ALPs searches with the First Large-Sized Telescope

IVANA BATKOVIĆ ON BEHALF OF CO-AUTHORS
MICHELE DORO AND GIACOMO D'AMICO
FOR THE LST COLLABORATION

RICAP 24

CTAO | LST COLLABORATION

Axion-like particles ✦ motivation

Strong CP problem

- R.D. Peccei and H. Quinn; 1977.
- Spontaneously broken global symmetry
- S. Weinberg and F. Wilczek; 1978.

Axion

$$m_a \simeq 6 \times 10^{-6} \mathrm{eV} \frac{10^{12}\ \mathrm{GeV}}{f_a}$$

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f_a – PQ axion decay constant ~ v_{weak} ~ 246 GeV

Axion-like particles (ALPs)

- Pseudo-Nambu-Goldstone bosons emerging from different theories
- Mass and coupling are independent

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Axion-like particles (ALPs)

- Pseudo-Nambu-Goldstone bosons emerging from different theories
- Mass and coupling are independent

Dark Matter

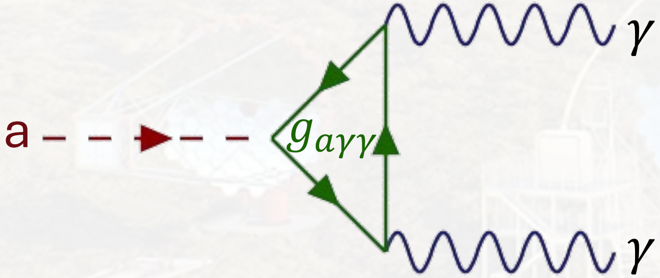
Can be produced in the early Universe through the misalignment mechanism*:

Dark Matter ALPs

*Arias, P.; Cadamuro, D.; Goodsell, M.; Jaeckel, J.; Redondo, J.; Ringwald, A.; **WISPy cold dark matter**. J. Cosmol. Astropart. Phys. 2012, 013

Axion-like particles ✦ motivation

- Observable through interaction with photons
- Extremely important for detection of axion, i.e. dark matter axions, solar axions…



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

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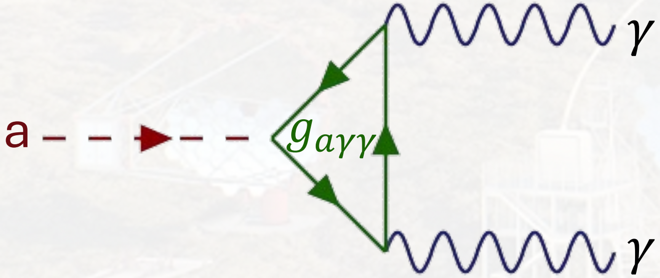

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- Magnetic field is "enabling mixing" between a VHE photon and an axion:

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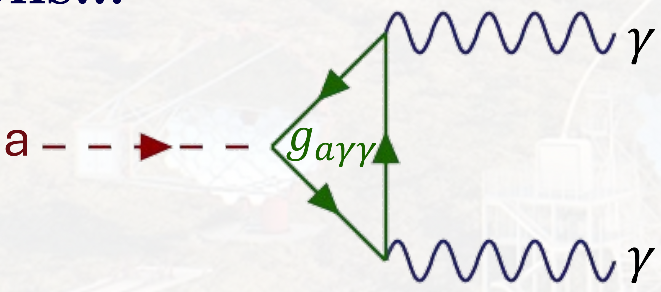
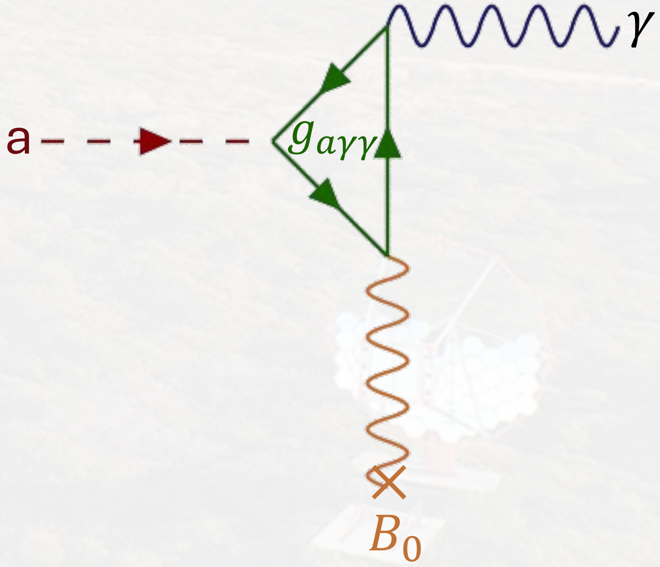


$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} F_{\mu\nu}\tilde{F}^{\mu\nu} a = g_{a\gamma\gamma}\vec{E}\cdot\vec{B}a$$

- Magnetic field is "enabling mixing" between a VHE photon and an axion:



Axion-like particles ✦ searches

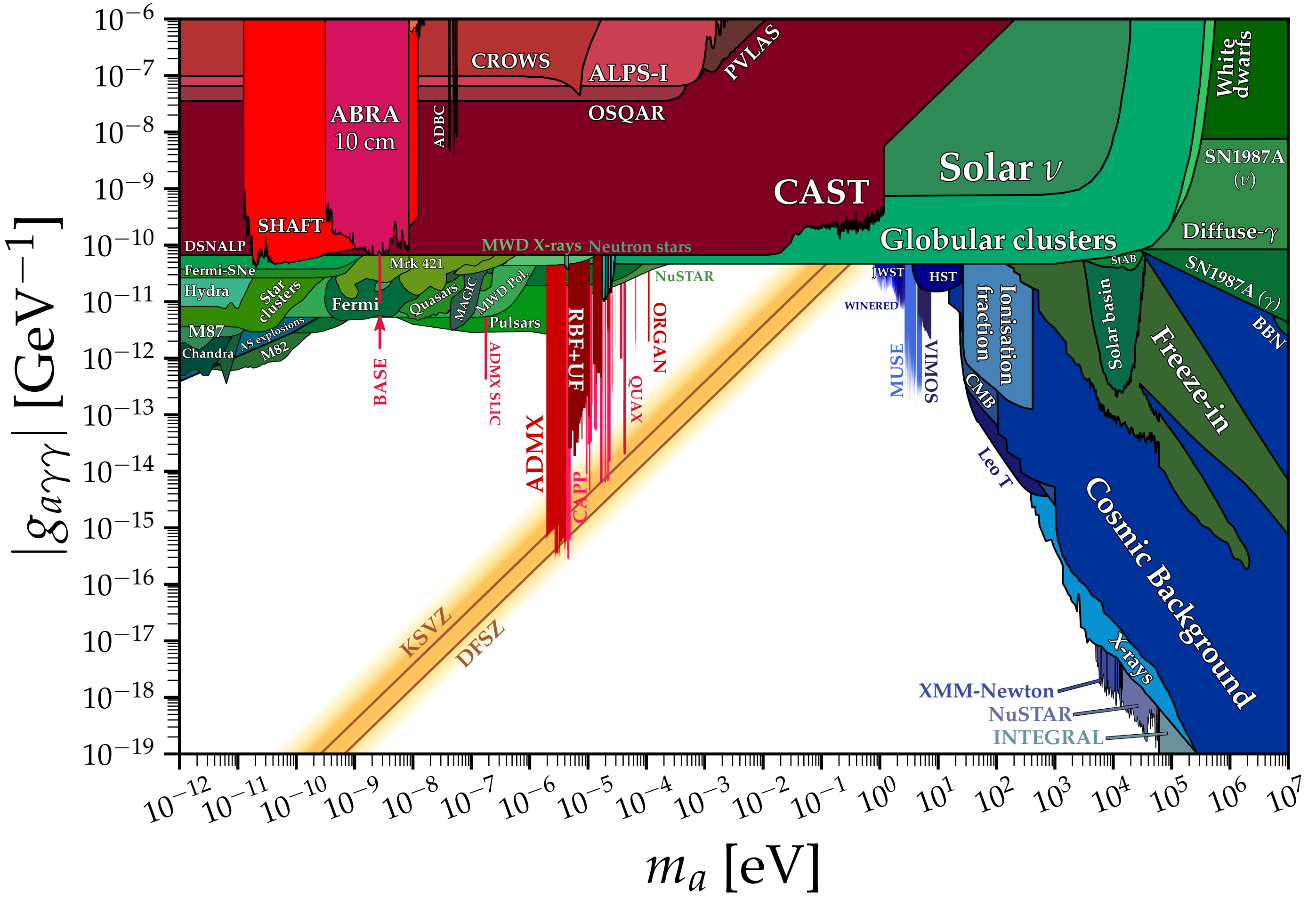
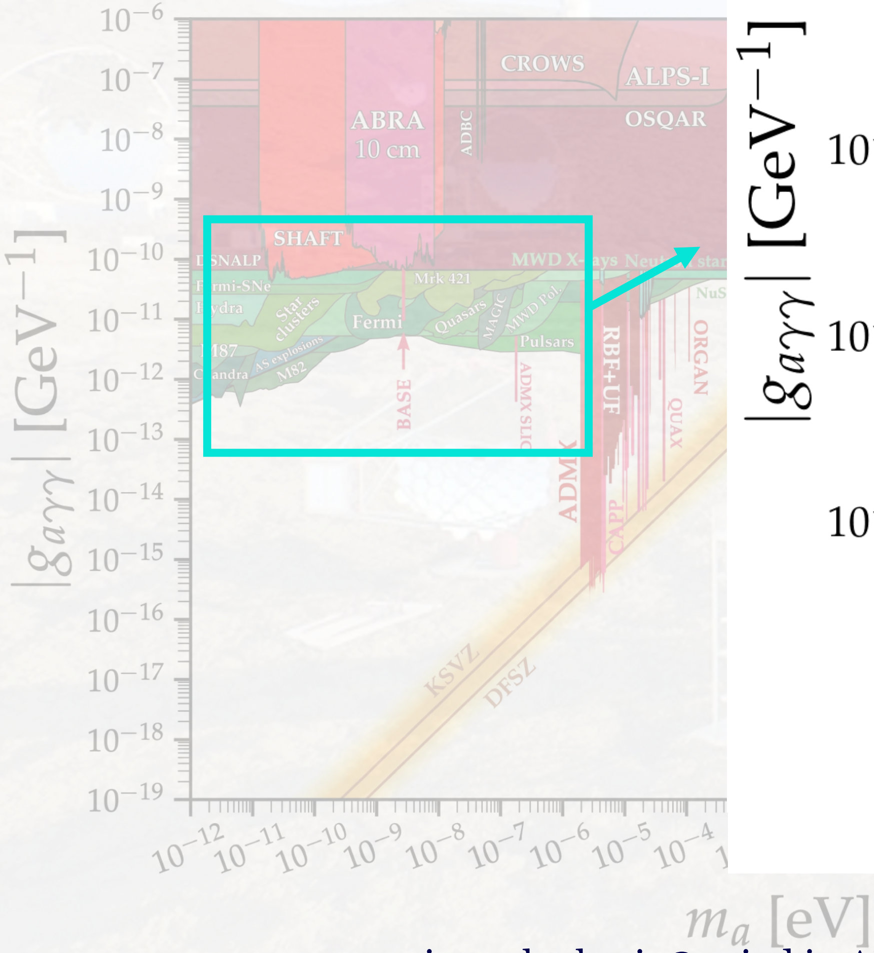
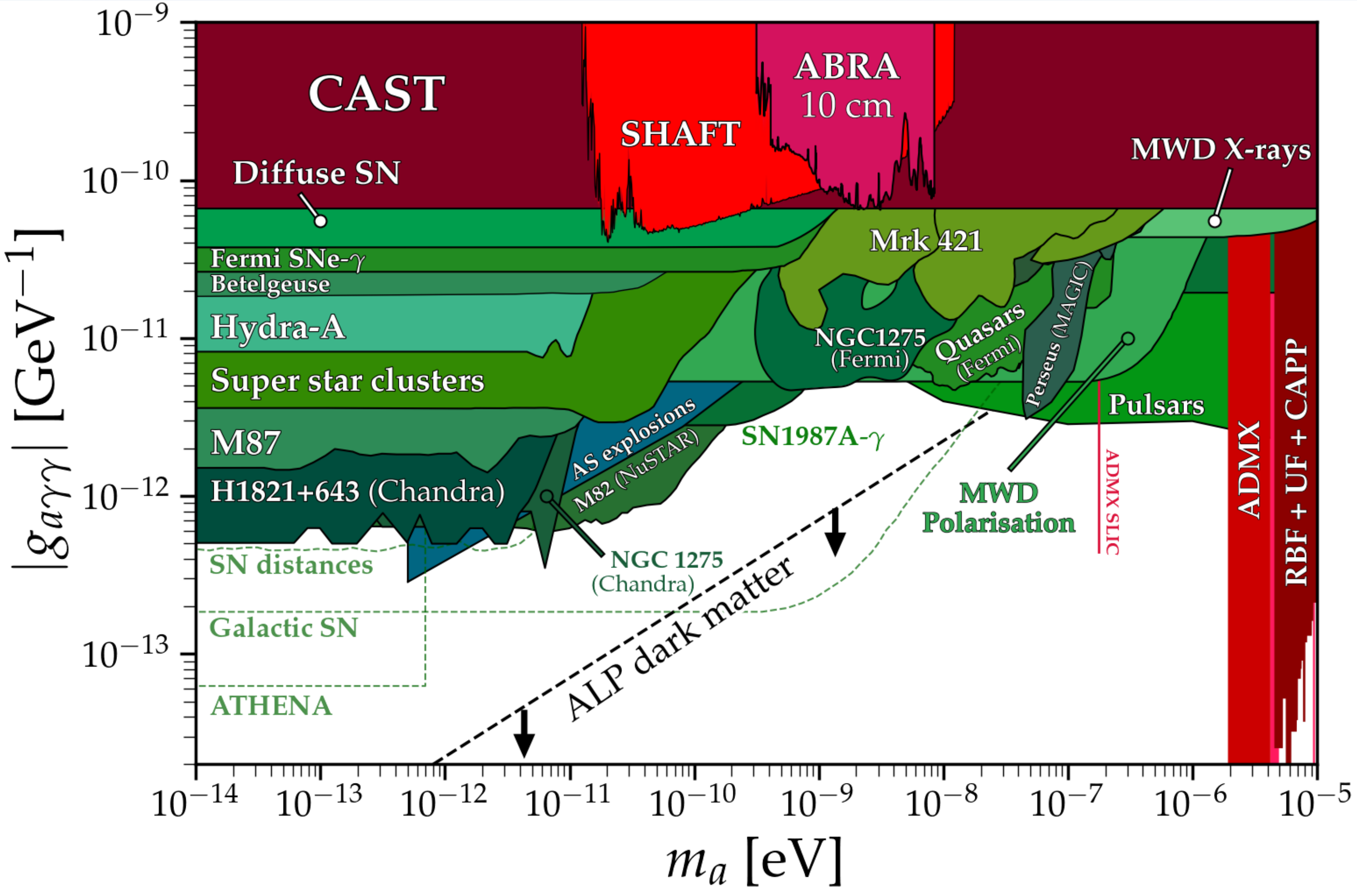


Figure 1. ALPs parameters space, from: C. O'Hare, github.com/cajohare/AxionLimits





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Axion-like particles ✦ searches

2007

ALPs searches with gamma rays
- Mirizzi et al, Phys.Rev.D76
- De Angelis et al., Phys.Lett.B659
- Hooper & Serpico, Phys.Rev.Lett.99

2009

”Hints of existence of ALPs…”
- Sanchez-Conde et al, Phys.Rev.D79

2012

ALPs signatures in spectra of FSQRs?
- Tavecchio et al., Phys.Rev.D86

2013

ALPs with H.ES.S
- PKS 2155-304, Phys.Rev.D88

2016

ALPs with Fermi-LAT
- NGC1275, Phys.Rev.Lett.116

2021

Future CTA prospects
- Abdalla et al., JCAP02.048

ALPs with 4FSRQs by Fermi-LAT
- Davies et al., Phys.Rev.D107

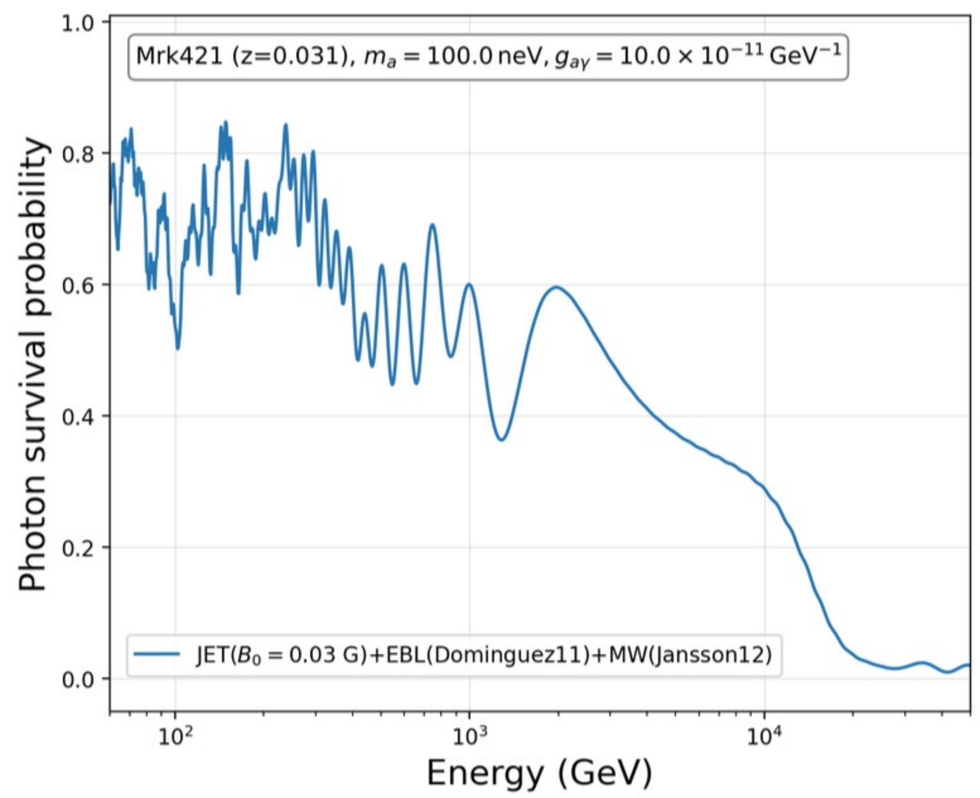
2024 …

ALPs with MAGIC
- Perseus GC, Phys.Dark.Univ.44

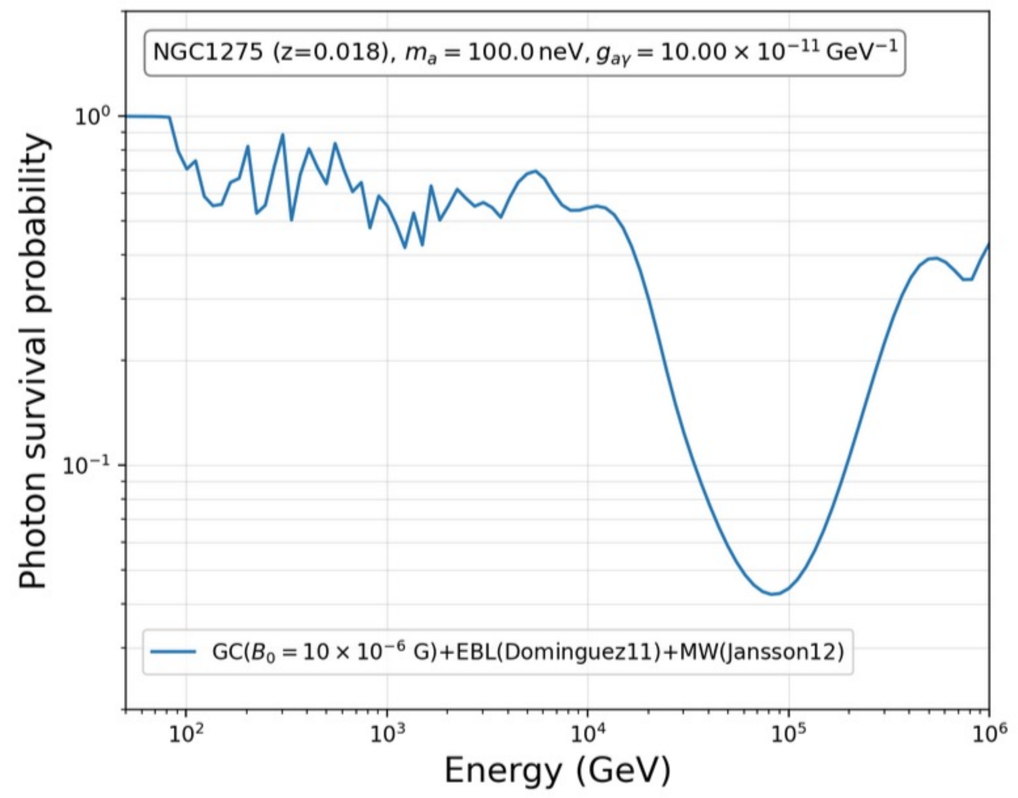
And many more…

Methodology ✦ signatures of ALPs

Irregularities

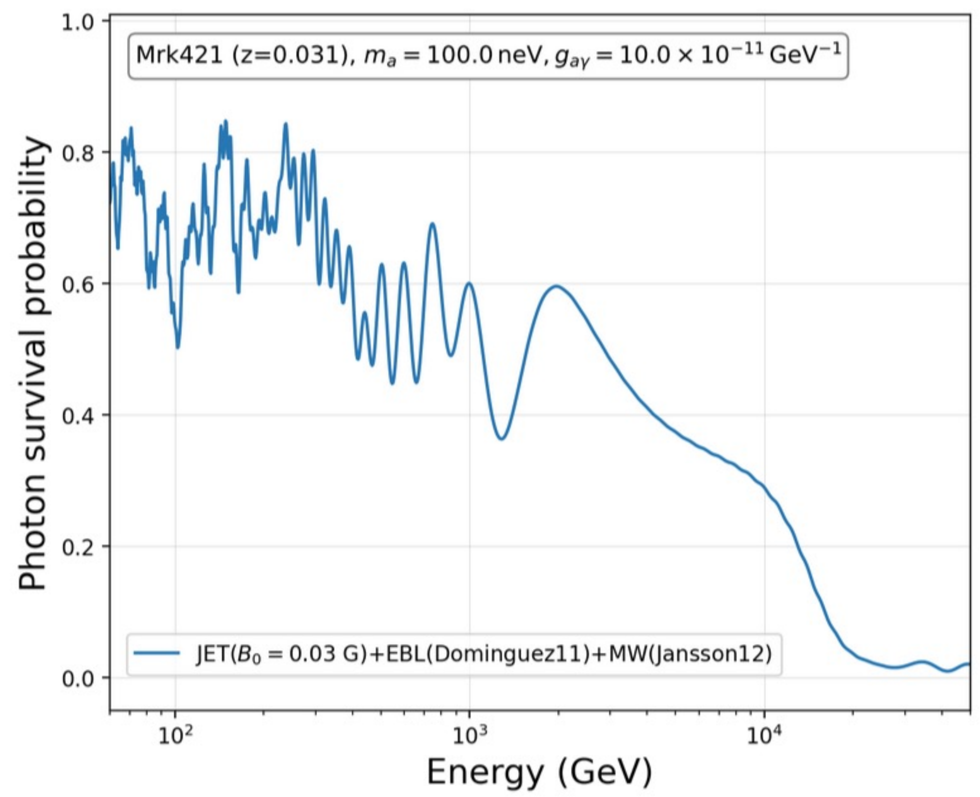


Recovery of photons



Methodology ✦ signatures of ALPs

Irregularities



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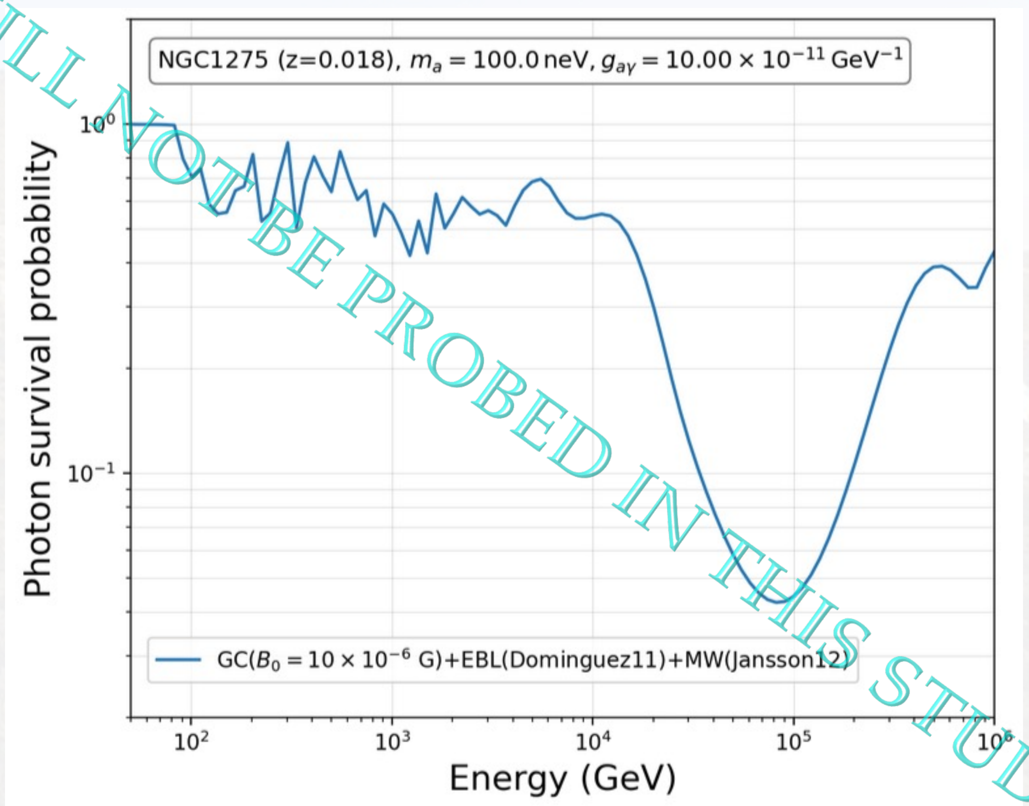

WILL NOT BE PROBED IN THIS STUDY

Methodology ✦ wiggles

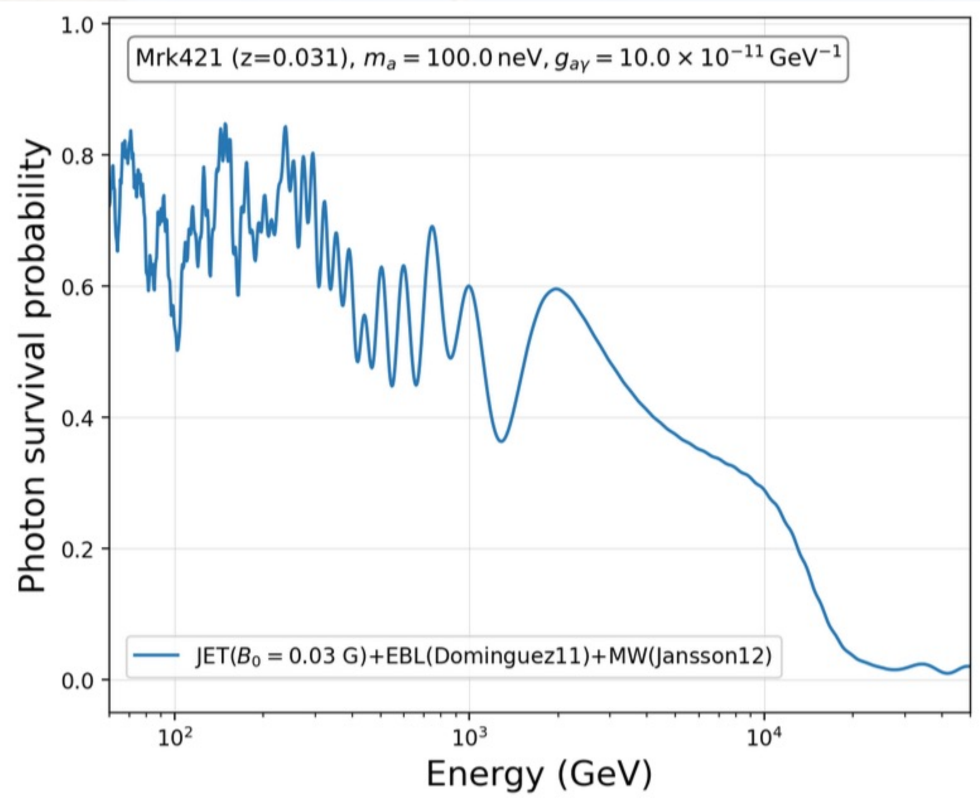

Figure 2. Photon survival probability vs. photon energy, obtained with gammaALPs

- Irregularities in the spectra of astrophysical objects due to the conversion of ALPs to photons in the external magnetic field
- Energy dependent

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

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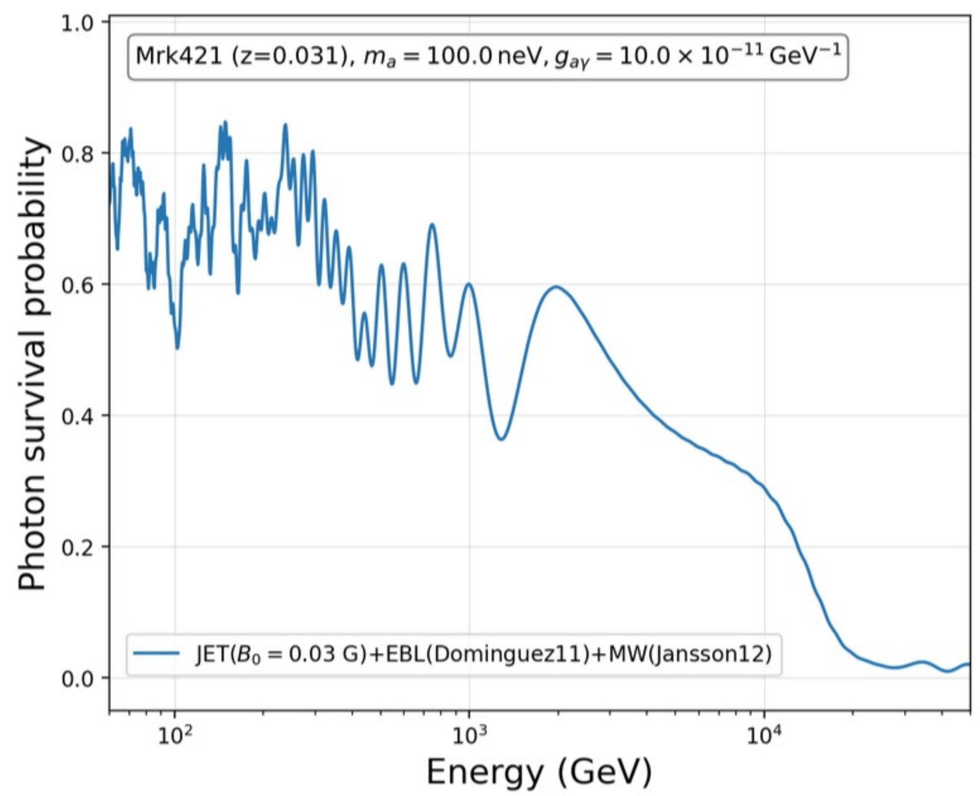

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CAN BE PROBED BY LST-1!

Methodology

- Mixing of the VHE photons causes irregularities in the observable spectrum
- https://gammaalps.readthedocs.io solves the equations of the propagation of photon-ALP system and calculates the $P_{\gamma\gamma}$

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

Observed flux

Intrinsic flux

Gamma-ray energy

Ambient magnetic field

Source's redshift

The First Large-Sized Telescope ✦ LST-1

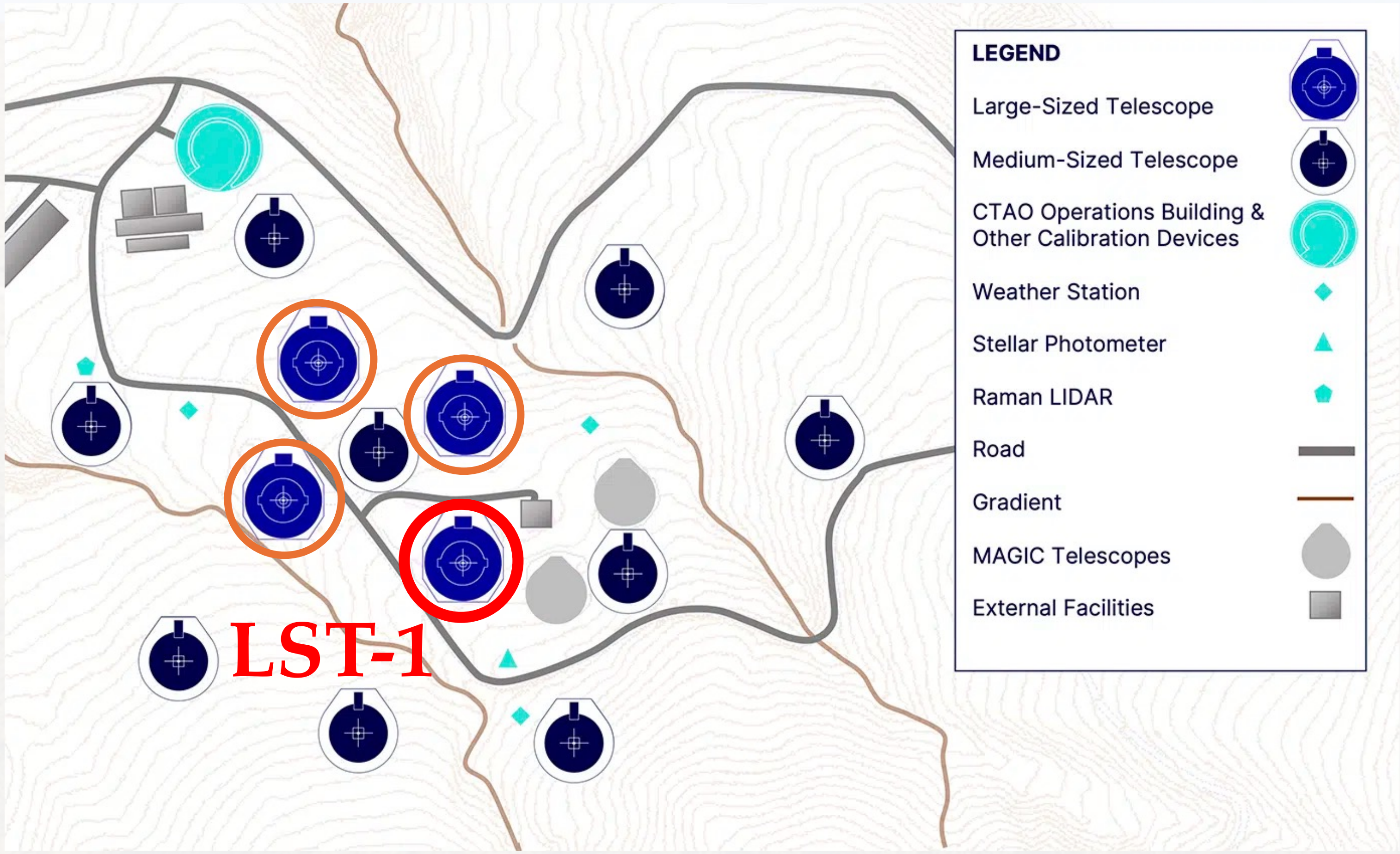

Figure 3. CTAO-North array layout

Figure 4. LST-1

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The First Large-Sized Telescope ✦ LST-1

- Among other 3 telescopes, it is the first LST built on the CTAO North array in La Palma, Spain, operating since 2020.
- Optimized for observations of gamma-rays down to ~ 20 GeV, covering the lowest energy region by CTAO
- Since the start of operations, it dedicated over 1000 hours to observations of Active Galactic Nuclei (AGNs)
- Check the talk Daniel Morcuende gave on Wednesday: "The roadmap to CTAO AGN Science: Early results on AGNs of LST-1"

Study of ALPs with LST-1 ✦ dataset

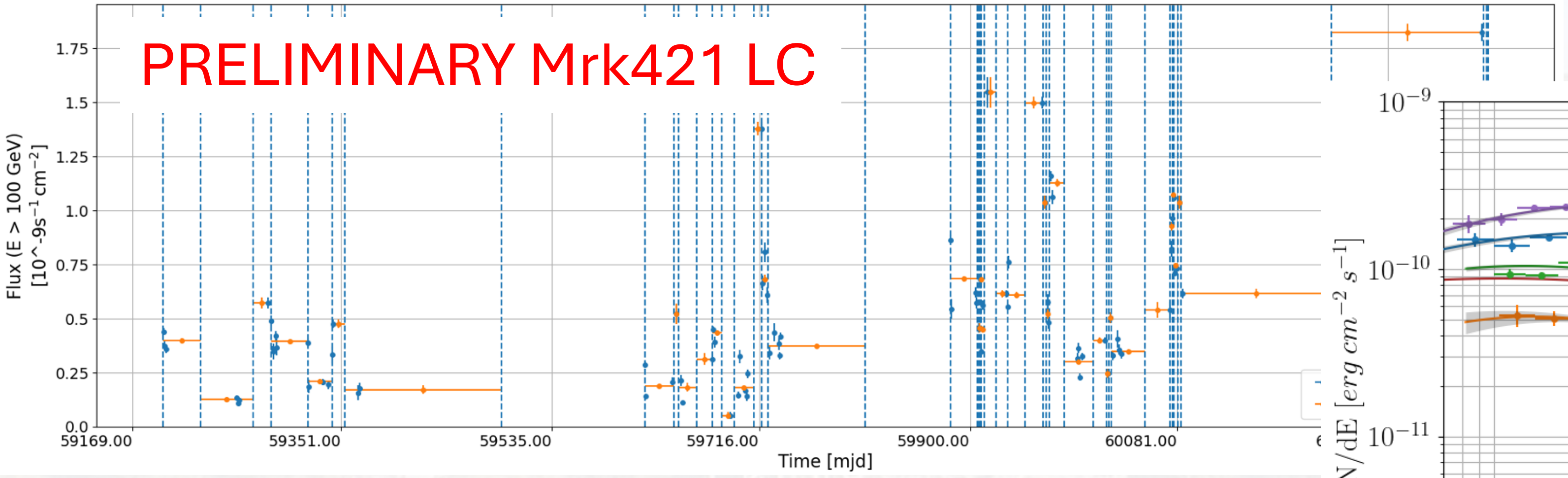
- Targets of interest: blazars – supermassive black holes in centers of galaxies – ultra-relativistic jet aligned with the line of sight

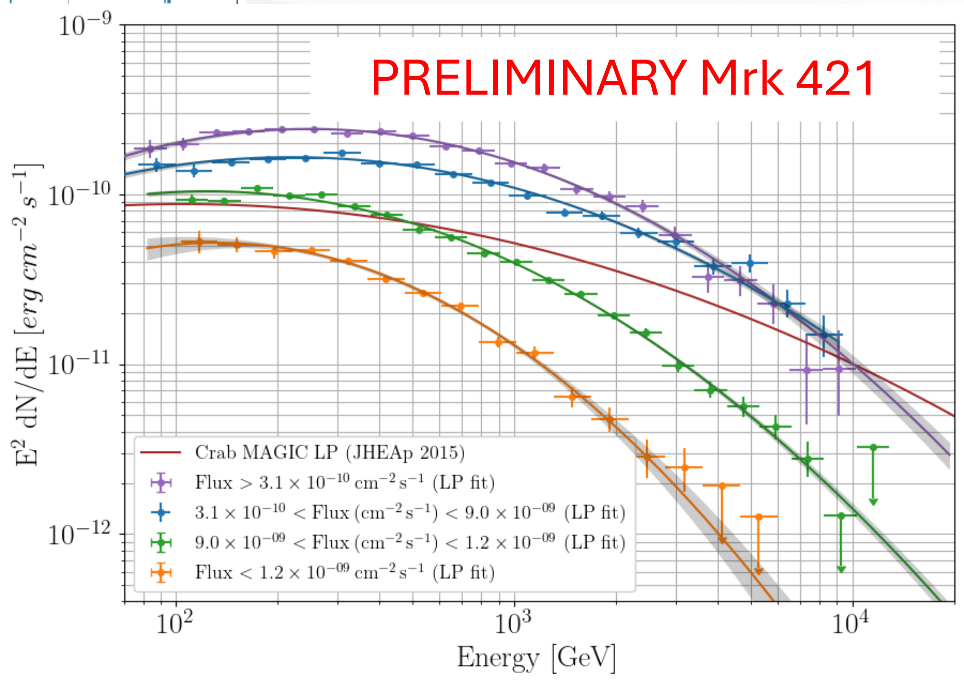
- LST-1 dataset:
  - **Mrk421 – 77.22 hrs**
  - **Mrk501 – 56.71 hrs**
  - **BL Lac – 50.00 hrs**
  - **1ES1959+650 – 16.272 hrs**

~ 200 hours of data

Study of ALPs with LST-1 ✦ spectral analysis

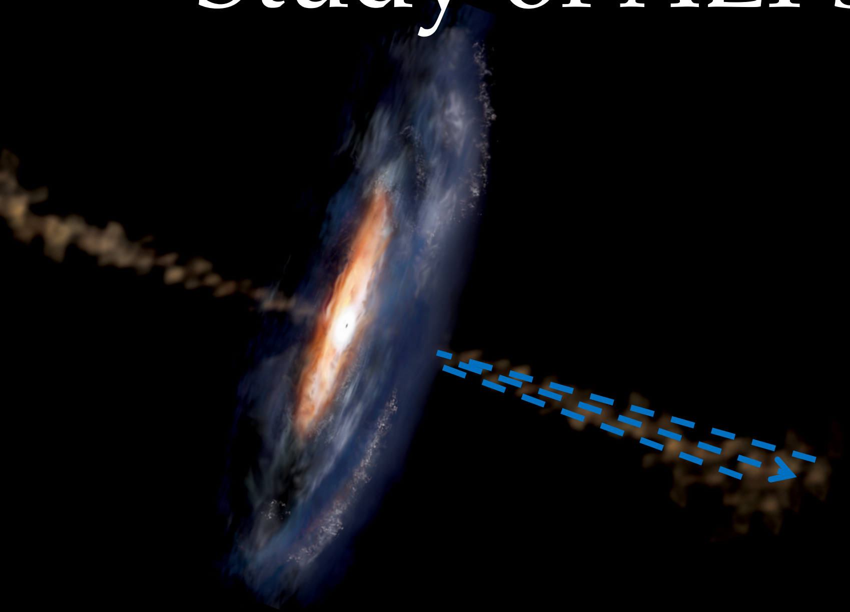
- Dividing the data from light curve into subsets of similar flux level – Bayesian block analysis





- Obtaining SED of each subset, fitted to a mathematical function – INTRINSIC FIT

Study of ALPs with LST-1 ✦ ALPs analysis



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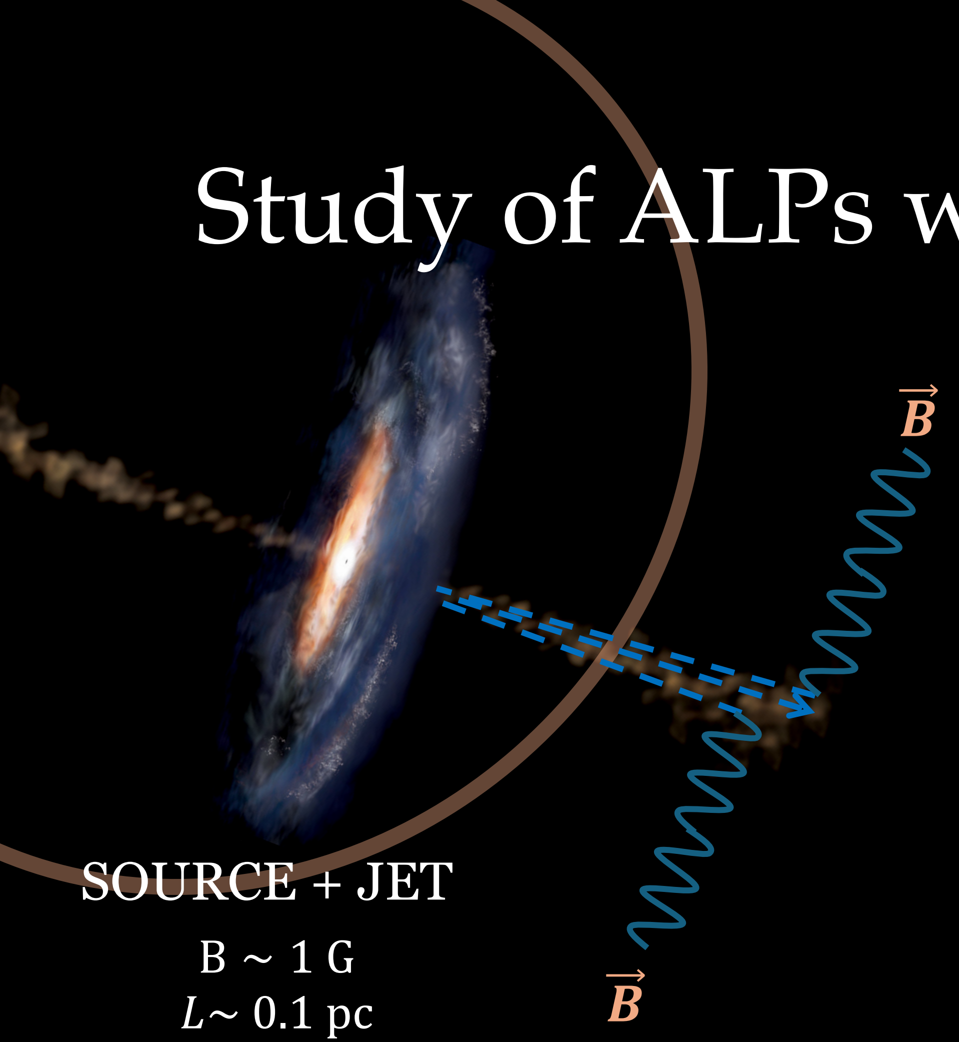

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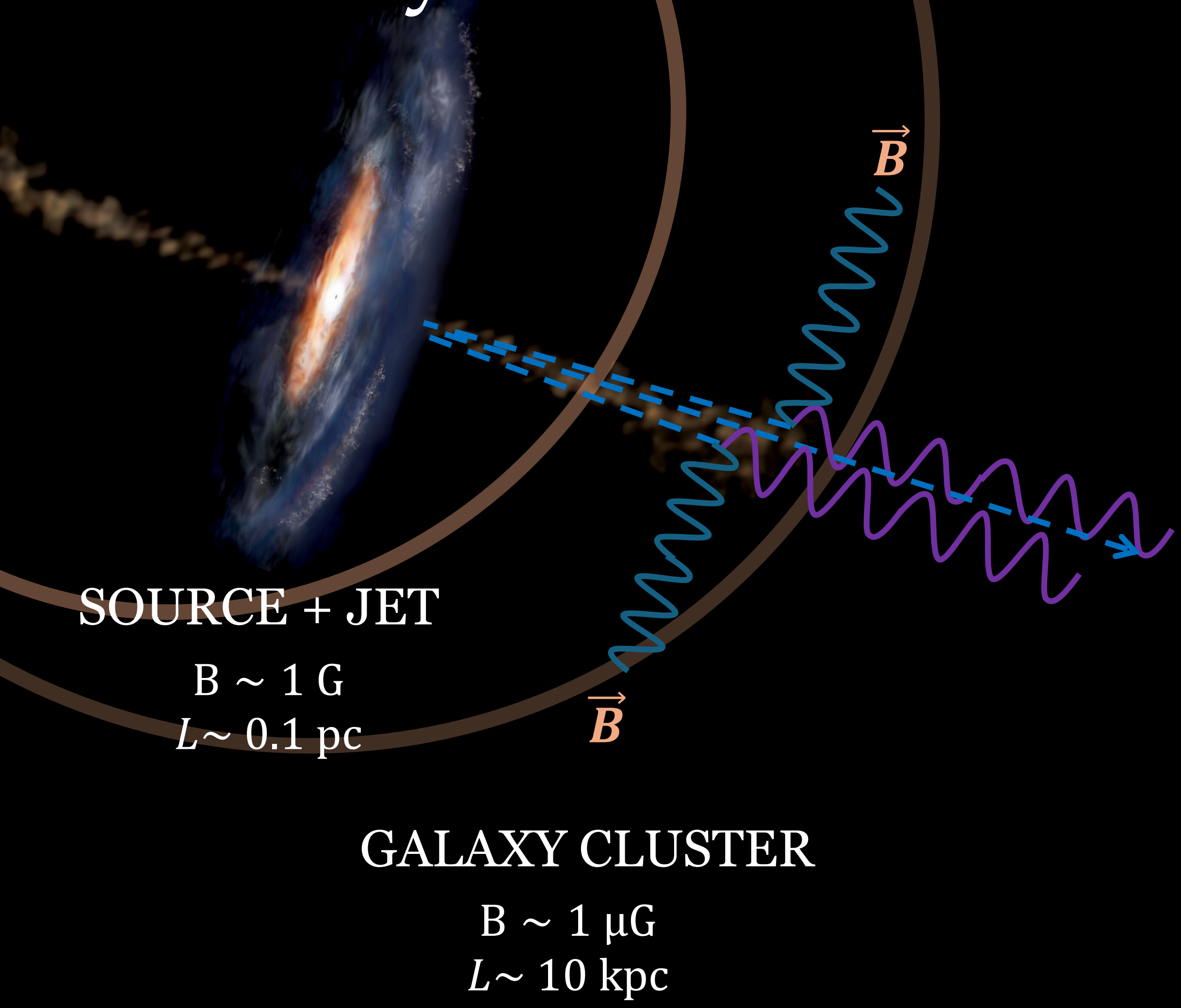

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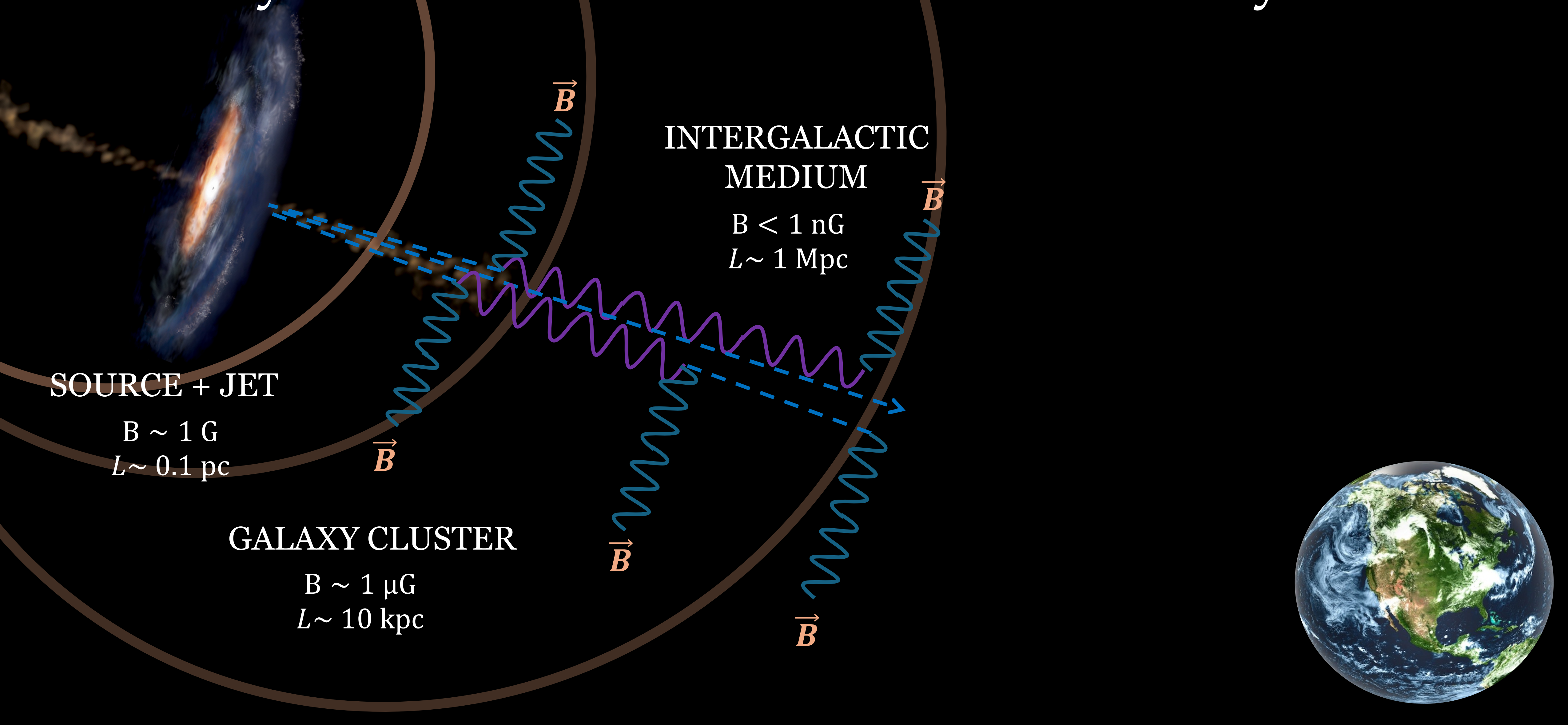

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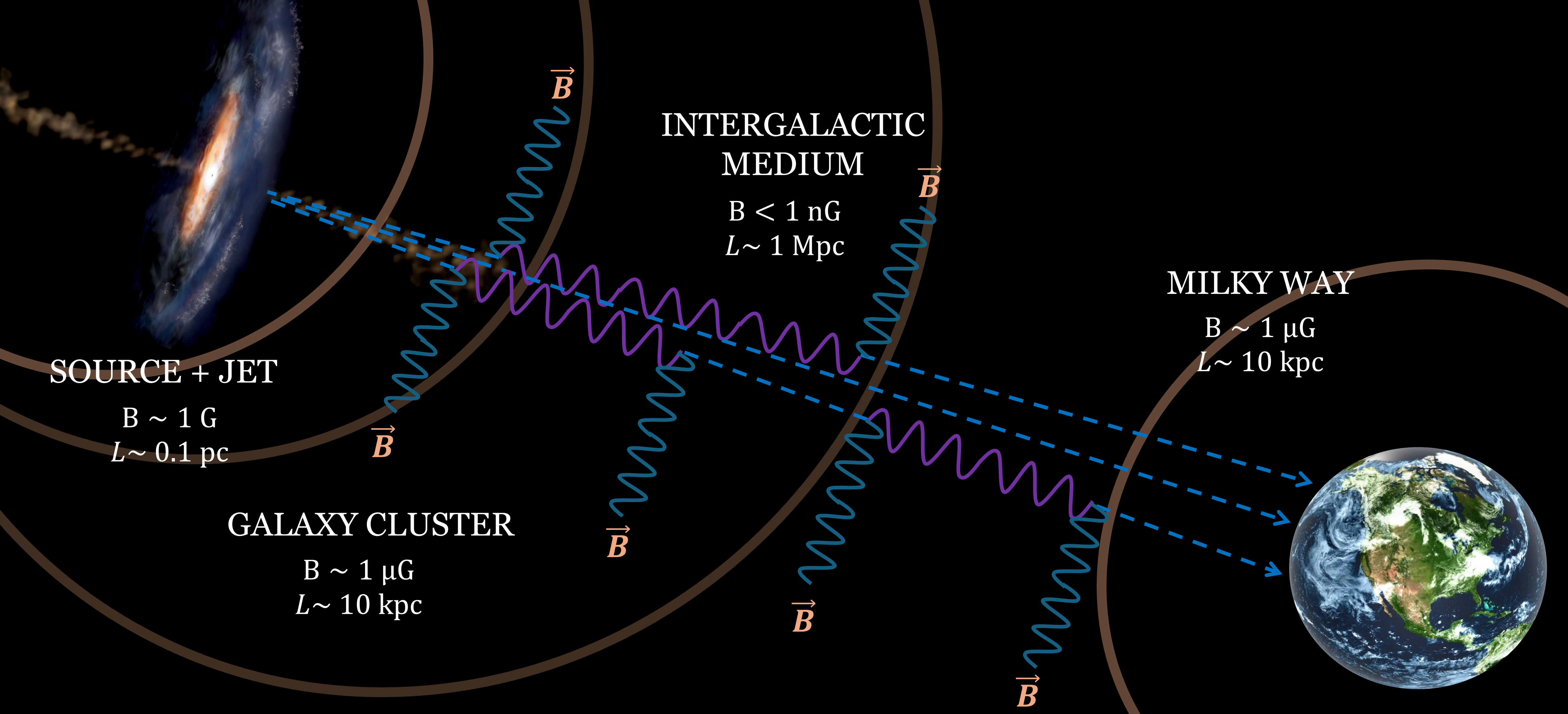

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Study of ALPs with LST-1 ✦ ALPs analysis

SOURCE + JET

$B \sim 1$ G
$L \sim 0.1$ pc

GALAXY CLUSTER

$B \sim 1\ \mu$G
$L \sim 10$ kpc

INTERGALACTIC MEDIUM

$B < 1$ nG
$L \sim 1$ Mpc

MILKY WAY

$B \sim 1\ \mu$G
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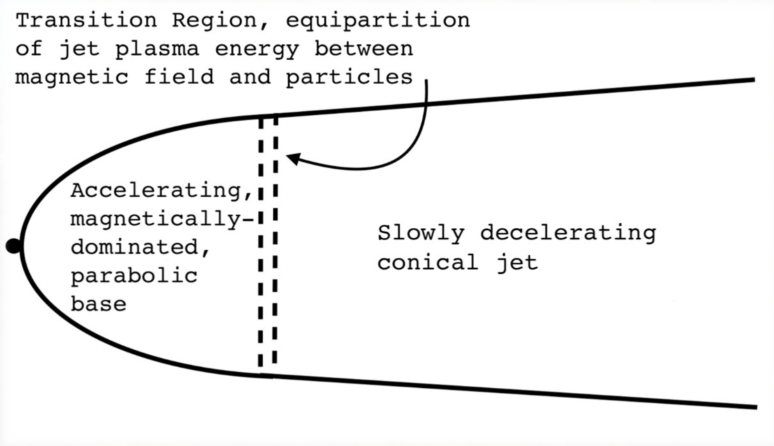

[1] Phys. Rev. D 103 (2021)
[2] MNRAS, 453 (2015)

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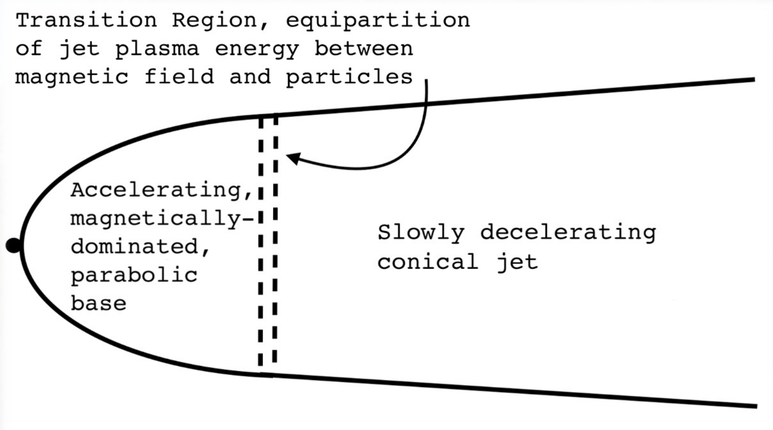

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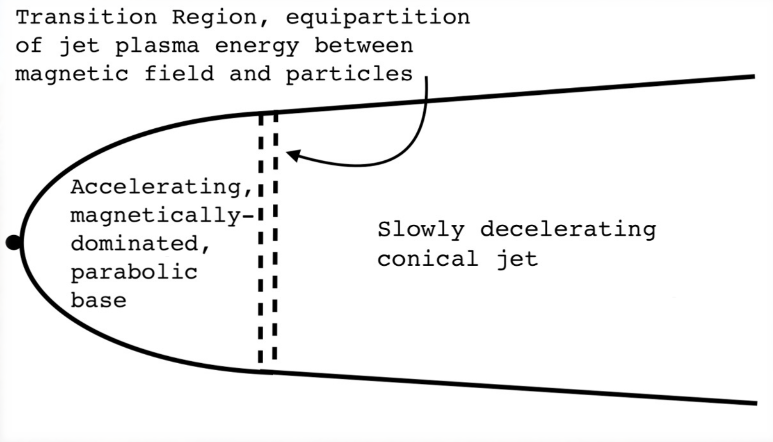

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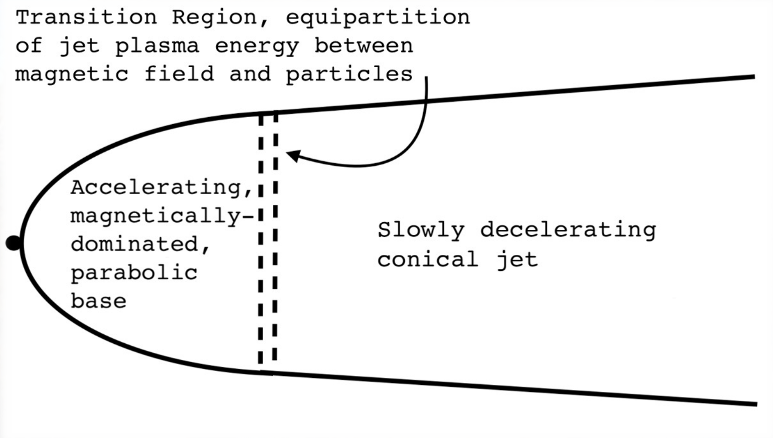
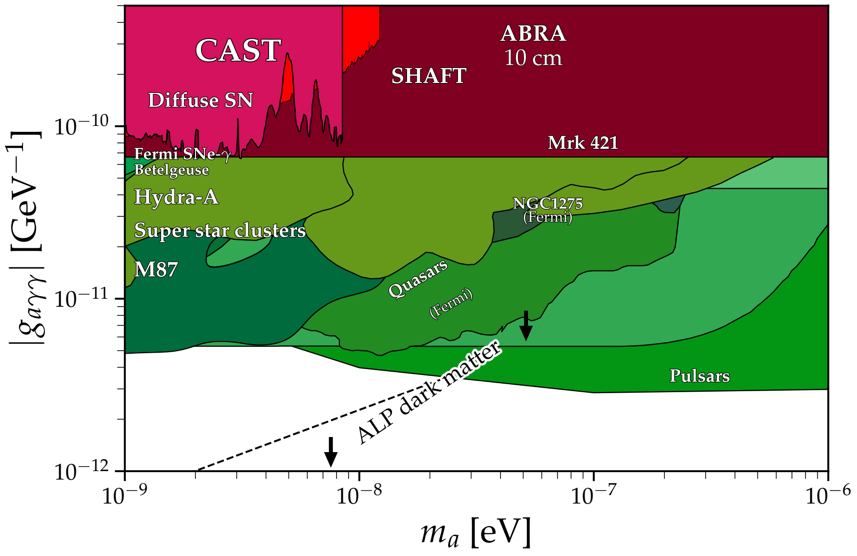
- Modelled with a turbulent and regular component [3]



[1] Phys. Rev. D 103 (2021)
[2] MNRAS, 453 (2015)
[3] Astrophys. J. 757 (2012)

Study of ALPs with LST-1 ✦ ALPs analysis

- 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

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

LIKELIHOOD

ALPs mass and coupling

Nuisance parameters: spectrum fit

Data: ON and OFF counts

i – datasets
k – bins

- For computing the ALPs exclusions, we introduce point-by-point computation of the correct coverage using the MC simulations

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Study of ALPs with LST-1 ✦ data storage

- For each source, we save .ecsv files where we store the relevant information
- Providing the likelihood, test statistic (TS) values and sigma values
- Once available, different sources can be combined for ALPs exclusions

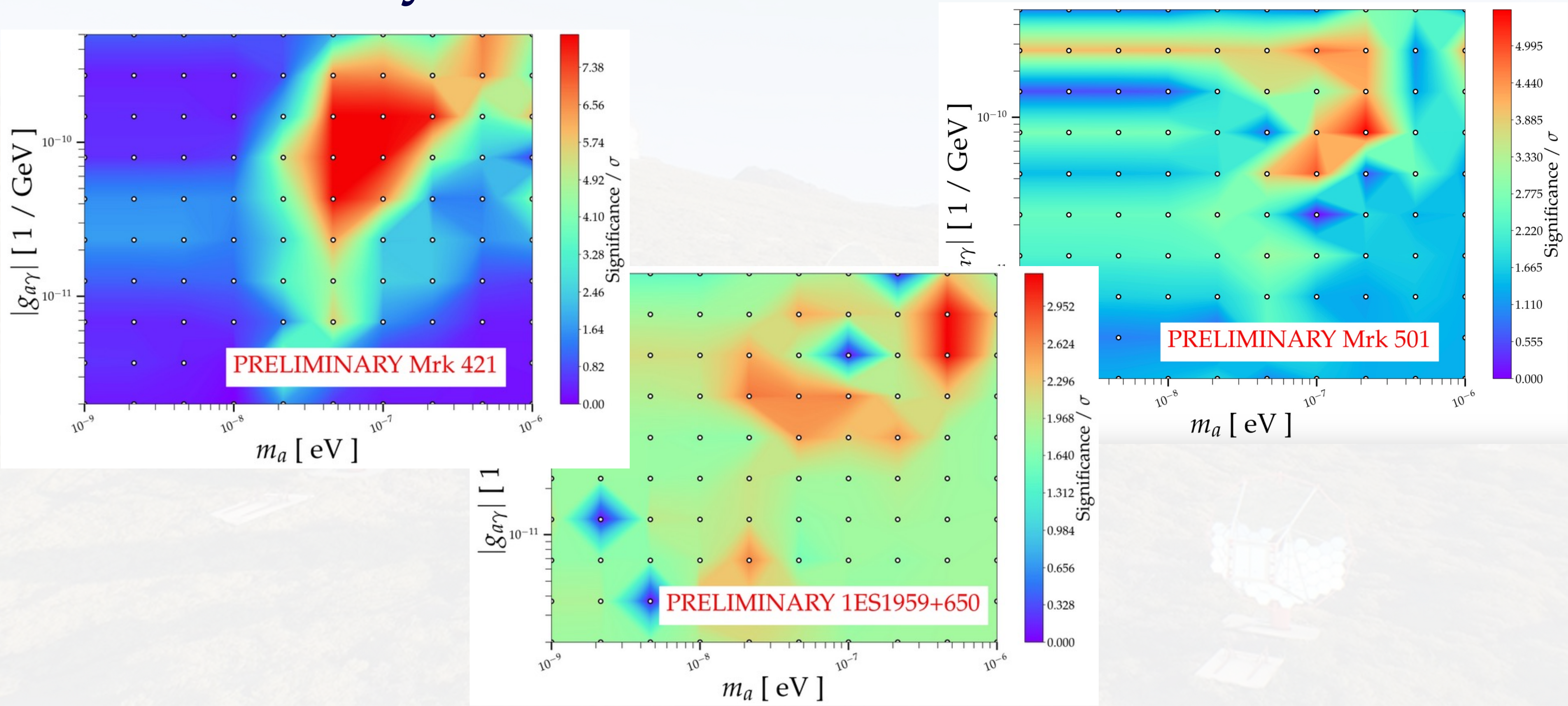
EXAMPLE

```
# %ECSV 0.9
# ---
# meta: !!omap
# - { Author: I. Batkovic }
# - { mail: ivana.batkovic@unipd.it }
# - { Date of file: 2024-16-05 }
# - { Source: Mrk421 }
# - { Source exposure: 82.8h }
# - { Source observation: 2020-13-12; 2024-12-02 }
# - { Instrument: LST1 }
# - { EBL model: Dominguez11 }
# - { B-field: JET (P&C) + EBL + MW (J&F12) }
# schema: astropy-2.0
# datatype:
# - {'name': 'm_a', 'unit': 'eV', 'datatype': 'float32', 'description': 'ALP mass'}
# - {'name': 'g_a\\gamma', 'unit': 'GeV', 'datatype': 'float32', 'description': 'ALP cross section'}
# - {'name': 'logL', 'unit': 'none', 'datatype': 'float32', 'description': 'log likelihood'}
# - {'name': 'TS', 'unit': 'none', 'datatype': 'float32', 'description': 'calibrated TS'}
# - {'name': 'z-score', 'unit': 'none', 'datatype': 'float32', 'description': 'z score'}

m_a      ;    g_a\gamma;  logL   ;    TS    ;     z-score
1.00e-09;    2.00e-12;   80.516 ;    28.569;     2.126;
2.15e-09;    2.00e-12;   80.528 ;    28.581;     2.125;
4.64e-09;    2.00e-12;   80.770 ;    28.823;     2.107;
```

LST COLLABORATION

Preliminary constraints



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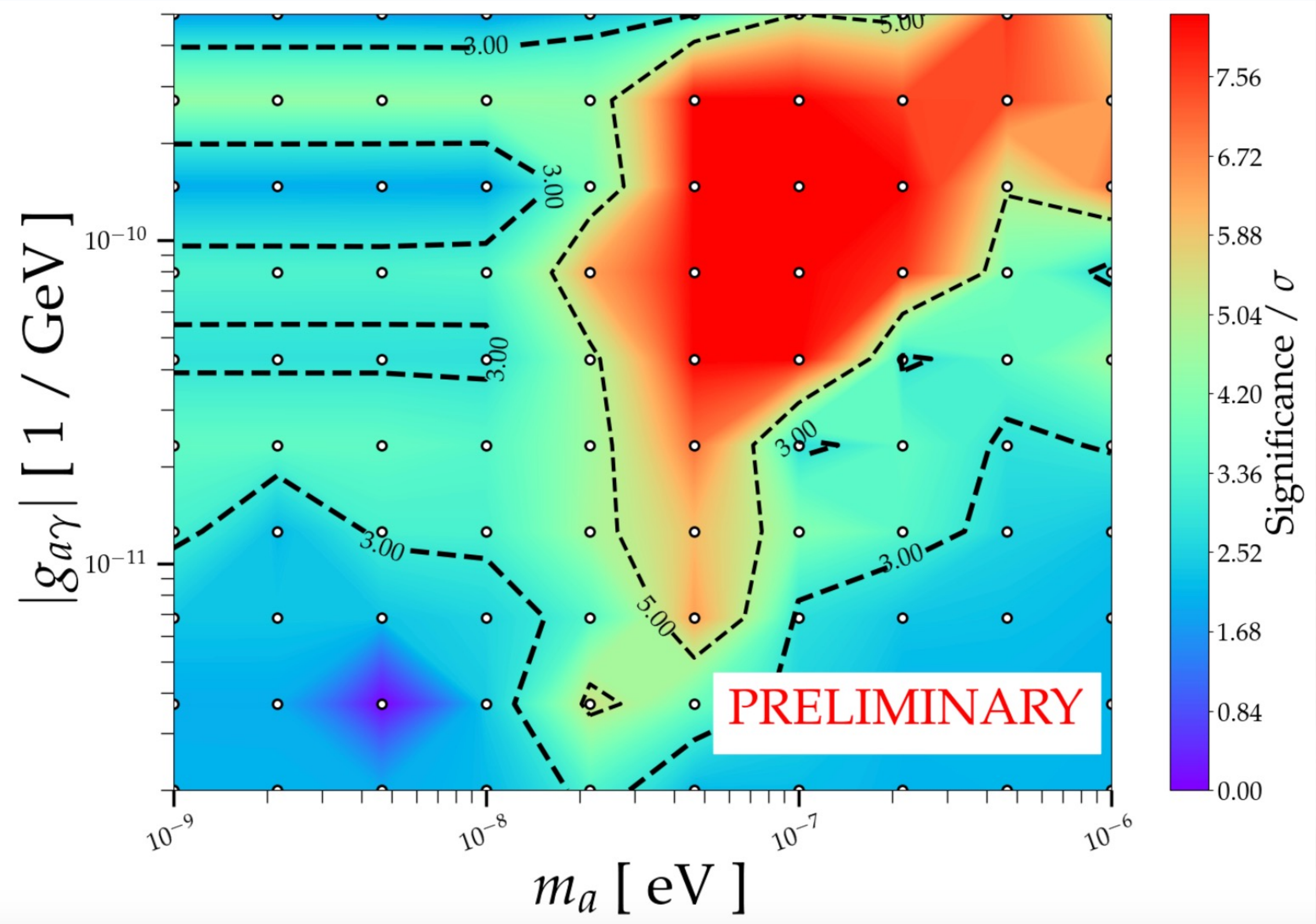

Figure 5.Preliminary constraints on the ALPs parameter space, obtained with LST-1 data of M421, Mrk501 and 1ES1959+650

Conclusions and future prospects

- Obtain complete constraints from the entire dataset
- Compute the CDF based on simulations and adjust the constraints
- Assess the systematical uncertainities, as well as statistical ones, especially those coming from the choice of magnetic fields configuration and spectral modelling
- Obtain the final, combined exclusion region in the ALPs parameter space
- Build a database containing .ecsv files with TS for all promising sources

- Addition of LST 2-4: lower energy threshold – better data reconstruction, more accurate spectrum estimation → more accurate (possibly stronger?) constraints

Thank you for your attention

Ivana Batković, University of Padova
ivana.batkovic@unipd.it

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Methodology

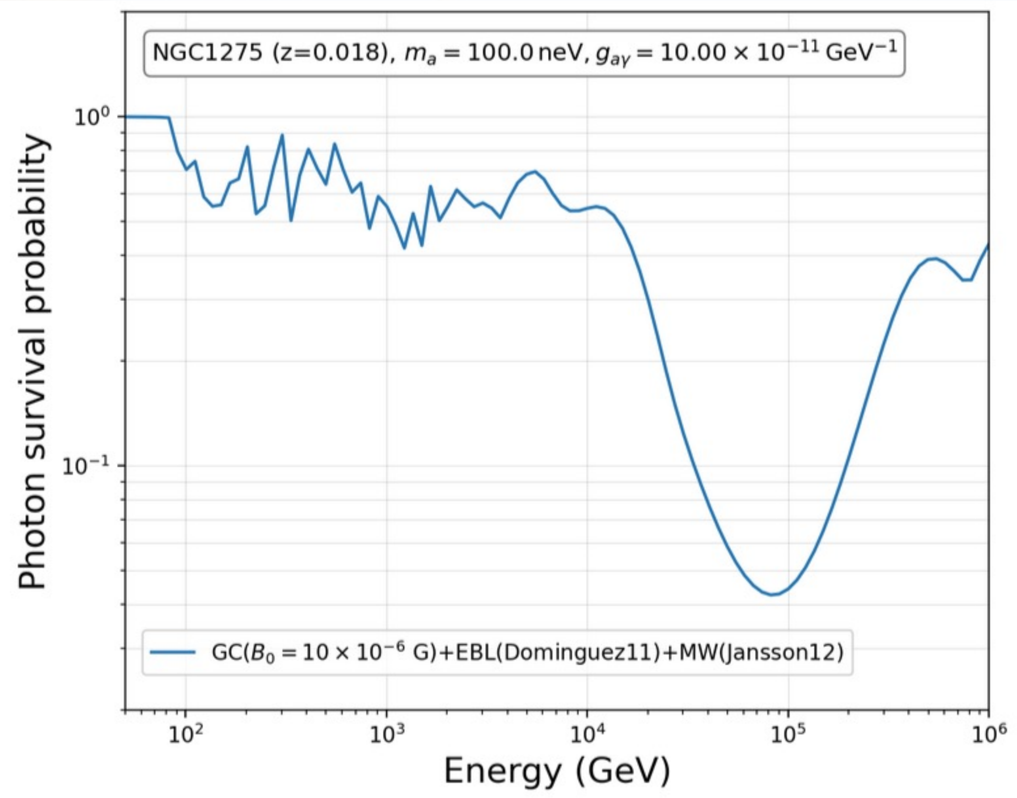
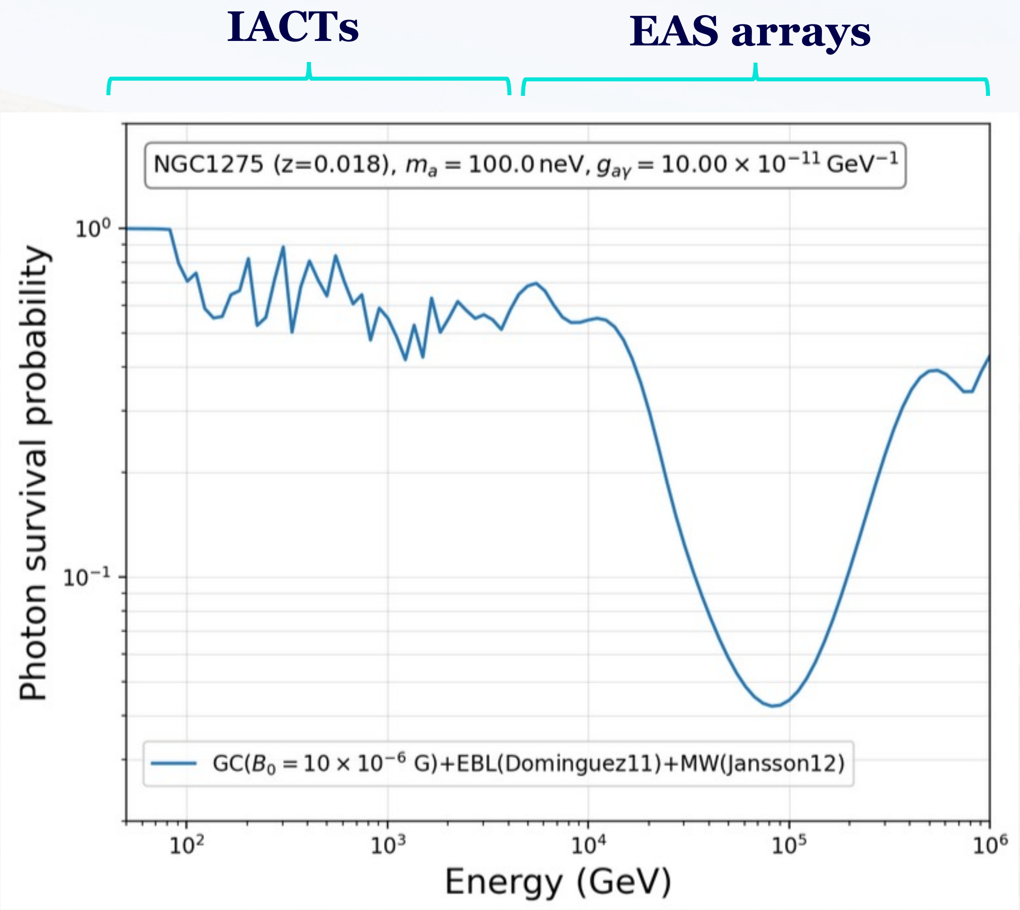


Figure 6. Photon survival probability vs. photon energy, obtained with gammaALPs

- Recovery of photons
  - Due to the back-conversion in the Galactic magnetic field,
  - Occurring on energies above several TeVs

Methodology



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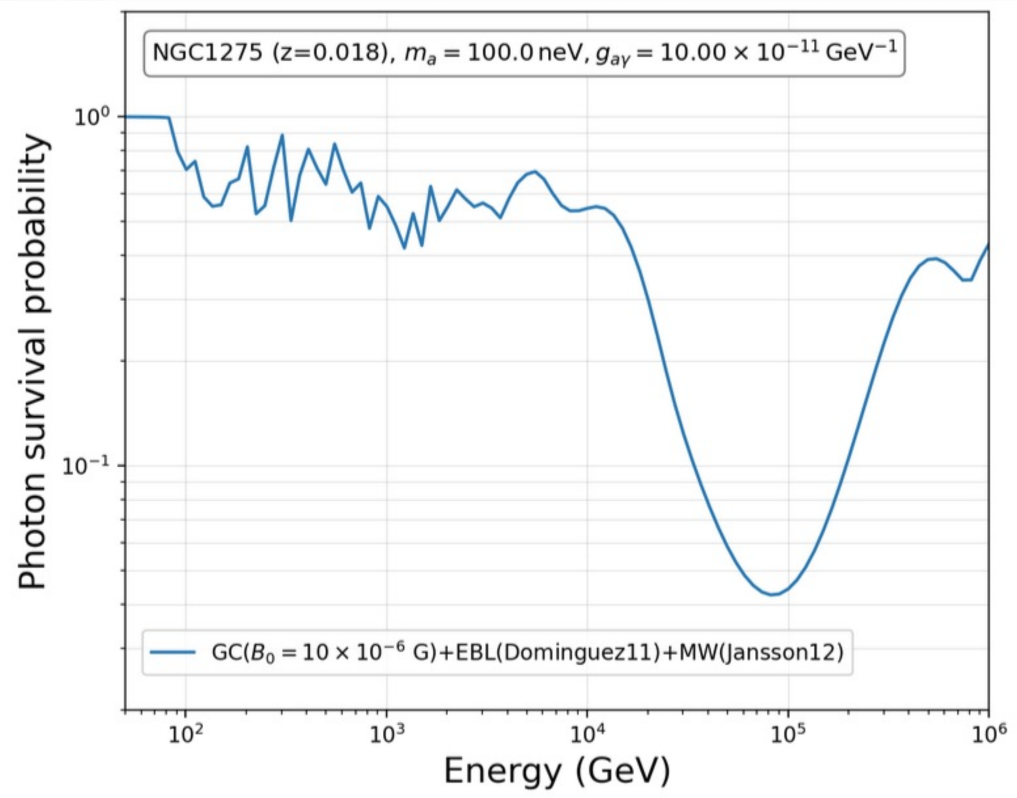
Methodology

IACTs — EAS arrays



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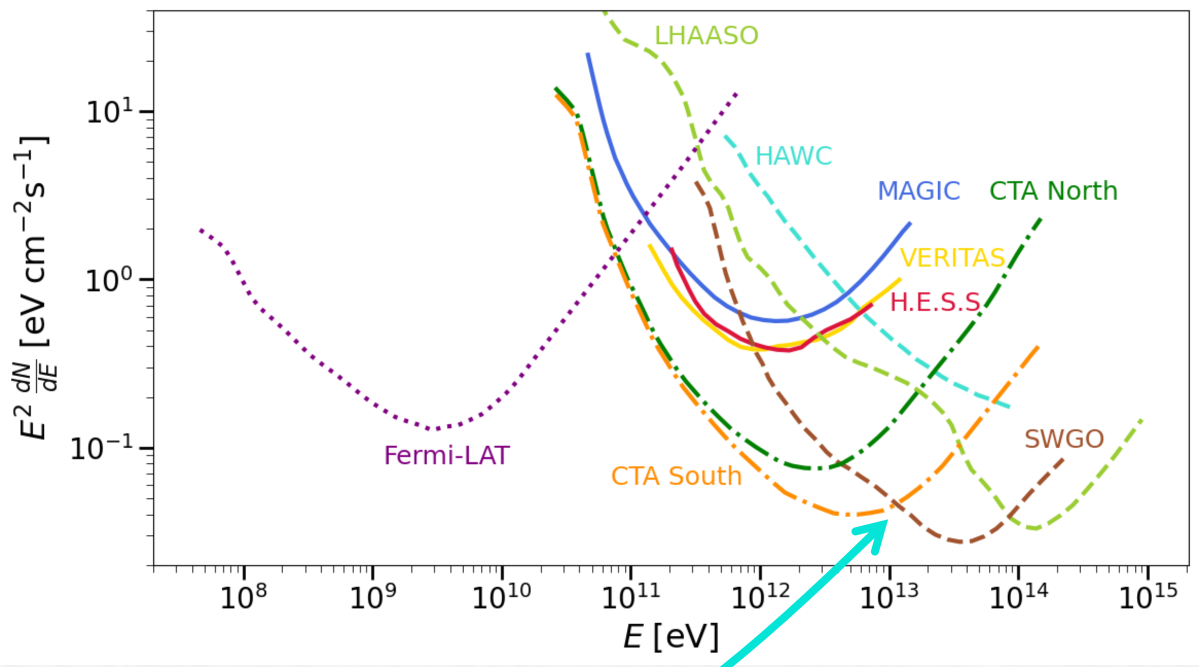

above several TeVs

Study of ALPs with LST-1 ✦ ALPs analysis

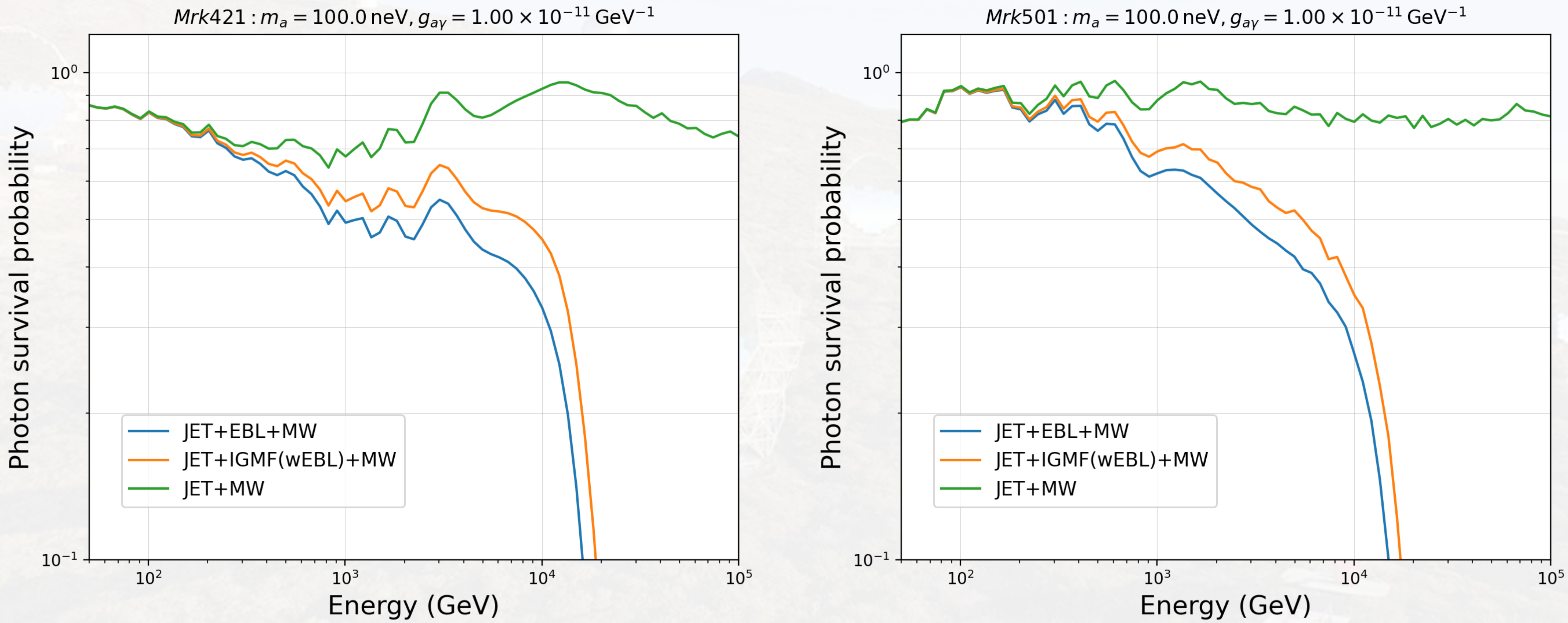

Figure 7. Photon survival probability vs. photon energy, obtained with gammaALPs

Backup slides

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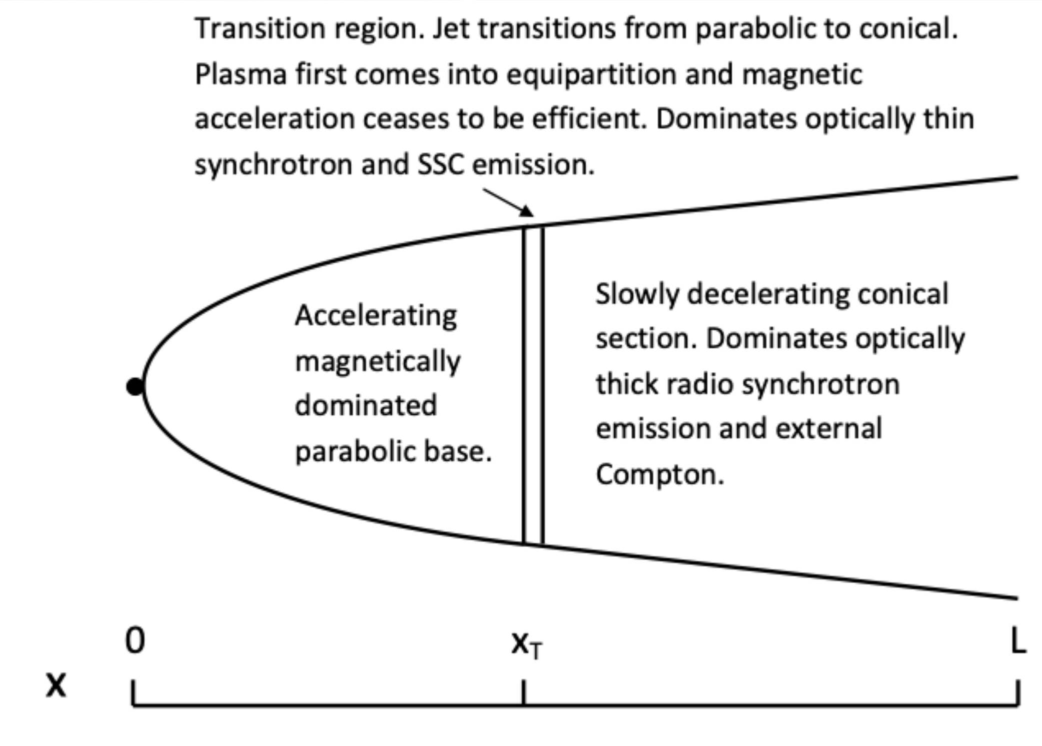

Important for the gammALPs:

- Jet geometry is linearly scaled from the observations of M87 using the eff. BH mass
- Transition region is consequently defined to occur at $10^5\ r_T$
- At the same time, r_T (distance of the transition region from the BH), can be calcluated from the formula for the gravitational radius:

$$r_T = \frac{2MG}{c^2}$$

Backup slides

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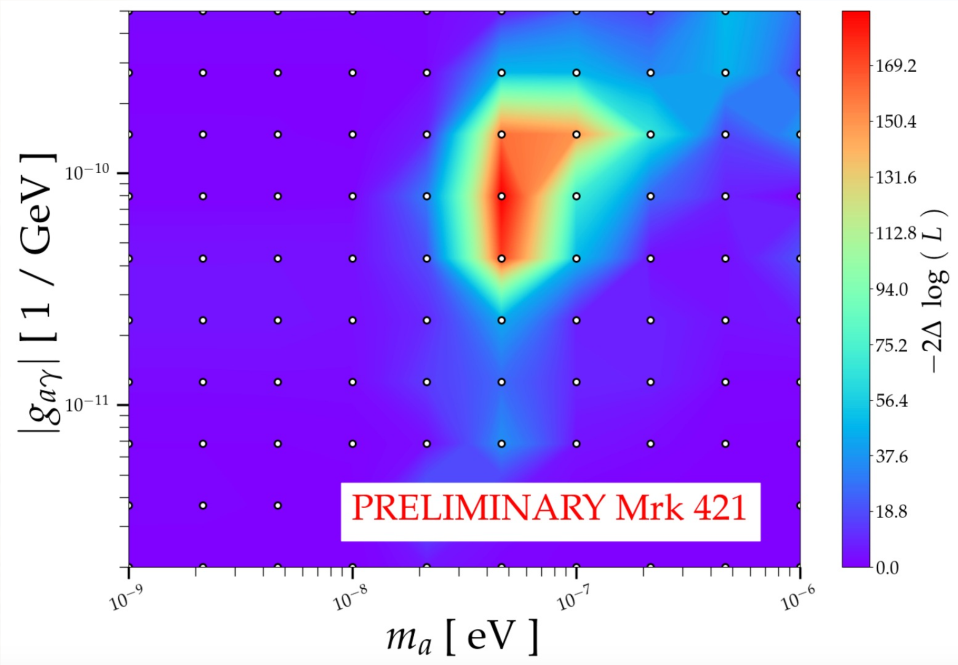
- Parameters for the modelling of the jet magnetic field

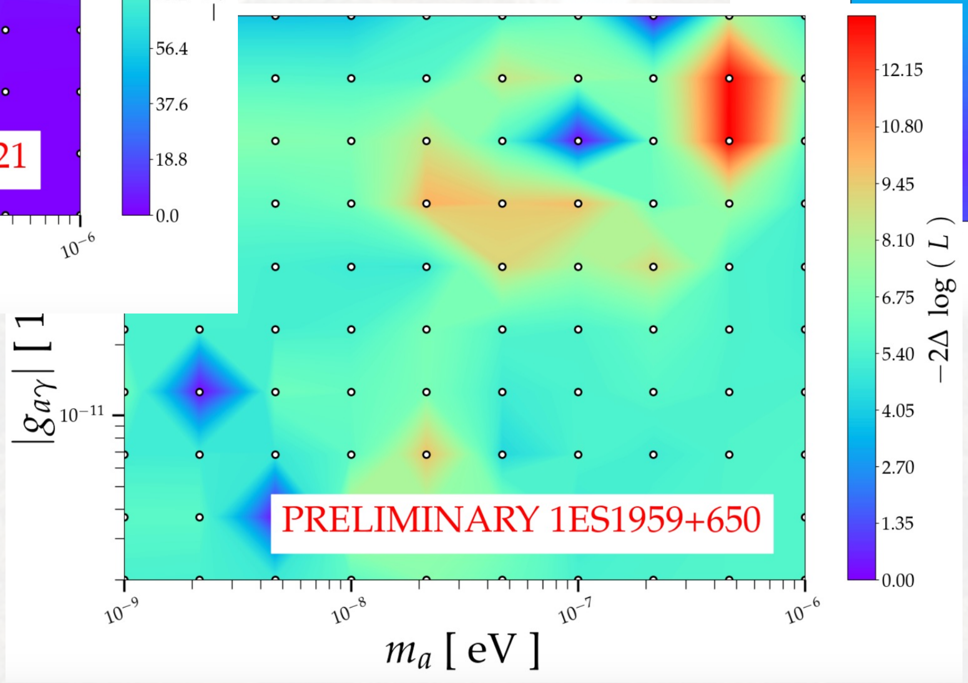
Source	z	r_T(pc)	r_{VHE}(pc)	r_{jet}(pc)	B_0(G)	α	r_T(pc)	g	$M(M_\odot)$	$n_0(\,cm^{-3})$*
Mrk 421	0.031	6.02	6.02	9.721×10^3	0.03	1.55	6.02	12	6.31×10^8	8.5×10^3
Mrk 501	0.034	0.3	0.3	3.240×10^3	0.8	1.68	0.3	9	3.16×10^7	4.5×10^4
BL Lac	0.069	0.12	0.12	16.204×10^3	2.68	1.95	0.12	8	1.26×10^7	8.0×10^5
1ES1959+650	0.048	0.96	0.96	3.241×10^4	1.88	1.6	0.96	8	1.00×10^7	7.2×10^2

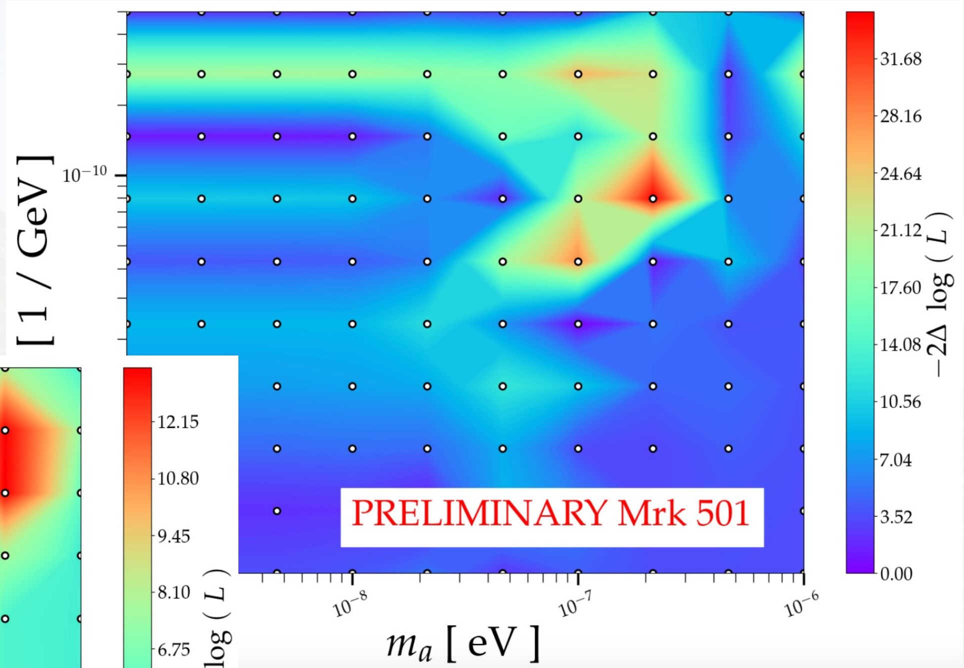
*taken from Tavecchio et al. , MNRAS. **401,** 1570–1586 (2010)

Backup slides - TS

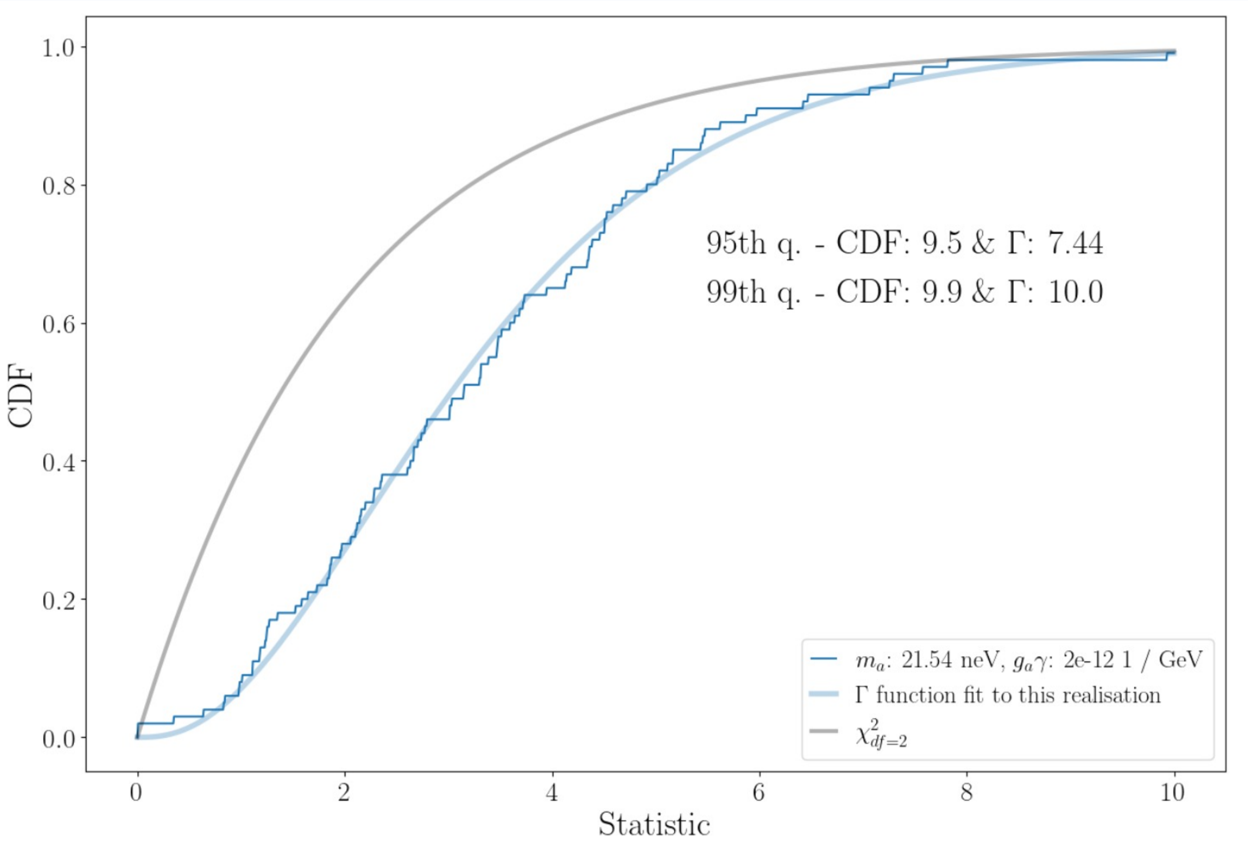
CTAO LST COLLABORATION







Backup slides



CDF distribution of the simulations of the most conservative ALP point (highest 95th quantile) for one Mrk 421 subset