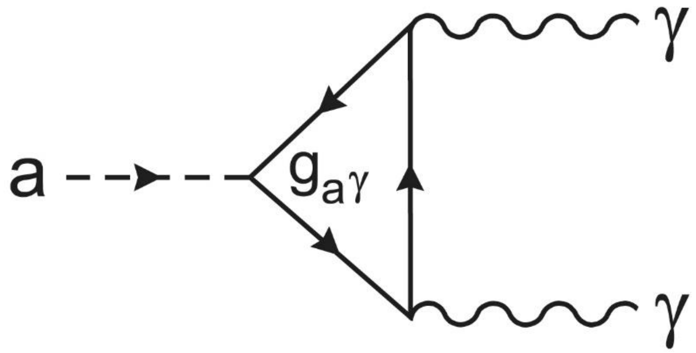
1st CTAO Summer School
Bertinoro, 21st June 2024

CTAO sensitivity to axion-like particles

Francesco Schiavone
Università degli Studi di Bari & INFN Bari
In collaboration with L. Di Venere and F. Giordano

INFN BARI | CTAO | A Python package for gamma-ray astronomy | Università degli Studi di Bari Aldo Moro

Axion-like particles (ALPs)



- Hypothetical pseudo-scalar particles with mass m_a and effective coupling to photons $g_{a\gamma}$ (essential for detection!)
- QCD axions: $m_a \propto g_{a\gamma\gamma}$
- ALPs: no clear relationship
- Effectively a «family» of axions

ALP-photon conversions

- Characterised by two energy scales
- In a constant magnetic field B:

$$E_{\text{min}} = 2.56\,\text{GeV}\,\frac{|m_{\text{neV}}^2 - 1.37\times 10^{-3} n_{\text{cm}^{-3}}|}{g_{11} B_{\mu\text{G}}}$$

$$E_{\text{max}} = \frac{2.14\times 10^{6}\,\text{GeV}}{B_{\mu\text{G}}^2 + 5.69}\, g_{11} B_{\mu\text{G}}$$

$$g_{11} = \frac{g_{a\gamma}}{10^{-11}\,\text{GeV}^{-1}} \qquad m_{\text{neV}} = \frac{m_a}{1\,\text{neV}} \qquad n_{\text{cm}^{-3}} = \frac{n_e}{1\,\text{cm}^{-3}} \qquad B_{\mu\text{G}} = \frac{B}{1\,\mu\text{G}}$$

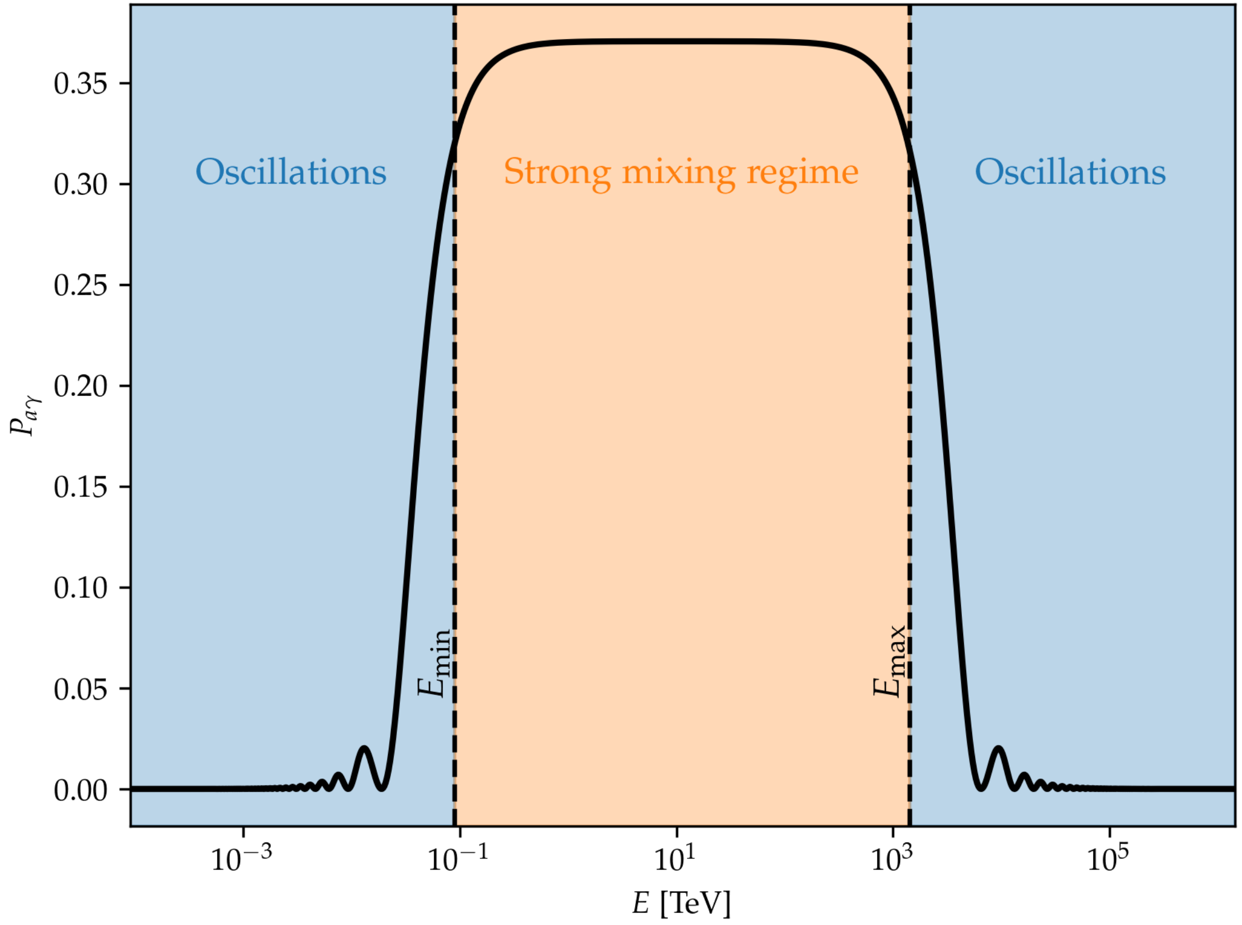
ALP-photon oscillation probability

$m_{\mathrm{neV}} = 12.2$

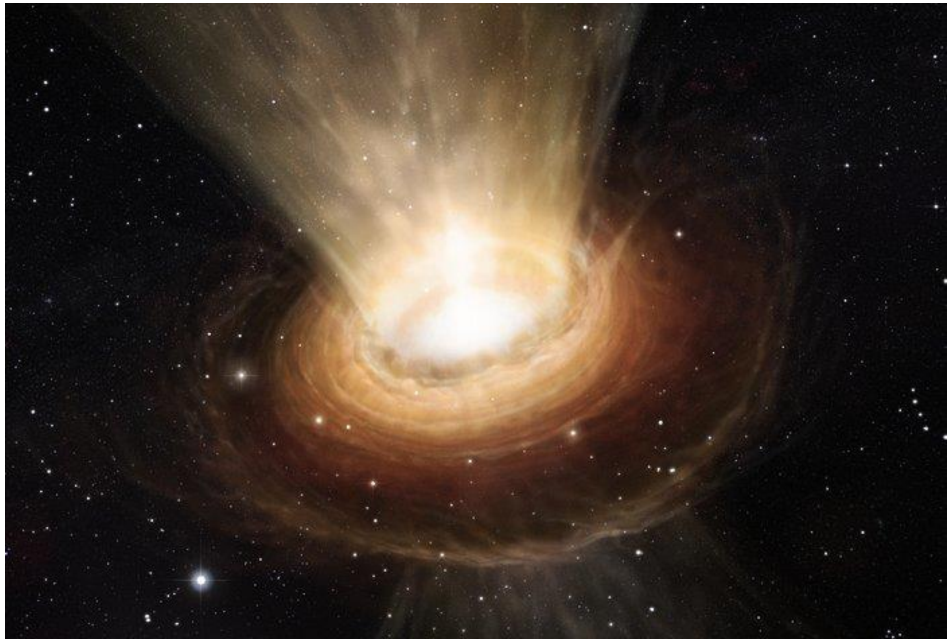
$g_{11} = 4.3$

$B_{\mu\mathrm{G}} = 1$

$n_{\mathrm{cm}^{-3}} = 10^{-3}$



Astrophysical magnetic fields



https://www.eso.org/public/images/eso1327a/

Source magnetic field

e.g. blazar jet field, $\mathcal{O}(\mathrm{G})$ over pc scales, or turbulent field in galaxy cluster, $\mathcal{O}(\mu\mathrm{G})$ over kpc scales

Milky Way magnetic field

Relatively well-known (Jansson & Farrar 2012), $\mathcal{O}(\mu\mathrm{G})$

Photon-ALP evolution

- Generally described by a 3×3 density matrix ρ obeying

$$i\frac{d\rho}{dx} = [\rho, \mathcal{M}_0] \qquad \rho_0 = \frac{1}{2}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

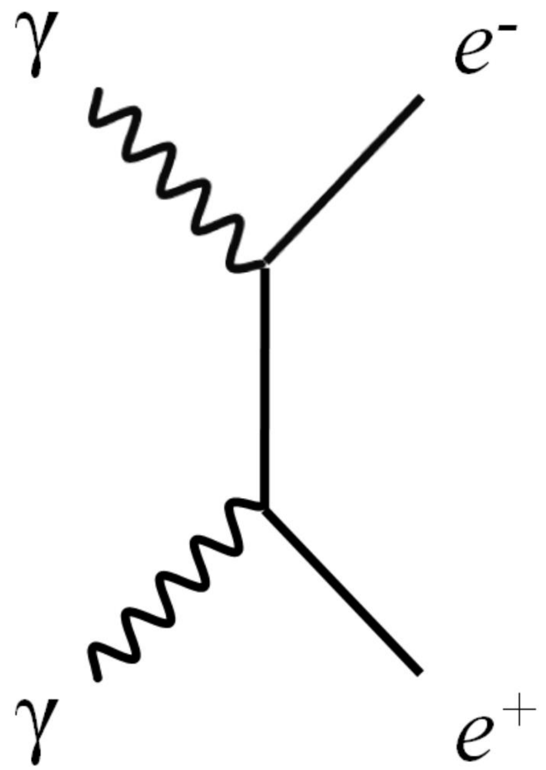
photon states (two polarizations)

ALP state

- $P_{a\gamma}$ is calculated by means of transfer matrices
- The dependance on ALP parameters $(m_a, g_{a\gamma})$ is highly nonlinear

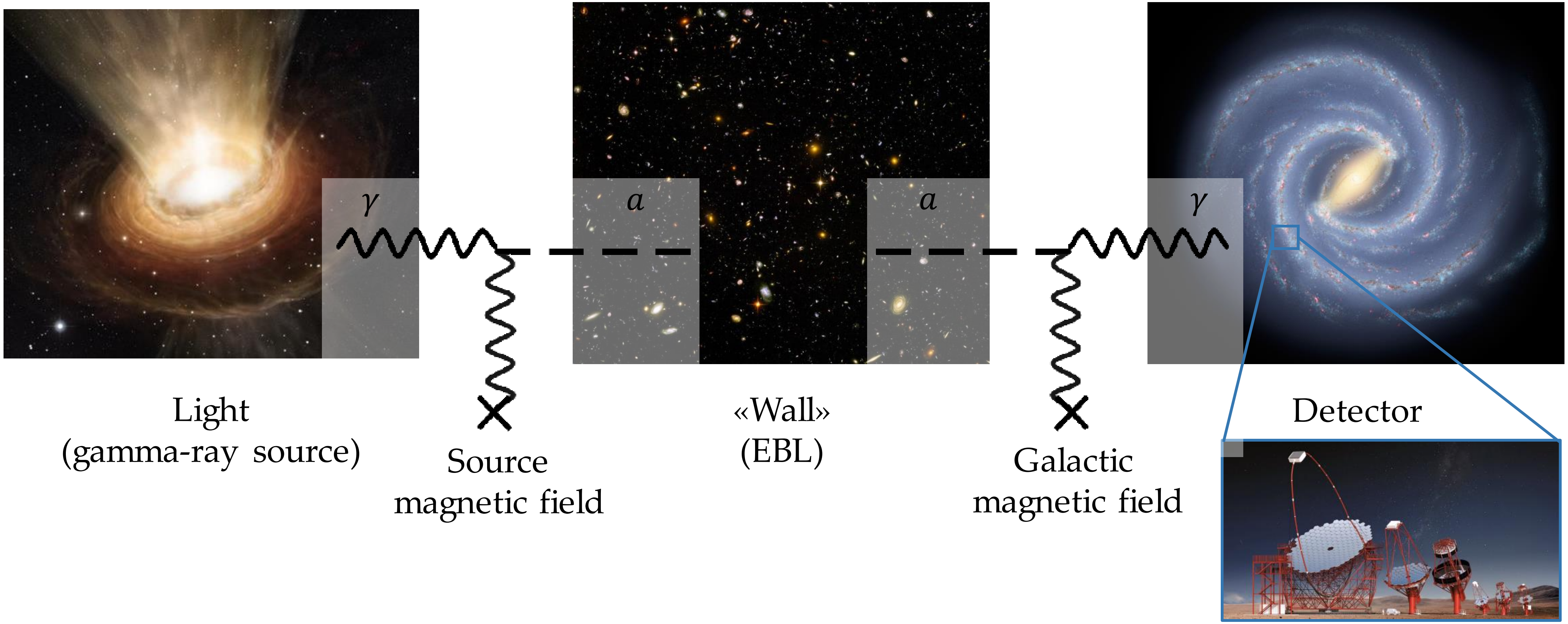
Gamma-ray opacity of the Universe

- Interaction of gamma rays with extragalactic background light (EBL) produces e^+e^- pairs
- Result: effective *absorption* of gamma rays, parametrized by optical depth $\tau(E, z)$
- Absorption generally increases with z and E: the Universe is *opaque* to faraway gamma-ray sources



ALPs can reduce gamma-ray opacity

A cosmic «light-shining-through-wall» experiment

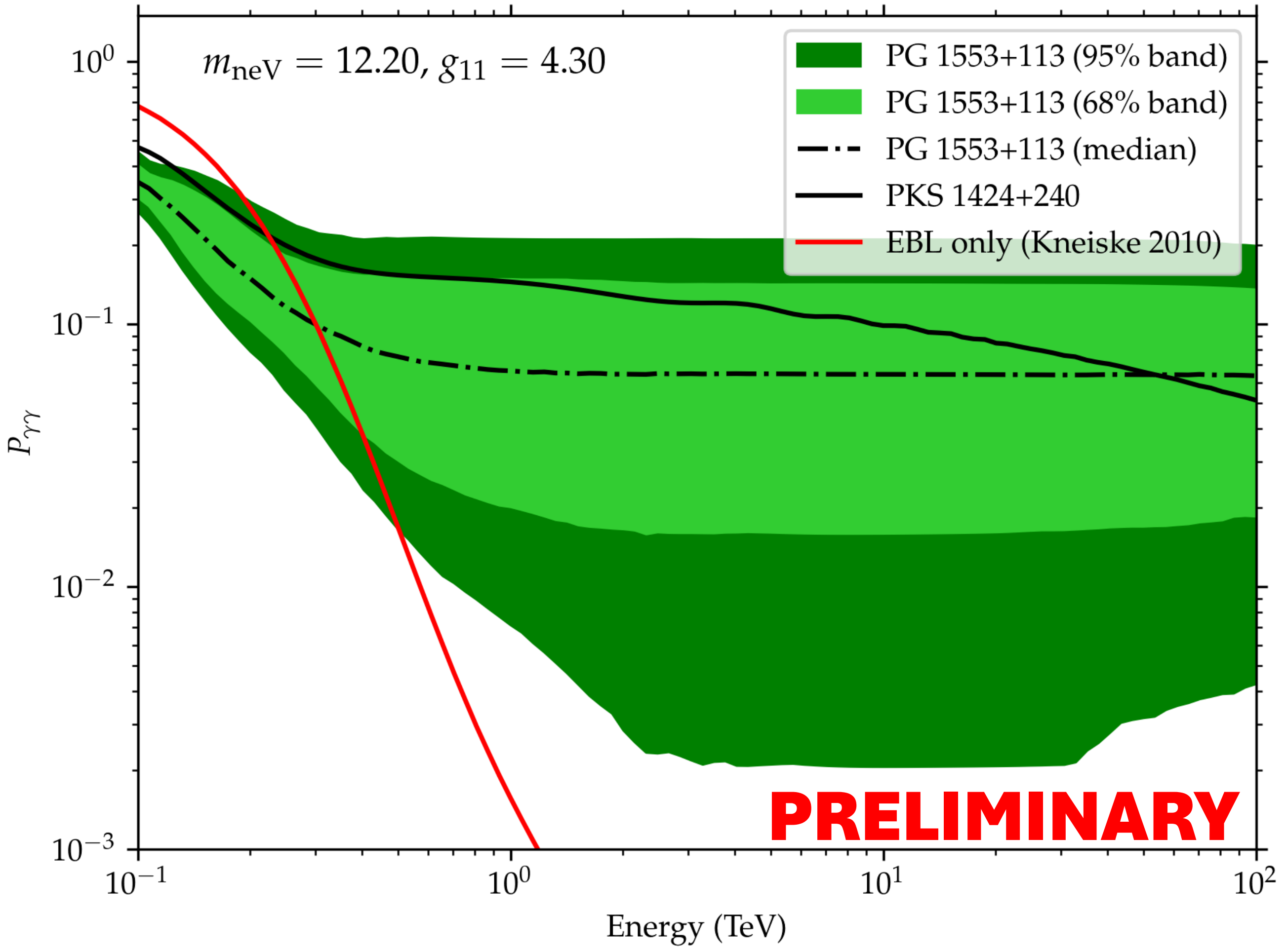


Benchmark sources

	PG 1553+113	PKS 1424+240
R.A.	238.93°	216.75°
Dec.	11.19°	23.8°
z	$\gtrsim 0.4$	$\gtrsim 0.6$
B type	Gaussian turbulent cluster field	jet coherent field
B strength	$\sim 1\,\mu$G	$\sim 0.03\,$G
B size	$\sim$ kpc	$\sim$ pc

(following Meyer et al., arXiv:1406.5972, arXiv:1410.1556)

Photon survival probability



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

Observed and intrinsic fluxes

Observed flux

$$\phi_{\text{obs}}(E) = P_{\gamma\gamma}(E,z)\phi_{\text{int}}(E)$$

[e.g. H.E.S.S. data points]

Photon survival probability

$$P_{\gamma\gamma}^{\text{EBL}}(E,z) = e^{-\tau(E,z)}$$

$P_{\gamma\gamma}^{\text{ALP}}(E,z)$ from gammaALPs

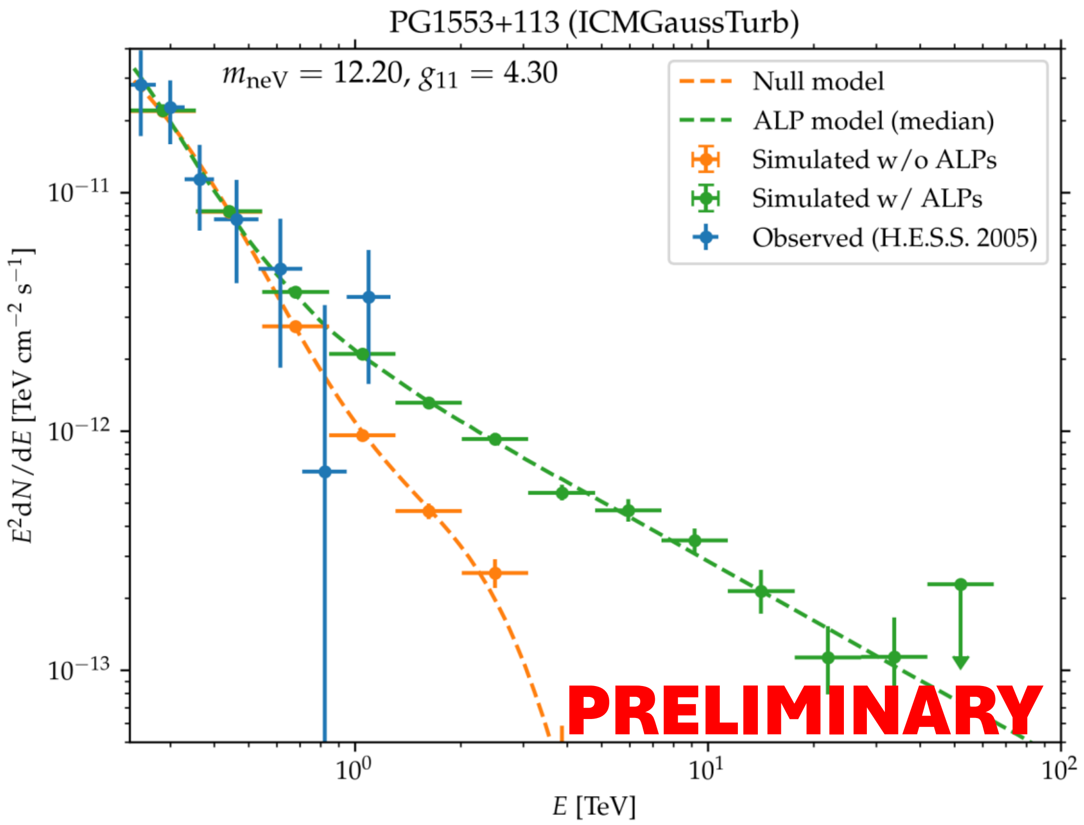
Intrinsic flux

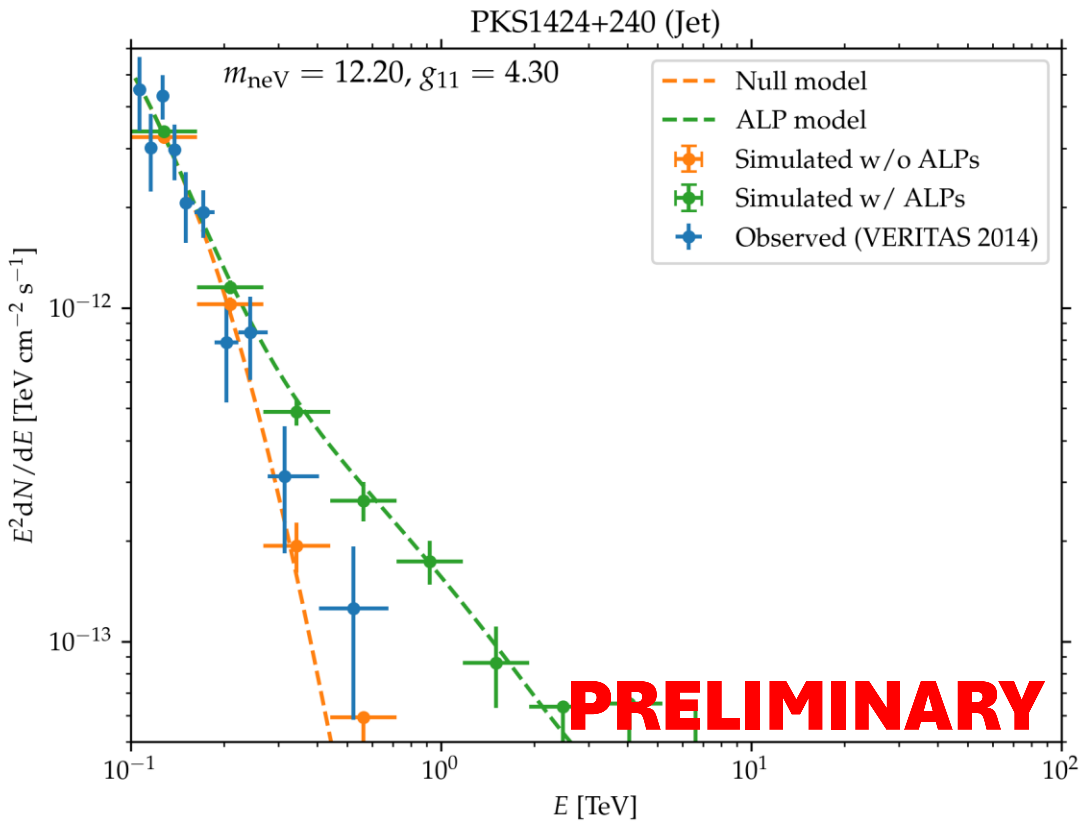
$$\phi_{\text{int}}(E) = \frac{\phi_{\text{obs}}(E)}{P_{\gamma\gamma}(E,z)}$$

Simulated flux

$$\phi_{\text{sim}}(E') = P_{\gamma\gamma}(E',z)\phi_{\text{int}}(E')$$

Simulated fluxes (CTAO South)



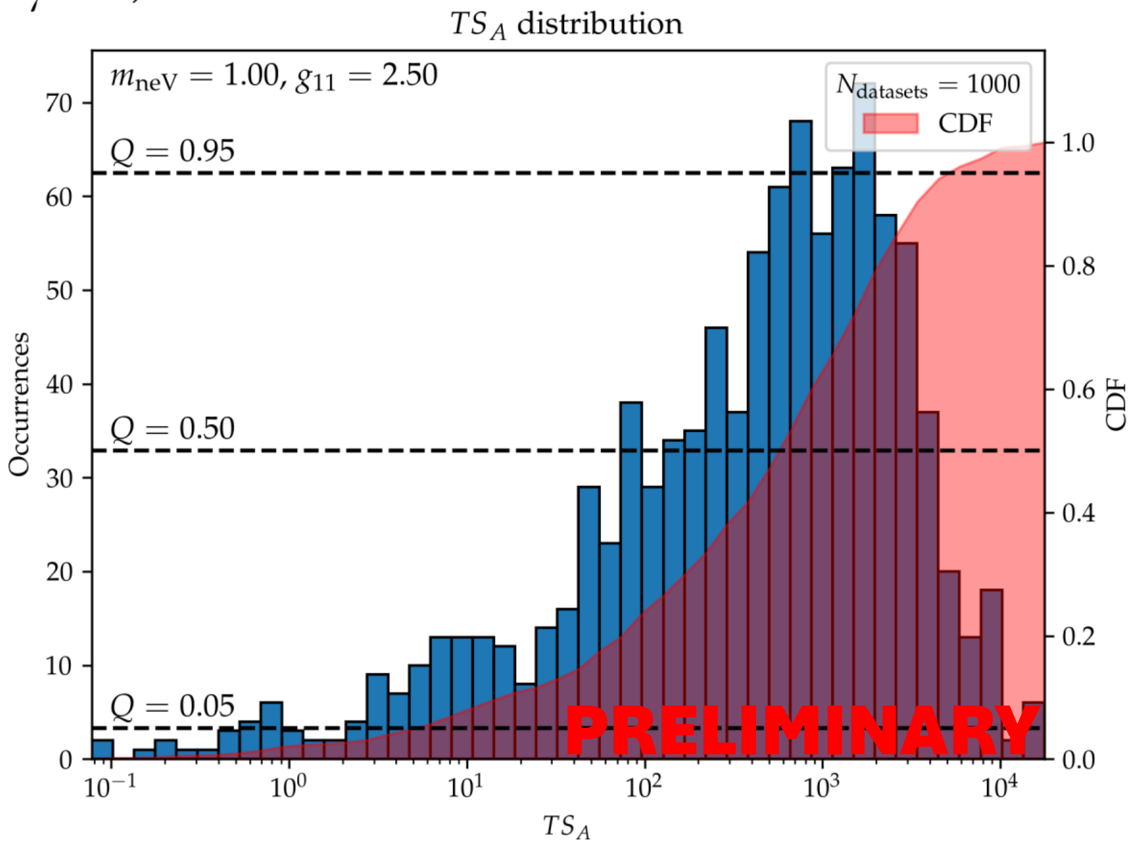


Observed data points obtained from the H.E.S.S. and VERITAS websites.
CTAO South 20deg 50h Prod5 IRFs from https://zenodo.org/records/5499840

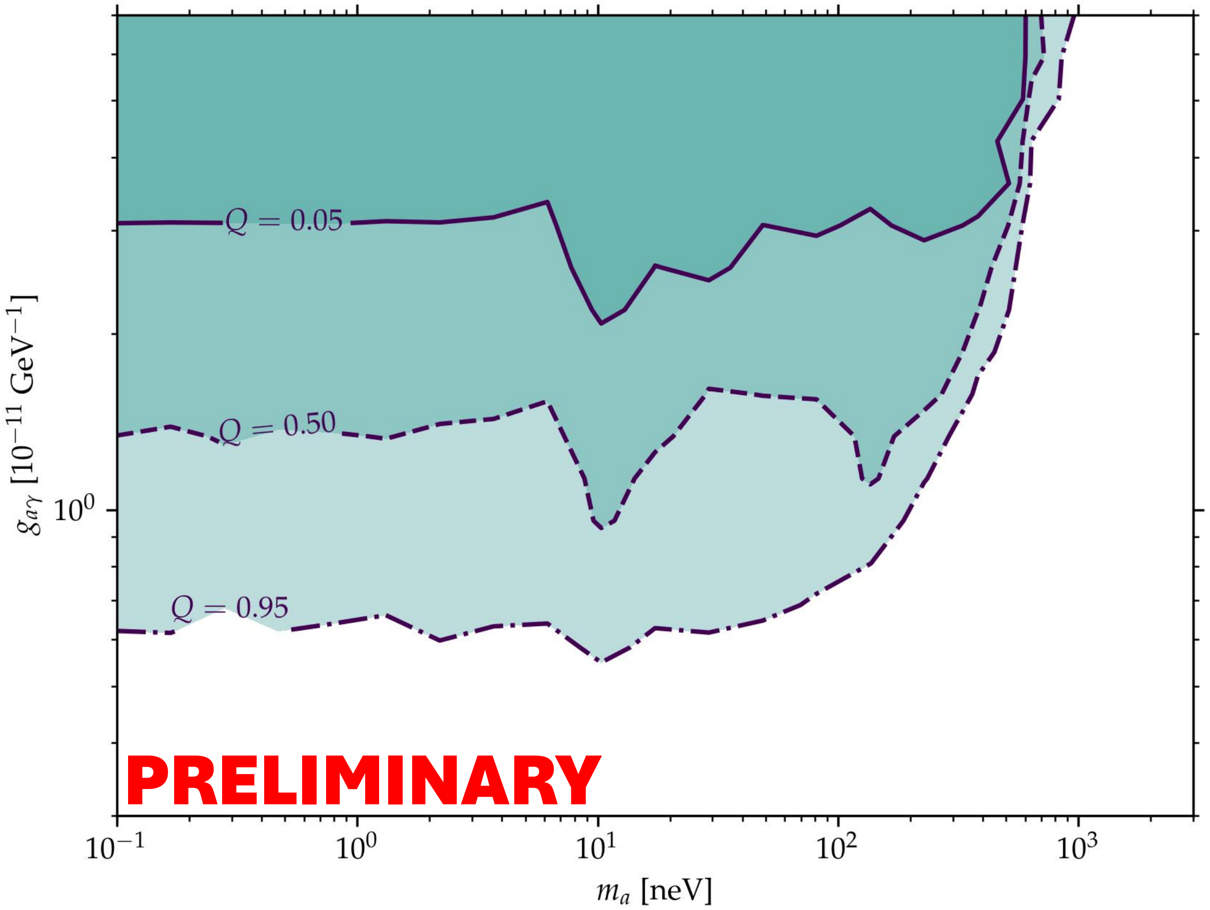
Test statistics distribution

$$\mathrm{TS}_A(m_a, g_{a\gamma}, B) = -2\ln\frac{\mathcal{L}(g_{a\gamma}=0)}{\mathcal{L}(m_a, g_{a\gamma}, B)} = \mathrm{WSTAT}_{\mathrm{no\,ALP}} - \mathrm{WSTAT}_{\mathrm{ALP}}$$

- For turbulent magnetic fields, a wide range of TS values exists for the same ALP parameters
- We evaluate a TS distribution over various realizations and consider its quantiles
- Using «Asimov datasets» reduces statistical fluctuations
- Significance is estimated against null TS distribution

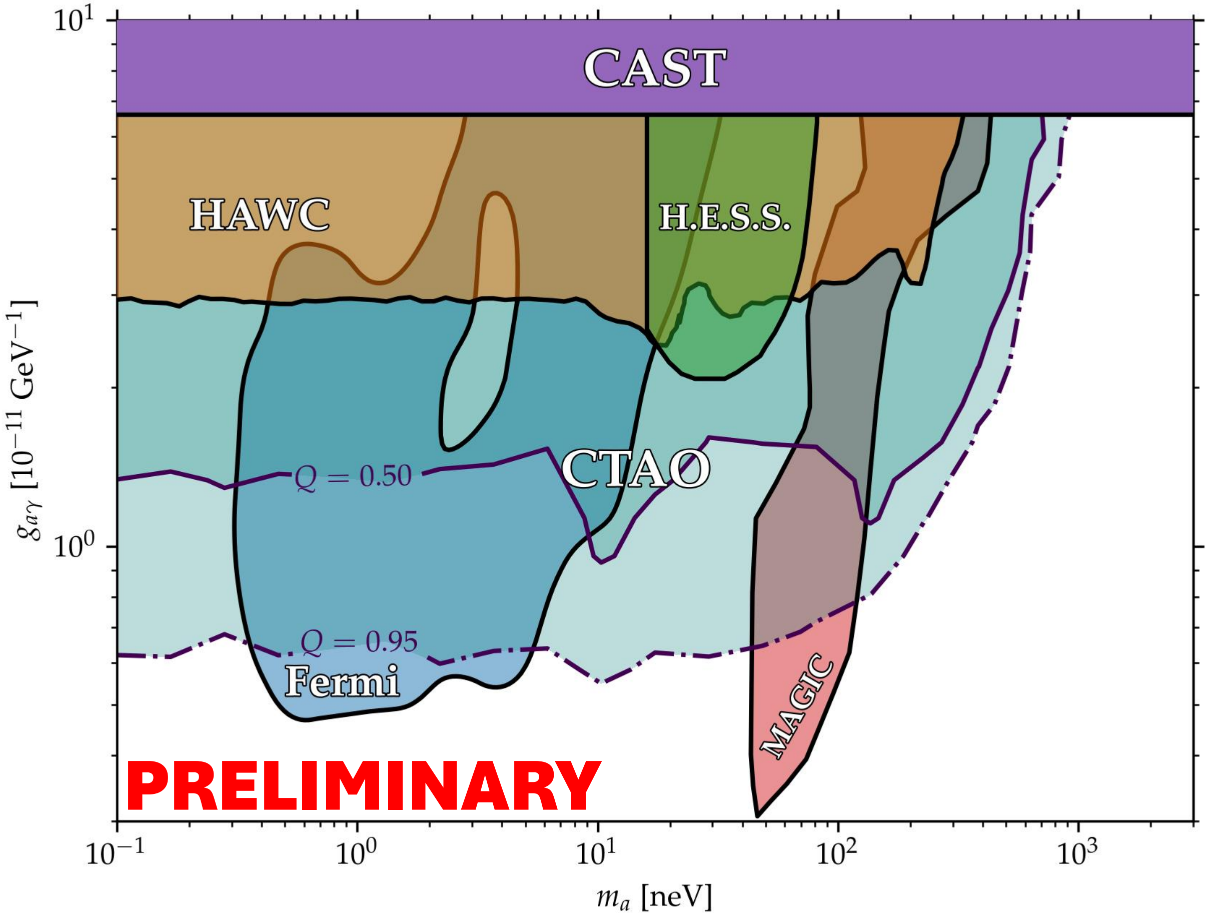


CTAO sensitivity limits



3σ sensitivity for discovering an ALP signal, combining both sources

Comparison with existing limits



Limits obtained from https://github.com/cajohare/AxionLimits/

What else to do…

- The effect of intergalactic magnetic fields, with ~ nG strengths but ~ Mpc extensions, may not be negligible [e.g. Montanino et al., arXiv:1703.07314]
- The CTA+ enhancement of the CTAO South site may unlock a greater sensitivity to low-energy spectral oscillations
- In any case, a better modelling of magnetic field environments and source spectra will be needed to give more accurate estimates
- Finally, considering more sources will increase statistics and thus sensitivity

Thank you for your attention!

All comments and suggestions welcome :)

francesco.schiavone@ba.infn.it

francesco.schiavone@cta-consortium.org

Backup

Null TS distribution

$$\mathrm{TS_{null}} = -2\ln\frac{\mathcal{L}(g_{a\gamma}=0)}{\mathcal{L}_{\max}} \qquad \mathcal{L}_{\max} = \mathcal{L}\big|_{\mu=N_{\mathrm{ON}}-\alpha N_{\mathrm{OFF}},\, b=N_{\mathrm{OFF}}}$$