CASH

Cosmological Axion Sarov Haloscope (CASH): search for dark-matter axions, dark photons and high-frequency gravitational waves beyond the quantum limit.

Petr Satunin (INR RAS)

PHYSICAL REVIEW D **112,** 035003 (2025)

Search for dark-matter axions beyond the quantum limit: The cosmological axion Sarov haloscope proposal

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(NSTU, IPM RAS,
INR RAS, NCPHM,
PNPI, SINP MSU and others..)

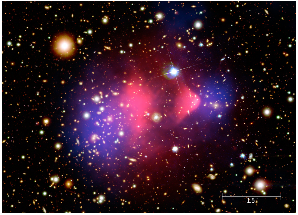
a A' h

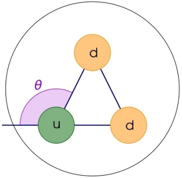
22 May 2026, Quarks-2026

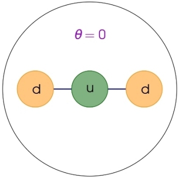
Introduction

- The Standard Model (SM) of particle physics is incomplete
- An unsolved puzzle of cosmology – which particle constitutes dark matter? None of the SM particles fit
- One of the puzzles of particle physics – the Strong CP problem (CP conservation in QCD)
- One solution to both problems – a new pseudoscalar particle “**Axion**”

Weinberg 1978, Wilczek 1978
Preskill et al 1983, Abbott et al 1983, Dine et al 1983







Properties of axion dark matter

- **Cold** dark matter: **non-relativistic** at the epoch of structure formation
- Non-thermal production mechanism (at the QCD phase transition)
- Distributed almost homogeneously in the Galaxy or clumped into miniclusters – still an open debate
- Energy density in the vicinity of the Solar System for a homogeneous distribution: $\rho_{\rm DM} = 0.45\,\text{GeV}/\text{cm}^3$
- Axions form a classical field with high coherence: $Q_{\rm DM} = \lambda_{\rm coh}/\lambda \sim 10^6$.
- Axion mass m_a is unknown.

- Axions with mass $10 - 100\ \mu$eV are predicted in many QCD models: Buschmann et al 2022, Sopov et al 2023, Benabou et al 2025

We search for axion dark matter in this mass range.

- A clean channel for axion search is their interaction with photons

Axion interaction with electromagnetic field

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

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

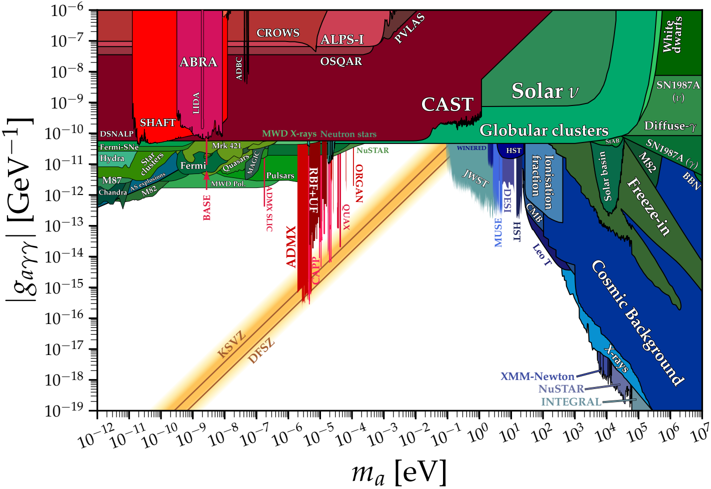
- Axion-Like Particles (ALP) – no relation between parameters ($g_{a\gamma\gamma}$, m_a)
- QCD axions – a band in parameter space,

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

Main models:

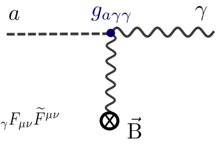
- KSVZ $C_\gamma \approx 1.92$ Kim, 1979, Shifman, Vainshtein, Zakharov 1979
- DFSZ $C_\gamma \approx 0.75$ Dine, 1981, Fischler, Srednicki, Zhitnitsky 1980

Axion-like particle parameters and constraints

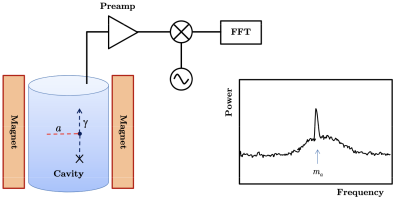


https://cajohare.github.io/AxionLimits/

Search for axion dark matter – the **haloscope** concept



$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \widetilde{F}^{\mu\nu}$



Pierre Sikivie PRL 1983

- An axion dark matter particle with energy ω (non-relativistic, $\omega \simeq m_a$) converts into a photon ω in the presence of an external magnetic field $\vec{B}$. *Sikivie effect*
- Resonance in the presence of a cavity with conducting walls (quality factor Q_0) if $\omega = m_a$ – one of the cavity eigenfrequencies, $m_a \in \omega_n \times [1 - Q_0^{-1}, 1 + Q_0^{-1}]$.
- Very **narrow** range of axion masses (for a fixed mode n), $\delta m_a \sim \frac{2 m_a}{Q_0}$

Signal power:

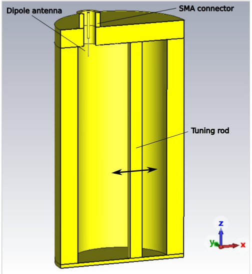
$$P_a = \left(\frac{g^2_{a\gamma\gamma}}{m_a^2} \rho_{\mathrm{DM}} \right) \times \left(F(\beta) \omega B^2 V C_{010} Q_0 \right)$$

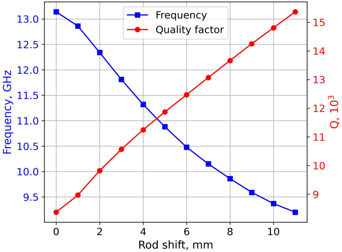
C_{010} – form factor for mode $n = TM010$, V – cavity volume, $F(\beta)$ – coupling coefficient.

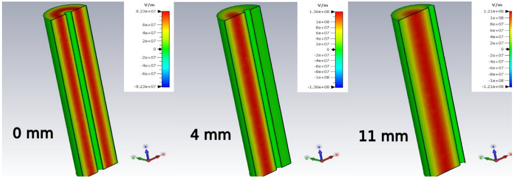
- To be sensitive to different m_a, we need to change the eigenfrequencies ω_n, e.g., by changing the cavity geometry.

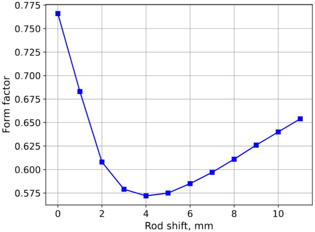
Changing cavity geometry – an example

Cavity tuning with a metallic rod

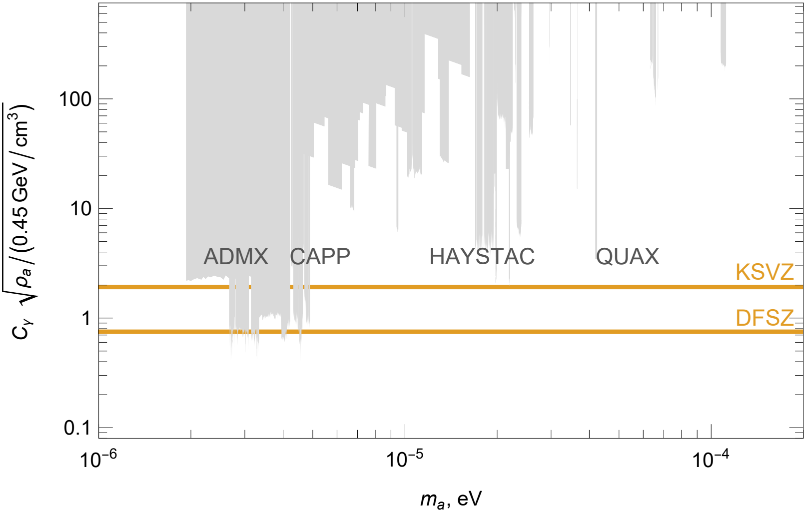








Current haloscope constraints on ALP parameters

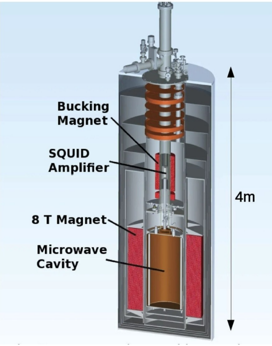


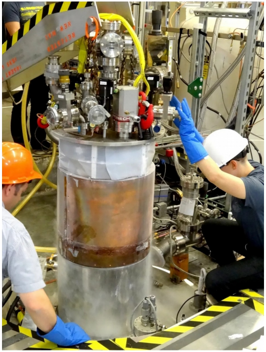
Full list of constraints obtained by collaborations – **https://cajohare.github.io/AxionLimits/**

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

Comparative size of haloscopes

ADMX:





HAYSTAC:

QUAX:

Photon detectors in the radio range 0.1 – 50 GHz

- Standard detectors for axion searches in the radio range – **linear amplifiers** (including quantum parametric amplifiers). The EM field amplitude is measured in equilibrium. Uncertainty principle: $[\hat{A}, \hat{N}] \neq 0$. Sensitivity limited by the standard quantum limit (SQL):

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

  Dicke radiometer equation:

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

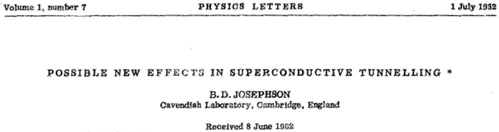
  Cooling below T_{noise} does not reduce the noise.
- SQL can be overcome:
  - Slightly ($T_{\rm noise} \lesssim T_{\rm SQL}$) using squeezed states in the detector (HAYSTAC coll. PRD 107 (2023) 7 arXiv:2301.09721)
  - By using macroscopic detectors in a quantum state, in a non-equilibrium regime $T_{\rm noise} \ll T_{\rm SQL}$ — single-photon detector (SPD)

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

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

Josephson junction

Josephson effect

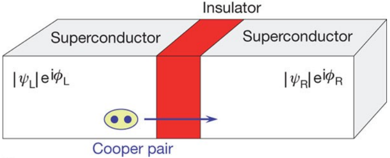


Volume 1, number 7 PHYSICS LETTERS 1 July 1962

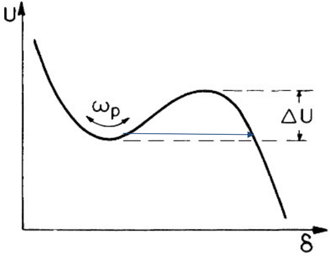
POSSIBLE NEW EFFECTS IN SUPERCONDUCTIVE TUNNELLING *

B. D. JOSEPHSON
Cavendish Laboratory, Cambridge, England

Received 8 June 1962



Macroscopic Quantum Tunneling (MQT)



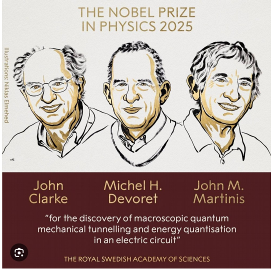
$$U(\delta) = -(I_0\Phi_0/2\pi)[\cos\delta + (I/I_0)\delta] \; .$$

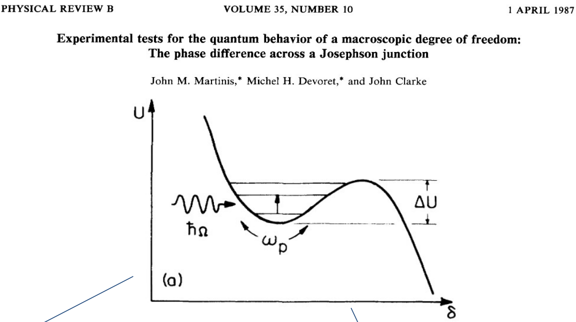
$$\Gamma_q = a_q \frac{\omega_p}{2\pi} \exp\left[-7.2\frac{\Delta U}{\hbar\omega_p}\left[1 + \frac{0.87}{Q} + \cdots\right]\right] ,$$

where

$$a_q \approx [120\pi(7.2\Delta U/\hbar\omega_p)]^{1/2} \; .$$

Single-photon detectors based on Josephson junctions



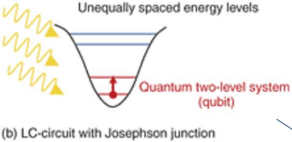

PHYSICAL REVIEW B VOLUME 35, NUMBER 10 1 APRIL 1987

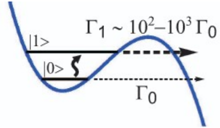
Experimental tests for the quantum behavior of a macroscopic degree of freedom: The phase difference across a Josephson junction

John M. Martinis,* Michel H. Devoret,* and John Clarke

qubits

Single photon detectors





quantum computers

Single-photon detector based on Josephson junctions

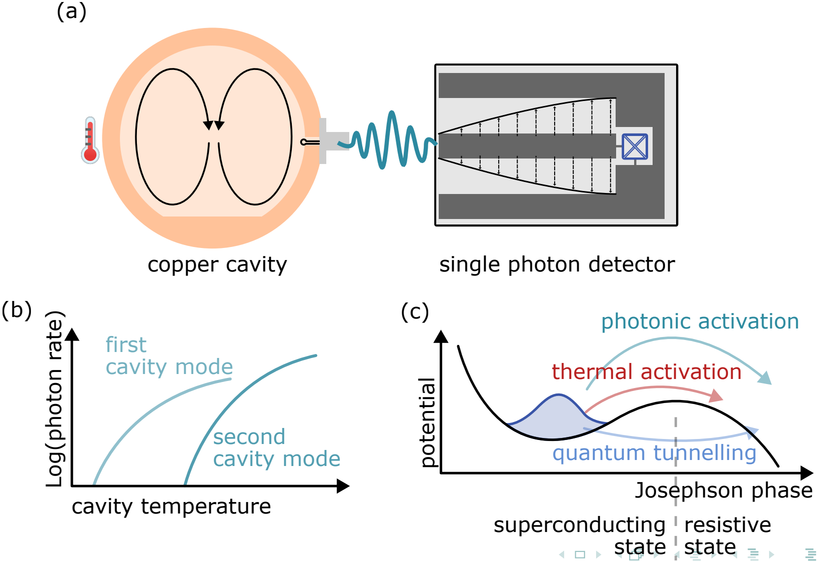
Marnites, Devoret, Clarke 1984-1988: Dark count rate: $10^2 - 10^6\ s^{-1}$ – too high for efficient operation as a single-photon counter.

Single-photon detectors with smaller Josephson junction width lower dark count rate (down to $10^{-2}\ s^{-1}$), at frequencies $5 - 15$ GHz – developed by group at NSTU n.a. R.E. Alekseev & IPM RAS in Nizhny Novgorod

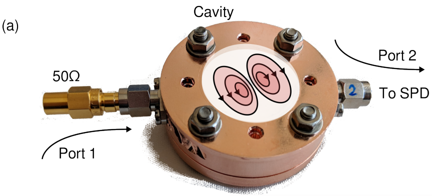
- L.S. Kuzmin et al. Single Photon Counter Based on a Josephson Junction at 14 GHz for Searching Galactic Axions. IEEE Trans. on Applied Superconductivity 28, 2400505 (2018).
- L.S. Revin et al. Microwave photon detection by an Al Josephson junction. Beilstein Journal of Nanotechnology 11, 960–965 (2020)
- A.L. Pankratov et al. Towards a microwave single-photon counter for searching axions. Quantum Information 8, 1–7 (2022).
- A.L.Pankratov et al. Quantum and phase diffusion crossovers in small Al Josephson junctions. Chaos, Solitons and Fractals 184 (2024) 114990
- 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

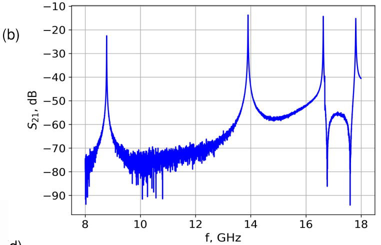
Single-photon detector based on Josephson junctions

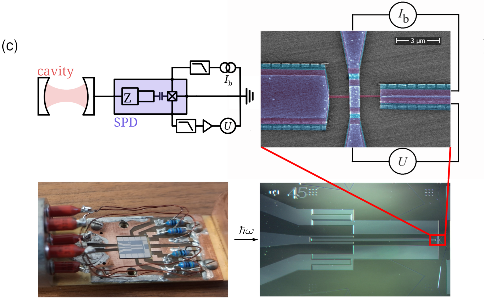
A.L.Pankratov et al. Observation of thermal microwave photons with a Josephson junction detector. arXiv:2404.10434 [quant-ph]. Nature Commun. 16 (2025) 1, 3457

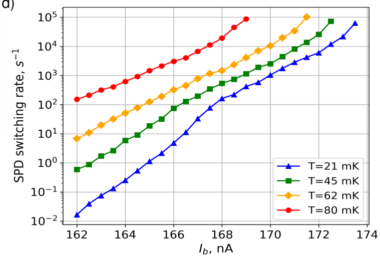


Single-photon detector based on Josephson junctions

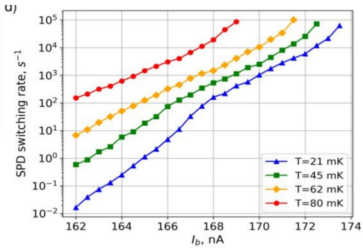


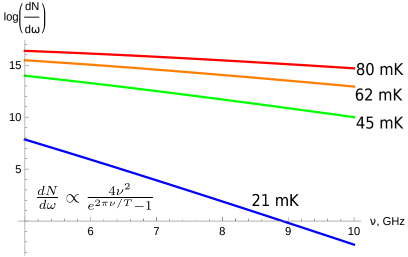


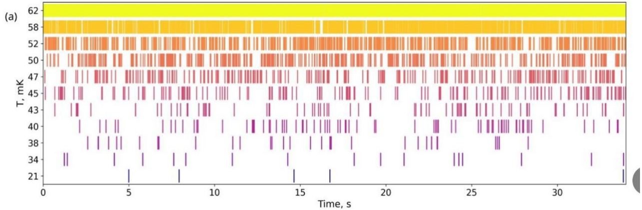




Regime without thermal photons

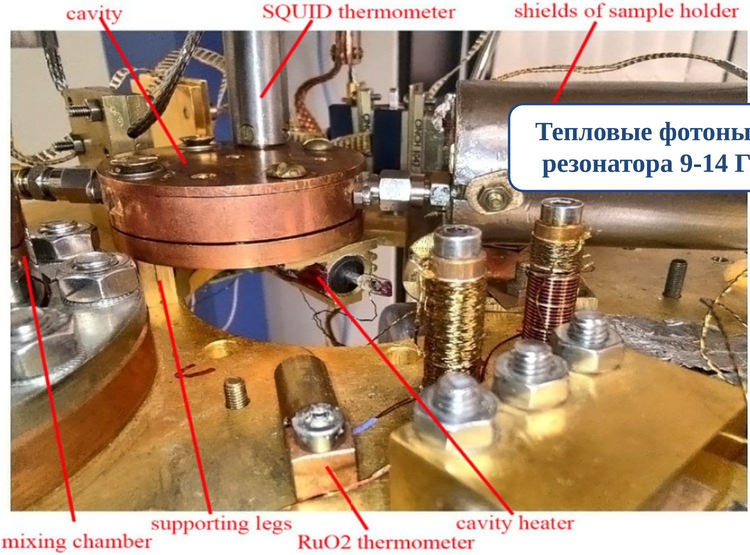






No thermal photons at 21 mK. 1 dark count (tunneling) in 100 seconds

Setup for measuring thermal photons with single-photon detectors based on Josephson junctions



Тепловые фотоны из резонатора 9-14 ГГц

Upgrading the setup for axion dark matter search. The CASH experiment proposal.

What needs to be added to the existing setup?

- High-quality cylindrical cavity
- Permanent magnet surrounding the cavity and fitting into the cryostat

  Available magnet 1.7 T !!
  verified, works with the cryostat
  in the future – for higher sensitivity to axion parameters a stronger magnet is desirable
- Magnetic field shields, bringing detectors to a region with minimal magnetic field.
- Mechanism for fast and careful frequency tuning of the cavity to probe a wide range of possible axion masses
  – not required for the first stage, first demonstrate operation at a single frequency

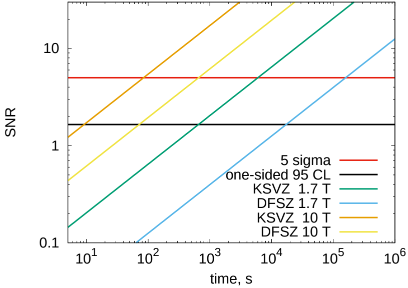
CASH-I – axion search at a fixed frequency

$$\mathrm{SNR} = \frac{N_{\rm sig}}{\sqrt{N_{\rm sig} + N_{\rm d.c.}}} = \frac{R_{\rm sig}}{\sqrt{R_{\rm sig} + R_{\rm d.c.}}}\sqrt{t}, \qquad R = N/t.$$

Statistical significance to reject $N_{\rm sig}$ if $N = N_{\rm d.c.}$ events are detected.

- Most sensitive region: $N_{\rm sig} \ll N_{\rm d.c.}$.
- But: $R_{\rm d.c.}$ – tunneling probability, cannot be calculated exactly; the error must be estimated from an independent measurement.
- It is necessary to measure the background without magnetic field, $t_{\rm noB} > 2t_{\rm B}$.
- The detector cannot be fully shielded from the magnetic field. However, the magnetic field may reduce $N_{\rm d.c.}$, while a possible axion signal would increase it.

CASH-I. Sensitivity estimation.



	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

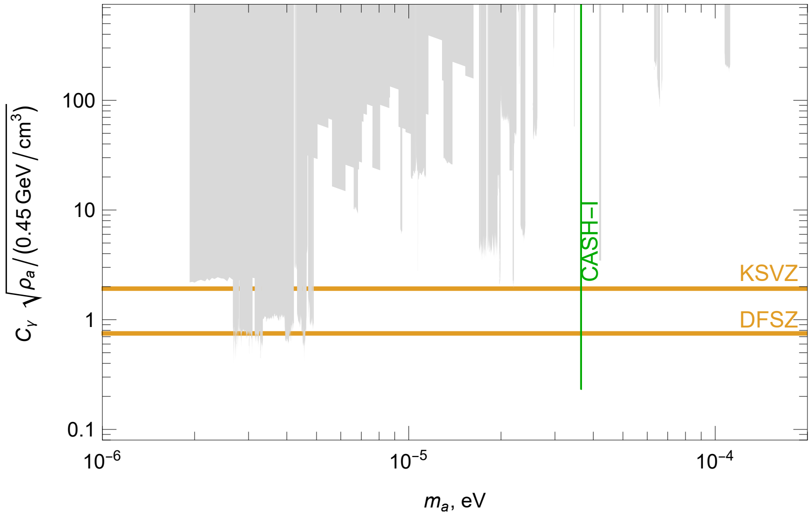
Measurement time to achieve 95% CL sensitivity $(\mathrm{SNR} = 1.65)$, $Q = 10^5$.

- Cylindrical copper cavity $R = 1.3$ cm, $L = 12$ cm $C_{010} = 0.69$, $Q_0 = 10^5$.
- $m_a = 36.5\,\mu$eV, $B = 1.7$ T , $T = 20$ mK, $t = 10^6$ s ≈ 12 days ($+ > 24$ days for background measurement without magnetic field)

Sensitivity to ALP parameters:

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

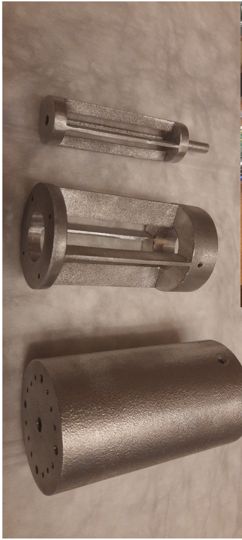
CASH-I. Sensitivity plot.

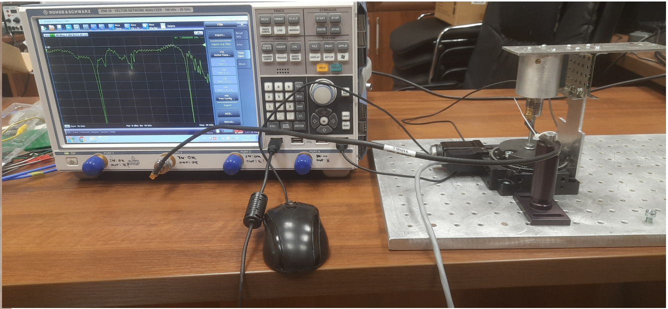


CASH-I: $t = 10^6$ s $\simeq 12$ days, $B = 1.7$ T. $m_a = 36.5\,\mu$eV. $C_\gamma = 0.27$

Tunable cavity

Разработка резонаторов с перестройкой частоты





Оригинальная конструкция резонатора с перестройкой частоты:

Идея и расчет: В. Иванов, ИФМ РАН

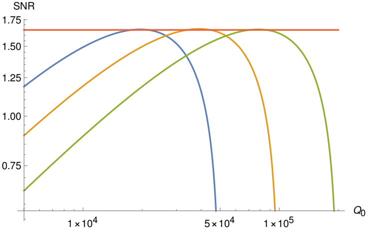
Печать на 3D принтере
из алюминиевых сплавов: С. Шотин, ННГУ

Создание измерительного стенда
и проведение измерений: А. Чигинев и А. Яблоков, ИФМ РАН

Магнит на 1.7 Тл
для тестов

CASH-II. Optimization of quality factor

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

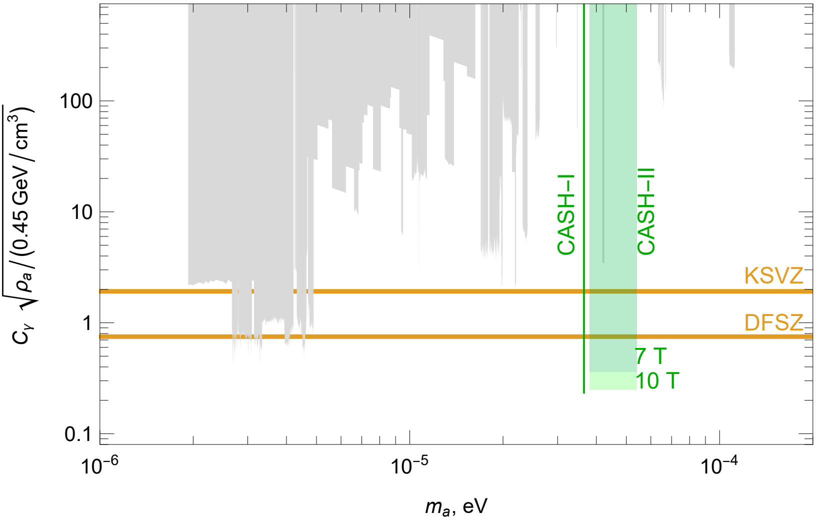


total time τ, years	0.25	0.5	1
optimal Q_0	2×10^4	4×10^4	8×10^4
number of steps N	3.5×10^3	7×10^3	1.4×10^4
C_γ for $B_0 = 7$ T	0.72	0.51	0.36
C_γ for $B_0 = 10$ T	0.50	0.36	0.25

Optimal measurement time at a fixed frequency $t = 1350$ seconds ≈ 22.6 minutes. $N_{d.c.} \approx 13.5$ dark counts. $\delta t = 15$ minutes for frequency tuning

- Detector bandwidth 10%. For the whole range, 4-5 detectors are needed. Background measurement for each detector – time is small compared to total time

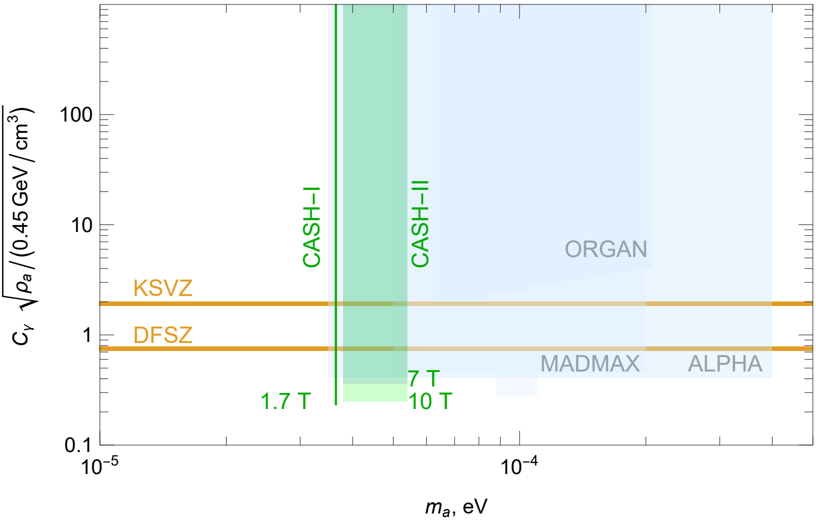
CASH-II. Sensitivity plot.



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

Corresponds to local 2σ. Actual constraints on real data will be worse

CASH-II. Comparison with other projects.



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

Sensitivity of CASH to dark photons

Dark matter candidate – dark photon Okun 1982, Holdom 1986

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

A'_μ – dark photon field, $m_{A'}$ – mass, χ – kinetic mixing.
Oscillations of dark photons (A') into ordinary photons. If the frequency matches the cavity eigenfrequency, the signal is enhanced by Q. The magnetic field in the haloscope does not affect the resonance for A'.

- In case of a signal detection, a measurement without magnetic field should also be performed. The axion signal would disappear, while the A' signal would not.
- Estimation of the background by measuring the signal at neighboring frequencies may be required.

Signal power:

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

Sensitivity of CASH to the mixing χ for large t:

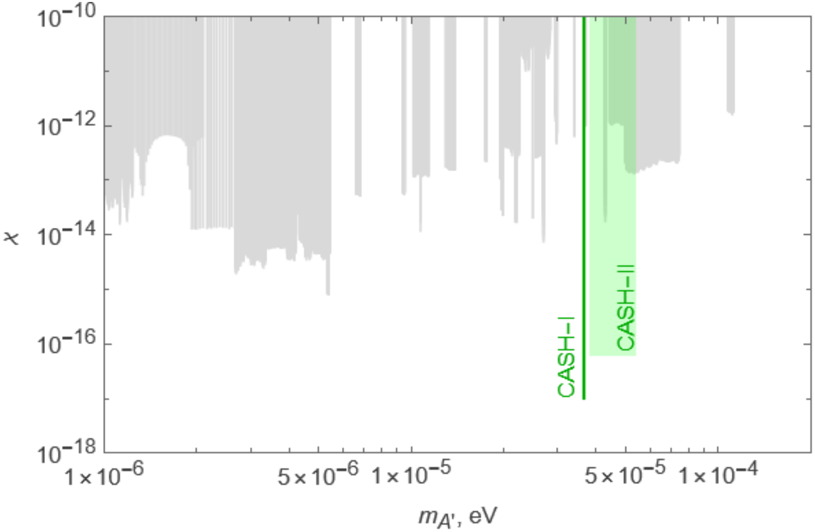
$$\chi = \left(\frac{1}{\rho_{A'}VQ_0C}\,\mathrm{SNR}\sqrt{\frac{R_{\mathrm{d.c.}}}{t}}\right)^{1/2}.$$

Additional effect – dependence on $\cos^2\theta$ where θ is the angle between the dark photon polarization vector and the haloscope axis. If these directions do not align, oscillations

Sensitivity of CASH to dark photons

Preliminary!

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



High-frequency gravitational waves (HFGW)

Gertsenshtein effect: a gravitational wave converts into a photon in a magnetic field

Gertsenshtein, Pustovoit, JETP Letters 1962

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

$$S_{h\gamma\gamma} = -\frac{1}{2}\int d^4x A^{\nu}\partial_{\nu}\left(\frac{1}{2}hF^{\mu\nu} + h^{\nu}_{\alpha}F^{\alpha\mu} - h^{\mu}_{\alpha}F^{\alpha\nu}\right), \qquad h \equiv \eta^{\mu\nu}h_{\mu\nu}$$

They convert into photons in a magnetic field. A HFGW source produces the same signal in the haloscope as axions and A'. Berlin, Blas et al, PRD 2022 (arXiv: 2112.11465)

Relativistic gravitons instead of **non-relativistic** DM.

Resonance when $\omega_h = \omega_{cav}$

Signal power induced by gravitational waves:

$$P_{sig} = \frac{1}{2}Q_0\omega_g^3 V_{cav}^{\frac{5}{3}}(\eta_n h_0 B)^2$$

CASH-I (TM010) : $h_0 = 1.5 \times 10^{-22}$ for $\nu = 8.8$ GHz, $B = 1.7\ T$

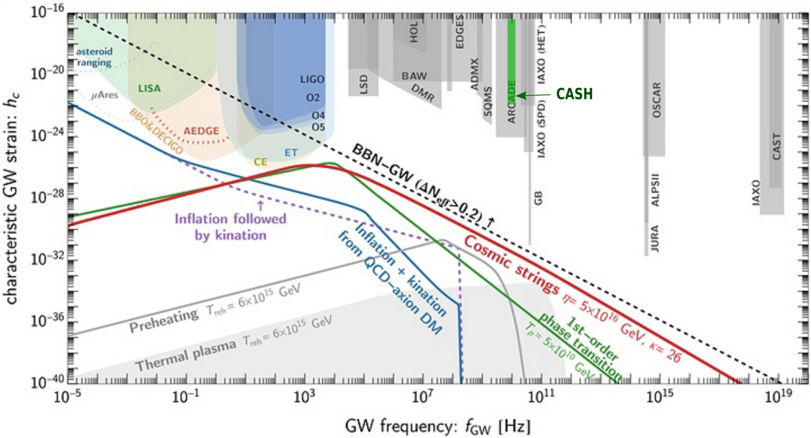
CASH-I (TM010) : $h_0 = 4 \times 10^{-23}$ for $\nu = 8.8$ GHz, $B = 7\ T$

... if HFGW are **coherent**. Otherwise, $Q \to 1$, $h_0 \to 10^{-20}$

- Cosmological HFGW (inflation, preheating, domain walls) – stochastic, not coherent!
- h_0 bounded by the number of relativistic degrees of freedom in the early Universe → $h_0 < 10^{-30}$ for $\nu \sim 10$ GHz.

Gravitational waves – constraints?

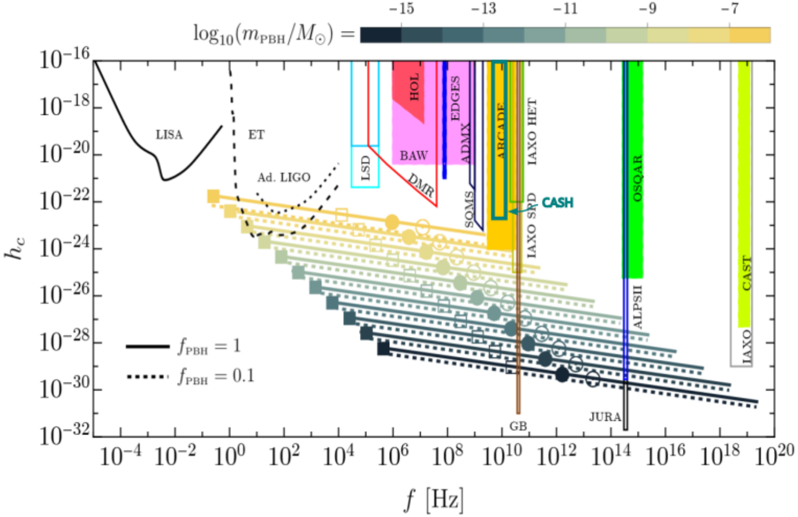
credit: Servant Simakachorn, 2024 (2312.09281)



ARCADE: balloon observation of galactic radio background (2006-2009). An excess, disappeared?

Gravitational waves from primordial black holes

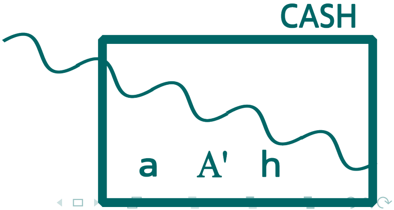
credit: Franciolini et al 2022 (2205.02153)



Conclusion

- CASH is a compact, low-cost project for dark matter search (axions, dark photons in the interesting mass range 38-56 μeV) with record sensitivity surpassing world analogues.
- The key element of the setup is single-photon detectors based on Josephson junctions, overcoming the quantum limit, with minimal noise (1 dark count per 100 seconds), which increases the sensitivity of the setup by 1-2 orders of magnitude compared to analogues. The fabrication technology has already been developed at NSTU & IPM RAS. World analogues are only being developed.
- In case of signal detection, additional analysis of the nature is required (operation without magnetic field)
- Additional program – search for high-frequency gravitational waves via the Gertsenshtein effect – work in progress

Thank you for your attention!



Backup slides

Supported by the Russian Science Foundation grant 25-22-00932

$$\mathrm{SNR} = \frac{N_{\mathrm{sig}}}{\sqrt{N_{\mathrm{sig}} + N_{\mathrm{d.c.}}}} = \frac{R_{\mathrm{sig}}}{\sqrt{R_{\mathrm{sig}} + R_{\mathrm{d.c.}}}}\sqrt{t}, \qquad R = N/t.$$

Statistical significance to reject N_{sig} if $N = N_{\mathrm{d.c.}}$ events are detected.

- Most sensitive region: $N_{\mathrm{sig}} \ll N_{\mathrm{d.c.}}$.
- But: $R_{\mathrm{d.c.}}$ – tunneling probability, cannot be calculated exactly; the error must be estimated from an independent measurement.
- The magnetic field is not fully shielded, it affects $R_{\mathrm{d.c.}}$. Need to measure background with the magnetic field on!
- At a fixed cavity frequency, the axion signal cannot be distinguished from background. Measurement at several frequencies assuming the signal can be present only at one frequency.

The CASH experiment proposal. Sensitivity estimation.

- k independent ranges, searching for a signal in one range – background estimated from the other $k-1$ ranges.
- Gaussian: $N_{k-1} \pm \mathrm{SNR} \cdot \sqrt{N_{k-1}}$
- Disadvantage – the background estimate may contain a signal
- More accurate method based on maximum likelihood – under development