POLARIMETRIC SEARCHES FOR AXION DARK MATTER AND HIGH-FREQUENCY GRAVITATIONAL WAVES USING OPTICAL CAVITIES

QUANTUM SENSING MEETS ULTRA-HIGH FREQUENCY GRAVITATIONAL WAVES

MAINZ INSTITUTE FOR THEORETICAL PHYSICS

JOHANNES GUTENBERG UNIVERSITY

JUNE 30, 2025

Camilo GARCIA-CELY

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CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

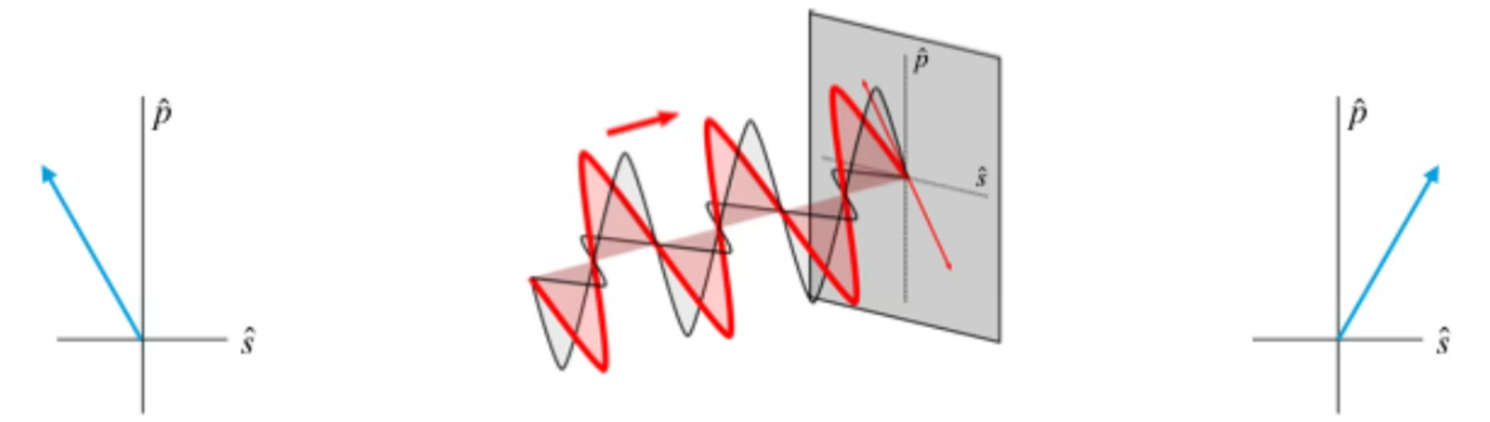
VNIVERSITAT DE VALÈNCIA

In collaboration with Luca Marsili, Andreas Ringwald and Aaron Spector

OUTLINE

1. Study of the polarization evolution of light in a slowly varying background of axions or gravitational fields, with particular emphasis on placing both phenomena on a unified framework.
2. Application to cavities.
3. ALPS II and sensitivity prospects on the axion-photon coupling and GW strain.
4. Conclusions

AXION BIREFRINGENCE

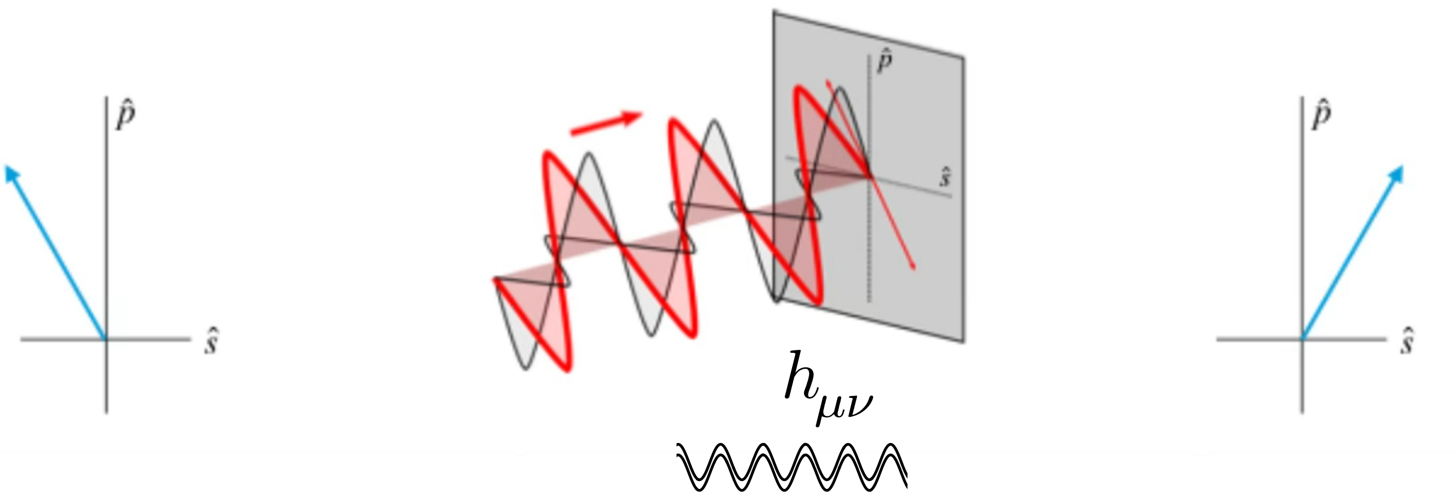


Geometrical
optics limit

↓

$$\frac{d\mathbf{e}}{dt} = -\frac{1}{2} g_{a\gamma\gamma} \dot{a}(t)\, \hat{\mathbf{k}} \times \mathbf{e}$$

BIREFRINGENCE DUE TO A GRAVITATIONAL WAVE

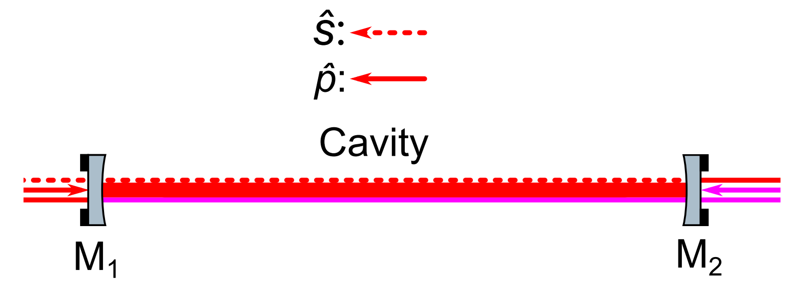


Geometrical optics limit

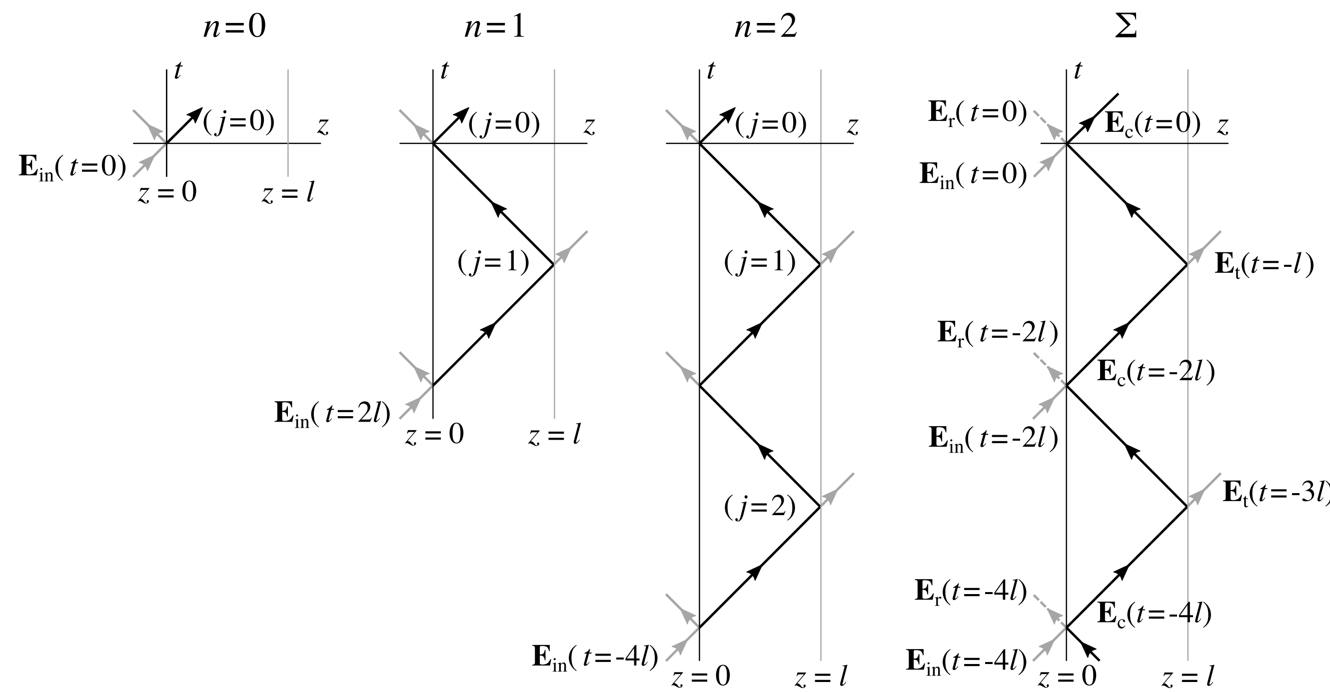
↓

$$\frac{de^i}{dt} = \left(\Gamma^0_{\rho\lambda}\frac{dx^i}{dt} - \Gamma^i_{\rho\lambda}\right)\frac{dx^\rho}{dt}e^\lambda$$

OPTICAL CAVITY



2025, CGC, Marsili, Ringwald, Spector



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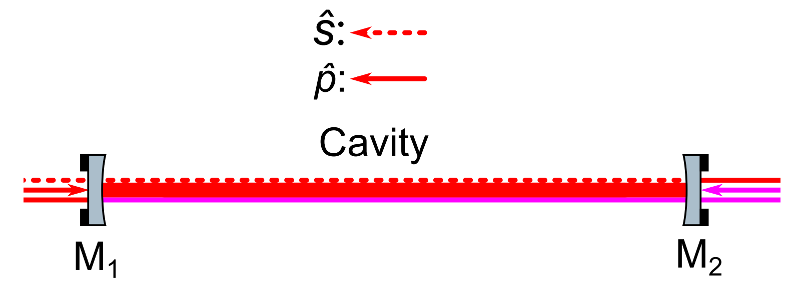

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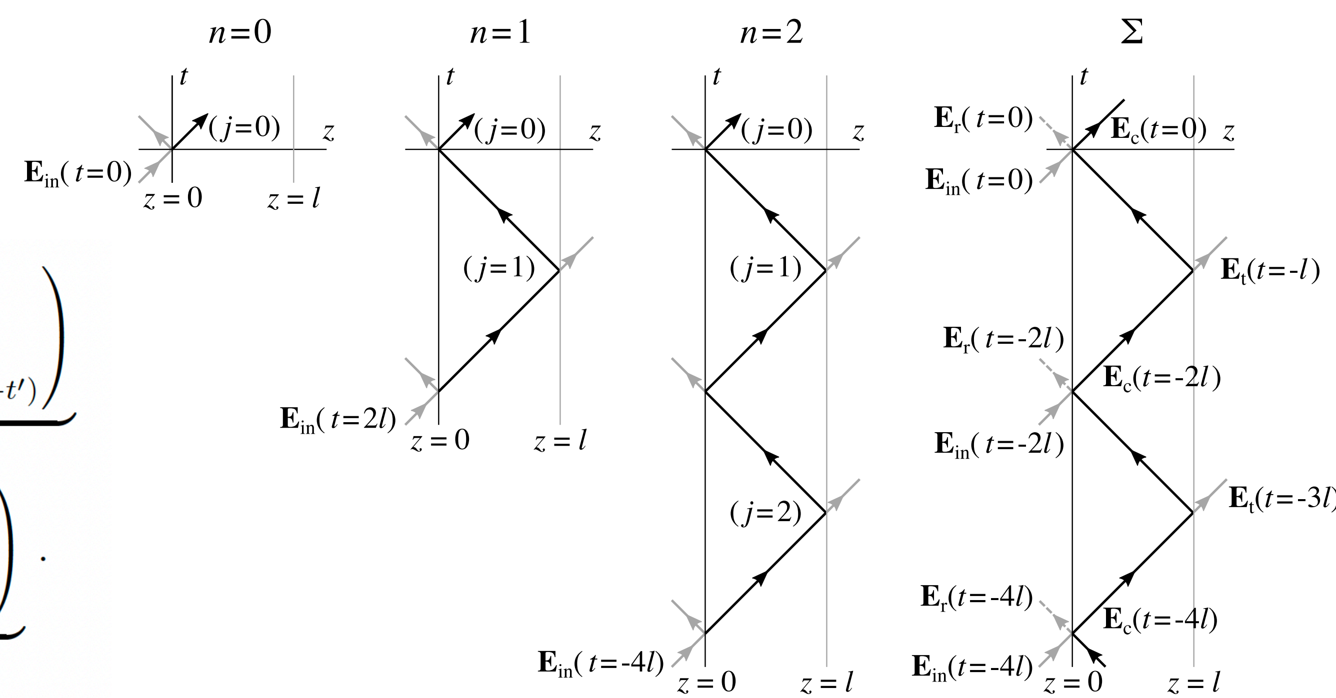


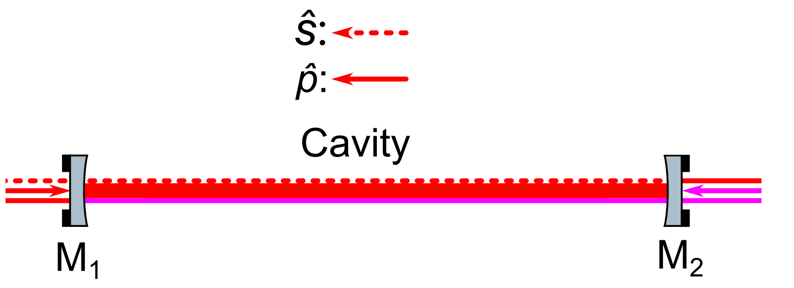
$$\mathbf{E}_1(0) = \left(\sum_{n=0}^{\infty} e^{i\phi_n} \prod_{j=0}^{n} L_j\right) t_1 \mathbf{E}_{\rm in}(0)\,,$$

$$L_j = \underbrace{r_1\mathcal{P}}_{\text{Reflection off mirror 1}} \times \underbrace{\left((\cdots)\,\mathbb{I} + \int_0^l dt'\,\mathcal{M}(t'-(2j+1)l)\Big|_{\mathbf{x}(t')=\hat{\mathbf{z}}\,(l-t')}\right)}_{\text{Path from mirror 2 to mirror 1}}$$

$$\times \underbrace{r_2\mathcal{P}}_{\text{Reflection off mirror 2}} \times \underbrace{\left((\cdots)\,\mathbb{I} + \int_0^l dt'\,\mathcal{M}(t'-(2j+2)l)\Big|_{\mathbf{x}(t')=\hat{\mathbf{z}}\,t'}\right)}_{\text{Path from mirror 1 to mirror 2}}\,.$$

$$\tilde{\mathcal{M}}^{ij} = \begin{cases} -\delta\tilde{c}(f)\epsilon^{ijn}k^n & \text{for axions,} \\ \left[(1-\hat{\mathbf{k}}\cdot\hat{\mathbf{q}})\,e^{ij}(\hat{\mathbf{q}}) - e^{in}(\hat{\mathbf{q}})\hat{k}^n\hat{q}^j + e^{jn}(\hat{\mathbf{q}})\hat{k}^n\hat{q}^i - e^{jn}(\hat{\mathbf{q}})\hat{k}^n\hat{k}^i\right] & \text{for GWs.} \\ \times i\pi f\tilde{h}(f)e^{2i\pi f\,\hat{\mathbf{q}}\cdot\mathbf{x}(t)} & \end{cases}$$

OPTICAL CAVITY



2025, CGC, Marsili, Ringwald, Spector

define a *response function due to polarization change*

$$\hat{\mathbf{s}}^\dagger \cdot \mathbf{E}_1(t) = t_1|\mathbf{E}_{\rm in}| \int_{-\infty}^{\infty} df\, s(f)\, \mathcal{H}(f) e^{2i\pi f t}\,,$$

$$\mathcal{H}_0(f) = \left(\frac{r_1 r_2 e^{-4i\pi f_L l}}{e^{-4i\pi f_L l} - r_1 r_2}\right)\left(\frac{1}{e^{-4i\pi (f_L+f) l} - r_1 r_2}\right)$$

$$\approx \frac{\mathcal{F}/\pi}{e^{-4i\pi f l} - r_1 r_2}\,, \quad \text{with} \quad \mathcal{F} = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1\, r_2}$$

The laser is held on the cavity resonance .

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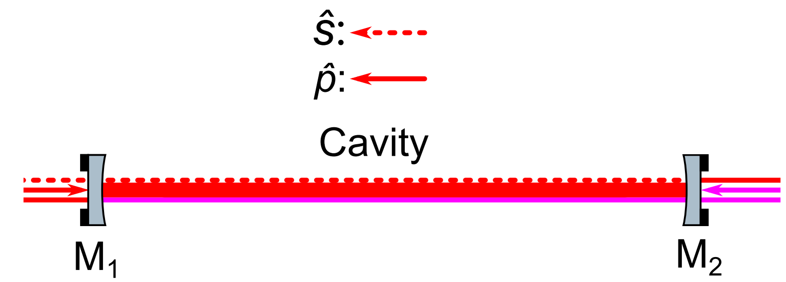

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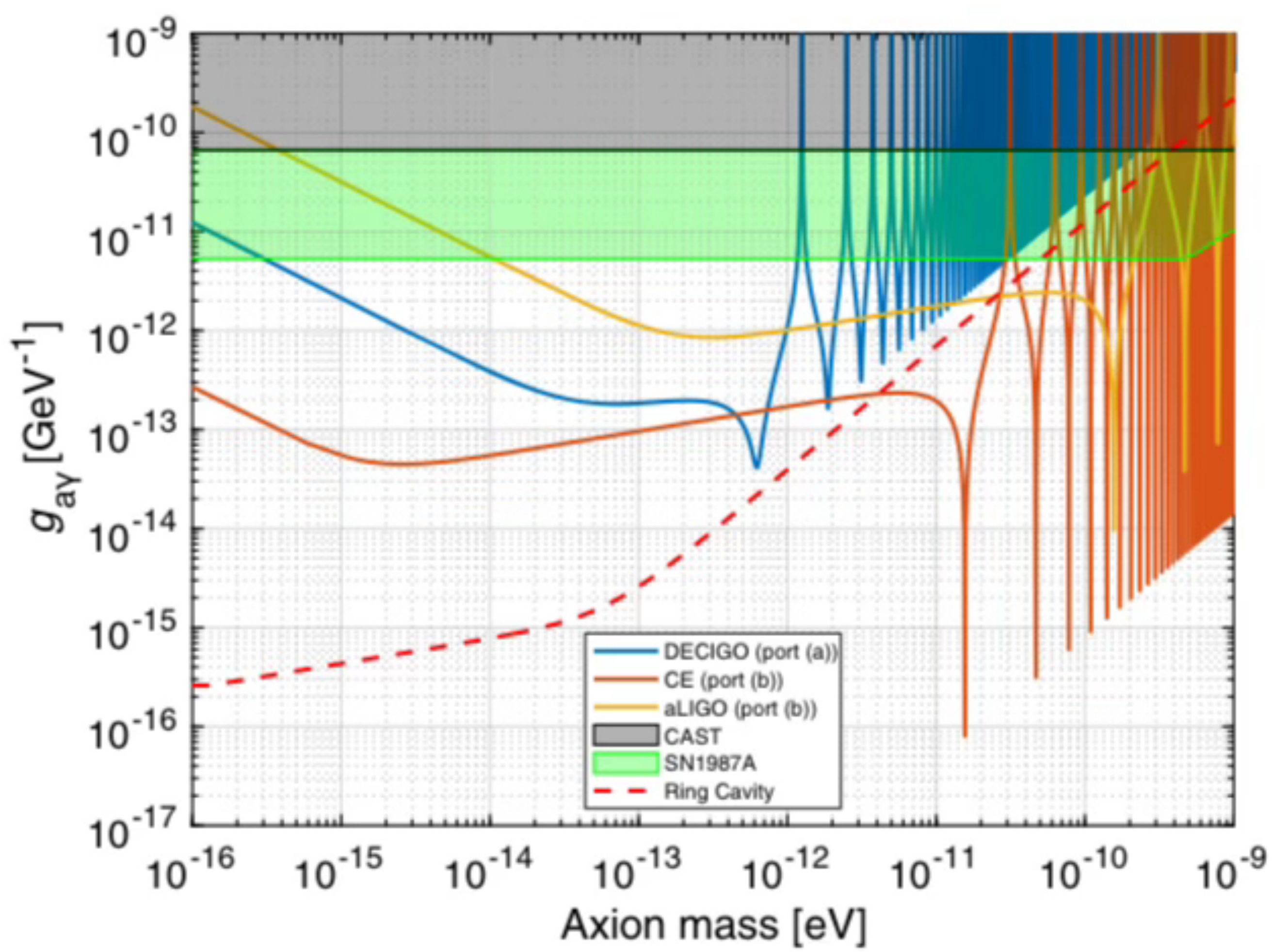
	$\mathcal{H}(f)/\mathcal{H}_0(f)$
Axions	$-\frac{i f_L}{f}\left(1 - e^{-2i\pi f l}\right)^2$
$h_\times$	$\frac{(1-e^{-2i\pi f l})^2 + 2e^{-2i\pi f l}(1-e^{2i\pi f l \cos\theta_h}) + 2(1-e^{-4i\pi f l})\cos\theta_h \cos^2\phi_h}{2\sqrt{2}}$
$h_\times(f=1/2l)$	$\frac{1+e^{i\pi\cos\theta_h}}{\sqrt{2}}$
$h_\times(f=1/l)$	$\frac{1-e^{2i\pi\cos\theta_h}}{\sqrt{2}}$
h_+	$\left(1 - e^{-4i\pi f l}\right)\frac{(3+\cos 2\theta_h)\sin 2\phi_h}{8\sqrt{2}}$
$h_+(f=1/2l)$	0
$h_+(f=1/l)$	0

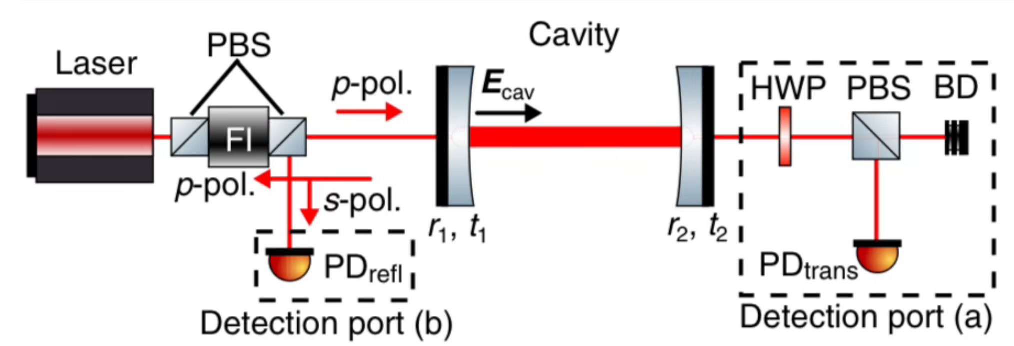
AXION DARK MATTER SENSITIVITY

PHYSICAL REVIEW LETTERS **123,** 111301 (2019)

Axion Dark Matter Search with Interferometric Gravitational Wave Detectors

Koji Nagano,[1] Tomohiro Fujita,[2,3] Yuta Michimura,[4] and Ippei Obata[1]



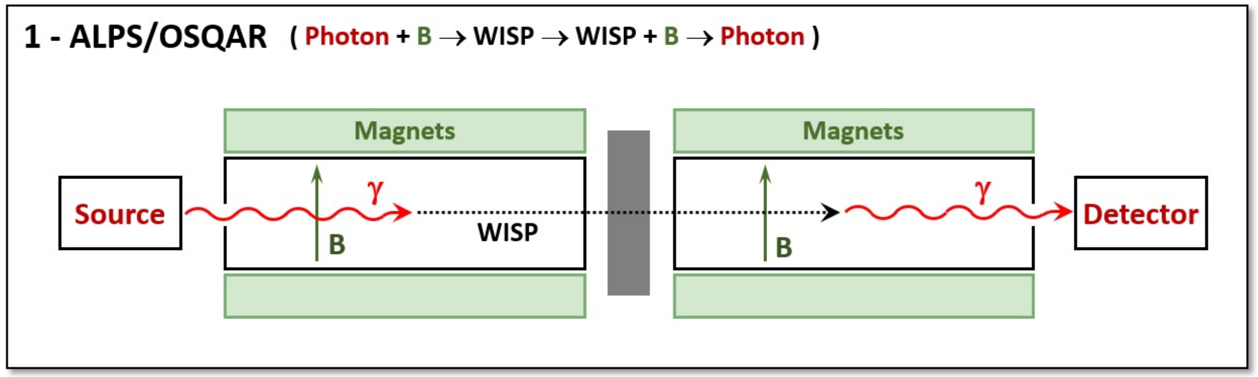


$$\mathbf{E}_{\mathrm{PD}}(t) = \left[t_1^2|\mathbf{E}_{\mathrm{in}}|\left(\alpha + \int_{-\infty}^{\infty} df\, s(f)\,\mathcal{H}(f) e^{2i\pi f t}\right) + \mathrm{E}_{\mathrm{noise}}(t)\right] e^{-2i\pi f_L t}\hat{\mathbf{s}}.$$

amilo García-Cely

THE ALPS EXPERIMENT

ALPs II experiment at DESY



Polarimetry enables use of these cavities without requiring a magnetic field.

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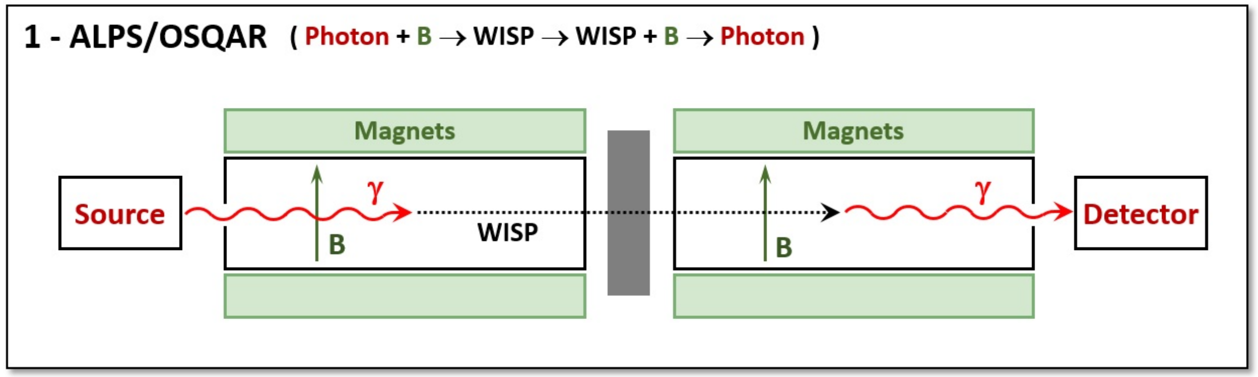

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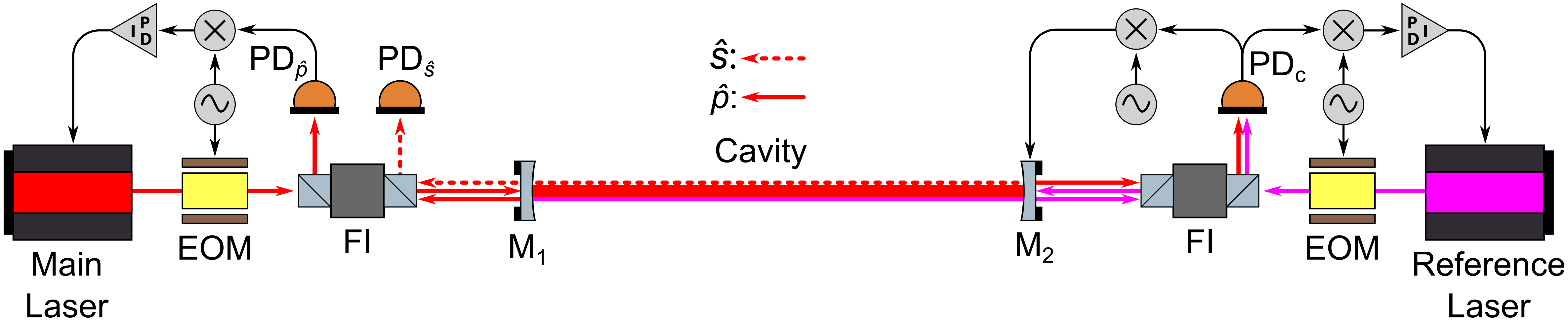
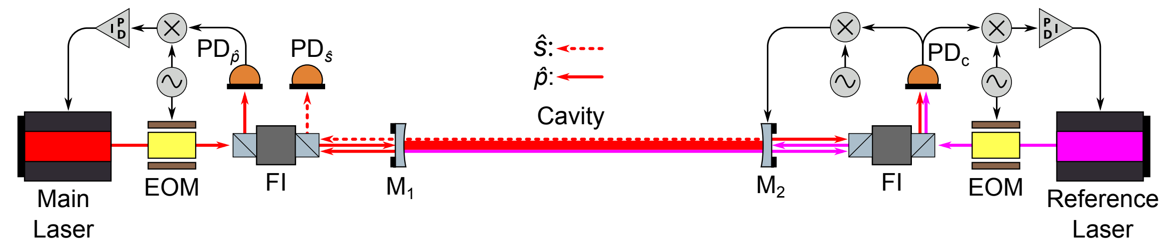


Polarimetric searches for axion dark matter and high-frequency gravitational waves using optical cavities

Camilo García-Cely (Valencia U., IFIC), Luca Marsili (Valencia U., IFIC), Andreas Ringwald (DESY), Aaron D. Spector (DESY)

Jan 14, 2025

OPTICAL CAVITY



2025, CGC, Marsili, Ringwald, Spector

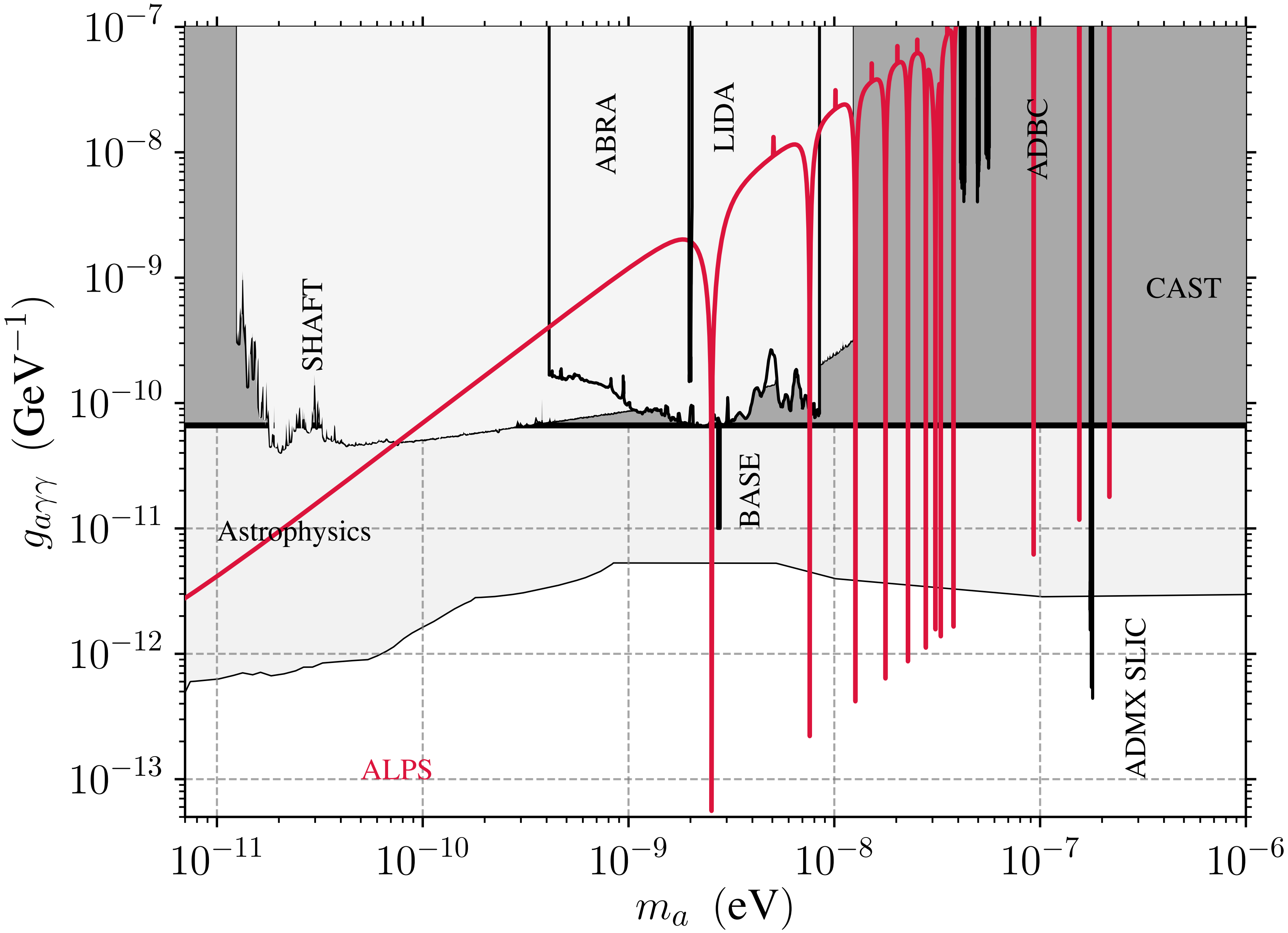
- At the MHz range the sensitivity is limited by the shot noise (light quantum fluctuations)
- The higher the frequency of the laser the higher the noise
- The higher the power reduces the lower the noise

$$P_{\rm signal} = 2\left|\mathbf{E}_{\rm in}\right|^2 \alpha t_1^4 \int_{-\infty}^{\infty} df \tilde{h}(f)\mathscr{H}(f) e^{i2\pi f t}$$

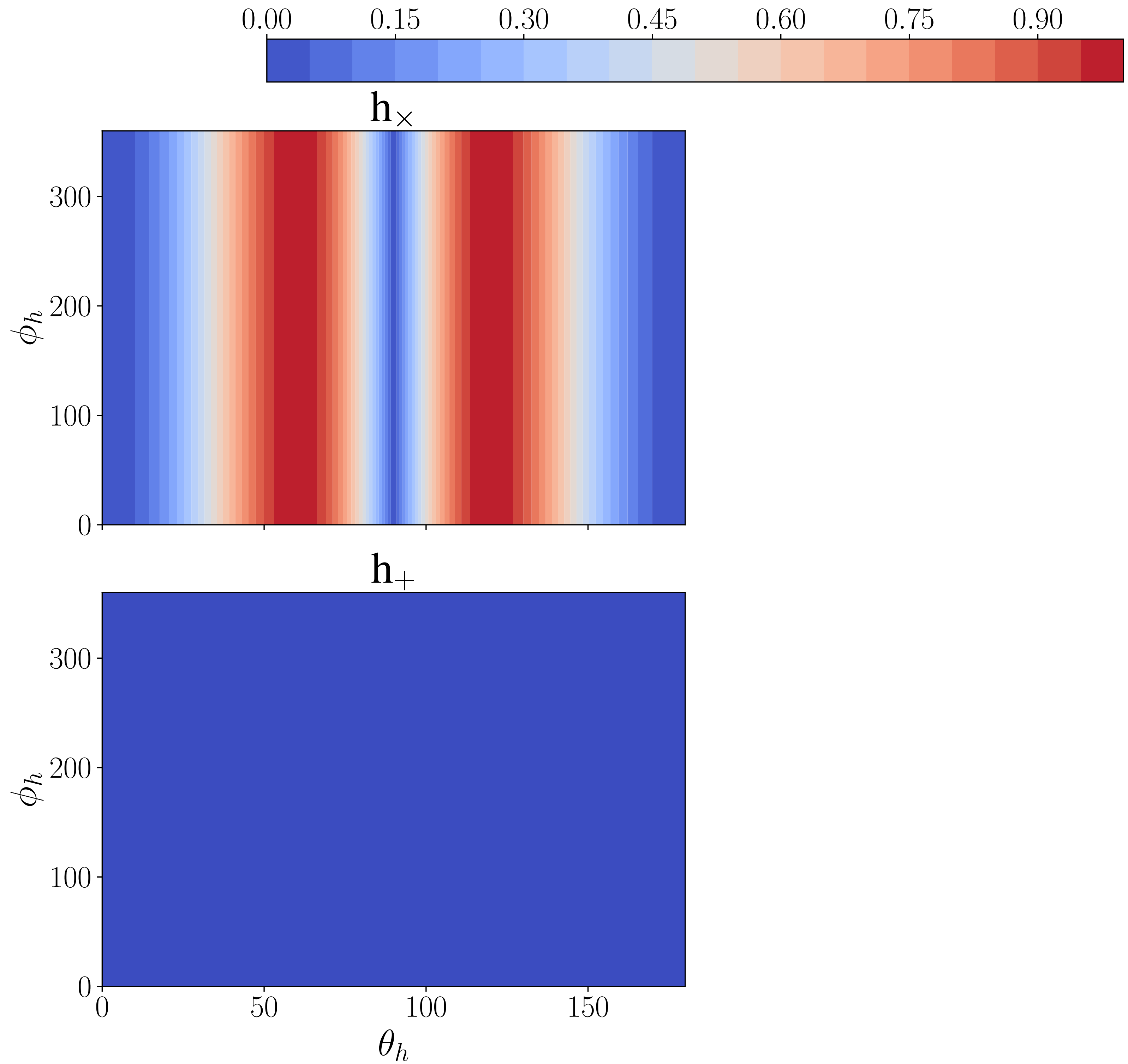
$$(S_h^{\rm noise})^{1/2} = \frac{1}{t_1^2 \mathscr{H}(f)}\sqrt{\frac{\omega_L}{2P_o}}$$

AXION DARK MATTER SENSITIVITY

2025, CGC, Marsili, Ringwald, Spector



PROJECTED SENSITIVITY FOR GRAVITATIONAL WAVES



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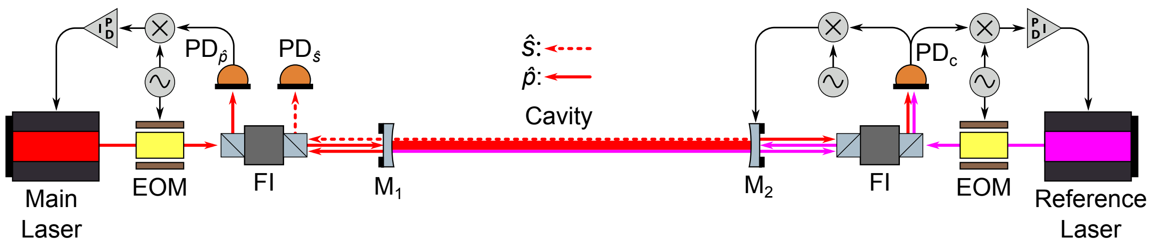

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$$\hat{\mathbf{s}}^{\dagger} \cdot \mathbf{E}_1(t) = t_1 |\mathbf{E}_{\text{in}}| \int_{-\infty}^{\infty} df\, s(f)\, \mathcal{H}(f) e^{2i\pi f t}$$

For GWs coming from the zenith

- The cross polarization has the same cavity response function as axions
- The plus polarization decouples

(selection rules)

	$\mathcal{H}(f)/\mathcal{H}_0(f)$
Axions	$-\frac{i f_L}{f}\left(1 - e^{-2i\pi f l}\right)^2$
$h_\times$	$\frac{(1-e^{-2i\pi f l})^2 + 2e^{-2i\pi f l}(1-e^{2i\pi f l \cos\theta_h}) + 2(1-e^{-4i\pi f l})\cos\theta_h \cos^2\phi_h}{2\sqrt{2}}$
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2023, Domcke, CGC, Lee, Rodd

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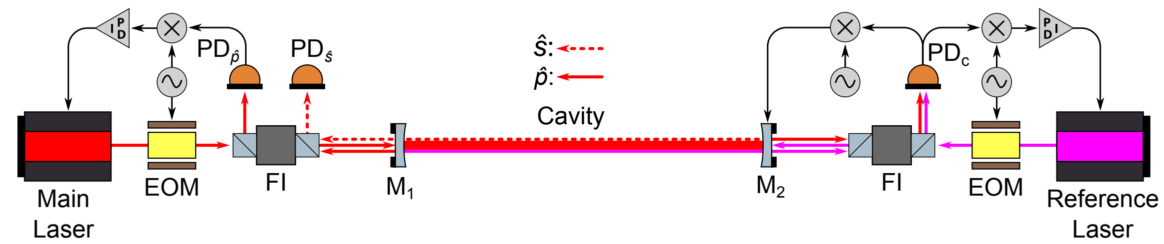

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For GWs coming from the zenith

- The cross polarization has the same cavity response function as axions
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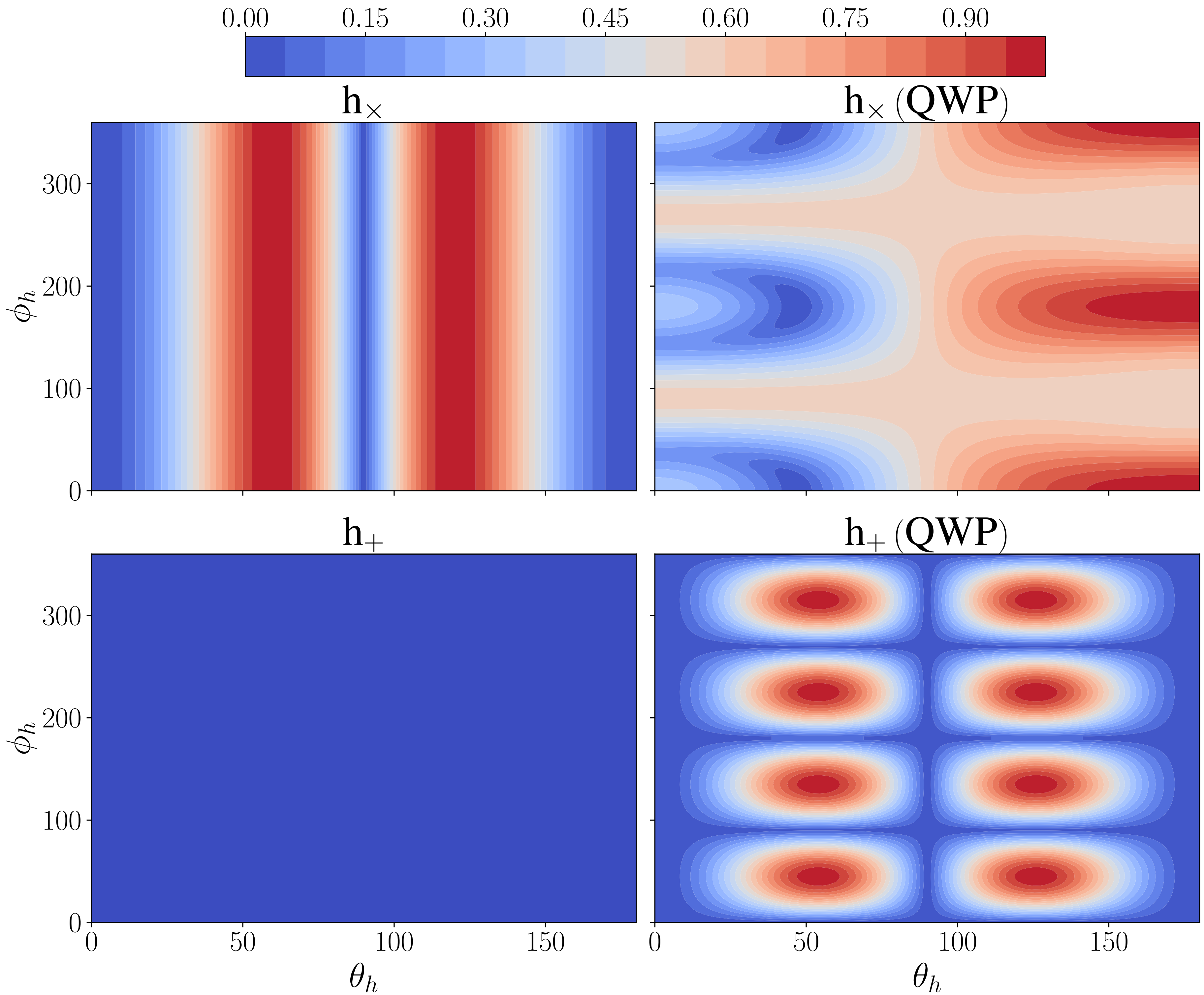
(selection rules)

Axions (QWP)	$-\frac{i f_L}{f}\left(1 - e^{-4i\pi f l}\right)$
$h_\times$ (QWP)	$\frac{1 - e^{-4i\pi f l} + 2\left(1 + e^{-4i\pi f l} - 2e^{-2i\pi f l(1-\cos\theta_h)}\right)\cos\theta_h \cos^2\phi_h}{2\sqrt{2}}$
$h_\times$ (QWP, $f = 1/2l$)	$\sqrt{2}\left(1 + e^{i\pi\cos\theta_h}\right)\cos\theta_h \cos^2\phi_h$
$h_\times$ (QWP, $f = 1/l$)	$\sqrt{2}\left(1 - e^{2i\pi\cos\theta_h}\right)\cos\theta_h \cos^2\phi_h$
h_+ (QWP)	$\left(1 + e^{-4i\pi f l} - 2\,e^{-2i\pi f l(1-\cos\theta_h)}\right)\frac{(3+\cos 2\theta_h)\sin 2\phi_h}{8\sqrt{2}}$
h_+ (QWP, $f = 1/2l$)	$\left(1 + e^{i\pi\cos\theta_h}\right)\frac{(3+\cos 2\theta_h)\sin 2\phi_h}{4\sqrt{2}}$
h_+ (QWP, $f = 1/l$)	$\left(1 - e^{2i\pi\cos\theta_h}\right)\frac{(3+\cos 2\theta_h)\sin 2\phi_h}{4\sqrt{2}}$

2023, Domcke, CGC, Lee, Rodd

PROJECTED SENSITIVITY FOR GRAVITATIONAL WAVES



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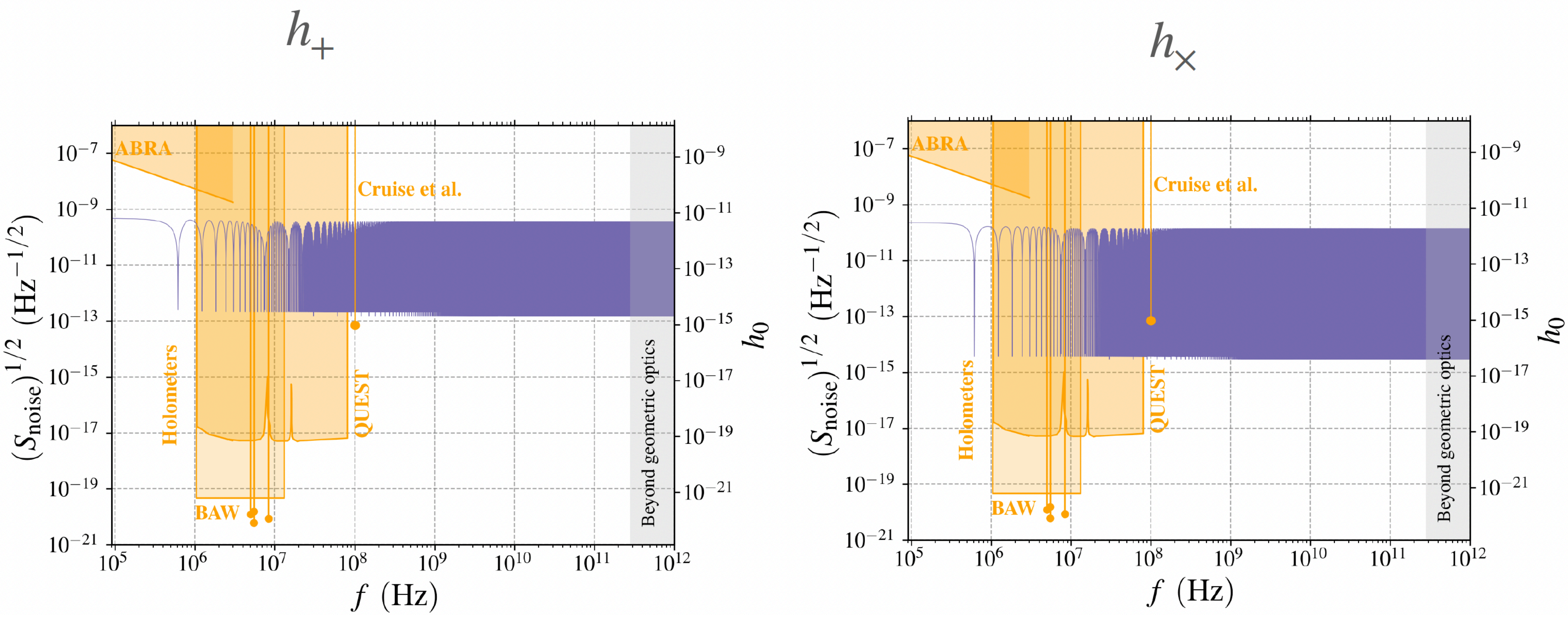

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CONCLUSIONS

- I discussed the evolution of light polarization as it propagates through the background of axion DM or that of a passing plane GW.
- For axions, the polarization vector of linearly polarized light rotates around the direction of propagation.
- For GWs, the polarization changes, though the effect goes beyond a simple rotation about the direction of motion.
- Geometric optics provide a unified treatment of these effects, demonstrating that the polarization evolution in all cases originates from the same underlying physics. Synergy between searches for axion DM and those for GWs.
- These effects can be exploited in the optical cavities of the ALPS II experiment, initially designed to observe the light-shining-through-a-wall induced by axions, but easily adaptable to measure polarization effects from other sources.
- For axions dark matter, this search is competitive with other laboratory-based experiments and with astrophysical searches, particularly near resonance frequencies.
- A natural application of this method is searching for GWs in optical cavities.
- With only minor modifications, the ALPS II experiment may be able to explore currently unconstrained parameter space by other strategies proposed to search for high-frequency GWs.
- In the future, other type of experiments, currently in R&D phase, could significantly enhance these prospects, though such advancements may not occur in the near term.

BACKUP

QWP	l [m]	$P_{\rm max}$ [kW]	(t_1^2, t_2^2, ℓ^2) (ppm)	$\mathcal{F}$	$m_{\rm max}$ (eV)	$\tau_{\rm storage}$ (ms)
No	245	150	(22, 2, 20)	1.4×10^5	4.2×10^{-8}	74.2
Yes	245	10	(1100, 100, 1000)	2.9×10^3	2.1×10^{-6}	1.48
No	20	50	(11, 1, 10)	2.9×10^5	2.6×10^{-7}	12.1
Yes	20	10	(1100, 100, 1000)	2.9×10^3	2.6×10^{-5}	0.121

Table 2. Properties of the cavities studied in this work, all utilizing a laser with a wavelength $\lambda = 1064$ nm. See text for details.