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AXION-LIKE PARTICLES SEARCHES

Gamma arQus school, UIB, September 2022

SUMMARY

1. What are axion-like particles (**ALPs**)?
2. Motivation – interaction with photons
3. Experimental search for axion-like particles (**ALPs**)
4. Imaging atmospheric Cherenkov telescopes – **MAGIC**
5. **HANDS - ON**

   ALPs study – **NGC1275**

   a. Data selection
   b. Spectrum analysis – fitting
   c. ALPs analysis – photon survival probability
   d. Likelihood calculations – ALPs constraints

WHAT ARE AXION-LIKE PARTICLES (**ALPS**)?

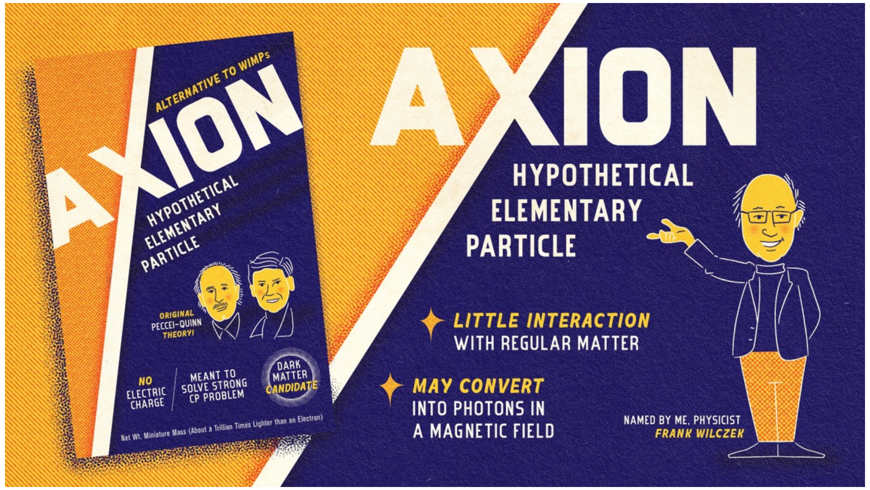
- Pseudoparticles of spin 0 – pseudobosons
- Solution to the strong CP problem in Standard model of particles - consequence of breaking of pseudosymmetry – **AXION**
- Generalisation of axion → axion – like particles
- Still not found! Would be a great success (free visit to Stockholm)

- In special cases they are great candidates for Dark Matter!

MOTIVATION-INTERACTION WITH PHOTONS

- Photon-ALP mixing in **the external magnetic field** – experimental search
  - Explanation of the irregularities in the AGN spectra?
  - Increasing the transparency of the Universe to the VHE gamma rays?

➢ Experimental search: helioscopes, haloscopes, **IACTs**...



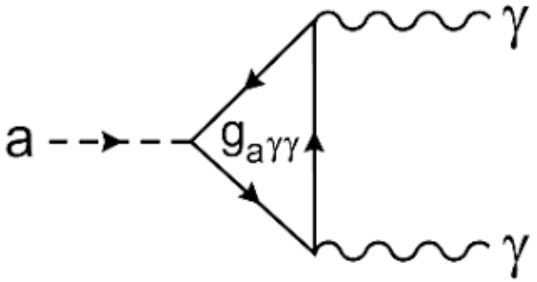


Figure 1: Feynman diagram of photon-**ALP** interaction

MOTIVATION-INTERACTION WITH PHOTONS

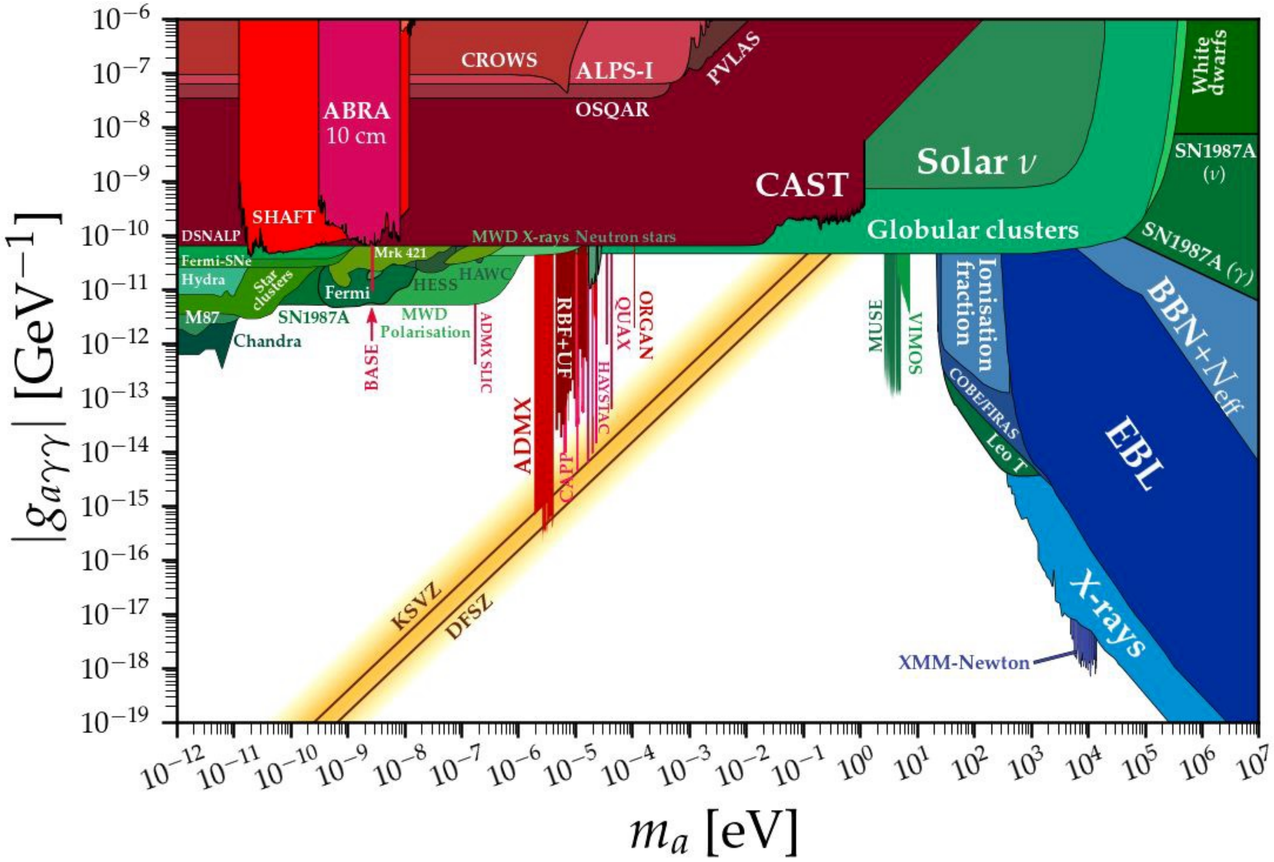


Figure 2: Constraints in the ALPs parameter space, credit: https://cajohare.github.io/AxionLimits/docs/ap.html

MOTIVATION-INTERACTION WITH PHOTONS

- **Observable effect 1:**
  - **Irregularities (wiggles)** in the spectrum of astrophysical objects – un-explained so far – failed attempts to explain them with the effects of EBL (Extragalactic background light – photons in the Universe coming from the evolution of the stars and active galactic nuclei (AGN))

    – possible solution: **ALPs!**

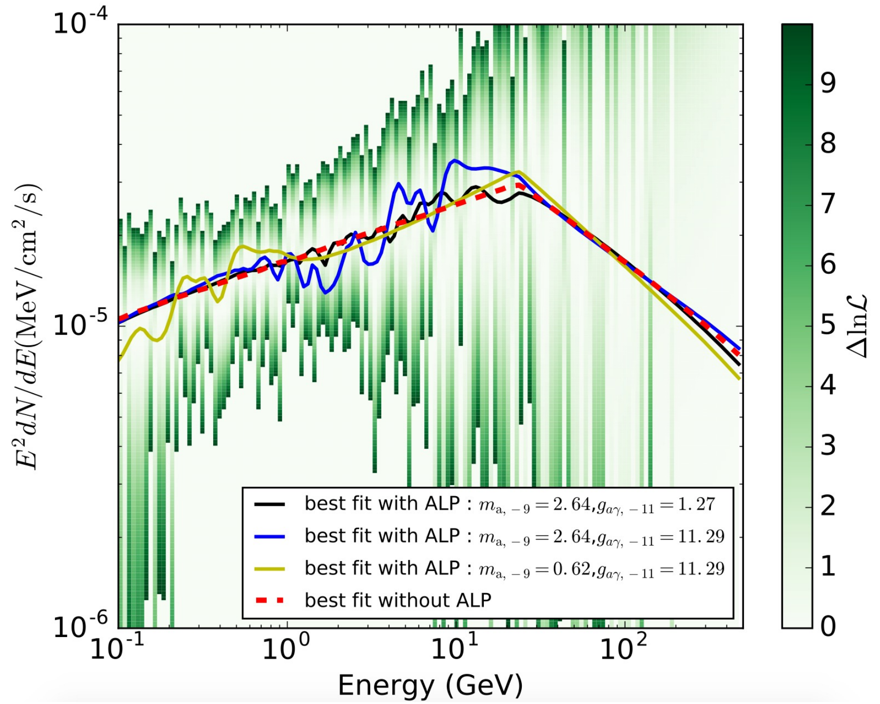


Figure 3: Spectrum fit of PKS2155-304 w & w/o ALPs, arXiv:1311.3148

MOTIVATION-INTERACTION WITH PHOTONS

- **Observable effect 2:**
  - **Spectral hardening**: increase of the photon count on the TeV energies - increasing the transparency of the Universe to the VHE gamma rays (E > 200 GeV) – EBL models not sufficient to explain it

    – possible solution: **ALPs!**

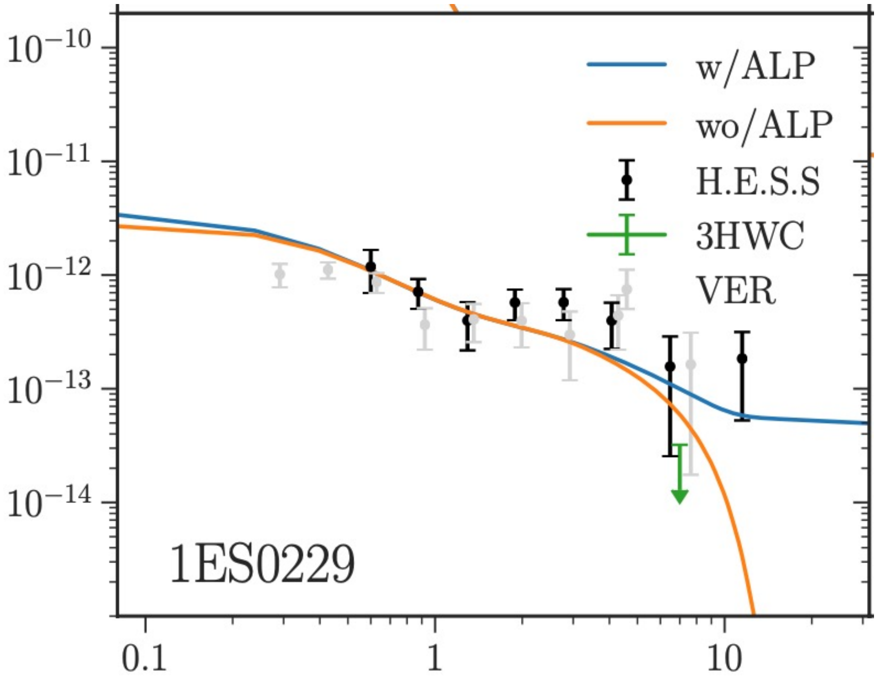


Figure 4: Simulated flux spectra w & w/o ALPs; Jacobsen et al., arXiv:2203.04332

MOTIVATION-INTERACTION WITH PHOTONS

1. Mixing in the blazar + jet

4. Mixing in the **Milky Way**

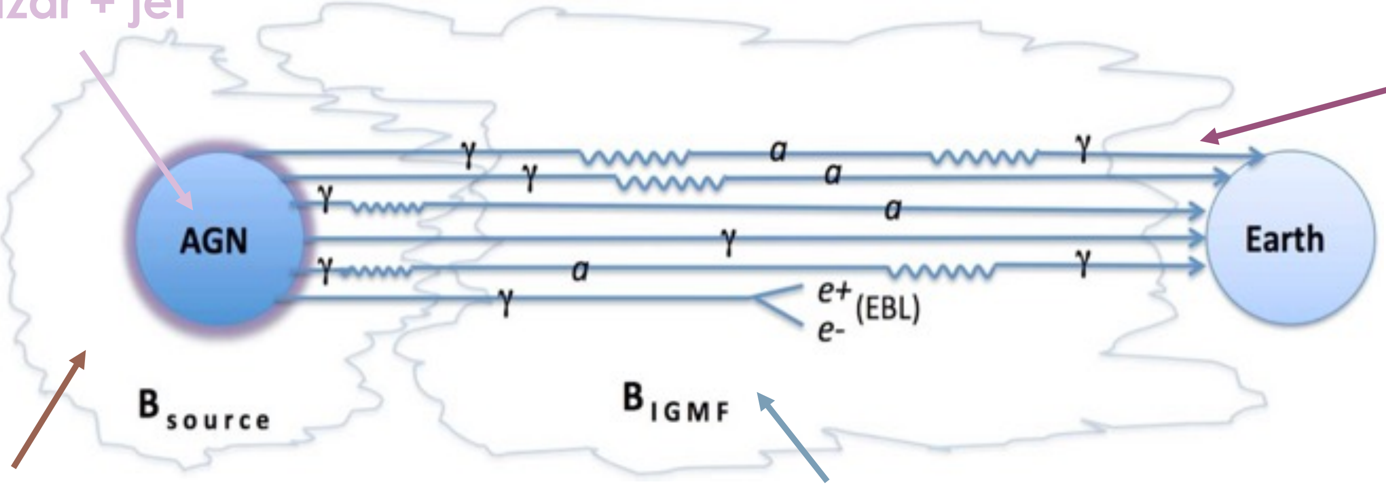


Figure 6: Photon-ALP mixing in the magnetic field, credit: arXiv:0905.3270

2. Mixing in the **galaxy cluster**

3. Mixing in the **extragalactic space** + ($\gamma + \gamma \rightarrow e^{+} + e^{-}$)

KNOWLEDGE OF THE **MAGNETIC FIELDS** IS FUNDAMENTAL FOR PRODUCING THE **ALPS** MODELS!

MOTIVATION-INTERACTION WITH PHOTONS

- We are searching for irregularities that occur around the critical energy:

$$E_{crit} = 2.5\ GeV \frac{\left|m^2_{a,neV} - \omega^2_{pl,,neV}\right|}{G_{11} B_{\mu G}}$$

- 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
- Parameter space to be searched (m_a , $g_{a\gamma}$) is determined by telescope's energy range, for **IACT**s;

$$10^{-9}\ \mathrm{neV} \leq\ m_a \leq 10^{-6}\ \mathrm{neV}$$

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

MOTIVATION-INTERACTION WITH PHOTONS

- **Photon survival probability**: probability that once emitted photon will be detected with the instrument
- Needed to create models of photon-**ALP** interaction effect on the photon flux from a gamma-ray source

HANDS-ON SPOILER

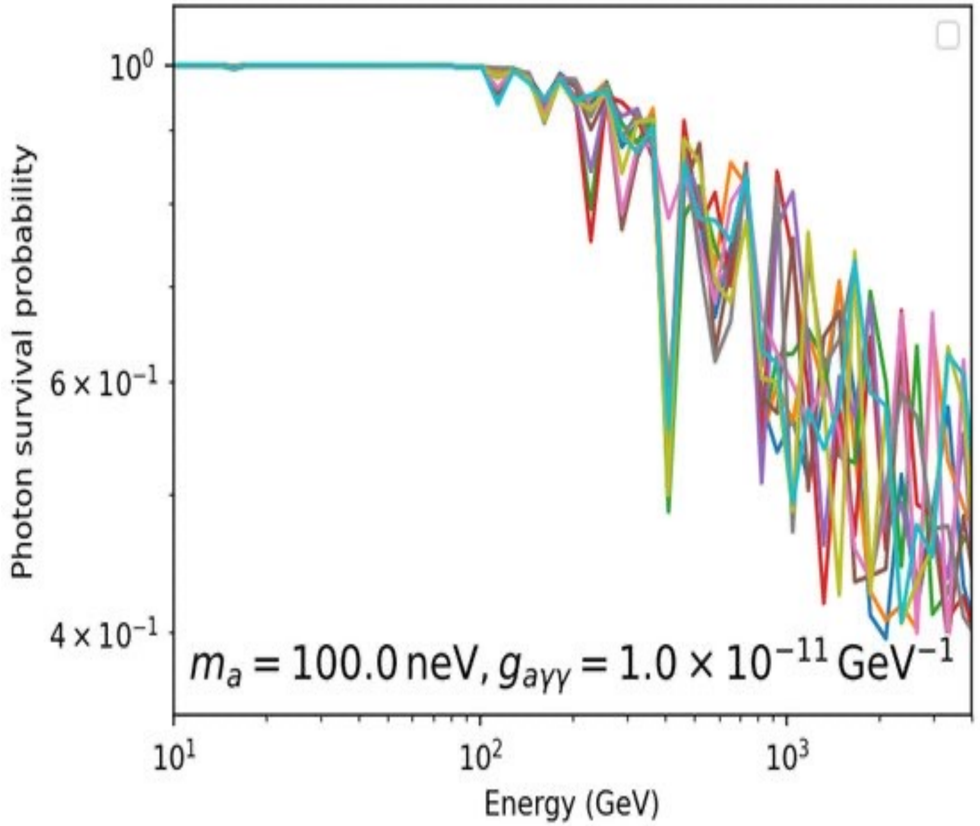


Figure 5: Photon surivial probability, (https://github.com/me-manu/gammaALPs)

EXPERIMENTAL SEARCH FOR **ALPS**

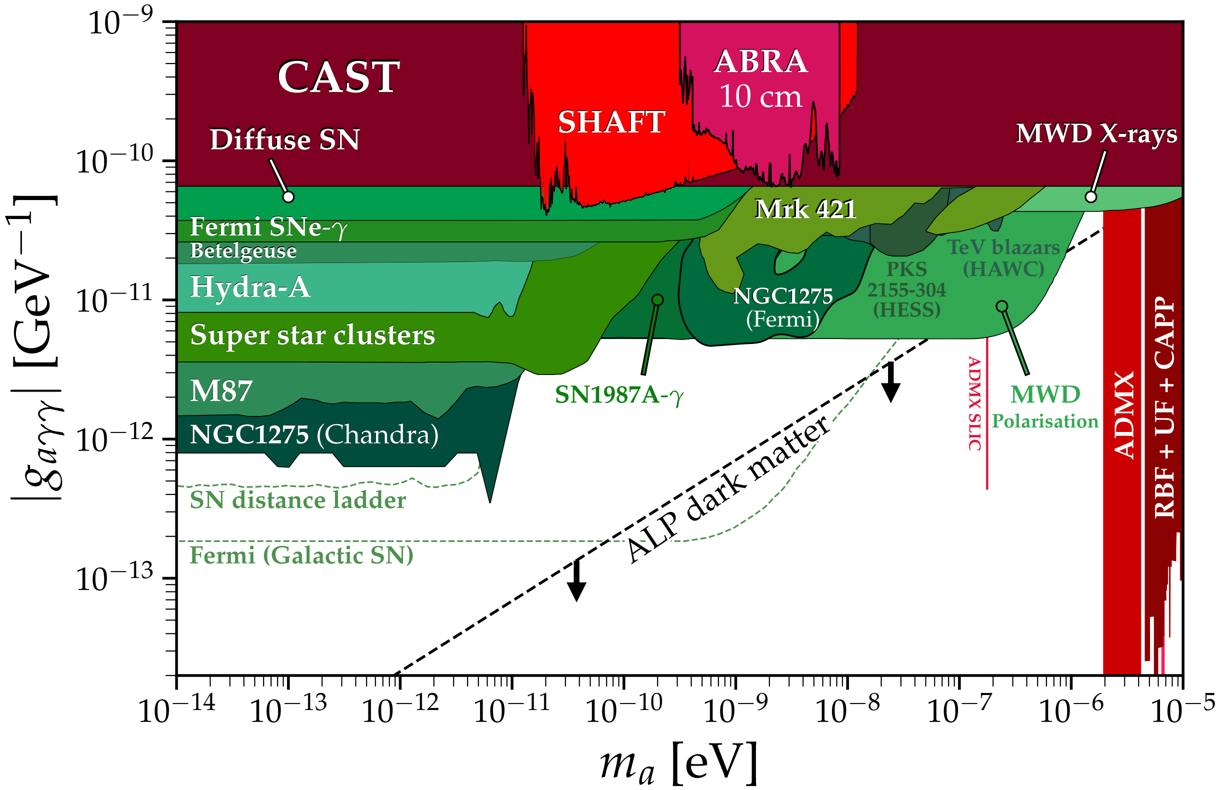


Figure 6: Constraints in the ALPs parameter space, astro closeup, credit: https://cajohare.github.io/AxionLimits/docs/ap.html

- **Helioscopes:** looking for solar axions, in e.g. CAST
- **Haloscopes:** resonanting microwave cavities looking for dark matter axions, in e.g. ADMX
- **Astrophysical constraints:** X-rays, γ-rays…(supernova, galaxy clusters, blazars…)

EXPERIMENTAL SEARCH FOR **ALPS**

- **Helioscopes**

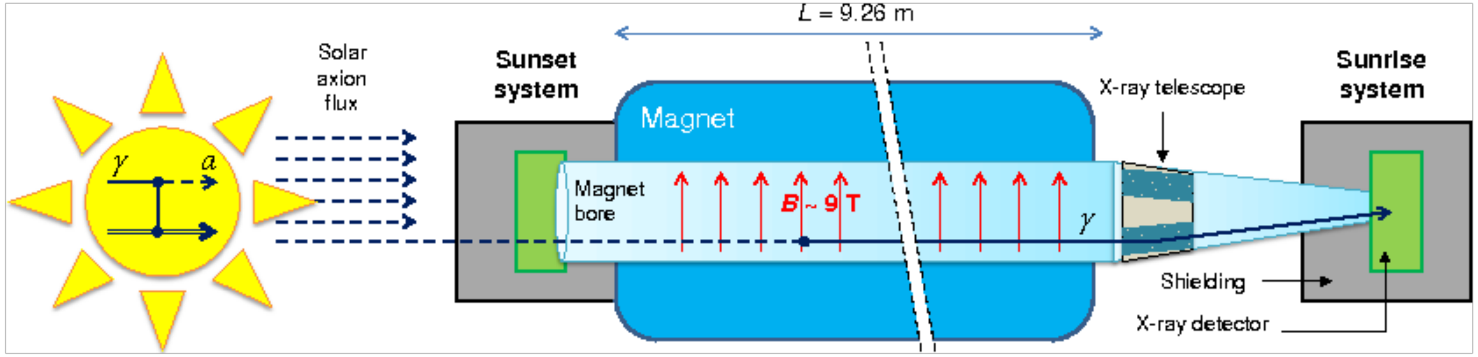


Figure 7: CAST experiment scheme, Nat. Phys., 13, 584–590 (2017)

Most stringent constraint on the axion coupling up to date (Nature Physics, 13, 584–590 (2017)):

$$g_{a\gamma} < 6.6 \times 10^{-11} GeV^{-1}$$

- Most famous example: **CAST**
- Uses a 9.26 m long superconductive magnet capable of producing magnetic field up to 9.5 T (former LHC magnet) to detect photons produced in Primakoff conversion of axions in the Sun's core

EXPERIMENTAL SEARCH FOR **ALPS**

- **Haloscopes**
- Most famous example: The Axion Dark Matter eXperiment (**ADMX**)
- Uses microwave cavity inside of a large superconducting magnet (8 T) with the possibility of shifting the frequency to search for axions with masses around μeV

Ruled out dark matter axions (Phys.Rev.Lett., 127, 26, 261803, 2021):
$\mathbf{3.3\ \mu eV < m_a < 4.2\ \mu eV}$

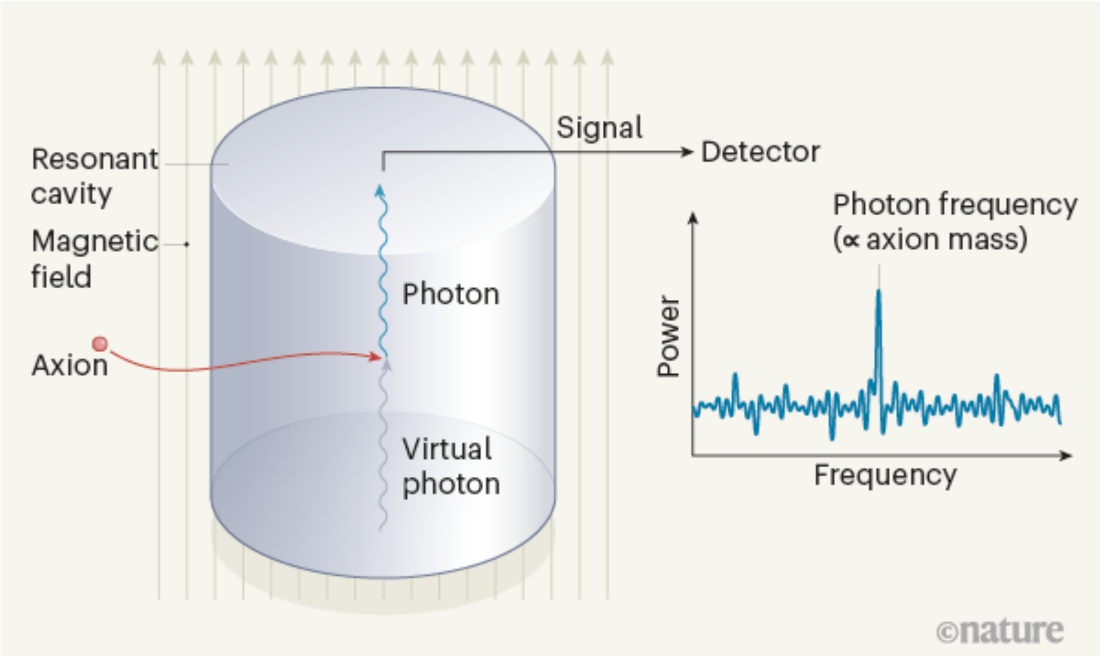


Figure 8: ADMX experiment scheme, Nature 590, 226-227 (2021)

EXPERIMENTAL SEARCH FOR **ALPS**

- **Astrophysical constraints**
- In example: IACTs (Imaging Atmospheric Cherenkov Telescope): Veritas, HESS, MAGIC
- Constraints so far:

  H.E.S.S.: Abramowski, A. et al.: *Phys. Rev. D* 2013, *88*, 102003.

  FERMi-LAT: Ajello, M. et al.: *Phys. Rev. Lett.* 2016, *116*, 161101.

  CTA: Abdalla, H. et al.:. *J. Cosmol. Astropart. Phys.* 2021, *2021*, 48

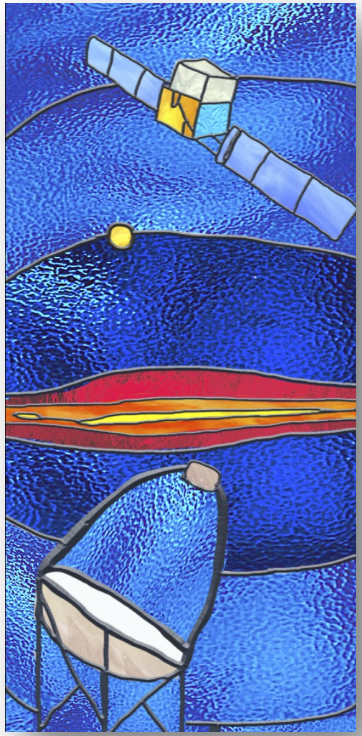


Figure 9: LST1 telescope

IMAGING ATMOSPHERIC CHERENKOV TELESCOPES (IACTS)

- **Observing extensive atmospheric showers**

- Cascades of subatomic particles in the atmosphere

  → Cherenkov light
- Detecting gamma-rays in the energy range of 25 GeV - 100 TeV
- Field of view ~ 3.5°
- Angular resolution ~ 0.1° (energy dependent)

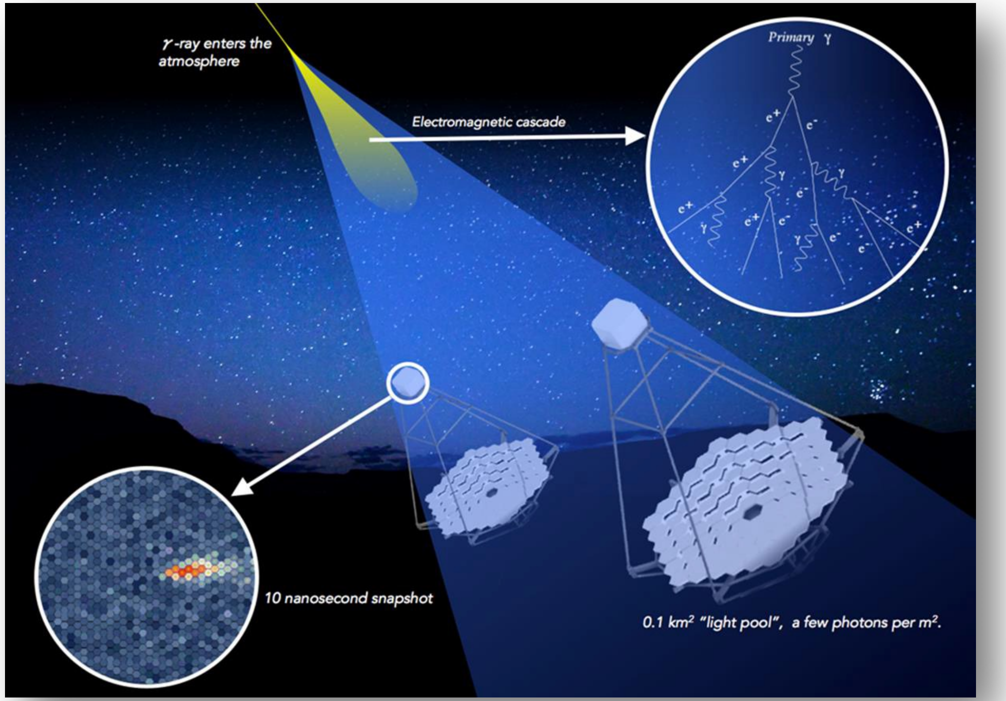


Figure 10: Detection of atmospheric showers, CTA Observatory

IACTS – MAGIC EXPERIMENT

- Two Imaging Atmospheric Cherenkov telescopes located in Observatory Roque del Muchachos on the Canary island of La Palma
- 17 m diameter
- Operating since 2003, in stereo mode from 2009
- At the altitude of ~ 2240 m
- International collaboration of about 300 members from 13 countries

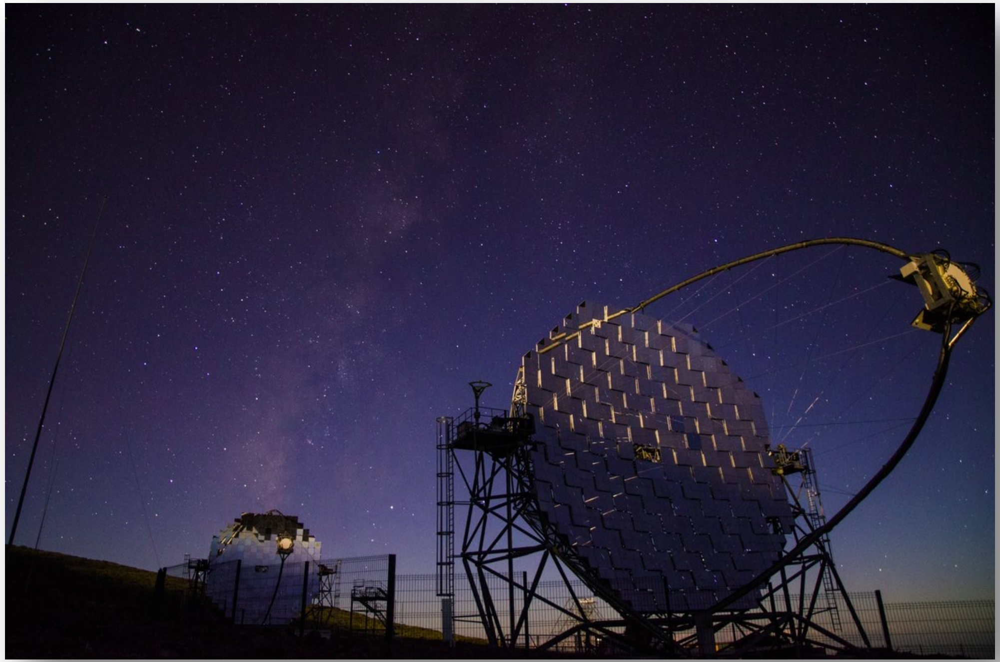


Figure 11: MAGIC telescopes, Credit: Chiara Righi

ALPS ANALYSIS OF IACT DATA - KEYWORDS

- **Active galactic nuclei** – active (accreting) supermassive black hole in the center of a galaxy
- **ɣ-ray flux** – rate of ɣ–rays per unit area $(cm^{-2}s^{-1})$
- **Gammapy –** open-source Python package for gamma-ray astronomy
- **Smooth function – PWL** (power-law), **EPWL** (power law with exponential cutoff), LP (log parabola), **ELP** (log parabola with exponential cutoff)

ALPS ANALYSIS OF IACT DATA – STEPS

1. Choose the source of the gamma-rays
2. Use the **gammapy** to obtain the source spectrum
3. Fit it with a smooth function (**PWL**, **EPWL**, **LP**, **ELP**...)
4. Calculate the photon survival probability using the **GammaALPs** package
5. Multiply the “**intrinsic fit**” with the photon survival probability
6. Evaluate the fit using the binned likelihood function and search for the nuisance parameters that maximise the likelihood
7. Set the constraints on the **ALPs** parameter space

CHOICE OF THE SOURCE

a. Extragalactic source of radiation – **ACTIVE GALACTIC NUCLEI**

b. Gamma-ray radiation – **Cherenkov telescopes**

c. Larger data base → more precise analysis and radiation spectrum

d. High flux states of the source: **flaring states**

Our choice:

NGC1275 in the center of the Perseus galaxy cluster
(distance: z=0.01 → 71,774,000 pc)

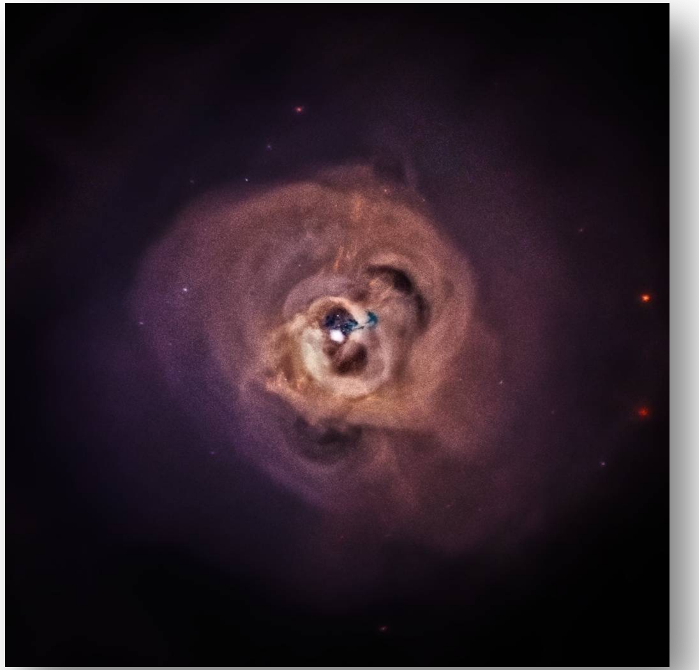


Figure 12: Perseus galaxy cluster, credit: NASA/CXC/SAO/E.Bulbul, et al.

IACT SPECTRAL ANALYSIS AND FITTING THE SPECTRUM TO A SMOOTH FUNCTION

- **Gammapy** package
- Ɣ-ray flux: $\Phi = \frac{d^2 N_\gamma}{dSdt}$
- Differential energy spectrum: $\frac{\mathrm{d}\Phi}{dE} = \frac{d^3 N_\gamma}{dSdtdE}$
- Spectral energy distribution (SED): $\mathrm{E}^2 \frac{d\Phi}{dE}$
- Fitting the SED to an EPWL
- HANDS-ON

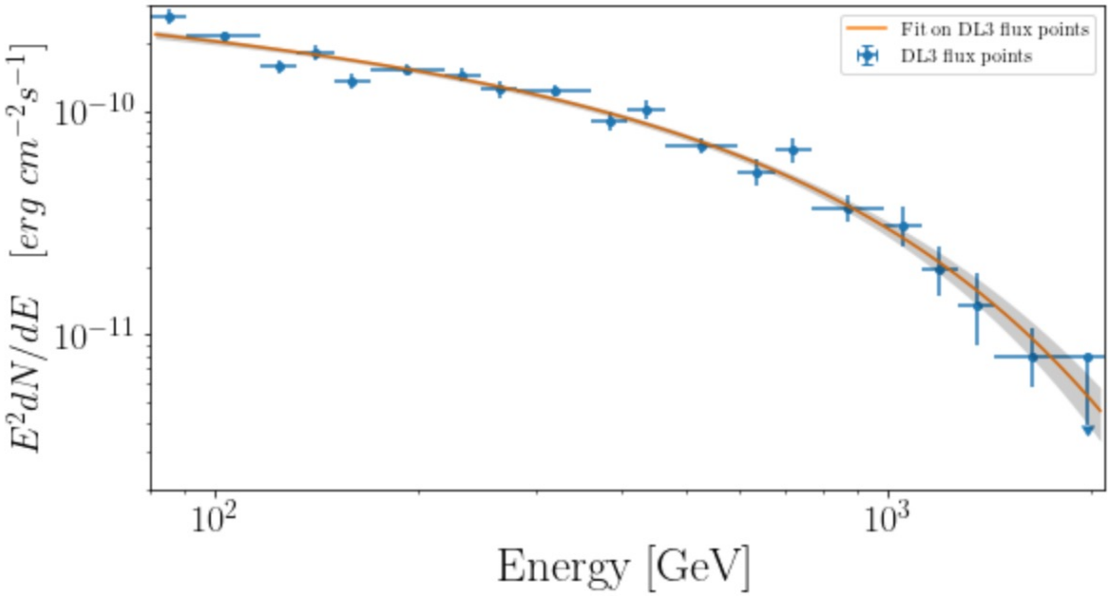


Figure 13: SED with intrinsic fit (EPWL)

PHOTON SURVIVAL PROBABILITY

- Using the **GammaALPs** code – HANDS-ON
- Photon survival probability:

$$P_{a\gamma\gamma} = \sin^2(2\theta)\sin^2\left[\frac{g_{a\gamma}Bs}{2}\sqrt{1+\left(\frac{\varepsilon}{E_\gamma}\right)^2}\right]$$

- Absorbed (with ALPs) spectrum:

$$EPWL \times p_{\gamma\gamma}$$

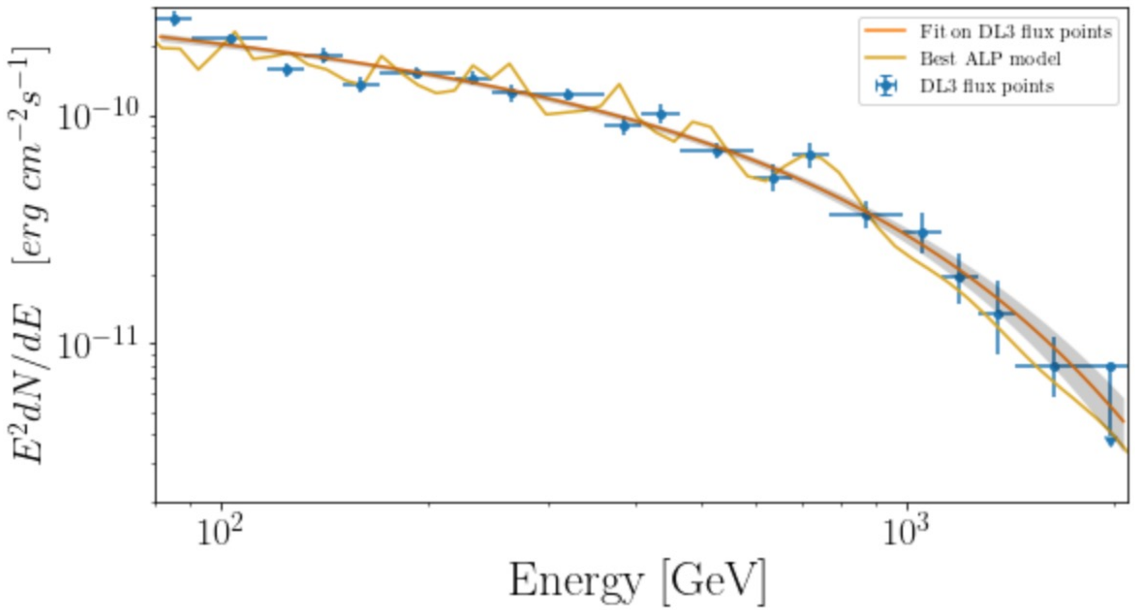


Figure 14: Comparison of ”intrinsic” and “ALP absorbed” spectrum

BINNED LIKELIHOOD

- Binned likelihood:

$$\mathcal{L}(\theta, b) = \mathcal{L}\left(m_a, g_{a\gamma}; B, \Gamma, \Phi_0, E_c \middle| b\right)$$

- We search for the nuisance parameters (Γ, Φ_0, E_c) that maximise the likelihood
- In the case of **ALPs**, due to the unknown magnetic field, random magnetic field realisations have to be employed to calibrate the test statistics for excluding the **ALPs** parameters.

CONSTRAINTS ON THE ALPS PARAMETER SPACE

- STANDARD PROCEDURE:

Use the Wilks' Theorem to convert a TS value into a significance with which one can reject the null hypothesis

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- STANDARD PROCEDURE:

Use the Wilks' Theorem to convert a TS value into a significance with which one can reject the null hypothesis

- Not applicable in this situation!

Reasons:

1. The spectral irregularities do not scale linearly with the ALP parameters
2. Under the null hypothesis, the likelihood values are independent of the magnetic-field realizations.
3. Photon-ALP oscillations are completely degenerate in coupling and magnetic field

CONSTRAINTS ON THE ALPS PARAMETER SPACE

SOLUTION:

SIMULATIONS OF THE DATASETS

- How is the TS distributed in our case, how in the case of the null hypothesis and how if we include the effects of the ALPS?

- HANDS ON – SNEAK PEEK

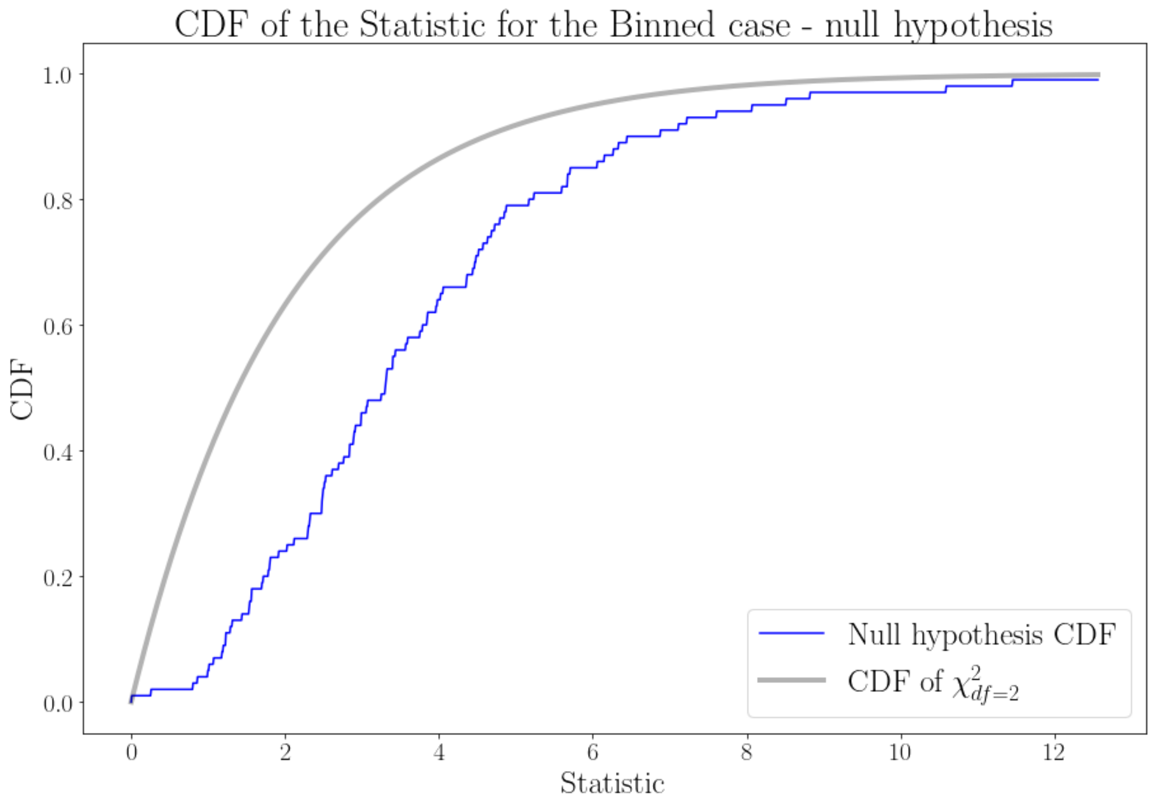

Figure 15: Distribution of the test statistics in the case of null hypothesis

CONSTRAINTS ON THE ALPS PARAMETER SPACE

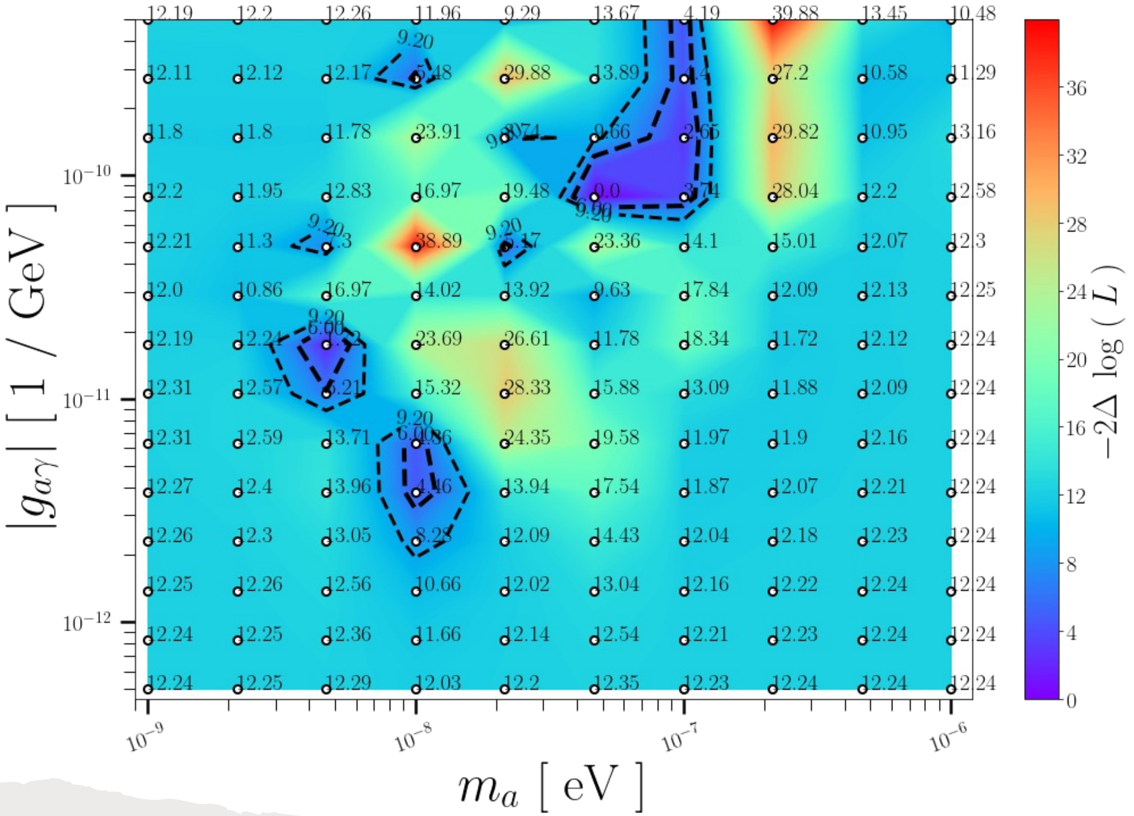

Figure 16: Constraints on the ALPs parameter space **BEFORE** the calibration of the TS

WHAT ABOUT AFTER THE CALIBRATION??

FUTURE PROSPECTS ON ALPS SEARCHES IN VHE RANGE

- CTA – projected limits
- Studies of blazars – detailed models for the jet magnetic field needed
- Improved understanding of the systematical uncertainties and statistical analysis
- ...

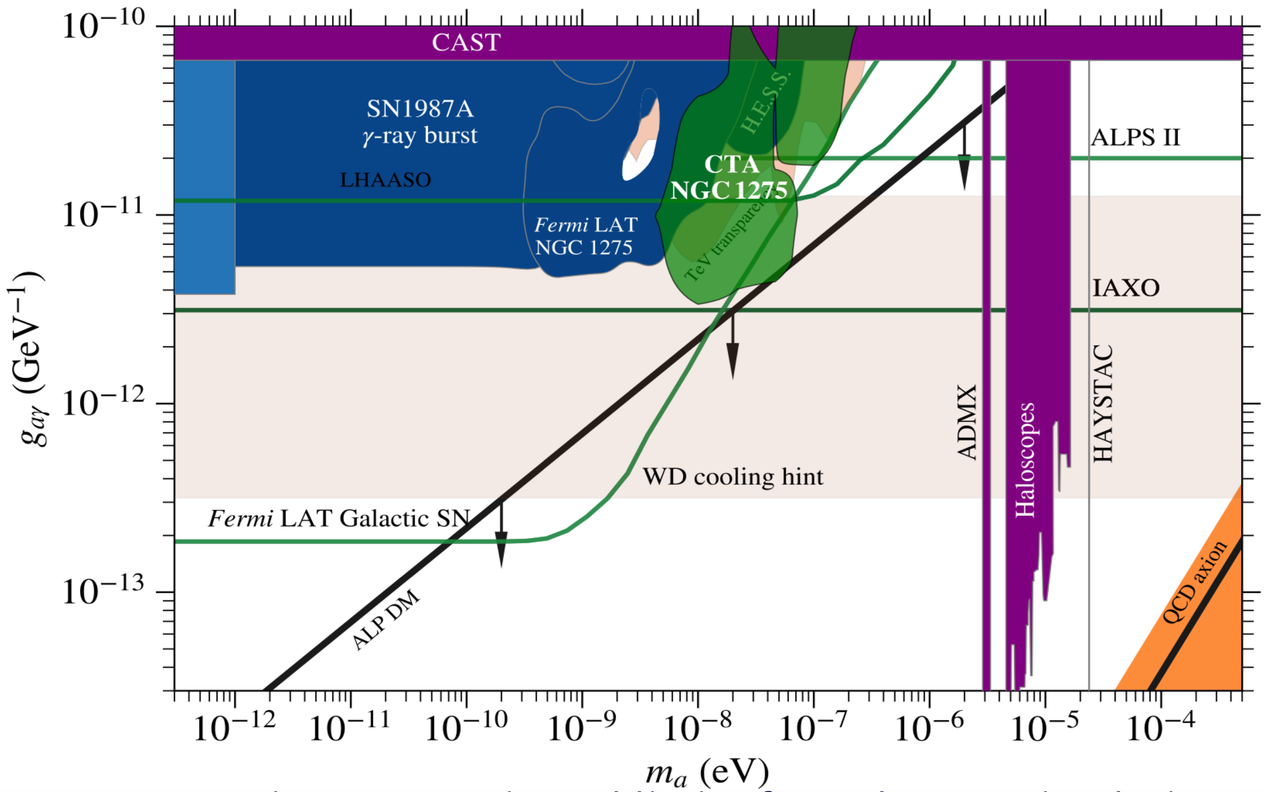

Figure 17: Projected limits from the CTA simulations, Abdalla, H. et al., doi:10.1088/1475-7516/2021/02/048

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THANK YOU FOR THE ATTENTION!

IT'S HANDS ON TIME!

HANDS ON

GammaALPs notebooks:

/arqus_school_2022/alps/gamma_intro/alps/Pyy_models/gammmaALPs_NGC1275.ipynb

Gammapy & **ALPs** analysis:

/arqus_school_2022/alps/gamma_intro/alps/ngc1275_alps_analysis.ipynb