The Dark Side of the Universe DSU2022

Proposals for searches of scalar field dark matter using cavity resonators and capacitors

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05 December 2022

UNSW
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Experimental Tests of the "Invisible" Axion

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(Received 13 July 1983)

Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

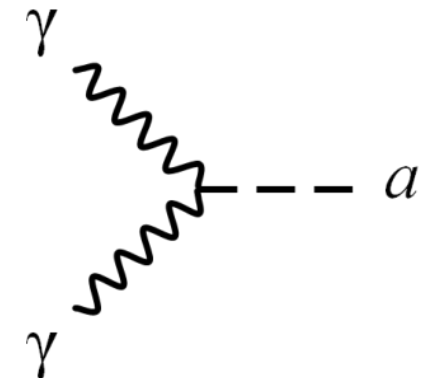### Detection rates for "invisible"-axion searches

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(Received 13 May 1985)

Experiments are described to search for axions floating about in the halo of our galaxy and for axions emitted by the sun. Expressions are given for the signal strengths in these experiments.

$$\mathcal{L}_{int} = \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

axion-photon coupling constant
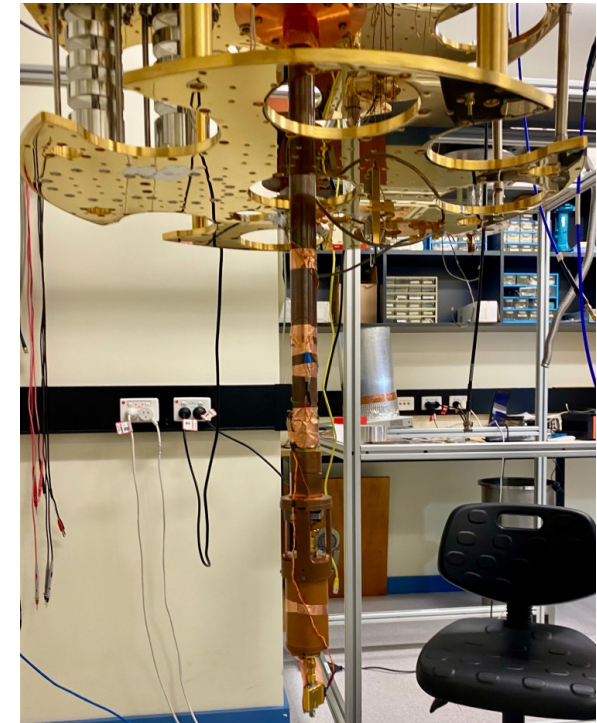
Introduction: Axion detection experiments

ADMX

CAST

ORGAN

Light shining through a wall

And others…

$$\mathcal{L}_{\text{int}} = -\frac{1}{4} g_{\phi\gamma\gamma} \phi F_{\mu\nu} F^{\mu\nu} = \frac{1}{2} g_{\phi\gamma\gamma} \phi (\vec{E}^2 - \vec{B}^2)$$

scalar-photon coupling constant

- φ is a dilaton-like scalar field motivated by e.g. string theory
- Are axion-search experiments sensitive to the scalar-photon coupling $g_{\varphi\gamma\gamma}$?
- How to maximize the sensitivity of these experiments to $g_{\varphi\gamma\gamma}$?
- New experimental techniques for searching scalar dark matter with the dilaton-like interaction?

$$\mathcal{L} = \frac{1}{2}(\epsilon\vec{E}^2 - \frac{1}{\mu}\vec{B}^2) + \frac{1}{2}g_{\phi\gamma\gamma}\phi(\vec{E}^2 - \vec{B}^2)$$

$$\phi = \text{Re}[\phi_0 e^{i(\vec{p}\cdot\vec{x} - \omega t)}]$$

$$\phi_0 = \frac{\sqrt{2\rho_{\text{DM}}}}{m_\phi}$$

local DM density

dielectric constant

magnetic permeability

scalar photon interaction

plane-wave solution

scalar field mass

Modified Maxwell equations

$$\nabla \cdot (\epsilon\vec{E} + g_{\phi\gamma\gamma}\phi\vec{E}) = 0$$
$$\nabla \times (\mu^{-1}\vec{B} + g_{\phi\gamma\gamma}\phi\vec{B}) - \partial_t(\epsilon\vec{E} + g_{\phi\gamma\gamma}\phi\vec{E}) = 0$$
$$\nabla \times \vec{E} + \partial_t\vec{B} = 0$$
$$\nabla \cdot \vec{B} = 0$$

E_0 and B_0 are static background electric and magnetic fields

$$\nabla \cdot (\epsilon\vec{E}) = \rho_\phi$$
$$\nabla \times (\mu^{-1}\vec{B}) - \partial_t(\epsilon\vec{E}) = \vec{j}_\phi$$

effective charge and current densities

$$\rho_\phi = -g_{\phi\gamma\gamma}\nabla \cdot (\phi\vec{E}_0),$$
$$\vec{j}_\phi = g_{\phi\gamma\gamma}\vec{E}_0\partial_t\phi - g_{\phi\gamma\gamma}\nabla \times (\phi\vec{B}_0)$$

Photon signal power

$$P = \frac{g_{\phi\gamma\gamma}^2 \rho_{\mathrm{DM}}}{16\pi^2\epsilon} \int d^3k\, \delta(|\vec{k}| - \omega) \left| \int_V d^3x\, e^{i(\vec{p}-\vec{k})\cdot\vec{x}} \vec{n} \times [\vec{E}_0 + \vec{\beta} \times \vec{B}_0] \right|^2$$

Compare with the power of axion-photon transformation

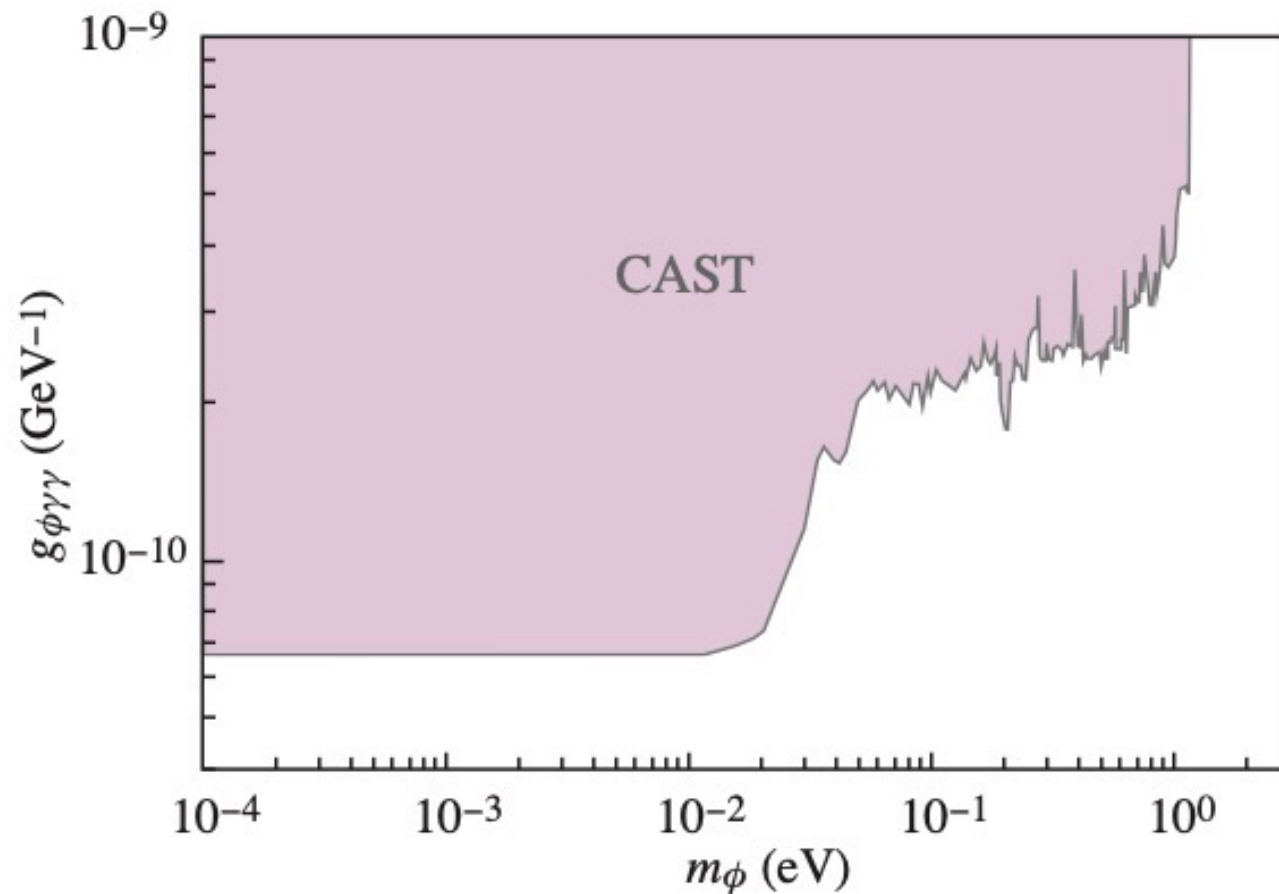[P. Sikivie, Phys. Rev. D 32, 2988 (1985)]

$$P_{\mathrm{axion}} = \frac{g_{a\gamma\gamma}^2 \rho_{\mathrm{DM}}}{16\pi^2\epsilon} \int d^3k\, \delta(|\vec{k}| - \omega) \left| \int_V d^3x\, e^{i(\vec{p}-\vec{k})\cdot\vec{x}} \vec{n} \times [\vec{B}_0 - \vec{\beta} \times \vec{E}_0] \right|^2$$

$$P = \frac{g_{\phi\gamma\gamma}^2 \rho_{\mathrm{DM}}}{16\pi^2\epsilon} \int d^3k\, \delta(|\vec{k}| - \omega) \left| \int_V d^3x\, e^{i(\vec{p}-\vec{k})\cdot\vec{x}} \vec{n} \times \vec{\beta} \times \vec{B}_0 \right|^2$$

- β=10^{-3} is the velocity of DM particles

$$|\vec{\beta} \times \vec{B}_0|^2 = \beta^2 B_0^2 \sin^2\theta$$

- β^2=10^{-6} is the suppression; $\sin^2\theta$ is responsible for signal modulation

- CAST experiment searches for axions produced in the Sun with β=1
- CAST experiment is equally sensitive to both axions and scalars thermally produced in the Sun!

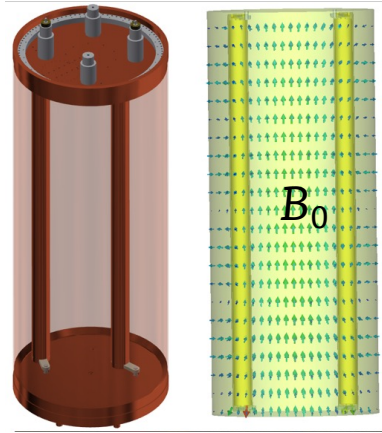Derived from Ref. [CAST Collaboration, Nature Physics 13, 584 (2017)] with a graphical accuracy

Axion signal
[Sikivie 1985]

B_0

Signal power

volume

$$P_{\text{axion}} = \frac{1}{m_a} g_{a\gamma\gamma}^2 \rho_{\text{DM}} B_0^2 V C_\alpha Q_\alpha$$

quality factor

Form factor

$$C_\alpha = \frac{\left| \int_V d^3x \, \vec{B}_0 \cdot \vec{E}_\alpha \right|^2}{B_0^2 V \int_V d^3x \, \epsilon \vec{E}_\alpha \cdot \vec{E}_\alpha}$$

Scalar field signal power in a cavity with electric E_0 and magnetic B_0 fields

$$P = \frac{1}{m_\phi} g_{\phi\gamma\gamma}^2 \rho_{\text{DM}} (B_0^2 + E_0^2) V C_\alpha Q_\alpha$$

Q_α is quality factor and C_α is the form factor

$$C_\alpha = \frac{1}{(B_0^2 + E_0^2)V} \frac{\left| \int_V d^3x \, e^{i\vec{p}\cdot\vec{x}} (\vec{B}_0 \cdot \vec{B}_\alpha + \vec{E}_0 \cdot \vec{E}_\alpha) \right|^2}{\frac{1}{2} \int_V d^3x (\mu^{-1} \vec{B}_\alpha \cdot \vec{B}_\alpha + \epsilon \vec{E}_\alpha \cdot \vec{E}_\alpha)}$$

E_α and B_α are eigenmodes of electric and magnetic fields in the cavity

Theory: Transformation in a resonant cavity

Cavity permeated by magnetic field B_0

$$P = \frac{1}{m_\phi} g_{\phi\gamma\gamma}^2 \rho_{\mathrm{DM}} B_0^2 V C_\alpha Q_\alpha \,,$$

$$C_\alpha = \frac{1}{B_0^2 V} \frac{\left| \int_V d^3x \, e^{i\vec{p}\cdot\vec{x}} \vec{B}_0 \cdot \vec{B}_\alpha \right|^2}{\int_V d^3x \, \mu^{-1} \vec{B}_\alpha \cdot \vec{B}_\alpha}$$

$$P = 1.3 \times 10^8 \mathrm{W} \left(\frac{g_{\phi\gamma\gamma}}{\mathrm{GeV}^{-1}} \right)^2 \left(\frac{3\mu\mathrm{eV}}{m_\phi} \right) \left(\frac{\rho_{\mathrm{DM}}}{0.45\mathrm{GeV/cm}^3} \right)$$
$$\times \left(\frac{B_0}{7.6\mathrm{T}} \right)^2 \left(\frac{V}{136\mathrm{L}} \right) \left(\frac{C_\alpha}{0.4} \right) \left(\frac{Q_\alpha}{30000} \right).$$

Cavity permeated by electric field E_0

$$P = \frac{1}{m_\phi} g_{\phi\gamma\gamma}^2 \rho_{\mathrm{DM}} E_0^2 V C_\alpha Q_\alpha \,,$$

$$C_\alpha = \frac{1}{E_0^2 V} \frac{\left| \int_V d^3x \, e^{i\vec{p}\cdot\vec{x}} \vec{E}_0 \cdot \vec{E}_\alpha \right|^2}{\int_V d^3x \, \epsilon \vec{E}_\alpha \cdot \vec{E}_\alpha}$$
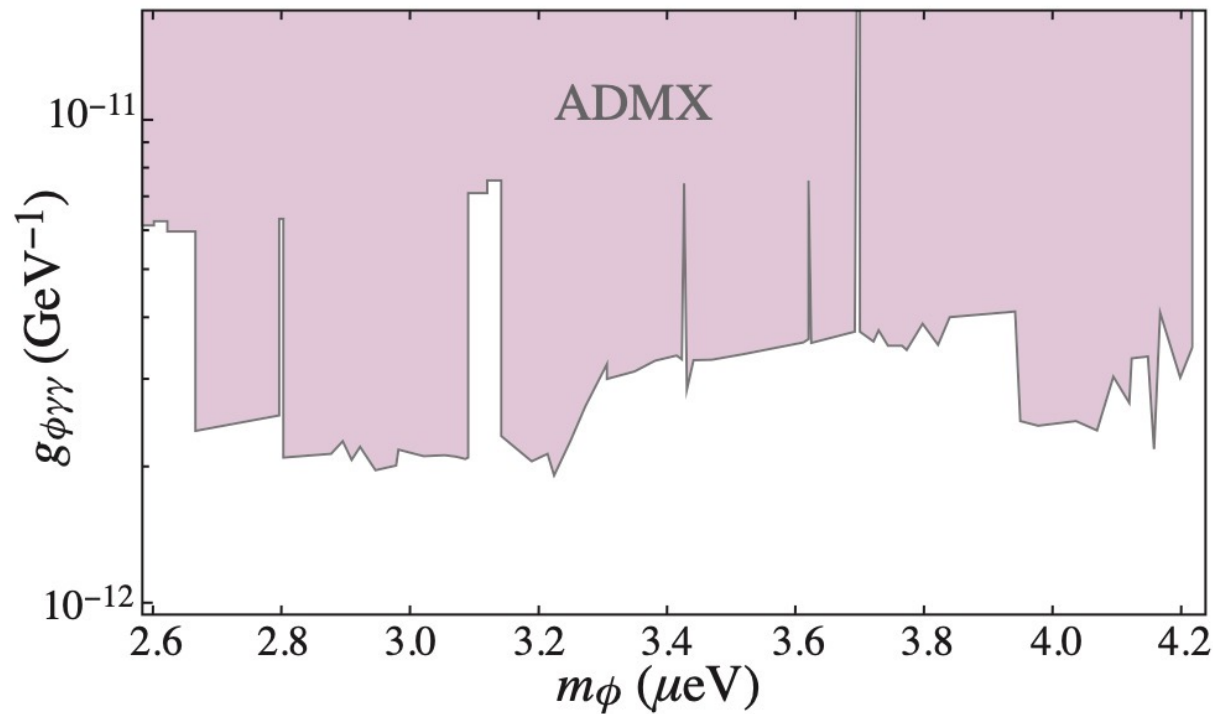
$$P = 38\mathrm{W} \left(\frac{g_{\phi\gamma\gamma}}{\mathrm{GeV}^{-1}} \right)^2 \left(\frac{3\mu\mathrm{eV}}{m_\phi} \right) \left(\frac{\rho_{\mathrm{DM}}}{0.45\mathrm{GeV/cm}^3} \right)$$
$$\times \left(\frac{E_0}{1\,\mathrm{MV/m}} \right)^2 \left(\frac{V}{136\,\mathrm{L}} \right) \left(\frac{C_\alpha}{0.4} \right) \left(\frac{Q_\alpha}{30000} \right).$$
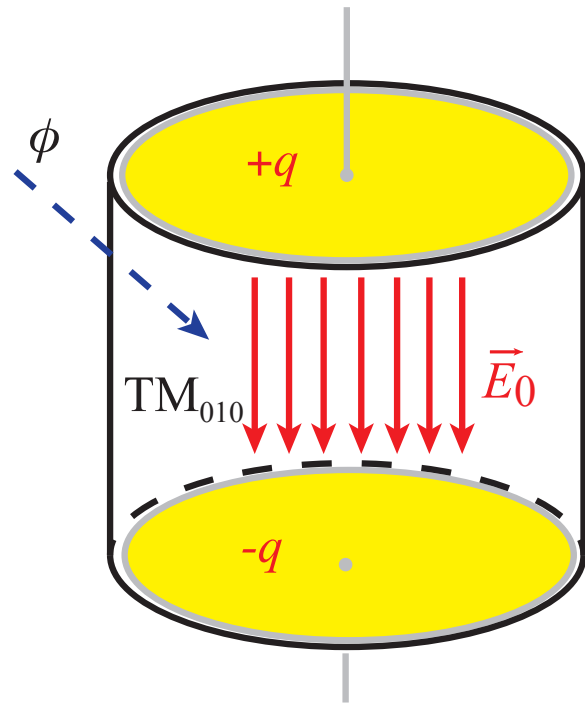
ADMX cavity scalar field form factor $\qquad C_\alpha \approx 10^{-12}$

ADMX sidecar scalar field form factor $\qquad C_\alpha \approx 10^{-8}$

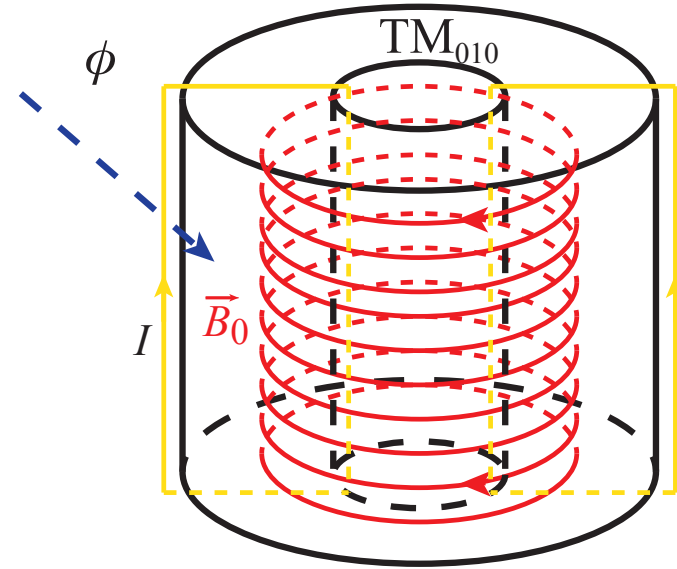Upper limits on the scalar-photon coupling constant

$$C_\alpha = 0.69$$

$$C_\alpha = O(1)$$
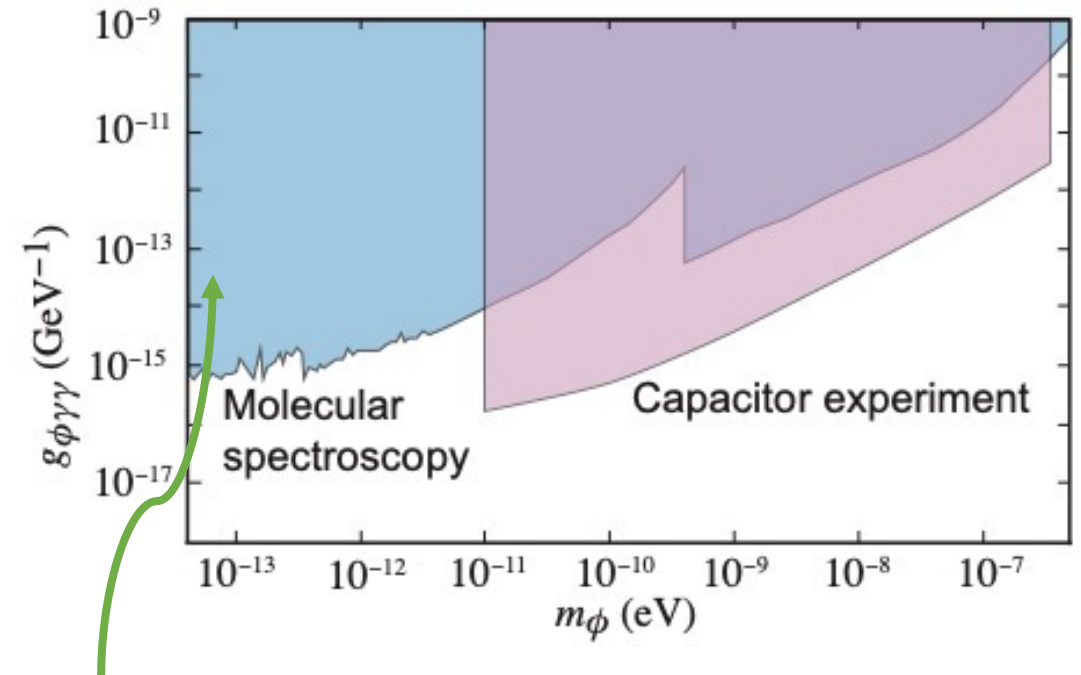
Estimated sensitivity of such experiment

Effective polarization $\qquad \vec{P}_\phi = g_{\phi\gamma\gamma}\phi\vec{E}_0$

Signal is AC voltage $\qquad \langle V_\phi \rangle = g_{\phi\gamma\gamma}\epsilon^{-1}V_0\dfrac{\sqrt{\rho_{\mathrm{DM}}}}{m_\phi}$

Applied voltage $\qquad V_0 \sim 600 \ \mathrm{kV}$

R. Oswald et al. arXiv:2111.06883 [hep-ph].

Summary

- Calculated the power of photon signal from scalar photon transformation in a resonant cavity

- New limits on the scalar-photon coupling constant from re-purposing the results of CAST and ADMX experiments

- Proposals for cavity experiments with maximized sensitivity to the scalar field dark matter

- A capacitor-based broadband experiment is proposed