Sensitivity of CTAO to axion-like particles from blazars

A machine learning approach

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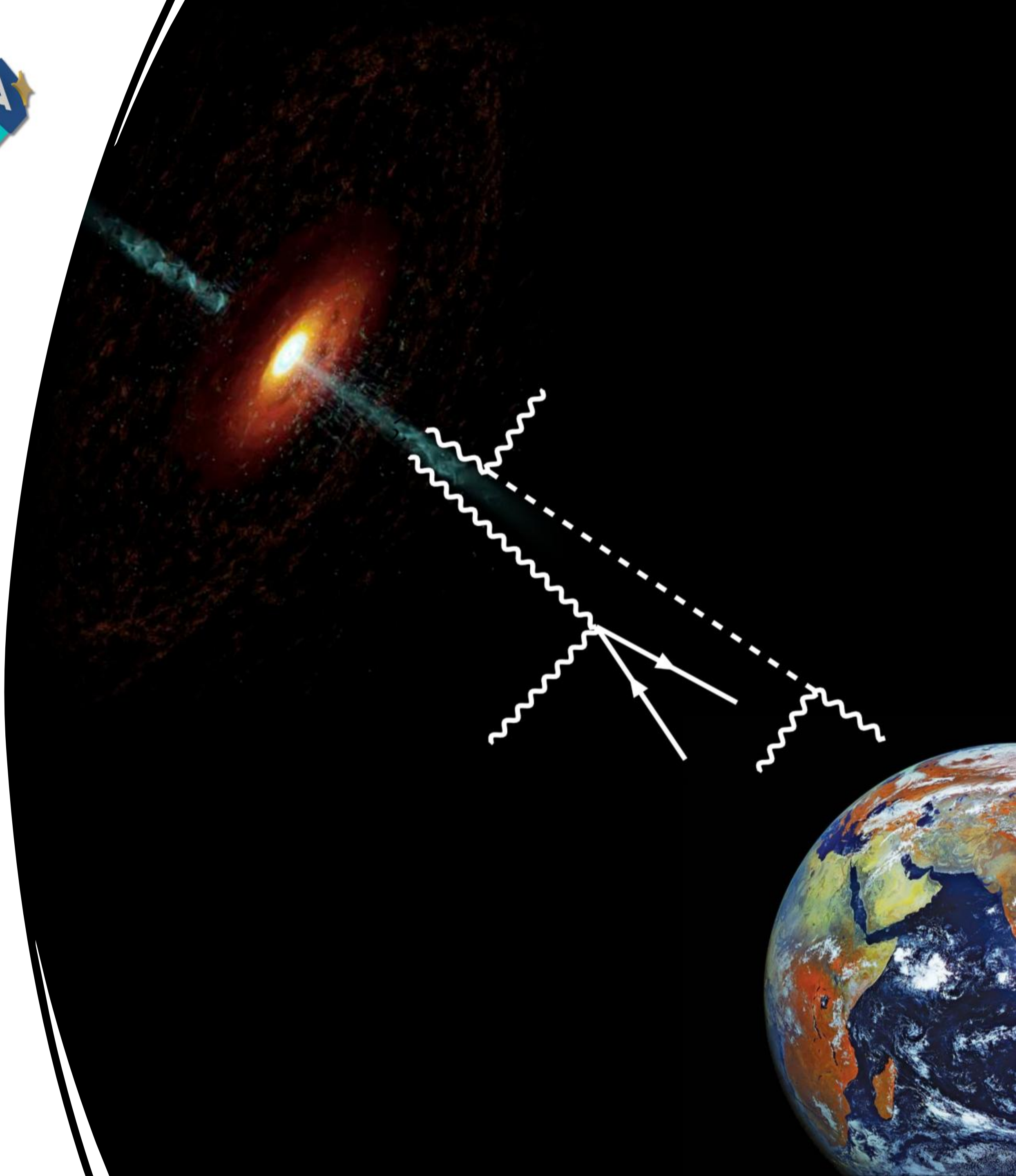
3rd General Meeting of COST Action COSMIC WISPers (CA21106)

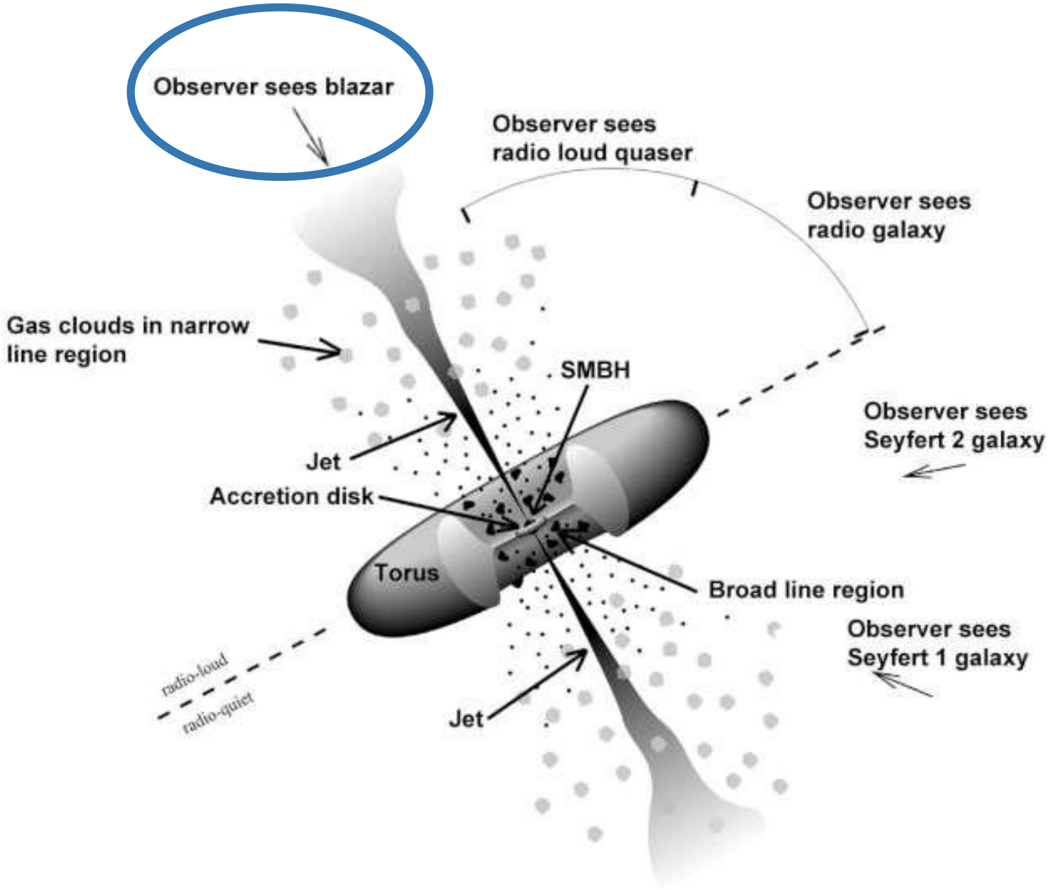
10 September 2025

University of Sofia, Bulgaria



Blazars

- Rare class of active galactic nuclei, with relativistic jets aligned with the line of sight from Earth
- High luminosity, extreme variability and polarised emission
- Almost all extragalactic sources observed in the gamma-rays are blazars



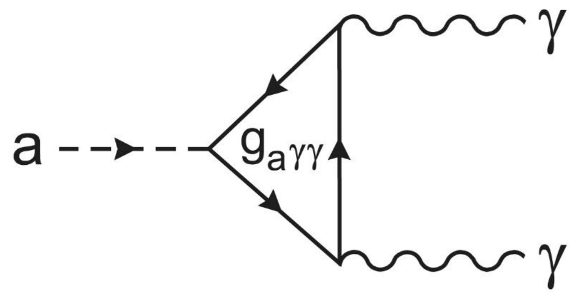
https://fermi.gsfc.nasa.gov/science/eteu/agn/

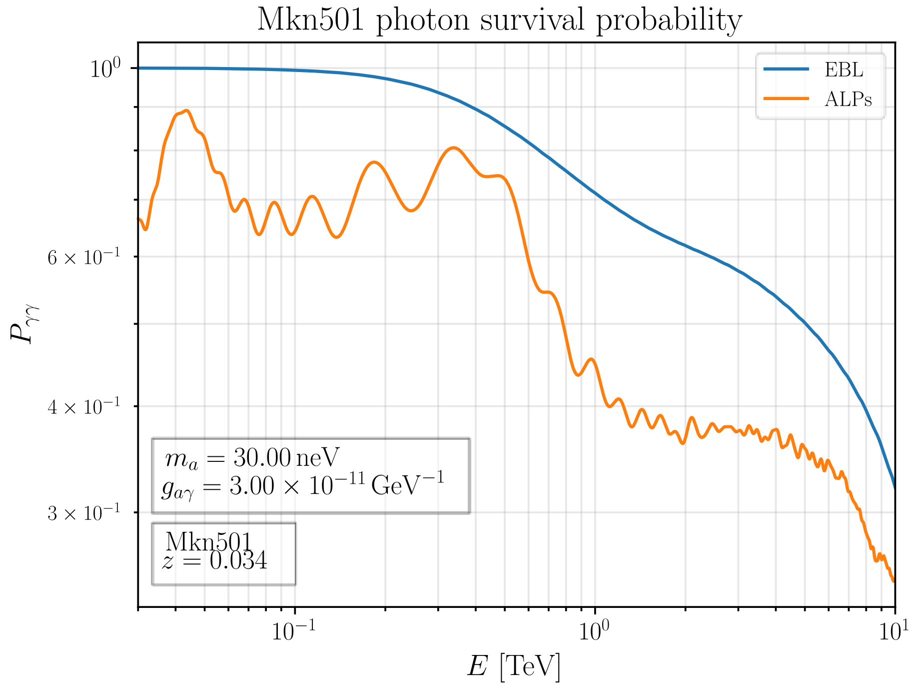
ALP-photon conversions in blazars

- The blazar jets feature ~ G magnetic fields over ~ pc distances
- Potential imprint on the gamma-ray spectra

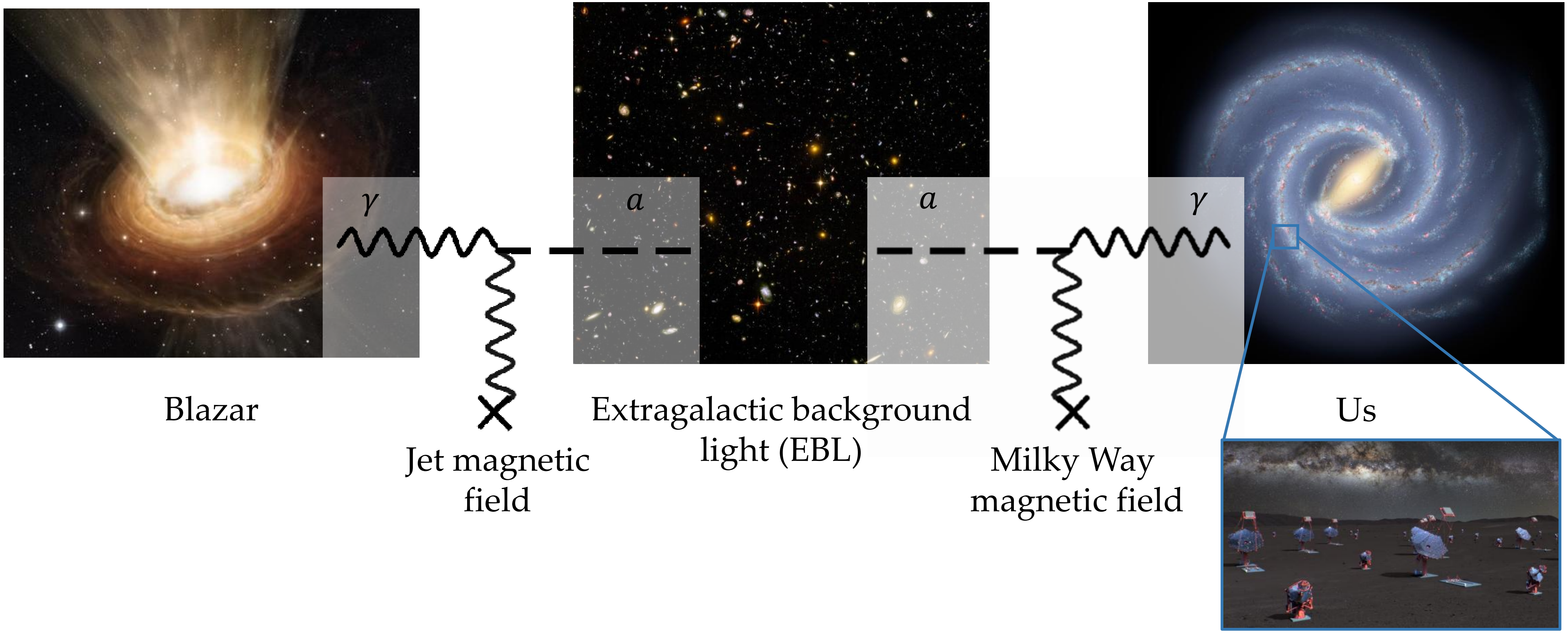
$$\phi_{\rm obs}(E) = \phi_{\rm int}(E) P_{\gamma\gamma}(E)$$

- Expected features:
  - Spectral «wiggles»
  - Increased fluxes at high energies, due to reduced EBL absorption





A «cosmic LSW experiment»

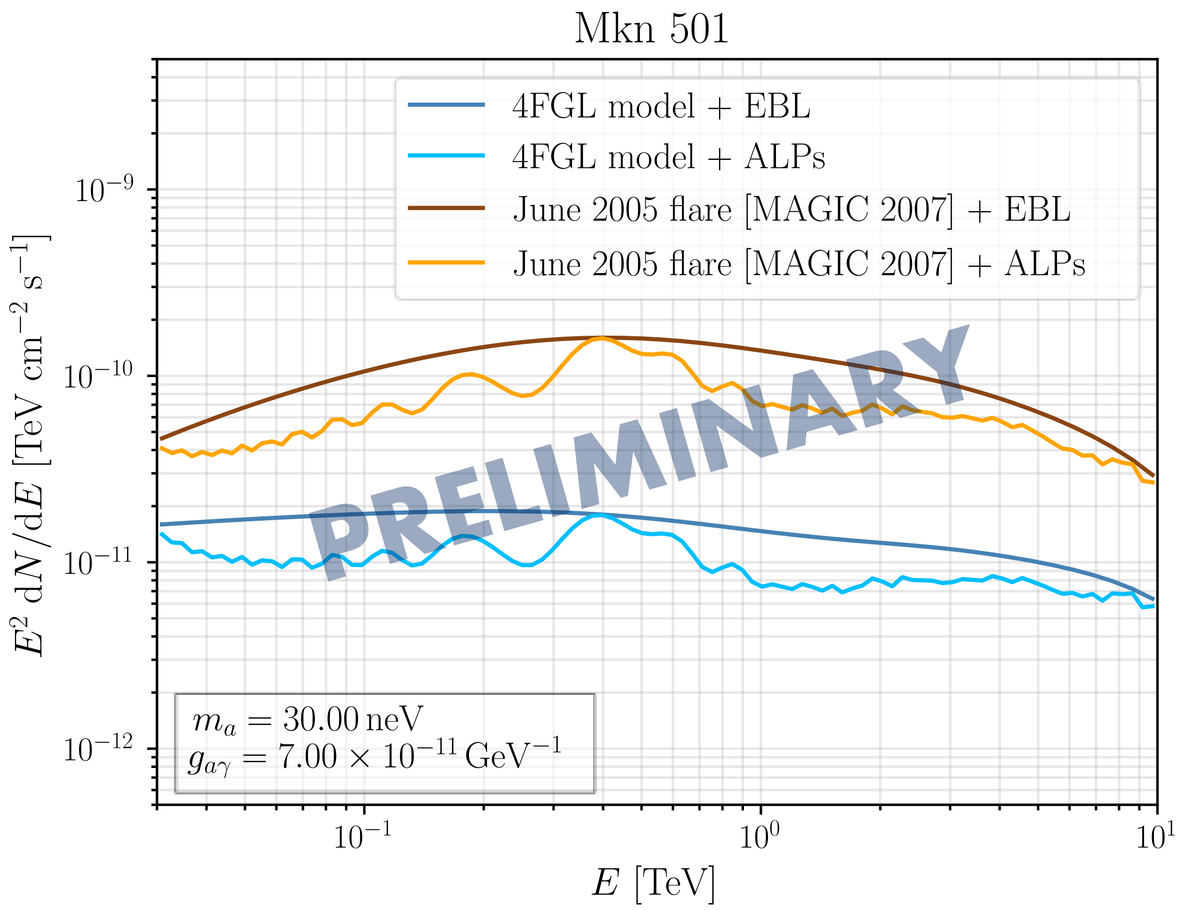


Spectral modelling

- Intrinsic spectral models (assumed valid between 30 GeV and 10 TeV):
  - Baseline states from the Fermi-LAT 4FGL-DR4 catalog
  - Flaring states from past IACT observations
- Photon survival probability $P_{\gamma\gamma}(E)$ computed using GammaALPs, including:
  - Jet magnetic field [Potter & Cotter 2015, arXiv:1508.00567]
  - Milky Way magnetic field [Jansson & Farrar 2012]
  - EBL absorption [Domínguez+ 2011]

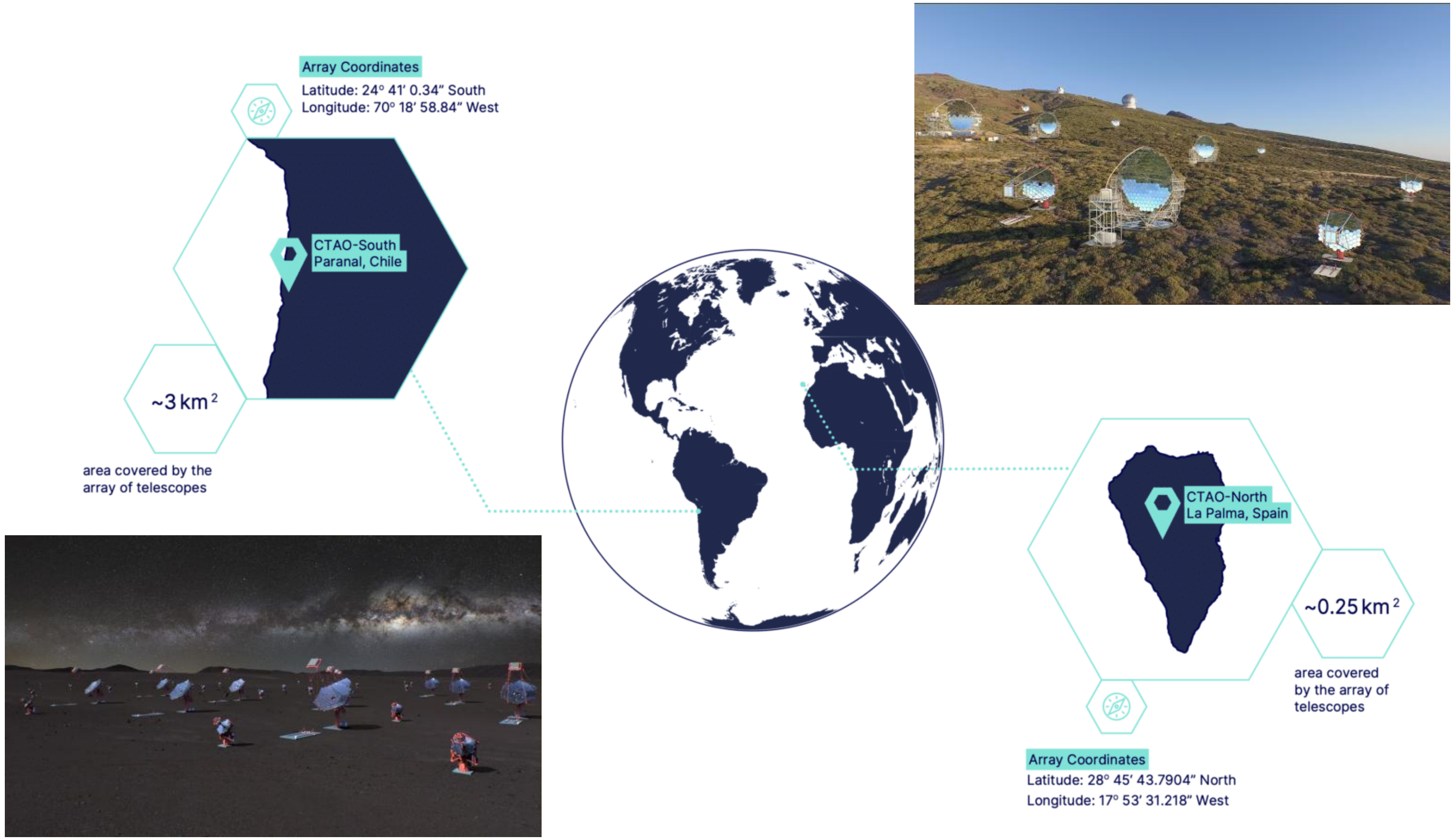
https://github.com/me-manu/gammaALPs/
https://gammaalps.readthedocs.io/

ALP effects on gamma-ray spectra



Cherenkov Telescope Array Observatory

- Next-generation gamma observatory
- 2 arrays planned in the Northern and Southern hemispheres
- ~70 telescopes total
- Better energy and spatial resolution, faster time response to transients, full sky coverage
- 20 GeV to 300 TeV sensitivity

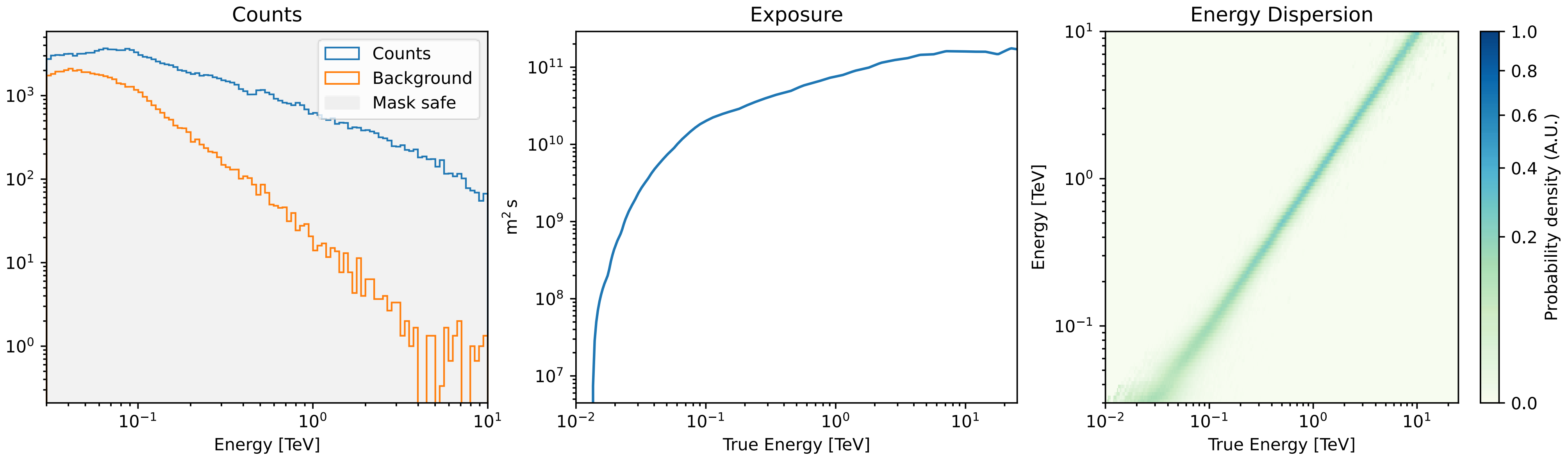


https://www.ctao.org/emission-to-discovery/array-sites/

Dataset simulation

A **Python** package for **gamma-ray** astronomy

- We employ the publicly available CTAO prod5 instrument response functions (IRFs)
- We simulate observations at a 20 deg zenith angle, using the ON-OFF technique ($\alpha = 1/3$, 0.7° offset) and 20 bins per energy decade



Example dataset for 50h observation of Mkn 501 baseline state

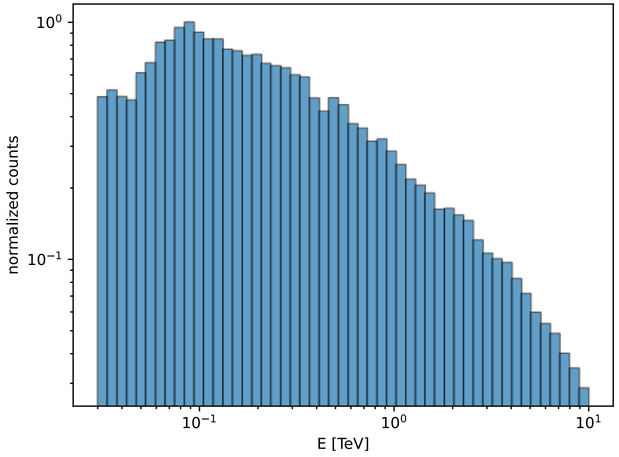
Project outline

- Motivation: CTAO's energy resolution and point-source sensitivity are well-suited to detect the spectral oscillations due to ALPs
- Goal: obtain (better) CTAO sensitivity limits on the ALP parameter space
- Standard method: likelihood-ratio test (applied e.g. to NGC 1275)
- Our method: define a grid of machine learning (ML) classifiers over the ALP parameter space
- Tested blazars:
  - Mrk 501 (this talk)
  - Mrk 421
  - PKS 2155—304

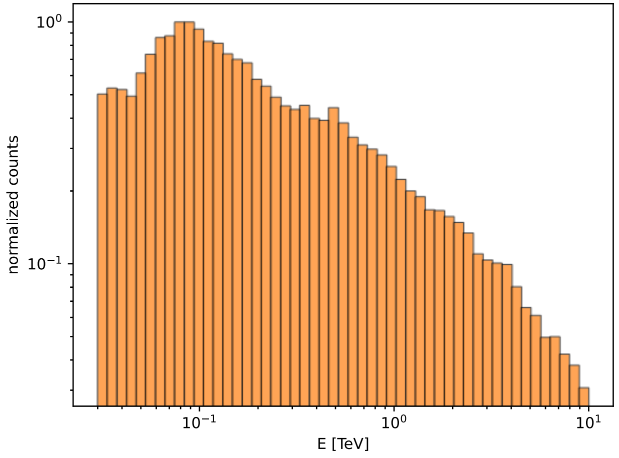
Classifier training

$\phi_{\text{int}}(E)$
+
$P_{\gamma\gamma}(E)$ computed by **gammaALPs** including
- Jet magnetic field
- Milky Way magnetic field
- EBL absorption

+
CTAO response functions



20 000 ALP-less datasets



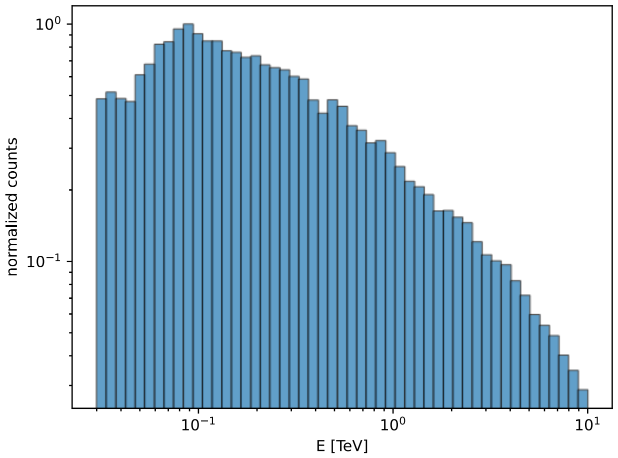
20 000 ALP-like datasets

XGBoost

$(m_a, g_{a\gamma})$

https://github.com/dmlc/xgboost
https://github.com/me-manu/gammaALPs/

Classifier evaluation



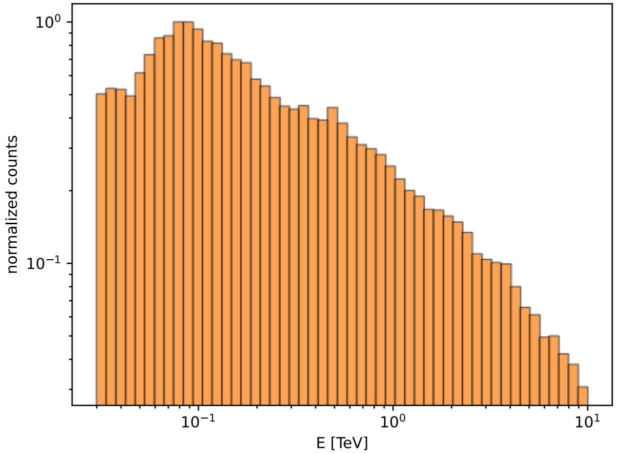
100 ALP-less datasets

$(m_a, g_{a\gamma})$

$p_{\mathrm{ALP}}(m_a, g_{a\gamma})$

«ALP-likeness» score

Estimation of confidence levels

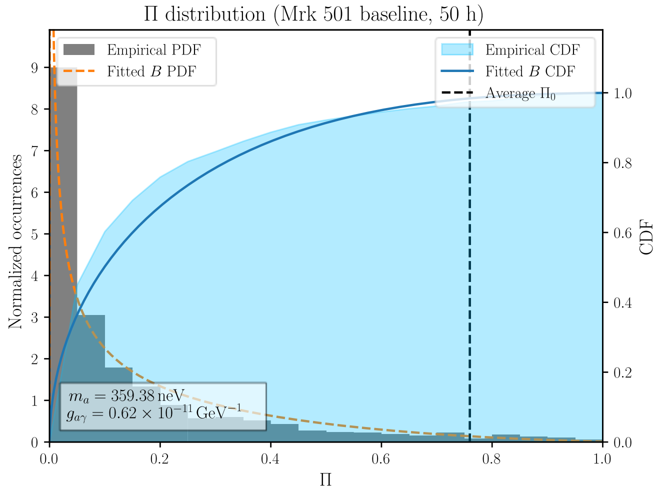


2000 ALP-like datasets

XGBoost

$(m_a, g_{a\gamma})$

$$\Pi(m_a, g_{a\gamma}) = 1 - p_{\mathrm{ALP}}(m_a, g_{a\gamma})$$

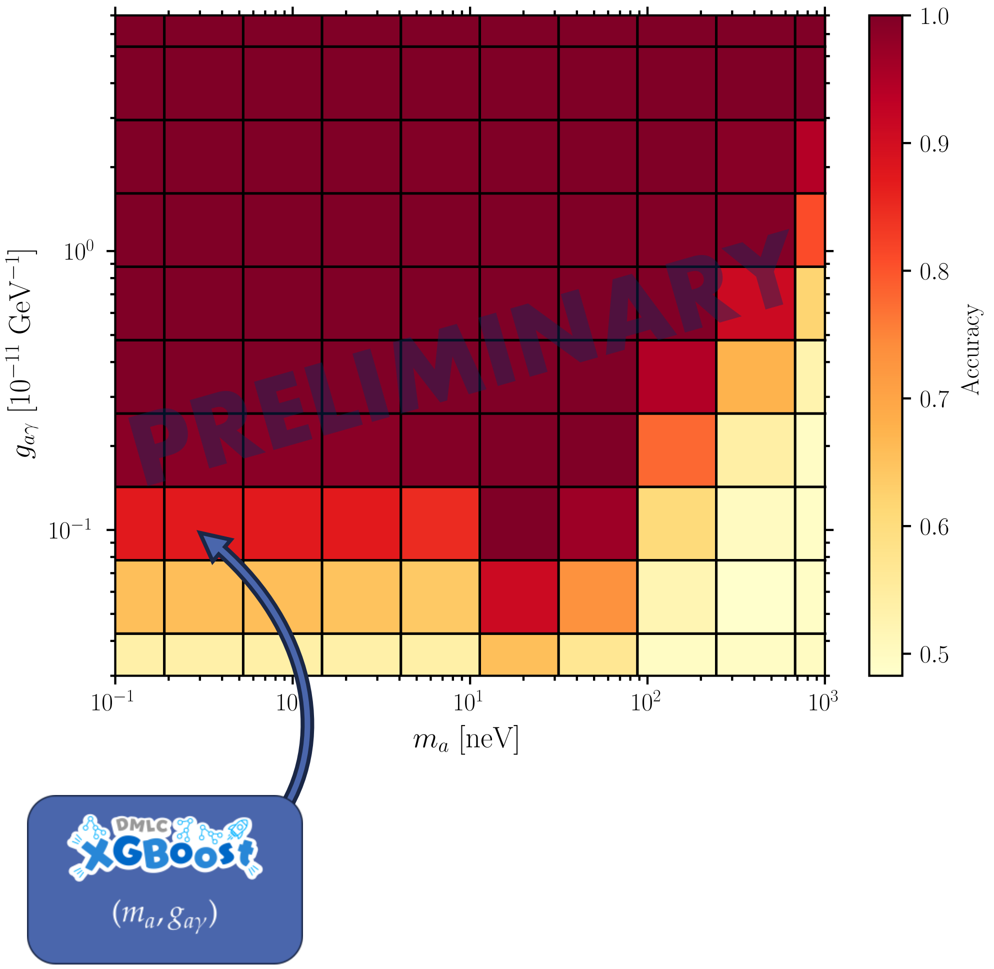


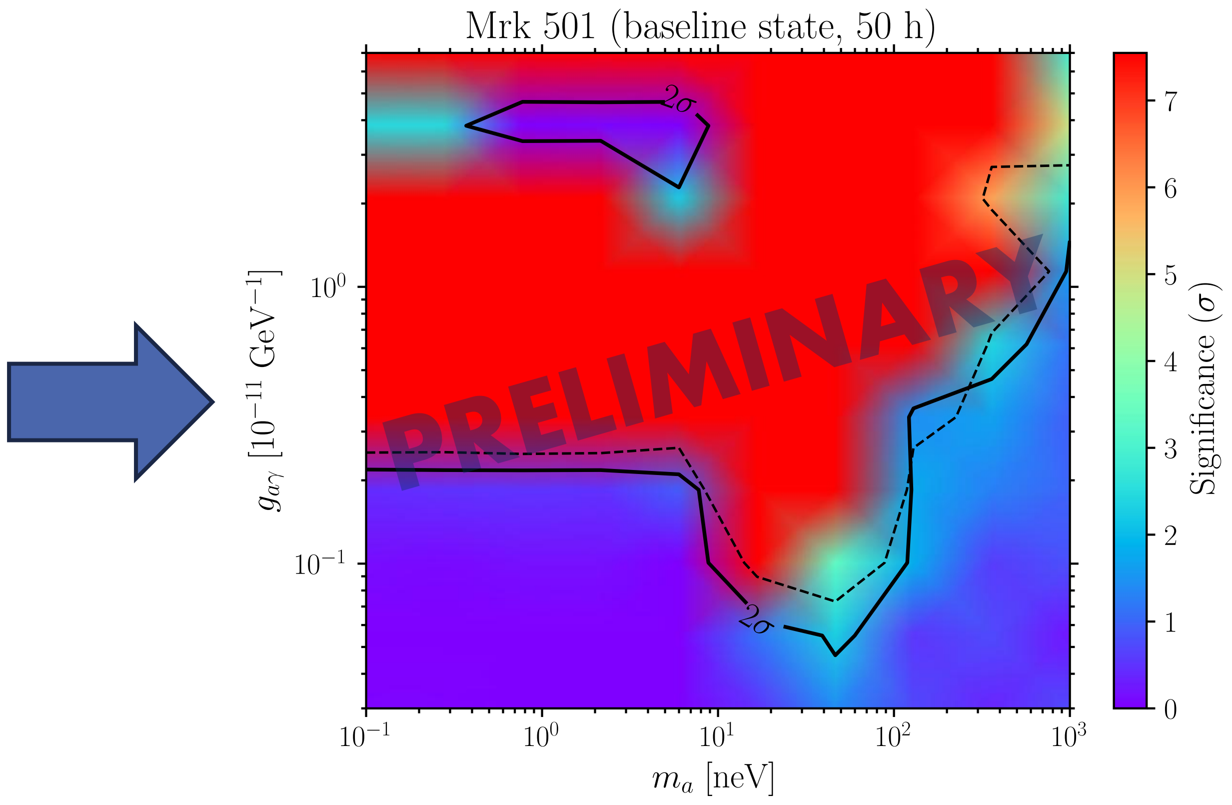
ALP exclusion confidence level

$$\mathrm{CL} = \int_0^{\Pi_0} f(x)\,\mathrm{d}x$$

Derivation of limits

«Classifier grid» over the ALP space

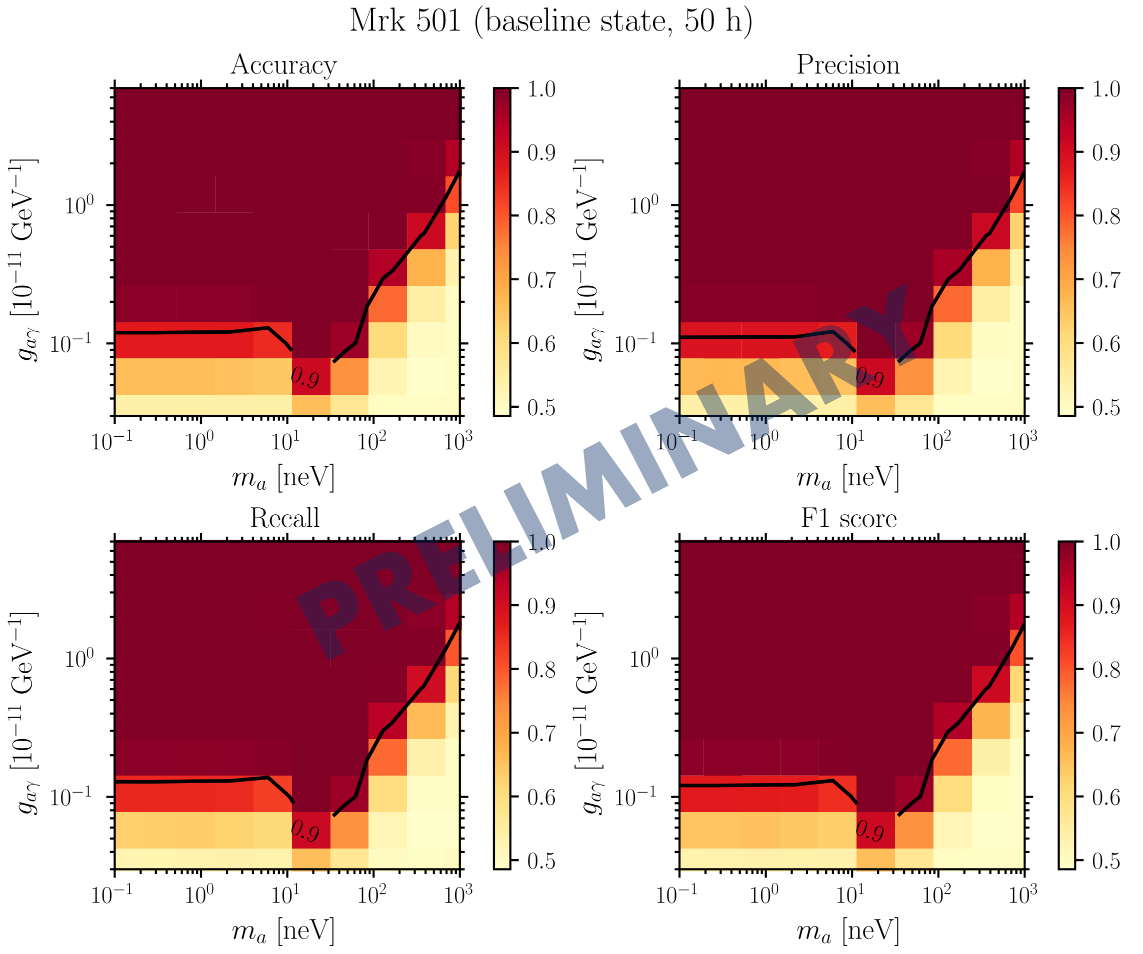




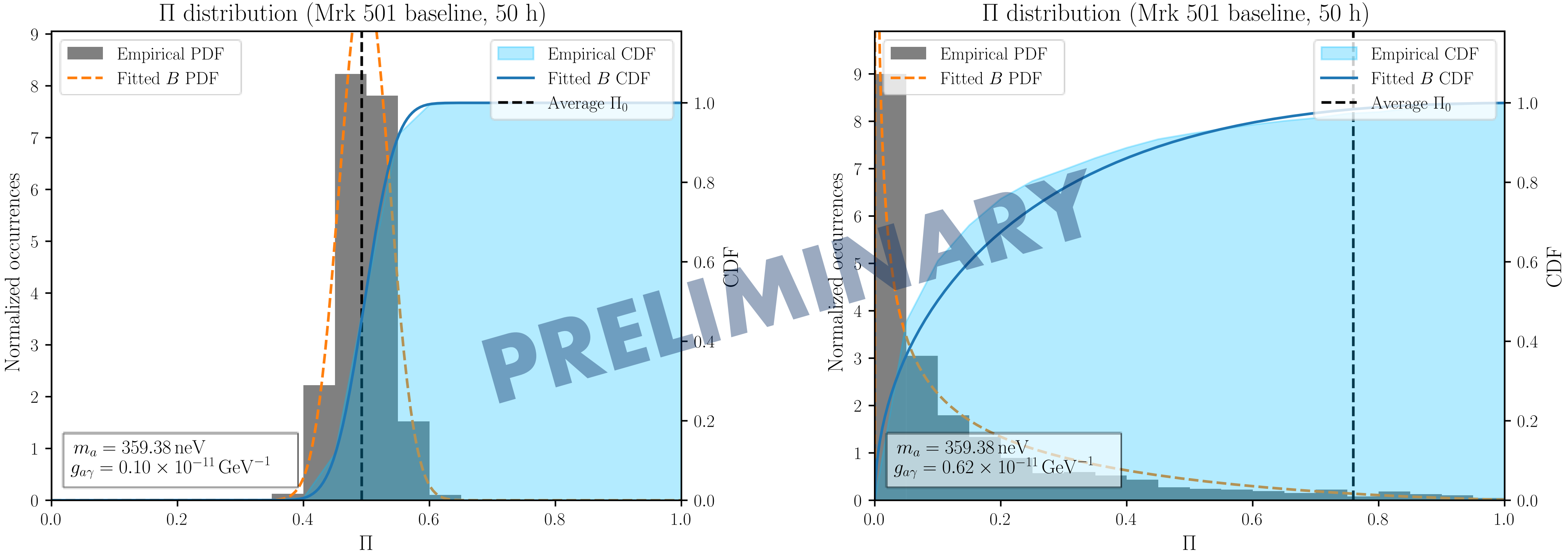
Classifier performance

- The algorithm choice was motivated by generally good performance on test datasets and ease of use
- As expected, the algorithm accuracy is better where the ALP signatures are stronger

```
xgb_kwargs = dict(n_estimators=100,
                  max_depth=3,
                  reg_lambda=500.,
                  reg_alpha=10.,
                  eta=.3,
                  random_state=1,
                  n_jobs=-1)
```



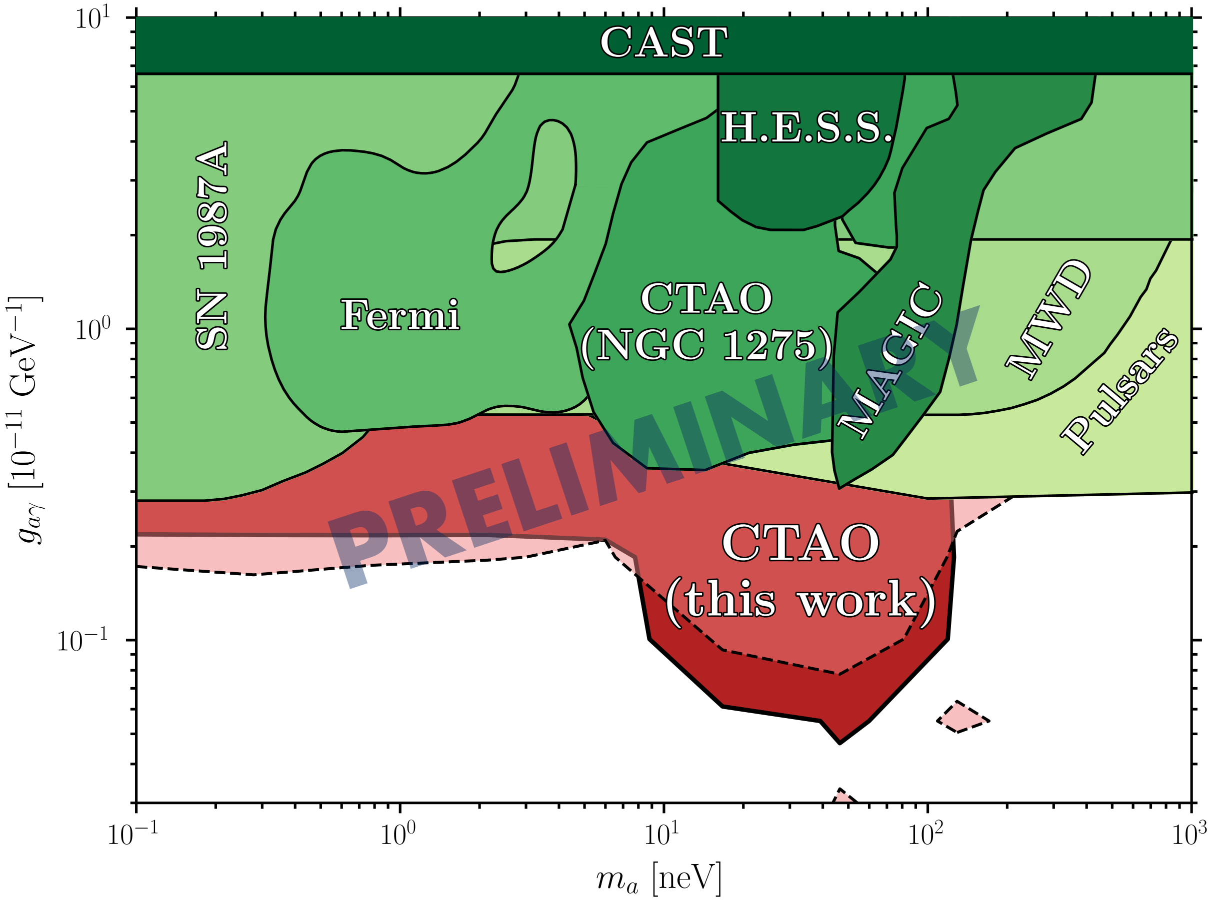
Example Π distributions



Uninformed classifier – no exclusion

Well-performing classifier – exclusion

Results (Mrk 501, 50h observation)



95% CL limits for a 50-hour observation of Mrk 501 are shown in red and compared to those obtained with a classical LRT (dashed contour)
Reference limits from https://github.com/cajohare/AxionLimits

Conclusions

- Among its many exciting prospects, CTAO will be a great tool to probe new fundamental physics
- Blazars in particular are ideal targets for ALP searches
- Previously unconstrained ALP parameter space can be covered
- Good agreement between «classic» LRT and new ML method
- A paper and a public GitHub repository are currently in preparation – stay tuned!

Thank you for your attention!

All questions and comments welcome :)

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Backup

Blazar selection

Source	z	RA [deg]	Dec [deg]
Mrk 501	0.034	253.47	39.76
Mrk 421	0.031	166.11	38.21
PKS 2155−304	0.116	329.72	−30.23

- Some of the most well-known and studied extragalactic gamma-ray sources
- High synchrotron peaked BL Lacs (HBLs) → significant TeV emission
- Available jet magnetic field models
- Included in the CTAO AGN Key Science Project → lots of data to be expected! [arXiv:1709.07997]

Source and simulation parameters

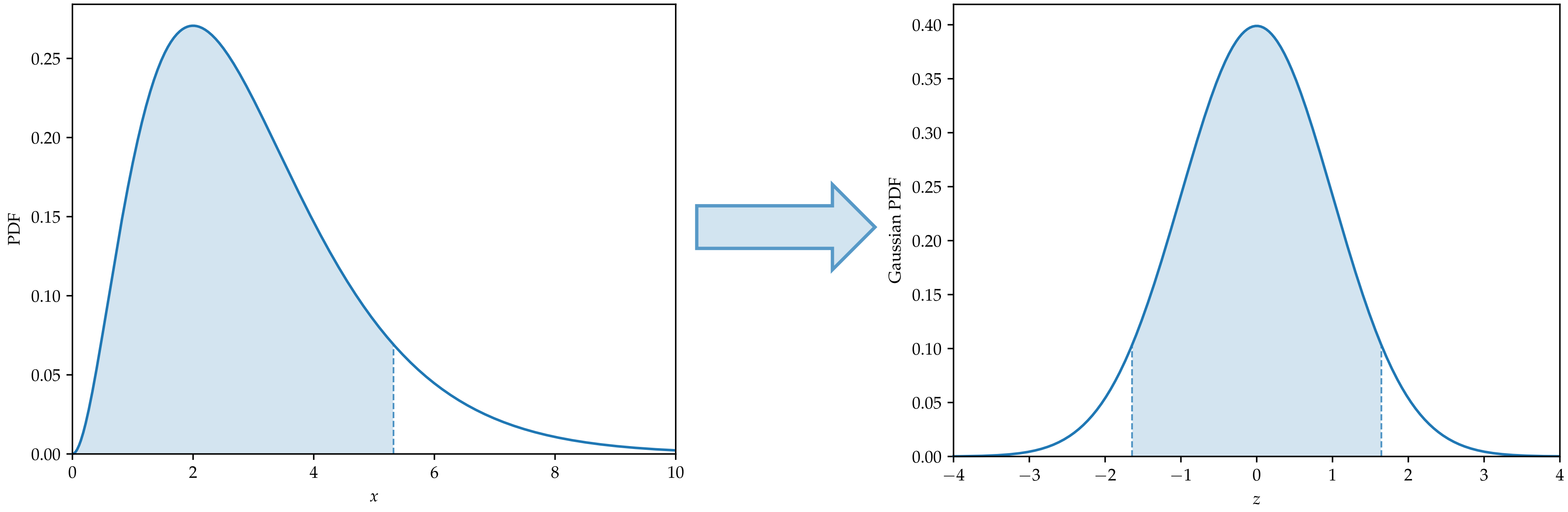
Source	z	RA (deg)	Dec (deg)	gammaALPs parameters: r_0 (pc)	B0 (G)	gmax	gmin	n0 (cm^{-3})	rjet (pc)	alpha
Mrk 501	0.034	253.47	39.76	0.36	0.81	9	2	4.5×10^4	3.2×10^3	1.68
Mrk 421	0.031	166.11	38.21	7.19	2.91×10^{-2}	12	9	8.5×10^3	9.7×10^4	1.55
PKS 2155-304	0.116	329.72	−30.23	0.33	0.82	15	7	1.65×10^4	3.2×10^3	1.70

Source	Livetime (h)	IRFs	Reference spectrum
Mrk 501 (baseline)	50	Prod5-North-20deg-AverageAz-4LSTs09MSTs.180000s	LP [52]
Mrk 421 (baseline)	50	Prod5-North-20deg-AverageAz-4LSTs09MSTs.180000s	SECPL [52]
PKS 2155−304 (baseline)	50	Prod5-South-20deg-AverageAz-14MSTs37SSTs.180000s	LP [52]
Mrk 501 (flaring)	5	Prod5-North-20deg-AverageAz-4LSTs09MSTs.18000s	LP [53]
Mrk 421 (flaring)	5	Prod5-North-20deg-AverageAz-4LSTs09MSTs.18000s	ECPL [54]
PKS 2155−304 (flaring)	5	Prod5-South-20deg-AverageAz-14MSTs37SSTs.18000s	ECPL [55]

PRELIMINARY

Source	Model	ϕ_0	E_0	α	β	E_{cut}	a	Γ_1	Γ_2	Ref.
	Baseline	[$MeV^{-1}\,cm^{-2}\,s^{-1}$]	[MeV]			[MeV]				
Mrk 501	LP	3.91×10^{-12}	1507.92	1.75	0.018	–	–	–	–	[52]
Mrk 421	SECPL	1.79×10^{-11}	1258.26	–	–	–	0.011	1.74	0.65	[52]
PKS 2155−304	LP	1.34×10^{-12}	1146.89	1.77	0.041	–	–	–	–	[52]
	Flaring	[$TeV^{-1}\,cm^{-2}\,s^{-1}$]	[TeV]			[TeV]				
Mrk 501	LP	1.86×10^{-9}	0.3	1.73	0.13	–	–	–	–	[53]
Mr 421	ECPL	3.58×10^{-10}	1.0	–	–	2.74	–	–	–	[54]
PKS 2155−304	ECPL	2.38×10^{-9}	1.0	–	–	1.0	–	–	–	[55]

Significance estimation



$$\mathrm{CDF}(\mathrm{TS}_A) \equiv 2\frac{1}{\sqrt{2\pi}}\int_0^z e^{-\frac{t^2}{2}}\,\mathrm{d}t = \frac{2}{\sqrt{\pi}}\int_0^{\frac{z}{\sqrt{2}}} e^{-t'^2}\mathrm{d}t' = \mathrm{erf}\left(\frac{z}{\sqrt{2}}\right)$$

ML classifier approach

- Define a grid of ML classifiers over the ALP space, based on the XGBoost algorithm
- Train each of those with 40000 simulated datasets with/without ALPs, using excess photon counts in each bin (normalized between 0 and 1) as features
- Present each classifier with the counts in 100 ALP-less datasets
- Compute average ALP-likeness score $p_{\mathrm{ALP},0}(m_a, g_{a\gamma})$

https://github.com/dmlc/xgboost
https://xgboost.readthedocs.io/en/release_3.0.0/

Derivation of limits

- Define $\Pi_A(m_a, g_{a\gamma}) = 1 - p_{\text{ALP}}(m_a, g_{a\gamma})$
- For each $(m_a, g_{a\gamma})$ point, compute a Π distribution from 2000 more simulated ALP datasets
  - small Π: ALP-like dataset
  - large Π: ALP-less dataset
- Fit with a Beta distribution and compute the CDF value at Π_0

$$f(x, \alpha, \beta) = \frac{\Gamma(\alpha+\beta) x^{\alpha-1}(1-x)^{\beta-1}}{\Gamma(\alpha)\Gamma(\beta)}$$

- Estimate exclusion significance in σ as $z = \sqrt{2}\,\text{erf}^{-1}(\text{CDF}_A)$

Standard derivation of limits (LRT)

- Compute the expected spectral model of the source for different ALP parameters
- Compute average likelihood-ratio $\mathrm{TS}_0(m_a, g_{a\gamma})$ from 100 ALP-less datasets

$$\mathrm{TS}(m_a, g_{a\gamma}|D) = -2\ln\frac{\mathcal{L}(m_a, g_{a\gamma}, \hat{\mu}, \hat{b}, \hat{\theta}|D)}{\hat{\mathcal{L}}(D)}$$ (cf. MAGIC paper)

- For each point in the ALP parameter space, simulate 100 observations with ALPs and compute a TS distribution
- Fit with a Gamma distribution and compute the CDF value at TS_0
- Estimate exclusion significance as $z = \sqrt{2}\,\mathrm{erf}^{-1}(\mathrm{CDF})$

Example TS distribution