Title: Searching for Axion Dark Matter with Birefringent Cavities

Date: Dec 04, 2018 01:00 PM

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Abstract: <p>Axion-like particles are a broad class of dark matter candidates which are expected to behave as a coherent, classical field with a weak coupling to photons. Research into the detectability of these particles with laser interferometers has recently revealed a number of promising experimental designs. Inspired by these ideas, we propose the Axion Detection with Birefringent Cavities (ADBC) experiment, a new axion interferometry concept using a cavity that exhibits birefringence between its two, linearly-polarized laser eigenmodes. This experimental concept overcomes several limitations of the designs currently in the literature, and can be practically realized in the form of a simple bowtie cavity with tunable mirror angles. Our design thereby increases the sensitivity to the axion-photon coupling over a wide range of axion masses.</p>

Searching for Axion Dark Matter with Birefringent Cavities

Hongwan Liu, Brodi D. Elwood, Matthew Evans and Jesse Thaler

1809.01656

Massachusetts Institute of Technology

Outline

1. Axions and Light
2. Optical Cavities
3. Axion Detection with Birefringent Cavities (ADBC)

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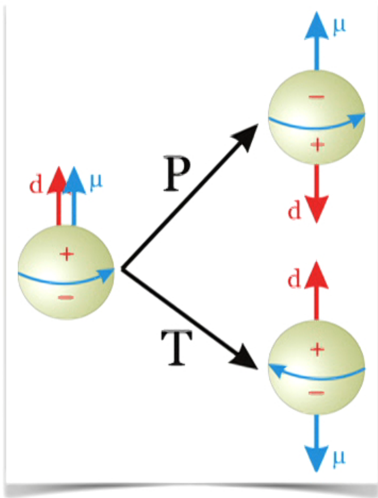
The QCD Axion

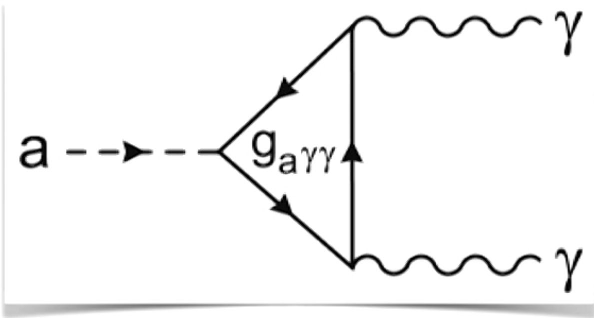


$$\mathscr{L} \supset \left(\bar{\theta} + \frac{a}{f_a}\right) G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Peccei and Quinn ‘77, Weinberg ‘78, Wilczek ‘78

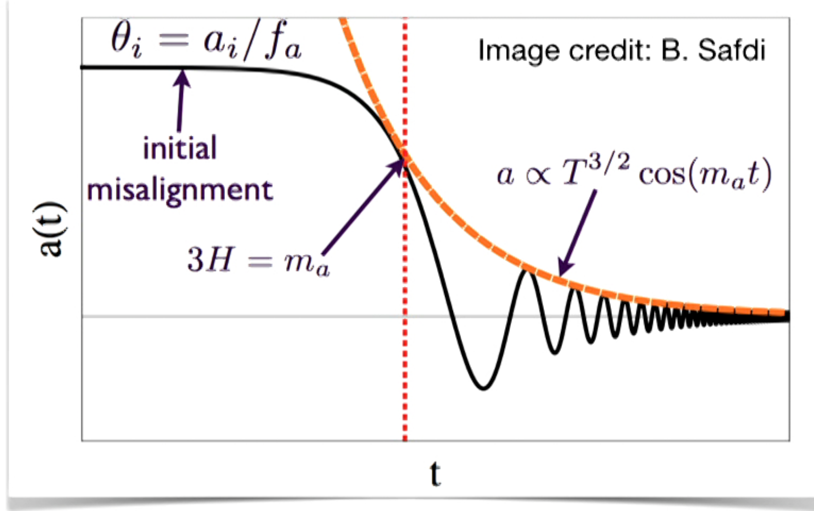
The **QCD axion** can potentially explain the **strong CP problem**: **small neutron EDM** seems to indicate **unnaturally small CP violation**, even though CP violation is expected.

The QCD Axion



$$\mathscr{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

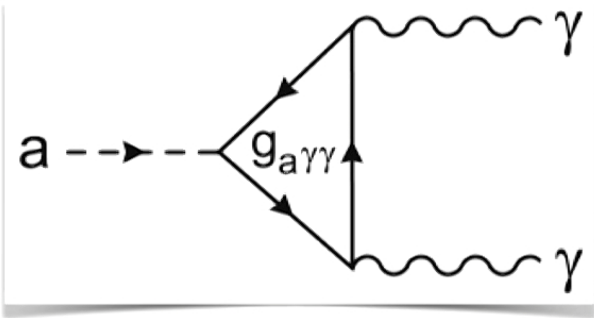
QCD effects give QCD axions a mass (**small** to be undiscovered), and **coupling to photons**.



Good dark matter candidate:
cold, coherent oscillating scalar field.

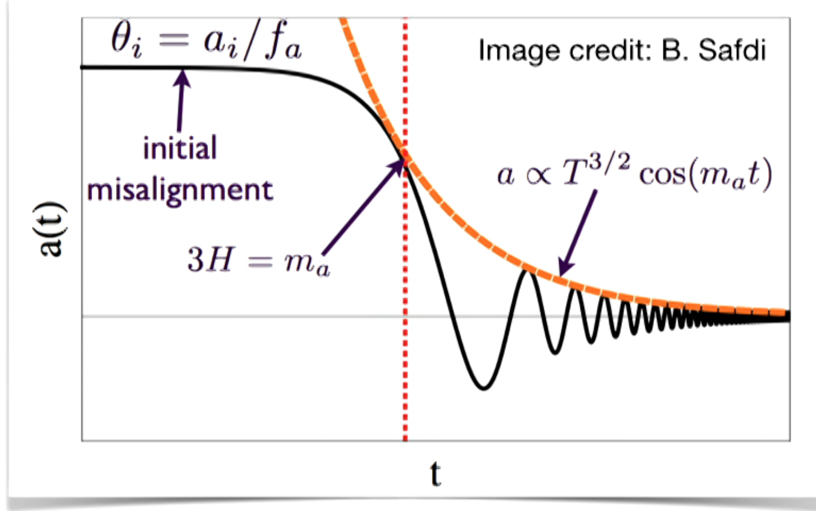
$$a = a_0 \cos(m_a t - k_a z)$$

"Axions"



$$\mathscr{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Throughout this talk: "axion" means "axion-like particles": any particle that interacts with EM as above.



Good dark matter candidate:
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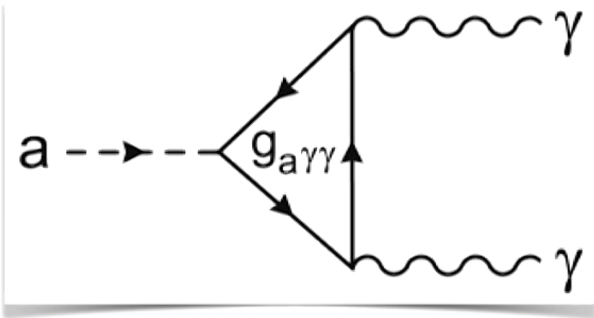
"Axions"



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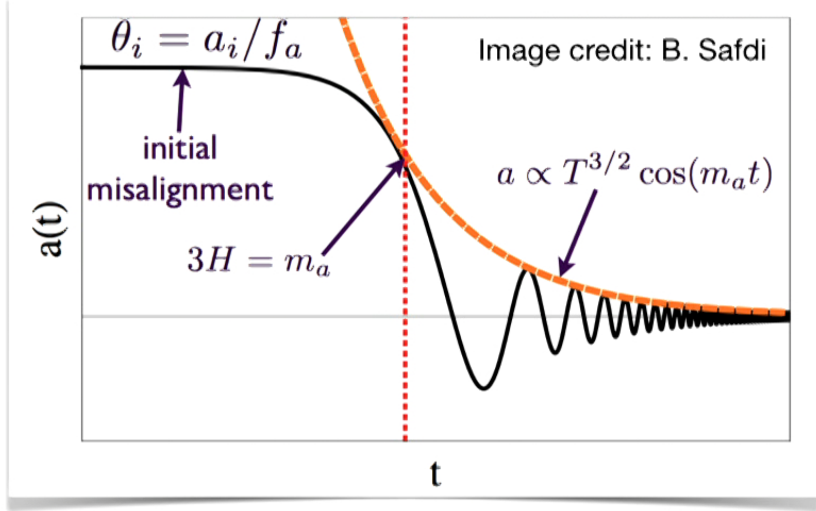

Throughout this talk: "axion" means "axion-like particles": any particle that interacts with EM as above.

Good dark matter candidate:
cold, coherent oscillating scalar field.

$$a = a_0 \cos(m_a t - k_a z)$$

Experiment size much smaller than axion wavelength: always spatially coherent!

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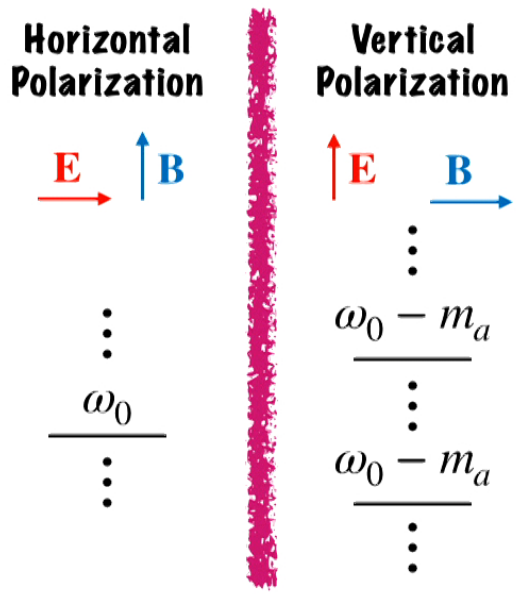
Axions and Light



Without axions, orthogonal, linear polarizations are **eigenmodes of free propagation**.

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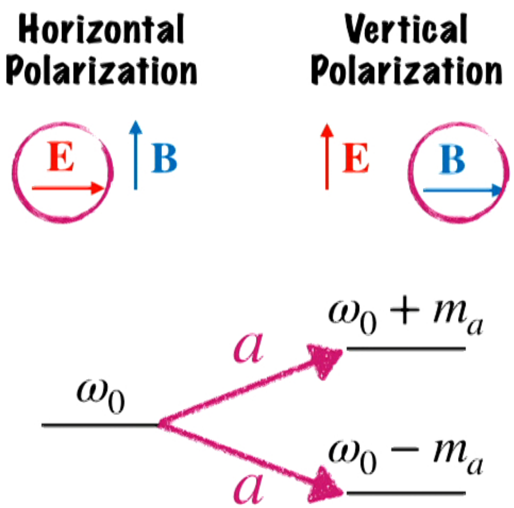
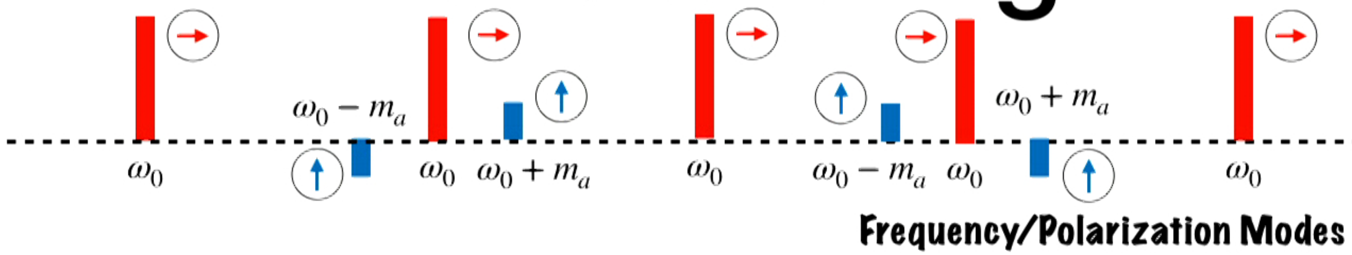
Axions and Light

$$\mathscr{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \propto a\mathbf{E}\cdot\mathbf{B}$$



Axions allow **transitions** between states of orthogonal polarization **separated by the axion mass**.

Axions and Light



Photon with frequency ω_0 converts into **orthogonal polarization** with difference in frequency given by the **axion mass**.

Time

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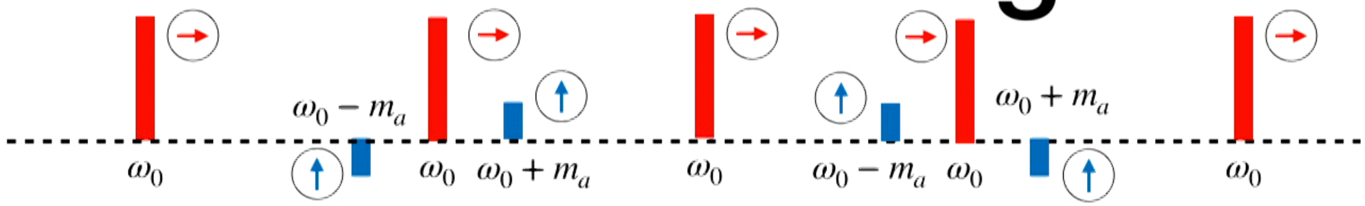
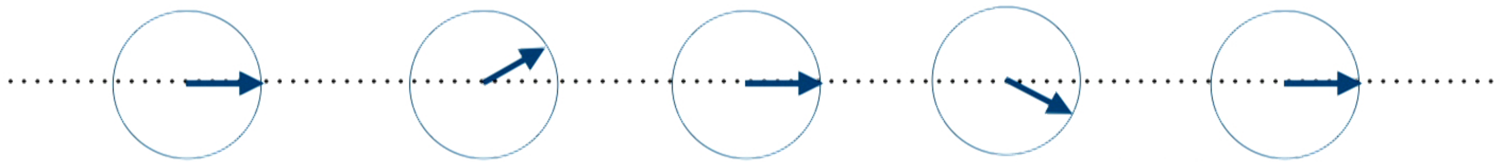
Axions and Light



Frequency/Polarization Modes



Linearly Polarized Light

For horizontally polarized light, the polarization **oscillates** slightly about the horizontal.

Time

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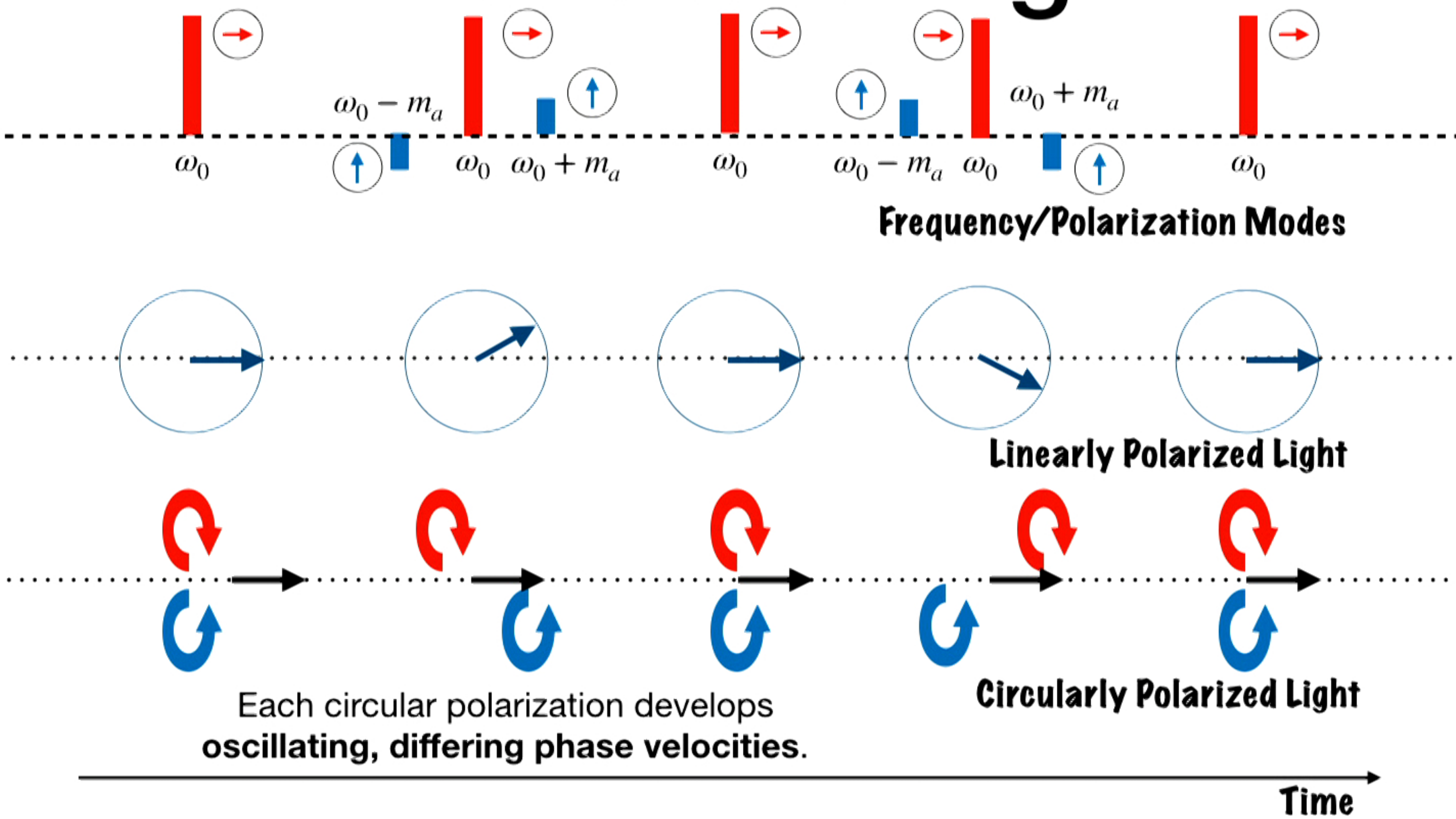
Axions and Light



Each circular polarization develops
oscillating, differing phase velocities.

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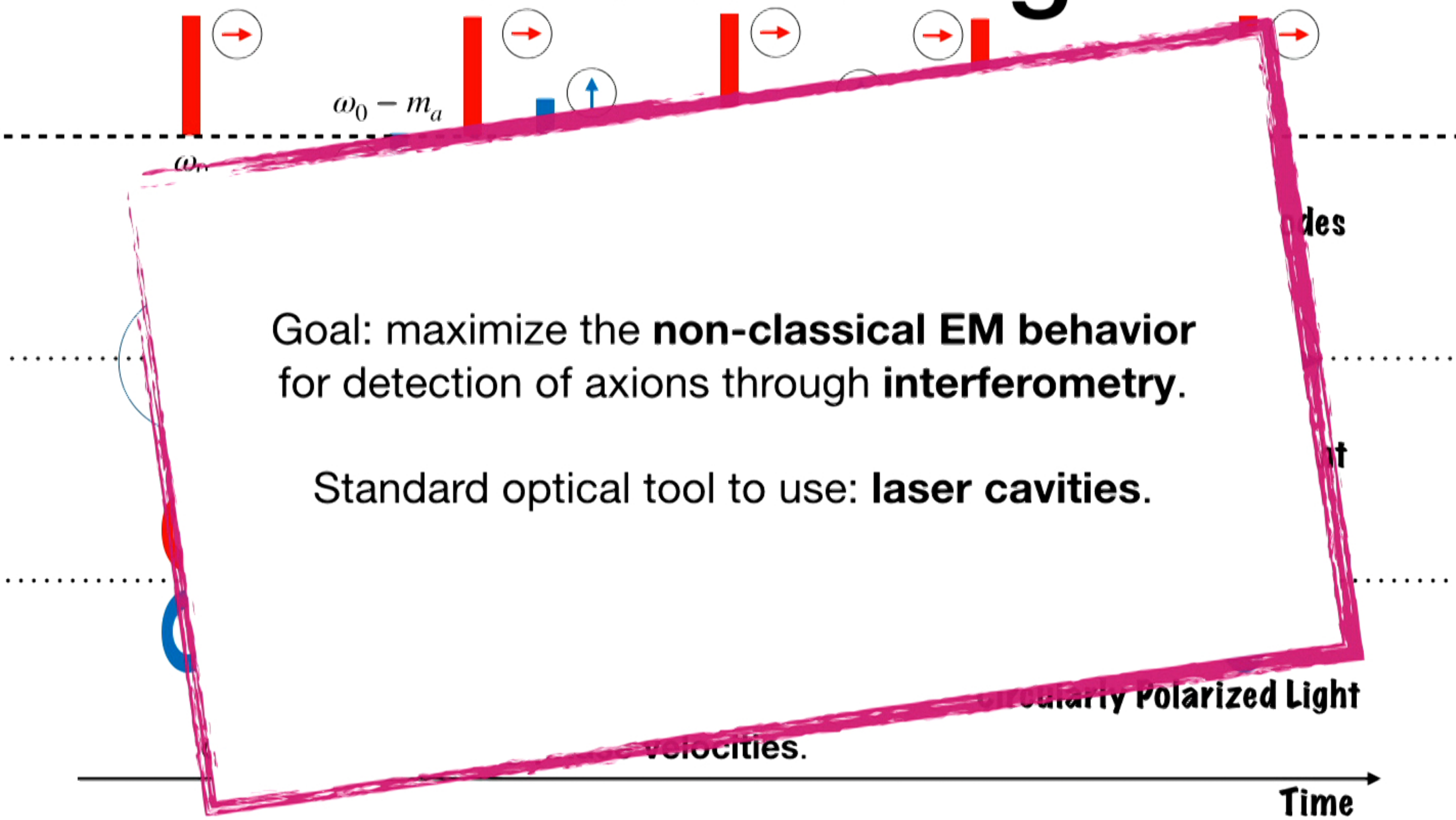
Axions and Light



Goal: maximize the **non-classical EM behavior** for detection of axions through **interferometry**.

Standard optical tool to use: **laser cavities**.

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A Poor Particle Physicist's Cookbook for Optical Cavities

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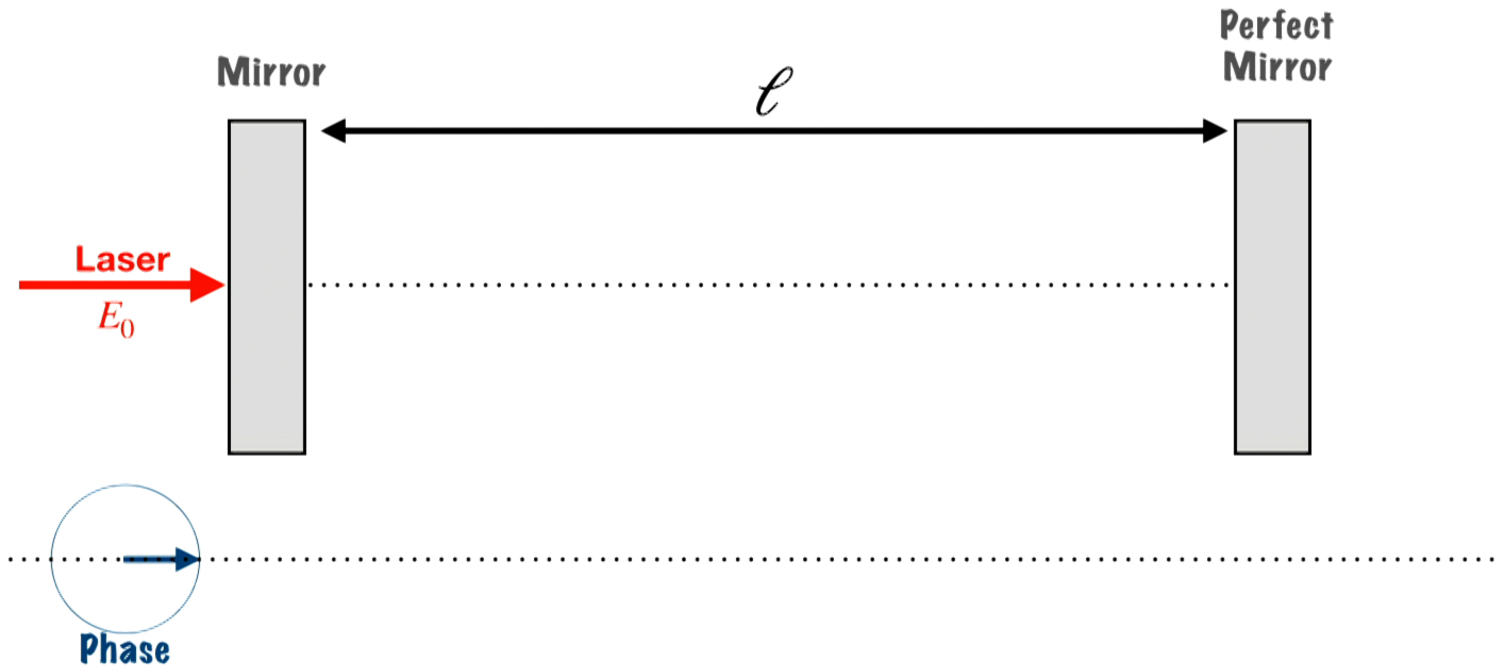
Fabry-Perot Cavity



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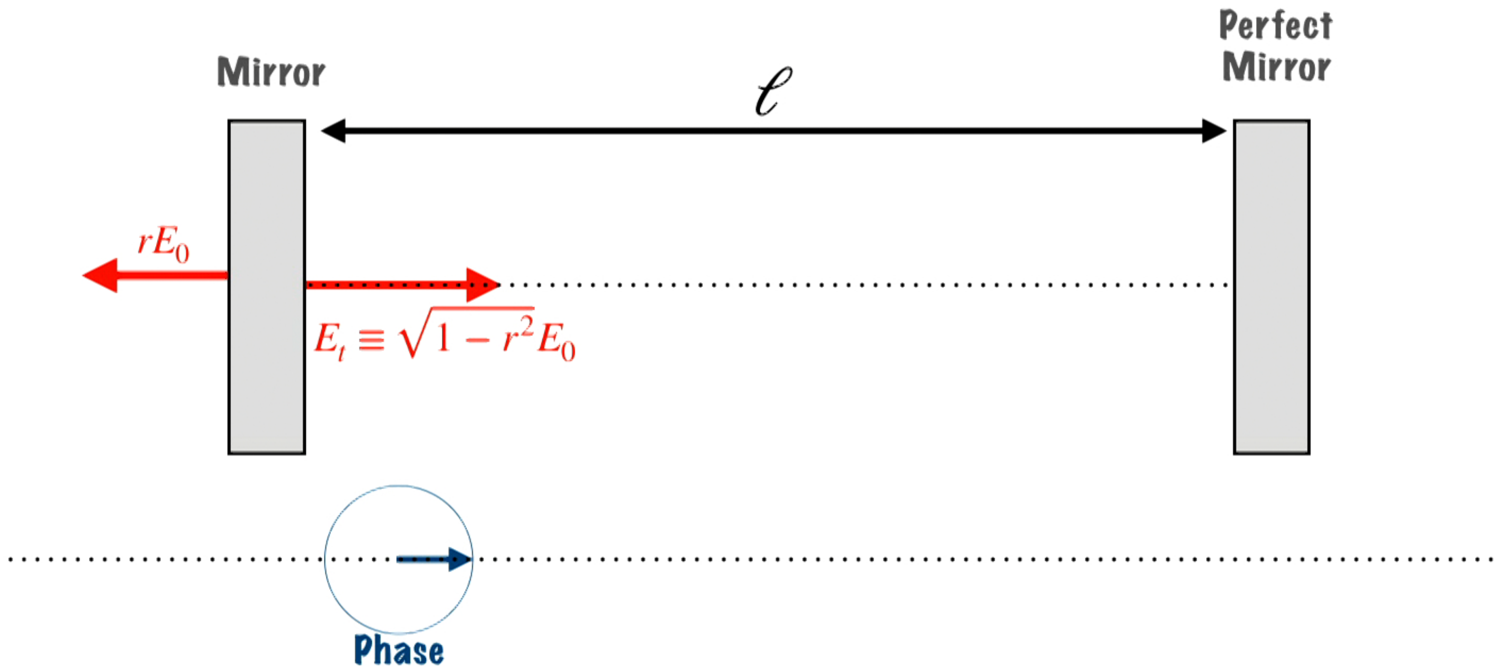
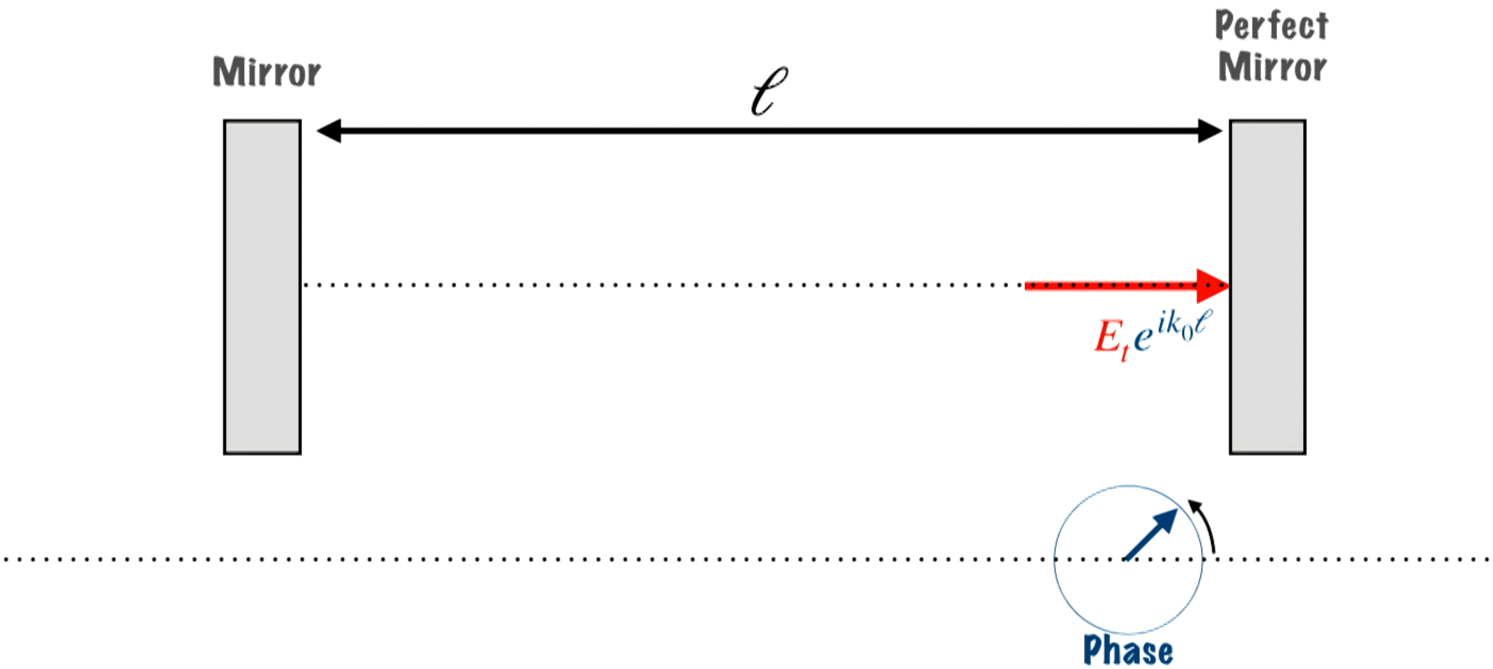
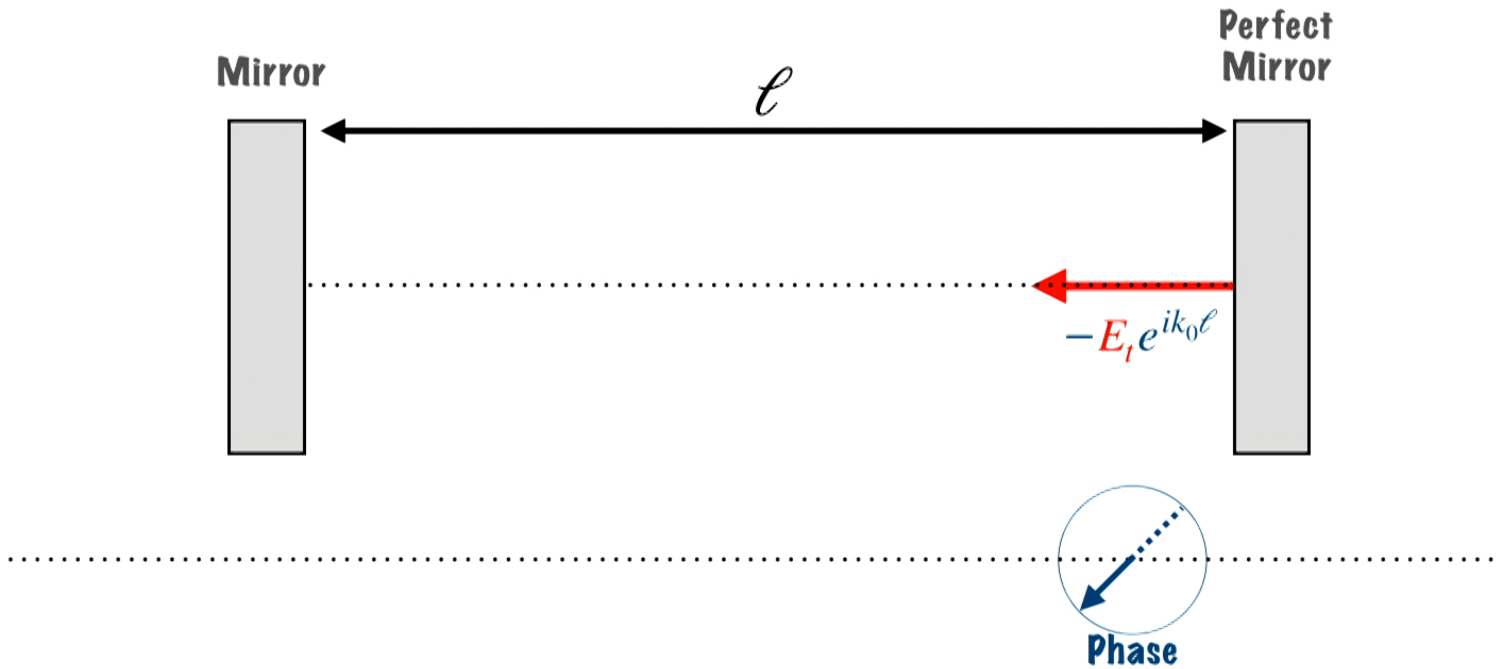
Fabry-Perot Cavity



Fabry-Perot Cavity



Fabry-Perot Cavity



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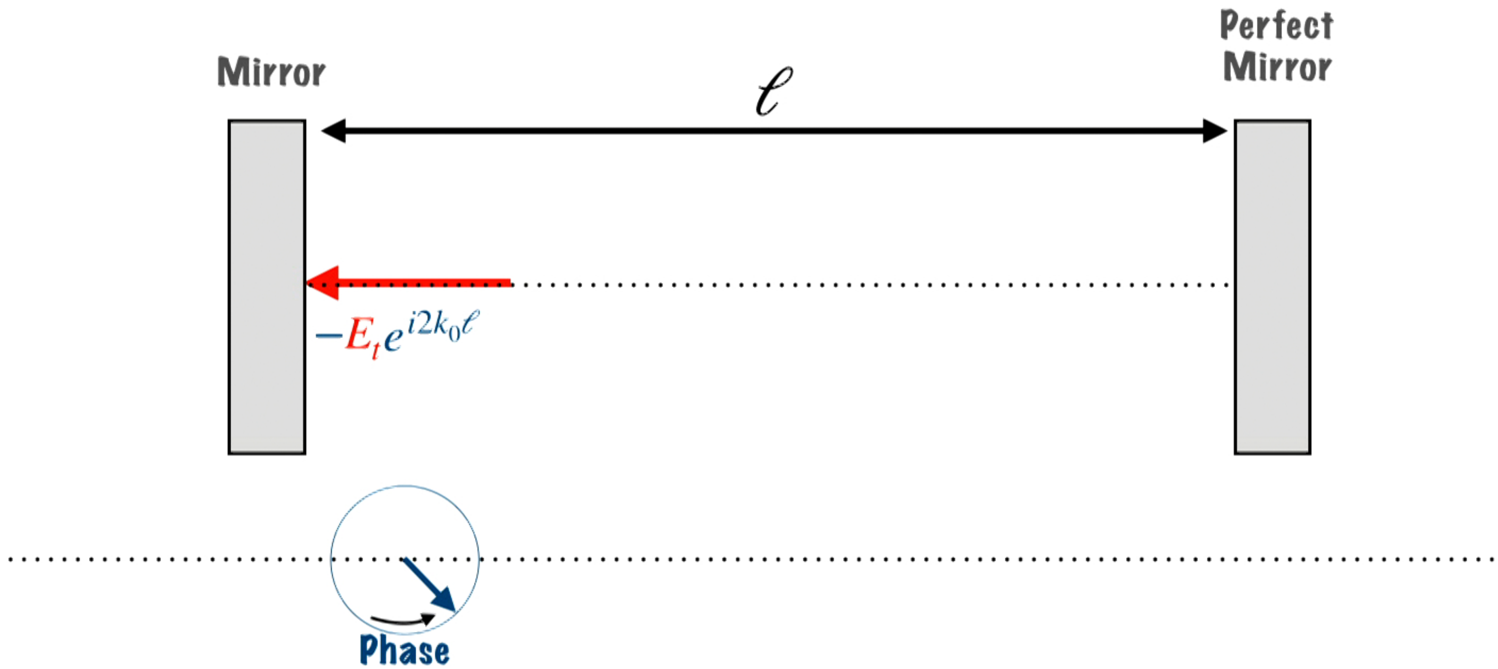
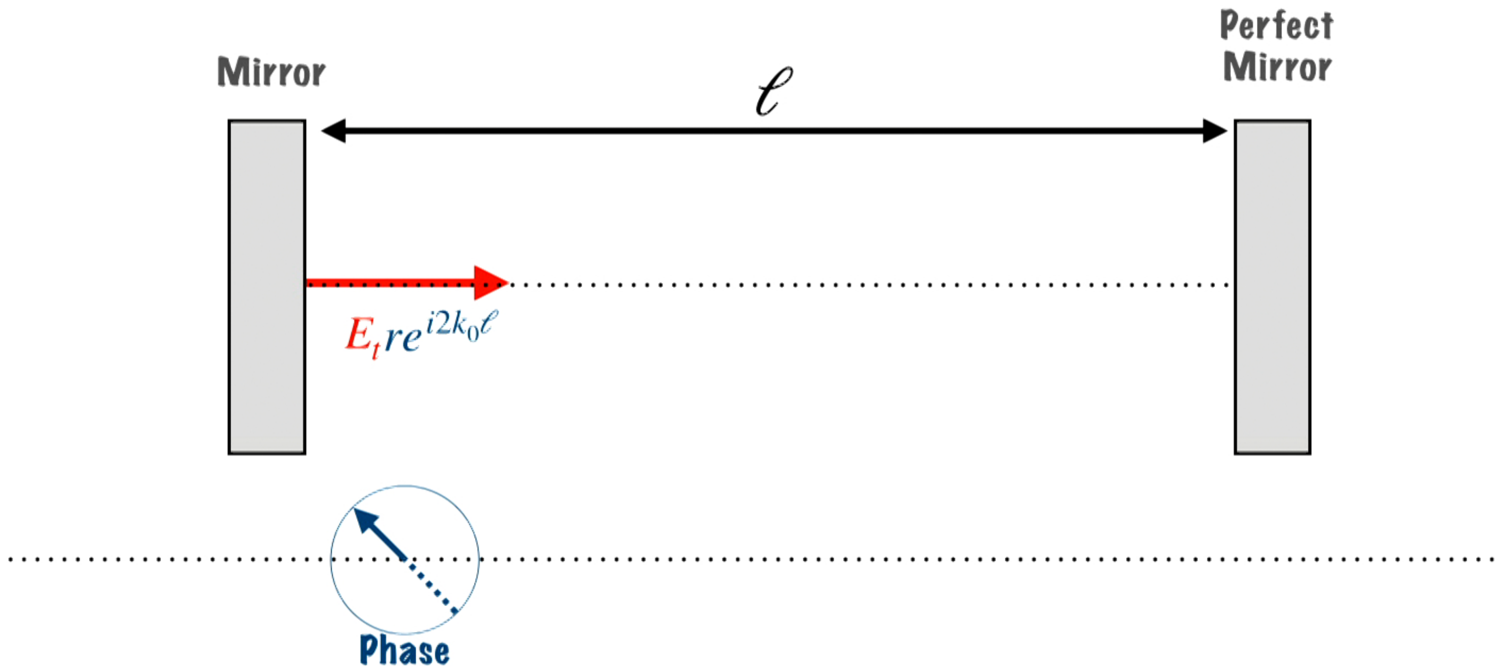
Fabry-Perot Cavity



Fabry-Perot Cavity



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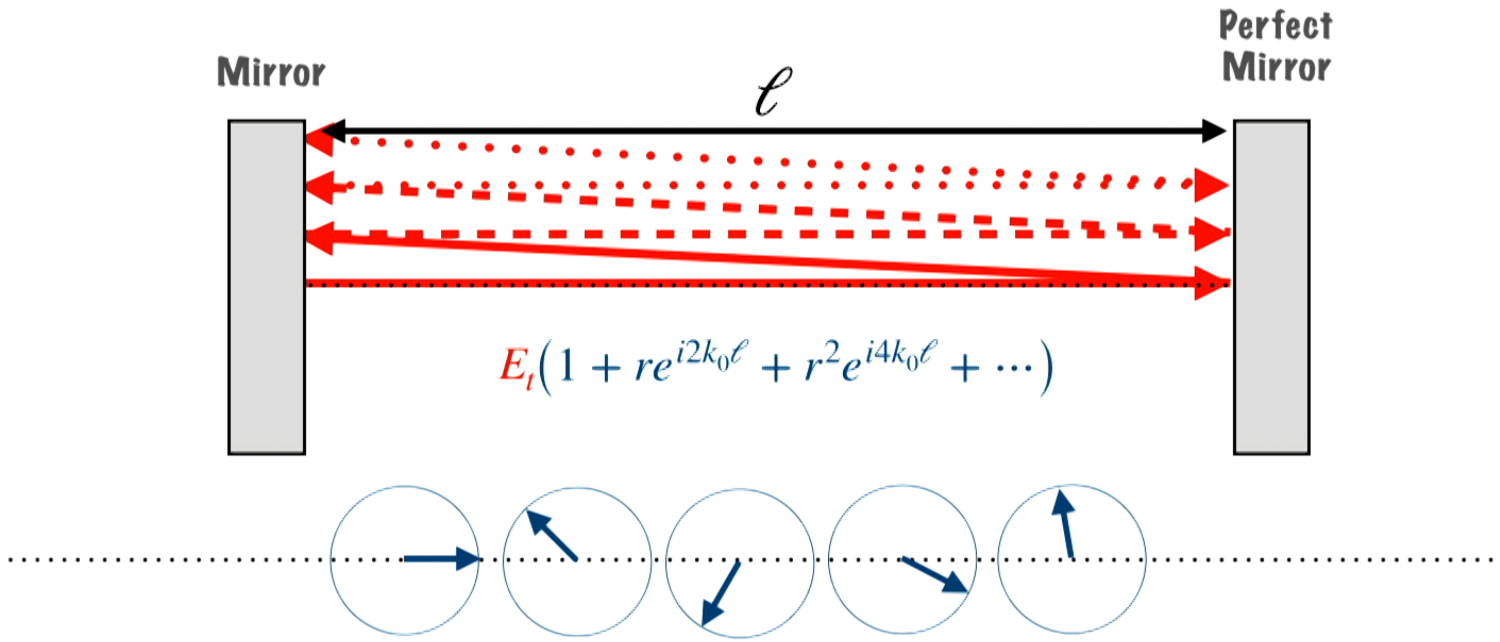
Fabry-Perot Cavity



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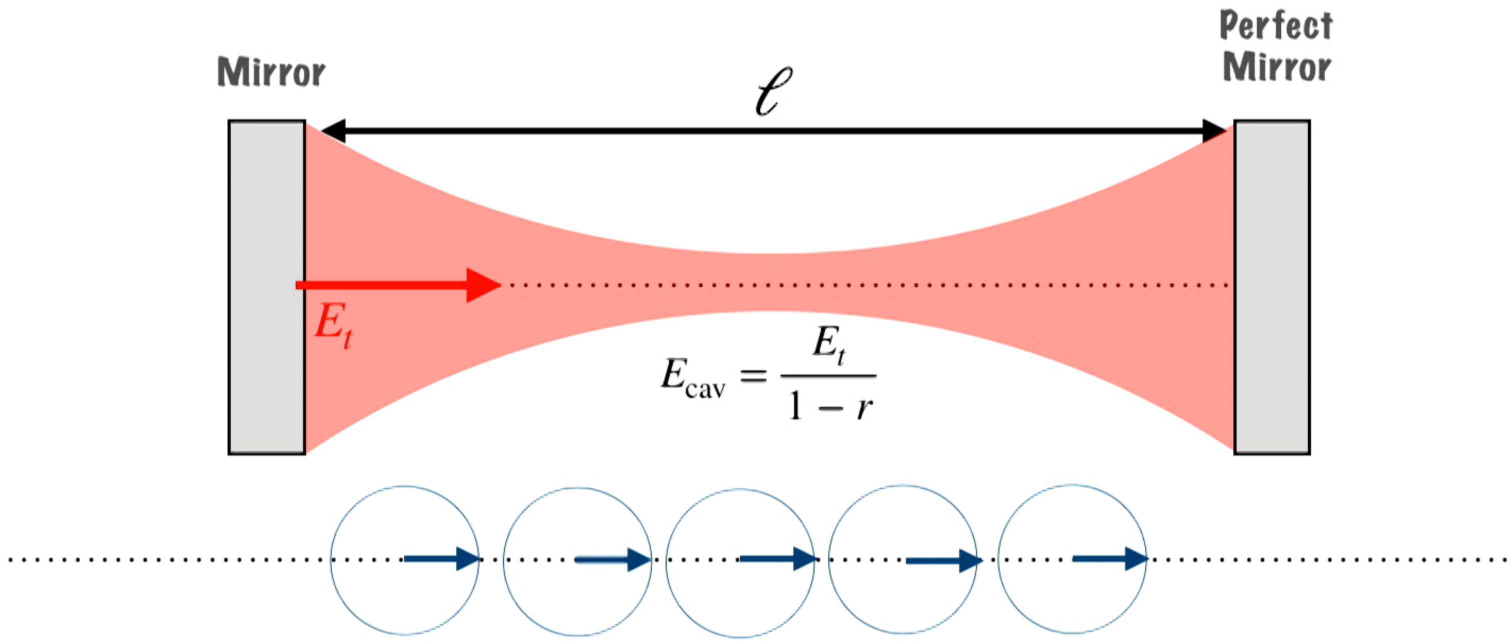
Fabry-Perot Cavity



Resonance achieved when $k_0\ell = n\pi$.
Large, coherent build-up of field as $r \to 1$.

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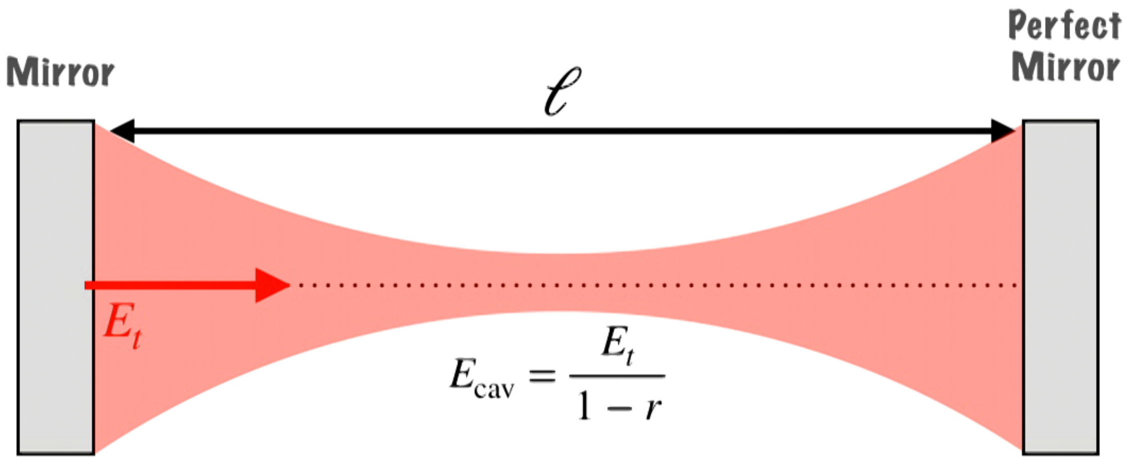
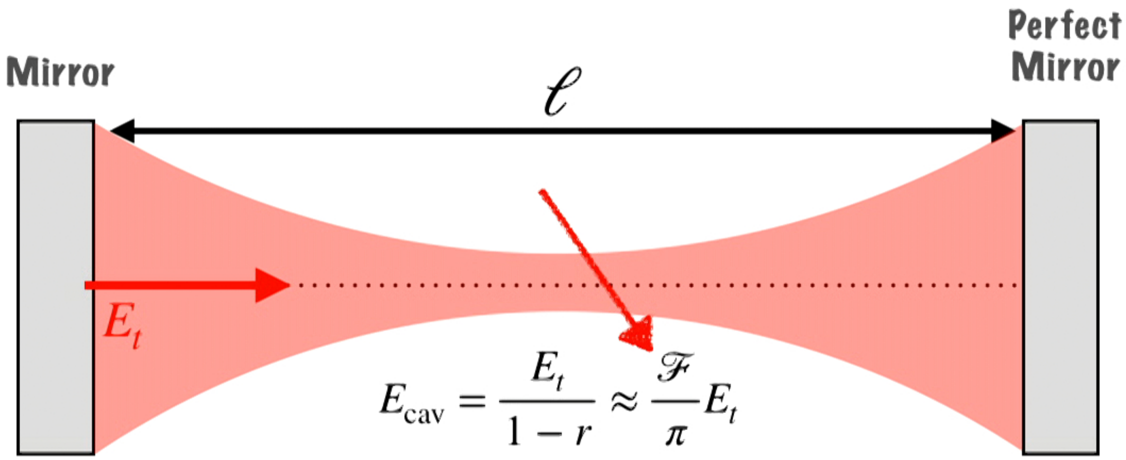
Finesse



The **finesse** is the **figure of merit** of the cavity.
The **more reflective** the mirrors are, the **larger the finesse**.

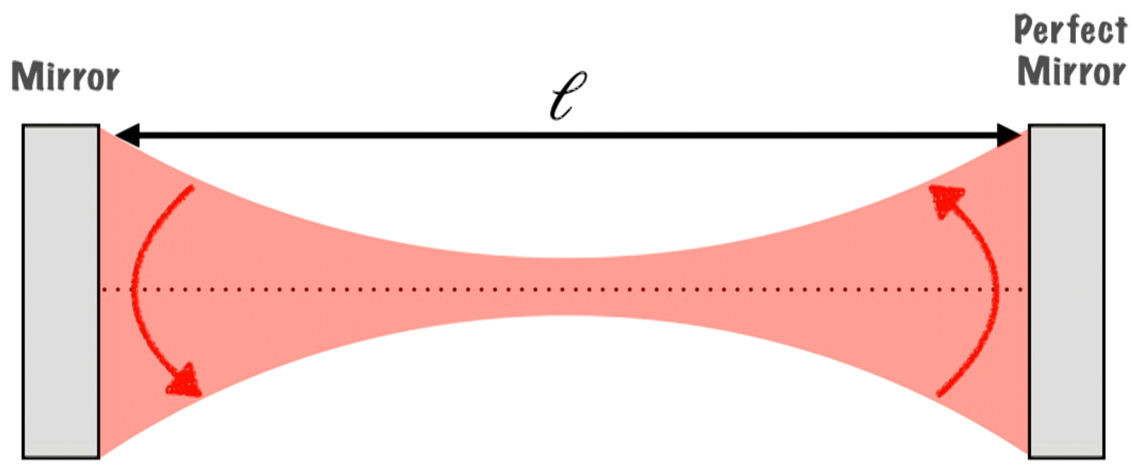
Finesse



$$E_{\text{cav}} = \frac{E_t}{1-r} \approx \frac{\mathcal{F}}{\pi} E_t$$

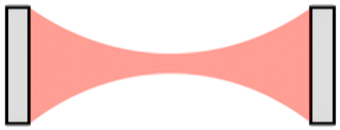
#1: The finesse tells you the **gain** of the **cavity field** with respect to the input field **at resonance**.

Finesse

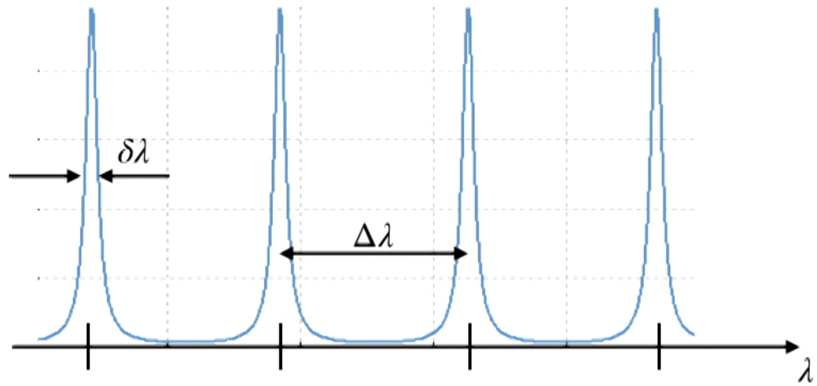


#2: The finesse tells you the **mean number of roundtrips** taken by light in the cavity.

Finesse



$k_0\ell = n\pi$ for resonance



#3: The finesse tells you the ratio of the **width of the resonance** to the **distance between resonances**, i.e. how **tuned** the cavity is.

$$\mathscr{F} = \frac{\Delta\lambda}{\delta\lambda}$$

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Axion Detection with Birefringent Cavities (ADBC)

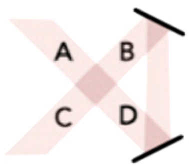

Image credit: J. Thaler

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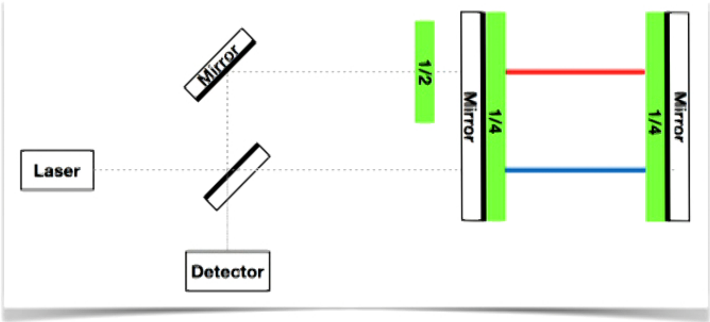
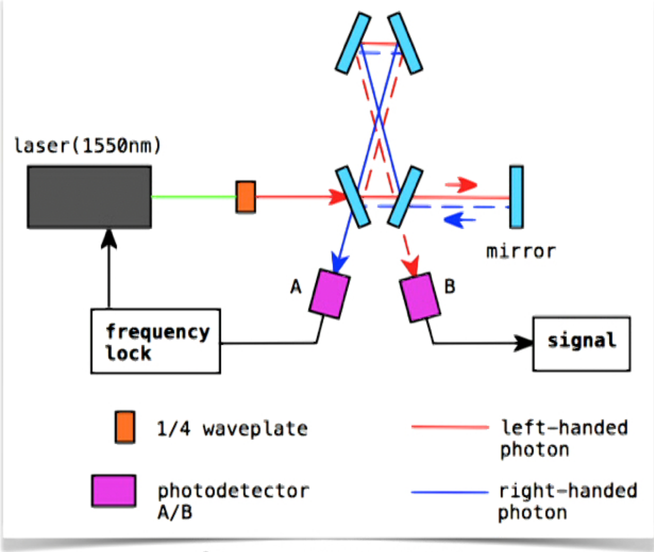
Previous Work



DeRocco and Hook 1802.07273



Obata+ 1805.11753

Groundbreaking conceptual work focused on using circularly polarized light.
Limited axion mass reach, **nontrivial experimental challenges** to overcome.

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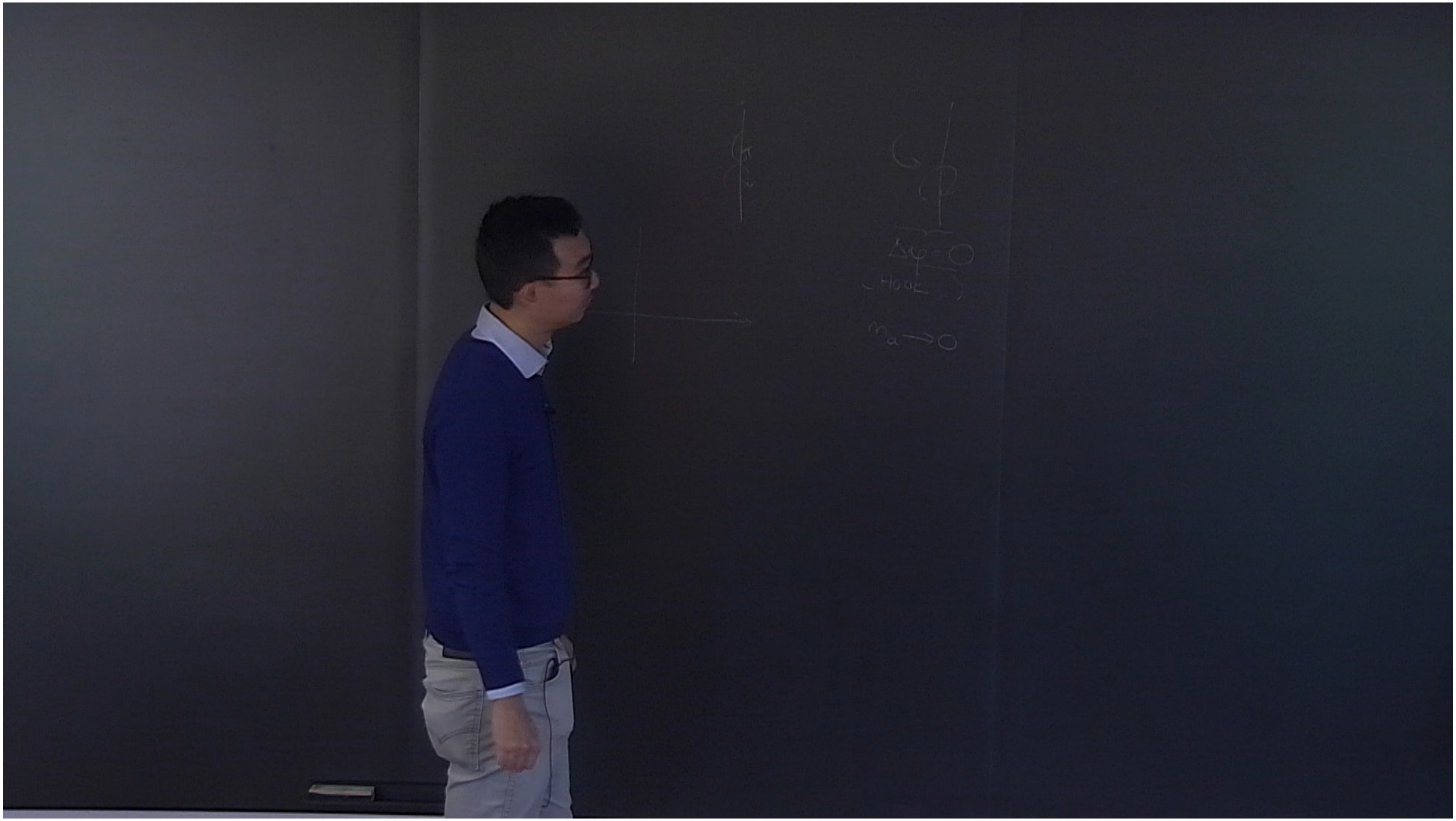
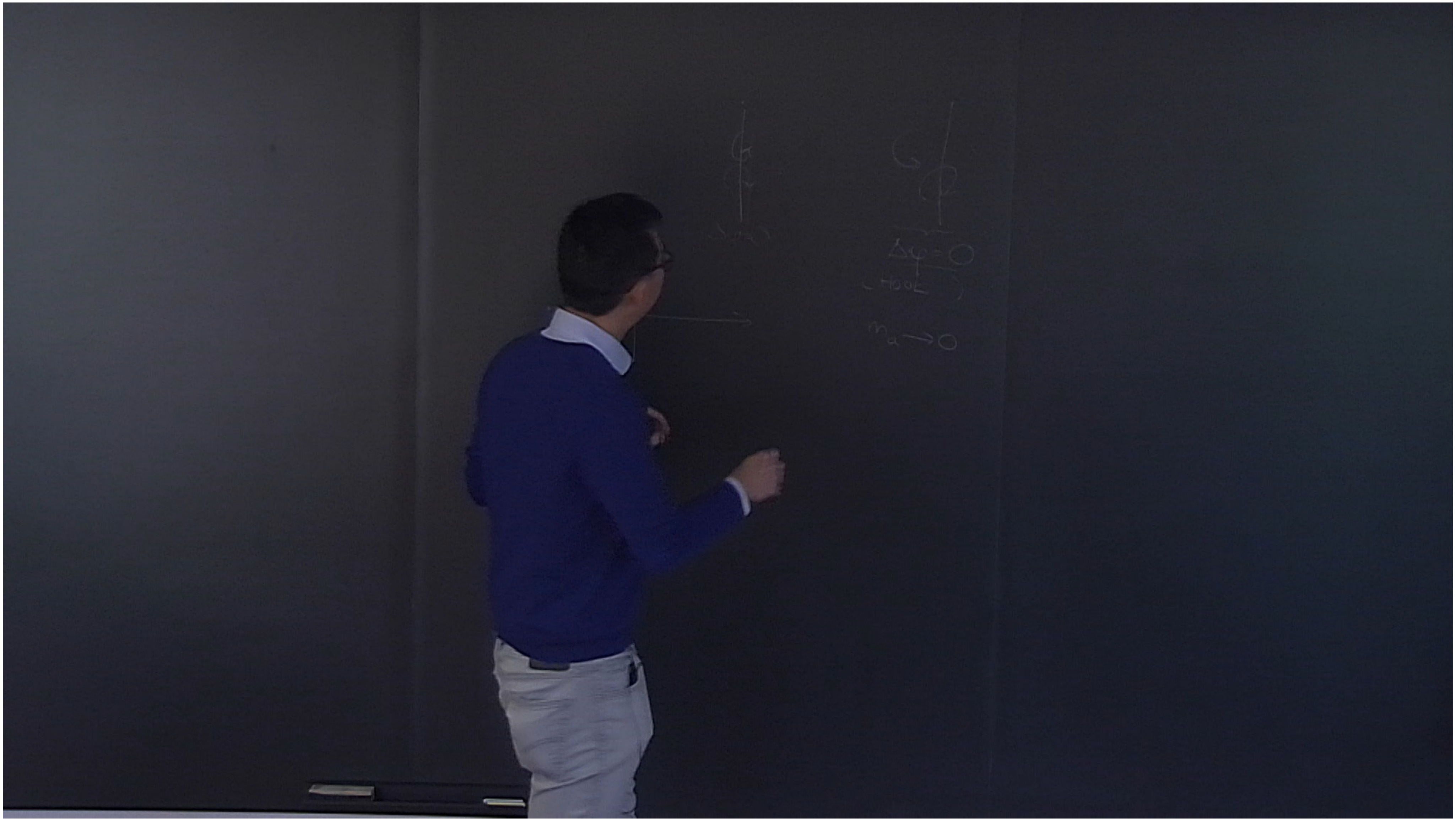
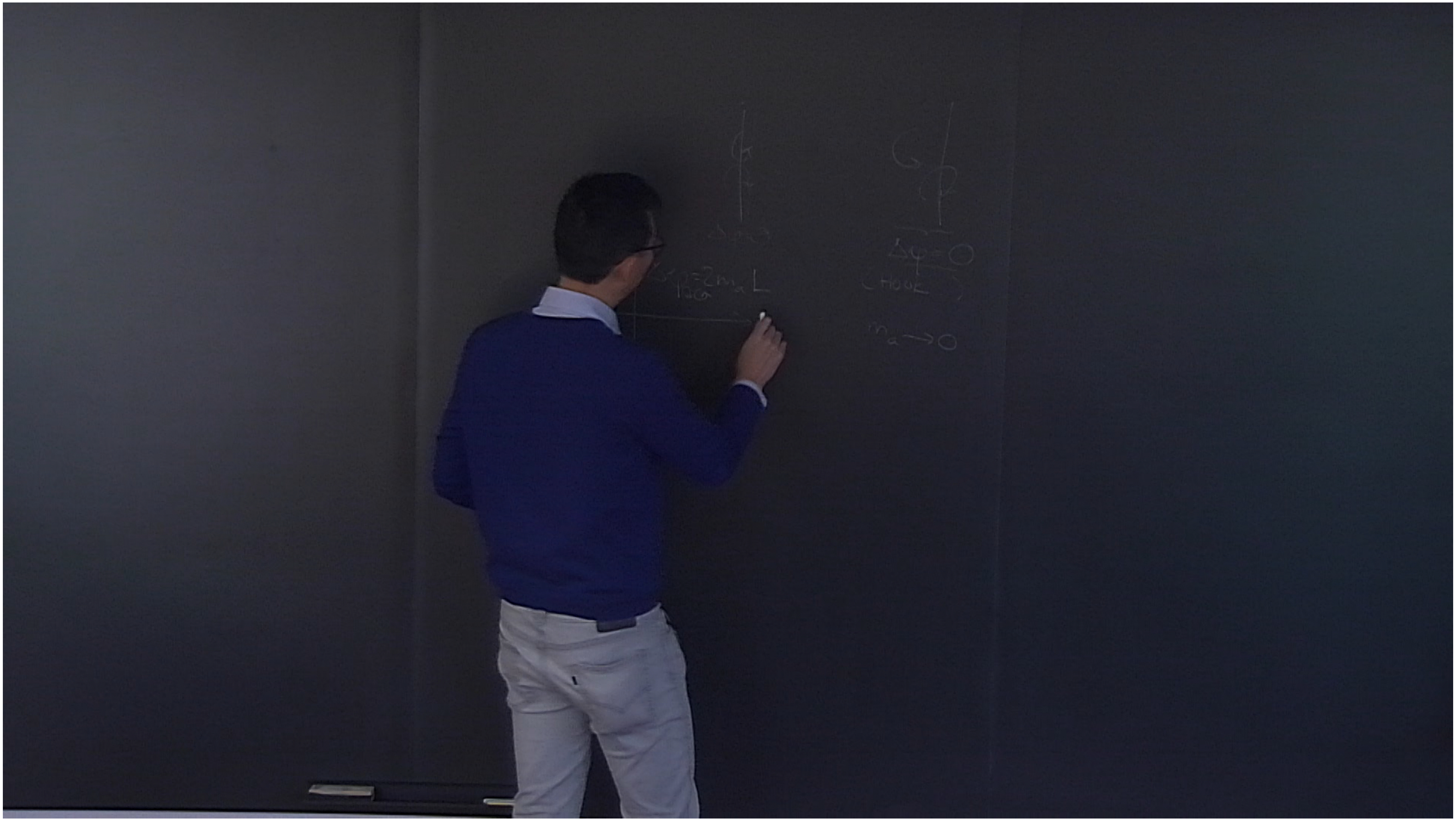
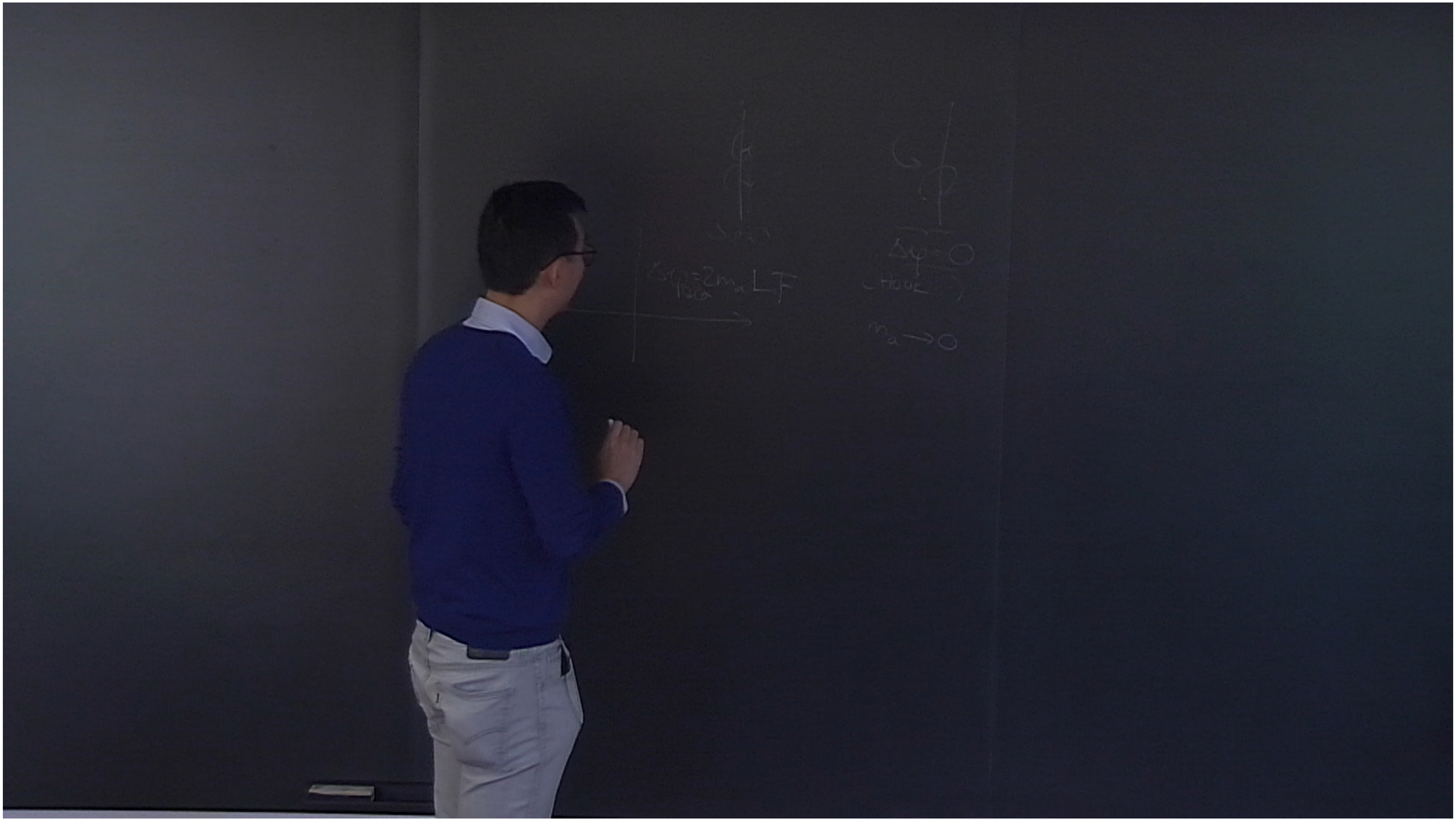
Δφ = 0

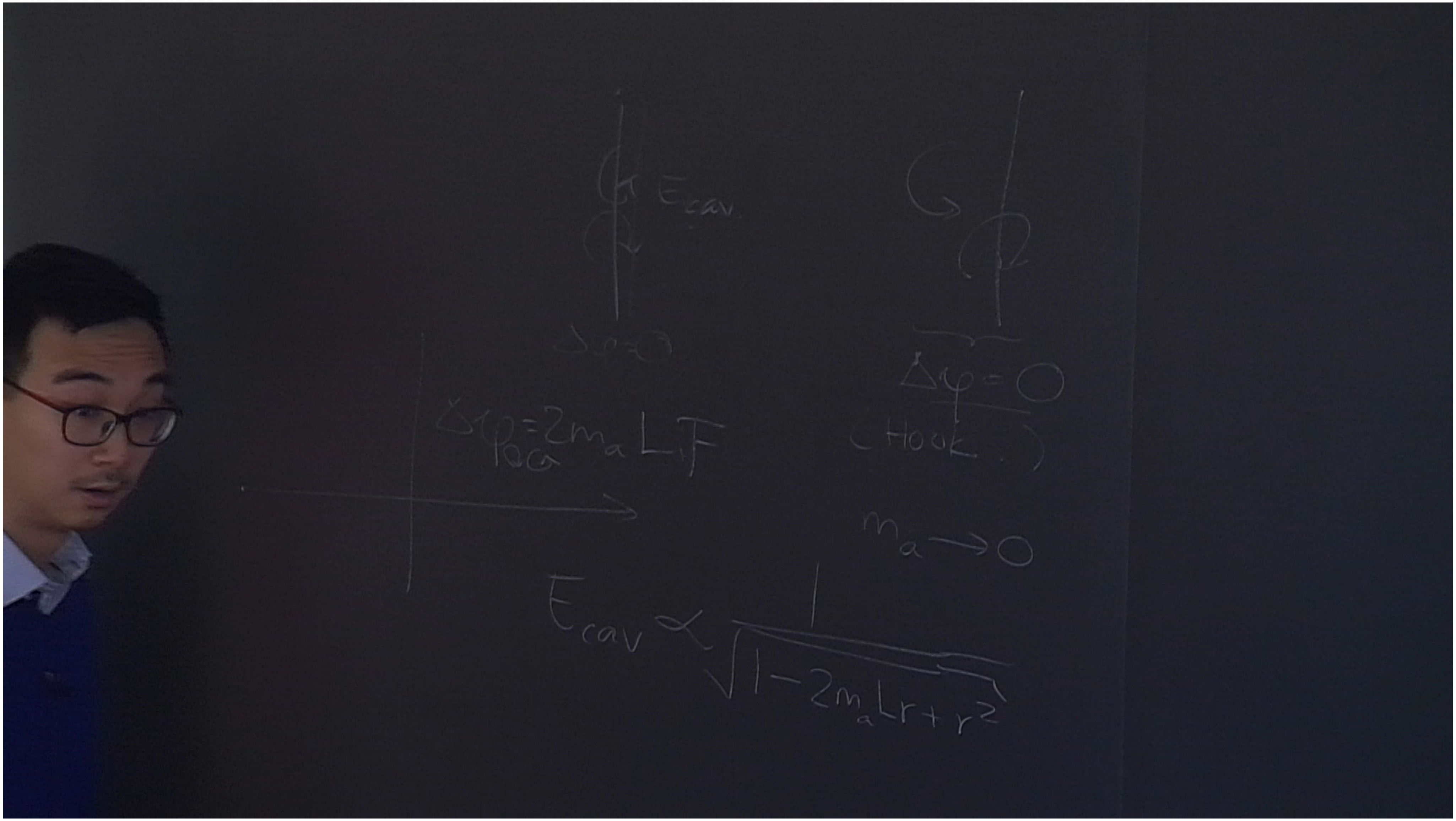

ΔΦ = 0
m_a → 0



$\Delta\varphi = 0$
$m_a \to 0$

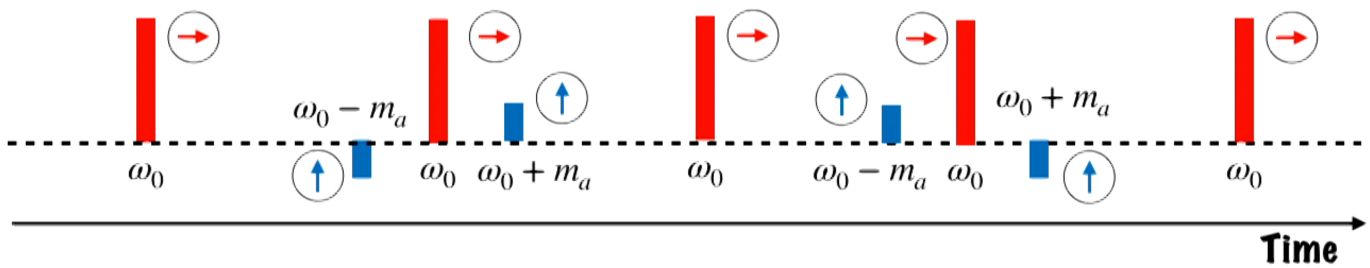

Δφ=0
m_a → 0


$= 2m_a L F$
$\Delta\varphi = 0$
$m_a \to 0$



E cav
Δφ = 0
Δφ = 2 m a L F
Δφ = 0
(Hook
m a → 0
E cav ∝ 1 / √(1 − 2 m a L r + r²)

Signal Sidebands



Photon with frequency ω_0 converts into **orthogonal polarization** with difference in frequency given by the **axion mass**.

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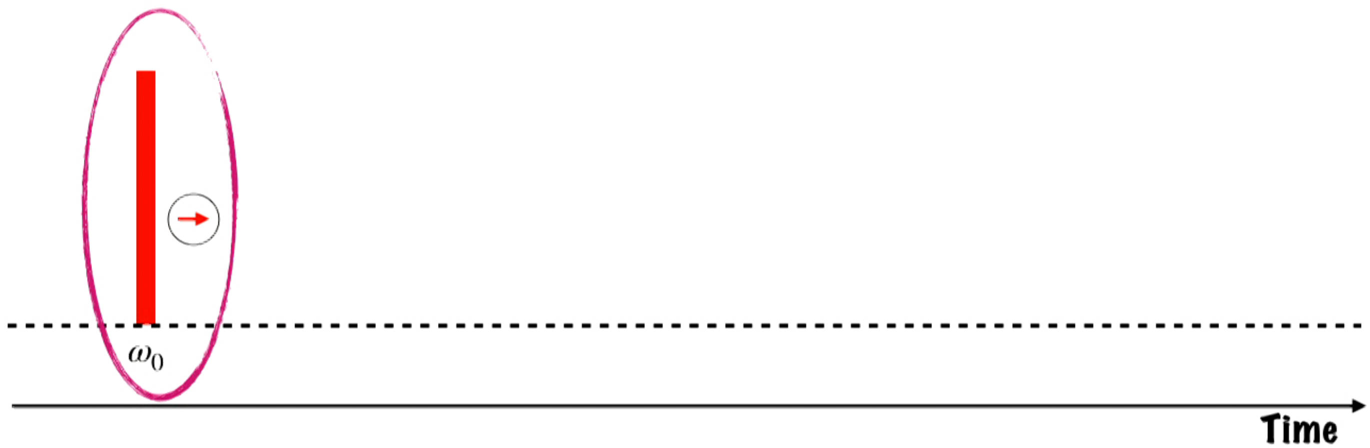
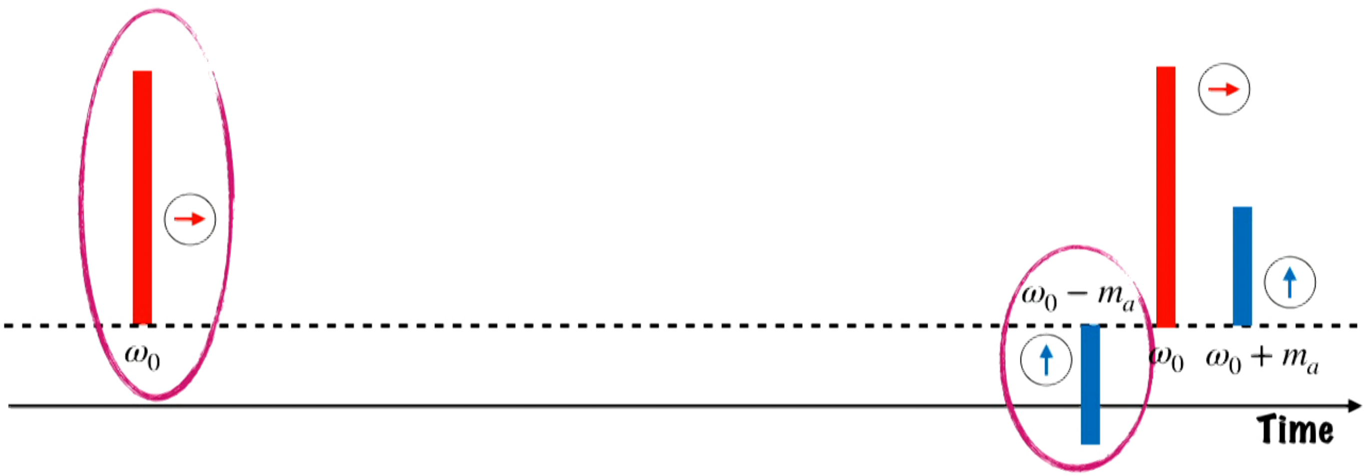
Strategy



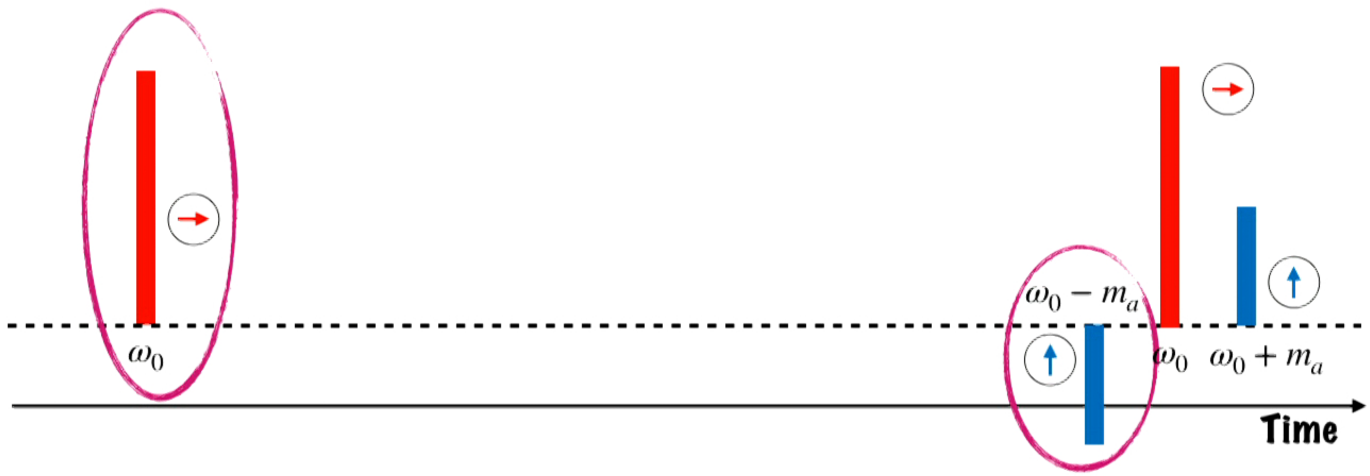
Feed **horizontally polarized** laser light into a **Fabry-Perot cavity** that is **resonant** at ω_0 …

Strategy



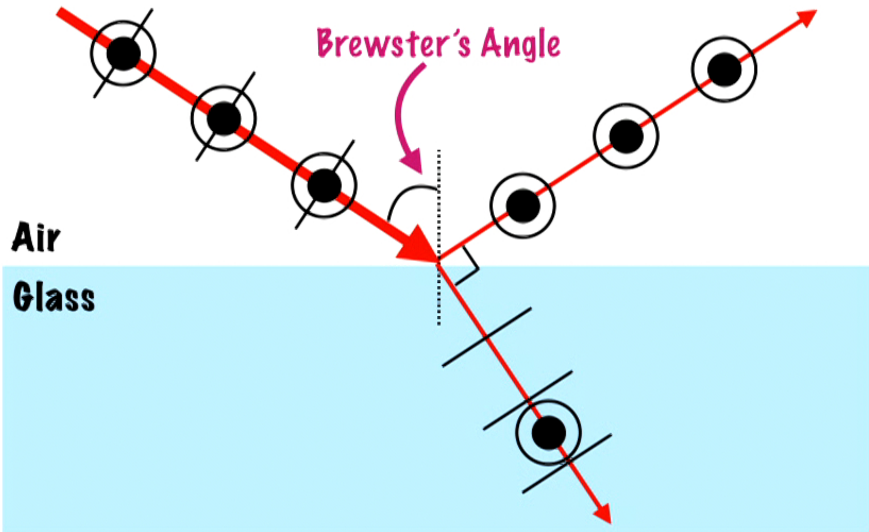
… that is also resonant in the **vertical polarization** at a frequency $\omega_0 \pm m_a$.

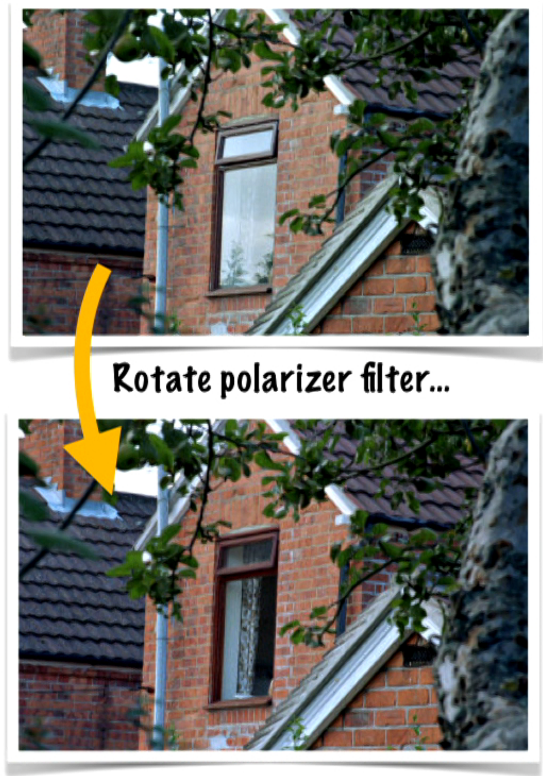
Strategy



This requires a cavity that is **birefringent** between the horizontal and the vertical polarization.

Birefringence from Oblique Reflection





Reflection at **oblique angles** introduces some **birefringence** between polarizations!

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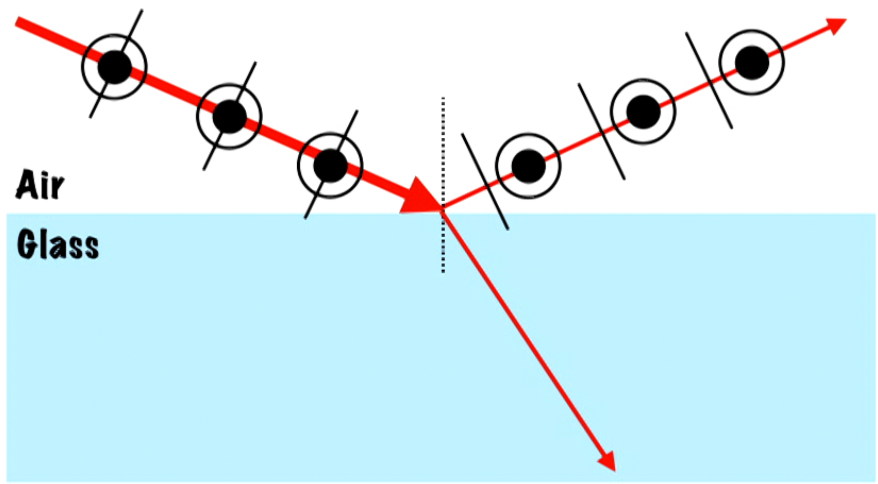
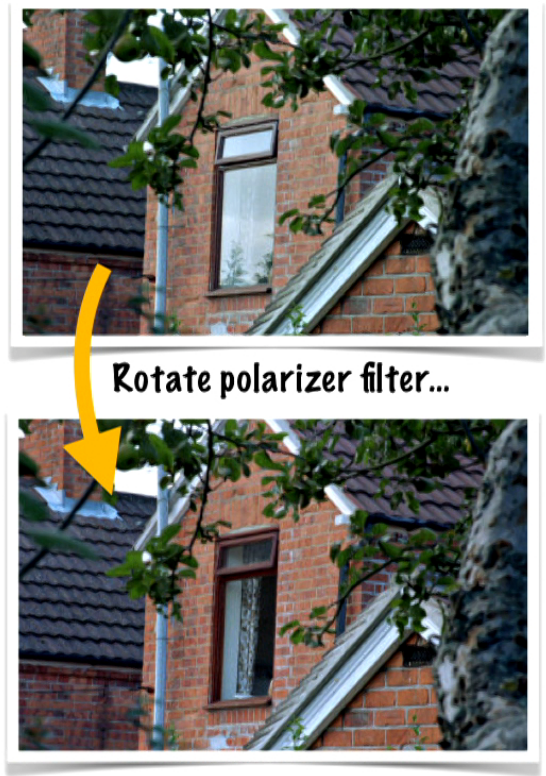
Birefringence from Oblique Reflection





Oblique reflection also introduces **phase difference** between orthogonal linear polarizations.

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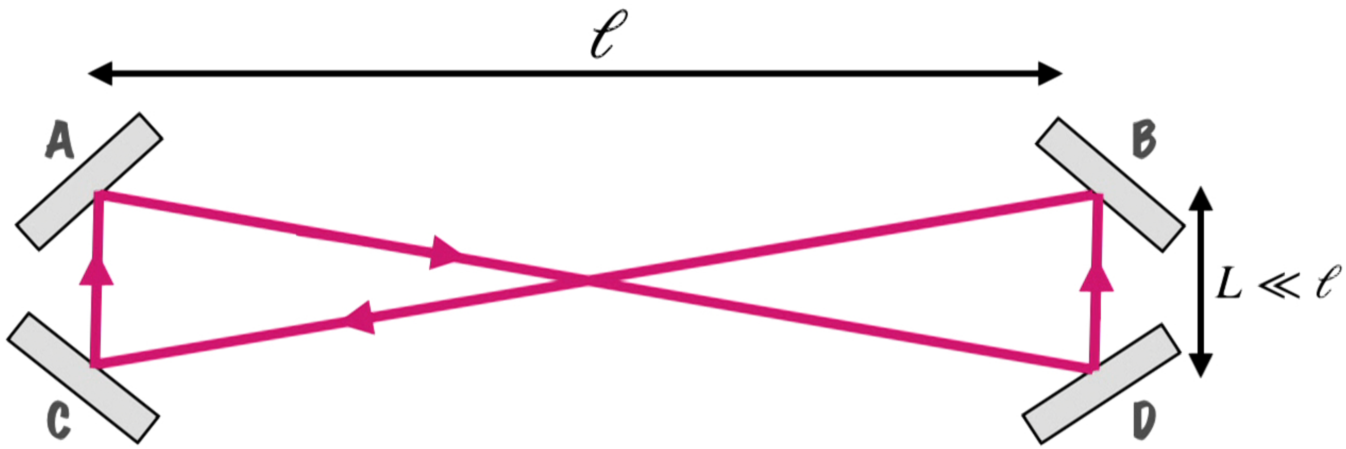
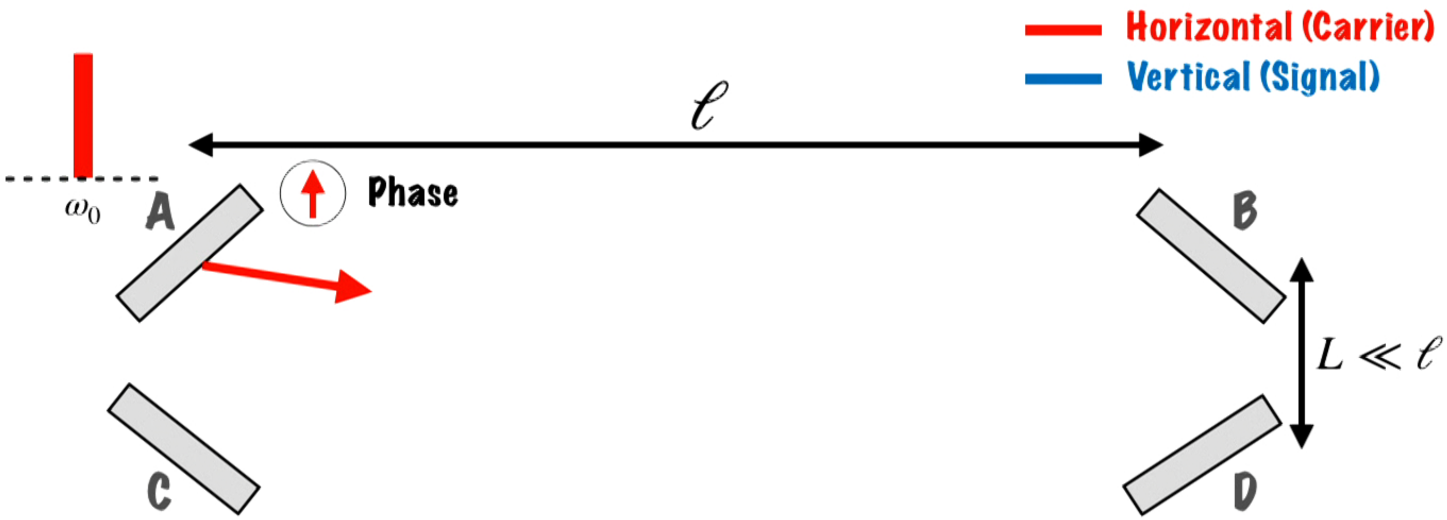
Bowtie Cavity



The **bowtie cavity**, with two oblique reflections at either end, has exactly the birefringence we need. This is the basic idea behind the **A**xion **D**etection with **B**irefringent **C**avities (**ADBC**) experiment.

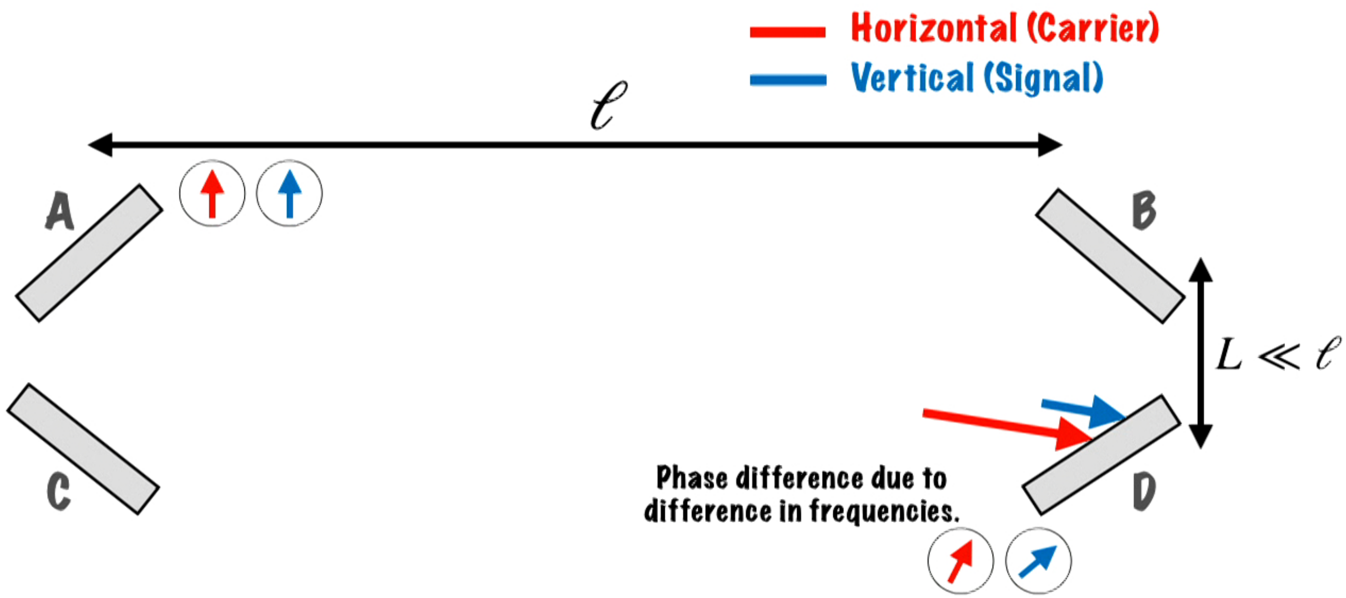
HL, Elwood, Evans and Thaler
1809.01656

ADBC Concept

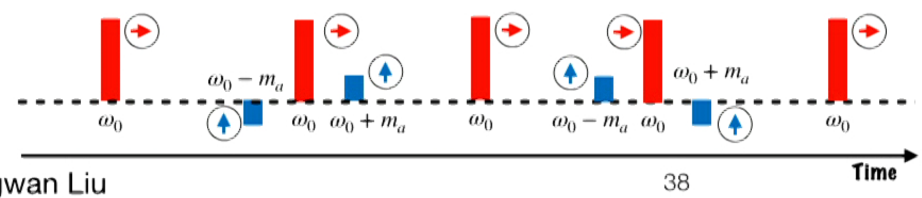


Input carrier in **horizontal polarization**, frequency ω_0.

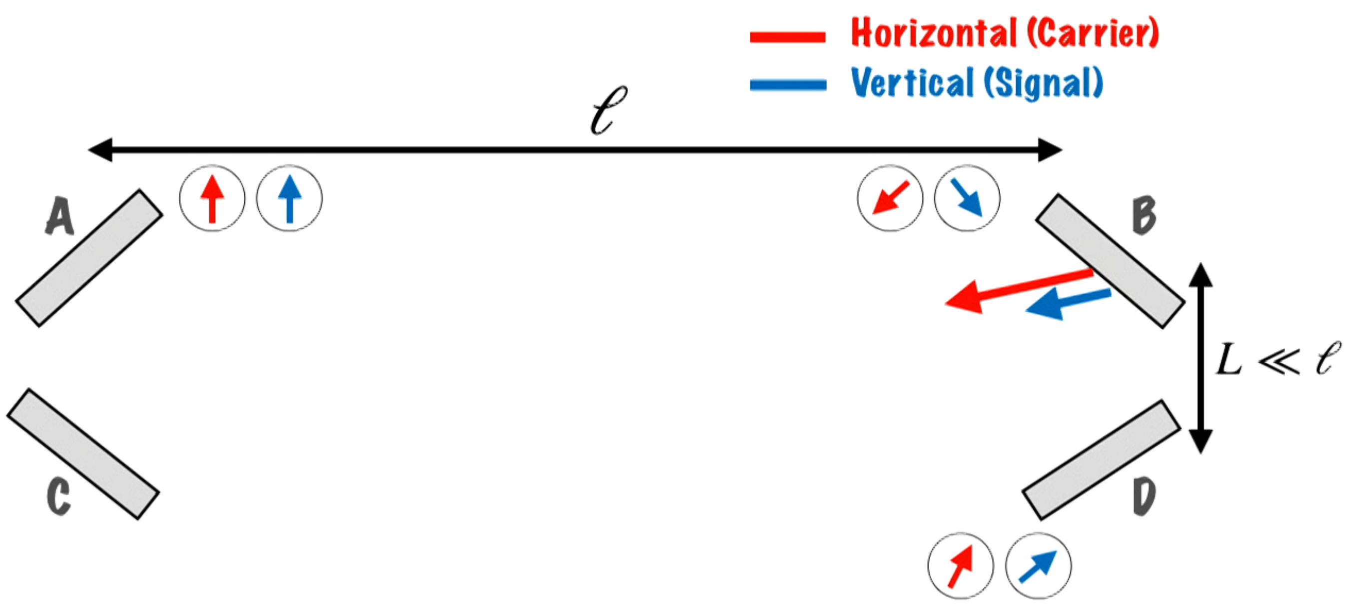
ADBC Concept



As the carrier propagates along the long arm of the cavity, axions generate **vertical signal sidebands**, frequency $\omega_0 \pm m_a$.



ADBC Concept



After two oblique reflections, the **change in phase** between the carrier and signal is **different**.

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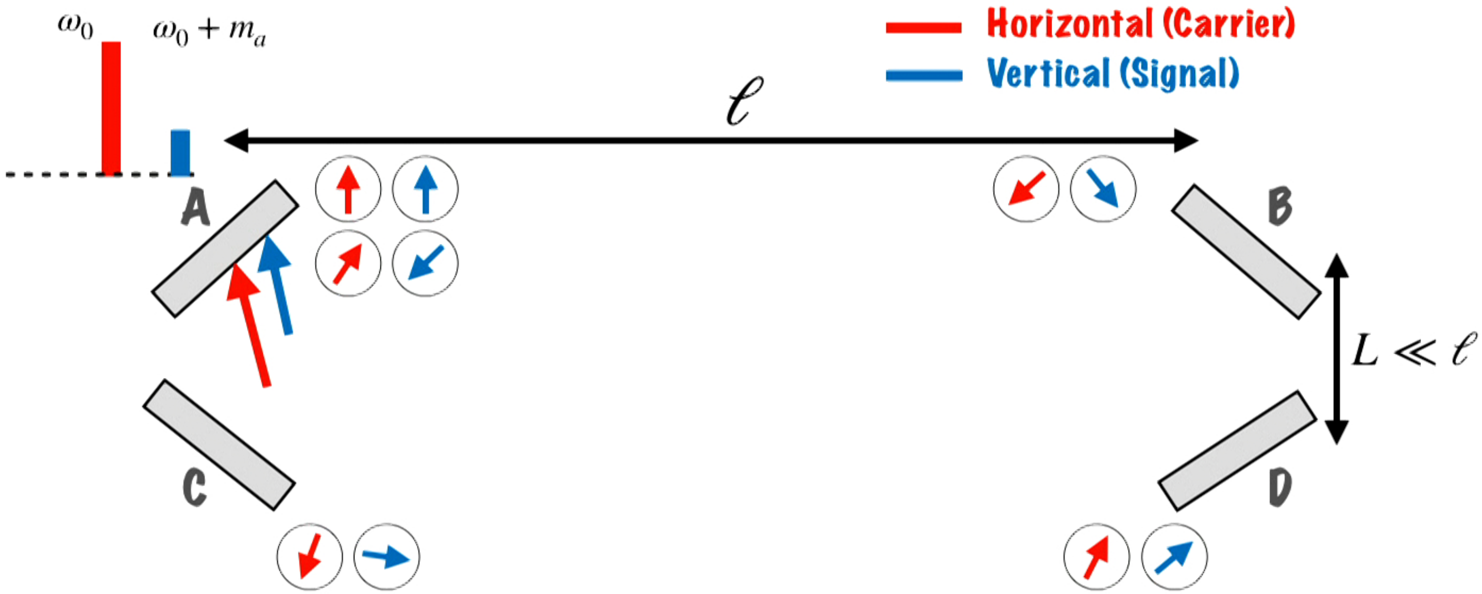
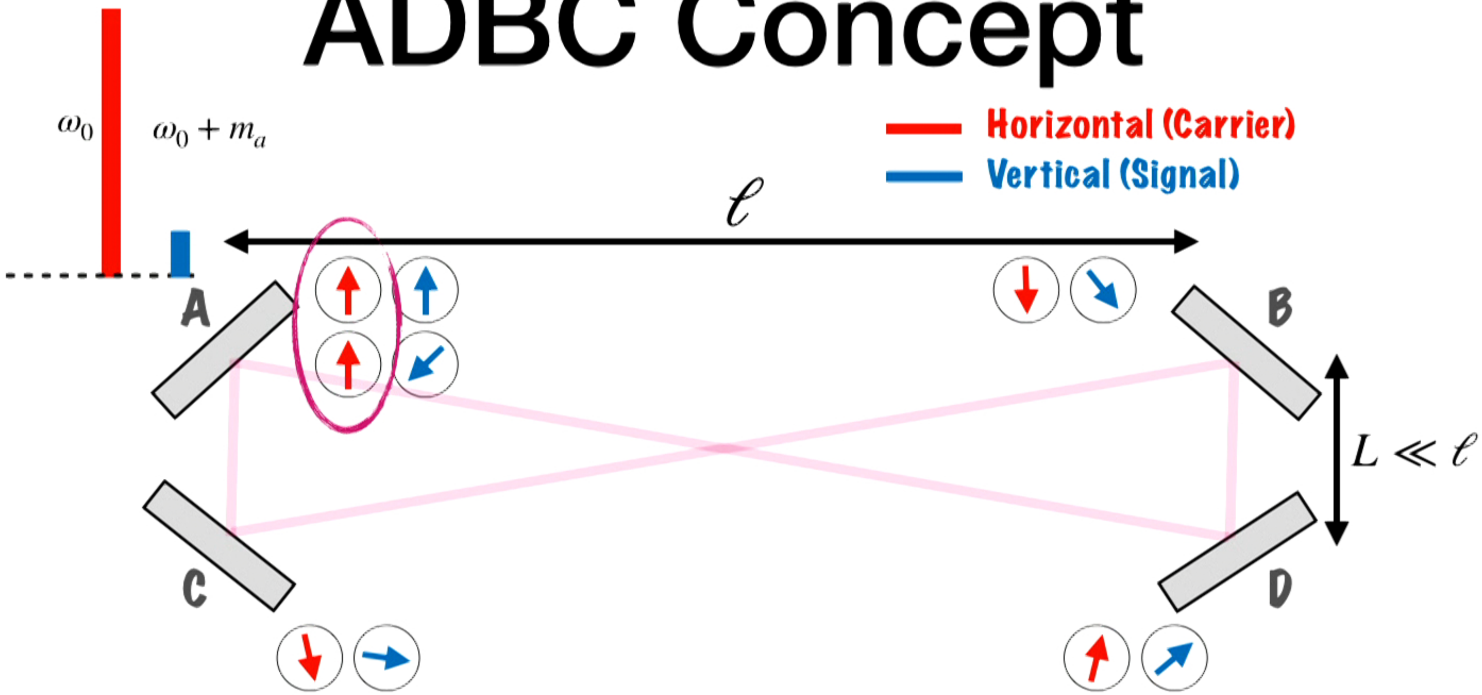
ADBC Concept



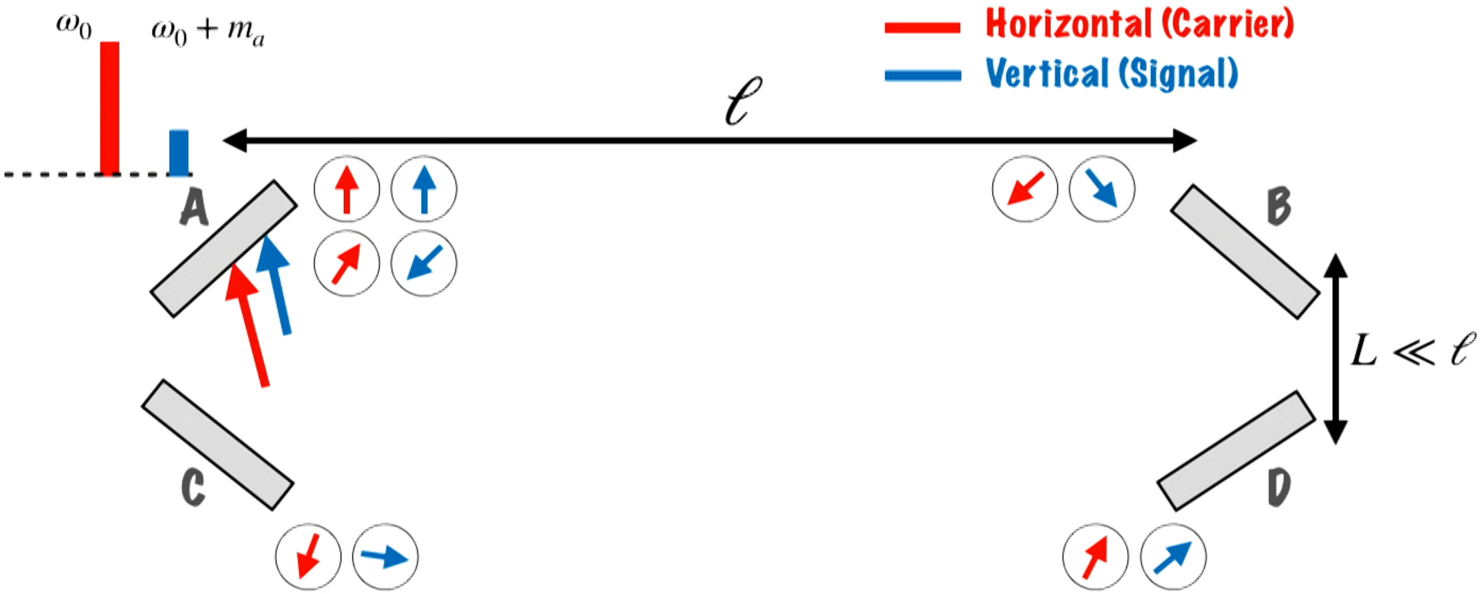
An additional phase shift is picked up before completing a round trip.

ADBC Concept



We can adjust the laser frequency slightly so that the cavity is **resonant** in the horizontal carrier polarization.

ADBC Concept



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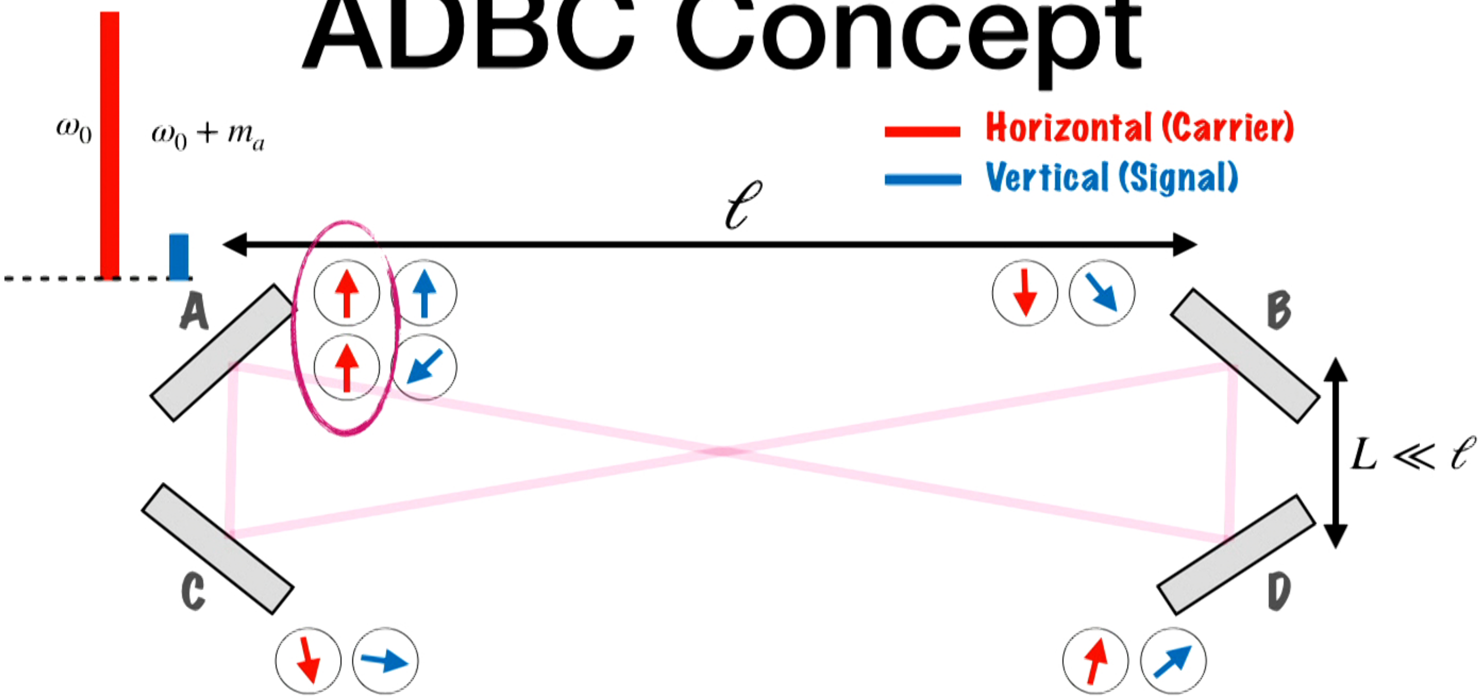
ADBC Concept



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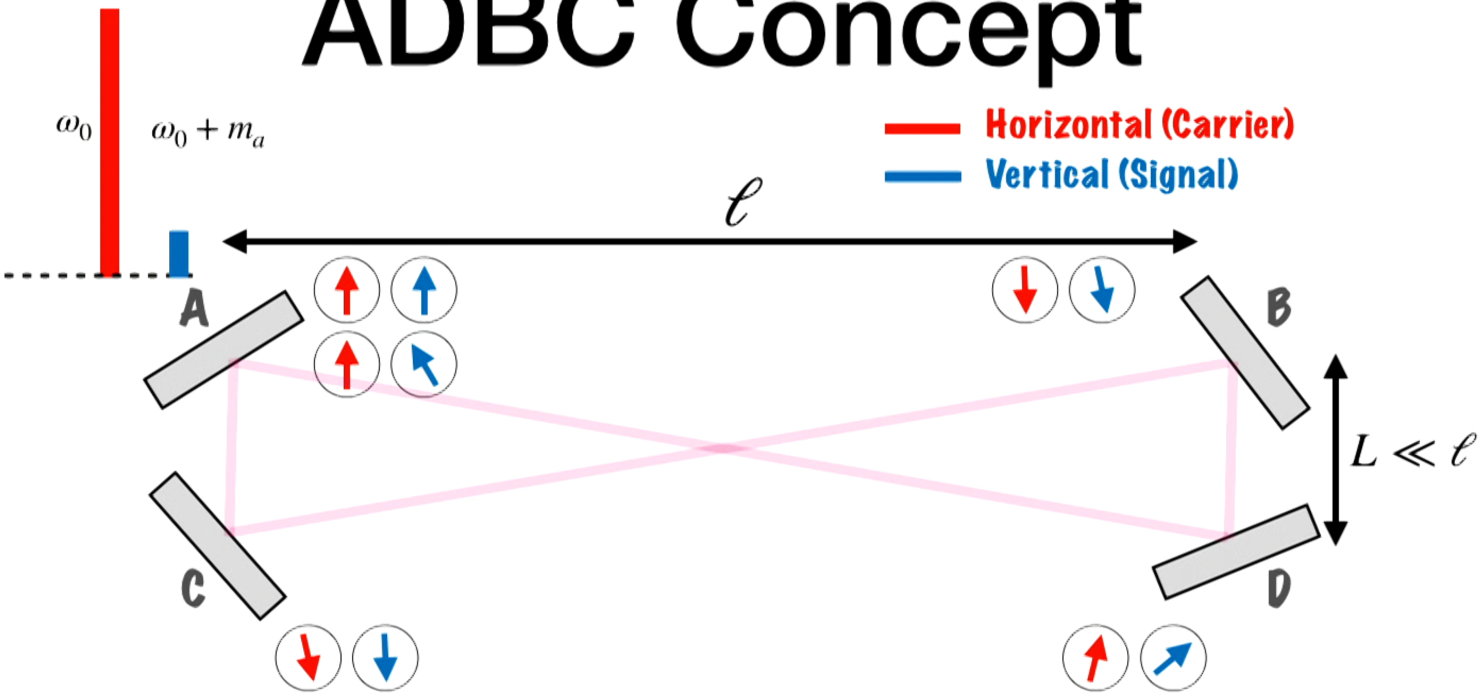

The difference in phase shift at each end can be altered by **rotating the mirrors**.

Optical path maintained by **fixing** the angle between AC or BD (acts like a **retroreflector**).

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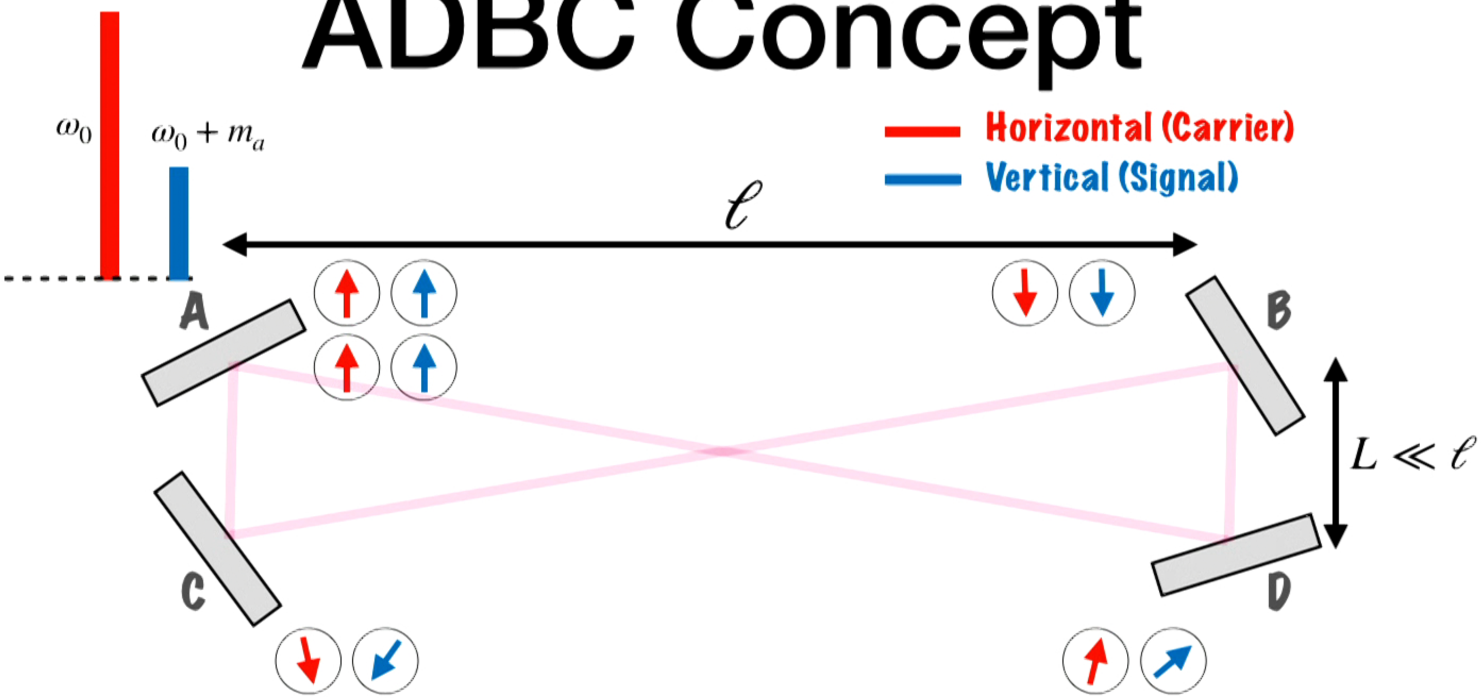
ADBC Concept



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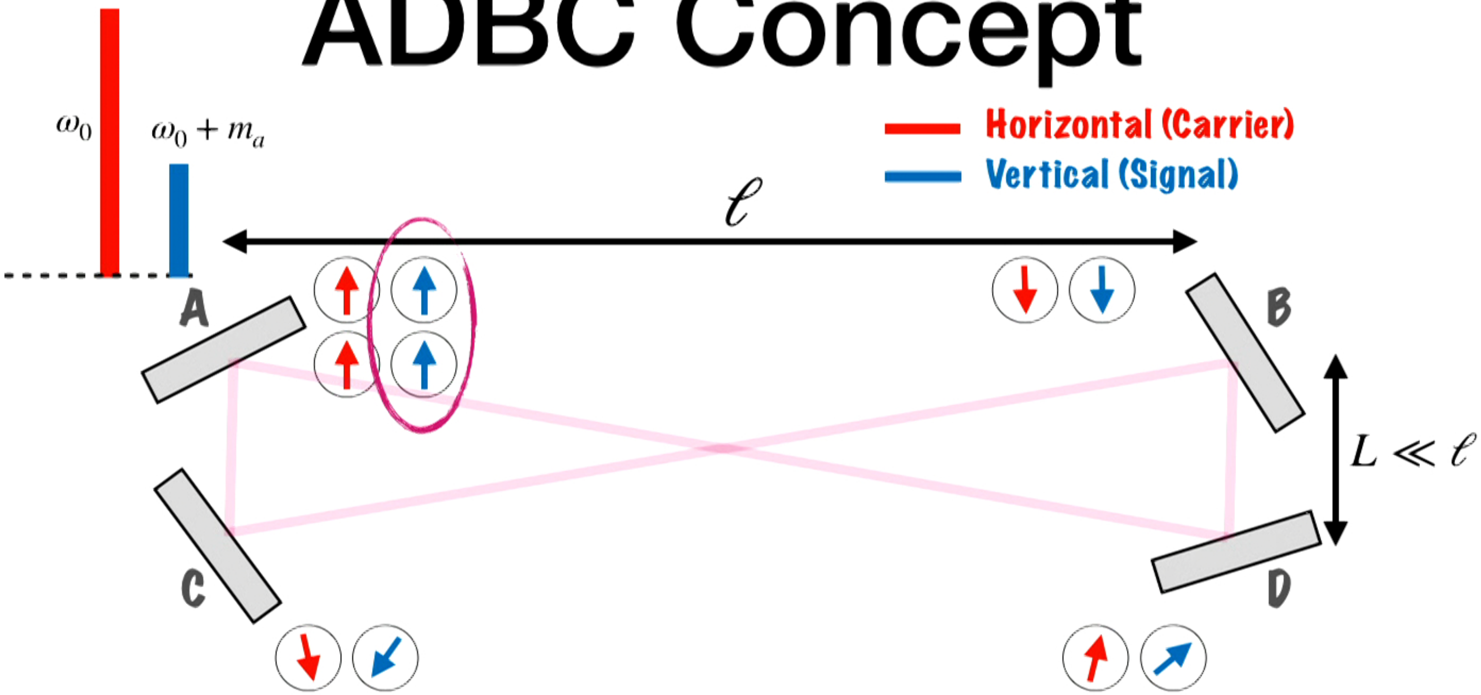
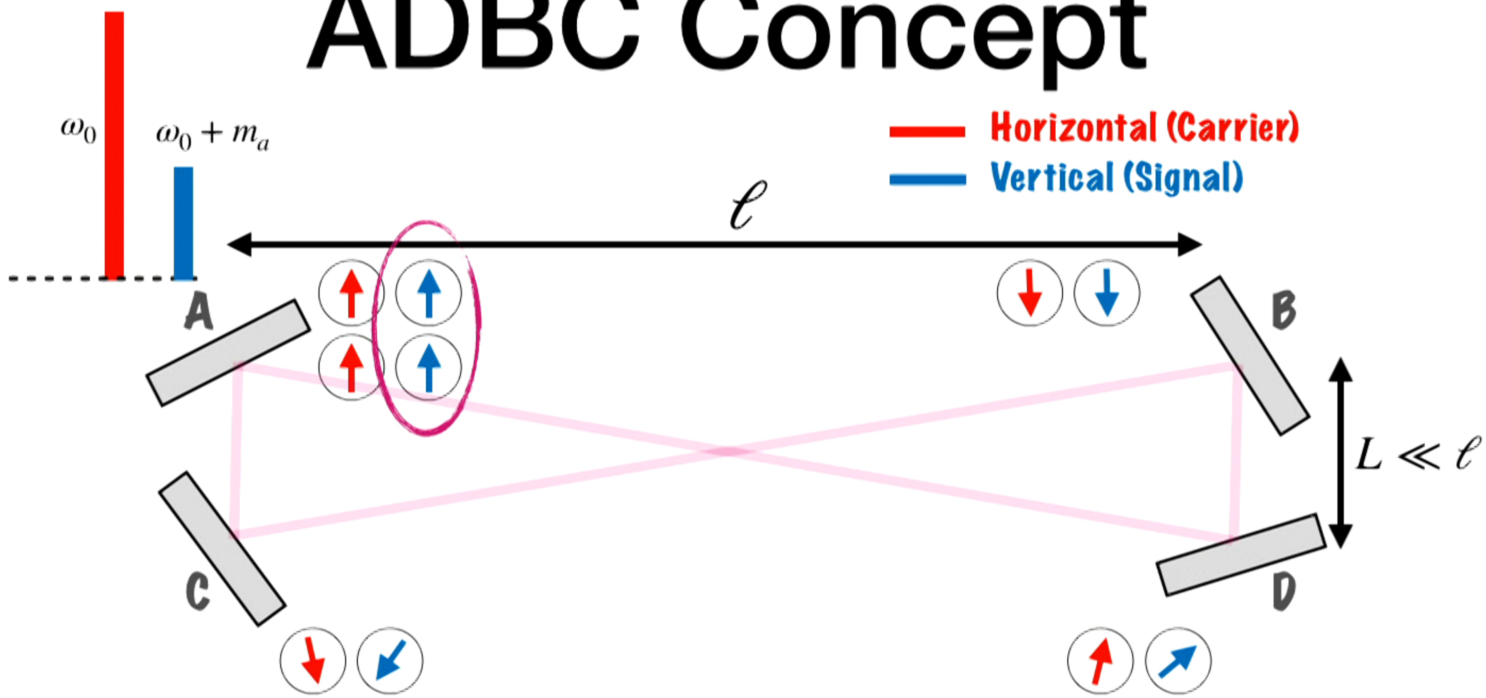


Resonance for vertical (signal) polarization achieved when phase difference due to **oblique reflection** $\Delta\varphi$ **cancels** the phase difference from **propagation**, i.e. $\Delta\varphi = m_a \ell$.

ADBC Concept



Rotating the mirrors allows us to **scan over** a broad range of axion masses, up to $m_a \lesssim 1/\ell$.

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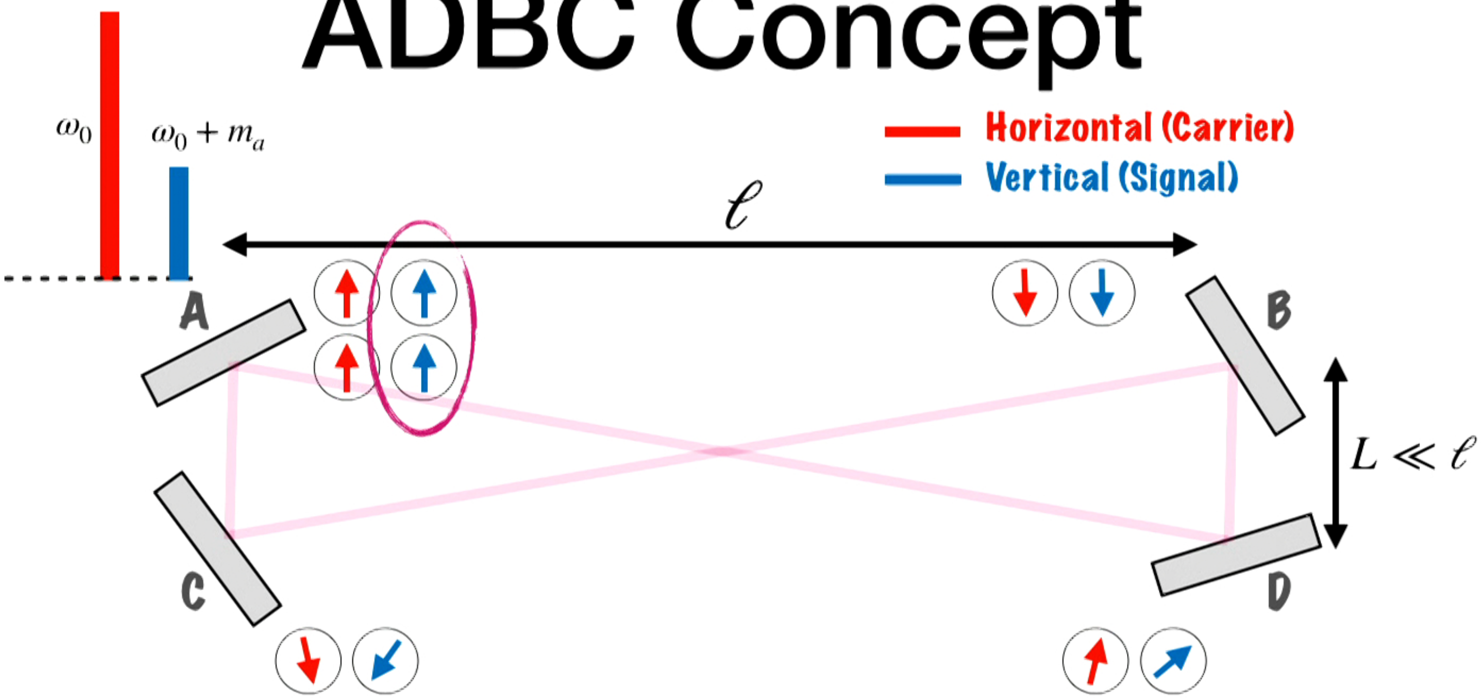
ADBC Concept



Rotating the mirrors allows us to **scan over** a broad range of axion masses, up to $m_a \lesssim 1/\ell$.

Improves on previous designs, which were limited to $m_a \lesssim 1/(\mathscr{F}\ell)$.

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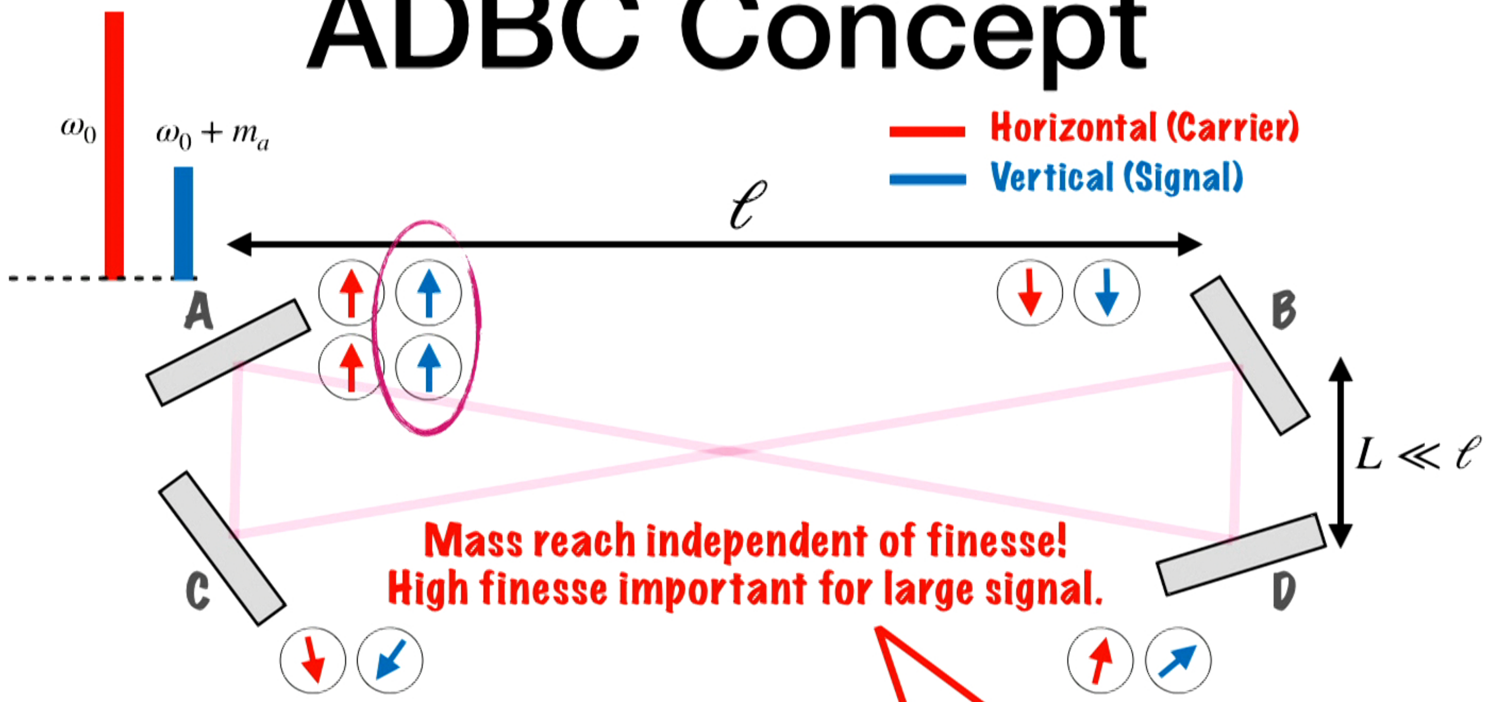
ADBC Concept



Rotating the mirrors allows us to **scan over** a broad range of axion masses, up to $m_a \lesssim 1/\ell$.

Improves on previous designs, which were limited to $m_a \lesssim 1/(\mathscr{F}\ell)$.

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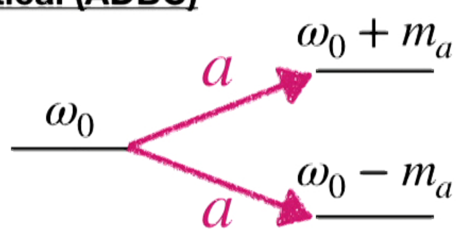
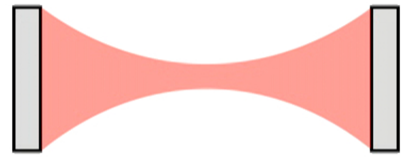
Optical vs Microwave Cavities

Optical (ADBC)

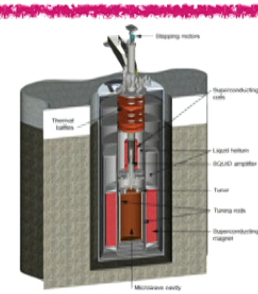




Signal power stored:

$$P \propto g_{a\gamma\gamma}^2 (\rho_{\rm DM}/m_a) E_{\rm laser}^2 V_{\rm cavity} Q$$

Microwave (ADMX)



Signal power stored:

$$P \propto g_{a\gamma\gamma}^2 (\rho_{\rm DM}/m_a) B_0^2 V_{\rm cavity} Q$$

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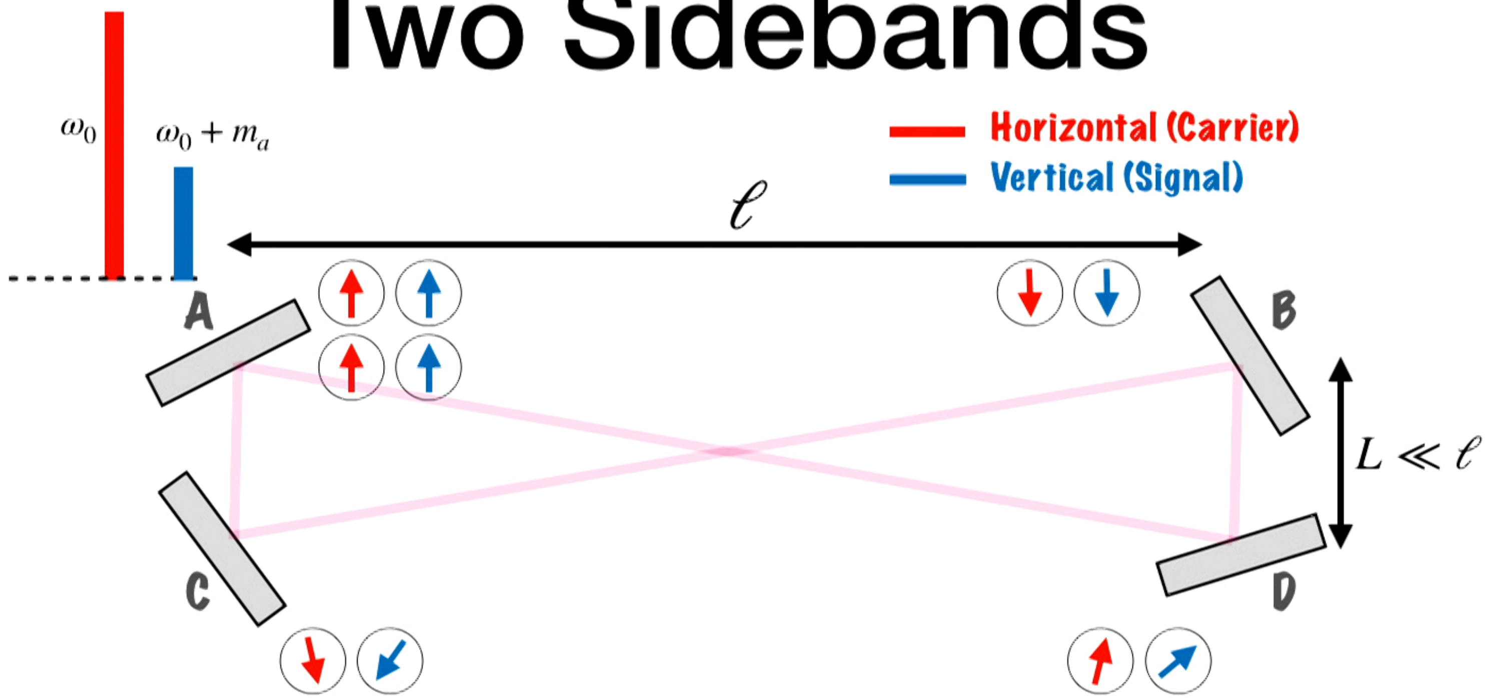
Two Sidebands



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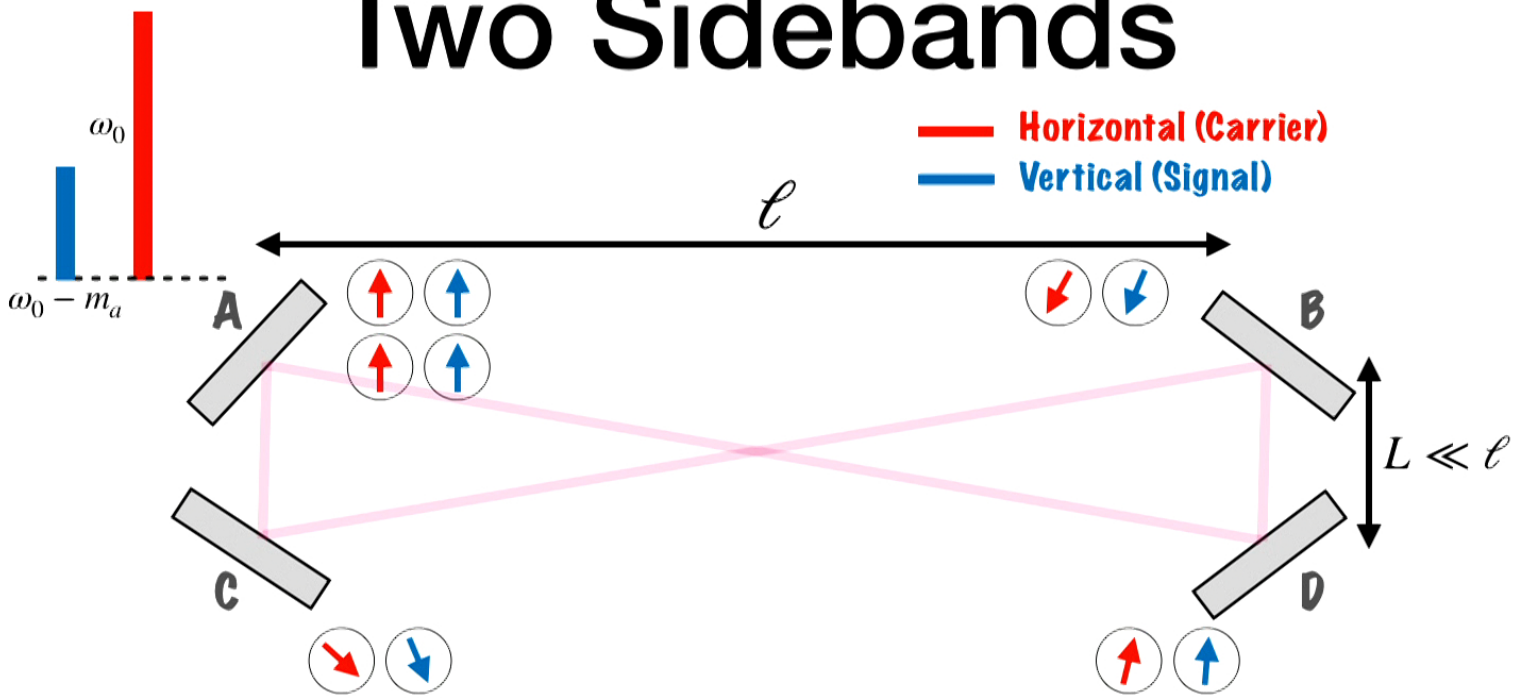
Two Sidebands



For a fixed axion mass, **two sidebands** produced. ADBC should see a signal when cavity is resonant at **either sideband**.

Useful check to confirm a signal.

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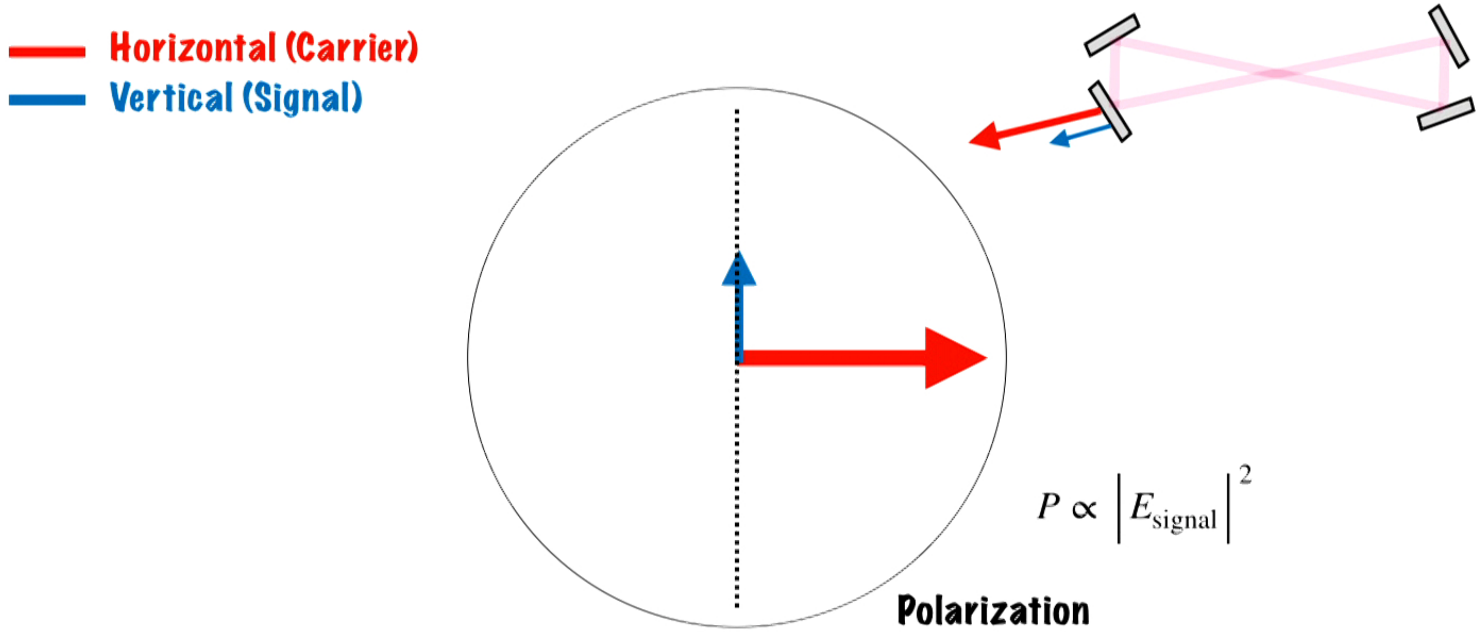
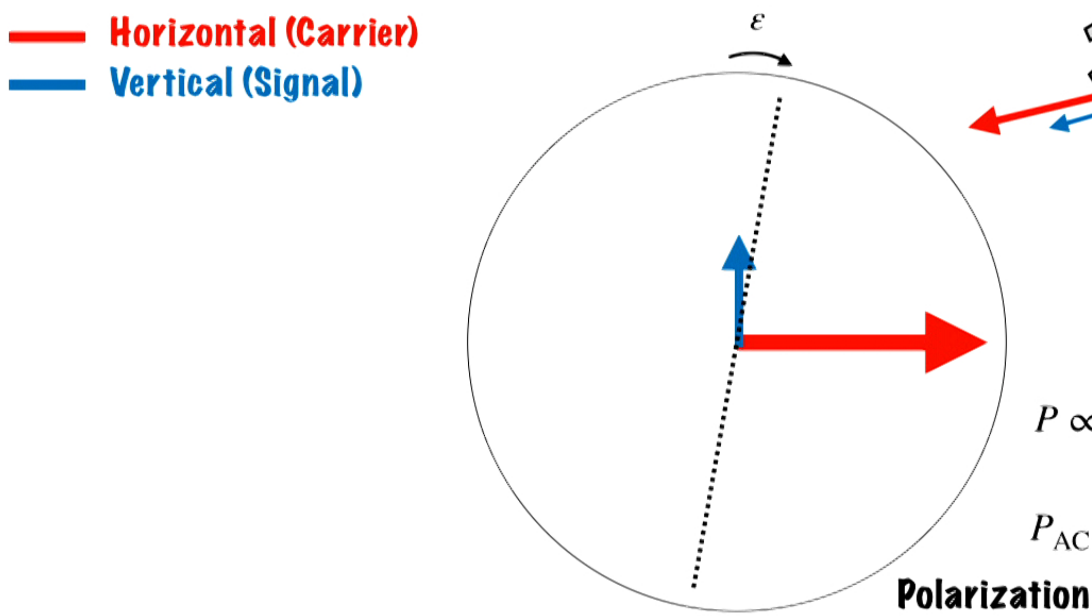
Heterodyne Detection

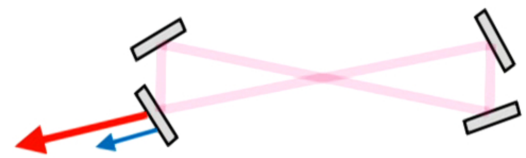


$$P \propto \left| E_{\text{signal}} \right|^2$$

Straightforward readout of the vertical (signal) polarization gives power proportional to $g_{a\gamma\gamma}^2$.

Heterodyne Detection





$$P \propto \left| \varepsilon E_{\text{carrier}} + E_{\text{signal}} e^{i m_a t} \right|^2$$

$$P_{\text{AC}} \sim \varepsilon E_{\text{carrier}} E_{\text{signal}} \cos(m_a t)$$

Heterodyne scheme: mix some of the horizontal (carrier) polarization into the vertical (signal) polarization, **axion-modulated cross term** proportional to $g_{a\gamma\gamma}$.

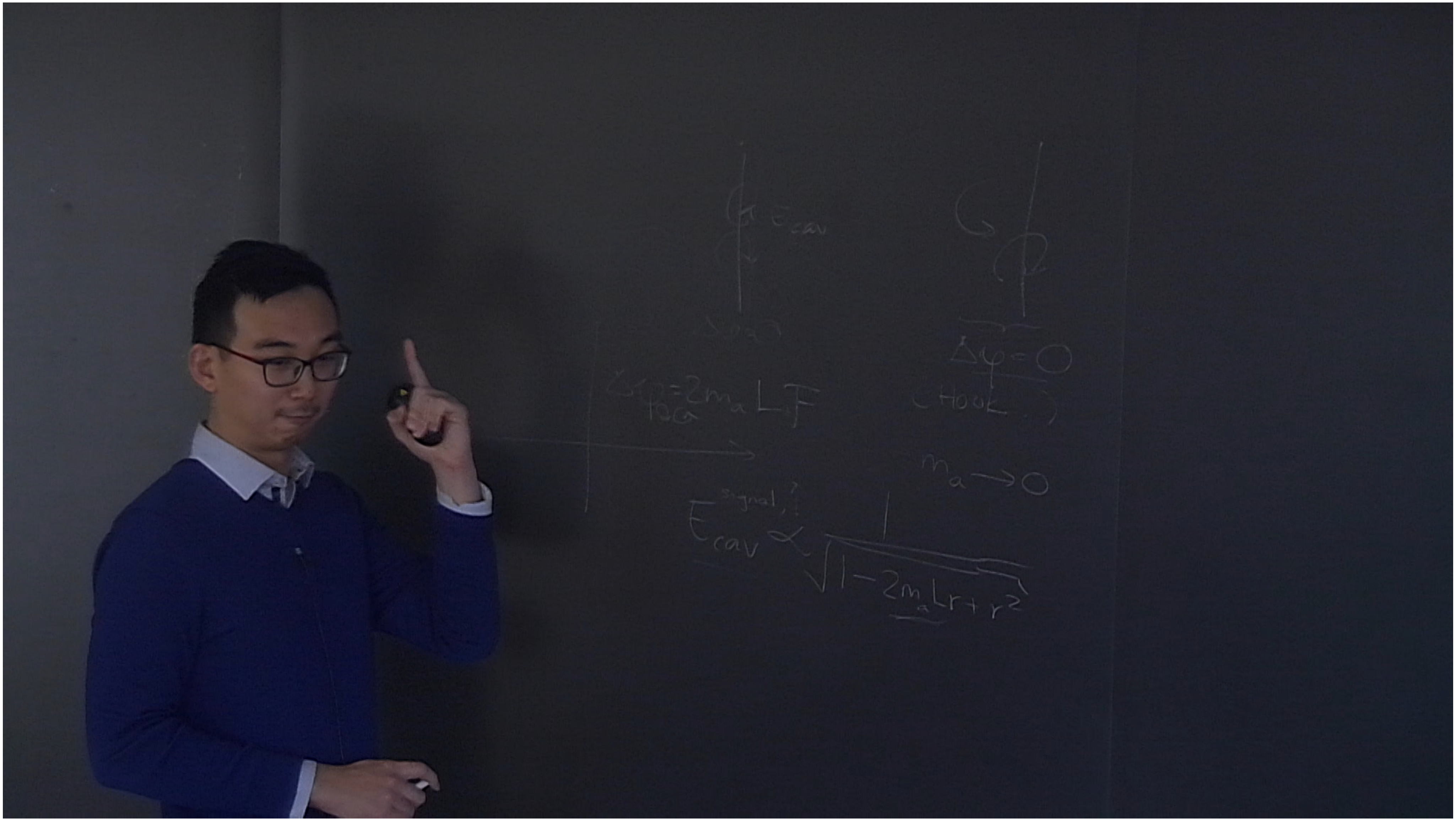
Signal-to-Noise Ratio

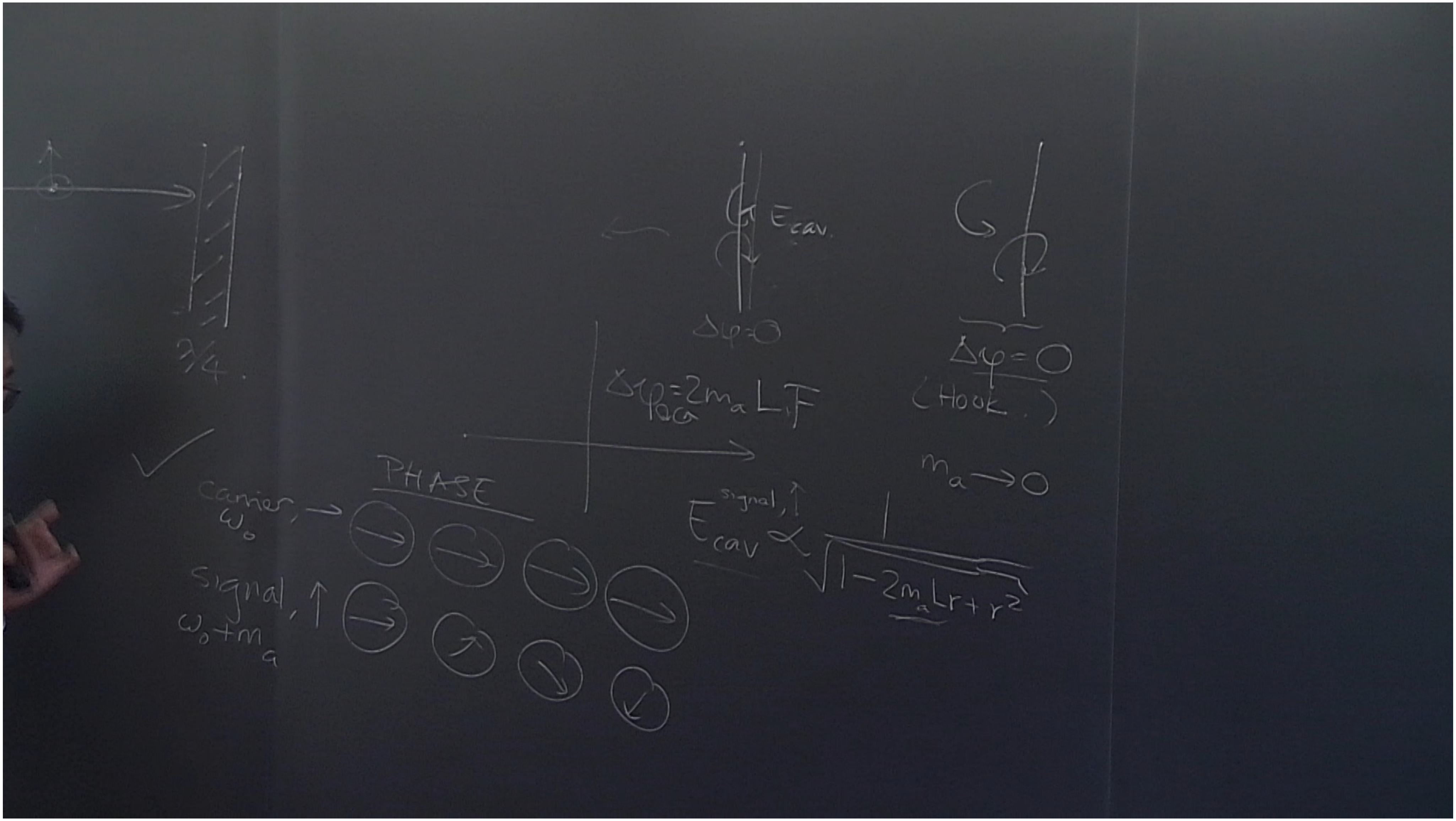
signal spectral density

$$\text{SNR} = \frac{P_{\text{AC}} T^{1/2}}{S_n^{1/2}}$$

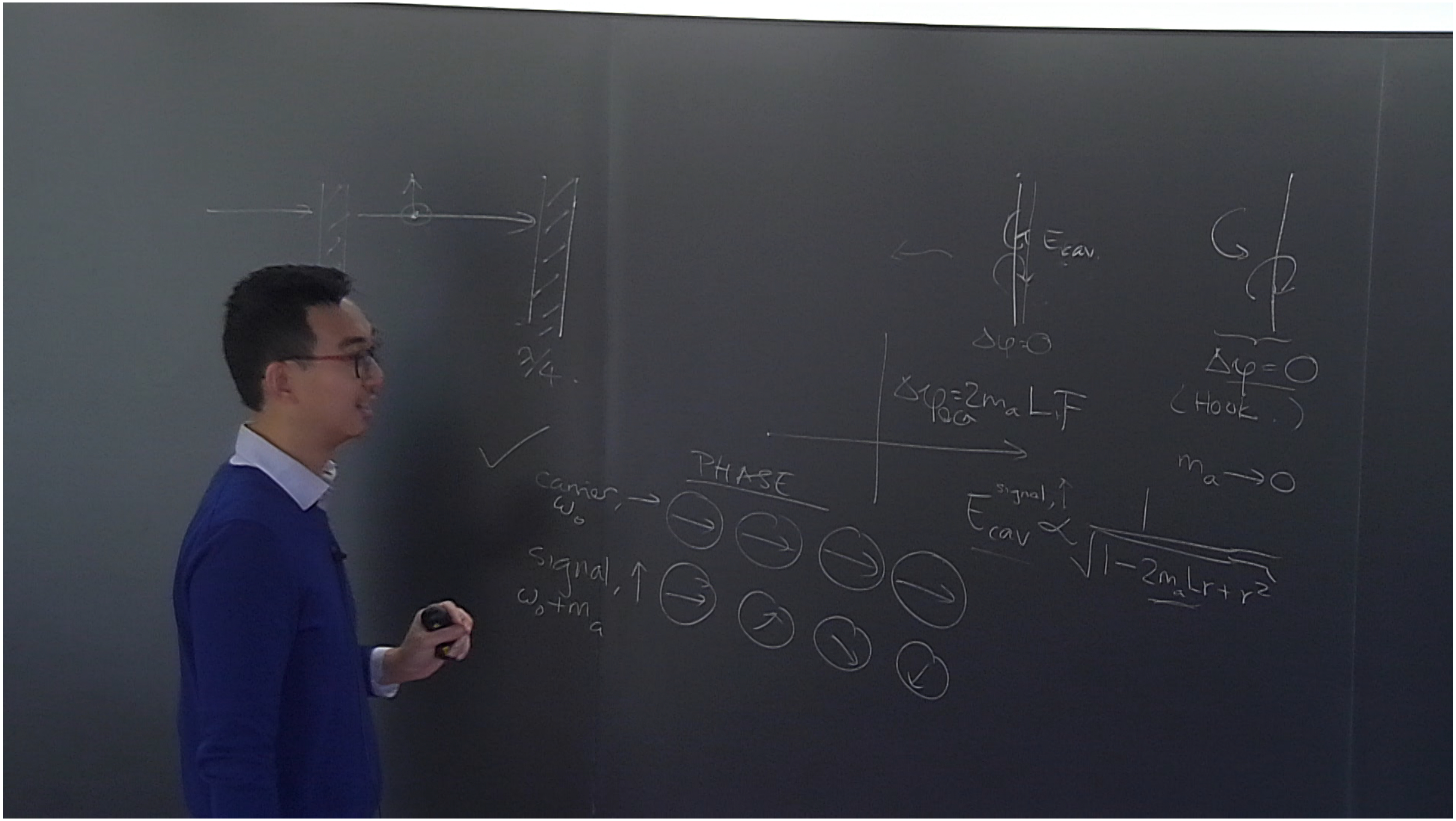
noise spectral density

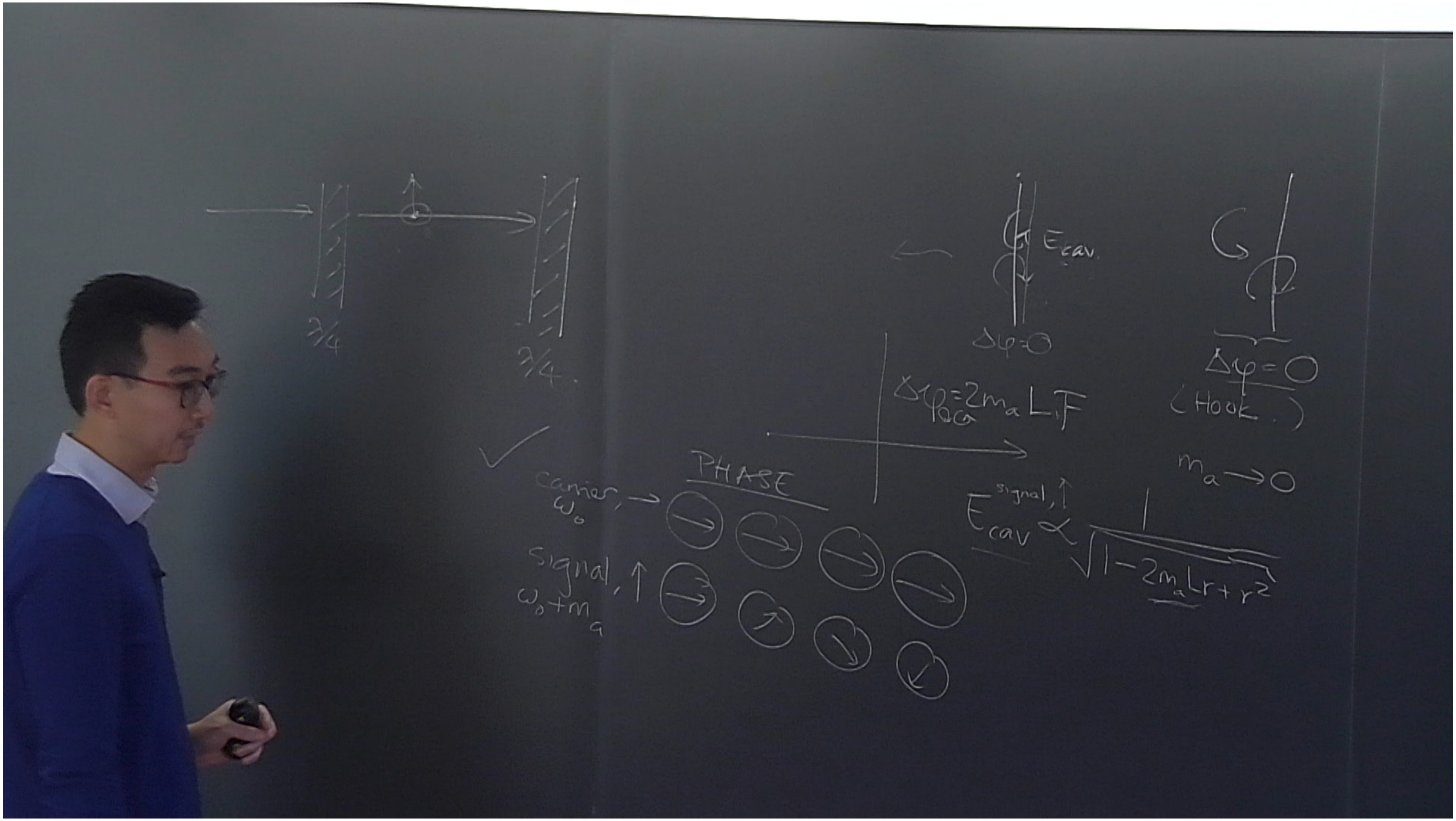
A **signal-to-noise ratio** of 1 is used to estimate the **sensitivity** of our experiment.


E_{cav}
$\Delta\varphi = 2m_a L_i F$
$\Delta\varphi = 0$
HOOK
$m_a \to 0$
signal?
$E_{cav} \propto \frac{1}{\sqrt{1-2m_a L r + r^2}}$



E cav.
Δφ=0
Δφ=0
(Hook.)
Δφ=2m_a L F
PHASE
carrier, →
ω₀
signal, ↑
ω₀+m_a
m_a → 0
signal, ↑
E_cav ∝ 1/√(1−2m_a Lr+r²)


λ/4
carrier, ω₀
signal, ω₀+mₐ
PHASE
E_cav
Δφ=0
Δφ=0
(Hook.)
mₐ→0


λ/4
λ/4.
E cav.
Δφ=0
Δφ=2m_a L,F
Δφ=0
(Hook.)
m_a → 0
PHASE
carrier, →
ω_0
signal, ↑
ω_0+m_a
E_cav ∝ 1/√(1−2m_a Lr+r²)

Signal-to-Noise Ratio

signal spectral density

$$\mathrm{SNR} = \frac{P_{\mathrm{AC}} T^{1/2}}{S_n^{1/2}} \rightarrow S_n^{1/2} \propto \sqrt{P_{\mathrm{DC}}}$$

shot noise

noise spectral density

The noise is dominated by **shot noise**, i.e.
Poisson fluctuation in the power of the laser.

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Signal-to-Noise Ratio

signal spectral density

axion coherence time

$$\mathrm{SNR} = \frac{P_{\mathrm{AC}}(T\tau)^{1/4}}{S_n^{1/2}} \qquad \tau = \frac{2\pi}{m_a v^2} \qquad v \sim 10^{-3}$$

noise spectral density

For integration times that are **longer than the axion coherence time**, the SNR becomes proportional to $T^{1/4}$ instead.

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Signal-to-Noise Ratio

signal spectral density

axion coherence time

$$\text{SNR} = \frac{P_{\text{AC}}(T\tau)^{1/4}}{S_n^{1/2}}$$

$$\tau = \frac{2\pi}{m_a v^2}$$

$$v \sim 10^{-3}$$

noise spectral density

For integration times that are **longer than the axion coherence time**, the SNR becomes proportional to $T^{1/4}$ instead.

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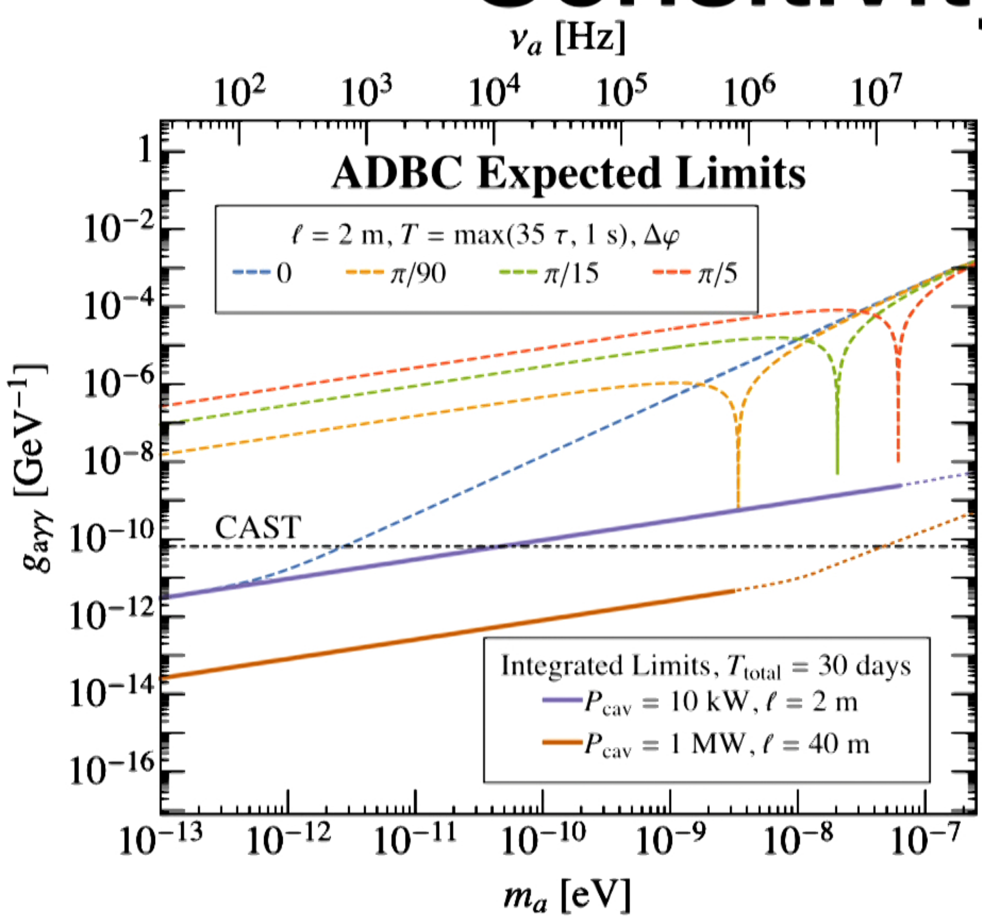
Sensitivity



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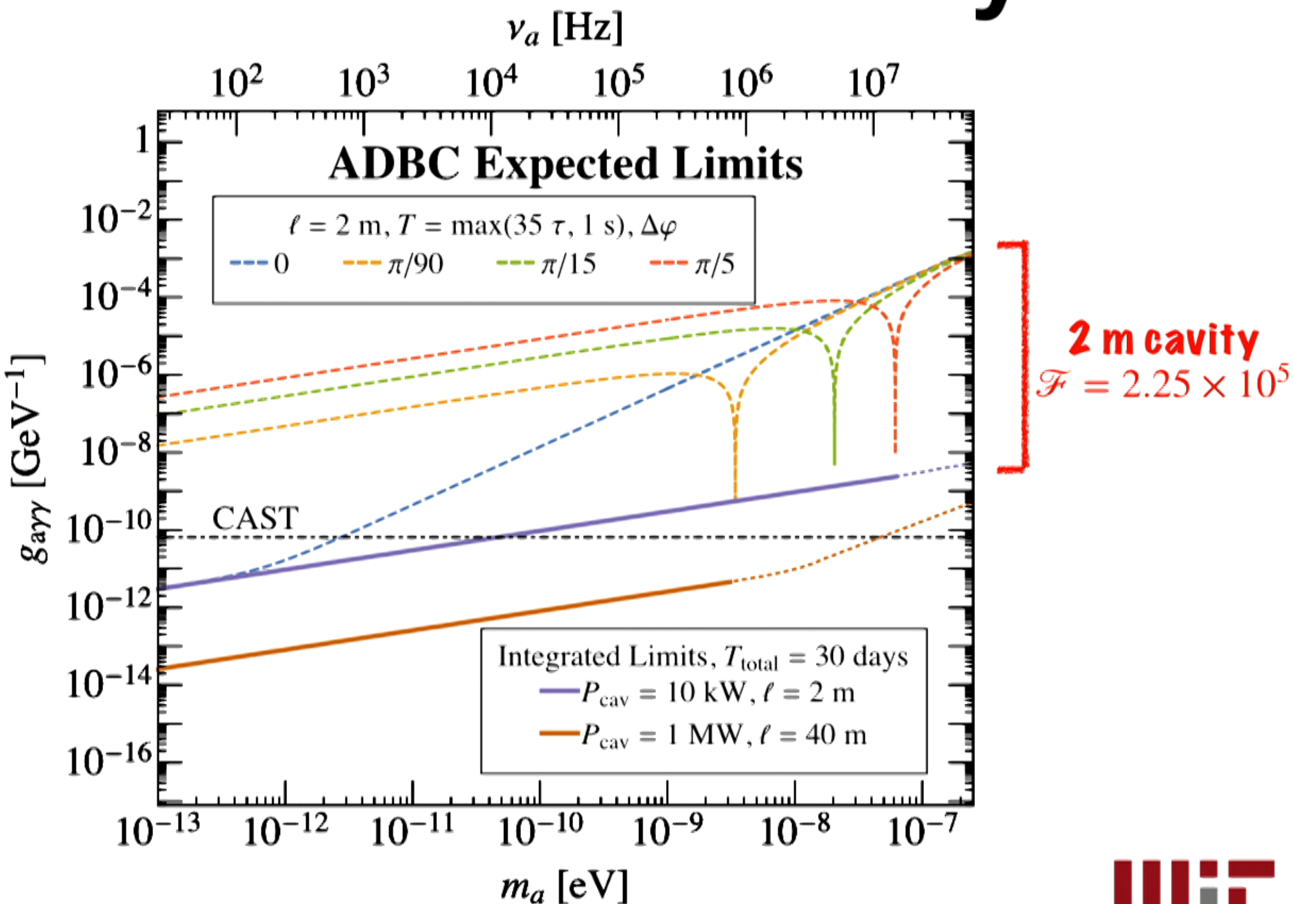
Sensitivity



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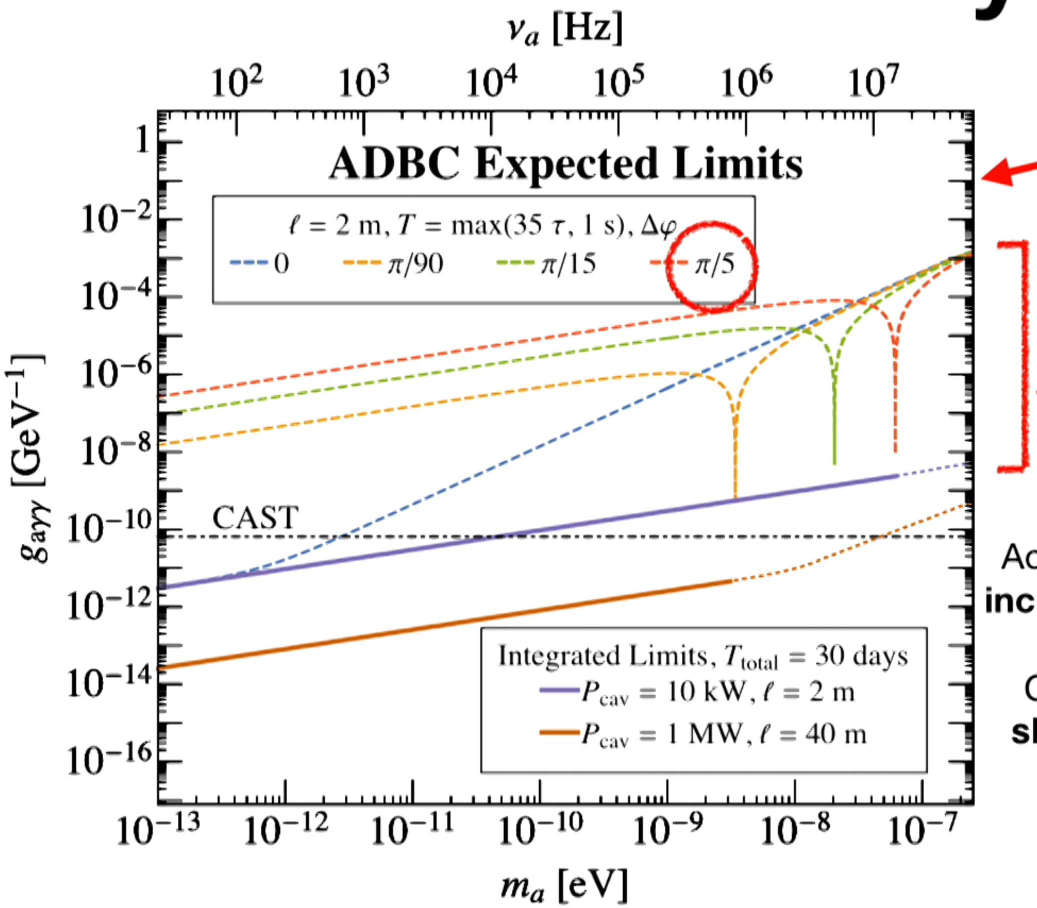
Sensitivity



Adjust mirrors so that **angle of incidence** sweeps over **59 - 65°**.

Generates a **relative phase shift** $\Delta\varphi$ between carrier and signal of 0 to $\pi/5$.

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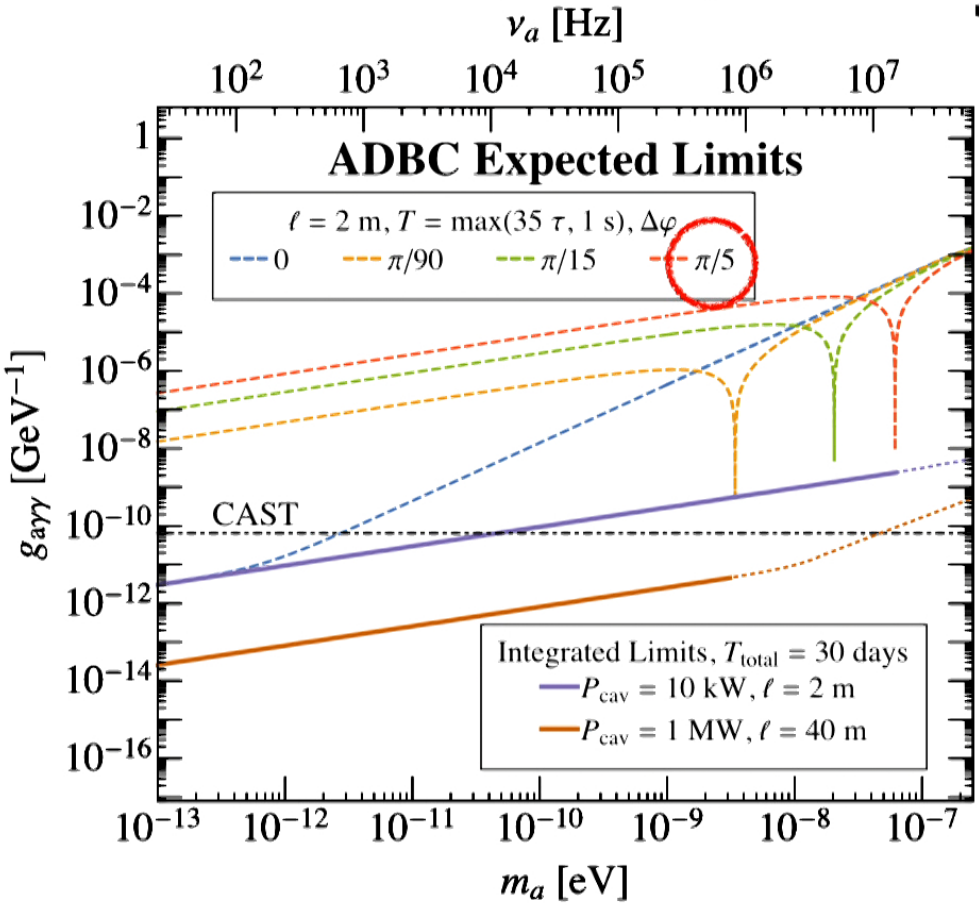
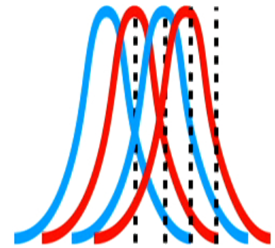
Sensitivity





2 m cavity
$\mathscr{F} = 2.25 \times 10^5$

Take $\mathscr{F}/5$ **steps**, so that all of the **resonances in axion mass** can cover the full mass range from 10^{-13} to 10^{-7} eV.

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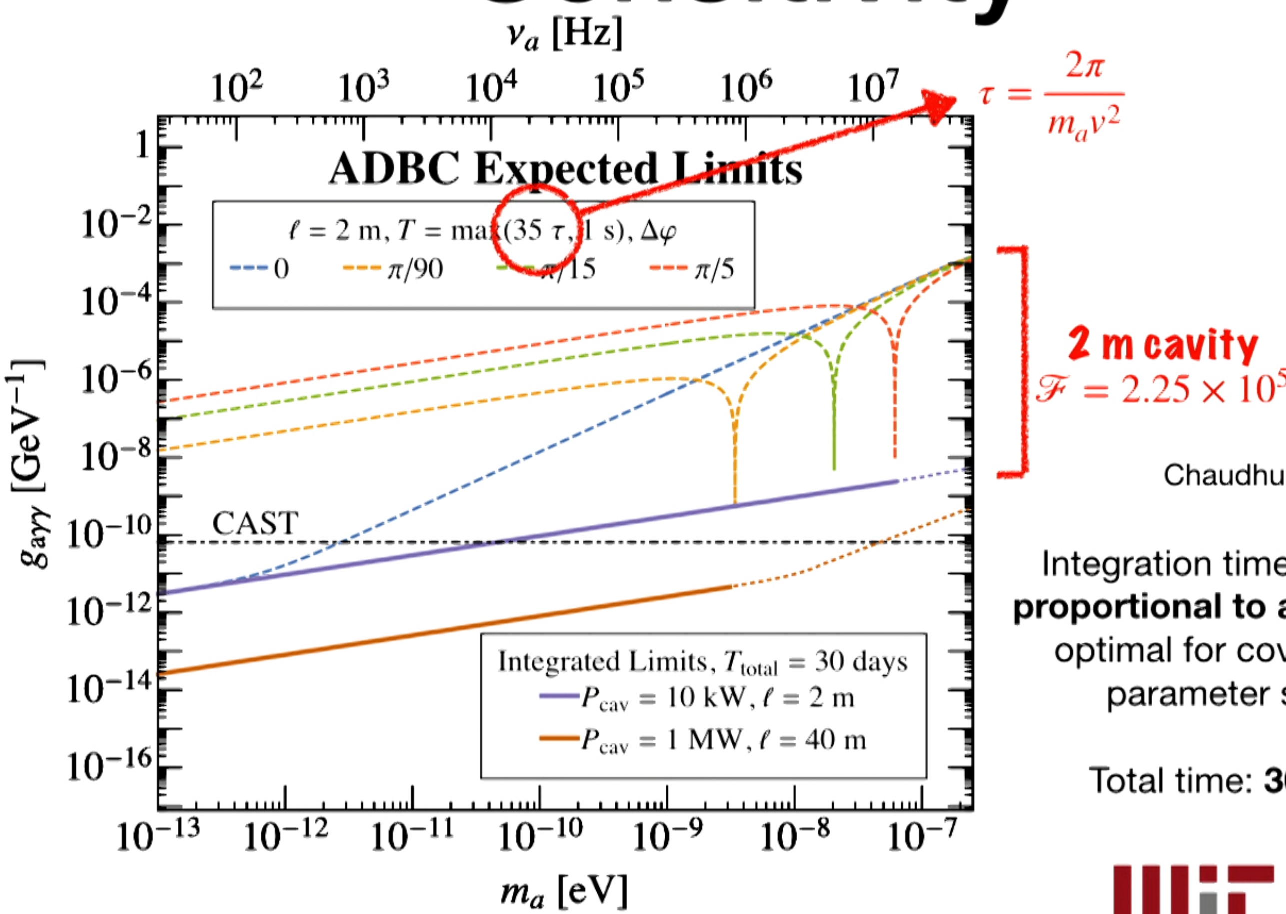
Sensitivity



Chaudhuri+ 1803.01627

Integration time **inversely proportional to axion mass**: optimal for covering this parameter space.

Total time: **30 days**.

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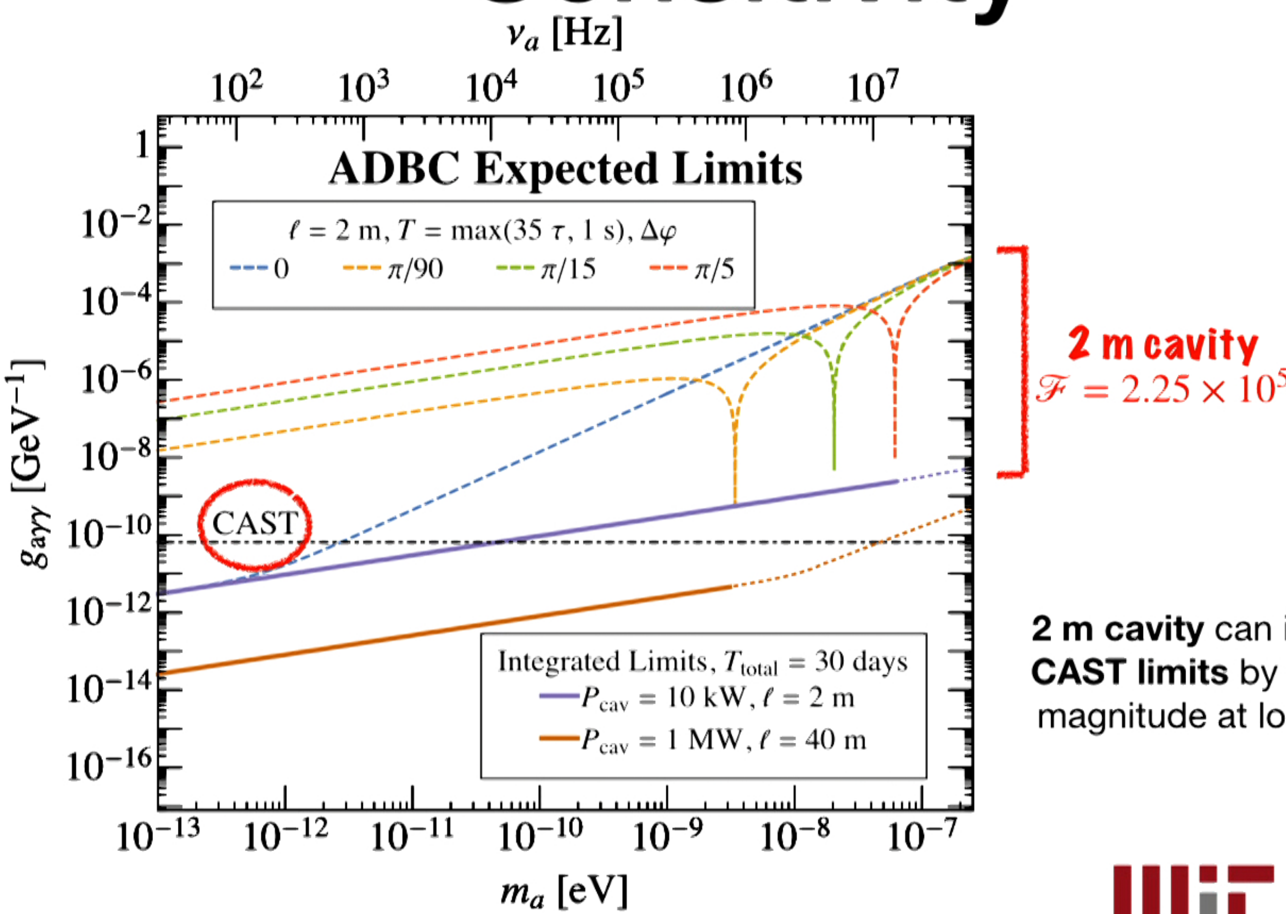
Sensitivity



2 m cavity can improve on **CAST limits** by an order of magnitude at low masses.

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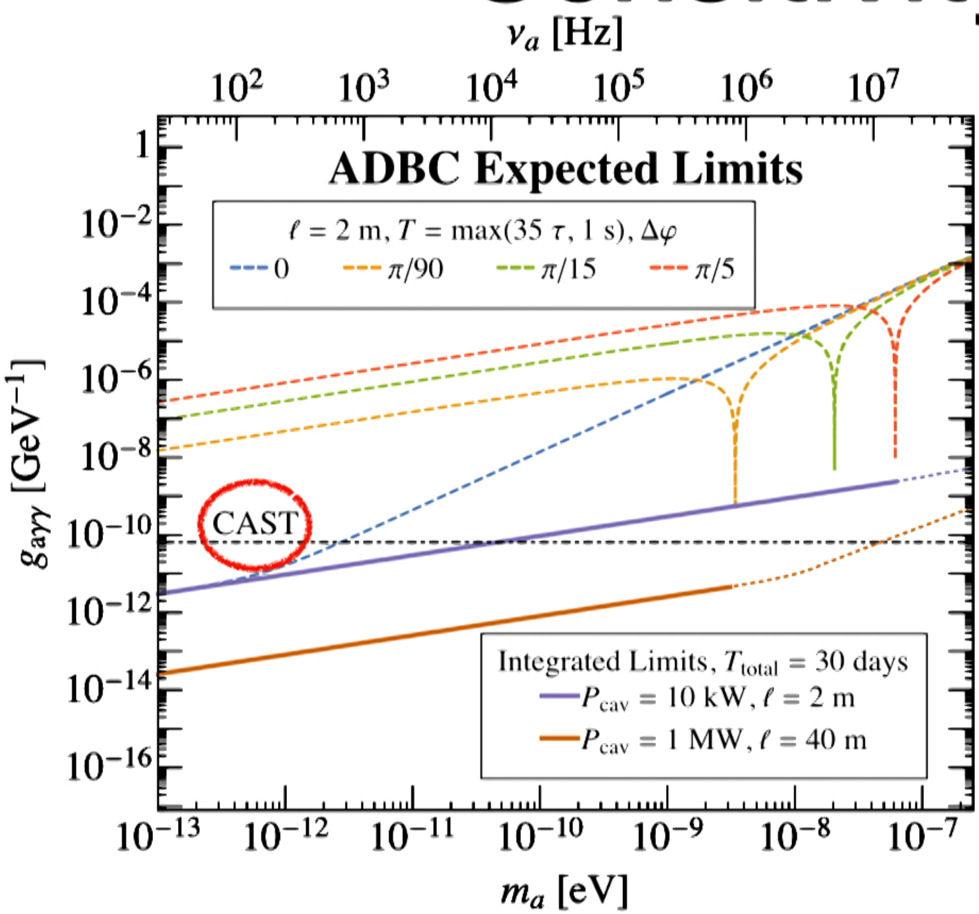
Sensitivity



40 m cavity can do much better with the same total integration time.

40 m cavity
$\mathscr{F} = 2.25 \times 10^5$
$P_{\rm cav} = 1$ MW

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Conclusion

1. Axions couple modes that have **orthogonal polarizations** and have energies **separated by the axion mass**.

2. The **A**xion **D**etection with **B**irefringent **C**avities (ADBC) experiment uses a **bowtie cavity** that is **resonant** in both a **horizontal laser carrier** and the **vertical polarization coupled by the axion**.

3. **Significant improvement in sensitivity to** $g_{a\gamma\gamma}$ over existing limits, **extended mass reach** compared to earlier axion interferometry experiments.

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