

Assessing the sensitivity to Axion Like Particles with VHE gamma-ray observations of selected AGN and galaxy cluster pairs

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Composite image of Centaurus A [ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray); CC BY 4.0]



Summary

I. Introduction

- Axion-Like Particles as Dark Matter candidate
- ALP signatures in γ -ray spectra
- IACTs observatories

II. Probing ALP-Photon oscillation in GC with mock observations

- AGN-GC Sources selection
- Data analysis method

III. Results

- Stacking analysis results
- Impact of EBL modeling
- Impact of EBL mismodeling
- ALP injection recovery

IV. Conclusion and outlook

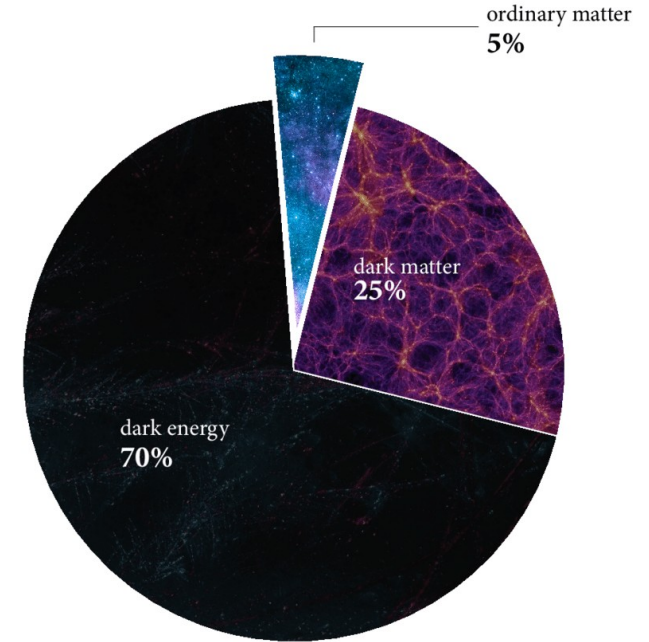
I. ALP as dark matter candidate

Dark Matter (DM)

- ~85% of the total matter in the Universe
- Implied by gravitational effect in formation and evolution of galaxies, gravitational lensing, etc.

A light DM candidate : Axion Like particles (ALP)

- Axion initially proposed to solve the strong CP problem in QCD
- Generalisation with ALP → independent mass and coupling parameters (less constrained parameter space)
- Neutral, light, weakly-interacting pseudo-scalar bosons
→ good candidate for DM



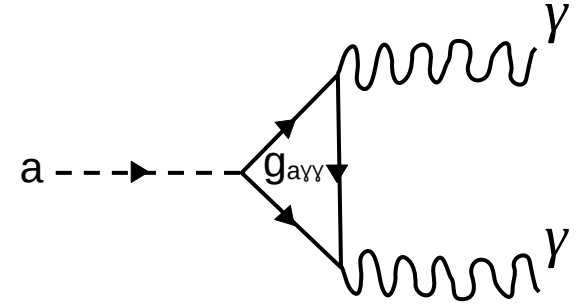
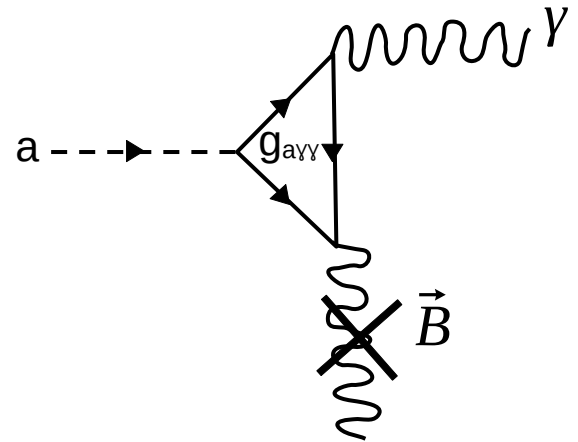
Constitution de l'Univers © Max-Planck-Institute for Astrophysics Garching and Pixabay, F. Wolz, Gravitational Closure of Matter Field Equations: General Theory and Perturbative Solutions, Thesis (2022)

I. ALP signature in γ spectra

Property of ALP $\rightarrow$ two photon vertex (Inverse primakoff effect)

In the presence of an **external magnetic field**
 $\rightarrow$ possibility to have ALP-Photon oscillations

$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} \vec{E} \cdot \vec{B} a$$



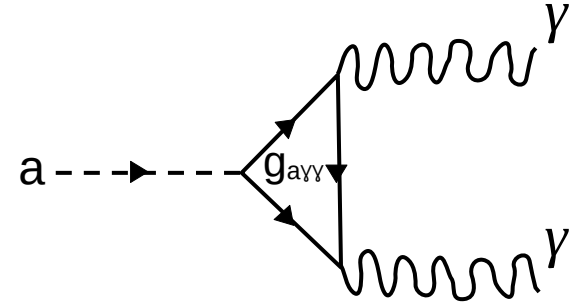
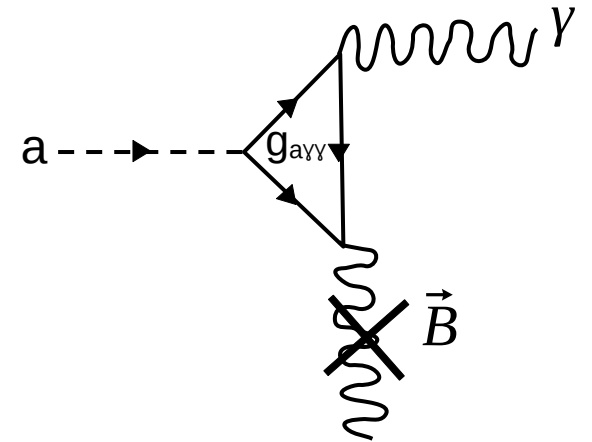
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Thus, VHE gamma ray travelling in an external magnetic field can mix with ALP with a given probability $P_{a\gamma\gamma}$



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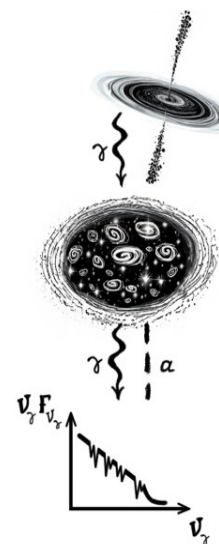
Observable effect in very high energy gamma-ray spectra

Photon survival probability $\rightarrow P_{\gamma\gamma} = 1 - P_{a\gamma\gamma}$

AGN

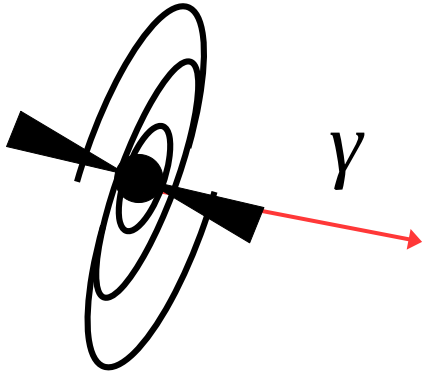


AGN+external magnetic field



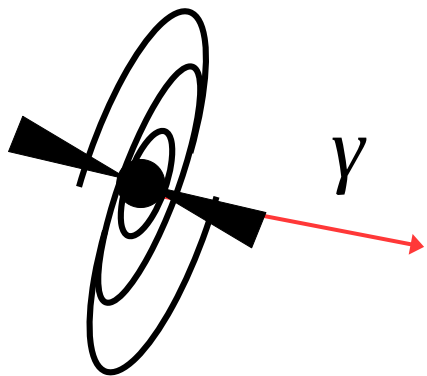
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The survival probability $P_{\gamma\gamma}$ is dependent on the magnetic field intensity and orientation as well as the number of magnetic domains and sizes $\rightarrow P_{\gamma\gamma} \propto B \times L$



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Source and Jet

$B \sim 1\text{G}$

$L \sim 100\text{ pc}$

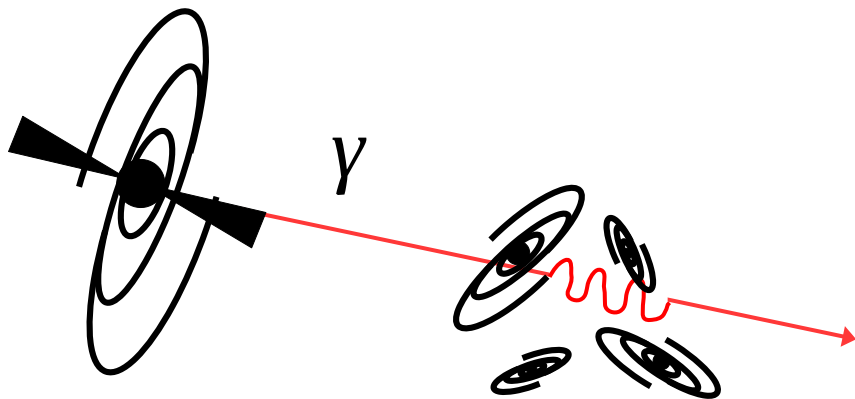
Strong B strength, small region

Need to know γ -ray path in the jet to get $P_{\gamma\gamma}$
 $\rightarrow$ Modelling of the magnetic field in the blazar jet



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Source and Jet
 $B \sim 1\text{G}$
 $L \sim 100\text{ pc}$

Galaxy Cluster
 $B \sim 1\mu\text{G}$
 $L \sim 500\text{ kpc}$

Weaker B strength, larger region

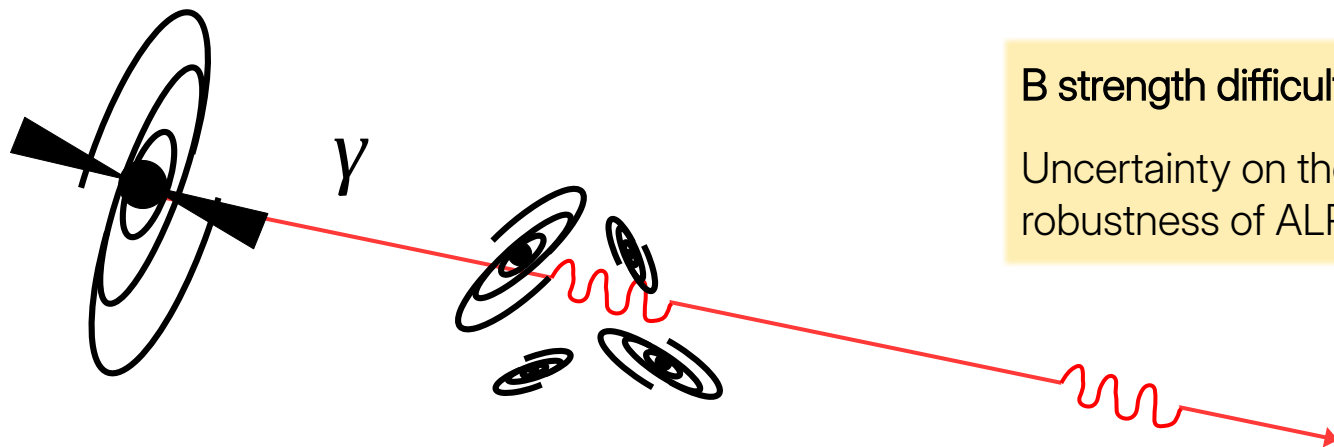
Existing estimation of the magnetic field strength

No reliable measurement of the orientation of the field in domains, of the domains lengths, etc



I. ALP signature in γ spectra

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B strength difficult to measure (only upper limit)

Uncertainty on the field strength limits the robustness of ALP-photon oscillations studies

Source and Jet

$B \sim 1\text{G}$

$L \sim 100\text{ pc}$

Galaxy Cluster

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Intergalactic medium

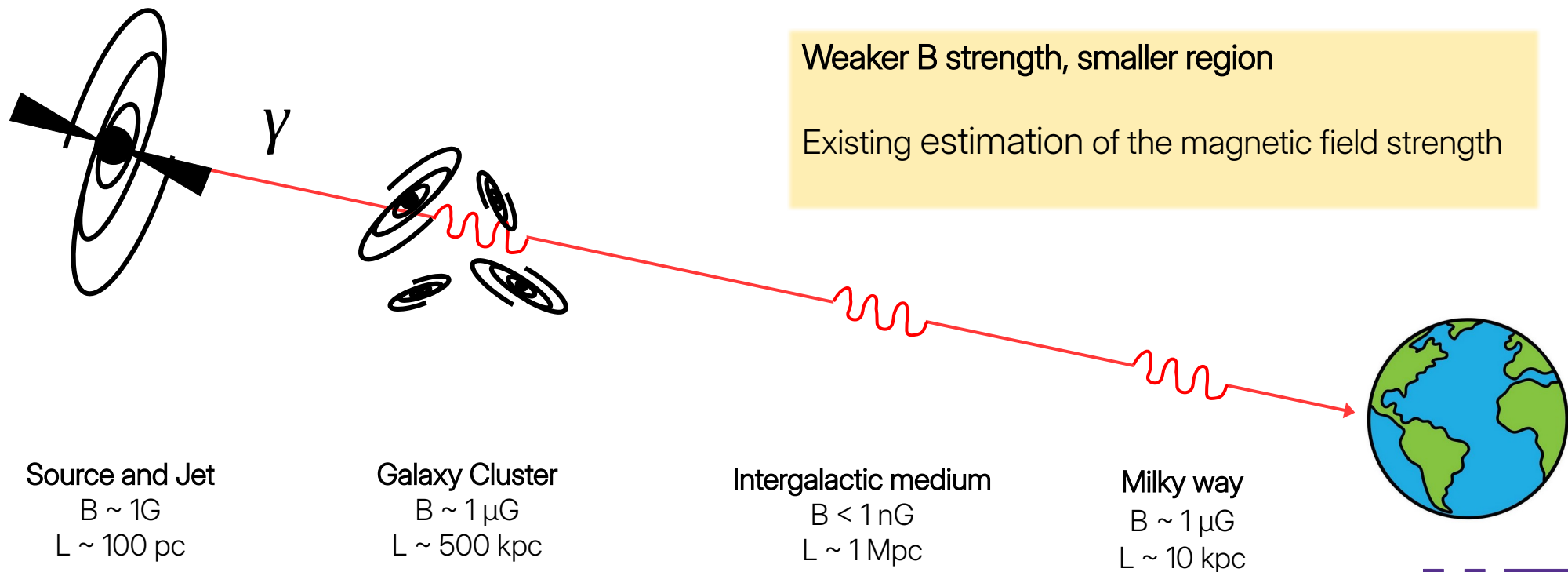
$B < 1\text{ nG}$

$L \sim 1\text{ Mpc}$



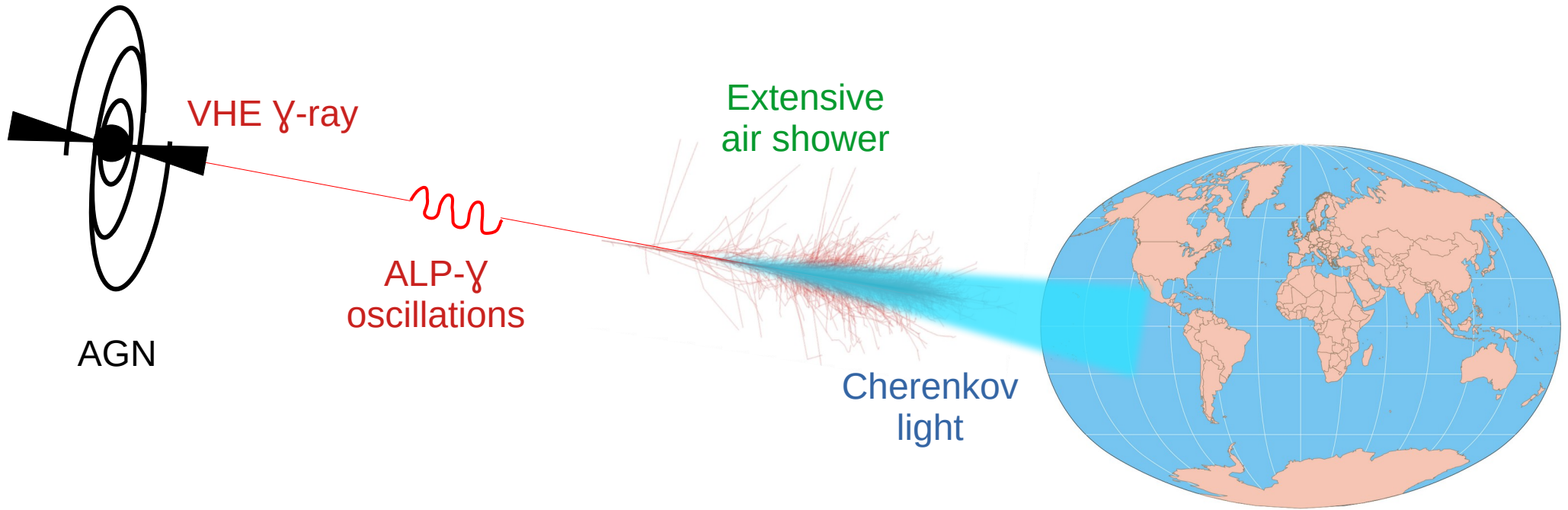
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I. IACTs observatories

One way to probe ALP-photon mixing is using observations with **Imaging Atmospheric Cherenkov Telescopes (IACTs)**



I. IACTs observatories



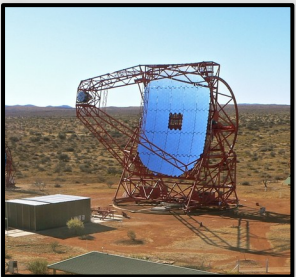
VERITAS

Four 12 m diameter IACTs
Sensitivity in [100 GeV – 50 TeV] range



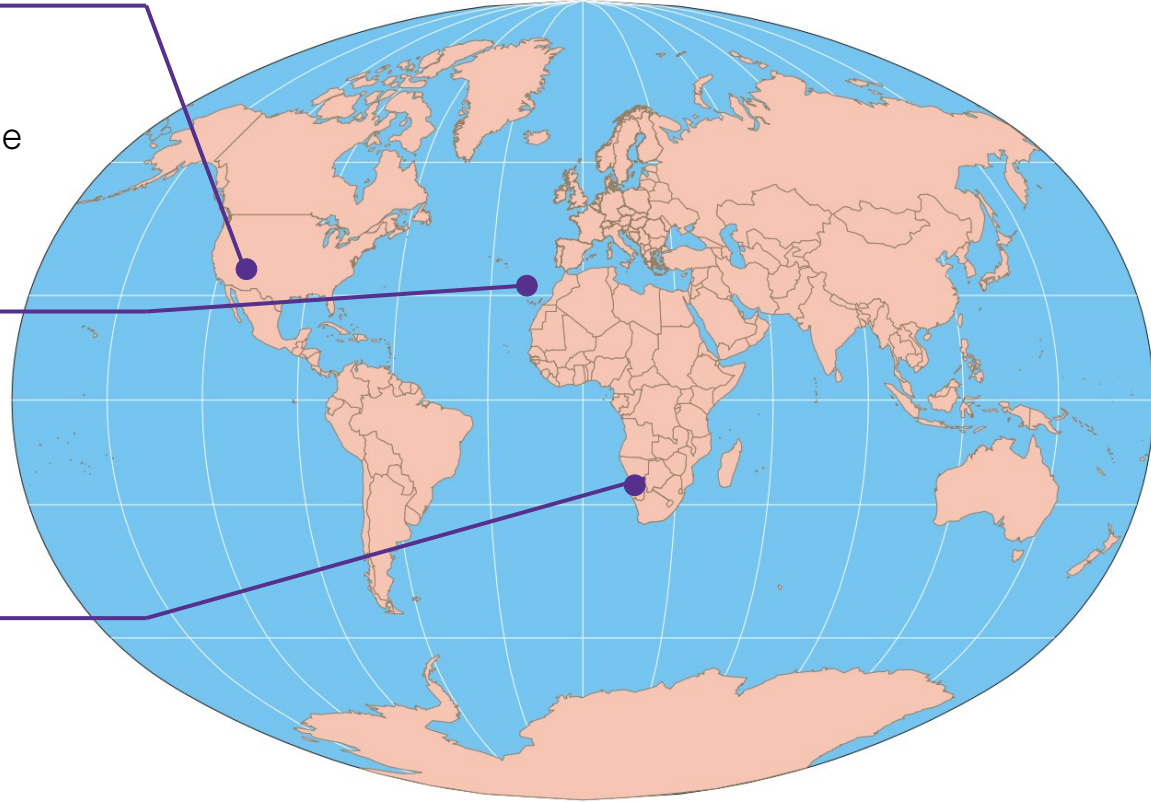
MAGIC

Two 17 m diameter IACTs
Sensitivity in [50 GeV – 30 TeV] range



H.E.S.S.

Four 12 m diameter IACTs + 28 m
diameter IACT
Sensitivity in [100 GeV – 100 TeV] range



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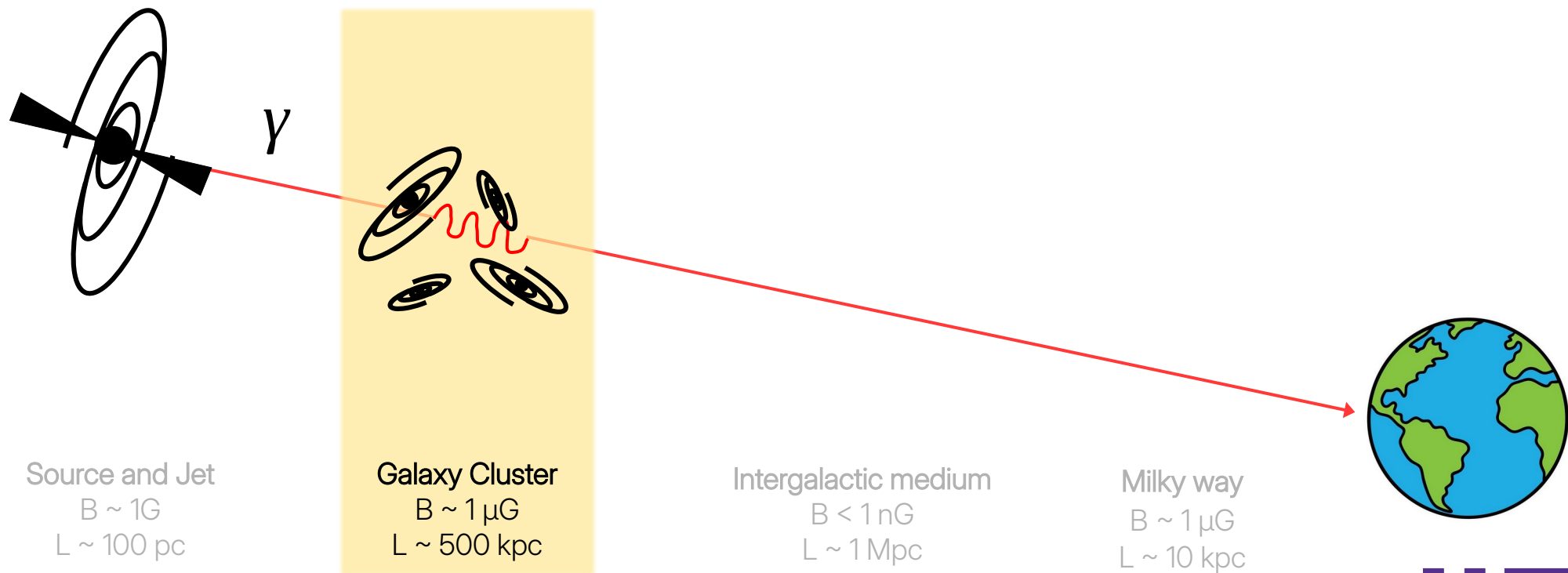
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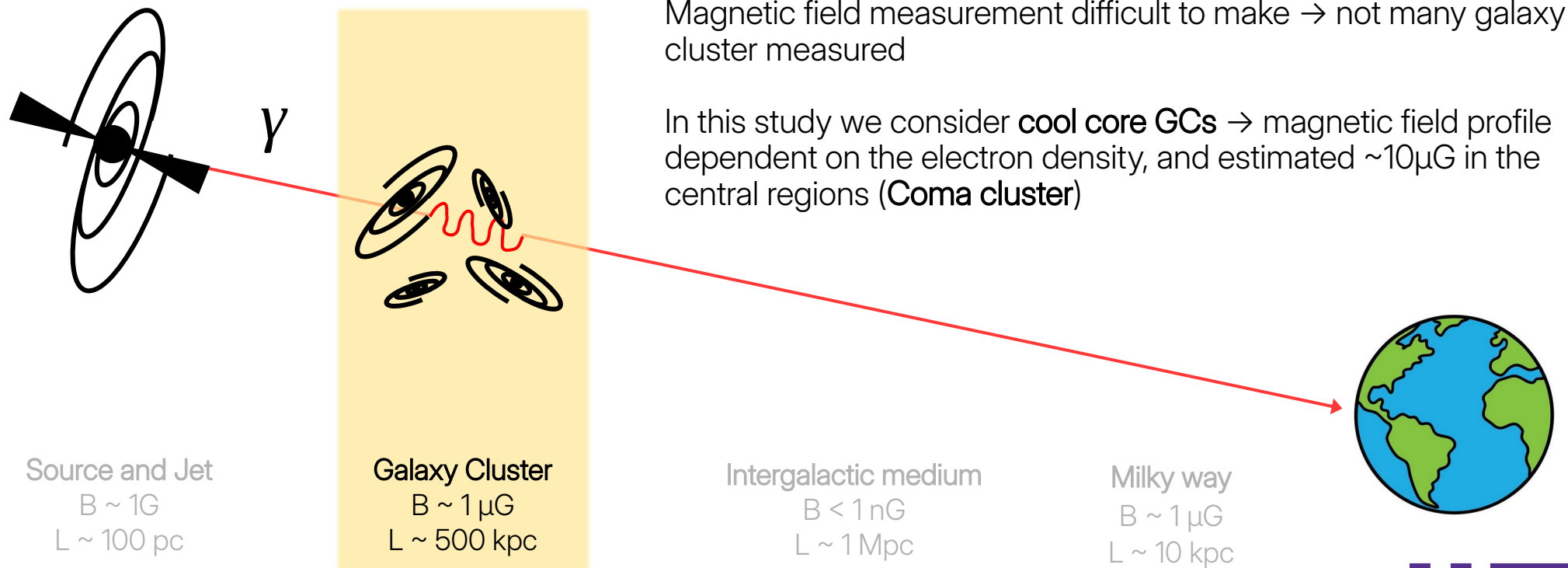
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GOAL of our analysis: Probing ALP- γ oscillations with observations of VHE γ -ray from AGN-GC pairs using a stacked analysis of several pairs



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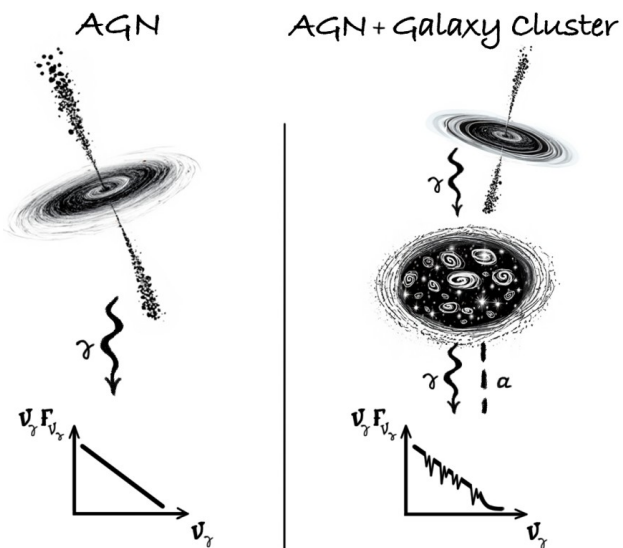
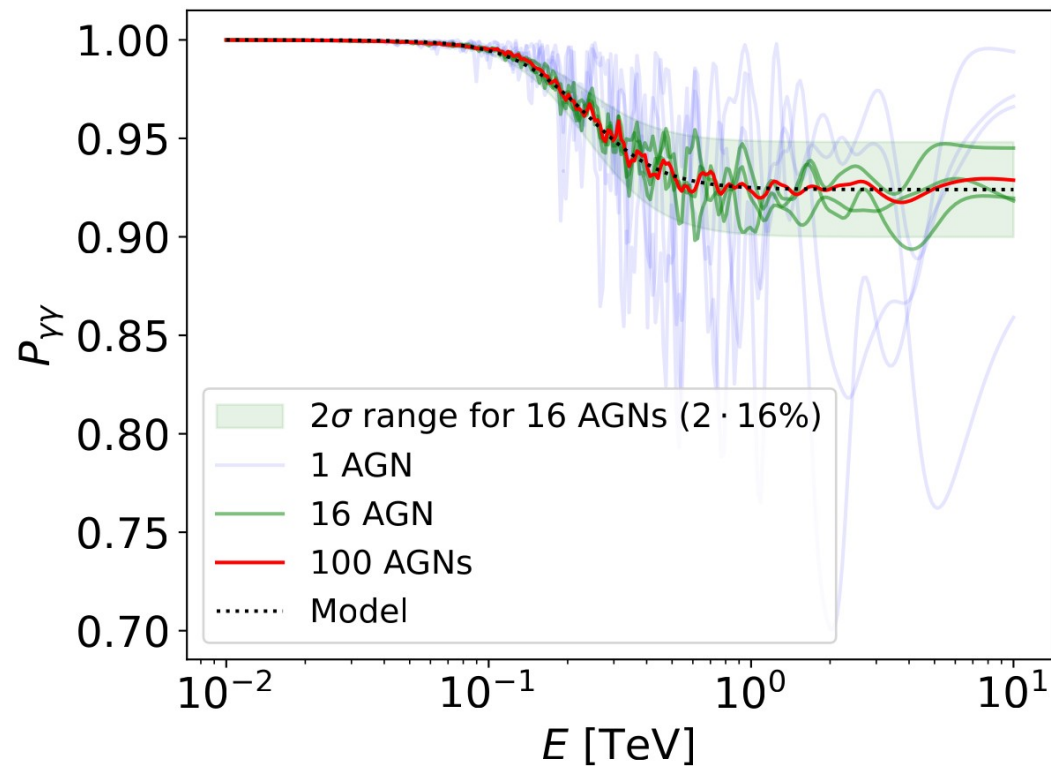
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For GC, no reliable measurement of the small-scale properties of the field (orientation, domain length)

Difficult to use only one AGN-GC pair:

→ need to marginalize over a large number of small-scale configuration of the magnetic field

→ thus deriving a weak constraint



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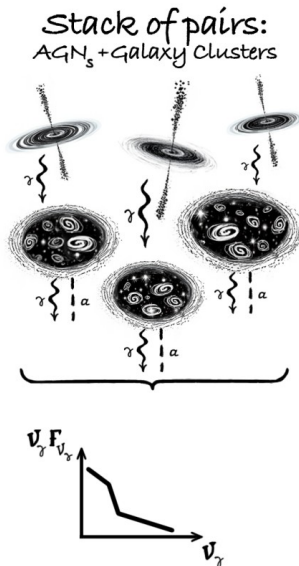
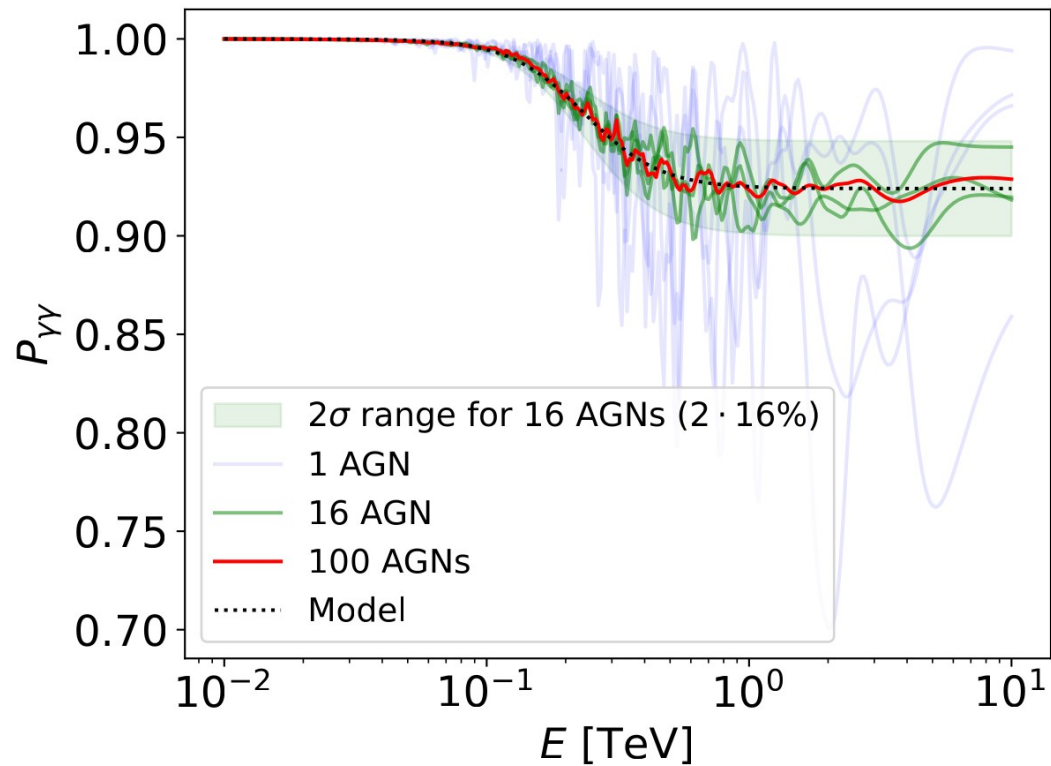
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INSTEAD

- stacking multiple AGN-GC pairs
- gives a smooth predictable spectral imprint to probe ALPs (step function)
- Photon survival probability parametrization:

$$P_{\gamma\gamma} = 1 - \frac{p_0}{(1 + (E/E_c)^k)}$$



II. AGN-GC sources selection

Crossmatching

- 4LAC catalog (γ-ray bright AGNs)
- with SZ catalog (GC)



CRITERIA

$$Z_{\text{AGN}} \geq Z_{\text{GC}}$$

Line of sight within 500
kpc from GC center



29 AGN-GC pairs selected

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Present in 3FHL catalog

Detected by Fermi-LAT $E > 10$ GeV



16 AGN-GC pairs selected



IACT Visibility

with zenith angle lower than 60° (meaning
visibility in favorable observational conditions)



41 Datasets

11 AGN-GC → H.E.S.S.
15 AGN-GC → MAGIC
15 AGN-GC → VERITAS

II. Mock data simulation

Expected observed γ -ray flux:

- Intrinsic flux

- Photon survival probability

- Extragalactic Background Light (EBL) attenuation (from e^+e^- pair production)

$$\frac{d\Phi^{obs}}{dE_\gamma} = \frac{d\Phi^{int}}{dE_\gamma} \times P_{\gamma\gamma}(E_\gamma, m_a, g_{a\gamma\gamma}, B_T) \times e^{-\tau(E_\gamma, \epsilon, z)}$$

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Expected number of counts per i bin:

- Observation time
- Detector's acceptance
- Detector's energy resolution

$$N_i^S = T_{obs} \int A_{eff}(E') G(E - E') \frac{d\Phi(E')}{dE'} dE'$$

Mock data simulated for $T_{obs} = 50$ h for each AGN-GC pairs, from 100 GeV to 60 TeV

II. Statistical analysis method

Compare spectra under two hypotheses:

Null: No ALPs

ALP: Modulated spectrum due to ALP-photon oscillations

We use binned Poisson likelihood for observed counts N^{ON} and predicted counts N^{S}
(for each k AGN-GC dataset and each i bins)

Then, for a given **object** k the likelihood is

$$\log \mathcal{L}_{ik} = N_{ik}^{\text{ON}} \log N_{ik}^{\text{S}} - N_{ik}^{\text{S}} - \log(N_{ik}^{\text{ON}}!)$$

$$\mathcal{L}_k = \prod_i \mathcal{L}_{ik}$$

Finally for the **stacked data** set the combined likelihood is

$$\mathcal{L}_{\text{comb}} = \prod_k^N \mathcal{L}_k$$

II. Statistical analysis method

Compare spectra under two hypotheses:

Null: No ALPs

ALP: Modulated spectrum due to ALP-photon oscillations

Compare the models by constructing the **loglikelihood ratio** as

$$\mathcal{L}(m_a, g_{a\gamma\gamma}, P^1, P^2) = -2 \log \frac{\prod_{i,k} \mathcal{L}_{ik}(N_{ik}^{ON}(m_a, g_{a\gamma\gamma}, P^1), N_{ik}^S)}{\prod_{i,k} \mathcal{L}_{ik}(N_{ik}^{ON}(m_a, g_{a\gamma\gamma}=0, P^2), N_{ik}^S)}$$

The **Test Statistic** (TS) is then defined by

$$TS(m_a, g_{a\gamma\gamma}) = \min_{P^1, P^2} \mathcal{L}(m_a, g_{a\gamma\gamma}, P^1, P^2)$$

With P_i parameters to minimize for a given hypotheses

A one-sided 95% CL upper limit then corresponds to $TS = 2.71$

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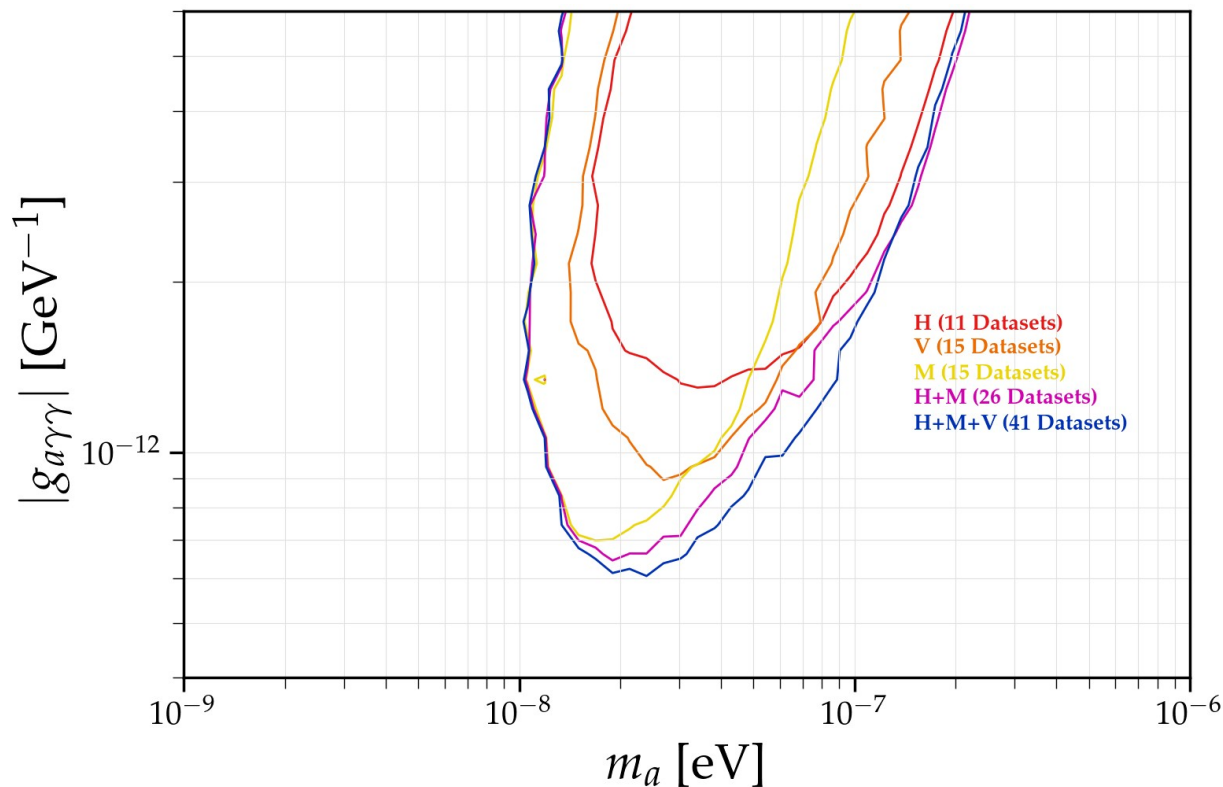
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III. Stacking analysis results

Performing the analysis for increasing number of combined datasets for H.E.S.S., MAGIC and VERITAS

For $m_a = 3 \times 10^{-8}$ eV $\rightarrow$ **x 3 sensitivity improvement** with $g_{a\gamma\gamma} = 6 \times 10^{-13}$ GeV $^{-1}$.



III. Stacking analysis results

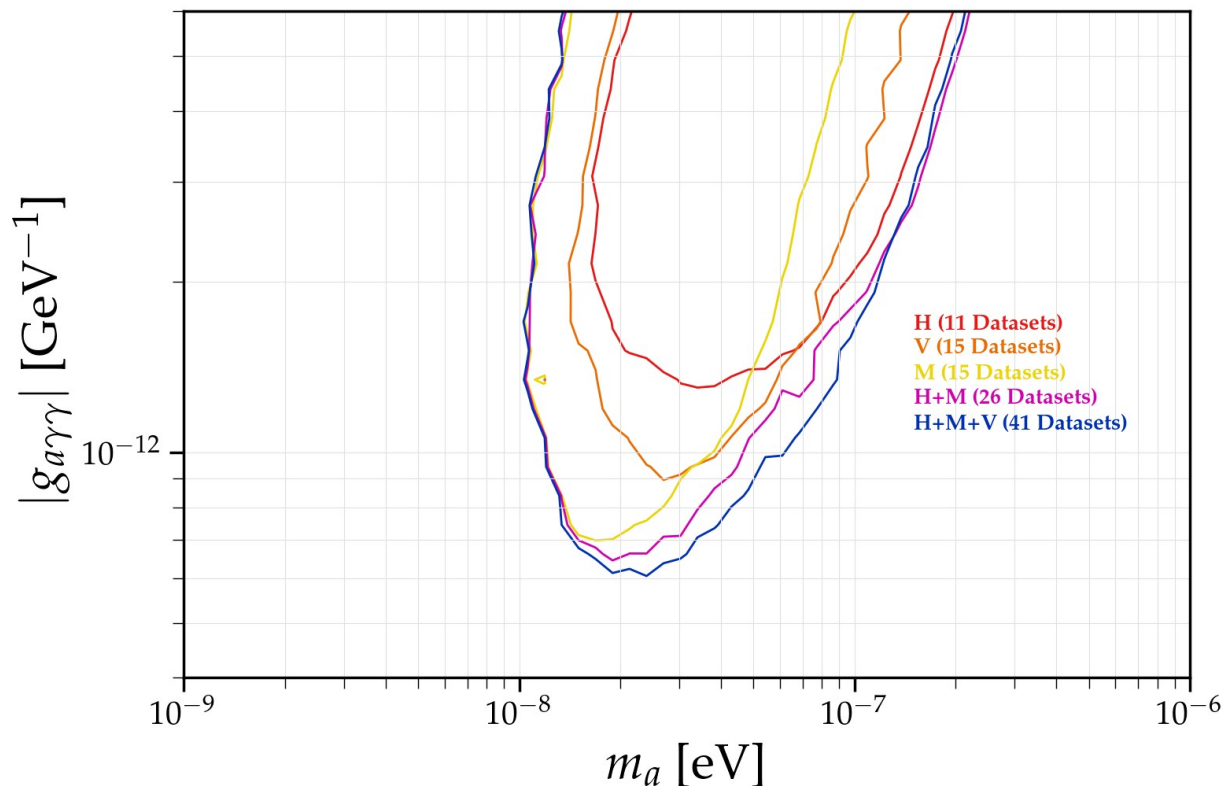
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Sensitivity decreases:

$\rightarrow m_a \sim 10^{-8}$ eV where critical energy gets closer to the IACTs low-energy threshold

$\rightarrow m_a = \sim 10^{-7}$ eV where critical energy falls into the strong EBL absorption regime



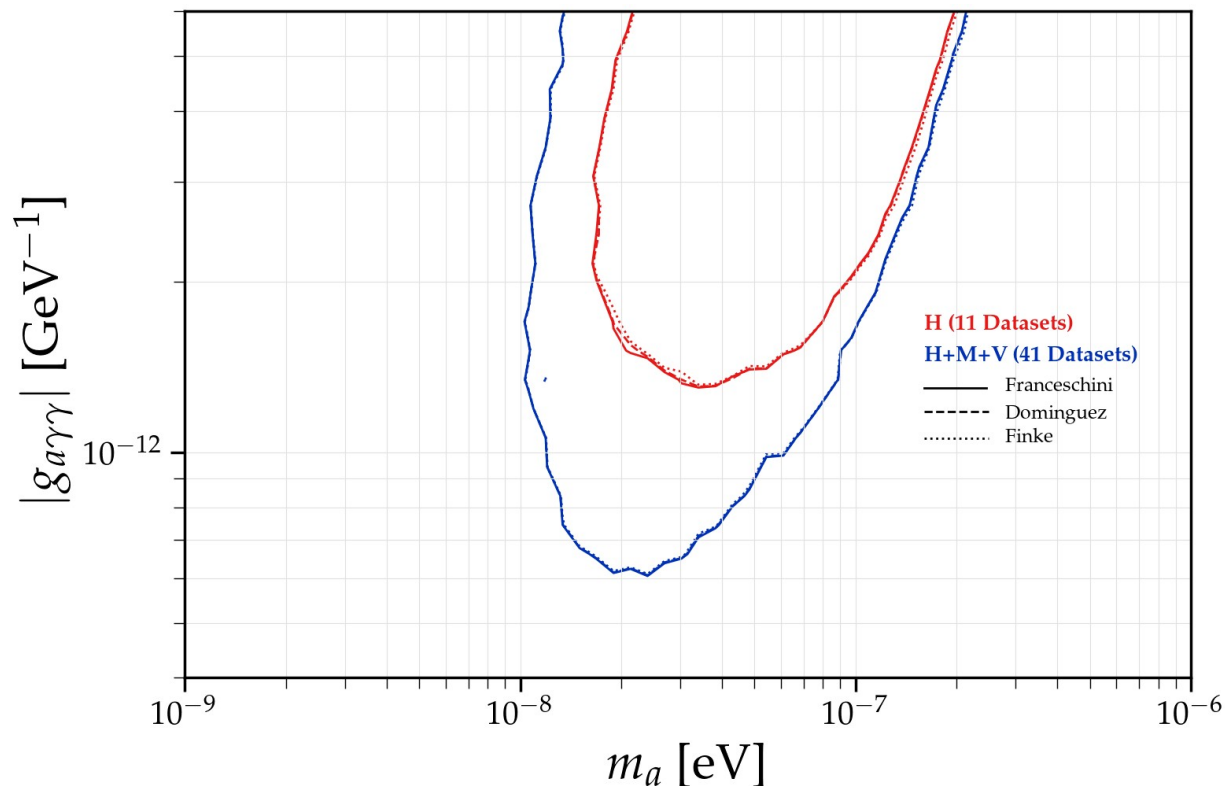
III. Impact of EBL modeling

We consider several **EBL absorption models**:

- Franceschini (baseline)
- Dominguez
- Finke

The impact of the EBL model (41 datasets):

- Limited to 3% below $m_a = 7 \times 10^{-8}$ eV
- Increases to 6% for $m_a = 2 \times 10^{-7}$ eV



III. Impact of EBL mismodeling

EBL mismodeling:

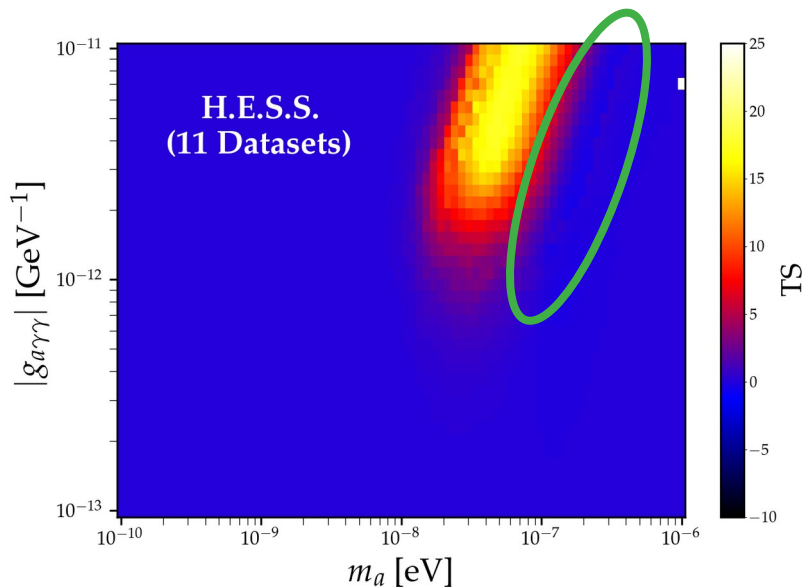
Mock data simulation → [Franceschini](#) EBL model

Maximizing the likelihood → [Finke](#) EBL model

For 11 datasets: Weak detection ($TS \sim -0.50$)

At $E < 10$ TeV → Finke EBL model induces stronger attenuation for sources with $z \leq 0.2$ compared to Franceschini

Need more γ -rays at $E \leq 10$ TeV → obtained by ALP- γ coupling



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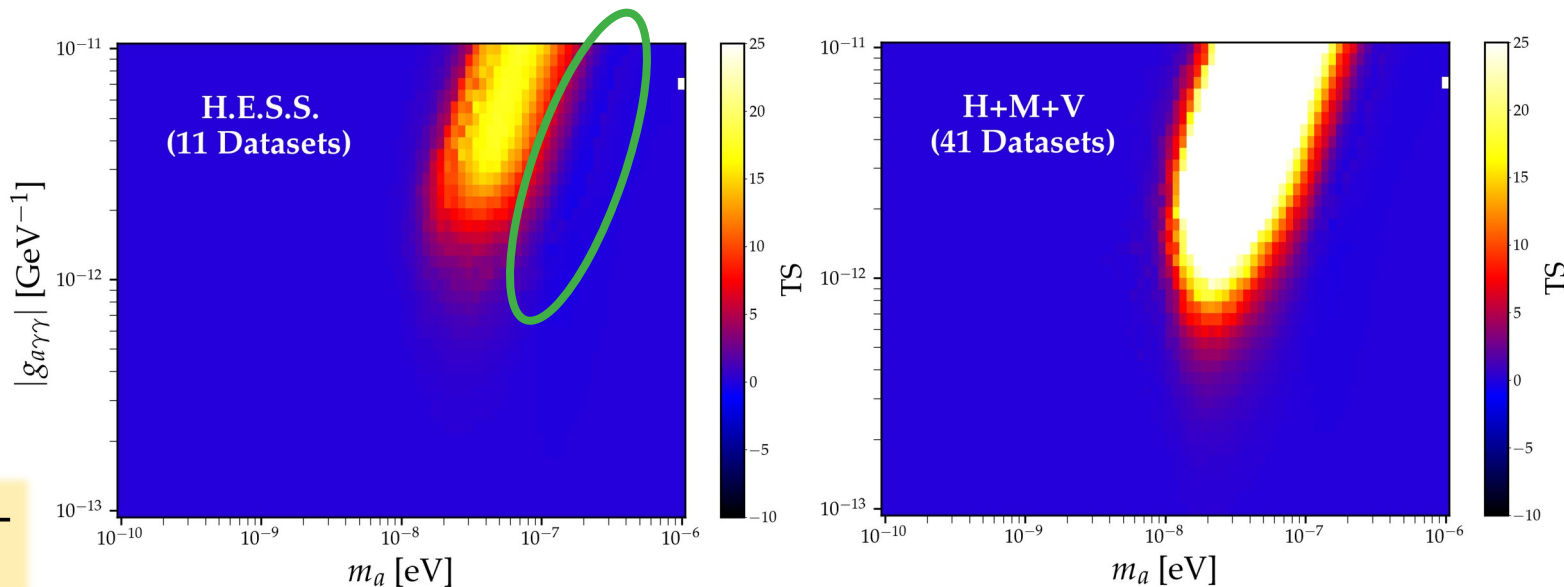
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For 41 datasets:

→ More high redshift sources

→ Reduces the relative impact of low-redshift sources the effect of EBL mismodelling.

Higher statistics, less EBL mismodeling impact



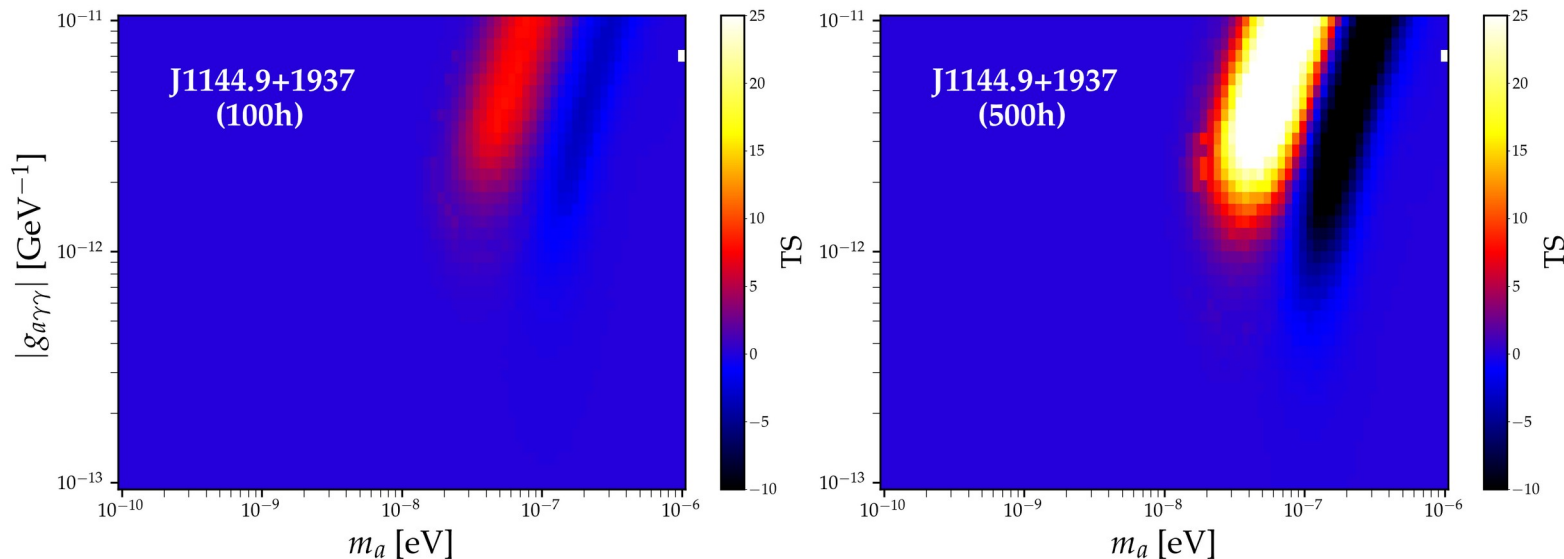
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Same investigation for one close source **J144.9+1937** ($z = 0.02$) for 100 hours and 500 hours of observation time

When the photon statistics increases $\rightarrow$ false detection becomes **more and more significant**.

$\rightarrow$ Strong observing time biased towards a single bright and close-by object results in a stronger EBL mismodelling impact

Importance in having a
**statistically
homogenous dataset** to
mitigate EBL
mismodeling effect



III. ALP signal injection

ALP-photon conversion injection:

$m_a = 7 \times 10^{-8}$ and range of $g_{a\gamma\gamma}^{\text{inc}}$

Using TS method $\rightarrow$ recover $g_{a\gamma\gamma}^{\text{rec}}$ with better than **4% bias** for coupling $> 10^{-12} \text{ GeV}^{-1}$

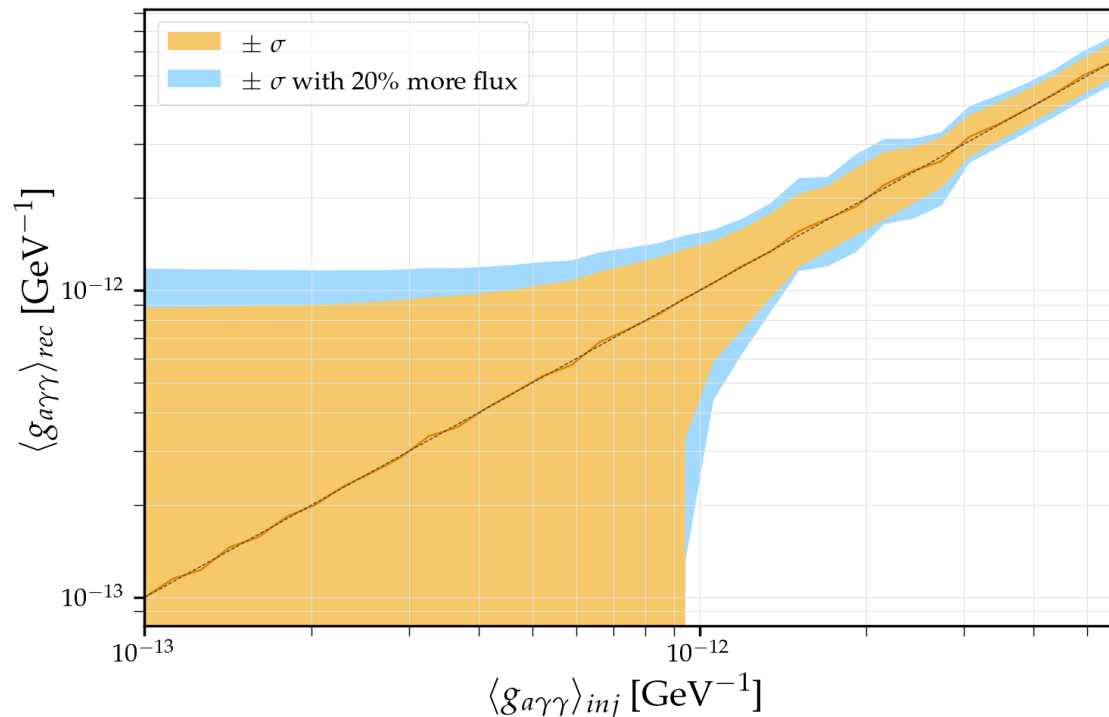
For lower coupling value

$\rightarrow$ Only upper limits derived

$\rightarrow$ Considerable statistical uncertainty on the ALP-photon coupling recovery

Same test but with **20% systematic** uncertainties on the flux normalisation

$\rightarrow$ band increase by **14 %** compared to statistical uncertainty only



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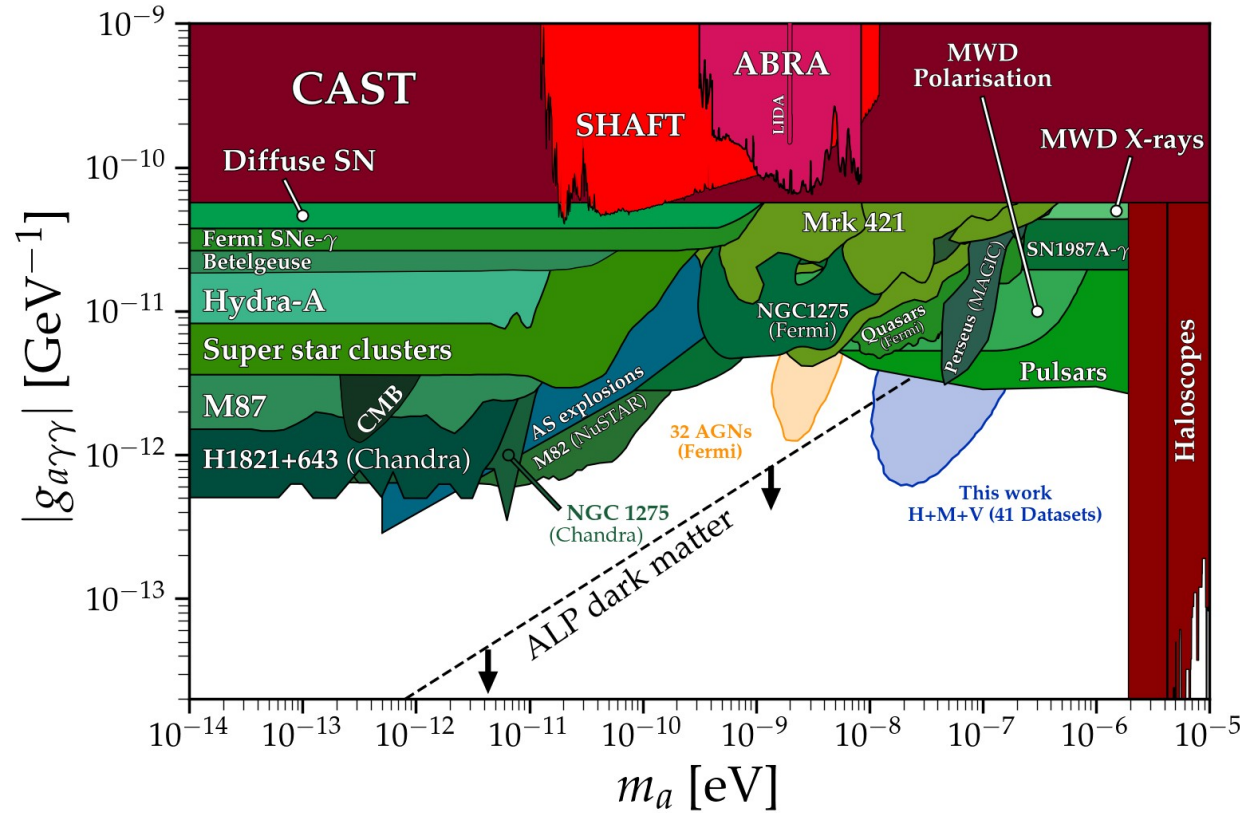
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Our approach enables to **probe uncovered region** in the 10-100 neV masse range where ALP can comprise all the DM

The strongest sensitivity reached at:

$$\rightarrow g_{a\gamma\gamma} = 5 \times 10^{-13} \text{ GeV}^{-1}$$

$$\rightarrow m_a = 2 \times 10^{-8} \text{ eV.}$$



Article in JCAP : [10.1088/1475-7516/2026/07/066](https://arxiv.org/abs/10.1088/1475-7516/2026/07/066)

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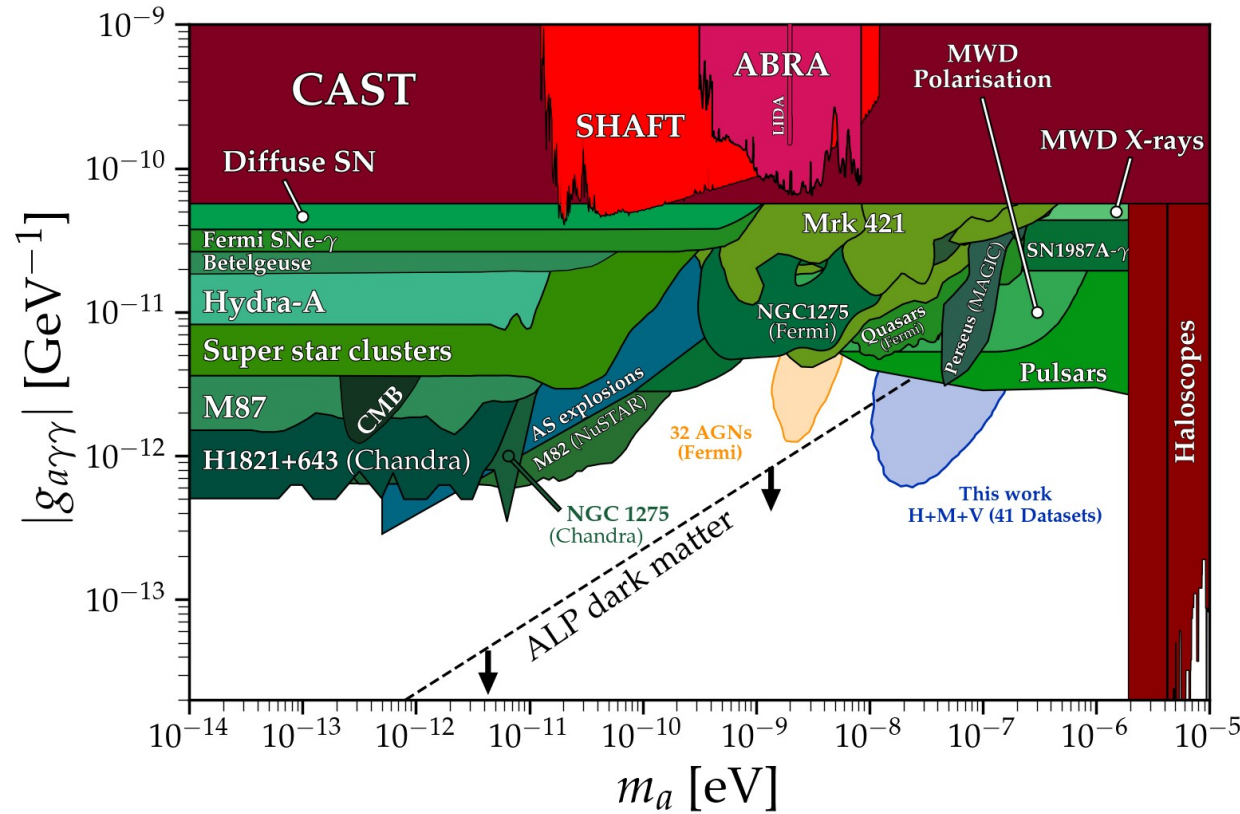
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Sensitivity reach is **statistics dominated**

$\rightarrow$ increasing data collection towards selected AGNs with ongoing IACTs remains important



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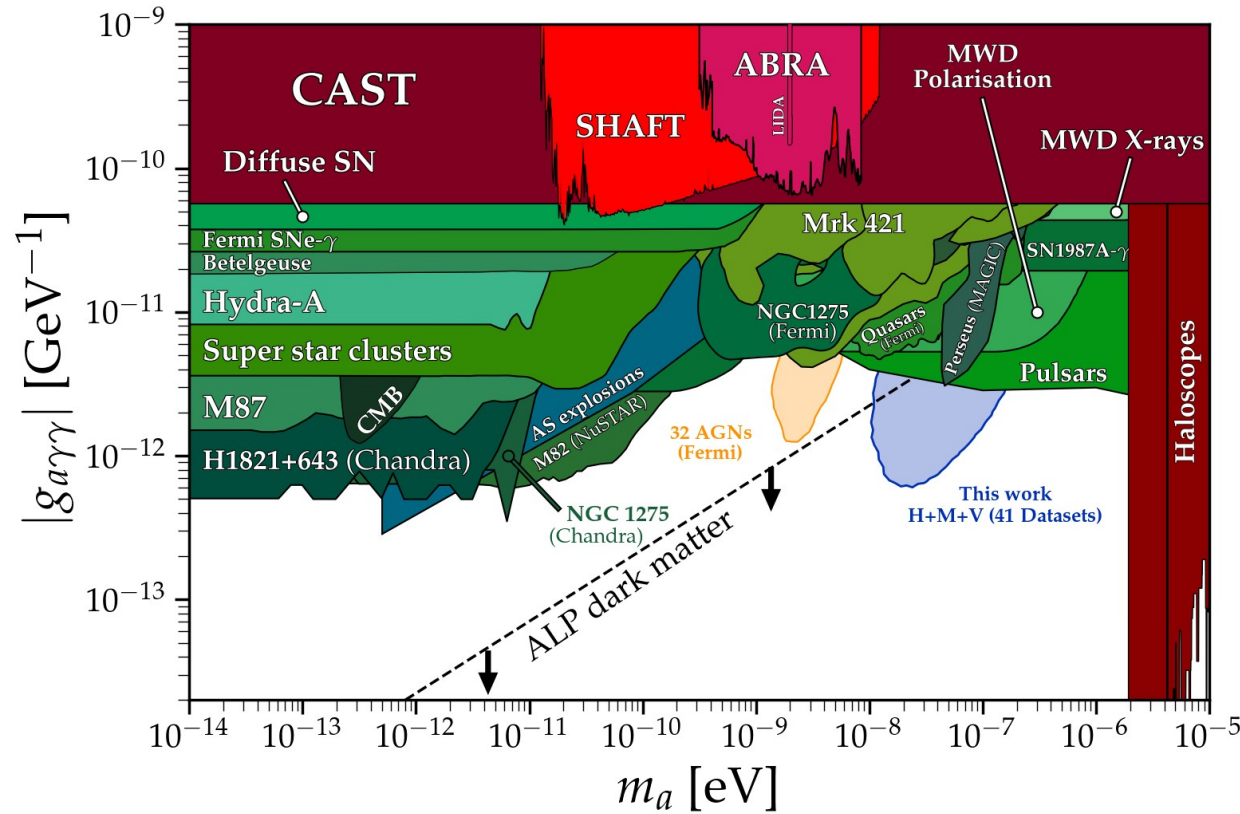
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The **impact of the EBL model** on the sensitivity reach is limited with **statistically homogeneous** datasets for AGNs distributed over a range of redshifts.



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Thank you !



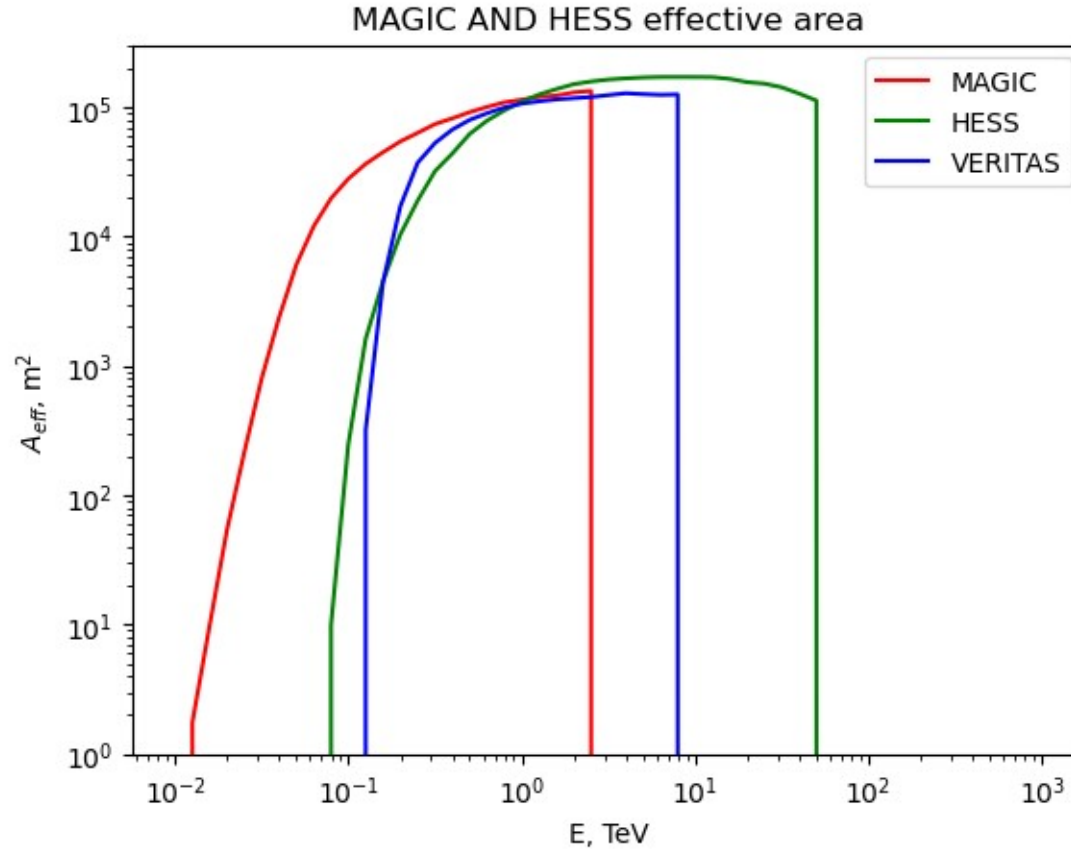
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Composite image of Centaurus A [ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray); CC BY 4.0]



IACTs effective area



Galactic cluster magnetic field modeling

We consider cool core GCs → magnetic field profile dependent on the **electron density**, and estimated $\sim 10\mu\text{G}$ in the central regions.

The thermal electron density is well represented by a standard β -model:

$$n_e(r) = n_0 \left(1 + \frac{r^2}{r_c^2} \right)^{-3\beta/2}$$

with $n_0 = 3.44 \times 10^{-3} \text{ cm}^{-3}$, $r_c = 291 \text{ kpc}$, and $\beta = 0.75$

$$B(r) = B_0 \left(\frac{n_e(r)}{n_0} \right)^{0.67}$$

The magnetic field strength scales with the local electron density as:

Faraday Rotation Measure

Coma cluster magnetic field modeling:

observational constraints from polarized radio emission (Faraday rotation especially)

Linearly polarized electromagnetic wave passes through a magnetized plasma

→ its polarization plane rotates due to the birefringent properties of the medium (difference in phase velocities of the left- and right-handed circular components)

The observed polarization angle Ψ_{obs} :

$$\Psi_{\text{obs}}(\lambda) = \Psi_{\text{int}} + \text{RM} \cdot \lambda^2$$

$$\text{RM} = 812 \int_{\text{source}}^{\text{observer}} n_e(l) B_{\parallel}(l) dl \quad [\text{rad} \cdot \text{m}^{-2}]$$

EBL models comparison

