EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Axions in physics and astrophysics

D. Malyshev,
A.Neronov, D.Semikoz, A.Santangelo, J.Jochum

Tübingen University

June 13, 2018

Overview

1. Not Only Theoretical motivation
   - QCD Lagrangian
   - Neutron electric dipole momentum
2. ALPs in cosmology
   - ALPs as a dark matter
   - Cosmological bounds
3. Indirect ALPs detection
   - Ways to detect
4. Astrophysical constraints on ALPs
   - Most interesting astrophysical constrains on ALPs
     - SN 1987A
     - TeV transparency of the Universe
     - Photon-Axion conversion in the clusters of galaxies
5. What's next?

Most generic QCD Lagrangian

A "text-book" QCD Lagrangian is CP-invariant

$$\mathcal{L}_{QCD} = -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + i\bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} M \psi$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu - \text{gluon field strength tensor}$$

$$A - \text{gluons}$$

$$\psi - \text{quarks}$$

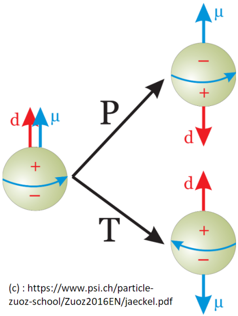
But it is not the most general form of 4-scalar built from G.
θ-term can be added:

$$\mathcal{L}^{VCP}_{QCD} \sim \mathcal{L}_{QCD} + \theta \varepsilon^{\mu\nu\alpha\beta} G_{\mu\nu} G_{\alpha\beta}$$

θ - term behaves similar to $\vec{E} \cdot \vec{B}$ in QED.
Due to θ-term $\mathcal{L}^{VCP}_{QCD}$ is **CP-violating** and **T-violating**

CP-violation... So what?

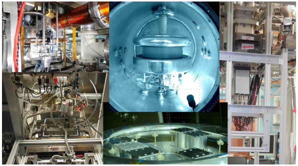
- Any quark-built particle with electric dipole and magnetic momenta violates T (and CP) symmetries (ok, we expect this with $\mathcal{L}_{QCD}^{VCP}$)
- Neutron consists of (udd) quarks and has very well measured magnetic momentum

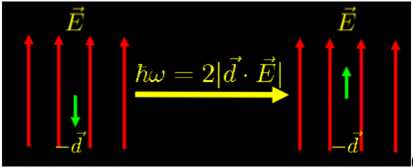


(c) : https://www.psi.ch/particle-zuoz-school/Zuoz2016EN/jaeckel.pdf

- Neutron electric dipole momentum (nEDM): $d \sim e \times \text{length} \times \theta \sim e \times \frac{m_q}{\Lambda_{QCD}^2} \times \theta \sim (3..30) \cdot 10^{-16} \times \theta [e \cdot \text{cm}]$
- Very similar result from naive estimation – neutron is a particle consisting of 3 charged quarks.

Strong CP problem





(c): psi.ch

nEDM $=0$ – CP holds ; nEDM >0 – CP violates

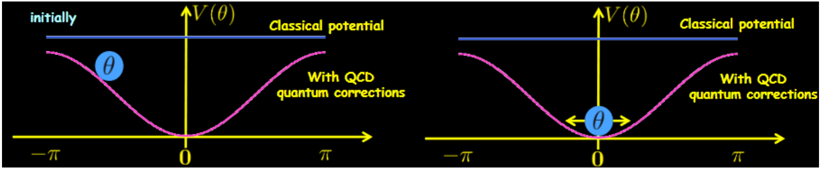
Strong CP problem:

- Current experimental limit $d < 3 \cdot 10^{-26}$ [$e\cdot$ cm]
- CP holds. Tiny, consistent with zero θ. Fine tuning!

Zero θ is just a coincidence? Don't think so...

- CP is *not* fundamental symmetry and is known to be violated in weak interactions (kaon, b-meson decays)
- Cosmological requirements for CP-violation (baryogenesis)

Introducing axion/ALP



(c):https://www.psi.ch/particle-zuoz-school/Zuoz2016EN/jaeckel.pdf

Solution for strong CP problem – make θ dynamical *variable*.

- Produced with non-zero value after some time it can relax to zero. New particle gained – *axion*! ($\sim$ 1977 Peccei,Quinn+)
- Historically axion – particle with specific $m_a - g_a$ relation
- More general type of particles – ALPs (axion-like particles)
- ALPs are (generally) light, since CP violation is tiny
- ALPs are WISPs – Weakly Interacting Sub-eV Particles

ALPs as a dark matter

Can ALPs play a role in cosmology/astrophysics ?

Successful dark matter candidate:

- Massive particles $\rightarrow$ ok!

ALPs as a dark matter

Can ALPs play a role in cosmology/astrophysics ?

Successful dark matter candidate:

- Massive particles → ok!
- Non-relativistic (CDM/WDM) → ok! (not that obvious!)
- Produced in Early Universe → ok! (not that obvious!)

- Despite of low mass ALPs indeed can be produced in early universe out of thermal equilibrium via vacuum realignment or topological production mechanisms (see e.g. 1712.03018 and 0904.3346)

ALPs as a dark matter

Can ALPs play a role in cosmology/astrophysics ?

Successful dark matter candidate:

- Massive particles → ok!
- Non-relativistic (CDM/WDM) → ok! (not that obvious!)
- Produced in Early Universe → ok! (not that obvious!)
- Weakly-interacting (to survive cosmological time) → ok!

ALPs as a dark matter

Can ALPs play a role in cosmology/astrophysics ?

Successful dark matter candidate:

- Massive particles → ok!
- Non-relativistic (CDM/WDM) → ok! (not that obvious!)
- Produced in Early Universe → ok! (not that obvious!)
- Weakly-interacting (to survive cosmological time) → ok!
- (Optional) Other than DM motivation/manifestation → ok!

ALPs as a dark matter

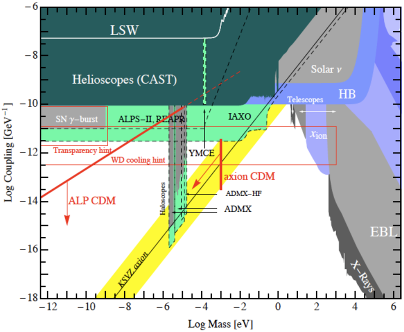
Can ALPs play a role in cosmology/astrophysics ?

Successful dark matter candidate:

- Massive particles → ok!
- Non-relativistic (CDM/WDM) → ok! (not that obvious!)
- Produced in Early Universe → ok! (not that obvious!)
- Weakly-interacting (to survive cosmological time) → ok!
- (Optional) Other than DM motivation/manifestation → ok!

- Indeed, ALPs are good dark matter candidate!
- Note: ALPs can exist and *not* to be a dark matter!

Cosmological bounds on ALPs parameters



(c):1306.6088

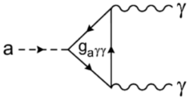
- Arise from comparison of (model-dependent) amount of ALPs produced in Early-Universe to Ω_{CDM}
- Not-unavoidable, but rather order-of-magnitude estimation!
- Functional form

$$\Omega_a \sim m_a^{1/2} g_a^{-2} = const \quad ; \text{see 1210.5081}$$

Ways to detect

Axions are coupled to "direct observables" – photons via triangle diagrams.

Axion-two photon decay

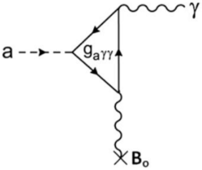


One-to-one correspondence between photon energy E_γ and axion mass m_a:

$$E_\gamma = m_a/2$$

$$\Gamma = 7.6 \cdot 10^{-26} \left(\frac{g_a}{10^{-10} GeV^{-1}}\right)^2 \left(\frac{m_a}{1eV}\right)^3 s^{-1}$$

Primakoff process



In a presence of (electro) magnetic field axion can be converted to a photon and v.v: photon-axion oscillations

Primakoff process

- General case:

$$(E - i\partial_z - M)\vec{A} = 0; \vec{A} = \begin{pmatrix} A_x \\ A_y \\ a \end{pmatrix}$$

M – real symmetric 3x3 matrix ; $M = M(m_a, g_a, \vec{B}(z), n_e(z))$
$P_{\gamma\to a} \propto |AA^\dagger|^2 = P_{\gamma\to a}(E_\gamma, s, \vec{B}, n_e, m_a, g_a)$

- Formal solution for $\vec{A}$ after traveling distance s with magnetic field domain size δz:

$$\vec{A} = \prod_{j=1}^{s/\delta z} \exp\left(iM(z_j)\delta z\right)\vec{A}(0)$$

- Exact $P_{\gamma\to a}$ known for 1 and ∞ magnetic domains.

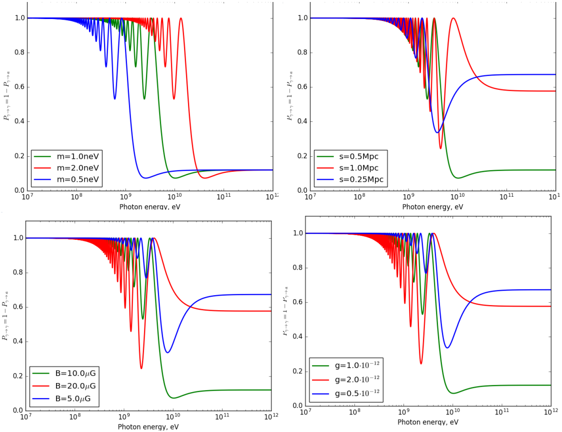
Primakoff process

- For fixed m_a $P_{\gamma\to a}$ has local maxima at certain photon energies $E_{\gamma,\max}(B, n_e)$ – resonant axion production. At these energies we expect features in spectra of astrophysical objects.
- NO one-to-one correspondence: m_a can be very different from $E_{\gamma,\max}$
- For objects with known $\vec{B}$ and n_e we can probe axion mass range for which $E_{\gamma,\max}$ are located in "preferable" band (keV, GeV, TeV).
- (Non)Detection of such spectral features can allow constrain $m_a - g_a$ parameter space or find axions.

Examples of $P_{\gamma\to a}$ in astrophysics

For most of astrophysical objects one of two regimes works:

- Magnetic field dominating regime:



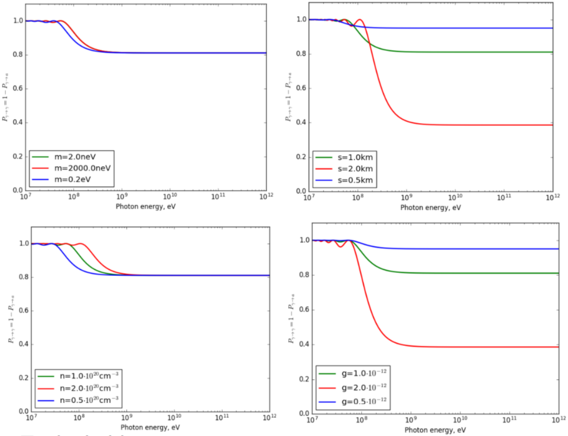
Oscillations' energy strongly correlate with m_a and strength – with g_a and B.
Generally strong constraints on $m_a - g_a$, but in narrow axion mass range

Typical object: cluster of galaxies: large distance, low B, $n_e \sim 0$

Examples of $P_{\gamma\to a}$ in astrophysics

For most of astrophysical objects one of two regimes works:

- Plasma dominating regime:



Oscillations' energy strongly correlate with n_e and strength – with g_a and B. $P_{\gamma\to a}$ almost does not depend on m_a! Weak constraints but in broad $m_a - g_a$ range.

Typical object: magnetars or SNs, small distance, high B and n_e

Astrophysical ways to constrain ALPs

1. Spectral line from axion-two photon decay can be used for searches of ALP-dark matter.

Astrophysical ways to constrain ALPs

1. Spectral line from axion-two photon decay can be used for searches of ALP-dark matter.
   - Remember: ALPs are not necessary dark matter!
   - Can be complicate for low (radio–optics) energies and axion mass (remember $E_\gamma = m_a/2$)

Astrophysical ways to constrain ALPs

1. Spectral line from axion-two photon decay can be used for searches of ALP-dark matter.
   - Remember: ALPs are not necessary dark matter!

2. Spectral features in spectra of astrophysical objects from Primakoff effect
   - Remember: m_a can be different from spectral feature energy!

Astrophysical ways to constrain ALPs

1. Spectral line from axion-two photon decay can be used for searches of ALP-dark matter.
   - Remember: ALPs are not necessary dark matter!

2. Spectral features in spectra of astrophysical objects from Primakoff effect
   - Remember: m_a can be different from spectral feature energy!
   - (non)detection of spectral feature in plasma/field dominated objects

Astrophysical ways to constrain ALPs

1. Spectral line from axion-two photon decay can be used for searches of ALP-dark matter.
   - Remember: ALPs are not necessary dark matter!

2. Spectral features in spectra of astrophysical objects from Primakoff effect
   - Remember: m_a can be different from spectral feature energy!
   - (non)detection of spectral feature in plasma/field dominated objects
   - (non)transparency of the medium to photons of some ($\sim$TeV) energies

Astrophysical ways to constrain ALPs

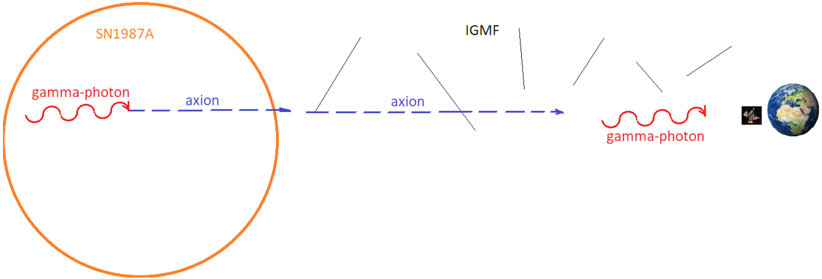
1. Spectral line from axion-two photon decay can be used for searches of ALP-dark matter.
   - Remember: ALPs are not necessary dark matter!

2. Spectral features in spectra of astrophysical objects from Primakoff effect
   - Remember: m_a can be different from spectral feature energy!
   - (non)detection of spectral feature in plasma/field dominated objects
   - (non)transparency of the medium to photons of some (∼TeV) energies
   - combination of both approaches

Astrophysical ways to constrain ALPs

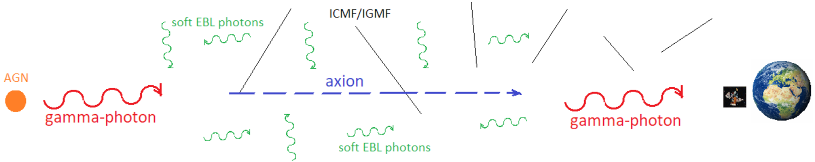
1. Spectral line from axion-two photon decay can be used for searches of ALP-dark matter.
    - Remember: ALPs are not necessary dark matter!
2. Spectral features in spectra of astrophysical objects from Primakoff effect
    - Remember: m_a can be different from spectral feature energy!
3. Changes in evolution of some objects (white dwarf cooling/massive stars evolution)

Most famous constraint: SN 1987A



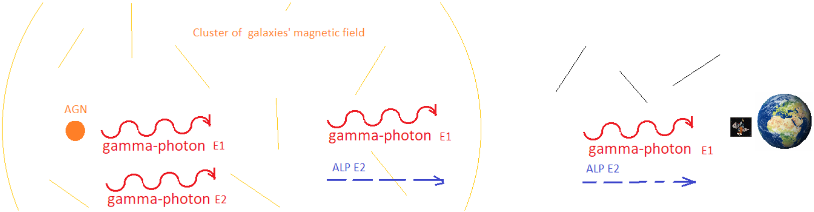
- Galactic supernova: first detection of astrophysical neutrino
- Neutrino signal implies high intrinsic photon flux – expected high ALP flux due to conversion in SN (dense plasma)
- ALPs travel through inter-galactic magnetic field to the Earth
- ALPs can be converted to photons during the travel
- no γ-rays have been seen (by SMM/GRS built for the Sun observations)
- tight, broad-band constraints on ALPs: $g_a < \ldots$

Most interesting constraint: lower-limit from transparency



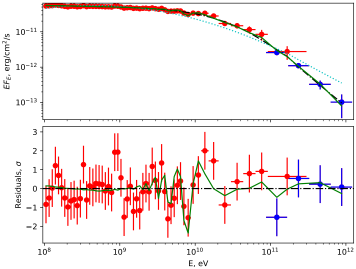
- VHE ($>$ 1 TeV) photons are effectively absorbed for distant sources (pair production with soft EBL photons)
- Some TeV signal/spectral hardening seen in distant AGNs
- Understood if some distance photons travel as ALPs
- *Lower* limit: $g_a > \ldots$
- A lot of assumptions: EBL spectral/density model ; ICMF/IGMF ; no intrinsic hardening of AGN spectra, etc...

Tightest constraints: AGN in galaxy cluster

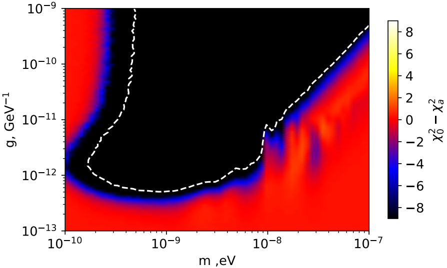


- Bright gamma/X-ray source (AGN) located within cluster of galaxies
- Spectral features ("absorption lines") can be produced by resonant photon-ALP conversion at certain energies
- Intrinsic spectrum believed to be featureless (powerlaw)
- Low-background objects at $\gtrsim$ 10 keV energies
- Key ingredient – magnetic field profile in a cluster

Photon-axion in Perseus cluster/NGC 1275



Fermi/LAT+MAGIC spectrum of NGC 1275 with the best-fit axion-absorption model



95% c.l. limits on $m_a - g_a$ parameter space derived from NGC 1275 spectrum; (c):1805.04388

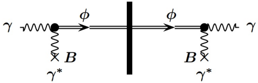
- Perseus cluster is one of the closest to us cluster of galaxies. NGC 1275 (central AGN) is a bright GeV-TeV source
- Fermi/LAT+MAGIC (0.01–1 TeV) data available
- Smooth spectrum with marginal ($\sim 2.5\sigma$ oscillations)
- Non-detection of oscillations $\rightarrow$ constraints on $m_a - g_a$

Few words on direct-detection experiments

Solarscope

- X-ray photons converted to axions inside of the Sun
- Converted back in a strong magnetic field
- Experiments: CAST, IAXO

Light through the wall



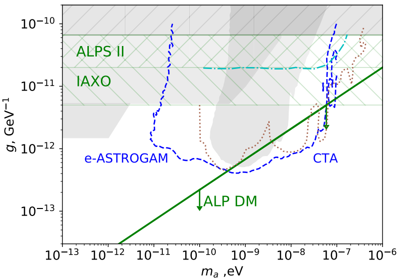
(c): https://alps.desy.de/

- Forth-and-back conversion in a magnetic field
- $\gamma \to a$
- wall
- $a \to \gamma$
- Experiments: ALPS, ALPS II

Resonant cavity

- DM axions resonantly convert to γ in a cavity with magnetic field
- Experiments: ADMX, ADMX-HF

What's next? Instead of conclusions



Next instruments within 10 years – e-ASTROGAM and CTA. Much broader energy range+higher data quality=better and broader exclusion region for ALP parameters (or detection?)

- Sensitivity of indirect searches is comparable to the sensitivity of the near future direct-detection experiments (IAXO,ALPS II), although in narrower mass range.
- See also arXiv:1805.04388

Really last slide!

- Any object with high magnetic field/plasma density can be used to probe "ALP-effects"
- Key element – knowledge of parameters $(\vec{B}, n_e)$ of the analyzed object
- Stacking analysis can significantly increase sensitivity
- This is not the end of the story with NGC 1275...

The End!

"One needs a particle to clean up a problem..."
–Frank Wilczek