Detecting HFGWs with polarimetry at ALPS

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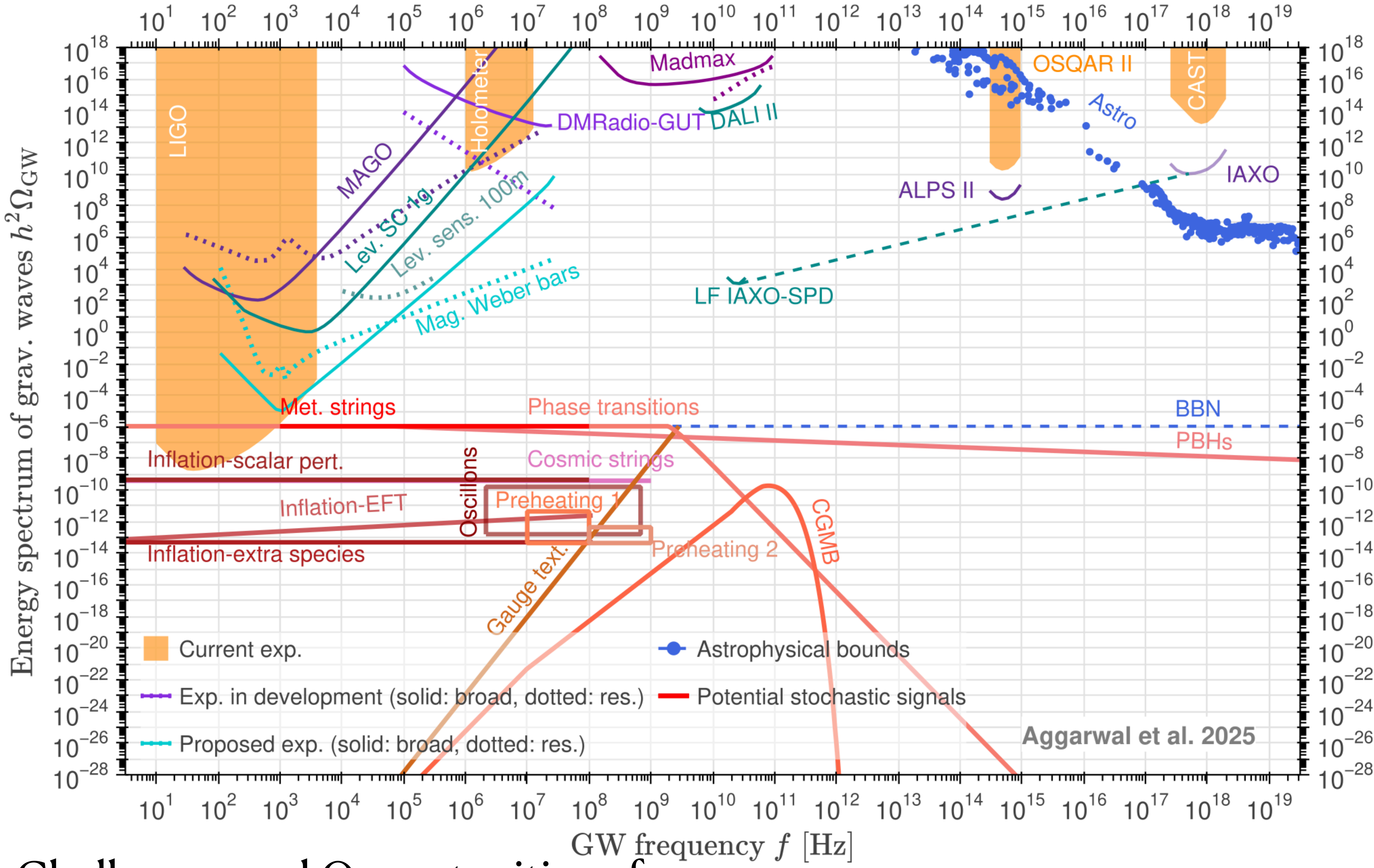
Looking for HFGW

- The region **beyond 10 KHz** is still mostly **unconstrained**

- Any discovery of GW beyond 10 KHz would come from **new physics**

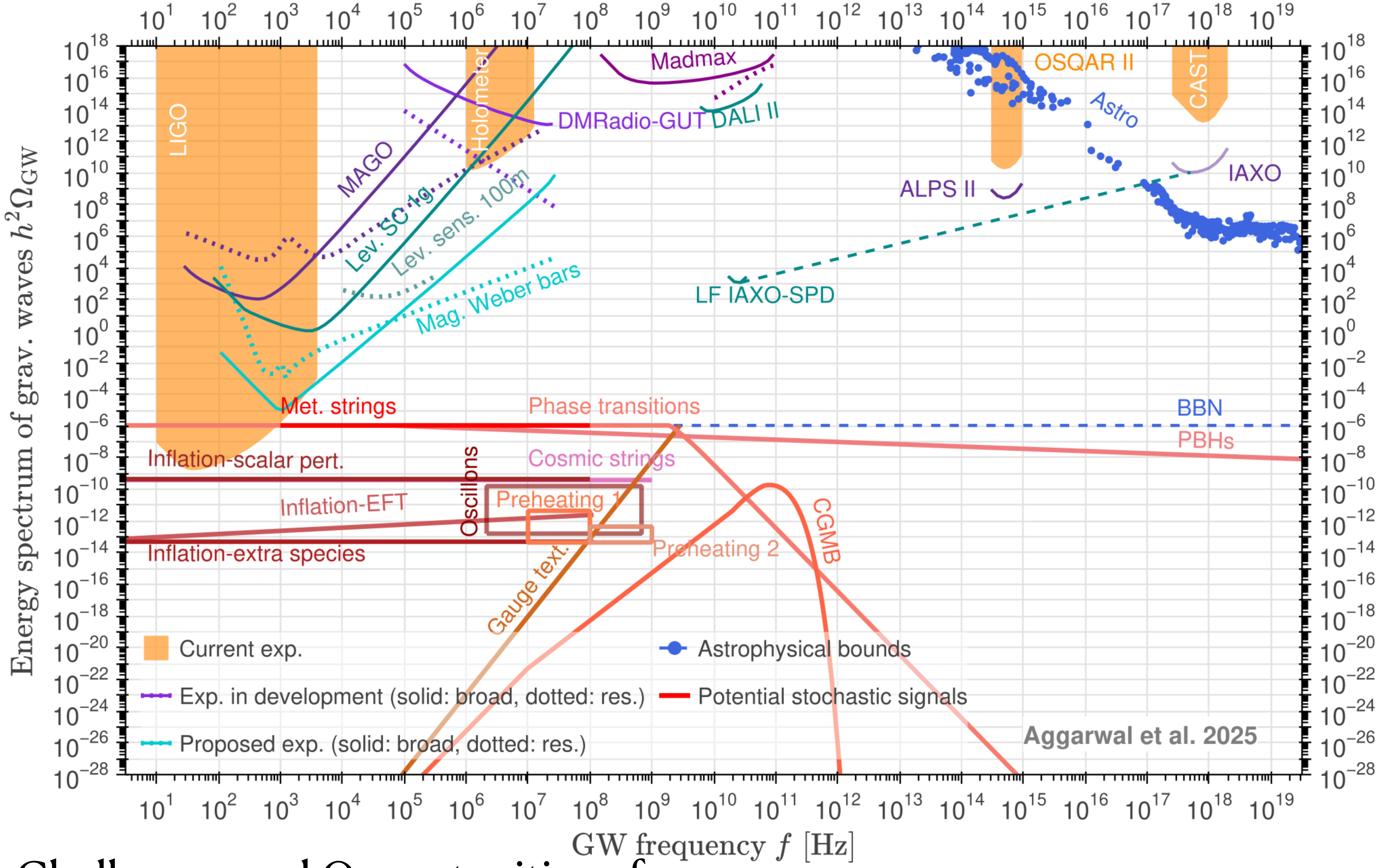


- Living Review, Challenges and Opportunities of Gravitational Wave Searches above 10 kHz 2501.11723

Looking for HFGW

- The **most stringent bound** on cosmological GW is **given by BBN**

- **Some** promising methods exploit the **similarity** between a**xion-photon** and **graviton-photon** coupling in presence of a magnetic field



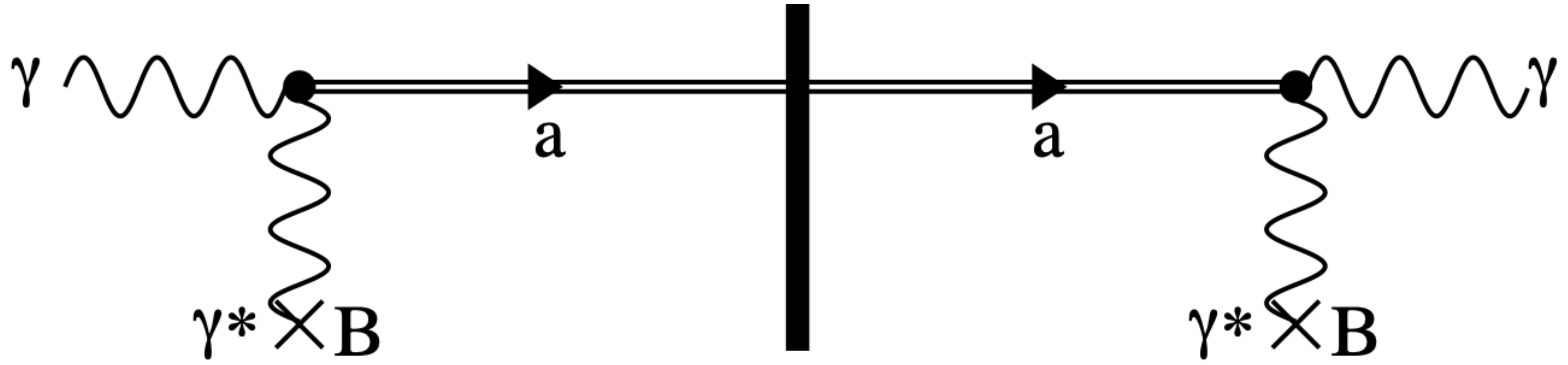
- Living Review, Challenges and Opportunities of Gravitational Wave Searches above 10 kHz 2501.11723

The ALPS experiment (so far)

ALPS

- **Any Light Particle Search** (ALPS) is located at DESY in Hamburg, Germany
- ALPS aims to detect axion-like particles through the **Light Shining through a Wall** (LSW) experiment
- We propose to use the ALPS's **cavities** as a GW detector using **polarimetry**

The ALPS experiment (so far)

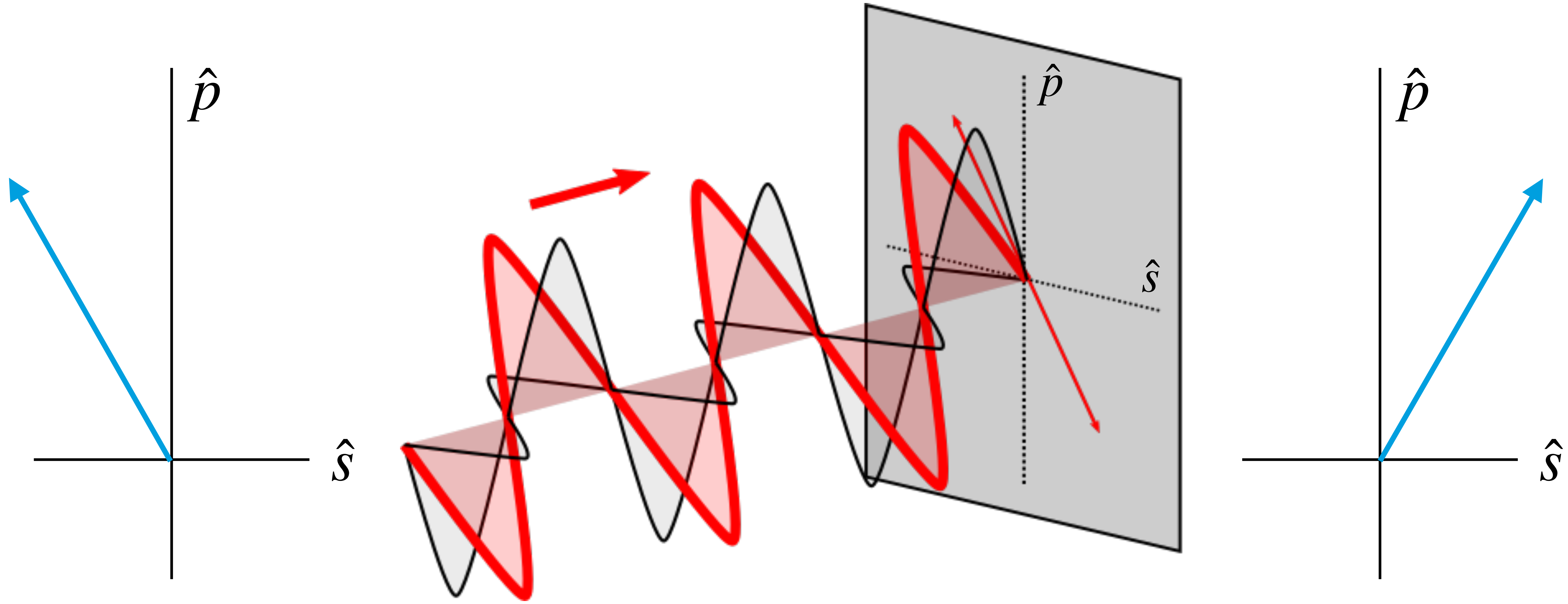


- A laser goes through a magnetic field and some photons can get converted to axions
- Then axions would get converted back to photons which would have "**shined through the wall**"
- This experiment works using **optical cavities**

The ALPS experiment (so far)

Polarimetry allows the use of these cavities without a magnetic field

Induced Polarimetry by GW



Credit: Aaron Spector

- The polarisation vector of a photon **rotates** when propagating through an **axion background** or a **gravitational wave**

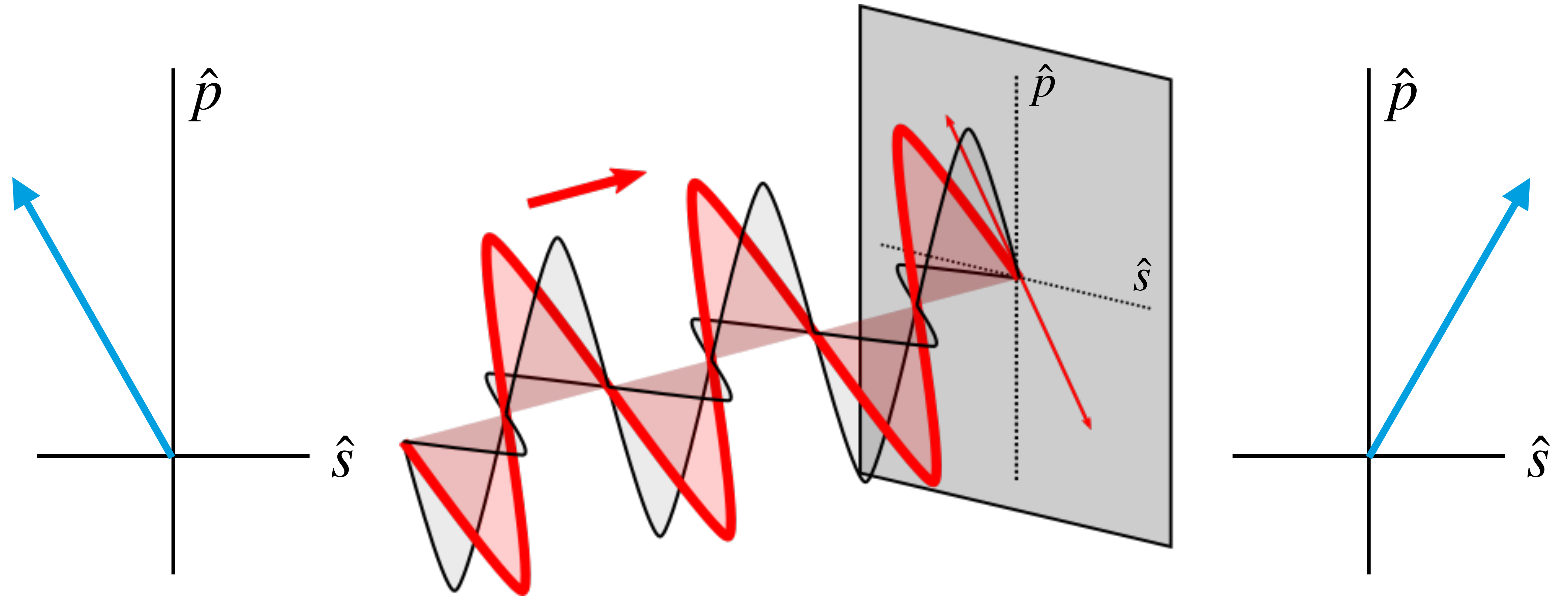
Nagano et al. PhysRevLett.123.111301

- They behave similarly to a **magnetic field (birefringence)**

Induced Polarimetry by GW

- **HFGW** can be detected through **polarimetry**

- It is possible to compute this by directly looking at the **parallel transport** of the **polarisation vector** of the photon in a curved spacetime

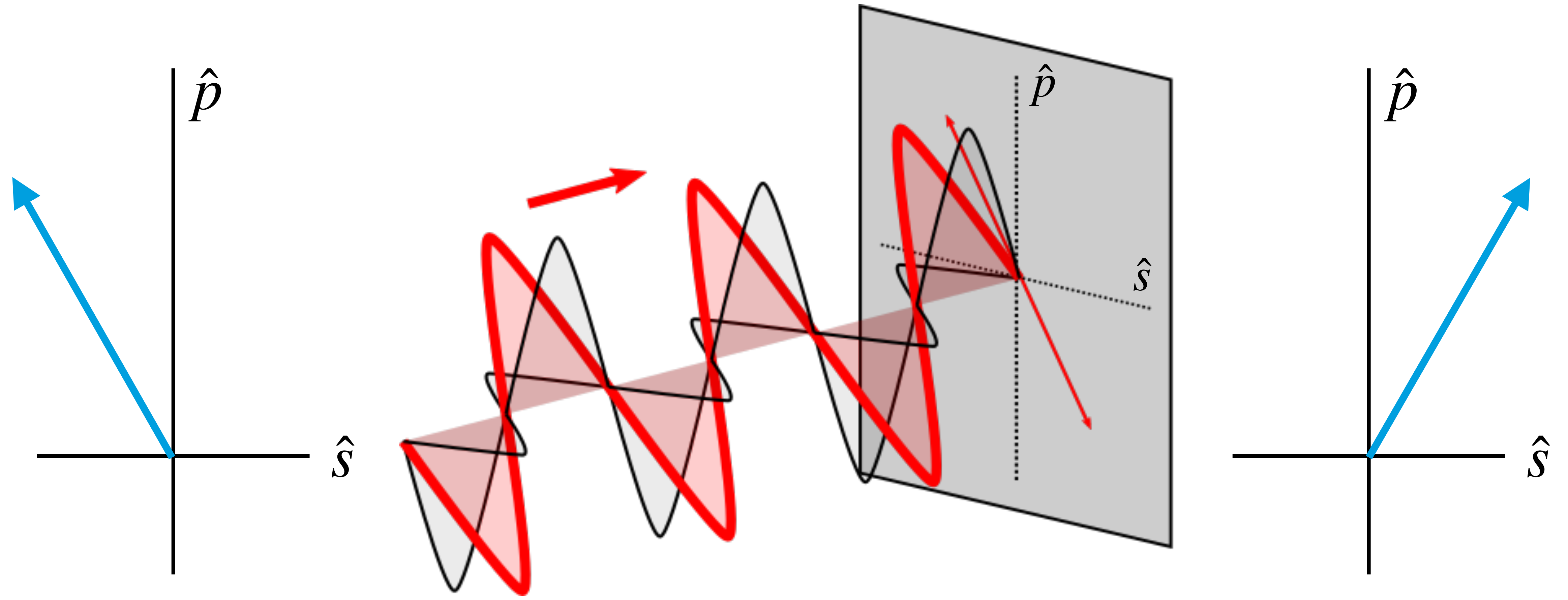


Credit: Aaron Spector

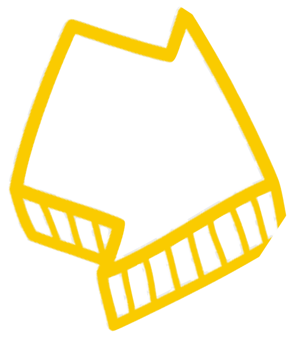
$$\frac{de^i}{dt} = \left(\Gamma^0_{\rho\lambda}\frac{dx^i}{dt} - \Gamma^i_{\rho\lambda}\right)\frac{dx^\rho}{dt}e^\lambda$$

Induced Polarimetry by GW

- Initially **p-polarised** laser (*carrier*)
- The laser acquires additional **s-polarised** modes (*sidebands*)

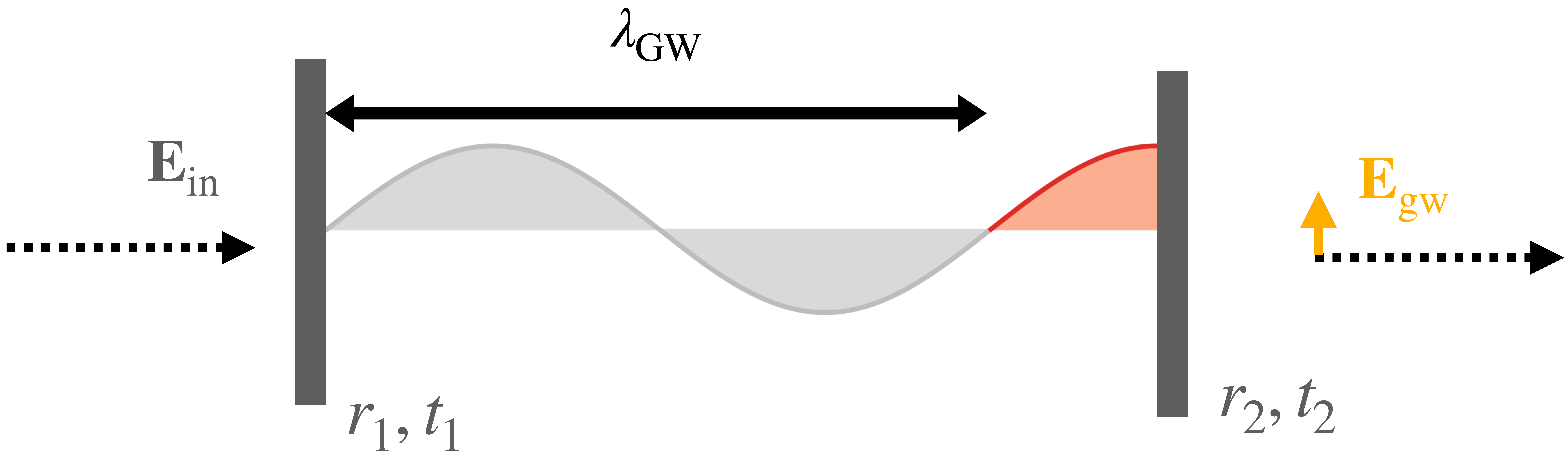


Credit: Aaron



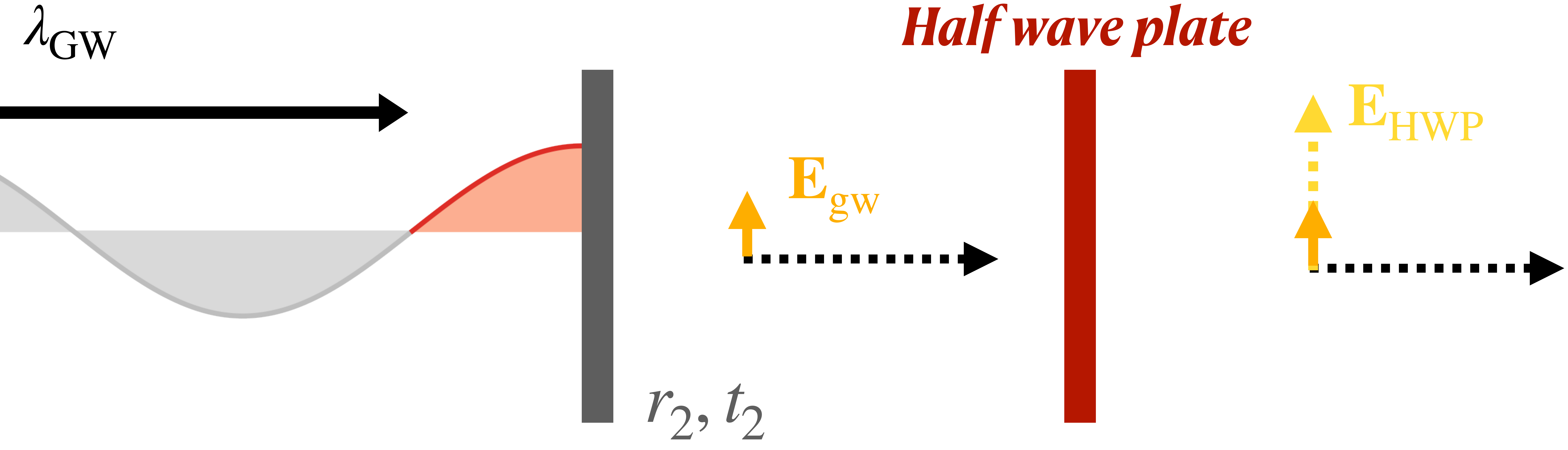
The goal is to **detect** the *sidebands* and **filter them** from the *carrier*

Bounds on GWs



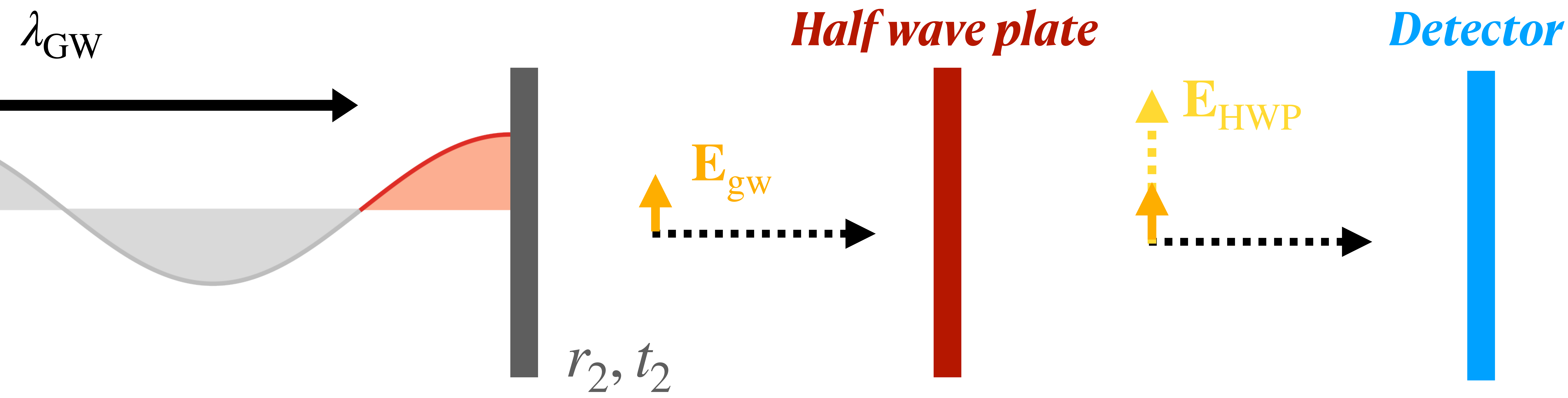
Induced birefringence from GW

Bounds on GWs



Induced birefringence from half-wave plate

Bounds on GWs



The GW signal modulates the half-wave plate birefringence

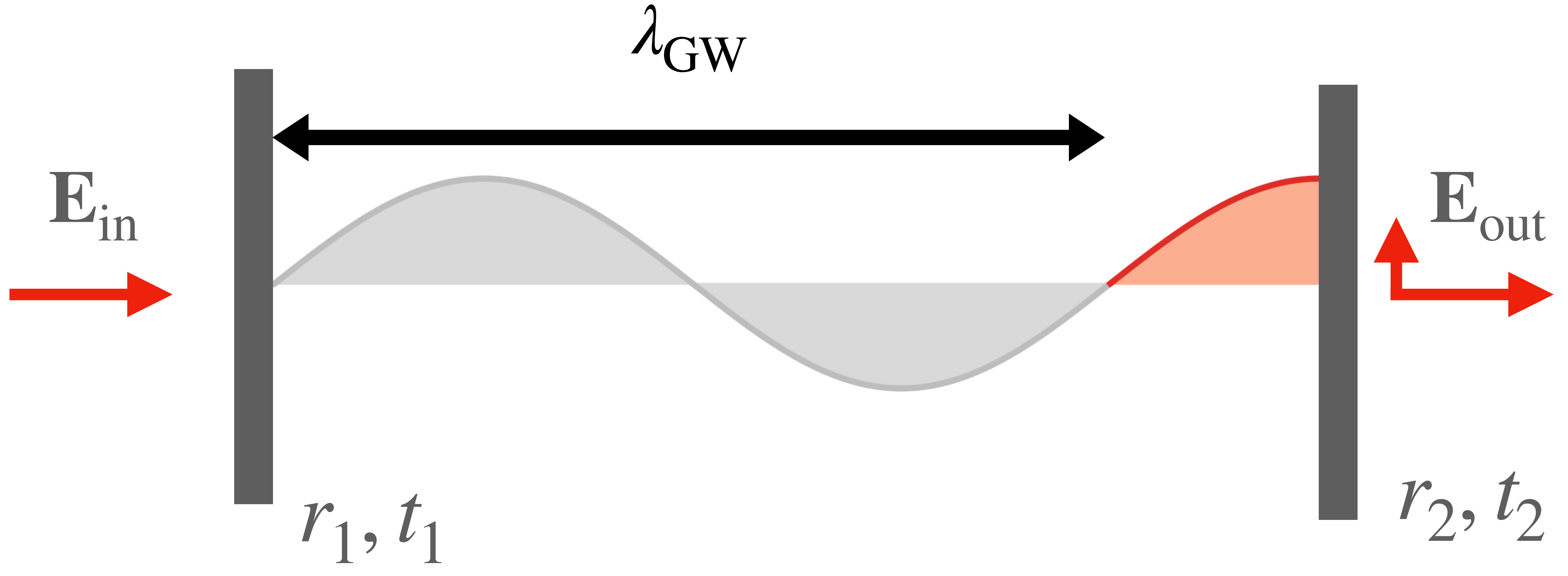
Linear in h_0

Bounds on GWs

- The effect **does not** accumulate
- With every full period the effect cancels

The sensitivity does not improve with the length of the cavity

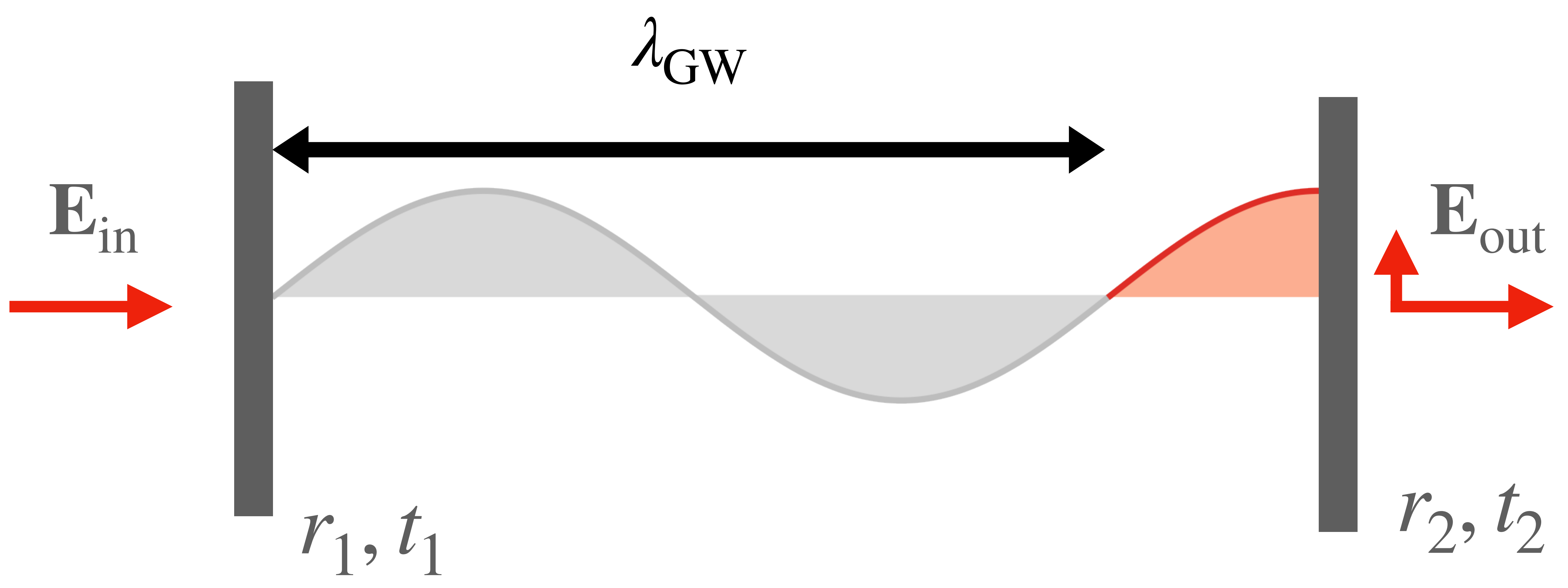
The sensitivity peaks are at $f_{\rm GW} L = n\pi$



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

Bounds on GWs

- To enhance the sensitivity we use **cavities**
- The *carrier* is **always** enhanced (*resonant cavity*)
- The *sidebands* are enhanced only when the GW frequency is a **multiple** of the laser



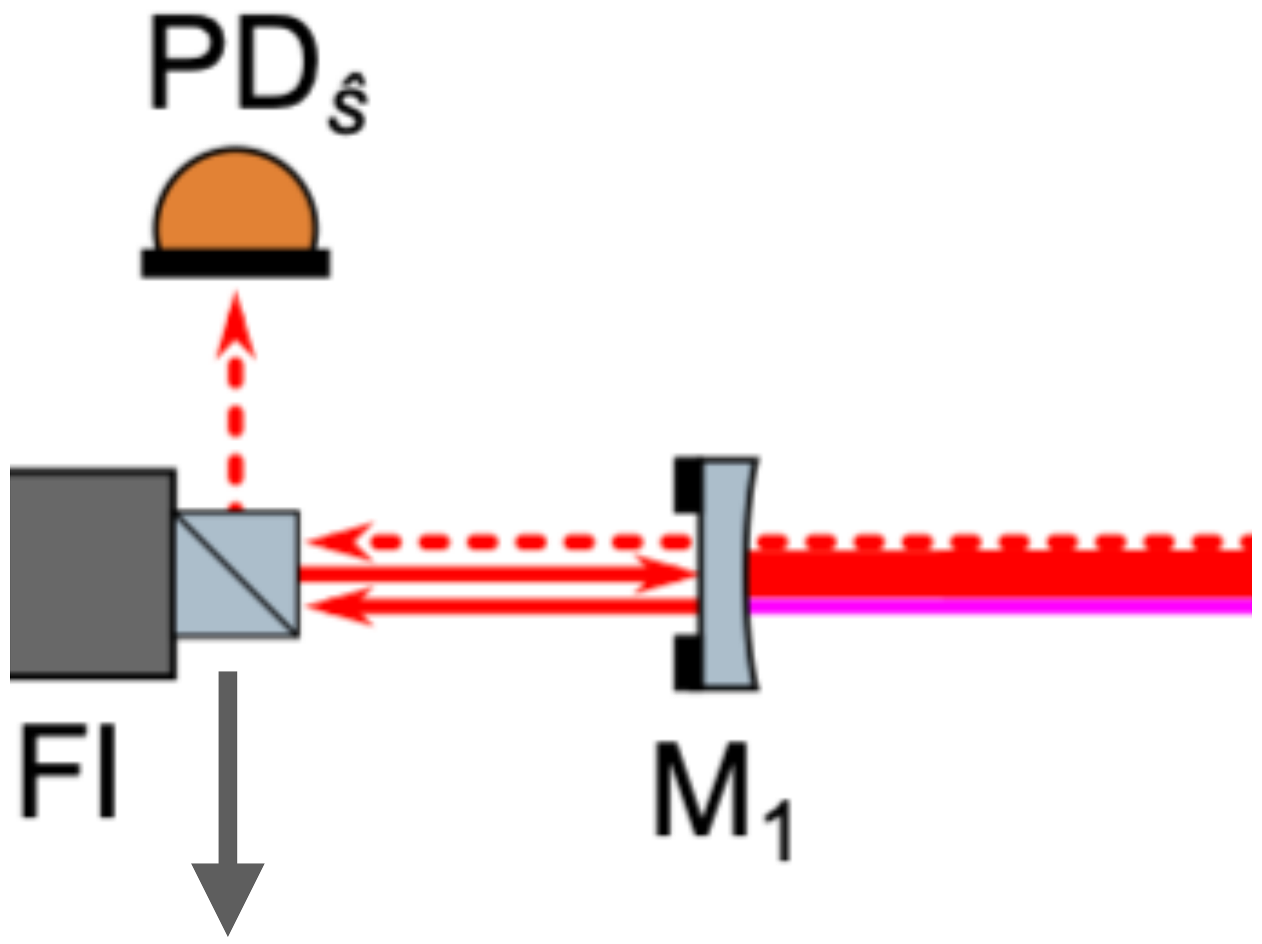
$$\mathscr{H}(f) = \left(\frac{r_1 r_2}{1 - r_1 r_2}\right)\left(\frac{1}{e^{-4ifl} - r_1 r_2}\right) f(\theta, \phi)$$

Polarimetry at ALPS

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

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

The goal is to measure the induced s-polarised **sidebands**

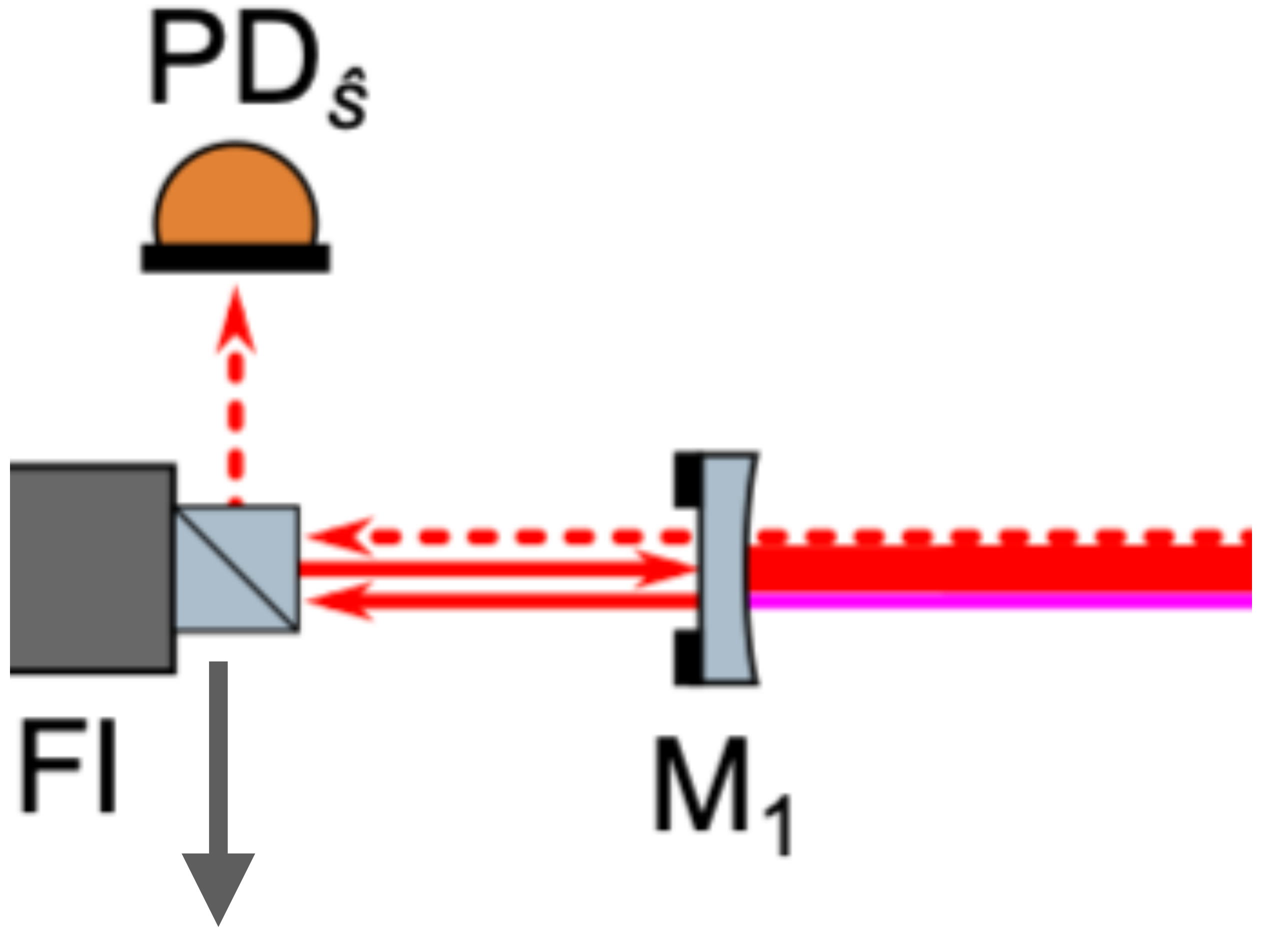


Beam splitter which separates **p** and **s** **polarisations**

Polarimetry at ALPS

- Sensitivity **linear in** h_0 and not squared
- **Limited** by the shot noise of the **carrier wave**

The goal is to measure the induced s-polarised **sidebands**



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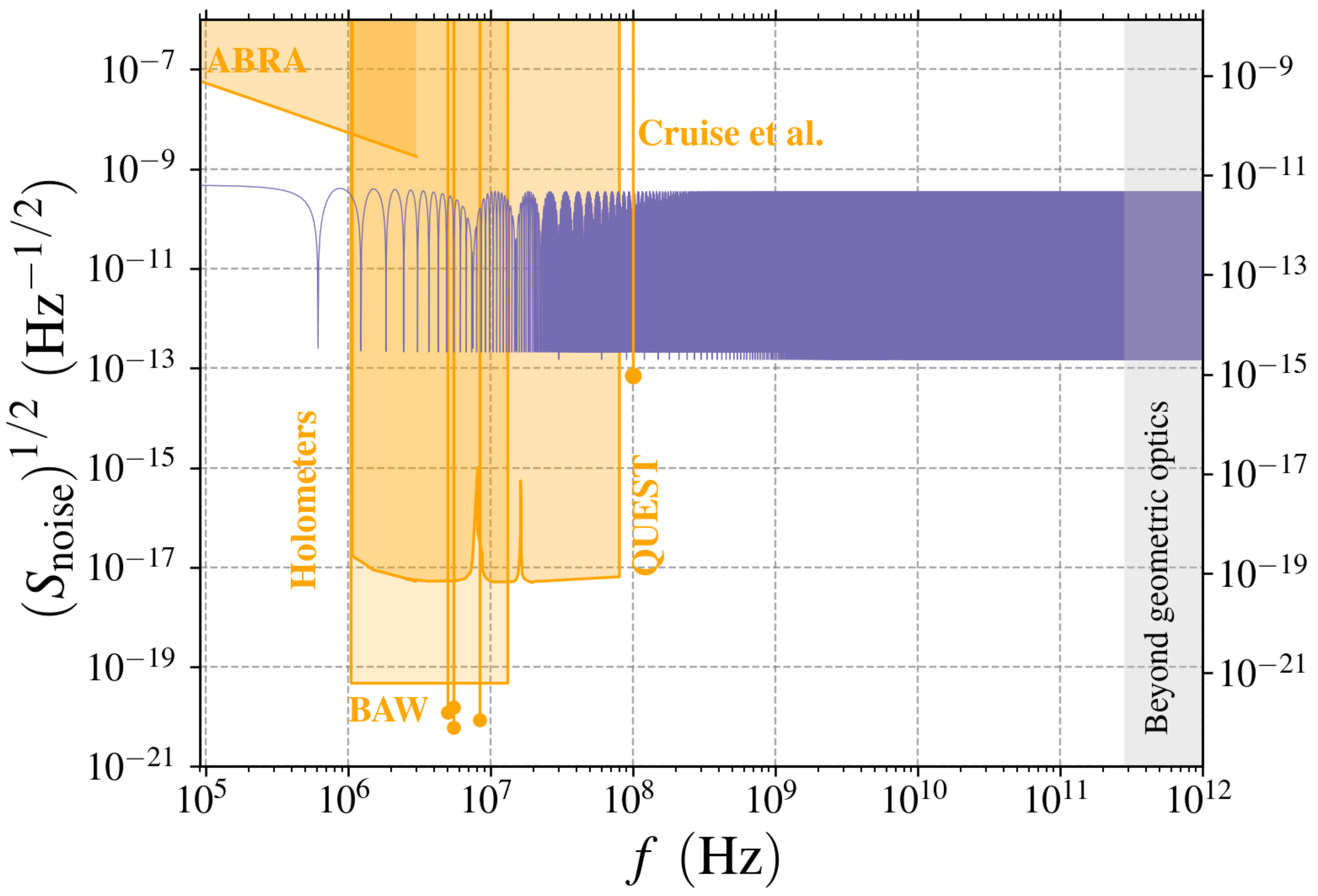
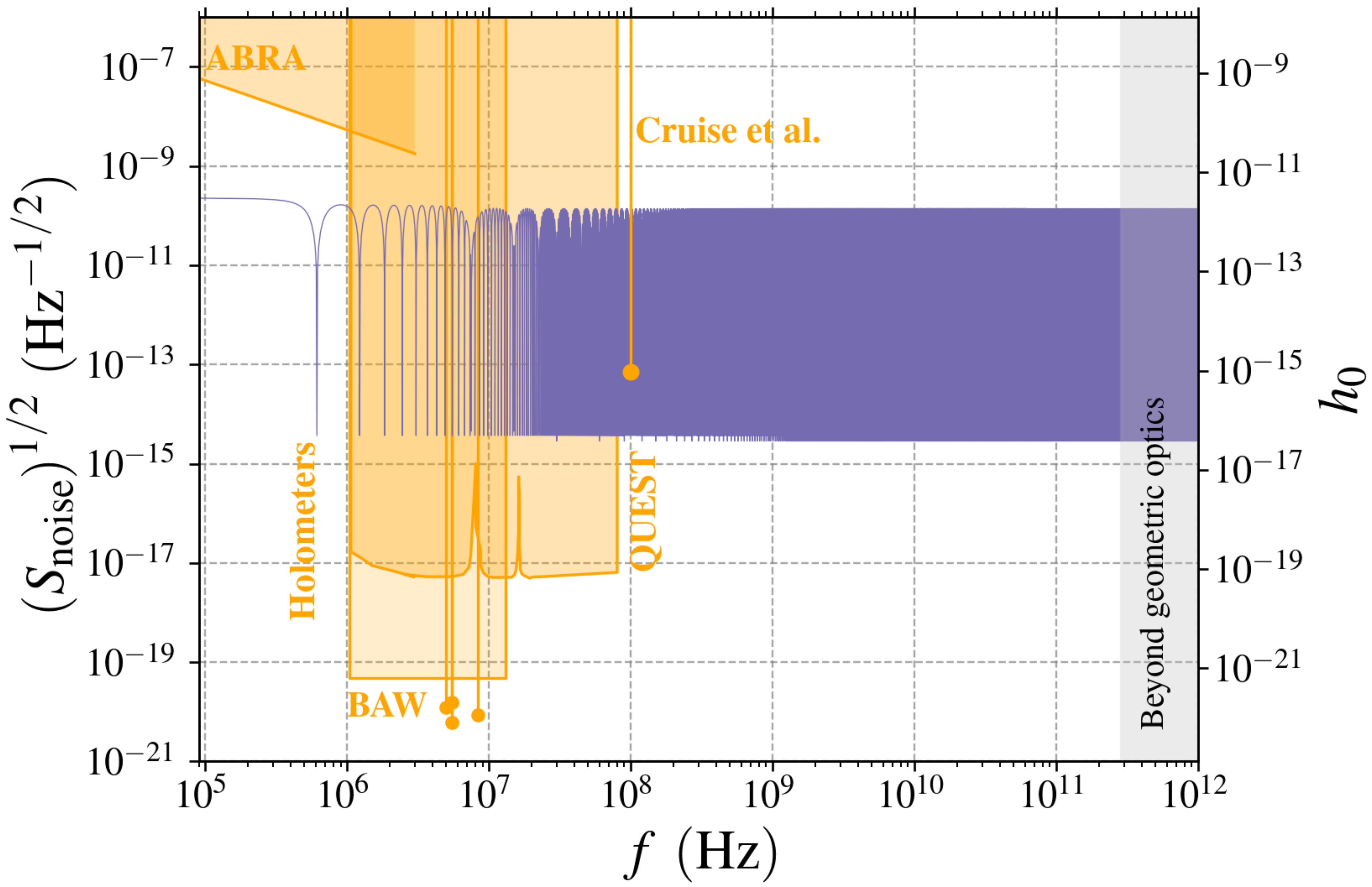
Beam splitter which separates **p** and **s** **polarisations**

Projected Sensitivity for GW

h_+



$h_\times$



Conclusions

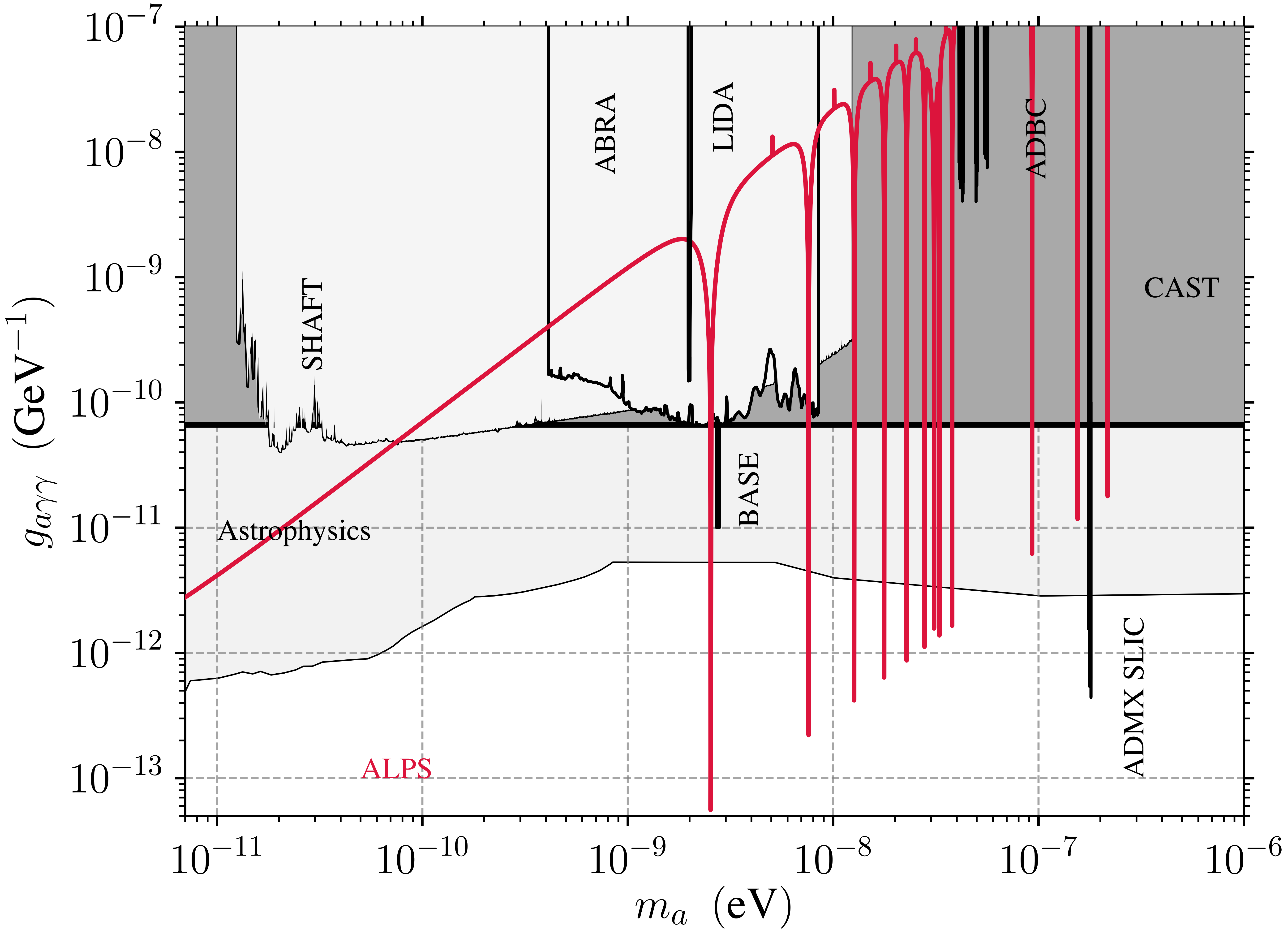
- The range of frequencies beyond 10 kHZ for GWs is **uncharted territory**, and a **discovery** would mean finding **new physics**

- We proposed to reutilise the **cavities** from **ALPS** as a **GW detector** using **polarimetry**

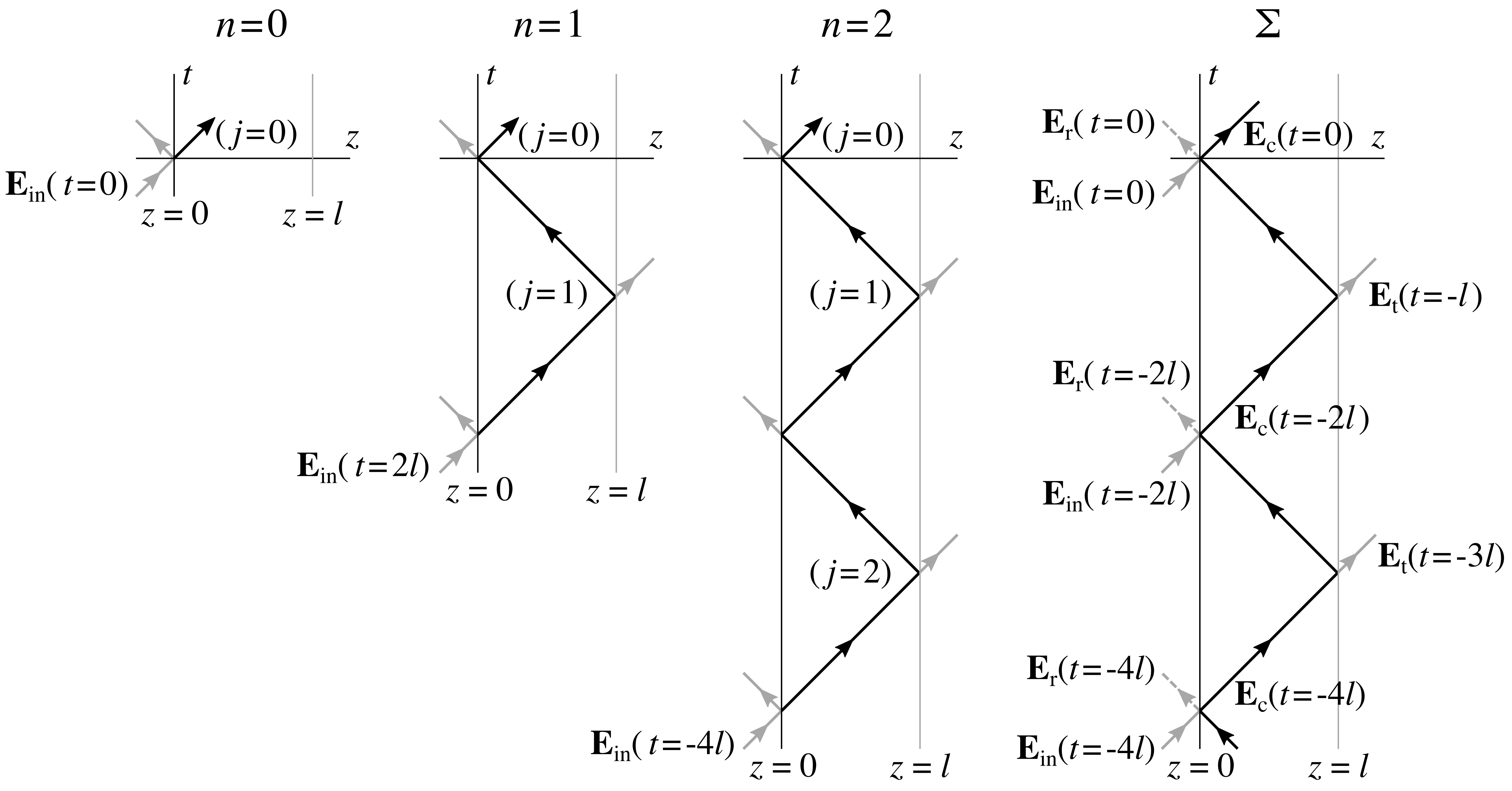
- This would be an experiment that **does not require a magnetic field**, making it easier to realize

Thank you

Axion DM Sensitivity



Cavity response function



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

Cavity response function

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

$$\times \underbrace{\mathcal{Q}}_{\text{QWP}} \quad \underbrace{r_2\mathcal{P}}_{\text{Reflection off mirror 2}} \quad \underbrace{\mathcal{Q}}_{\text{QWP}} \times \underbrace{\left((\cdots)\,\mathbb{I} + \int_0^l dt'\, \mathcal{M}(t' - (2j+2)l)\Big|_{\mathbf{x}(t')=\hat{\mathbf{z}}\,t'} \right)}_{\text{Path from mirror 1 to mirror 2}} . \quad (3.2$$

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

Cavity response function

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

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

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Bounds for GWs, different cases