

POLARIMETRIC SEARCHES FOR AXION DARK MATTER WITH OPTICAL CAVITIES

Identification of Dark Matter 2026

University of Zaragoza
JUNE 2, 2026

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EXCELENCIA
SEVERO
OCHOA

ei AGENCIA
ESTATAL DE
INVESTIGACIÓN

 **CSIC**
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

BASED ON

PHYSICAL REVIEW D **112**, 023031 (2025)

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

Camilo García-Cely ¹, Luca Marsili ¹, Andreas Ringwald ² and Aaron D. Spector²

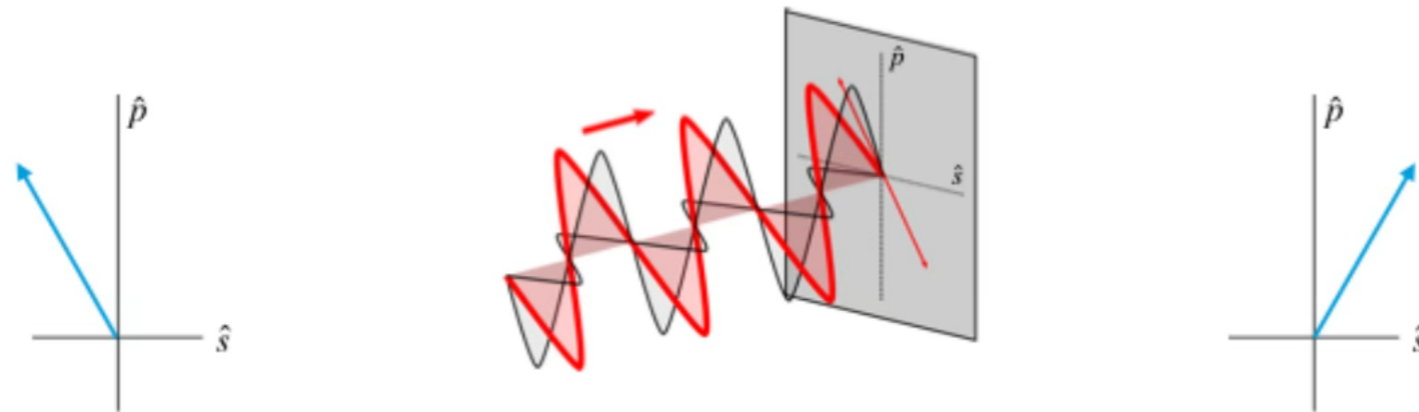


OUTLINE

1. ALPS II and sensitivity prospects due to axion birefringence
2. High frequency gravitational waves.
3. Conclusions

AXION BIREFRINGENCE

AXION BIREFRINGENCE

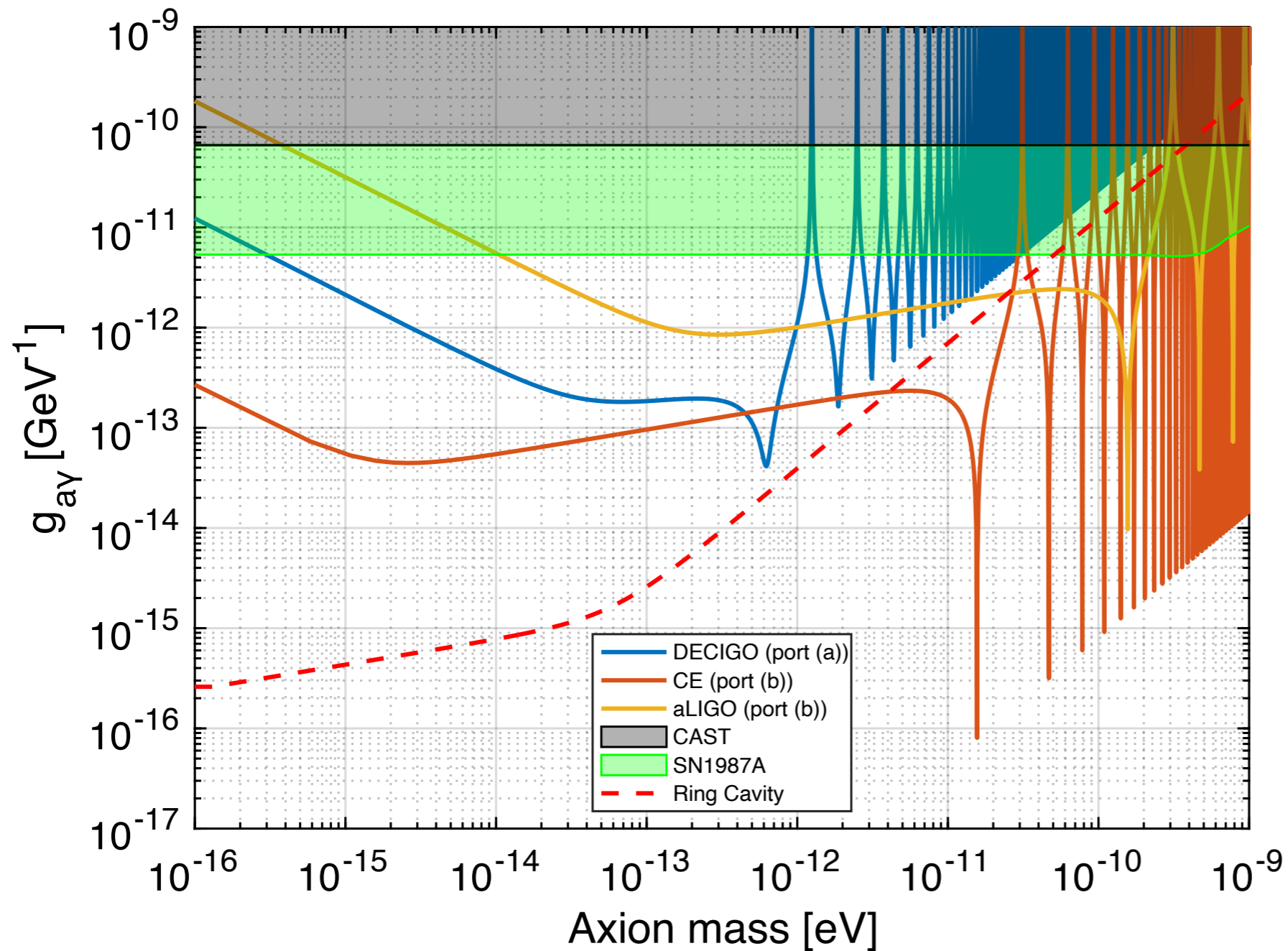


Geometric optics limit



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

AXION BIREFRINGENCE



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

Axion Dark Matter Search with Interferometric Gravitational Wave Detectors

Koji Nagano¹, Tomohiro Fujita,^{2,3} Yuta Michimura,⁴ and Ippei Obata¹

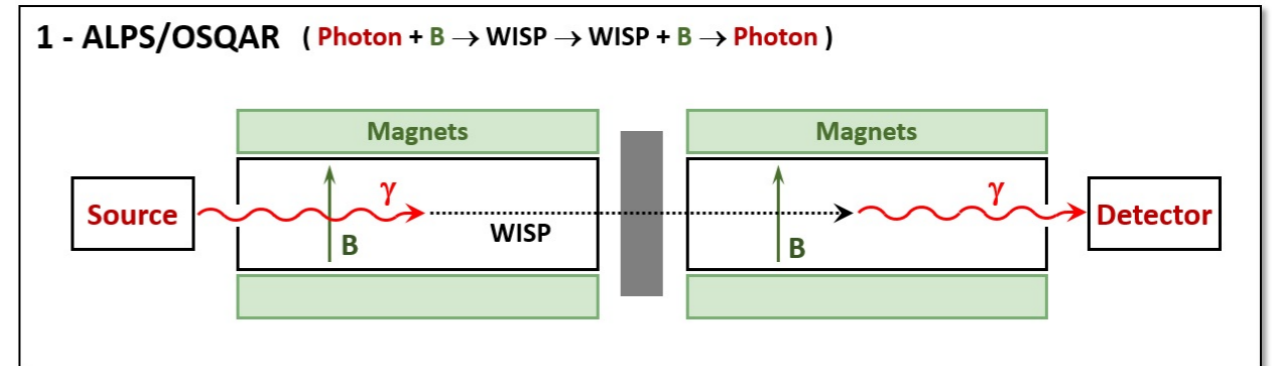
See also e.g.

Cameron et al., Phys. Rev. D 47 (1993) 3707;
 Tam & Yang, Phys. Lett. B 716 (2012) 435;
 Della Valle et al., Eur. Phys. J. C 76 (2016) 24;
 Liu et al., Phys. Rev. D 100 (2019) 023548;
 Martynov & Miao, Phys. Rev. D 101 (2020) 095034;
 Obata et al., Phys. Rev. Lett. 121 (2018) 161301;
 DeRocco & Hook, Phys. Rev. D 98 (2018) 035021;
 Nagano et al., Phys. Rev. Lett. 123 (2019) 111301;
 Nagano et al., Phys. Rev. D 104 (2021) 062008.

THE ALPS EXPERIMENT



ALPs II experiment at DESY

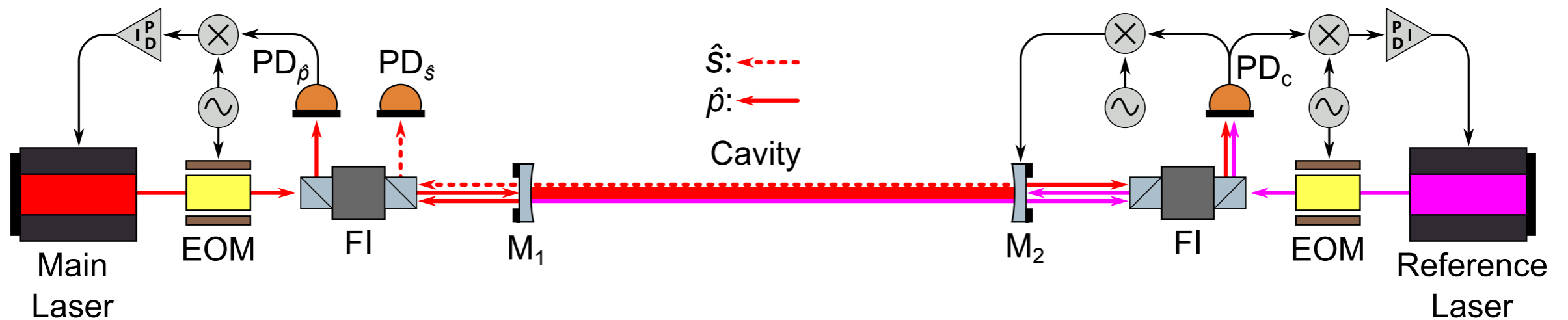


THE ALPS EXPERIMENT



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

ALPs II experiment at DESY

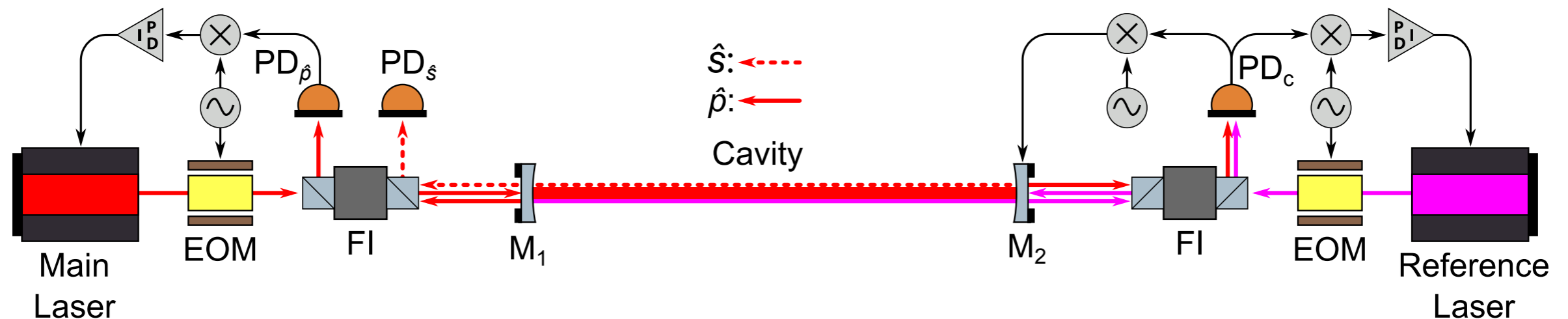


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- Polarimetry enables use of these cavities without requiring a magnetic field.
- Similar optical infrastructure is now being considered for a Standard-Model measurement of vacuum magnetic birefringence; see by Spector et al., arXiv:2510.14064

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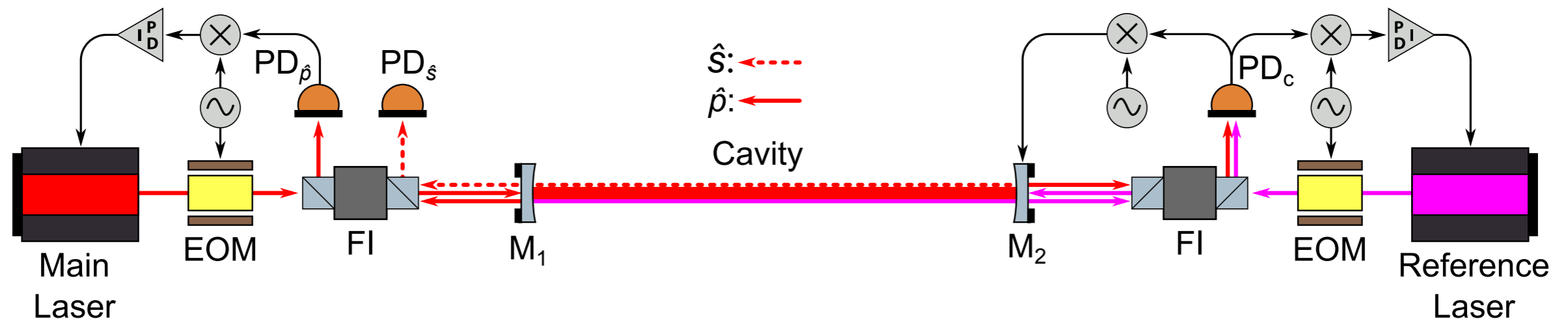


THE ALPS EXPERIMENT



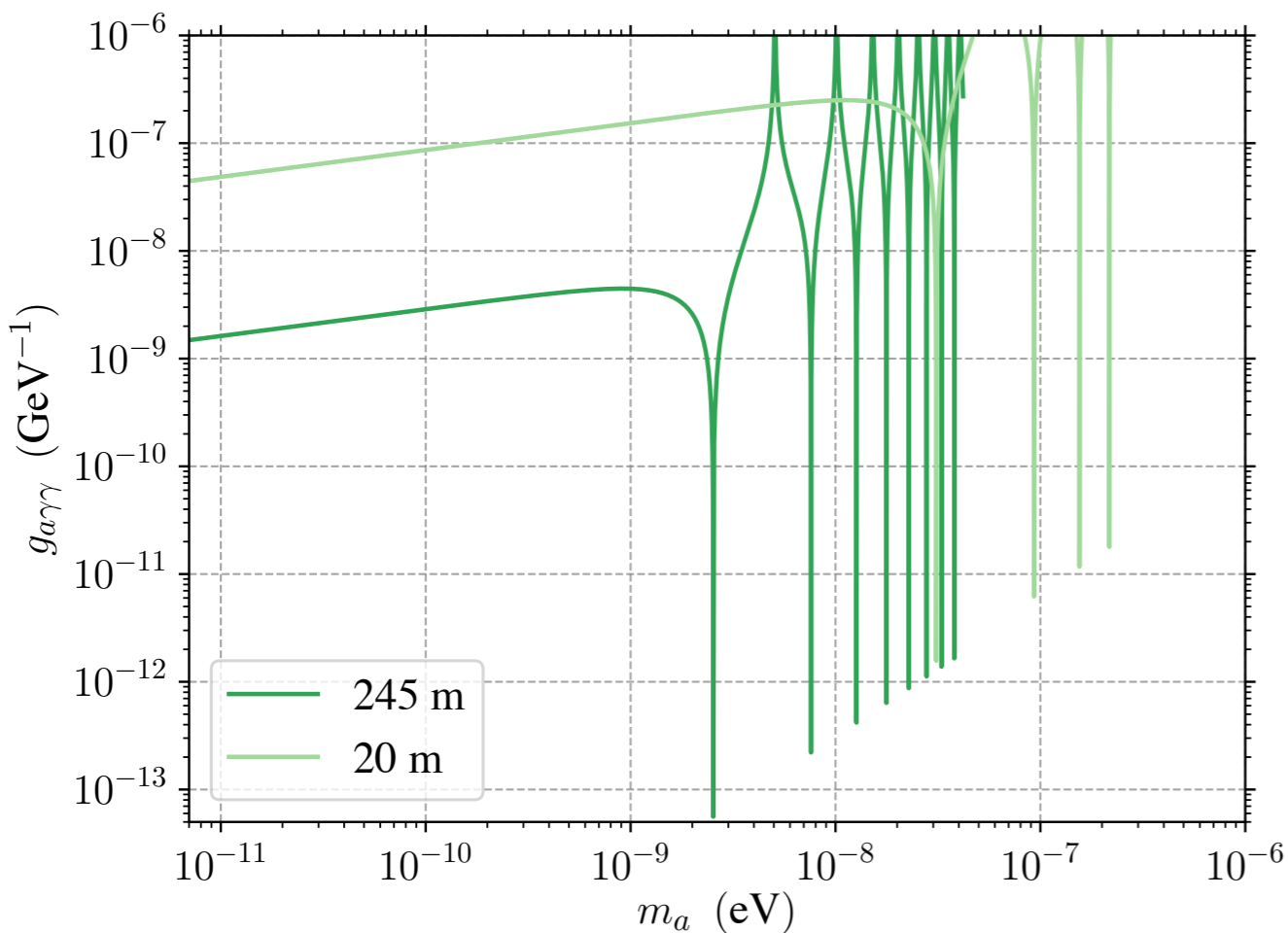
ALPs II experiment at DESY

- Polarimetry enables use of these cavities without requiring a magnetic field.
- Similar optical infrastructure is now being considered for a Standard-Model measurement of vacuum magnetic birefringence; see by Spector et al., arXiv:2510.14064
- At the MHz range, limited by the shot noise. The higher the frequency of the laser the higher the noise. The higher the power, the lower the noise.



AXION DARK MATTER SENSITIVITY

QWP	l [m]	P_{\max} [kW]	(t_1^2, t_2^2, ℓ^2) (ppm)	\mathcal{F}
No	245	150	(22, 2, 20)	1.4×10^5
Yes	245	10	(1100, 100, 1000)	2.9×10^3
No	20	50	(11, 1, 10)	2.9×10^5
Yes	20	10	(1100, 100, 1000)	2.9×10^3



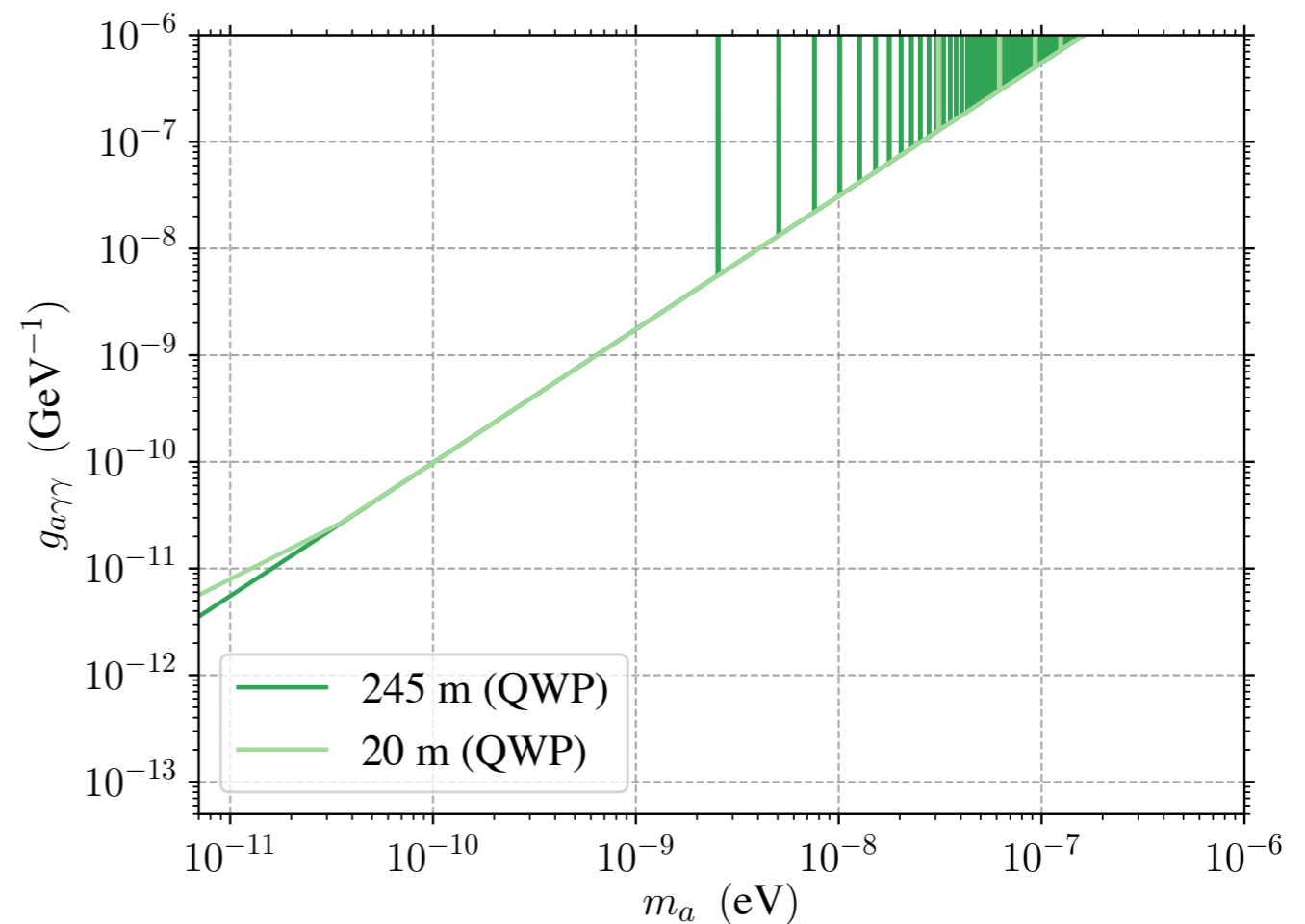
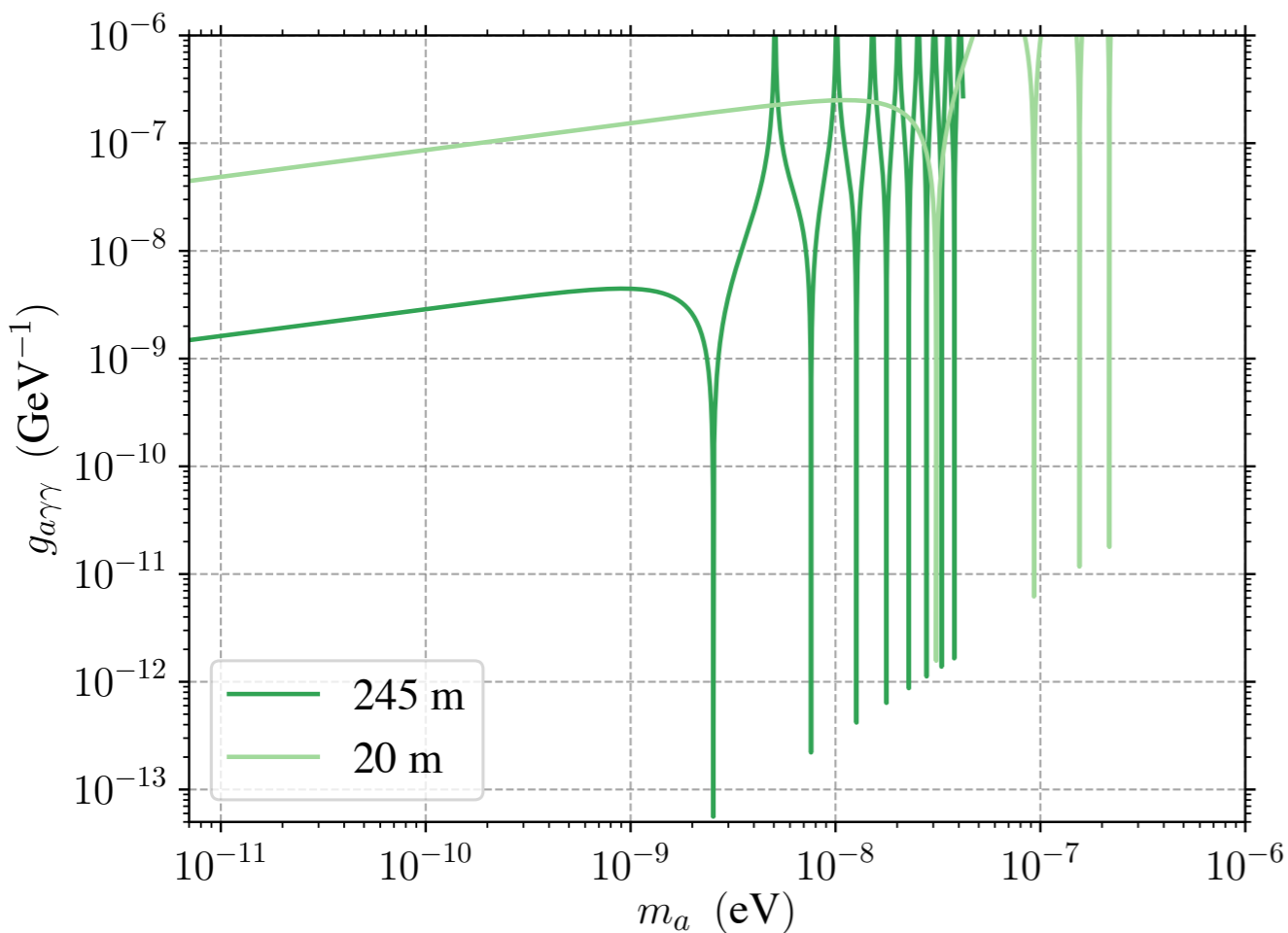
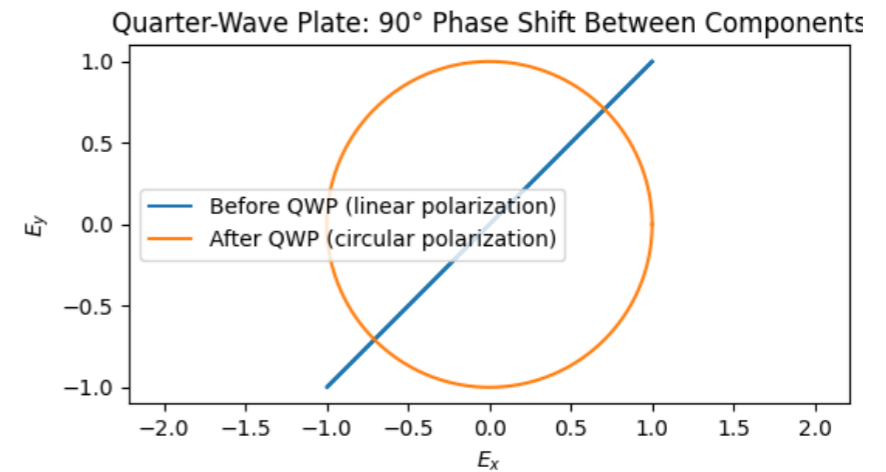
2025, CGC, Marsili, Ringwald, Spector

Camilo García-Cely



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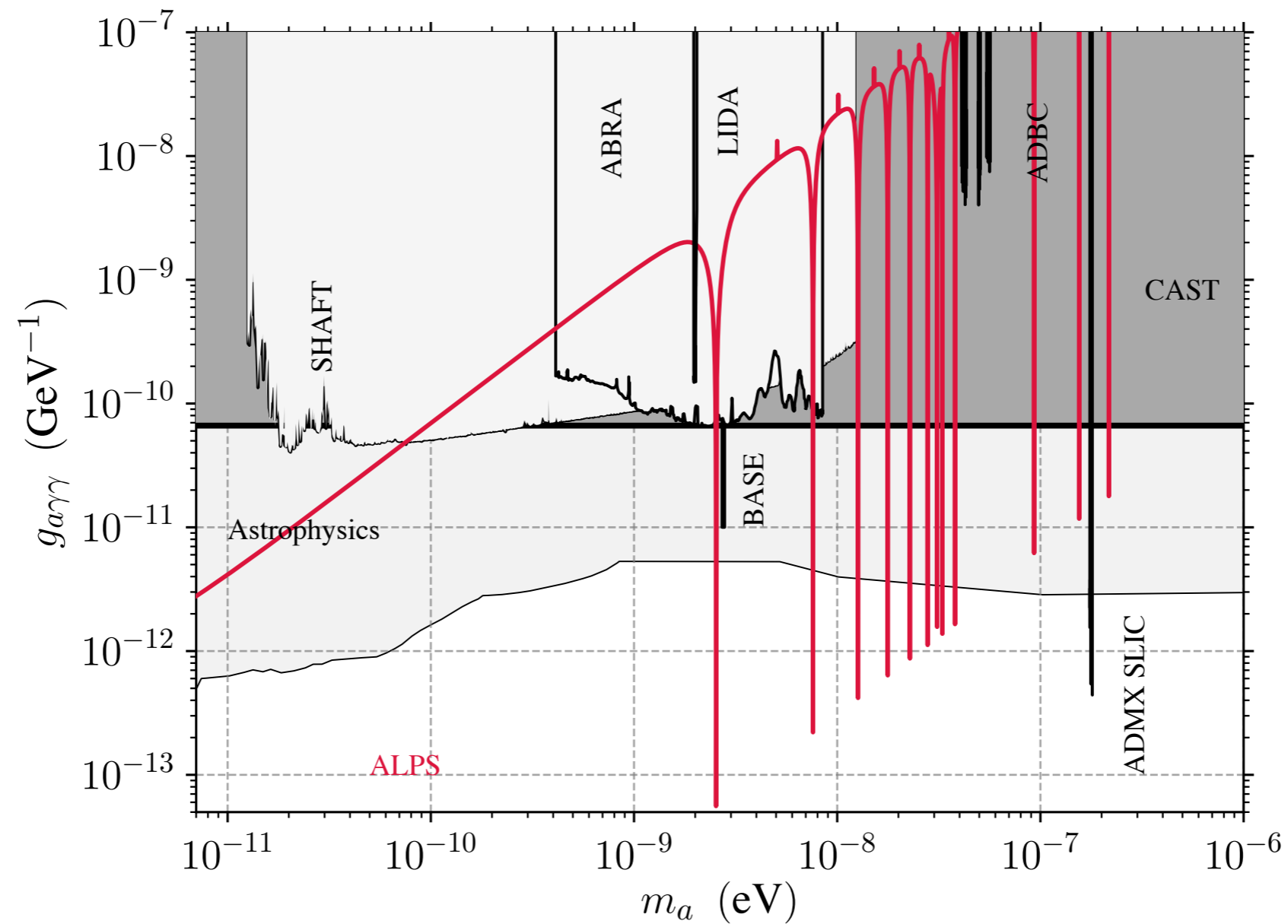
2025, CGC, Marsili, Ringwald, Spector

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AXION DARK MATTER SENSITIVITY

2025, CGC, Marsili, Ringwald, Spector



HIGH-FREQUENCY GRAVITATIONAL WAVES

High-frequency gravitational waves

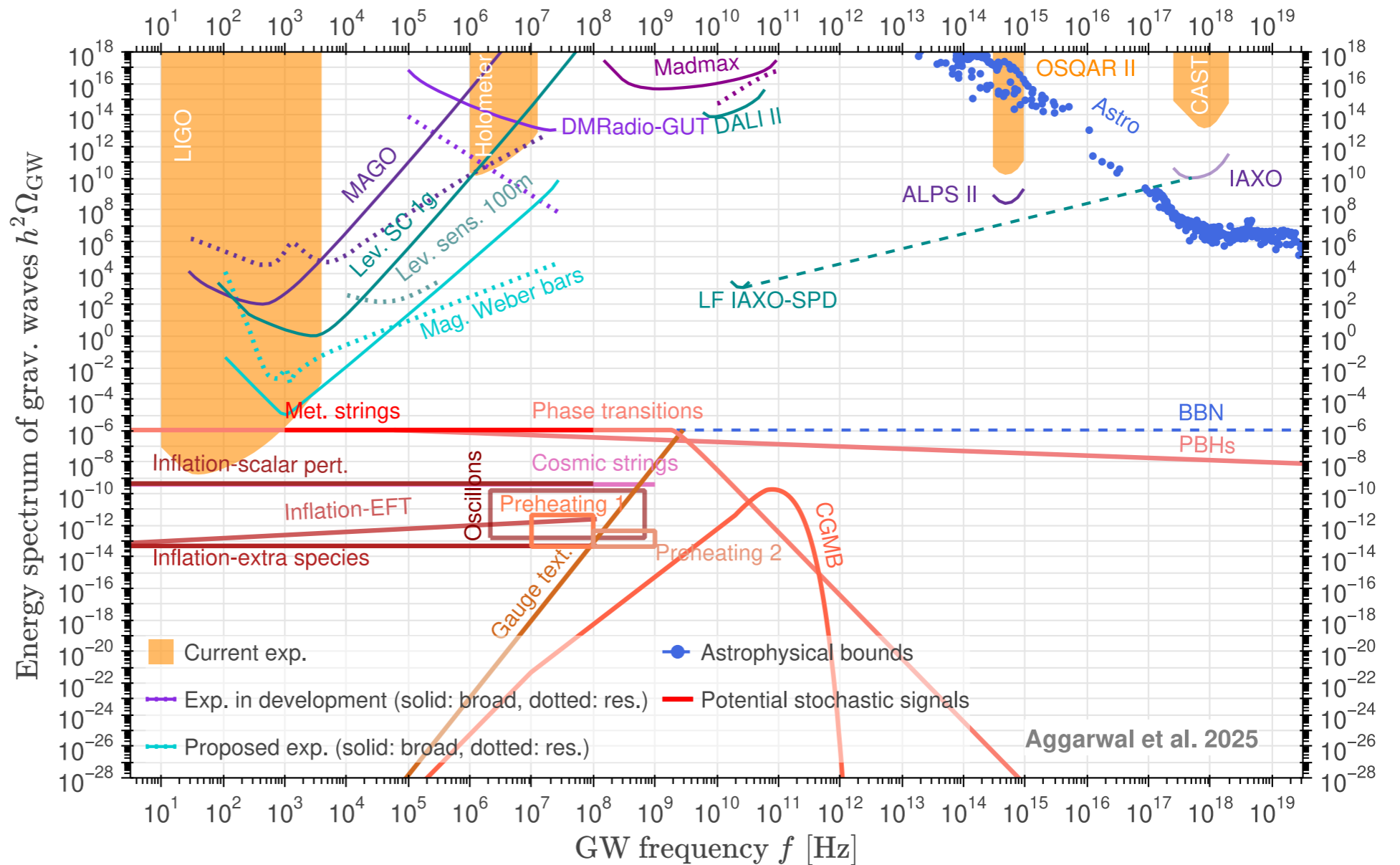
A growing community is seriously considering the search of high frequency gravitational waves

General Relativity and Quantum Cosmology

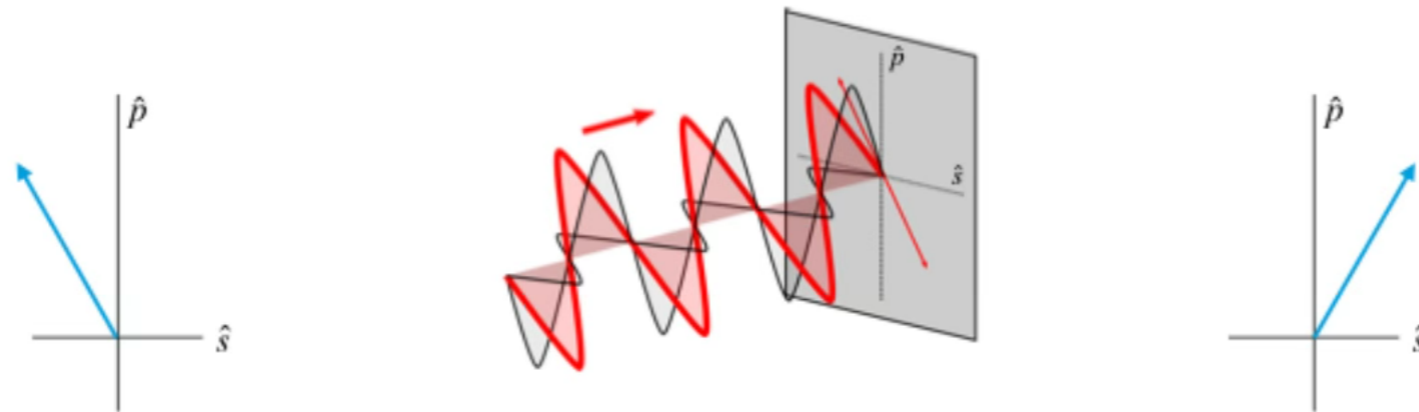
[Submitted on 20 Jan 2025]

Challenges and Opportunities of Gravitational Wave Searches above 10 kHz

Nancy Aggarwal, Odylio D. Aguiar, Diego Blas, Andreas Bauswein, Giancarlo Cella, Sebastian Clesse, Adrian Michael Cruise, Valerie Domcke, Sebastian Ellis, Daniel G. Figueroa, Gabriele Franciolini, Camilo Garcia-Cely, Andrew Geraci, Maxim Goryachev, Hartmut Grote, Mark Hindmarsh, Asuka Ito, Joachim Kopp, Sung Mook Lee, Killian Martineau, Jamie McDonald, Francesco Muia, Nikhil Mukund, David Ottaway, Marco Peloso, Krisztian Peters, Fernando Quevedo, Angelo Ricciardone, Andreas Ringwald, Jessica Steinlechner, Sebastian Steinlechner, Sichun Sun, Carlos Tamarit, Michael E. Tobar, Francisco Torrenti, Caner Ünal, Graham White



AXION BIREFRINGENCE

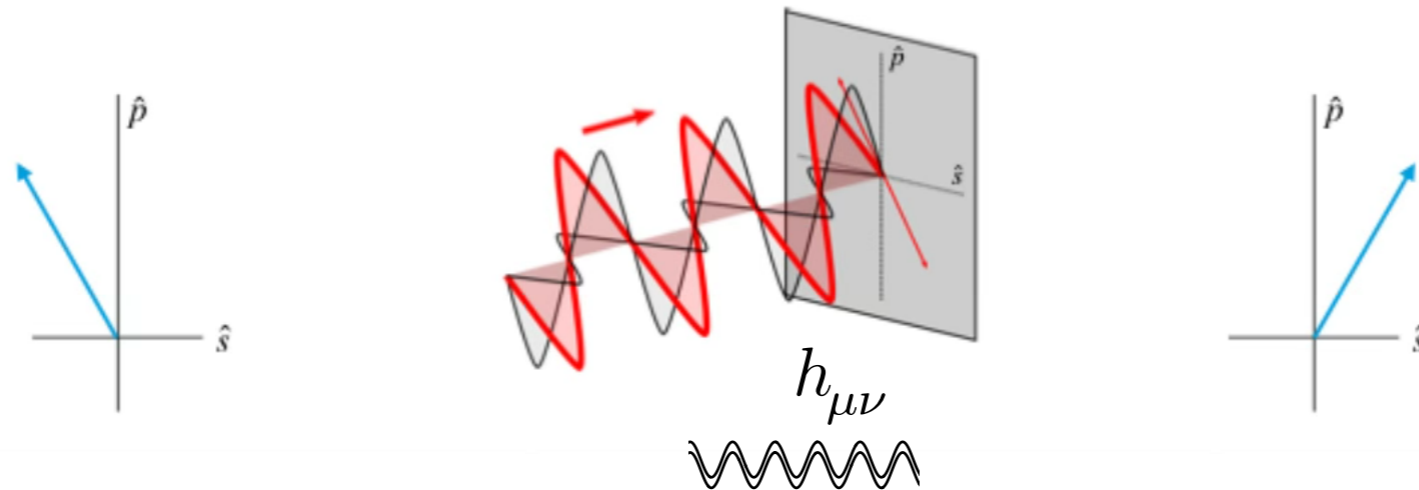


Geometric optics limit



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

BIREFRINGENCE DUE TO A GRAVITATIONAL WAVE



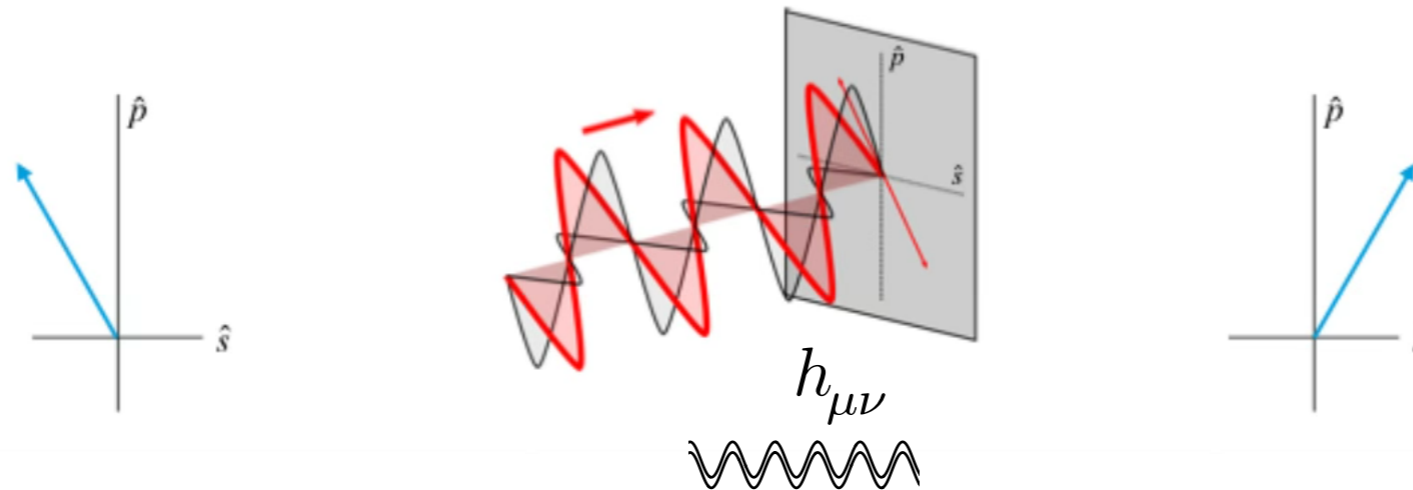
Geometric optics limit



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

See e.g. Weinberg 2008

BIREFRINGENCE DUE TO A GRAVITATIONAL WAVE

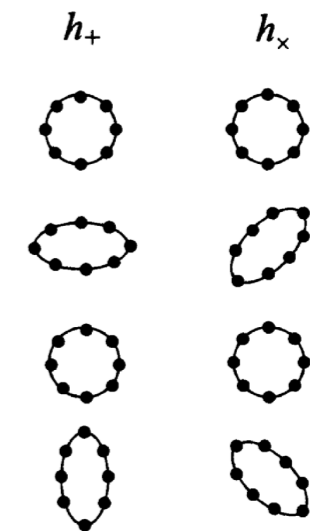


The effect depends on the polarization and the direction

Geometric optics limit

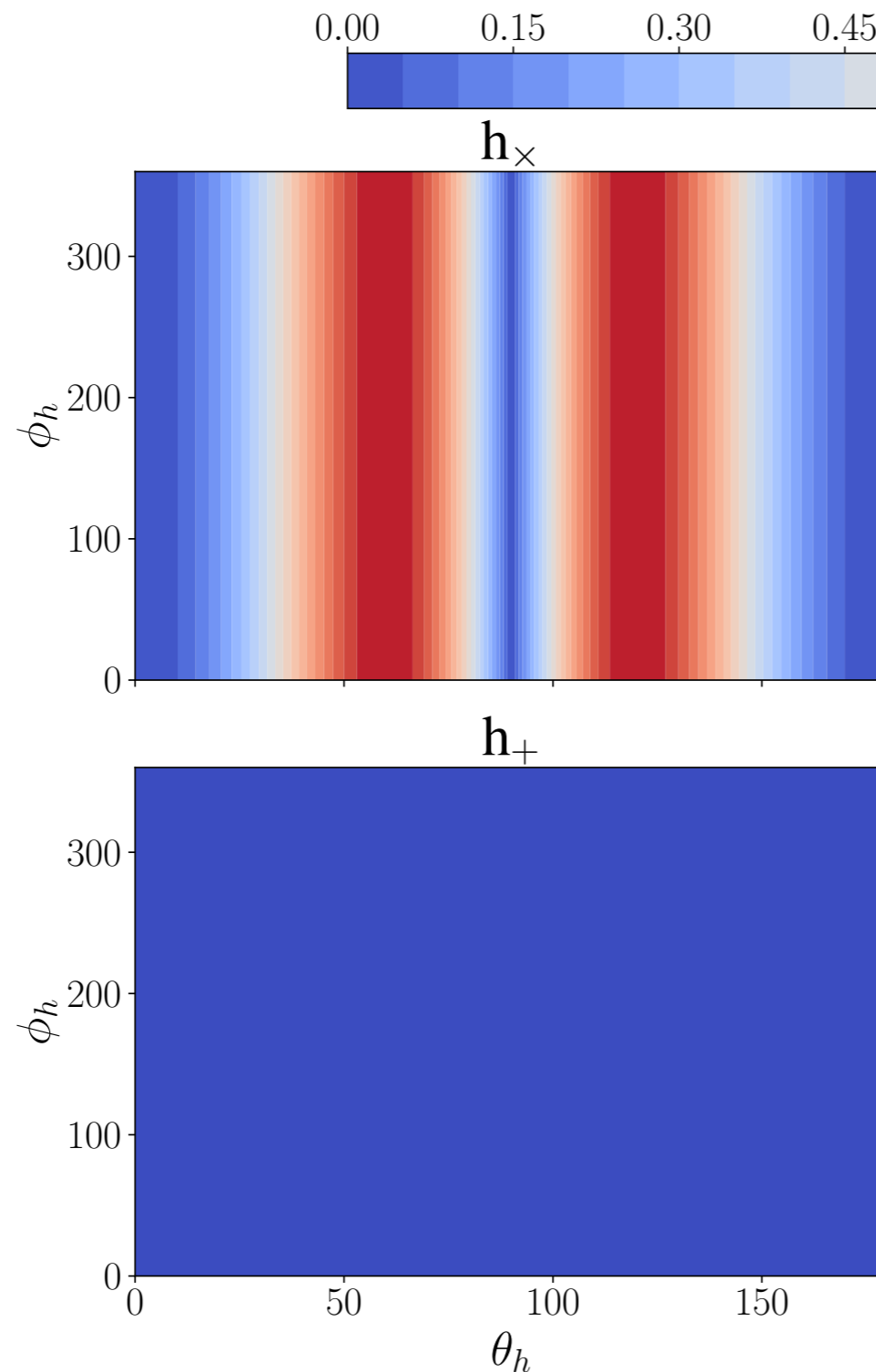


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See e.g. Weinberg 2008

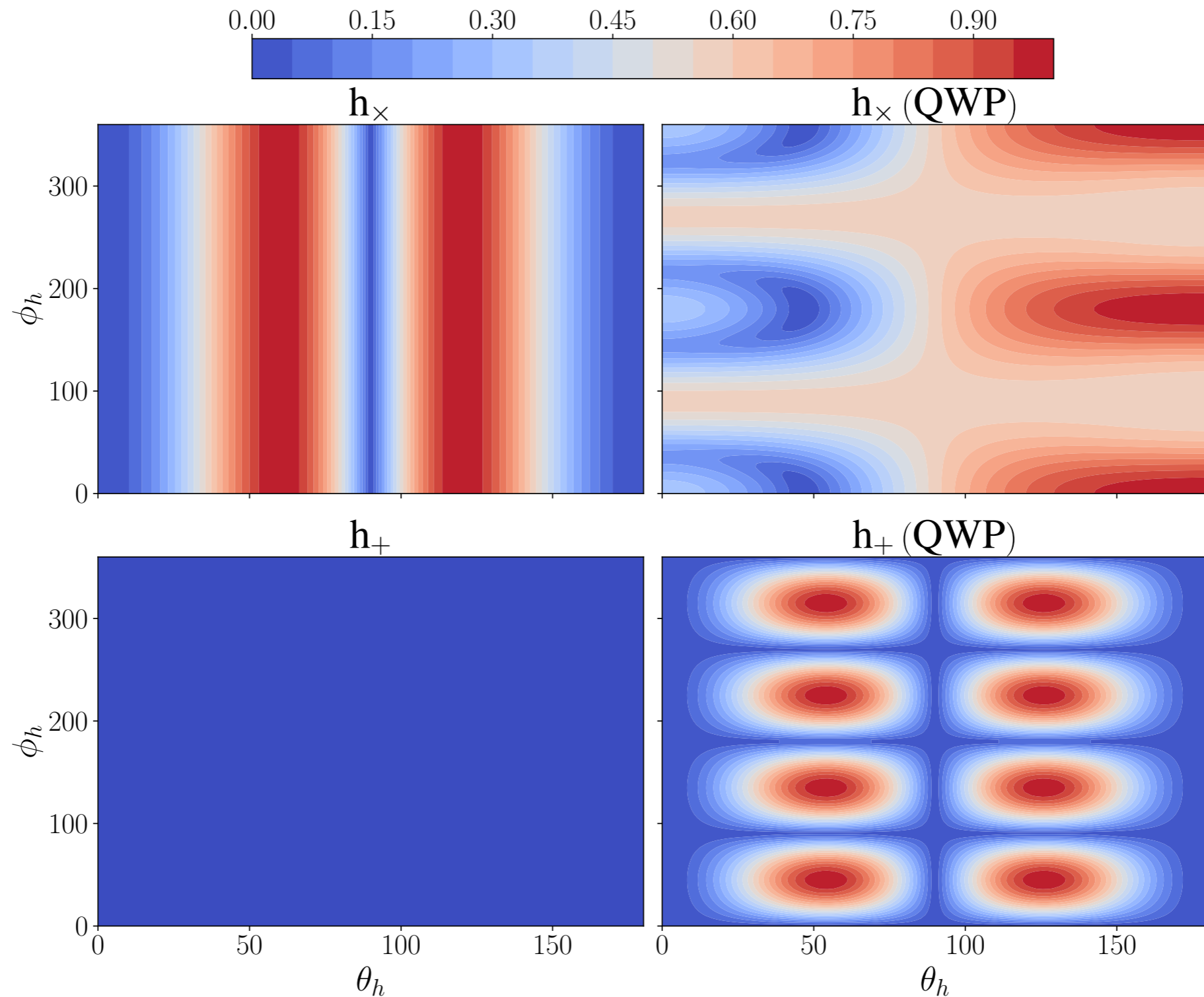
PROJECTED SENSITIVITY FOR GRAVITATIONAL WAVES



- For GWs coming from the zenith, the cross polarization has the same cavity response function as axions
- The plus polarization decouples (selection rules)

2023, Domcke, CGC, Lee, Rodd

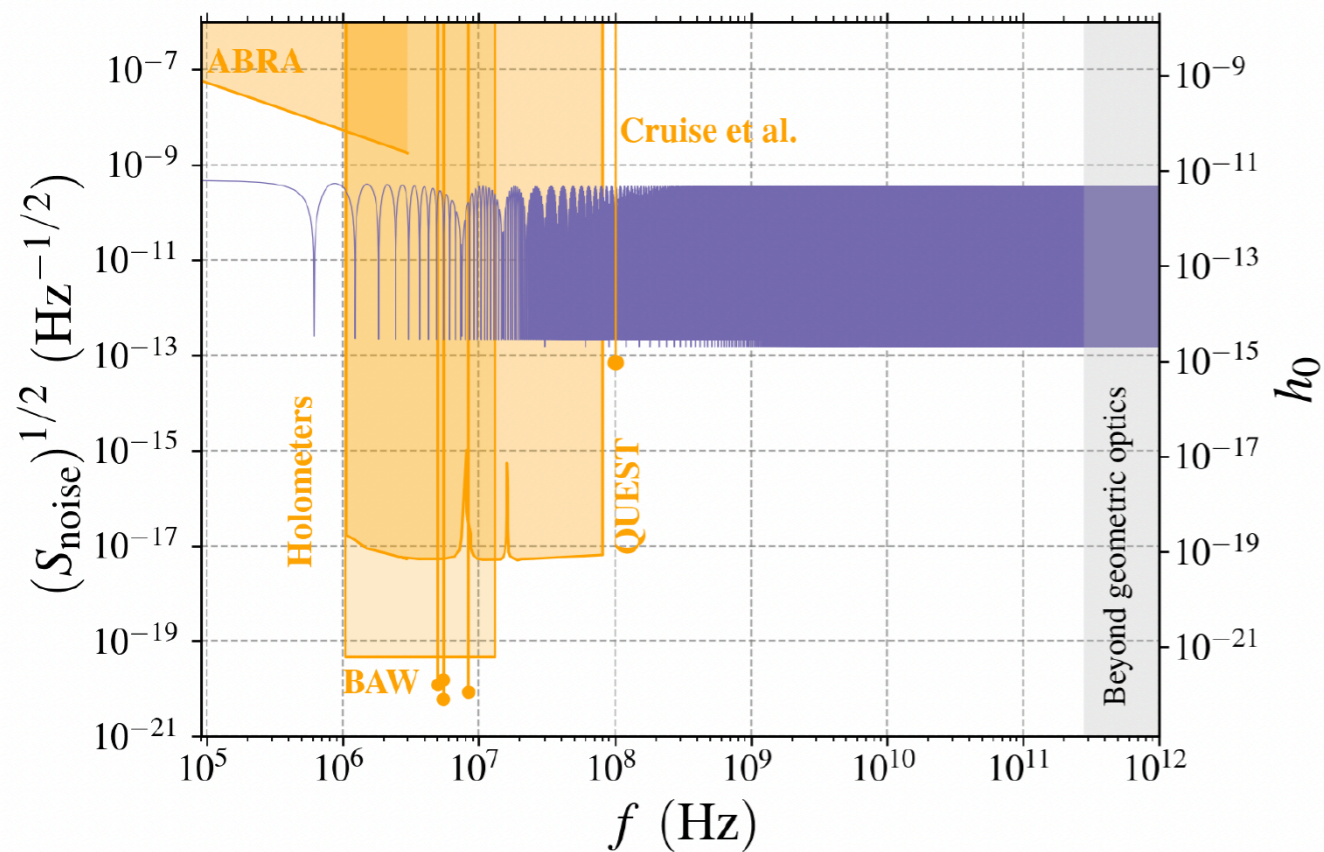
PROJECTED SENSITIVITY FOR GRAVITATIONAL WAVES



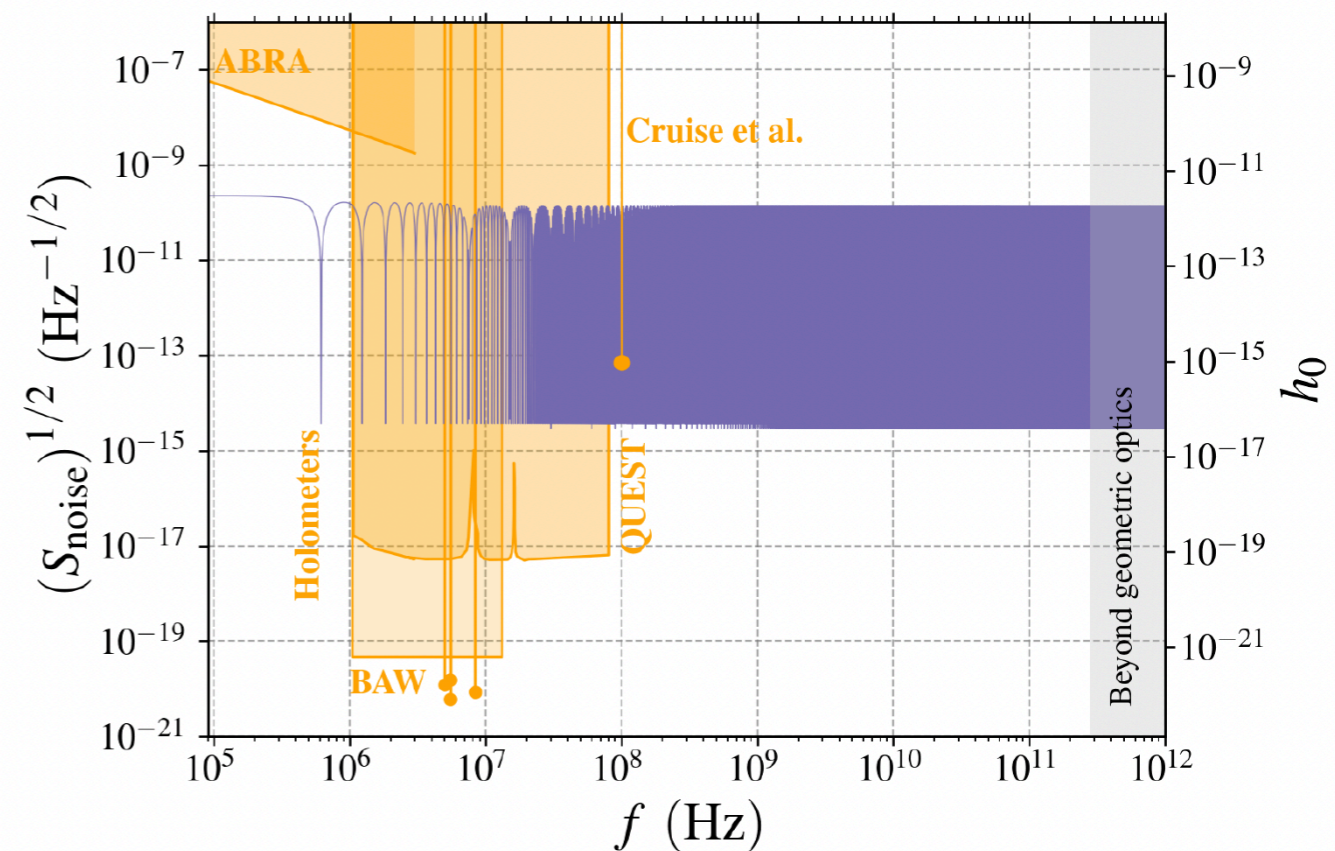
PROJECTED SENSITIVITY FOR GRAVITATIONAL WAVES

2025, CGC, Marsili, Ringwald, Spector

h_+



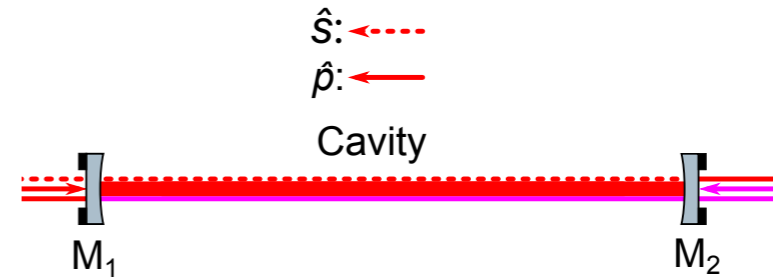
h_x



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.
- 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.

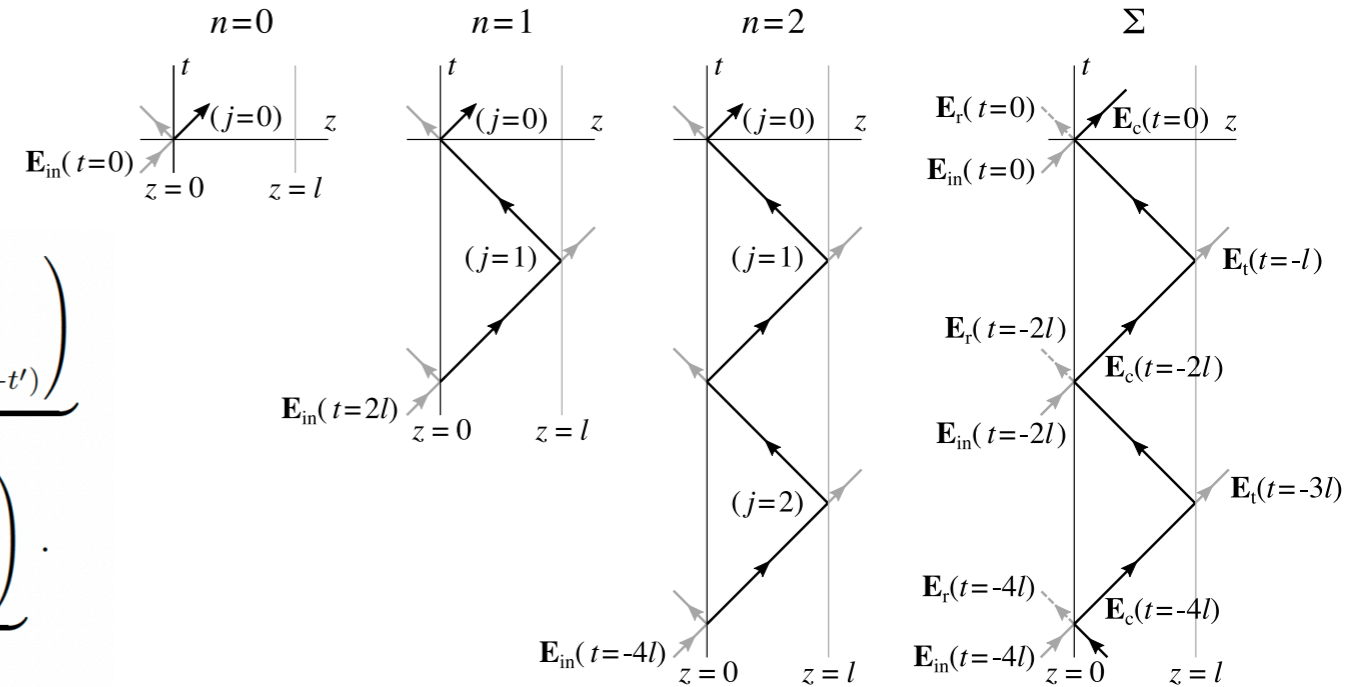
OPTICAL CAVITY



2025, CGC, Marsili, Ringwald, Spector

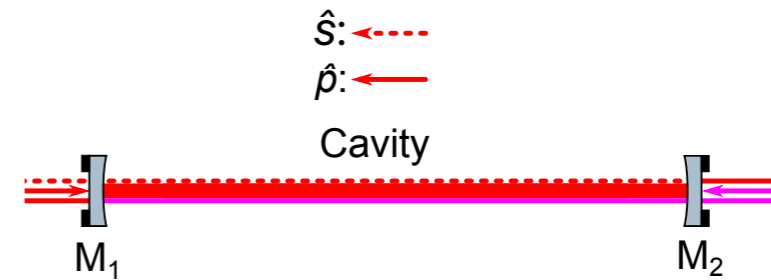
$$\mathbf{E}_1(0) = \left(\sum_{n=0}^{\infty} e^{i\phi_n} \prod_{j=0}^n L_j \right) t_1 \mathbf{E}_{\text{in}}(0),$$

$$L_j = \underbrace{r_1 \mathcal{P}}_{\text{Reflection off mirror 1}} \times \underbrace{\left((\dots) \mathbb{1} + \int_0^l dt' \mathcal{M}(t' - (2j+1)l) \Big|_{\mathbf{x}(t')=\hat{\mathbf{z}}(l-t')} \right)}_{\text{Path from mirror 2 to mirror 1}} \\ \times \underbrace{r_2 \mathcal{P}}_{\text{Reflection off mirror 2}} \times \underbrace{\left((\dots) \mathbb{1} + \int_0^l dt' \mathcal{M}(t' - (2j+2)l) \Big|_{\mathbf{x}(t')=\hat{\mathbf{z}} t'} \right)}_{\text{Path from mirror 1 to mirror 2}}.$$



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

OPTICAL CAVITY



2025, CGC, Marsili, Ringwald, Spector

define a *response function due to polarization change*

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

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

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

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

The laser is held on the cavity resonance .