Search for dark-matter axions beyond the quantum limit: Cosmological Axion Sarov Haloscope (CASH) proposal

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Outline

- Haloscope concepcion for axion dark matter search
- Josephson Junction Single Photon detector
- Cavity frequency tuning
- CASH sensitivity plot & comparison to other projects
- Additional scientific program for CASH:
  - Dark Photon Dark Matter
  - High Frequency Gravitational Waves
- Current experimental plans and conclusion.

Intro

- Standard Model (SM) of particle physics is incomplete
- One of particle physics puzzle - Strong CP-problem
  (CP-parity concerved in QCD)
- One of the puzzles of cosmology — dark matter. What particles compose it?
  None of the particles (or fields) in the Standard Model are suitable candidates
- One of the solutions for both puzzles — new pseudoscalar particle "axion"

  Peccei Quinn, 1977

  Preskill 1982, Abbott 1982, Dine 1982

Axion interaction with electromagnetic field

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2} m_a^2 \, a^2 - \frac{1}{4} g_{a\gamma\gamma} \, a \, F_{\mu\nu} \widetilde{F}^{\mu\nu} \qquad (\hbar = c = 1)$$

$$F_{\mu\nu} \widetilde{F}^{\mu\nu} = -4 \vec{E} \cdot \vec{B}$$

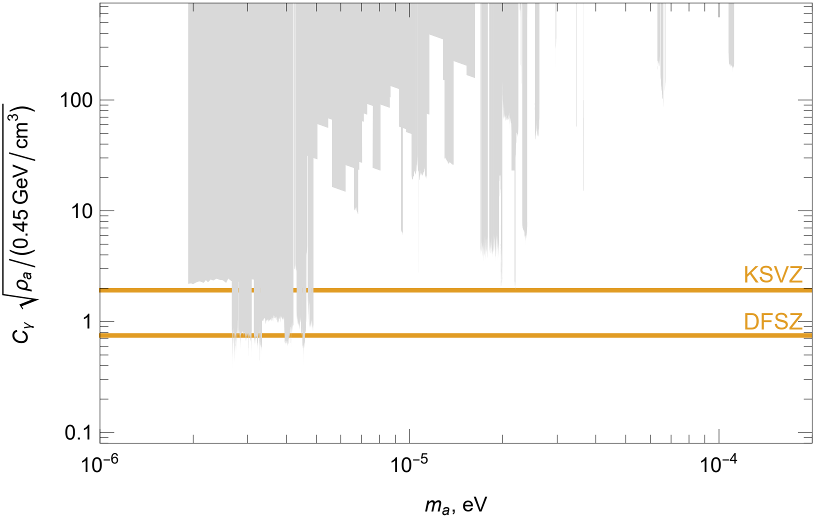
- Axion-like particles (ALP) — arbitrary parameters ($g_{a\gamma\gamma}$, m_a)
- QCD axions — a stripe in the parametric space,

$$g_{a\gamma\gamma} = 10^{-10} \, \mathrm{GeV}^{-1} \, C_\gamma \, \frac{m_a}{0.5 \, \mathrm{eV}}, \qquad C_\gamma \sim 1$$

Benchmark models:

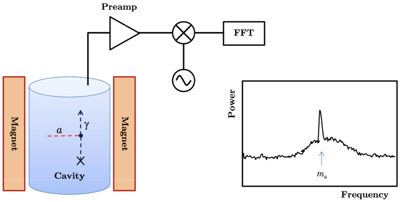
- KSVZ $C_\gamma \approx 1.92$ Kim, 1979, Shifman, Vainshtein, Zakharov 1979
- DFSZ $C_\gamma \approx 0.75$ Dine, 1981, Fischler, Srednicki, Zhitnitsky 1980

ALP parameters & bounds



$$g_{a\gamma\gamma} = 10^{-10}\,\mathrm{GeV}^{-1}\,C_\gamma\,\frac{m_a}{0.5\,\mathrm{eV}}$$

Search for axion dark matter – a haloscope concept



Pierre Sikivie PRL 1983

- Dark matter - axionic condensate $a(t) = a_0 \sin(m_a t)$. Energy density $\rho_a = \frac{1}{2} m_a^2 a_0^2 = 0.45\,\mathrm{GeV/cm^3}$, m_a - unknown. Non-relativistic: $v \ll 1$
- Resonance detection in magnetic field B with radiofrequency cavity (volume V, unloaded quality factor Q_0). Cavity gabarites $L \sim \lambda_a$.
- Disadvantage - resonance only if cavity frequency ω coincides with a certain axion mass m_a (very narrow band, $\delta m_a \sim \frac{m_a}{Q}$). Tuning of cavity geometry to test different m_a.
- Energy power of axion-induced electromagnetic signal

$$P_a = \left(\frac{g_{a\gamma\gamma}^2}{m_a^2} \rho_a \right) \times \left(F(\beta) \omega B^2 V C_{010} Q_0 \right)$$

C_{010} - form factor, $F(\beta)$ - cavity-detector connection.

Detectors

- Standard detectors for axion searches in radio waverange – **linear amplifiers**. Noise is fundamentally limited by the quantum limit.

$$T_{\text{noise}} > T_{\text{SQL}} \approx 50\,\text{mK} \times \frac{\omega}{\text{GHz}}$$

  Dicke radiometer equation:

$$\text{SNR} = \frac{P_{sig}}{P_{noise}} = \frac{P_{sig}}{T_{eff}}\sqrt{\frac{t}{\Delta\nu}}$$

  Cooling below T_{noise} is ineffective.
- Alternatives to linear amplifiers are necessary – **Single Photon Detectors (SPD)** Lamoreaux et al 2013

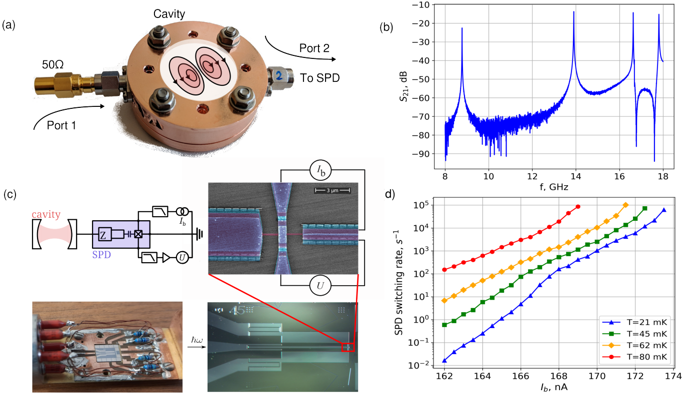
$$\text{SNR} = \frac{N_{\text{sig}}}{\sqrt{N_{\text{sig}} + N_{\text{d.c.}}}} = \frac{R_{\text{sig}}}{\sqrt{R_{\text{sig}} + R_{\text{d.c.}}}}\sqrt{t}$$

  Rate $R = P/\omega = N/t$. d.c. – dark counts, non-thermal noise.
  Thermal Planck noise is suppressed, $e^{-\omega/T}$ for $T \ll \omega$.

Josephson Junction Single Photon Detector

SPD on Josephson Junctions for 5 – 15 GHz waverange have been constructed by a group in Nizhny Novgorod Technical University

A.L.Pankratov et al. Observation of thermal microwave photons with a Josephson junction detector. arXiv:2404.10434 [quant-ph]. Nature Commun. 16 (2025) 1, 3457

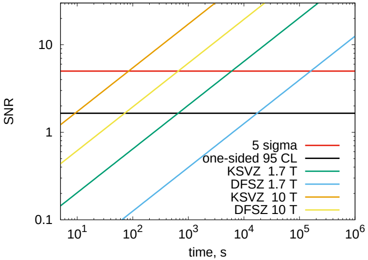


No thermal photons at 21 mK. 1 dark count in 100 seconds

Time dependence

$$\mathrm{SNR} = \frac{R_{\mathrm{sig}}}{\sqrt{R_{\mathrm{sig}} + R_{\mathrm{d.c.}}}}\sqrt{t},$$

$$R_{sig} = C_\gamma^2\, B_0^2\, Q_0 \times G, \qquad G = 0.14\ \mathrm{GeV}^{-3}, \qquad R_{d.c.} = 0.01\, s^{-1}$$



	B, T	t
KSVZ	1.7	400 s $\simeq$ 6.5 min
DFSZ	1.7	9 200 s $\simeq$ 2.5 hours
KSVZ	7	14 s
DFSZ	7	112 s

Necessary observation time to reach 95% CL sensitivity ($\mathrm{SNR} = 1.65$), $Q = 10^5$.

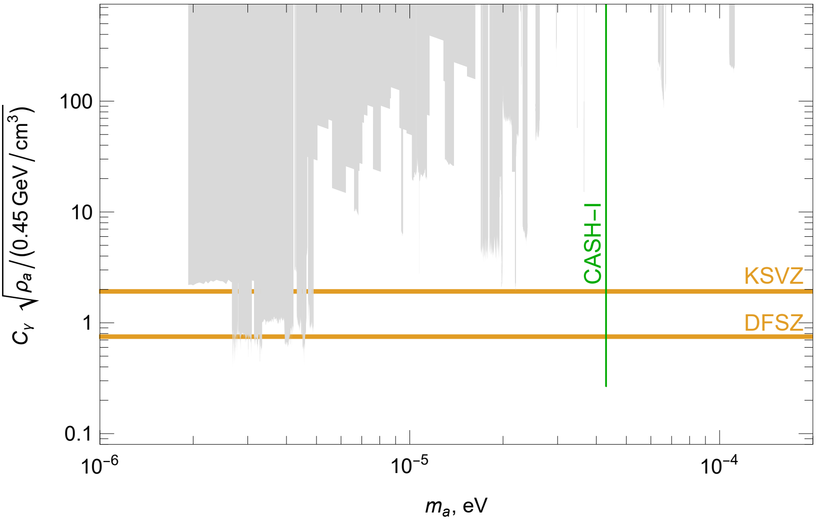
CASH-I. No tuning

- Cavity params: cylinder, $R = 1.3$ cm, $L = 12$ cm. $C_{010} = 0.69$, $Q_0 = 10^5$.
- Resonant mass $m_a = 36.5\,\mu$eV.
- $B = 1.7$ T
- $T = 20$ mK, $R_{d.c.} = 0.01\,s^{-1}$. $R_{th.} \ll R_{d.c.}$
- SNR$= 1.65$
- $t = 10^6$ s ≈ 12 days

Sensitivity to ALP parameters:

$$C_\gamma = 0.27, \quad \text{or} \quad g_{a\gamma\gamma} = 2.3 \cdot 10^{-15}\ \text{GeV}^{-1}$$

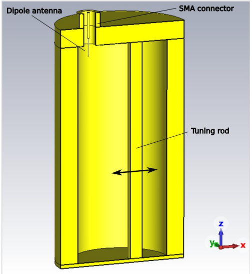
CASH-I. Sensitivity plot.

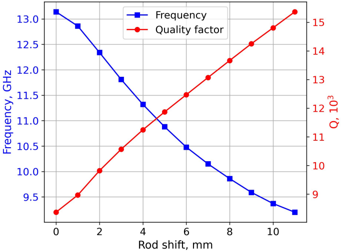


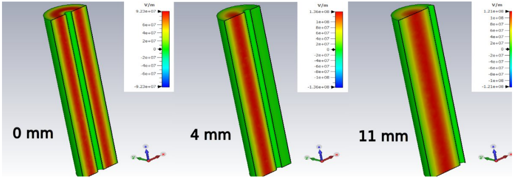
CASH-I: $t = 10^6$ s, $B = 1.7$ T.

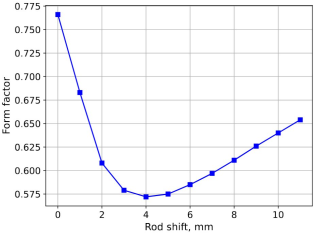
CASH-II. Frequency tuning

Cavity tuning with a metallic rod









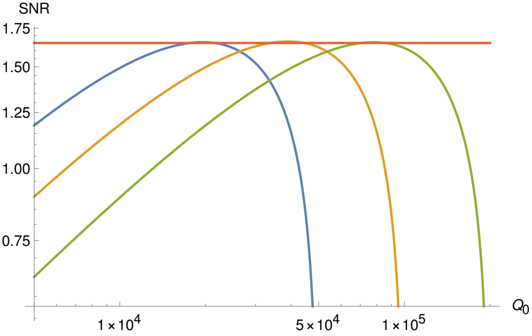
$Q \propto \omega$. Q can be changed by changing conductivity.

CASH-II. Frequency tuning

- Rude estimation $C_{010} \simeq 0.69$. $Q_0 \approx$ const with frequency changing.
- Time of single frequency tuning $\delta t \sim 15$ min.
- Sensitive for mass range $m_a \equiv (m_L - m_R) = (38 - 54)\,\mu$eV.
- Width of resonance line $2m_a/Q_0$
- Number of steps $N = Q_0/2 \log(m_R/m_L) = \log 1.4/2\, Q_0$.
- The sensitivity for fixed cavity frequency grows with Q_0
- The bandwidth for a fixed frequency narrows with increasing Q_0, so the number of frequency shifts N increases, and the measurement time at a fixed frequency decreases. The sensitivity also decreases.

$$\mathrm{SNR} = \frac{C_\gamma^2\ B_0^2 G Q_0}{\sqrt{C_\gamma^2\ B_0^2 G Q_0 + R_{\mathrm{d.c.}}}} \sqrt{\frac{2\tau}{Q_0 \log 1.4} - \delta t}.$$

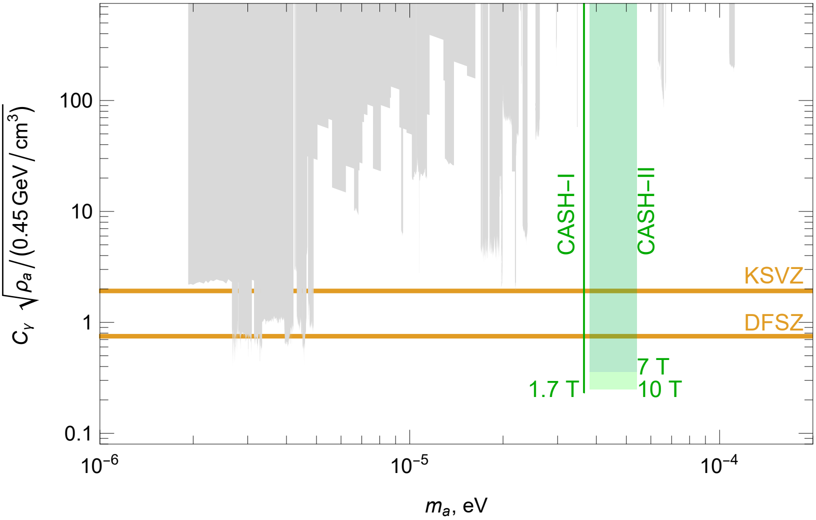
CASH-II. Quality factor optimization



total time τ, years	0.25	0.5	1
optimal Q_0	2×10^4	4×10^4	8×10^4
N	3.5×10^3	7×10^3	1.4×10^4
C_γ for $B_0 = 7$ T	0.72	0.51	0.36
C_γ for $B_0 = 10$ T	0.50	0.36	0.25

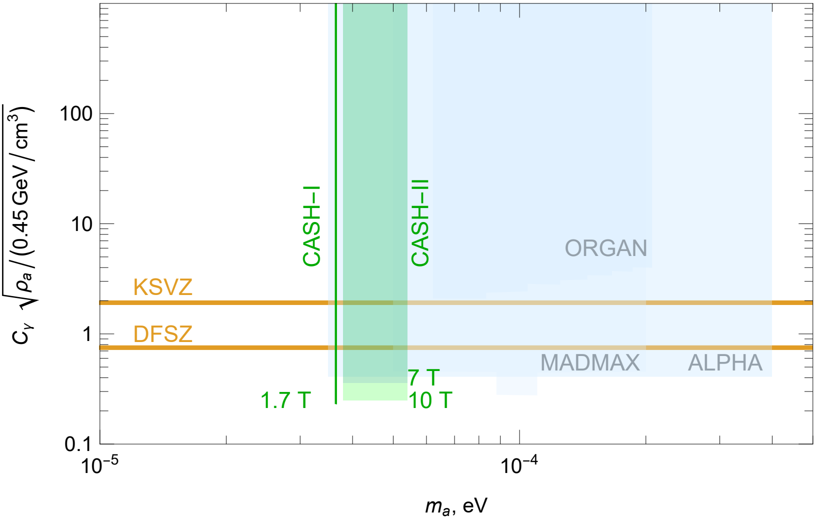
Optimal time of measurement at fixed freq $t = 1350$ sec ≈ 22.6 min. $N_{d.c.} \approx 13.5$ background events. $\delta t = 15$ minutes for frequency tuning

CASH-II. Sensitivity plot.



CASH-II: 1 year of operation, $B_0 = 7$ and 10 T.

CASH-II. Comparison with other projects.



CASH-II: 1 year of operation, $B_0 = 7$ and 10 T.

Additional scientific program for CASH: Dark Photons

Another dark matter candidate - Dark Photon Okun 1982, Holdom 1986

$$\mathcal{L} = -\frac{1}{4}F^2_{\mu\nu} - \frac{1}{4}F'^2_{\mu\nu} - \frac{m_{A'}}{2}^2 A'_\mu A'^\mu + \frac{\chi}{2}F_{\mu\nu}F'^{\mu\nu}$$

A'_μ - dark photon field, $m_{A'}$ - the mass, χ - kinetic mixing. Dark photon field transfers to normal photons in a haloscope **without a magnetic field**.
The signal power:

$$P_s(\nu) = m_{A'}\rho_{A'}\chi^2 VCQ_0F(\beta)$$

CASH sensitivity to χ for large t:

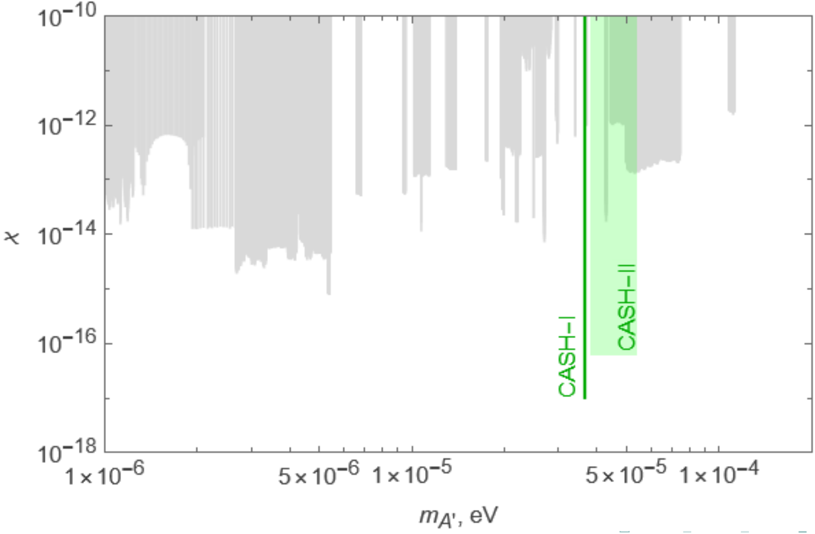
$$\chi = \left(\frac{1}{\rho_{A'}VQ_0C}SNR\sqrt{\frac{R_{d.c.}}{t}}\right)^{1/2}.$$

C includes angle dependence $\cos^2\theta$, θ is the angle between dark photon polarization and haloscope axis, we use the averaged value. Oscillations are subleading.

CASH sensitivity to Dark Photons

Preliminary!

CASH-I: $t = 10^6$ s, $\chi = 10^{-17}$,   CASH-II: $t = 1350$ s for a certain $m_{A'}$, $\chi = 6.2 \times 10^{-17}$.



Additional scientific program for CASH: High Frequency Gravitational Waves (HFGV)

Gertsenshtein effect: gravitational wave transfers into photon in magnetic field Gertsenshtein and Pustovoit, 1962

$$S = \int d^4x\sqrt{-g}\left(-\frac{1}{4}g^{\mu\alpha}g^{\nu\beta}F_{\mu\nu}F_{\alpha\beta}\right), \qquad g^{\mu\nu} = \eta^{\mu\nu} + h^{\mu\nu}$$

Can be done in a haloscope. **Relativistic** gravitons instead of **non-relativistic** dark matter. Berlin et al. arXiv:2112.11465 (PRD) Signal power:

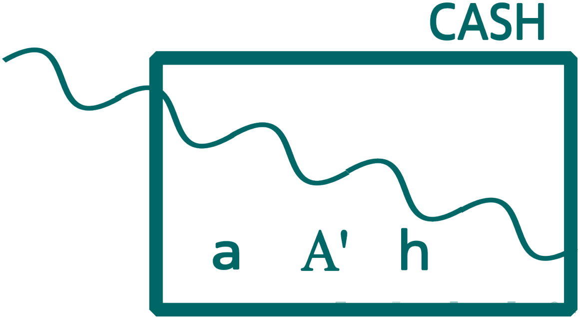
$$P_{sig} = \frac{1}{2}Q\omega_g^3 V_{cav}^{\frac{5}{3}}(\eta_n h_0 B)^2$$

$$\text{CASH-I(TM010)}: \qquad h_0 = 2.6\times 10^{-22} \quad \text{for } \nu = 8.8\text{ GHz},\ B = 1.7\ T$$

or an order of magnitude better for special higher cavity modes.
Potential Sources of HFGW: Primordial Black Holes or other compact ($L \sim 1$ cm) objects merging; GWs of cosmological origin.
General predictions: $h_0 \sim 10^{-26}$ or lower but may be higher for specific models
...work in progress!

Conclusions

- CASH is a compact low-budget experimental project with unprecedented high sensitivity to QCD axion and dark photon dark matter of masses 38-56 μeV, and to High Frequency Gravitational Waves.
- SPD on JJ - key feature of the setup. 2 orders of magnitude greater sensitivity than linear amplifiers
- In case of a signal detection an additional analysis of its nature is necessary
- **Current experimental plans.** CASH-I: No freq. tuning, t=10^6 s $\sim$ 12 days of measurement at 20 mK, B = 1.7 T. Planned to be held in Autumn 2025 at Nizhny Novgorod Technical University



Thank you for your attention!