New Directions in Axion Detection

Surjeet Rajendran,
The Johns Hopkins University

Light Weakly Coupled Bosons

Goal: Solve theoretical problems of the Standard Model
(Strong CP, flavor, hierarchy...)

Strategy: Propose global symmetry at some high scale, broken at low energy

Generic Prediction: Light weakly coupled Goldstone Boson
(Axion, axion-like-particle, familon, relaxion...)

Light Weakly Coupled Bosons

Goal: Solve theoretical problems of the Standard Model
(Strong CP, flavor, hierarchy...)

Strategy: Propose global symmetry at some high scale, broken at low energy

Generic Prediction: Light weakly coupled Goldstone Boson
(Axion, axion-like-particle, familon, relaxion...)

Technically Natural Interactions

$$\frac{\phi}{f_a} F\tilde{F}, \frac{\phi}{f_a} G\tilde{G}, \frac{\partial_\mu \phi}{f_a} \bar{\Psi}\gamma^\mu\gamma_5\Psi, g\phi h^2$$

Vector Cousin

$$\frac{F'_{\mu\nu}}{\Lambda} \bar{\Psi}\sigma^{\mu\nu}\Psi, J^\mu A'_\mu, \epsilon F F'$$

Light Weakly Coupled Bosons

Goal: Solve theoretical problems of the Standard Model
(Strong CP, flavor, hierarchy...)

Strategy: Propose global symmetry at some high scale, broken at low energy

Generic Prediction: Light weakly coupled Goldstone Boson
(Axion, axion-like-particle, familon, relaxion...)

Technically Natural Interactions

$$\frac{\phi}{f_a} F\tilde{F}, \frac{\phi}{f_a} G\tilde{G}, \frac{\partial_\mu \phi}{f_a} \bar{\Psi}\gamma^\mu\gamma_5\Psi, g\phi h^2$$

Vector Cousin

$$\frac{F'_{\mu\nu}}{\Lambda} \bar{\Psi}\sigma^{\mu\nu}\Psi, J^\mu A'_\mu, \epsilon F F'$$

Potentially Natural Interactions

$$g\phi\bar{\Psi}\Psi$$

Light Weakly Coupled Bosons

Goal: Solve theoretical problems of the Standard Model
(Strong CP, flavor, hierarchy...)

Strategy: Propose global symmetry at some high scale, broken at low energy

Generic Prediction: Light weakly coupled Goldstone Boson
(Axion, axion-like-particle, familon, relaxion...)

Technically Natural Interactions

$$\frac{\phi}{f_a} F\tilde{F}, \frac{\phi}{f_a} G\tilde{G}, \frac{\partial_\mu \phi}{f_a} \bar{\Psi}\gamma^\mu\gamma_5\Psi, g\phi h^2$$

Vector Cousin

$$\frac{F'_{\mu\nu}}{\Lambda} \bar{\Psi}\sigma^{\mu\nu}\Psi, J^\mu A'_\mu, \epsilon F F'$$

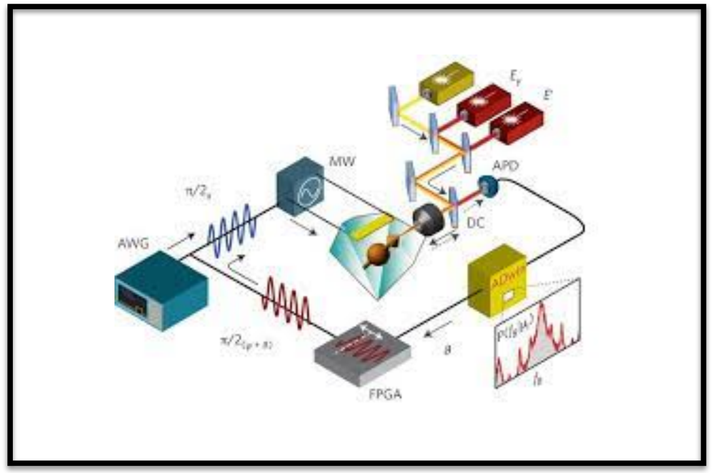
Potentially Natural Interactions

$$g\phi\bar{\Psi}\Psi$$

How do we find them?

Light Boson Detection

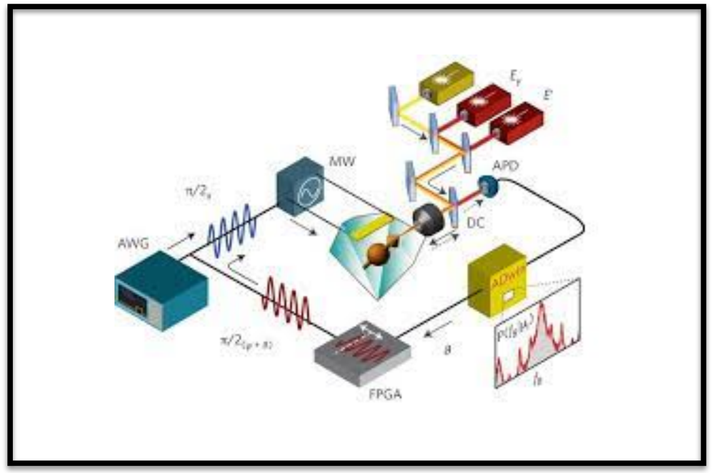
(1) Local Source



Null result directly relevant. Premium to produce and detect

Light Boson Detection

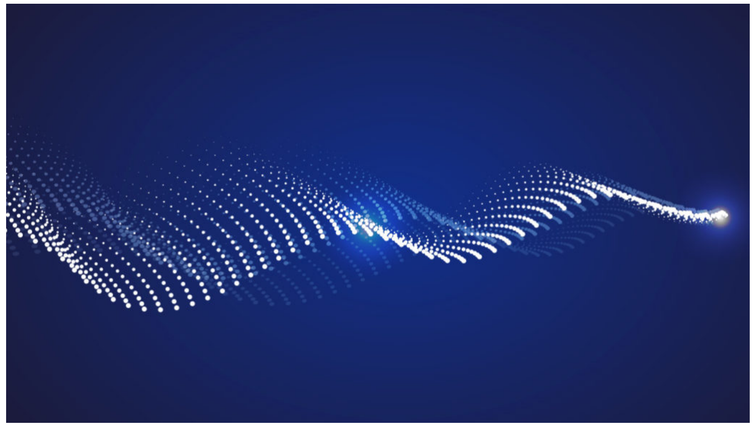
(1) Local Source

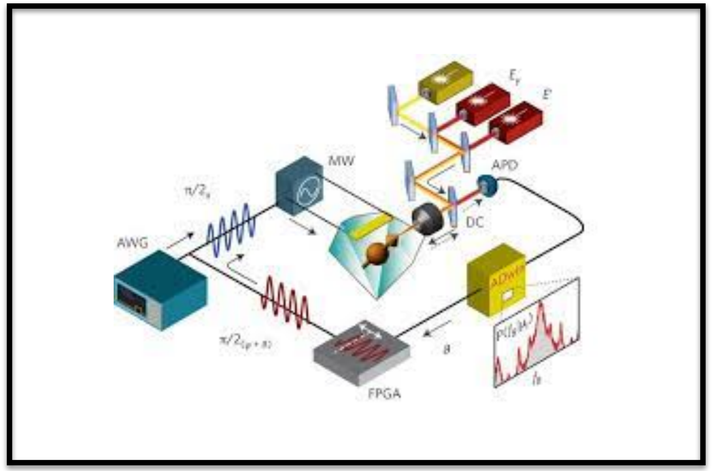


Null result directly relevant. Premium to produce and detect

(2) Cosmic Source

Ultra-light dark matter (<< 1 eV)

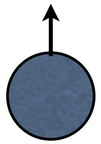




The Axion Landscape

Local Source

$g\phi\bar{\Psi}\Psi$



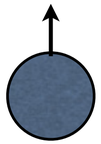
$$\frac{\partial_\mu \phi}{f_a}\bar{\Psi}\gamma^\mu\gamma_5\Psi$$

Spin Sensor

The Axion Landscape

Local Source

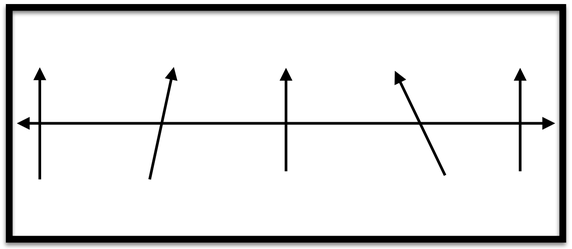
$g\phi\bar{\Psi}\Psi$



$\frac{\partial_\mu \phi}{f_a}\bar{\Psi}\gamma^\mu\gamma_5\Psi$

Spin Sensor

$\frac{\phi}{f_a}F\tilde{F}$

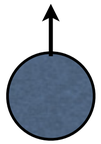


Polarization Rotation
(Spin Sensor)

The Axion Landscape

Local Source

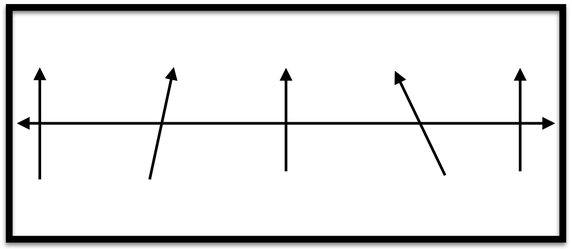
$g\phi\bar{\Psi}\Psi$



$\frac{\partial_\mu \phi}{f_a}\bar{\Psi}\gamma^\mu\gamma_5\Psi$

Spin Sensor

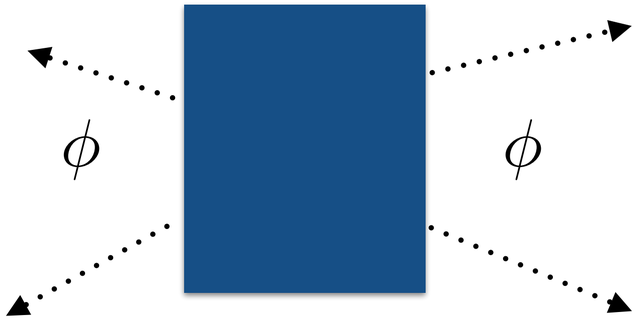
$\frac{\phi}{f_a}F\tilde{F}$



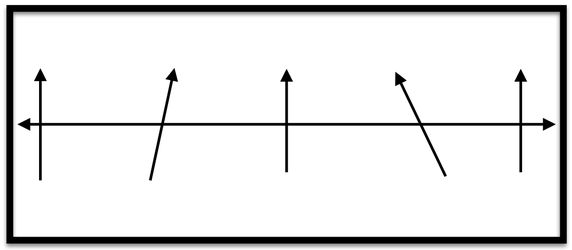
$\vec{B}$

Polarization Rotation
(Spin Sensor)

New opportunities?



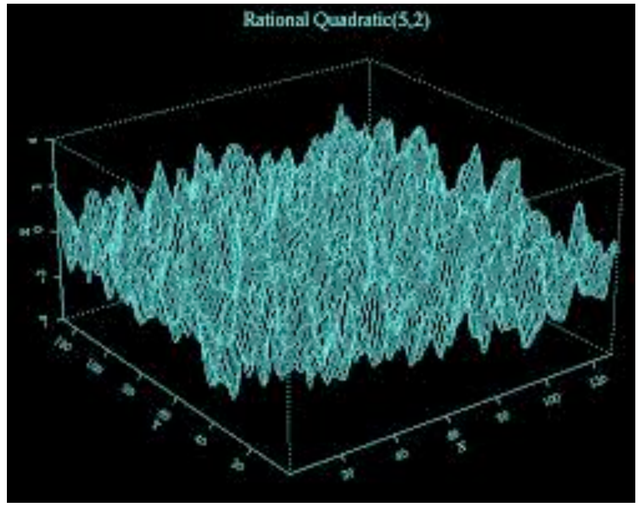
$g\phi\bar{\Psi}\Psi$



$\frac{\phi}{f_a}F\tilde{F}$

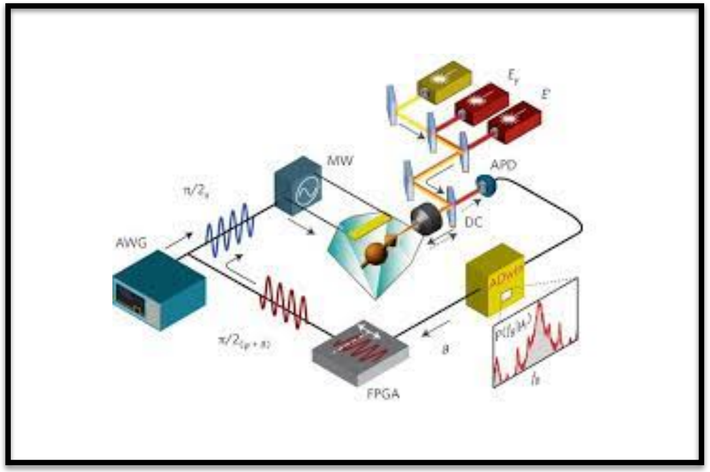
The Axion Landscape

Cosmological Source



Axion Dark Matter

Oscillating signal, narrow band
($Q \sim 10^6$)



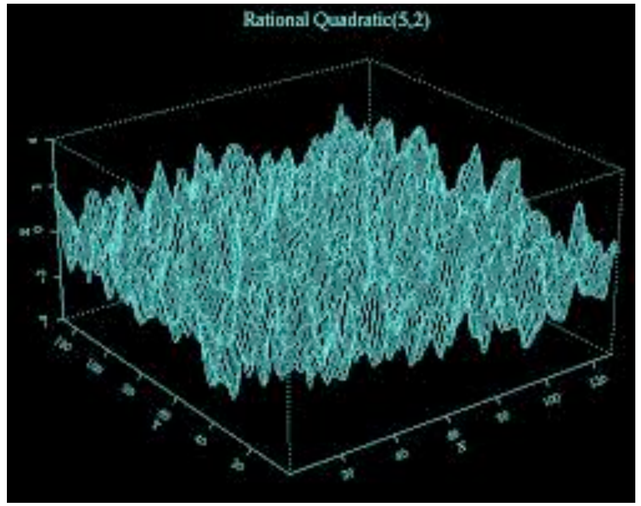
Detect Using suitable Resonator

nHz kHz MHz GHz 10 GHz

CASPEr DMRadio ADMX HAYSTAC

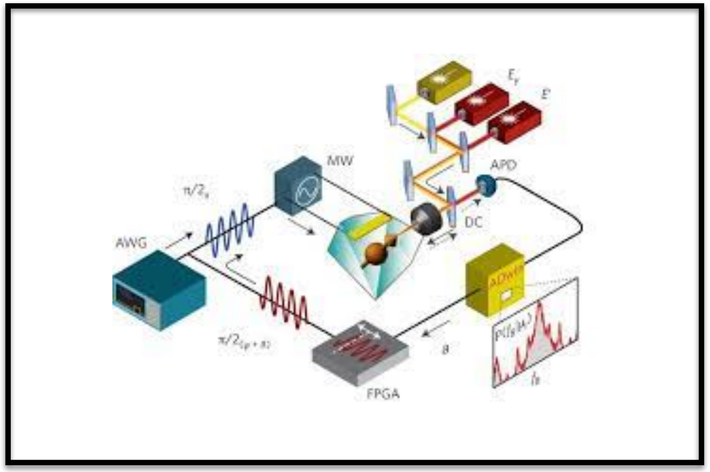
The Axion Landscape

Cosmological Source



Axion Dark Matter

Oscillating signal, narrow band
($Q \sim 10^6$)



Detect Using suitable Resonator

nHz kHz MHz GHz 10 GHz

CASPEr DMRadio ADMX HAYSTAC Resonators?

Outline

1. Photon Polarization Search

2. Axion Dark Matter with Nonlinear Optics

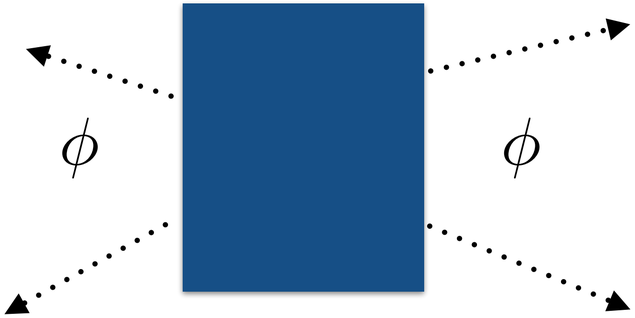
3. Conclusions

Photon Polarization Search

(MAGPI)

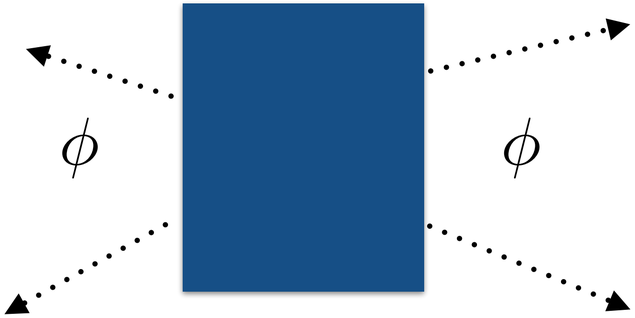
With Michael Fedderke, David Kaplan + SQMS Collaboration at Fermilab

Photon Polarization Search

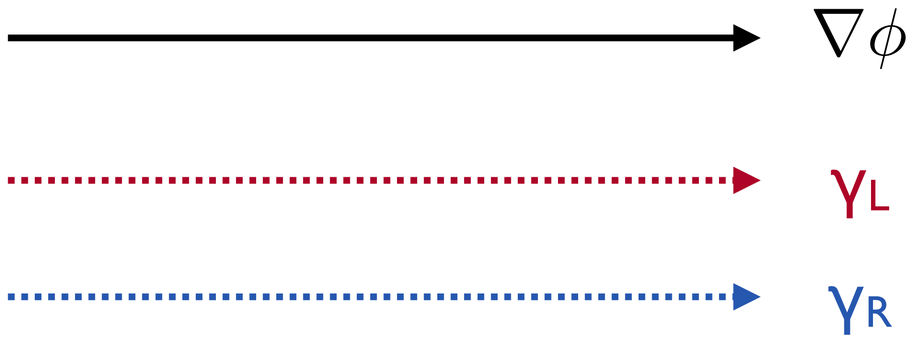


$g\phi\bar{\Psi}\Psi$

Photon Polarization Search

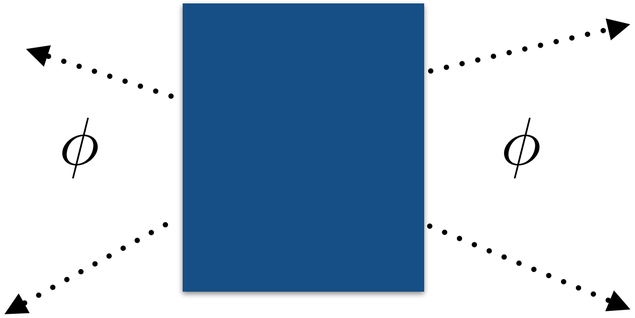


$$g\phi\bar{\Psi}\Psi$$

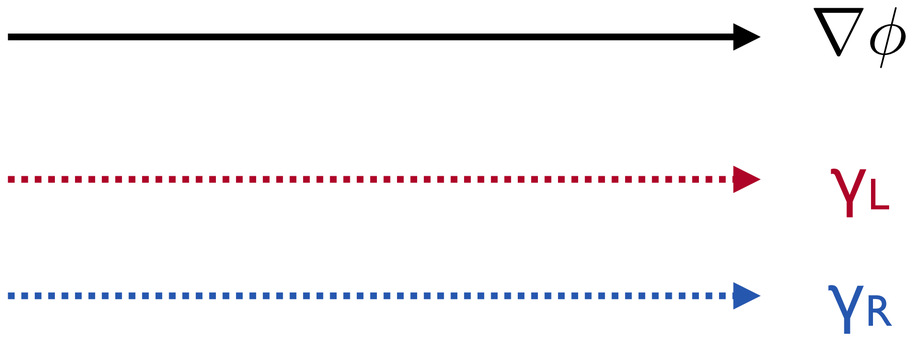


$$\frac{\phi}{f_a}F\tilde{F}$$

Photon Polarization Search



$$g\phi\bar{\Psi}\Psi$$

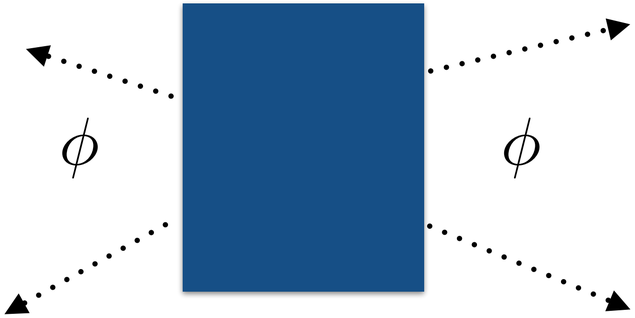


$$\frac{\phi}{f_a}F\tilde{F}$$

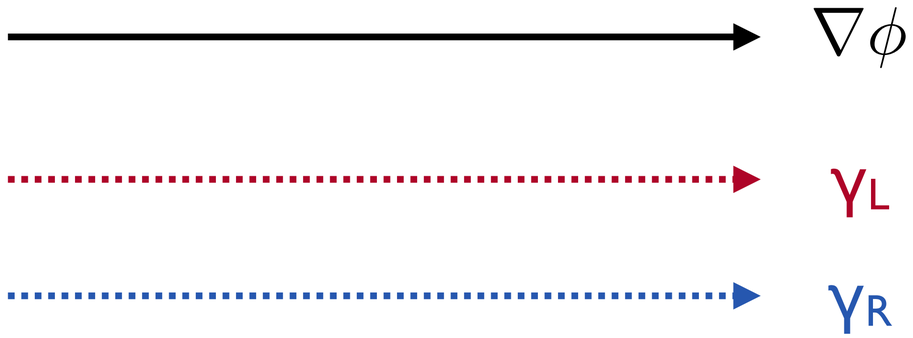
$$\delta k = k_L - k_R = \frac{\nabla\phi}{f_a}$$

Frequency Independent

Photon Polarization Search



$$g\phi\bar{\Psi}\Psi$$



$$\frac{\phi}{f_a}F\tilde{F}$$

$$\delta k = k_L - k_R = \frac{\nabla\phi}{f_a}$$

Frequency Independent

Measure Interferometrically

$$\delta\phi = \delta k L$$

Setup

$$\delta k = k_L - k_R = \frac{\nabla \phi}{f_a}$$

$$\delta \phi = \delta k L$$

Want large L

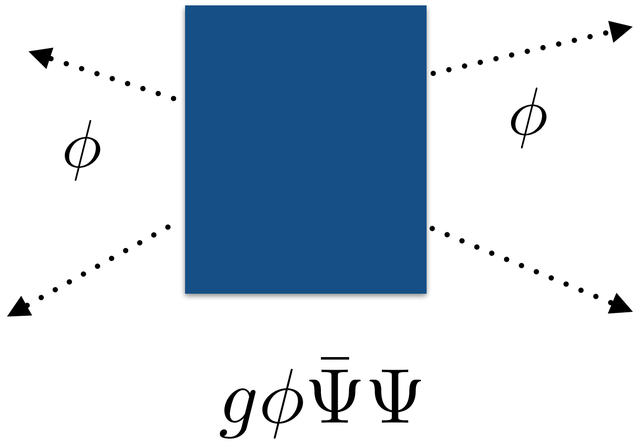
Setup

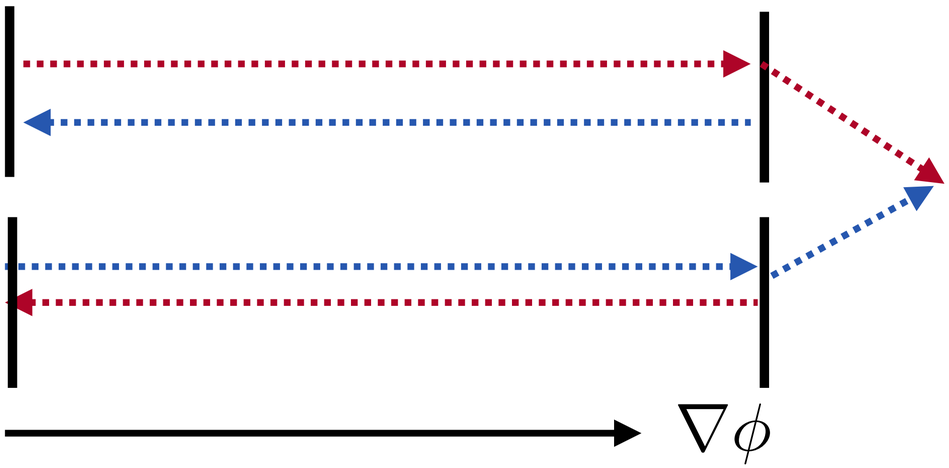
$$\delta k = k_L - k_R = \frac{\nabla \phi}{f_a}$$

$$\delta \phi = \delta k L$$

Want large L

Trap light in Fabry Perot cavity, compare phase shift between left and right circularly polarized light





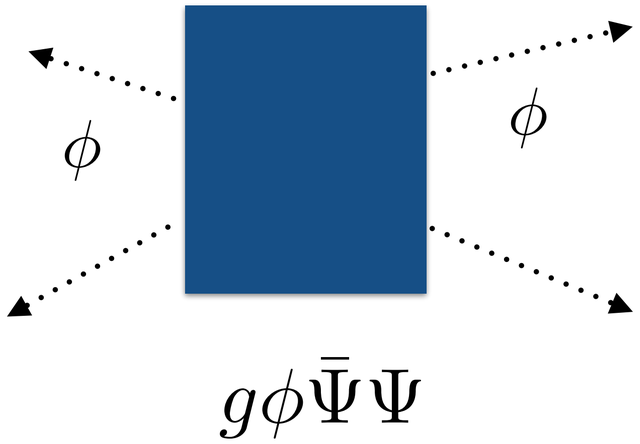
Setup

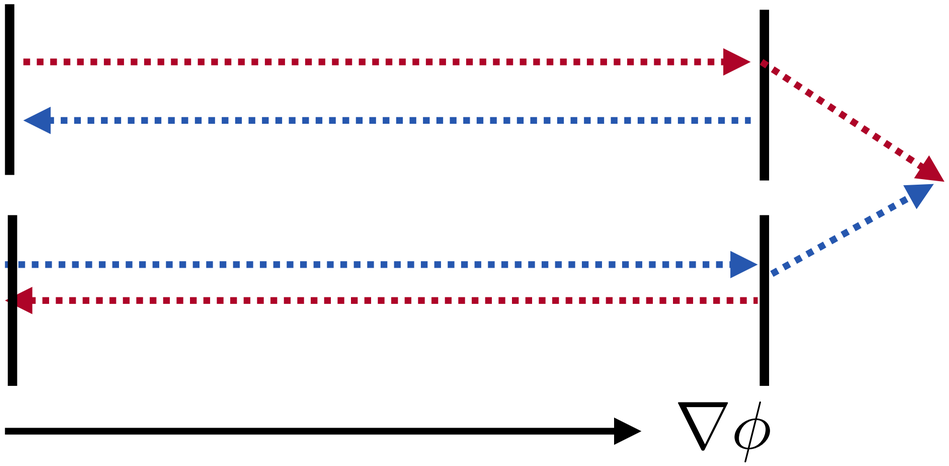
$$\delta k = k_L - k_R = \frac{\nabla \phi}{f_a}$$

$$\delta \phi = \delta k L$$

Want large L

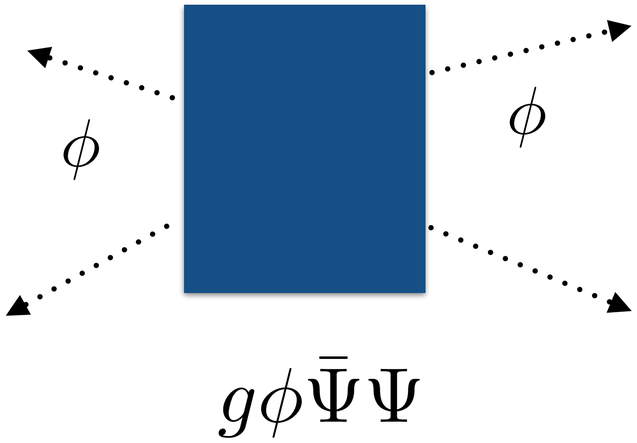
Trap light in Fabry Perot cavity, compare phase shift between left and right circularly polarized light



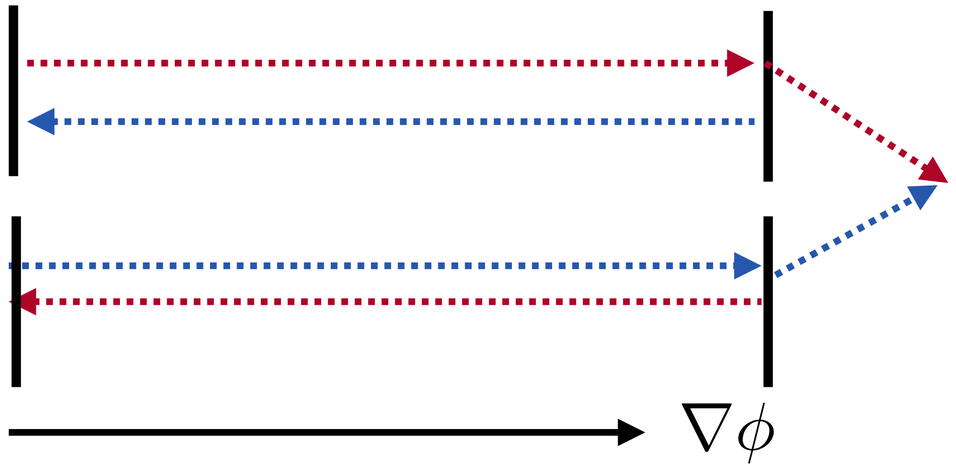


$$\delta\phi = F\delta k L = F\frac{\nabla\phi}{f_a}L = \frac{1}{\sqrt{N_\gamma}}$$

Experimental Realization

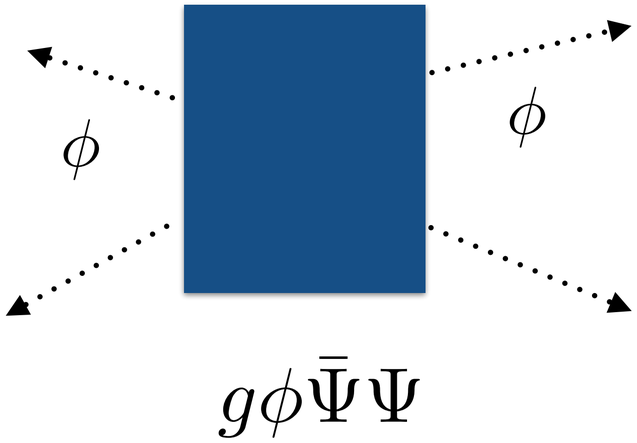


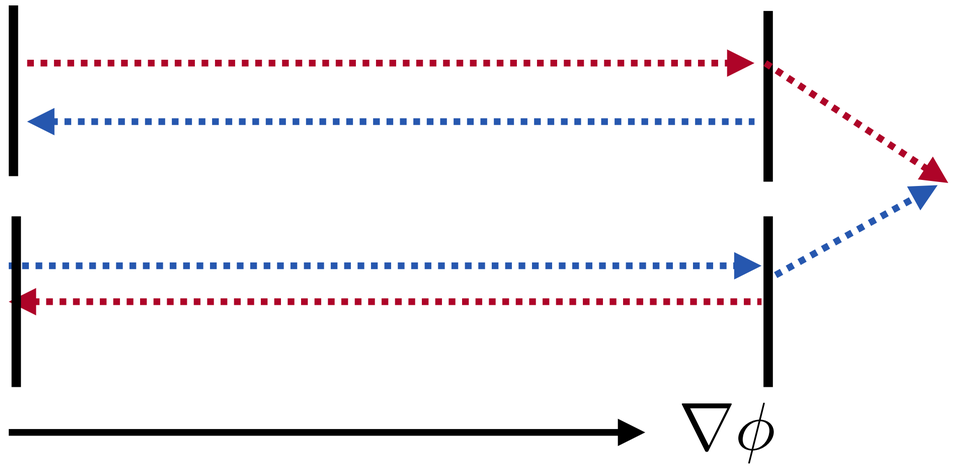
$$g\phi\bar{\Psi}\Psi$$



$$\delta\phi = F\delta kL = F\frac{\nabla\phi}{f_a}L = \frac{1}{\sqrt{N_\gamma}}$$

Experimental Realization

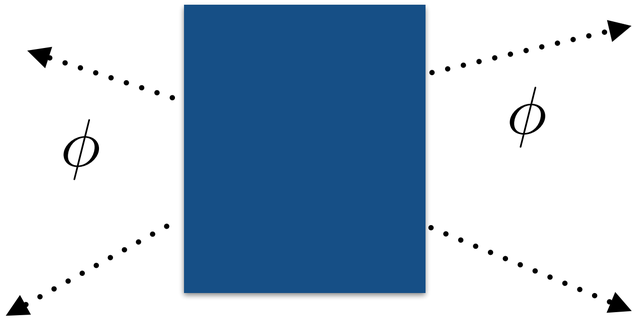




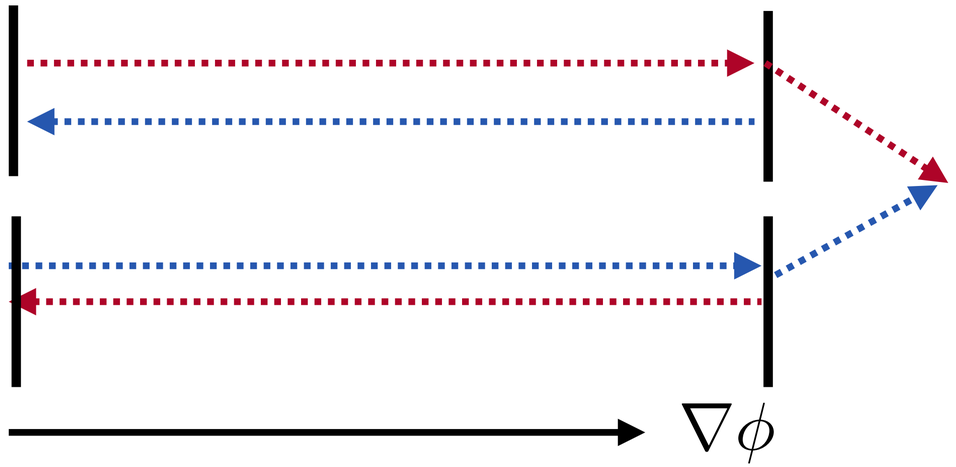
$$\delta\phi = F\delta kL = F\frac{\nabla\phi}{f_a}L = \frac{1}{\sqrt{N_\gamma}}$$

Independent of frequency - can realize in optical or superconducting RF

Experimental Realization



$$g\phi\bar{\Psi}\Psi$$

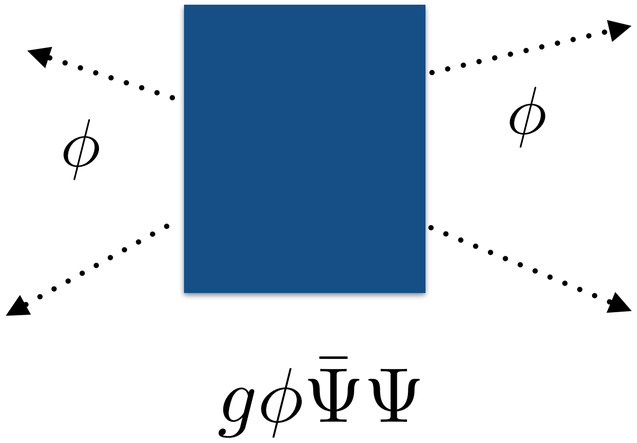


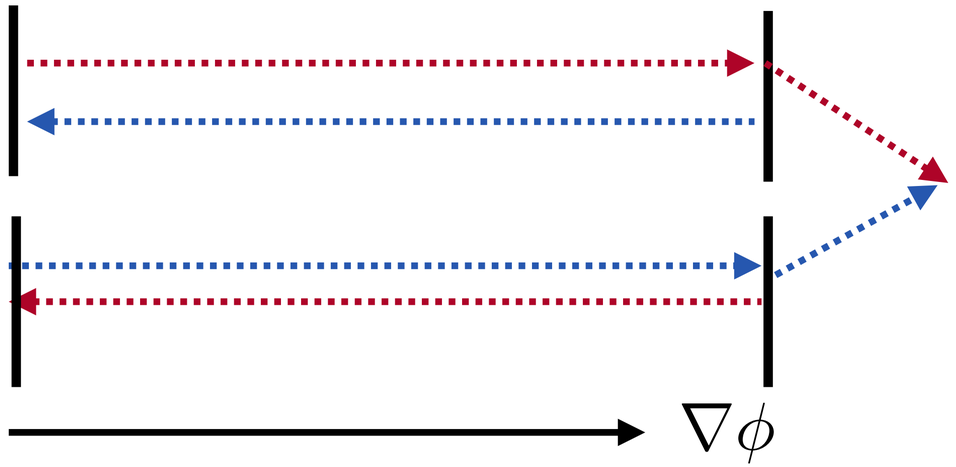
$$\delta\phi = F\delta kL = F\frac{\nabla\phi}{f_a}L = \frac{1}{\sqrt{N_\gamma}}$$

Independent of frequency - can realize in optical or superconducting RF

Optical: Smaller mirrors, lower F

Experimental Realization





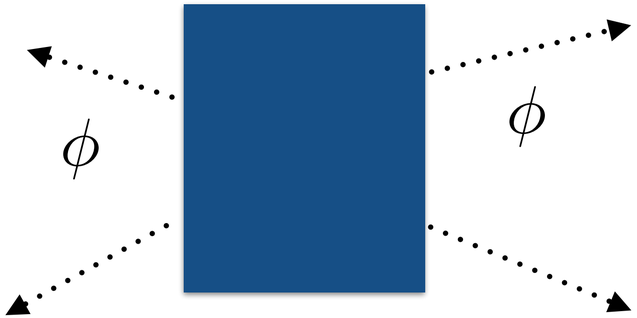
$$\delta\phi = F\delta kL = F\frac{\nabla\phi}{f_a}L = \frac{1}{\sqrt{N_\gamma}}$$

Independent of frequency - can realize in optical or superconducting RF

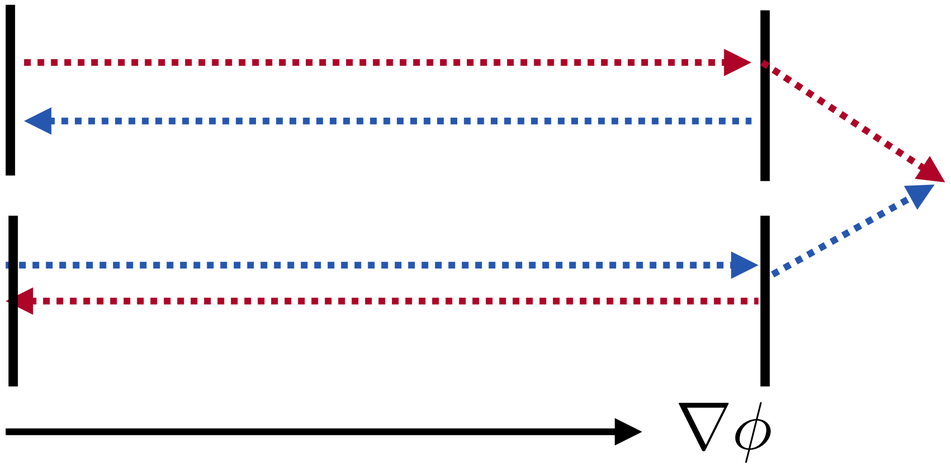
Optical: Smaller mirrors, lower F

RF: Large mirrors, high F

Systematics



$g\phi\bar{\Psi}\Psi$



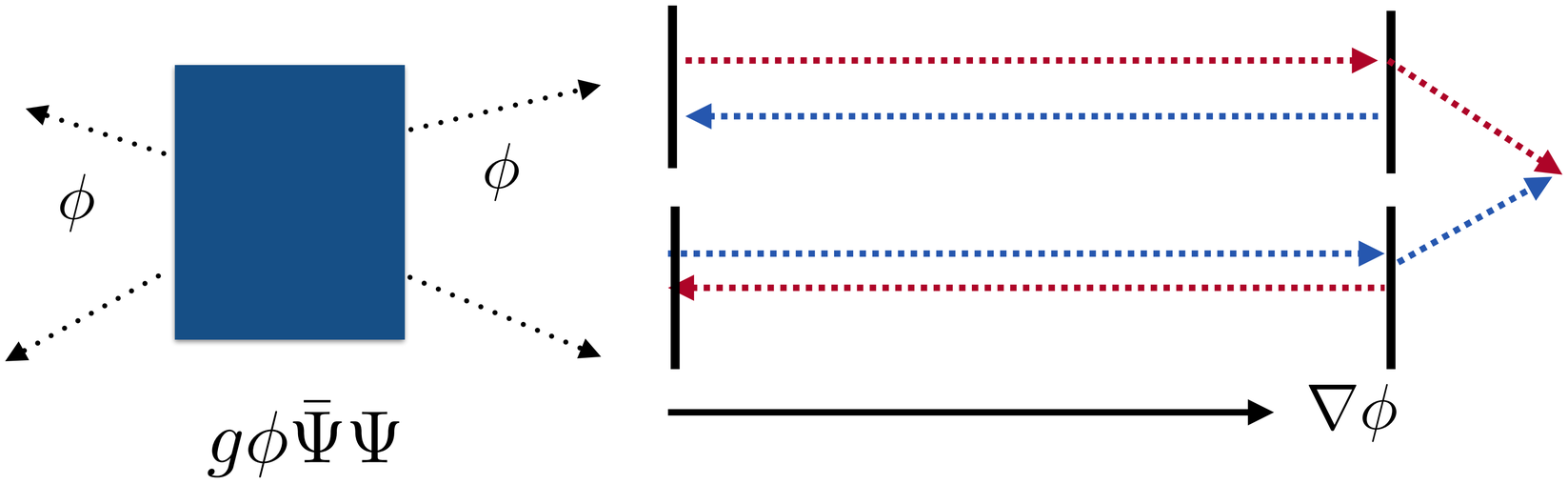
$$\delta\phi = F\delta kL = F\frac{\nabla\phi}{f_a}L = \frac{1}{\sqrt{N_\gamma}}$$

Issues

Cavity Length Fluctuations - phase shift depends on frequency

Strain in mirror induces phase - scales with F but not L

Systematics



$$\delta\phi = F\delta kL = F\frac{\nabla\phi}{f_a}L = \frac{1}{\sqrt{N_\gamma}}$$

Issues

Cavity Length Fluctuations - phase shift depends on frequency

Strain in mirror induces phase - scales with F but not L

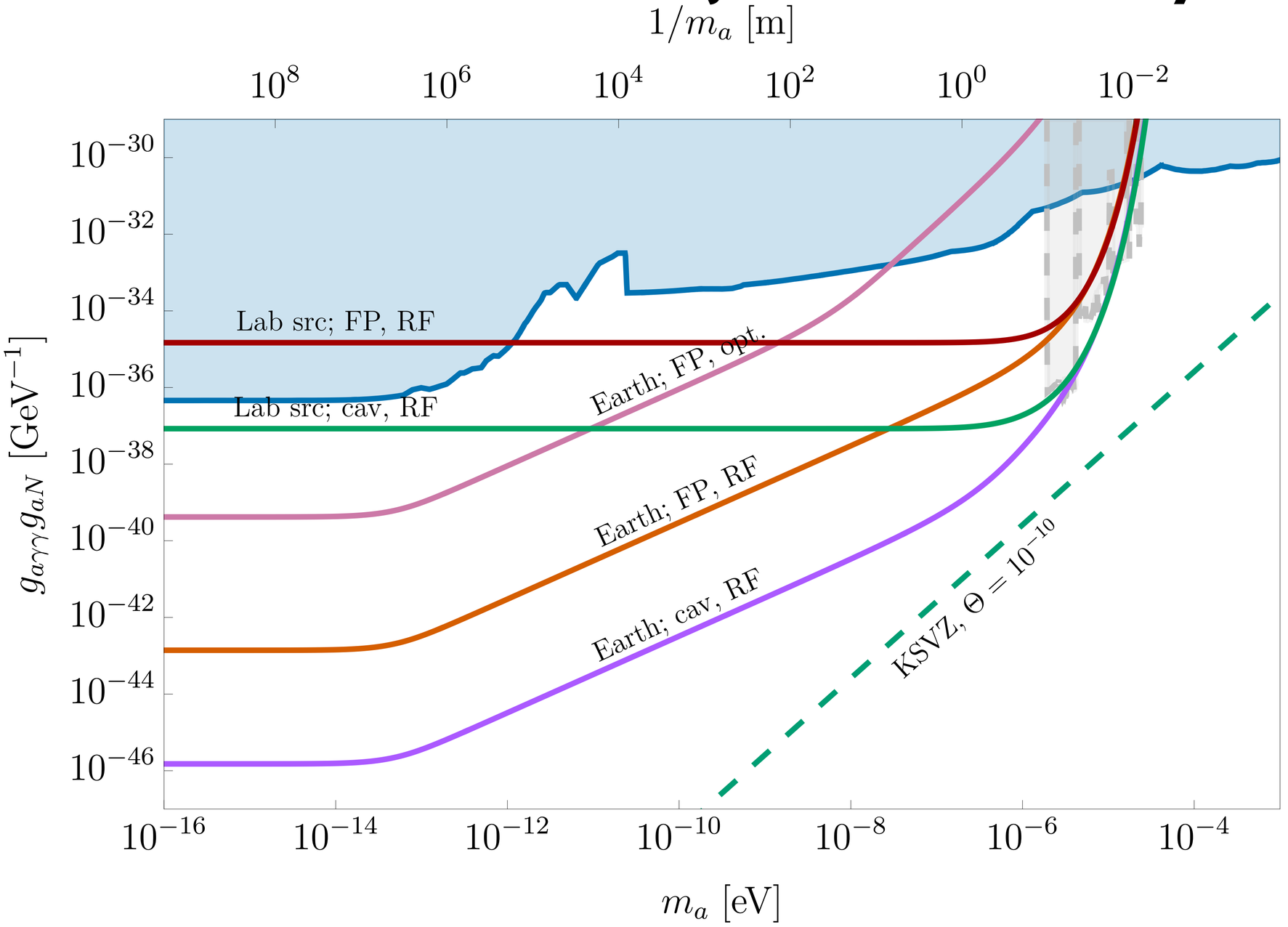
Handles

Use two different frequencies - differential measurement retains signal

Modulate L, but fix F - mirror strain remains same, signal changes

Modulate orientation relative to source or distance

Projected Sensitivity



RF Cavity

Q ~ 10^{11}, L ~ 1 m,
Mass ~ 100 kg

Optical Cavity

F ~400, L ~ 10 m,
1064 nm light

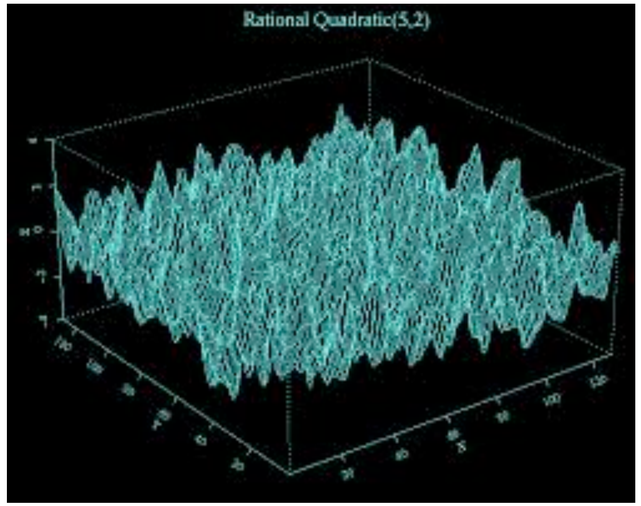
Axion Dark Matter with Non-Linear Optics

(GALILEO)

With Reza Ebadi, David Kaplan and Ron Walsworth

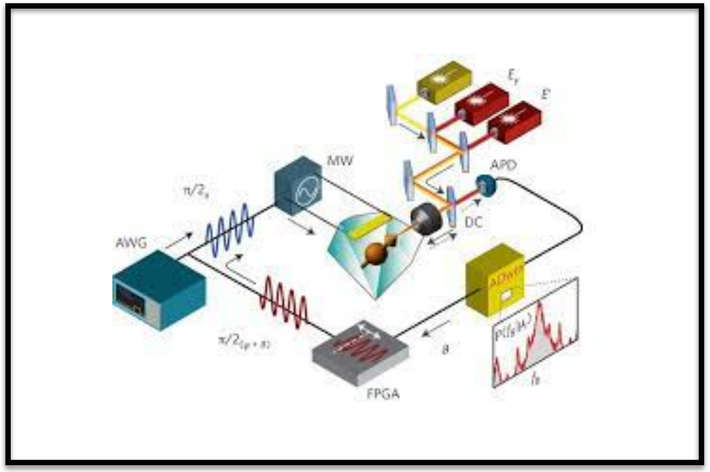
The Axion Landscape

Cosmological Source



Axion Dark Matter

Oscillating signal, narrow band
($Q \sim 10^6$)



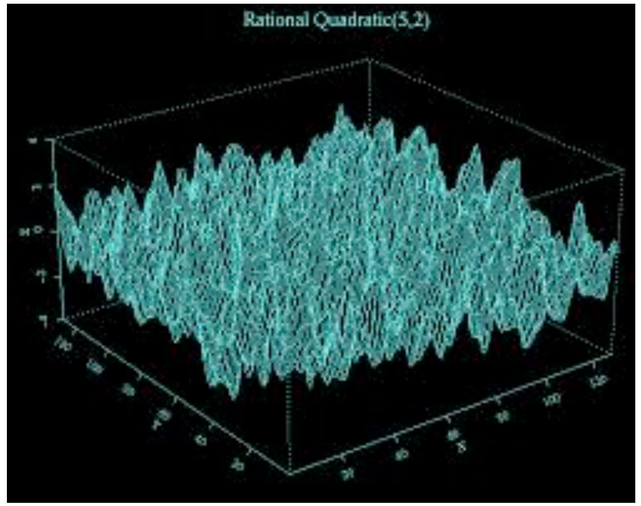
Detect Using suitable Resonator

nHz kHz MHz GHz 10 GHz

CASPEr DMRadio ADMX HAYSTAC

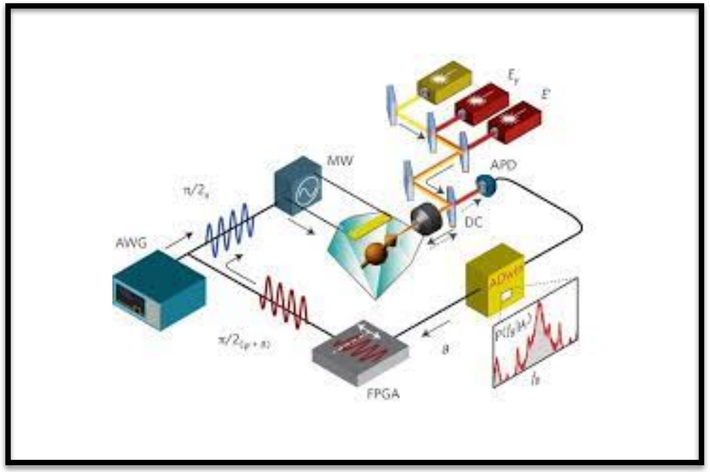
The Axion Landscape

Cosmological Source



Axion Dark Matter

Oscillating signal, narrow band
($Q \sim 10^6$)



Detect Using suitable Resonator

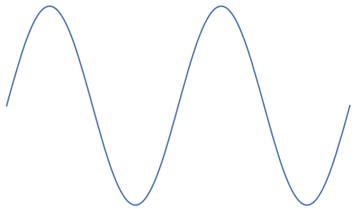
nHz kHz MHz GHz 10 GHz

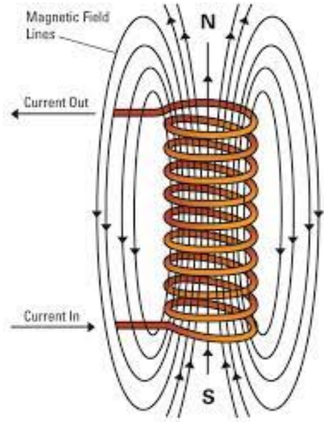
CASPEr DMRadio ADMX HAYSTAC Resonators?

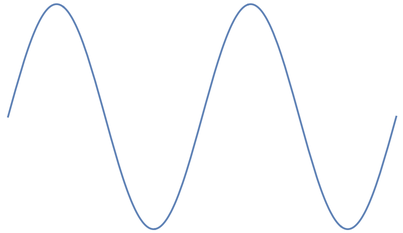
High Frequency Resonators

High Frequency Resonators

CASPEr DMRadio ADMX HAYSTAC Resonators?







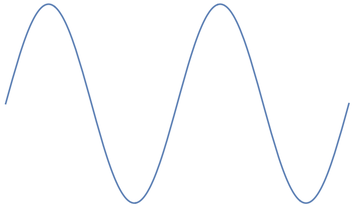
oscillating axion field

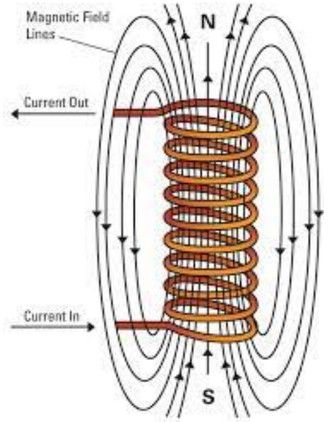
oscillating electric field

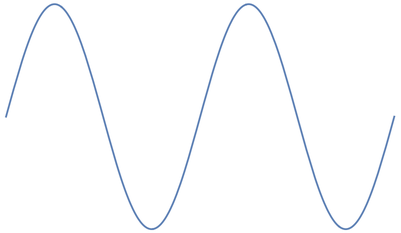
High Frequency Resonators

nHz kHz MHz GHz 10 GHz

CASPEr DMRadio ADMX HAYSTAC Resonators?







oscillating axion field

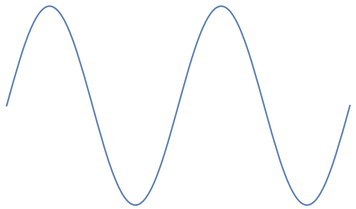
oscillating electric field

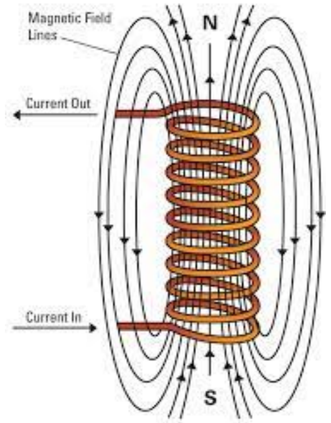
oscillating E' field (dark matter)

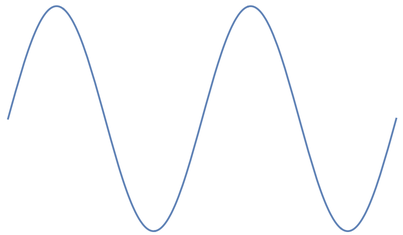
Charge sees small oscillating electric field

High Frequency Resonators

CASPEr DMRadio ADMX HAYSTAC Resonators?







oscillating axion field

oscillating electric field

oscillating E' field (dark matter)

Charge sees small oscillating electric field

Detect high frequency oscillating electric field

Nonlinear Optics

Detect high frequency oscillating electric field

Crystal with index of refraction with a linear dependence on electric field
(e.g. Lithium Niobate)

Create Optical Cavity with Lithium Niobate - choose length to set resonance frequency

Send light through optical resonator - measure phase shift

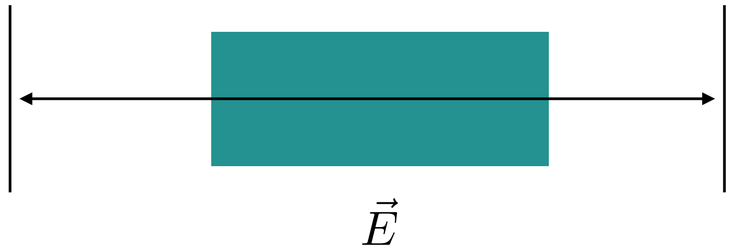
Nonlinear Optics

Detect high frequency oscillating electric field

Crystal with index of refraction with a linear dependence on electric field
(e.g. Lithium Niobate)

Create Optical Cavity with Lithium Niobate - choose length to set resonance frequency

Send light through optical resonator - measure phase shift



Phase shift depends on index of refraction -
measures time varying electric field

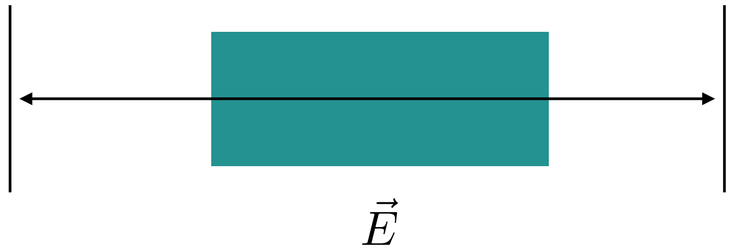
Nonlinear Optics

Detect high frequency oscillating electric field

Crystal with index of refraction with a linear dependence on electric field
(e.g. Lithium Niobate)

Create Optical Cavity with Lithium Niobate - choose length to set resonance frequency

Send light through optical resonator - measure phase shift



Phase shift depends on index of refraction -
measures time varying electric field

Lowest frequency set by absorption length of light (~km)

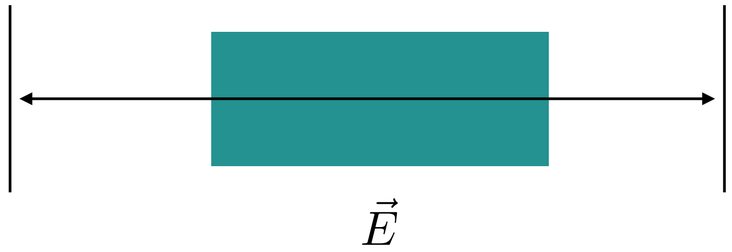
Nonlinear Optics

Detect high frequency oscillating electric field

Crystal with index of refraction with a linear dependence on electric field
(e.g. Lithium Niobate)

Create Optical Cavity with Lithium Niobate - choose length to set resonance frequency

Send light through optical resonator - measure phase shift

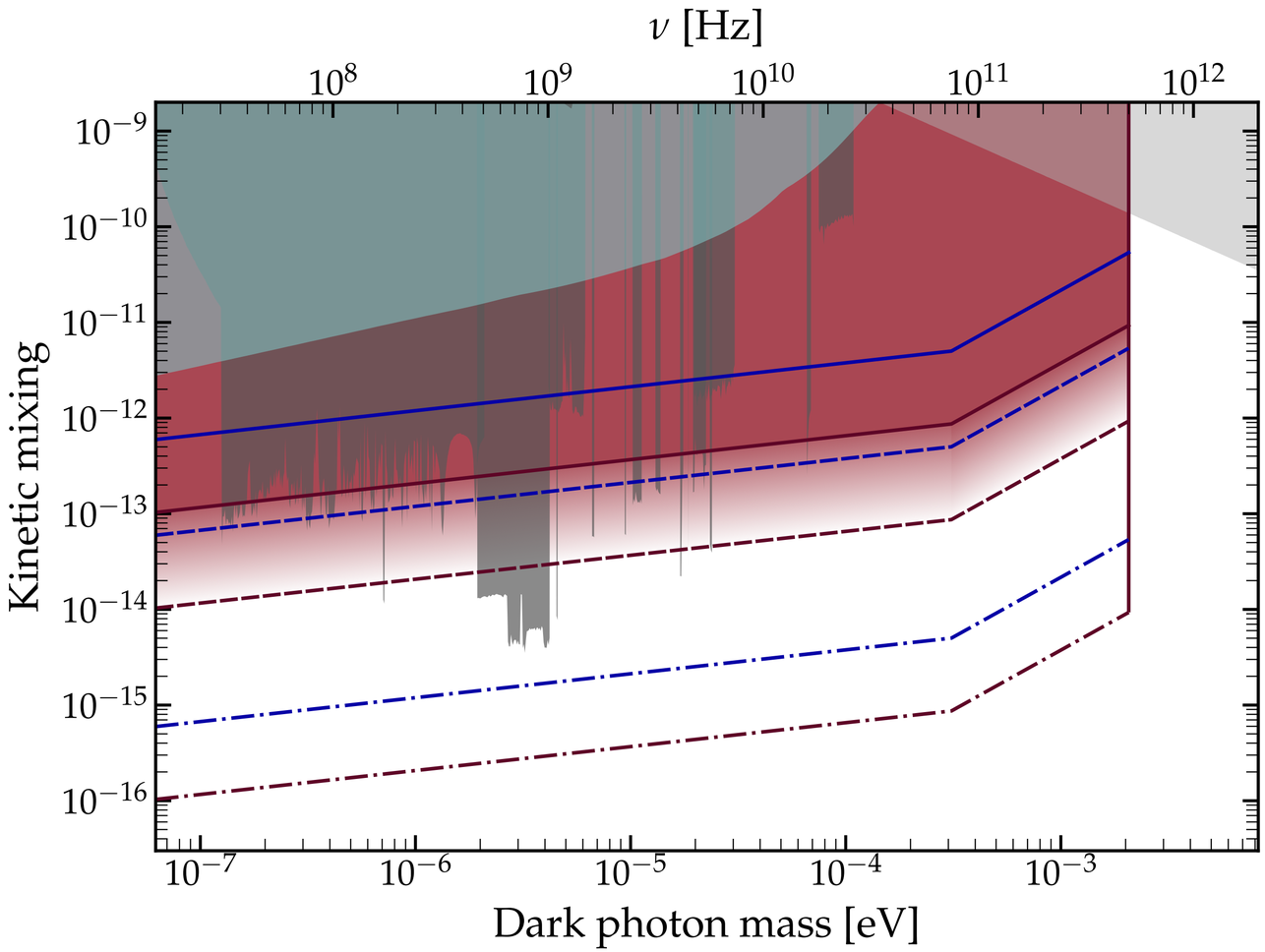


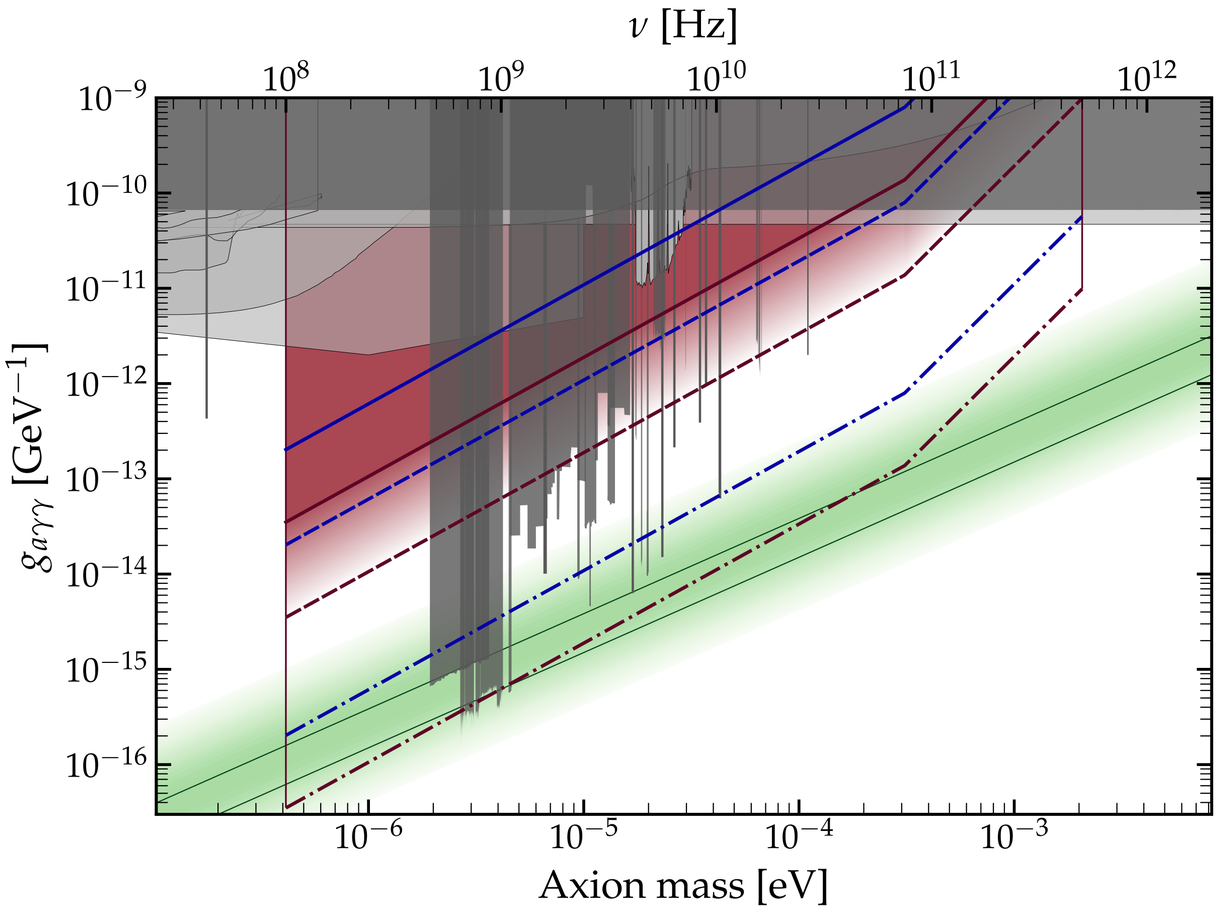
Phase shift depends on index of refraction -
measures time varying electric field

Lowest frequency set by absorption length of light (~km)

High frequency cut-off: Nyquist limit, response time of
crystal (> THz)

Projected Sensitivity





Conservative Solid Lines: 1 s averaging

Super aggressive dot dashed: ~ 1 yr averaging, 10 db Squeezing, 10 W

Conclusions

1. Important to search broad range of couplings and frequencies

2. Exciting opportunities in the RF for polarization searches

3. Exploit non-linear optics for high frequency resonators