ALP searches at IAXO,
The International Axion Observatory
Javier Redondo
Outline

- axion-like particles (ALPs) in PBSM

- “hints” of the existence of ALPs
  - strong CP and axions
  - stellar evolution
  - TeV-gamma-ray transparency of the universe
  - Dark Matters

- Solar heliosopes, IAXO
IAXO is an Axion-like particle detector

Axion-like particle $\phi$ (small mass and small coupling to two photons)

$$\mathcal{L}_\phi = -\frac{g_{\phi\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} \phi$$

ALPs are produced inside the Sun via the two photon coupling (and others) and scape easily

- B’s of order 3 T,
- L’s of order 20 m
- order Zero backgrounds
Theory provides us with ALP candidates

pseudo Nambu Goldstone bosons

Global continuous symmetry spontaneously broken at high energy scale $M$ implies a low mass particle (Nambu-Goldstone boson) with weak couplings

$$g \sim \frac{\alpha}{2\pi M}$$

Existing examples: $\pi^0, \eta, \eta', \ldots$

Hypothetical fancies: axion, majoron, R-axion, familons, and a loooong etc.

stringy ‘axions’ & string Axiverse


Scalars and pseudoscalars that govern the sizes and deformations of extra dimensions, gauge couplings, etc... (typically there are $O(100)$ of these)

$$g \sim \frac{\alpha}{2\pi M_{\text{string}}}$$

Moduli, Radion, Dilatons
Phenomenology offers some hints - I

We expect P and T to be violated in a generic QCD-like theory, the size of the violation is set by:

\[ \mathcal{L}_\theta = \frac{\alpha_s}{8\pi} \text{tr} \left\{ G^\mu\nu_{a\alpha} \tilde{G}_{a\mu\nu} \right\} \theta \]

However, NO neutron Electric Dipole Moment, nor any other sign of P, T or CP violation in the strong interactions has ever been measured!!

\[ \theta < 10^{-11} \]

Peccei-Quinn-Weinberg-Wilczek showed that a pseudo Nambu-Goldstone boson, solves the problem


\[ \mathcal{L}_\theta = \frac{\alpha_s}{8\pi} \text{tr} \left\{ G^\mu\nu_{a\alpha} \tilde{G}_{a\mu\nu} \right\} \left( \theta + \frac{a}{f_a} \right) \]

- Relevant AXION couplings to SM particles, always suppressed by \( 1/f_a \)

- Mixing with pseudoscalar mesons gives the AXION a mass

\[ m_a \simeq \frac{m_\pi f_i}{f_a} \simeq 6 \text{ meV} \frac{10^9 \text{GeV}}{f_a} \]
Phenomenology offers some hints - II

White dwarf cooling

Axion emission can accelerate the WD cooling between neutrino and surface dominated cooling periods.

\[ g_{ae} \equiv \frac{C_e m_e}{f_a} \]

Period decrease of G117–B15A

Corsico et al. arXiv:1205.6180

WD luminosity function

Miller Bertolami, Isern et al. arXiv:1406.7712

\[ g_{ae} = 0, 1.4, 2.8 \times 10^{-13} \]
Phenomenology offers some hints - II

Axion emission delays the Helium flash makes Red giants grow brighter

\[ g_{ae} \equiv \frac{C e m_e}{f a} \]

Viaux, Redondo, Raffelt et al  arXiv:1311.1669
Phenomenology offers some hints - II

CAS A neutron star observations for 10 years (Chandra)
- Evidence for n cooper pairing + neutrino emission? ... factor of 2 missing

\[ n + n \rightarrow ^3 P_2 + a \] (coupling to neutrons)

Leinson, arXiv:1405.6873

**Chandra x-ray image of non-pulsar compact remnant**

\[ C_n m_a \sim 2.4 \text{ meV} \]
Phenomenology offers some hints - III

Transparency of the universe to gamma rays

Gamma rays pair-produce electron/positron pairs from the extragalactic background light … some cannot arrive to earth

However, they do … (Roncadelli et al PRD 84, Sanchez-Conde et al JCAP 1111, Horns and Meyer JCAP 1202)

Excess persists at $2 - 4\sigma$
Phenomenology offers some hints - III

Transparency of the universe to gamma rays and ALPs

Photons can convert into ALPs in galactic or extra galactic magnetic fields and reconvert back close to us.

Points to ALP couplings (Meyer 2012)

$g_{\phi\gamma} \sim 10^{-11} \text{GeV}^{-1}$

Requires $\sim$neV ALP masses
Phenomenology offers some hints - IV

Cosmology demands 2(3) new substances:
the 3 of them can be ALPs

- Dark Energy (very weakly coupled or chameleons)
- Dark Radiation (only hints so far)
- Dark Matter (cold or mildly warm; non-thermal)

$N_{\text{eff}} = 3.90 \pm 0.44(1\sigma)$

$\Omega_{\text{cDM}} = 0.22(3)$

$\Omega_{\text{DE}} = 0.73(3)$

PDG 2012; Nollet and Holler arXiv:1112.2683
Axion/ALP hot/warm Dark Matter

ALPs are thermally produced in the early universe by a number of processes

\[ \gamma \quad \cdots \quad q \]

- They can also decay and affect cosmology \( \phi \to \gamma \gamma \)

They can explain the 3.5 keV line

Jaeckel, Redondo, Ringwald arXiv:1402.7335

If light, they should be a subdominant component of DM

\[ \frac{\Omega_{hDM,a}}{\Omega_{DM,obs}} < 0.03 \]

Hannestad et al. JCAP 1008

Or Dark radiation

\[ N_{\text{eff}} \sim 0.04 \]

Cadamuro arXiv:1110.2895

Moduli decay into ALPs can be much more efficient

\[ N_{\text{eff}} \sim O(4) \]


+ soft X-ray excess + 3.5 keV line!!
Axion/ALP cold Dark Matter

Vacuum realignment mechanism

\[ \Phi(x) = \rho(x) e^{i \frac{a(x)}{f_a}} \]

\[ V(\Phi) = \frac{\lambda}{4} (|\Phi|^2 - f_a)^2 + \Lambda^4 \left( 1 - \cos \left( \frac{a}{f_a} \right) \right) \]

- Early times \( m_a t < 1 \), vacuum homogeneizes (modes \( k t < 1 \) decay)
- At \( m_a t \approx 1 \), \( a \) rolls to its minimum and oscillates

\[ \rho_{cDM} \sim \Lambda^4 \left( \frac{R_{osc}}{R(t)} \right)^3 \]

energy density redshifts as CDM!

String-wall decay

- Cosmic strings form
- Scaling #/horizon \( \approx 1 \)
- Oscillations and loop decay
- At \( m_a t \approx 1 \) walls collapse the strings \( \rightarrow \) more axions
\[ \rho_{cDM} \sim \Lambda^4 \left( \frac{R_{osc}}{R(t)} \right)^3 \propto [m_\phi^2 f_\phi^2]^2 m_\phi^{-3/2} \propto \frac{\sqrt{m_\phi}}{g_{\phi\gamma}^2} \]

\[ \log_{10} g_{\phi\gamma} [\text{GeV}^{-1}] \]

\[ \log_{10} m_\phi [\text{eV}] \]

3.5 keV line; Jaeckel, Redondo, Ringwald \texttt{arXiv:1402.7335}

**ALP Cold dark matter**

Arias, Redondo et al.: \texttt{arXiv:1201.5902}

Standard

Inflation singles out initial condition

CAST+Sumico

EBL

HB

QCD Axions

Optical

\[ x_{\text{ion}} \]

EBL

CAST+Sumico

EBL

HB

QCD Axions

Optical

EBL

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The International Axion Observatory
IAXO is an Axion-like particle detector

Axion-like particle $\phi$ (small mass and small coupling to two photons)

$$\mathcal{L}_\phi \propto -\frac{g_{\phi \gamma}}{4} F_{\mu \nu} \tilde{F}^{\mu \nu} \phi$$

ALPs are produced inside the Sun via the two photon coupling (and others) and escape easily

- $B$’s of order 3 T,
- $L$’s of order 20 m
- Order Zero backgrounds
Solar Axion-like particle flux well understood

\[ \mathcal{L}_\phi \in - \frac{g_{\phi \gamma}}{4} F_{\mu \nu} \tilde{F}^{\mu \nu} \phi \]

Photon-ALP coupling

\[ \mathcal{L}_\phi \in \frac{g_{\phi e}}{2m_e} [\bar{\psi}_e \gamma_\mu \gamma_5 \psi_e] \partial^\mu \phi \]

Electron-ALP coupling

\[ g_{\phi \gamma} = 10^{-12} \frac{1}{\text{GeV}} \quad g_{\phi e} = 10^{-13} \]

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Detection: coherent Inverse Primakoff

In a B-field, ALPs and photons are NOT propagation eigenstates

\[ \mathcal{L}_\phi \equiv -\frac{g_{\phi\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} \phi = g_{\phi\gamma} \mathbf{E} \cdot \mathbf{B} \phi \]

\[
\begin{pmatrix}
\Box 
& 
\begin{pmatrix}
1 & 0 \\
0 & 1 
\end{pmatrix}
& \begin{pmatrix}
0 & -g_{\alpha\gamma} |\mathbf{B}| \omega \\
-g_{\alpha\gamma} |\mathbf{B}| \omega & m_a^2 
\end{pmatrix}
\end{pmatrix}
\begin{pmatrix}
A \parallel \\
a 
\end{pmatrix}
= \begin{pmatrix}
0 \\
0 
\end{pmatrix}.
\]

Axion-Photon conversion probability after a length \( L \)

\[
P(\phi \rightarrow \gamma) = \left( \frac{2g_{\phi\gamma} B \omega}{m_{\phi}^2} \right)^2 \sin^2 \left( \frac{m_{\phi}^2 L}{4\omega} \right)
\]

Small mass (Energy and mass independent)

\[
P(\phi \rightarrow \gamma) \rightarrow \left( \frac{g_{\phi\gamma} B L}{2} \right)^2 \sim 10^{-21} \left( \frac{g_{\phi\gamma}}{10^{-12}\text{GeV}^{-1}} \right)^2 \left( \frac{B}{3\text{T}} \right)^2 \left( \frac{L}{20\text{m}} \right)^2
\]

Photons expected ... not many!

\[
\frac{N_\gamma}{dA d\omega dt} \sim \frac{0.14}{\text{m}^2 \text{year keV}} \left( \frac{g_{\phi\gamma}}{3 \times 10^{-12}\text{GeV}^{-1}} \right)^4 \left( \frac{B}{3\text{T}} \right)^2 \left( \frac{L}{20\text{m}} \right)^2
\]

\[
\frac{N_\gamma}{dA d\omega dt} \sim \frac{14}{\text{m}^2 \text{year keV}} \left( \frac{g_{\phi\gamma}}{3 \times 10^{-12}\text{GeV}^{-1}} \right)^2 \left( \frac{g_{\phi e}}{3 \times 10^{-13}} \right)^2 \left( \frac{B}{3\text{T}} \right)^2 \left( \frac{L}{20\text{m}} \right)^2
\]
Predecessors

SUMICO (Tokyo U.)

B-field ~ 4 T
L ~ 2.3 m

CAST (CERN)

B-field ~ 9 T
L ~ 10 m
Sensitivity


Electron (production) + Photon (det.) coupling arXiv:1302.6283
How much better than CAST can we do?


... New TOROIDAL magnet, AREA!, optics, detectors

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- Magnet Dimensions

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- Background

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- Meas. time

- S/B improvement

X-ray optics

ultra-low back. MICROMEGAS detectors

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IAXO, International Axion Observatory

- 90 signatures, 38 Institutions (CAST + new collaborations), Europe, US, Japan, Korea
- Next steps: Memorandum of understanding, apply for funding!
- R&D already going on (magnet, optics, detectors)

magnet design (CERN/Saclay)

optics (LLNL, DTU)

detectors (Zaragoza U./Saclay)
IAXO sensitivity

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

\[ m_\phi[\text{eV}] \]
Direct Axion/ALP DM searches in IAXO

DM Axions convert into MW photons in a resonant cavity (mass oriented design)

Many such cavities can be fit in IAXO (Redondo, Patras 2014)

+ Dish-Antenna experiments to search for transients
- prediction on miniclusters of axion CDM

\[ M_{mc} \sim 10^{-12} M_\odot \]
\[ \Omega_{mc}/\Omega_{aCDM} \sim O(1) \]

Zurek et al 07, See also Kolb & Tkachev 94

(Horns et al JCAP1304016, Jaeckel & JR JCAP1311016, PRD 88, 2013)
Direct Axion/ALP DM searches in IAXO

\[ g_{a\gamma} = c_{\gamma} \frac{\alpha}{2\pi f_a} \]
Can IAXO clarify the hints? ... yes!

**Strong CP problem**

IAXO can find the axion up to $m_a \gtrsim 1 \sim 10 \text{meV}$
- Through the photon or electron couplings
- In this range, IAXO can measure, coupling and mass

**WD, RG, NS cooling**

If the axion is responsible, IAXO can find it $m_a \gtrsim 1 \sim 10 \text{meV}$
If it is an ALP, it can strongly depend (photon coupling might be very small)

**Transparency of the universe due to ALPs**

IAXO will settle this issue (recall $g_{\phi\gamma} \sim 10^{-11} \text{GeV}^{-1}$, $m_\phi \lesssim n \text{eV}$)

**Dark matter**

- In the strong CS&DW-contribution scenario, $m_a \sim \text{meV}$, IAXO is the only experiment proposed up-to-date that can find these axions.
- Also if they are a sub-dominant contribution of DM
- Direct DM search can reach sensitivities to detect axions and cover huge ALP parameter space

**Dark radiation**

- Discovering the axion or an ALP immediately implies a DM and DR candidate