Experimental searches for axions

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TeV Particle Astrophysics (TeVPA2016), CERN,
12 September 2016
Axions: theory motivation

- Peccei-Quinn solution to the strong CP problem or why QCD seems not to violate CP, while one would expect to do so
- New U(1) symmetry introduced in the SM: Peccei Quinn symmetry of scale $f_a$
- The AXION appears as the Nambu-Goldstone boson of the spontaneous breaking of the PQ symmetry

This QCD term is CP violating.

$$\mathcal{L}_{CP} = \theta \frac{\alpha_s}{8\pi} G \tilde{G}$$

Experimentally $\theta < 10^{-11}$ while O(1) would be expected

$\theta$ absorbed in the definition of $a$

$$\theta = \frac{\alpha_s}{8\pi f_a} \frac{aG\tilde{G}}{f_a}$$

$\theta = \frac{a}{f_a}$ relaxes to zero...

CP conservation is preserved “dynamically”

$a \rightarrow$ New field: the axion. Very light:

$$m_a \simeq 0.6 \text{ eV} \frac{10^7 \text{GeV}}{f_a}$$
Axion phenomenology

- **Axion-photon coupling present in every model.**

\[ \mathcal{L}_{a\gamma} = g_{a\gamma\gamma}(E \cdot B)a \quad g_{a\gamma\gamma} = \frac{\alpha_s}{2\pi f_a} \left( \frac{E}{N} - 1.92 \right) \]

- **Axion-photon conversion** in the presence of an electromagnetic field (Primakoff effect)

This is probably the most relevant of axion properties.
Most axion detection strategies are based on the axion-photon coupling
Beyond axions

- Many extensions of SM predict axion-like particles
  - Higher scale symmetry breaking

**Generic ALPs parameter space**

**Weakly Interacting Sub-eV Particles (WISPs)**

**Axion Like particles (ALPs)**

- Stringy ALPs
- Arion
- Majoron
- Familon

**AXIONS**

- Hidden Photons (HPs)
- Millicharged Particles
- Chameleons

String theory predicts a plenitude of ALPs
Non thermal cosmological axions

Axion realignment

As the Universe cools down below $T_{QCD}$, space is filled with low energy axion field fluctuations. Their density depends on the initial value of $\langle a_{phys} \rangle$ ("misalignment angle")

But also... topological defects

But inflation may "wipe out" topological defects... Did inflation happen before or after the creation of defects (PQ transition) ? pre-inflation or post-inflation scenarios
Axion/ALP parameter space

Laboratory experiments (ALPS)

Helioscopes (CAST)

Telescopes

Haloscopes

ALP

Axion as CDM

Pre-inflation models

Anthropic

m_{axion}(eV)

m_{axion}(eV)
Axion/ALP parameter space

- Laboratory experiments (ALPS)
- Helioscopes (CAST)
- Haloscopes
- Telescopes
- Axion as CDM

- HESS
- Transp. Joint
- ADMX
- KSNZ
- Subdominant
- Post-inflation

$g_{\text{ay}}$ (GeV$^{-1}$)

$m_{\text{axion}}$ (eV)
Axion/ALP parameter space

Laboratory experiments (ALPS)

Helioscopes (CAST)

HALP

Halosopes

HoDM

Post-inflation (N_{ewf}>1)

WISPy CDM

JCAP06(2012)013
Astrophysical hints for axions

- Gama ray telescopes like MAGIC or HESS observe HE photons from very distant sources...

\[ g_{a\gamma} \sim 10^{-12} - 10^{-10} \text{ GeV}^{-1} \]
\[ m_a \lesssim 10^{-(10-7)} \text{ eV} \]
Astrophysical hints for axions (II)

- Most stellar systems seem to cool down faster than expected.
- Presence of axions/ALPs offer a good joint explanation (Giannotti et al. JCAP05(2016)057 [arXiv:1512.08108])
- Parameters at reach of IAXO
Axion/ALP parameter space

Transparency of the Universe

Helioscopes (CAST)

Laboratory experiments (ALPS)

Stellar cooling hints

ALP

HESI

TeVeS

ADMX

KSVZ

Stellar cooling hints

HB stars

TeVeS 2016, CERN

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Axion motivation in a nutshell

• Most compelling solution to the Strong CP problem of the SM

• Axion-like particles (ALPs) predicted by many extensions of the SM (e.g. string theory)

• Axions, like WIMPs, may solve the DM problem for free. (i.e. not ad hoc solution to DM)

• Astrophysical hints for axion/ALPs?
  – Transparency of the Universe to UHE gammas
  – Stellar anomalous cooling \( g_{a\gamma} \sim \text{few } 10^{-11} \text{ GeV}^{-1} / m_a \sim \text{few } \text{meV} \) ?

• Relevant axion/ALP parameter space at reach of current and near-future experiments

• Still too little experimental efforts devoted to axions when compared e.g. to WIMPs…
Detection of axions

- Axion – photon coupling \textit{generically} present in every axion model.

- \textbf{Axion-photon conversion} in the presence of an electromagnetic field (\textit{Primakoff effect})

- Most detection techniques based on the axion-to-photon conversion inside magnets

  - Other couplings possible, but less generic (model dependent)
    - axion-electron coupling
    - axion-nucleon coupling
# Detection of axions

<table>
<thead>
<tr>
<th>Source</th>
<th>Experiments</th>
<th>Model &amp; Cosmology dependency</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relic axions</td>
<td>ADMX, X3, CASPER, CAPP, ...</td>
<td>High</td>
<td>New ideas emerging, Active R&amp;D going on,...</td>
</tr>
<tr>
<td>Lab axions</td>
<td>ALPS, OSQAR, fifth force exps,...</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Solar axions</td>
<td>SUMICO, CAST, IAXO</td>
<td>Low</td>
<td>Ready for large scale experiment</td>
</tr>
</tbody>
</table>
Detecting DM axions: “haloscopes”

- Assumption: DM is mostly axions
- Resonant cavities (Sikivie, 1983)
  - Primakoff conversion inside a “tunable” resonant cavity
  - Energy of photon = $m_a c^2 + O(b^2)$

Primakoff conversion of DM axions into microwave photons inside cavity

$$P_0 = g_{a\gamma}^2 V B^2 C \frac{\rho_a}{m_a} Q$$

Axion DM field
Non-relativistic
Frequency $\leftrightarrow$ axion mass

Cavity dimensions smaller than de Broglie wavelength of axions

If cavity tuned to the axion frequency, conversion is “boosted” by resonant factor (Q quality factor)
ADMX

- Leading haloscope experiment
- Many years of R&D
- high Q cavity (1 m x 60 cm Ø)
- 8 T superconducting solenoid
- Low noise receivers based on SQUIDs + dilution refrigeration at 100 mK.
- Sensitivity to few $\mu$eV proven
- Good support through Gen 2 DM US program
- Current program will surely cover 1-10 $\mu$eV with high sensitivity (i.e. reaching ever pessimistic coupling). What about higher masses?
Haloscopes at higher axion masses

- Problematic: higher $m_a \rightarrow$ lower $V \rightarrow$ lower sensitivity
- Active R&D inside ADMX
- X3 (before ADMX-HF)
- CAPP in Korea $\rightarrow$ very important effort
  - CULTASK & others...
- CAST as haloscope: CAST-CAPP, RADES.

Also...
- Dish antennas
- CASPER
Beyond haloscopes...

- **Dish antennas:**
  - No resonance, but large area possible...
  - Realistic sensitivity limited, but boost possible with dielectric multilayer
  - Directionality possible

Horns et al. JCAP 1304 (2013) 016
Jaeckel, Redondo JCAP 1311 (2013)

MADMAX Prototype setup at MPI Munich

ORPHEUS in Seattle

Plot from Ballesteros et al 1608.05414

\[
P \sim |E|^2 A_{\text{dish}} \sim 10^{-26} \left( \frac{B}{5T} \frac{c_\gamma}{2} \right)^2 \frac{A_{\text{dish}}}{1 \text{ m}^2} \text{ Watt}
\]
Beyond haloscopes…

- DM-induced spin precession?: CASPEr experiment (Mainz-Berkeley)
- Competitive at very low $m_a$

- Also QUAX experiment (Padova):
  - Sensitive to “axion DM wind” through axion-electron coupling

\[
\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}
\]
Coupling to gluon field CASPEr Electric

\[
\frac{\partial_{\mu} a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f
\]
Coupling to fermions CASPEr Wind

Light shining through wall

Standard configuration \( \rightarrow \)

Enhanced “resonant” configuration (future) \( \rightarrow \)

ALPS @ DESY-Hamburg

Any Light Particle Search @ DESY: ALPS I concluded in 2010

- ALP II under preparation
- (resonant, 10+10 magnets,...)
- Also: OSQAR@CERN, CROWS@CERN, PVLAS @ Ferrara, GammeV & REAPR @ Fermilab, US, BMV @ Toulouse

<table>
<thead>
<tr>
<th>parameter</th>
<th>scaling</th>
<th>ALPS I</th>
<th>ALPS IIc</th>
<th>sens. gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B L$ (total)</td>
<td>$g_{ay} \propto (B L)^{-1}$</td>
<td>22 Tm</td>
<td>468 Tm</td>
<td>21</td>
</tr>
<tr>
<td>PC built up ($P_{laser,eff}$)</td>
<td>$g_{ay} \propto P_{RC}^{-1/4}$</td>
<td>1 (kW)</td>
<td>150 (kW)</td>
<td>3.5</td>
</tr>
<tr>
<td>rel. photon flux $n_{prod}$</td>
<td>$g_{ay} \propto n_{prod}^{-1/4}$</td>
<td>1 (532 nm)</td>
<td>2 (1064 nm)</td>
<td>1.2</td>
</tr>
<tr>
<td>RC built up $\beta_{RC}$</td>
<td>$g_{ay} \propto \beta_{RC}^{-1/4}$</td>
<td>1</td>
<td>40,000</td>
<td>14</td>
</tr>
<tr>
<td>detector eff. $DE$</td>
<td>$g_{ay} \propto DE^{-1/4}$</td>
<td>0.9</td>
<td>0.75</td>
<td>0.96</td>
</tr>
<tr>
<td>detector noise $DC$</td>
<td>$g_{ay} \propto DC^{1/8}$</td>
<td>$1.8 \cdot 10^{-3}$ s$^{-1}$</td>
<td>$10^{-6}$ s$^{-1}$</td>
<td>2.6</td>
</tr>
<tr>
<td>combined</td>
<td></td>
<td></td>
<td></td>
<td>3082</td>
</tr>
</tbody>
</table>
Axion-mediated macroscopic forces

Axions could be detected as short-range deviation of gravity…
(but traditionally though without enough sensitivity to QCD axions)

Recently proposed: ARIADNE experiment
Short-range force by NMR technique

Good prospects for sub-meV axion

Arvanitaki, Geraci
Solar Axions

- Solar axions produced by photon-to-axion conversion of the solar plasma photons in the solar core

\[ \frac{d\Phi_a}{dE} = 6.02 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} g_{10}^2 E^{2.481} e^{-E/1.205} \]

\[ g_{10} = g_{a\gamma}/10^{-10} \text{ GeV}^{-1} \]

van Bibber PRD 39 (89)
CAST JCAP 04(2007)010
Solar Axions

- In addition to Primakoff, “ABC axions” may be x100 more intense… but model-dependent.

* if the axion couples with the electron ($g_{ae}$) *(non hadronic axion)*

Non-hadronic “ABC” Solar axion flux at Earth

*JCAP 1312 008*
Axion helioscopes

Axion helioscope concept
P. Sikivie, 1983
(use of buffer gas)

\[
P_{\alpha\gamma} = 2.6 \times 10^{-17} \left( \frac{B}{10 \text{ T}} \right)^2 \left( \frac{L}{10 \text{ m}} \right)^2 \left( g_{\alpha\gamma} \times 10^{10} \text{ GeV} \right)^2 \mathcal{F}
\]
Buffer gas for higher masses

Coherence condition ($qL \ll 1$) is recovered for a narrow mass range around $m_\gamma$

$$|q| = \frac{m_a^2 - m_\gamma^2}{2E}$$

$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = 28.9 \sqrt{\frac{Z}{A}} \rho \text{ eV}$$

N$_e$ : number of electrons/cm$^3$
ρ : gas density (g/cm$^3$)

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Other types of helioscope

• Instead of magnetic field, one can use the electromagnetic field of crystals…

• "Primakoff-Bragg" effect

• WIMP-like experiments provide limit to axions: SOLAX, COSME, DAMA, EDELWEISS, CDMS, etc…

• Characteristical temporal pattern:

"
Other types of helioscope

- «TPC in a magnetic field»: conversion and absorption happening in the gas
- Competitive only for high axion mass
- Old idea recently studied

Galán et al., arXiv:1508.03006
CAST experiment @ CERN

- Decommissioned LHC test magnet (L=10m, B=9 T)
- Moving platform $\pm 8^\circ V \pm 40^\circ H$ (to allow up to 50 days / year of alignment)
- 4 magnet bores to look for X rays
- 3 X rays detector prototypes being used.
- X ray Focusing System to increase signal/noise ratio.
### CAST results

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
</table>
| 2003 – 2004 | **CAST phase I**  
  - vacuum in the magnet bores                                               |
| 2006     | **CAST phase II - \(^4\)He Run**  
  - axion masses explored up to 0.39 eV (160 P-steps)                        |
| 2007     | **\(^3\)He Gas system implementation**                                      |
| 2008 - 2011 | **CAST phase II - \(^3\)He Run**  
  - axion masses explored up to 1.17 eV  
  - bridging the dark matter limit                                           |
| 2012     | **Revisit \(^4\)He Run with improved detectors**                           |
| 2013-2015 | **Revisit vacuum phase with improved detectors**  
  - Analysis ongoing.  
  - New result soon available                                                |

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IAXO – Concept


$4^4 g_{a\gamma} \propto b^{1/2} \varepsilon^{-1} \times a^{1/2} \varepsilon_o^{-1} \times (BL)^{-2} A^{-1} \times t^{-1/2}$

4+ orders of magnitude better SNR that CAST (JCAP 1106:013)
IAXO – Conceptual Design

- Large toroidal 8-coil magnet $L = \sim 20$ m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating platform with services
IAXO technologies – Baseline

**IAXO magnet**
- Superconducting “detector” magnet.
- Toroidal geometry (8 coils)
- Based on ATLAS toroid technical solutions.
- CERN+CEA expertise
- 8 bores / 20 m long / 60 cm Ø per bore

**IAXO magnet**
- Slumped glass technology with multilayers
- Cost-effective to cover large areas
- Based on NuSTAR developments
- Focal length ~5 m
- 60-70% efficiency
- LLNL+UC+DTU+MIT expertise

**IAXO detectors**
- Micromegas gaseous detectors
- Radiopure components + shielding
- Discrimination from event topology in gas
- Long trajectory in CAST
- Zaragoza + CEA (+ others) expertise
- Also considered: Ingrid, MMCs, CCDs

Baseline developed at:
IAXO Letter of Intent: CERN-SPSC-2013-022

TeVPA 2016, CERN

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Few meV scale QCD axion accessible to IAXO

Transparency ALP hints accessible to IAXO & ALPS-II

1-10 μeV axionDM accessible to ADMX

ALPS-II

Laboratory experiments (ALPS)

Haloscopes (CAST)

ADM

KSVZ

ALP CDM

TeVPA

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36
Few meV scale QCD axion accessible to IAXO

Transparency ALP hints accessible to IAXO & ALPS-II

ALPS-II

IAXO

Haloscopes (CAST)

1-10 μeV axionDM accessible to ADMX

10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 m_{\text{axion}}(eV)

Oscillating EDM

ALP CDM

R&D permitting

Dish antennas? NMR?

HF cavities?

KSVZ

Laboratory experiments (ALPS)
Conclusions

- Increasing interest for axions:
  - Beyond axions: ALPs / WISPs
- Increasing experimental effort (still small!)
- Consolidation of classical detection lines: ADMX, CAST, ALPs,…
  - ADMX and CAST have firstly probed interesting (small) fraction of par space.
- Helioscopes: IAXO next generation
- Haloscopes: ADMX, CAPP → R&D to go higher $m_a$
- New ideas to tackle new regions: Dish antenna, dielectric layers, NMR,…
- Large fraction of parameter space at reach of near-future experiments
  - chances of discovery!
  
  Good timing for axions… stay tuned
Backup slides...
Axions: theory motivation

• Axion: introduced to solve the strong CP problem

• In QCD, nothing prevents from introducing a term like:

\[ \mathcal{L}_{CP} = \theta \frac{\alpha_s}{8\pi} G \tilde{G} \]

This term is CP violating.

\[ \theta = \bar{\theta} + \arg \det M \]

From non-observation of neutron electric dipole moment:

\[ |\theta| < 0.7 \times 10^{-11} \]

• Why so small?

• High fine-tunning required for this to work in the SM
Axions: theory motivation

- Peccei-Quinn solution to the strong CP problem or why QCD seems not to violate CP, while one would expect to do so
- New U(1) symmetry introduced in the SM: Peccei Quinn symmetry of scale $f_a$
- The AXION appears as the Nambu-Goldstone boson of the spontaneous breaking of the PQ symmetry

\[
\mathcal{L}_a = \frac{1}{2} (\partial_\mu a)^2 - \frac{\alpha_s}{8\pi f_a} aG\tilde{G}
\]

θ absorbed in the definition of $a$

θ = $a/f_a$ relaxes to zero… CP conservation is preserved “dynamically”
The axion

- The PQ scenario solves the strong CP-problem. But a most interesting consequence is the appearance of this new particle, the *axion*.

  (Weinberg, Wilcek)

- **Basic properties:**
  - Pseudoscalar particle
  - Neutral
  - Gets very small mass through mixing with pions
  - Stable (for practical purposes)
  - Phenomenology driven by the PQ scale $f_a$.
    (couplings inversely proportional to $f_a$)

\[ \mathcal{L}_a = \frac{1}{2} (\partial_\mu a)^2 - \frac{\alpha_s}{8\pi f_a} a G \tilde{G} \]

\[ m_a \approx 0.6 \text{ eV} \frac{10^7 \text{GeV}}{f_a} \]
OSQAR @ CERN

Also:

- GammeV & REAPR @ Fermilab, US
- BMV @ Toulouse
- PVLAS @ Ferrara
- CROWS @ CERN
- ...
Axion Helioscopes

• Previous helioscopes:
  – First implementation at Brookhaven (just few hours of data) [Lazarus et at. PRL 69 (92)]
  – TOKYO Helioscope (SUMICO): 2.3 m long 4 T magnet

• Presently running:
  – CERN Axion Solar Telescope (CAST)
IAXO magnet

TOROIDAL CONFIGURATION specifically built for axion physics

Each conversion bore (between coils) 600 mm diameter

Magnetic length 20 m Total cryostat length 25 m
IAXO magnet concept presented in:


**IAXO magnet**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cryostat dimensions:</strong></td>
<td>Overall length (m)</td>
</tr>
<tr>
<td></td>
<td>Outer diameter (m)</td>
</tr>
<tr>
<td></td>
<td>Cryostat volume (m³)</td>
</tr>
<tr>
<td><strong>Toroid size:</strong></td>
<td>Inner radius, (R_{in}) (m)</td>
</tr>
<tr>
<td></td>
<td>Outer radius, (R_{out}) (m)</td>
</tr>
<tr>
<td></td>
<td>Inner axial length (m)</td>
</tr>
<tr>
<td></td>
<td>Outer axial length (m)</td>
</tr>
<tr>
<td><strong>Mass:</strong></td>
<td>Conductor (tons)</td>
</tr>
<tr>
<td></td>
<td>Cold Mass (tons)</td>
</tr>
<tr>
<td></td>
<td>Cryostat (tons)</td>
</tr>
<tr>
<td></td>
<td>Total assembly (tons)</td>
</tr>
<tr>
<td><strong>Coils:</strong></td>
<td>Number of racetrack coils</td>
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<tr>
<td></td>
<td>Winding pack width (mm)</td>
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<td></td>
<td>Winding pack height (mm)</td>
</tr>
<tr>
<td></td>
<td>Turns/coil</td>
</tr>
<tr>
<td></td>
<td>Nominal current, (I_{op}) (kA)</td>
</tr>
<tr>
<td></td>
<td>Stored energy, (E) (MJ)</td>
</tr>
<tr>
<td></td>
<td>Inductance (H)</td>
</tr>
<tr>
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<td>Peak magnetic field, (B_p) (T)</td>
</tr>
<tr>
<td></td>
<td>Average field in the bores (T)</td>
</tr>
<tr>
<td><strong>Conductor:</strong></td>
<td>Overall size (mm²)</td>
</tr>
<tr>
<td></td>
<td>Number of strands</td>
</tr>
<tr>
<td></td>
<td>Strand diameter (mm)</td>
</tr>
<tr>
<td></td>
<td>Critical current @ 5 T, (I_c) (kA)</td>
</tr>
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<td>Operating temperature, (T_{op}) (K)</td>
</tr>
<tr>
<td></td>
<td>Operational margin</td>
</tr>
<tr>
<td></td>
<td>Temperature margin @ 5.4 T (K)</td>
</tr>
<tr>
<td></td>
<td>at 4.5 K (W)</td>
</tr>
<tr>
<td></td>
<td>at 60-80 K (kW)</td>
</tr>
</tbody>
</table>
IAXO x-ray optics

- X-rays are focused by means of grazing angle reflection (usually 2)
- Many techniques developed in the x-ray astronomy field. But usually costly due to exquisite imaging requirements
IAXO x-ray optics

- Each bore equipped with an x-ray optics
- Exquisite imaging not required
- BUT need cost-effective way to build 8 (+1 spare) optics of 600 mm diameter each
IAXO x-ray optics

- Technique of choice for IAXO: optics made of slumped glass substrates coated to enhance reflectivity in the energy regions for axions
- Same technique successfully used in NuSTAR mission, recently launched

- The specialized tooling to shape the substrates and assemble the optics is now available
- Hardware can be easily configured to make optics with a variety of designs and sizes
- Key institutions in NuSTAR optics: LLNL, U. Columbia, DTU Denmark. All in IAXO!
IAXO low background detectors
Optics+detector pathfinder system in CAST

- IAXO optics+detector joint system
  - Newly designed MM detector (following IAXO CDR)
  - New x-ray optics fabricated following technique proposed for IAXO (but much smaller, adapted to CAST bore)
  - First time low background + focusing in the same system
  - Very important operative experience for IAXO

- Installed & commissioned successfully in CAST last september. Now taking data
Additional IAXO physics cases

• Detection of “ABC”-produced solar axions (with relevant $g_{ae}$ values)
• More specific WISPs models at the **low energy frontier** of particle physics:
  – Paraphotons / hidden photons
  – Chamaleons
  – Non-standard scenarios of axion production
• Possible addition technologies to push E thresholds down:

![Diagram](image-url)

- GridPix/Ingrid detectors
- Magnetic Metallic Calorimeter (MMC)
- Low-noise CCDs

IAXO as “generic axion/ALP facility”
**AXION Cosmology**

- **Axions are produced** in the early Universe by a number of processes:

  - Axion realignment
  - Decay of axion strings
  - Decay of axion walls

\[
\begin{align*}
\text{NON-RELATIVISTIC (COLD) AXIONS} \\
\text{RELATIVISTIC (HOT) AXIONS}
\end{align*}
\]
AXION Cosmology

- Axion realignment:

When $T > T_{QCD}$
\[ <a_{\text{phys}} > \text{ is arbitrary} \]

When $T \sim T_{QCD}$
\[ <a_{\text{phys}} > \rightarrow 0 \]

As the Universe cools down below $T_{QCD}$, space is filled with low energy axion field fluctuations.

Their density depends on the initial value of $<a_{\text{phys}}>$

(“misalignment angle”)
Axion Cosmology

- The **CDM axion relic density** is uncertain as it depends on several factors:

- Inflation before PQ transition **CASE 1**
  - “initial misalignment angle” $<a_{phys}>_0$ varies spatially $\rightarrow$ Averaged.
  - Contributions from axion strings and domain walls must be computed $\rightarrow$ difficult (see Sikivie astro-ph/0610440)

- Late-inflation scenario (inflation after PQ transition) **CASE 2**
  - The “initial misalignment angle” $<a_{phys}>_0$ unique for all visible universe.
  - Strings and walls wiped out by inflation. Not contributing. And in any case difficult to compute their contribution.

- Very approximately:

$$\Omega_a \sim 0.15 \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6} \left( \frac{0.7}{h} \right)^2 \alpha_1^2$$

CASE 2

$$\sim 0.7 \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6} \left( \frac{0.7}{h} \right)^2$$

CASE 1

Sikivie astro-ph/0610440
Axion Cosmology

- Which value for $f_a$ (and therefore mass) gives the right amount of axion density?
  - Late-inflation: Wide range of mass possible if initial misalignment “tuned”
  - Late-inflation: Mass determined but calculation uncertain.

- In general...
  - Range of axion masses of $10^{-6}$ – $10^{-3}$ eV are of interest for the axion to be the (main component of the) CDM.

$\Omega_a \sim 0.5 \left( \frac{10^{-5} \text{ eV}}{m_a} \right)^{7/6}$

J. Hamann et al. arXiv:0904.0647
Axion Cosmology

- **Relativistic axions (HDM)** are created by thermal production:
  - At high $T$, axions are in creation-annihilation equilibrium with the rest of particles (thermal population of axions, satisfying Boltzmann equation).
  - When the Universe cools down below $T_{Df}$, the axion freeze-out temperature, the thermal population decouples and its density red-shifts till today.

\[ T_{D} \sim 5 \times 10^{11} \text{ GeV} \left( \frac{f_{a}}{10^{12} \text{ GeV}} \right)^{2} \]

- In order to have substantial relativistic axion density, the axion mass must be close to 1 eV. ($m_{a} > 1.02$ eV gives densities too much in excess to be compatible with latest CMB data)

From Wantz 2010
The cooling of white dwarfs

- Luminosity function (WD’s per unit magnitude) altered by axion cooling
- Claim of detection of new cooling mechanism (Isern 2008)
- Axion-electron coupling of $\sim 1 \times 10^{-13}$ ($\rightarrow$ axion masses of 2-5 meV or larger) fits data.
The cooling of white dwarfs

- meV masses seem out of reach of even for an improved axion helioscope... BUT
- Axion-electron coupling provides extra axion emission from the Sun...
- Extra emission concentrated at lower energies (~1 keV)

- Such axion could produce a detectable signal in IAXO
IAXO sensitivity prospects

- Factor $\sim 20$ better in $g_{a\gamma}$ ($\sim 10^{4-5}$ in signal strength!!)