17th Patras Workshop on
Axions, WIMPs and WISPs

08 August 2022

Proposals for searches of scalar field dark matter using cavity resonators

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arXiv: 2207.14437

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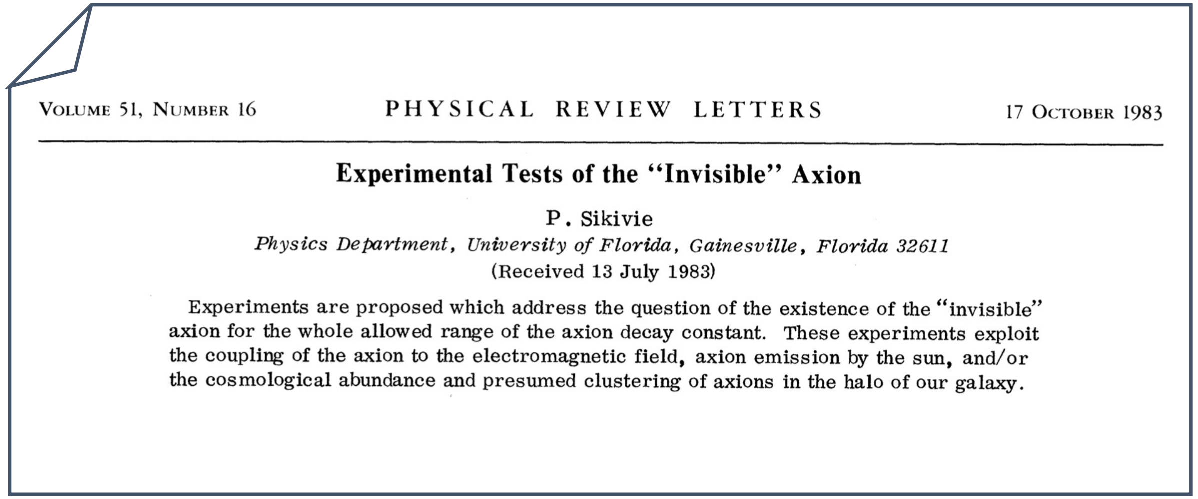
Introduction: The axion story



Volume 51, Number 16 PHYSICAL REVIEW LETTERS 17 October 1983

Experimental Tests of the "Invisible" Axion

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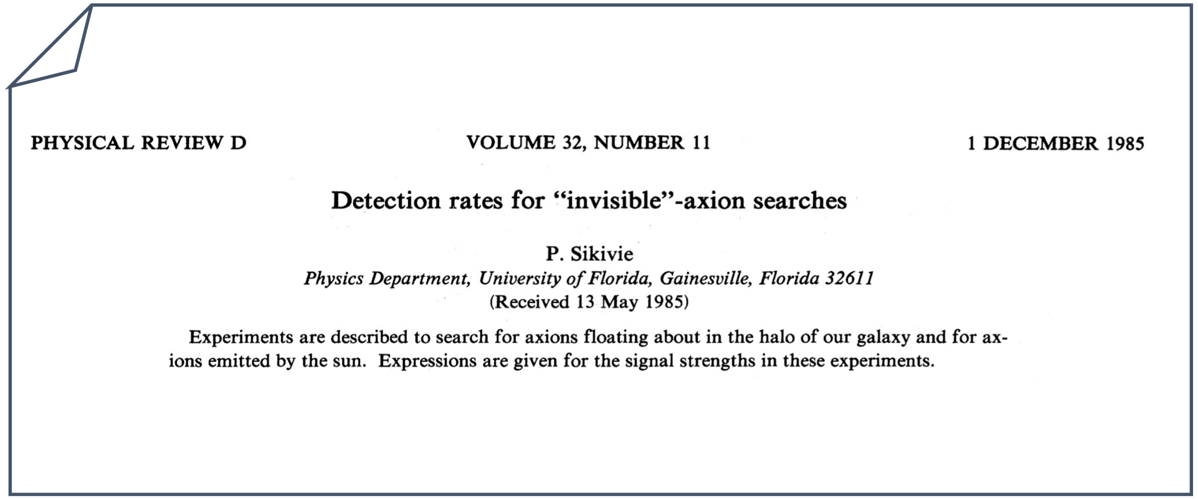
(Received 13 July 1983)

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.



PHYSICAL REVIEW D VOLUME 32, NUMBER 11 1 DECEMBER 1985

Detection rates for "invisible"-axion searches

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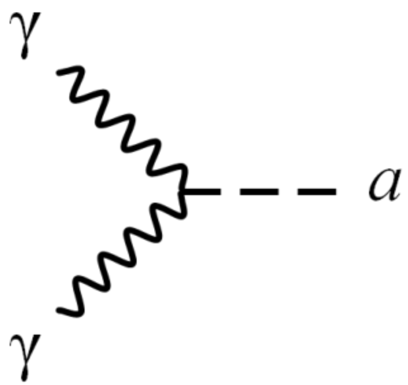
(Received 13 May 1985)

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

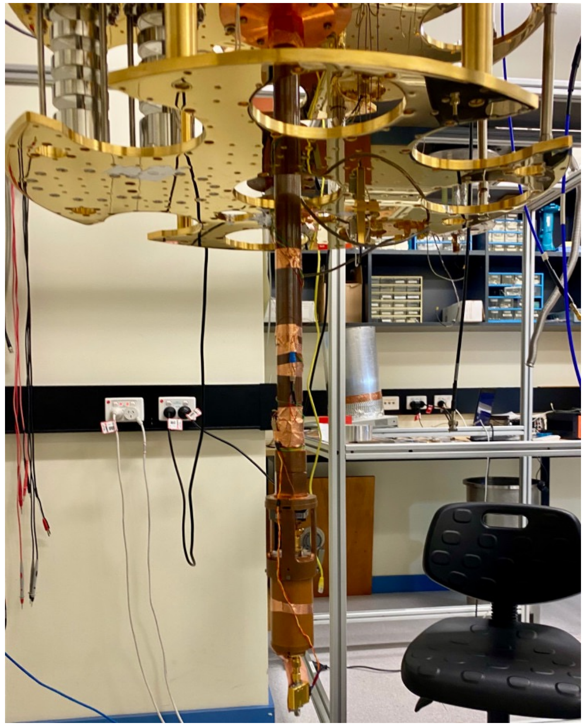


Introduction: Axion detection experiments

ADMX

CAST

ORGAN



Light shining through a wall

And others…

Introduction: scalar field dark matter

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

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 $g_{\phi\gamma\gamma}$?
- How to maximize the sensitivity of these experiments to $g_{\phi\gamma\gamma}$?
- New experimental techniques for searching scalar dark matter with the dilaton-like interaction?

Theory: scalar-photon interaction

$$\mathcal{L} = \frac{1}{2}\left(\epsilon\vec{E}^2 - \frac{1}{\mu}\vec{B}^2\right) + \underbrace{\frac{1}{2}g_{\phi\gamma\gamma}\phi\left(\vec{E}^2 - \vec{B}^2\right)}_{\text{scalar photon interaction}}$$

dielectric constant

magnetic susceptibility

scalar photon interaction

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

plane-wave solution

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

local DM density

scalar field mass

Modified Maxwell equations

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

$$\Rightarrow$$

E_0 and B_0 are static background electric and magnetic fields

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

effective charge and current densities

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

Theory: Scalar-photon transformation

Photon signal power

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

Compare with the power of axion-photon transformation

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

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

Theory: Scalar-photon transformation (E_0=0)

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

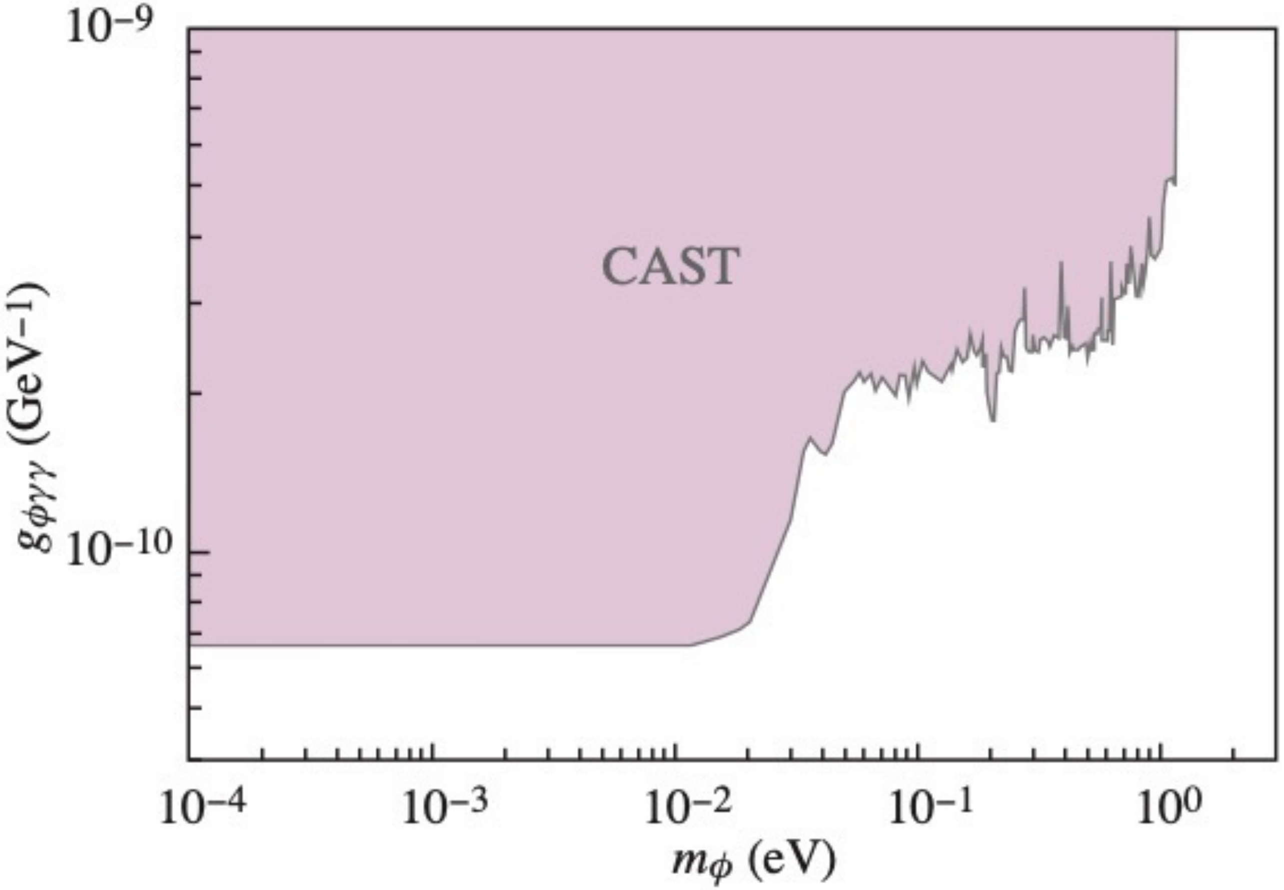
- β=10^{-3} is the velocity of DM particles

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

- 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!

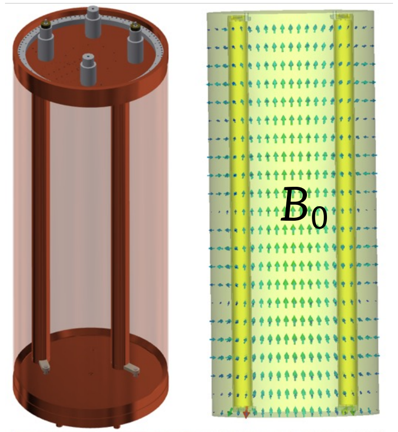
Results: Limits from CAST Experiment



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

Theory: Transformation in a resonant cavity

Axion signal
[Sikivie 1985]



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

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

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

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

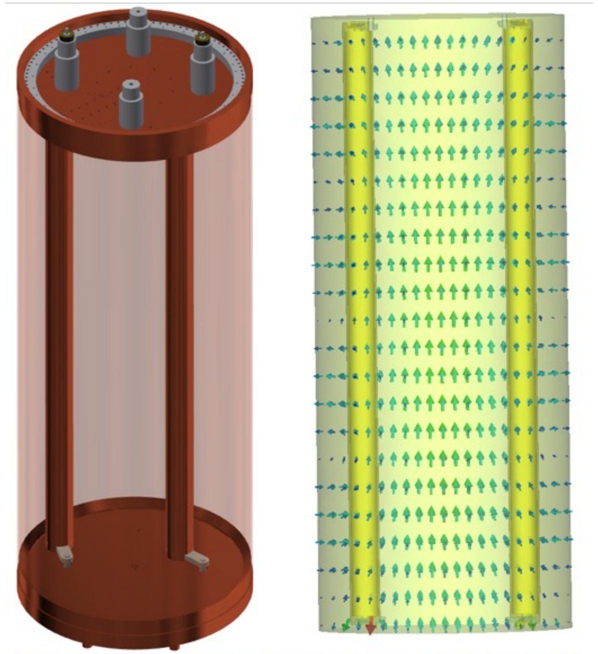
Cavity permeated by electric field E_0

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

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

$$P = 38{\rm W} \left(\frac{g_{\phi\gamma\gamma}}{\rm GeV^{-1}}\right)^2 \left(\frac{3\mu{\rm eV}}{m_\phi}\right) \left(\frac{\rho_{\rm DM}}{0.45{\rm GeV/cm}^3}\right) \times \left(\frac{E_0}{1\,{\rm MV/m}}\right)^2 \left(\frac{V}{136\,{\rm L}}\right) \left(\frac{C_\alpha}{0.4}\right) \left(\frac{Q_\alpha}{30000}\right) .$$

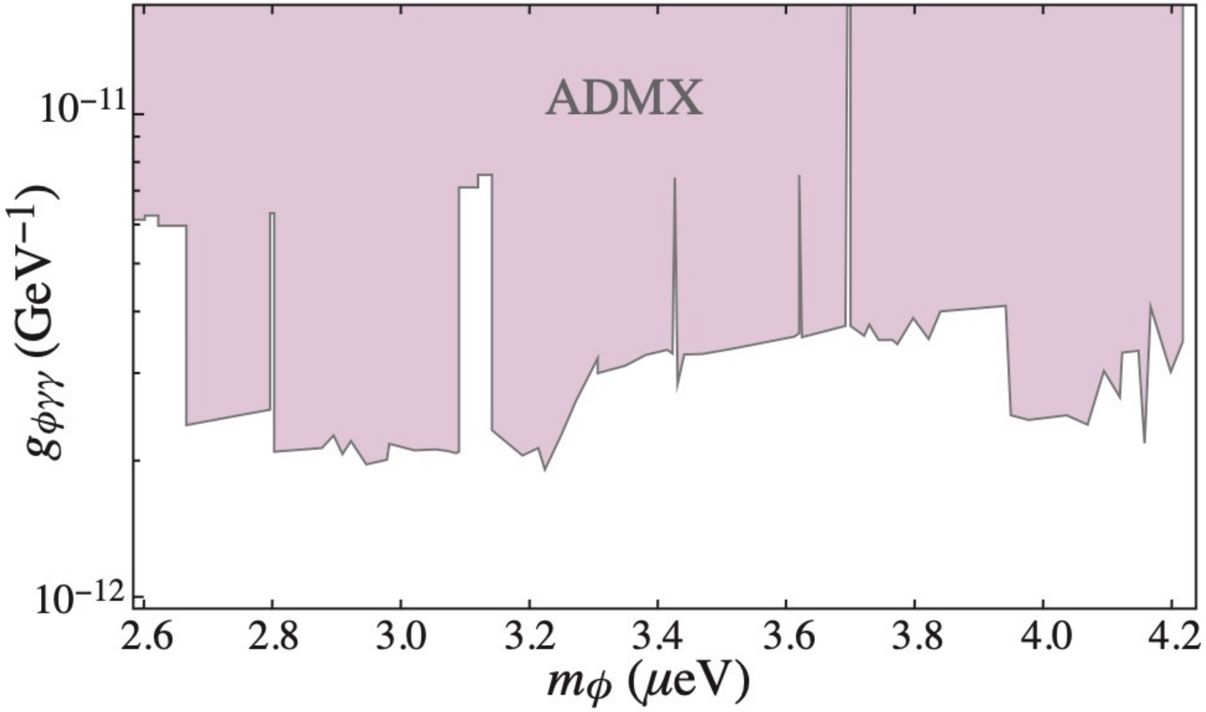
Results: Constraints from ADMX



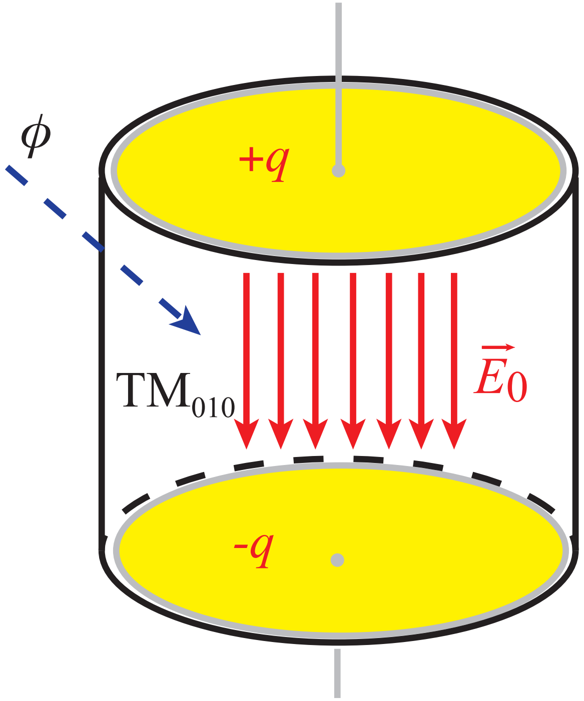
ADMX cavity scalar field form factor $C_\alpha \approx 10^{-12}$

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

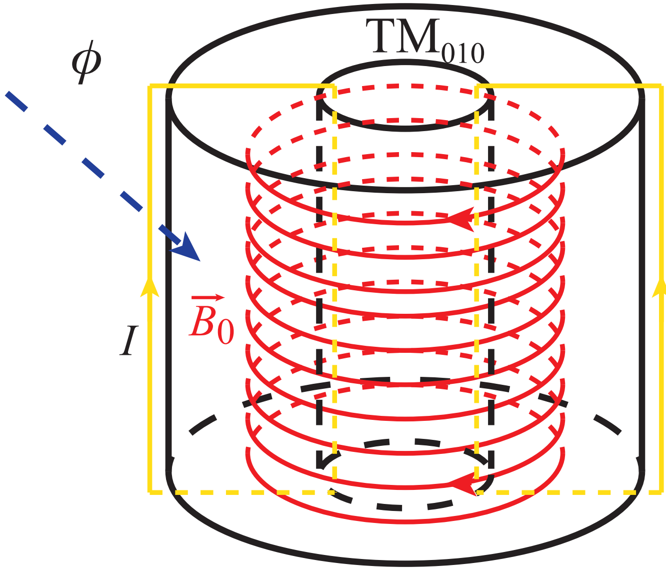
Upper limits on the scalar-photon coupling constant



Results: Cavity resonators proposals with maximized form factors to the scalar field DM

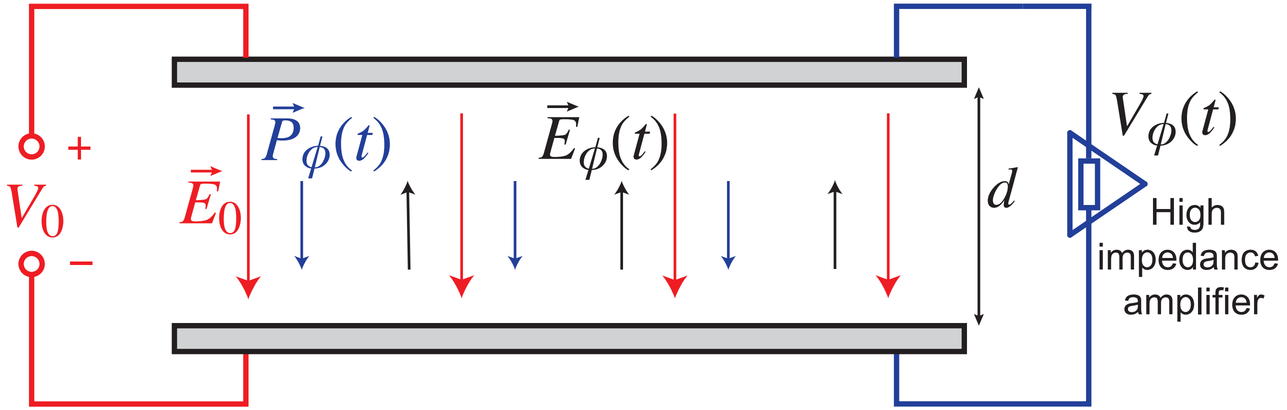


$$C_\alpha = 0.69$$

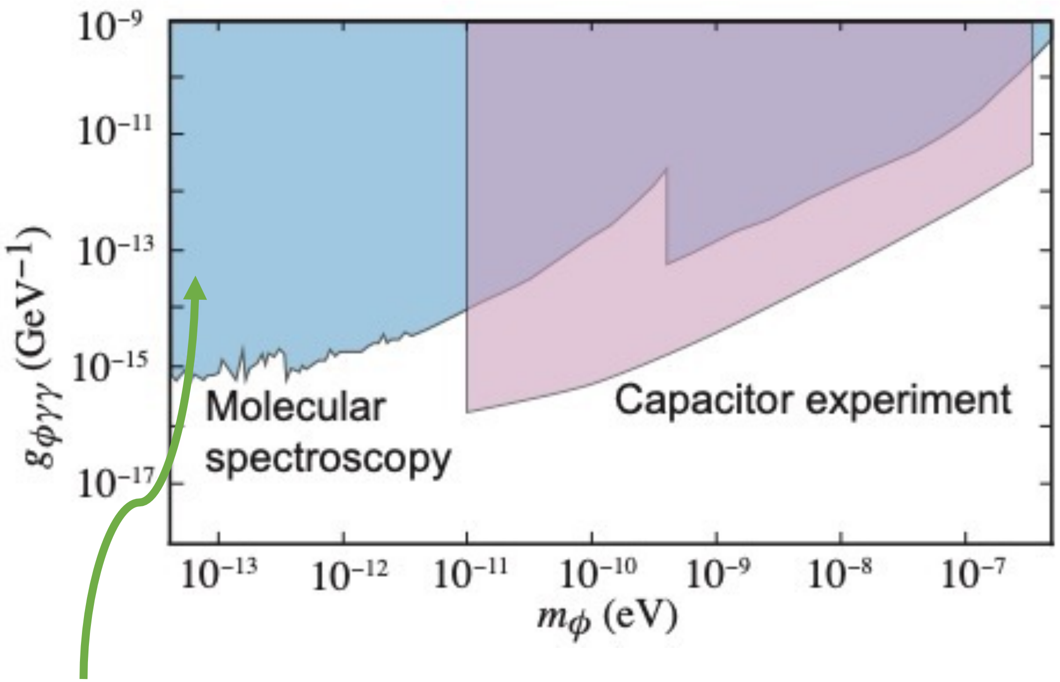


$$C_\alpha = O(1)$$

Results: Proposal for a broadband detection with a capacitor



Estimated sensitivity of such experiment



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

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

Applied voltage $V_0 \sim 600 \text{ kV}$

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