Detecting String-Scale QCD Axion Dark Matter

Blas Cabrera
Scott Thomas

<u>Strong CP Problem</u> :

$$\mathcal{L} \supset \theta \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Violates Parity and Time Reversal – (Renormalizable)

No Violation of Parity or Timer Reversal Has Ever Been Observed in Strong Interactions !!!

Bounds on Electric Dipole Moments of Neutron and Atoms

$$\theta \lesssim 10^{-10}$$

Strong CP Problem :

$$\mathcal{L} \supset \theta \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

$$\theta \lesssim 10^{-10}$$

- CP Symmetry – Spontaneously Broken

  $\theta_{CKM} \sim O(1)$ while $\theta < 10^{-10}$

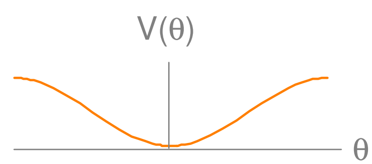
- Massless up-Quark $e^{i\,\theta_p} = e^{i\,\theta} \mathrm{Det}(m_q)$

- Peccei-Quinn Mechanism (Peccei, Quinn; Weinberg; Wilczek)

  Spontaneously Broken $U(1)_{PQ}$ -

  QCD Anomaly

  Goldstone – Axion $\theta = \theta(x)$



Dynamical Symmetry Restoration

Relic Dark Matter Axions : (Preskill, Wise, Wilczek; Abbott, Sikive; Dine, Fischler)

A COSMOLOGICAL BOUND ON THE INVISIBLE AXION

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Received 14 September 1982

The production of axions in the early universe is studied. Axion models which break the $U(1)_{PQ}$ symmetry above 10^{12} GeV are found to produce an unacceptably large axion energy density.

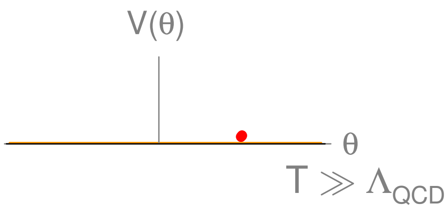
$$d^2\phi_A/dt^2 + 3H(t)d\phi_A/dt + m_A^2(T)\phi_A = 0$$

Relic Dark Matter Axions :

- Coherent Production

Axion Exists as a Goldstone During and After Inflation

$\theta_i(x) \simeq$ Constant over Observable Universe + Random



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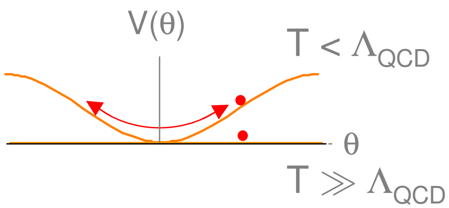

$$\Omega_a h^2 \sim 0.4 \left(\frac{f_a/N}{10^{12}\ \mathrm{GeV}} \right)^{7/6} \theta_i^2 \qquad \Omega_{\mathrm{CDM}} h^2 \simeq 0.11$$

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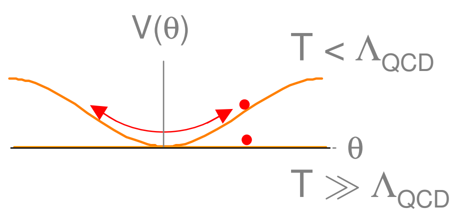

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Fixed ↑   Distribution ↑ $\langle\, \theta_i^2 \,\rangle = \pi^2/3$

$$\langle\, \Omega_a h^2 \,\rangle \simeq 0.1 \quad \Rightarrow \quad f_a/N \sim 10^{11\text{-}12}\ \mathrm{GeV}$$

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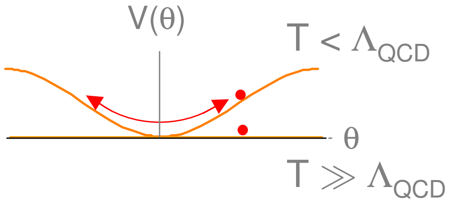

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Fixed Distribution

$\Omega_a h^2 \simeq 0.1 \quad \Rightarrow \quad f_a/N > 10^{11\text{-}12}$ GeV

ρ_{DM} Selection Effects !?

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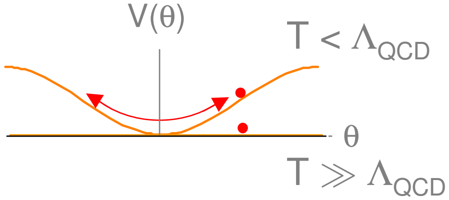

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Distribution Distribution

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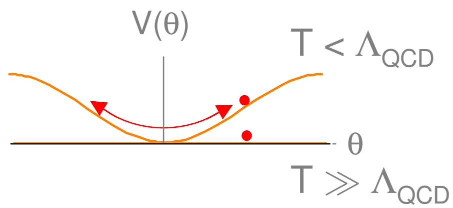

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Distribution Distribution

$\Omega_a h^2 \simeq 0.1 \quad \Rightarrow \quad f_a/N > 10^{11\text{-}12}$ GeV $\qquad \rho_{DM}$ Selection Effects !?

- Large Classes of String Vacua $\quad f_a/N \sim 10^{16+-1}$ GeV $\qquad$ (Svrcek,Witten)

Moduli - p-Form Fields on Cycles – Shift Symmetry

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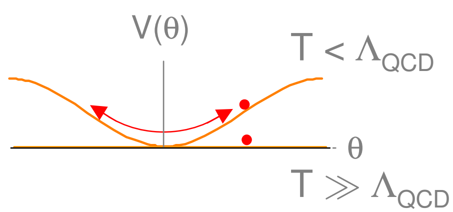

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Moduli - p-Form Fields on Cycles – Shift Symmetry

Possible to Detect ?

Axion Electrodynamics : (Sikive)

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Experimental Tests of the "Invisible" Axion

P. Sikivie
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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.

PACS numbers: 14.80.Gt, 11.30.Er, 95.30.Cq

$$\mathfrak{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{e^2N}{12\pi^2}\frac{a}{v}F_{\mu\nu}\tilde{F}^{\mu\nu} + \tfrac{1}{2}\partial_\mu a\partial^\mu a - \tfrac{1}{2}m_a{}^2a^2[1+O(a^2/v^2)]$$

$$\nabla\cdot\vec{\mathrm{E}} = \frac{e^2N}{3\pi^2 v}\vec{\mathrm{B}}\cdot\nabla a, \quad \nabla\times\vec{\mathrm{B}} - \frac{\partial\vec{\mathrm{E}}}{\partial t} = \frac{e^2N}{3\pi^2 v}\left[\vec{\mathrm{E}}\times\nabla a - \vec{\mathrm{B}}\frac{\partial a}{\partial t}\right], \quad \Box a = \frac{e^2N}{3\pi^2 v}\vec{\mathrm{E}}\cdot\vec{\mathrm{B}} - m_a{}^2 a$$

Axion Electrodynamics : (Sikive)

$$\mathcal{L} = \frac{1}{2}\epsilon_0 \mathbf{E}^2 - \frac{1}{2\mu_0}\mathbf{B}^2 - \frac{3}{4}\xi\frac{\alpha}{2\pi\mu_0 c}\frac{a}{f_a/N}\,\mathbf{E}\cdot\mathbf{B}$$

$$\xi \simeq \frac{4}{3}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}\right) \qquad z = m_u/m_d$$

	E/N	ξ
DFSZ	8/3	0.97
KSVZ	0	-2.59

$$\nabla\cdot\mathbf{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla\times\mathbf{B} = \mu_0\epsilon_0\frac{\partial\mathbf{E}}{\partial t} + \mu_0\mathbf{j}$$

$$\rho = \frac{3}{4}\xi\frac{\alpha}{2\pi\mu_0 c}\frac{a}{f_a/N}\,\mathbf{B}\cdot\nabla a$$

$$\mathbf{j} = \frac{3}{4}\xi\frac{\alpha}{2\pi\mu_0 c}\frac{a}{f_a/N}\left(\mathbf{E}\times\nabla a - \mathbf{B}\frac{\partial a}{\partial t}\right)$$

Galactic Dark Matter Axions $\quad \frac{\partial a}{\partial t} \simeq m_a a \qquad \nabla a \simeq m_a v a \qquad v \sim 10^{-3}c$

Constant Fields in Laboratory $\quad \mathbf{B}_{\text{lab}} \gg \frac{1}{c}\mathbf{E}_{\text{lab}}$

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Galactic Dark Matter Axions :

$$\rho_{\rm DM} c^2 \simeq 0.3 \text{ GeV cm}^{-3}$$

$$z = m_u / m_d \simeq 0.56$$

$$\rho_a c^2 \simeq \frac{1}{2} \frac{m_a^2 a_0^2}{(\hbar c)^3}$$

$$m_a \simeq \frac{\sqrt{z}}{1+z} \frac{f_\pi m_\pi}{f_a/N}$$

$$\theta = \frac{a}{f_a/N}$$

$$\theta_0 \simeq 3.6 \times 10^{-19}$$

- On length scales $D < \hbar / (m_a v)$

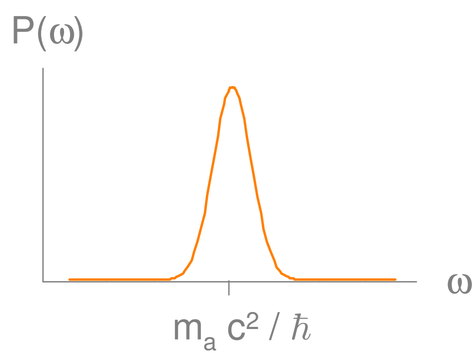
$$\theta(\mathbf{x}, t) \simeq \theta_0 e^{i\omega t}$$

$$\omega = \frac{m_a c^2}{\hbar}$$

$$\mathbf{j}(x,t) \simeq \frac{3}{4} \xi \frac{\alpha}{2\pi \mu_0 c} \theta_0 \omega \mathbf{B}(x) \, e^{i\omega t}$$

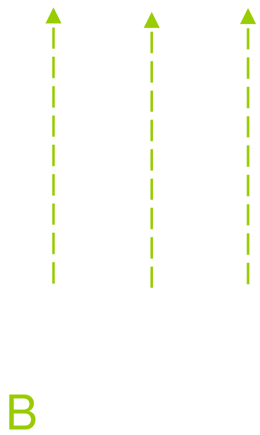
f_a/N	$\nu = \omega / 2\pi$
10^{12} GeV	1.5 GHz
10^{16} GeV	150 KHz

- Stochastic Spectrum



$$\frac{\Delta \omega}{\omega} \sim \frac{v^2}{c^2} \sim \frac{1}{Q_a} \sim 10^{-6}$$

Dark Matter Axion Detection :



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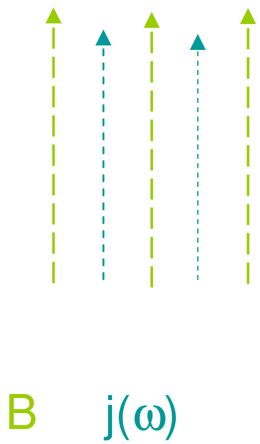

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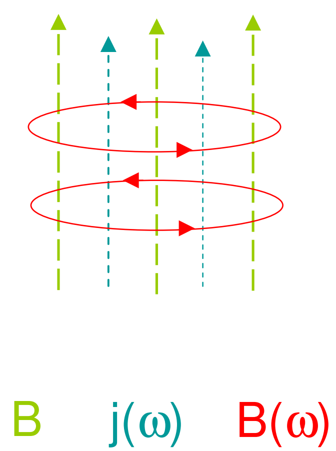
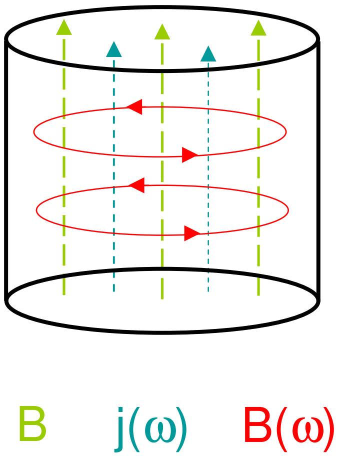


$$\nabla \times \mathbf{E} = -i\omega\mathbf{B}$$

For $D \sim \hbar / m_a$ $\quad \dfrac{E}{c} \sim B$

Dark Matter Axion Detection :

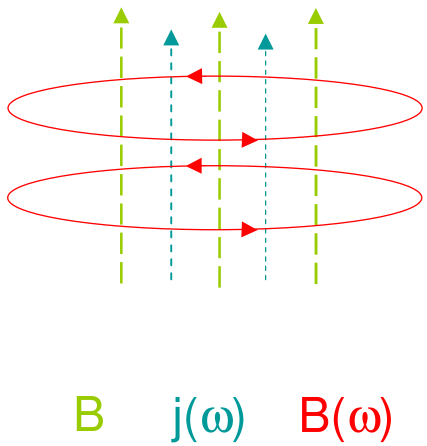
- Resonant Cavity TM_{010}



$$\omega_{010} \simeq 4.8\ c\ /\ D$$

f_a /N	D
10^{12} GeV	15 cm
10^{16} GeV	1.5 km

Dark Matter Axion Detection – Large f_a/N :



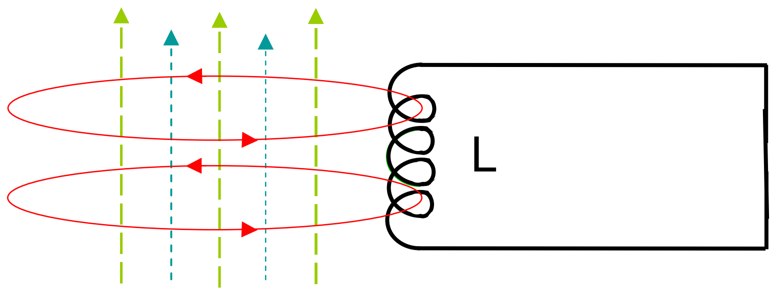
$$\nabla \times \mathbf{E} = -i\omega \mathbf{B}$$

For $D \ll \hbar / m_a = c / \omega$ $\qquad \frac{E}{c} \ll B$

Adiabatic Limit

<u>Dark Matter Axion Detection</u> – Large f_a/N :

- Inductor L



Link Slowly Changing Magnetic Flux with Inductor

B   j(ω)   B(ω)

$$L\dot{I} = \mathcal{E} = M\dot{I}_a$$

$$I_a = \int \mathbf{j} \cdot d\mathbf{A}$$

$$I = \frac{M}{L} I_a$$

$$\Phi = LI = MI_a$$

Dark Matter Axion Detection – Large f_a/N :

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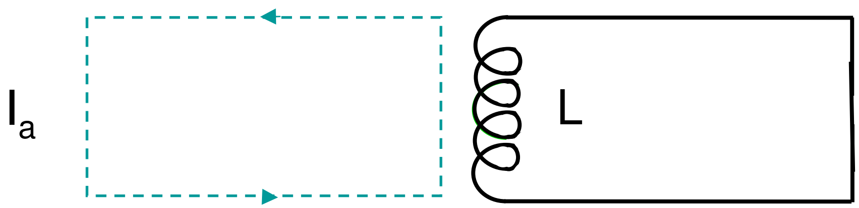

Axion induced Current
One Turn Arm

Inductor
N Turn Arm

Transformer

$$L\dot{I} = \mathcal{E} = M\dot{I}_a$$

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$$I = \frac{M}{L} I_a$$

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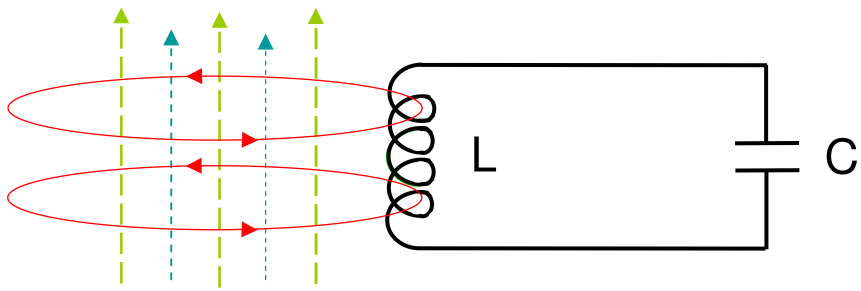
Dark Matter Axion Detection – Large f_a/N :

- Resonant LC Circuit



$\omega_0^2 = 1 / LC$

$\gamma = R/L = \omega_0/Q$

B   j(ω)   B(ω)

$$\left(-\omega^2 L - i\omega R + \frac{1}{C}\right) q = \mathcal{E}$$

$$I = \frac{i\omega \mathcal{E}/L}{\omega_0^2 - \omega^2 - i\gamma\omega}$$

On Resonance $\quad U = \frac{1}{2} L |I|^2 = \frac{1}{2} Q^2 \frac{M^2}{L} |I_a|^2$

Dark Matter Axion Detection – Large f_a/N :

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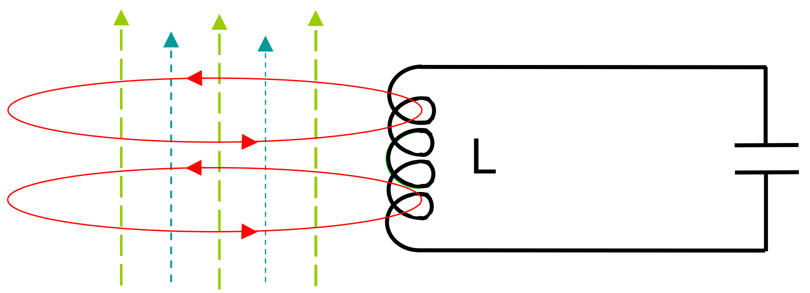

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Inductane :

- Number of Turns N

$$M \propto N$$

$$L \propto N^2$$

$$M^2 / L \propto N^0$$

Inductane :


- Number of Turns N

$M \propto N$

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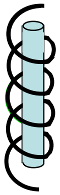
$M^2 / L \propto N^0$

- Permeability

$M^2 / L \sim \mu\, h$

$\mu = \mu_r\, \mu_0$

$\mu_r \sim 10^{4\text{-}5\text{-}6}$



Overcome Grain Cohesive Forces at
Low Temperature with $B=B(\omega')$

Large Permeability Resonant Transformer

Quality Factor:

- Core Losses

  Eddy Currents → Joule Heating   Lamination, Powder

  * Hysteresis

$$\frac{U_{\text{loss}}}{V} = \oint H\ dB \qquad B = \mu H \qquad Q \sim 10^{2\text{-}3}$$

- Radiation Resistance

  Capacitor – Electric Dipole Antenna

  Inductor – Magnetic Dipole Antenna

  Small Antennas Inefficient Radiators

- Resistive Losses

Axion Induced Current :

$$|I_a| = \int |\mathbf{j} \cdot d\mathbf{A}| \simeq \frac{3}{4}\xi \frac{\alpha}{2\pi\mu_0 c}\,\omega\theta_0\Phi$$

$$\Phi = \int \mathbf{B} \cdot d\mathbf{A}$$

Magnetic Flux :

	D (m)	h (m)	B (T)	Φ (Weber)
LLNL Axion	0.6	1	8	2
ANL 12 ft Bubble Chamber	4.8	3	1.8	30
CMS Solenoid	6.5	12	4	130

Maximum B ~ Limited

Compact Muon Solenoid:

$D = 6.5$ m

$h = 12$ m

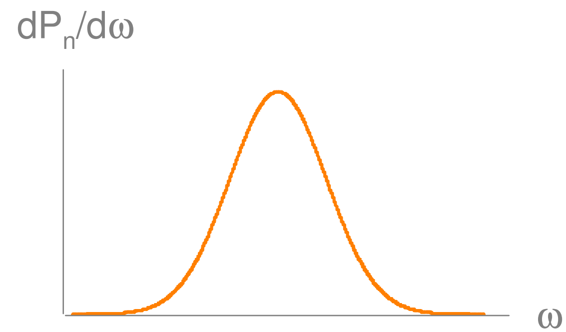
$B = 4$ T

Signal and Noise Temperature :

- Noise Power and Temperature

$$P_n = \frac{1}{2}|I_n|^2 R = \frac{U_n R}{L} = U_n \gamma = \frac{U_n \omega_0}{Q}$$

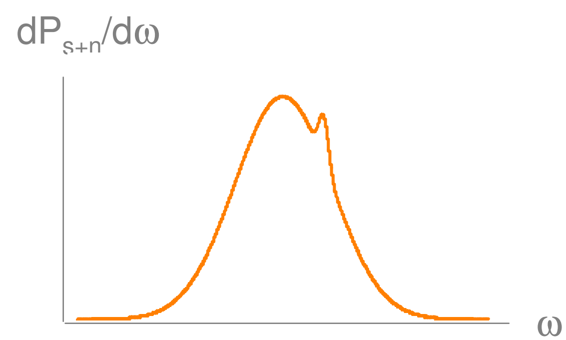
$$\left.\frac{dP_n}{d\omega}\right|_0 = \frac{2U_n}{\pi} \equiv \frac{2kT_n}{\pi}$$



- Signal Temperature

$$\frac{2kT_s}{\pi} \equiv \left.\frac{dP_s}{d\omega}\right|_0$$

$$kT_s = \frac{1}{2} Q Q_a \frac{M^2}{L} |I_a|^2 = \frac{Q_a}{Q} U_s$$



Scanning Time :

Noise Limited

- Time for Significance S in Signal Bandwidth $\Delta\omega = \omega / Q_a$

$$t \sim \mathcal{S}^2 \frac{T_n^2}{T_s^2} \frac{Q_a}{\omega}$$

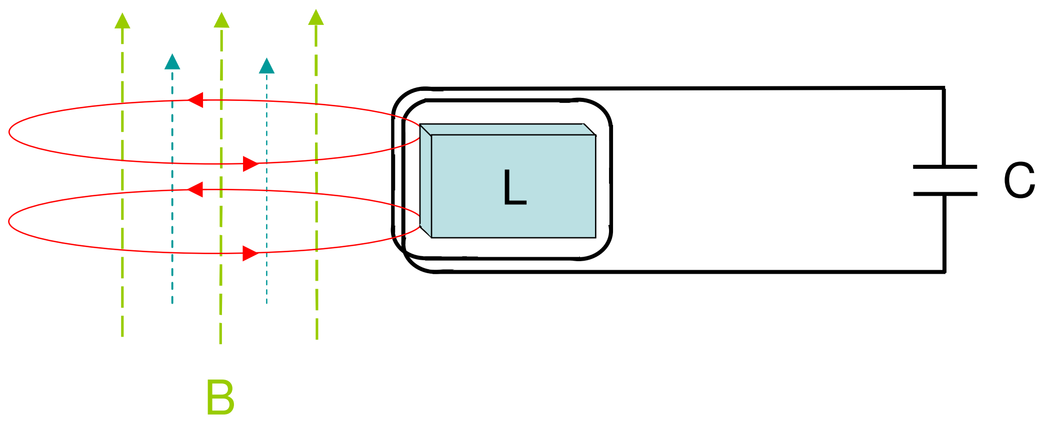
- Time to Scan an Octave $t_{oct} \sim Q\,t$

$$t_{\rm oct} \sim \mathcal{S}^2 \frac{T_n^2}{T_s^2} \frac{Q_a Q}{\omega} = \mathcal{S}^2 \left(\frac{L\ kT_n}{M^2 |I_a|^2} \right)^2 \frac{1}{Q_a Q \omega}$$

- For fixed S and Q_a

$$t_{\rm oct} \propto \frac{T_n^2\ f_a^5}{Q\ \mu_r^2\ h^2\ \Phi^4}$$

$$\frac{M^2}{L} \propto \mu_r h$$



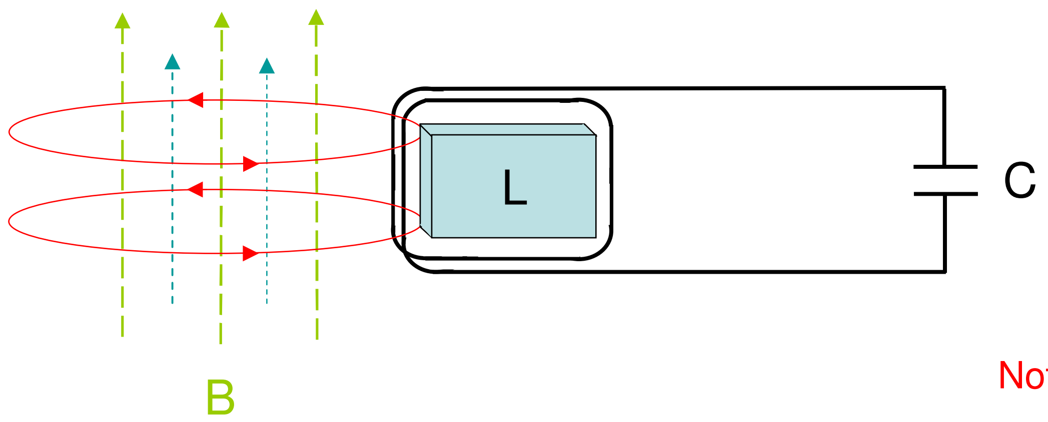
$L \sim 100\text{-}1000$ mH

$Q \sim 10^2$ $C \sim 10\text{-}100$ pF

$T_n \sim 2$ K $R \sim 1\text{-}10$ kΩ

- For $t_{oct} \sim 1$ yr with $S \sim 5$ DFSZ

	Φ	h	μ_r	f_a/N	ν	T_S	T_Q
ANL	30 Weber	3 m	3×10^4	10^{15} GeV	1.5 MHz	7 mK	350 μ K
CMS	130 Weber	12 m	10^5	10^{16} GeV	150 kHz	18 mK	35 μ K



Note Strong Dependence

$$t_{\rm oct} \propto \frac{T_n^2 f_a^5}{Q \mu_r^2 h^2 \Phi^4}$$

$L \sim$ 100-1000 mH

$Q \sim 10^2$ $C \sim$ 10-100 pF

$T_n \sim$ 2 K $R \sim$ 1-10 kΩ

Sizeable Permeability μ_r
and
Large Flux Φ Required

- For $t_{oct} \sim$ 1 yr with $S \sim 5$ DFSZ

	Φ	h	μ_r	f_a/N	ν	T_S	T_Q
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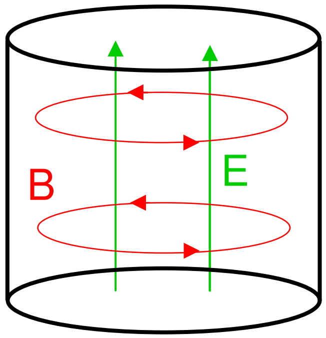
Resonant Cavity :

- Cylindrical TM_{010}



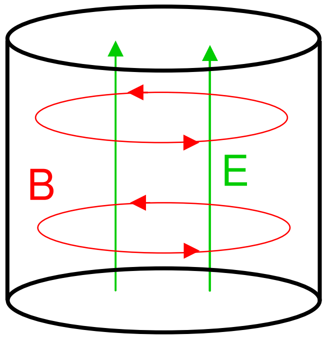
$$C \sim \frac{\epsilon_0 A}{h}$$

$$L \sim \frac{M^2}{L} \sim \frac{\mu_0 h}{2\pi}$$

$$\omega_0 \sim \frac{4c}{D}$$

Resonant Cavity :

- Cylindrical TM_{010}

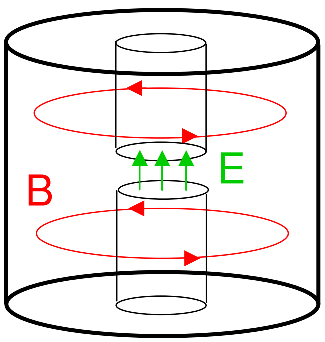


$$C \sim \frac{\epsilon_0 A}{h}$$

$$L \sim \frac{M^2}{L} \sim \frac{\mu_0 h}{2\pi}$$

$$\omega_0 \sim \frac{4c}{D}$$

- Lower ω_0 with Geometry + Permittivity



$$C \sim \frac{\epsilon A'}{h'}$$

$$L \sim \frac{M^2}{L} \sim \frac{\mu_0 h}{2\pi}$$

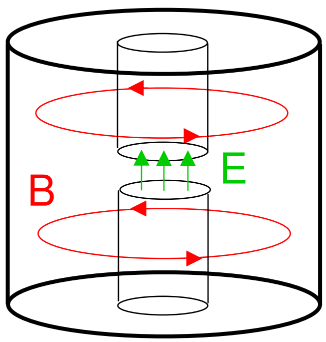
$$\omega_0 \sim \frac{4c}{D'}\sqrt{\frac{h'}{\epsilon_r h}}$$

Adiabatic limit - E and B modes small overlap

Resonant Cavity :

- Lower ω_0 with Geometry + Permittivity +

  Increase M^2/L with Permeability



$$C \sim \frac{\epsilon_0 A'}{h'}$$

$$L \sim \frac{M^2}{L} \sim \frac{\mu h}{2\pi}$$

$$\omega_0 \sim \frac{4c}{D'}\sqrt{\frac{h'}{\mu_r \epsilon_r h}}$$

Identical to LC Circuit with one turn
Toroidal Inductor

- Detector: SQUID Internal Antenna Coupled to B

  $Q^{-1} = Q_0^{-1} + Q_D^{-1}$ Match Q_0 and Q_D

Conclusion :

Axion Dark Matter Detection $f_a/N \sim 10^{13} - 10^{15\text{-}16}$ GeV

(Low f_a/N Covered Rapidly)

LC Resonant Circuit

||

Modified Resonant Cavity

- Large Flux Magnet *
- Modified LC Resonant Cavity *
- Large Permeability Core *

  (Cool Large Mass)