Frequency and Quantum Metrology Research Group

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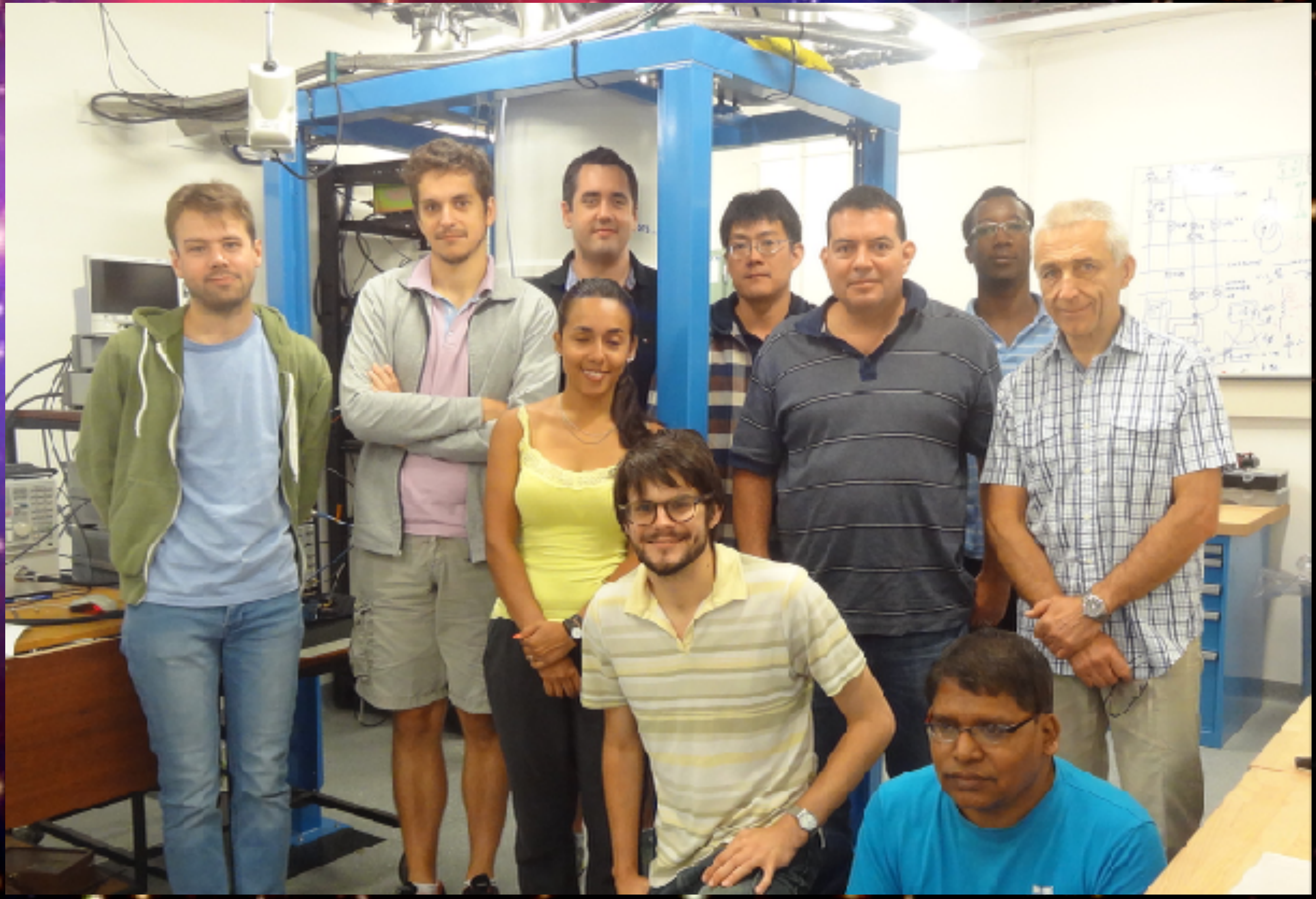
Australian Research Council Centre of Excellence for Engineered Quantum Systems

- Research Staff
- Michael Tobar
- Eugene Ivanov
- John McFerran
- Alexey Veryaskin
- Sascha Schediwy
- Maxim Goryachev
- Jeremy Bourhill

- Students
- Ben McAllister
- Akhter Hoissan
- Graeme Flower
- Scott Hardie
- Lewis Teixeira
- Catriona Thomas



Modified Axion Electrodynamics and the BEAST Experiment

- Axion modified electrodynamics as a magnetization and polarization of the vacuum
- Polarizations and magnetisations induced by a DC Magnetic Field
- Magnetizations and polarizations induced by a DC Electric Field
- Broadband low-mass experiments
  - Inductor in DC Electric Field
  - Capacitor in DC Magnetic Field
  - Broadband Electric Axion Sensing Technique (BEAST)

Modified Axion Electrodynamics

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

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

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

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

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

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

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PHYSICAL REVIEW LETTERS

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Two Applications of Axion Electrodynamics

Frank Wilczek

Institute for Theoretical Physics, University of California, Santa Barbara, Santa Barbara, California 93106

(Received 27 January 1987)

$$\Delta\mathcal{L} = \kappa a \mathbf{E}\cdot\mathbf{B}, \tag{1}$$

where κ is a coupling constant. The resulting equations are

$$\nabla\cdot\mathbf{E} = \tilde{\rho} - \kappa\nabla a\cdot\mathbf{B}, \tag{2}$$

$$\nabla\times\mathbf{E} = -\partial\mathbf{B}/\partial t, \tag{3}$$

$$\nabla\cdot\mathbf{B} = 0, \tag{4}$$

$$\nabla\times\mathbf{B} = \partial\mathbf{E}/\partial t + \tilde{\mathbf{j}} + \kappa(\dot{a}\mathbf{B} + \nabla a\times\mathbf{E}), \tag{5}$$

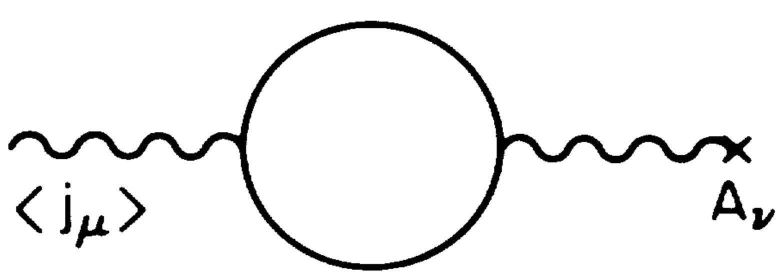


FIG. 3. Expectation of the current in a background field is derived from the vacuum polarization.

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

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

$$\vec{\nabla} \times \overrightarrow{H_a} = \vec{J_f} + \frac{\partial \overrightarrow{D_a}}{\partial t}$$

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

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

Similar to Standard Model Extension Modifications for Lorentz Invariance Violations

Modification in the Constitutive Relations

$$\overrightarrow{D_a} = \epsilon_0 \vec{E} + \vec{P} + \overrightarrow{P_a}$$

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

$$\overrightarrow{H_a} = \frac{1}{\mu_0}\vec{B} - \vec{M} - \overrightarrow{M_a}$$

$$\overrightarrow{M_a} = g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}(a\vec{E})$$

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

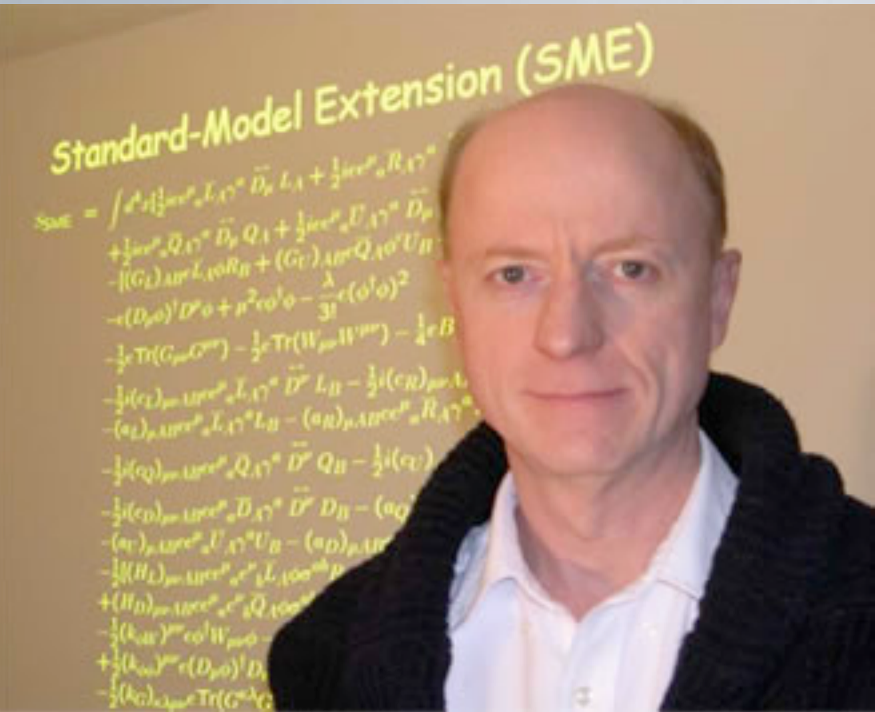
Michael Edmund Tobar,[1,*] Peter Wolf,[2,3] Alison Fowler,[1] and John Gideon Hartnett[1]
[1]*University of Western Australia, School of Physics, M013, 35 Stirling Highway, Crawley 6009 WA, Australia*
[2]*Bureau International des Poids et Mesures, Pavillon de Breteuil, 92312 Sèvres Cedex, France*
[3]*BNM-SYRTE,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

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

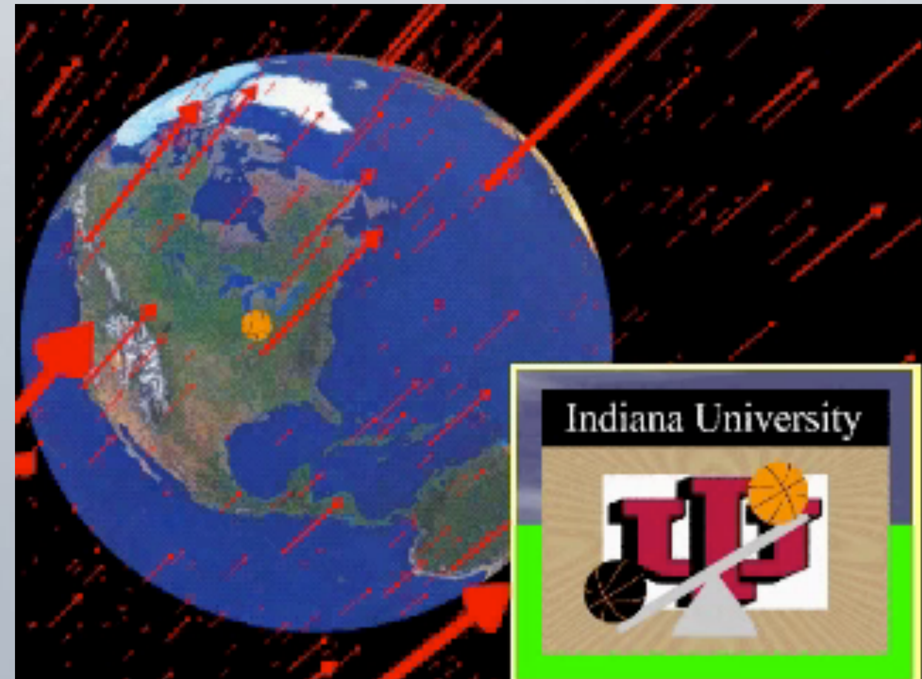
$$g_{a\gamma\gamma}a \sim \kappa_{DB} \quad \kappa_{HE}$$

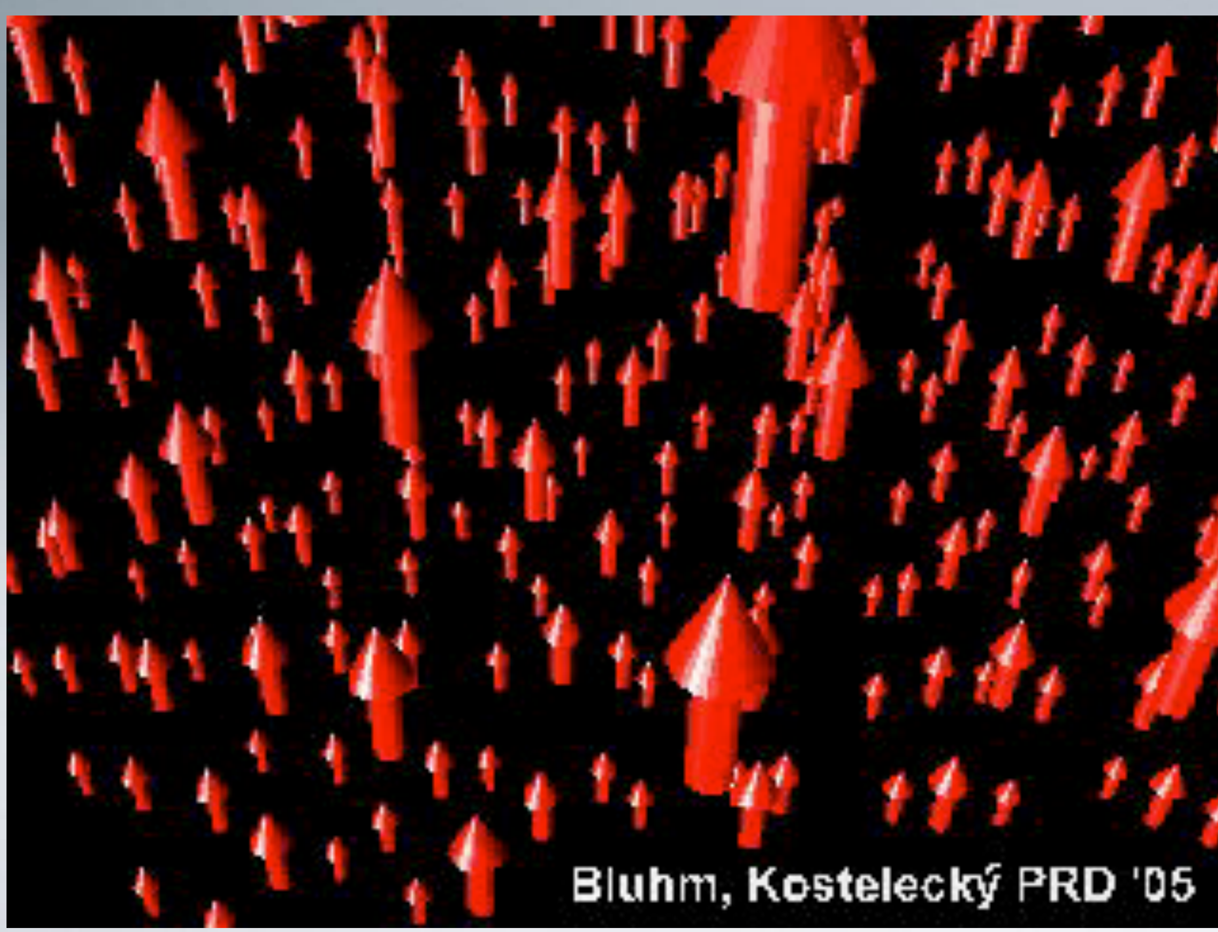
Axion Interaction similar to odd parity Lorentz Invariance Violation

Sidereal Modulations of Constant Background Fields



www.physics.indiana.edu/~kostelec/





Axion is similar to an oscillating odd parity background SME Lorentz invariance violation field.

Cannot shield against these type of violations -> Source Terms.

Oscillating Background Fields Create EM Radiation

Asymptotic Freedom*

1.2. Antiscreening as Paramagnetism: The Importance of Spin

Frank Wilczek†

School of Natural Sciences

Institute for Advanced Study

Olden Lane

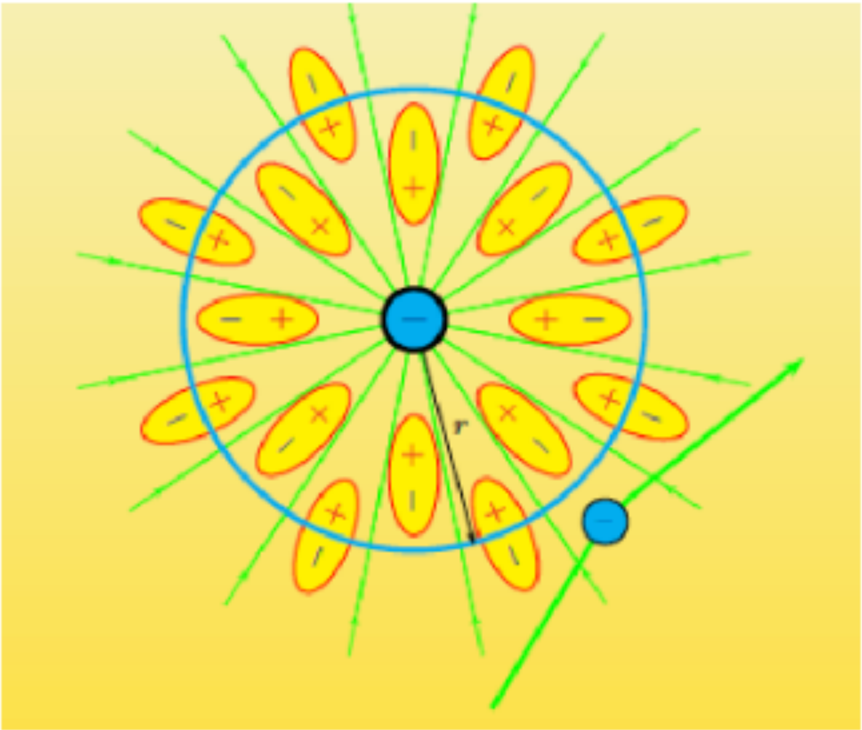
Princeton, N.J. 08540

Vacuum acts as Dielectric and Paramagnet!

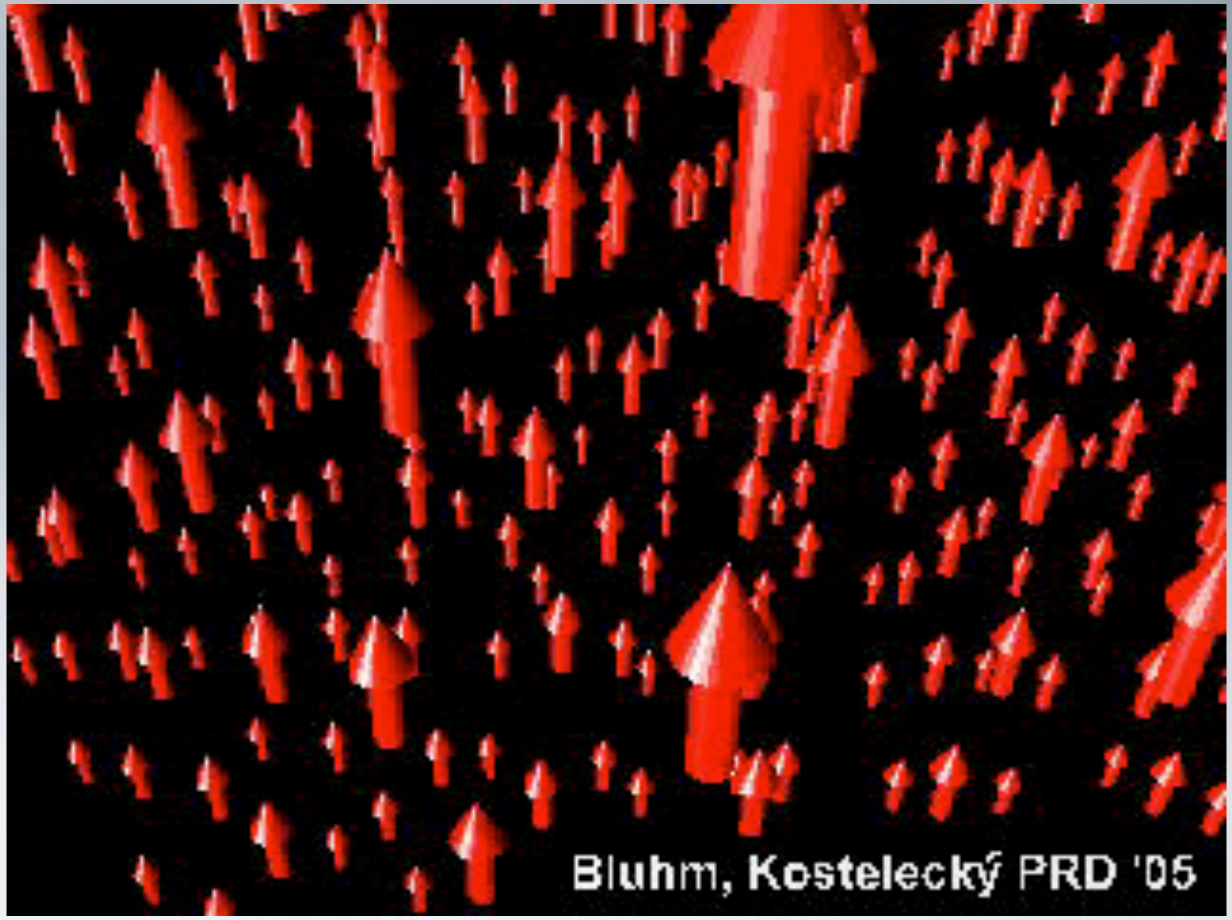
Axion-Photon Interaction as Oscillating Vacuum Polarization and Magnetization Fields

*Vacuum polarizations and magnetisation cause running of the fine structure constant α

* Magnetic anti-screening and Electric screening gives α =1/137 at low energy and 1/128 at 90 GeV



Representation of the vacuum polarization phenomenon causing charge screening by virtual pairs.



*Tiny oscillating refractive index or fine structure constant

* Similar to Brillouin scattering in media nonlinear -> Frequency Shift Goryachev (Tomorrow)

Axion Induced Virtual Bound Charges and Currents

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

Virtual Particle Bound Charge

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

$$\vec{J}_a = \frac{\partial \vec{P}_a}{\partial t}$$

Virtual Particle Polarizarion Current

$$\nabla\cdot\vec{J}_a = -\frac{\partial\rho_a}{\partial t}$$

Satisfies the Continuity Equation

$$\vec{J}b_a = \vec{\nabla}\times\vec{M}_a = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\vec{\nabla}\times(a\vec{E})$$

Virtual Particle Bound Current

Boundary Conditions

Calculate from integral form of modified Maxwell's equations
(no free charges and currents)

$$\vec{E}_1^{||} - \vec{E}_2^{||} = 0 \qquad \vec{B}_1^{\perp} - \vec{B}_2^{\perp} = 0$$

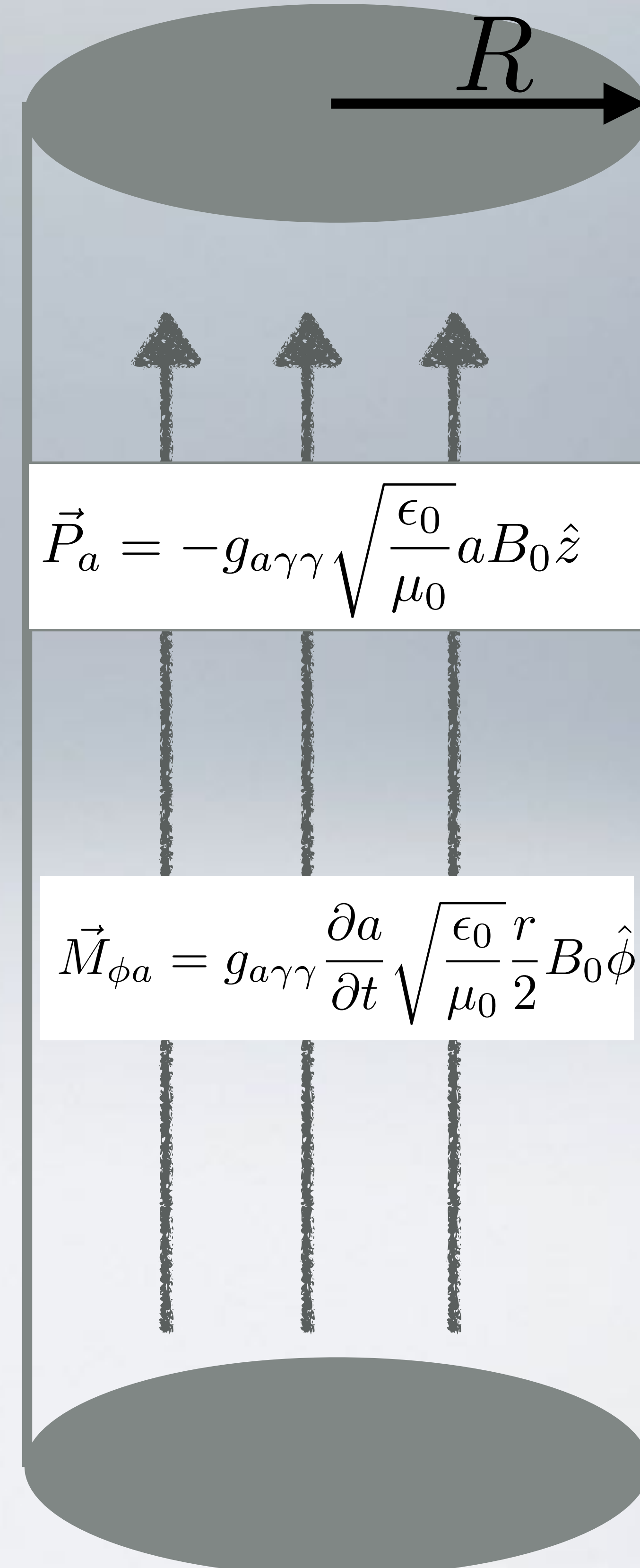
$$\vec{D}_{a1}^{\perp} - \vec{D}_{a2}^{\perp} = 0 \qquad \vec{H}_{a1}^{||} - \vec{H}_{a2}^{||} = 0$$

Axion induced Polarization and Magnetization Fields under DC Magnetic Field

1) Assume Infinite Solenoid

$$\vec{E} = 0$$

$$\vec{B} = B_0 \hat{z}$$



$$\vec{P}_a = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}aB_0\hat{z}$$

$$\vec{M}_{\phi a} = g_{a\gamma\gamma}\frac{\partial a}{\partial t}\sqrt{\frac{\epsilon_0}{\mu_0}}\frac{r}{2}B_0\hat{\phi}.$$

Effective/Pseudo Fields

$$\vec{E}_a^{\text{eff}} = \vec{P}_a/(\epsilon_0\epsilon_r) = -g_{a\gamma\gamma}a\frac{c}{\epsilon_r}B_0\hat{z}$$

$$\vec{B}_a^{\text{eff}} = -\mu_0\mu_r\vec{M}_{\phi a} = -g_{a\gamma\gamma}\frac{\mu_r}{c}\frac{\partial a}{\partial t}\frac{r}{2}B_0\hat{\phi}$$

Calculate Vacuum Magnetization

$$\oint_C \vec{M}_{\phi a}\cdot d\vec{l} = -\frac{\partial}{\partial t}\int\int_S \vec{P}_a\cdot d\vec{S}.$$

Match Boundary Conditions

$$\vec{H}_{a1}^{||} - \vec{H}_{a2}^{||} = 0$$

$$\frac{\vec{B}_{\phi a}}{\mu_0} = -\vec{M}_{\phi a}$$

$$\vec{B}_{\phi a} = -g_{a\gamma\gamma}\frac{\partial a}{\partial t}\frac{1}{c}\frac{R}{2}B_0\hat{\phi} \quad (r = R)$$

$$\vec{B}_{\phi a}(r) = -g_{a\gamma\gamma}\frac{\partial a}{\partial t}\frac{1}{c}\frac{R^2}{2r}B_0\hat{\phi} \quad (r > R)$$

DC Solenoid of Finite Length

2) Finite Solenoid->Dipole Field

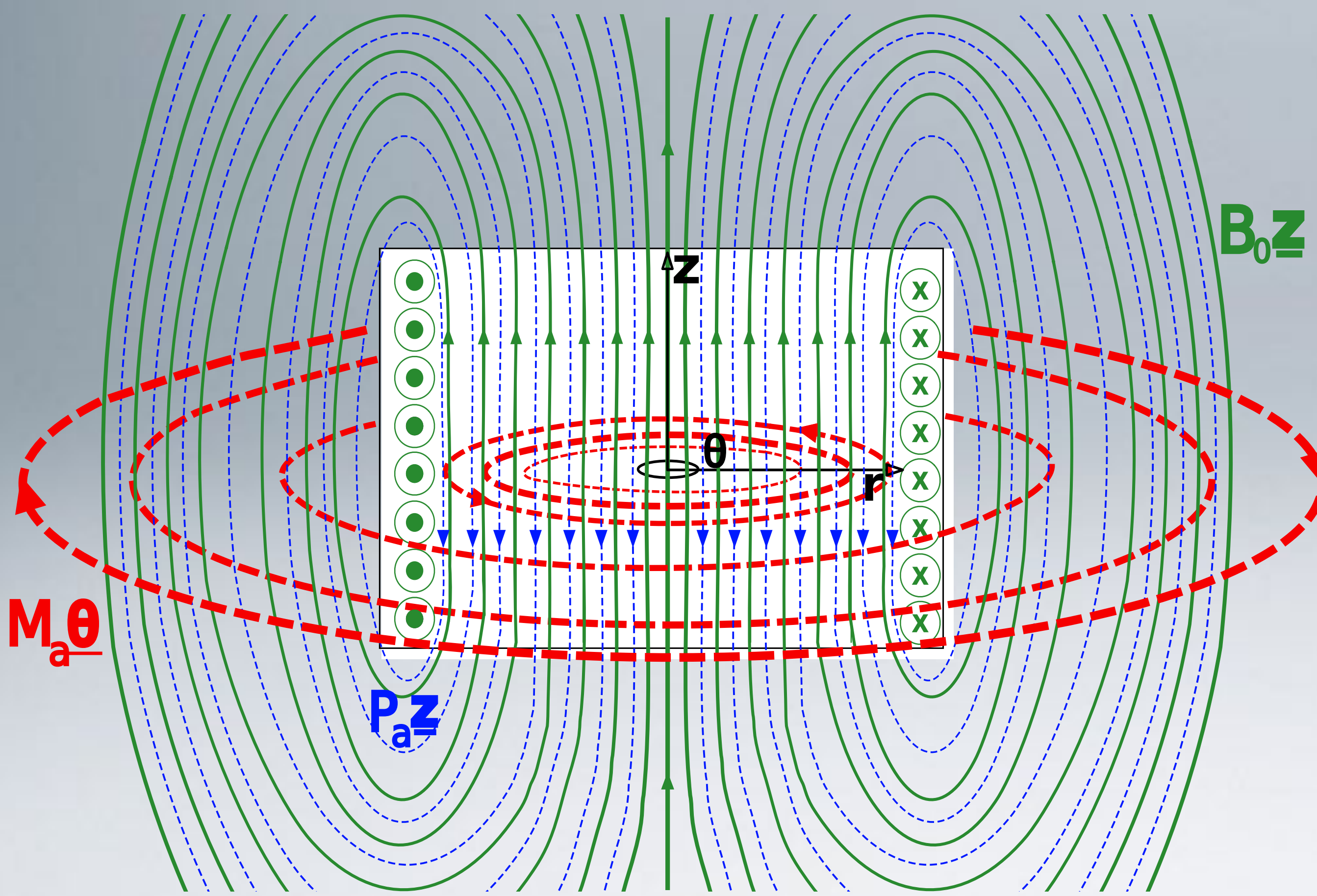


FIG. 1: A sketch of a finite solenoid, showing the the static magnetic field (green) and the axion-induced fields (blue and red).

3) Finite Solenoid with ideal Field Cancelation Above and Below

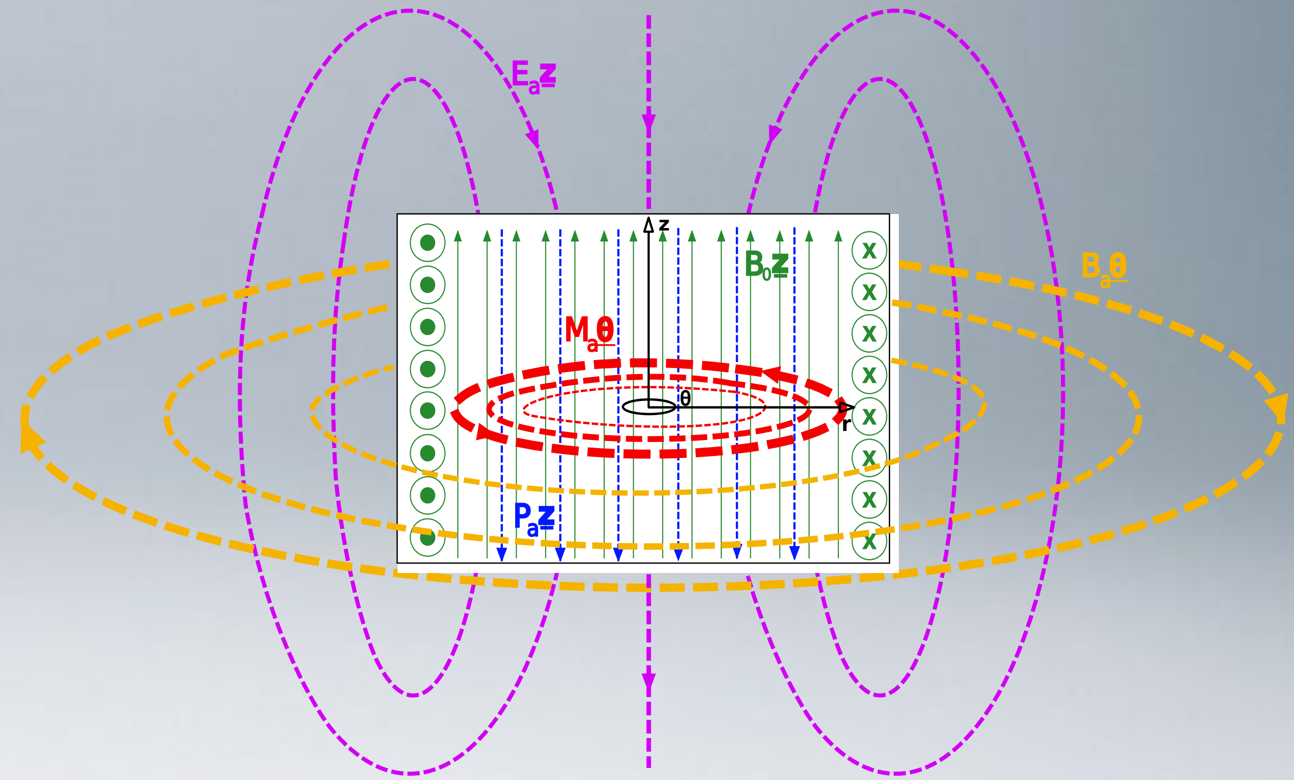


FIG. 2: A finite solenoid with idealised field cancelation above and below the inner region together with the static magnetic field (green), the axion-induced oscillating $\vec{P}_a$ and $\vec{M}_a$ fields (blue and red) and the axion induced oscillating $\vec{E}_a$ and $\vec{B}_a$ fields outside the DC magnetic field (pink and orange).

Axion induced Magnetization and Polarization Fields under DC Electric Field

1) Assume Infinite Capacitor no Fringing Field

$$\vec{B} = 0$$

$$\vec{E} = E_0 \hat{z}$$

$$\vec{M}_{za} = \begin{cases} -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}} a E_0 \hat{z}, r < R, \\ 0, r > R. \end{cases}$$

At boundary r=R

$$K b_a \hat{\phi} = g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}} a E_0 \hat{\phi}$$

DC E-field from Finite Length Capacitor

$$\vec{\nabla} \times \vec{M}_a = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}a(t)\vec{\nabla} \times \vec{E}(r,z) \qquad Jb_{\phi a}\hat{\phi} = -\vec{\nabla} \times \vec{M}_a = \frac{\partial P_{\phi a}}{\partial t}\hat{\phi}.$$

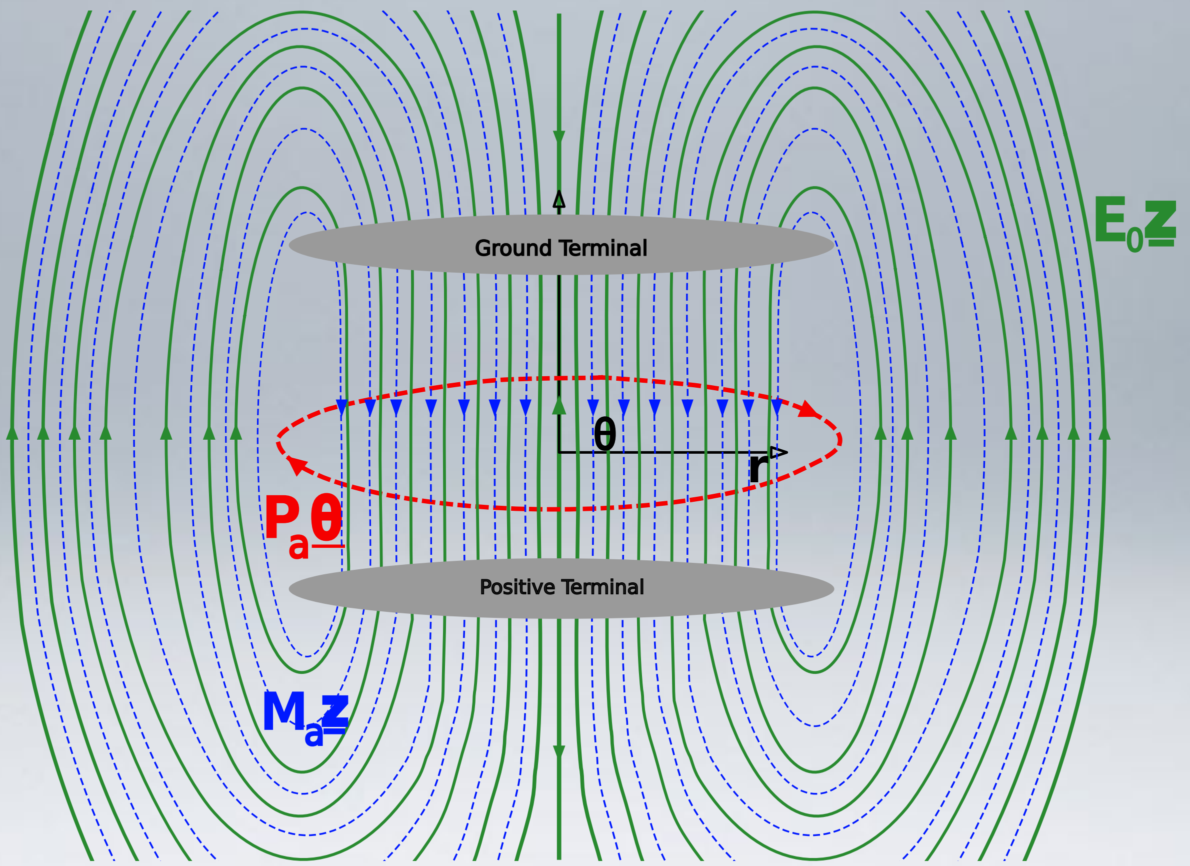


FIG. 3: A pair of capacitor plates, showing the the static electric field (green) and the axion-induced fields (blue and red).

Inductor in a DC Electric Field

$$M_{az} = \ -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}aE_0\hat{z}$$

$$\Phi_a = -\mu_0\mu_r A M_{az} = g_{a\gamma\gamma}\frac{\mu_r}{c}AaE_0$$

$$i_a = \frac{N\Phi}{L} = g_{a\gamma\gamma}\frac{\mu_r}{c}\frac{AN}{L}aE_0$$

$$v_a = -g_{a\gamma\gamma}\frac{\mu_r}{c}AN\frac{da}{dt}E_0$$

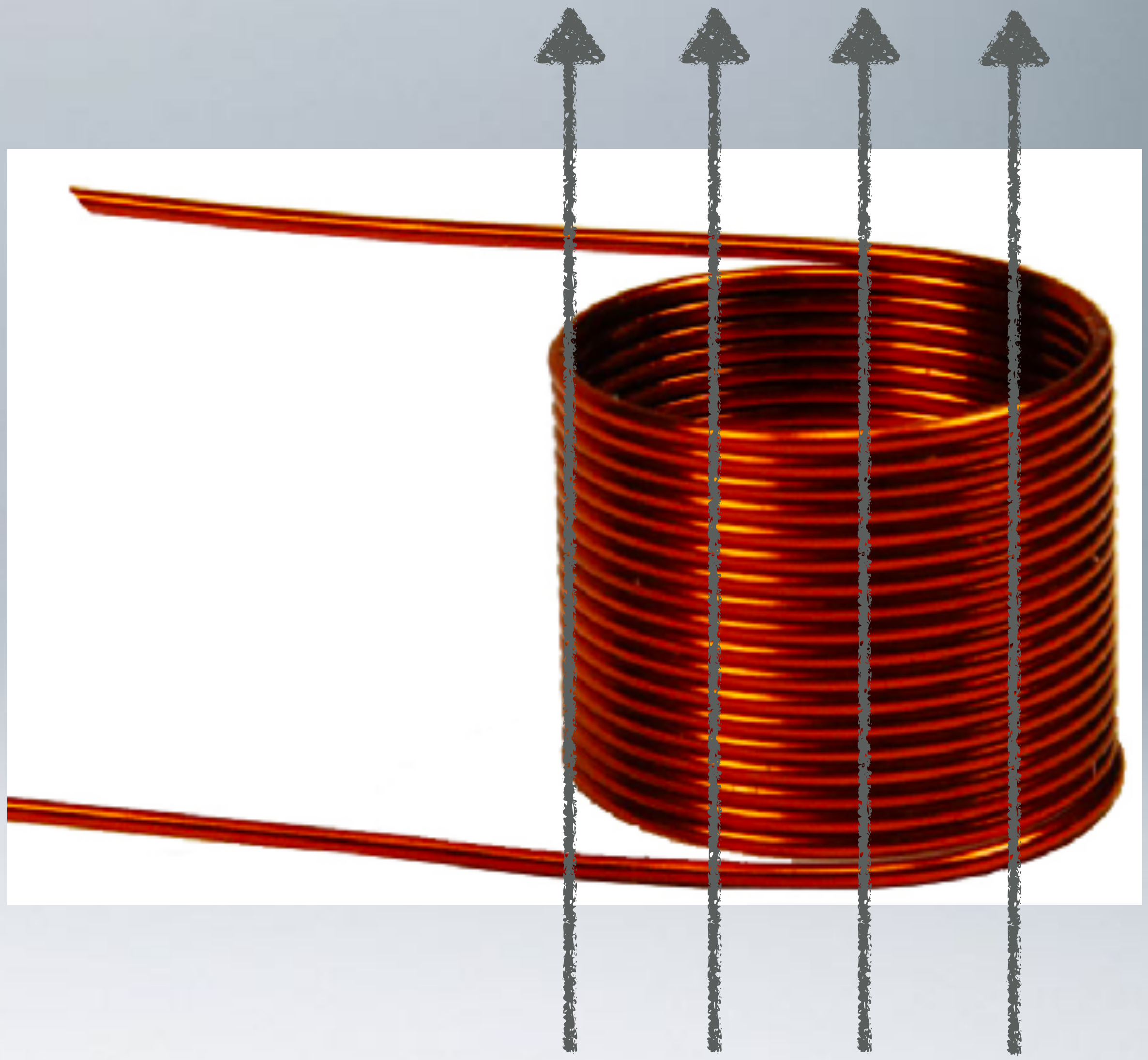
$$a = a_0\cos(\omega_a t) \qquad a_0 = \sqrt{\frac{2\rho_a}{c}\frac{\hbar}{m_a}}$$

$$V_a^{\mathrm{RMS}} = g_{a\gamma\gamma}\mu_r A N E_0\sqrt{\rho_a c}$$

$$L = \frac{\mu_0\mu_r N^2 A}{d}$$

$$I_a^{\mathrm{RMS}} = g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\left(\frac{c}{\omega_a}\right)\frac{d}{N}E_0\sqrt{\rho_a c}$$

$$\vec{E} = E_0\hat{z}$$



$$\vec{B} = 0$$

Paper to be Posted on ArXiv Very Soon

Modified Axion Electrodynamics as Oscillating Polarization and Magnetization of the Vacuum

Michael E. Tobar,[1,*] Ben T. McAllister,[1] and Maxim Goryachev[1]

[1] *ARC Centre of Excellence For Engineered Quantum Systems, Department of Physics, School of Physics and Mathematics, University of Western Australia, 35 Stirling Highway, Crawley WA 6009, Australia.*

(Dated: August 23, 2018)

We present a reformulation of modified axion electrodynamics where the four Maxwell's equations maintain a similar form to the unmodified versions, with all modifications redefined within the constitutive relations between the $\vec{D}$, $\vec{H}$, $\vec{B}$ and $\vec{E}$ fields. In this reformulation the axion induced bound charge density, polarization current density and bound current density are identified along with the associated axion induced vacuum polarization and magnetization, which are shown to satisfy the charge-current continuity equation. This representation is consistent with Wilczek's original calculations from the polarization of vacuum fields. The reformulation is important when considering conversions of axions into photons, relevant in many experimental contexts. For example, when a DC $\vec{B}$-field is applied, oscillating bound vacuum charges and polarization currents are induced at a frequency equivalent to the axion mass. In contrast, when a large DC $\vec{E}$ field is applied, an oscillating bound current or magnetization of the vacuum is induced at a frequency equivalent to the axion mass. Moreover, the integral forms of the equations can be used to clearly define the boundary conditions between distinct media either with or without axion induced vacuum polarization or magnetization. This provides clarity when considering experiments sensitive to axion induced electric and/or magnetic effects inside or outside the high DC field region. For example, a capacitor in a high DC magnetic field can act as a detector for low-mass axions without suppression of of the signal due to electromagnetic shielding. Also, we calculate the voltages and currents induced by axions in an inductive sensor under a DC electric field, which is the dual experiment to a capcitive sensor under a DC magnetic field.

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FACULTY OF SCIENCE

Broadband Electric-field Axion Sensing Technique (BEAST)

Broadband Axion Dark Matter Haloscopes via Electric Sensing

Ben T. McAllister,[1,*] Maxim Goryachev,[1] Jeremy Bourhill,[1] Eugene N. Ivanov,[1] and Michael E. Tobar[1,†]

[1] *ARC Centre of Excellence For Engineered Quantum Systems, Department of Physics, School of Physics and Mathematics, University of Western Australia, 35 Stirling Highway, Crawley WA 6009, Australia.*

(Dated: August 21, 2018)

The mass of axion dark matter is only weakly bounded by cosmological observations, necessitating a variety of detection techniques over several orders of magnitude of mass ranges. Axions haloscopes based on resonant cavities have become the current standard to search for dark matter axions. Such structures are inherently narrowband and for low masses the volume of the required cavity becomes prohibitively large. Broadband low-mass detectors have already been proposed using inductive magnetometer sensors and a gapped toroidal solenoid magnet. In this work we propose an alternative, which uses electric sensors in a conventional solenoidal magnet aligned in the laboratory z-axis, as implemented in standard haloscope experiments. In the presence of the DC magnetic field, the inverse Primakoff effect causes a time varying electric vacuum polarization (or displacement current) in the z-direction to oscillate at the axion Compton frequency. We propose non-resonant techniques to detect this oscillating polarization by implementing a capacitive sensor or an electric dipole antenna coupled to a low noise amplifier. We present the theoretical foundation for this proposal, and the first experimental results. Preliminary results constrain $g_{a\gamma\gamma} >\sim 2.35 \times 10^{-12}$ GeV^{-1} in the mass range of 2.08×10^{-11} to 2.2×10^{-11} eV, and demonstrate potential sensitivity to axion-like dark matter with masses in the range of 10^{-12} to 10^{-8} eV.

Paper rewritten with respect to Axion Modified Electrodynamics as discussed previously

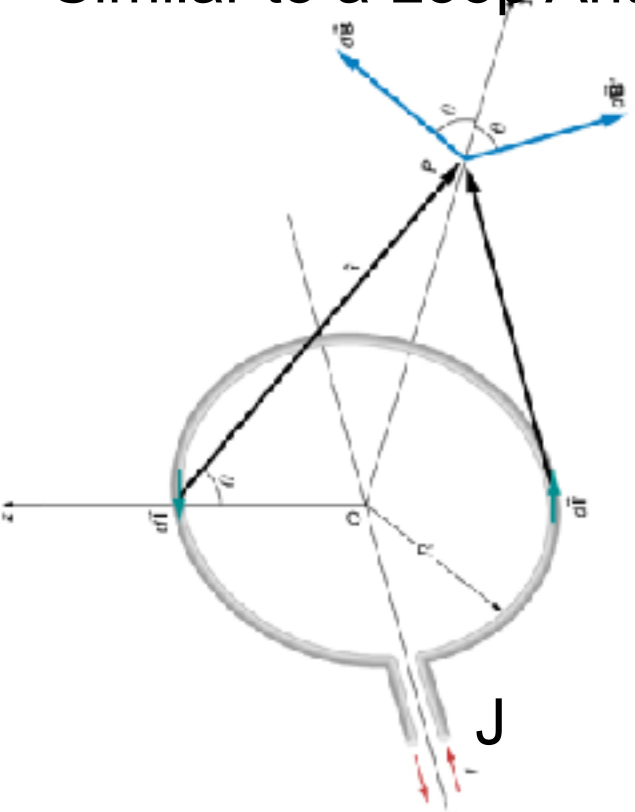
$$\vec{E}_a^{\text{eff}} = \vec{P}_a/(\epsilon_0\epsilon_r) = -g_{a\gamma\gamma}a\frac{c}{\epsilon_r}B_0\hat{z}$$

Vacuum polarisation term, not E-field, so low-mass signals not suppressed

Geometry Comparison with ABRACADABRA

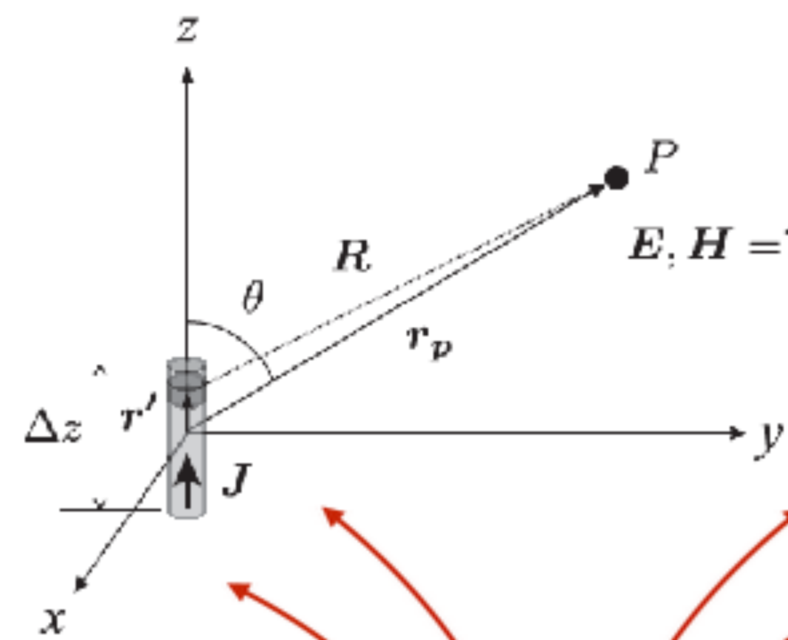
ABRACADABRA (Axion Magnetic Dipole)

Similar to a Loop Antenna

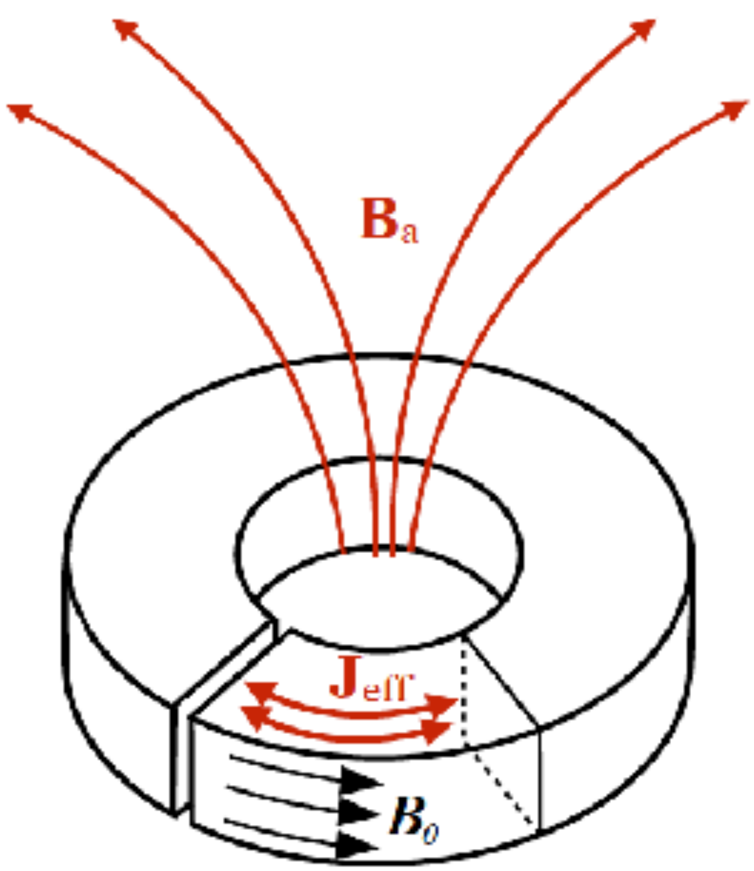


BEAST (Axion Electric Dipole)

Similar to Hertzian Dipole Antenna



E fields inside antenna conductors are due to oscillating free currents:
$J = \sigma E$
σ (metal conductivity)

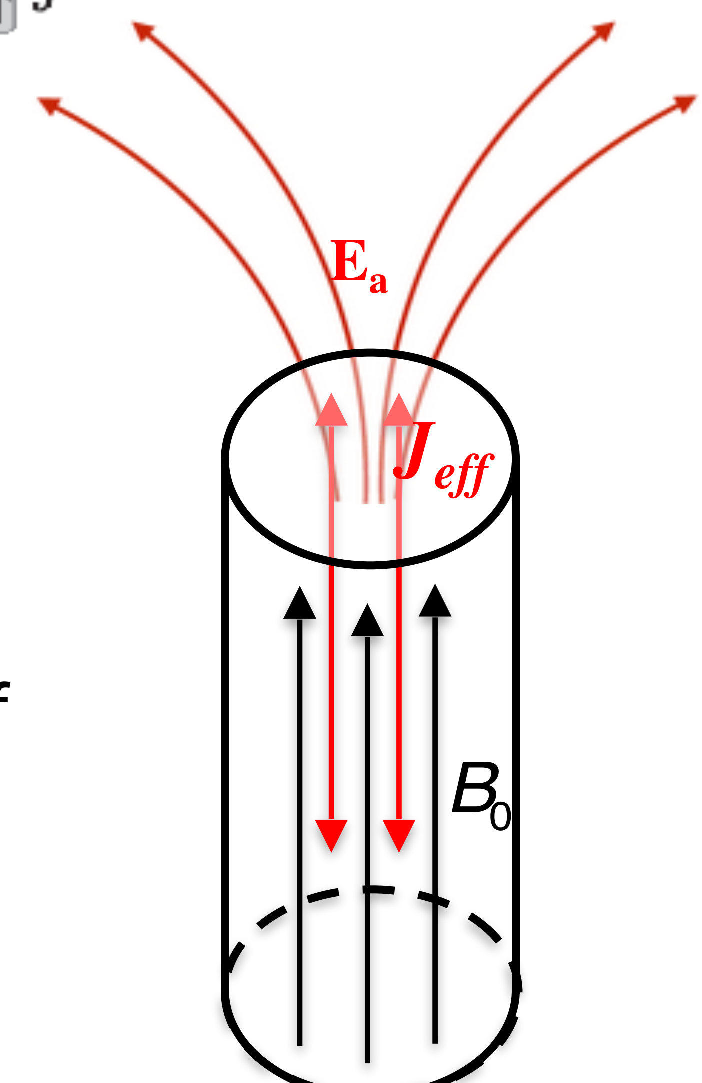


What causes the Axion induced J_{eff}?

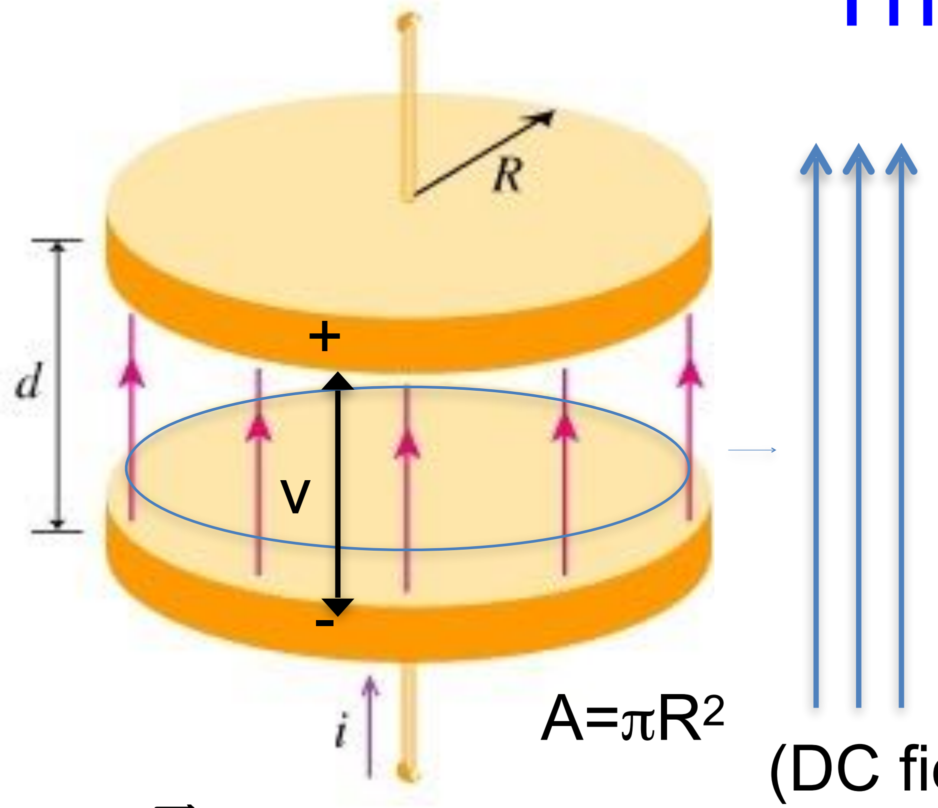
-> No conduction electrons

-> Caused by small oscillations of vacuum polarization

-> Bound Displacement Current



The BEAST Experiment



$$\vec{E} = 0 \qquad \vec{B} = B_0\hat{z}$$

$$\vec{J}_a = \frac{\partial \vec{P}_a}{\partial t} = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\vec{B}_0\frac{\partial a}{\partial t}$$

$$\vec{P}_{za} = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}aB_0\hat{z} = \epsilon_0\epsilon_r\vec{E}_{a\ eff}$$

$$\vec{M}_{\phi a} = g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\frac{r}{2}B_0\frac{\partial a}{\partial t}\hat{\phi} = -\frac{1}{\mu_0\mu_r}\vec{B}_{a\ eff}$$

$$a = a_0\cos(\omega_a t) \qquad a_0 = \sqrt{\frac{2\rho_a}{c}}\frac{\hbar}{m_a}$$

Measure Currents and Voltages

$$I_{a_{RMS}} = g_{a\gamma\gamma}A\sqrt{\frac{\epsilon_0}{\mu_0}}B_0\sqrt{\rho_a c^3} \qquad V_{a_{RMS}} = \frac{1}{\epsilon_r}g_{a\gamma\gamma}d\left(\frac{c}{\omega_a}\right)B_0\sqrt{\rho_a c^3}.$$

Measure with SQUID (current) or High Impedance Amplifier (HIA) (voltage)

To improve sensitivity with SQUID -> Large Plate Area

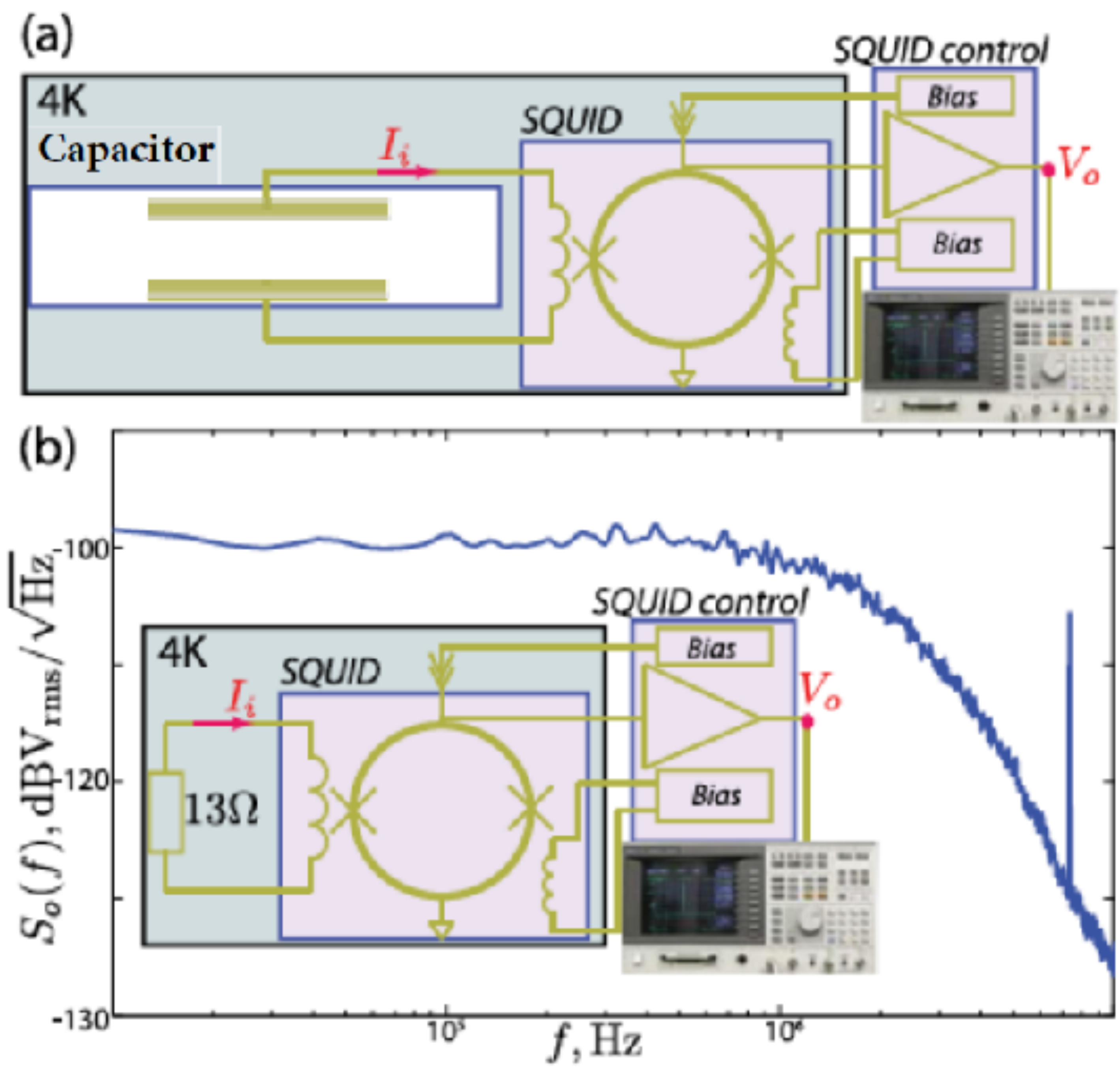
To improve sensitivity with HIA -> Large Plate Separation

$$I_{a_{RMS}} = 6.38\times10^{-19}\times\frac{g_{a\gamma\gamma}}{1.55\times10^{-18}\ GeV^{-1}}\times\frac{\epsilon}{\epsilon_0}\times\frac{A}{0.0079\ m^2}\times\frac{B_0}{7\ T}\times\sqrt{\frac{\rho_a}{0.45\ GeV}}$$

$$V_{a_{RMS}} = 1.46\times10^{-13}\times\frac{g_{a\gamma\gamma}}{1.55\times10^{-18}\ GeV^{-1}}\times\frac{1}{\epsilon_r}\times\frac{B_0}{7\ T}\times\sqrt{\frac{\rho_a}{0.45\ GeV}}\times\frac{2\pi\times10^6\ rad\ s^{-1}}{\omega}\times\frac{d}{0.1\ m}$$

Built Experiment With a SQUID

DC SQUID in a copper holder to be attached to the “cold finger” of the pulse-tube dilution fridge

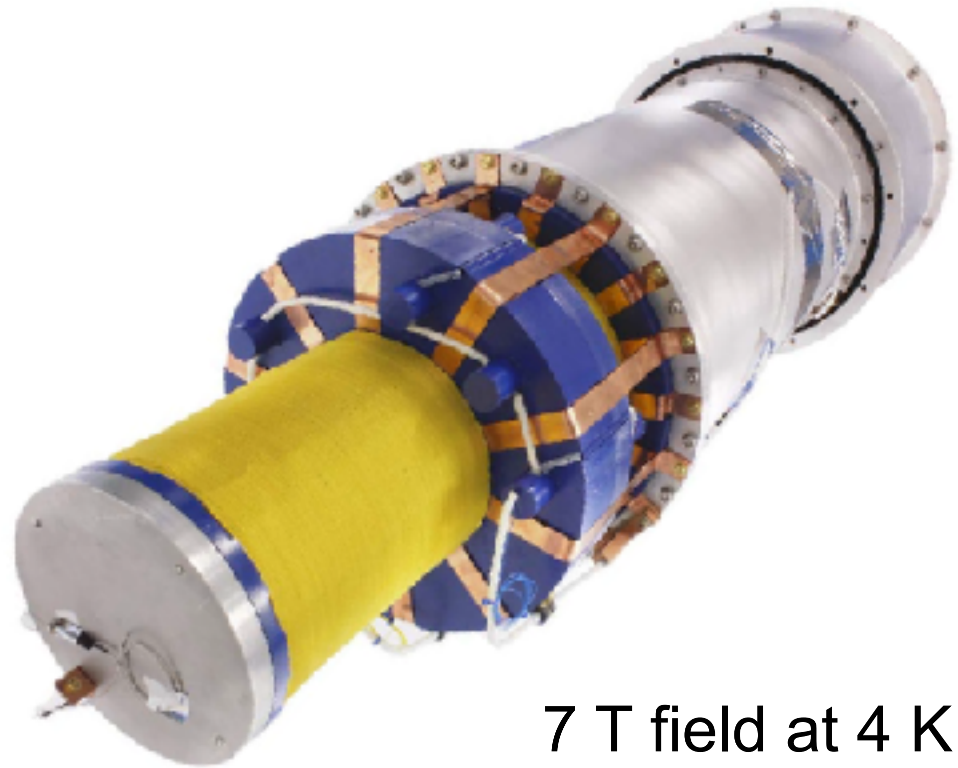


Calibration: Use resistors instead of capacitors
-> Derive SQUID transimpedance ~ 1.2 MΩ
-3dB low pass bandwidth of 2.1 MHz

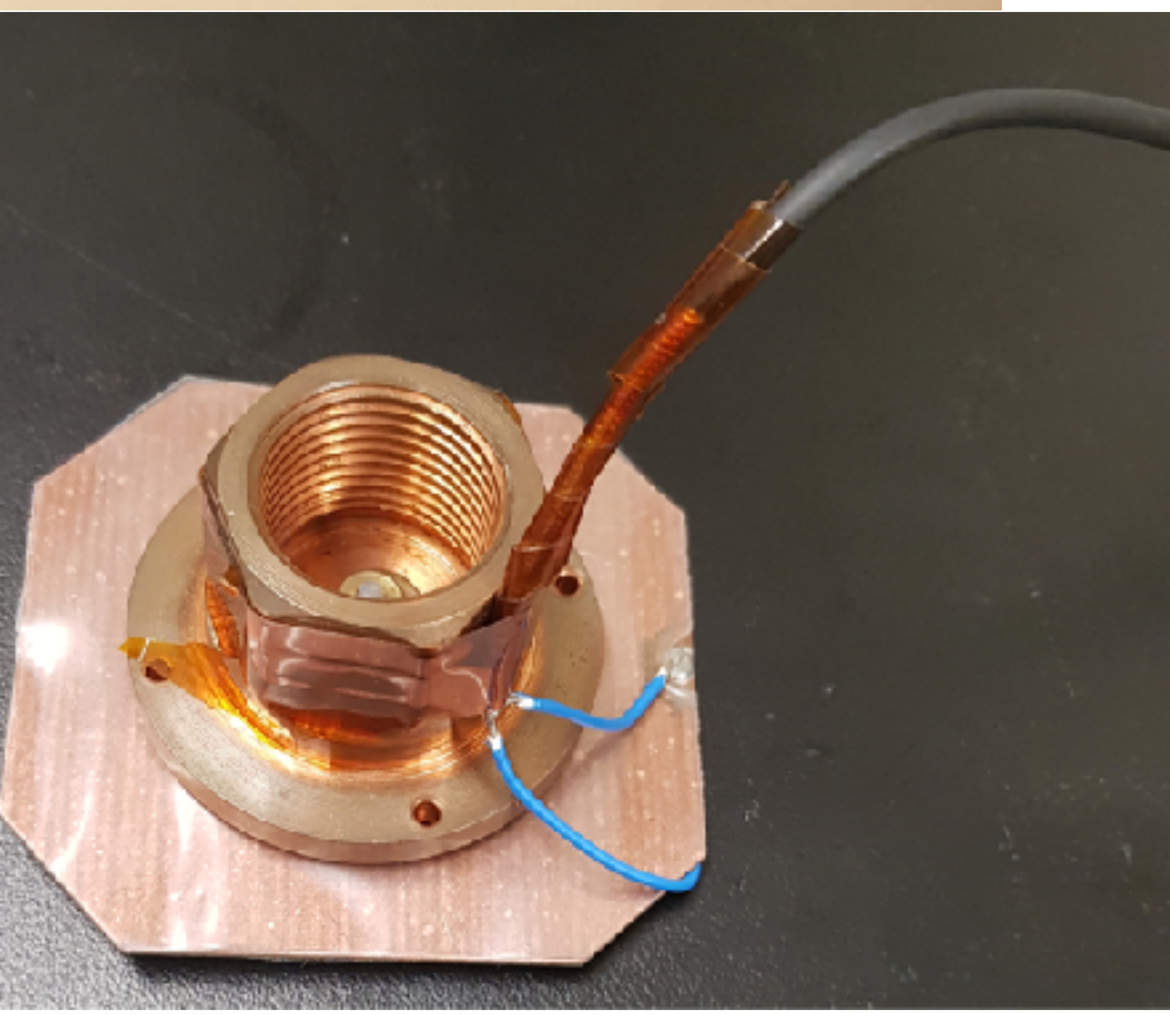
SQUID RMS current spectral density, ~ $pA/\sqrt{Hz}$

SQUID

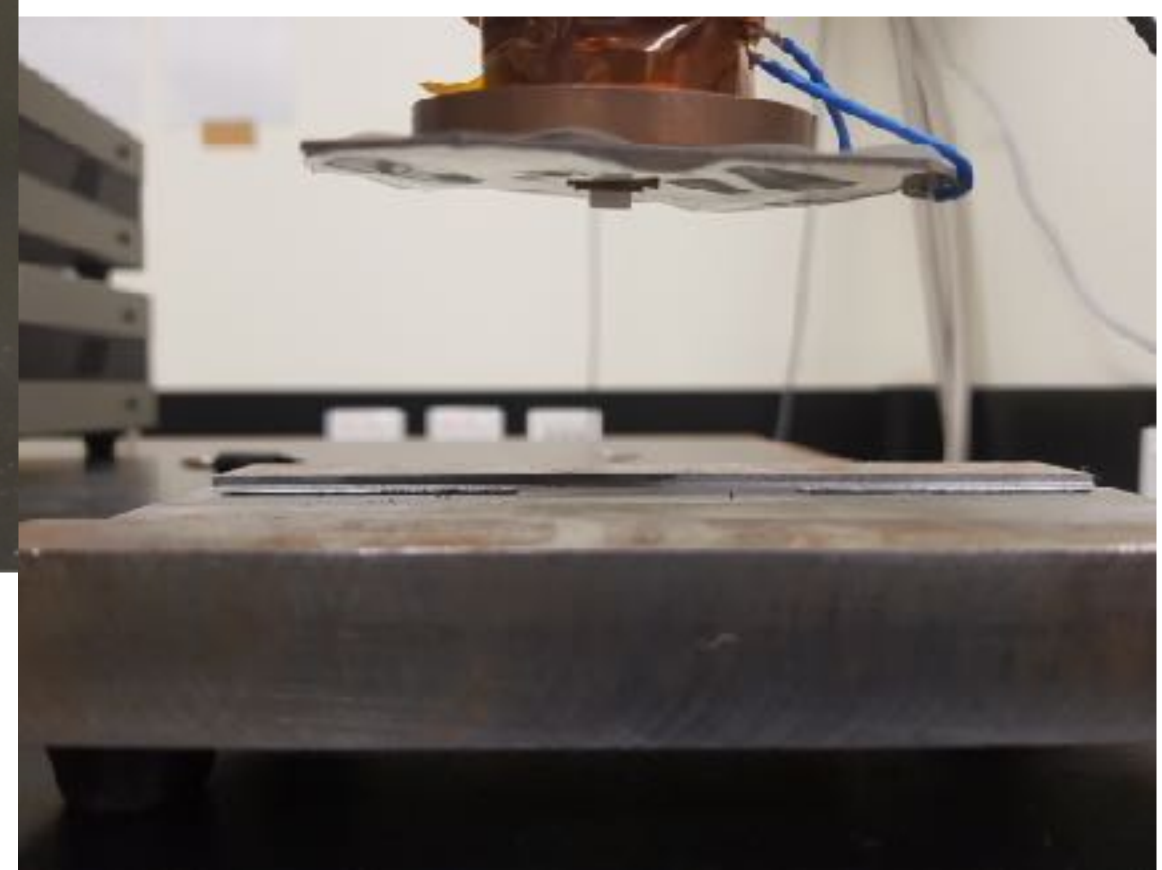
7 T Magnet (10 cm bore)



7 T field at 4 K for 8 days of observation time



Large Area Capacitor Plate
7.5 x 7 cm



Beast Spectral Density

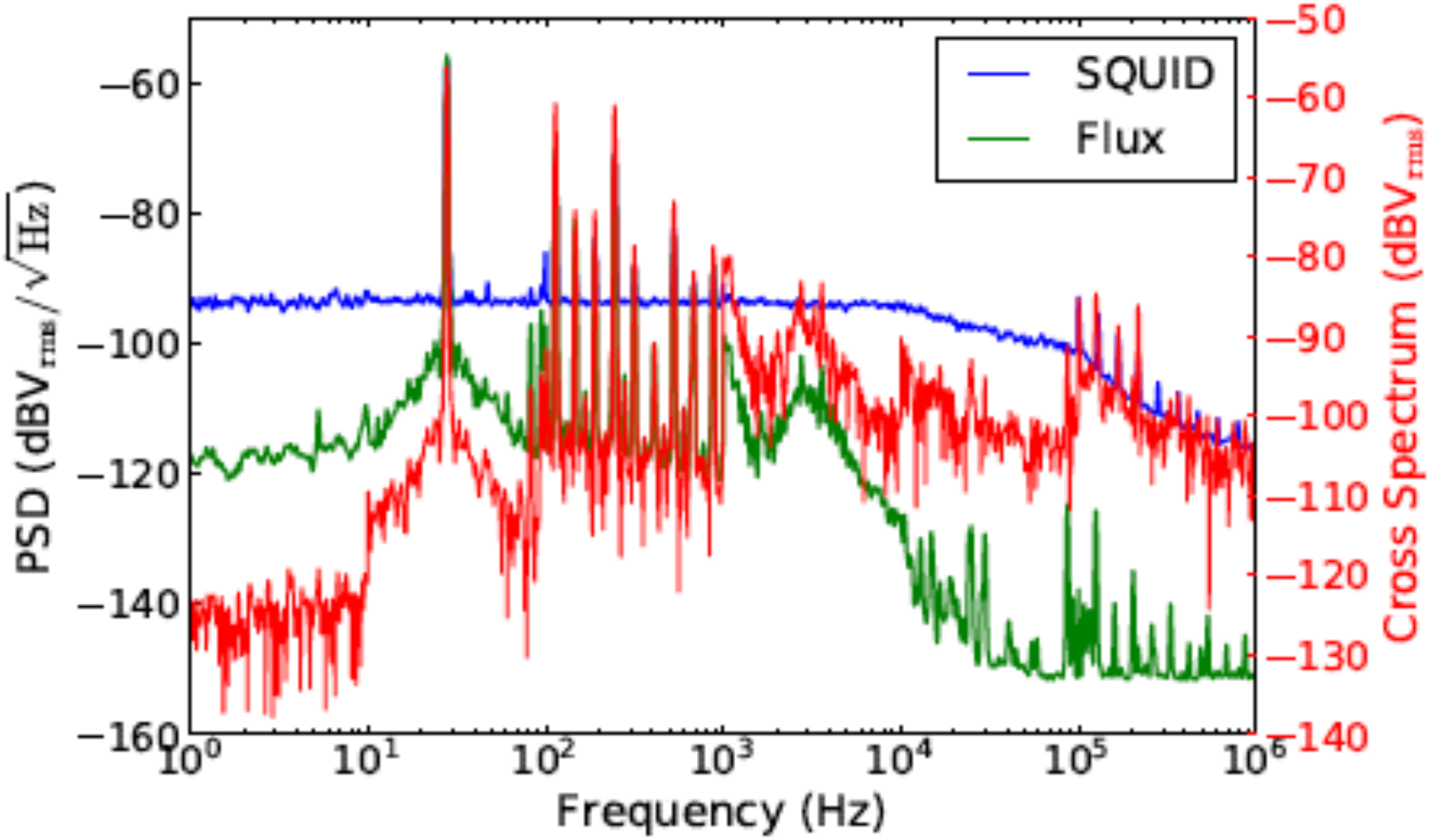


FIG. 3: Voltage noise spectra at the output of the SQUID in the first run of BEAST. The blue (green) trace corresponds to the SQUID (flux) line, whilst the red trace corresponds to the cross-spectrum.

Possible to discriminate against these spurious signals with the flux line, which is susceptible to spurious RF signals in the lab.

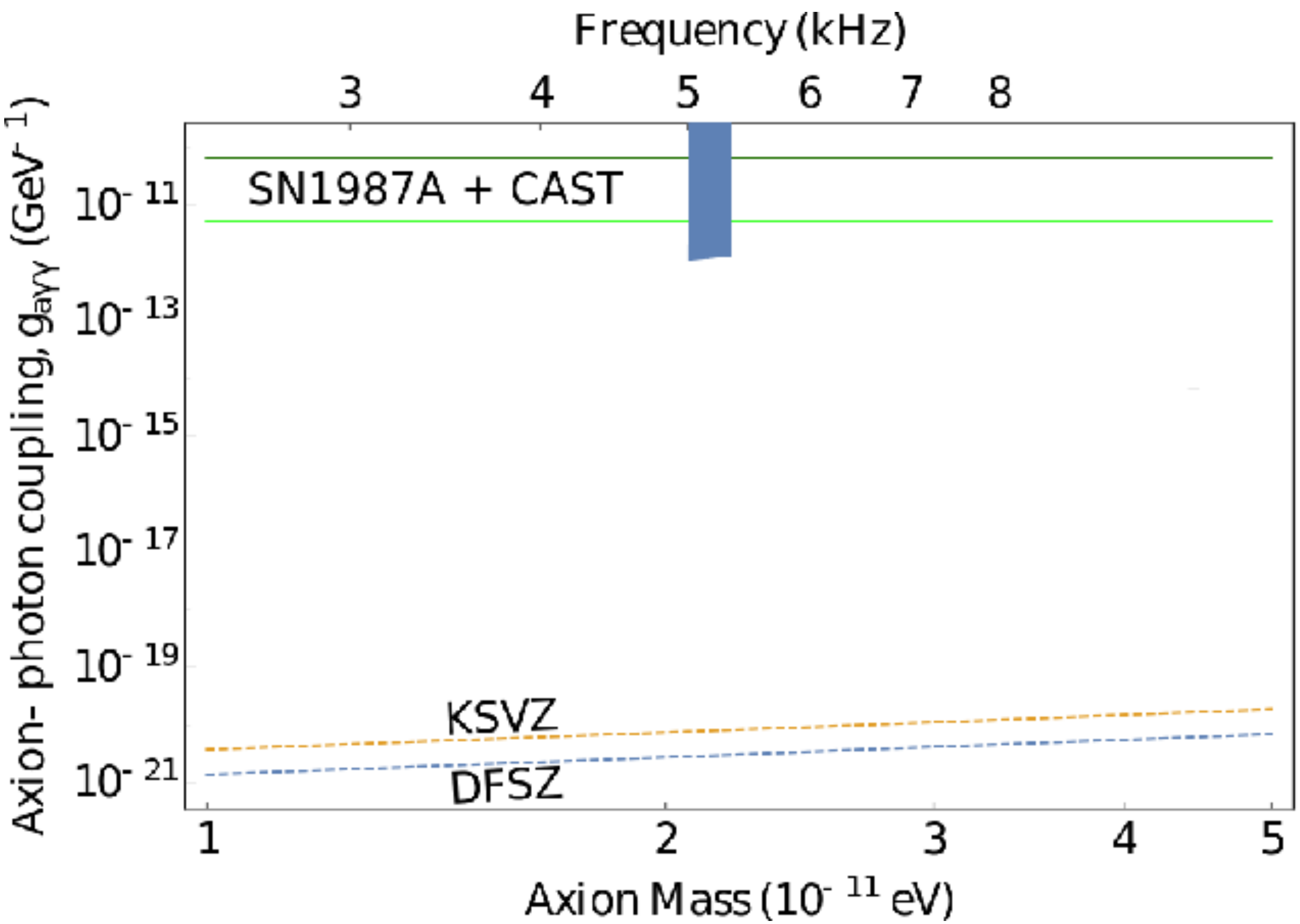
This spectra do not have the requisite to resolution to resolve axion signals with an effective line width of $10^{-6}\omega_a$

BEAST: First Limits

Higher resolution search was conducted around 5 kHz, with the minimal spectral resolution of 4.5 mHz (increasing at higher frequencies)

All sharp peaks greater than 4.4 standard deviations from the mean originating from the SQUID were able to be excluded, due to a similar signal appearing in the flux line

Using this data, we may place the 95 % confidence exclusion limits on axion-photon coupling



Possible Improvements

- **HIA V_{RMS} readout**
  - -> *A* unimportant
  - -> *d* important

Suggests many long and skinny "noodle" capacitors to improve sensitivity

- **SQUID I_{RMS} readout**
  - -> A important
  - -> d unimportant

Suggests many long flat "pan cake" capacitors to improve sensitivity

Element cross capacitance stray capacitance and grounding needs to be modeled carefully

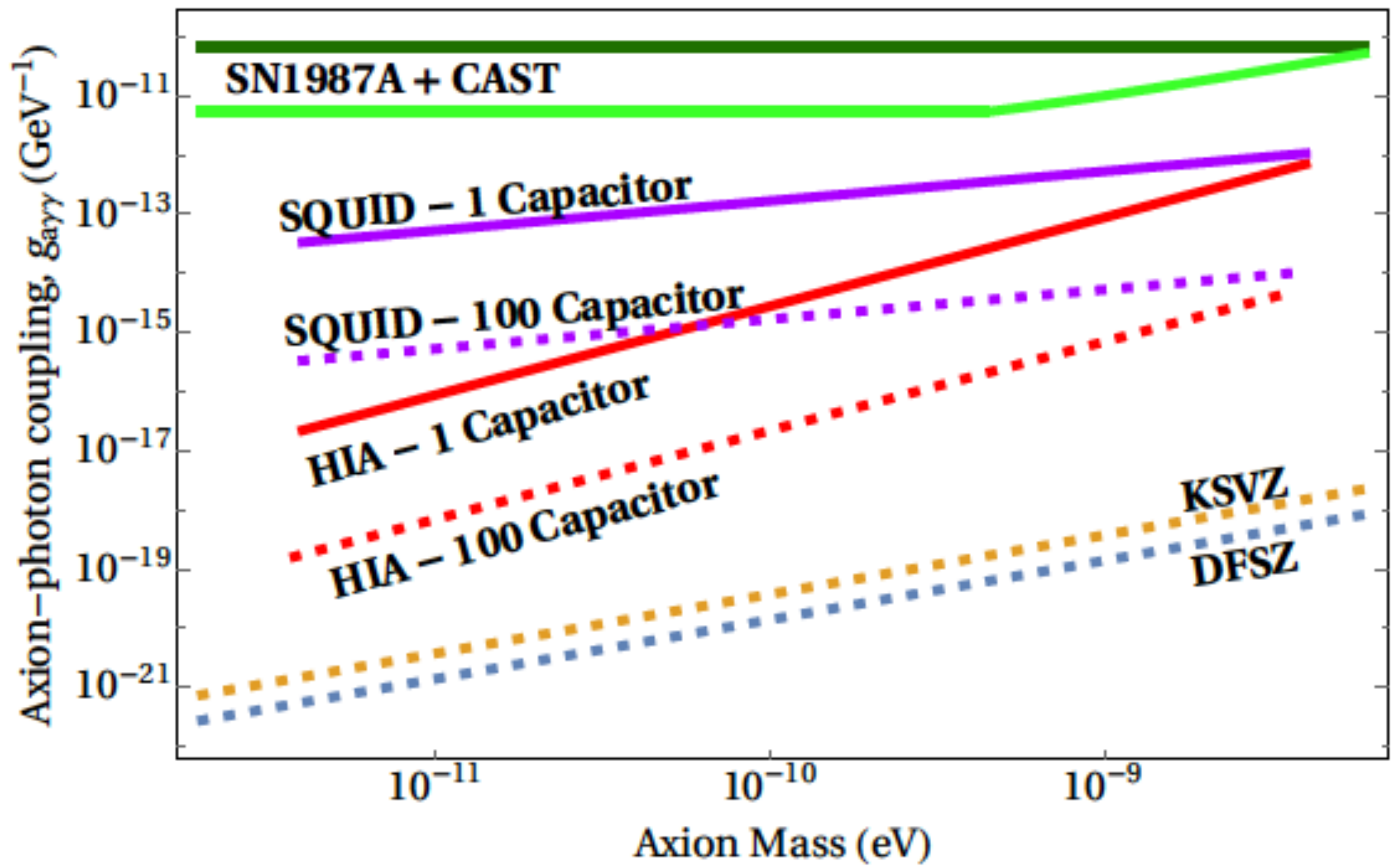


FIG. 1: Projected limits for the BEAST experiment, utilizing: a single capacitor (purple) and 100 capacitors (purple, dashed) coupled to a SQUID, and a single capacitor (red) and 100 capacitors (red, dashed) coupled to a high-impedance amplifier. Current best limits in the region from CAST (green) SN1987A (light green) are also plotted. Also shown are popular axion model bands, KSVZ (gold, dashed) and DFSZ (blue, dashed).

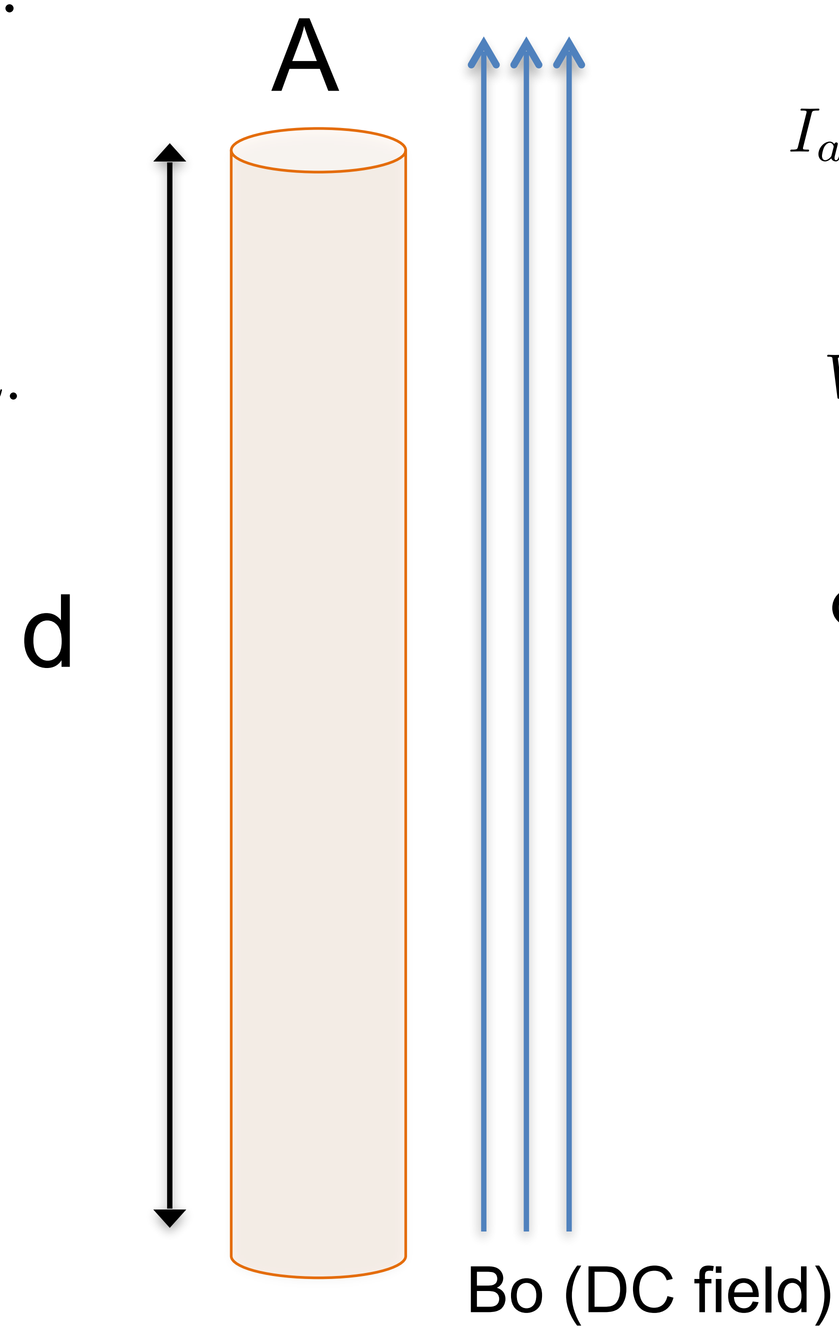
Long “Noodle” Capacitors not likely: Wire dipole antennas instead? Response of a Conductor to Axion Conversion?

Free current density induced in a conductor due to axion

$$\vec{J}_{fa} = g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\vec{B}_0\frac{\partial a}{\partial t}.$$

$$\rho_{fa} = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\vec{B}_0\vec{\nabla}\cdot a.$$

$$I_{fa} = J_{fa} * A$$



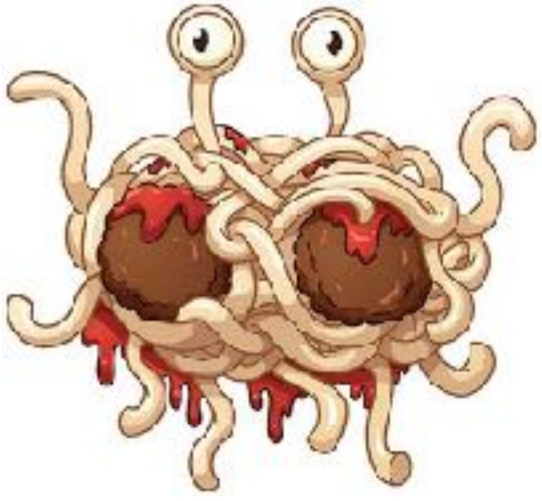
Basically governed by Ohms law with current and voltage in phase

Minimizes stray capacitances

$$I_{a_{RMS}} = g_{a\gamma\gamma}A\sqrt{\frac{\epsilon_0}{\mu_0}}B_0\sqrt{\rho_a c^3}$$

$$V_{a_{RMS}} = g_{a\gamma\gamma}\frac{d}{\kappa}\sqrt{\frac{\epsilon_0}{\mu_0}}B_0\sqrt{\rho_a c^3}$$

conductivity of the wire, κ



Noodle BEAST

Frequency and Quantum Metrology Research Group

THE UNIVERSITY OF WESTERN AUSTRALIA

SEEK WISDOM

EQUS
Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

- Research Staff
- Michael Tobar
- Eugene Ivanov
- John McFerran
- Alexey Veryaskin
- Sascha Schediwy
- Maxim Goryachev
- Jeremy Bourhill

- Students
- Ben McAllister
- Akhter Hoissan
- Graeme Flower
- Scott Hardie
- Lewis Teixeira
- Catriona Thomas