Probing the Parameter Space of Axion-Like Particles Using Simulation-Based Inference

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On behalf of CTAO Collaboration

Co-funded by the European Union

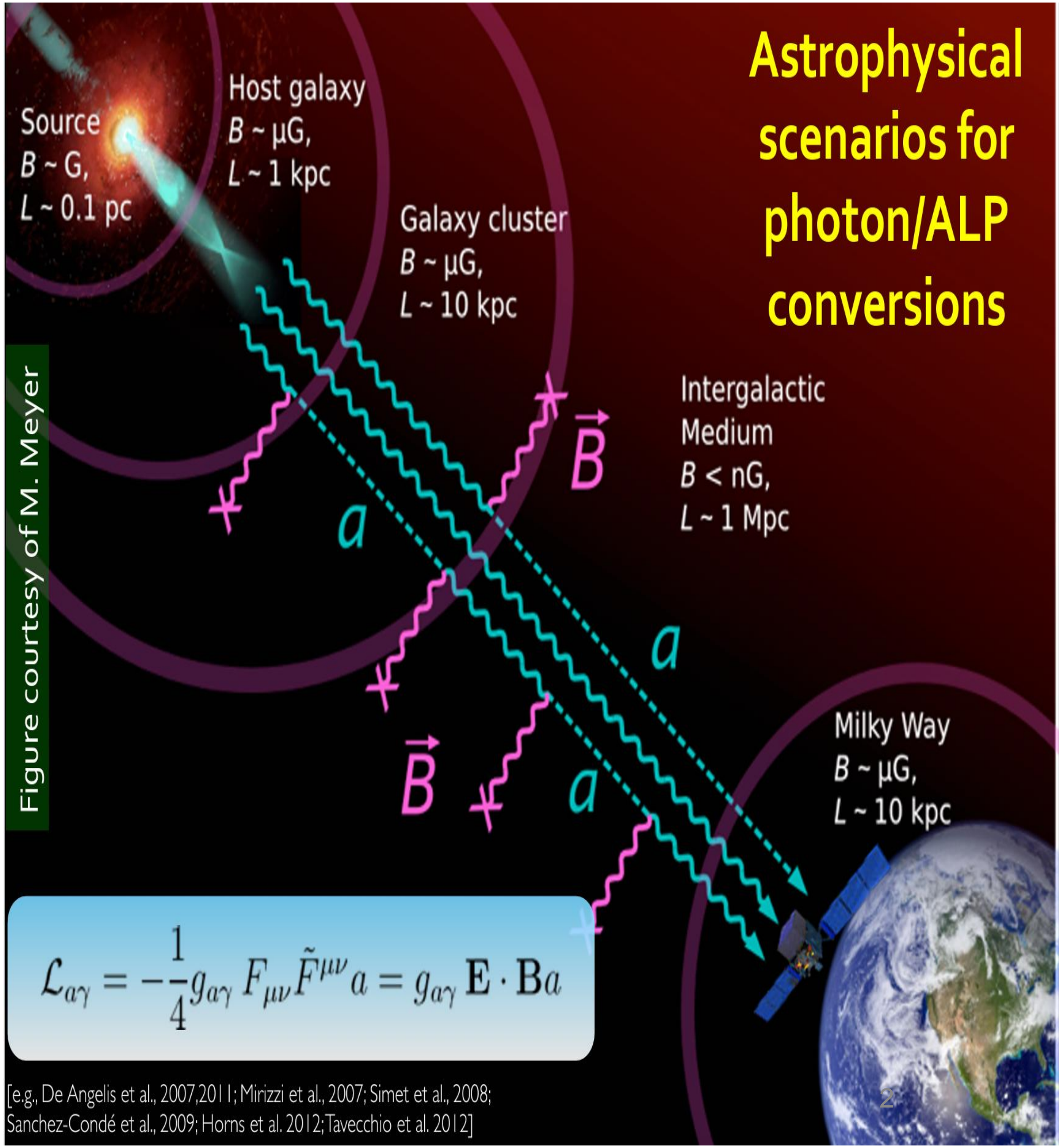
TeV Particle Astrophysics TeVPA 2026

Tendo Japan

August 30 - September 4, 2026

Outlook

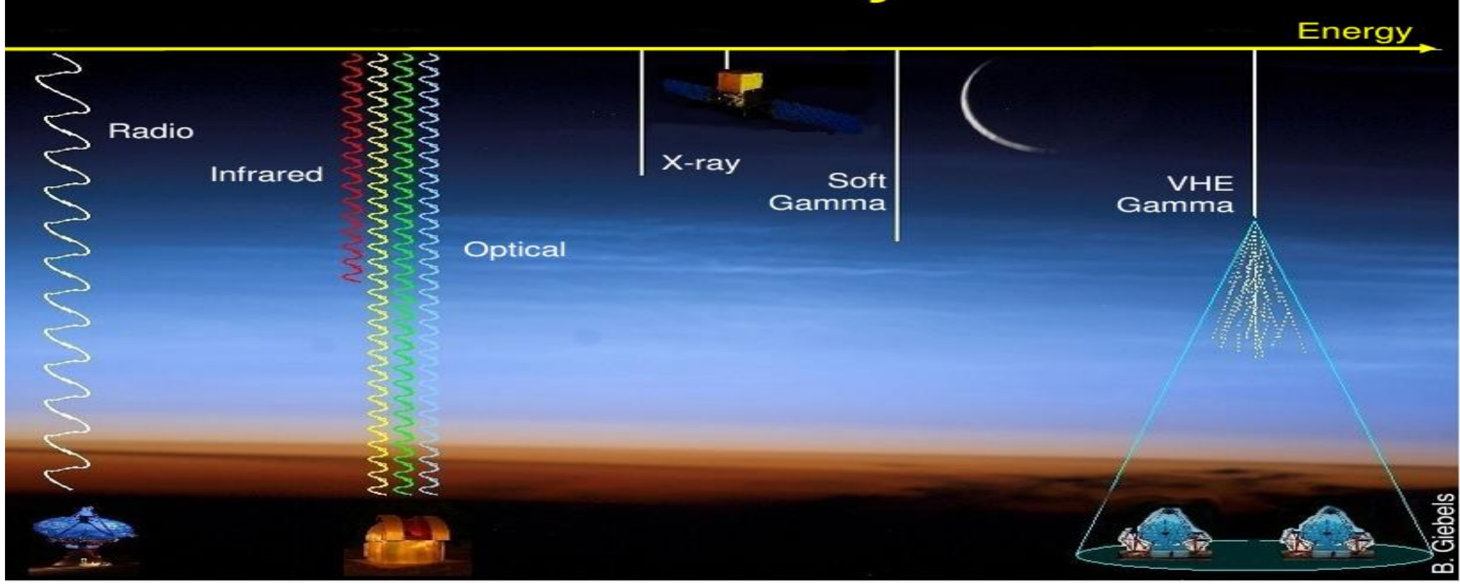
- **What are Axion-like particles (ALPs)**
- **How to detect ALPs**
- **Cherenkov Telescope Array Observatory (CTAO) and ALPs detection**
- **Advantage of Simulation-Based Inference (SBI)**
- **Current status and Future Prospects**



What are Axion-like Particles (ALPs)

- Axions were proposed by R. D. Peccei & H. Quinn, and later developed by S. Weinberg & F. Wilczek, **as new particles to address a long-standing puzzle in the strong force known as the Strong CP problem.**
- **Axion-like particles (ALPs) are extremely light, spin-zero, neutral particles.**
- Unlike axion, **ALPs have independent masses and couplings**, spanning significantly wider parameter space and making them compelling **candidates for dark matter.**
- In the presence of magnetic field, **ALPs oscillate into gamma rays** and could lead to irregularities in the spectra of astrophysical objects.

  → **Mixing/ "wiggles" happens near the critical energy, E_{crit}**, and is directly testable with current/future telescopes.

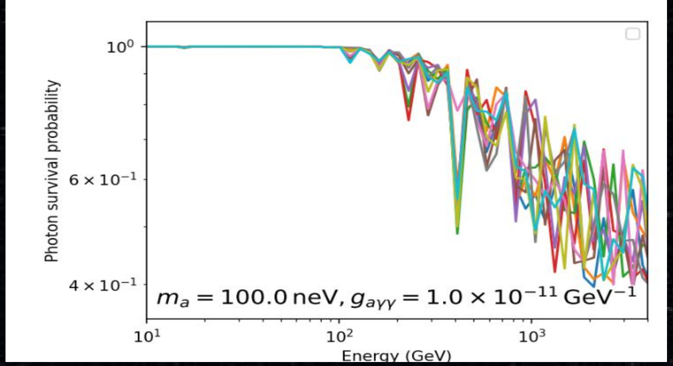


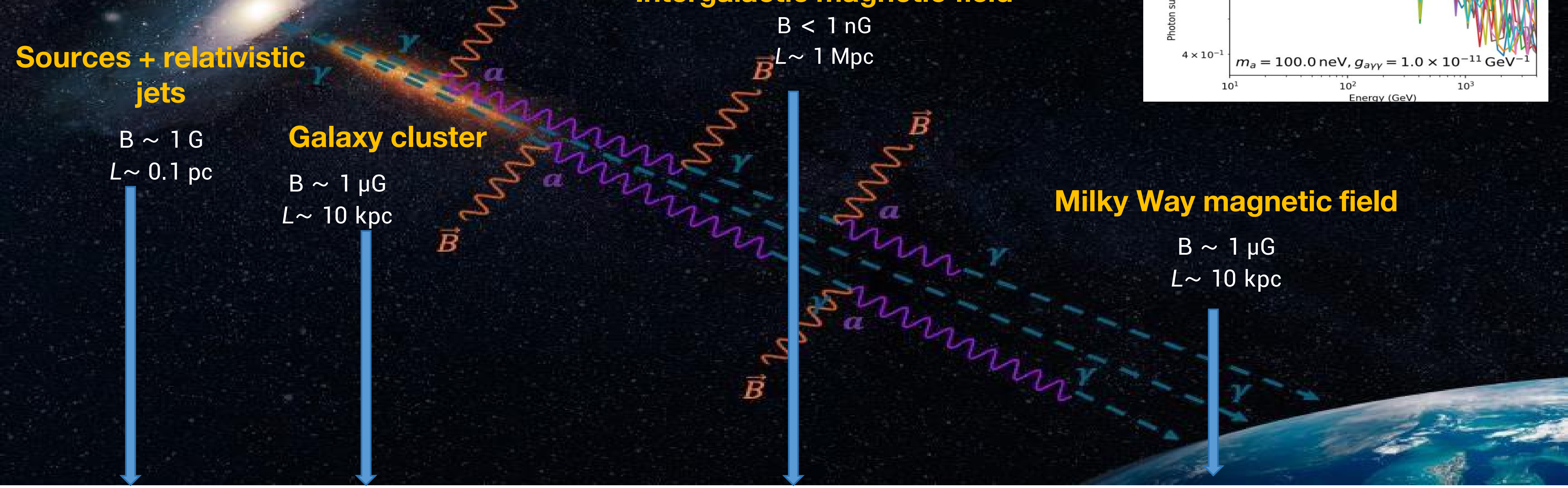
How to detect ALPs in very high energy (VHE) gamma rays

→ Understand how ALP-photon mixing occurs in external magnetic field

→ ALP with CTAO's Sensitivity

ALP-photon conversion in magnetic fields





Sources + relativistic jets

B ~ 1 G
L~ 0.1 pc

Galaxy cluster

B ~ 1 μG
L~ 10 kpc

Intergalactic magnetic field

B < 1 nG
L~ 1 Mpc

Milky Way magnetic field

B ~ 1 μG
L~ 10 kpc

Mixing is crucial for blazars, where jets are closely aligned with our line of sight.
Davies et al., PRD 103, 023008 (2021)

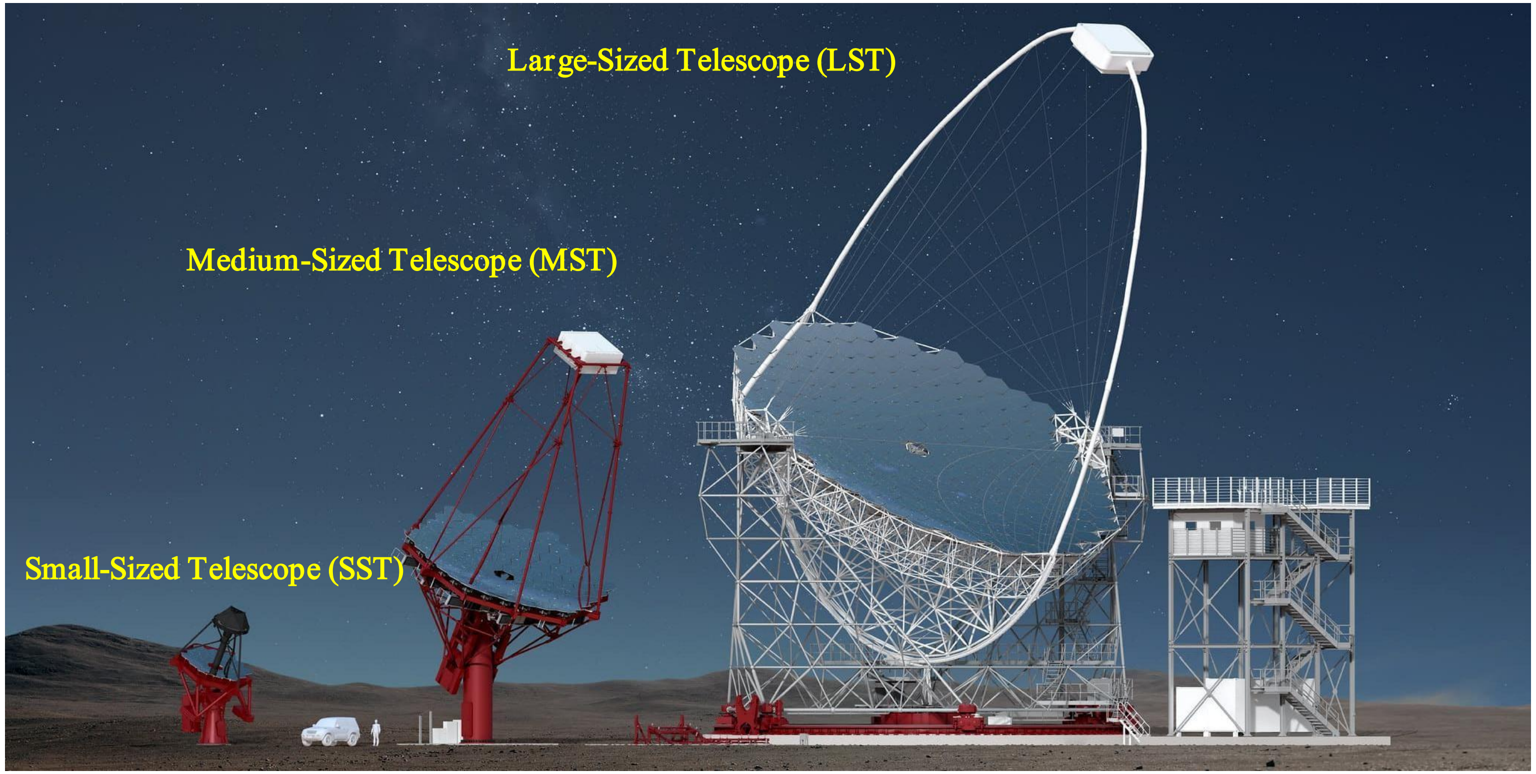
Gaussian turbulent random field (homogeneous, isotropic)
Meyer et al., JCAP 09 (2014) 003.

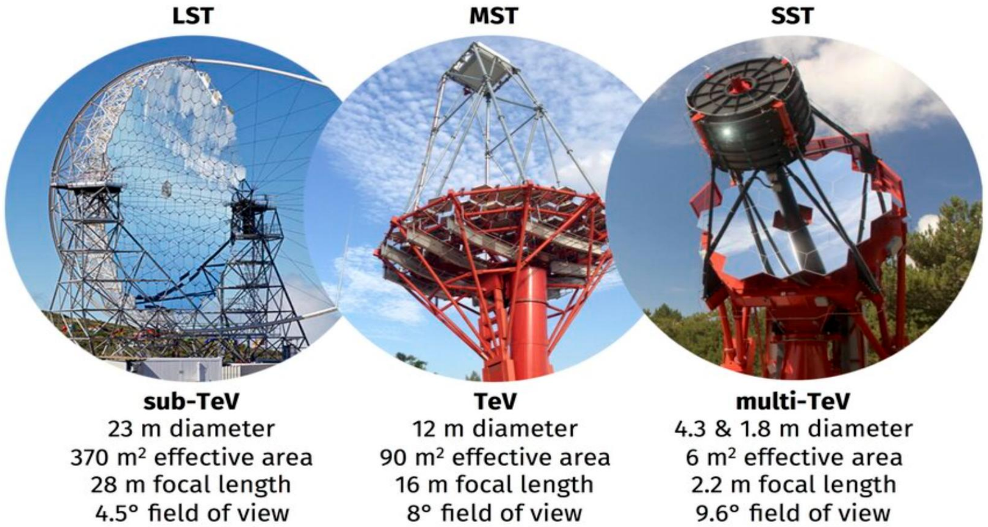
Weak field but its irregularity depends on target and distance. Extragalactic Background Light (EBL) also plays a role here
(A. Dominguez et. al, 2011)

Mixing occurs in the turbulent and regular component of stable Galactic magnetic field.
(Jansson & Farrar, 2012)

Cherenkov Telescope Array Observatory (CTAO)

- Next-generation gamma-ray observatory with two sites (La Palma & Paranal) covering 20 GeV–300 TeV.
- Consists of Large, Medium, and Small Telescopes to achieve broad energy coverage for full sky.
- 5–10× higher sensitivity than current IACTs.
- Better energy and spatial resolution, faster time response to transients.





https://www.ctao.org/for-scientists/technical-specifications/

Current status of our Neural Ration Estimation treatment for ALPs with CTAO

Targets

1) The Perseus Cluster- NGC 1275

2) Blazars:

- Mrk421
- Mrk501
- Bl Lac
- 1ES1959+650
- Joint

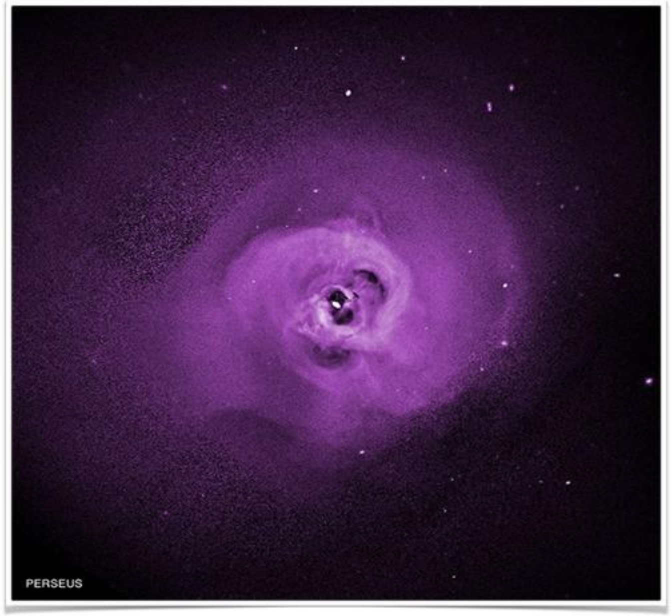
Target:
The Perseus Cluster and NGC 1275

■ The Perseus galaxy cluster is the brightest X-ray galaxy cluster in the sky, and is located at a **redshift of 0.0176** **(~75Mpc)**. It displays a dense population of electrons and a strong magnetic field at its core.

■ In its center, **Perseus hosts a very bright TeV-emitting radio galaxy: NGC 1275** which hosts a very bright Active Galactic Nucleus (AGN).

■ **Perseus cluster contains a strong magnetic field, as large as 25 μG** that makes it an excellent target to search for ultralight ALPs.

■ **Literature data available to test our trained network on ALP limits** from NGC 1275 - *[MAGIC collab., Phys.Dark Univ. 44 (2024)], [Fermi-LAT collab., PRL 116 (2016) 16], [The CTA Consortium; JCAP 02 (2021) 048]*



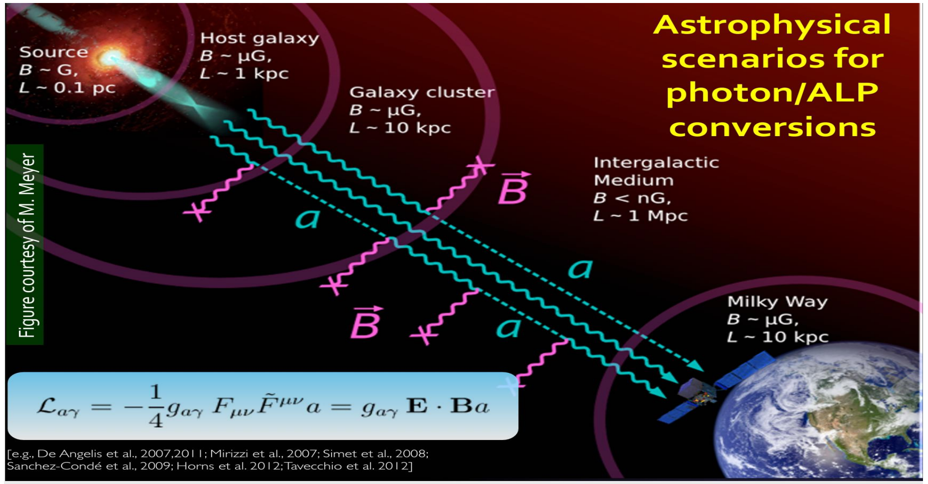
Perseus cluster in X-ray. Credit: NASA, Chandra

Target:

2) Blazars →

BL Lacertae objects (BL Lacs)

- Mrk 421 (z=0.031)
- Mrk 501 (z=0.034)
- Bl Lac (z=0.048)
- 1ES1959+650 (z=0.069)
- Joint



Why?

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

Simulation-Based Inference (Neural Ratio Estimation)

The Likelihood Ratio Trick

Given two distributions $p_1(\boldsymbol{x})$ and $p_{2}(\boldsymbol{x})$, where x_i is observed counts:

$\boldsymbol{x}_0, \boldsymbol{x}_2, \boldsymbol{x}_4, \boldsymbol{x}_6, \ldots \sim p_1(\boldsymbol{x})$

$\boldsymbol{x}_1, \boldsymbol{x}_3, \boldsymbol{x}_5, \boldsymbol{x}_7, \ldots \sim p_2(\boldsymbol{x})$

1. Draw many samples $(\boldsymbol{x}_i, m_i, g_i)$

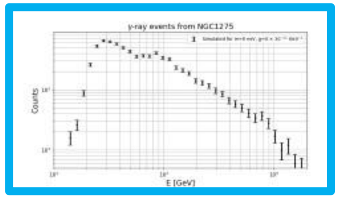
from $p(\boldsymbol{x}|m,g)p(m,g)$

i.e. Sample (m_i, g_i) from the prior $p(m,g)$, then simulate $\boldsymbol{x}_i$ from (m_i, g_i).

and from $p(\boldsymbol{x})p(m,g)$

i.e. Sample (m_j, g_j) from the prior $p(m,g)$, then simulate $\boldsymbol{x}_i$ from (m_j, g_j). Then draw (m_i, g_i) from the prior.

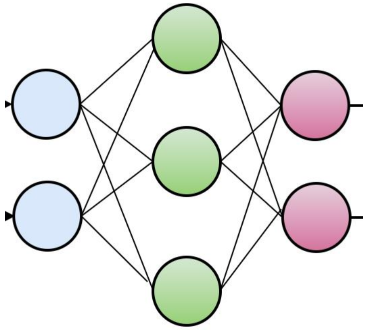
2. Train network to distinguish the samples

$\boldsymbol{x}_i =$ 

$m_i = 2$ neV

$g_i = 3 \times 10^{-11}$ GeV^{-1}

Input



Trained Neural network

Modified Output

$$\frac{p(\boldsymbol{x}_i \mid m_i, g_i)\ \cancel{p(m_i, g_i)}}{p(\boldsymbol{x}_i)\ \cancel{p(m_i, g_i)}} = \frac{p(m_i, g_i|\boldsymbol{x}_i)}{p(m_i, g_i)}$$

By Bayes' theorem

Posterior!

Prior

Vary m_i and g_i to scan parameter space

Posterior = Modified Output x Prior

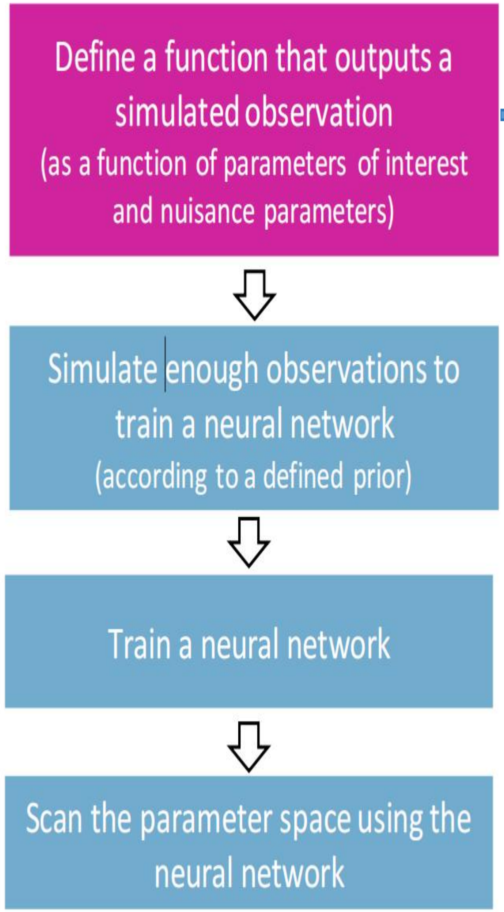
The quantity stored in Swyft's `logratios` is

$$\log r(\theta, x) = \log\left(\frac{d}{1-d}\right).$$

probability d $\in$ (0, 1), with binary cross-entropy loss ← d / (1 - d) = p1(x) / p2(x)

Credit: Gert Kluge, TeVPA, 2023

Analysis Workflow

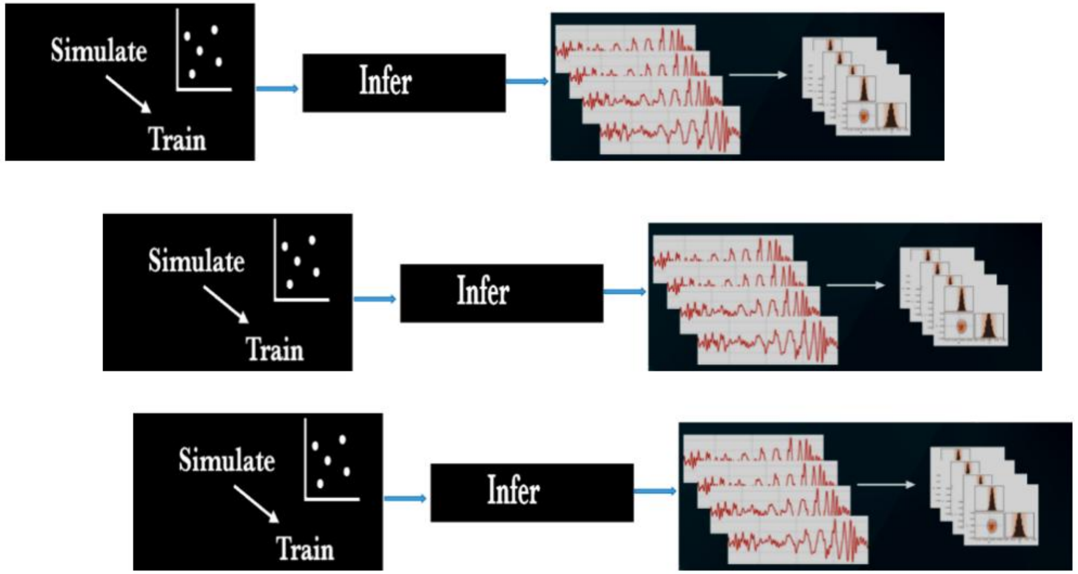


Credit: Gert Kluge, TeVPA, 2023

gammapy version:1.3
https://gammapy.org/
gammaALPs by Manuel Meyer
https://gammaalps.readthedocs.io/

SBI with **SWYFT** v0.4.0
https://swyft.readthedocs.io/en/stable/

Neural network trained on simulated spectra



Credit: James Alvey, EuCaifCon 2025

Setup:

~ 10^6 simulations used in training

Prior: uniform on log scale

Assumed observation time = 10 hr for flare and 300 hr for steady (baseline)

200 energy bins in range between 10 GeV and 100 TeV

Define a function that outputs a simulated observation (as a function of parameters of interest and nuisance parameters)

Parameters from ALP model

- ALP mass, m
- ALP coupling to photons, g
- NGC1275 intrinsic spectrum amplitude
- NGC1275 intrinsic spectral index
- NGC1275 intrinsic cut-off energy
- Magnetic field strength of NGC1275
- Magnetic field configuration
- Extension of Perseus cluster
- 7 electron density-related parameters
- 3 turbulence-related parameters

Parameters of interest (ALP mass, ALP coupling, NGC1275 intrinsic spectrum amplitude, spectral index, cut-off energy)

Nuisance parameters (intrinsic spectrum amplitude, spectral index, cut-off energy, magnetic field strength, magnetic field configuration, extension of Perseus cluster, electron density-related and turbulence-related parameters)

Simulated data

Search for imprints of ALPs in the simulated spectrum of targets

γ-rays spectra

×

Instrument response (**Prod5-North-20deg-AverageAz-4LSTs09MSTs.180000s-v0.1.fits.gz**)

×

Absorption from **EBL**

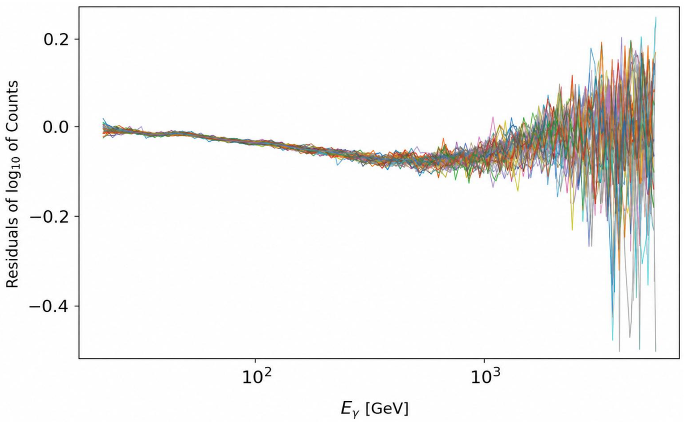
x

"Wiggles" from photon-ALP-oscillations

Residual of counts (ALP-No-ALP)+Poisson Noise, will be used as input while training.

Parameter of interest (Intrinsic + ALP)

ALP mass, ***ma*** **(vary)**
ALP coupling to photons, ***gaγ*** **(vary)** ①
Intrinsic spectrum amplitude **(vary)**
intrinsic spectral index **(vary)** ②
intrinsic cut-off energy **(fixed)**
Other Nuisance **(fixed)**



Results

For SBI:

- Data Recovery after training
- Coverage Test
- Exclusion limits on ALP parameter space
  - While varying only m_a and $g_{a\gamma}$ ①
  - While varying two additional nuisance parameters ②

Parameter of interest (Intrinsic + ALP)

ALP mass, m_a **(vary)**
ALP coupling to photons, $g_{a\gamma}$ **(vary)** } ①
Intrinsic spectrum amplitude **(vary)**
intrinsic spectral index **(vary)** } ②
intrinsic cut-off energy **(fixed)**
Other Nuisance **(fixed)**

Posterior plot - Data Recovery

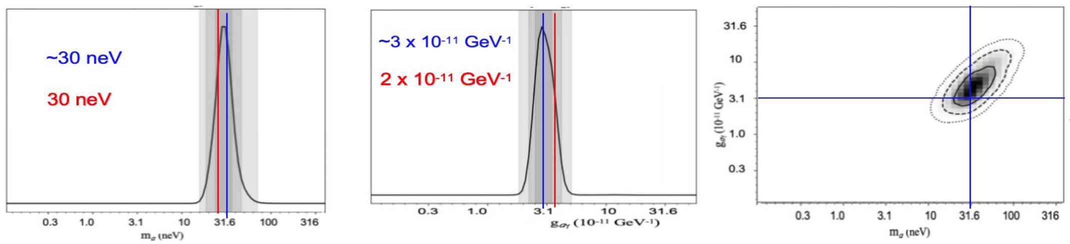
10^6 simulations used in training

PRELIMINARY

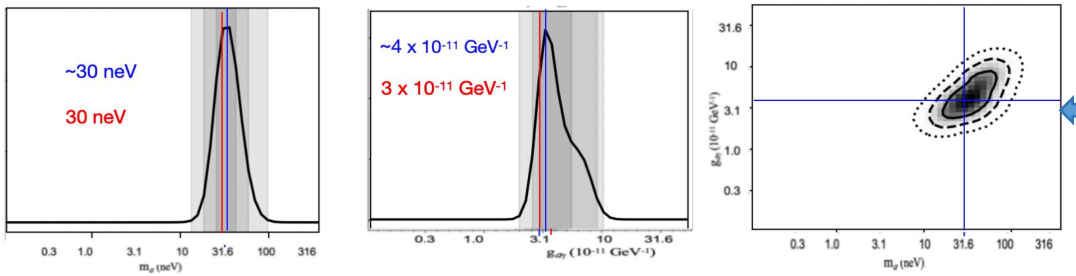
Only vary m_a and $g_{a\gamma}$

True Value
Posterior Peak

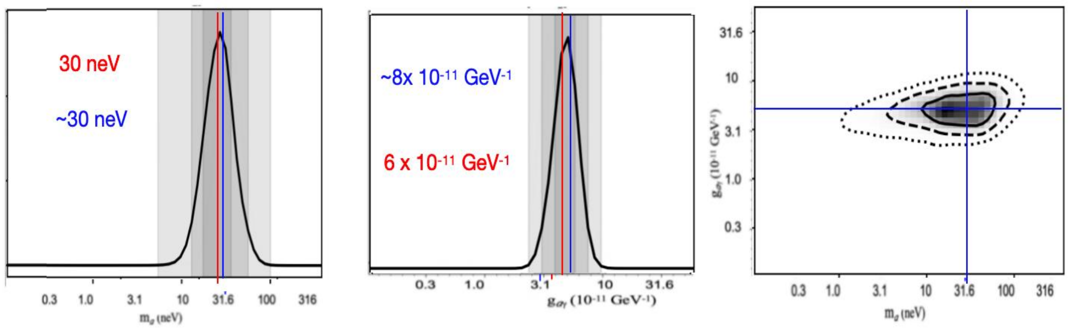
m_a and $g_{a\gamma}$ in uniform log-scale



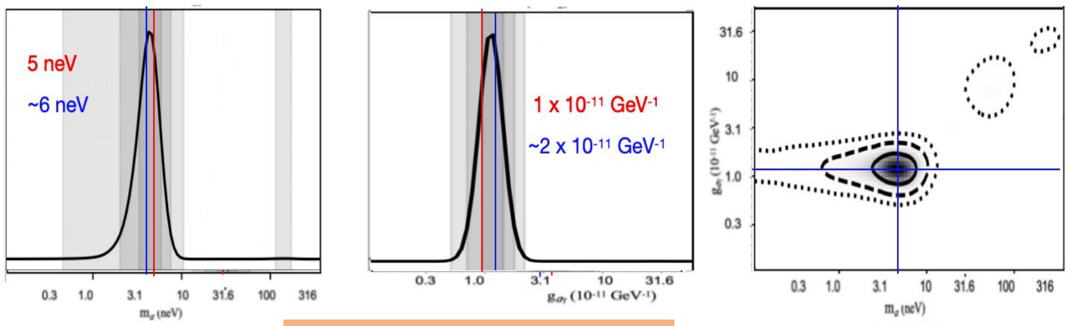
Mrk 421



Mrk 501

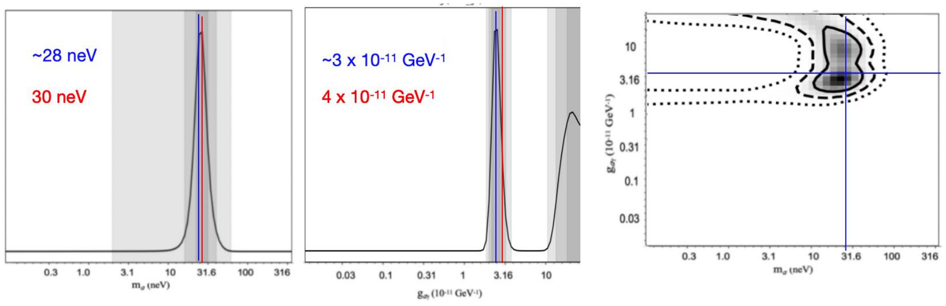


BL Lac

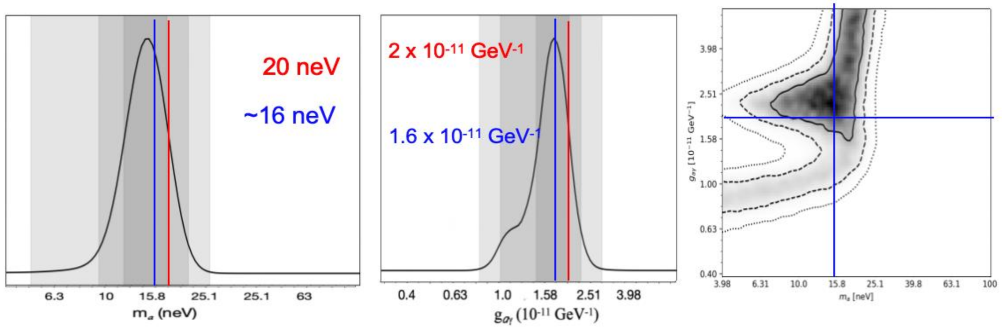


1ES1959+650

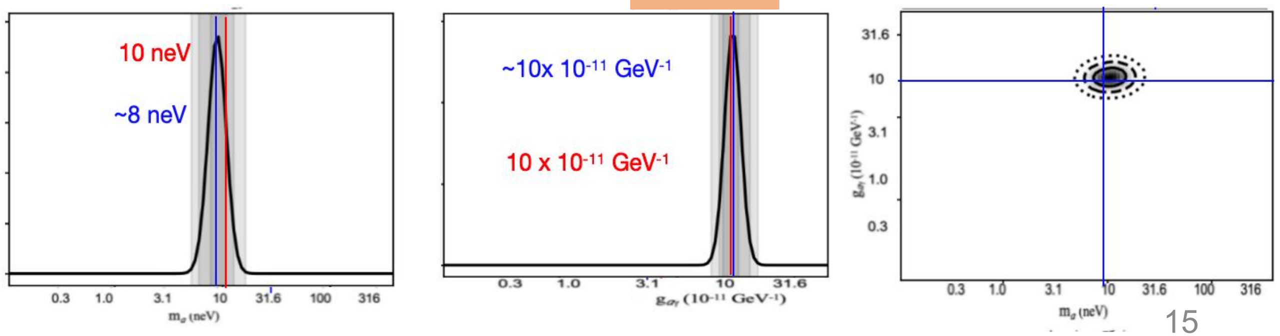
NGC 1275 Baseline



NGC 1275 Flare



Joint



Results

Posterior peaks near true values, seems to be sensitive in our chosen parameter space.

Coverage Test

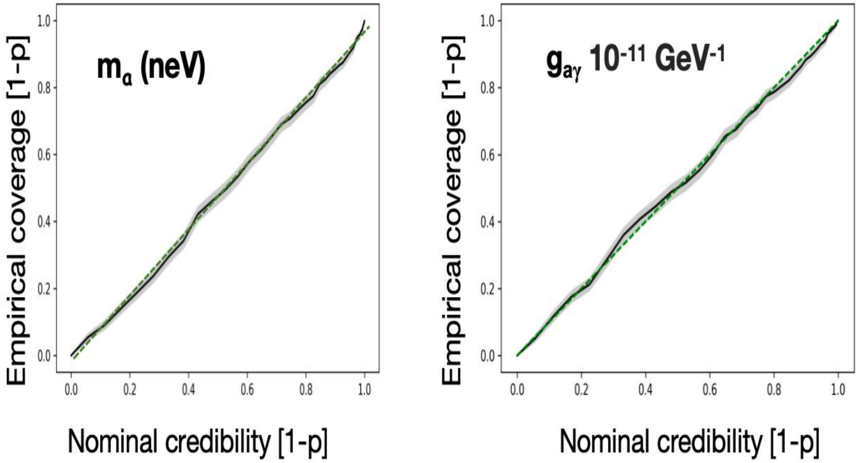
PP plot tracks the diagonal line well.

Only vary m_a and $g_{a\gamma}$

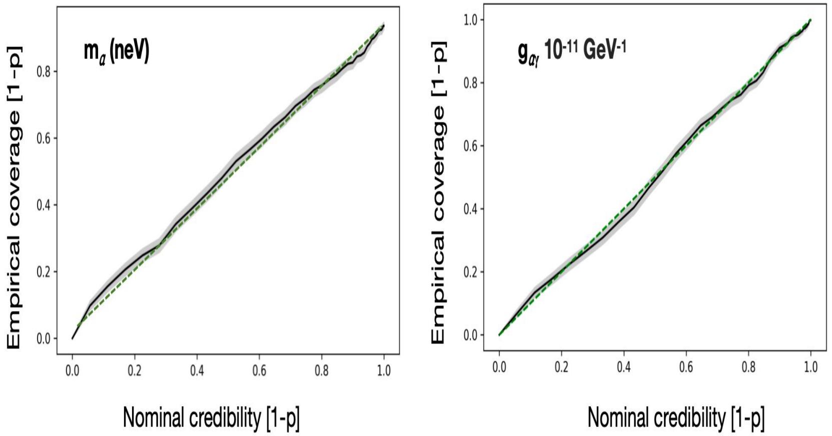
Expected Coverage Probability (ECP) test compares the empirical coverage of credibility regions to their nominal credibility.

PRELIMINARY

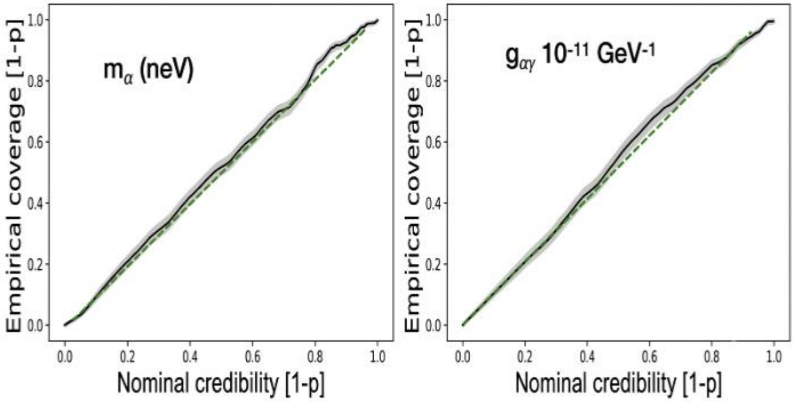
NGC 1275 -Flare



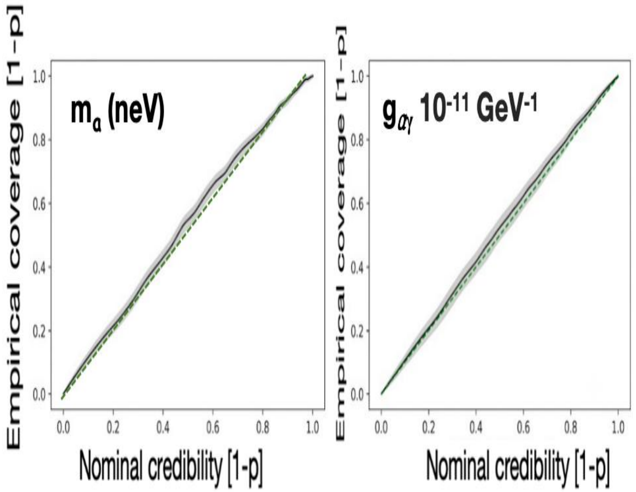
NGC 1275 -Baseline



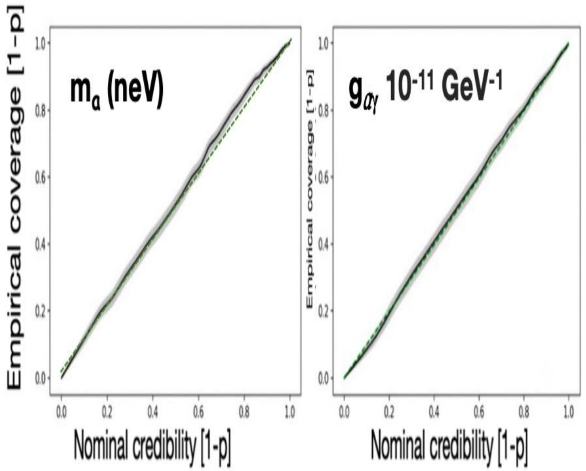
Joint



Mrk 421



Mrk 501



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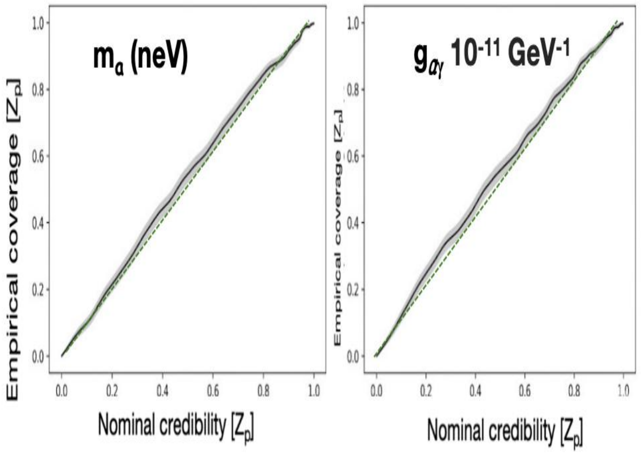
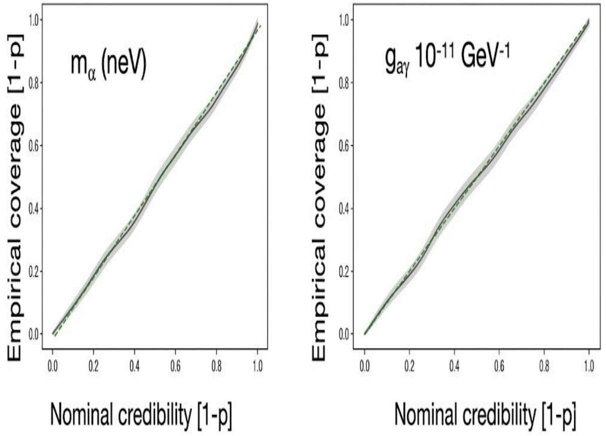


1ES1959+650



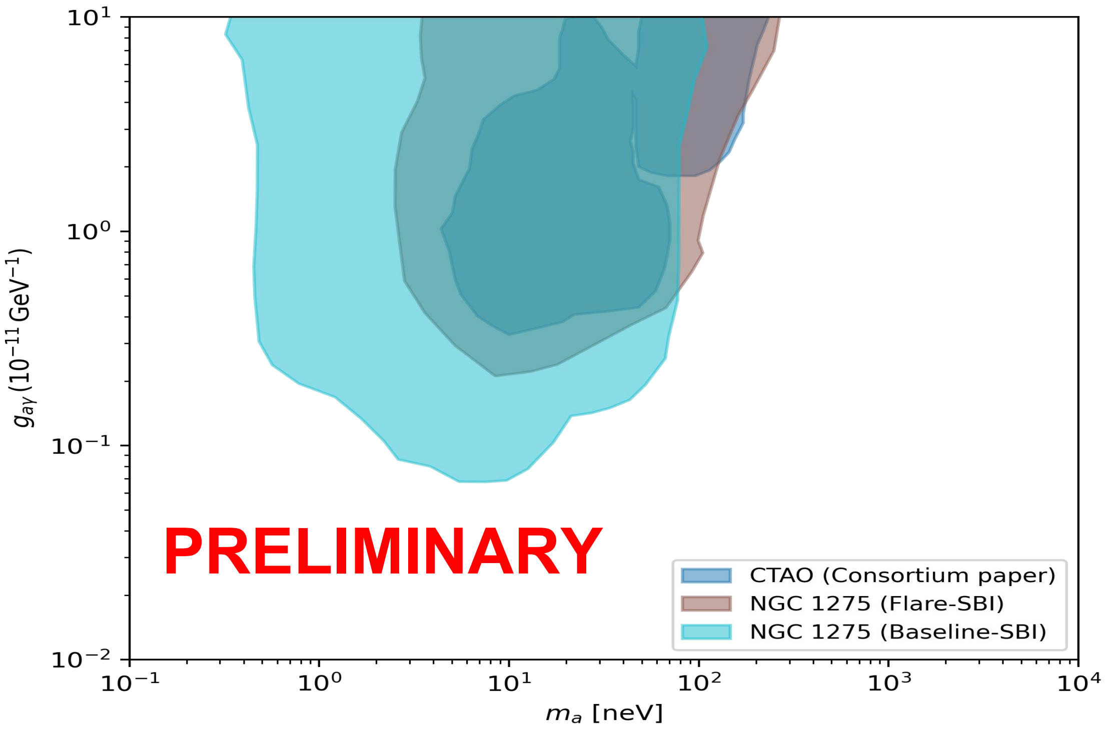
Results

Coverage test- The trained neural posterior estimator is well calibrated

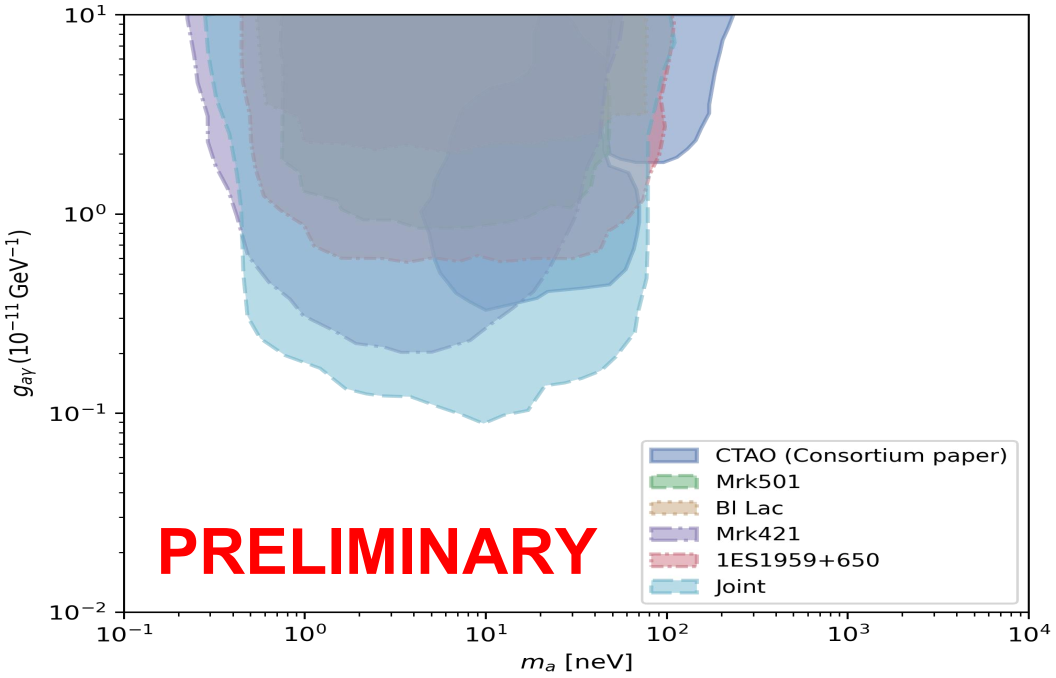
Exclusion limits

while varying m_a and $g_{a\gamma}$

NGC 1275



Blazars

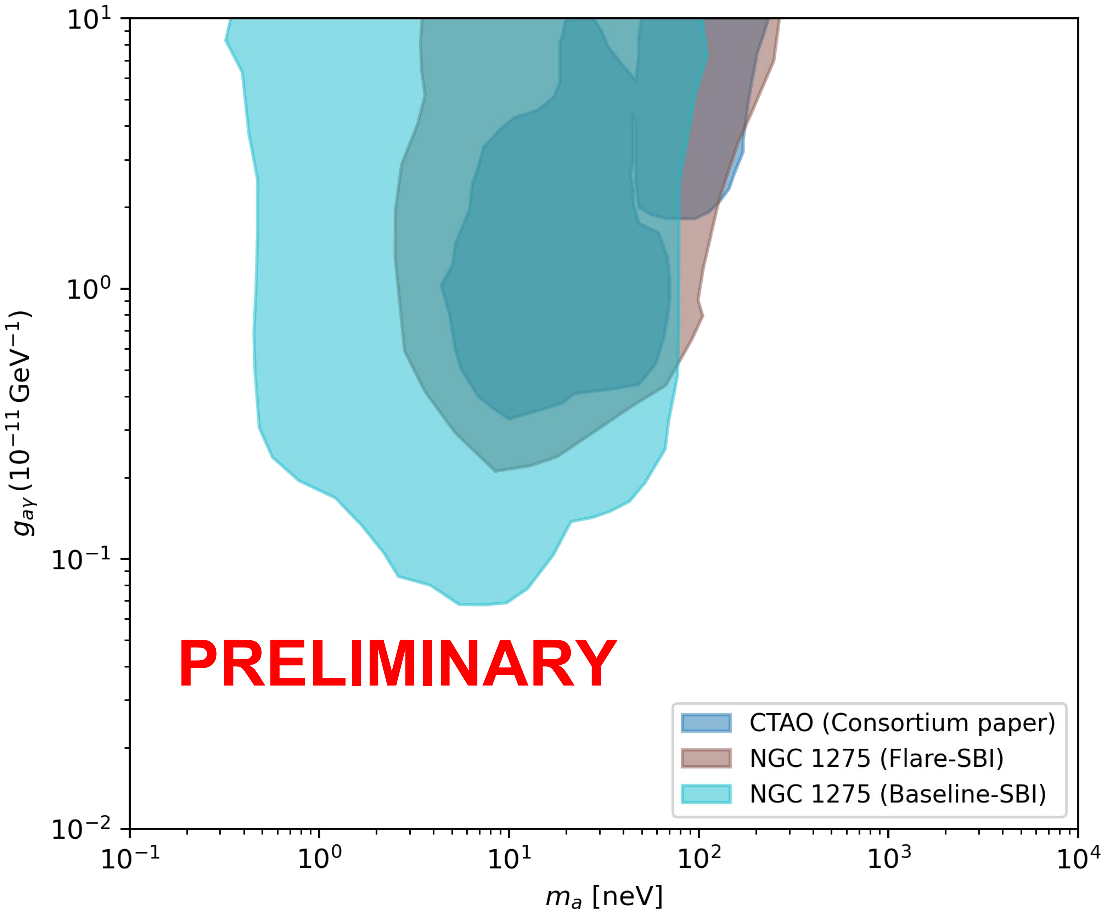


The larger exclusion relative to CTAO arises from **fixing nuisance parameters**, which reduces parameter degeneracies.

For SBI, **we get the exclusion plot from posterior pair plot for no-ALP case.**

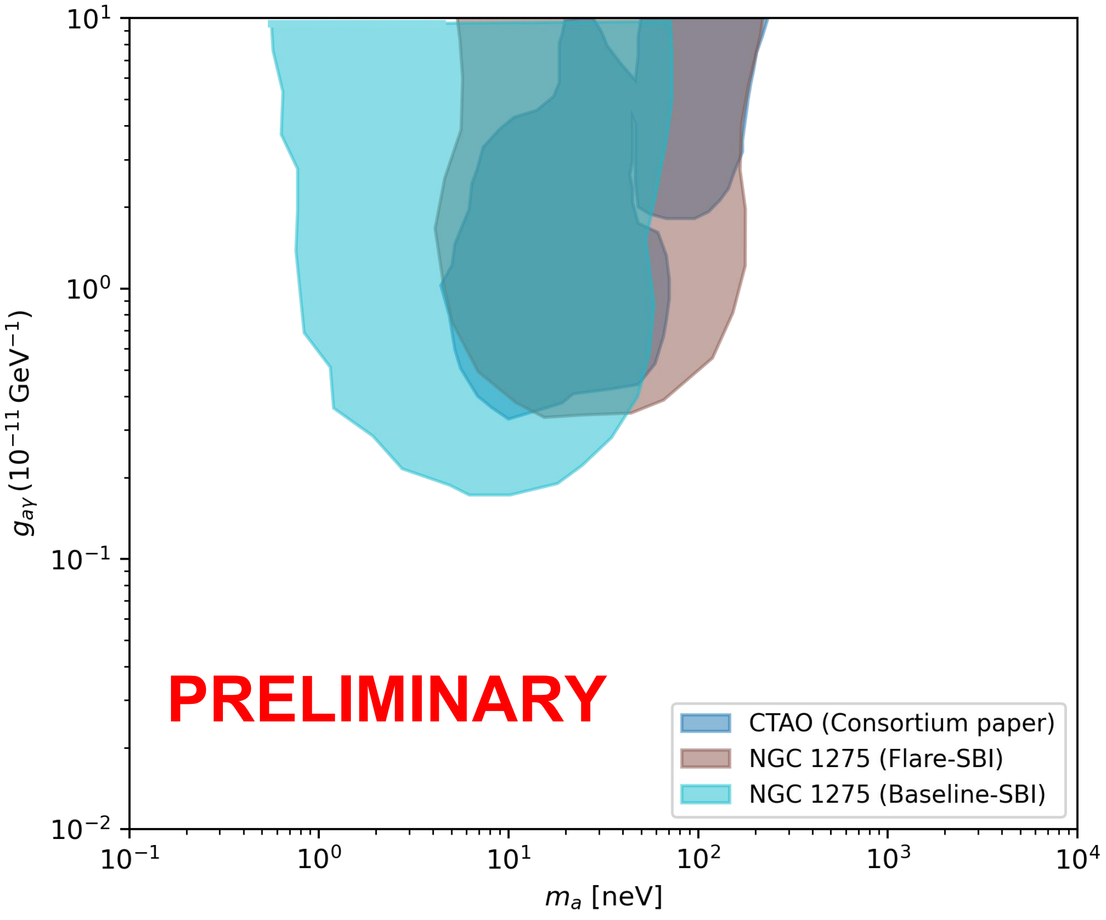
Exclusion limits - NGC 1275

vary m_a and $g_{a\gamma}$



1) Vary m_a and $g_{a\gamma}$ and

2) Nuisance parameters**, amplitude and spectral index/alpha**



Exclusion limits- Blazars

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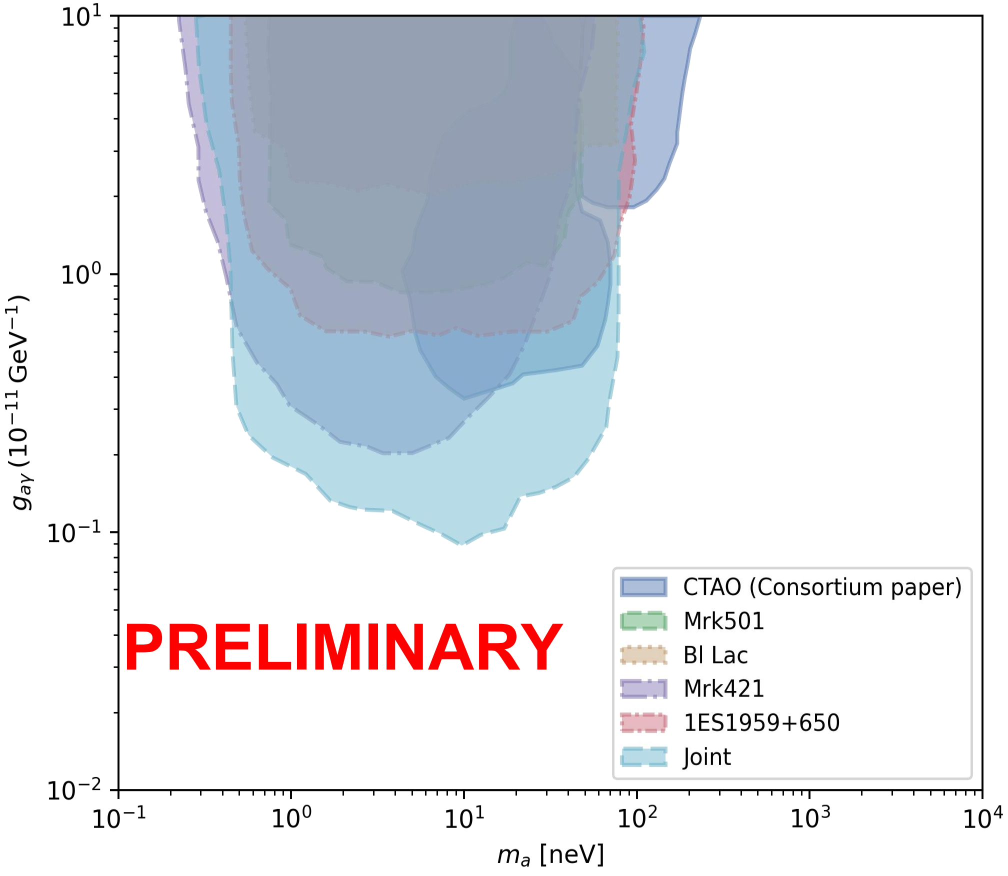

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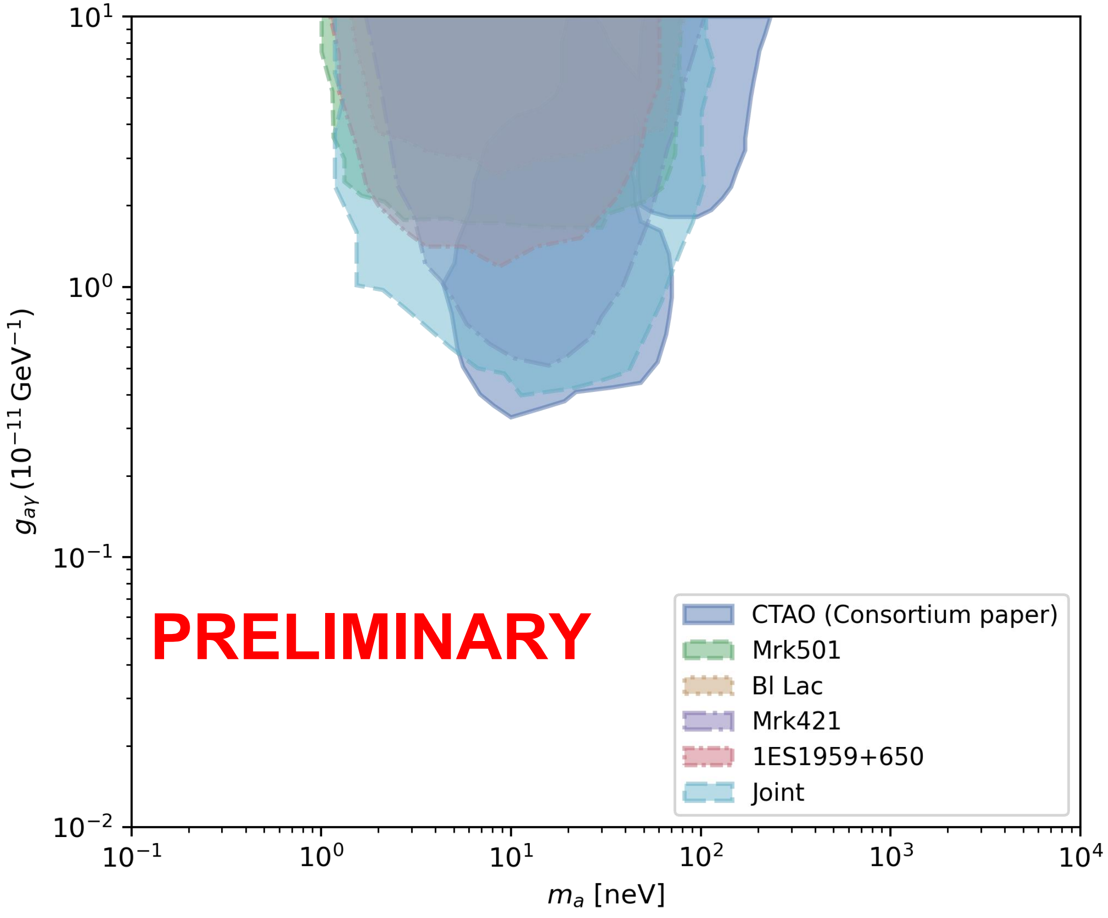


Results

Comparison- Exclusion limits

- **For NGC 1275 Flaring state, SBI exclusion limits (2σ) overlap with CTAO limits** reported by consortium paper, showing agreement between simulated constraints and CTAO sensitivity.

- The larger exclusion relative to CTAO arises from **fixing nuisance parameters**, which reduces parameter degeneracies. **Improvement is visible** by directly comparing the exclusion limits obtained **before and after including the nuisance parameters.**

- **Exclusion limits from NGC 1275 steady state and Blazars (joint)** provides complementary sensitivity for boarder parameter space.

- **The joint analysis combines the information from all blazars** and provides the **strongest overall constraint over a broad region of the ALP parameter space.**

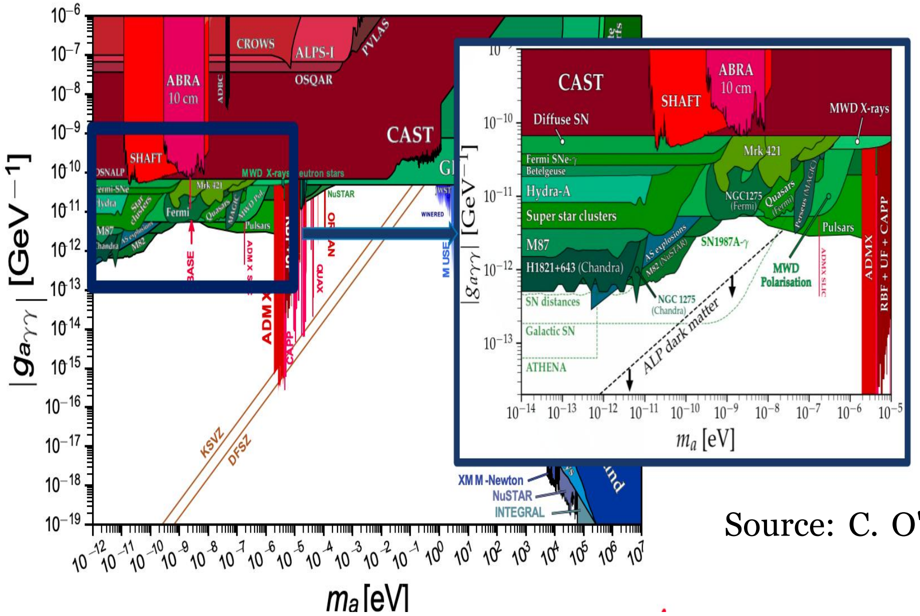
ALP searches - Future prospects

- ALP models are complex, with numerous nuisance parameters.
- Our preliminary results shows agreement between classical likelihood ratio test and SBI method for NGC 1275.
- SBI approach allows us to combining data from multiple targets and instruments to enhance sensitivity- something not easily achievable with a likelihood approach.

Next Step

- Check with different realization of magnetic fields.
- Check with other nuisance parameters
- Perform joint study for NGC 1275 and blazars.
- Draft is in preparation (CTAO non-consortium paper).

Final Limits



Source: C. O'Hare, github.com/cajohare/AxionLimits

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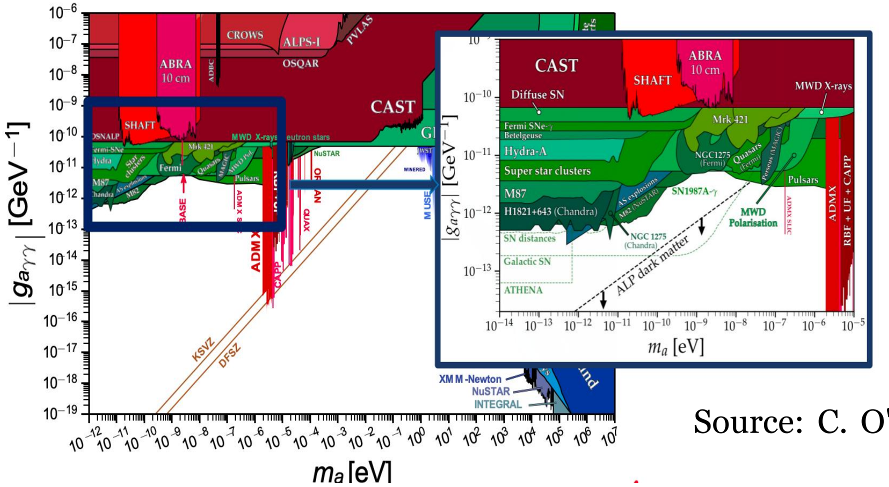


Source: C. O'Hare, github.com/cajohare/AxionLimits

Thank you for your attention!!!

Backup slides

Spectral model = Either flare/high state or baseline

CTAO consortium paper: JCAP 02 (2021) 048

NGC 1275 Flaring state

10 h of flaring states

Spectral_model = Exp cutoff power law x wiggles
EXPCustomSpectralModel(amplitude=1.54e^{-9} cm-2 s-1 TeV-1, reference=0.3 TeV, index=2.11, ecut=0.56 TeV,
m_a=m_a neV,
$g_{a\gamma}$=$g_{a\gamma}$ *10^{-11} GeV^{-1})

NGC 1275 Baseline

300 h of steady states

Spectral_model = PowerLawSpectral Model x wiggles
PLCustomSpectralModel(amplitude=2.11e^{-11} TeV^{-1} cm^{-2} s^{-1}, index=3.6, reference=0.2 TeV,
m_a=m_a neV,
g_a=" $g_{a\gamma}$ *10^{-11} GeV^{-1})

Mrk 421

10 h of flaring states

Spectral_model = LogParabolaSpectral Model x wiggles
LPCustomSpectralModel(amplitude=15.8e^{-10} TeV^{-1} cm^{-2} s^{-1}, alpha=2.02, beta=0.10, reference=0.3 TeV,
m=" m_a neV",
g=$g_{a\gamma}$ *10^{-11}GeV^{-1})

LST-1 paper,https://arxiv.org/pdf/2510.03702

Mrk 501

10 h of high states

Spectral_model = LogParabolaSpectral Model x wiggles
LPCustomSpectralModel(amplitude=3.53e^{-10} TeV^{-1} cm^{-2} s^{-1}, alpha=2.14, beta=0.12, reference=0.3 TeV,
m=" m_a neV",
g=$g_{a\gamma}$ *10^{-11}GeV^{-1})

1ES1959+650

10 h of high states

Spectral_model = LogParabolaSpectral Model x wiggles
LPCustomSpectralModel(amplitude=4.44e^{-10} TeV^{-1} cm^{-2} s^{-1}, alpha=2.28, beta=0.11, reference=0.3 TeV,
m=" m_a neV",
g=$g_{a\gamma}$ *10^{-11}GeV^{-1})

BL Lac

10 h of flaring states

Spectral_model = LogParabolaSpectral Model x wiggles
LPCustomSpectralModel(amplitude=4.05e^{-10} TeV^{-1} cm^{-2} s^{-1}, alpha=3.0, beta=0.10, reference=0.226 TeV,
m=" m_a neV",
g=$g_{a\gamma}$ *10^{-11}GeV^{-1})

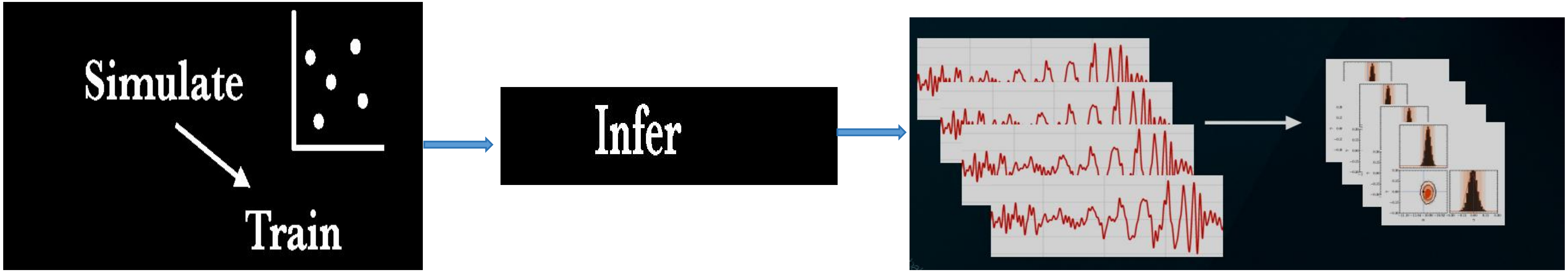
LST-1 paper,**https://arxiv.org/pdf/2309.09715**

Why Machine Learning (ML) Application for ALPs?

- **ALP-photon conversion** is strongly dependent on the **propagation environment and the treatment of the uncertainties of magnetic fields.**

- **Traditional Likelihood test often struggles** when we deal with a large number of parameters with uncertainties and biases our results. For a complex system like ALPs, it is not practically feasible without making significant simplifying assumptions, **which decrease the reliability of the inference.**

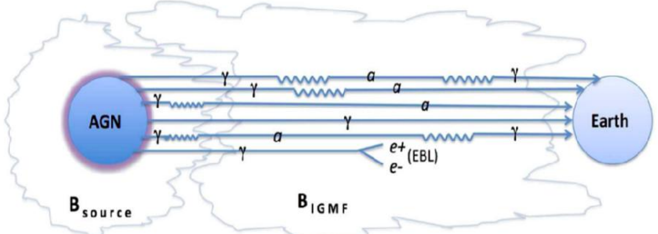
- To address this, we adopt **Simulation-Based Inference (SBI) using Truncated Marginal Neural Ratio Estimation (TMNRE)**, a likelihood-free approach suited to complex, nonlinear forward models.



Credit: James Alvey, EuCaifCon 2025

"Wiggles" from photon-ALP-oscillations

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



Parameters we need to calculate photon survival probability

gammapy version:1.3
https://gammaalps.readthedocs.io/

NGC 1275

```
ml.add_propagation("ICMGaussTurb",
                   0, # position of module counted from the source.
                   nsim=10, # number of random B-field realizations
                   B0=10.,  # rms of B field in muG
                   n0=3.9e-2,  # normalization of electron density in cm-3
                   n2=4.05e-3, # second normalization of electron density, see Churazov et a
                   r_abell=500., # extension of the cluster in kpc
                   r_core=80.,   # electron density parameter, see Churazov et al. 2003, Eq
                   r_core2=280., # electron density parameter, see Churazov et al. 2003, Eq
                   beta=1.2,  # electron density parameter, see Churazov et al. 2003, Eq. 4
                   beta2=0.58, # electron density parameter, see Churazov et al. 2003, Eq. 4
                   eta=0.5, # scaling of B-field with electron denstiy
                   kL=0.18, # maximum turbulence scale in kpc^-1, taken from A2199 cool-core
                   kH=9.,  # minimum turbulence scale, taken from A2199 cool-core cluster, s
                   q=-2.80, # turbulence spectral index, taken from A2199 cool-core cluster,
                   seed=0 # random seed for reproducability, set to None for random seed.
                  )
ml.add_propagation("EBL",1, eblmodel='dominguez') # EBL attenuation comes second, after bea
ml.add_propagation("GMF",2, model='jansson12') # finally, the beam enters the Milky Way Fie
```

B_0	n_0	n_2	r_{abell}	r_{core}	r_{core2}	β	β_2	η	k_L	k_H	q_B
μG	cm^{-3}	cm^{-3}	kpc	kpc	kpc				kpc^{-1}	kpc^{-1}	
10.	3.9×10^{-2}	4.05×10^{-3}	500.	80.	280.	1.2	0.58	0.5	0.18	9.	−2.80

Taken from **Ajello et al, 2016**

Blazars

```
ml.add_propagation("JetHelicalTangled",
                   0,  # position of module counted from the source.
                   ndom=400,
                   ft=0.7,  # fraction of magnetic field energy density in tangled field
                   Bt_exp=-1.,  # exponent of the transverse component of the helical field
                   r_T=0.3,  # radius at which helical field becomes toroidal in pc
                   r0=0.3, # radius where B field is equal to b0 in pc
                   B0=0.8, # Bfield strength in G
                   n0=1.e4,  # electron density at r0 in cm**-3
                   rjet=98.3e+3,  # jet length in pc
                   rvhe=0.3, # distance of gamma-ray emission region from BH in pc
                   alpha=1.68,  # power-law index of electron energy distribution function
                   l_tcor='jetwidth',  # tangled field coherence average length in pc if a c
                   #jwf = 1.,  # jet width factor used when calculating l_tcor = jwf*jetwidt
                   jwf_dist='Uniform' # type of distribution for jet width factors (jwf)
                  )
```

Source	z	RA [deg]	Dec [deg]	r_0 [pc]	B_0 [G]	g_{max}	g_{min}	n_0 [cm^{-3}]	r_{jet} [pc]	α_e
Mrk 421	0.031	166.11	38.21	6.02	0.03	12	9	8.5×10^3	9.731×10^3	1.55
Mrk 501	0.034	253.47	39.76	0.3	0.8	9	2	4.5×10^4	3.240×10^3	1.68
1ES1959+650	0.048	299.99	65.15	0.96	1.88	8	5	7.2×10^2	3.241×10^4	1.6
BL Lac	0.069	330.68	42.28	0.12	2.68	8	5	8.0×10^5	1.620×10^4	1.95

Taken from **Tavecchio et al, 2010, and Potter & Cotter, 2015**

Coverage Test

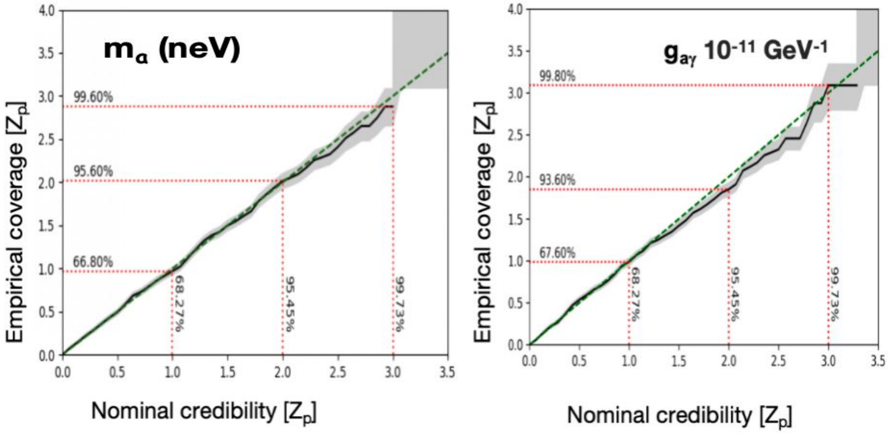
ZZ plot

vary ma and gaγ

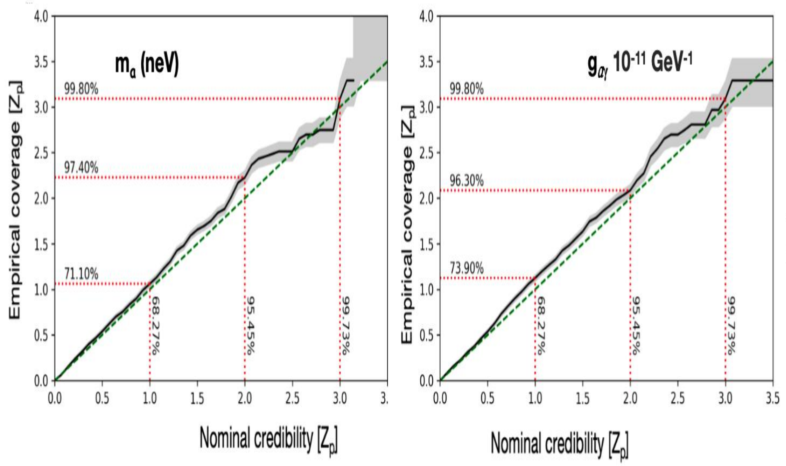
Z--Z plots confirm that the inferred posteriors remain well calibrated up to the high-credibility region.

PRELIMINARY

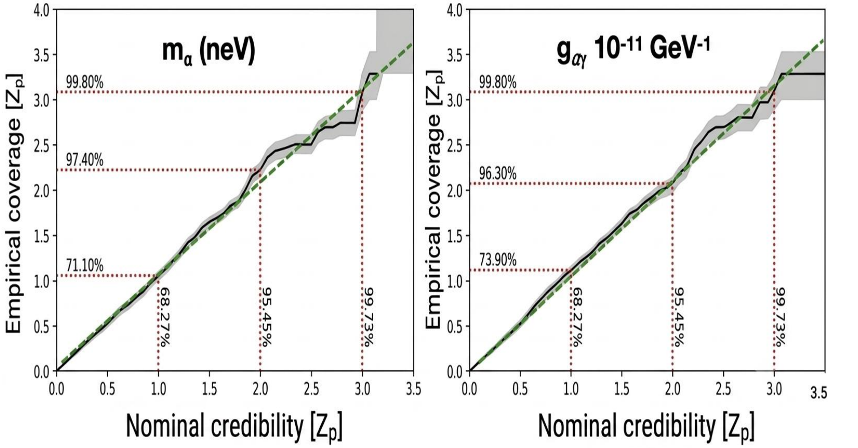
NGC 1275 -Flare



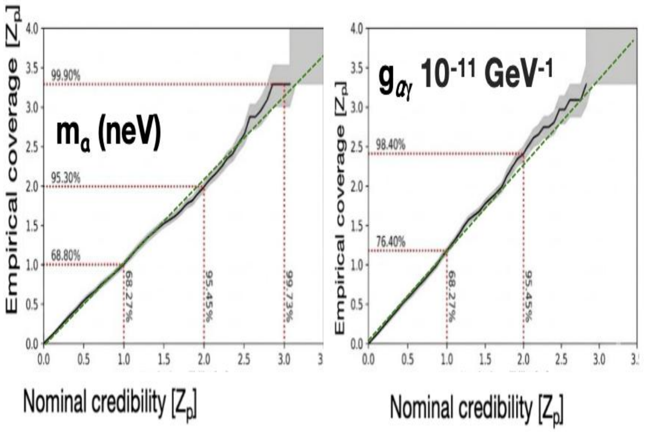
NGC 1275 -Baseline



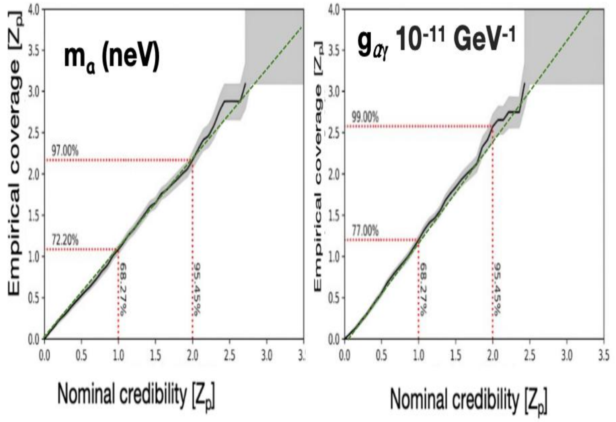
Joint



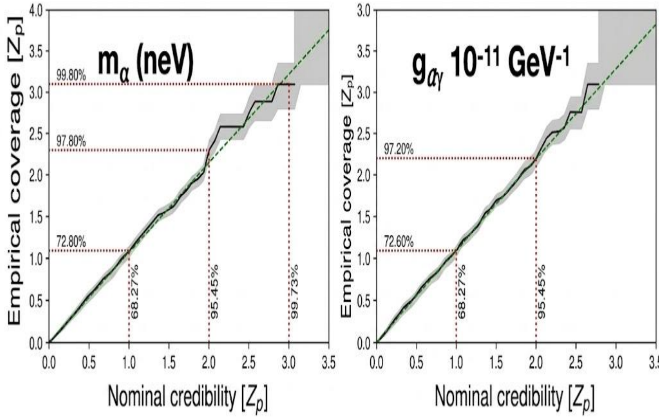
Mrk 421



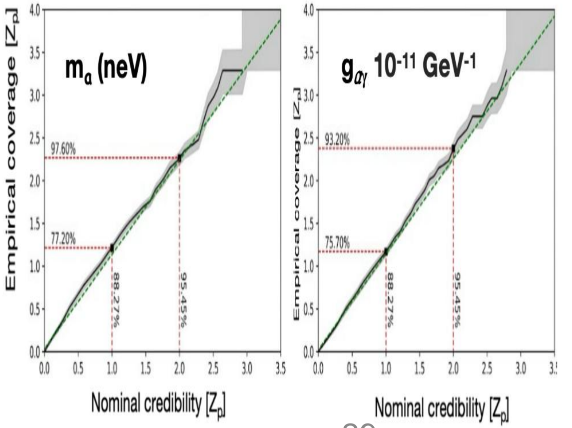
Mrk 501



BL Lac



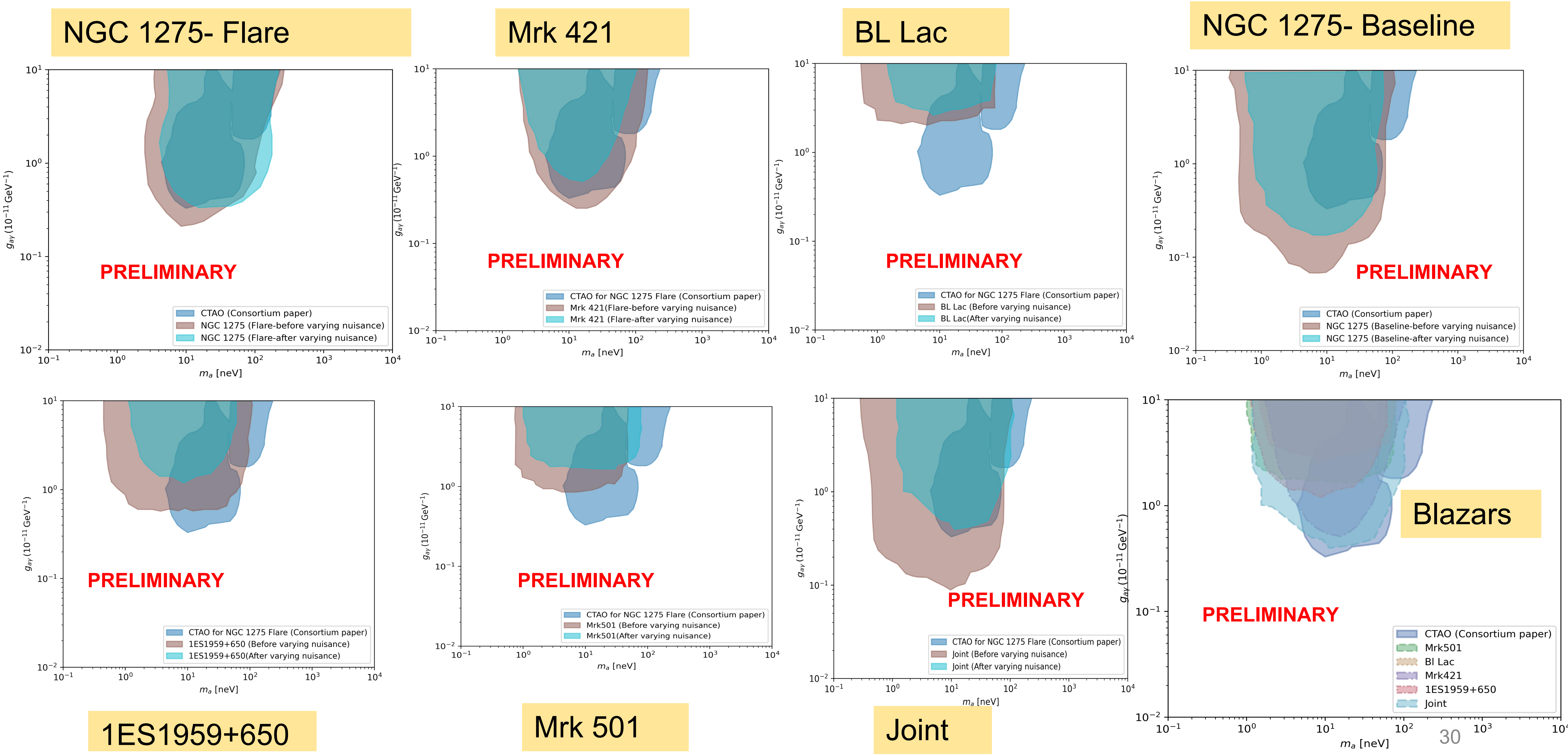
1ES1959+650



Exclusion limits

1) Vary m_a and $g_{a\gamma}$ and

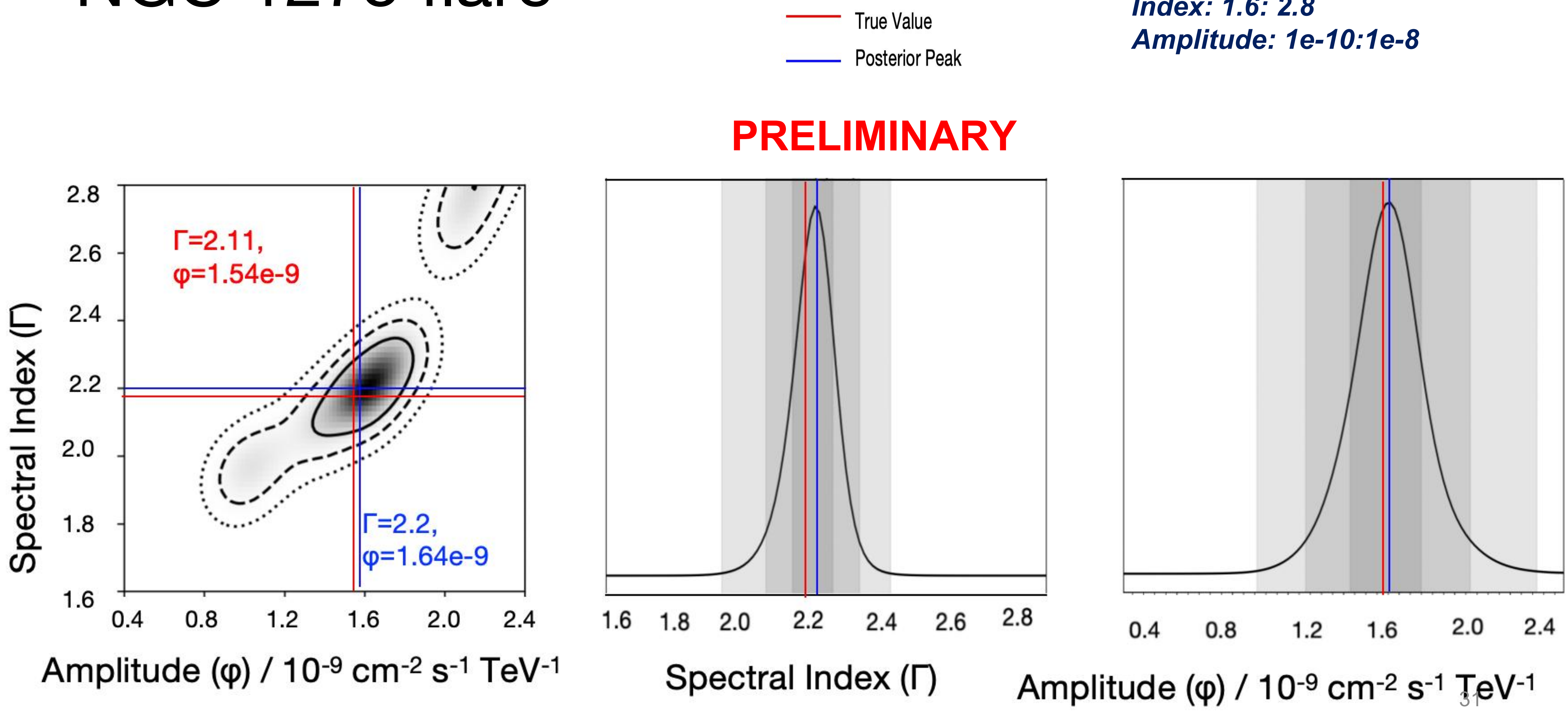
2) Nuisance parameters, **amplitude and spectral index/alpha**



Posterior for nuisance parameter NGC 1275 flare

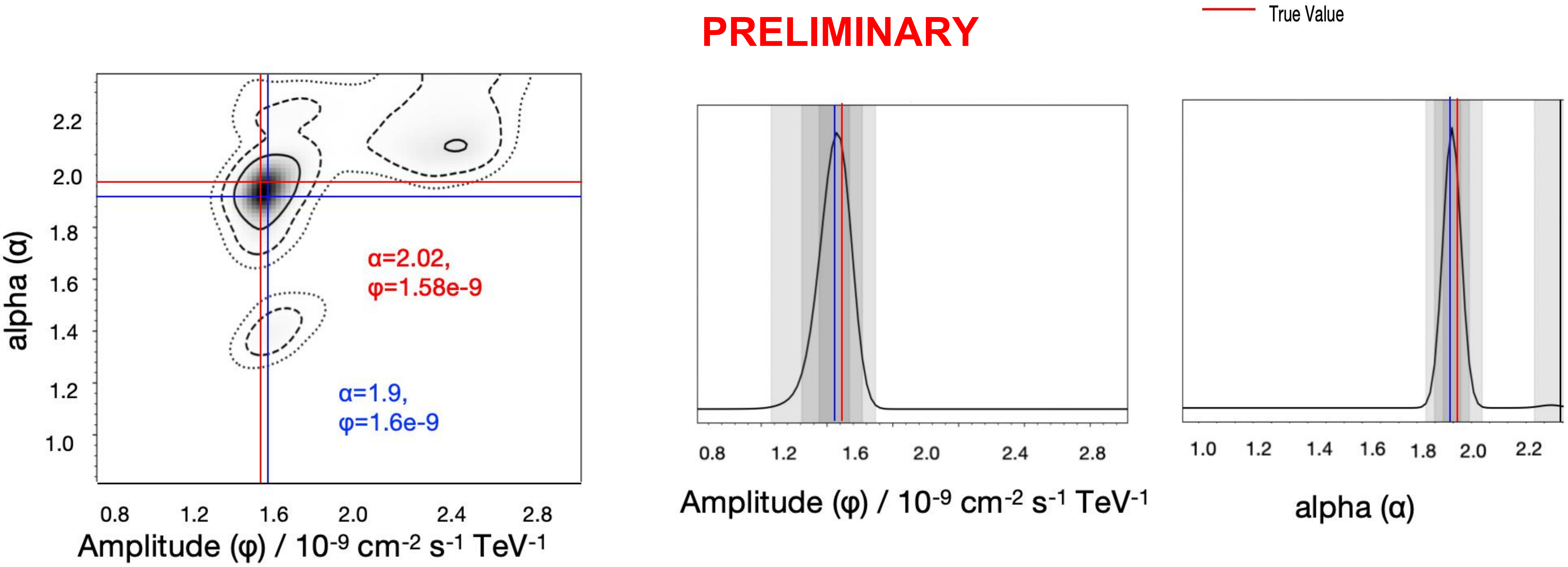
ma: [0.1: 400] neV
gaγ: [0:01: 20] 10^{-11} GeV^{-1}
Index: 1.6: 2.8
Amplitude: 1e-10:1e-8

PRELIMINARY

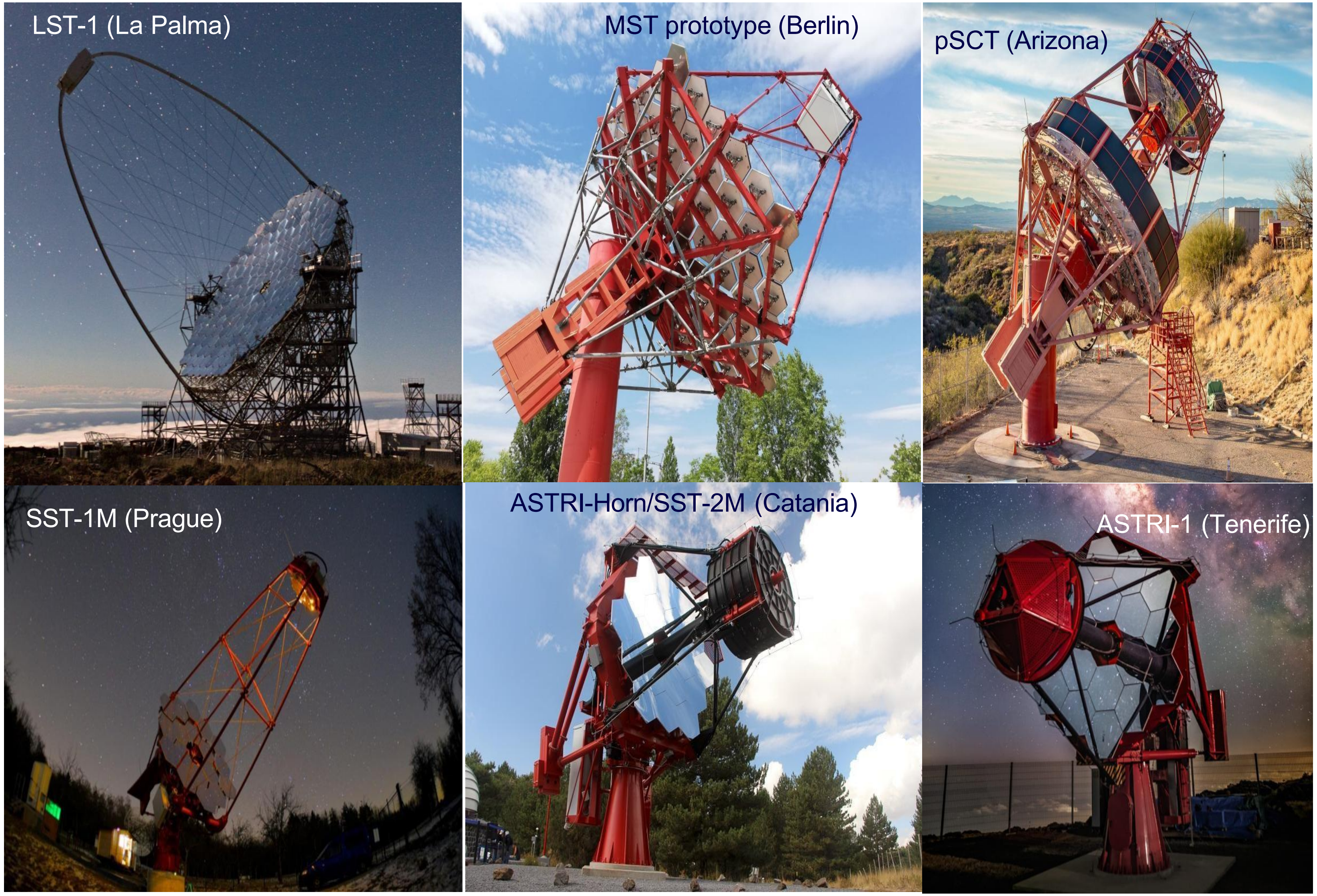


posterior for nuisance parameter Mrk 421

m_a: [0.1: 400] neV
$g_{a\gamma}$: [0:01: 50] 10^{-11} GeV^{-1}
Alpha: 0.8: 3.0
Amplitude: 1e-10:1e-8



CTAO prototypes at different location



Sites Locations

- LST-1 in La Palma
- MST prototype in Berlin
- ASTRI-Horn/SST-2M in Catania
- ASTRI-1 in Tenerife
- SST-1M in Prague
- Schwarzschild-Couder Telescope prototype (pSCT) in Arizona, US

Simulation-Based Inference (Neural Ratio Estimation)

Given two distributions $p_1(\boldsymbol{x})$ and $p_{2}(\boldsymbol{x})$, where *xi* is observed counts:

$\boldsymbol{x}_0, \boldsymbol{x}_2, \boldsymbol{x}_4, \boldsymbol{x}_6, \ldots \sim p_1(\boldsymbol{x})$

$\boldsymbol{x}_1, \boldsymbol{x}_3, \boldsymbol{x}_5, \boldsymbol{x}_7, \ldots \sim p_2(\boldsymbol{x})$

1. Draw many samples $(\boldsymbol{x}_i, m_i, g_i)$

from $p(\boldsymbol{x}|m, g)p(m, g)$

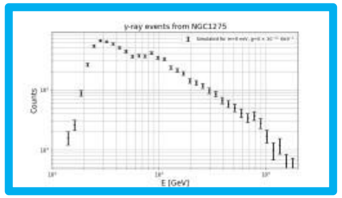
i.e. Sample (m_i, g_i) from the prior $p(m, g)$, then simulate $\boldsymbol{x}_i$ from (m_i, g_i).

2. Train network to distinguish the samples

and from $p(\boldsymbol{x})p(m, g)$

i.e. Sample (m_j, g_j) from the prior $p(m, g)$, then simulate $\boldsymbol{x}_i$ from (m_j, g_j). Then draw (m_i, g_i) from the prior.

$\boldsymbol{x}_i =$

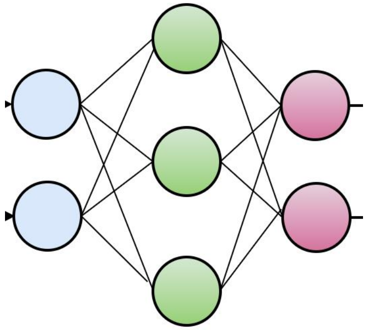


$m_i = 2$ neV

$g_i = 3 \times 10^{-11}$ GeV^{-1}

Vary m_i and g_i to scan parameter space

Input



Neural network

Modified Output

$$\frac{p(\boldsymbol{x}_i \mid m_i, g_i)}{p(\boldsymbol{x}_i)} \text{ x Prior} = \textbf{Posterior!}$$

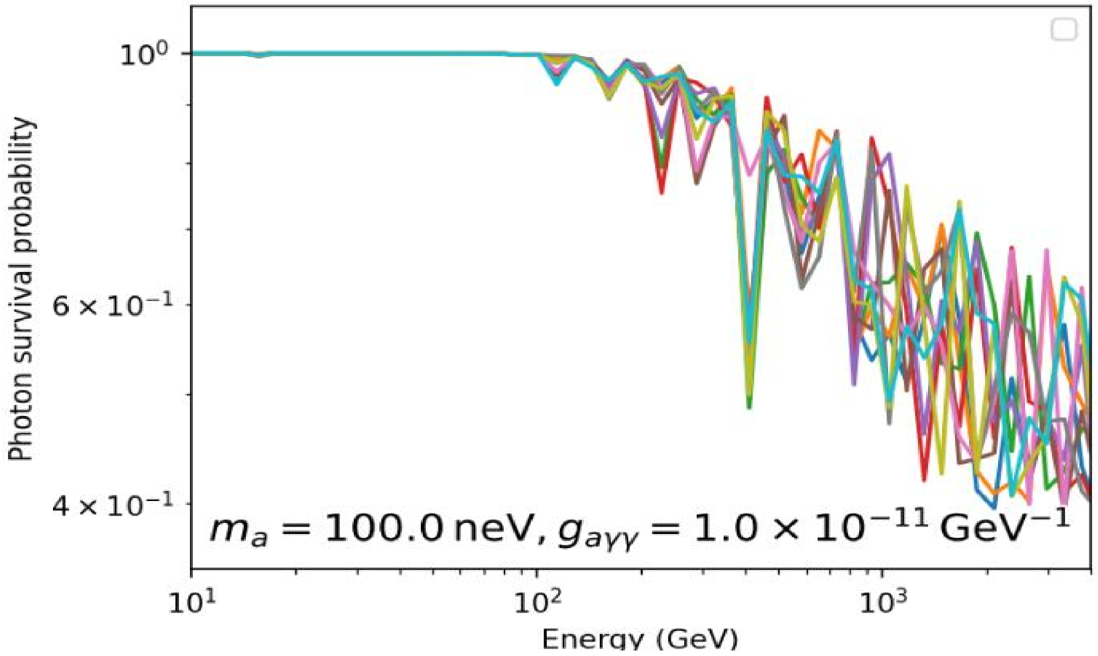
Posterior = Modified Output x Prior

Slide Credit: Gert Kluge, TeVPA, 2023

Photon Survival Probability

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



Obtained using the GAMMAALPs code: https://github.com/me-manu/gammaALPs

Conversion/oscillation in the presence of magnetic field

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