Axion searches

10th Terascale Detector Workshop 2017

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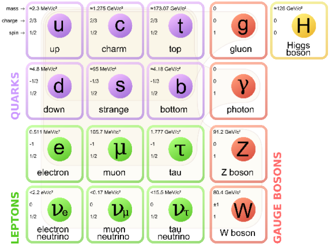
April 13th, 2017

Introduction

Status quo:

- The Standard Model of particle physics describes three of the four fundamental forces

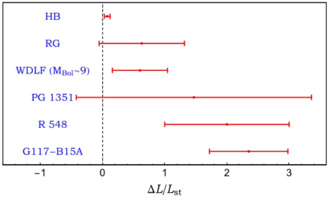
$\Rightarrow$ A wide variety of experimental results are explained by the Standard Model



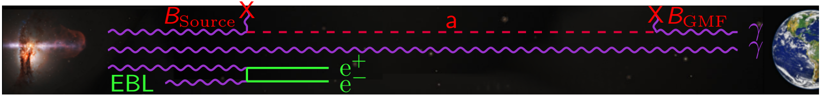
[Wikipedia]

Still some things are not explained by the Standard Model. E.g.:

- TeV transparency
- Energy loss in stars at different evolution stages
- Dark matter



[Maurizio Giannotti et al JCAP05(2016)057]



[Limits in arXiv: 1302.1208]

QCD axion and SM extension

Axion

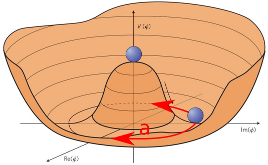
[Peccei,Quinn 77; Weinberg; Wilczek 78]

Pseudo scalar field that solves the strong CP-problem in QCD.

- The axion is a CP conserving dynamic field that explains the small value of the static CP viol. angle θ in QDC ($\mathcal{L}_\theta = \theta \frac{g}{32\pi} G_a^{\mu\nu} \tilde{G}_{a\mu\nu}$, $\theta \to \frac{a(x)}{f_a}$)
- The θ term produces an electric dipole moment of the neutron: $d_n = \approx \theta 10^{-16}$ ecm, $d_n^{\mathrm{exp}} < 2.9 \times 10^{-26}$ ecm

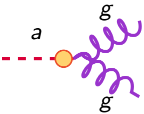
QCD axion and SM extension

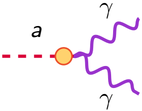
Introduce a singlet complex scalar σ featuring a global $U(1)$ symmetry, which is spontaneously broken at the scale $f_a = v_\sigma / C_{ag}$.

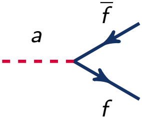


[Adopted from Nature physics 7, 2011]

$$\mathcal{L}_{\text{int.}} \supset -\frac{\alpha_s}{8\pi} C_{ag} \frac{a}{v_\sigma} G^c_{\mu\nu} \tilde{G}^{c\mu\nu} - \frac{\alpha}{8\pi} C_{a\gamma} \frac{a}{v_\sigma} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} C_{af} \frac{\partial_\mu a}{v_\sigma} \bar{\psi}_f \gamma^\mu \gamma_5 \psi_f$$







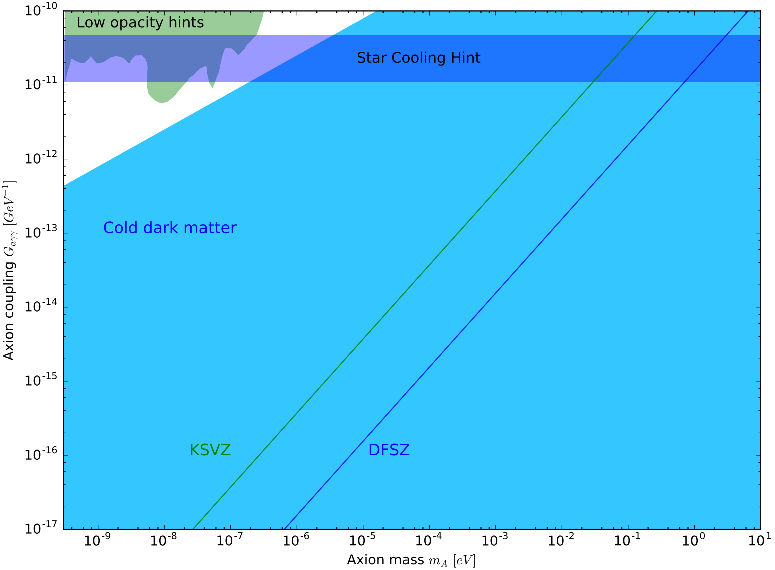
Axion (Peccei-Quinn):

- Solves the strong CP-problem
- It acts as CP conserving dynamic field

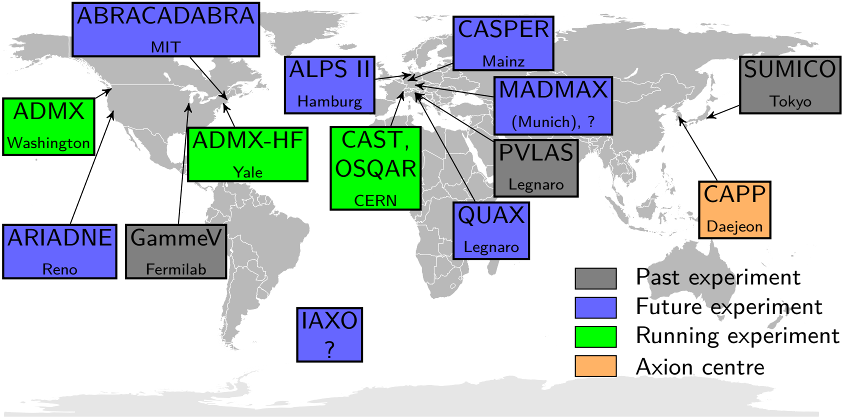
Axion like particles (ALPs):

- Similar to axions with different $C_{a\gamma}$, C_{af}, C_{ag}
- Can explain different observations

Axion and ALP hints



Incomplete list of ALP experiments worldwide

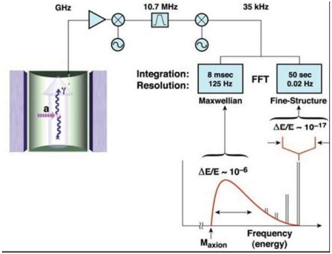


[By Frank Bennett [Public domain], via Wikimedia Commons]

Axion sources

Haloscopes:

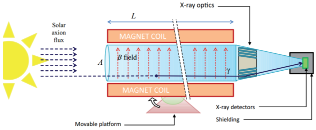
- Local Milky Way dark matter halo ALPs interact with the experiments magnetic field



[ADMX web page]

Helioscopes:

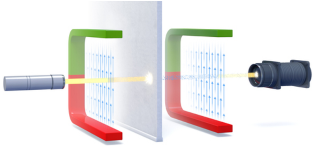
- ALPs produced in the sun interact with the experiments magnetic field



[IAXO LoI, CERN-SPEC-2013-022]

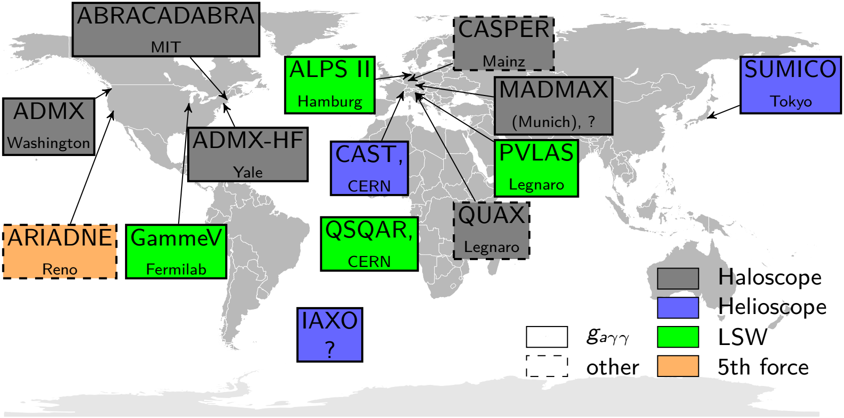
Light shining through wall:

- ALPs are produced and detected by the experiment



[ALPS web page]

Incomplete list of ALP experiments worldwide



[By Frank Bennett [Public domain], via Wikimedia Commons]

Axion Dark Matter Experiment (ADMX) [Sikivie 1983]

Experimental setup:

- 8 T superconducting magnet
- Cavity cylinder: $1\,\mathrm{m} \times 0.5\,\mathrm{m}$

$\Rightarrow$ high-Q tunable microwave cavity

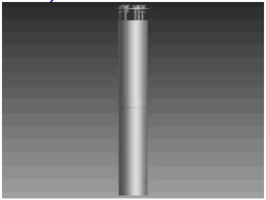
- Ultra low-noise microwave receiver
- Amplifier: SQUID + low noise cryogenic HFET

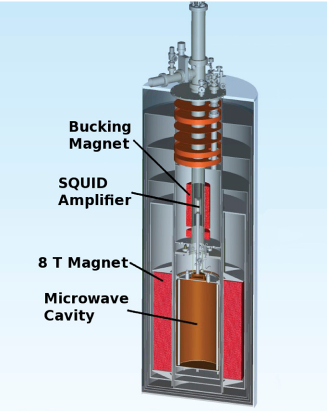
Dominant background:

- Thermal noise arising from the cavity
- Electronics noise from the receiver

Sensitivity:

- Signals down to 10^{-24} W can be detected (equivalent to 1 axion decay per minute)





[ADMX web page]

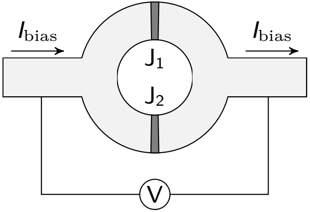
Superconducting Quantum Interference Device (SQUID)

First DC SQUID realized in 1964, Ford Research Labs

SQUID

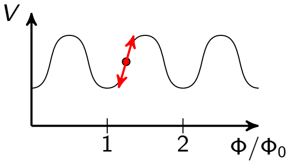
Combines the phenomena of flux quantization in superconducting rings with Josephson tunneling.

- Most sensitive detectors of magnetic flux ⇒ Minimum measurable flux variation $\sim 10^{-6}\Phi_0$; $\Phi_0 = 2 \times 10^{-15}\,\mathrm{Tm}^2$



ADMX:

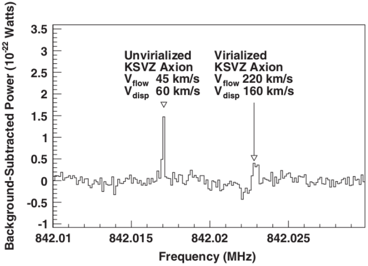
- Antenna in the cavity picks up current
- A coil above the SQUID translates current to magnetic field

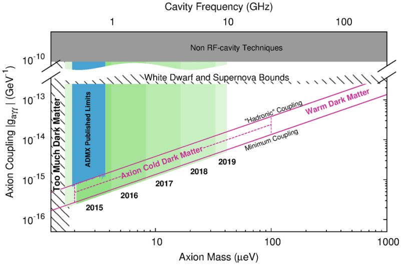


ADMX analysis

Data taking:

- Cavity power is averaged ($T_{\mathrm{av.bin}} \approx 25\,\mathrm{min}$) until S/N exceeds a confident detection threshold per 125 Hz bin
- Cavity is tuned every 80 s in steps of $\approx 2\,\mathrm{kHz}$
- Reducing the noise from 2 K (resistor amplifier) to 50 mK (SQUID) $\Rightarrow$ speed-up by factor of 1000
- Dicke radiometer eq. : $\frac{S}{N} = \frac{P_{\mathrm{signal}}}{k_B T_{\mathrm{noise}}}\sqrt{\frac{t}{b}}$





[PRL 104, 041301 (2010), AMDX web page]

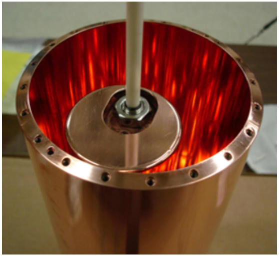
ADMX-HF @ Yale University

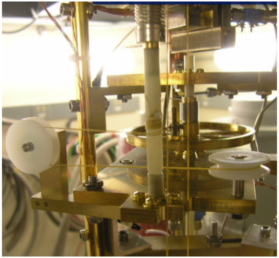
Haloscope At Yale Sensitive To Axion CDM (HAYSTAC)

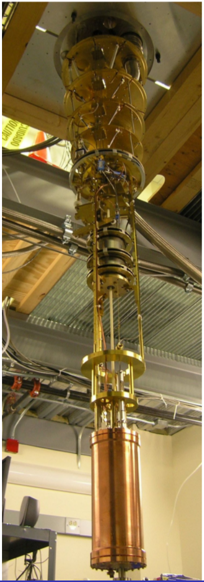
Experimental setup:

- 5 T magnet, $r = 5\,\text{cm}$, $h = 25\,\text{cm}$
- $Q = 20000$, tunable from 3.5 GHz to 5.85 GHz $\Rightarrow m_\mathrm{a}$: 19 μeV to 24 μeV

Sensitivity: $2.5 \times 10^{-23}\,\text{W}$







[Ben Brubaker, 2017]

Dish Antennas

Idea

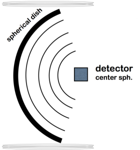
arXiv:1212.2970 [hep-ph]

The photon field arising in a magnetic field from the Axion causes the radiation of photons due to the boundary condition of a vanishing electric field parallel to the reflecting surface of the dish antenna ($E_{\|} \stackrel{!}{=} 0$).

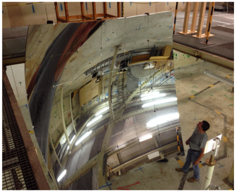
- E-field in vacuum:
  $E_a(t) = -\frac{\alpha}{2\pi\epsilon} C_{a\gamma} B\theta(t)$
- Inside the mirror: $E \simeq 0$

$\Rightarrow$ Continuity at the mirror surface requires the emission of an EM wave of amplitude $|E_a|$

- $P_{\text{center}} \sim \left(\frac{B}{5\,\text{T}} \frac{C_{a\gamma}}{2}\right)^2 \frac{A}{1\,\text{m}^2} 10^{-26}\,\text{W}$



[Redondo, 2014]

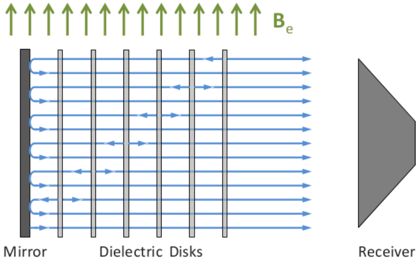


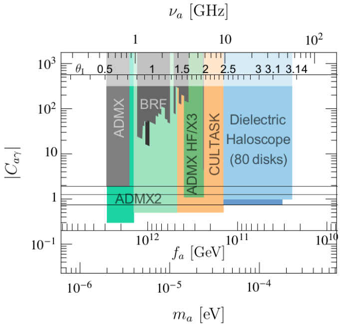
[FUNK, Karlsruhe]

MADMAX – *boosted dish antenna*

Concept:

- Combine multiple dielectric discs (up to 80, $\varnothing \sim 1\,\mathrm{m}$, $\epsilon_r(\mathrm{LaAlO_3}) \sim 25$) that emit em-waves in magnetic field (10 T)
- Position the discs such that constructive interference between the plane waves is achieved
- Aimed mass range: 40 μeV to 400 μeV (10 GHz to 100 GHz)





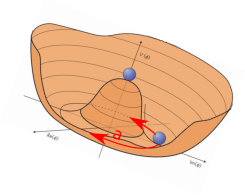
[Phys. Rev. Lett.,2017, 118, 091801]

Cosmic Axion Spin Precession Experiment (CASPEr)

Remember:

$$d_n \approx \theta 10^{-16}\,\text{ecm} = \frac{a_0 \cos(m_a t)}{f_a} 10^{-16}\,\text{ecm}$$

$$\langle a_0 \rangle = 0$$



[Nature physics 7, 2011]

Idea: static EDM ⇒ oscillating EDM

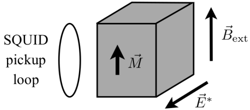
[arXiv:1306.6088,arXiv:1306.6089]

- Nuclei interact with background axion dark matter ⇒ acquire time varying CP-odd nuclear moment (e.g. electric dipole moment)
- Analog to nuclear magnetic resonance: nuclear moment causes precession of nuclear spin in material sample in presence of an electric field
- This can be measured via precision magnetometry

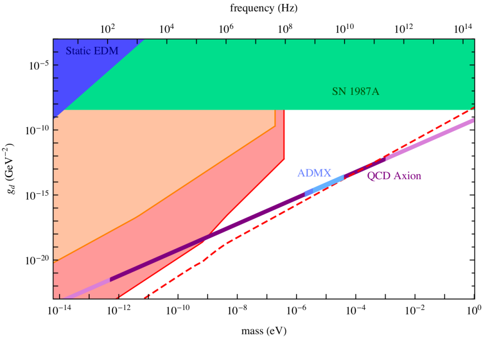
CASPEr sensitivity

$$M(t) \approx np\mu E^* \epsilon_S d_n \frac{\sin\left[\left(\frac{\omega_L - m_a c^2}{\hbar}\right) t\right]}{\frac{\omega_L - m_a c^2}{\hbar}} \sin(\omega_L t) \qquad \omega_L = 2\mu B_{ext}.$$

- SQUID sensitivity is required: $\approx 10^{-16}\,\mathrm{T}/\sqrt{\mathrm{Hz}}$
- External magnetic filed limits the sensitivity to higher masses (10 T/20 T)



- $d_n(t) \sim g_d a(t)$
- $g_d = \frac{2.4 \times 10^{-16}\,\mathrm{ecm}}{f_a}$



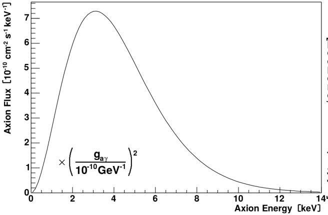
[arXiv:1306.6089]

CERN Axion Solar Telescope (CAST)

Experimental setup:

- 9 T, 10 m LHC superconducting magnet
- ±8° vertical movement ⇒ 1.5 h observation ever sunrise/sunset
- ±40° horizontal covers almost the full azimuthal movement of the sun during the year
- Two focusing X-ray telescopes ⇒ increase signal-to-background ratio by a factor of 100
- Background measurements when sun is not reachable

[CAST web page]

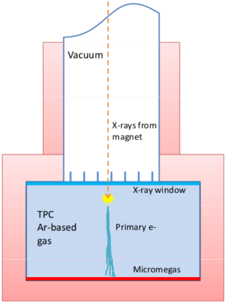


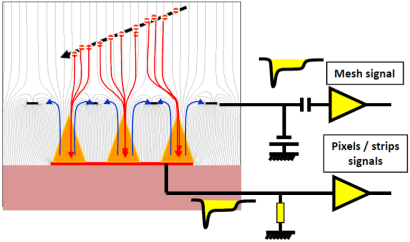
[arXiv:hep-ex/0507007]

CAST detectors

2 magnet bores → 4 detector positions:

- 2 bores on one side covered by a TPC (2003 – 2004) → 2 MicroMegas
- 1 bore on the opposite side with X-ray focussing optic → equipped with CCD, SSD, InGrid detector
- 1 bore with MicroMegas





[2014 JINST 9 P01001]

CAST detectors

2 magnet bores $\rightarrow$ 4 detector positions:

- 2 bores on one side covered by a TPC (2003 – 2004) $\rightarrow$ 2 MicroMegas
- 1 bore on the opposite side with X-ray focussing optic $\rightarrow$ equipped with CCD, SSD, InGrid detector
- 1 bore with MicroMegas

Background levels:

- Beam pipes and detectors are shielded against X-rays using copper and lead
- MicroMegas: $6 \times 10^{-7}\,\mathrm{keV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [2013 JINST 8 C12042]

Experimental setups:

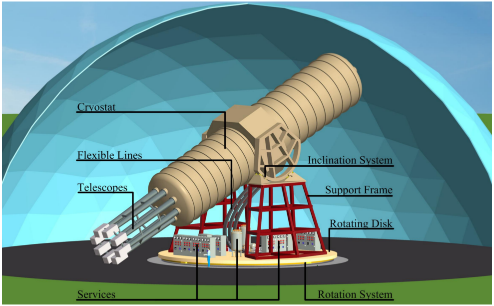
- In the beginning vacuum in the bores was used $\Rightarrow$ sensitive to $m_\mathrm{a} < 0.02\,\mathrm{eV}$
- To increase the sensitivity to higher masses gas (He^3 and He^4) at different pressure was inside the bores $\Rightarrow$ $m_\mathrm{a} < 1.18\,\mathrm{eV}$

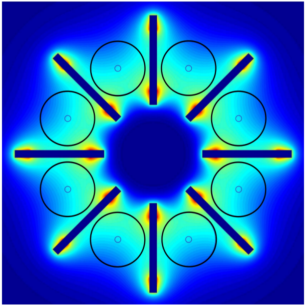
International Axion Observatory (IAXO)

[CERN-SPSC-2013-022,2014 JINST 9 T05002]

Next generation of helioscopes:

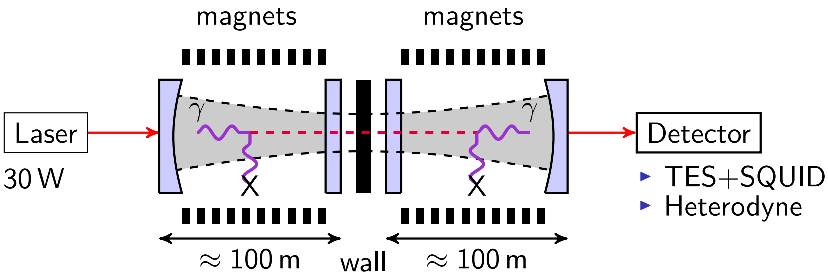
- 8 bores for instrumentation equipped with X-ray telescopes
- New magnet designed to suit the needs (peak field: 5.4 T, average field: 2.5 T, length: 20 m)
- Base line detector: MicroMegas





Light shining though a wall experiment

[Okun 1982, Skivie 1983, Ansel'm 1985, Van Bibber et al. 1987]



Physics:

- Number of photons produced via the Primakoff effect:

$$N_{\gamma\to\phi\to\gamma} = \frac{\eta^2}{16}\beta_{\mathrm{PC}}\beta_{\mathrm{RC}}\frac{P_{\mathrm{laser}}}{E_\gamma}\left(\frac{g_{a\gamma\gamma}}{\mathrm{GeV}}\frac{B}{\mathrm{T}}\frac{l}{\mathrm{m}}\right)^4\Delta t$$

- For $g_{a\gamma\gamma} = 10^{-11}$ this corresponds to 1 photon per 2 weeks!

Light shining though a wall experiment

$$N_{\gamma\to\phi\to\gamma} = \frac{\eta^2}{16}\beta_{\mathrm{PC}}\beta_{\mathrm{RC}}\frac{P_{\mathrm{laser}}}{E_\gamma}\left(\frac{g_{a\gamma\gamma}}{\mathrm{GeV}}\frac{B}{\mathrm{T}}\frac{l}{\mathrm{m}}\right)^4\Delta t$$

LSW ingredients

- Strong, long magnets ⇒ DESY
- Intense light source
- Optical resonators on the production and regeneration side
- Extremely sensitive detection scheme to detect a single photon per day or even week

Benefit of LSW approach

LSW is in contrast to dark matter or solar axion searches a model independent approach with full control of the signal creation!

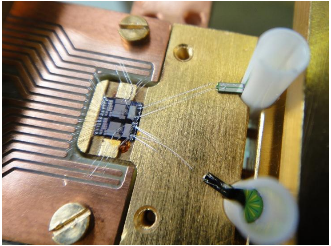
Transition Edge Sensor

Transition Edge Sensor

Microcalorimeter measuring the temperature difference induced by a particle/photon in an absorber material.

Advantages of a TES (NIST):

- High efficiency (95 % at 1064 nm)
- Low dark count rate ($10^{-4}\,\mathrm{s}^{-1}$)
- Long term stability
- Good energy resolution ($< 8\,\%$)
- Good time resolution



NIST TES:

- Sensitive area (tungsten): $25\,\mu\mathrm{m} \times 25\,\mu\mathrm{m}$ ($T_c = 150\,\mathrm{mK}$)
- Readout with Superconducting Quantum Interference Devices (SQUID)

TES working principle

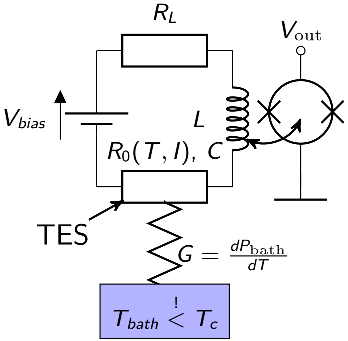


Figure: TES readout circuit.

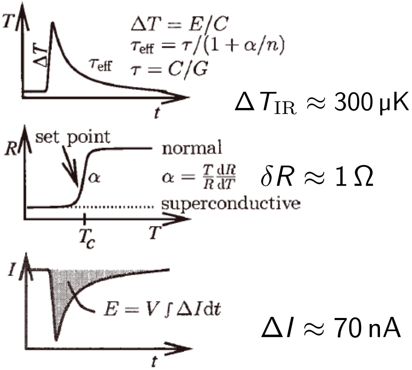


Figure: Sketch of TES characteristics [de Korte et al. (2003), Proc. SPIE 4851].

NIST TES:

- $T_{\text{bath}} = 80\,\text{mK}$, $T_c = 150\,\text{mK}$
- $\tau_{\text{eff.}} \approx 1.5\,\mu\text{s}$ ($\tau_{\text{therm.}} = 38\,\mu\text{s}$)

Neg. electrothermal feedback

For $R_0 \gg R_L$: $R_0' = R_0 + \delta R$

ARIADNE

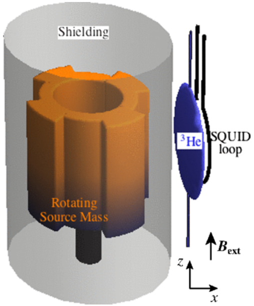
Idea [Phys. Rev. Lett., 2014, 113, 161801]

Probe a new spin dependent long range CP-violating force between macroscopic bodies.

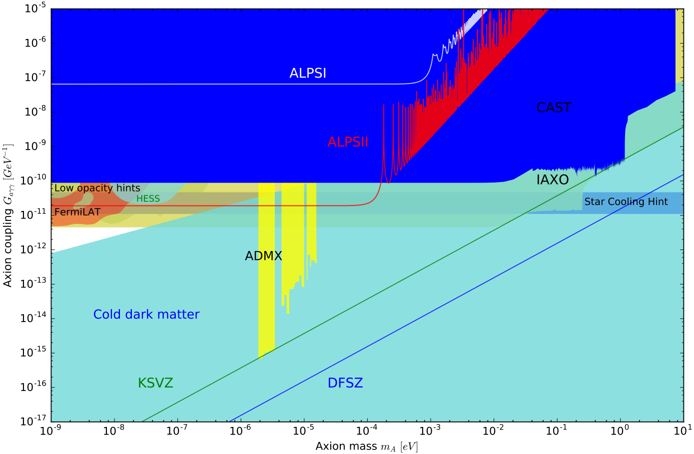
- Mediator: axion
- Charge: spin

Ariadne:

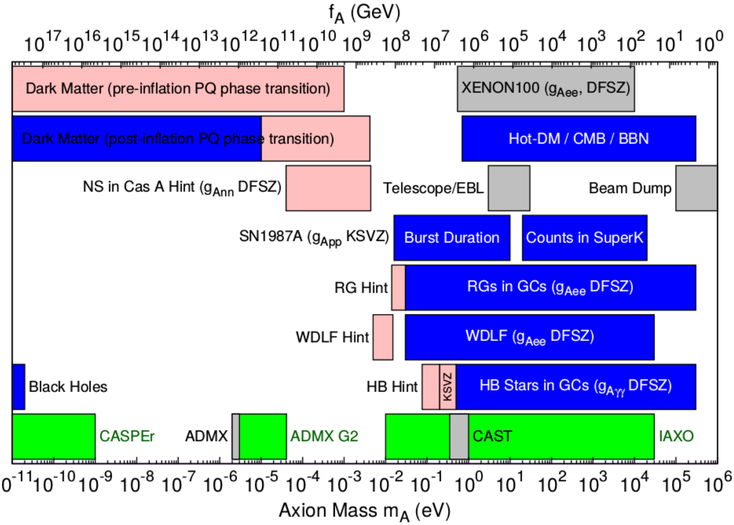
- Spins will precess in the NRM material off the axis of polarization
- Range: $100\,\mu\mathrm{m} < l < 10\,\mathrm{cm} \Rightarrow 10^{-6}\,\mathrm{eV} < m_a < 10^{-3}\,\mathrm{eV}$
- Source mass unpolarized/polarized to test monopole-dipole/dipole-dipole coupling



$g_{a\gamma\gamma}$ parameter space



QDC axion limits



Summary

So far no ALP or Axion has been discovered BUT the interesting phase space is just to be covered by the next generation experiments that require:

- High magnetic field strength
- High quality micro wave cavities/ optical resonators with low noise amplifiers
- Novel detectors like SQUIDs, MicroMegas, InGrid

Axion physics brings together experts from:

- NMR
- Optics
- X-ray
- Cryogenics
- Radio astronomy
- . . . particle physicists

So stay tuned. . . a new discovery might just be ahead!

[www.colgate.ph, https://clipartfest.com]

Backup

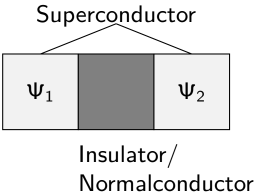
Superconducting Quantum Interference Device (SQUID)

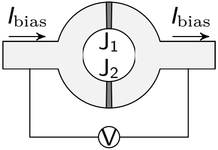
First DC SQUID realized in 1964, Ford Research Labs

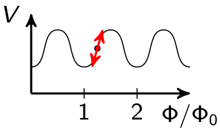
SQUID

Combines the phenomena of flux quantization in superconducting rings with Josephson tunneling.

- Interference of macroscopic wave functions: $\Psi_i = \sqrt{n_i}\mathrm{e}^{i\theta_i}$
- Superconducting loop with one (RF SQUID) or two (DC SQUID) Josephson junctions
- Most sensitive detectors of magnetic flux $\Rightarrow$ Minimum measurable flux variation $\sim 10^{-6}\Phi_0$; $\Phi_0 = 2 \times 10^{-15}\,\mathrm{Tm}^2$



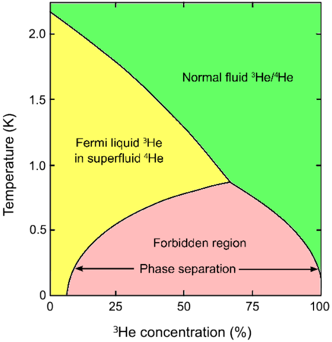




Working principle

Key is the mixture of He^3/He^4:

- Phase separation below a critical temperature of 0.86 K:
  - *concentrated phase* (He^3-rich) with almost only He^3 (on top due to lower density)
  - *diluted phase* (He^3-poor) with about 6 % He^3



Cooling:

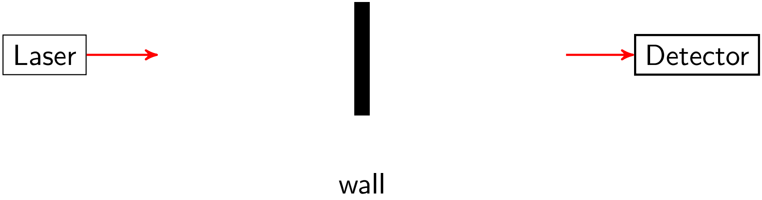
- Remove He^3 from the dilute phase

⇒ The fraction of He^3 can not be below 6.5 %

⇒ He^3 is diluted as it flows from the concentrated phase through the phase boundary into the dilute phase

⇒ Heat necessary for the dilution is the useful cooling power of the refrigerator

Light shining though a wall experiment



Laser:

- Laser power (CW): 30 W @ 1064 nm

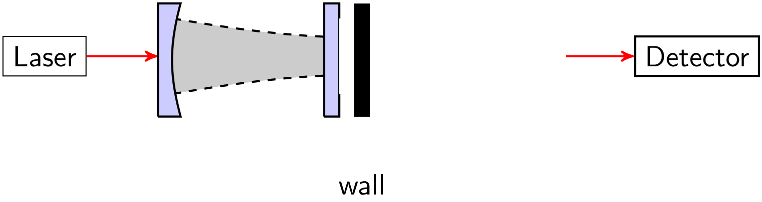
$\Rightarrow$ Similar laser as used by LIGO

- Polarised light with respect to a magnetic field for ALP search

Detector:

- Single photon counter (TES detection scheme)
- Heterodyne detection scheme

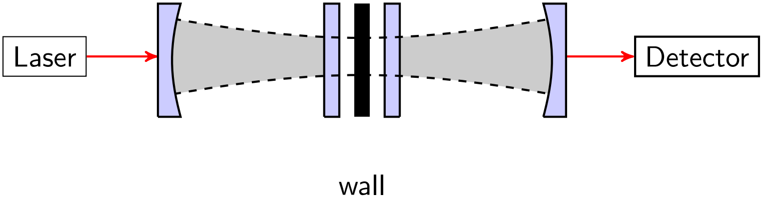
Light shining though a wall experiment



Optical cavity:

- Fabry Perot cavity in the production (PC)
- Number of round trips in the cavity define the power build up
- Power build up: 5000 (150 kW in the cavity)
- Resonance condition is maintained by acting on the input mirror and the laser frequency

Light shining though a wall experiment



Cavity in the regeneration region (RC):

- Resonantly enhance also the back conversion (power build up of 40000)

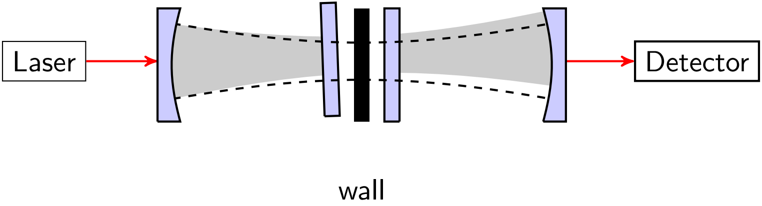
$\Rightarrow$ Both cavities need to share the same beam mode (95 % spacial overlap)

- Resonance condition can not be maintained using the signal wave length!

$\Rightarrow$ Frequency doubling $\Rightarrow$ 532 nm light used to keep the RC resonant for the signal photons (1064 nm)

- Alignment of mirrors on the central bread board needs to be

Light shining though a wall experiment



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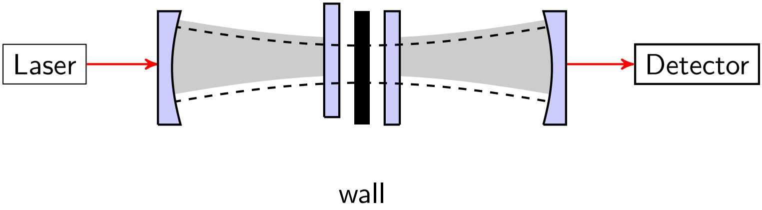

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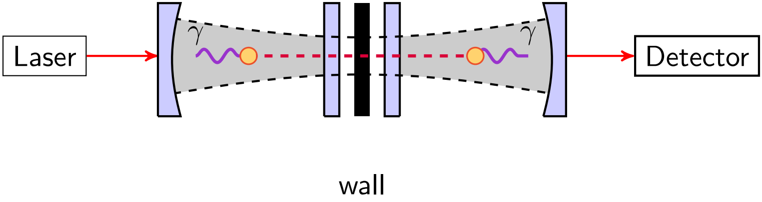


Physics:

- Hidden photon search
- Gauge boson of extra U(1) gauge group

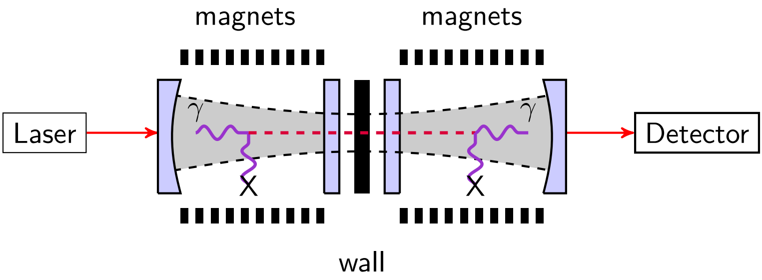
$\Rightarrow$ Generic feature of field and string-theory extensions of the SM

- Conversion via kinetic mixing

LWS main advantage

LSW is a model independent approach, where we have full control of the signal creation!

Light shining though a wall experiment

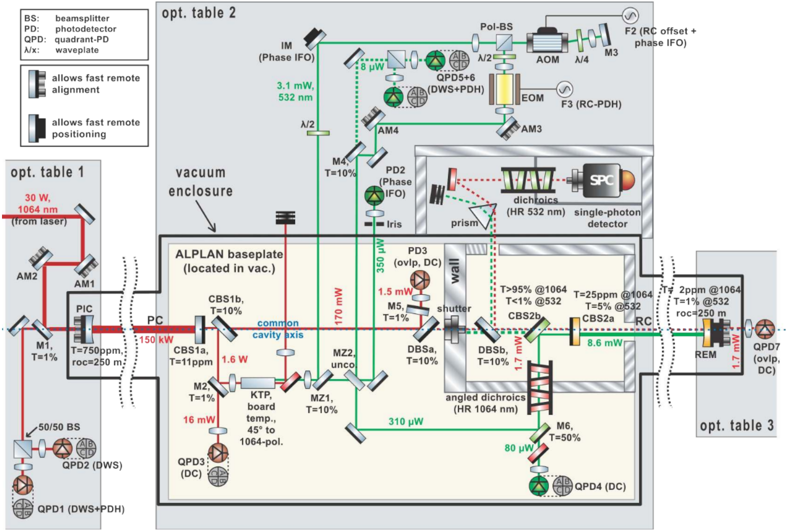


Physics:

- Search for axion like particles requires magnetic field (Primakoff effect)

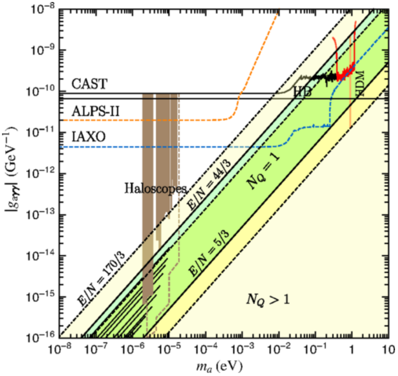
$$
\begin{aligned}
P_{\gamma\to\phi\to\gamma} &= \frac{1}{16}\mathcal{F}_{\mathrm{PC}}\mathcal{F}_{\mathrm{RC}}\left(g_{a\gamma\gamma}Bl\right)^4 \\
&= 6\times 10^{-38}\mathcal{F}_{\mathrm{PC}}\mathcal{F}_{\mathrm{RC}}\left(\frac{g_{a\gamma\gamma}}{10^{-10}\,\mathrm{GeV}}\frac{B}{1\,\mathrm{T}}\frac{l}{10\,\mathrm{m}}\right)
\end{aligned}
$$

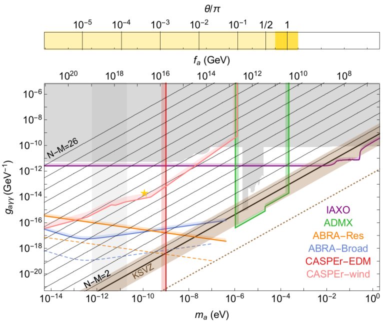
Optics layout



Detect Axions with ALPS II

[arXiv:1610.07593, arXiv:1611.09855]

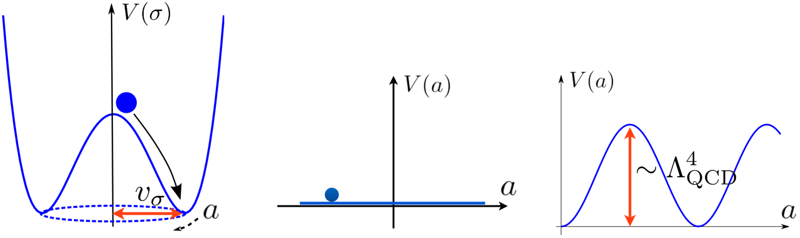




Axion potential

Below the QCD scale $\Lambda_{\rm QCD} \sim \mathcal{O}(100)$GeV, topological charge fluctuations in QCD vacuum induce the potential energy

$$V(a) = \left\langle \frac{\alpha_s}{8\pi} \frac{a}{f_a} G^c_{\mu\nu} \tilde{G}^{c\mu\nu} \right\rangle \sim \Lambda^4_{\rm QCD} \left(1 - \cos \frac{a}{f_a}\right)$$

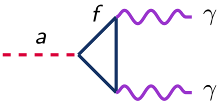


[Ken'ichi Saikawa, 2016]

QDC axion models

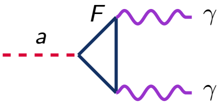
DFSZ:

- All SM fermions have Peccei-Quinn charge
- This model requires the introduction of a 2 Higgs doublet (like in MSSM)



KSVZ:

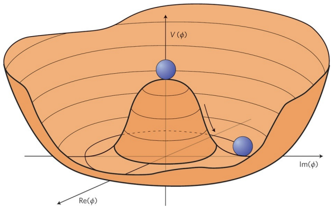
- New heavy fermion with Peccei-Quinn charge
- SM particle don't carry Peccei-Quinn charge



SM extension

Introduce a singlet complex scalar σ featuring a global $U(1)$ symmetry, which is spontaneously broken in vacuum:

$$\sigma(x) = \frac{1}{\sqrt{2}} \left(v_\sigma + \rho(x)\right) \mathrm{e}^{ia(x)/v_\sigma}$$



[Nature physics 7, 2011]

Leaving the vacuum state:

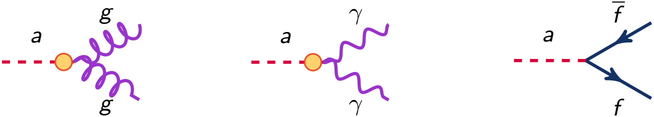
- Along the buttom: $m_a = 0$, spin: $0 \Rightarrow$ Nambu-Goldstone-Boson
- Quantum fluctuations in radial direction: $m_\rho \propto v_\sigma$, spin:0 $\Rightarrow$ Analog to the Higgs

To realize feeble interactions with the SM:

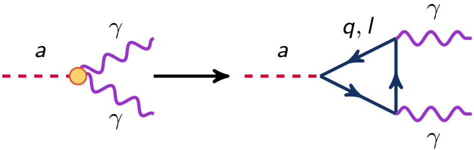
$$v_\sigma \gg v = 246\,\mathrm{GeV}$$

SM interactions

$$\mathcal{L}_{\text{int.}} \supset -\frac{\alpha_s}{8\pi} C_{ag} \frac{a}{v_\sigma} G^c_{\mu\nu} \tilde{G}^{c\mu\nu} - \frac{\alpha}{8\pi} C_{a\gamma} \frac{a}{v_\sigma} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} C_{af} \frac{\partial_\mu a}{v_\sigma} \bar{\psi}_f \gamma^\mu \gamma_5 \psi_f$$



- C_{ag} and $C_{a\gamma}$ are determined by loops over fermions charged under $U(1)$:



- Axion mass: $m_A = 57.0(7)\,\mu\text{eV}\left(\frac{10^{11}\,\text{GeV}}{f_A}\right)$ [Borsanyi et al. 2016]

Axions in the inflationary universe

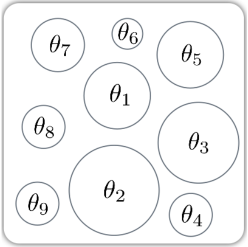
- Initial field value $\theta^{\text{ini}} = \frac{a^{\text{ini}}}{f_a}$ depends on the history of the early universe (e.g. inflation)
- If the PQ symmetry is broken before inflation, the axion field takes a single value θ^{ini} in our universe

$\Rightarrow$ Axions can explain dark matter with $f_a \gg O(10^{11})$GeV if $|\theta^{\text{ini}} \ll O(1)$

- If the PQ symmetry is broken after inflation, topological defects are formed, which also produces cold axions

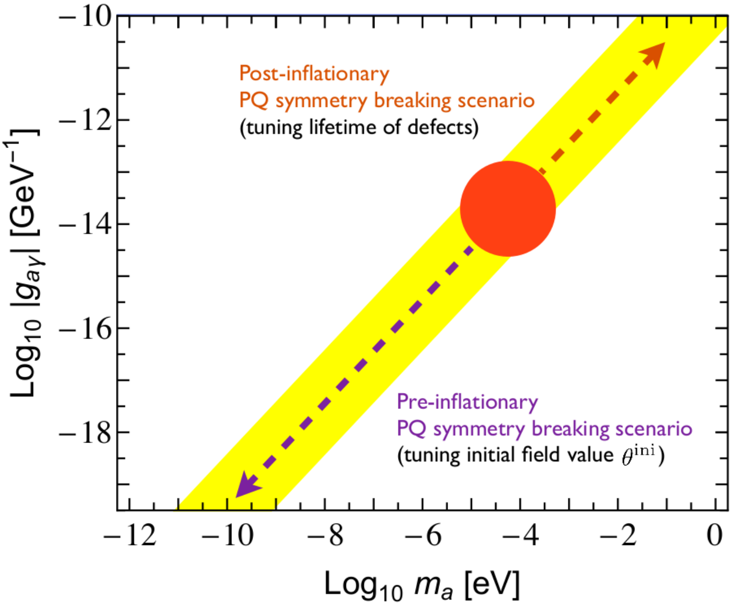
$\Rightarrow$ Axions can be dark matter for $f_a \ll O(10^{11})$GeV up to the lifetime of topological defects

Post-inflationary PQ breaking



Pre-inflationary PQ breaking

[Ken'ichi Saikawa]


−10
−12
−14
−16
−18
−12
−10
−8
−6
−4
−2
0
Log10 |gaγ| [GeV−1]
Log10 ma [eV]
Post-inflationary
PQ symmetry breaking scenario
(tuning lifetime of defects)
Pre-inflationary
PQ symmetry breaking scenario
(tuning initial field value θini)