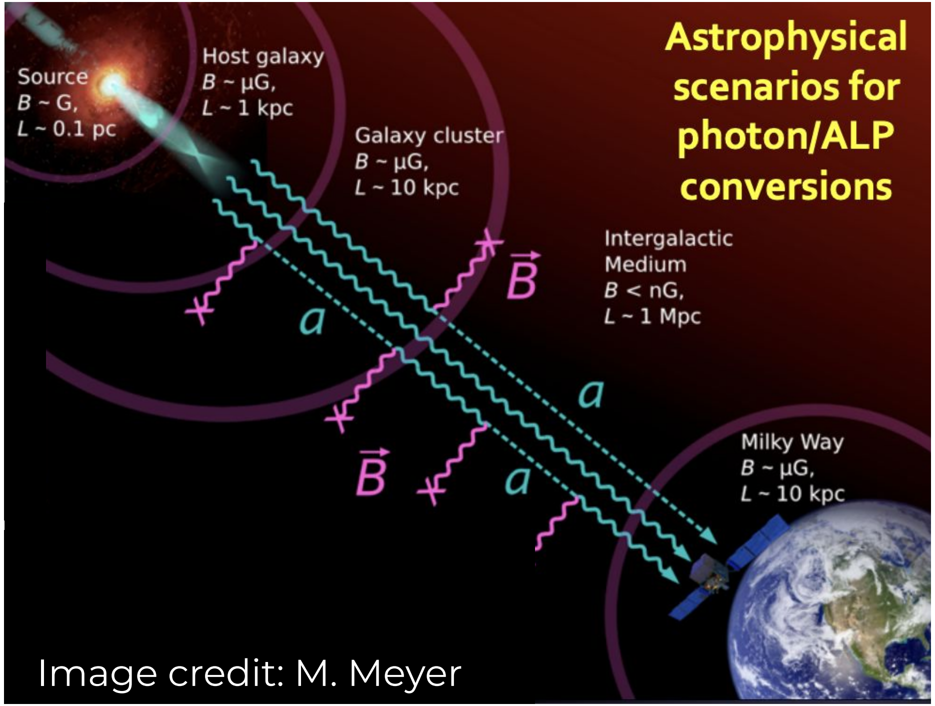
Probing ALPs with gamma rays



Photon survival probability

$$P_{\gamma\gamma} = \frac{1}{3}\left(1 - \exp\left(-\frac{3}{2}NP_{\gamma\to a}\right)\right)$$

$$P_{\gamma\to a} = \sin^2(2\theta)\sin^2\left[\frac{g_{a\gamma\gamma}Bd}{2}\sqrt{1+\left(\frac{E_c}{E}\right)^2}\right]$$

$$E_{crit} \sim 2.5\,\mathrm{GeV}\,\frac{|m^2_{a,neV} - \omega^2_{pl,neV}|}{g_{11}B_{\mu G}}$$

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Probing ALPs with gamma rays

$$\frac{d\Phi_{obs}}{dE} = \frac{d\Phi_{em}}{dE} \cdot P(E_\gamma; m_a, g_{a\gamma}, \mathbf{B}, z)$$

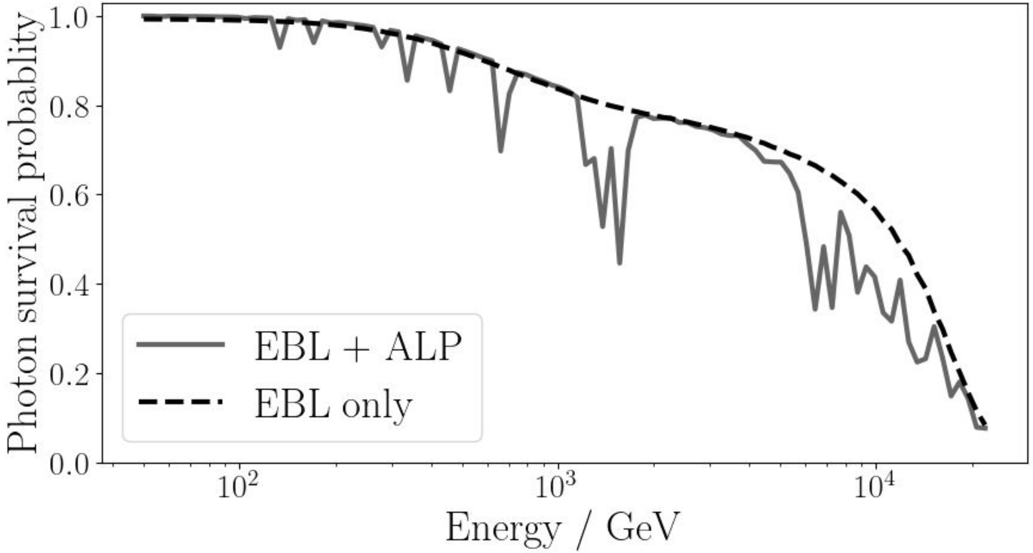
Observed flux

Intrinsic flux

Gamma-ray energy

Ambient magnetic field

redshift



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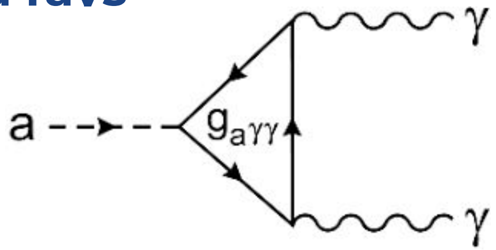
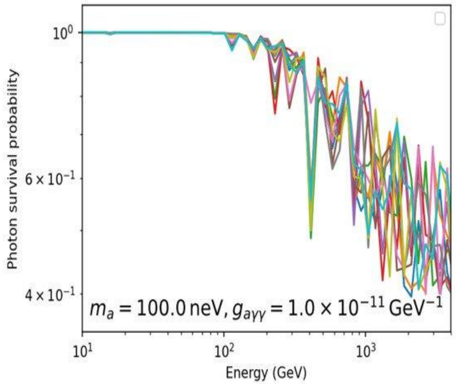
Probing ALPs with gamma rays



Feynman diagram of photon-axion interaction

- ALPs □ axion - solution to the Strong CP problem
- Photon-ALP mixing in the external magnetic field
- Irregularities (wiggles) in the spectra of astrophysical targets
- Knowledge of the magnetic fields is fundamental for producing the ALPs models



Photon survival probability
(https://github.com/me-manu/gammaALPs)

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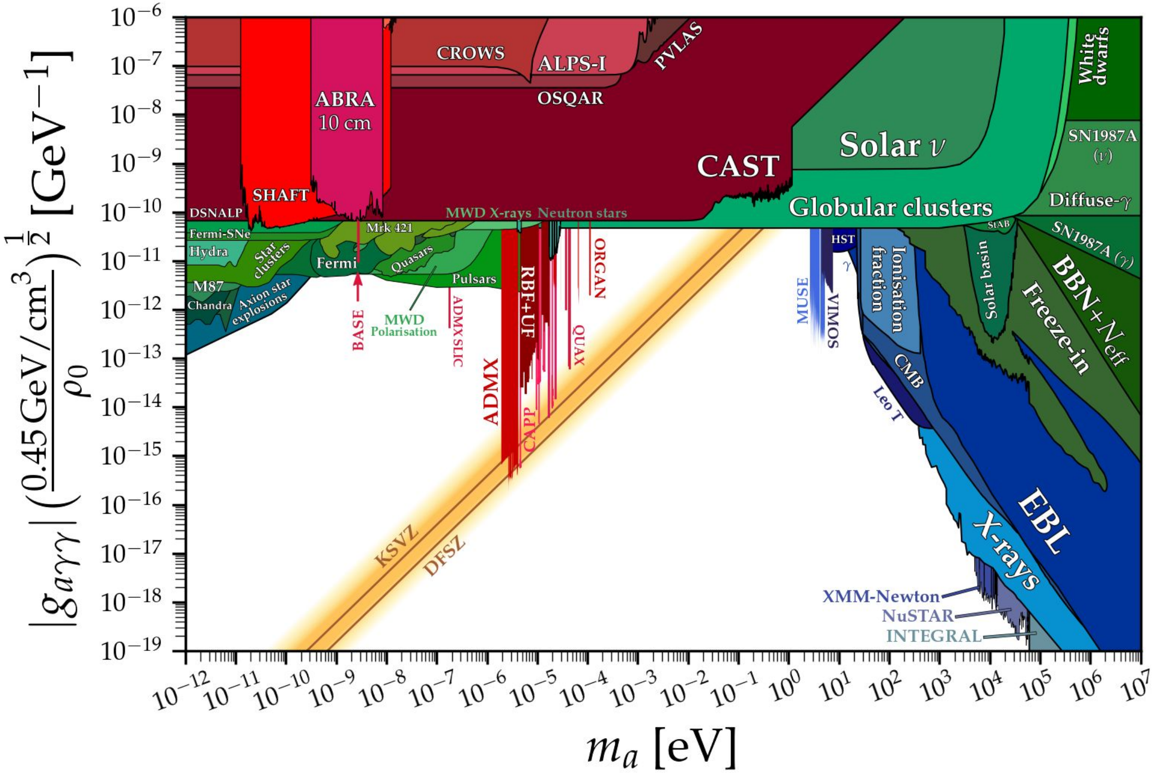

ALPs parameter space with current constraints, (https://cajohare.github.io/AxionLimits/), on the date 28/08/2023

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MAGIC telescopes: Characteristics

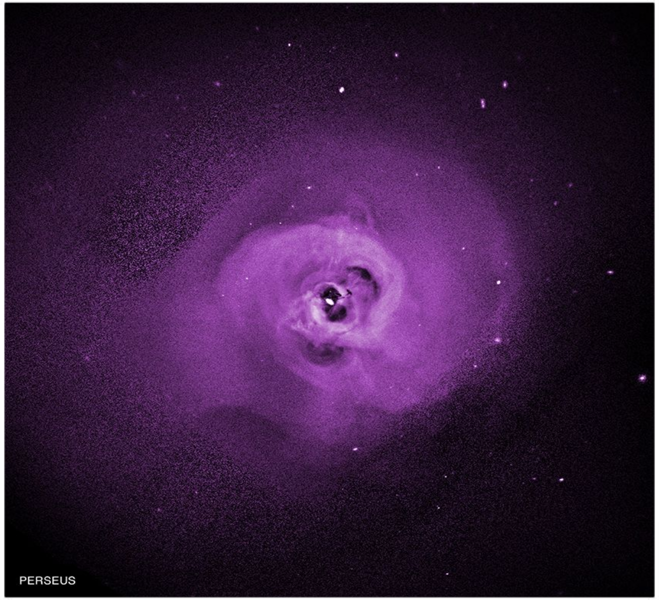
- MAGIC I from 2004, MAGIC II from 2009
- Located in the Canary island of La Palma, 2200m a.s.l
- Mirror dish diameter: 17 m
- Active reflective mirror surface: 236^2 m
- Upgrade of MAGIC I camera and readout system in 2012
- 1039 PMTs cameras (FoV 3.5°)
- Energy range: 30 GeV to 100 TeV
- Fast repositioning (180° in less than 30s)
- Energy threshold can be lowered to 15 GeV
- Sensitivity above 220 GeV is ~0.66% of the Crab nebula flux (for 50 hs)
- In total 300 MAGICians from 12 countries

The Perseus Galaxy Cluster

Target	Date	Duration [h]	N_{on}	N_{off}	N_{exc}	$S_{Li\&Ma}$
NGC 1275	1 Jan 17	2.5	6632	6703	4397	61.3
	02-03 Jan '17	2.8	4376	6060	2356	37.8
	Sep '16 - Feb '17	36.0	28830	68943	5849	31.8
IC 310	13 Nov '12	1.9	1469	2384	674	18.0
Sum		43.2	41307	84090	13276	63.0

Dataset previously analyzed by the MAGIC coll. and published in:

- NGC 1275: Astronomy & Astrophysics 617 (2018): A91.
- IC 310: Science 346.6213 (2014): 1080-1084.

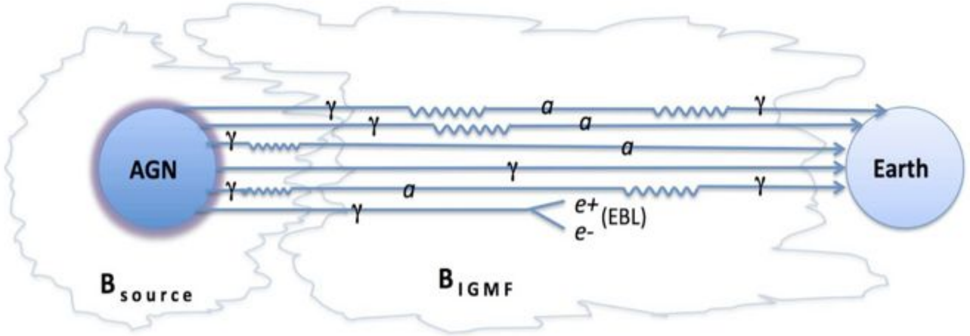


Perseus cluster in X-ray. Credit: NASA, Chandra

Distance ~ 75 Mpc (z = 0.01756)

ALPs searches in the Perseus cluster

- Photon-ALP mixing -> external magnetic field
- Flaring states -> increased constraining power
- 40.2 hours of NGC1275 data & 3.5 hours of IC310 data



- mixing in the blazar + jet
- mixing in the magnetic field of the galaxy cluster
- mixing in the extragalactic magnetic field + ($\gamma + \gamma \rightarrow e^+ + e^-$)
- back-conversion in the galactic magnetic field

Photon-ALP mixing in the magnetic field, credit: M.A. Sanchez Conde et al., 2009, Phys.Rev.D79:123511

ALPs searches in the Perseus cluster

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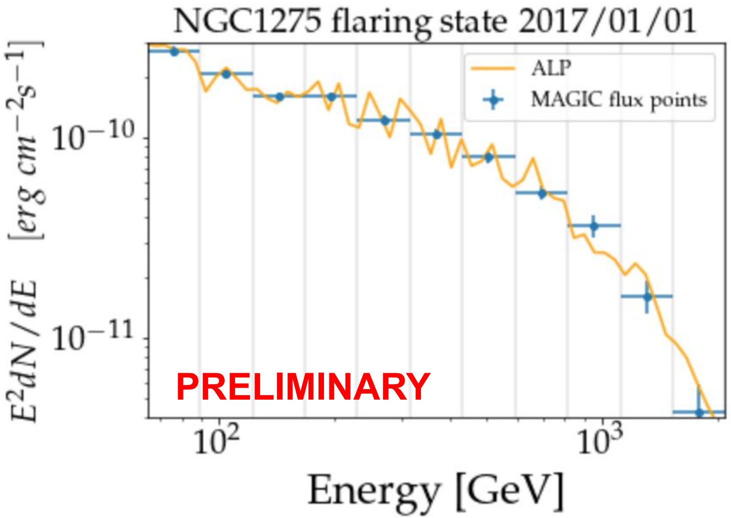
Binned likelihood $-\mathcal{L}(\theta, b) = \mathcal{L}(m_a, g_{a\gamma}; B, \Gamma, \Phi_0, E_c | b)$



- Model with fixed magnetic field realisation
- In the case of ALPs, due to the unknown magnetic field, random magnetic field realisations have to be employed to calibrate the test statistics for excluding the ALPs parameters.

Comparison of the MAGIC flux points with and w/out the ALPs model included.
MAGIC collaboration, in preparation, 2023, leading author Ivana Batković

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The Perseus Galaxy Cluster

Assuming no ALPs effect, the observation can be described with a

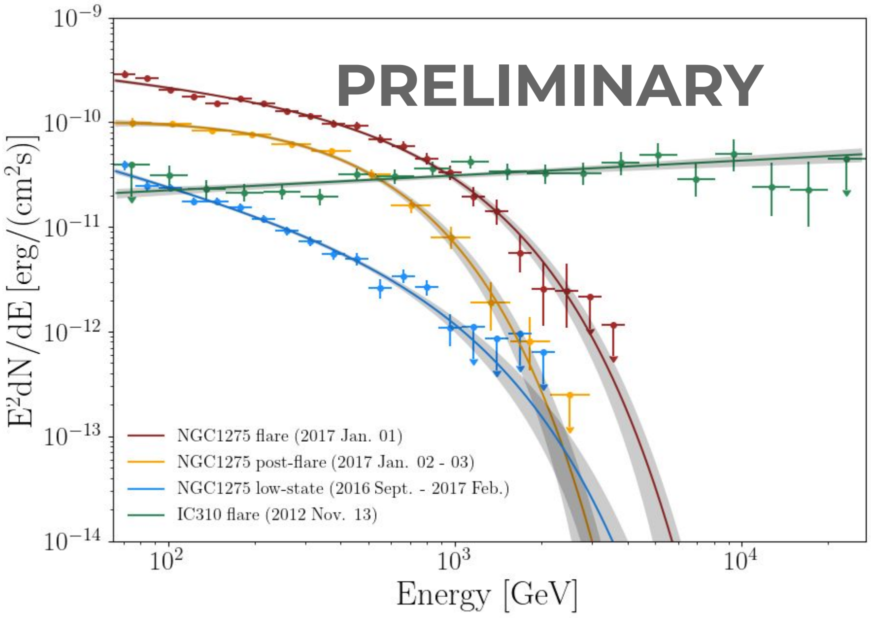
- Power law with an exponential cut-off (EPWL) for NGC 1275:

$$\phi^i_{int}(E) = \phi^i_0 \left(\frac{E}{E_0}\right)^{\Gamma^i} e^{E/E^i_k}$$

- Power law (PWL) for IC 310:

$$\phi_{int}(E') = \phi_0 \left(\frac{E'}{E_0}\right)^{\Gamma}$$

Target	Spectrum	Γ	$\Phi_0/10^{-10}$	E_k
		$[\mathrm{cm^{-2}s^{-1}TeV^{-1}}]$	TeV	
NGC 1275	EPWL	-2.31 ± 0.06	12.2 ± 1.0	0.72 ± 0.11
	EPWL	-1.79 ± 0.14	11.4 ± 2.1	0.29 ± 0.04
	EPWL	-2.54 ± 0.13	1.1 ± 0.2	0.5 ± 0.12
IC 310	PWL	-1.86 ± 0.04	1.8 ± 0.1	–



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Magnetic field modelling

- Milky Way:
  strength of the order of , modeled according to Ref. [1]
- Intra-cluster magnetic (ICM) field in the Perseus cluster: modeled as a random field with Gaussian turbulence in accordance with the A2199 cool-core cluster [2] with the following parameters [3]

	B_0 μG	η	n_0 cm^{-3}	n_2 cm^{-3}	r_{core}/r_{core_2} kpc	β/β_2
B	10	0.5	$39 \cdot 10^{-3}$	$4.05 \cdot 10^{-3}$	80 / 280	1.2 / 0.58

- Jet magnetic field:
  photon-ALP mixing in the magnetic field of AGN jets is negligible since viewing angles with respect to the line of sight are large
- Intergalactic magnetic field (IGMF):
  negligible for photon-ALP mixing

https://github.com/me-manu/gammaALPs

Turbulent magnetic field superposed on an optical image of M51. Credits: NASA, the SOFIA science team, A. Borlaff; NASA, ESA, S. Beckwith (STScI) and the Hubble Heritage Team (STScI/AURA).

[1] Astrophys. J. 757 (2012)
[2] A2199, A&A 540 (Apr., 2012) A38
[3] Phys. Rev. Lett. 116 (2016) 161101

Statistical framework

- Likelihood: $$\mathcal{L}(g_{a\gamma}, m_a, \boldsymbol{\mu}, \boldsymbol{b}, B|\boldsymbol{D}) = \prod_{i,k} \mathcal{L}_{i,k}(g_{a\gamma}, m_a, \boldsymbol{\mu_i}, b_{i,k}, B|D_{i,k})$$

Parameters of interest: ALPs mass and coupling

Nuisance parameters: SED pars., Magnetic field

Data: On and Off counts

Product over all datasets and energy bins

$$\mathcal{L}_{i,k} = \mathcal{P}\left(N_{\text{on}}^{i,k} \mid s_{i,k} + \alpha\, b_{i,k}\right) \times \mathcal{P}\left(N_{\text{off}}^{i,k} \mid b_{i,k}\right)$$

$$\mathcal{P}(n|r) = r^n e^{-r}/n!$$

- Expected signal counts:

$$s_{i,k} = \int_{\Delta E_k} dE\; \Phi^i_{obs}(E;\; g_{a\gamma}, m_a, \boldsymbol{\mu_i}, B, z)$$

- Observed flux::

$$\Phi^i_{obs} = \int dE'\; \Phi^i_{int}(E'; \boldsymbol{\mu_i}) P^{a,\text{EBL}}_{\gamma\gamma}(E') \cdot \text{IRF}^i(E|E')$$

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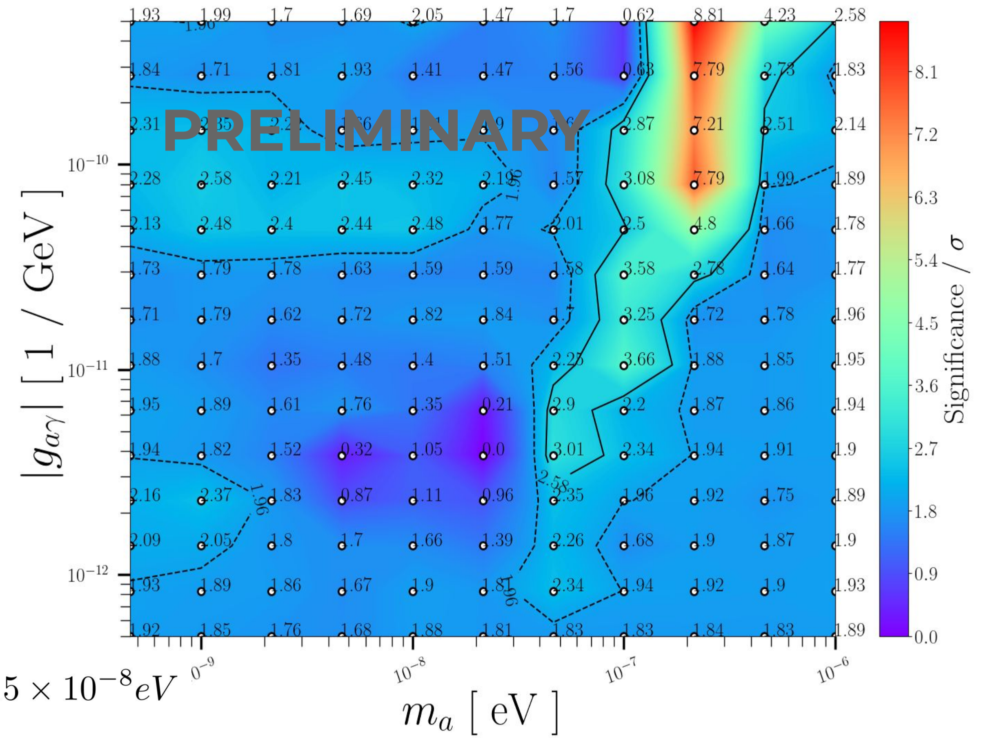
Constraints to ALPs

- We analyzed 154 points in the ALP parameters space where IACTs are sensitive to ALP effects

$$5 \cdot 10^{-8} eV < m_a < 10^{-6} eV$$

$$5 \cdot 10^{-13} GeV^{-1} < g_{a\gamma} < 5 \cdot 10^{-10} GeV^{-1}$$

- For each point, the obtained statistic is computed and converted into an exclusion significance
- The null hypothesis (no ALP effect) is excluded with a significance of 1.7σ (not enough to claim ALP)
- The excluded regions at 95% and 99% CL are delimited with a black dashed and solid line respectively
- The best agreement with the data is for $m_a = 2.15 \times 10^{-8} eV$ and $g_{a\gamma} = 3.81 \times 10^{-12} GeV^{-1}$



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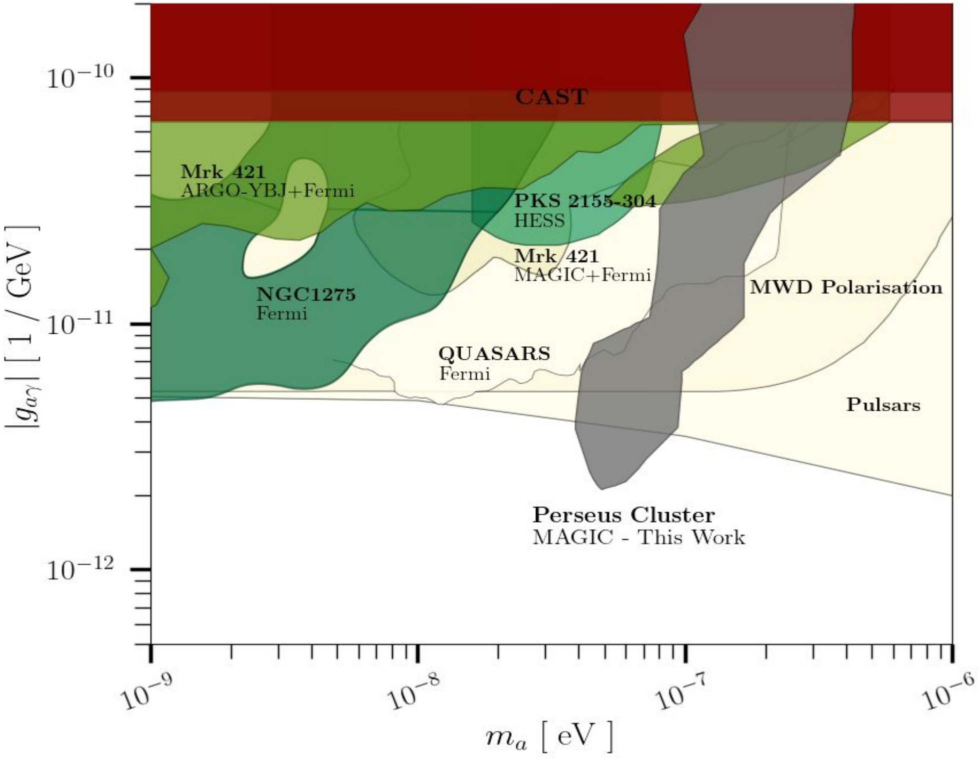
Constraints to ALPs

- The excluded area match those from earlier results

- To date, these results offer the strongest constraints on ALP masses in the range of 40-90 neV with the greatest sensitivity for ALP masses of m_a = 50 neV, reaching the photon-ALP coupling down to $g_{a\gamma} = 2 \times 10^{-12}$ GeV^{-1}

PRELIMINARY



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Thanks for your attention!

Image Credit: Chiara Righi (@chirighi)

@MAGICtelescopes

Special thanks to Giacomo D'Amico and Ivana Batković for borrowing me their slides :)