Axion Haloscope Experiments at the University of Western Australia

Michael Tobar

https://arxiv.org/a/tobar_m_1.html

EQUS
Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

THE UNIVERSITY OF WESTERN AUSTRALIA

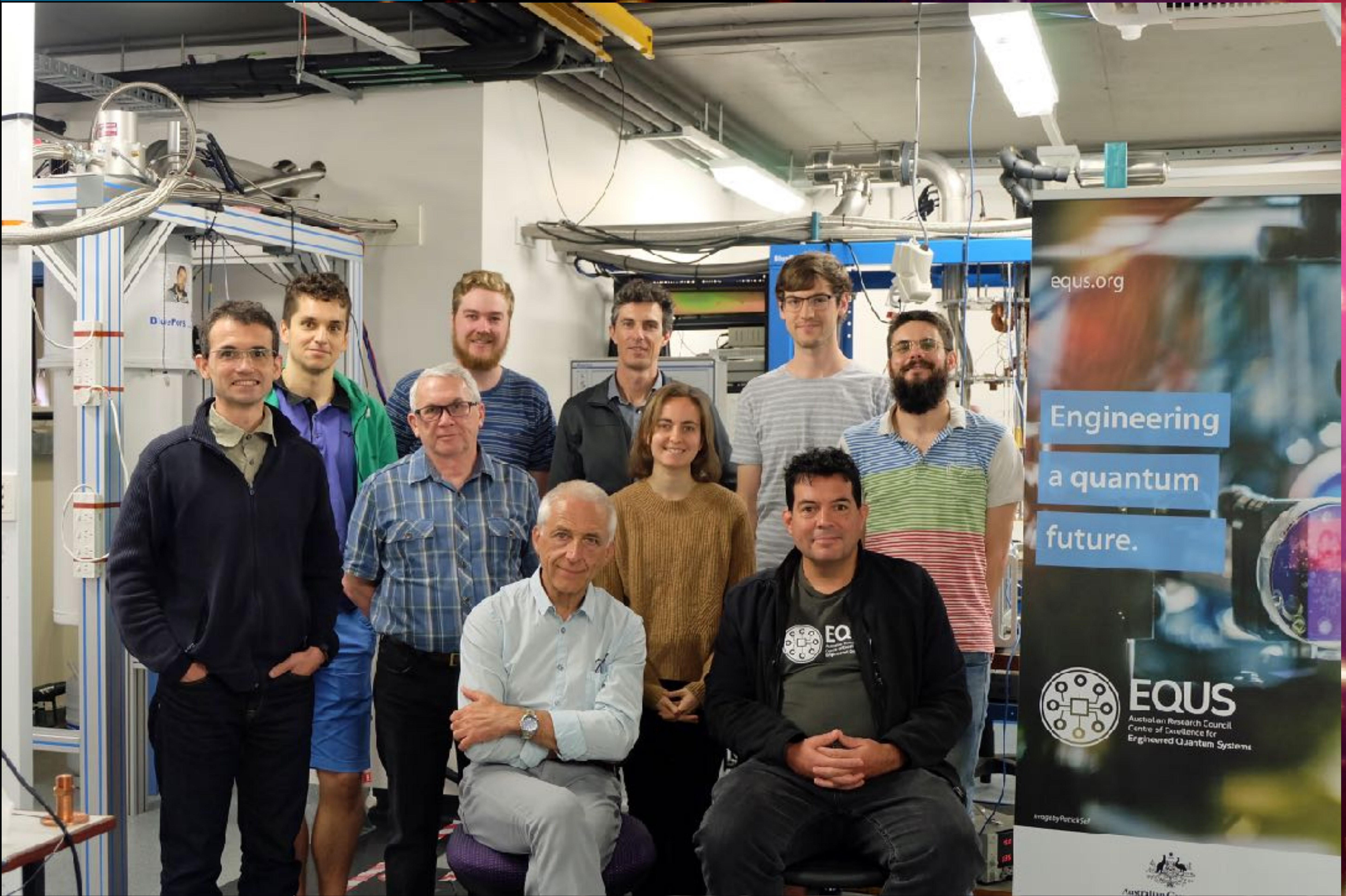
EQUS

Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

Frequency and Quantum Metrology Research Group at UWA

THE UNIVERSITY OF WESTERN AUSTRALIA

SEEK WISDOM



ACADEMIC STAFF

Michael Tobar
Eugene Ivanov
John McFerran
Alexey Veryaskin

POSTDOCS

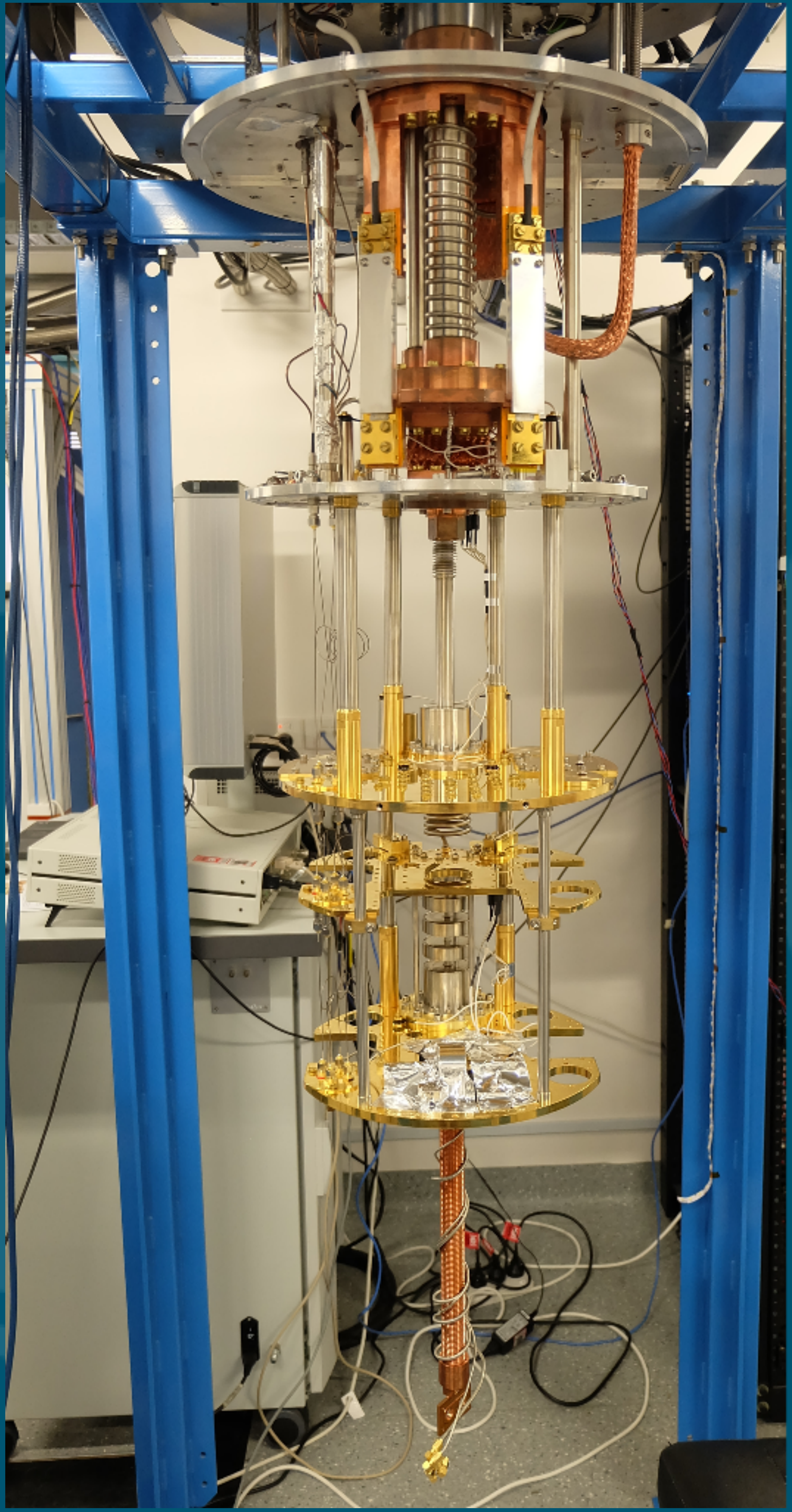
Sascha Schediwy
Maxim Goryachev
Ben Kaebe
Ben McAllister

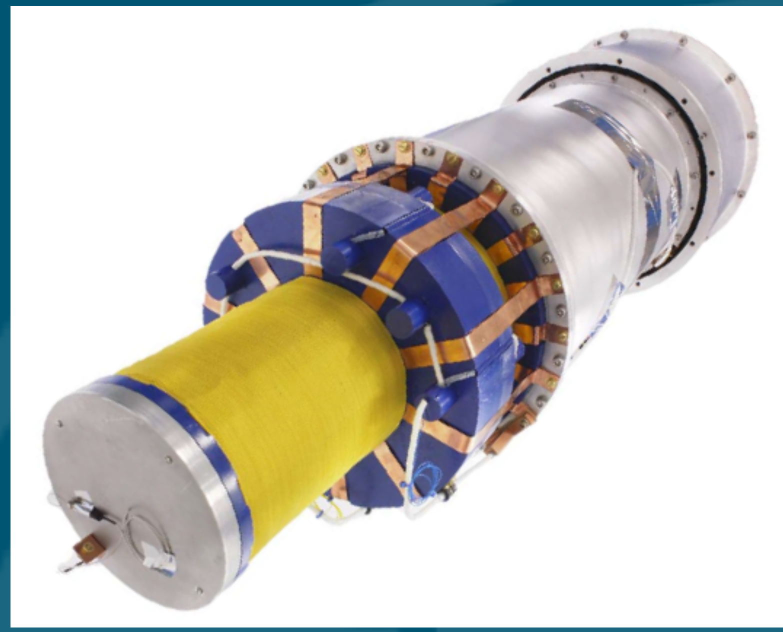
STUDENTS

Graeme Flower
Ben Dix-Mathews
Catriona Thomas
Jacob Ma
William Campbell
Aaron Quiskamp
Elrina Hartman
Rayman Watson
Brett Leask
Mushfiq Shah
Naijiao Jin
Ignasius Setiaputra

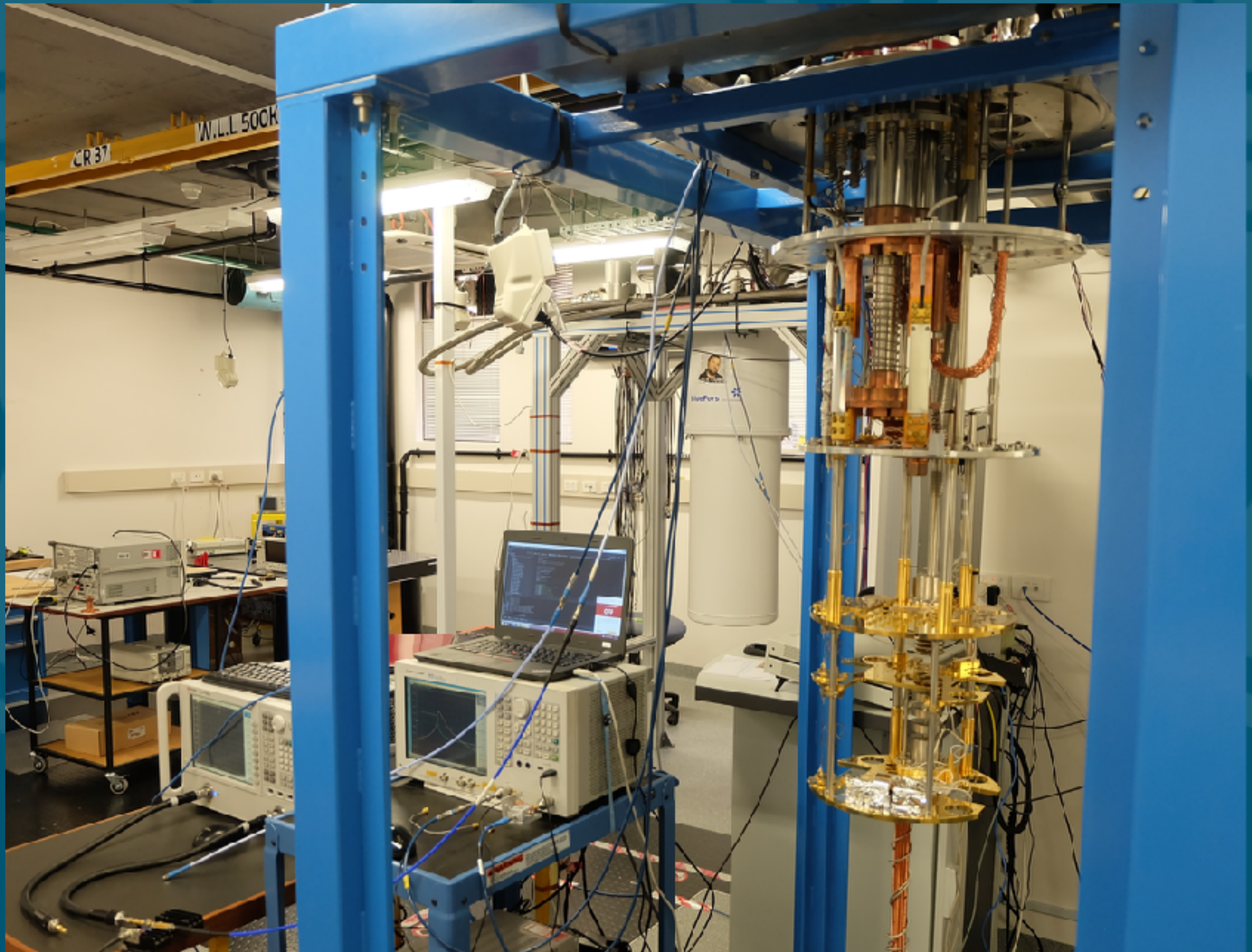
Dark Matter Experiments at UWA

Dilution Fridge Lab





7 T Magnet (10 cm bore)



Cavity-Magnon Polariton Axion Detection Experiment

arXiv:1811.09348v3 [physics.ins-det]

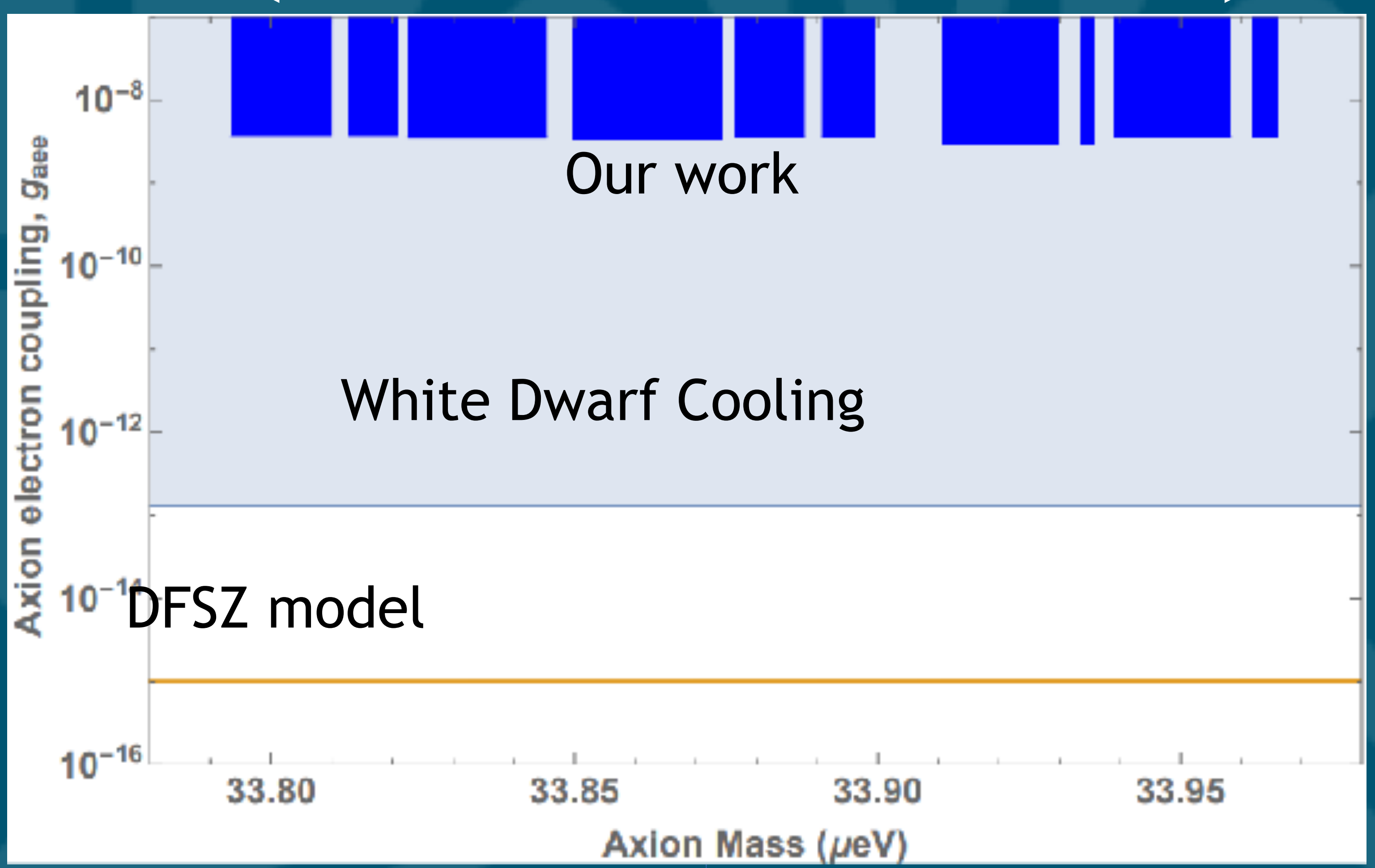
$g_{aee} > 3.7 \times 10^{-9}$ in the range 33.79 μeV< m_a < 33.94 μeV with 95% confidence.

$$\frac{H}{\hbar} = \omega_c a^\dagger a + \omega_m b^\dagger b + g_{cm}(a^\dagger + a)(b^\dagger + b)$$

Photons | Magnons | Interaction

36MHz in 6 MHz blocks from 8hrs of averages

Centred at 8.2GHz



Physics of the Dark Universe 25 (2019) 100306

Contents lists available at ScienceDirect

Physics of the Dark Universe

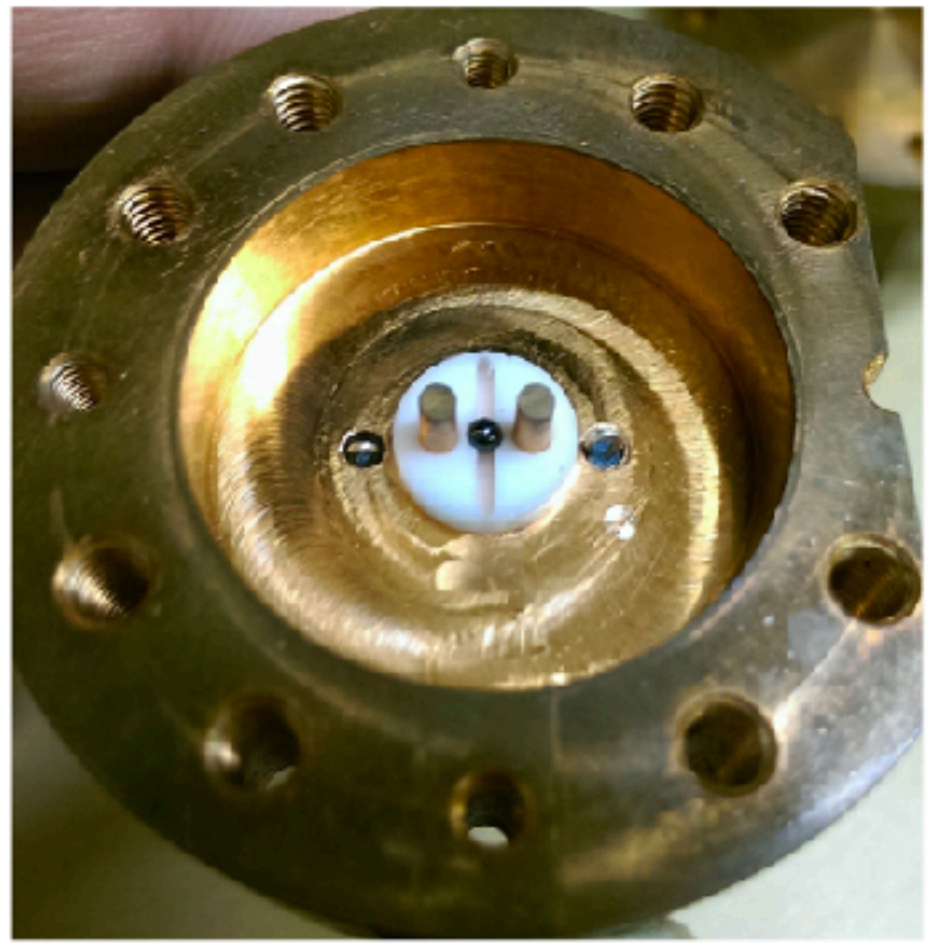
journal homepage: www.elsevier.com/locate/dark

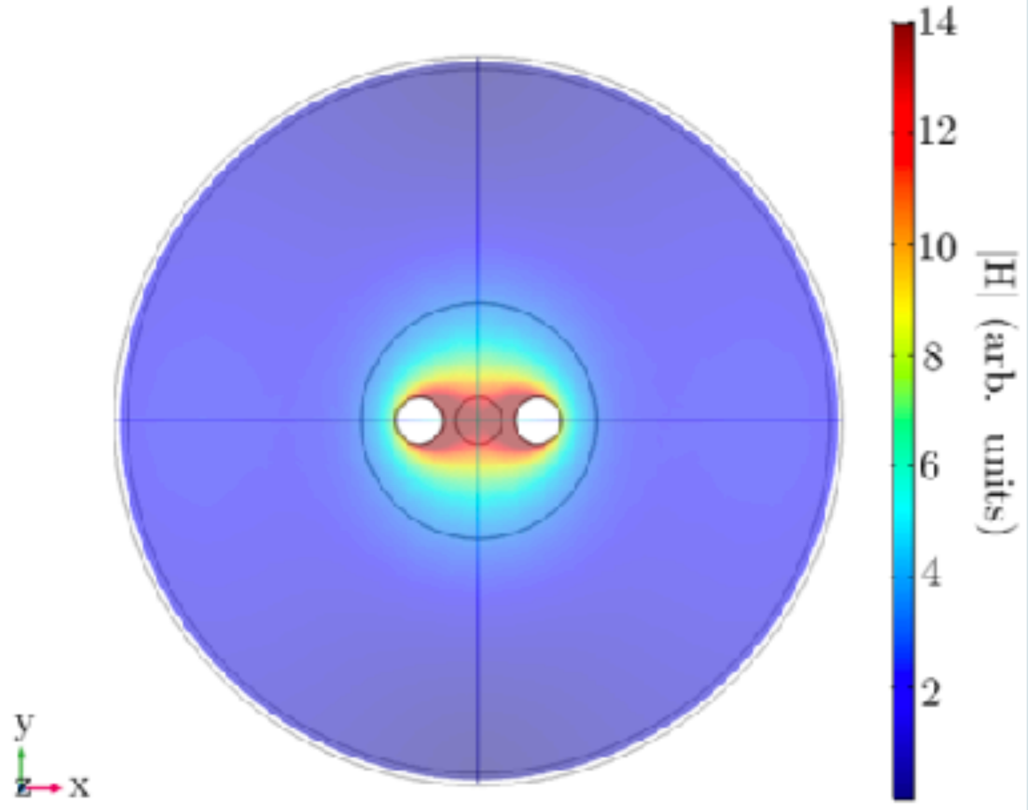
ELSEVIER

Broadening frequency range of a ferromagnetic axion haloscope with strongly coupled cavity–magnon polaritons

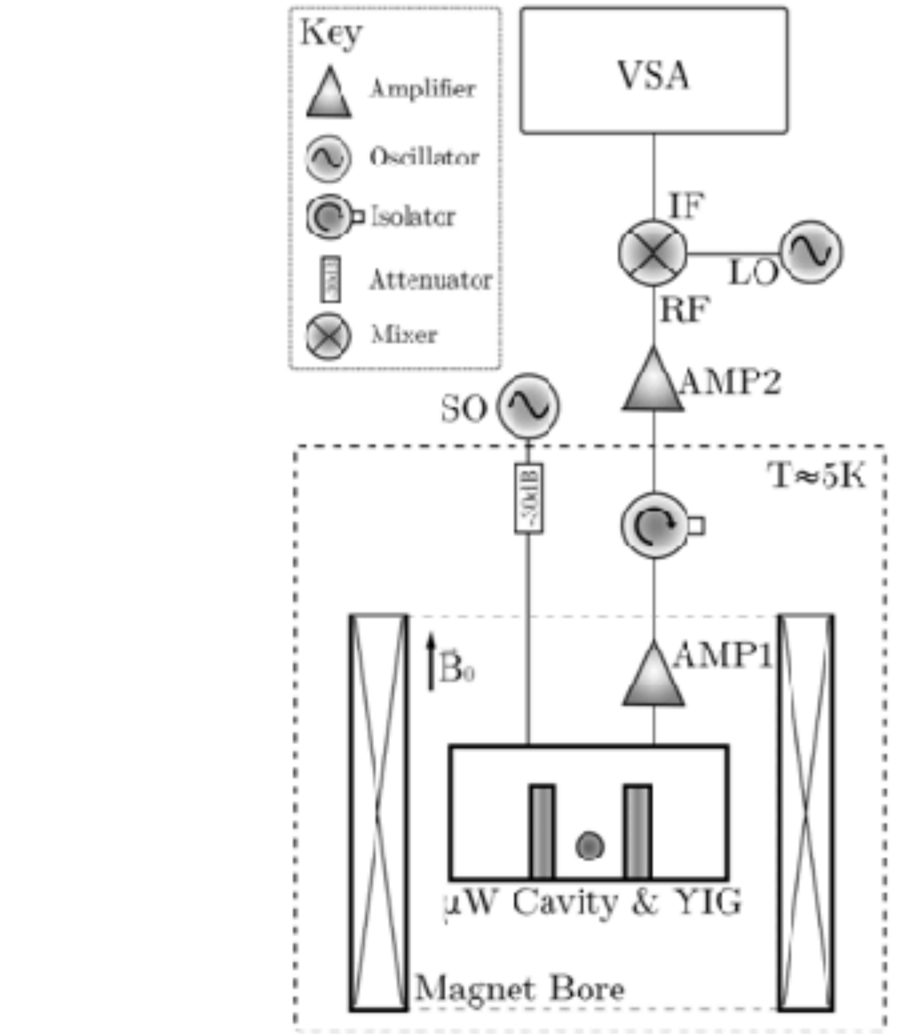
Graeme Flower*, Jeremy Bourhill, Maxim Goryachev, Michael E. Tobar

ARC Centre of Excellence for Engineered Quantum Systems, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia

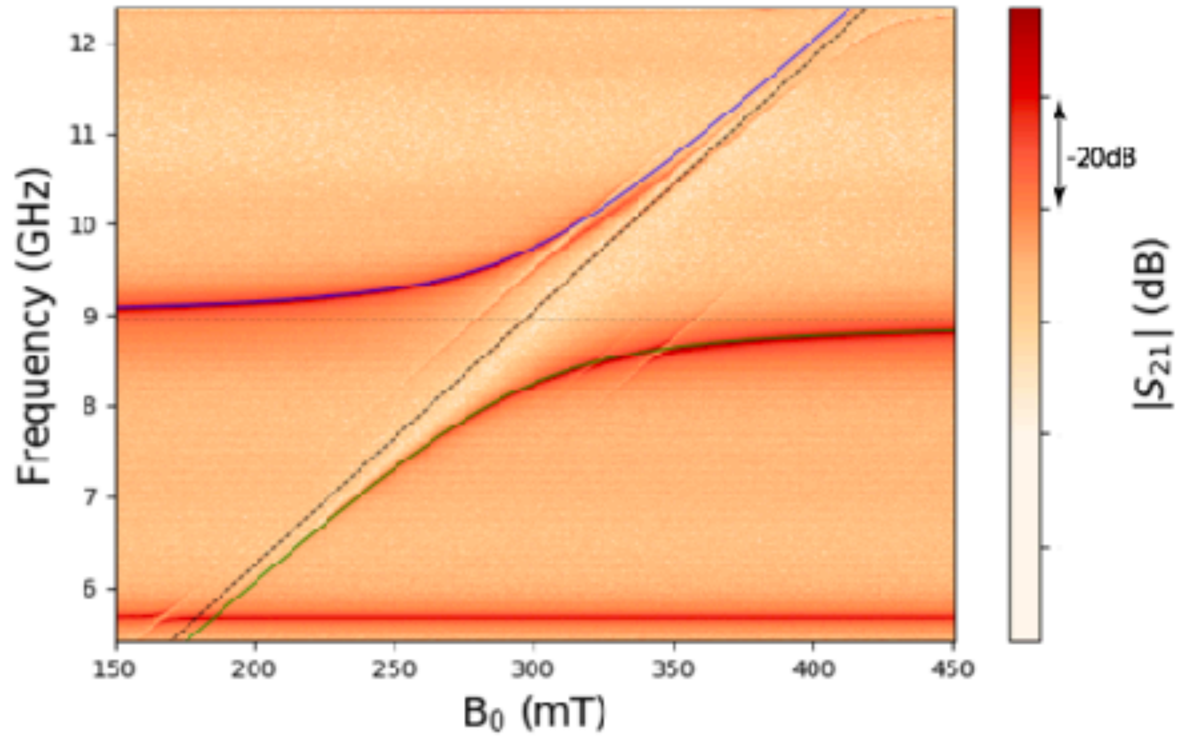




(A)



B)



Cavity-Magnon Polariton Axion Detection Experiment

arXiv:1811.09348v3 [physics.ins-det]

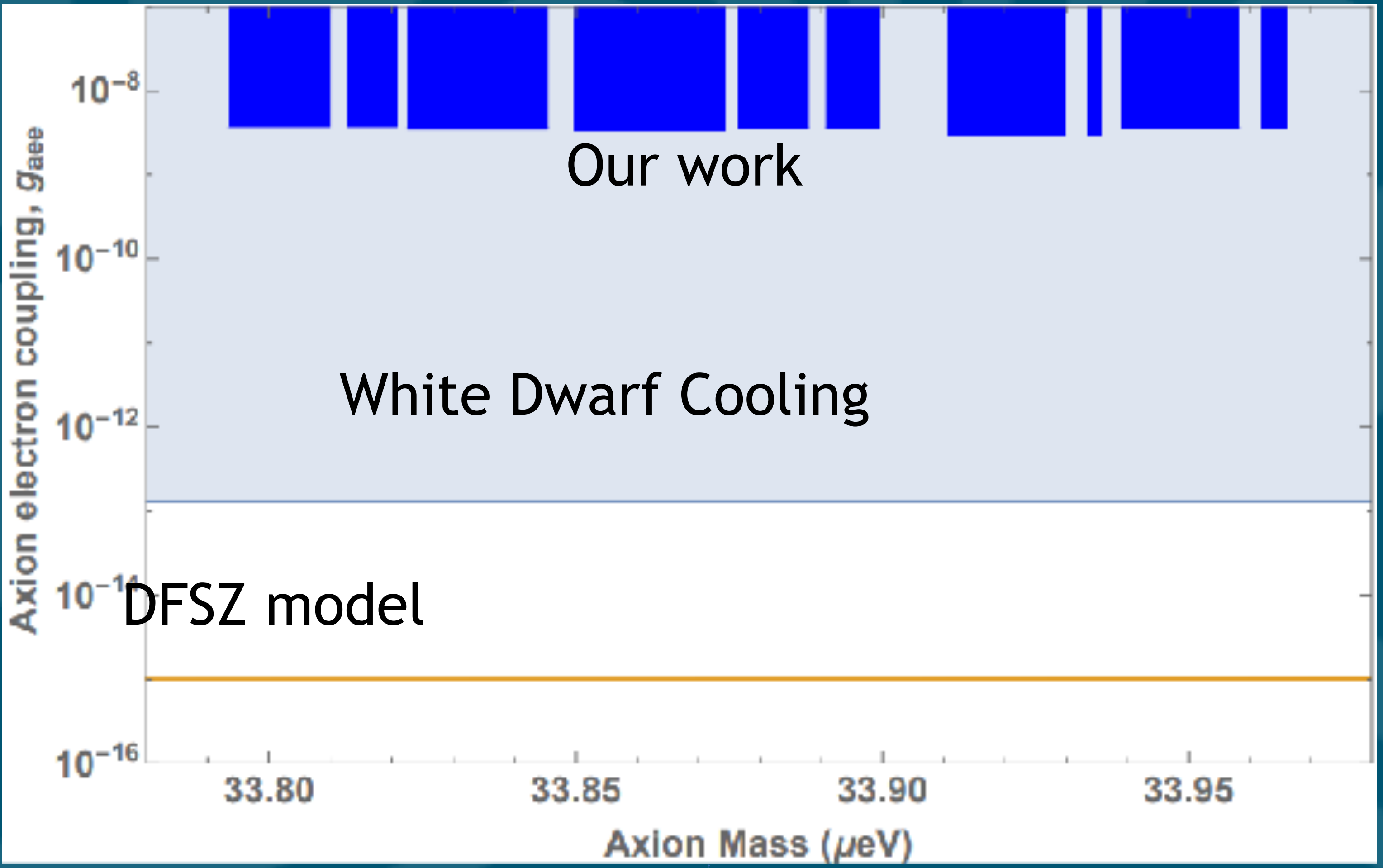
$g_{aee} > 3.7 \times 10^{-9}$ in the range $33.79\ \mu\text{eV} < m_a < 33.94\ \mu\text{eV}$ with 95% confidence.

$$\frac{H}{\hbar} = \omega_c a^\dagger a + \omega_m b^\dagger b + g_{cm}(a^\dagger + a)(b^\dagger + b)$$

Photons | Magnons | Interaction

36MHz in 6 MHz blocks from 8hrs of averages

Centred at 8.2GHz



Physics of the Dark Universe 25 (2019) 100306

Contents lists available at ScienceDirect

Physics of the Dark Universe

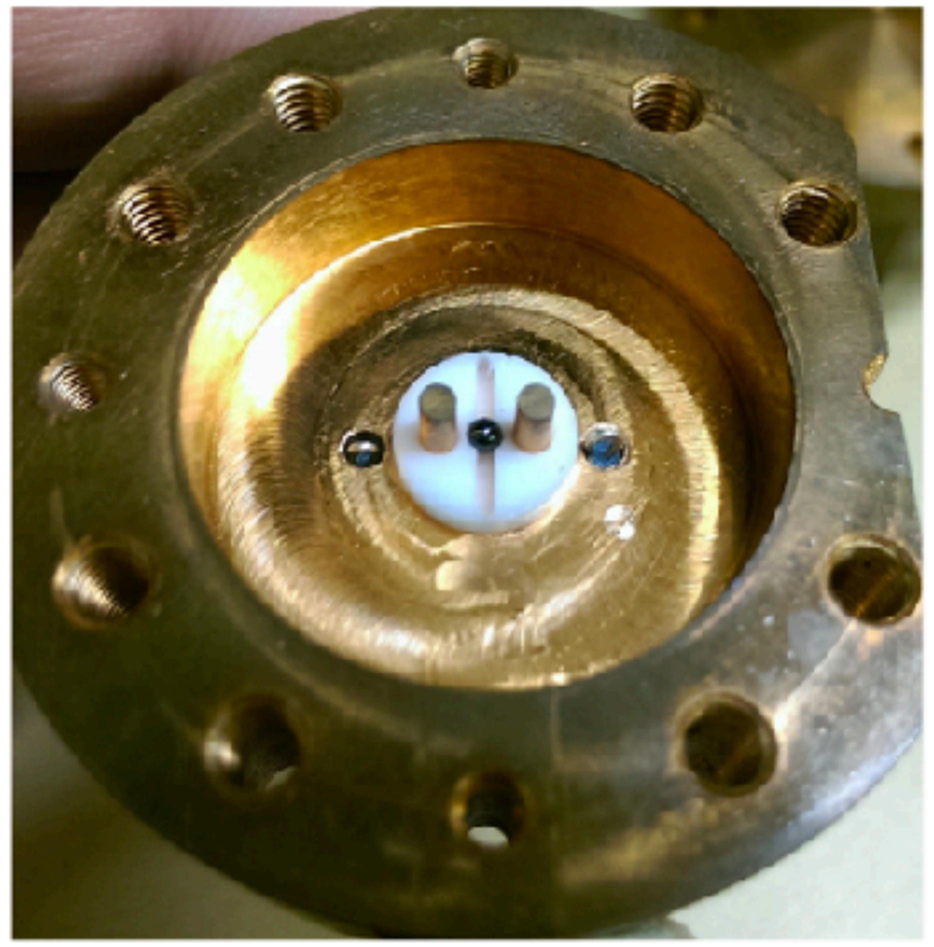
journal homepage: www.elsevier.com/locate/dark

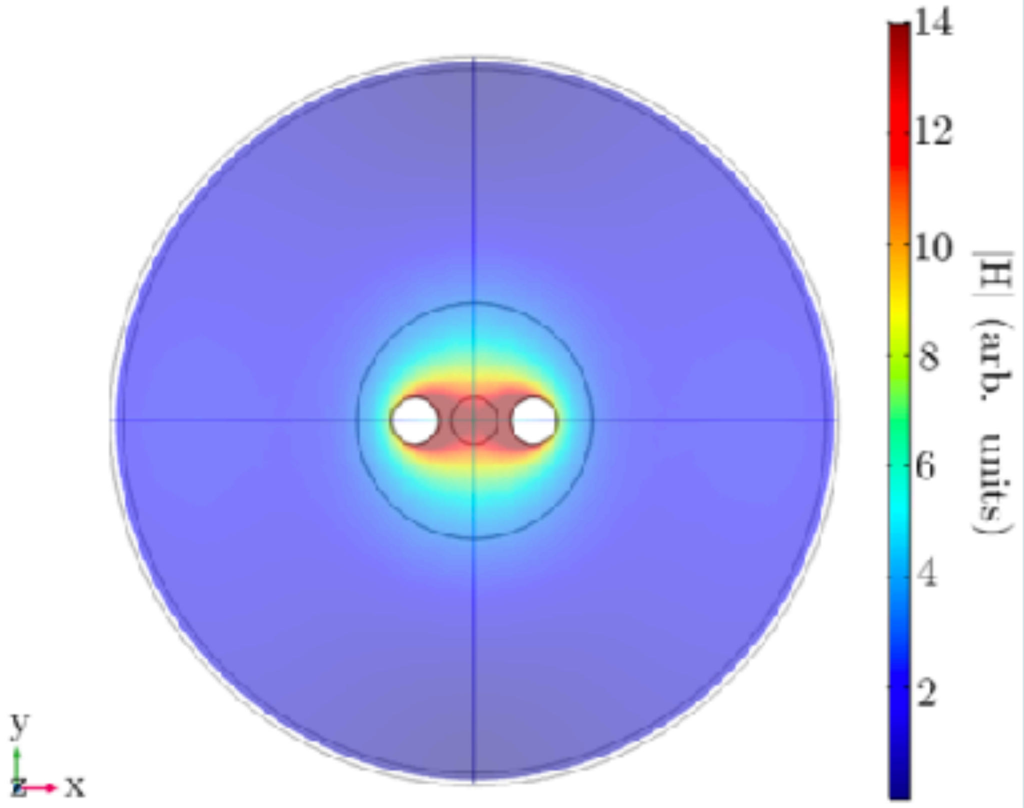
ELSEVIER

Broadening frequency range of a ferromagnetic axion haloscope with strongly coupled cavity–magnon polaritons

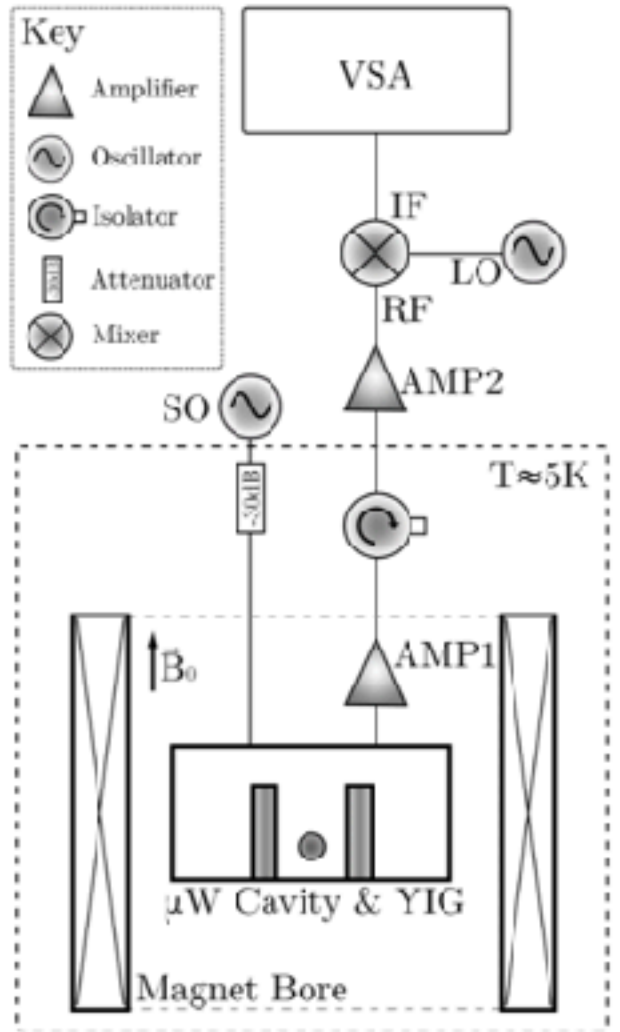
Graeme Flower*, Jeremy Bourhill, Maxim Goryachev, Michael E. Tobar

ARC Centre of Excellence for Engineered Quantum Systems, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia

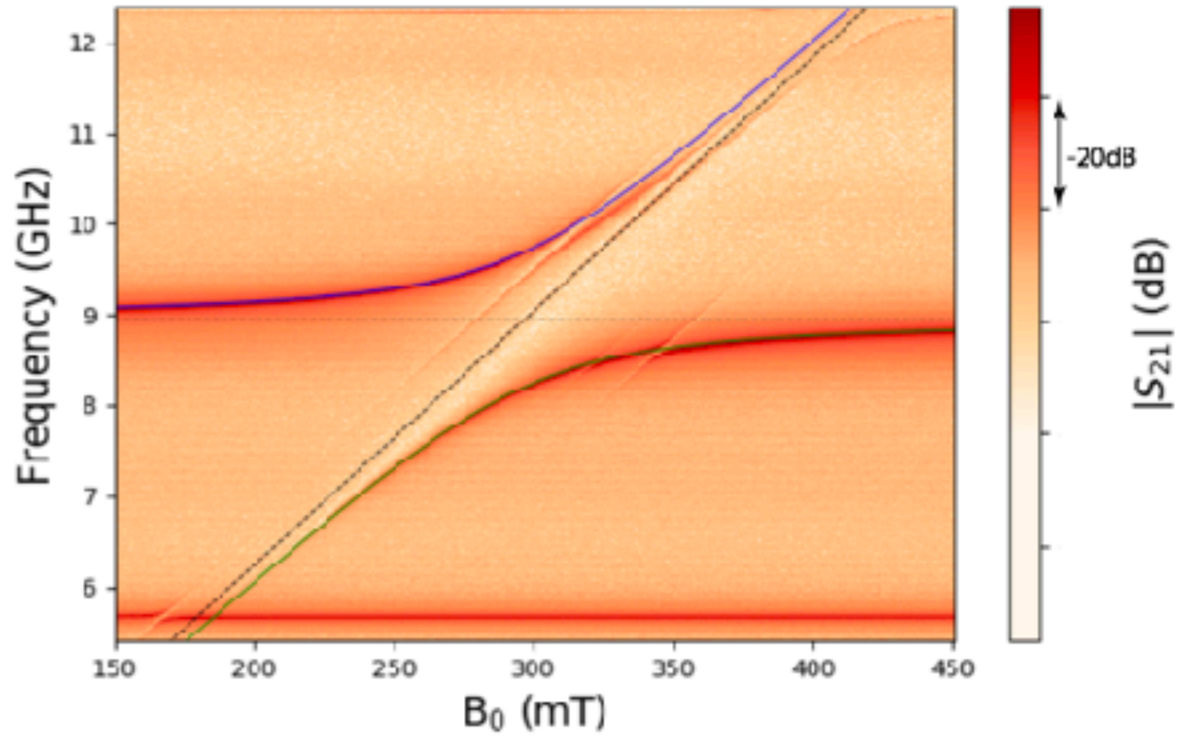




(A)



B)



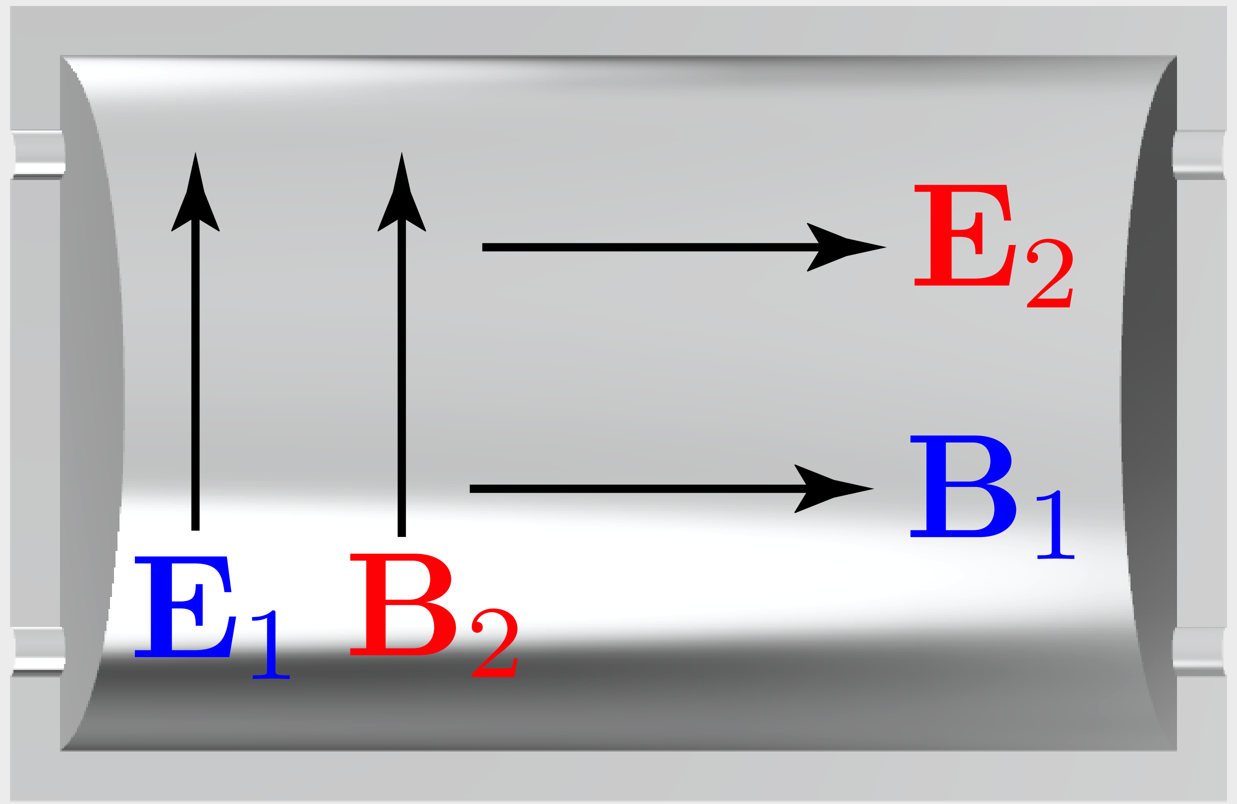
Poster Session1 Tuesday, June 4, 14:40:

Broadening Frequency Range of a Ferromagnetic Axion Haloscope with Strongly Coupled Cavity-Magnon Polaritons: **Graeme Flower**

Axion Detection with Precision Frequency Metrology

arXiv:1806.07141

photonic cavity with two mutually orthogonal modes



Axion UpConversion

$$\omega_a = \omega_2 - \omega_1$$

$$H_{\mathrm{U}} = i\hbar g_{\mathrm{eff}}\xi_{-}(a^* c_1 c_2^{\dagger} - a c_1^{\dagger} c_2)$$

beam splitter

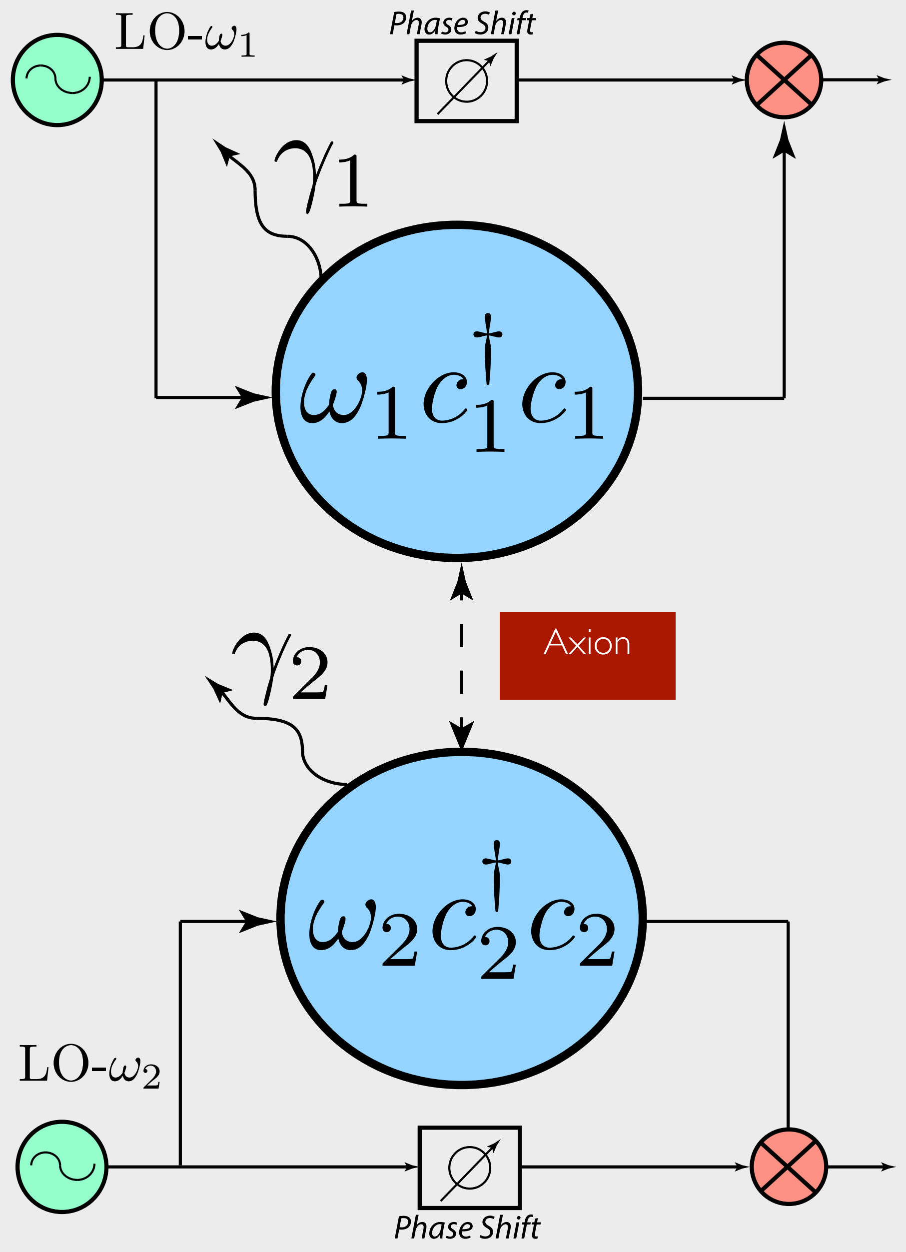
Axion DownConversion

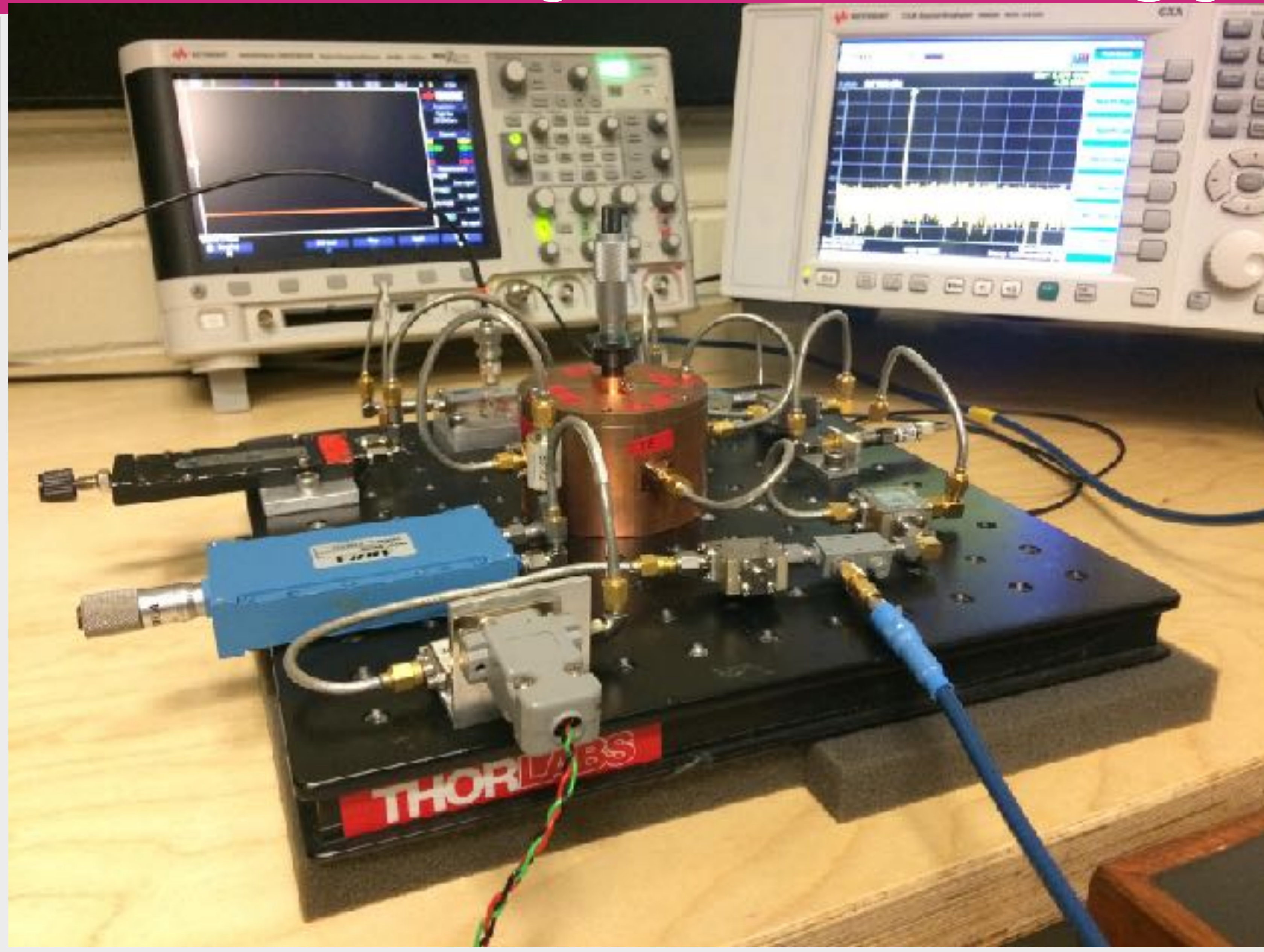
$$\omega_a = \omega_2 + \omega_1$$

$$H_{\mathrm{D}} = i\hbar g_{\mathrm{eff}}\xi_{+}(a c_1^{\dagger} c_2^{\dagger} - a^* c_1 c_2)$$

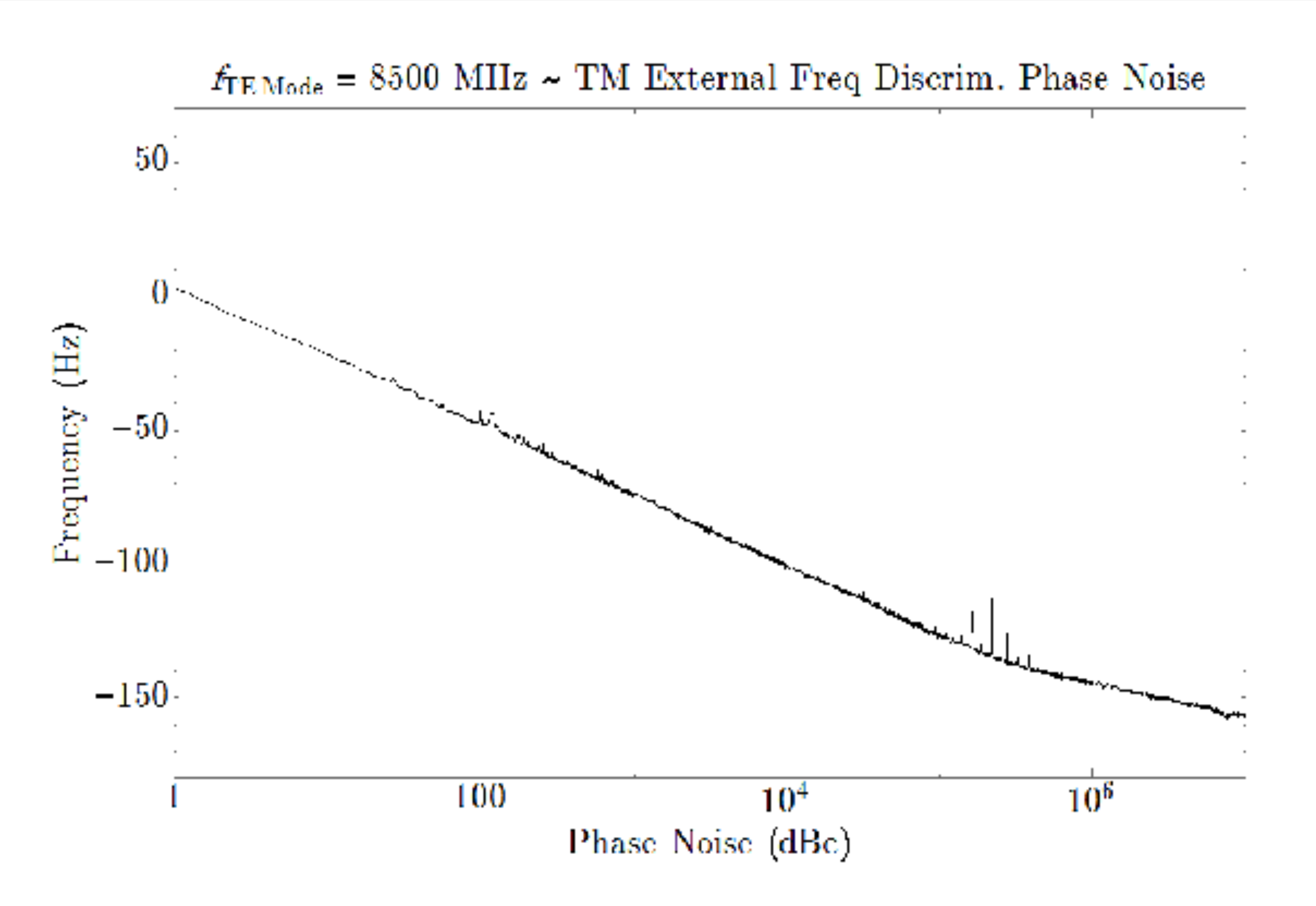
parametric amplification

Eigenfrequency Shift





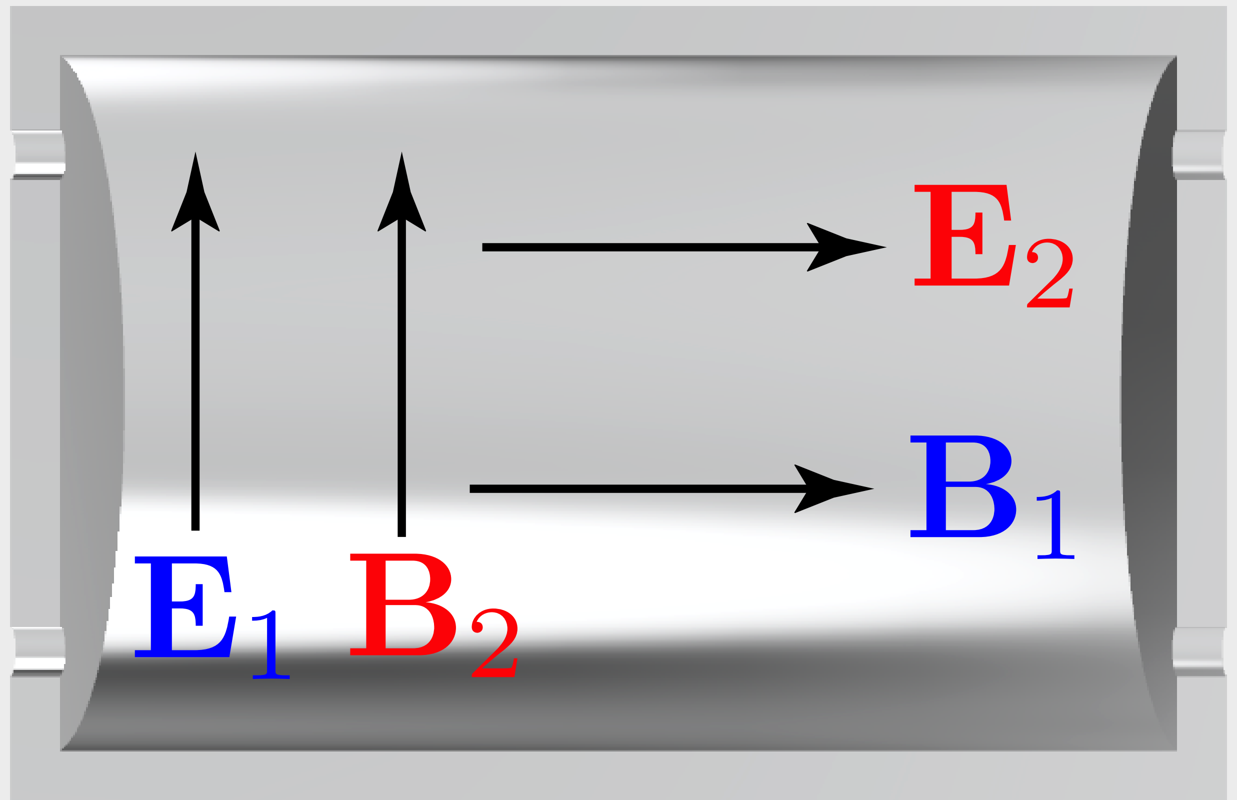
Proto-type built and taking data with first limits
Graduate Student: Catriona Thomas



Axion Detection with Precision Frequency Metrology

arXiv:1806.07141

photonic cavity with two mutually orthogonal modes



Axion UpConversion

$$\omega_a = \omega_2 - \omega_1$$

$$H_{\rm U} = i\hbar g_{\rm eff}\xi_{-}(a^* c_1 c_2^\dagger - a c_1^\dagger c_2)$$

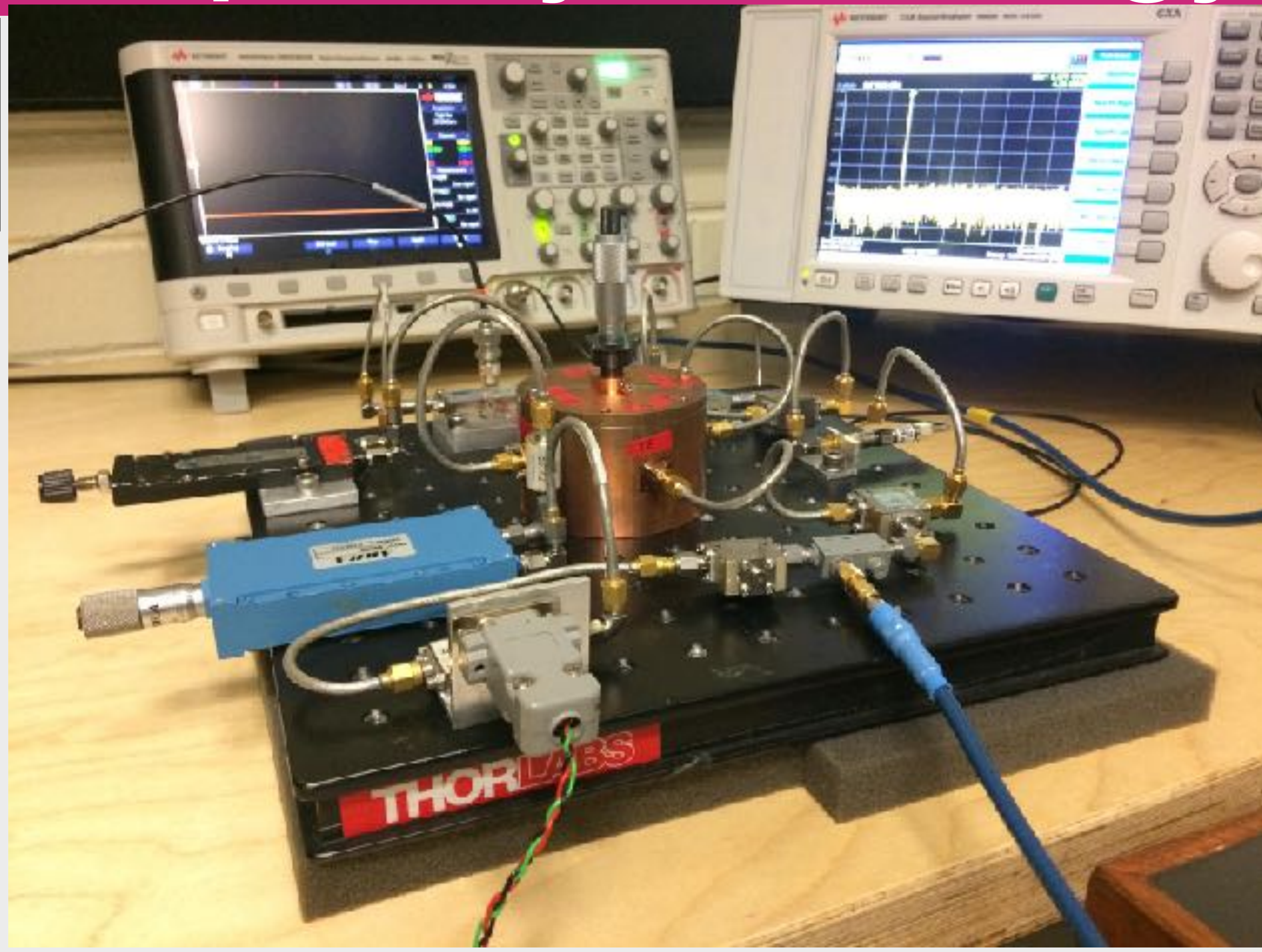
beam splitter

Axion DownConversion

$$\omega_a = \omega_2 + \omega_1$$

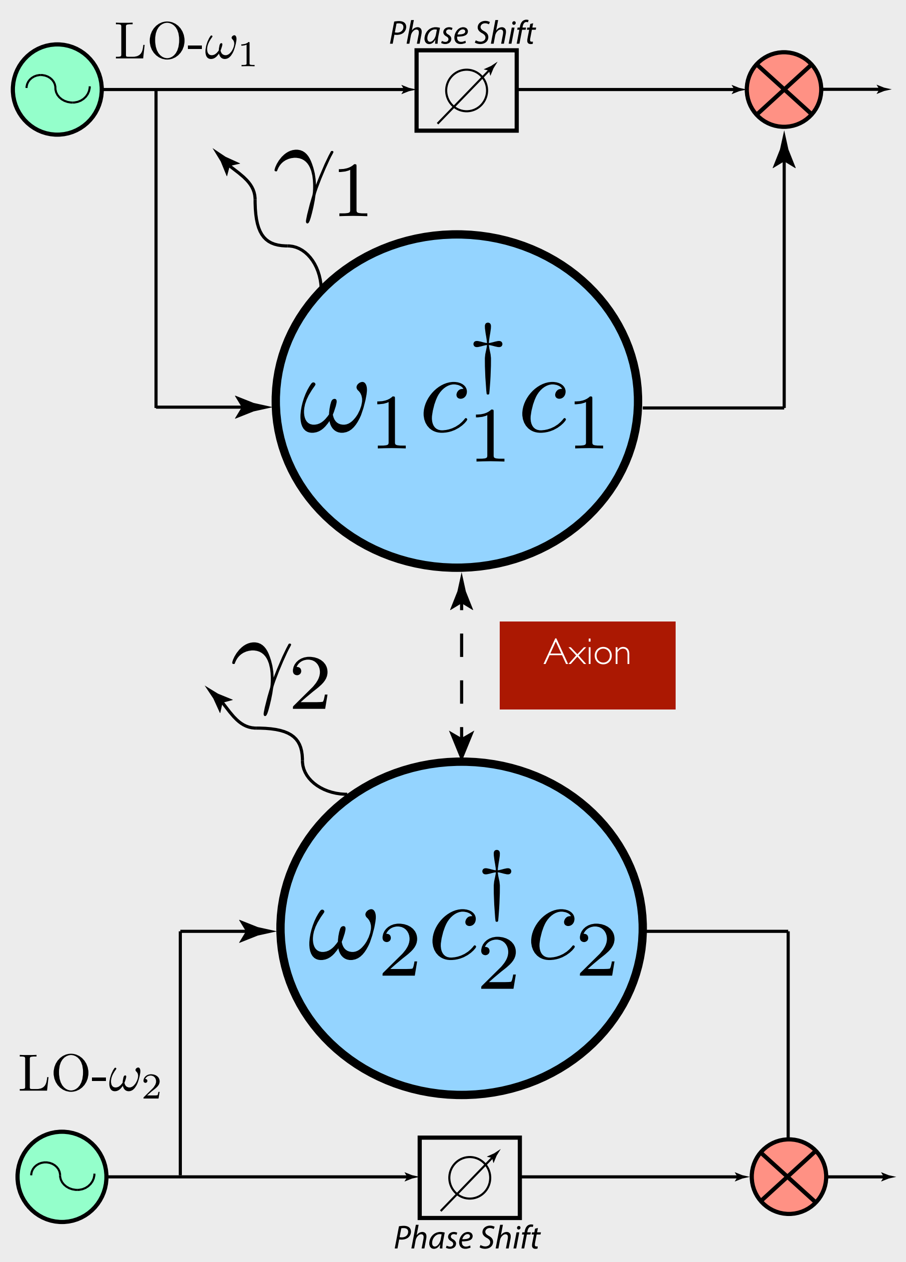
$$H_{\rm D} = i\hbar g_{\rm eff}\xi_{+}(a c_1^\dagger c_2^\dagger - a^* c_1 c_2)$$

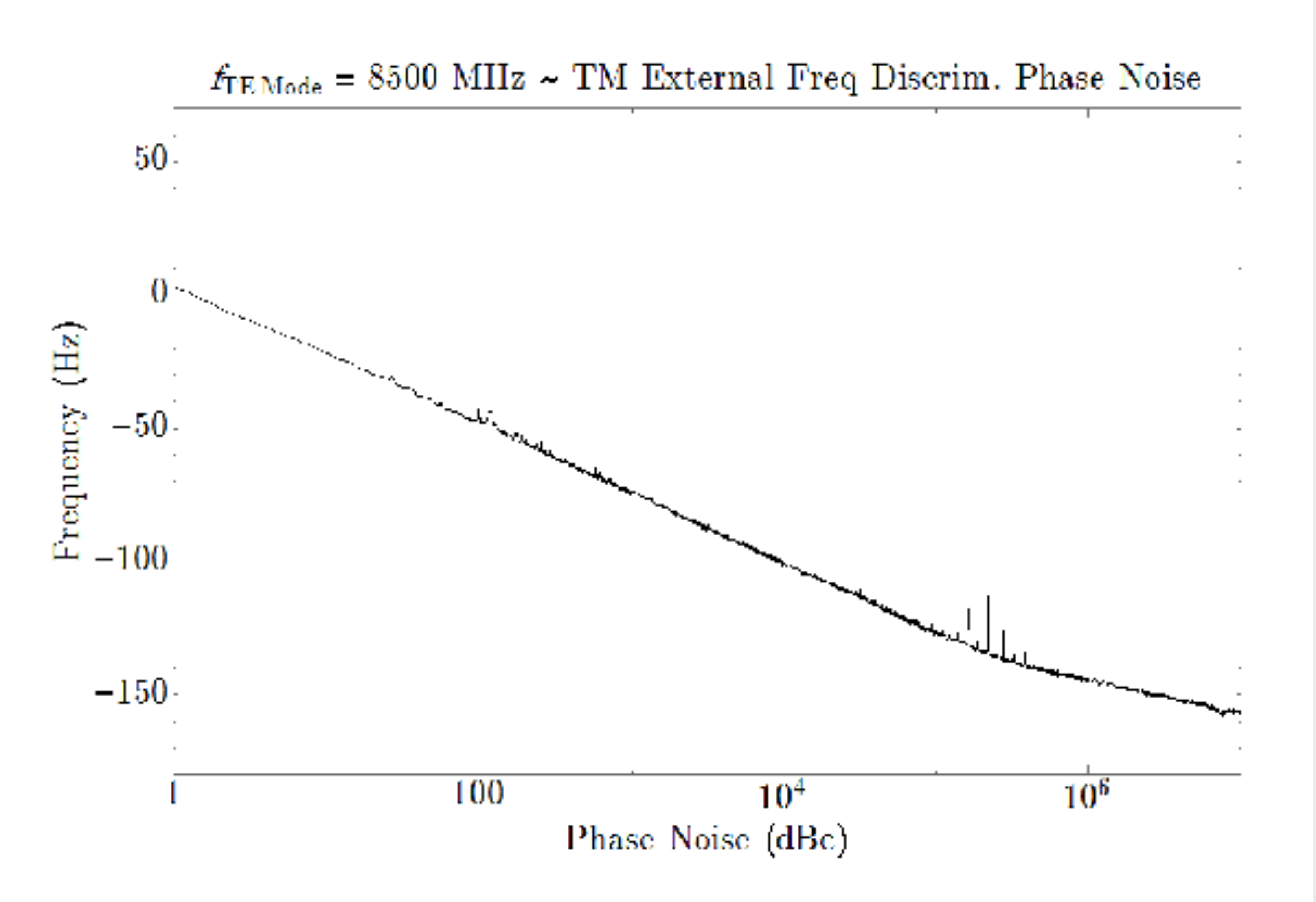
parametric amplification



Proto-type built and taking data with first limits
Graduate Student: Catriona Thomas

Eigenfrequency Shift



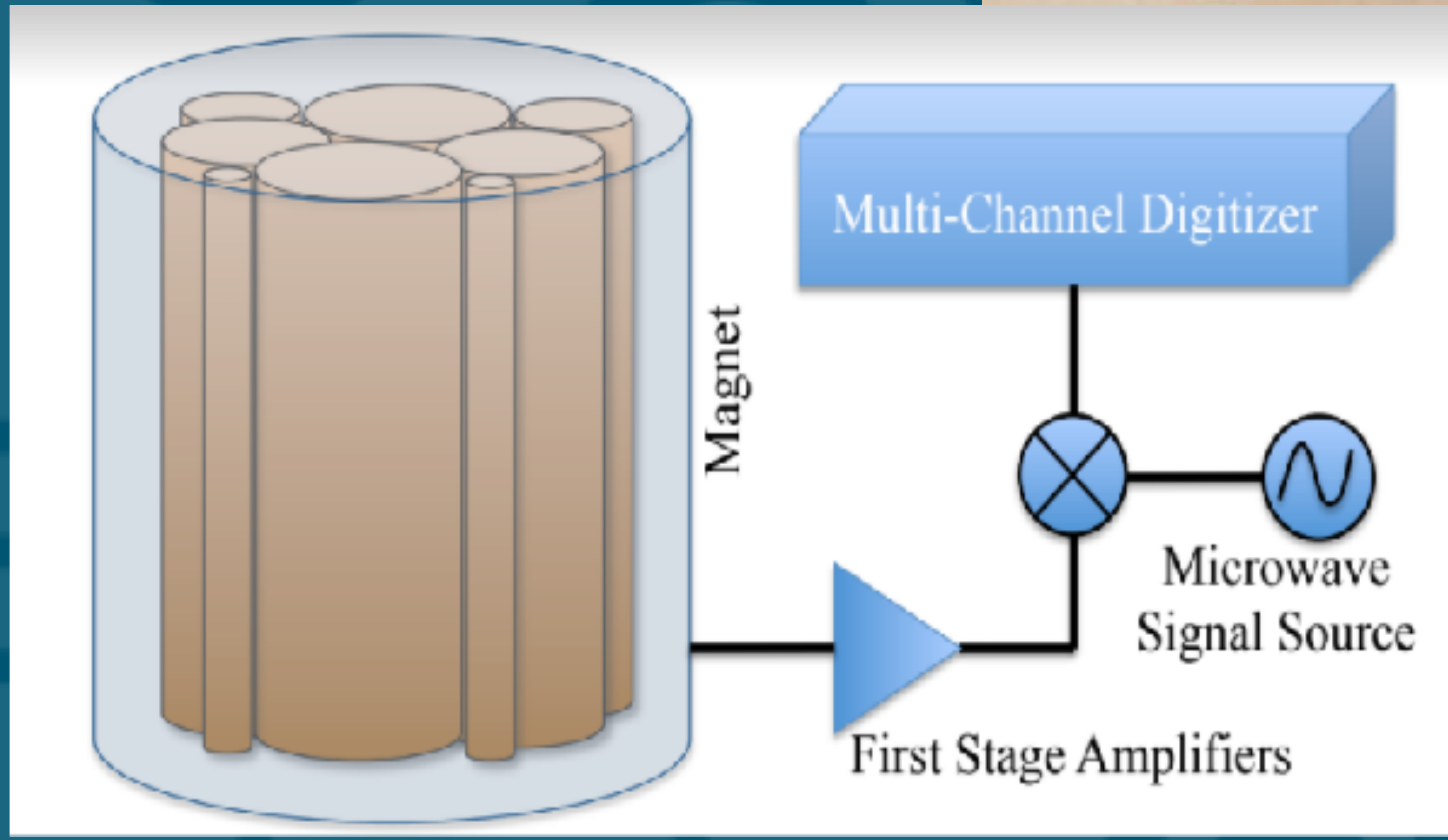


Maxim Goryachev
Tuesday, June 4 11:05 AM

Employing Precision Frequency Metrology for Axion Detection

The ORGAN Experiment:

26 GHz
Haloscope



Australian Research Council Centre of Excellence for Engineered Quantum Systems

EQUS

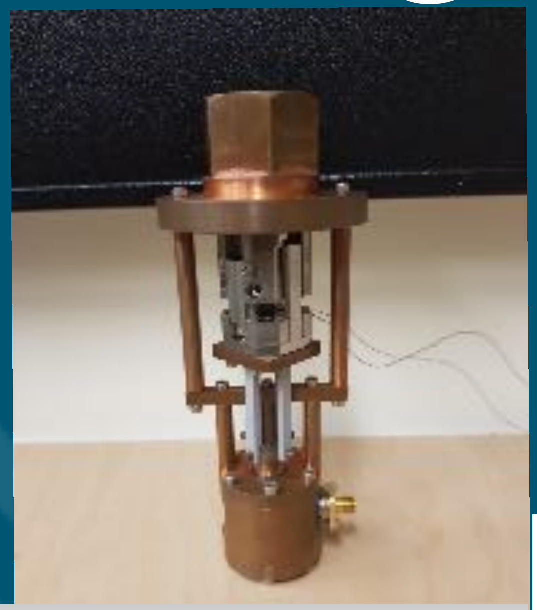
The ORGAN Experiment:

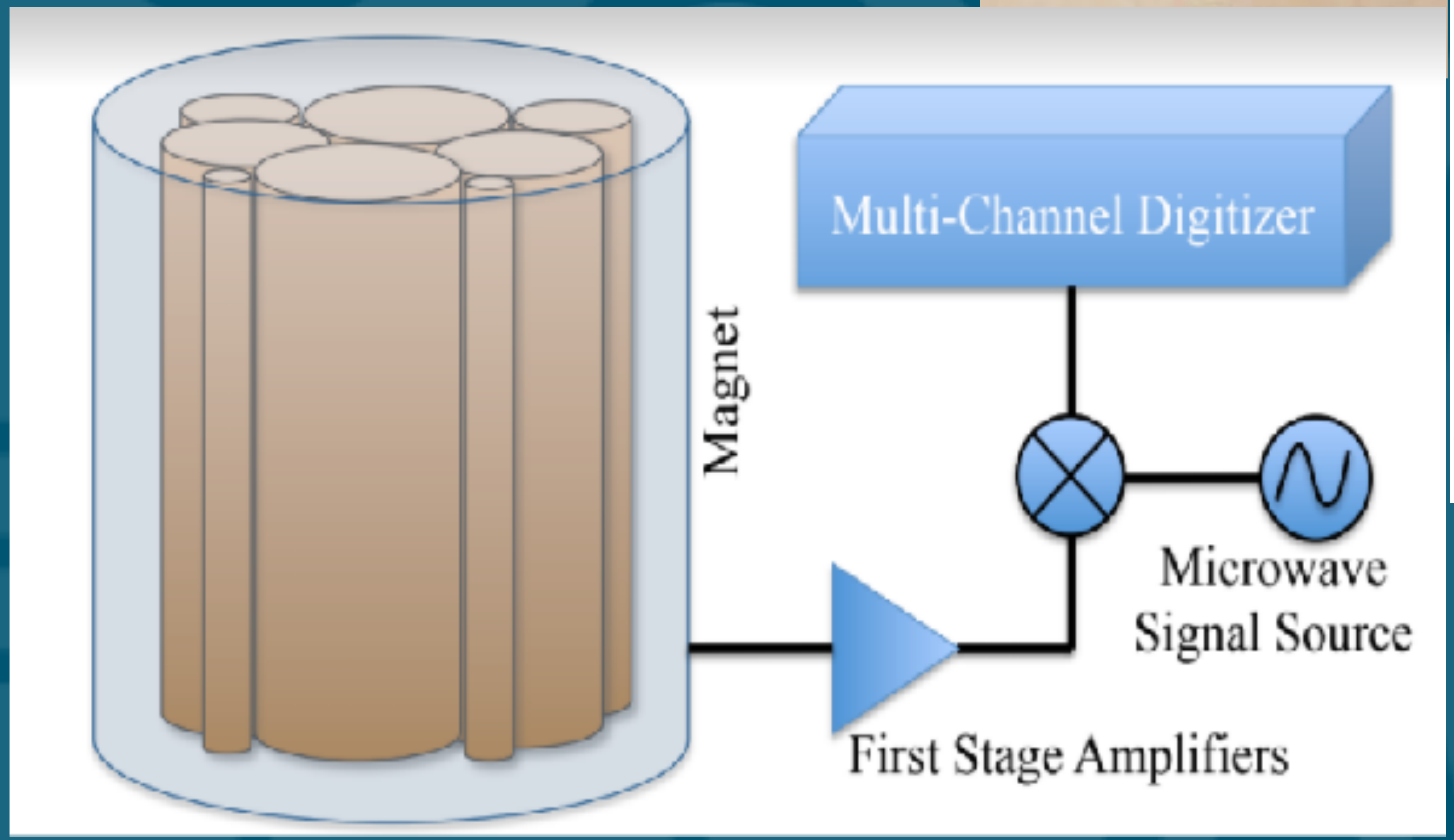
STATUS: First Stage Run Completed

Second Stage: Dil Fridge +14 T mag Lab upgrade: by 10/19

New Research Grant; includes Joining ADMX 2019-21

26 GHz Haloscope





Physics of the Dark Universe 18 (2017) 67–72

Contents lists available at ScienceDirect

Physics of the Dark Universe

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

ELSEVIER

The ORGAN experiment: An axion haloscope above 15 GHz

Ben T. McAllister[a,*], Graeme Flower[a], Eugene N. Ivanov[b], Maxim Goryachev[a], Jeremy Bourhill[a], Michael E. Tobar[a]

[a] ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia

[b] School of Physics, The University of Western Australia, Crawley 6009, Australia

PHYSICAL REVIEW APPLIED 9, 014028 (2018)

Tunable Supermode Dielectric Resonators for Axion Dark-Matter Haloscopes

Ben T. McAllister,[1,*] Graeme Flower,[1] Lucas E. Tobar,[1,2] and Michael E. Tobar[1,†]

[1] ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia

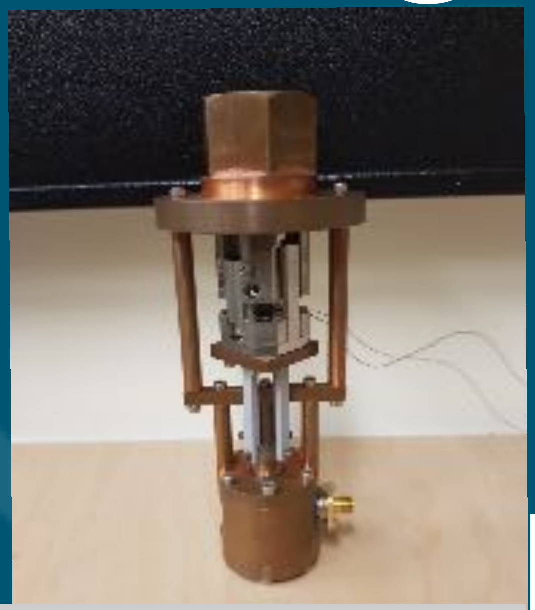
[2] Department of Electrical and Computer Systems Engineering, Monash University, Clayton 3800, Australia

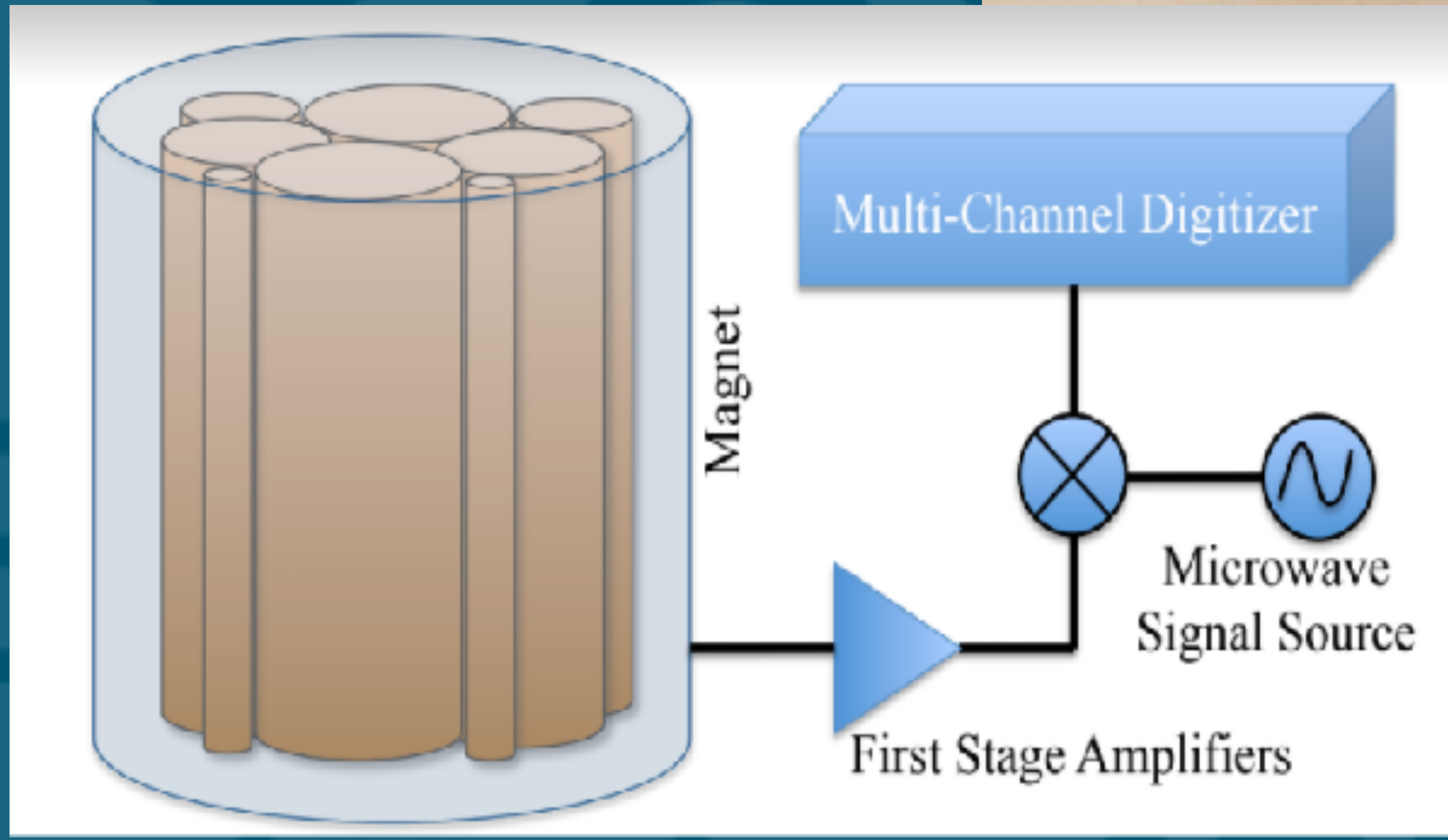
The ORGAN Experiment:

EQUS
Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

STATUS: First Stage Run Completed
Second Stage: Dil Fridge +14 T mag Lab upgrade: by 10/19
New Research Grant; includes Joining ADMX 2019-21

26 GHz
Haloscope





Physics of the Dark Universe 18 (2017) 67–72

Contents lists available at ScienceDirect

Physics of the Dark Universe

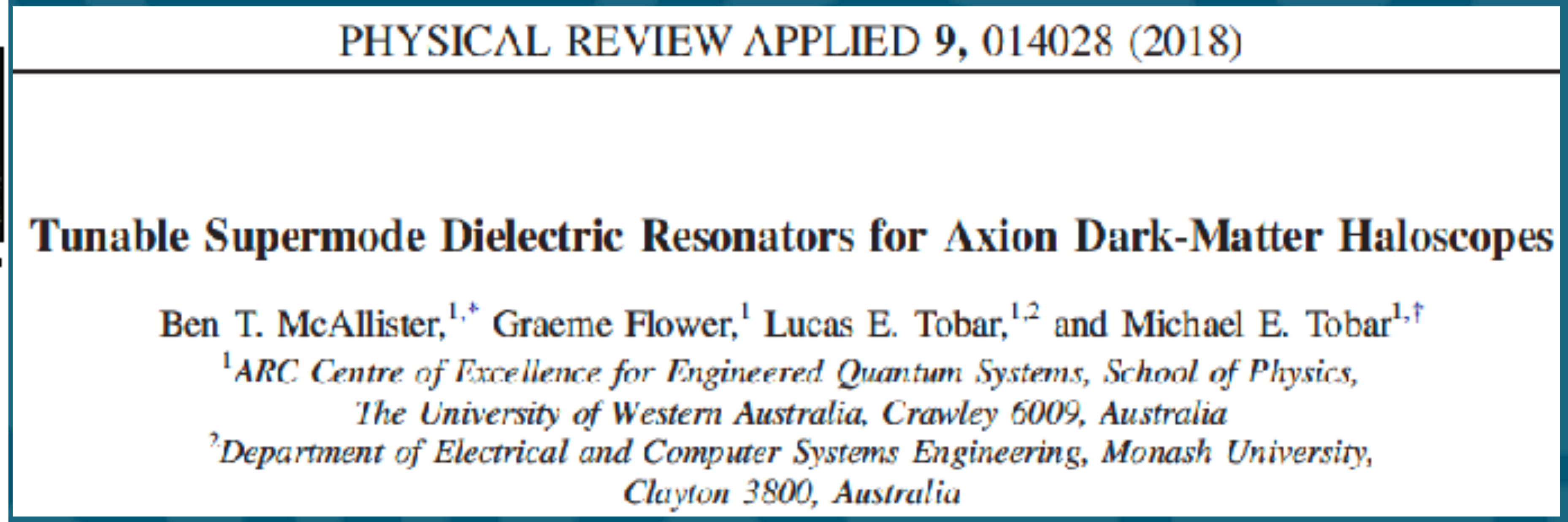
journal homepage: www.elsevier.com/locate/dark

ELSEVIER

The ORGAN experiment: An axion haloscope above 15 GHz

Ben T. McAllister[a,*], Graeme Flower[a], Eugene N. Ivanov[b], Maxim Goryachev[a], Jeremy Bourhill[a], Michael E. Tobar[a]

[a] ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia
[b] School of Physics, The University of Western Australia, Crawley 6009, Australia



PHYSICAL REVIEW APPLIED 9, 014028 (2018)

Tunable Supermode Dielectric Resonators for Axion Dark-Matter Haloscopes

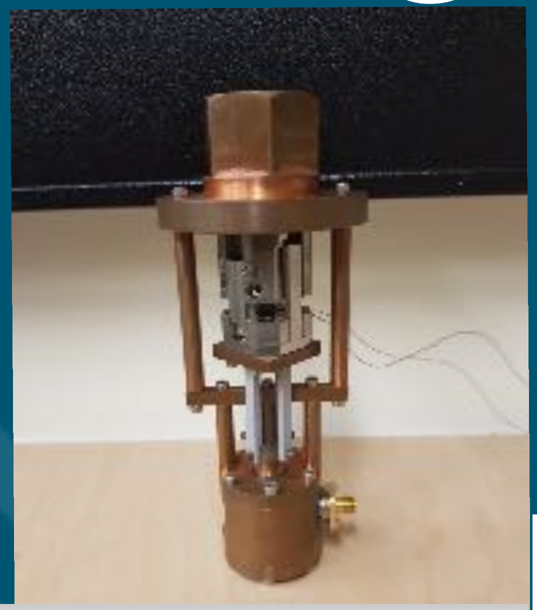
Ben T. McAllister,[1,*] Graeme Flower,[1] Lucas E. Tobar,[1,2] and Michael E. Tobar[1,†]
[1]*ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia*
[2]*Department of Electrical and Computer Systems Engineering, Monash University, Clayton 3800, Australia*

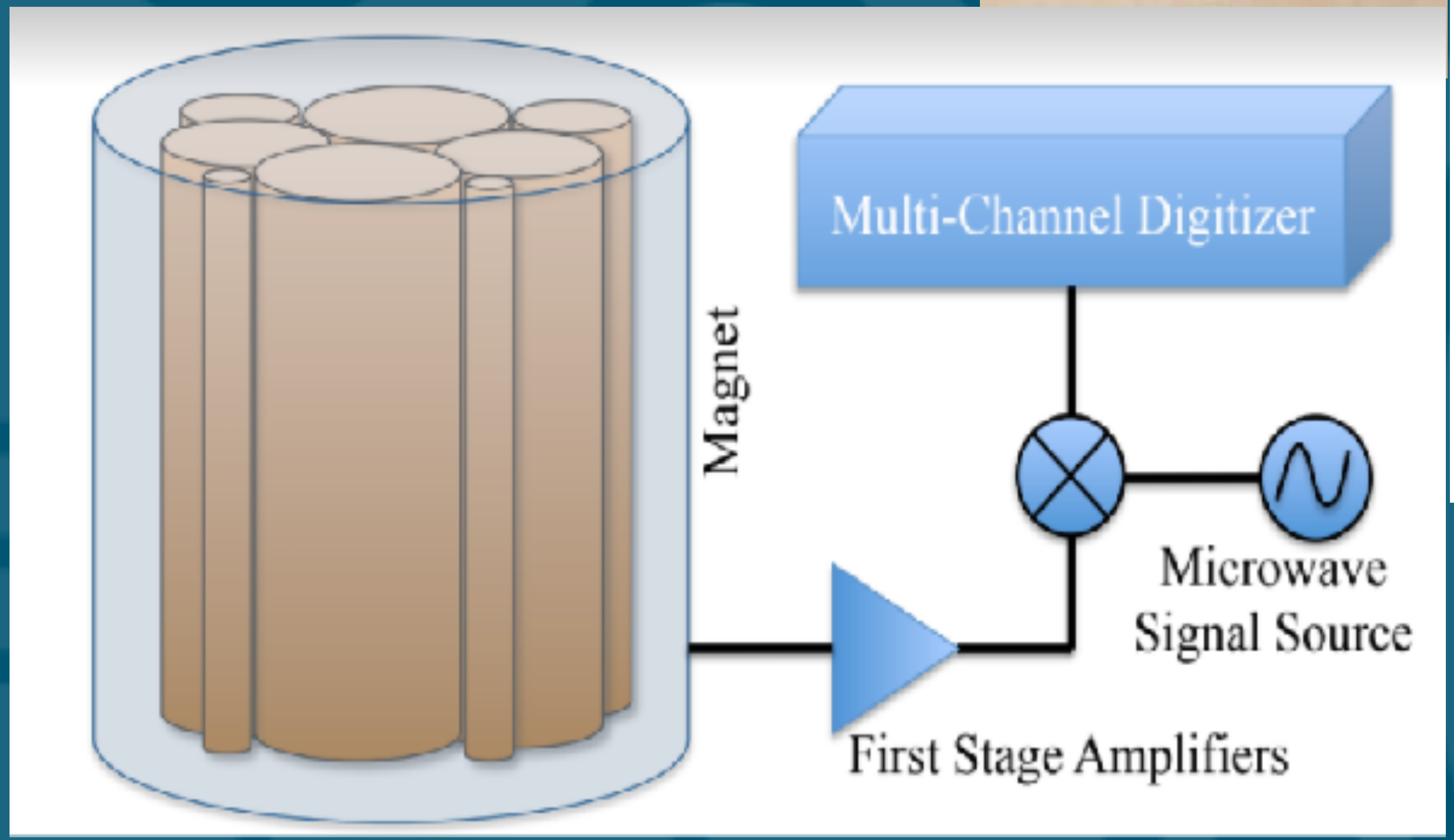
Developing Tuneable Cavities:

The ORGAN Experiment:

STATUS: First Stage Run Completed
Second Stage: Dil Fridge +14 T mag Lab upgrade: by 10/19
New Research Grant; includes Joining ADMX 2019-21

26 GHz
Haloscope





Physics of the Dark Universe 18 (2017) 67–72

Contents lists available at ScienceDirect

Physics of the Dark Universe

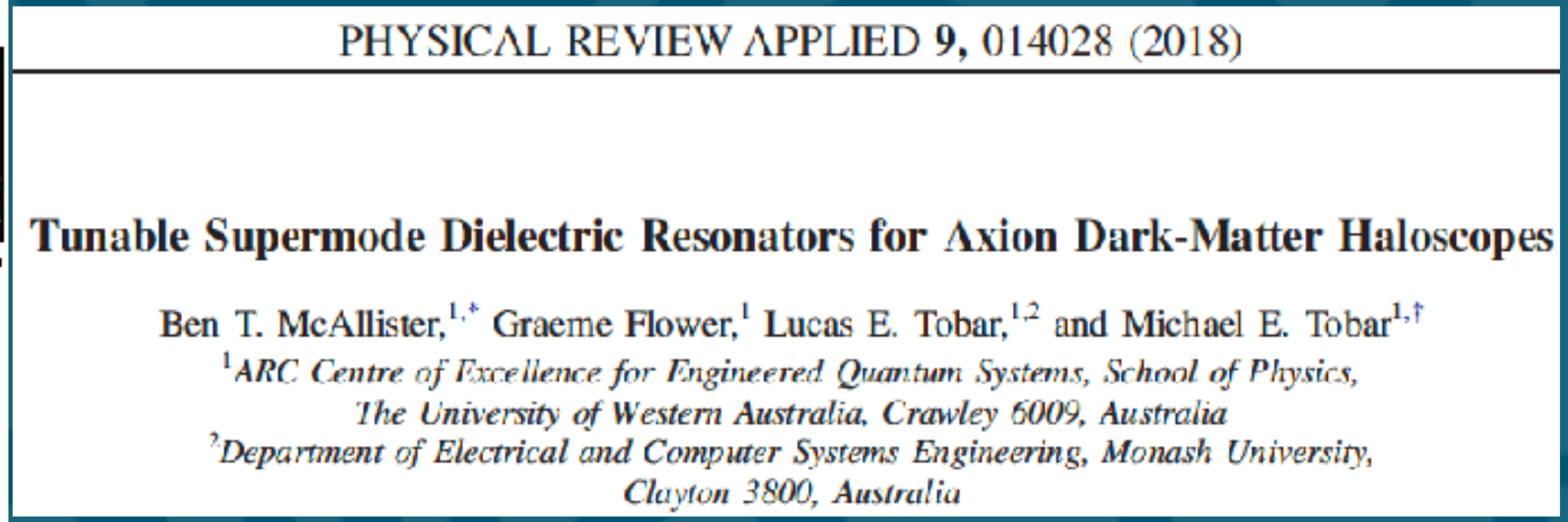
journal homepage: www.elsevier.com/locate/dark

ELSEVIER

The ORGAN experiment: An axion haloscope above 15 GHz

Ben T. McAllister[a,*], Graeme Flower[a], Eugene N. Ivanov[b], Maxim Goryachev[a], Jeremy Bourhill[a], Michael E. Tobar[a]

[a] ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia
[b] School of Physics, The University of Western Australia, Crawley 6009, Australia



PHYSICAL REVIEW APPLIED 9, 014028 (2018)

Tunable Supermode Dielectric Resonators for Axion Dark-Matter Haloscopes

Ben T. McAllister,[1,*] Graeme Flower,[1] Lucas E. Tobar,[1,2] and Michael E. Tobar[1,†]

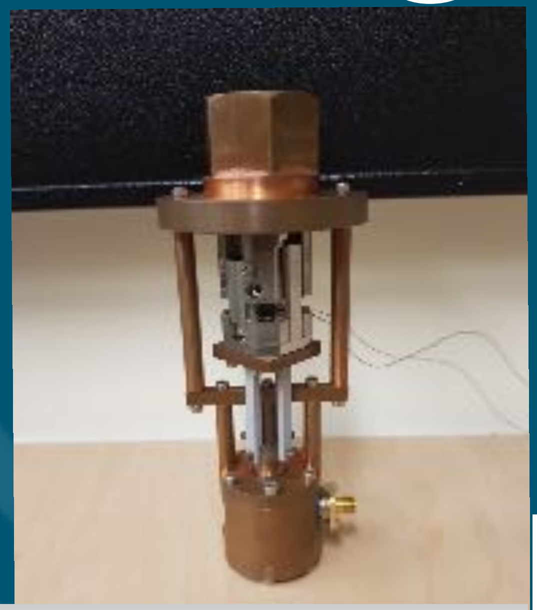
[1]ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia
[2]Department of Electrical and Computer Systems Engineering, Monash University, Clayton 3800, Australia

Developing Tuneable Cavities:

1) Collaboration with ADMX on New Haloscopes for ORGAN and ADMX Extended Frequency Range 2-4 GHz (No updates)

The ORGAN Experiment:

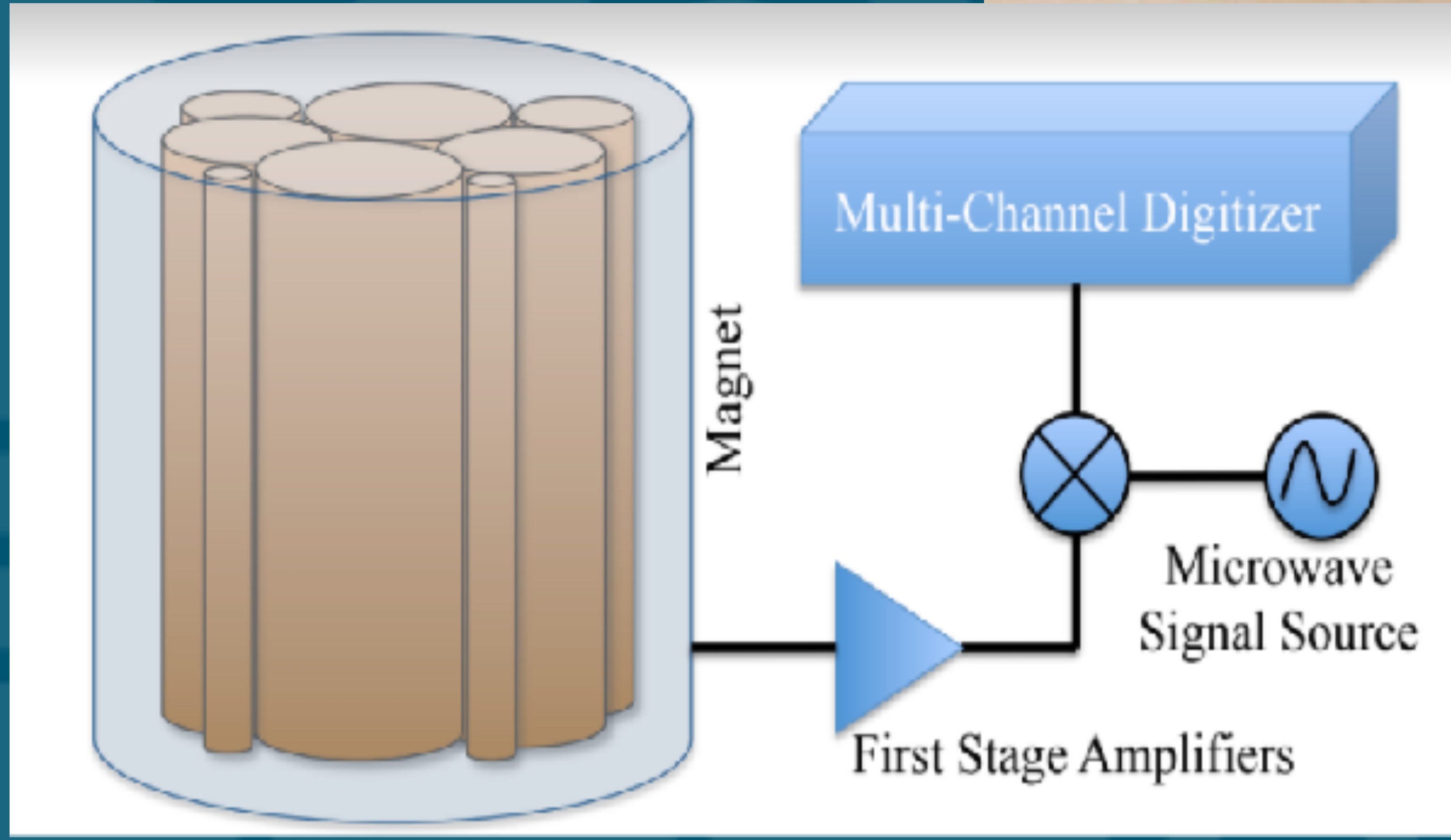
26 GHz Haloscope



STATUS: First Stage Run Completed

Second Stage: Dil Fridge +14 T mag Lab upgrade: by 10/19

New Research Grant; includes Joining ADMX 2019-21




Physics of the Dark Universe 18 (2017) 67–72

Contents lists available at ScienceDirect

Physics of the Dark Universe

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

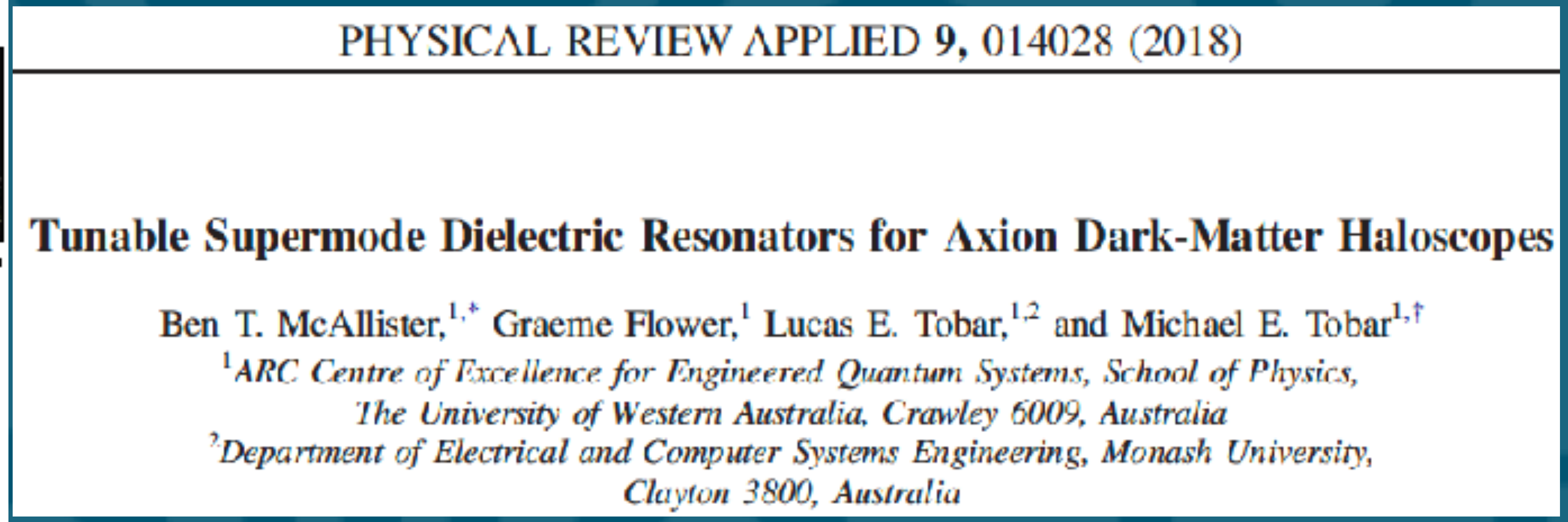
ELSEVIER

The ORGAN experiment: An axion haloscope above 15 GHz

Ben T. McAllister[a,*], Graeme Flower[a], Eugene N. Ivanov[b], Maxim Goryachev[a], Jeremy Bourhill[a], Michael E. Tobar[a]

[a] ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia

[b] School of Physics, The University of Western Australia, Crawley 6009, Australia


PHYSICAL REVIEW APPLIED 9, 014028 (2018)

Tunable Supermode Dielectric Resonators for Axion Dark-Matter Haloscopes

Ben T. McAllister,[1,*] Graeme Flower,[1] Lucas E. Tobar,[1,2] and Michael E. Tobar[1,†]

[1] ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia

[2] Department of Electrical and Computer Systems Engineering, Monash University, Clayton 3800, Australia

Developing Tuneable Cavities:

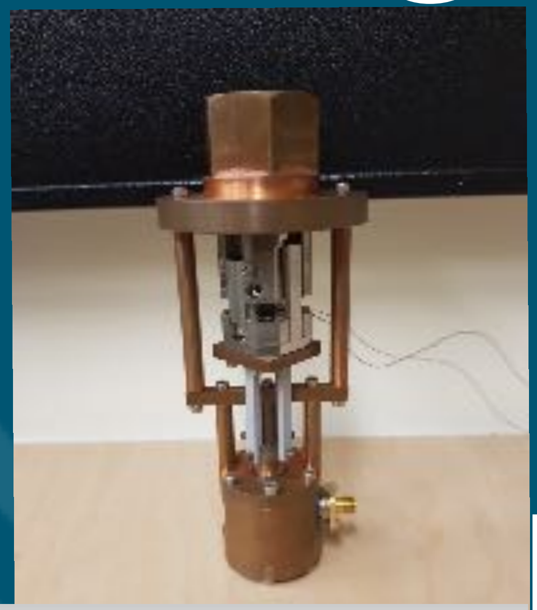
1) Collaboration with ADMX on New Haloscopes for ORGAN and ADMX Extended Frequency Range 2-4 GHz (No updates)

2) Developing Quantum Technologies for low noise readout:

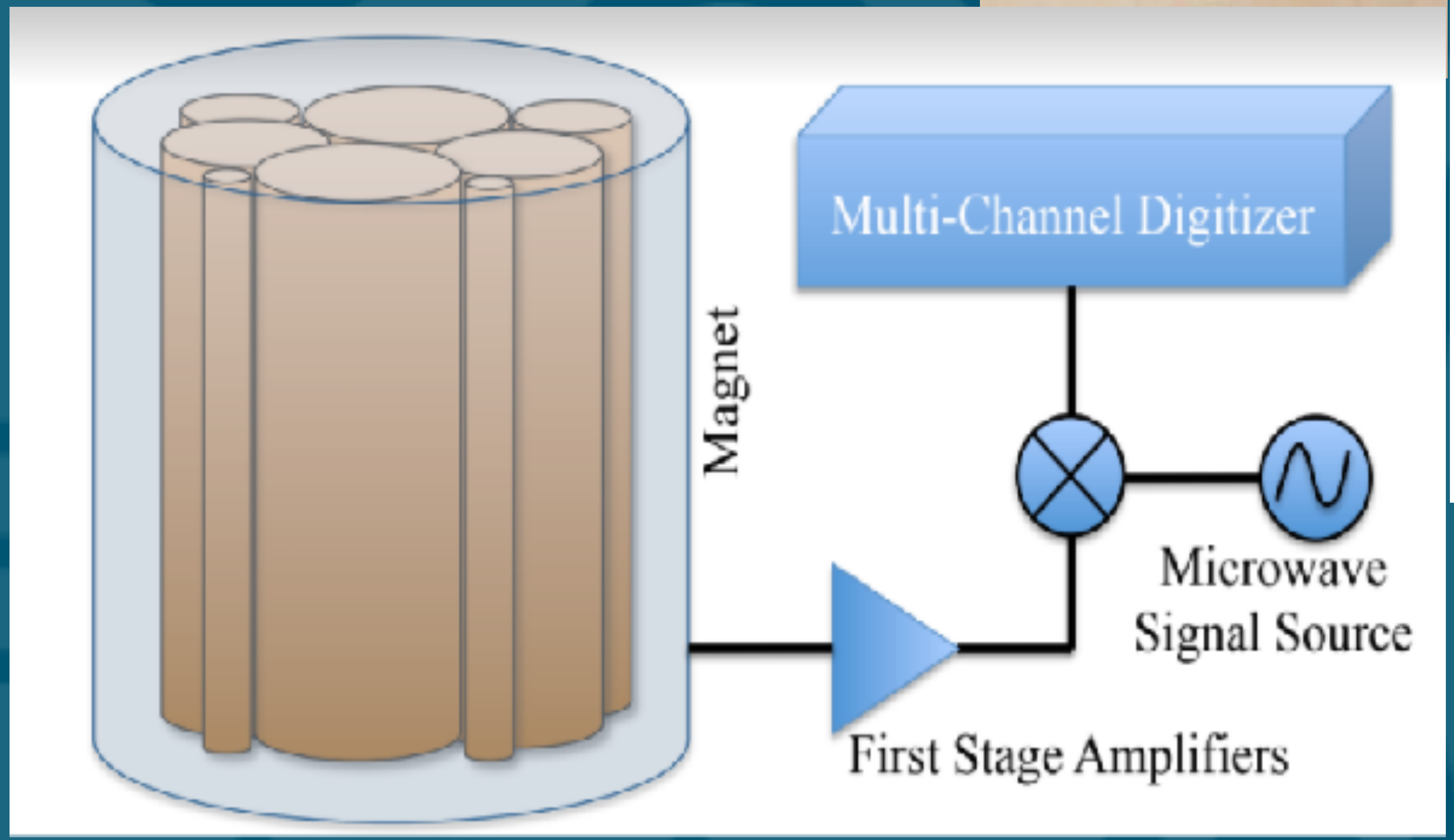
EQUS
Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

The ORGAN Experiment:

26 GHz
Haloscope



STATUS: First Stage Run Completed
Second Stage: Dil Fridge +14 T mag Lab upgrade: by 10/19
New Research Grant; includes Joining ADMX 2019-21



Physics of the Dark Universe 18 (2017) 67–72

Contents lists available at ScienceDirect

Physics of the Dark Universe

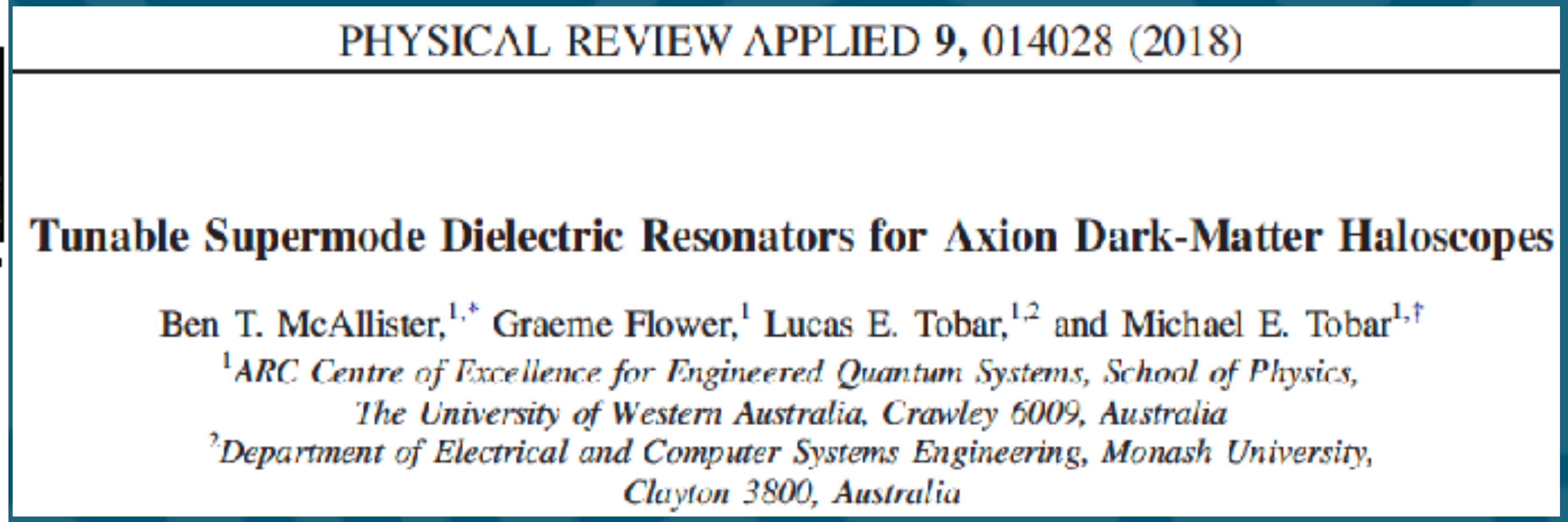
journal homepage: www.elsevier.com/locate/dark

ELSEVIER

The ORGAN experiment: An axion haloscope above 15 GHz

Ben T. McAllister[a,*], Graeme Flower[a], Eugene N. Ivanov[b], Maxim Goryachev[a], Jeremy Bourhill[a], Michael E. Tobar[a]

[a] ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia
[b] School of Physics, The University of Western Australia, Crawley 6009, Australia



PHYSICAL REVIEW APPLIED 9, 014028 (2018)

Tunable Supermode Dielectric Resonators for Axion Dark-Matter Haloscopes

Ben T. McAllister,[1,*] Graeme Flower,[1] Lucas E. Tobar,[1,2] and Michael E. Tobar[1,†]

[1] ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia
[2] Department of Electrical and Computer Systems Engineering, Monash University, Clayton 3800, Australia

Developing Tuneable Cavities:

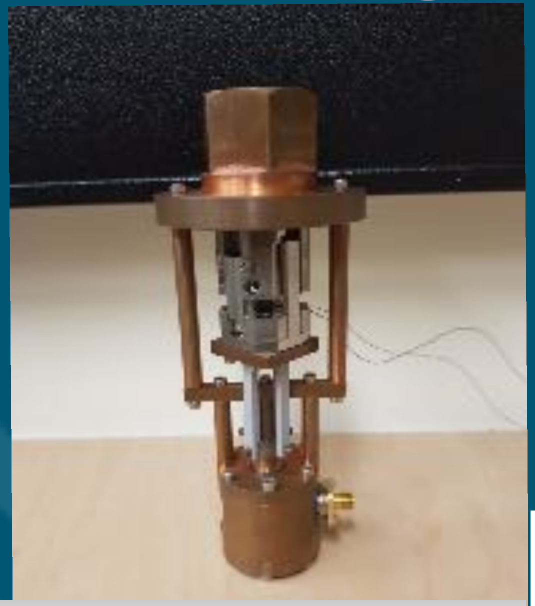
1) Collaboration with ADMX on New Haloscopes for ORGAN and ADMX Extended Frequency Range 2-4 GHz (No updates)

2) Developing Quantum Technologies for low noise readout:
   a) EQUS; Parametric Amplifiers at 26 GHz

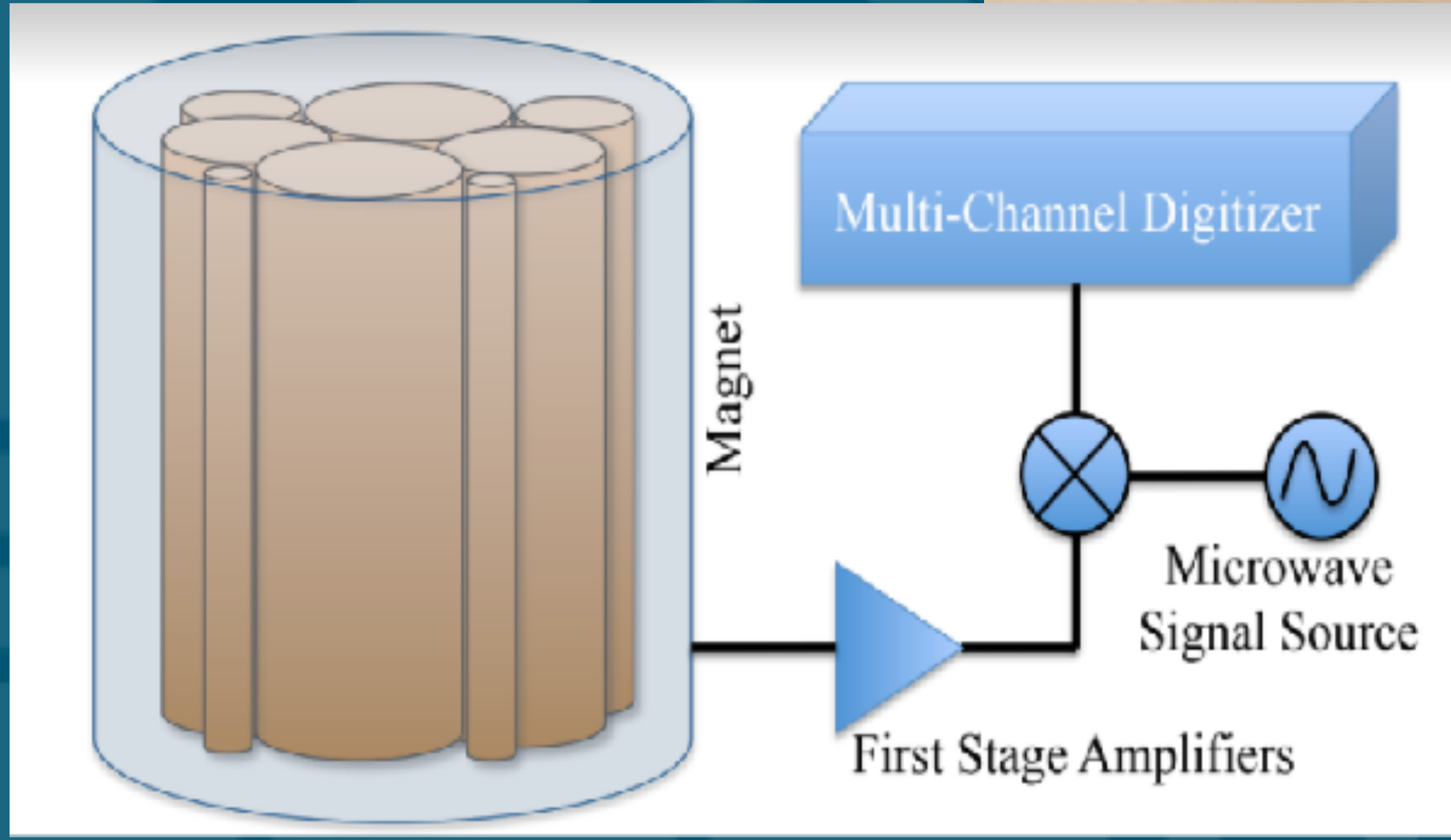
The ORGAN Experiment:

EQUS
Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

26 GHz
Haloscope



STATUS: First Stage Run Completed
Second Stage: Dil Fridge +14 T mag Lab upgrade: by 10/19
New Research Grant; includes Joining ADMX 2019-21



Physics of the Dark Universe 18 (2017) 67–72
Contents lists available at ScienceDirect
Physics of the Dark Universe
journal homepage: www.elsevier.com/locate/dark
ELSEVIER

The ORGAN experiment: An axion haloscope above 15 GHz

Ben T. McAllister[a,*], Graeme Flower[a], Eugene N. Ivanov[b], Maxim Goryachev[a], Jeremy Bourhill[a], Michael E. Tobar[a]
[a] ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia
[b] School of Physics, The University of Western Australia, Crawley 6009, Australia

PHYSICAL REVIEW APPLIED 9, 014028 (2018)

Tunable Supermode Dielectric Resonators for Axion Dark-Matter Haloscopes

Ben T. McAllister,[1,*] Graeme Flower,[1] Lucas E. Tobar,[1,2] and Michael E. Tobar[1,†]
[1]ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia
[2]Department of Electrical and Computer Systems Engineering, Monash University, Clayton 3800, Australia

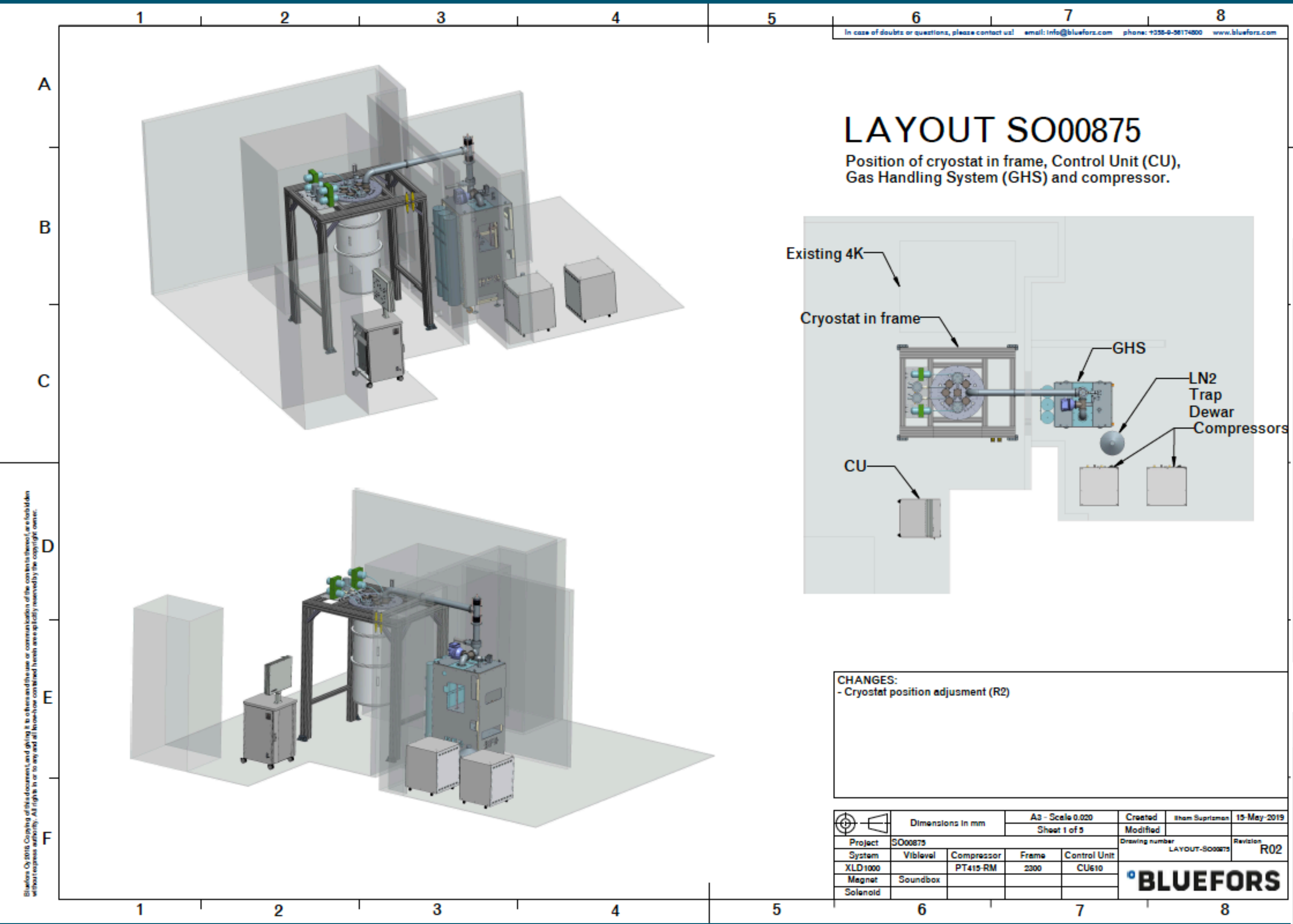
McGillivary Organ at UWA

Developing Tuneable Cavities:

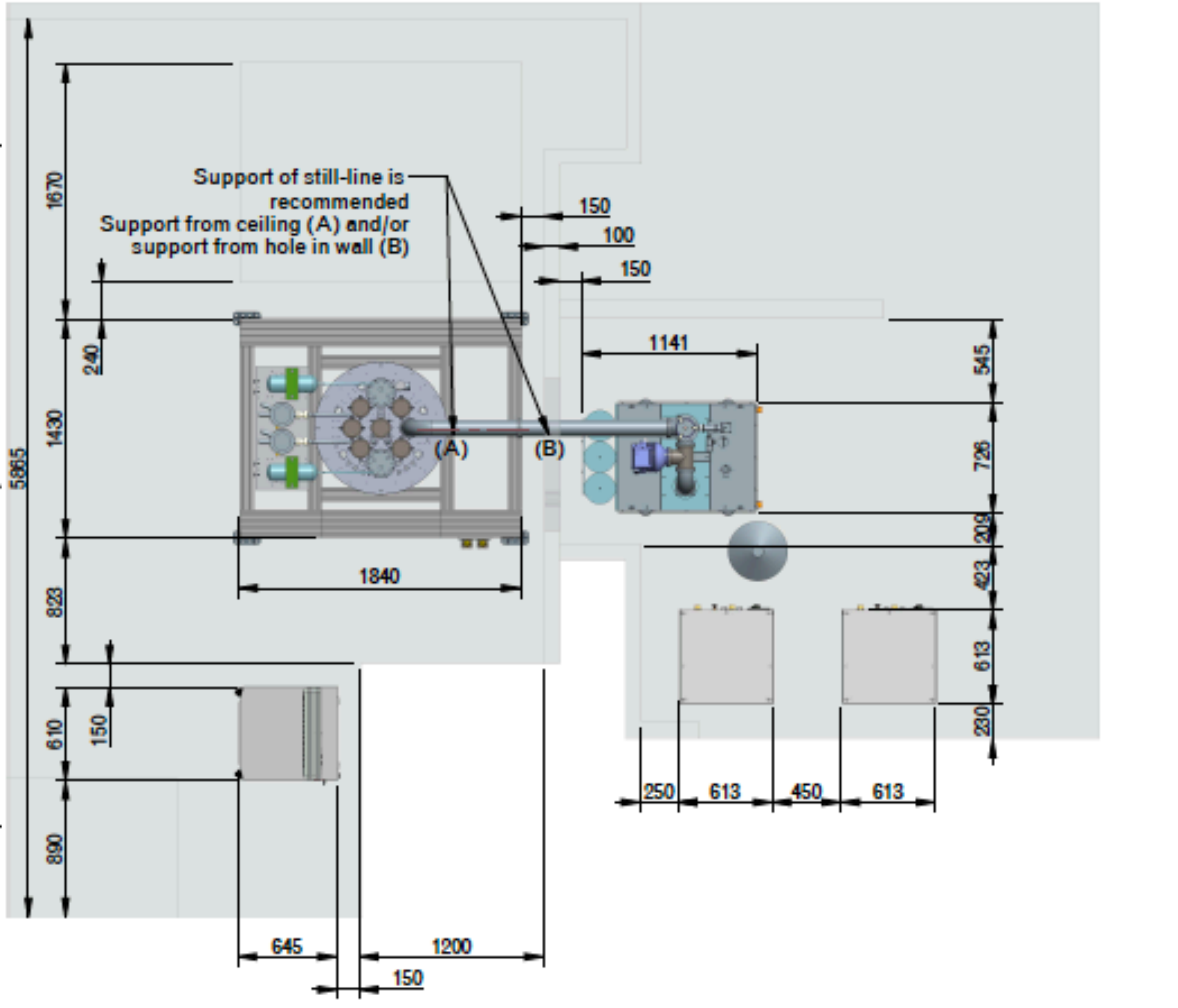
1) Collaboration with ADMX on New Haloscopes for ORGAN and ADMX Extended Frequency Range 2-4 GHz (No updates)

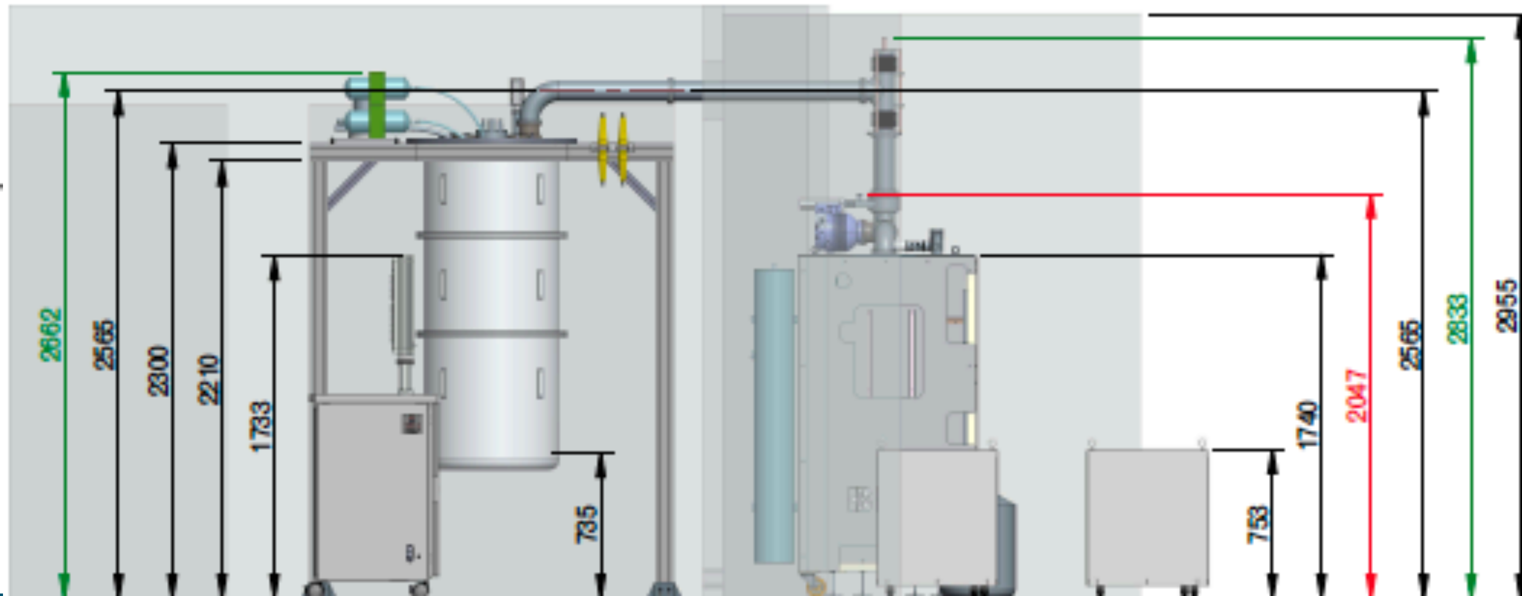
2) Developing Quantum Technologies for low noise readout:
 a) EQUS; Parametric Amplifiers at 26 GHz
 b) Leonid Kuzmin, Thursday, June 6: Single Photon Counter at 14 and 26 GHz for searching Galactic Axions within the QUAX and ORGAN projects

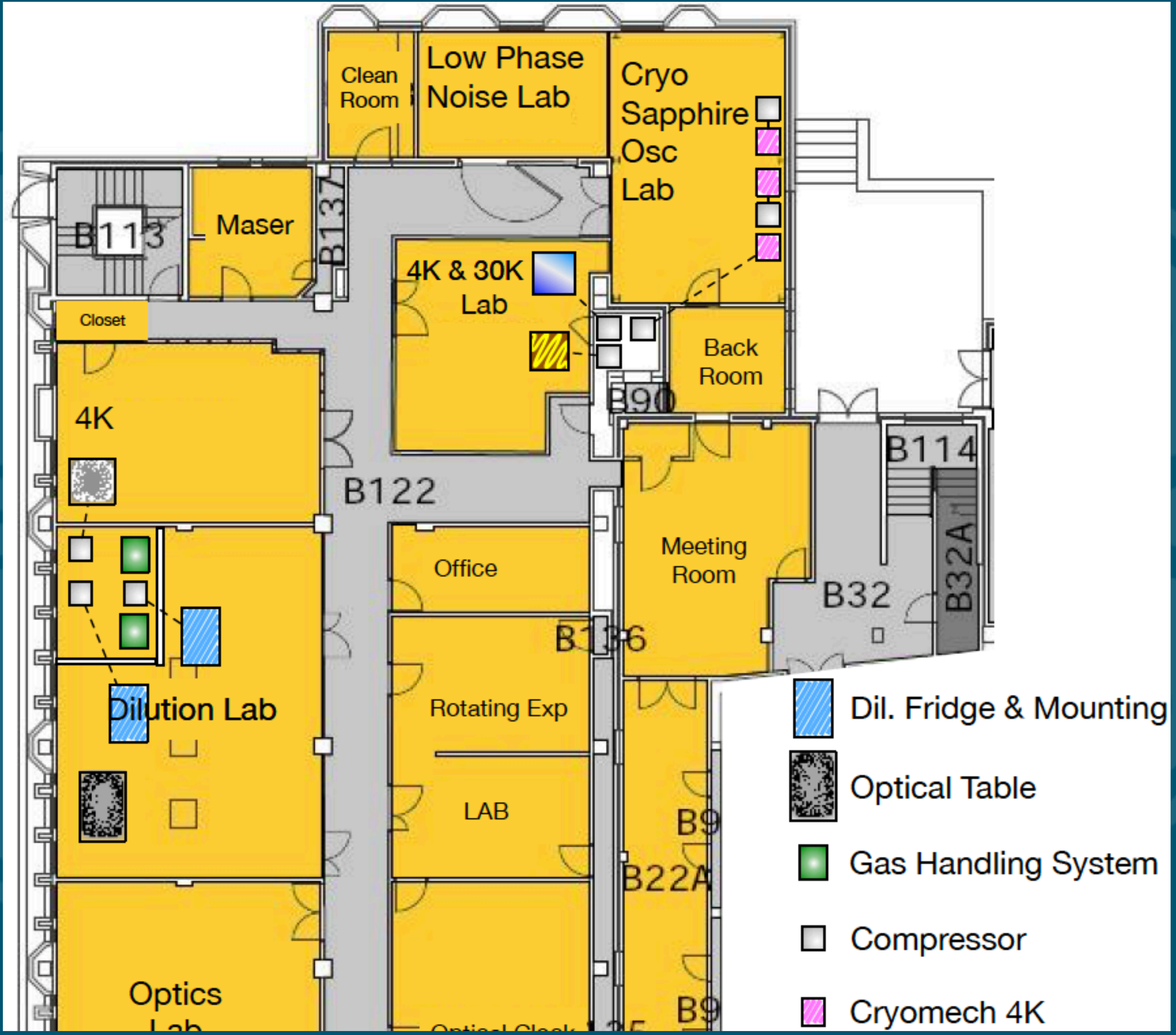
BF-XLD1000 with 14T-65mm Cryogen-Free Solenoid Magnet

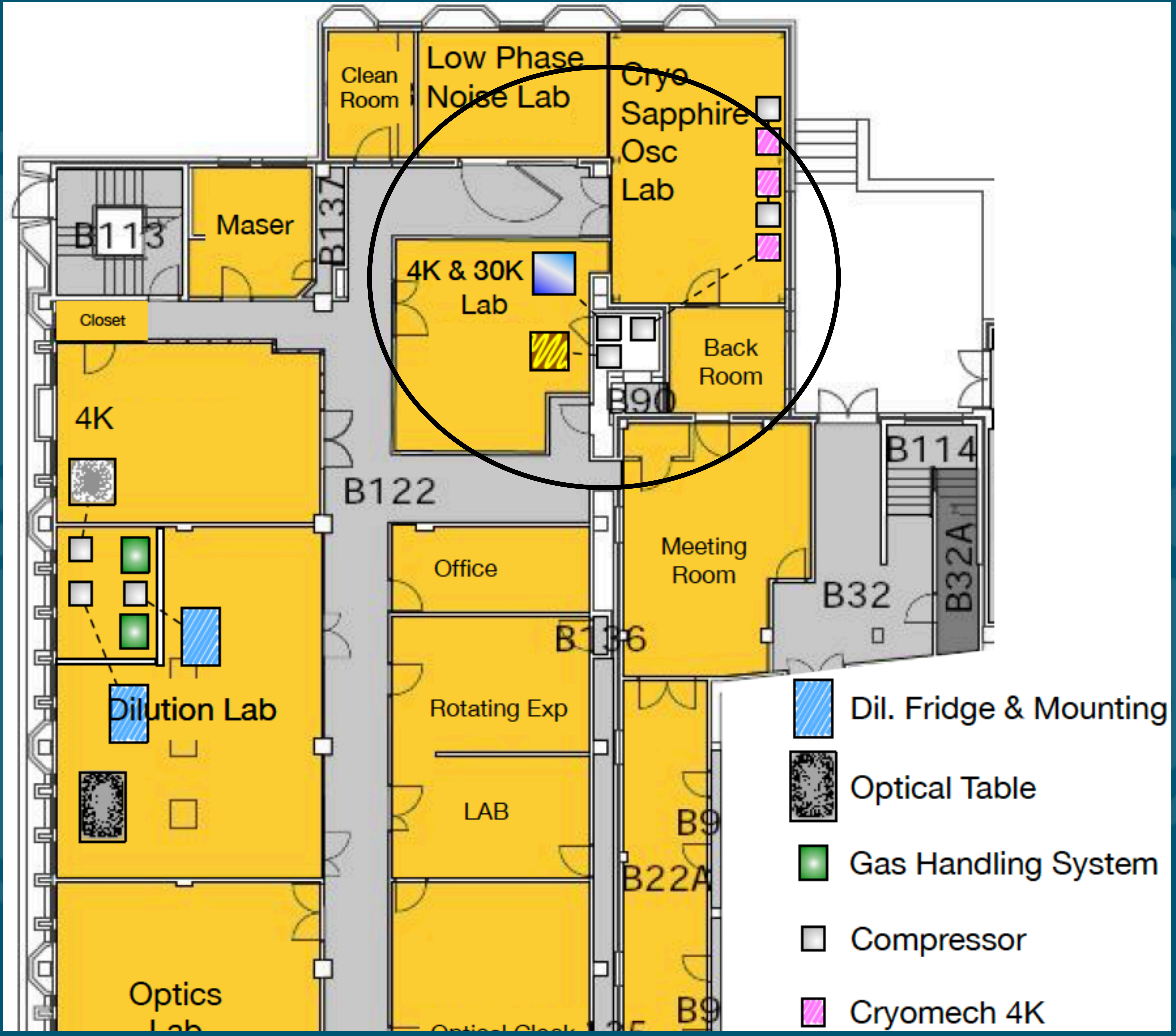


Lab upgrades and installation to be finished October 2019

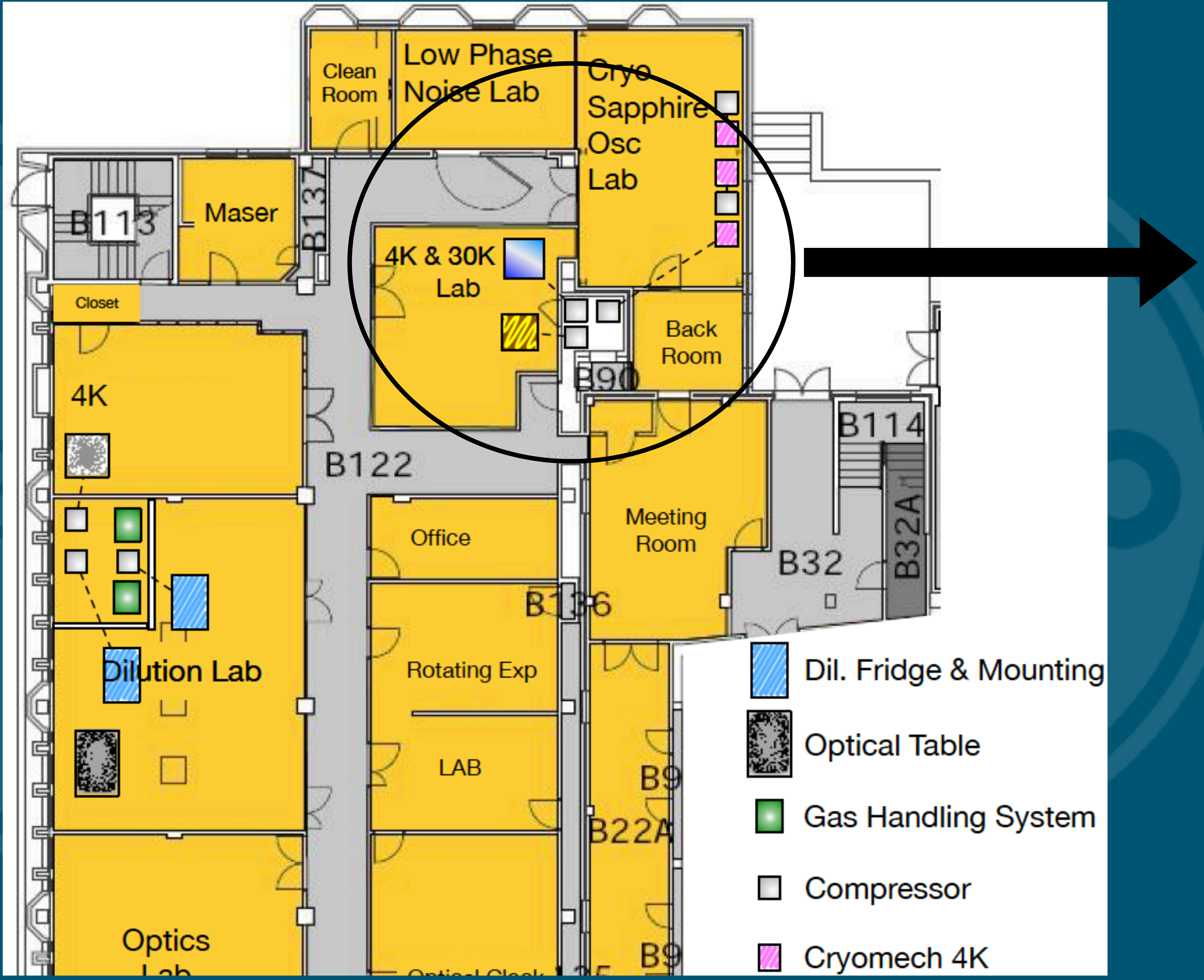





Clean Room
Low Phase Noise Lab
Cryo Sapphire Osc Lab
B113
Maser
B137
4K & 30K Lab
Closet
Back Room
B90
4K
B122
B114
Meeting Room
Office
B32
B32A
Dilution Lab
Rotating Exp
LAB
B9
B22A
B9
Optics
Dil. Fridge & Mounting
Optical Table
Gas Handling System
Compressor
Cryomech 4K

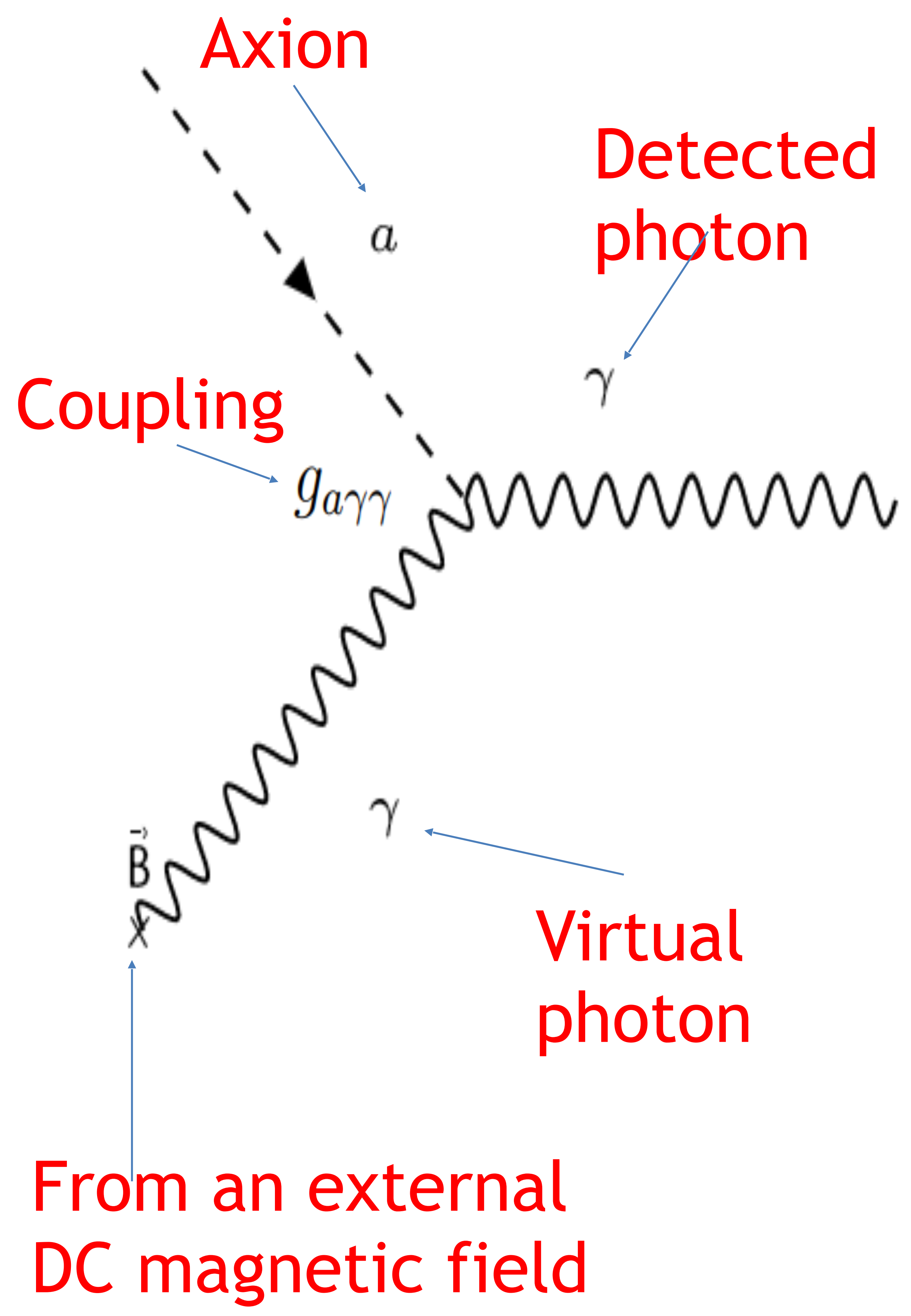


Clean Room
Low Phase Noise Lab
Cryo Sapphire Osc Lab
B113
Maser
B137
4K & 30K Lab
Closet
Back Room
B90
4K
B122
B114
Meeting Room
Office
B32
B32A
B136
Dilution Lab
Rotating Exp
LAB
B22A
Optics Lab
Dil. Fridge & Mounting
Optical Table
Gas Handling System
Compressor
Cryomech 4K


Clean Room
Low Phase Noise Lab
Cryo Sapphire Osc Lab
B113
Maser
B137
4K & 30K Lab
Closet
Back Room
B90
4K
B122
B114
Meeting Room
Office
B32
B32A
B136
Dilution Lab
Rotating Exp
LAB
B22A
Optics Lab
Dil. Fridge & Mounting
Optical Table
Gas Handling System
Compressor
Cryomech 4K

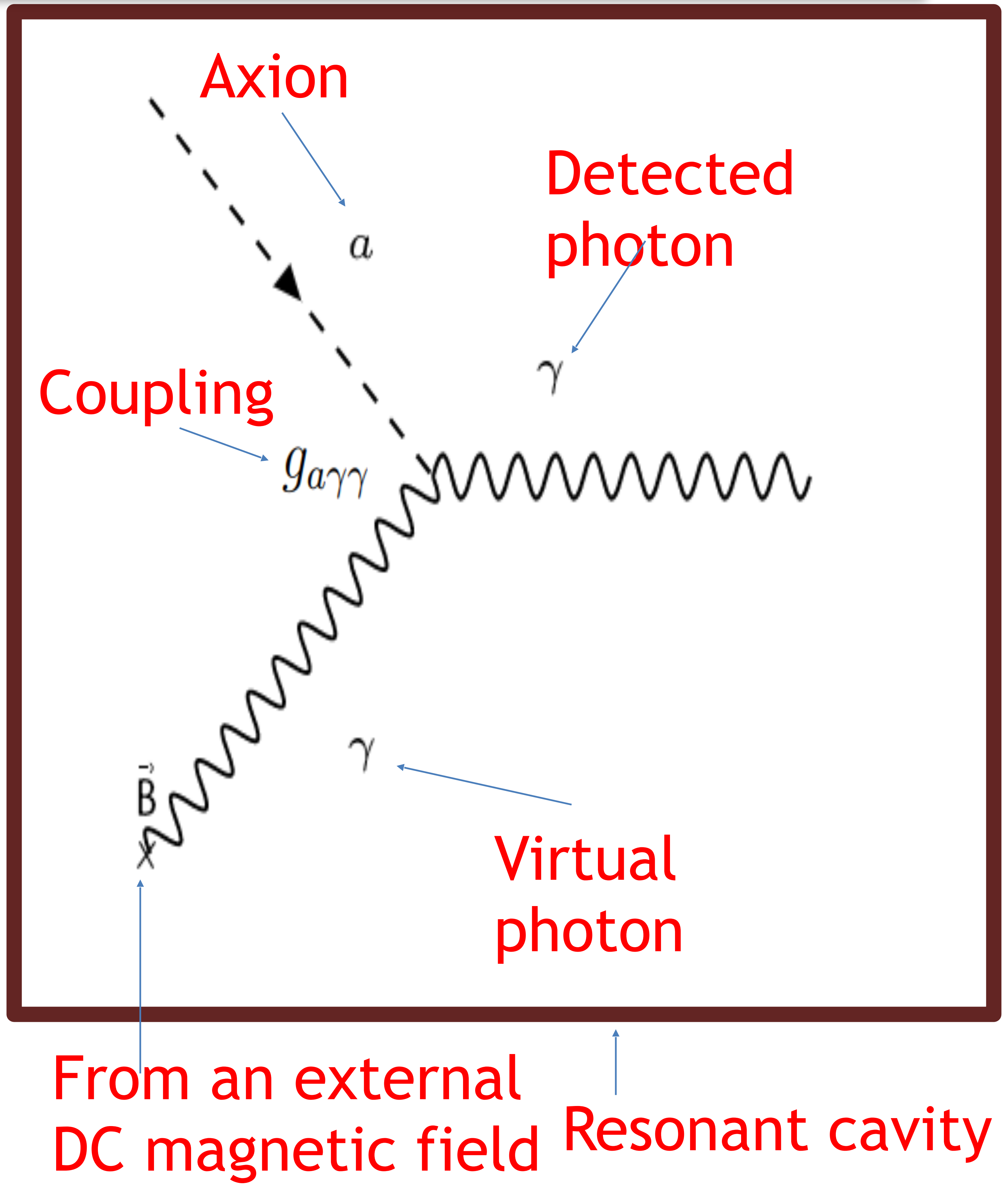
Clean Room
Low Phase Noise Lab
Cryo Sapphire Osc Lab
B113
Maser
B137
4K & 30K Lab
Back Room
B90
Closet
4K
B122
B114
Meeting Room
B32
B32A
Office
Dilution Lab
Rotating Exp
LAB
B22A
Optics
Dil. Fridge & Mounting
Optical Table
Gas Handling System
Compressor
Cryomech 4K
Cryo Sph Osc 4K
Cryo Sph Osc 4K
Cryo Dual Mode DM Osc 4K
Lumped Element Axion 4K
Axion Frequency Measurement 4K
MAGNON 7T 4K
ORGAN 14 T DilF
GHS
DILUTION FRIDGE ROOM
new vinyl flooring

The Axion Haloscope Technique



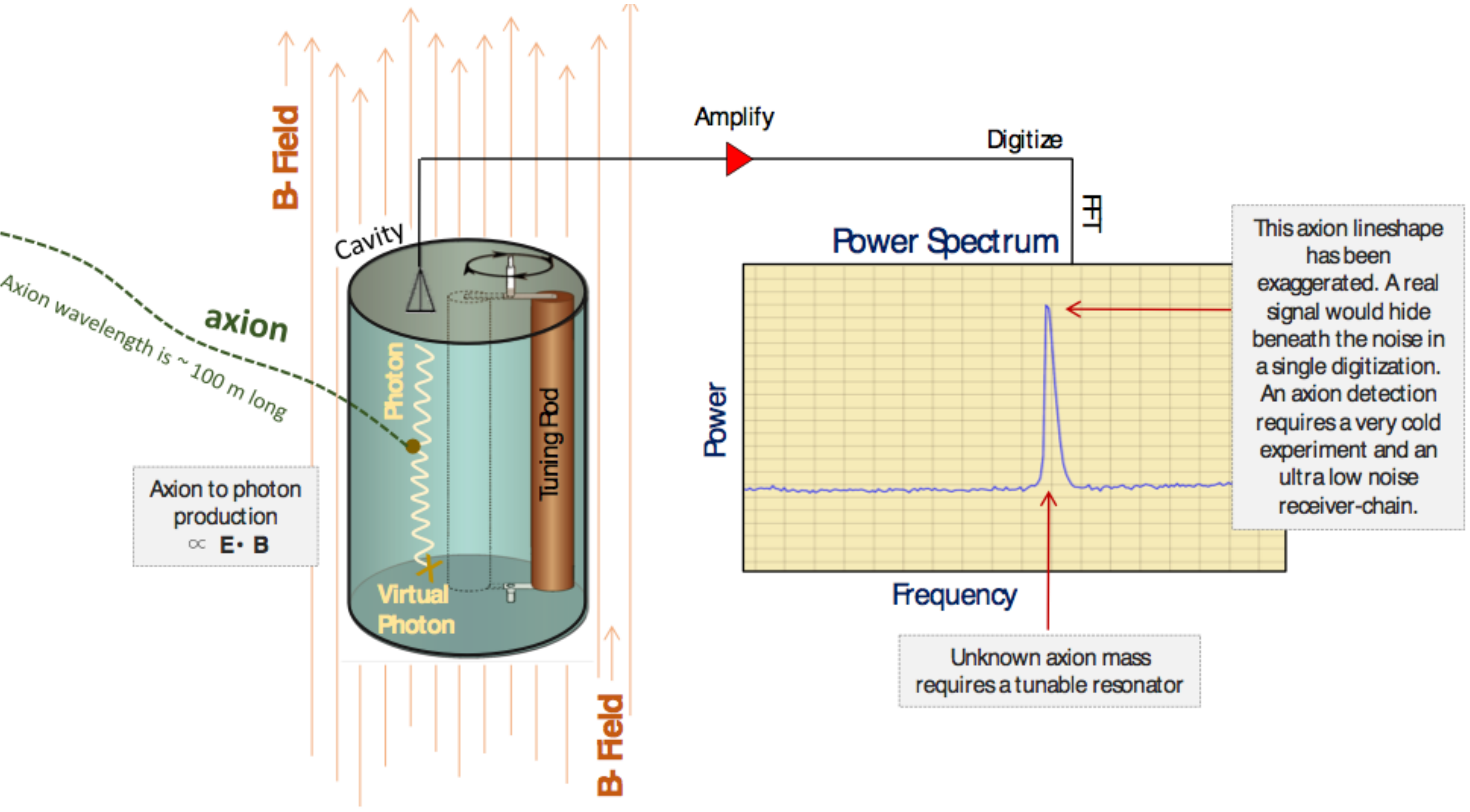

Pierre Sikivie

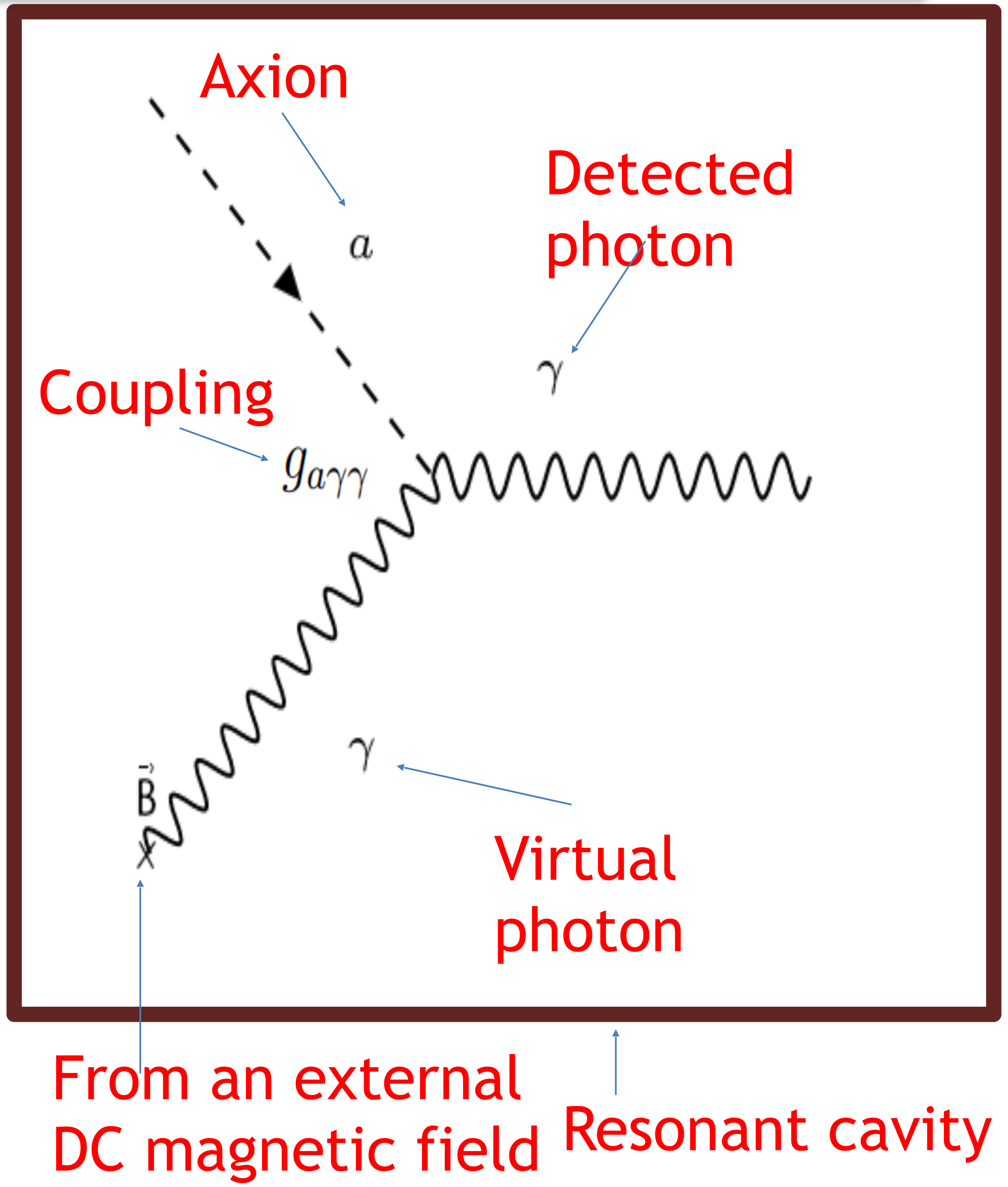
The Axion Haloscope Technique



Pierre Sikivie

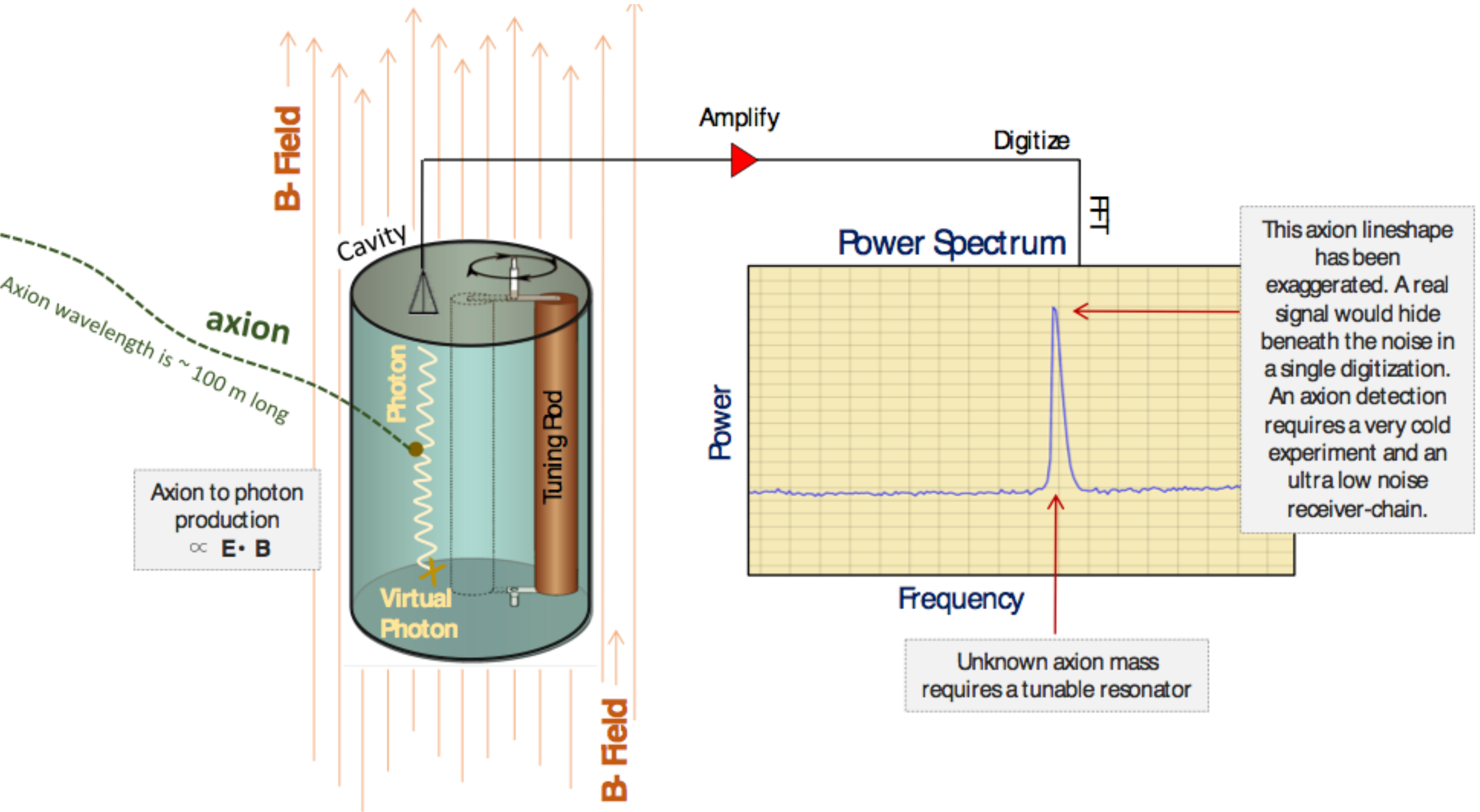
The Axion Haloscope Technique

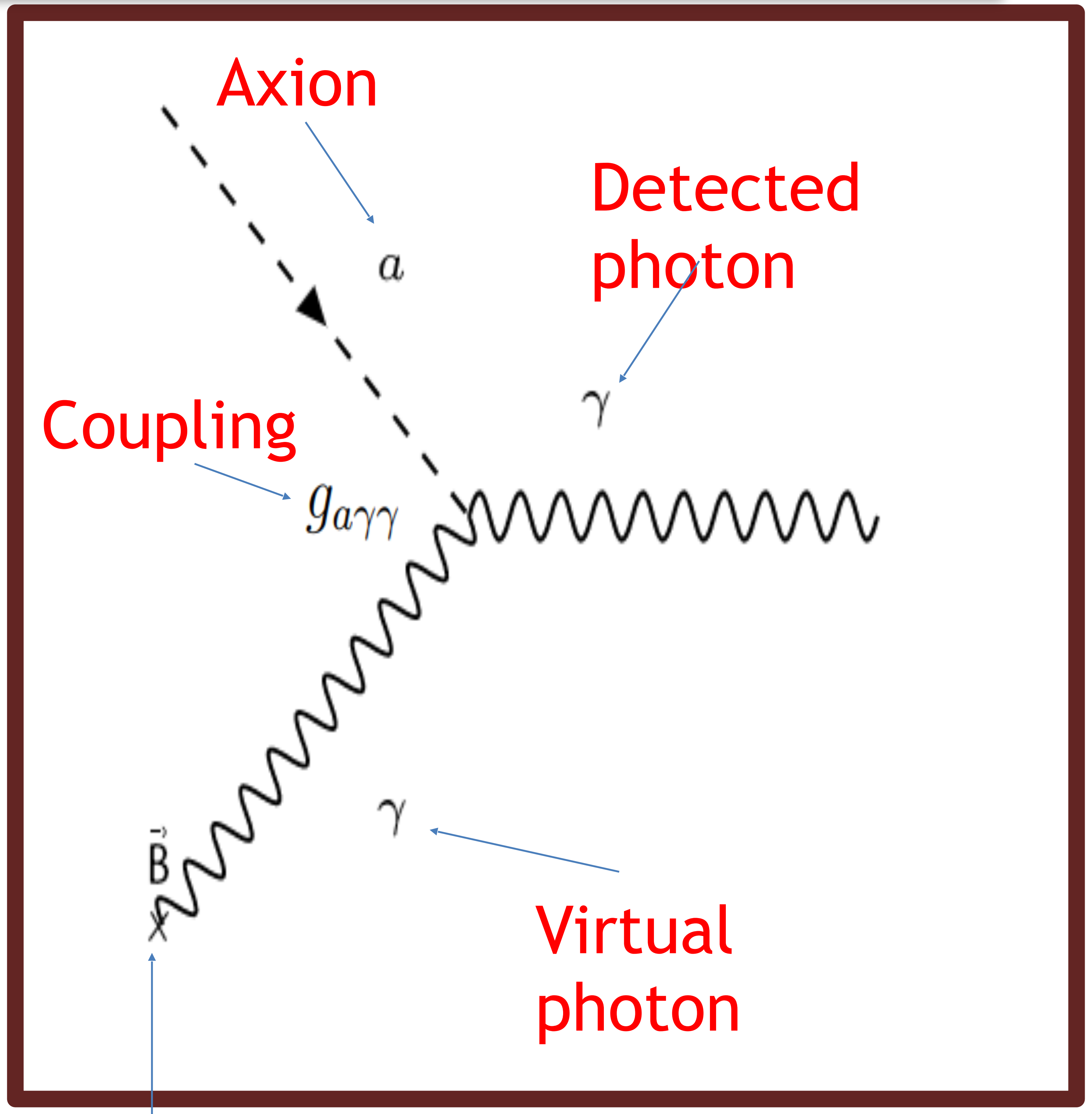




Pierre Sikivie

The Axion Haloscope Technique





From an external DC magnetic field

Resonant cavity

Pierre Sikivie

$$\mathscr{L} \propto a g_{a\gamma\gamma} \vec{E}_{cavity} \bullet \vec{B}_{ext}$$

Lagrangian gives effective strength

Low-Mass Axion Detection with Lumped Elements; Implications of Modified Electrodynamics

ABRACADABRA

PHYSICAL REVIEW D **94**, 042001 (2016)

3D lumped LC resonators as low mass axion haloscopes

Ben T. McAllister,[*] Stephen R. Parker, and Michael E. Tobar[†]
ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, 35 Stirling Highway, Crawley 6009, Western Australia, Australia
(Received 18 May 2016; published 11 August 2016)

PRL **112**, 131301 (2014) PHYSICAL REVIEW LETTERS week ending 4 APRIL 2014

Proposal for Axion Dark Matter Detection Using an *LC* Circuit

P. Sikivie, N. Sullivan, and D. B. Tanner
Department of Physics, University of Florida, Gainesville, Florida 32611, USA
(Received 31 October 2013; revised manuscript received 22 January 2014; published 31 March 2014)

Controversy at Low Mass; Compton Wavelength of Axion is Large

[1] arXiv:1904.05774 [pdf, other]

Electrodynamics of Impressed Bound and Free Charge Voltage Sources

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

Subjects: **Classical Physics (physics.class-ph)**

[4] arXiv:1809.01654 [pdf, other]

Modified Axion Electrodynamics as Impressed Electromagnetic Sources Through Oscillating Background Polarization and Magnetization

Michael Edmund Tobar, Ben T. McAllister, Maxim Goryachev

Comments: This version shows that axion electrodynamics under DC magnetic field is driven by an electric vector potential

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Astrophysics of Galaxies (astro-ph.GA); General Relativity and Quantum Cosmology (gr-qc); Instrumentation and Detectors (physics.ins-det)

[13] arXiv:1803.07755 [pdf, other]

Broadband Axion Dark Matter Haloscopes via Electric Sensing

Ben T. McAllister, Maxim Goryachev, Jeremy Bourhill, Eugene N. Ivanov, Michael E. Tobar

Comments: 6 pages, 4 figures. V4: Updated figures/text/appendices

Subjects: **Instrumentation and Detectors (physics.ins-det)**; General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Experiment (hep-ex); High Energy Physics - Phenomenology (hep-ph)

Axion Electrodynamics

$$\theta \frac{e^2}{32\pi^2} \varepsilon^{\alpha\beta\mu\nu} F_{\alpha\beta} F^{\mu\nu} \equiv \theta \frac{e^2}{32\pi^2} \tilde{F}_{\mu\nu} F^{\mu\nu} \sim \overrightarrow{E} \cdot \overrightarrow{B}$$

Axion Electrodynamics

$$\theta\frac{e^2}{32\pi^2}\varepsilon^{\alpha\beta\mu\nu}F_{\alpha\beta}F^{\mu\nu} \equiv \theta\frac{e^2}{32\pi^2}\tilde{F}_{\mu\nu}F^{\mu\nu} \sim \overrightarrow{E}\cdot\overrightarrow{B}$$

Parity or Time-reversal: $\overrightarrow{E}\cdot\overrightarrow{B} \rightarrow -\overrightarrow{E}\cdot\overrightarrow{B}$ CP odd interaction

Axion Electrodynamics

$$\theta \frac{e^2}{32\pi^2} \varepsilon^{\alpha\beta\mu\nu} F_{\alpha\beta} F^{\mu\nu} \equiv \theta \frac{e^2}{32\pi^2} \tilde{F}_{\mu\nu} F^{\mu\nu} \sim \overrightarrow{E} \cdot \overrightarrow{B}$$

Parity or Time-reversal: $\overrightarrow{E} \cdot \overrightarrow{B} \rightarrow - \overrightarrow{E} \cdot \overrightarrow{B}$ CP odd interaction

Total Derivative $\varepsilon^{\alpha\beta u\nu} F_{\alpha\beta} F^{\mu\nu} = \partial_\mu \left(\varepsilon^{\alpha\beta u\nu} A_\nu F_{\alpha\beta} \right)$ Does not change Equation of motion but adds CP odd interaction

Axion Electrodynamics

$$\theta\frac{e^2}{32\pi^2}\varepsilon^{\alpha\beta\mu\nu}F_{\alpha\beta}F^{\mu\nu} \equiv \theta\frac{e^2}{32\pi^2}\tilde{F}_{\mu\nu}F^{\mu\nu} \sim \overrightarrow{E}\cdot\overrightarrow{B}$$

Parity or Time-reversal: $\overrightarrow{E}\cdot\overrightarrow{B} \to -\overrightarrow{E}\cdot\overrightarrow{B}$ CP odd interaction

Total Derivative $\varepsilon^{\alpha\beta u\nu}F_{\alpha\beta}F^{\mu\nu} = \partial_\mu\left(\varepsilon^{\alpha\beta u\nu}A_\nu F_{\alpha\beta}\right)$ Does not change Equation of motion but adds CP odd interaction

QCD

$\varepsilon^{\alpha\beta\mu\nu}G_{\alpha\beta}G^{\mu\nu} = \partial_\mu\varepsilon^{\alpha\beta u\nu}\left(A_\nu F_{\alpha\beta} + A_\alpha A_\beta A_\nu\right)$ Instanton -> can not ignore the surface terms!!!!

Axion Electrodynamics

$$\theta\frac{e^2}{32\pi^2}\varepsilon^{\alpha\beta\mu\nu}F_{\alpha\beta}F^{\mu\nu} \equiv \theta\frac{e^2}{32\pi^2}\tilde{F}_{\mu\nu}F^{\mu\nu} \sim \vec{E}\cdot\vec{B}$$

Parity or Time-reversal: $\vec{E}\cdot\vec{B} \rightarrow -\vec{E}\cdot\vec{B}$ CP odd interaction

Total Derivative $\varepsilon^{\alpha\beta u\nu}F_{\alpha\beta}F^{\mu\nu} = \partial_\mu\left(\varepsilon^{\alpha\beta u\nu}A_\nu F_{\alpha\beta}\right)$ Does not change Equation of motion but adds CP odd interaction

QCD

$\varepsilon^{\alpha\beta\mu\nu}G_{\alpha\beta}G^{\mu\nu} = \partial_\mu\varepsilon^{\alpha\beta u\nu}\left(A_\nu F_{\alpha\beta} + A_\alpha A_\beta A_\nu\right)$ Instanton -> can not ignore the surface terms!!!!

$$\int d^4x\varepsilon^{\alpha\beta u\nu}G_{\alpha\beta}G^{\mu\nu} \neq 0$$

Axion Electrodynamics

$$\theta\frac{e^2}{32\pi^2}\varepsilon^{\alpha\beta\mu\nu}F_{\alpha\beta}F^{\mu\nu} \equiv \theta\frac{e^2}{32\pi^2}\tilde{F}_{\mu\nu}F^{\mu\nu} \sim \vec{E}\cdot\vec{B}$$

Parity or Time-reversal: $\vec{E}\cdot\vec{B} \rightarrow -\vec{E}\cdot\vec{B}$ CP odd interaction

Total Derivative $\varepsilon^{\alpha\beta u\nu}F_{\alpha\beta}F^{\mu\nu} = \partial_\mu\left(\varepsilon^{\alpha\beta u\nu}A_\nu F_{\alpha\beta}\right)$ Does not change Equation of motion but adds CP odd interaction

QCD

$$\varepsilon^{\alpha\beta\mu\nu}G_{\alpha\beta}G^{\mu\nu} = \partial_\mu\varepsilon^{\alpha\beta u\nu}\left(A_\nu F_{\alpha\beta} + A_\alpha A_\beta A_\nu\right)$$

Instanton -> can not ignore the surface terms!!!!

$$\int d^4x\varepsilon^{\alpha\beta u\nu}G_{\alpha\beta}G^{\mu\nu} \neq 0$$

Electrodynamics -> surface term due to <u>impressed large DC current</u> -> creates the DC magnetic field -> Excitation (or forcing) term (excites the system but does not change equation of motion)

Axion Electrodynamics

$$\theta\frac{e^2}{32\pi^2}\varepsilon^{\alpha\beta\mu\nu}F_{\alpha\beta}F^{\mu\nu} \equiv \theta\frac{e^2}{32\pi^2}\tilde{F}_{\mu\nu}F^{\mu\nu} \sim \vec{E}\cdot\vec{B}$$

Parity or Time-reversal: $\vec{E}\cdot\vec{B} \rightarrow -\vec{E}\cdot\vec{B}$ CP odd interaction

Total Derivative $\varepsilon^{\alpha\beta u\nu}F_{\alpha\beta}F^{\mu\nu} = \partial_\mu\left(\varepsilon^{\alpha\beta u\nu}A_\nu F_{\alpha\beta}\right)$ Does not change Equation of motion but adds CP odd interaction

QCD

$\varepsilon^{\alpha\beta\mu\nu}G_{\alpha\beta}G^{\mu\nu} = \partial_\mu\varepsilon^{\alpha\beta u\nu}\left(A_\nu F_{\alpha\beta} + A_\alpha A_\beta A_\nu\right)$ Instanton -> can not ignore the surface terms!!!!

$$\int d^4x\varepsilon^{\alpha\beta u\nu}G_{\alpha\beta}G^{\mu\nu} \neq 0$$

Electrodynamics -> surface term due to <u>impressed large DC current</u> -> creates the DC magnetic field -> Excitation (or forcing) term (excites the system but does not change equation of motion)

$$\int d^4x\varepsilon^{\alpha\beta u\nu}F_{\alpha\beta}F^{\mu\nu} \neq 0$$

Modified Axion Electrodynamics as Impressed Electromagnetic Sources Through Oscillating Background Polarization and Magnetization

$$\vec{\nabla}\cdot\vec{D} = \rho_f + g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\vec{B}\cdot\vec{\nabla}a$$

$$\vec{\nabla}\times\vec{H} = \vec{J}_f + \frac{\partial\vec{D}}{\partial t} - g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\left(\vec{B}\frac{\partial a}{\partial t} + \vec{\nabla}a\times\vec{E}\right)$$

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

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

$$\vec{D} = \epsilon_0\vec{E} + \vec{P}$$

$$\vec{H} = \frac{\vec{B}}{\mu_0} - \vec{M}$$

THE UNIVERSITY OF WESTERN AUSTRALIA

EQUS
Australian Research Council Centre of Excellence for Engineered Quantum Systems

Modified Axion Electrodynamics as Impressed Electromagnetic Sources Through Oscillating Background Polarization and Magnetization

$$\vec{\nabla}\cdot\vec{D} = \rho_f + g_{a\gamma\gamma}\cancel{\sqrt{\frac{\epsilon_0}{\mu_0}}\vec{B}\cdot\vec{\nabla} a}$$

Apply DC B-field

$$\vec{\nabla}\times\vec{H} = \vec{J}_f + \frac{\partial\vec{D}}{\partial t} - g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\left(\vec{B}\frac{\partial a}{\partial t} + \cancel{\vec{\nabla} a\times\vec{E}}\right)$$

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

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

$$\vec{D} = \epsilon_0\vec{E} + \vec{P}$$

$$\vec{H} = \frac{\vec{B}}{\mu_0} - \vec{M}$$

Usual lumped element experiments assume

$$\vec{\nabla} a = 0$$

Fine, but approximation made too early

THE UNIVERSITY OF WESTERN AUSTRALIA

EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems

Modified Axion Electrodynamics as Impressed Electromagnetic Sources Through Oscillating Background Polarization and Magnetization

$$\vec{\nabla}\cdot\vec{D} = \rho_f + g_{a\gamma\gamma}\cancel{\sqrt{\frac{\epsilon_0}{\mu_0}}}\vec{B}\cdot\vec{\nabla}a$$

Apply DC B-field

$$\vec{\nabla}\times\vec{H} = \vec{J}_f + \frac{\partial\vec{D}}{\partial t} \boxed{+\vec{J}_{aB}} + \cancel{\vec{\nabla}a\times\vec{E}})$$

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

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

$$\vec{D} = \epsilon_0\vec{E} + \vec{P}$$

$$\vec{H} = \frac{\vec{B}}{\mu_0} - \vec{M}$$

Usual lumped element experiments assume

$$\vec{\nabla}a = 0$$

Fine, but approximation made too early

THE UNIVERSITY OF WESTERN AUSTRALIA

EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems

Modified Axion Electrodynamics as Impressed Electromagnetic Sources Through Oscillating Background Polarization and Magnetization

$$\vec{\nabla}\cdot\vec{D} = \rho_f + g_{a\gamma\gamma}\cancel{\sqrt{\frac{\epsilon_0}{\mu_0}}\vec{B}}\cdot\vec{\nabla}a$$

Apply DC B-field

$$\vec{\nabla}\times\vec{H} = \vec{J}_f + \frac{\partial\vec{D}}{\partial t}\boxed{+\vec{J}_{aB}} + \cancel{\vec{\nabla}a\times\vec{E}}\Big)$$

Usually it is assumed the axion current is non-interacting
NOT TRUE ignores surface term

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

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

$$\vec{D} = \epsilon_0\vec{E} + \vec{P}$$

$$\vec{H} = \frac{\vec{B}}{\mu_0} - \vec{M}$$

Usual lumped element experiments assume

$$\vec{\nabla}a = 0$$

Fine, but approximation made too early

THE UNIVERSITY OF WESTERN AUSTRALIA

EQUS
Australian Research Council Centre of Excellence for Engineered Quantum Systems

Modified Axion Electrodynamics as Impressed Electromagnetic Sources Through Oscillating Background Polarization and Magnetization

$$\vec{\nabla} \cdot \vec{D} = \rho_f + g_{a\gamma\gamma}\cancel{\sqrt{\frac{\epsilon_0}{\mu_0}}\vec{B} \cdot \vec{\nabla} a}$$

Apply DC B-field

$$\vec{\nabla} \times \vec{H} = \vec{J}_f + \frac{\partial \vec{D}}{\partial t} \boxed{+ \vec{J}_{aB}} + \cancel{\vec{\nabla} a \times \vec{E}})$$

Usually it is assumed the axion current is non-interacting
NOT TRUE ignores surface term

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

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

Usual lumped element experiments assume

$$\vec{\nabla} a = 0$$

Fine, but approximation made too early

Rearrange Axion Electrodynamics to reflect

$$\mathscr{L}'_{a\gamma} = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\vec{E}_T \cdot (a\vec{B}_0)$$

$$\vec{D} = \epsilon_0 \vec{E} + \vec{P}$$

$$\vec{H} = \frac{\vec{B}}{\mu_0} - \vec{M}$$

THE UNIVERSITY OF WESTERN AUSTRALIA

EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems

Vector Identities

$$\vec{B} \cdot \vec{\nabla} a = \vec{\nabla} \cdot (a\vec{B}) + a(\vec{\nabla} \cdot \vec{B})$$

$$\vec{\nabla} a \times \vec{E} = \left(\vec{\nabla} \times (a\vec{E})\right) - a\left(\vec{\nabla} \times \vec{E}\right)$$

Vector Identities

$$\vec{B} \cdot \vec{\nabla} a = \vec{\nabla} \cdot (a\vec{B}) + a(\vec{\nabla} \cdot \vec{B}) \qquad \vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} a \times \vec{E} = \left(\vec{\nabla} \times (a\vec{E})\right) - a\left(\vec{\nabla} \times \vec{E}\right)$$

Vector Identities

$$\vec{B} \cdot \vec{\nabla} a = \vec{\nabla} \cdot (a\vec{B}) + a(\vec{\nabla} \cdot \vec{B}) \qquad \vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} a \times \vec{E} = \left(\vec{\nabla} \times (a\vec{E})\right) - a\left(\vec{\nabla} \times \vec{E}\right) \qquad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Vector Identities

$$\vec{B} \cdot \vec{\nabla} a = \vec{\nabla} \cdot (a\vec{B}) + a(\vec{\nabla} \cdot \vec{B}) \qquad \vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} a \times \vec{E} = \left(\vec{\nabla} \times (a\vec{E})\right) - a\left(\vec{\nabla} \times \vec{E}\right) \qquad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Modified Gauss' Law and Ampere's Law

Vector Identities

$$\vec{B} \cdot \vec{\nabla} a = \vec{\nabla} \cdot (a\vec{B}) + a(\vec{\nabla} \cdot \vec{B}) \qquad \vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} a \times \vec{E} = \left(\vec{\nabla} \times (a\vec{E})\right) - a\left(\vec{\nabla} \times \vec{E}\right) \qquad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Modified Gauss' Law and Ampere's Law

$$\vec{\nabla} \cdot \vec{D} = \rho_f + g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\vec{\nabla} \cdot (a\vec{B})$$

Vector Identities

$$\vec{B} \cdot \vec{\nabla} a = \vec{\nabla} \cdot (a\vec{B}) + a(\vec{\nabla} \cdot \vec{B}) \qquad \vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} a \times \vec{E} = \left(\vec{\nabla} \times (a\vec{E})\right) - a\left(\vec{\nabla} \times \vec{E}\right) \qquad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Modified Gauss' Law and Ampere's Law

$$\vec{\nabla} \cdot \vec{D} = \rho_f + g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\vec{\nabla} \cdot (a\vec{B})$$

$$\vec{\nabla} \times \vec{H} = \vec{J}_f + \frac{\partial \vec{D}}{\partial t} - g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\left(\frac{\partial (a\vec{B})}{\partial t} + \vec{\nabla} \times (a\vec{E})\right)$$

Reformulate Modified Electrodynamics

$$\vec{\nabla} \cdot \overrightarrow{D_T} = \rho_f$$

$$\vec{\nabla} \times \overrightarrow{H_T} = \vec{J_f} + \frac{\partial \overrightarrow{D_T}}{\partial t}$$

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

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

Reformulate Modified Electrodynamics

$$\vec{\nabla} \cdot \overrightarrow{D_T} = \rho_f$$

$$\vec{\nabla} \times \overrightarrow{H_T} = \vec{J_f} + \frac{\partial \overrightarrow{D_T}}{\partial t}$$

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

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

Modification in the Constitutive Relations

Reformulate Modified Electrodynamics

$$\vec{\nabla} \cdot \overrightarrow{D_T} = \rho_f$$

$$\vec{\nabla} \times \overrightarrow{H_T} = \vec{J_f} + \frac{\partial \overrightarrow{D_T}}{\partial t}$$

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

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

Modification in the Constitutive Relations

$$\overrightarrow{D_T} = \epsilon_0 \vec{E} + \vec{P} + \overrightarrow{P_{aE}} \qquad \overrightarrow{P_{aE}} = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}(a\vec{B})$$

Reformulate Modified Electrodynamics

$$\overrightarrow{\nabla} \cdot \overrightarrow{D_T} = \rho_f$$

$$\overrightarrow{\nabla} \times \overrightarrow{H_T} = \overrightarrow{J_f} + \frac{\partial \overrightarrow{D_T}}{\partial t}$$

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

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

Modification in the Constitutive Relations

$$\overrightarrow{D_T} = \epsilon_0 \overrightarrow{E} + \overrightarrow{P} + \overrightarrow{P_{aE}} \qquad \overrightarrow{P_{aE}} = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}(a\overrightarrow{B})$$

$$\overrightarrow{H_T} = \frac{1}{\mu_0}\overrightarrow{B} - \overrightarrow{M} - \overrightarrow{M_{aE}} \qquad \overrightarrow{M_{aE}} = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}(a\overrightarrow{E})$$

Reformulate Modified Electrodynamics

$$\overrightarrow{\nabla} \cdot \overrightarrow{D_T} = \rho_f$$

$$\overrightarrow{\nabla} \times \overrightarrow{H_T} = \overrightarrow{J_f} + \frac{\partial \overrightarrow{D_T}}{\partial t}$$

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

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

Similar to Standard Model Extension Modifications for Lorentz Invariance Violations

Modification in the Constitutive Relations

$$\overrightarrow{D_T} = \epsilon_0 \overrightarrow{E} + \overrightarrow{P} + \overrightarrow{P_{aE}}$$

$$\overrightarrow{P}_{aE} = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}(a\overrightarrow{B})$$

$$\overrightarrow{H_T} = \frac{1}{\mu_0}\overrightarrow{B} - \overrightarrow{M} - \overrightarrow{M_{aE}}$$

$$\overrightarrow{M}_{aE} = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}(a\overrightarrow{E})$$

Reformulate Modified Electrodynamics

$$\vec{\nabla} \cdot \overrightarrow{D_T} = \rho_f$$

$$\vec{\nabla} \times \overrightarrow{H_T} = \overrightarrow{J_f} + \frac{\partial \overrightarrow{D_T}}{\partial t}$$

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

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

Similar to Standard Model Extension Modifications for Lorentz Invariance Violations

Modification in the Constitutive Relations

$$\overrightarrow{D_T} = \epsilon_0 \vec{E} + \vec{P} + \overrightarrow{P_{aE}} \longrightarrow \overrightarrow{P_{aE}} = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}(a\vec{B})$$

$$\overrightarrow{H_T} = \frac{1}{\mu_0}\vec{B} - \vec{M} - \overrightarrow{M_{aE}} \qquad \overrightarrow{M_{aE}} = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}(a\vec{E})$$

Reformulate Modified Electrodynamics

$$\vec{\nabla} \cdot \overrightarrow{D_T} = \rho_f$$

$$\vec{\nabla} \times \overrightarrow{H_T} = \vec{J_f} + \frac{\partial \overrightarrow{D_T}}{\partial t}$$

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

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

Similar to Standard Model Extension Modifications for Lorentz Invariance Violations

Modification in the Constitutive Relations

$$\overrightarrow{D_T} = \epsilon_0 \vec{E} + \vec{P} + \overrightarrow{P_{aE}} \longrightarrow \overrightarrow{P_{aE}} = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}(a\vec{B})$$

$$\overrightarrow{H_T} = \frac{1}{\mu_0}\vec{B} - \vec{M} - \overrightarrow{M_{aE}} \longrightarrow \overrightarrow{M_{aE}} = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}(a\vec{E})$$

PHYSICAL REVIEW D **66**, 056005 (2002)

Signals for Lorentz violation in electrodynamics

V. Alan Kostelecký and Matthew Mewes
Physics Department, Indiana University, Bloomington, Indiana 47405
(Received 20 May 2002; published 23 September 2002)

$$\vec{\nabla}\times\vec{H}-\partial_0\vec{D}=0,\quad \vec{\nabla}\cdot\vec{D}=0,$$
$$\vec{\nabla}\times\vec{E}+\partial_0\vec{B}=0,\quad \vec{\nabla}\cdot\vec{B}=0.$$

$$\begin{pmatrix}\vec{D}\\ \vec{H}\end{pmatrix}=\begin{pmatrix}1+\kappa_{DE} & \kappa_{DB}\\ \kappa_{HE} & 1+\kappa_{HB}\end{pmatrix}\begin{pmatrix}\vec{E}\\ \vec{B}\end{pmatrix}$$

PHYSICAL REVIEW D **71,** 025004 (2005)

New methods of testing Lorentz violation in electrodynamics

Michael Edmund Tobar,[1,*] Peter Wolf,[2,3] Alison Fowler,[1] and John Gideon Hartnett[1]
[1]*University of Western Australia, School of Physics, M013, 35 Stirling Highway, Crawley 6009 WA, Australia*
[2]*Bureau International des Poids et Mesures, Pavillon de Breteuil, 92312 Sèvres Cedex, France*
[3]*BNM-SYRTE, Observatoire de Paris, 61 Avenue de l'Observatoire, 75014 Paris, France*
(Received 1 September 2004; published 7 January 2005)

$$\begin{pmatrix}\boldsymbol{D}\\ \boldsymbol{H}\end{pmatrix}=\begin{pmatrix}\epsilon_0(\tilde{\epsilon}_r+\kappa_{DE}) & \sqrt{\frac{\epsilon_0}{\mu_0}}\kappa_{DB}\\ \sqrt{\frac{\epsilon_0}{\mu_0}}\kappa_{HE} & \mu_0^{-1}(\tilde{\mu}_r{}^{-1}+\kappa_{HB})\end{pmatrix}\begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{B}\end{pmatrix}$$

PHYSICAL REVIEW D **66**, 056005 (2002)

Signals for Lorentz violation in electrodynamics

V. Alan Kostelecký and Matthew Mewes
Physics Department, Indiana University, Bloomington, Indiana 47405
(Received 20 May 2002; published 23 September 2002)

$$\vec{\nabla}\times\vec{H}-\partial_0\vec{D}=0, \quad \vec{\nabla}\cdot\vec{D}=0,$$
$$\vec{\nabla}\times\vec{E}+\partial_0\vec{B}=0, \quad \vec{\nabla}\cdot\vec{B}=0.$$

$$\begin{pmatrix}\vec{D}\\ \vec{H}\end{pmatrix}=\begin{pmatrix}1+\kappa_{DE} & \kappa_{DB}\\ \kappa_{HE} & 1+\kappa_{HB}\end{pmatrix}\begin{pmatrix}\vec{E}\\ \vec{B}\end{pmatrix}$$

PHYSICAL REVIEW D **71,** 025004 (2005)

New methods of testing Lorentz violation in electrodynamics

Michael Edmund Tobar,[1,*] Peter Wolf,[2,3] Alison Fowler,[1] and John Gideon Hartnett[1]
[1]*University of Western Australia, School of Physics, M013, 35 Stirling Highway, Crawley 6009 WA, Australia*
[2]*Bureau International des Poids et Mesures, Pavillon de Breteuil, 92312 Sèvres Cedex, France*
[3]*BNM-SYRTE, Observatoire de Paris, 61 Avenue de l'Observatoire, 75014 Paris, France*
(Received 1 September 2004; published 7 January 2005)

$$\begin{pmatrix}\boldsymbol{D}\\ \boldsymbol{H}\end{pmatrix}=\begin{pmatrix}\epsilon_0(\tilde{\epsilon}_r+\kappa_{DE}) & \sqrt{\frac{\epsilon_0}{\mu_0}}\kappa_{DB}\\ \sqrt{\frac{\epsilon_0}{\mu_0}}\kappa_{HE} & \mu_0^{-1}(\tilde{\mu}_r{}^{-1}+\kappa_{HB})\end{pmatrix}\begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{B}\end{pmatrix}$$

$$g_{a\gamma\gamma}a \quad \sim \kappa_{DB} \quad \kappa_{HE}$$

PHYSICAL REVIEW D **66**, 056005 (2002)

Signals for Lorentz violation in electrodynamics

V. Alan Kostelecký and Matthew Mewes
Physics Department, Indiana University, Bloomington, Indiana 47405
(Received 20 May 2002; published 23 September 2002)

$$\vec{\nabla}\times\vec{H}-\partial_0\vec{D}=0,\quad \vec{\nabla}\cdot\vec{D}=0,$$
$$\vec{\nabla}\times\vec{E}+\partial_0\vec{B}=0,\quad \vec{\nabla}\cdot\vec{B}=0.$$

$$\begin{pmatrix}\vec{D}\\ \vec{H}\end{pmatrix}=\begin{pmatrix}1+\kappa_{DE} & \kappa_{DB}\\ \kappa_{HE} & 1+\kappa_{HB}\end{pmatrix}\begin{pmatrix}\vec{E}\\ \vec{B}\end{pmatrix}$$

PHYSICAL REVIEW D **71**, 025004 (2005)

New methods of testing Lorentz violation in electrodynamics

Michael Edmund Tobar,[1,*] Peter Wolf,[2,3] Alison Fowler,[1] and John Gideon Hartnett[1]
[1]*University of Western Australia, School of Physics, M013, 35 Stirling Highway, Crawley 6009 WA, Australia*
[2]*Bureau International des Poids et Mesures, Pavillon de Breteuil, 92312 Sèvres Cedex, France*
[3]*BNM-SYRTE, Observatoire de Paris, 61 Avenue de l'Observatoire, 75014 Paris, France*
(Received 1 September 2004; published 7 January 2005)

$$\begin{pmatrix}\boldsymbol{D}\\ \boldsymbol{H}\end{pmatrix}=\begin{pmatrix}\epsilon_0(\tilde{\epsilon}_r+\kappa_{DE}) & \sqrt{\frac{\epsilon_0}{\mu_0}}\kappa_{DB}\\ \sqrt{\frac{\epsilon_0}{\mu_0}}\kappa_{HE} & \mu_0^{-1}(\tilde{\mu}_r{}^{-1}+\kappa_{HB})\end{pmatrix}\begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{B}\end{pmatrix}$$

$$g_{a\gamma\gamma}a \sim \kappa_{DB} \quad \kappa_{HE}$$

$$\boxed{\text{Axion Interaction similar to odd parity Lorentz Invariance Violation}}$$

PHYSICAL REVIEW D **66**, 056005 (2002)

Signals for Lorentz violation in electrodynamics

V. Alan Kostelecký and Matthew Mewes
Physics Department, Indiana University, Bloomington, Indiana 47405
(Received 20 May 2002; published 23 September 2002)

$$\vec{\nabla}\times\vec{H}-\partial_0\vec{D}=0, \quad \vec{\nabla}\cdot\vec{D}=0,$$
$$\vec{\nabla}\times\vec{E}+\partial_0\vec{B}=0, \quad \vec{\nabla}\cdot\vec{B}=0.$$

$$\begin{pmatrix}\vec{D}\\ \vec{H}\end{pmatrix}=\begin{pmatrix}1+\kappa_{DE} & \kappa_{DB}\\ \kappa_{HE} & 1+\kappa_{HB}\end{pmatrix}\begin{pmatrix}\vec{E}\\ \vec{B}\end{pmatrix}$$

PHYSICAL REVIEW D **71**, 025004 (2005)

New methods of testing Lorentz violation in electrodynamics

Michael Edmund Tobar,[1,*] Peter Wolf,[2,3] Alison Fowler,[1] and John Gideon Hartnett[1]
[1]*University of Western Australia, School of Physics, M013, 35 Stirling Highway, Crawley 6009 WA, Australia*
[2]*Bureau International des Poids et Mesures, Pavillon de Breteuil, 92312 Sèvres Cedex, France*
[3]*BNM-SYRTE, Observatoire de Paris, 61 Avenue de l'Observatoire, 75014 Paris, France*
(Received 1 September 2004; published 7 January 2005)

$$\begin{pmatrix}\mathbf{D}\\ \mathbf{H}\end{pmatrix}=\begin{pmatrix}\epsilon_0(\tilde{\epsilon}_r+\kappa_{DE}) & \sqrt{\frac{\epsilon_0}{\mu_0}}\kappa_{DB}\\ \sqrt{\frac{\epsilon_0}{\mu_0}}\kappa_{HE} & \mu_0^{-1}(\tilde{\mu}_r^{-1}+\kappa_{HB})\end{pmatrix}\begin{pmatrix}\mathbf{E}\\ \mathbf{B}\end{pmatrix}$$

$$g_{a\gamma\gamma}a \sim \kappa_{DB} \quad \kappa_{HE}$$

Axion Interaction similar to odd parity Lorentz Invariance Violation

PHYSICAL REVIEW D **66**, 056005 (2002)

Signals for Lorentz violation in electrodynamics

V. Alan Kostelecký and Matthew Mewes
Physics Department, Indiana University, Bloomington, Indiana 47405
(Received 20 May 2002; published 23 September 2002)

$$\vec{\nabla}\times\vec{H}-\partial_0\vec{D}=0, \quad \vec{\nabla}\cdot\vec{D}=0,$$
$$\vec{\nabla}\times\vec{E}+\partial_0\vec{B}=0, \quad \vec{\nabla}\cdot\vec{B}=0.$$

$$\begin{pmatrix}\vec{D}\\ \vec{H}\end{pmatrix}=\begin{pmatrix}1+\kappa_{DE} & \kappa_{DB}\\ \kappa_{HE} & 1+\kappa_{HB}\end{pmatrix}\begin{pmatrix}\vec{E}\\ \vec{B}\end{pmatrix}$$

PHYSICAL REVIEW D **71,** 025004 (2005)

New methods of testing Lorentz violation in electrodynamics

Michael Edmund Tobar,[1,*] Peter Wolf,[2,3] Alison Fowler,[1] and John Gideon Hartnett[1]
[1]*University of Western Australia, School of Physics, M013, 35 Stirling Highway, Crawley 6009 WA, Australia*
[2]*Bureau International des Poids et Mesures, Pavillon de Breteuil, 92312 Sèvres Cedex, France*
[3]*BNM-SYRTE, Observatoire de Paris, 61 Avenue de l'Observatoire, 75014 Paris, France*
(Received 1 September 2004; published 7 January 2005)

$$\begin{pmatrix}\boldsymbol{D}\\ \boldsymbol{H}\end{pmatrix}=\begin{pmatrix}\epsilon_0(\tilde{\epsilon}_r+\kappa_{DE}) & \sqrt{\frac{\epsilon_0}{\mu_0}}\kappa_{DB}\\ \sqrt{\frac{\epsilon_0}{\mu_0}}\kappa_{HE} & \mu_0^{-1}(\tilde{\mu}_r^{-1}+\kappa_{HB})\end{pmatrix}\begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{B}\end{pmatrix}$$

$$g_{a\gamma\gamma}a \sim \kappa_{DB} \quad \kappa_{HE}$$

Axion Interaction similar to odd parity Lorentz Invariance Violation

Axion Induced Background Bound Charges and Currents

Background Bound Charge

$$\rho_{aB} = g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\vec{\nabla}\cdot(a\vec{B})$$

Background Polarization Current (or Displacement Current)

$$\overrightarrow{P_{aE}} = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}(a\vec{B})$$

$$\vec{J}_{aB} = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\frac{\partial(a\vec{B})}{\partial t} = \frac{\partial\vec{P}_{aB}}{\partial t}$$

$$\nabla\cdot\vec{J}_{aB} = -\frac{\partial\rho_{aB}}{\partial t}$$

Satisfies the Continuity Equation

Axion Modifications as Impressed Sources (Harrington)

$$\vec{E}_T = \frac{1}{\epsilon_r \epsilon_0} \vec{D}_T = \vec{E} + \vec{E}_{aB}, \textbf{ where } \vec{E}_{aB} = -\, g_{a\gamma\gamma} \frac{c}{\epsilon_r} (a \vec{B})$$

$$\vec{B}_T = \mu_r \mu_0 \vec{H}_T = \vec{B} + \vec{B}_{aE}, \textbf{ where } \vec{B}_{aE} = g_{a\gamma\gamma} \frac{\mu_r}{c} (a \vec{E})$$

Axion Modifications as Impressed Sources (Harrington)

$$\vec{E}_T = \frac{1}{\epsilon_r \epsilon_0}\vec{D}_T = \vec{E} + \vec{E}_{aB},\ \textbf{where}\ \vec{E}_{aB} = -\,g_{a\gamma\gamma}\frac{c}{\epsilon_r}(a\vec{B})$$

curl free

$$\vec{B}_T = \mu_r \mu_0 \vec{H}_T = \vec{B} + \vec{B}_{aE},\ \textbf{where}\ \vec{B}_{aE} = g_{a\gamma\gamma}\frac{\mu_r}{c}(a\vec{E})$$

Axion Modifications as Impressed Sources (Harrington)

$$\vec{E}_T = \frac{1}{\epsilon_r \epsilon_0}\vec{D}_T = \vec{E} + \vec{E}_{aB}, \text{ where } \vec{E}_{aB} = -g_{a\gamma\gamma}\frac{c}{\epsilon_r}(a\vec{B})$$

curl free

divergence free or solenoidal

$$\vec{B}_T = \mu_r \mu_0 \vec{H}_T = \vec{B} + \vec{B}_{aE}, \text{ where } \vec{B}_{aE} = g_{a\gamma\gamma}\frac{\mu_r}{c}(a\vec{E})$$

Axion Modifications as Impressed Sources (Harrington)

$$\vec{E}_T = \frac{1}{\epsilon_r \epsilon_0}\vec{D}_T = \vec{E} + \vec{E}_{aB},\ \textbf{where}\ \vec{E}_{aB} = -\,g_{a\gamma\gamma}\frac{c}{\epsilon_r}(a\vec{B})$$

curl free

divergence free or solenoidal

$$\vec{B}_T = \mu_r \mu_0 \vec{H}_T = \vec{B} + \vec{B}_{aE},\ \textbf{where}\ \vec{B}_{aE} = g_{a\gamma\gamma}\frac{\mu_r}{c}(a\vec{E})$$

Axion Modifications as Impressed Sources (Harrington)

$$\vec{E}_T = \frac{1}{\epsilon_r\epsilon_0}\vec{D}_T = \vec{E} + \vec{E}_{aB}, \textbf{ where } \vec{E}_{aB} = -\,g_{a\gamma\gamma}\frac{c}{\epsilon_r}(a\vec{B})$$

curl free

divergence free or solenoidal

$$\vec{B}_T = \mu_r\mu_0\vec{H}_T = \vec{B} + \vec{B}_{aE}, \textbf{ where } \vec{B}_{aE} = g_{a\gamma\gamma}\frac{\mu_r}{c}(a\vec{E})$$

$$\vec{\nabla}\cdot\vec{E}_T = \frac{\rho_f}{\epsilon_r\epsilon_0} \qquad \vec{\nabla}\times\vec{B}_T - \frac{\epsilon_r\mu_r}{c^2}\frac{\partial\vec{E}_T}{\partial t} = \mu_r\mu_0\vec{J}_f$$

Axion Modifications as Impressed Sources (Harrington)

$$\vec{E}_T = \frac{1}{\epsilon_r \epsilon_0}\vec{D}_T = \vec{E} + \vec{E}_{aB}, \text{ where } \vec{E}_{aB} = -g_{a\gamma\gamma}\frac{c}{\epsilon_r}(a\vec{B})$$

curl free

divergence free or solenoidal

$$\vec{B}_T = \mu_r \mu_0 \vec{H}_T = \vec{B} + \vec{B}_{aE}, \text{ where } \vec{B}_{aE} = g_{a\gamma\gamma}\frac{\mu_r}{c}(a\vec{E})$$

$$\vec{\nabla} \cdot \vec{E}_T = \frac{\rho_f}{\epsilon_r \epsilon_0} \qquad \vec{\nabla} \times \vec{B}_T - \frac{\epsilon_r \mu_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_r \mu_0 \vec{J}_f$$

To First Order in $g_{a\gamma\gamma}a$ can Show

Axion Modifications as Impressed Sources (Harrington)

$$\vec{E}_T = \frac{1}{\epsilon_r \epsilon_0}\vec{D}_T = \vec{E} + \vec{E}_{aB}, \textbf{ where } \vec{E}_{aB} = -\, g_{a\gamma\gamma}\frac{c}{\epsilon_r}(a\vec{B})$$

curl free

divergence free or solenoidal

$$\vec{B}_T = \mu_r \mu_0 \vec{H}_T = \vec{B} + \vec{B}_{aE}, \textbf{ where } \vec{B}_{aE} = g_{a\gamma\gamma}\frac{\mu_r}{c}(a\vec{E})$$

$$\vec{\nabla}\cdot\vec{E}_T = \frac{\rho_f}{\epsilon_r \epsilon_0} \qquad \vec{\nabla}\times\vec{B}_T - \frac{\epsilon_r \mu_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_r \mu_0 \vec{J}_f$$

To First Order in $g_{a\gamma\gamma}a$ can Show

$$\vec{B}_T \approx \vec{B} + g_{a\gamma\gamma}\frac{\mu_r}{c}(a\vec{E}_T) \qquad \vec{E}_T \approx \vec{E} - g_{a\gamma\gamma}\frac{c}{\epsilon_r}(a\vec{B}_T)$$

Axion Modifications as Impressed Sources (Harrington)

$$\vec{E}_T = \frac{1}{\epsilon_r \epsilon_0}\vec{D}_T = \vec{E} + \vec{E}_{aB}, \textbf{ where } \vec{E}_{aB} = -g_{a\gamma\gamma}\frac{c}{\epsilon_r}(a\vec{B})$$

curl free

divergence free or solenoidal

$$\vec{B}_T = \mu_r \mu_0 \vec{H}_T = \vec{B} + \vec{B}_{aE}, \textbf{ where } \vec{B}_{aE} = g_{a\gamma\gamma}\frac{\mu_r}{c}(a\vec{E})$$

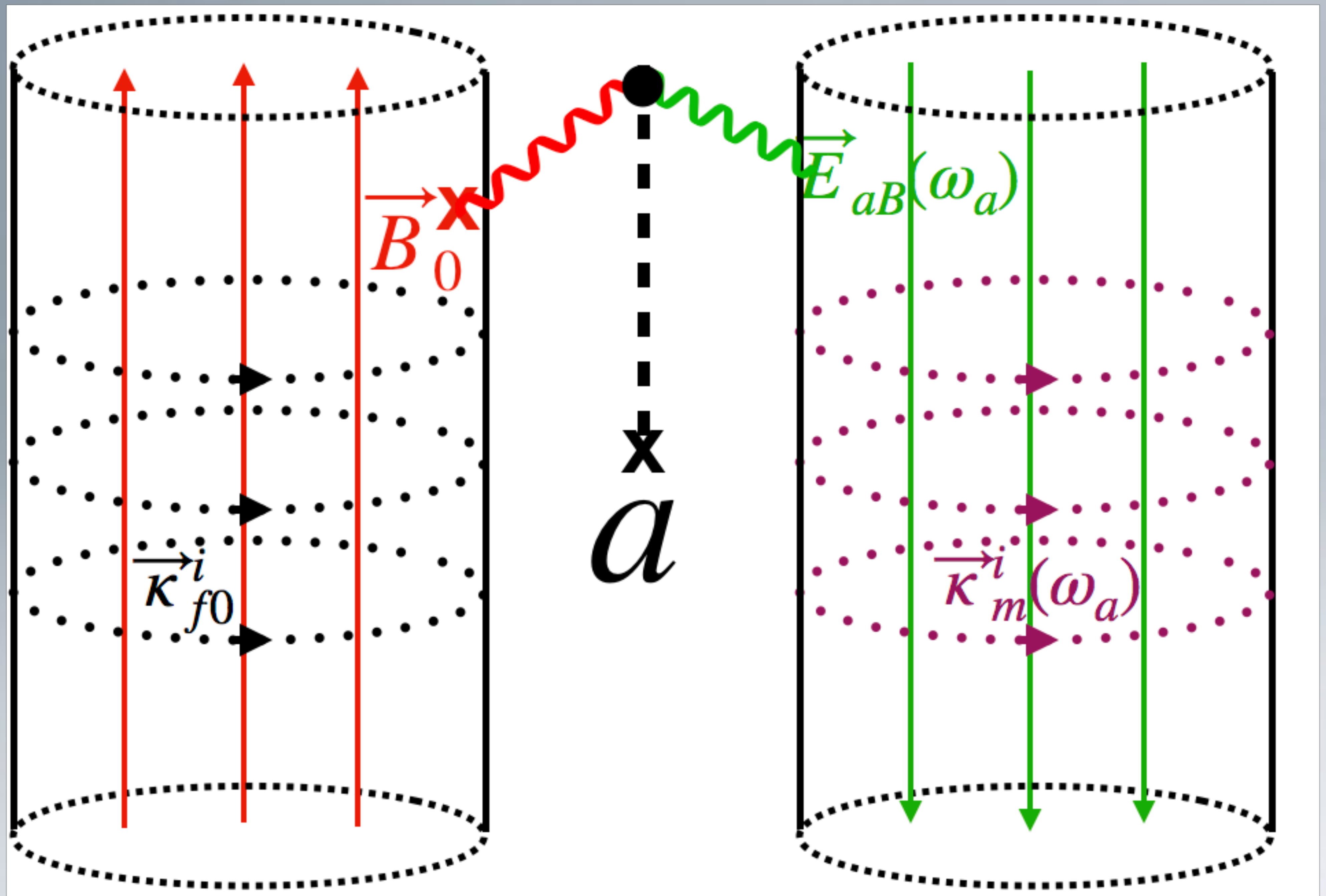
$$\vec{\nabla}\cdot\vec{E}_T = \frac{\rho_f}{\epsilon_r \epsilon_0} \qquad \vec{\nabla}\times\vec{B}_T - \frac{\epsilon_r \mu_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_r \mu_0 \vec{J}_f$$

To First Order in $g_{a\gamma\gamma}a$ can Show

$$\vec{B}_T \approx \vec{B} + g_{a\gamma\gamma}\frac{\mu_r}{c}(a\vec{E}_T) \qquad \vec{E}_T \approx \vec{E} - g_{a\gamma\gamma}\frac{c}{\epsilon_r}(a\vec{B}_T)$$

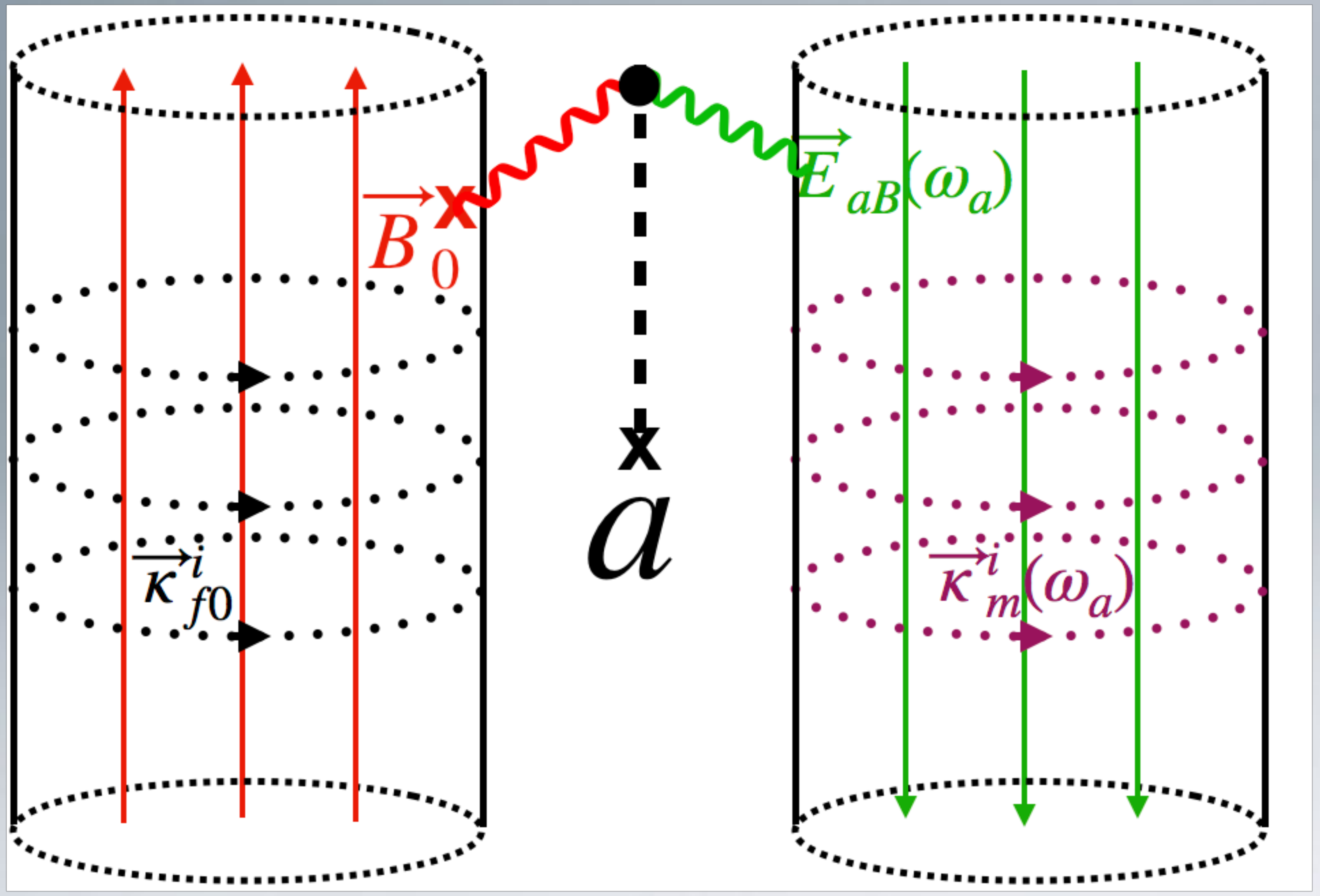
$$\vec{\nabla}\cdot\vec{B}_T = -g_{a\gamma\gamma}a\frac{c}{\epsilon_r}\mu_r\mu_0\rho_f \qquad \vec{\nabla}\times\vec{E}_T + \frac{\partial \vec{B}_T}{\partial t} = -g_{a\gamma\gamma}a\frac{c}{\epsilon_r}\mu_r\mu_0\vec{J}_f$$

Axion Induced Oscillating Sources and Fields under a DC Magnetic field



Axion Induced Oscillating Sources and Fields under a DC Magnetic field

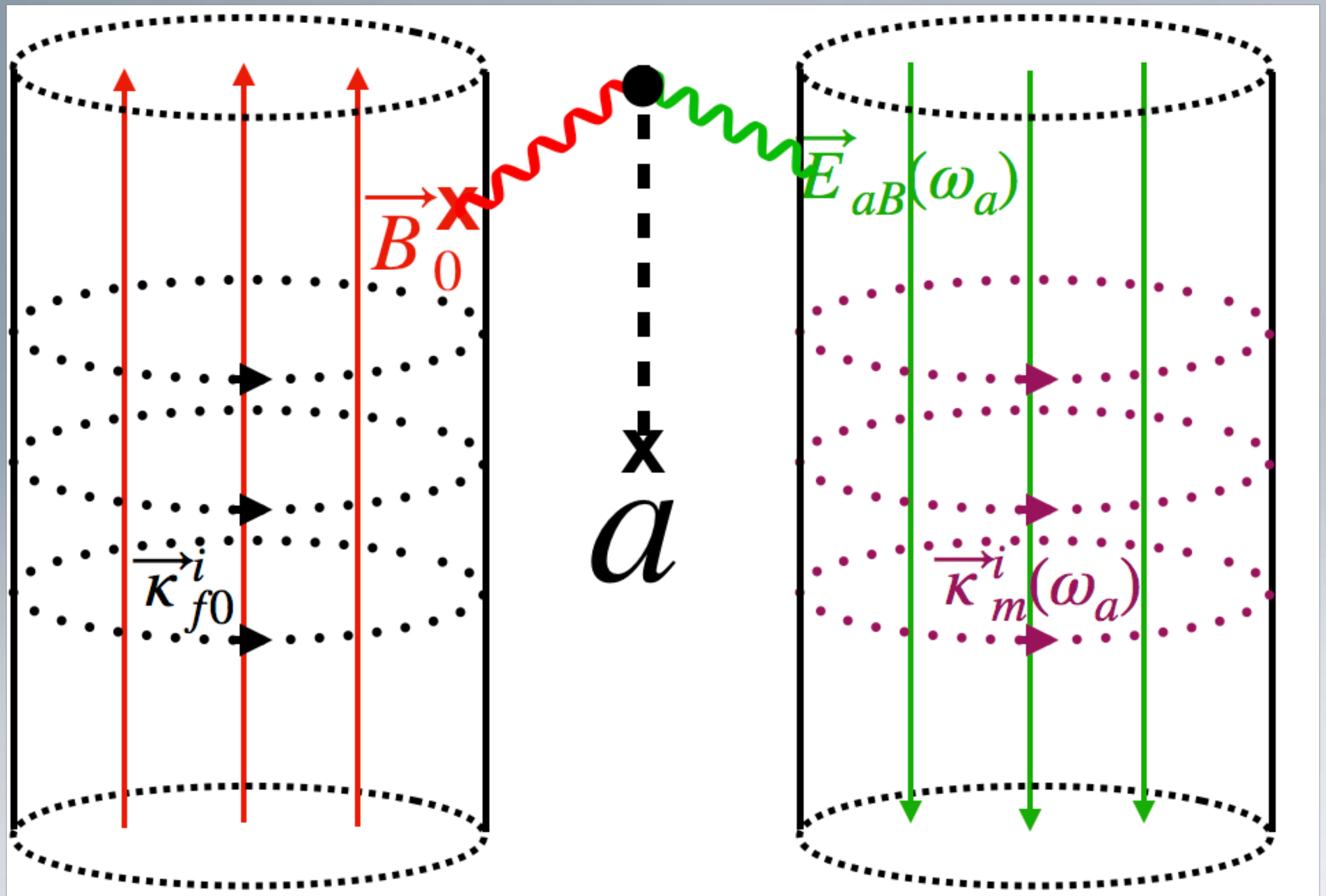
- Assume Lossless Dielectric under a DC Magnetic field $\quad \vec{E} = 0 \;\; \therefore \; \vec{B}_{aE} = 0$



Axion Induced Oscillating Sources and Fields under a DC Magnetic field

- Assume Lossless Dielectric under a DC Magnetic field $\vec{E} = 0 \;\therefore\; \vec{B}_{aE} = 0$

$$\mu_r = 1,\ \rho_f = 0,\ \vec{J}_f = \vec{J}_f^{\,c} + \vec{J}_f^{\,i},\ \vec{J}_f^{\,c} = 0$$

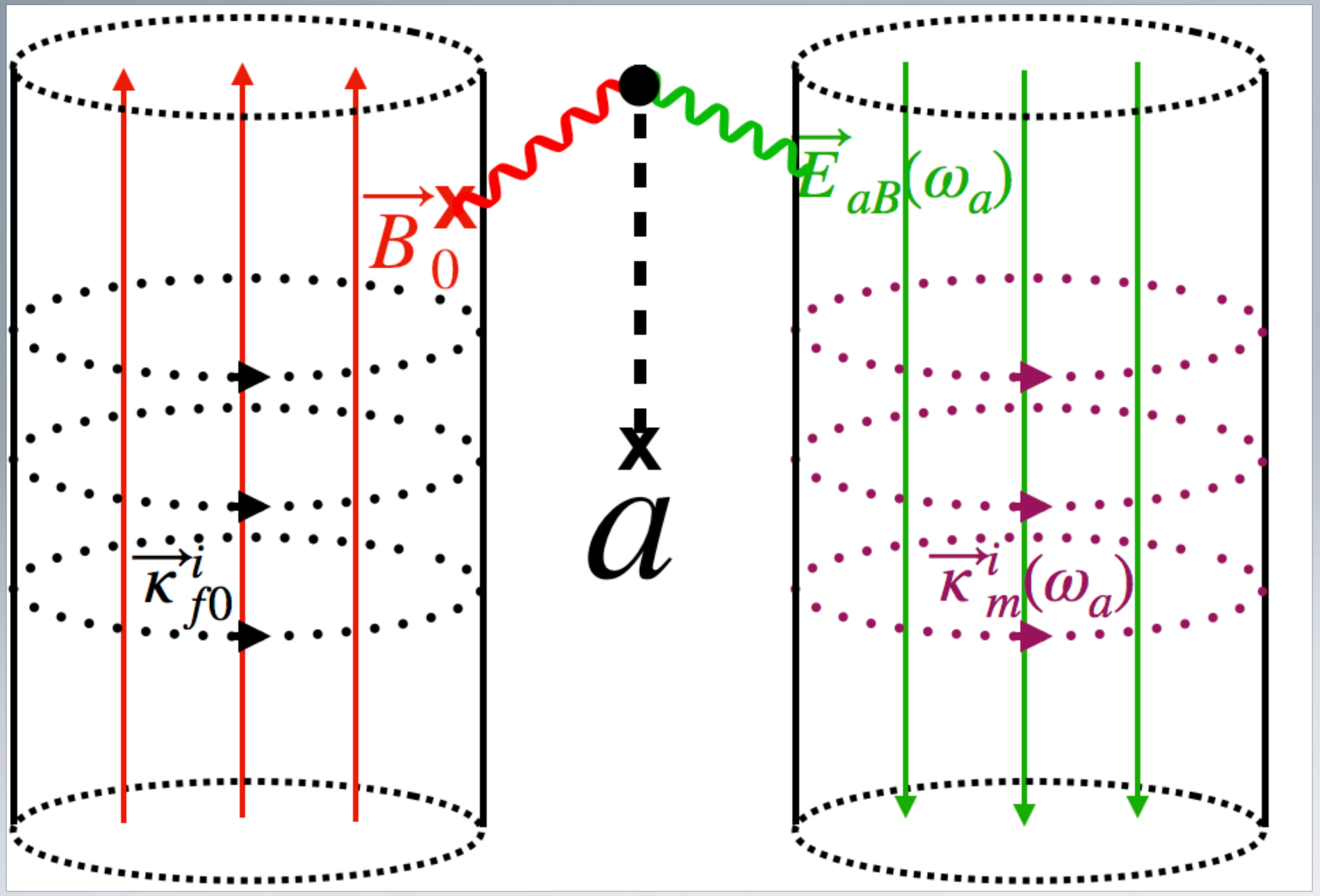


Axion Induced Oscillating Sources and Fields under a DC Magnetic field

- Assume Lossless Dielectric under a DC Magnetic field $\quad \vec{E} = 0 \;\; \therefore \; \vec{B}_{aE} = 0$

$$\mu_r = 1, \; \rho_f = 0, \;\; \vec{J}_f = \vec{J}^{\,c}_f + \vec{J}^{\,i}_f, \;\; \vec{J}^{\,c}_f = 0$$

lossless

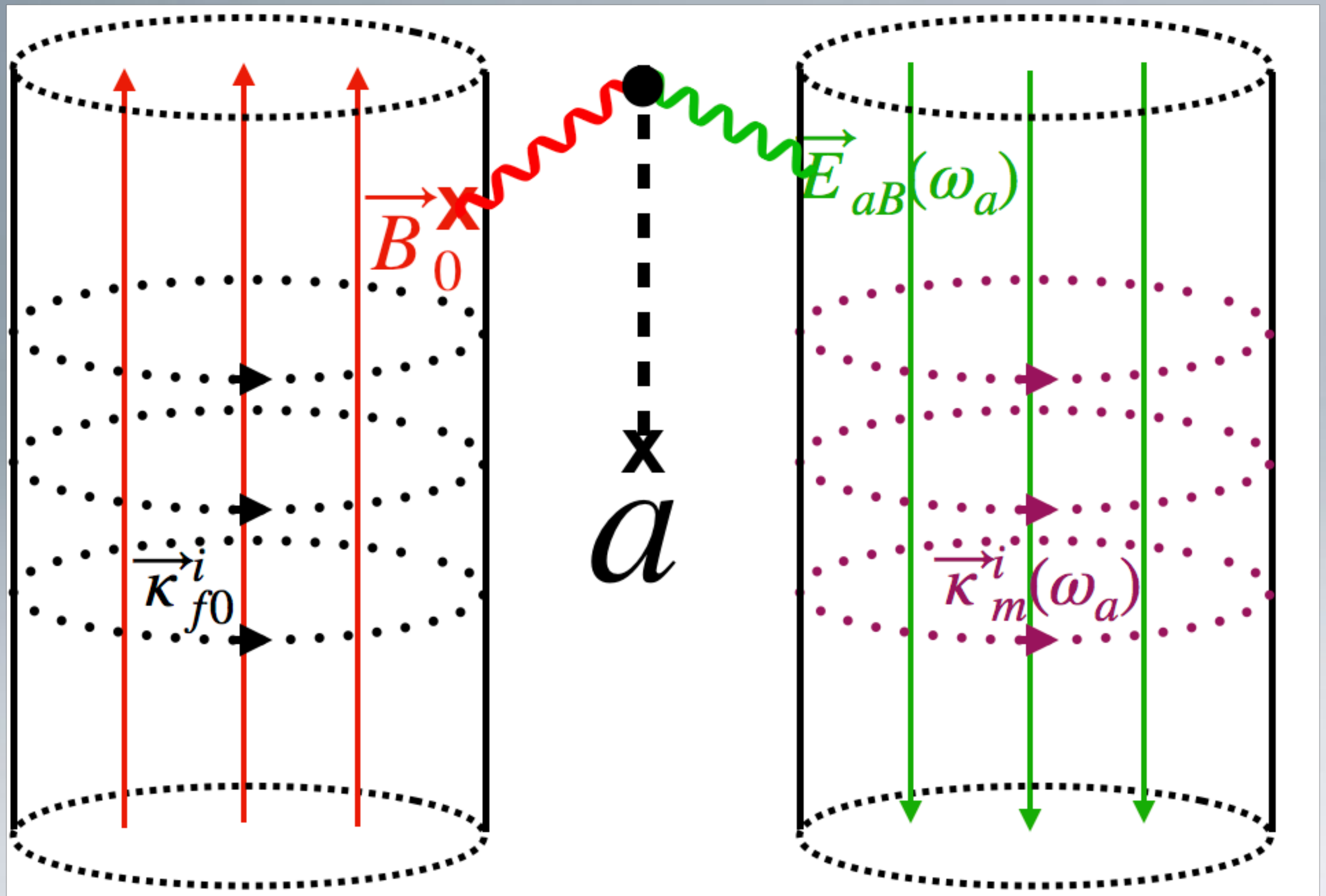


Axion Induced Oscillating Sources and Fields under a DC Magnetic field

- Assume Lossless Dielectric under a DC Magnetic field $\quad \vec{E} = 0 \ \therefore \ \vec{B}_{aE} = 0$

$$\mu_r = 1, \ \underbrace{\rho_f = 0}_{\text{lossless}}, \ \vec{J}_f = \vec{J}^c_f + \vec{J}^i_f, \ \underbrace{\vec{J}^c_f = 0}_{\text{lossless}}$$

- Large Impressed Current to Create DC B-field $\quad \vec{J}_f = \vec{J}^i_f$



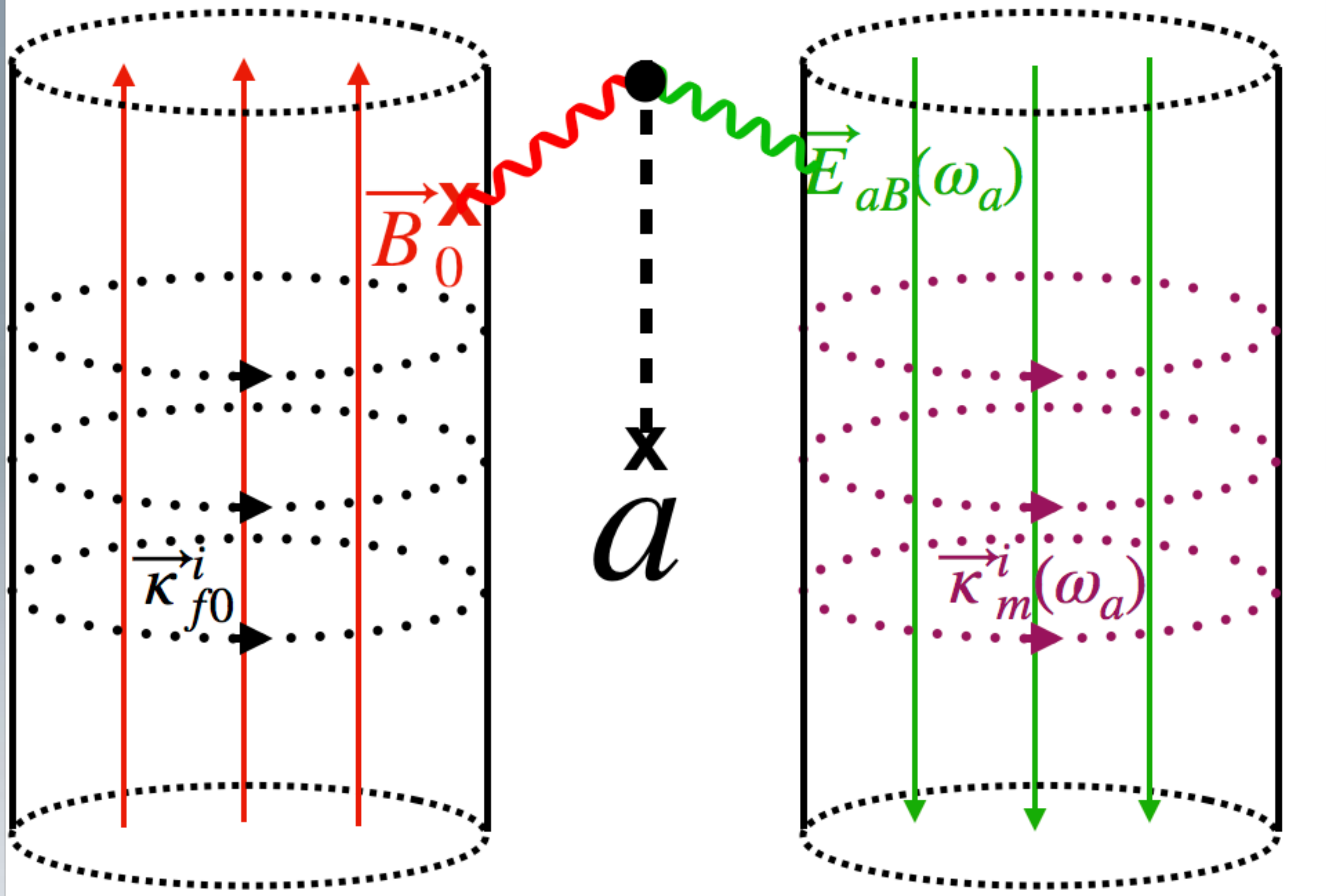
Axion Induced Oscillating Sources and Fields under a DC Magnetic field

- Assume Lossless Dielectric under a DC Magnetic field $\quad \vec{E} = 0 \;\therefore\; \vec{B}_{aE} = 0$

$$\mu_r = 1,\ \rho_f = 0,\ \vec{J}_f = \vec{J}^c_f + \vec{J}^i_f,\ \vec{J}^c_f = 0$$

lossless

- Large Impressed Current to Create DC B-field $\quad \vec{J}_f = \vec{J}^i_f$



$$\vec{\nabla} \cdot \vec{E}_T = 0$$

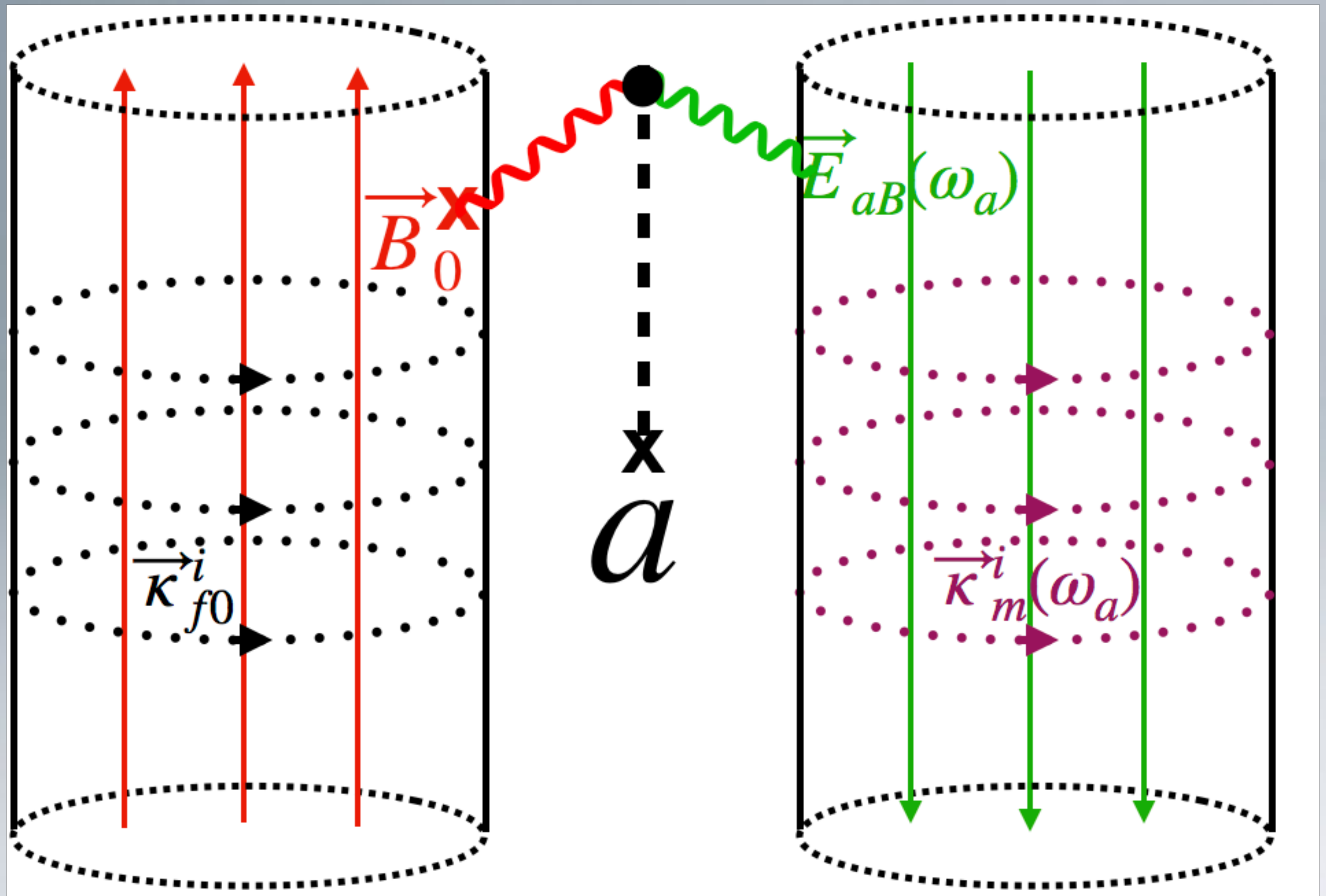
Axion Induced Oscillating Sources and Fields under a DC Magnetic field

- Assume Lossless Dielectric under a DC Magnetic field $\quad \vec{E} = 0 \;\therefore\; \vec{B}_{aE} = 0$

$$\mu_r = 1,\ \rho_f = 0,\ \vec{J}_f = \vec{J}^c_f + \vec{J}^i_f,\ \vec{J}^c_f = 0$$

lossless

- Large Impressed Current to Create DC B-field $\quad \vec{J}_f = \vec{J}^i_f$



$$\vec{\nabla} \cdot \vec{E}_T = 0 \qquad \vec{\nabla} \times \vec{B} - \frac{\epsilon_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_0 \vec{J}^i_{f_0}$$

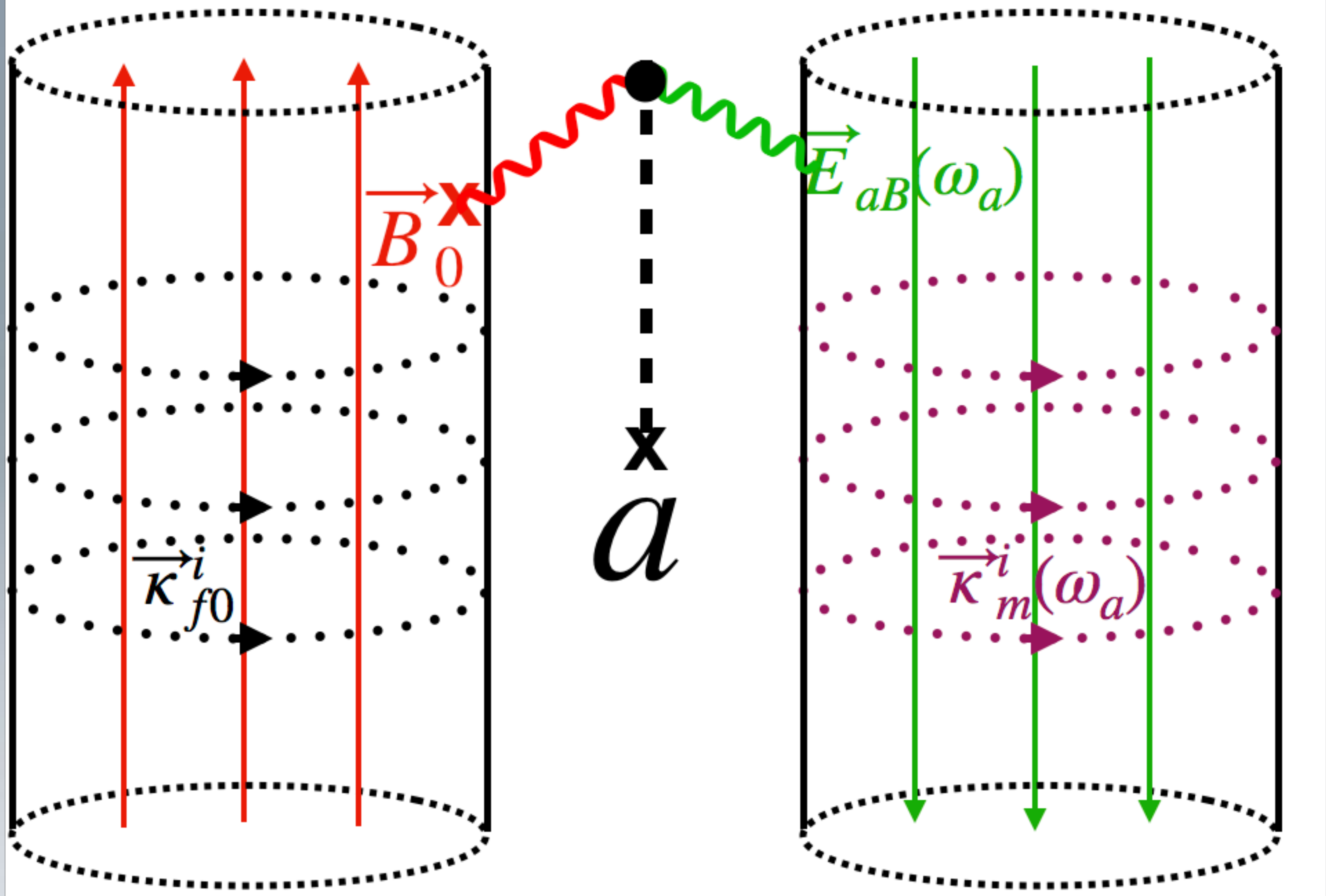
Axion Induced Oscillating Sources and Fields under a DC Magnetic field

- Assume Lossless Dielectric under a DC Magnetic field $\quad \vec{E} = 0 \ \therefore \vec{B}_{aE} = 0$

$$\mu_r = 1,\ \rho_f = 0,\ \vec{J}_f = \vec{J}^c_f + \vec{J}^i_f,\ \vec{J}^c_f = 0$$

lossless

- Large Impressed Current to Create DC B-field $\quad \vec{J}_f = \vec{J}^i_f$



$$\vec{\nabla} \cdot \vec{E}_T = 0 \qquad \vec{\nabla} \times \vec{B} - \frac{\epsilon_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_0 \vec{J}^i_{f0}$$

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

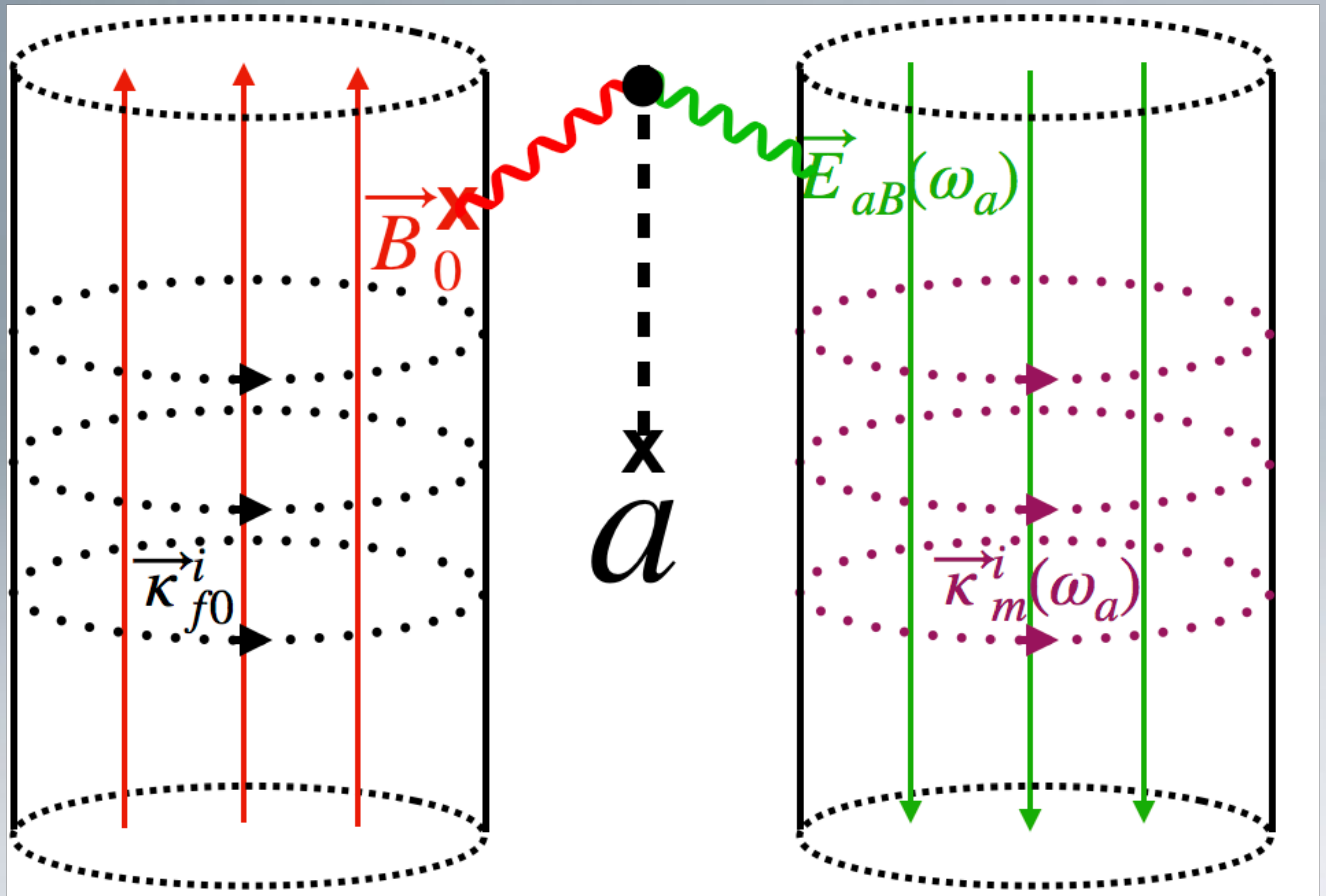
Axion Induced Oscillating Sources and Fields under a DC Magnetic field

- Assume Lossless Dielectric under a DC Magnetic field $\vec{E} = 0 \;\therefore\; \vec{B}_{aE} = 0$

$$\mu_r = 1,\ \rho_f = 0,\ \vec{J}_f = \vec{J}^c_f + \vec{J}^i_f,\ \vec{J}^c_f = 0$$

lossless

- Large Impressed Current to Create DC B-field $\vec{J}_f = \vec{J}^i_f$



$$\vec{\nabla} \cdot \vec{E}_T = 0 \qquad \vec{\nabla} \times \vec{B} - \frac{\epsilon_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_0 \vec{J}^i_{f_0}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{E}_T + \frac{\partial \vec{B}}{\partial t} = -\, g_{a\gamma\gamma} a \frac{c}{\epsilon_r} \mu_0 \vec{J}^i_{f_0} = -\, \vec{J}^i_{ma}$$

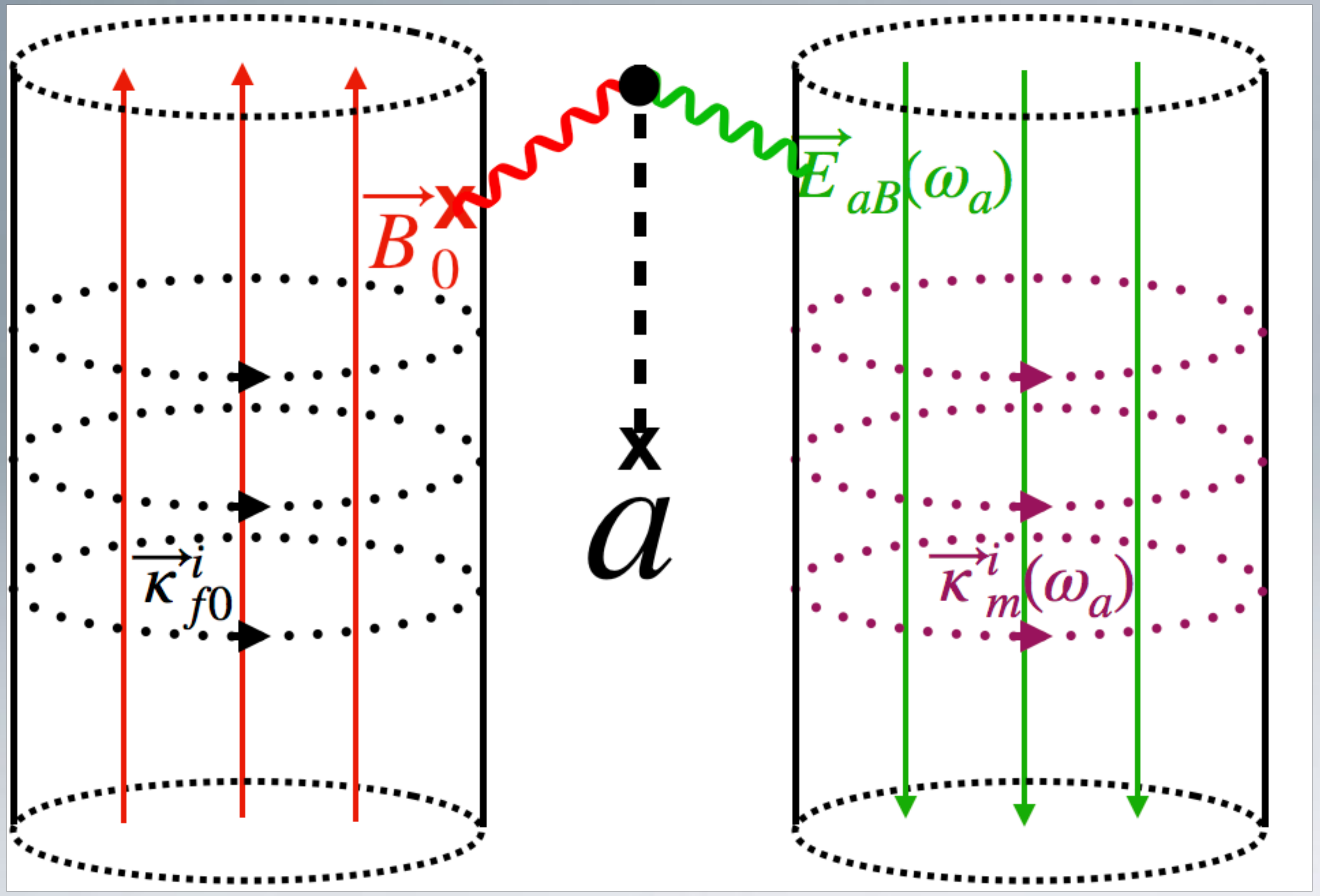
Axion Induced Oscillating Sources and Fields under a DC Magnetic field

- Assume Lossless Dielectric under a DC Magnetic field $\quad \vec{E} = 0 \;\therefore\; \vec{B}_{aE} = 0$

$\mu_r = 1,\ \rho_f = 0,\ \vec{J}_f = \vec{J}_f^c + \vec{J}_f^i,\ \vec{J}_f^c = 0$

lossless

- Large Impressed Current to Create DC B-field $\quad \vec{J}_f = \vec{J}_f^i$



$$\vec{\nabla} \cdot \vec{E}_T = 0 \qquad \vec{\nabla} \times \vec{B} - \frac{\epsilon_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_0 \vec{J}^i_{f_0}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{E}_T + \frac{\partial \vec{B}}{\partial t} = -\, g_{a\gamma\gamma} a \frac{c}{\epsilon_r} \mu_0 \vec{J}^i_{f_0} = -\, \vec{J}^i_{ma}$$

$$\vec{J}^i_{ma} = g_{a\gamma\gamma} a \frac{c}{\epsilon_r} \mu_0 \vec{J}^i_{f_0}$$

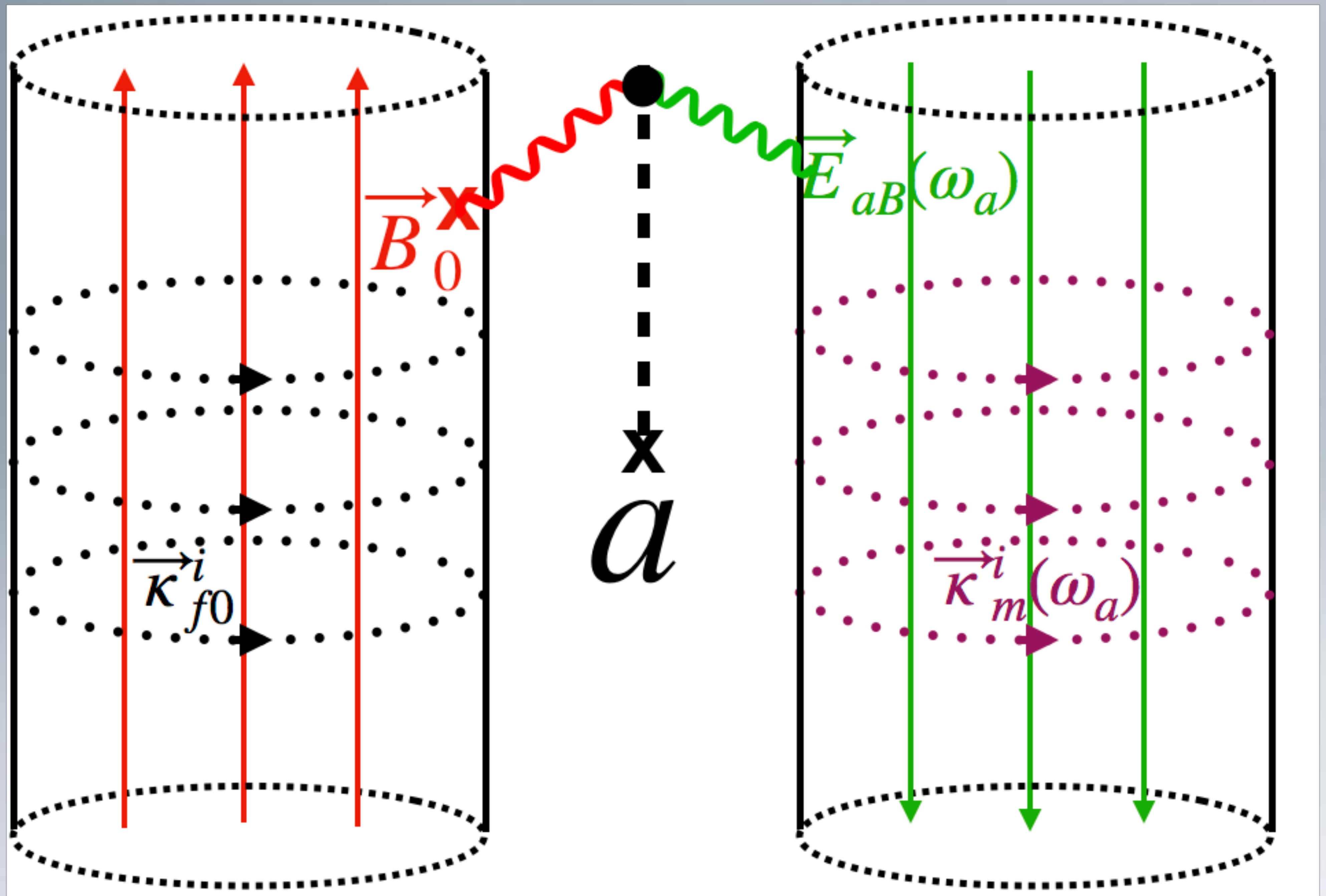
Axion Induced Oscillating Sources and Fields under a DC Magnetic field

- Assume Lossless Dielectric under a DC Magnetic field $\quad \vec{E} = 0 \;\therefore\; \vec{B}_{aE} = 0$

$$\mu_r = 1,\ \rho_f = 0,\ \vec{J}_f = \vec{J}_f^{\,c} + \vec{J}_f^{\,i},\ \vec{J}_f^{\,c} = 0$$

lossless

- Large Impressed Current to Create DC B-field $\quad \vec{J}_f = \vec{J}_f^{\,i}$



$$\vec{\nabla} \cdot \vec{E}_T = 0 \qquad \vec{\nabla} \times \vec{B} - \frac{\epsilon_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_0 \vec{J}^{\,i}_{f_0}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{E}_T + \frac{\partial \vec{B}}{\partial t} = -\,g_{a\gamma\gamma} a \frac{c}{\epsilon_r} \mu_0 \vec{J}^{\,i}_{f_0} = -\,\vec{J}^{\,i}_{ma}$$

$$\vec{J}^{\,i}_{ma} = g_{a\gamma\gamma} a \frac{c}{\epsilon_r} \mu_0 \vec{J}^{\,i}_{f_0}$$

$$\vec{\kappa}^{\,i}_{ma} = g_{a\gamma\gamma} a \frac{c}{\epsilon_r} \mu_0 \vec{\kappa}^{\,i}_{f_0}$$

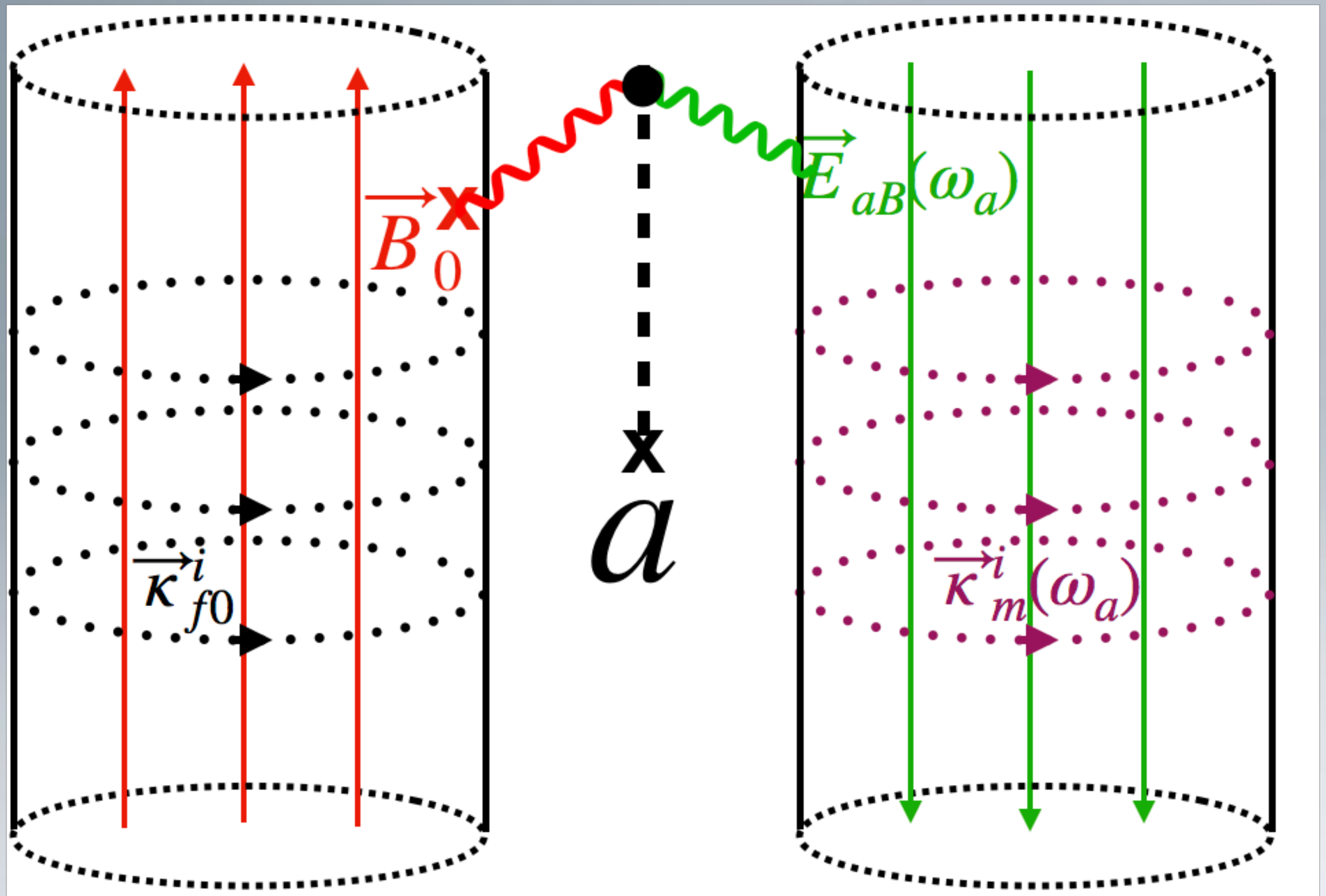
Axion Induced Oscillating Sources and Fields under a DC Magnetic field

- Assume Lossless Dielectric under a DC Magnetic field $\quad \vec{E} = 0 \ \therefore \ \vec{B}_{aE} = 0$

$$\mu_r = 1,\ \rho_f = 0,\ \vec{J}_f = \vec{J}_f^c + \vec{J}_f^i,\ \vec{J}_f^c = 0$$

lossless

- Large Impressed Current to Create DC B-field $\quad \vec{J}_f = \vec{J}_f^i$



$$\vec{\nabla} \cdot \vec{E}_T = 0 \qquad \vec{\nabla} \times \vec{B} - \frac{\epsilon_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_0 \vec{J}_{f_0}^i$$

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{E}_T + \frac{\partial \vec{B}}{\partial t} = -\,g_{a\gamma\gamma} a \frac{c}{\epsilon_r}\mu_0 \vec{J}_{f_0}^i = -\,\vec{J}_{ma}^i$$

$$\vec{J}_{ma}^i = g_{a\gamma\gamma} a \frac{c}{\epsilon_r}\mu_0 \vec{J}_{f_0}^i$$

$$\vec{\kappa}_{ma}^i = g_{a\gamma\gamma} a \frac{c}{\epsilon_r}\mu_0 \vec{\kappa}_{f_0}^i$$

The impressed DC current density induces an impressed magnetic current (or voltage source) oscillating at the axion Compton frequency through the inverse Primakoff effect

Where are the Voltage Sources in Maxwell’s Equations?

Where are the Voltage Sources in Maxwell's Equations?

PHYSICAL REVIEW D **99**, 055010 (2019)

Solutions to axion electrodynamics in various geometries

Jonathan Ouellet* and Zachary Bogorad

Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 27 September 2018; published 12 March 2019)

Where are the Voltage Sources in Maxwell's Equations?

PHYSICAL REVIEW D **99**, 055010 (2019)

Solutions to axion electrodynamics in various geometries

Jonathan Ouellet* and Zachary Bogorad

Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 27 September 2018; published 12 March 2019)

We consider a detector with primary fields driven by a *static* current $\mathbf{J}_e(\mathbf{x})$ and charge distribution $\rho_e(\mathbf{x})$. For example, these can be thought of as currents driving a magnet or producing an electric field and driven externally by a power supply. For simplicity, we calculate only the

Where are the Voltage Sources in Maxwell's Equations?

PHYSICAL REVIEW D **99**, 055010 (2019)

Solutions to axion electrodynamics in various geometries

Jonathan Ouellet* and Zachary Bogorad
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 27 September 2018; published 12 March 2019)

We consider a detector with primary fields driven by a *static* current $\mathbf{J}_e(\mathbf{x})$ and charge distribution $\rho_e(\mathbf{x})$. For example, these can be thought of as currents driving a magnet or producing an electric field and driven externally by a power supply. For simplicity, we calculate only the

Electrodynamics of Driven Currents and Voltages MUST be IMPRESSED into Maxwell's Equation

Where are the Voltage Sources in Maxwell's Equations?

PHYSICAL REVIEW D **99**, 055010 (2019)

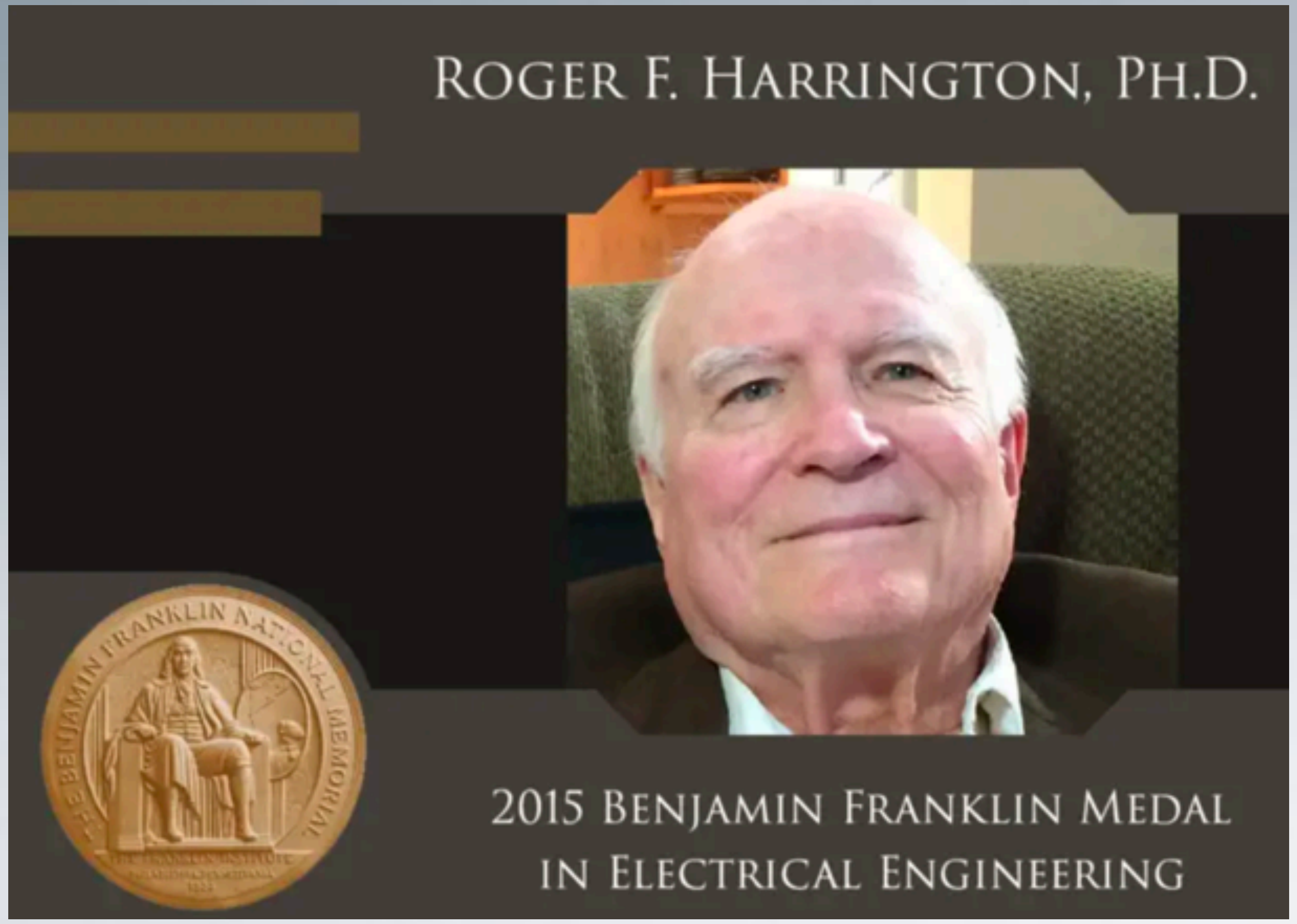
Solutions to axion electrodynamics in various geometries

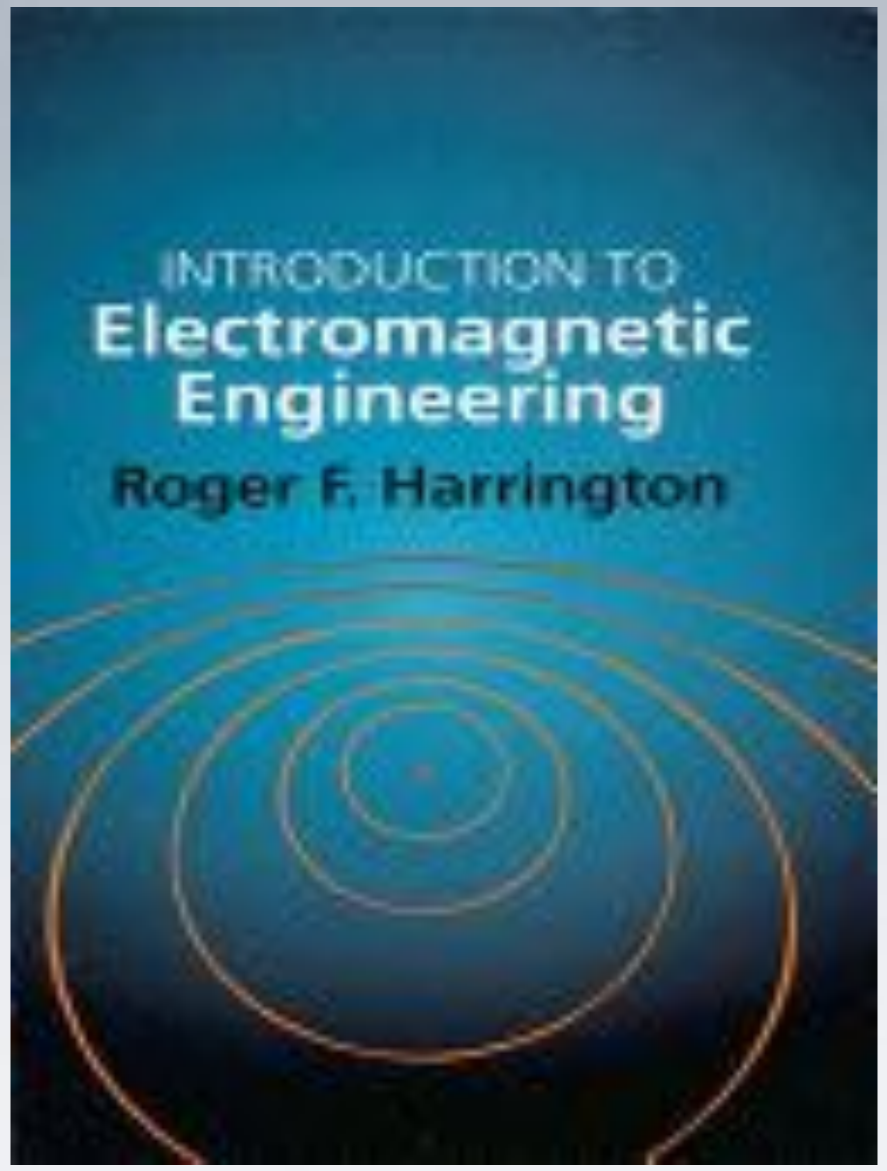
Jonathan Ouellet* and Zachary Bogorad
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 27 September 2018; published 12 March 2019)

We consider a detector with primary fields driven by a *static* current $\mathbf{J}_e(\mathbf{x})$ and charge distribution $\rho_e(\mathbf{x})$. For example, these can be thought of as currents driving a magnet or producing an electric field and driven externally by a power supply. For simplicity, we calculate only the

Electrodynamics of Driven Currents and Voltages MUST be IMPRESSED into Maxwell's Equation





Where are the Voltage Sources in Maxwell's Equations?

PHYSICAL REVIEW D **99,** 055010 (2019)

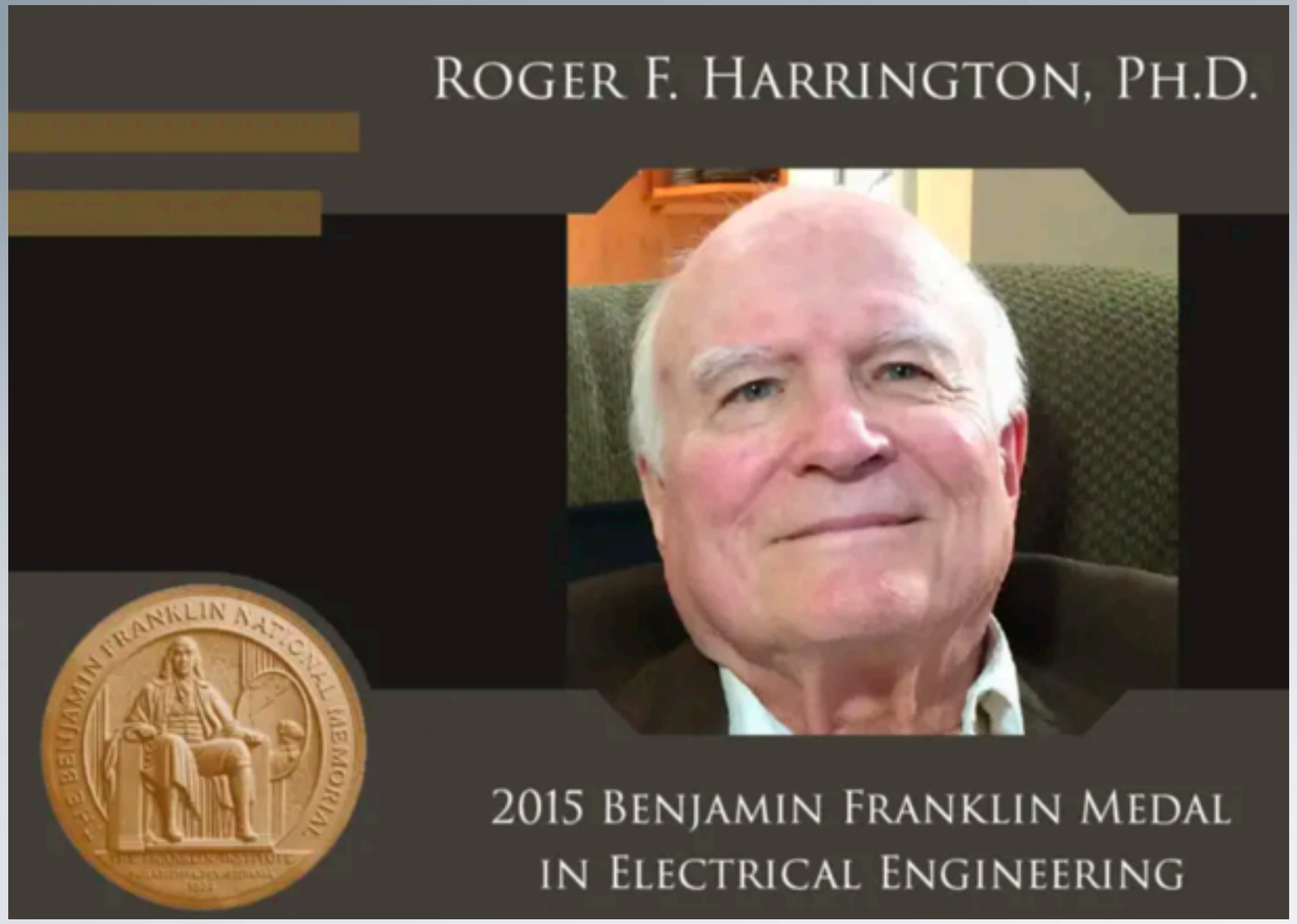
Solutions to axion electrodynamics in various geometries

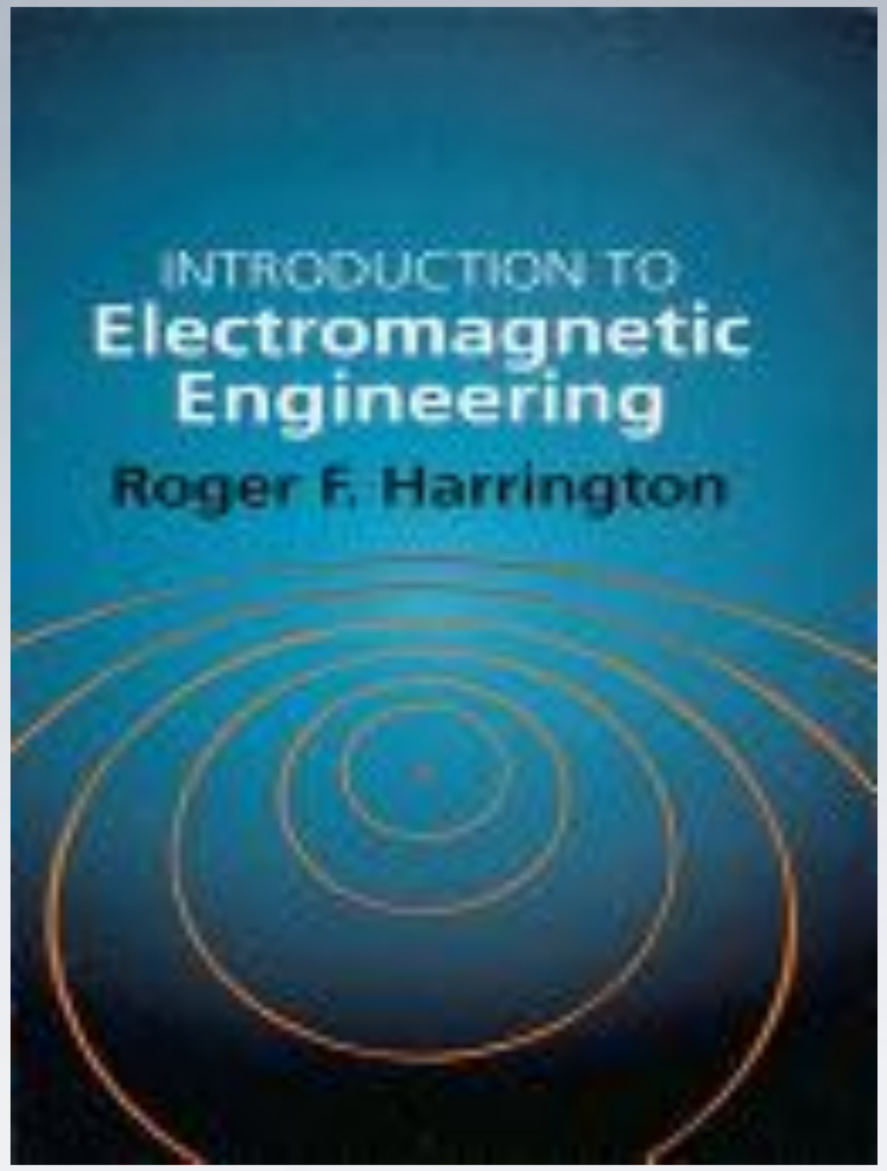
Jonathan Ouellet* and Zachary Bogorad
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

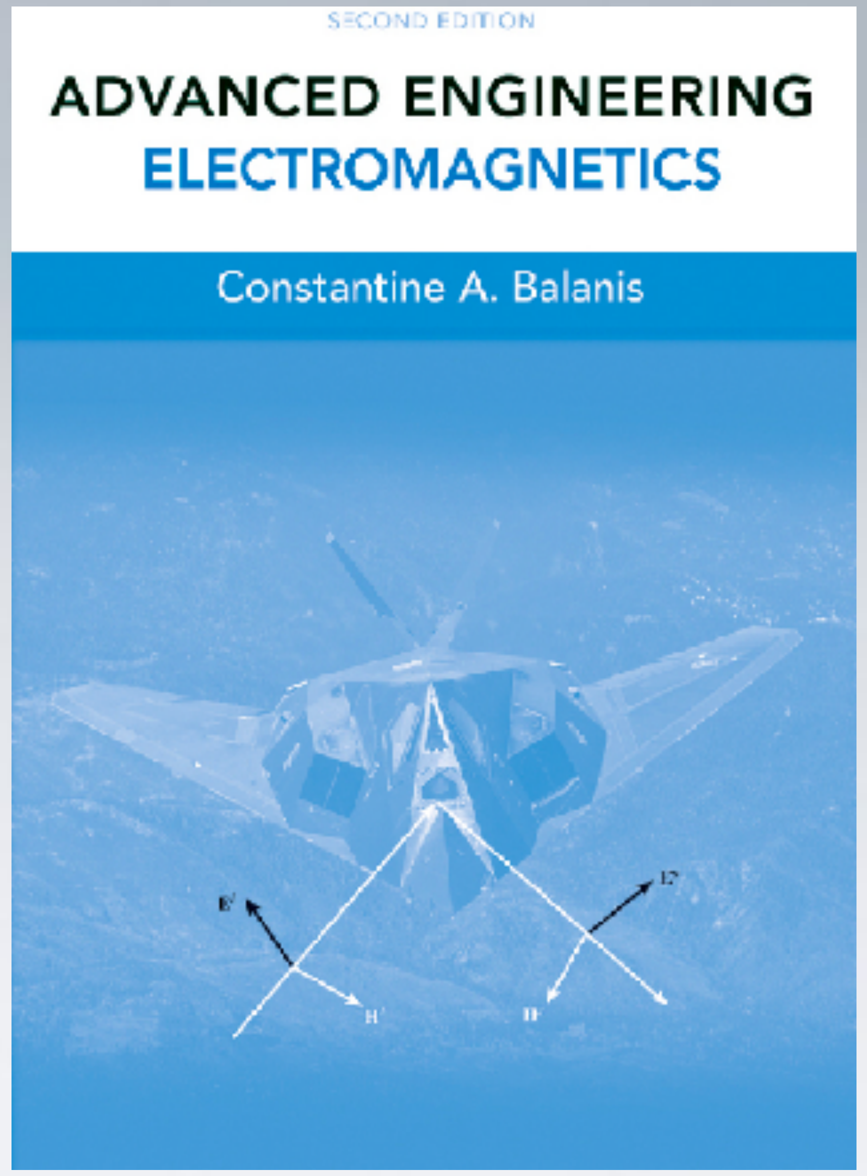
(Received 27 September 2018; published 12 March 2019)

We consider a detector with primary fields driven by a *static* current $\mathbf{J}_e(\mathbf{x})$ and charge distribution $\rho_e(\mathbf{x})$. For example, these can be thought of as currents driving a magnet or producing an electric field and driven externally by a power supply. For simplicity, we calculate only the

Electrodynamics of Driven Currents and Voltages MUST be IMPRESSED into Maxwell's Equation

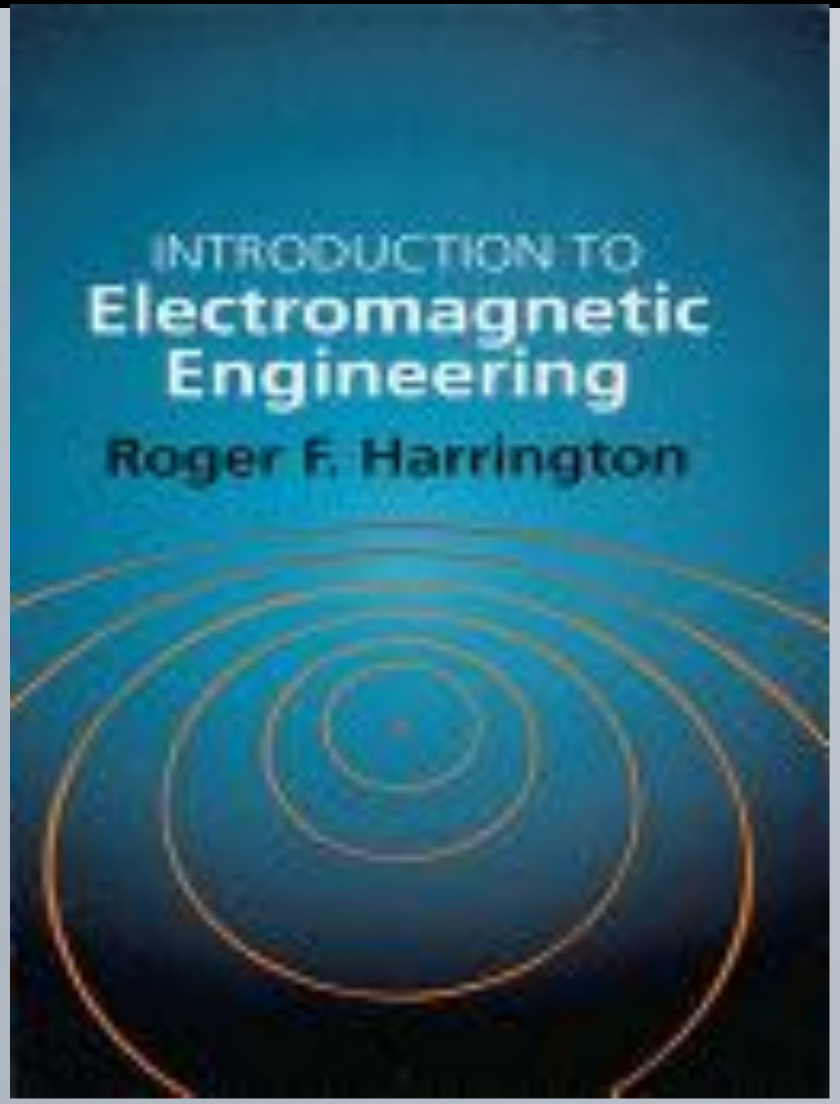




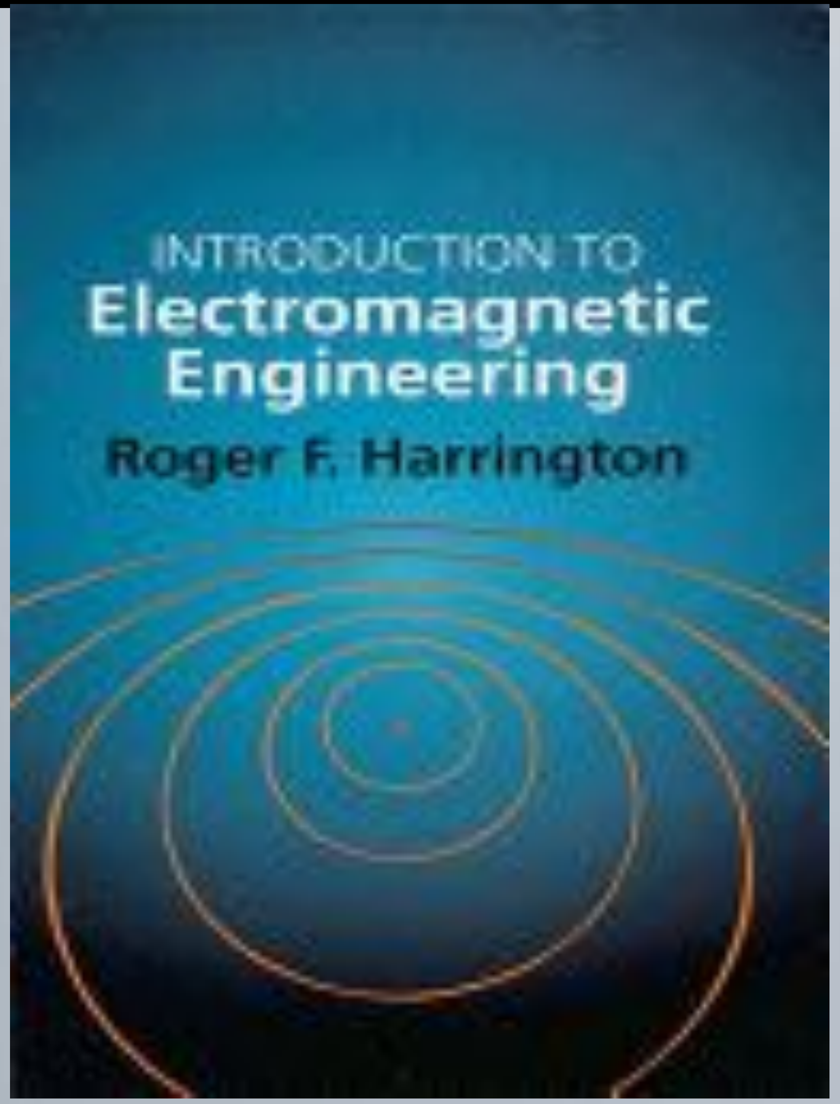


Where are the Voltage Sources in Maxwell’s Equations?

Where are the Voltage Sources in Maxwell’s Equations?

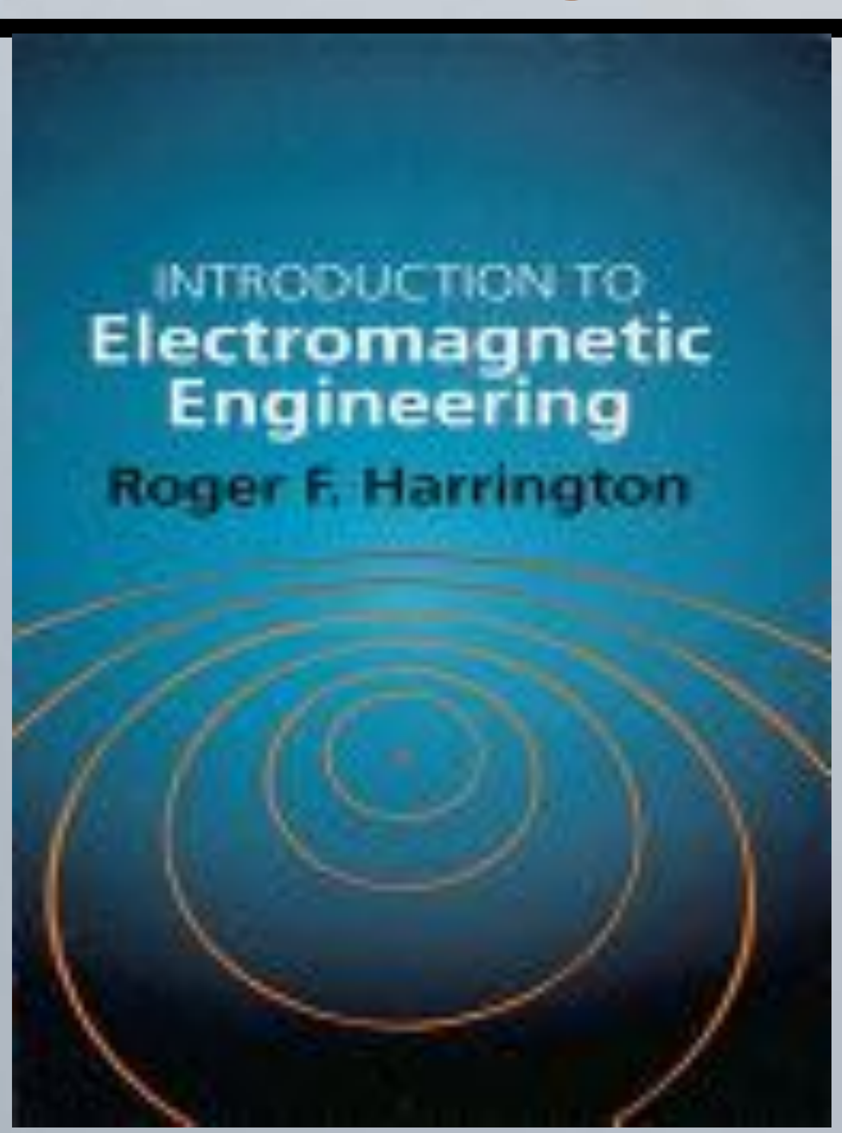


Where are the Voltage Sources in Maxwell's Equations?



Answer is Chapter 10 in Harrington

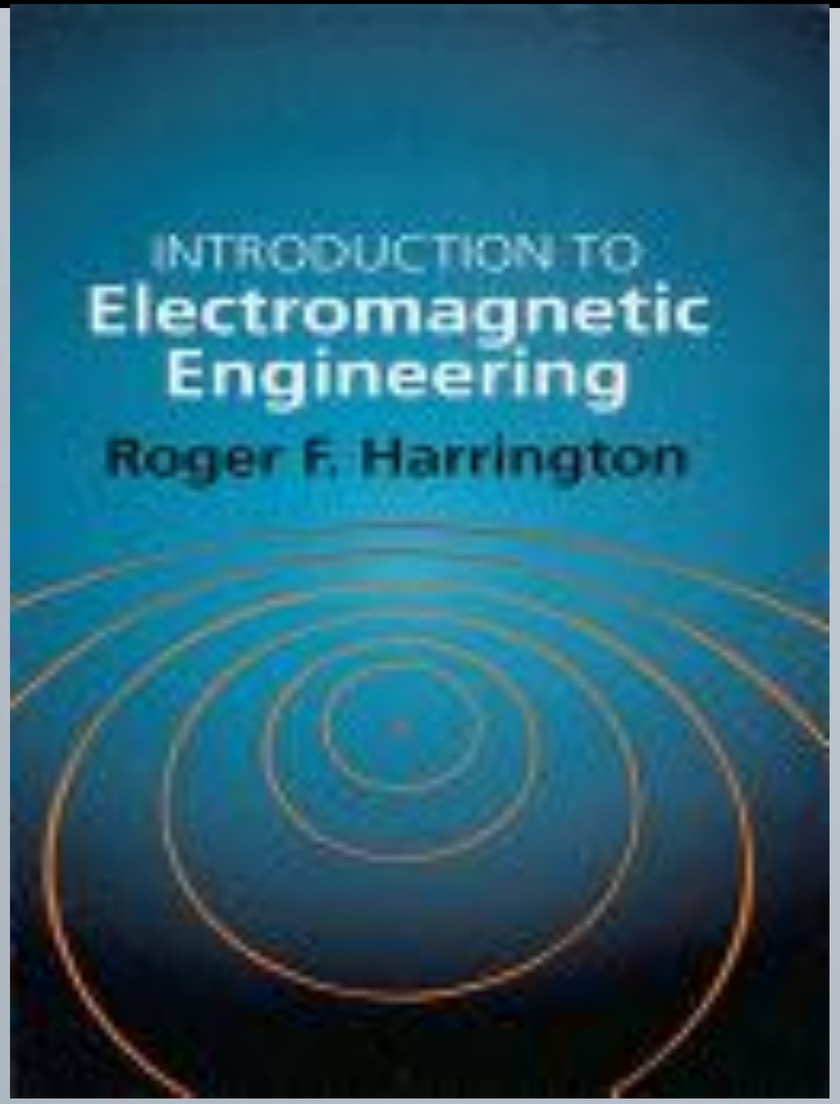
Where are the Voltage Sources in Maxwell's Equations?



Answer is Chapter 10 in Harrington

1. **Total NetCharge in a voltage source = 0**

Where are the Voltage Sources in Maxwell's Equations?



Answer is Chapter 10 in Harrington

1. **Total NetCharge in a voltage source = 0**
2. **Also, if fields drive the charges and currents, and we assume a lossless system -> volume charge and conduction current=0**

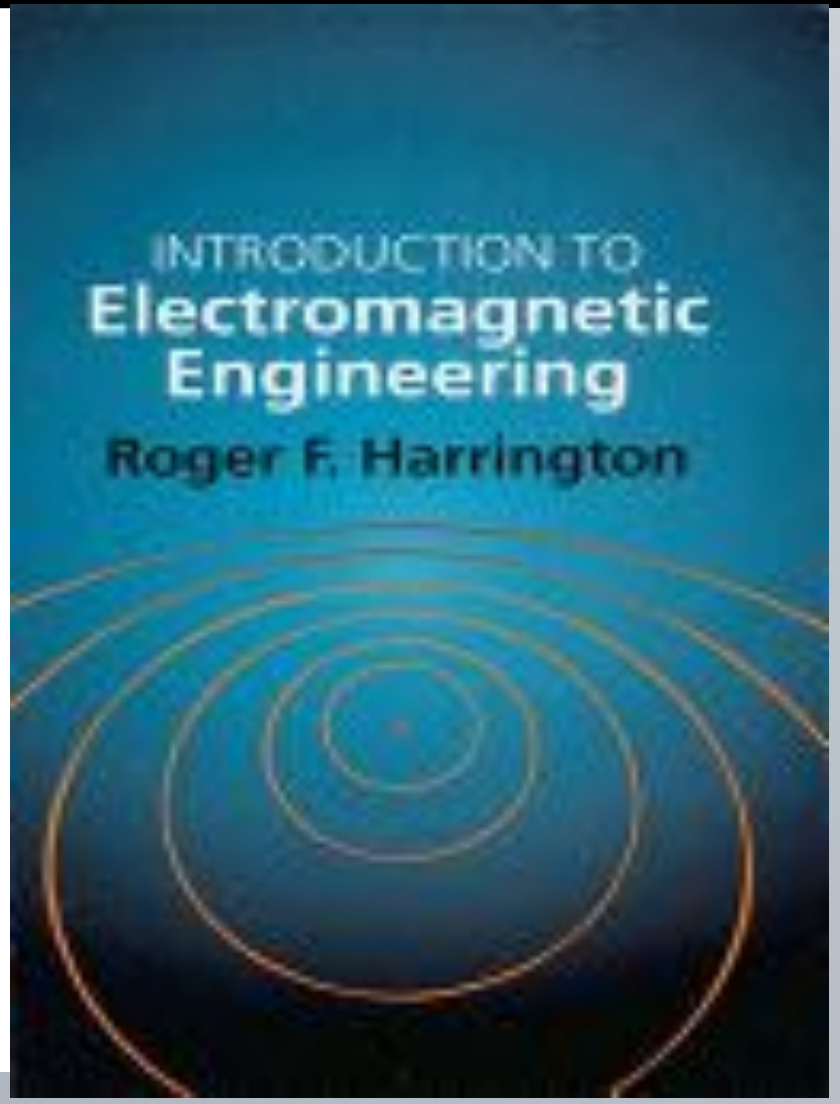
Where are the Voltage Sources in Maxwell's Equations?

$$\vec{\nabla} \cdot \vec{D} = \rho_f,$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}_f + \mu_0 \frac{\partial \vec{D}}{\partial t},$$

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

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



Answer is Chapter 10 in Harrington

1. **Total NetCharge in a voltage source = 0**

2. **Also, if fields drive the charges and currents, and we assume a lossless system -> volume charge and conduction current=0**

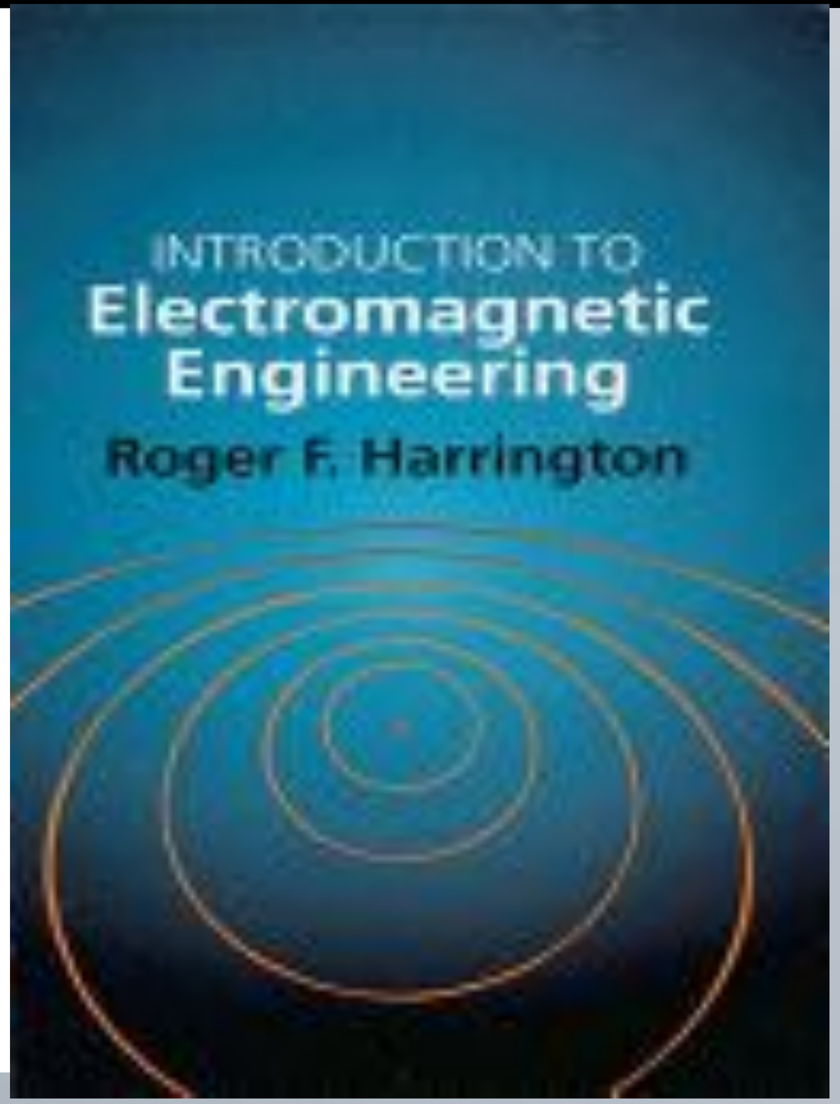
Where are the Voltage Sources in Maxwell's Equations?

$$\vec{\nabla} \cdot \vec{D} = \rho_f,$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}_f + \mu_0 \frac{\partial \vec{D}}{\partial t},$$

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

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



Answer is Chapter 10 in Harrington

1. **Total NetCharge in a voltage source = 0**

2. **Also, if fields drive the charges and currents, and we assume a lossless system -> volume charge and conduction current=0**

$$\rho_f = 0, \ \overrightarrow{J}_f = \overrightarrow{J}_f^c = 0$$

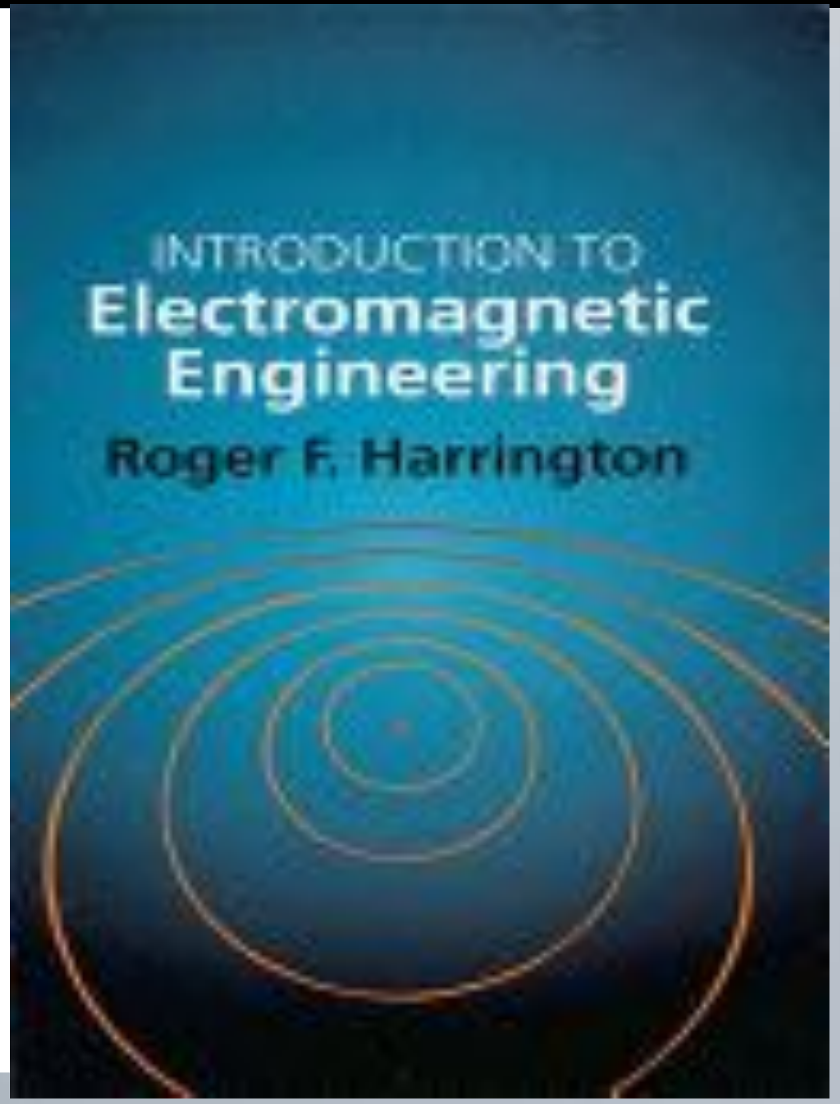
Where are the Voltage Sources in Maxwell’s Equations?

$$\vec{\nabla} \cdot \vec{D} = \rho_f,$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}_f + \mu_0 \frac{\partial \vec{D}}{\partial t},$$

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

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



Answer is Chapter 10 in Harrington

1. **Total NetCharge in a voltage source = 0**

2. **Also, if fields drive the charges and currents, and we assume a lossless system -> volume charge and conduction current=0**

$$\rho_f = 0, \ \overrightarrow{J}_f = \overrightarrow{J}_f^c = 0$$

*** When Fields drive charges and currents -> loss terms (Energy Flows Out of System as Heat)**

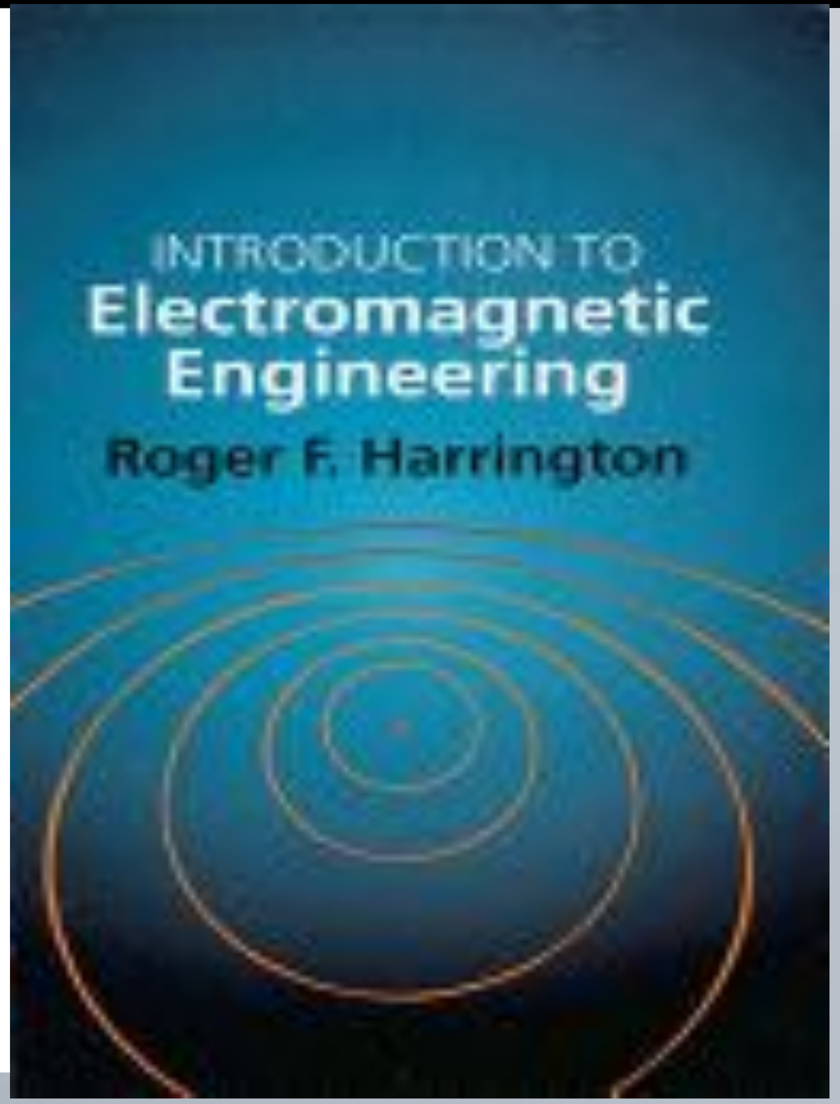
Where are the Voltage Sources in Maxwell’s Equations?

$$\vec{\nabla}\cdot\vec{D} = \rho_f,$$

$$\vec{\nabla}\times\vec{B} = \mu_0\vec{J}_f + \mu_0\frac{\partial\vec{D}}{\partial t},$$

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

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



Answer is Chapter 10 in Harrington

1. **Total NetCharge in a voltage source = 0**

2. **Also, if fields drive the charges and currents, and we assume a lossless system -> volume charge and conduction current=0**

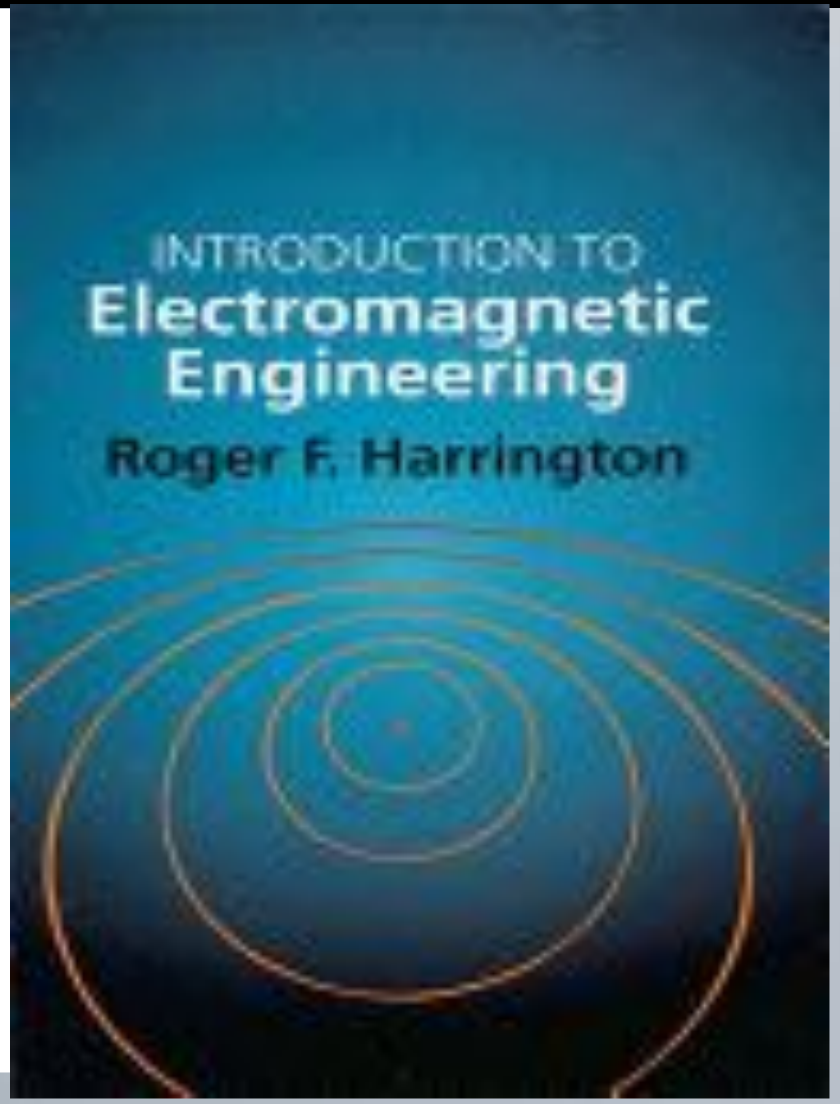
$$\rho_f = 0,\ \overrightarrow{J}_f = \overrightarrow{J}_f^{c} = 0$$

*** When Fields drive charges and currents -> loss terms (Energy Flows Out of System as Heat)**

*** When sources drive fields -> must be impressed into Maxwell’s Equations as excitations (Energy flows Into the system converted from another energy source)**

Where are the Voltage Sources in Maxwell's Equations?

$$\vec{\nabla} \cdot \vec{D} = \rho_f,$$
$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}_f + \mu_0 \frac{\partial \vec{D}}{\partial t},$$
$$\vec{\nabla} \cdot \vec{B} = 0,$$
$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}.$$



Answer is Chapter 10 in Harrington

1. **Total NetCharge in a voltage source = 0**
2. **Also, if fields drive the charges and currents, and we assume a lossless system -> volume charge and conduction current=0**

$$\rho_f = 0, \ \overrightarrow{J}_f = \overrightarrow{J}_f^{c} = 0$$

* **When Fields drive charges and currents -> loss terms (Energy Flows Out of System as Heat)**

* **When sources drive fields -> must be impressed into Maxwell's Equations as excitations (Energy flows Into the system converted from another energy source)**

* **To impress a current source - obvious we do it in Ampere's Law**

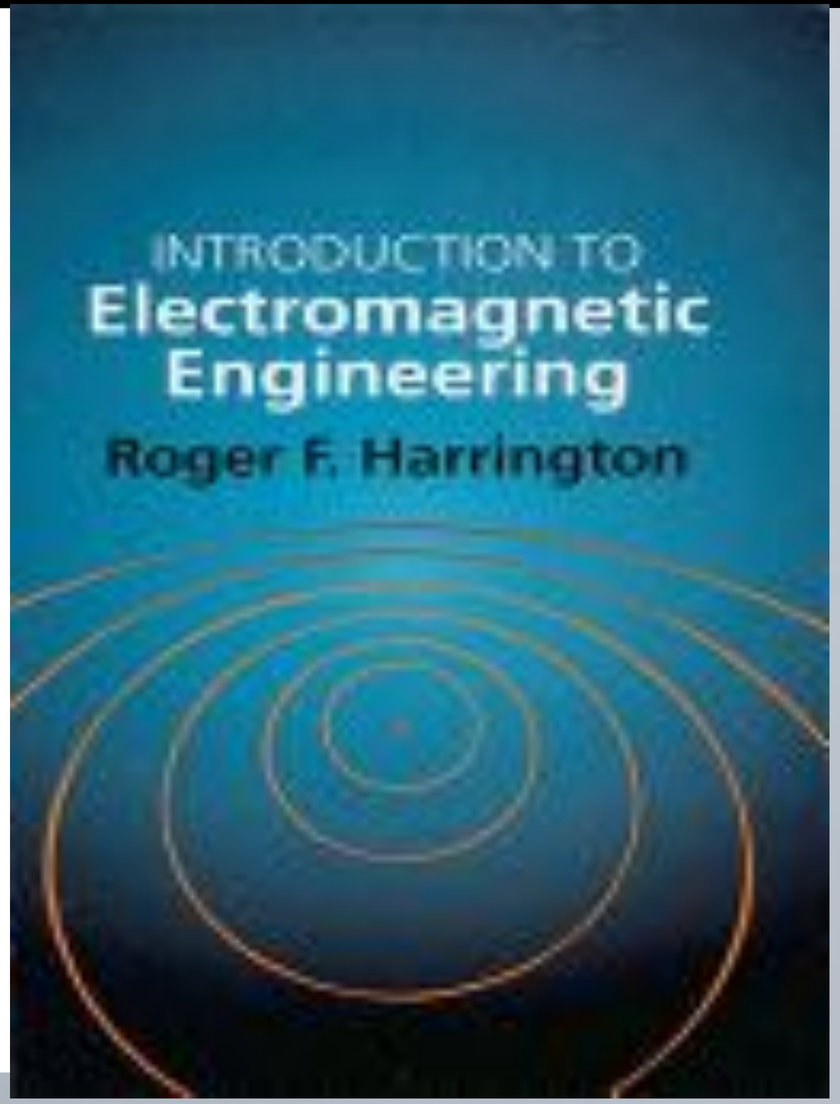
Where are the Voltage Sources in Maxwell's Equations?

$$\vec{\nabla}\cdot\vec{D} = \rho_f,$$

$$\vec{\nabla}\times\vec{B} = \mu_0\vec{J}_f + \mu_0\frac{\partial\vec{D}}{\partial t},$$

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

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



Answer is Chapter 10 in Harrington

1. **Total NetCharge in a voltage source = 0**

2. **Also, if fields drive the charges and currents, and we assume a lossless system -> volume charge and conduction current=0**

$$\rho_f = 0,\ \overrightarrow{J}_f = \overrightarrow{J}_f^{\,c} = 0$$

*** When Fields drive charges and currents -> loss terms (Energy Flows Out of System as Heat)**

*** When sources drive fields -> must be impressed into Maxwell's Equations as excitations (Energy flows Into the system converted from another energy source)**

*** To impress a current source - obvious we do it in Ampere's Law**

*** To impress a voltage source we do NOT use Gauss' Law**

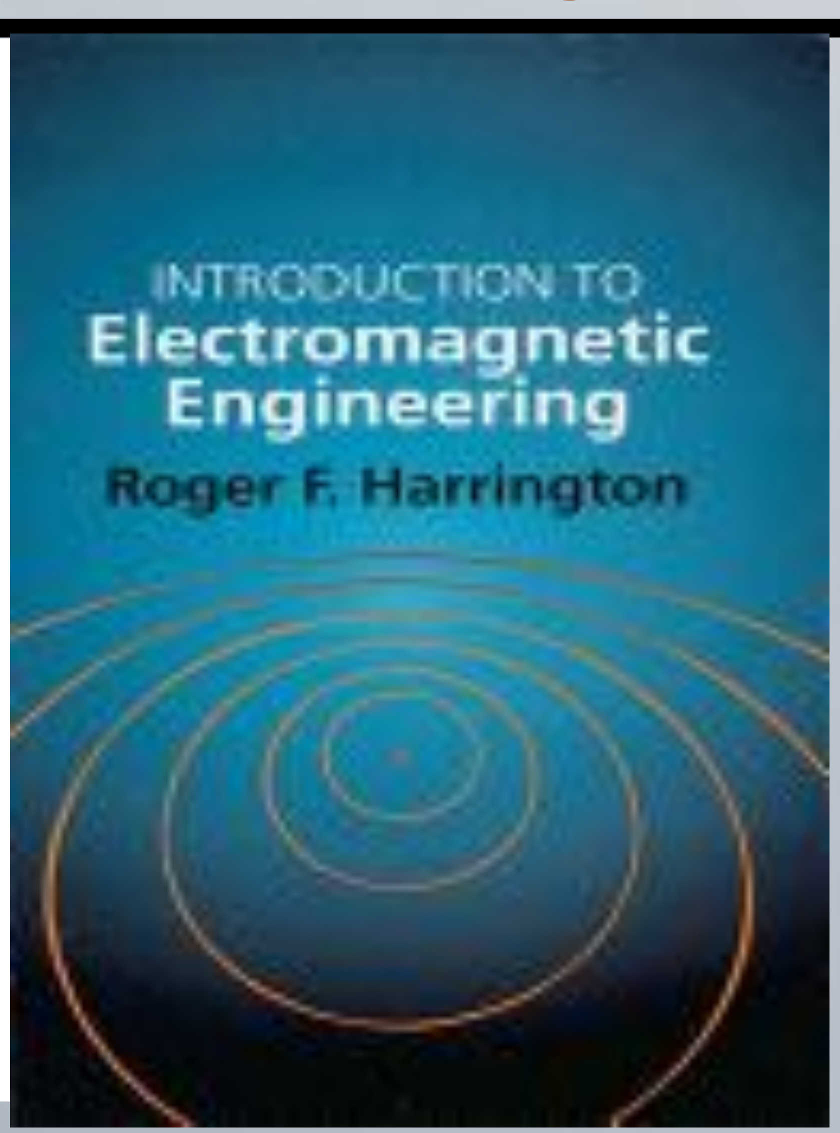
Where are the Voltage Sources in Maxwell's Equations?

$$\vec{\nabla} \cdot \vec{D} = \rho_f,$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}_f + \mu_0 \frac{\partial \vec{D}}{\partial t},$$

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

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



Answer is Chapter 10 in Harrington

1. **Total NetCharge in a voltage source = 0**
2. **Also, if fields drive the charges and currents, and we assume a lossless system -> volume charge and conduction current=0**

$$\rho_f = 0, \ \overrightarrow{J}_f = \overrightarrow{J}_f^c = 0$$

*** When Fields drive charges and currents -> loss terms (Energy Flows Out of System as Heat)**

*** When sources drive fields -> must be impressed into Maxwell's Equations as excitations (Energy flows Into the system converted from another energy source)**

*** To impress a current source - obvious we do it in Ampere's Law**

*** To impress a voltage source we do NOT use Gauss' Law**

*** A voltage source has a zero net charge and generates a non-conservative E-field, the ideal voltage source is modelled as a Magnetic Current in Faraday's Law**

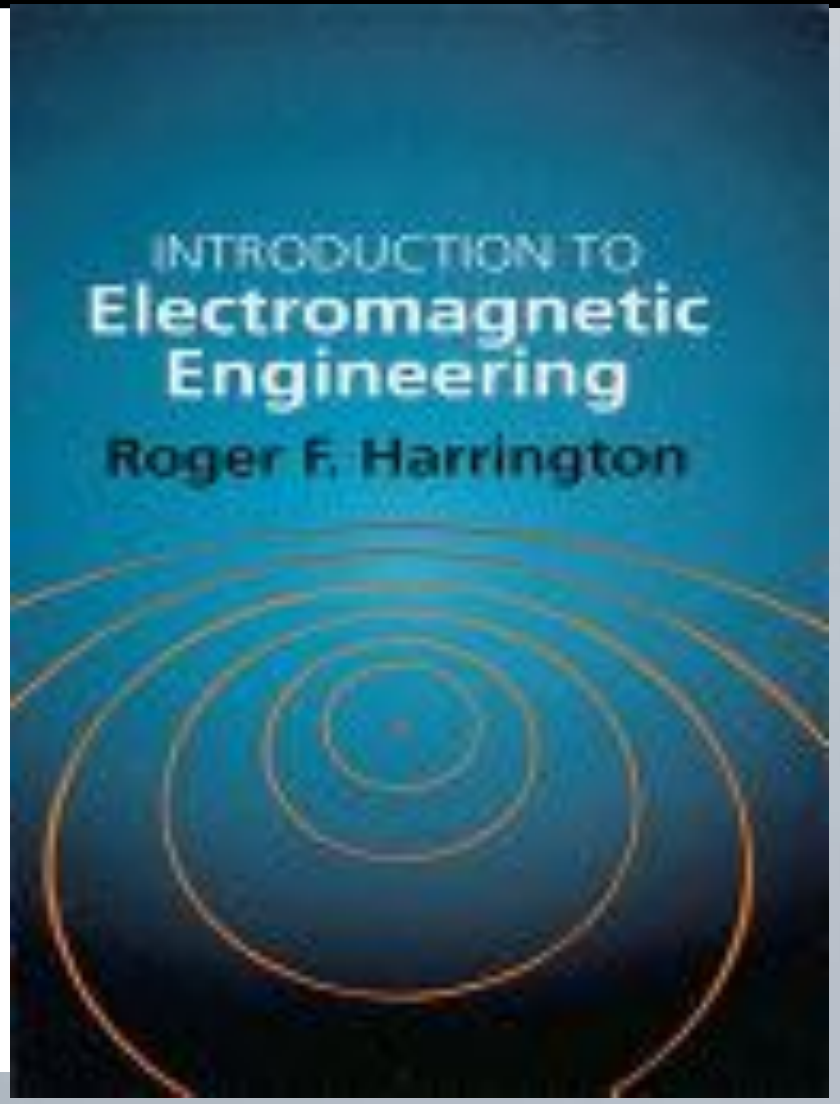
Where are the Voltage Sources in Maxwell's Equations?

$$\vec{\nabla} \cdot \vec{D} = \rho_f,$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}_f + \mu_0 \frac{\partial \vec{D}}{\partial t},$$

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

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



Answer is Chapter 10 in Harrington

1. **Total NetCharge in a voltage source = 0**
2. **Also, if fields drive the charges and currents, and we assume a lossless system -> volume charge and conduction current=0**

$$\rho_f = 0, \ \overrightarrow{J}_f = \overrightarrow{J}_f^c = 0$$

* **When Fields drive charges and currents -> loss terms (Energy Flows Out of System as Heat)**

* **When sources drive fields -> must be impressed into Maxwell's Equations as excitations (Energy flows Into the system converted from another energy source)**

* **To impress a current source - obvious we do it in Ampere's Law** $\overrightarrow{J}_f = \overrightarrow{J}_e$

* **To impress a voltage source we do NOT use Gauss' Law**

* **A voltage source has a zero net charge and generates a non-conservative E-field, the ideal voltage source is modelled as a Magnetic Current in Faraday's Law**

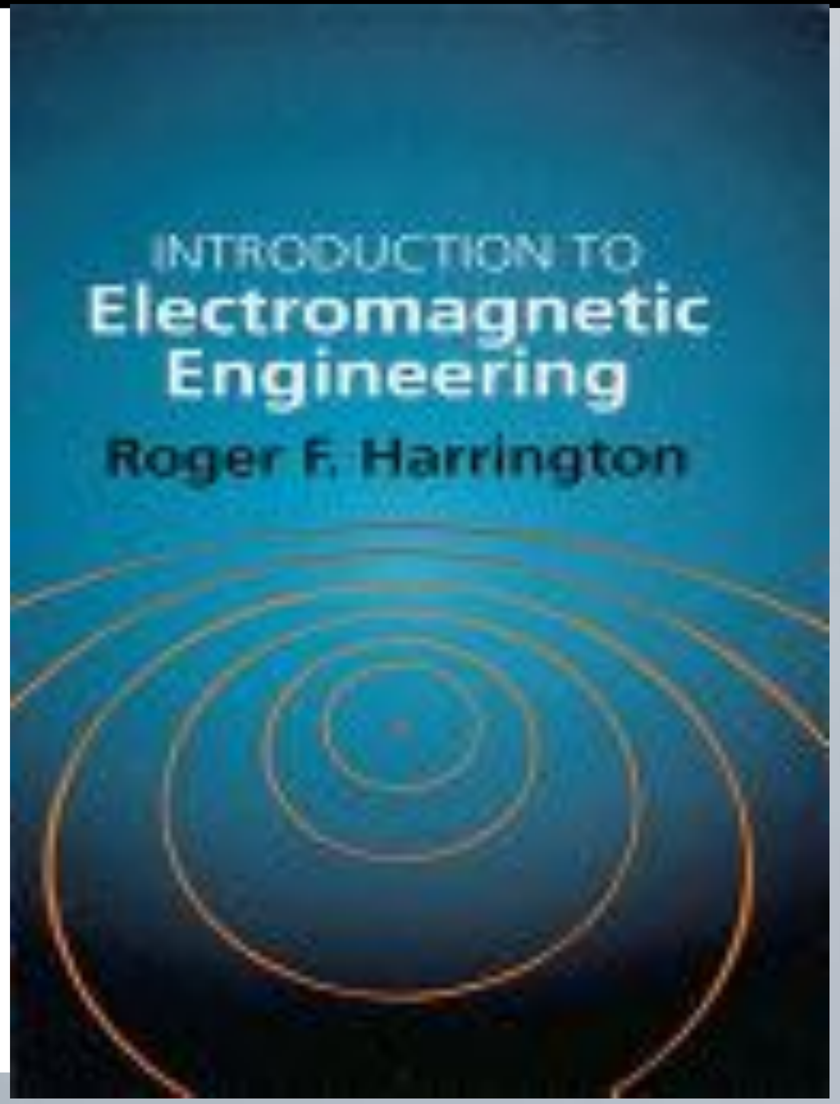
Where are the Voltage Sources in Maxwell's Equations?

$$\vec{\nabla} \cdot \vec{D} = \rho_f,$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}_f + \mu_0 \frac{\partial \vec{D}}{\partial t},$$

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

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



Answer is Chapter 10 in Harrington

1. **Total NetCharge in a voltage source = 0**

2. **Also, if fields drive the charges and currents, and we assume a lossless system -> volume charge and conduction current=0**

$$\rho_f = 0, \ \overrightarrow{J}_f = \overrightarrow{J}_f^c = 0$$

* **When Fields drive charges and currents -> loss terms (Energy Flows Out of System as Heat)**

* **When sources drive fields -> must be impressed into Maxwell's Equations as excitations (Energy flows Into the system converted from another energy source)**

* **To impress a current source - obvious we do it in Ampere's Law** $\overrightarrow{J}_f = \overrightarrow{J}_e$

* **To impress a voltage source we do NOT use Gauss' Law** $\rho_f = 0$

* **A voltage source has a zero net charge and generates a non-conservative E-field, the ideal voltage source is modelled as a Magnetic Current in Faraday's Law**

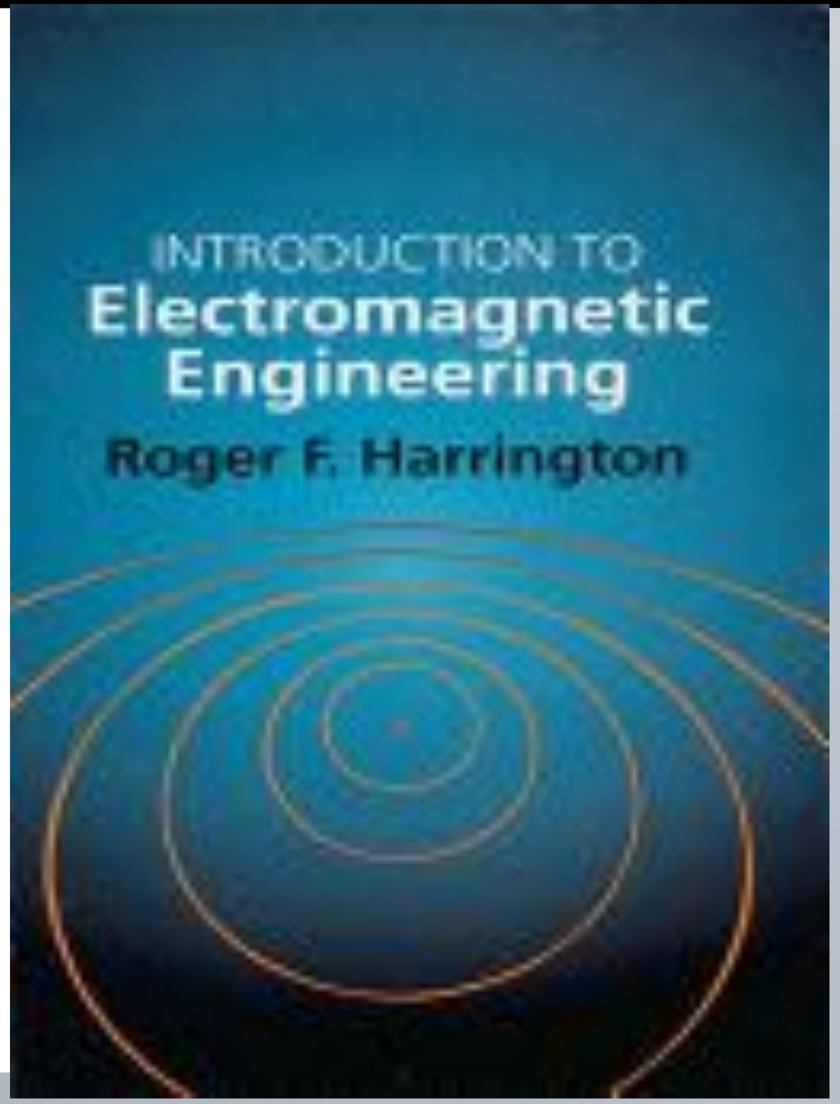
Where are the Voltage Sources in Maxwell's Equations?

$$\vec{\nabla} \cdot \vec{D} = \rho_f,$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}_f + \mu_0 \frac{\partial \vec{D}}{\partial t},$$

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

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}. - \vec{J}_m$$



Answer is Chapter 10 in Harrington

1. **Total NetCharge in a voltage source = 0**
2. **Also, if fields drive the charges and currents, and we assume a lossless system -> volume charge and conduction current=0**

$$\rho_f = 0, \ \vec{J}_f = \vec{J}_f^{\,c} = 0$$

* **When Fields drive charges and currents -> loss terms (Energy Flows Out of System as Heat)**

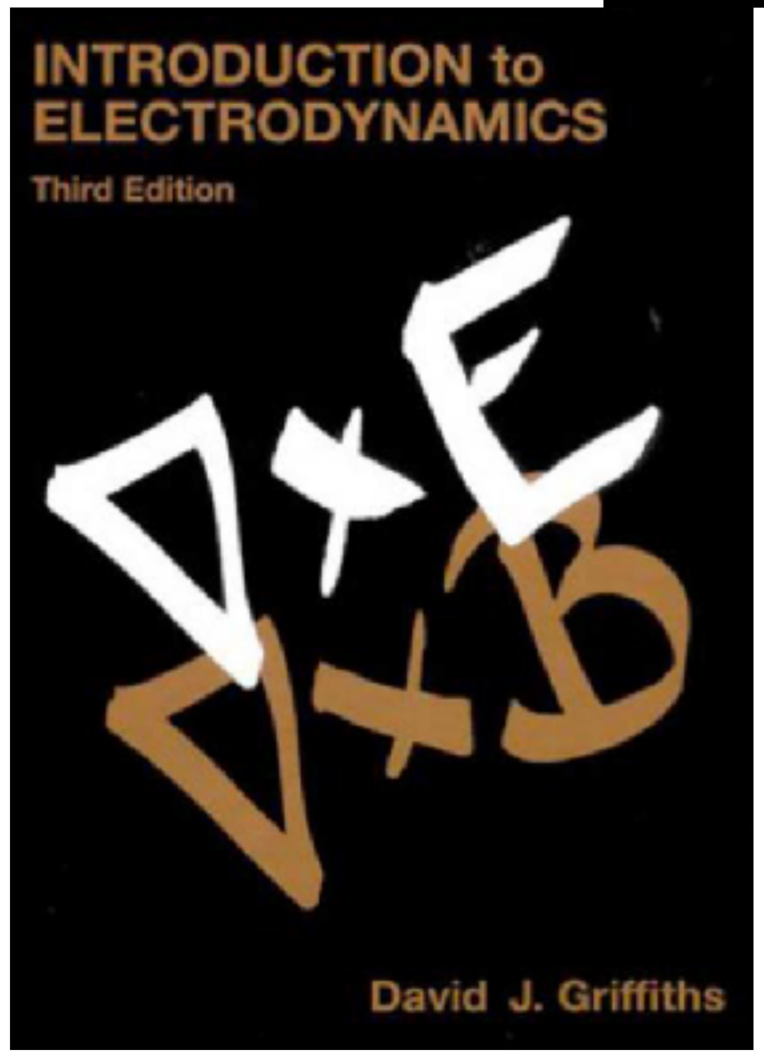
* **When sources drive fields -> must be impressed into Maxwell's Equations as excitations (Energy flows Into the system converted from another energy source)**

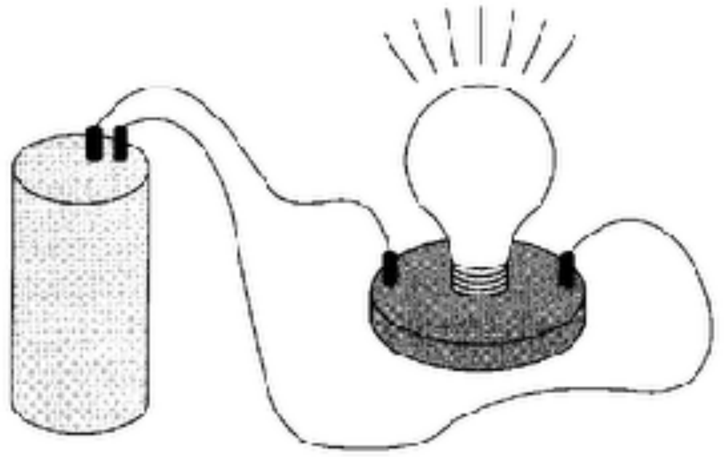
* **To impress a current source - obvious we do it in Ampere's Law** $\vec{J}_f = \vec{J}_e$

* **To impress a voltage source we do NOT use Gauss' Law** $\rho_f = 0$

* **A voltage source has a zero net charge and generates a non-conservative E-field, the ideal voltage source is modelled as a Magnetic Current in Faraday's Law**

IMPRESSED VOLTAGE SOURCE TERMS





Chapter 7

7.1.2 Electromotive Force

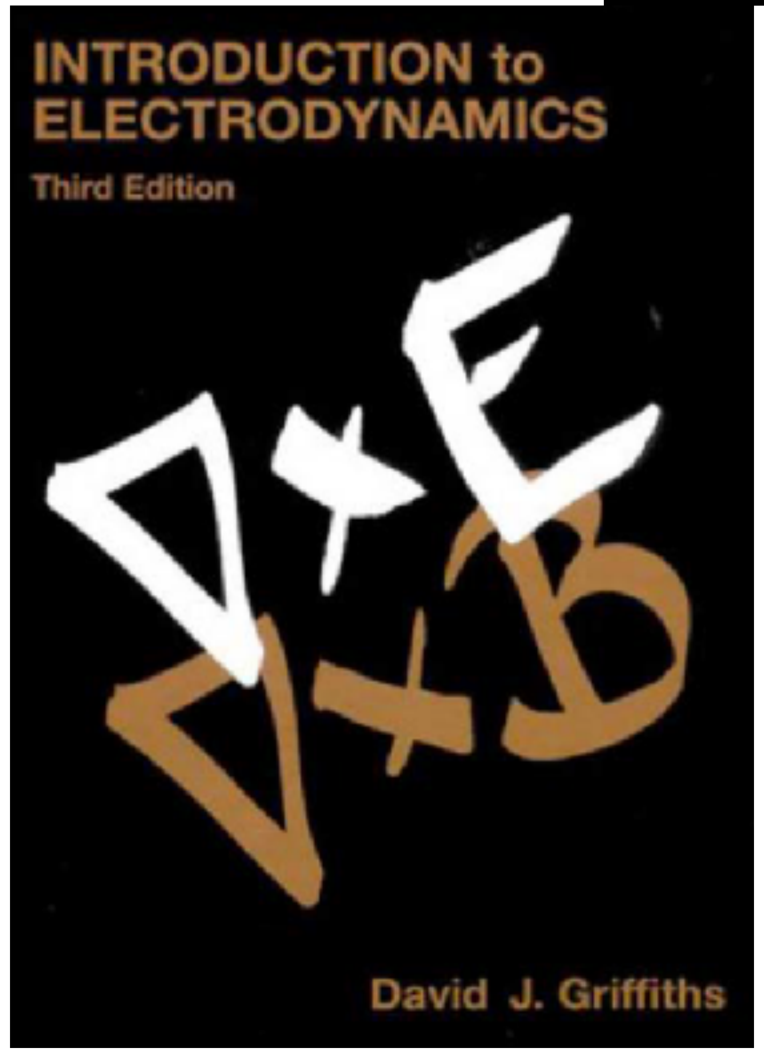
The upshot of all this is that there are really *two* forces involved in driving current around a circuit: the *source*, $\mathbf{f}_s$, which is ordinarily confined to one portion of the loop (a battery, say), and the *electrostatic* force, which serves to smooth out the flow and communicate the influence of the source to distant parts of the circuit:

$$\mathbf{f} = \mathbf{f}_s + \mathbf{E}. \tag{7.8}$$

The physical agency responsible for $\mathbf{f}_s$ can be any one of many different things: in a battery it's a chemical force; in a piezoelectric crystal mechanical pressure is converted into an

$$\boxed{\mathcal{E} \equiv \oint \mathbf{f} \cdot d\mathbf{l} = \oint \mathbf{f}_s \cdot d\mathbf{l}.}$$

IMPRESSED VOLTAGE SOURCE TERMS



Chapter 7

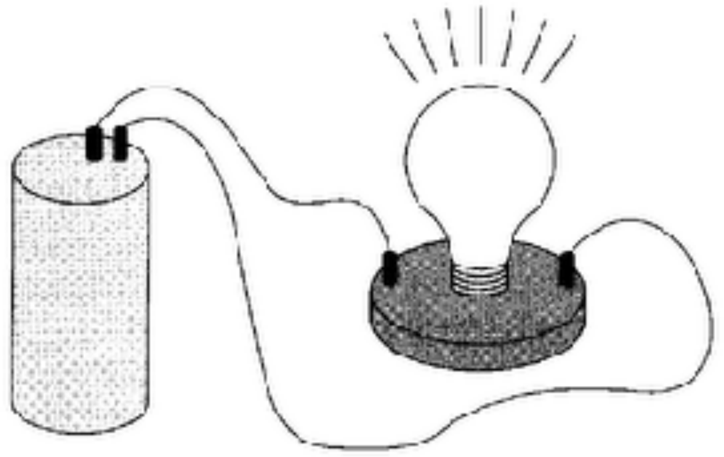
7.1.2 Electromotive Force

The upshot of all this is that there are really *two* forces involved in driving current around a circuit: the *source*, $\mathbf{f}_s$, which is ordinarily confined to one portion of the loop (a battery, say), and the *electrostatic* force, which serves to smooth out the flow and communicate the influence of the source to distant parts of the circuit:

$$\mathbf{f} = \mathbf{f}_s + \mathbf{E}. \tag{7.8}$$

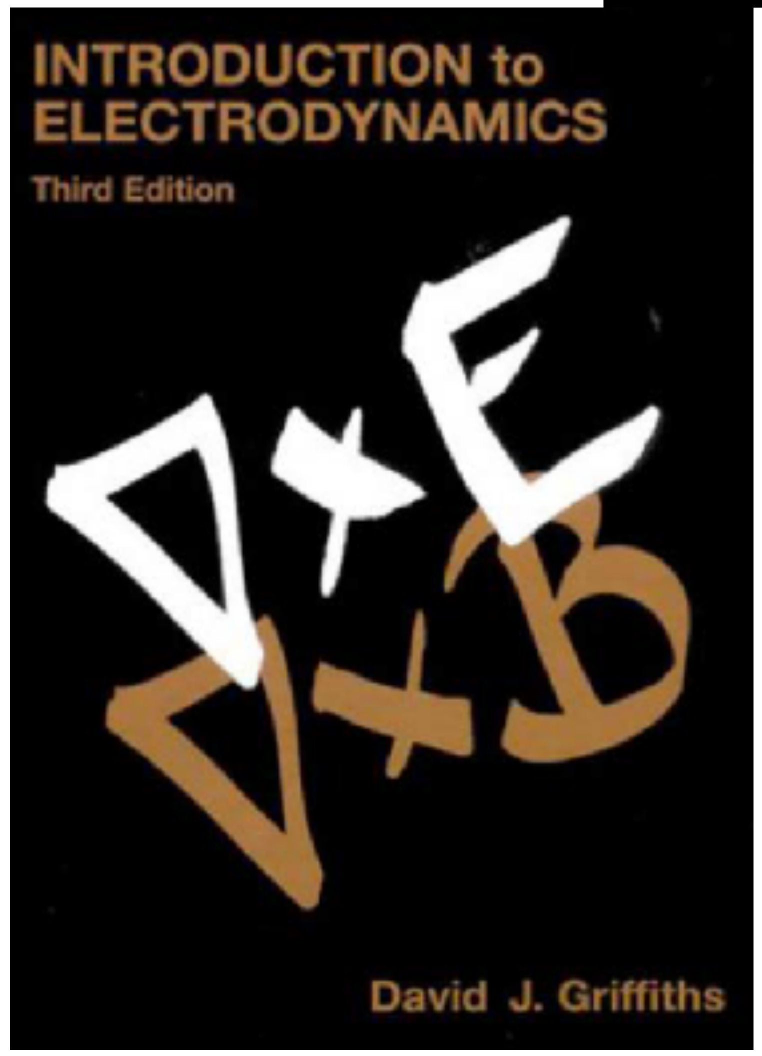
The physical agency responsible for $\mathbf{f}_s$ can be any one of many different things: in a battery it's a chemical force; in a piezoelectric crystal mechanical pressure is converted into an

$$\boxed{\mathcal{E} \equiv \oint \mathbf{f} \cdot d\mathbf{l} = \oint \mathbf{f}_s \cdot d\mathbf{l}.}$$



$$\vec{f}_T = \vec{f}_f + \vec{E}$$

IMPRESSED VOLTAGE SOURCE TERMS



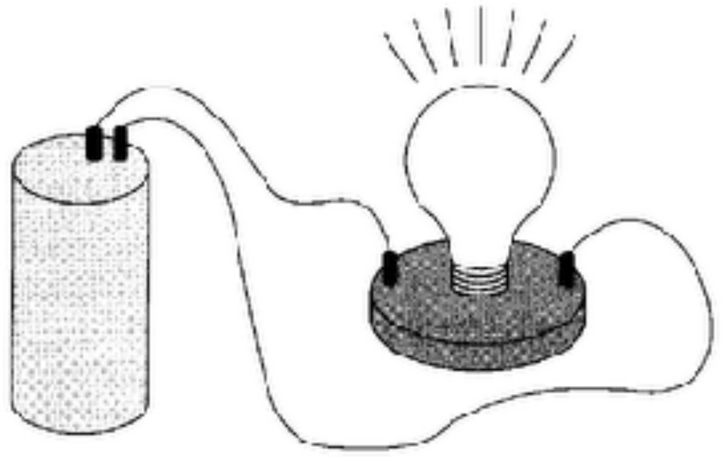
Chapter 7 7.1.2 Electromotive Force

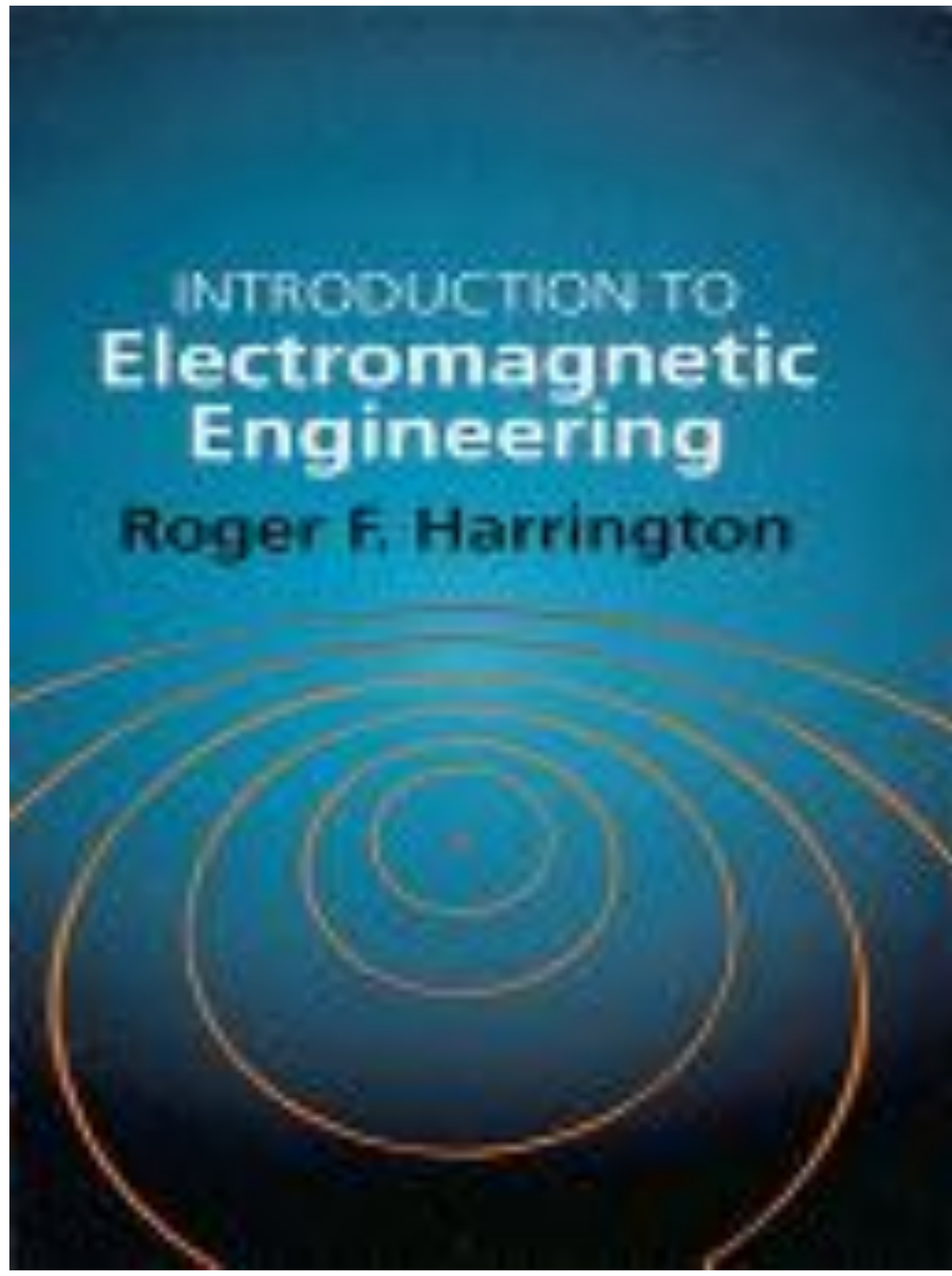
The upshot of all this is that there are really *two* forces involved in driving current around a circuit: the *source*, $\mathbf{f}_s$, which is ordinarily confined to one portion of the loop (a battery, say), and the *electrostatic* force, which serves to smooth out the flow and communicate the influence of the source to distant parts of the circuit:

$$\mathbf{f} = \mathbf{f}_s + \mathbf{E}. \tag{7.8}$$

The physical agency responsible for $\mathbf{f}_s$ can be any one of many different things: in a battery it's a chemical force; in a piezoelectric crystal mechanical pressure is converted into an

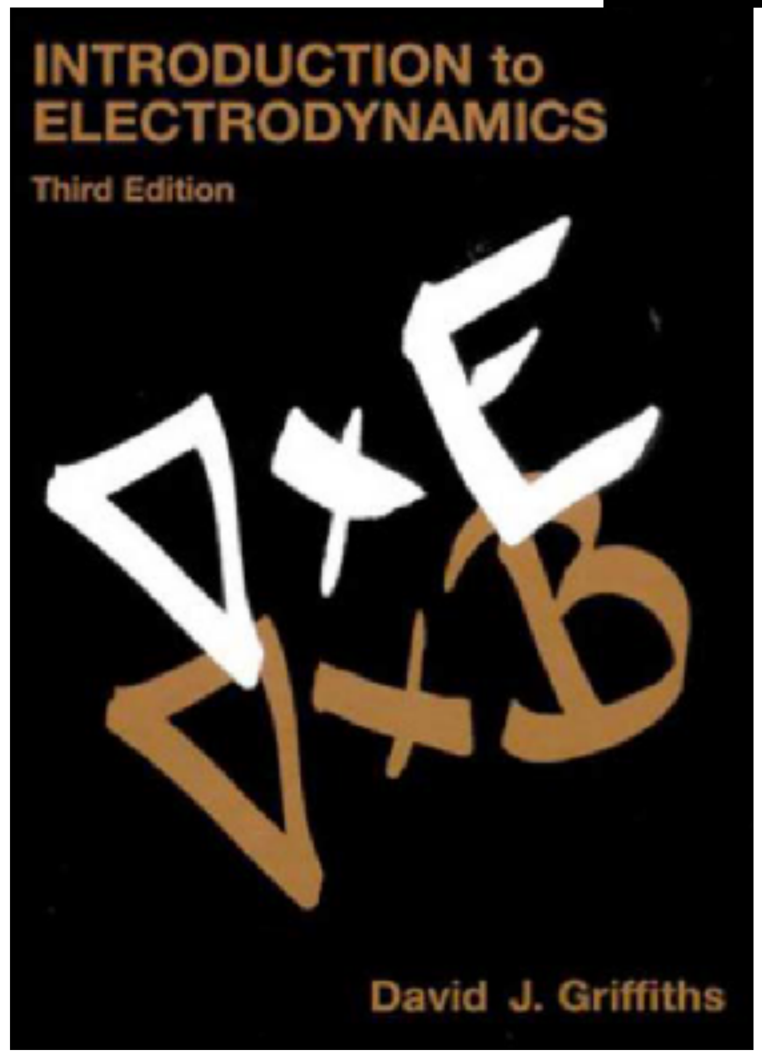
$$\boxed{\mathcal{E} \equiv \oint \mathbf{f} \cdot d\mathbf{l} = \oint \mathbf{f}_s \cdot d\mathbf{l}.}$$





$$\vec{f}_T = \vec{f}_f + \vec{E}$$

IMPRESSED VOLTAGE SOURCE TERMS



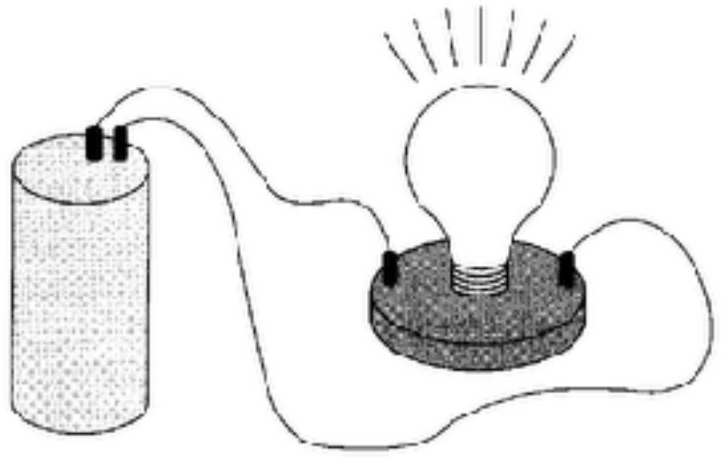
Chapter 7 **7.1.2 Electromotive Force**

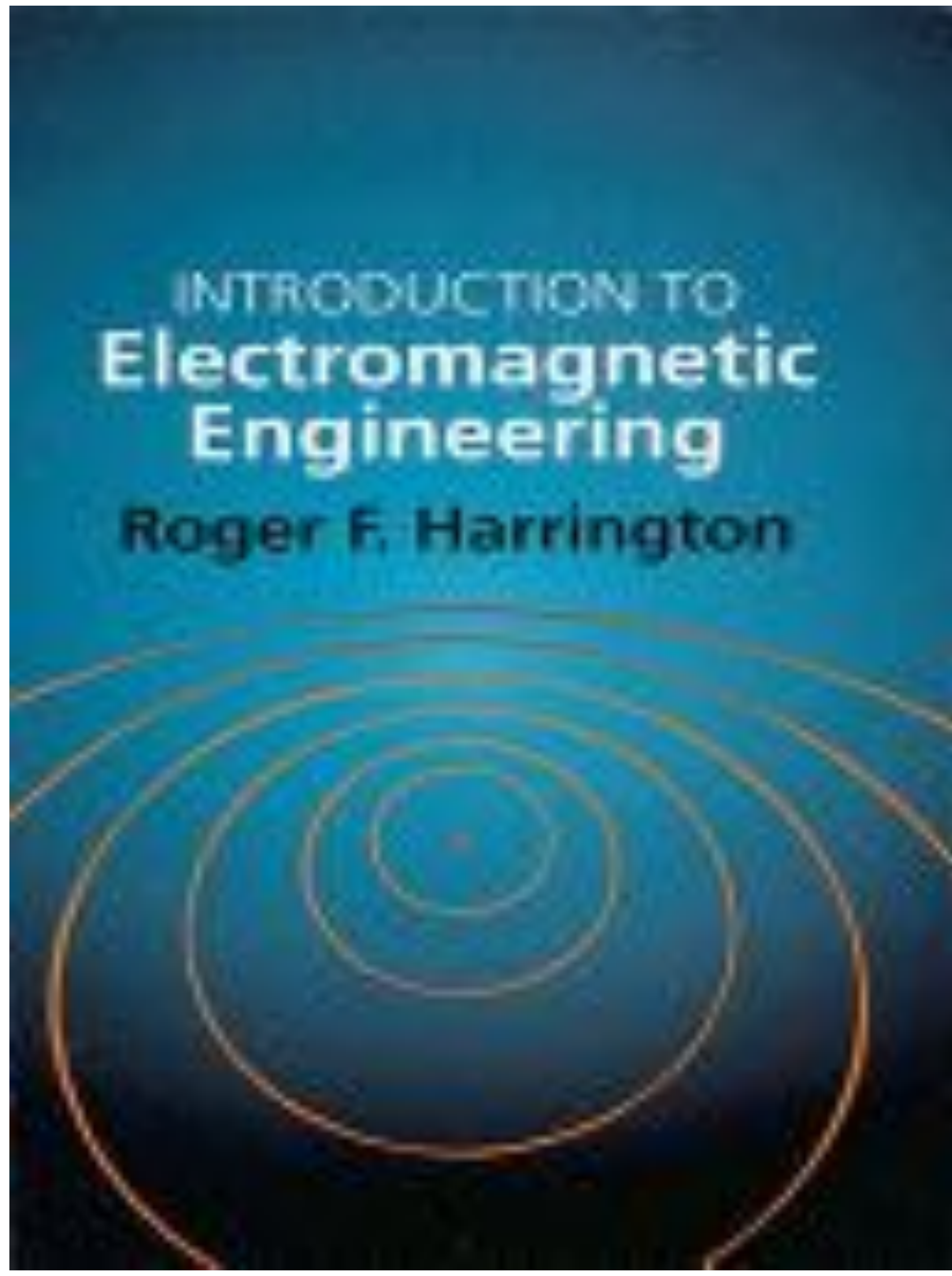
The upshot of all this is that there are really *two* forces involved in driving current around a circuit: the *source*, $\mathbf{f}_s$, which is ordinarily confined to one portion of the loop (a battery, say), and the *electrostatic* force, which serves to smooth out the flow and communicate the influence of the source to distant parts of the circuit:

$$\mathbf{f} = \mathbf{f}_s + \mathbf{E}. \tag{7.8}$$

The physical agency responsible for $\mathbf{f}_s$ can be any one of many different things: in a battery it's a chemical force; in a piezoelectric crystal mechanical pressure is converted into an

$$\boxed{\mathcal{E} \equiv \oint \mathbf{f} \cdot d\mathbf{l} = \oint \mathbf{f}_s \cdot d\mathbf{l}.}$$

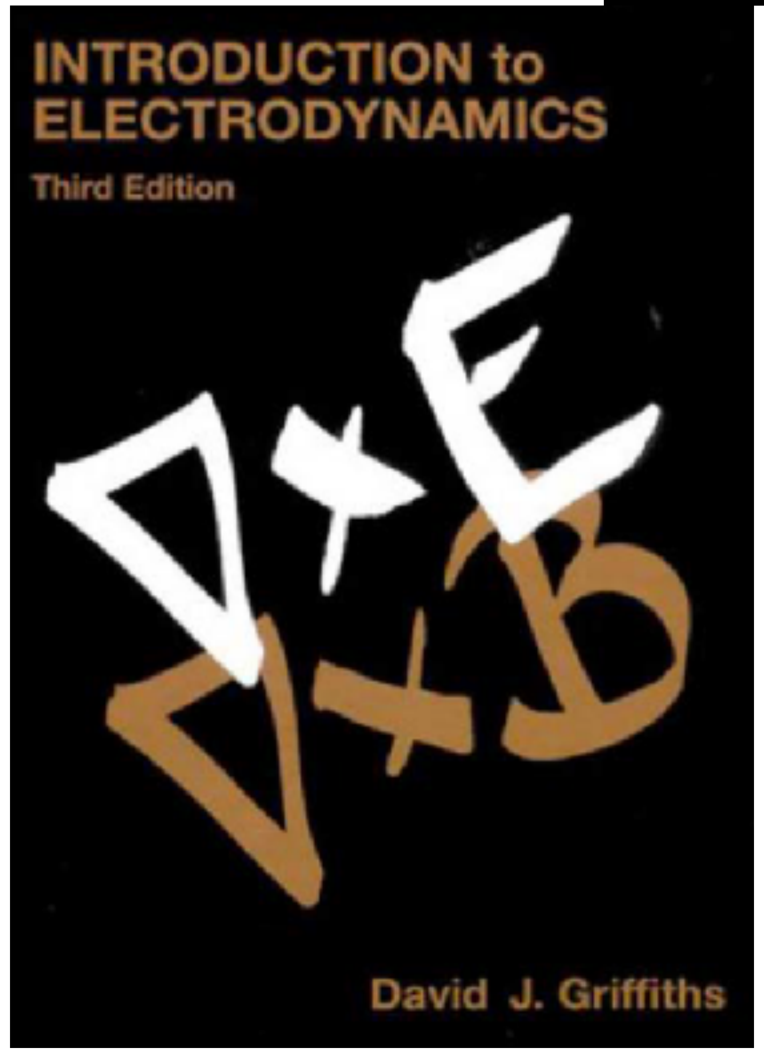




$$\vec{f}_T = \vec{f}_f + \vec{E}$$

$$\vec{E}_T = \vec{E}^i_f + \vec{E}$$

IMPRESSED VOLTAGE SOURCE TERMS



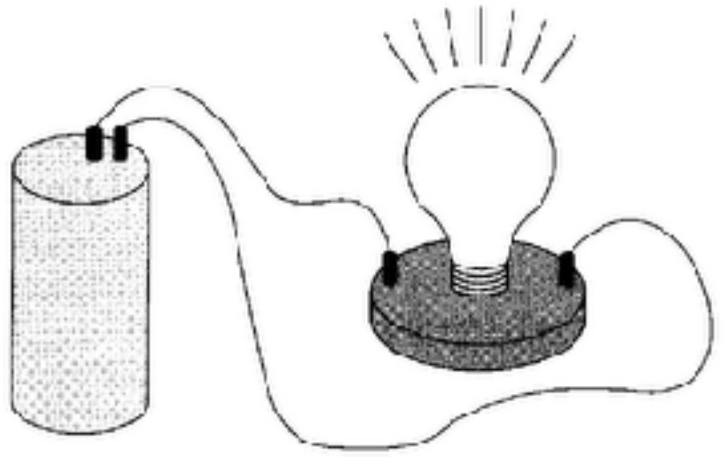
Chapter 7 **7.1.2 Electromotive Force**

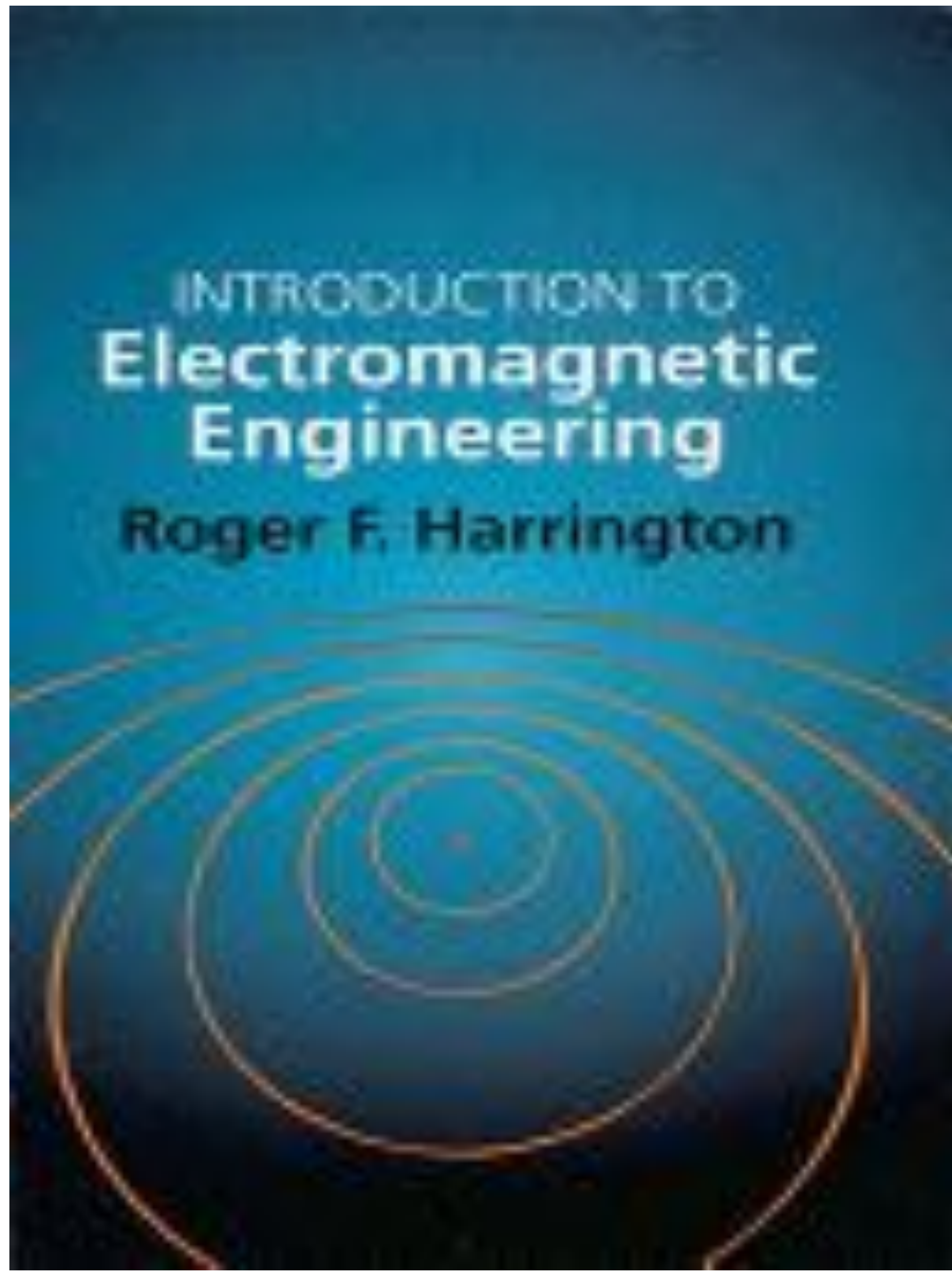
The upshot of all this is that there are really *two* forces involved in driving current around a circuit: the *source*, $\mathbf{f}_s$, which is ordinarily confined to one portion of the loop (a battery, say), and the *electrostatic* force, which serves to smooth out the flow and communicate the influence of the source to distant parts of the circuit:

$$\mathbf{f} = \mathbf{f}_s + \mathbf{E}. \tag{7.8}$$

The physical agency responsible for $\mathbf{f}_s$ can be any one of many different things: in a battery it's a chemical force; in a piezoelectric crystal mechanical pressure is converted into an

$$\boxed{\mathcal{E} \equiv \oint \mathbf{f} \cdot d\mathbf{l} = \oint \mathbf{f}_s \cdot d\mathbf{l}.}$$



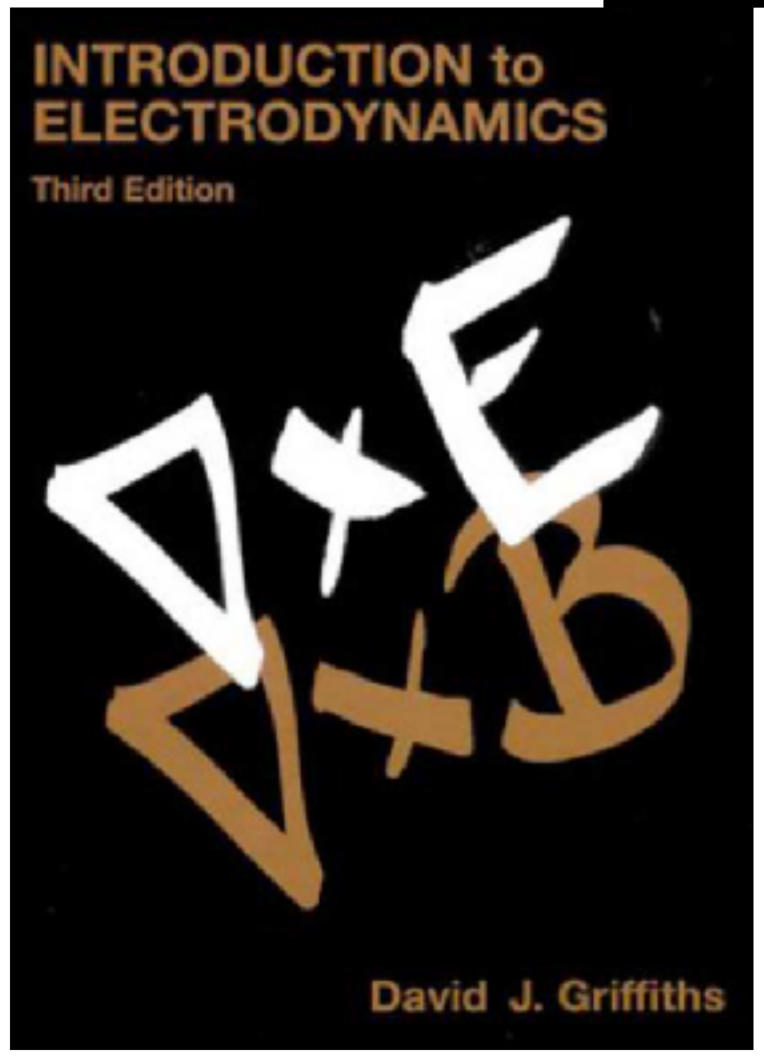


$$\vec{f}_T = \vec{f}_f + \vec{E}$$

$$\vec{P}_f^i = \epsilon_0 \vec{E}_f^i = \epsilon_0 \vec{f}_f$$

$$\vec{E}_T = \vec{E}_f^i + \vec{E}$$

IMPRESSED VOLTAGE SOURCE TERMS



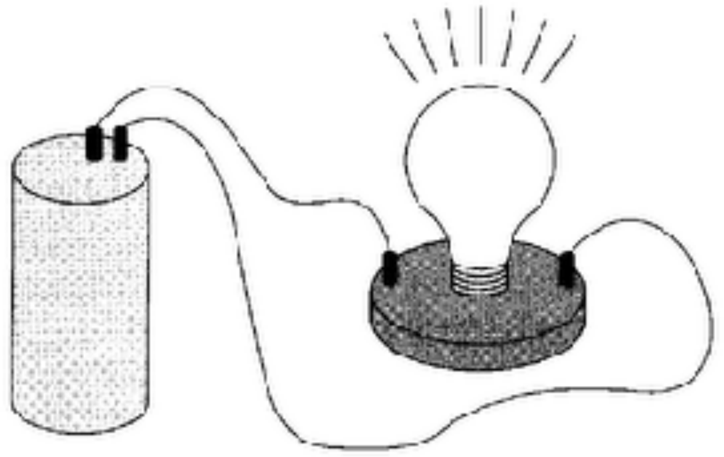
Chapter 7 7.1.2 Electromotive Force

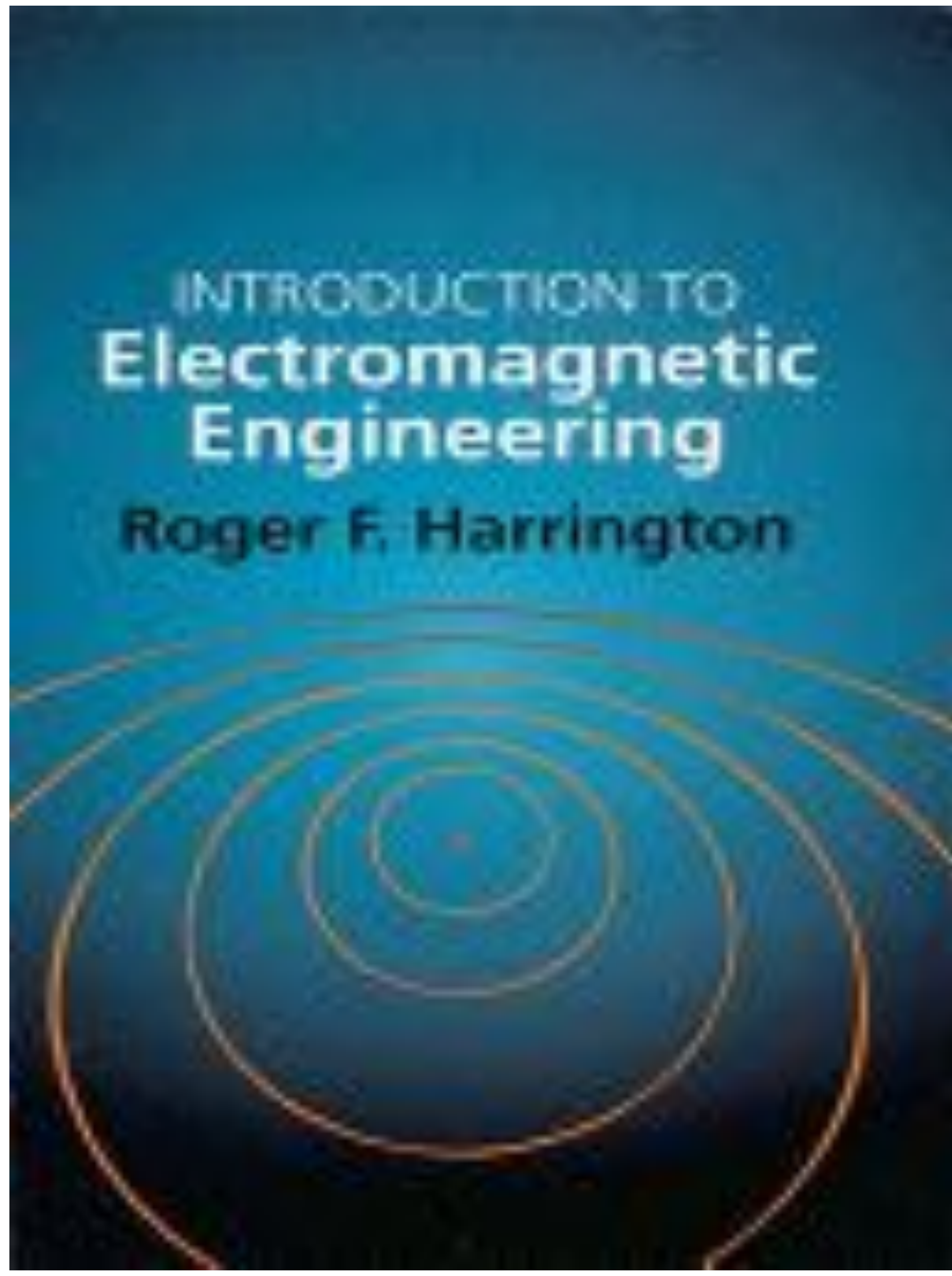
The upshot of all this is that there are really *two* forces involved in driving current around a circuit: the *source*, $\mathbf{f}_s$, which is ordinarily confined to one portion of the loop (a battery, say), and the *electrostatic* force, which serves to smooth out the flow and communicate the influence of the source to distant parts of the circuit:

$$\mathbf{f} = \mathbf{f}_s + \mathbf{E}. \tag{7.8}$$

The physical agency responsible for $\mathbf{f}_s$ can be any one of many different things: in a battery it's a chemical force; in a piezoelectric crystal mechanical pressure is converted into an

$$\boxed{\mathcal{E} \equiv \oint \mathbf{f} \cdot d\mathbf{l} = \oint \mathbf{f}_s \cdot d\mathbf{l}.}$$



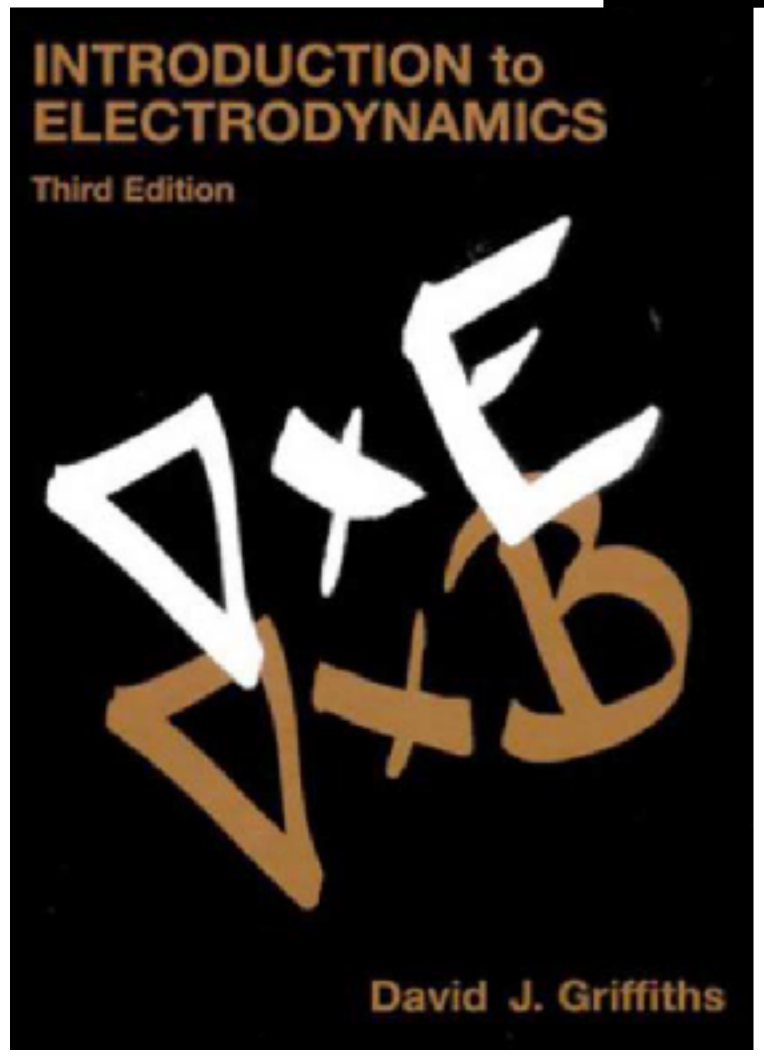


$$\vec{E}_T = \vec{E}^i_f + \vec{E}$$

$$\vec{f}_T = \vec{f}_f + \vec{E}$$

$$\vec{P}^i_f = \epsilon_0 \vec{E}^i_f = \epsilon_0 \vec{f}_f \qquad \vec{D} = \epsilon_0 \vec{E} + \vec{P}^i_f$$

IMPRESSED VOLTAGE SOURCE TERMS



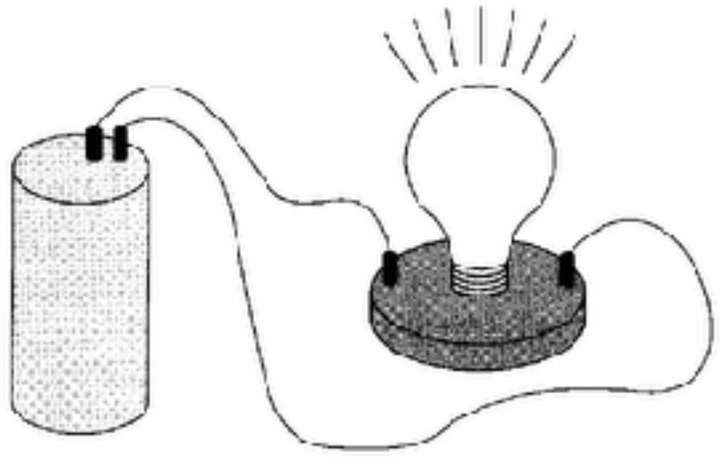
Chapter 7 **7.1.2 Electromotive Force**

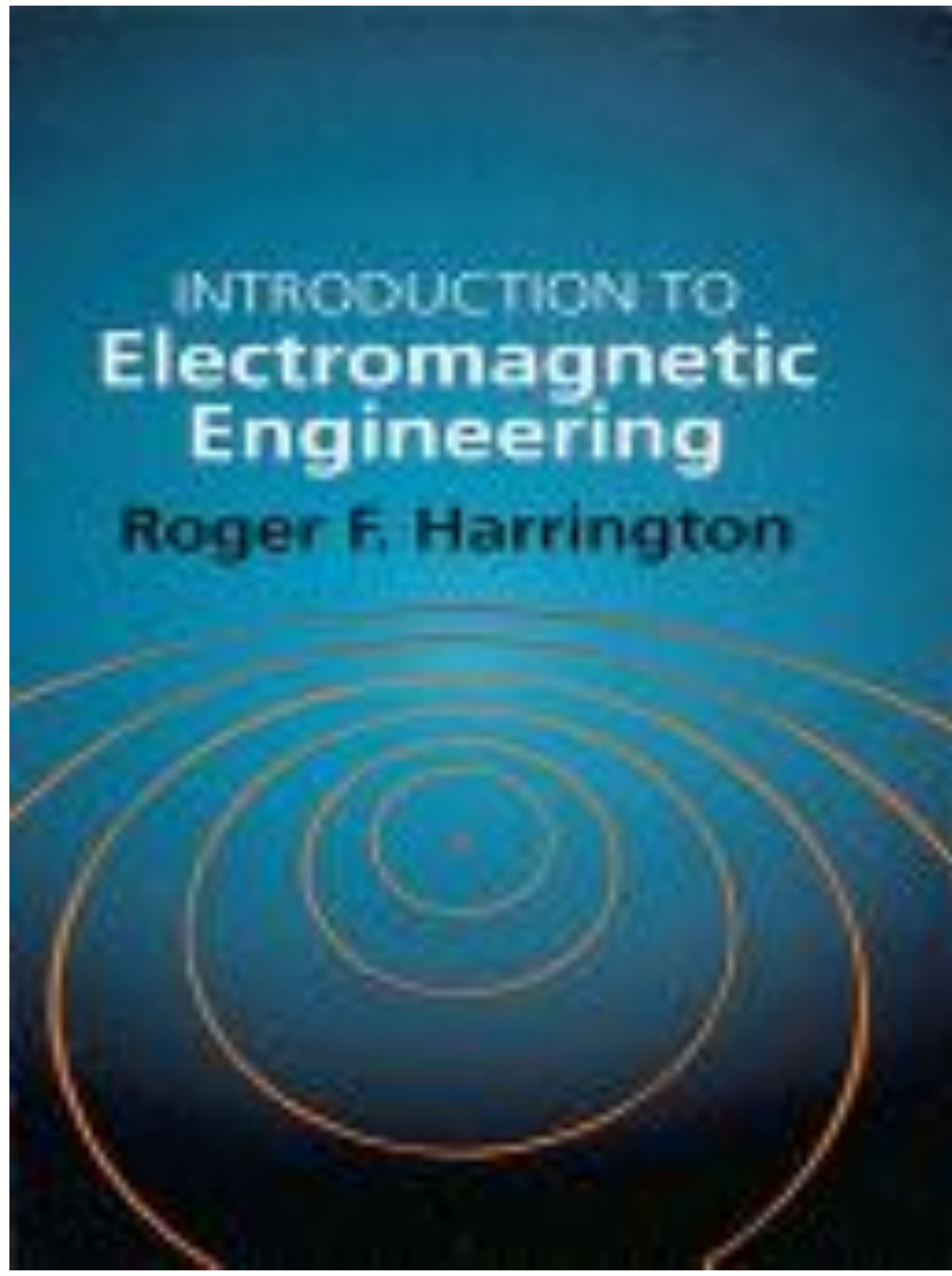
The upshot of all this is that there are really *two* forces involved in driving current around a circuit: the *source*, $\mathbf{f}_s$, which is ordinarily confined to one portion of the loop (a battery, say), and the *electrostatic* force, which serves to smooth out the flow and communicate the influence of the source to distant parts of the circuit:

$$\mathbf{f} = \mathbf{f}_s + \mathbf{E}. \tag{7.8}$$

The physical agency responsible for $\mathbf{f}_s$ can be any one of many different things: in a battery it's a chemical force; in a piezoelectric crystal mechanical pressure is converted into an

$$\boxed{\mathcal{E} \equiv \oint \mathbf{f} \cdot d\mathbf{l} = \oint \mathbf{f}_s \cdot d\mathbf{l}.}$$





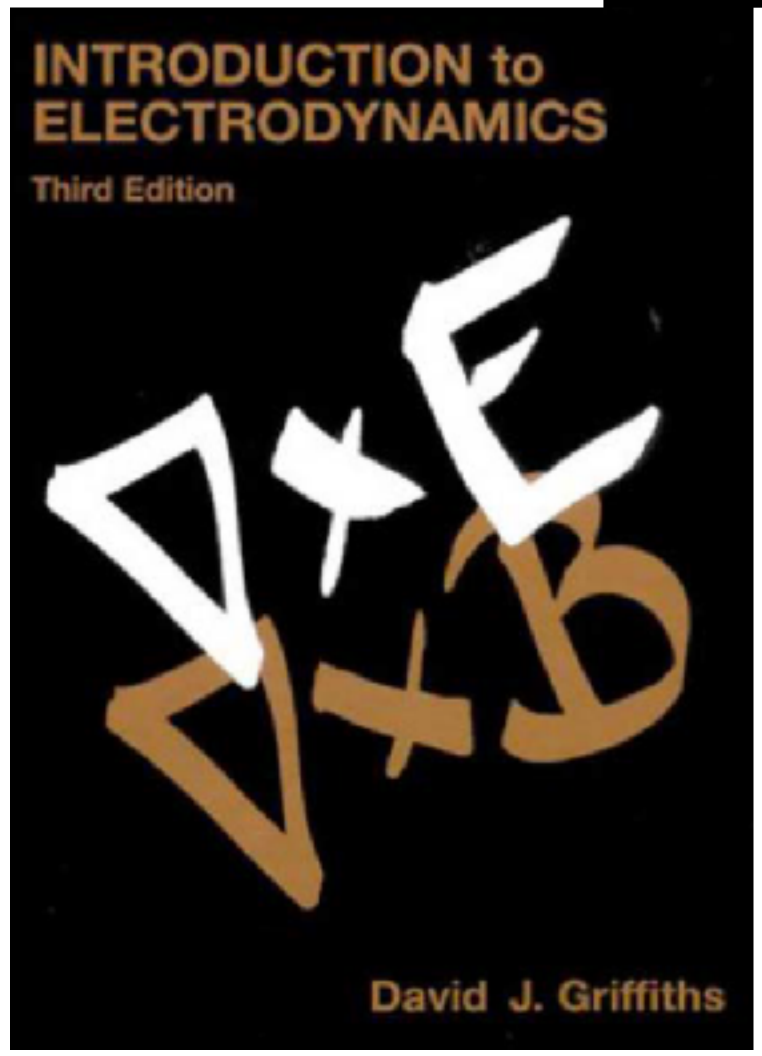
$$\vec{f}_T = \vec{f}_f + \vec{E}$$

$$\vec{E}_T = \vec{E}^i_f + \vec{E}$$

$$\vec{P}^i_f = \epsilon_0 \vec{E}^i_f = \epsilon_0 \vec{f}_f \qquad \vec{D} = \epsilon_0 \vec{E} + \vec{P}^i_f$$

$$\vec{J}^i_{mf} = \vec{\nabla} \times \vec{P}^i_f / \epsilon_0 = \vec{\nabla} \times \vec{E}^i_f$$

IMPRESSED VOLTAGE SOURCE TERMS



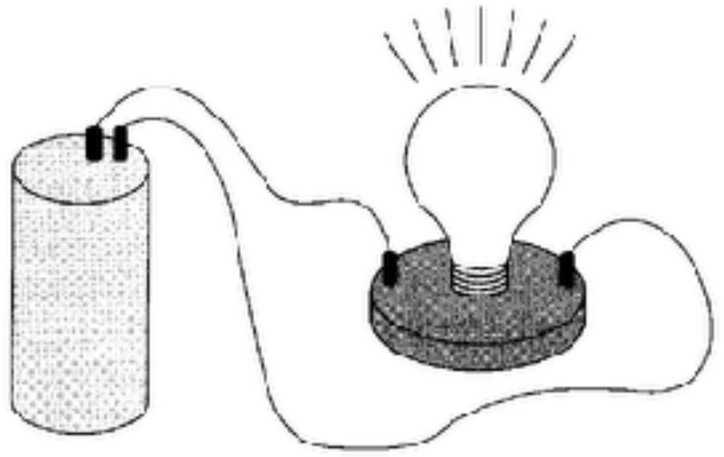
Chapter 7 **7.1.2 Electromotive Force**

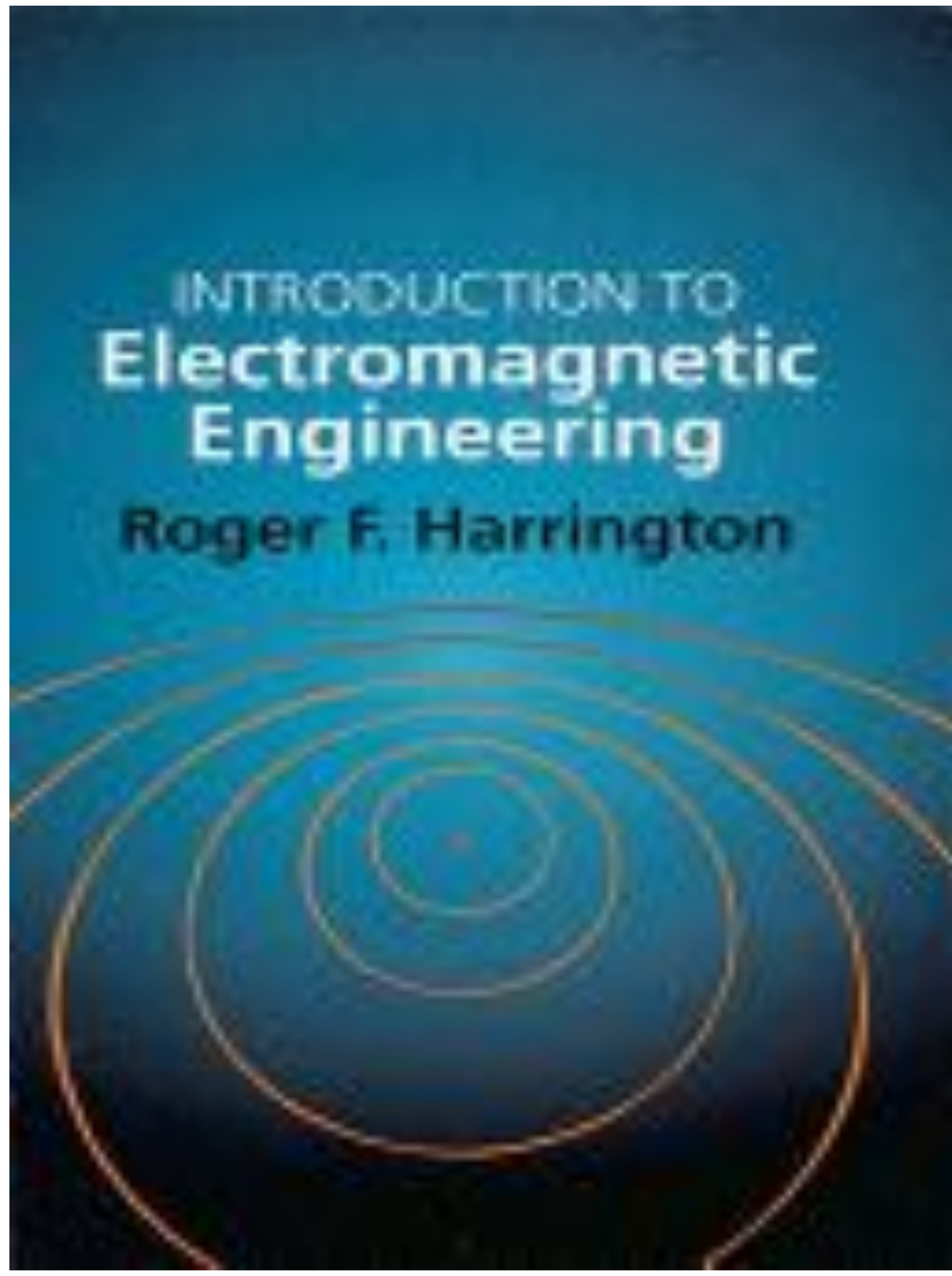
The upshot of all this is that there are really *two* forces involved in driving current around a circuit: the *source*, $\mathbf{f}_s$, which is ordinarily confined to one portion of the loop (a battery, say), and the *electrostatic* force, which serves to smooth out the flow and communicate the influence of the source to distant parts of the circuit:

$$\mathbf{f} = \mathbf{f}_s + \mathbf{E}. \tag{7.8}$$

The physical agency responsible for $\mathbf{f}_s$ can be any one of many different things: in a battery it's a chemical force; in a piezoelectric crystal mechanical pressure is converted into an

$$\boxed{\mathcal{E} \equiv \oint \mathbf{f} \cdot d\mathbf{l} = \oint \mathbf{f}_s \cdot d\mathbf{l}.}$$





$$\vec{f}_T = \vec{f}_f + \vec{E}$$

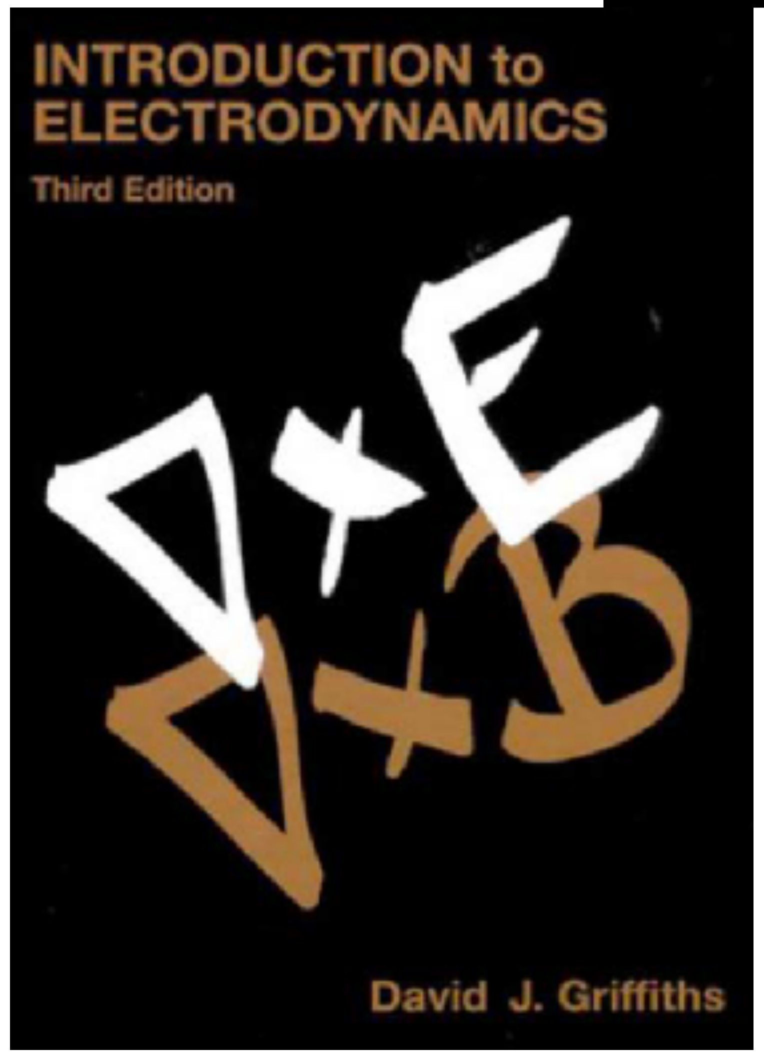
$$\vec{E}_T = \vec{E}^i_f + \vec{E}$$

$$\vec{P}^i_f = \epsilon_0 \vec{E}^i_f = \epsilon_0 \vec{f}_f \qquad \vec{D} = \epsilon_0 \vec{E} + \vec{P}^i_f$$

$$\vec{J}^i_{mf} = \vec{\nabla} \times \vec{P}^i_f / \epsilon_0 = \vec{\nabla} \times \vec{E}^i_f$$

$$\vec{\nabla} \times \vec{E}_T = -(\frac{\partial \vec{B}}{\partial t} + \vec{J}^i_{mf})$$

IMPRESSED VOLTAGE SOURCE TERMS



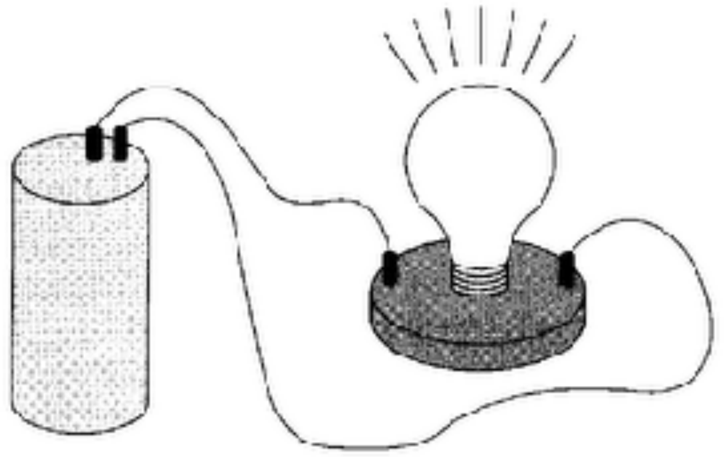
Chapter 7 **7.1.2 Electromotive Force**

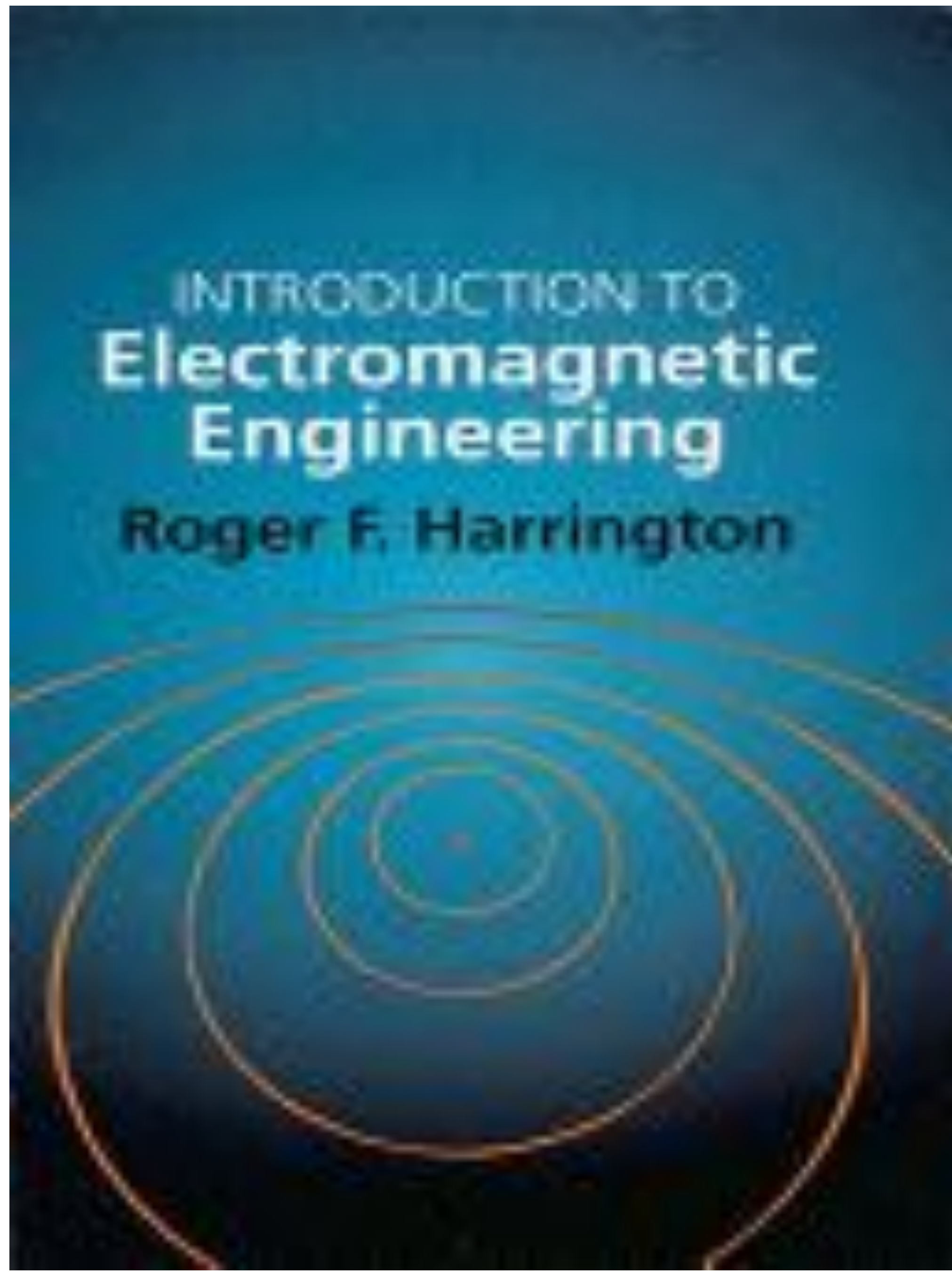
The upshot of all this is that there are really *two* forces involved in driving current around a circuit: the *source*, $\mathbf{f}_s$, which is ordinarily confined to one portion of the loop (a battery, say), and the *electrostatic* force, which serves to smooth out the flow and communicate the influence of the source to distant parts of the circuit:

$$\mathbf{f} = \mathbf{f}_s + \mathbf{E}. \tag{7.8}$$

The physical agency responsible for $\mathbf{f}_s$ can be any one of many different things: in a battery it's a chemical force; in a piezoelectric crystal mechanical pressure is converted into an

$$\boxed{\mathcal{E} \equiv \oint \mathbf{f} \cdot d\mathbf{l} = \oint \mathbf{f}_s \cdot d\mathbf{l}.}$$





$$\vec{f}_T = \vec{f}_f + \vec{E}$$

$$\vec{E}_T = \vec{E}^i_f + \vec{E}$$

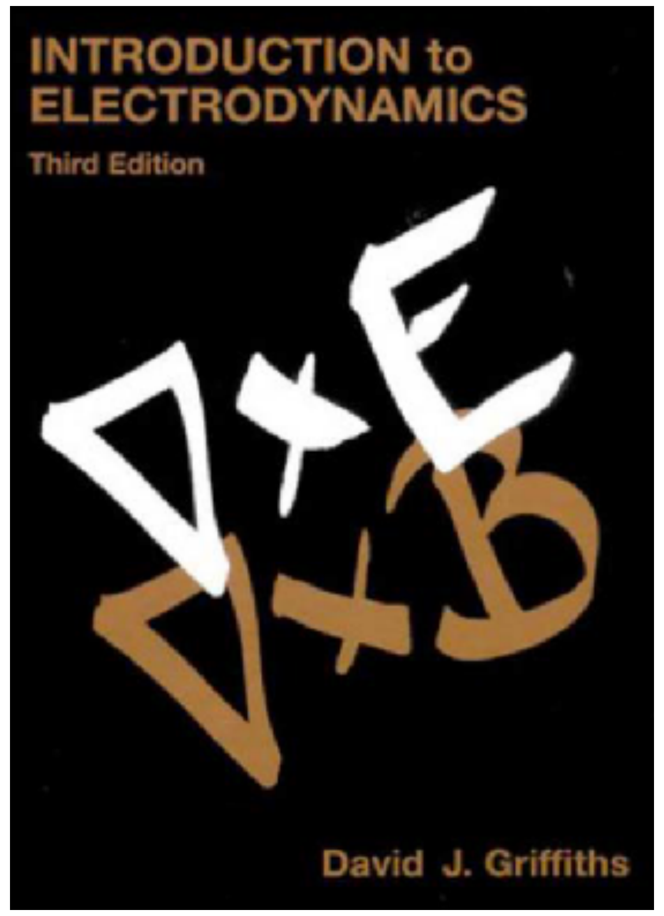
$$\vec{P}^i_f = \epsilon_0 \vec{E}^i_f = \epsilon_0 \vec{f}_f \qquad \vec{D} = \epsilon_0 \vec{E} + \vec{P}^i_f$$

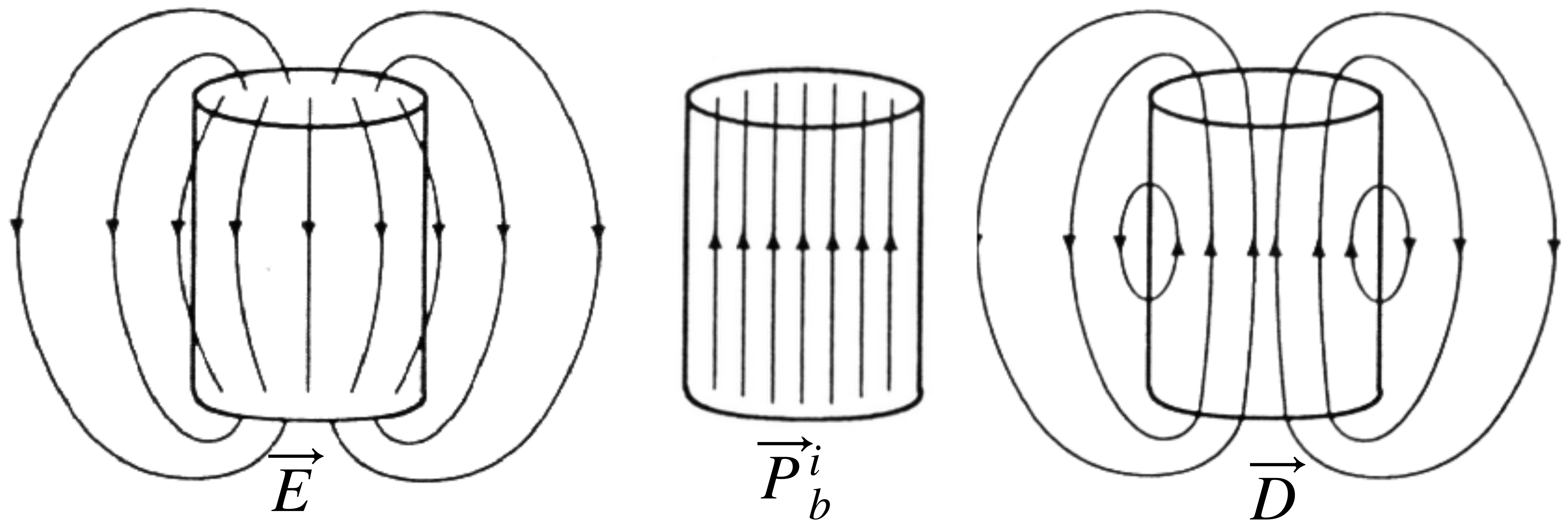
$$\vec{J}^i_{mf} = \vec{\nabla} \times \vec{P}^i_f / \epsilon_0 = \vec{\nabla} \times \vec{E}^i_f$$

$$\vec{\nabla} \times \vec{E}_T = -(\frac{\partial \vec{B}}{\partial t} + \vec{J}^i_{mf})$$

Define an impressed free charge polarization or impressed electric field vector

TIME VARYING BOUND CHARGE VOLTAGE SOURCE: BAR ELECTRET





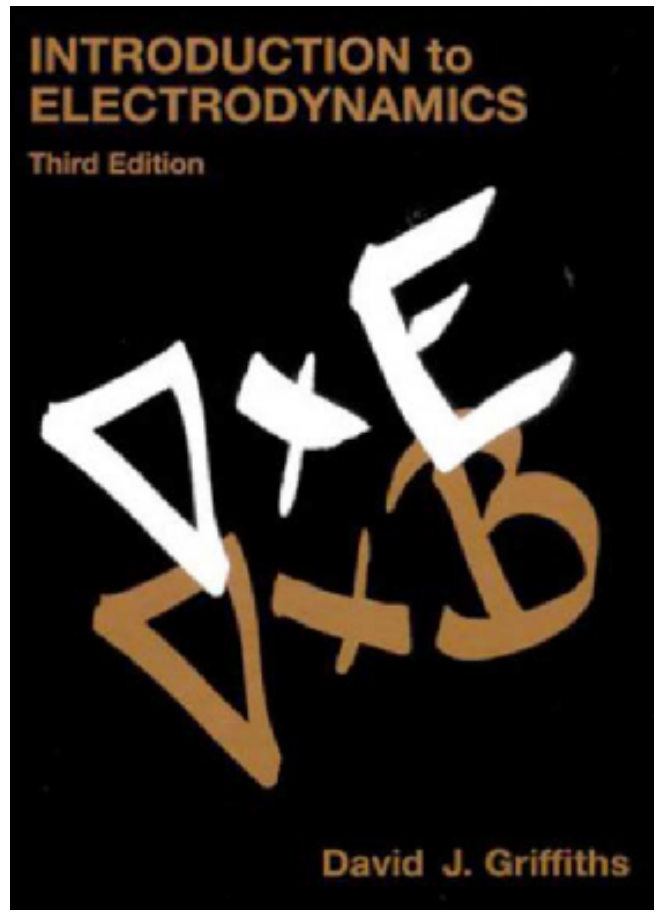
$$\vec{\nabla} \cdot \vec{D} = 0,$$

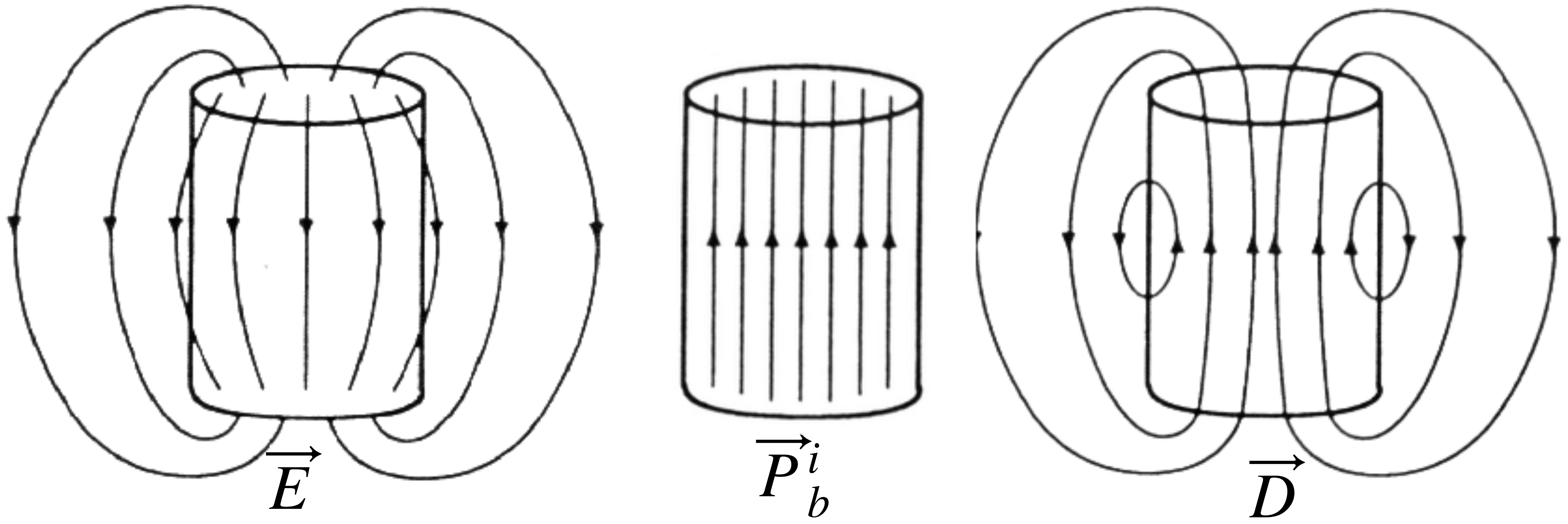
$$\vec{\nabla} \times \vec{B} = \mu_0 \frac{\partial \vec{D}}{\partial t},$$

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

$$\vec{\nabla} \times \vec{D} = -\epsilon_0 \epsilon_r \frac{\partial \vec{B}}{\partial t} + \vec{\nabla} \times \vec{P}_b^i$$

TIME VARYING BOUND CHARGE VOLTAGE SOURCE: BAR ELECTRET





$$\vec{D} = \epsilon_0 \vec{E} + \vec{P}$$

$$\vec{P} = \chi_e \epsilon_0 \vec{E} + \vec{P}^i_b$$

$$\vec{D} = \epsilon_0 \epsilon_r \vec{E} + \vec{P}^i_b$$

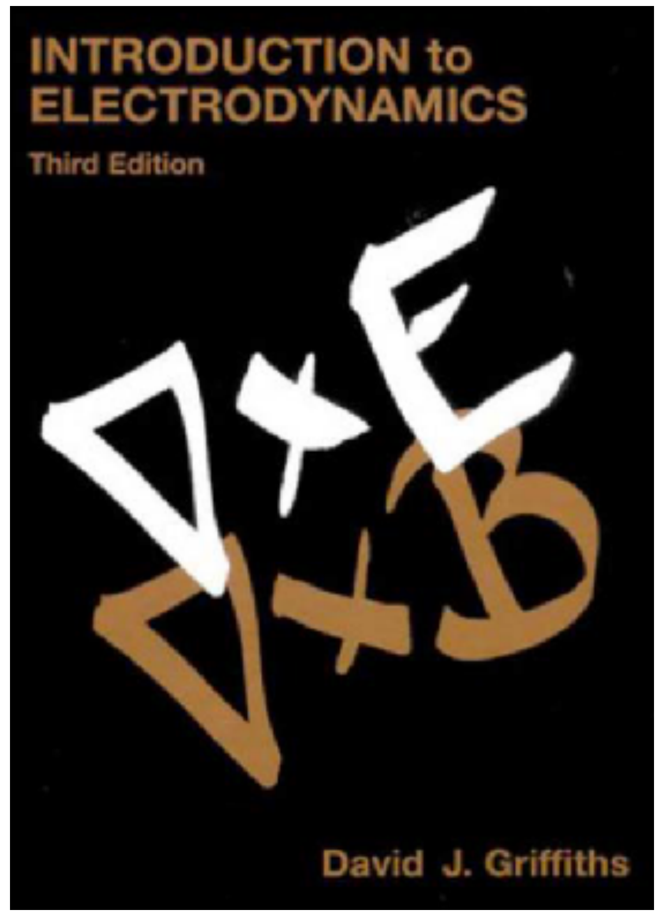
$$\vec{\nabla} \cdot \vec{D} = 0,$$

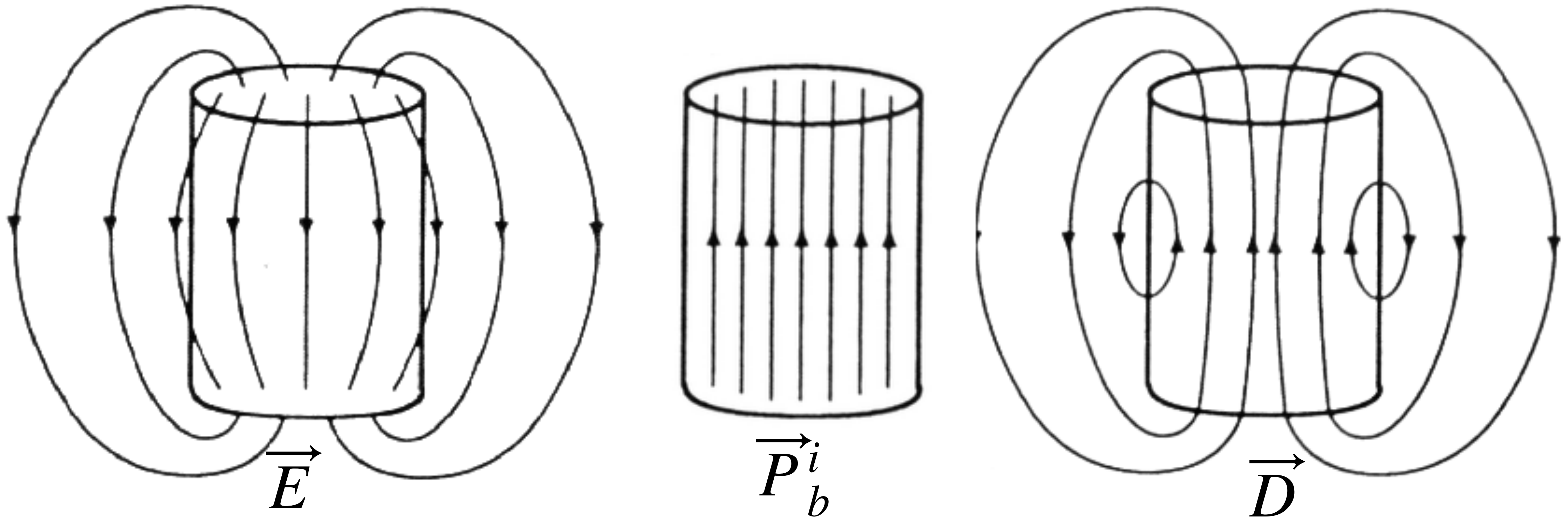
$$\vec{\nabla} \times \vec{B} = \mu_0 \frac{\partial \vec{D}}{\partial t},$$

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

$$\vec{\nabla} \times \vec{D} = -\epsilon_0 \epsilon_r \frac{\partial \vec{B}}{\partial t} + \vec{\nabla} \times \vec{P}^i_b$$

TIME VARYING BOUND CHARGE VOLTAGE SOURCE: BAR ELECTRET





$$\vec{D} = \epsilon_0 \vec{E} + \vec{P}$$

$$\vec{P} = \chi_e \epsilon_0 \vec{E} + \vec{P}_b^i$$

$$\vec{D} = \epsilon_0 \epsilon_r \vec{E} + \vec{P}_b^i$$

$$\vec{\nabla} \cdot \vec{D} = 0,$$

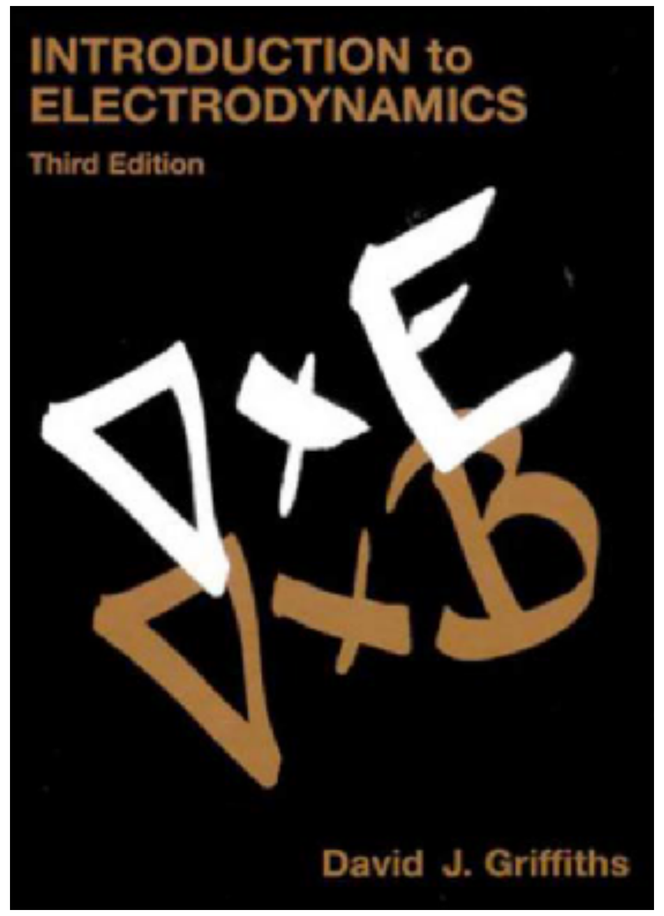
$$\vec{\nabla} \times \vec{B} = \mu_0 \frac{\partial \vec{D}}{\partial t},$$

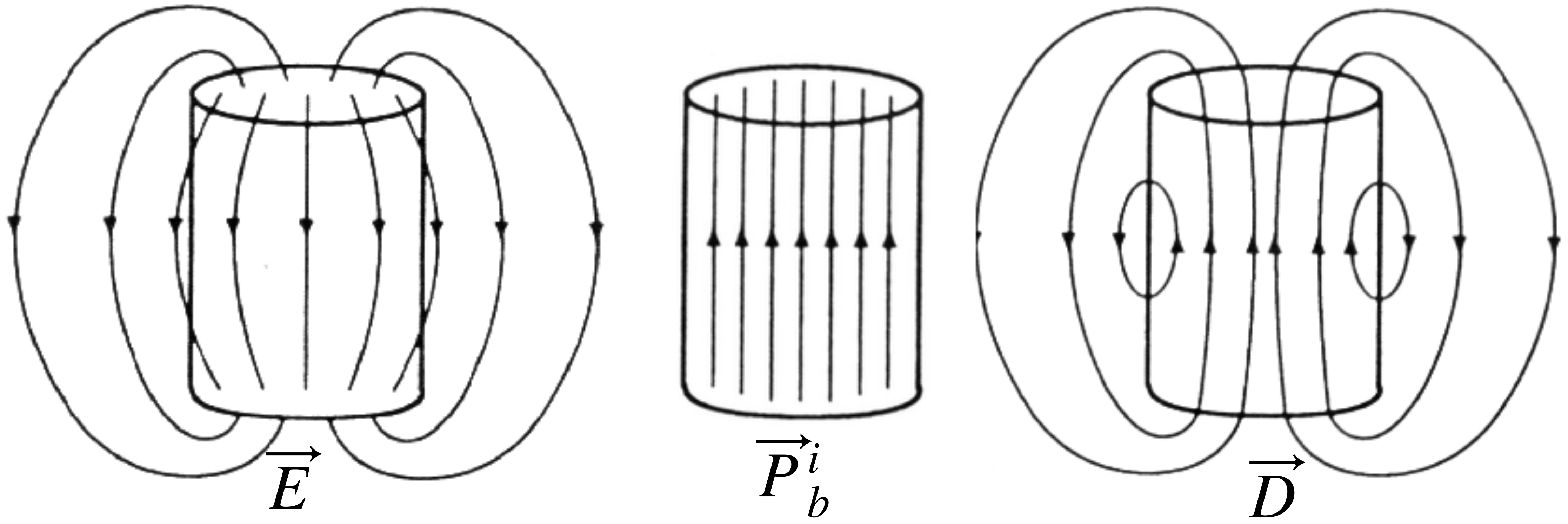
$$\vec{\nabla} \cdot \vec{B} = 0,$$

$$\vec{\nabla} \times \vec{D} = -\epsilon_0 \epsilon_r \frac{\partial \vec{B}}{\partial t} + \vec{\nabla} \times \vec{P}_b^i$$

$$\nabla \cdot \vec{P}_b^i = 0$$

TIME VARYING BOUND CHARGE VOLTAGE SOURCE: BAR ELECTRET





$$\vec{D} = \epsilon_0 \vec{E} + \vec{P}$$

$$\vec{P} = \chi_e \epsilon_0 \vec{E} + \vec{P}^i_b$$

$$\vec{D} = \epsilon_0 \epsilon_r \vec{E} + \vec{P}^i_b$$

$$\vec{\nabla} \cdot \vec{D} = 0,$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \frac{\partial \vec{D}}{\partial t},$$

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

$$\vec{\nabla} \times \vec{D} = -\epsilon_0 \epsilon_r \frac{\partial \vec{B}}{\partial t} + \vec{\nabla} \times \vec{P}^i_b$$

$$\nabla \cdot \vec{P}^i_b = 0$$

[1] arXiv:1904.05774 [pdf, other]

Electrodynamics of Impressed Bound and Free Charge Voltage Sources

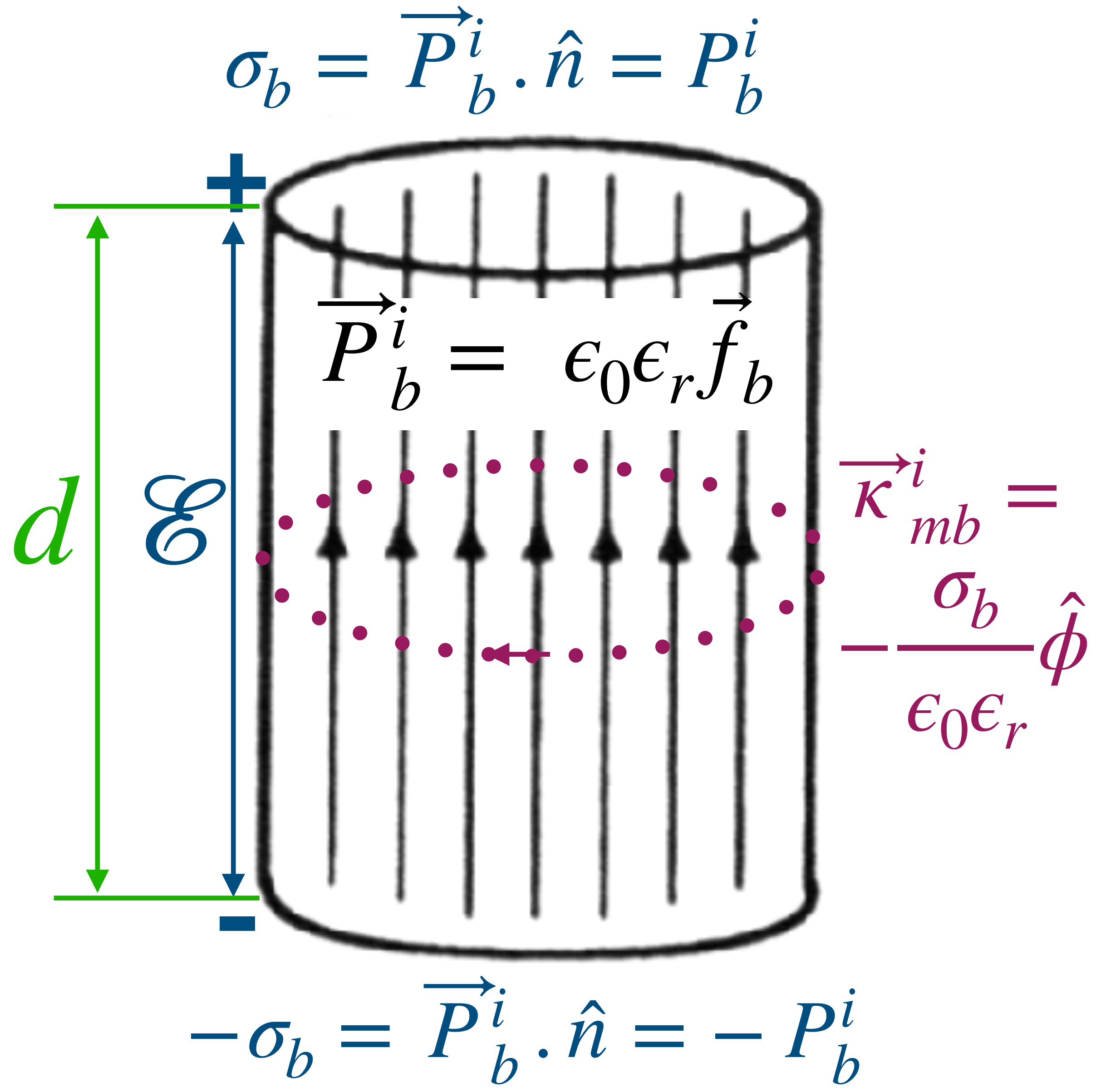
Michael E. Tobar, Ben T. McAllister, Maxim Goryachev

Subjects: **Classical Physics (physics.class-ph)**

Two-Potential Formulation of Electrodynamics

$$\vec{E}_T = \vec{f}_T = \vec{D}/(\epsilon_0\epsilon_r) = \vec{E} + \vec{E}^i \text{ where } \vec{E}^i = \vec{P}^i_b/(\epsilon_0\epsilon_r)$$

$$\vec{E}^i = \vec{E}_C = -\frac{1}{\epsilon_0\epsilon_r}\nabla \times \vec{C}, \qquad \vec{E}_A = -\frac{\partial \vec{A}}{\partial t} - \nabla V,$$

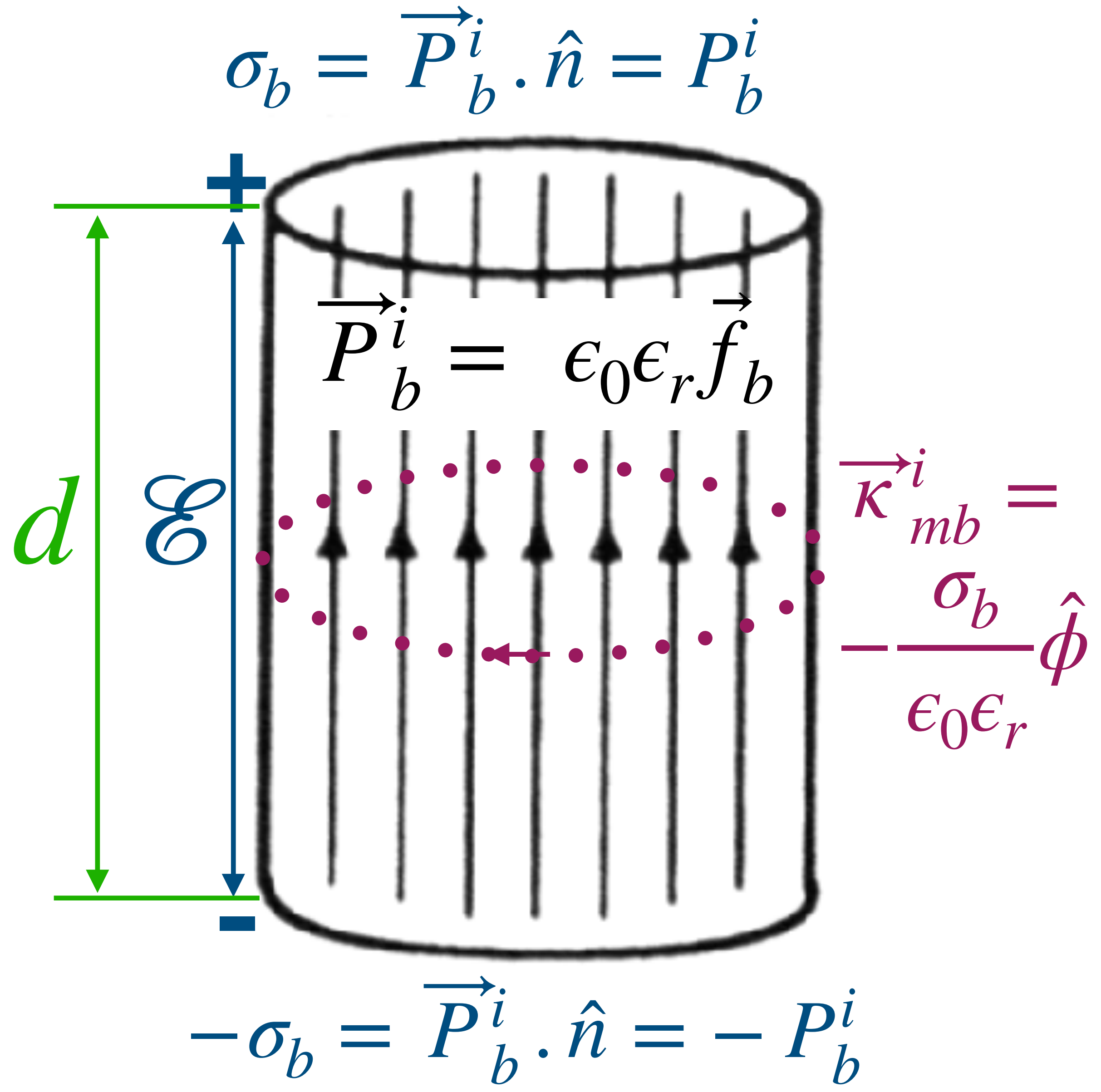


Two-Potential Formulation of Electrodynamics

$$\vec{E}_T = \vec{f}_T = \vec{D}/(\epsilon_0\epsilon_r) = \vec{E} + \vec{E}^i \text{ where } \vec{E}^i = \vec{P}_b^i/(\epsilon_0\epsilon_r)$$

$$\vec{E}^i = \vec{E}_C = -\frac{1}{\epsilon_0\epsilon_r}\nabla\times\vec{C}, \qquad \vec{E}_A = -\frac{\partial\vec{A}}{\partial t} - \nabla V;$$

In the quasi-static limit we can ignore $\frac{\partial\vec{A}}{\partial t}$



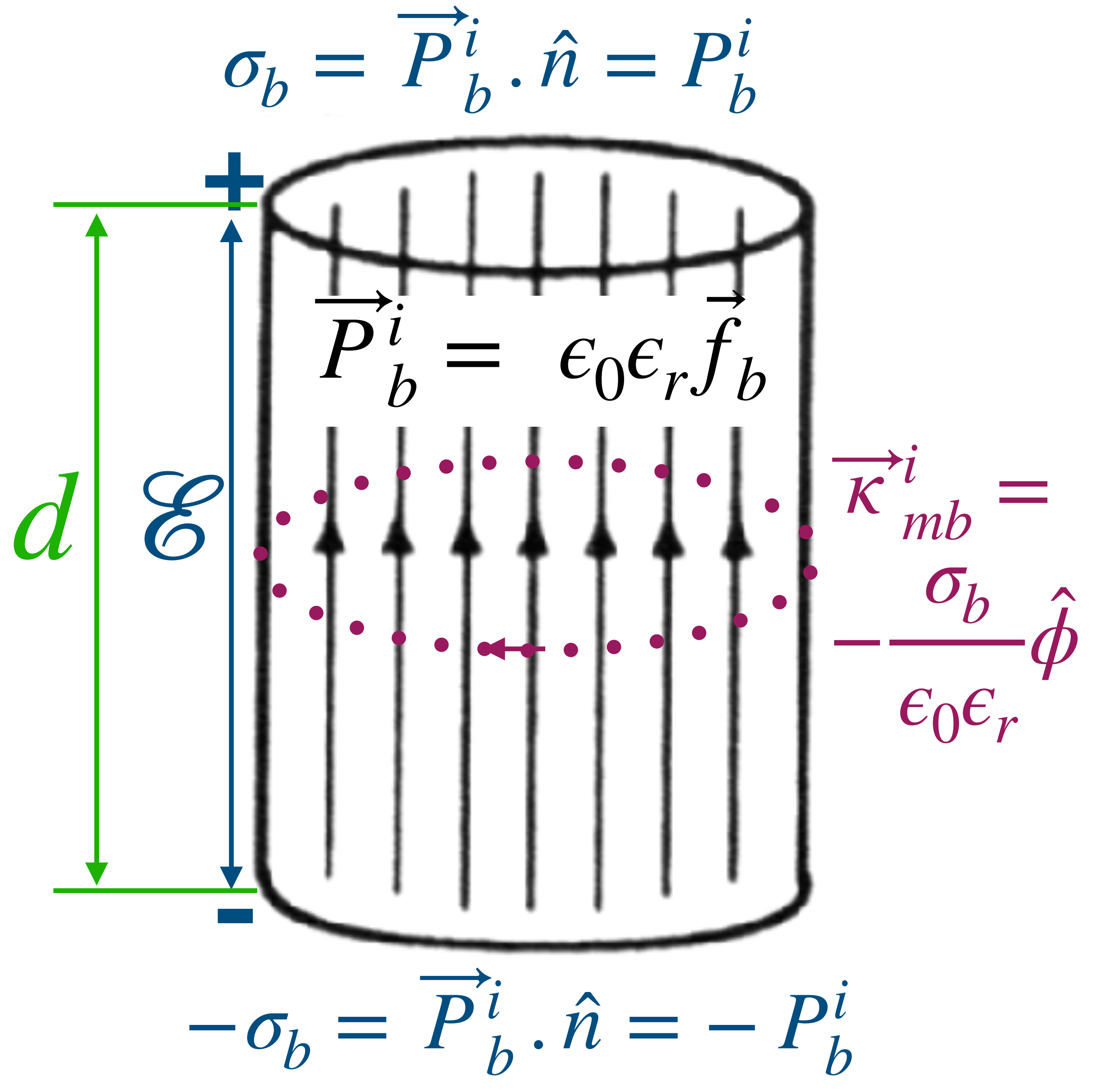
Two-Potential Formulation of Electrodynamics

$$\vec{E}_T = \vec{f}_T = \vec{D}/(\epsilon_0\epsilon_r) = \vec{E} + \vec{E}^i \text{ where } \vec{E}^i = \vec{P}_b^i/(\epsilon_0\epsilon_r)$$

$$\vec{E}^i = \vec{E}_C = -\frac{1}{\epsilon_0\epsilon_r}\nabla\times\vec{C}, \qquad \vec{E}_A = -\frac{\partial\vec{A}}{\partial t} - \nabla V;$$

In the quasi-static limit we can ignore $\frac{\partial\vec{A}}{\partial t}$

$$\vec{C}(\vec{r},t) = \frac{\epsilon_0\epsilon_r}{4\pi}\int_{S_1}\frac{\vec{\kappa}^i_{mb}(\vec{r}',t')}{|\vec{r}-\vec{r}'|}\mathrm{d}^2\vec{r}'$$



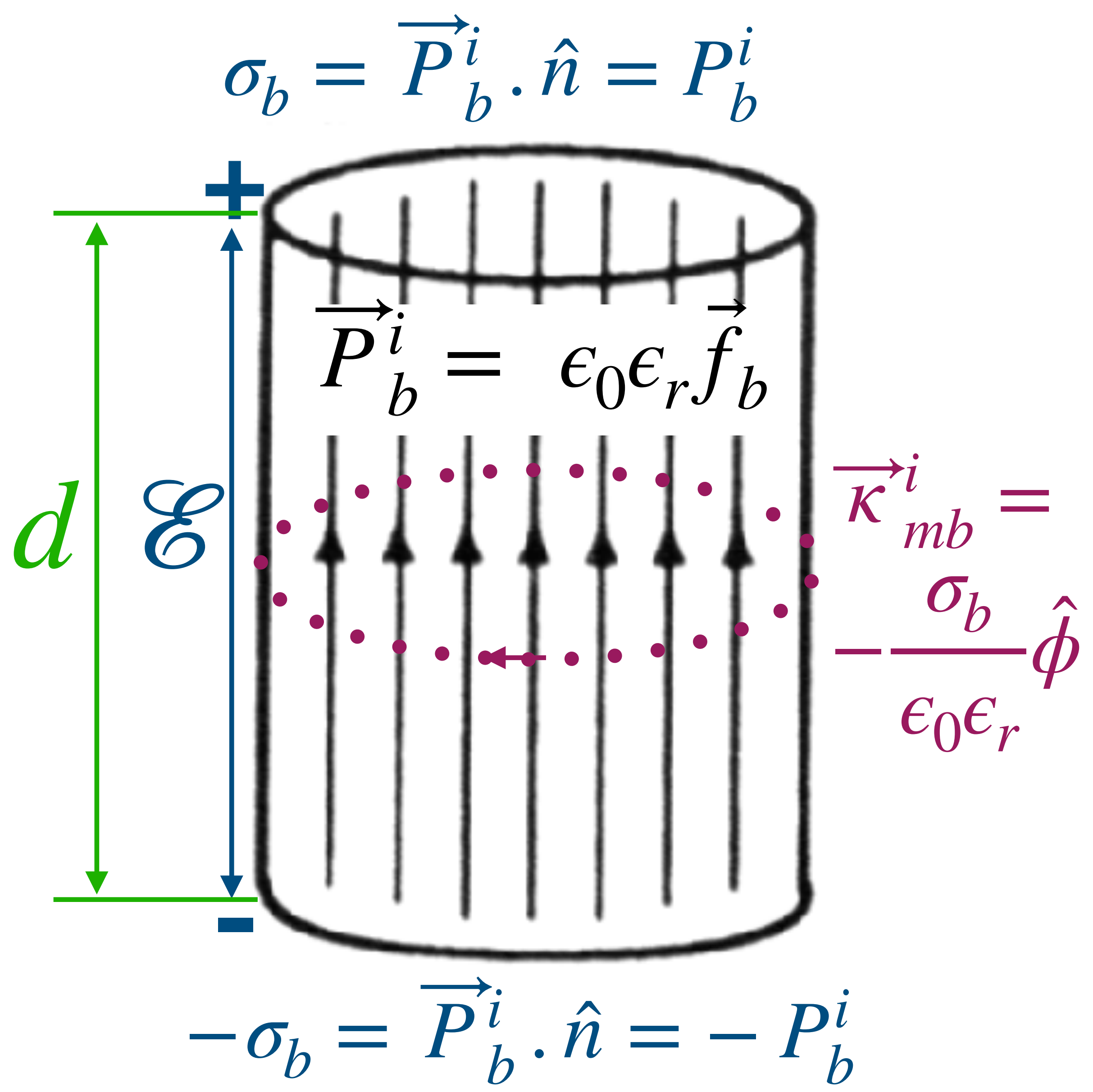
Two-Potential Formulation of Electrodynamics

$$\vec{E}_T = \vec{f}_T = \vec{D}/(\epsilon_0\epsilon_r) = \vec{E} + \vec{E}^i \text{ where } \vec{E}^i = \vec{P}_b^i/(\epsilon_0\epsilon_r)$$

$$\vec{E}^i = \vec{E}_C = -\frac{1}{\epsilon_0\epsilon_r}\nabla \times \vec{C}, \qquad \vec{E}_A = -\frac{\partial \vec{A}}{\partial t} - \nabla V,$$

In the quasi-static limit we can ignore $\frac{\partial \vec{A}}{\partial t}$

$$\vec{C}(\vec{r},t) = \frac{\epsilon_0\epsilon_r}{4\pi}\int_{S_1}\frac{\vec{\kappa}^i_{mb}(\vec{r}',t')}{|\vec{r}-\vec{r}'|}\mathrm{d}^2\vec{r}' \qquad V(\vec{r},t) = \frac{1}{4\pi\epsilon_0\epsilon_r}\int_{S_3,S_2}\frac{\sigma_b(\vec{r}',t')}{|\vec{r}-\vec{r}'|}\mathrm{d}^2\vec{r}'$$



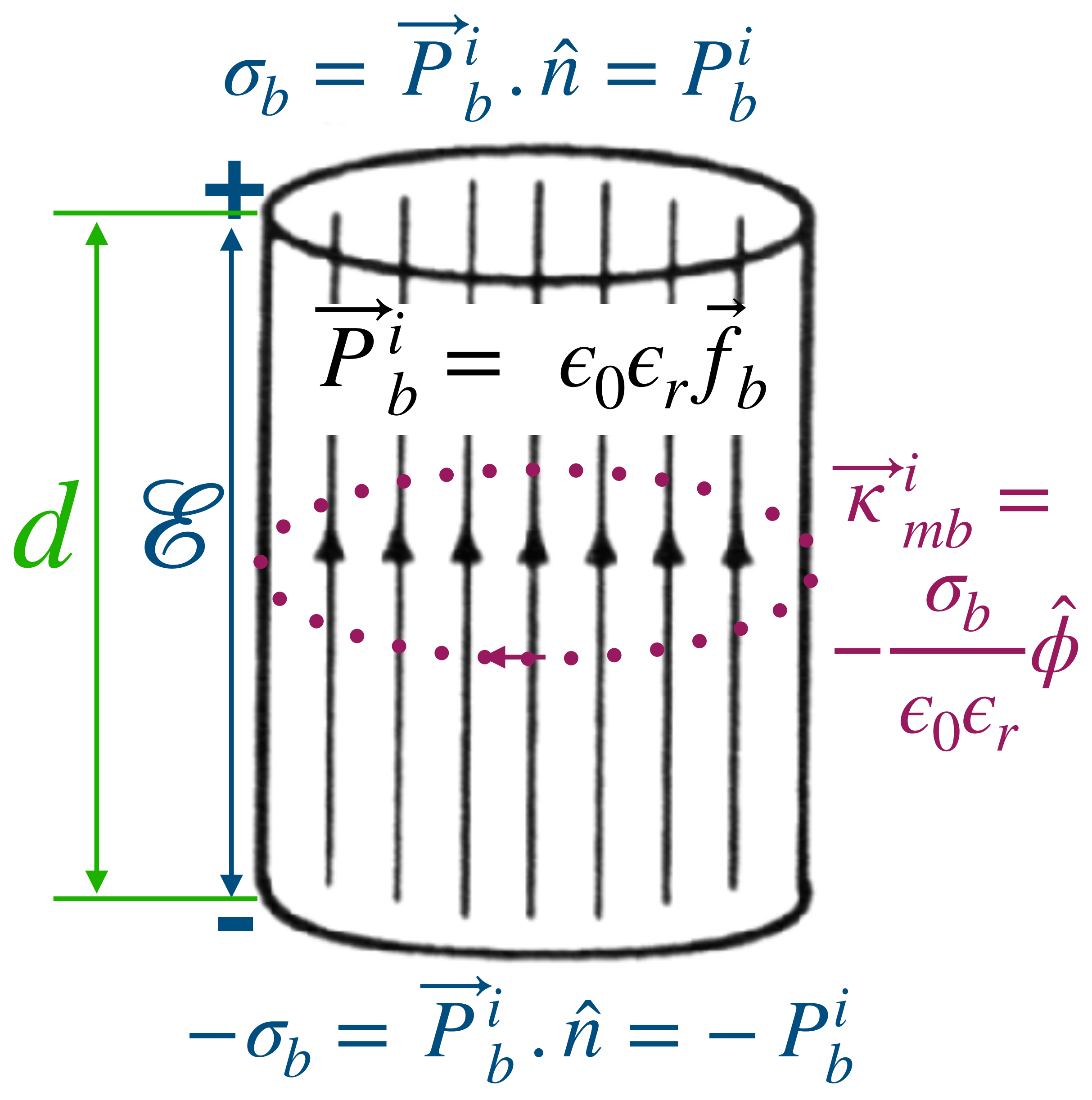
Two-Potential Formulation of Electrodynamics

$$\vec{E}_T = \vec{f}_T = \vec{D}/(\epsilon_0\epsilon_r) = \vec{E} + \vec{E}^i \text{ where } \vec{E}^i = \vec{P}_b^i/(\epsilon_0\epsilon_r)$$

$$\vec{E}^i = \vec{E}_C = -\frac{1}{\epsilon_0\epsilon_r}\nabla\times\vec{C}, \qquad \vec{E}_A = -\frac{\partial\vec{A}}{\partial t} - \nabla V,$$

In the quasi-static limit we can ignore $\frac{\partial\vec{A}}{\partial t}$

$$\vec{C}(\vec{r},t) = \frac{\epsilon_0\epsilon_r}{4\pi}\int_{S_1}\frac{\vec{\kappa}^i_{mb}(\vec{r}',t')}{|\vec{r}-\vec{r}'|}\mathrm{d}^2\vec{r}' \qquad V(\vec{r},t) = \frac{1}{4\pi\epsilon_0\epsilon_r}\int_{S_3,S_2}\frac{\sigma_b(\vec{r}',t')}{|\vec{r}-\vec{r}'|}\mathrm{d}^2\vec{r}'$$



Apply Superposition(See Harrington and Balanis)

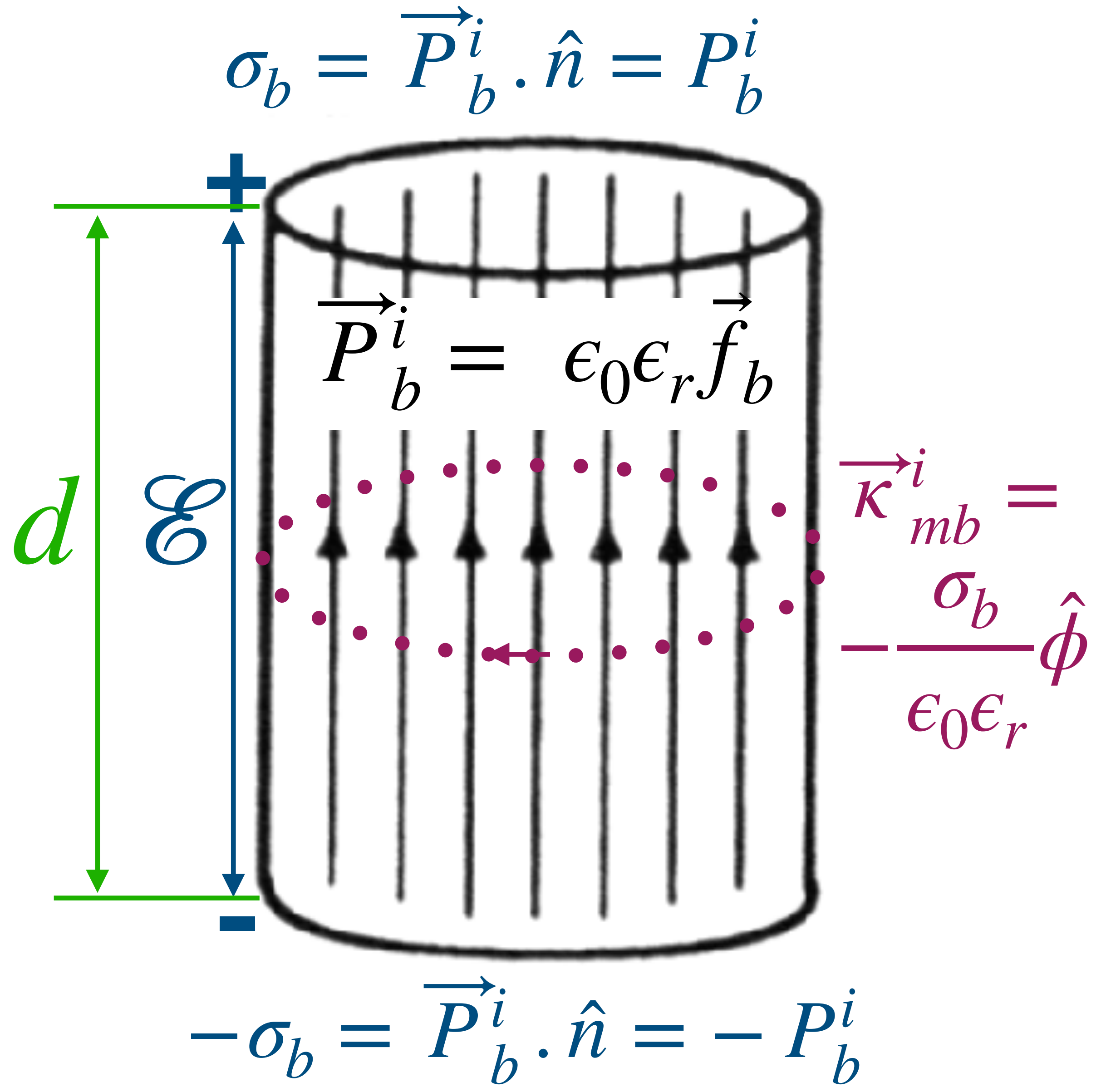
Two-Potential Formulation of Electrodynamics

$$\vec{E}_T = \vec{f}_T = \vec{D}/(\epsilon_0\epsilon_r) = \vec{E} + \vec{E}^i \text{ where } \vec{E}^i = \vec{P}^i_b/(\epsilon_0\epsilon_r)$$

$$\vec{E}^i = \vec{E}_C = -\frac{1}{\epsilon_0\epsilon_r}\nabla \times \vec{C}, \qquad \vec{E}_A = -\frac{\partial \vec{A}}{\partial t} - \nabla V;$$

In the quasi-static limit we can ignore $\frac{\partial \vec{A}}{\partial t}$

$$\vec{C}(\vec{r},t) = \frac{\epsilon_0\epsilon_r}{4\pi}\int_{S_1}\frac{\vec{\kappa}^i_{mb}(\vec{r}',t')}{|\vec{r}-\vec{r}'|}\mathrm{d}^2\vec{r}' \qquad V(\vec{r},t) = \frac{1}{4\pi\epsilon_0\epsilon_r}\int_{S_3,S_2}\frac{\sigma_b(\vec{r}',t')}{|\vec{r}-\vec{r}'|}\mathrm{d}^2\vec{r}'$$



Apply Superposition(See Harrington and Balanis)

Two-Potential Formulation of Electrodynamics

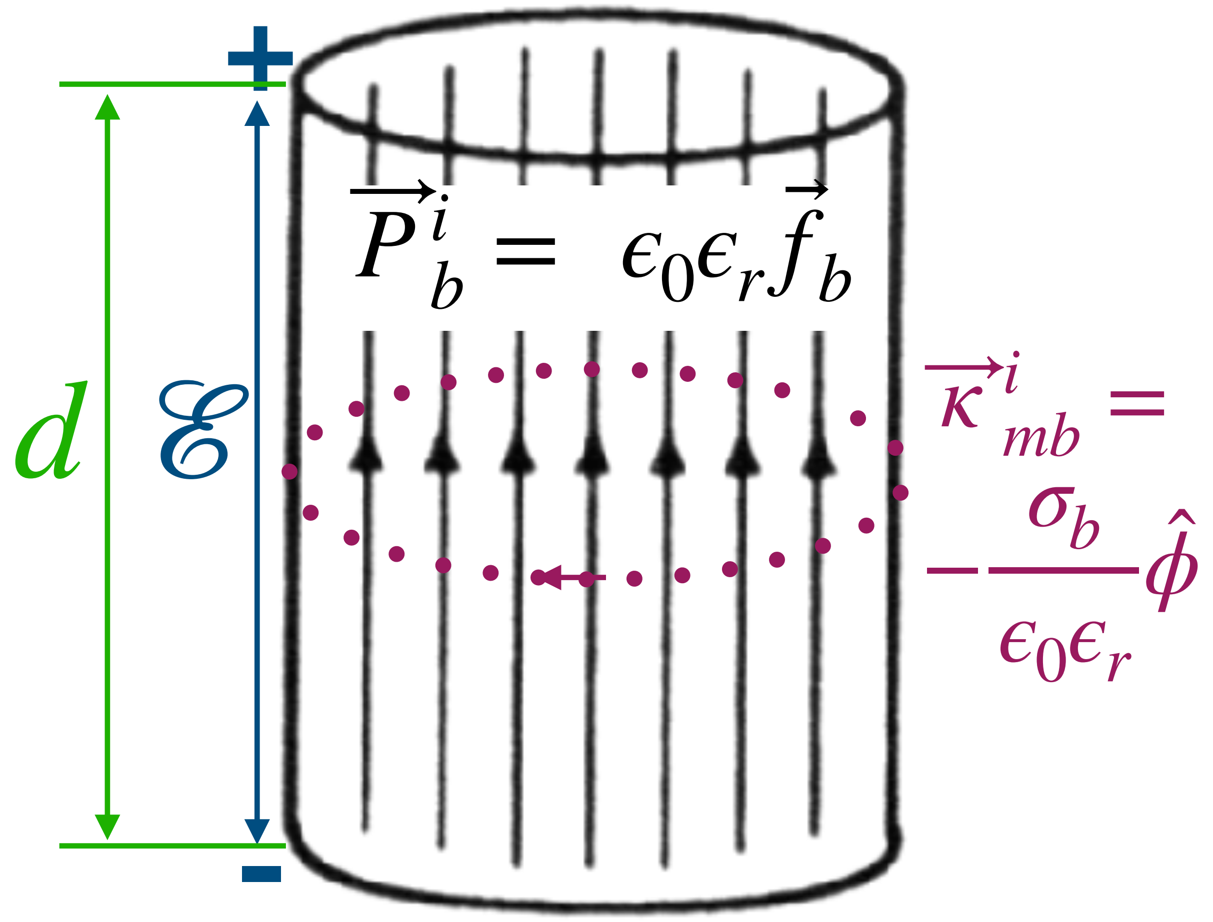
$$\vec{E}_T = \vec{f}_T = \vec{D}/(\epsilon_0\epsilon_r) = \vec{E} + \vec{E}^i \text{ where } \vec{E}^i = \vec{P}^i_b/(\epsilon_0\epsilon_r)$$

$$\vec{E}^i = \vec{E}_C = -\frac{1}{\epsilon_0\epsilon_r}\nabla\times\vec{C}, \qquad \vec{E}_A = -\frac{\partial\vec{A}}{\partial t} - \nabla V;$$

In the quasi-static limit we can ignore $\frac{\partial\vec{A}}{\partial t}$

$$\vec{C}(\vec{r},t) = \frac{\epsilon_0\epsilon_r}{4\pi}\int_{S_1}\frac{\vec{\kappa}^i_{mb}(\vec{r}',t')}{|\vec{r}-\vec{r}'|}\mathrm{d}^2\vec{r}' \qquad V(\vec{r},t) = \frac{1}{4\pi\epsilon_0\epsilon_r}\int_{S_3,S_2}\frac{\sigma_b(\vec{r}',t')}{|\vec{r}-\vec{r}'|}\mathrm{d}^2\vec{r}'$$

$\sigma_b = \vec{P}^i_b.\hat{n} = P^i_b$



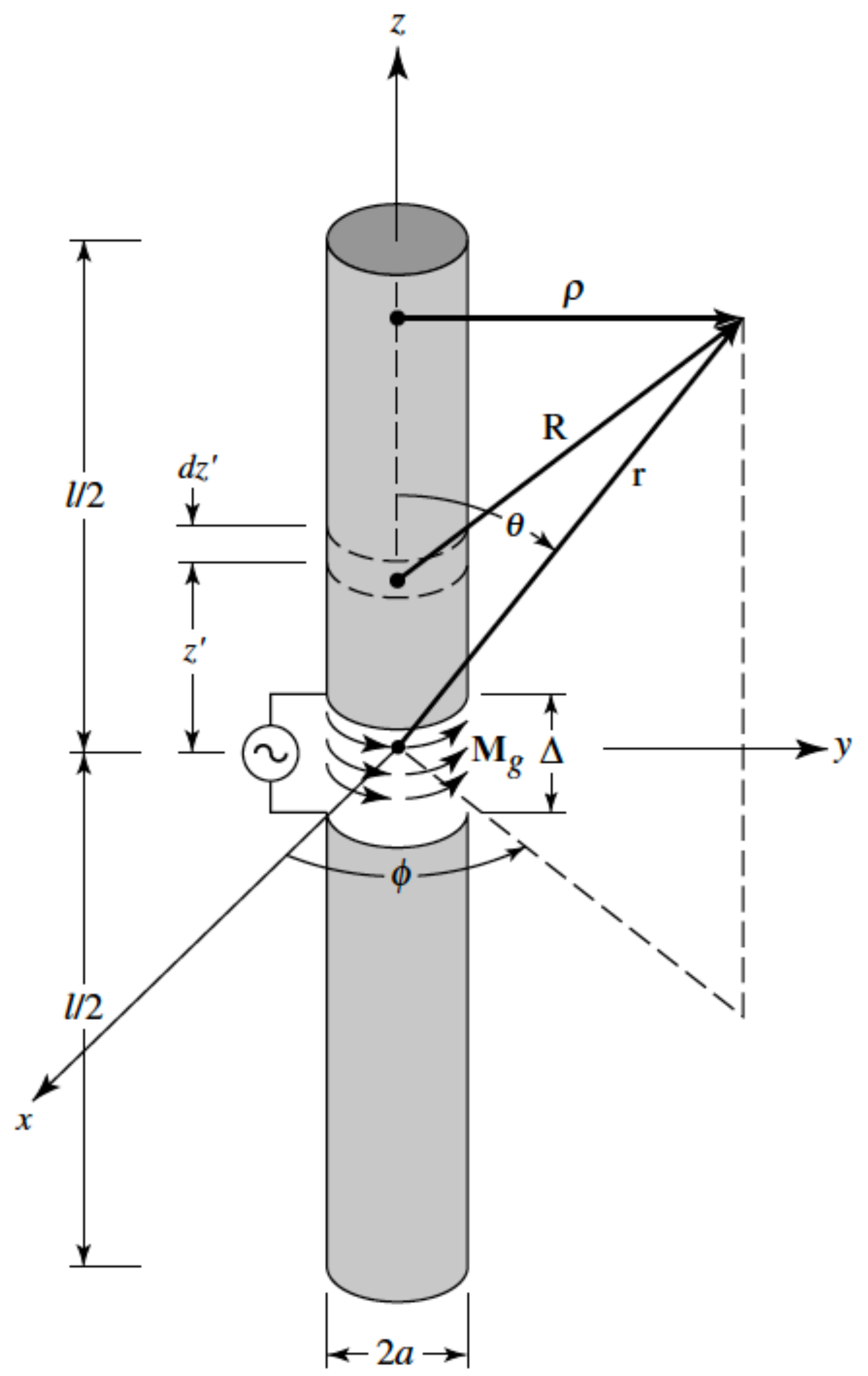
$-\sigma_b = \vec{P}^i_b.\hat{n} = -P^i_b$

Apply Superposition(See Harrington and Balanis)

$$\vec{E}_T = \vec{E}_A + \vec{E}_C = -\frac{\partial\vec{A}}{\partial t} - \nabla V - \frac{1}{\epsilon_0\epsilon_r}\nabla\times\vec{C}$$

$$\vec{B}_T = \vec{B}_A + \vec{B}_C = \nabla\times\vec{A} - \mu_0\frac{\partial\vec{C}}{\partial t}.$$

Another example is modelling antenna near and far fields driven by a voltage source -> Modelled by a magnetic current and Two-Potential formulation.



(a) Dipole

PHYSICAL REVIEW D **99**, 055010 (2019)

Solutions to axion electrodynamics in various geometries

Jonathan Ouellet* and Zachary Bogorad
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 27 September 2018; published 12 March 2019)

PHYSICAL REVIEW D **99,** 055010 (2019)

Solutions to axion electrodynamics in various geometries

Jonathan Ouellet[*] and Zachary Bogorad
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 27 September 2018; published 12 March 2019)

$$\vec{\nabla} \cdot \vec{P}_a = 0$$

Does not mean no Net field, just means lines are parallel, true for any lossless system.

PHYSICAL REVIEW D **99,** 055010 (2019)

Solutions to axion electrodynamics in various geometries

Jonathan Ouellet* and Zachary Bogorad
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 27 September 2018; published 12 March 2019)

$$\vec{\nabla} \cdot \vec{P}_a = 0$$

Does not mean no Net field, just means lines are parallel, true for any lossless system.

This paper ignores the Curl

PHYSICAL REVIEW D **99,** 055010 (2019)

Solutions to axion electrodynamics in various geometries

Jonathan Ouellet[*] and Zachary Bogorad
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 27 September 2018; published 12 March 2019)

$$\vec{\nabla} \cdot \vec{P}_a = 0$$

Does not mean no Net field, just means lines are parallel, true for any lossless system.

This paper ignores the Curl

$$\vec{\nabla} \times \vec{P}_a = -\, g_{a\gamma\gamma} \vec{\nabla} \times (a \vec{B}_0) = -\, g_{a\gamma\gamma} a \vec{J}_f = -\, \vec{J_m}$$

For axion at low-mass, only vector potential exists, scalar potential suppressed

PHYSICAL REVIEW D **99**, 055010 (2019)

$$\vec{\nabla} \cdot \vec{P}_a = 0$$

Does not mean no Net field, just means lines are parallel, true for any lossless system.

Solutions to axion electrodynamics in various geometries

Jonathan Ouellet* and Zachary Bogorad
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

This paper ignores the Curl

$$\vec{\nabla} \times \vec{P}_a = -g_{a\gamma\gamma}\vec{\nabla} \times (a\vec{B}_0) = -g_{a\gamma\gamma}a\vec{J}_f = -\vec{J}_m$$

(Received 27 September 2018; published 12 March 2019)

For axion at low-mass, only vector potential exists, scalar potential suppressed

$$\begin{aligned}\mathcal{E} = &\oint_C [\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}] \cdot d\boldsymbol{\ell} \\ &+ \frac{1}{q}\oint_C \text{Effective chemical forces} \cdot d\boldsymbol{\ell} \\ &+ \frac{1}{q}\oint_C \text{Effective thermal forces} \cdot d\boldsymbol{\ell}\,, \\ &+ \frac{1}{q}\oint_C \text{Effective axion forces} \cdot d\boldsymbol{\ell}\end{aligned}$$

PHYSICAL REVIEW D **99**, 055010 (2019)

Solutions to axion electrodynamics in various geometries

Jonathan Ouellet[*] and Zachary Bogorad
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 27 September 2018; published 12 March 2019)

$$\vec{\nabla} \cdot \vec{P}_a = 0$$

Does not mean no Net field, just means lines are parallel, true for any lossless system.

This paper ignores the Curl

$$\vec{\nabla} \times \vec{P}_a = -g_{a\gamma\gamma}\vec{\nabla} \times (a\vec{B}_0) = -g_{a\gamma\gamma}a\vec{J}_f = -\vec{J}_m$$

For axion at low-mass, only vector potential exists, scalar potential suppressed

$$\mathcal{E} = \oint_C [\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}] \cdot d\boldsymbol{\ell} + \frac{1}{q}\oint_C \text{Effective chemical forces} \cdot d\boldsymbol{\ell} + \frac{1}{q}\oint_C \text{Effective thermal forces} \cdot d\boldsymbol{\ell}\,, + \frac{1}{q}\oint_C \text{Effective axion forces} \cdot d\boldsymbol{\ell}$$

arXiv:1809.01654 [hep-ph]

$$\vec{\nabla} \times \vec{E}_T + \frac{\partial \vec{B}}{\partial t} = -g_{a\gamma\gamma}a\frac{c}{\epsilon_r}\mu_0 \vec{J}^{\,i}_{f_0} = -\vec{J}^{\,i}_{ma}$$

Axion Induced Effective Magnetic Current under DC Magnetic Field: an Impressed Voltage Source

Modified Electrodynamics

$$\vec{\nabla} \cdot \vec{E}_T = 0, \tag{29}$$

$$\vec{\nabla} \times \vec{B} - \frac{\epsilon_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_0 \vec{J}^i_{f_0}, \tag{30}$$

$$\vec{\nabla} \cdot \vec{B} = 0, \tag{31}$$

$$\vec{\nabla} \times \vec{E}_T + \frac{\partial \vec{B}}{\partial t} = -g_{a\gamma\gamma} a \frac{c}{\epsilon_r} \mu_0 \vec{J}^i_{f_0} = -\vec{J}^i_{ma}. \tag{32}$$

Axion Induced Effective Magnetic Current under DC Magnetic Field: an Impressed Voltage Source

Modified Electrodynamics

$$\vec{\nabla} \cdot \vec{E}_T = 0, \tag{29}$$

$$\vec{\nabla} \times \vec{B} - \frac{\epsilon_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_0 \vec{J}^i_{f_0}, \tag{30}$$

$$\vec{\nabla} \cdot \vec{B} = 0, \tag{31}$$

$$\vec{\nabla} \times \vec{E}_T + \frac{\partial \vec{B}}{\partial t} = -g_{a\gamma\gamma} a \frac{c}{\epsilon_r} \mu_0 \vec{J}^i_{f_0} = -\vec{J}^i_{ma}. \tag{32}$$

$$\vec{E}_T = \vec{E}_{aB} + \vec{E}$$

$$\vec{f}_{aB} = \vec{P}_{aB}/(\epsilon_r \epsilon_0) = \vec{E}_{aB} = -g_{a\gamma\gamma}\frac{c}{\epsilon_r}(a\vec{B}_0)$$

Axion Induced Effective Magnetic Current under DC Magnetic Field: an Impressed Voltage Source

Modified Electrodynamics

$$\vec{\nabla} \cdot \vec{E}_T = 0, \tag{29}$$

$$\vec{\nabla} \times \vec{B} - \frac{\epsilon_r}{c^2} \frac{\partial \vec{E}_T}{\partial t} = \mu_0 \vec{J}^i_{f_0}, \tag{30}$$

$$\vec{\nabla} \cdot \vec{B} = 0, \tag{31}$$

$$\vec{\nabla} \times \vec{E}_T + \frac{\partial \vec{B}}{\partial t} = -g_{a\gamma\gamma} a \frac{c}{\epsilon_r} \mu_0 \vec{J}^i_{f_0} = -\vec{J}^i_{ma}. \tag{32}$$

$$\vec{E}_T = \vec{E}_{aB} + \vec{E}$$

$$\vec{f}_{aB} = \vec{P}_{aB}/(\epsilon_r \epsilon_0) = \vec{E}_{aB} = -g_{a\gamma\gamma} \frac{c}{\epsilon_r} (a\vec{B}_0)$$

Force per unit charge supplied by the inverse Primakoff effect, ie. is a voltage source

Axion Induced Effective Magnetic Current under DC Magnetic Field: an Impressed Voltage Source

Modified Electrodynamics

$$\vec{\nabla} \cdot \vec{E}_T = 0, \tag{29}$$

$$\vec{\nabla} \times \vec{B} - \frac{\epsilon_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_0 \vec{J}^i_{f_0}, \tag{30}$$

$$\vec{\nabla} \cdot \vec{B} = 0, \tag{31}$$

$$\vec{\nabla} \times \vec{E}_T + \frac{\partial \vec{B}}{\partial t} = -g_{a\gamma\gamma} a \frac{c}{\epsilon_r}\mu_0 \vec{J}^i_{f_0} = -\vec{J}^i_{ma}. \tag{32}$$

$$\overrightarrow{E}_T = \overrightarrow{E}_{aB} + \overrightarrow{E}$$

$$\vec{f}_{aB} = \vec{P}_{aB}/(\epsilon_r \epsilon_0) = \vec{E}_{aB} = -g_{a\gamma\gamma}\frac{c}{\epsilon_r}(a\vec{B}_0)$$

Force per unit charge supplied by the inverse Primakoff effect, ie. is a voltage source

$$\mathcal{E} = \oint_P \vec{f}_{aB} \cdot d\vec{l} = \frac{1}{\epsilon_0 \epsilon_r}\oint_P \vec{P}_{aB} \cdot d\vec{l} = E_{aB} \times d$$

Axion Induced Effective Magnetic Current under DC Magnetic Field: an Impressed Voltage Source

Modified Electrodynamics

$$\vec{\nabla} \cdot \vec{E}_T = 0, \tag{29}$$

$$\vec{\nabla} \times \vec{B} - \frac{\epsilon_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_0 \vec{J}^i_{f_0}, \tag{30}$$

$$\vec{\nabla} \cdot \vec{B} = 0, \tag{31}$$

$$\vec{\nabla} \times \vec{E}_T + \frac{\partial \vec{B}}{\partial t} = -g_{a\gamma\gamma} a \frac{c}{\epsilon_r} \mu_0 \vec{J}^i_{f_0} = -\vec{J}^i_{ma}. \tag{32}$$

$$\vec{E}_T = \vec{E}_{aB} + \vec{E}$$

$$\vec{f}_{aB} = \vec{P}_{aB}/(\epsilon_r \epsilon_0) = \vec{E}_{aB} = -g_{a\gamma\gamma}\frac{c}{\epsilon_r}(a\vec{B}_0)$$

Force per unit charge supplied by the inverse Primakoff effect, ie. is a voltage source

$$\mathcal{E} = \oint_P \vec{f}_{aB} \cdot d\vec{l} = \frac{1}{\epsilon_0 \epsilon_r} \oint_P \vec{P}_{aB} \cdot d\vec{l} = E_{aB} \times d$$

$$E_{aB} = \mathcal{E}/d$$

Axion Induced Effective Magnetic Current under DC Magnetic Field: an Impressed Voltage Source

Modified Electrodynamics

$$\vec{\nabla}\cdot\vec{E}_T = 0, \tag{29}$$

$$\vec{\nabla}\times\vec{B} - \frac{\epsilon_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_0 \vec{J}^{i}_{f0}, \tag{30}$$

$$\vec{\nabla}\cdot\vec{B} = 0, \tag{31}$$

$$\vec{\nabla}\times\vec{E}_T + \frac{\partial \vec{B}}{\partial t} = -g_{a\gamma\gamma}a\frac{c}{\epsilon_r}\mu_0\vec{J}^{i}_{f0} = -\vec{J}^{i}_{ma}. \tag{32}$$

$$\vec{E}_T = \vec{E}_{aB} + \vec{E}$$

$$\vec{f}_{aB} = \vec{P}_{aB}/(\epsilon_r\epsilon_0) = \vec{E}_{aB} = -g_{a\gamma\gamma}\frac{c}{\epsilon_r}(a\vec{B}_0)$$

Force per unit charge supplied by the inverse Primakoff effect, ie. is a voltage source

$$\mathcal{E} = \oint_P \vec{f}_{aB}\cdot d\vec{l} = \frac{1}{\epsilon_0\epsilon_r}\oint_P \vec{P}_{aB}\cdot d\vec{l} = E_{aB}\times d$$

$$E_{aB} = \mathcal{E}/d$$

$$\vec{E}_{aB} = -\frac{1}{\epsilon_0\epsilon_r}\vec{\nabla}\times\vec{C}$$

Axion Induced Effective Magnetic Current under DC Magnetic Field: an Impressed Voltage Source

Modified Electrodynamics

$$\vec{\nabla} \cdot \vec{E}_T = 0, \tag{29}$$

$$\vec{\nabla} \times \vec{B} - \frac{\epsilon_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_0 \vec{J}^i_{f0}, \tag{30}$$

$$\vec{\nabla} \cdot \vec{B} = 0, \tag{31}$$

$$\vec{\nabla} \times \vec{E}_T + \frac{\partial \vec{B}}{\partial t} = -g_{a\gamma\gamma} a \frac{c}{\epsilon_r} \mu_0 \vec{J}^i_{f0} = -\vec{J}^i_{ma}. \tag{32}$$

$$\vec{E}_T = \vec{E}_{aB} + \vec{E}$$

$$\vec{f}_{aB} = \vec{P}_{aB}/(\epsilon_r \epsilon_0) = \vec{E}_{aB} = -g_{a\gamma\gamma}\frac{c}{\epsilon_r}(a\vec{B}_0)$$

Force per unit charge supplied by the inverse Primakoff effect, ie. is a voltage source

$$\mathcal{E} = \oint_P \vec{f}_{aB} \cdot d\vec{l} = \frac{1}{\epsilon_0 \epsilon_r} \oint_P \vec{P}_{aB} \cdot d\vec{l} = E_{aB} \times d$$

$$E_{aB} = \mathcal{E}/d$$

$$\vec{E}_{aB} = -\frac{1}{\epsilon_0 \epsilon_r} \vec{\nabla} \times \vec{C}$$

SCALAR POTENTIAL IS SUPPRESSED ->
VECTOR POTENTIAL ACTS ON CHARGES

Axion Induced Effective Magnetic Current under DC Magnetic Field: an Impressed Voltage Source

Modified Electrodynamics

$$\vec{\nabla} \cdot \vec{E}_T = 0, \tag{29}$$

$$\vec{\nabla} \times \vec{B} - \frac{\epsilon_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_0 \vec{J}^{i}_{f_0}, \tag{30}$$

$$\vec{\nabla} \cdot \vec{B} = 0, \tag{31}$$

$$\vec{\nabla} \times \vec{E}_T + \frac{\partial \vec{B}}{\partial t} = -g_{a\gamma\gamma} a \frac{c}{\epsilon_r}\mu_0 \vec{J}^{i}_{f_0} = -\vec{J}^{i}_{ma}. \tag{32}$$

$$\vec{E}_T = \vec{E}_{aB} + \vec{E}$$

$$\vec{f}_{aB} = \vec{P}_{aB}/(\epsilon_r\epsilon_0) = \vec{E}_{aB} = -g_{a\gamma\gamma}\frac{c}{\epsilon_r}(a\vec{B}_0)$$

Force per unit charge supplied by the inverse Primakoff effect, ie. is a voltage source

$$\mathcal{E} = \oint_P \vec{f}_{aB} \cdot d\vec{l} = \frac{1}{\epsilon_0\epsilon_r}\oint_P \vec{P}_{aB} \cdot d\vec{l} = E_{aB} \times d$$

$$E_{aB} = \mathcal{E}/d$$

$$\vec{E}_{aB} = -\frac{1}{\epsilon_0\epsilon_r}\vec{\nabla} \times \vec{C}$$

SCALAR POTENTIAL IS SUPPRESSED ->
VECTOR POTENTIAL ACTS ON CHARGES

$$\vec{C}(\vec{r},t) = \frac{\epsilon_0\epsilon_r}{4\pi}\int_\Omega \frac{\vec{J}^{i}_{ma}(\vec{r}',t')}{|\vec{r}-\vec{r}'|}\mathrm{d}^3\vec{r}' = \frac{g_{a\gamma\gamma}a}{4\pi c}\int_\Omega \frac{\vec{J}^{i}_{f_0}(\vec{r}',t')}{|\vec{r}-\vec{r}'|}\mathrm{d}^3\vec{r}'$$

Axion Induced Effective Magnetic Current under DC Magnetic Field: an Impressed Voltage Source

Modified Electrodynamics

$$\vec{\nabla} \cdot \vec{E}_T = 0, \tag{29}$$

$$\vec{\nabla} \times \vec{B} - \frac{\epsilon_r}{c^2}\frac{\partial \vec{E}_T}{\partial t} = \mu_0 \vec{J}^{i}_{f_0}, \tag{30}$$

$$\vec{\nabla} \cdot \vec{B} = 0, \tag{31}$$

$$\vec{\nabla} \times \vec{E}_T + \frac{\partial \vec{B}}{\partial t} = -g_{a\gamma\gamma} a \frac{c}{\epsilon_r} \mu_0 \vec{J}^{i}_{f_0} = -\vec{J}^{i}_{ma}. \tag{32}$$

$$\vec{E}_T = \vec{E}_{aB} + \vec{E}$$

$$\vec{f}_{aB} = \vec{P}_{aB}/(\epsilon_r \epsilon_0) = \vec{E}_{aB} = -g_{a\gamma\gamma}\frac{c}{\epsilon_r}(a\vec{B}_0)$$

Force per unit charge supplied by the inverse Primakoff effect, ie. is a voltage source

$$\mathcal{E} = \oint_P \vec{f}_{aB} \cdot d\vec{l} = \frac{1}{\epsilon_0 \epsilon_r}\oint_P \vec{P}_{aB} \cdot d\vec{l} = E_{aB} \times d$$

$$E_{aB} = \mathcal{E}/d$$

$$\vec{E}_{aB} = -\frac{1}{\epsilon_0 \epsilon_r}\vec{\nabla} \times \vec{C}$$

SCALAR POTENTIAL IS SUPPRESSED -> VECTOR POTENTIAL ACTS ON CHARGES

$$\vec{C}(\vec{r},t) = \frac{\epsilon_0 \epsilon_r}{4\pi}\int_\Omega \frac{\vec{J}^{i}_{ma}(\vec{r}',t')}{|\vec{r}-\vec{r}'|} \mathrm{d}^3\vec{r}' = \frac{g_{a\gamma\gamma} a}{4\pi c}\int_\Omega \frac{\vec{J}^{i}_{f_0}(\vec{r}',t')}{|\vec{r}-\vec{r}'|} \mathrm{d}^3\vec{r}'$$

$$\vec{C}(\vec{r},t) = \frac{g_{a\gamma\gamma} a}{4\pi}\int_{S_1} \frac{\vec{\kappa}^{i}_{fm}(\vec{r}',t')}{|\vec{r}-\vec{r}'|} \mathrm{d}^2\vec{r}'$$

QUANTUM FIELD CALCULATION

1. arXiv:1812.05487 [pdf, other]

Axion-electrodynamics: a quantum field calculation

Marc Beutter, Andreas Pargner, Thomas Schwetz, Elisa Todarello

Comments: 16 pages, 1 figure. Minor corrections. Matches published version in JCAP

Subjects: **High Energy Physics - Phenomenology (hep-ph)**

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Axion-electrodynamics: a quantum field calculation

Marc Beutter, Andreas Pargner, Thomas Schwetz and Elisa Todarello

Institut für Kernphysik, Karlsruhe Institute of Technology (KIT),
Hermann-von-Helmholtz-Platz 1, Eggenstein-Leopoldshafen, 76344 Germany

E-mail: marc.beutter@student.kit.edu, andreas.pargner@kit.edu, schwetz@kit.edu, elisa.todarello@kit.edu

QUANTUM FIELD CALCULATION

1. arXiv:1812.05487 [pdf, other]

Axion-electrodynamics: a quantum field calculation

Marc Beutter, Andreas Pargner, Thomas Schwetz, Elisa Todarello

Comments: 16 pages, 1 figure. Minor corrections. Matches published version in JCAP

Subjects: **High Energy Physics - Phenomenology (hep-ph)**

We can write the induced potential, eq. (2.10) in terms of the external E and B fields:

$$A_0^{\rm ind}(x) = i g_{a\gamma} a_0 \int \frac{d^3q}{(2\pi)^3}\frac{d^3p}{(2\pi)^3}\, a(\vec p)\, \frac{e^{-i\omega t} e^{i(\vec q+\vec p)\cdot\vec x}}{m_a^2 - \vec q^{\,2} - 2\vec q\cdot\vec p + i\epsilon}\, \vec p\cdot \vec B^{\rm ext}(\vec q) \tag{2.11}$$

$$\vec A^{\rm ind}(x) = i g_{a\gamma} a_0 \int \frac{d^3q}{(2\pi)^3}\frac{d^3p}{(2\pi)^3}\, a(\vec p)\, \frac{e^{-i\omega t} e^{i(\vec q+\vec p)\cdot\vec x}}{m_a^2 - \vec q^{\,2} - 2\vec q\cdot\vec p + i\epsilon} \left[\omega \vec B^{\rm ext}(\vec q) + \vec p\times \vec E^{\rm ext}(\vec q)\right] \tag{2.12}$$

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Axion-electrodynamics: a quantum field calculation

Marc Beutter, Andreas Pargner, Thomas Schwetz and Elisa Todarello

Institut für Kernphysik, Karlsruhe Institute of Technology (KIT),
Hermann-von-Helmholtz-Platz 1, Eggenstein-Leopoldshafen, 76344 Germany

E-mail: marc.beutter@student.kit.edu, andreas.pargner@kit.edu, schwetz@kit.edu, elisa.todarello@kit.edu

QUANTUM FIELD CALCULATION

1. arXiv:1812.05487 [pdf, other]

Axion-electrodynamics: a quantum field calculation

Marc Beutter, Andreas Pargner, Thomas Schwetz, Elisa Todarello

Comments: 16 pages, 1 figure. Minor corrections. Matches published version in JCAP

Subjects: **High Energy Physics - Phenomenology (hep-ph)**

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Axion-electrodynamics: a quantum field calculation

Marc Beutter, Andreas Pargner, Thomas Schwetz and Elisa Todarello

Institut für Kernphysik, Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, Eggenstein-Leopoldshafen, 76344 Germany

E-mail: marc.beutter@student.kit.edu, andreas.pargner@kit.edu, schwetz@kit.edu, elisa.todarello@kit.edu

We can write the induced potential, eq. (2.10) in terms of the external E and B fields:

$$A_0^{\rm ind}(x) = i g_{a\gamma} a_0 \int \frac{d^3q}{(2\pi)^3}\frac{d^3p}{(2\pi)^3}\, a(\vec p)\frac{e^{-i\omega t}e^{i(\vec q+\vec p)\cdot\vec x}}{m_a^2-\vec q^{\,2}-2\vec q\cdot\vec p+i\epsilon}\,\vec p\cdot\vec B^{\rm ext}(\vec q) \tag{2.11}$$

$$\vec A^{\rm ind}(x) = i g_{a\gamma} a_0 \int \frac{d^3q}{(2\pi)^3}\frac{d^3p}{(2\pi)^3}\, a(\vec p)\frac{e^{-i\omega t}e^{i(\vec q+\vec p)\cdot\vec x}}{m_a^2-\vec q^{\,2}-2\vec q\cdot\vec p+i\epsilon}\left[\omega\vec B^{\rm ext}(\vec q)+\vec p\times\vec E^{\rm ext}(\vec q)\right] \tag{2.12}$$

$$\vec E^{\rm ind}(x) = -\frac{\partial\vec A^{\rm ind}}{\partial t} = -g_{a\gamma}a_0 m_a^2\, e^{-im_a t}\int\frac{d^3q}{(2\pi)^3}\frac{e^{i\vec q\cdot\vec x}}{m_a^2-\vec q^{\,2}+i\epsilon}\vec B^{\rm ext}(\vec q)\,, \tag{2.15}$$

$$\vec B^{\rm ind}(x) = \vec\nabla\times\vec A^{\rm ind} = -g_{a\gamma}a_0 m_a\, e^{-im_a t}\int\frac{d^3q}{(2\pi)^3}\frac{e^{i\vec q\cdot\vec x}}{m_a^2-\vec q^{\,2}+i\epsilon}\vec q\times\vec B^{\rm ext}(\vec q)\,. \tag{2.16}$$

QUANTUM FIELD CALCULATION

1. arXiv:1812.05487 [pdf, other]

Axion-electrodynamics: a quantum field calculation

Marc Beutter, Andreas Pargner, Thomas Schwetz, Elisa Todarello

Comments: 16 pages, 1 figure. Minor corrections. Matches published version in JCAP

Subjects: **High Energy Physics - Phenomenology (hep-ph)**

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Axion-electrodynamics: a quantum field calculation

Marc Beutter, Andreas Pargner, Thomas Schwetz and Elisa Todarello

Institut für Kernphysik, Karlsruhe Institute of Technology (KIT),
Hermann-von-Helmholtz-Platz 1, Eggenstein-Leopoldshafen, 76344 Germany

E-mail: marc.beutter@student.kit.edu, andreas.pargner@kit.edu, schwetz@kit.edu, elisa.todarello@kit.edu

We can write the induced potential, eq. (2.10) in terms of the external E and B fields:

$$A_0^{\rm ind}(x) = i g_{a\gamma} a_0 \int \frac{d^3q}{(2\pi)^3}\frac{d^3p}{(2\pi)^3}\, a(\vec p)\, \frac{e^{-i\omega t} e^{i(\vec q+\vec p)\cdot\vec x}}{m_a^2 - \vec q^{\,2} - 2\vec q\cdot\vec p + i\epsilon}\, \vec p\cdot \vec B^{\rm ext}(\vec q) \tag{2.11}$$

$$\vec A^{\rm ind}(x) = i g_{a\gamma} a_0 \int \frac{d^3q}{(2\pi)^3}\frac{d^3p}{(2\pi)^3}\, a(\vec p)\, \frac{e^{-i\omega t} e^{i(\vec q+\vec p)\cdot\vec x}}{m_a^2 - \vec q^{\,2} - 2\vec q\cdot\vec p + i\epsilon} \left[\omega \vec B^{\rm ext}(\vec q) + \vec p \times \vec E^{\rm ext}(\vec q)\right] \tag{2.12}$$

$$\vec E^{\rm ind}(x) = -\frac{\partial \vec A^{\rm ind}}{\partial t} = -g_{a\gamma} a_0 m_a^2\, e^{-i m_a t} \int \frac{d^3q}{(2\pi)^3} \frac{e^{i\vec q\cdot\vec x}}{m_a^2 - \vec q^{\,2} + i\epsilon} \vec B^{\rm ext}(\vec q)\,, \tag{2.15}$$

$$\vec B^{\rm ind}(x) = \vec\nabla \times \vec A^{\rm ind} = -g_{a\gamma} a_0 m_a\, e^{-i m_a t} \int \frac{d^3q}{(2\pi)^3} \frac{e^{i\vec q\cdot\vec x}}{m_a^2 - \vec q^{\,2} + i\epsilon} \vec q \times \vec B^{\rm ext}(\vec q)\,. \tag{2.16}$$

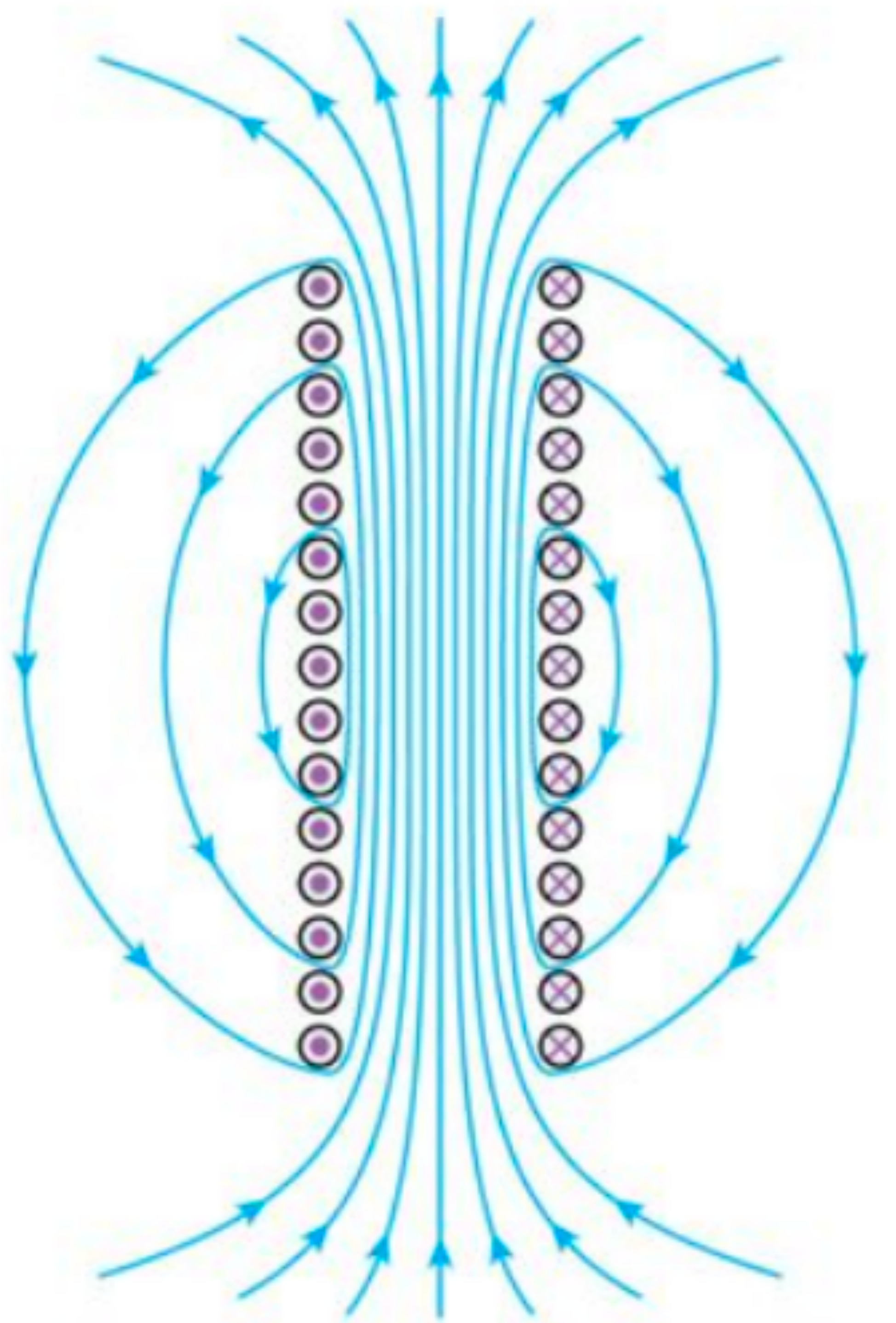
IGNORES THE ELECTRIC VECTOR POTENTIAL

Effective Approximation of Electromagnetism for Axion Haloscope Searches

Younggeun Kim, Dongok Kim, Junu Jung, Jinsu Kim, Yun Chang Shin, Yannis K. Semertzidis

(Submitted on 4 Oct 2018 (v1), last revised 1 Feb 2019 (this version, v4))

We applied an effective approximation into Maxwell's equations with an axion interaction for haloscope searches. A set of Maxwell's equations acquired from this approximation describes just the reacted fields generated by the anomalous interaction. Unlike other approaches, this set of Maxwell's equations inherently satisfies the boundary conditions for haloscope searches. The electromagnetic field solutions from the Maxwell's equations were evaluated for both cylindrical and toroidal cavity geometries including when the axion mass becomes ultra-light (sub-meV). A small but non-zero difference between the electric and magnetic stored energies appeared in both cases. The difference may come from an anomalous non-dissipating current induced by oscillating axions.



$$\nabla \cdot (\mathbf{E} - c g_{a\gamma\gamma} a \mathbf{B}) = \frac{\rho_e}{\varepsilon},$$

$$\nabla \cdot \mathbf{B} = 0,$$

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

$$\nabla \times (c\mathbf{B} + g_{a\gamma\gamma} a \mathbf{E}) = \frac{1}{c}\frac{\partial}{\partial t}(\mathbf{E} - c g_{a\gamma\gamma} a \mathbf{B}) + c\mu \mathbf{J}_e.$$

- zero current : $\mathbf{J_e} = 0$,
- zero charge density : $\rho_e = 0$,
- zero external electric field : $\mathbf{E}_{\text{ext}} = 0$,
- nonzero external magnetic field : $\mathbf{B} = \mathbf{B}_{\text{ext}}$,
- curlless magnetic field : $\nabla \times \mathbf{B} = \nabla \times \mathbf{B}_{\text{ext}} = 0$,
- time independent magnetic field : $\dot{\mathbf{B}} = 0$.

Boundary Conditions

$$\oiint_S \vec{E}_T \cdot d\vec{a} = 0,$$

$$\oint_P \vec{B} \cdot d\vec{l} = \mu_0 I^i_{f_0 enc} + \mu_0 \epsilon_r \epsilon_0 \frac{d}{dt} \int_S \vec{E}_T \cdot d\vec{a}$$

$$\oiint_S \vec{B} \cdot d\vec{a} = 0,$$

$$\oint_P \vec{E}_T \cdot d\vec{l} = -\frac{d}{dt} \int_S \vec{B} \cdot d\vec{a} - g_{a\gamma\gamma} a \frac{c}{\epsilon_r} \mu_0 I^i_{f_0 enc}$$

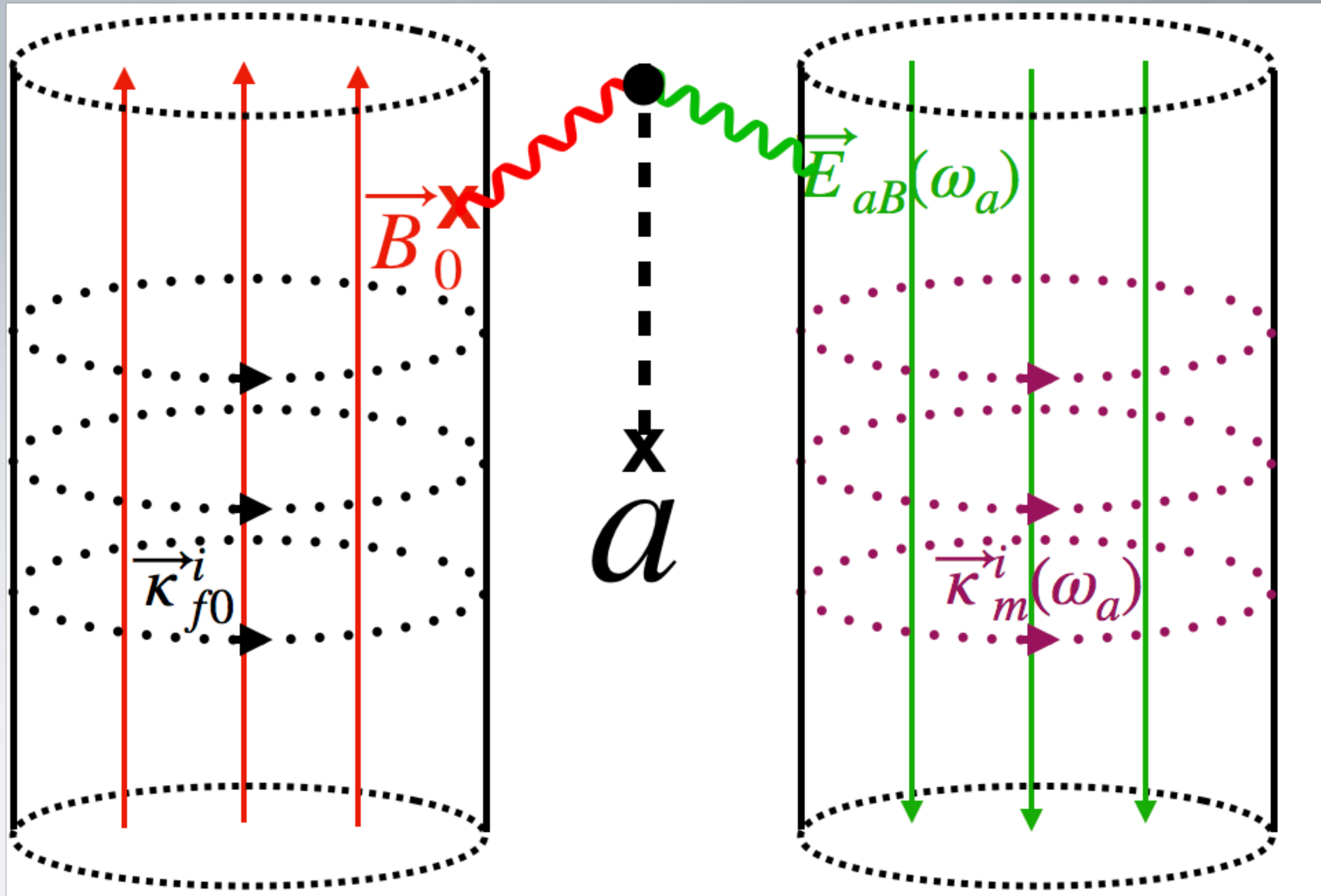
Here, $I^i_{f_0 enc} = \int_S \vec{J}^i_{f_0} \cdot d\vec{a}$.

$$\vec{E}^{\parallel}_{T1} - \vec{E}^{\parallel}_{T2} = -g_{a\gamma\gamma} a \frac{c}{\epsilon_r} \mu_0 \vec{\kappa}^i_{f_0} \times \hat{n} = -\vec{\kappa}^i_{f_m} \times \hat{n} = \vec{E}_{aB}$$

$$\vec{E}^{\perp}_{T1} = \vec{E}^{\perp}_{T2},$$

$$\vec{B}^{\parallel}_1 - \vec{B}^{\parallel}_2 = \mu_0 \vec{\kappa}^i_{f_0} \times \hat{n},$$

$$\vec{B}^{\perp}_1 = \vec{B}^{\perp}_2.$$



THE END: THANK YOU

QUESTIONS?

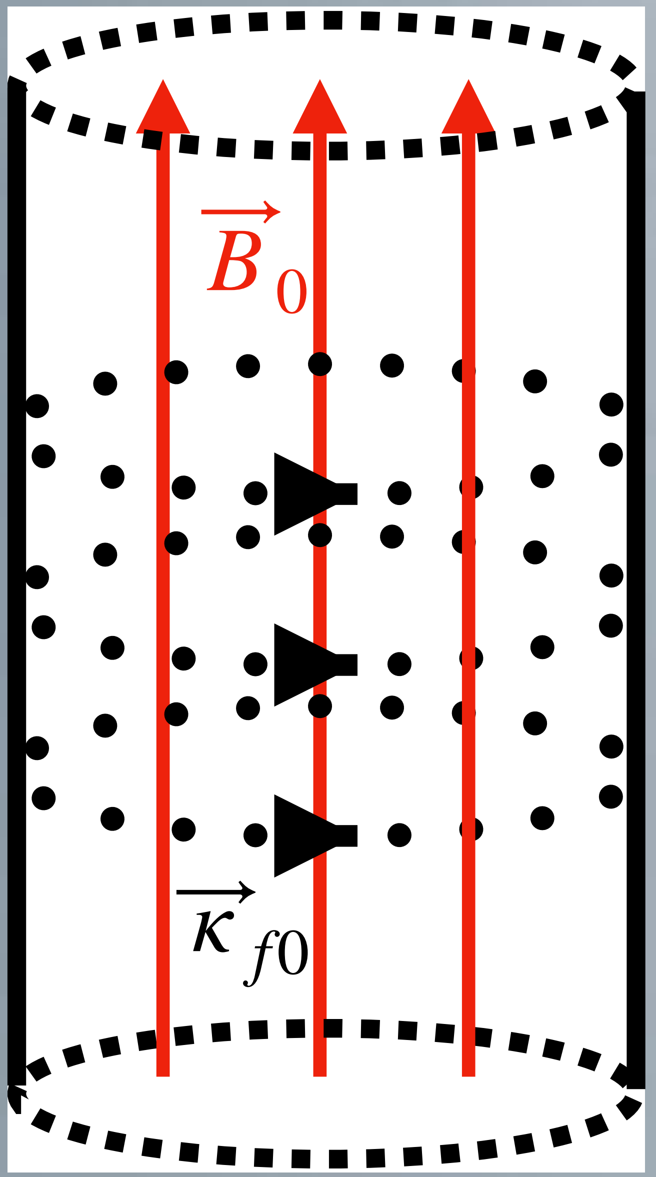
What is the Orthogonality of E and B in the Low-Mass Limit under DC Magnetic Field?

$$\mathscr{L}_{a\gamma} = \frac{g_{a\gamma}}{4} aF\tilde{F} = -g_{a\gamma\gamma} a \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot \vec{B}$$

Axion Two Photon Coupling

$$a(t) \approx a_0 \cos(\omega_a t)$$

What is the Orthogonality of E and B in the Low-Mass Limit under DC Magnetic Field?



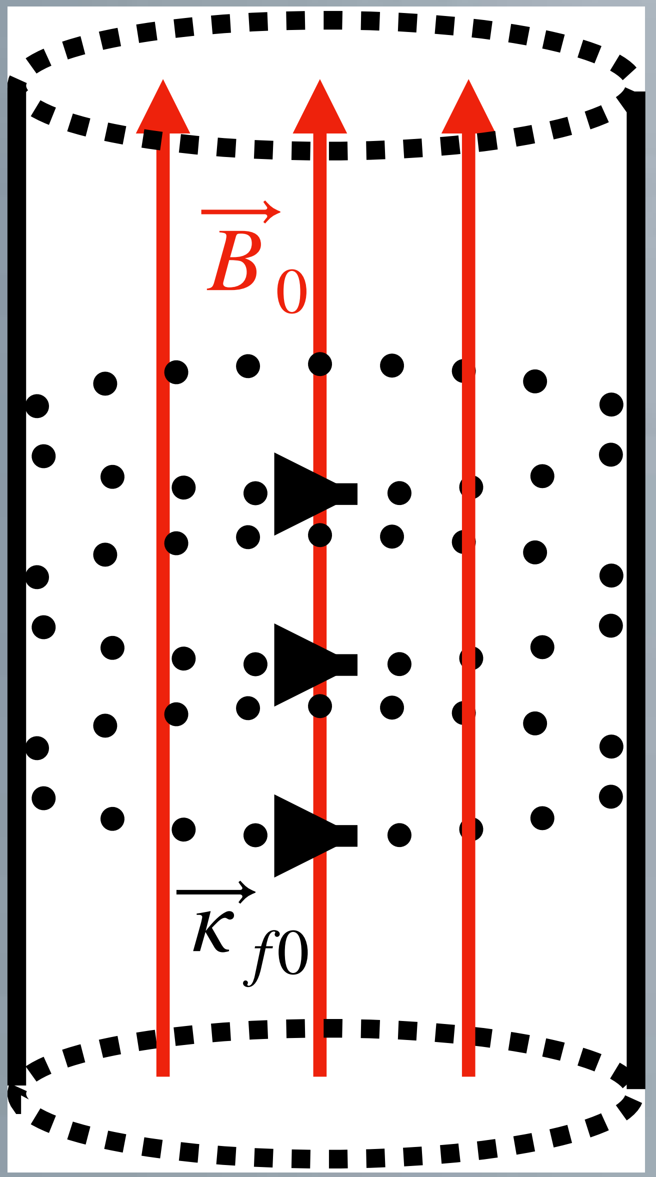
$$\mathscr{L}_{a\gamma} = \frac{g_{a\gamma}}{4} aF\tilde{F} = -g_{a\gamma\gamma}a\sqrt{\frac{\epsilon_0}{\mu_0}}\vec{E}\cdot\vec{B}$$

Axion Two Photon Coupling

$$\vec{B} = \vec{B}_0$$

$$a(t) \approx a_0 \cos(\omega_a t)$$

What is the Orthogonality of E and B in the Low-Mass Limit under DC Magnetic Field?



Axion Two Photon Coupling

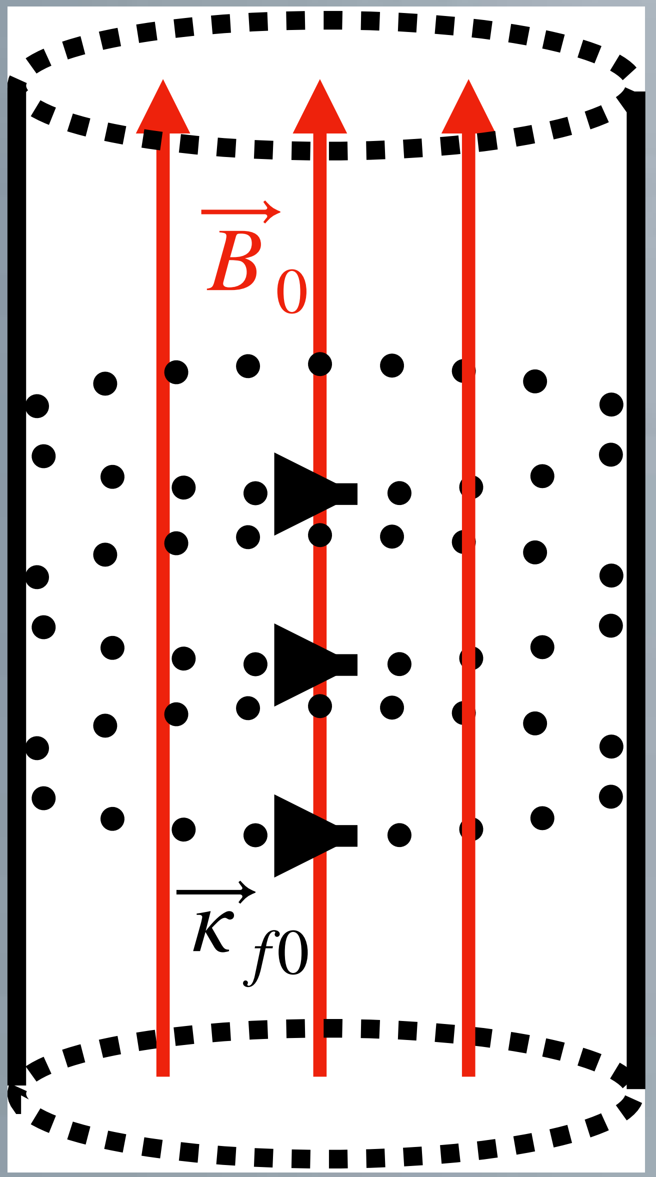
$$\mathcal{L}_{a\gamma} = \frac{g_{a\gamma}}{4} aF\tilde{F} = -g_{a\gamma\gamma} a \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot \vec{B}$$

$$\vec{B} = \vec{B}_0$$

$$\mathcal{L}_{a\gamma} = -g_{a\gamma\gamma} \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot (a\vec{B}_0)$$

$$a(t) \approx a_0 \cos(\omega_a t)$$

What is the Orthogonality of E and B in the Low-Mass Limit under DC Magnetic Field?



$$\mathcal{L}_{a\gamma} = \frac{g_{a\gamma}}{4} aF\tilde{F} = -g_{a\gamma\gamma} a \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot \vec{B}$$

Axion Two Photon Coupling

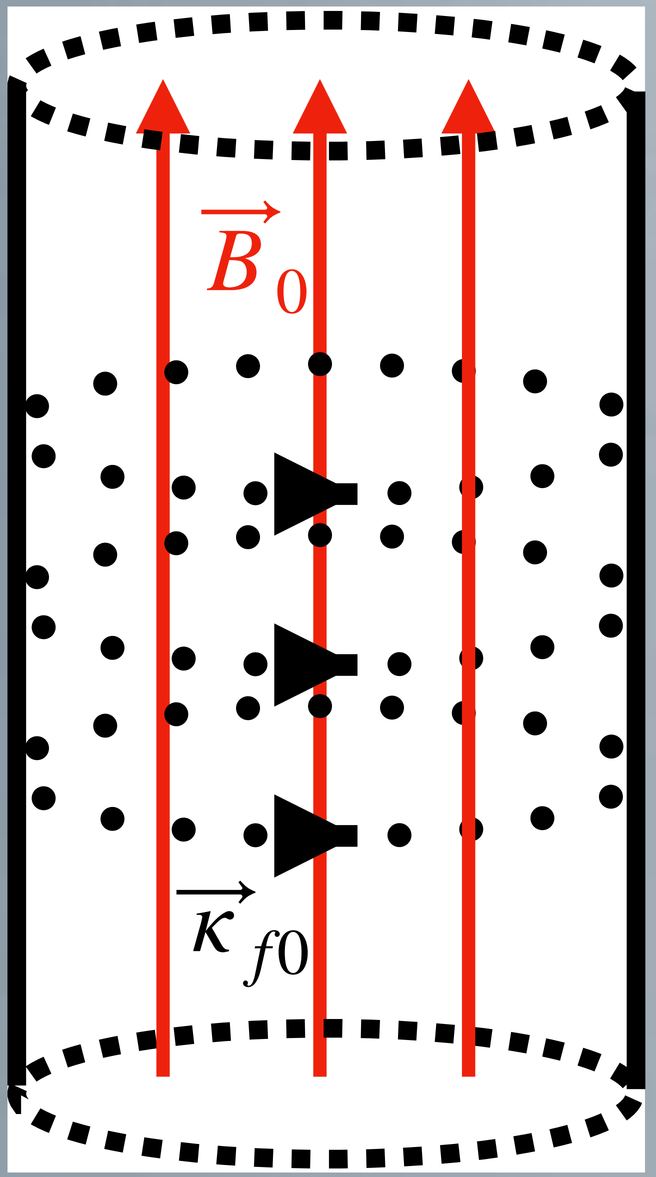
$$\vec{B} = \vec{B}_0$$

$$\mathcal{L}_{a\gamma} = -g_{a\gamma\gamma} \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot (a\vec{B}_0)$$

Solenoidal oscillating at axion Compton frequency

$$a(t) \approx a_0 \cos(\omega_a t)$$

What is the Orthogonality of E and B in the Low-Mass Limit under DC Magnetic Field?



$$\mathscr{L}_{a\gamma} = \frac{g_{a\gamma}}{4} aF\tilde{F} = -g_{a\gamma\gamma} a \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot \vec{B}$$

Axion Two Photon Coupling

$$\vec{B} = \vec{B}_0$$

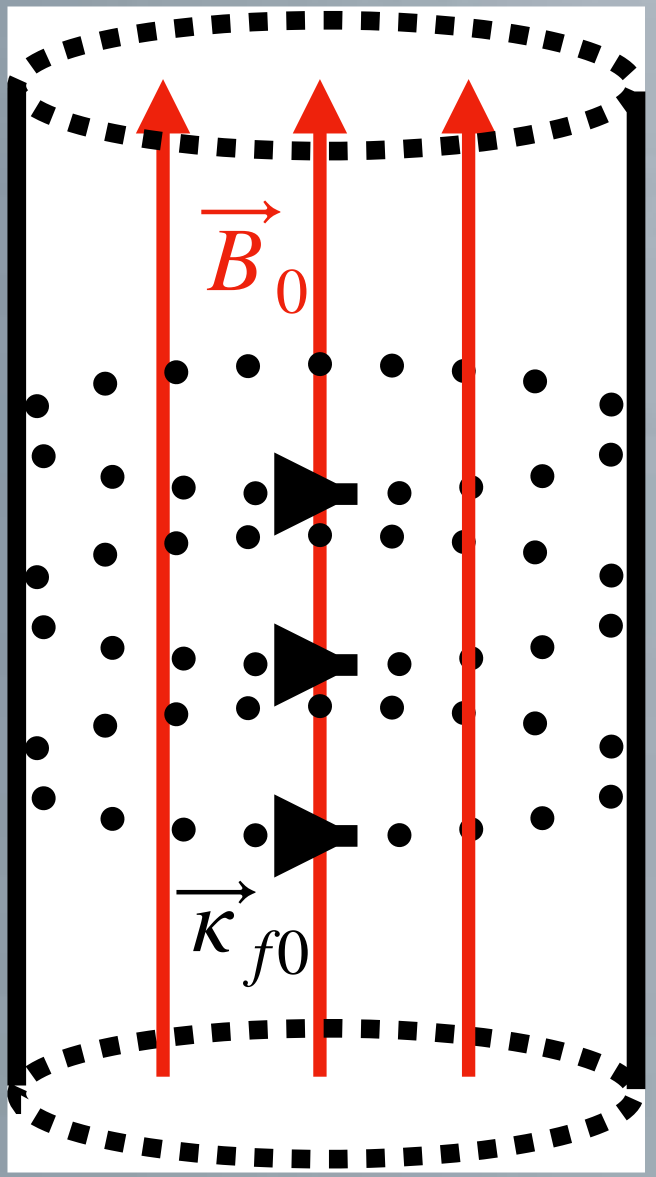
$$\mathscr{L}_{a\gamma} = -g_{a\gamma\gamma} \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot (a\vec{B}_0)$$

Solenoidal oscillating at axion Compton frequency

$$a(t) \approx a_0 \cos(\omega_a t)$$

- -> To get direct sensitivity E must have non-zero Curl (i.e. a Voltage Source)!

What is the Orthogonality of E and B in the Low-Mass Limit under DC Magnetic Field?



$$\mathscr{L}_{a\gamma} = \frac{g_{a\gamma}}{4} aF\tilde{F} = -g_{a\gamma\gamma} a \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot \vec{B}$$

Axion Two Photon Coupling

$$\vec{B} = \vec{B}_0$$

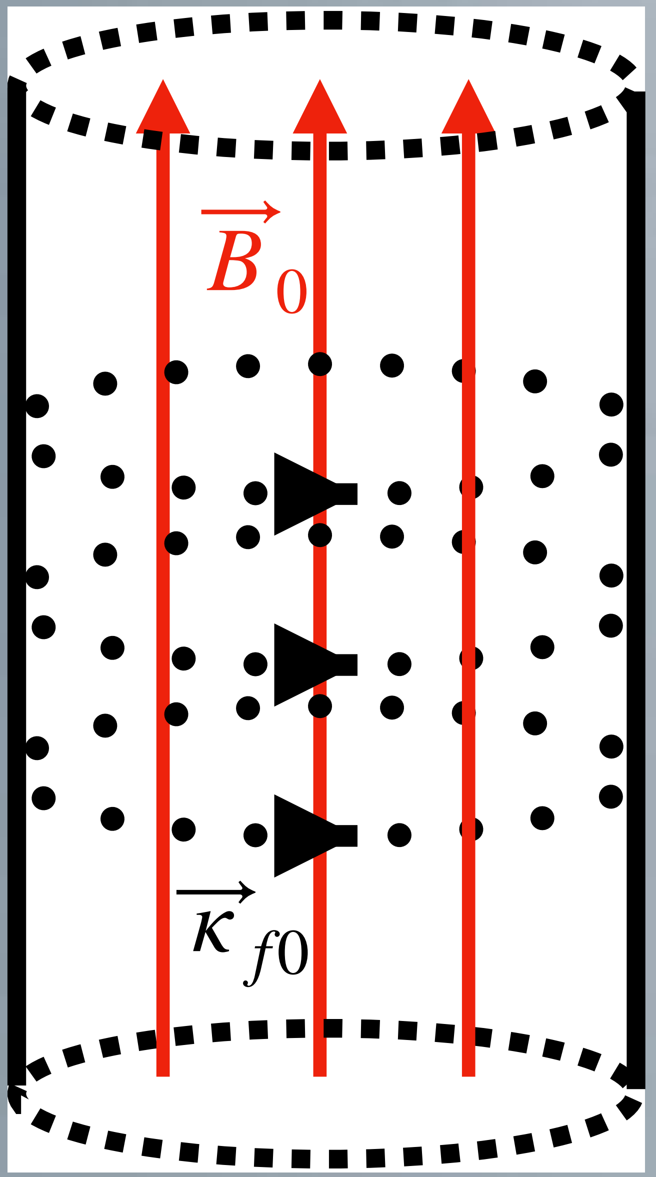
$$\mathscr{L}_{a\gamma} = -g_{a\gamma\gamma} \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot (a\vec{B}_0)$$

Solenoidal oscillating at axion Compton frequency

$$a(t) \approx a_0 \cos(\omega_a t)$$

- -> To get direct sensitivity E must have non-zero Curl (i.e. a Voltage Source)!
- -> Answer is that need to Redefine E and B fields to include the axion modified parts!

What is the Orthogonality of E and B in the Low-Mass Limit under DC Magnetic Field?



$$\mathcal{L}_{a\gamma} = \frac{g_{a\gamma}}{4} aF\tilde{F} = -g_{a\gamma\gamma} a \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot \vec{B}$$

Axion Two Photon Coupling

$$\vec{B} = \vec{B}_0$$

$$\mathcal{L}_{a\gamma} = -g_{a\gamma\gamma} \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot (a\vec{B}_0)$$

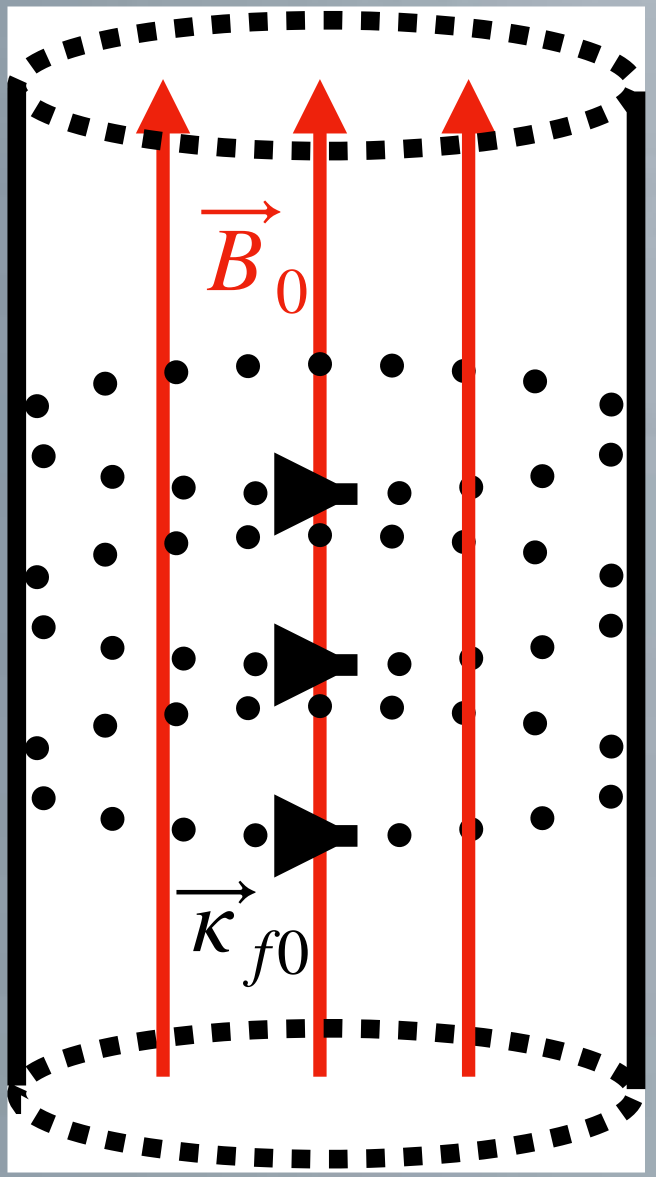
Solenoidal oscillating at axion Compton frequency

$$a(t) \approx a_0 \cos(\omega_a t)$$

- -> To get direct sensitivity E must have non-zero Curl (i.e. a Voltage Source)!
- -> Answer is that need to Redefine E and B fields to include the axion modified parts!

$$\vec{E} -> \vec{E}_T = \vec{E}_{aB} + \vec{E}$$

What is the Orthogonality of E and B in the Low-Mass Limit under DC Magnetic Field?



$$\mathscr{L}_{a\gamma} = \frac{g_{a\gamma}}{4} aF\tilde{F} = -g_{a\gamma\gamma} a \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot \vec{B}$$

Axion Two Photon Coupling

$$\vec{B} = \vec{B}_0$$

$$\mathscr{L}_{a\gamma} = -g_{a\gamma\gamma} \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot (a\vec{B}_0)$$

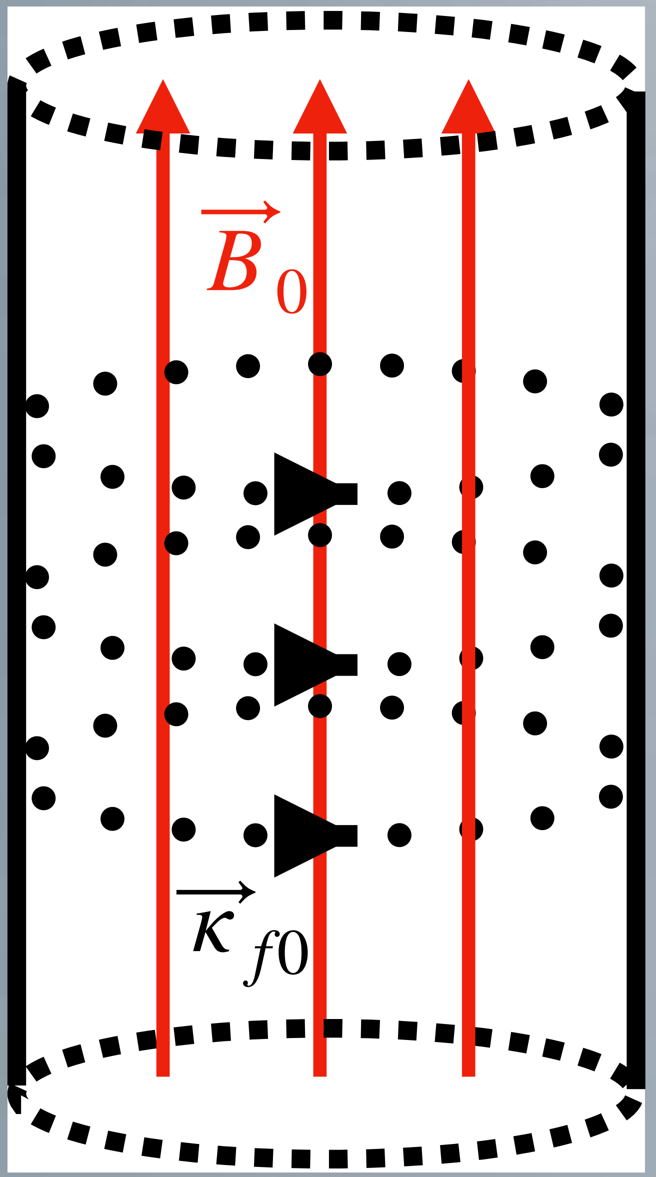
Solenoidal oscillating at axion Compton frequency

$$a(t) \approx a_0 \cos(\omega_a t)$$

- -> To get direct sensitivity E must have non-zero Curl (i.e. a Voltage Source)!
- -> Answer is that need to Redefine E and B fields to include the axion modified parts!

$$\vec{E}_{aB} = -g_{a\gamma\gamma} \frac{c}{\epsilon_r} (a\vec{B}_0) \qquad \vec{E} -> \vec{E}_T = \vec{E}_{aB} + \vec{E}$$

What is the Orthogonality of E and B in the Low-Mass Limit under DC Magnetic Field?



$$\mathscr{L}_{a\gamma} = \frac{g_{a\gamma}}{4} aF\tilde{F} = -g_{a\gamma\gamma} a \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot \vec{B}$$

Axion Two Photon Coupling

$$\vec{B} = \vec{B}_0$$

$$\mathscr{L}_{a\gamma} = -g_{a\gamma\gamma} \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot (a\vec{B}_0)$$

Solenoidal oscillating at axion Compton frequency

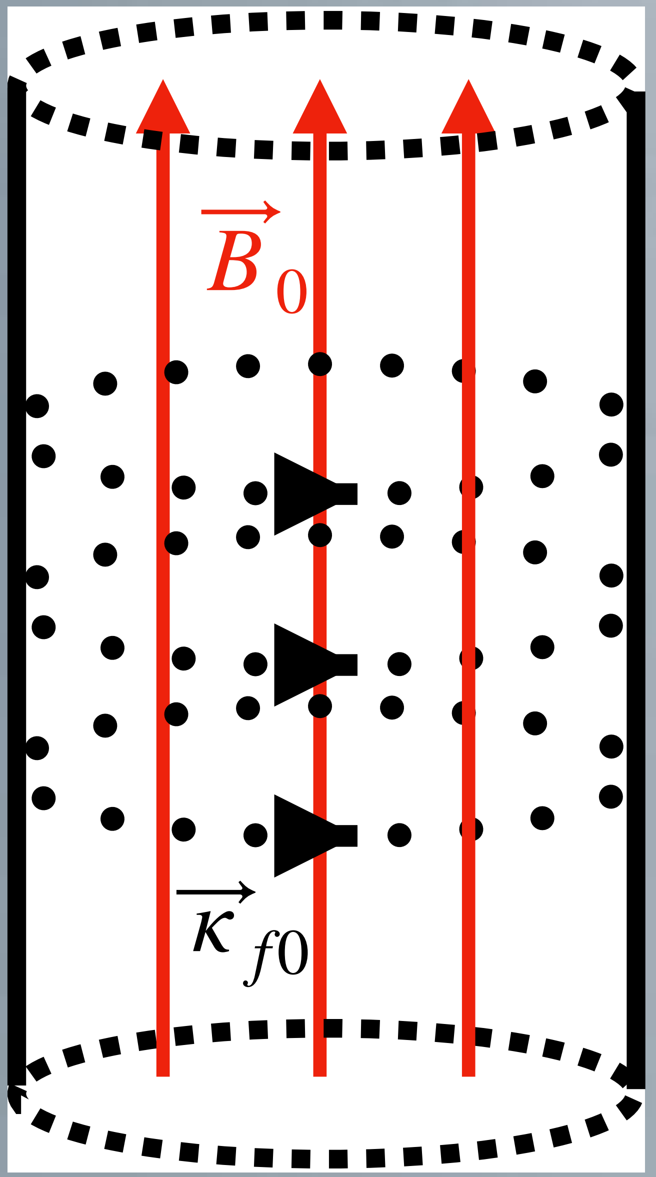
$$a(t) \approx a_0 \cos(\omega_a t)$$

- -> To get direct sensitivity E must have non-zero Curl (i.e. a Voltage Source)!
- -> Answer is that need to Redefine E and B fields to include the axion modified parts!

$$\vec{E}_{aB} = -g_{a\gamma\gamma} \frac{c}{\epsilon_r} (a\vec{B}_0) \qquad \vec{E} -> \vec{E}_T = \vec{E}_{aB} + \vec{E}$$

Solenoidal oscillating at axion Compton frequency

What is the Orthogonality of E and B in the Low-Mass Limit under DC Magnetic Field?



$$\mathcal{L}_{a\gamma} = \frac{g_{a\gamma}}{4} aF\tilde{F} = -g_{a\gamma\gamma} a \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot \vec{B}$$

Axion Two Photon Coupling

$$\vec{B} = \vec{B}_0$$

$$\mathcal{L}_{a\gamma} = -g_{a\gamma\gamma} \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot (a\vec{B}_0)$$

Solenoidal oscillating at axion Compton frequency

$$a(t) \approx a_0 \cos(\omega_a t)$$

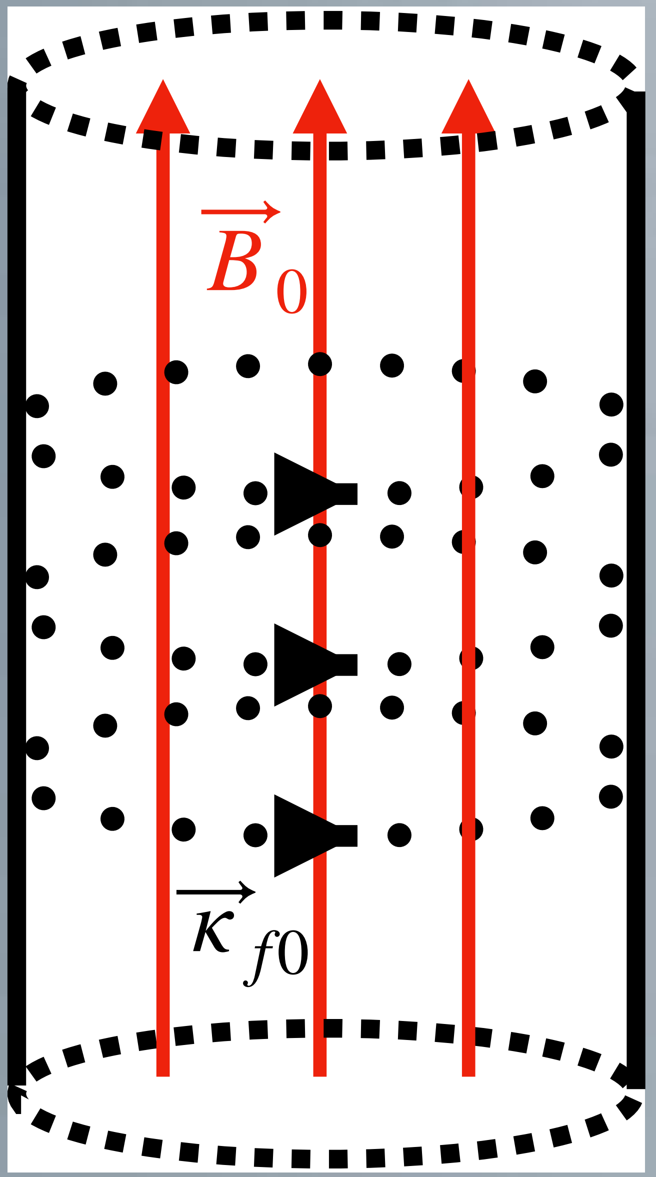
- -> To get direct sensitivity E must have non-zero Curl (i.e. a Voltage Source)!
- -> Answer is that need to Redefine E and B fields to include the axion modified parts!

$$\vec{E}_{aB} = -g_{a\gamma\gamma} \frac{c}{\epsilon_r} (a\vec{B}_0) \qquad \vec{E} -> \vec{E}_T = \vec{E}_{aB} + \vec{E}$$

Solenoidal oscillating at axion Compton frequency

Solenoidal oscillating at axion Compton frequency

What is the Orthogonality of E and B in the Low-Mass Limit under DC Magnetic Field?



$$\mathscr{L}_{a\gamma} = \frac{g_{a\gamma}}{4} aF\tilde{F} = -g_{a\gamma\gamma} a \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot \vec{B}$$

Axion Two Photon Coupling

$$\vec{B} = \vec{B}_0$$

$$\mathscr{L}_{a\gamma} = -g_{a\gamma\gamma} \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot (a\vec{B}_0)$$

Solenoidal oscillating at axion Compton frequency

$$a(t) \approx a_0 \cos(\omega_a t)$$

- -> To get direct sensitivity E must have non-zero Curl (i.e. a Voltage Source)!
- -> Answer is that need to Redefine E and B fields to include the axion modified parts!

$$\vec{E}_{aB} = -g_{a\gamma\gamma} \frac{c}{\epsilon_r} (a\vec{B}_0)$$

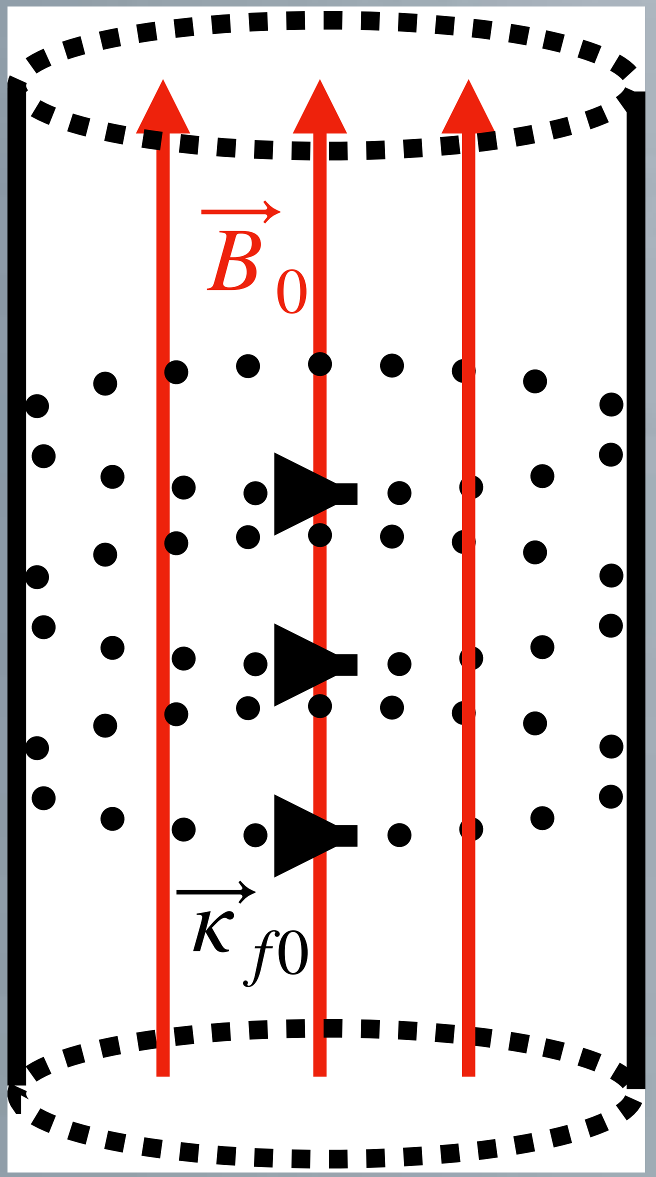
Solenoidal oscillating at axion Compton frequency

$$\vec{E} -> \vec{E}_T = \vec{E}_{aB} + \vec{E}$$

Solenoidal oscillating at axion Compton frequency

$$\mathscr{L}'_{a\gamma} = -g_{a\gamma\gamma} \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E}_T \cdot (a\vec{B}_0)$$

What is the Orthogonality of E and B in the Low-Mass Limit under DC Magnetic Field?



$$\mathcal{L}_{a\gamma} = \frac{g_{a\gamma}}{4} aF\tilde{F} = -g_{a\gamma\gamma} a \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot \vec{B}$$

Axion Two Photon Coupling

$$\vec{B} = \vec{B}_0$$

$$\mathcal{L}_{a\gamma} = -g_{a\gamma\gamma} \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E} \cdot (a\vec{B}_0)$$

Solenoidal oscillating at axion Compton frequency

$$a(t) \approx a_0 \cos(\omega_a t)$$

- -> To get direct sensitivity E must have non-zero Curl (i.e. a Voltage Source)!
- -> Answer is that need to Redefine E and B fields to include the axion modified parts!

$$\vec{E}_{aB} = -g_{a\gamma\gamma} \frac{c}{\epsilon_r} (a\vec{B}_0)$$

Solenoidal oscillating at axion Compton frequency

$$\vec{E} -> \vec{E}_T = \vec{E}_{aB} + \vec{E}$$

Solenoidal oscillating at axion Compton frequency

$$\mathcal{L}'_{a\gamma} = -g_{a\gamma\gamma} \sqrt{\frac{\epsilon_0}{\mu_0}} \vec{E}_T \cdot (a\vec{B}_0)$$

$$\mathcal{L}'_{a\gamma} = \frac{1}{\mu_0 \epsilon_r} g_{a\gamma}^2 (a\vec{B}_0)^2$$