Axions and dark sector searches

Javier Redondo
(Zaragoza U. & MPP)
- 1 big picture
- 2 types of ALPs
- 3 types of interactions
- 4 ~ hints of existence
- 5 ... Experiments to find them
- 6 Conclusions

Based on ...

New experimental approaches in the search for axion-like particles
References | BibTeX | LaTeX(US) | LaTeX(EU) | HarvMac | EndNote
ADS Abstract Service
Registro completo - Citado por 1 registro
Energy describes extremely well particle physics (at low energies).
Energy Standard Model

Describes extremely well particle physics (at low energies) but it is certainly ...

INCOMPLETE
Answers wait in the high energy frontier where more symmetric beautiful theories arise.
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Answers wait in the high energy frontier where more symmetric beautiful theories arise ... often implying new low energy physics!
Axion-like particles (ALPs)

pseudo Goldstone Bosons

- Global symmetry spontaneously broken

\[
\phi(x) = \rho(x) e^{i\theta(x)}
\]

- massless Goldstone Boson @ Low Energy

shift symmetry \( \theta(x) \rightarrow \theta(x) + \alpha \)

\[
\mathcal{L}_{\text{kin}} = \frac{1}{2} (\partial_{\mu} \theta)(\partial^{\mu} \theta) f^2
\]

- HE decay constant, \( f = \langle \rho \rangle \)

- small symmetry breaking \( \rightarrow \) small mass

stringy axions

- Im parts of moduli fields (control sizes)

- O(100) candidates in compactification

- “decay constant”, string scale \( M_s \)

- masses from non-perturbative effects
Low-energy effective action

- Shift symmetry allows some generic types of interactions

\[ \mathcal{L}_a = \frac{1}{2} (\partial_{\mu} a)(\partial^{\mu} a) + \sum_f g_{a\bar{f} f} [\bar{f} \gamma^{\mu} \gamma_5 f] a - \frac{g_a \gamma}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a \]

(canonically normalised)

- SS breaking terms induce mass + new interactions (one example ...)

\[ N \frac{\alpha}{8\pi} \left\{ G_{\mu\nu} \tilde{G}^{\mu\nu} \right\} \theta \equiv \frac{\alpha_s}{8\pi} \left\{ G_{\mu\nu} \tilde{G}^{\mu\nu} \right\} \frac{A}{f_A} \]

\[ V(A) \sim \frac{1}{2} \chi_{QCD} \left( \frac{A}{f_A} \right)^2 = \frac{1}{2} m_A^2 A^2 \]

**photon coupling**

\[ -\frac{g_a\gamma}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a \]

**electron coupling**

\[ g_{ef} [\bar{e} \gamma_5 e] a \]

**nucleon coupling**

\[ g_N f [\bar{N} \gamma_5 N] a \]

**\(\mathcal{C}\P\) Neutron electric dipole**

\[ \propto \frac{1}{m_n} [F_{\mu\nu} \tilde{n} \sigma^{\mu\nu} \gamma_5 n] \frac{A}{f_A} \]
Strong CP problem / PQ solution

\[ \{ G_{\mu\nu}, \tilde{G}^{\mu\nu} \} \theta_{\text{SM}} \rightarrow d_n \sim \frac{e}{m_n} \theta_{\text{SM}} < 5 \times 10^{-12} \frac{e}{m_n} \]

**why!!** \( \theta_{\text{SM}} < 10^{-11}!! \)
The QCD Axion cancels the effect of any constant $\theta_{\text{SM}}$.
### Strong CP problem / PQ solution

\[ \{ G_{\mu\nu} \tilde{G}^{\mu\nu} \} \left( \theta_{\text{SM}} + \frac{A}{f_A} \right) \rightarrow d_n \propto \left( \theta_{\text{SM}} + \frac{\langle A \rangle}{f_A} \right) \]

Potential min.
\[ \langle A \rangle / f_A = -\theta_{\text{SM}} \]

The QCD Axion cancels the effect of any constant \( \theta_{\text{SM}} \)

### Dark matter / vacuum realignment

Pick up a vacuum when quasi-degenerate ups! not the lowest ... oscillate!

Cold DM in oscillations [cosmology dependent]

\[ \Omega h_c^2 \approx 0.12 \sqrt{\frac{m_a}{\text{meV}}} \left( \frac{a_i}{3 \times 10^{12} \text{ GeV}} \right)^2 \]
4 hints

**Strong CP problem / PQ solution**

\[
\{G_{\mu\nu}, \tilde{G}^{\mu\nu}\} \left( \theta_{\text{SM}} + \frac{A}{f_A} \right) \quad \Rightarrow \quad d_n \propto \left( \theta_{\text{SM}} + \frac{\langle A \rangle}{f_A} \right)
\]

\[
V(A) \sim \frac{1}{2} \chi \left( \theta_{\text{SM}} + \frac{A}{f_A} \right)^2
\]

The QCD Axion cancels the effect of any constant \( \theta_{\text{SM}} \)

**Anomalous Star cooling / ALP emission**

Theory fits better some observations with ALPs

**Dark matter / vacuum realignment**

pick up a vacuum when quasi-degenerate ups! not the lowest ... oscillate!

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\]

Giannotti 2016
4 hints

**Strong CP problem / PQ solution**

\[ \{ G_{\mu\nu}, \tilde{G}^{\mu\nu} \} \left( \theta_{SM} + \frac{A}{f_A} \right) \rightarrow d_n \propto \left( \theta_{SM} + \frac{\langle A \rangle}{f_A} \right) \]

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**Potential min.**

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![Chart showing energy levels and transitions]

Giannotti 2016

**Dark matter / vacuum realignment**

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**\( \gamma \)-ray transparency / photon regeneration**

Too many gamma-rays from far away sources?

Low estimate of opacity vs ALP-mediated regeneration

Trotski 2017
Hints and constraints (example)

Strong CP problem

DARK MATTER

STAR COOLING

KSVZ axion

ADMX

LSW

CAST

BBN

CMB

X-Rays

DAMA

Global Sun

Telescopes

HB

BBN

LEP 2/3γ

LHC

Beam Dump

SN1987a

Virginia

-15

-10

-5

0

5

10

\log g_{a\gamma} [\text{GeV}^{-1}]

\log m_a [\text{eV}]

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Strong CP problem

DARK MATTER

SN1987a

SN $\gamma$-burst

FERMI

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BBN

EBL

X-Rays

Telescopes

CMB

X-ion

HB

CAST

DAMA

KSVZ axion

ASP

Υ($1S$)

Beam Dump

LEP 2/3γ

LHC

LSW

PVLAS

CAST Global Sun

LSW COOLING

STAR COOLING

TRANSPA

KSVZ axion

ADMX

UTKBF

Strong CP problem

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log $g_{\alpha\gamma}$ [GeV$^{-1}$]

log $m_a$ [eV]
Strong CP problem

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birds and stones ...
Strong CP problem

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x-ion

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STAR COOLING

TRANSPA

birds and stones ...

STAR COOLING

Strong CP problem

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log $g_{a\gamma}$ [GeV$^{-1}$]

log $m_a$ [eV]

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birds and stones ...

...
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Strong CP problem

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log $g_{a\gamma}$[GeV$^{-1}$]

log $m_a$[eV]
Direct Detection of ALPs
Lab experiments 2011

- ADMX, Wash. U
- GammeV, Fermilab
- ADMX-HF, Yale
- BMV, Toulouse
- CAST, CERN
- OSQAR, CERN
- ALPS, DESY
- PVLAS, Legnaro

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Light shining through walls

Resonant regeneration in the receiving cavity (see later)
ALPS IIc reach

but much earlier than IAXO ...
ALPS IIC reach

but much earlier than IAXO ...
ALPS IIc reach

but much earlier than IAXO ...
STAX, ALPS III and beyond
Long-range forces between macroscopic bodies

p-p forces are spin-spin ... very hard to measure!

In some case a tiny s-coupling can lead to a larger effect

s-p forces are number-spin ... much easier
ARIADNE reach

\[ g_s^N \quad g_p^e \quad g_s^N \quad g_p^e \quad g_p^e \quad g_p^e \]

bulk \quad \alpha \quad bulk \quad \alpha \quad spin \quad \alpha \quad spin

\[ \log m_a (\text{eV}) \]

\[ \log g_{aN} \quad \sqrt{g_{aN} g_{aN}} \]

ARIAIDNE

ultimate sens.

axion
The Sun is a copious emitter of ALPs!

 photon coupling

 electron coupling

$$g_{ae} = 10^{-13}$$

$$g_{a\gamma} = 10^{-12}$$
The Sun is a copious emitter of ALPs!

Helioscopes (search solar ALPs)

convert into X-rays

focus

detect

$g_{ae} = 10^{-13}$

$g_{a\gamma} = 10^{-12}$

Sikivie PRL 1983

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The Sun is a copious emitter of ALPs!

Coherent Conversion along the B-field

\[ P(\alpha \leftrightarrow \gamma) = \left( \frac{2g_a \gamma B T \omega}{m_a^2} \right)^2 \sin^2 \left( \frac{m_a^2 L}{4\omega} \right) \]

\[ g_{ae} = 10^{-13} \]
\[ g_{a\gamma} = 10^{-12} \]
Large toroidal 8-coil magnet $L = \sim 20\,\text{m}$
8 bores: 600 mm diameter each
8 x-ray optics + 8 detection systems
Rotating platform with services

- NGAG paper JCAP 1106:013, 2011
- Conceptual design report IAXO 2014 JINST 9 T05002
- LOI submitted to CERN, TDR in preparation
- Possibility of Direct Axion DM experiments (cavities, ABRACA)
IAXO detectors

Goal background level for IAXO: $\frac{10^{-7} \rightarrow 10^{-8}}{\text{keV cm}^2 \text{s}}$

- Small Micromegas-TPC chambers:
  - Shielding
  - Radiopure components
  - Offline discrimination

Already demonstrated: $\frac{8 \times 10^{-7}}{\text{keV cm}^2 \text{s}}$ (in CAST 2014 result) $\frac{10^{-7}}{\text{keV cm}^2 \text{s}}$ (underground at LSC)

- Gridpix/InGrid
- MMC
- Low noise CCDs
IAXO reach

Strong CP problem

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KSVZ axion

X_{ion}

X-Ray's

BBN

CMB

EBL

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IAXO reach

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\[ \log g_{\alpha \gamma} \text{[GeV}^{-1}] \]

\[ \log m_\alpha \text{[eV]} \]

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QCD axions, IAXO and ARIADNE

Example DFSZ axion model, 1-free parameter $\tan \beta$

$f_a \,[\text{GeV}]$

M. Giannotti et al JCAP10(2017)010
Detecting Dark Matter

\[ \rho = \frac{3}{2} \gamma \Gamma a^2 + \frac{1}{2} m^2 a^2 = \frac{1}{2} m^2 a f^2 \]

- for the QCD axion

\[ m^2 A = QCD \]

- Axions in Galaxy are non-relativistic

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Detecting Dark Matter

**Imperfect Vacuum realignment**  \[ \theta(t) = \theta_0 \cos(m_a t) \]

\[ \rho_{\text{CDM}} = 0.3 \text{ GeV/cm}^3 \equiv \frac{1}{2} \dot{a}^2 + \frac{1}{2} m_a^2 a^2 = \frac{1}{2} m_a f_a \theta_0^2 \]

**QCD axion**  \[ m_A^2 f_A^2 = \chi_{\text{QCD}} \quad \theta_0 \sim 3.6 \times 10^{-19} \]

**Non-zero velocity in galaxy -> finite width**  \[ \omega \simeq m_a (1 + v^2/2 + \ldots) \approx 10^{-6} \]

\[ \delta \omega = \frac{m_a v^2}{2} \]

\[ \frac{\delta \omega}{\omega} \sim 10^{-6} \]
Detecting Dark Matter

**Imperfect Vacuum realignment**  \[ \theta(t) = \theta_0 \cos(m_a t) \]

\[ \rho_{\text{CDM}} = 0.3 \frac{\text{GeV}}{\text{cm}^3} \equiv \frac{1}{2}(\ddot{a})^2 + \frac{1}{2}m_a^2a^2 = \frac{1}{2}m_a^2f_a^2\theta_0^2 \]

**QCD axion**  \[ m_A^2f_A^2 = \chi_{\text{QCD}} \rightarrow \theta_0 \sim 3.6 \times 10^{-19} \]

**Non-zero velocity in galaxy -> finite width**  \[ \omega \simeq m_a(1 + v^2/2 + ...) \]

\[ \sim 10^{-6} \]

\[ \delta \omega = \frac{m_a v^2}{2} \]

\[ \frac{\delta \omega}{\omega} \sim 10^{-6} \]

\[ \delta L \sim \frac{1}{\delta p} \sim 20 \sqrt{\frac{10^{-5} \text{eV}}{m_a}} \]
Spin precession

Atomic transitions

LC-circuit

MIRRORS

Cavities

e-spin precession

Single real photon

Virtual photon

Thursday, 1 February 18
- EDM + Large E-fields in PbTiO3
- Mainz (D. Budker’s group) & Berkeley
- B-field, coherence time, sensitivity to m < neV
- Mass range limited by B-field strength

Oscillating EDM, effects add up, transverse magnetisation grows if

$$m_a = \omega = \mu |\vec{B}_{\text{ext}}|$$
Axion DM in a B-field

\[ \mathcal{L}_I = -C a \gamma \frac{\alpha}{2\pi} \frac{a}{f_a} B \cdot E \]

- In a static magnetic field, the oscillating axion field generates EM-fields

\[ \mathcal{L}_I = -C a \gamma \frac{\alpha}{2\pi} \theta(t) B_{\text{ext}} \cdot E \]

- Electric fields \( E_a = C a \gamma \frac{\alpha B_{\text{ext}}}{2\pi} \theta_0 \cos(m_a t) \)

- Oscillating at a frequency \( \omega \sim m_a \)

- B-fields \( \propto \nabla \theta \) \hspace{1cm} |B_a| \sim \langle \nu \rangle |E_a|

- All experiments are sensitive to light dark photon dark matter! (kin. mix)
Dish antenna experiment?

The $E_a$-field excites surface electrons coherently
EM radiation from a reflecting surface

\[ P \sim |E_a|^2 A_{\text{dish}} \sim 10^{-26} \left( \frac{B}{5T} \frac{C_{a\gamma}}{2} \right)^2 \frac{A_{\text{dish}}}{1 \text{ m}^2} \text{ Watt} \]
Magnetised surface (Hamburg U.)

FUNK (KIT Karlsruhe) (1711.02961)
Cavity resonators (Haloscopes)

- Haloscope (Sikivie 83)

\[ P \sim Q|E_a|^2 (V m_a)\mathcal{G}\kappa \quad \text{(on Resonance)} \]

- comparison with Dish antenna \( P \sim |E_a|^2 A_{\text{dish}} \)

\[ V \sim 1/m_a^3 \]

extra factor of \( Q \approx 10^5 \)
on a \( m_a/Q \) band

Scanning over frequencies
MADMAX: MAgnetised Disk and Mirror Axion eXperiment

Emitted EM-waves from each interface + internal reflections ...

\[ P \sim |E_a|^2 \text{Area} \times \mathcal{O}(N^2) \]

Caldwell 2017
MADMAX: MAGnetised Disk and Mirror Axion eXperiment

Emission of EM-waves from each interface + internal reflections ...

\[ P \sim |E_a|^2 \text{Area} \times \mathcal{O}(N^2) \]

First prototype setup at MPI

Effective N

\[ \Delta \nu_\beta = 200 \text{ MHz} \]
\[ \Delta \nu_\beta = 50 \text{ MHz} \]
\[ \Delta \nu_\beta = 1 \text{ MHz} \]

Caldwell 2017
~80 dielectric discs $\epsilon \approx 24$ | spacing ~cm for 10-100GHz boost

metal disc

10T magnet

~10K cryogenic environment

receiver

parabolic mirror
Summary plot

Strong CP problem

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LHC

LSW

PVLAS

ADMX

UF / RBF

-10

-15

-10

-5

0

5

10

10^{-5}

10^{-10}

10^{-15}

log g_{a\gamma}[GeV^{-1}]

log m_a[eV]

Strong CP problem

DARK MATTER

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Summary plot
Low mass Dark Photons
- Beyond the SM with extremely low energies

- Detect an ALP, new energy scale!

- Generic interactions

- hints: Strong CP problem, DM, Stellar evolution, Transparency of Gamma’s

- Good Experimental ideas

- Still a lot of parameter space to explore!