UHF GWs and Heterodyne Detection

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Ultra-high frequency gravitational waves: where to next?

CERN, 04/12/2023

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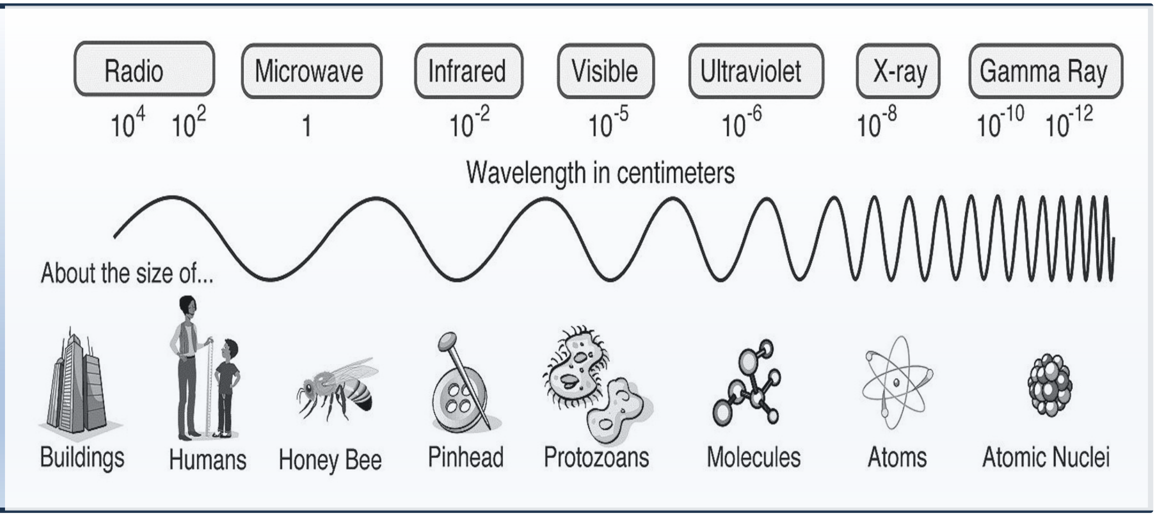
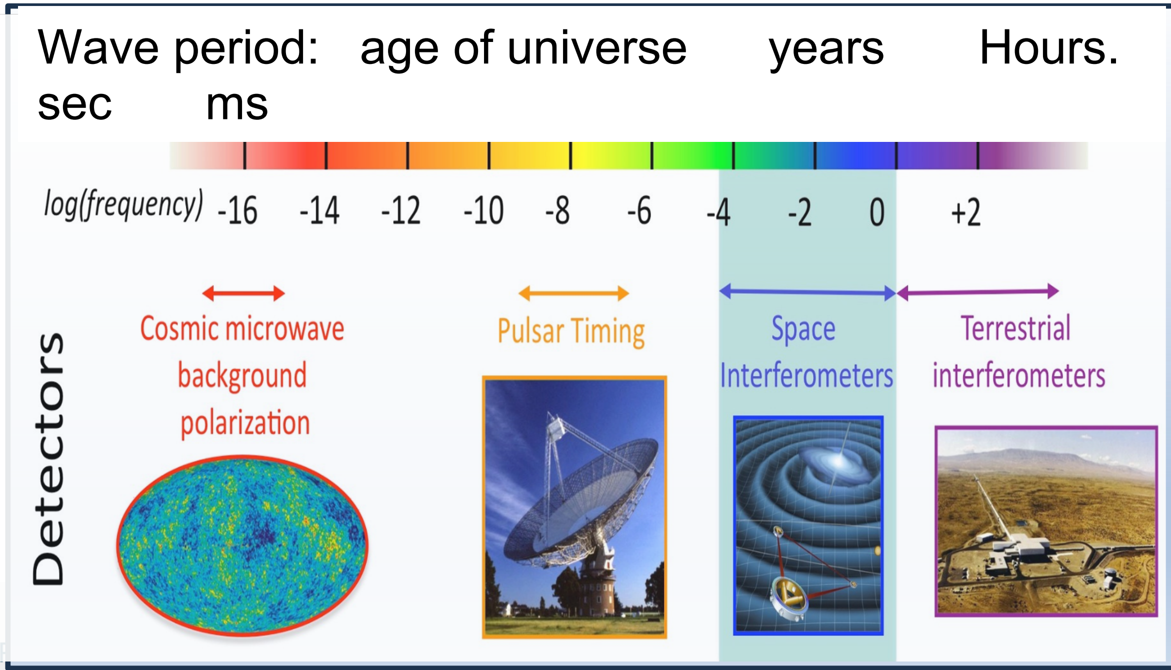
EM radiation

- Extremely low-frequency (ELF)
- Super low-frequency (SLF)

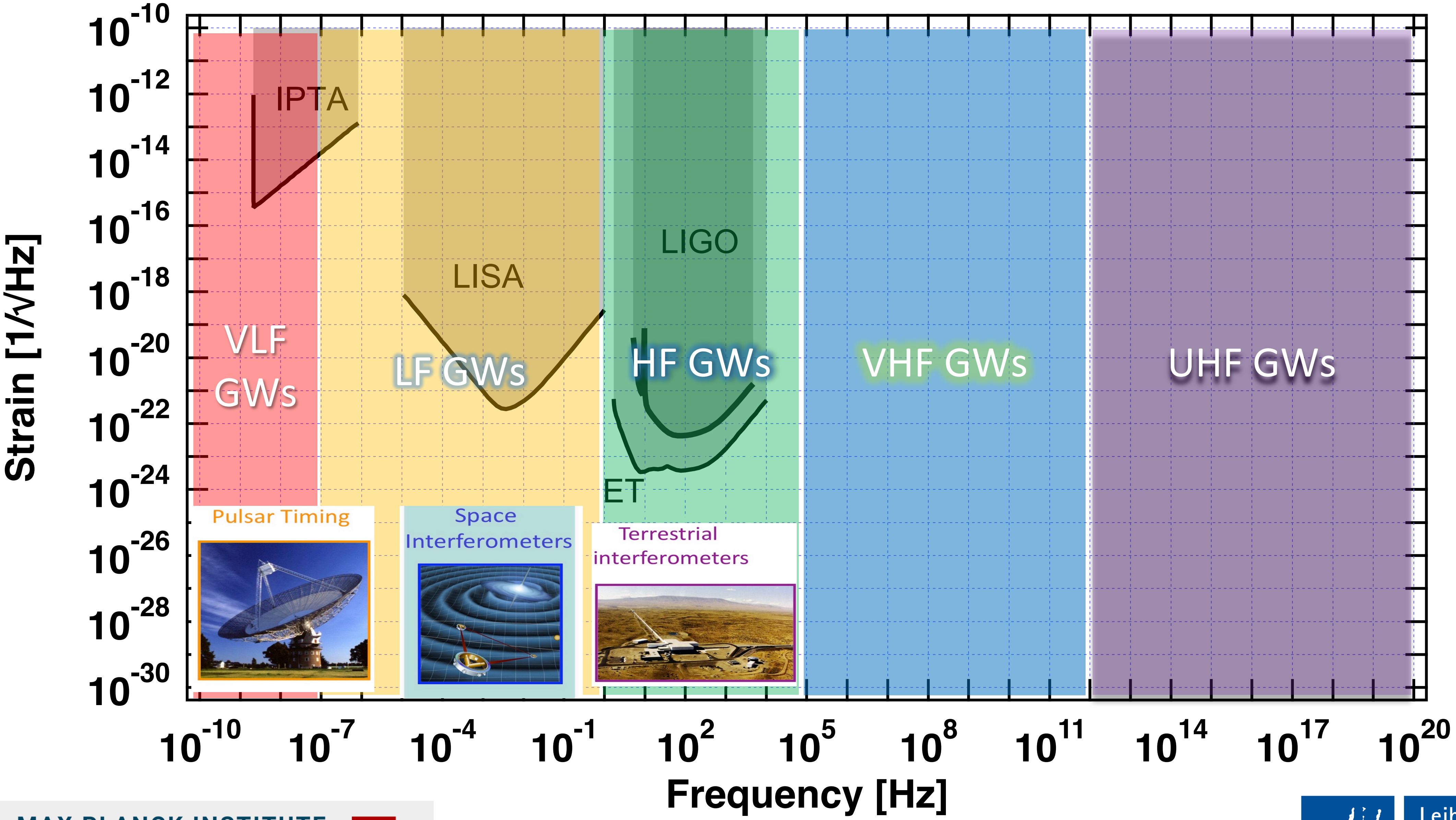


GW radiation



UHF GW

Definition



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W.-T. Ni, World Sci. (Singapore) **1**, 461–464 (2016)

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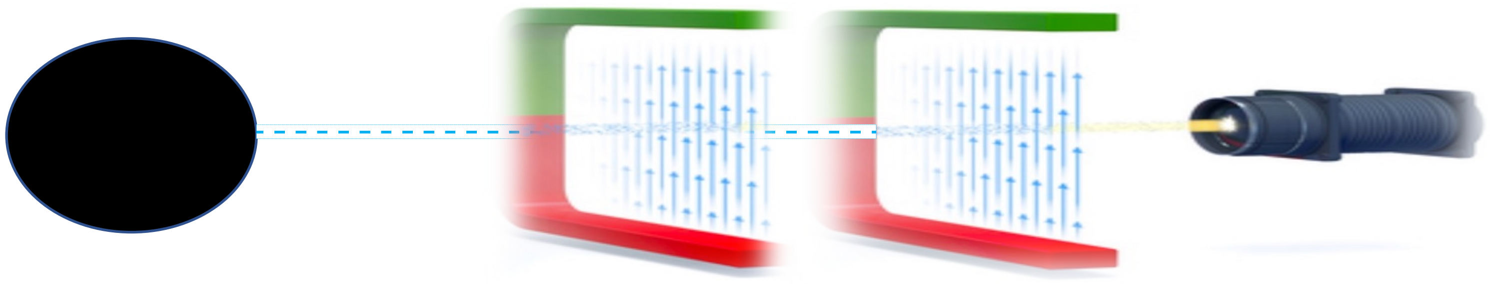
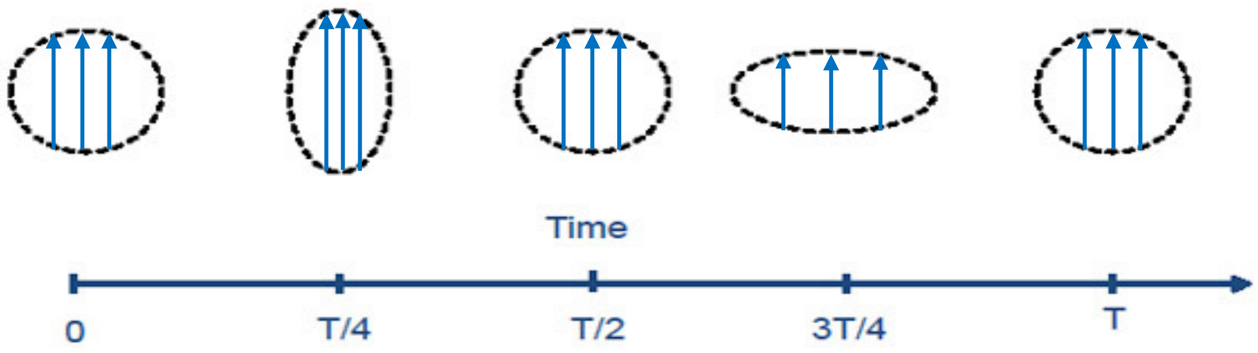
Conversion of GWs into photons in a static magnetic field

Gertsenshtein, Sov. Phys., JETP 14, 84 (1962), G. A. Lupanov JETP 25, 76 (1967)

Source | Magnetic field | Photon detector





$$|h_{\mathrm{ij}}|\mathbf{B}_{\mathrm{ext}}$$

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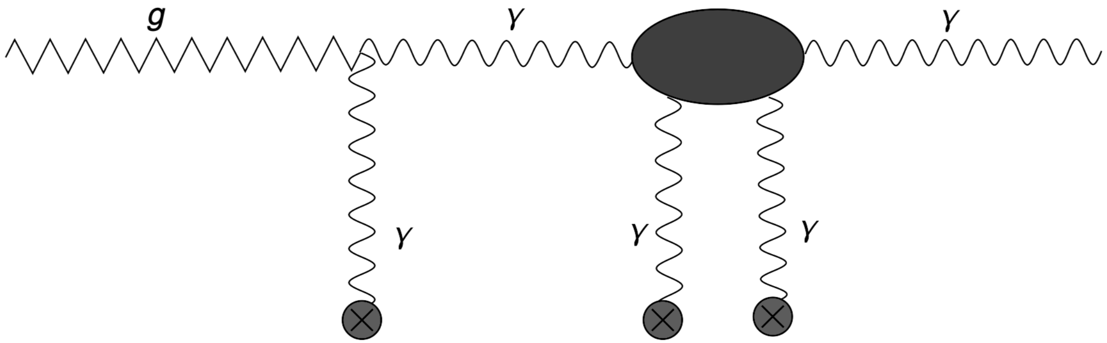
GWs propagating in transverse static magnetic fields

$$S = \int d^4x\sqrt{-g}\mathcal{L}$$



$$\mathcal{L} = \mathcal{L}_{\rm gr} + \mathcal{L}_{\rm em}$$

$$\mathcal{L}_{\rm gr} = \frac{1}{\kappa^2}R, \quad \mathcal{L}_{\rm em} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\int d^4x' A_\mu(x)\Pi^{\mu\nu}(x,x')A_\nu(x')$$

Converted EMWs stochastic flux

$$\Phi_\gamma^{\rm graph}(z,\omega_f;t) \simeq \int_{\omega_i}^{\omega_f} \frac{B^2\, z^2\, h_c^2(0,\omega)\,\omega}{4}d\omega$$

Measured EMWs flux from the CCD

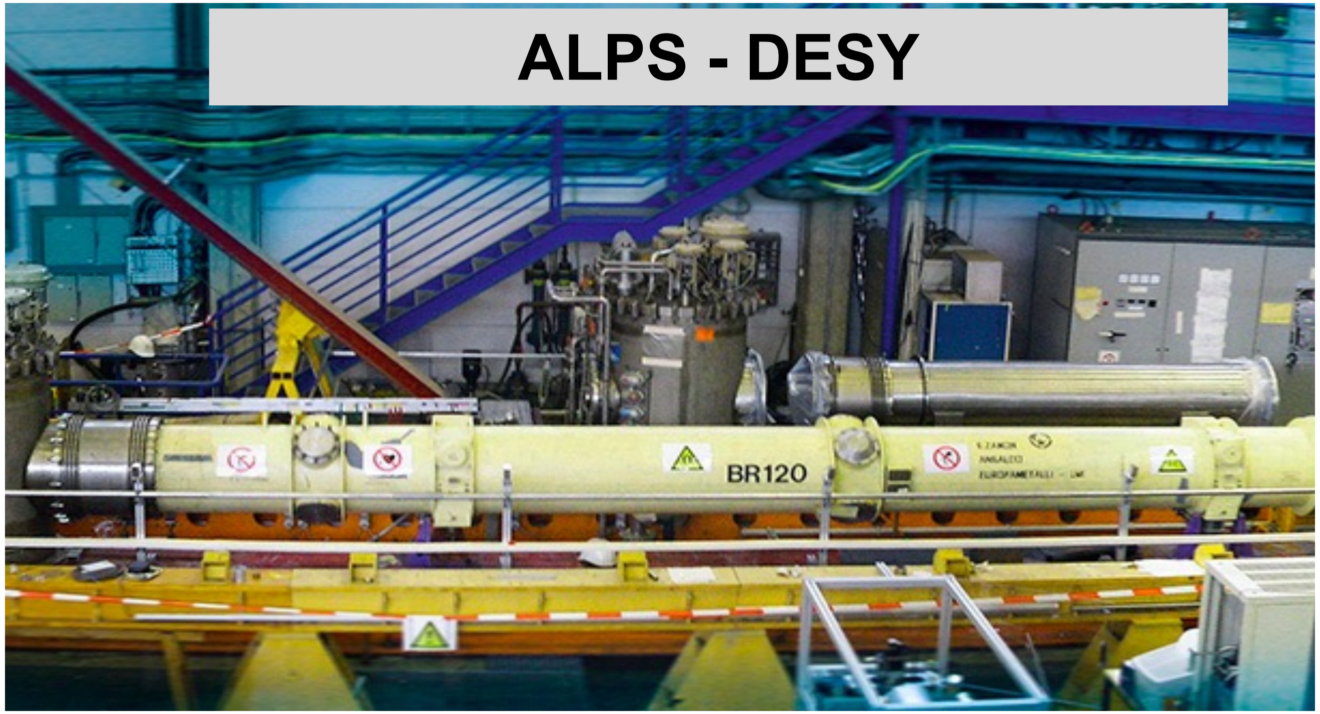
$$\Phi_\gamma^{\rm CCD}(z,\omega_f;t) = \int_{\omega_i}^{\omega_f} \frac{1}{A(z)}\frac{N(\omega,t)\,\omega}{\epsilon_\gamma(\omega)}\,d\omega$$

$$N(\omega,t) = N_{\rm exp}/\Delta\omega$$

$$h_c^{\rm min}(0,\omega) \simeq \sqrt{\frac{4\,N_{\rm exp}}{A\,B^2\,L^2\,\epsilon_\gamma(\omega)\,\Delta\omega}} \simeq 1.6\times 10^{-16}\sqrt{\left(\frac{N_{\rm exp}}{1\ \rm Hz}\right)\left(\frac{1\ \rm m^2}{A}\right)\left(\frac{1\ \rm T}{B}\right)^2\left(\frac{1\ \rm m}{L}\right)^2\left(\frac{1\ \rm Hz}{\Delta f}\right)\left(\frac{1}{\epsilon_\gamma(\omega)}\right)}$$

CAST - CERN

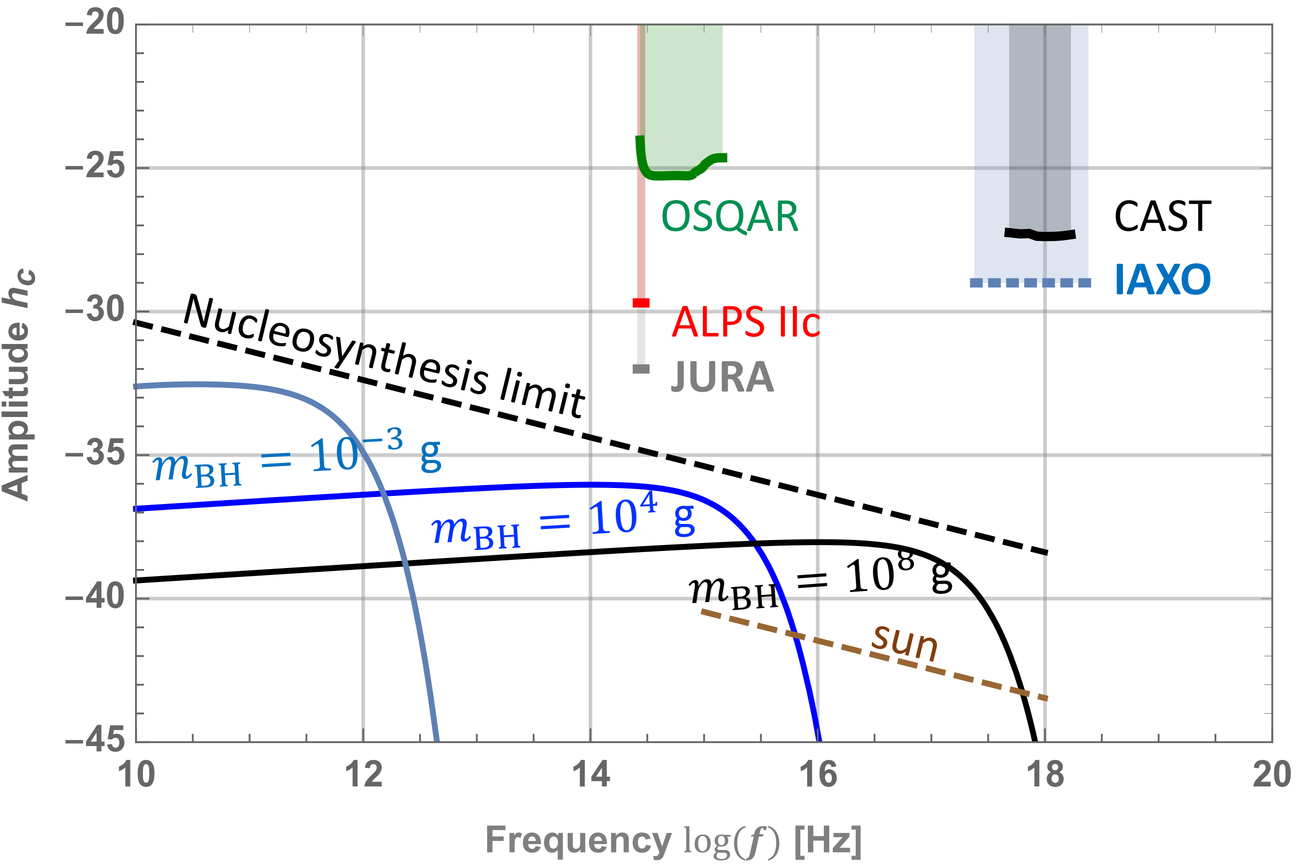
ALPS - DESY



OSQAR - CERN

AXION-LIKE PARTICLE SEARCH EXPERIMENTS

Upper limits and prospects for future detectors



Eur. Phys. J. C (2019) 79:1032
https://doi.org/10.1140/epjc/s10052-019-7542-5

THE EUROP... PHYSICAL J...

Regular Article - Theoretical Physics

Upper limits on the amplitude of ultra-high-frequency gravitational waves from graviton to photon conversion

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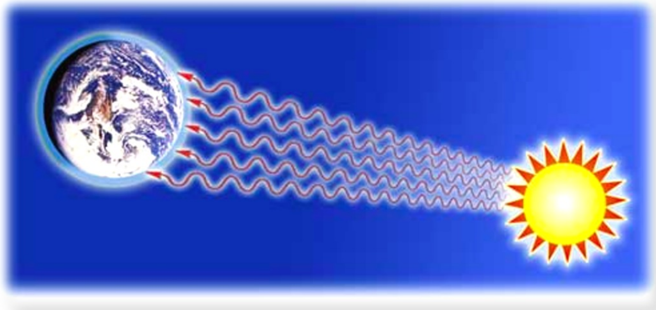
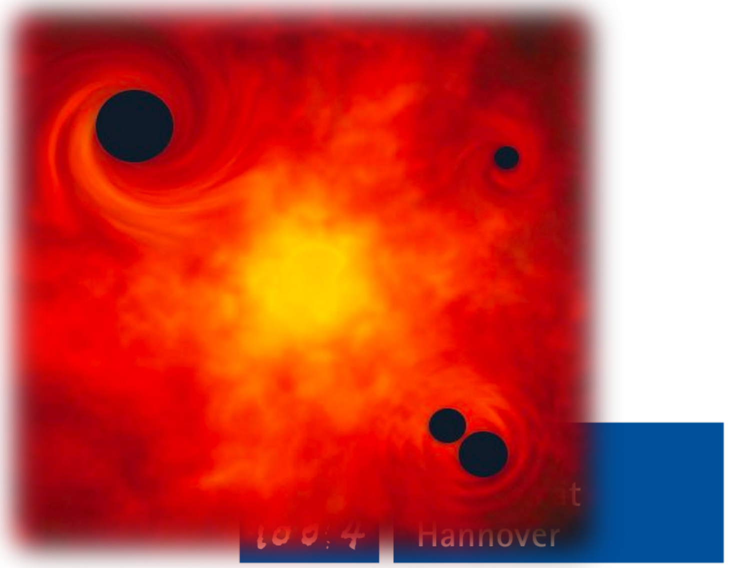
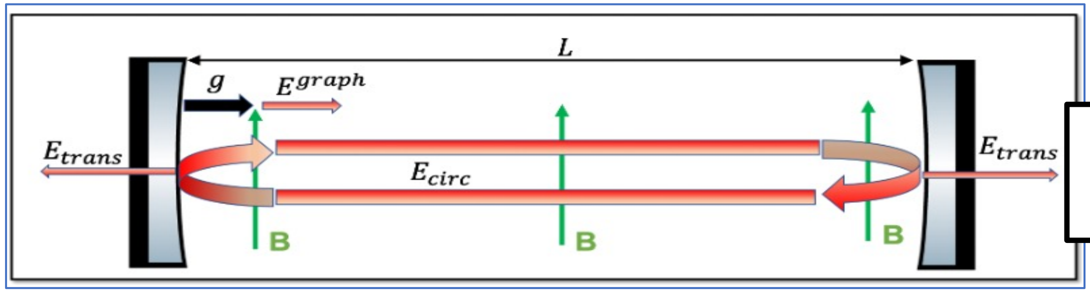
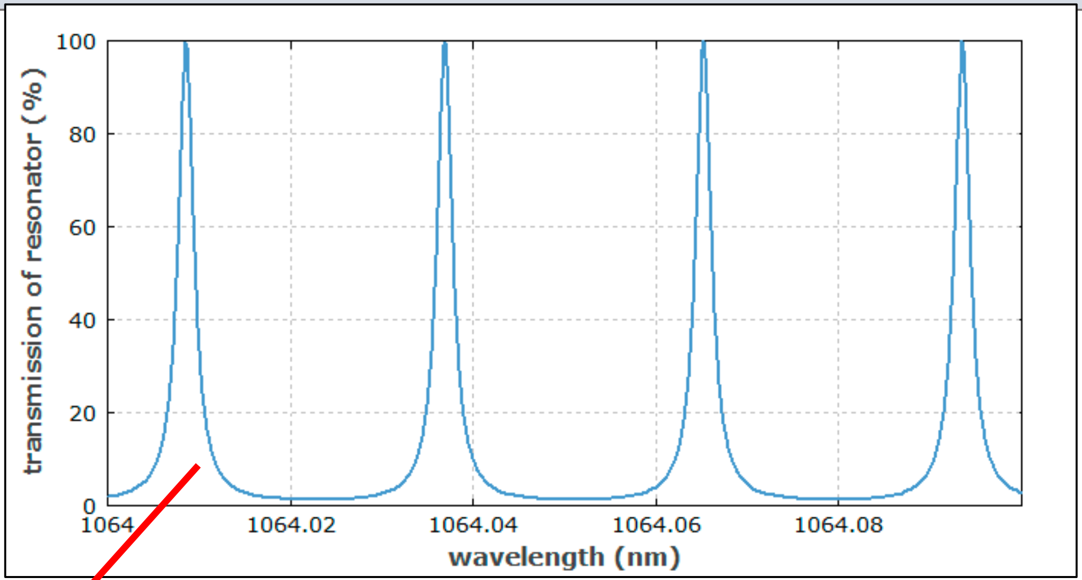


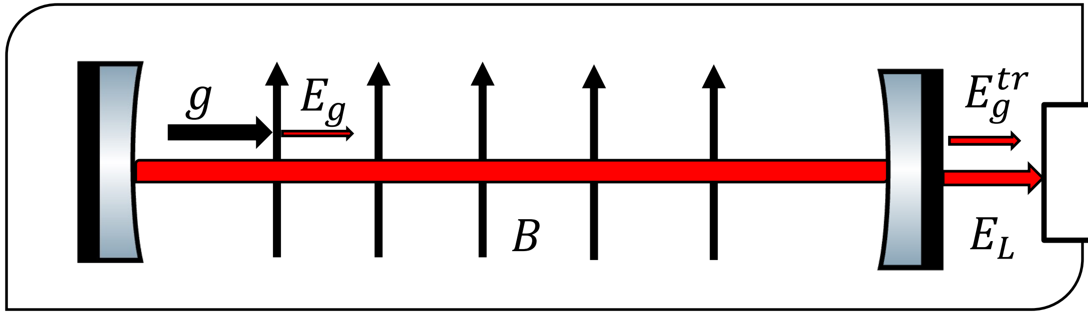


UHF Gravitational Wave: ALPS II Heterodyne Detection



TES



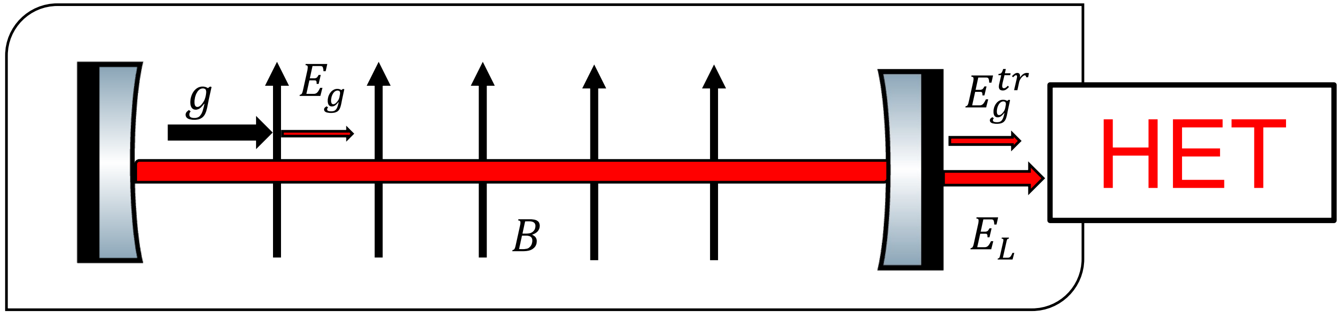


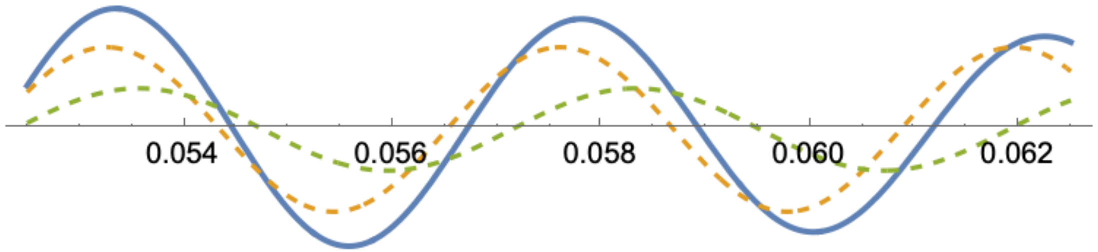
HET

$$E_0^2 = E_L^2 + E_g^2 + 2E_gE_L\cos((\omega_g - \omega_L)t)$$

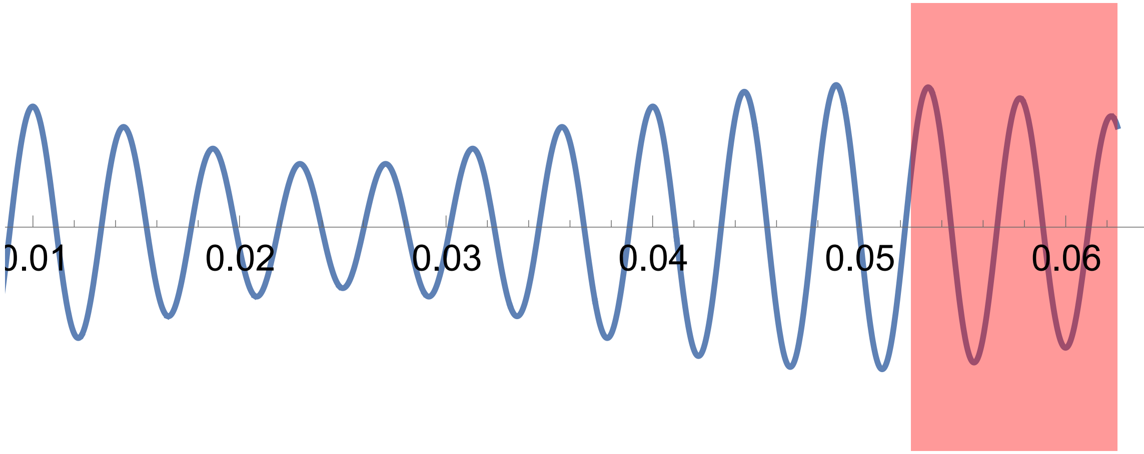
$$h_c^{\min}(0,\omega^*) \simeq 2.8\times10^{-16}\sqrt{\left(\frac{1}{\mathcal{F}}\right)\left(\frac{N_{\text{dark}}}{1\ \text{Hz}}\right)\left(\frac{1\ \text{m}^2}{A}\right)\left(\frac{1\ \text{T}}{B}\right)^2\left(\frac{1\ \text{m}}{L}\right)^2\left(\frac{1\ \text{Hz}}{\Delta f}\right)\left(\frac{1}{\epsilon_\gamma(\omega)}\right)}$$

Principles of Heterodyne Detection





$$S(t) = \left| E_{\mathrm{GW}} e^{i(\omega_1 t + \phi)} + E_{LO} e^{i\omega_2 t} \right|^2$$
$$= E_{\mathrm{LO}}^2 + 2E_{\mathrm{LO}} E_{\mathrm{GW}} \cos\left(\Omega t + \phi\right)$$

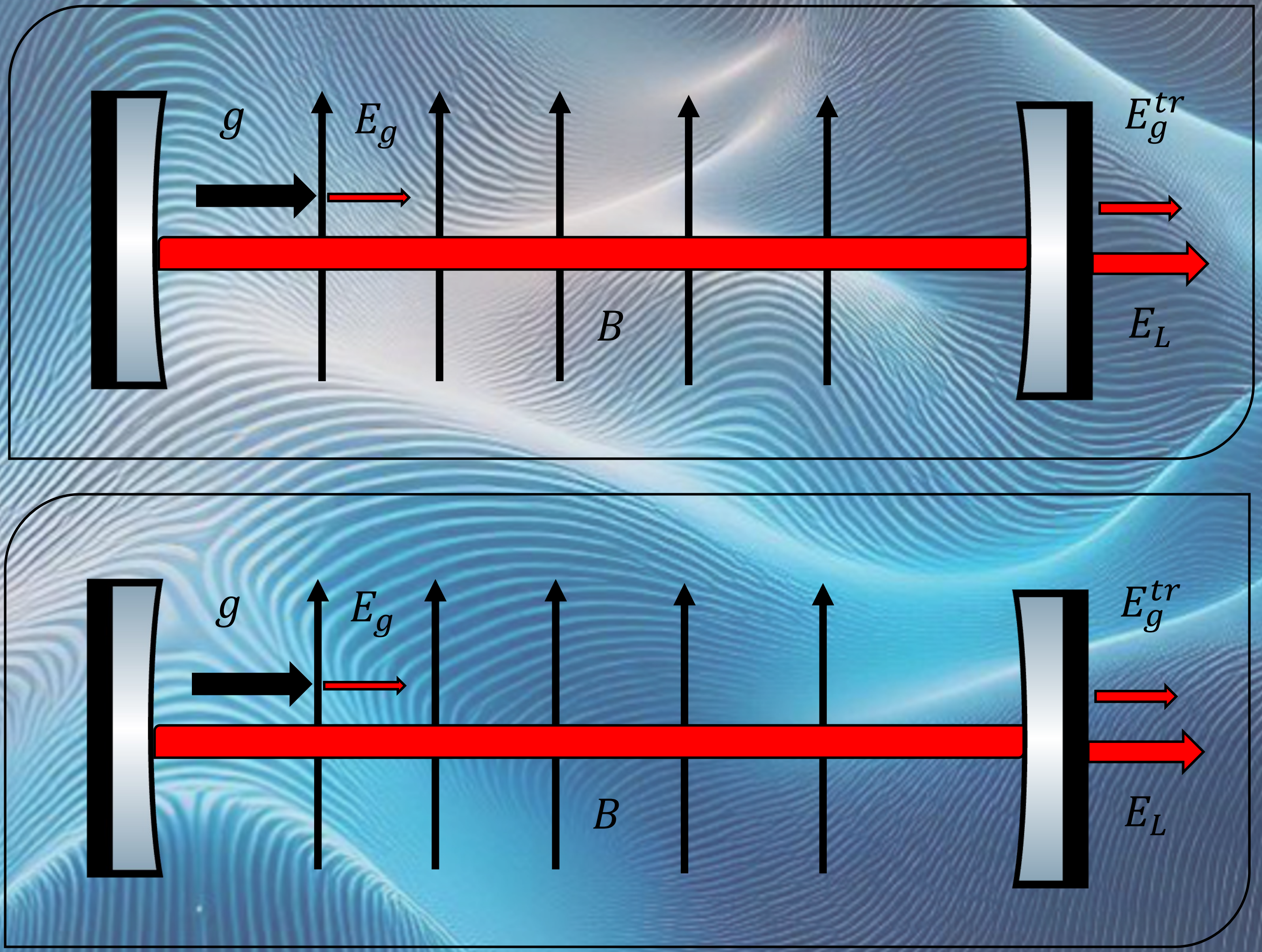


Stochastic GWs background and cross correlation

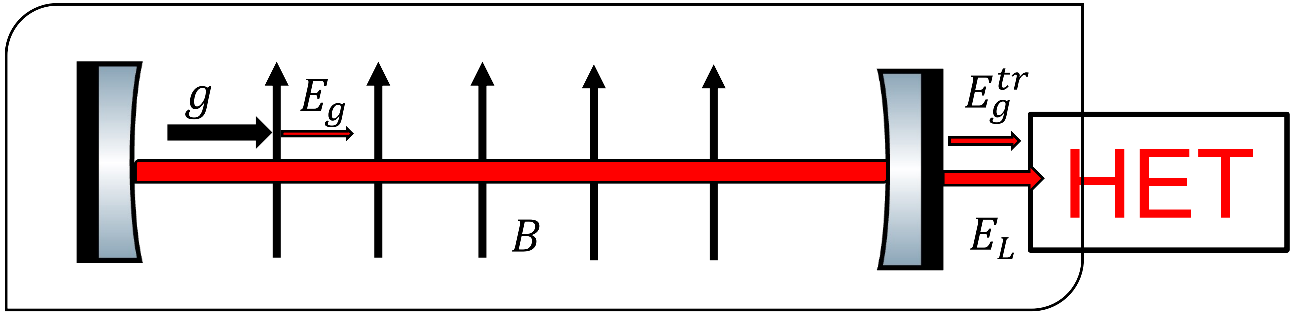
- **Co-located detectors experience a correlated gravitational wave field.**

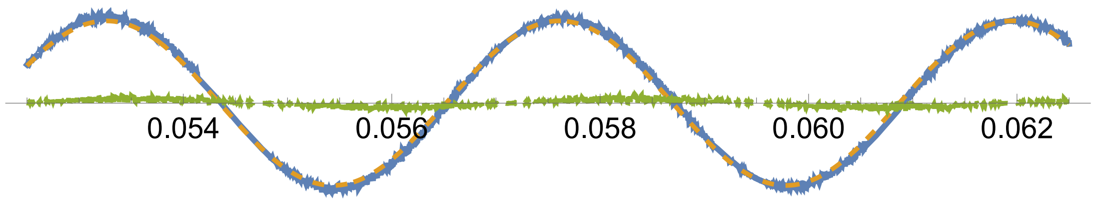
- **The proximity of detectors induces similar spacetime variations, contributing to signal correlation.**

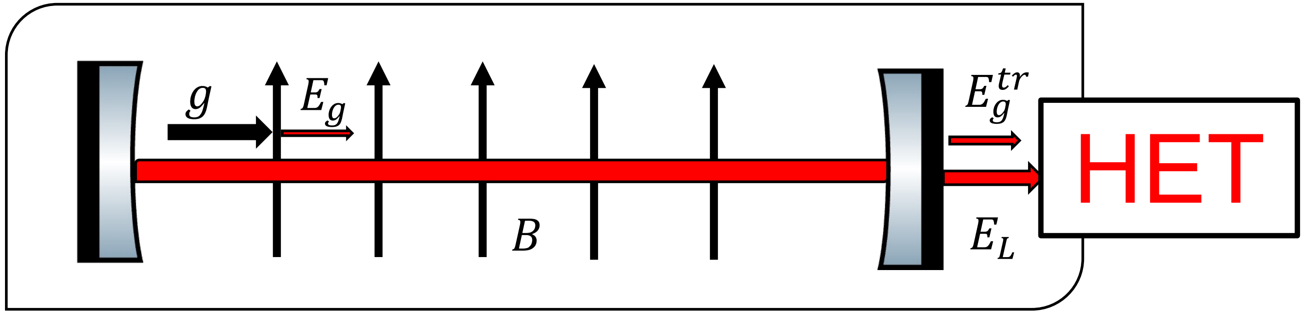
- **Similar detector designs result in shared sensitivity and response to gravitational waves.**

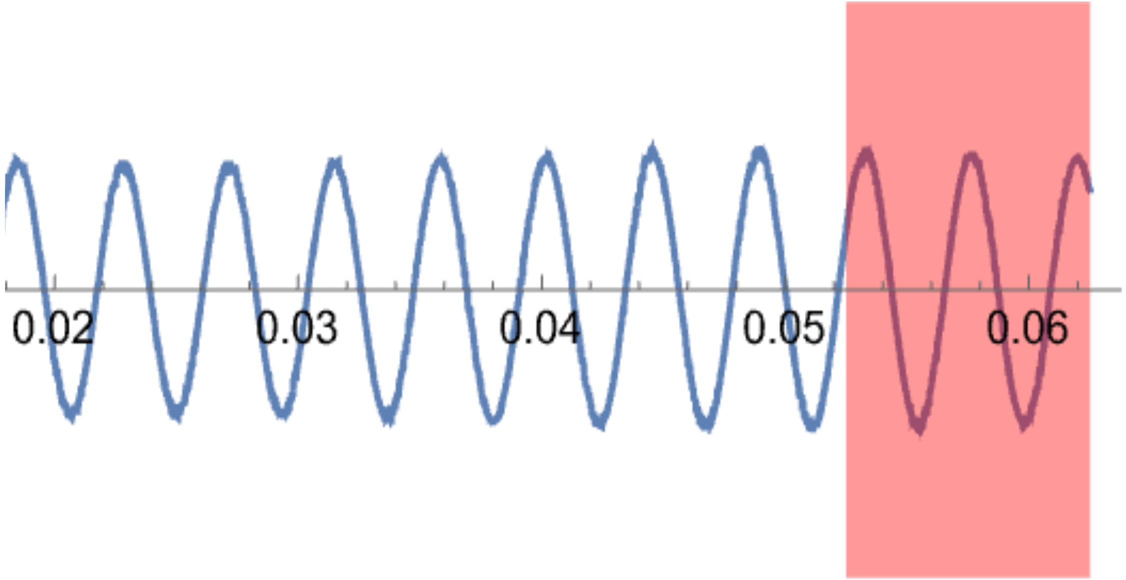


Principles of Heterodyne Detection





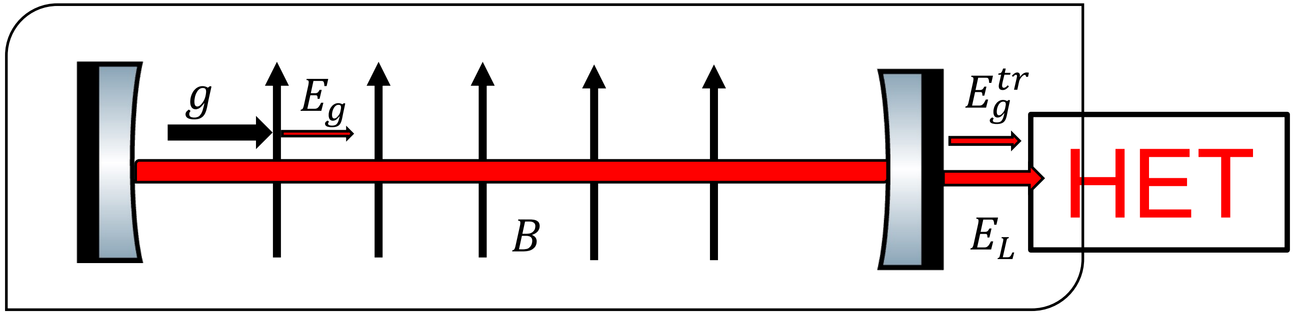


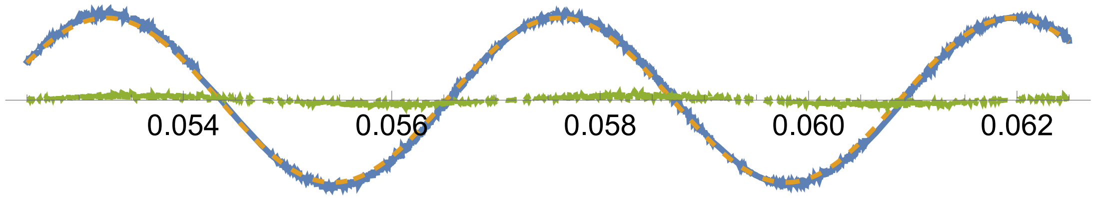


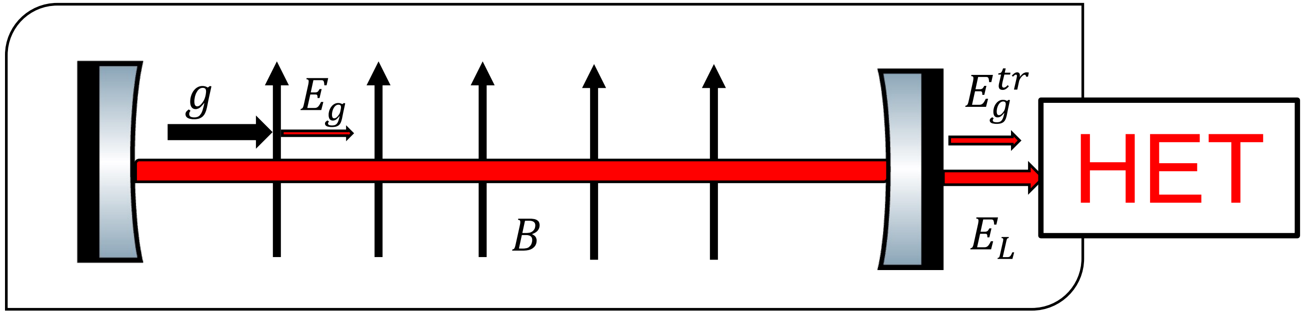
$$S_1(t) = \left| E_{\mathrm{GW}} e^{i(\omega_1 t + \phi)} + E_{LO} e^{i\omega_2 t} \right|^2$$

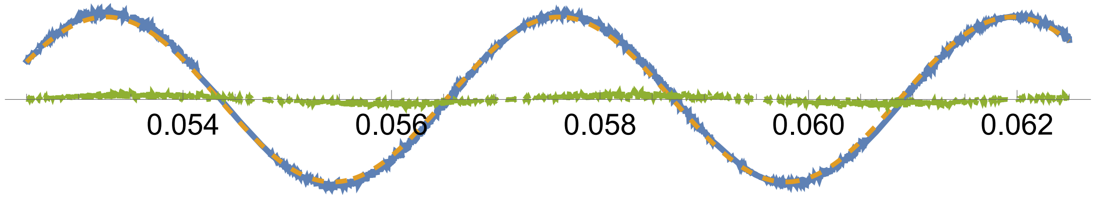
$$S_2(t) = \left| E_{\mathrm{GW}} e^{i(\omega_1 t + \phi)} + E_{LO} e^{i\omega_3 t} \right|^2$$

"Co-located" Heterodyne Detectors









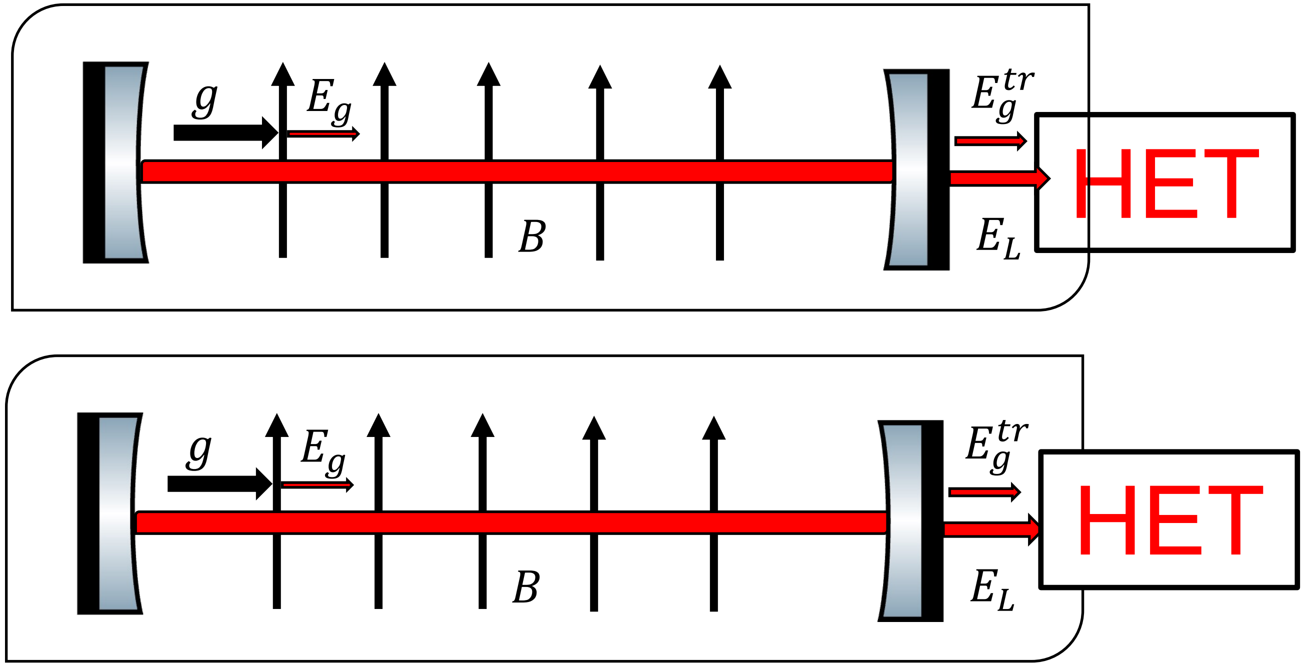
$$S_1(t) = E_{\mathrm{LO}}^2 + 2E_{\mathrm{LO}}E_{\mathrm{GW}}\cos\left(\Omega_1 t + \phi\right)$$

$$S_2(t) = E_{\mathrm{LO}}^2 + 2E_{\mathrm{LO}}E_{\mathrm{GW}}\cos\left(\Omega_2 t + \phi\right)$$

$$C_{12}(\tau) = \langle S_1(t) S_2(t+\tau)\rangle$$

Cross-correlation

“Co-located” Heterodyne Detectors



$$S_\Sigma = 2\sqrt{N_{\rm LO} N_\gamma^{\rm GW}}, \qquad \sigma_\Sigma = 2\sqrt{N_{\rm LO}}$$

$$\frac{S_\Sigma}{\sigma_\Sigma} = \sqrt{N_\gamma^{\rm GW}}\sqrt{\tau}$$

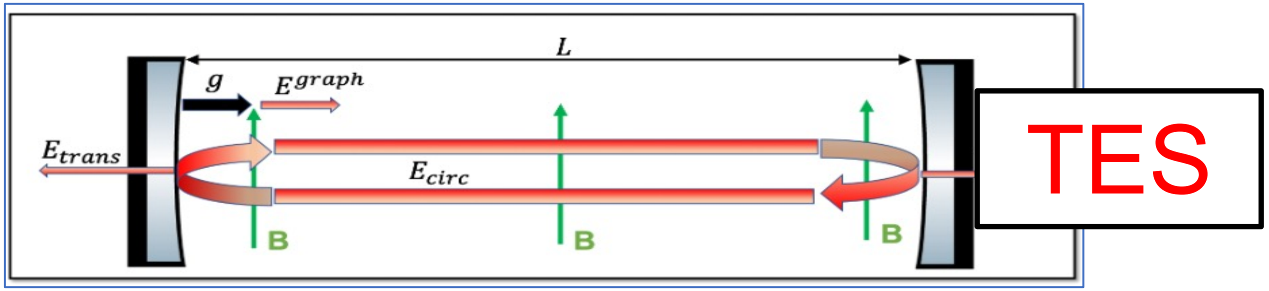
$$\Phi_\gamma^{\rm GW} \simeq \int_{\omega_i}^{\omega_f} \frac{B^2\, z^2\, h_c^2 \omega}{4} d\omega$$

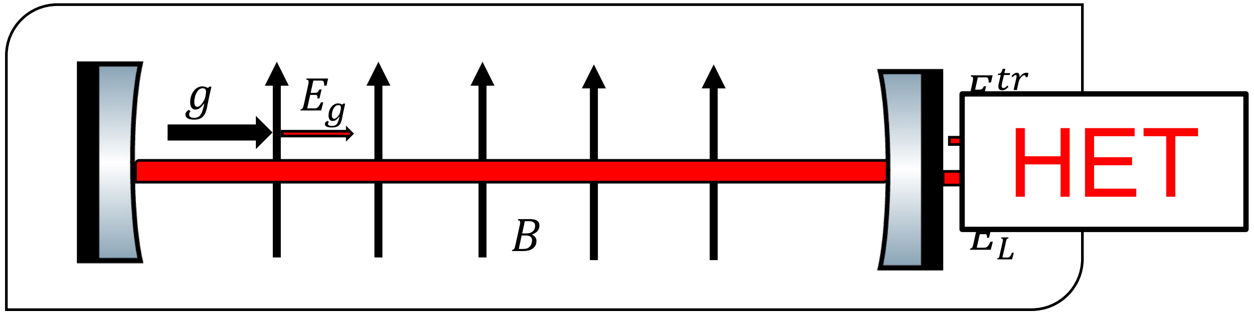
$$\frac{S_\Sigma}{\sigma_\Sigma} = \sqrt{\frac{\Phi_\gamma^{\rm GW}\ \tau\ A}{\omega\ \epsilon}}$$

$$\begin{aligned} S_1(t) &= E_{\rm LO}^2 + 2E_{\rm LO}E_{\rm GW}\cos\left(\Omega_1 t + \phi\right) \\ S_2(t) &= E_{\rm LO}^2 + 2E_{\rm LO}E_{\rm GW}\cos\left(\Omega_2 t + \phi\right) \\ C_{12}(\tau) &= \langle S_1(t) S_2(t+\tau)\rangle \end{aligned}$$

Cross-correlation

UHF Gravitational Wave and Heterodyne Detection





$$h_c^{\mathrm{TES}} \simeq 2.8\times10^{-16}\sqrt{\left(\frac{1}{\mathcal{F}}\right)\left(\frac{N_{\mathrm{dark}}}{1\ \mathrm{Hz}}\right)\left(\frac{1\ \mathrm{m}^2}{A}\right)\left(\frac{1\ \mathrm{T}}{B}\right)^2\left(\frac{1\ \mathrm{m}}{L}\right)^2\left(\frac{1\ \mathrm{Hz}}{\Delta f_{\mathrm{TES}}}\right)\left(\frac{1}{\epsilon_\gamma}\right)}.$$

$$h_c^{\mathrm{HET}} \simeq 2.8\times10^{-16}\sqrt{\left(\frac{1}{\mathcal{F}}\right)\left(\frac{1\ \mathrm{m}^2}{A}\right)\left(\frac{1\ \mathrm{T}}{B}\right)^2\left(\frac{1\ \mathrm{m}}{L}\right)^2\left(\frac{1\ s}{\tau}\right)\left(1\ \mathrm{Hz}\ \frac{\delta f_{\mathrm{bin}}}{\Delta f_{\mathrm{HET}}^2}\right)\left(\frac{1}{\epsilon_\gamma}\right)}.$$

Cross-correlation

Precision Interferometry and Fundamental Interactions
MPI for GW Physics (AEI)

Polarimetry with Heterodyne Interferometry

1	**Vacuum Magnetic Birefringence**
2	**Pseudoscalar/scalar field Dark Matter**
3	**UHF Gravitational Waves**

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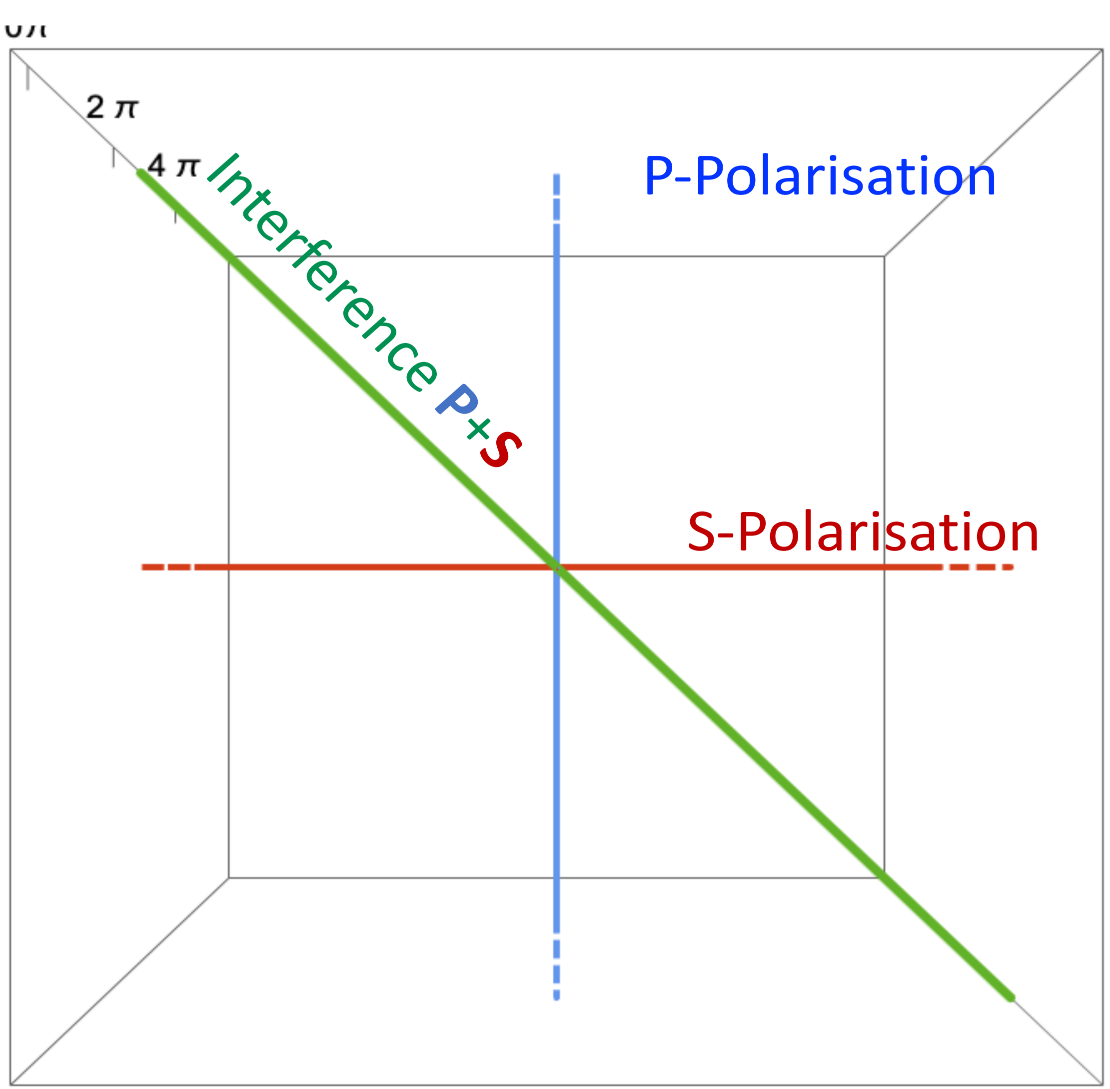
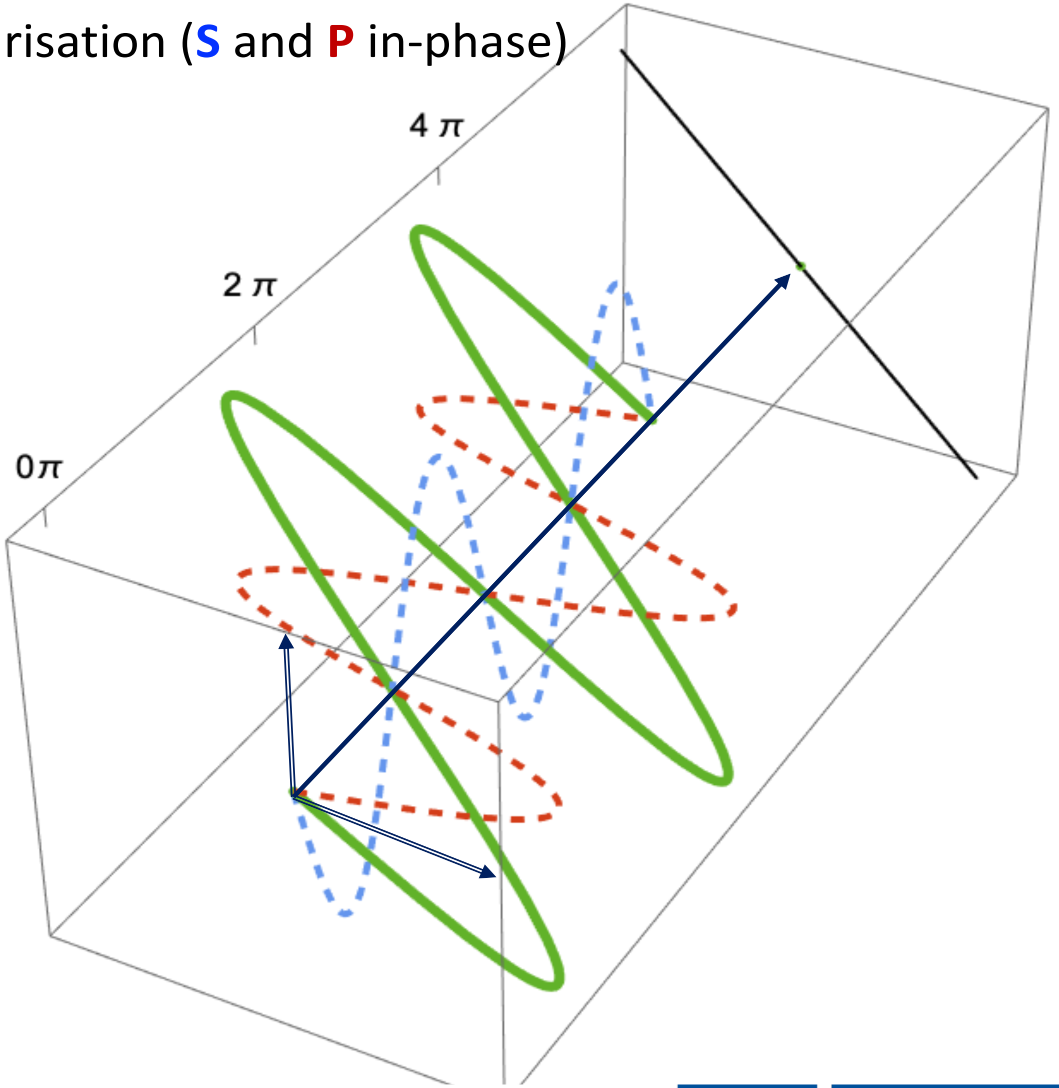
Polarimetry can probe **rotation** of the EM field





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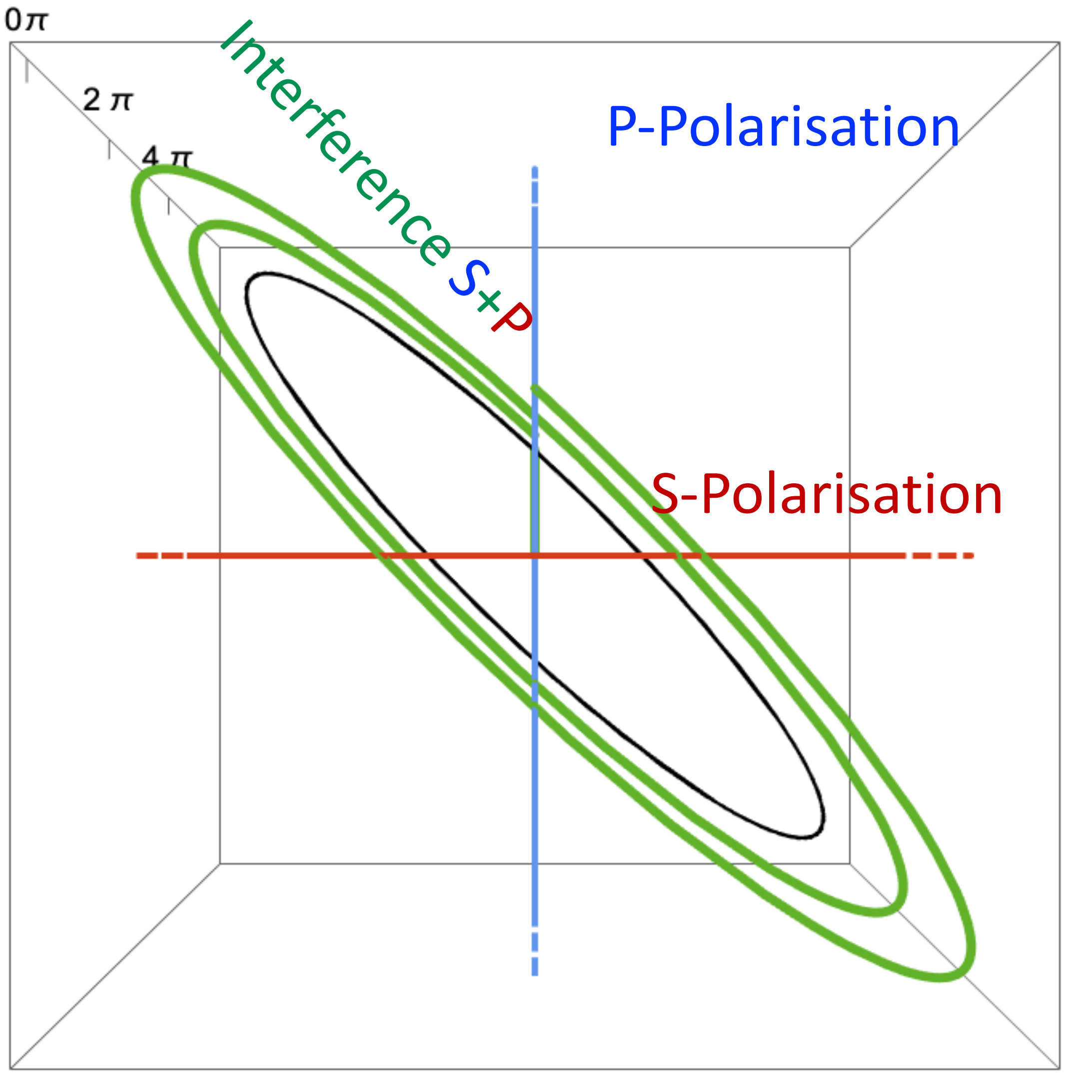
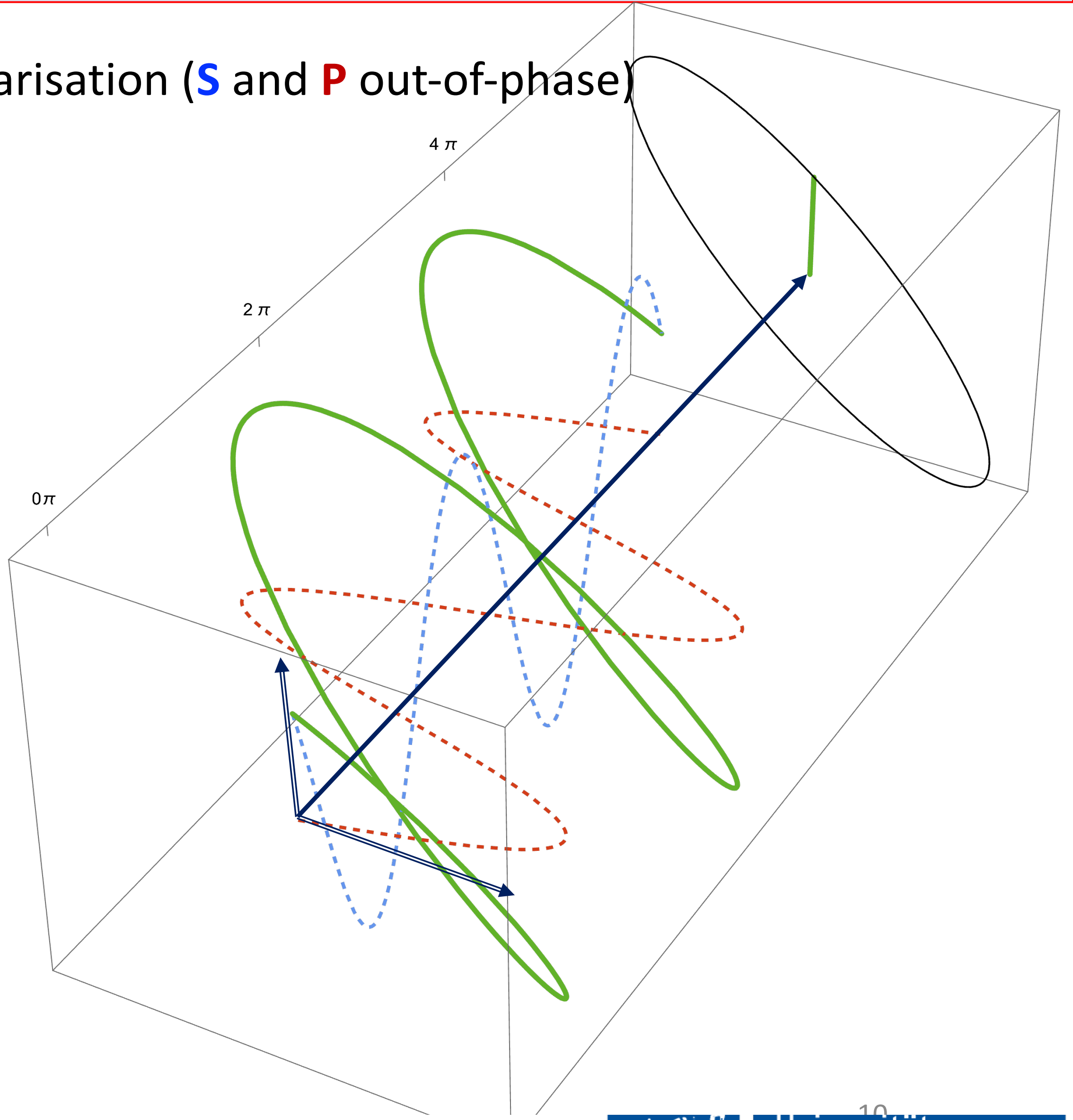
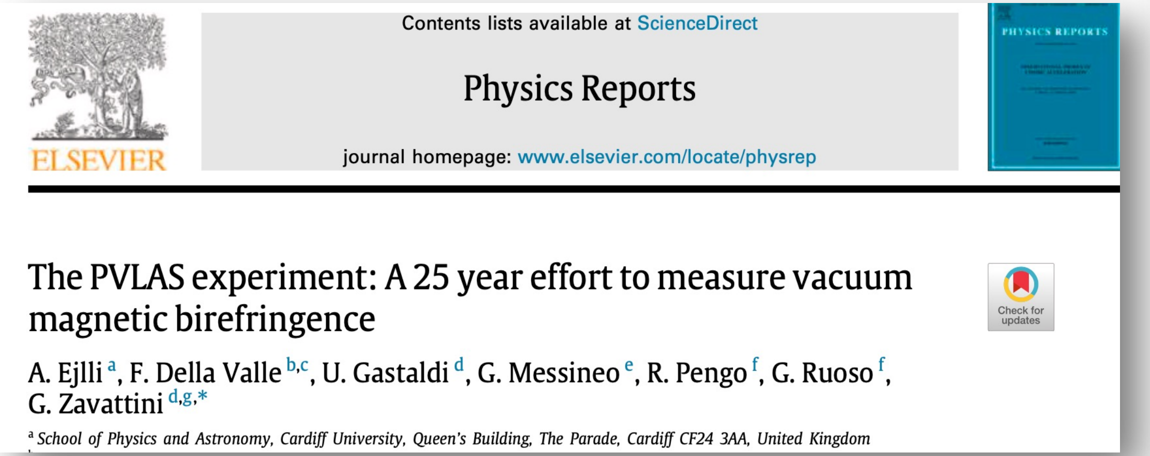
Polarimetry can probe **ellipticity** of the EM field



Elliptical Polarisation (**S** and **P** out-of-phase)



Polarimetry for Vacuum Magnetic Birefringence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ELSEVIER

The PVLAS experiment: A 25 year effort to measure vacuum magnetic birefringence

A. Ejlli [a], F. Della Valle [b,c], U. Gastaldi [d], G. Messineo [e], R. Pengo [f], G. Ruoso [f], G. Zavattini [d,g,*]

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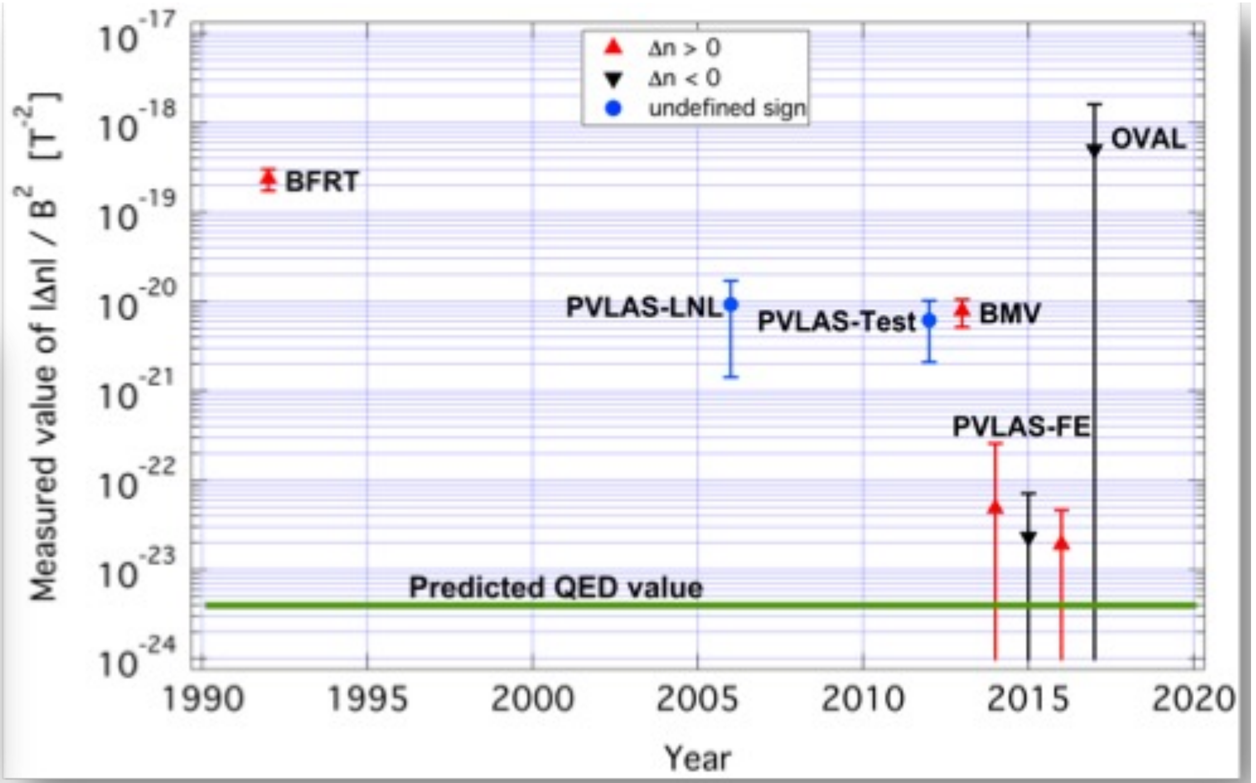
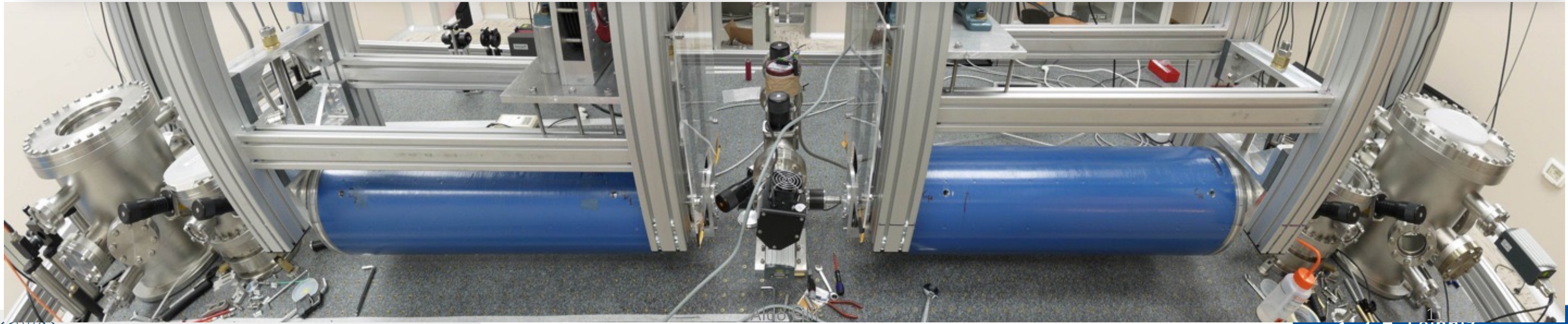
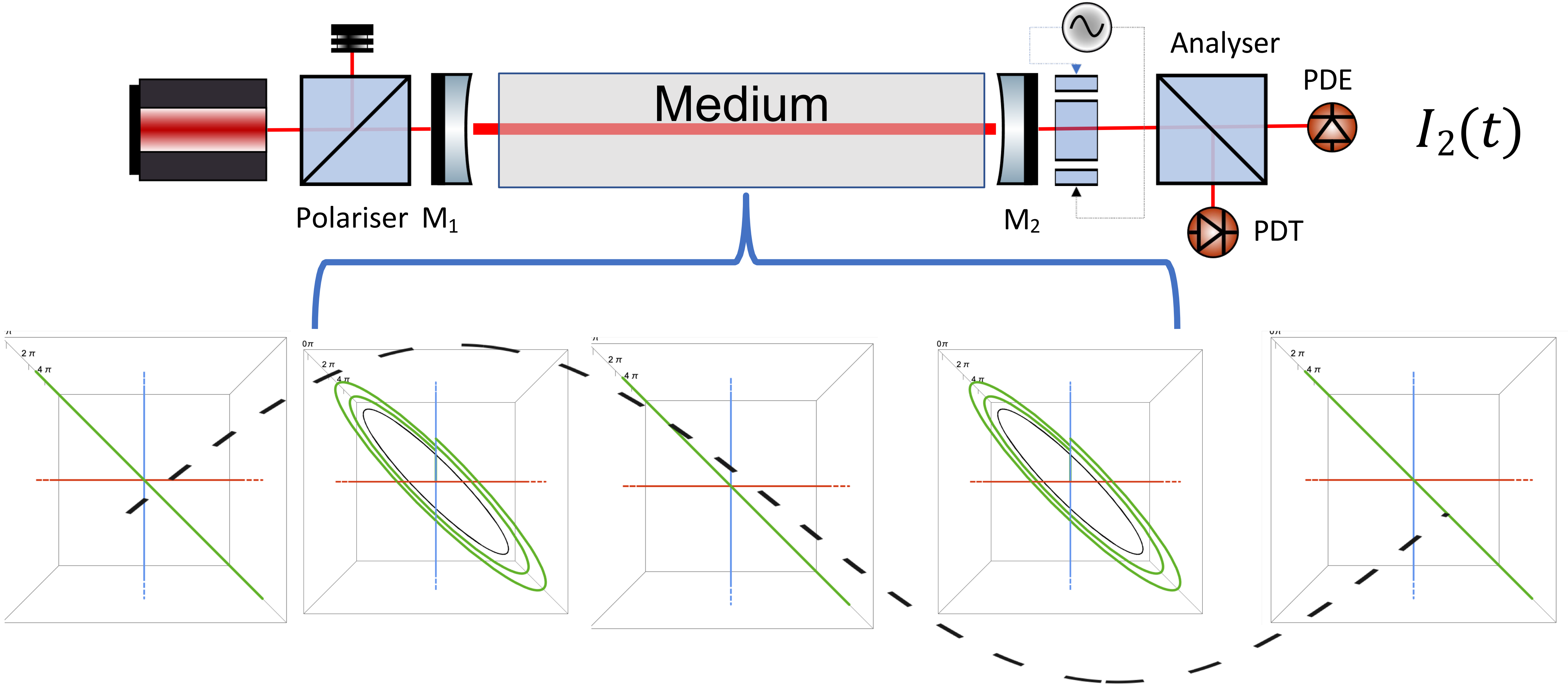


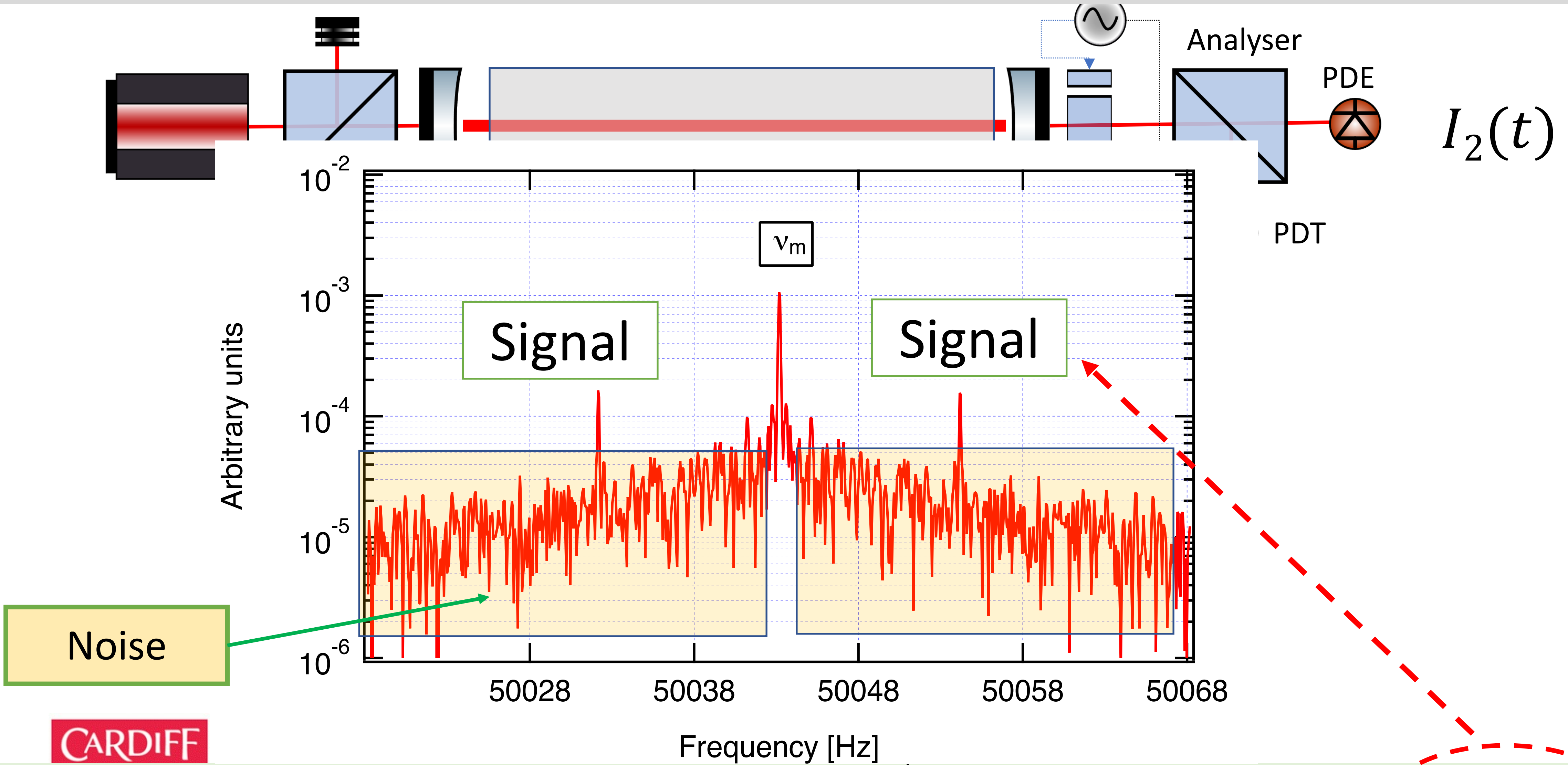


Polarimetry strategy



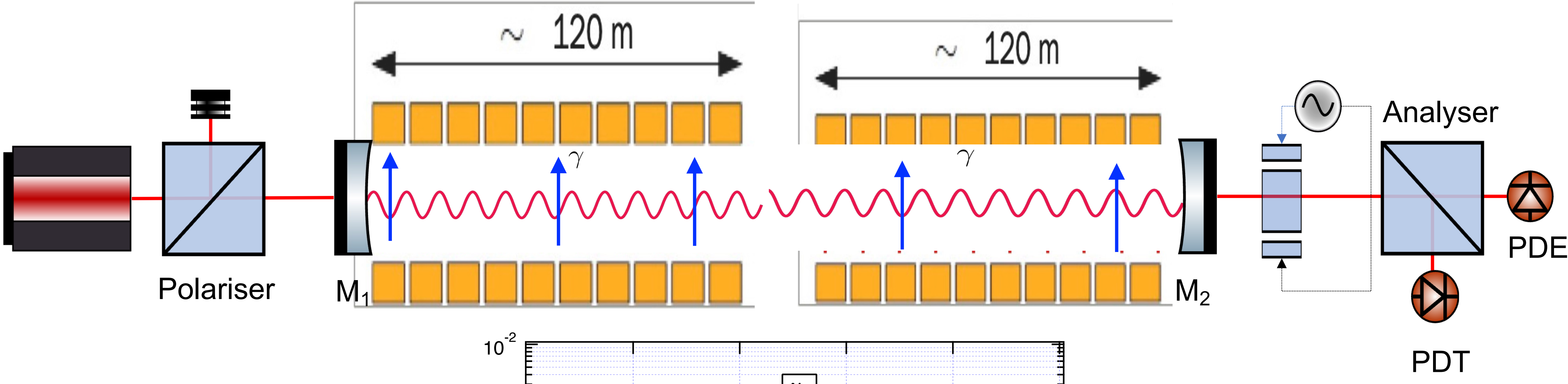
$$I_2(t) = I_0\left(\sigma^2 + |i\psi(t) + i\eta(t) + \epsilon(t)|^2\right) = I_0\Big(\sigma^2+\psi^2(t)+\eta^2(t)+\epsilon(t)^2+2\psi(t)\eta(t)\Big)$$

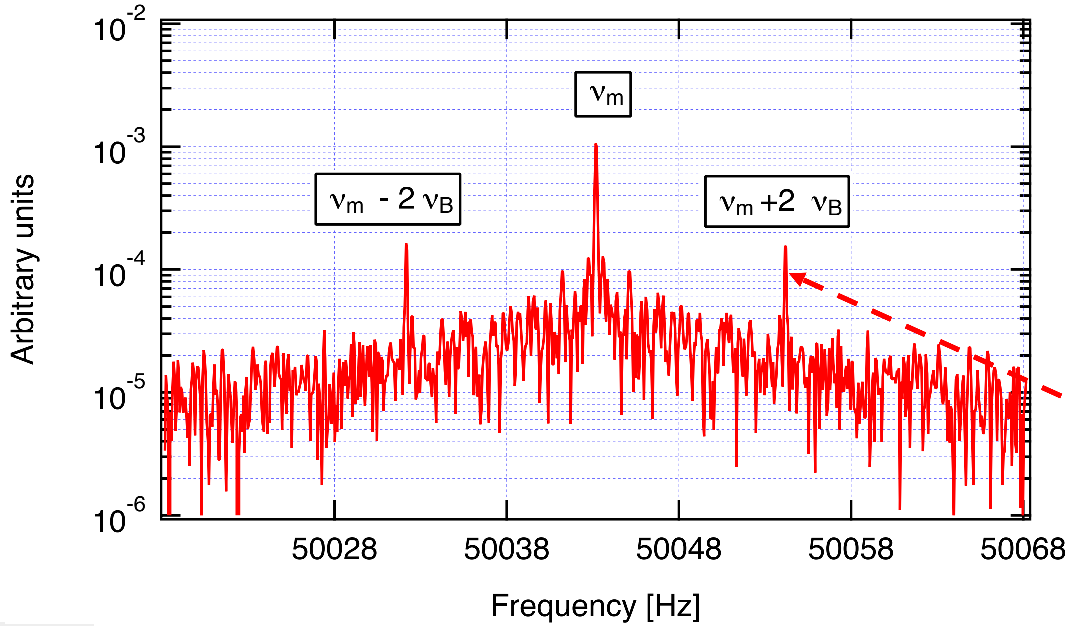
Polarimetry strategy: heterodyne interferometry



$$I_2(t) = I_0\left(\sigma^2 + |i\psi(t) + i\eta(t) + \epsilon(t)|^2\right) = I_0\left(\sigma^2 + \psi^2(t) + \eta^2(t) + \epsilon(t)^2 + 2\psi(t)\eta(t)\right)$$

ALPS II-VMB

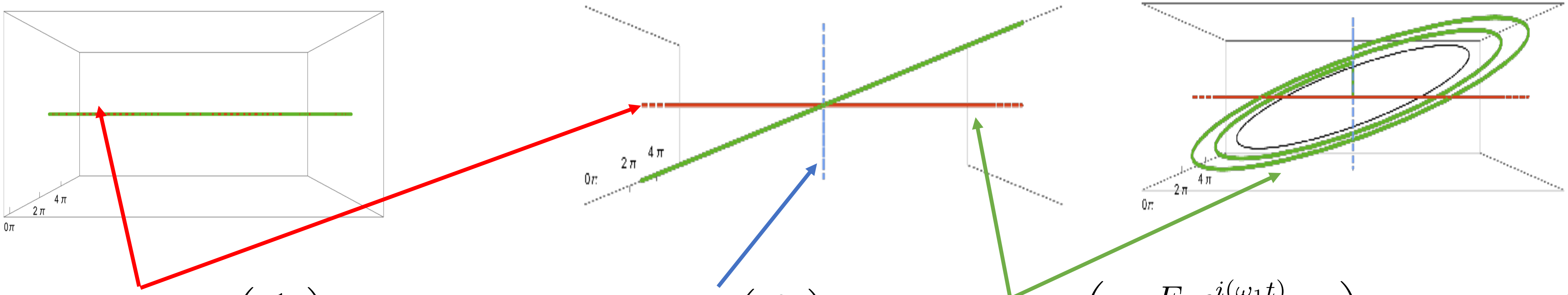




Heterodyne detection

$$I_2(t) = I_0\left(\sigma^2 + |i\psi(t) + i\eta(t) + \epsilon(t)|^2\right) = I_0\Big(\sigma^2 + \psi^2(t) + \eta^2(t) + \epsilon(t)^2 + 2\psi(t)\eta(t)\Big)$$

Polarimetry and UHF GWs: Heterodyne Interferometry

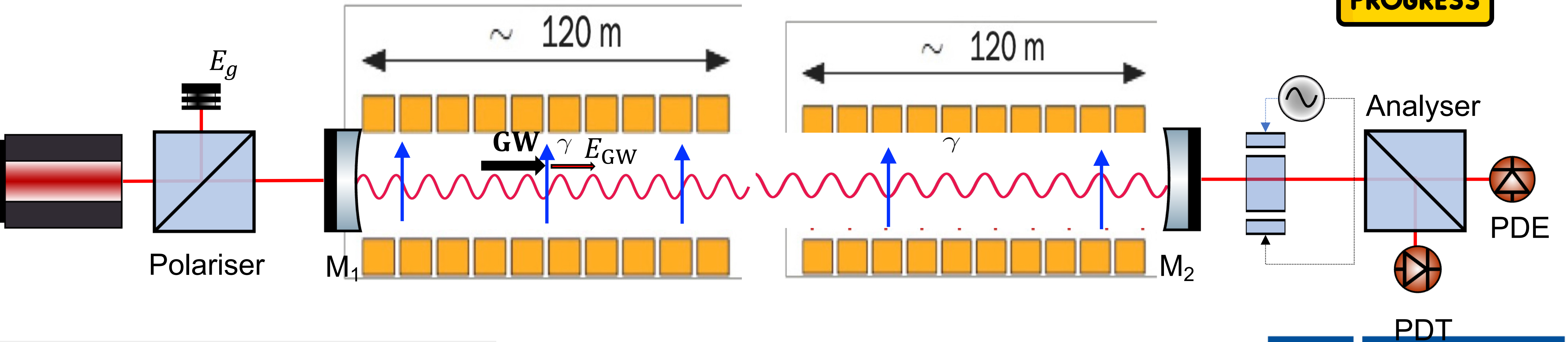


$E_{\mathrm{L}} e^{i(\omega t+\phi)} \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix}$

$E_{\mathrm{GW}} e^{i(\omega_1 t+\phi)} \cdot \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

$\mathcal{E}(t) = \begin{pmatrix} E_{\mathrm{L}} e^{i(\omega_1 t)} \\ E_{\mathrm{GW}} e^{i(\omega_2 t+\phi)} \end{pmatrix}$

WORK IN PROGRESS



Polarimetry for low-mass (sub-eV) bosonic field dark matter

PHYSICAL REVIEW D **107**, 083035 (2023)

Probing dark matter with polarimetry techniques

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(Received 17 November 2022; accepted 31 March 2023; published 28 April 2023)

- Produced in early Universe, manifests as oscillating field with local density ρ_{local}

$$\phi(t,\vec{r}) = \left[\frac{\hbar\sqrt{2\,\rho_{\text{local}}}}{m_\phi\, c}\right] \cos\left(\omega_\phi\, t - \vec{k}_\phi \cdot \vec{r}\right)$$

- Trapped and virialised in gravitational potential wells of e.g. galaxies

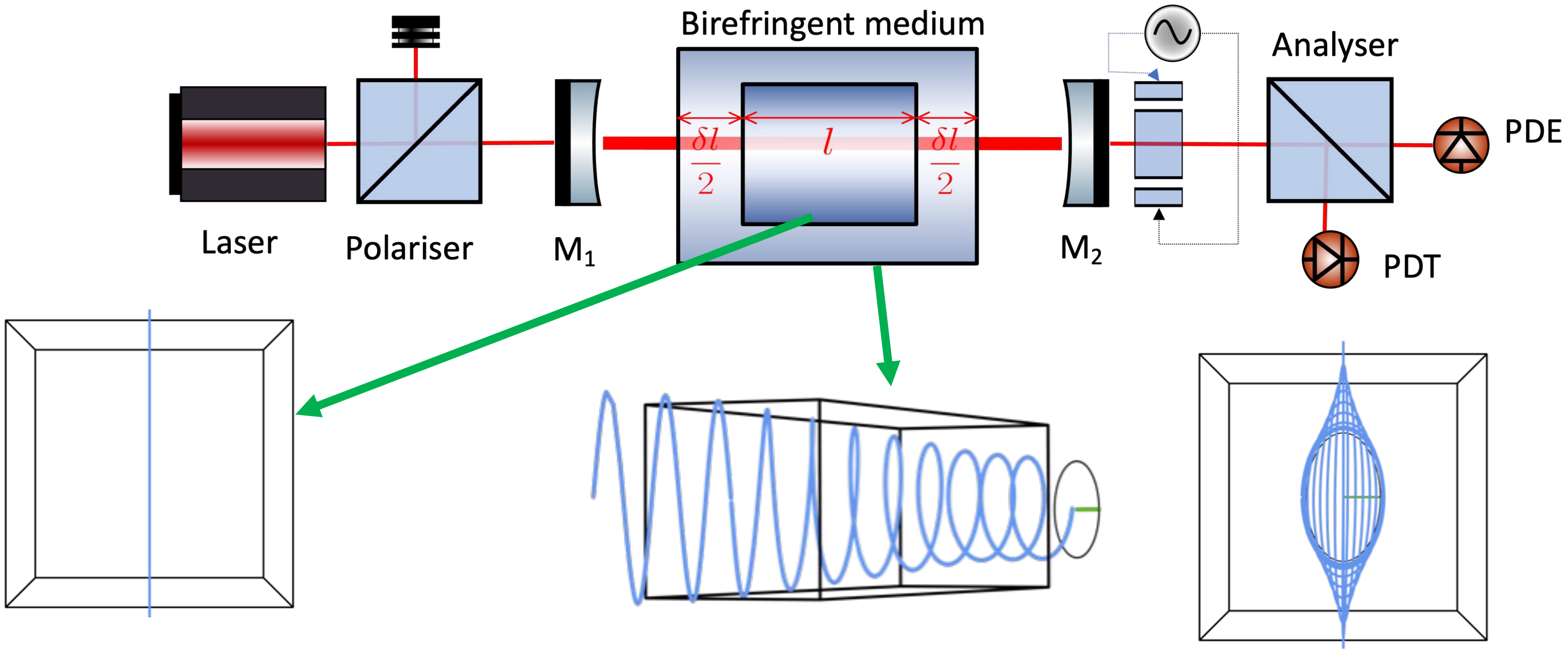
- Scalar Field

$$\mathcal{L}_{\text{int}} = \frac{\phi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} - \frac{\phi}{\Lambda_e} m_e \bar{\psi}_e \psi_e$$

- Pseudoscalar Axion

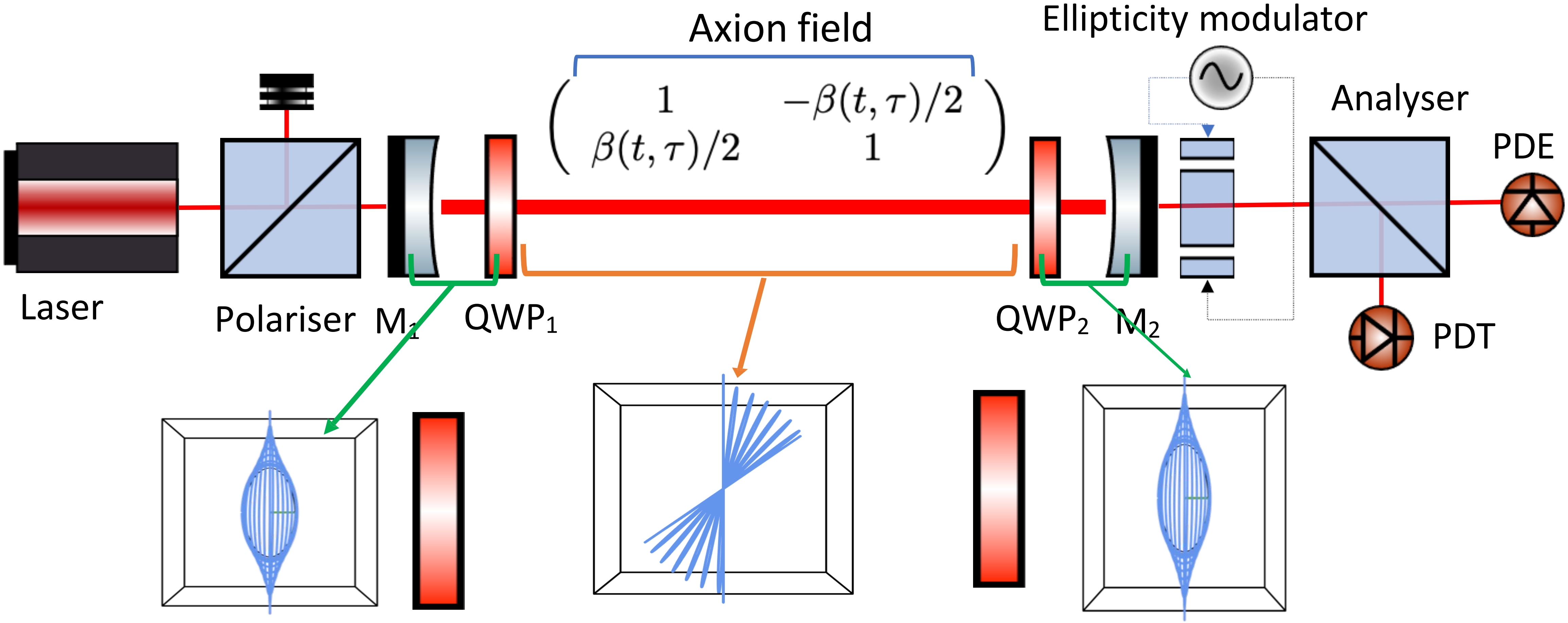
$$\mathcal{L}_{\text{int}} = \frac{a g_{a\gamma}}{4} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Polarimetry for scalar filed DM



$$\frac{\delta\beta}{\beta} = \frac{S_{\mathrm{P}}^{(\mathrm{tot})}\lambda\sqrt{P^2 + 4\sin^2\pi\nu\tau}}{2\pi d\Delta n}.$$

Polarimetry for Axion DM

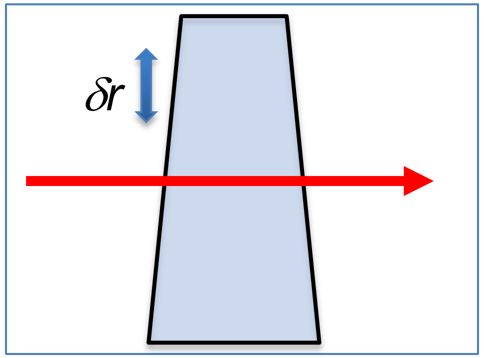


$$g_{a\gamma} = \frac{S_{\mathrm{P}}^{(\mathrm{tot})}}{2\tau}\sqrt{\frac{P_{\mathrm{AR}}^2 + 4\sin^2\left(\pi\nu_{\mathrm{a}}\tau\right)}{2\rho_{\mathrm{local}}}}$$

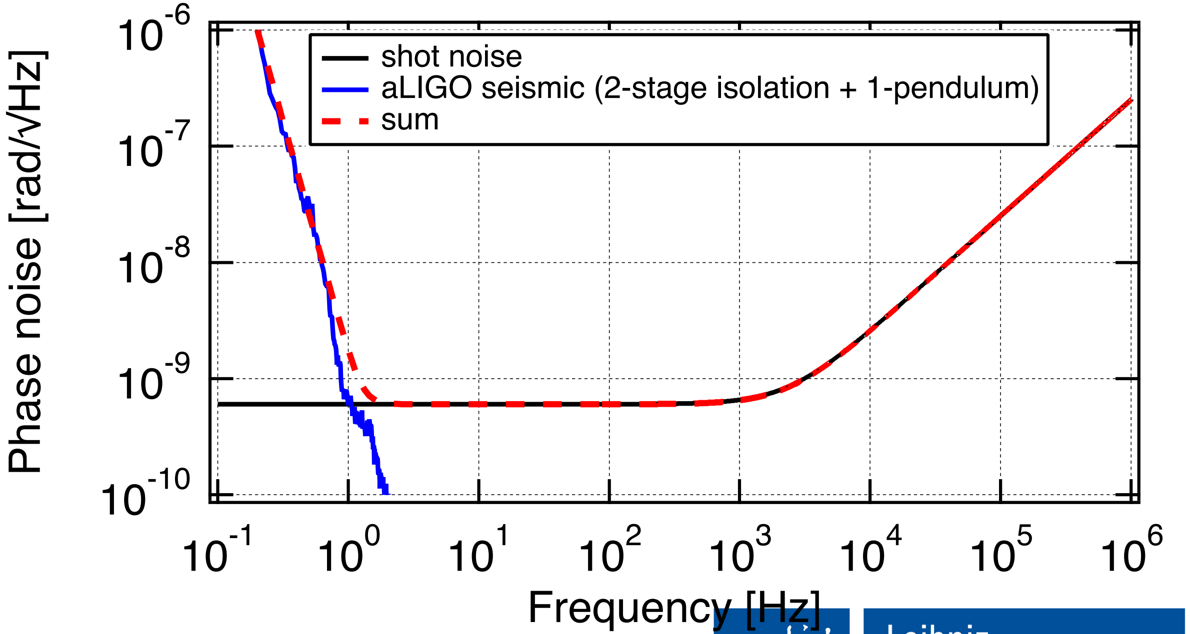
Noise budget

$$S_{\mathrm{P}}^{(\mathrm{tot})} \approx \sqrt{S_{\mathrm{P}}^{(\mathrm{shot})\,2} + S_{\mathrm{P}}^{(\mathrm{seismic})\,2} + S_{\mathrm{P}}^{(\mathrm{RIN})\,2} + S_{\mathrm{P}}^{(\mathrm{dark})\,2}}$$

$$S_{\mathrm{P}}^{(\mathrm{seismic})} = 2\pi \frac{N\,\delta r\,\theta}{\lambda}\,\Delta n \gamma(L, f)$$



Input power	I_0	1 W
PDE quantum efficiency	q	0.7 A/W
PDE gain	G	$10^6\ \Omega$
Extinction ratio	σ^2	2×10^{-7}
Dark noise	i_{dark}	$25\ \mathrm{fA_{rms}}/\sqrt{\mathrm{Hz}}$
Modulation amplitude	η_0	1.5×10^{-3}
Modulation frequency	ν_{PEM}	50 kHz
RIN	$N_{\nu_{\mathrm{PEM}}}^{(\mathrm{RIN})}$	$3 \times 10^{-7}/\sqrt{\mathrm{Hz}}$
Seismic noise coupling	γ	0.1
Cavity build-up	N	20 000
Solid/QWP wedge	θ	1 μrad
Yttrium Vanadate	C	12×10^{-3}
Sapphire	C	6.6×10^{-3}



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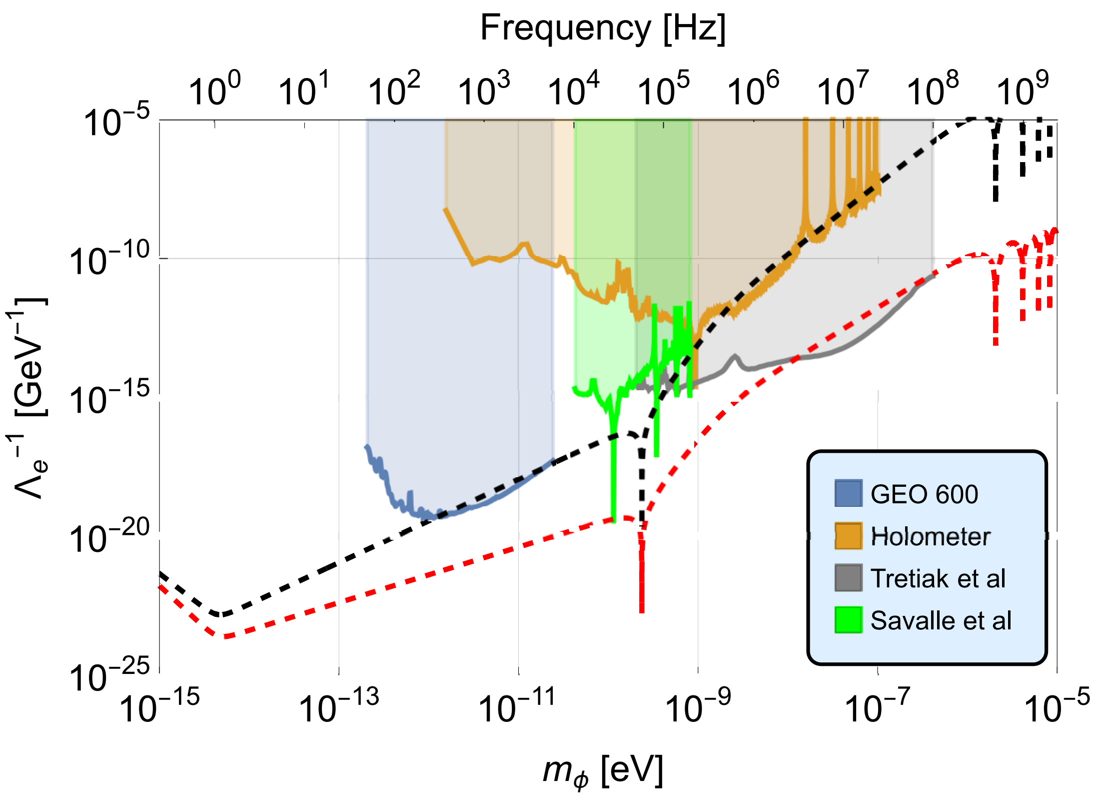
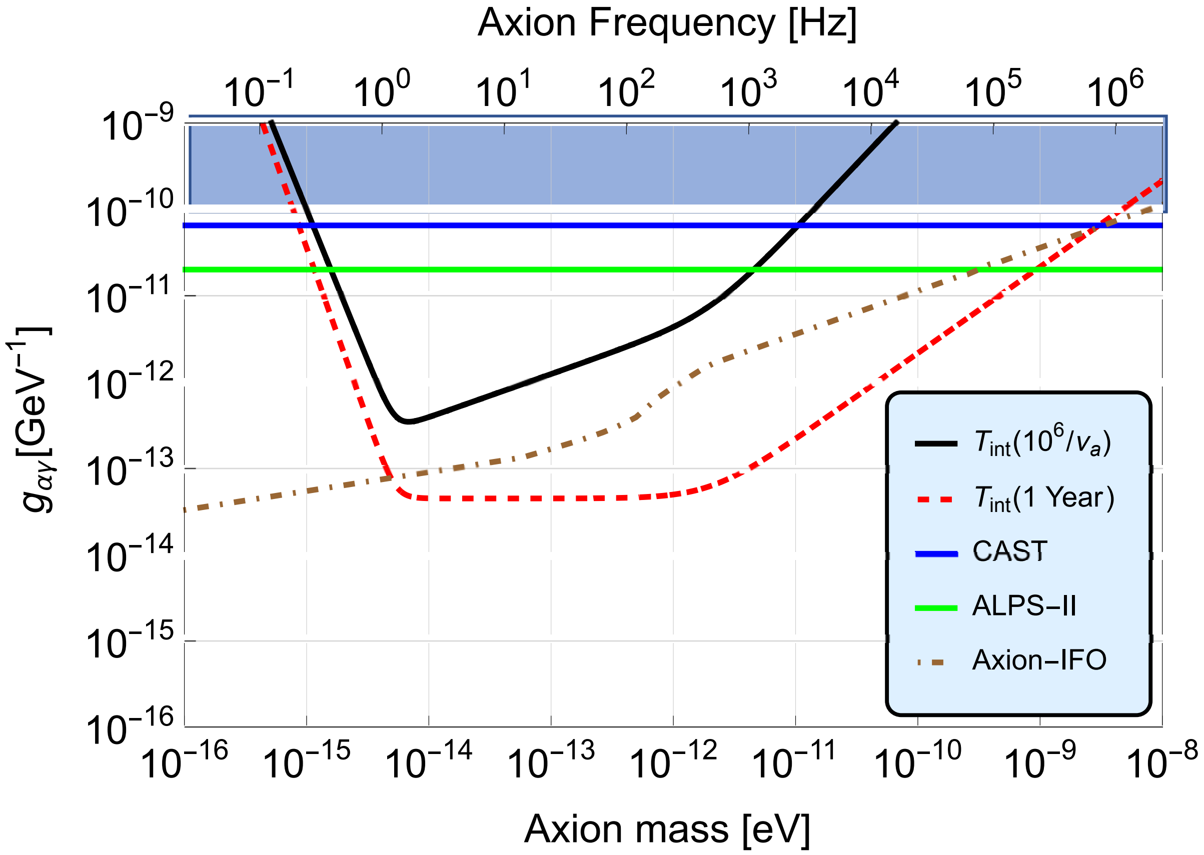
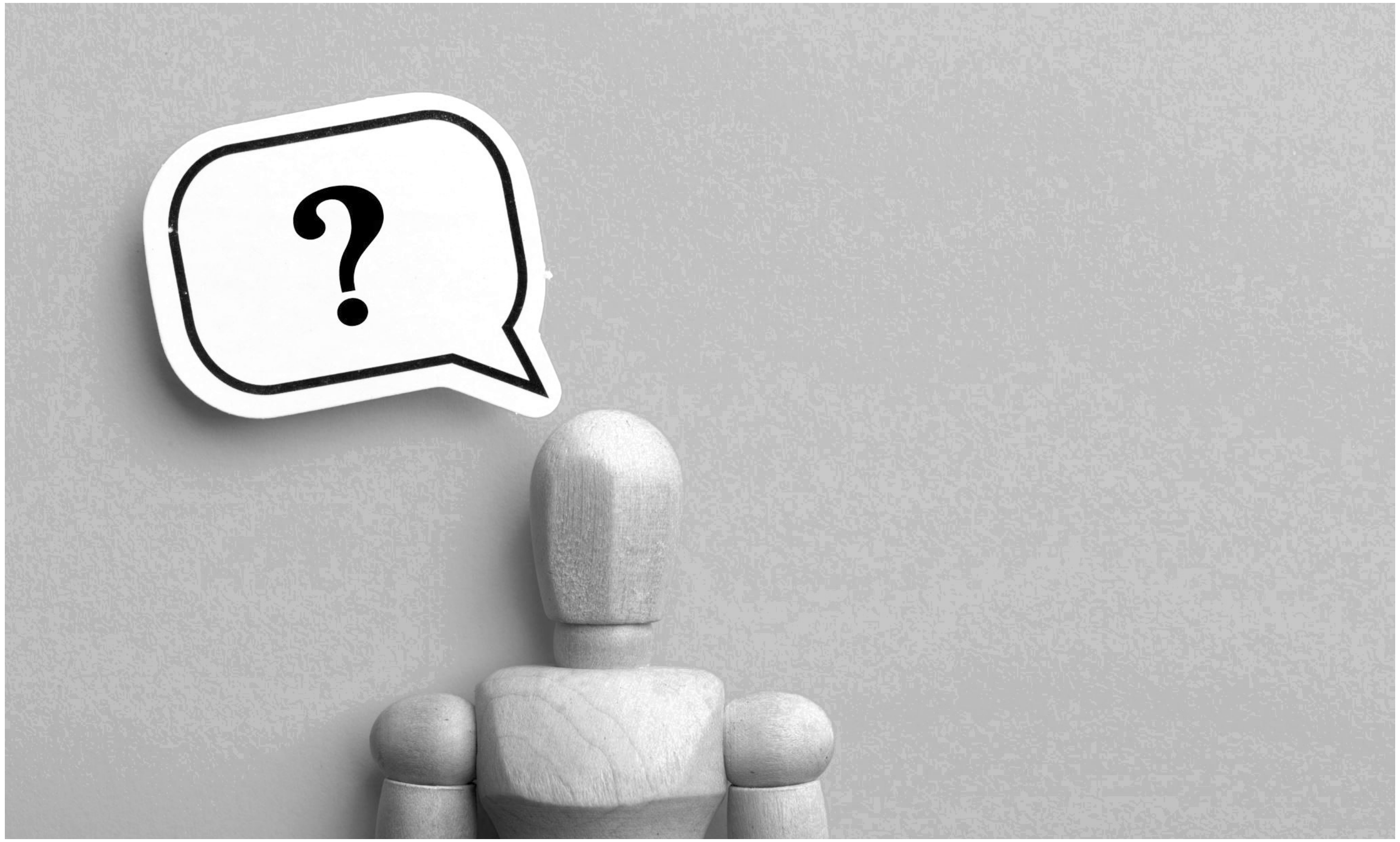
Prospects for scalar and axion field dark matter





Thank you for your attention



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