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

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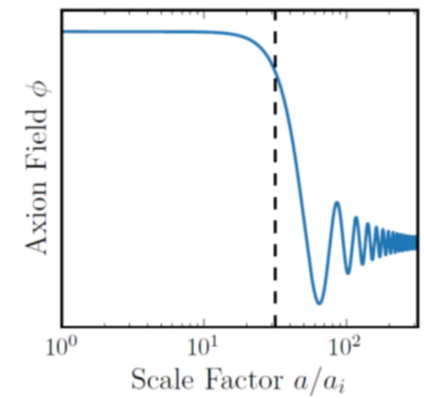
SYSU workshop
2022/07/24

Outline

- *Resonance* in ‘haloscopes’
- $\vec{E}$ field induced current
- $\vec{E}$ field as conversion medium
- $\vec{E}$ field as the signal

Axion / ALPs as DM

For theory review, see 1510.07633



A fast oscillating field at the bottom of a $V(\phi) \sim (\phi - \phi_0)^2$ potential 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: $\delta f / f \sim 10^{-6}$.

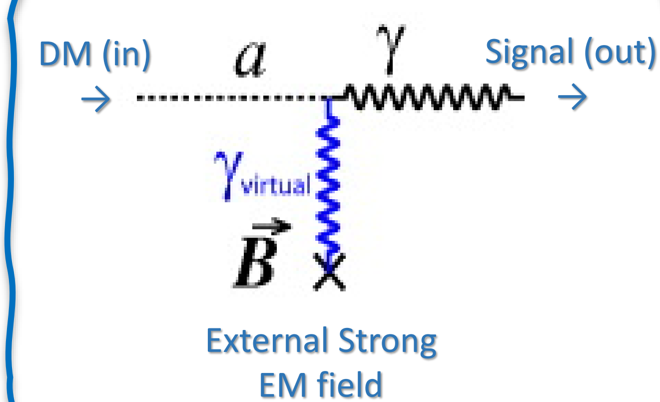
For terrestrial labs, as a coherent wave:

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

Local DM velocity

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

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



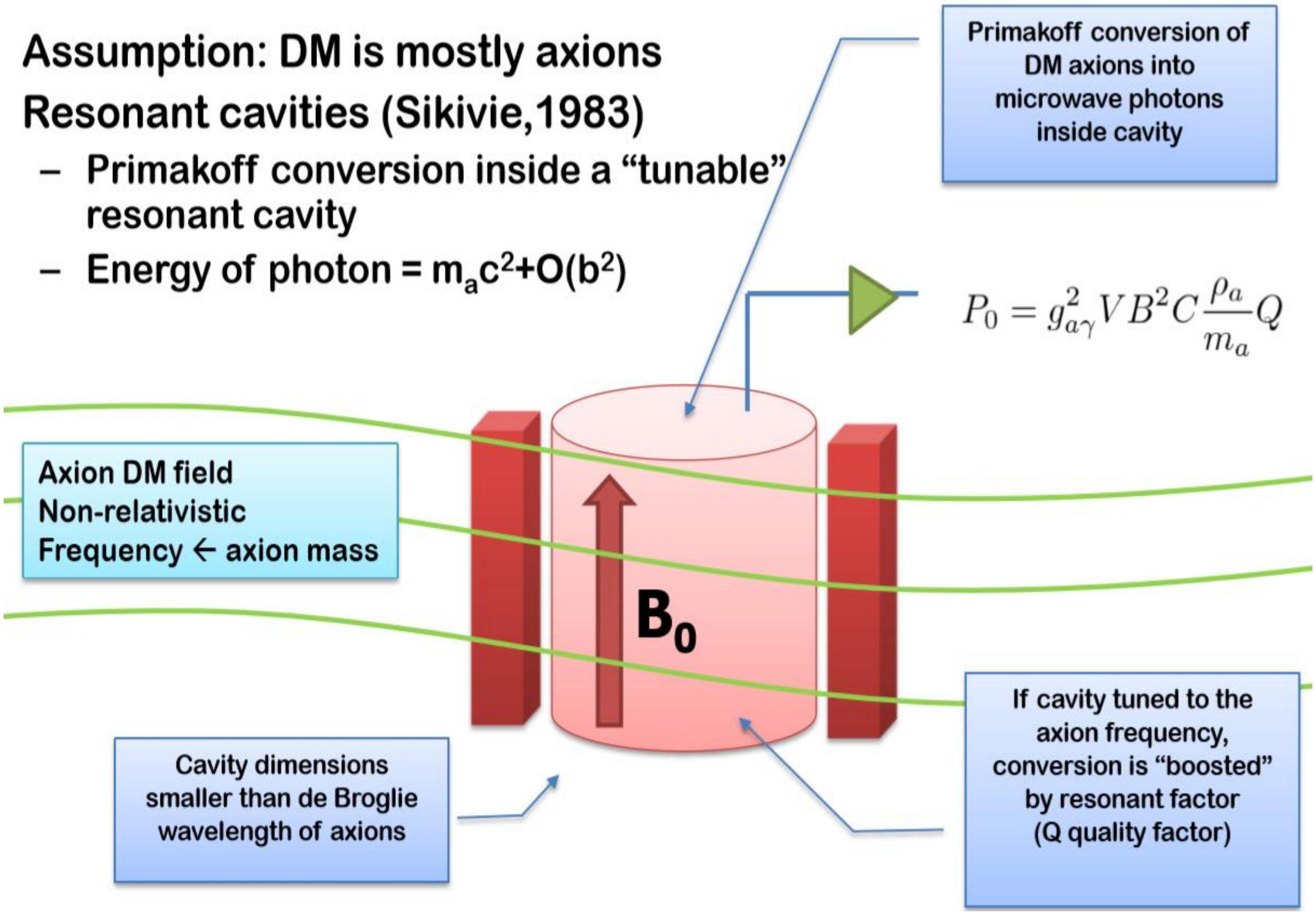
Axion DM - `haloscope'

QCD axion has a ***preferred*** microwave parameter range.

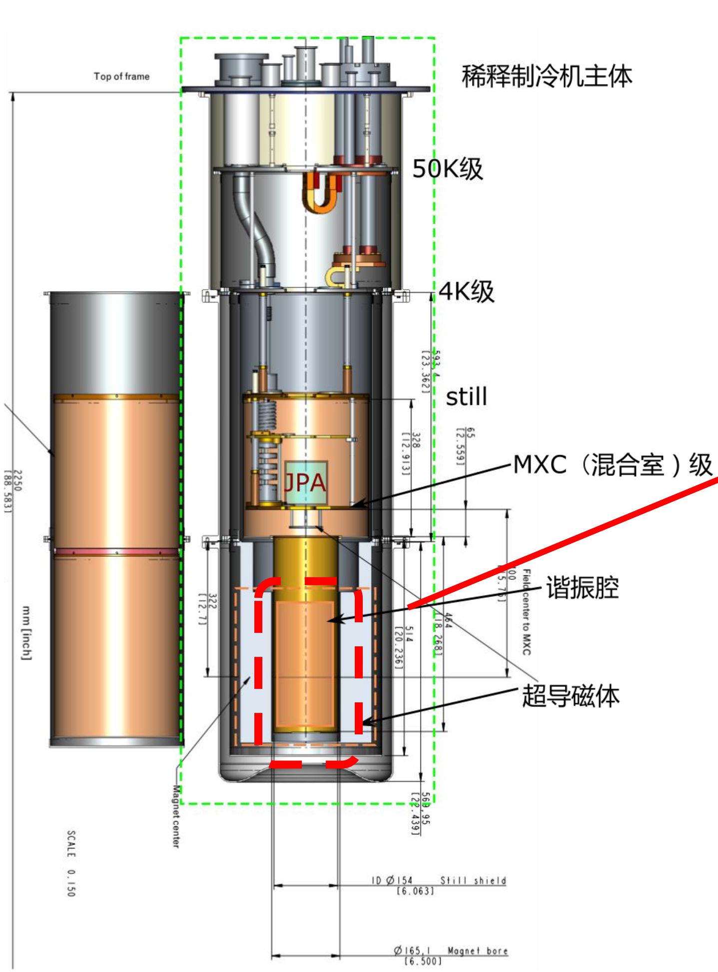
Assumption: DM is mostly axions

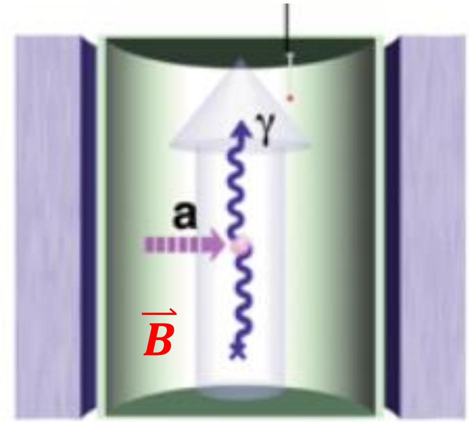
Resonant cavities (Sikivie,1983)

- **Primakoff conversion inside a "tunable" resonant cavity**
- **Energy of photon = $m_a c^2 + O(b^2)$**



Cryogenic resonant EM cavity





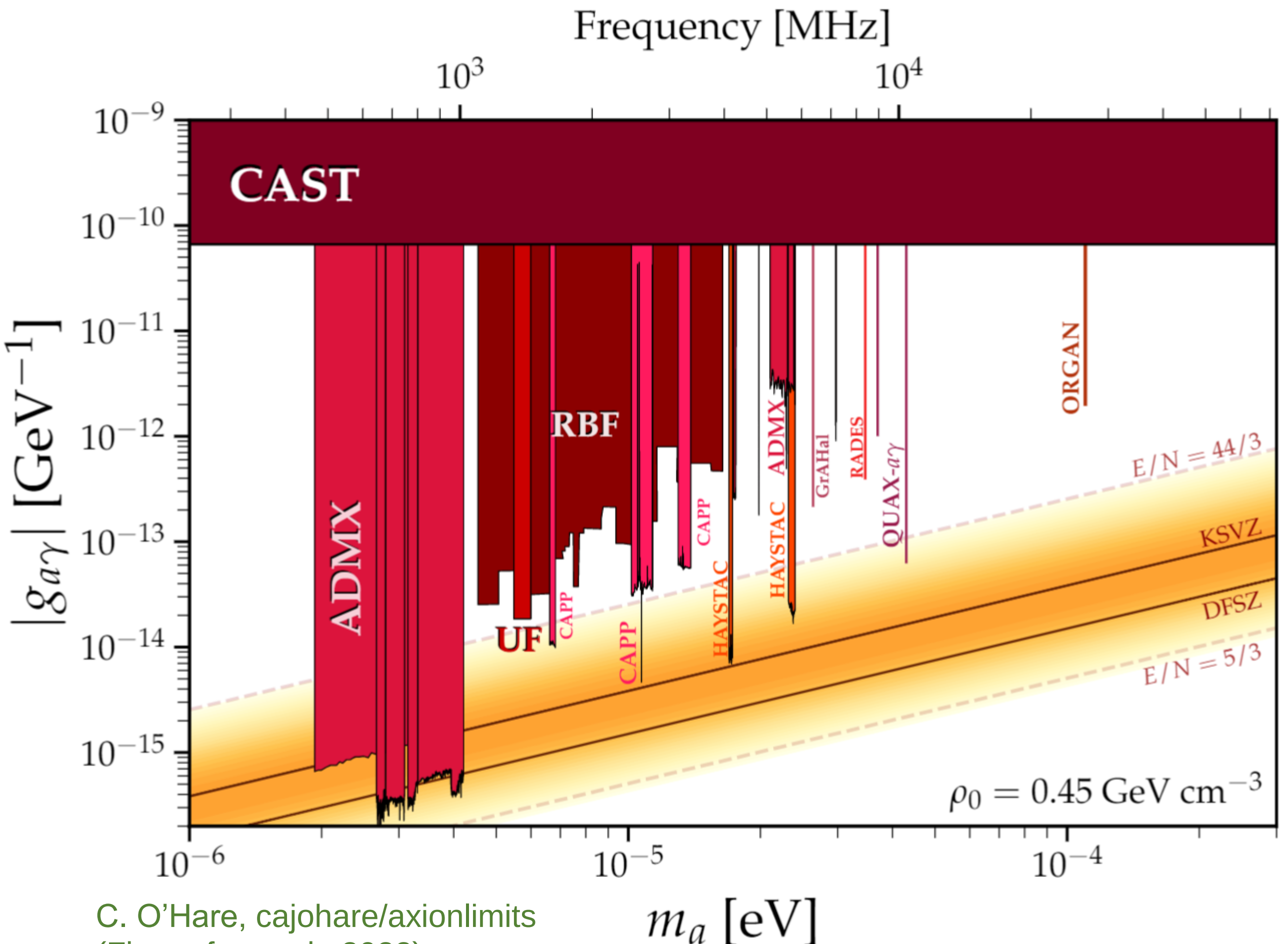
Cavity frequency tuned to expected axion decay signal frequency

QCD axion DM: emergence of a microwave signal

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

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

Cavity Haloscopes: sharpest limits, so far.



C. O'Hare, cajohare/axionlimits
(Figure from pdg 2022)

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.

High-Q resonance

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

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

$Q \sim 10^6$ 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

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

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

2201.08291

$$\begin{aligned} R &= \left| \int_0^t \langle 1| H_I |0\rangle e^{i(\omega_k - \omega_a)t} dt \right|^2 \\ &= \left(g_{a\gamma\gamma} \frac{\sqrt{2\rho_a}}{m_a} B_0 \int dx^3 \hat{z} \cdot |\langle 1| \vec{E} |0\rangle| \right)^2 \delta(\omega_k - \omega_a) \\ &= g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} B_0^2 C_k V \sum_k \omega_k \delta(\omega_k - \omega_a) \end{aligned}$$

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

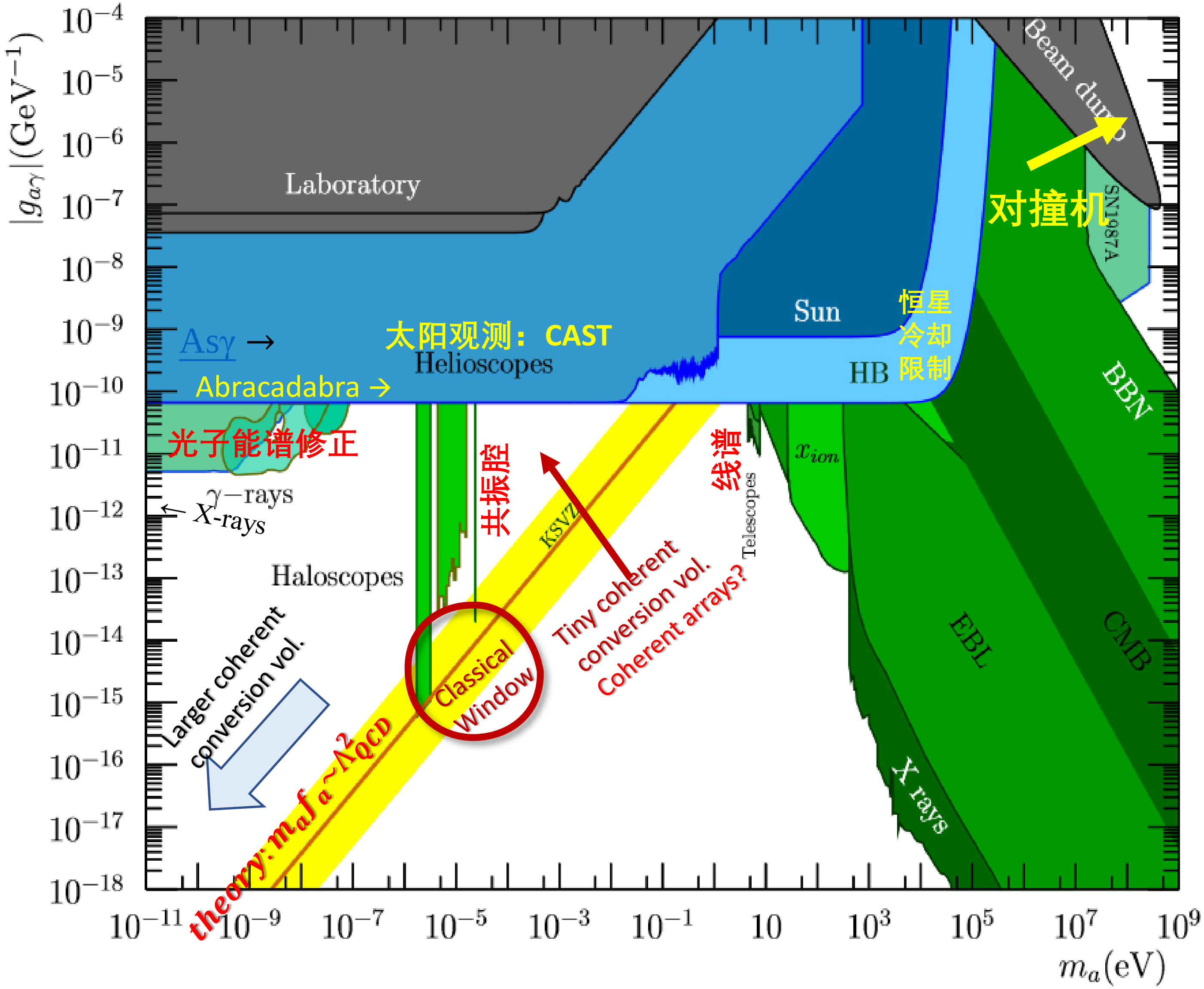
(for any DM axion wave's $Q_a \leq Q_{\text{cavity}}$)

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.

(this is consistent with classical oscillation calculations)

For classical, see P. Sikivie, 84'

What about lower/higher m_a?



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 $\partial_\mu j_a^\mu = 0$)

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

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

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

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

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

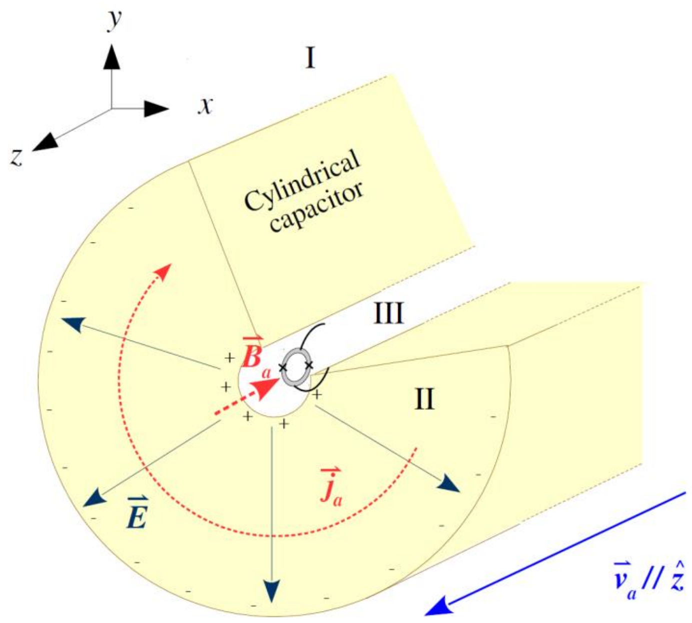
Axio-electric current $\vec{j}_a = g\vec{E} \times \vec{\nabla} a$

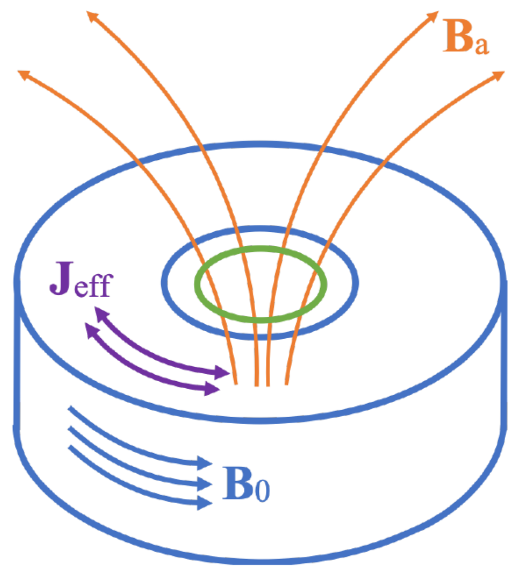
Axion's effective sources:

effective (moving) charge &
effective displacement currents

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

Sketch of axio-electric and axio-magnetic effective currents





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

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

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

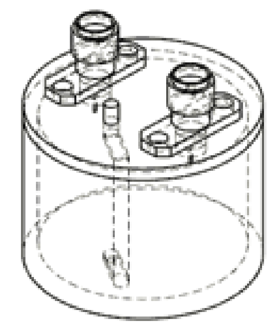
Resonance without a cavity

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

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

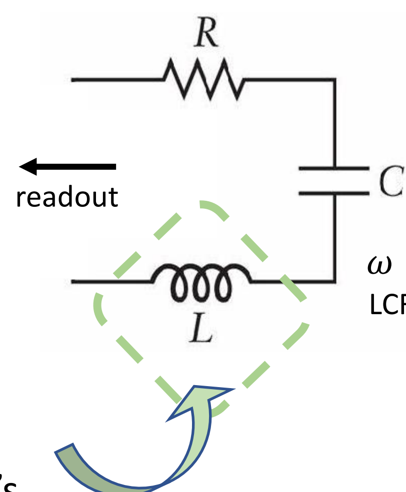
tunable cavity

$\omega_{010} = \omega_a$



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

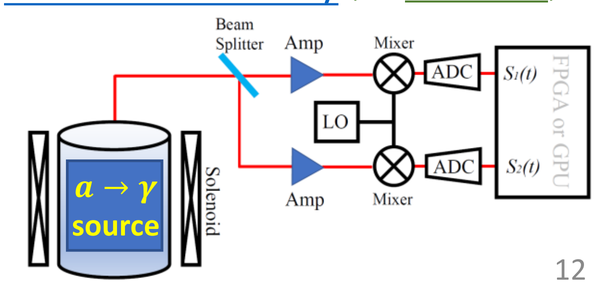
Long wavelength



$\omega = 1/\sqrt{LC}$
LCR resonance

Coupled to axion's j_a - induced signal with ω_a

Inter-disciplinary:
Lower freq. means more severe noises.
Input from Quantum Optics,
HBT interferometry (see 2201.08291) etc.



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

[As the medium]

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

  * 1 Tesla ~ 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
- E field is cheaply maintained as a static field ⟶ less fluctuation

[As the signal]

- Both E and B signals can be quite efficiently measured nowadays. (down to ~ single photon level)
- Typical E field signal:
  * cavity's resonance modes.
  * voltages differences.
- Typical B field signal:
  * magnetic flux by induction

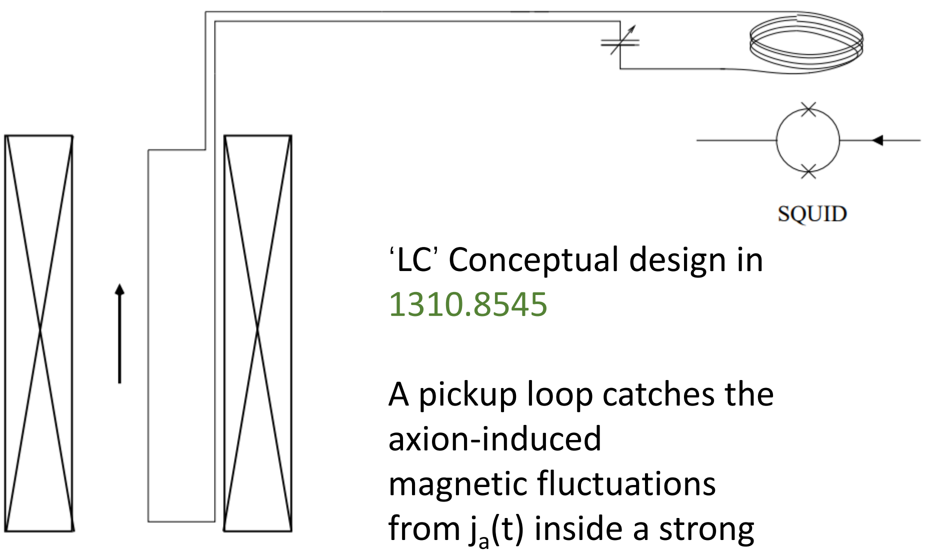
- Pick E or B that easily distinguishes from the experimental background.

  (Cavity: *E* signal from solenoid B)

Magnetic signal from B field

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

Enhanced by LC resonance and measured with a quantum magnetometer

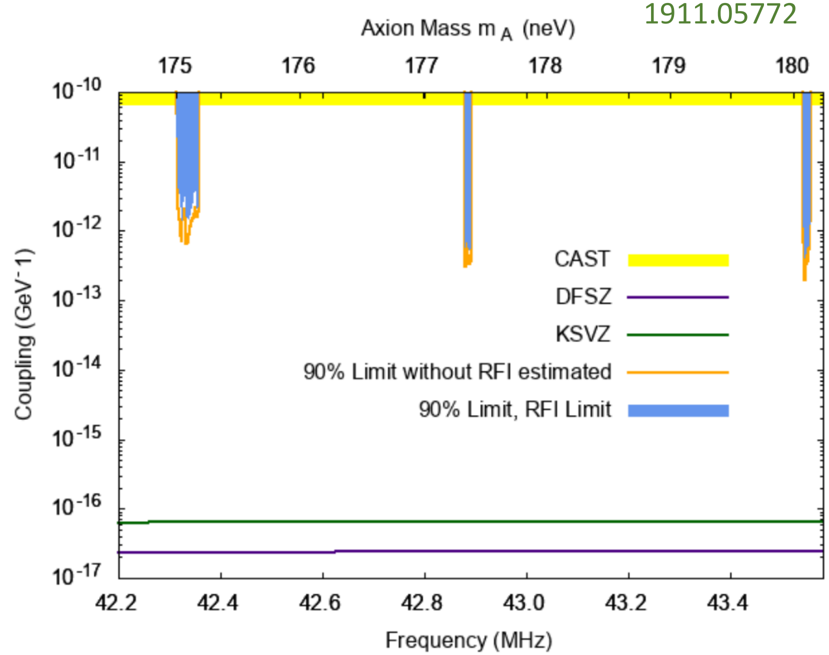


‘LC’ Conceptual design in 1310.8545

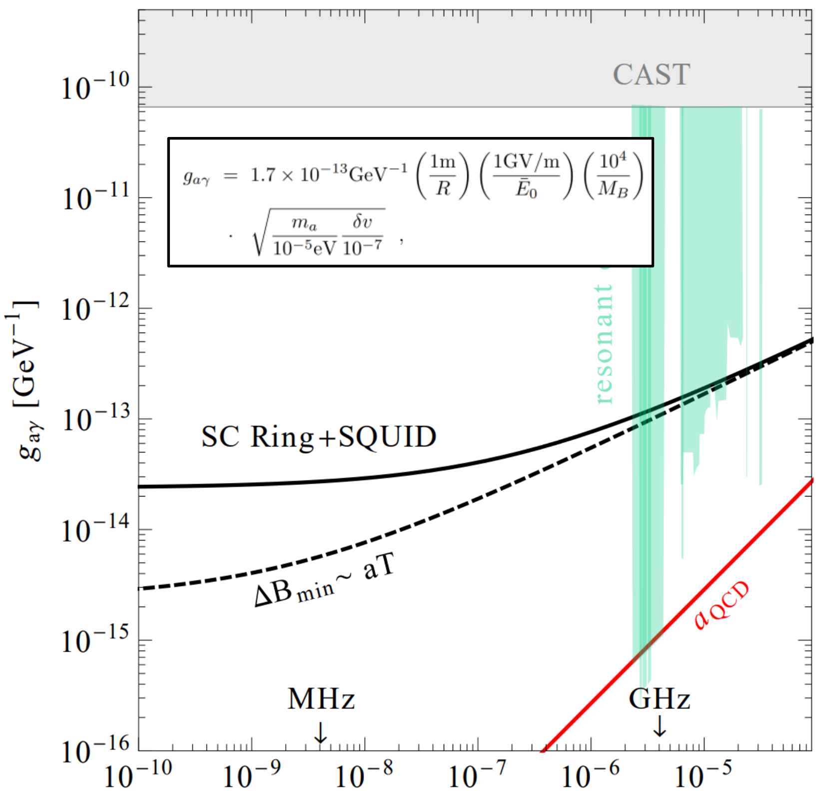
A pickup loop catches the axion-induced magnetic fluctuations from $j_a(t)$ inside a strong lab *B* field

Realization in ADMX-SLIC (2019)

1911.05772

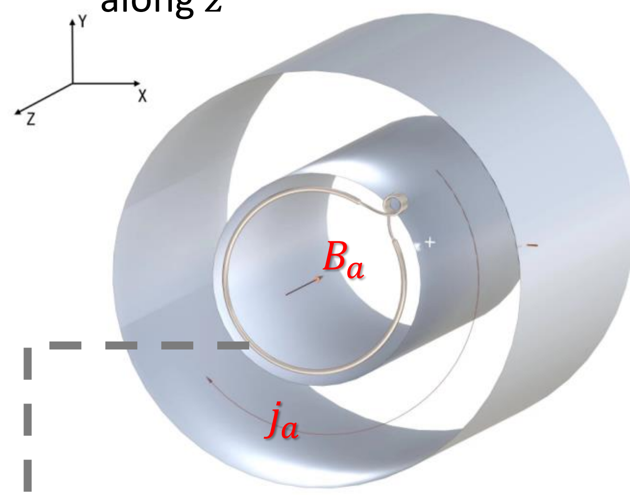


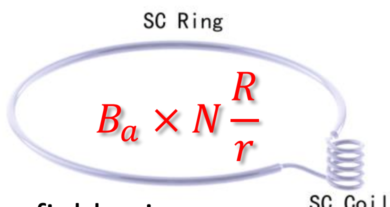
Magnetic signal from *E* field (non-Res.)



[2012.13946](https://arxiv.org/abs/2012.13946)

DM axion flow along $\hat{z}$





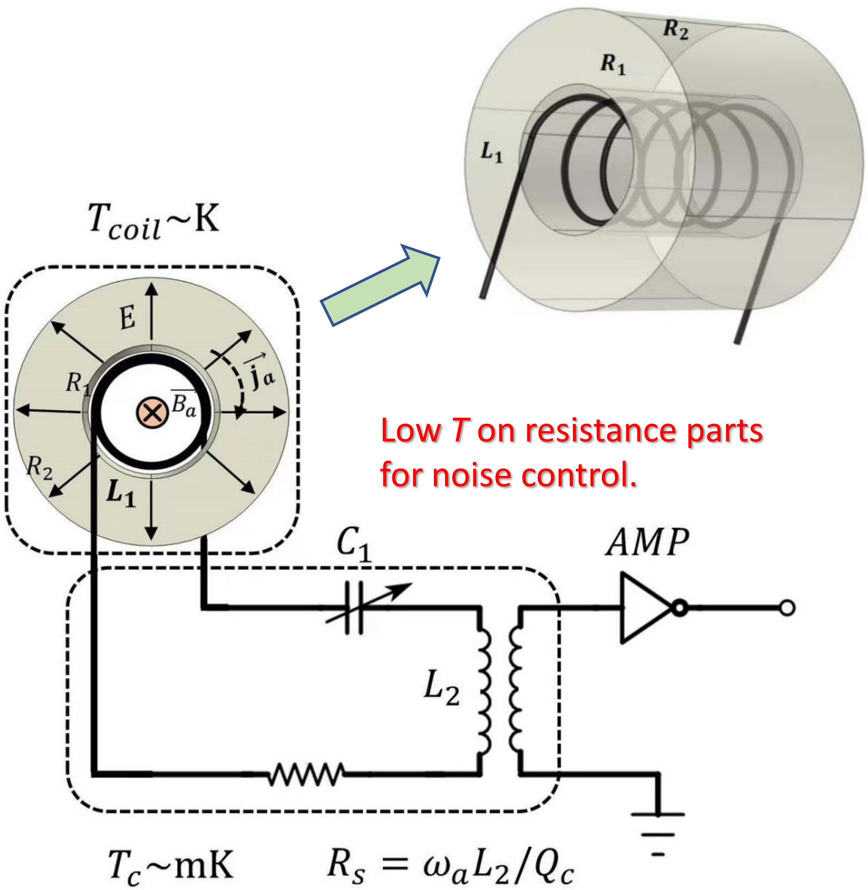
SC pickup coils:
Low noise, high mag. field gain.
Broad-band: non-resonance enhanced

- **Cylindrical capacitor**: j_a forms circular alternating currents between plate electrodes.
- Modern SQUIDS sensitive to $\delta B \sim 10^{-15}$ T

Magnetic signal from *E* field (Res.)

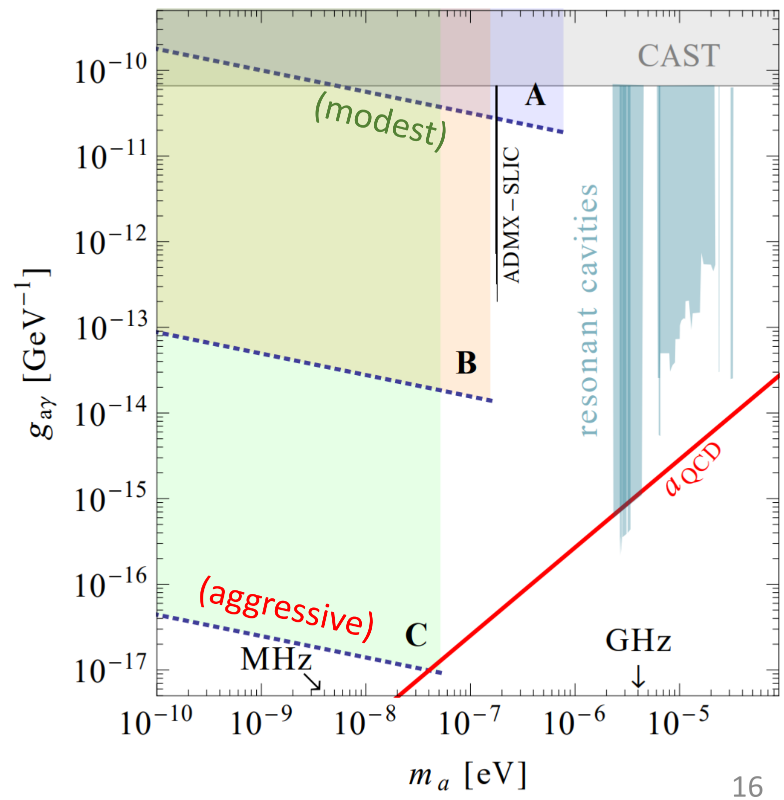
2204.14033

Cylindrical capacitor + resonance enhancement



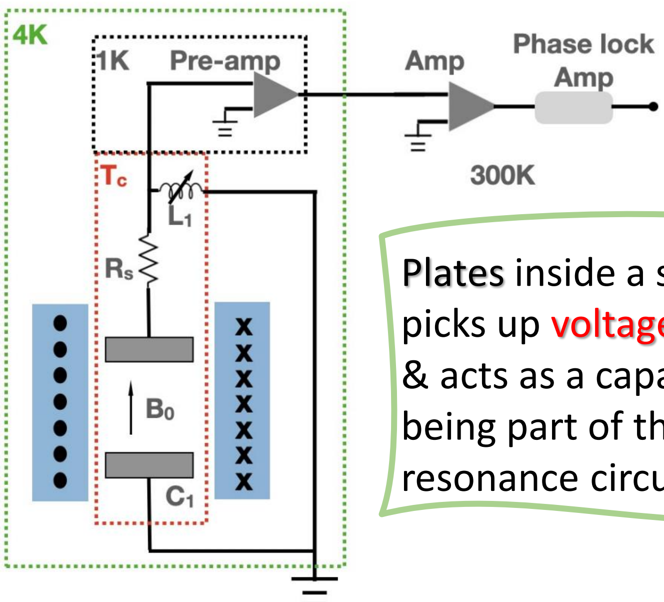
Low *T* on resistance parts for noise control.

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

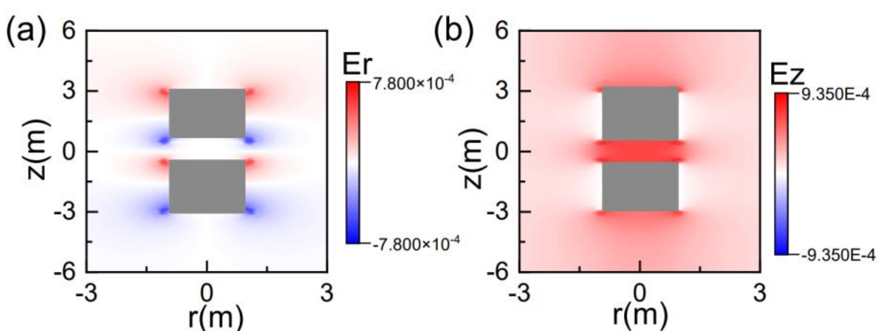


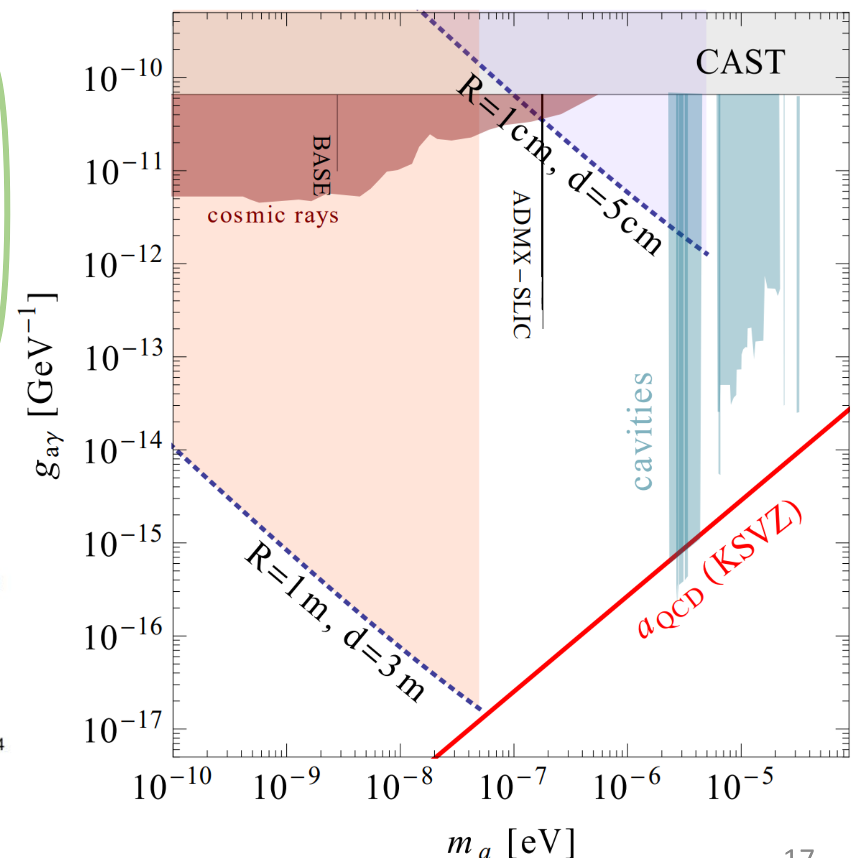
*E*lectric sensing in *B* field (Res.)

1803.07755
j_a induced electric signal inside a solenoid 1812.05487
Resonance-enhanced design 2206.13543
** ready to go with most cryo. magnets.*

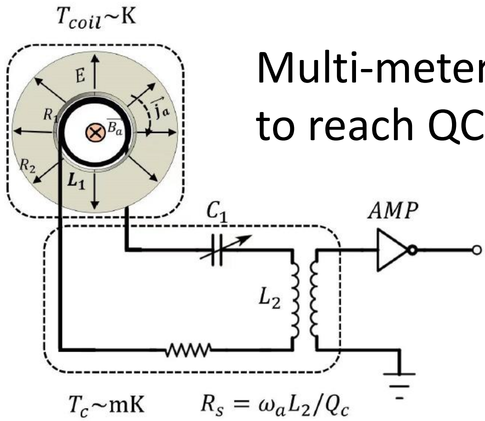


Plates inside a solenoid picks up voltage signals, & acts as a capacitor, being part of the LCR resonance circuit.



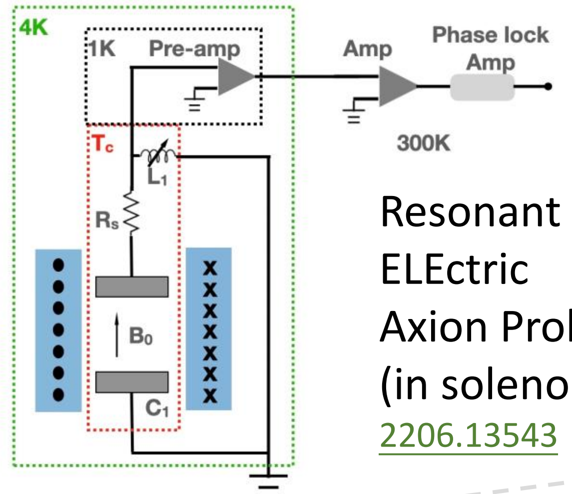


New haloscopes: open up $m_a < \mu eV$ range

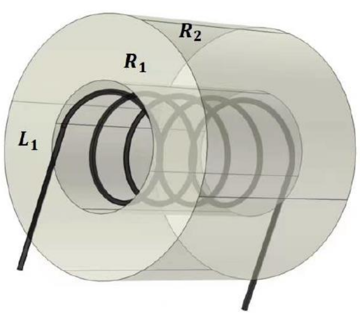


Multi-meter scale
to reach QCD axion f_a

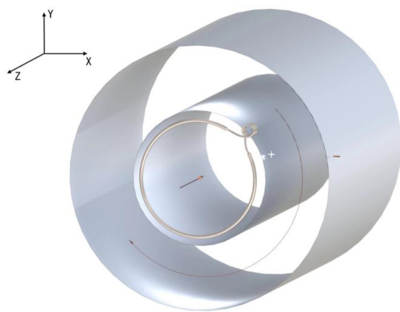
More ideas?



Resonant
ELEctric
Axion Probe
(in solenoid)
2206.13543



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.)

DM-Radio
Magnetic signal
from DM axion
in a strong B field
2203.11246