Axion Haloscope Meets the $\vec{E}$ Field

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2012.13946
2201.08291
2204.14033
2206.13543
2305.00877

Outline

- *Resonance* in the 'haloscope', at *QM level*
- Axio-electric current in an $\vec{E}$ field
- $\vec{E}$ field as conversion medium
- $\vec{E}$ field as signal: capability study

Axion / ALPs as DM

Axion as a fast oscillating field at the bottom of the its instanton potential $V(\phi) \sim (\phi - \phi_0)^2$ behaves on ave. as matter-like: $\rho(z) \sim (1+z)^3$

M. Turner, 83'

- `Wave-like' DM candidates via misalignment mech.
- Nearly monochromatic signal: $\delta f / f \sim 10^{-6}$.

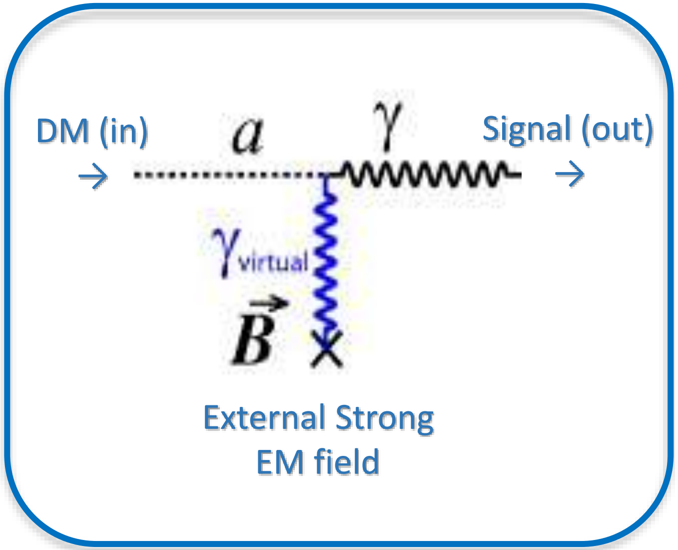
For terrestrial labs, as a coherent wave:

$$a(x,t) \approx a_0 \cos\left[m_a \vec{v}_a \cdot \vec{x} - \left(m_a + \frac{m_a}{2} v_a^2\right) t\right]$$

Local DM velocity

Can coherently convert into photon/EM fields via 'axion-like' interaction

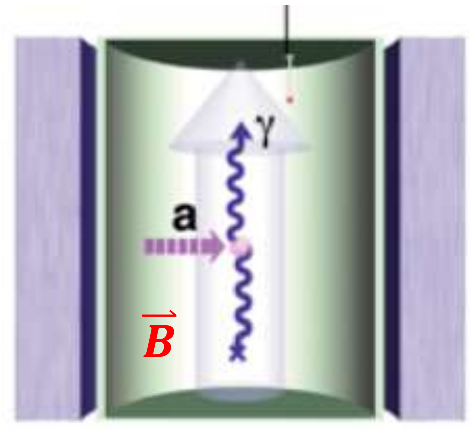
$$\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma} a \vec{E} \cdot \vec{B}$$



Axion Haloscope:

A resonant DM axion -> photon converter (P. Sikivie, 83')

- Primakoff Effect: a under a strong EM field
- DM in QCD axion theory predicts a microwave frequency band.
- High `Quality factor' – given by DM energy dispersion
- Tunable resonator to scan over a mass range



Cavity tuned to expected axion signal frequency

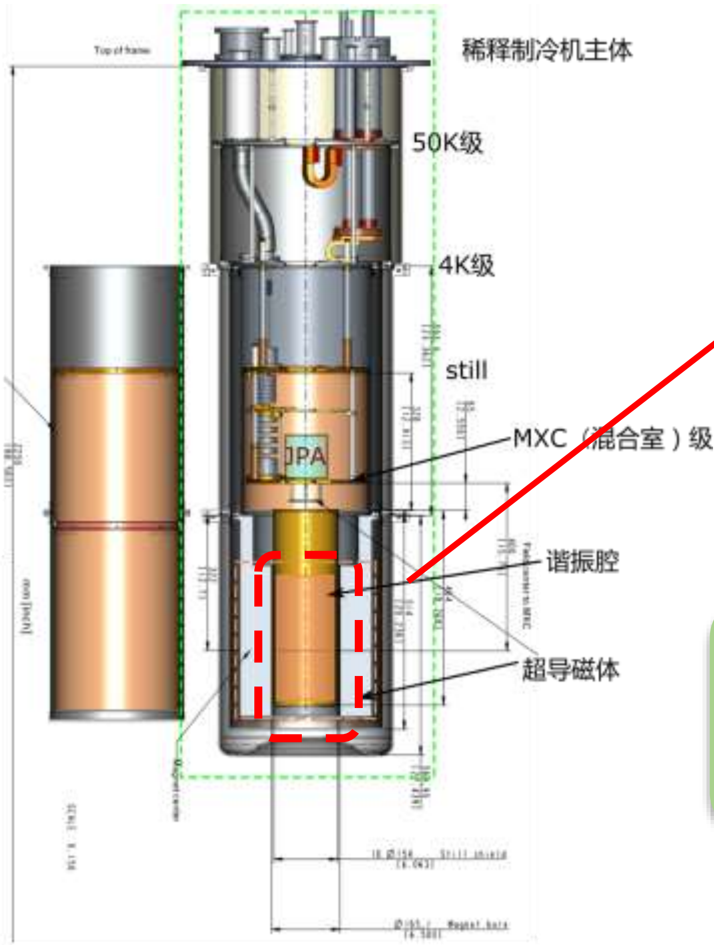
A new `f^{-1}' frontier:

Search for high $U(1)_{PQ}$ scale physics at a low $\sim \frac{\Lambda_{QCD}^2}{\Lambda_{PQ}}$ scale

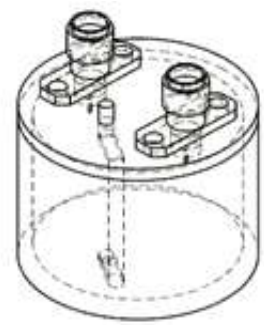
QCD axion dark matter: typically ~ O(50) μeV. →
General ALP(s): m_a- f_a not restricted.

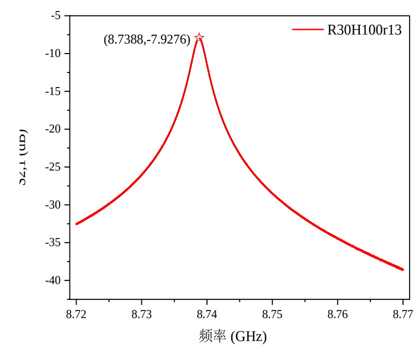
m_a = 60−150 μeV (T. Hiramatsu, et.al. 2012')
m_a = 26.5±3.4 μeV (Klaer, Moore, 2017')

Cryogenic resonant EM cavity



tunable cavity





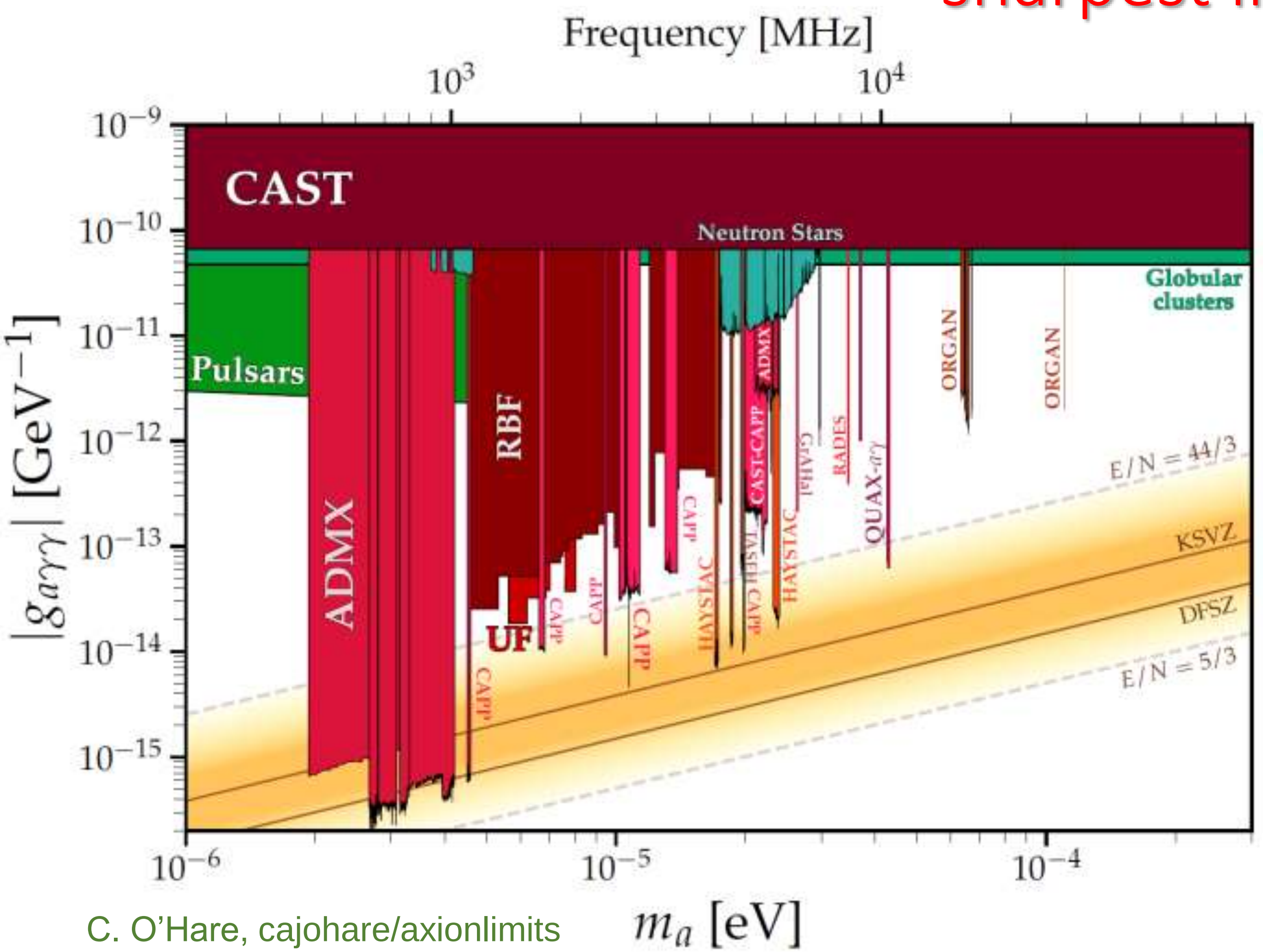
Measurement at Cavity's resonant freq.

Emergence of EM signal from inside the cavity

$$P_{\text{axion}} = 2.2 \cdot 10^{-23}\ \text{W}\left(\frac{V}{136\ \text{L}}\right)\left(\frac{B}{7.6\ \text{T}}\right)^2\left(\frac{C}{0.4}\right) \cdot \left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{\rho_a}{0.45\ \text{GeV cm}^{-3}}\right)\left(\frac{f}{740\ \text{MHz}}\right)\left(\frac{Q}{30000}\right)$$

- single photon level: O(10) photons s^{-1}

Haloscope with strong B field:
sharpest limits, so far.



C. O'Hare, cajohare/axionlimits
(Figure from [PDG 2024])

ADMX,HAYSTAC:
achieved sensitivity
to theoretical par. space
(DFSZ / KSVZ models)

Recent players:
CAPP/IBS (2020)
QUAX-aγ (2019)
CAST-RADES(2021)
TASEH (2022)

*Higher freq. detectors
(10 GHz or higher?)

+ many others.

Success with a High-*Q*

- Key to cavity's achievements: ***high quality factor***

For classical, see P. Sikivie, 84'

$$R = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} B_0^2 C_k V \cdot Q$$

Q ~ 10^6 Provide both resonant $a \to \gamma$ enhancement & bkg suppression

Thermal noise power: $$P_{Bkg} \sim 4 k_B T \frac{m_a}{2\pi \cdot Q}$$

Quantum mechanically, interaction between a cavity-mode $\vec{E}(x)$ and the plane wave:

2201.08291

$$\begin{aligned} H_I &= -\int d^3x \mathcal{L}_{a\gamma\gamma} \\ &= \left(g_{a\gamma\gamma} \frac{\sqrt{2\rho_a}}{m_a} B_0 \int dx^3 \hat{z} \cdot \vec{E}\right) \cos(\omega_a t) \end{aligned}$$

So at the QM level!

Cavity's $|0\rangle \longrightarrow |1\rangle$ rate is enhanced by the incident wave's Q – factor.

$$R = \left| \int_0^t \langle 1| H_I |0\rangle e^{i(\omega_k - \omega_a)t} dt \right|^2$$

$$= \left(g_{a\gamma\gamma} \frac{\sqrt{2\rho_a}}{m_a} B_0 \int dx^3 \hat{z} \cdot | \langle 1| \vec{E} |0\rangle | \right)^2 \delta(\omega_k - \omega_a)$$

$$R \approx \frac{\pi}{2} g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} B_0^2 V \sum_k C_k \omega_k \delta(\omega_k - \omega_a)$$

$$\int d\omega (\omega / d\omega) \delta(\omega - \omega_a) \approx Q$$

(for any DM axion wave's $Q_a \leq Q_{\text{cavity}}$)

Cavity's $|0\rangle \longrightarrow |1\rangle$ state transition rate is **indeed enhanced** by the cavity quality factor that matches with the DM wave's.

2201.08291

* This is consistent with classical oscillation calculations.

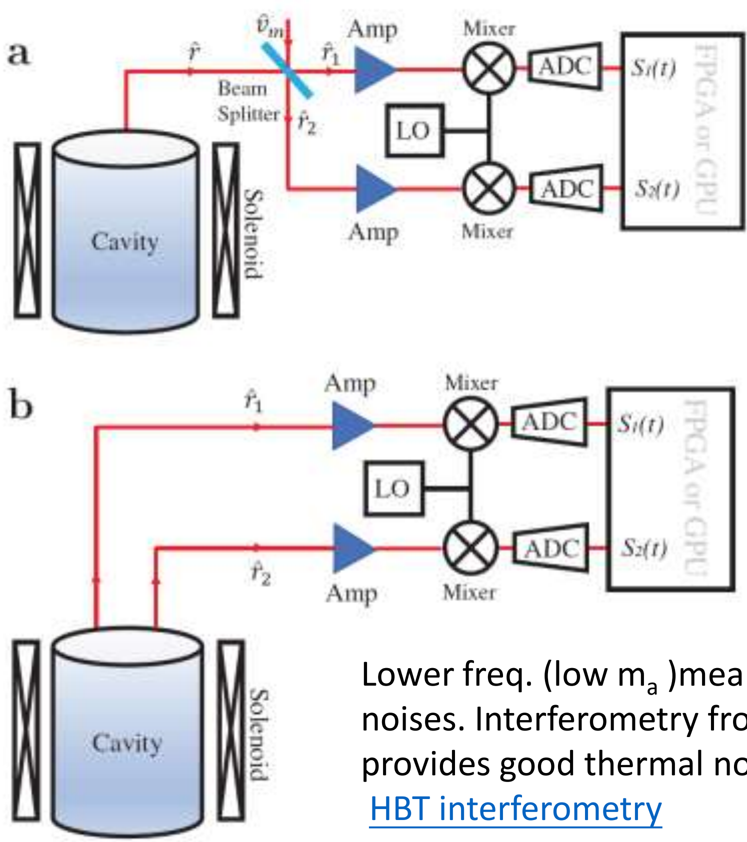
* Opens up new methods based on single photons: dual-path HBT, antibunching…

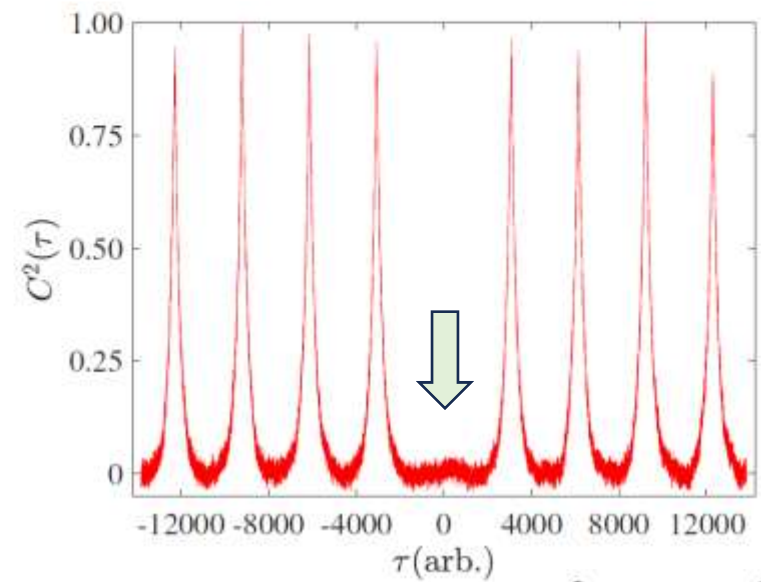
Inter-disciplinary:

The haloscope's low Cavity's $|0\rangle \longrightarrow |1\rangle$ state transition rate leads to a low average occupation number:

(2201.08291)

Axion conversion signal resembles a *`pure state'* $|1\rangle$ in quantum optics.





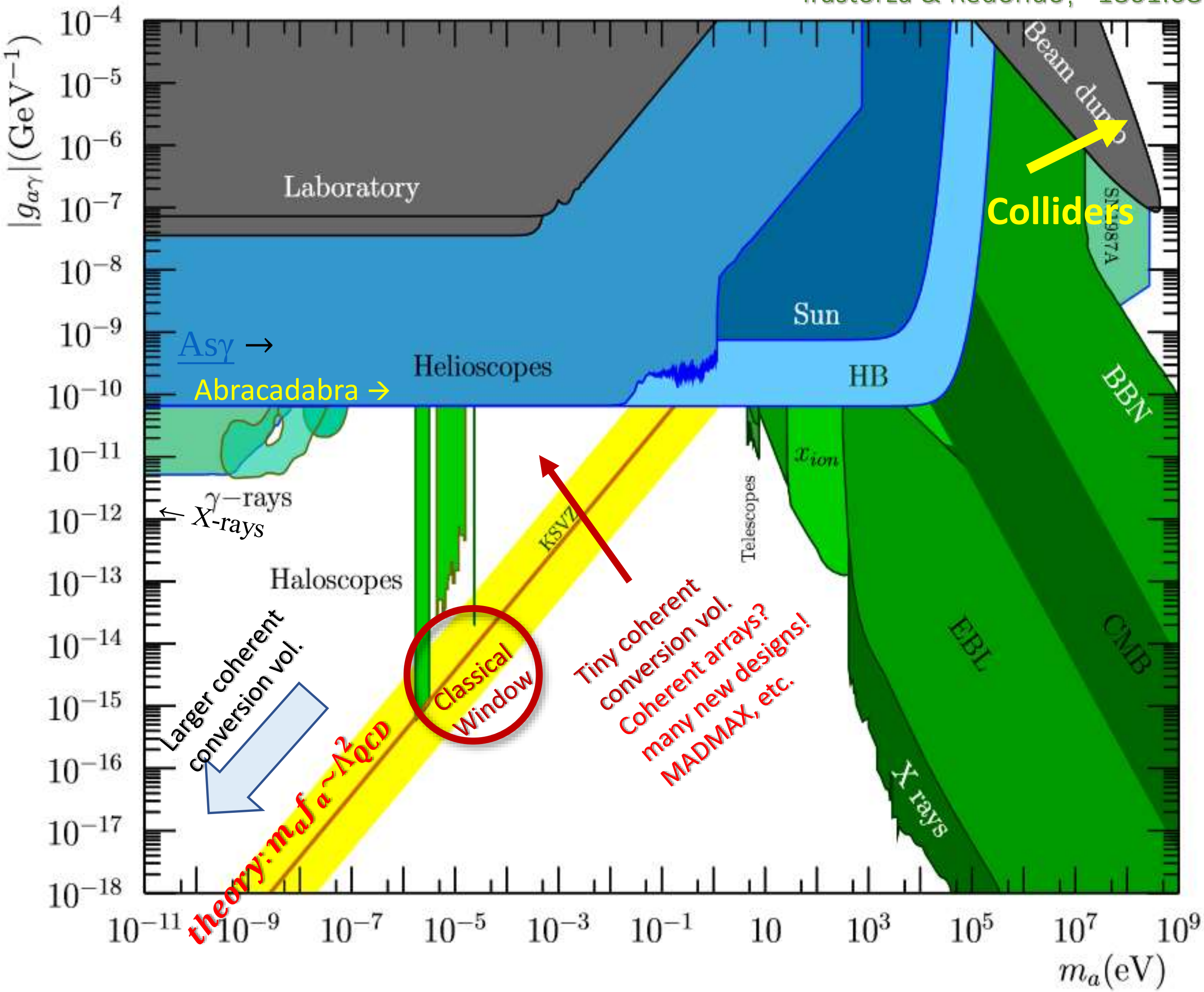
$$C^2(0) < C^2(\tau)$$

Lower freq. (low m_a)means severe thermal noises. Interferometry from Quantum Optics provides good thermal noise removal:
HBT interferometry

Simulated corr. function C^2:
A possibility with antibunching, as a post-discovery *test of the signal's QM state.*

What about lower/higher m_a?

Irastorza & Redondo, 1801.08127



W/O cavity? – `aQED' induction effects

- axion-modified Maxwell equations:

Effective charge: (suppressed as $v_a \ll 1$)
(j^0 of the locally conserved 4-current $\partial_\mu j_a^\mu = 0$)

$$\vec{\nabla}\cdot\vec{E} = \rho_e + g\vec{B}\cdot\nabla a$$

$$\vec{\nabla}\times\vec{B} - \frac{\partial\vec{E}}{\partial t} = g\vec{E}\times\vec{\nabla}a - g\vec{B}\frac{\partial a}{\partial t} + \vec{j}_e$$

$$\vec{\nabla}\cdot\vec{B} = 0$$

$$\vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t},$$

Axio-magnetic current:
ADMX-SLIC(LC), Abracadabra, DM-Radio, etc

Axio-electric current $\vec{j}_a = g\vec{E}\times\vec{\nabla}a$

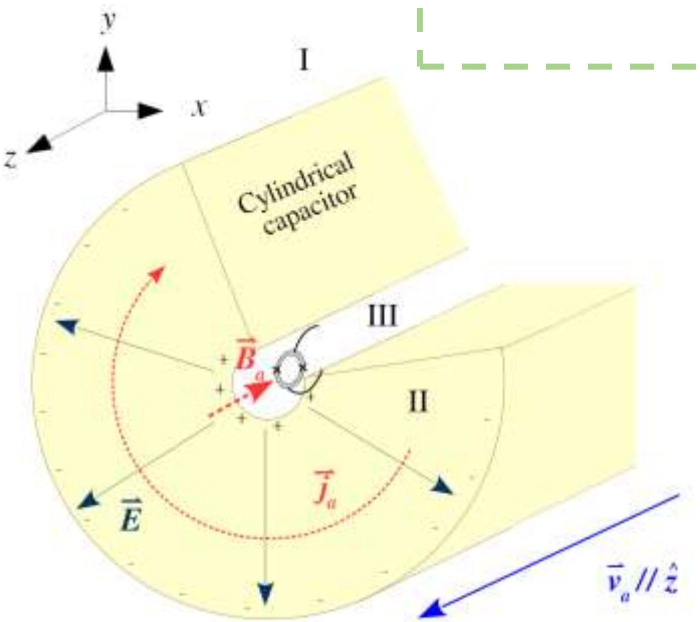
DM axion flow Induces a magnetic signal inside E field: see 2012.13946 (broad-band) & 2204.14033 (narrow-band)

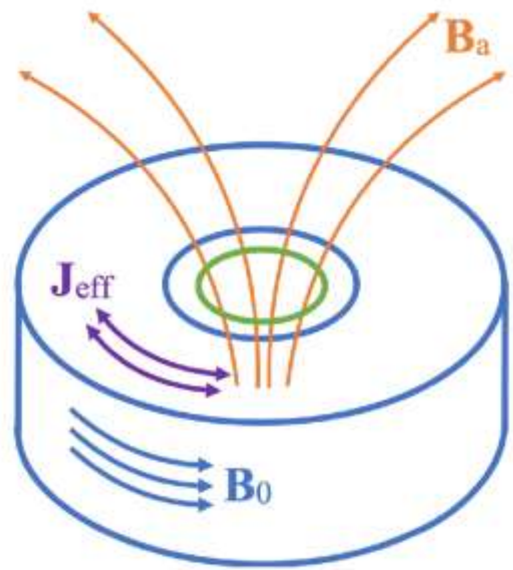
Axion's effective sources:

effective (moving) charge & effective displacement currents

Axio-electric & axio-magnetic effective currents

Signal field ~ ϑ_a * External field
* *geometric form factor* $O(\omega R)^{-n}$





$\vec{E} \times \vec{k}_a$

j_a under *E* field:
Depend on both E field
and axion flow directions

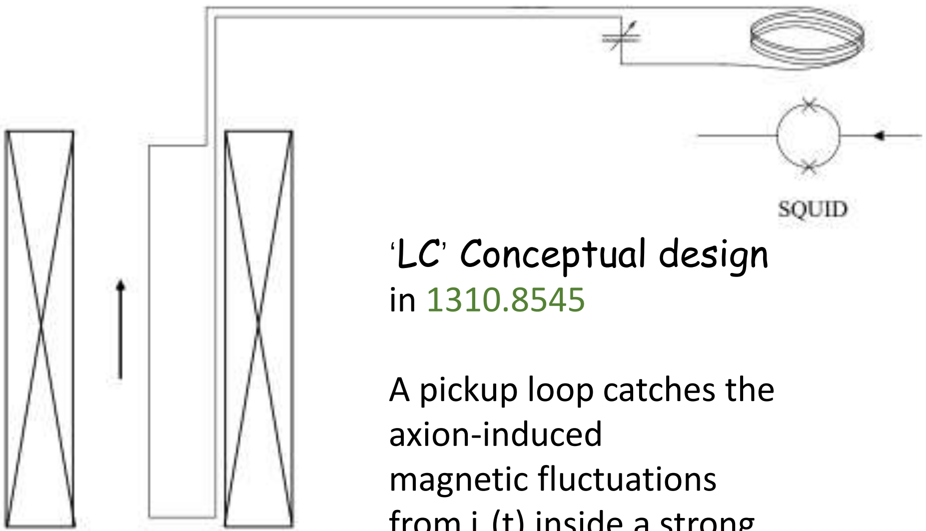
j_a under *B* field:
(anti)parallel with
B field direction

$\vec{B} \cdot \partial_t a$

Magnetic signal from B field

- ‘LC’-type designs: ADMX-SLIC, Abracadabra, DM-Radio, etc.

Enhanced by LC resonance and measured with a quantum magnetometer

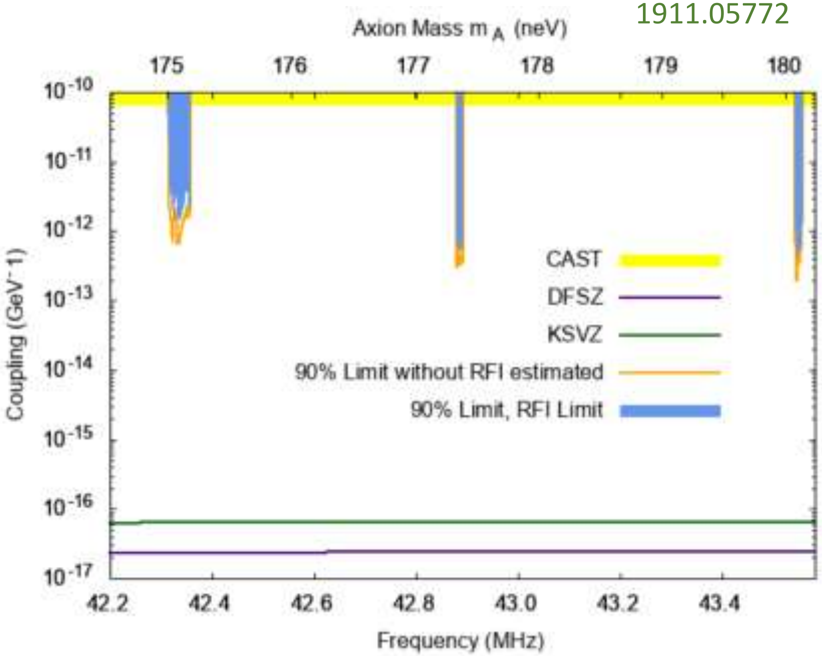


‘LC’ Conceptual design
in 1310.8545

A pickup loop catches the axion-induced magnetic fluctuations from $j_a(t)$ inside a strong lab *B* field

Realization in ADMX-SLIC (2019)

1911.05772

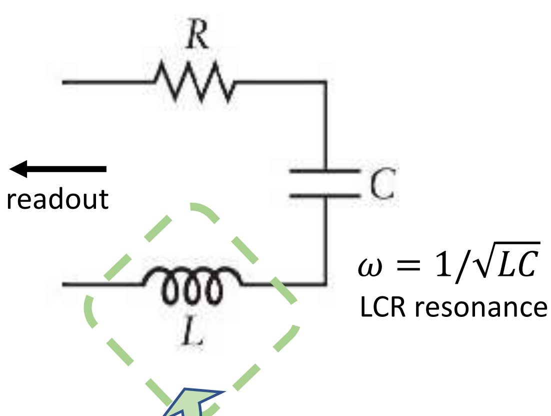


Resonance without a cavity

High quality factor filtering is still essential for non-cavity.

$$R = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} B_0^2 C_k V Q$$

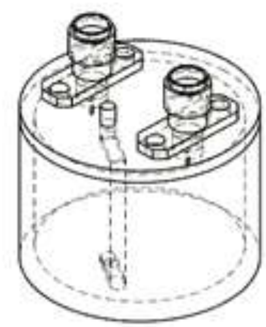
Popular solution: electronic (LC) circuit (P.Sikivie,13') resonance tuned to axion frequency (used in ADMX-SLIC, ABRACADABRA, BASE, etc.)



Long wavelength

tunable cavity

$\omega_{010} = \omega_a$



Coupled to axion's

j_a - induced signal with ω_a

Signal field ~ ϑ_a * External field

* *geometric form factor* $O(\omega R)^{-n}$ *& phase lag*

$\vec{E}$ field or $\vec{B}$ field?

[As the medium]

- Both induce effective currents
- *B* field is (*by Nature's choice*) more effective in *conversion rate:*

  * 10 Tesla ~ v_{DM}*10^{13} V/m

  * j_a in *E* has velocity suppression.

- Strong solenoid *B* field: instabilities?
- *E* field: j_a has directional dependance – 24 hr modulation
- *E* field: apparatus orientation dependance – bkg veto

[As the signal]

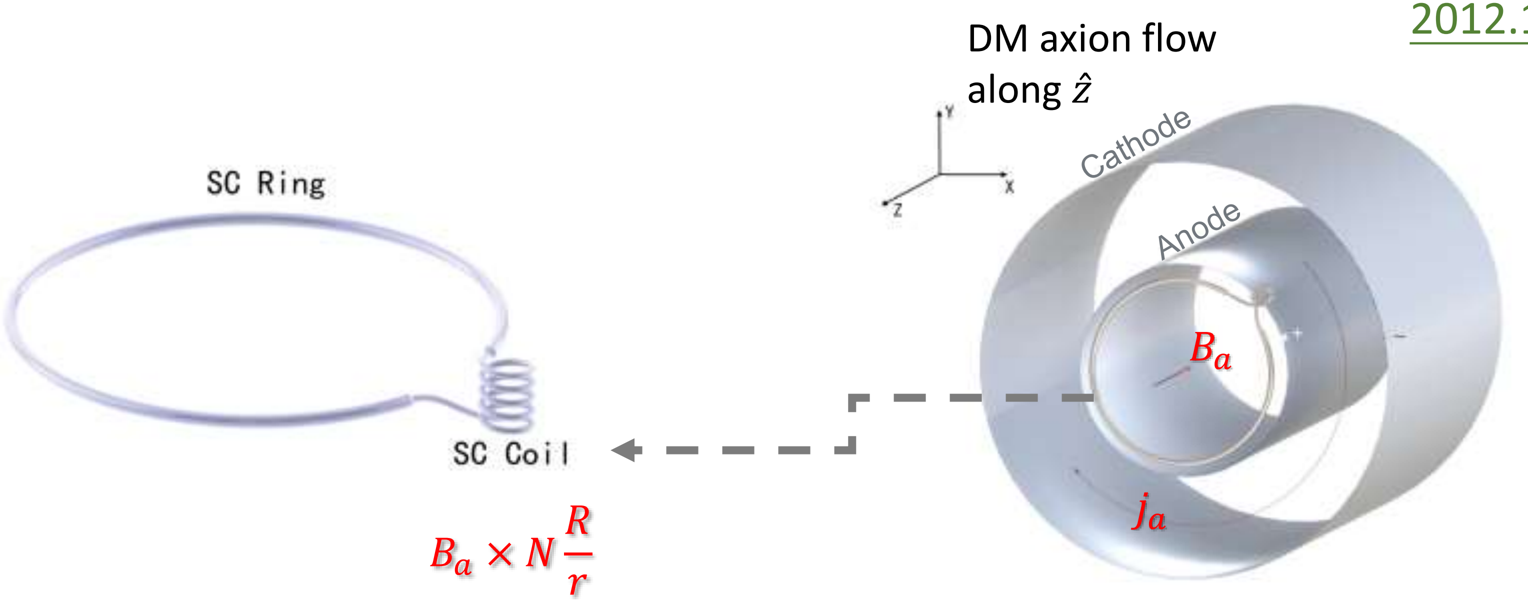
- Both E and B signals can be quite efficiently measured. (down to ~ single photon level)
- Typical E field signal:
  - * cavity's resonance modes.
  - * voltage differences.
- Typical B field signal:
  - * induced magnetic flux
- Very different form factors

- Pick E or B that easily distinguishes from the experimental background.

  (Cavity: *E* signal from solenoid *B*)

Magnetic signal from *E* field (broadband)

2012.13946



Pure inductance SC pickup coils:
Low noise, high signal gain.
Broad-band:
* not resonance enhanced
* compared signal magnitude to detector sensitivity.

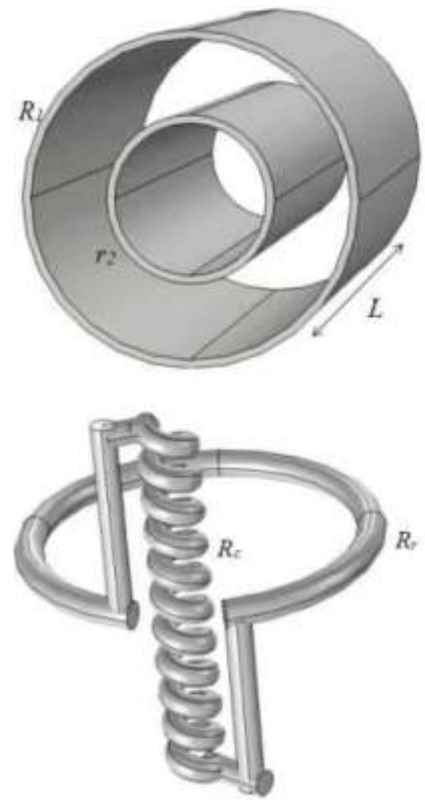
- **Cylindrical capacitor**: radial static E field, j_a forms alternating loops.
- SQUIDS sensitivity $\delta B \sim 10^{-15}$ T
- **No strong B field** near pickup ring
- **Mild frequency dependance**

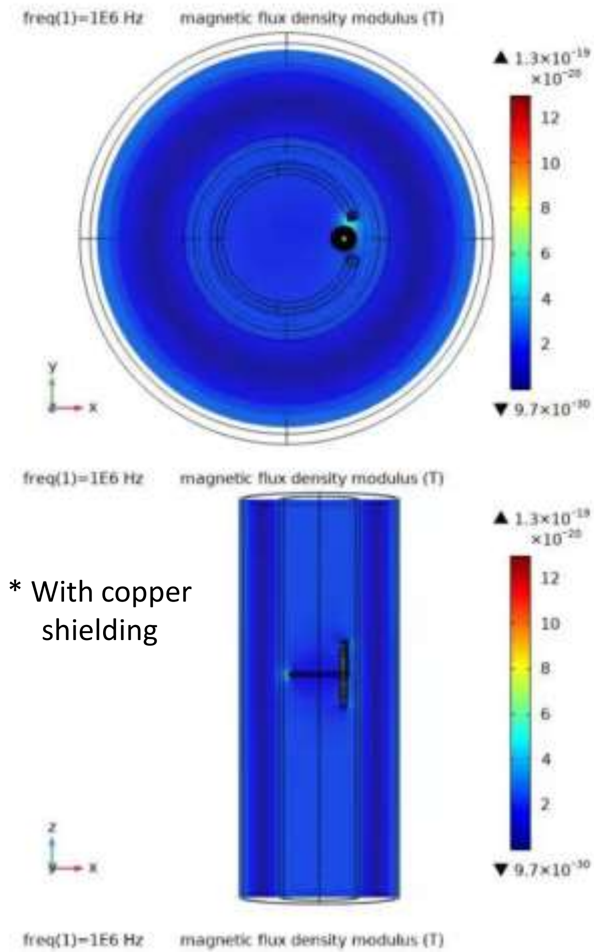
A realization in EM simulation: form-factor evaluations

R_1	1m	The outer radius of the shell of the cylinder
r_2	0.5m	The outer radius of the inner shell of the cylinder
ΔR, Δr	0.05m	The thickness of the shells
L	5m	The height of the cylinder
R_r	0.365m	The radius of the ring
R_c	0.04m	The radius of the coil
N	10.6	The number of coil turns
The Cylindrical Shell	Material	Solid Silicon
Ring	Material	Gold
Coil	Material	Gold
Other Areas	Material	Air
Boundary	Without *	Air
Boundary	With *	Copper shell

$$B_1 \approx F_r N \left(\frac{r_2}{r_1}\right) B_a = M_B B_a$$

Freq.	Eq. 8 (T)	B_a (T)	B_1 (T)	F_r
50 Hz	6.36×10^{-20}	2.13×10^{-20}	1.09×10^{-19}	0.053
50 Hz*	6.36×10^{-20}	3.18×10^{-20}	1.75×10^{-19}	0.057
1 MHz	6.36×10^{-20}	1.86×10^{-20}	1.3×10^{-19}	0.072
1 MHz*	6.36×10^{-20}	2.57×10^{-20}	2.01×10^{-19}	0.081

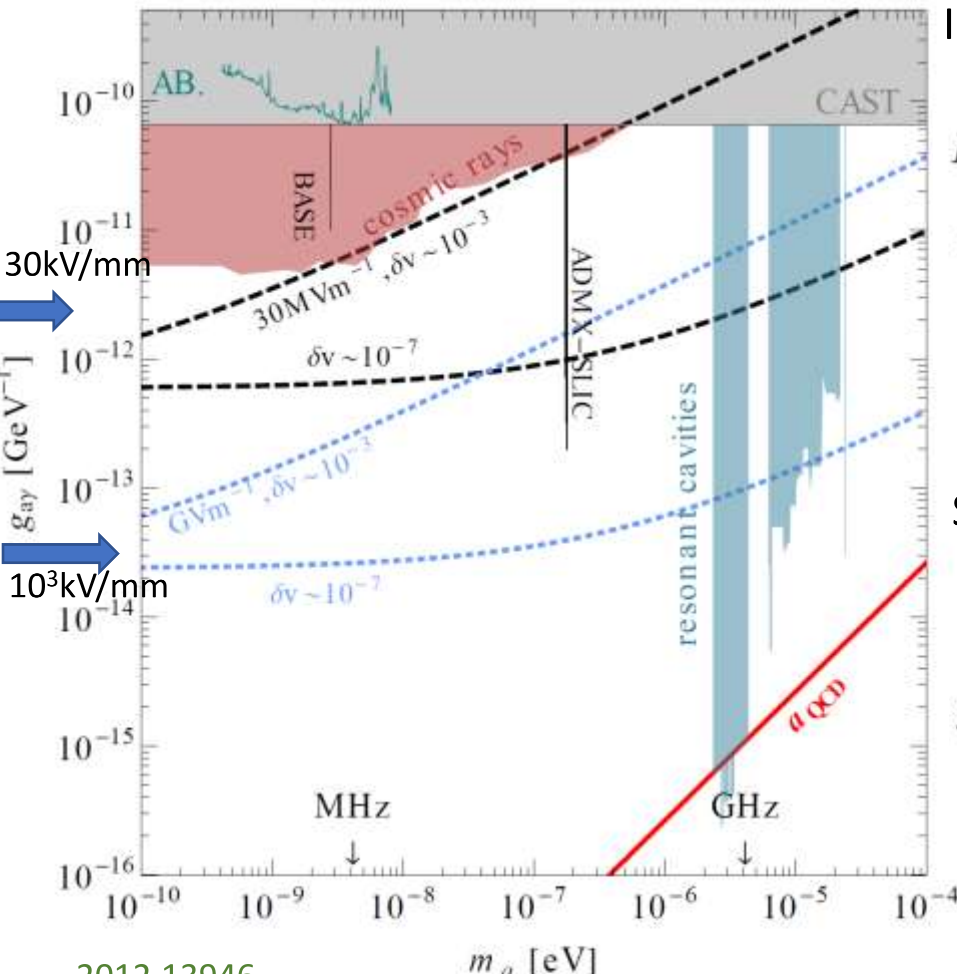




**Broadband: No low-f suppression in form factor*

E ~ 30kV/mm

E ~ 10^3kV/mm



2012.13946

Induction signal along cylinder axis:

$$B_a = \mu_0 R j_a = g_{a\gamma}\bar{E}_0 v\sqrt{2\rho_{CDM}}R\cos(\omega_a t)$$
$$= 2.0\times10^{-7}\mathrm{T}\left(\frac{g_{a\gamma}}{\mathrm{GeV}^{-1}}\right)\left(\frac{\bar{E}_0}{\mathrm{Gvolt/m}}\right)\left(\frac{R}{1\mathrm{m}}\right)$$
$$\times\ \cos(\omega_a t)$$

SQUID sensitivity reach

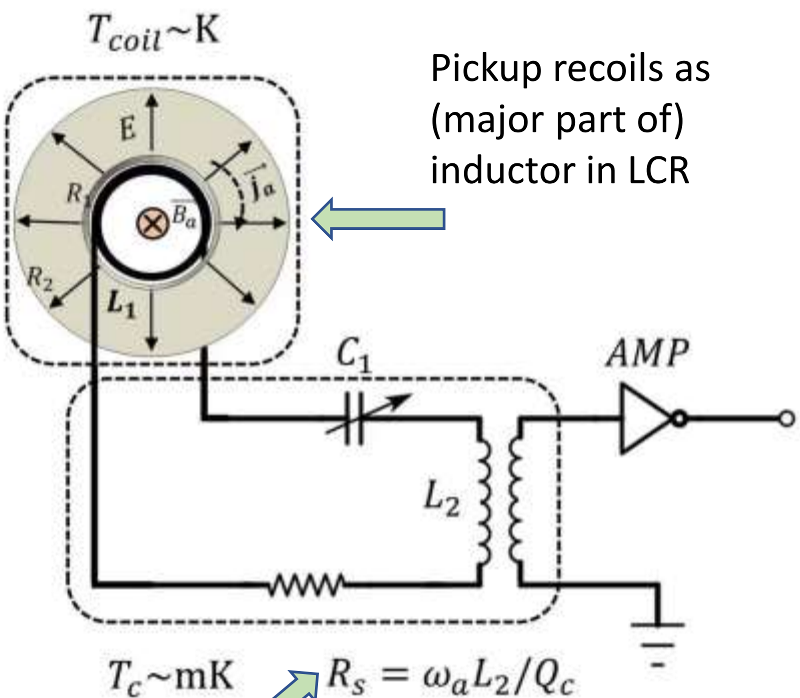
$$\Delta B \sim 10^{-16}\ \mathrm{Tesla}\cdot\sqrt{\Delta f/\mathrm{Hz}} + \Delta B_{\min}$$

$$g_{a\gamma} = 1.7\times10^{-13}\mathrm{GeV}^{-1}\left(\frac{1\mathrm{m}}{R}\right)\left(\frac{1\mathrm{GV/m}}{\bar{E}_0}\right)\left(\frac{10^4}{M_B}\right)\cdot\sqrt{\frac{m_a}{10^{-5}\mathrm{eV}}\frac{\delta v}{10^{-7}}}$$

Directionality: signal is daily modulated
and depends on apparatus orientation

Magnetic signal from *E* field (LC-res.)

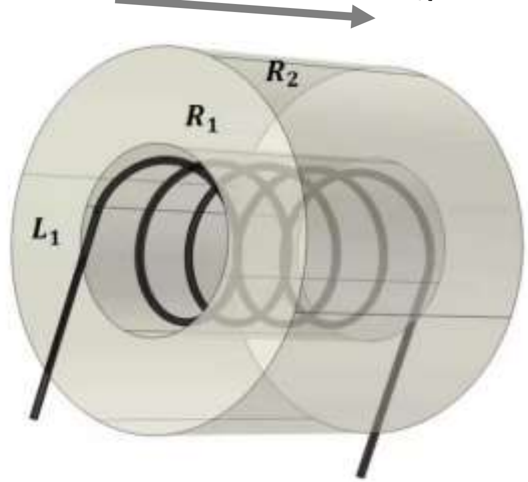
2204.14033 Cylindrical capacitor
+ LCR resonance enhancement



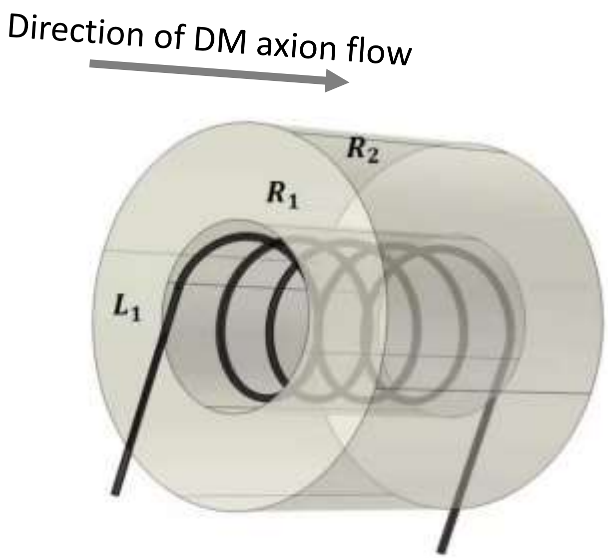
Pickup recoils as (major part of) inductor in LCR

Low *T* on resistance parts for noise control.

Direction of DM axion flow



* Originate from the search for the (dipole) radiating power from an alternating j_a loop
* Connect a LCR circuit to the coil pickup
* High *Q* resonant point requires relatively low resistance – need SC parts.
* Fast resonance saturation (~ f^{-1})
* Loose winding to let in the induced signal



Pickup Inductance ~ 10μH per meter for mm–diameter wiring

SC: Lenient on pickup temperature:
NbTi superconductor transition ~ 9.7K
Allow for a sizeable pick coil.

Axion-induced B field strength:

$$B_a = g_{a\gamma} E_0 v_{\rm DM} c_R \sqrt{2\rho_{\rm DM}} R_1$$
$$\sim 2\times 10^{-10}{\rm T}\cdot\left(\frac{g_{a\gamma}}{\rm GeV^{-1}}\right)\left(\frac{E_0}{10^7{\rm V/m}}\right)\left(\frac{R_1}{0.1{\rm m}}\right)$$

Signal current:

$$I_a = Q_c\cdot(\pi R_1^2 N_1 B_a L^{-1})\cos\omega t$$

LCR capacitance (~ 0.1 GHz)

$$C = (2\pi f)^{-2}/L \sim 0.3{\rm pF}\,(\mu{\rm H}/L)\,(0.1\ {\rm GHz}/f)^2$$

$Q_c = \omega_a L/R_s$ matches with axion's Q~10^6.

Maximal LCR dissipation power:
(saturate to axion conversion)

$$P_{\rm dis.} = Q_c\cdot(N_1\Phi_a/L)^2\omega_a L/2$$

Low resistance @ LCR resonance:

$$R_s = \omega L/Q_c = \ 0.04\Omega \cdot (f/\mathrm{GHz})$$

Helps reduce thermal noise under cryogenic cond. (T_c ~ mK)
SC coils need a less stringent temperature (K)
(yet its thermal noise should not exceed that in LCR)

Assuming the LCR's noise (it's amplified) dominates total noise

$$P_n = k_B T_c \Delta f + k_B T_D \Delta f$$

$$\begin{aligned} \mathrm{SNR} &= \frac{(Q_c N_1 \Phi_a/L)^2 R_s}{2 k_B T_c}\sqrt{\frac{t}{\Delta f}}\ , \\ &= \frac{Q_c (N_1 \cdot \pi R_1^2 B_a)^2}{2 L k_B T_c}\sqrt{Q_c \cdot 2\pi\omega_a \cdot t} \end{aligned}$$

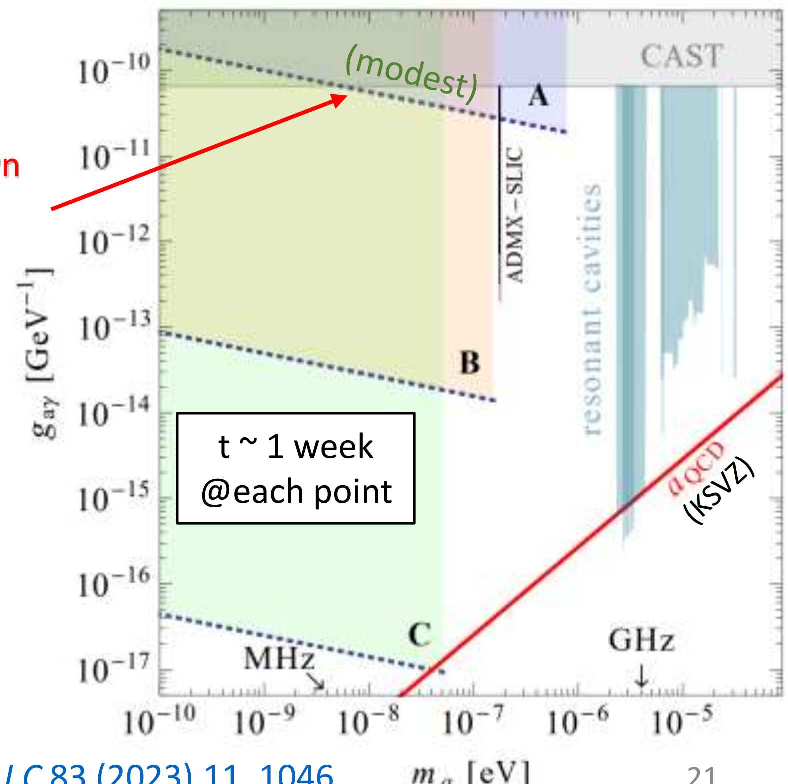
$$\begin{aligned} g_{a\gamma} &= \frac{\sqrt{\mathrm{SNR}\cdot 2N_1 L_{1,0}\cdot k_B T_c}}{(\pi R_1^3 N_1 E_0 v_a c_R \sqrt{2\rho_{\mathrm{DM}}})\sqrt[4]{Q_c^3\ 2\pi\omega_a t}}, \\ &\approx 1.6\times 10^{-12}\ \mathrm{GeV}^{-1}\left(\frac{R_1}{1\ \mathrm{m}}\right)^{-3}\left(\frac{E_0}{\mathrm{MVm}^{-1}}\right) \\ &\times \left(\frac{m_a}{10^{-6}\ \mathrm{eV}}\cdot\frac{t}{\mathrm{hr}}\right)^{-1/4}, \end{aligned}$$

Modest, medium & optimistic setups

Benchmark	R_1(m)	N_1	E(V/m)	T_c(mK)
A	0.2	5	10^6	10
B	1	10	10^7	1
C	3	20	10^9	1

Insulators:
- Dry Air: ~ kV/mm
- Mica: ~ 10^2-10^3 kV/mm
- Diamond: ~ 10^4 kV/mm

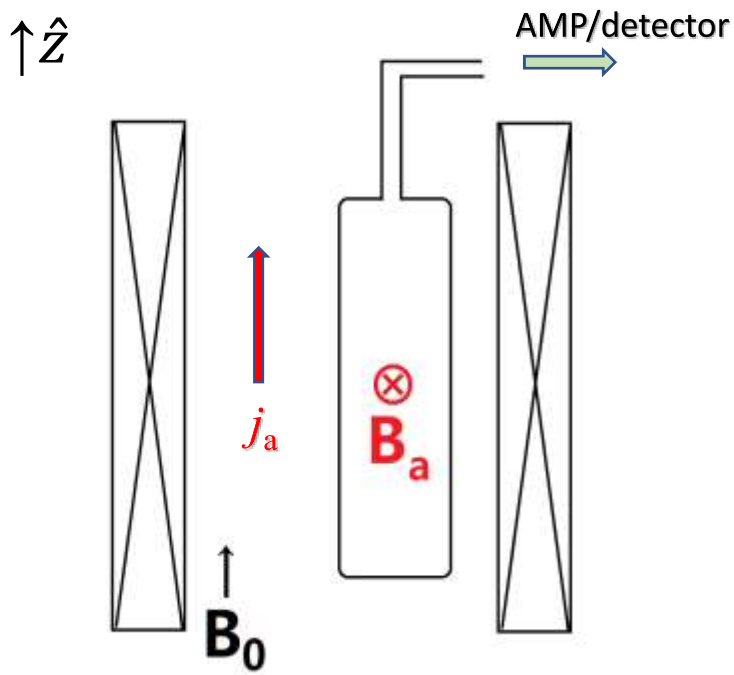
~ Air breakdown field can reach below CAST



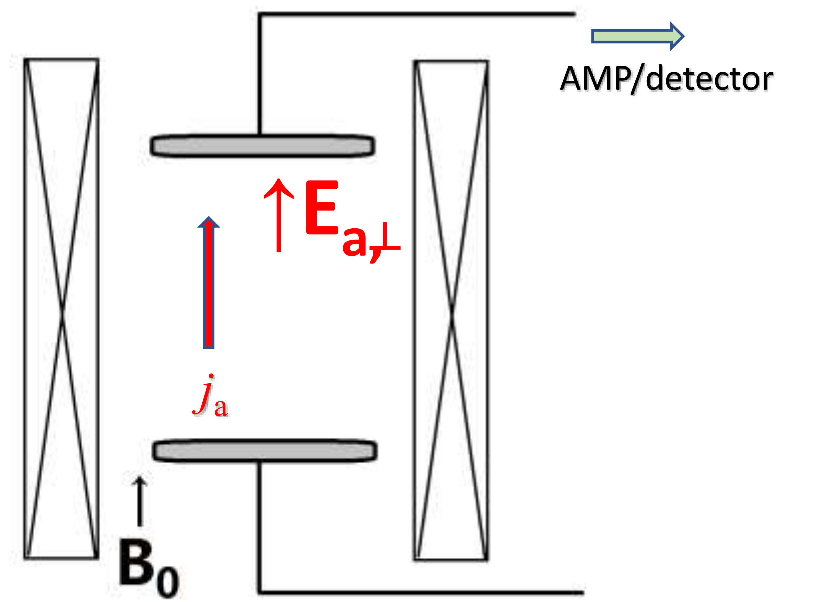
Eur.Phys.J.C 83 (2023) 11, 1046

Electric field as the signal

Effective current j_a (under a static B field) induces both time-variant mag. & ele. signals



See 1803.07755 for a broadband attempt (UWA)



B_a signal: magnetic flux at pickup loop

$$P_{sig.} = \frac{\langle \Phi^2 \rangle}{L} \omega$$

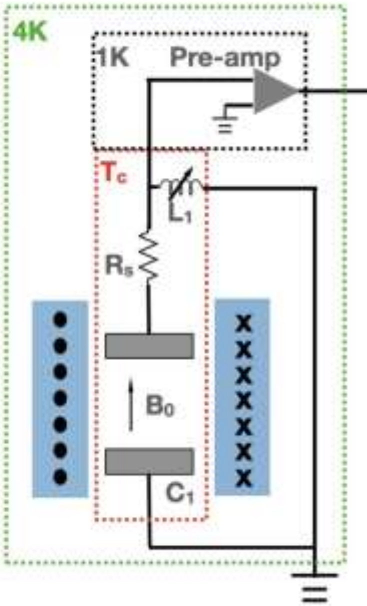
E_a signal: charge buildup on surface(s)

$$P_{sig.} = \frac{\langle q^2 \rangle}{C} \omega$$

E Signal power strength

Is E_a signal a good way to catch the DM axion oscillation signal?

Experimental sizes/detectors/noises vary.
Yet we can compare the axion conversion (signal) power.



Charge accumulation on plate surface: $q = \int \vec{E} \cdot \mathrm{d}\vec{A}$

Pair of parallel plates form a capacitor: $C \sim \pi R^2/d$

Use a LCR enhancement on current: $I_a = Q_c \cdot q_0 \omega \cos(\omega t)$

Geometric form factor: η $= q/q_{max}$
(ratio of actual/max charge)

$$\eta(\omega) \equiv \frac{\int \vec{E}_a \cdot \mathrm{d}\vec{A}}{\int g_{a\gamma} a \vec{B}_0 \cdot \mathrm{d}\vec{A}}$$

actual charge build up

theoretical upper limit: $E \sim g_{a\gamma} * a * B$

at `optimal' frequencies one would have η~O(1)

As good as a cavity haloscope?

LCR enhanced signal power:

$$P_{\rm sig} = \frac{(Q_c \omega q_0)^2}{2 Q_c \omega C}$$
$$= Q_c \cdot \left(g_{a\gamma}^2 \eta(\omega)^2 \cdot \frac{\rho_{\rm DM}}{m_a} B_0^2 \right) \cdot \pi R^2 d$$

A volume-dimension quantity: grasps the size of the region that axion field converts coherently to EM.

At the maximal wavelength (half-wave cutoff)

$$V \sim \left(\frac{\lambda}{2}\right)^3 = (\pi/m_a)^3$$

$$P_{\rm sig} = \mathcal{C} Q_c \cdot g_{a\gamma}^2 \cdot \frac{\rho_{\rm DM}}{m_a} B_0^2 \cdot V$$

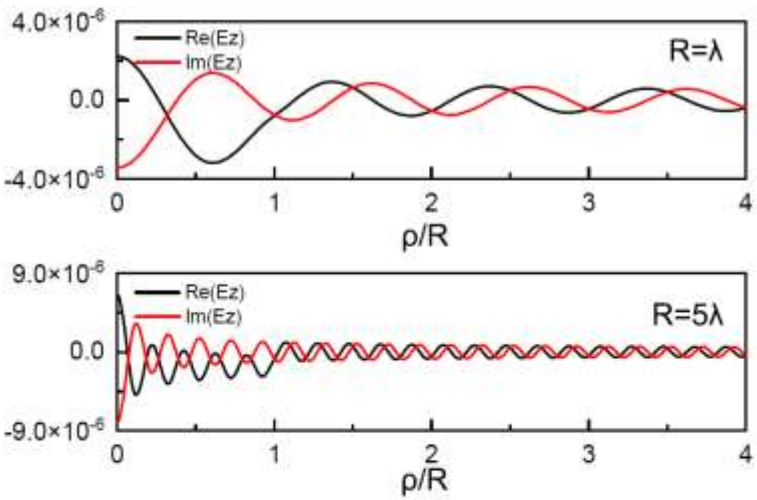
Form factor $\mathcal{C} = \eta^2 f_c^{-1}$ is around unity at cut-off

$$P_{\rm sig} < \mathcal{O}(1) \cdot Q \cdot \pi^3 \cdot \frac{g_{a\gamma}^2 \rho_{\rm DM} B_0^2}{m_a^4}$$

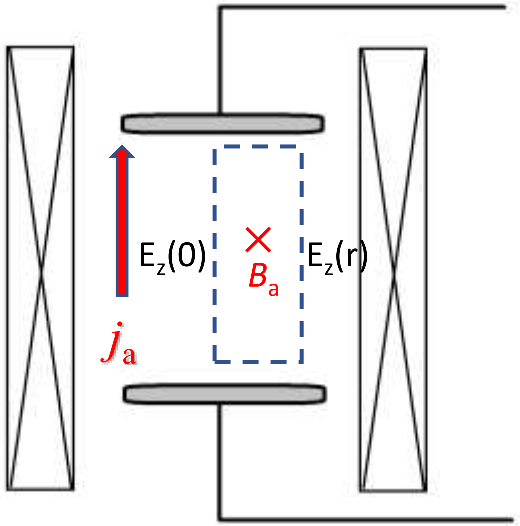
(→ same signal power as in a cavity haloscope)

Complication w geometric factors

Long solenoid analytic solutions,
see 1803.07755, 1812.05487



Simulated Ez distribution, 2206.13543



*E*z isn't homogeneous; form factor depends on freq.

Evenly distributed ja generates a difference btw $E_z(r \neq 0)$ and $E_z(0)$

$$\eta(\omega) \approx \frac{1}{\pi R^2}\left|\int_0^R [\alpha(\omega) J_0(\omega r) - 1]\cdot 2\pi r dr\right| = \left|i\pi J_1(\omega R) H_1^+(\omega R) - 1\right|$$

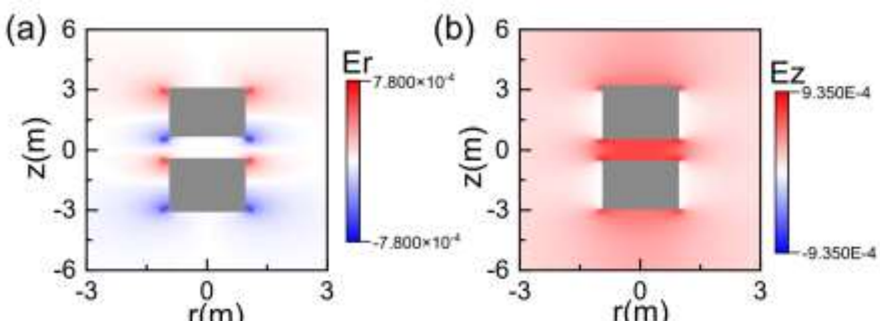
E_z field is $(\omega R)^2$ suppressed

*E*lectric sensitivity (w LCR res.)

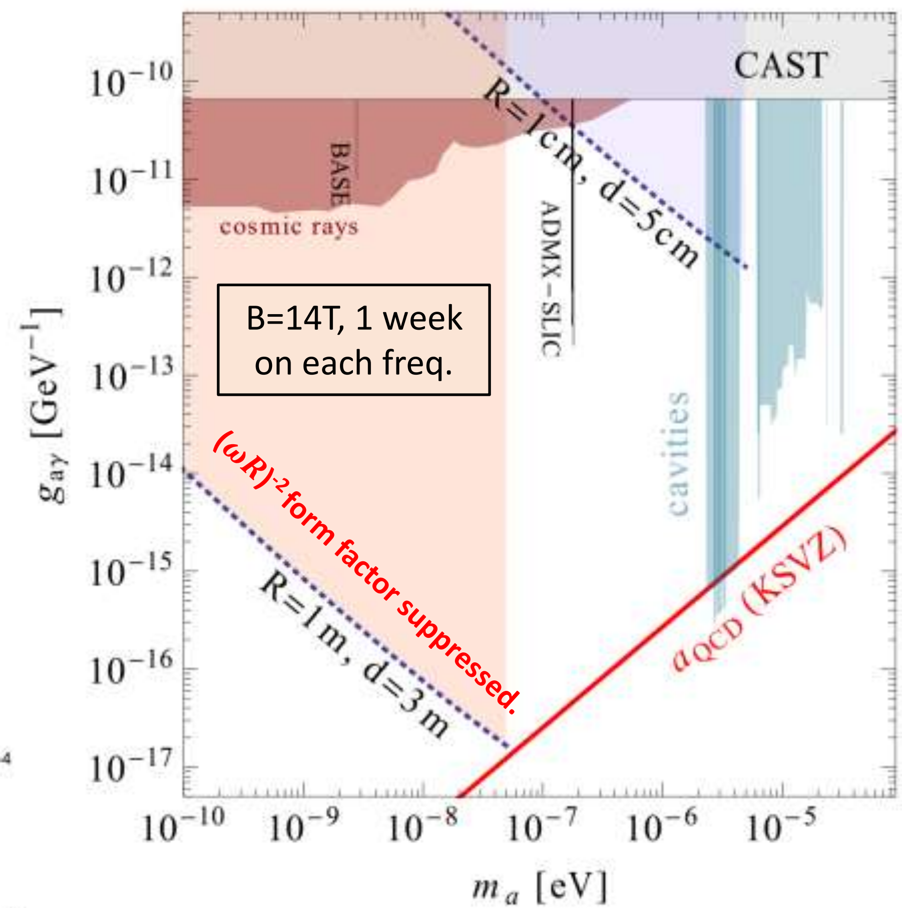
j_a induced electric signal inside a solenoid
Resonance-enhanced design 2206.13543
* *ready to go with most cryo. magnets.*
* *R*esonant *ELE*ctric *A*xion *P*robe (ReLEAP)

* Best sensitivity at larger frequency
* other geometric setups are possible

$$g_{a\gamma}^{\mathrm{limit}} = \left(\frac{\mathrm{SNR} \cdot 2k_B T_N}{\eta^2 f_c^{-1} R^2 d \ \rho_{\mathrm{DM}} B_0^2 \sqrt{\Delta t}} \right)^{1/2} \left(\frac{m_a}{2\pi Q_c} \right)^{3/4}$$



EM sim by Comsol



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*E*lectric sens. of GW

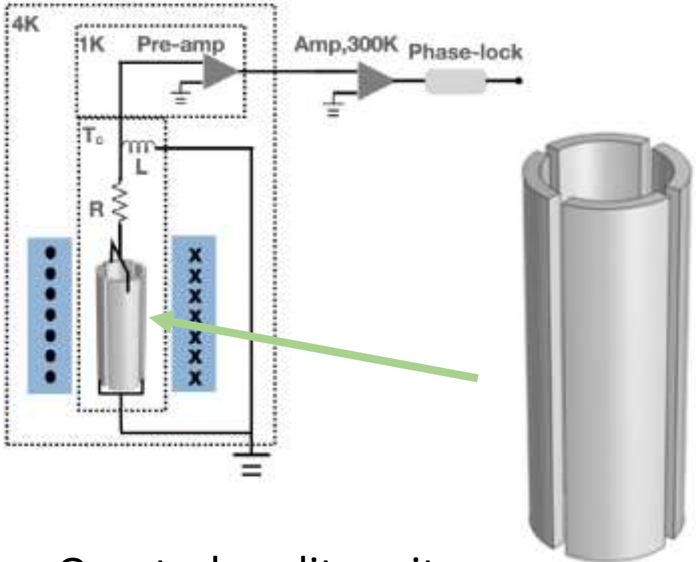
2305.00877

- Inverse Gertsentshein effect ($g \to \gamma$)
- **Potential indication of *Quantum* GW**

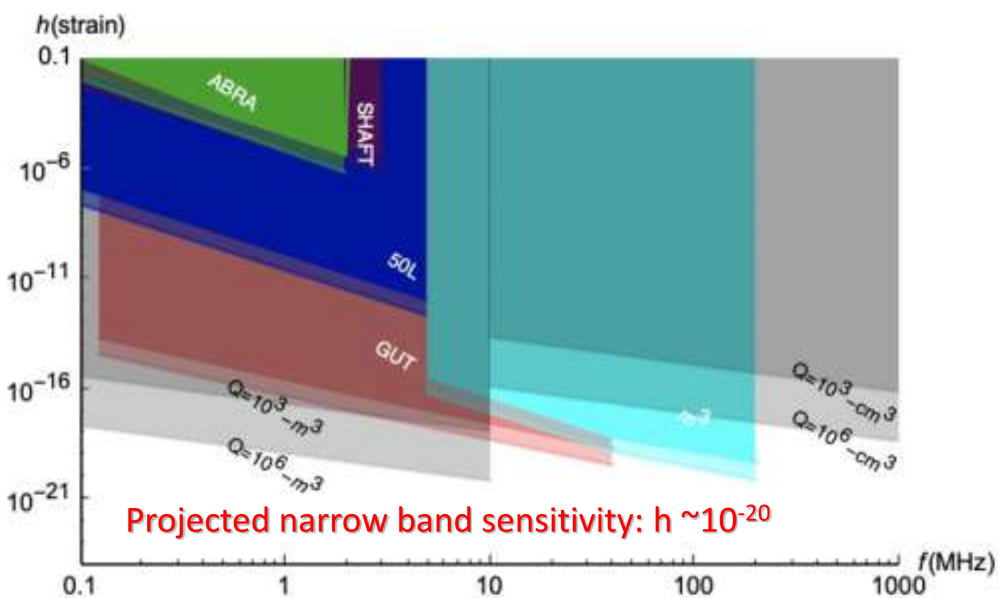
$$S = \int d^4x \sqrt{-g} \left(-\frac{1}{4} g^{\mu\alpha} g^{\nu\beta} F_{\mu\nu} F_{\alpha\beta} \right)$$

$$j^\mu_{\rm eff} \equiv \partial_\nu \left(\frac{1}{2} h F^{\mu\nu} + h^\nu_\alpha F^{\alpha\mu} - h^\mu_\alpha F^{\alpha\nu} \right)$$

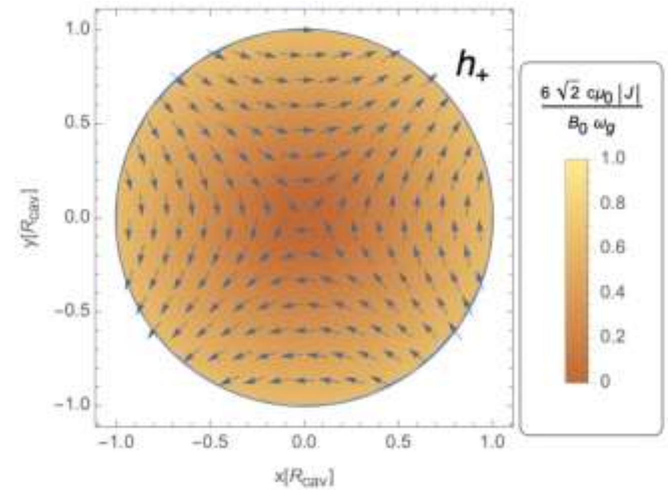
Generates effective currents inside strong B field



Quarterly split cavity:
* spin-2 symmetry (TE_{211})
* LC-filter for both Narrow/Broad band



Projected narrow band sensitivity: h ~10^{-20}



High voltage for indirect monopole search?

QEMD: Modified electrodynamics assuming magnetic monopoles exist.

Daniel Zwanziger, 1971
A. Sokolov & A. Ringwald, 2205.02605

Introduces extra U(1) to the theory and predict extra couplings: g_{aMM}, g_{aEM} when it comes to the axion's couplings.

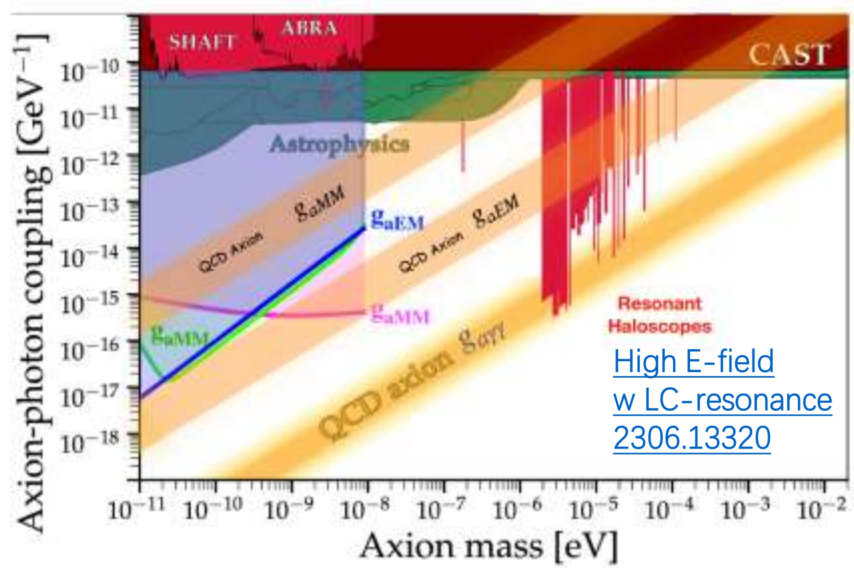
$$\vec{\nabla}\cdot\vec{E}_1 = g_{a\gamma\gamma}c\vec{B}_0\cdot\vec{\nabla}a - \underline{g_{aEM}\vec{E}_0\cdot\vec{\nabla}a} + \epsilon_0^{-1}\rho_{e1},$$

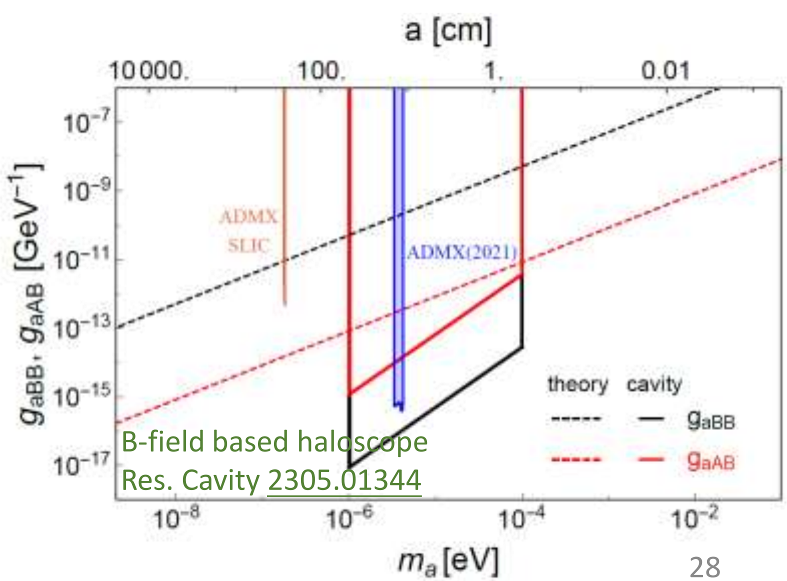
$$\mu_0^{-1}\vec{\nabla}\times\vec{B}_1 = \epsilon_0\partial_t\vec{E}_1 + \vec{J}_{e1} + g_{a\gamma\gamma}c\epsilon_0\left(-\vec{\nabla}a\times\vec{E}_0 - \partial_t a\vec{B}_0\right) + \underline{g_{aEM}\epsilon_0\left(-\vec{\nabla}a\times c^2\vec{B}_0 + \partial_t a\vec{E}_0\right)},$$

$$\vec{\nabla}\cdot\vec{B}_1 = -\frac{g_{aMM}}{c}\vec{E}_0\cdot\vec{\nabla}a + \underline{g_{aEM}\vec{B}_0\cdot\vec{\nabla}a},$$

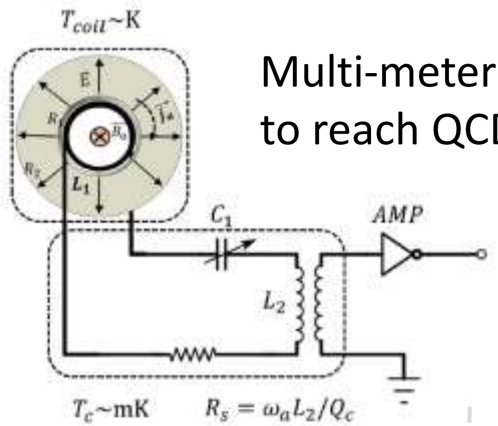
$$\vec{\nabla}\times\vec{E}_1 = -\partial_t\vec{B}_1 + \frac{g_{aMM}}{c}\left(c^2\vec{\nabla}a\times\vec{B}_0 - \partial_t a\vec{E}_0\right) + \underline{g_{aEM}\left(\vec{\nabla}a\times\vec{E}_0 + \partial_t a\vec{B}_0\right)},$$

Further Modified EM dynamics:



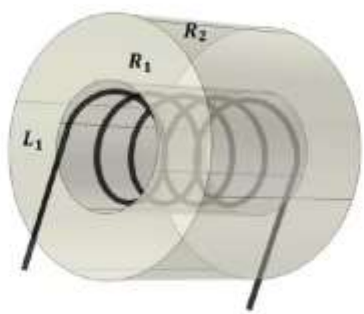


New haloscopes: open up a wider m_a range

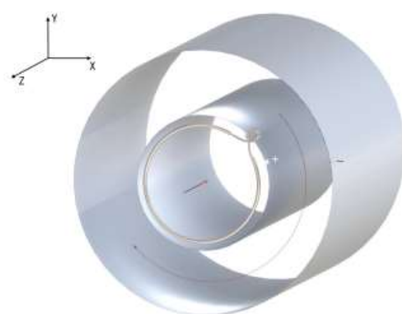


Multi-meter scale
to reach QCD axion f_a

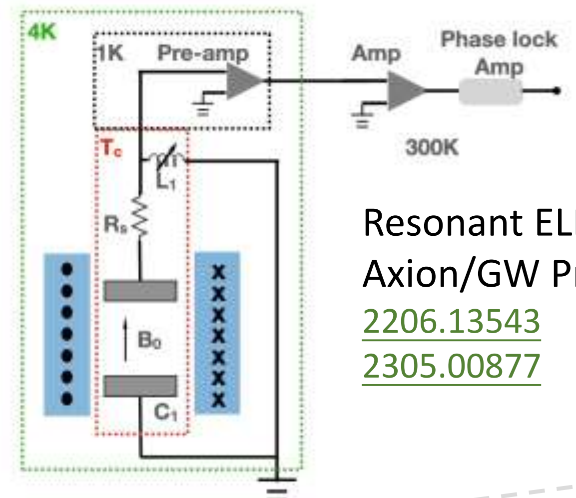
More ideas?



Magnetic signal
from DM axion wind
through a strong *E* field
2204.14033



Broadband probe
with state-of-art
magnetometers
2012.13946
Also see:
spin-based sensors:
(Diamond NV, etc.)



Resonant ELEctric
Axion/GW Probe
2206.13543
2305.00877

ADMX-SLIC
1911.05772
& DM-Radio
Magnetic signal
from DM axion
in a strong B field
2203.11246