Axions and Wave Like Dark Matter

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Michael Tobar

THE UNIVERSITY OF WESTERN AUSTRALIA

SEEK WISDOM

QDM

Searching for Putative Wave-Like Dark Matter

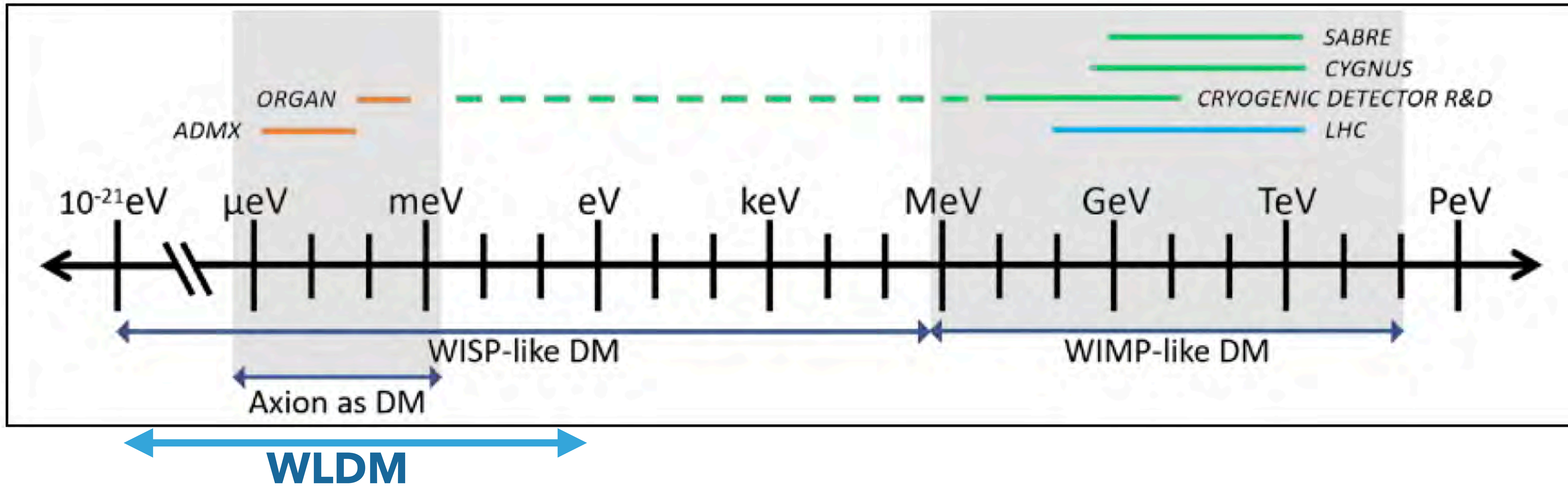

Figure 4: Dark matter mass ranges to be searched in Centre WIMP and WISP direct detection experiments and the LHC Program.

SNOWMASS

Cosmic Frontier:
Wave-Like Dark Matter

Joerg Jaeckel
University of Heidelberg

Gray Rybka
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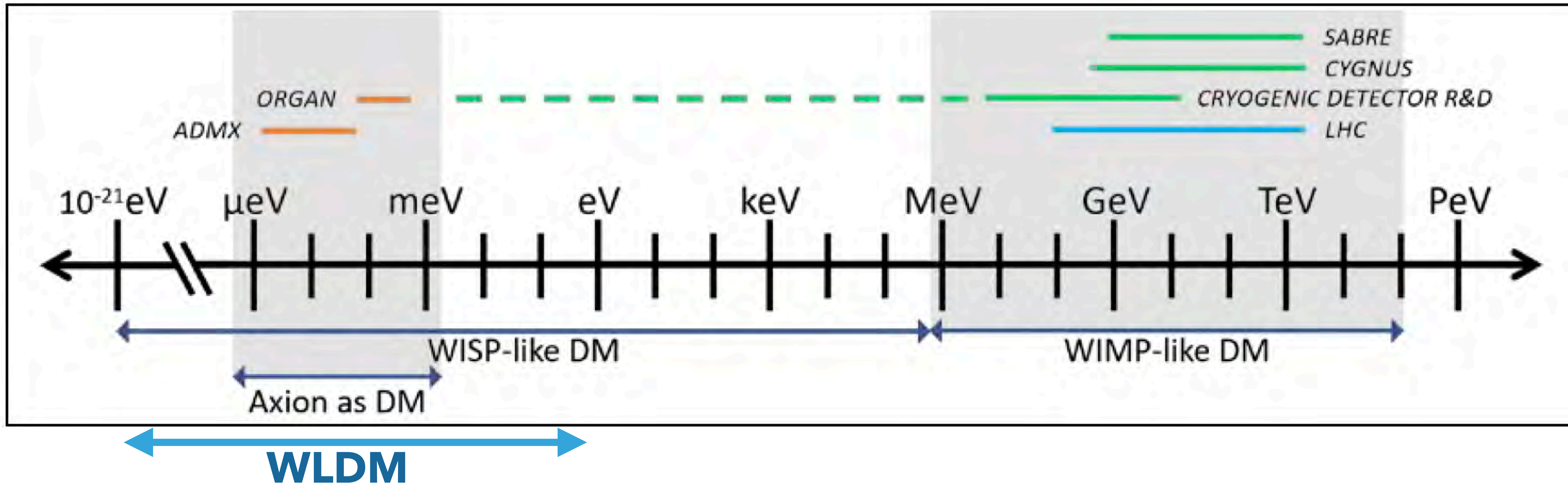

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WLDM: GENERIC EXPERIMENT

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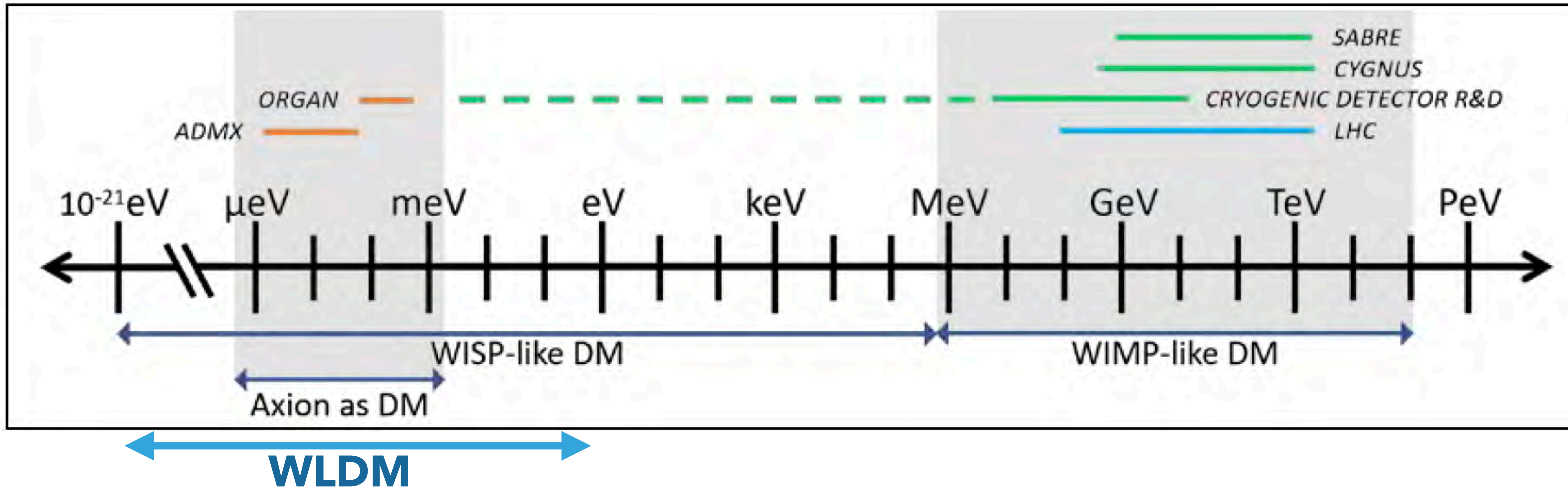

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Design Physics Package:

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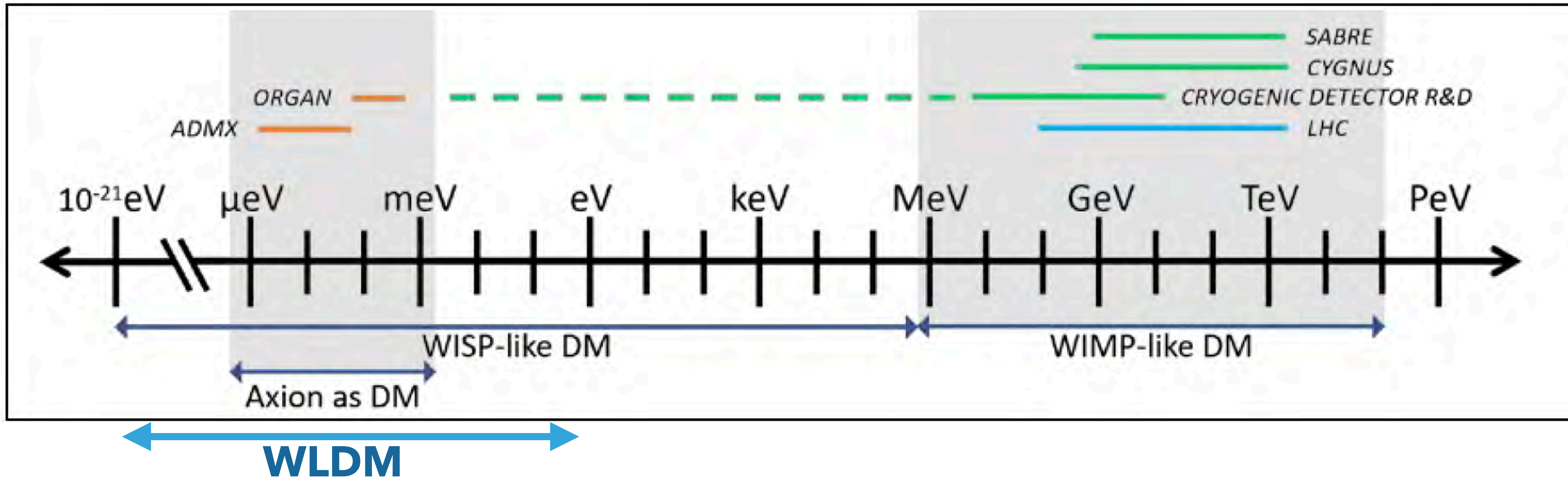

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Design Physics Package:

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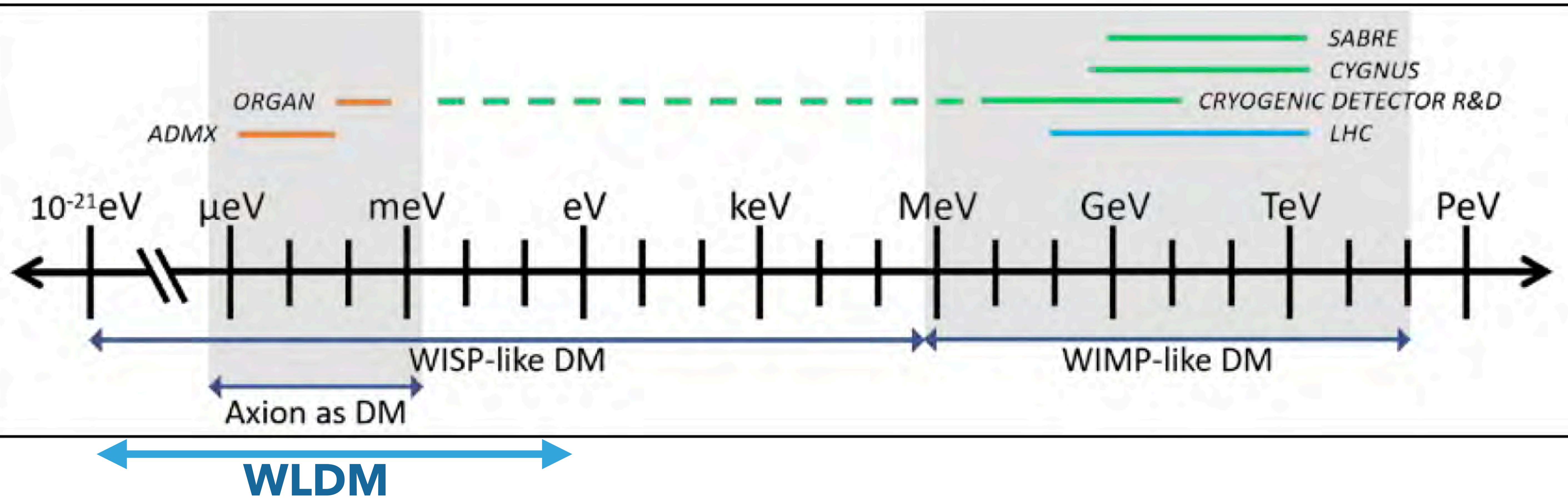

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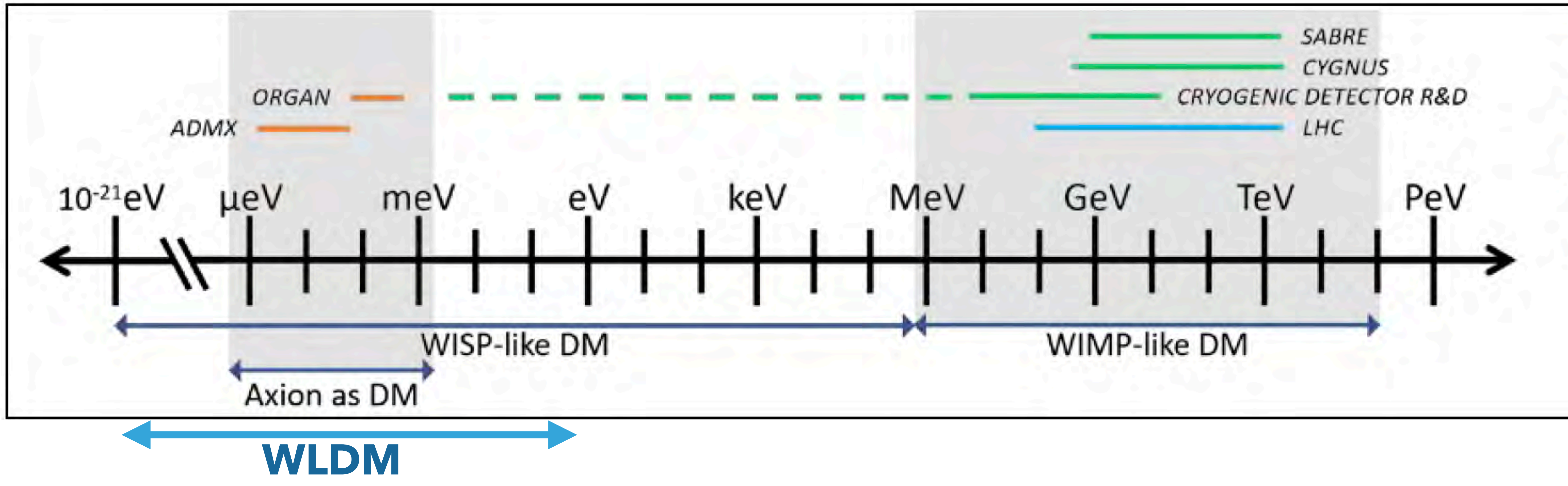

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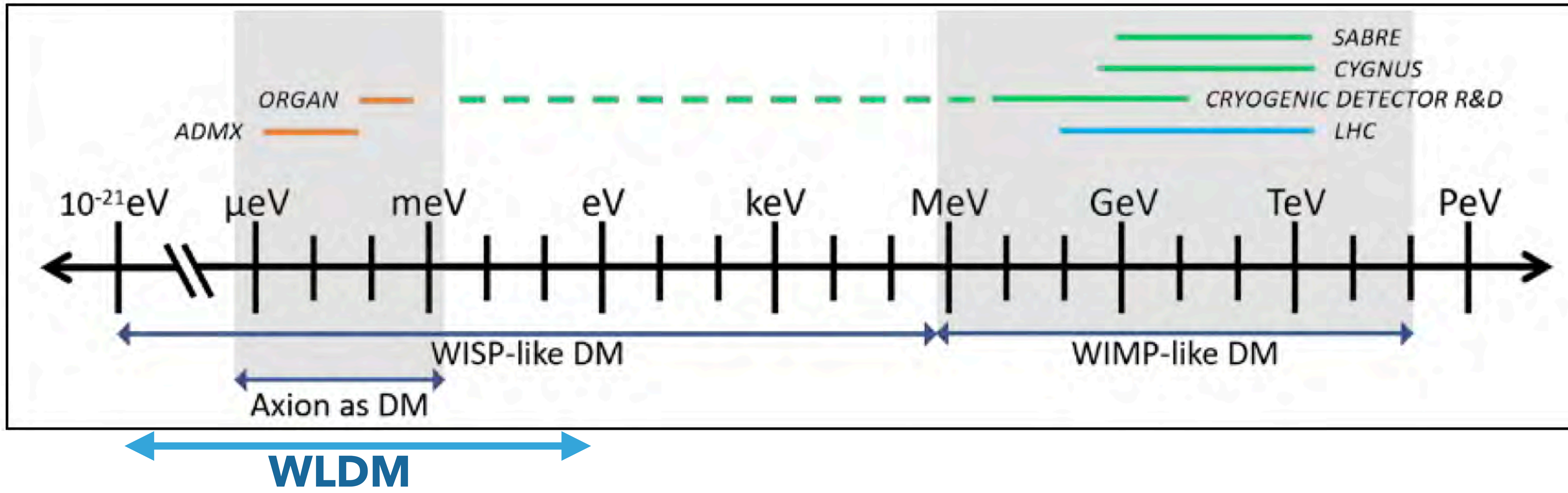

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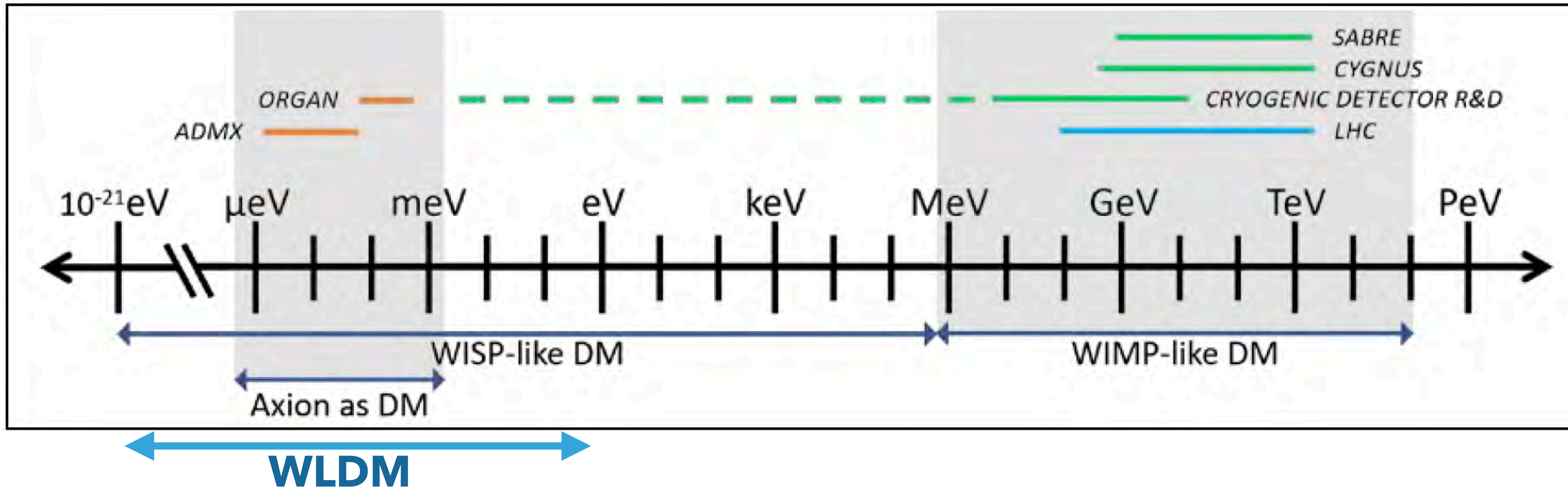

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-> Surpass Quantum Limit: Quantum Metrology

STATUS AND PLANS

CURRENT AXION DM PROGRAMS

ORGAN

UPLOAD

ADMX Collaboration

STATUS AND PLANS

CURRENT AXION DM PROGRAMS	NEW AXION DM PROGRAMS
ORGAN	TWISTED ANYON
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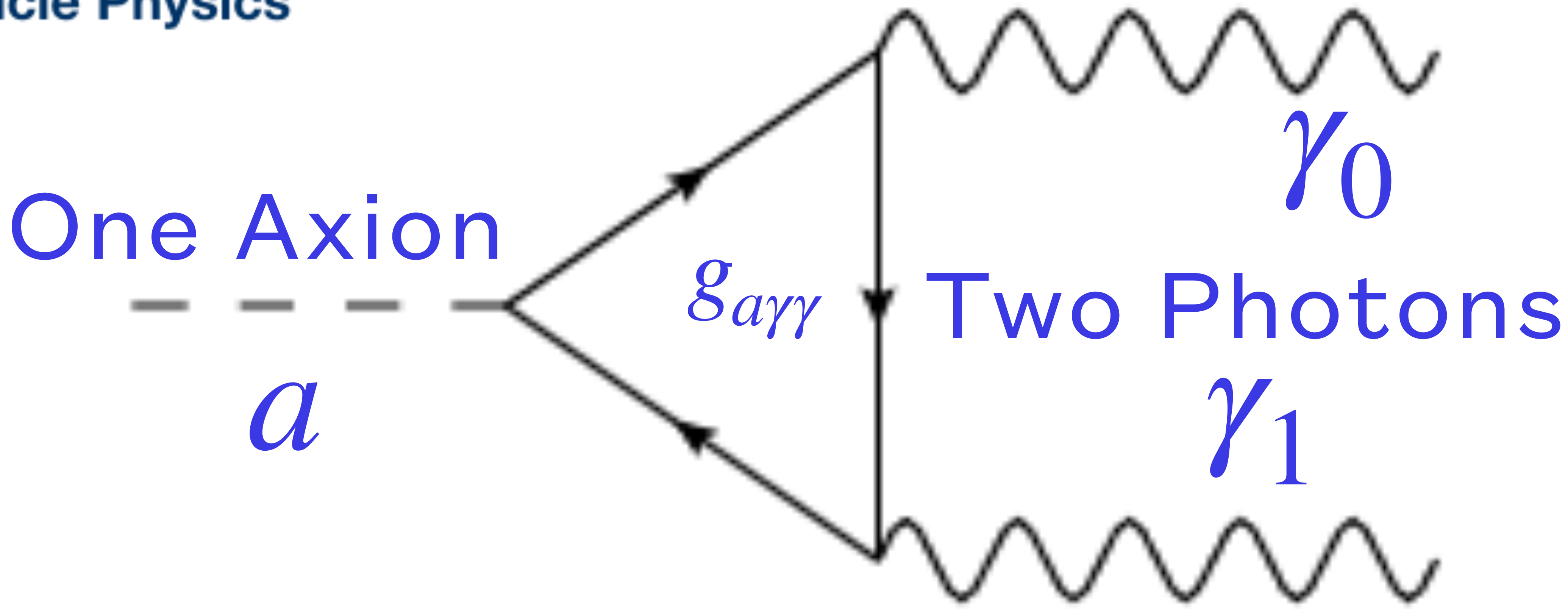

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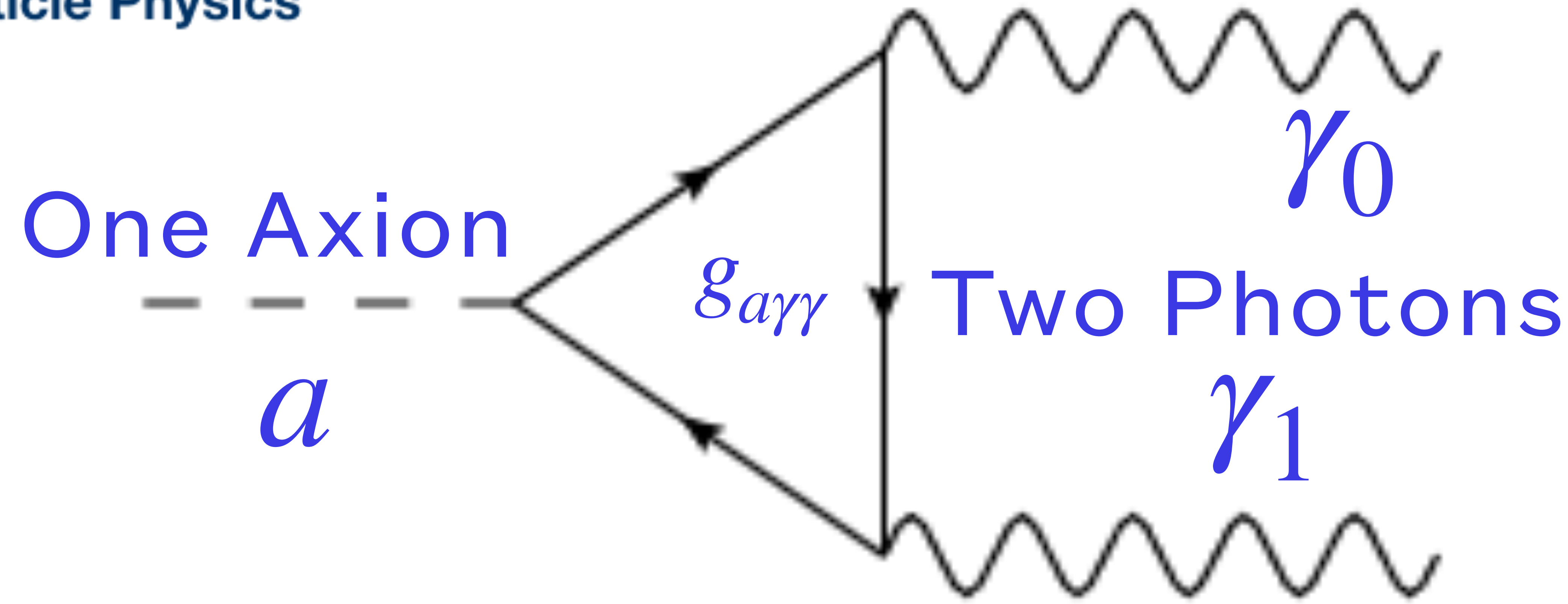

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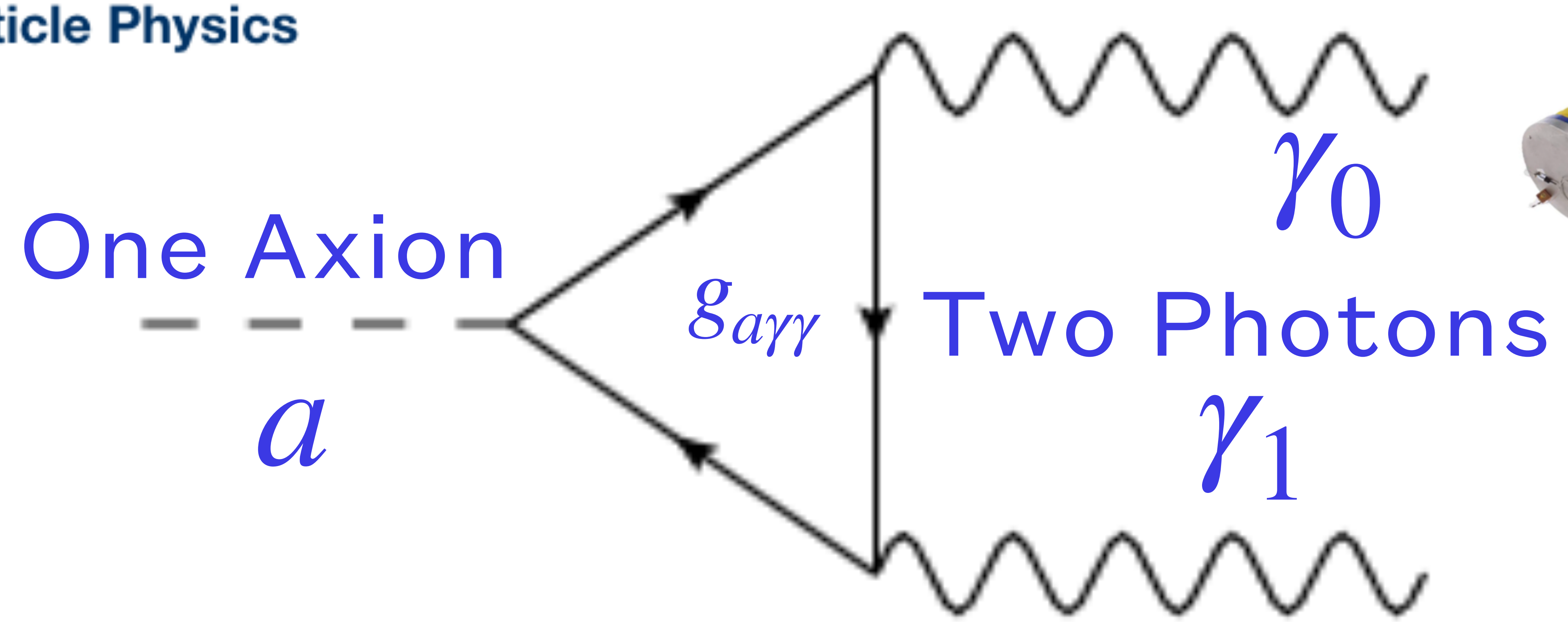

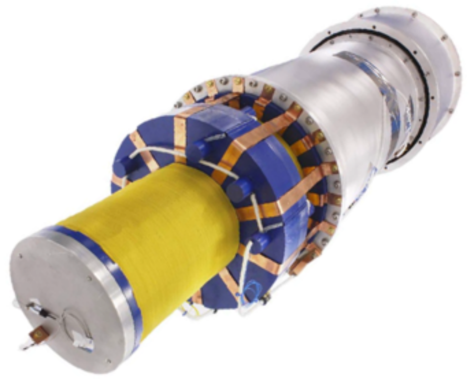

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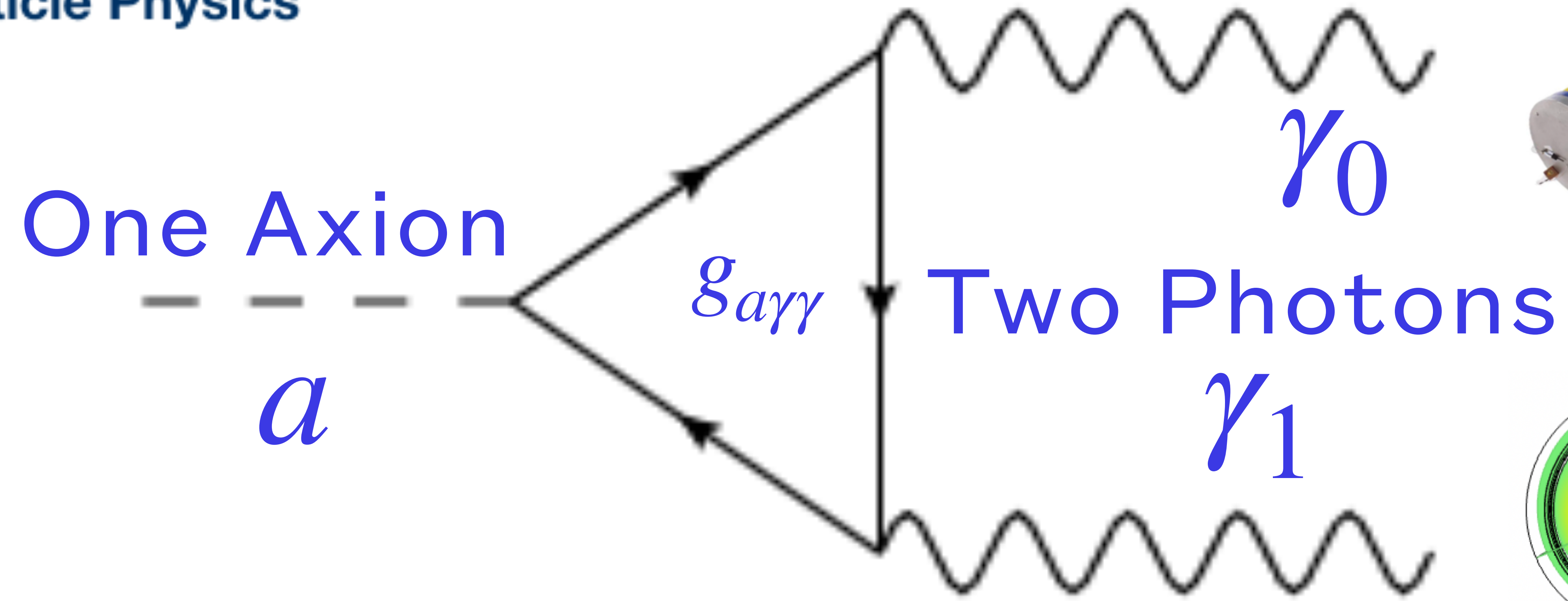
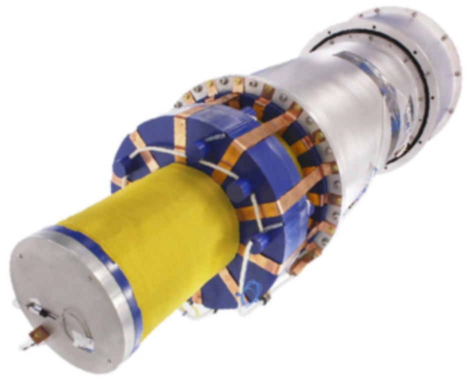
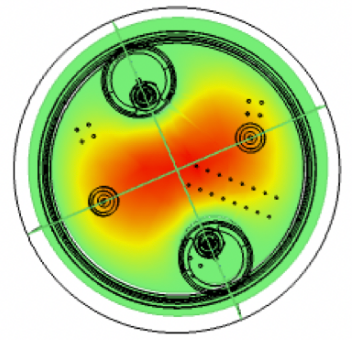
Frank Wilczek

axion-photon coupling $g_{a\gamma\gamma}$ -> chiral anomaly

2020 J. J. Sakurai Prize for Theoretical Particle Physics



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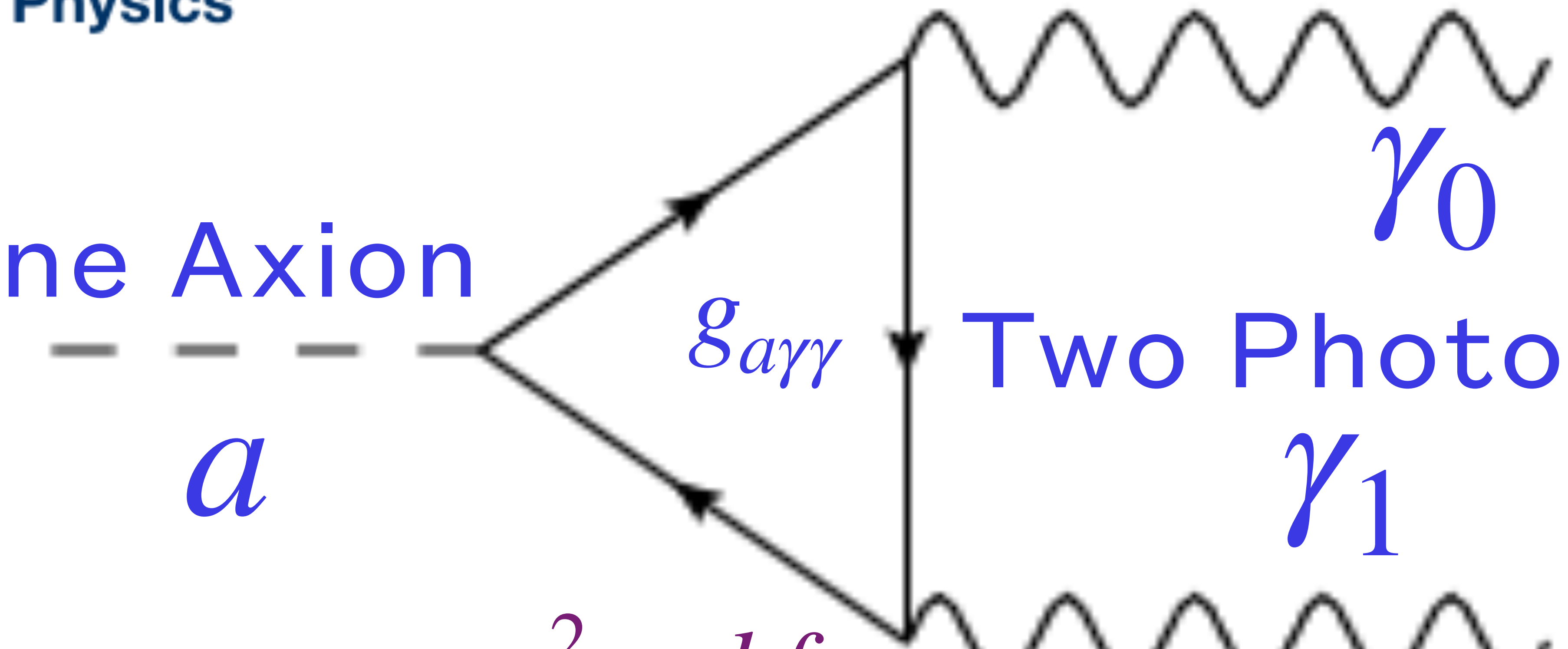
One Axion

a



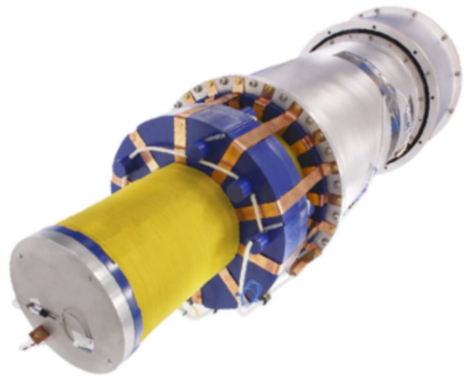
$g_{a\gamma\gamma}$

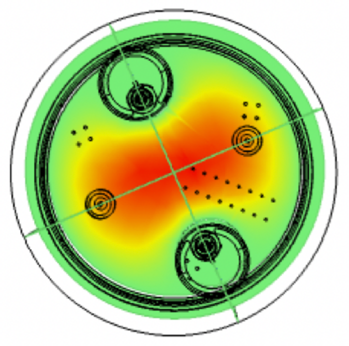
γ_0

Two Photons

γ_1

$m_a c^2 = hf_1$





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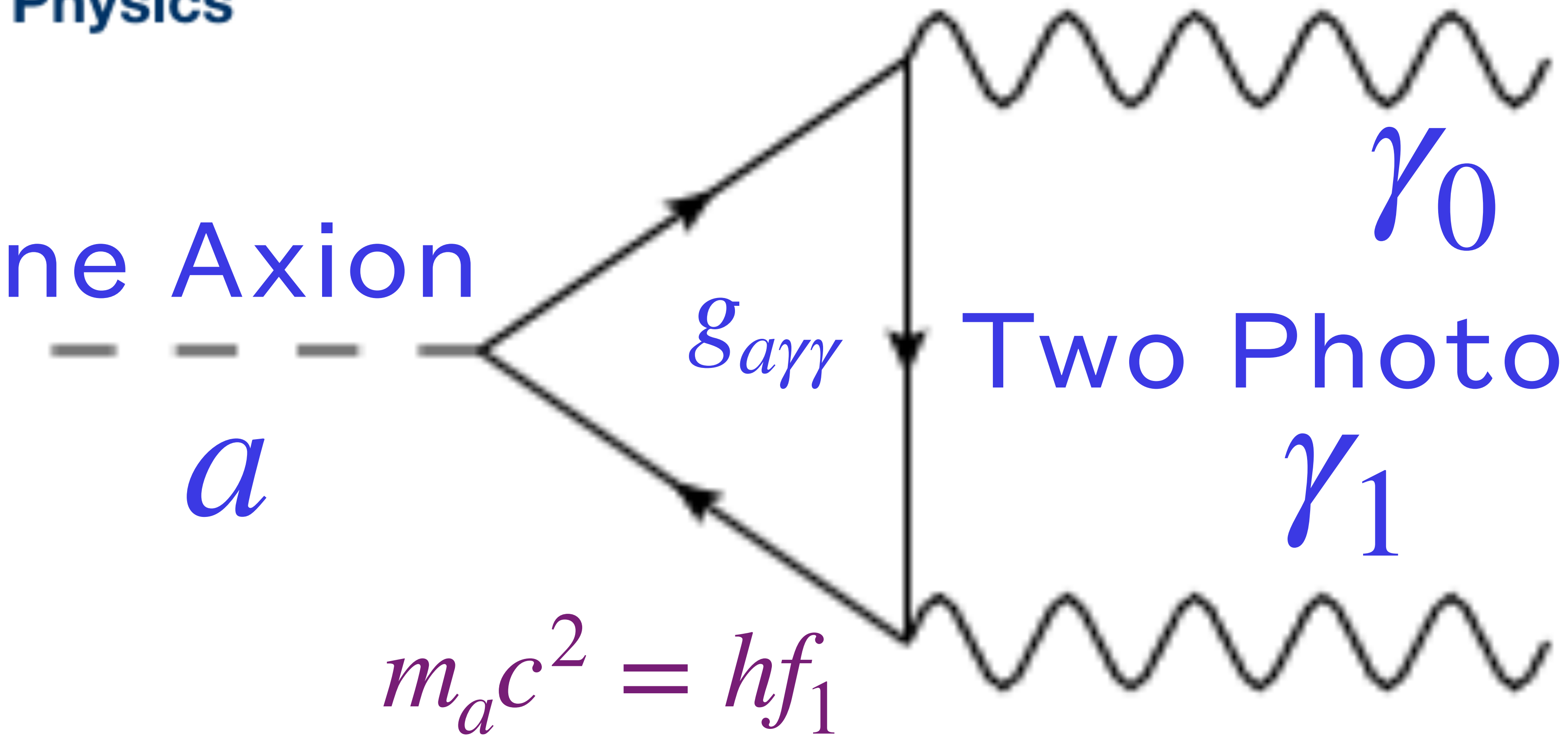

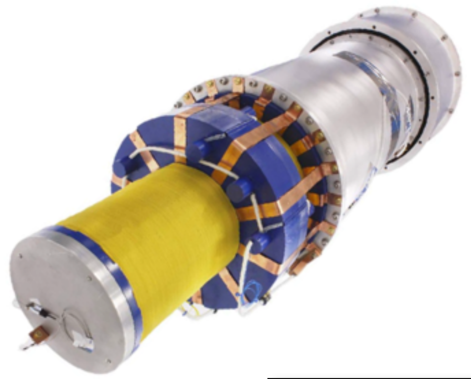

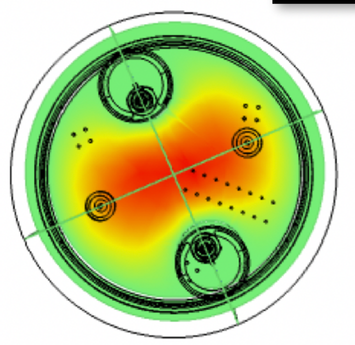

Measure

$$\mathcal{H}_{int} = \epsilon_0 c g_{a\gamma\gamma} a \mathbf{E}_1 \cdot \mathbf{B}_0$$

Photon Haloscopes

Modified Axion Electrodynamics

(Represents two photons)

Axion Equation of Motion:

Klein–Gordon equation for massive spin 0 particle

$$a(t) = \frac{1}{2}\left(\tilde{a}e^{-j\omega_a t} + \tilde{a}^* e^{j\omega_a t}\right)$$
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$$\nabla \cdot \vec{E} = \frac{\rho_e}{\varepsilon_0} + c g_{a\gamma\gamma}\vec{B} \,.\, \nabla a$$

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Source Terms Generate Photons-> From Background Fields Mixing with Axion

Photonic Haloscope Equations in terms of Auxiliary Fields

Measure Created Photon

$$\nabla \cdot \left(\vec{E}_1(\vec{r},t) - g_{a\gamma\gamma} a(t) c \vec{B}_0(\vec{r},t) \right) = \frac{\rho_{e_1}}{\epsilon_0}$$

$$\nabla \times \left(\vec{B}_1(\vec{r},t) + \frac{g_{a\gamma\gamma} a(t)}{c} \vec{E}_0(\vec{r},t) \right)$$

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$$\nabla \cdot \vec{B}_1(\vec{r},t) = 0$$

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Applied Background Field

$$\nabla \times \vec{B}_0 = \mu_0 \epsilon_0 \partial_t \vec{E}_0 + \mu_0 \vec{J}_{e_0}$$

$$\nabla \times \vec{E}_0 = -\partial_t \vec{B}_0$$

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Measure Created Photon

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→

$$\nabla \cdot \vec{D}_1 = \rho_{e_1}$$

$$\nabla \times \vec{H}_1 - \partial_t \vec{D}_1 = \vec{J}_{e_1}$$

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$$\nabla \cdot \vec{D}_1 = \rho_{e_1}$$

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Photonic Haloscope Equations in terms of Auxiliary Fields

Measure Created Photon

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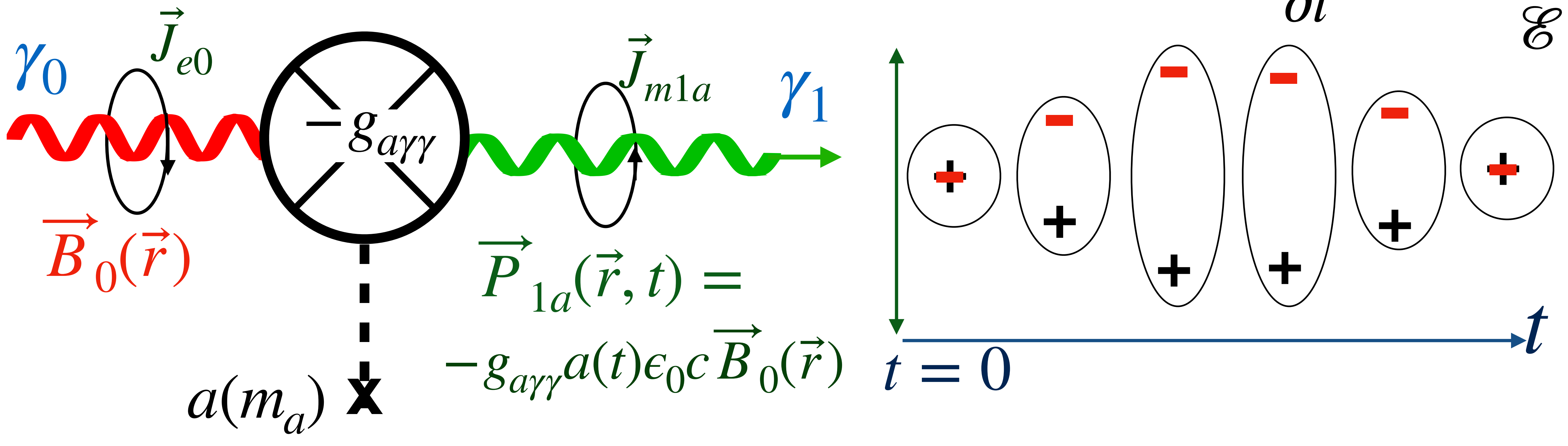
$$\vec{J}_{ab}(\vec{r},t) = \frac{\partial\vec{P}_{a1}(\vec{r},t)}{\partial t}$$

$$\mathscr{E} = \oint_P \vec{P}_{a1} \cdot d\vec{l}$$



Physics of the Dark Universe 26 (2019) 100339

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Physics of the Dark Universe

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Modified axion electrodynamics as impressed electromagnetic sources through oscillating background polarization and magnetization

Michael E. Tobar *, Ben T. McAllister, Maxim Goryachev

ARC Centre of Excellence For Engineered Quantum Systems, Department of Physics, School of Physics, Mathematics and Computing, University of Western Australia, 35 Stirling Highway, Crawley WA 6009, Australia

Physics of the Dark Universe 30 (2020) 100624

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Broadband electrical action sensing techniques with conducting wires for low-mass dark matter axion detection

Michael E. Tobar *, Ben T. McAllister, Maxim Goryachev

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PHYSICAL REVIEW D **108,** 076021 (2023)

Few thoughts on θ and the electric dipole moments

Ariel Zhitnitsky *

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PHYSICAL REVIEW RESEARCH **3**, 023011 (2021)

Electric polarization as a nonquantized topological response and boundary Luttinger theorem

Xue-Yang Song,[1,2] Yin-Chen He,[2] Ashvin Vishwanath,[1] and Chong Wang[2]

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*

[2]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*

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Emergent electric field from magnetic resonances in a one-dimensional chiral magnet

Kotaro Shimizu,[1] Shun Okumura,[1] Yasuyuki Kato,[1] and Yukitoshi Motome[1]

[1]*Department of Applied Physics, The University of Tokyo, Tokyo 113-8656, Japan*

(Dated: July 18, 2023)

The emergent electric field (EEF) is a fictitious electric field acting on conduction electrons through the Berry phase mechanism.

DC Magnetic Haloscopes

- Axions convert into photons in presence of strong magnetic field: Mass is unknown

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- So: narrowband photon signal of an unknown frequency is generated (need to scan frequency)

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$$\lambda_a = \frac{h}{m_a c}$$

$\longleftrightarrow$ m_a

$$\omega_a \approx \frac{m_a c^2}{\hbar}$$

$$m_a[eV] \equiv \frac{m_a[kg]c^2}{q_e}$$

$$1eV = 1.8 \times 10^{-36}[kg]$$

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$$\lambda_a \sim d_{exp} \sim 1cm \rightarrow 1m \qquad \frac{\omega_a}{2\pi} \sim 300\ MHz \rightarrow 30\ GHz \qquad m_a \sim 1\ \mu eV \rightarrow 100\ \mu eV$$

DC Magnetic Haloscopes

Type Depends on Axion Compton Wavelength $\lambda_a = \frac{h}{cm_a}$

$300\ MHz$ — $30\ GHz$ — $\frac{\omega_a}{2\pi}\ Hz$

$\lambda_a > d_{exp}$ — 1.25×10^{-6} — $\lambda_a \sim d_{exp}$ — 1.25×10^{-4} — $\lambda_a < d_{exp}$ — $m_a\ eV$

DC Magnetic Haloscopes

Type Depends on Axion Compton Wavelength $\lambda_a = \frac{h}{cm_a}$

Low Mass: Lumped Element Reactive

	$300\ MHz$		$30\ GHz$		$\frac{\omega_a}{2\pi}\ Hz$
$\lambda_a > d_{exp}$	1.25×10^{-6}	$\lambda_a \sim d_{exp}$	1.25×10^{-4}	$\lambda_a < d_{exp}$	$m_a\ eV$

ADMX SLIC

RE-ENTRANT CAVITY

ABRACADABRA

SHAFT

DM RADIO

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$300\ MHz$ $30\ GHz$ $\frac{\omega_a}{2\pi}\ Hz$

$\lambda_a > d_{exp}$ 1.25×10^{-6} $\lambda_a \sim d_{exp}$ 1.25×10^{-4} $\lambda_a < d_{exp}$ $m_a\ eV$

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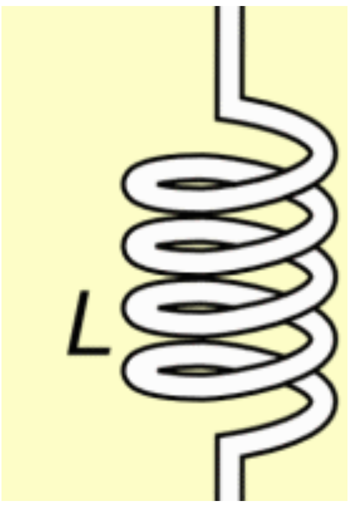

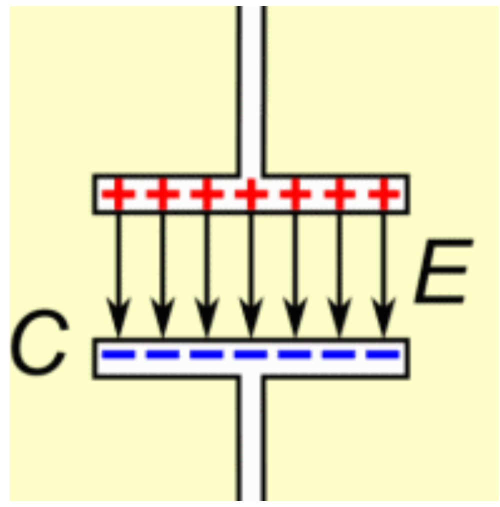

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Low Mass: Lumped Element
Reactive

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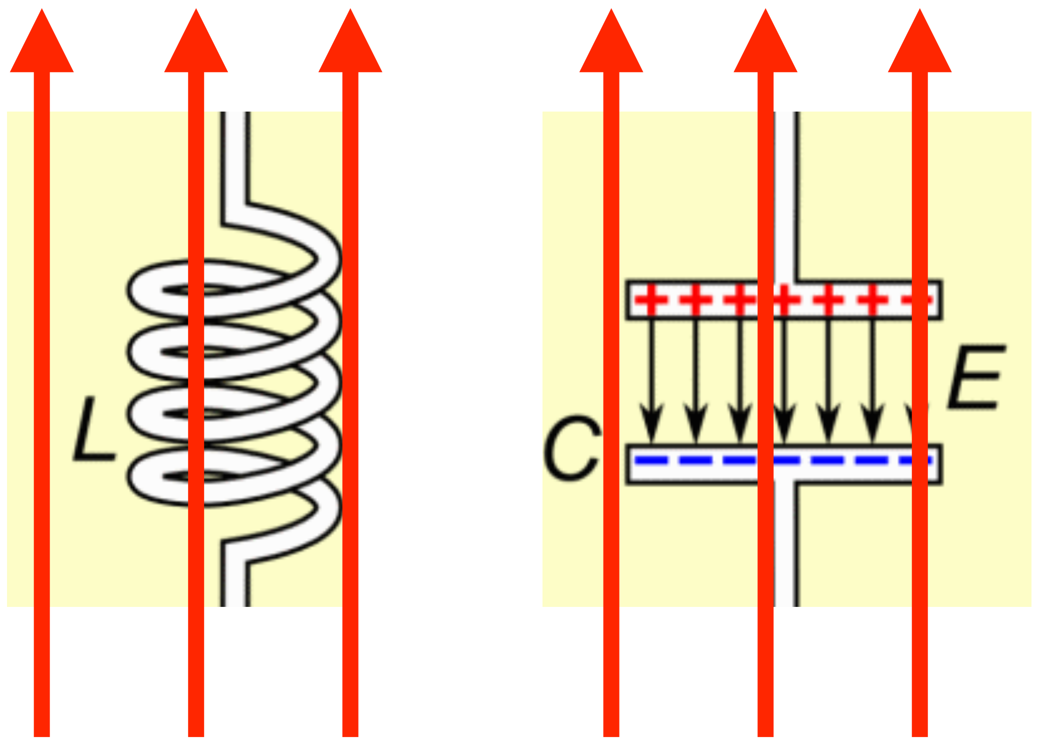

$\vec{B} = B_{DC}\hat{z}$

DC Magnetic Haloscopes

Type Depends on Axion Compton Wavelength $\lambda_a = \frac{h}{cm_a}$

Low Mass: Lumped Element
Reactive

Middle Mass: Resonant Cavity
Reactive and Dissipative

$300\ MHz$ | $30\ GHz$ | $\frac{\omega_a}{2\pi}\ Hz$

$\lambda_a > d_{exp}$ | 1.25×10^{-6} | $\lambda_a \sim d_{exp}$ | 1.25×10^{-4} | $\lambda_a < d_{exp}$ | $m_a\ eV$

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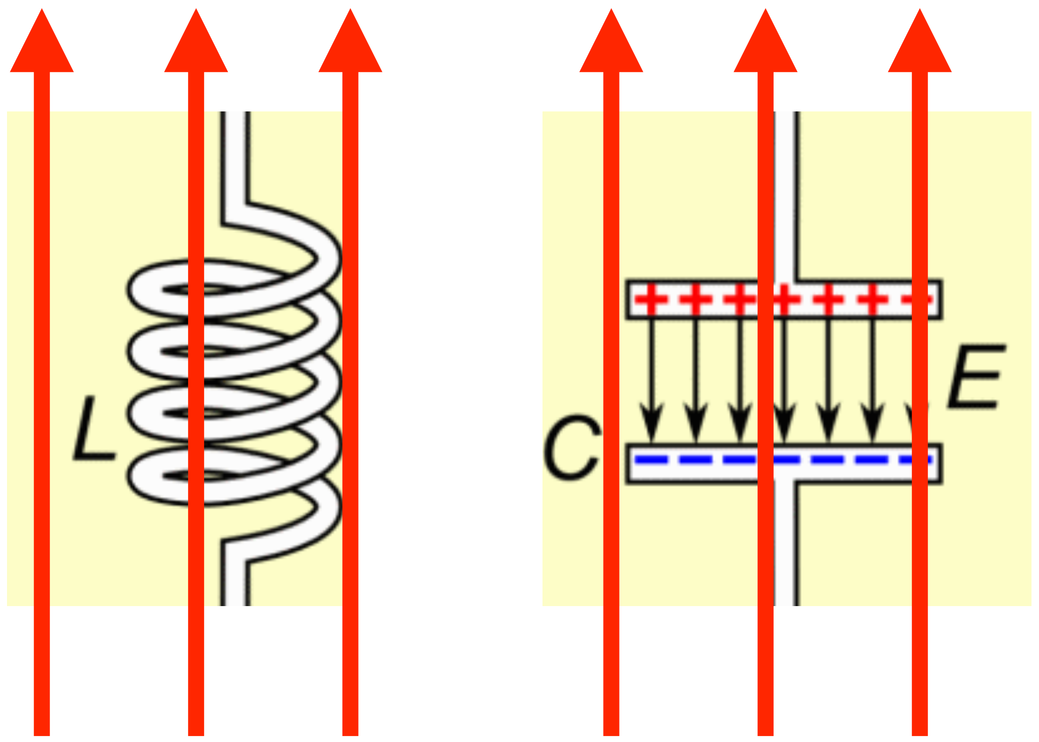

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DC Magnetic Haloscopes

Type Depends on Axion Compton Wavelength $\lambda_a = \frac{h}{cm_a}$

Middle Mass: Resonant Cavity
Reactive and Dissipative

Low Mass: Lumped Element
Reactive

$300\ MHz$ | $30\ GHz$ | $\frac{\omega_a}{2\pi}\ Hz$

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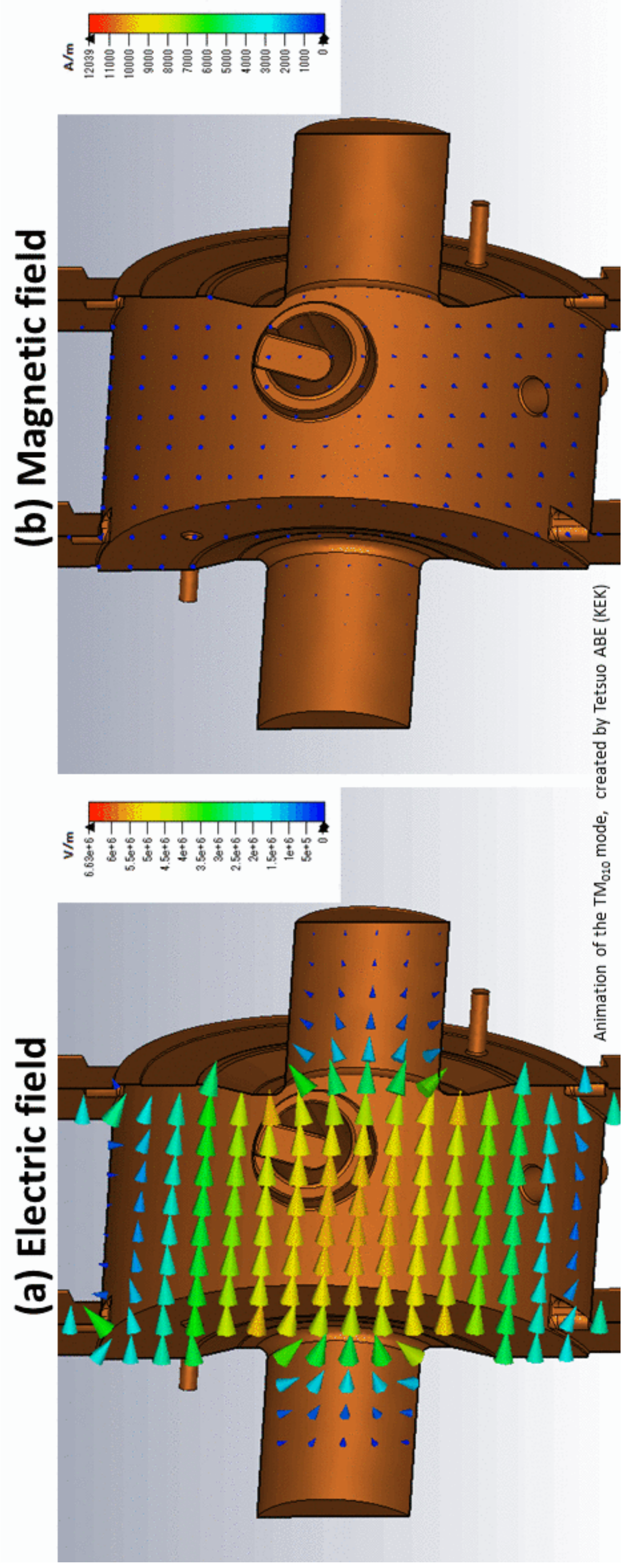

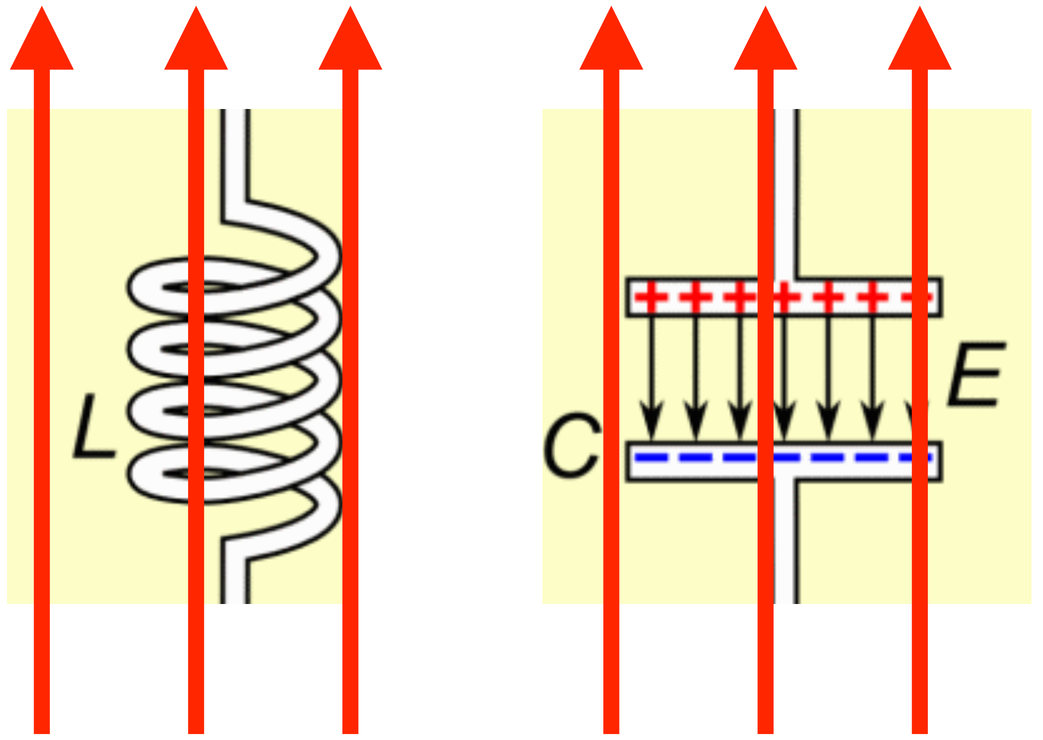

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DC Magnetic Haloscopes

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Low Mass: Lumped Element
Reactive

300 MHz

Middle Mass: Resonant Cavity
Reactive and Dissipative

30 GHz

$\frac{\omega_a}{2\pi}$ Hz

$\lambda_a > d_{exp}$ 1.25×10^{-6} $\lambda_a \sim d_{exp}$ 1.25×10^{-4} $\lambda_a < d_{exp}$ m_a eV

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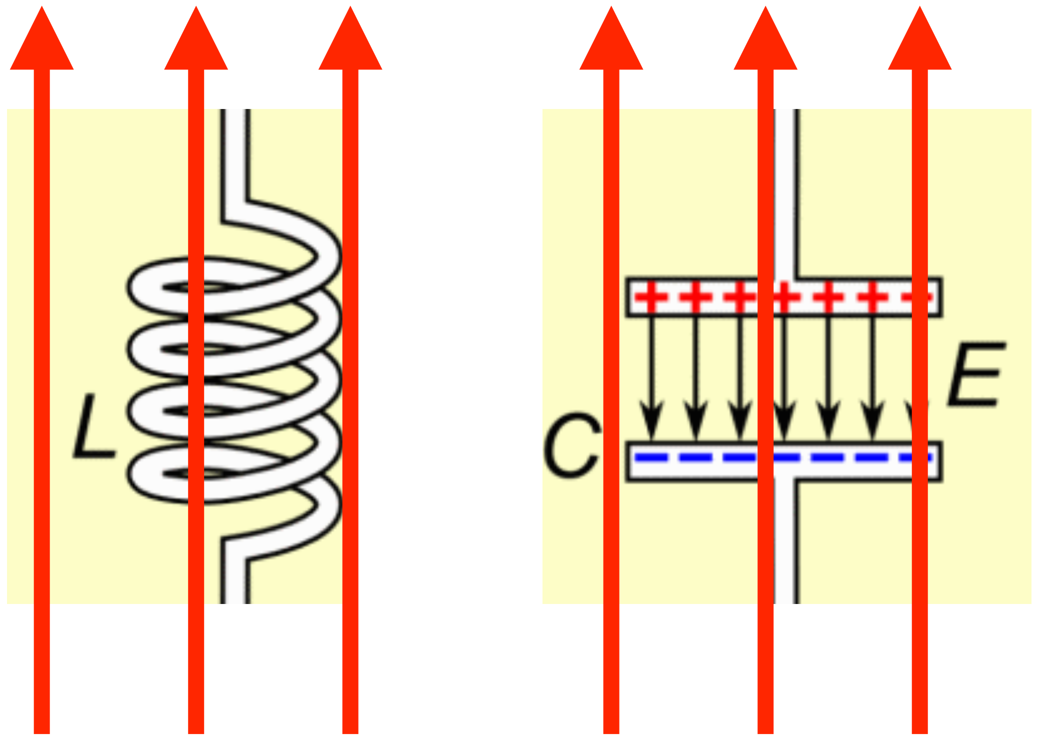

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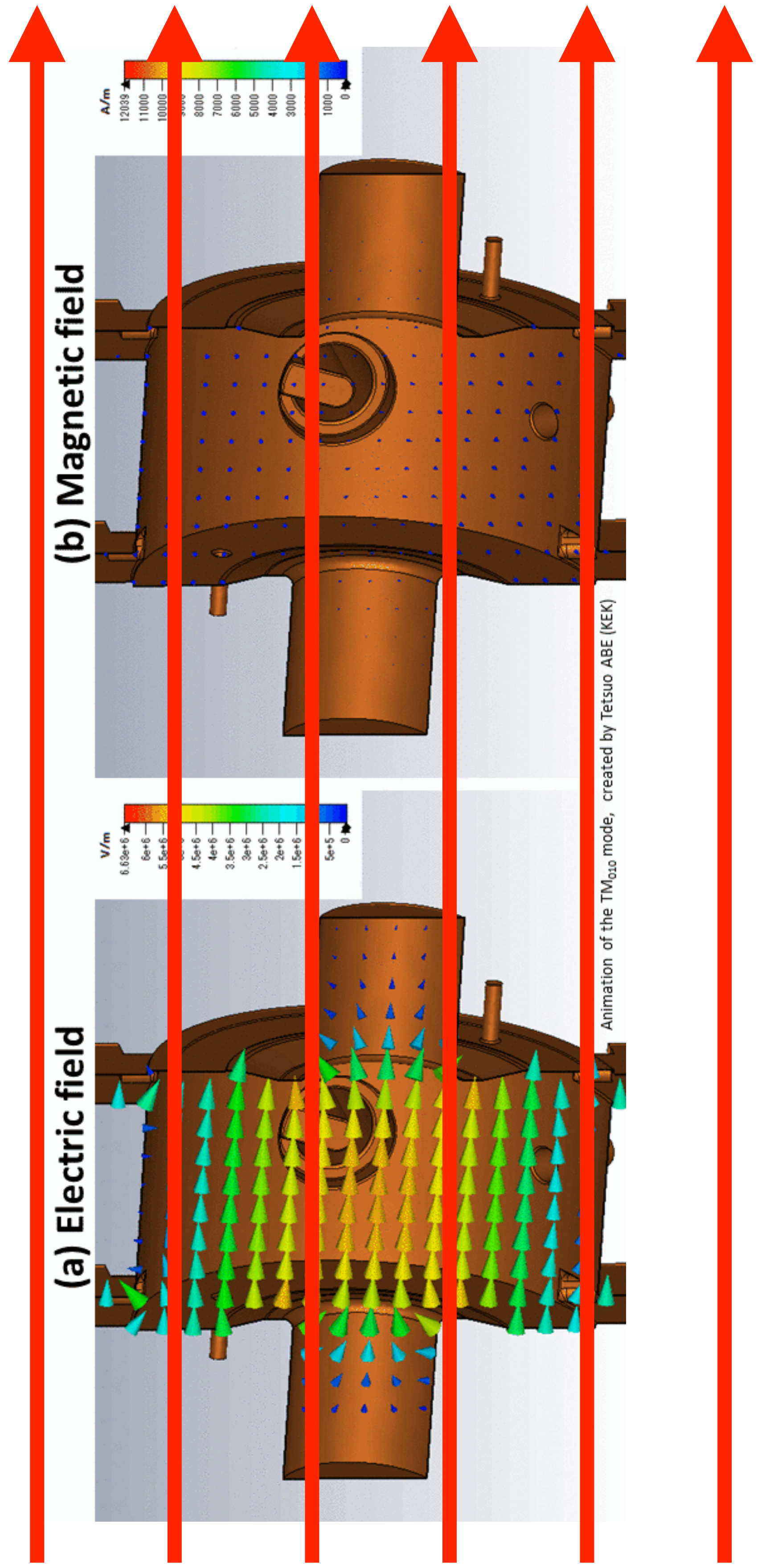

DC Magnetic Haloscopes

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Low Mass: Lumped Element
Reactive

$300\ MHz$ — 1.25×10^{-6}

Middle Mass: Resonant Cavity
Reactive and Dissipative

$30\ GHz$ — 1.25×10^{-4}

High Mass: Propagating

$\frac{\omega_a}{2\pi}\ Hz$

$m_a\ eV$

$\lambda_a > d_{exp}$

$\lambda_a \sim d_{exp}$

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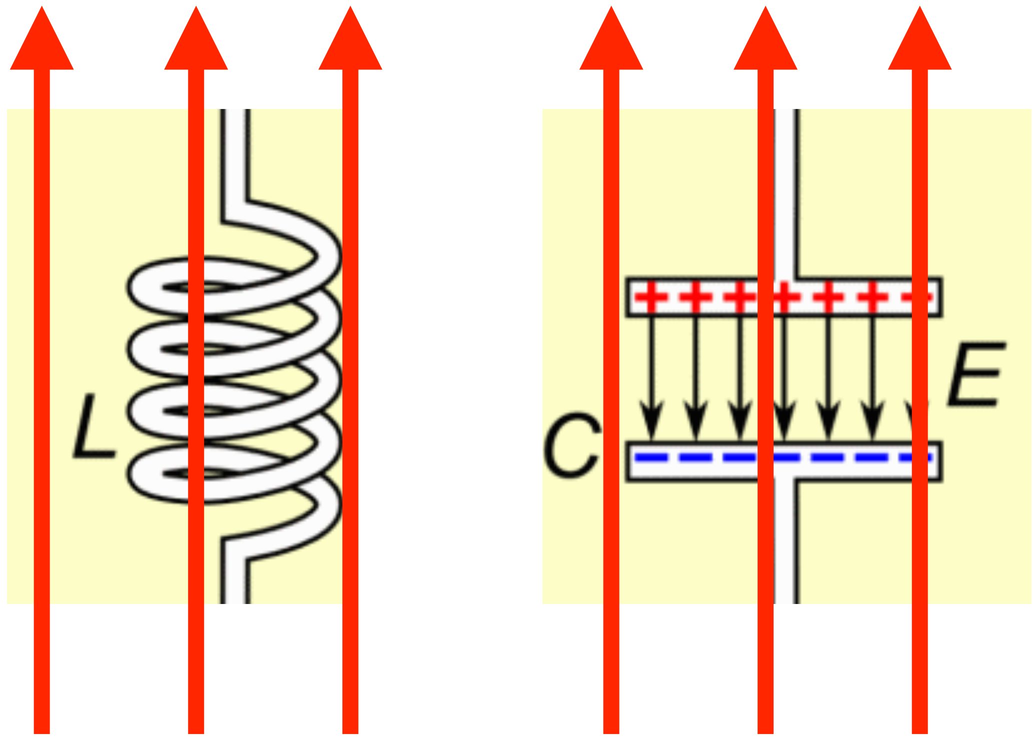

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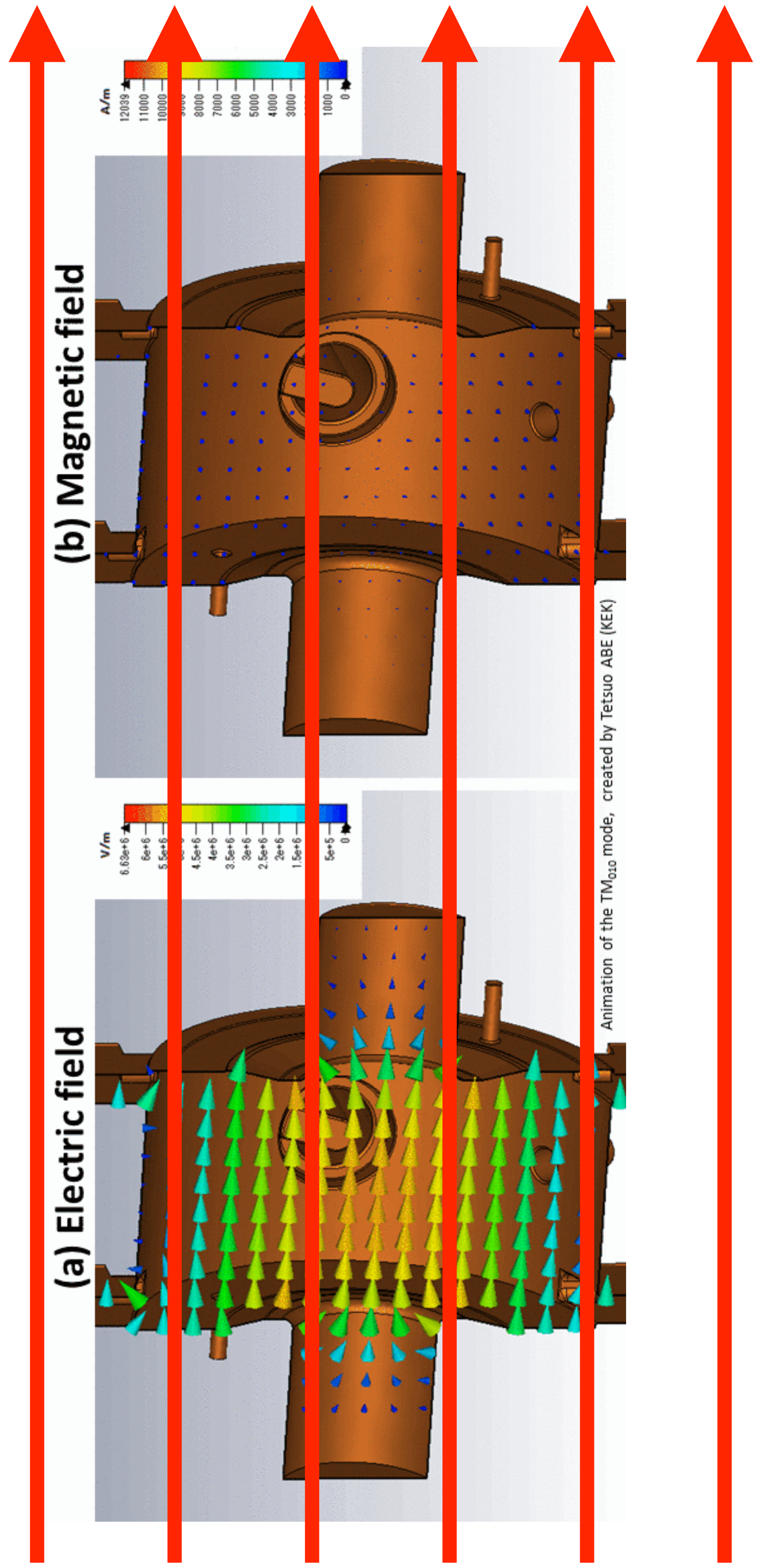

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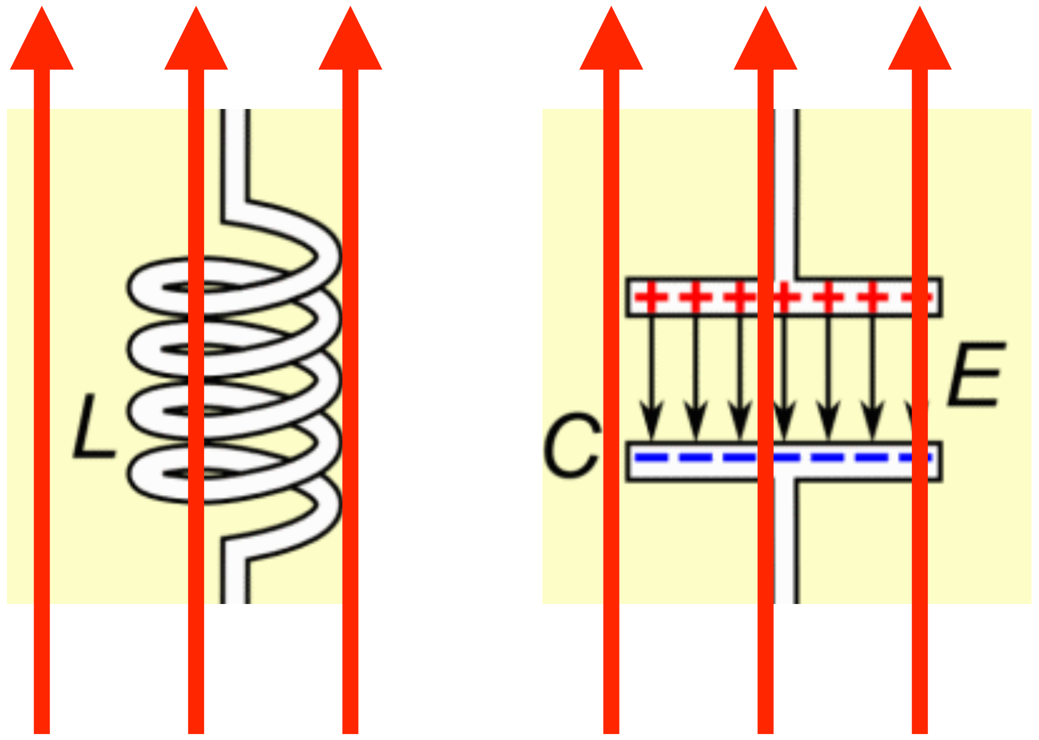

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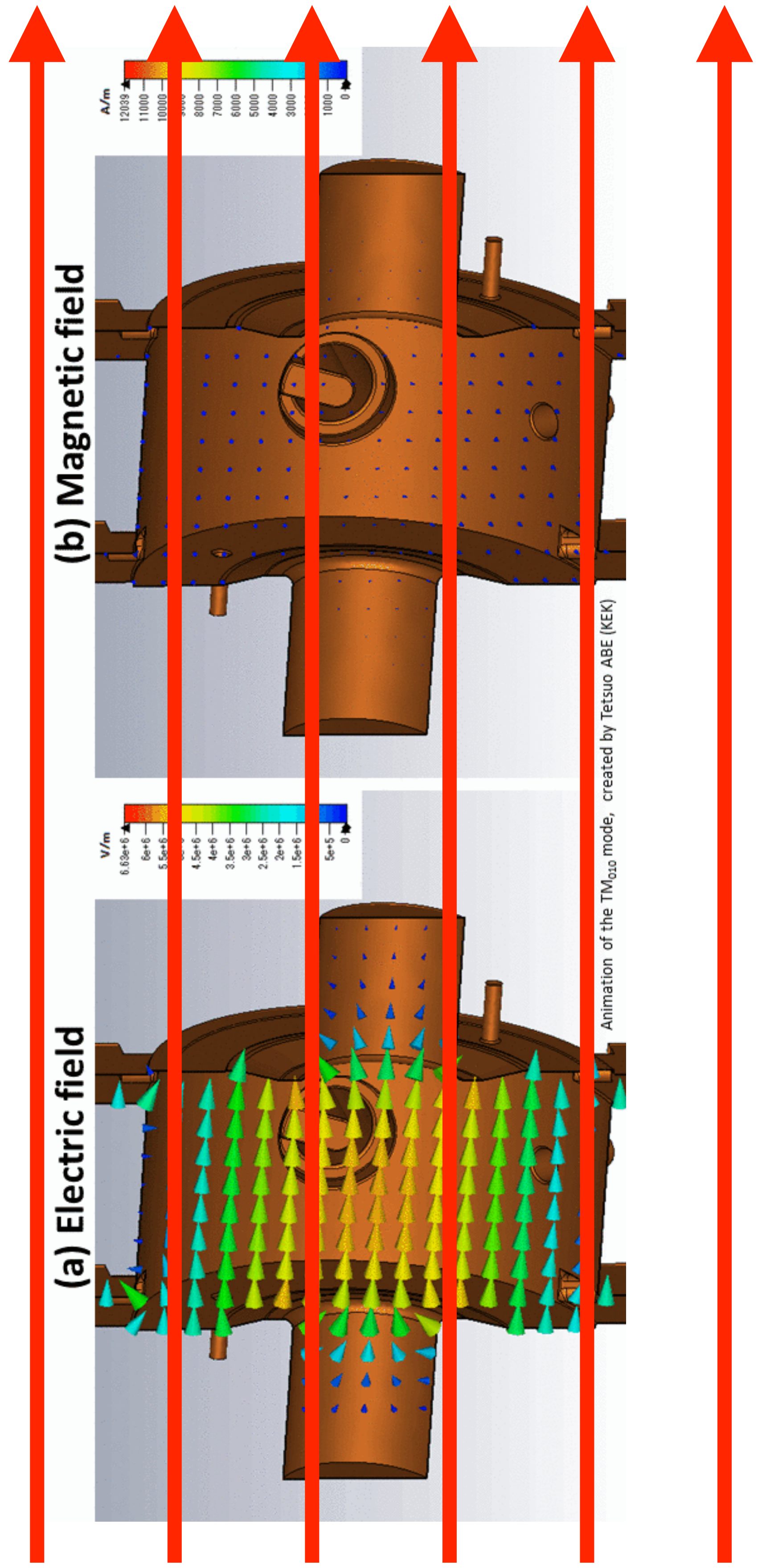

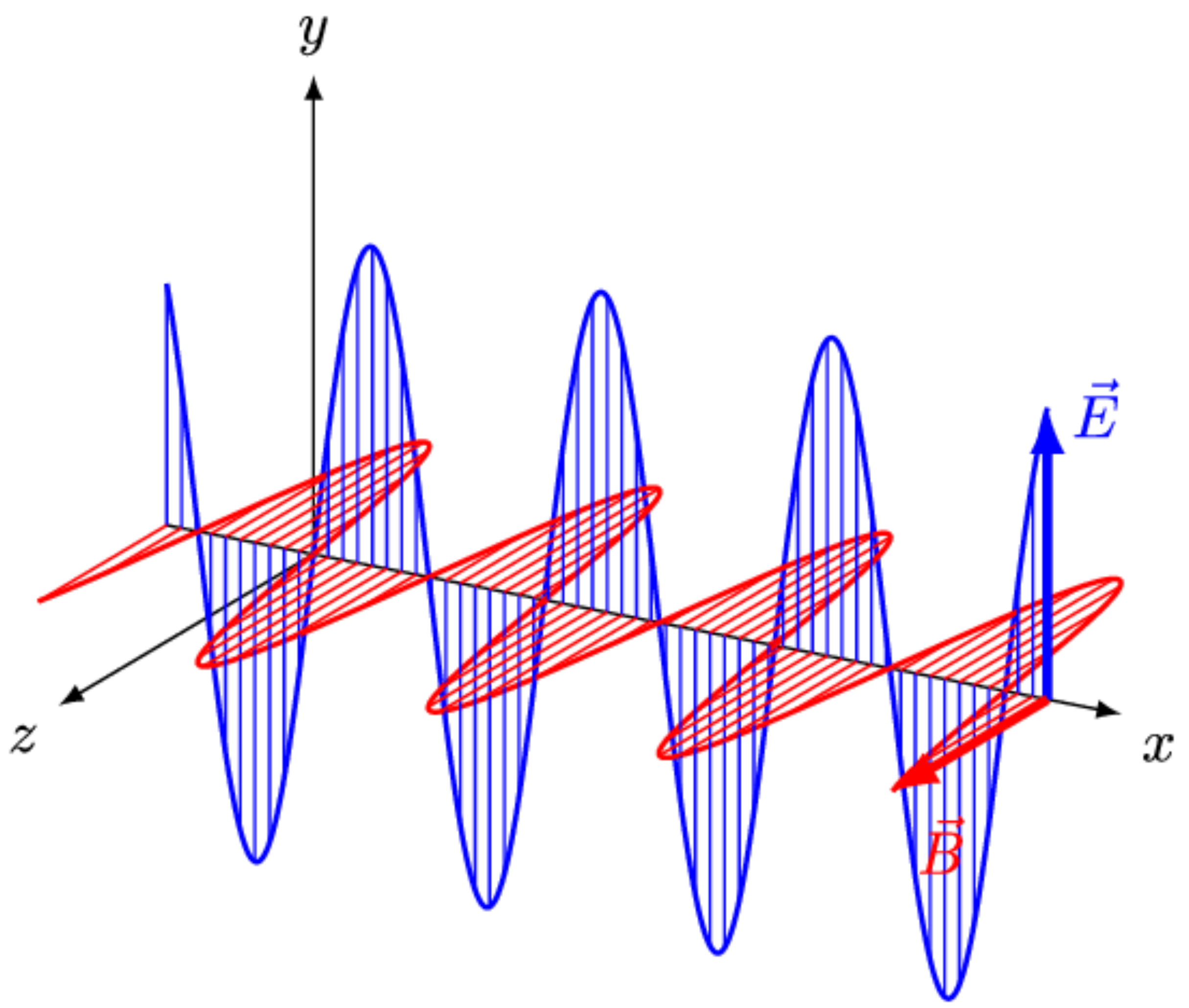

DC Magnetic Haloscopes

Type Depends on Axion Compton Wavelength $\lambda_a = \frac{h}{c m_a}$

Low Mass: Lumped Element Reactive		Middle Mass: Resonant Cavity Reactive and Dissipative		High Mass: Propagating	
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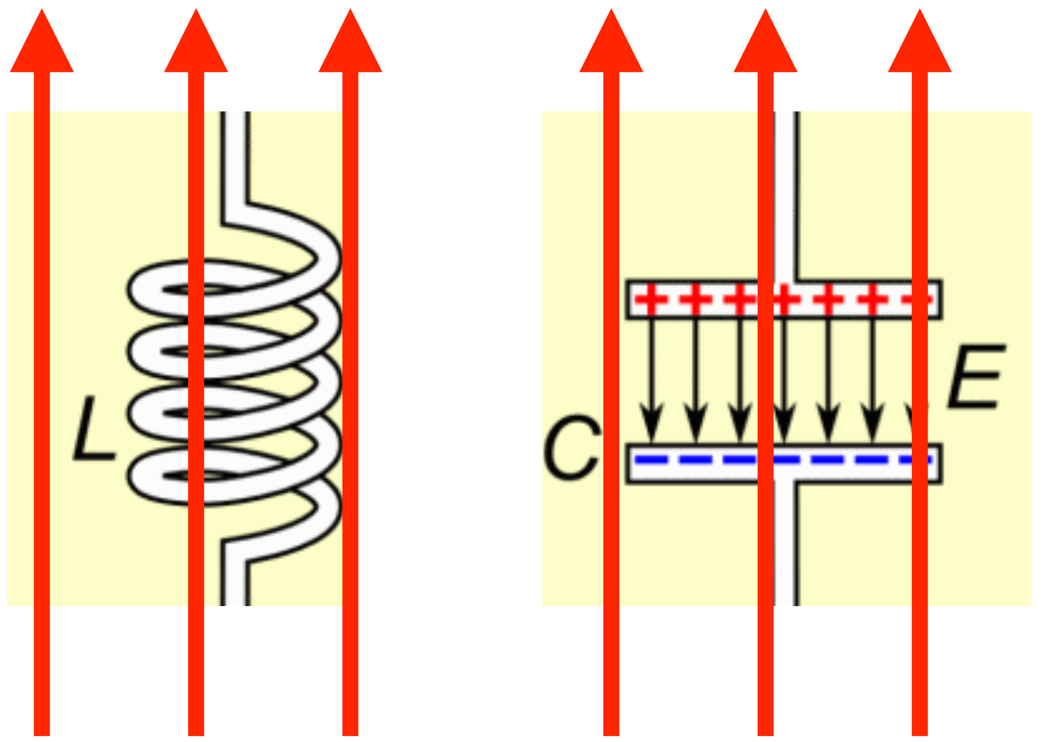

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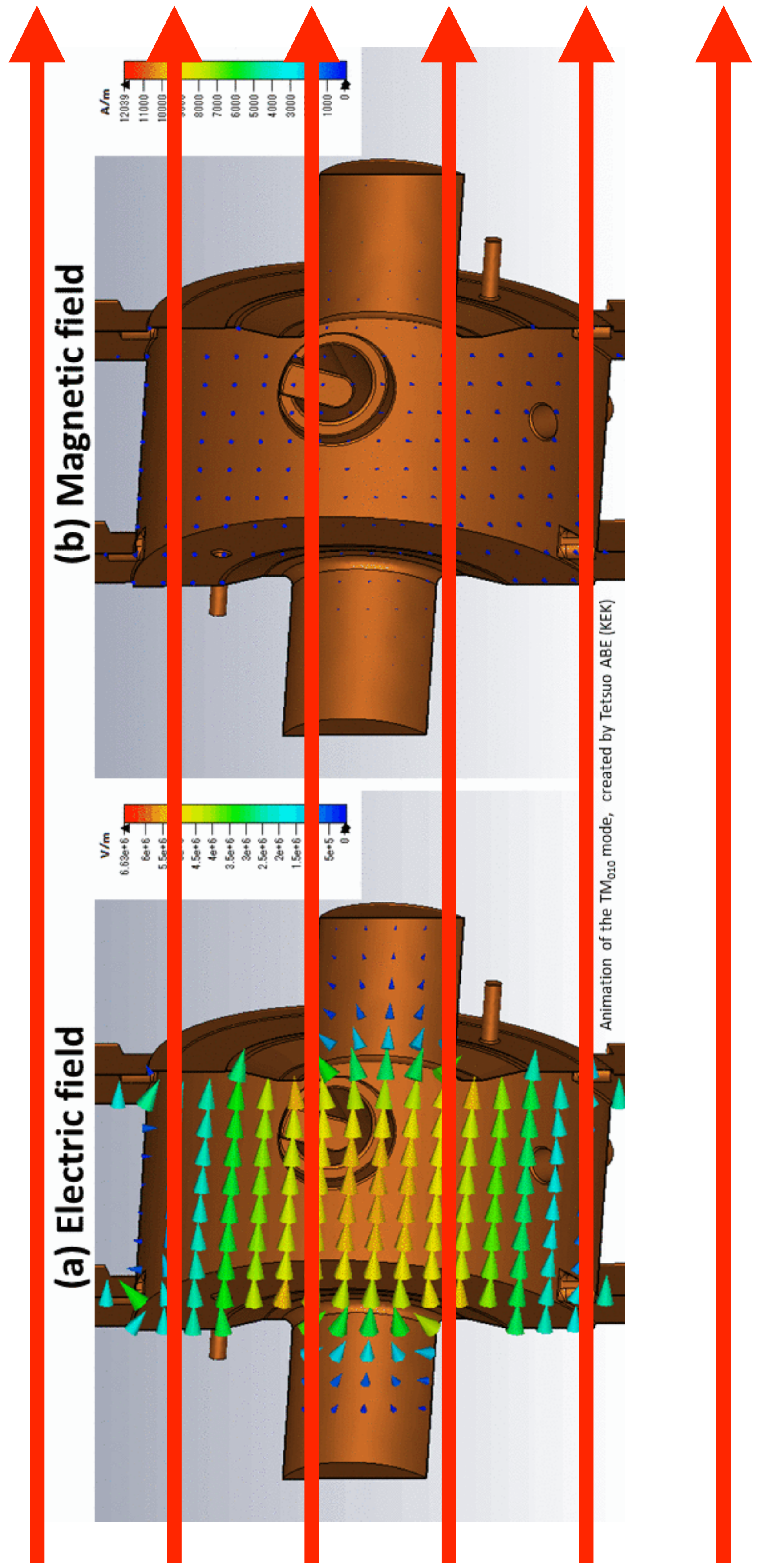

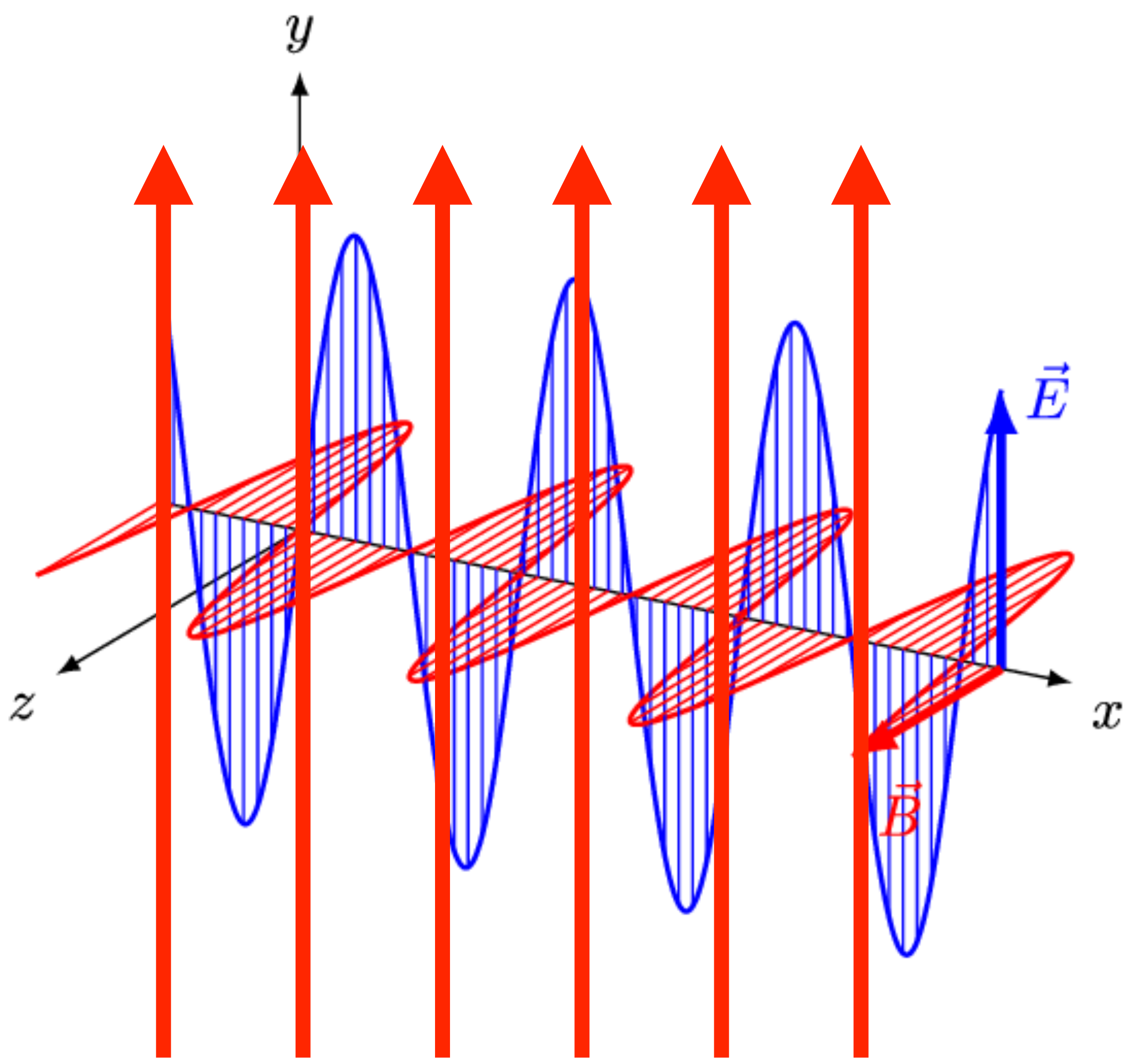

POYNTING THEOREM

- The basic conservation law for electromagnetic energy (EM)

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Instantaneous Poynting vector

$$\vec{S}_1(t) = \frac{1}{\mu_0}\vec{E}_1(t) \times \vec{B}_1(t) = \frac{1}{2}\left(\mathbf{E}_1 e^{-j\omega_1 t} + \mathbf{E}_1^* e^{j\omega_1 t}\right) \times \frac{1}{2\mu_0}\left(\mathbf{B}_1 e^{-j\omega_1 t} + \mathbf{B}_1^* e^{j\omega_1 t}\right)$$

$$= \frac{1}{2\mu_0}\mathrm{Re}\left(\mathbf{E}_1 \times \mathbf{B}_1^*\right) + \frac{1}{2\mu_0}\mathrm{Re}\left(\mathbf{E}_1 \times \mathbf{B}_1\ e^{-j2\omega_1 t}\right),$$

$$\langle \vec{S}_1 \rangle = \frac{1}{T}\int_0^T \vec{S}_1(t)dt = \frac{1}{T}\int_0^T \left[\frac{1}{2}\mathrm{Re}\left(\mathbf{E}_1 \times \mathbf{B}_1^*\right) + \frac{1}{2}\mathrm{Re}\left(\mathbf{E}_1 \times \mathbf{B}_1 e^{-2j\omega t}\right)\right] dt = \frac{1}{2}\mathrm{Re}\left(\mathbf{E}_1 \times \mathbf{B}_1^*\right)$$

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$$= \frac{1}{2\mu_0}\mathrm{Re}\left(\mathbf{E}_1 \times \mathbf{B}_1^*\right) + \frac{1}{2\mu_0}\mathrm{Re}\left(\mathbf{E}_1 \times \mathbf{B}_1\ e^{-j2\omega_1 t}\right),$$

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Complex Poynting vector

- The corresponding phasor form of the Poynting vector

$$\mathbf{S}_1 = \frac{1}{2\mu_0}\mathbf{E}_1 \times \mathbf{B}_1^* \quad \text{and} \quad \mathbf{S}_1^* = \frac{1}{2\mu_0}\mathbf{E}_1^* \times \mathbf{B}_1,$$

$$\mathrm{Re}\left(\mathbf{S}_1\right) = \frac{1}{2}(\mathbf{S}_1 + \mathbf{S}_1^*) \quad \text{and} \quad j\,\mathrm{Im}\left(\mathbf{S}_1\right) = \frac{1}{2}(\mathbf{S}_1 - \mathbf{S}_1^*).$$

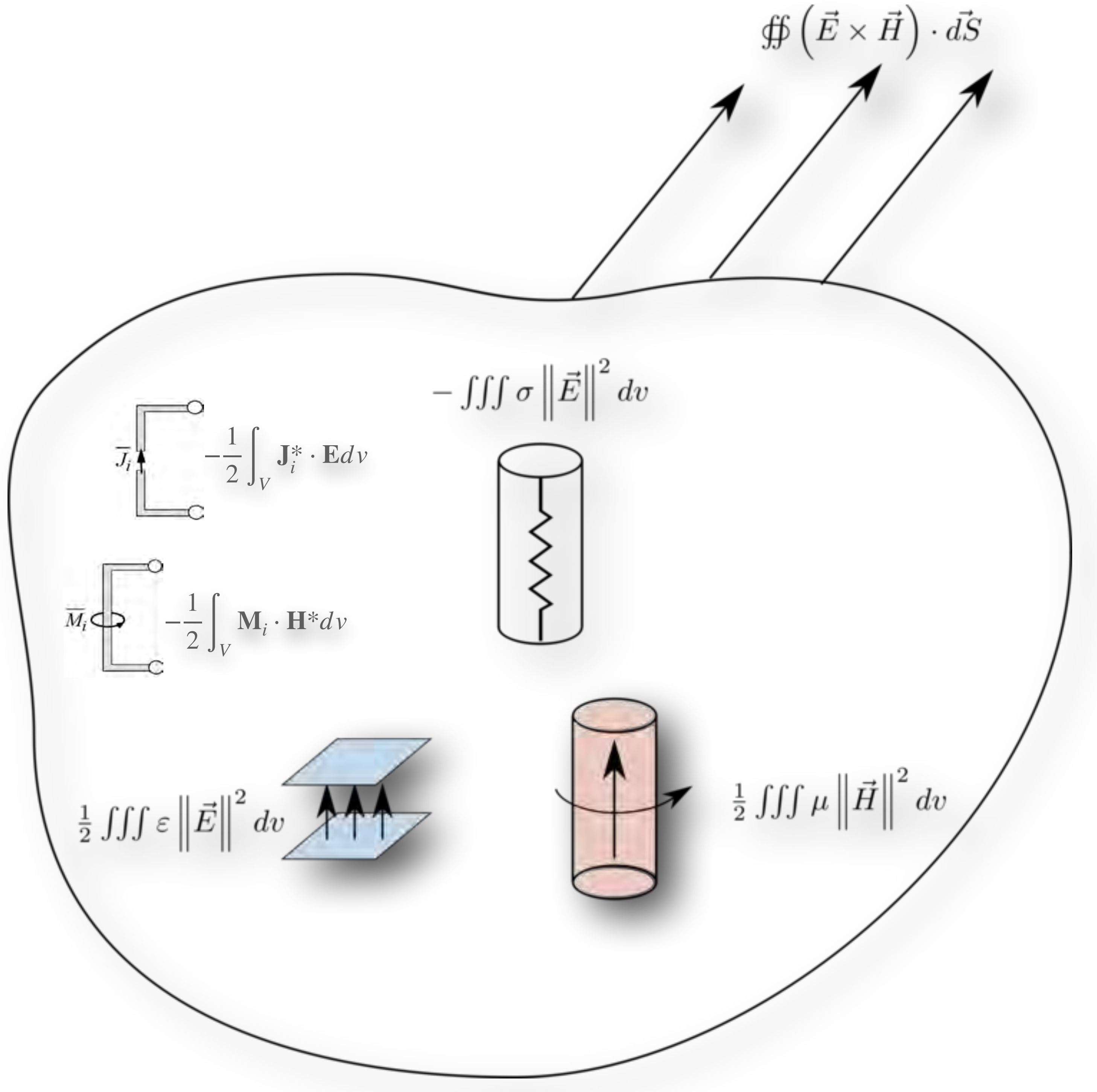
Time Average Power

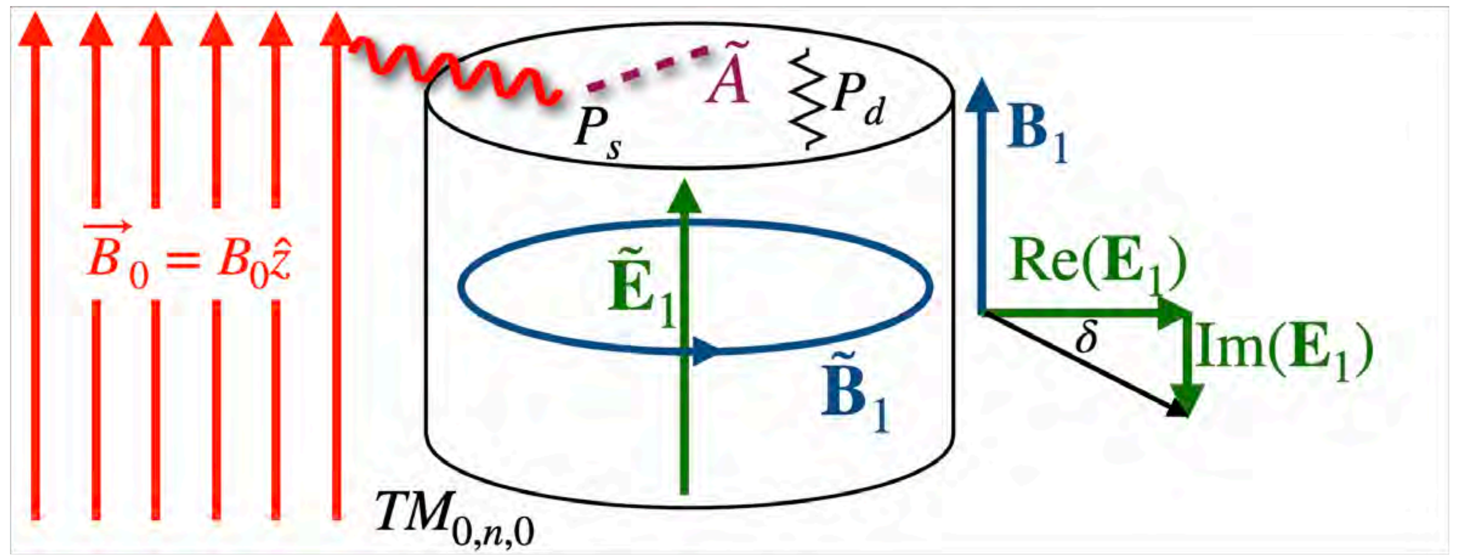
Reactive Power

Sensitivity of a Resonant Haloscope

$$P_{av} = \frac{1}{2}\mathrm{Re}\oint_{S_c} (\mathbf{E}\times\mathbf{H}^*)\cdot d\mathbf{s}$$

Average radiated power outside volume





PHYSICAL REVIEW D **105,** 045009 (2022)

Poynting vector controversy in axion modified electrodynamics

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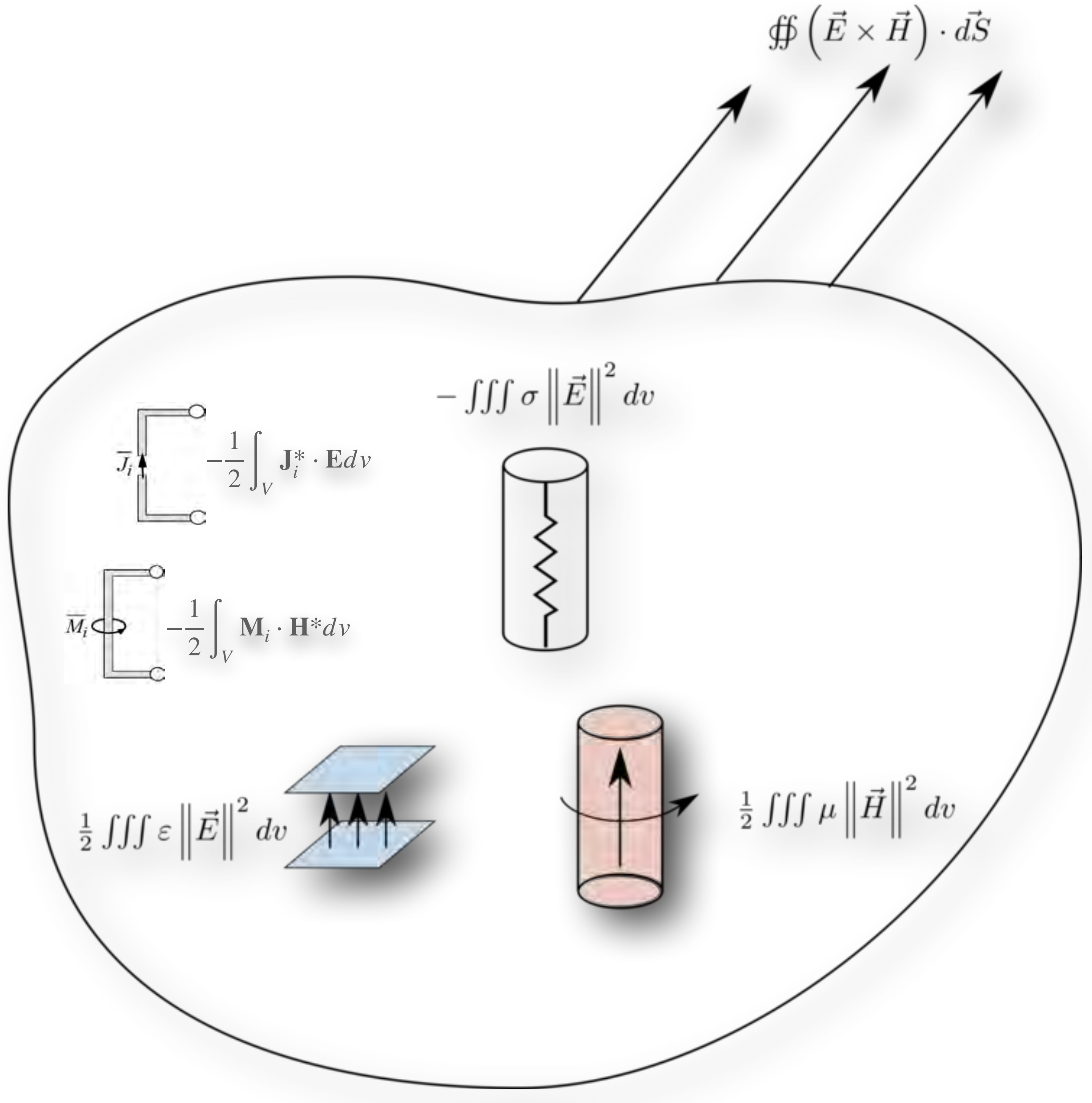

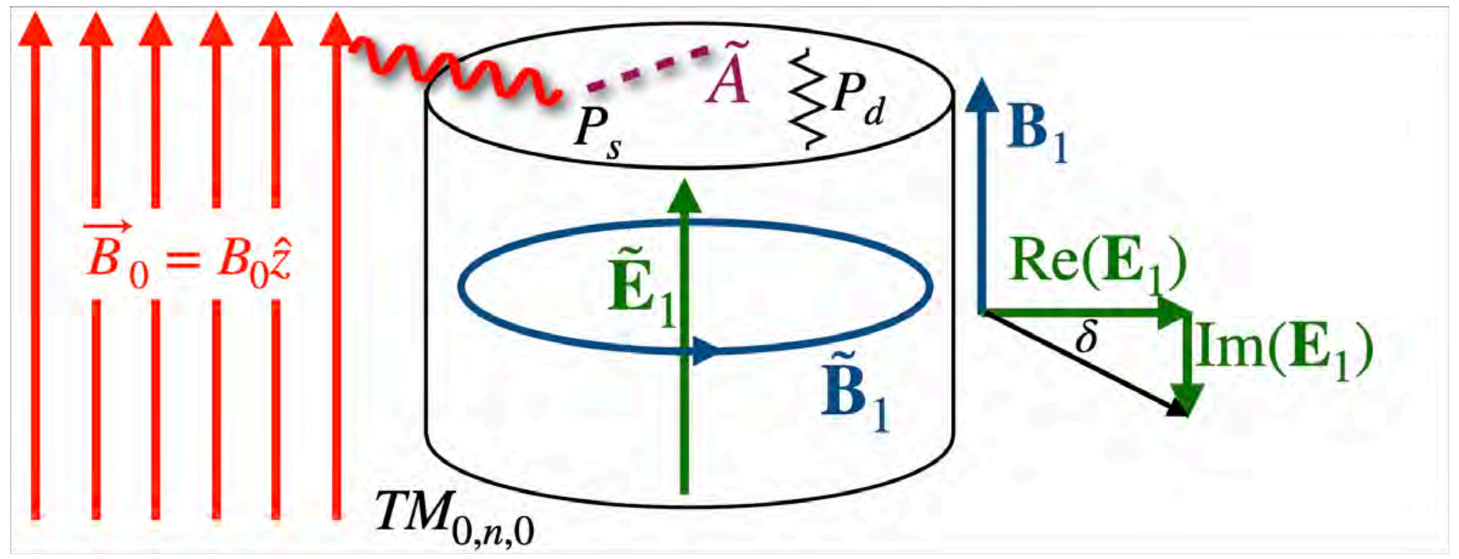

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On resonance: Real part of Complex Poynting Theorem = 0 for closed system

$$\oint \mathrm{Re}\,(\mathbf{S}) \cdot \hat{n} ds = \frac{j\omega_a g_{a\gamma\gamma}\epsilon_0 c}{4}\int (\mathbf{E}_1 \cdot \tilde{a}^*\mathbf{B}_0^* - \mathbf{E}_1^* \cdot \tilde{a}\mathbf{B}_0)\, d\tau - \frac{1}{4}\int (\mathbf{E}_1 \cdot \mathbf{J}_{e1}^* + \mathbf{E}_1^* \cdot \mathbf{J}_{e1})\, d\tau$$

P_s Axion power input

P_d Cavity power distribution

Sensitivity of a Resonant Haloscope

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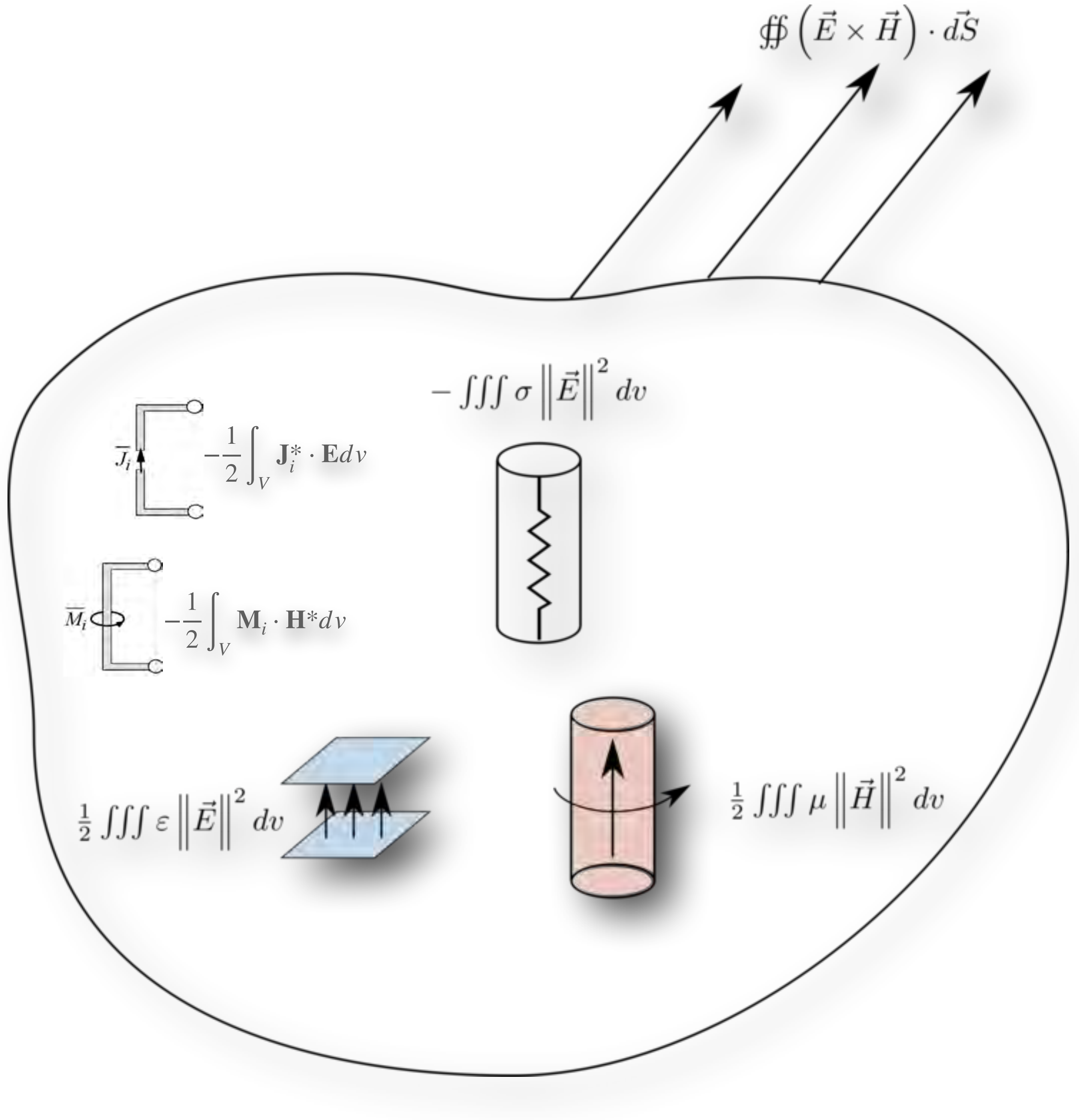

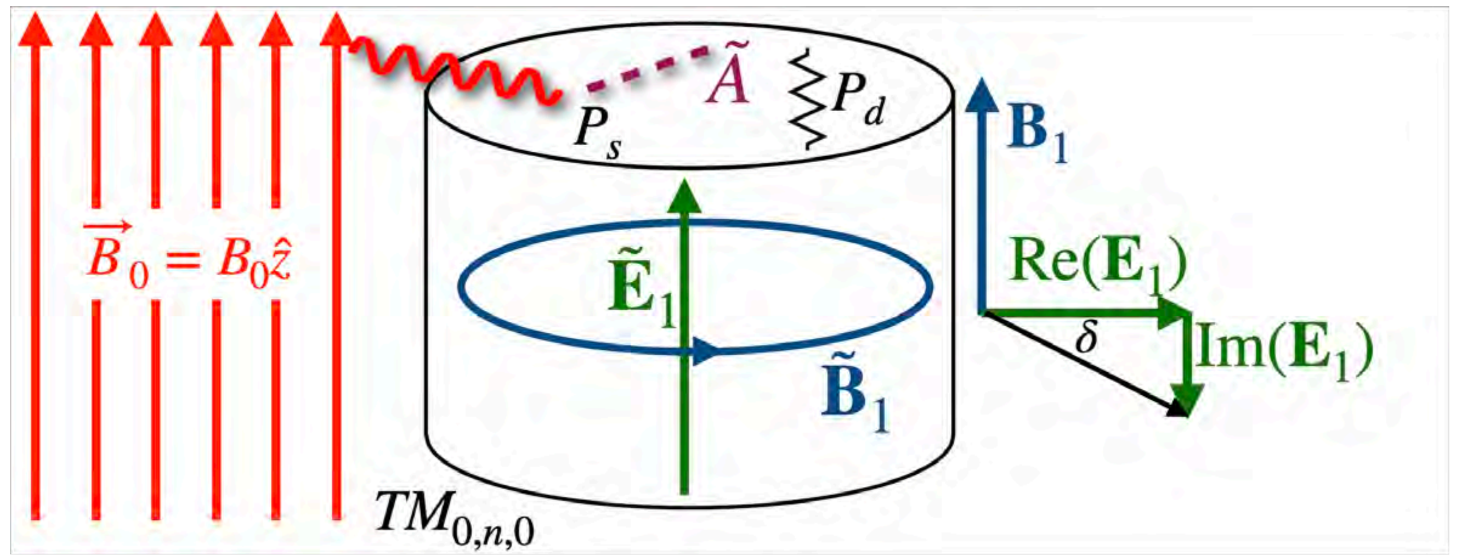

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Sensitivity of a Resonant Haloscope

PHYSICAL REVIEW D **105**, 045009 (2022)

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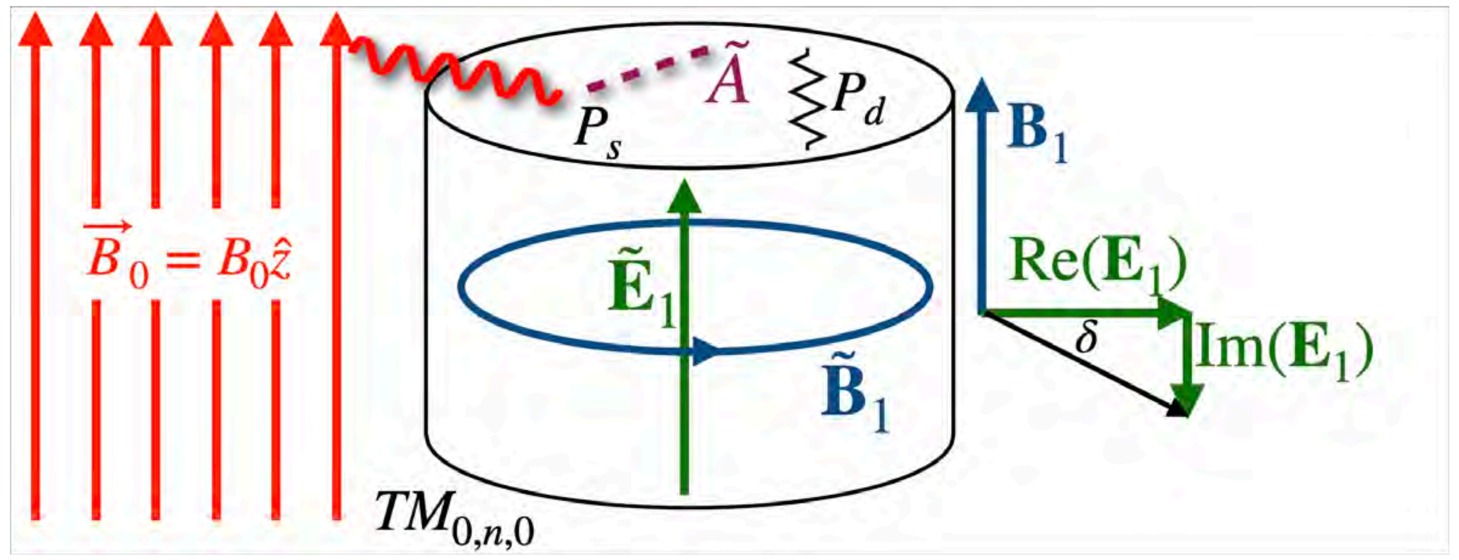

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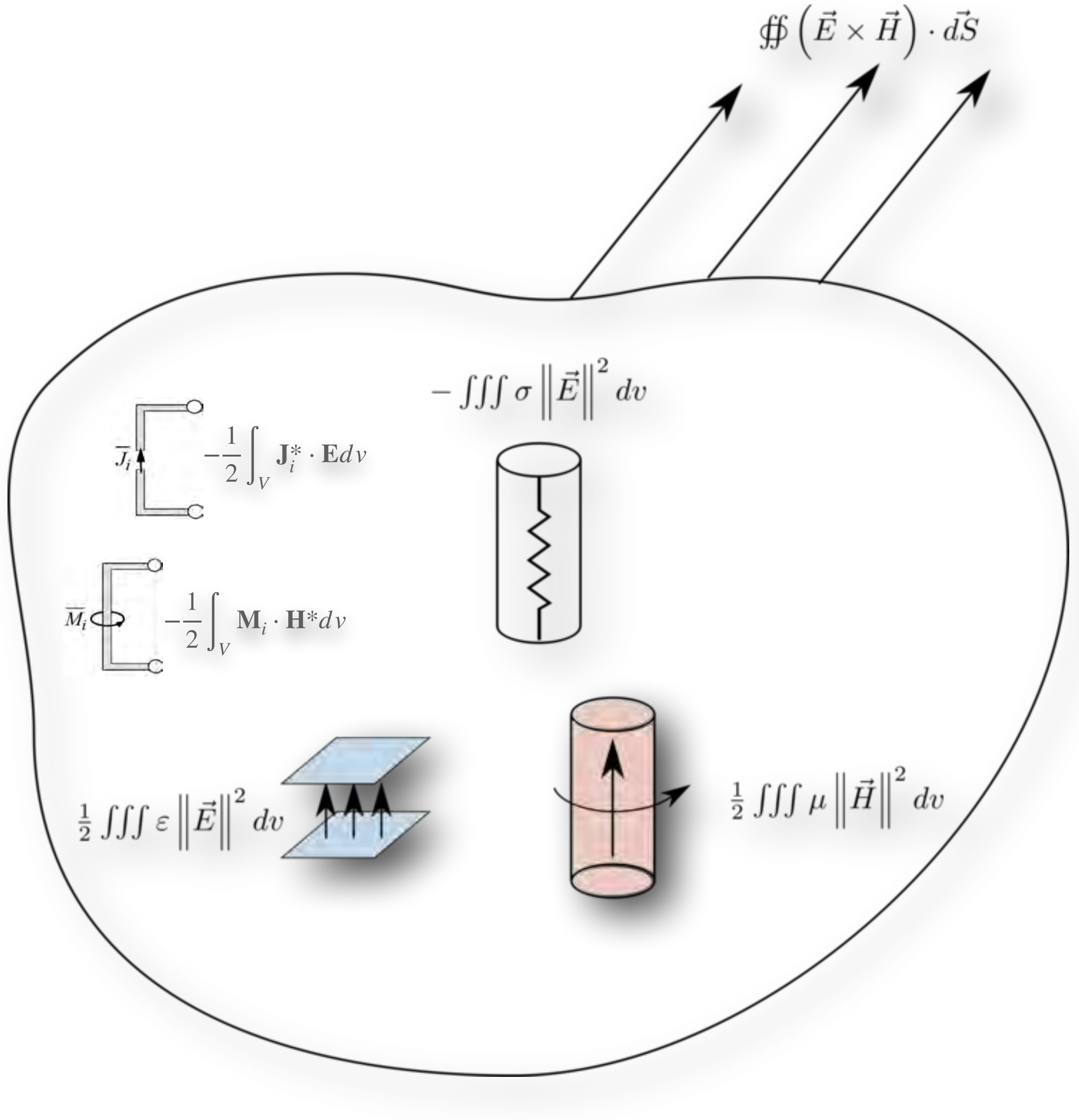

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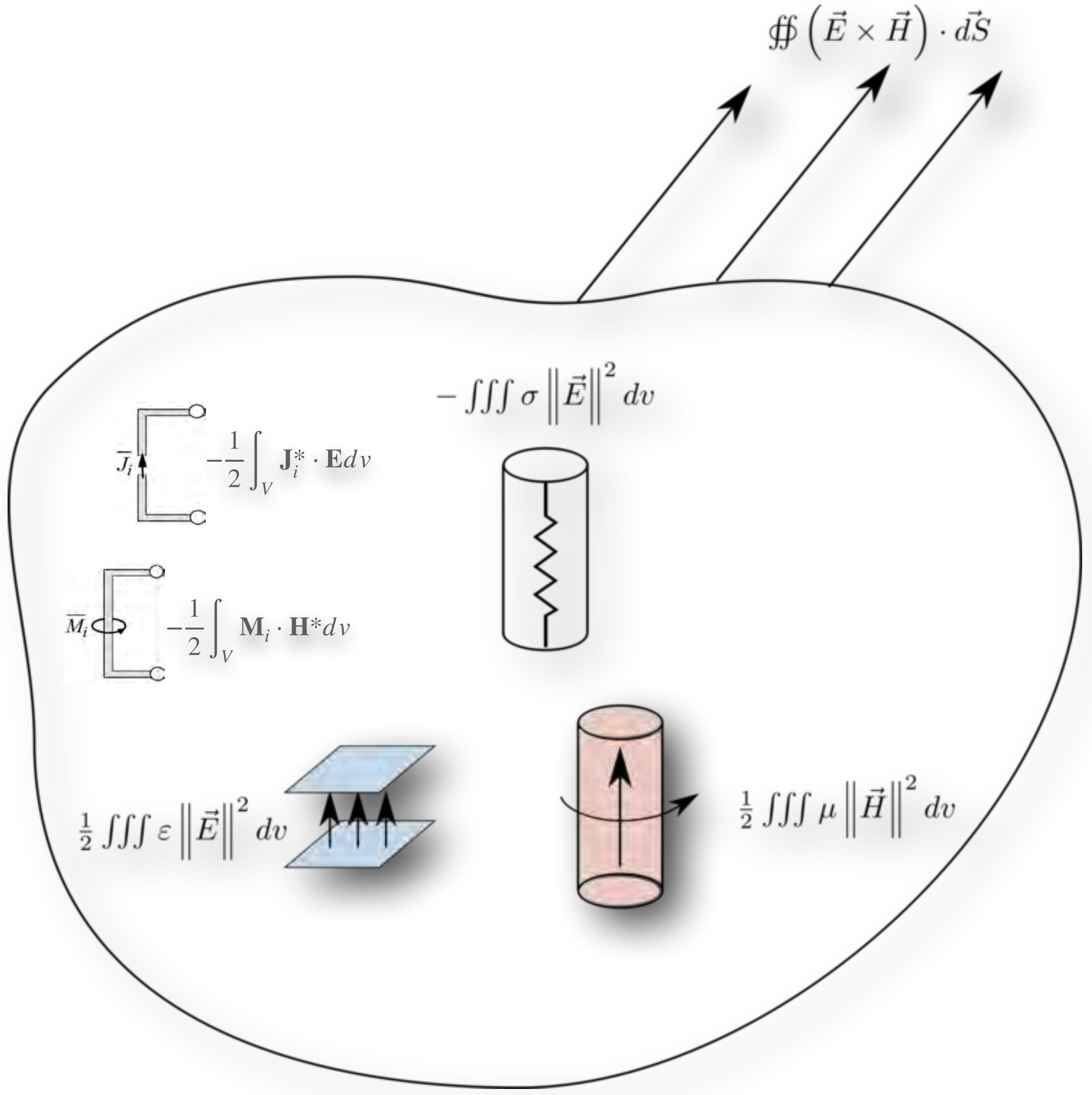
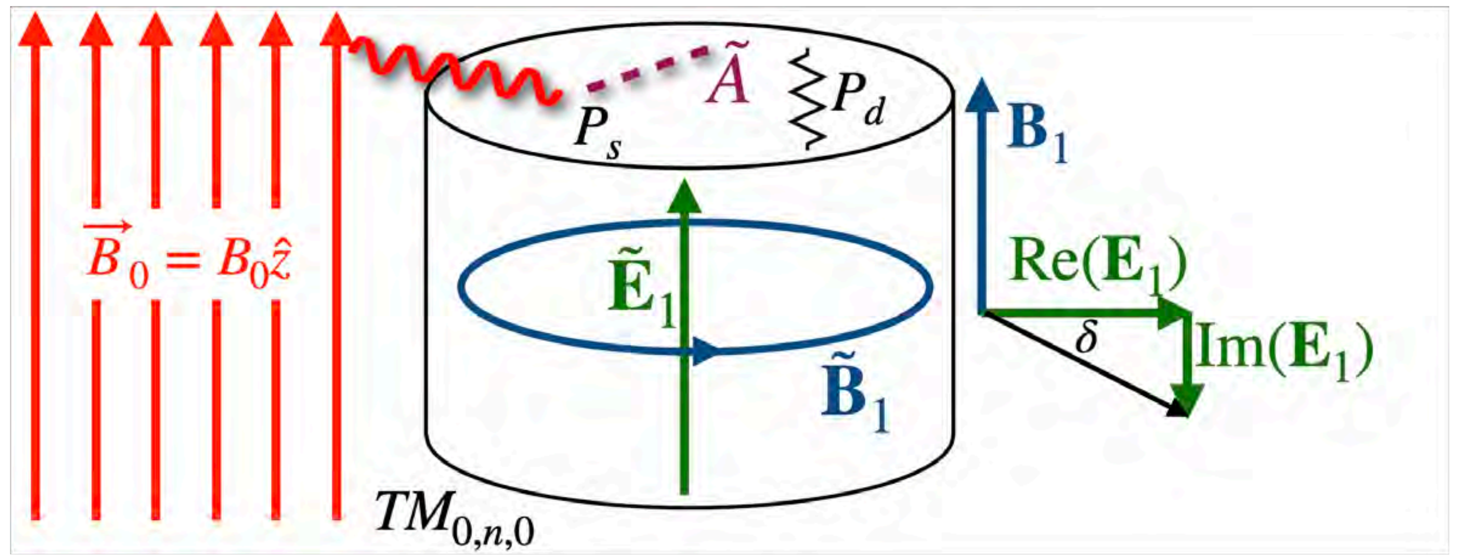
$$P_{a1} = \frac{\omega_a g_{a\gamma\gamma} a_0 \epsilon_0 c}{2Q_1}\int (Re(\mathbf{E}_1) \cdot Re(\mathbf{B}_0))\, d\tau = P_d = \frac{\omega_1 U_1}{Q_1}$$

Sensitivity of a Resonant Haloscope

$$P_{av} = \frac{1}{2}\mathrm{Re}\oint_{S_c} (\mathbf{E}\times\mathbf{H}^*)\cdot ds$$

Average radiated power outside volume





PHYSICAL REVIEW D **105**, 045009 (2022)

Poynting vector controversy in axion modified electrodynamics

Michael E. Tobar,* Ben T. McAllister, and Maxim Goryachev

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(Received 9 September 2021; accepted 28 January 2022; published 15 February 2022)

$$\mathbf{S} = \frac{1}{2\mu_0}\mathbf{E}_1\times\mathbf{B}_1^* \text{ and } \mathbf{S}^* = \frac{1}{2\mu_0}\mathbf{E}_1^*\times\mathbf{B}_1$$

$$\nabla\cdot\mathbf{S} = \frac{1}{2\mu_0}\nabla\cdot(\mathbf{E}_1\times\mathbf{B}_1^*) = \frac{1}{2\mu_0}\mathbf{B}_1^*\cdot(\nabla\times\mathbf{E}_1) - \frac{1}{2\mu_0}\mathbf{E}_1\cdot(\nabla\times\mathbf{B}_1^*)$$

$$\nabla\cdot\mathbf{S}^* = \frac{1}{2\mu_0}\nabla\cdot(\mathbf{E}_1^*\times\mathbf{B}_1) = \frac{1}{2\mu_0}\mathbf{B}_1\cdot(\nabla\times\mathbf{E}_1^*) - \frac{1}{2\mu_0}\mathbf{E}_1^*\cdot(\nabla\times\mathbf{B}_1)$$

On resonance: Real part of Complex Poynting Theorem = 0 for closed system

$$\oint \mathrm{Re}\,(\mathbf{S})\cdot\hat{n}ds = \frac{j\omega_a g_{a\gamma\gamma}\epsilon_0 c}{4}\int(\mathbf{E}_1\cdot\tilde{a}^*\mathbf{B}_0^* - \mathbf{E}_1^*\cdot\tilde{a}\mathbf{B}_0)\,d\tau - \frac{1}{4}\int(\mathbf{E}_1\cdot\mathbf{J}_{e1}^* + \mathbf{E}_1^*\cdot\mathbf{J}_{e1})\,d\tau$$

P_s Axion power input

P_d Cavity power dissipation

$$P_d = \frac{1}{4}\int(\mathbf{E}_1\cdot\mathbf{J}_{e1}^* + \mathbf{E}_1^*\cdot\mathbf{J}_{e1})\,d\tau = \frac{\omega_1\epsilon_0}{2Q_1}\int\mathbf{E}_1\cdot\mathbf{E}_1^*\,dV = \frac{\omega_1 U_1}{Q_1}$$

$$P_{a1} = \frac{\omega_a g_{a\gamma\gamma}a_0\epsilon_0 c}{2Q_1}\int(Re(\mathbf{E}_1)\cdot Re(\mathbf{B}_0))\,d\tau = P_d = \frac{\omega_1 U_1}{Q_1}$$

$$P_{a1} = \omega_a Q U_1 = g_{a\gamma\gamma}^2\langle a_0\rangle^2\omega_a Q_1\epsilon_0 c^2 B_0^2 V_1 C_1,$$

$$C_1 = \frac{\left(\int\vec{B}_0\cdot\mathrm{Re}(\mathbf{E}_1)\,d\tau\right)^2}{B_0^2 V_1\int\mathbf{E}_1\cdot\mathbf{E}_1^*\,d\tau},$$

Sensitivity of a Resonant Haloscope

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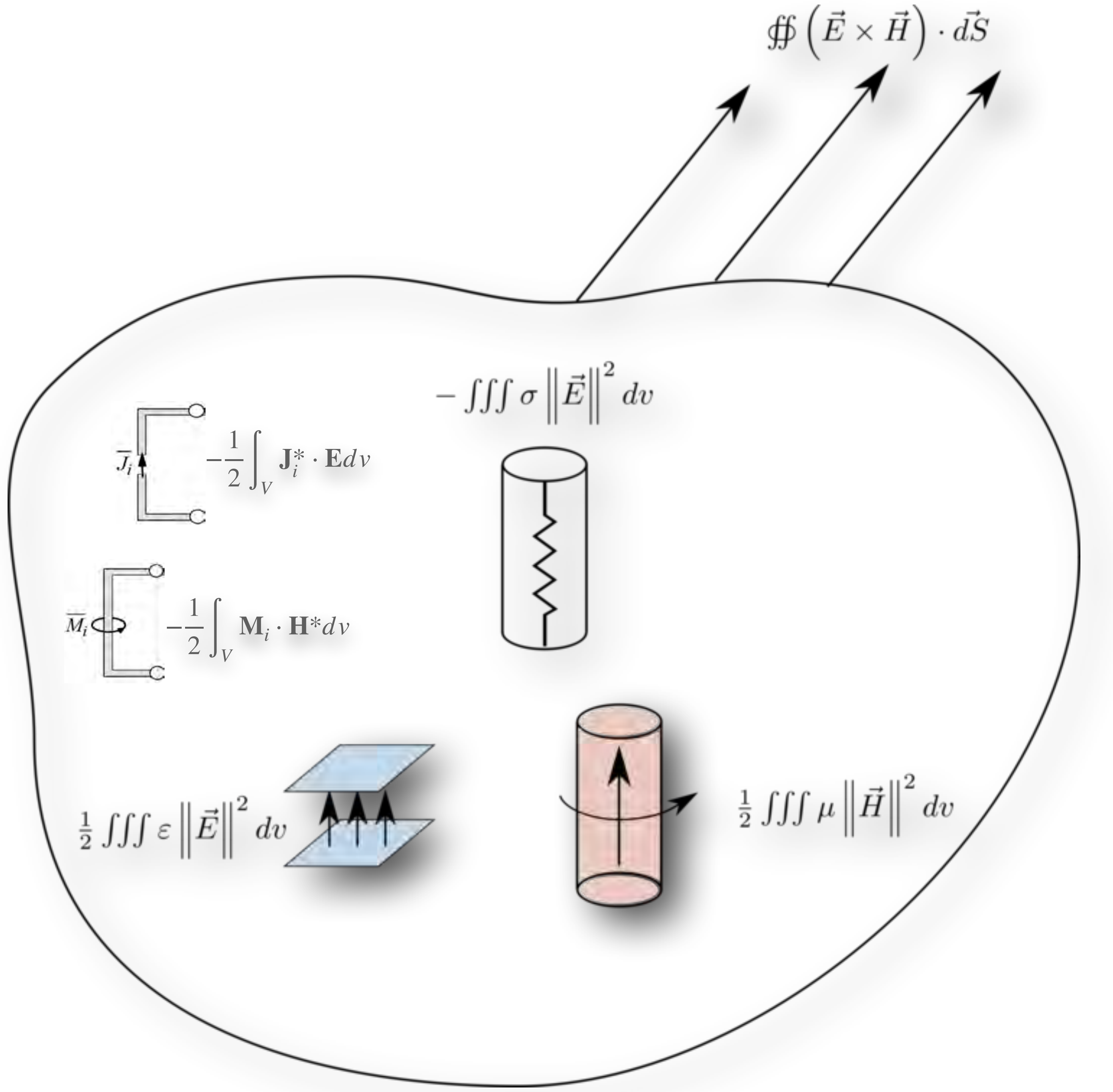

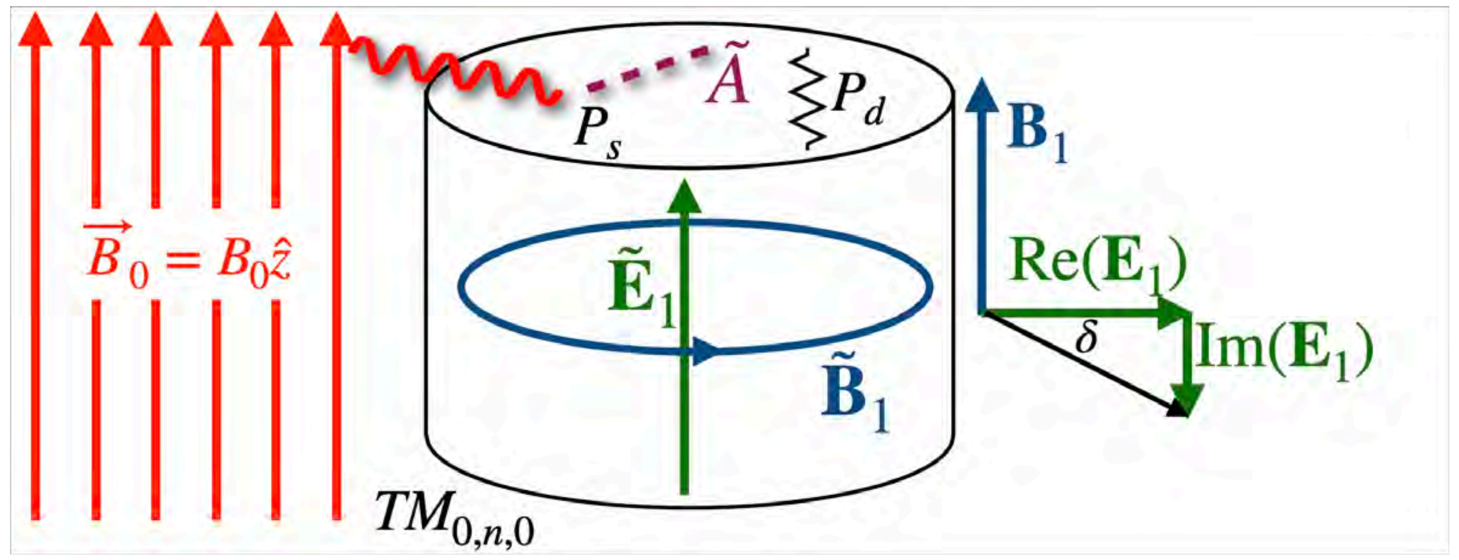

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P_s Axion power input

P_d Cavity power distribution

$$\oint j\,\mathrm{Im}\,(\mathbf{S})\cdot\hat{n}ds = \int\Big(\frac{j\omega_1}{2}\big(\frac{1}{\mu_0}\mathbf{B}_1^*\cdot\mathbf{B}_1 - \epsilon_0\mathbf{E}_1\cdot\mathbf{E}_1^*\big) + \frac{j\omega_a}{4}\epsilon_0 g_{a\gamma\gamma}c\vec{B}_0\cdot(\tilde{a}^*\mathbf{E}_1 + \tilde{a}\mathbf{E}_1^*) - \frac{1}{4}(\mathbf{E}_1\cdot\mathbf{J}_{e1}^* - \mathbf{E}_1^*\cdot\mathbf{J}_{e1})\Big)\,d\tau$$

Resonant Haloscope, on resonance, Reactive Power = 0

$$P_d = \frac{1}{4}\int(\mathbf{E}_1\cdot\mathbf{J}_{e1}^* + \mathbf{E}_1^*\cdot\mathbf{J}_{e1})\,d\tau = \frac{\omega_1\epsilon_0}{2Q_1}\int\mathbf{E}_1\cdot\mathbf{E}_1^*\,dV = \frac{\omega_1 U_1}{Q_1}$$

$$P_{a1} = \frac{\omega_a g_{a\gamma\gamma}a_0\epsilon_0 c}{2Q_1}\int(Re(\mathbf{E}_1)\cdot Re(\mathbf{B}_0))\,d\tau = P_d = \frac{\omega_1 U_1}{Q_1}$$

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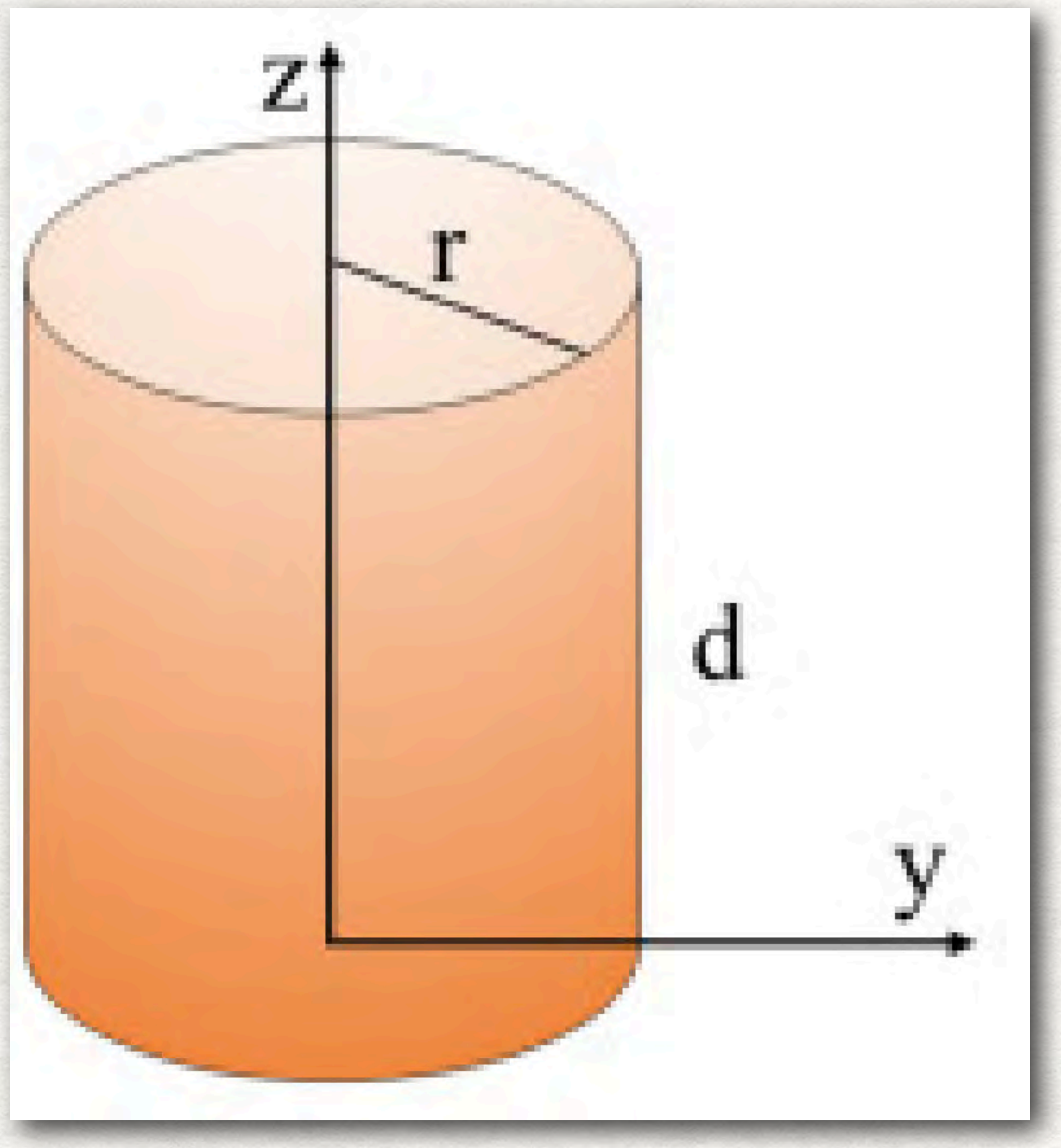
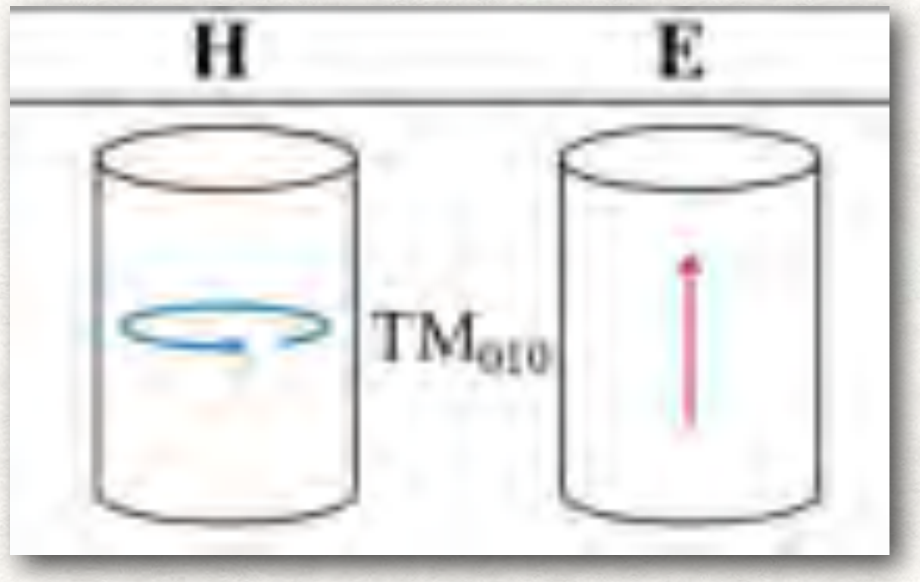
IMAGINARY POYNTING VECTOR INSIDE CAVITY



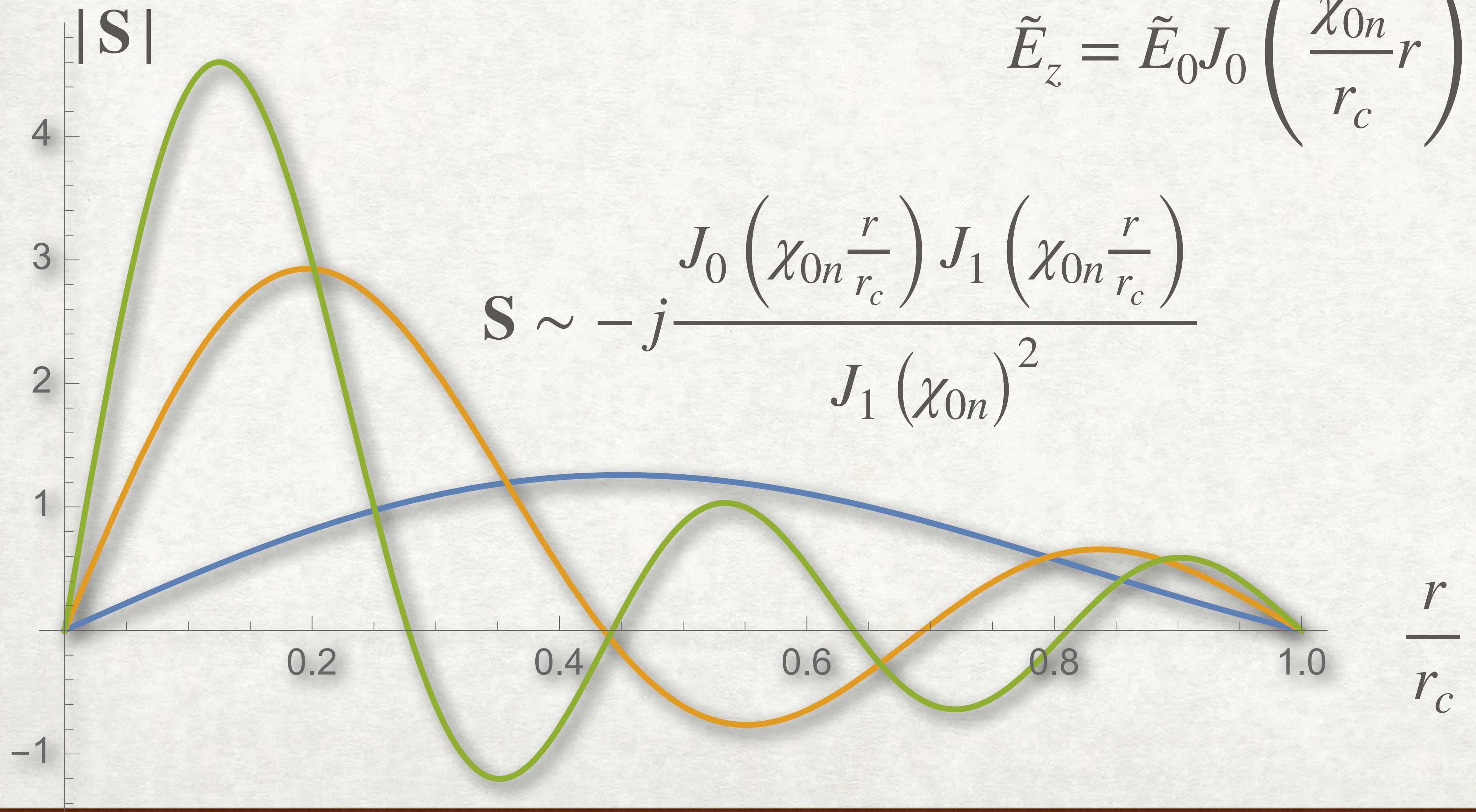


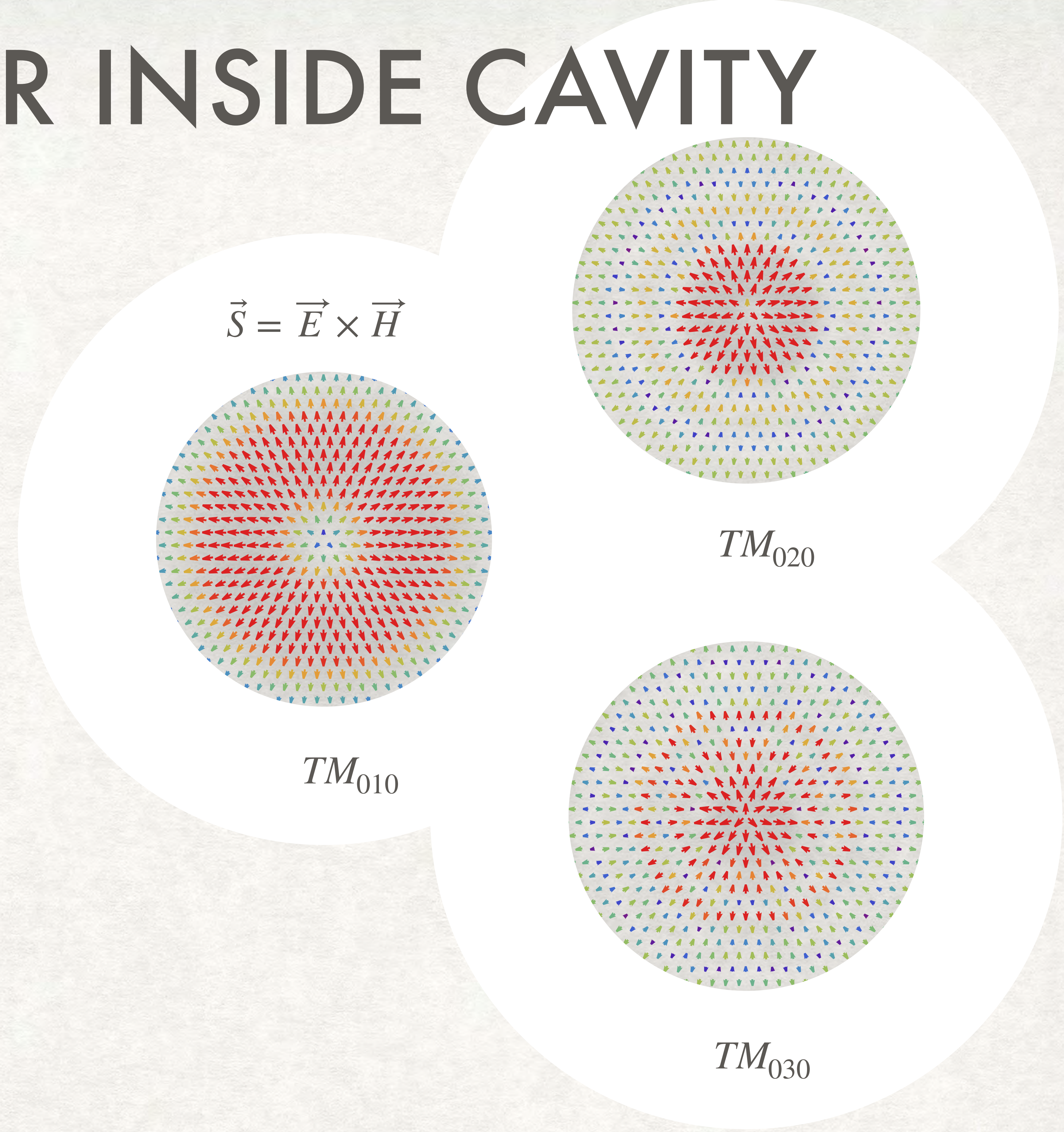
TM_{0n0}

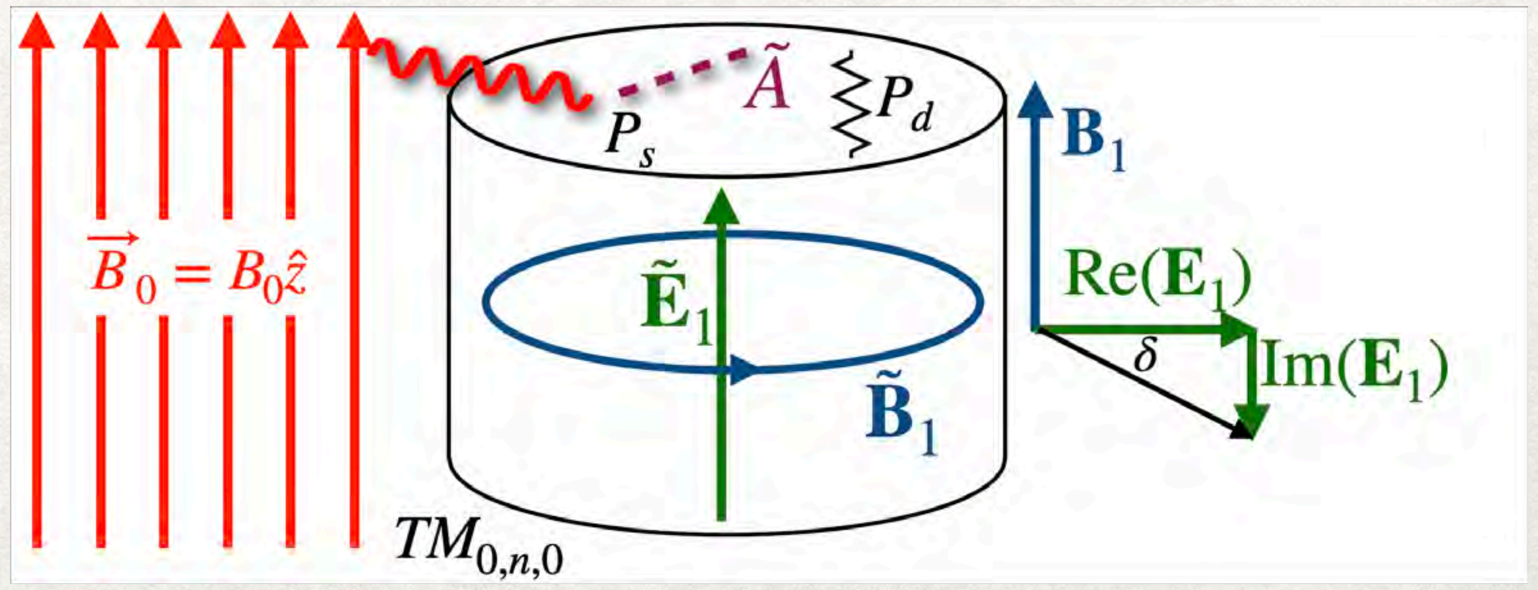
$$\tilde{H}_\phi = -j\tilde{E}_0(\omega\epsilon)\frac{r_c}{\chi_{0n}}J_0'\left(\frac{\chi_{0n}}{r_c}r\right)$$

$$\tilde{E}_z = \tilde{E}_0 J_0\left(\frac{\chi_{0n}}{r_c}r\right)$$

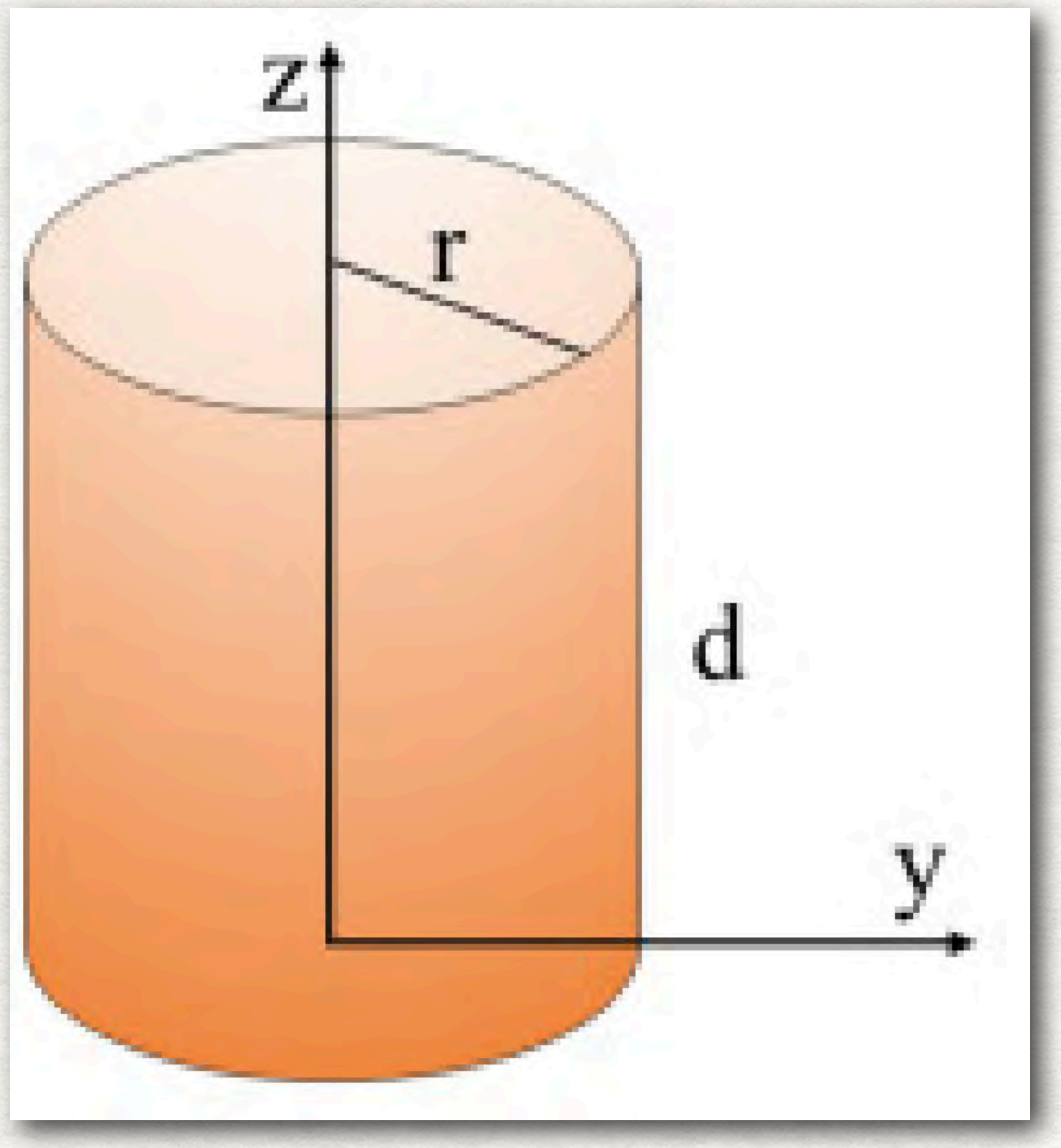
$$\mathbf{S} \sim -j\frac{J_0\left(\chi_{0n}\frac{r}{r_c}\right)J_1\left(\chi_{0n}\frac{r}{r_c}\right)}{J_1\left(\chi_{0n}\right)^2}$$

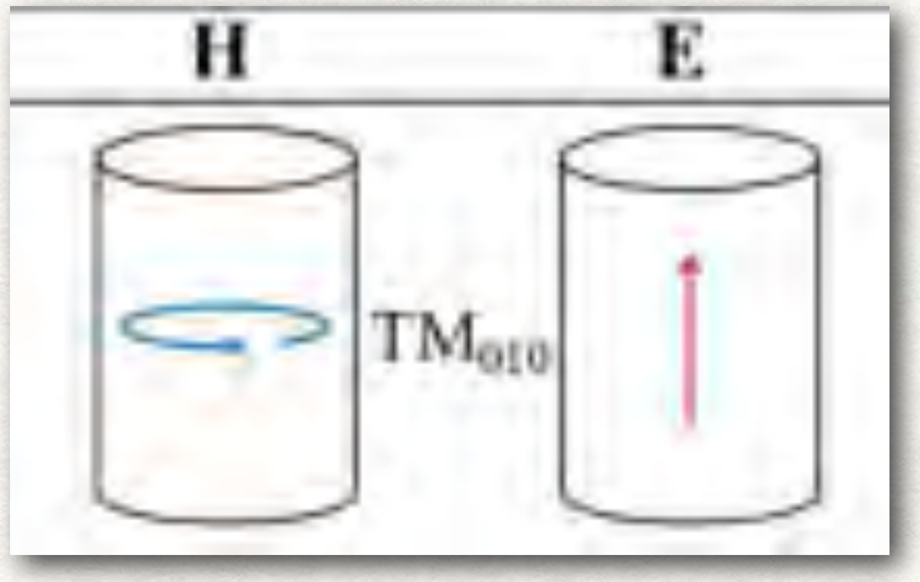






IMAGINARY POYNTING VECTOR INSIDE CAVITY





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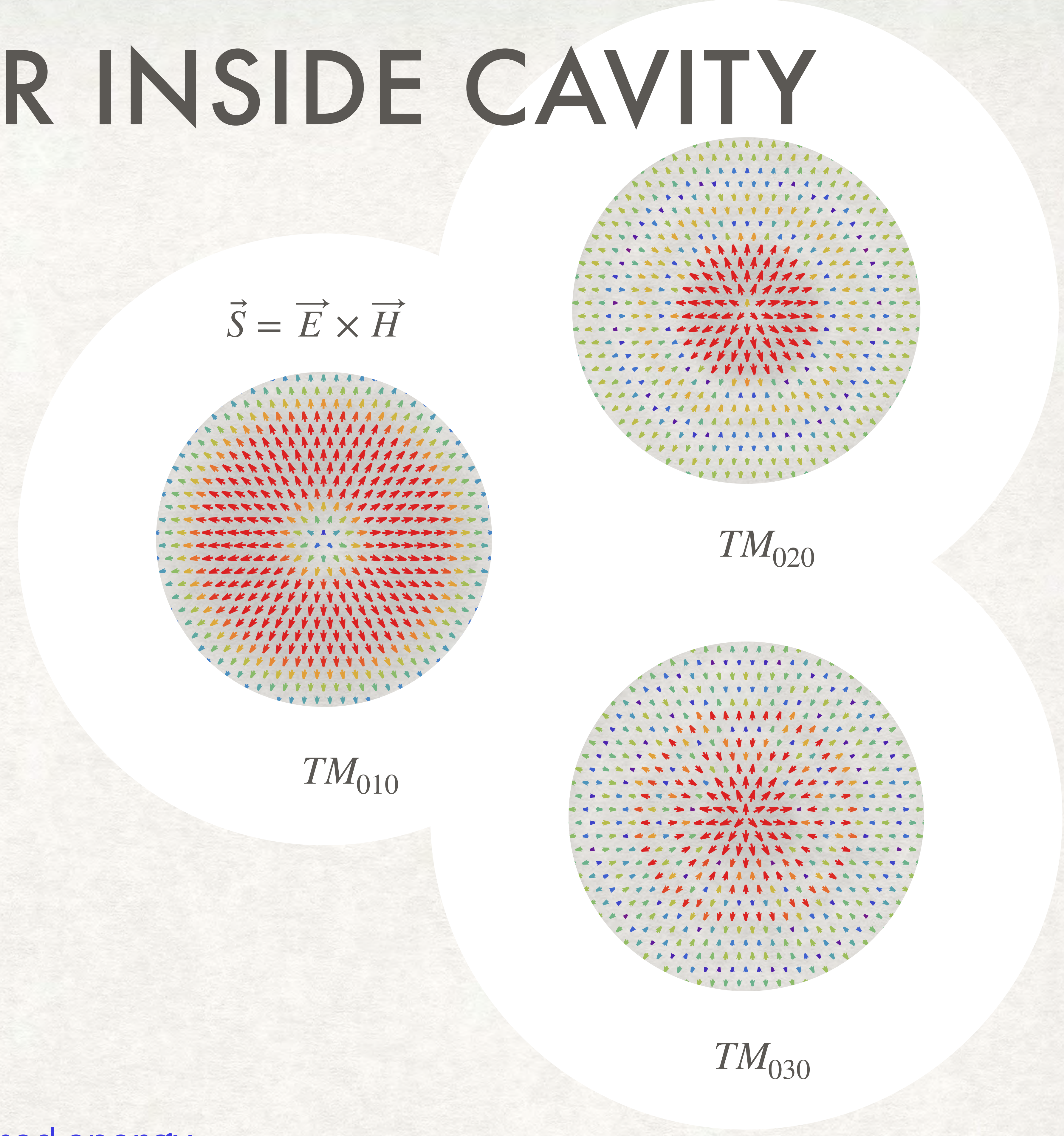
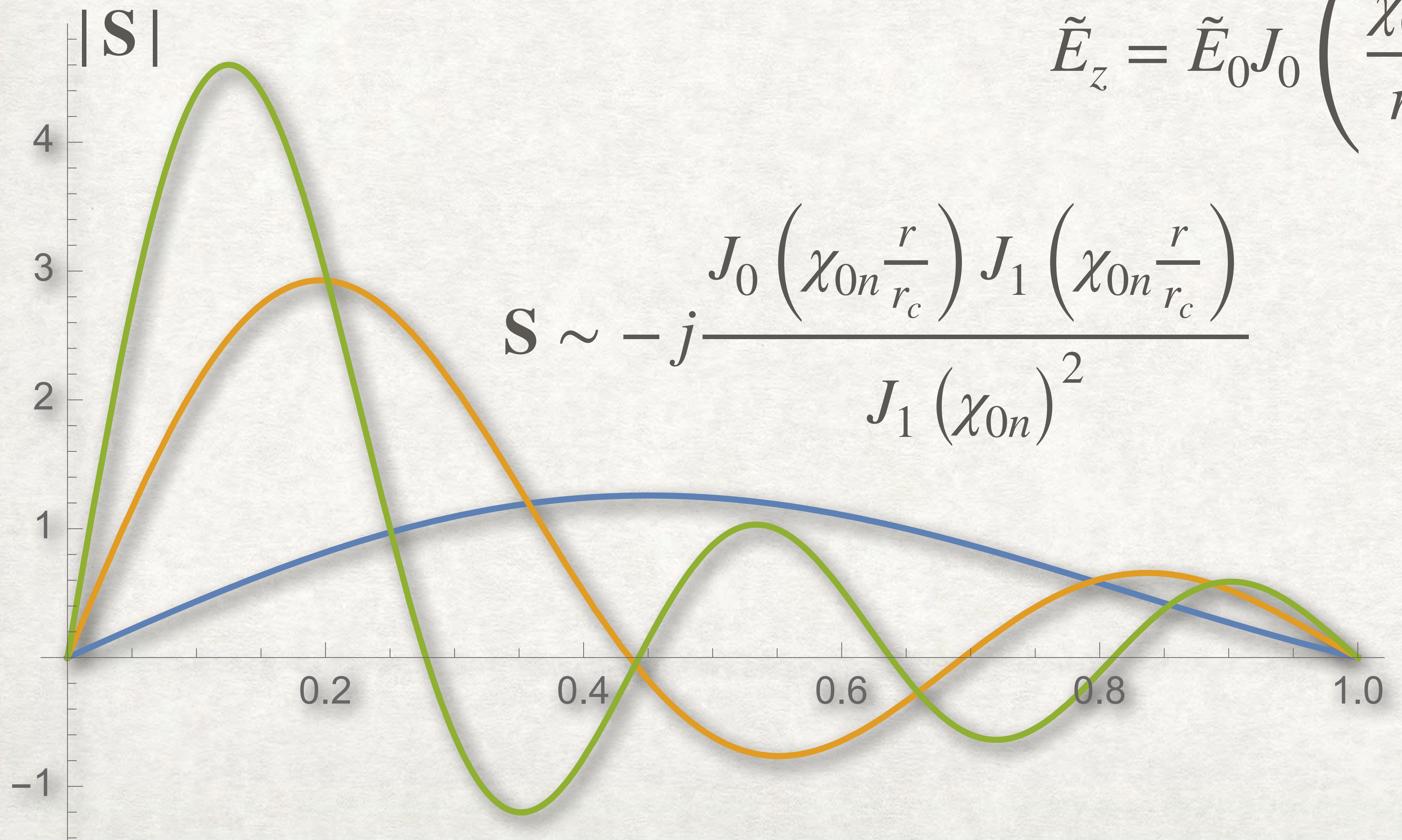
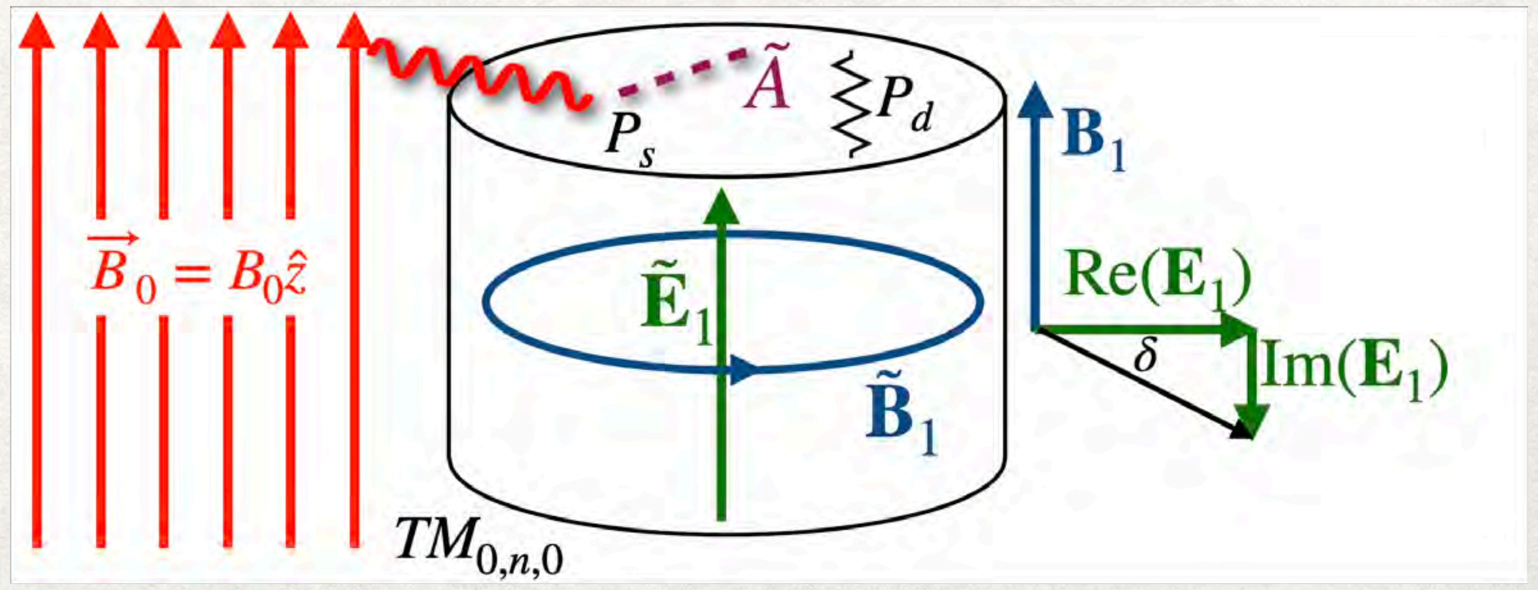




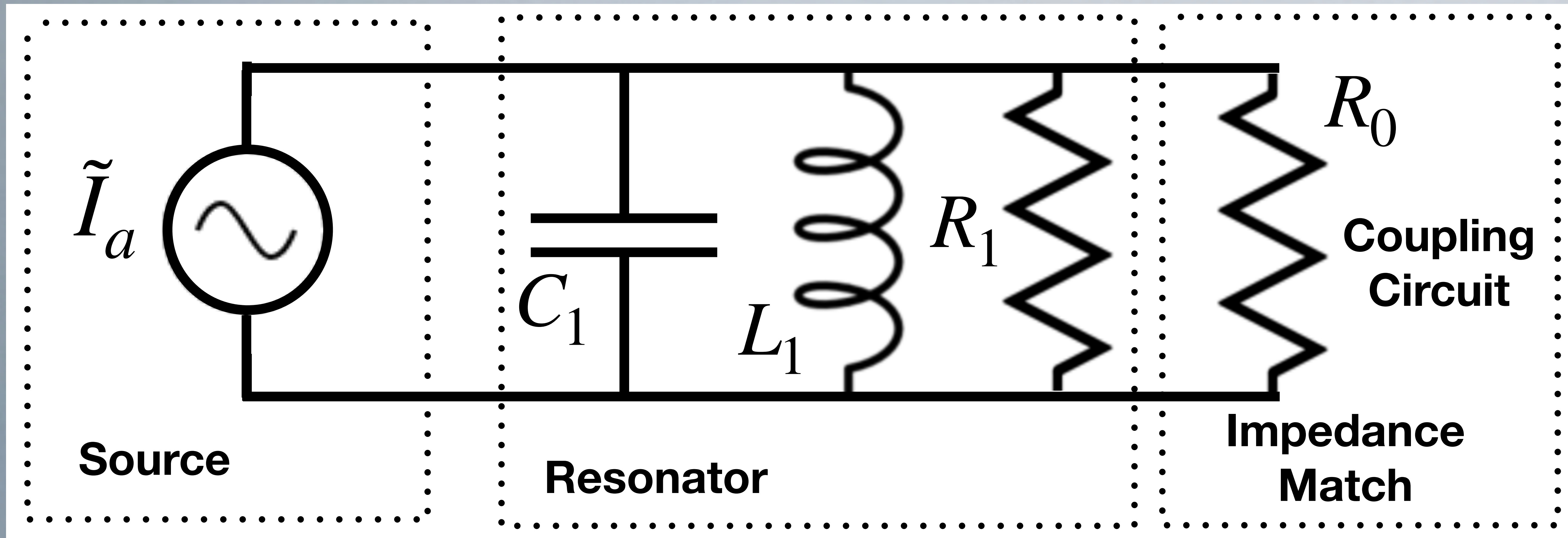
$$\mathbf{S} \sim -j\frac{J_0\left(\chi_{0n}\frac{r}{r_c}\right)J_1\left(\chi_{0n}\frac{r}{r_c}\right)}{J_1\left(\chi_{0n}\right)^2}$$

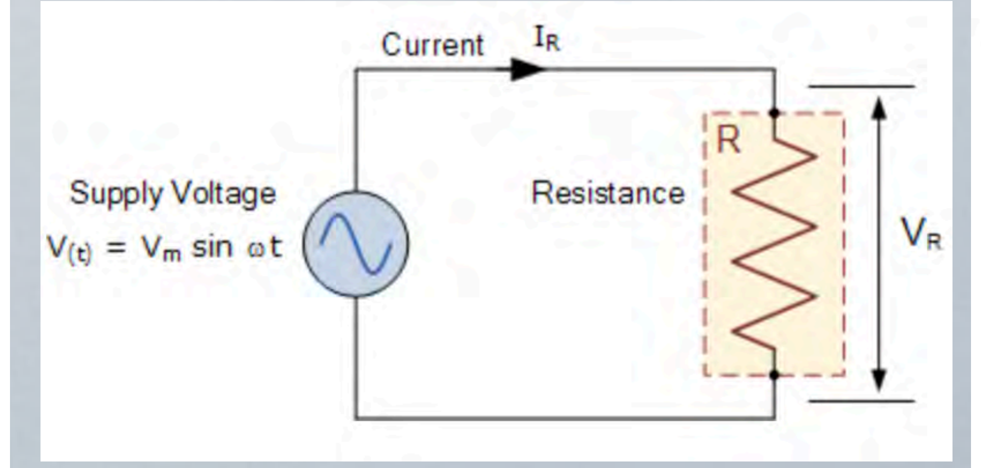
$$Q = \omega_1\frac{U_{tot}}{P_d} = 2\pi\frac{\text{stored energy}}{\text{energy dissipated during one period}}$$

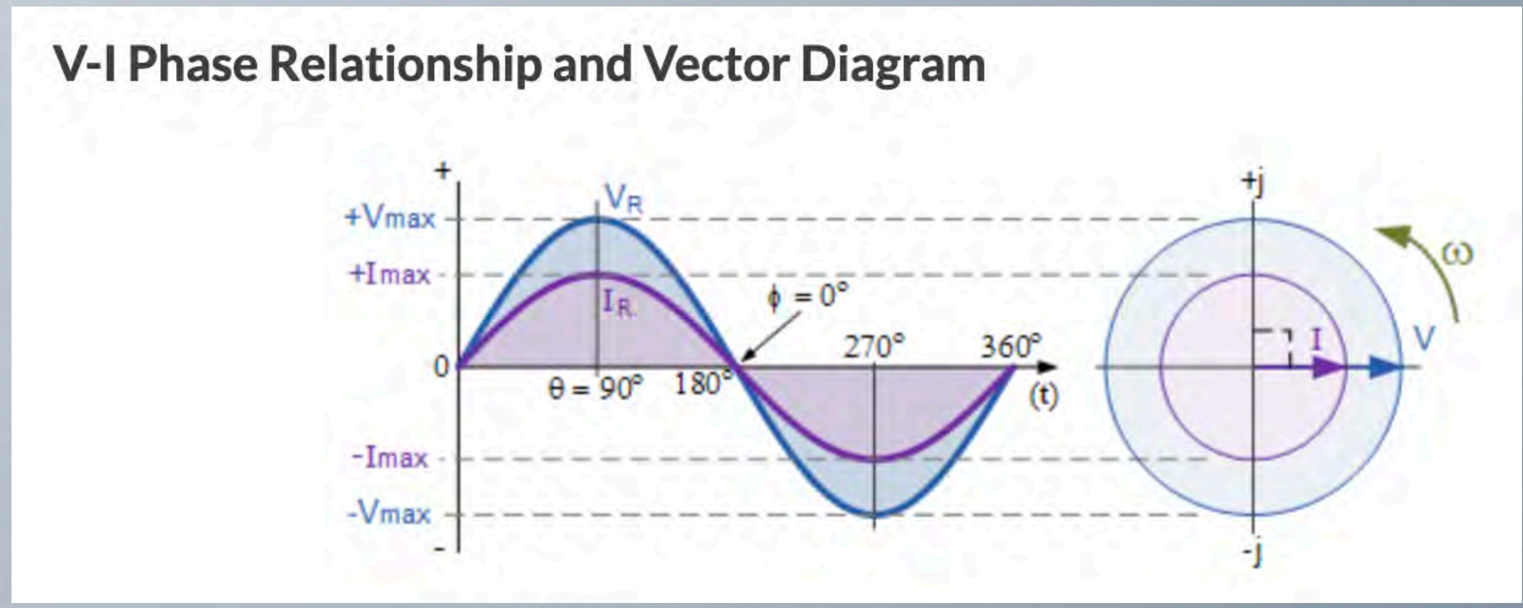
$$P_d = \frac{\omega_1 U_{tot}}{Q}$$



Resonator Measurement: Impedance match; set coupling =1; Take Photons from Source







Real Power Measurement, Absorbs Energy: $P_a = I_0^2 R_o = \dfrac{V_0^2}{R_0}$

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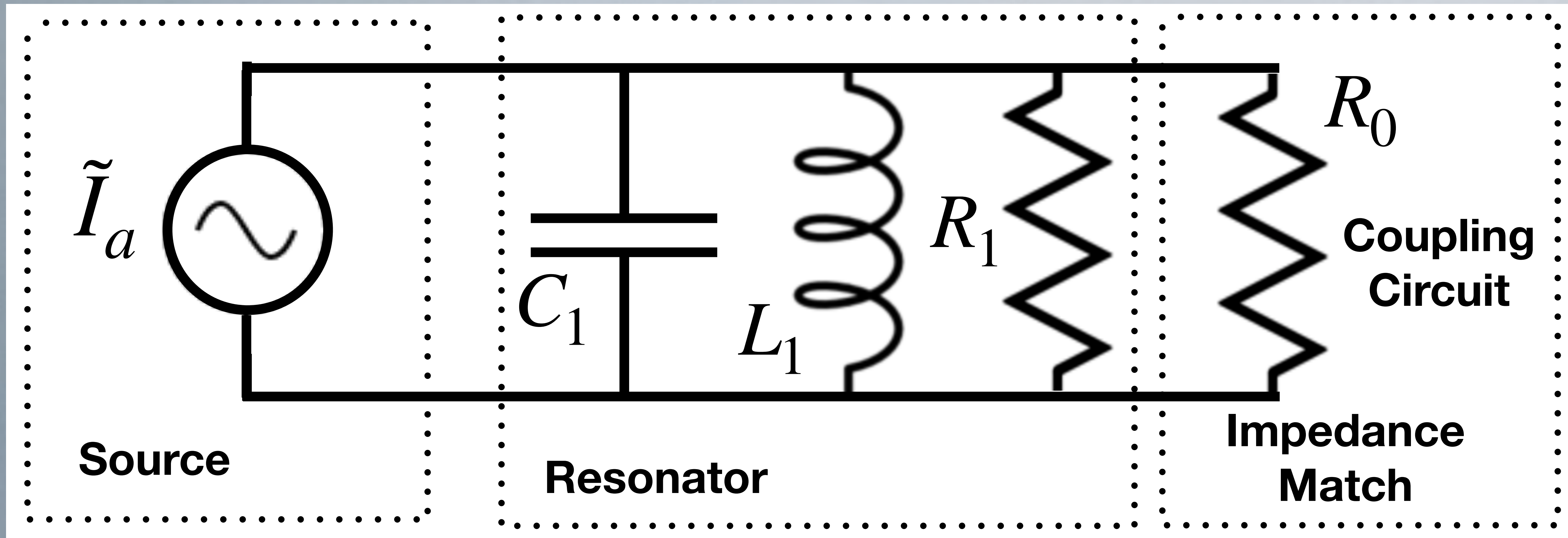

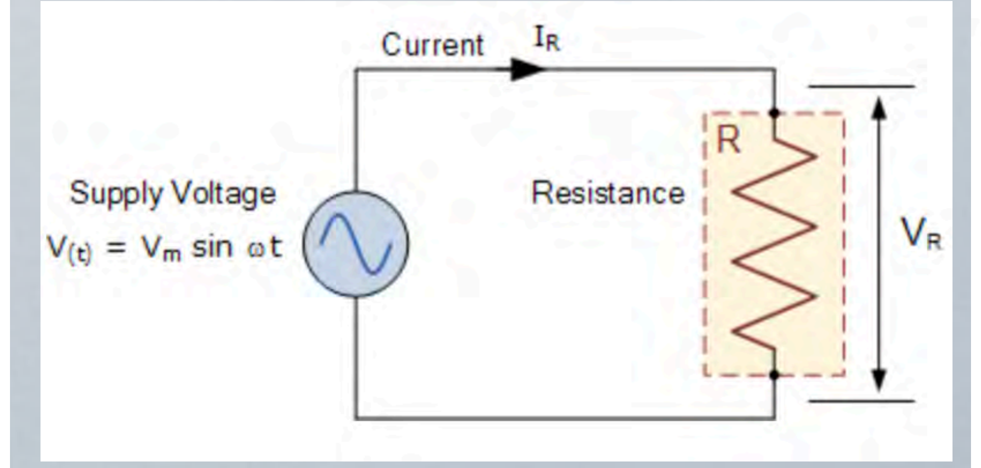

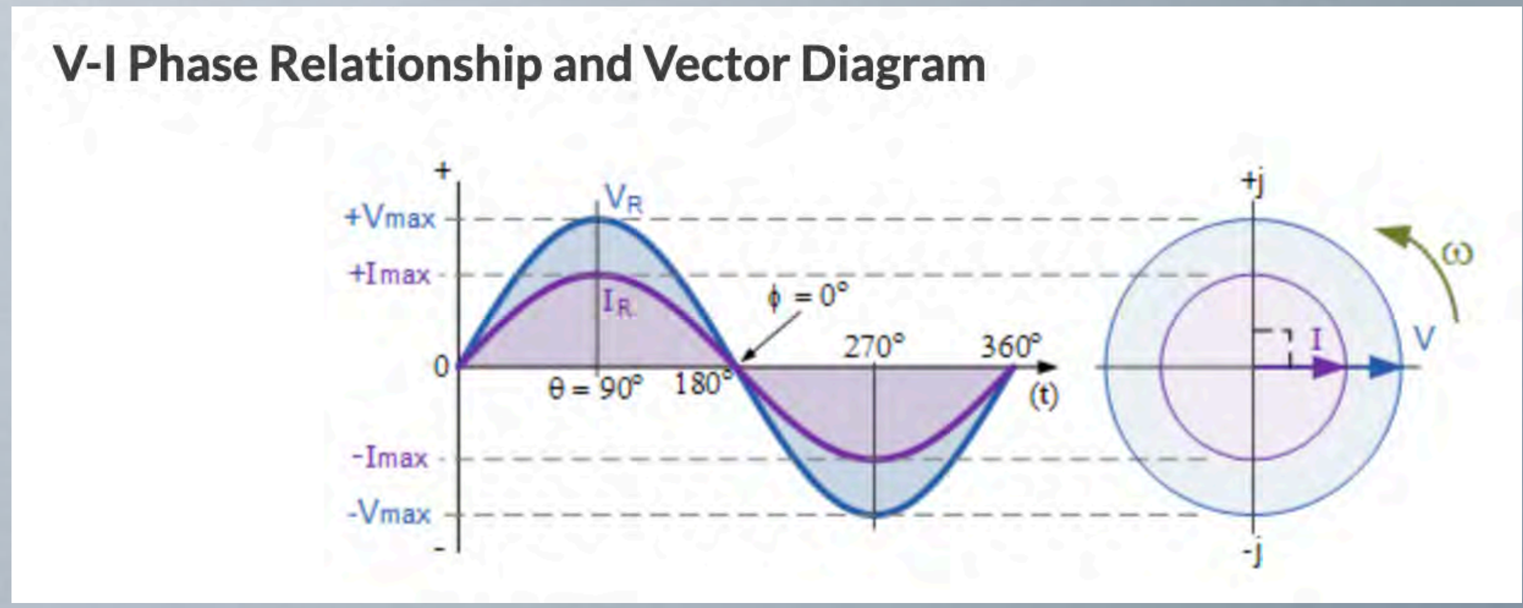

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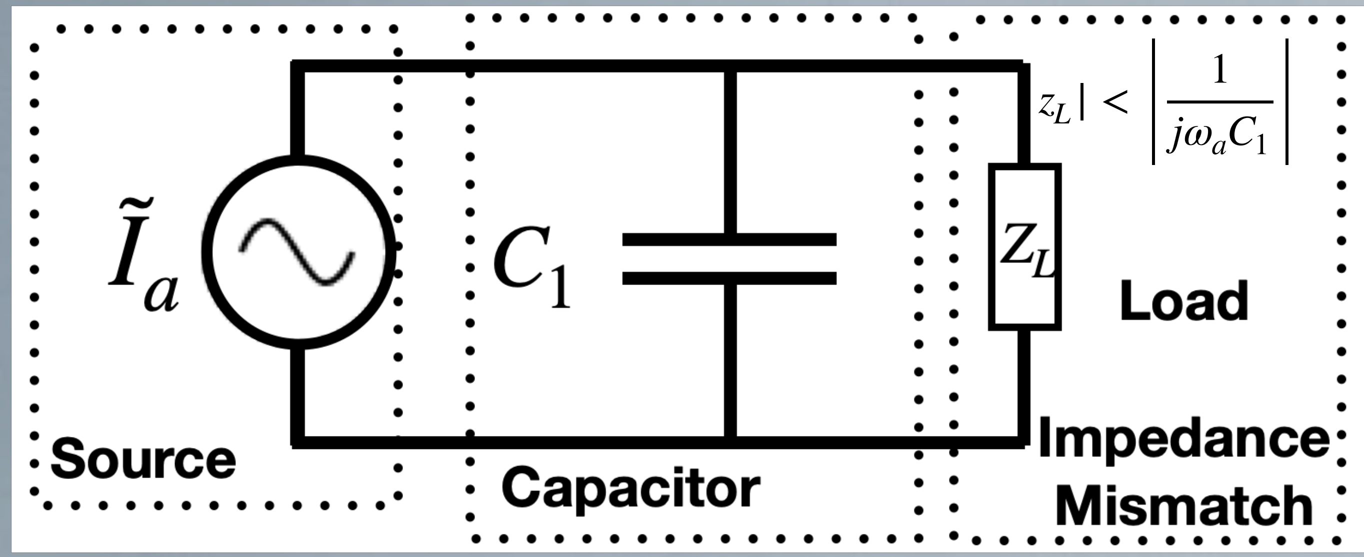

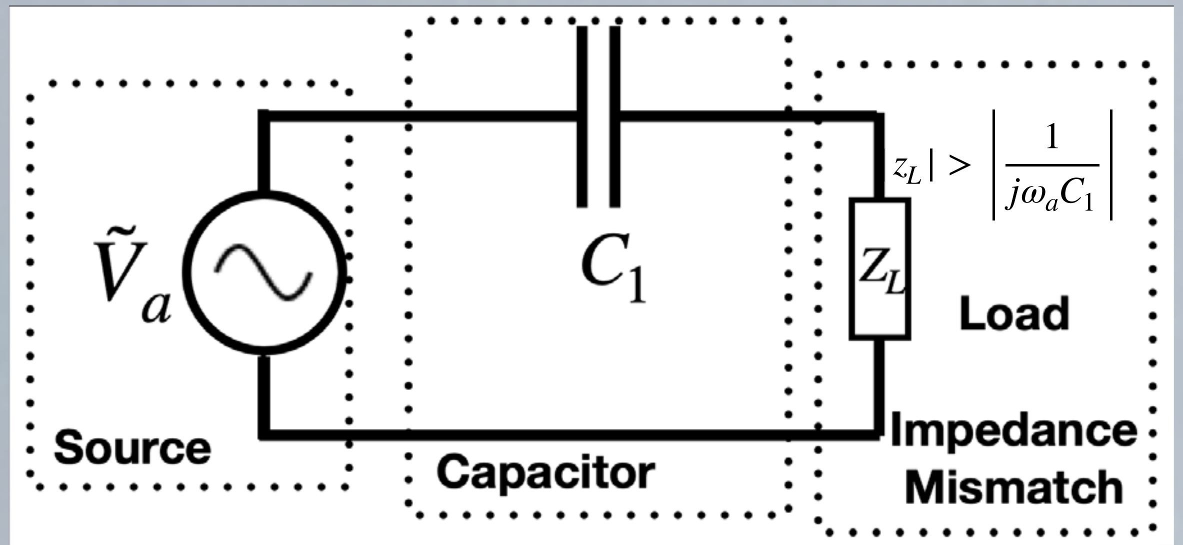

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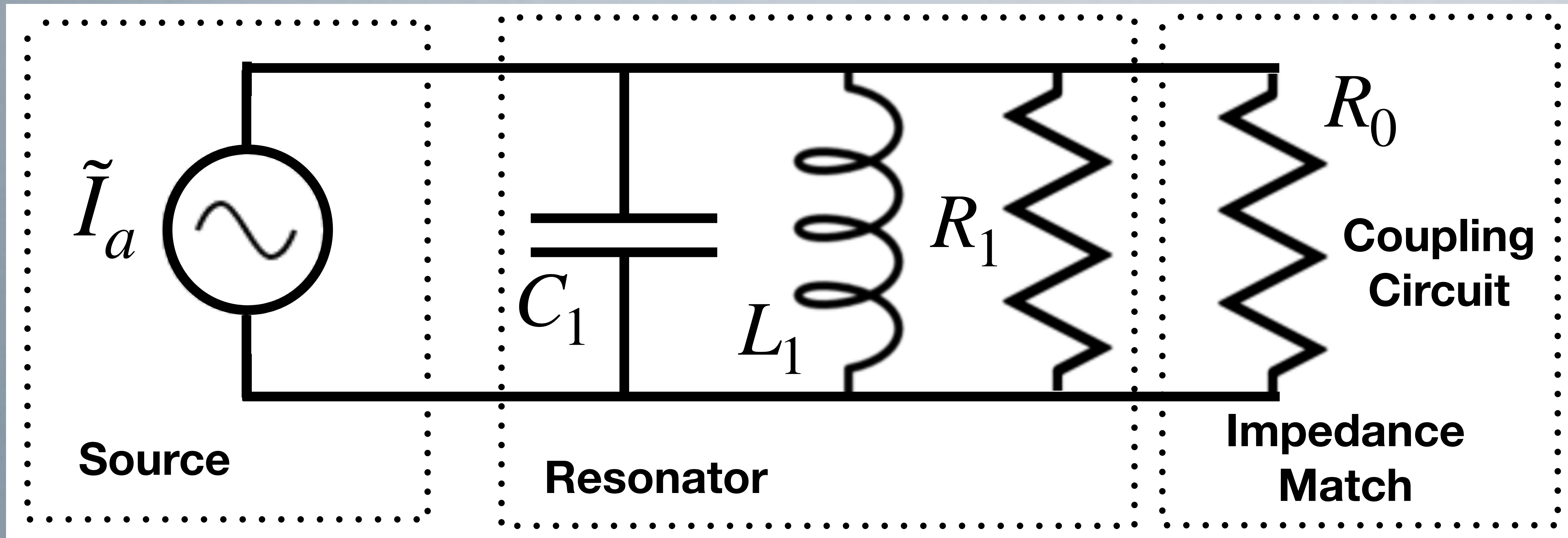

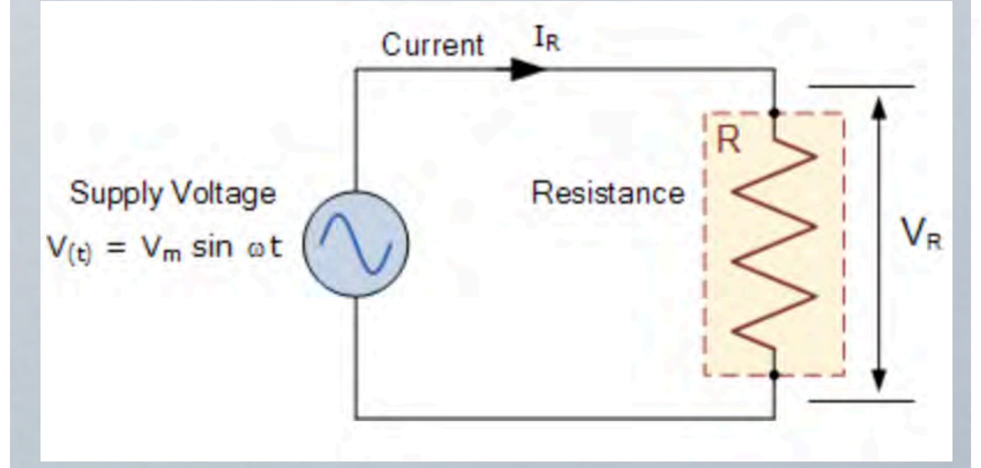

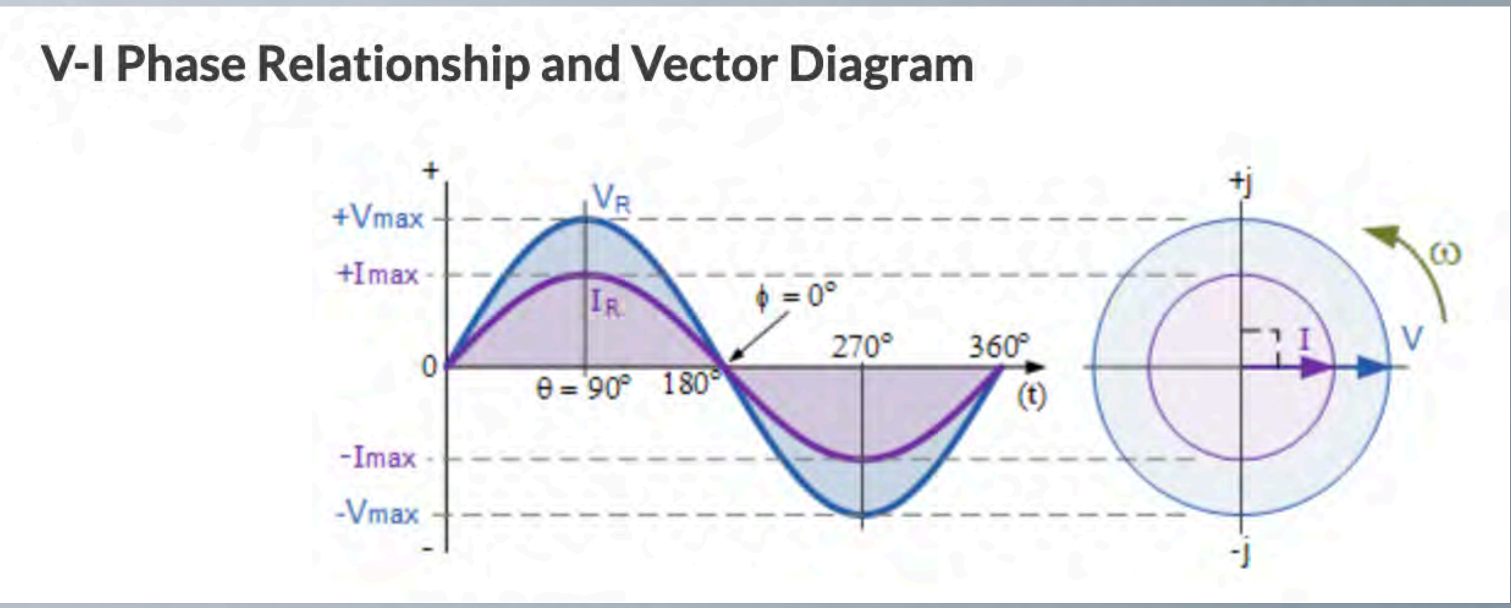

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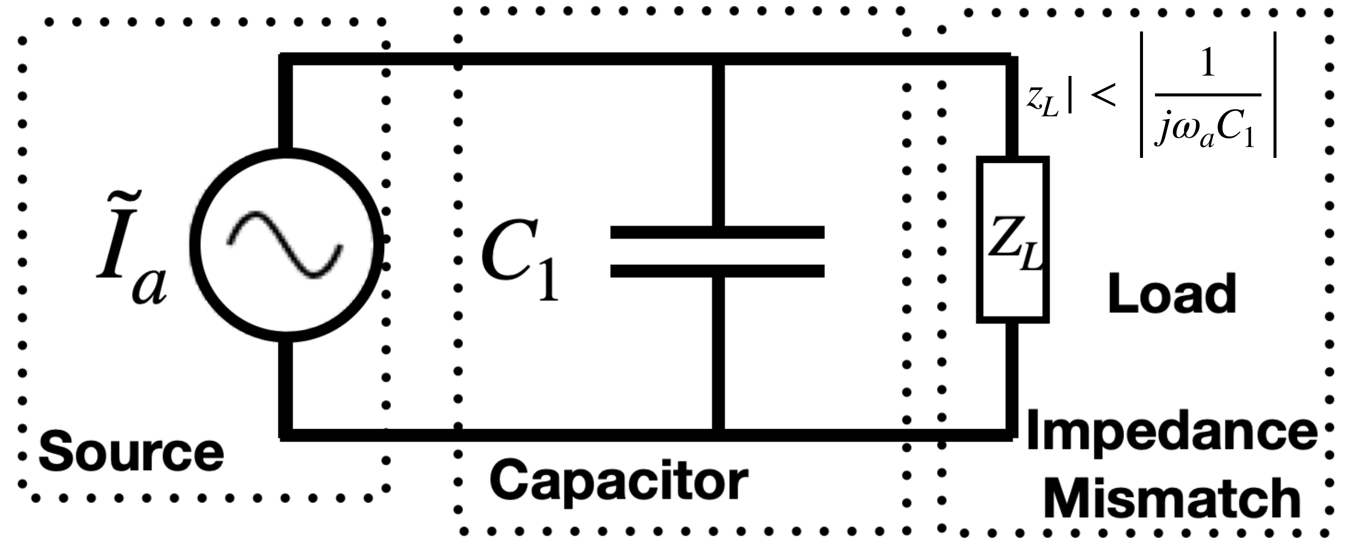
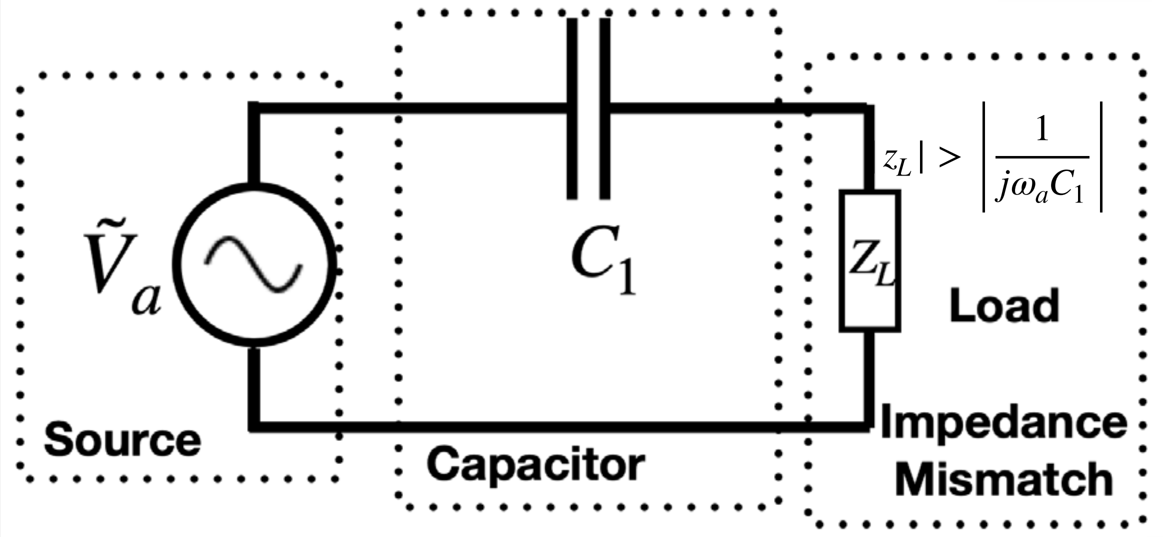
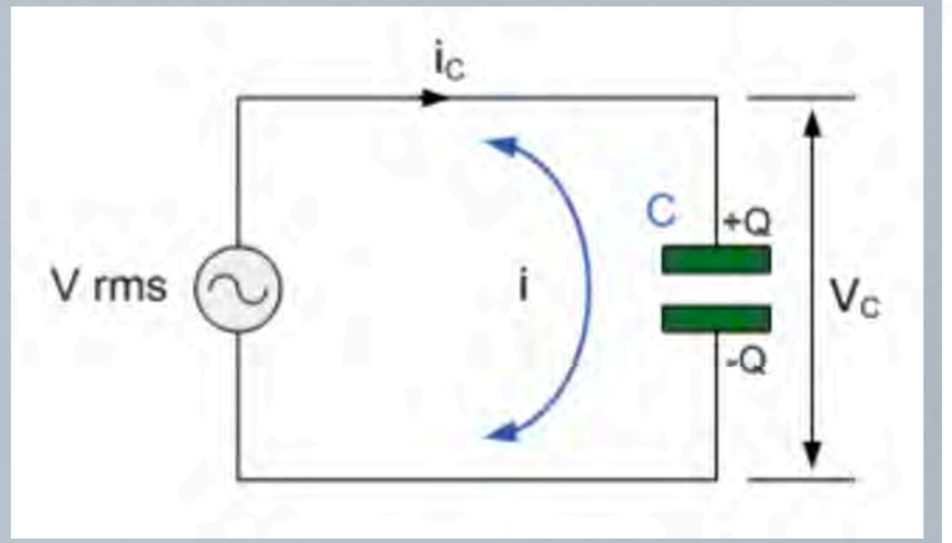
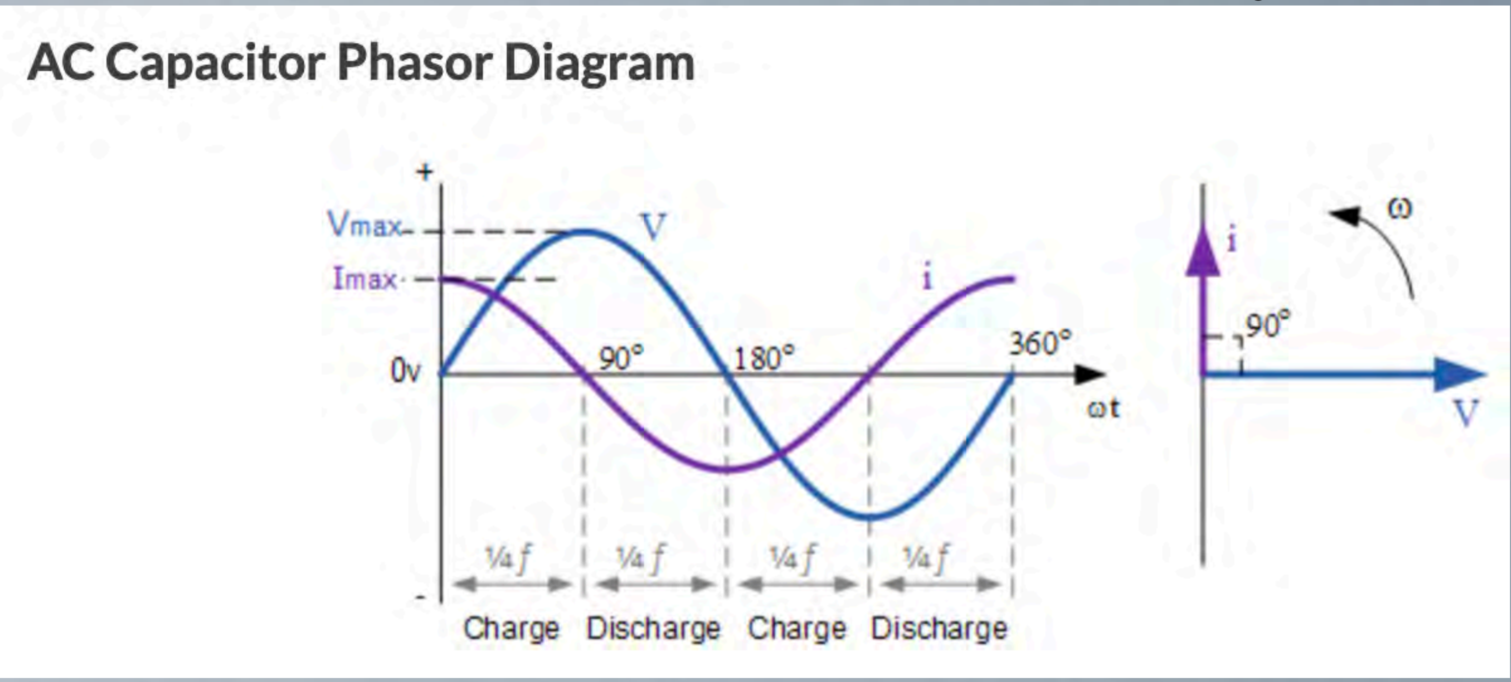
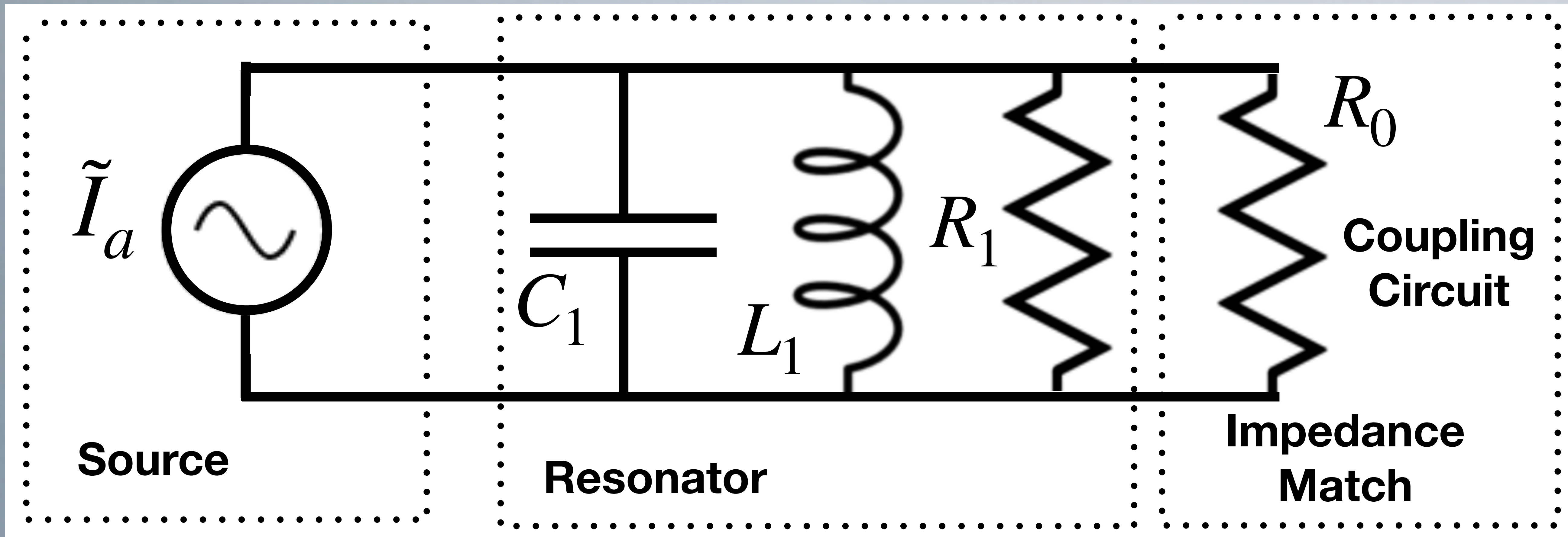


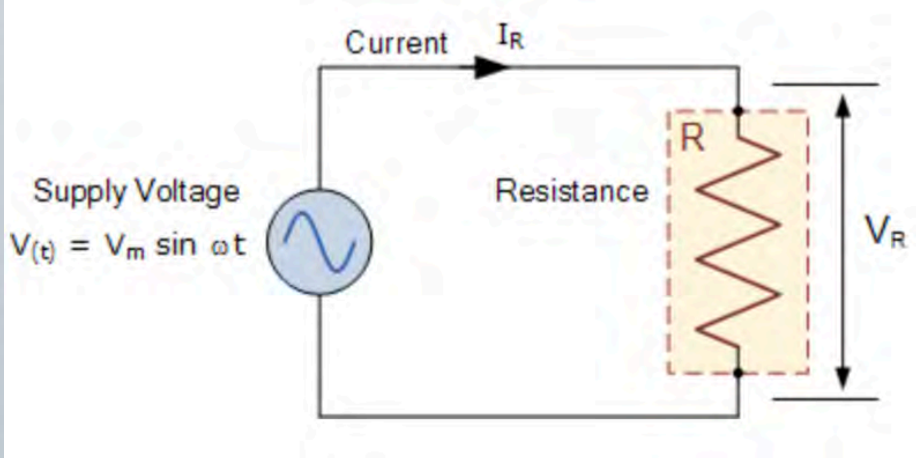


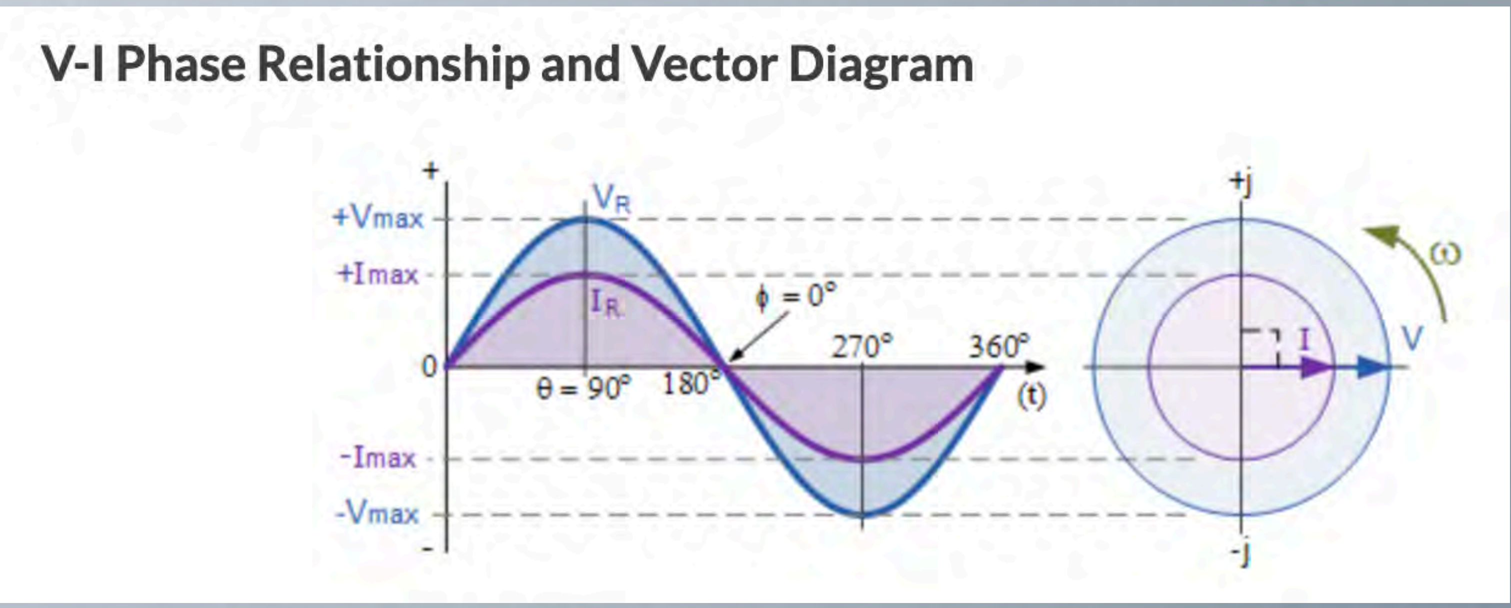




Resonator Measurement: Impedance match; set coupling =1; Take Photons from Source







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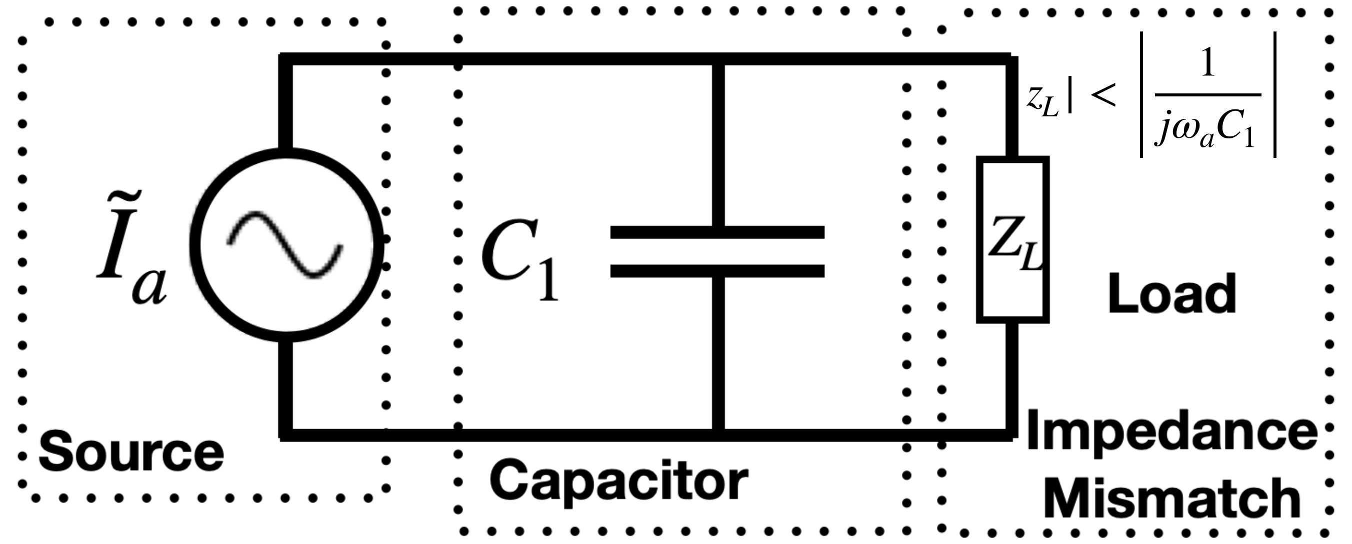
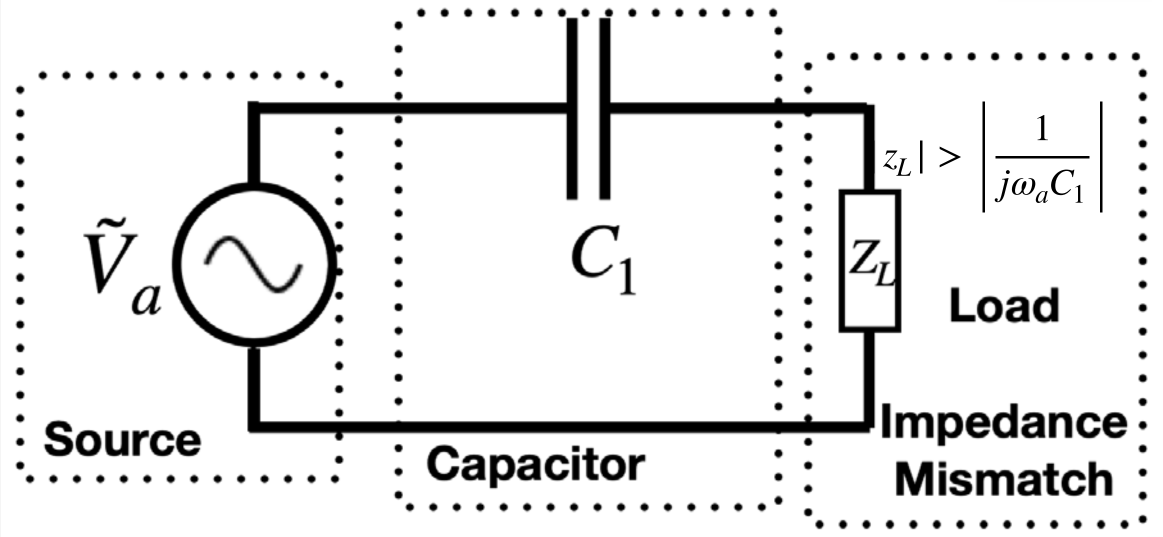
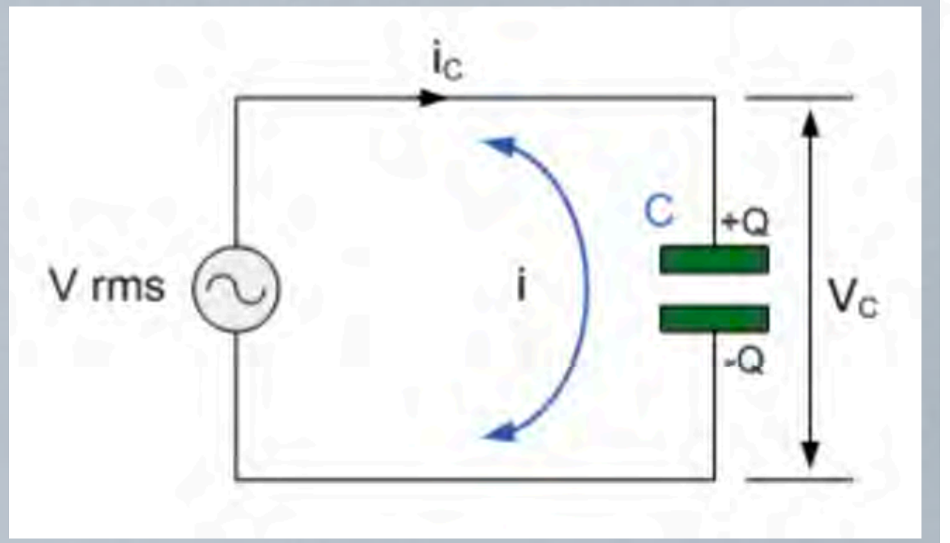
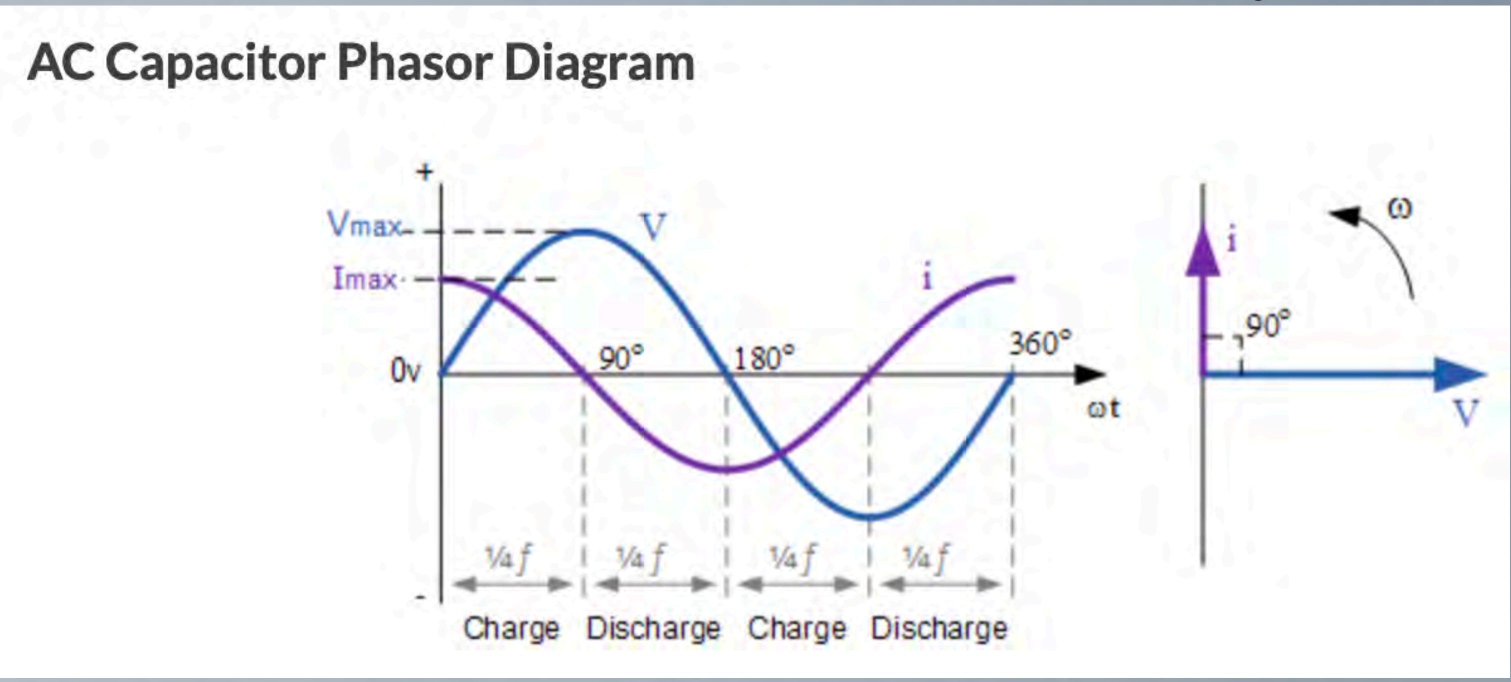


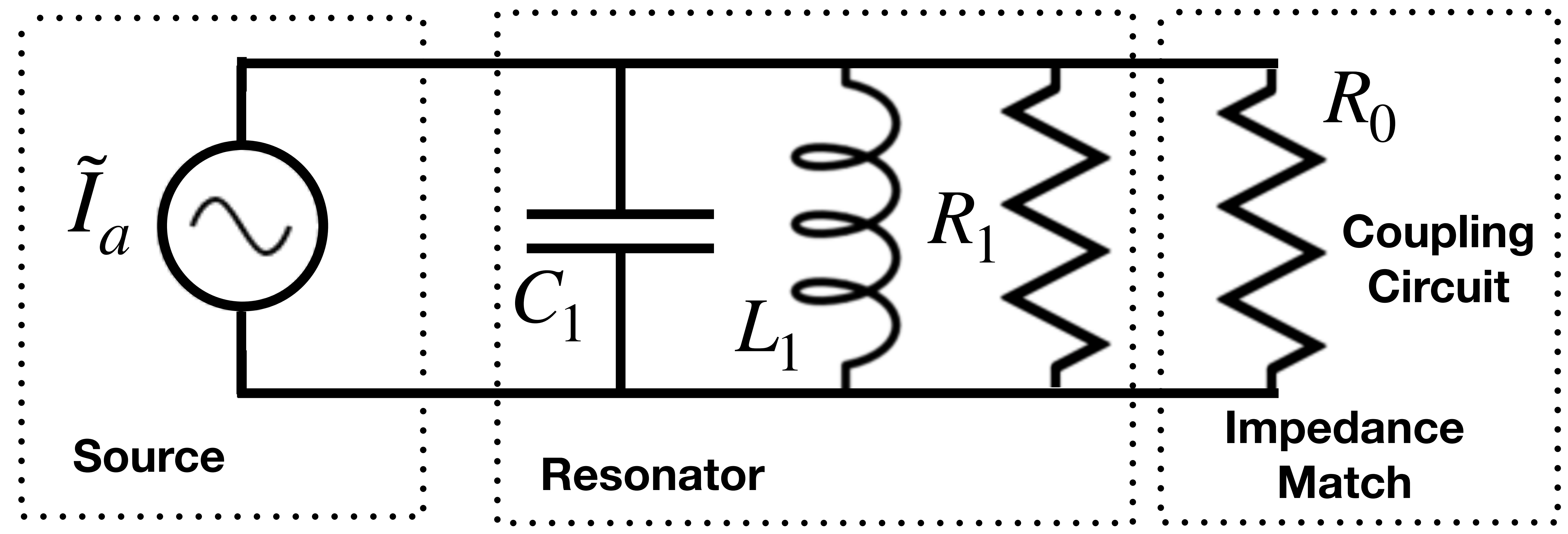


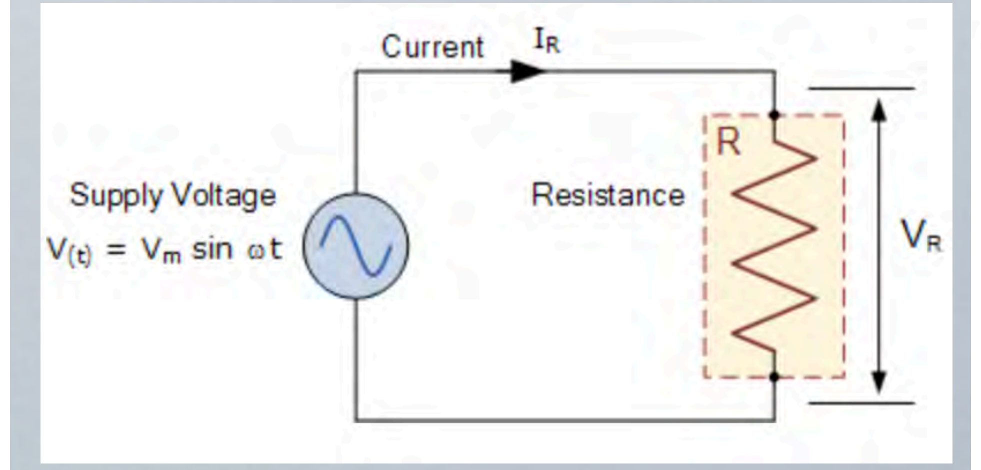


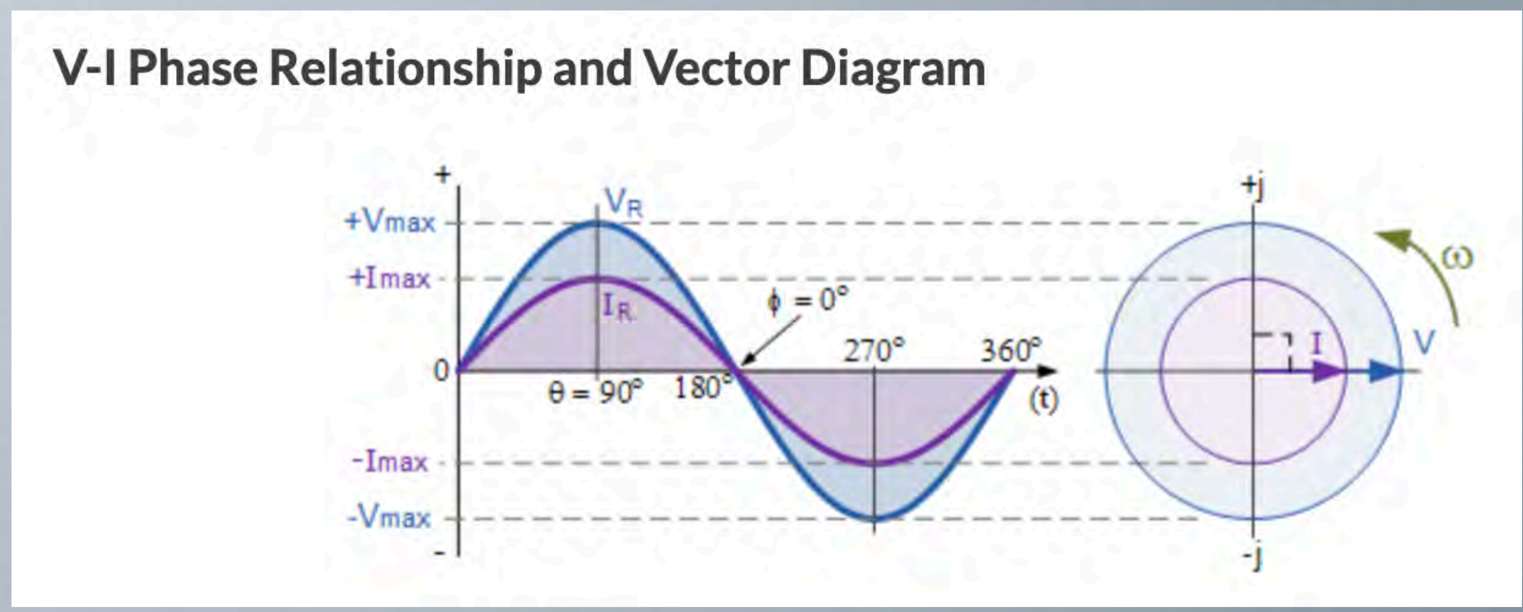


Reactive Power Measurement, Does Not Absorb Energy:

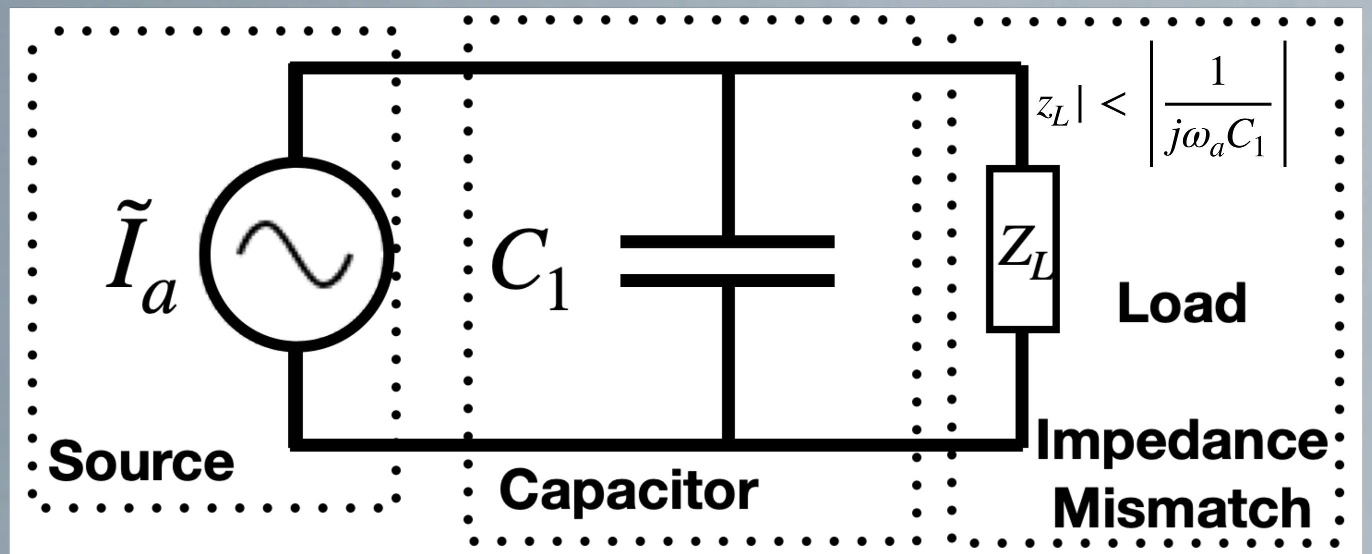
Resonator Measurement: Impedance match; set coupling =1; Take Photons from Source

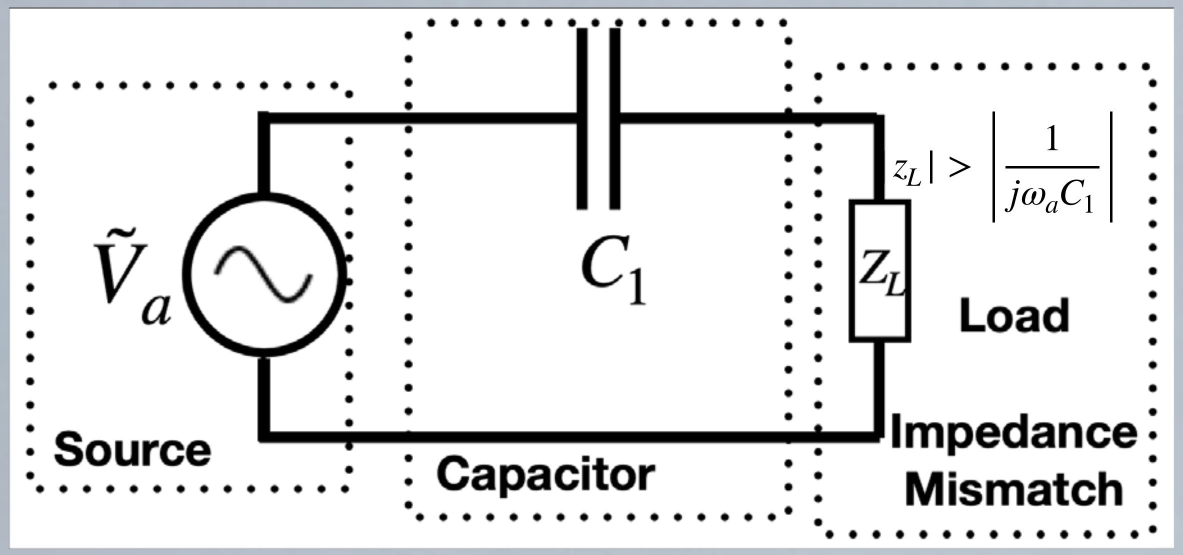


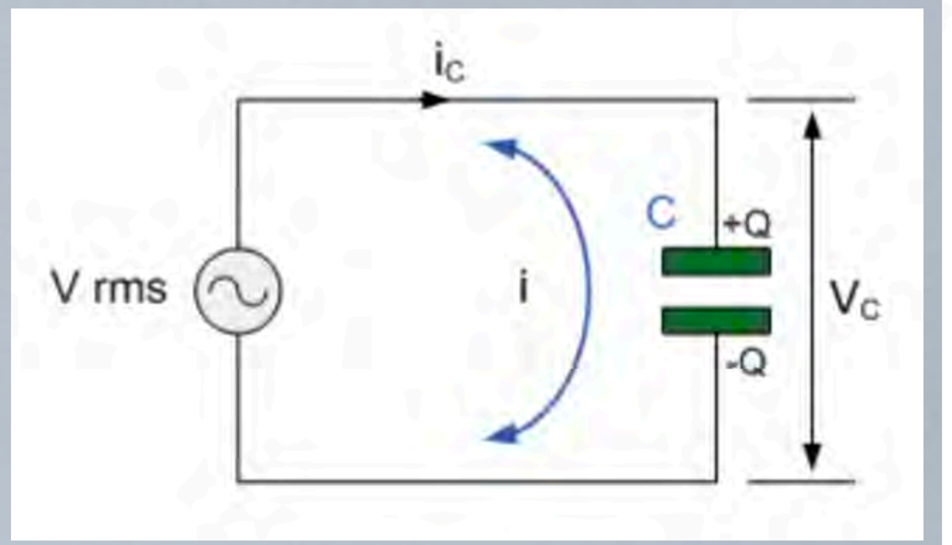


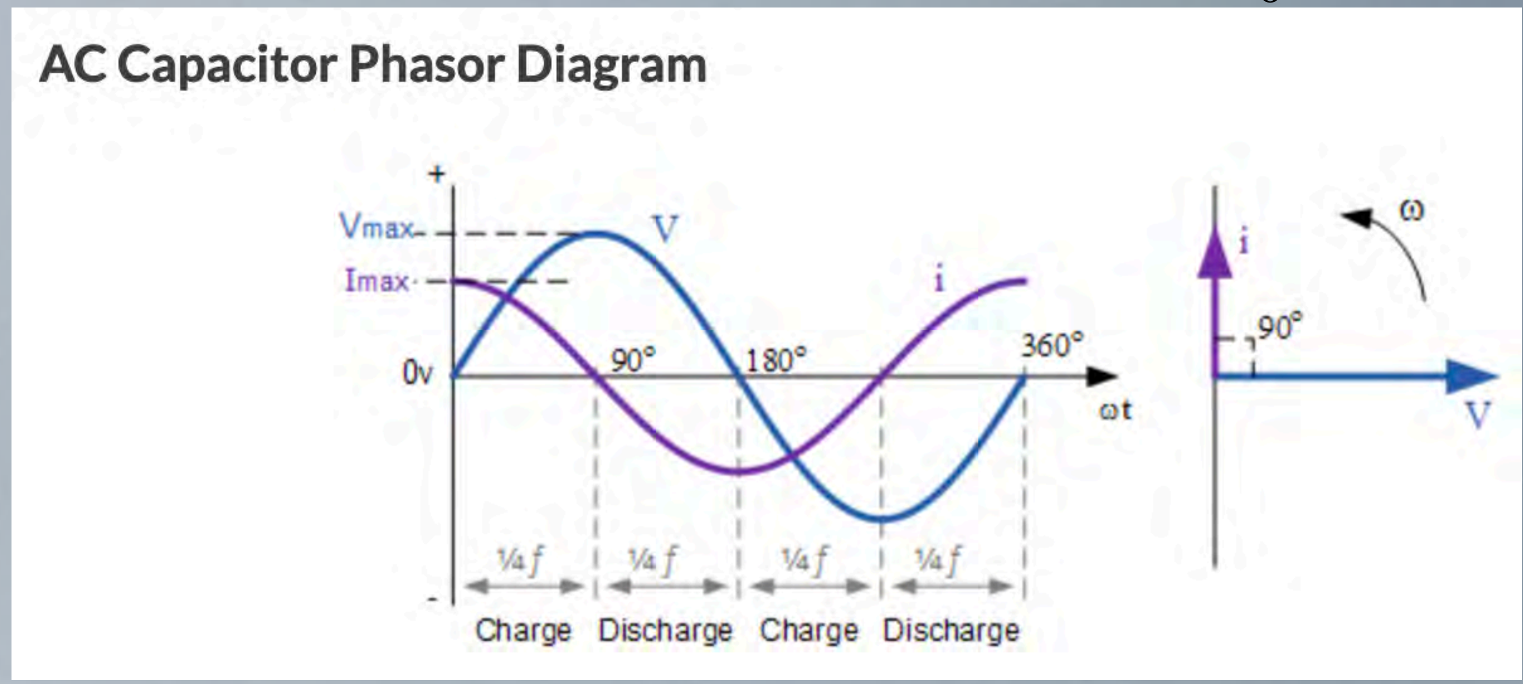


Real Power Measurement, Absorbs Energy: $P_a = I_0^2 R_o = \dfrac{V_0^2}{R_0}$





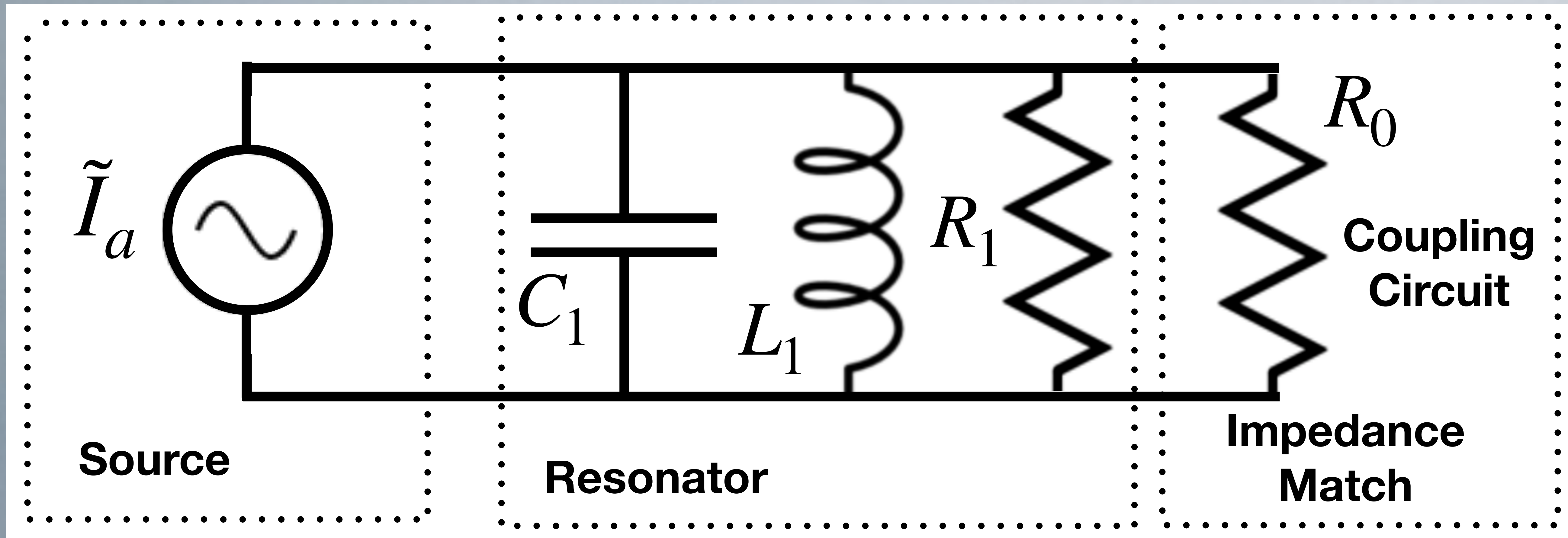


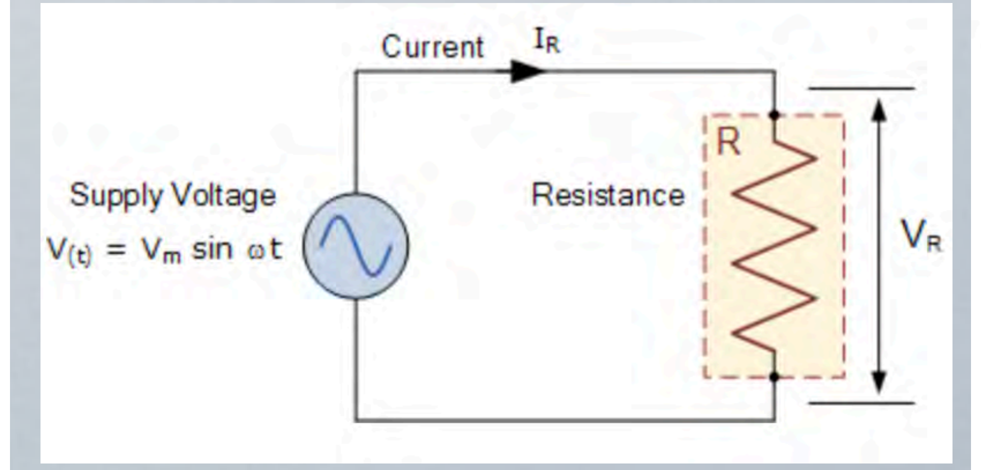


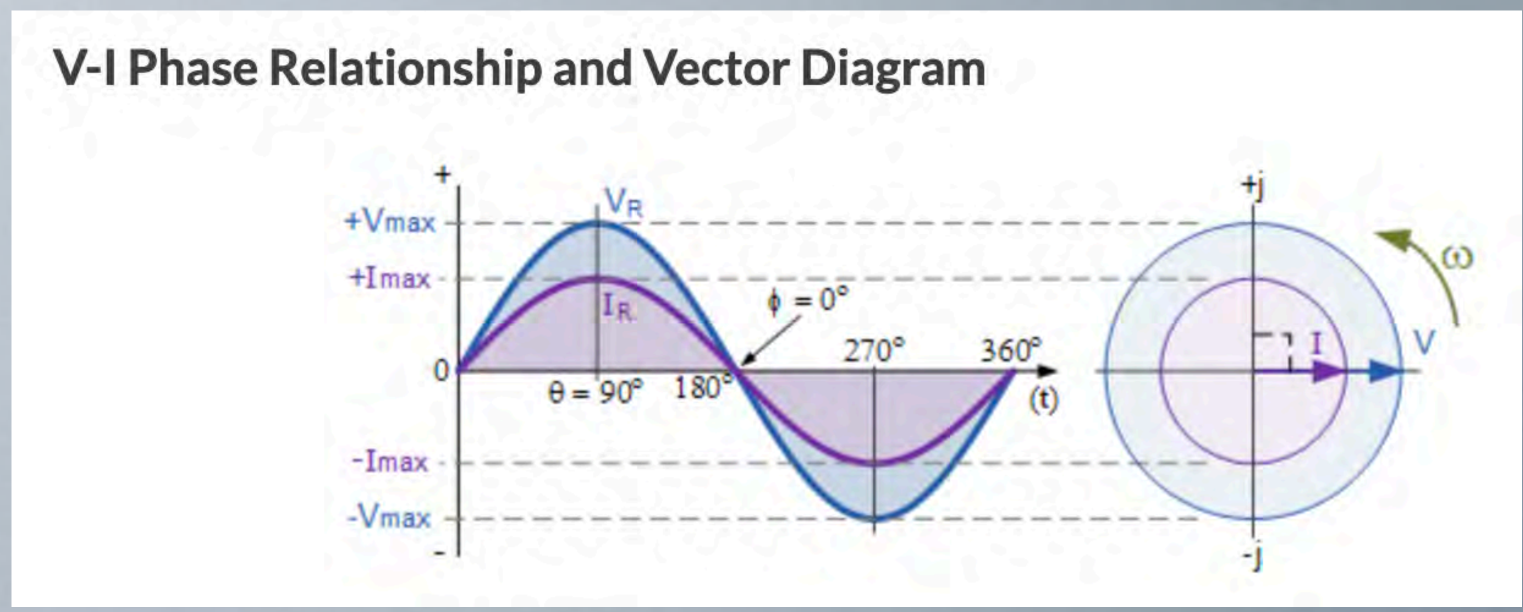
Reactive Power Measurement, Does Not Absorb Energy:

Left eg. Inductive couple SQUID Amplifier (Current of Mag Flux)

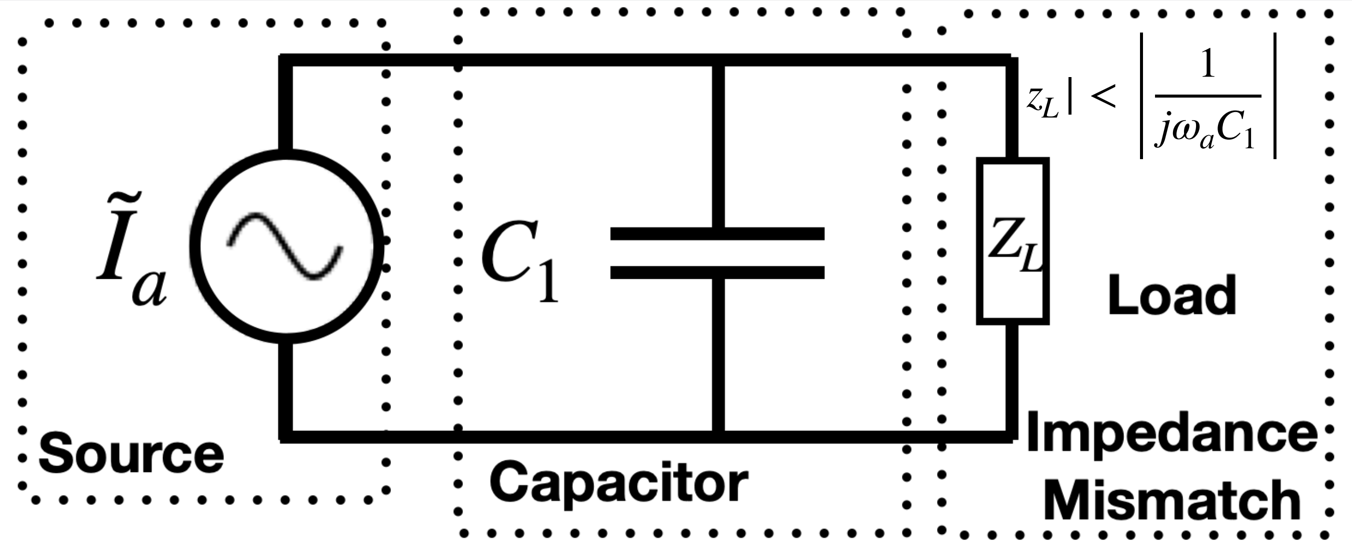
Resonator Measurement: Impedance match; set coupling =1; Take Photons from Source

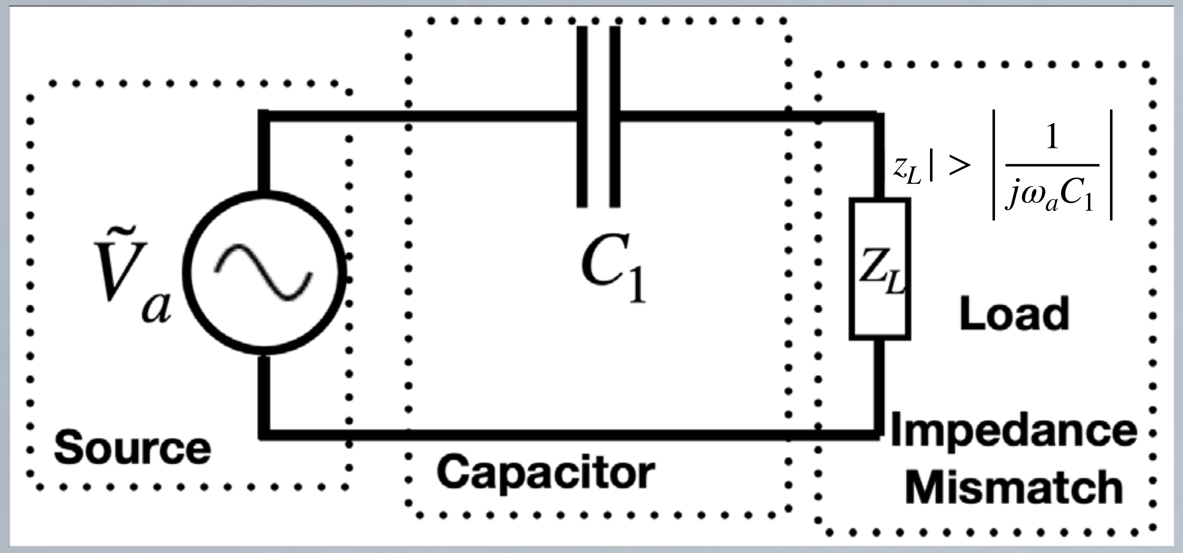


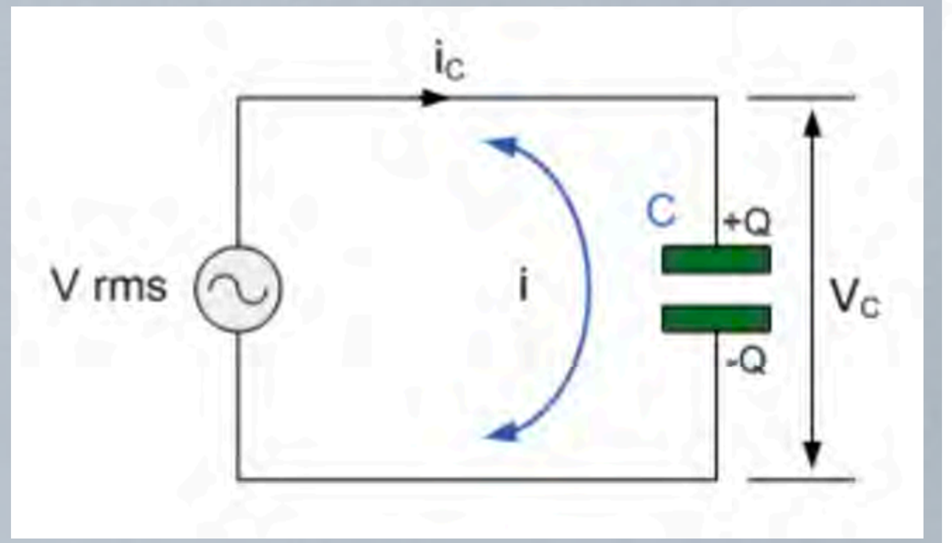


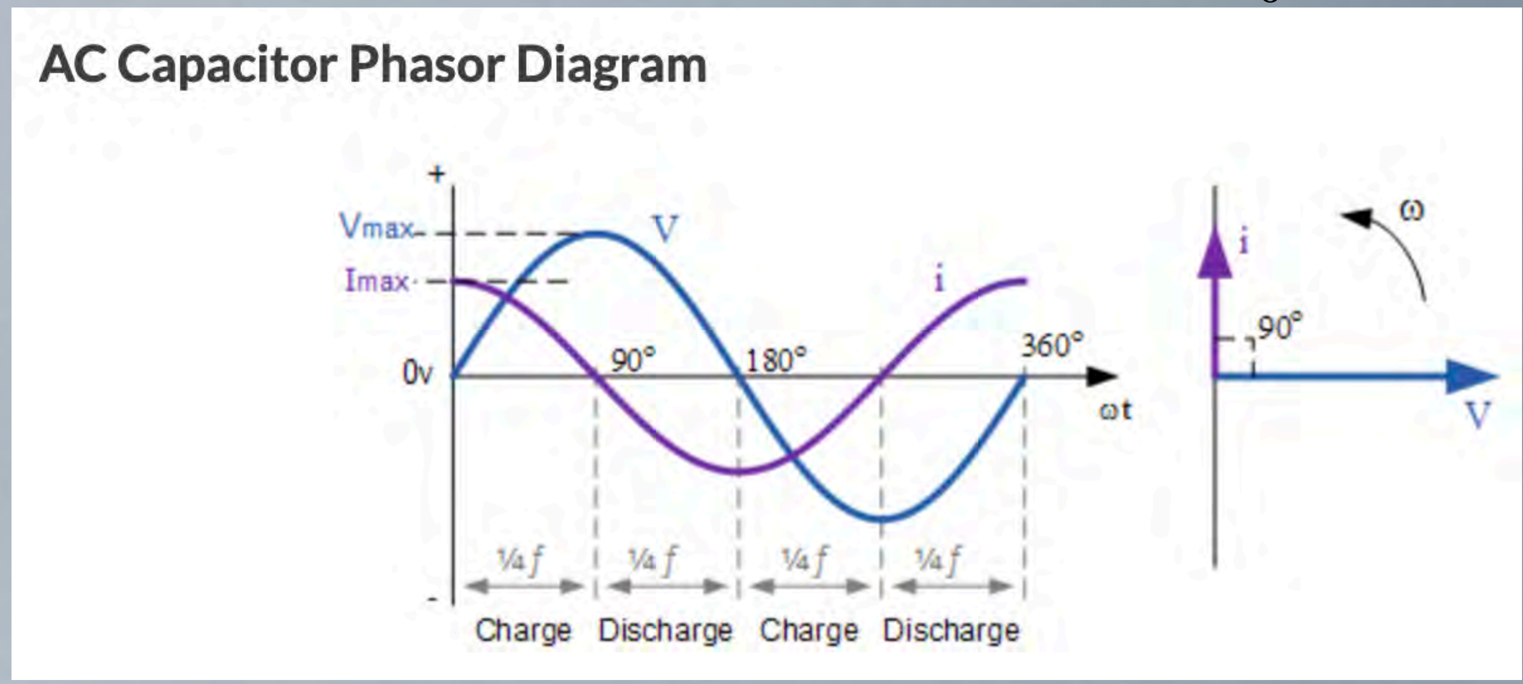


Real Power Measurement, Absorbs Energy: $P_a = I_0^2 R_o = \dfrac{V_0^2}{R_0}$







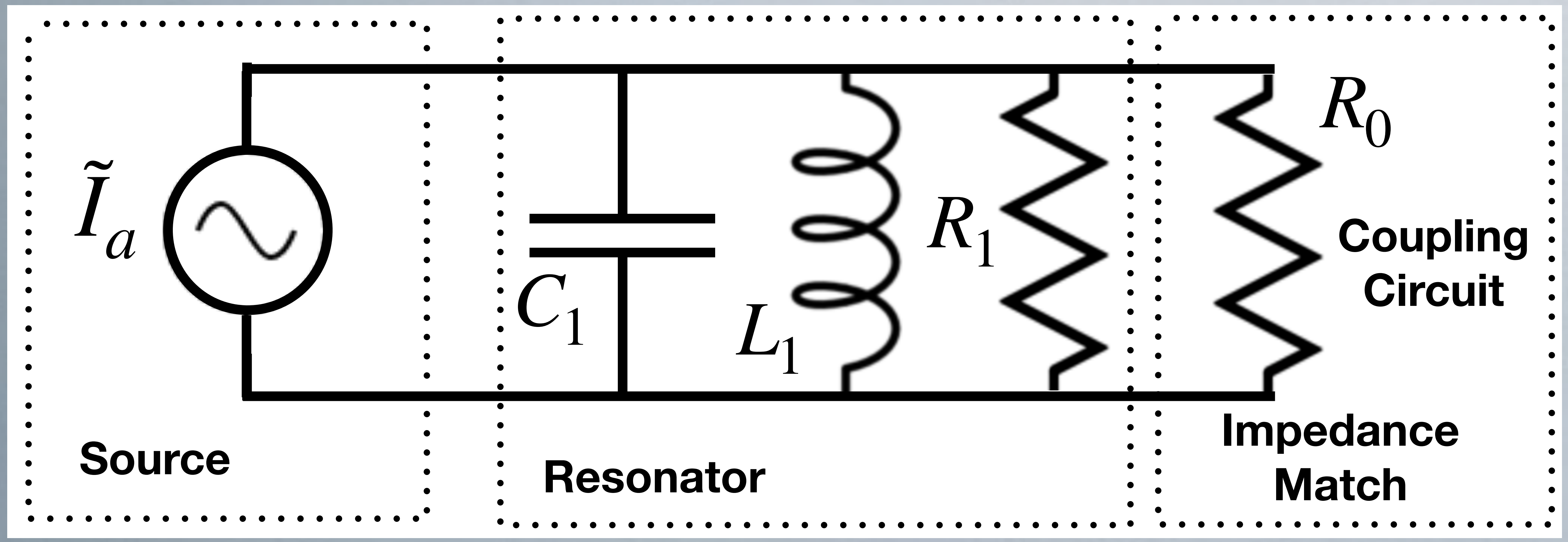


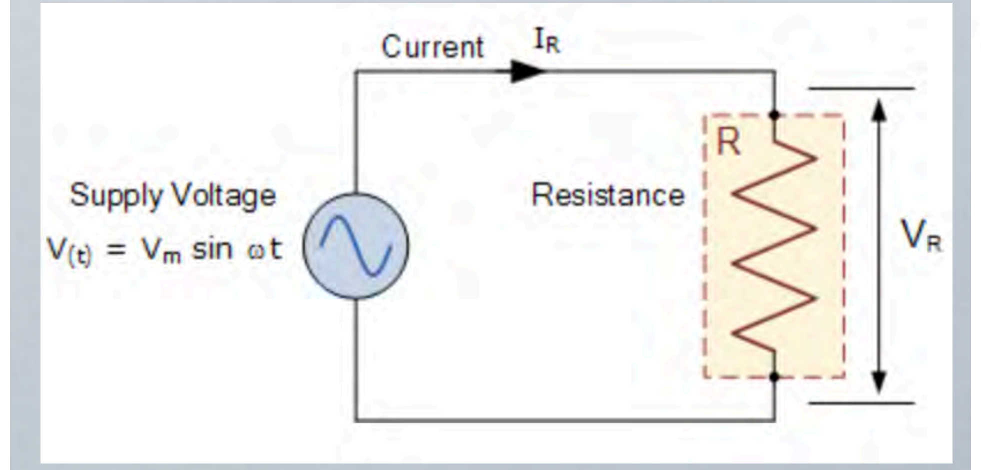
Reactive Power Measurement, Does Not Absorb Energy:

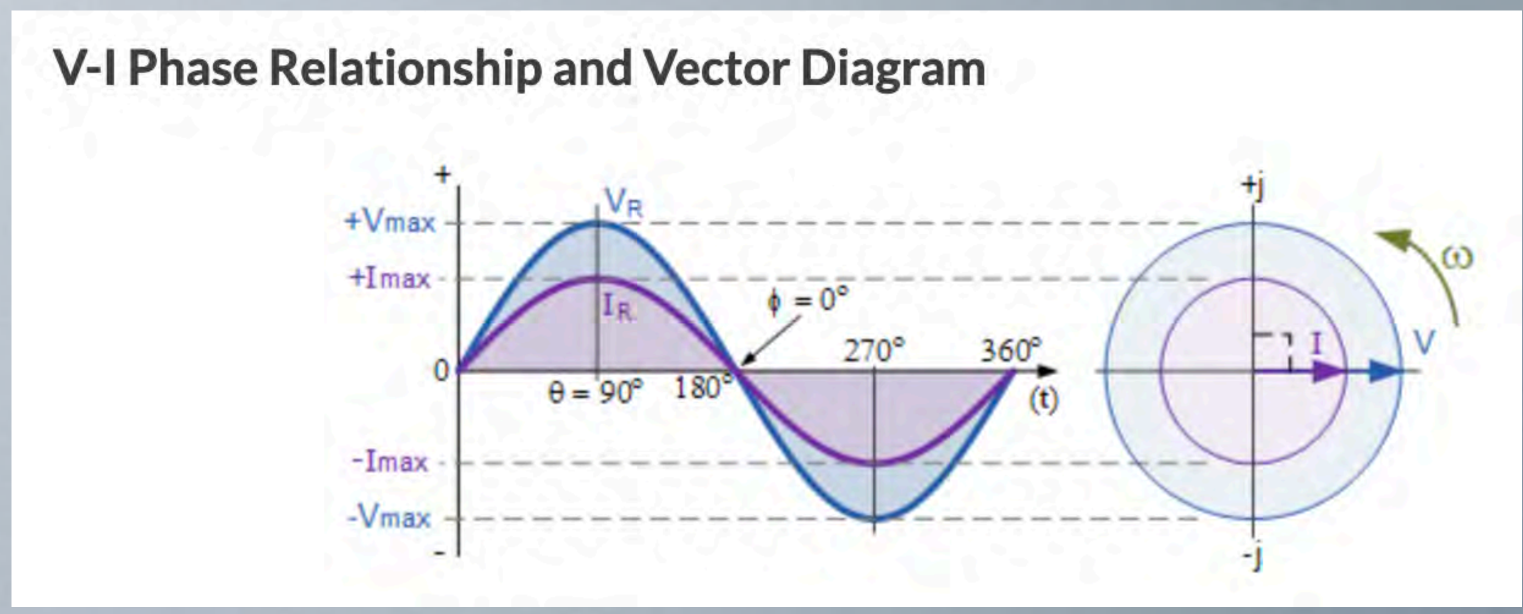
Left eg. Inductive couple SQUID Amplifier (Current of Mag Flux)

Right eg. Capacitive coupled High Impedance Amplifier (Voltage)

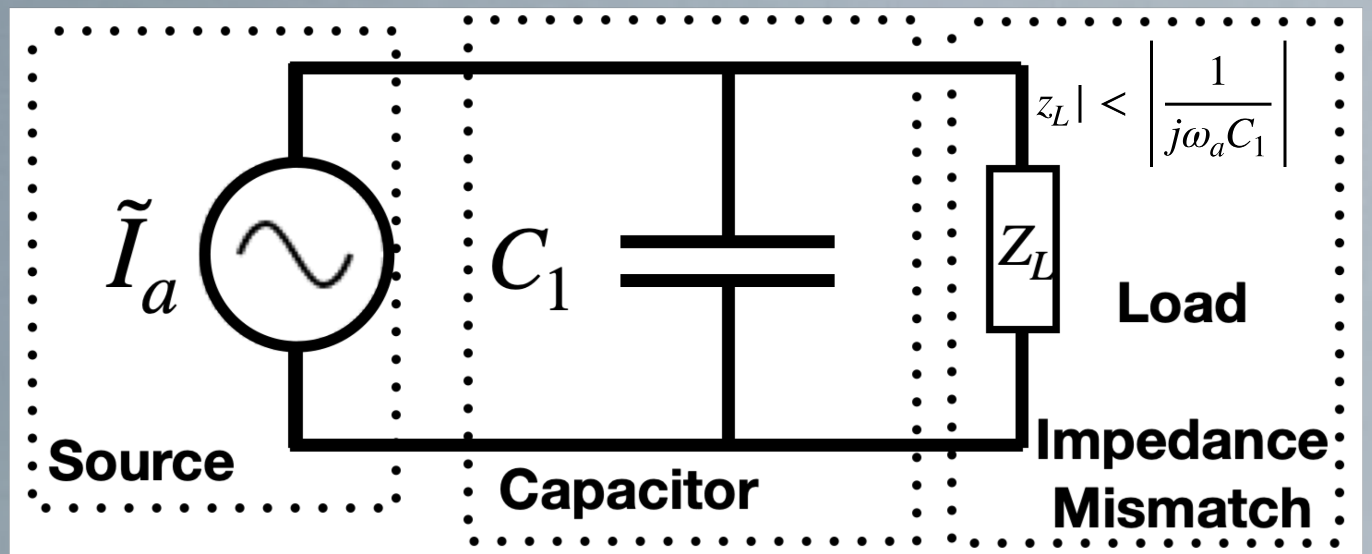
Resonator Measurement: Impedance match; set coupling =1; Take Photons from Source

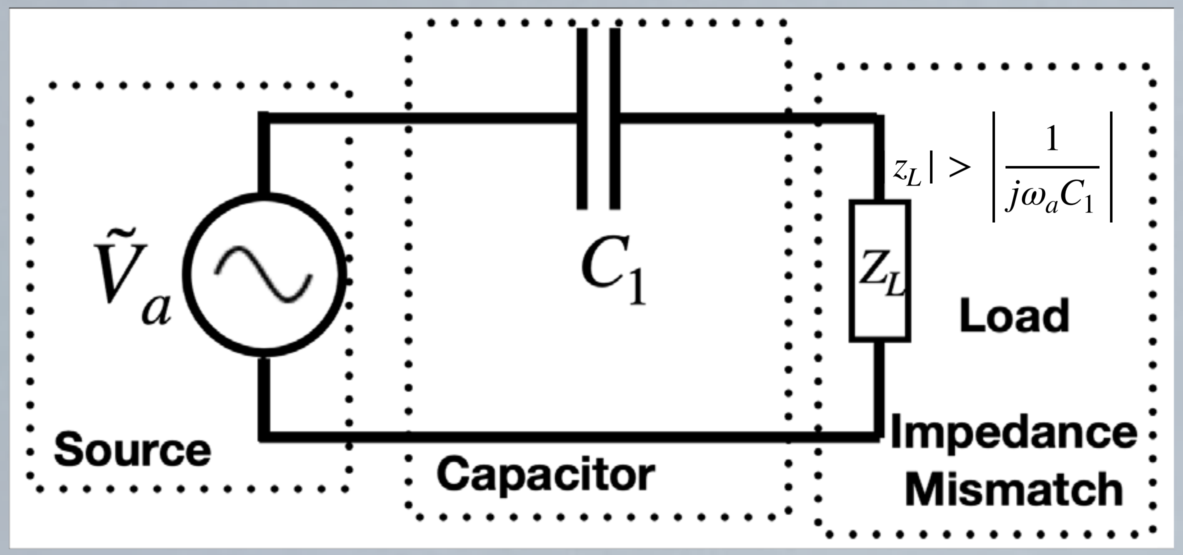


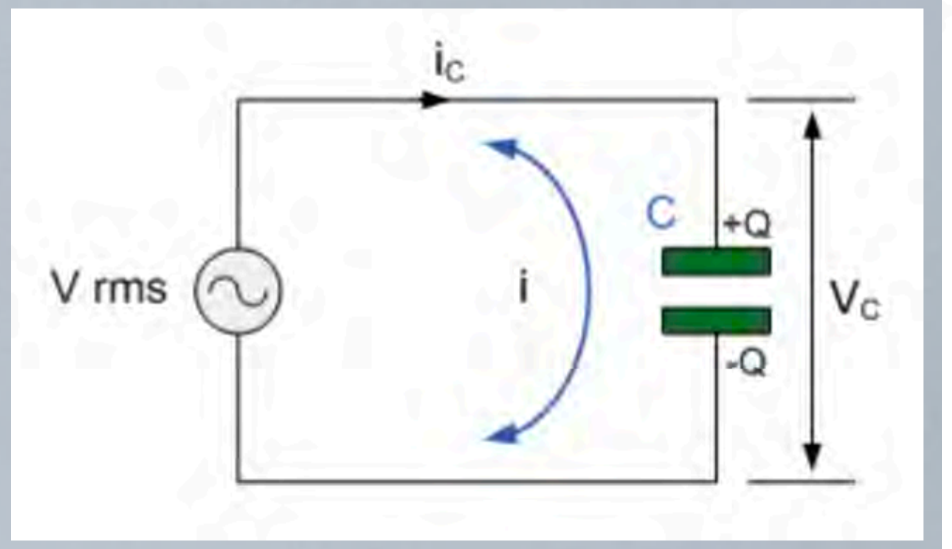


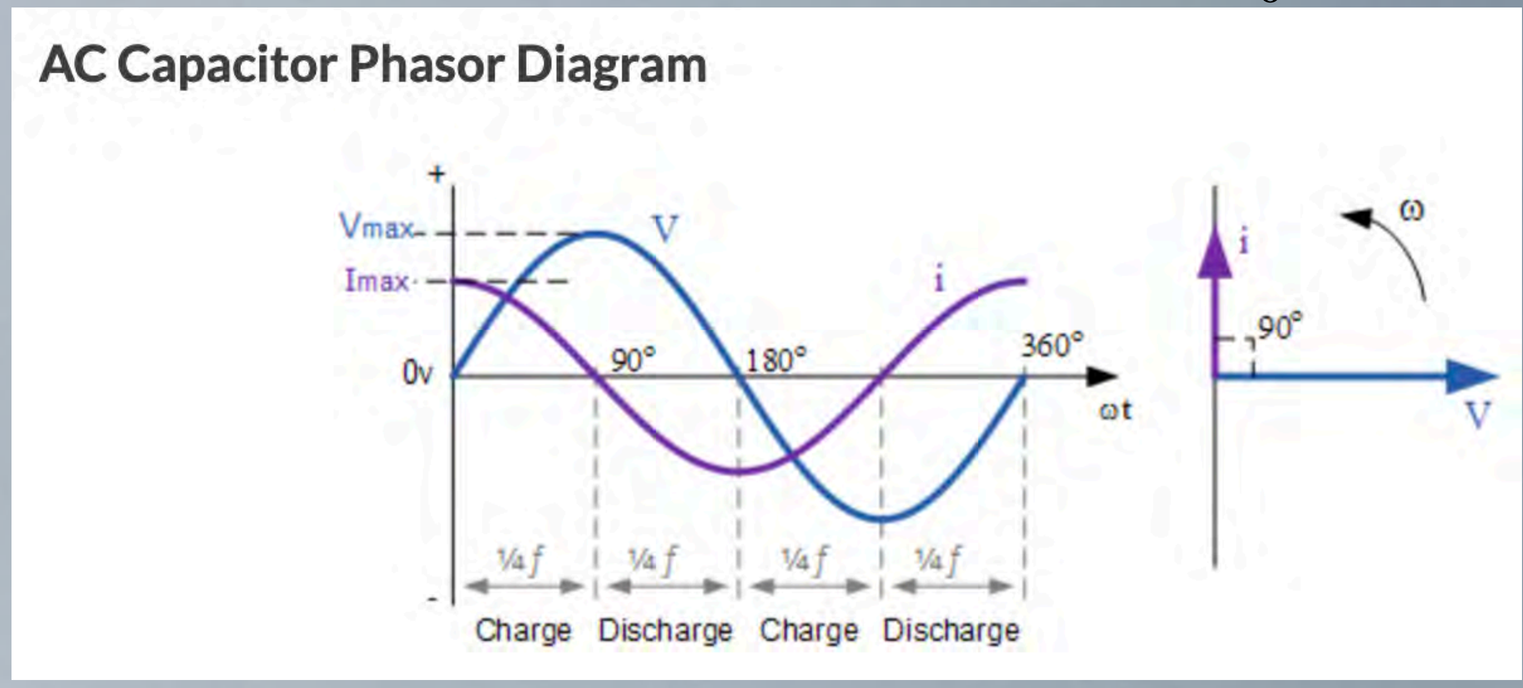


Real Power Measurement, Absorbs Energy: $P_a = I_0^2 R_o = \dfrac{V_0^2}{R_0}$









Reactive Power Measurement, Does Not Absorb Energy:

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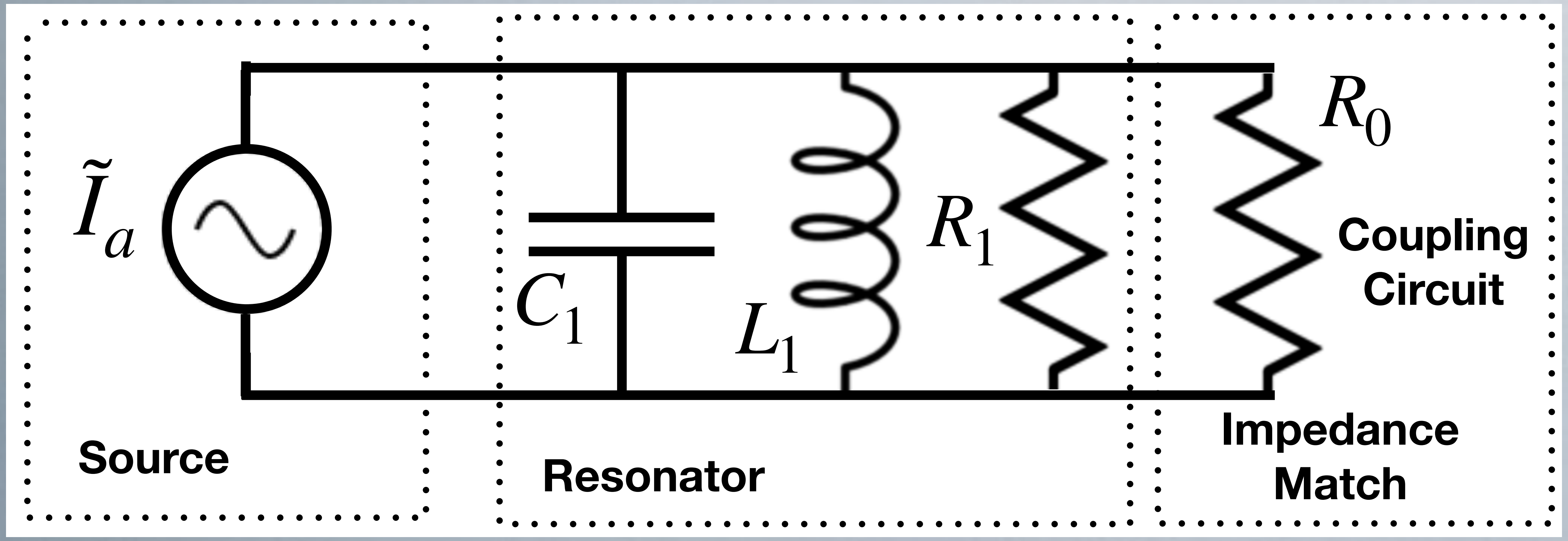

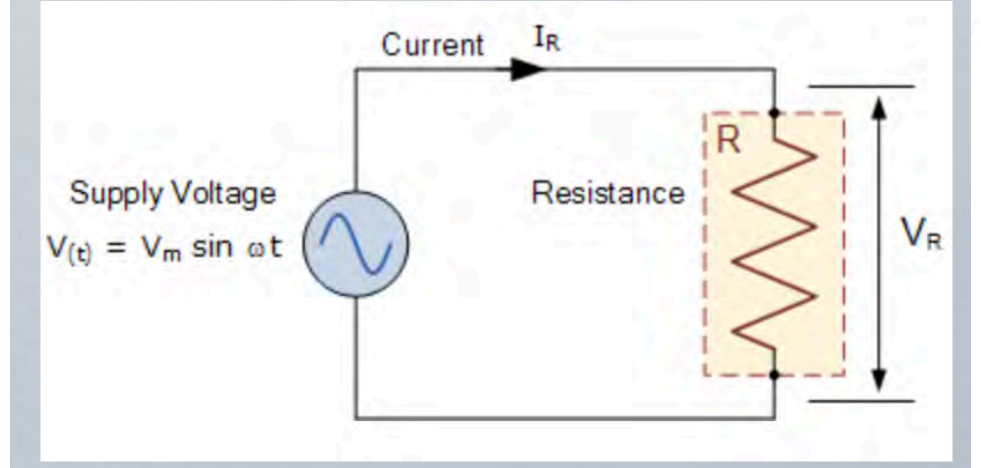

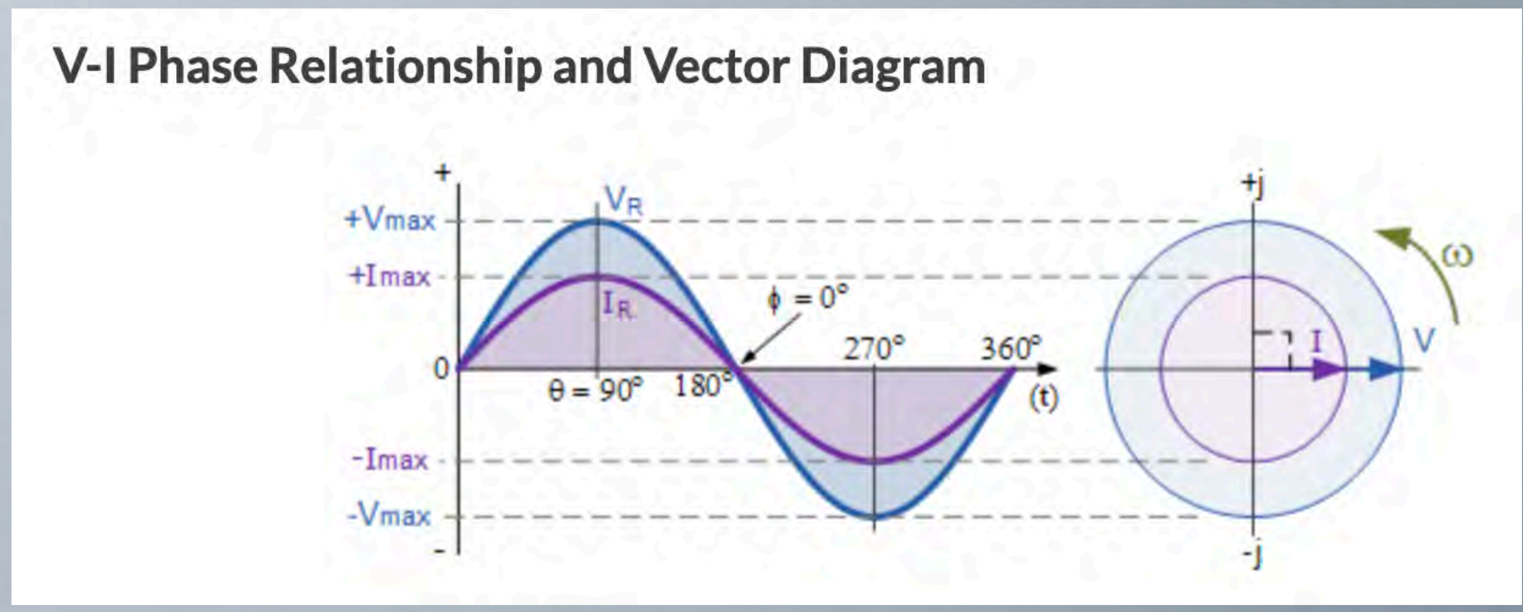

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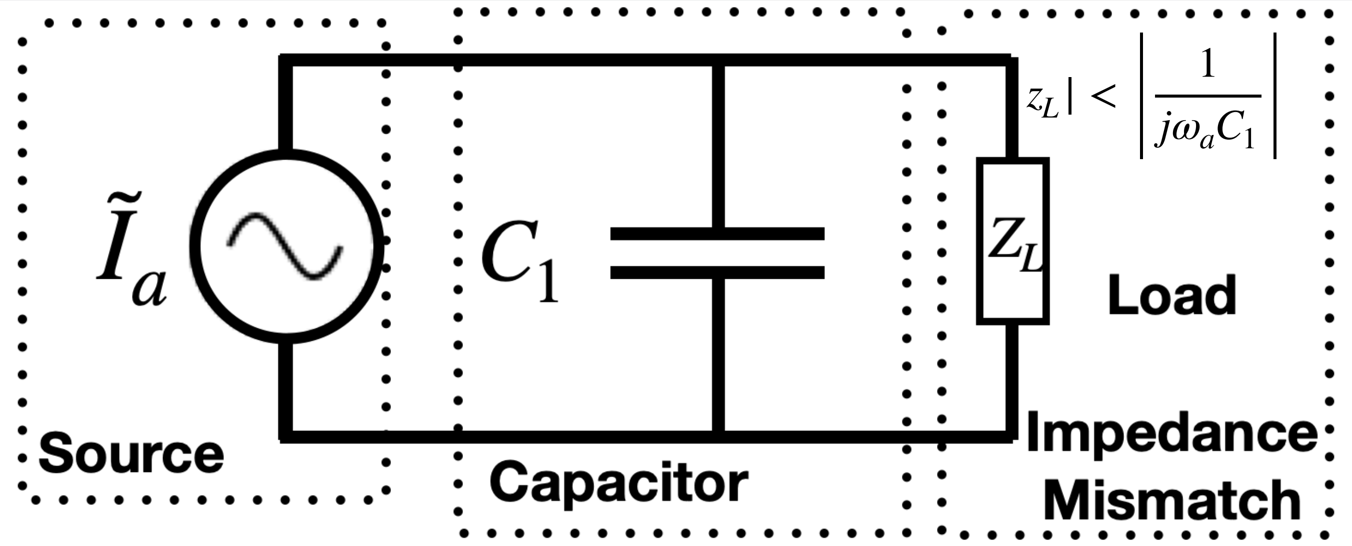

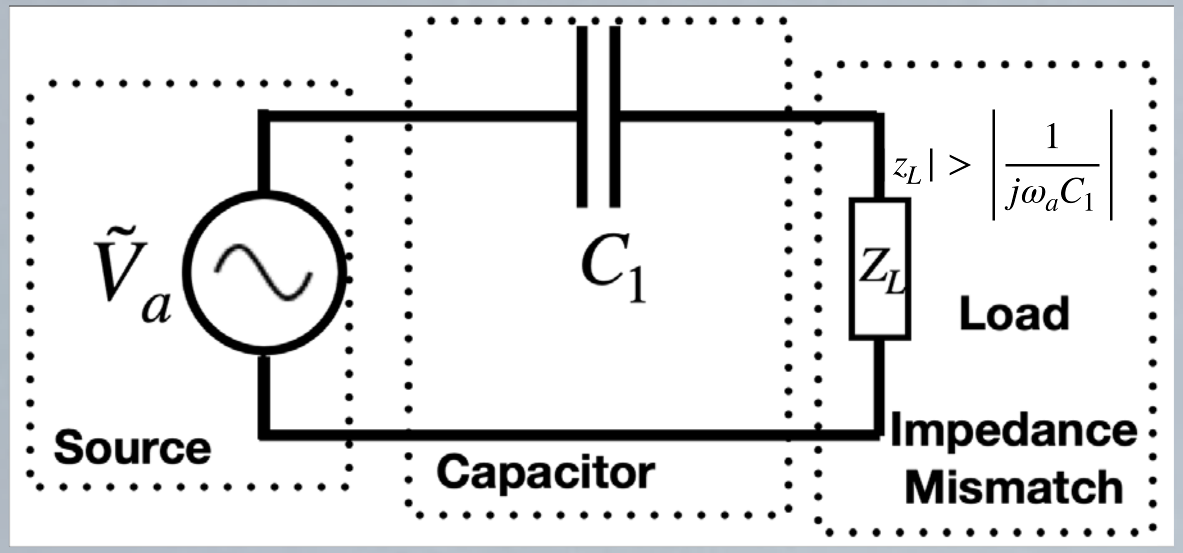

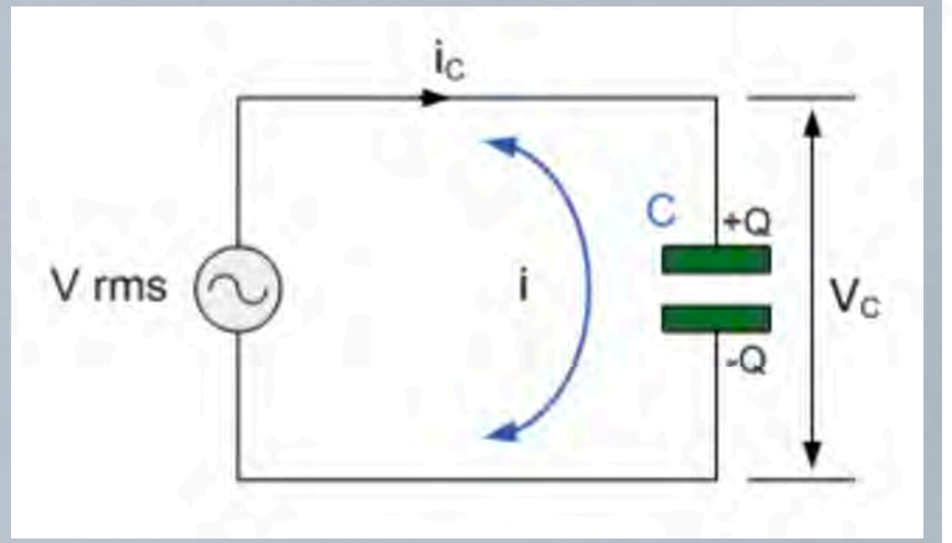

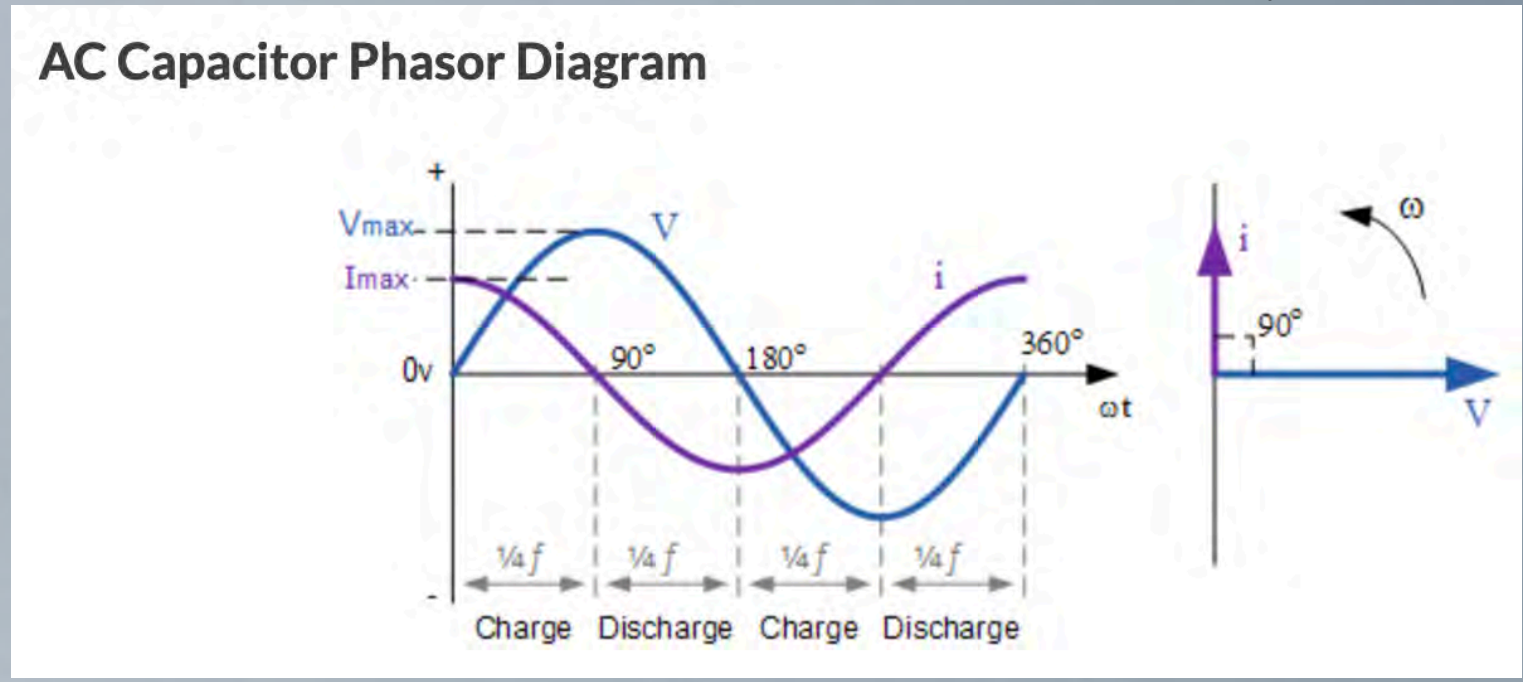

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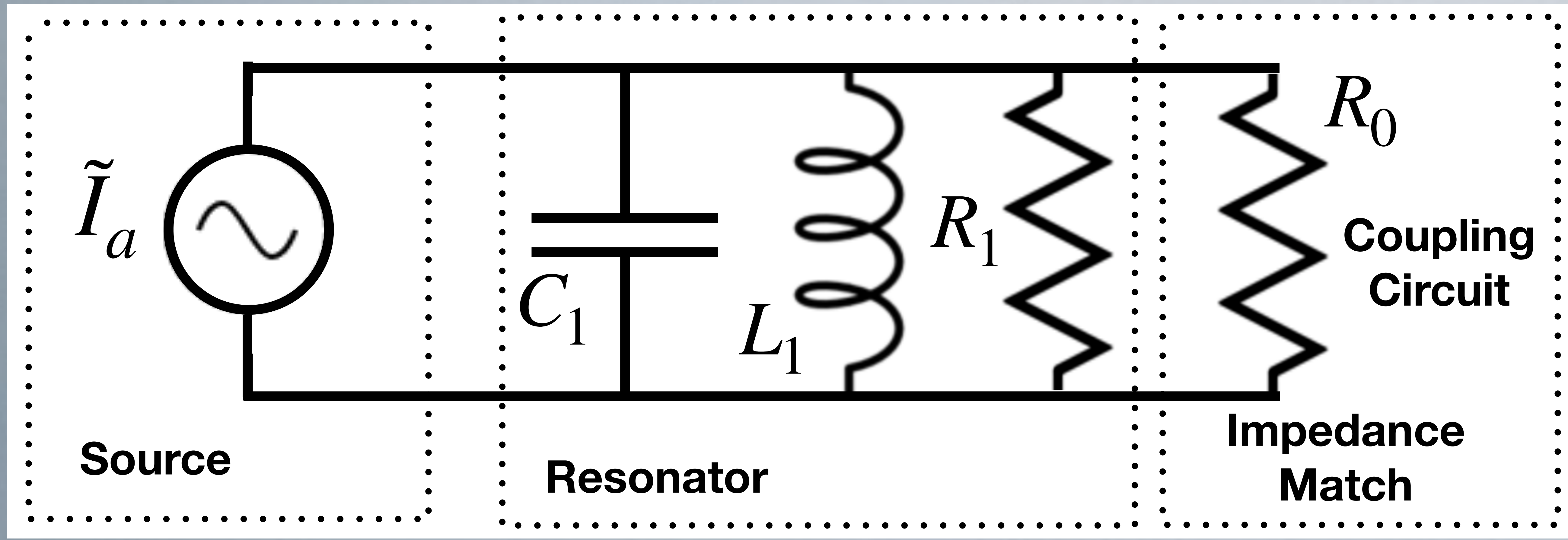

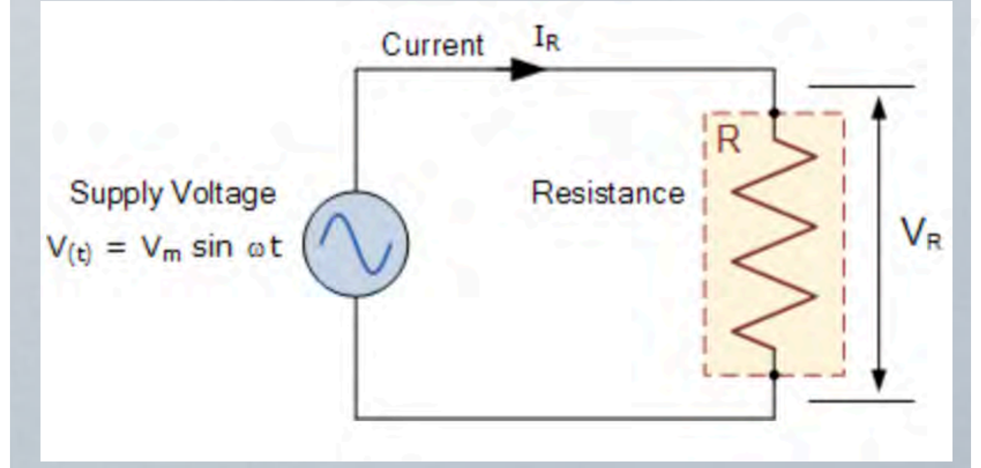

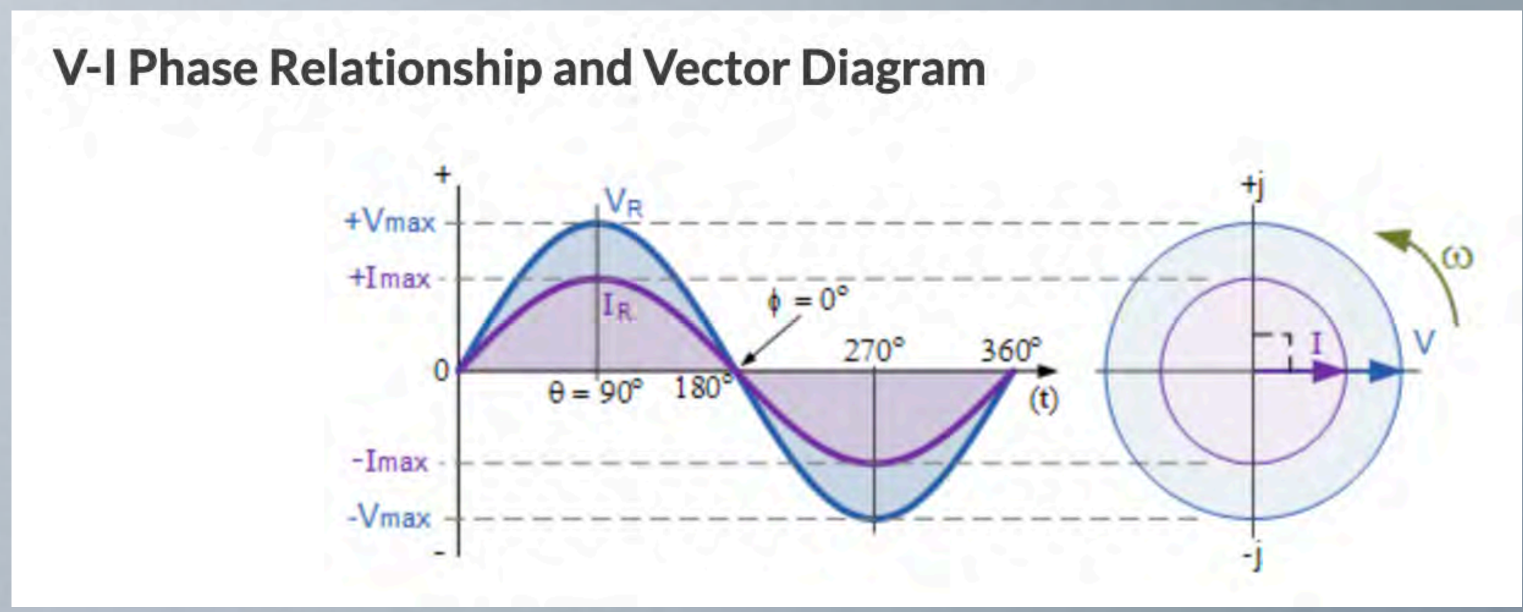

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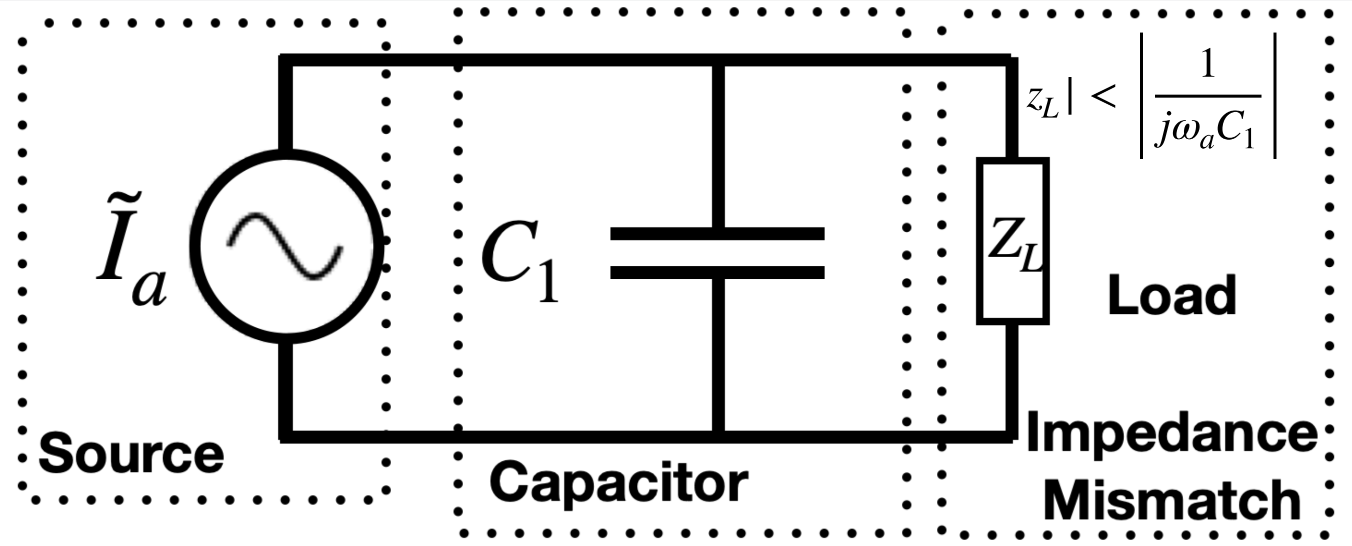

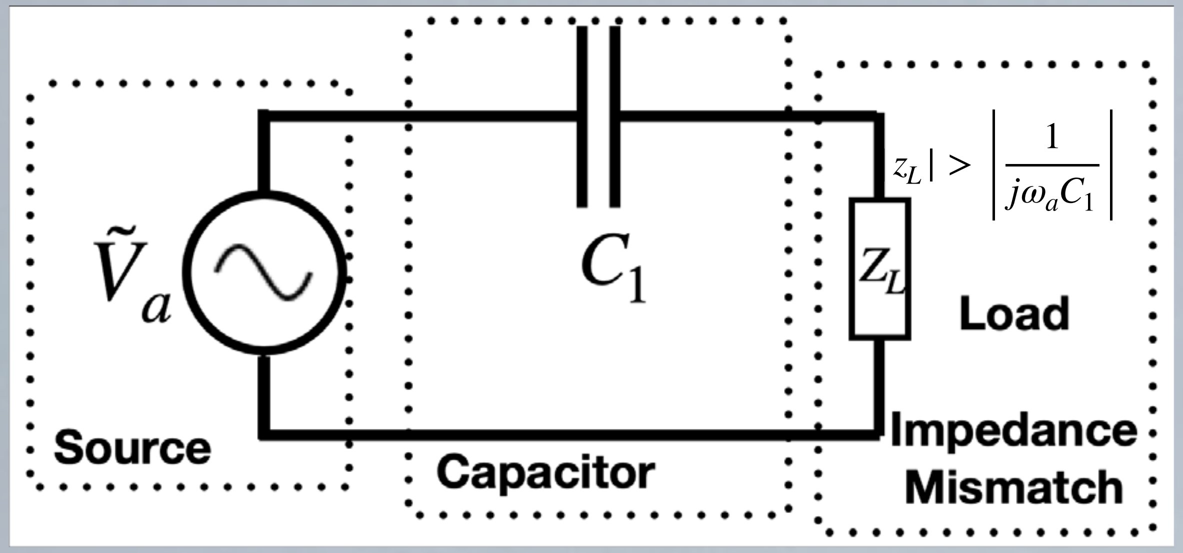

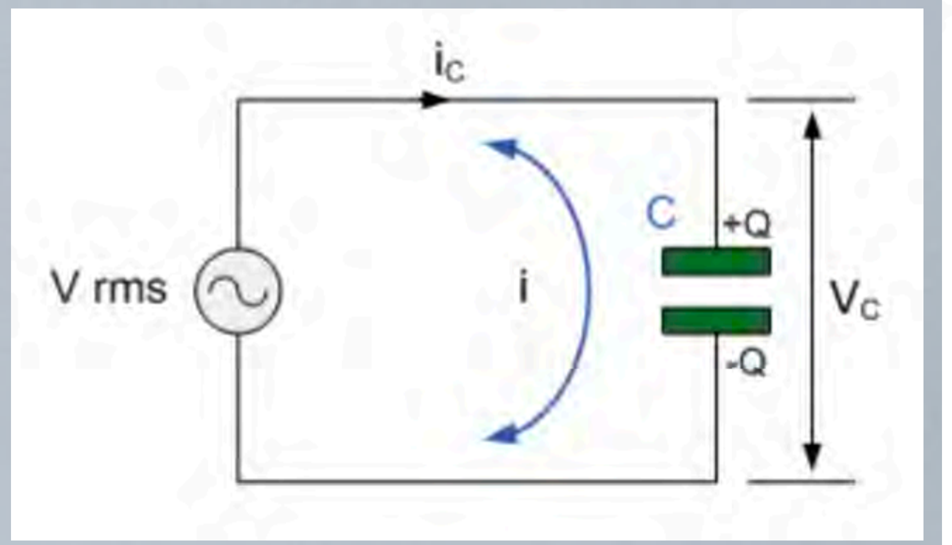

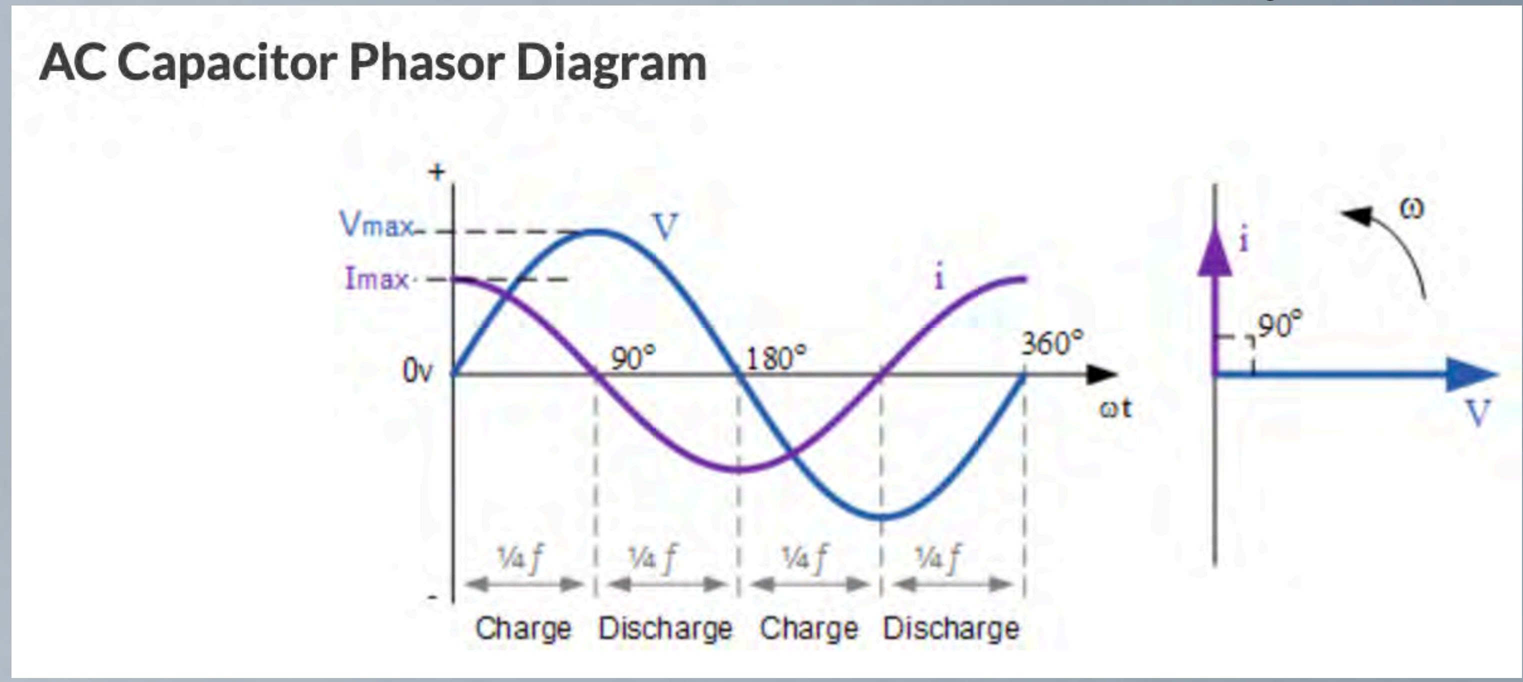

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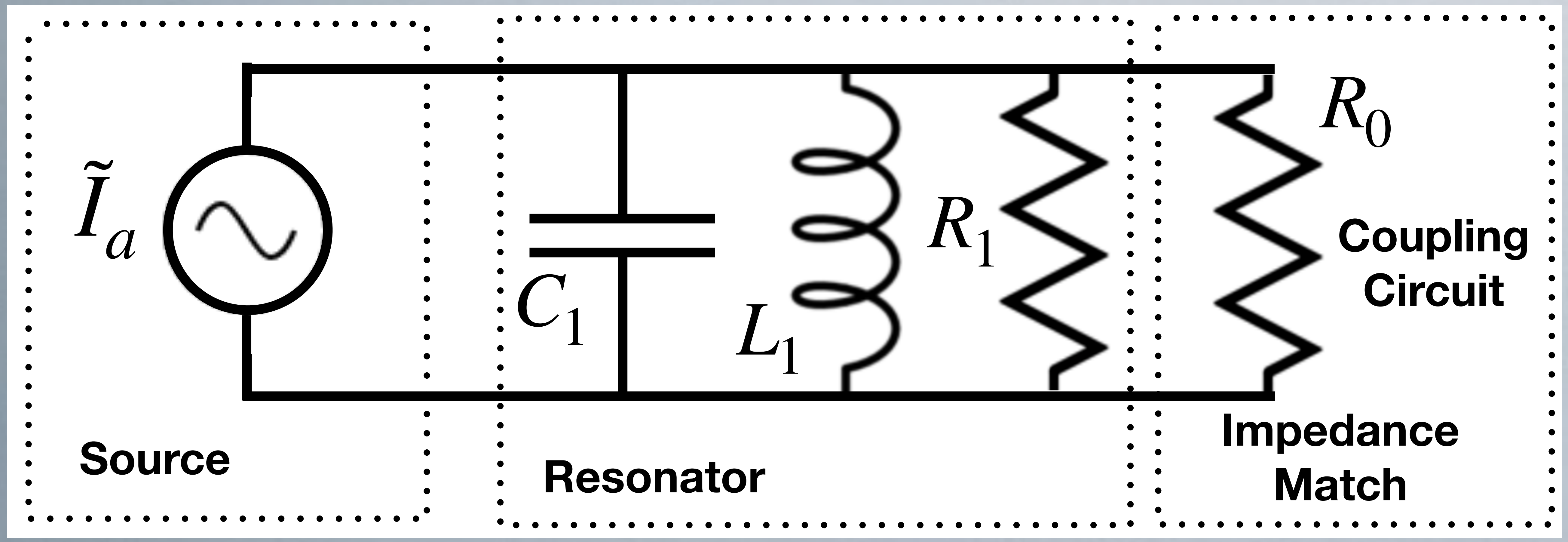
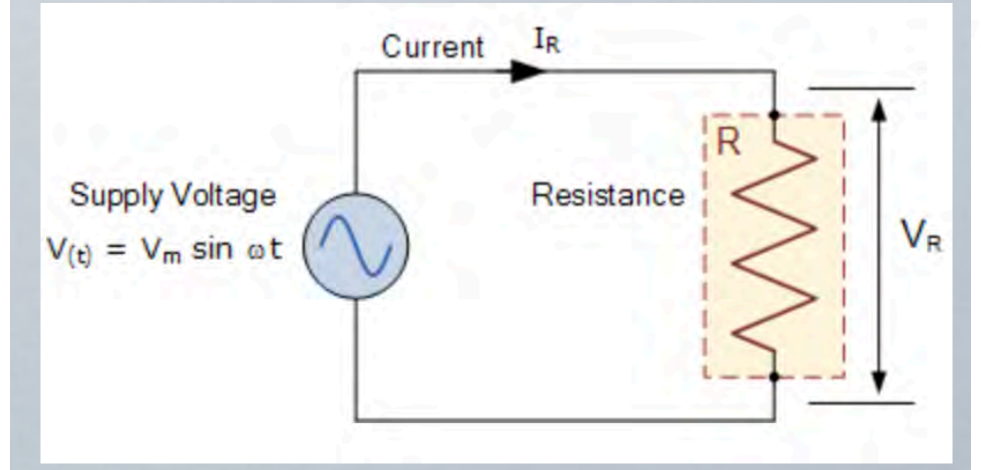
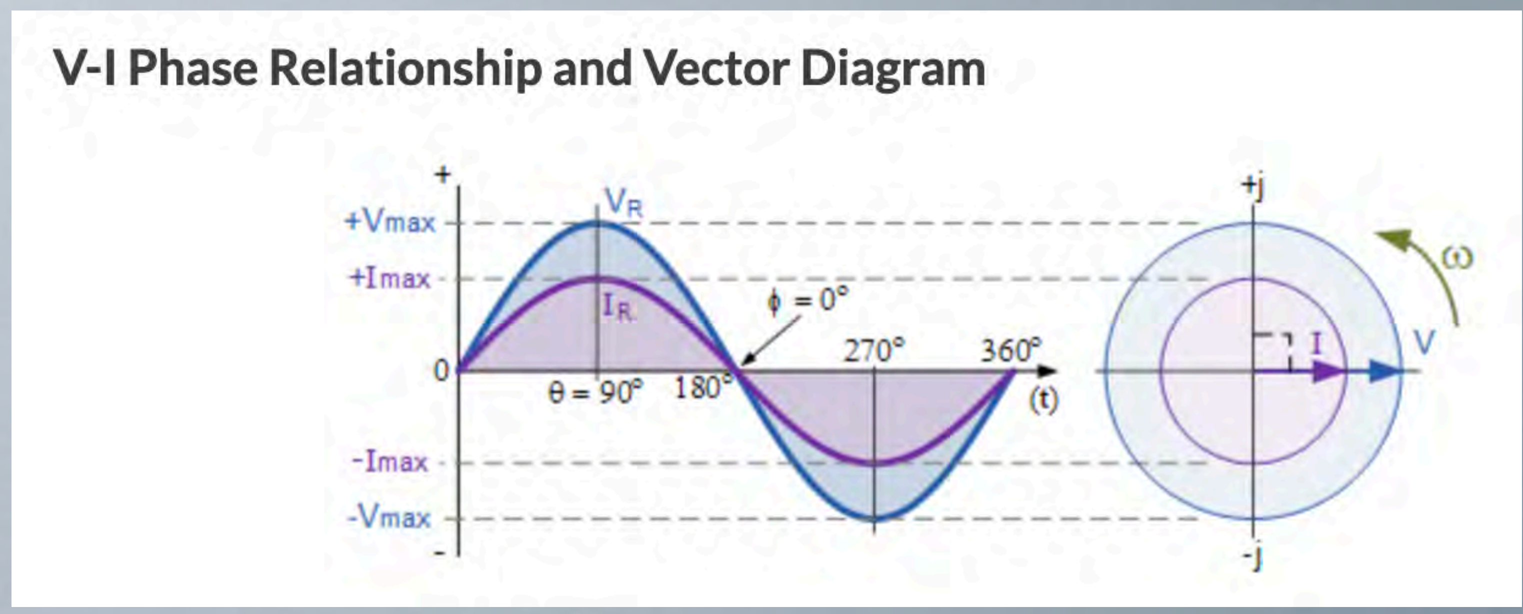
Reactive power does not propagate or dissipate out of the volume of the detector (ie. no loss): Oscillates in and out of volume

Resonator Measurement: Impedance match; set coupling =1; Take Photons from Source







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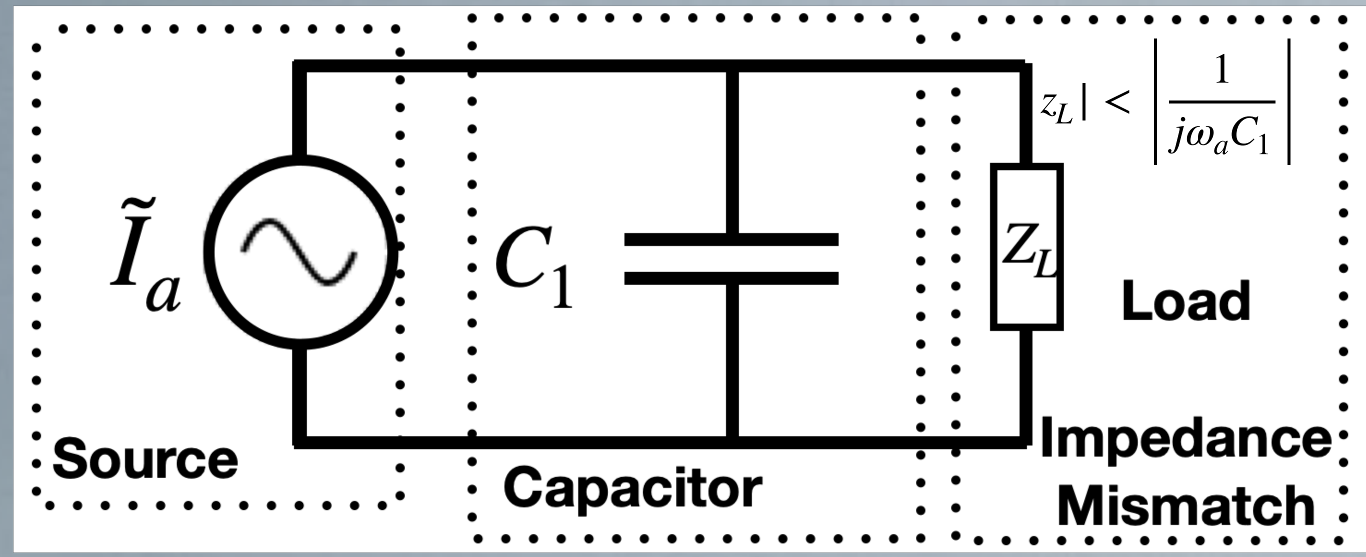

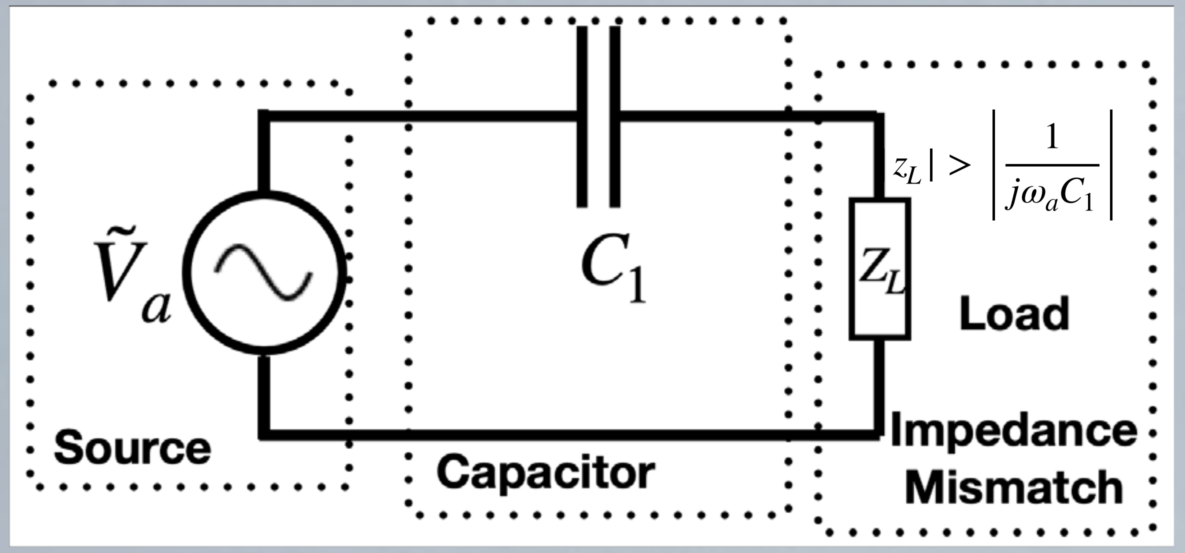

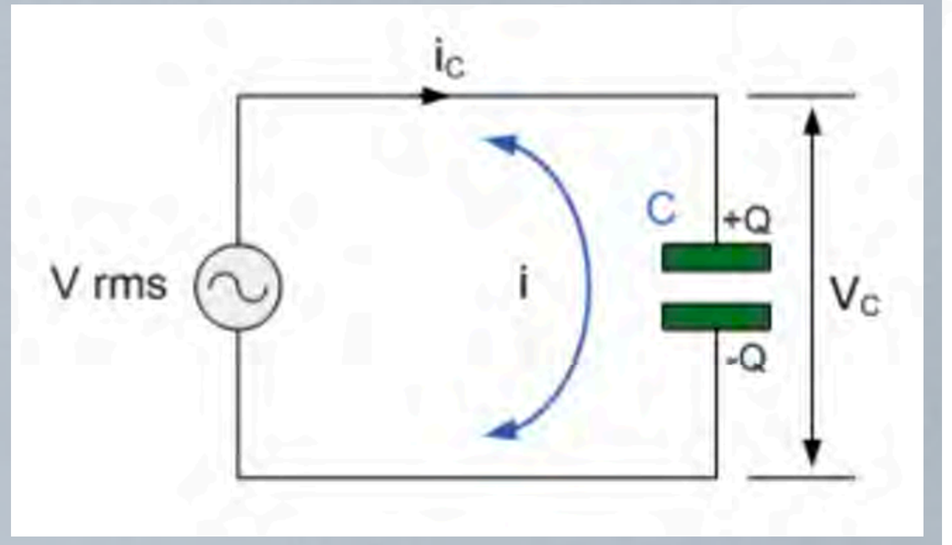

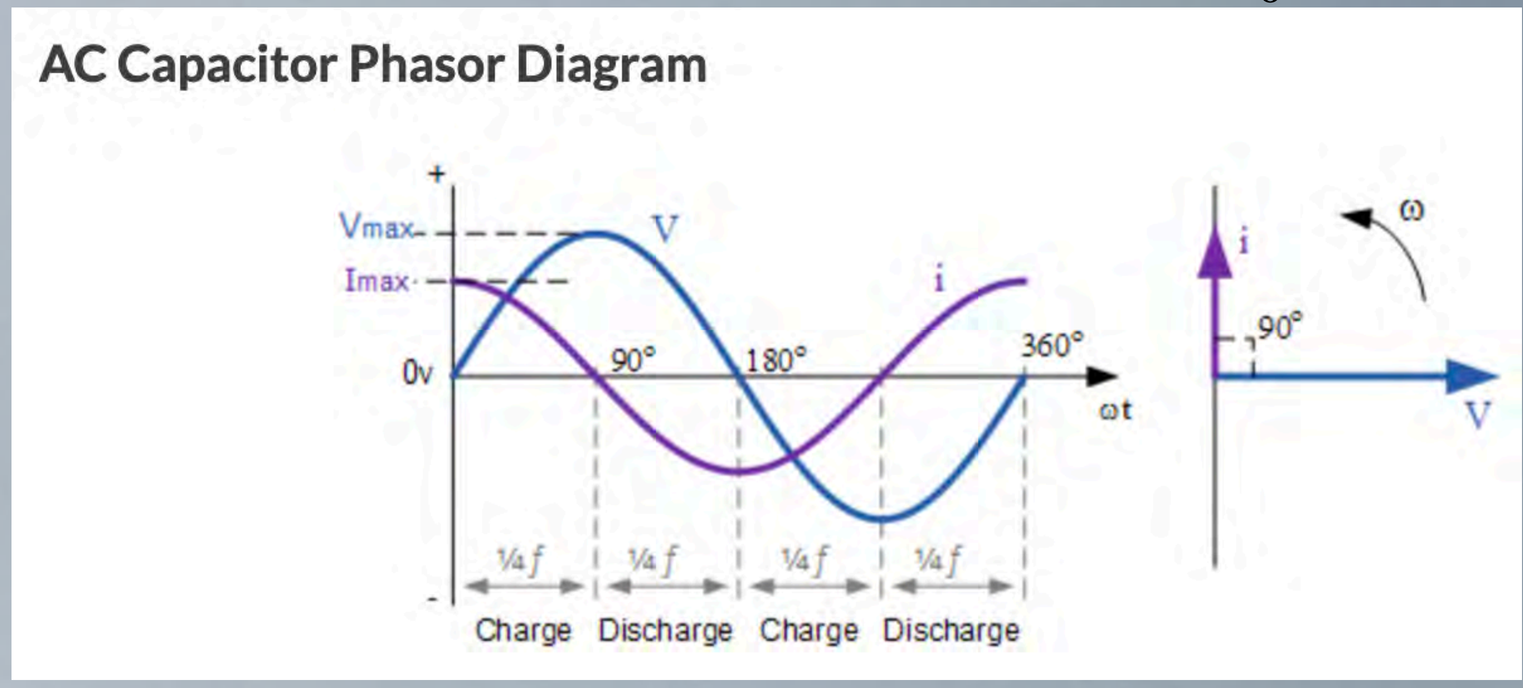

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Reactive power does not propagate or dissipate out of the volume of the detector (ie. no loss): Oscillates in and out of volume

Does not need to be the order of the Compton wavelength in size (sub wavelength phenomena)

Resonant Axion Haloscopes @ UWA

$$\mathcal{H}_{int} = \epsilon_0 c g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

Resonant Axion Haloscopes @ UWA

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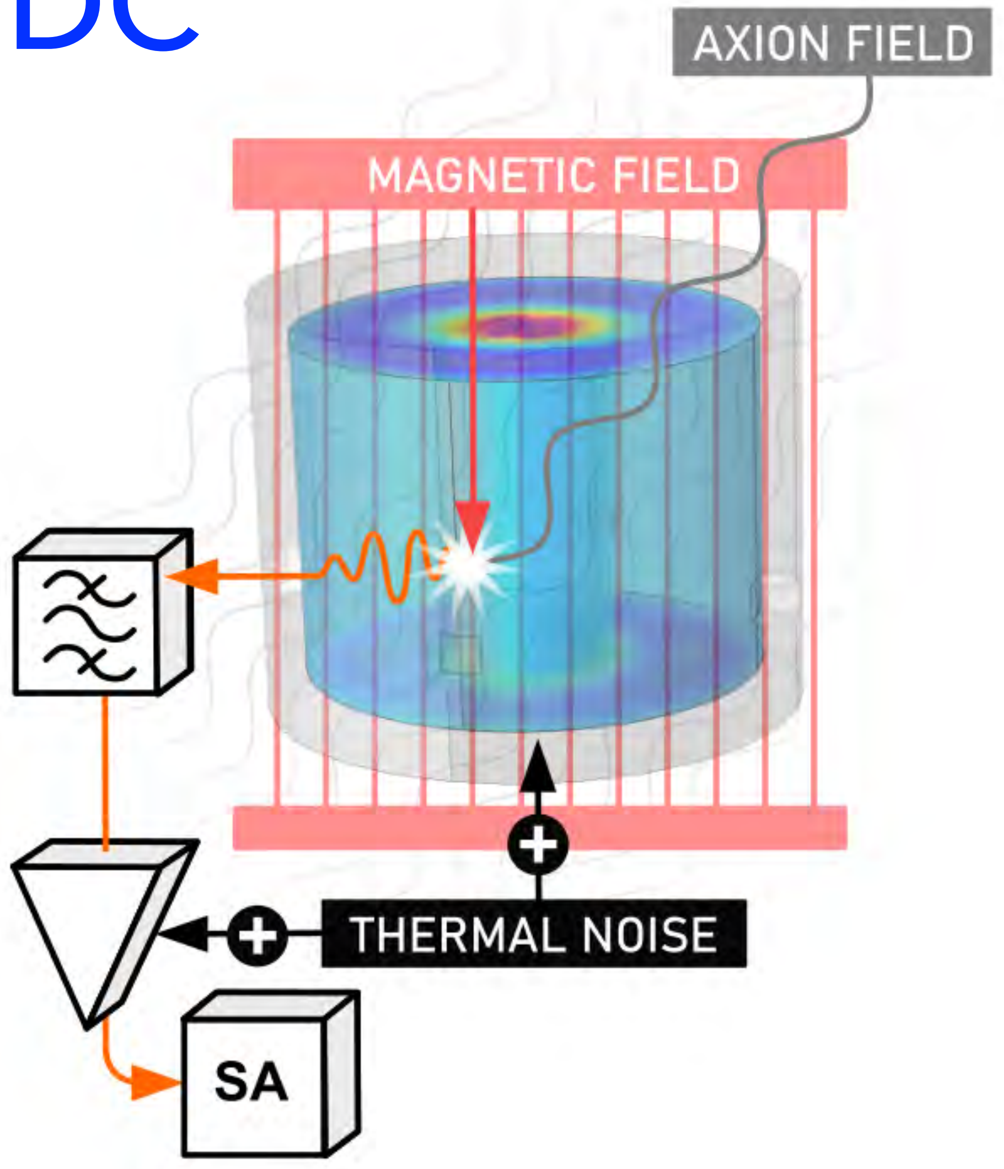
DC



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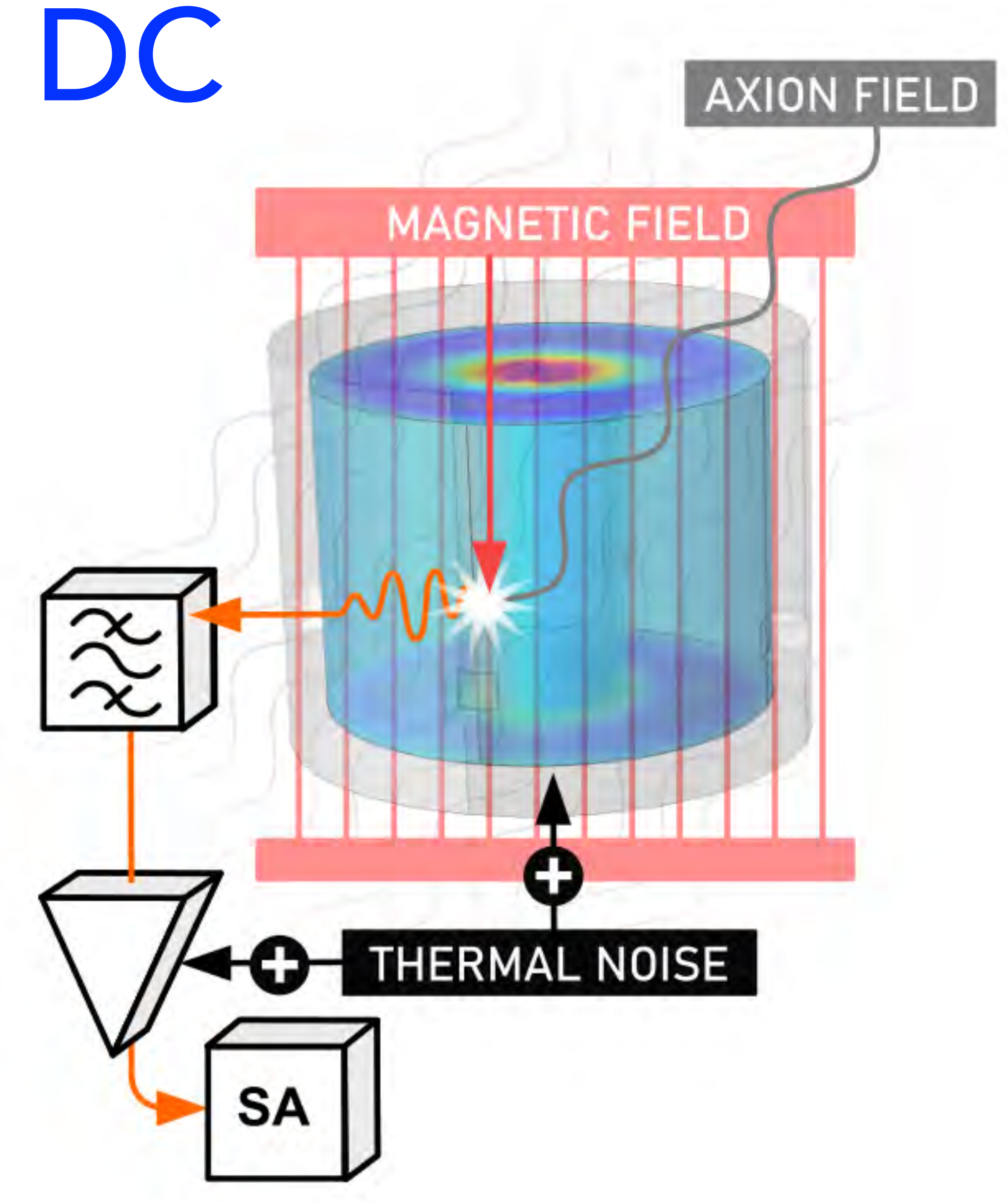

Photon 1: E field of cavity's resonant transverse magnetic mode, $m_a = f_1 + \delta f$

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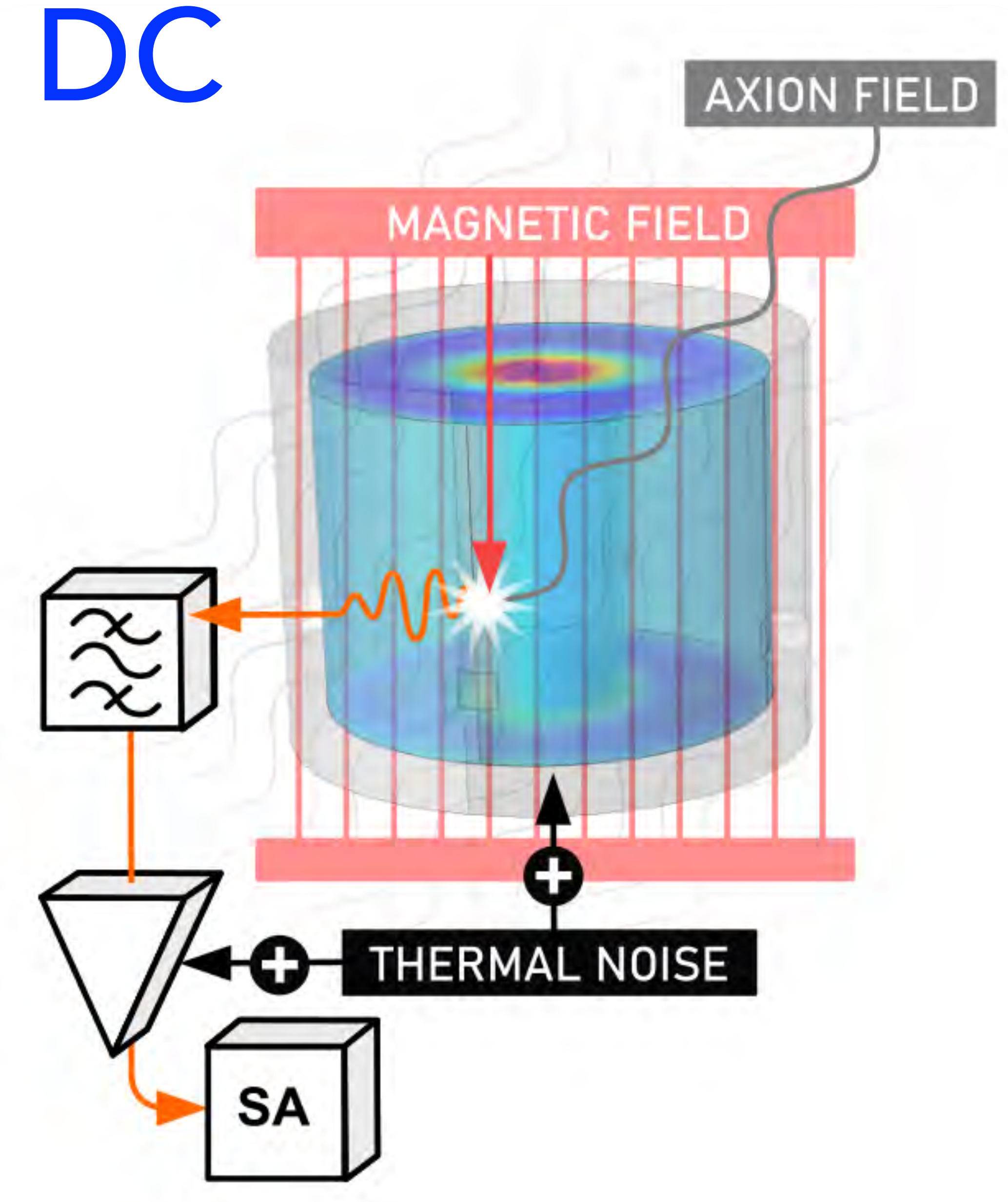

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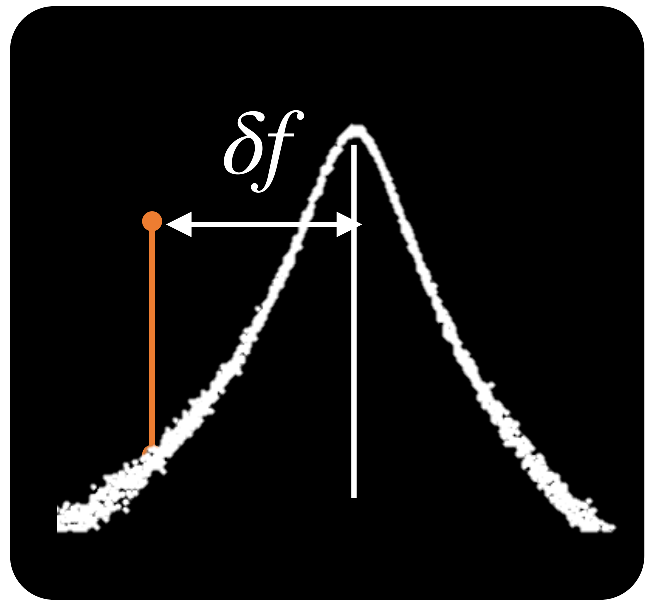

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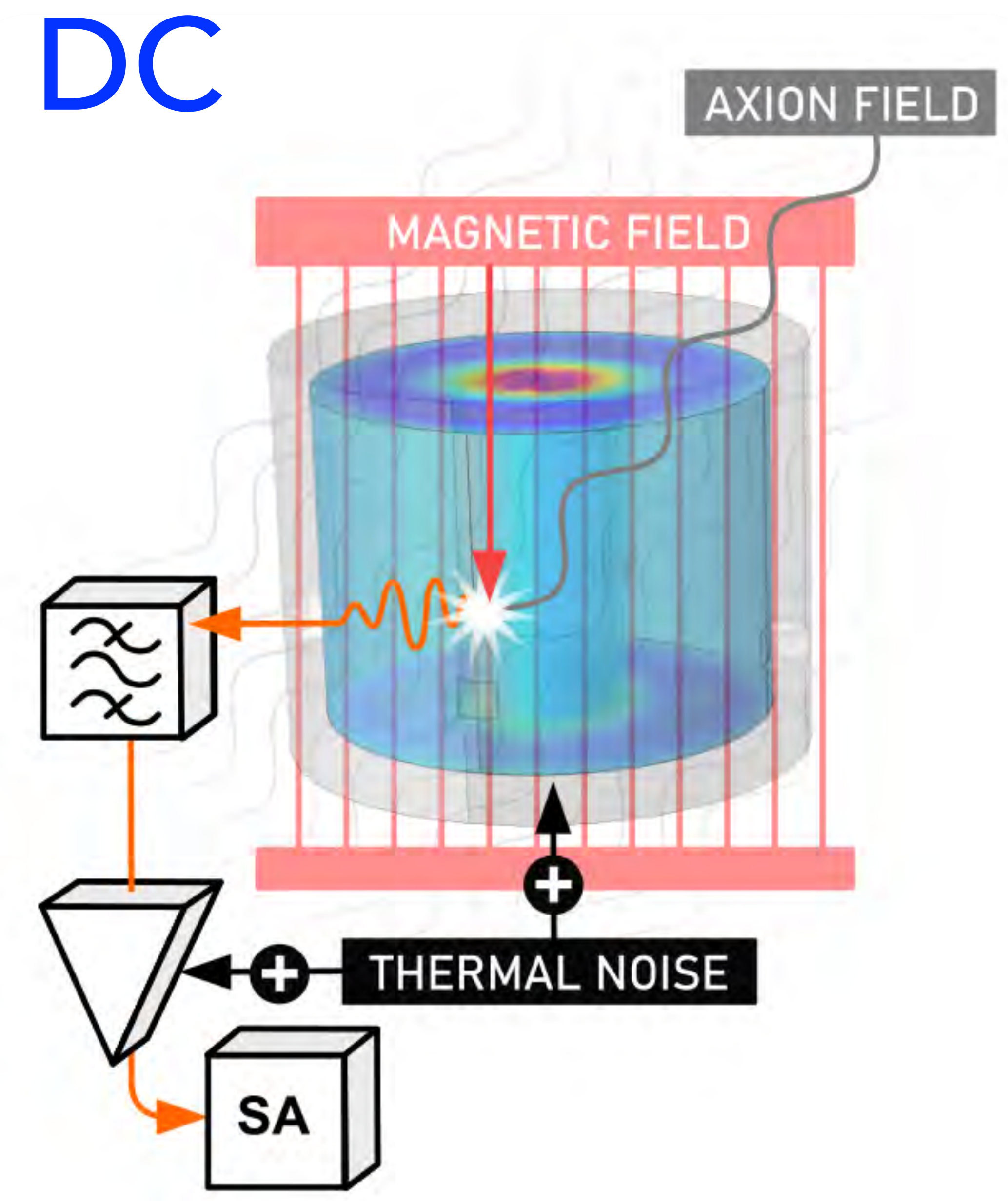

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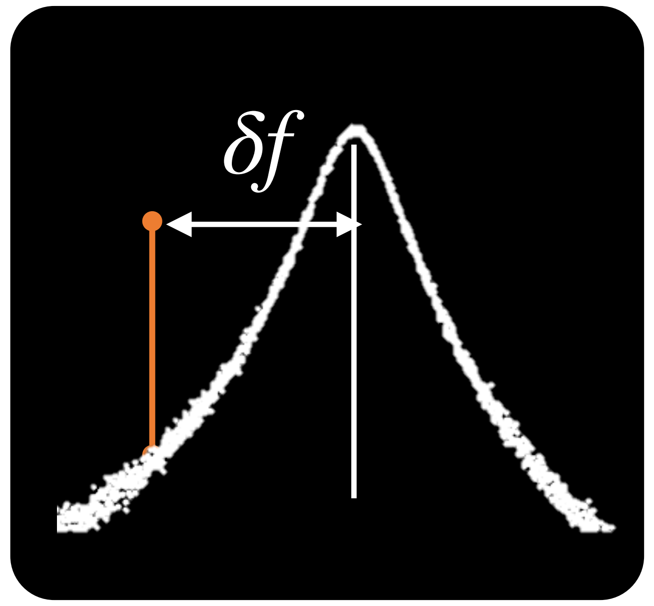
Photon 0, Back ground DC B field of surrounding magnet



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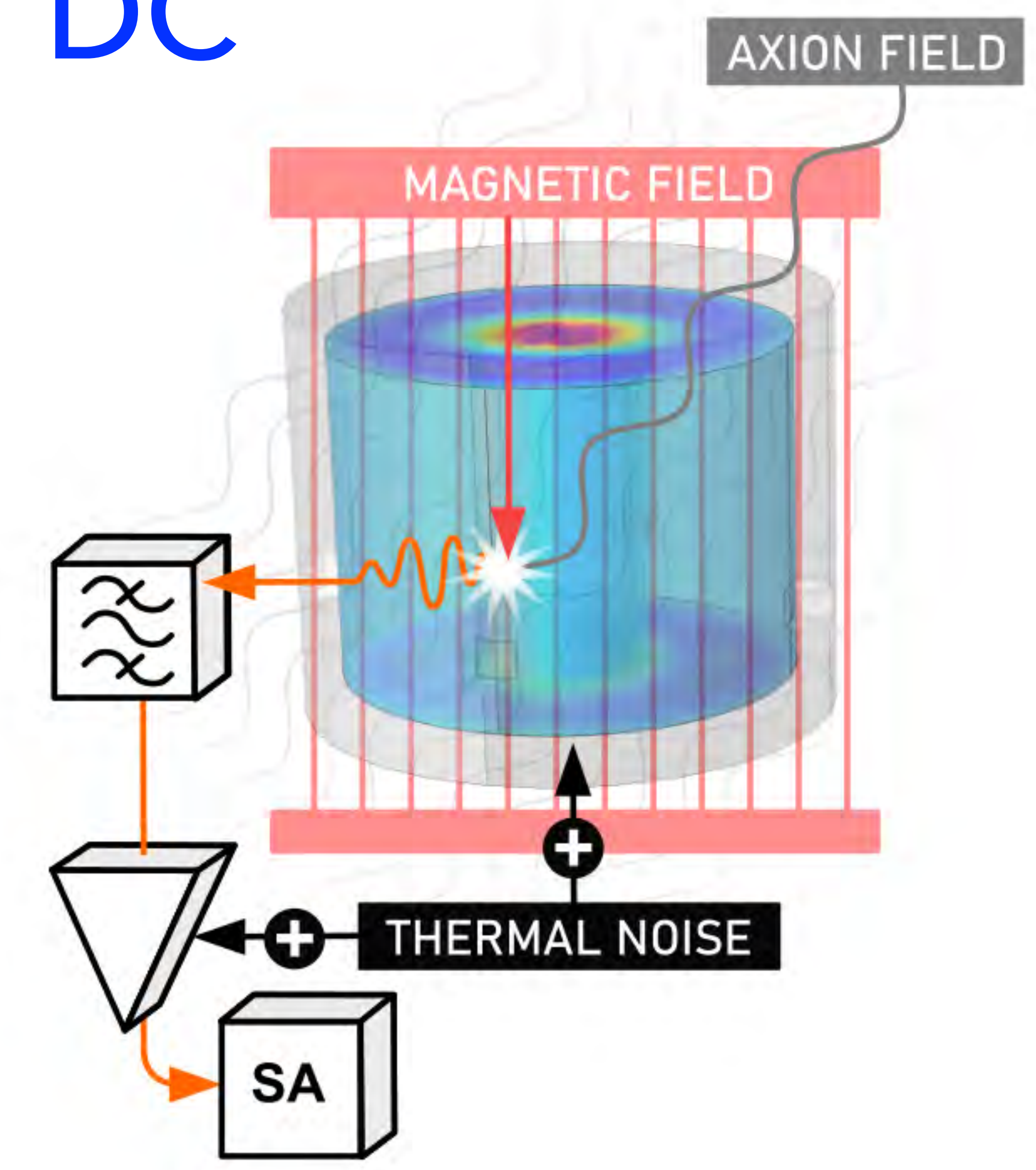

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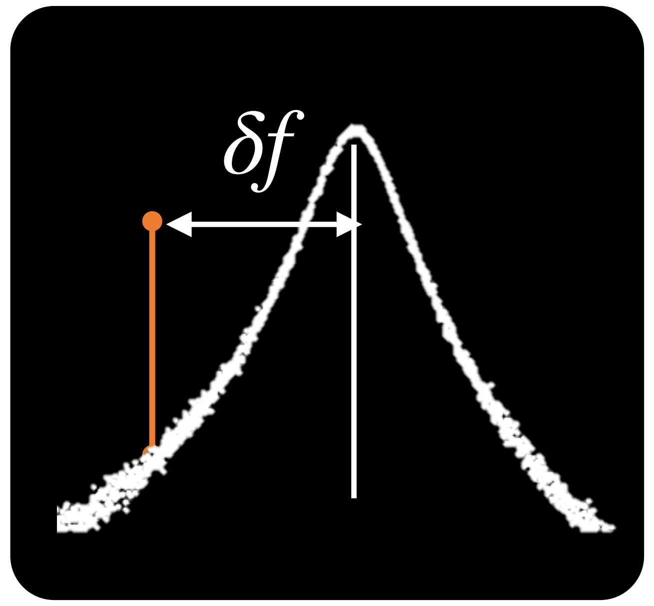

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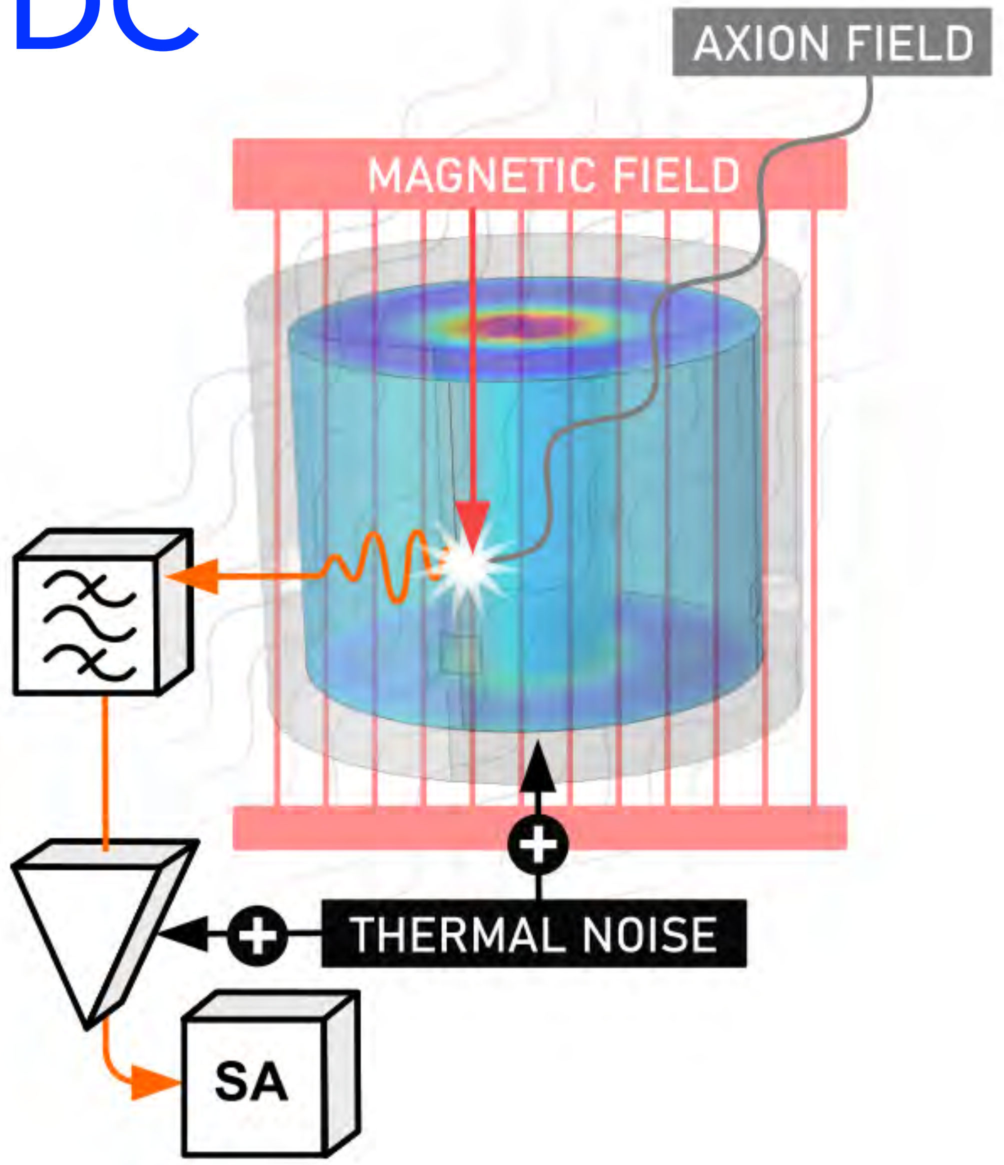
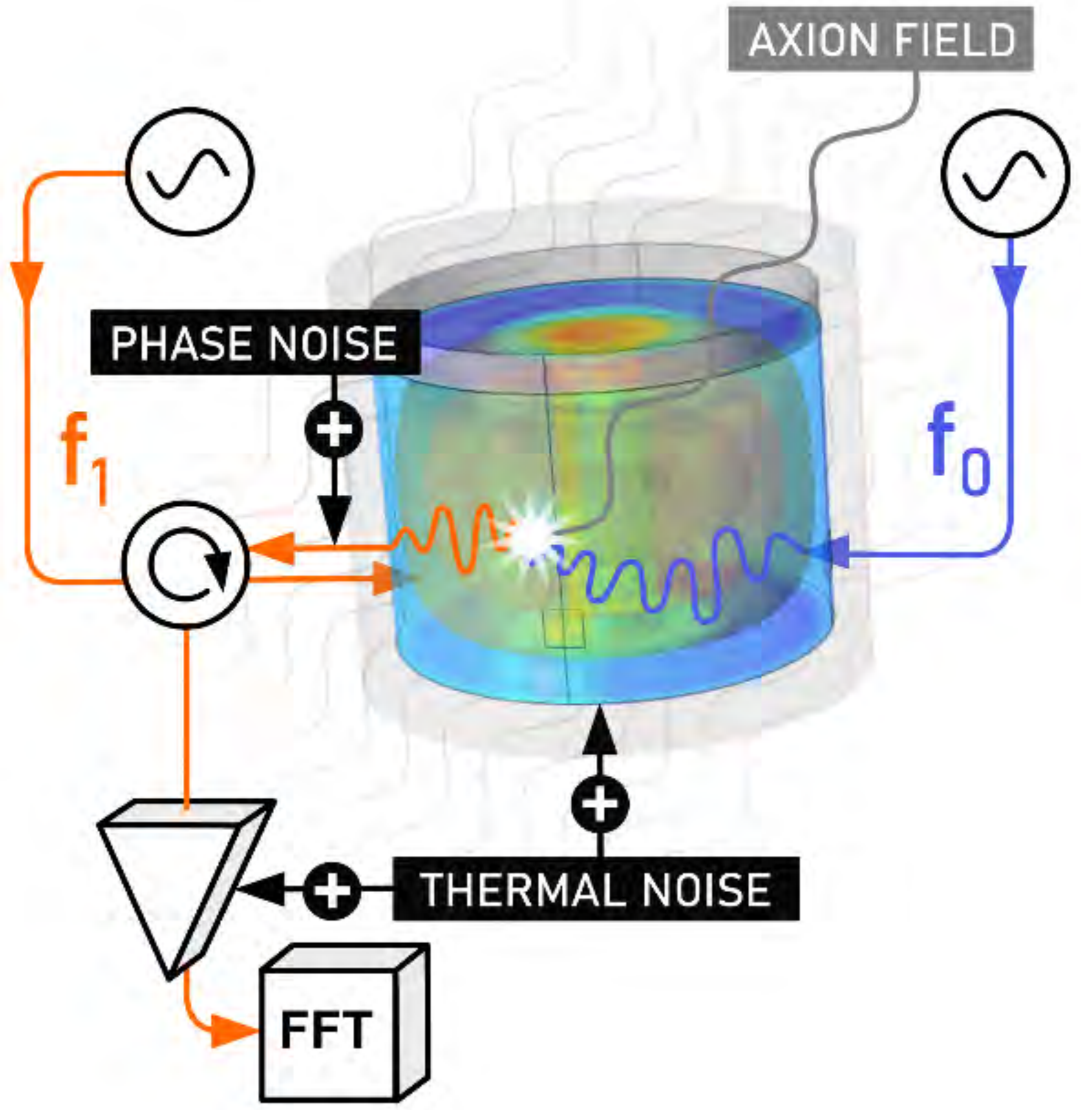
AC Frequency

DC





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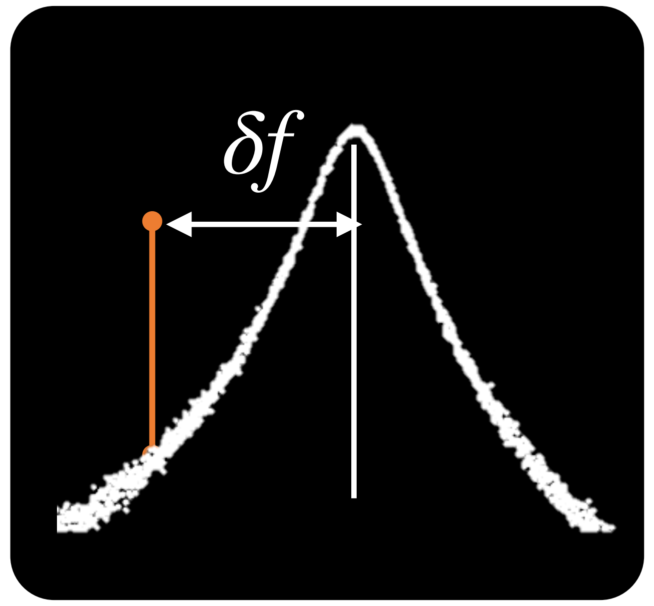

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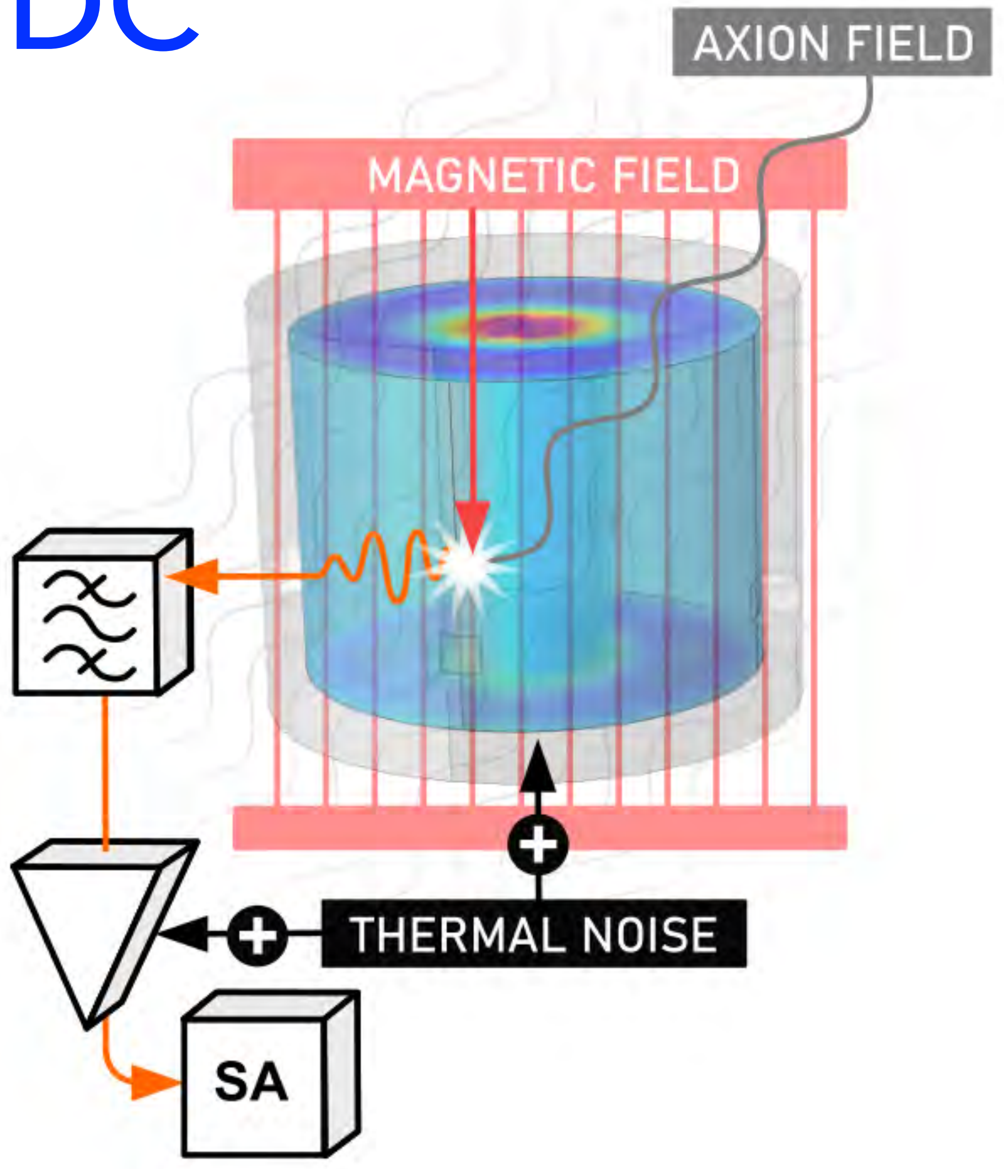

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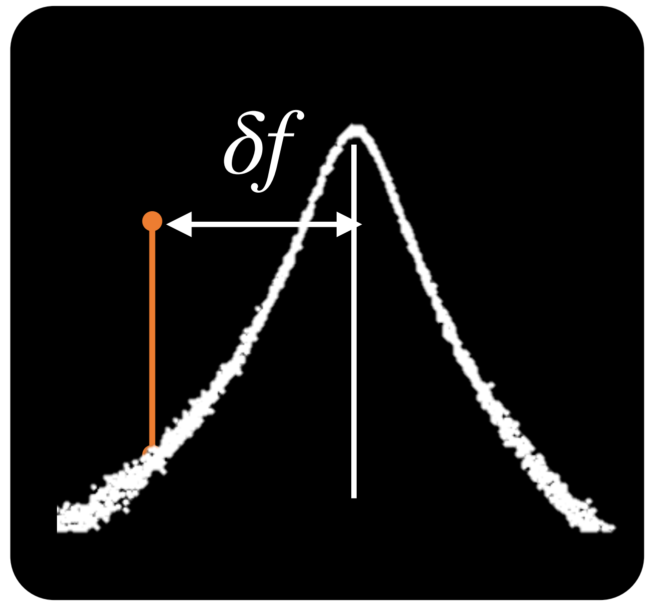

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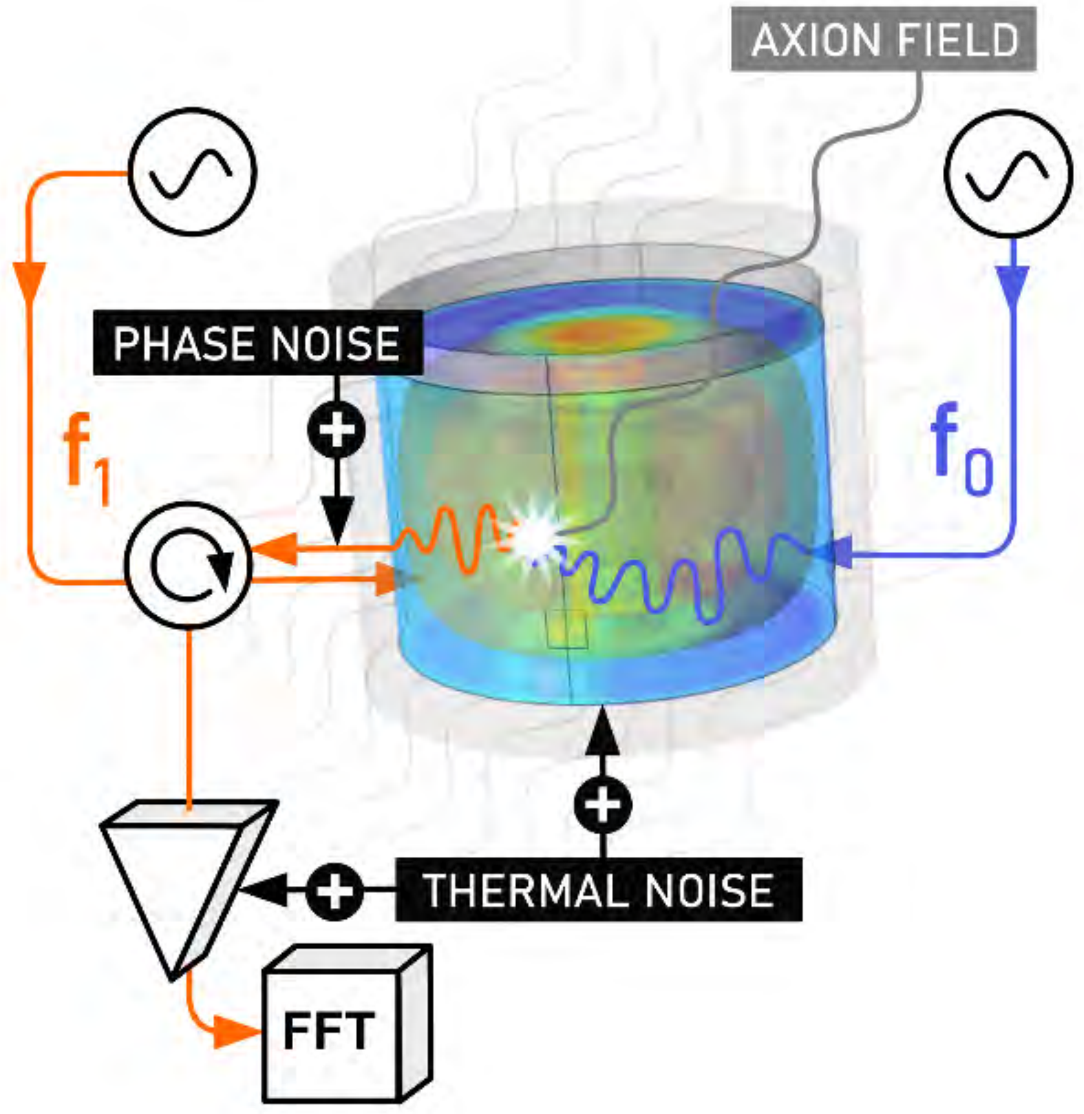
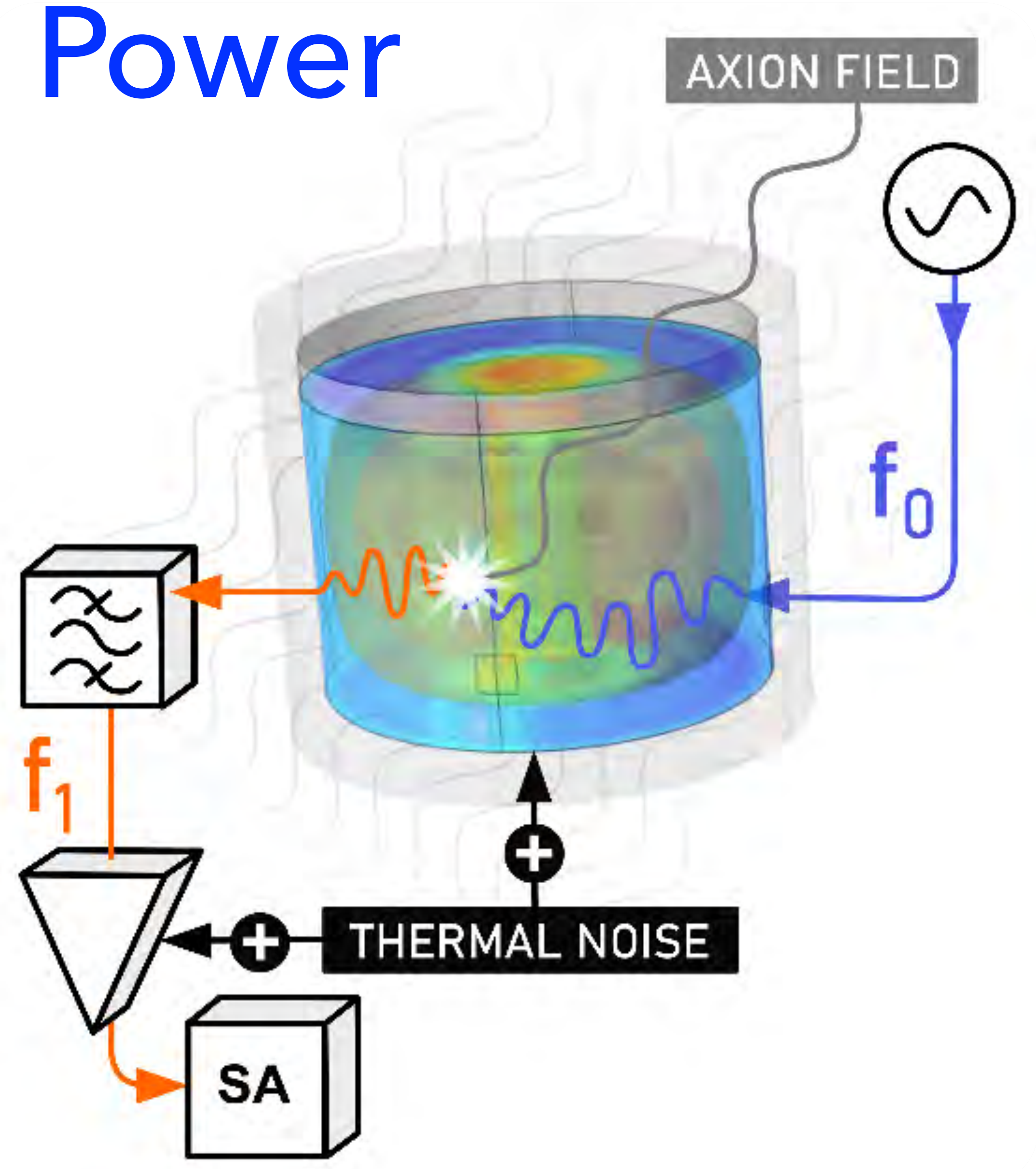


AC Power



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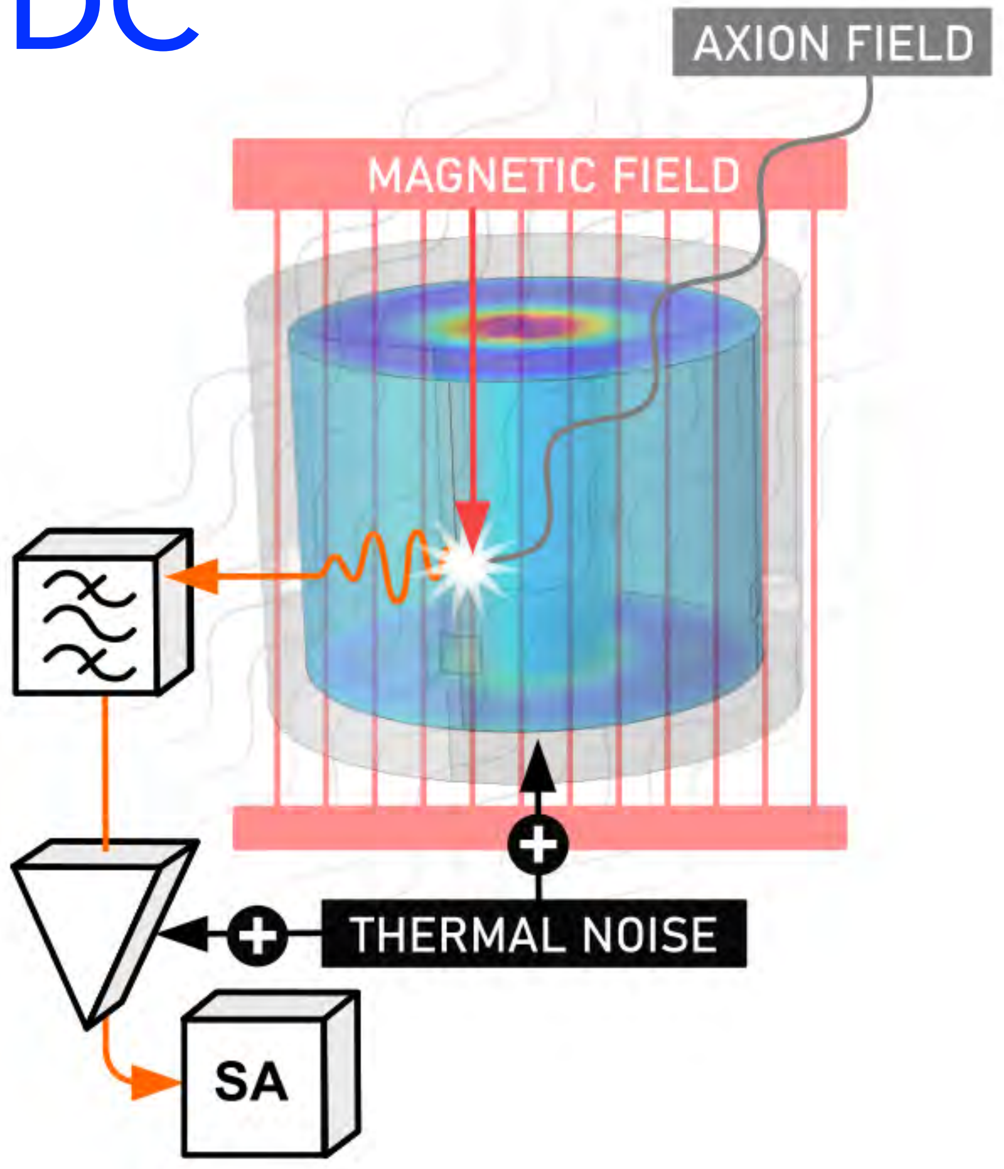

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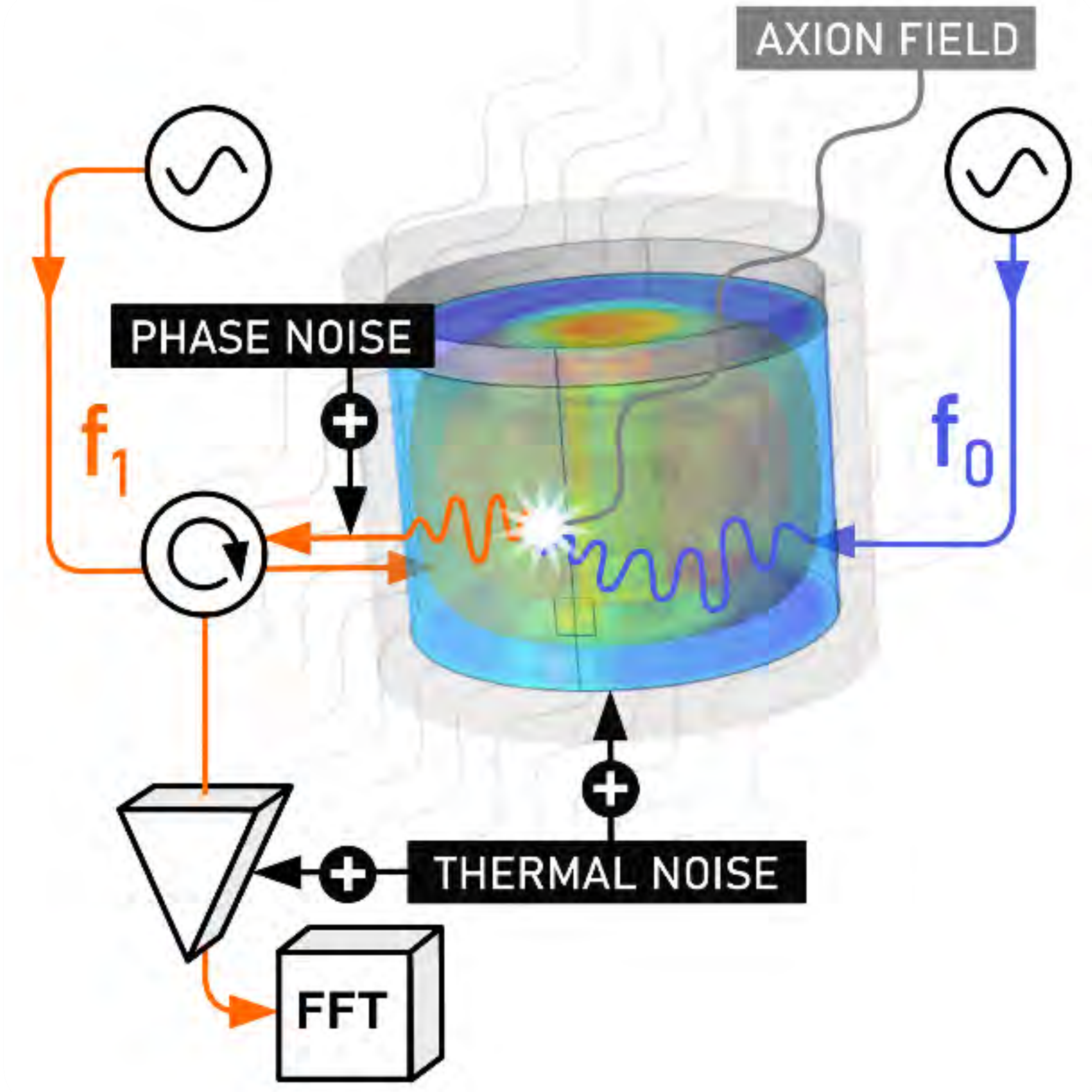

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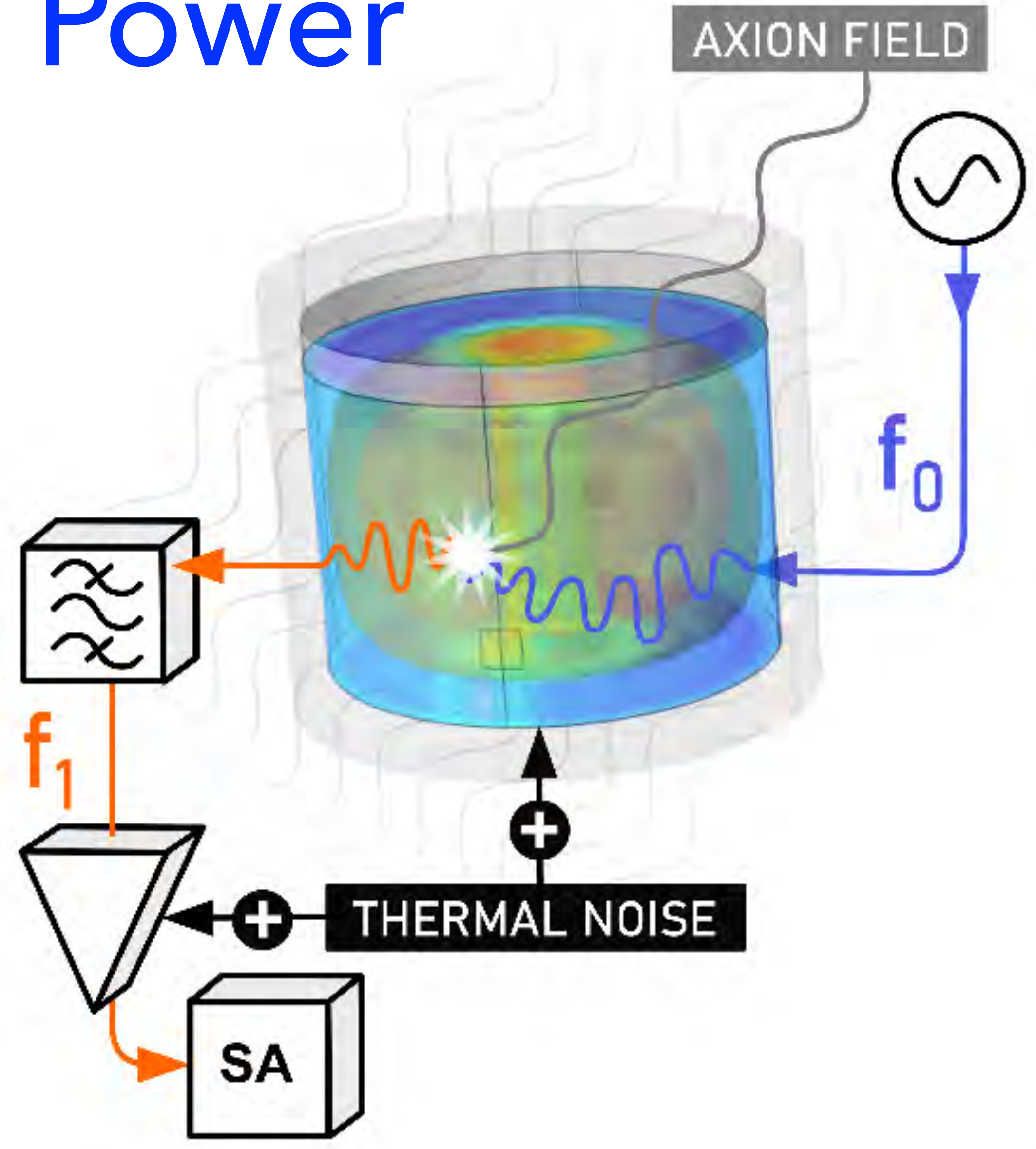

• Use a mode 0 as the background "magnetic field" AC source

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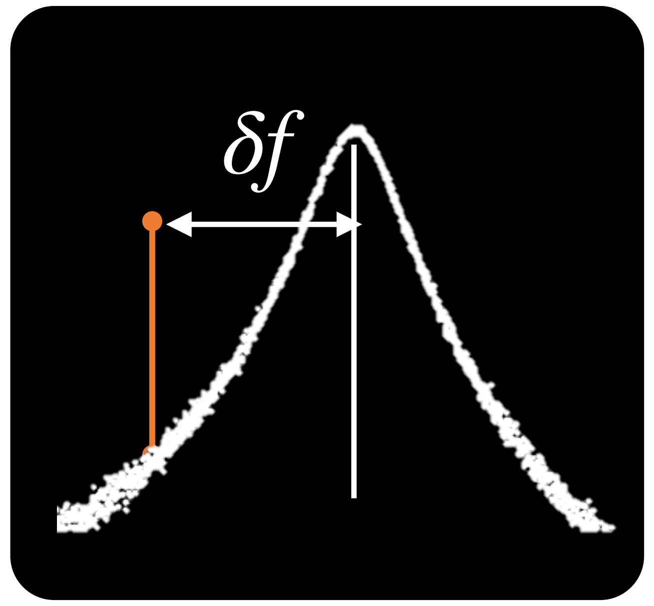

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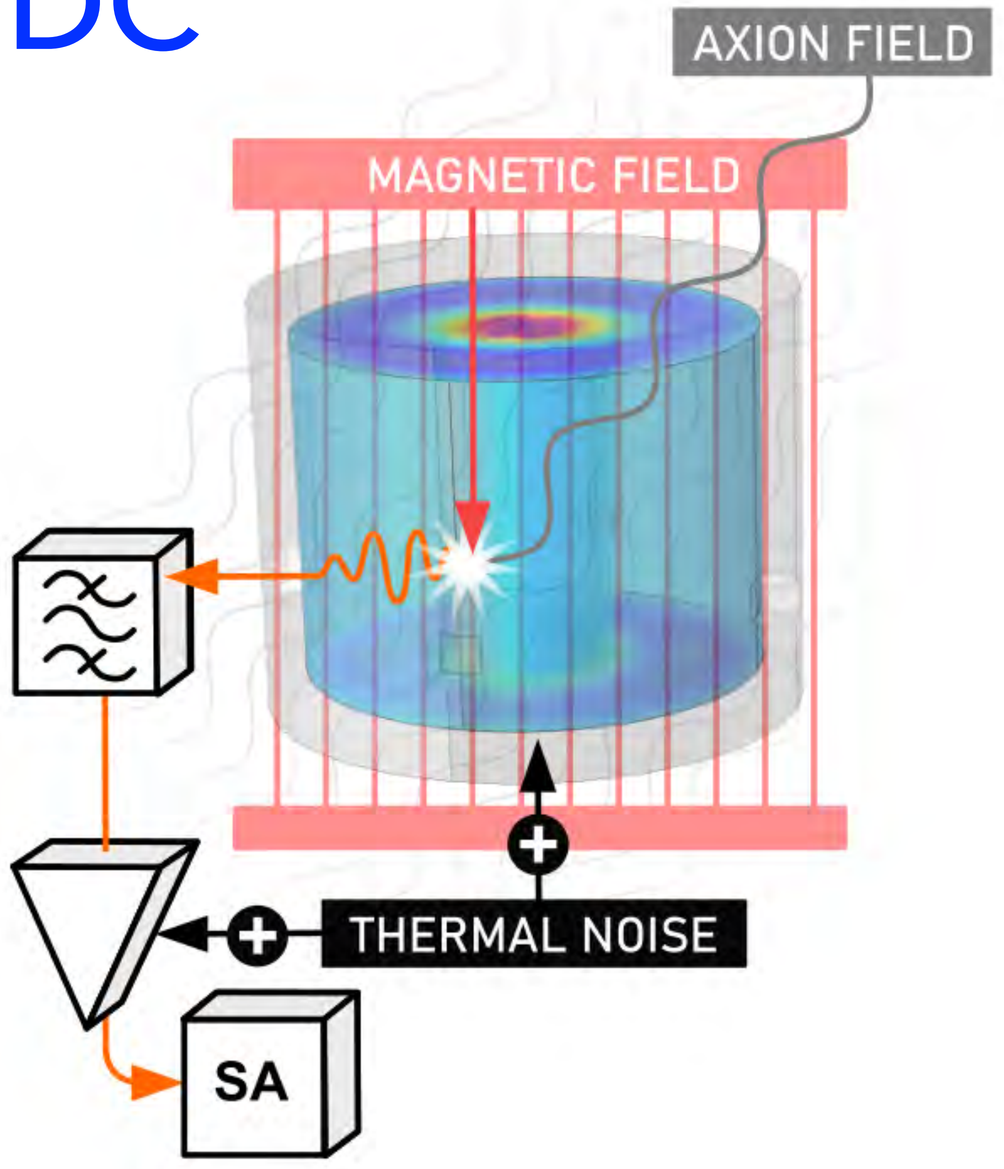

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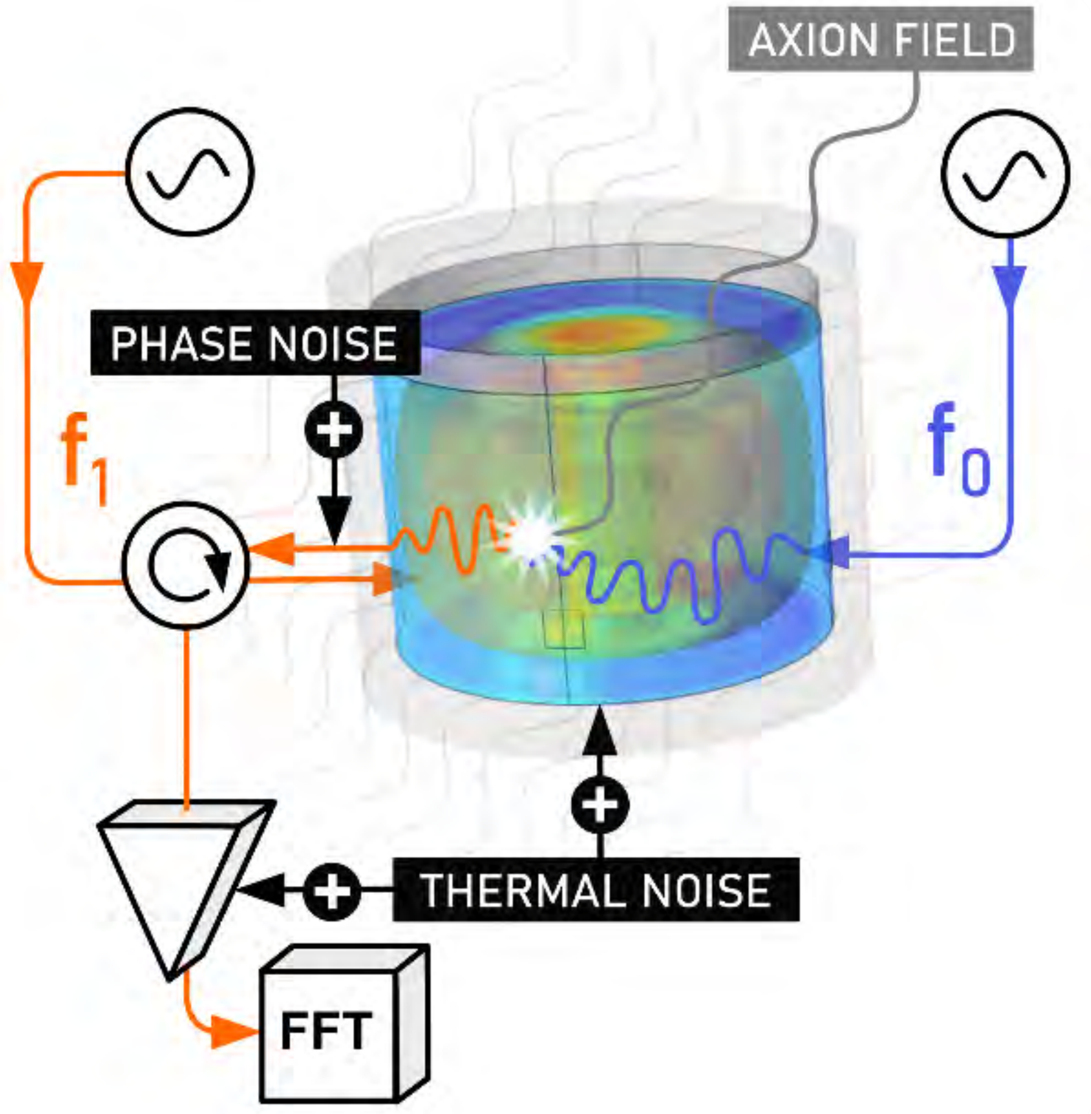

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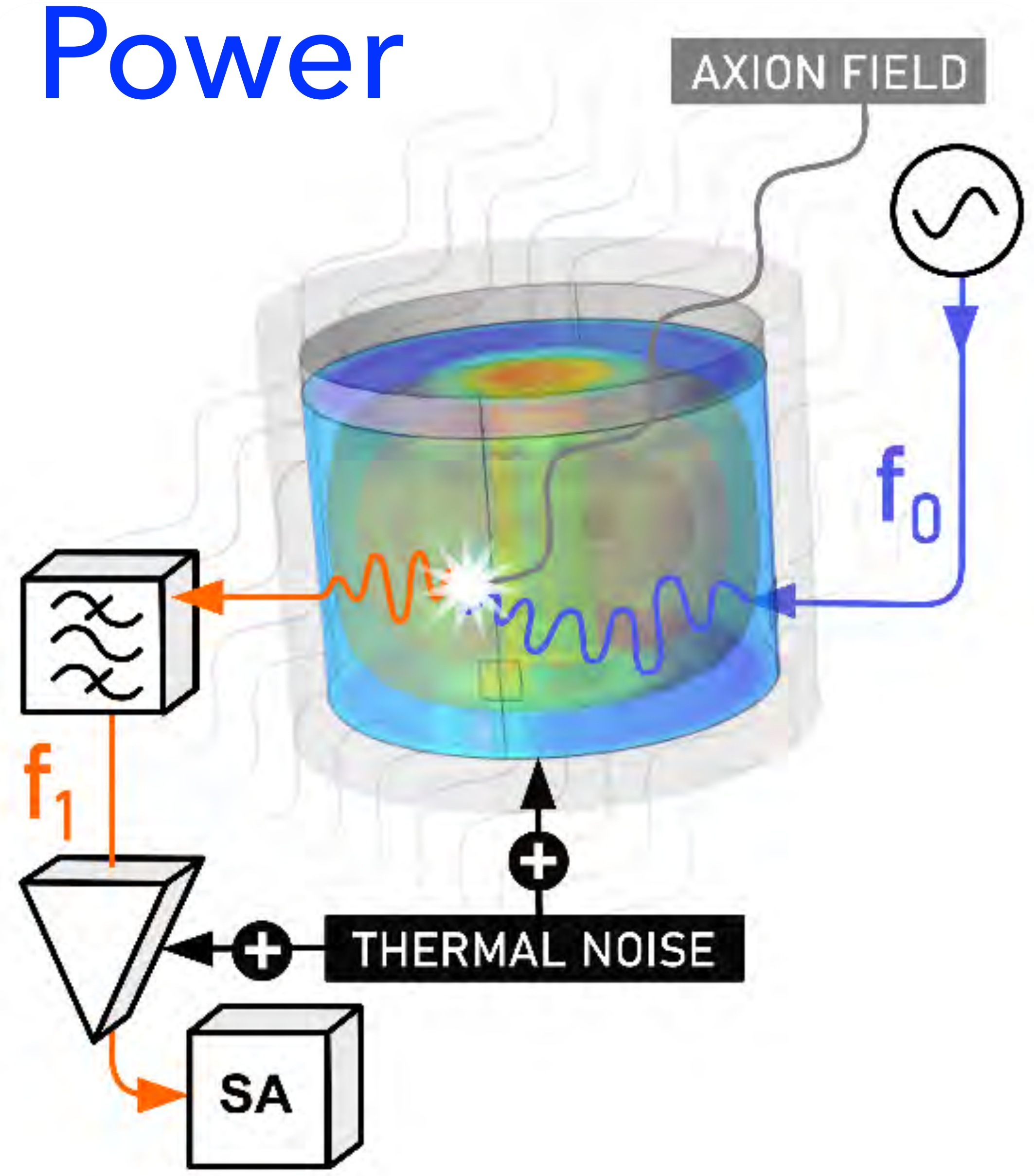

- Use a mode 0 as the background “magnetic field” AC source
- Two modes in one cylindrical cavity

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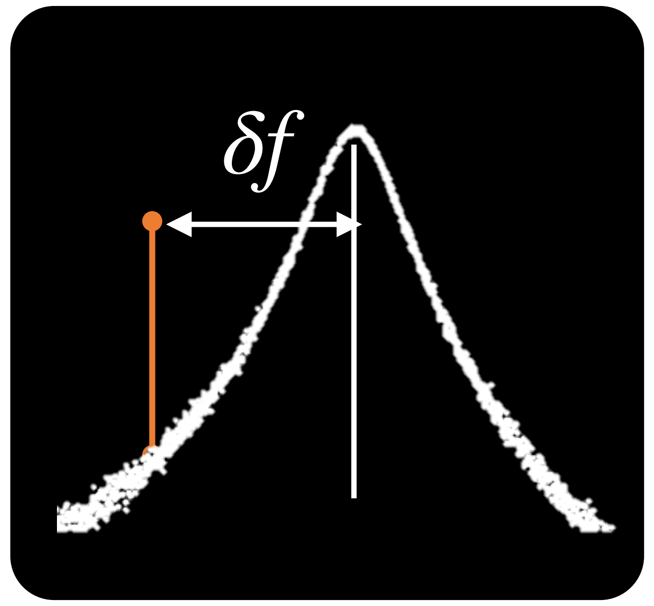

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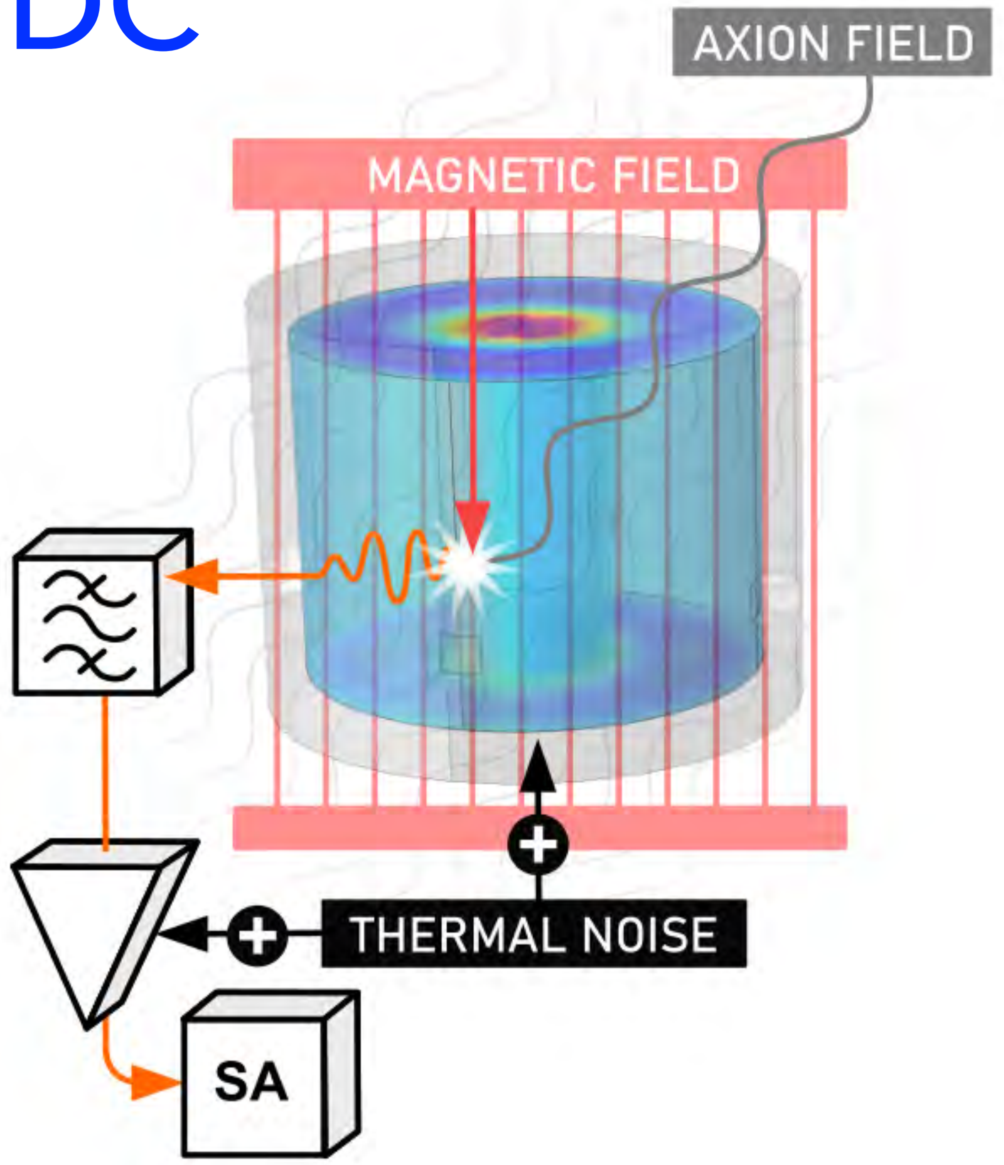

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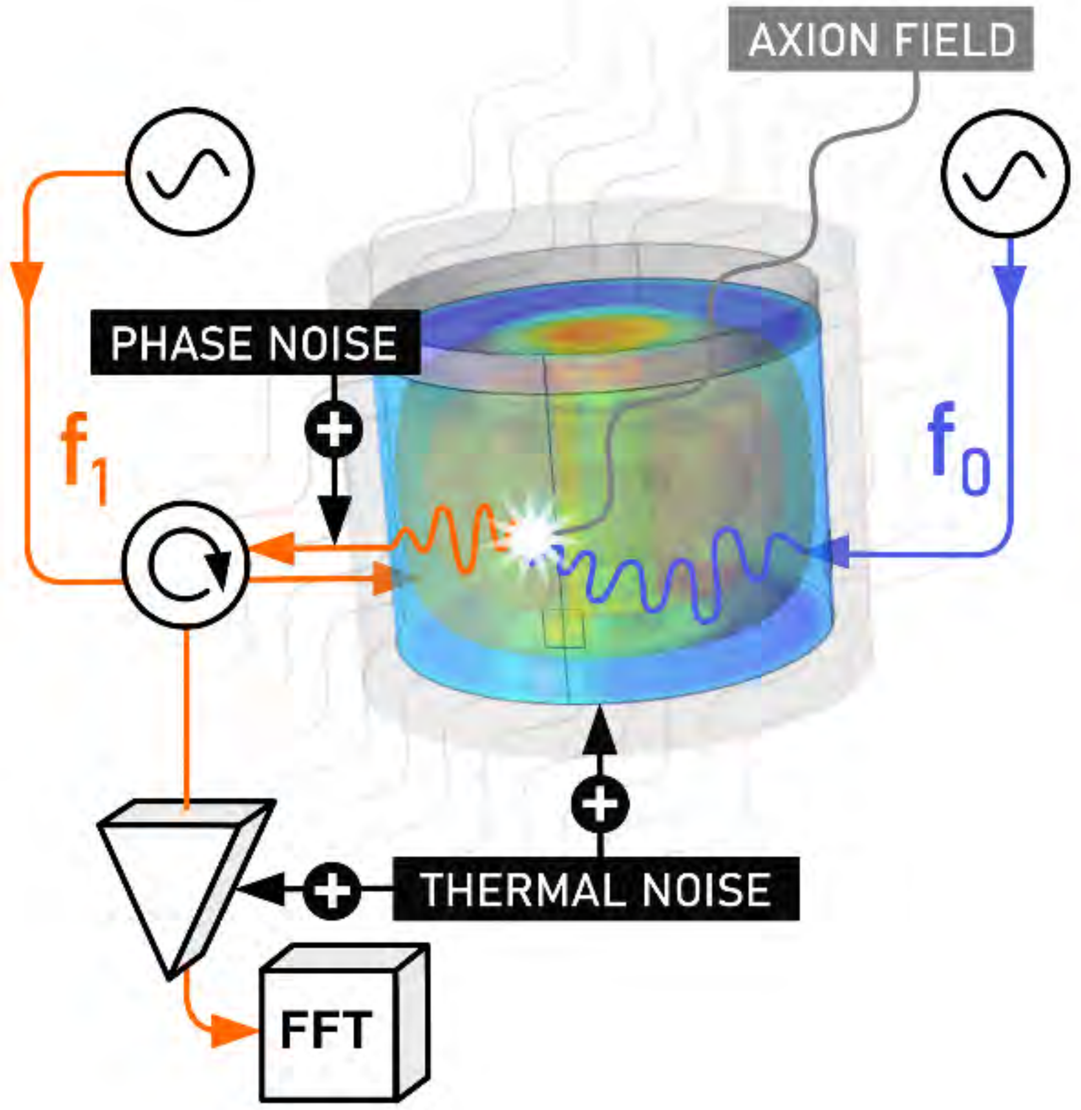

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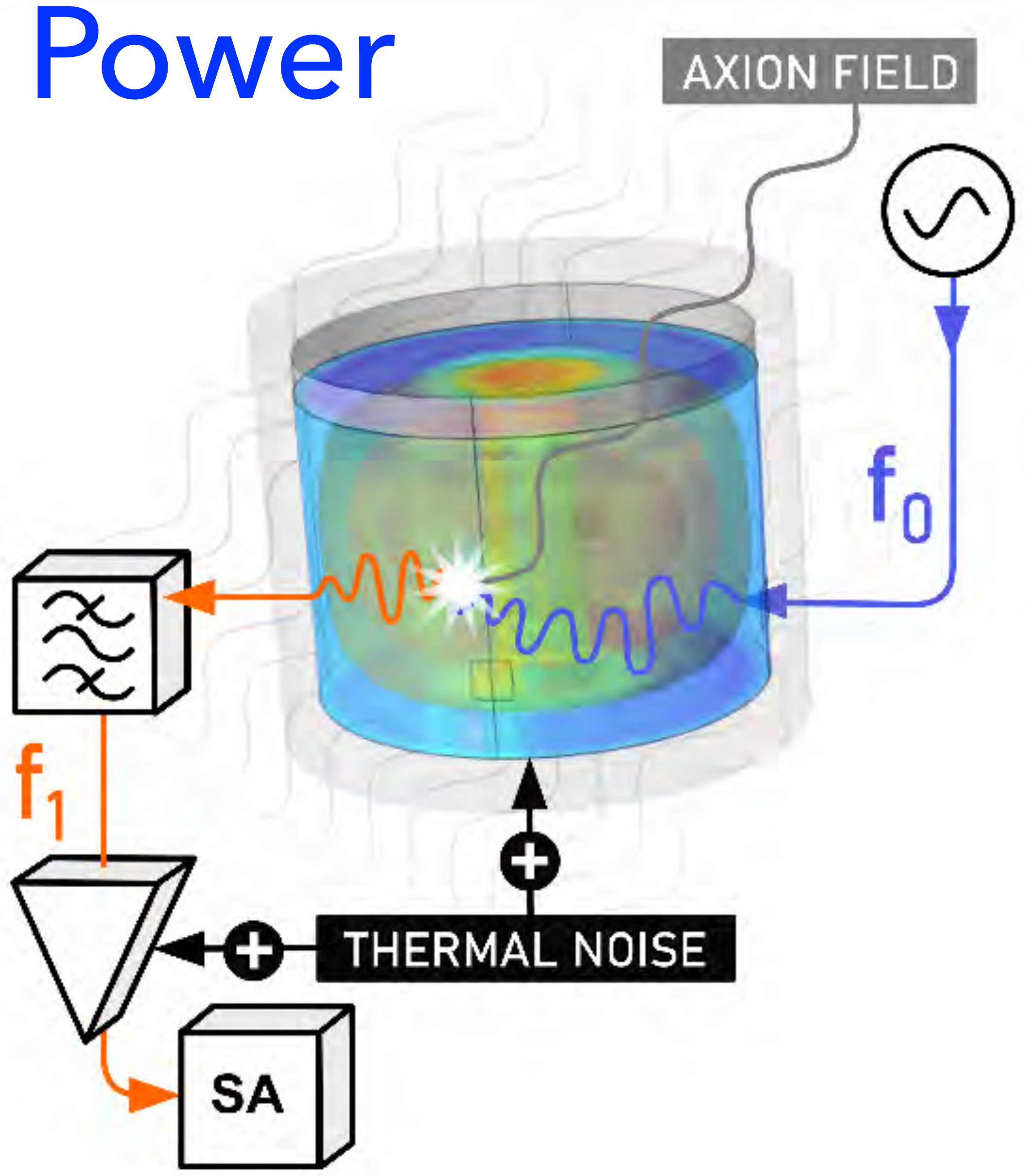

- Use a mode 0 as the background "magnetic field" AC source
- Two modes in one cylindrical cavity
- Upconversion limit $m_a = |f_1 - f_0| + \delta f$

Photon 1: E field of cavity's resonant transverse magnetic mode, $m_a = f_1 + \delta f$

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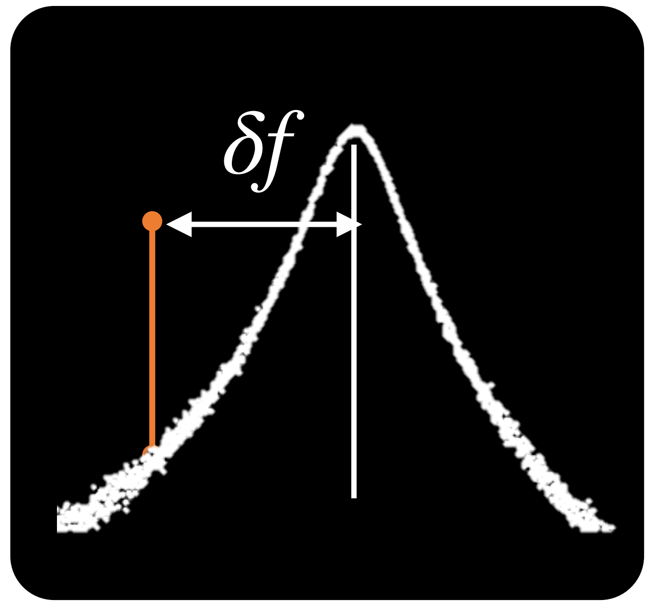

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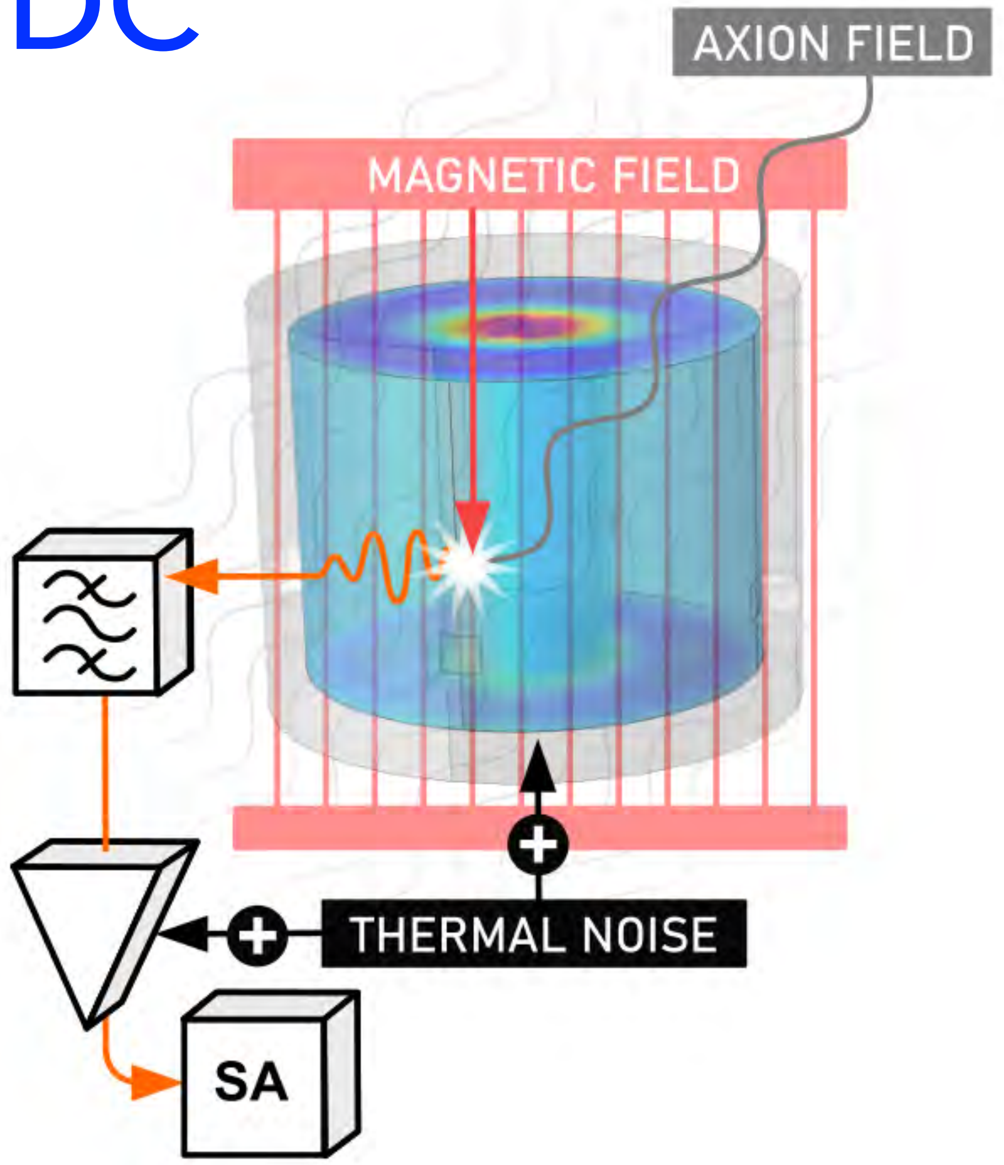

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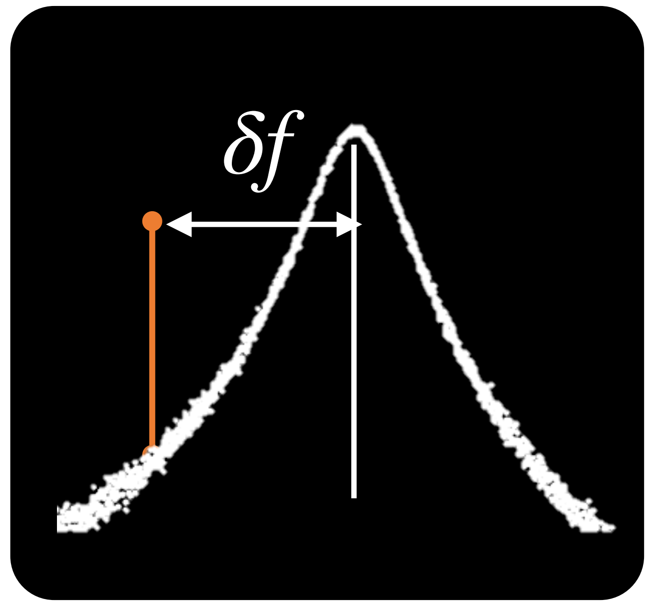

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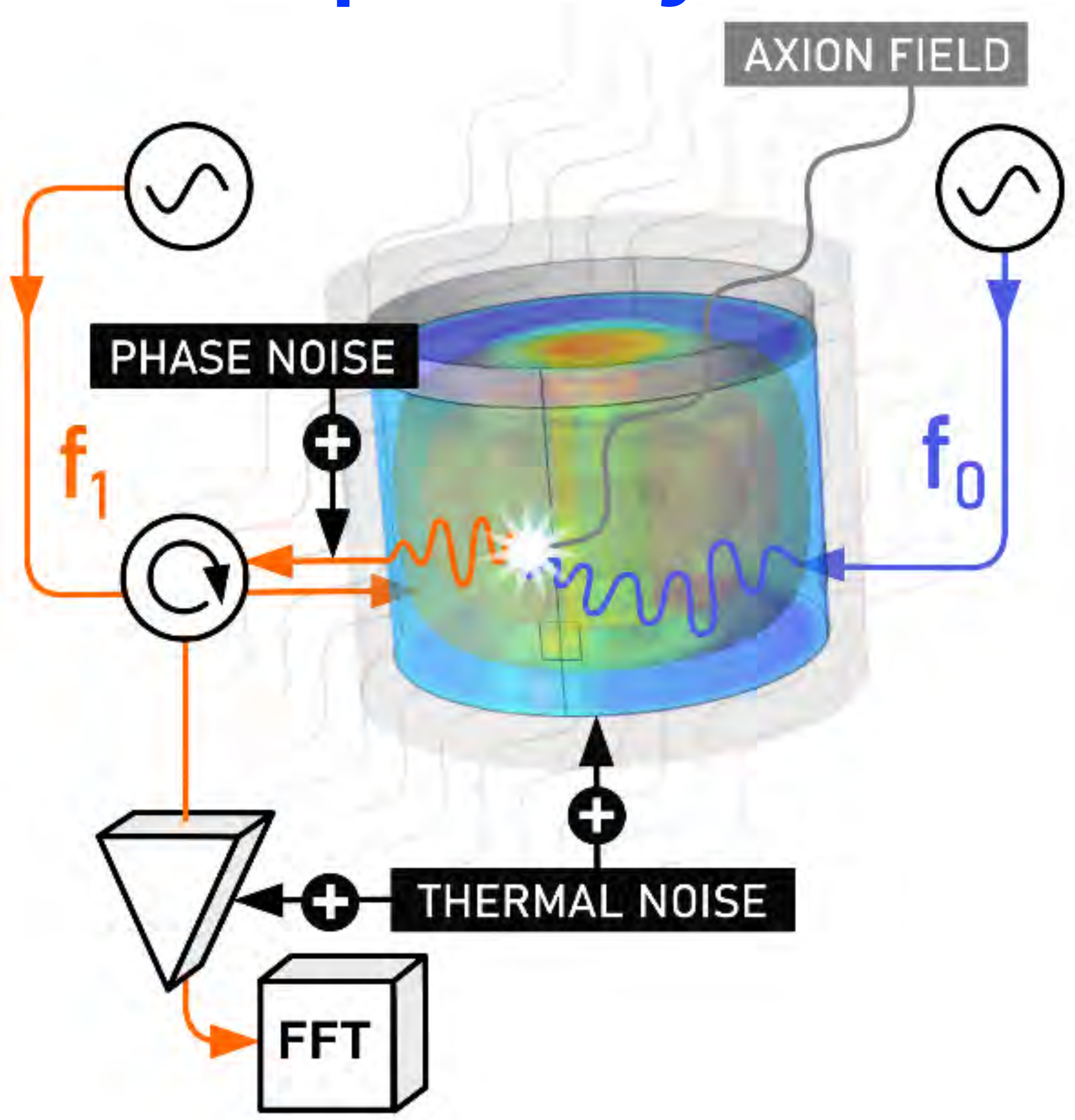

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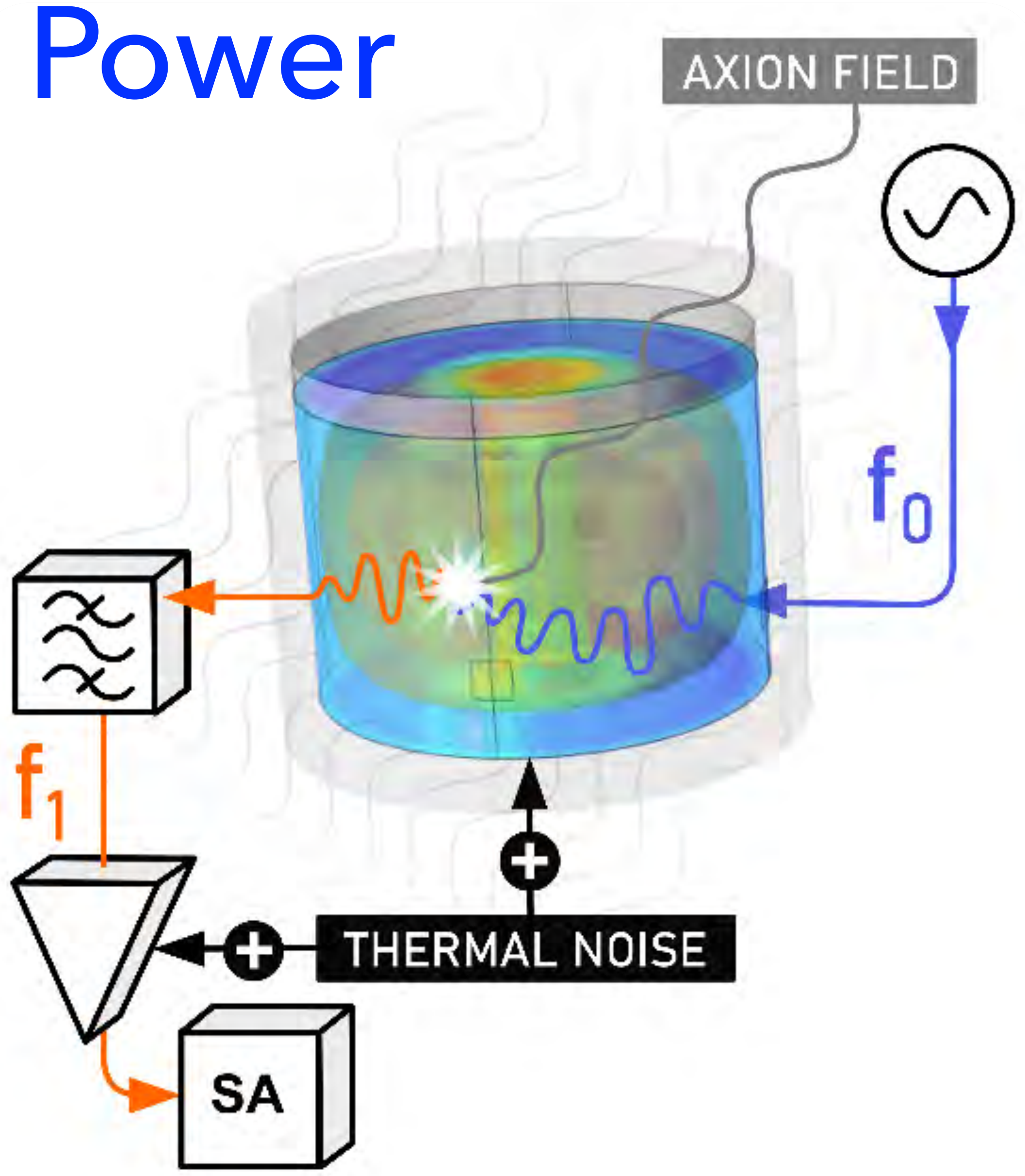

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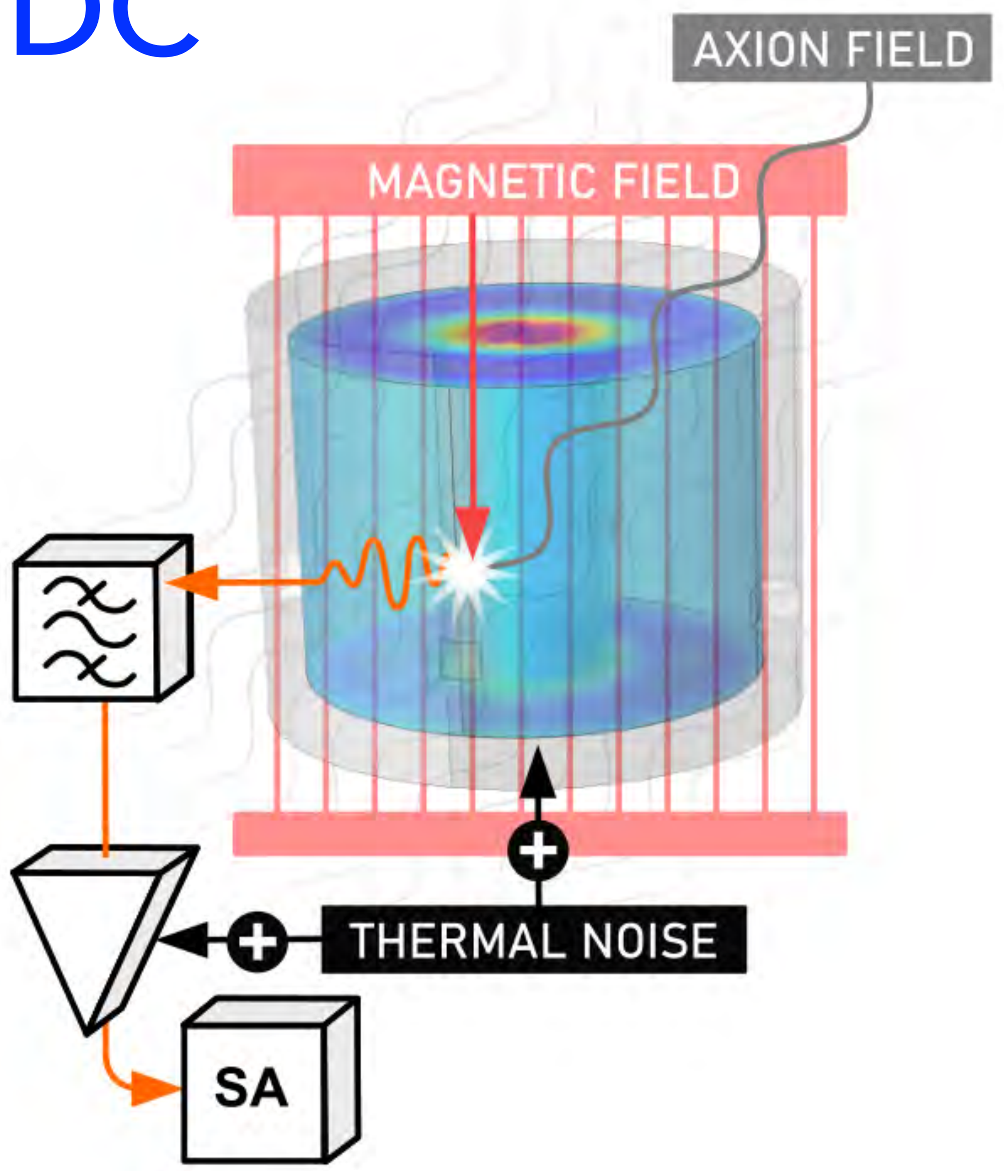
Photon 1: Transverse Magnetic Mode

(Longitudinal Electric)

Resonant Axion Haloscopes @ UWA

$$\mathcal{H}_{int} = \epsilon_0 c g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

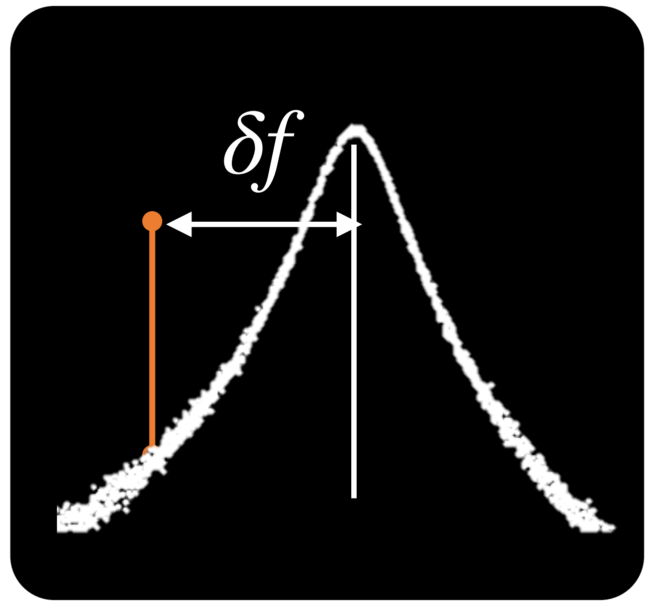
DC



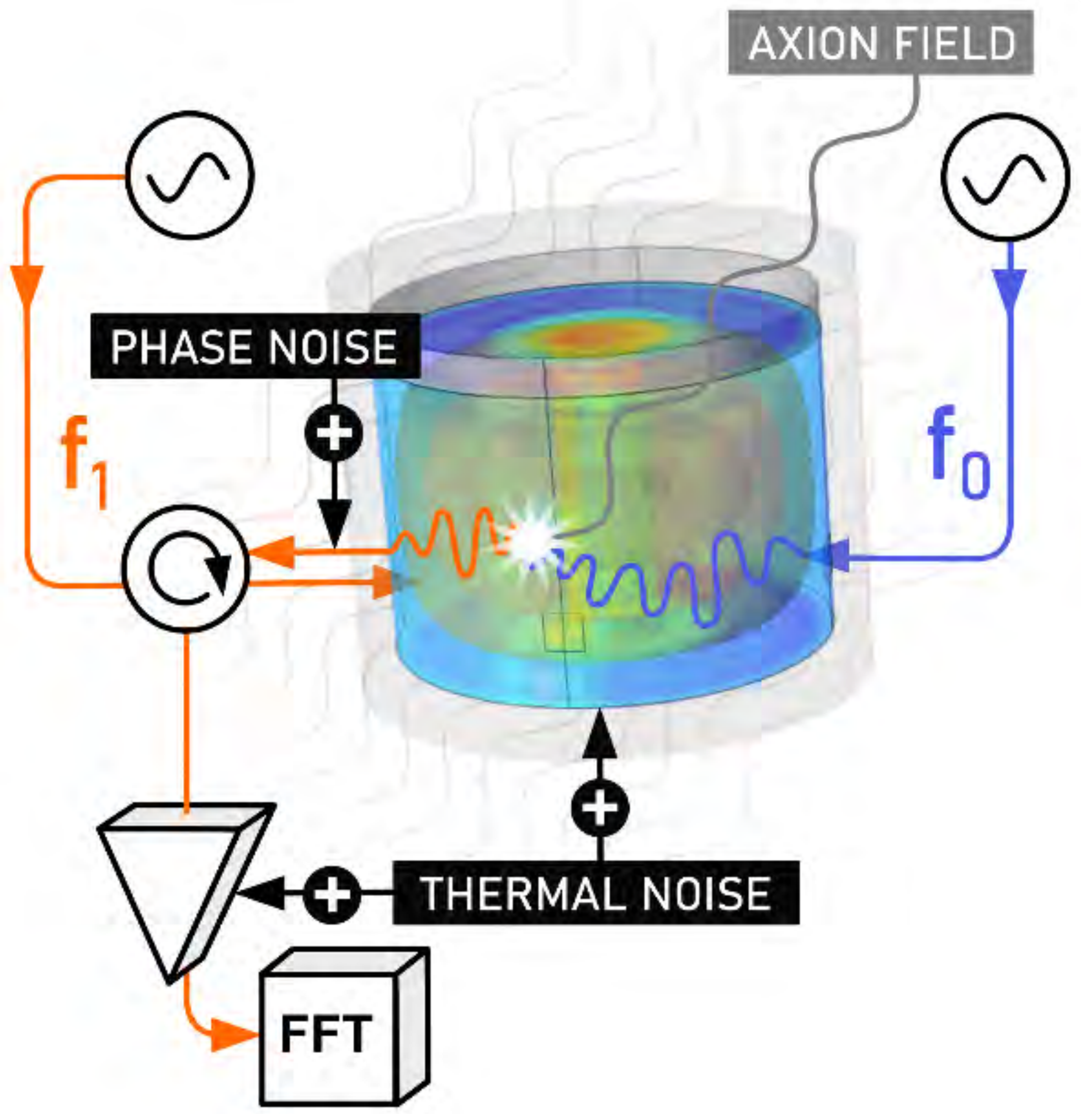
Photon 1: E field of cavity's resonant transverse magnetic mode, $m_a = f_1 + \delta f$

Photon 0, Back ground DC B field of surrounding magnet

eg.
- ADMX
- ORGAN (UWA)
- CAPP
- HAYSTAC



AC Frequency



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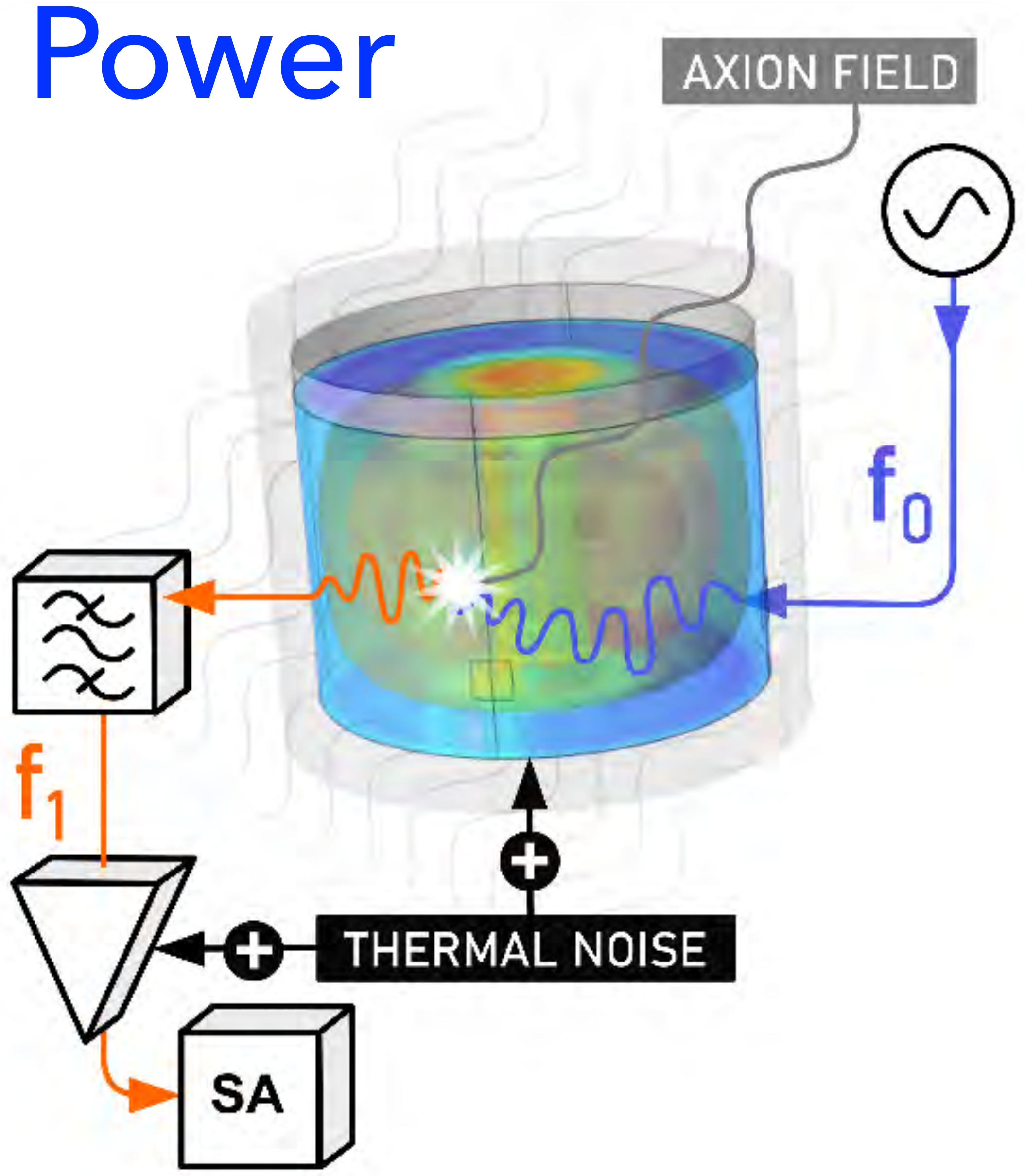

- Use a mode 0 as the background "magnetic field" AC source
- Two modes in one cylindrical cavity
- Upconversion limit $m_a = |f_1 - f_0| + \delta f$

Photon 1: Transverse Magnetic Mode

(Longitudinal Electric)

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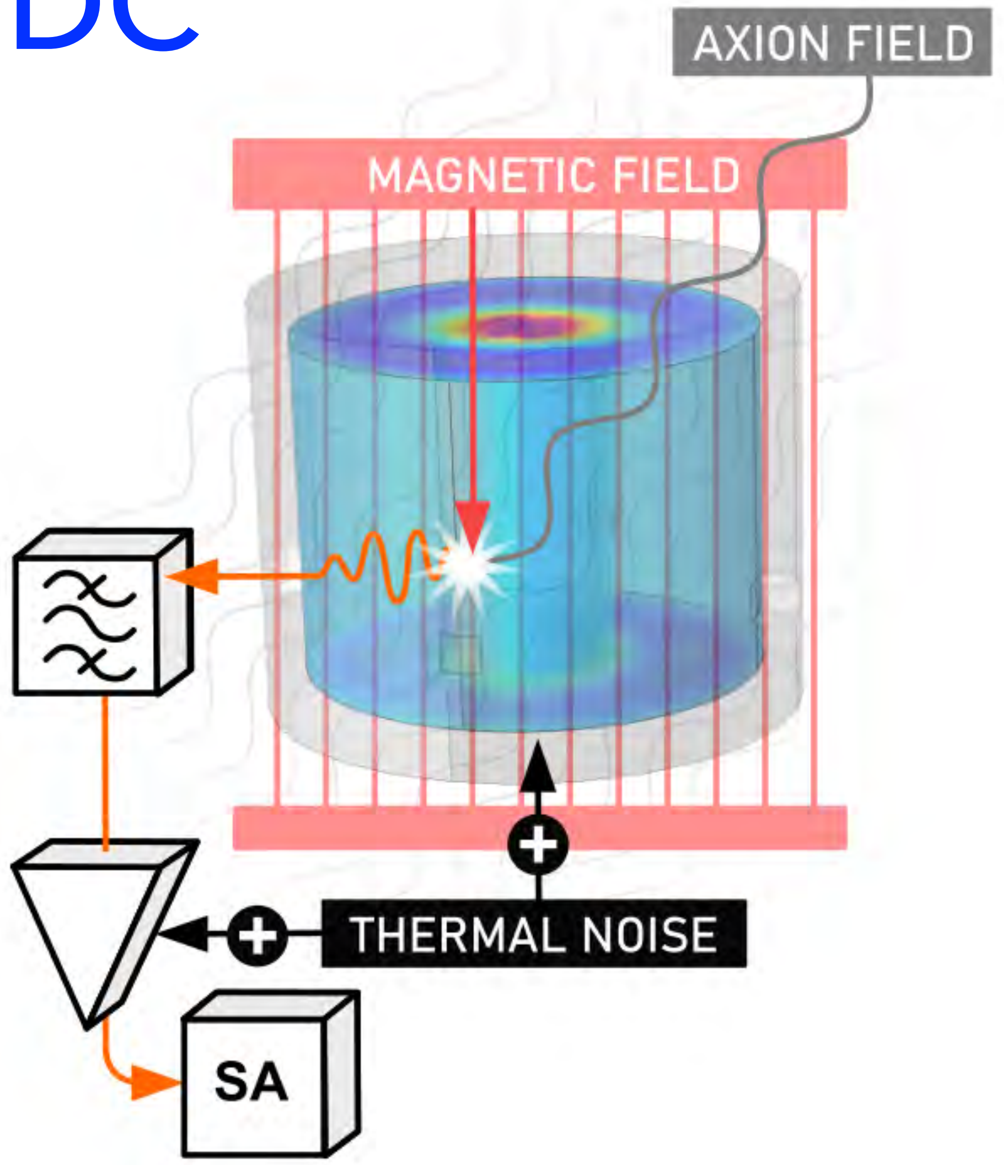

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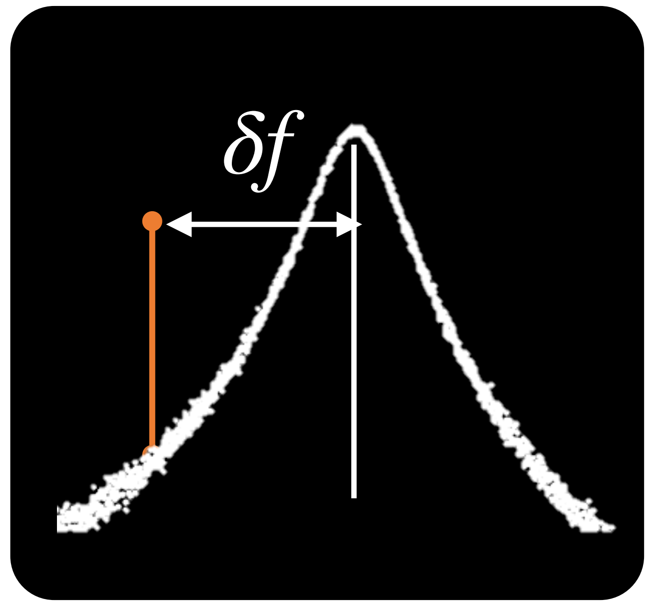

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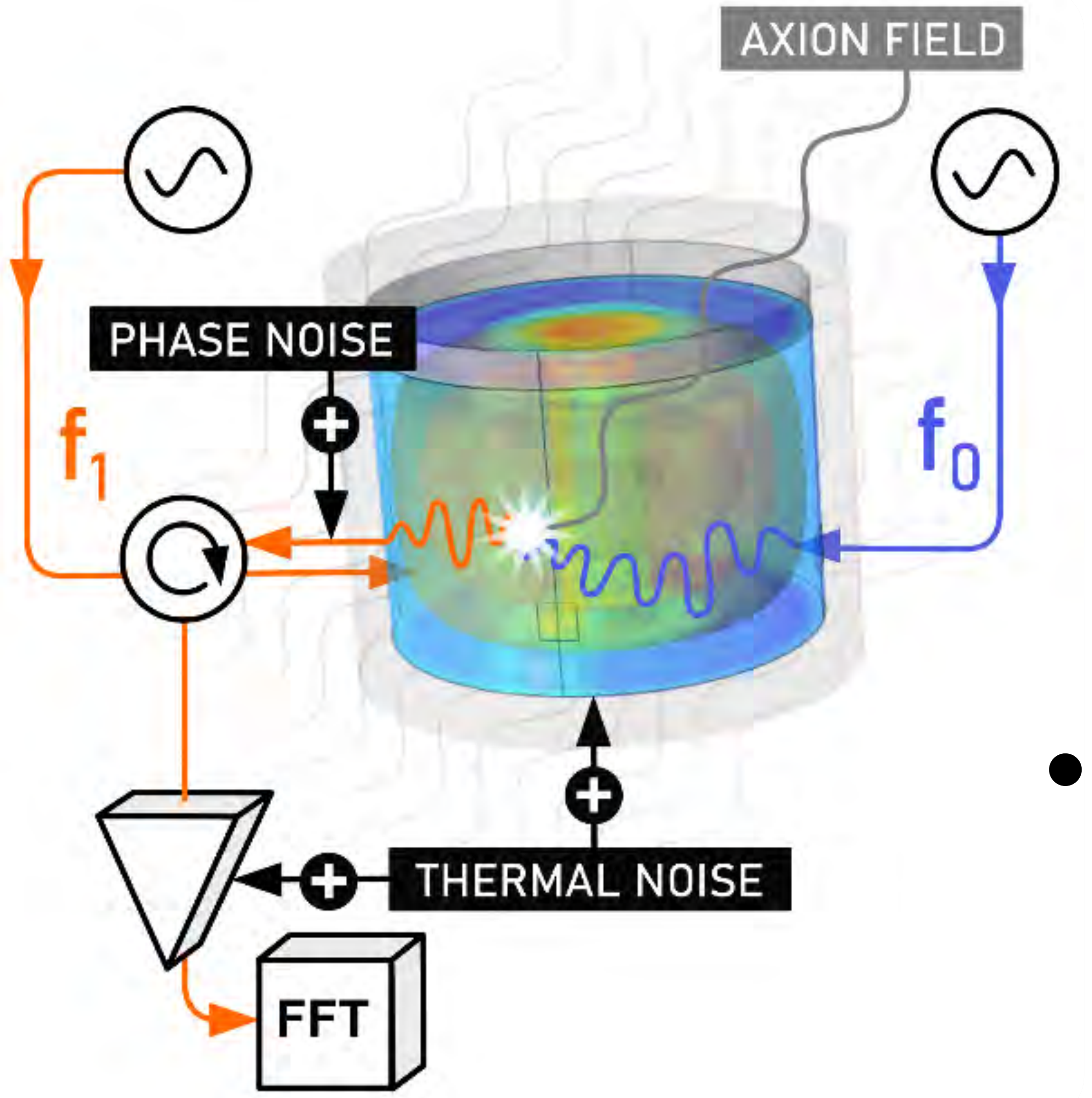

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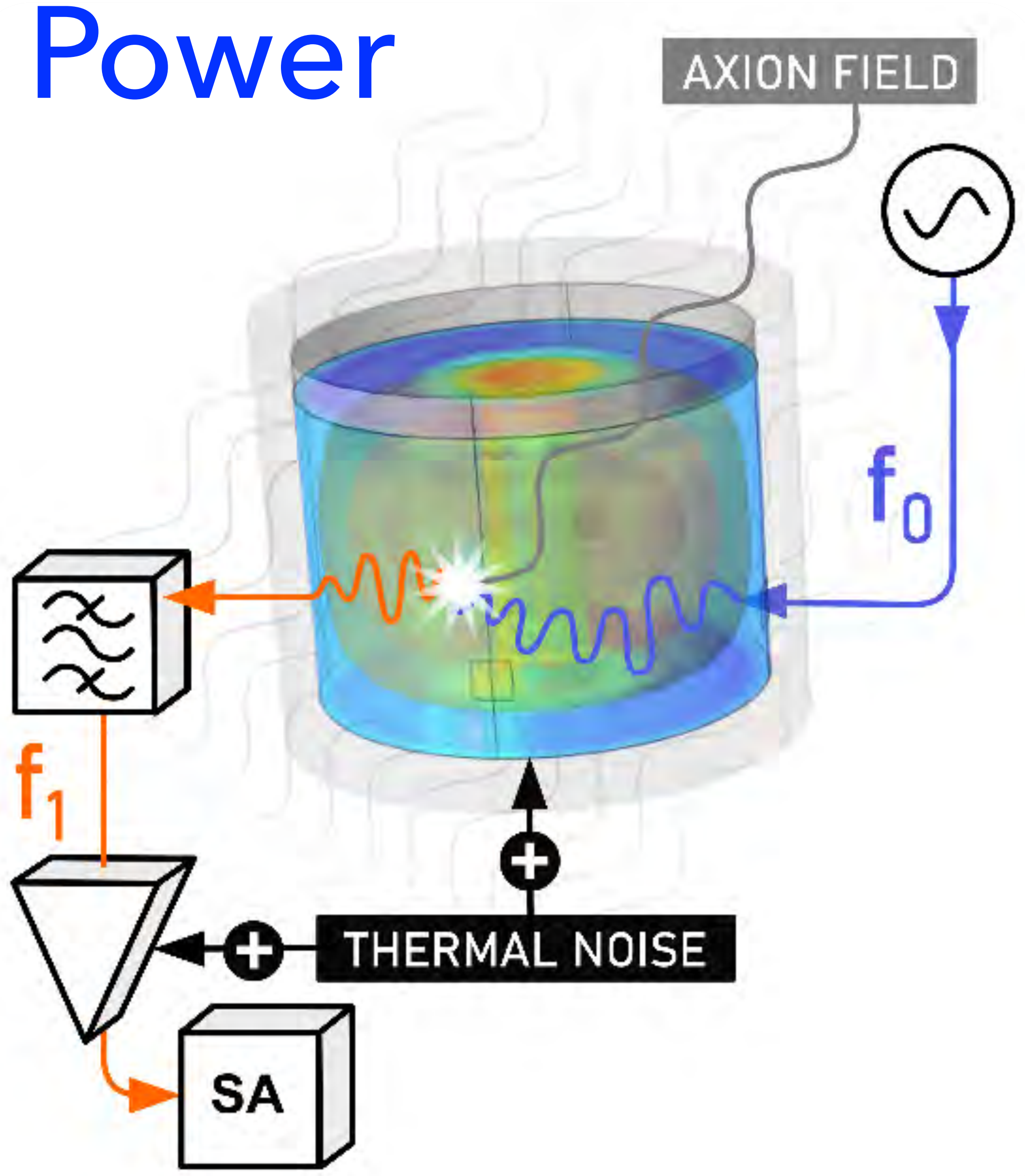

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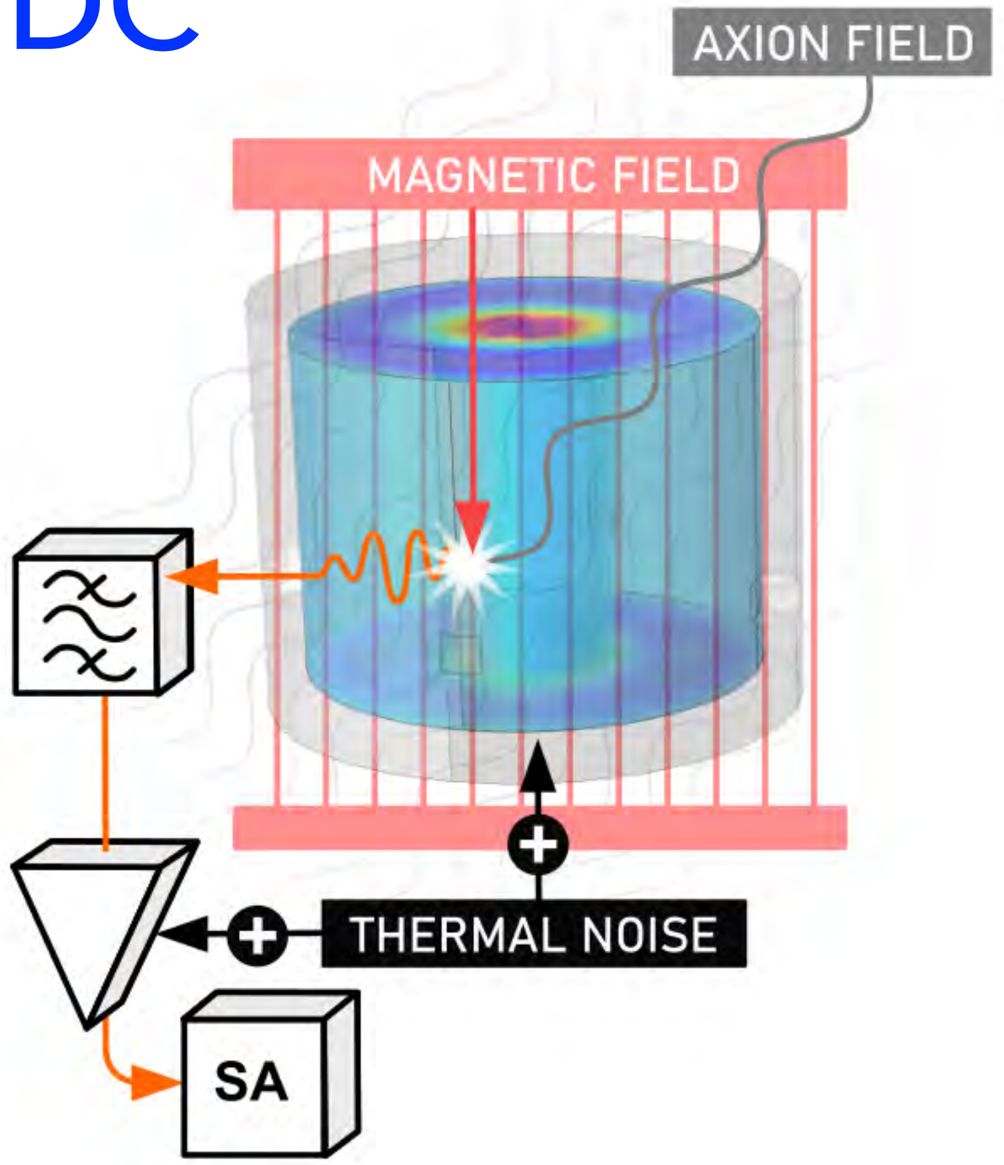

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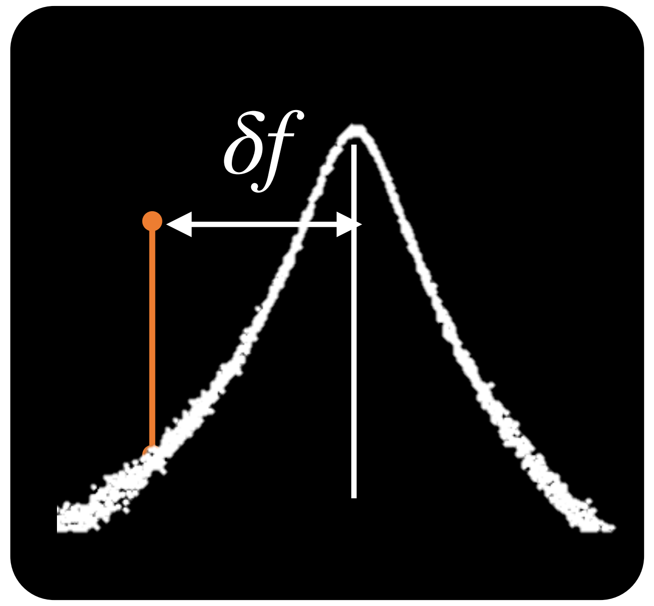

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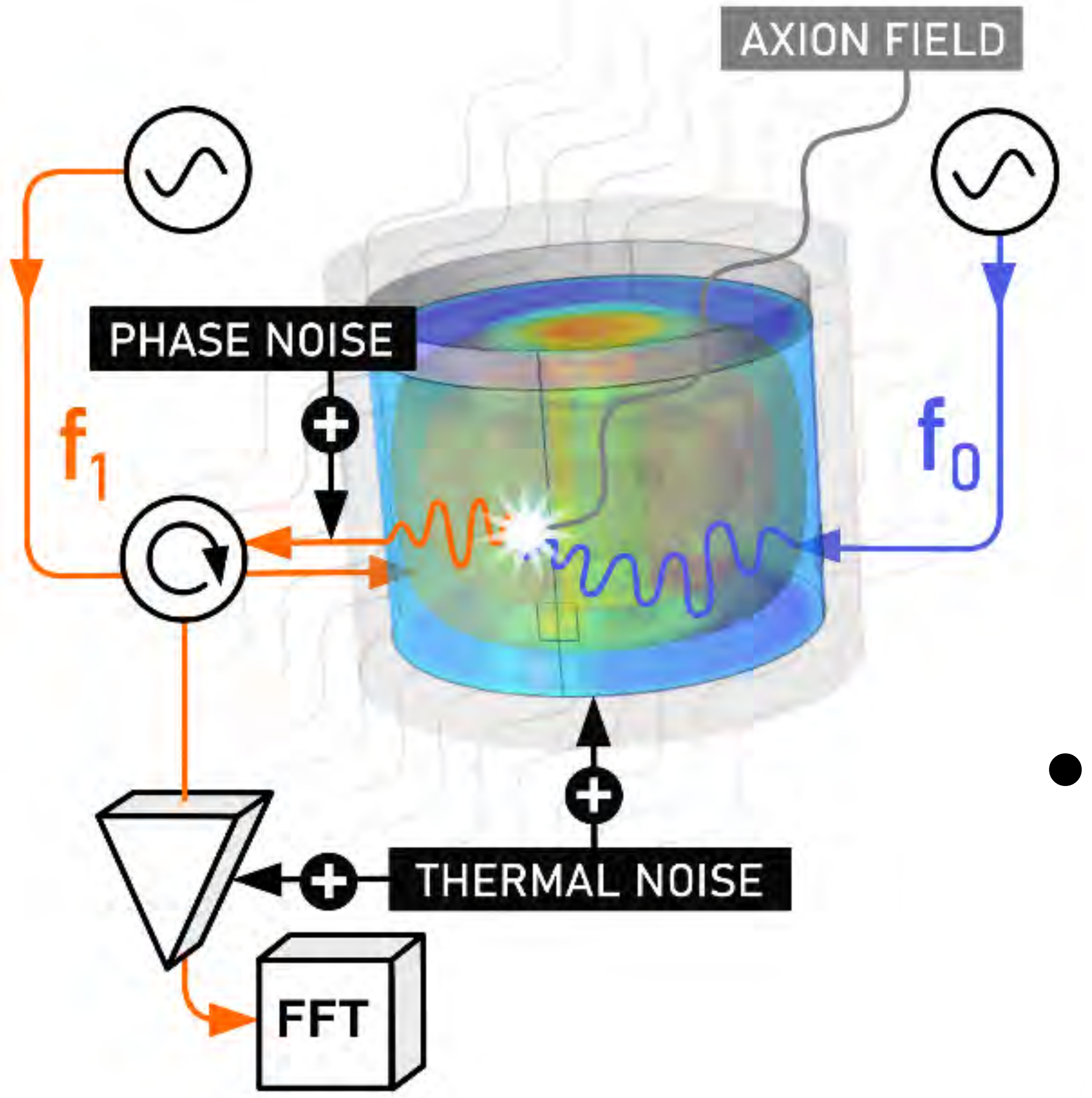

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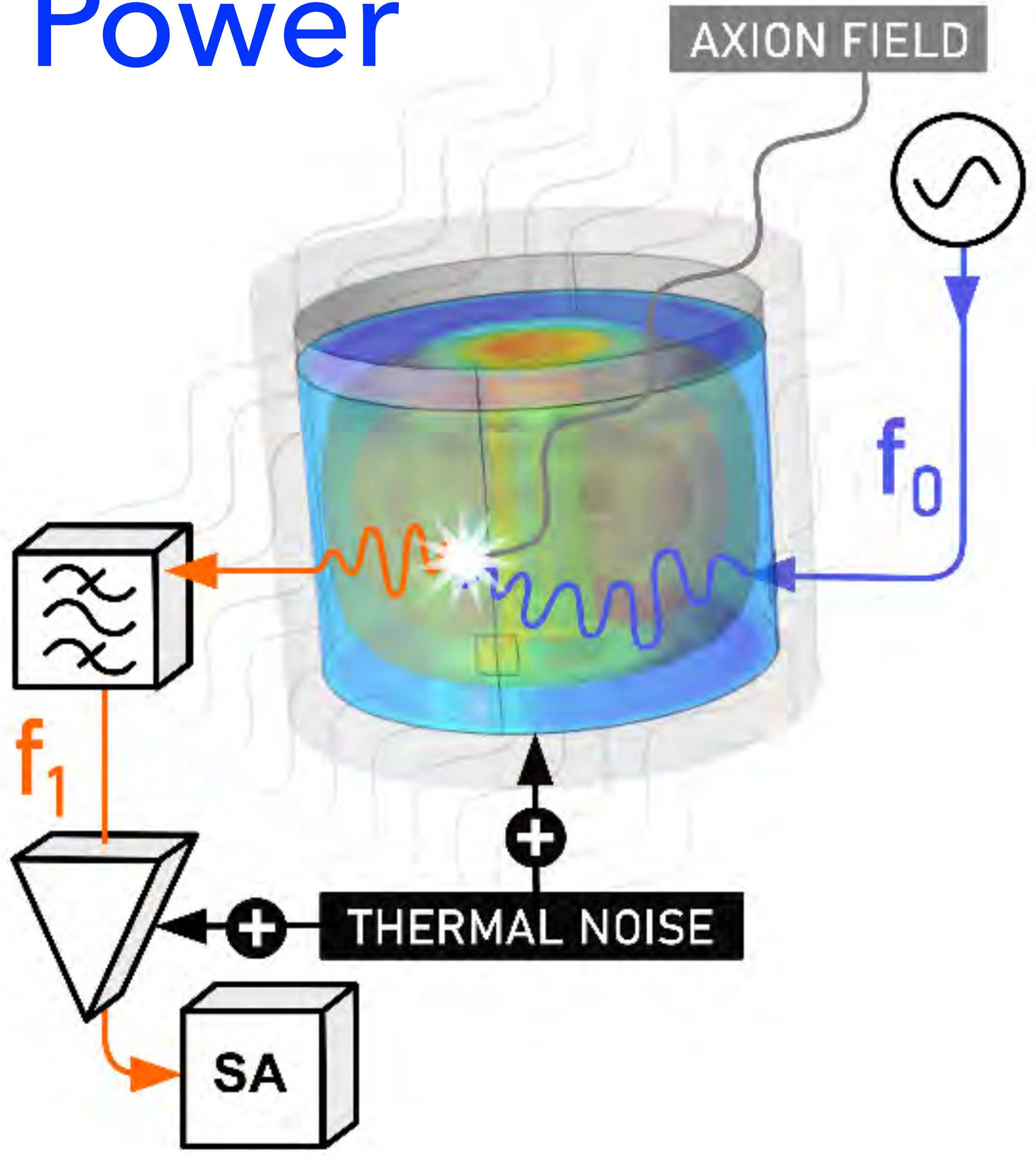

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AC Frequency: Excite two modes: Measure f_1 Frequency Fluctuation Spectrum

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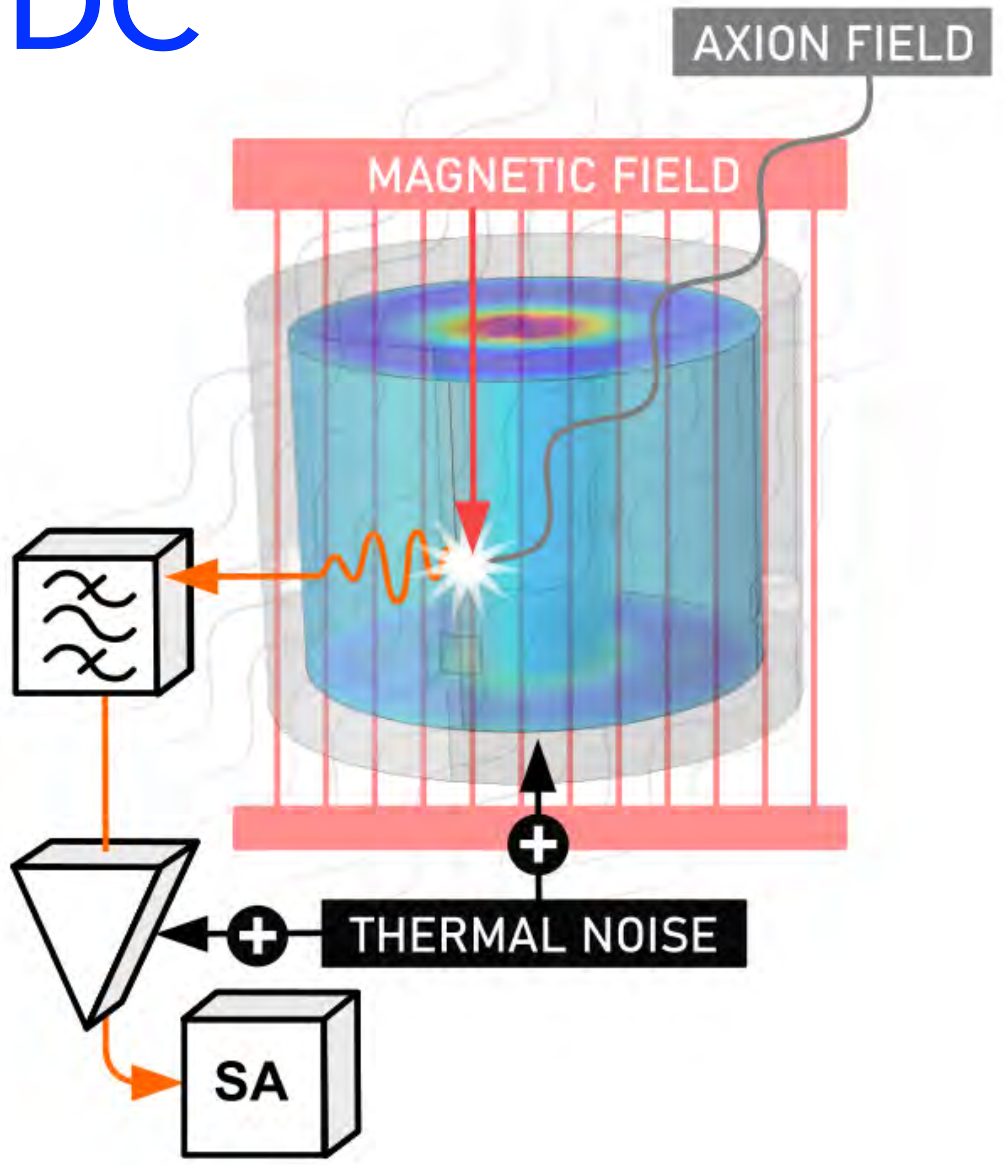

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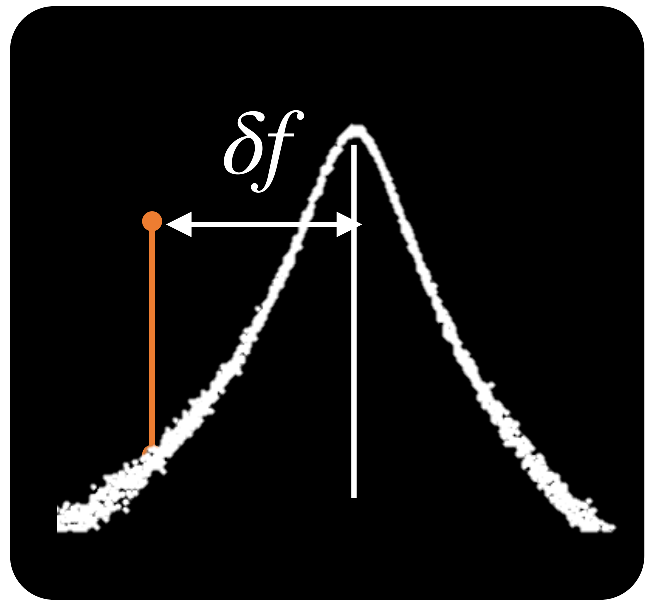

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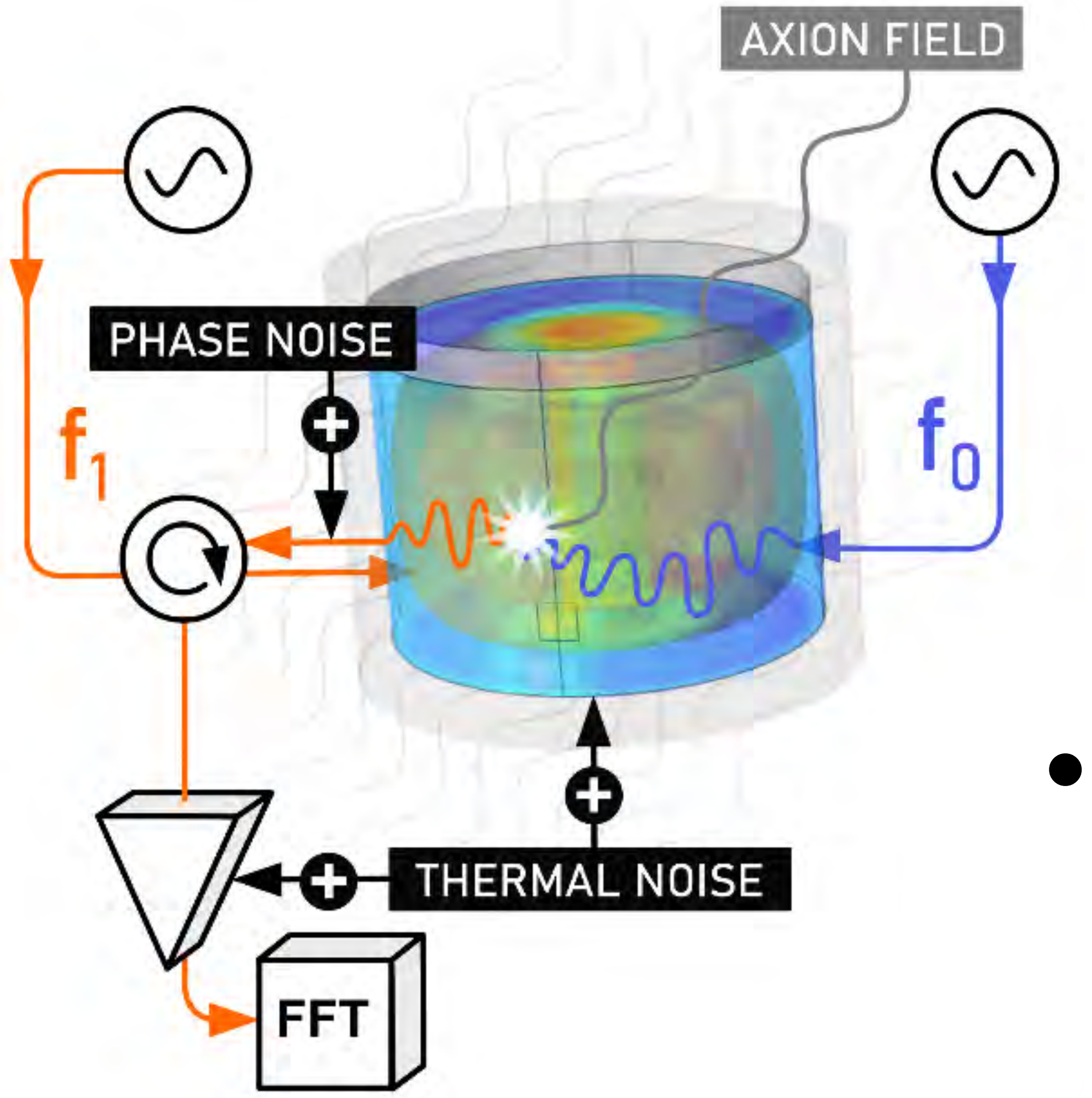

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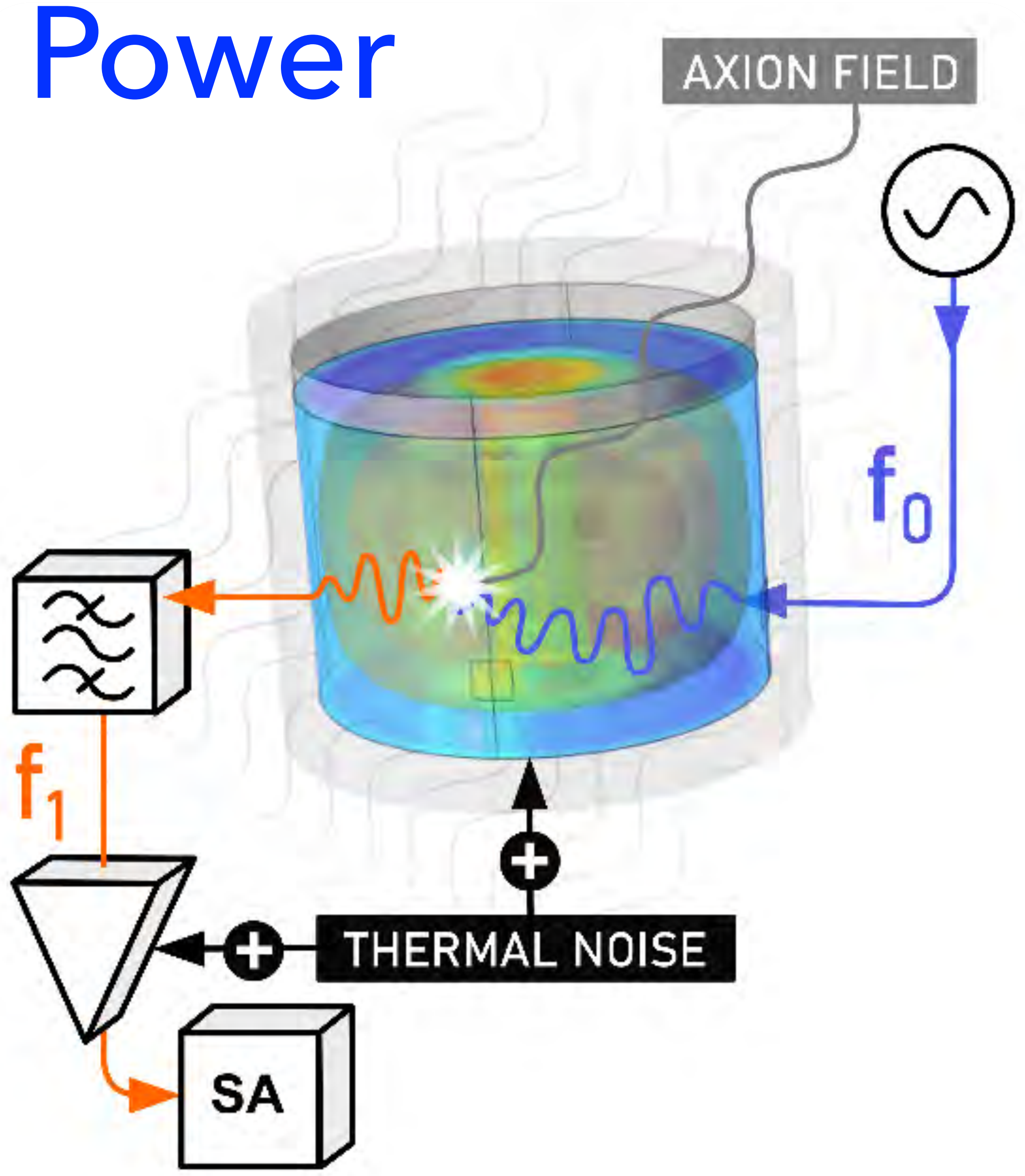

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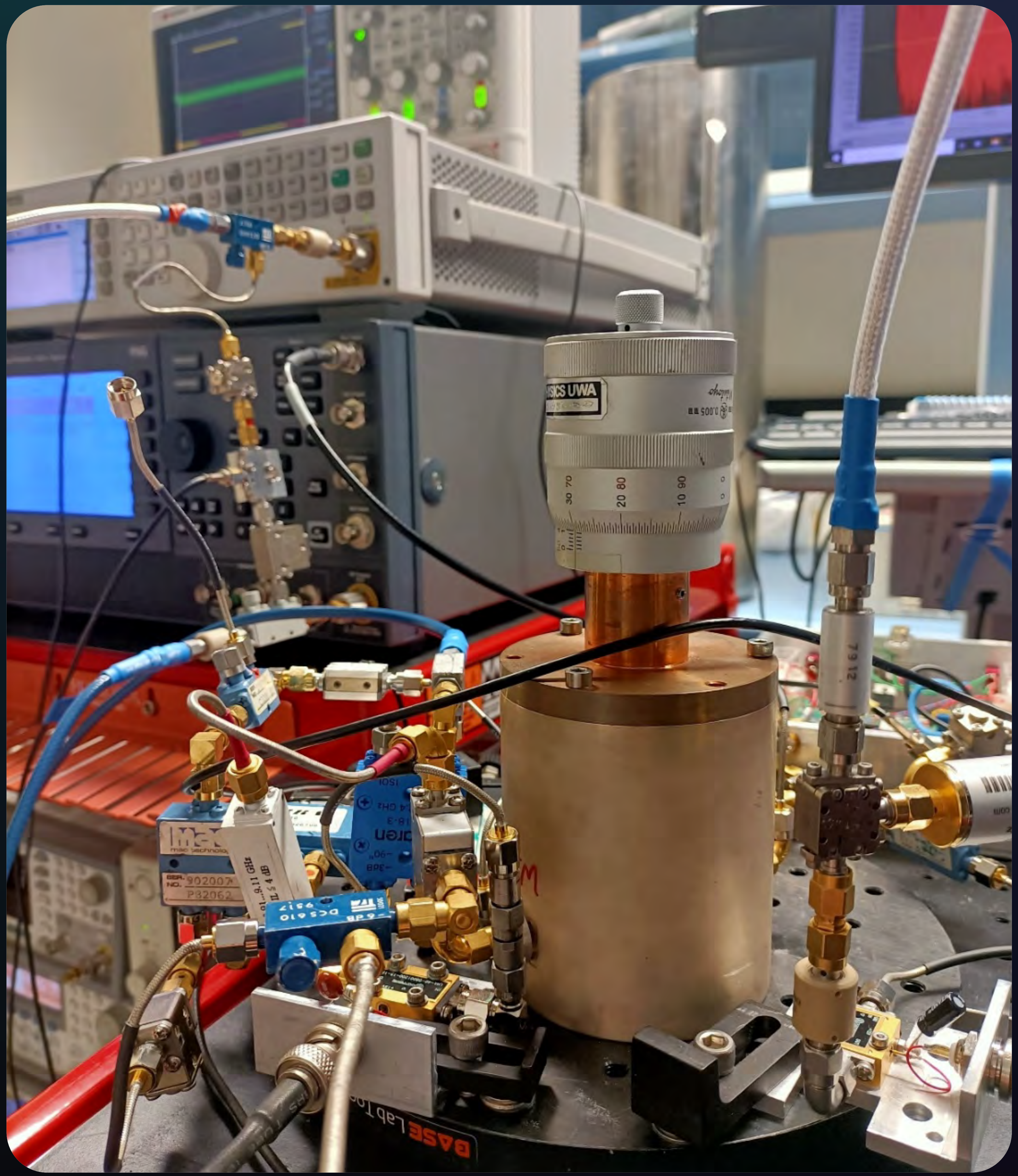
AC Power: Excite f_0: Measure f_1 Power Fluctuation Spectrum

UPLOA

UPconversion Low-Noise Oscillator Axion Detector

UPconversion Low-Noise Oscillator Axion Detection Experiment

- Cavity resonator haloscope
- No externally applied magnetic field
- TM and TE modes (~ 9 GHz modes)
- Height Tunable
- Accessing MHz axions via upconversion



PHYSICAL REVIEW D **107**, 112003 (2023)

Searching for low-mass axions using resonant upconversion

Catriona A. Thomson,[1,*] Maxim Goryachev,[1] Ben T. McAllister,[1,2] Eugene N. Ivanov,[1] Paul Altin,[3] and Michael E. Tobar[1,†]

[1]*Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia*

[2]*Centre for Astrophysics and Supercomputing, Swinburne University of Technology, John St, Hawthorn, Victoria 3122, Australia*

[3]*ARC Centre of Excellence For Engineered Quantum Systems, The Australian National University, Canberra, Australian Capital Territory 2600 Australia*

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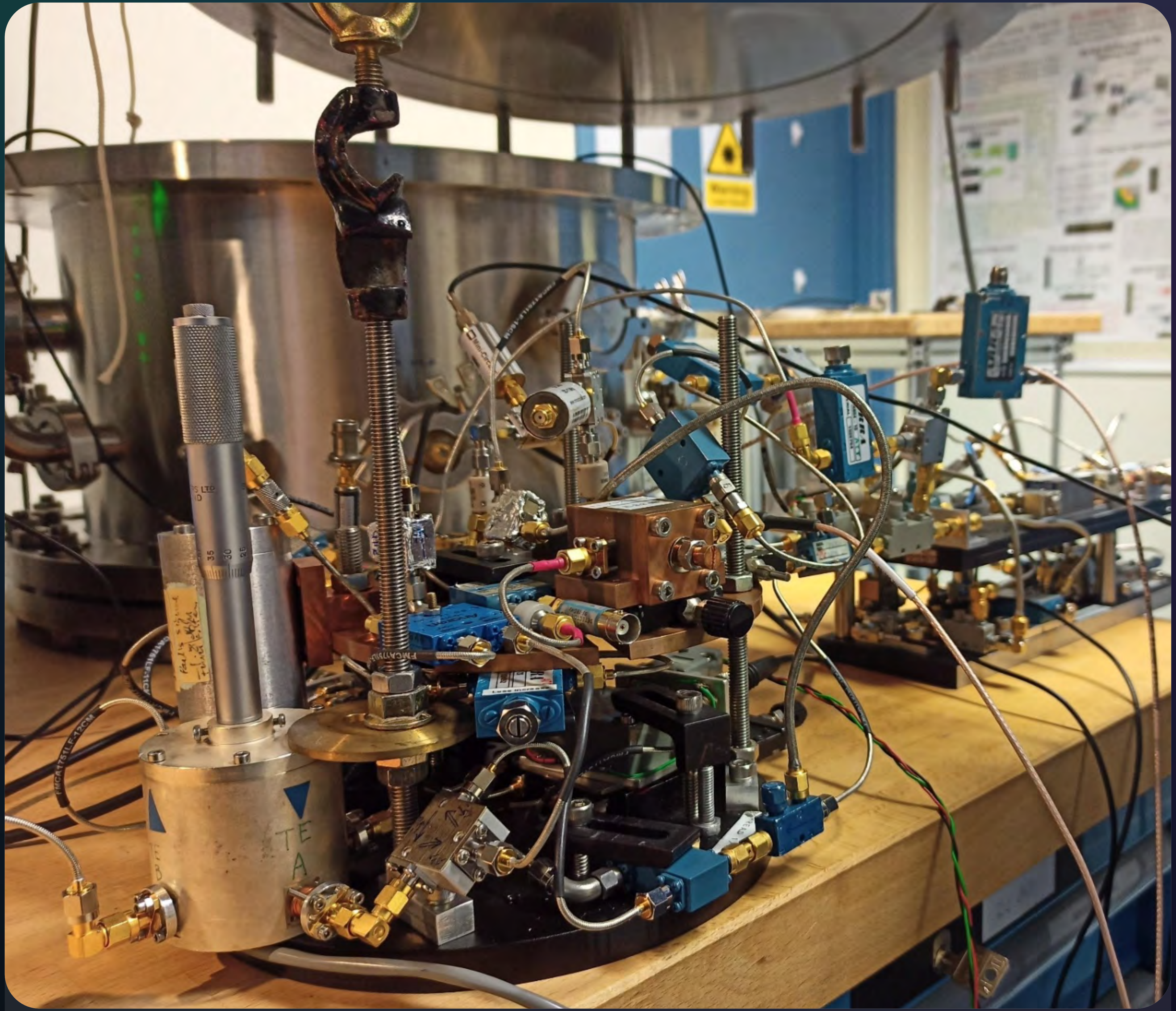
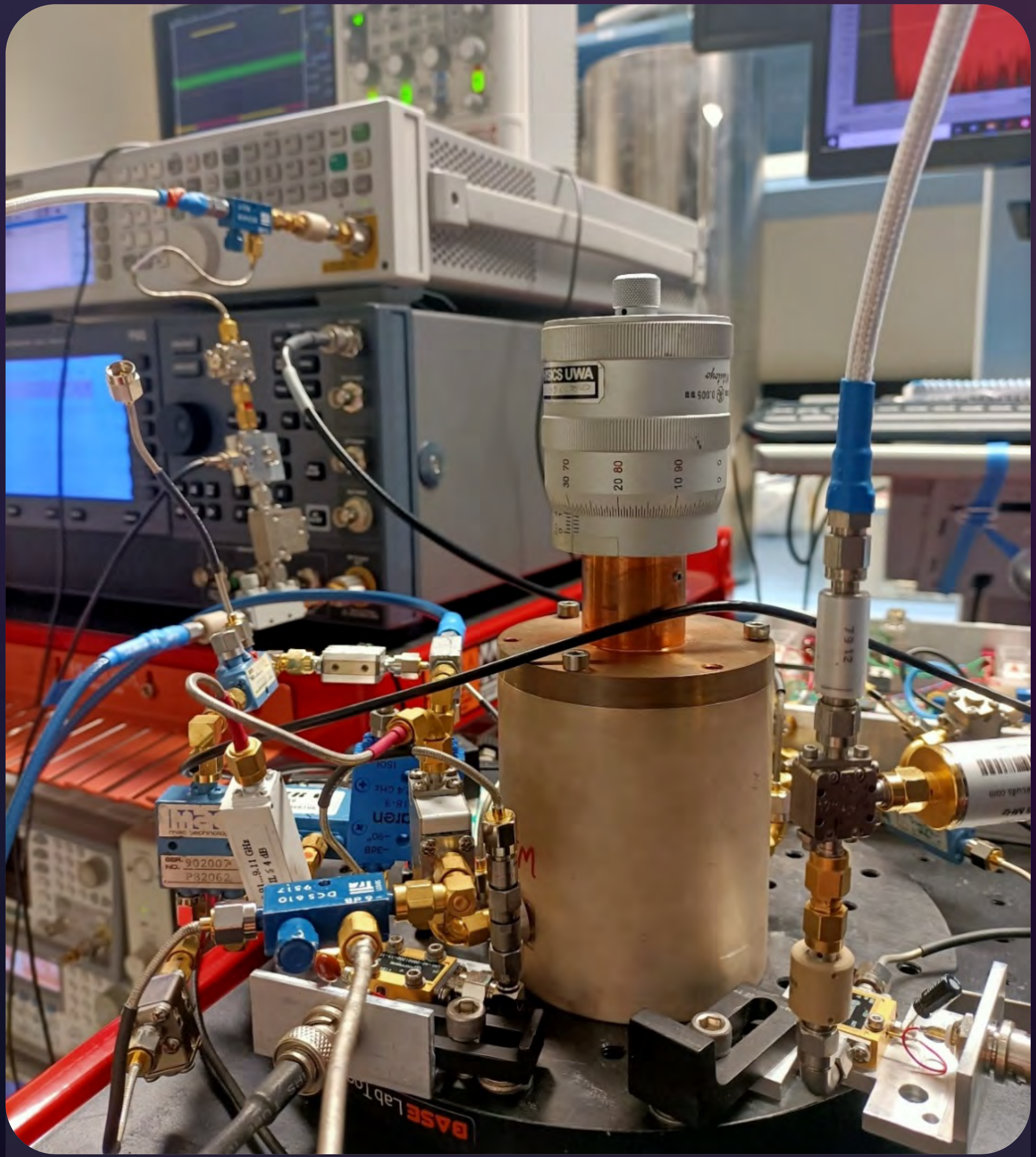


V1: readout via frequency metrology



V2: readout via thermal noise peak (power)

UPLOAD V2: Exclusion limits

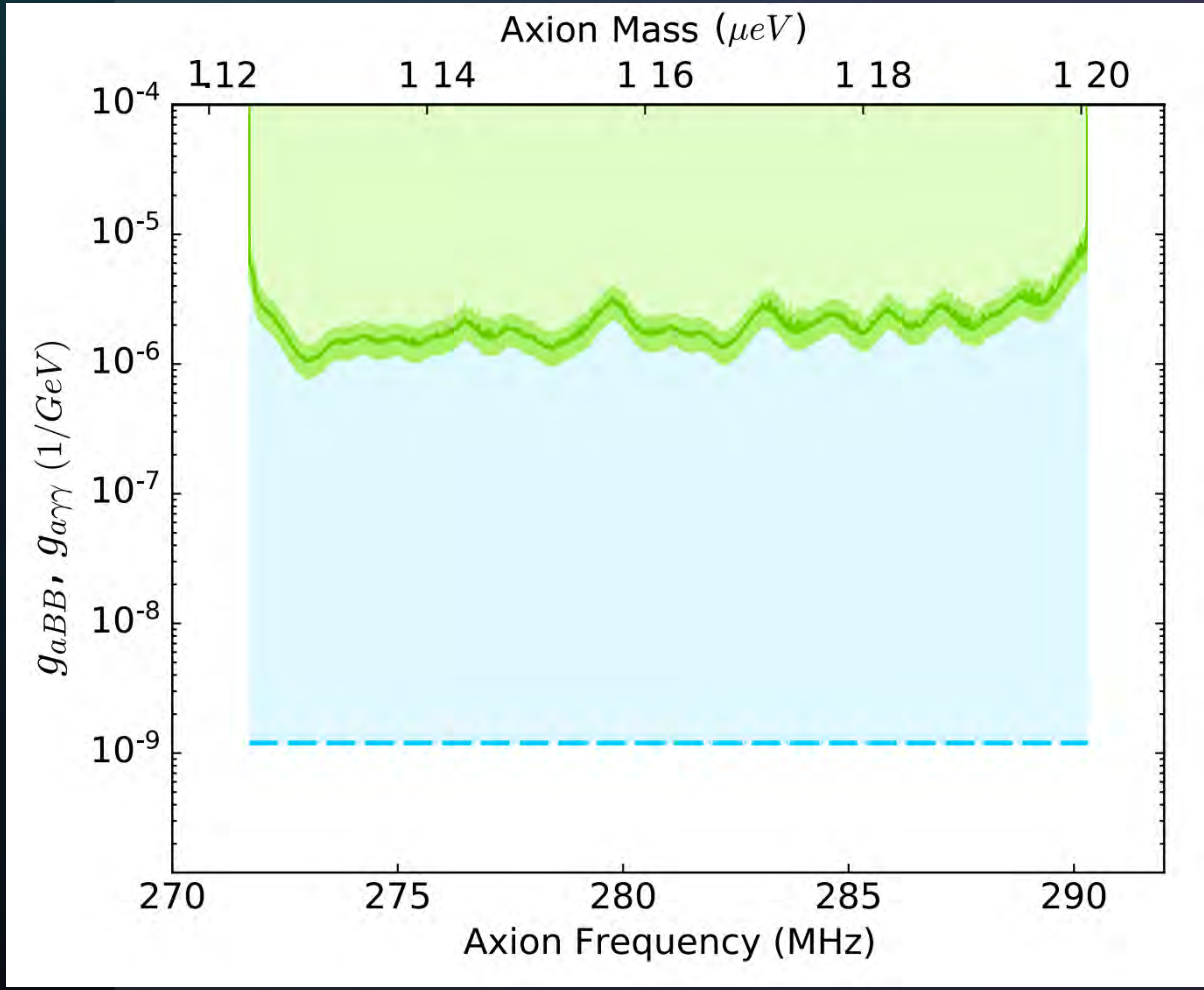


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FIG. 7. In green, the 95% confidence axion exclusion zone for both $g_{a\gamma\gamma}$ and g_{aBB} for the measured mass range between 1.12 – 1.20 μeV (271.7 MHz—290.3 MHz) for a measurement period of 30 days, which is an improvement of 3 orders of magnitude over our previous result [29]. The bright green region represents the uncertainty on excluded $g_{a\gamma\gamma}$, which is detailed in Appendix C. The blue dashed line represents the approximate sensitivity achievable with a niobium resonator of loaded quality factors around 10^7 and cooled to a temperature of 4 K, measuring for a period of 30 days, and using a cryogenic amplifier of noise temperature 4 K. Construction for this setup is underway.

UPLOAD V3: Cryogenic Niobium

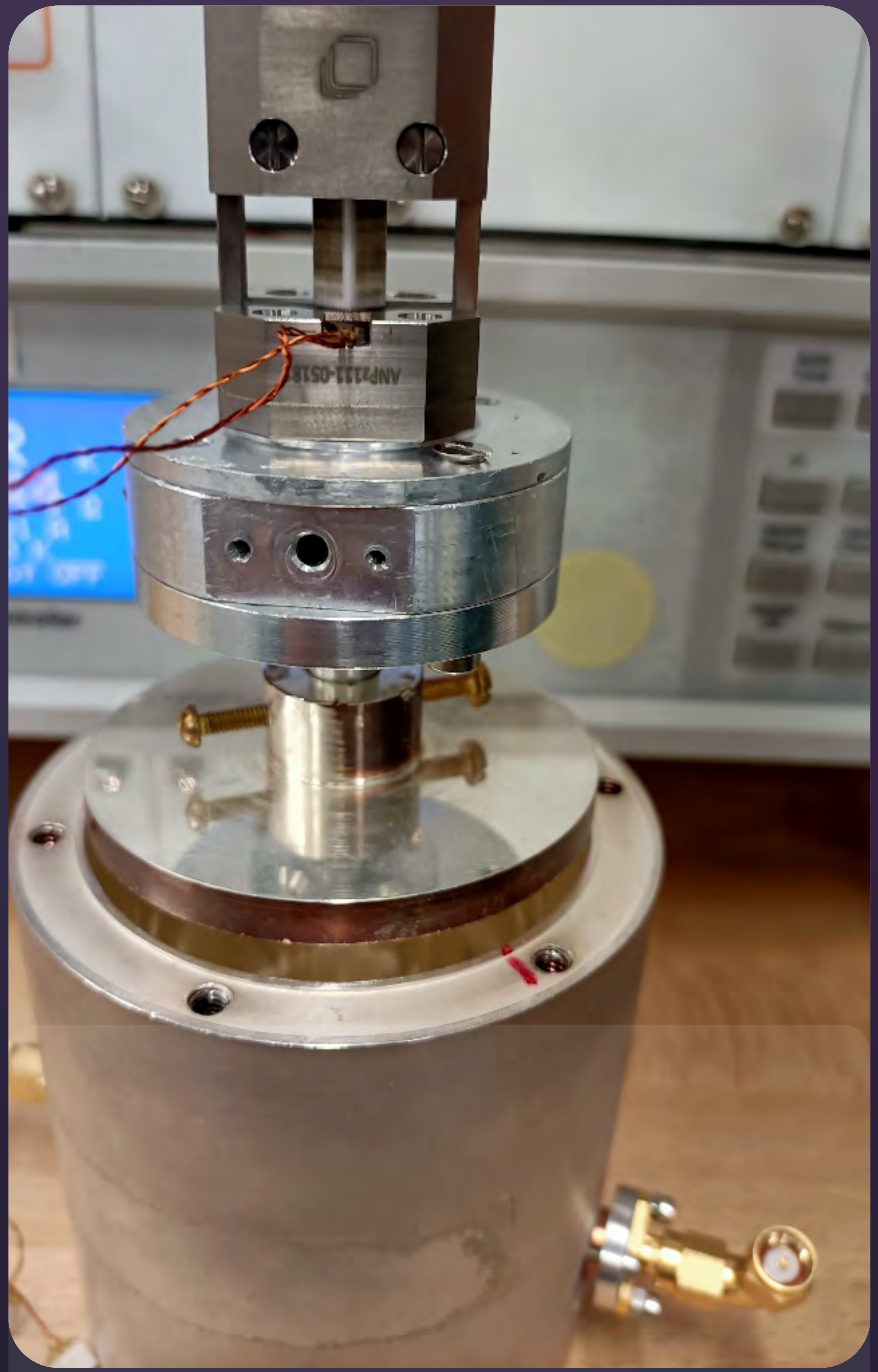
An experiment targeting 350 MHz axions with a dual mode cavity (~12 GHz), height tuning with a piezo actuated lid. Gain in noise temperature and quality factor.

290 K → 4 K

$$\langle H \rangle = k_{\mathrm{B}} T$$

$$g_{a\gamma\gamma} = \frac{\sqrt{P_a}}{\frac{f_a}{\sqrt{f1 * f0}} \frac{(2\sqrt{2}\sqrt{\beta_1 \beta_0})}{\sqrt{1+\beta_1}(\beta_0+1)} \sqrt{\frac{1}{1+4(Q_{L1})^2(\frac{f_a+f_0-f_1}{f1})^2}} \sqrt{Q_{L1} Q_{L0} F F P_{0inc}}} \frac{2\pi f_a}{\sqrt{\rho c^3}}$$

Q ~ 13,000 → > 20,000,000



Trialing attocube actuator in silver plated cavity

If Magnetic Charge Exist at High Energy

-> Further Modifications to Axion Electrodynamics

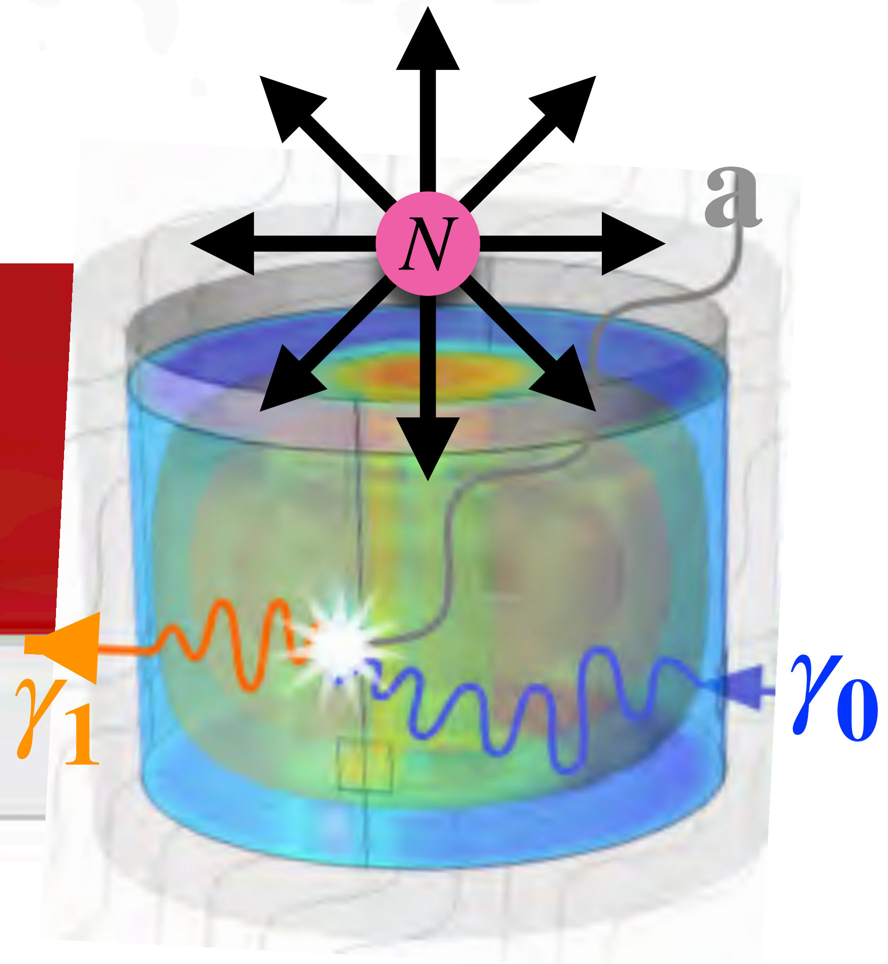
arXiv > hep-ph > arXiv:2303.10170

High Energy Physics – Phenomenology

[Submitted on 17 Mar 2023]

Generic axion Maxwell equations: path integral approach

Anton V. Sokolov, Andreas Ringwald



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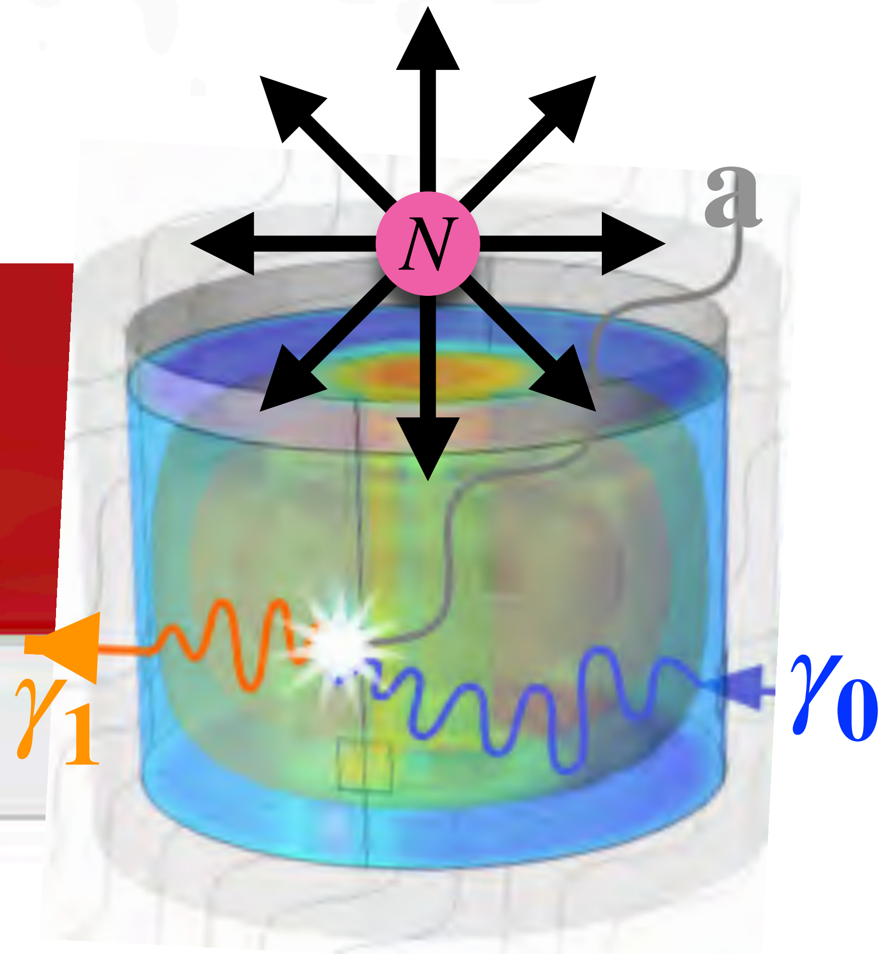

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Axion-photon coupling parameter space is expanded from one parameter to three

$$g_{a\gamma\gamma} \rightarrow (g_{a\gamma\gamma}, g_{aEM}, g_{aMM})$$

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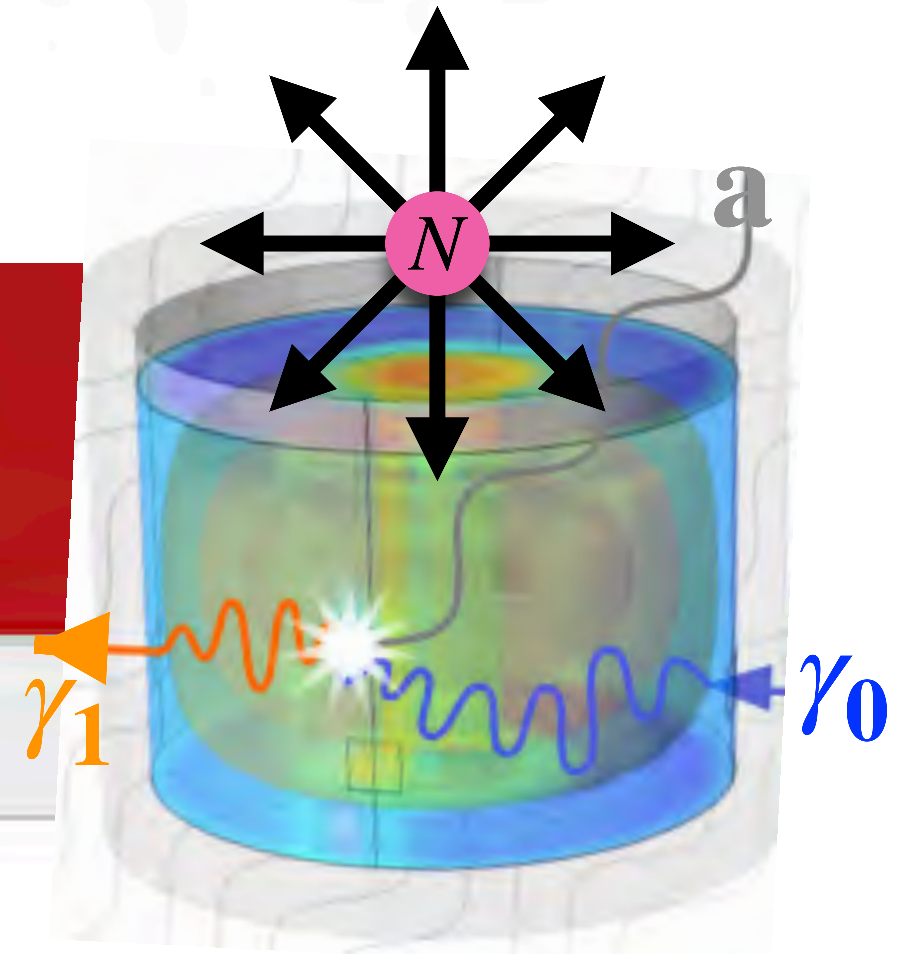

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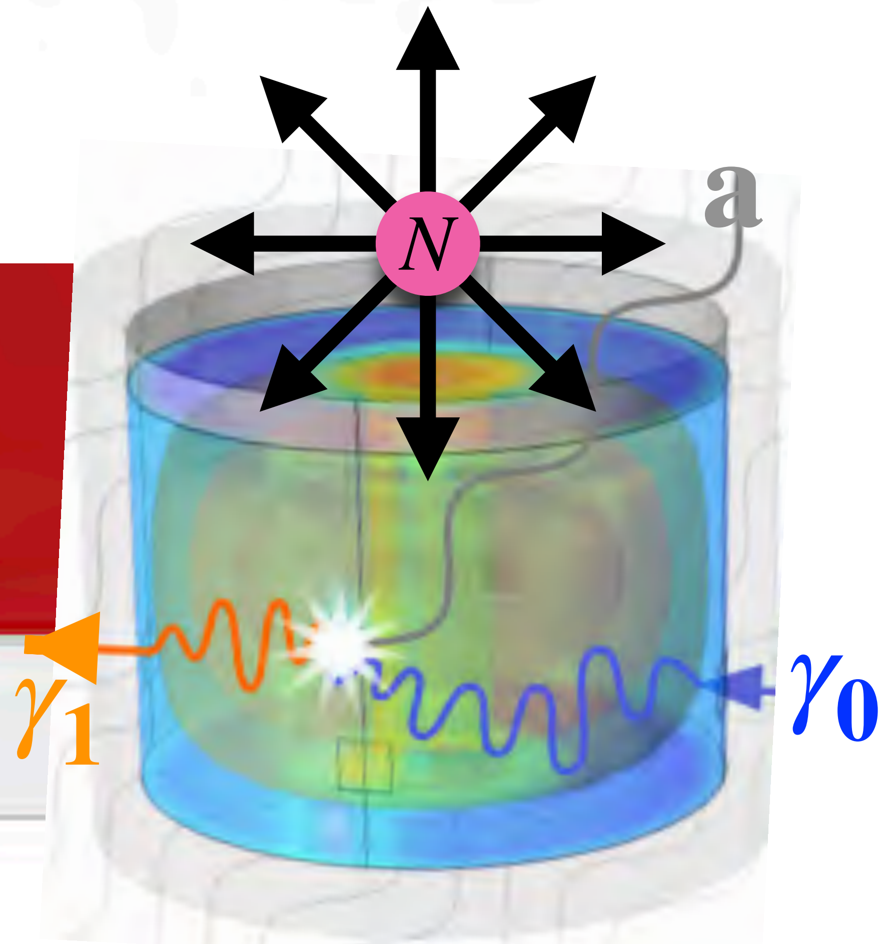

$$\vec{\nabla} \cdot \vec{E}_1 = g_{a\gamma\gamma} c \vec{B}_0 \cdot \vec{\nabla} a - g_{aEM} \vec{E}_0 \cdot \vec{\nabla} a + \epsilon_0^{-1} \rho_{e1},$$

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

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

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

Calculate Form Factors for Resonant Experiment with Static and Time varying Background Electric and Magnetic Fields -> Poynting Theorem

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Reactive Experiment with Static Background Electric and Magnetic Field -> Imaginary Poynting Theorem

PHYSICAL REVIEW D **108,** 035024 (2023)

Searching for GUT-scale QCD axions and monopoles with a high-voltage capacitor

Michael E. Tobar,[1,*] Anton V. Sokolov,[2] Andreas Ringwald,[3] and Maxim Goryachev[1]
[1]*Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia*
[2]*Department of Mathematical Sciences, University of Liverpool, Liverpool, L69 7ZL, United Kingdom*
[3]*Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22607 Hamburg, Germany*

(Received 20 June 2023; accepted 2 August 2023; published 17 August 2023)

arXiv:2306.13320v1 [hep-ph] 23 Jun 2023

SENSITIVITY OF AXION RESONANT HALOSCOPES UNDER DC MAGNETIC FIELDS

$$P_{s1} = P_d = \frac{\omega_1 U_1}{Q_1} = g_{a\gamma\gamma}\frac{\omega_a \epsilon_0 \langle a_0 \rangle}{\sqrt{2}Q_1}\int \vec{B}_0 \cdot \mathrm{Re}(\mathbf{E}_1)\ dV + g_{aEM}\frac{\omega_a \epsilon_0 \langle a_0 \rangle c}{\sqrt{2}Q_1}\int \vec{B}_0 \cdot \mathrm{Re}(\mathbf{B}_1)\ dV$$

$$\sqrt{P_1} = \sqrt{\omega_a Q_1 U_1} = (g_{a\gamma\gamma}\sqrt{C_{1a\gamma\gamma}} + g_{aEM}\sqrt{C_{1aEM}})\langle a_0 \rangle c B_0 \sqrt{\omega_a Q_1 \epsilon_0 V_1} = (g_{a\gamma\gamma}\sqrt{C_{1a\gamma\gamma}} + g_{aEM}\sqrt{C_{1aEM}}) B_0 \sqrt{\frac{\rho_a Q_1 \epsilon_0 c^5 V_1}{\omega_a}}$$

Form Factors

$$C_{1a\gamma\gamma} = \frac{(\int \vec{B}_0 \cdot \mathrm{Re}(\mathbf{E}_1) dV)^2}{B_0^2 V_1 \int \mathbf{E}_1 \cdot \mathbf{E}_1^* dV} \qquad C_{1EM} = \frac{(\int \vec{B}_0 \cdot \mathrm{Re}(\mathbf{B}_1) dV)^2}{B_0^2 V_1 \int \mathbf{B}_1 \cdot \mathbf{B}_1^* dV}$$

SENSITIVITY OF AXION RESONANT HALOSCOPES UNDER DC ELECTRIC FIELDS

$$\sqrt{P_1} = \sqrt{\omega_a Q_1 U_1} = (g_{aMM}\sqrt{C_{1aMM}} + g_{aEM}\sqrt{C_{1aEMm}})\langle a_0\rangle E_0\sqrt{\omega_a Q_1 \epsilon_0 V_1} = (g_{aMM}\sqrt{C_{1aMM}} + g_{aEM}\sqrt{C_{1aEMm}})E_0\sqrt{\frac{\rho_a Q_1 \epsilon_0 c^3 V_1}{\omega_a}},$$

Form Factors

$$C_{1aEMm} = \frac{(\int \overrightarrow{E}_0 \cdot \mathrm{Re}(\mathbf{E}_1)dV)^2}{E_0^2 V_1 \int \mathbf{E}_1 \cdot \mathbf{E}_1^* dV} \qquad C_{1aMM} = \frac{(\int \overrightarrow{E}_0 \cdot \mathrm{Re}(\mathbf{B}_1)dV)^2}{E_0^2 V_1 \int \mathbf{B}_1 \cdot \mathbf{B}_1^* dV},$$

PHYSICAL REVIEW D **108**, 035024 (2023)

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[1] *Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia*

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[3] *Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22607 Hamburg, Germany*

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The QCD axion has been postulated to exist because it solves the strong-*CP* problem. Furthermore, if it exists axions should be created in the early Universe and could account for all the observed dark matter. In particular, axion masses of order 10^{-10} eV to 10^{-7} eV correspond to axions in the vicinity of the grand unified theory scale (GUT-scale). In this mass range many experiments have been proposed to search for the axion through the standard QED coupling parameter $g_{a\gamma\gamma}$. Recently axion electrodynamics has been expanded to include two more coupling parameters, g_{aEM} and g_{aMM}, which could arise if heavy magnetic monopoles exist. In this work we show that both g_{aMM} and g_{aEM} may be searched for using a high-voltage capacitor. Since the experiment is not sensitive to $g_{a\gamma\gamma}$, it gives a new way to search for effects of heavy monopoles if the GUT-scale axion is shown to exist, or to simultaneously search for both the axion and the monopole at the same time.

DOI: 10.1103/PhysRevD.108.035024

arXiv:2306.13320v1 [hep-ph] 23 Jun 2023

AC Capacitor: Apply Poynting Theorem: Sensitive to g_{aEM}

Vector Phasor Amplitudes

$$\oint \mathrm{Im}\left(\mathbf{S}_1\right) \cdot \hat{n} ds = \omega_a \int \left(\left(\frac{1}{2\mu_0} \mathbf{B}_1^* \cdot \mathbf{B}_1 - \frac{\epsilon_0}{2} \mathbf{E}_1 \cdot \mathbf{E}_1^* \right) - \frac{g_{aEM} a_0 \epsilon_0}{4} (\mathbf{E}_1 + \mathbf{E}_1^*) \cdot \vec{E}_0 + \frac{g_{aMM} a_0 \epsilon_0}{4} (\mathbf{B}_1 + \mathbf{B}_1^*) \cdot \vec{E}_0 \right) dV \, .$$

AC Capacitor: Apply Poynting Theorem: Sensitive to g_{aEM}

Vector Phasor Amplitudes

$$\oint \mathrm{Im}\left(\mathbf{S}_1\right) \cdot \hat{n} ds = \omega_a \int \left((\frac{1}{2\mu_0}\mathbf{B}_1^* \cdot \mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1 \cdot \mathbf{E}_1^*) - \frac{g_{aEM} a_0 \epsilon_0}{4}(\mathbf{E}_1 + \mathbf{E}_1^*) \cdot \vec{E}_0 + \frac{g_{aMM} a_0 \epsilon_0}{4}(\mathbf{B}_1 + \mathbf{B}_1^*) \cdot \vec{E}_0) \right) dV .$$

$$U_1 = \frac{\epsilon_0 a_0^2 \left(\int \left(g_{aEM}\left(\mathbf{E}_1^* + \mathbf{E}_1\right) - g_{aMM} c \left(\mathbf{B}_1^* + \mathbf{B}_1\right) \right) \cdot \vec{E}_0 dv \right)^2}{8 \int \left(\left(c^2 \mathbf{B}_1^* \cdot \mathbf{B}_1 - \mathbf{E}_1 \cdot \mathbf{E}_1^* \right) \right) dv}$$

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$$U_1 = \frac{\epsilon_0 a_0^2\left(\int\left(g_{aEM}\left(\mathbf{E}_1^*+\mathbf{E}_1\right) - g_{aMM}c\left(\mathbf{B}_1^*+\mathbf{B}_1\right)\right)\cdot\vec{E}_0 dv\right)^2}{8\int\left(\left(c^2\mathbf{B}_1^*\cdot\mathbf{B}_1 - \mathbf{E}_1\cdot\mathbf{E}_1^*\right)\right)dv}$$

$$\mathbf{B}_1+\mathbf{B}_1^*\sim 0 \quad \mathbf{E}_1+\mathbf{E}_1^*\sim 2\mathbf{E}_1$$

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$$\mathbf{B}_1 + \mathbf{B}_1^* \sim 0 \quad \mathbf{E}_1 + \mathbf{E}_1^* \sim 2\mathbf{E}_1$$

$$U_1 \approx -\frac{g_{aEM}^2 a_0^2 \epsilon_0 \left(\int \mathbf{E}_1 \cdot \vec{E}_0 dv \right)^2}{2 \int \mathbf{E}_1 \cdot \mathbf{E}_1^* dv}$$

AC Capacitor: Apply Poynting Theorem: Sensitive to g_{aEM}

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$$U_1 = \frac{\epsilon_0 a_0^2\left(\int\left(g_{aEM}\left(\mathbf{E}_1^*+\mathbf{E}_1\right) - g_{aMM}c\left(\mathbf{B}_1^*+\mathbf{B}_1\right)\right)\cdot\vec{E}_0 dv\right)^2}{8\int\left(\left(c^2\mathbf{B}_1^*\cdot\mathbf{B}_1 - \mathbf{E}_1\cdot\mathbf{E}_1^*\right)\right)dv}$$

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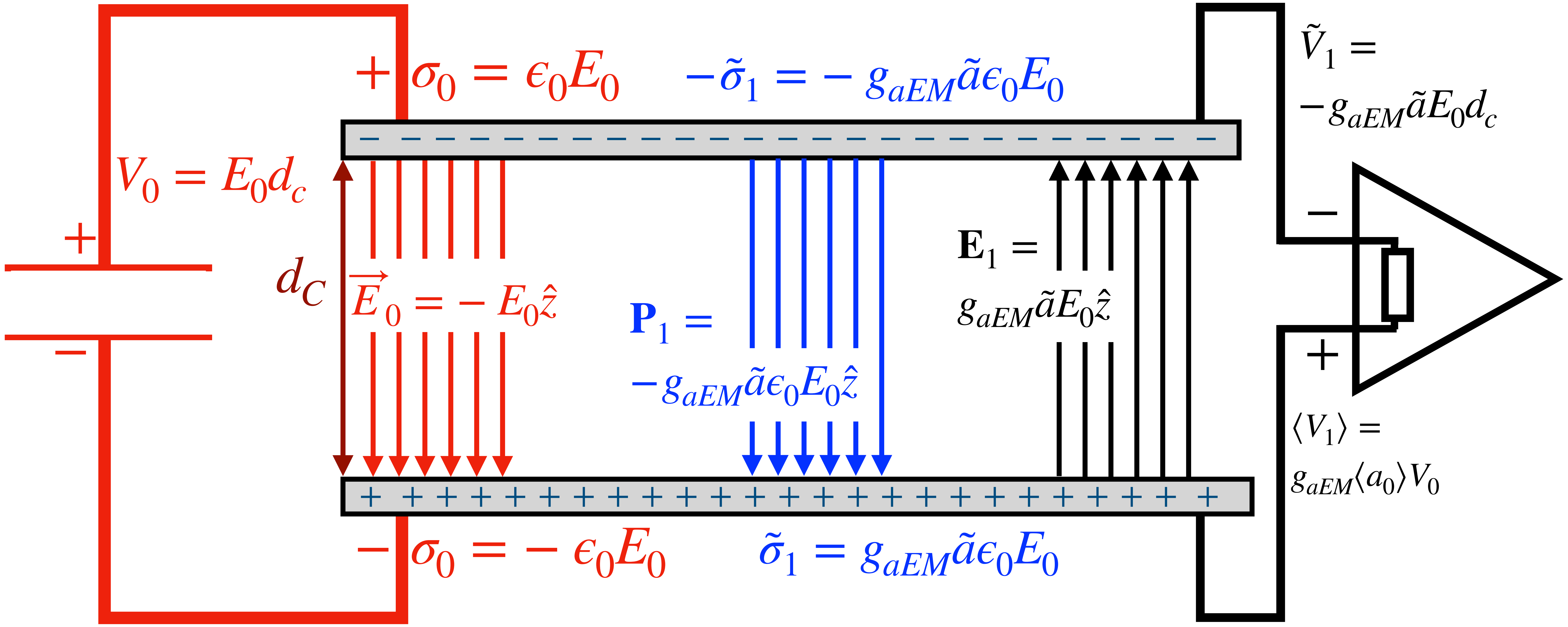
Axion generated Electric Field



AC Capacitor: Apply Poynting Theorem: Sensitive to g_{aEM}

Vector Phasor Amplitudes

$$\oint \mathrm{Im}\left(\mathbf{S}_1\right)\cdot\hat{n}ds = \omega_a \int \left(\left(\frac{1}{2\mu_0}\mathbf{B}_1^*\cdot\mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1\cdot\mathbf{E}_1^*\right) - \frac{g_{aEM}a_0\epsilon_0}{4}(\mathbf{E}_1+\mathbf{E}_1^*)\cdot\vec{E}_0 + \frac{g_{aMM}a_0\epsilon_0}{4}(\mathbf{B}_1+\mathbf{B}_1^*)\cdot\vec{E}_0\right) dV .$$

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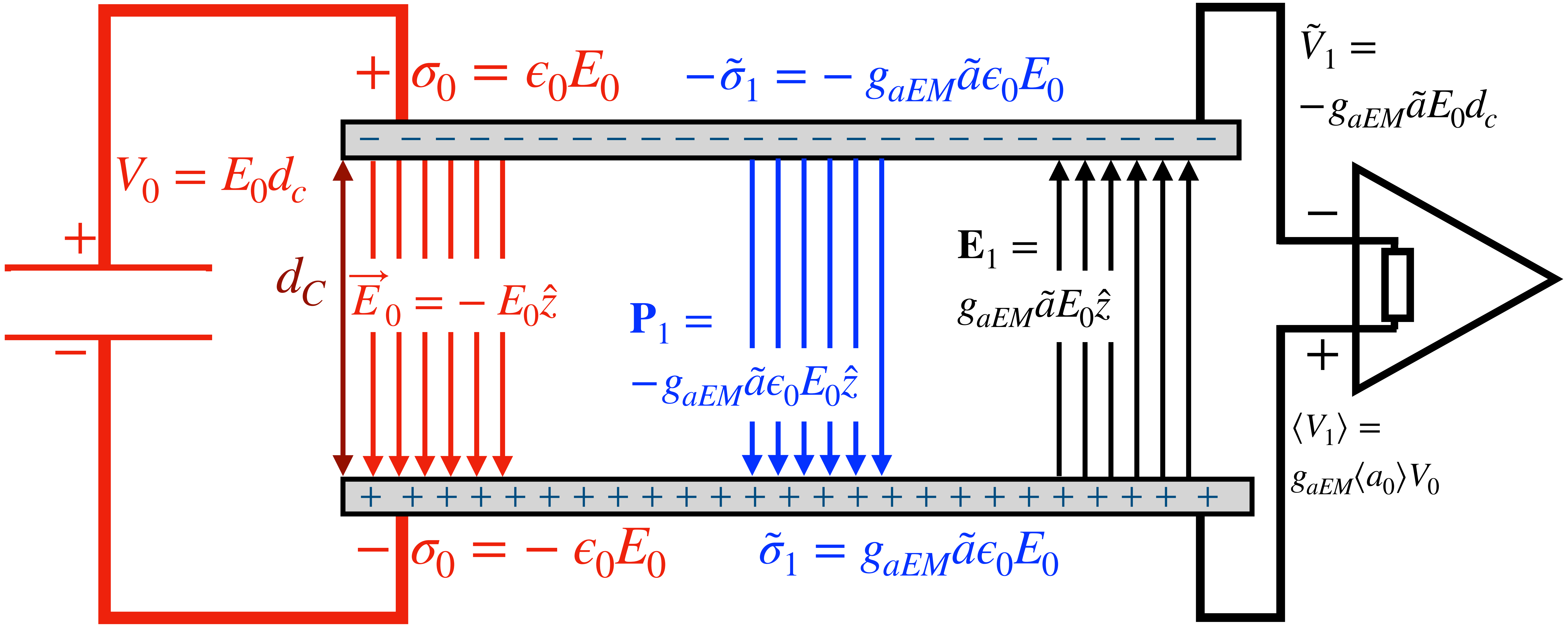
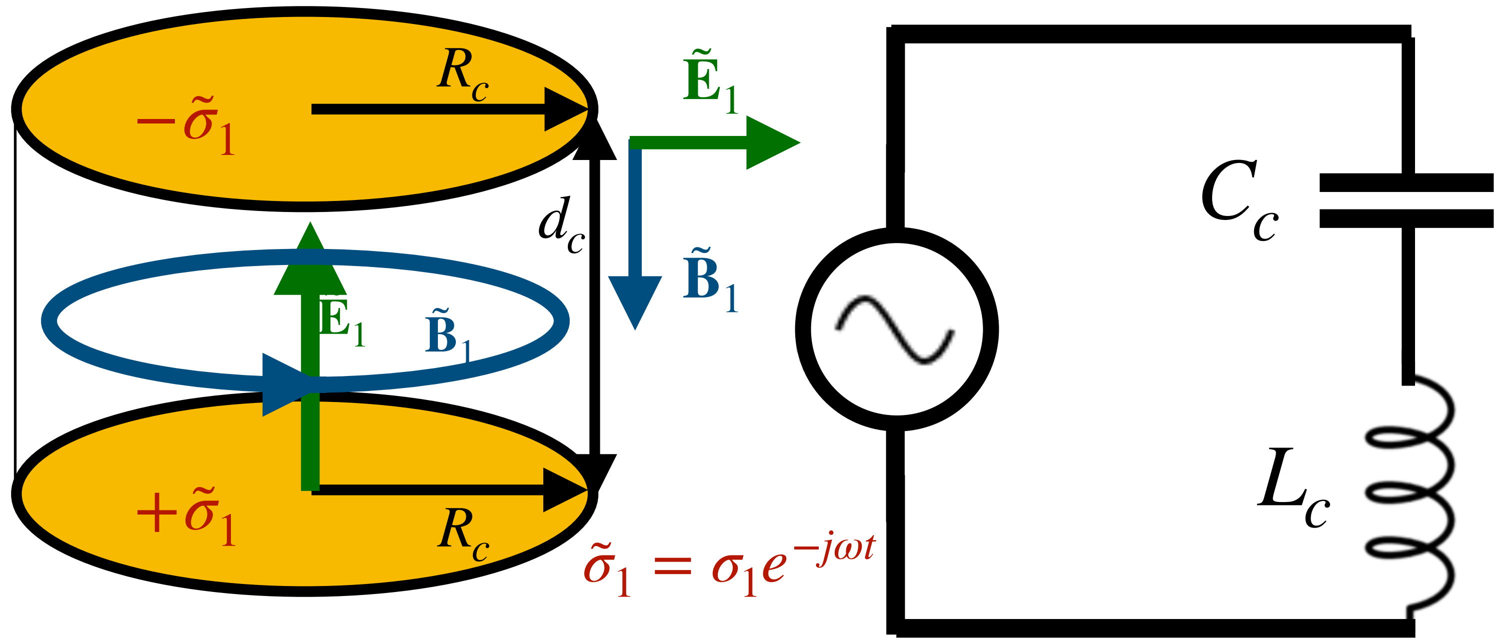
Axion generated Electric Field



Cylindrical // Plate Capacitor

$$\tilde{\mathbf{E}}_1 = \tilde{E}_{01}J_0\left(\frac{\omega_1}{c}r\right)e^{-j\omega_1 t}\hat{z}$$

$$\tilde{\mathbf{B}}_1 = -j\frac{\tilde{E}_{01}}{c}J_1\left(\frac{\omega_1}{c}r\right)e^{-j\omega_1 t}\hat{\varphi} \qquad \tilde{E}_{01} = \frac{\tilde{q}_1}{\pi R_c^2\epsilon_0}$$



Axion Generated Magnetic Field-> Magnetic Circuit Readout Sensitive to g_{aMM}

$$\frac{\oint \mathrm{Im}\left(\mathbf{S}_1\right)\cdot\hat{n}ds}{\omega_a} = \int\left((\frac{1}{2\mu_0}\mathbf{B}_1^*\cdot\mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1\cdot\mathbf{E}_1^*) - \frac{g_{aEM}a_0\epsilon_0}{4}(\mathbf{E}_1+\mathbf{E}_1^*)\cdot\overrightarrow{E}_0 + \frac{g_{aMM}a_0\epsilon_0 c}{4}(\mathbf{B}_1+\mathbf{B}_1^*)\cdot\overrightarrow{E}_0)\right)dV$$

$$\mathbf{E}_1+\mathbf{E}_1^* \sim 0 \quad \mathbf{B}_1+\mathbf{B}_1^* \sim 2\mathbf{B}_1$$

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$$U_1 = \frac{\left(\frac{g_{aMM} a_0 \epsilon_0 c}{2} \int \mathbf{B}_1 \cdot \vec{E}_0 \, dV \right)^2}{\int \left(\frac{1}{2\mu_0} \mathbf{B}_1^* \cdot \mathbf{B}_1 - \frac{\epsilon_0}{2} \mathbf{E}_1 \cdot \mathbf{E}_1^* \right) dV}$$

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Axion Generated Magnetic Field-> Magnetic Circuit Readout Sensitive to g_{aMM}

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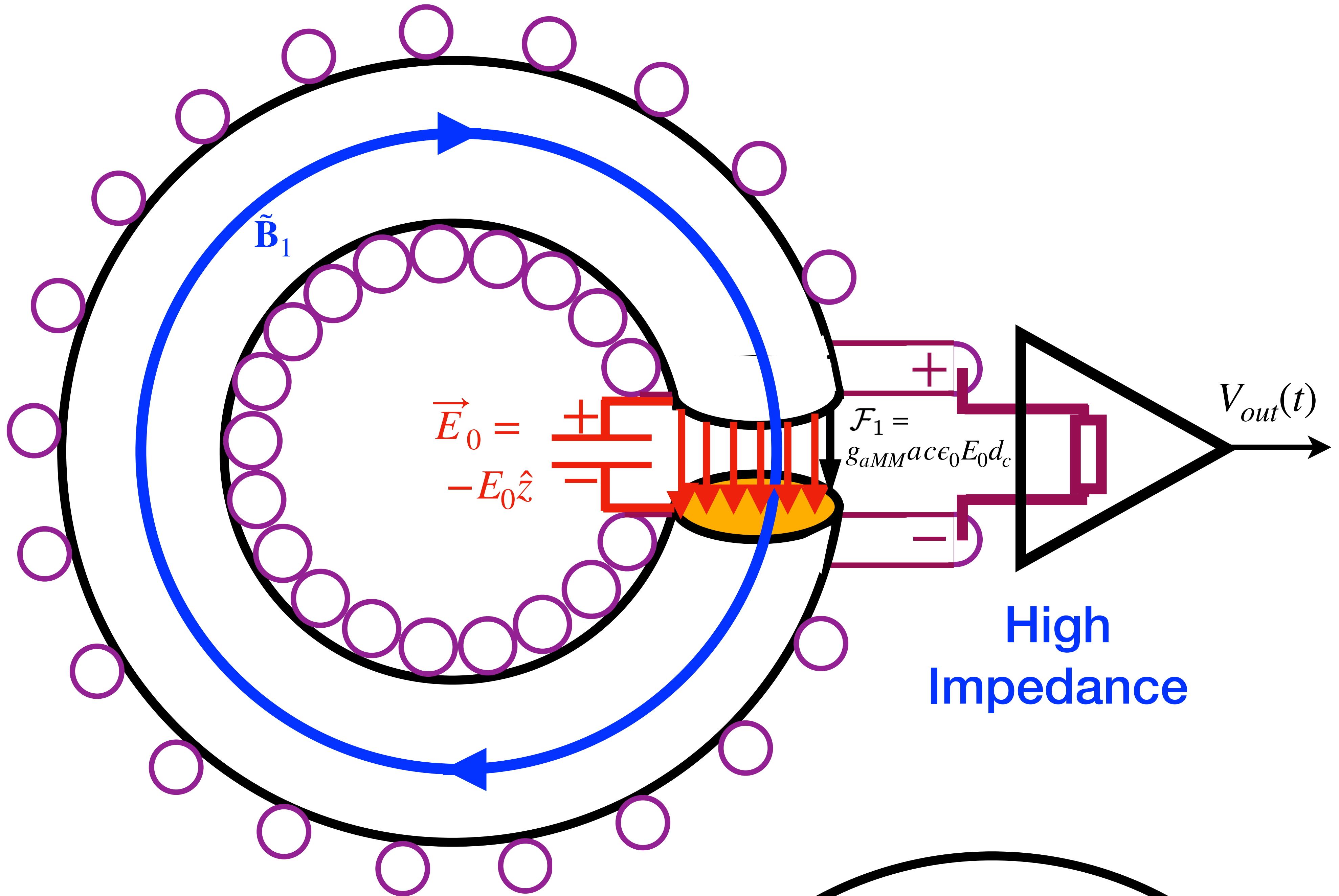

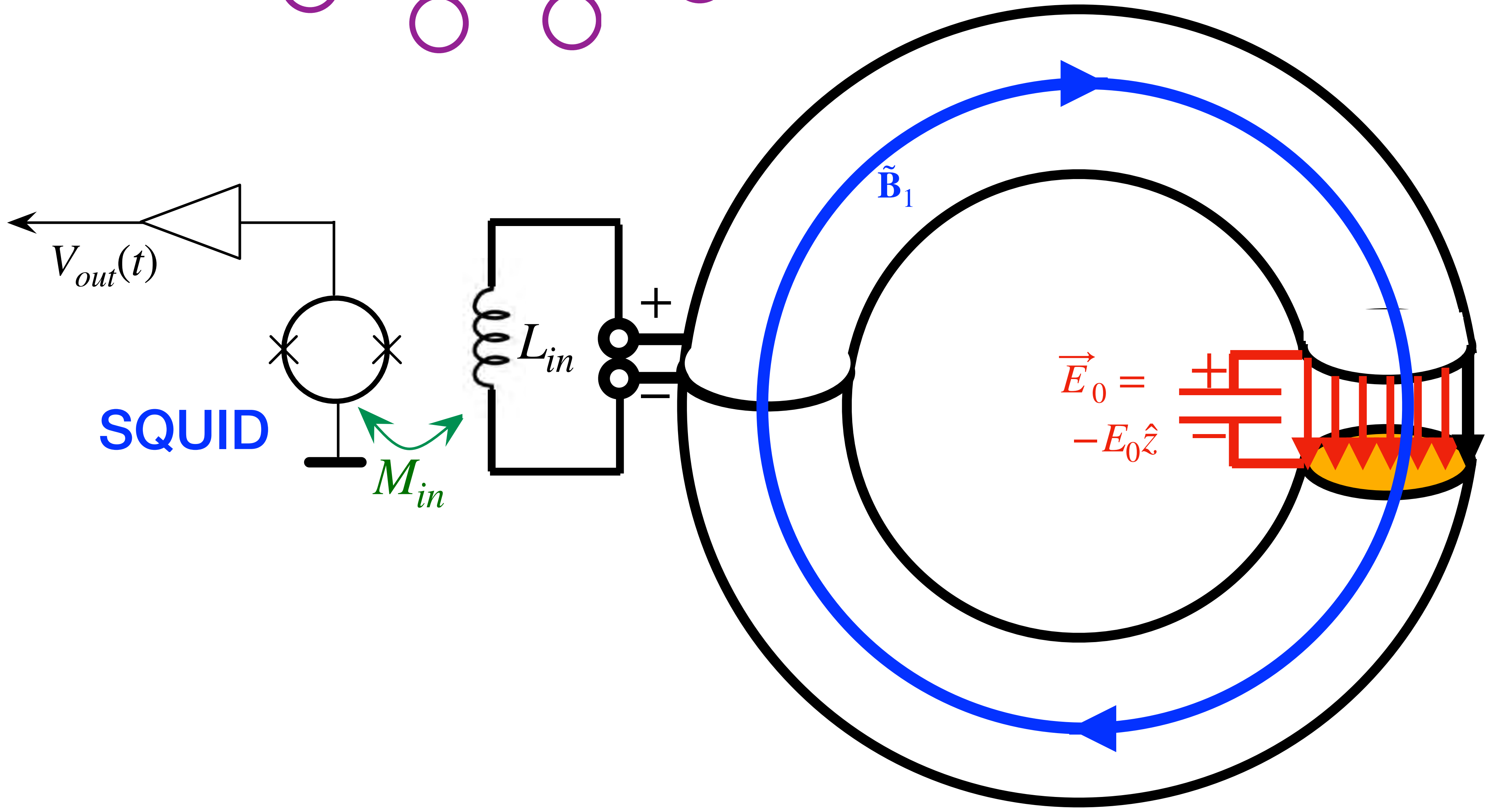

Axion Generated Magnetic Field-> Magnetic Circuit Readout Sensitive to g_{aMM}

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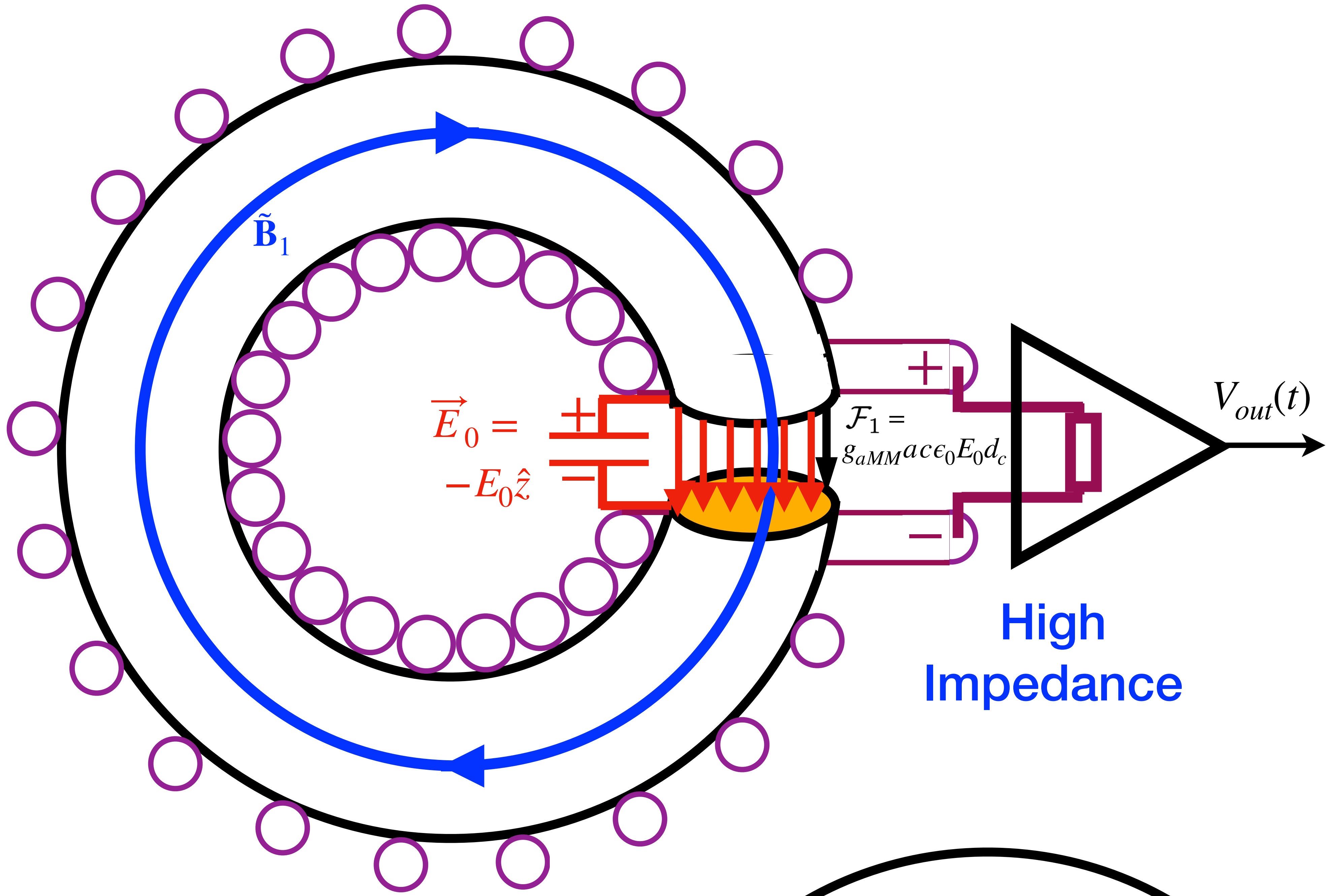
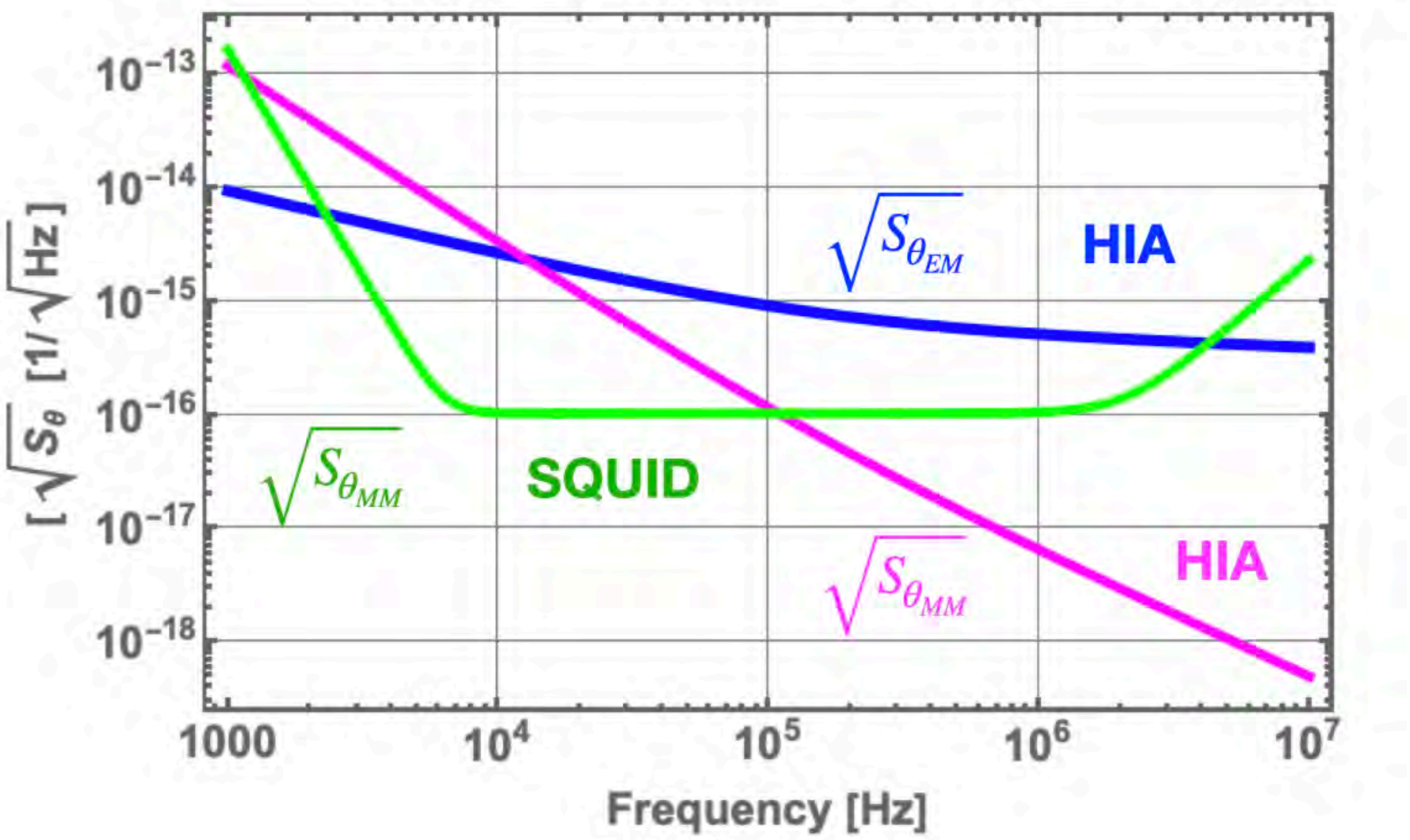
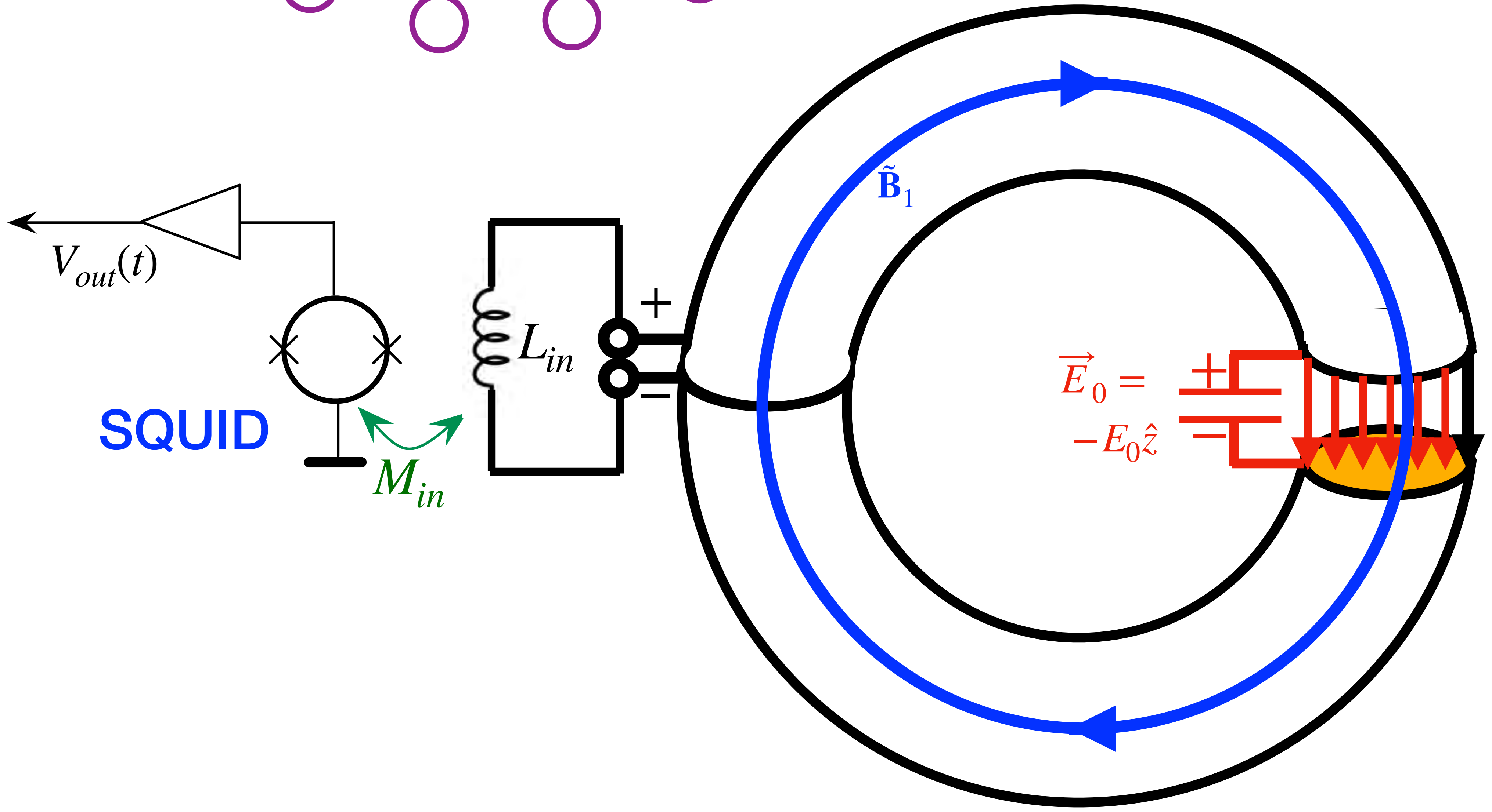
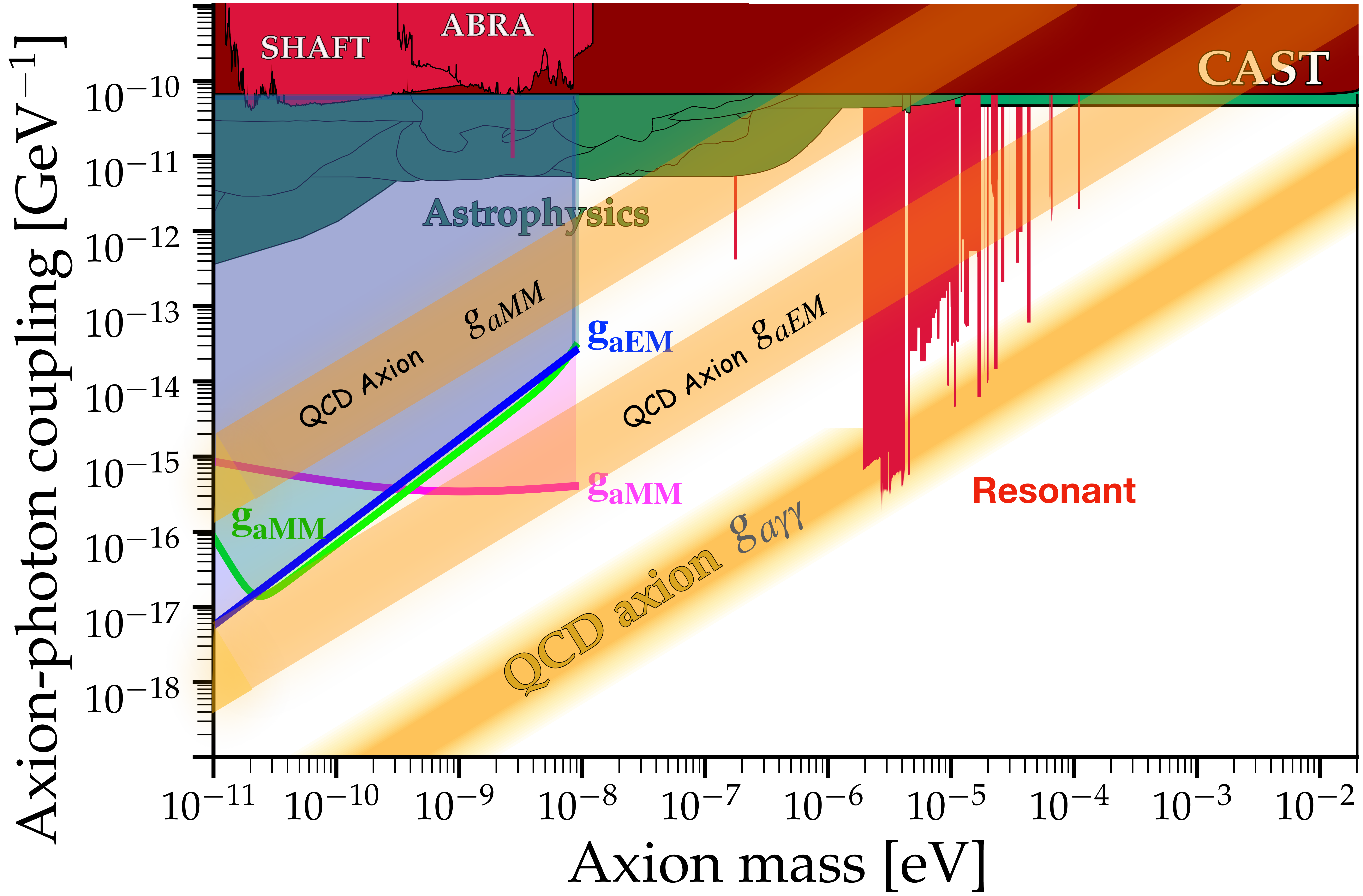






Low-Mass Sensitivity to the QCD Axion



18 days of continuous data taking

SCALAR DARK MATTER: ELECTROMAGNETIC TECHNIQUES

PHYSICAL REVIEW D **106**, 055037 (2022)

Searching for scalar field dark matter using cavity resonators and capacitors

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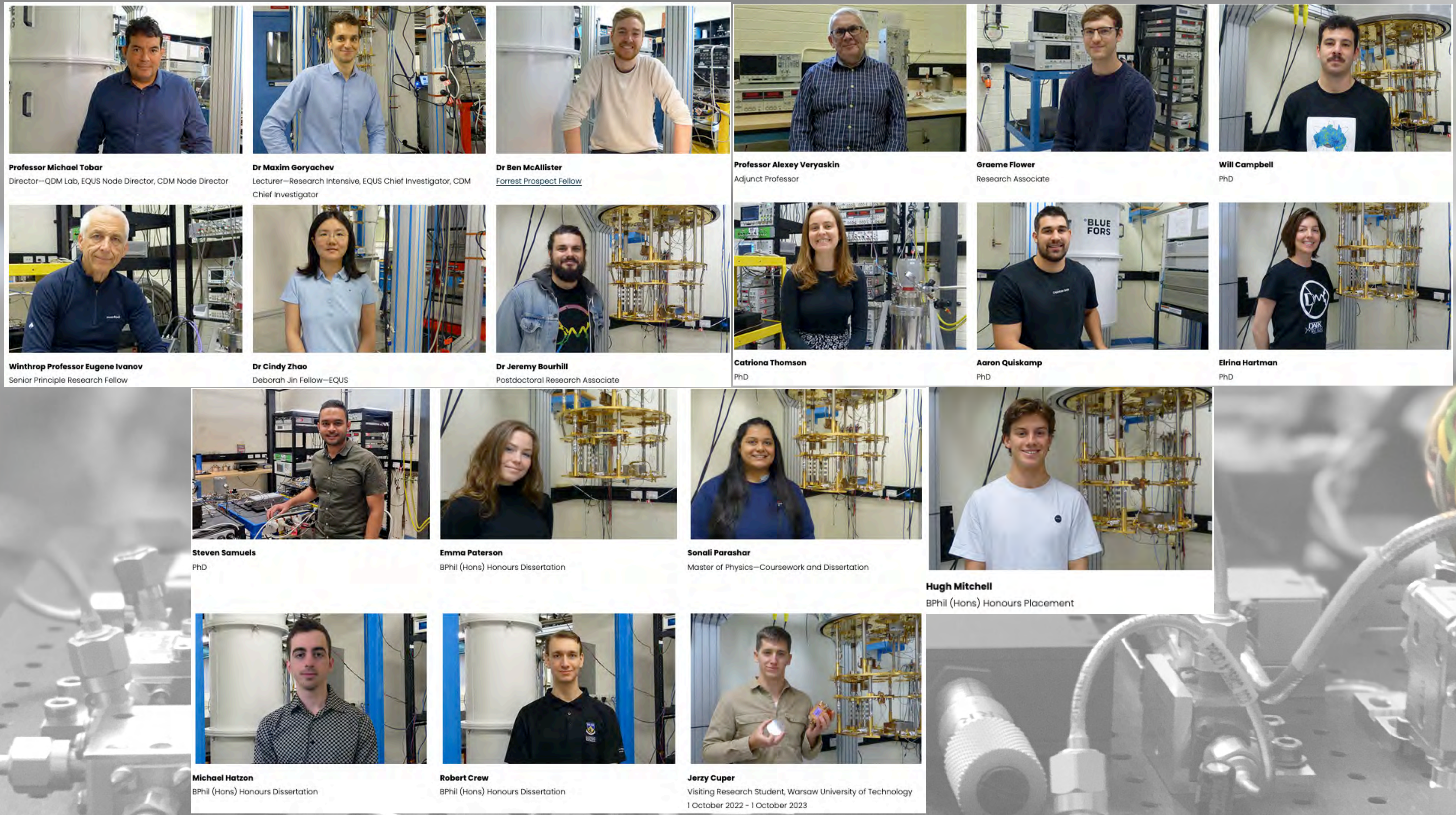
[3]*ARC Centre of Excellence for Dark Matter Particle Physics, Centre for Astrophysics and Supercomputing, Swinburne University of Technology, John St, Hawthorn VIC 3122, Australia*

$$g_{aEM} \equiv g_{\phi\gamma\gamma}$$

The Team



QDM Quantum Technologies and Dark Matter Research Lab

EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems

ARC Centre of Excellence for Dark Matter Particle Physics

The University of Western Australia — Seek Wisdom