The quest for axions and ALPs

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
Describes extremely well particle physics (at low energies)
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Answers wait in the high energy frontier where more symmetric beautiful theories arise.
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Axion-like particles (ALPs)

**pseudo Goldstone Bosons**
- Global symmetry spontaneously broken
- massless Goldstone Boson @ Low Energy
  - shift symmetry $\theta(x) \rightarrow \theta(x) + \alpha$
  - $L_{\text{kin}} = \frac{1}{2} (\partial_\mu \theta)(\partial^\mu \theta) f^2$
- 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

\[ \mathcal{L}_a = \frac{1}{2} (\partial_\mu \theta)(\partial^\mu \theta) f^2 + \sum_f c_f [\bar{f} \gamma^\mu \gamma_5 f] \partial_\mu \theta - E \frac{\alpha}{8\pi} F_{\mu\nu} \tilde{F}^{\mu\nu} \theta \]

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

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

\[ N \frac{\alpha}{8\pi} \left\{ G_{\mu\nu} \tilde{G}^{\mu\nu} \right\} \theta \equiv \frac{\alpha_s}{8\pi} \left\{ G_{\mu\nu} \tilde{G}^{\mu\nu} \right\} \frac{A}{f_A} \quad \rightarrow \quad V(A) \sim \frac{1}{2} \chi_{QCD} \left( \frac{A}{f_A} \right)^2 = \frac{1}{2} m_A^2 A^2 \]

<table>
<thead>
<tr>
<th>photon coupling</th>
<th>electron coupling</th>
<th>nucleon coupling</th>
<th>Neutron electric dipole</th>
</tr>
</thead>
<tbody>
<tr>
<td>(- \frac{g_{a\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a)</td>
<td>(g_{ef} [\bar{e} \gamma_5 e] a)</td>
<td>(g_{Nf} [\bar{N} \gamma_5 N] a)</td>
<td>(\propto \frac{1}{m_n} \left[ F_{\mu\nu} \bar{n} \sigma^{\mu\nu} \gamma_5 n \right] \frac{A}{f_A})</td>
</tr>
</tbody>
</table>
Strong CP problem / PQ solution

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

**why!!** \( \theta_{SM} < 10^{-11}!! \)
Strong CP problem / PQ solution

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

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

potential min.

\[ \langle A \rangle / f_A = -\theta_{SM} \]

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

**Strong CP problem / PQ solution**

\[
\begin{align*}
\{ G_{\mu\nu}, \widetilde{G}^{\mu\nu} \} \left( \theta_{SM} + \frac{A}{f_A} \right) & \quad \Rightarrow \quad d_n \propto \left( \theta_{SM} + \frac{\langle A \rangle}{f_A} \right) \\
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The QCD Axion cancels the effect of any constant \( \theta_{SM} \)

**Dark matter / vacuum realignment**

pick up a vacuum when quasi-degenerate
4 hints

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

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**Dark matter / vacuum realignment**

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

**cold DM in oscillations [cosmology dependent]**

\[
\Omega h_c^2 \simeq 0.12 \sqrt{\frac{m_a}{\text{meV}}} \left( \frac{a_i}{3 \times 10^{12} \text{ GeV}} \right)^2
\]
### Strong CP problem / PQ solution

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

---

### Anomalous Star cooling / ALP emission

Theory fits better some observations with ALPs

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### Dark matter / vacuum realignment

- pick up a vacuum when quasi-degenerate
- ups! not the lowest ... oscillate!
- cold DM in oscillations [cosmology dependent]

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\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
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Giannotti 2016

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4 hints

**Strong CP problem / PQ solution**

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\left\{ G_{\mu\nu}, \tilde{G}^{\mu\nu} \right\} \left( \theta_{SM} + \frac{A}{f_A} \right) \quad \mapsto \quad d_n \propto \left( \theta_{SM} + \frac{\langle A \rangle}{f_A} \right)
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**Anomalous Star cooling / ALP emission**

Theory fits better some observations with ALPs

![ALP bremstrahlung](Giannotti 2016)

**Dark matter / vacuum realignment**

![Vacuum realignment](pick up a vacuum when quasi-degenerate, ups! not the lowest ... oscillate!)

Cold DM in oscillations [cosmology dependent]

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

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

Too many gamma-rays from far away sources?

Low estimate of opacity vs ALP-mediated regeneration

![\( \gamma \)-ray transparency](Troitski 2017)
Strong CP problem

DARK MATTER

SN1987a

SN

γ-burst

FERMI

HESS

BBN

EBL

X-Rays

Telescopes

CMB

HB

CAST

Global Sun

DAMA

KSVZ axion

ASP

Υ(1S)

Beam Dump

LEP 2/3γ

LHC

LSW

PVLAS

TRANSPA

STAR COOLING

Strong CP problem

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

log \( m_a \) [eV]
Strong CP problem

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birds and stones ...
birds and stones ...
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birds and stones ...
birds and stones ...
Direct Detection of ALPs
The Sun is a copious emitter of ALPs!

Photon coupling

Electron coupling

\[ g_{ae} = 10^{-13} \]
\[ g_{a\gamma} = 10^{-12} \]
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The Sun is a copious emitter of ALPs!

Coherent Conversion along the B-field

\[ P(a \leftrightarrow \gamma) = \left( \frac{2g_{a\gamma}B_T\omega}{m_a^2} \right)^2 \sin^2 \left( \frac{m_a^2 L}{4\omega} \right) \]

\[ g_{ae} = 10^{-13} \]

\[ g_{a\gamma} = 10^{-12} \]
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)
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
Strong CP problem

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IAXO reach

\log g_{\text{a,\gamma}} [\text{GeV}^{-1}] \\
\log m_a [\text{eV}]
IAXO reach

Strong CP problem

DARK MATTER

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-10

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-5

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5

10

log \( m_a \) [eV]

log \( g_{\gamma\gamma} \) [GeV]^{-1}
Light shining through walls

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

but much earlier than IAXO ...
but much earlier than IAXO...
ALPS IIc reach

but much earlier than IAXO ...
Long-range forces between macroscopic bodies

\[ g^e_p \quad g^e_p \]

\[ \text{spin} \quad \alpha \quad \text{spin} \]

\[ g^N_s \quad g^e_p \]

\[ \text{bulk} \quad \alpha \quad \text{spin} \]

\[ B_{\text{ext}} \]

\[ \text{ARIADNE, University of Nevada in Reno} \]

- **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**
Detecting Dark Matter

- Wiggles in the vacuum (particles)
- $\mathcal{CDM} = 0.3 \text{ GeV cm}^{-1}$
- $\dot{a}^2 + \frac{1}{2} m_a^2 a = \frac{1}{2} m_f^2 a f^2$
- $\mathcal{QCD} \mathcal{0} \mathcal{\ll 3 \times 10^{19}}$
- Axions in Galaxy are non-relativistic
- Detecting Dark Matter
Imperfect Vacuum realignment \( \theta(t) = \theta_0 \cos(m_a t) \)

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

QCD axion \( m_A^2 f_A^2 = \chi_{QCD} \) \( \theta_0 \sim 3.6 \times 10^{-19} \)

\(~ 10^{-6} ~\)
Imperfect Vacuum realignment \[ \theta(t) = \theta_0 \cos(m_a t) \]

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QCD axion \[ m_A^2 f_A^2 = \chi_{QCD} \]

\[ \theta_0 \sim 3.6 \times 10^{-19} \]

Non-zero velocity in galaxy -> finite width

\[ \omega \simeq m_a (1 + v^2/2 + \ldots) \]

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

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

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

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

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Imperfect Vacuum realignment

\[ \theta(t) = \theta_0 \cos(m_a t) \]

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QCD axion

\[ m_A^2 f_A^2 = \chi_{\text{QCD}} \]

\[ \theta_0 \sim 3.6 \times 10^{-19} \]

coherence time

\[ \delta t \sim \frac{1}{\delta \omega} \sim 0.13 \text{ms} \left( \frac{10^{-5} \text{eV}}{m_a} \right) \]
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} (\dot{a})^2 + \frac{1}{2} m_a^2 a^2 = \frac{1}{2} m_a^2 f_a^2 \theta_0^2
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QCD axion  \( \frac{m_A^2 f_A^2}{\lambda_{\text{QCD}}} \rightarrow \theta_0 \sim 3.6 \times 10^{-19} \)

Non-zero velocity in galaxy -> finite width

\( \omega \approx m_a (1 + v^2/2 + ...) \)

\( \sim 10^{-6} \)

\[
\delta t \sim \frac{1}{\delta \omega} \sim 0.13 \, \text{ms} \left( \frac{10^{-5} \text{eV}}{m_a} \right)
\]

coherence time

\[
\delta L \sim \frac{1}{\delta p} \sim 20 \, \text{m} \left( \frac{10^{-5} \text{eV}}{m_a} \right)
\]

coherence length
CASPER at Mainz

- 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 \[ m_a = \omega = \mu |\vec{B}_{\text{ext}}| \]

- EDM + Large E-fields in PbTiO3
- Mainz (D. Budker’s group) & Berkeley
- B-field, coherence time, sensitivity to \( m < \text{neV} \)
- Mass range limited by B-field strength
\[ \sim \frac{1}{m_n f_A} \]
Axion DM in a B-field

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

- 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

\[ \omega \simeq m_a \]

- B-fields

\[ \propto \nabla \theta \quad |B_a| \sim \langle v \rangle |E_a| \]
Dish antenna experiment?

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

$$P \sim |E_a|^2 A_{\text{dish}} \sim 10^{-26} \left( \frac{B}{5T} \frac{C_{a\gamma}}{2} \right)^2 \frac{A_{\text{dish}}}{1 \text{ m}^2} \text{ Watt}$$
Cavity resonators (Haloscopes)

- **Haloscope (Sikivie 83)**

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

- **Naive ADMX scaling (e.g. an ADMX every octave)**

- **Signal**

\[ (V \propto m_a^{-3}) \quad P_{\text{out}} \propto V m_a \sim \frac{1}{m_a^2} \]

- **Noise**

\[ P_{\text{noise}} = T_{\text{sys}} \Delta \nu_a \propto m_a^2 \]

- **Signal/noise in \( \Delta \nu_a \) of time, \( t \),**

\[ \frac{S}{N} = \frac{P_{\text{out}}}{P_{\text{noise}}} \sqrt{\Delta \nu_a t} \]

- **Scanning rate**

\[ \frac{1}{m_a} \frac{d\Delta m_a}{dt} \propto \frac{C_A^4}{m_a^7} \]

**Scanning over frequencies**
Emitted EM-waves from each interface + internal reflections ...

\[ P \sim |E_\alpha|^2 \text{Area} \times \mathcal{O}(N^2) \]
Emitted EM-waves from each interface + internal reflections ...

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

Strong CP problem

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log m_a [eV]

log g_{a,γ} [GeV^{-1}]

Strong CP problem

DARK MATTER
Summary plot

osc. EDM

LC

ADMX

CULTASK

ARIADNE

Atomic transitions?

Excluded

IAXO

CAST

Telescope

$f_a[\text{GeV}]$

$m_a[\text{eV}]$
Conclusions

- 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!
Axion dark matter scenarios

- Axion DM scenarios

Initial conditions set by:

**Inflation smooth**

\[ \Omega_{aDM} h^2 \simeq \theta_i^2 \left( \frac{80 \, \mu eV}{m_a} \right)^{1.19} \]

**Phase transition (N=1)**

strings+unstable DW’s

**Phase transition (N>1)**

strings+long-lived DWs
Axion dark matter scenarios

**Dark Matter tiny parameter space!**

Initial conditions set by:

- **Inflation smooth**
  \[ \Omega_{aDM} h^2 \approx \theta_f^2 \left( \frac{80 \mu eV}{m_a} \right)^{1.19} \]

- **Phase transition (N=1)**
  strings+unstable DW’s

- **Phase transition (N>1)**
  strings+long-lived DWs

Excluded (too much DM)

- Ok
- Sub
- Tuned

Excluded (too much DM)

- Tuned

Axion DM scenarios