Axions and Wave Like Dark Matter

ARC CENTRE OF EXCELLENCE FOR
DARK MATTER
PARTICLE PHYSICS

Michael Tobar

THE UNIVERSITY OF
WESTERN
AUSTRALIA

QDM

Searching for Putative Wave-Like Dark Matter

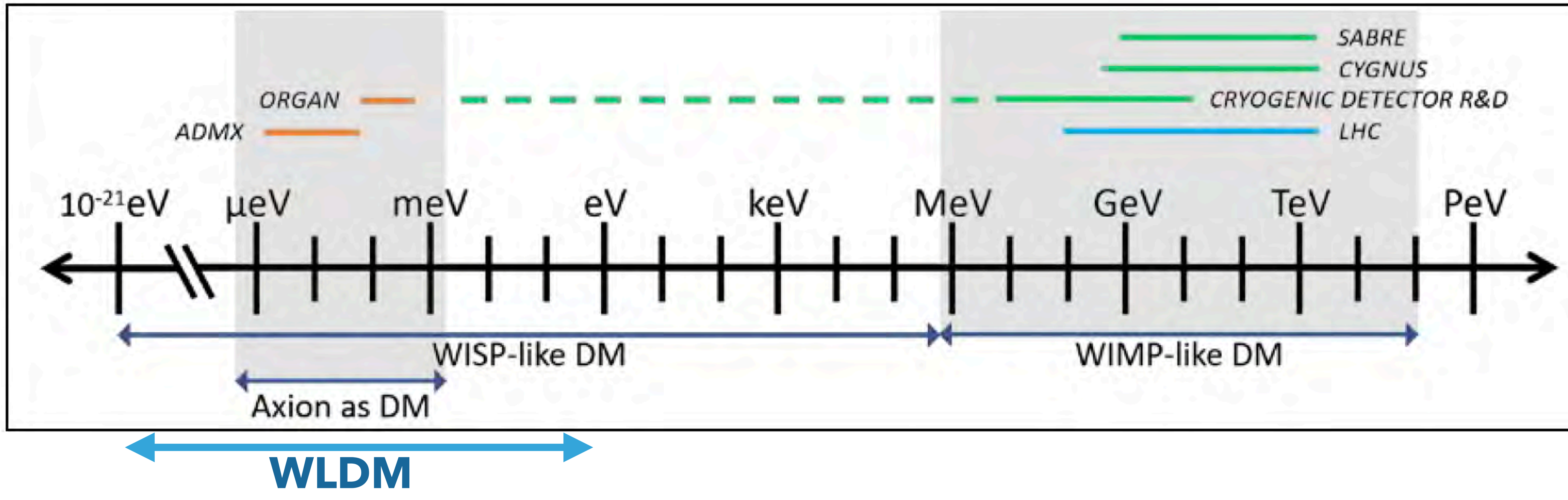

Figure 4: Dark matter mass ranges to be searched in Centre WIMP and WISP direct detection experiments and the LHC Program.

SNOWMASS

Cosmic Frontier:
Wave-Like Dark Matter

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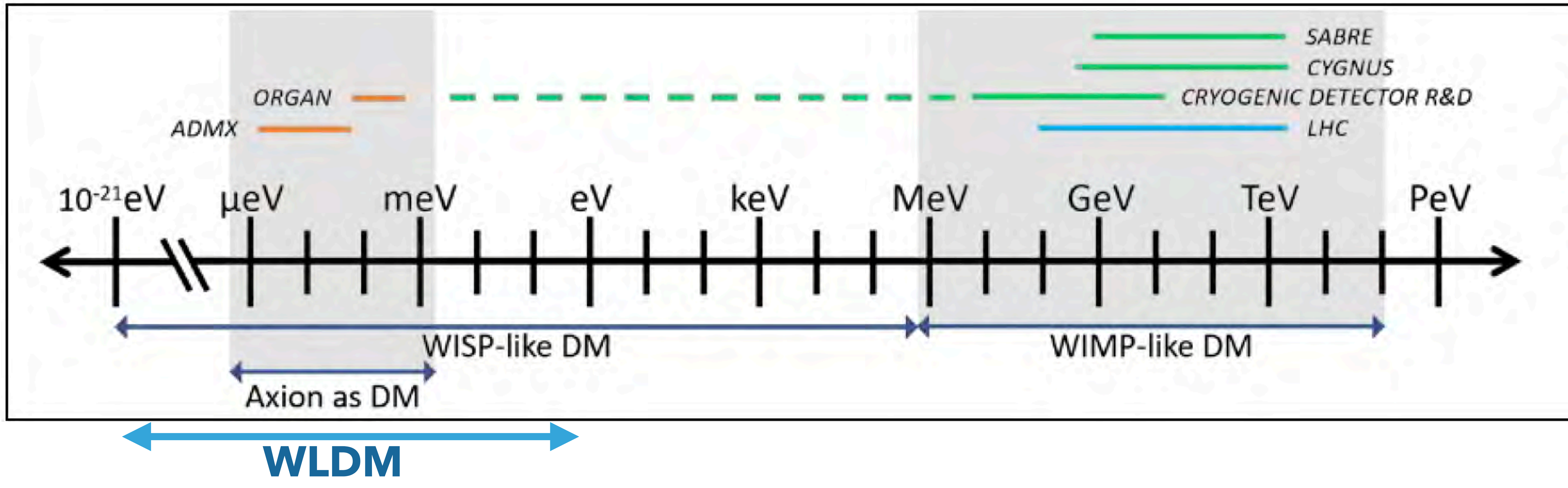

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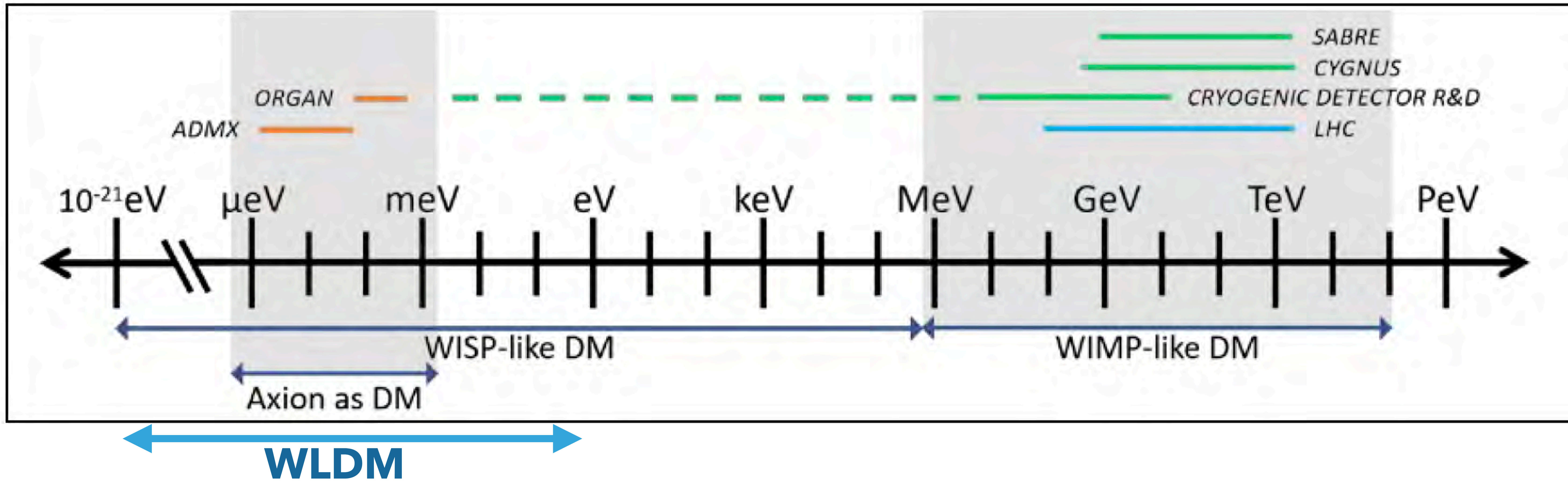

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Design Physics Package:

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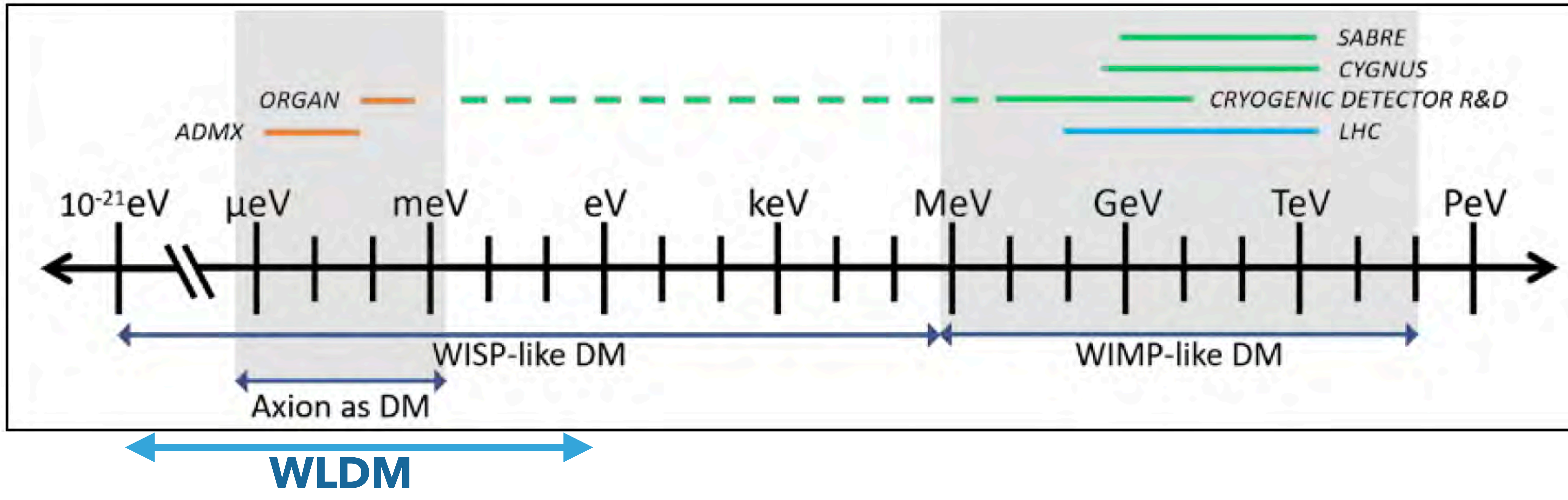

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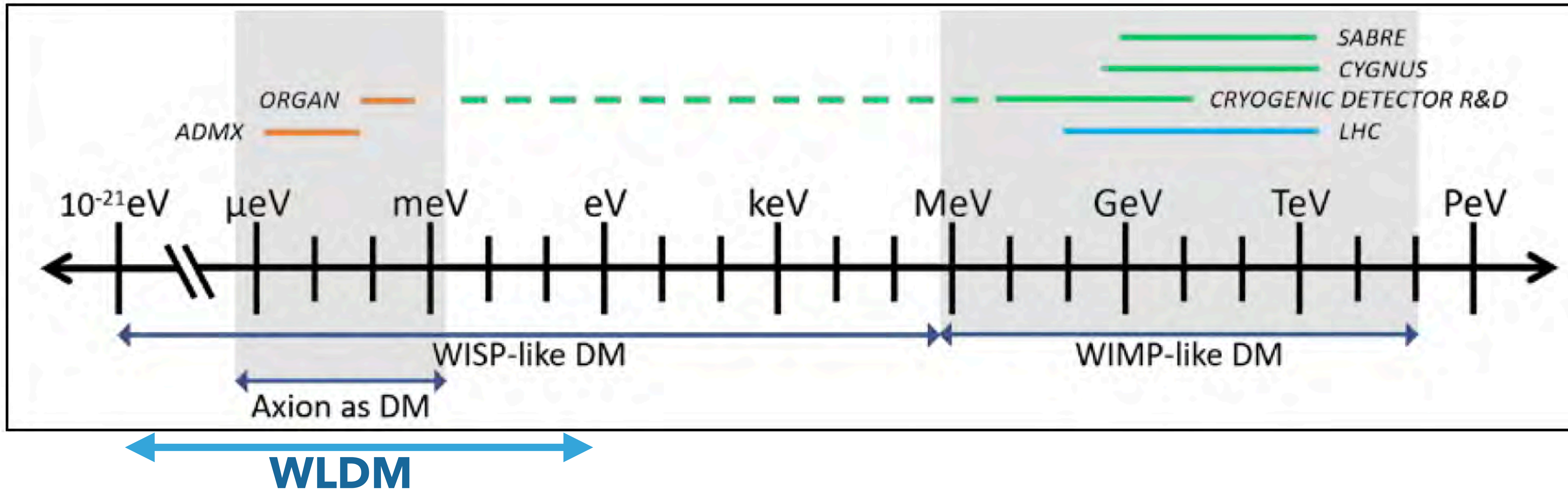

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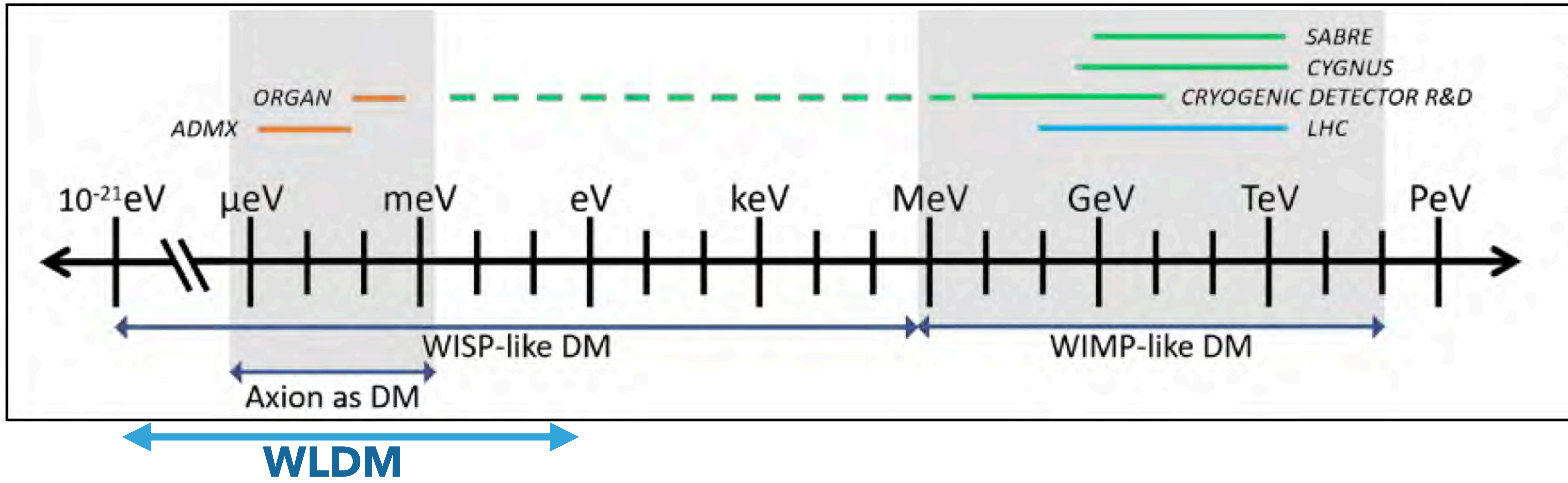

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-> Theory interacts with Experiment: How Dark Matter interacts with SM Particles: Optimise Signal

Searching for Putative Wave-Like Dark Matter

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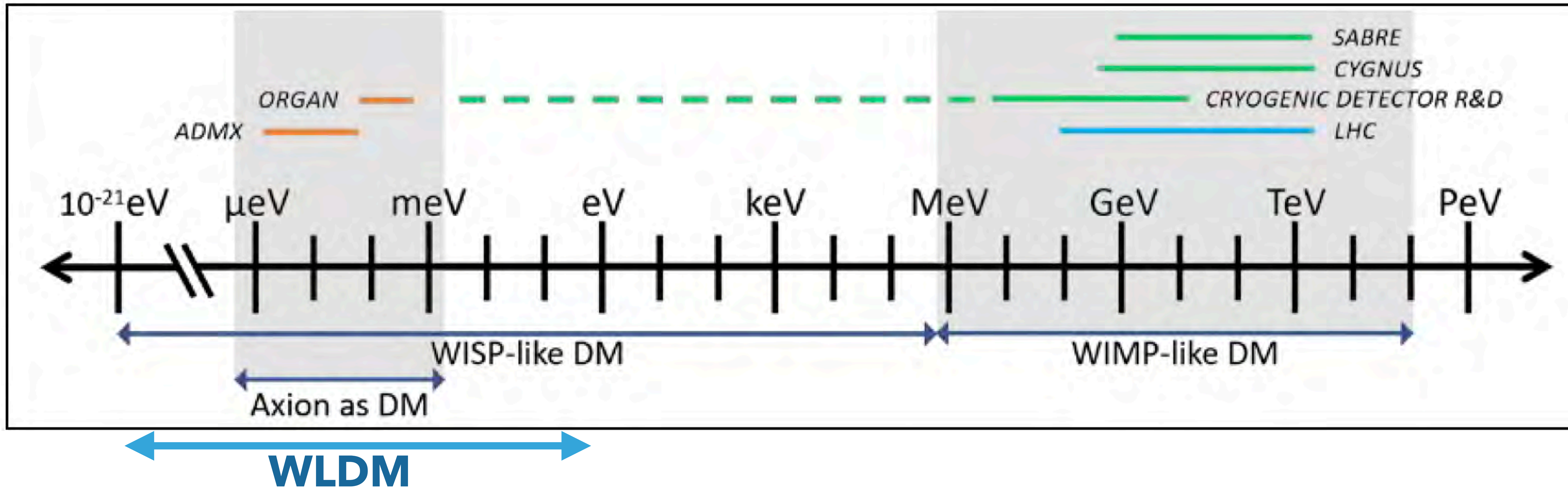

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Searching for Putative Wave-Like Dark Matter

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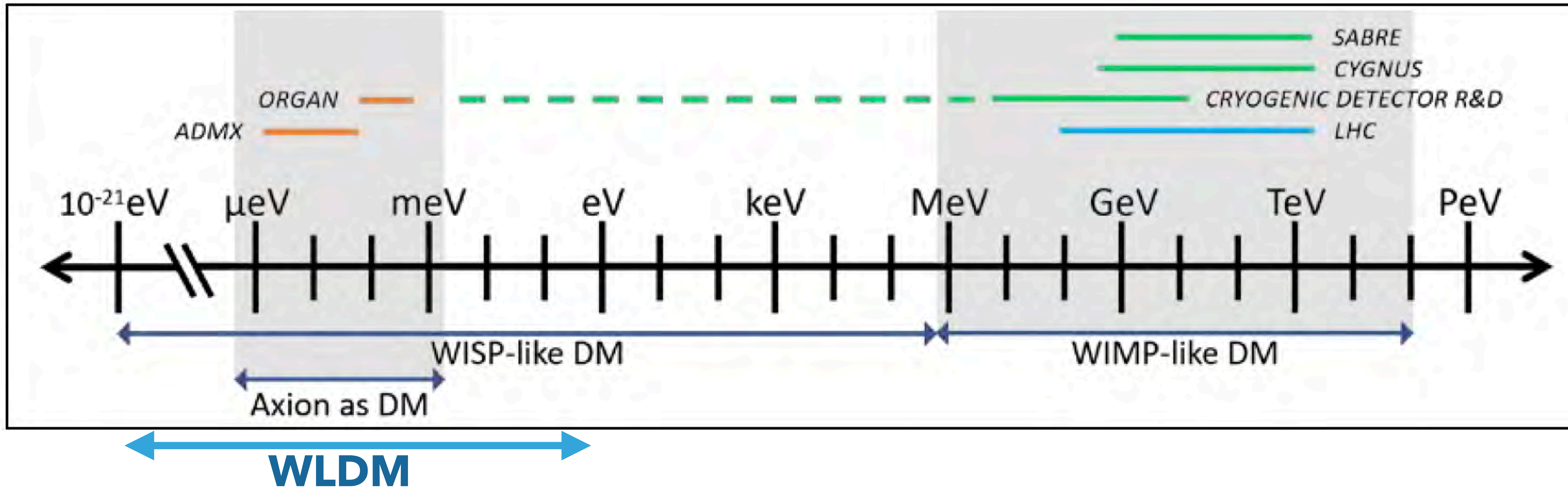

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-> Reduce Noise, Fundamental Limit is Quantum Noise

-> Surpass Quantum Limit: Quantum Metrology

STATUS AND PLANS

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The Axion Particle Should it Exist!

1) Solves Strong CP Problem
2) Predicted to form in Early Universe
3) Is Dark Matter the Axion?

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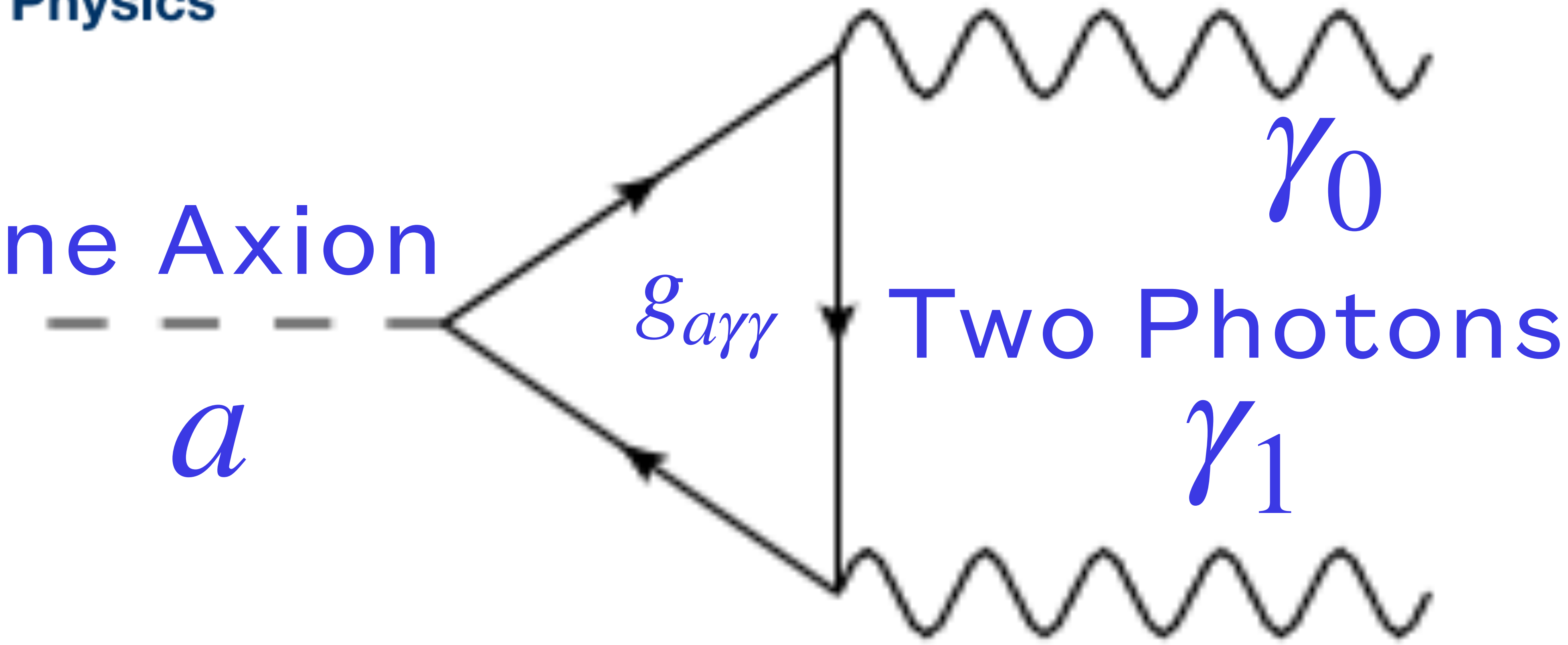

One Axion

a

$g_{a\gamma\gamma}$

γ_0

Two Photons

γ_1

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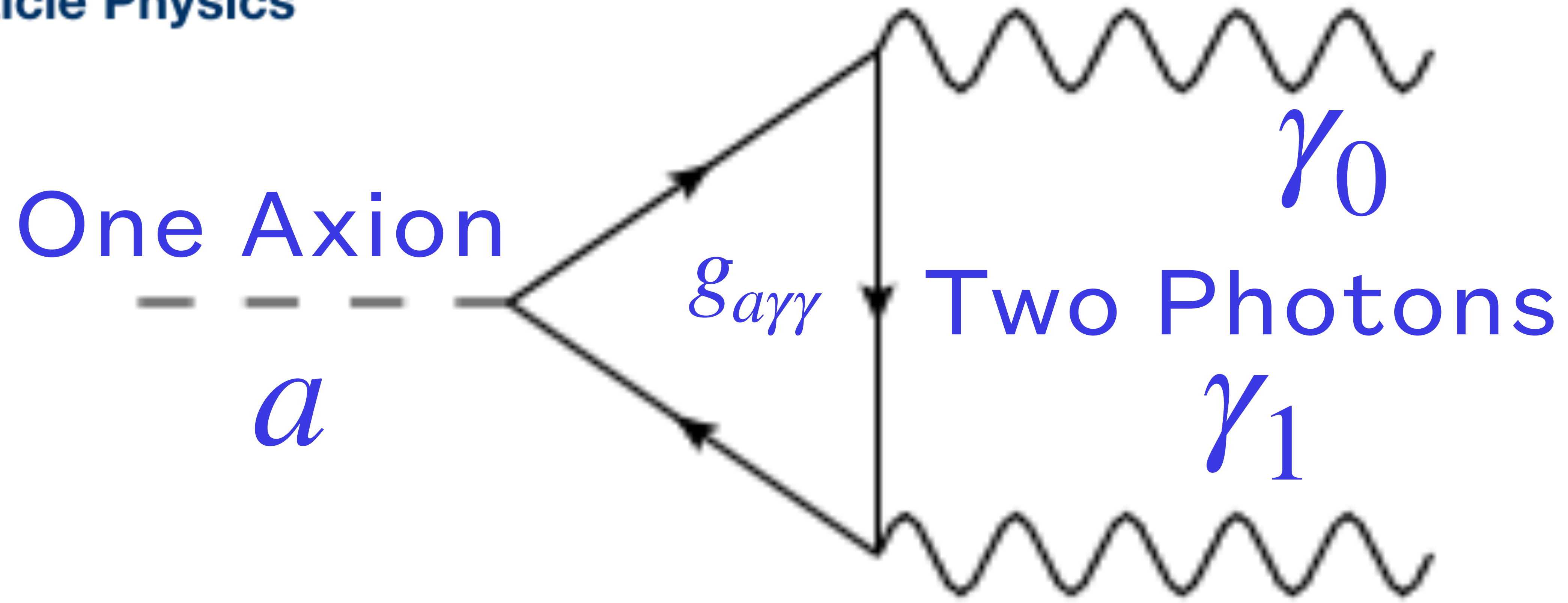
axion-photon coupling $g_{a\gamma\gamma}$ -> chiral anomaly



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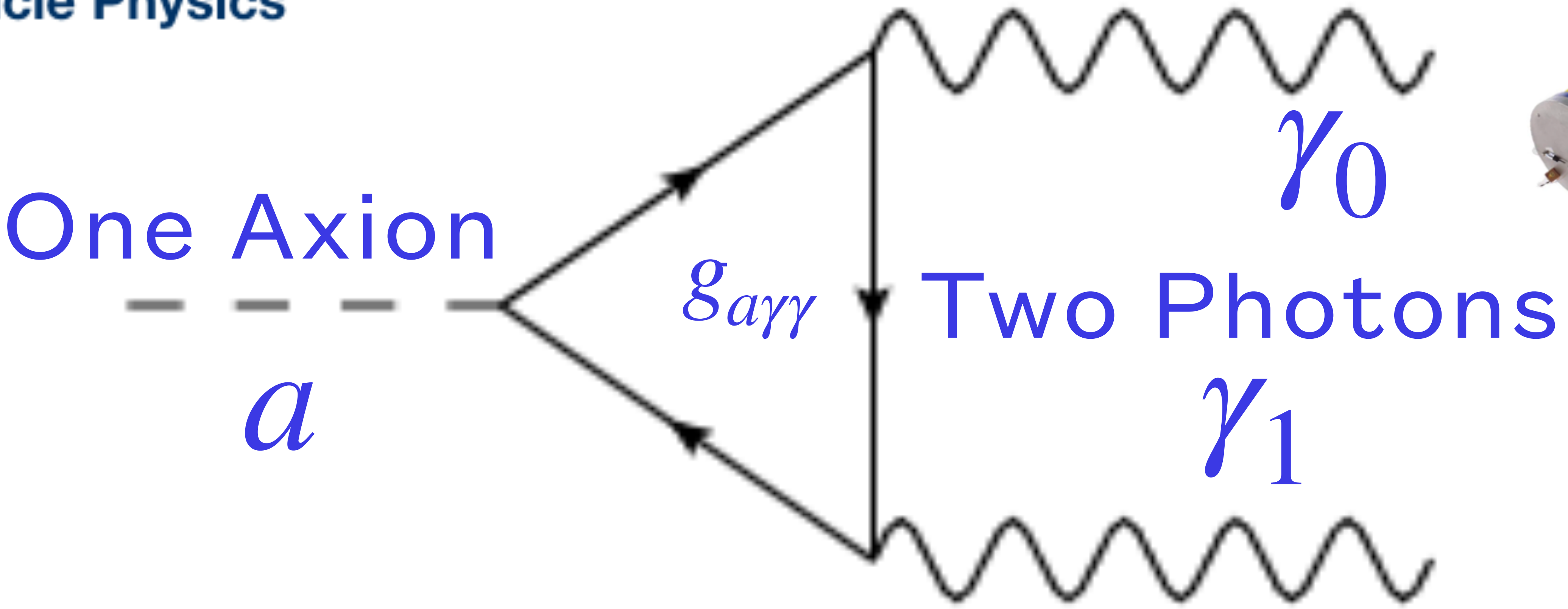

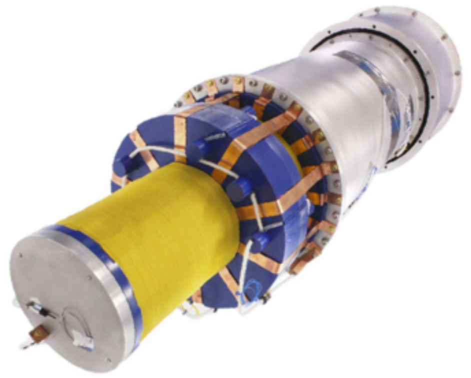

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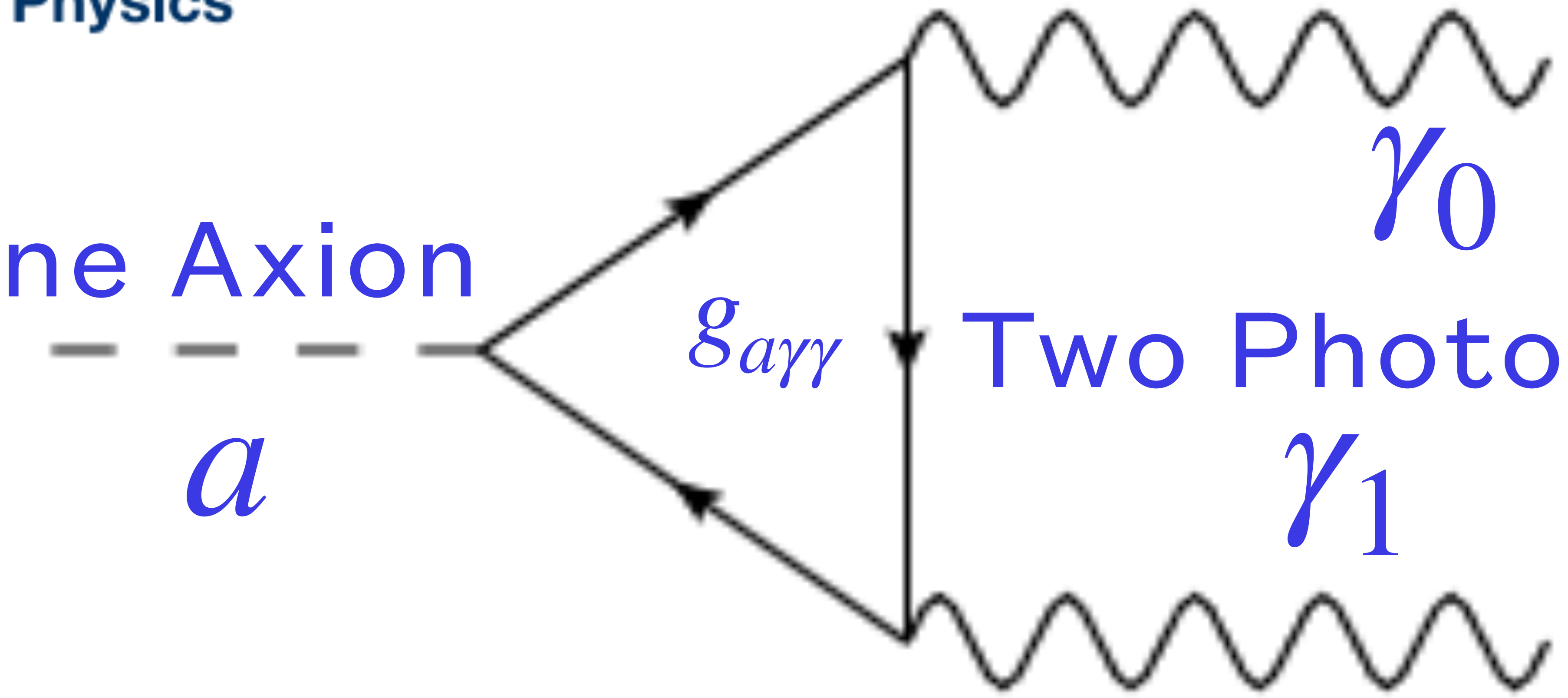

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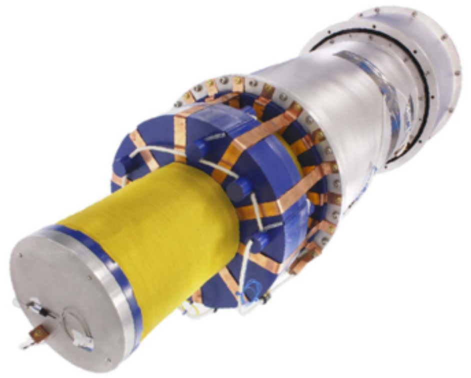

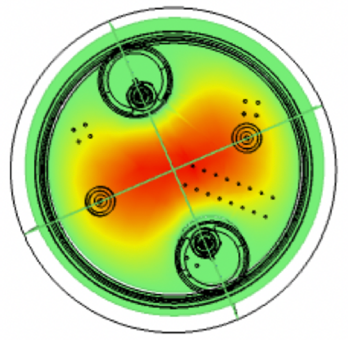

Measure

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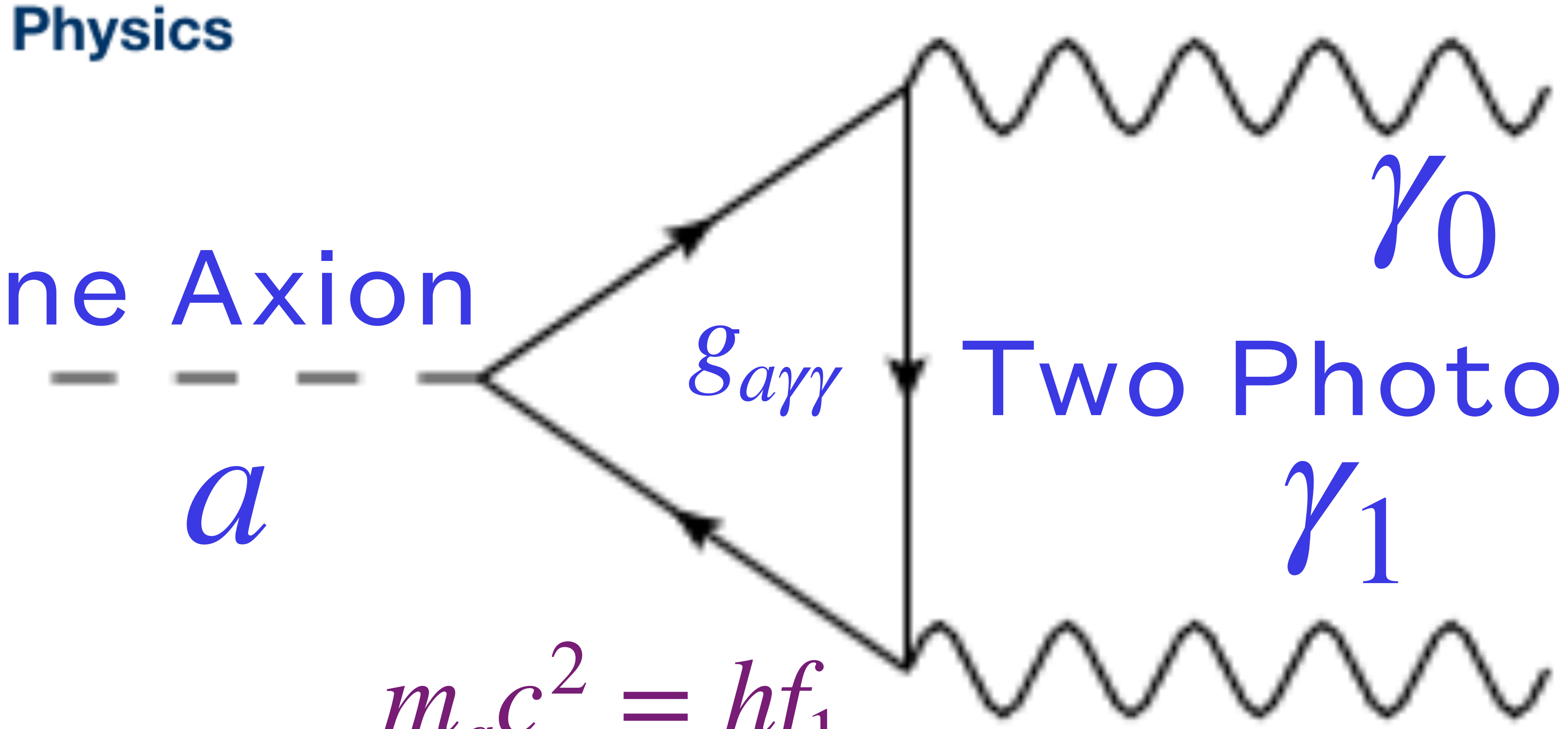

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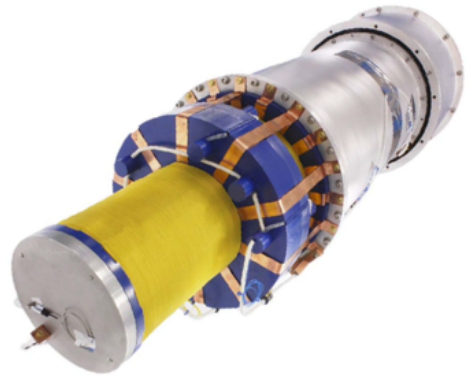
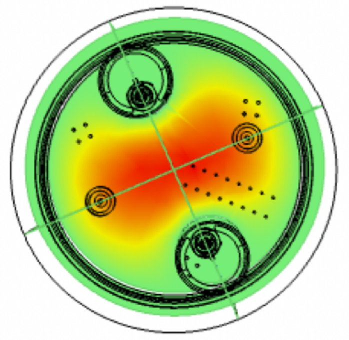
$m_a c^2 = hf_1$





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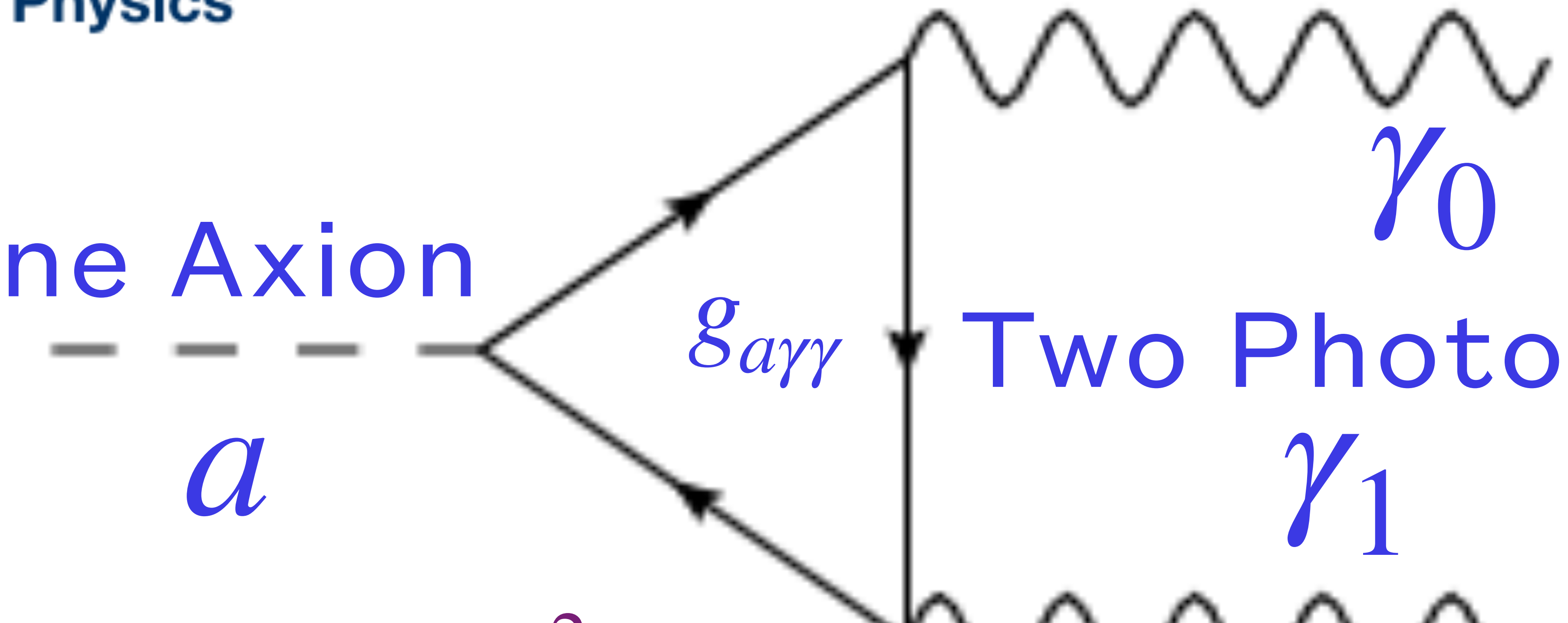

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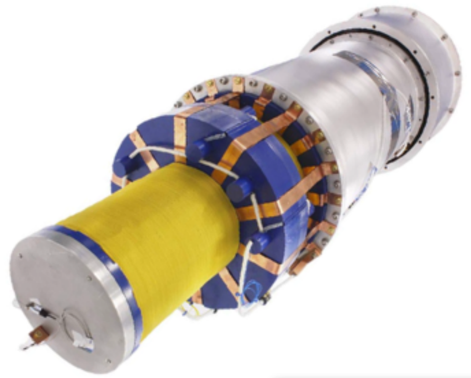
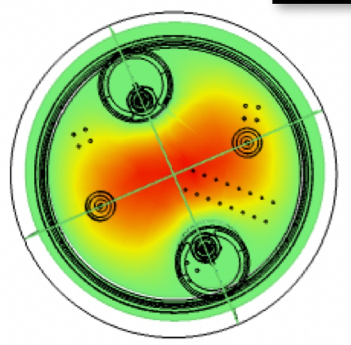


$$\boxed{\mathcal{H}_{int} = \epsilon_0 c g_{a\gamma\gamma} a \mathbf{E}_1 \cdot \mathbf{B}_0}$$



Measure

Photon Haloscopes

Axion Equation of Motion:

Klein-Gordon equation
for massive spin 0
particle

$$a(t) = \frac{1}{2}\left(\tilde{a}e^{-j\omega_a t} + \tilde{a}^{*}e^{j\omega_a t}\right)$$

$$= \mathrm{Re}\left(\tilde{a}e^{-j\omega_a t}\right)$$

Modified Axion Electrodynamics

(Represents two photons)

$$\nabla \cdot \overrightarrow{E} = \frac{\rho_e}{\varepsilon_0} + c g_{a\gamma\gamma}\overrightarrow{B} \,.\, \nabla a$$

$$\nabla \times \overrightarrow{B} - \frac{1}{c^2}\partial_t \overrightarrow{E} =$$

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$$\vec{J}_{ab} = -g_{a\gamma\gamma}\epsilon_0 c \partial_t \left(a(t)\vec{B}_0(\vec{r},t)\right)$$
$$\vec{J}_{ae} = -g_{a\gamma\gamma}\epsilon_0 c \nabla \times \left(a(t)\vec{E}_0(\vec{r},t)\right)$$
$$\nabla \cdot \vec{J}_{ab} = -\partial_t \rho_{ab}$$

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

Photonic Haloscope Equations in terms of Auxiliary Fields

Measure Created Photon

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

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

$$-\frac{1}{c^2} \partial_t \left(\overrightarrow{E}_1(\vec{r},t) - g_{a\gamma\gamma} a(\vec{r},t) c \overrightarrow{B}_0(\vec{r},t) \right) = \mu_0 \vec{J}_{e_1}$$

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

$$\nabla \times \overrightarrow{E}_1(\vec{r},t) + \partial_t \overrightarrow{B}_1(\vec{r},t) = 0.$$

Applied Background Field

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

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

$$\nabla \cdot \overrightarrow{B}_0 = 0$$

$$\nabla \cdot \overrightarrow{E}_0 = \epsilon_0^{-1} \rho_{e_0}$$

Photonic Haloscope Equations in terms of Auxiliary Fields

Measure Created Photon

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

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

$$- \frac{1}{c^2} \partial_t \left(\vec{E}_1(\vec{r},t) - g_{a\gamma\gamma} a(\vec{r},t) c \vec{B}_0(\vec{r},t) \right) = \mu_0 \vec{J}_{e_1}$$

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

$$\nabla \times \vec{E}_1(\vec{r},t) + \partial_t \vec{B}_1(\vec{r},t) = 0.$$

$\longrightarrow$

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

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

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

$$\nabla \times \vec{E}_1(\vec{r},t) + \partial_t \vec{B}_1(\vec{r},t) = 0,$$

Applied Background Field

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

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

$$\nabla \cdot \vec{B}_0 = 0$$

$$\nabla \cdot \vec{E}_0 = \epsilon_0^{-1} \rho_{e_0}$$

Photonic Haloscope Equations in terms of Auxiliary Fields

Measure Created Photon

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

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

$$-\frac{1}{c^2}\partial_t\left(\vec{E}_1(\vec{r},t)-g_{a\gamma\gamma}a(\vec{r},t)c\vec{B}_0(\vec{r},t)\right)=\mu_0\vec{J}_{e_1}$$

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

$$\nabla\times\vec{E}_1(\vec{r},t)+\partial_t\vec{B}_1(\vec{r},t)=0.$$

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

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

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

$$\nabla\times\vec{E}_1(\vec{r},t)+\partial_t\vec{B}_1(\vec{r},t)=0,$$

Constitutive Relations(Include Matter)
Effective Magnetisation and Polarisation

Applied Background Field

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

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

$$\nabla\cdot\vec{B}_0=0$$

$$\nabla\cdot\vec{E}_0=\epsilon_0^{-1}\rho_{e_0}$$

Photonic Haloscope Equations in terms of Auxiliary Fields

Measure Created Photon

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

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

$$-\frac{1}{c^2}\partial_t\left(\vec{E}_1(\vec{r},t)-g_{a\gamma\gamma}a(\vec{r},t)c\vec{B}_0(\vec{r},t)\right)=\mu_0\vec{J}_{e_1}$$

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

$$\nabla\times\vec{E}_1(\vec{r},t)+\partial_t\vec{B}_1(\vec{r},t)=0.$$

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

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

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

$$\nabla\times\vec{E}_1(\vec{r},t)+\partial_t\vec{B}_1(\vec{r},t)=0,$$

Constitutive Relations(Include Matter)
Effective Magnetisation and Polarisation

$$\vec{H}_1(\vec{r},t)=\frac{\vec{B}_1}{\mu_0}-\vec{M}_1-\vec{M}_{a1};$$

$$\vec{D}_1(\vec{r},t)=\epsilon_0\vec{E}_1+\vec{P}_1+\vec{P}_{a1}$$

Applied Background Field

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

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

$$\nabla\cdot\vec{B}_0=0$$

$$\nabla\cdot\vec{E}_0=\epsilon_0^{-1}\rho_{e_0}$$

Photonic Haloscope Equations in terms of Auxiliary Fields

Measure Created Photon

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

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

$$-\frac{1}{c^2}\partial_t\left(\vec{E}_1(\vec{r},t)-g_{a\gamma\gamma}a(\vec{r},t)c\vec{B}_0(\vec{r},t)\right)=\mu_0\vec{J}_{e_1}$$

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

$$\nabla\times\vec{E}_1(\vec{r},t)+\partial_t\vec{B}_1(\vec{r},t)=0.$$

→

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

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

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

$$\nabla\times\vec{E}_1(\vec{r},t)+\partial_t\vec{B}_1(\vec{r},t)=0,$$

Constitutive Relations(Include Matter)
Effective Magnetisation and Polarisation

$$\vec{H}_1(\vec{r},t)=\frac{\vec{B}_1}{\mu_0}-\vec{M}_1-\boxed{\vec{M}_{a1};}$$

$$\vec{D}_1(\vec{r},t)=\epsilon_0\vec{E}_1+\vec{P}_1+\boxed{\vec{P}_{a1}}$$

Applied Background Field

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

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

$$\nabla\cdot\vec{B}_0=0$$

$$\nabla\cdot\vec{E}_0=\epsilon_0^{-1}\rho_{e_0}$$

Photonic Haloscope Equations in terms of Auxiliary Fields

Measure Created Photon

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

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

$$-\frac{1}{c^2}\partial_t\left(\vec{E}_1(\vec{r},t)-g_{a\gamma\gamma}a(\vec{r},t)c\vec{B}_0(\vec{r},t)\right)=\mu_0\vec{J}_{e_1}$$

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

$$\nabla\times\vec{E}_1(\vec{r},t)+\partial_t\vec{B}_1(\vec{r},t)=0.$$

→

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

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

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

$$\nabla\times\vec{E}_1(\vec{r},t)+\partial_t\vec{B}_1(\vec{r},t)=0,$$

Constitutive Relations(Include Matter)
Effective Magnetisation and Polarisation

$$\vec{H}_1(\vec{r},t)=\frac{\vec{B}_1}{\mu_0}-\vec{M}_1-\boxed{\vec{M}_{a1};}$$

$$\vec{D}_1(\vec{r},t)=\epsilon_0\vec{E}_1+\vec{P}_1+\boxed{\vec{P}_{a1}}$$

$$\vec{M}_{a1}=-g_{a\gamma\gamma}a(t)c\epsilon_0\vec{E}_0(\vec{r},t)$$

$$\frac{1}{\epsilon_0}\vec{P}_{a1}=-g_{a\gamma\gamma}a(t)c\vec{B}_0(\vec{r},t)$$

Applied Background Field

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

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

$$\nabla\cdot\vec{B}_0=0$$

$$\nabla\cdot\vec{E}_0=\epsilon_0^{-1}\rho_{e_0}$$

Photonic Haloscope Equations in terms of Auxiliary Fields

Measure Created Photon

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

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

$$-\frac{1}{c^2} \partial_t \left(\vec{E}_1(\vec{r},t) - g_{a\gamma\gamma} a(\vec{r},t) c \vec{B}_0(\vec{r},t) \right) = \mu_0 \vec{J}_{e_1}$$

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

$$\nabla \times \vec{E}_1(\vec{r},t) + \partial_t \vec{B}_1(\vec{r},t) = 0.$$

→

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

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

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

$$\nabla \times \vec{E}_1(\vec{r},t) + \partial_t \vec{B}_1(\vec{r},t) = 0,$$

Constitutive Relations(Include Matter)
Effective Magnetisation and Polarisation

$$\vec{H}_1(\vec{r},t) = \frac{\vec{B}_1}{\mu_0} - \vec{M}_1 - \boxed{\vec{M}_{a1};}$$

$$\vec{D}_1(\vec{r},t) = \epsilon_0 \vec{E}_1 + \vec{P}_1 + \boxed{\vec{P}_{a1}}$$

$$\vec{M}_{a1} = -\, g_{a\gamma\gamma} a(t) c \epsilon_0 \vec{E}_0(\vec{r},t)$$

$$\frac{1}{\epsilon_0} \vec{P}_{a1} = -\, g_{a\gamma\gamma} a(t) c \vec{B}_0(\vec{r},t)$$

$$\nabla \times \vec{D}_1(\vec{r},t) = -\, \partial_t \vec{B}_1(\vec{r},t) + \nabla \times (\vec{P}_1 + \vec{P}_{a1})$$

Applied Background Field

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

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

$$\nabla \cdot \vec{B}_0 = 0$$

$$\nabla \cdot \vec{E}_0 = \epsilon_0^{-1} \rho_{e_0}$$

Photonic Haloscope Equations in terms of Auxiliary Fields

Measure Created Photon

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

$$\begin{aligned}&\nabla\times\left(\vec{B}_1(\vec{r},t)+\frac{g_{a\gamma\gamma}a(t)}{c}\vec{E}_0(\vec{r},t)\right)\\&-\frac{1}{c^2}\partial_t\left(\vec{E}_1(\vec{r},t)-g_{a\gamma\gamma}a(\vec{r},t)c\vec{B}_0(\vec{r},t)\right)=\mu_0\vec{J}_{e_1}\end{aligned}$$

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

$$\nabla\times\vec{E}_1(\vec{r},t)+\partial_t\vec{B}_1(\vec{r},t)=0.$$

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

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

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Constitutive Relations(Include Matter)
Effective Magnetisation and Polarisation

$$\vec{H}_1(\vec{r},t)=\frac{\vec{B}_1}{\mu_0}-\vec{M}_1-\boxed{\vec{M}_{a1};}$$

$$\vec{D}_1(\vec{r},t)=\epsilon_0\vec{E}_1+\vec{P}_1+\boxed{\vec{P}_{a1}}$$

$$\vec{M}_{a1}=-g_{a\gamma\gamma}a(t)c\epsilon_0\vec{E}_0(\vec{r},t)$$

$$\frac{1}{\epsilon_0}\vec{P}_{a1}=-g_{a\gamma\gamma}a(t)c\vec{B}_0(\vec{r},t)$$

$$\nabla\times\vec{D}_1(\vec{r},t)=-\partial_t\vec{B}_1(\vec{r},t)+\nabla\times(\vec{P}_1+\vec{P}_{a1})$$

$$\nabla\times\vec{P}_{a1}\neq 0=-g_{a\gamma\gamma}a(t)c\nabla\times\vec{B}_0(\vec{r},t)\quad(\nabla a=0)$$

Applied Background Field

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

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

$$\nabla\cdot\vec{B}_0=0$$

$$\nabla\cdot\vec{E}_0=\epsilon_0^{-1}\rho_{e_0}$$

Photonic Haloscope Equations in terms of Auxiliary Fields

Measure Created Photon

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

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

$$-\frac{1}{c^2} \partial_t \left(\vec{E}_1(\vec{r},t) - g_{a\gamma\gamma} a(\vec{r},t) c \vec{B}_0(\vec{r},t) \right) = \mu_0 \vec{J}_{e_1}$$

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

$$\nabla \times \vec{E}_1(\vec{r},t) + \partial_t \vec{B}_1(\vec{r},t) = 0.$$

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

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

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

$$\nabla \times \vec{E}_1(\vec{r},t) + \partial_t \vec{B}_1(\vec{r},t) = 0,$$

Constitutive Relations(Include Matter)
Effective Magnetisation and Polarisation

$$\vec{H}_1(\vec{r},t) = \frac{\vec{B}_1}{\mu_0} - \vec{M}_1 - \boxed{\vec{M}_{a1};}$$

$$\vec{D}_1(\vec{r},t) = \epsilon_0 \vec{E}_1 + \vec{P}_1 + \boxed{\vec{P}_{a1}}$$

$$\vec{M}_{a1} = -\, g_{a\gamma\gamma} a(t) c \epsilon_0 \vec{E}_0(\vec{r},t)$$

$$\frac{1}{\epsilon_0} \vec{P}_{a1} = -\, g_{a\gamma\gamma} a(t) c \vec{B}_0(\vec{r},t)$$

$$\nabla \times \vec{D}_1(\vec{r},t) = -\, \partial_t \vec{B}_1(\vec{r},t) + \nabla \times (\vec{P}_1 + \vec{P}_{a1})$$

$$\nabla \times \vec{P}_{a1} \neq 0 = -\, g_{a\gamma\gamma} a(t) c \nabla \times \vec{B}_0(\vec{r},t) \quad (\nabla a = 0)$$

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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Photonic Haloscope Equations in terms of Auxiliary Fields

Measure Created Photon

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

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

$$-\frac{1}{c^2}\partial_t\left(\vec{E}_1(\vec{r},t)-g_{a\gamma\gamma}a(\vec{r},t)c\vec{B}_0(\vec{r},t)\right)=\mu_0\vec{J}_{e_1}$$

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

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

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

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

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Constitutive Relations(Include Matter)
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$$\vec{H}_1(\vec{r},t)=\frac{\vec{B}_1}{\mu_0}-\vec{M}_1-\boxed{\vec{M}_{a1};}$$

$$\vec{D}_1(\vec{r},t)=\epsilon_0\vec{E}_1+\vec{P}_1+\boxed{\vec{P}_{a1}}$$

$$\vec{M}_{a1}=-g_{a\gamma\gamma}a(t)c\epsilon_0\vec{E}_0(\vec{r},t)$$

$$\frac{1}{\epsilon_0}\vec{P}_{a1}=-g_{a\gamma\gamma}a(t)c\vec{B}_0(\vec{r},t)$$

$$\nabla\times\vec{D}_1(\vec{r},t)=-\partial_t\vec{B}_1(\vec{r},t)+\nabla\times(\vec{P}_1+\vec{P}_{a1})$$

$$\nabla\times\vec{P}_{a1}\neq 0=-g_{a\gamma\gamma}a(t)c\nabla\times\vec{B}_0(\vec{r},t)\quad(\nabla a=0)$$

Applied Background Field

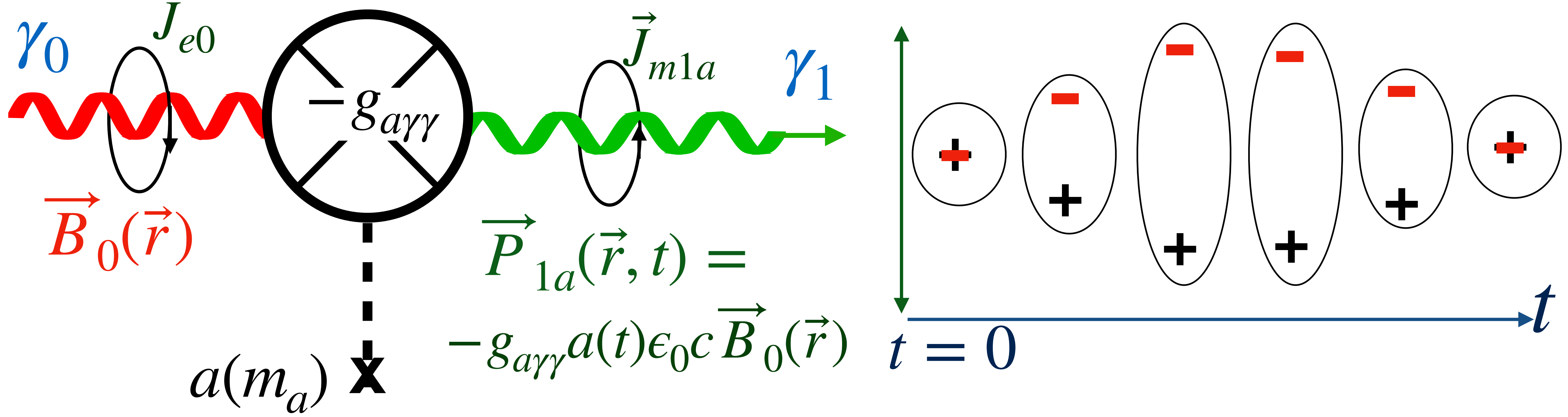
$$\nabla\times\vec{B}_0=\mu_0\epsilon_0\partial_t\vec{E}_0+\mu_0\vec{J}_{e_0}$$

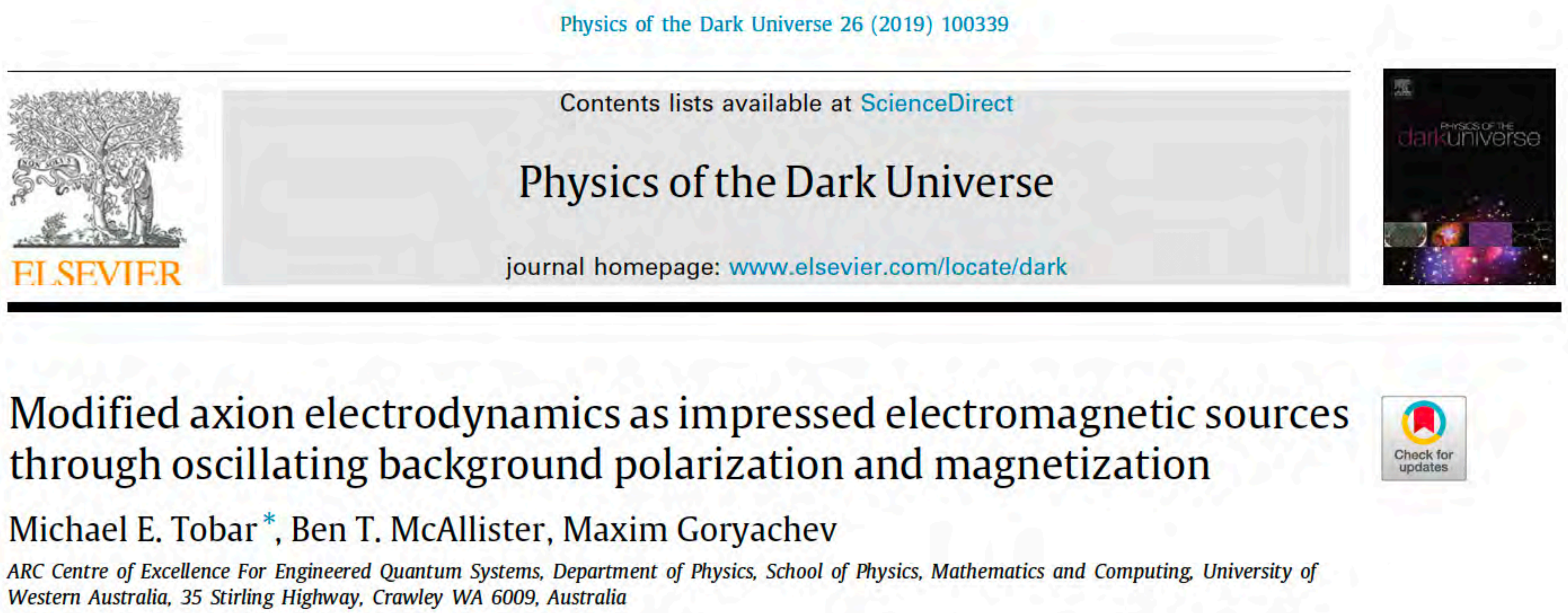
$$\nabla\times\vec{E}_0=-\partial_t\vec{B}_0$$

$$\nabla\cdot\vec{B}_0=0$$

$$\nabla\cdot\vec{E}_0=\epsilon_0^{-1}\rho_{e_0}$$

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




Physics of the Dark Universe 26 (2019) 100339

Contents lists available at ScienceDirect

Physics of the Dark Universe

journal homepage: www.elsevier.com/locate/dark

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

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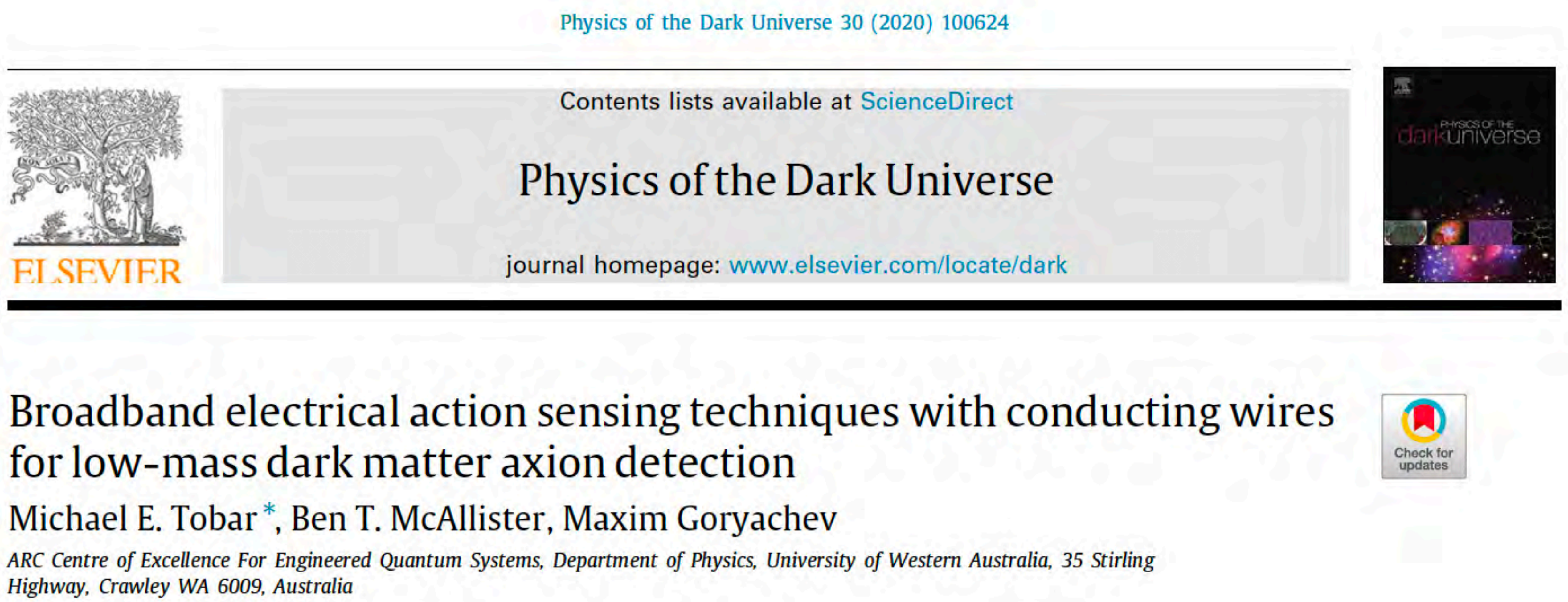
Physics of the Dark Universe 30 (2020) 100624

Contents lists available at ScienceDirect

Physics of the Dark Universe

journal homepage: www.elsevier.com/locate/dark

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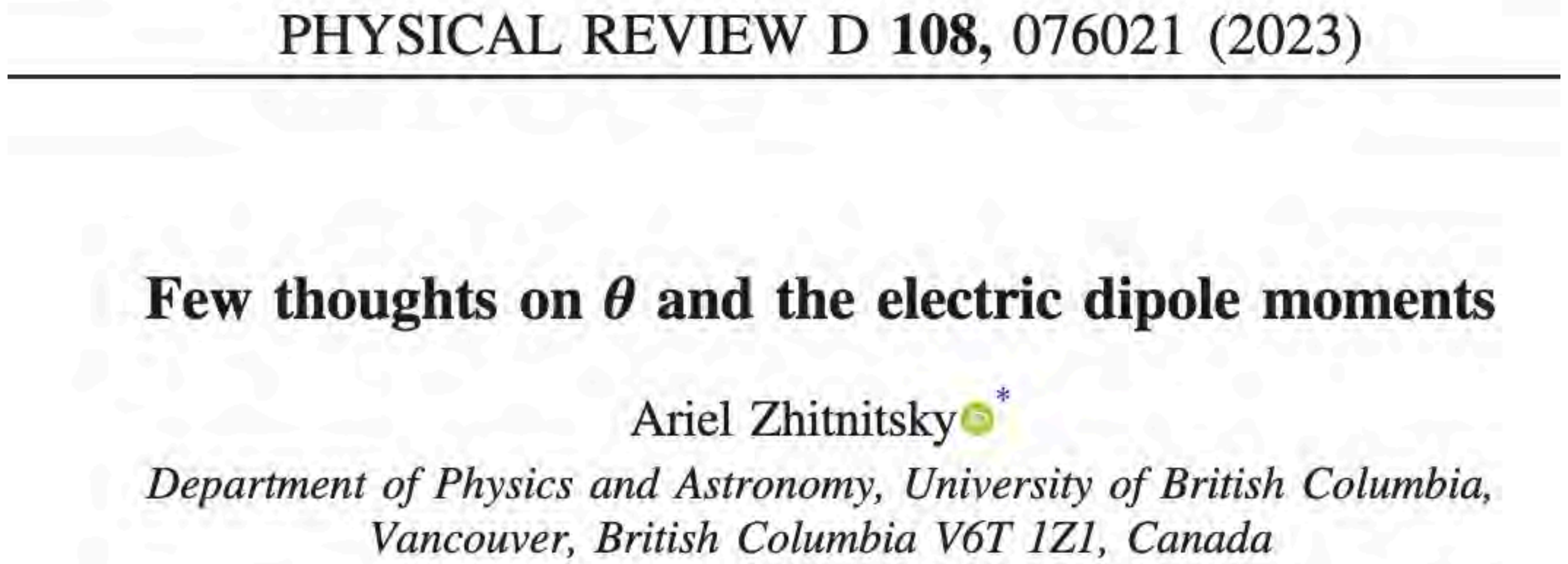
PHYSICAL REVIEW D **108,** 076021 (2023)

Few thoughts on θ and the electric dipole moments

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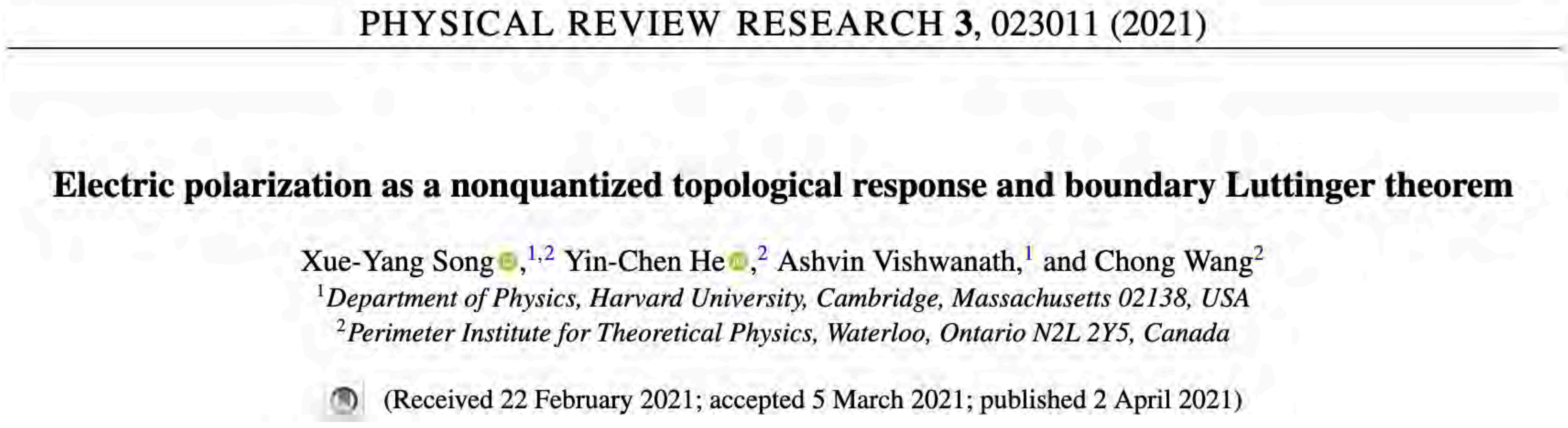
PHYSICAL REVIEW RESEARCH **3**, 023011 (2021)

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]

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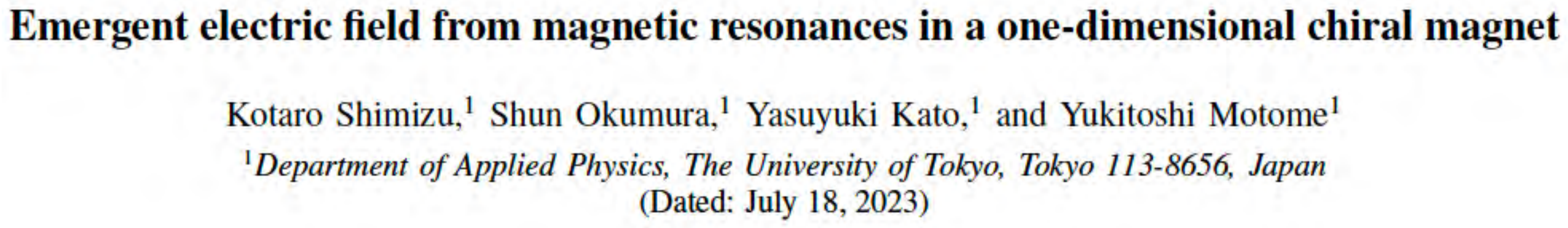
(Received 22 February 2021; accepted 5 March 2021; published 2 April 2021)


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]

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(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

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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$\lambda_a > d_{exp}$ $\lambda_a \sim d_{exp}$ $\lambda_a < d_{exp}$

DC Magnetic Haloscopes

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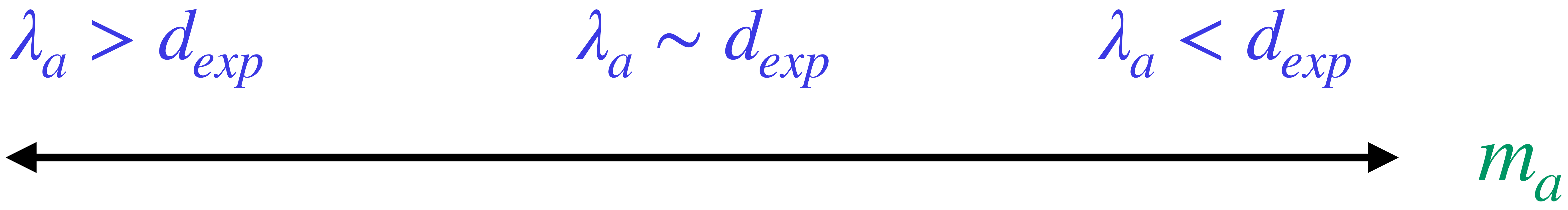

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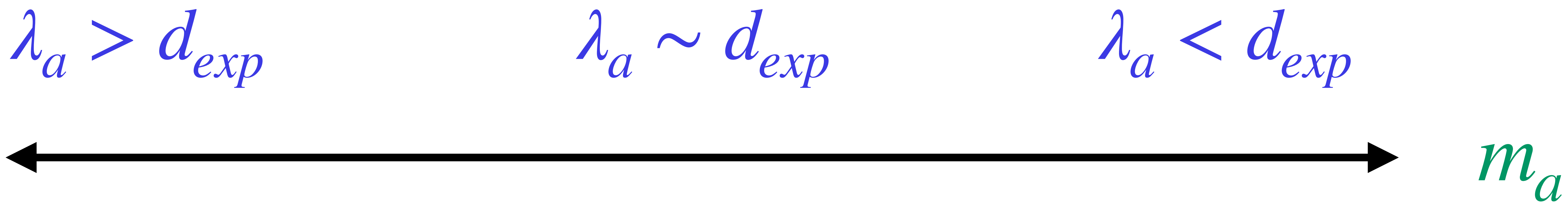

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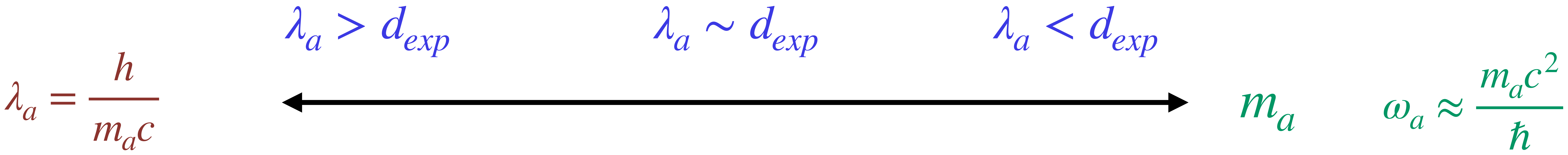

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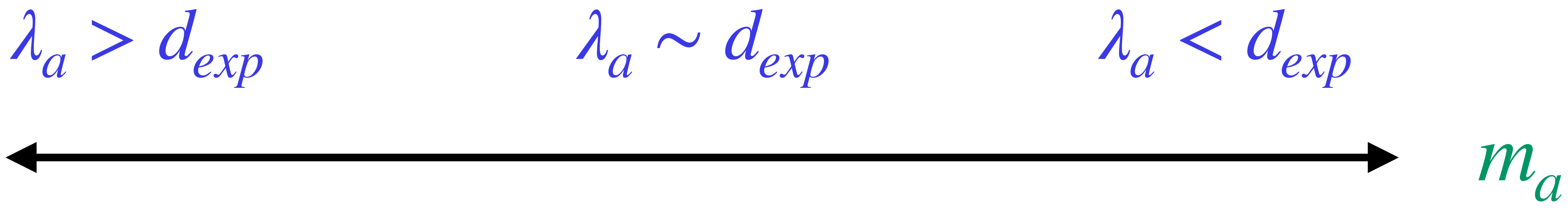

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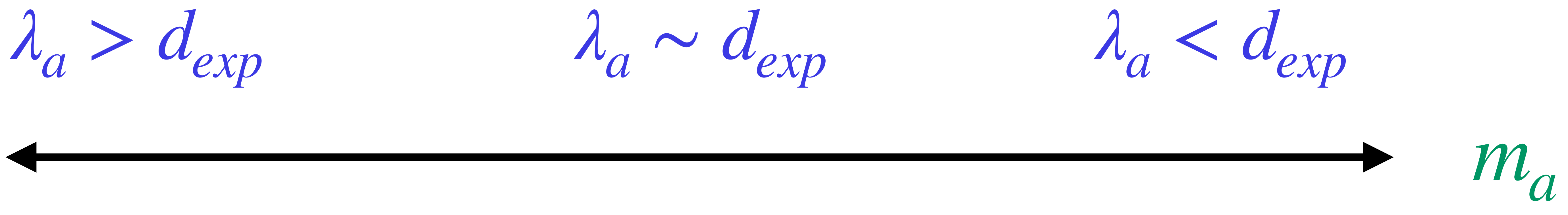

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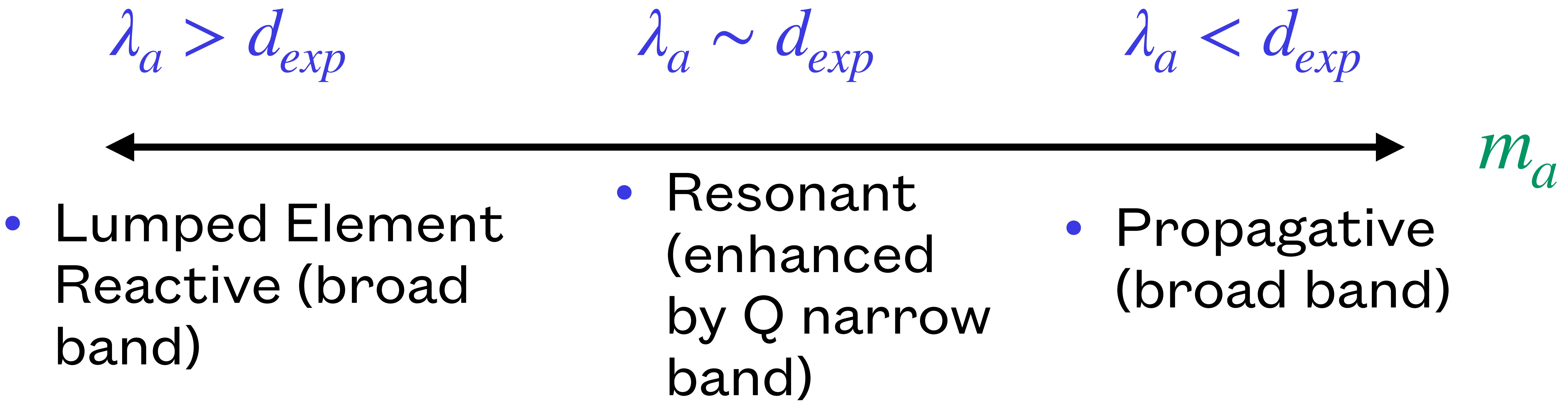

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Type Depends on Axion Compton Wavelength

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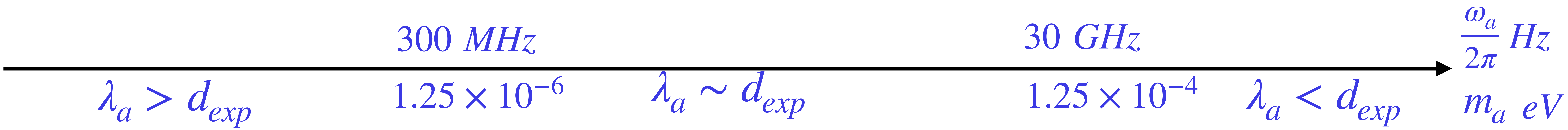

$300\ MHz$ $\quad$ $30\ GHz$ $\quad$ $\frac{\omega_a}{2\pi}\ Hz$

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

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ADMX SLIC
RE-ENTRANT CAVITY
ABRACADABRA
SHAFT
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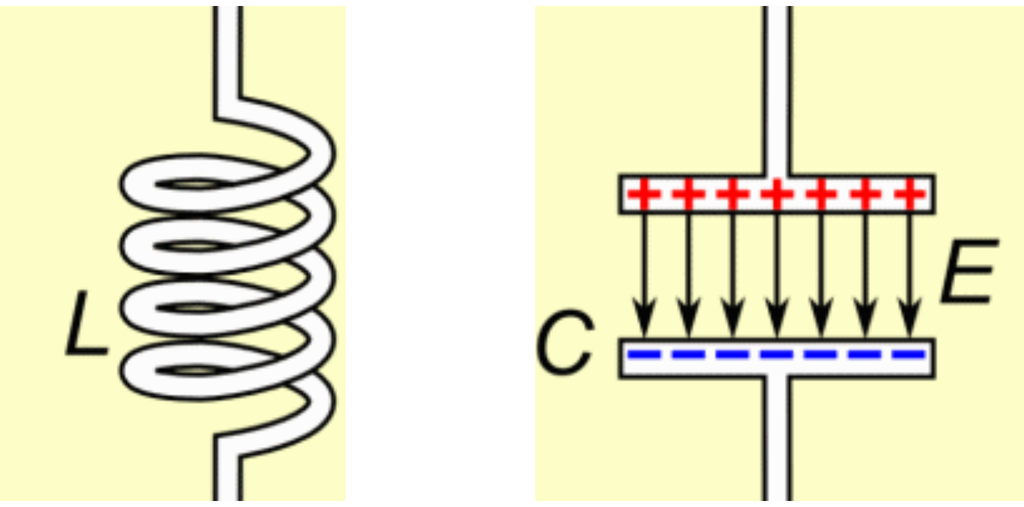

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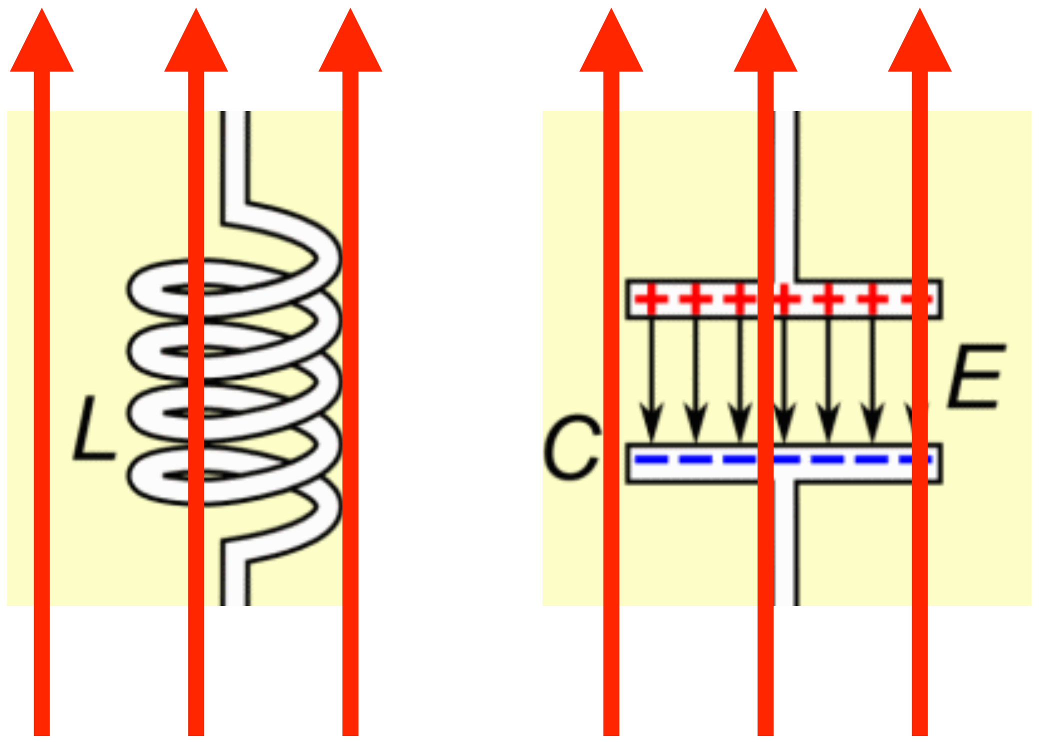

$\vec{B} = B_{DC}\hat{z}$

DC Magnetic Haloscopes

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Low Mass: Lumped Element
Reactive

$\lambda_a > d_{exp}$

$300\ MHz$

1.25×10^{-6}

Middle Mass: Resonant Cavity
Reactive and Dissipative

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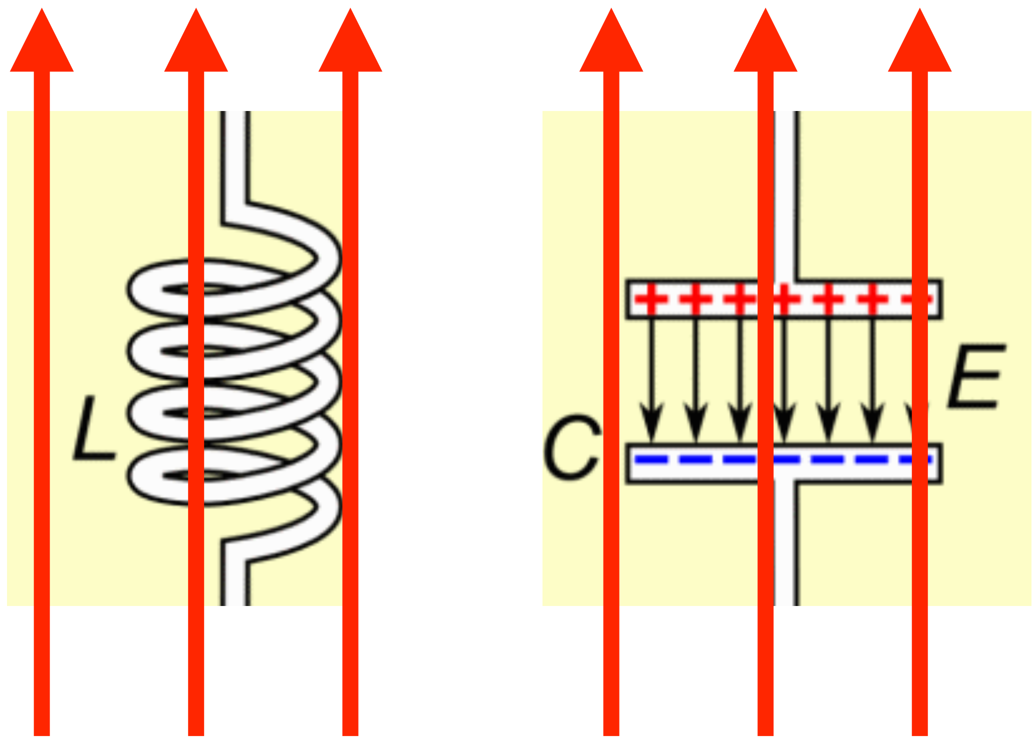

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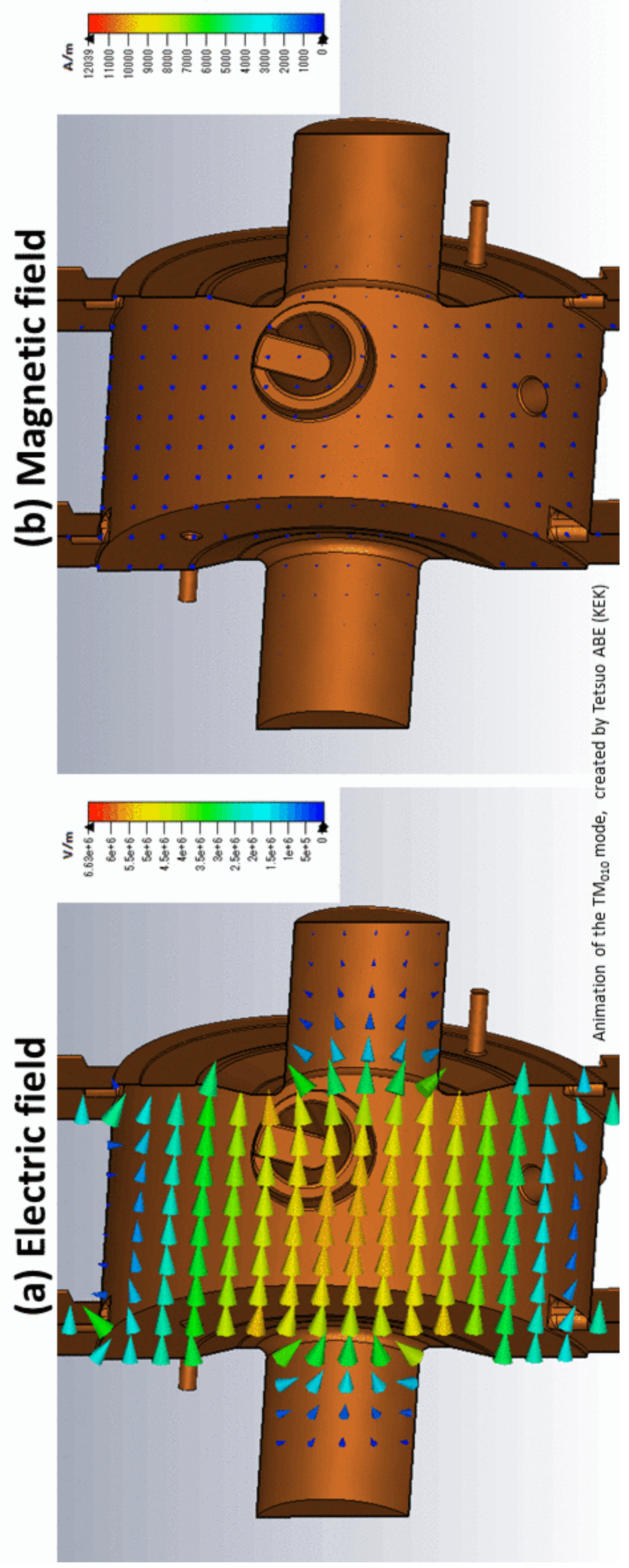

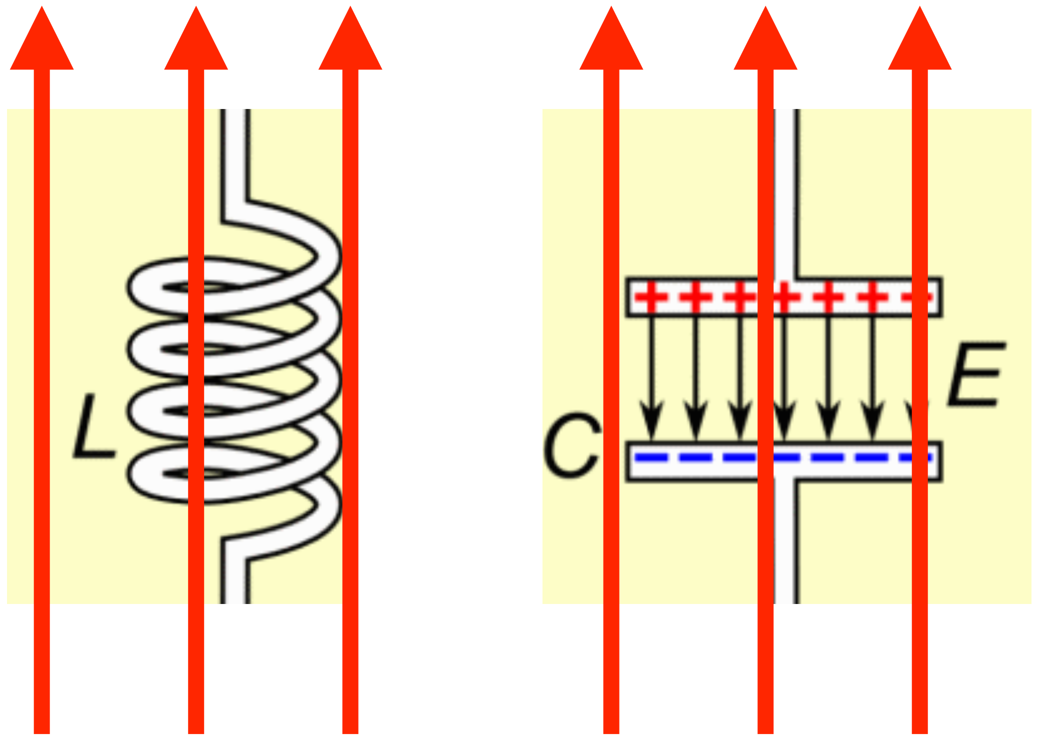

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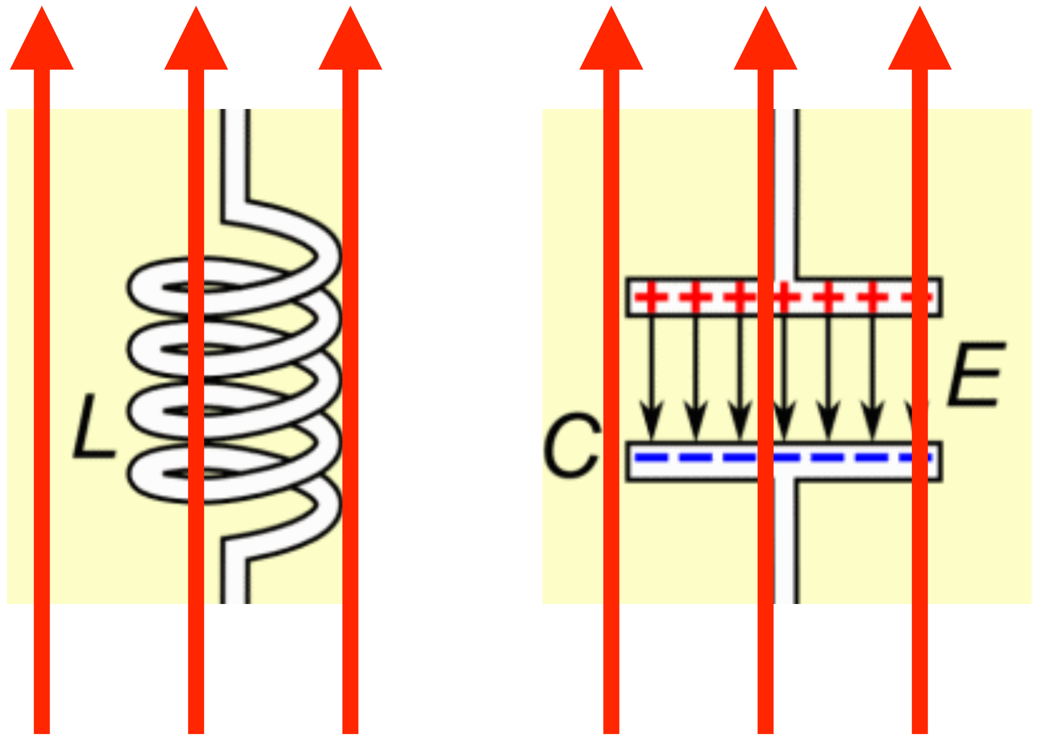

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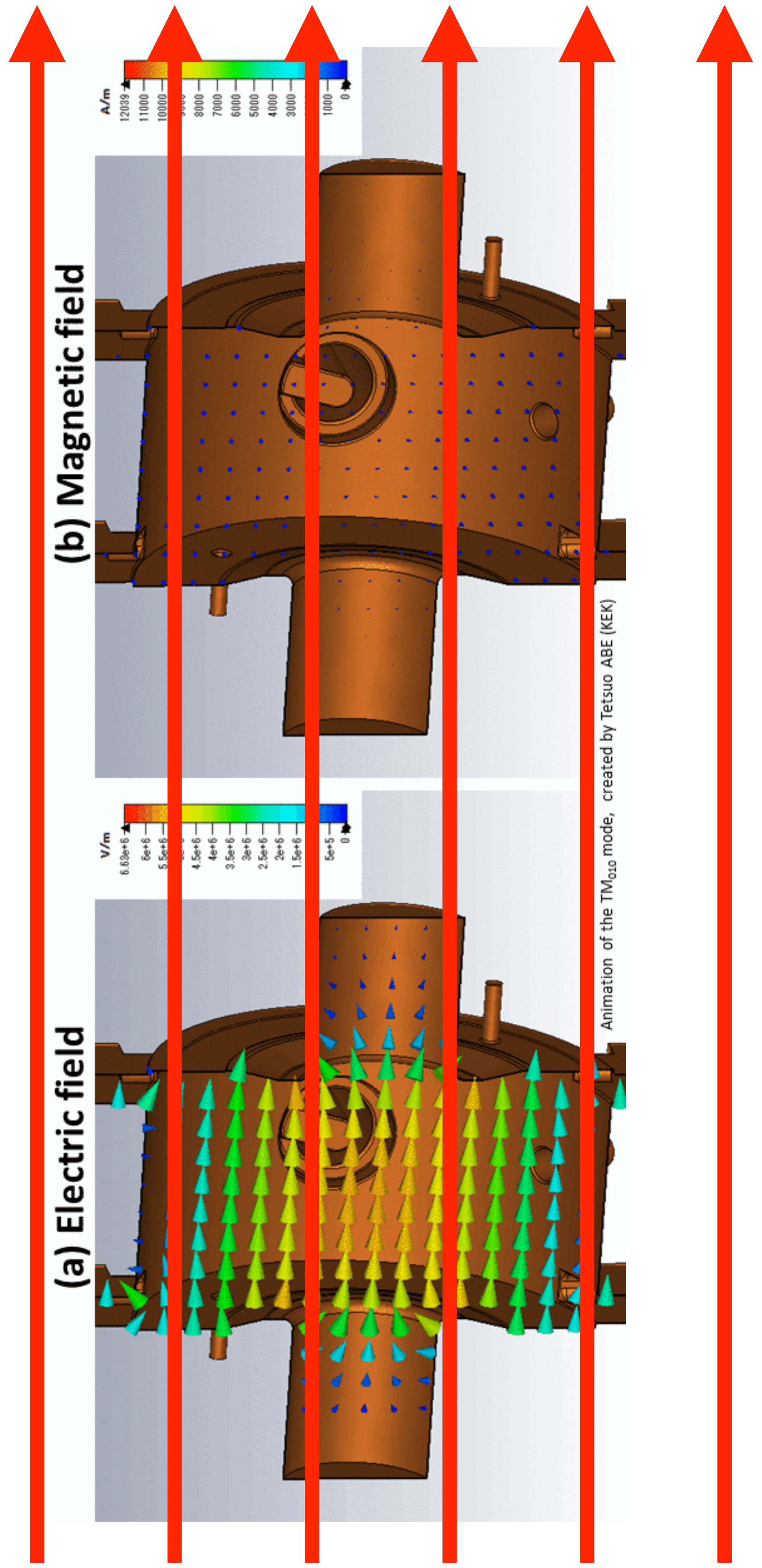

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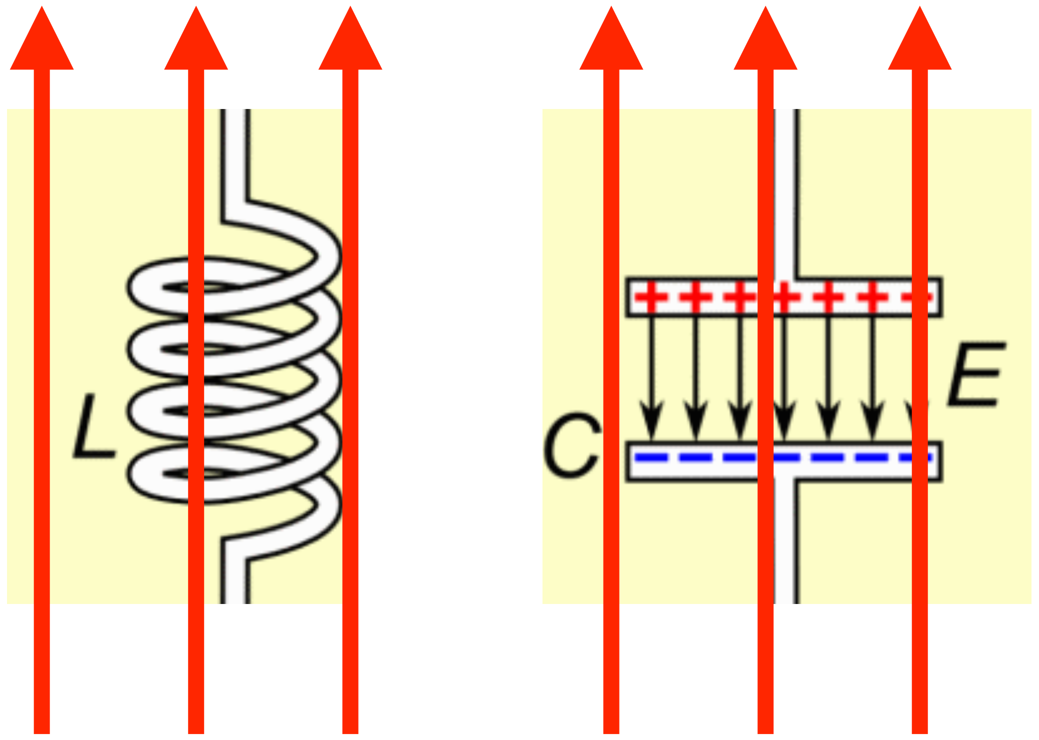

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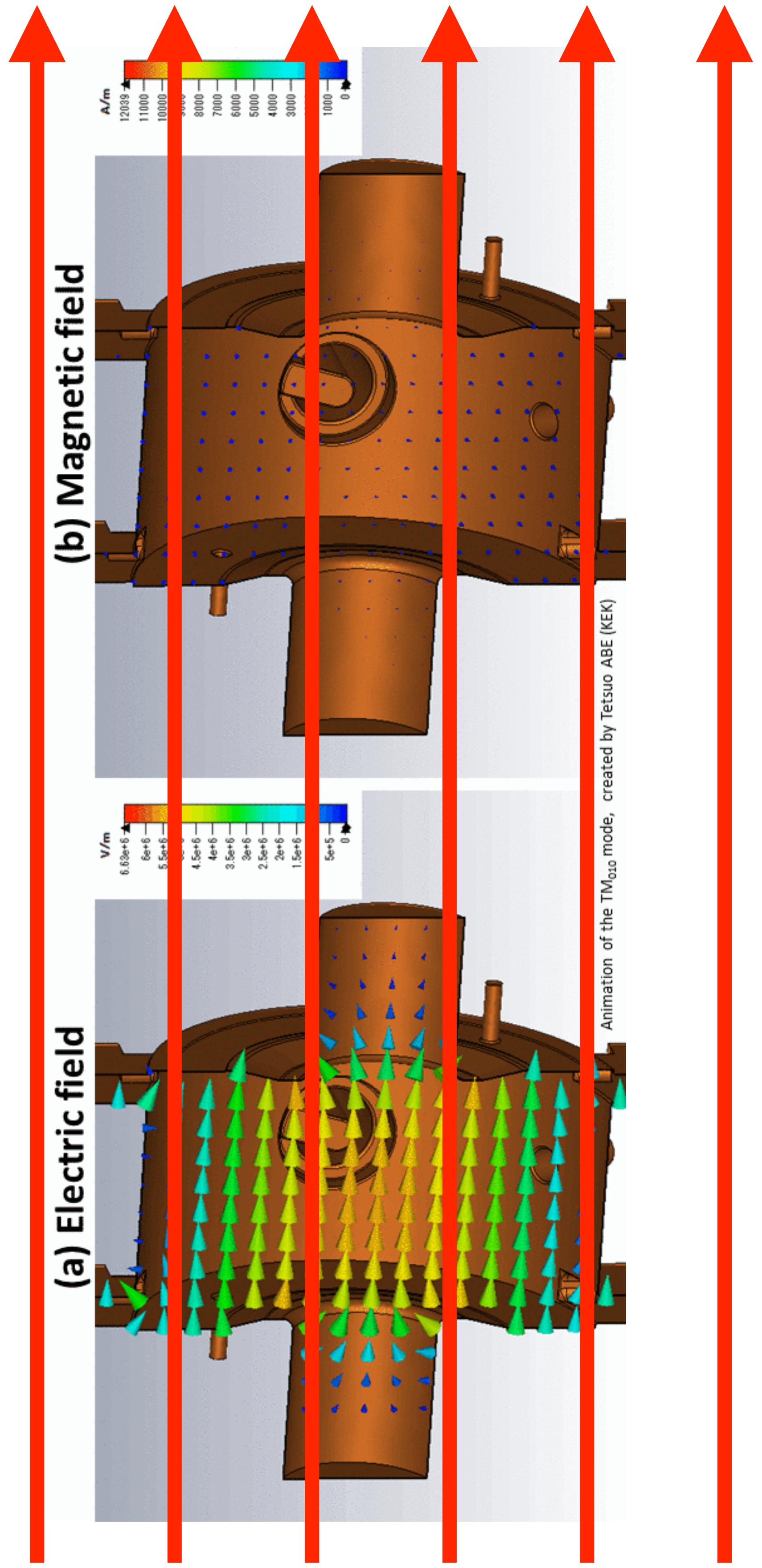

Animation of the TM_{010} mode, created by Tetsuo ABE (KEK)

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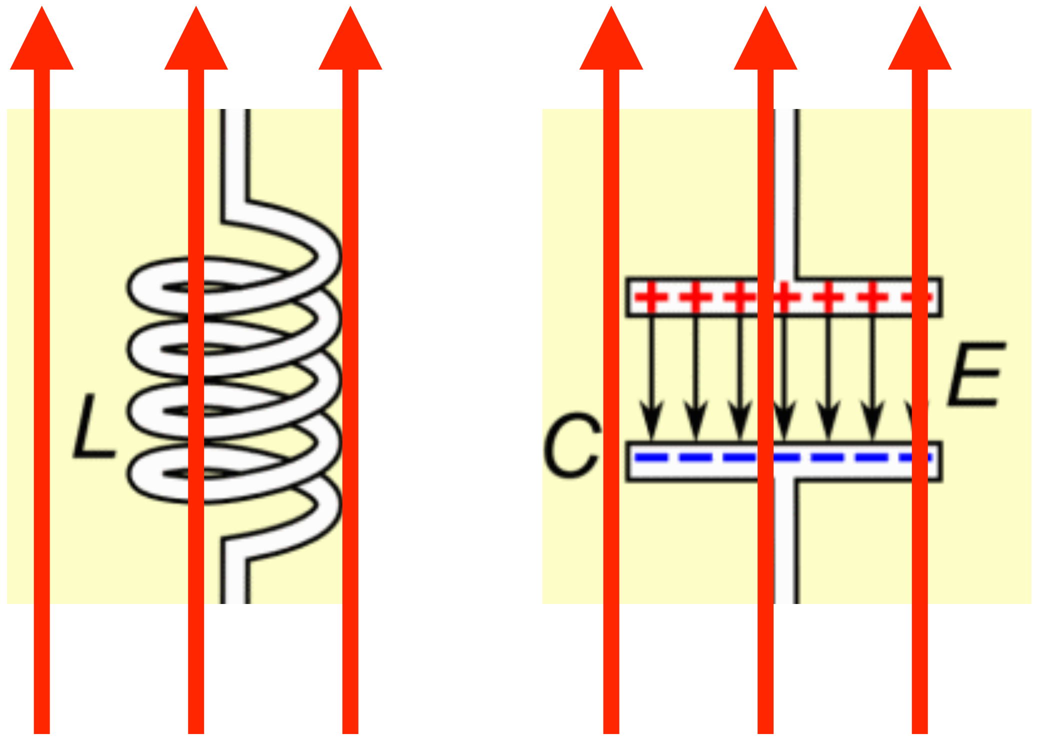

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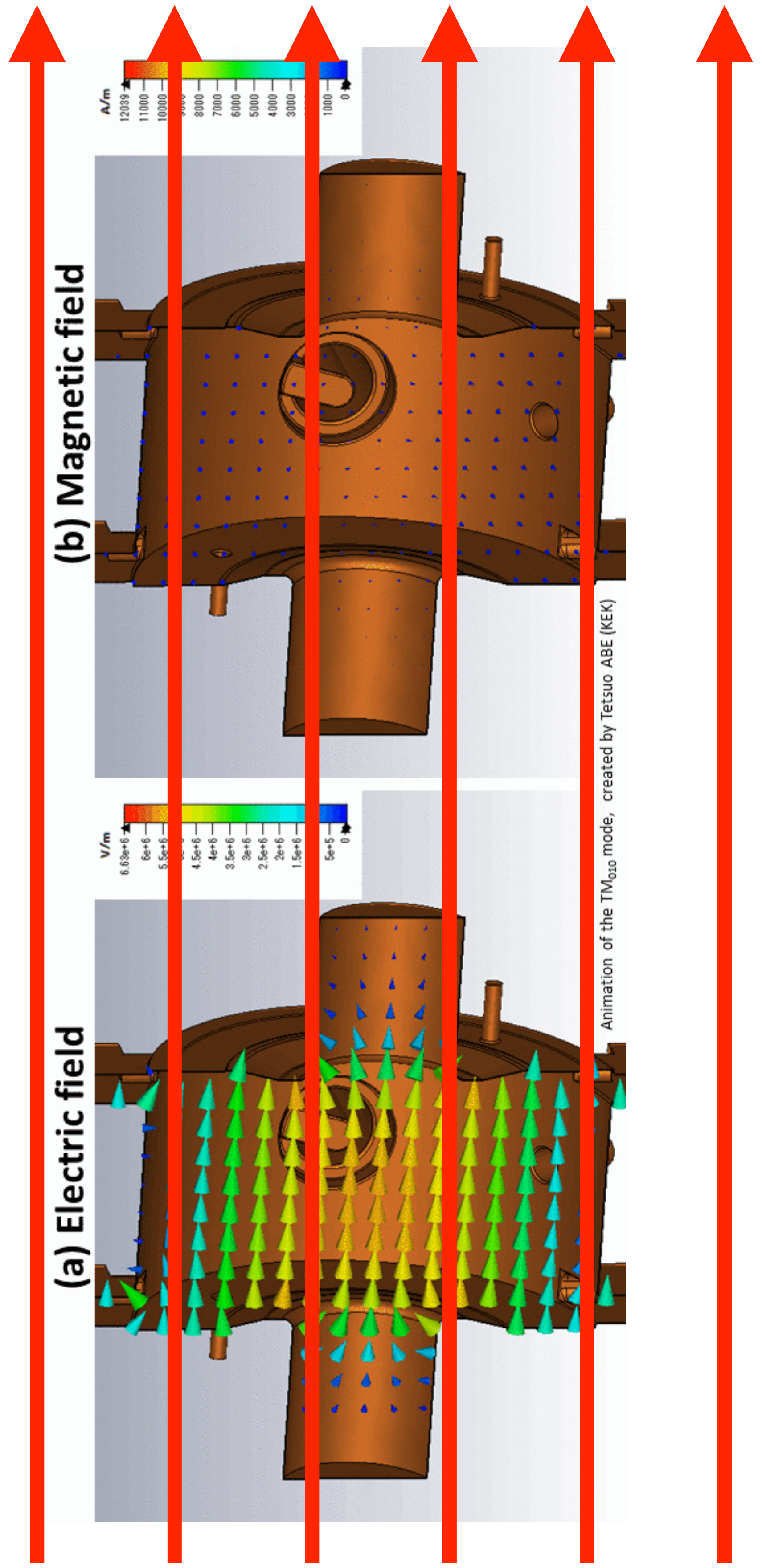

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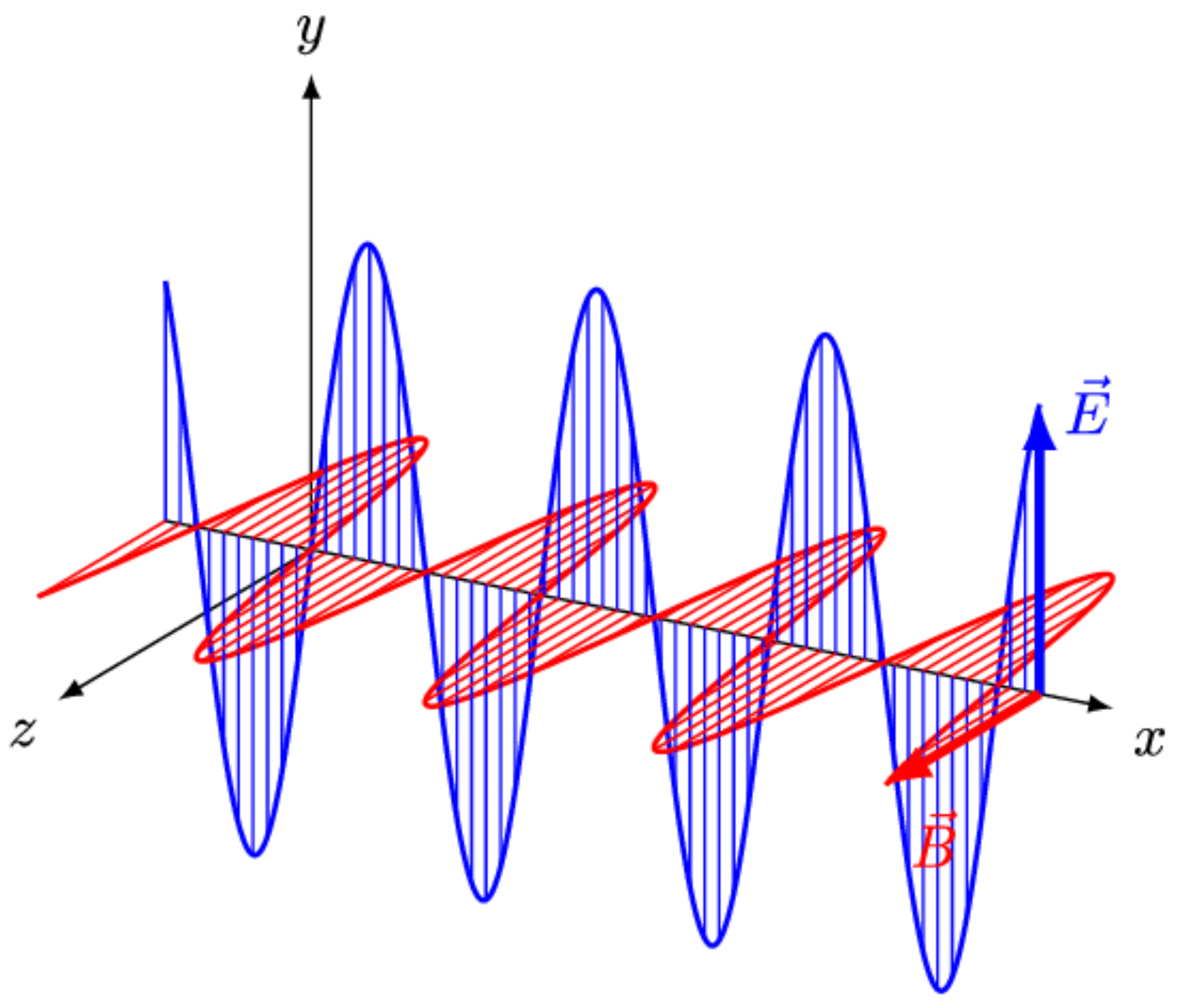

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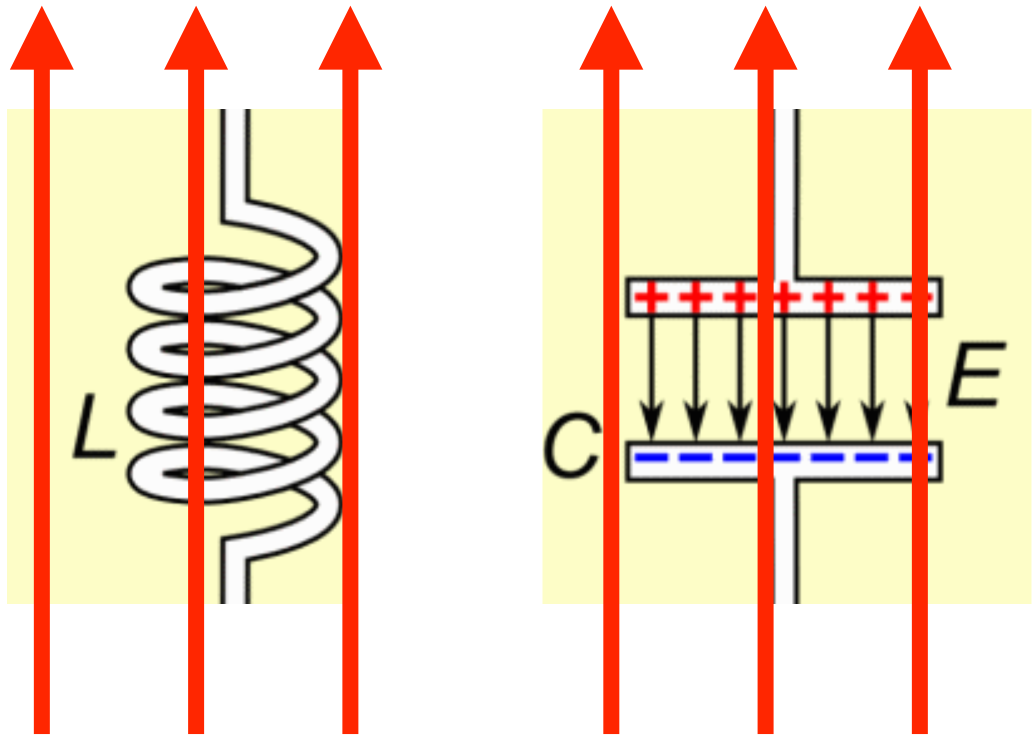

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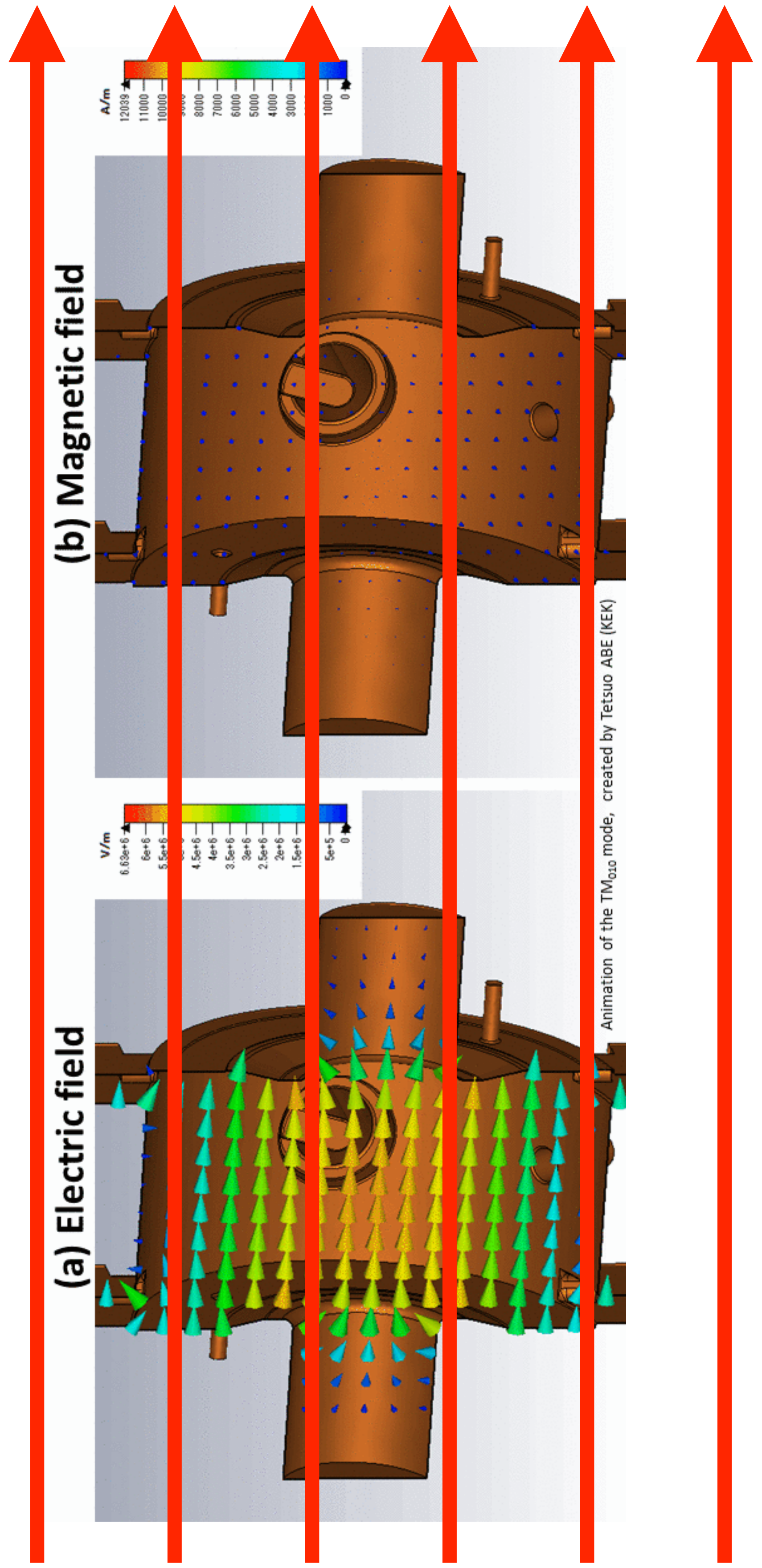

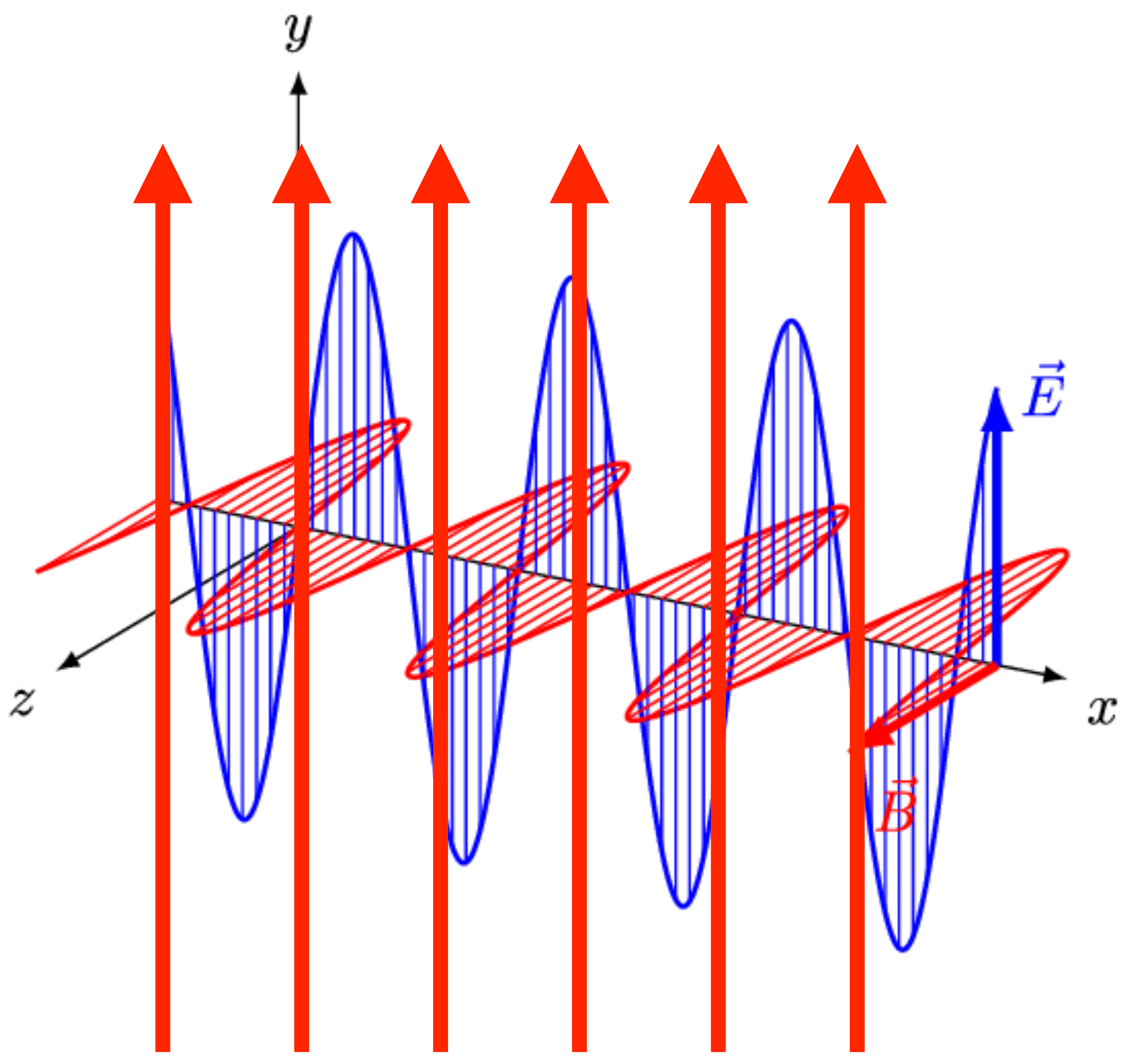

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Instantaneous Poynting vector

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

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

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

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Complex Poynting vector

- The corresponding phasor form of the Poynting vector

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

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

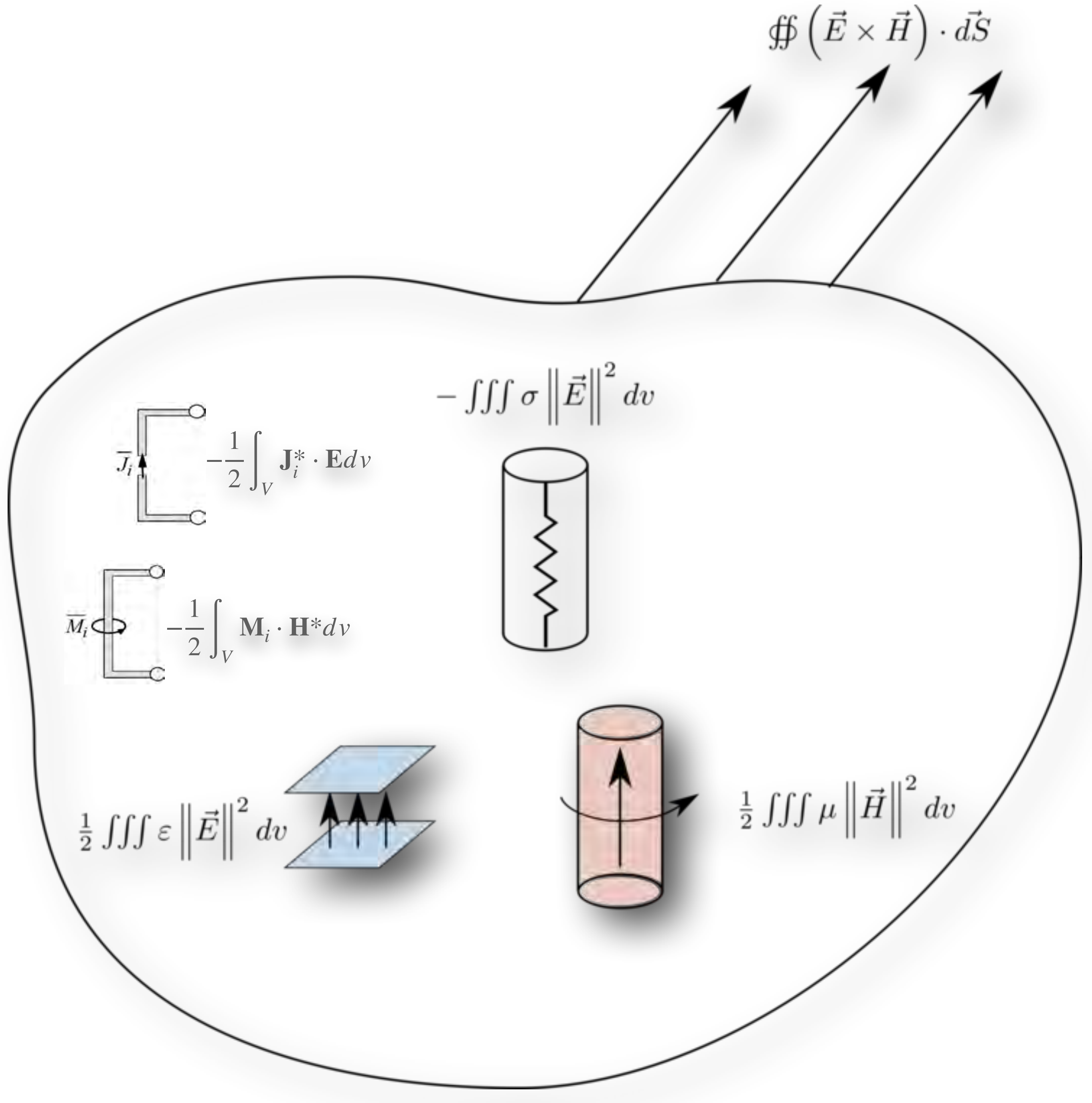
Time Average Power

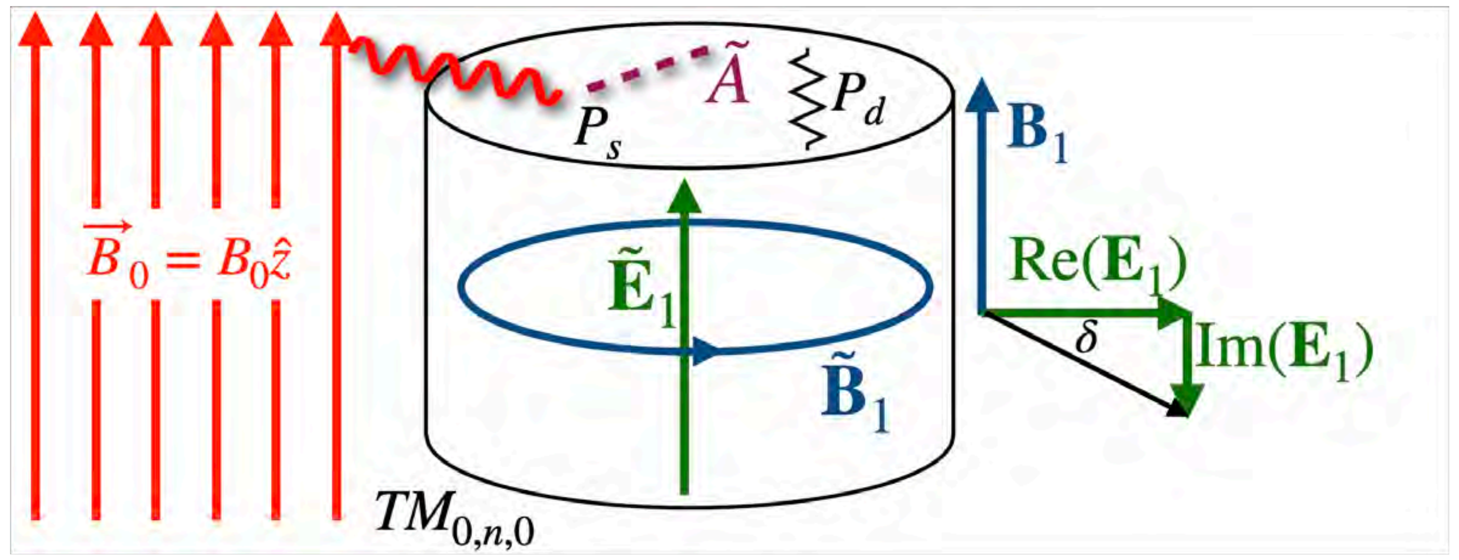
Reactive Power

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

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

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Sensitivity of a Resonant Haloscope

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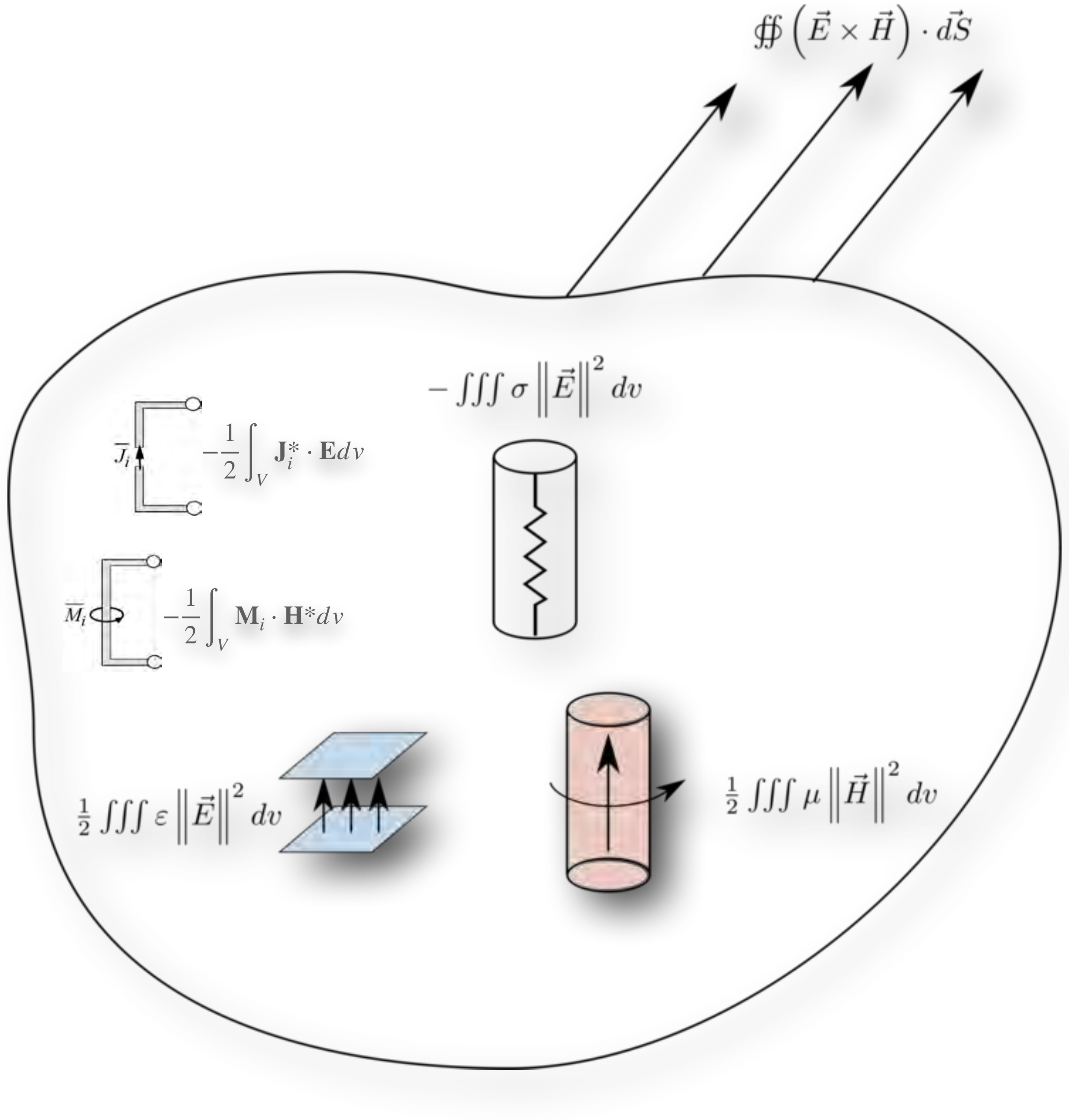

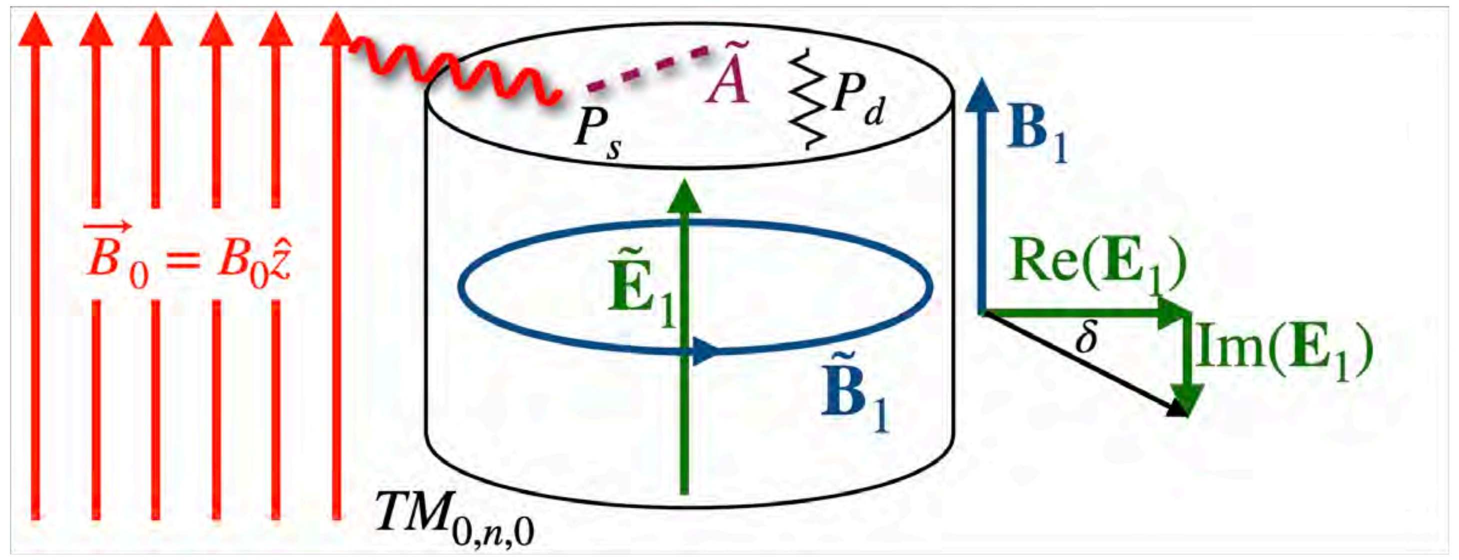


PHYSICAL REVIEW D **105,** 045009 (2022)

Poynting vector controversy in axion modified electrodynamics

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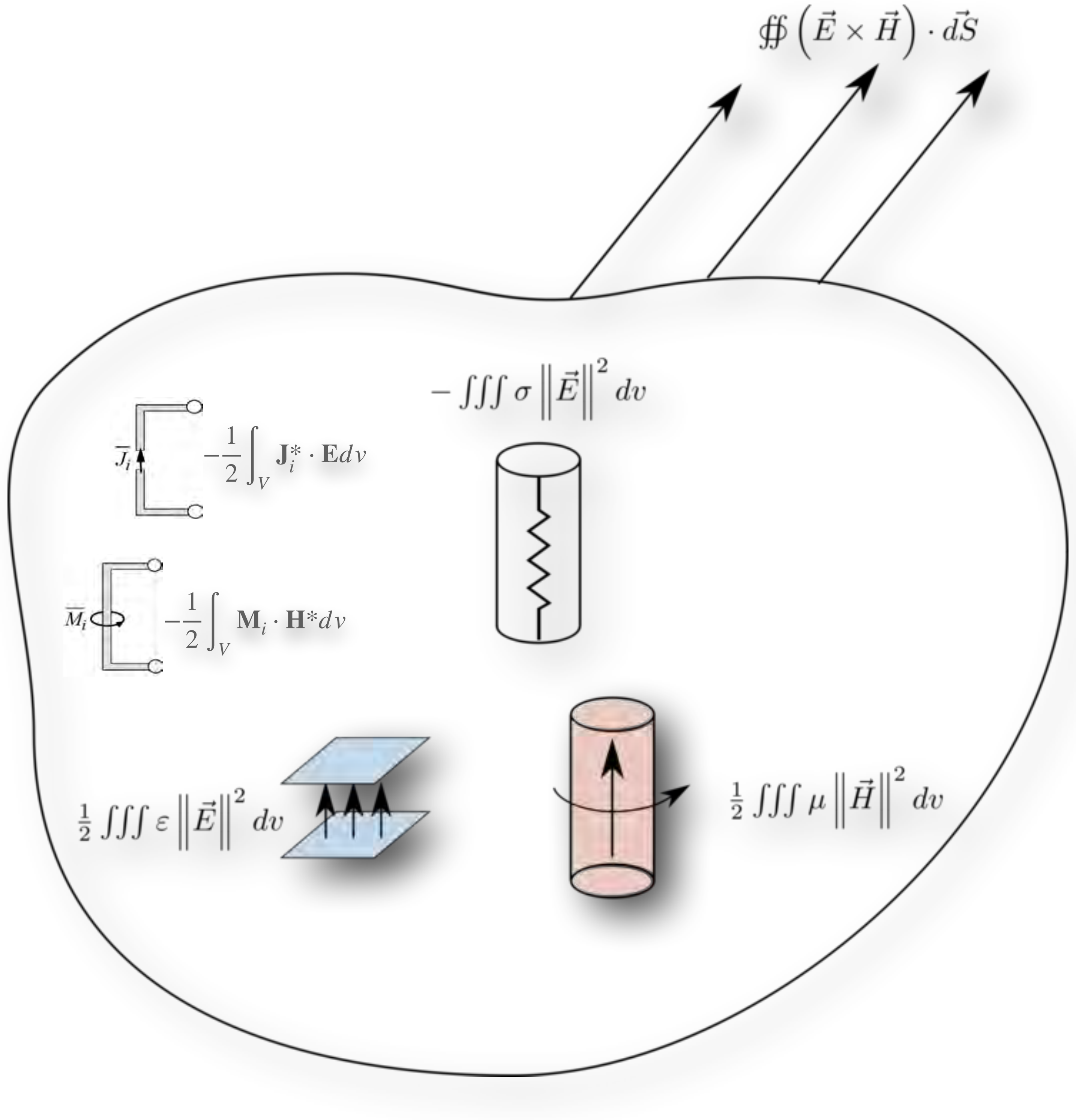

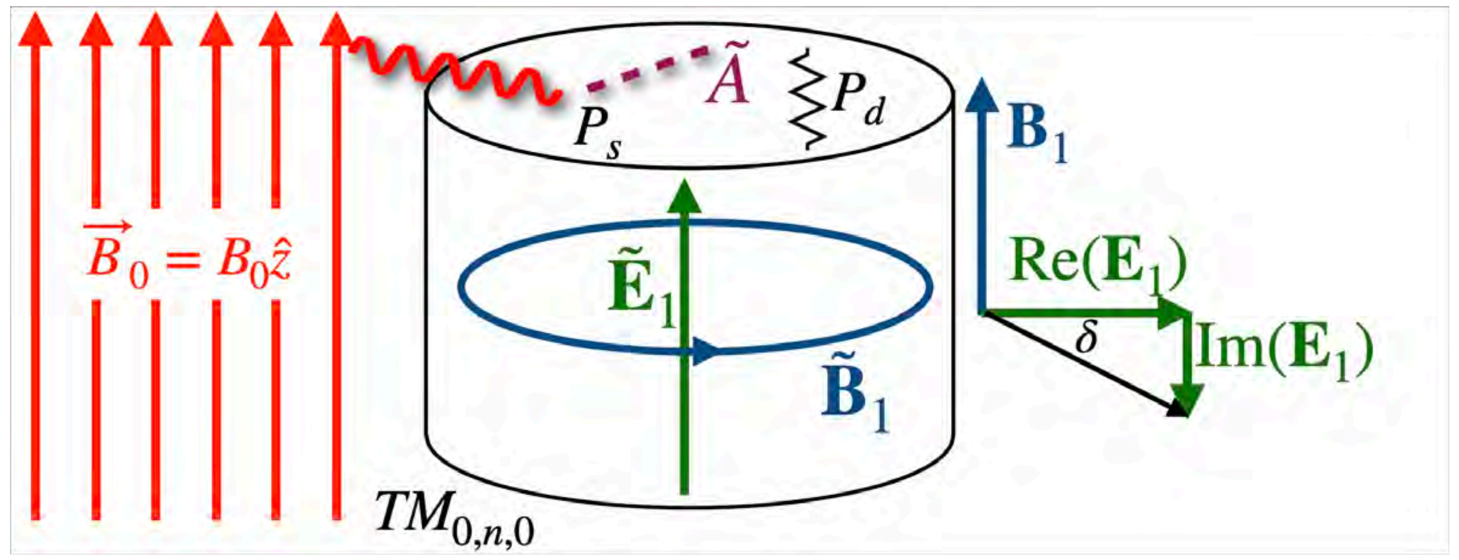

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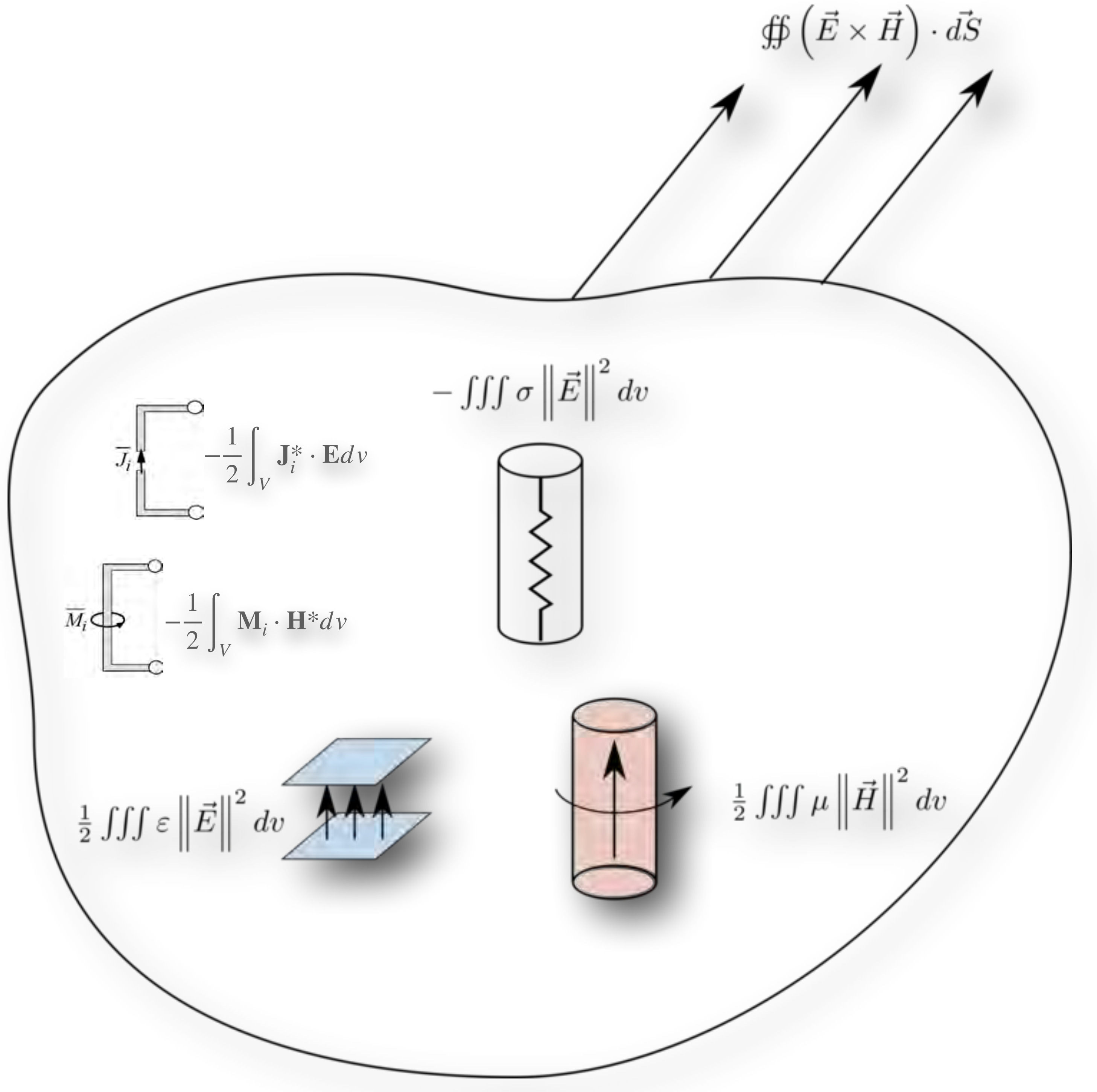

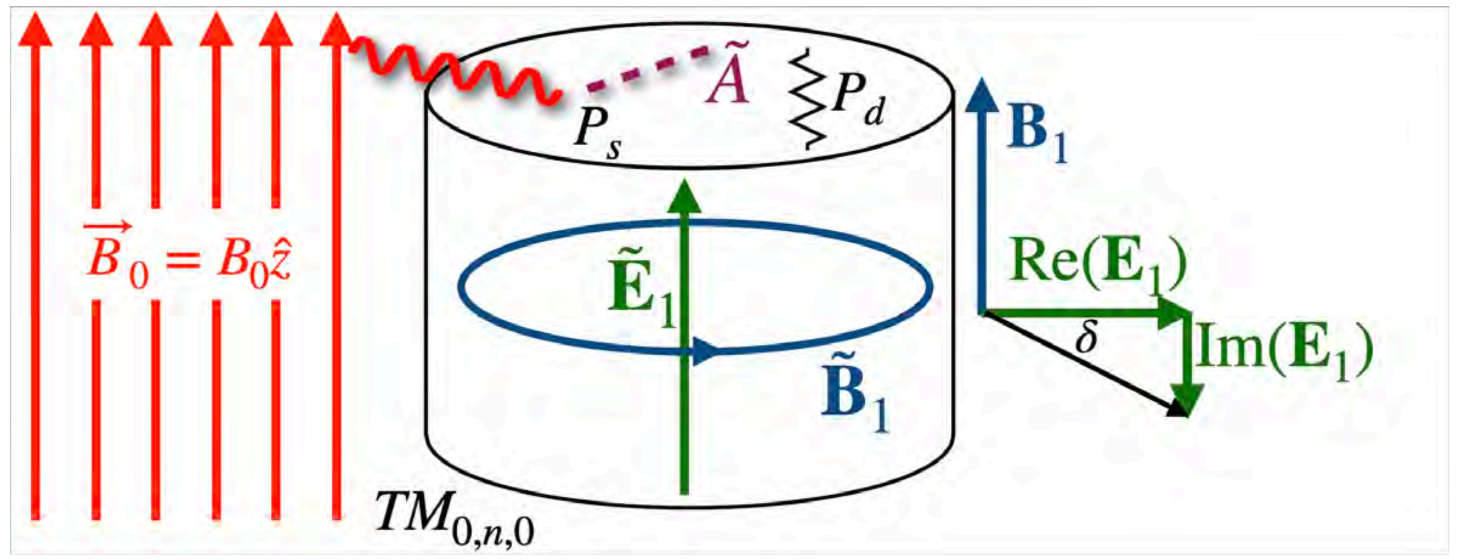

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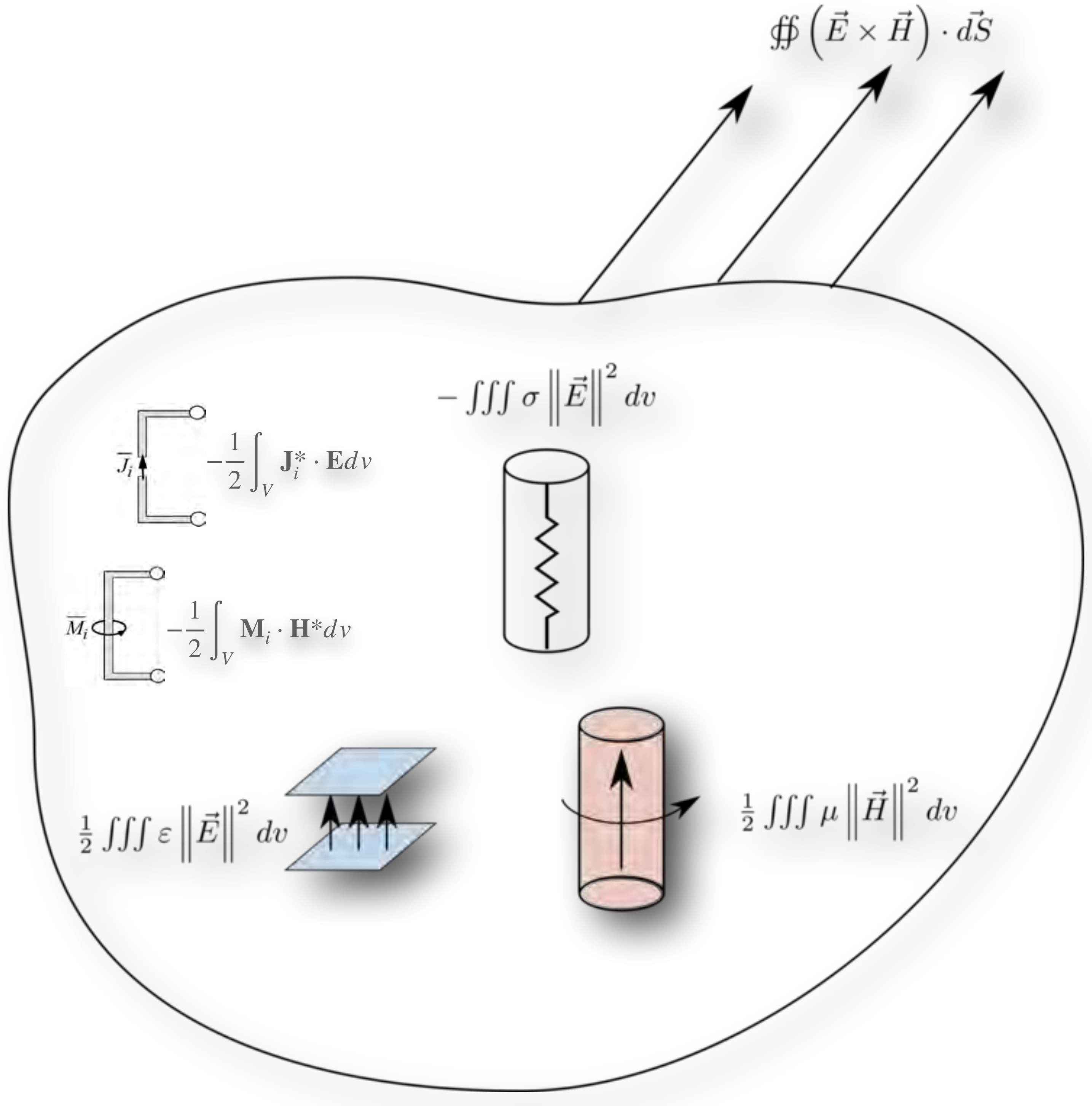

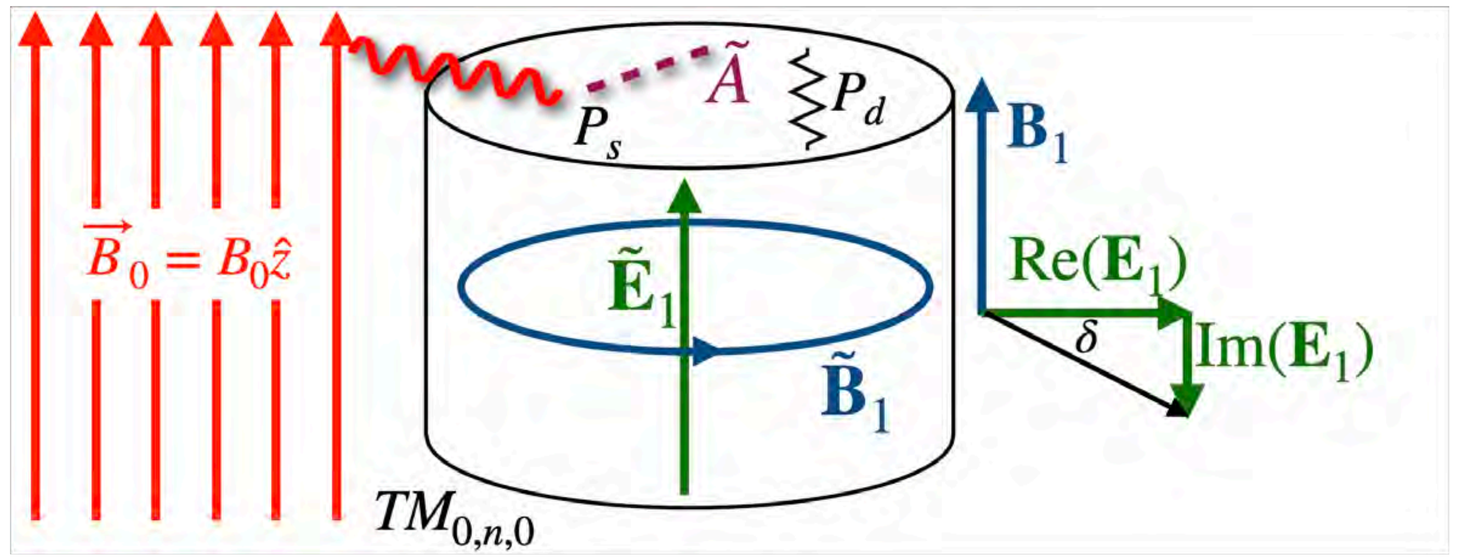


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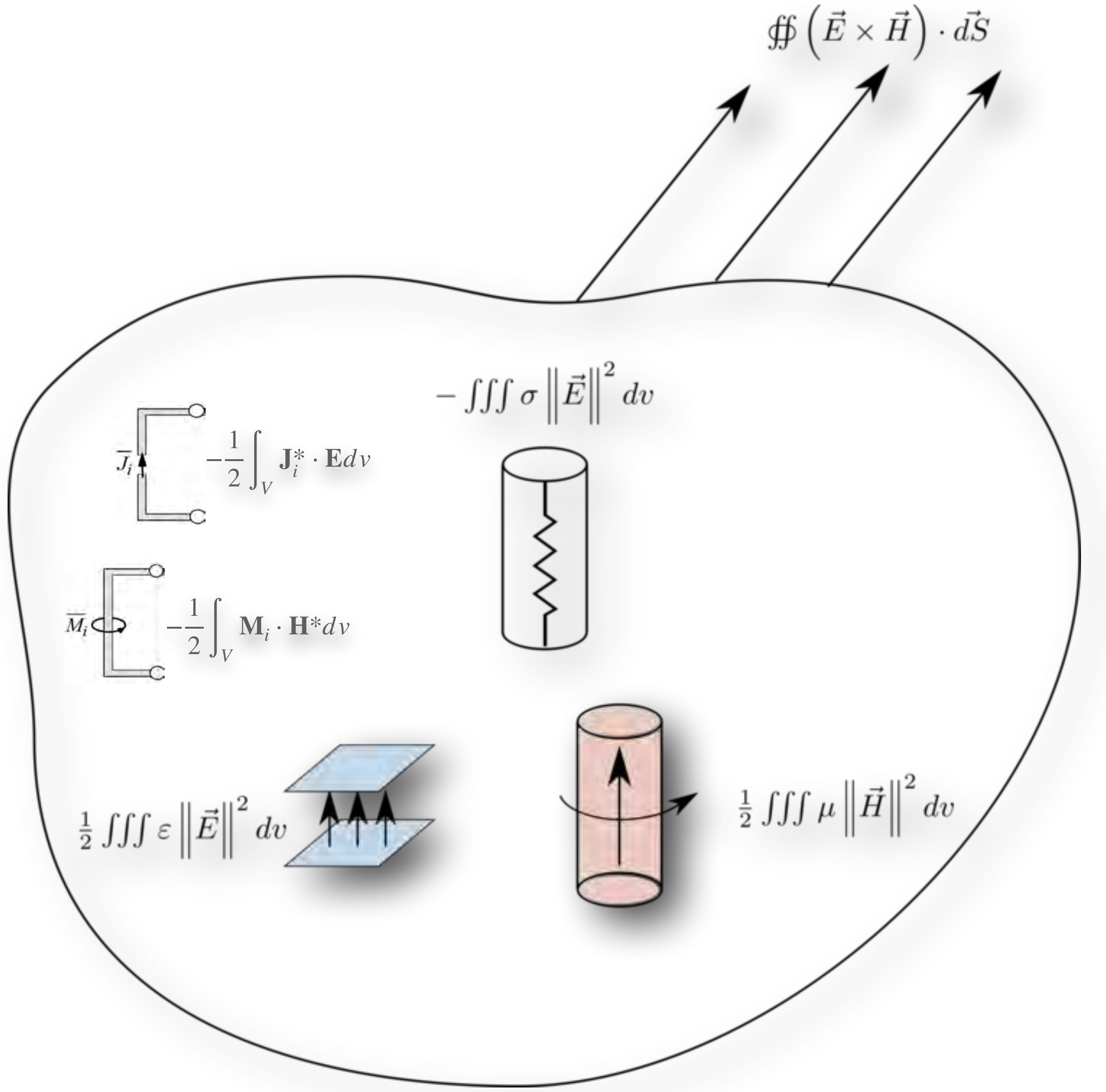
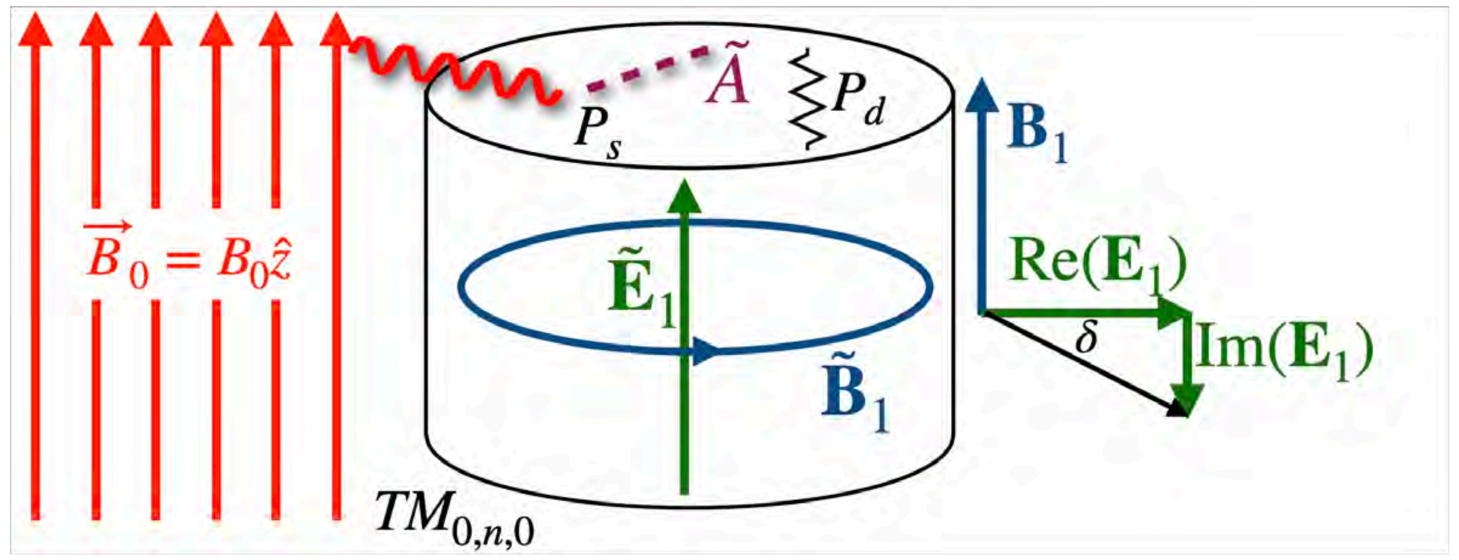


$$\oint j\,\mathrm{Im}\left(\mathbf{S}\right)\cdot\hat{n}ds = \int\Big(\frac{j\omega_1}{2}\big(\frac{1}{\mu_0}\mathbf{B}_1^*\cdot\mathbf{B}_1-\epsilon_0\mathbf{E}_1\cdot\mathbf{E}_1^*\big) + \frac{j\omega_a}{4}\epsilon_0 g_{a\gamma\gamma}c\vec{B}_0\cdot(\tilde{a}^*\mathbf{E}_1+\tilde{a}\mathbf{E}_1^*)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

Resonant Haloscope, on resonance,
Reactive Power = 0



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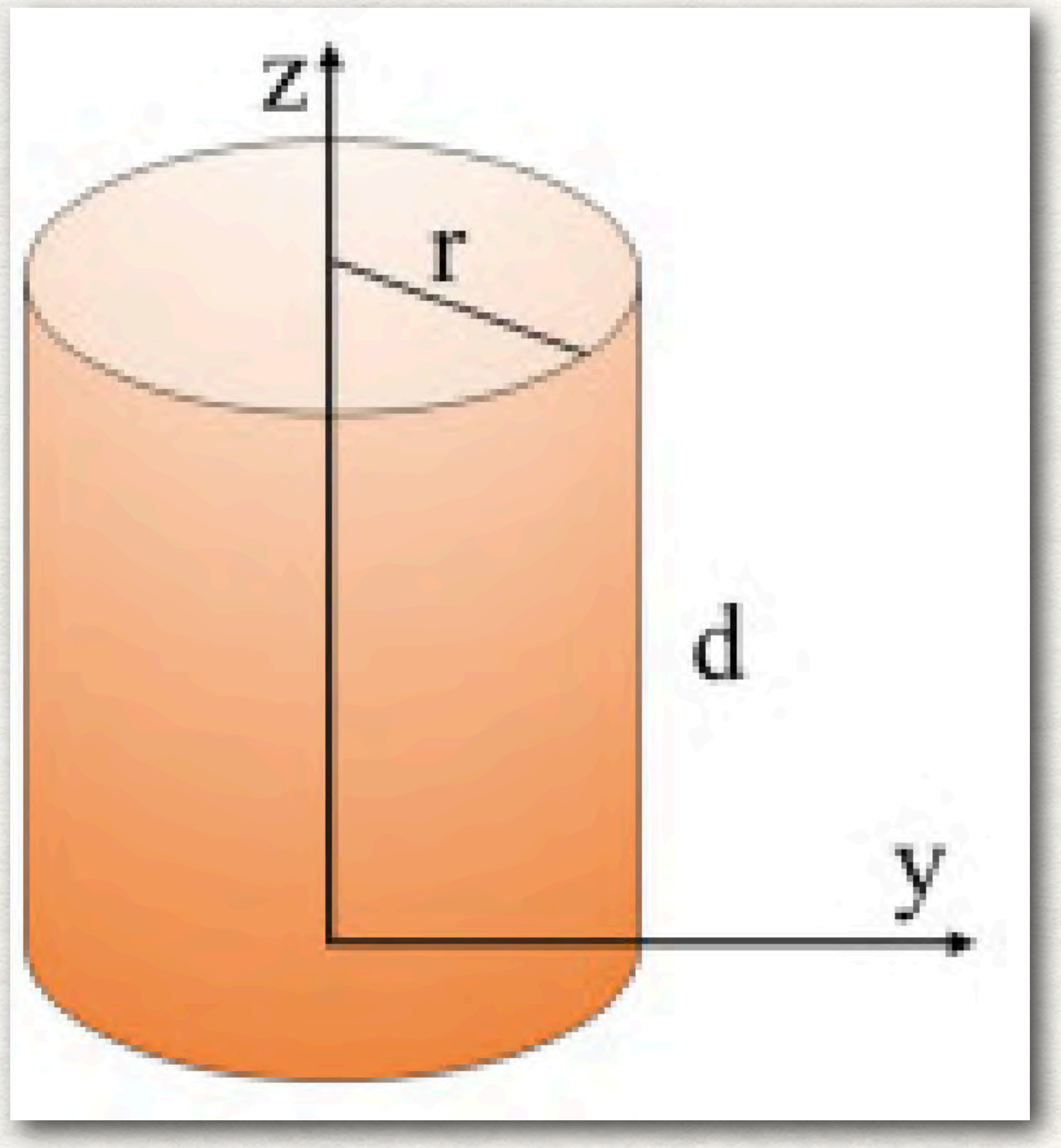
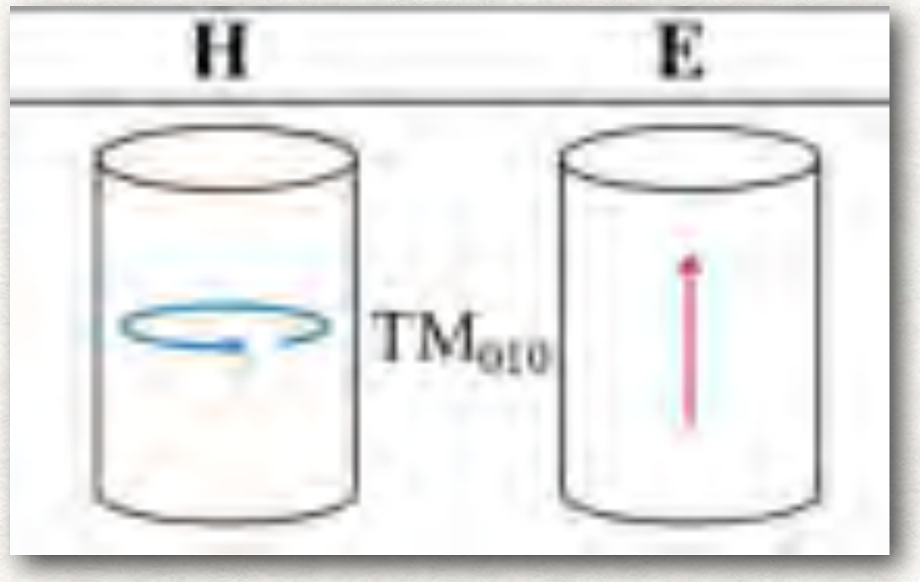
IMAGINARY POYNTING VECTOR INSIDE CAVITY

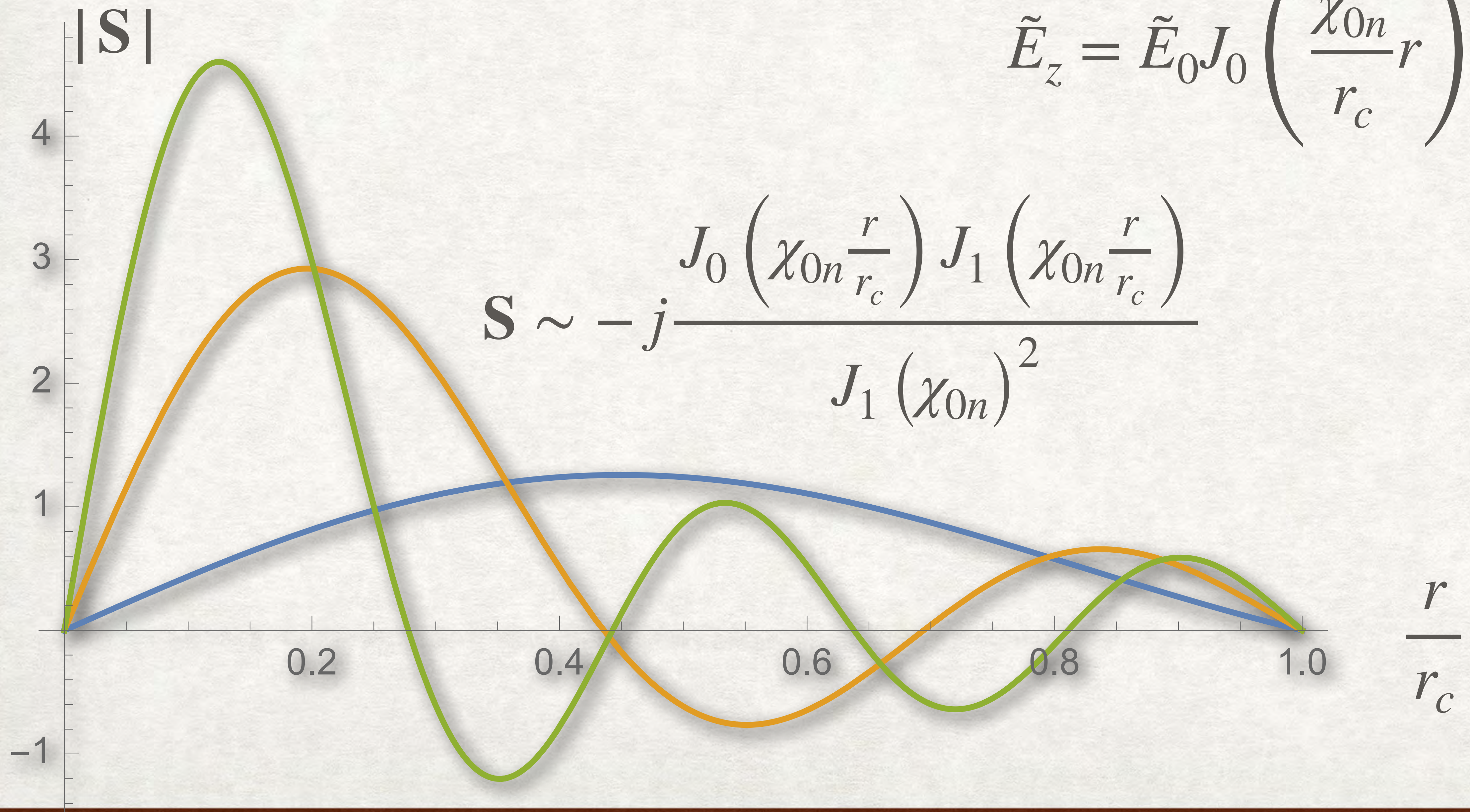




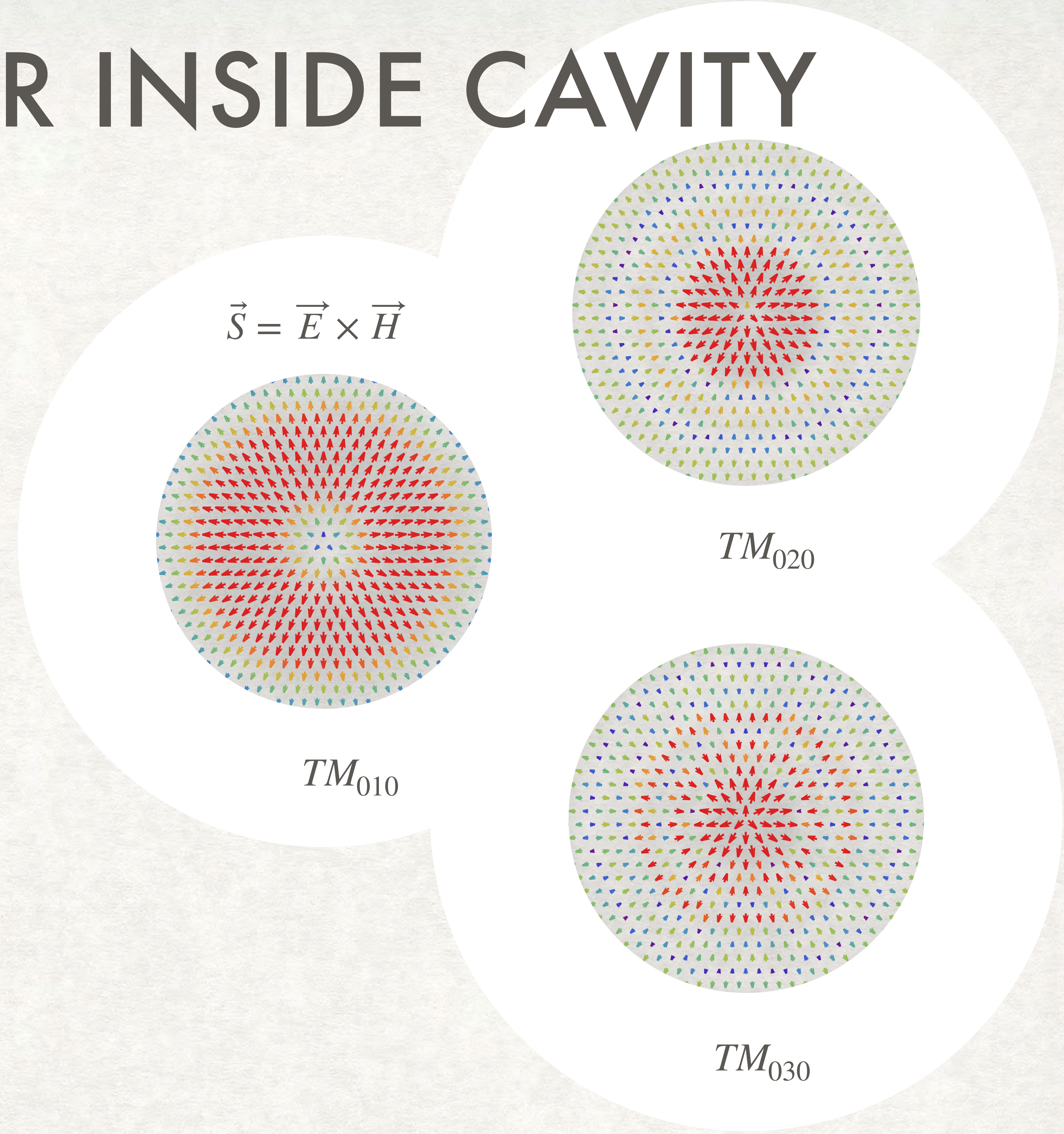
TM_{0n0}

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

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



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

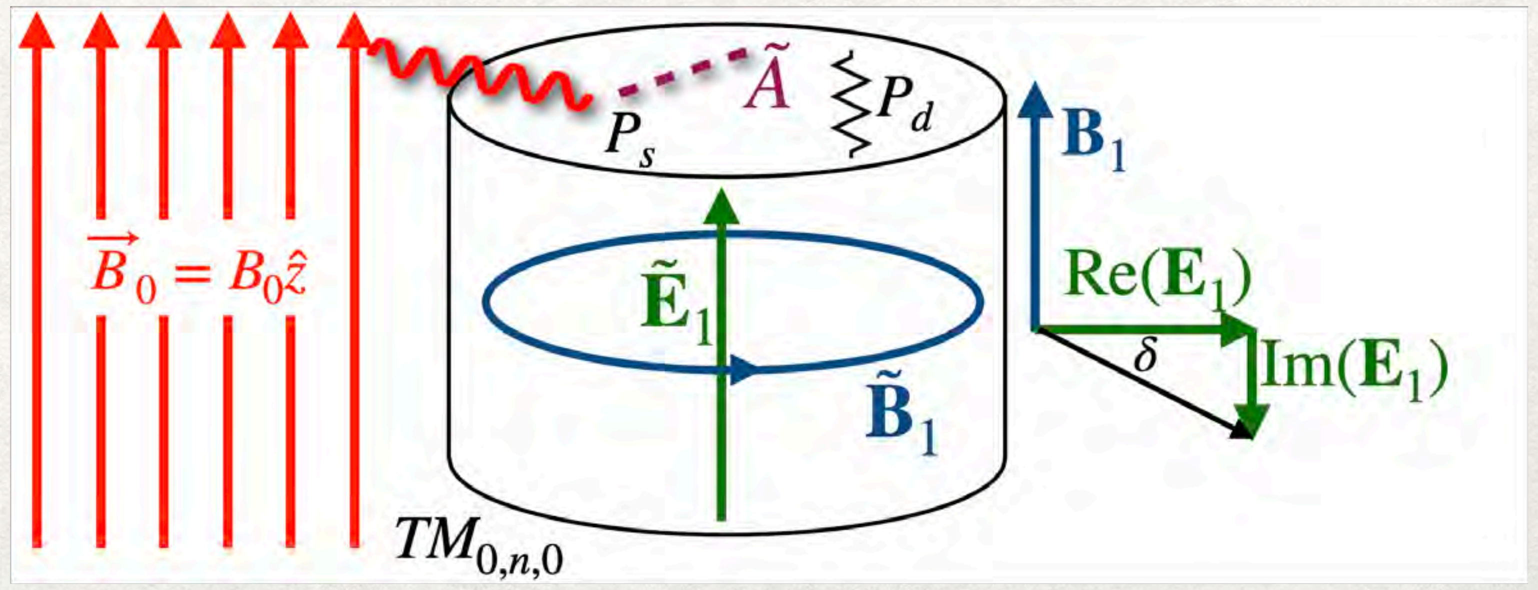


$\vec{S} = \vec{E} \times \vec{H}$

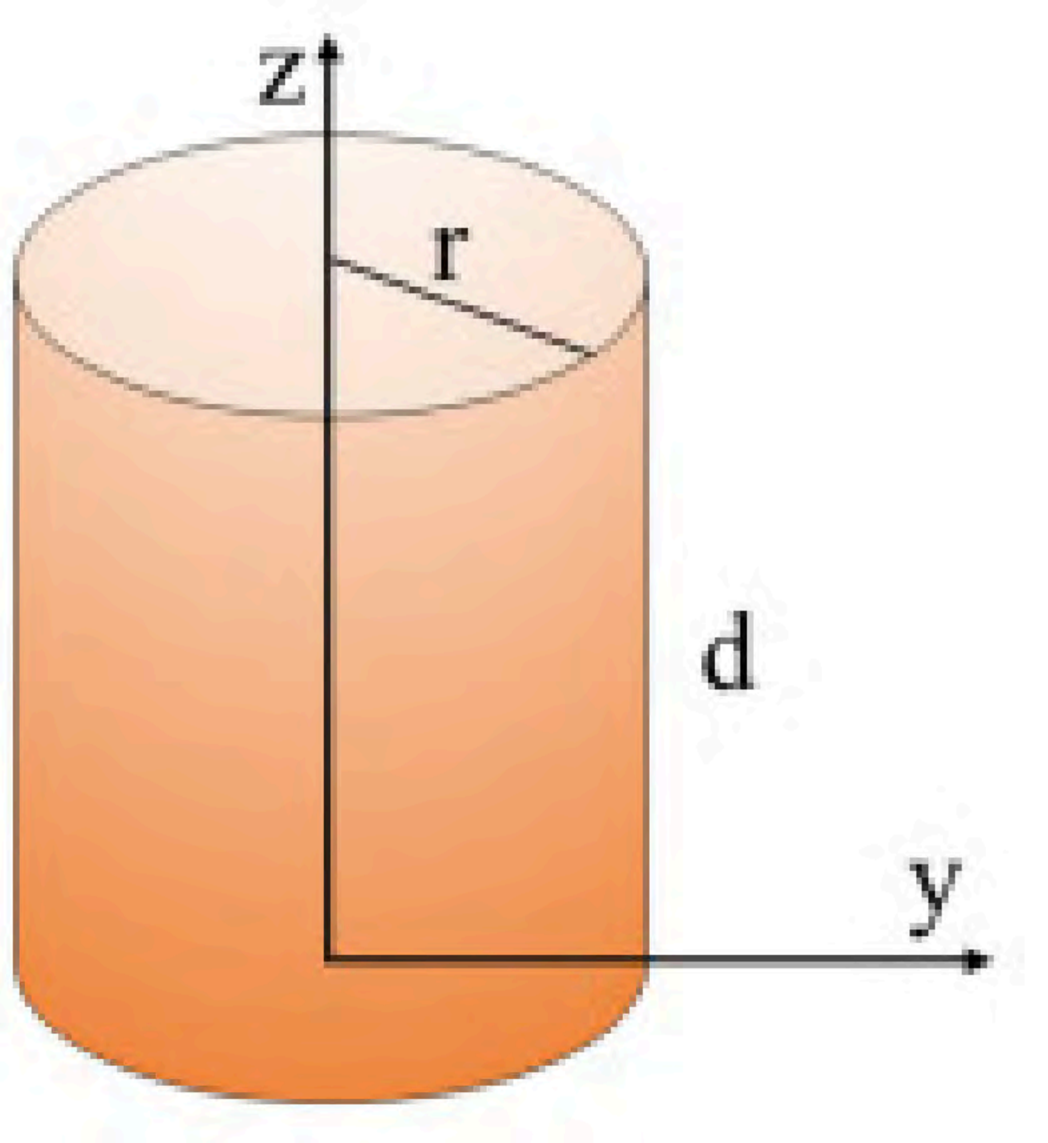
TM_{010}

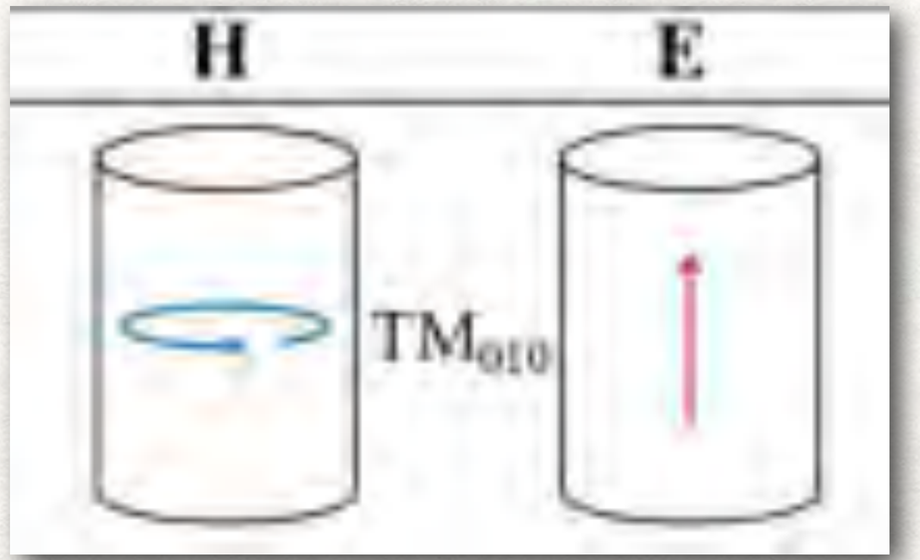
TM_{020}

TM_{030}



IMAGINARY POYNTING VECTOR INSIDE CAVITY





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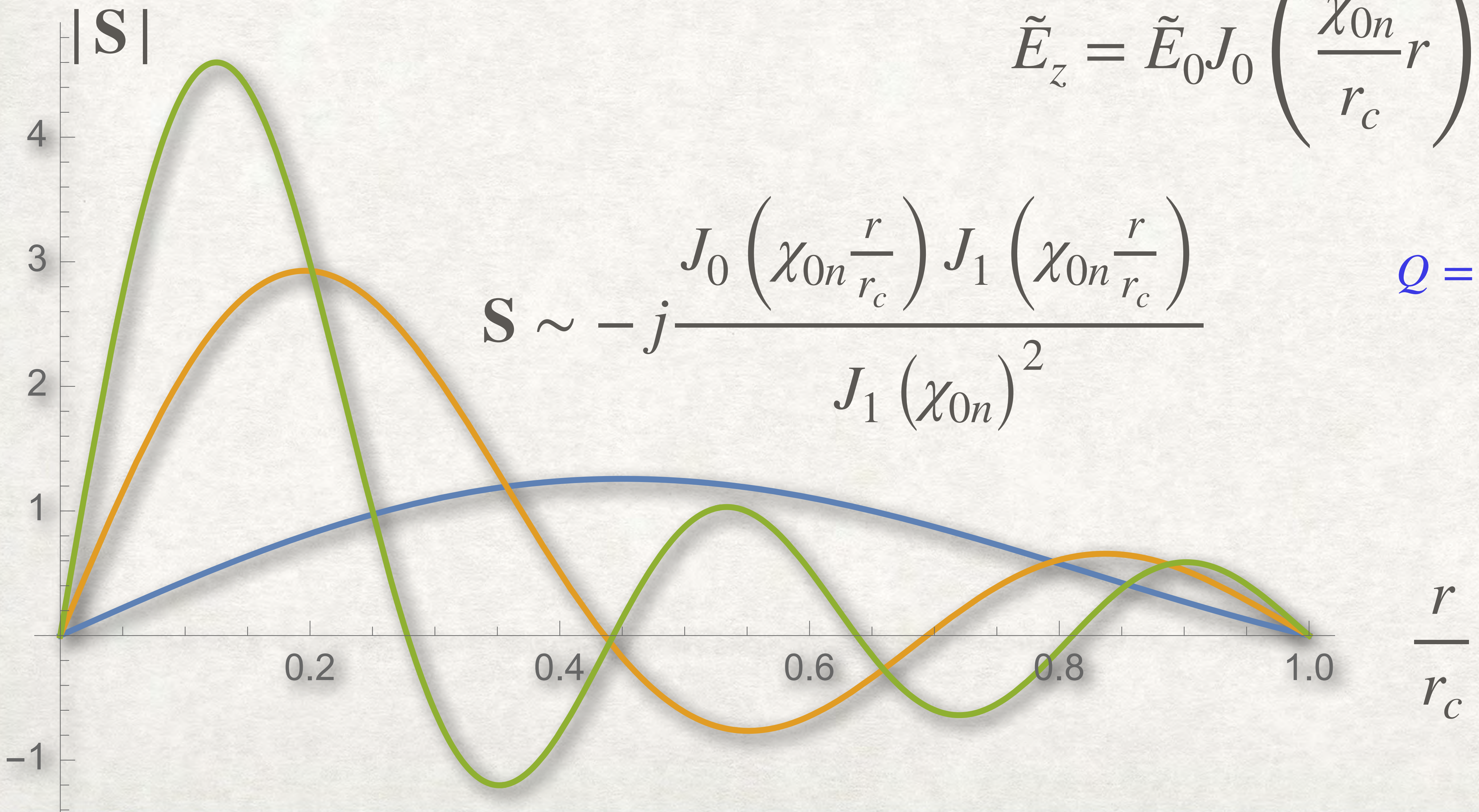

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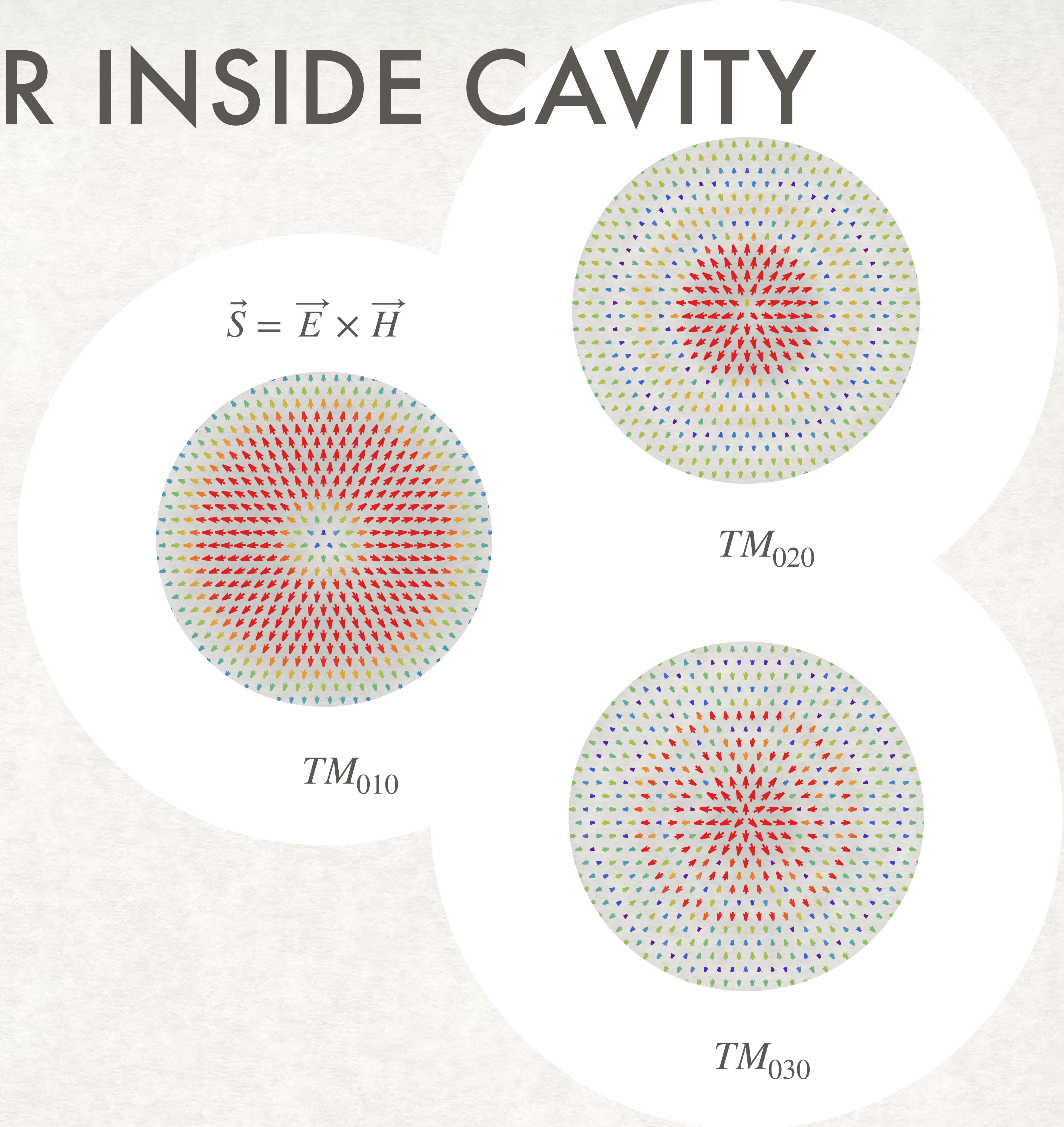
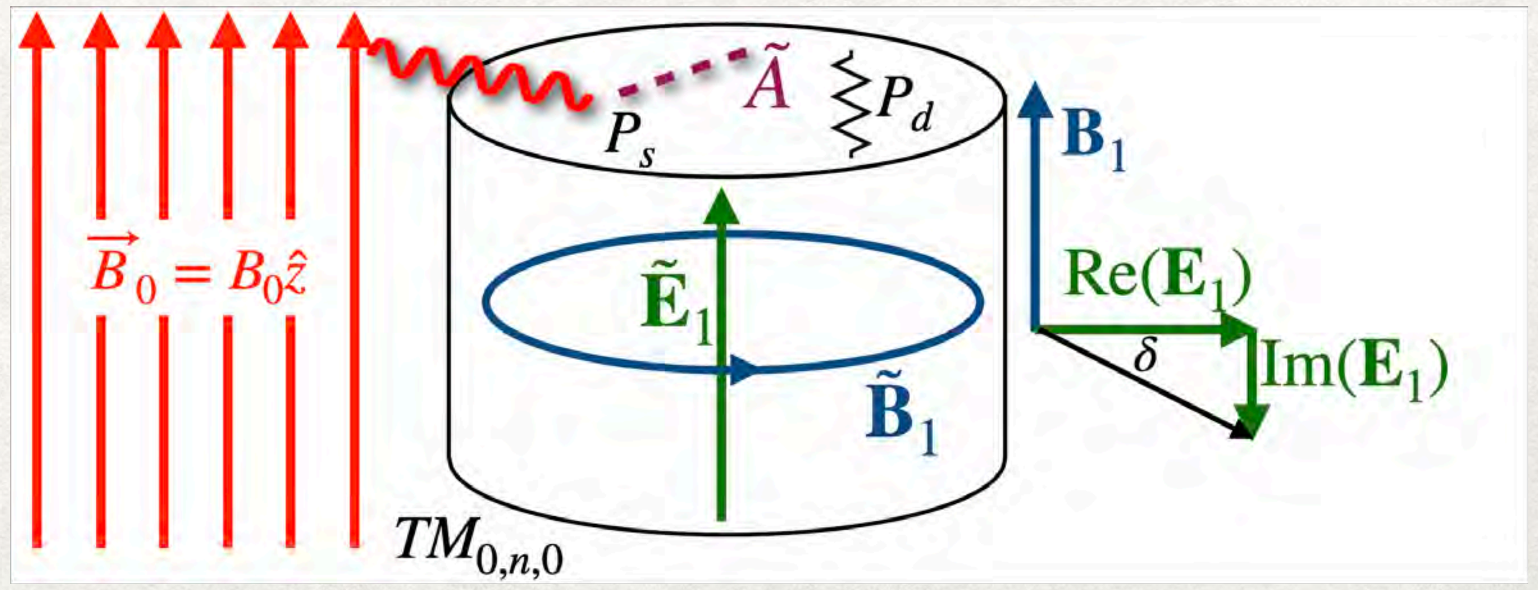
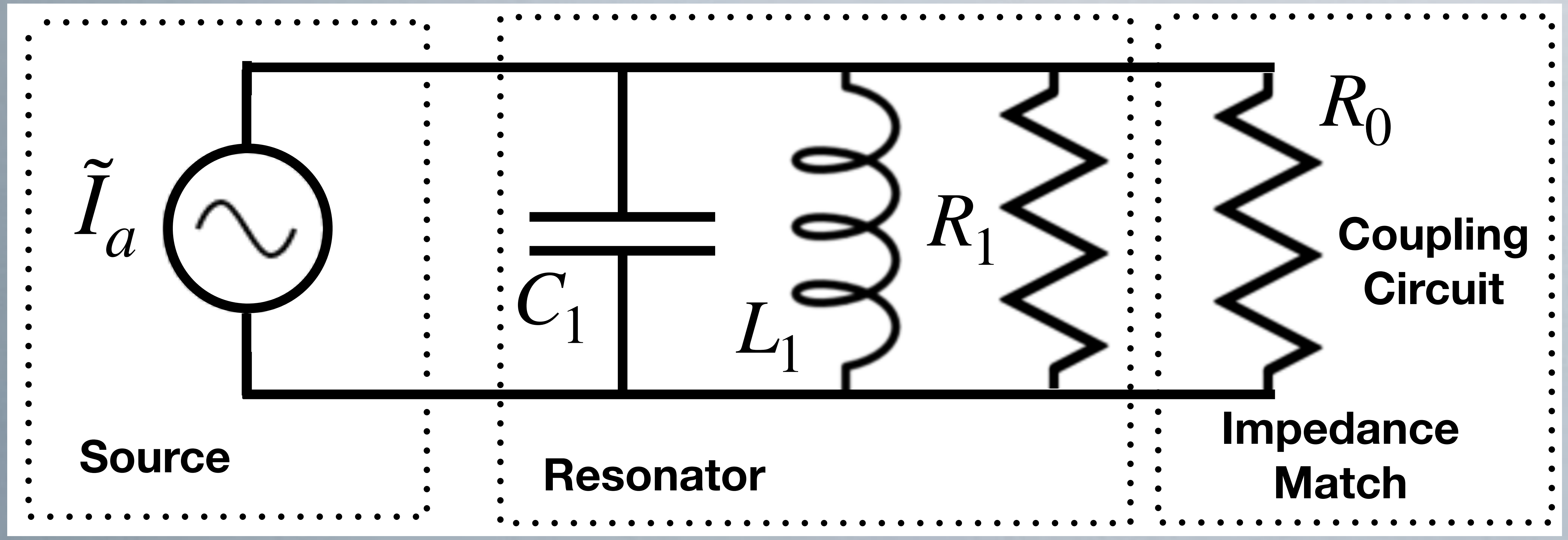
$$Q = \omega_1\frac{U_{tot}}{P_d} = 2\pi\frac{\text{stored energy}}{\text{energy dissipated during one period}}$$

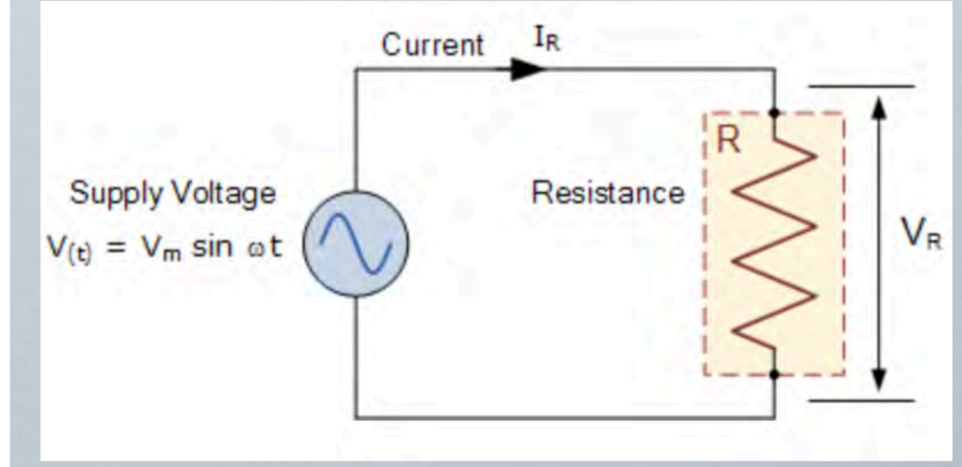
$$P_d = \frac{\omega_1 U_{tot}}{Q}$$

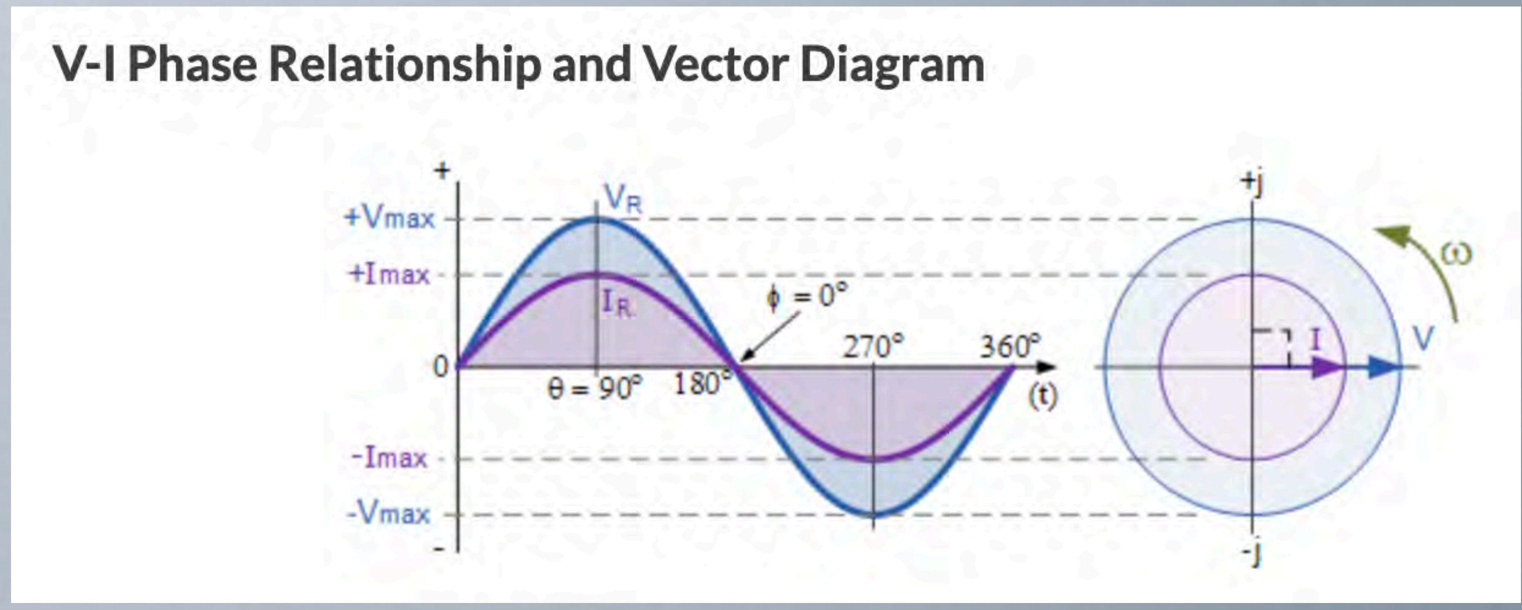




Resonator Measurement: Impedance match; set coupling =1; Take Photons from Source







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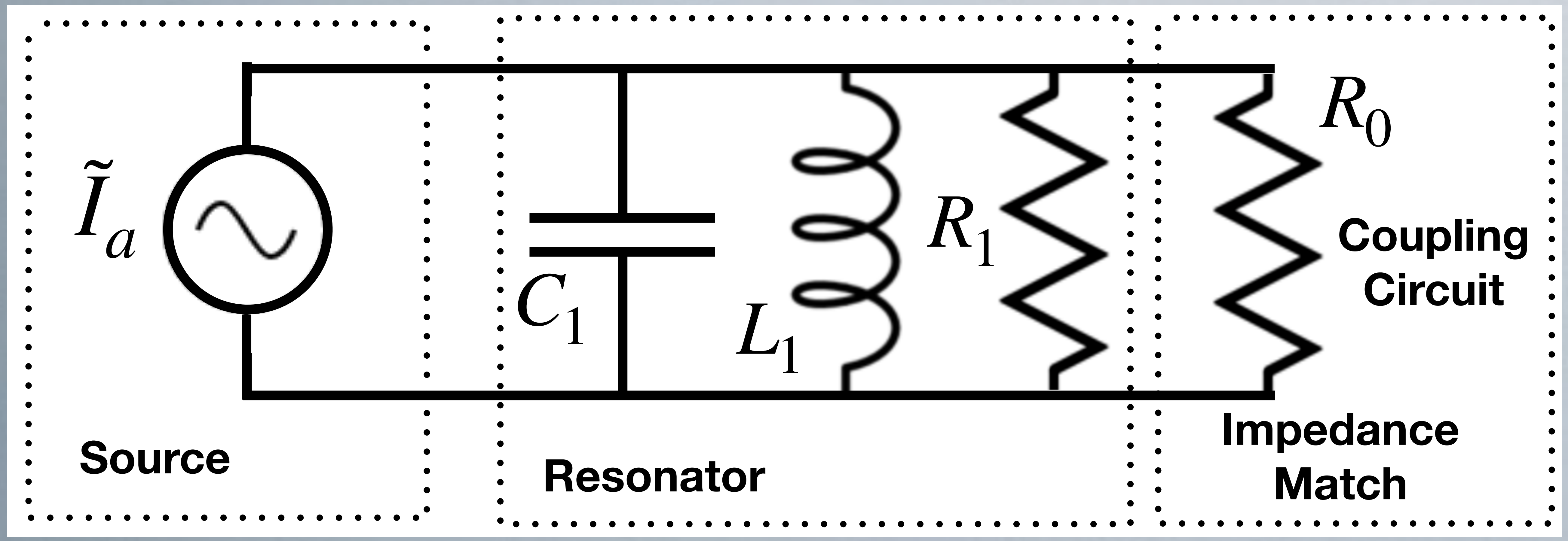

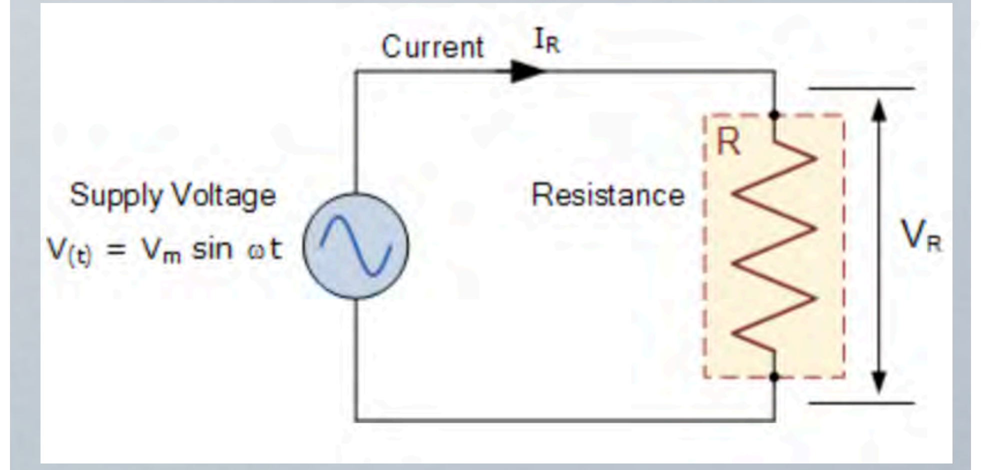

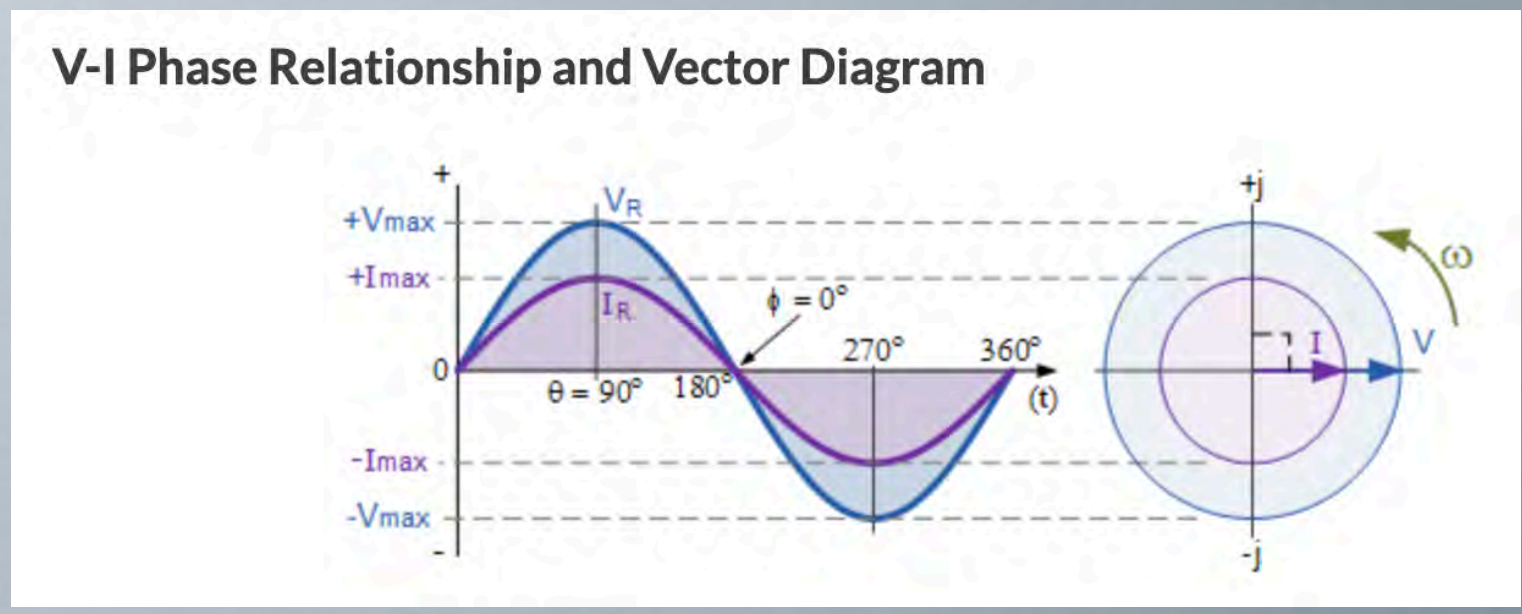

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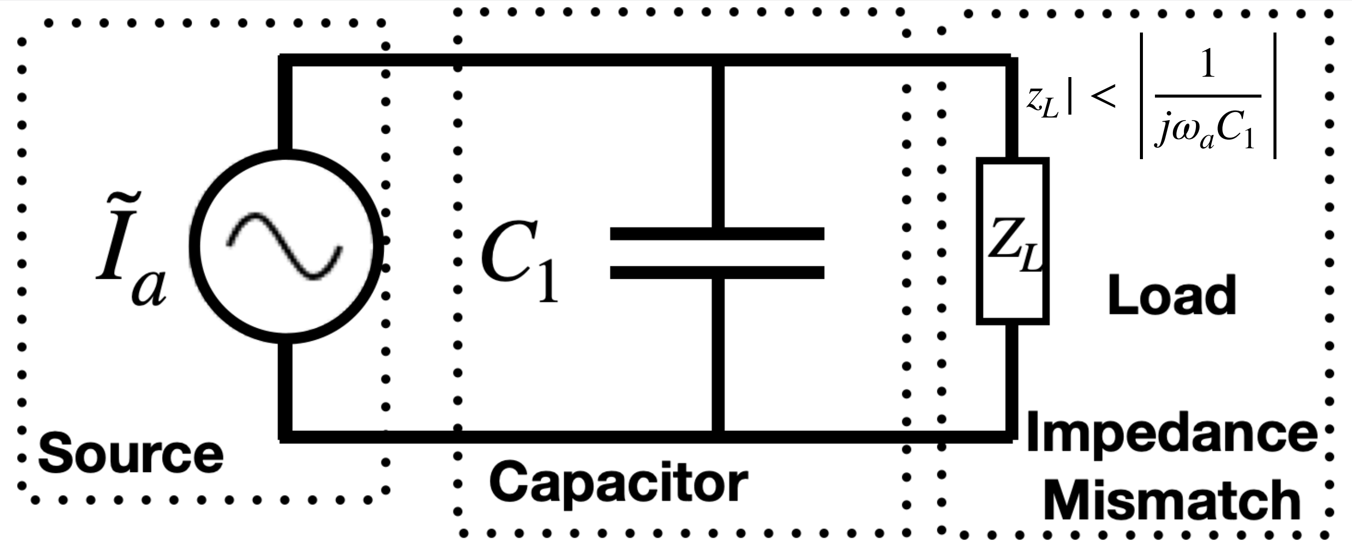

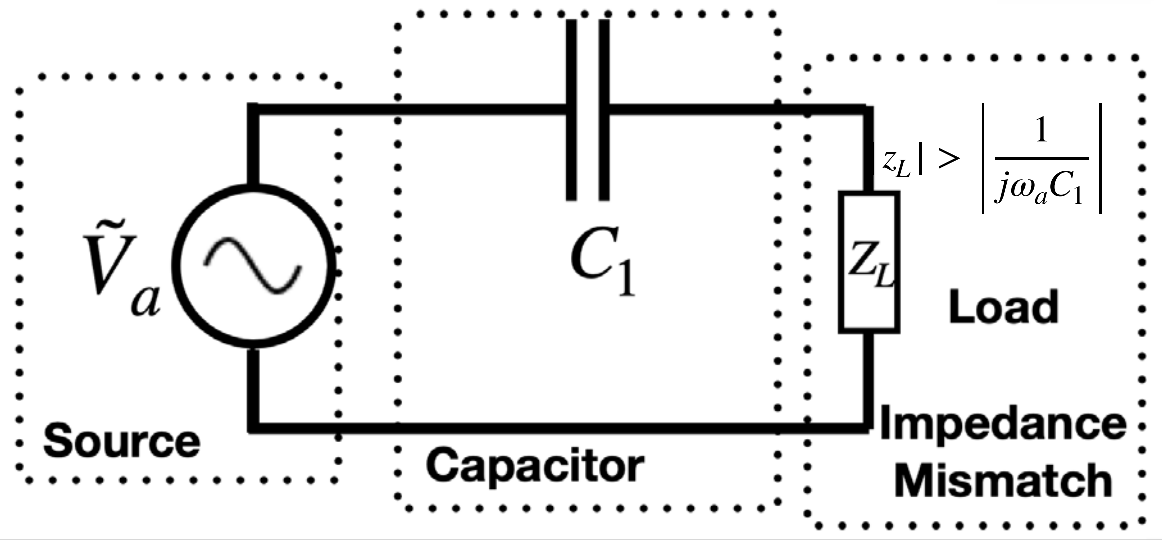

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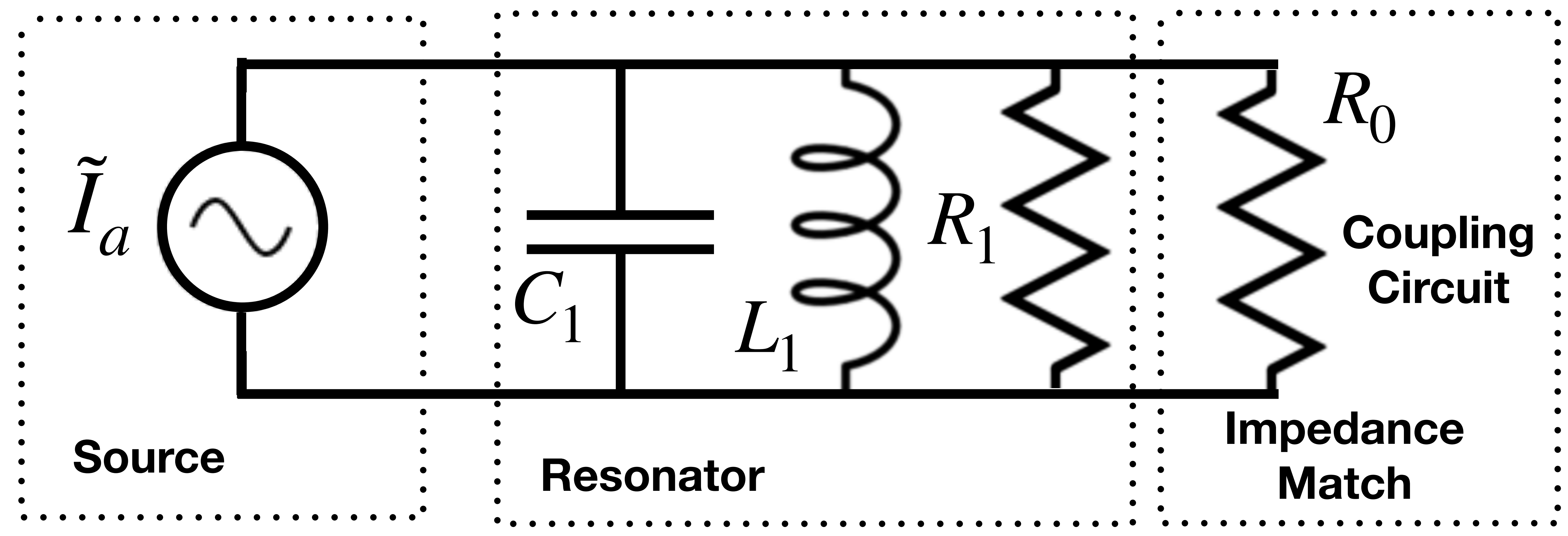
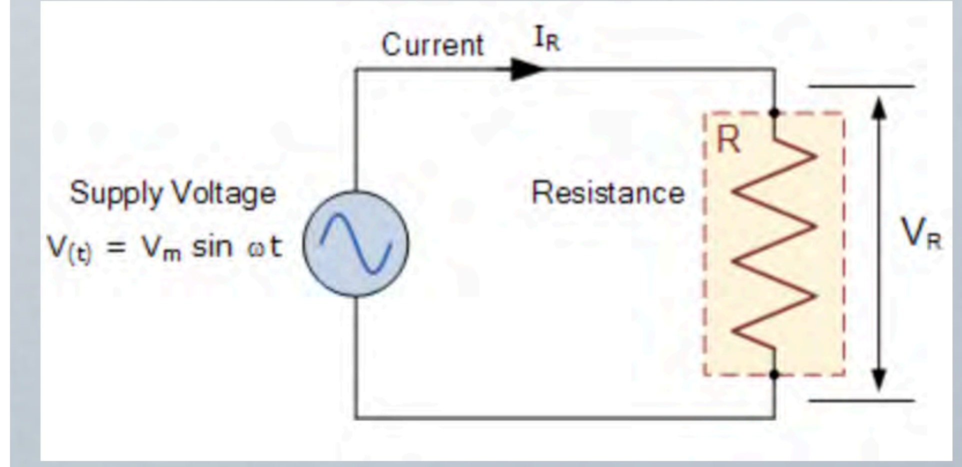
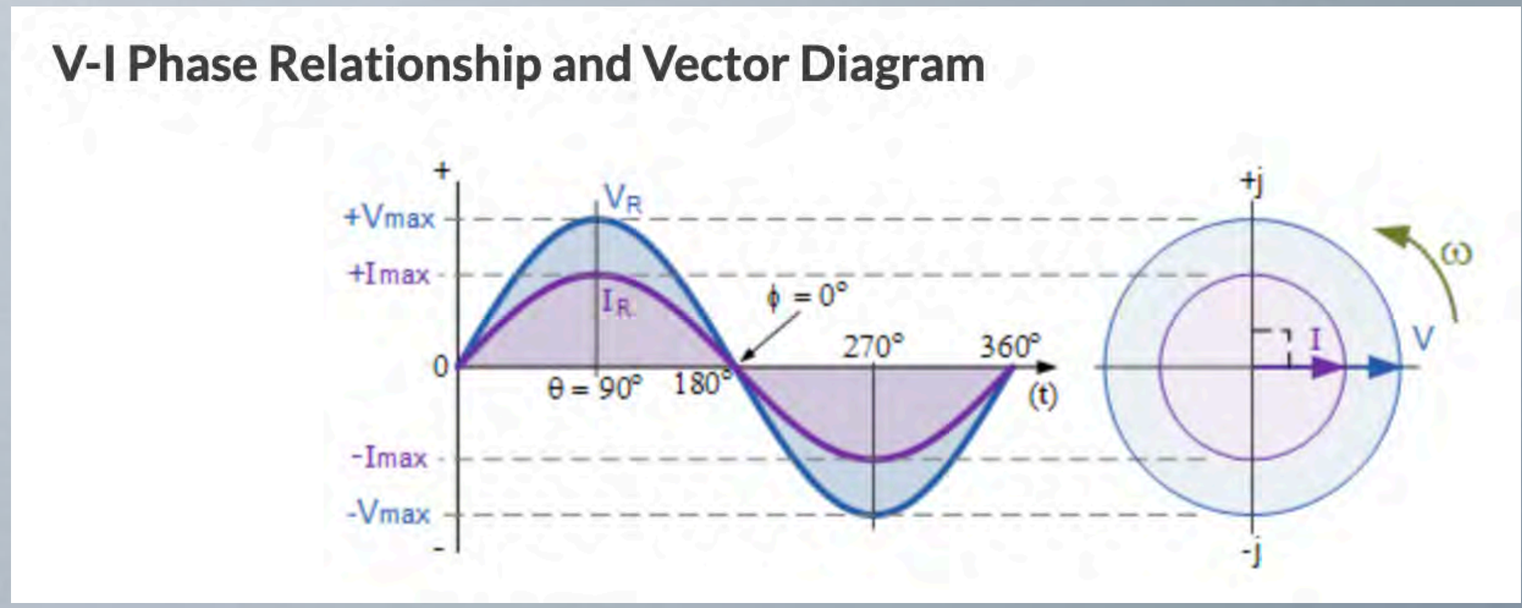
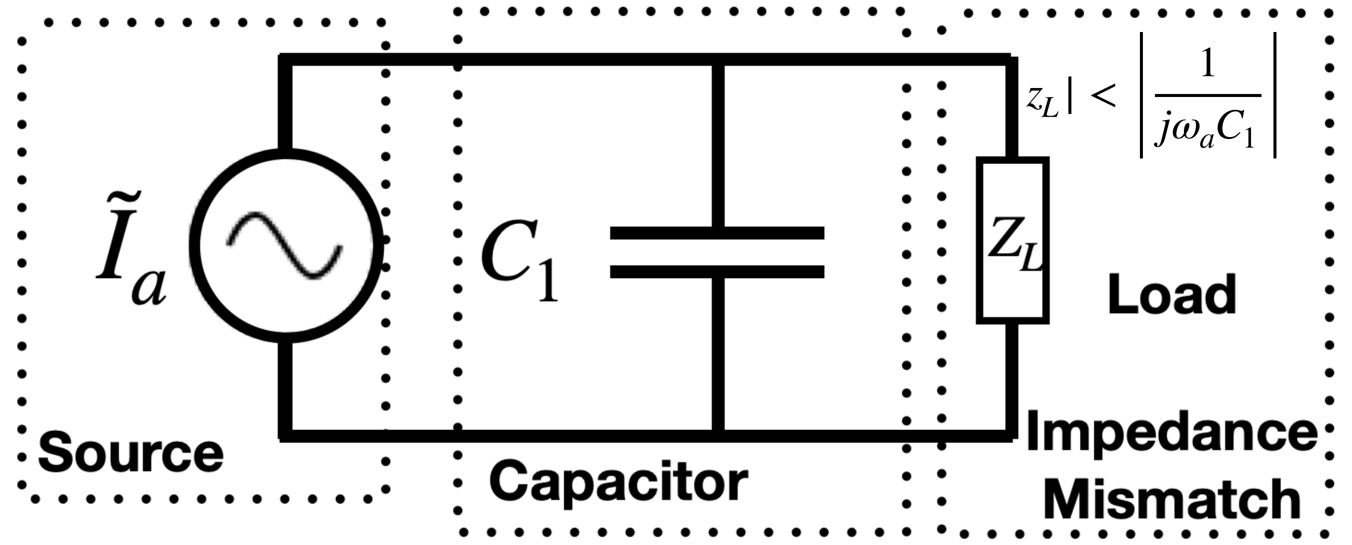
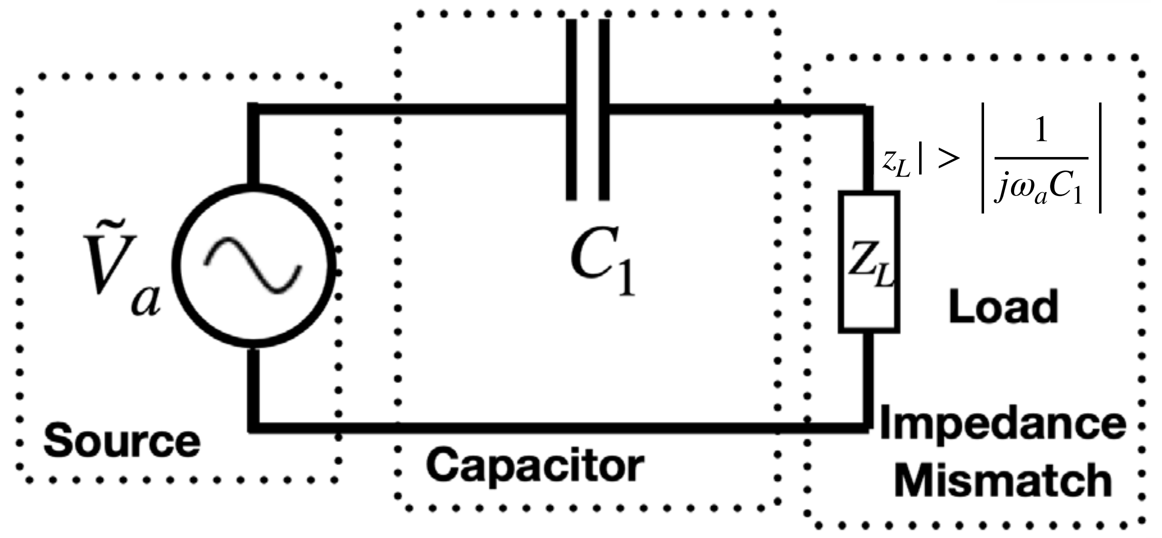


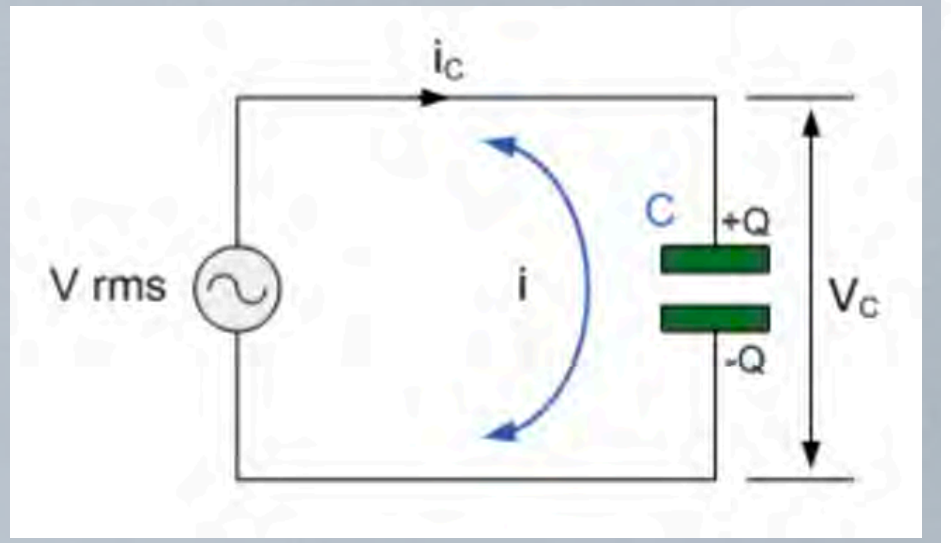


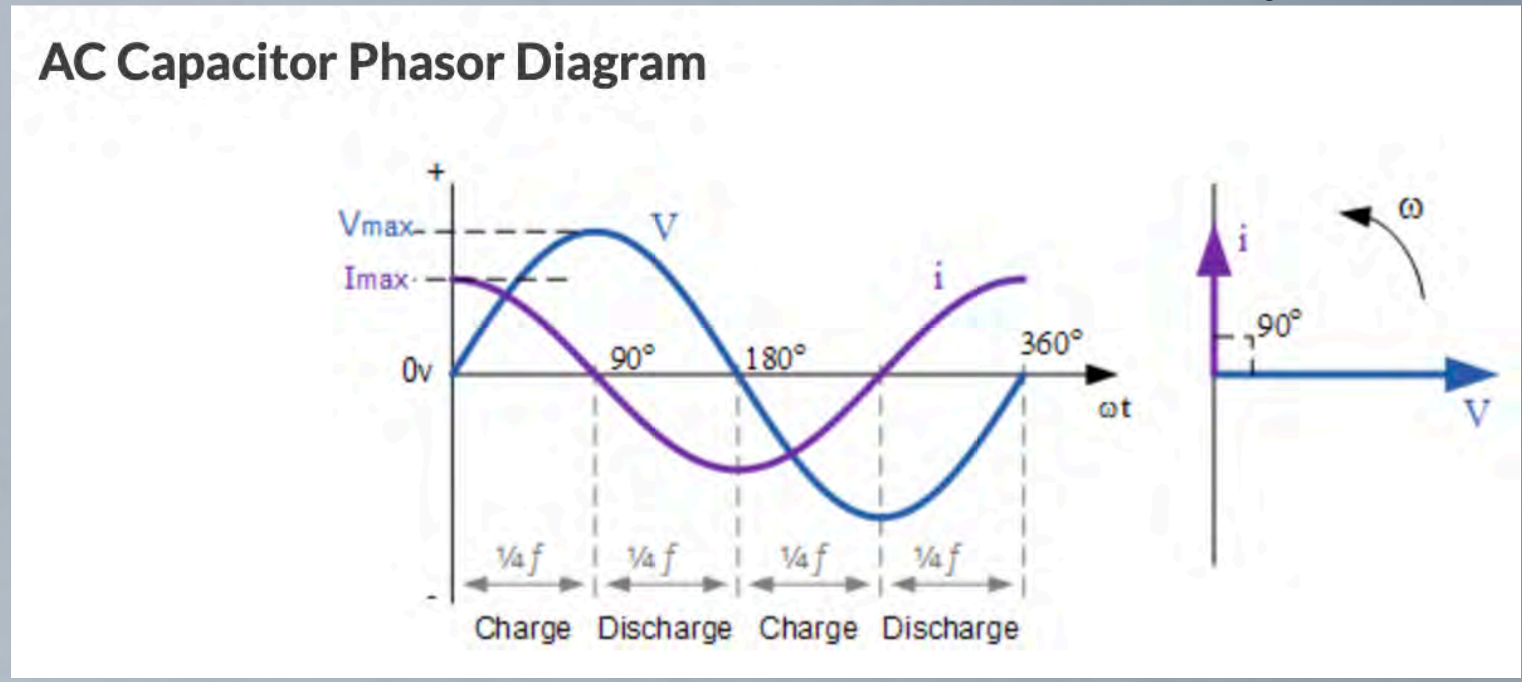

V-I Phase Relationship and Vector Diagram

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

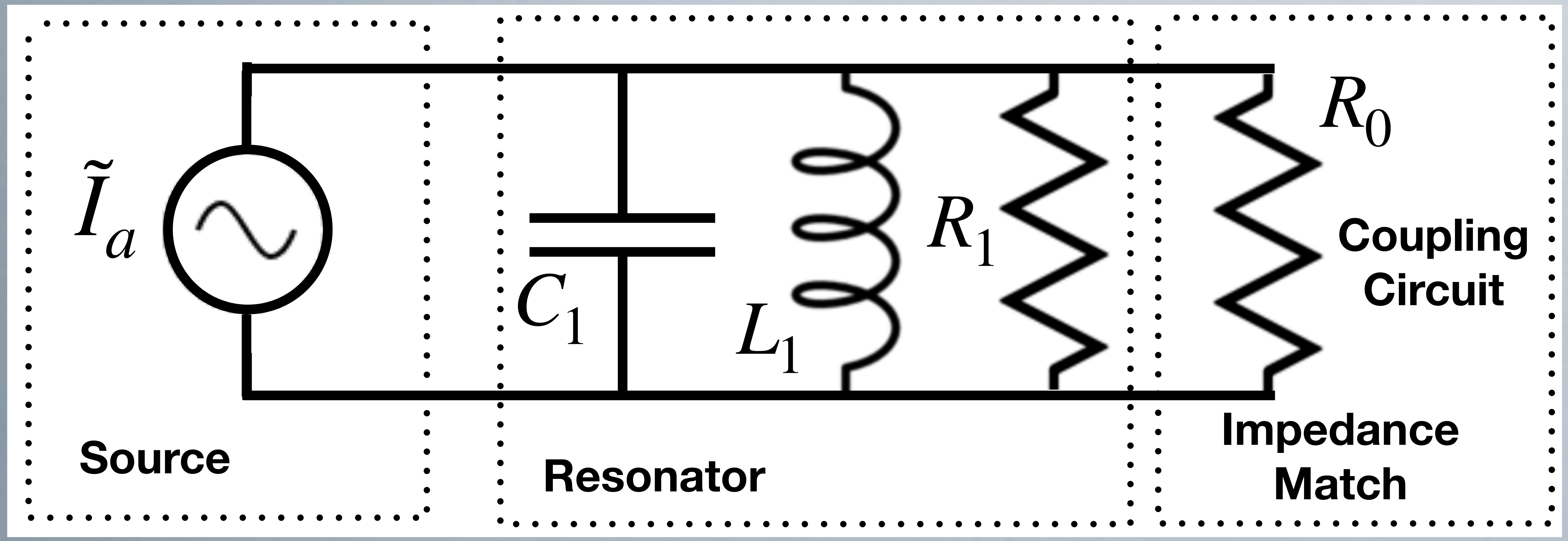


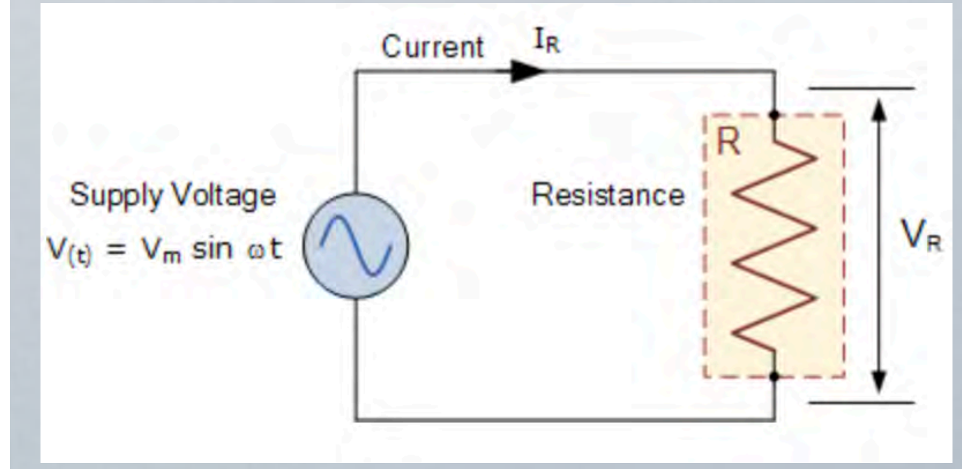


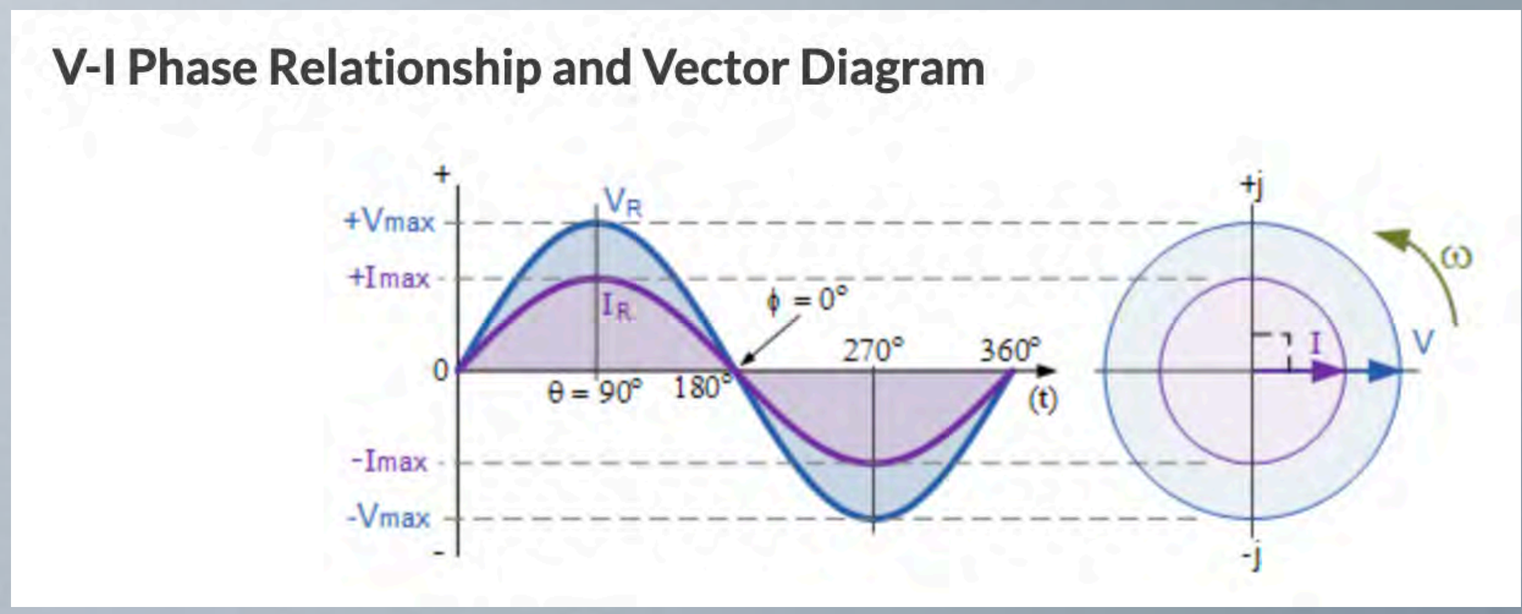



AC Capacitor Phasor Diagram

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







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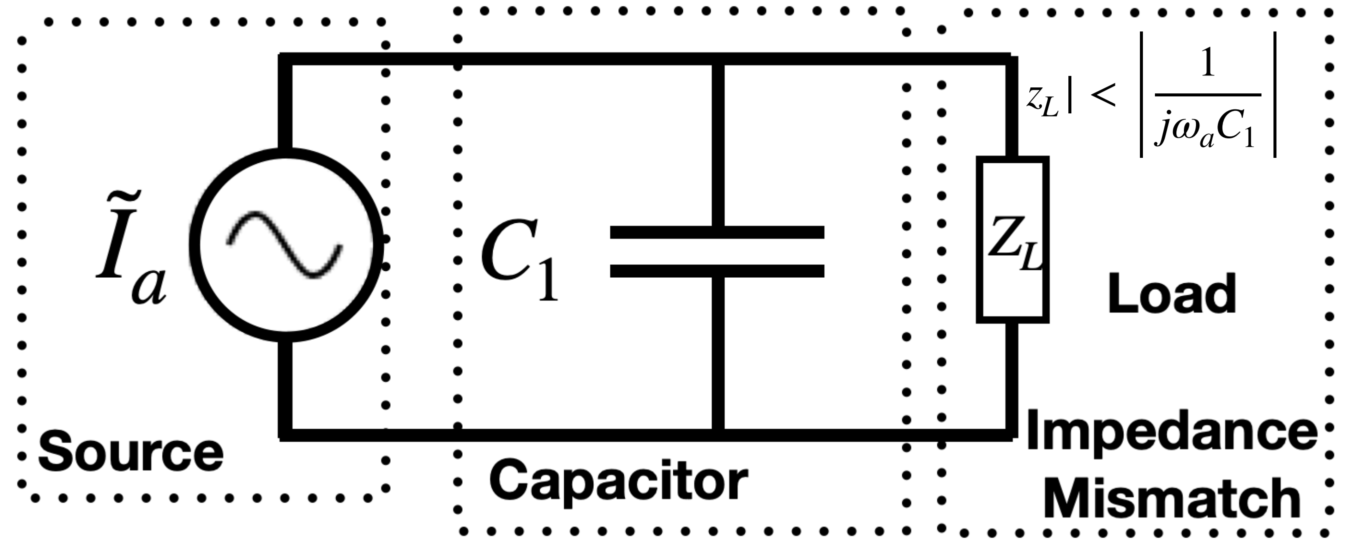

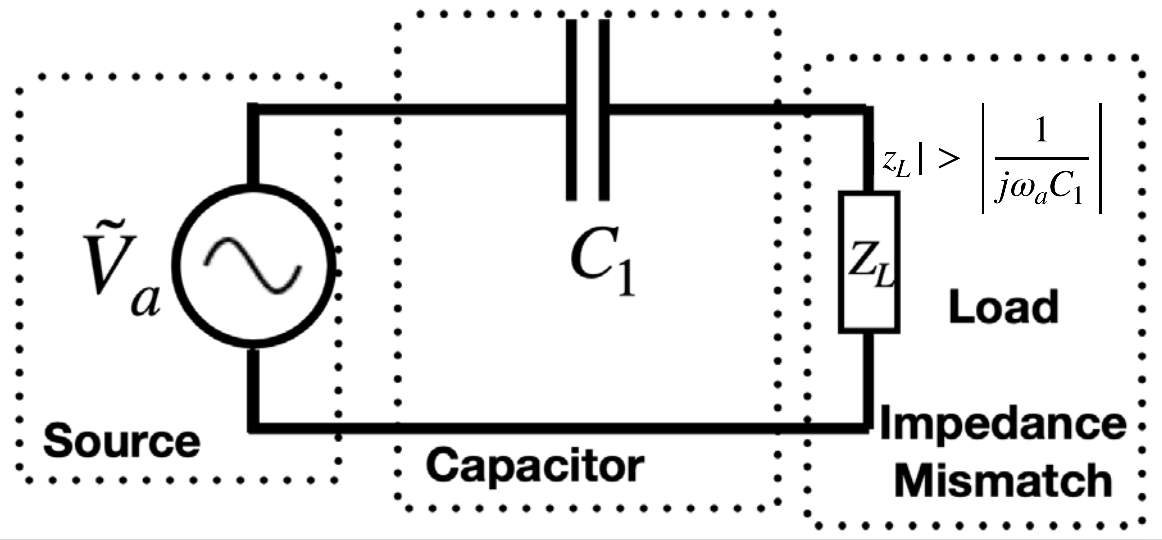

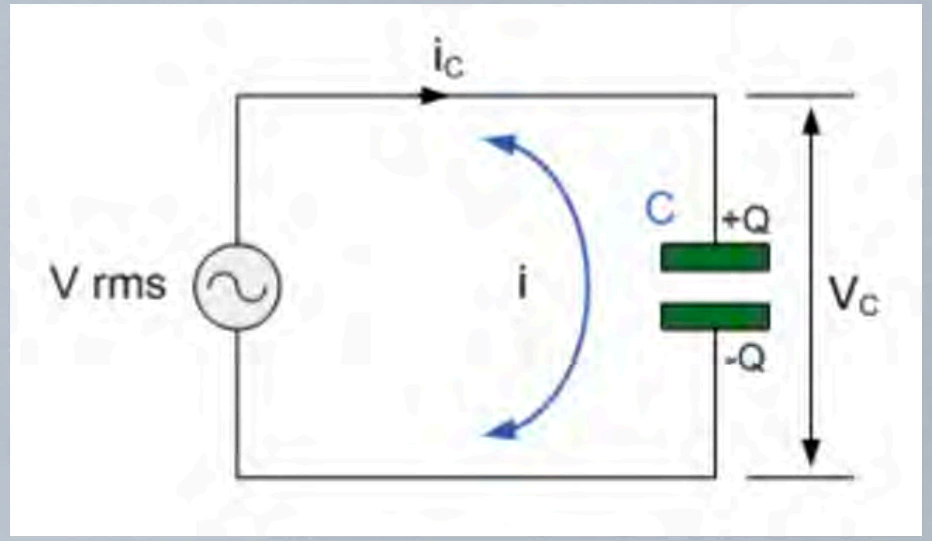

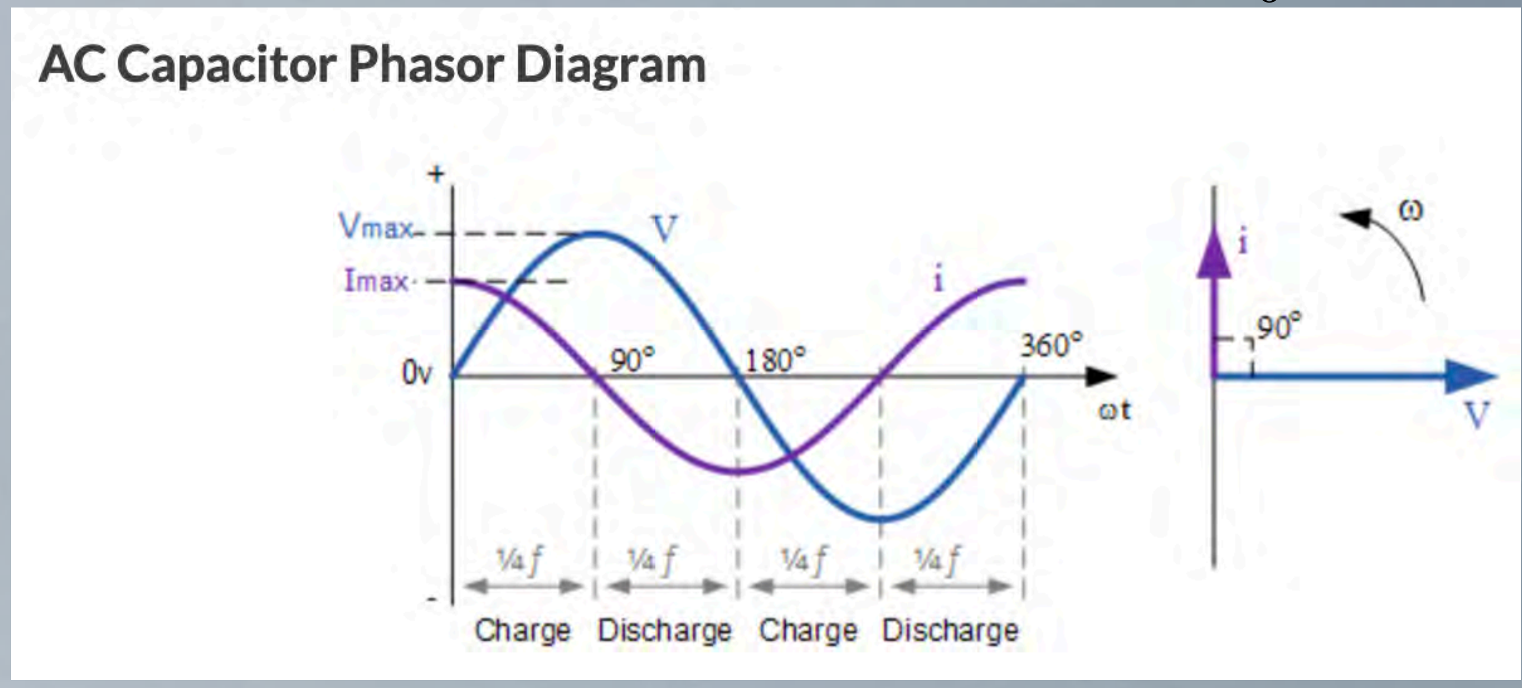

Reactive Power Measurement, Does Not Absorb Energy:

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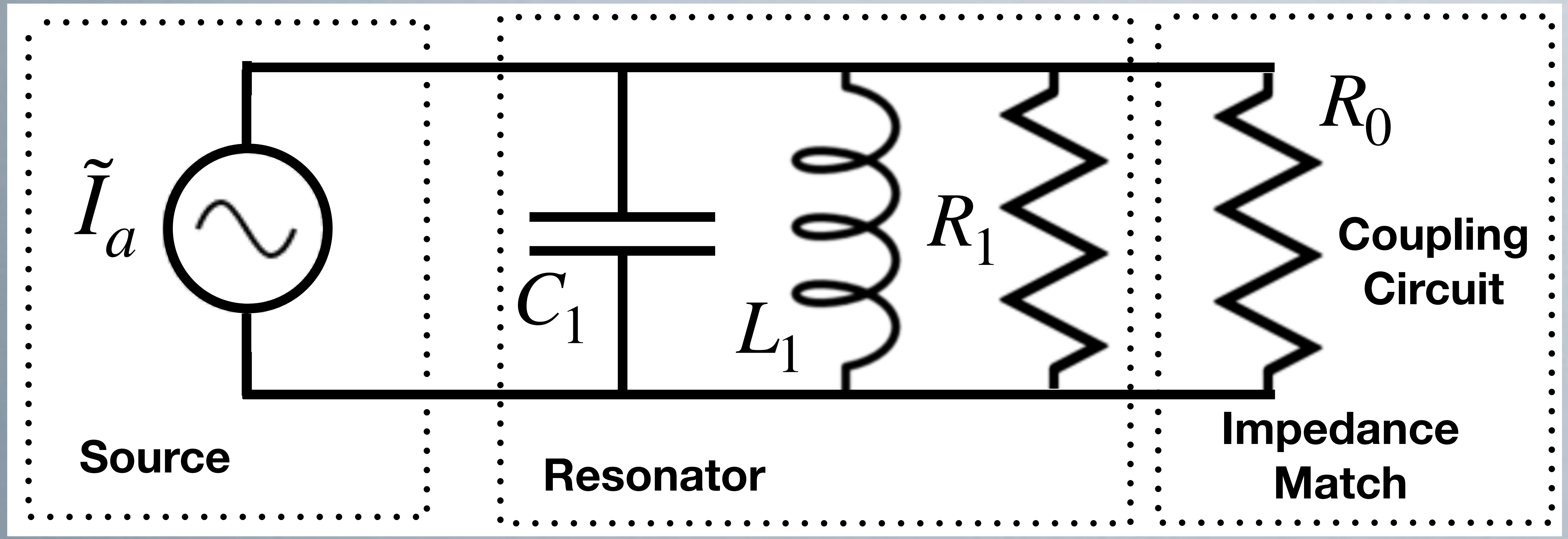

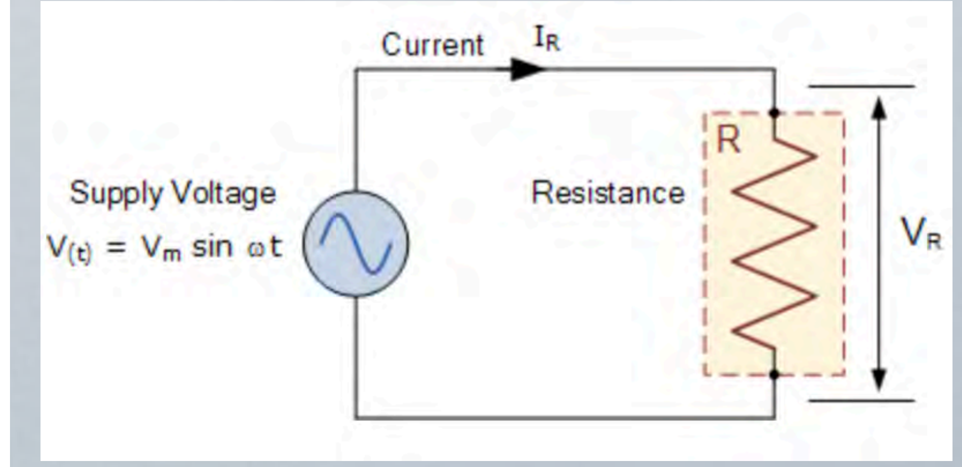

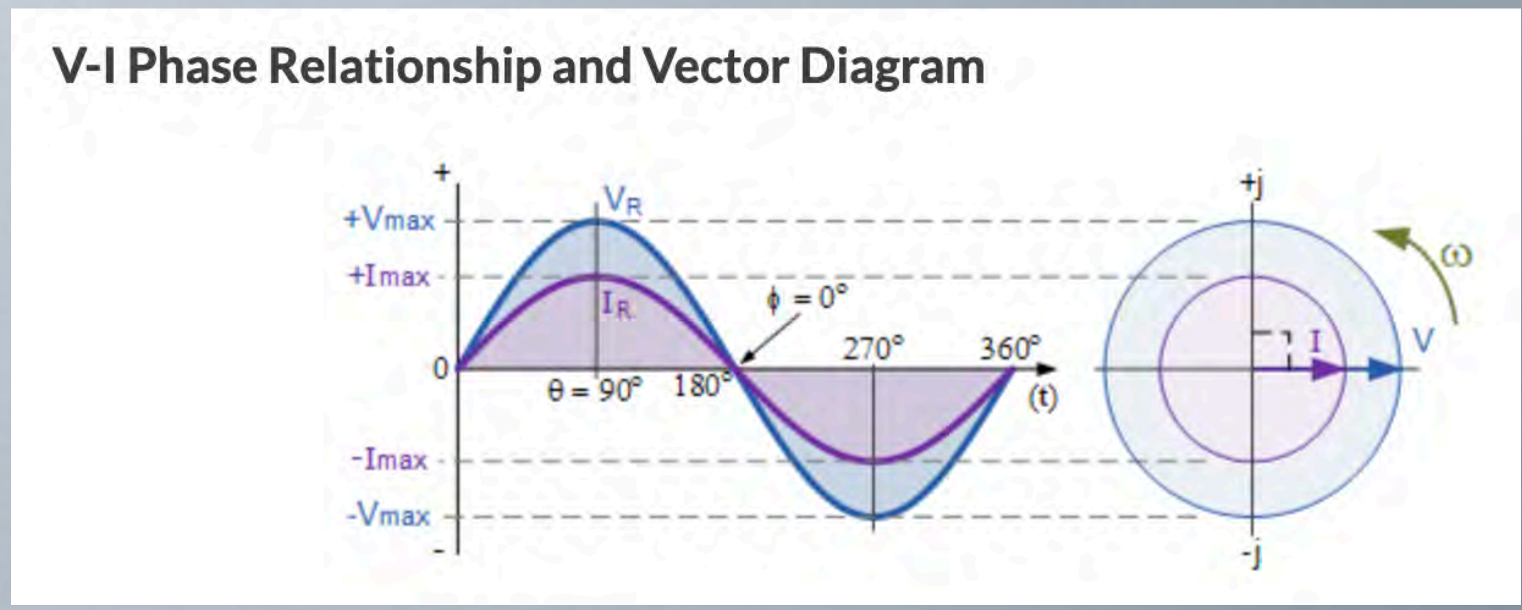

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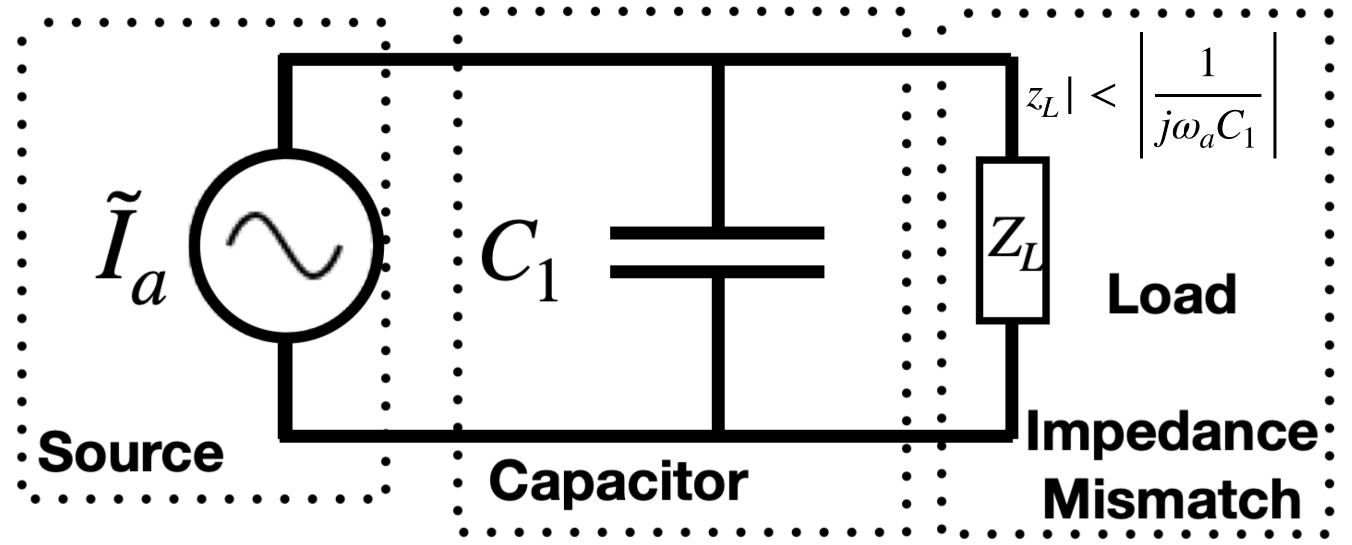

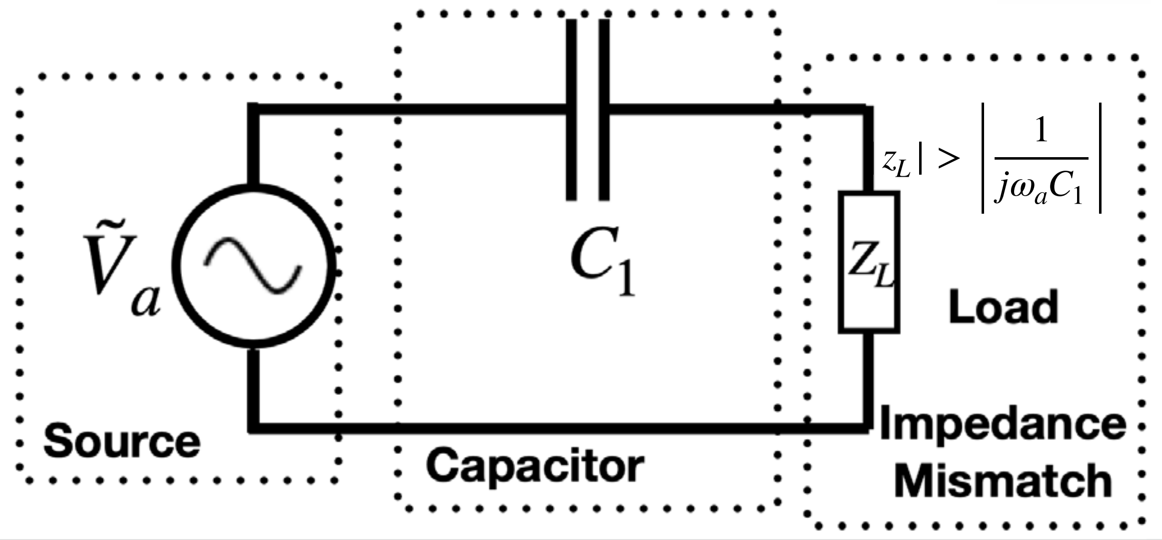

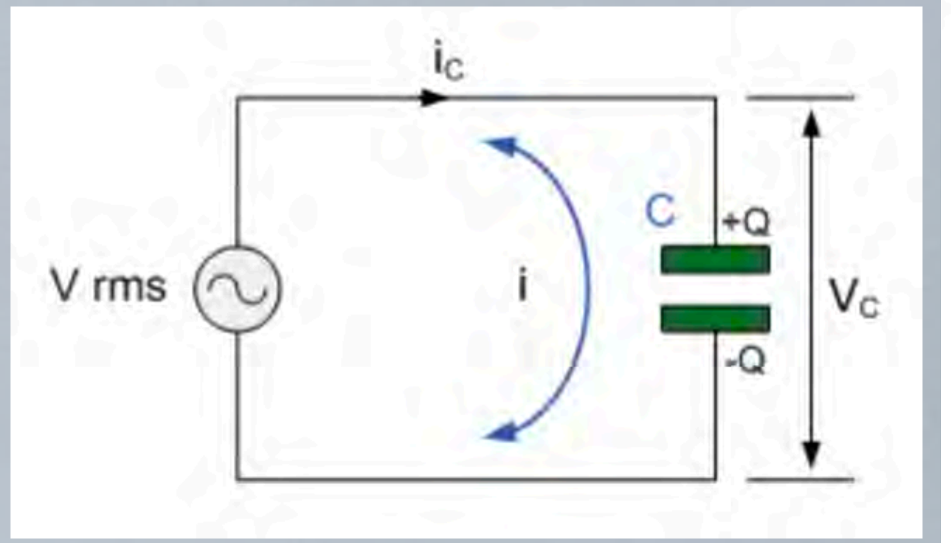

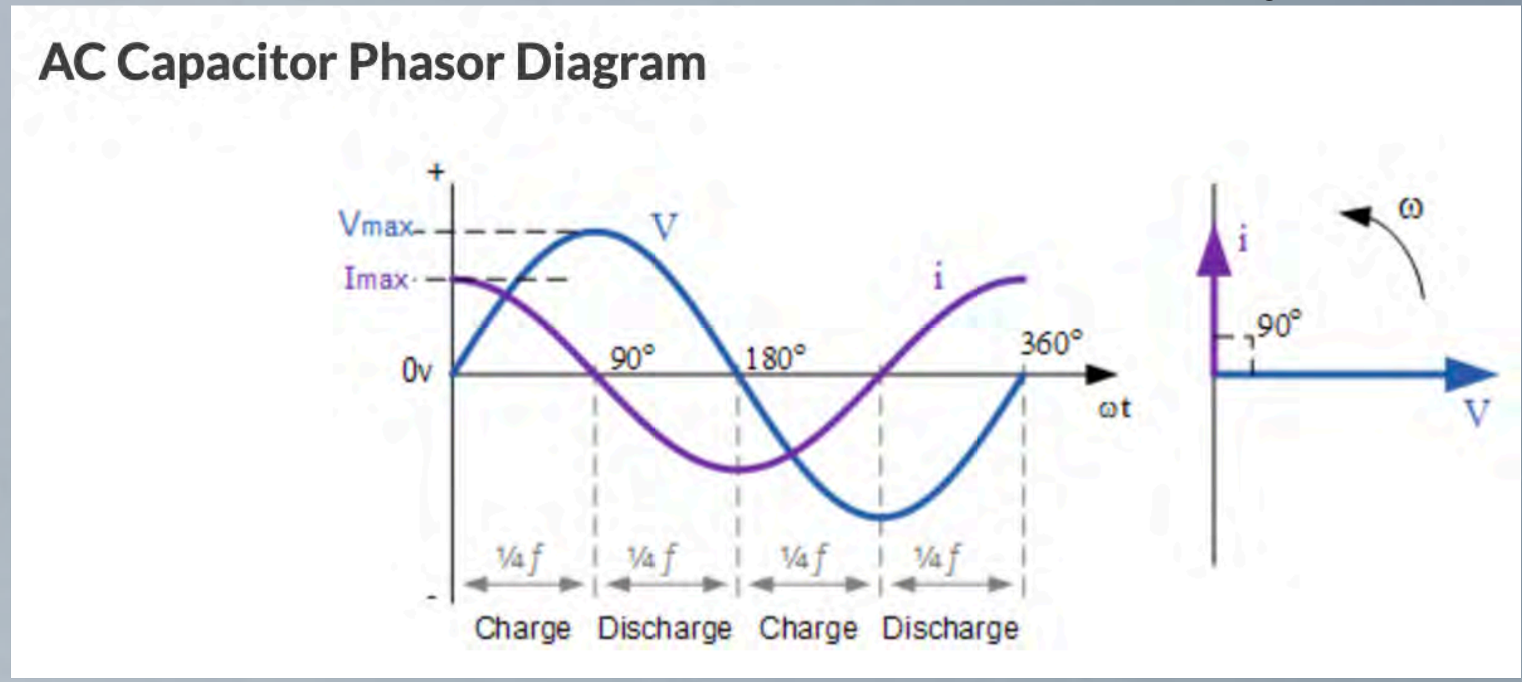

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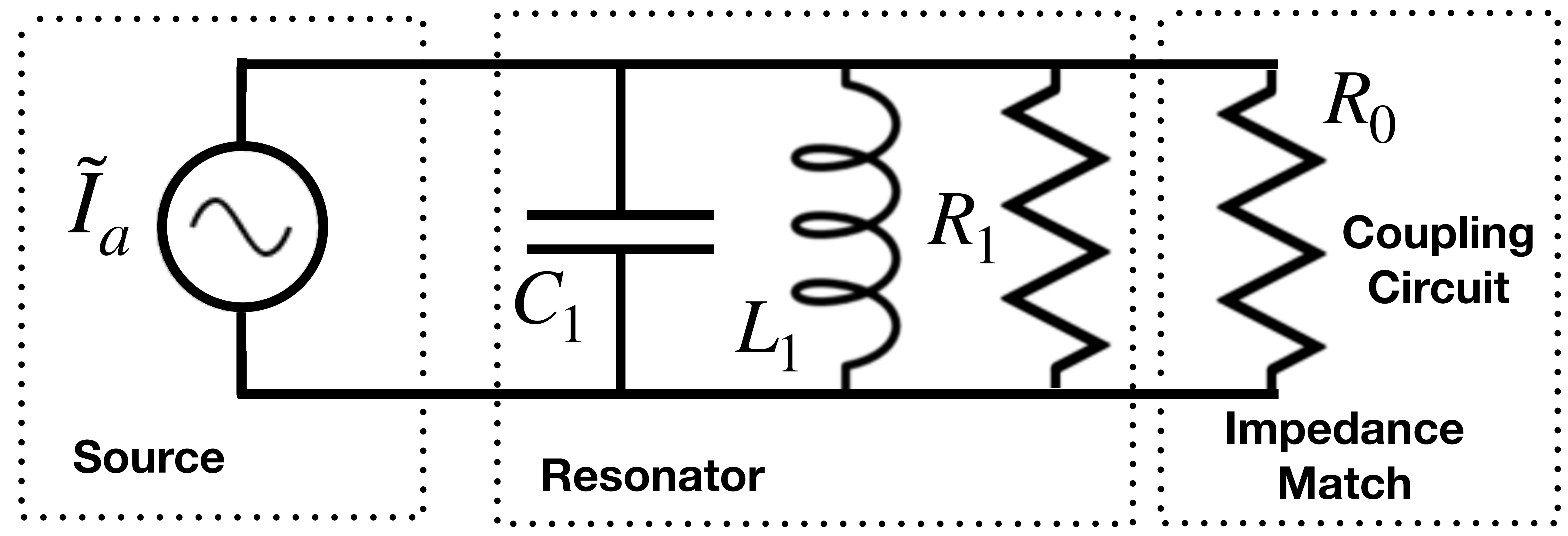

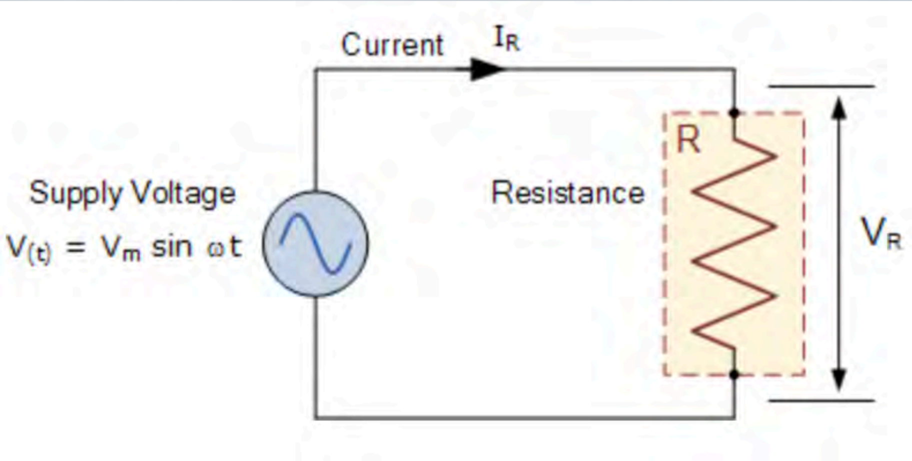

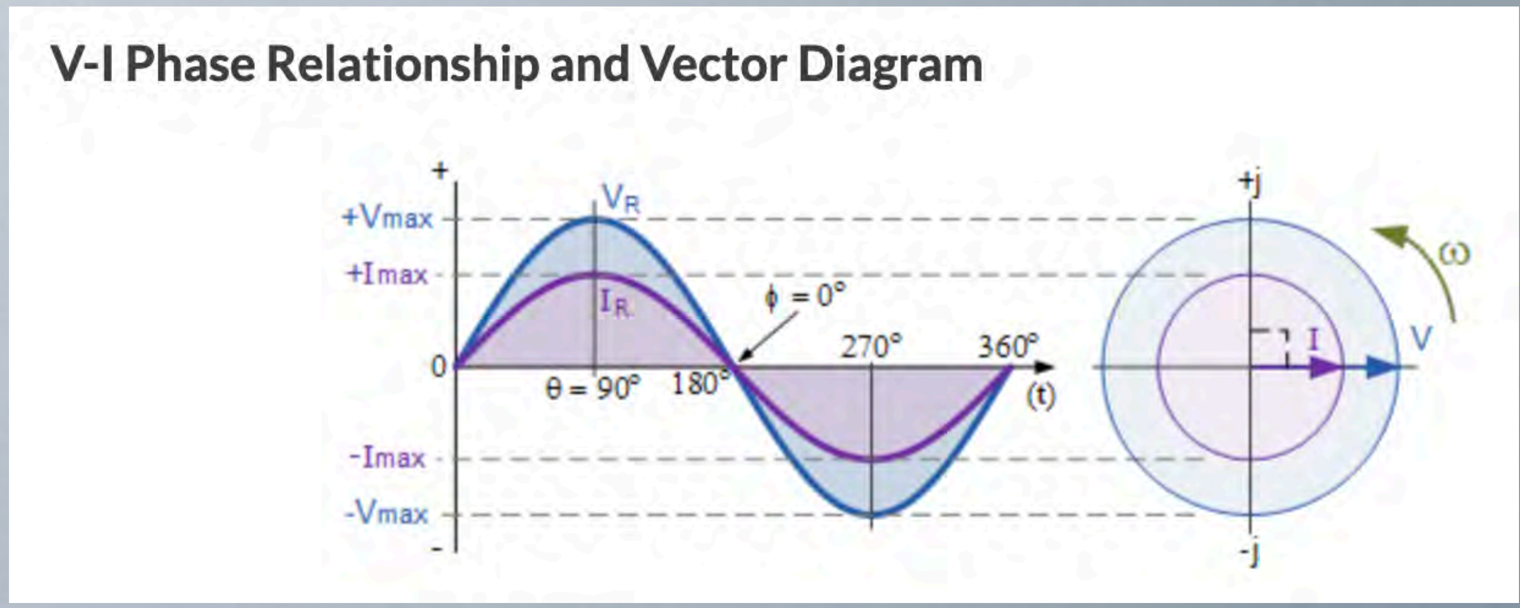

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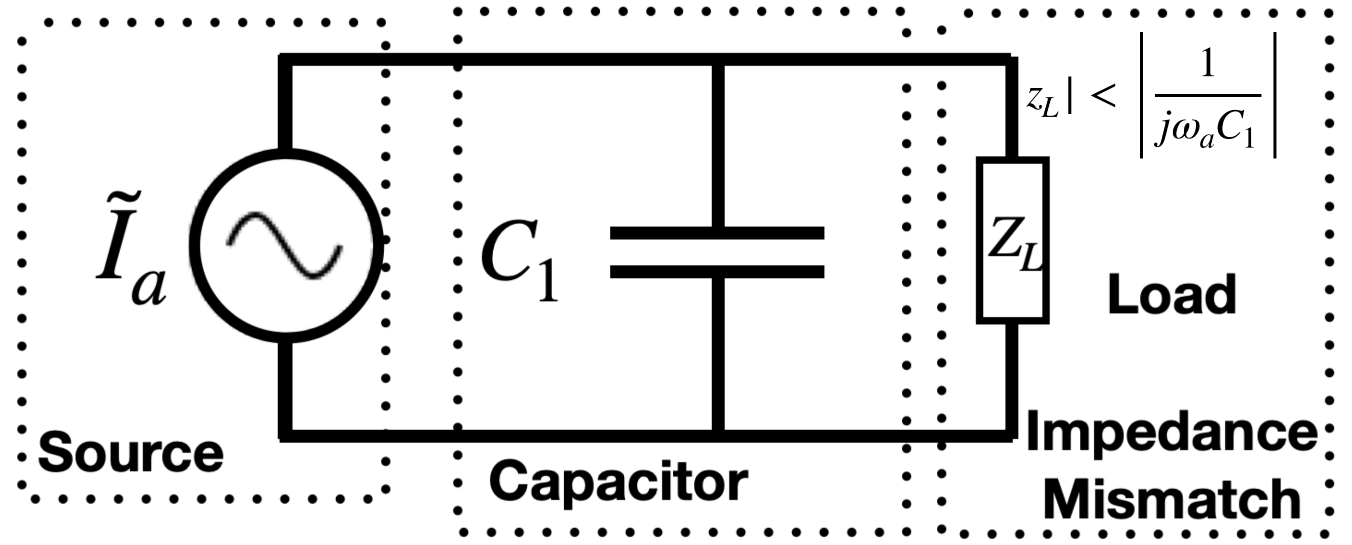

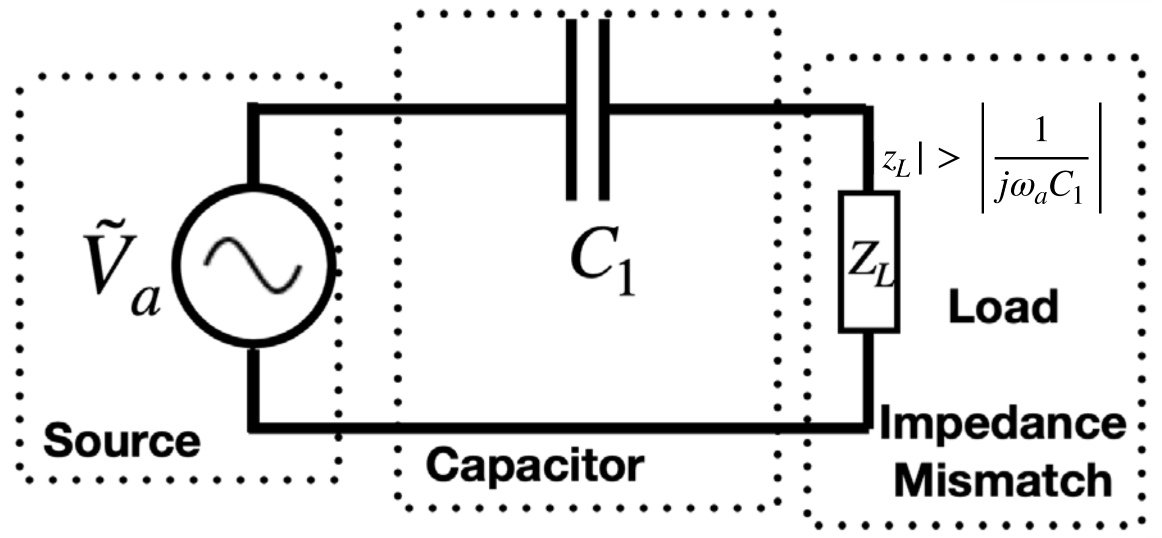

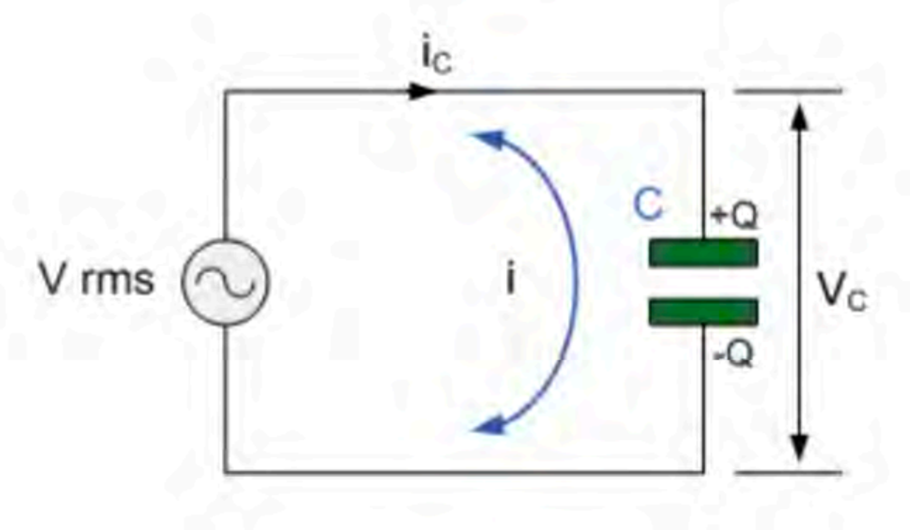

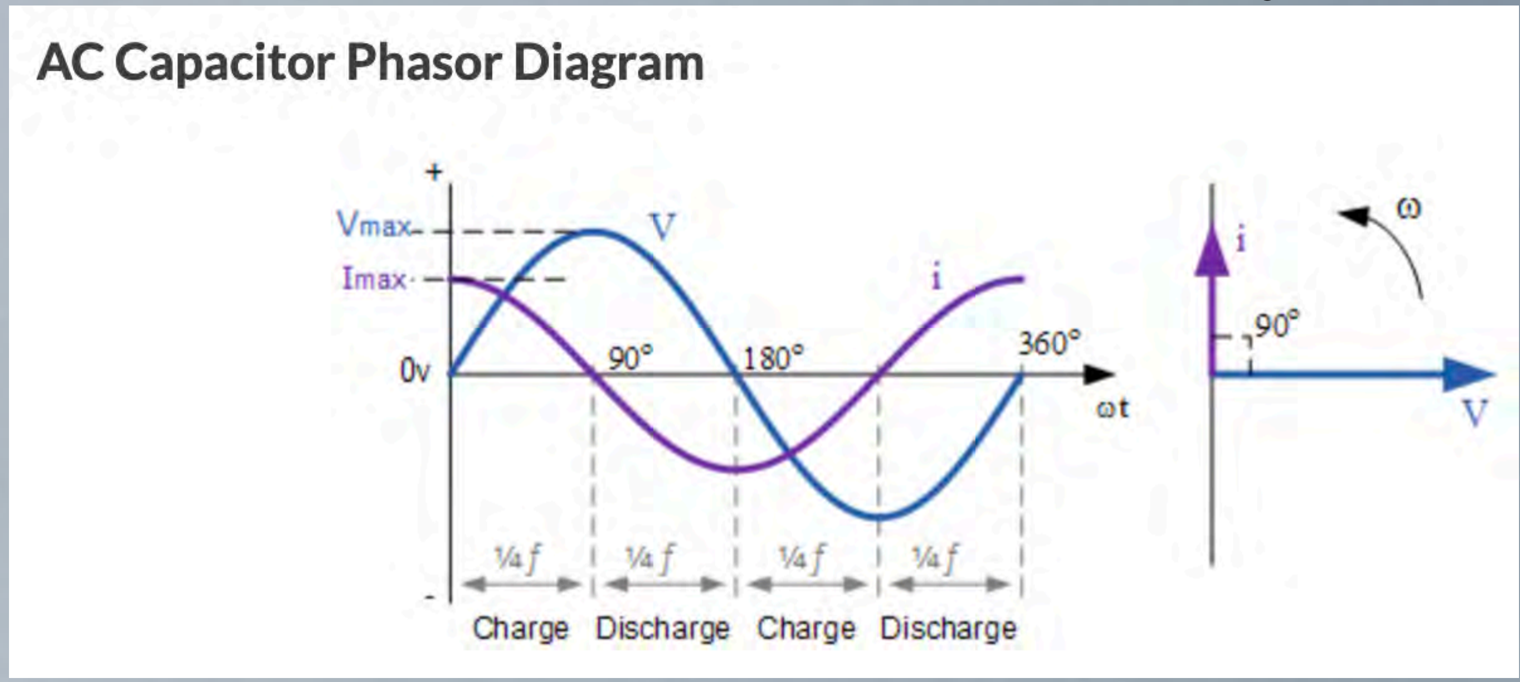

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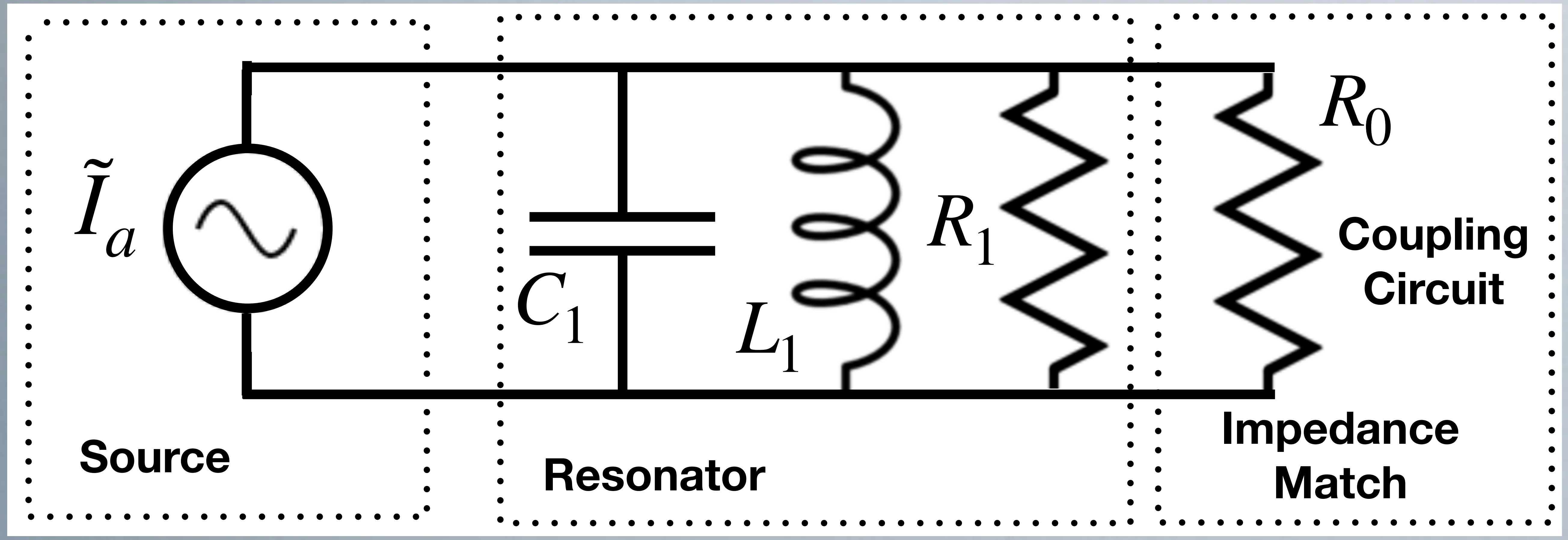

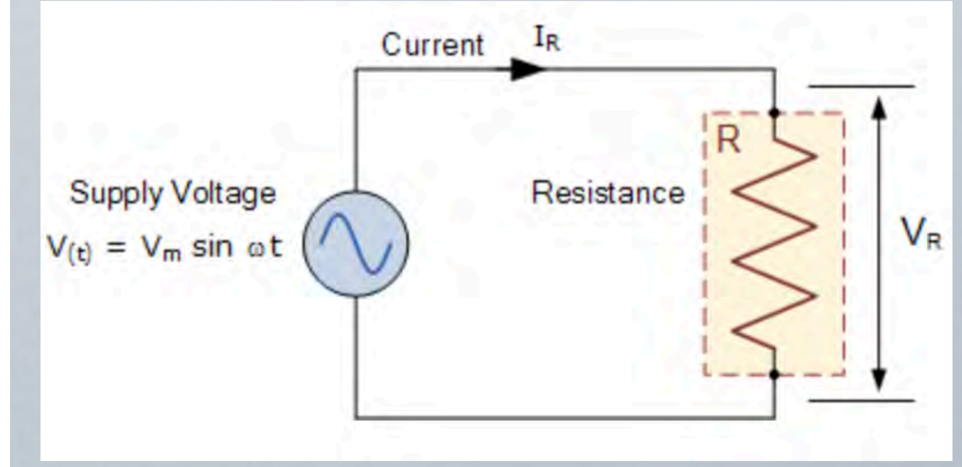

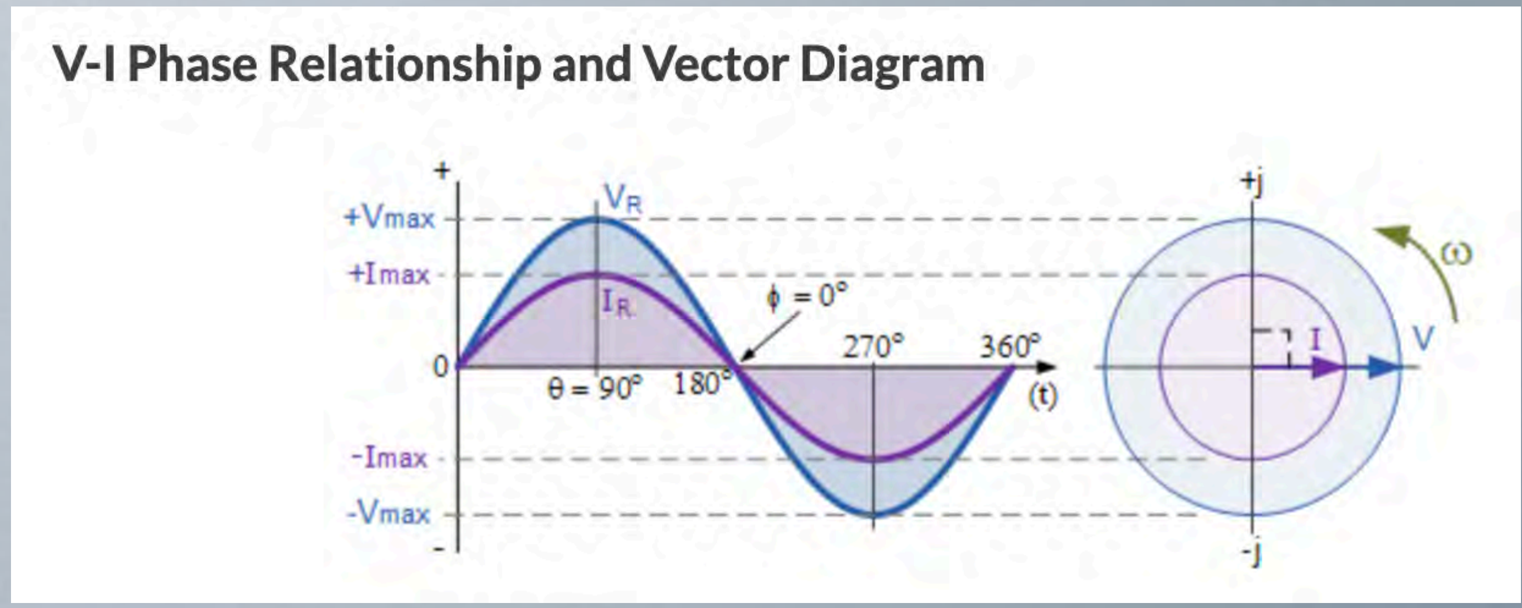

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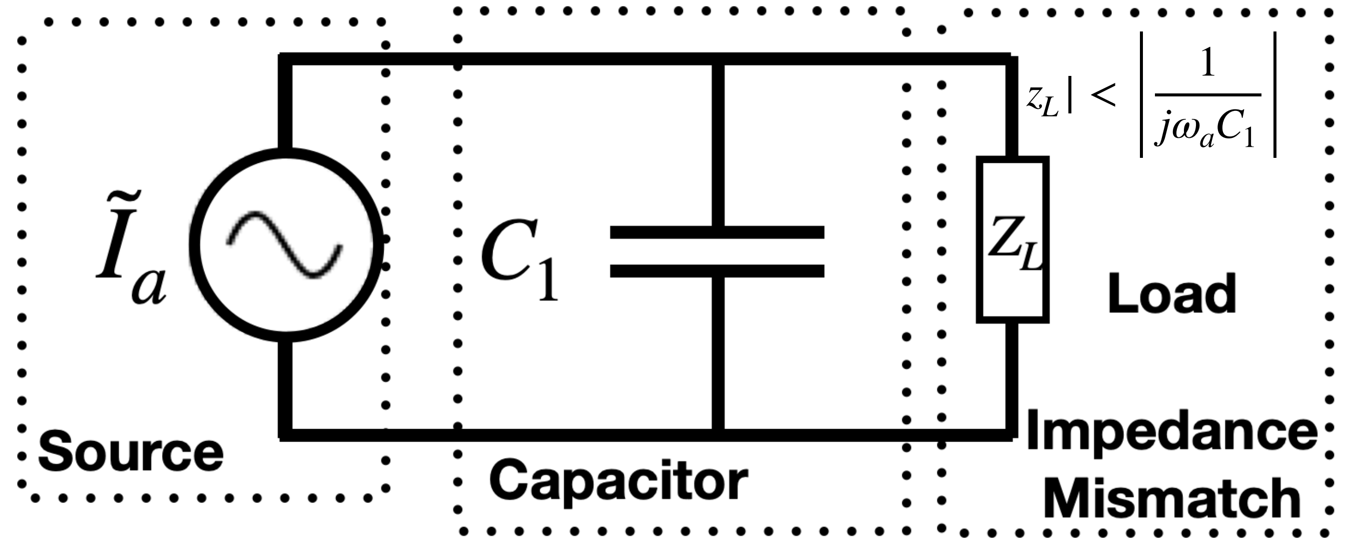

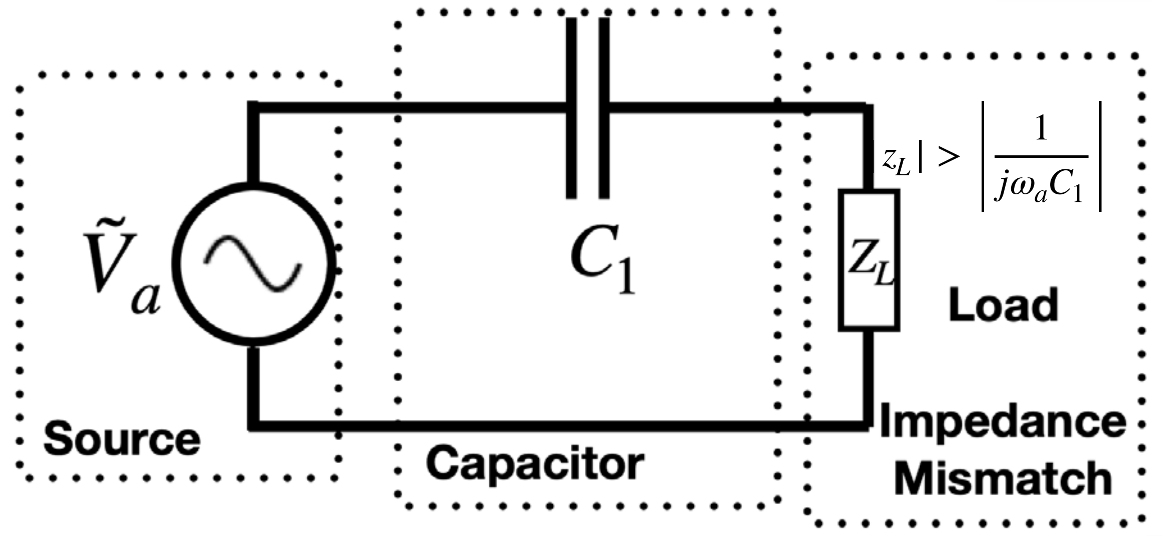

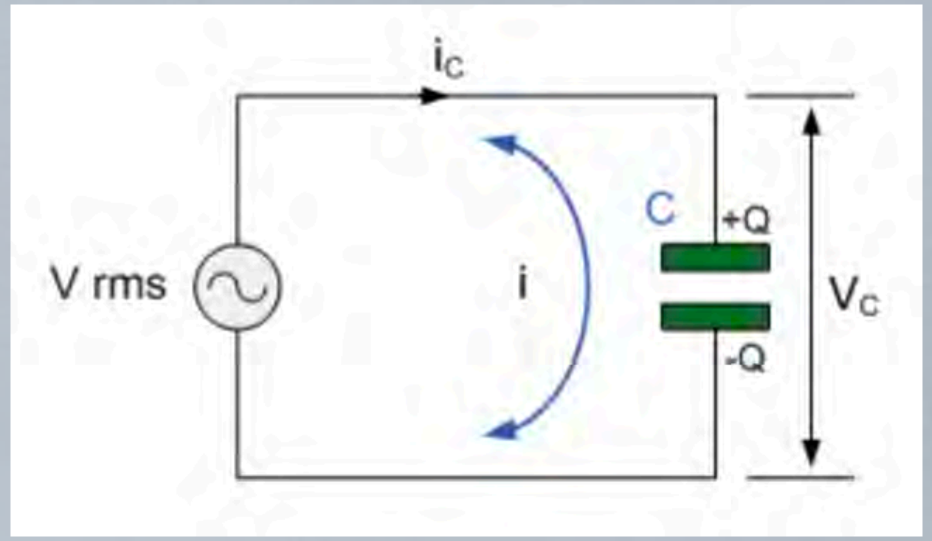

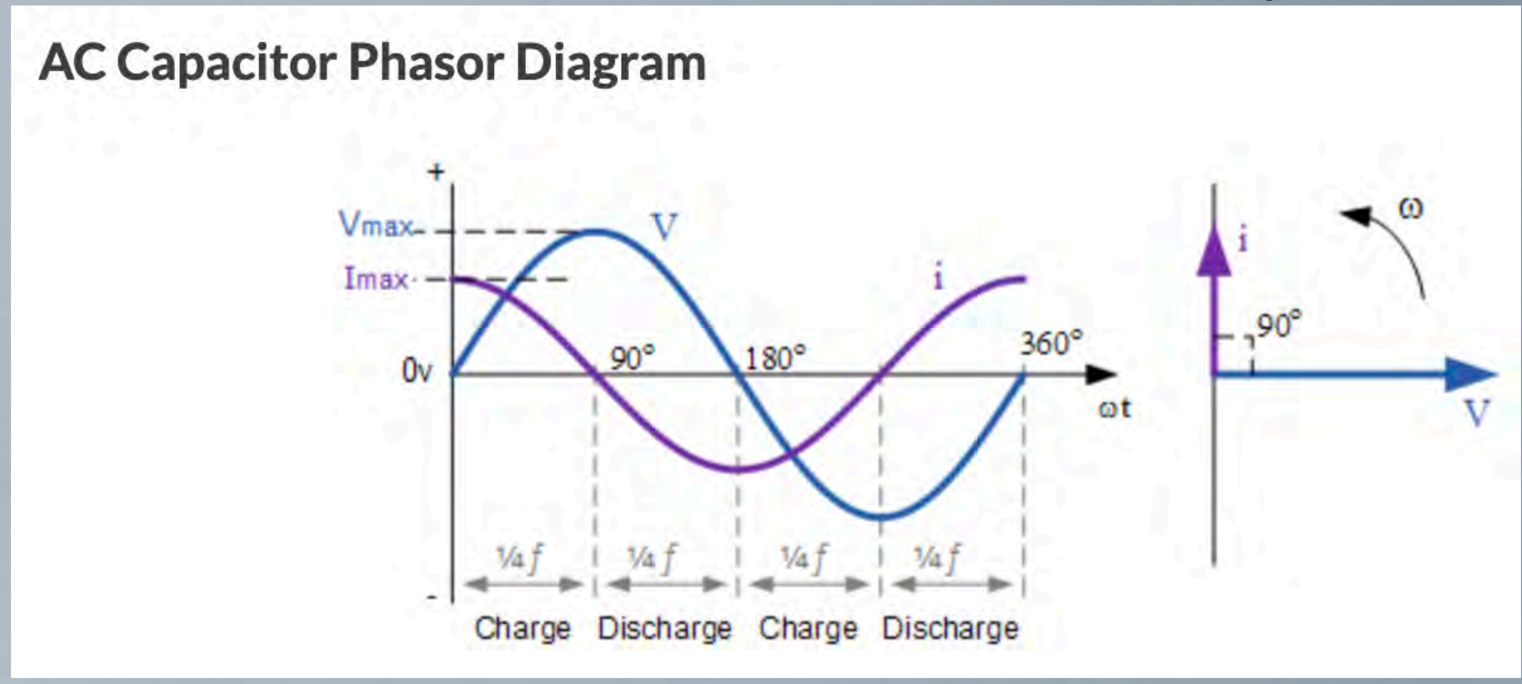

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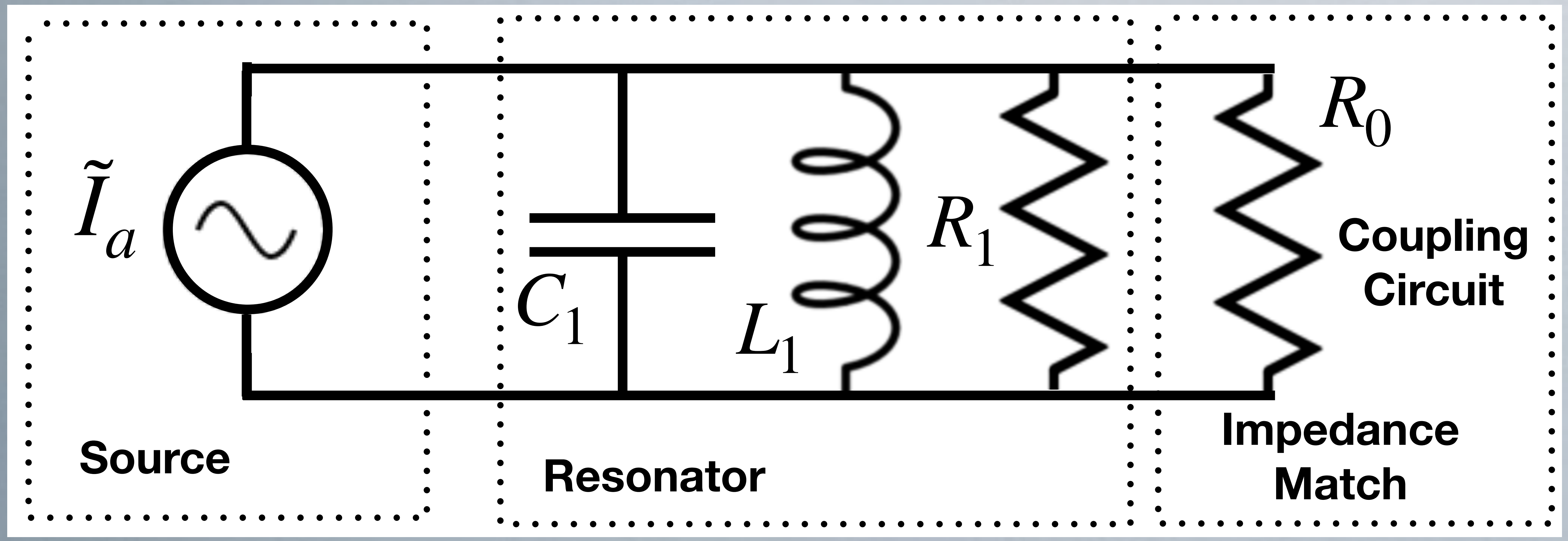

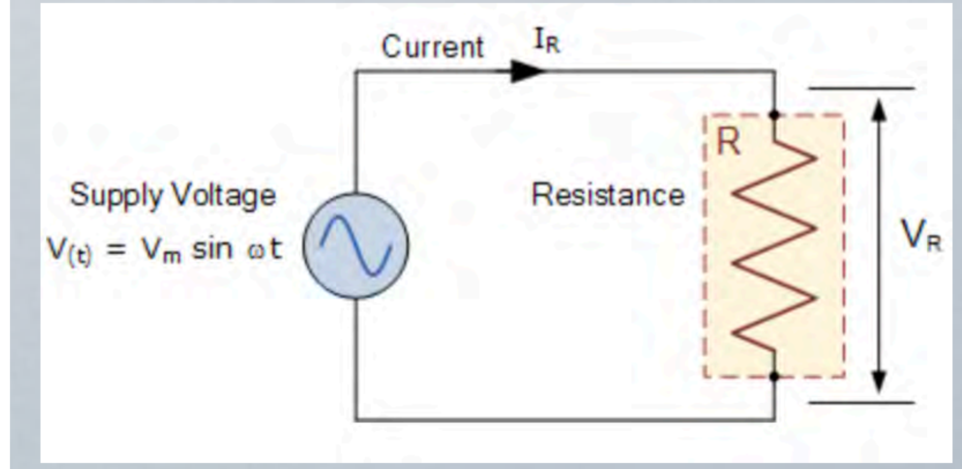

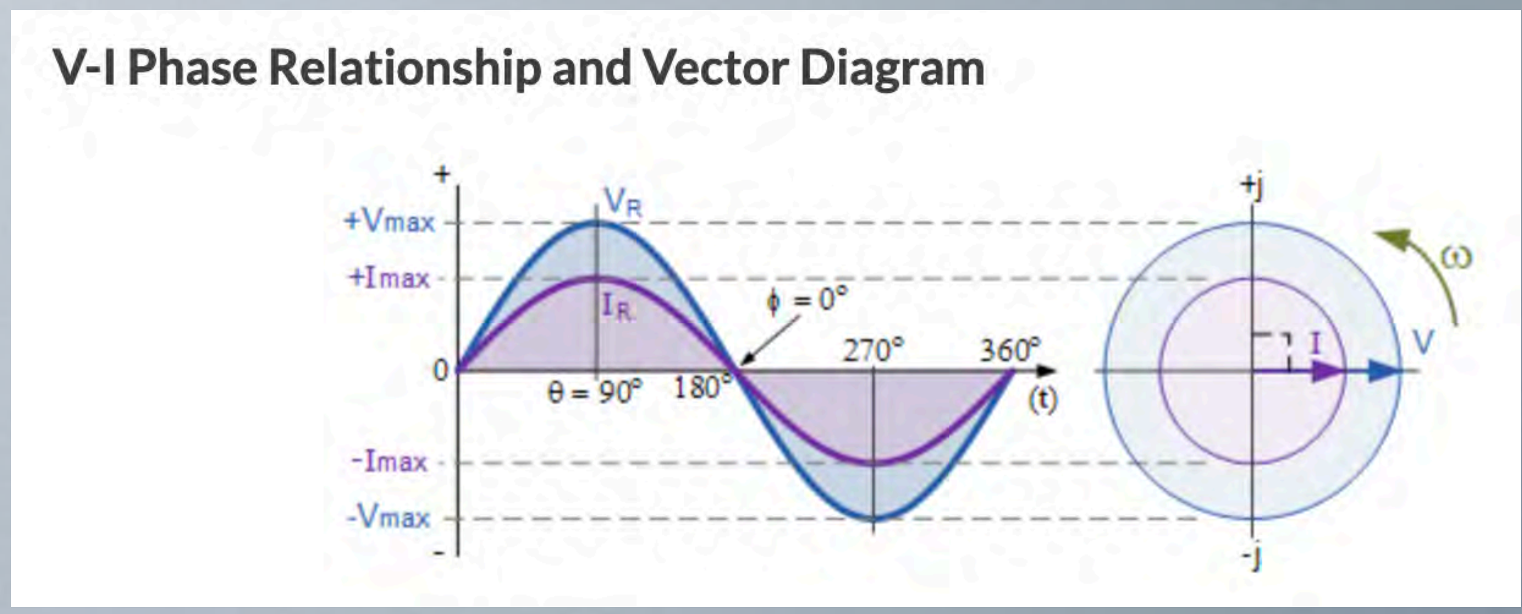

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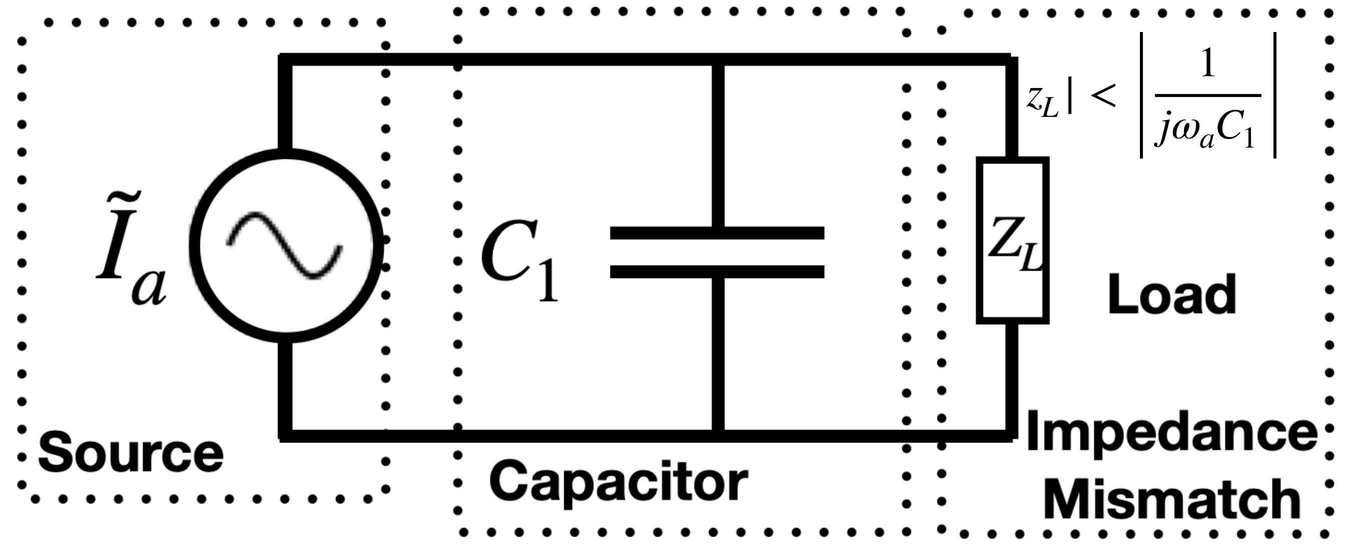

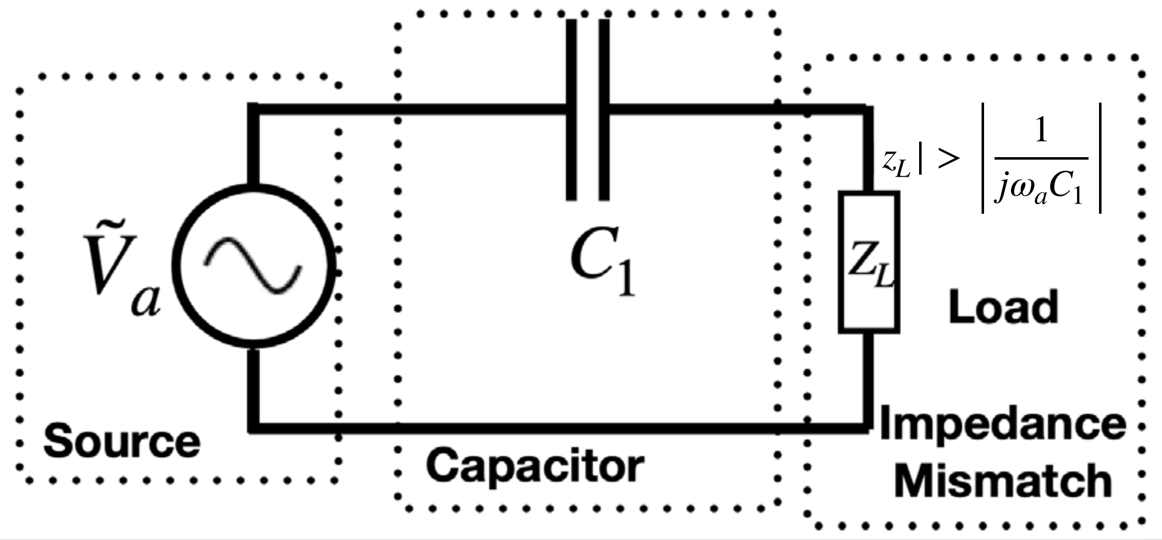

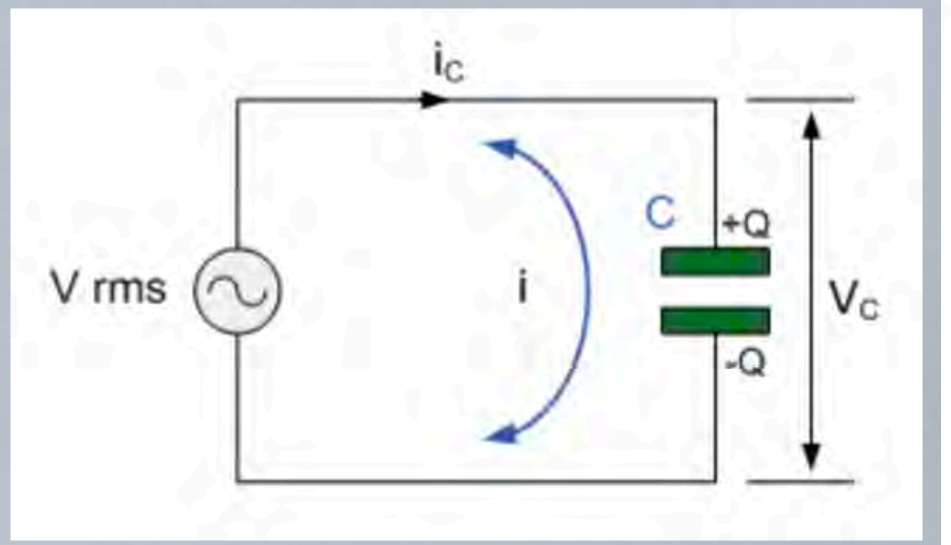

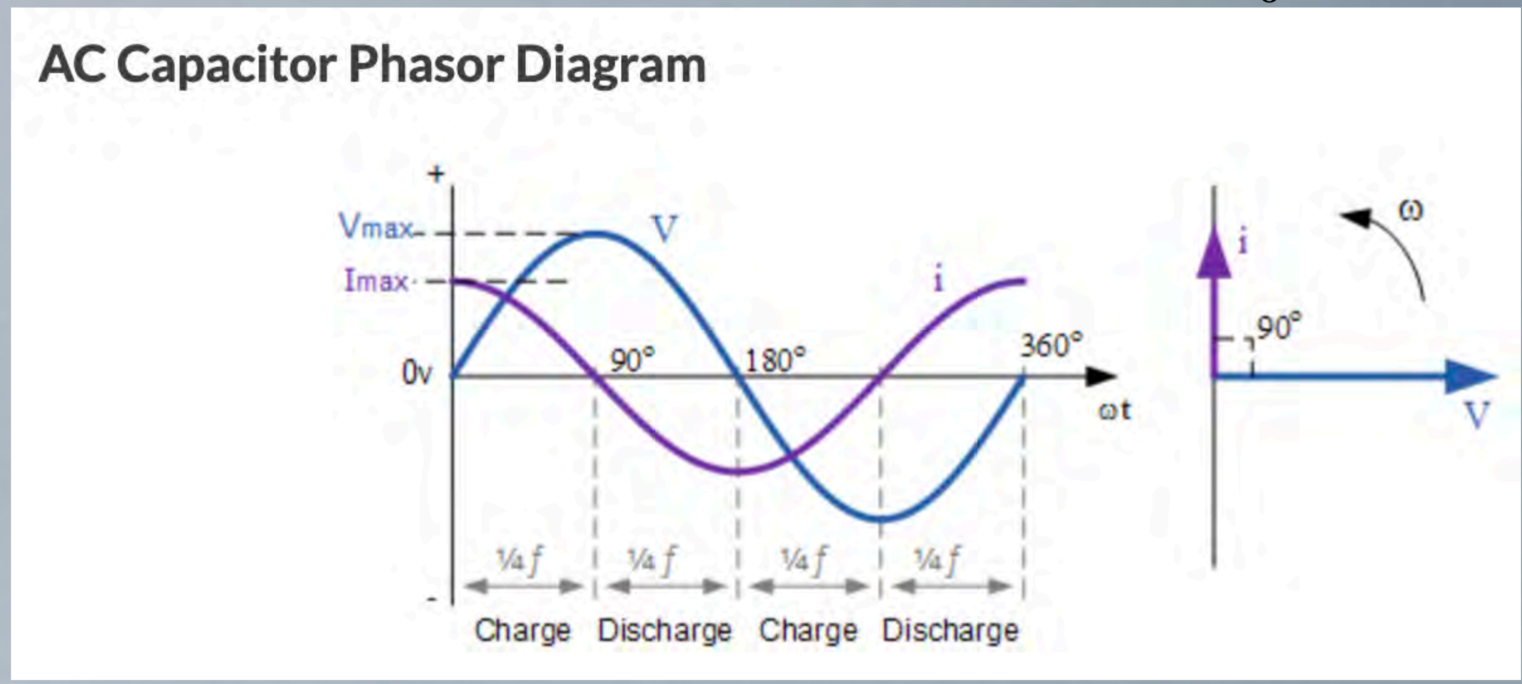

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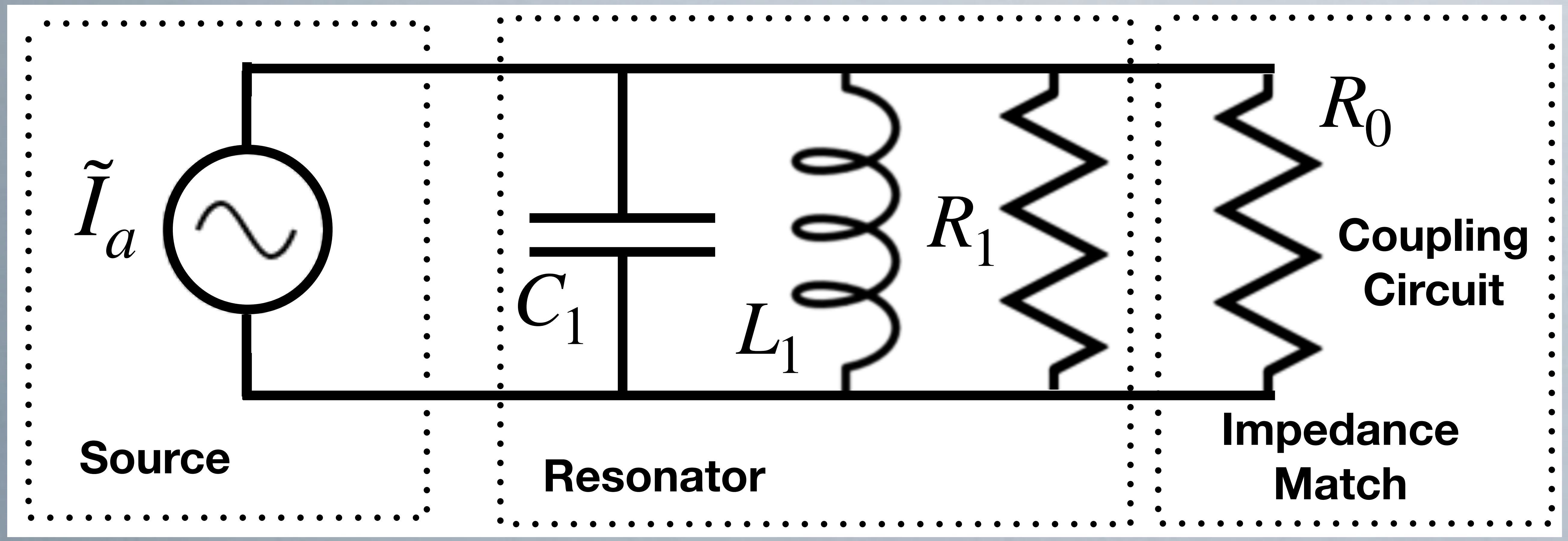

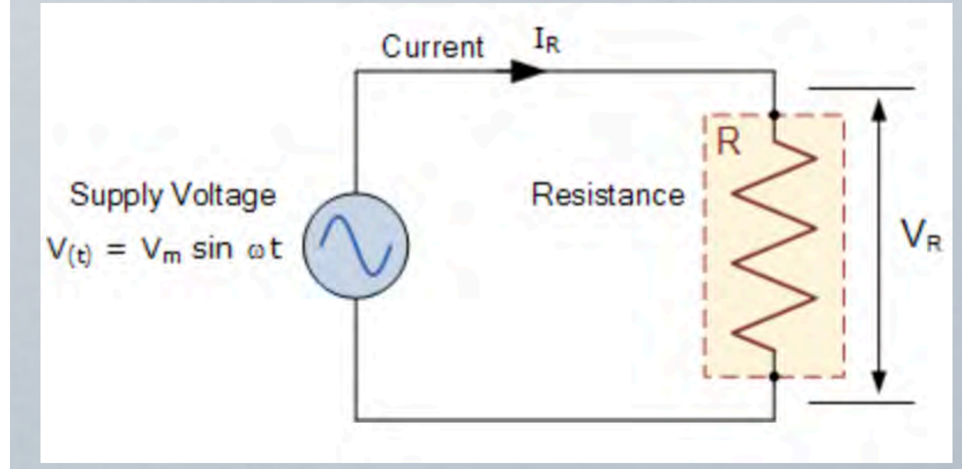

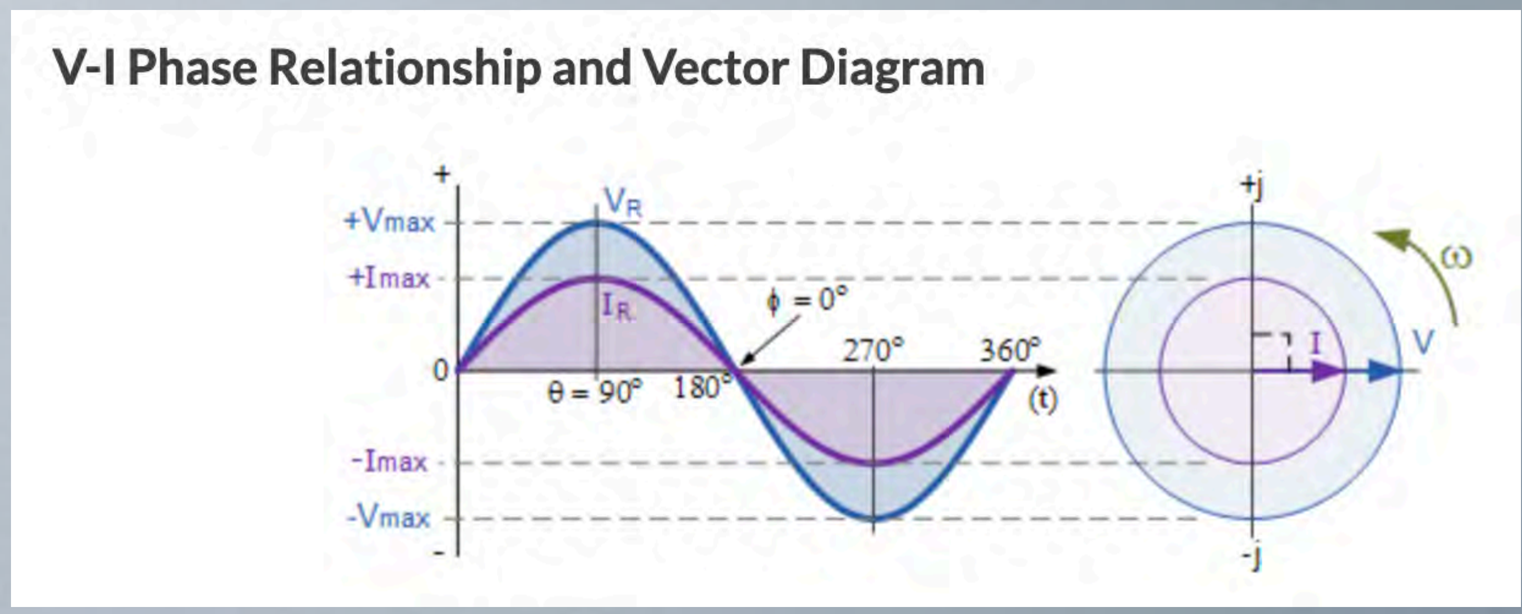

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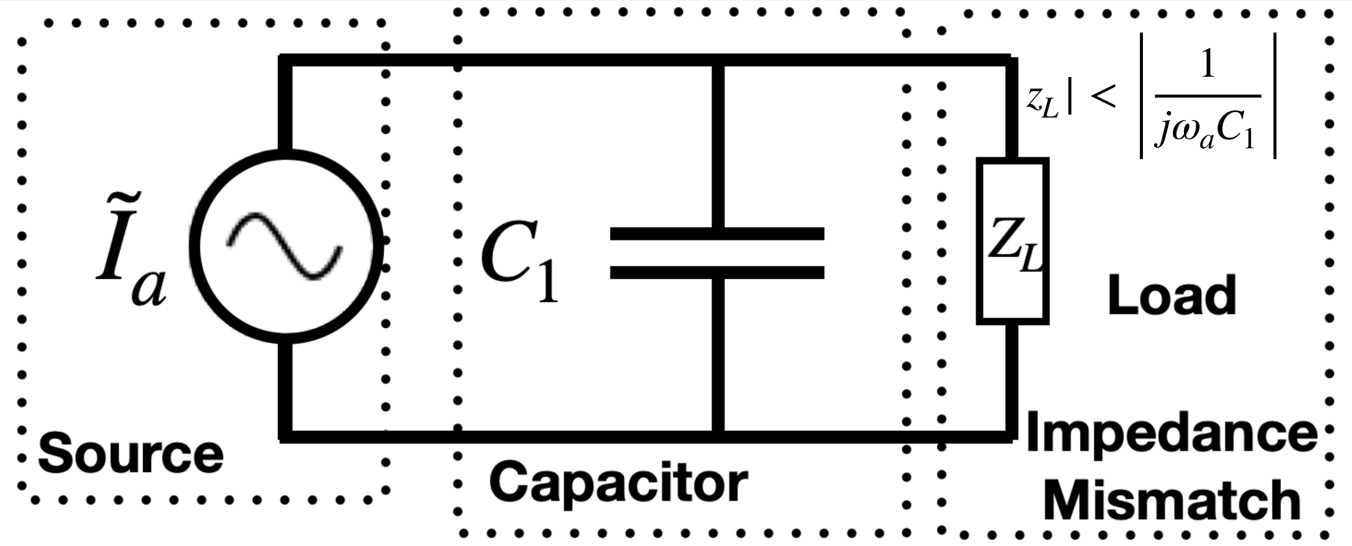

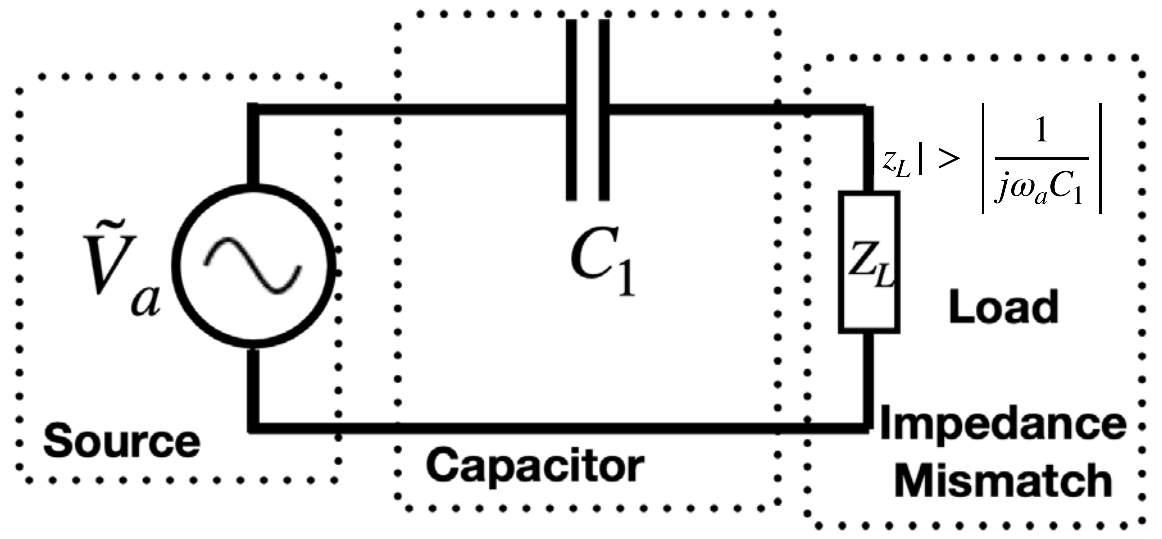

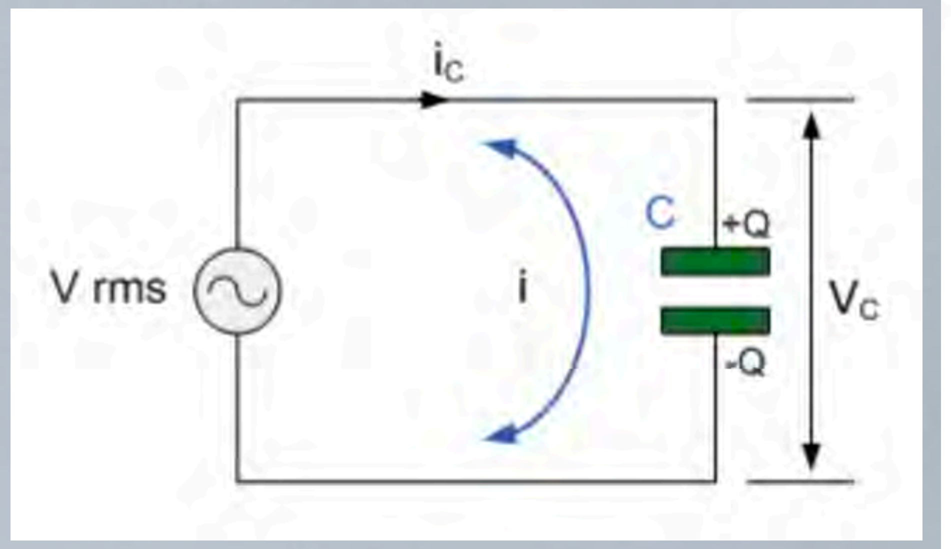

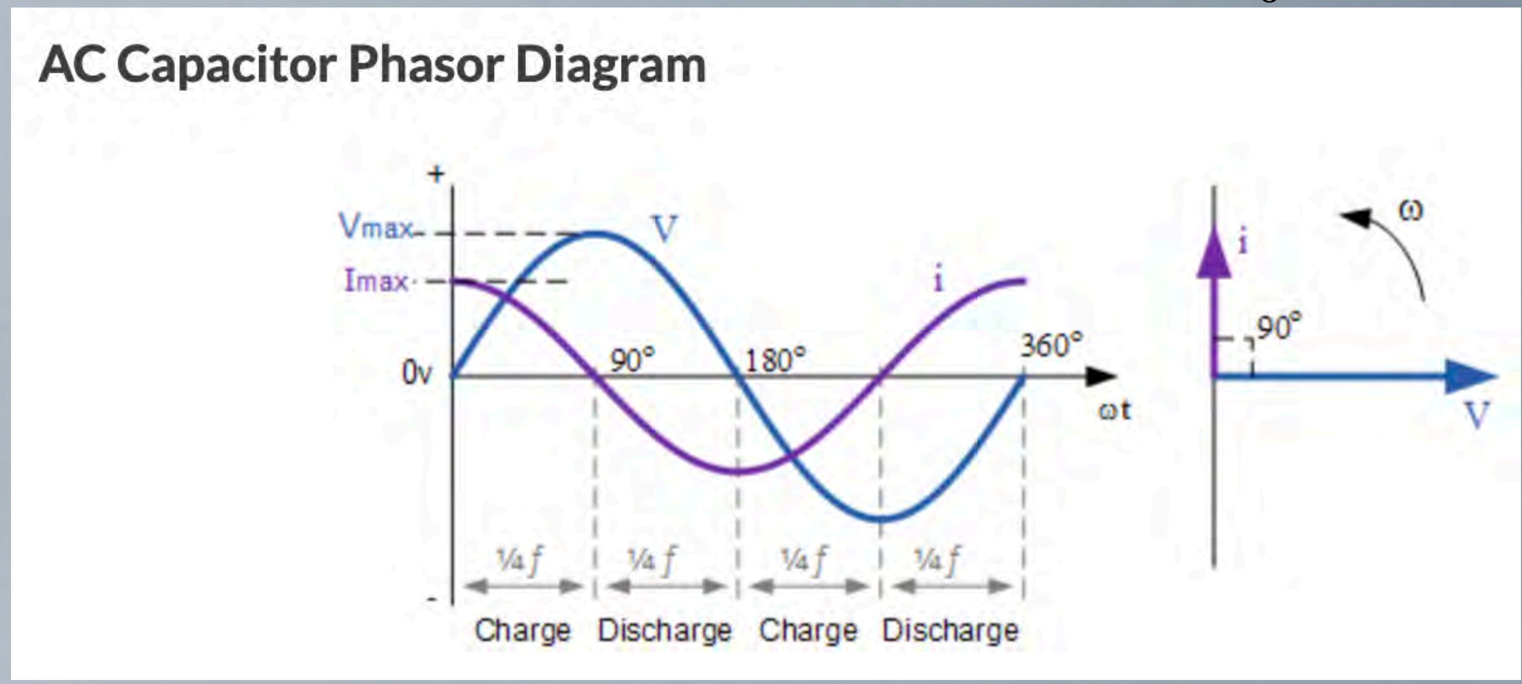

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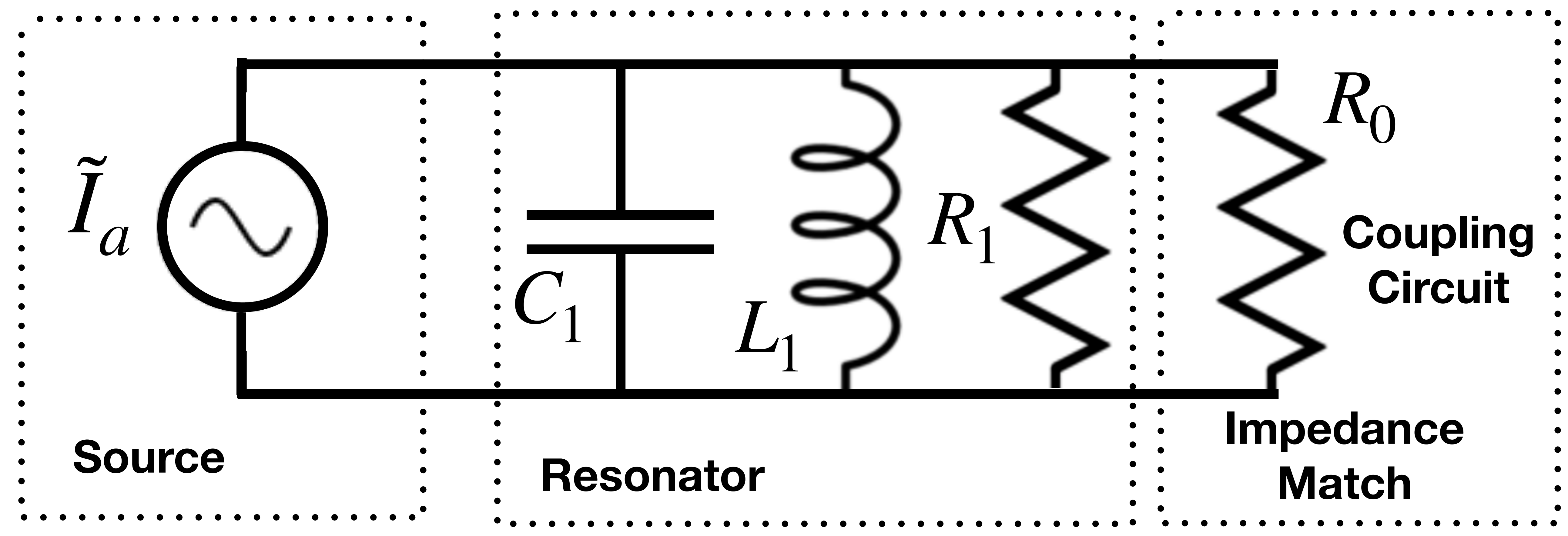
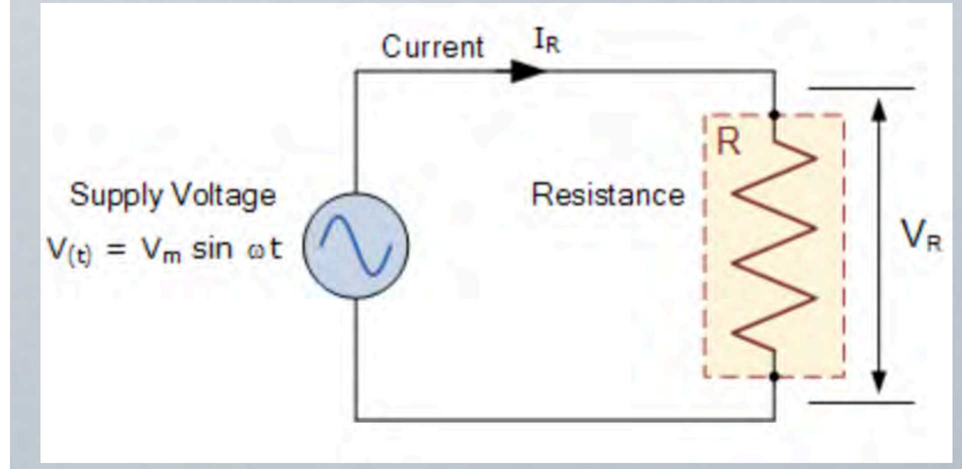
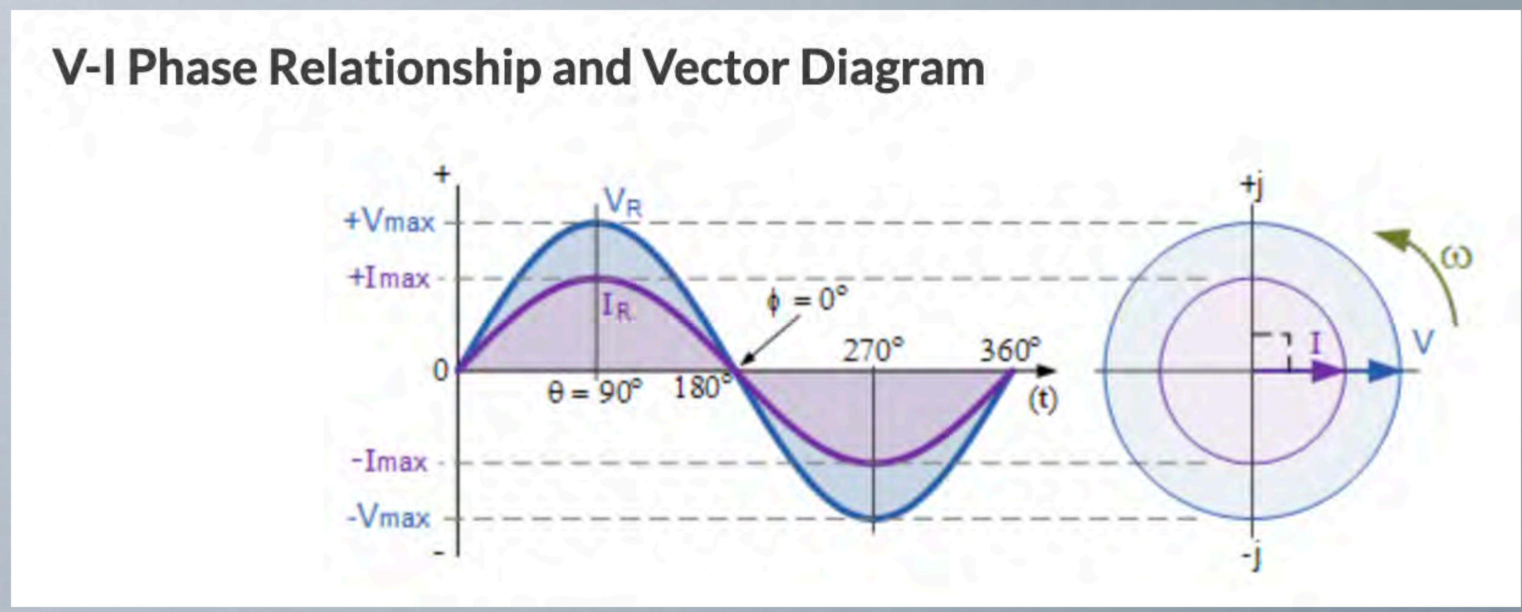
Resonator Measurement: Impedance match; set coupling =1; Take Photons from Source







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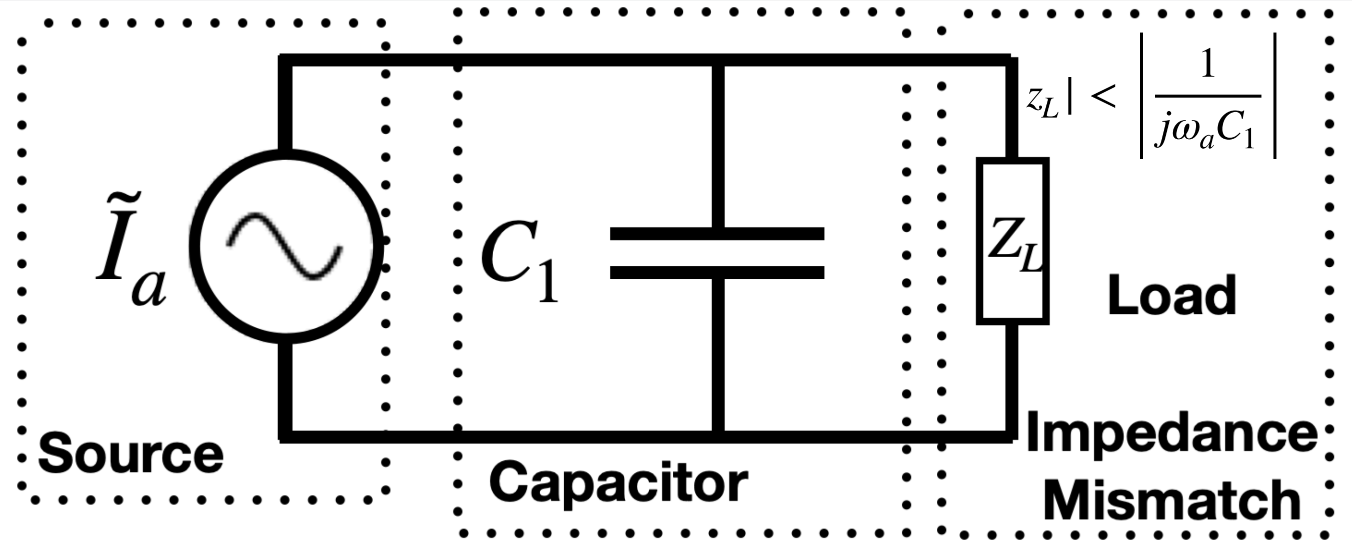

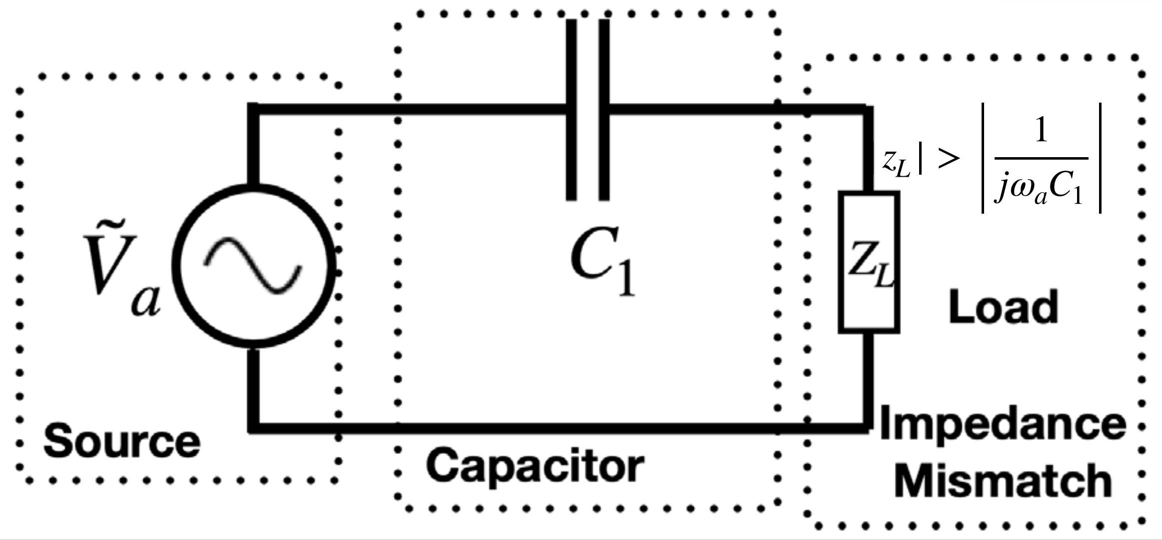

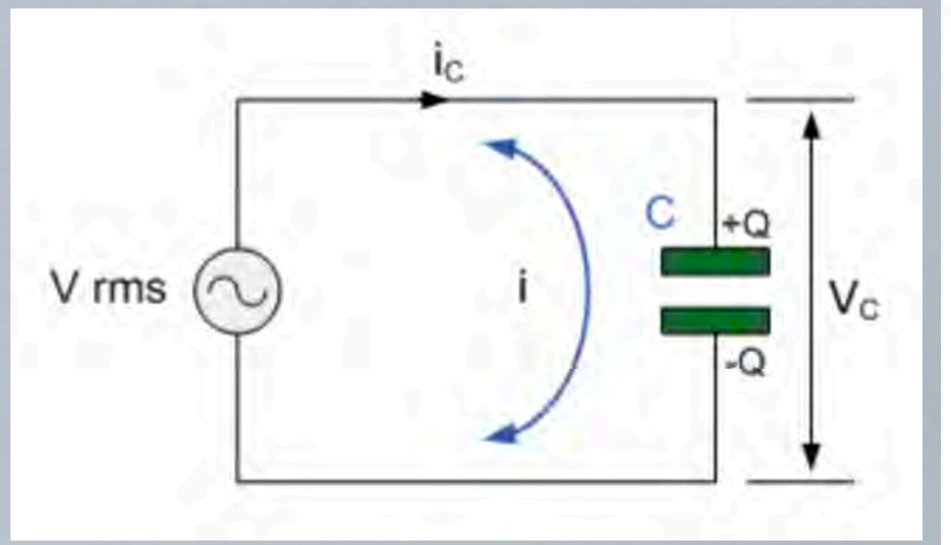

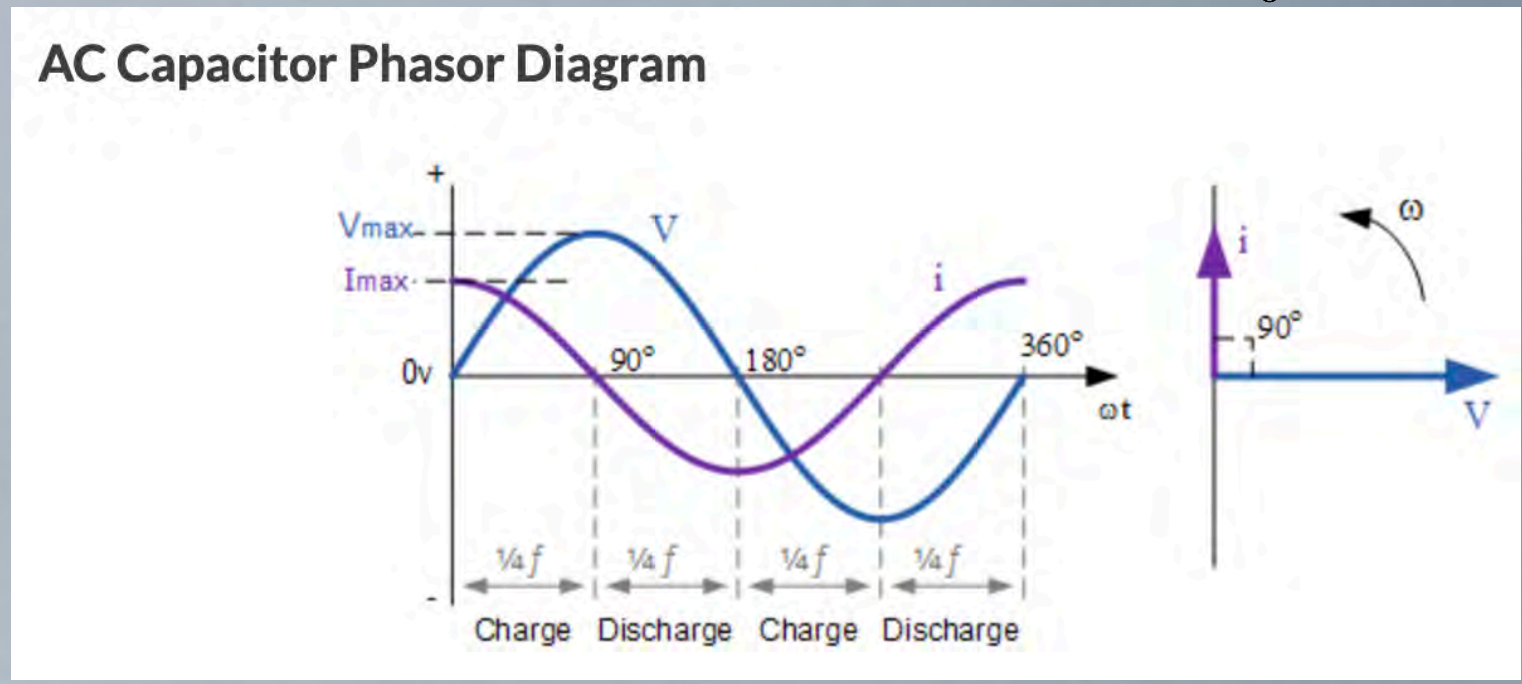

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Does not need to be the order of the Compton wavelength in size (sub wavelength phenomena)

Resonant Axion Haloscopes @ UWA

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

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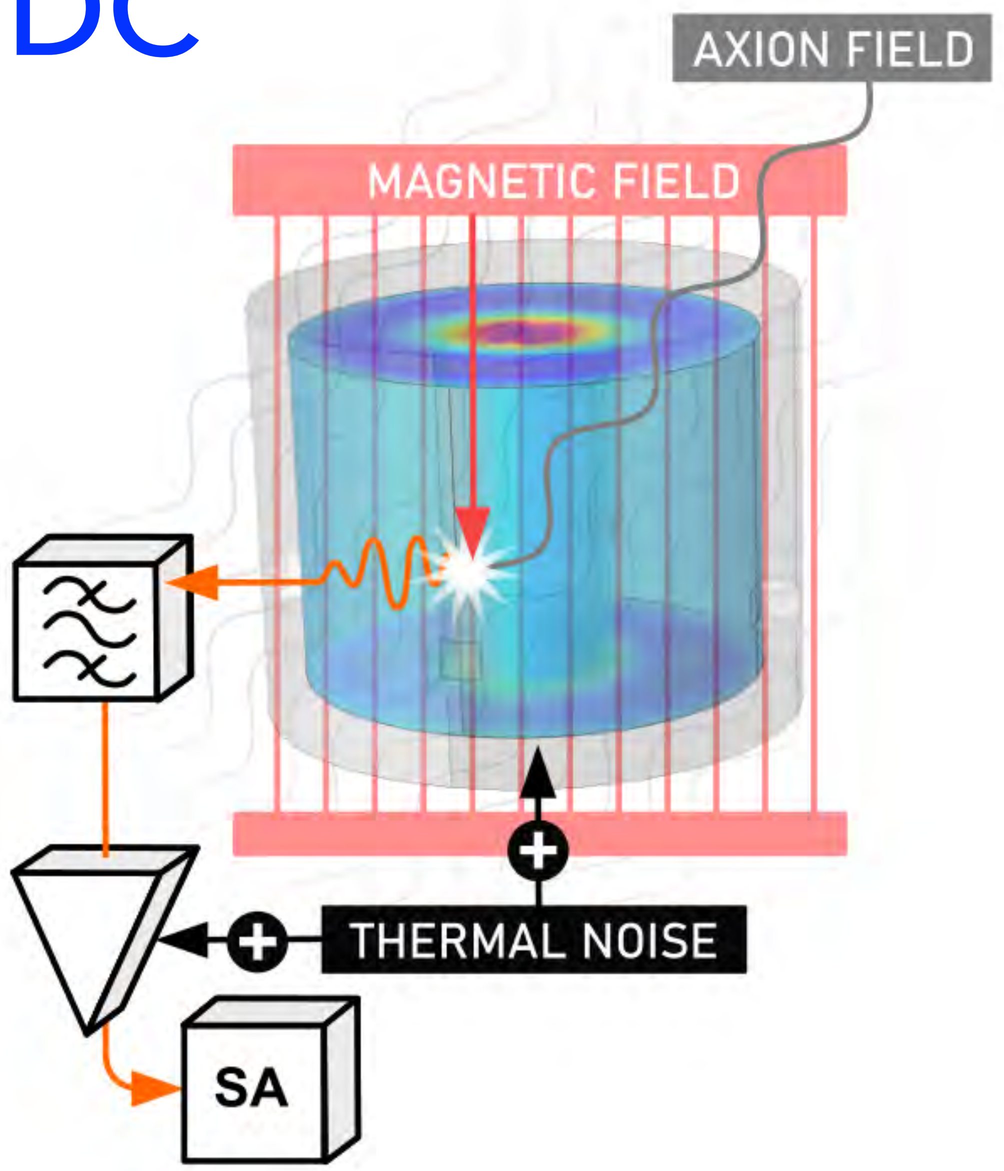
DC



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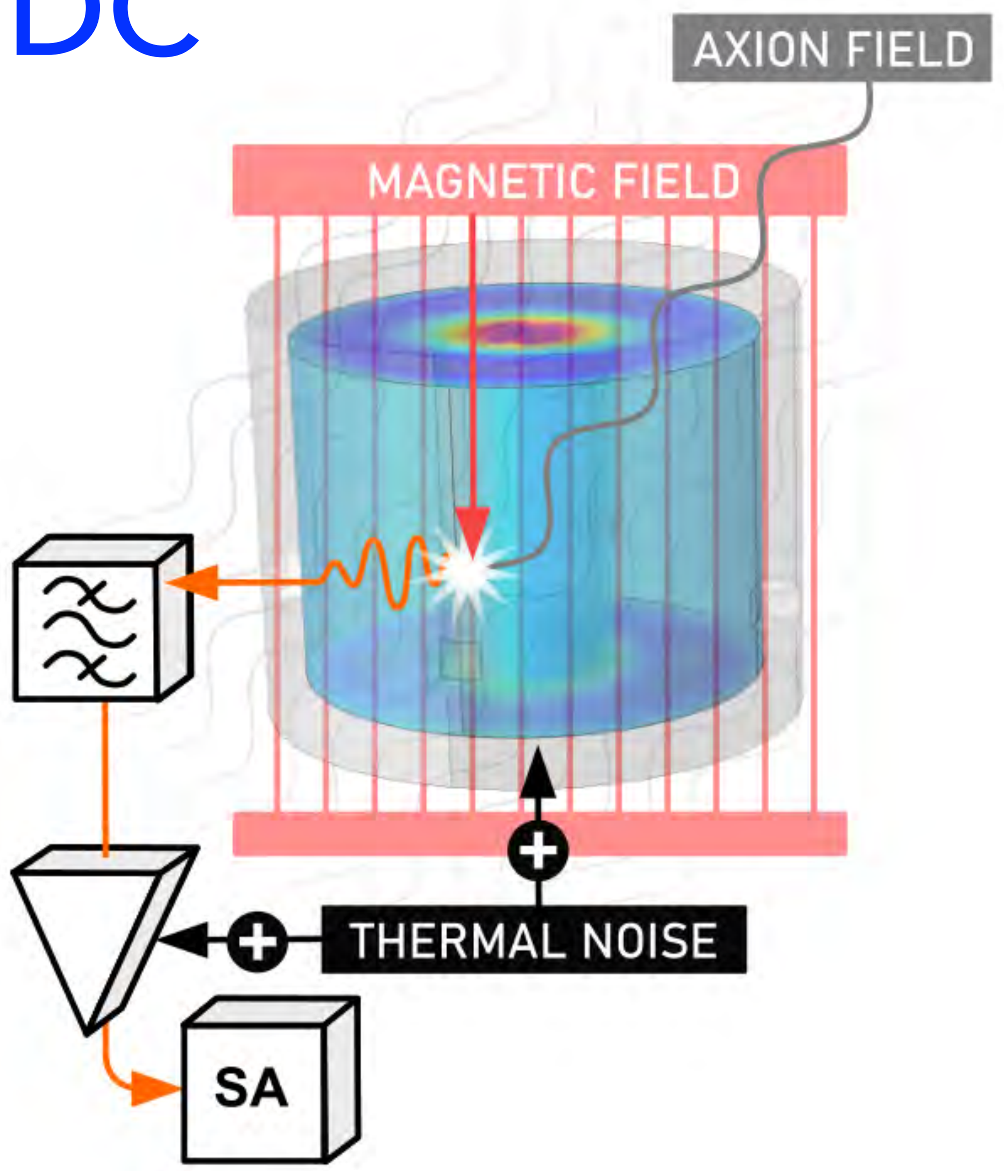

Photon 1: E field of cavity's resonant transverse magnetic mode, $m_a = f_1 + \delta f$

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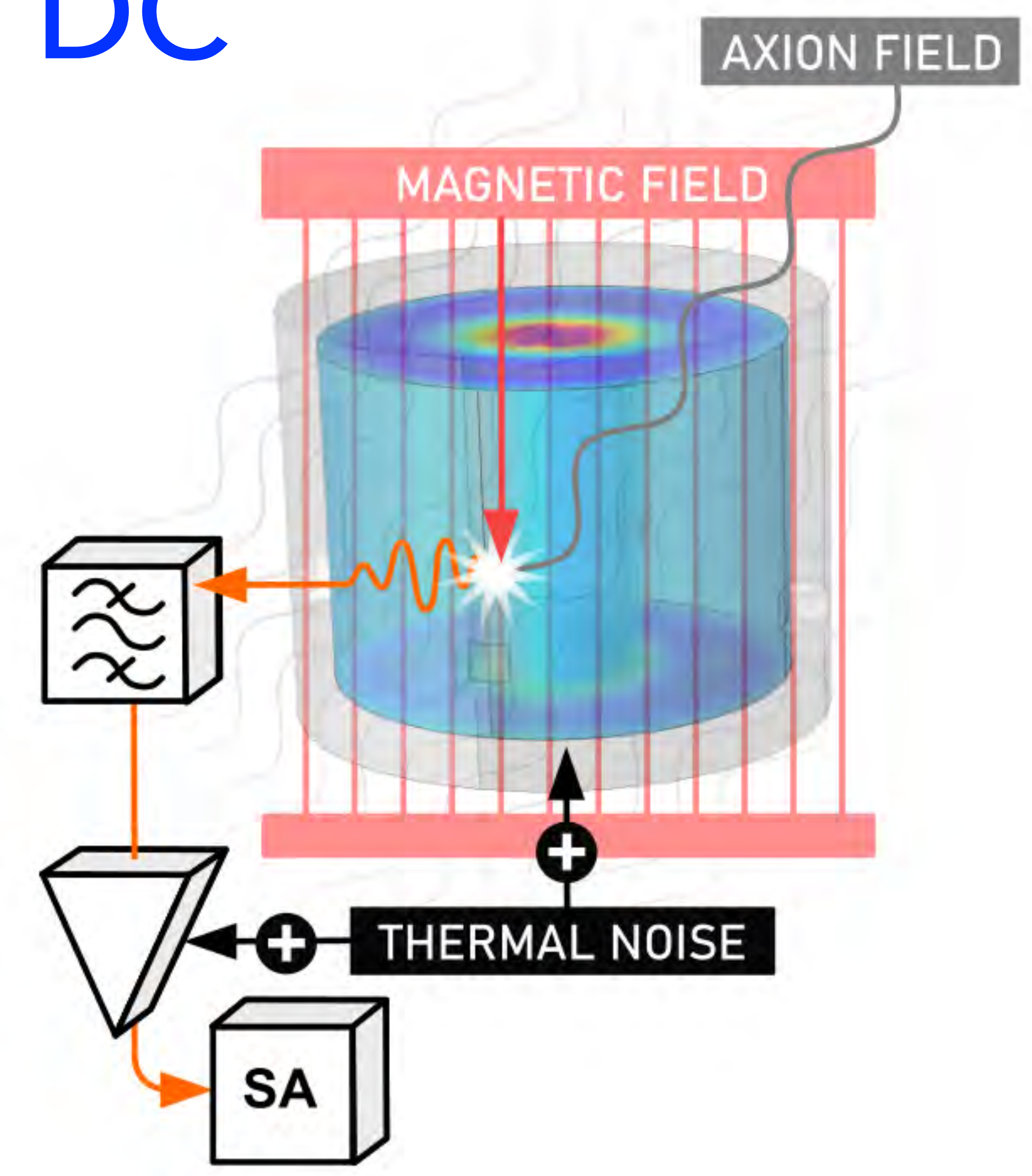

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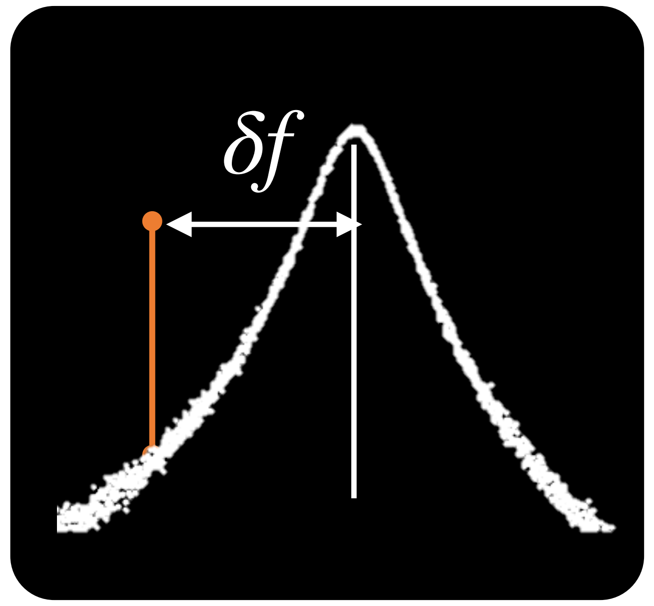

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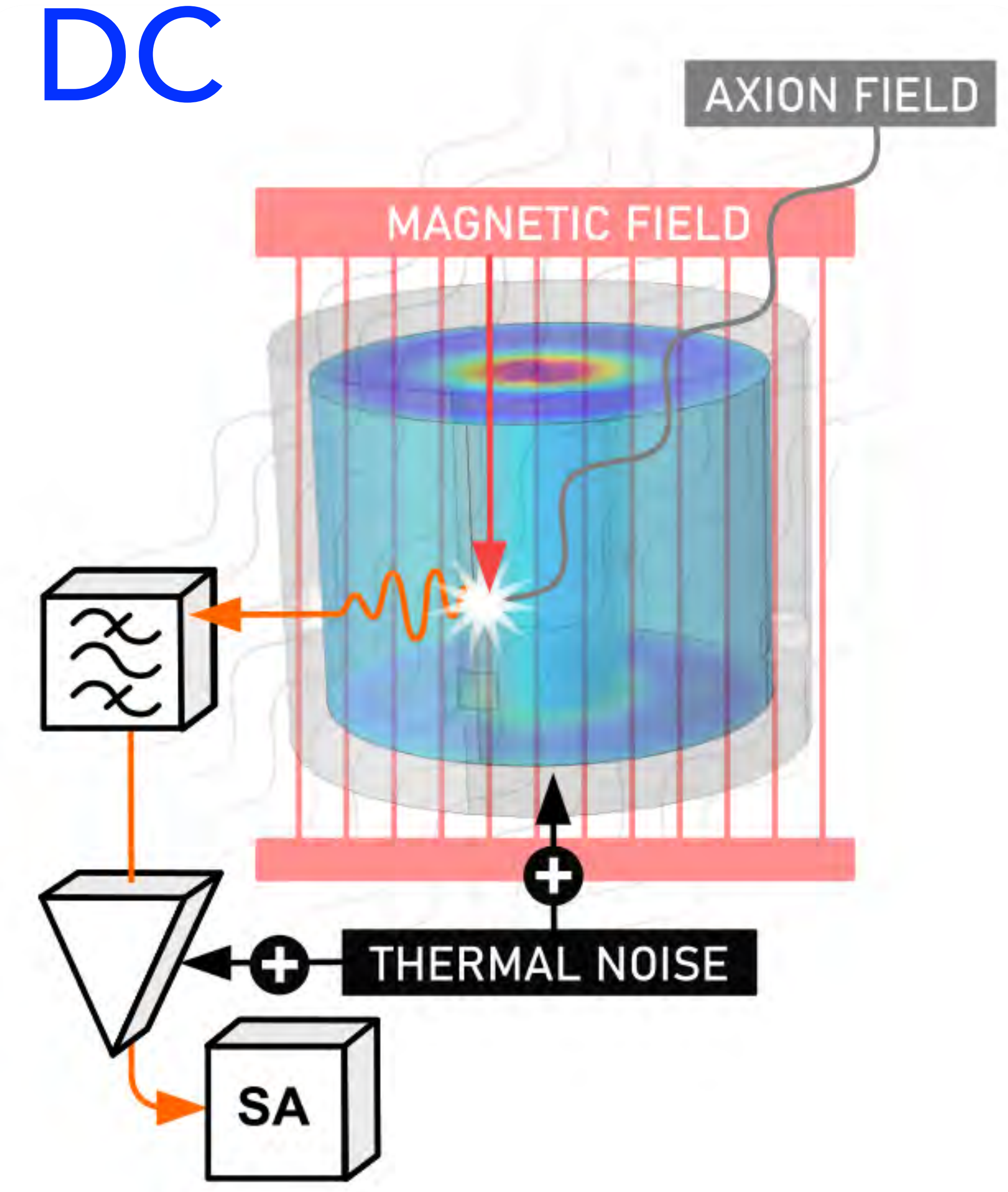

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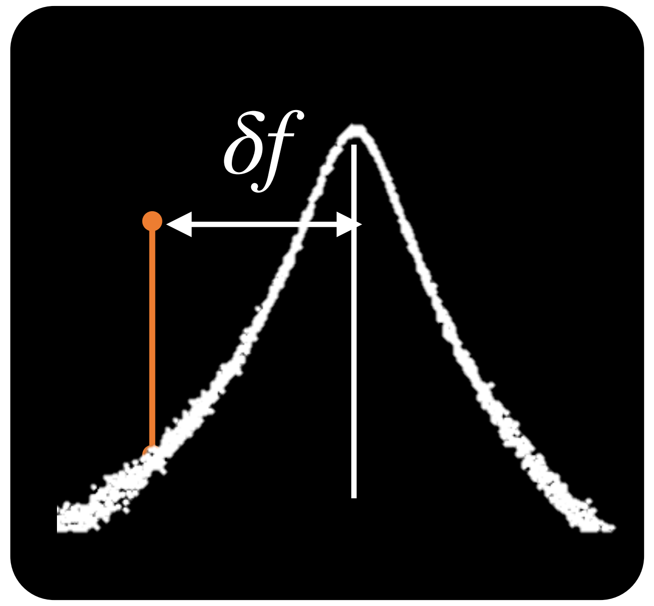
Photon 0, Back ground DC B field of surrounding magnet



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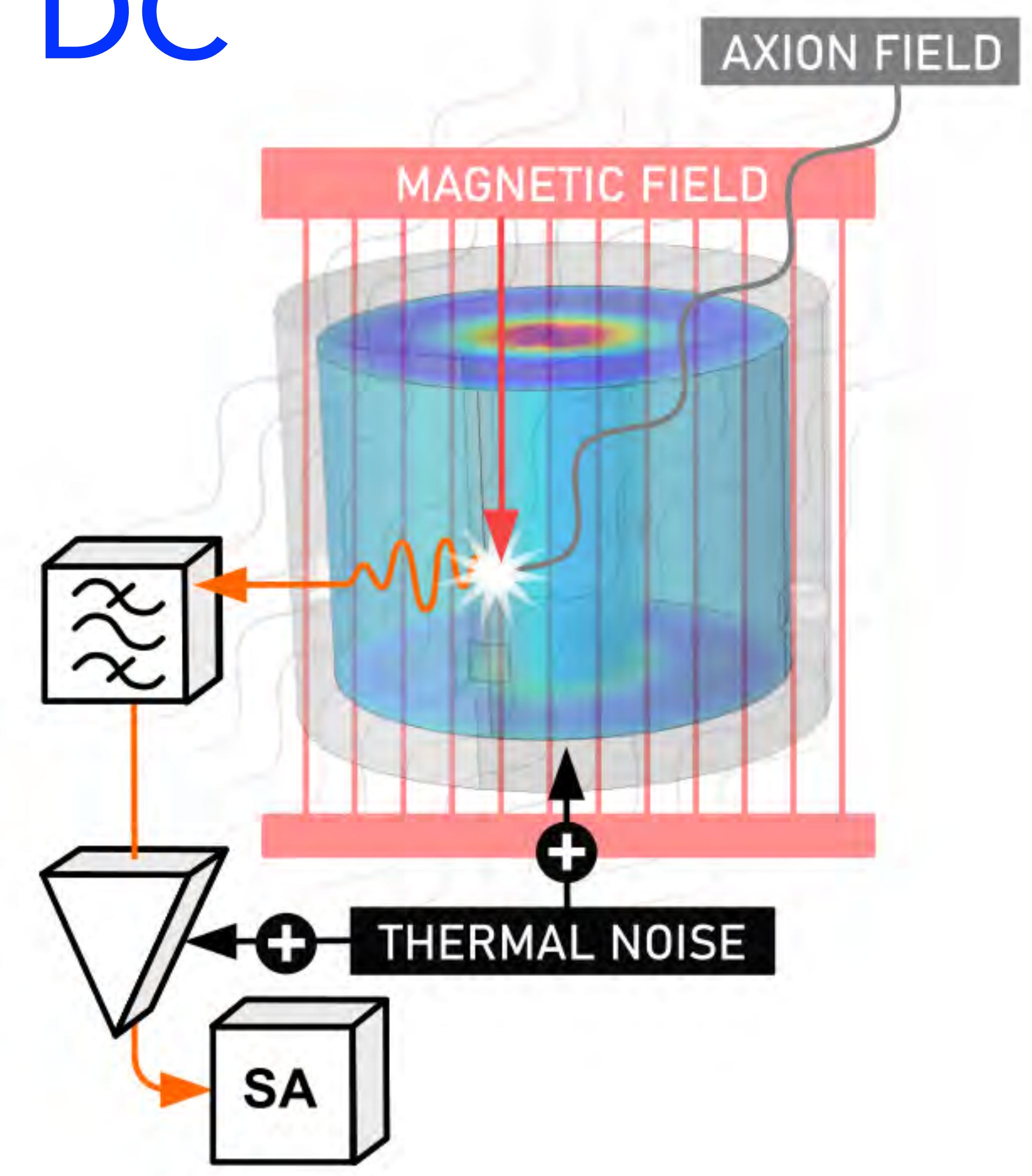

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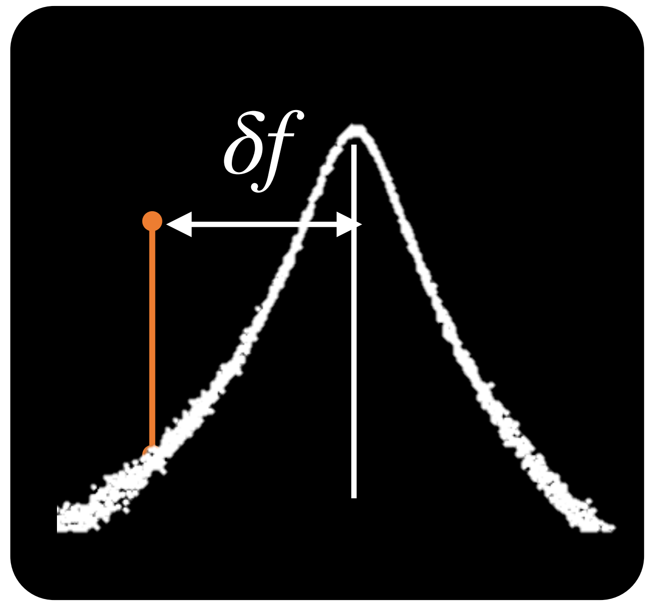
eg.
- ADMX
- ORGAN (UWA)
- CAPP
- HAYSTAC

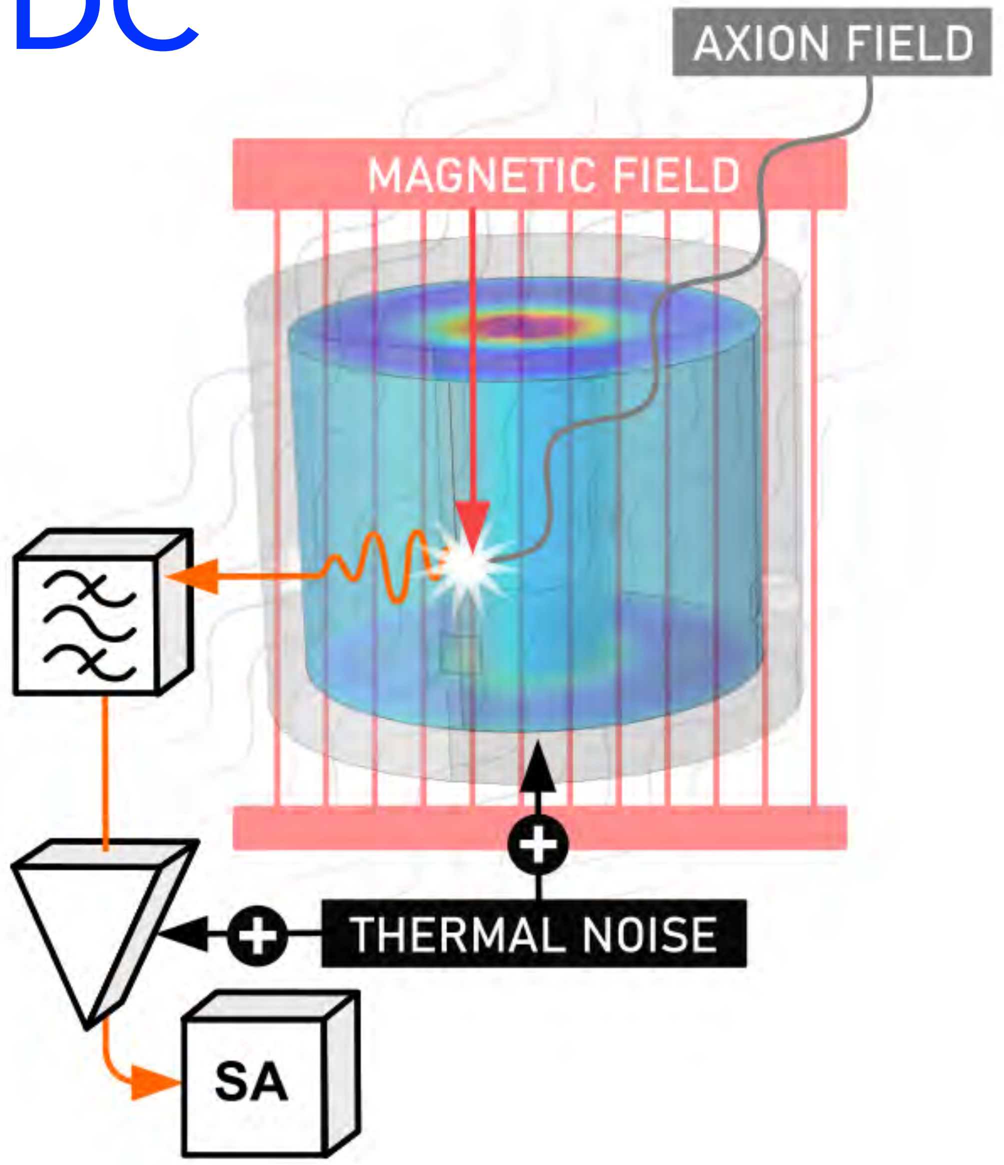


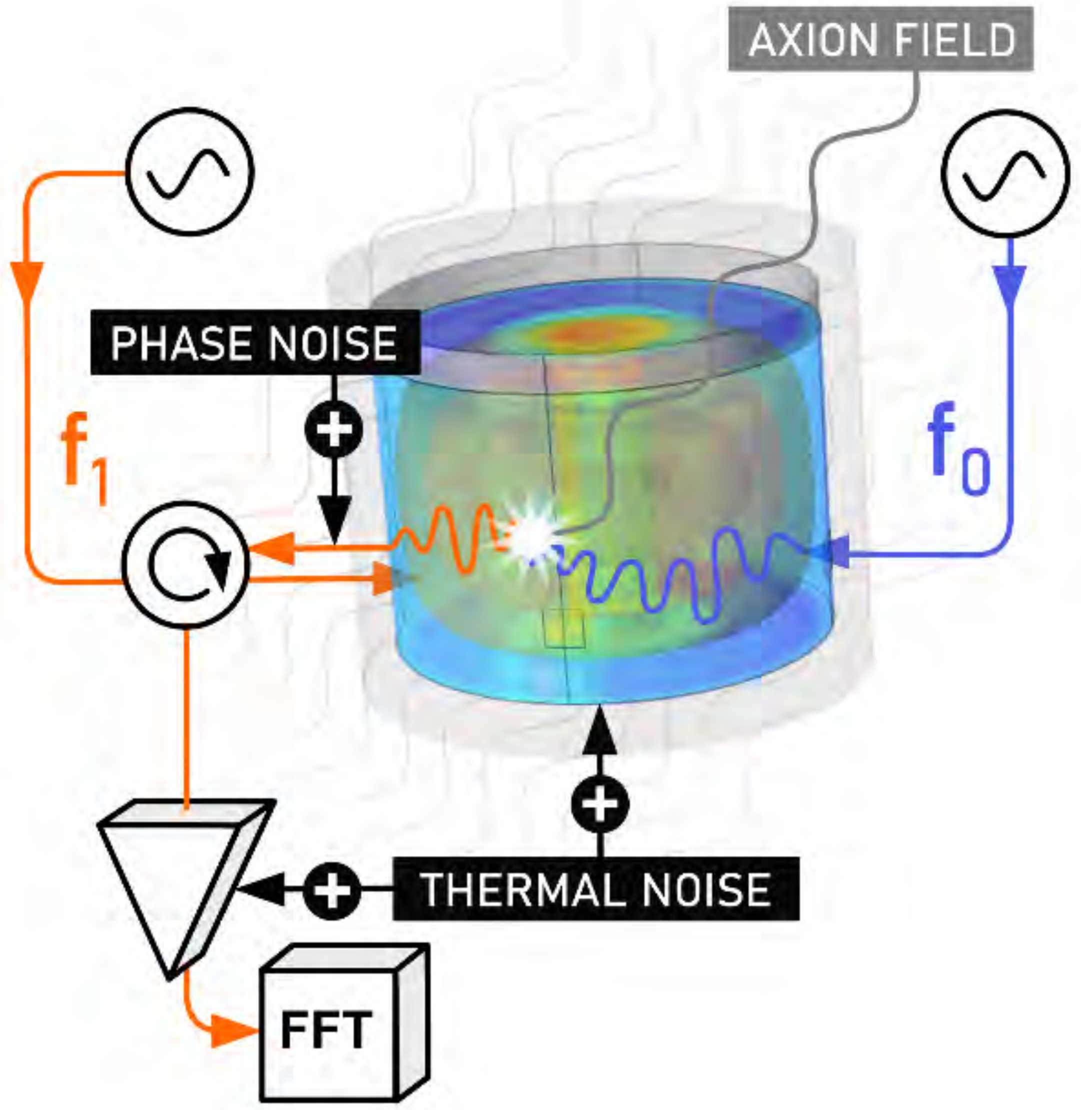
Resonant Axion Haloscopes @ UWA

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

AC Frequency

DC

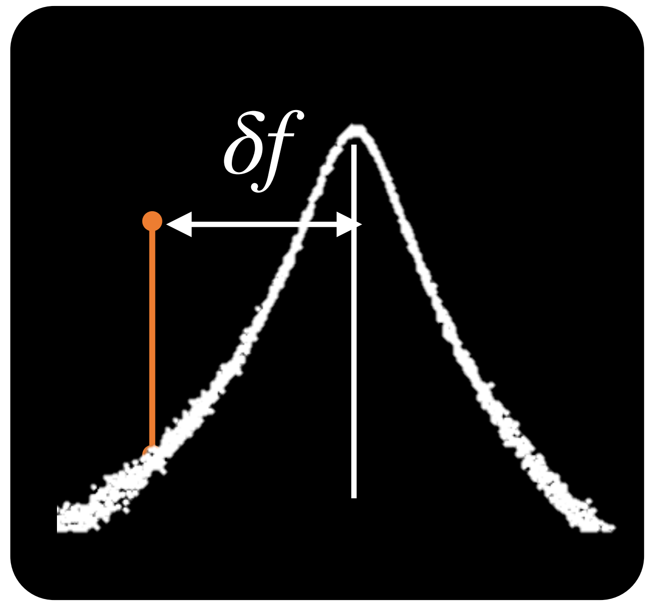




Photon 1: E field of cavity's resonant transverse magnetic mode, $m_a = f_1 + \delta f$

Photon 0, Back ground DC B field of surrounding magnet

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



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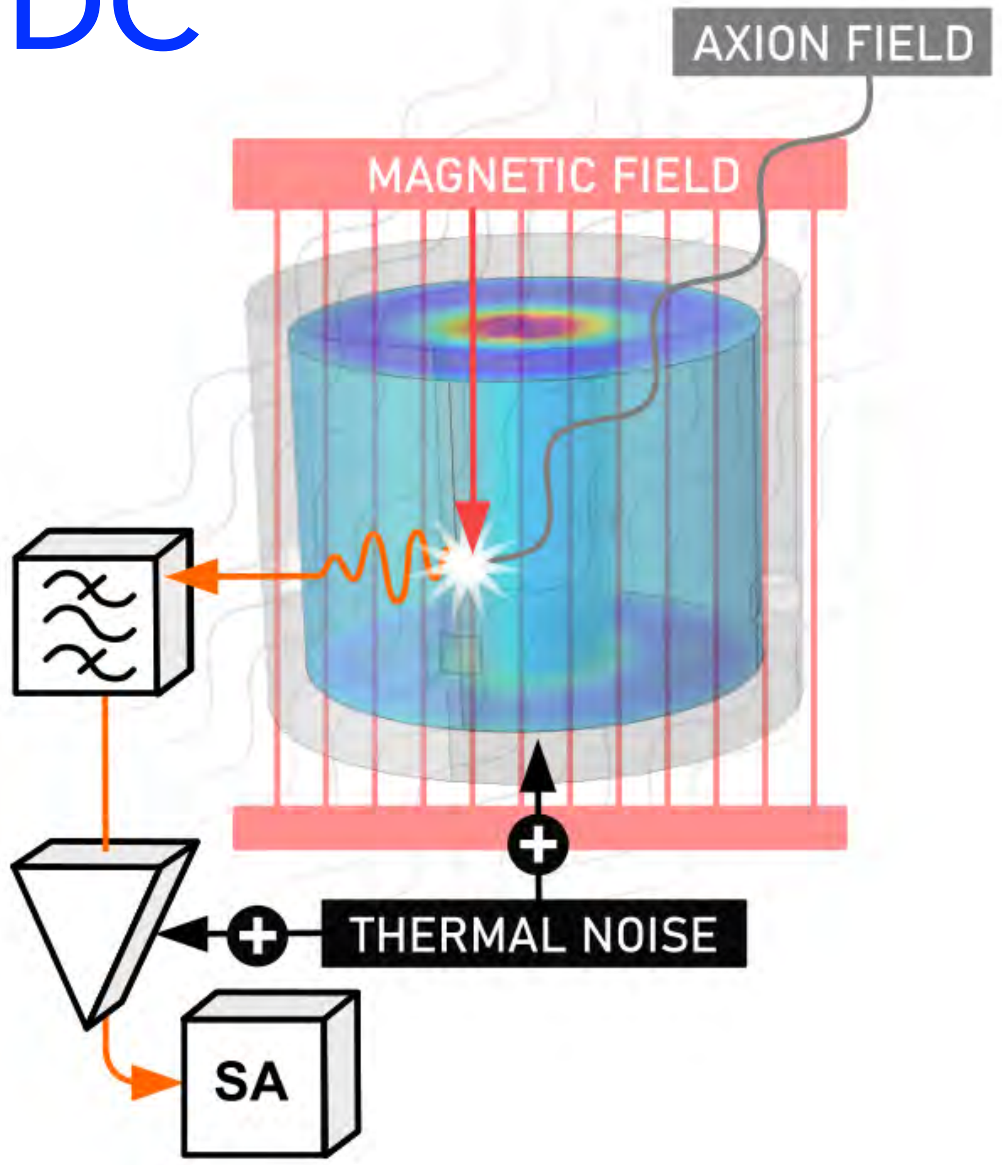

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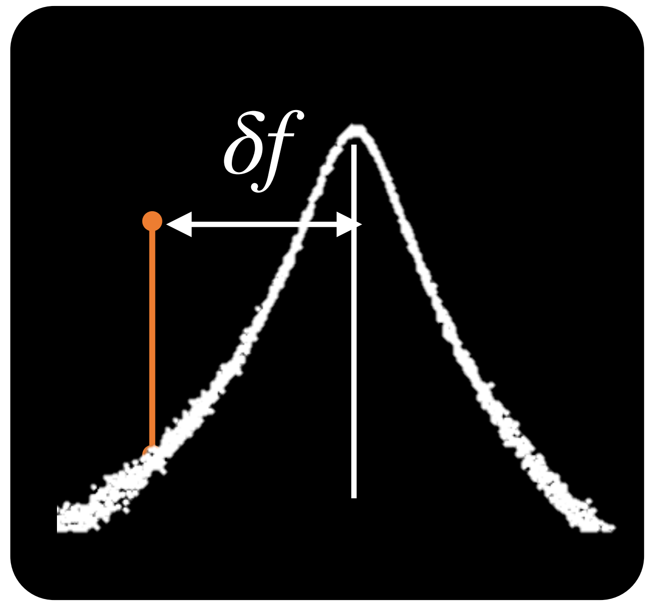
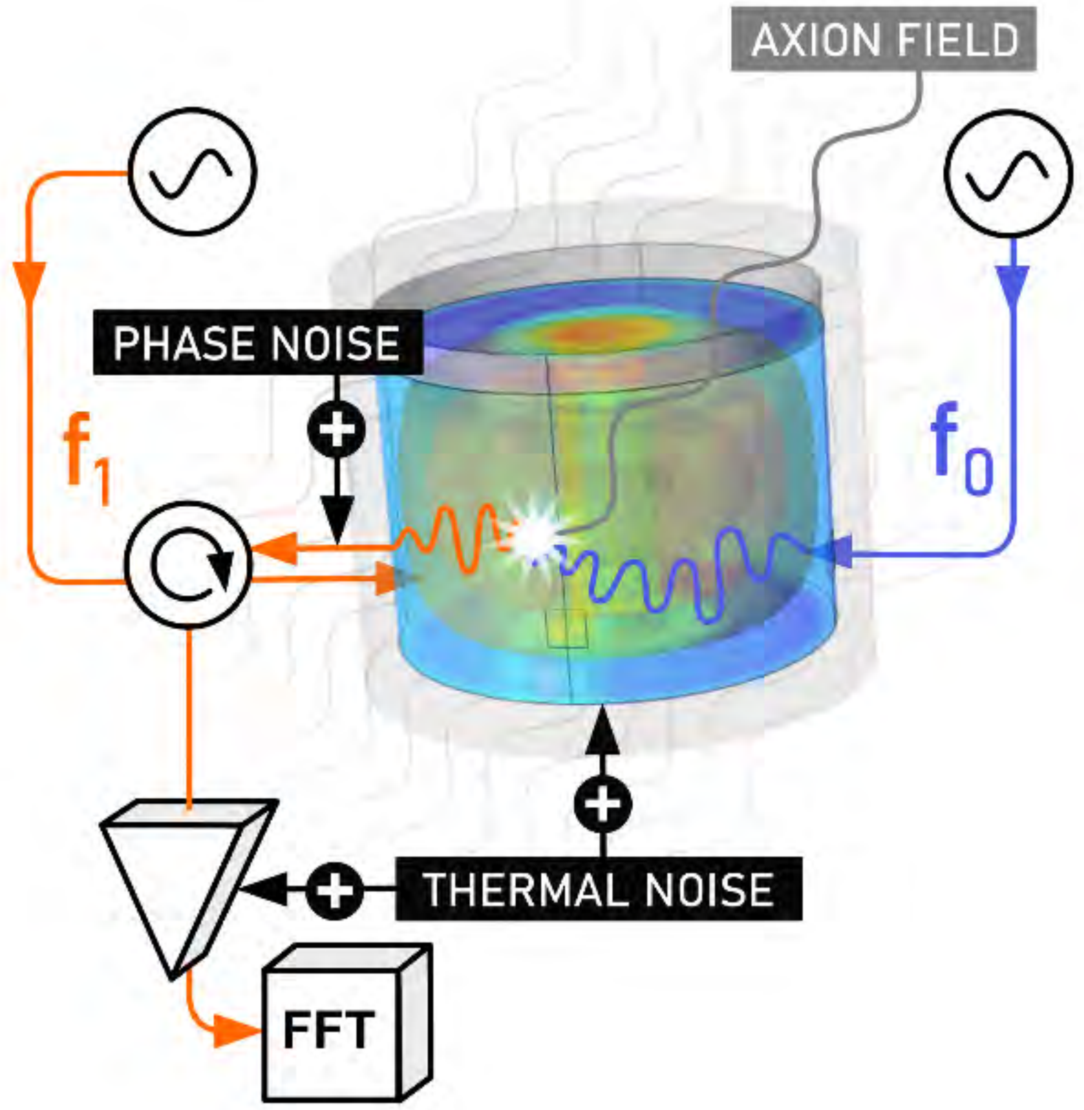
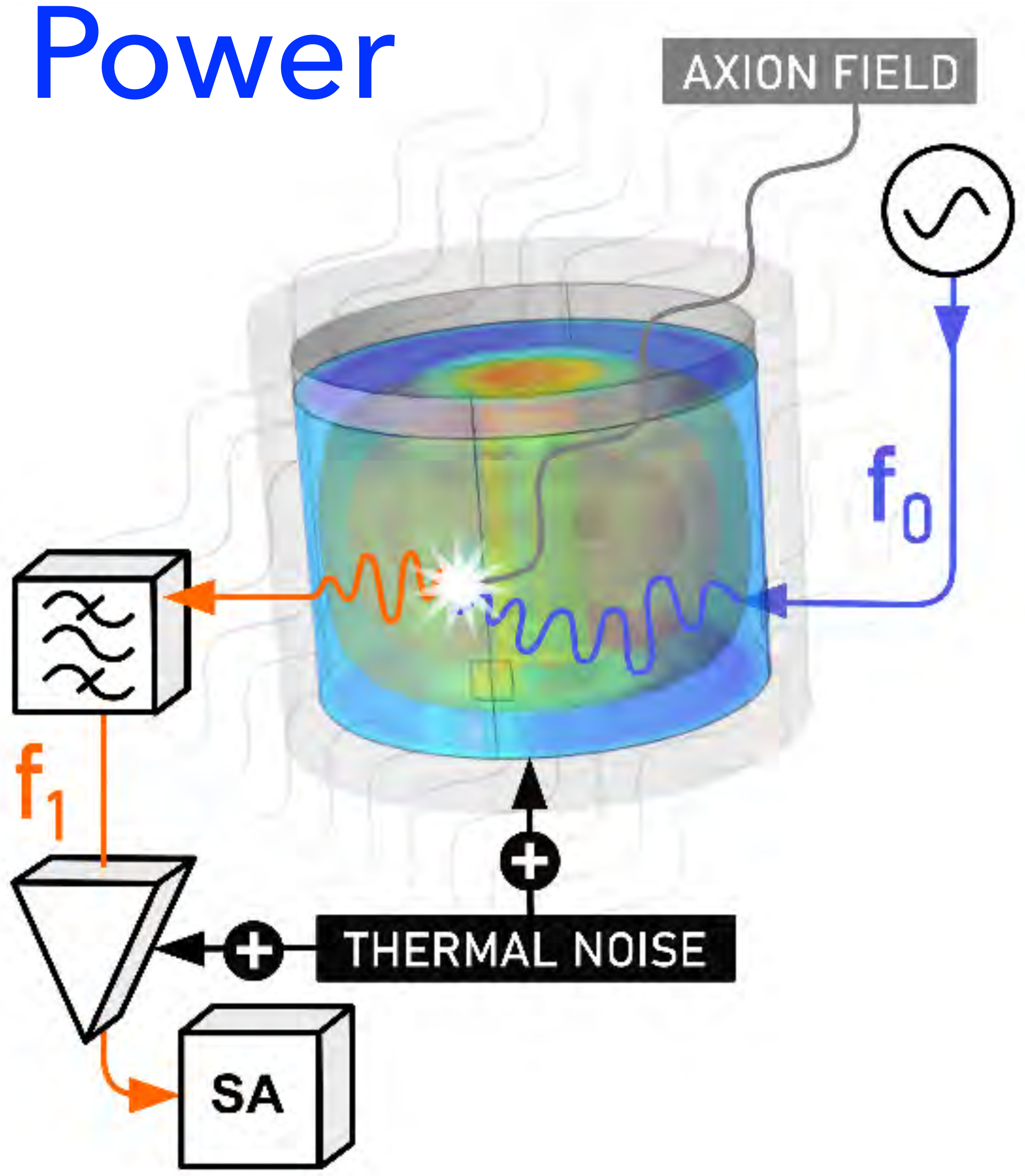


AC Frequency



AC Power



Resonant Axion Haloscopes @ UWA

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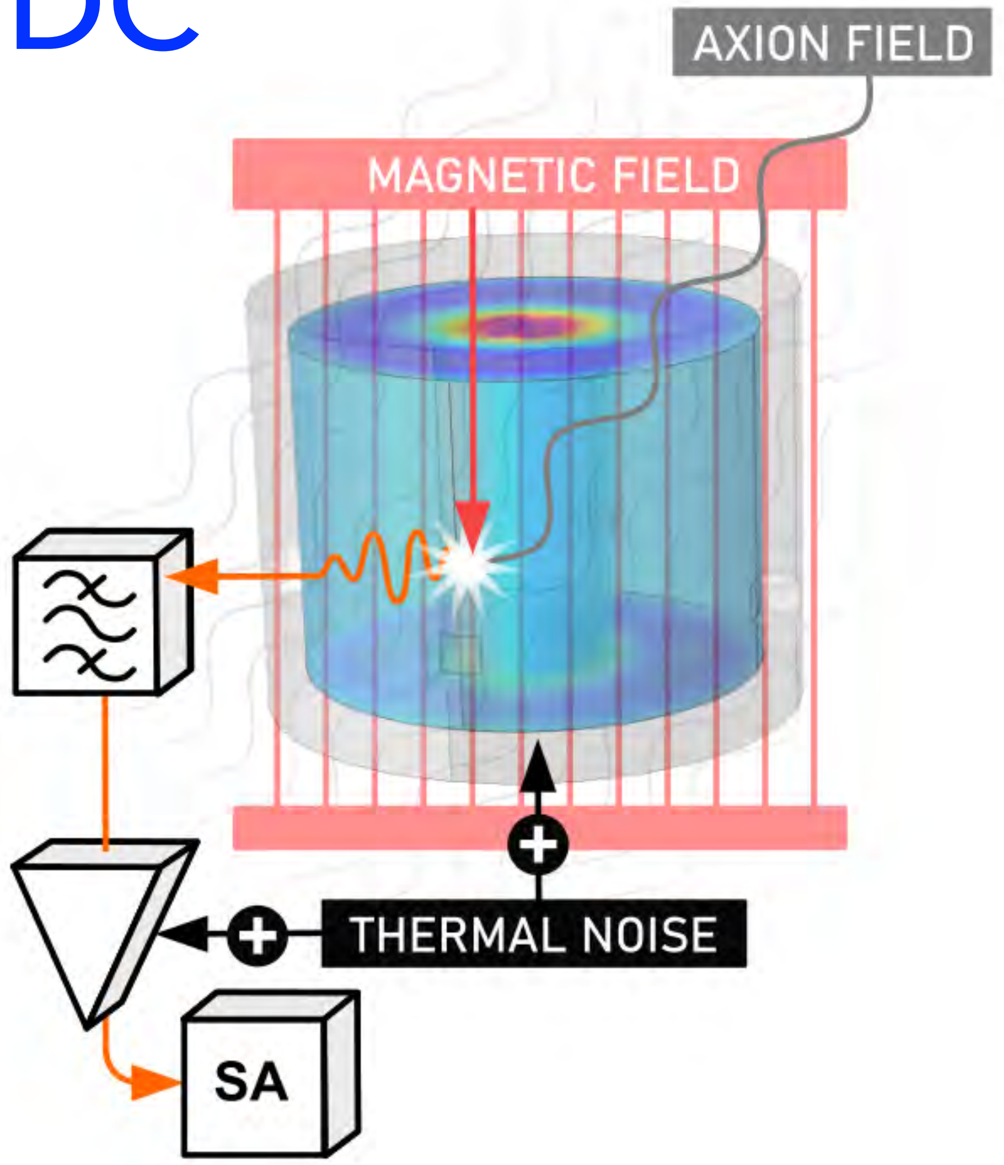
DC



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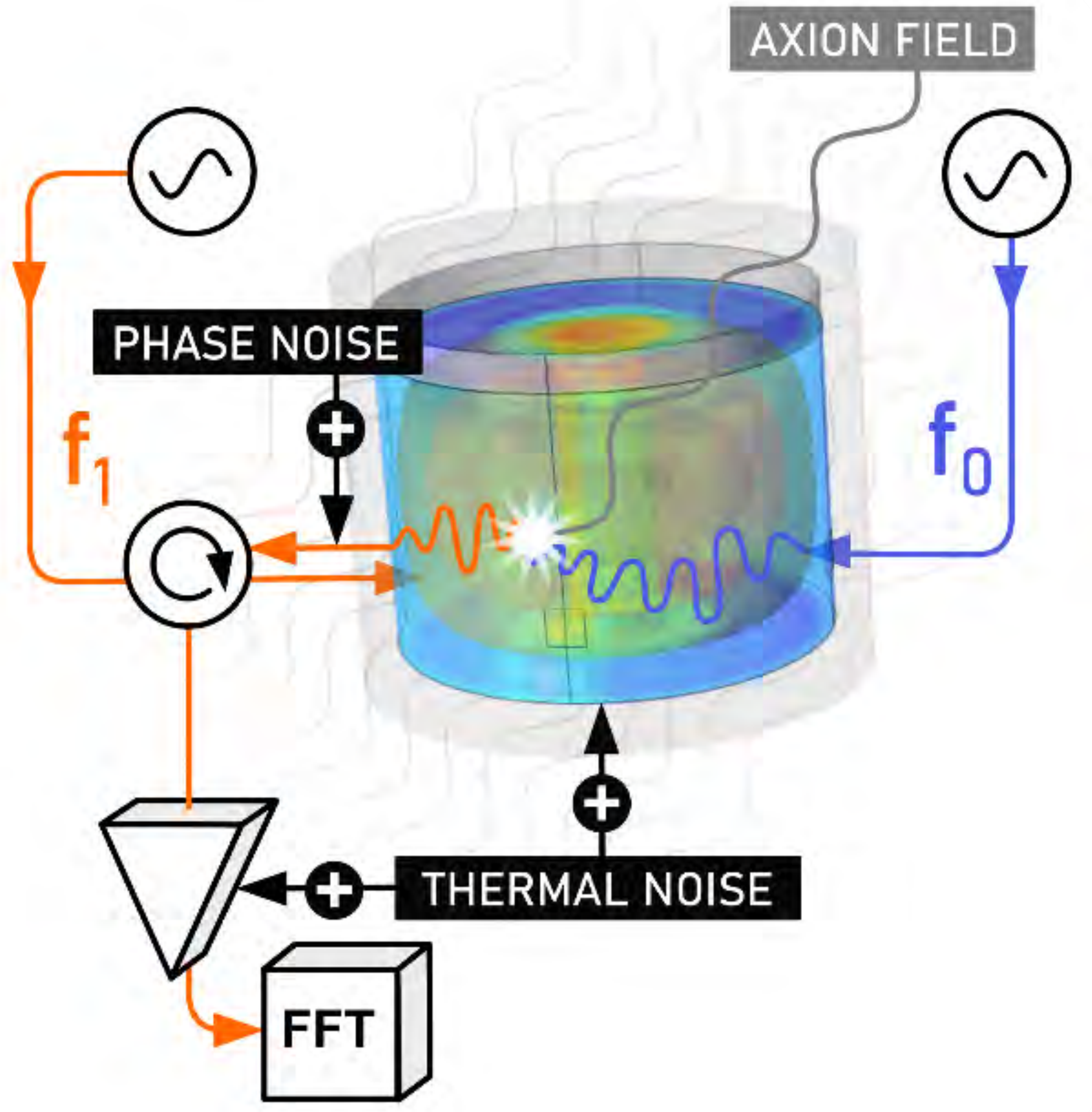
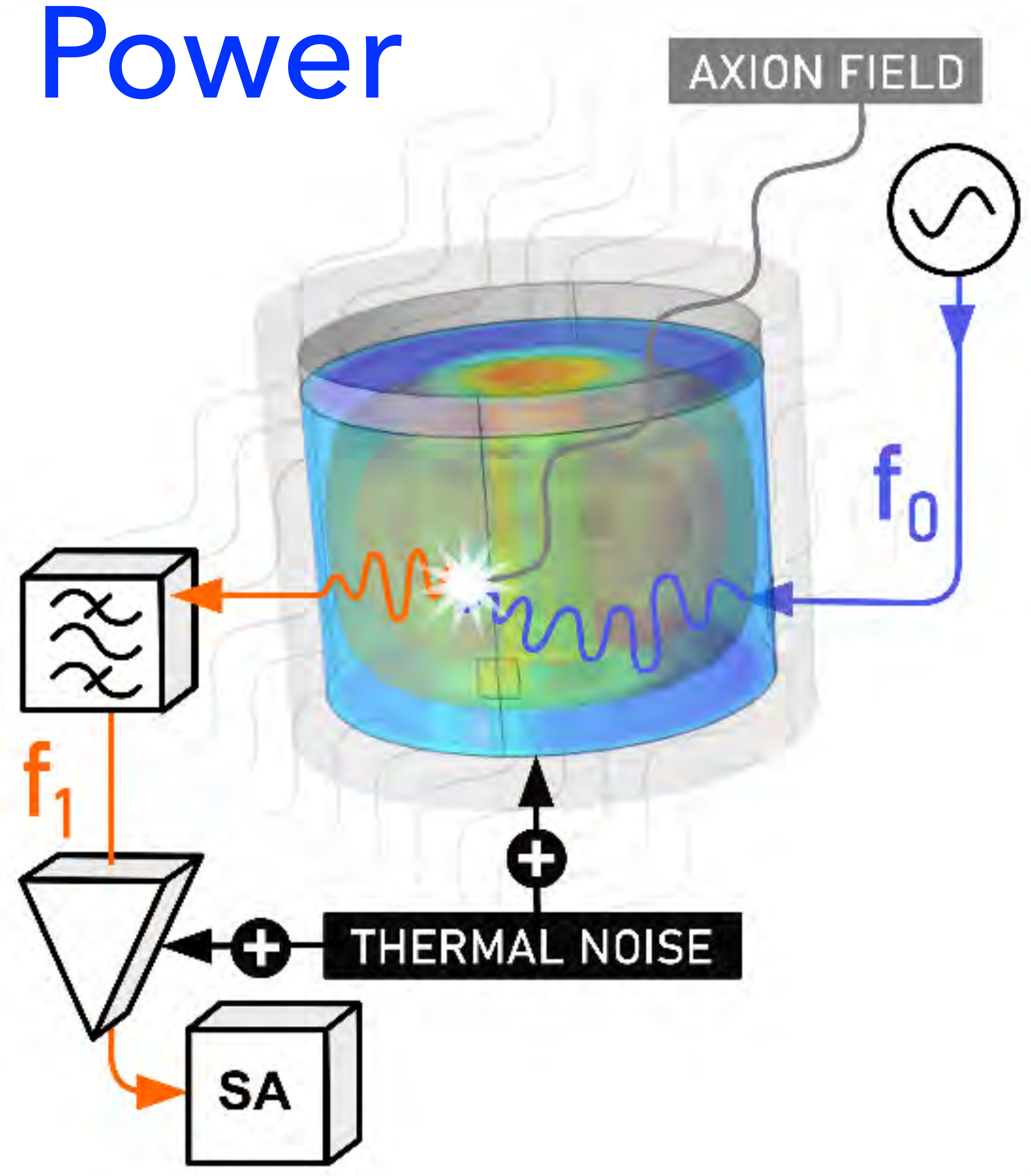


AC Power



- Use a mode 0 as the background “magnetic field” AC source

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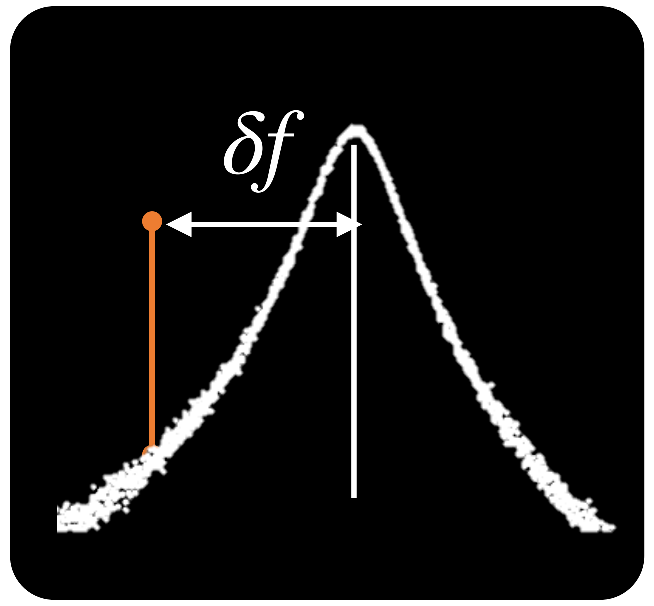

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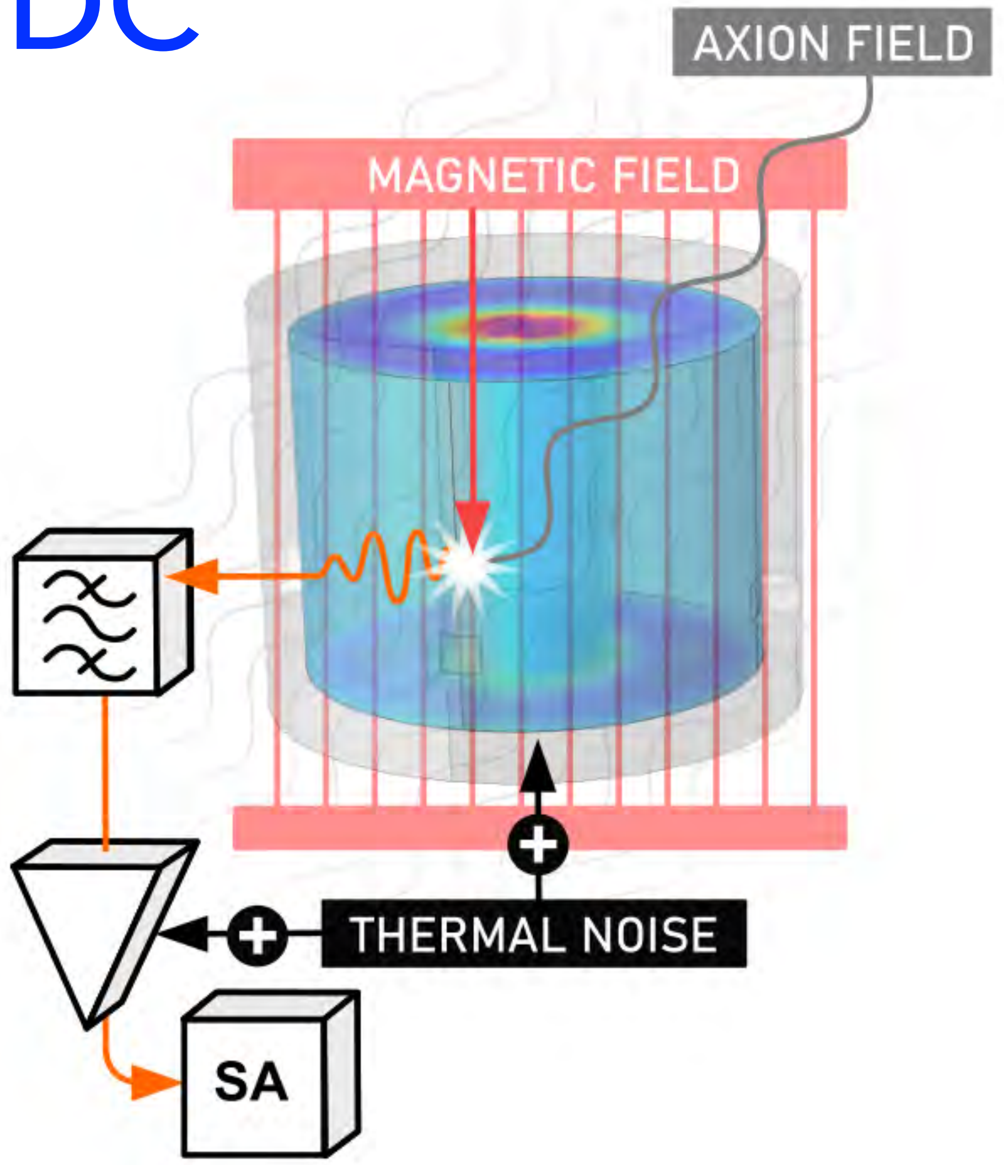

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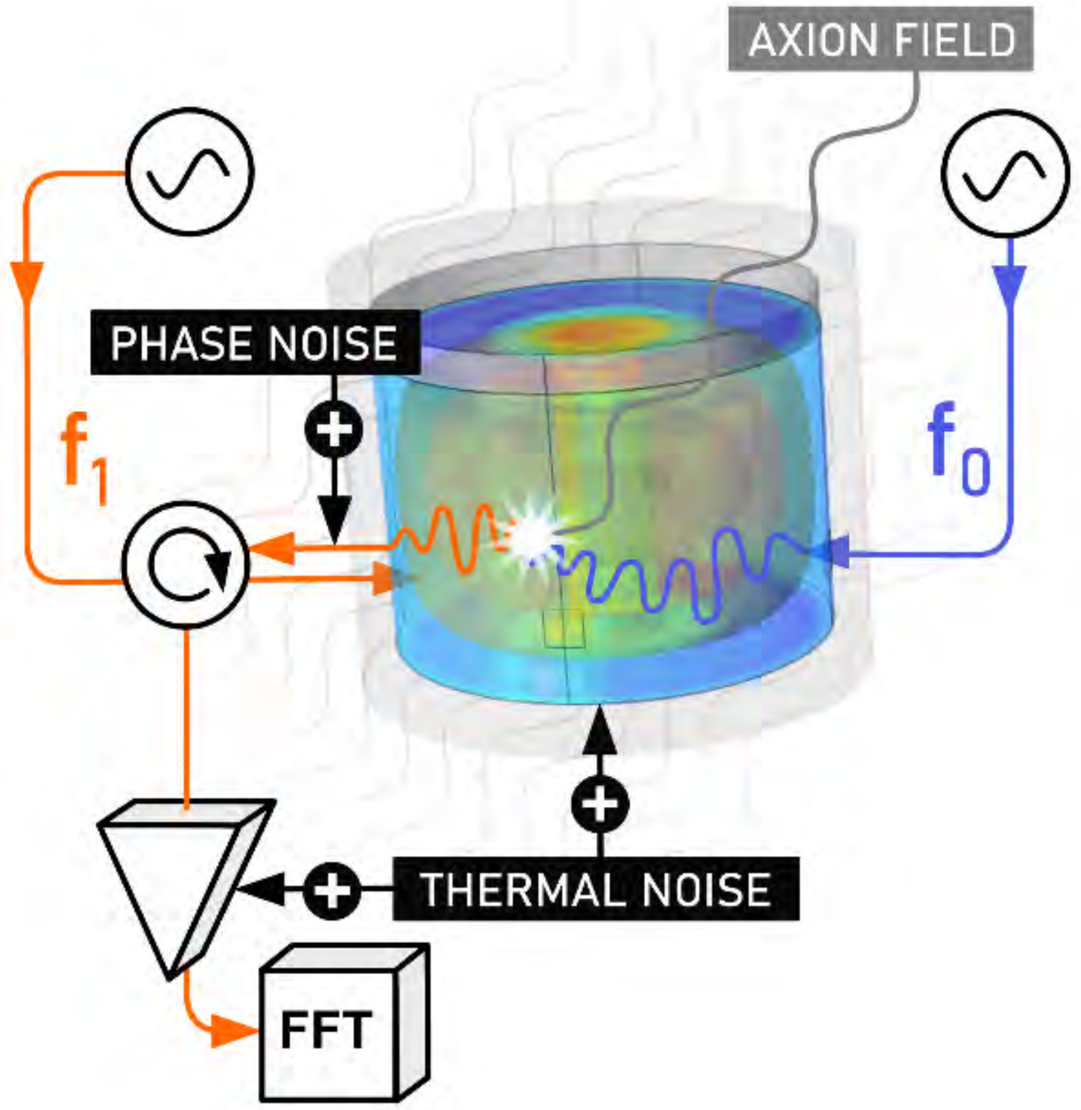

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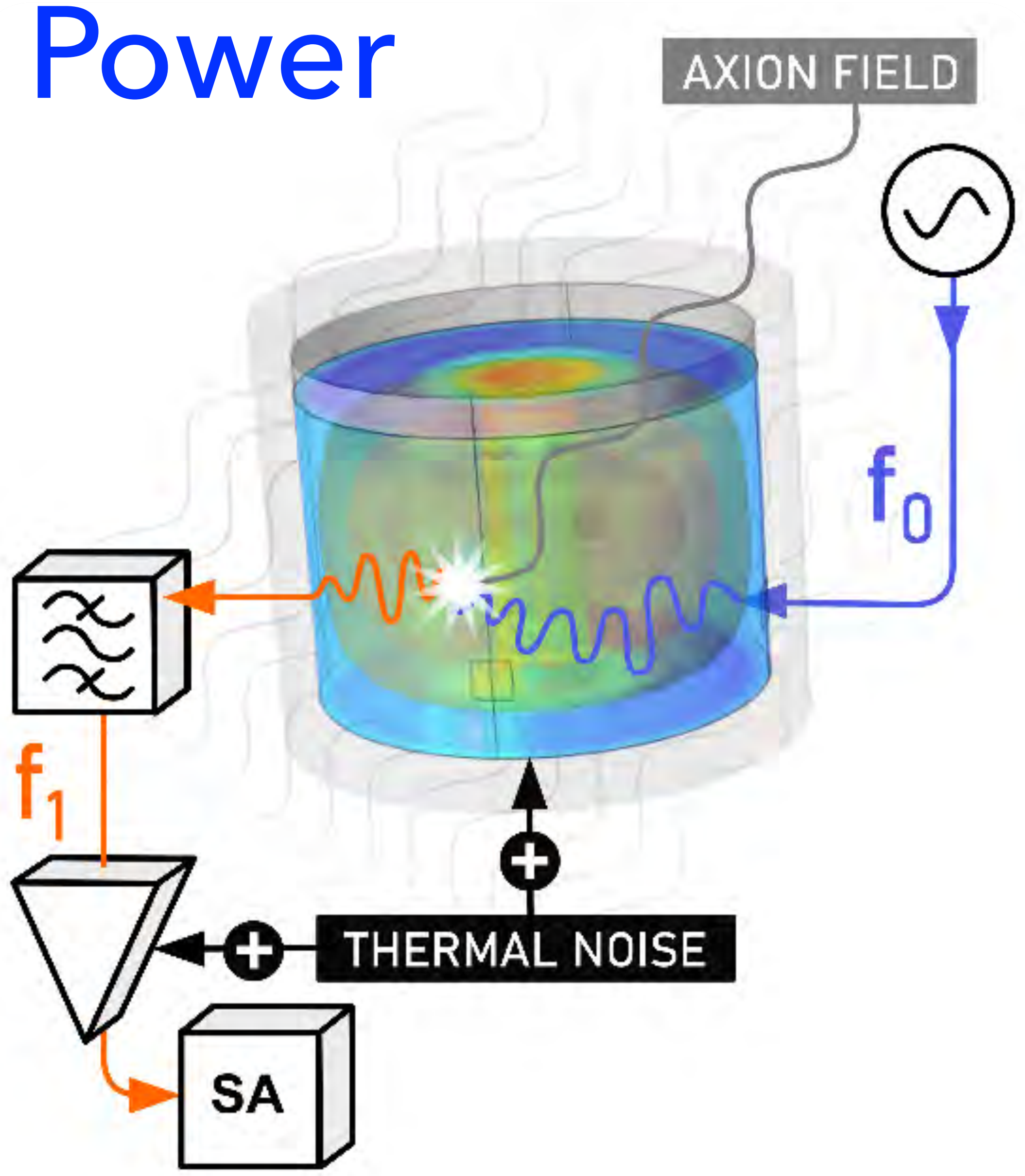

- Use a mode 0 as the background “magnetic field” AC source
- Two modes in one cylindrical cavity

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

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eg.
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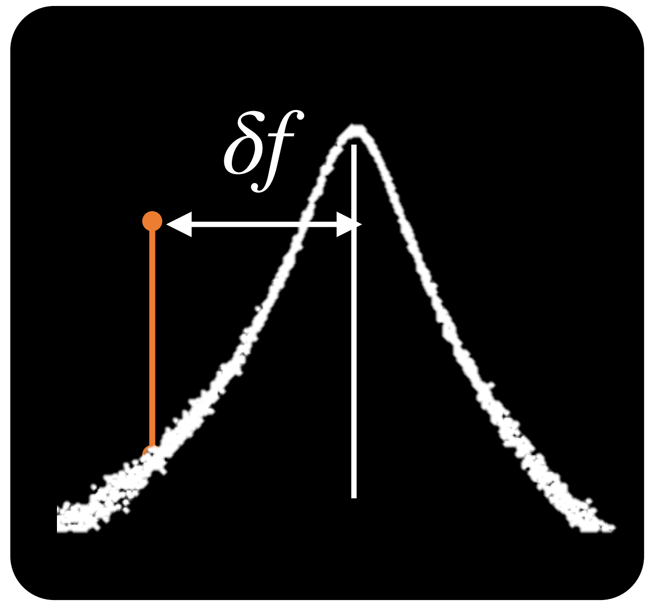

Resonant Axion Haloscopes @ UWA

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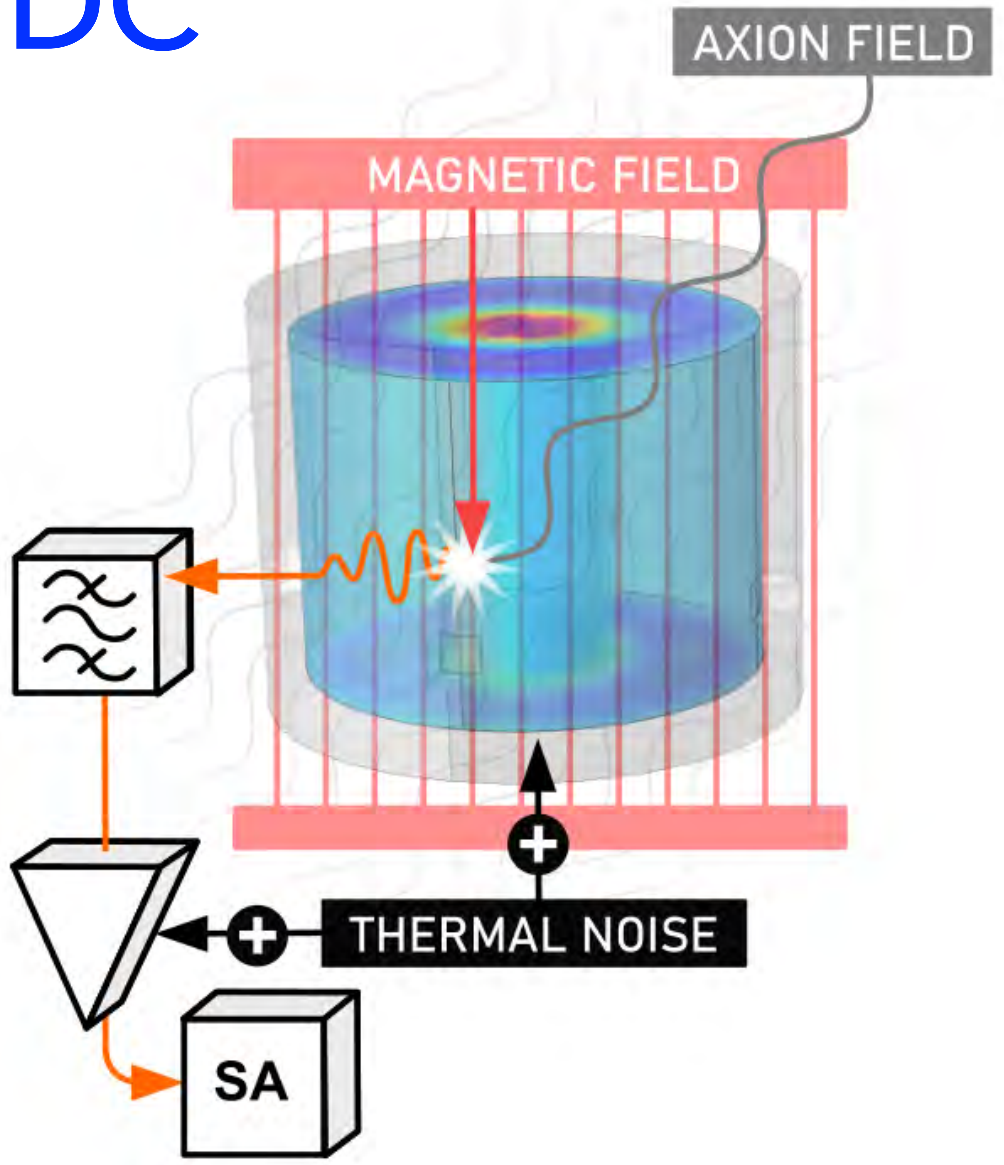

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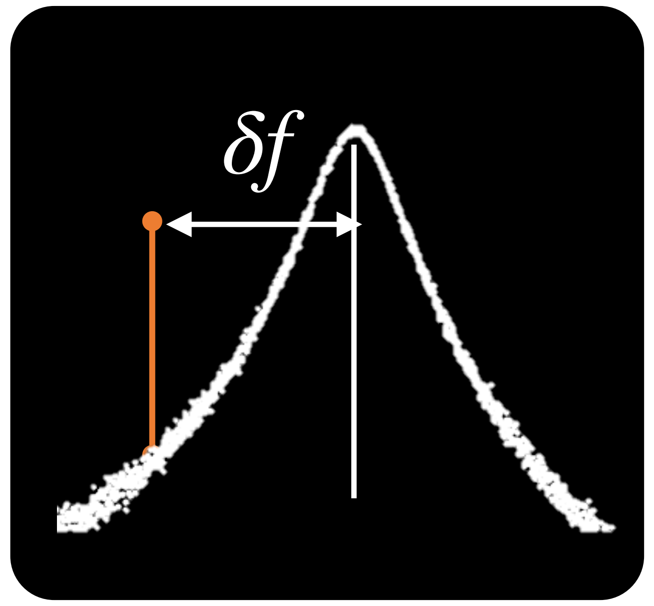

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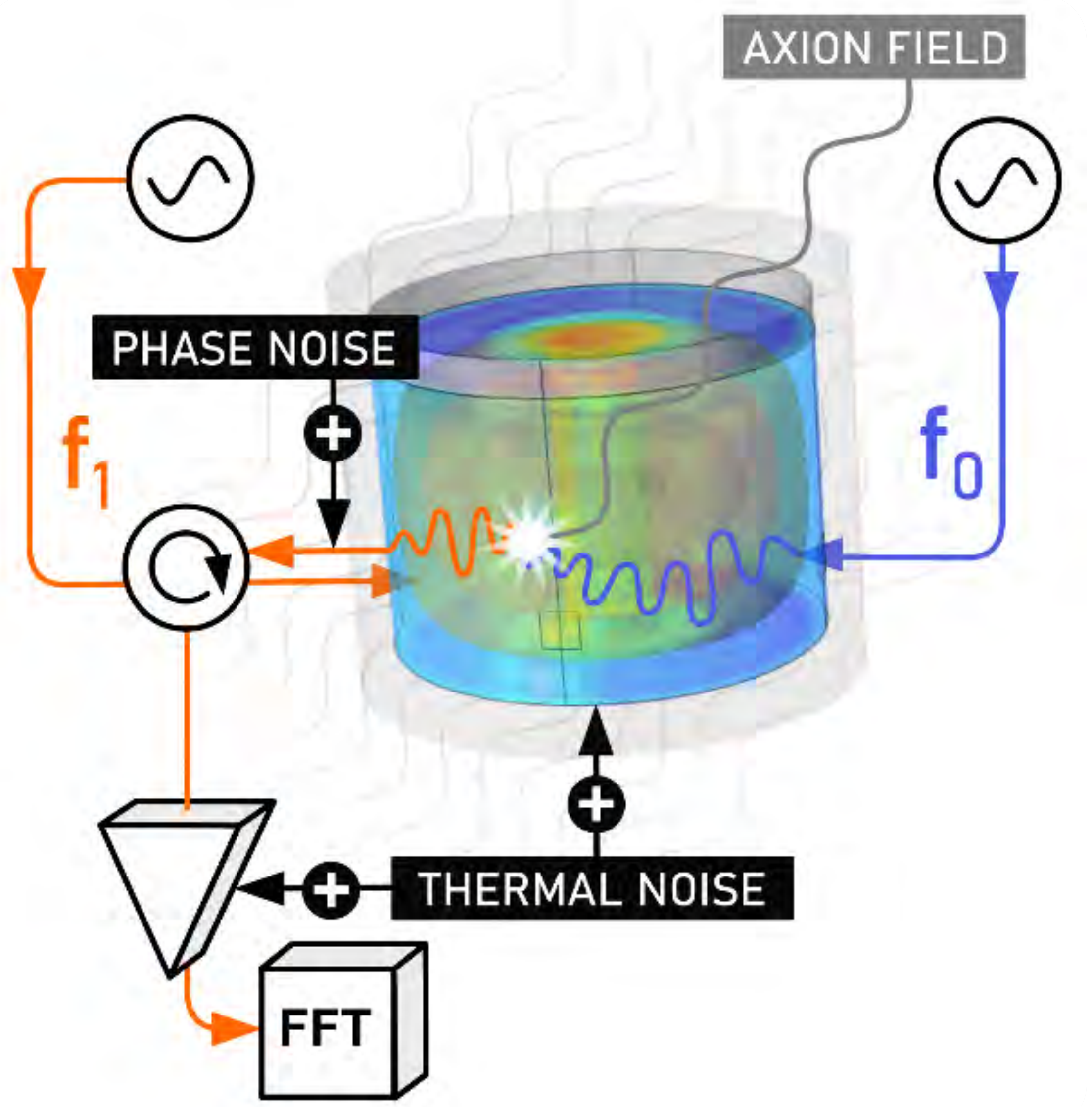

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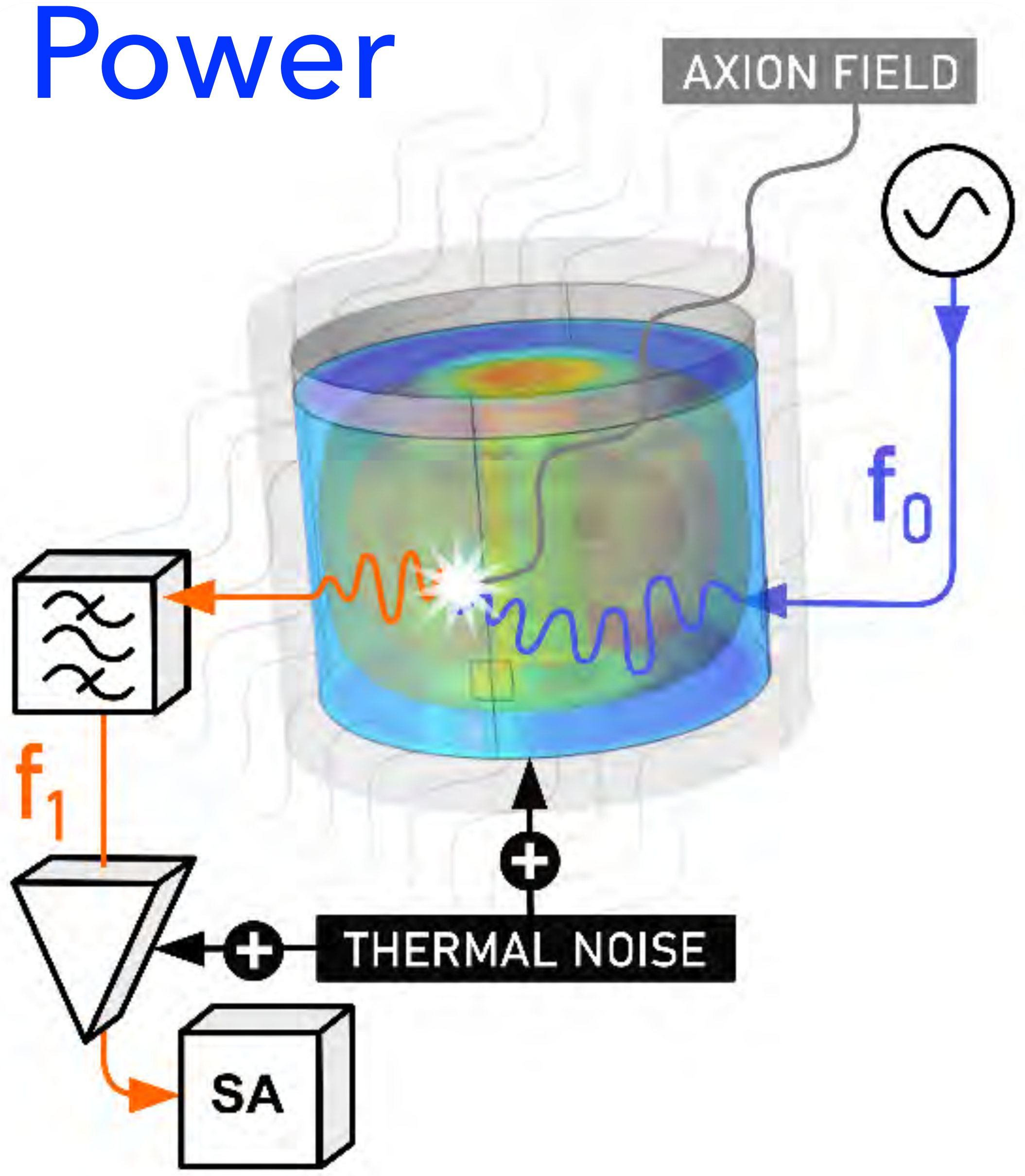

- Use a mode 0 as the background "magnetic field" AC source
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- Upconversion limit $m_a = |f_1 - f_0| + \delta f$

Resonant Axion Haloscopes @ UWA

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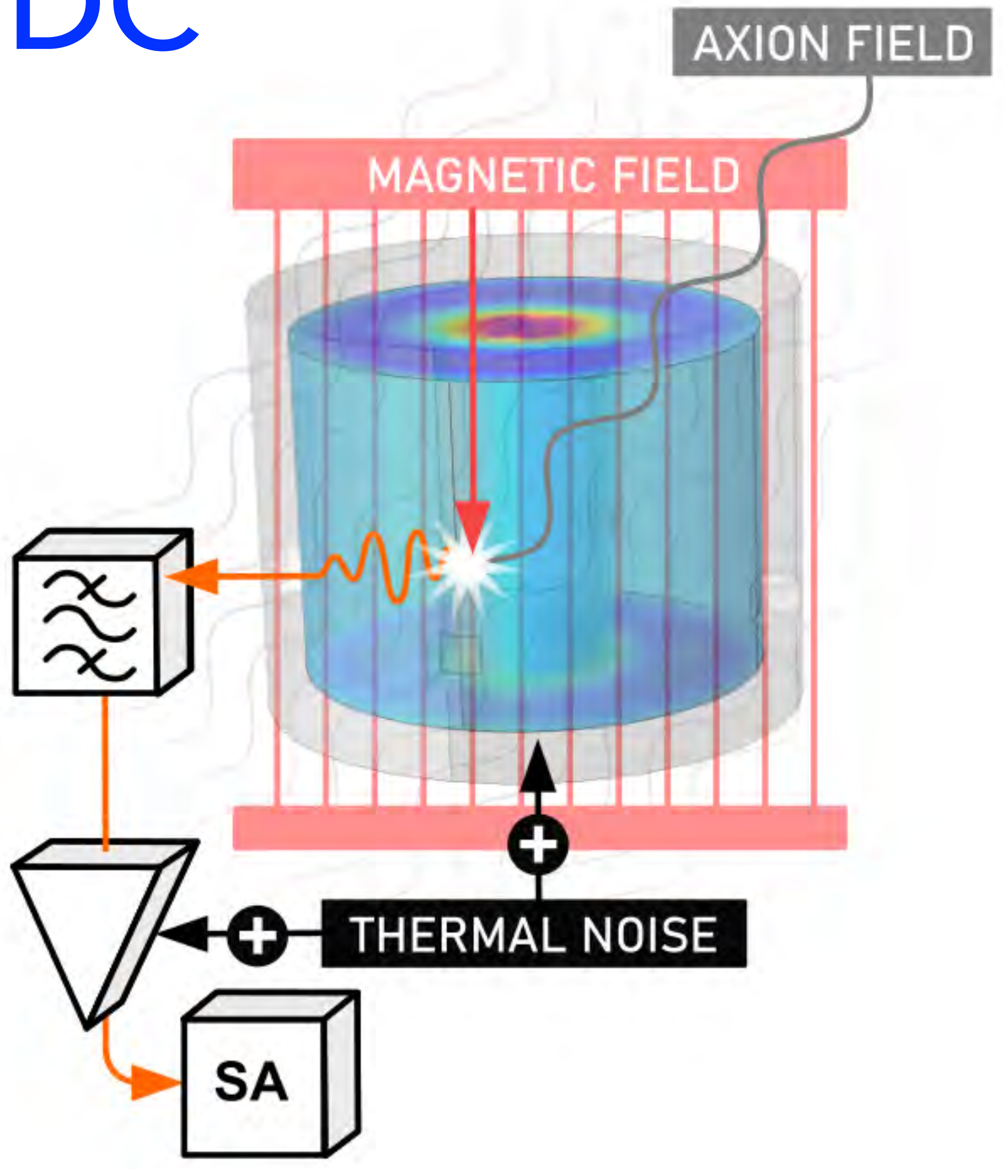

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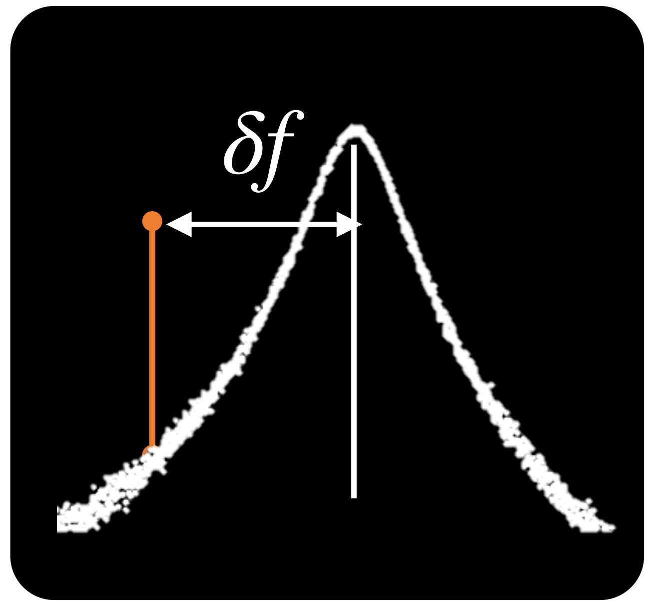

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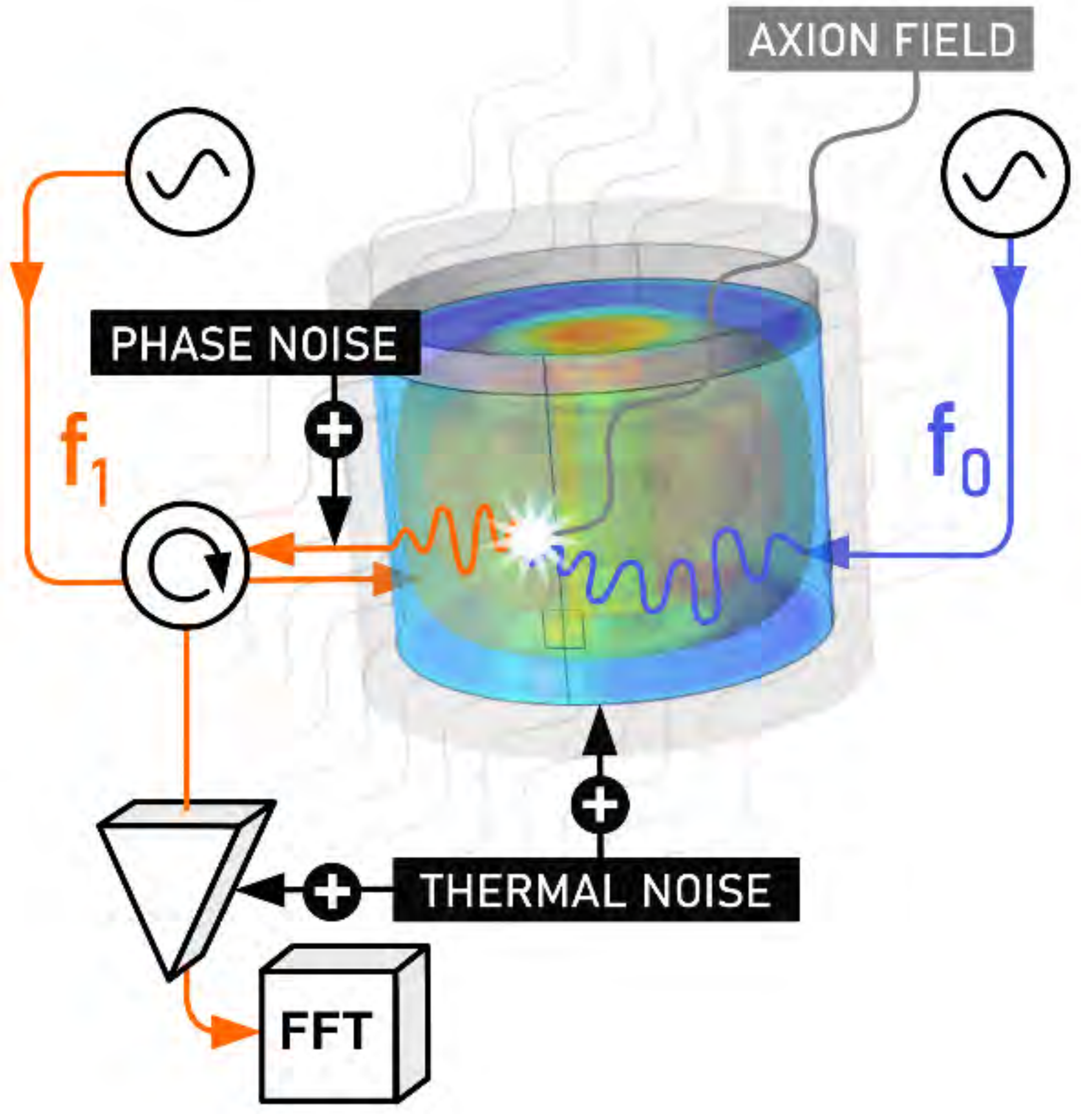

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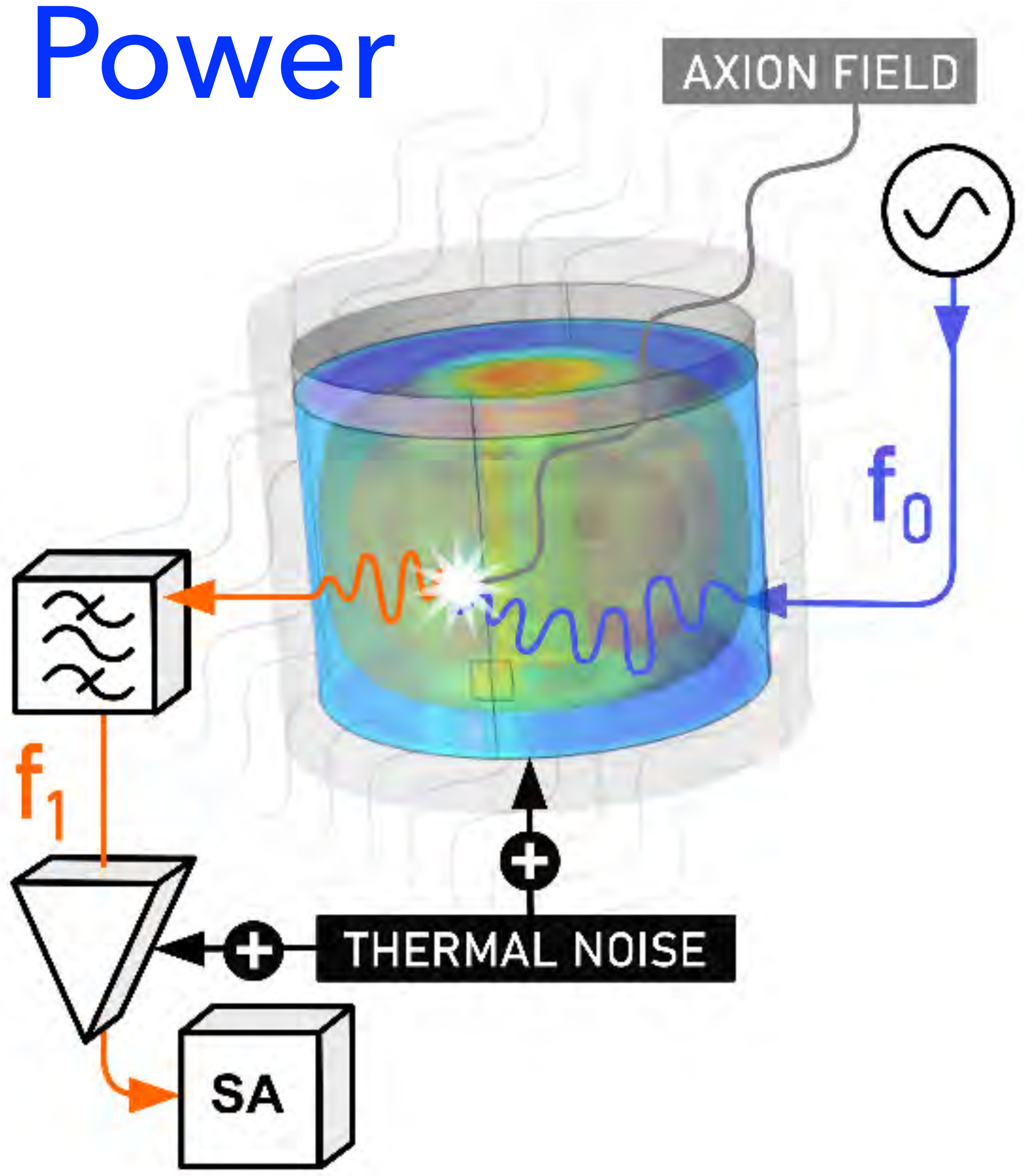

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- Two modes in one cylindrical cavity
- Upconversion limit $m_a = |f_1 - f_0| + \delta f$

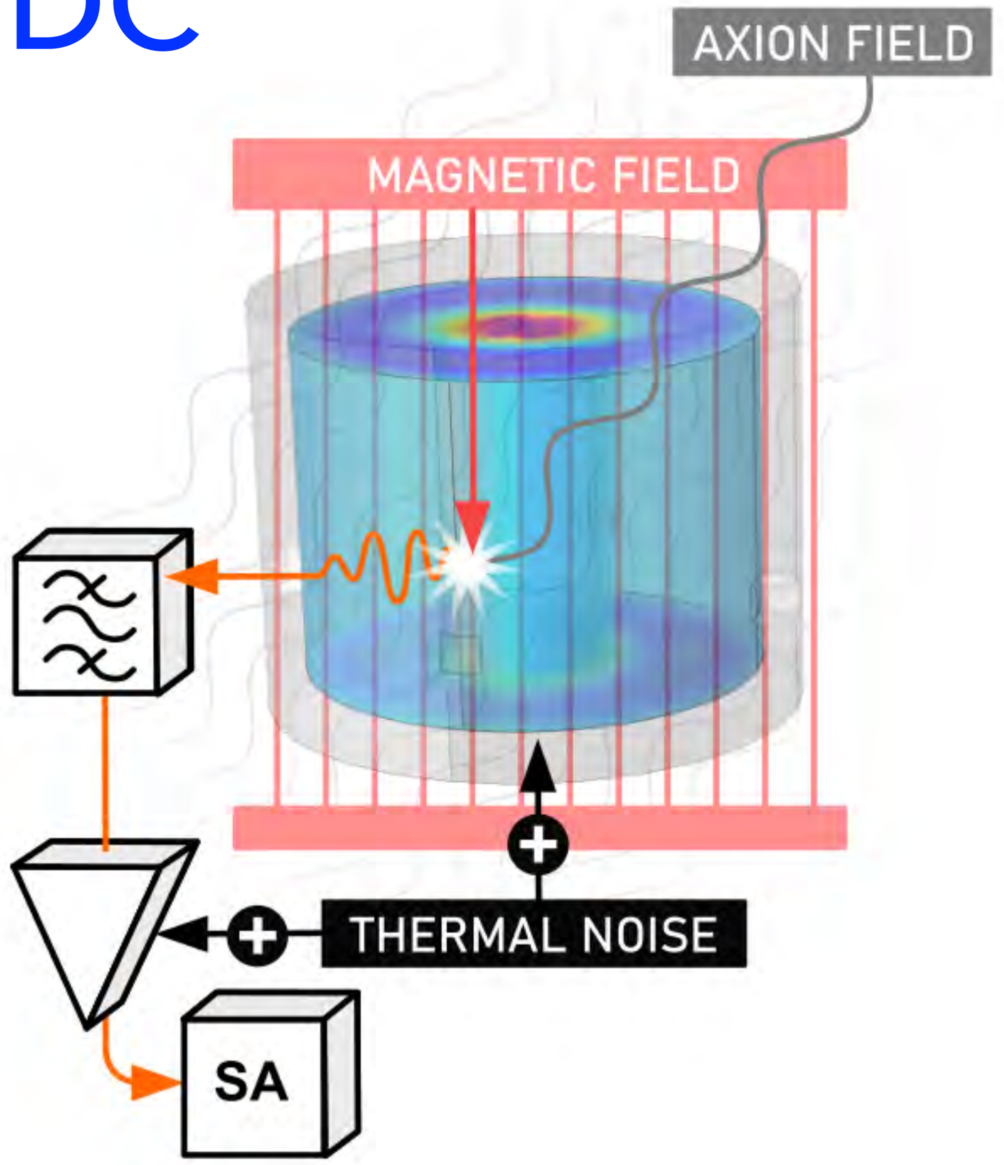
Photon 1: Transverse Magnetic Mode

(Longitudinal Electric)

Resonant Axion Haloscopes @ UWA

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

DC



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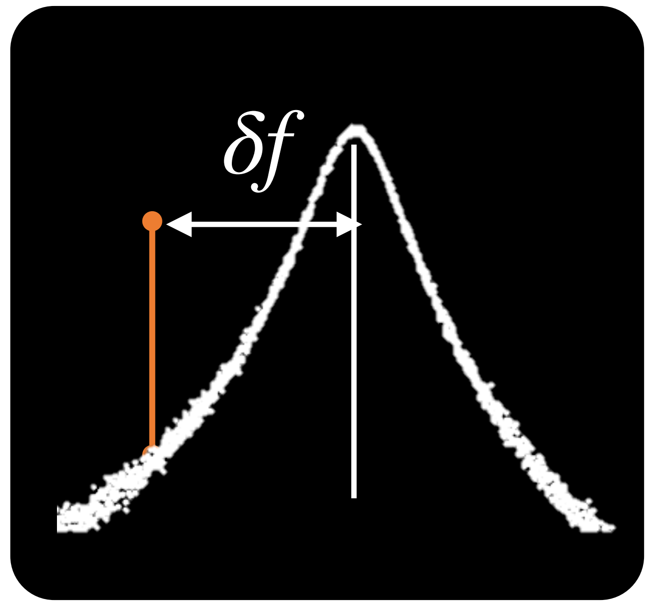

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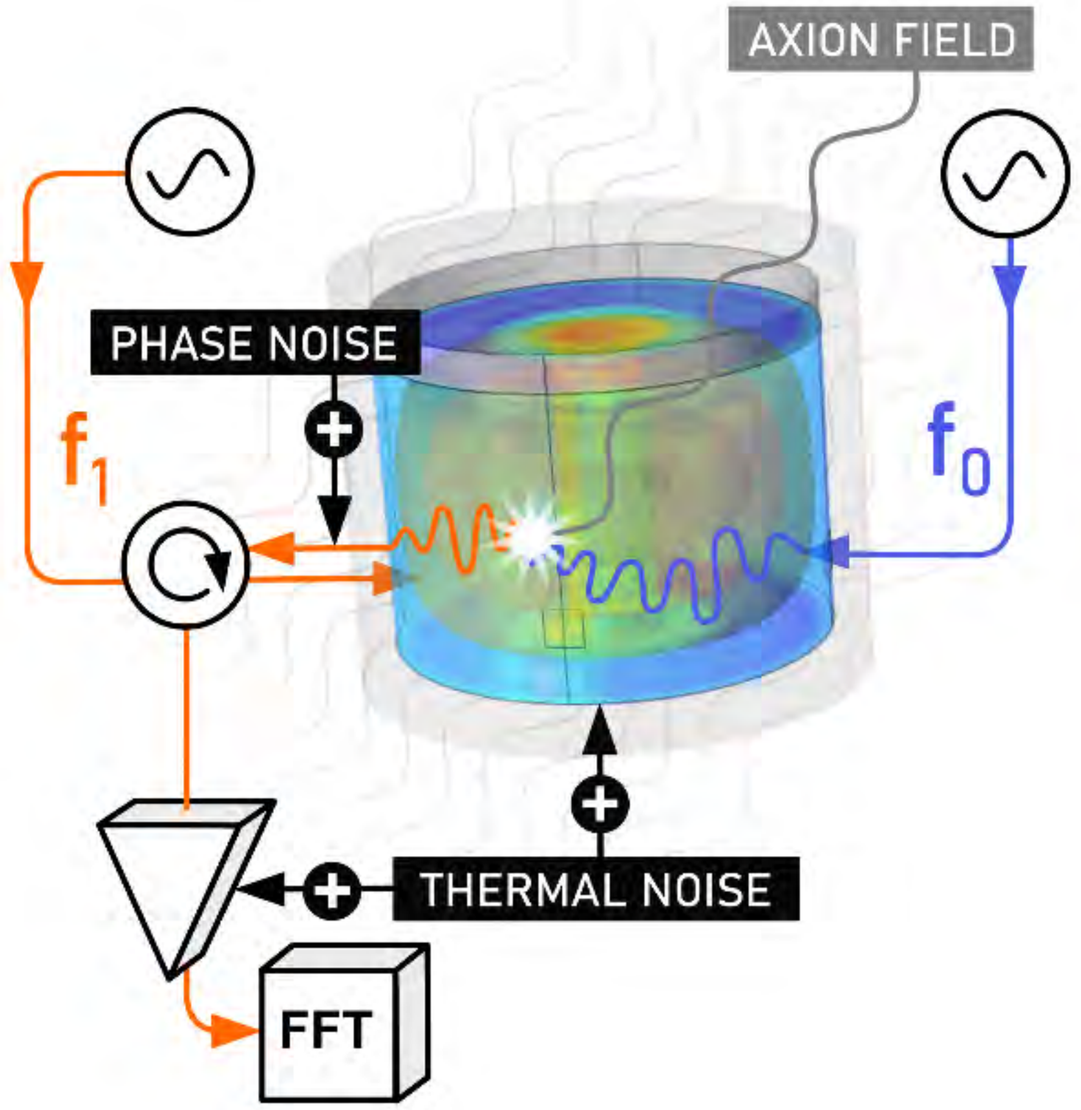

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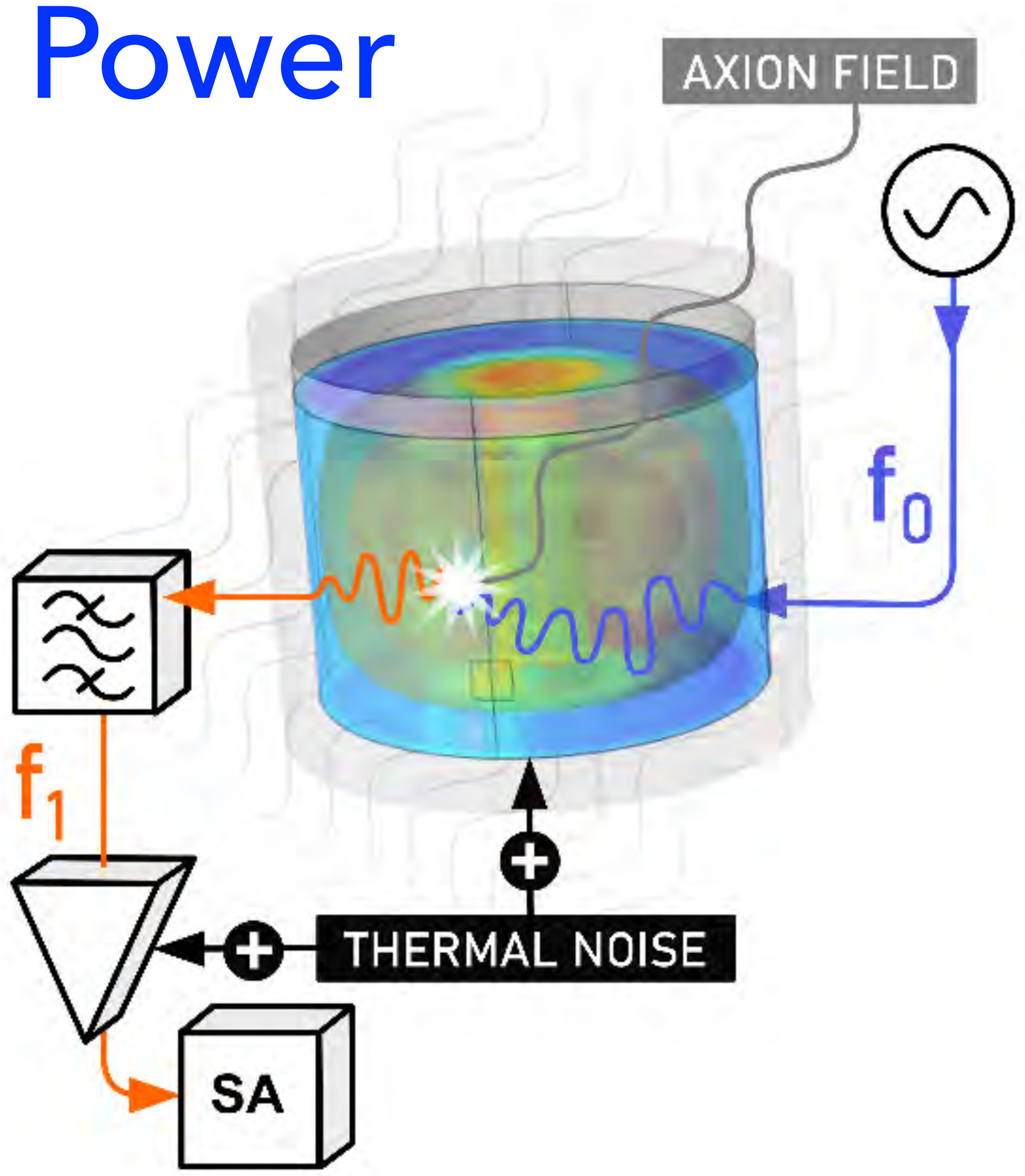

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Photon 1: Transverse Magnetic Mode

(Longitudinal Electric)

Photon 0: Transverse Electric Mode

(Longitudinal Magnetic)

Resonant Axion Haloscopes @ UWA

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

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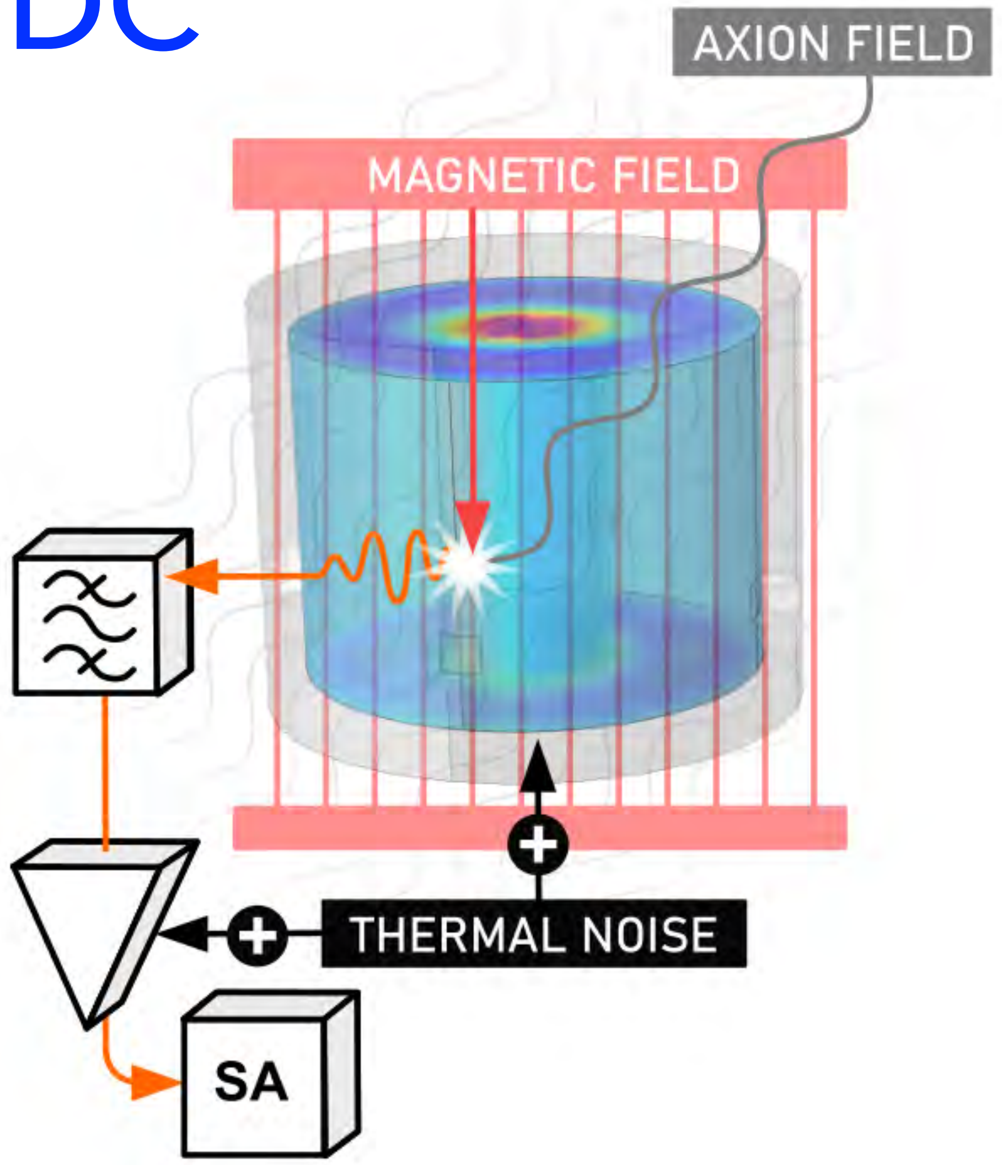

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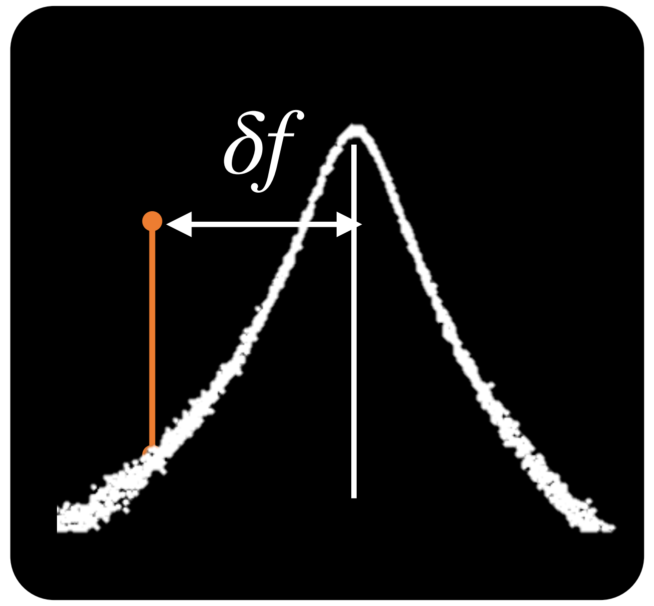

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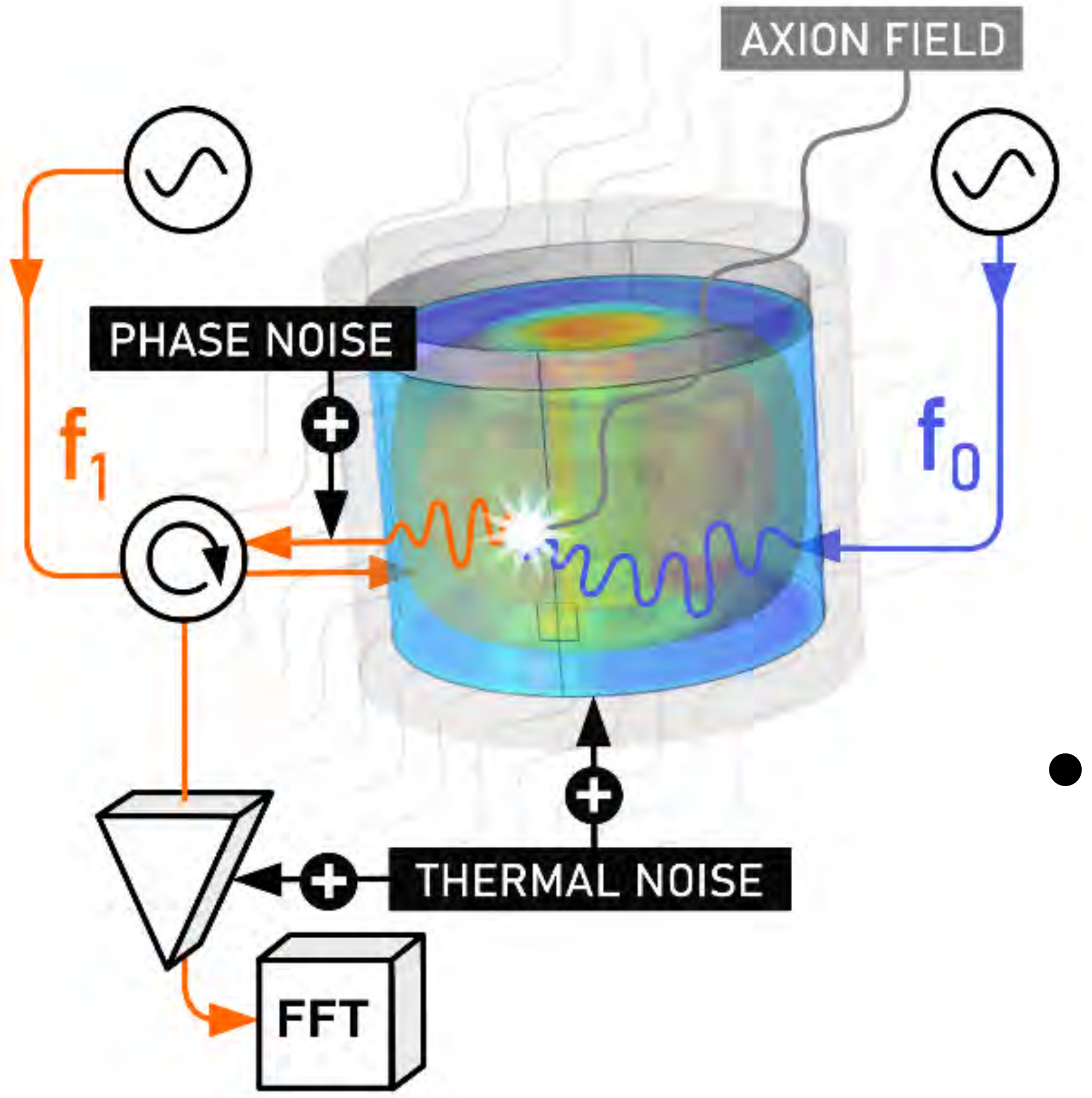
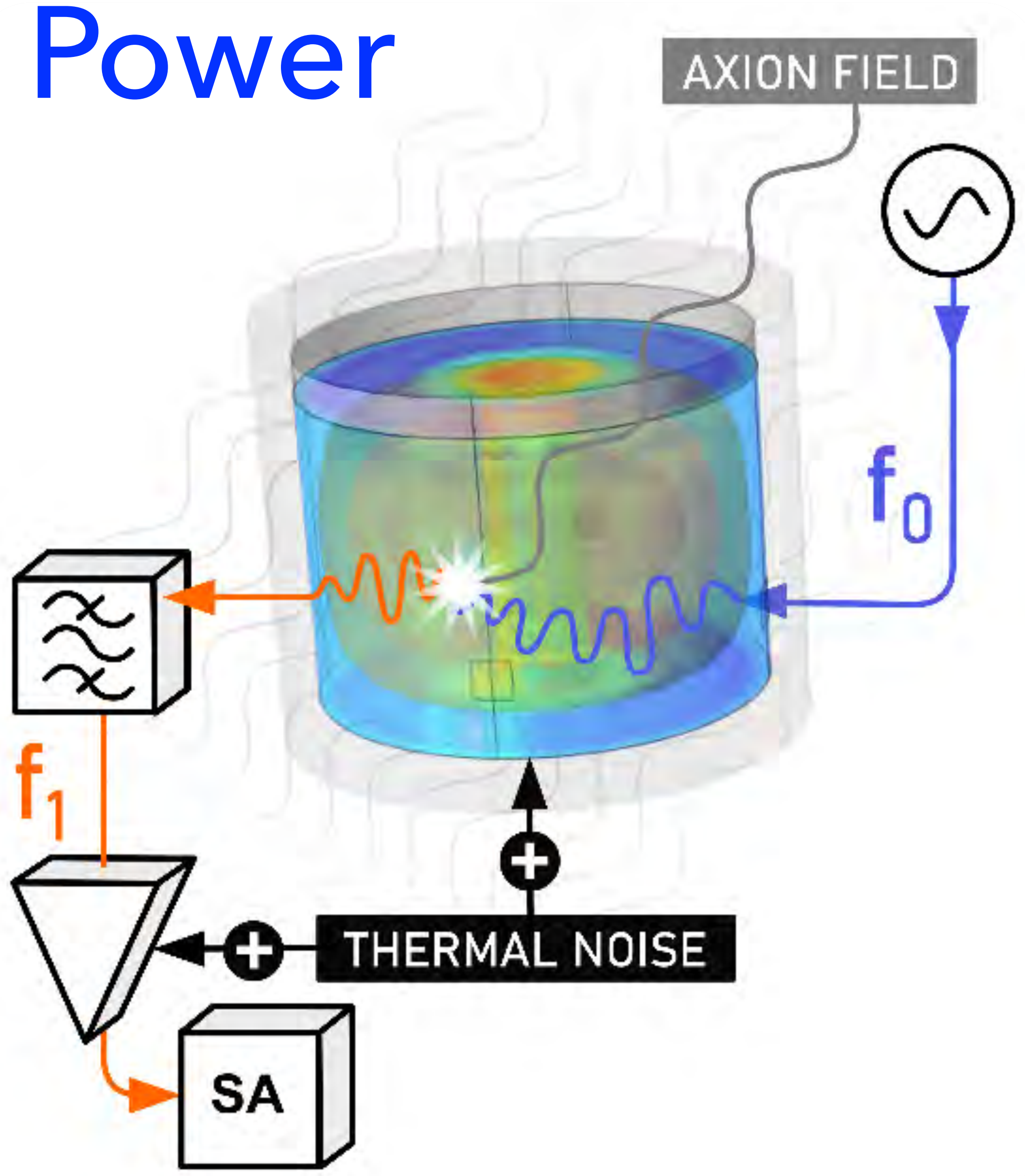


AC Power



- UPLOAD

- 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)

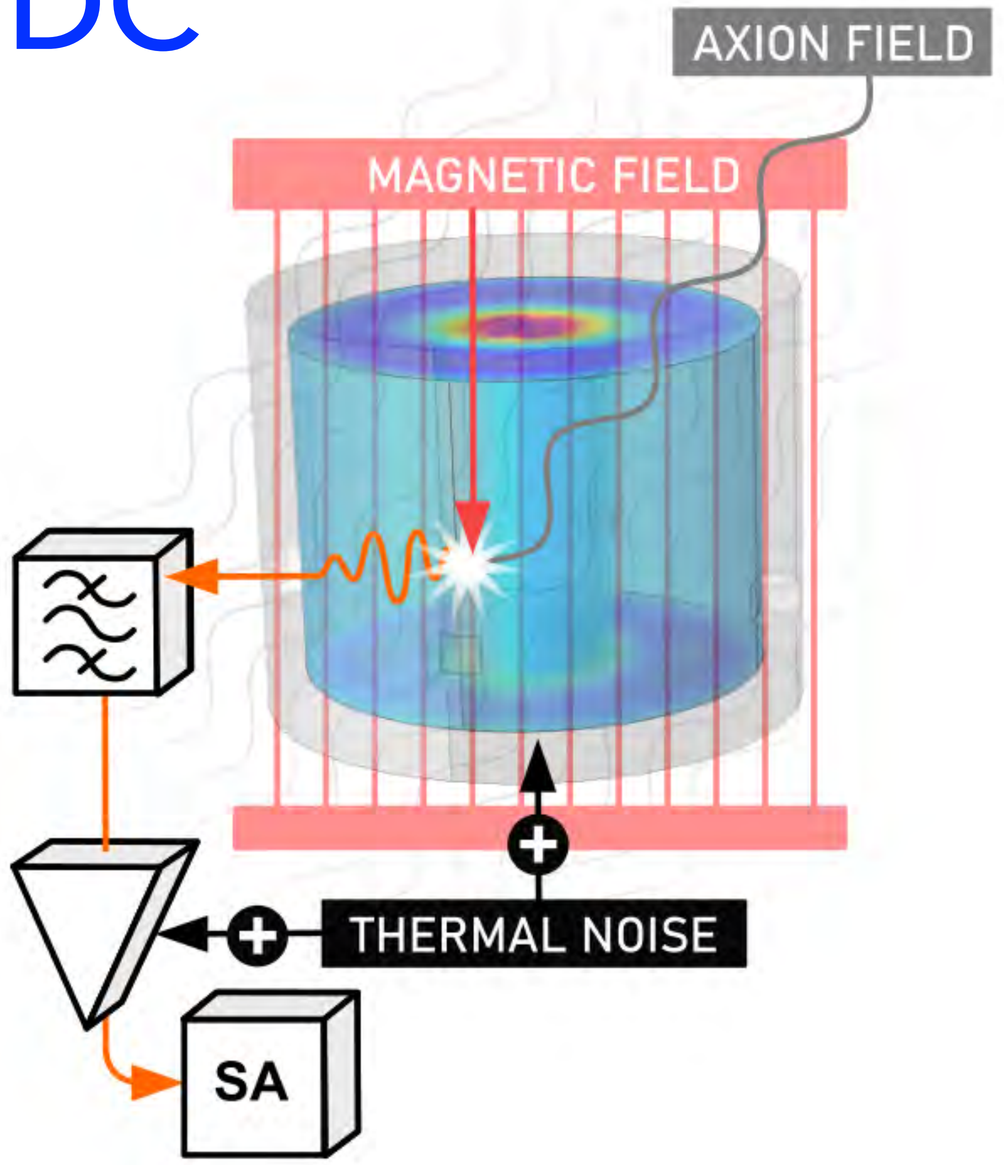
Photon 0: Transverse Electric Mode

(Longitudinal Magnetic)

Resonant Axion Haloscopes @ UWA

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

DC



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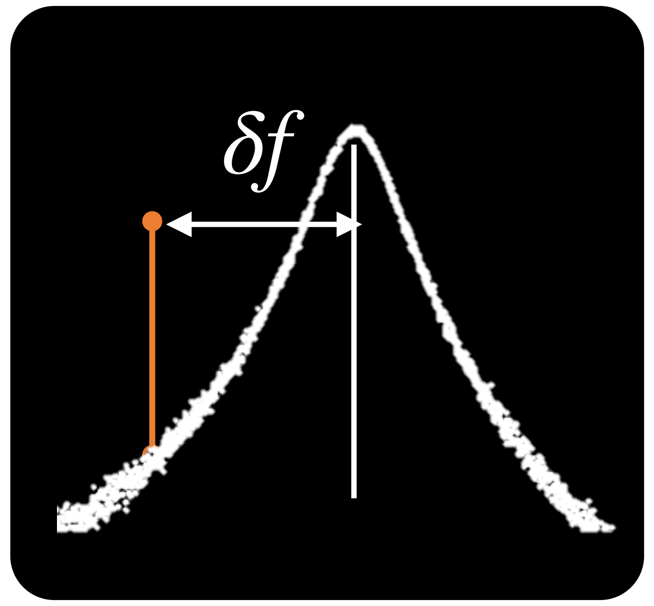

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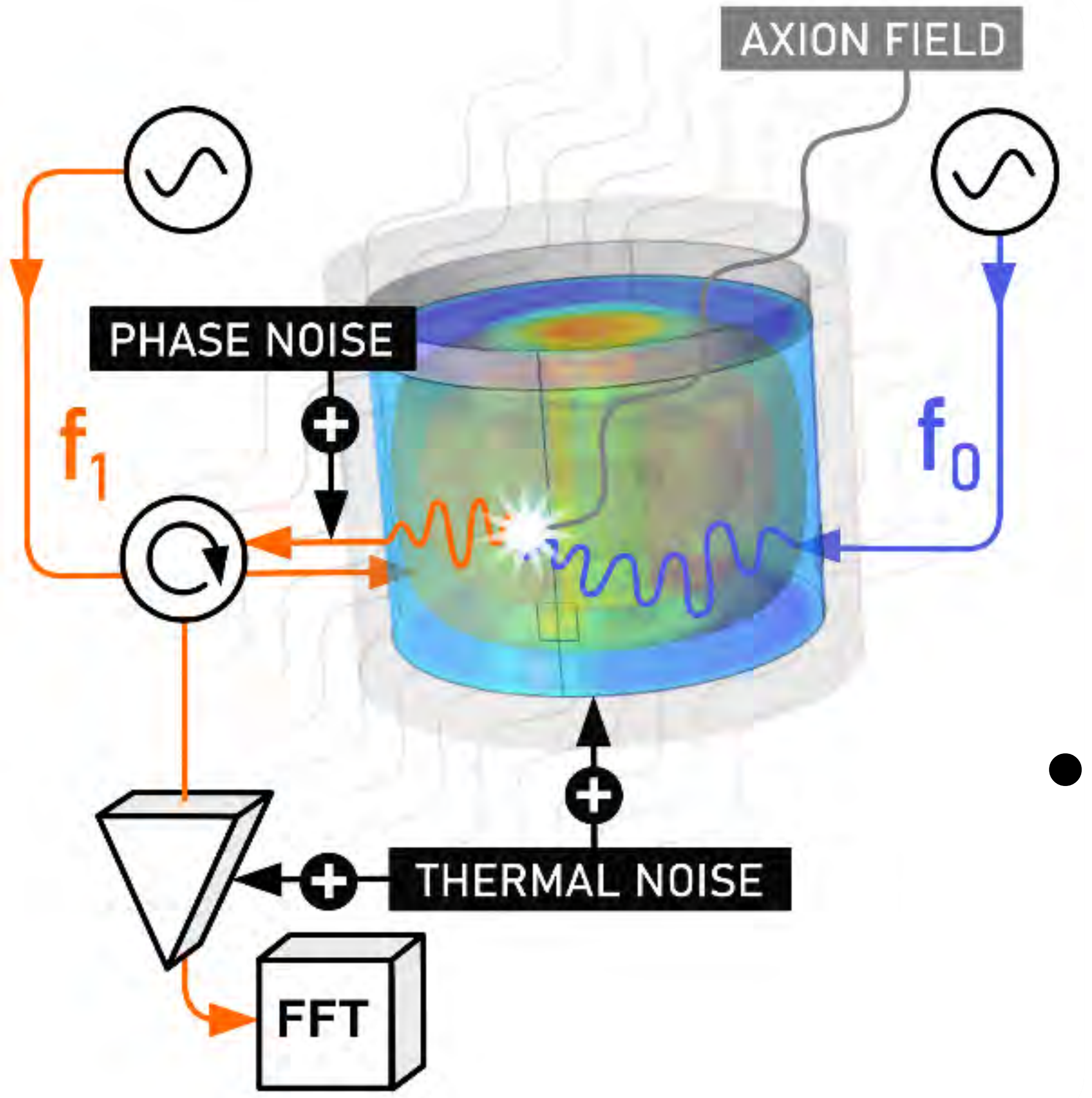

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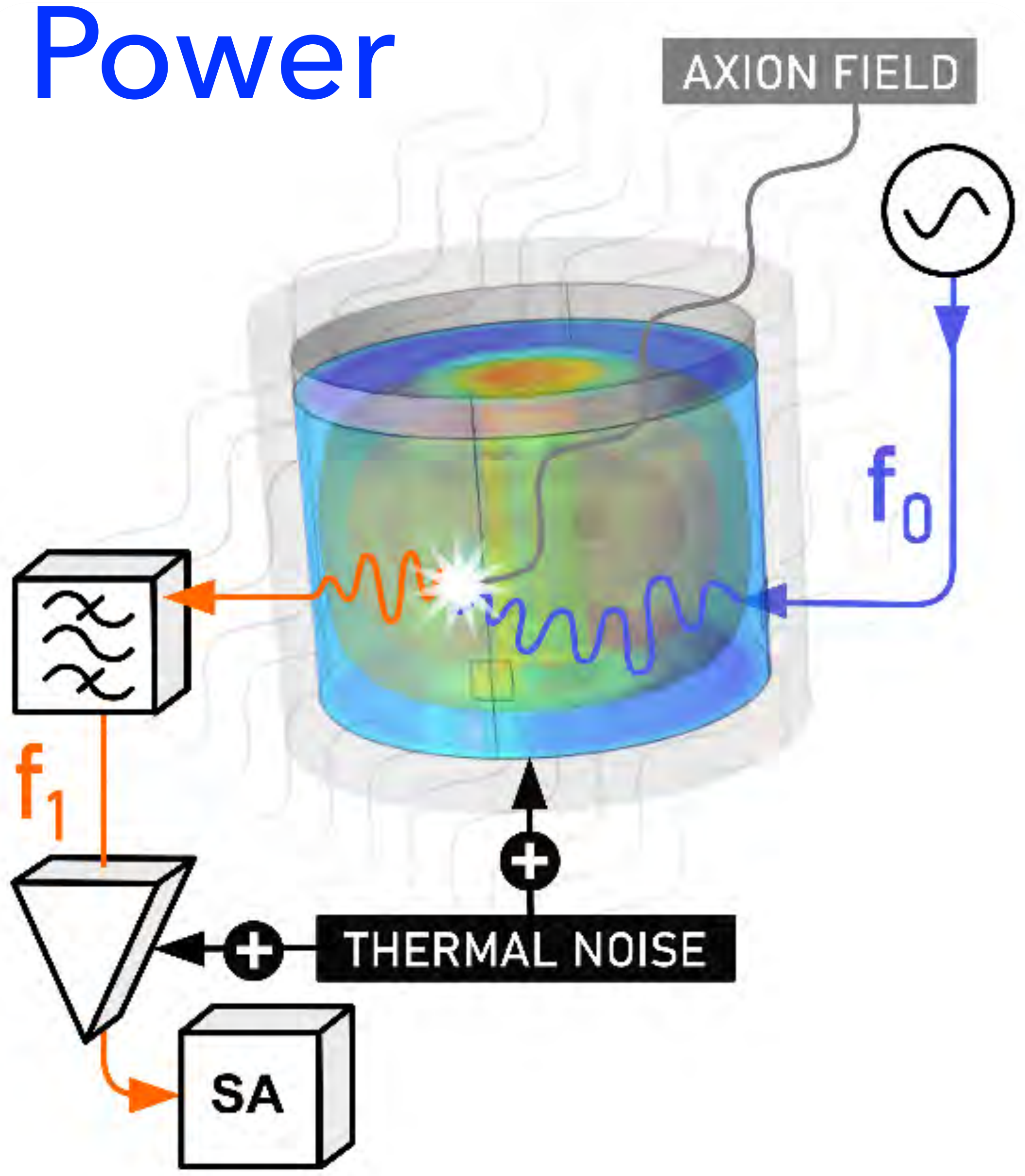

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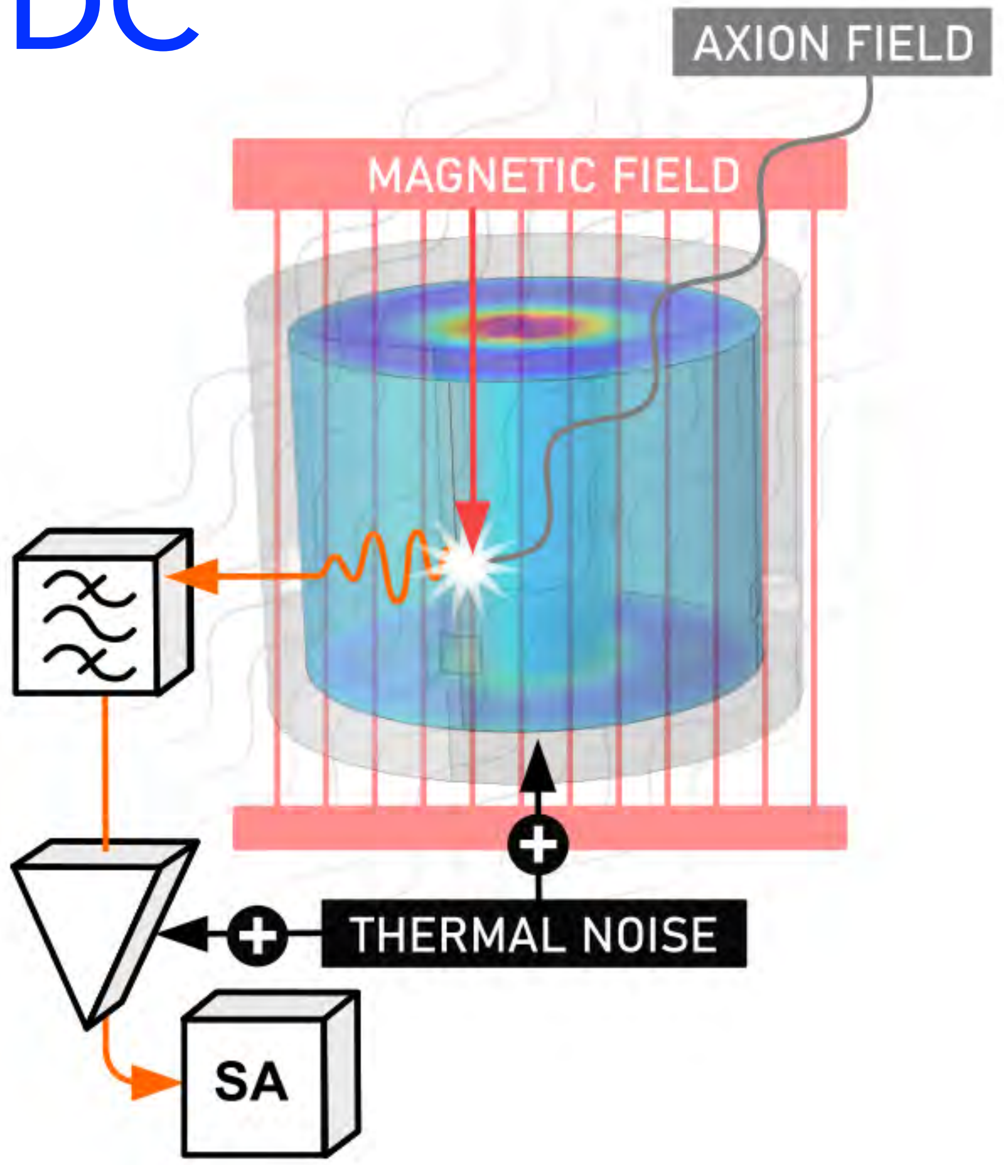
Photon 1: Transverse Magnetic Mode	Photon 0: Transverse Electric Mode
(Longitudinal Electric)	(Longitudinal Magnetic)

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

Resonant Axion Haloscopes @ UWA

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

DC



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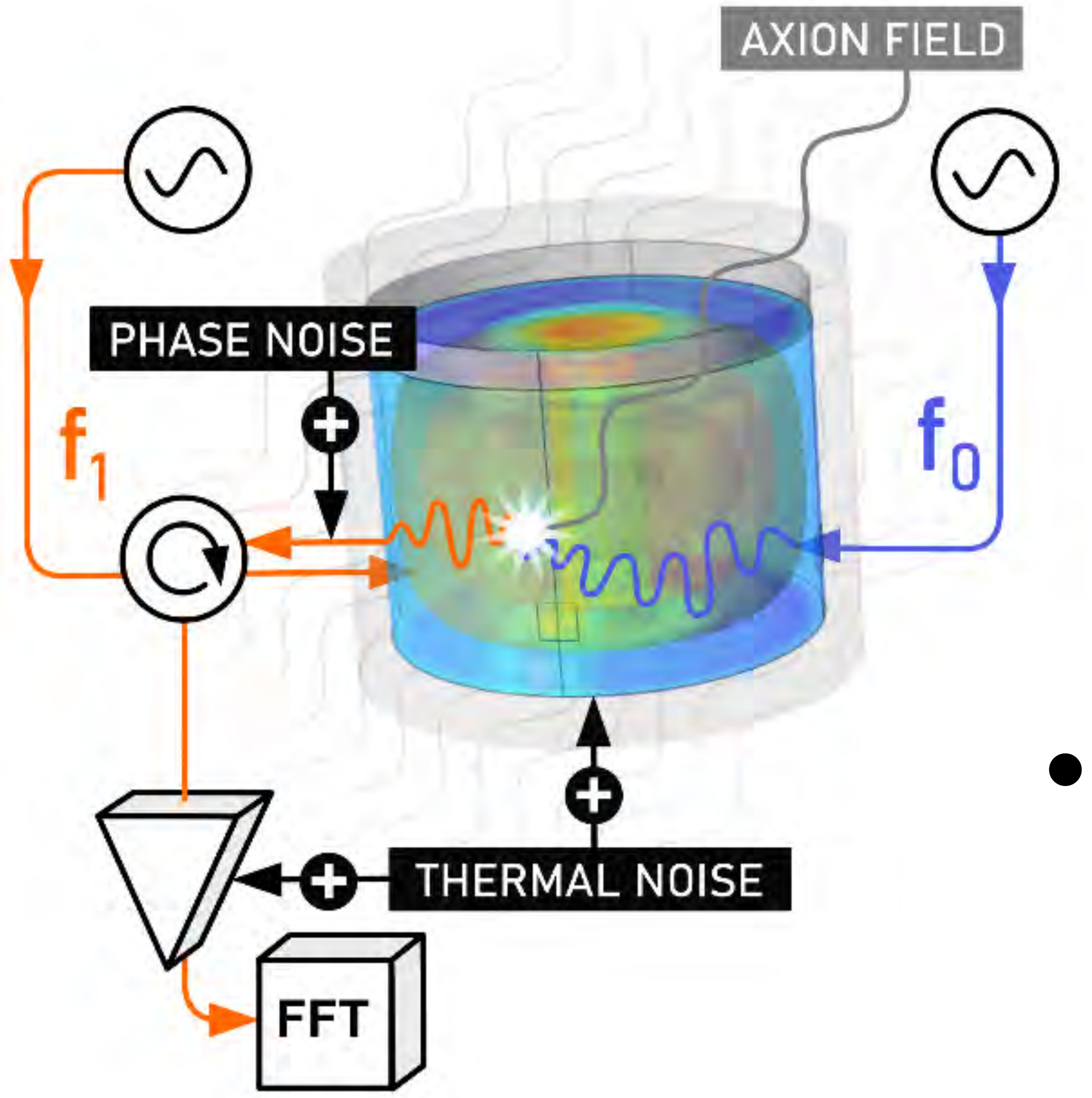

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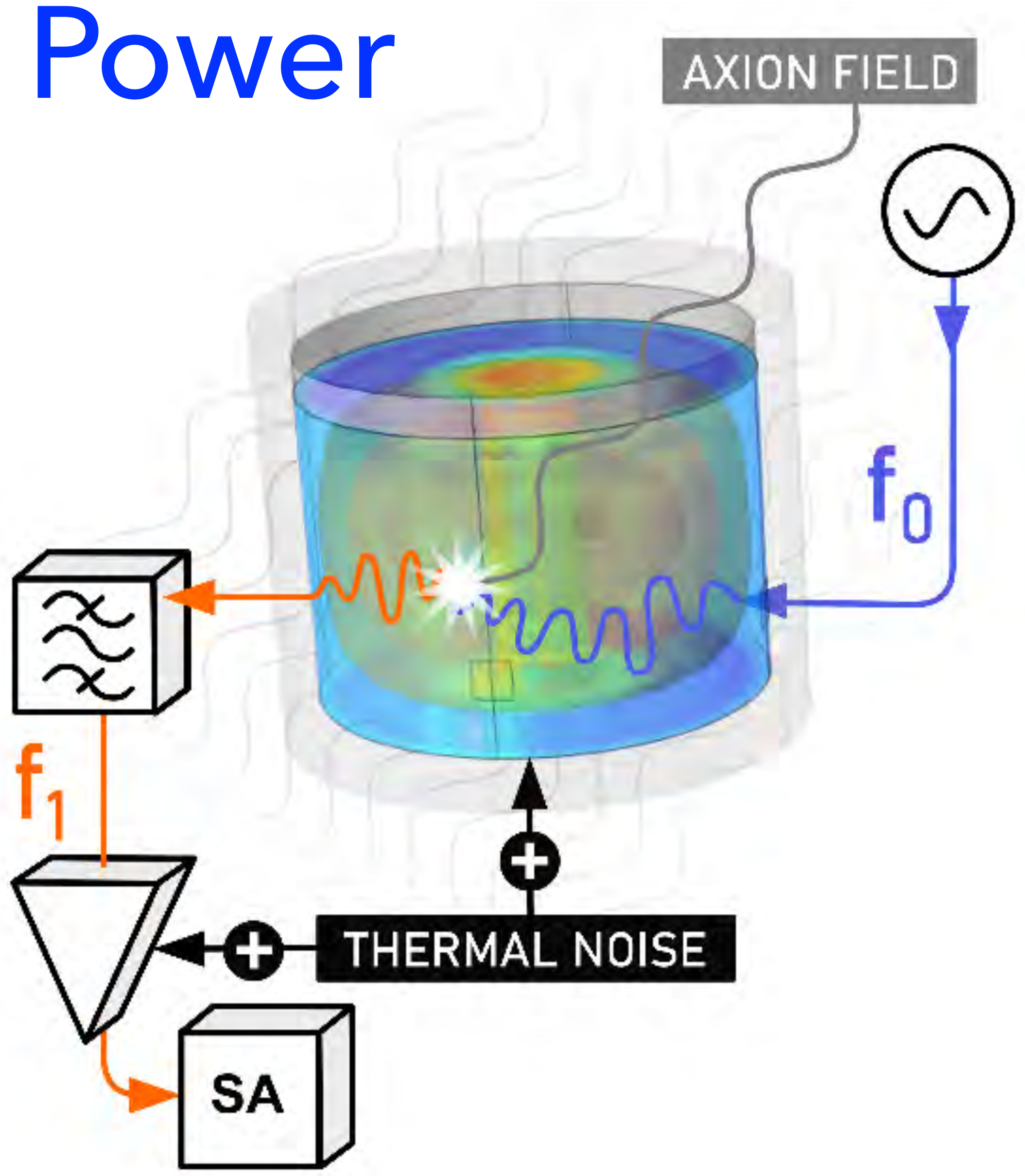

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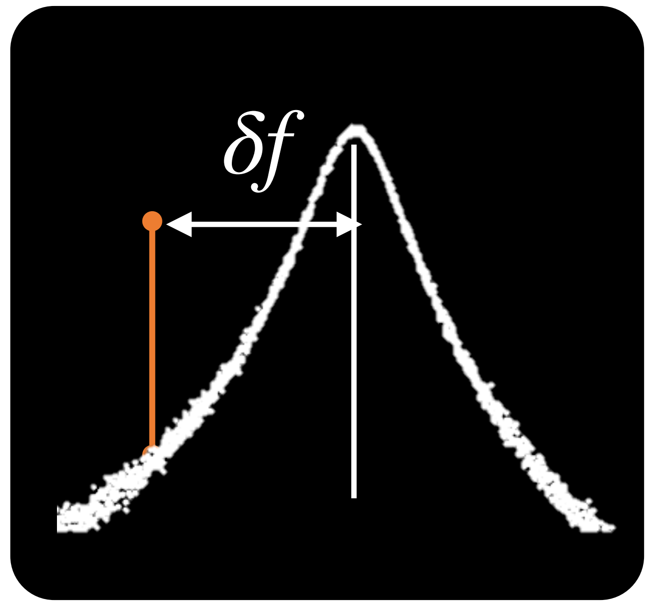

- Use a mode 0 as the background "magnetic field" AC source
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(Longitudinal Electric)	(Longitudinal Magnetic)

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

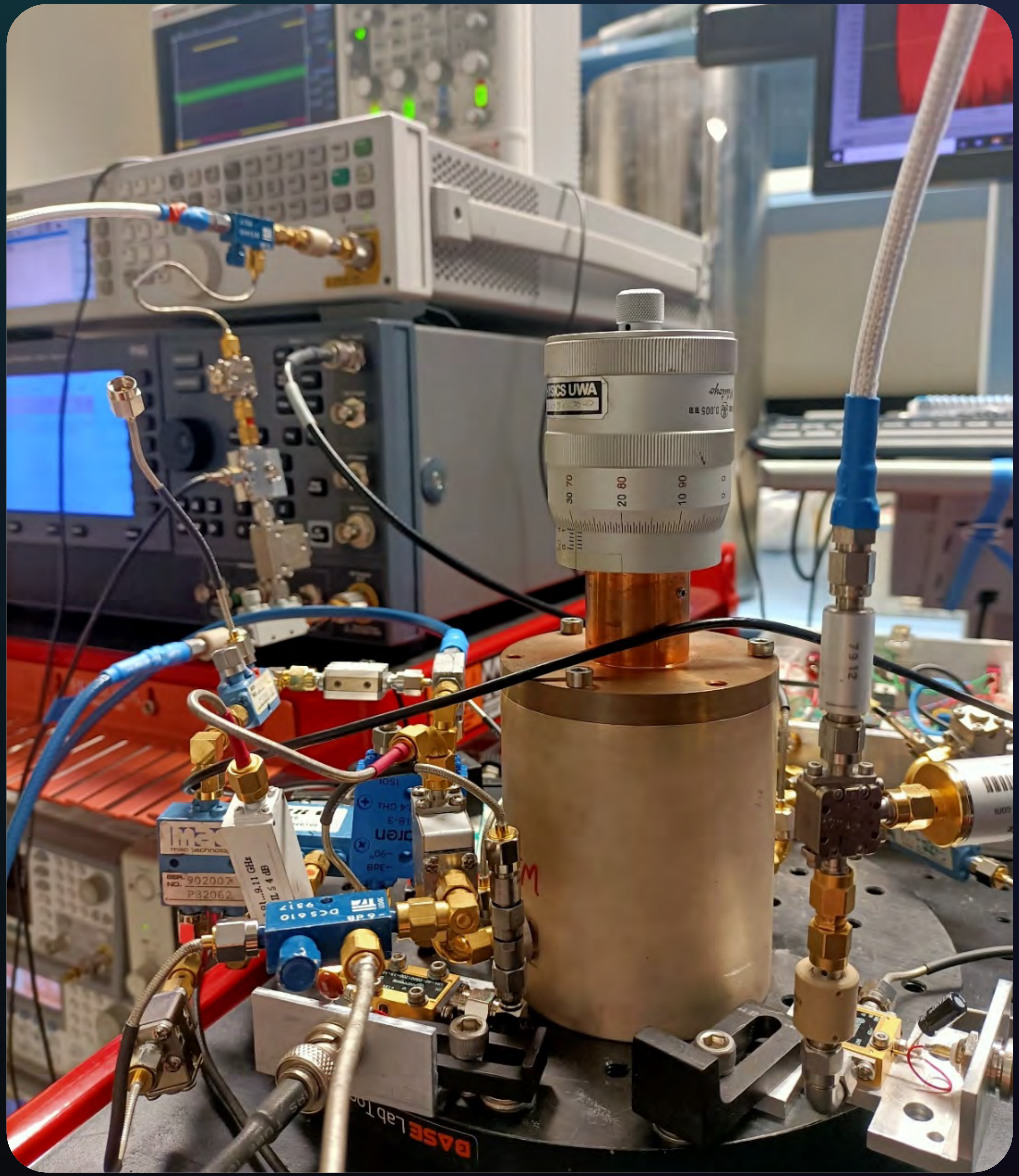
AC Power: Excite f_0: Measure f_1 Power Fluctuation Spectrum

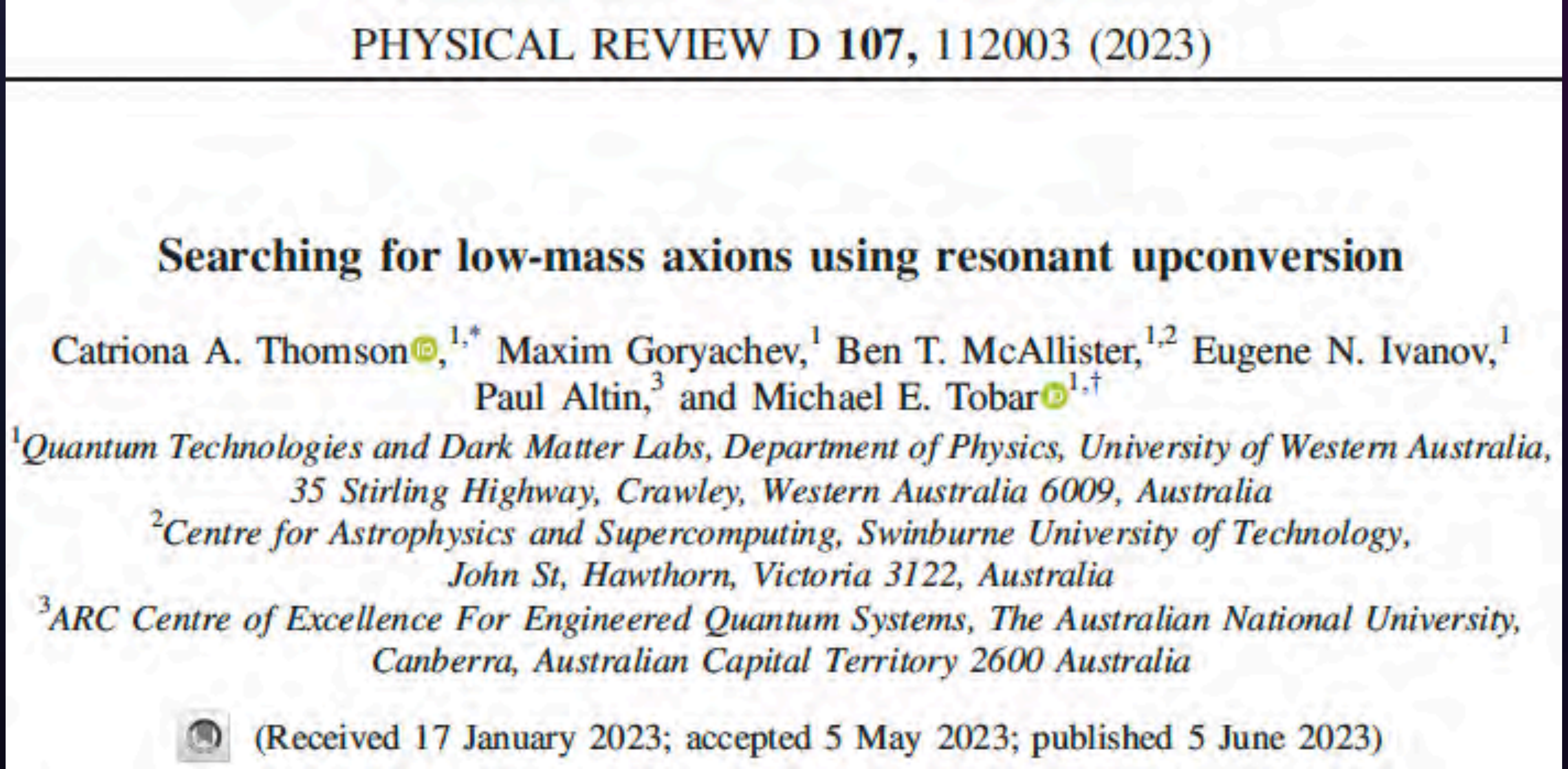
UPLOA

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

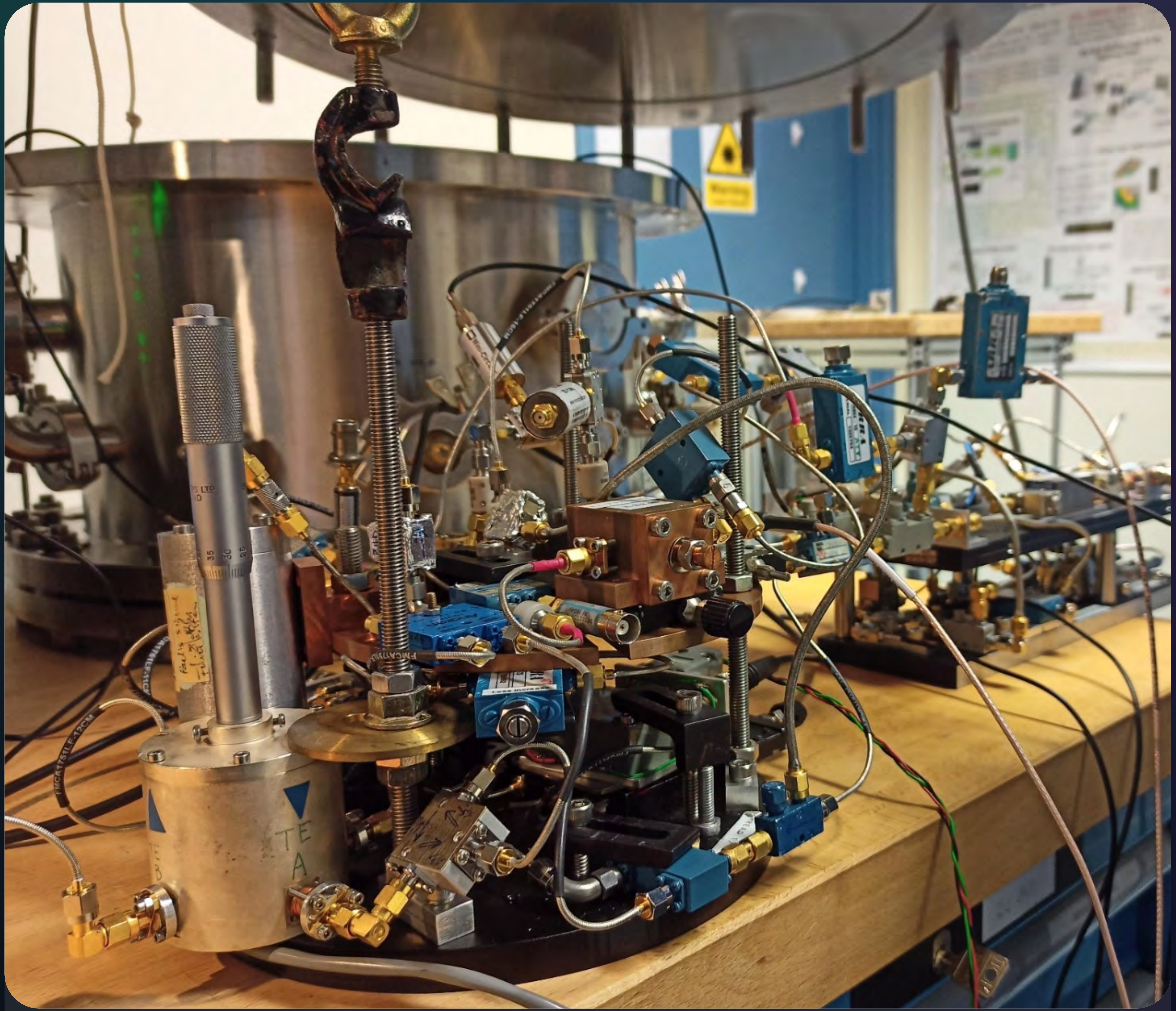
Catriona A. Thomson,[1,*] Maxim Goryachev,[1] Ben T. McAllister,[1,2] Eugene N. Ivanov,[1]
Paul Altin,[3] and Michael E. Tobar[1,†]

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

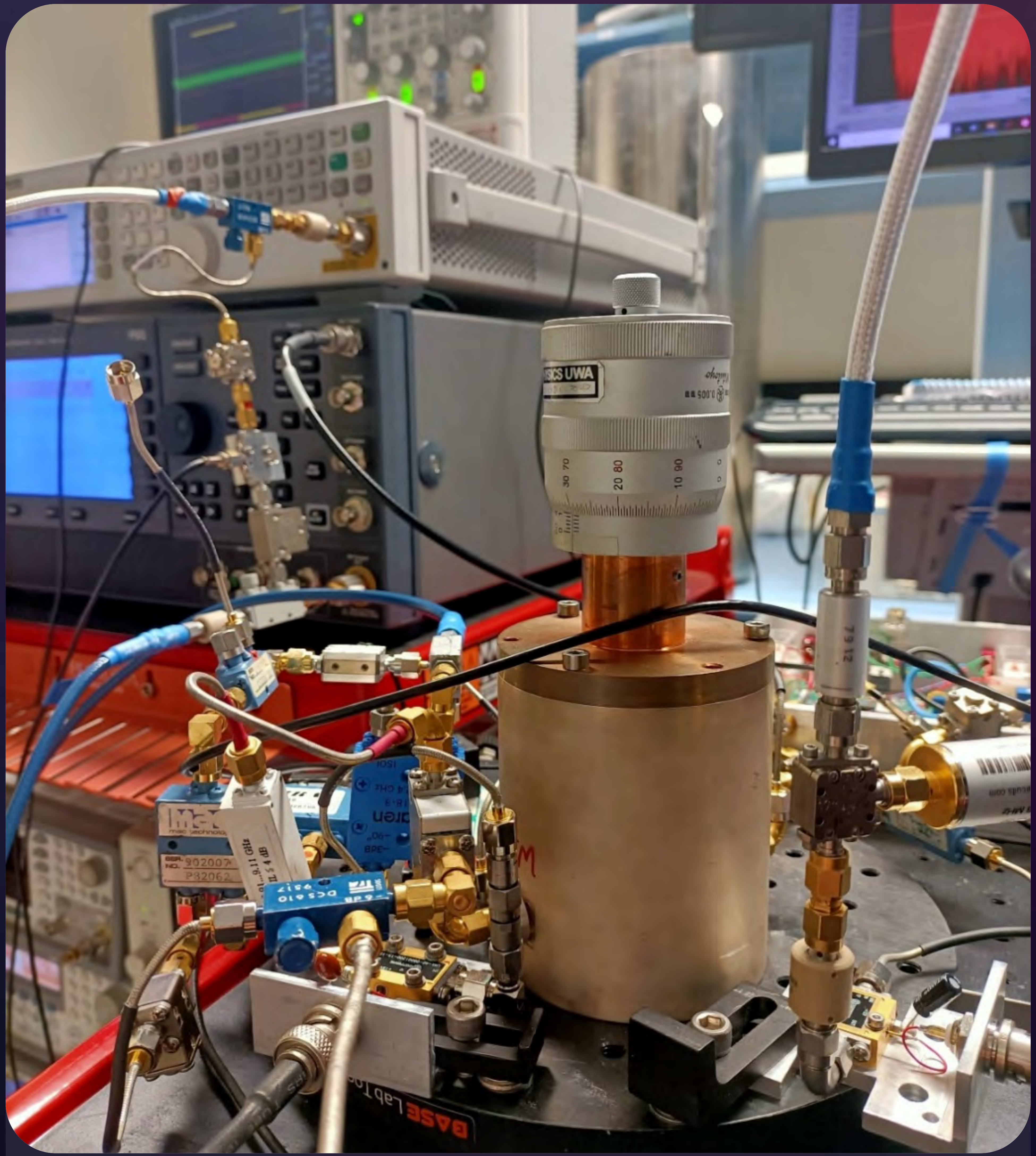
[2]*Centre for Astrophysics and Supercomputing, Swinburne University of Technology, John St, Hawthorn, Victoria 3122, Australia*

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

(Received 17 January 2023; accepted 5 May 2023; published 5 June 2023)

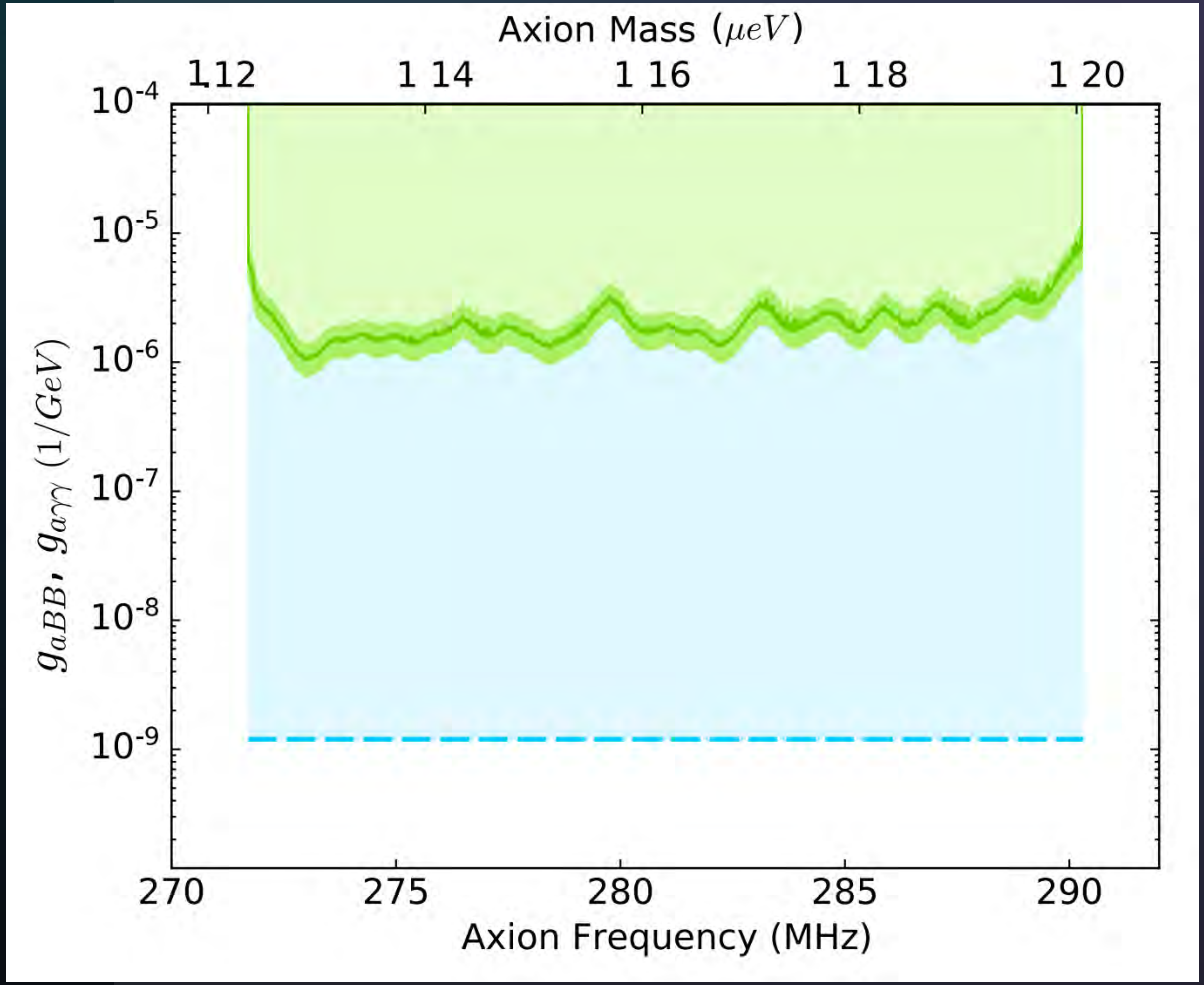


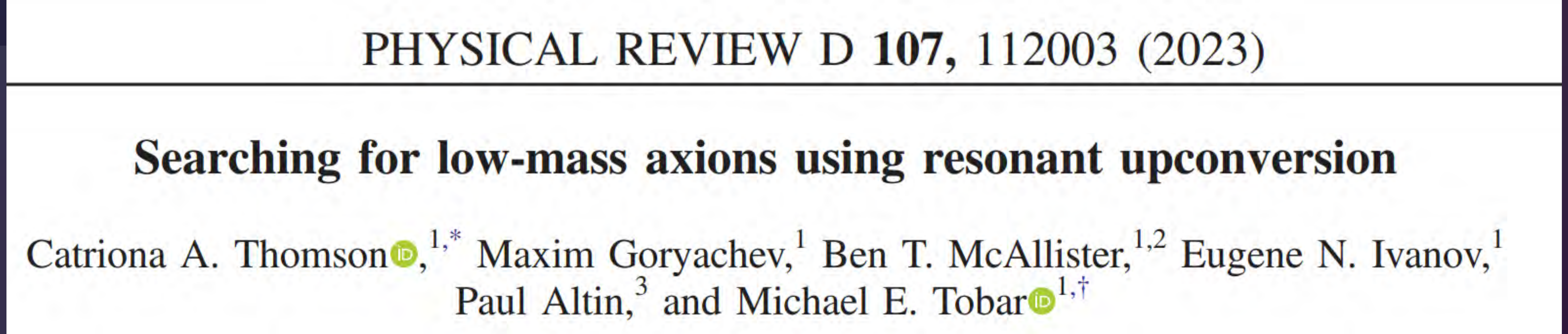
V1: readout via frequency metrology



V2: readout via thermal noise peak (power)

UPLOAD V2: Exclusion limits

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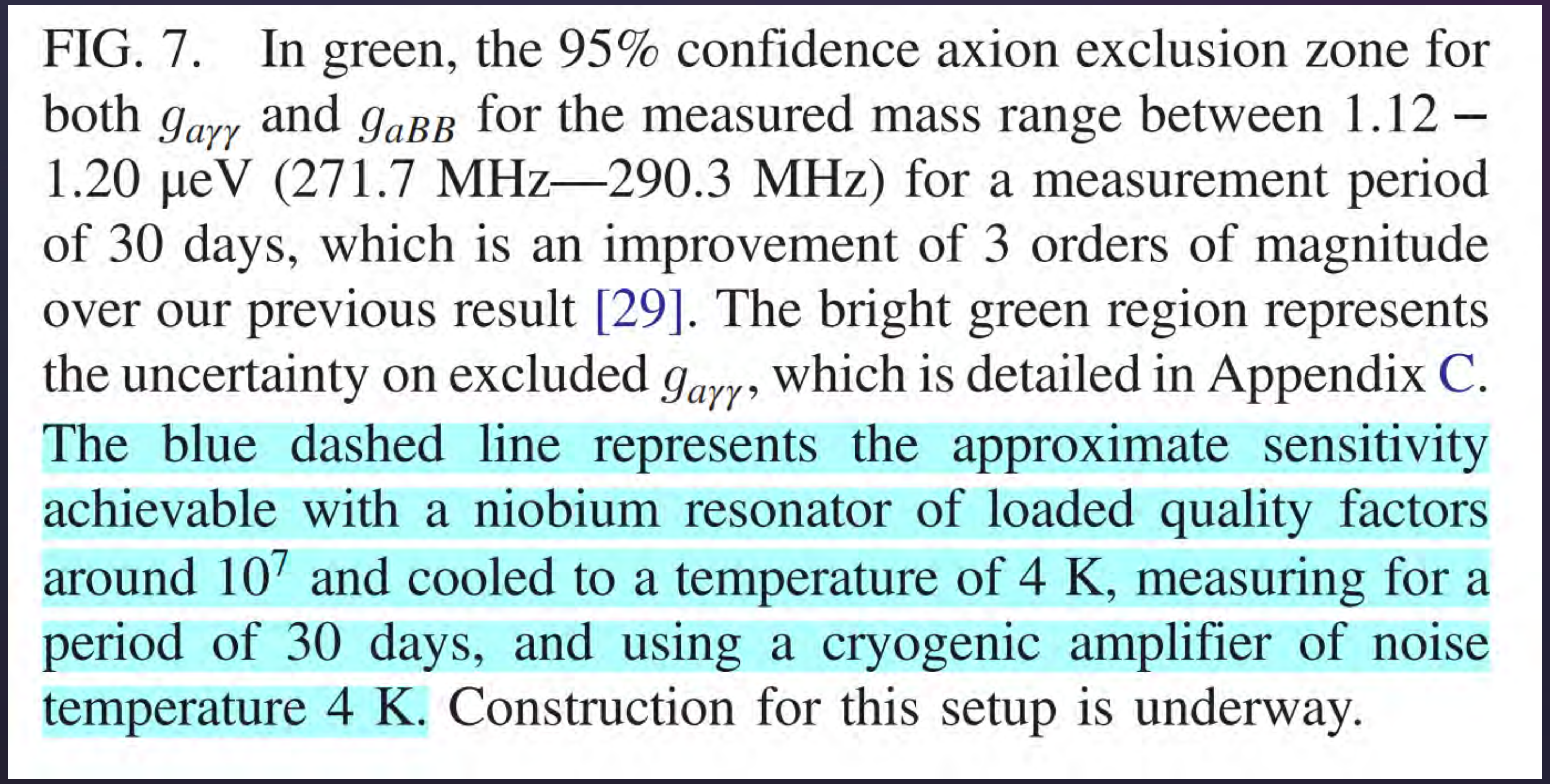


FIG. 7. In green, the 95% confidence axion exclusion zone for both $g_{a\gamma\gamma}$ and g_{aBB} for the measured mass range between 1.12 – 1.20 µeV (271.7 MHz—290.3 MHz) for a measurement period of 30 days, which is an improvement of 3 orders of magnitude over our previous result [29]. The bright 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

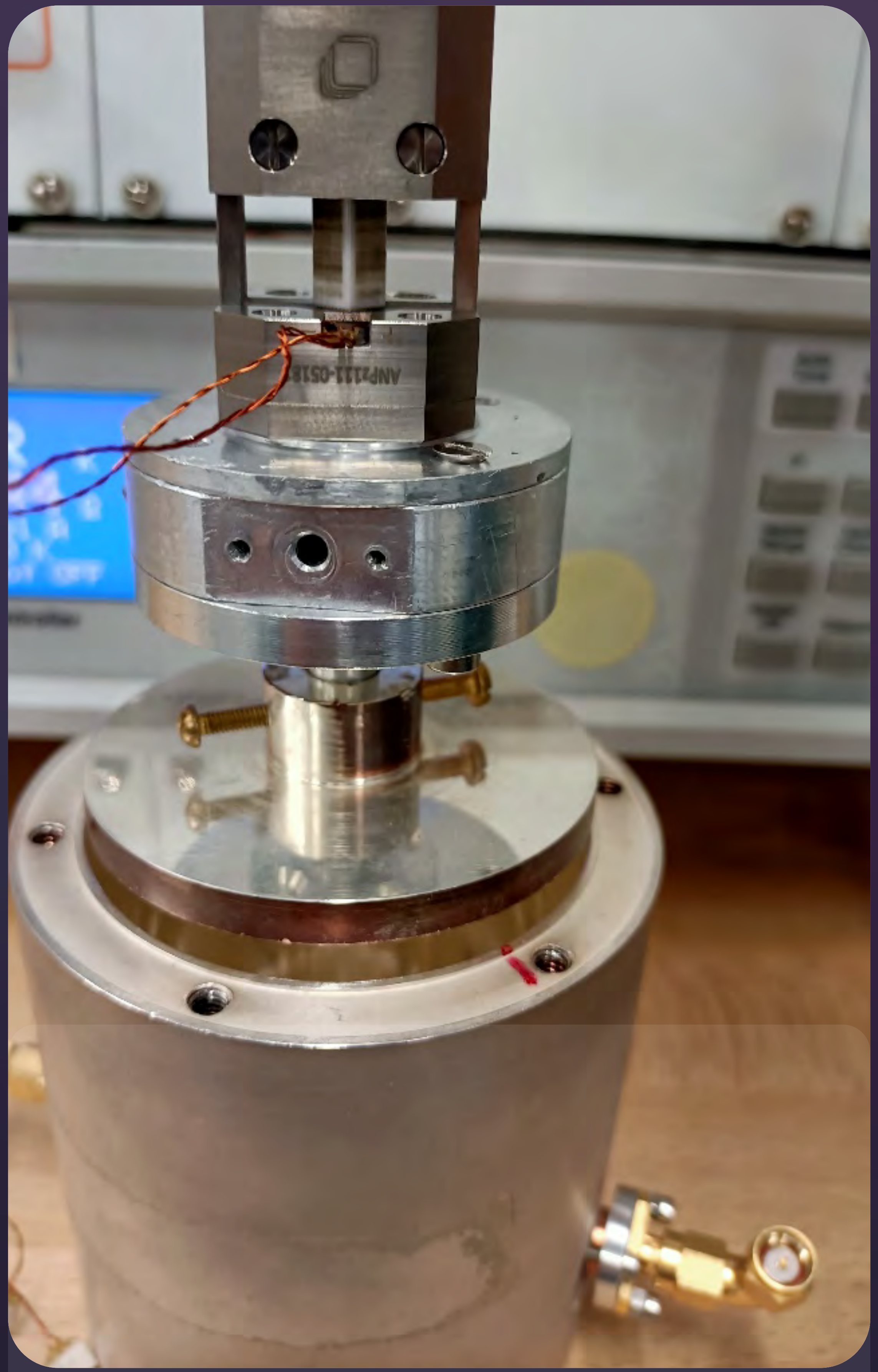
An experiment targeting 350 MHz axions with a dual mode cavity (~12 GHz), height tuning with a piezo actuated lid. Gain in noise temperature and quality factor.

290 K → 4 K

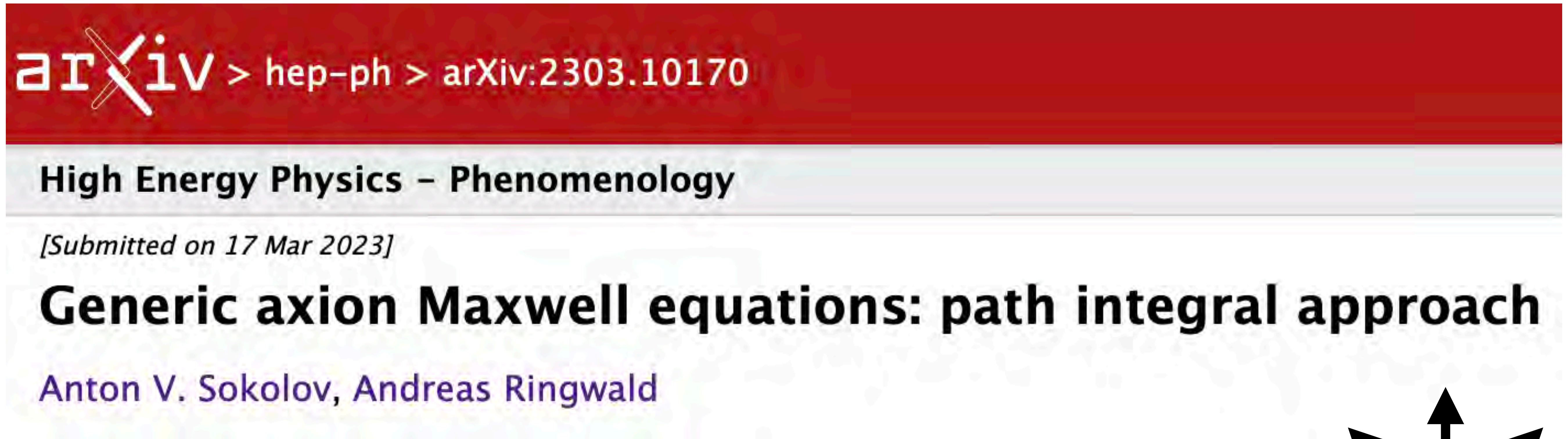
$$\langle H \rangle = k_{\mathrm{B}} T$$

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

Q ~ 13,000 → > 20,000,000



Trialing attocube actuator in silver plated cavity



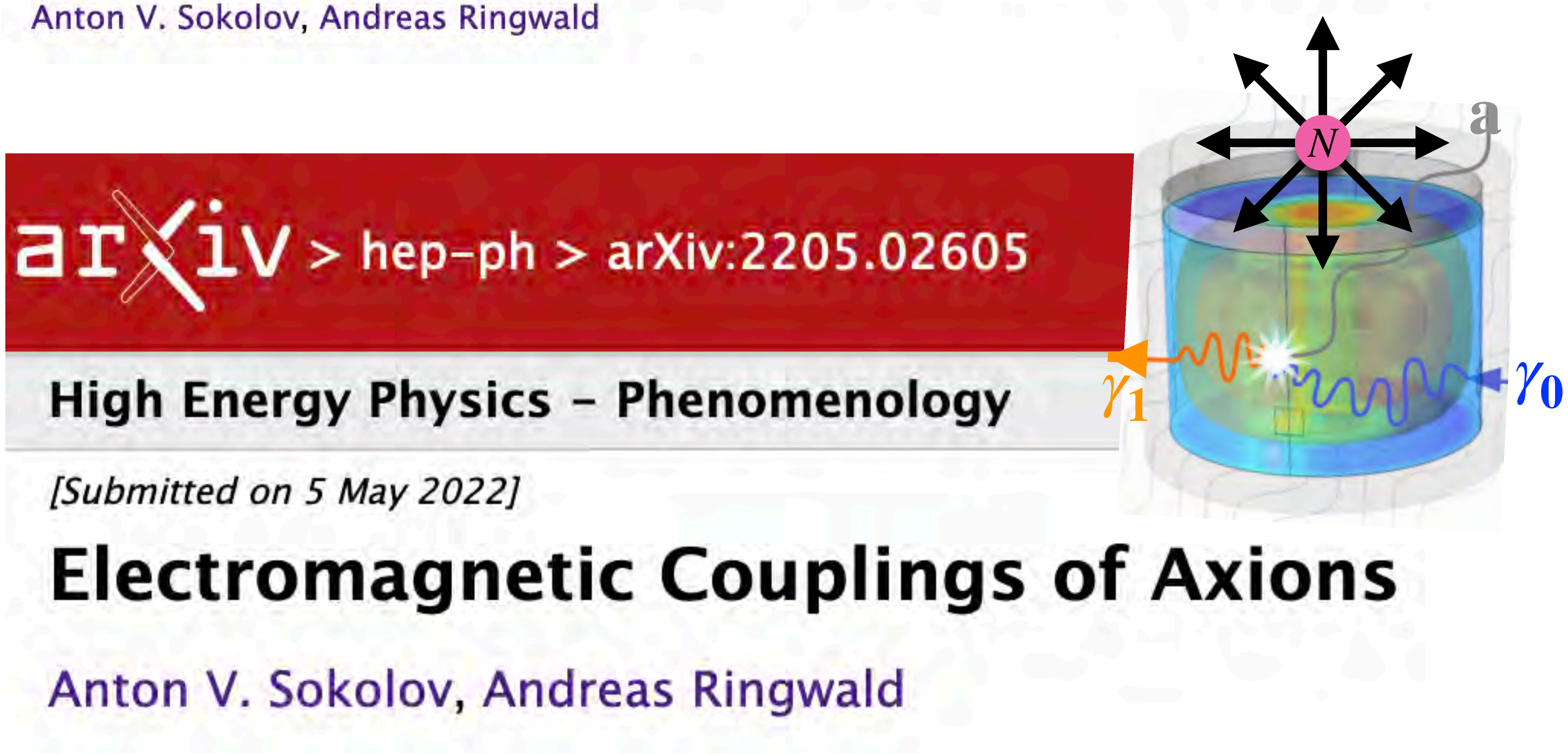
arXiv > hep-ph > arXiv:2303.10170

High Energy Physics – Phenomenology

[Submitted on 17 Mar 2023]

Generic axion Maxwell equations: path integral approach

Anton V. Sokolov, Andreas Ringwald



arXiv > hep-ph > arXiv:2205.02605

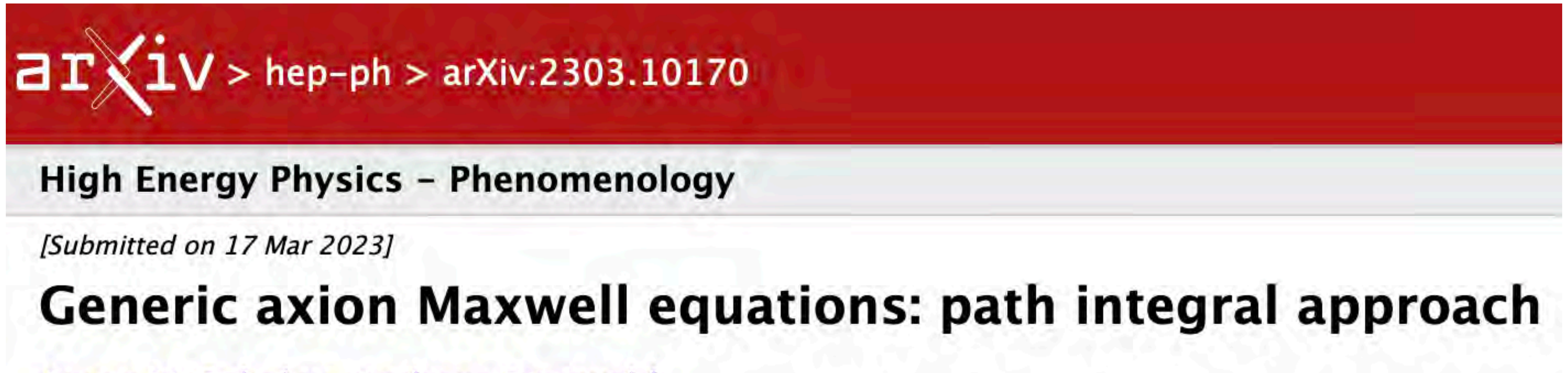
High Energy Physics – Phenomenology

[Submitted on 5 May 2022]

Electromagnetic Couplings of Axions

Anton V. Sokolov, Andreas Ringwald

If Magnetic Charge Exist at High Energy



arXiv > hep-ph > arXiv:2303.10170

High Energy Physics – Phenomenology

[Submitted on 17 Mar 2023]

Generic axion Maxwell equations: path integral approach

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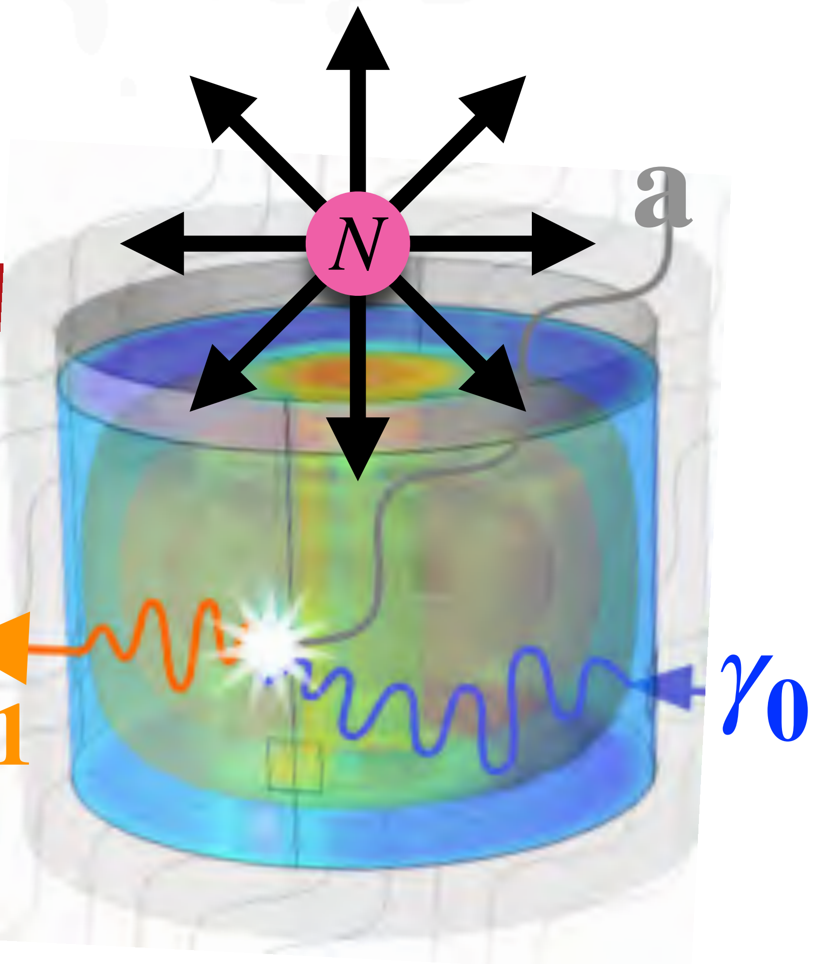

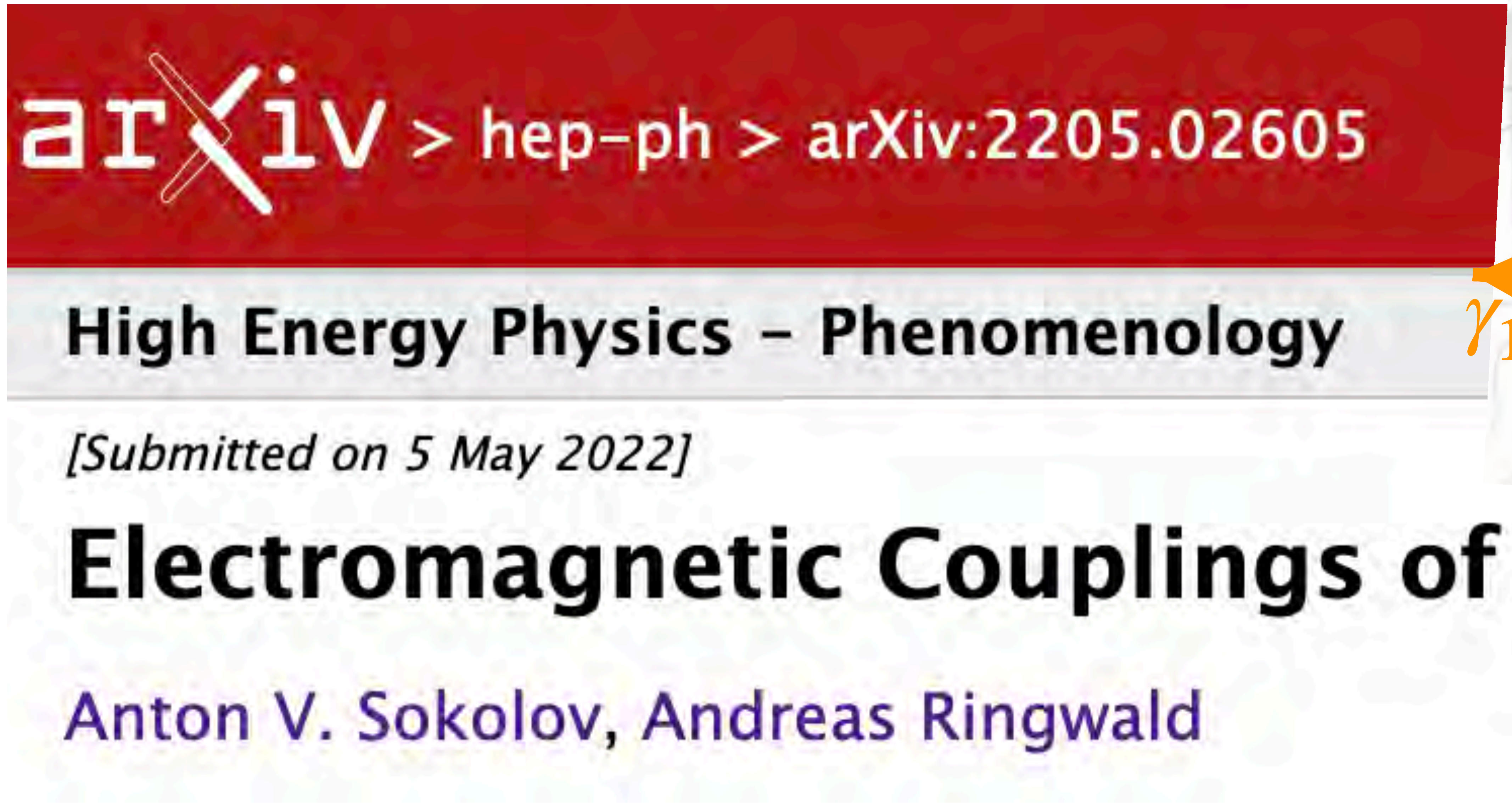

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High Energy Physics – Phenomenology

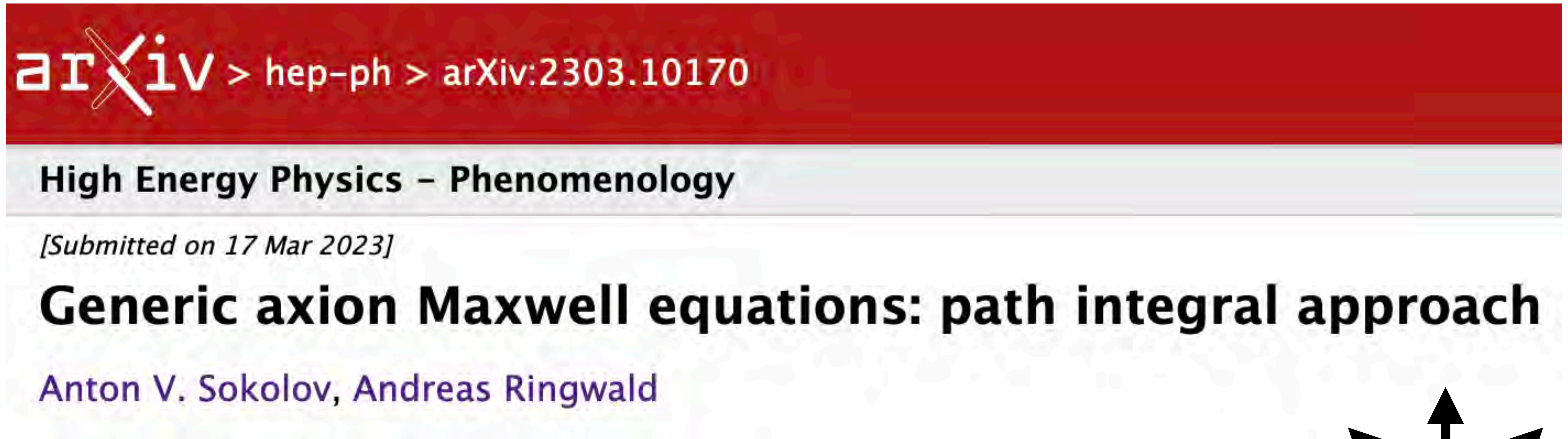
[Submitted on 5 May 2022]

Electromagnetic Couplings of Axions

Anton V. Sokolov, Andreas Ringwald

If Magnetic Charge Exist at High Energy

-> Further Modifications to Axion Electrodynamics



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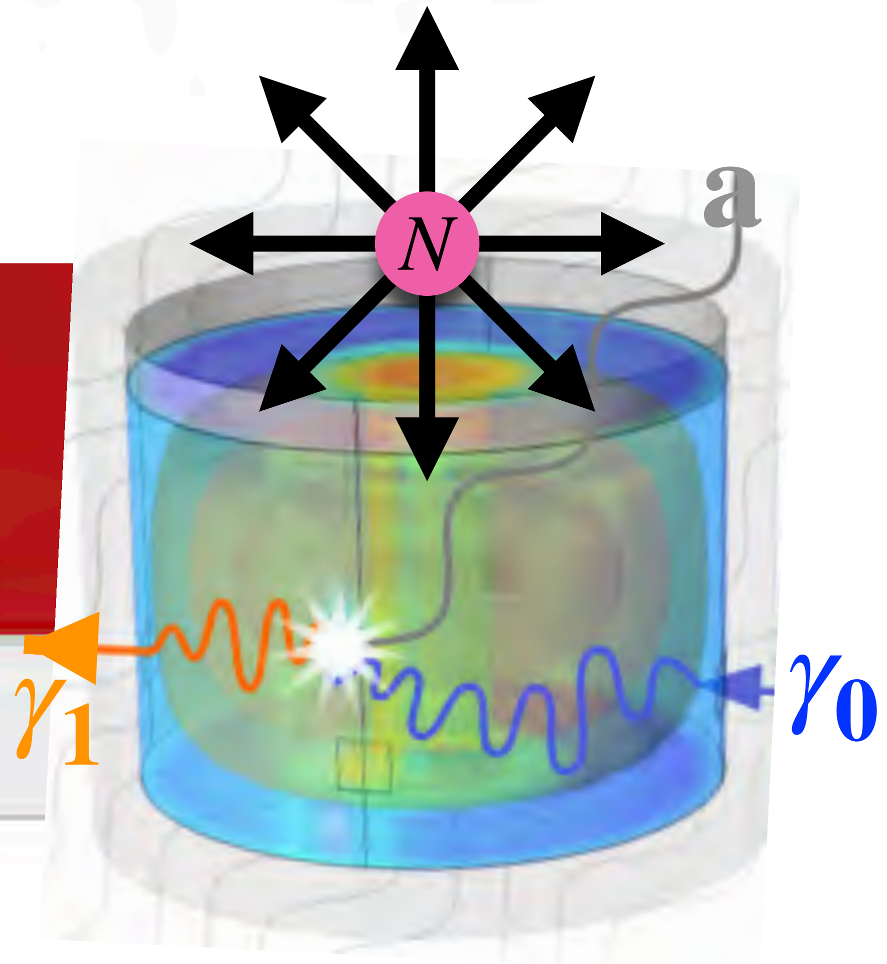

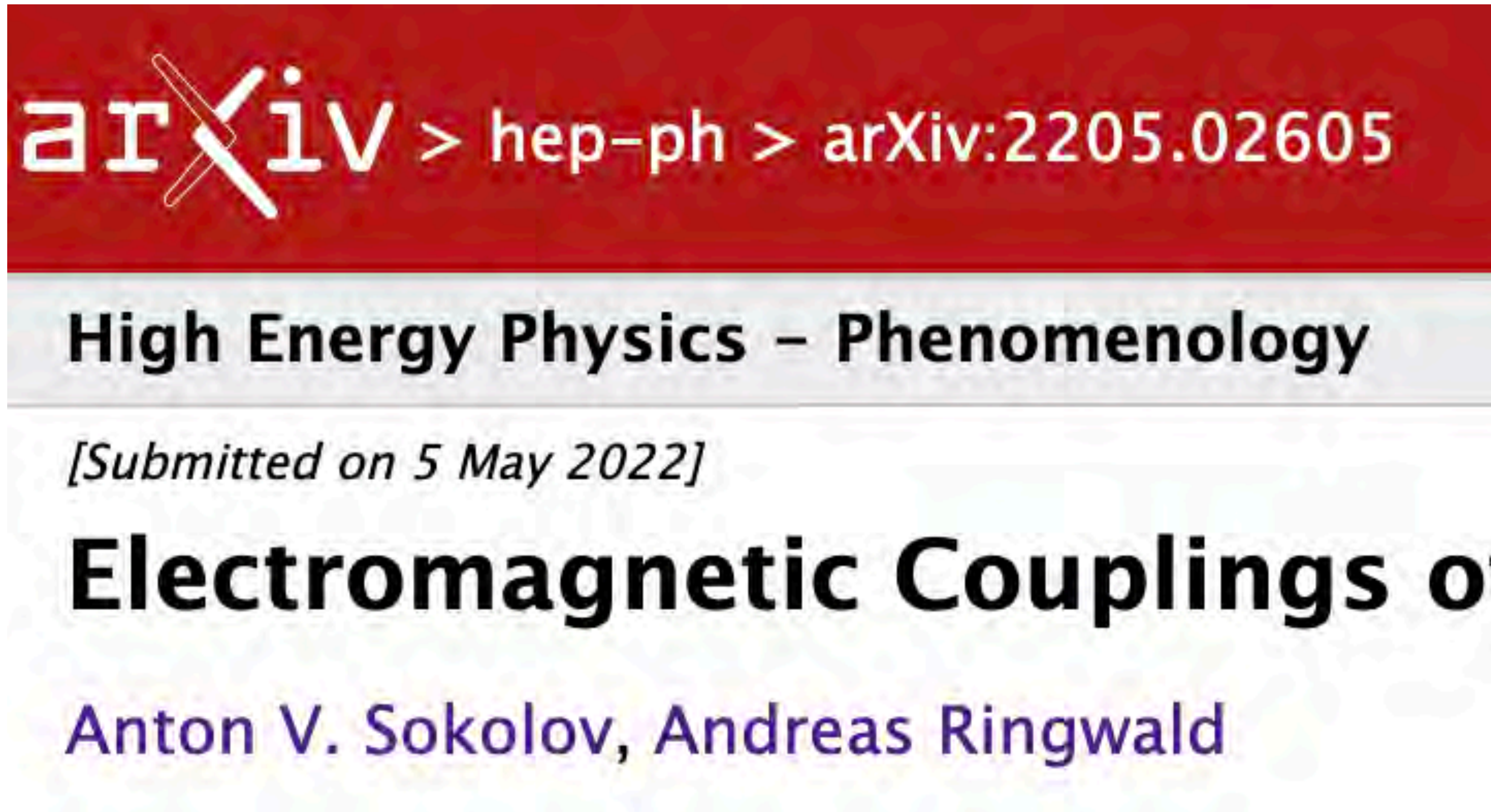

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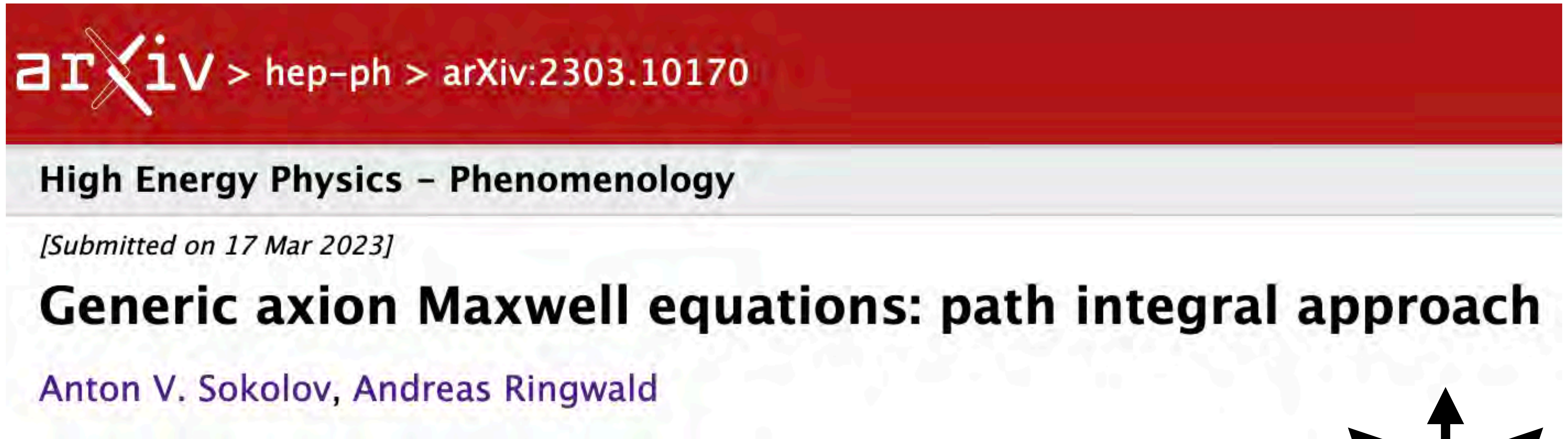

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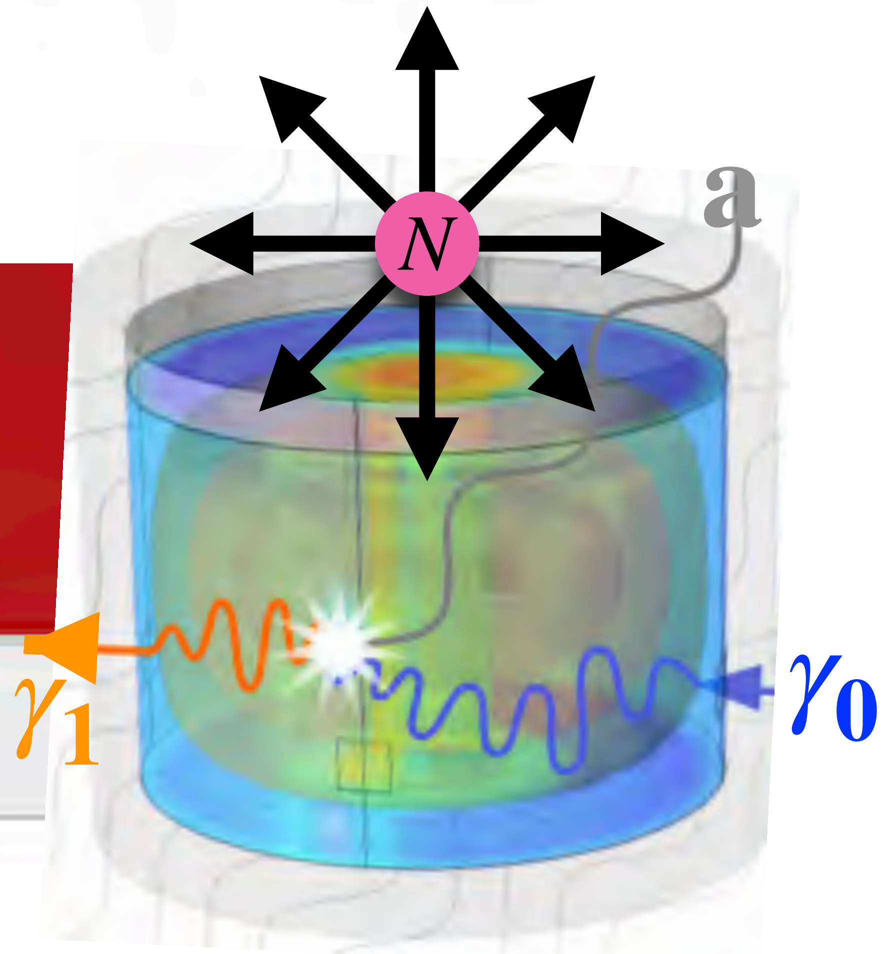

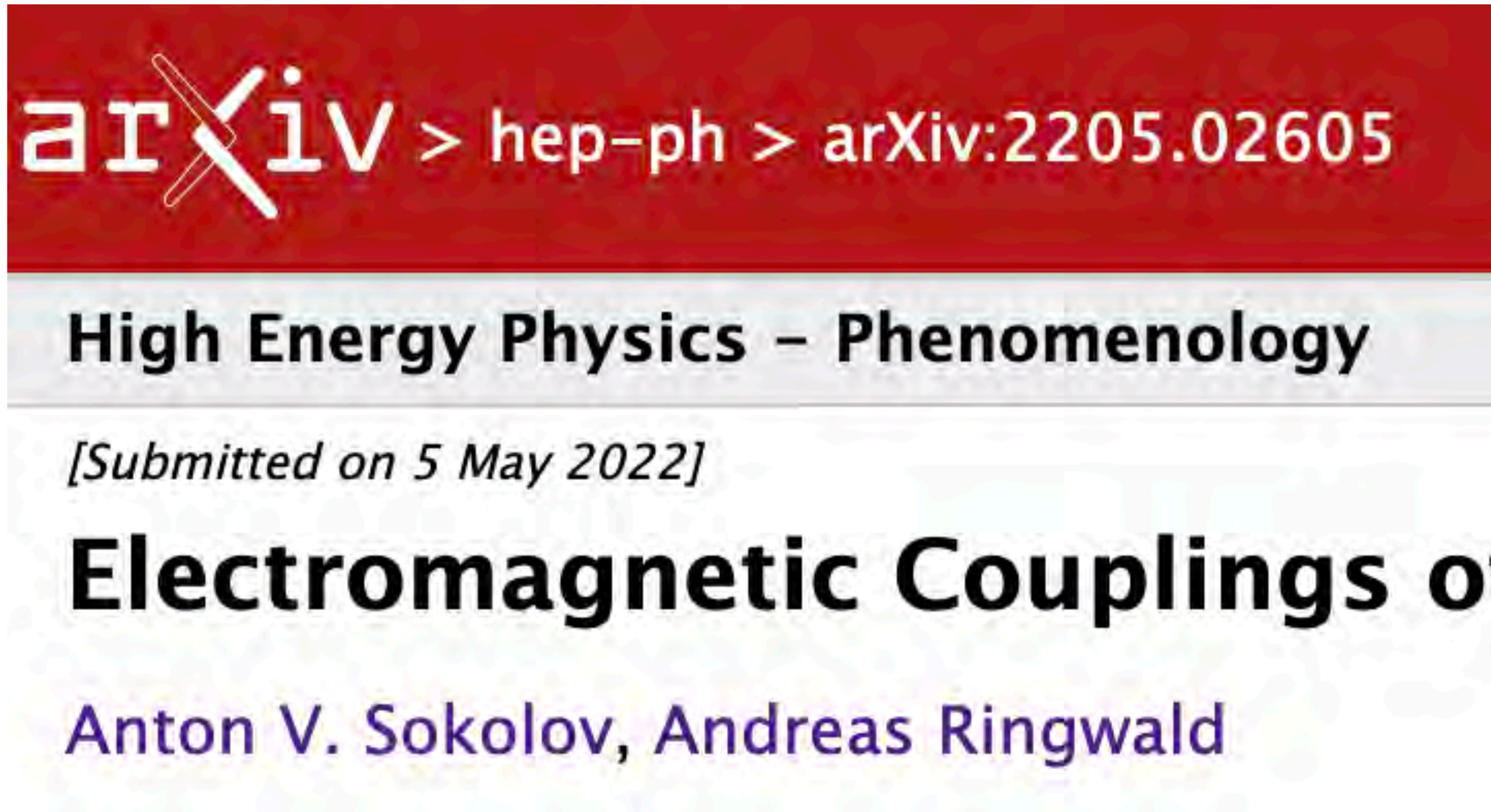

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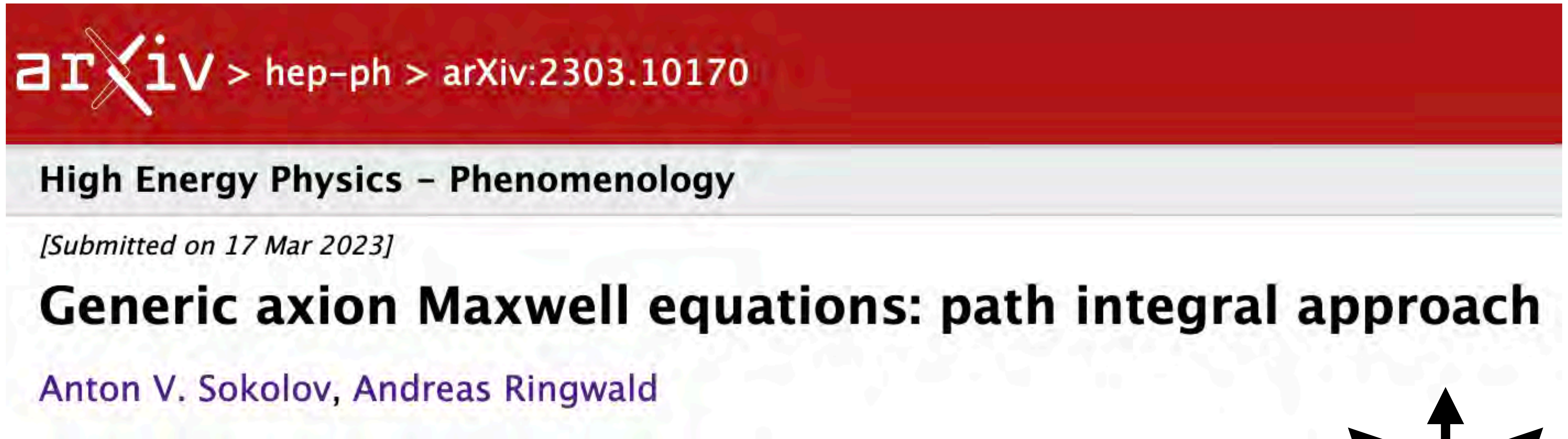
Axion-photon coupling parameter space is expanded from one parameter to three

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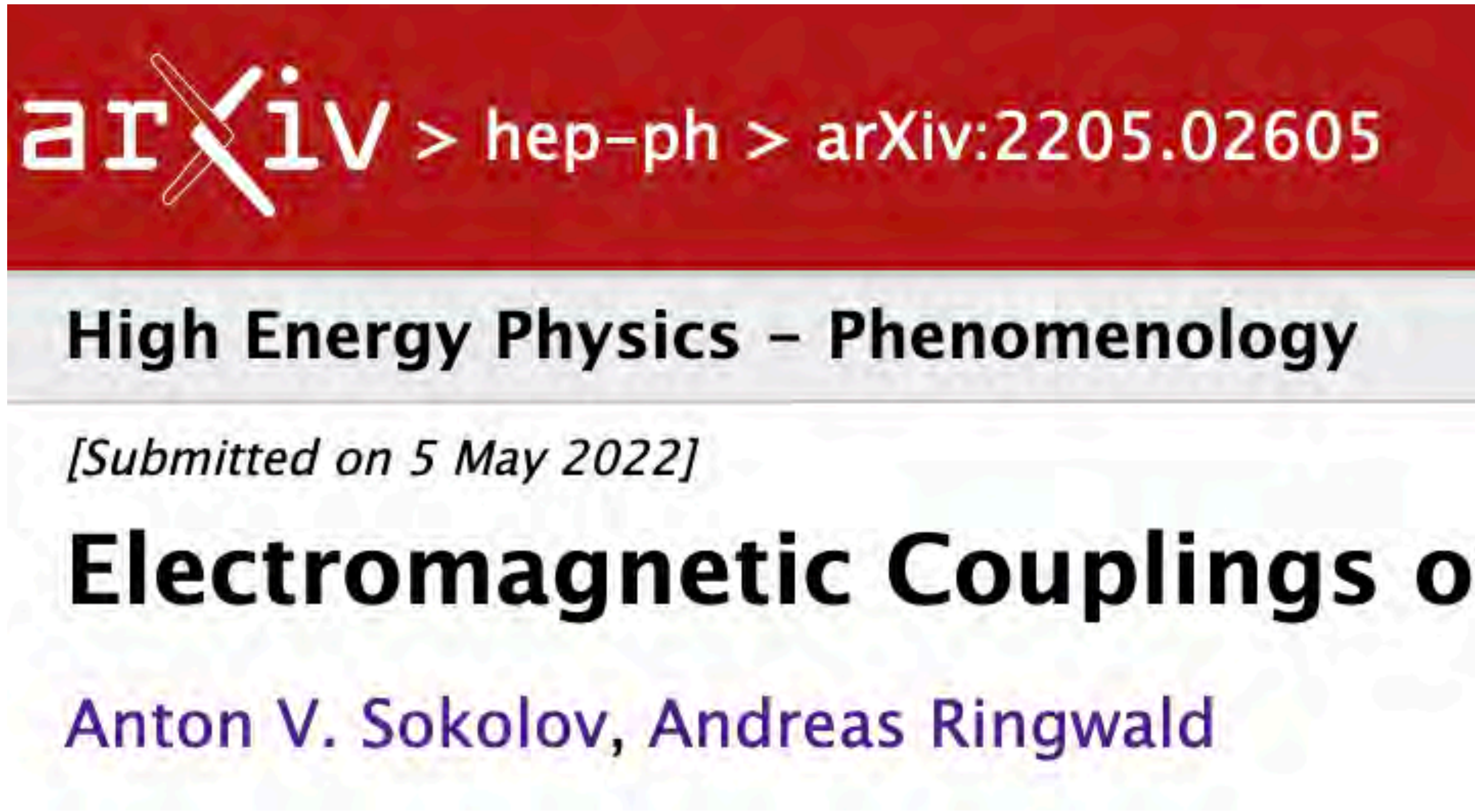
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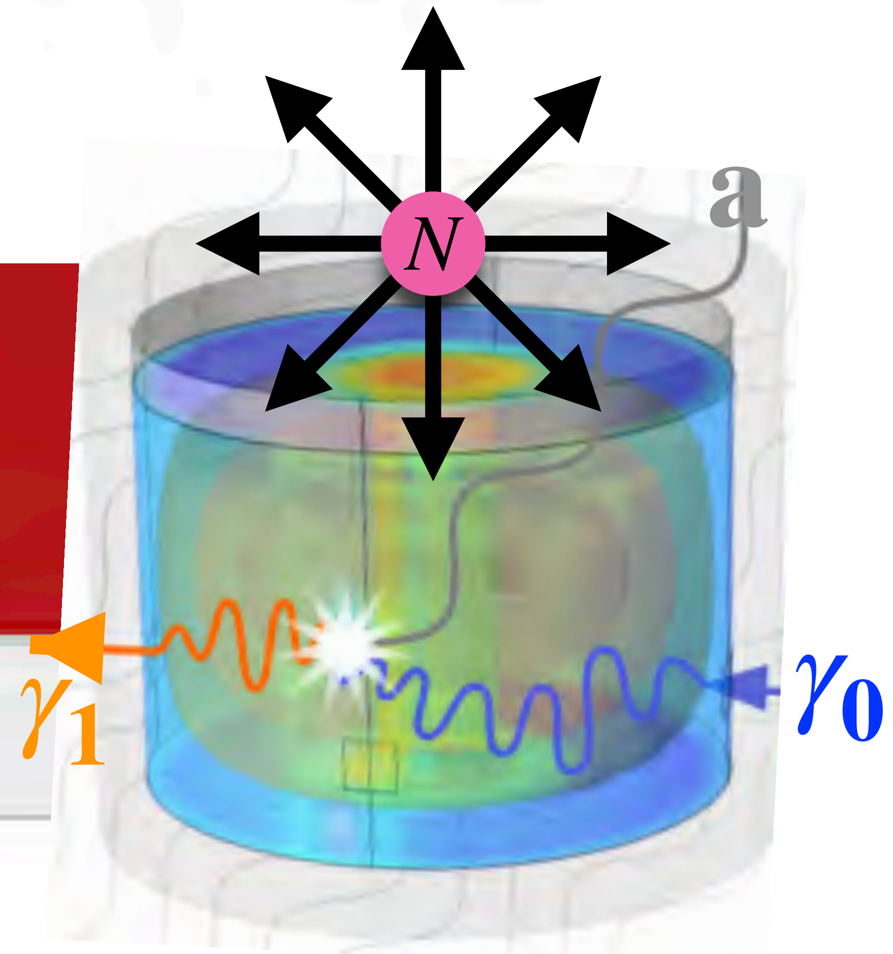

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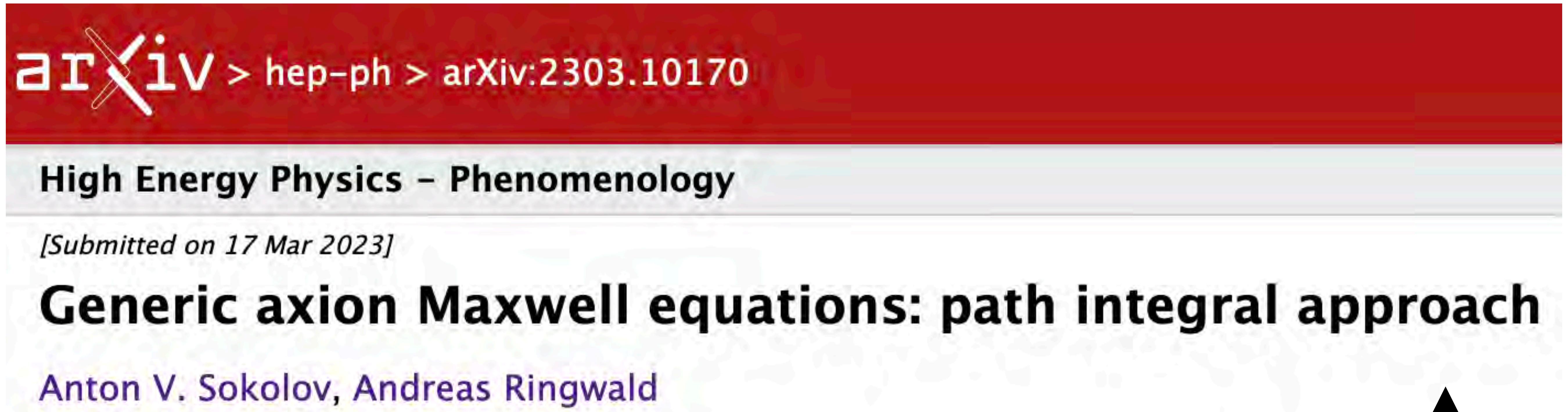
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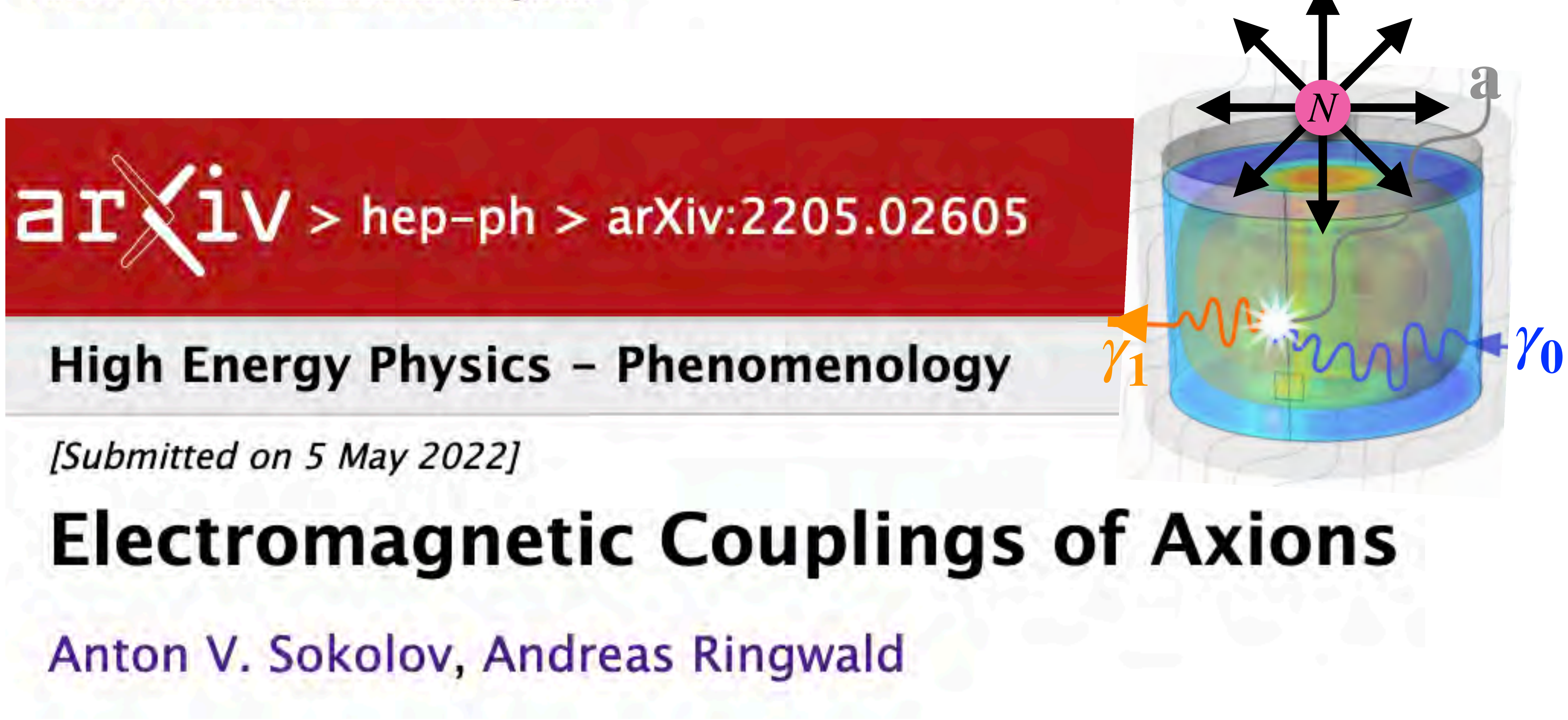
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$$\vec{\nabla} \cdot \vec{E}_1 = g_{a\gamma\gamma} c \vec{B}_0 \cdot \vec{\nabla} a - g_{aEM} \vec{E}_0 \cdot \vec{\nabla} a + \epsilon_0^{-1} \rho_{e1},$$

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

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

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

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

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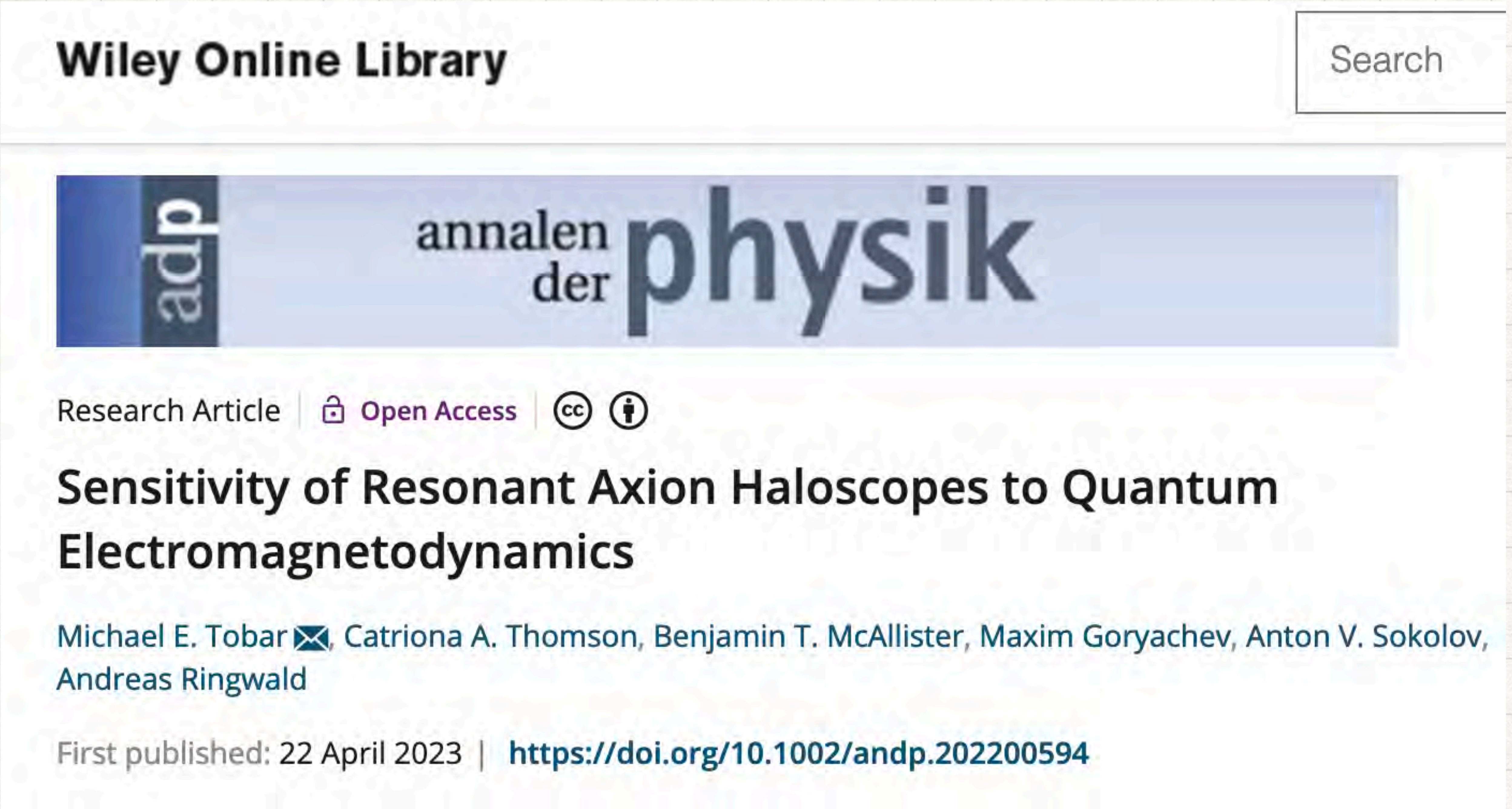

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Sensitivity of Resonant Axion Haloscopes to Quantum Electromagnetodynamics

Michael E. Tobar, Catriona A. Thomson, Benjamin T. McAllister, Maxim Goryachev, Anton V. Sokolov, Andreas Ringwald

First published: 22 April 2023 | https://doi.org/10.1002/andp.202200594

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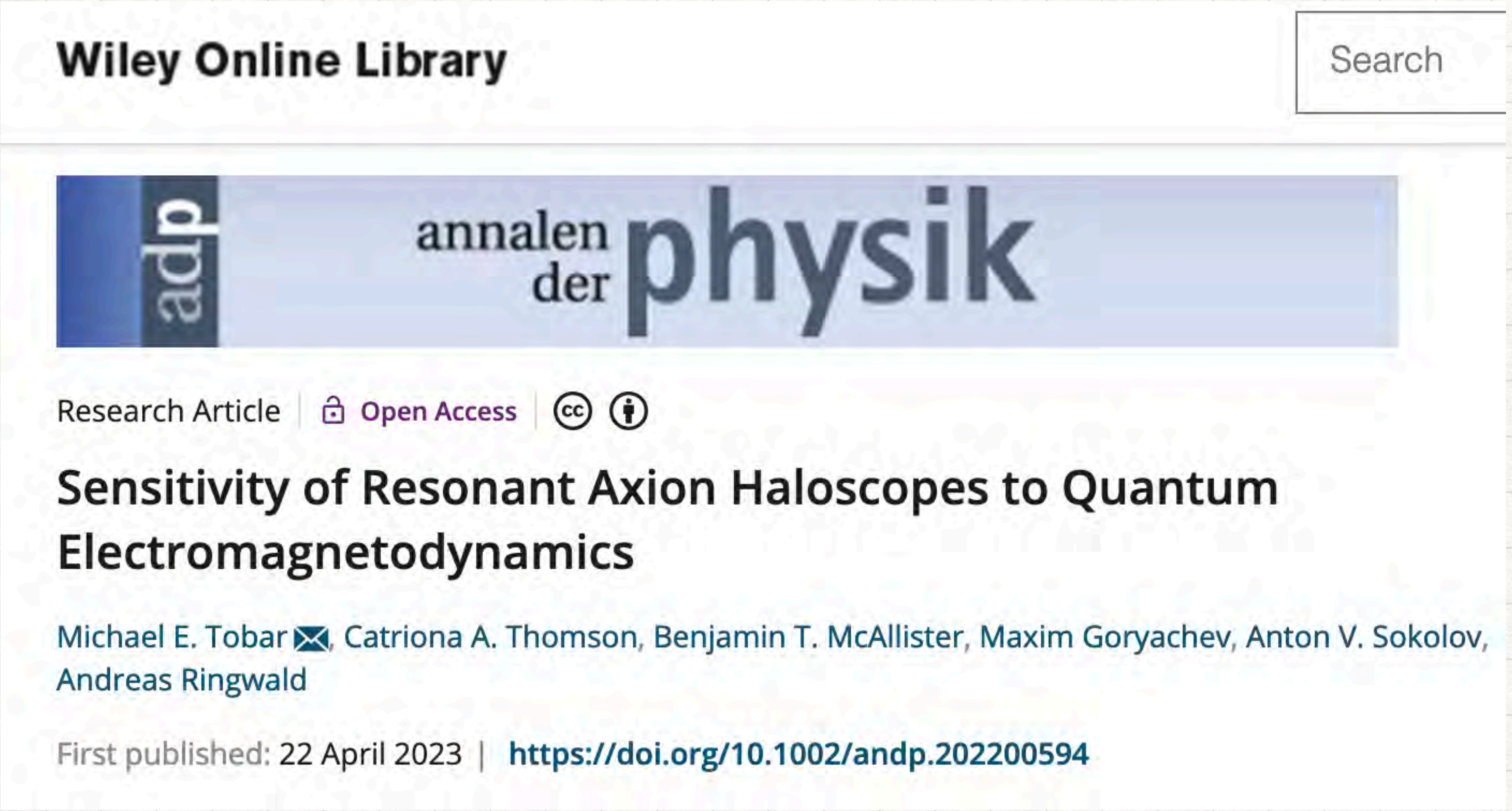

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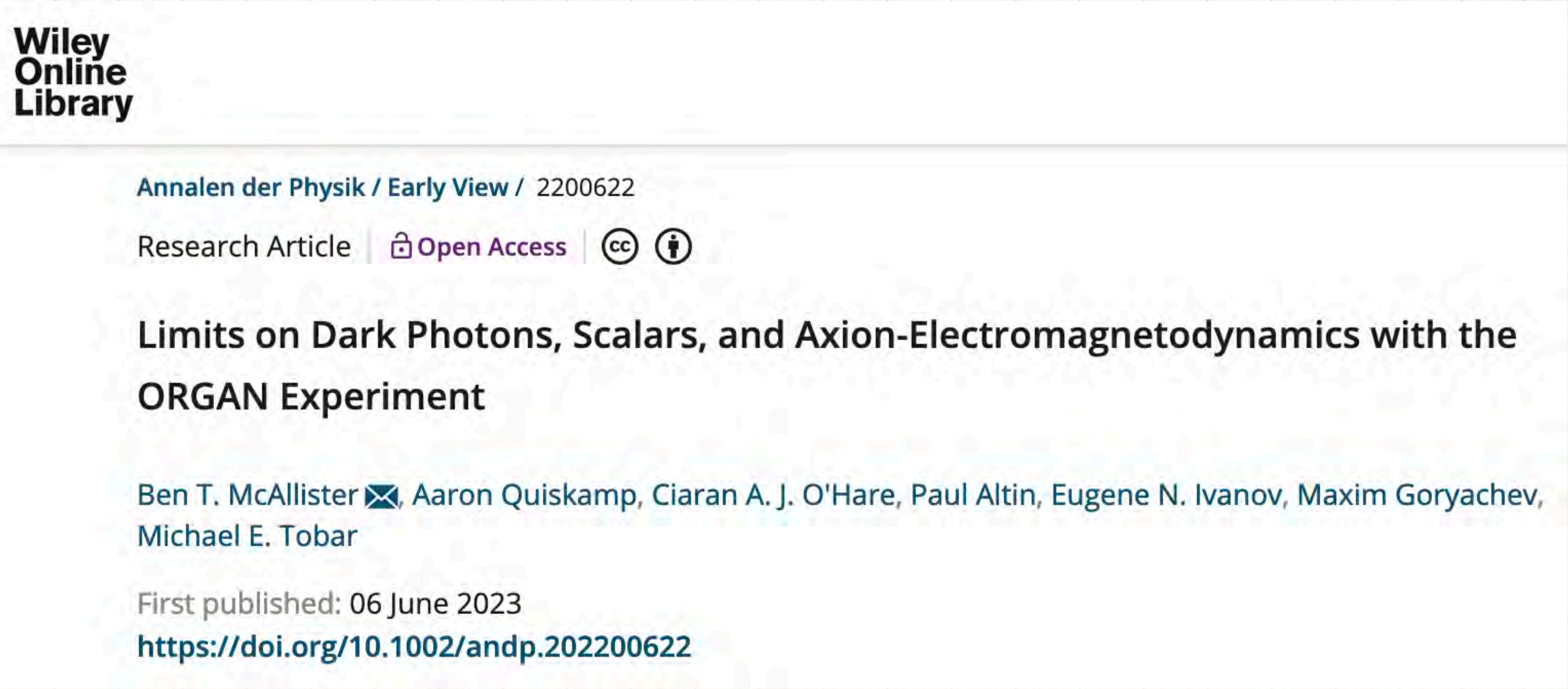

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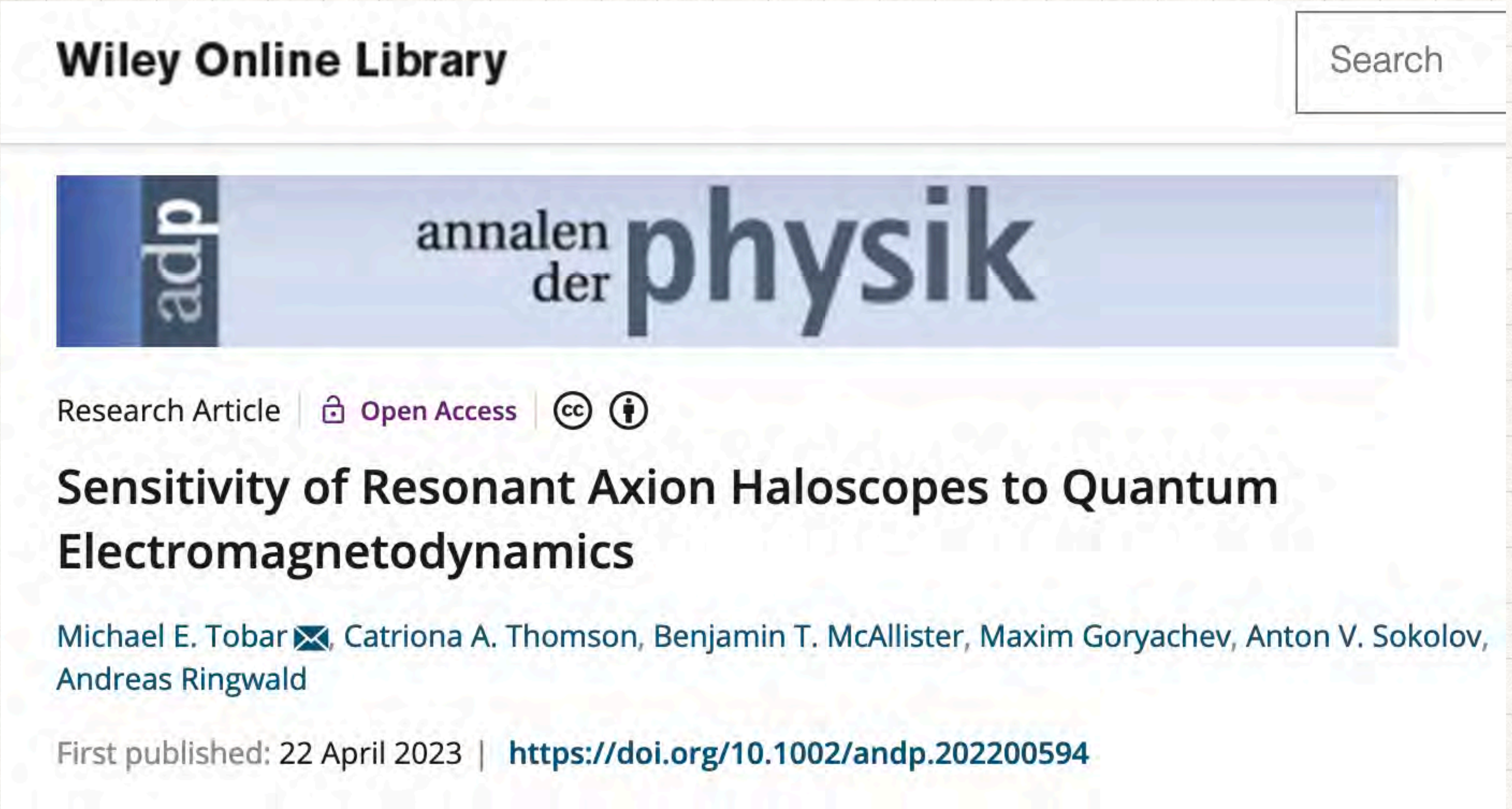

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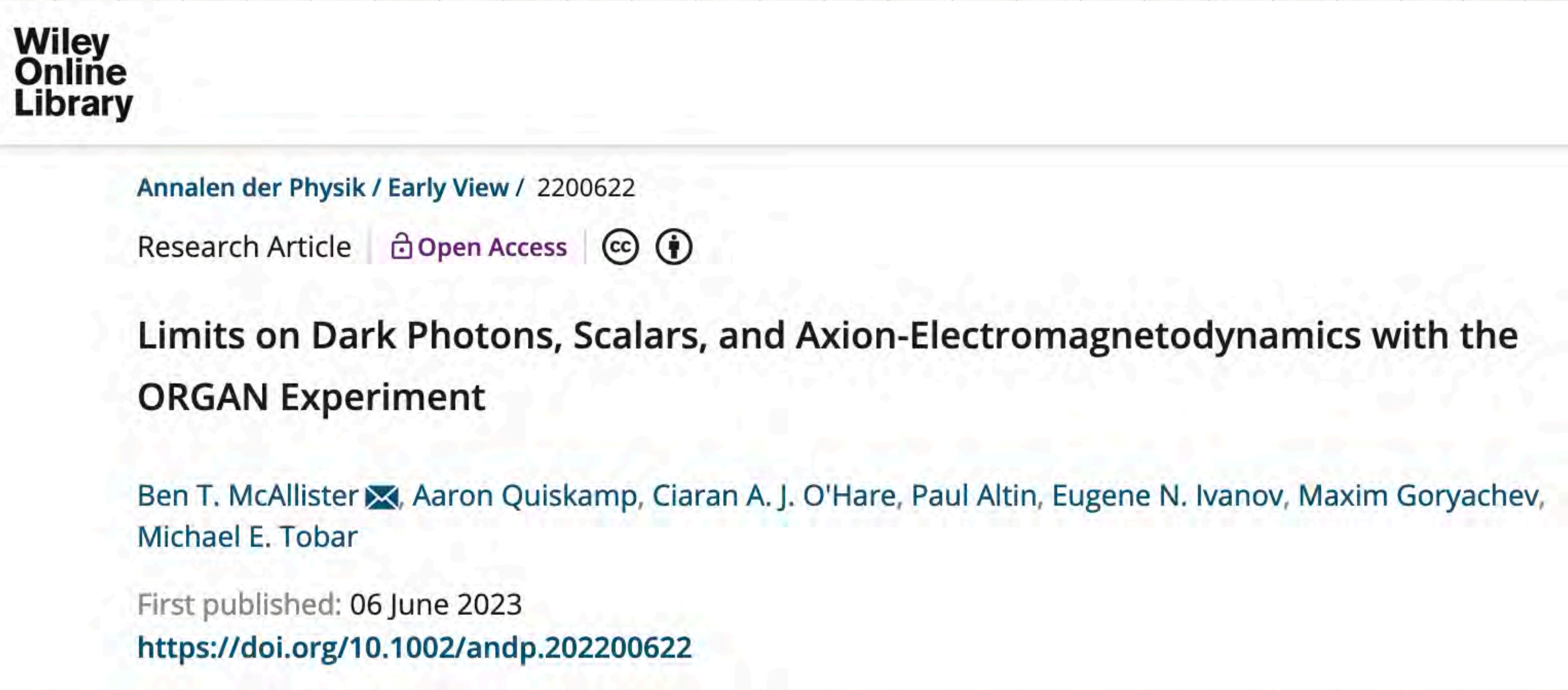

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Reactive Experiment with Static Background Electric and Magnetic Field -> Imaginary Poynting Theorem

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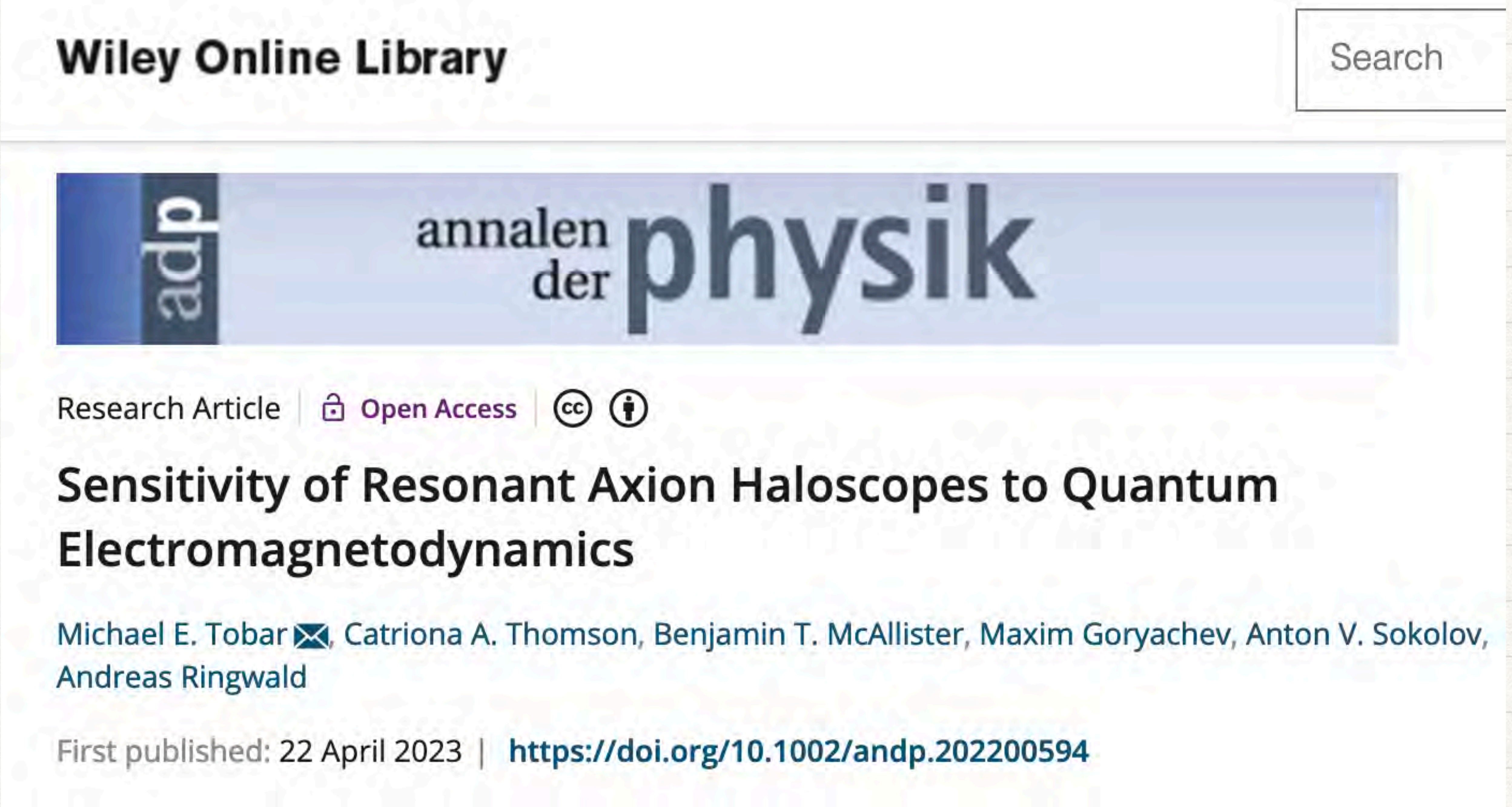

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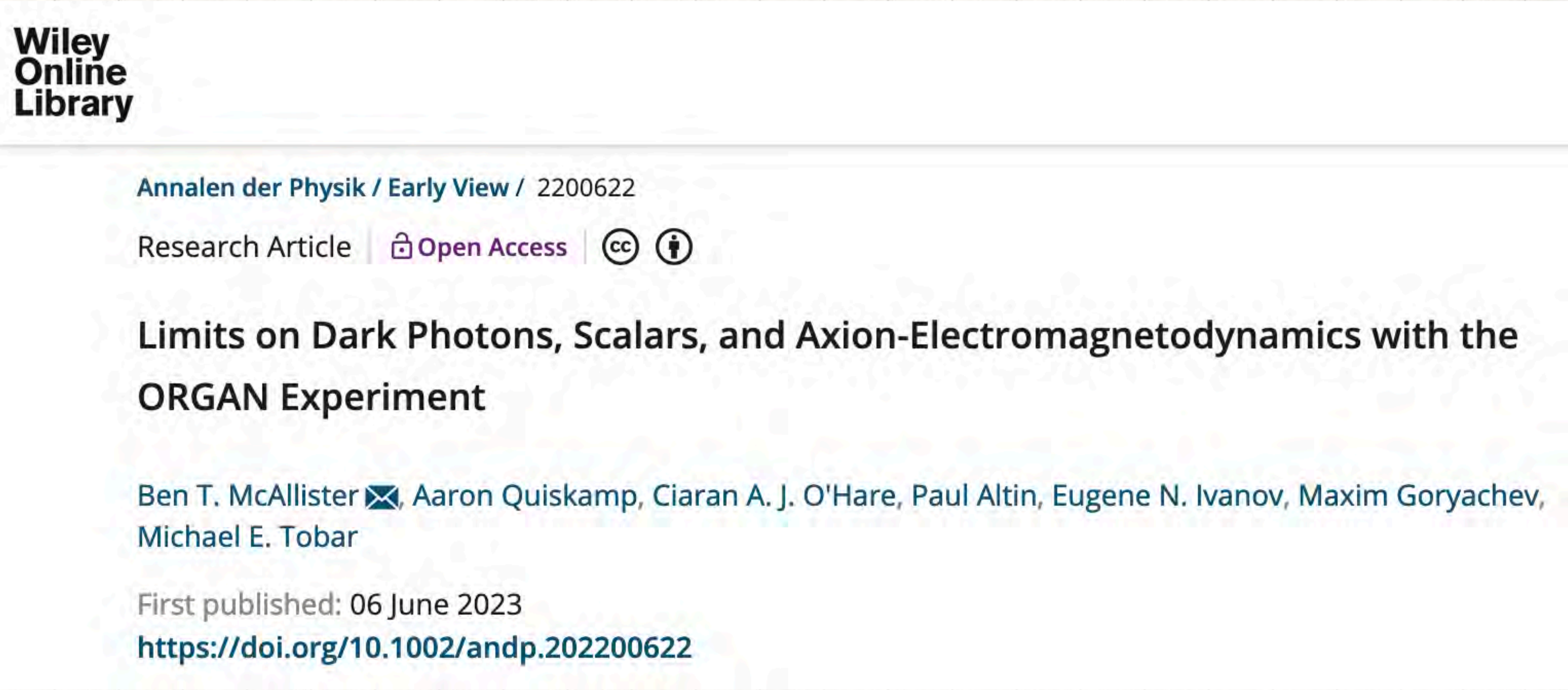

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PHYSICAL REVIEW D **108,** 035024 (2023)

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

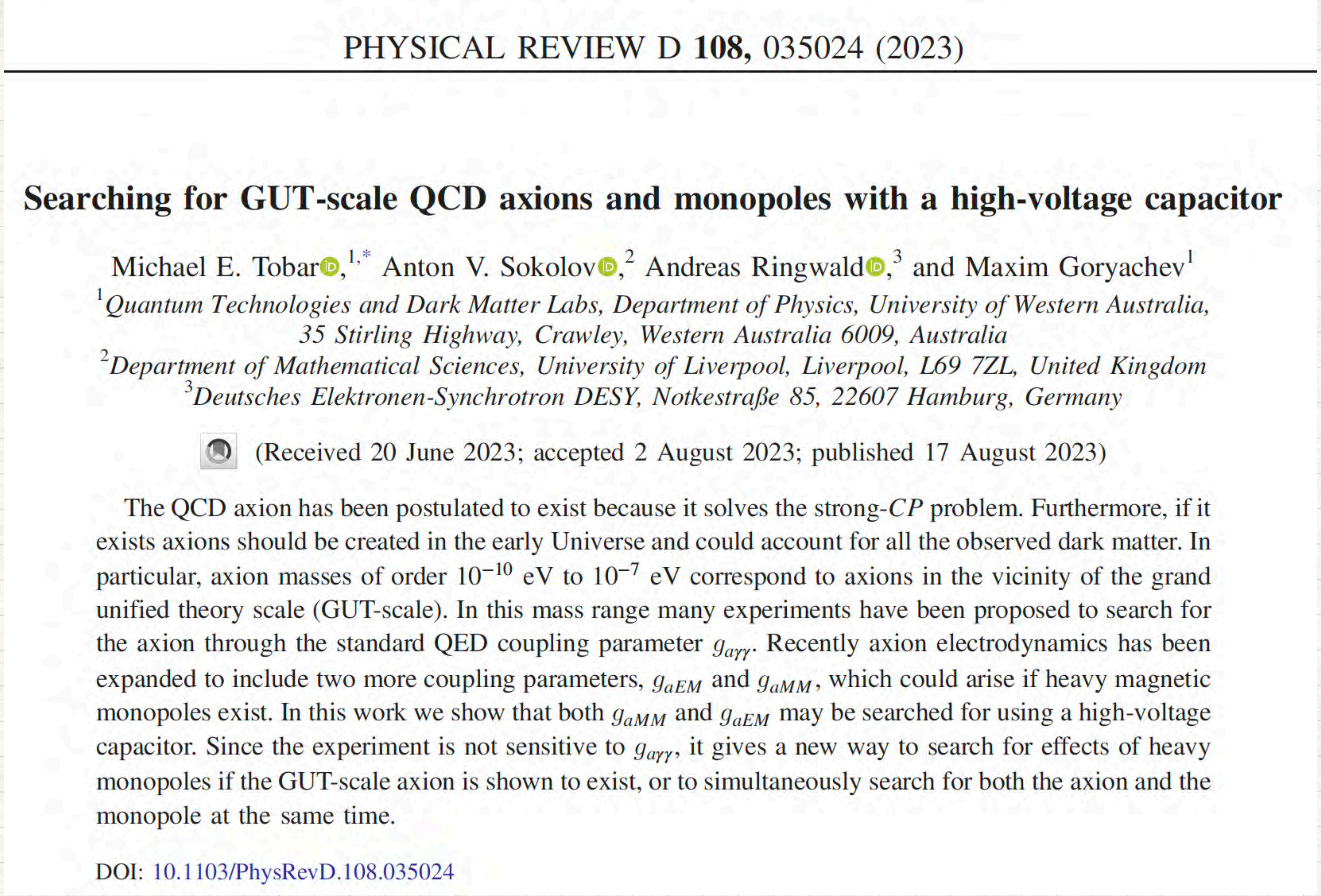
$$C_{1a\gamma} = \frac{(\int \vec{B}_0 \cdot \mathrm{Re}(\mathbf{E}_1) dV)^2}{B_0^2 V_1 \int \mathbf{E}_1 \cdot \mathbf{E}_1^* dV} \qquad C_{1EM} = \frac{(\int \vec{B}_0 \cdot \mathrm{Re}(\mathbf{B}_1) dV)^2}{B_0^2 V_1 \int \mathbf{B}_1 \cdot \mathbf{B}_1^* dV}$$

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

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



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[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)

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

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

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

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

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

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

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

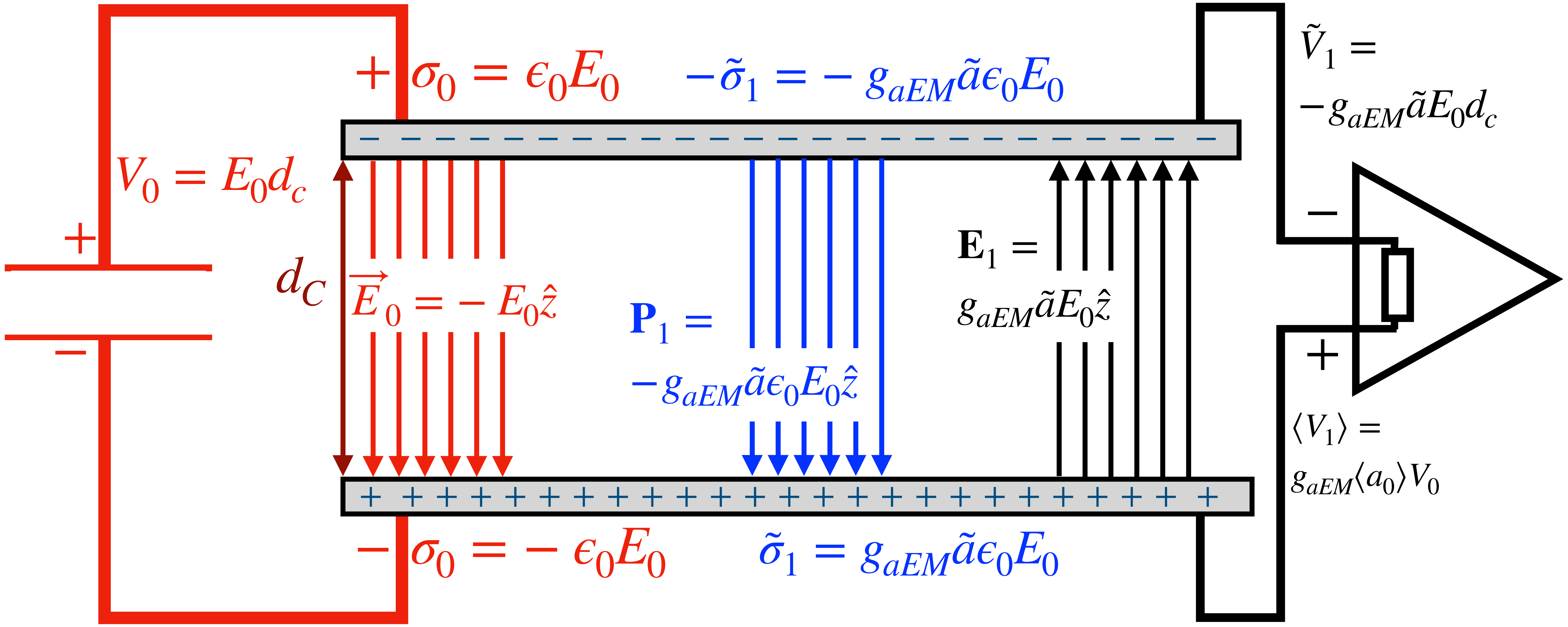
AC Capacitor: Apply Poynting Theorem: Sensitive to g_{aEM}

Vector Phasor Amplitudes

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

$$U_1 = \frac{\epsilon_0 a_0^2\left(\int\left(g_{aEM}\left(\mathbf{E}_1^*+\mathbf{E}_1\right) - g_{aMM}c\left(\mathbf{B}_1^*+\mathbf{B}_1\right)\right)\cdot\vec{E}_0 dv\right)^2}{8\int\left(\left(c^2\mathbf{B}_1^*\cdot\mathbf{B}_1 - \mathbf{E}_1\cdot\mathbf{E}_1^*\right)\right)dv} \qquad \mathbf{B}_1+\mathbf{B}_1^* \sim 0 \quad \mathbf{E}_1+\mathbf{E}_1^* \sim 2\mathbf{E}_1 \qquad U_1 \approx -\frac{g_{aEM}^2 a_0^2\epsilon_0\left(\int\mathbf{E}_1\cdot\vec{E}_0 dv\right)^2}{2\int\mathbf{E}_1\cdot\mathbf{E}_1^* dv}$$

Axion generated Electric Field



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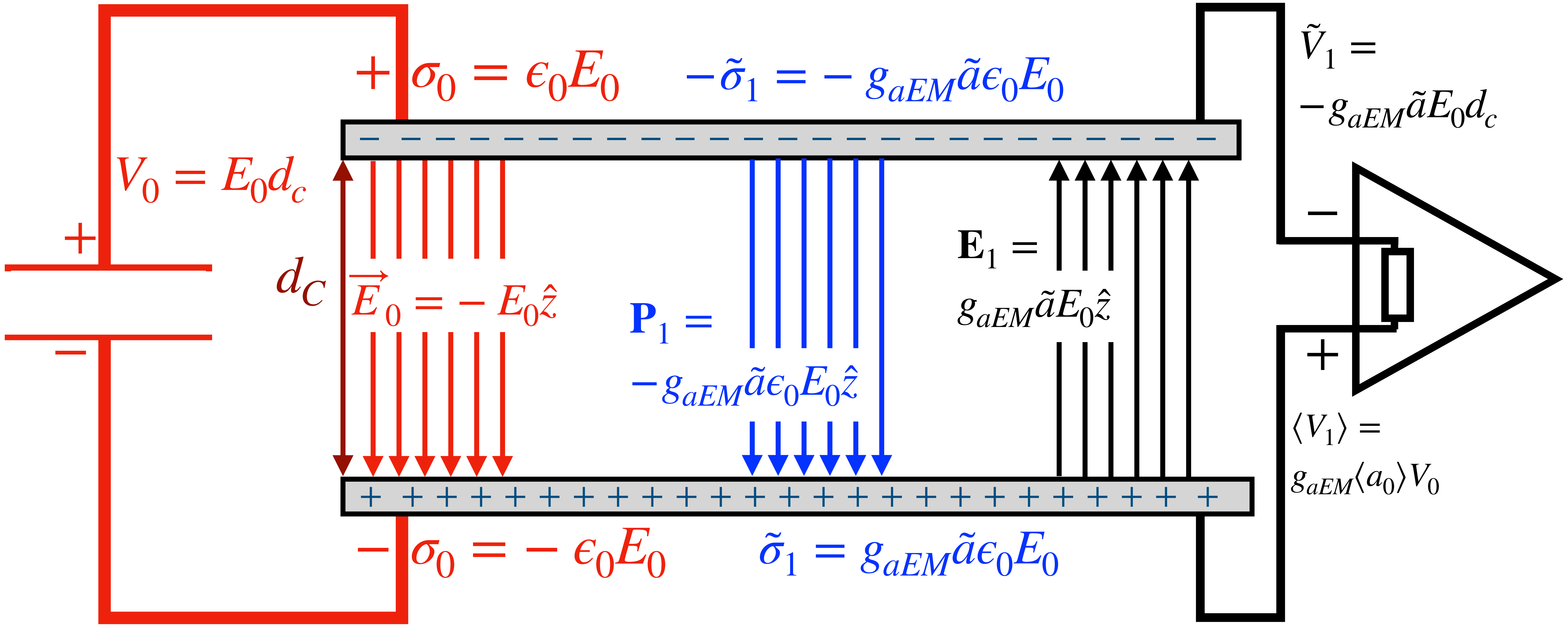
$$\oint \mathrm{Im}\left(\mathbf{S}_1\right)\cdot\hat{n}ds = \omega_a \int \Big(\big(\frac{1}{2\mu_0}\mathbf{B}_1^*\cdot\mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1\cdot\mathbf{E}_1^*\big) - \frac{g_{aEM}a_0\epsilon_0}{4}(\mathbf{E}_1+\mathbf{E}_1^*)\cdot\vec{E}_0 + \frac{g_{aMM}a_0\epsilon_0}{4}(\mathbf{B}_1+\mathbf{B}_1^*)\cdot\vec{E}_0\Big)\,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

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

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

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

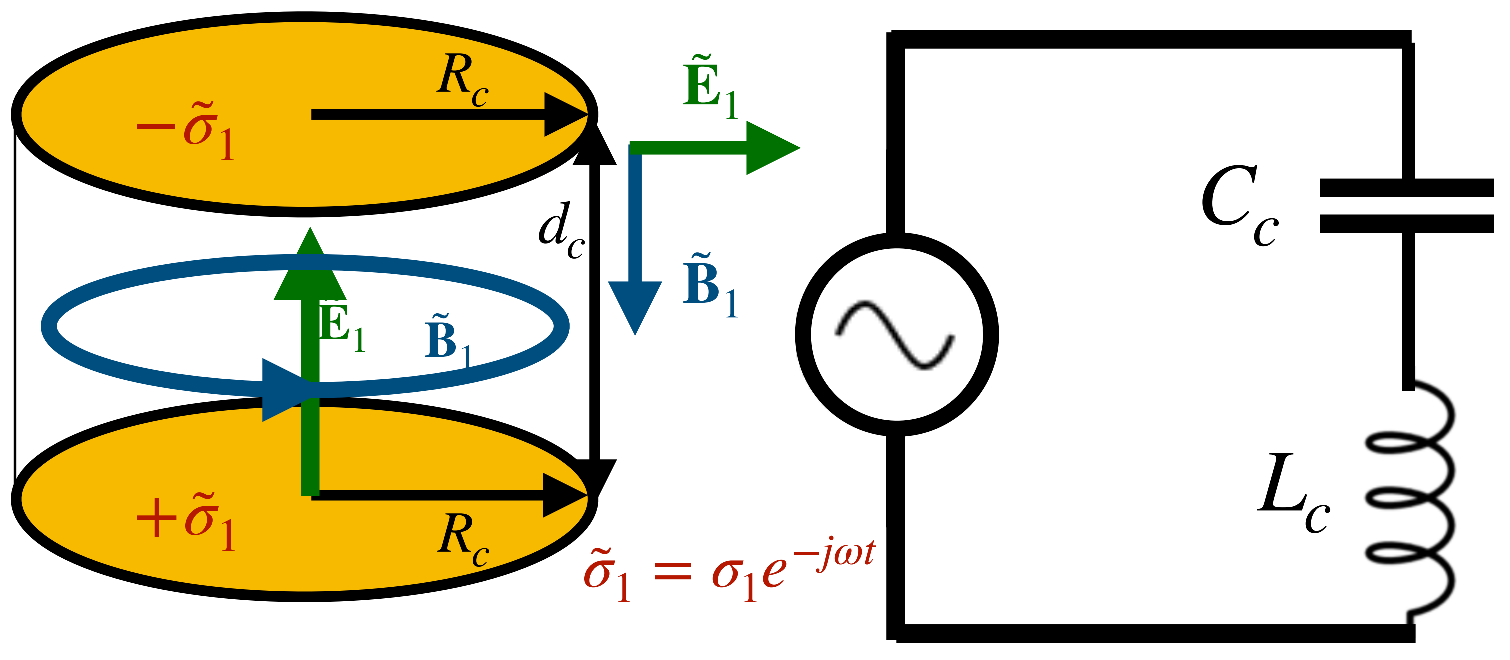
Axion generated Electric Field



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}

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

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

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

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

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

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

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

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

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

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

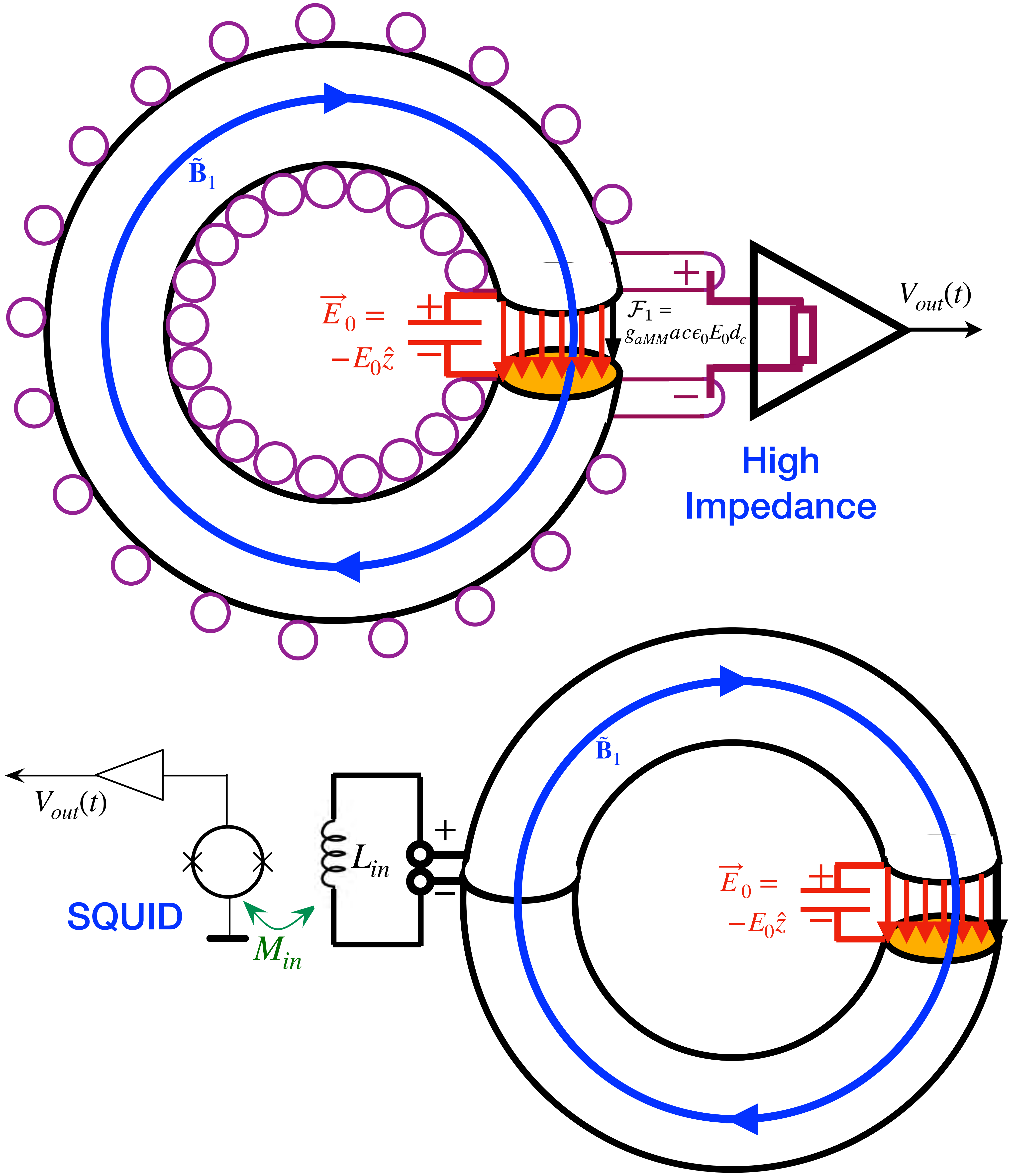
Axion Generated Magnetic Field-> Magnetic Circuit Readout Sensitive to g_{aMM}

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

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

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

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

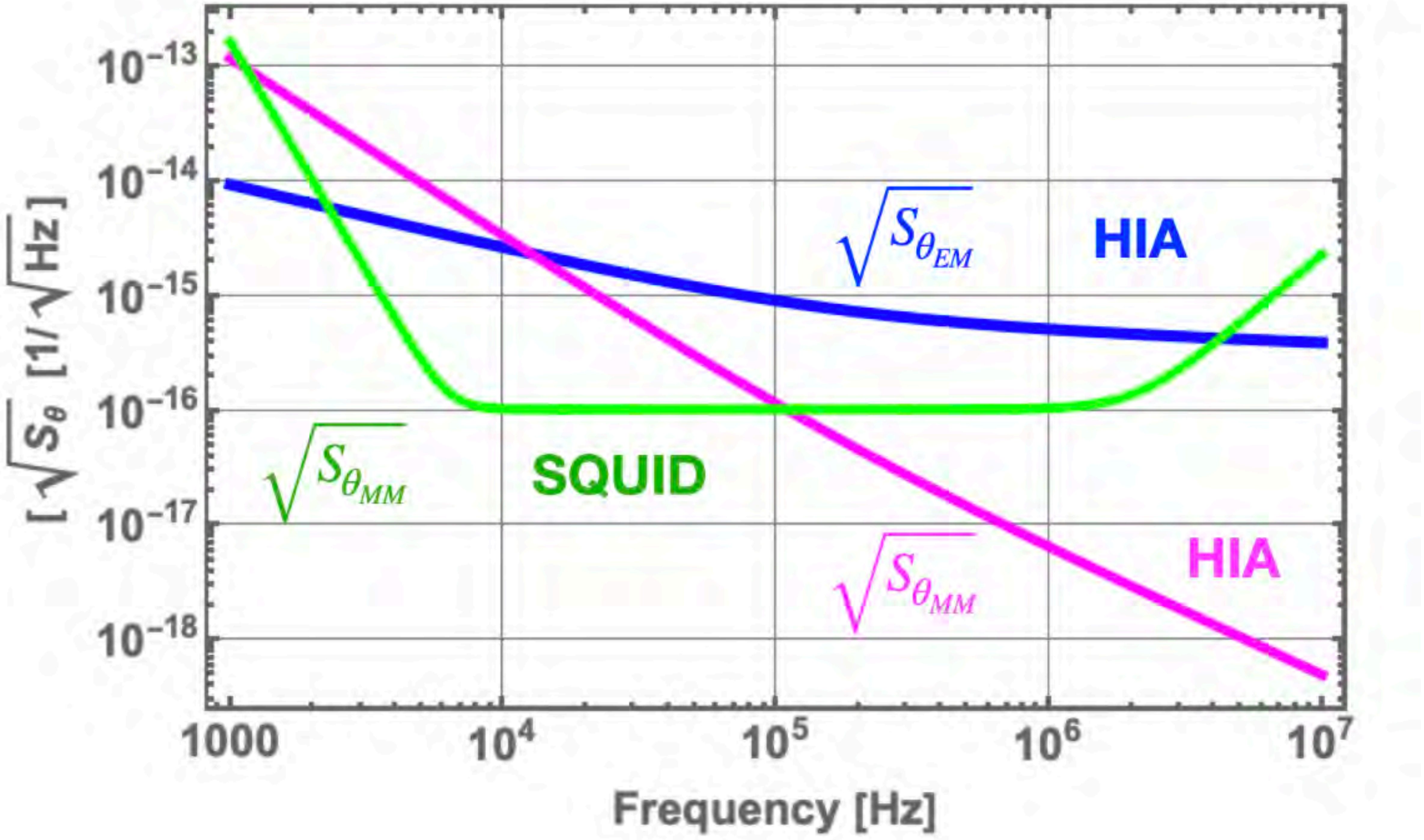


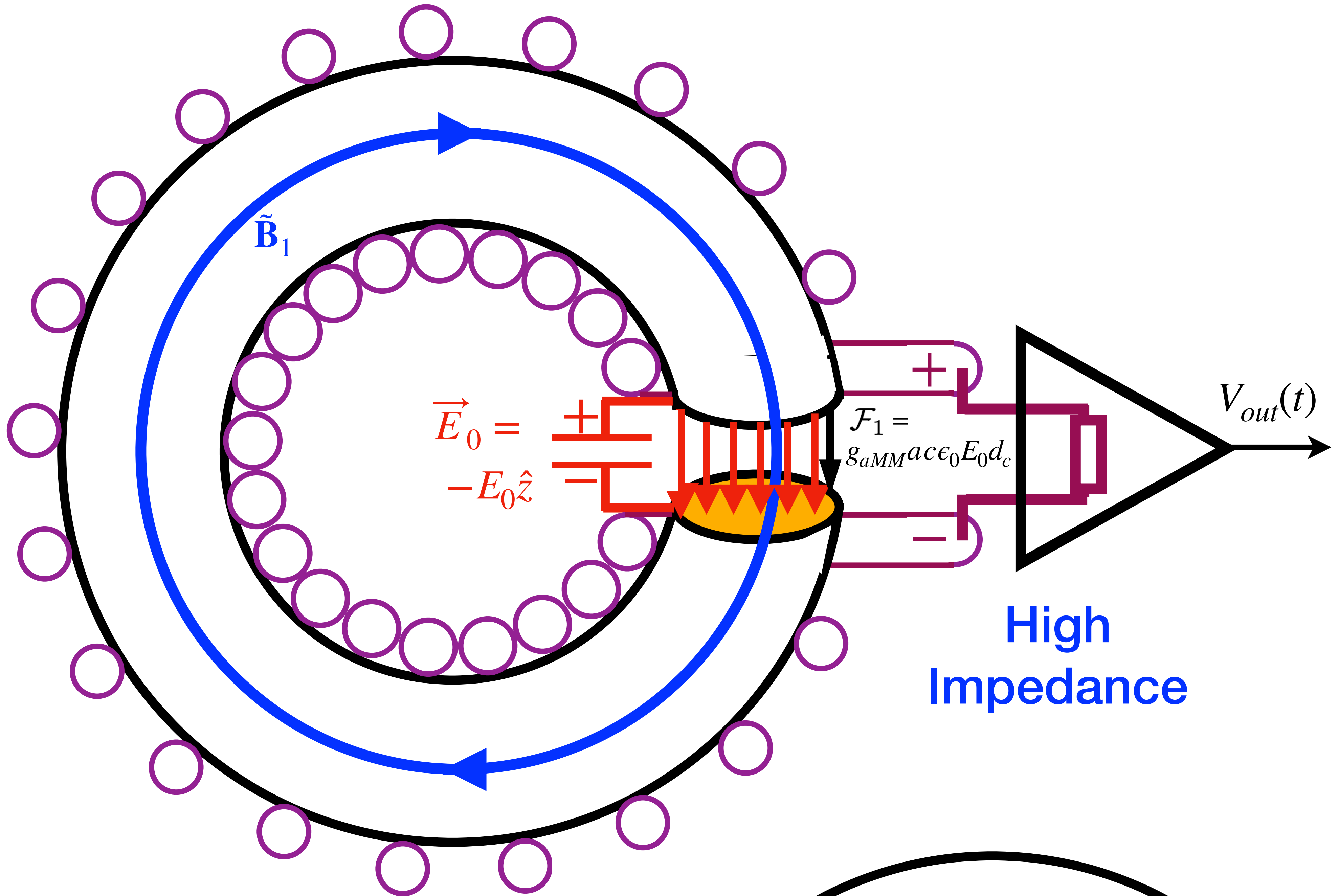
Axion Generated Magnetic Field-> Magnetic Circuit Readout Sensitive to g_{aMM}

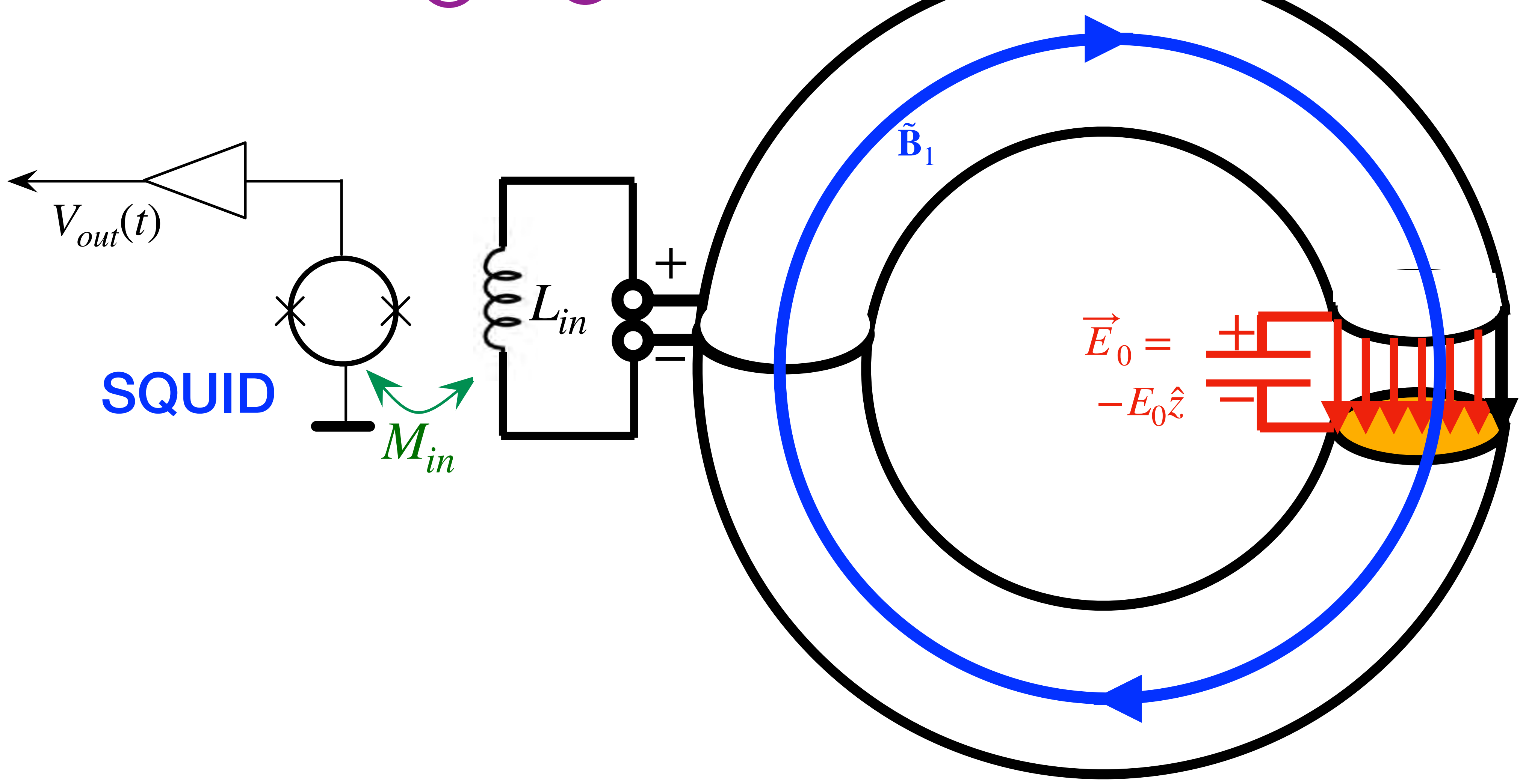
$$\frac{\oint \mathrm{Im}\left(\mathbf{S}_1\right)\cdot\hat{n}ds}{\omega_a} = \int\left(\left(\frac{1}{2\mu_0}\mathbf{B}_1^*\cdot\mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1\cdot\mathbf{E}_1^*\right) - \frac{g_{aEM}a_0\epsilon_0}{4}(\mathbf{E}_1+\mathbf{E}_1^*)\cdot\vec{E}_0 + \frac{g_{aMM}a_0\epsilon_0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

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

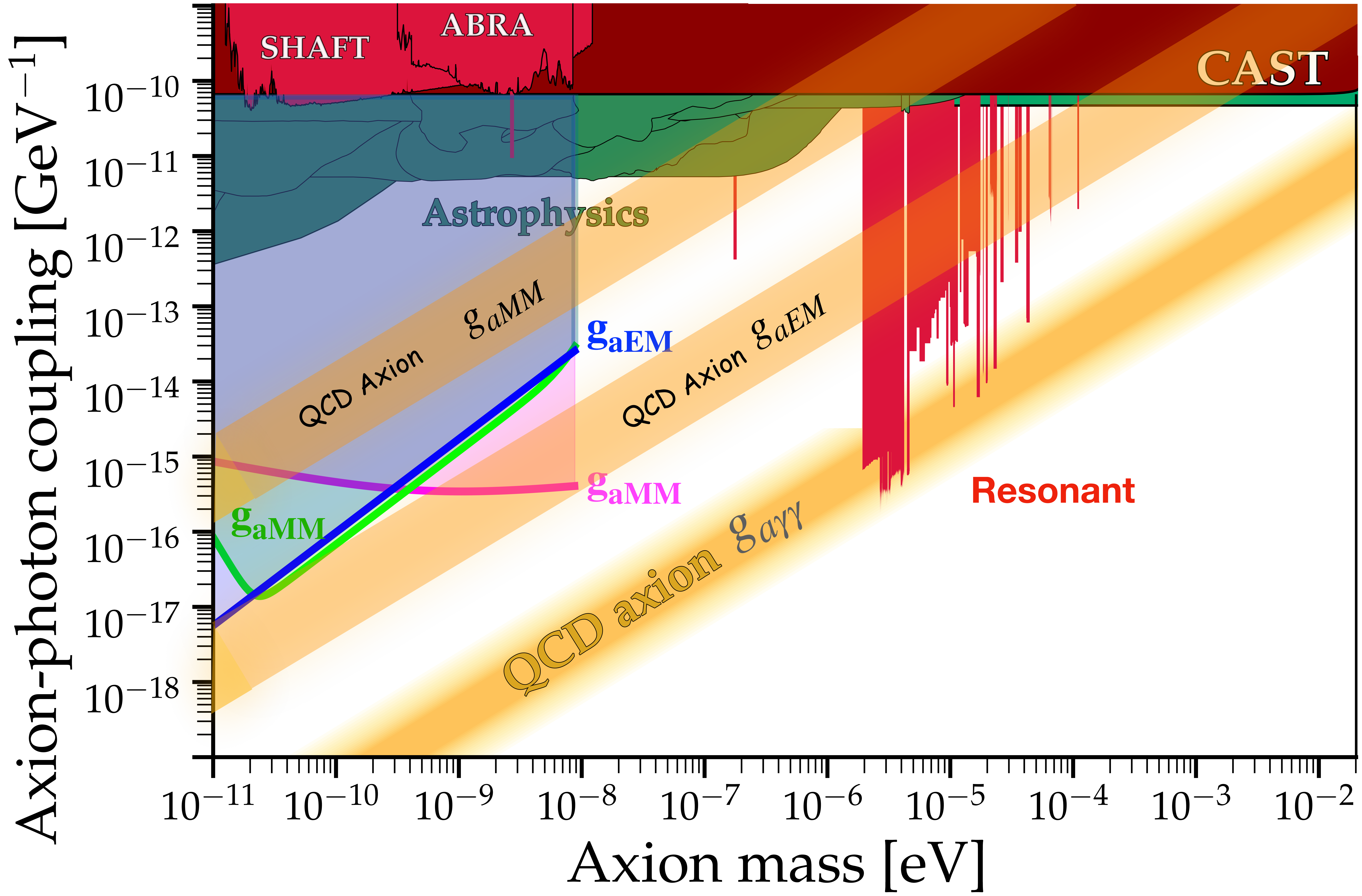
$$U_1 = \frac{\left(\frac{g_{aMM}a_0\epsilon_0 c}{2}\int \mathbf{B}_1\cdot\vec{E}_0\,dV\right)^2}{\int\left(\frac{1}{2\mu_0}\mathbf{B}_1^*\cdot\mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1\cdot\mathbf{E}_1^*\right)dV} \qquad U_1 \approx \frac{g_{aMM}^2 a_0^2\epsilon_0}{2}\frac{\left(\int \mathbf{B}_1\cdot\vec{E}_0\,dV\right)^2}{\int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





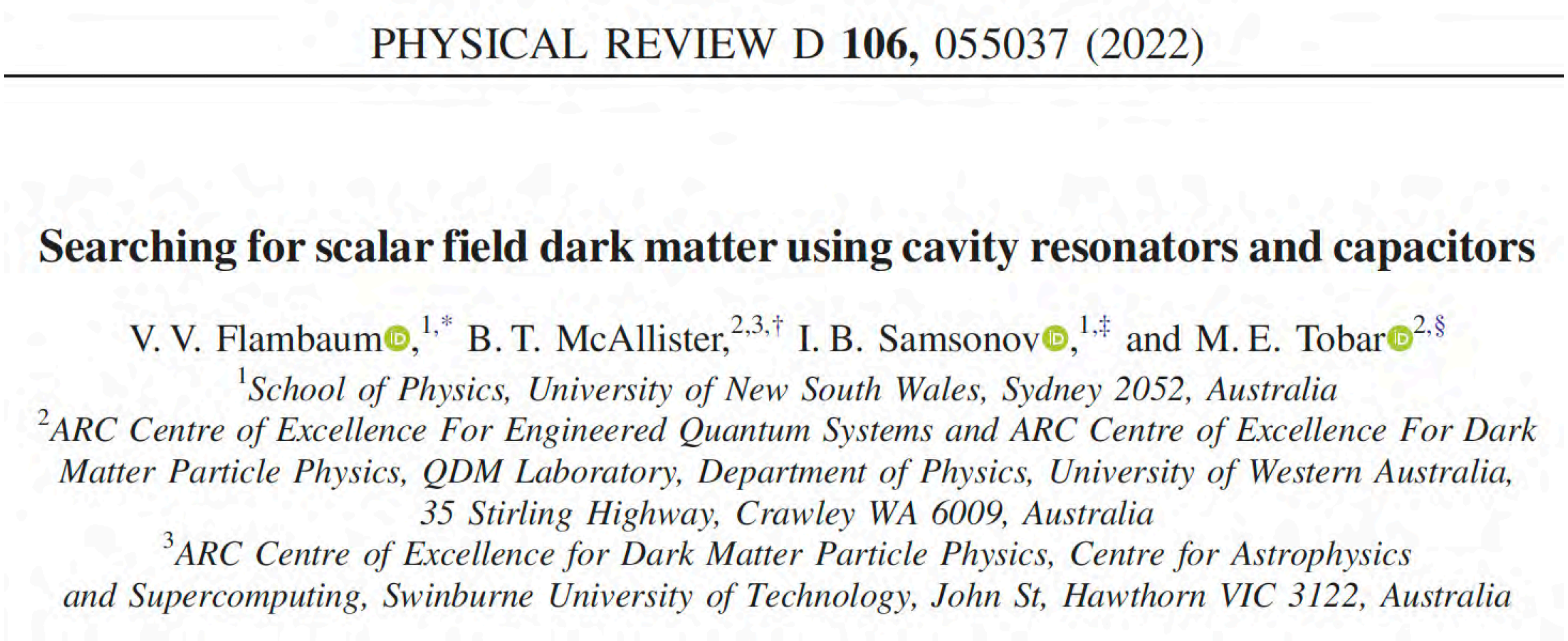


Low-Mass Sensitivity to the QCD Axion



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

The Team


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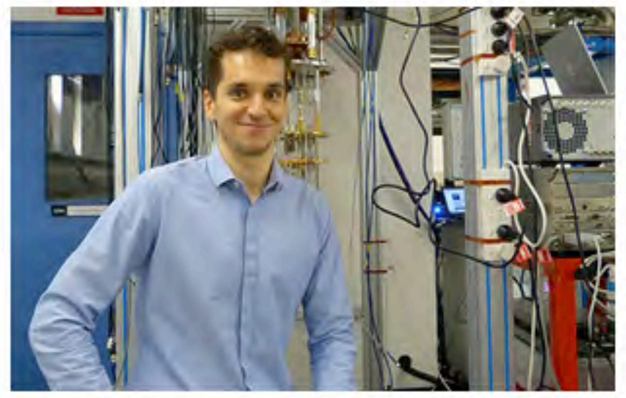
Director—QDM Lab, EQUS Node Director, CDM Node Director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Lecturer—Research Intensive, EQUS Chief Investigator, CDM Chief Investigator

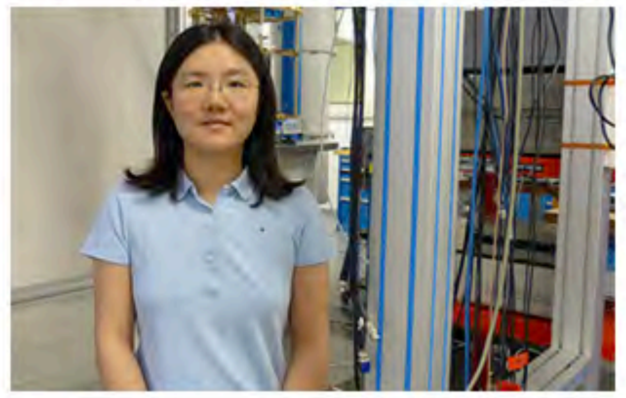

Dr Ben McAllister
Forrest Prospect Fellow

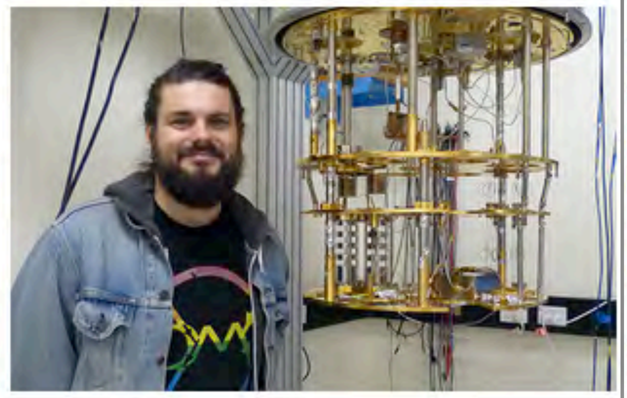

Professor Alexey Veryaskin
Adjunct Professor

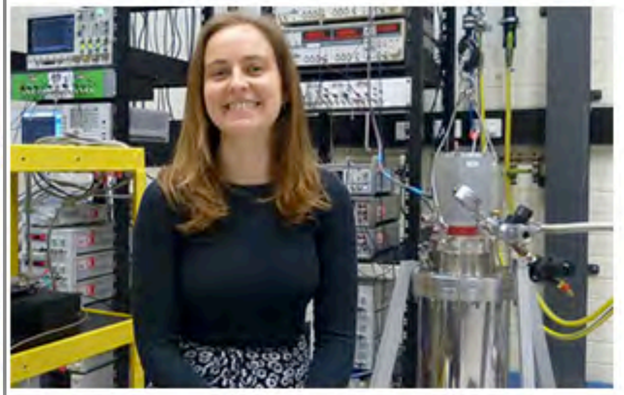

Graeme Flower
Research Associate


Will Campbell
PhD

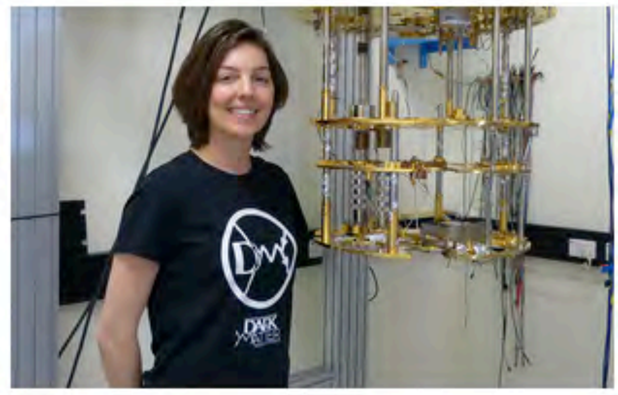

Winthrop Professor Eugene Ivanov
Senior Principle Research Fellow


Dr Cindy Zhao
Deborah Jin Fellow—EQUS

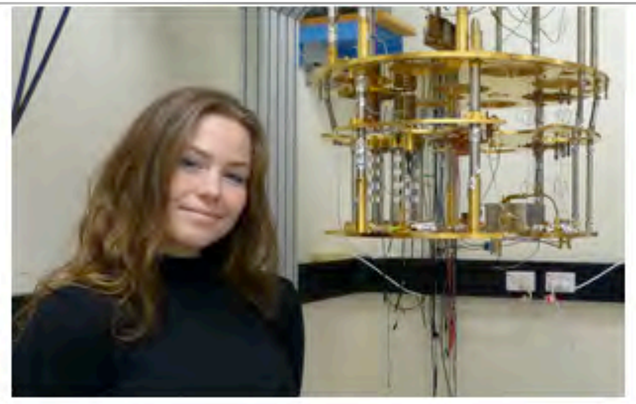

Dr Jeremy Bourhill
Postdoctoral Research Associate

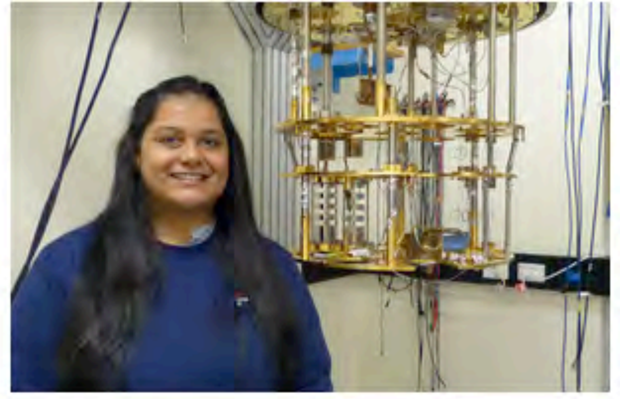

Catriona Thomson
PhD

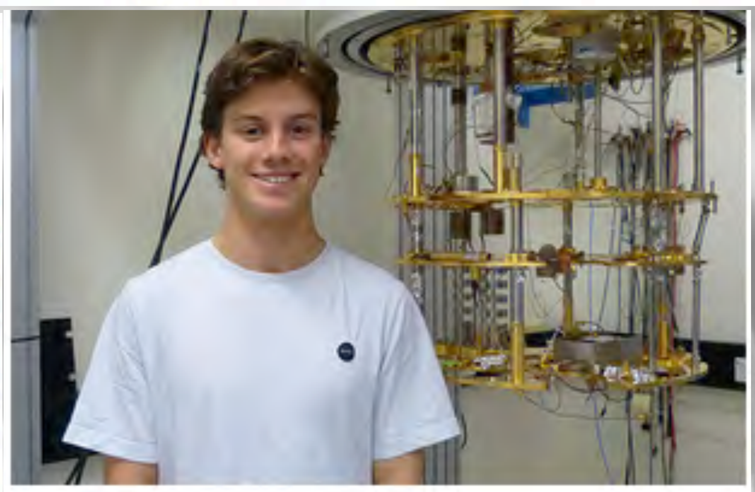

Aaron Quiskamp
PhD

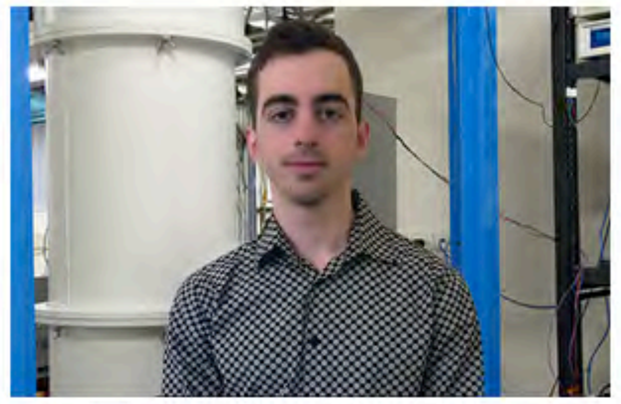

Elrina Hartman
PhD


Steven Samuels
PhD

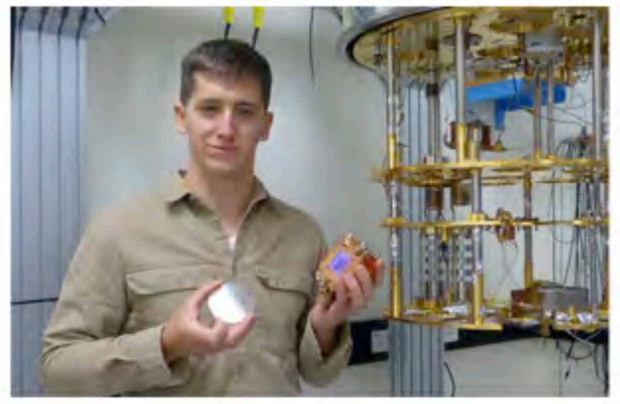

Emma Paterson
BPhil (Hons) Honours Dissertation


Sonali Parashar
Master of Physics—Coursework and Dissertation


Hugh Mitchell
BPhil (Hons) Honours Placement


Michael Hatzon
BPhil (Hons) Honours Dissertation


Robert Crew
BPhil (Hons) Honours Dissertation


Jerzy Cuper
Visiting Research Student, Warsaw University of Technology
1 October 2022 - 1 October 2023

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