20th PATRAS WORKSHOP ON AXIONS WIMPS & WISPS
Tenerife. September 22-26. 2025

# Axion-like Particles in the Very-High-Energy Sky: From MAGIC to CTAO

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MAGIC Major Atmospheric Gamma Imaging Cerenkov Telescopes

CTAO LST COLLABORATION

# Summary

- Why **ALPs**?
- ALPs in **astrophysics**
- How do we search for ALPs?
- ALPs and IACTs: **MAGIC** & **LST-1**

# Why ALPs?

- Axion – R. D. Peccei & H. Quinn, S. Weinberg & F. Wilczek: proposed as a solution to the Strong CP problem
- Generalisation - Pseudo Nambu Goldstone bosons from spontaneously broken global symmetries:

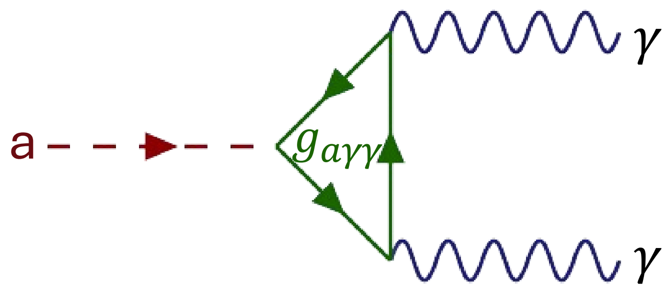
**Axion-like particles (independent mass and coupling)**

- Production in the Early Universe through the misalignment mechanism:

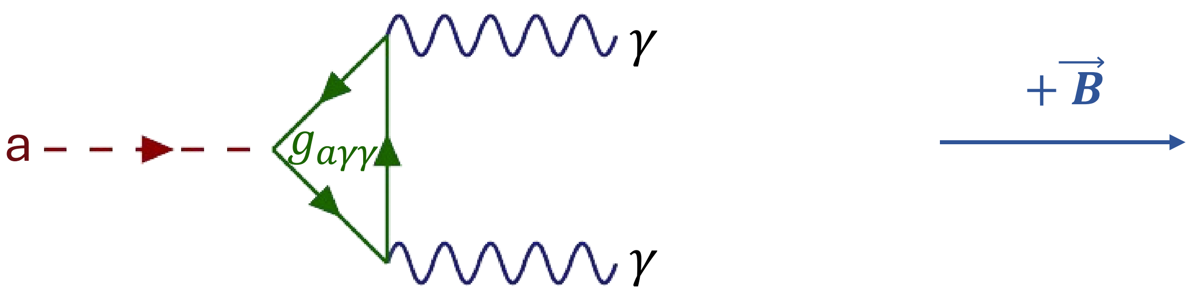
**Dark Matter candidate**

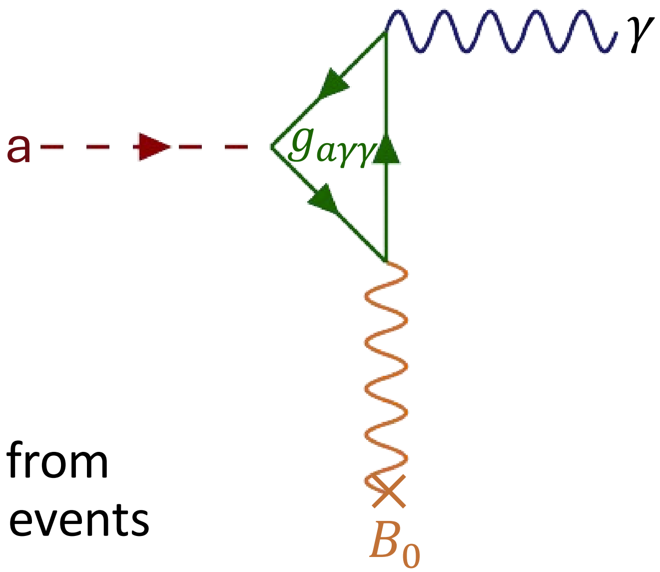
**HOW CAN WE OBSERVE THEIR**

**INTERACTION WITH PHOTONS?**



# Why ALPs?




- Interaction with photons – experimental search for ALPs
- Dark matter axions, solar axions, axions from supernovae, axions from astrophysical objects such as Active Galactic Nuclei and transient events

- Magnetic field is enabling “conversion” of an axion into a gamma ray photon

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

# ALPs in astrophysics

- In the vast pool of experiments searching for ALPs…

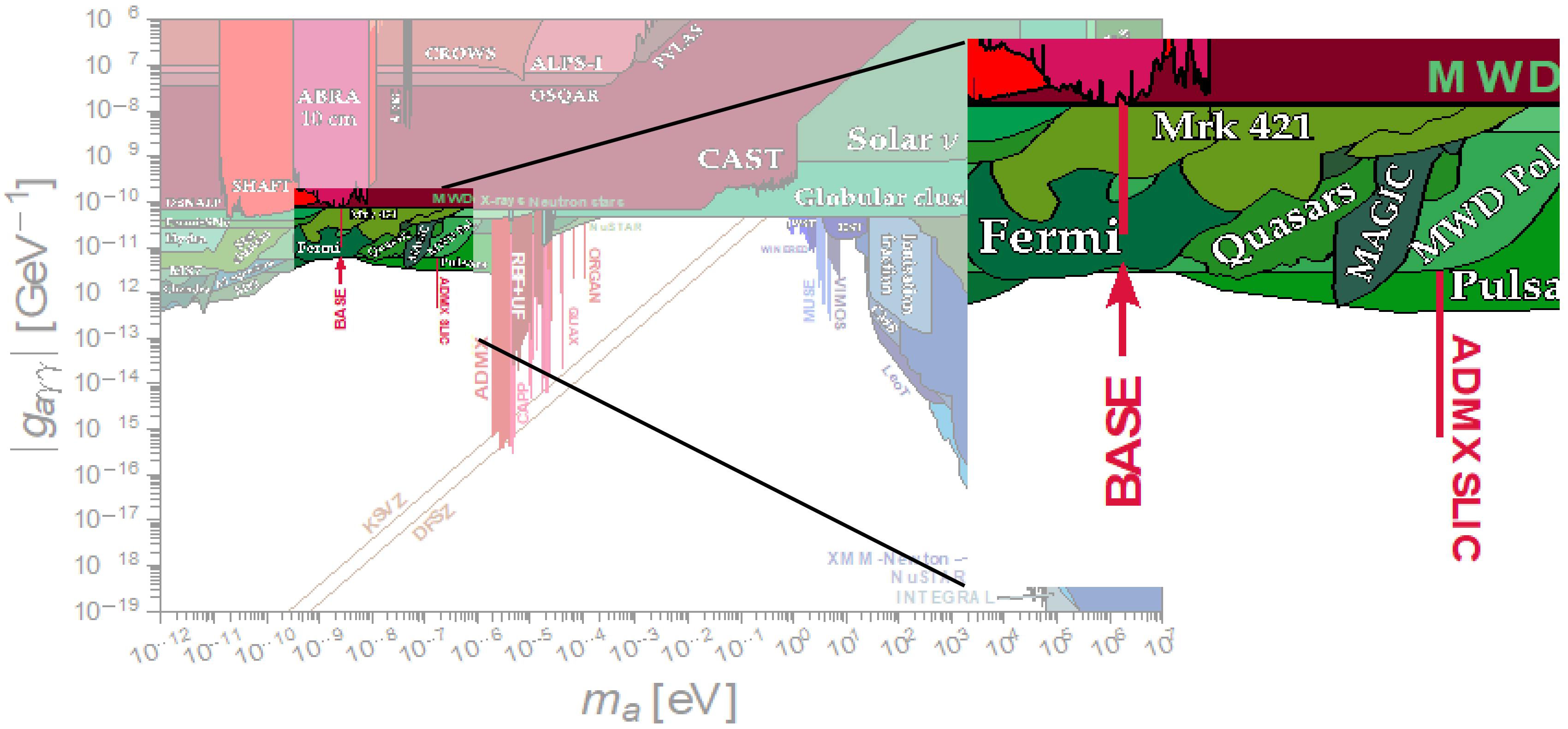
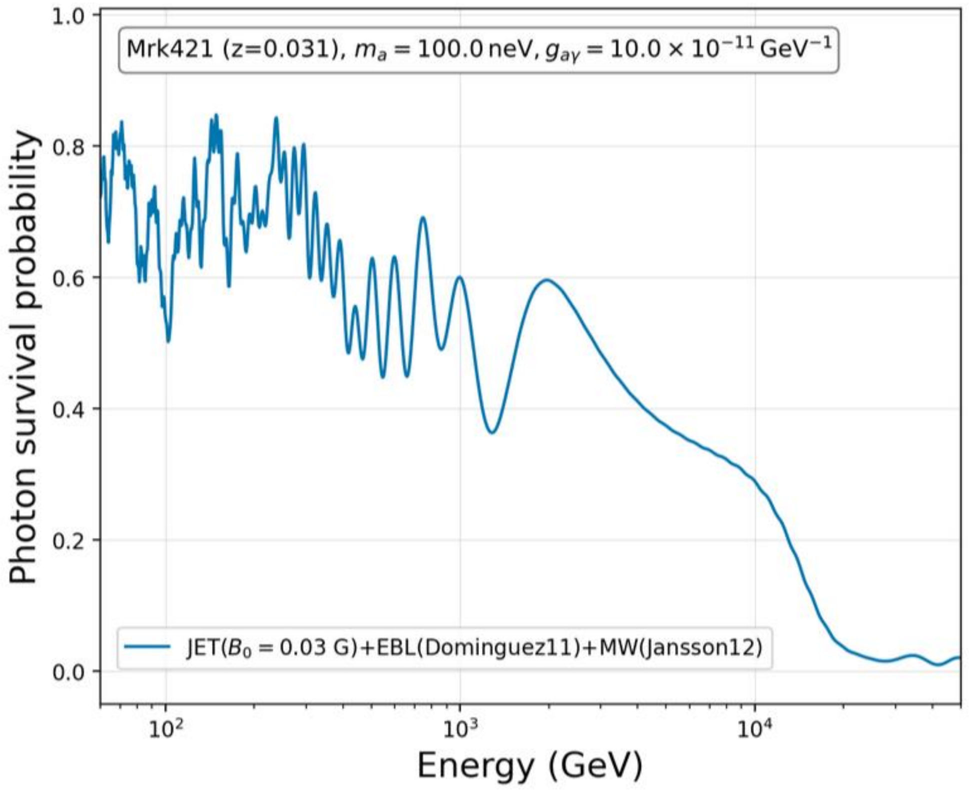



Figure 1: ALPs parameters space, from: C. O'Hare, github.com/cajohare/AxionLimits

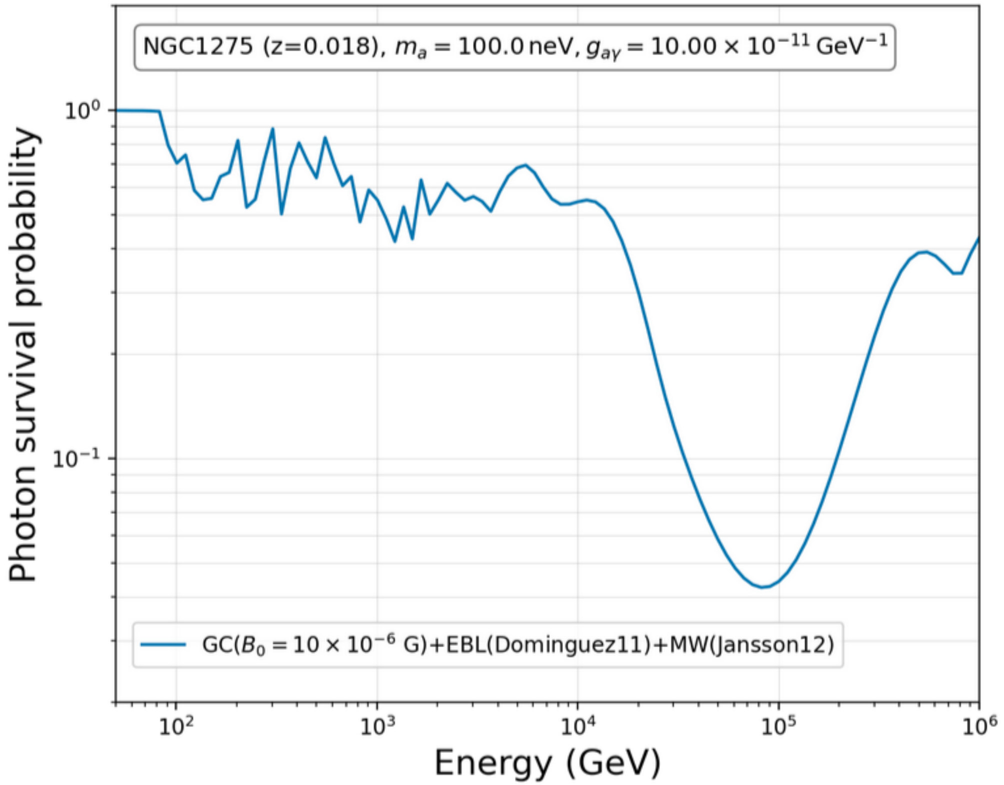
# ALPs in astrophysics

- Signatures of ALPs in VHE gamma-ray spectra

Photon-ALP oscillations




Recovery (resurrection) of photons



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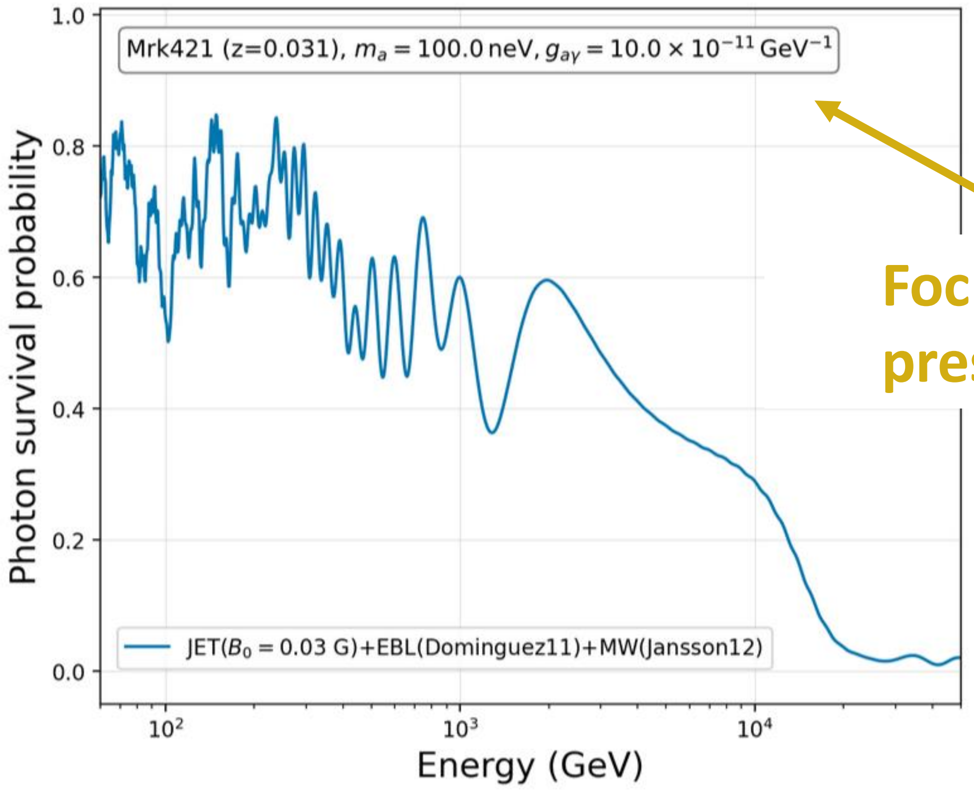
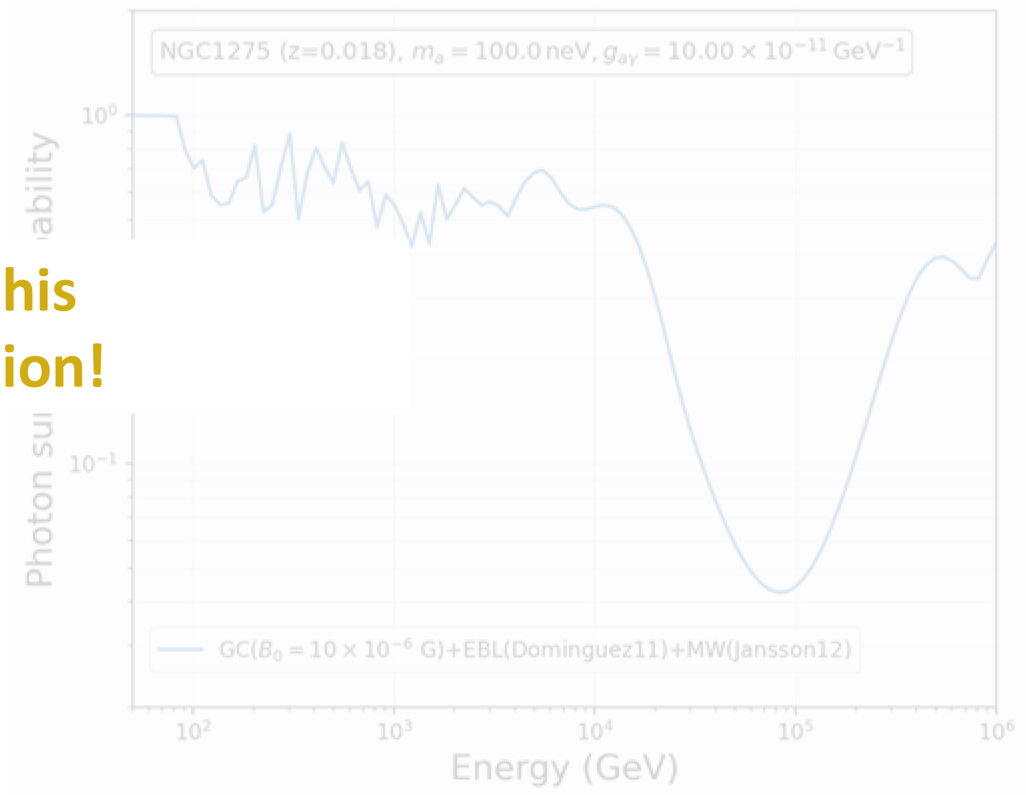



Focus of this presentation!

Recovery (resurrection) of photons



# ALPs in astrophysics

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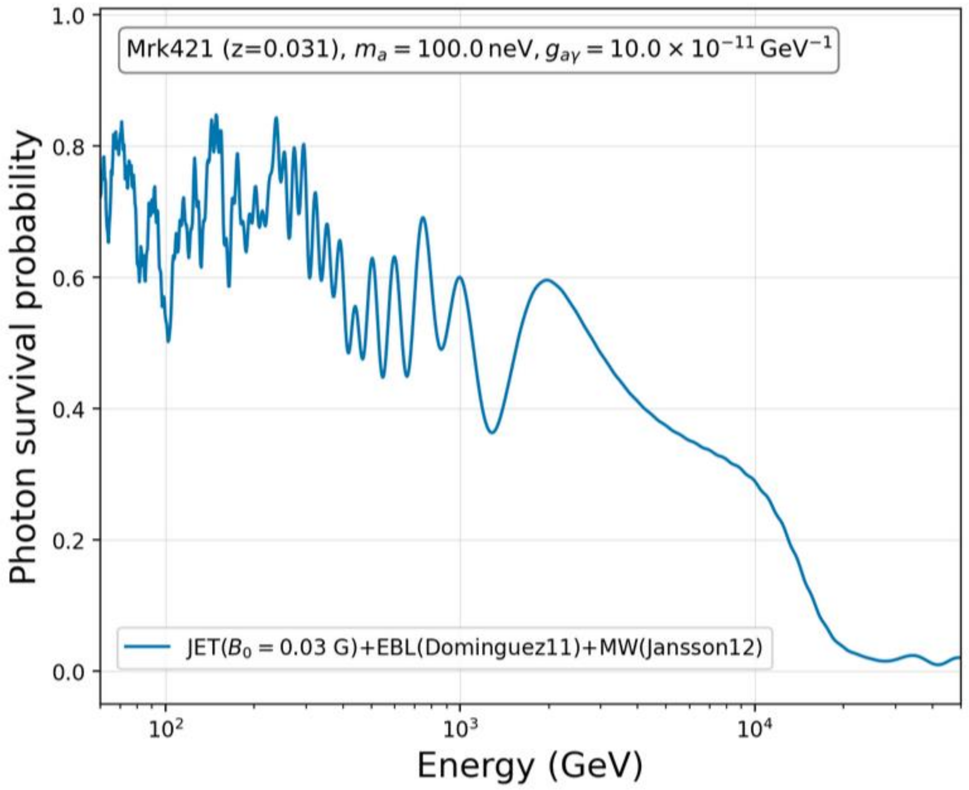


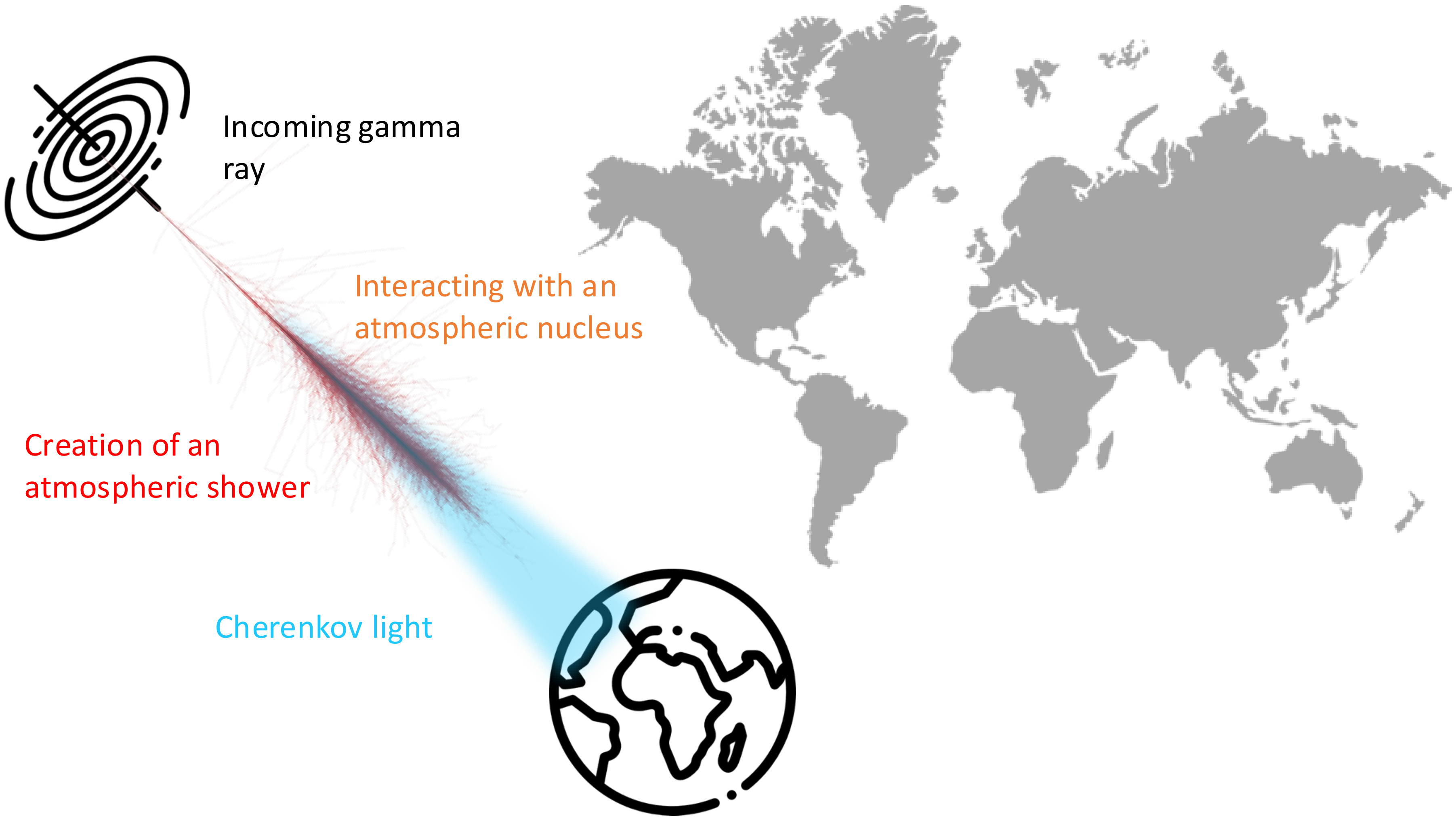

- Mixing occurs around the critical energy $E_{crit}$ :

$$E_{crit} = 2.5\ GeV \frac{|m_{a,neV}^2 - \omega_{pl,,neV}^2|}{G_{11} B_{\mu G}}$$

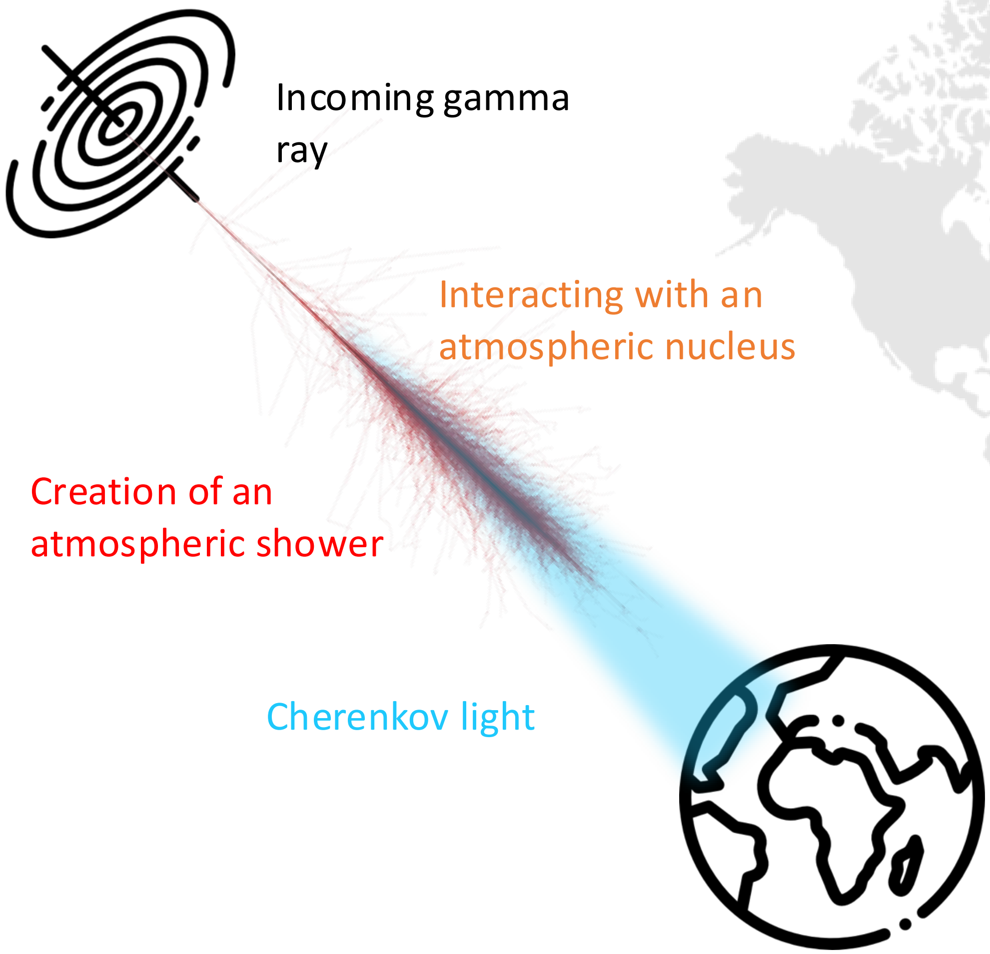
- https://gammaalps.readthedocs.io - solves the equations of motion of the photon-ALP system and calculates the $P_{\gamma\gamma}$

$$\frac{d\Phi_{obs}}{dE} = \frac{d\Phi_{int}}{dE} \times P_{\gamma\gamma}^{a,EBL}(E_\gamma; m_a, g_{a\gamma}, B; z)$$

# ALPs in astrophysics



# ALPs in astrophysics




- Located at La Palma
- Detecting gamma rays with energies of 25 GeV - 100 TeV

MAGIC (two 17m diameter telescopes) & LST-1 (23m)
- Field of view ~ 3.5° (4.3°)
- Energy resolution ~15% (30%)
- Angular res. ~ 0.1°(0.3°) (energy dependent)

# How do we search for ALPs?

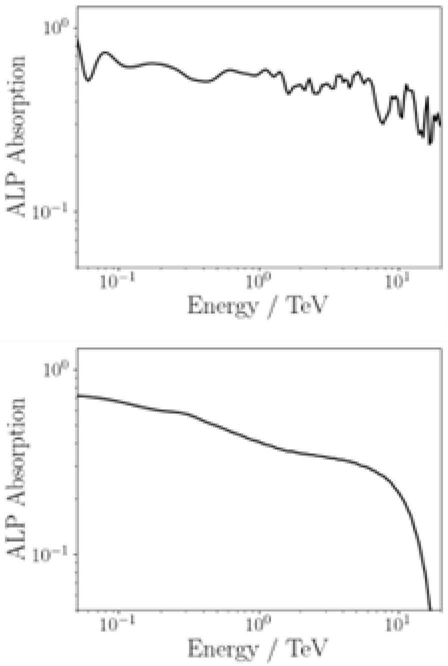
## ALP hypothesis

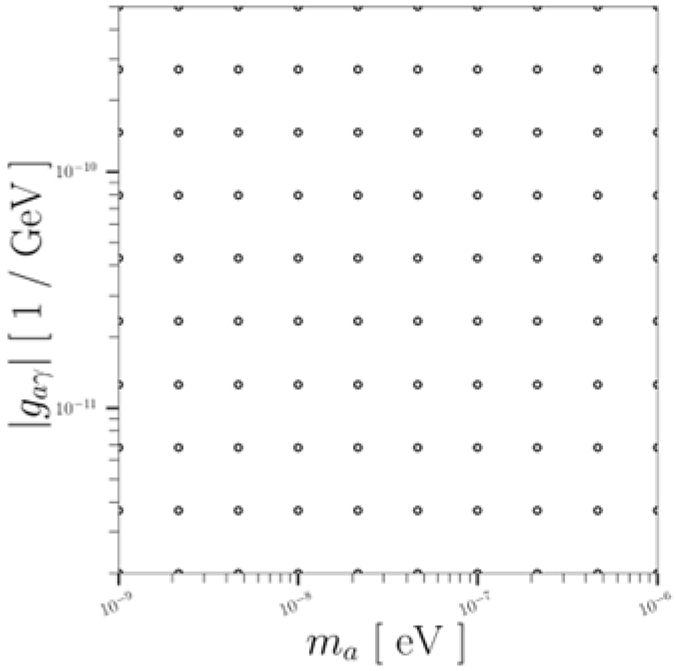
$$\frac{d\Phi_{obs}}{dE} = \frac{d\Phi_{int}}{dE} \times P_{\gamma\gamma}^{a,EBL}(E_\gamma; m_a, g_{a\gamma}, B; z)$$

Observed flux | Intrinsic flux | Gamma-ray energy

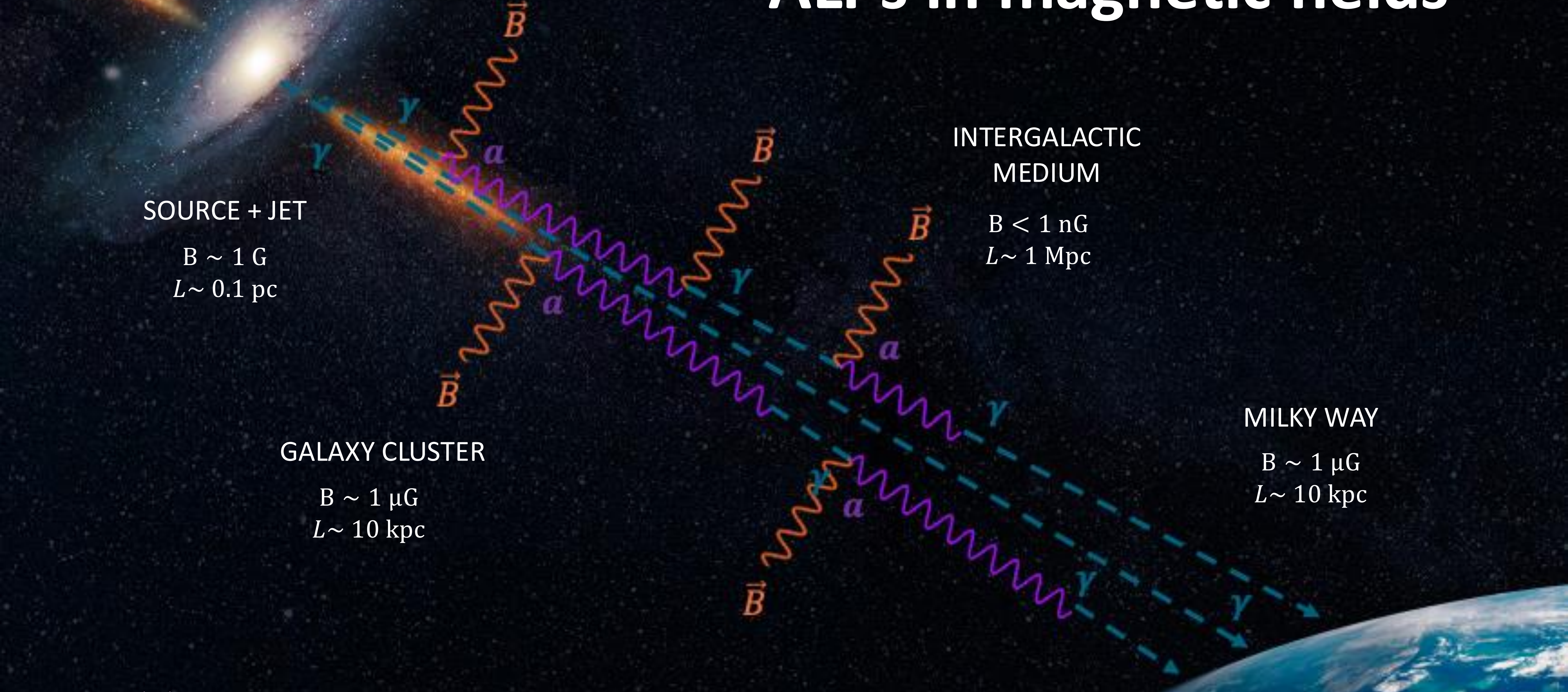
*B* - Ambient magnetic field
*z* - Source's redshift

We "build" a grid of $(m_a, g_{a\gamma})$ points, used for producing ALPs models



# ALPs in magnetic fields



# ALPs in magnetic fields

**Source and jet magnetic field**

$\mathrm{B} \sim 1\ \mathrm{G}$

$L \sim 0.1\ \mathrm{kpc}$

- Relevant for sources with observed relativistic jets and/or in regions (galaxy clusters) with sparse magnetic field; blazars
- Negligible impact for sources whose viewing angle is big with respect to the line of sight; i.e. radio galaxies

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**Galaxy cluster magnetic field**

$B \sim 1$ μG

$L \sim 10$ kpc

- Modelled as a random field assuming the Gaussian turbulence, following model described in Meyer *et al.* JCAP09(14')003

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**Intergalactic magnetic field**

$B < 1\ \mathrm{nG}$

$L \sim 1\ \mathrm{Mpc}$

- Importance of the inclusion of the mixing is evaluated based on the choice of the source, its distance, tested mass and coupling.
- Extragalactic background light absorption included

# ALPs in magnetic fields

### Source and jet magnetic field

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### Milky Way magnetic field

$B \sim 1\ \mu$G

$L \sim 10$ kpc

- Modelled with a turbulent and regular component [2]
- Mixing occurring in the coherent component of the Galactic magnetic field
- Several modelling options: Pshirkov et al. 11', Jansson & Farrar 12', Unger & Farrar 23'

# Constraints on ALPs by MAGIC

***Constraints on axion-like particles with the Perseus Galaxy Cluster with MAGIC***, Batković, D'Amico et al. (MAGIC Collaboration), PDU, Volume 44, May 2024, 101425, https://doi.org/10.1016/j.dark.2024.101425

- NGC1275 - Perseus Galaxy cluster
- Data (41.3 hrs) divided by the activity states
- Fit of the intrinsic spectrum (no ALPs):

EPWL (power-law with an exponential cutoff)

$$\Phi_{int}(E') = \phi_0^i \left(\frac{E}{E_0}\right)^{\Gamma_i} e^{\frac{E_i}{E_k^i}}$$

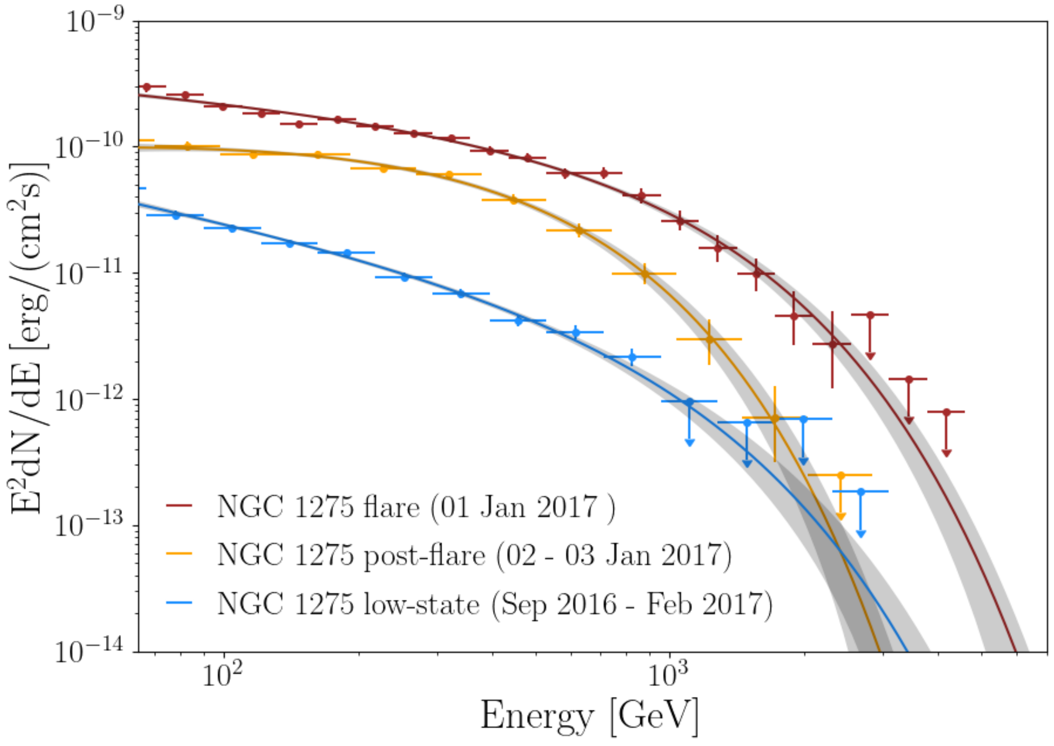


Figure 2: SED of three activity states of NGC1275 observed by MAGIC

# Constraints on ALPs by MAGIC

## Statistical framework

Evaluating the hypotheses on the existence of ALPs – null hypothesis assumes no ALP effects present

$$S(g_{a\gamma}, m_a) = -2\, ln \frac{\mathcal{L}(g_{a\gamma}, m_a, \hat{\mu}, \hat{B} | D)}{\hat{\mathcal{L}}}$$

TEST STATISTICS

$$\mathcal{L}(m_a, g_{a\gamma}; \mu \,| D) = \prod_{i,k} \mathcal{L}_{i,k}, (m_a, g_{a\gamma}; \mu_i \,| D_{i,k})$$

BINNED LIKELIHOOD

ALPs mass and coupling

Nuisance parameters: spectrum fit, B

Data: ON and OFF counts

$i$ – datasets
$k$ – bins

- Included magnetic fields: **Perseus galaxy cluster, EBL absorption, Milky Way magnetic field**
- For computing the ALPs exclusions, we introduce point-by-point computation of the correct coverage using the MC simulations

# Constraints on ALPs by MAGIC

## Results

Setting the 95% and 99% exclusion regions allows excluding the ALPs hypothesis at $2.03\ \sigma$ confidence level → cannot claim the existence of ALPs

Obtained constraints agree with the ones set previously by other studies

Most stringent exclusions up to date for the masses $m_a = (40 - 70) \times 10^{-9}$ eV

Greatest sensitivity in the mass range $m_a = (40 - 400) \times 10^{-9}$ eV reaching the photon-ALP coupling down to $g_{a\gamma} = 3 \times 10^{-12}$ GeV$^{-1}$

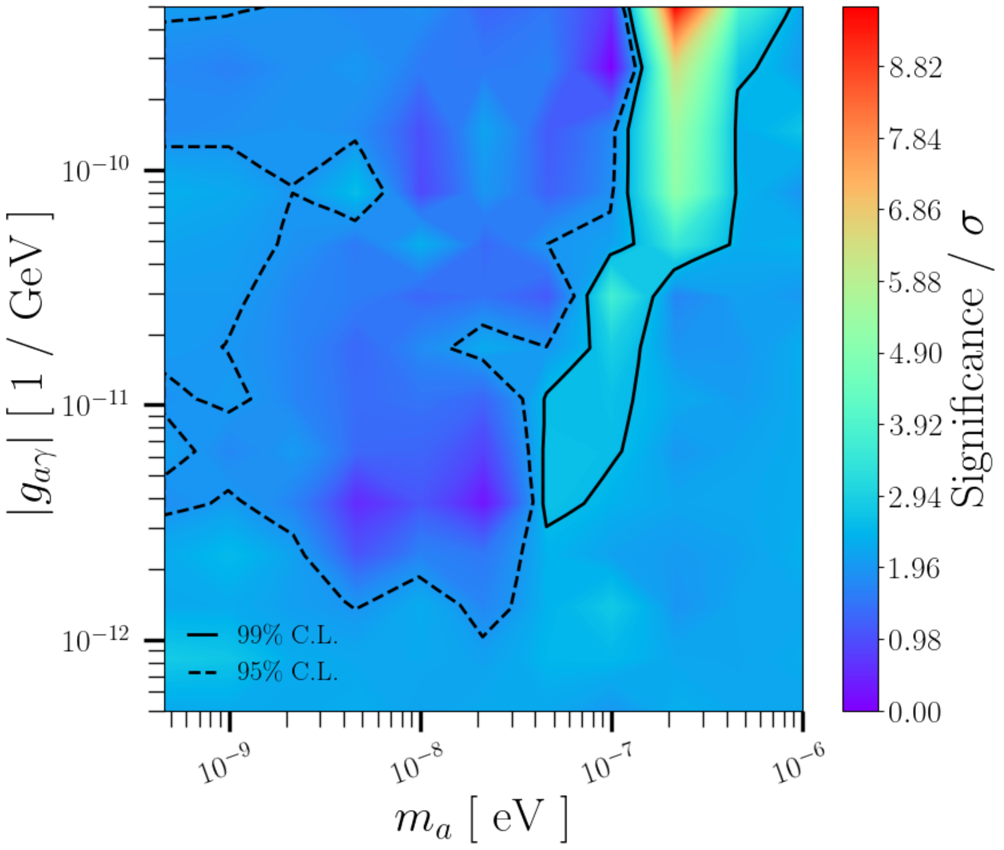


Figure 3: Constraints on the ALPs parameter space set by MAGIC using NGC1275 data

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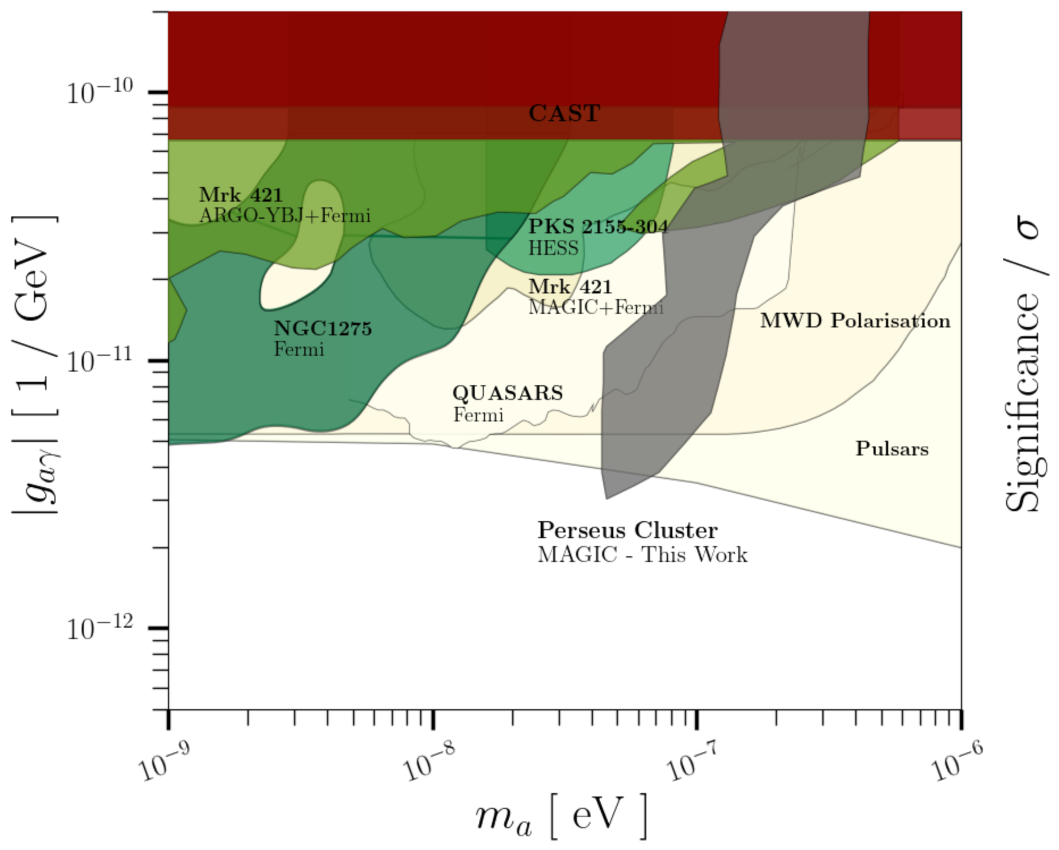



Figure 4: Constraints on the ALPs parameter space set by MAGIC using NGC1275 data in comparison to other studies

# Constraints on ALPs with AutoMAGIC

- Team: Francesco Schiavone (UNI Bari, **check his poster on CTAO ALPs study tomorrow**), Ivana Batković, Michele Doro (UNI Padova), and Cyrus Walther (TU Dortmund)
- Goal is to obtain limits on ALPs by analysing data of blazars observed by MAGIC → planning to combine results with LST-1
- Considering spectra from different activity states of each source
- Using AutoMAGIC → proprietary software for semi-automatic analysis of MAGIC data
- Processing data of 3 blazars from 2014 – 2024 → two sources already analyzed

# Constraints on ALPs by LST-1

PRELIMINARY

## Motivation

1. No blazar studies from an array in the Northern hemisphere!
2. No studies with combined constraints from several sources!

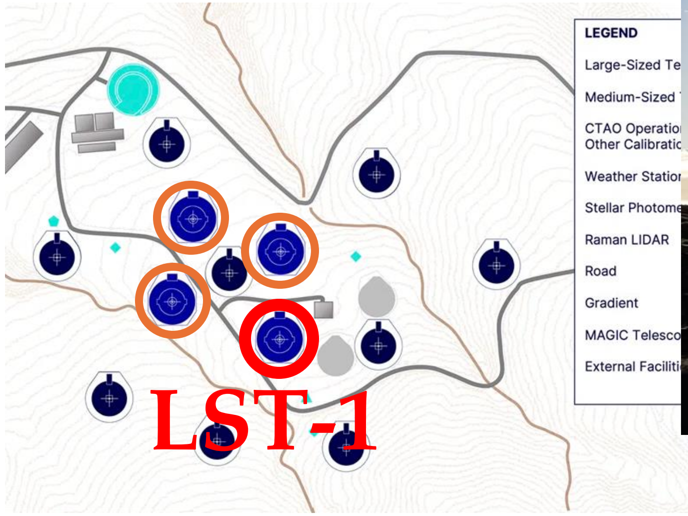
**First ALPs study with LST-1 data**

Targets of interest: blazars – supermassive black holes in centers of galaxies – ultra-relativistic jet aligned with the line of sight

LST-1 dataset (Aug 20 – Feb 24):

- Mrk421 ~ 87 hrs
- Mrk501 ~ 24 hrs
- 1ES1959+650 ~ 14 hrs
- BL Lac ~ 32 hrs

**Team**: Ivana Batković, Giacomo D'Amico (IFAE) and Michele Doro (UNIPD)




Outline of the CTAO North (left), LST-1 telescope (up)

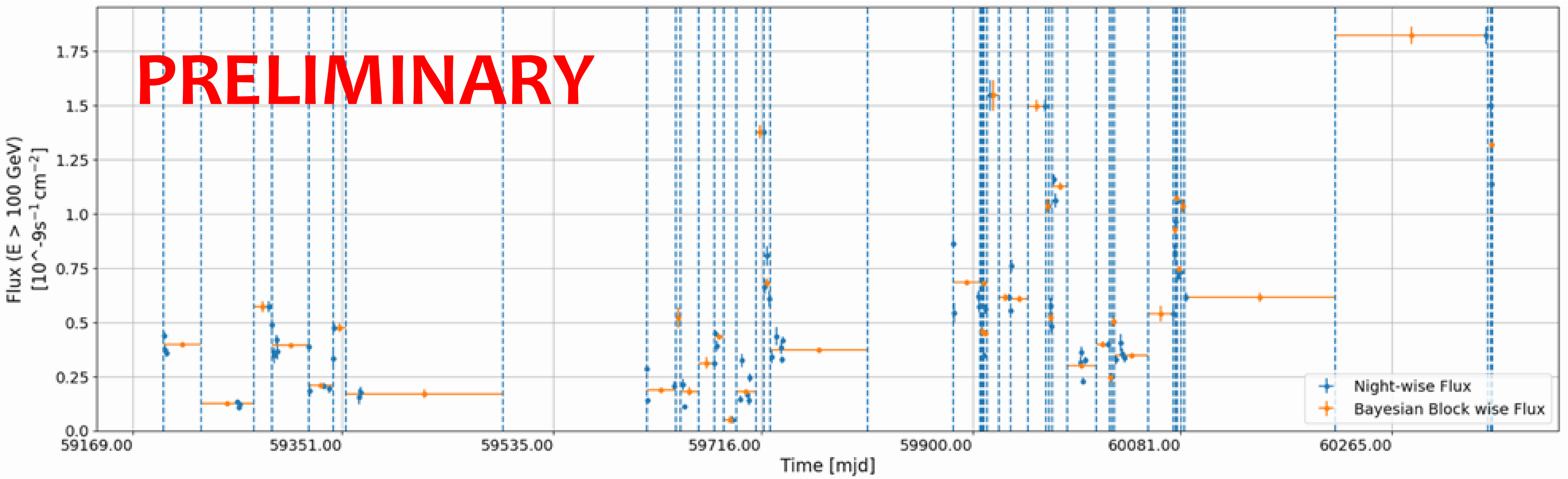
# Constraints on ALPs by LST-1

## Methodology

- Datasets are divided in groups using Bayesian block analysis.
- Spectral analysis is performed, while leveraging between number of bins and "smoothness" of the spectrum.

- **Mrk421 ~ 87 hrs**
- **Mrk501 ~ 24 hrs**
- **1ES1959+650 ~ 14 hrs**
- **BL Lac ~ 32 hrs**

**TOTAL: 73 Bayesian Blocks!**

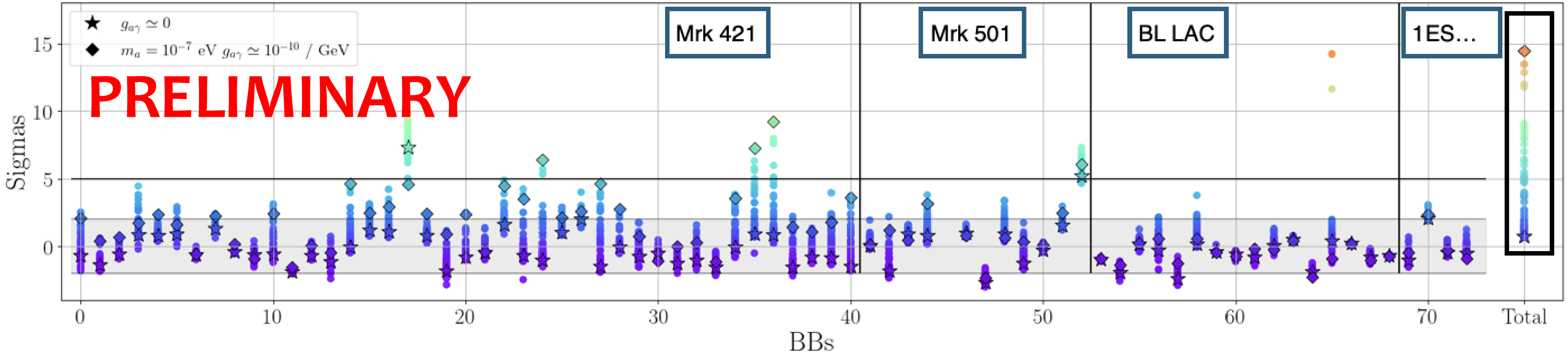


# Constraints on ALPs by LST-1

## Statistical framework

Exp. $\gamma$ counts | On counts | Exp. bkg counts | Off counts

$$\chi^2(m, g, \theta) = \sum_i \left( \left( \frac{s_i + \alpha b_i}{n_i} \right)^{n_i} e^{-(s_i + \alpha b_i) + n_i} \times \left( \frac{b_i}{m_i} \right)^{m_i} e^{-b_i + m_i} \right)$$




- Included magnetic fields: **Helical and tangled jet magnetic field model by Potter & Cotter 2016 (Synchrotron self-Compton modelling framework), EBL absorption, Milky Way magnetic field**

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# Constraints on ALPs by LST-1

## Preliminary results

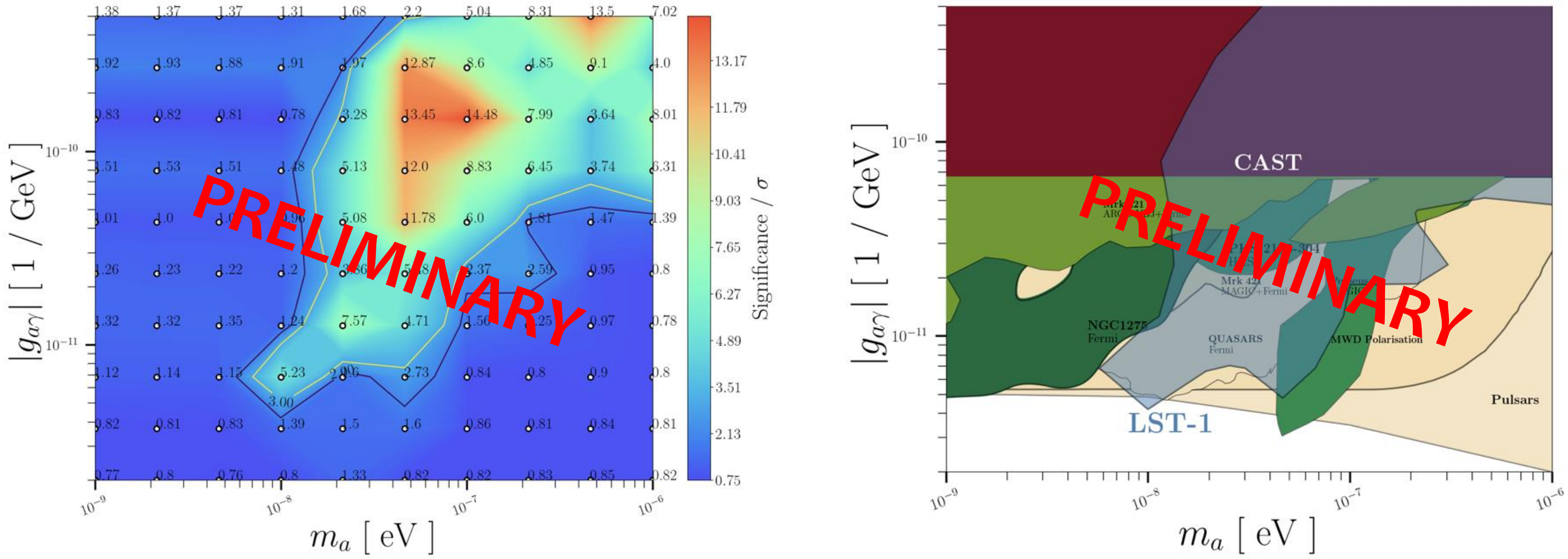


Figure 5: Preliminary constraints on the ALPs parameter space (95% and 99% exclusion limits left, 95% exclusion limit right), obtained with LST-1 data of M421, Mrk501, BLLac and 1ES1959+650.

# Conclusions

- Several studies are on-going (AutoMAGIC and LST-1), to be concluded by the end of 2025/26
    - Add systematics related to energy reconstruction and magnetic fields
    - Analysis of the whole dataset processed with AutoMAGIC software
    - Compute the final exclusions on ALPs parameters and compare with the existing limits
- In general - new constraints on ALPs are almost a daily news
- Ongoing search for axion and ALPs is in full power and with the upcoming experiments -> **POSSIBILITIES ARE (ALMOST) UNLIMITED**

20th PATRAS Tenerife. September 22-26. 2025 WORKSHOP ON AXIONS WIMPS & WISPS

# Thank you for your attention!

Contact: ivana.batkovic@unipd.it

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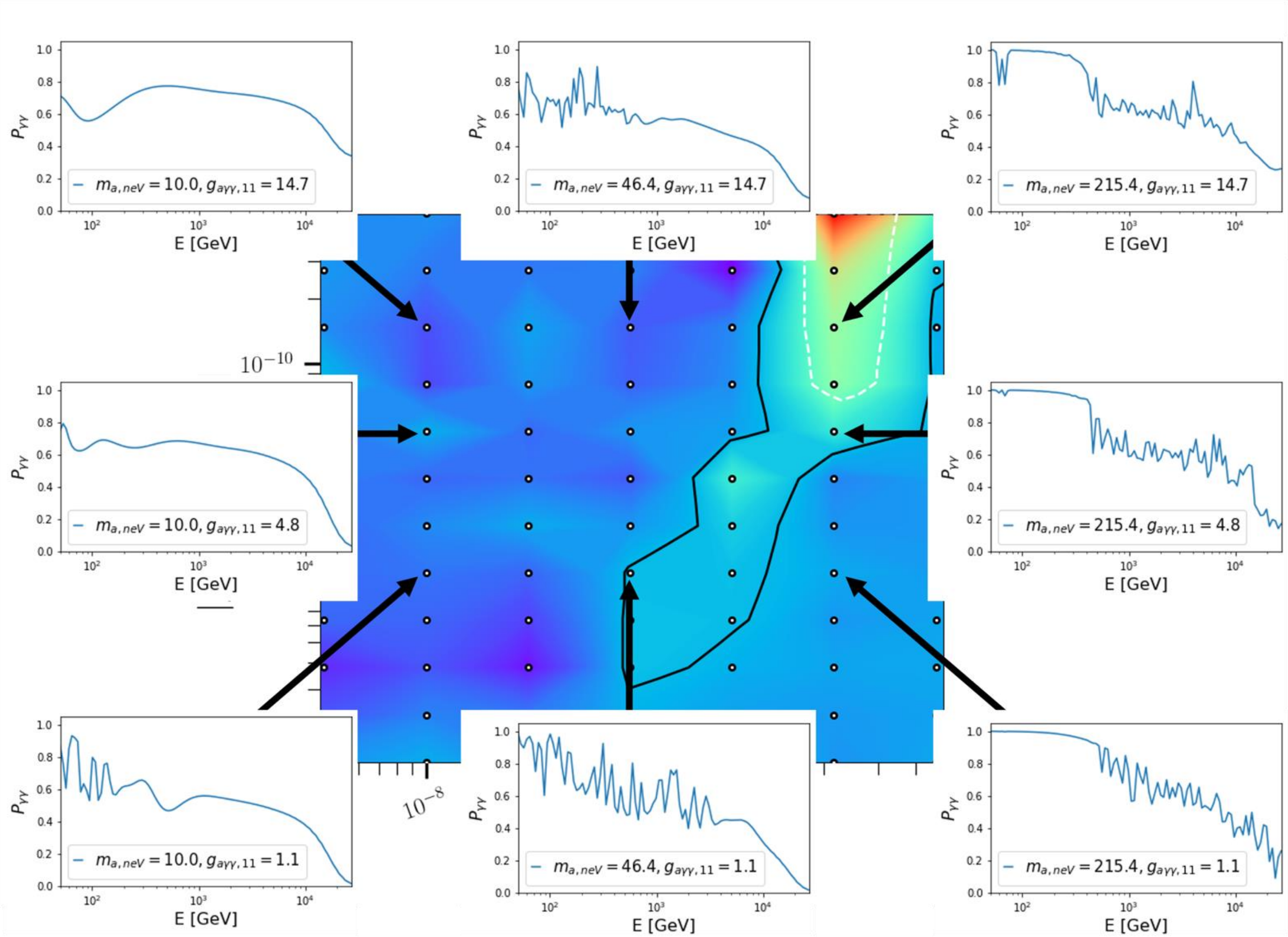
# Backup

## "Wiggles" vs. jumps

- We conclude that despite the initial idea about searching for the spectral irregularities, so-called "wiggles", our data is instead sensitive to sudden jumps in $P_{\gamma\gamma}$

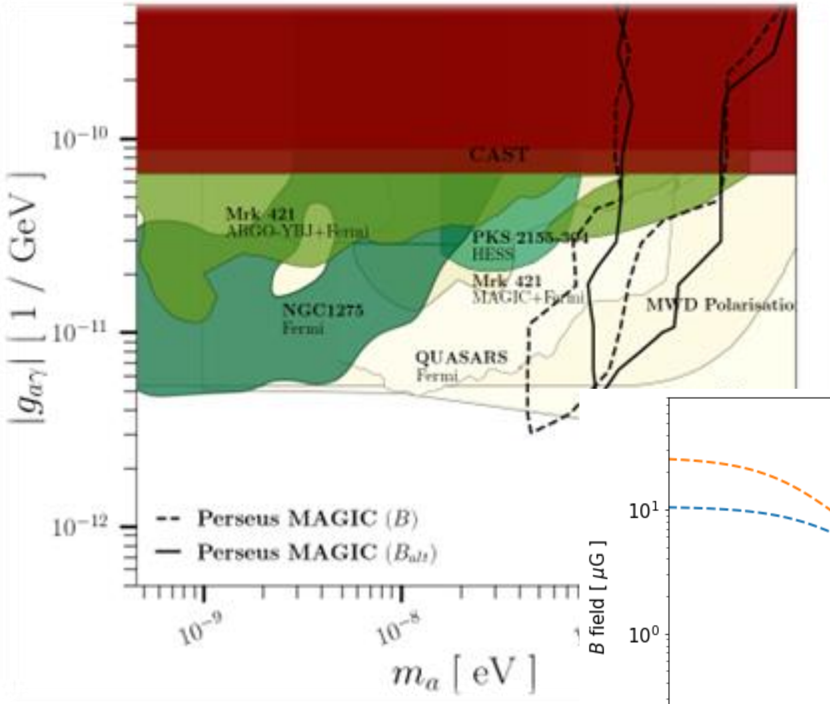


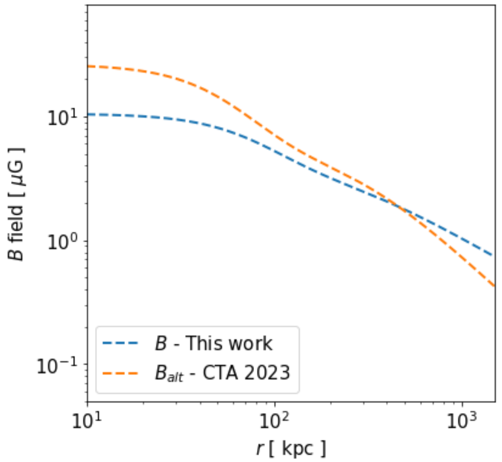

$P_{\gamma\gamma}$ of selected models along with the obtained CL in the ALPs parameter space, from: Abe et al., *Phys. Dark Univ.* 44, 101425, (2024)

# Backup

## Results – systematic uncertainities

- Checks on the systematics: magnetic field modelling
- We repeat the analysis using the magnetic field model used in CTA, arXiv:2309.03712




Dependence of the constraints on the magnetic field modelling, from: Abe et al., *Phys. Dark Univ.* 44, 101425, (2024)

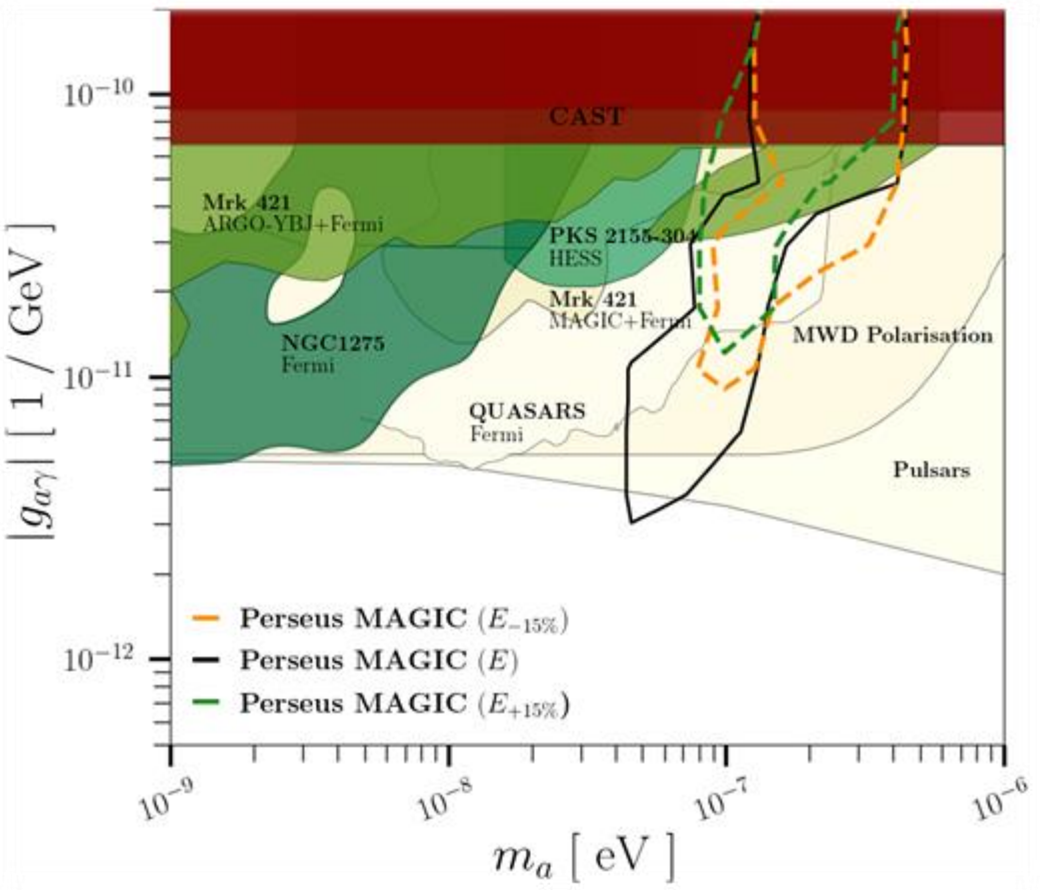
| | $B_0[\mu G]$ | $\eta$ | $n_0$ $[cm^{-3}]$ | $n_2$ $[cm^{-3}]$ | $\frac{r_{core}}{r_{core2}}$ $[kpc]$ | $\beta/\beta_2$ |
|---|---|---|---|---|---|---|
| **B** | 10 | 0.5 | 0.04 | 0.005 | 80/280 | 1.2/0.6 |
| $\mathbf{B_{alt}}$ | 25 | 2/3 | 0.05 | 0.004 | 57/278 | 1.2/0.7 |

Comparison of magnetic field models of the Perseus galaxy cluster magnetic field from our work (*Phys. Dark Univ.* 44, 101425, 2024) and Abe et al. arXiv:2309.03712

# Backup

## Results – systematic uncertainities

- Checks on the systematics: energy resolution of MAGIC
- We repeat the analysis, ”adding” the +15% and -15% on the ALP effect on the spectrum of the source




Dependence of the constraints on the energy resolution, from: Abe et al., *Phys. Dark Univ.* 44, 101425, (2024)

# Backup

Check of the impact of different Milky Way magnetic field models in the photon survival probability for Mrk 421: