Probing the connection between axion-like particles and dark matter with the Cherenkov Telescope Array through Machine Learning

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Outlook

- Introduction
- Motivation of the Project
- Objectives & Methodology
- Priliminary result
- Final outlook

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Introduction

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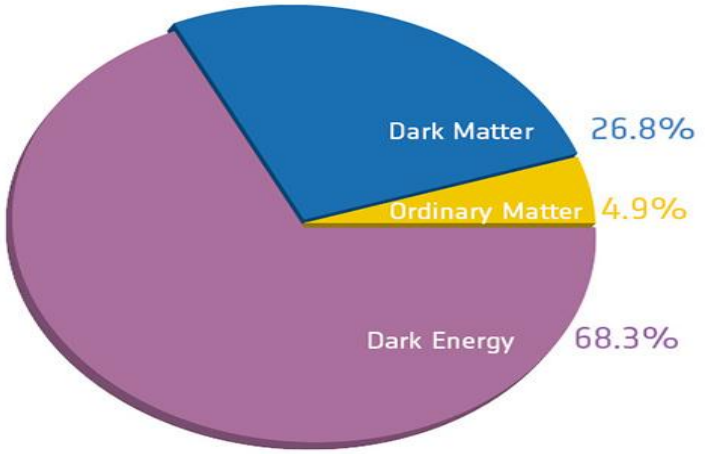
What is dark matter (DM)?

Not baryonic and carry no electric or colour charges.

Neither emit nor absorb light.

Not composed of particles of the standard model.

Only interact via gravity.



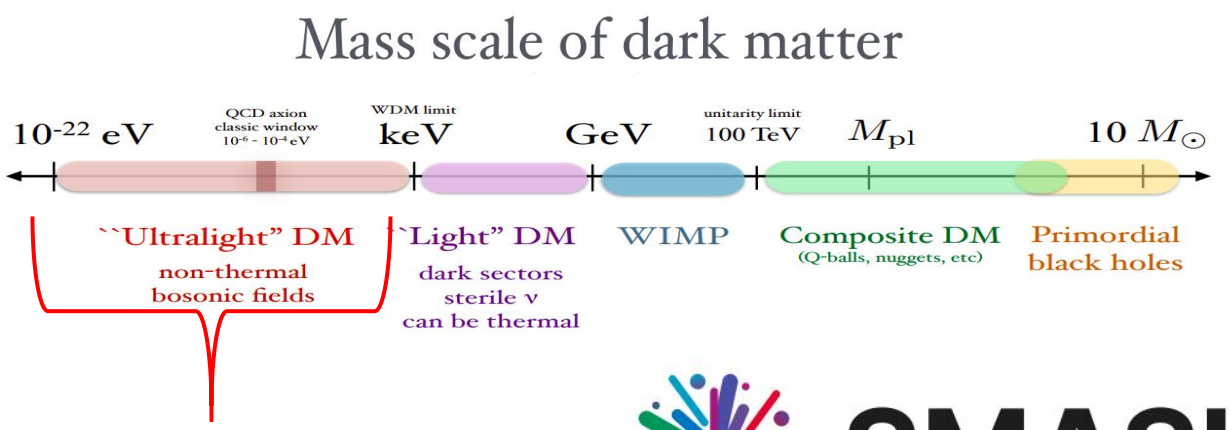
T. Lin, arxiv:1904.07915

Axion-like Particles (ALPs)

Candidates

One of the motivated DM candidates.

Their existence can be probed by the spectra of astrophysical sources.



Axion-like Particles (ALPs)

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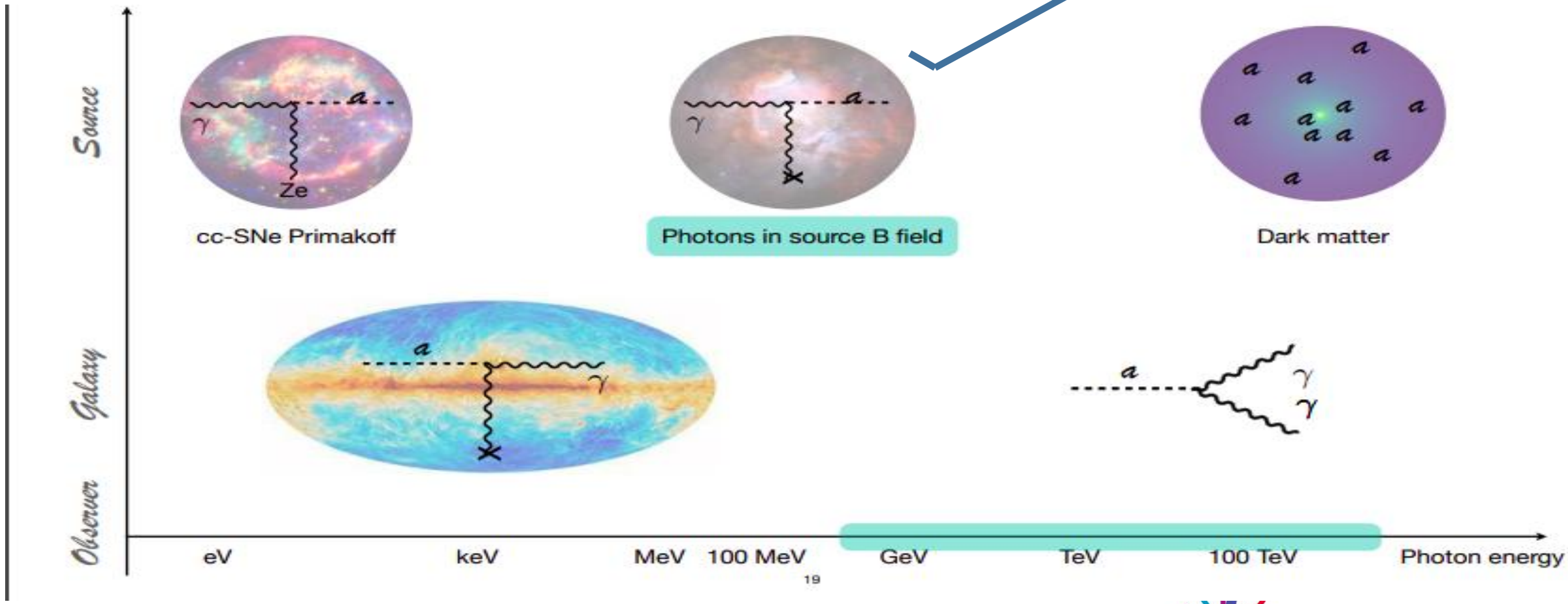
Targets



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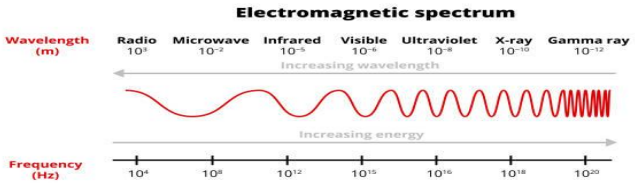
One of the best target for ALPs

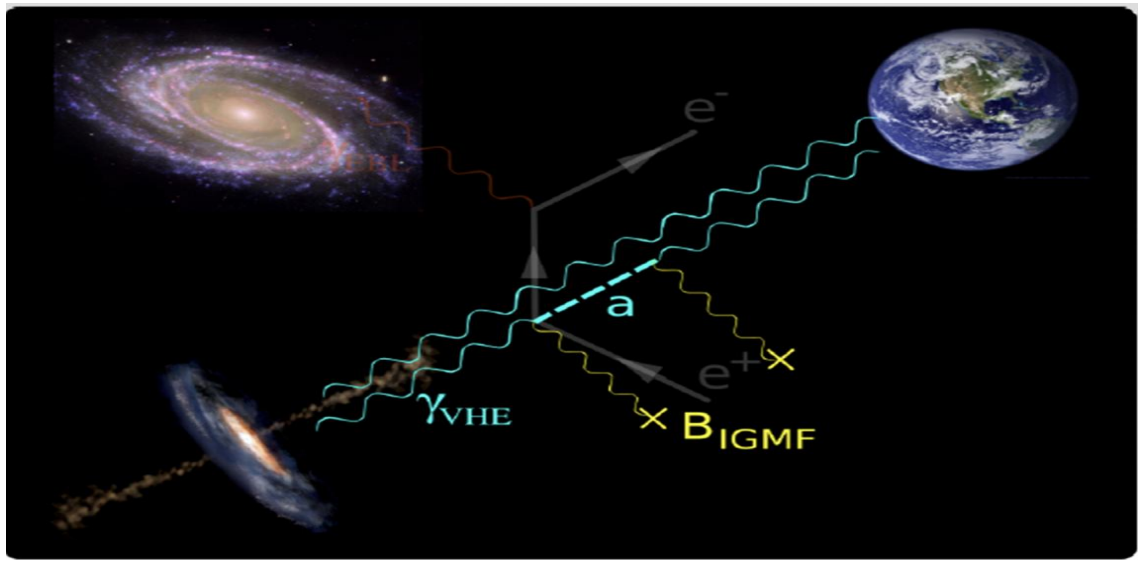
Blazars with strong magnetic field and strong signal (flares) → **gamma-ray emission**

Blazars are the type of **active galactic nuclei (AGN).**

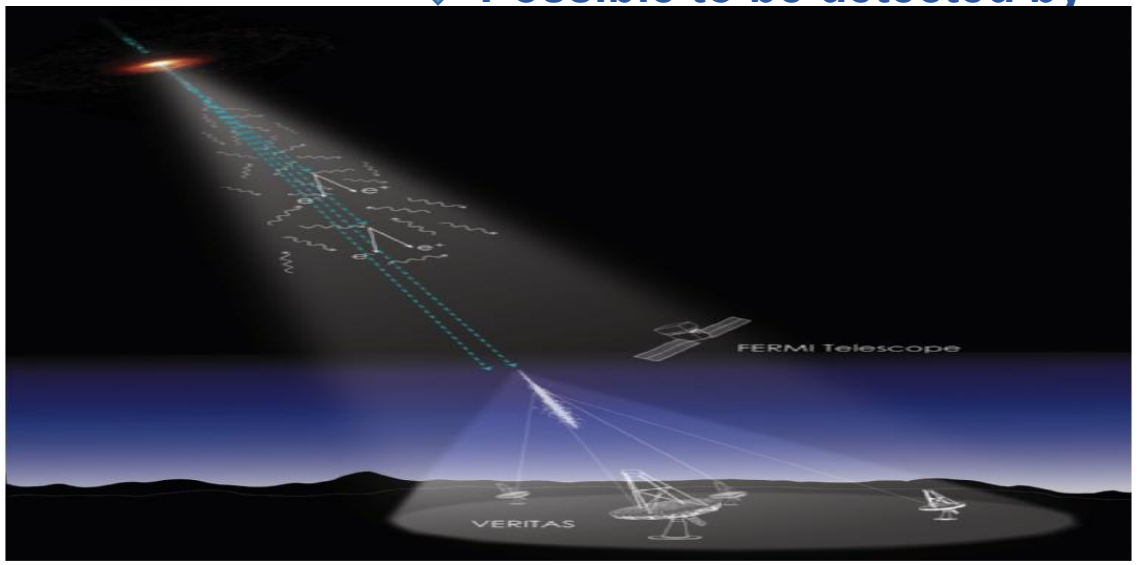
In the presence of **an external magnetic field,** the coupling between the **ALP and photons** would also lead to **ALP-photon oscillation.**



Possible to be detected by



Propagation of ALPs from Blazar to Earth



Gamma-ray spaced/ground based telescopes

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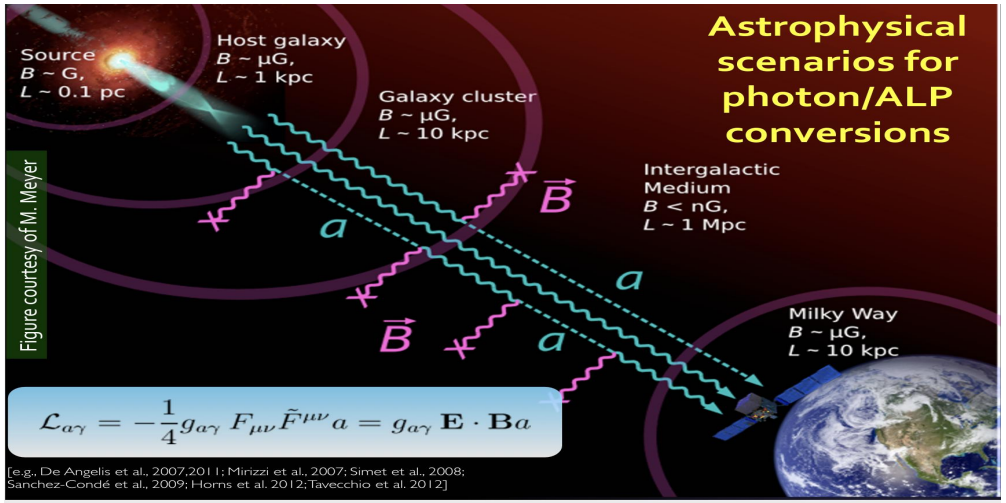
Photons, ALPs & magnetic field

Photons can convert to ALPs by mixing induced in the external magnetic field –

causing the so called “wiggles”, irregularities in the spectra of astrophysical objects



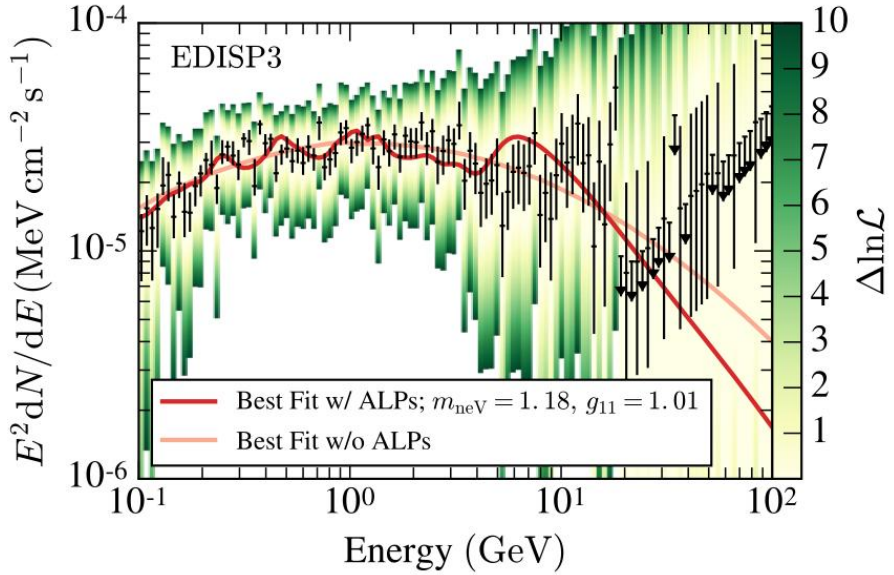


Figure 1: Best fit with & w/out ALPs for the spectrum of NGC1275, Ajello M. +, Phys. Rev. Lett. 116, 161101 (2016)

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Motivation

1) Why Axion-like Particles (ALPs)?

- **Popular candidates for dark matter** and physics beyond the standard model
- **Can oscillate into photons (gamma rays)** in the **presence of magnetic fields.**

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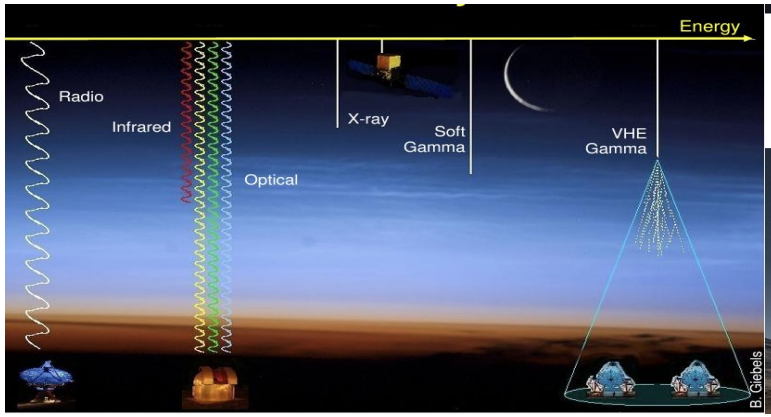
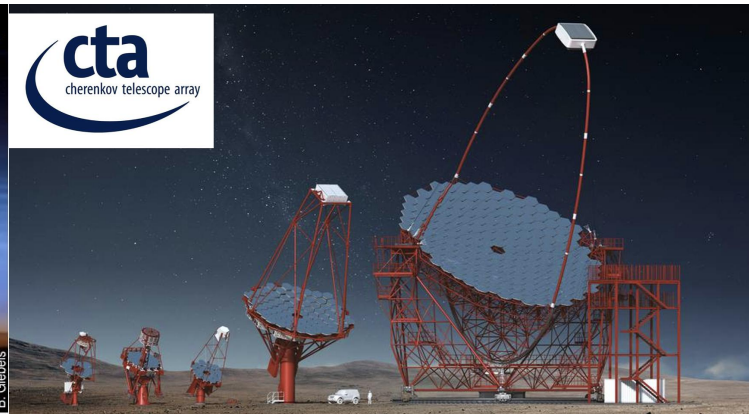
Motivation





2) How can we probe ALPs with Cherenkov Telescope Array (CTA)?

- CTA is the next-generation **ground-based gamma-ray telescope.**
- **10 times better sensitivity** than existing telescopes.
- Covers **wide energy range from 20GeV to 200TeV.**
- The **first telescopes of CTA, Large Size Telescope (LST-1)** has already started taking data.

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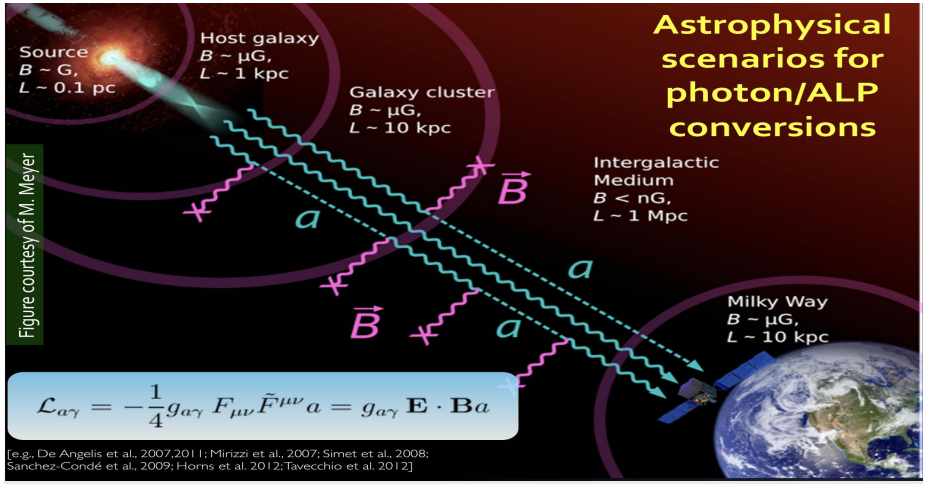
Motivation



3) Why Blazars as our target?

- **Emits relativistic plasma jets** emitted towards us.
- Rank among **the brightest gamma-ray sources in the sky.**
- **Strong magnetic field (~0.1-10 G).**

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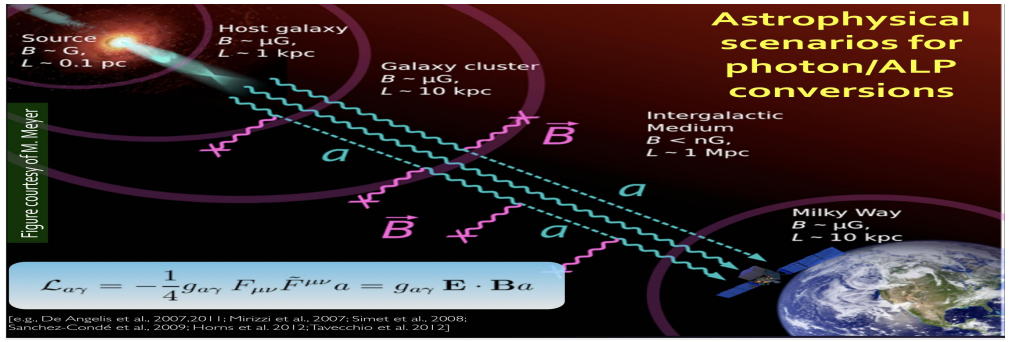
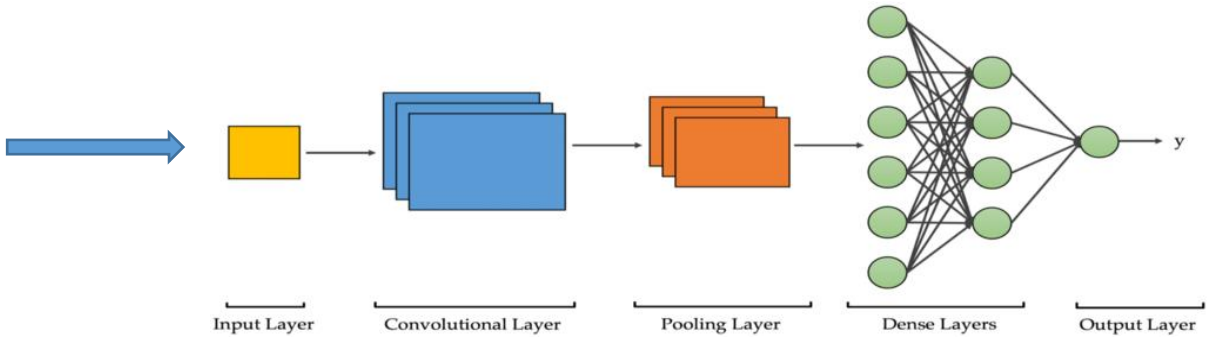
Motivation





4) Why Machine Learning (ML)?

- **ALP-photon conversion** strongly dependent on the **propagation environment and the treatment of the uncertainties of magnetic fields.**
- **Typical Likelihood test fails** when we deal with **large number of parameters with uncertainities** and biased our results.
- **Convolutional Neural Networks (CNNs)** is expected to **excel** in scenarios where **traditional likelihood-based methods face challenges.**
- We probably use the **“Bayesian Neural Networks”** to obtain the **robust ALP-photon conversion probability for their complex surroundings.**

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Objectives & Methodology planned for SMASH

1) Modeling of the Blazar jets

2) Impact of photon propagation towards us

3) Machine Learning approach to study photon-ALP mixing

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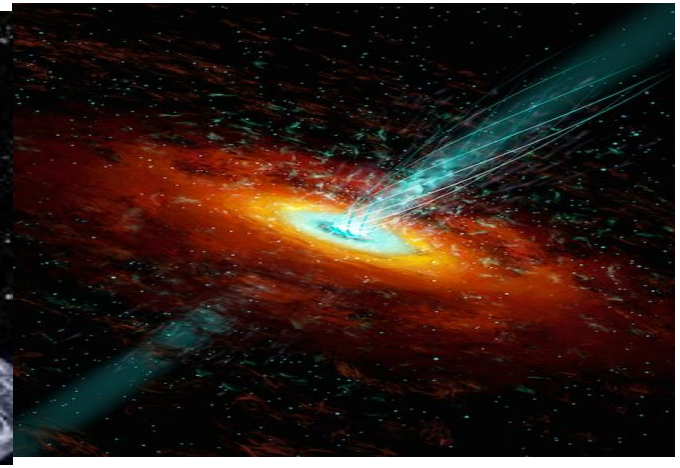
Objectives & Methodology



1) Modeling of the Blazar jets:

- **The impact of the blazar jet magnetic field on ALP-photon mixing** will be a very crucial part of this project.
- We will run the **cosmic ray simulation tool, Cosmic Ray Propagation Framework (CRPropa) to study the behavior and structure of the magnetic field and particles within the blazar jets.**
- Establish the **validation of numerical simulation with observational polarimetric data.**

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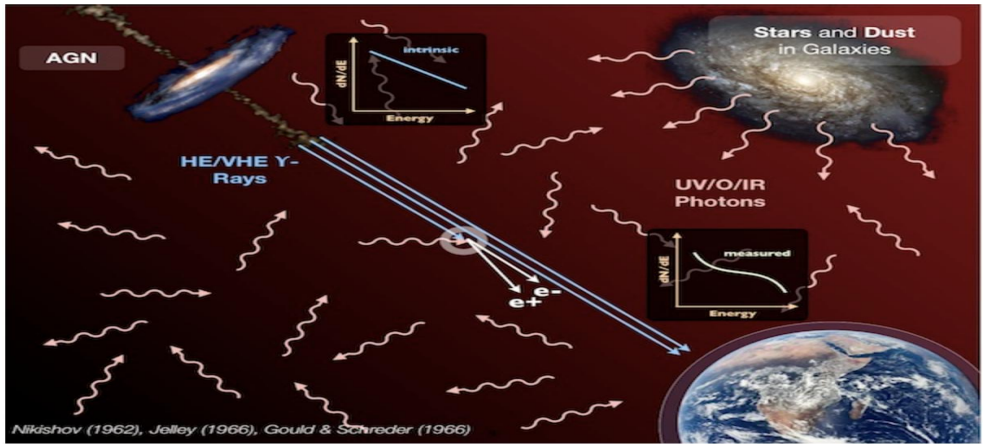
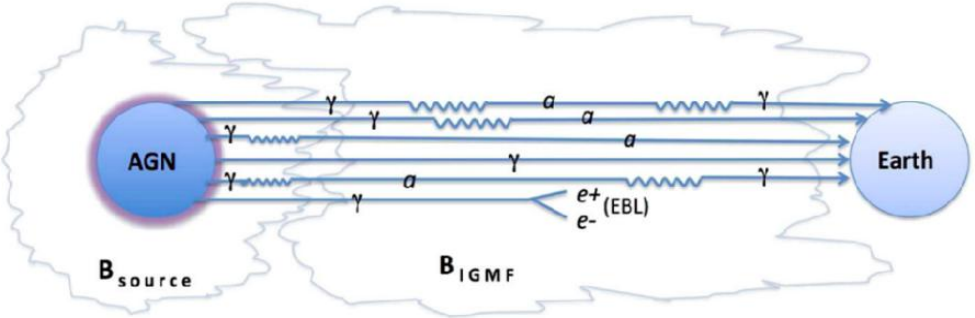
Objectives & Methodology



M. Sánchez-Conde, D. Paneque et al., 0905.3270



2) Impact of photon propagation towards us:

- Examine the **impact of intergalactic magnetic field (IGMF) and extragalactic background light (EBL) on ALP-photon survival probability.**
- Derive the **intrinsic spectra of blazars as** they are **significant for very high energy range and high-redshift object.**

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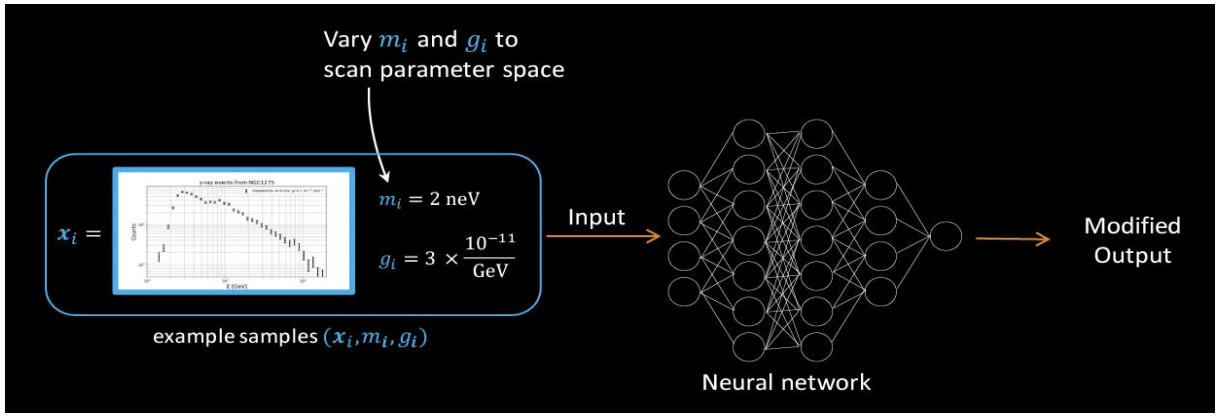
Objectives & Methodology



3) Machine Learning approach to study photon-ALP mixing:

- **Train the CNN network with a large amount of real and simulated data available from LST-1 and CTA** to distinguish between with and without ALPs.
- **Find ALP signal and place bounds on the coupling between photons and ALPs for various condition of magnetic field.**
- **Validate our obtained bounds** on ALP parameter space **with future (and also with present) experiments.**
- **Bayesian neural network to deal with the uncertainties.**

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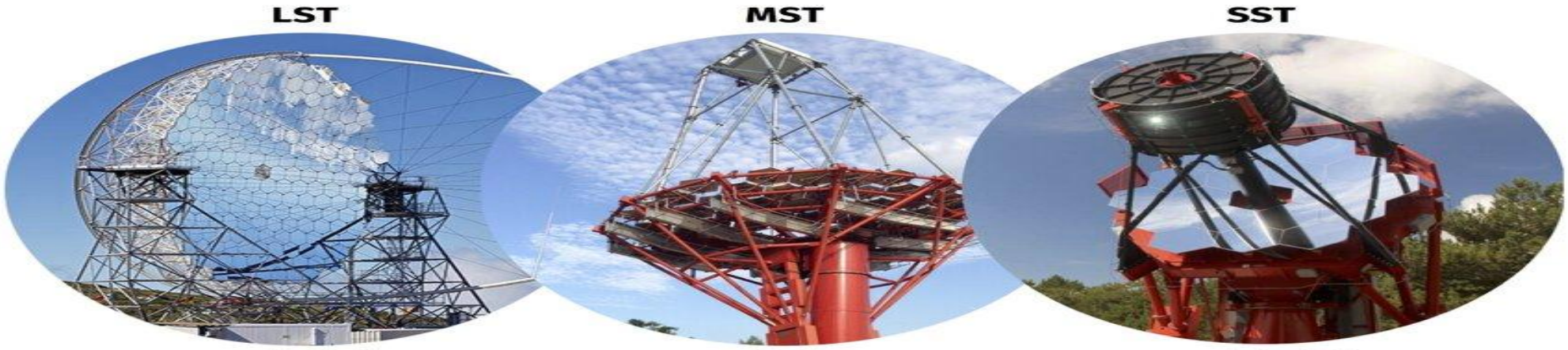
Preliminary result from LST-1 analysis



LST - Large Size Telescope of CTA

LST-1 is first prototype of CTA

- Started taking the data since 2021

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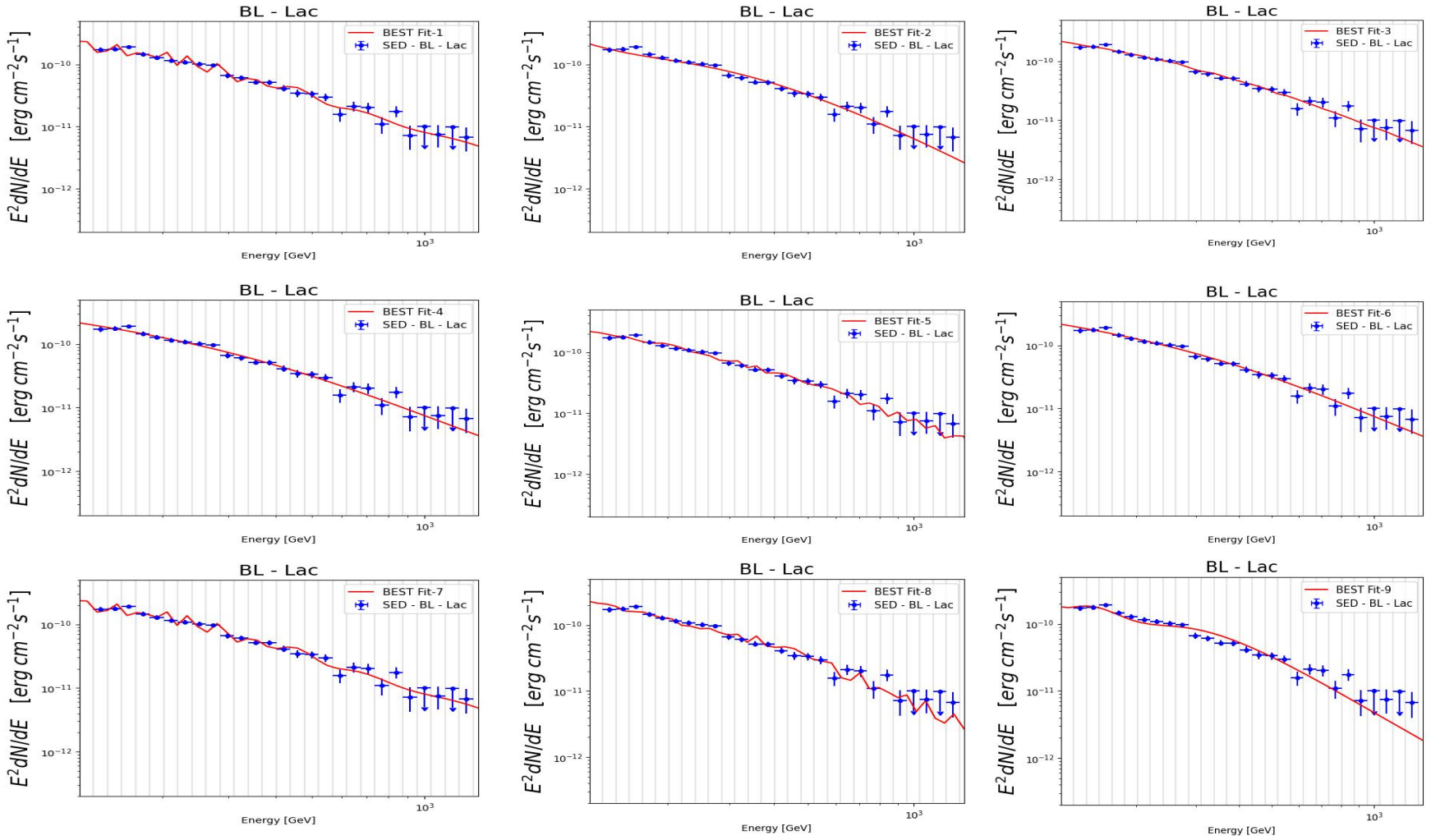
SED from MC Simulation



Traditional likelihood-based
No ML Approach

PRELIMINARY
with LST–1 data

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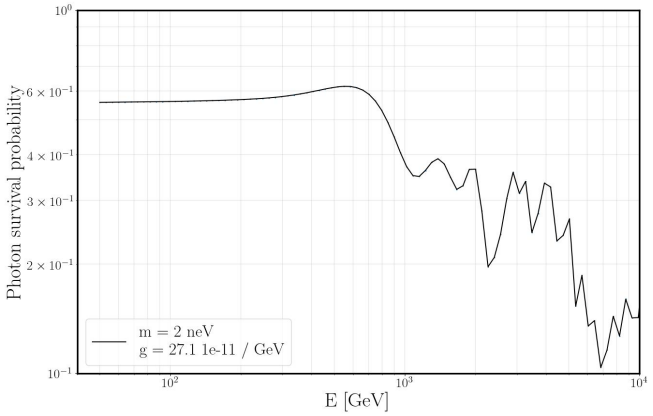
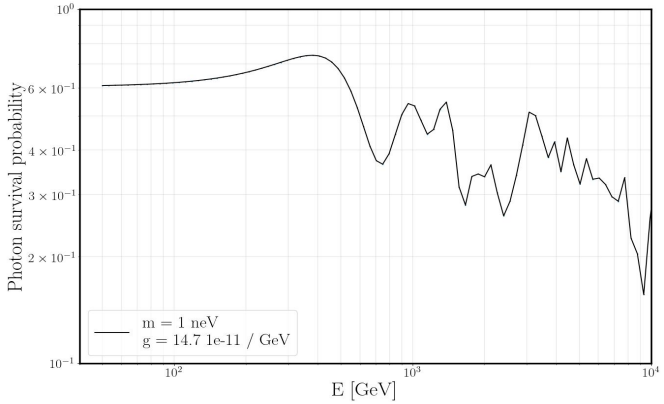
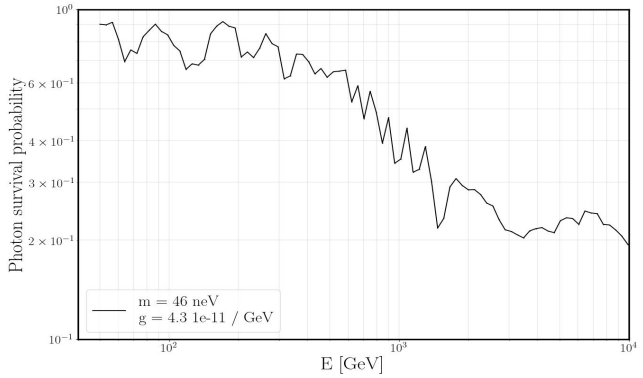
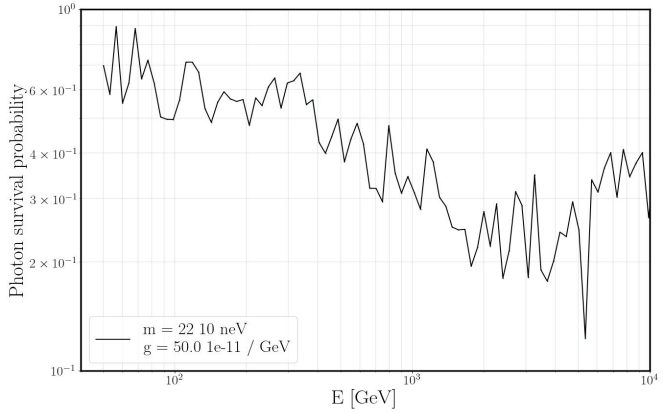
Photon survival probability









Four Different Combination of ALP mass (m) and Coupling constant (g)

We used the following:

- **GMF= The Jansson & Farrar model**
- **EBL= A. Domí nguez et. al**

But **Photon survival probability** strongly depends on the **GMF** and **jet magnetic field.**

→ **Need to be tested further!!!**

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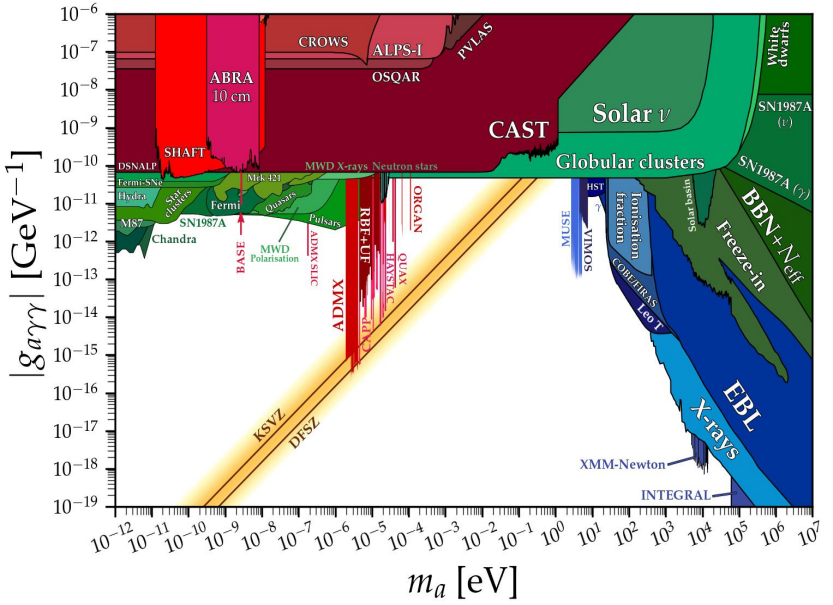
Possible Outcome and Beyond state-of-the-art

- We aim to **refine the current limits of ALP-DM theories from blazar spectra.**
- For the first time to our knowledge, **we will perform the combined study of LST-1 and CTA data with the CNN architecture.**
- With ML approach, **we seek to yield robust constraints on ALP-photon interactions.**
- We aim to perform a **global structural study of blazar jets with open source simulation tool** which will include the validation from X-ray polarization measurement.



Ciaran O'Hare, 2024

This project will contribute to the understanding of DM, a fundamental puzzle in the universe, and investigate the potential existence and properties of ALPs, which is a significant topic of interest in particle physics and astrophysics.

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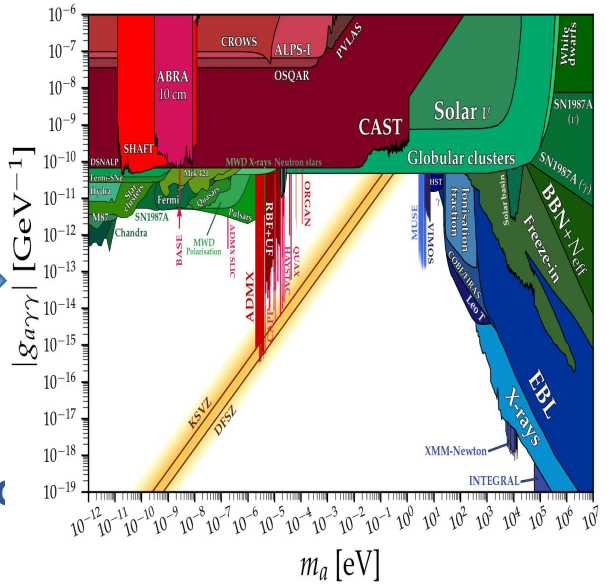

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Thank You!

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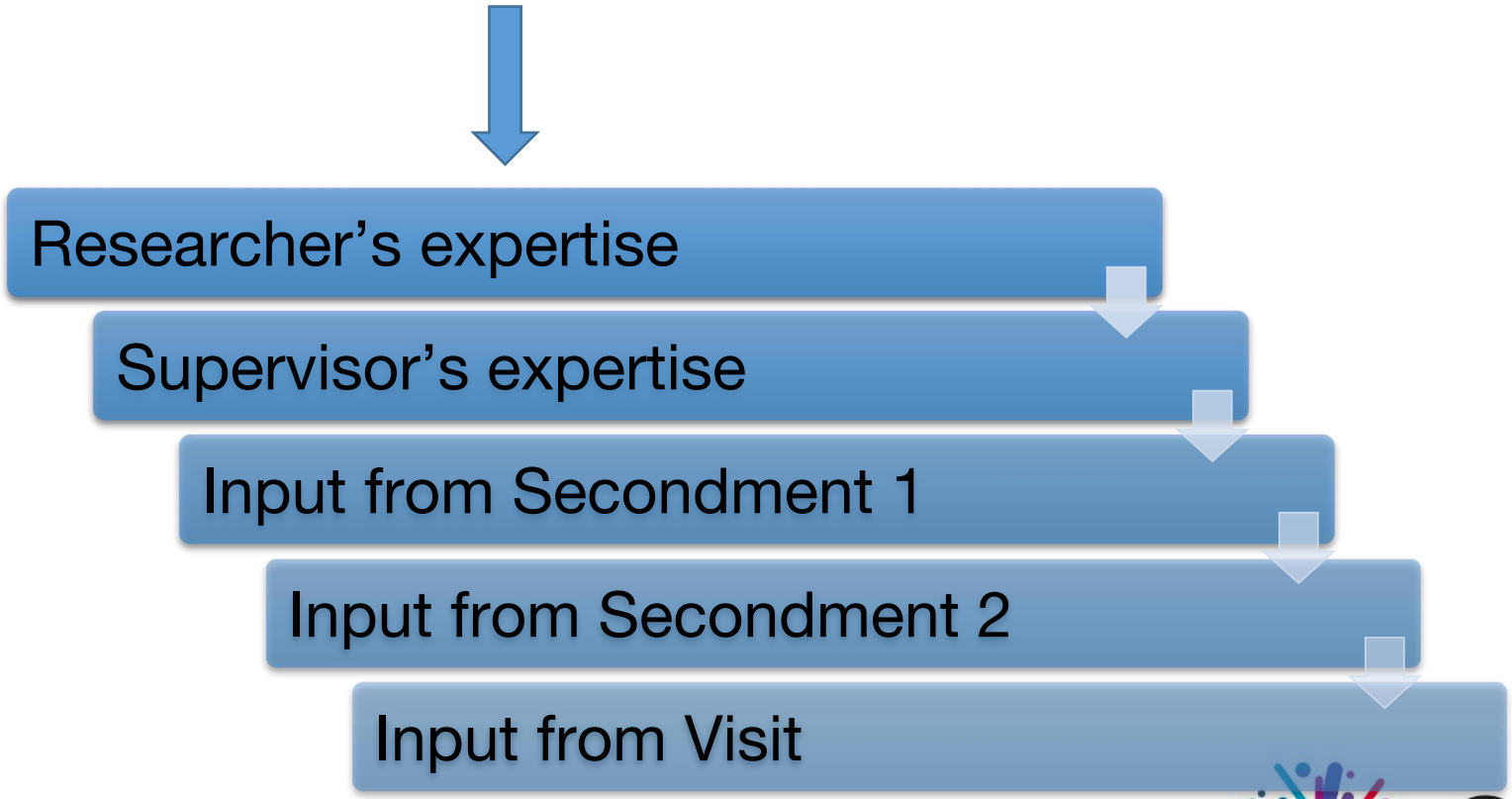
Interdisciplinary aspect within SMASH

- This interdisciplinary project **focused on the motivation for developing the project within SMASH**



Contribution to the broader scientific context

- The researcher will **develop an open-source pipeline/workflow for ALP studies with both LST-1 and CTA data.** The pipeline will be written in Jupyter Notebook and **will be uploaded to a public code repository, such as Github or Gitlab.**

- Our results will be useful for **several disciples of physicists, such as experimentalists, phenomenologists, theoreticians, etc.**

- The researcher will write the summary of the results as an **online blog to reach the boarder class of audiences** and to **encourage young minds, particularly from under-represented communities.**

- The researcher will positively take part in **outreach activities to communicate scientific knowledge to general audiences.**

- The researcher will participate in the **“Science for All” festival** that includes a variety of initiatives, labs and events engaging children, schools, families, and citizens.

Photons, ALPs & magnetic field

- Mixing occurs around the critical energy: $E_{crit} = 2.5\ GeV \frac{|m^2_{a,neV} - \omega^2_{pl,neV}|}{G_{11} B_{\mu G}}$
- Using the GammaALPs code by M. Meyer: https://gammaalps.readthedocs.io
  - Solves the equations of motion of photon–ALP system
  - Inputs: magnetic field models, EBL model, mass of ALPs , coupling to photons
  - Including the source (jet), galaxy cluster magnetic field, intergalactic magnetic field, EBL and back–conversion in Milky Way
- Parameter space to be searched (m_a , $g_{a\gamma}$) is determined by telescope's energy range, for IACTs;

$$10^{-9}\ \text{eV} \leq m_a \leq 10^{-6}\ \text{eV}$$

$$10^{-12}\ \text{GeV}^{-1} \leq g_{a\gamma} \leq 5 \times 10^{-10}\ \text{GeV}^{-1}$$

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