Exploring dark matter and quantum space-time fluctuations through precision laser interferometry

Aldo Ejlli

Gravity Exploration Institute – Cardiff University

Searching for New Physics at the Quantum Technology Frontier

Ascona (Ticino), Switzerland

July 4th, 2023

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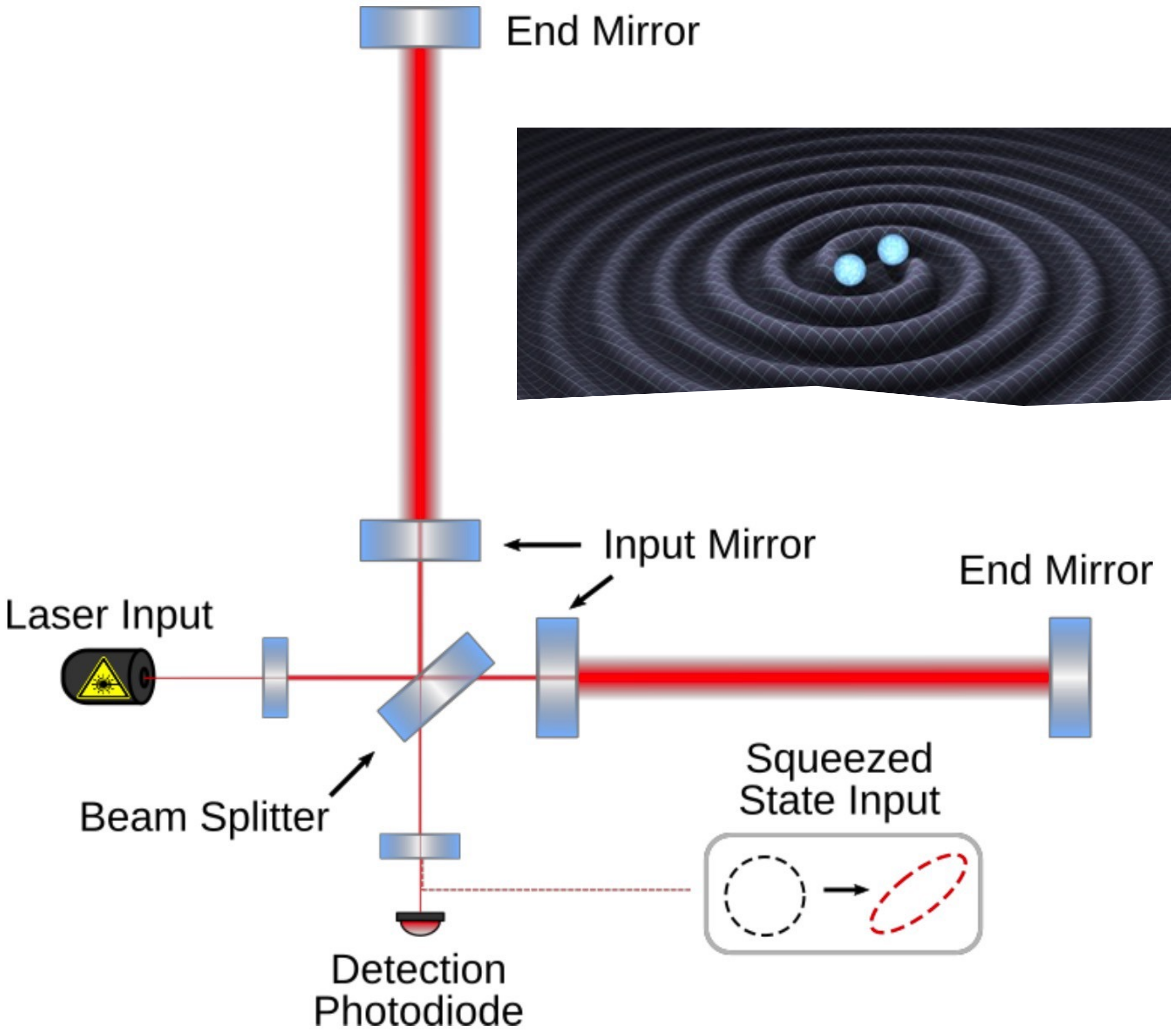
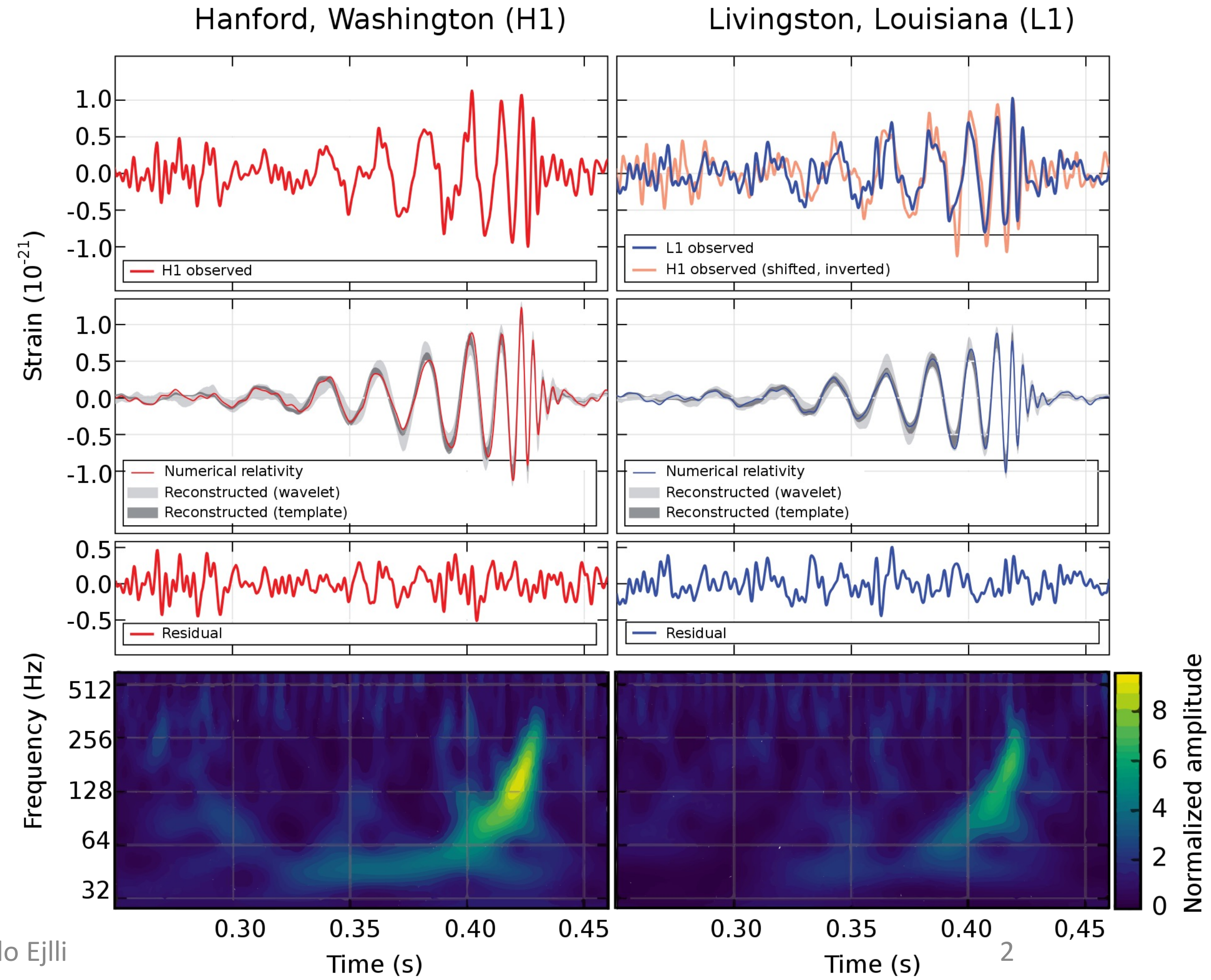
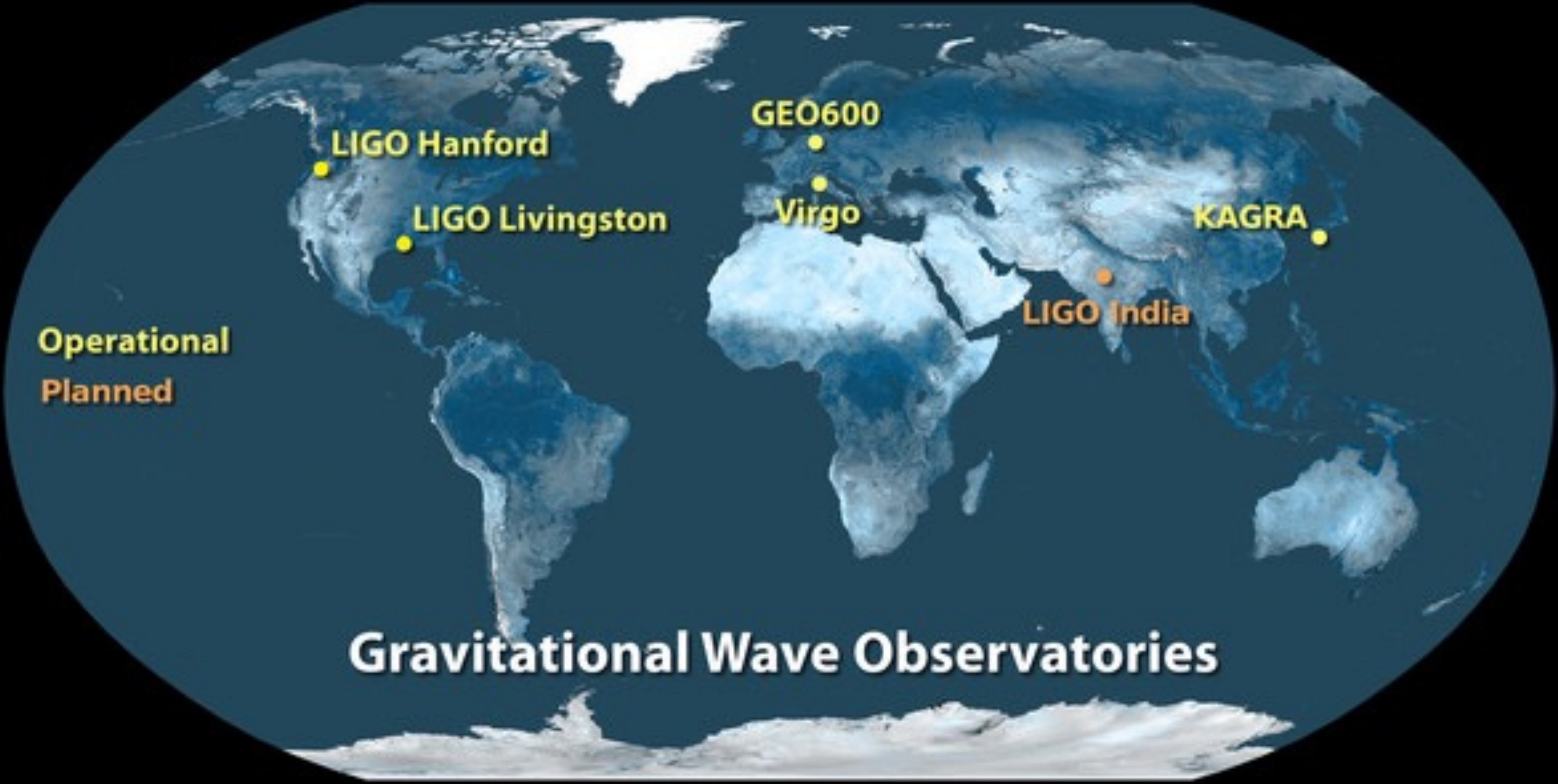
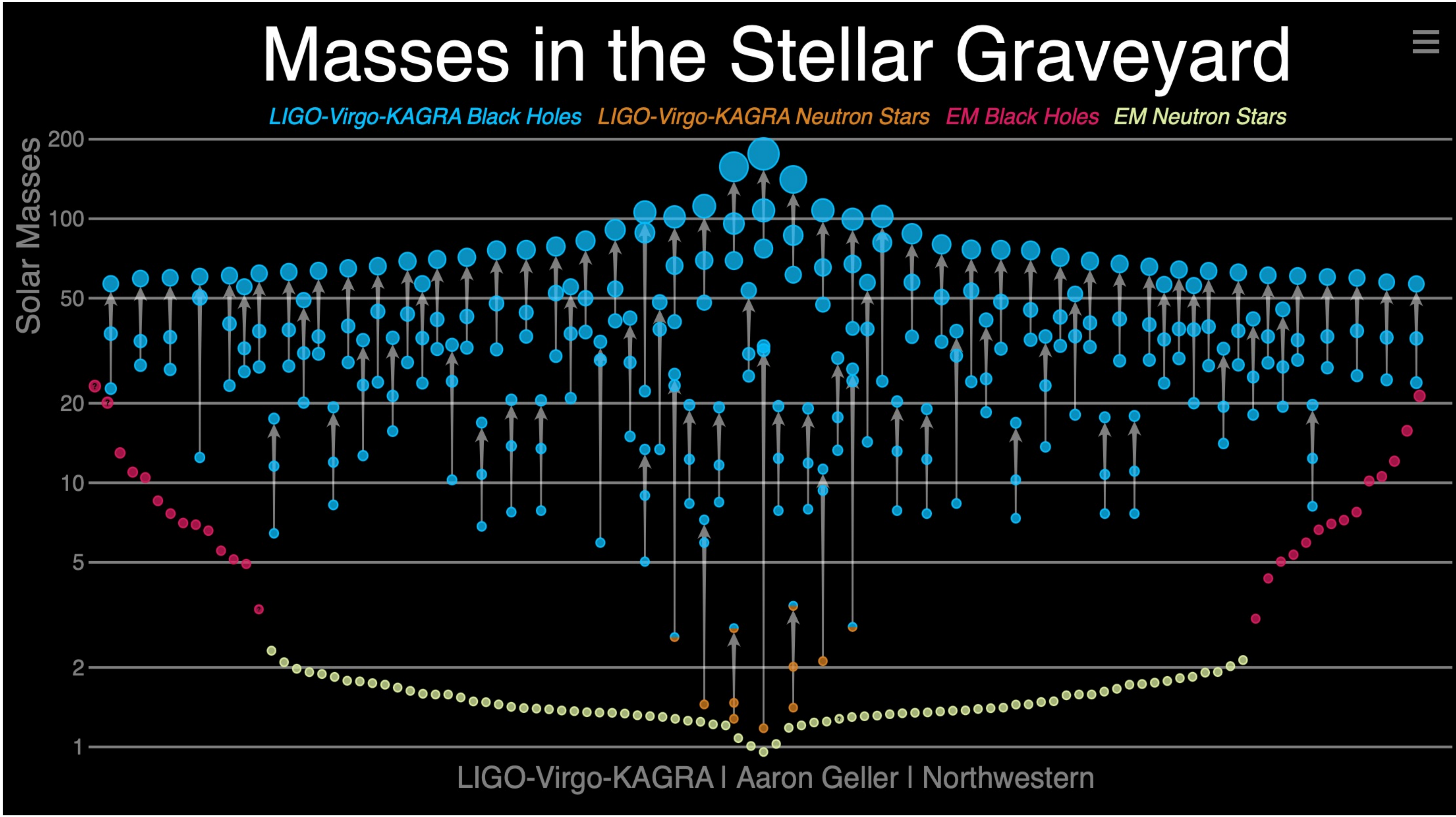
The Success of Laser Interferometry: GW Detection

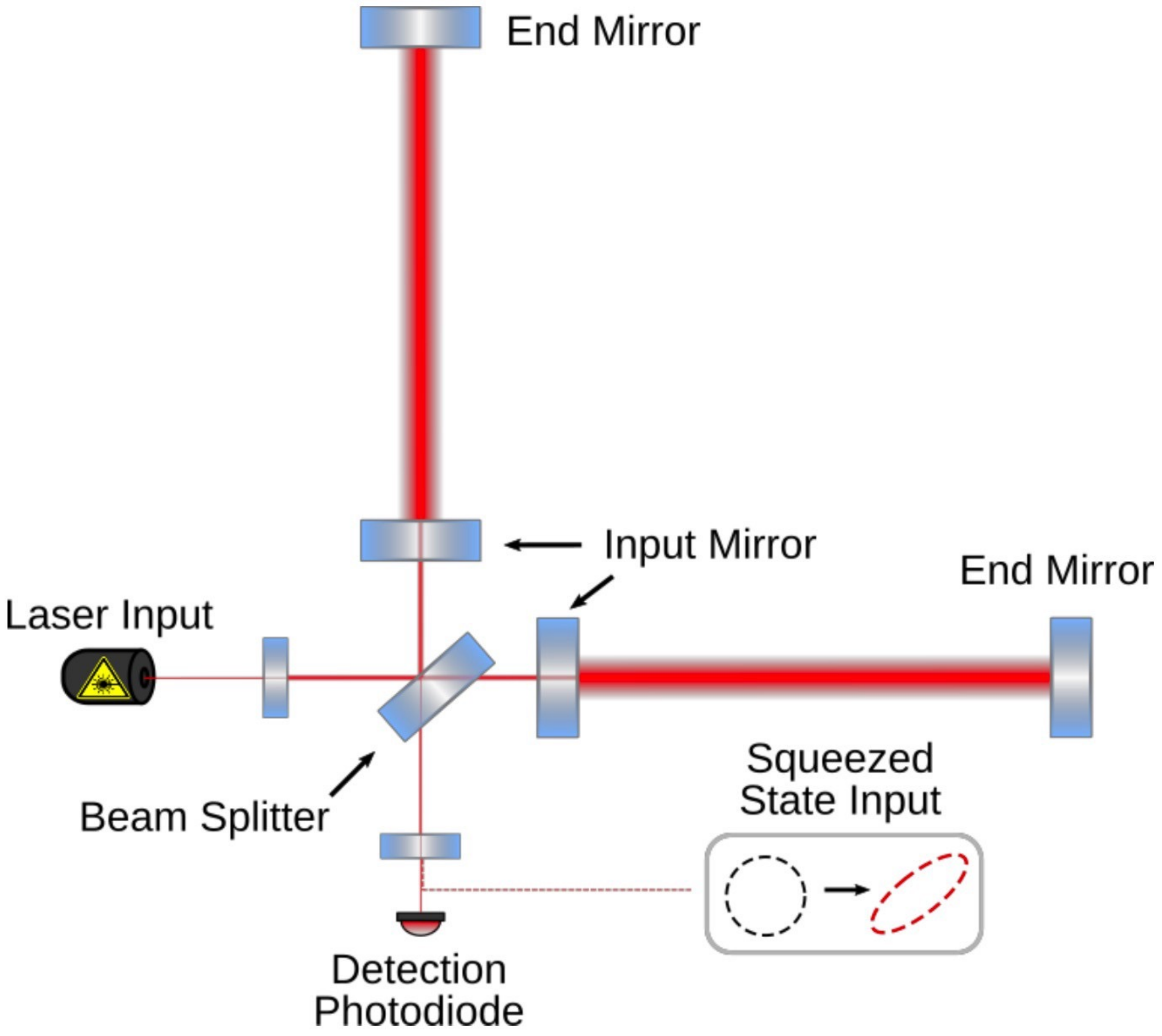





GEO600
LIGO Hanford
Virgo
LIGO Livingston
KAGRA
LIGO India
Operational
Planned
Gravitational Wave Observatories


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Potential of Laser Interferometry



Can laser interferometry be used for investigating:

- Quantum spacetime?
- Fundamental physics?
- Dark matter?

Potential of Laser Interferometry

- **Quantum spacetime**
- Fundamental physics
- Dark matter

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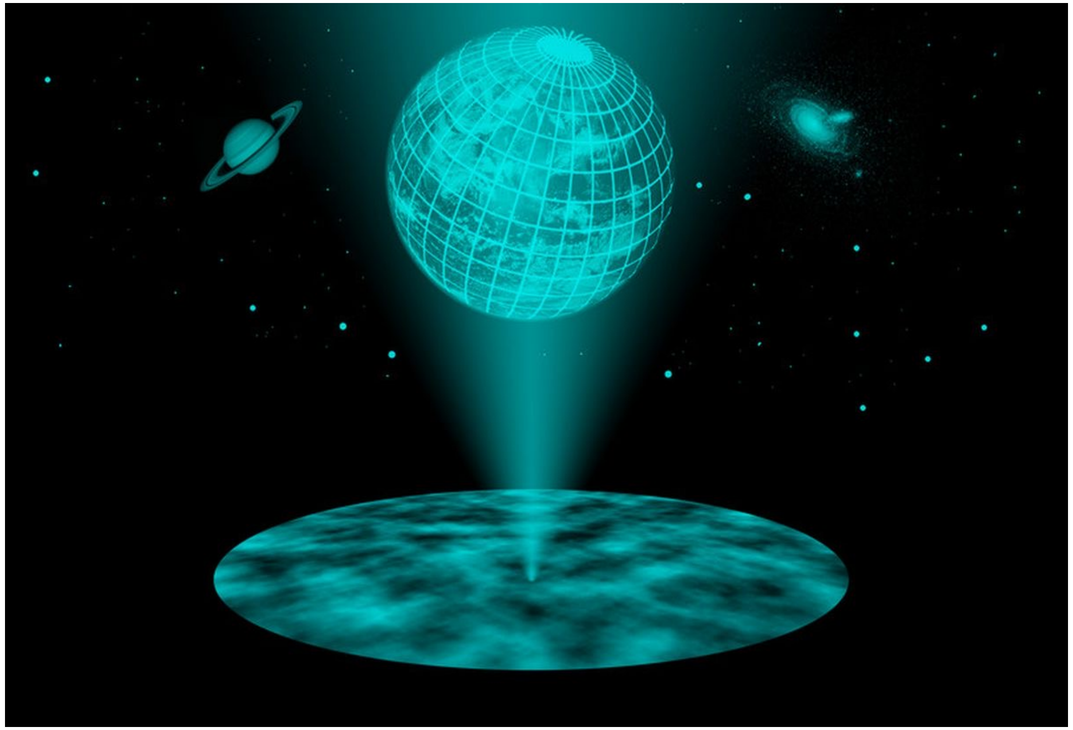
Holographic principle



Measurements of a distance will show fluctuations:

$$\delta L \propto (l_{\mathrm{P}})^{\alpha}(L)^{1-\alpha}$$

The scaling constant depends on different models of spacetime:

- Alpha = 1/2 : Verlinde&Zurek, Hogan&Kwon

$$\delta L \propto \sqrt{(1.62 \times 10^{-35}\ \mathrm{m})}\sqrt{(1\ \mathrm{m})} = 4 \times 10^{-18}\ \mathrm{m}$$

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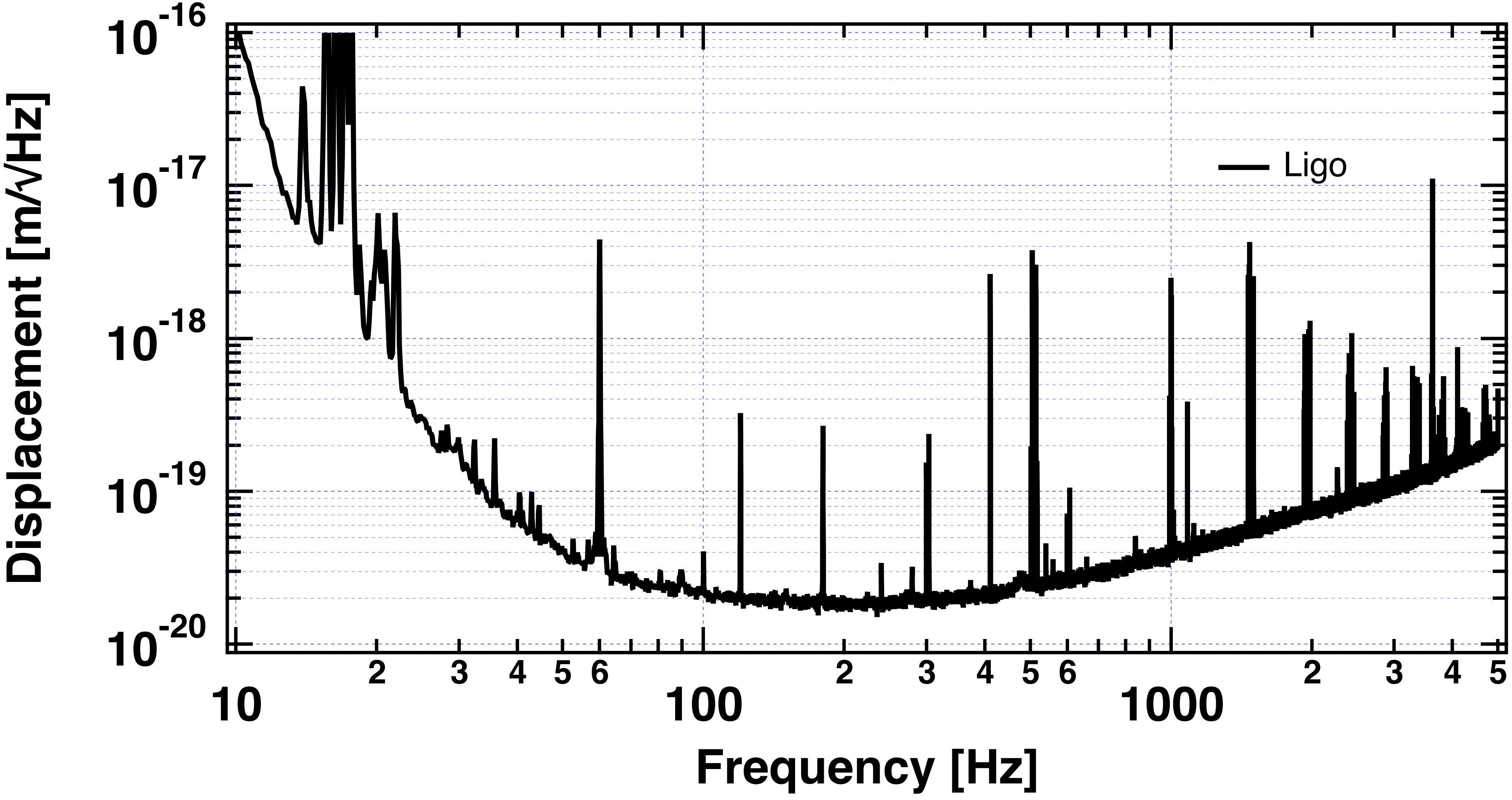
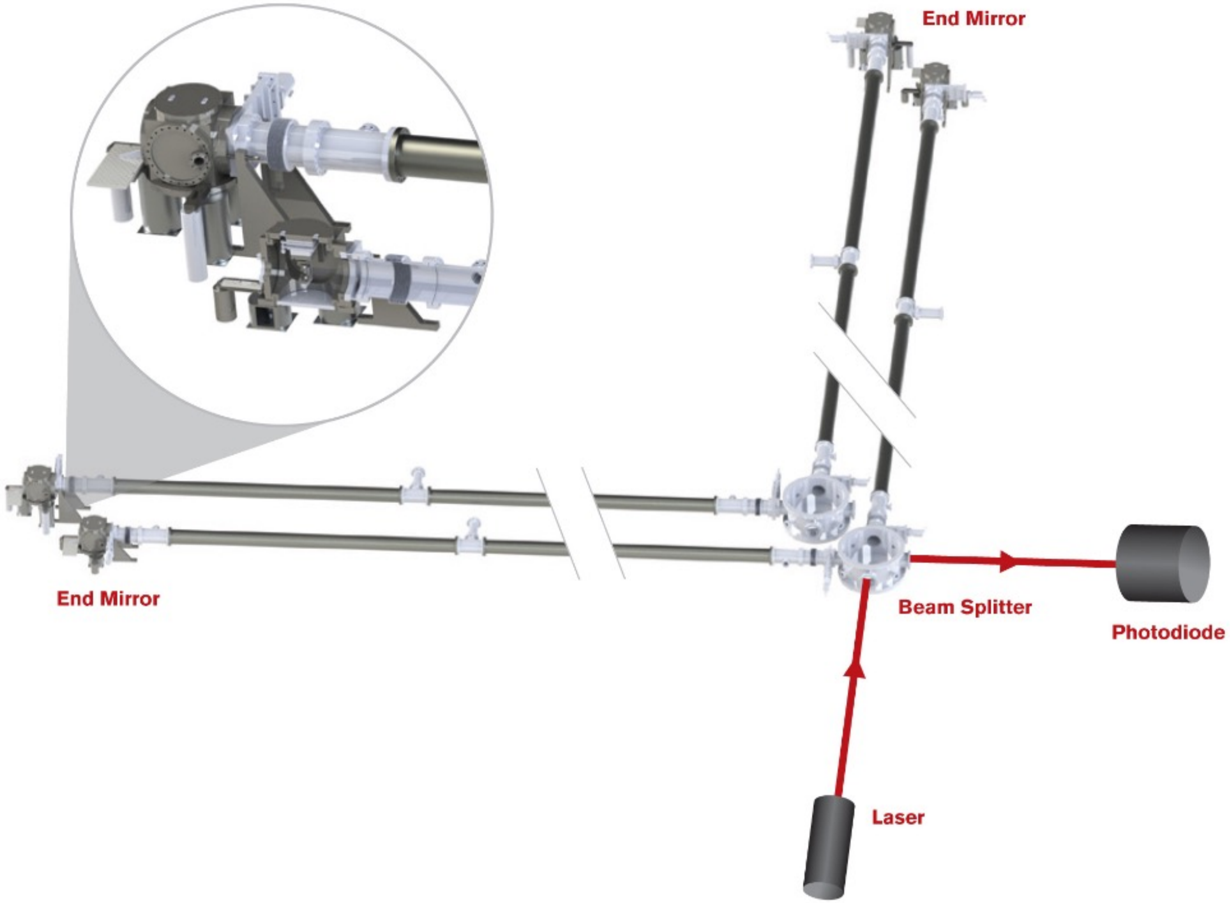
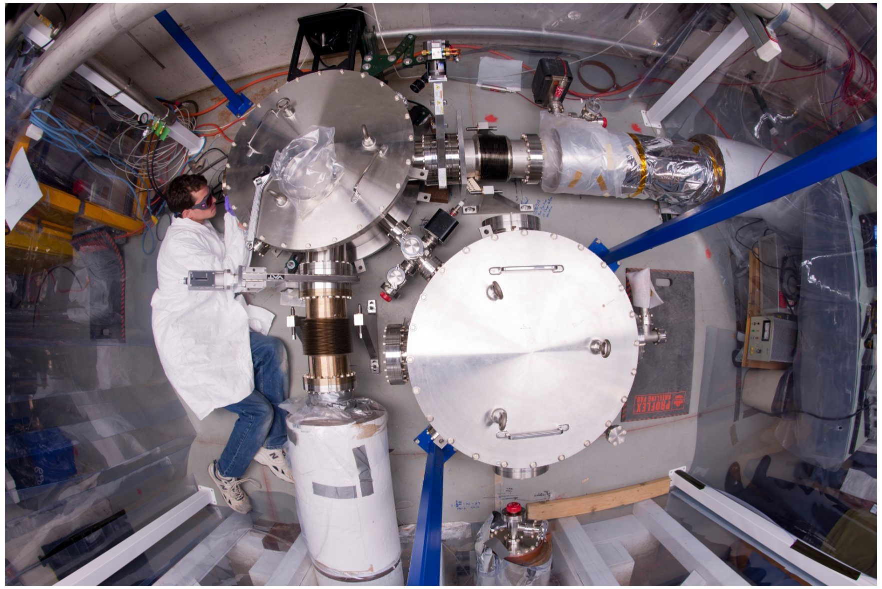
Displacement sensitivity: GW detectors



Fermilab Holometer: Laser Interferometry to detect Spacetime Fluctuations



Fermilab



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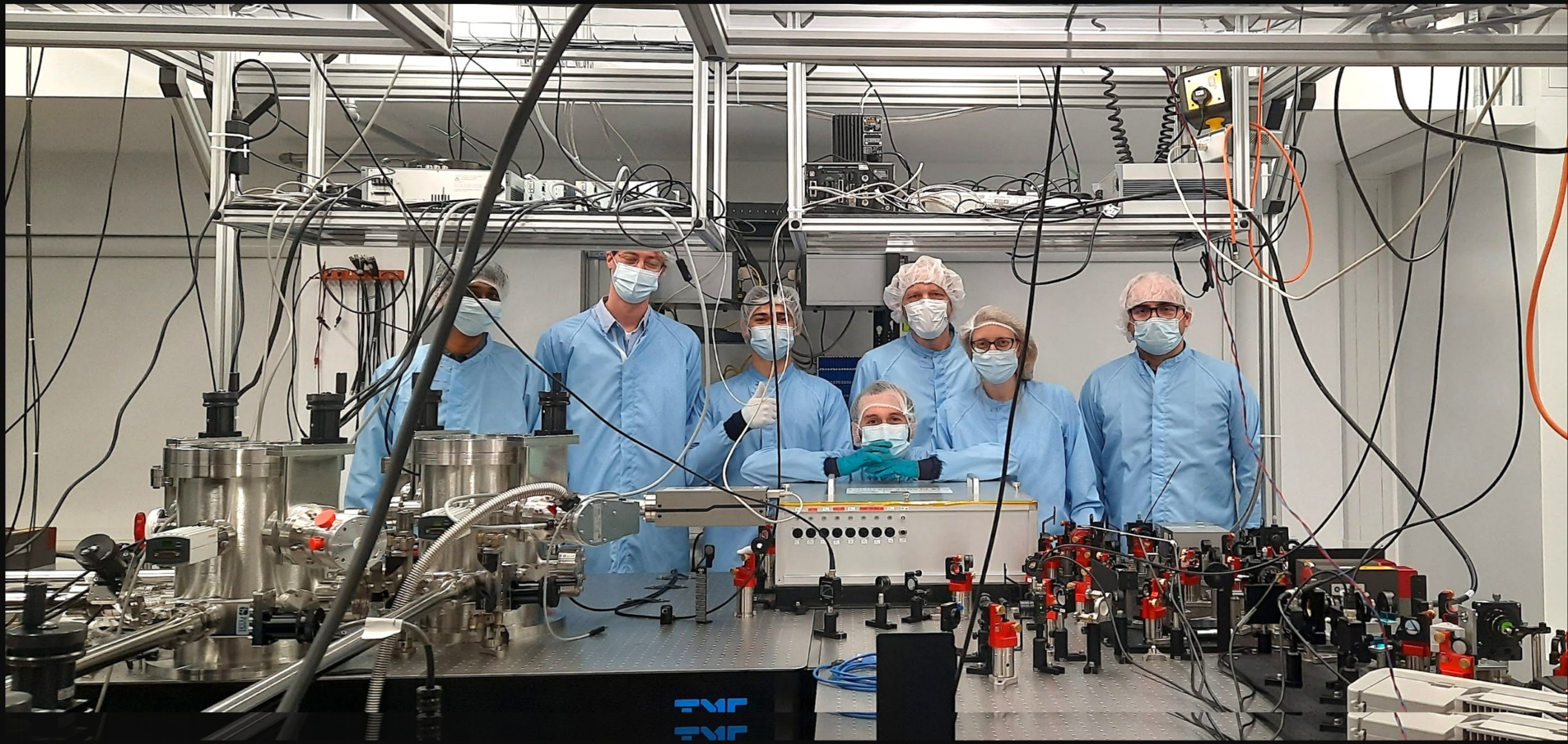
QUEST Experiment



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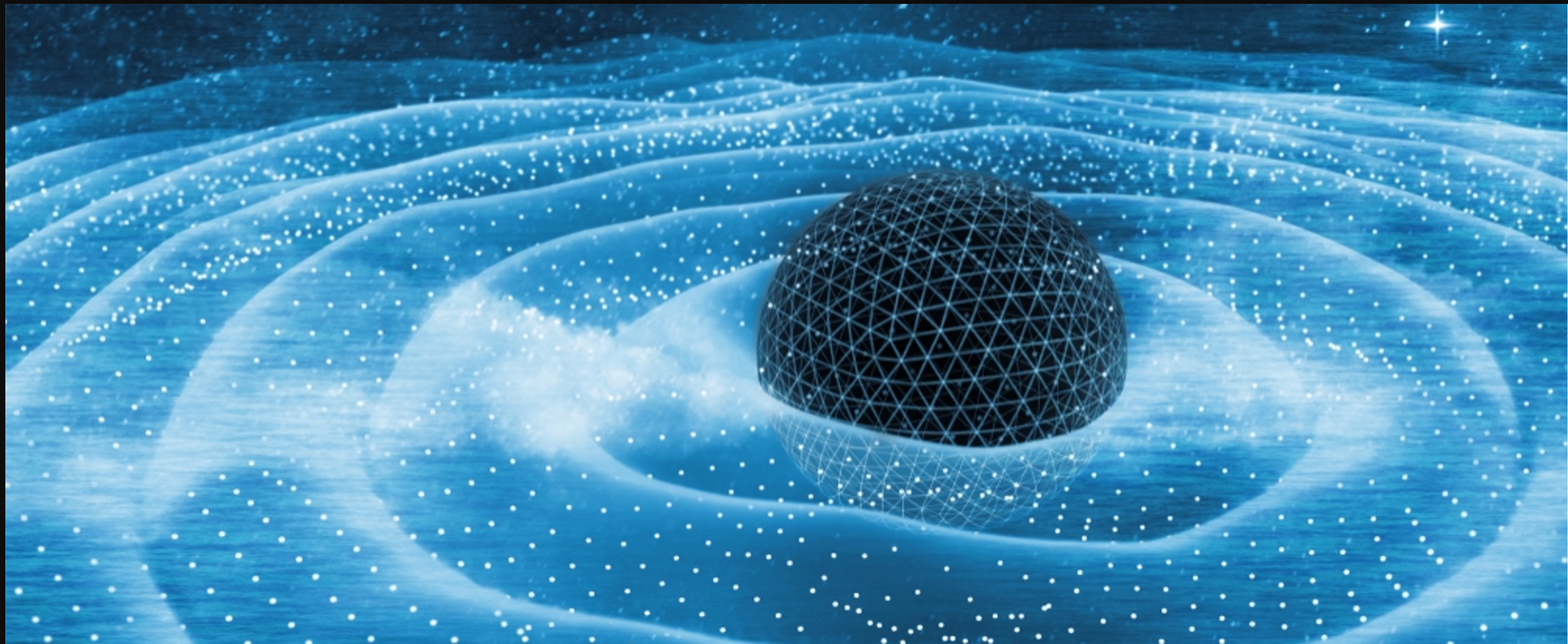


QUEST: Improvements

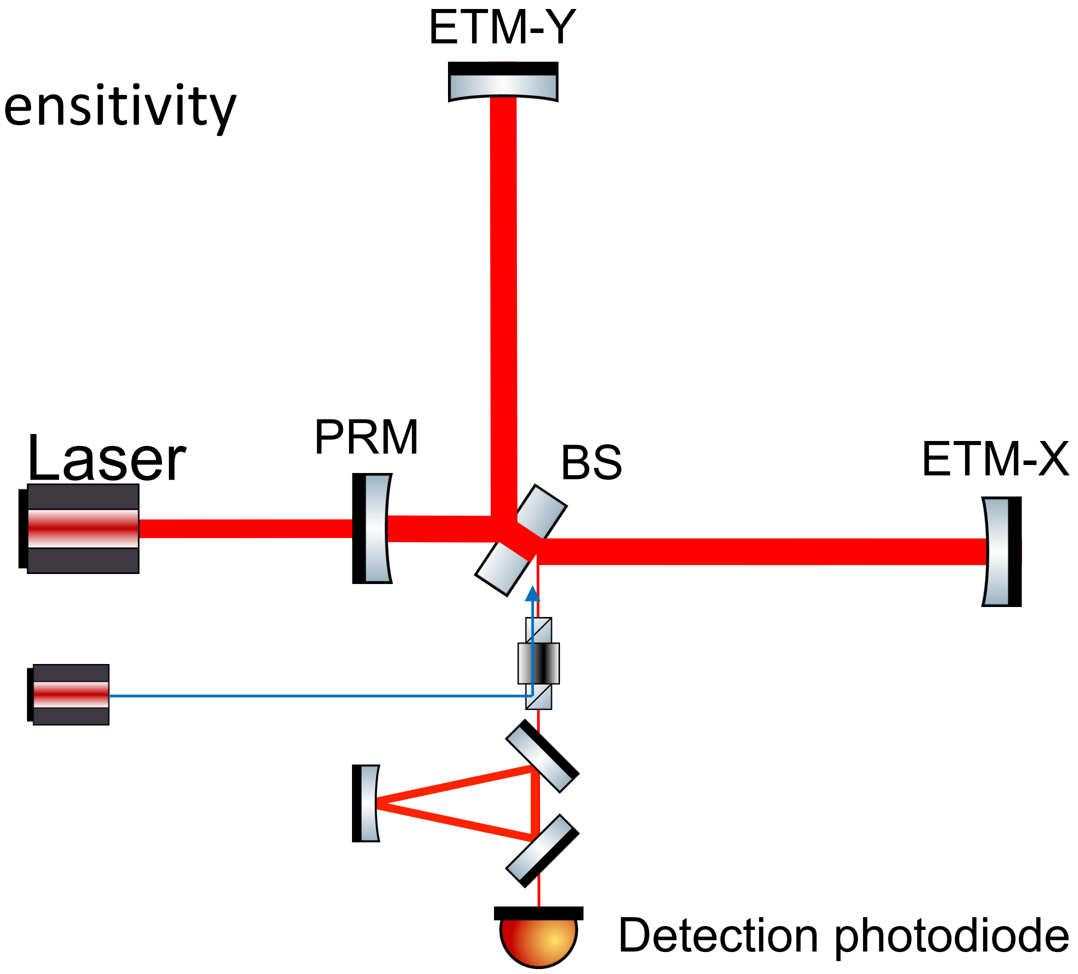
Target: one order of magnitude improved sensitivity with respect to the Holometer

- Upgrades with respect to the Holometer:

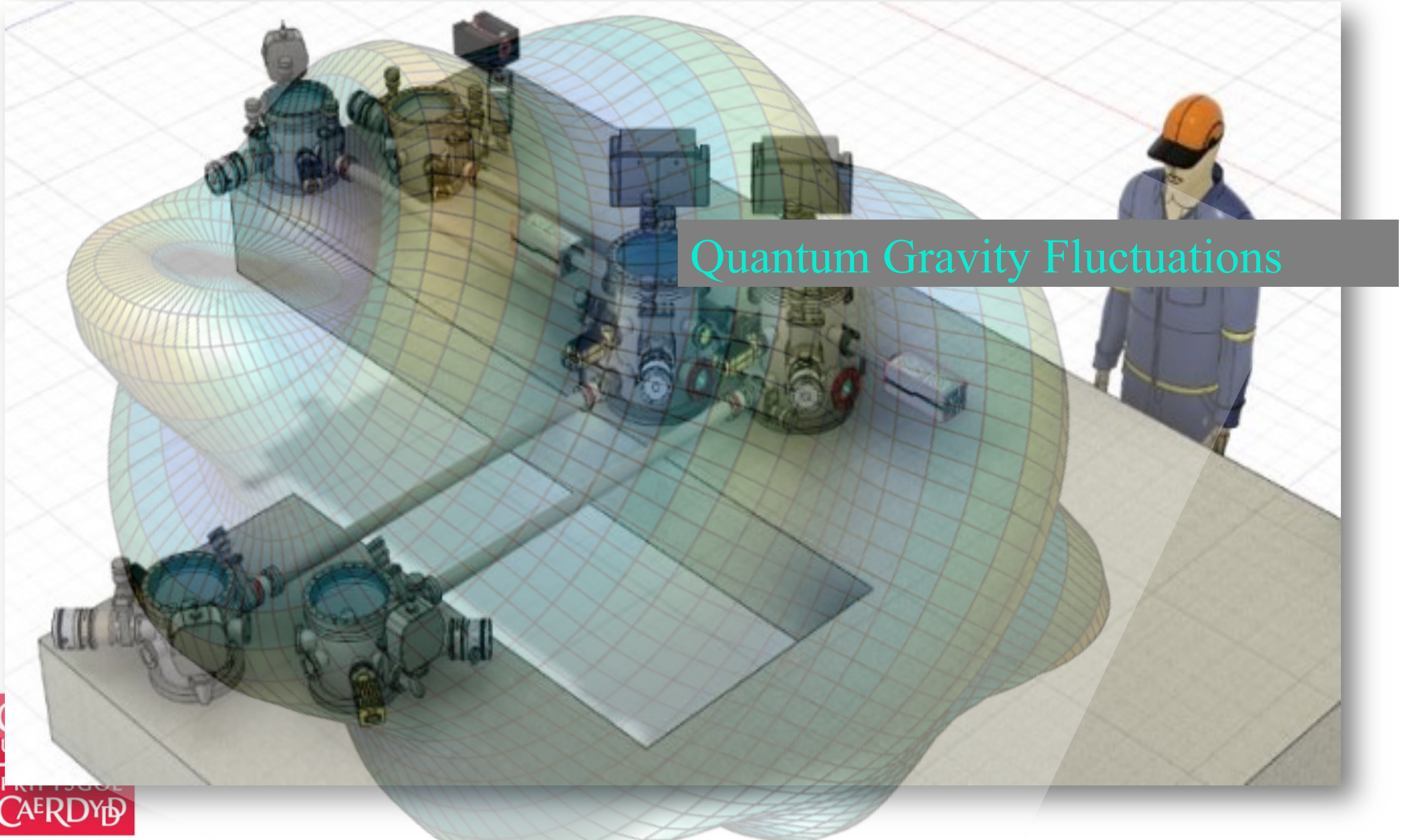
- Higher input power

- Output Mode Cleaner

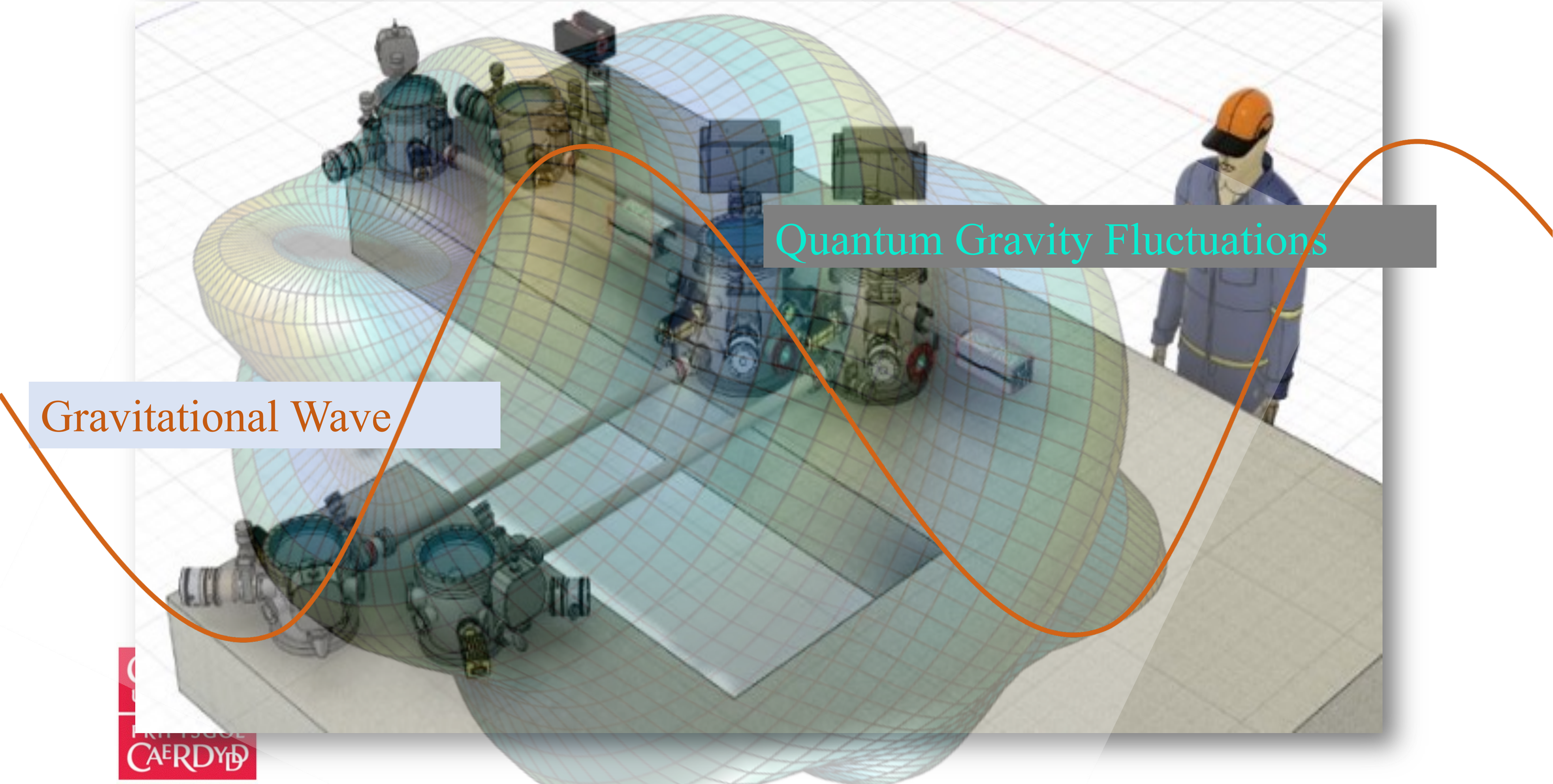
- Squeezed states of light



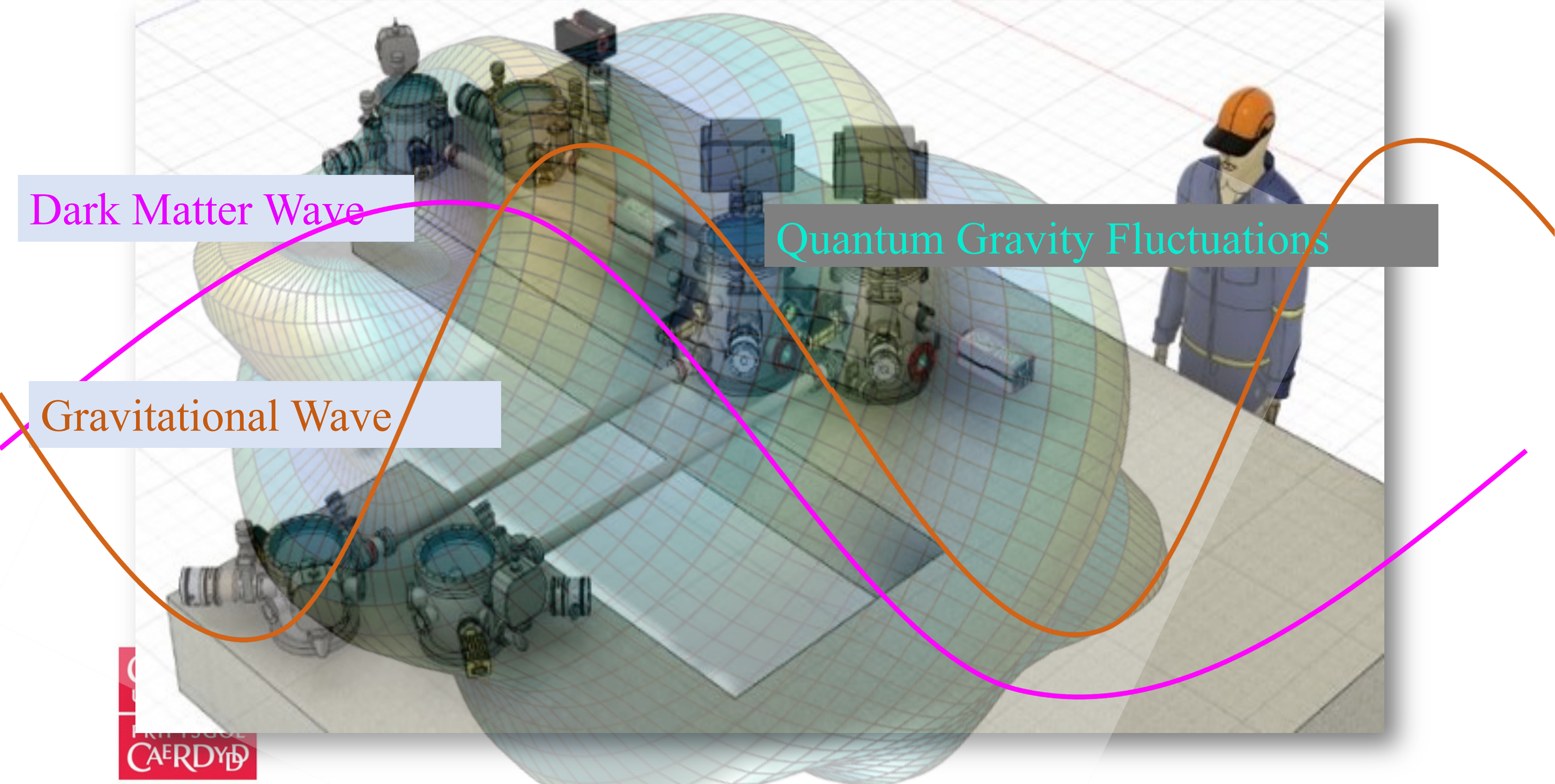
QUEST experiment: two co-located Interferometers



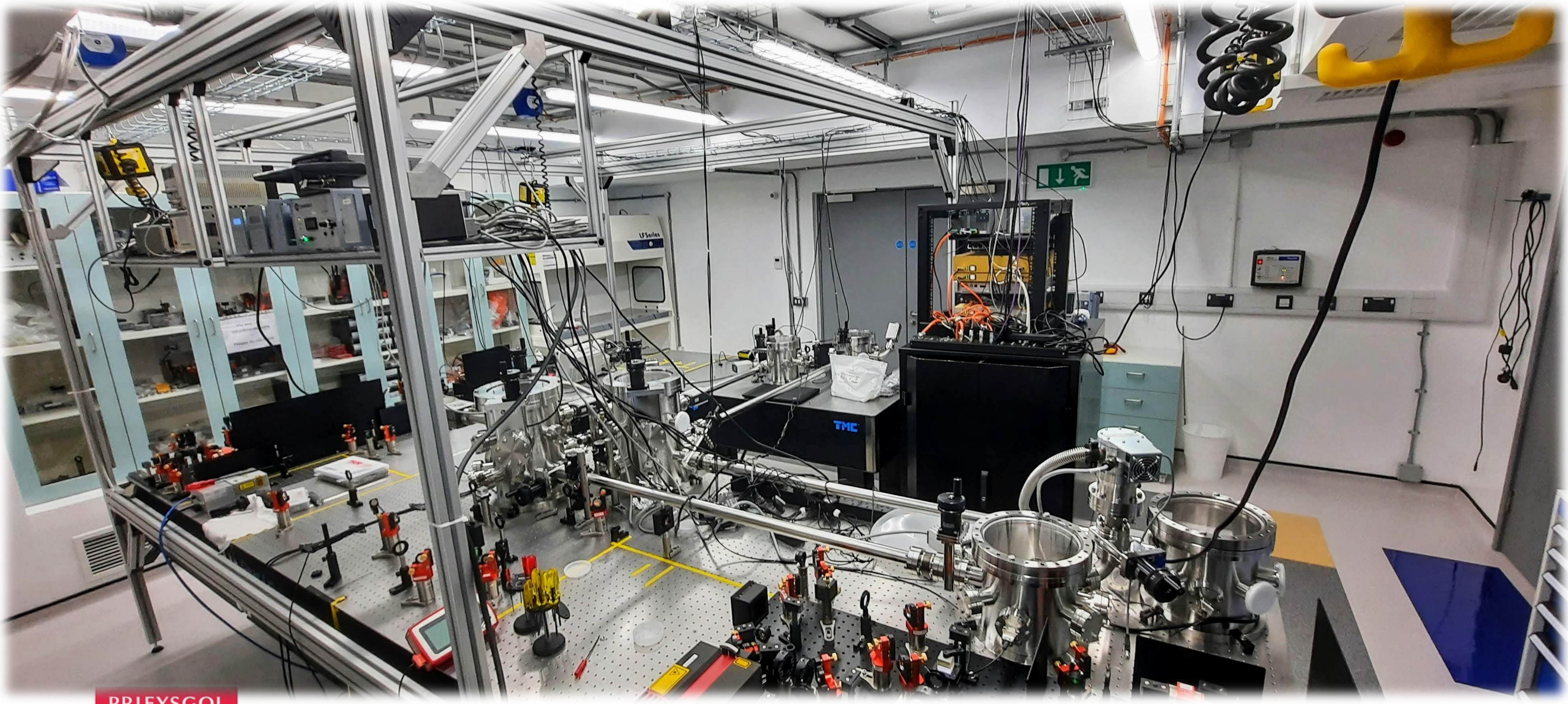
QUEST experiment: two co-located Interferometers



QUEST experiment: two co-located Interferometers



QUEST currently under commissioning



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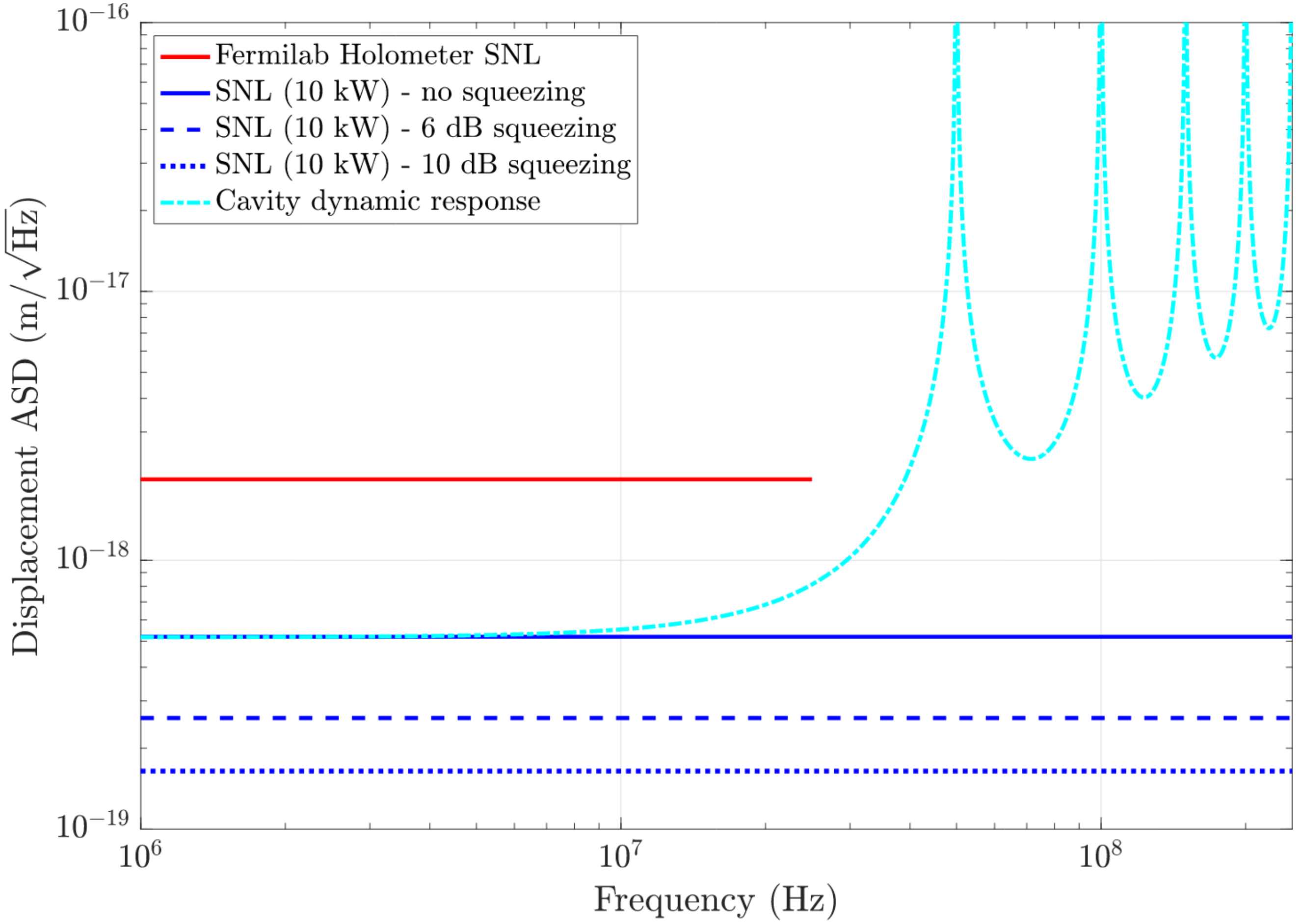
Planned sensitivity



Class. Quantum Grav. **38** (2021) 085008 (24pp) https://doi.org/10.1088/1361-6382/abe757

An experiment for observing quantum gravity phenomena using twin table-top 3D interferometers

S M Vermeulen*, **L Aiello**, **A Ejlli**, **W L Griffiths**, **A L James**, **K L Dooley** and **H Grote**

Gravity Exploration Institute, Cardiff University, Cardiff CF24 3AA, United Kingdom

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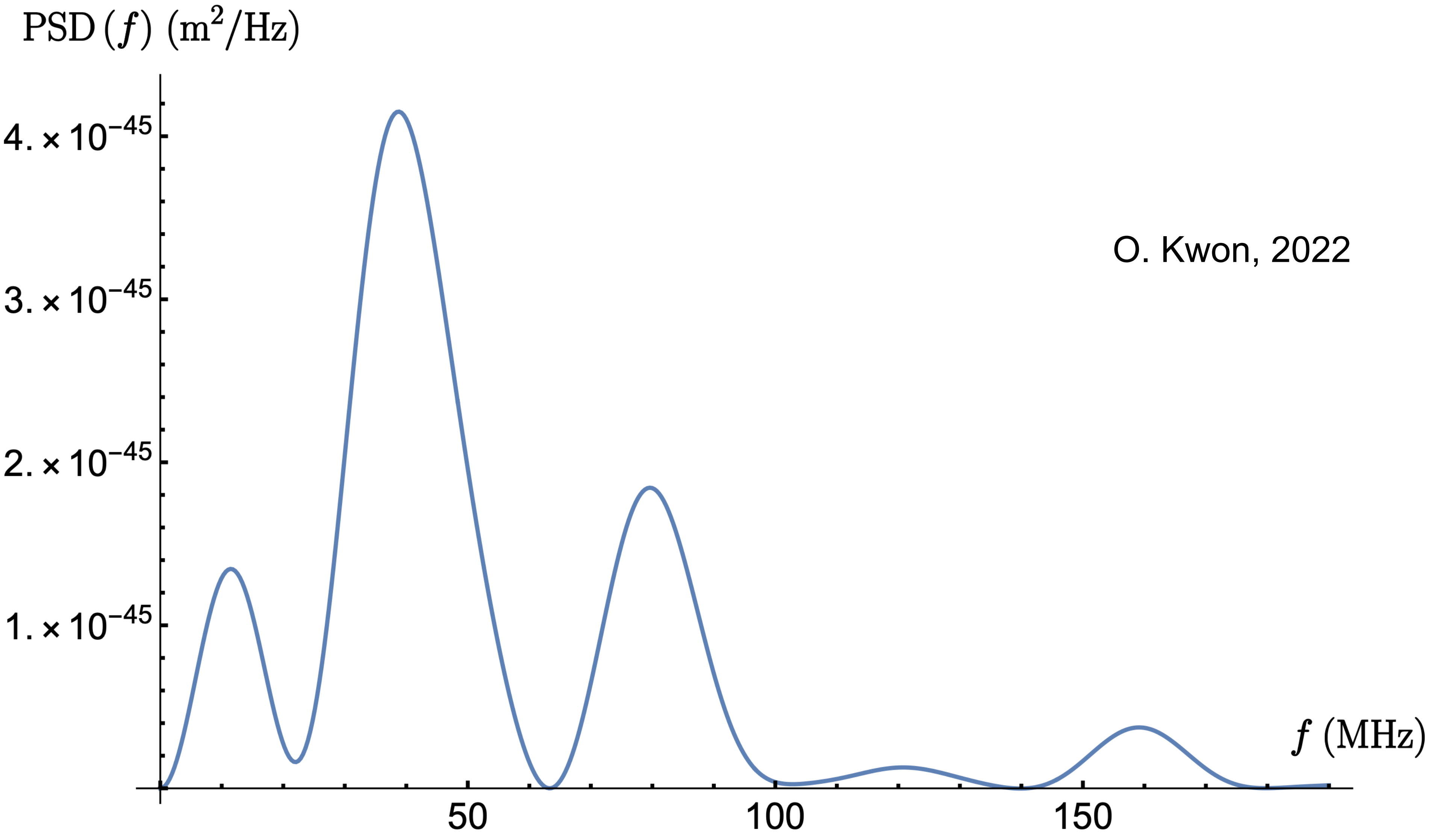
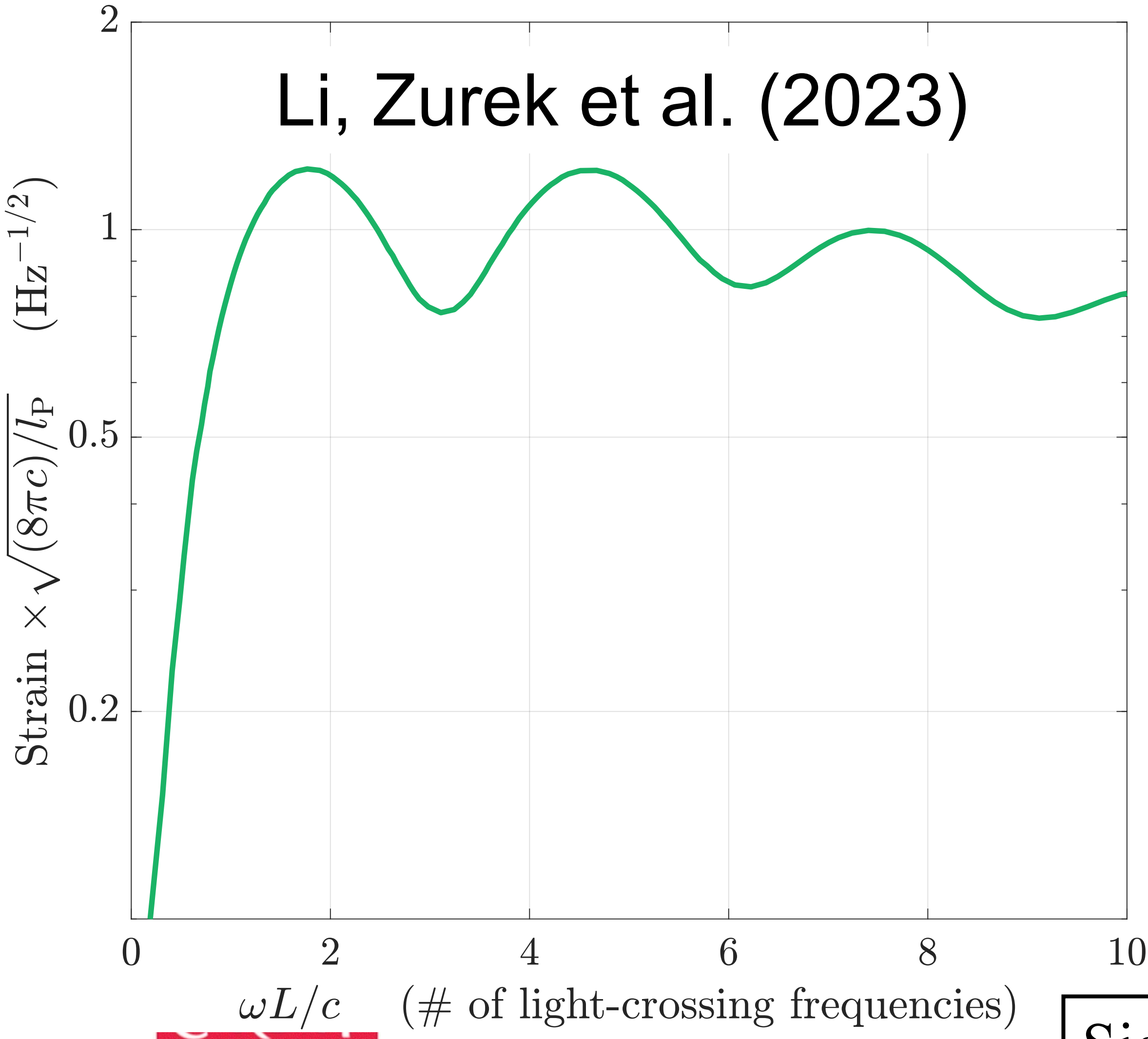
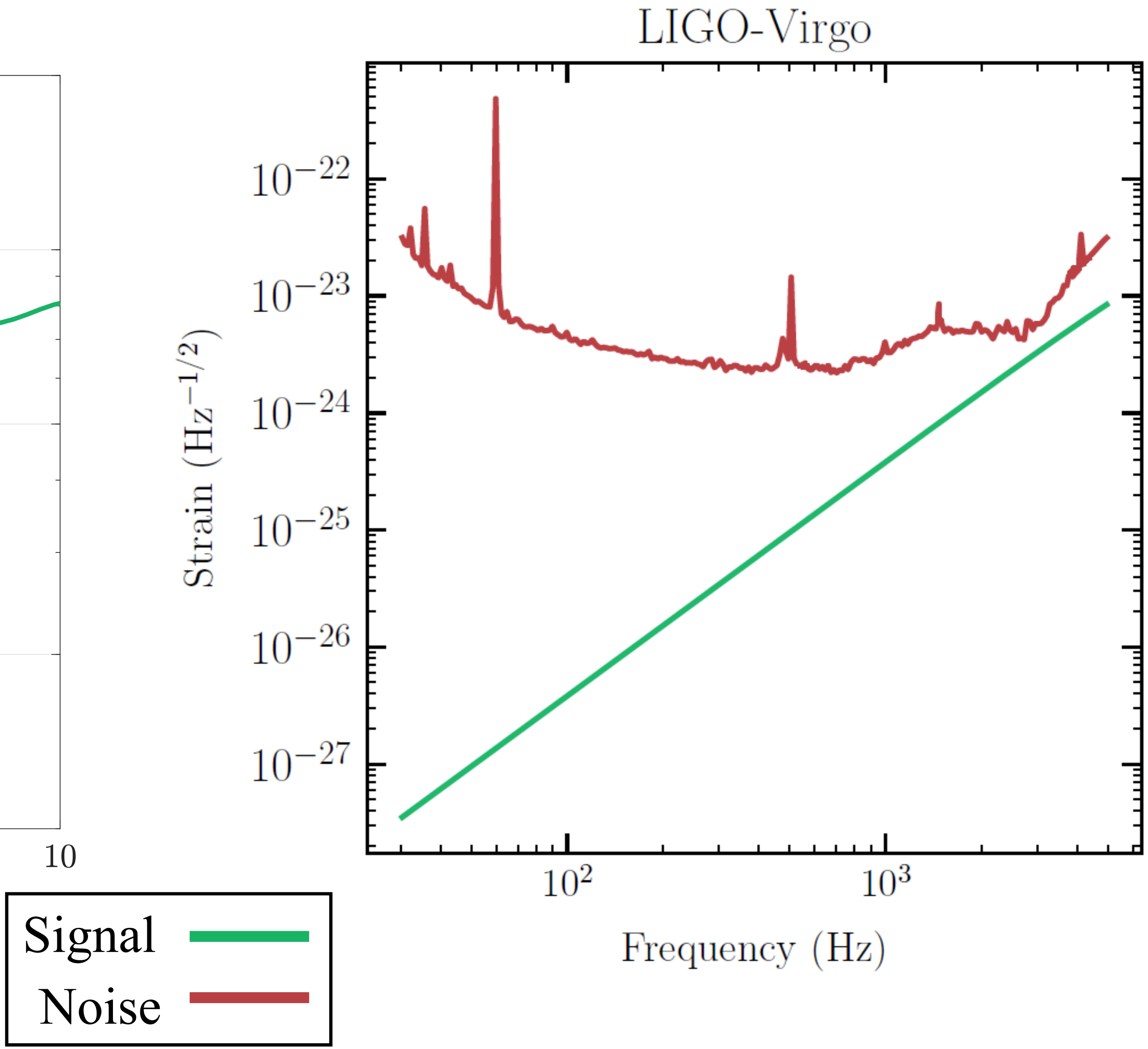
Rotational/Transverse Quantum Gravity Fluctuations

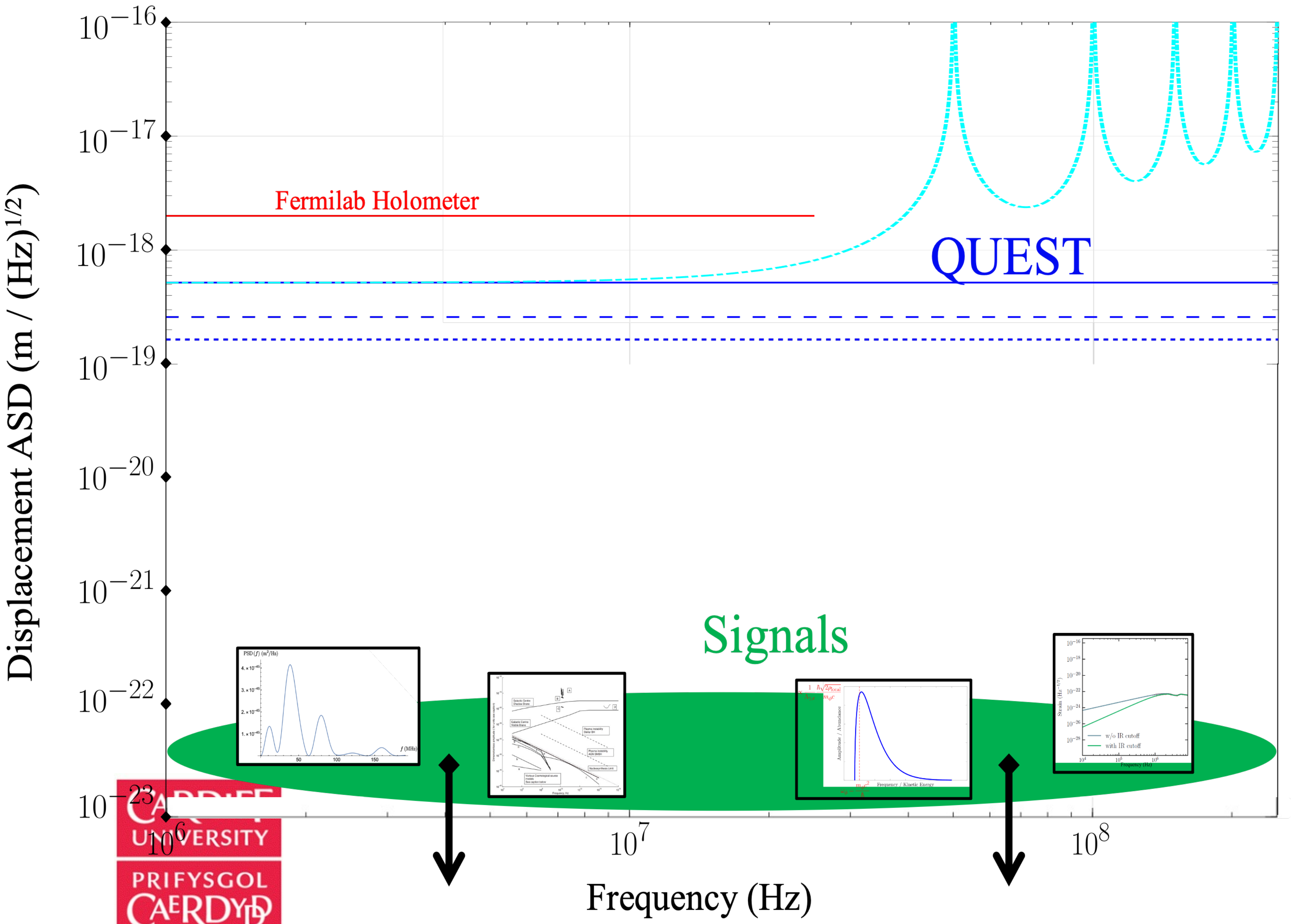


Quantum Gravity Fluctuations





Planned sensitivity



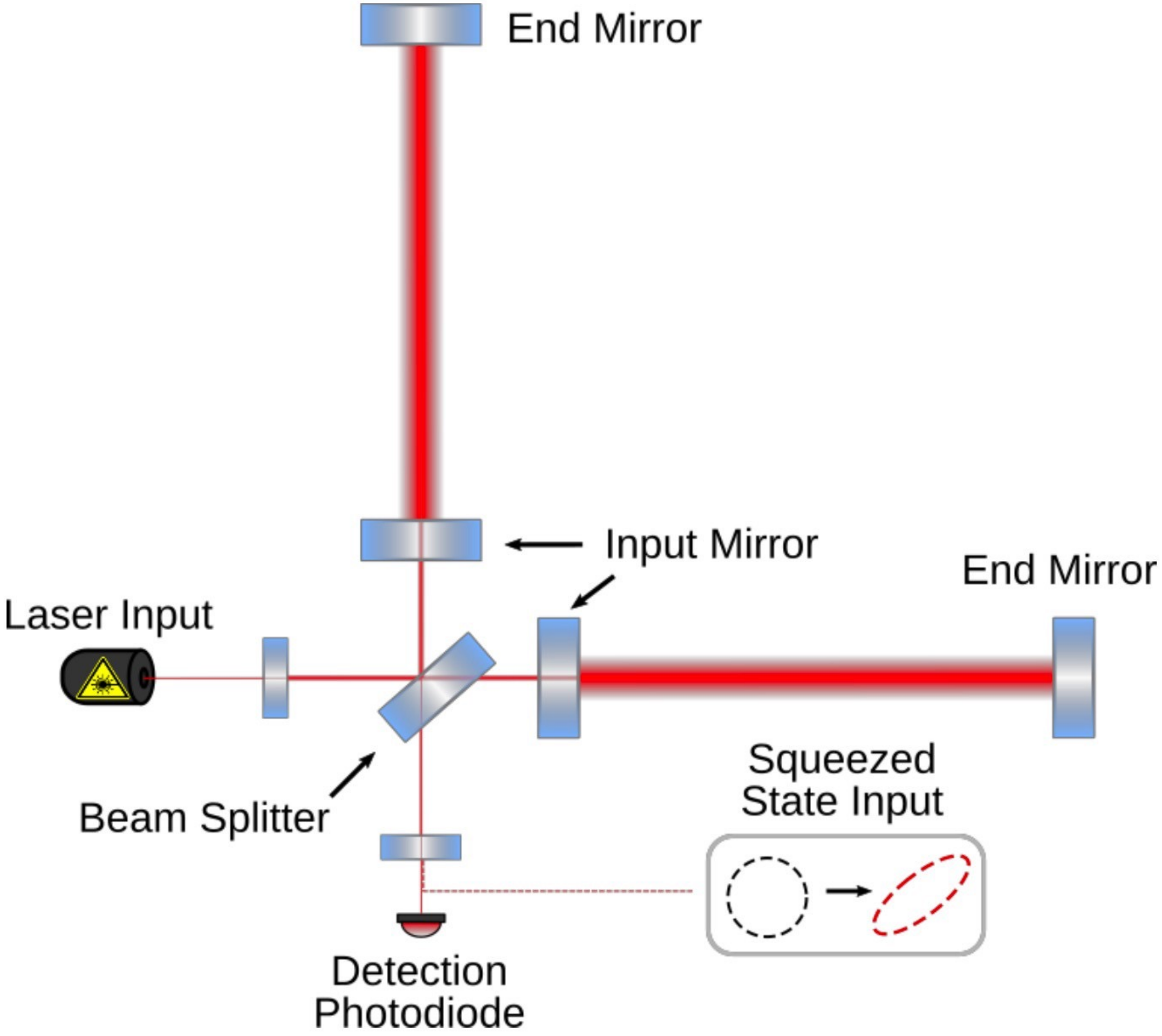
Time integration/cross-correlation:

$$\text{Noise} \propto \frac{1}{\sqrt{T}}$$

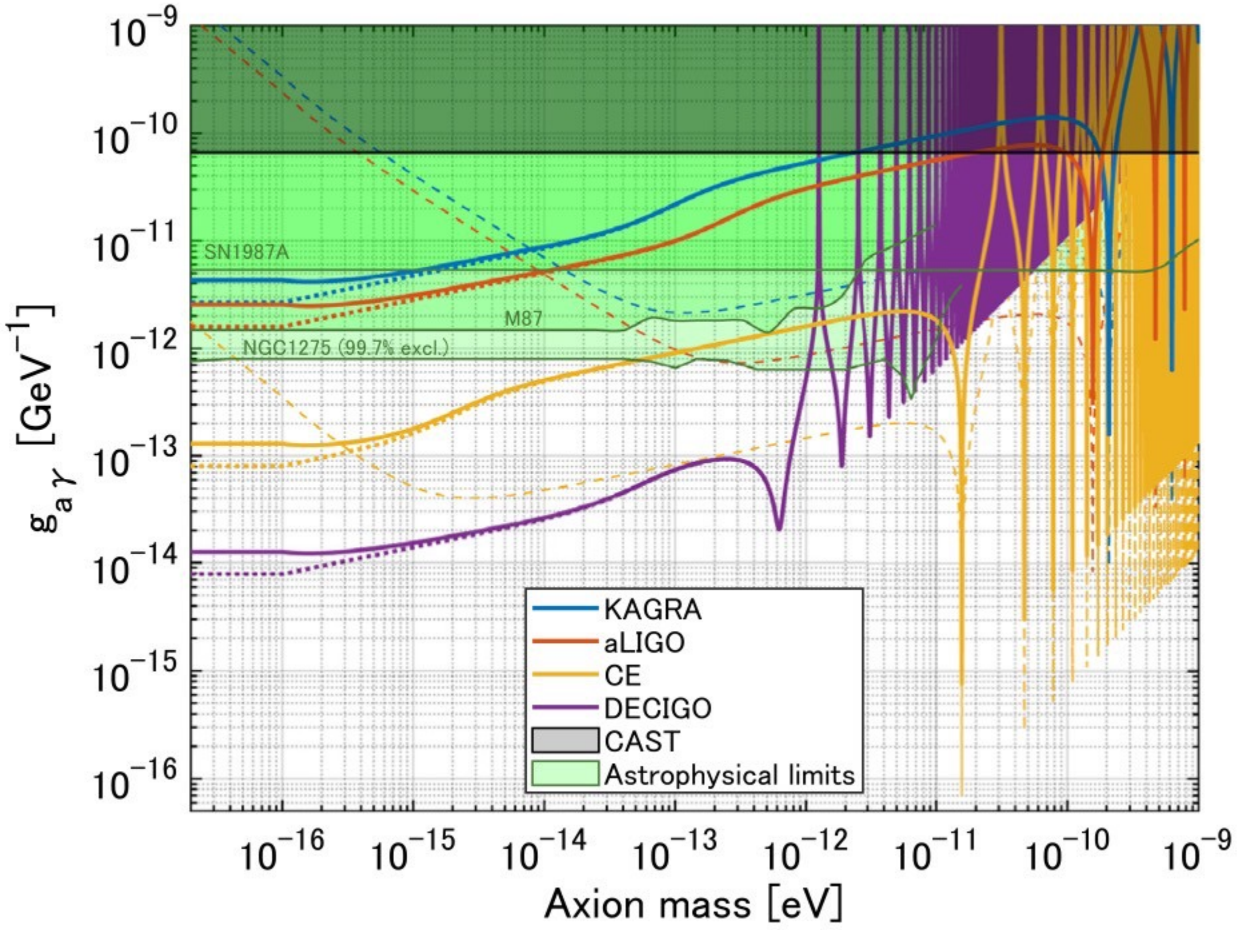
Potential Laser Interferometry

- Quantum spacetime
- **Fundamental physics**
- **Dark matter**

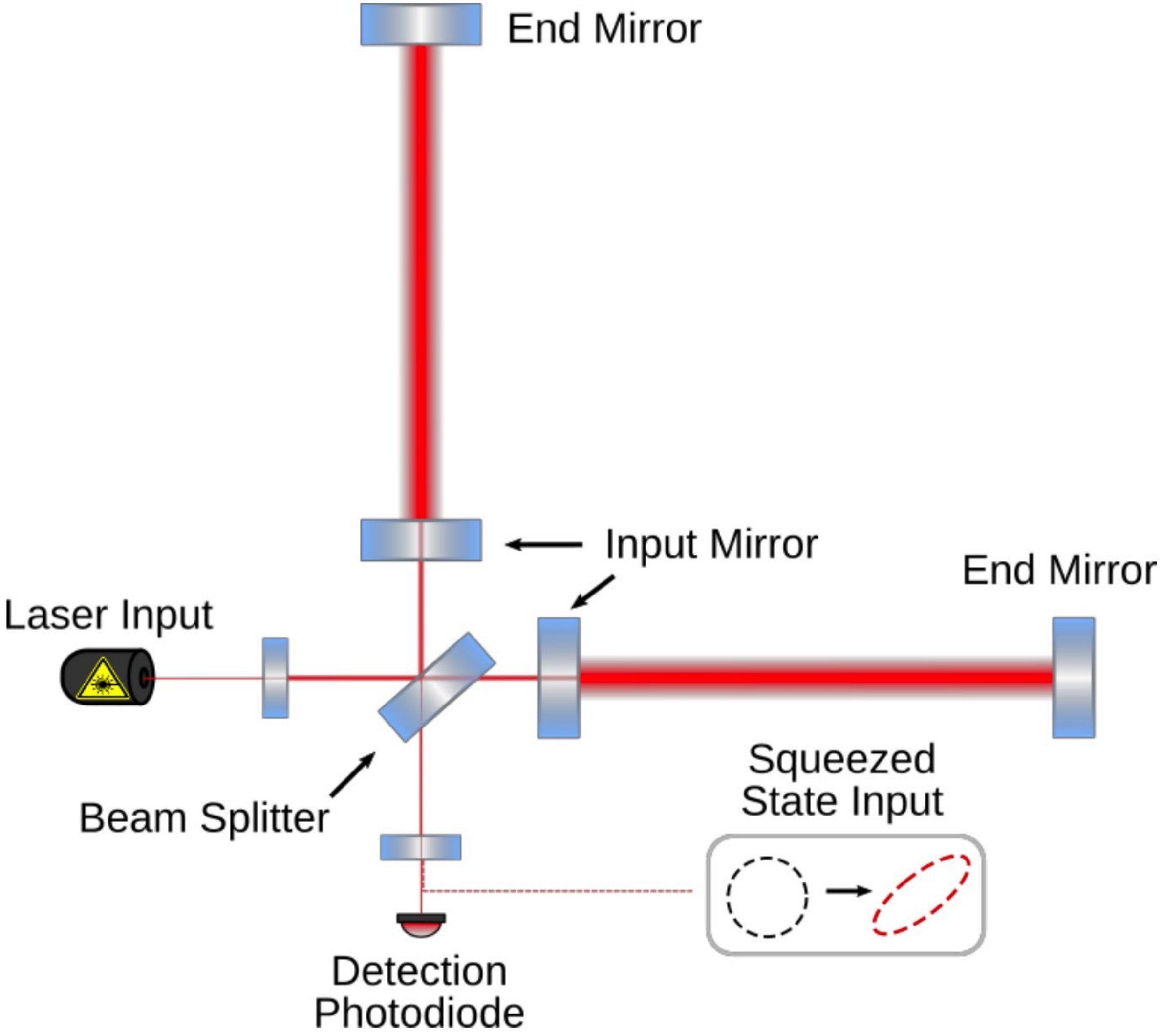
GW detectors and axion search



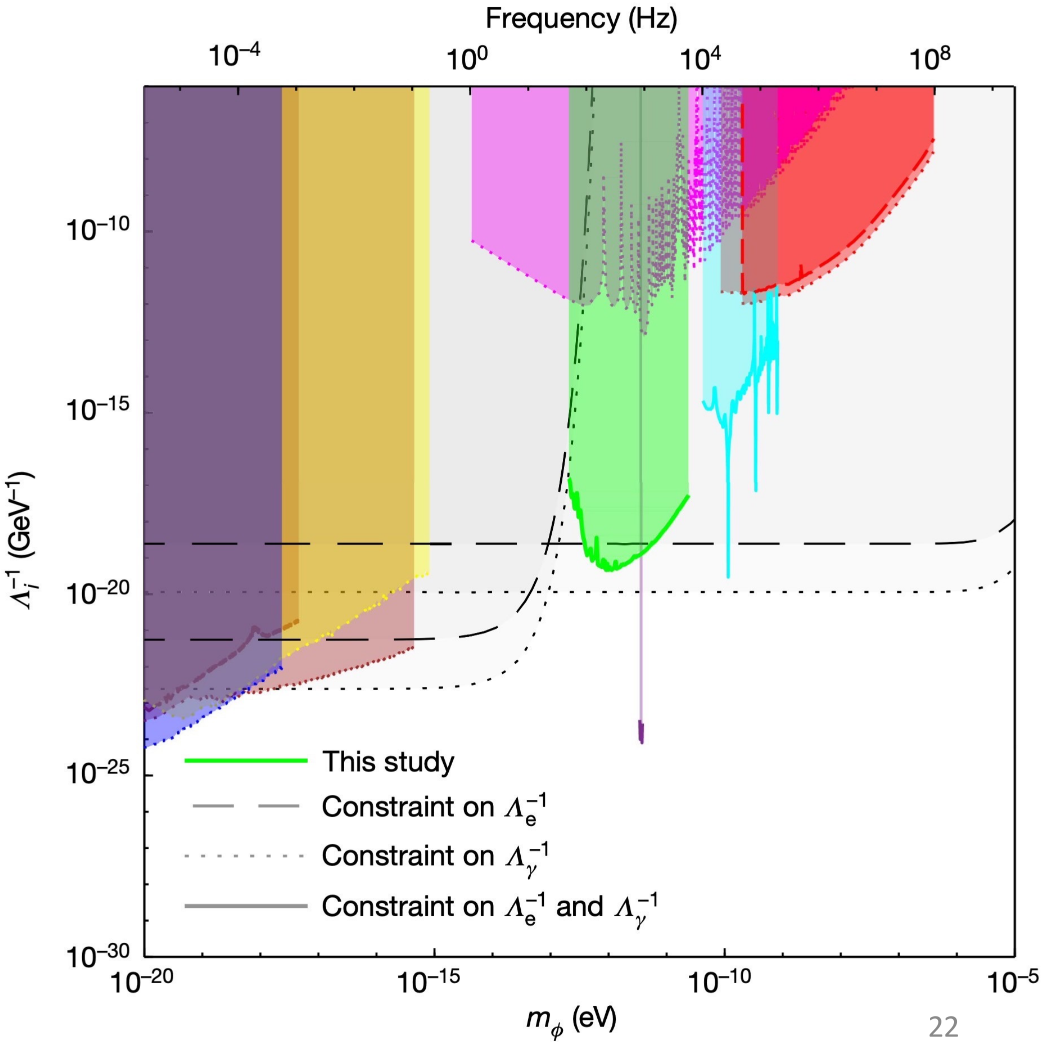
K. Nagano, *et al*
PHYS. REV. D **104**, 062008 (2021)



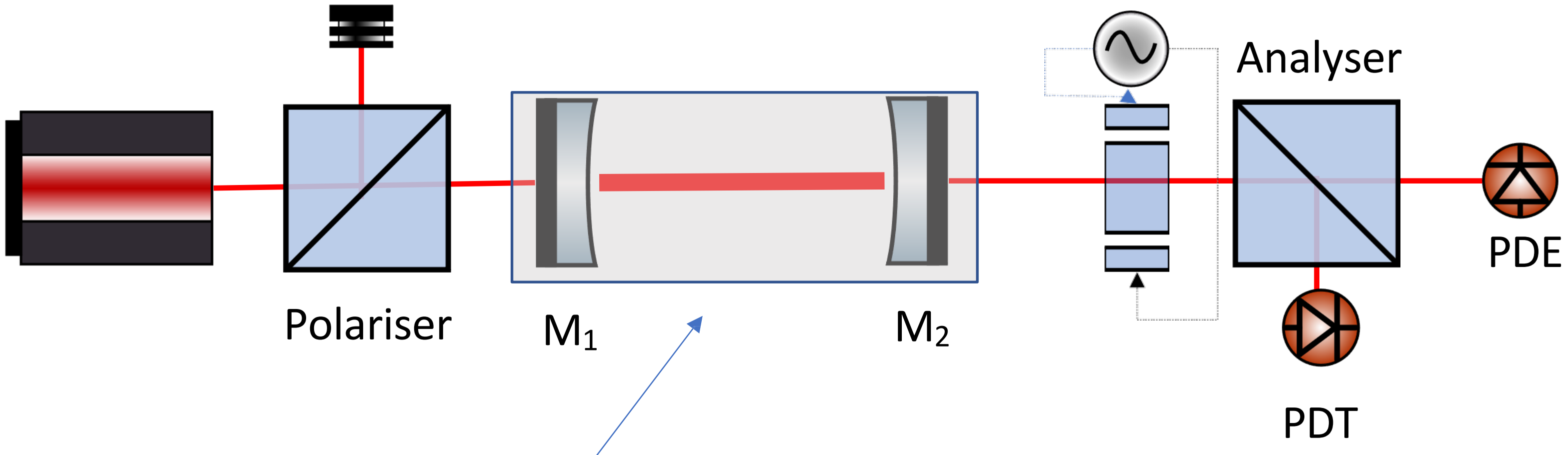
GW Detectors and Constraints on Scalar Field Dark Matter

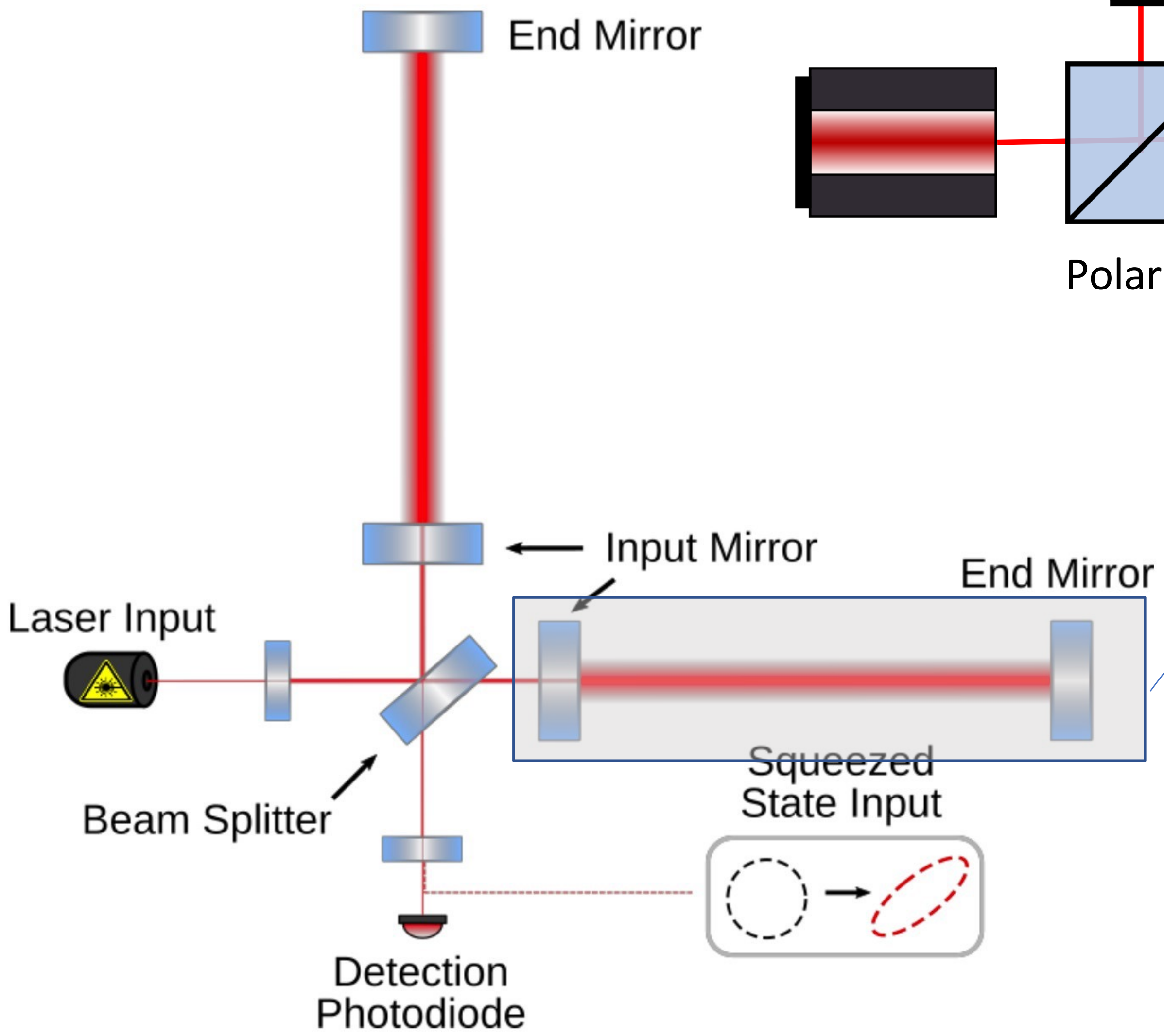


Sander M. Vermeulen, *et al*
Nature **600,** 424–428 (2021)



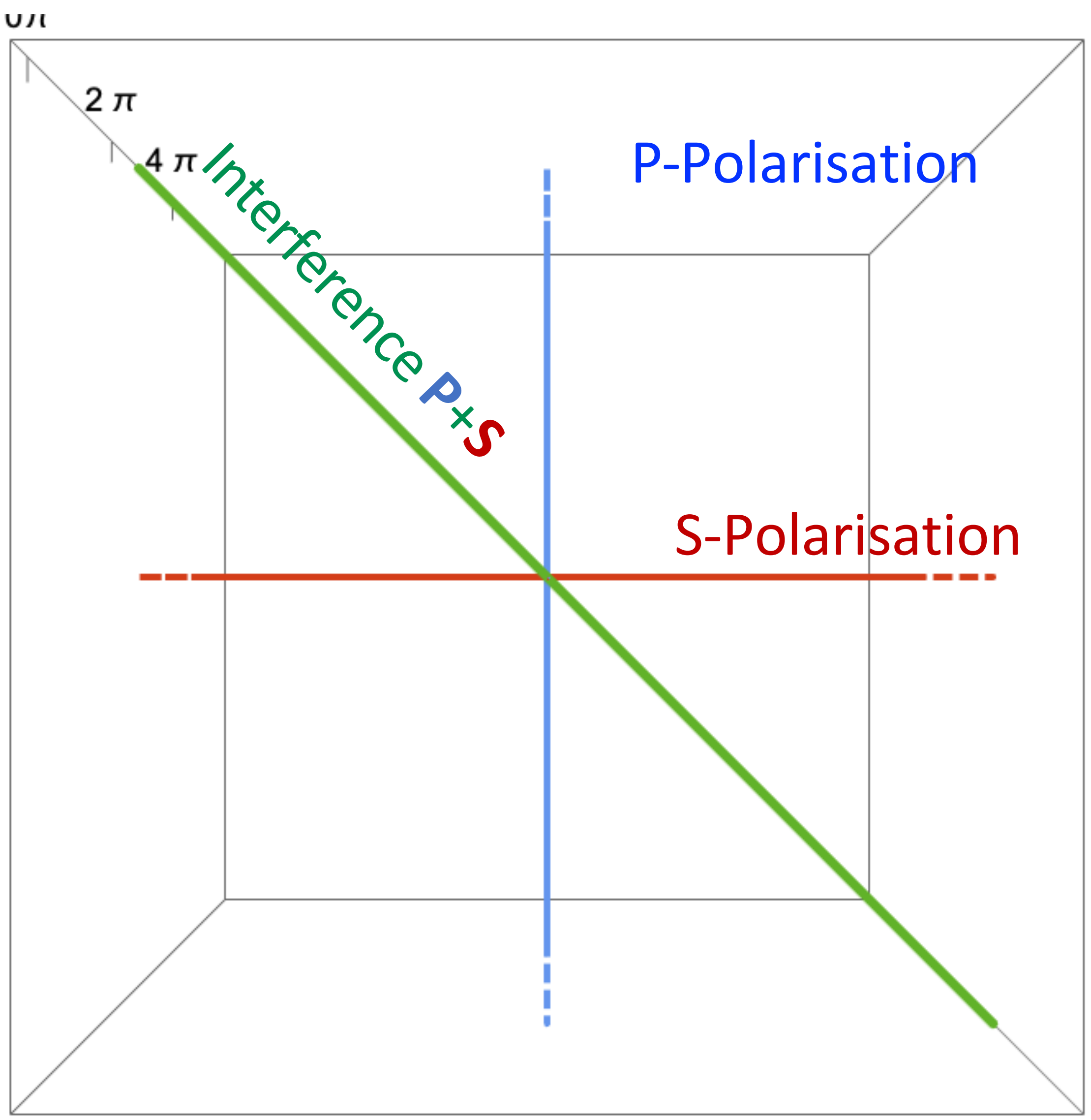
Potential of the polarimetry technique



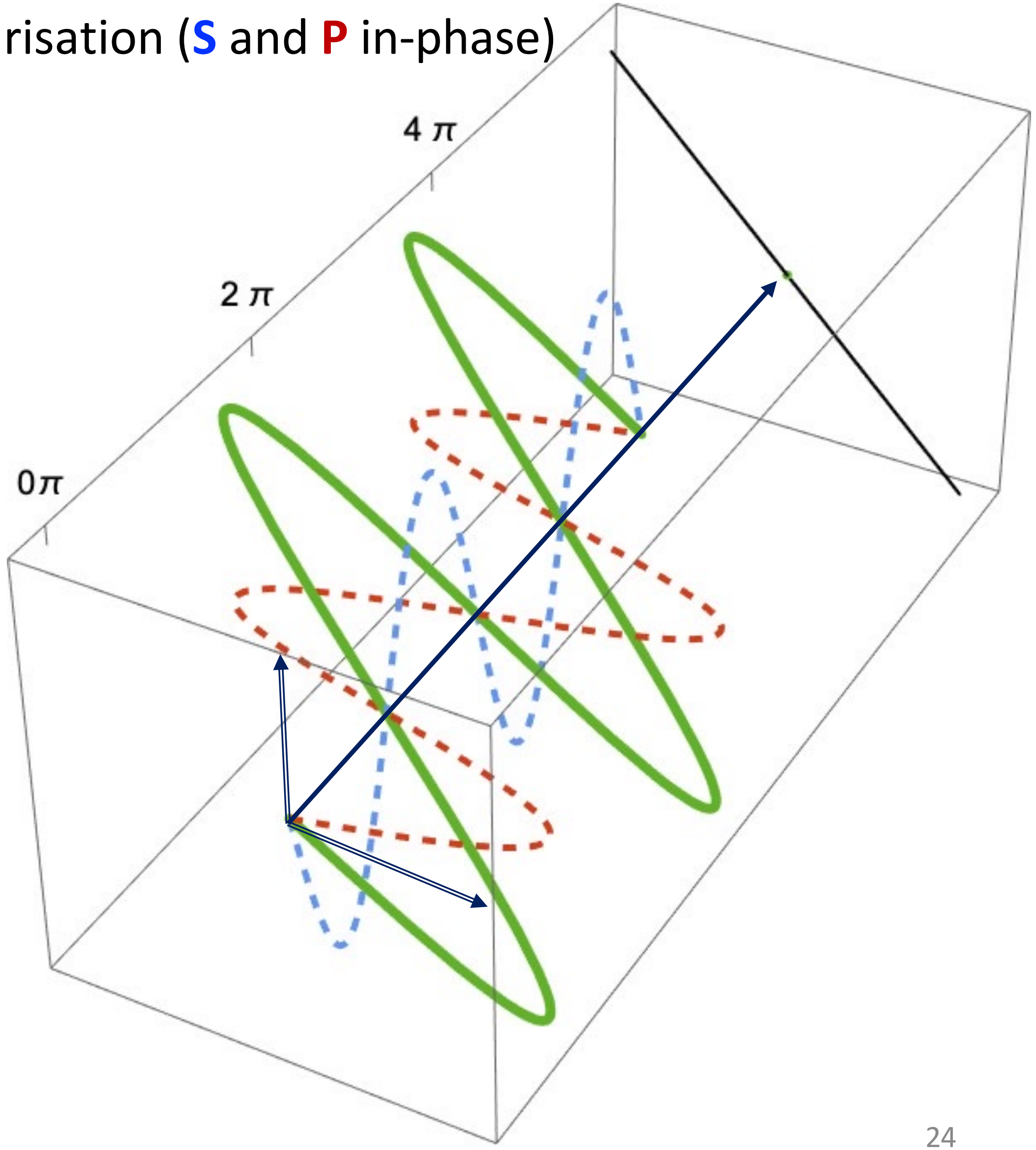


- Compact table-top setup compared to large-scale gravitational wave detectors.
- Less expensive to build and operate.
- Potential to search for the polarization patterns

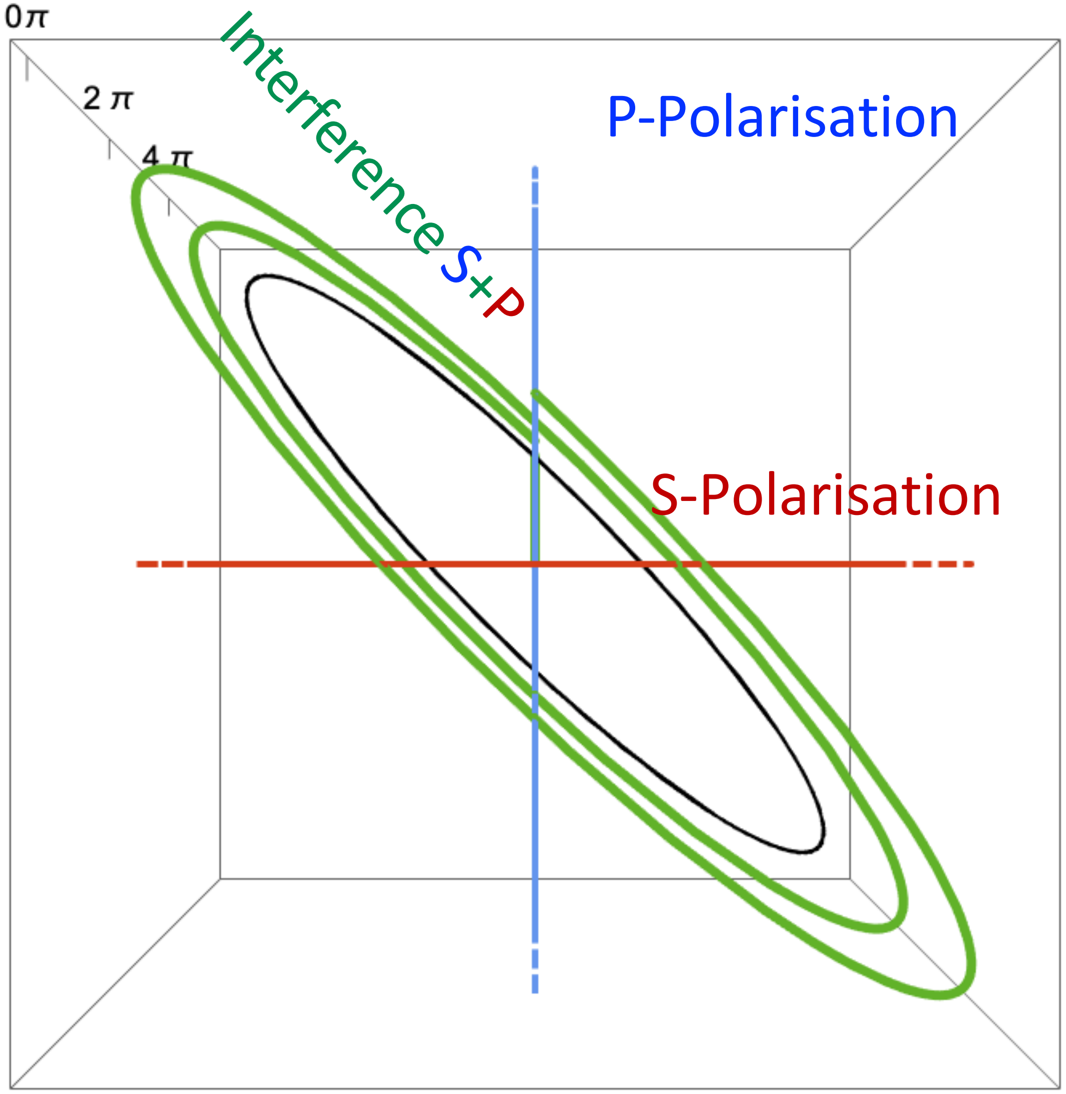
Polarimetry can probe rotation of the EM field



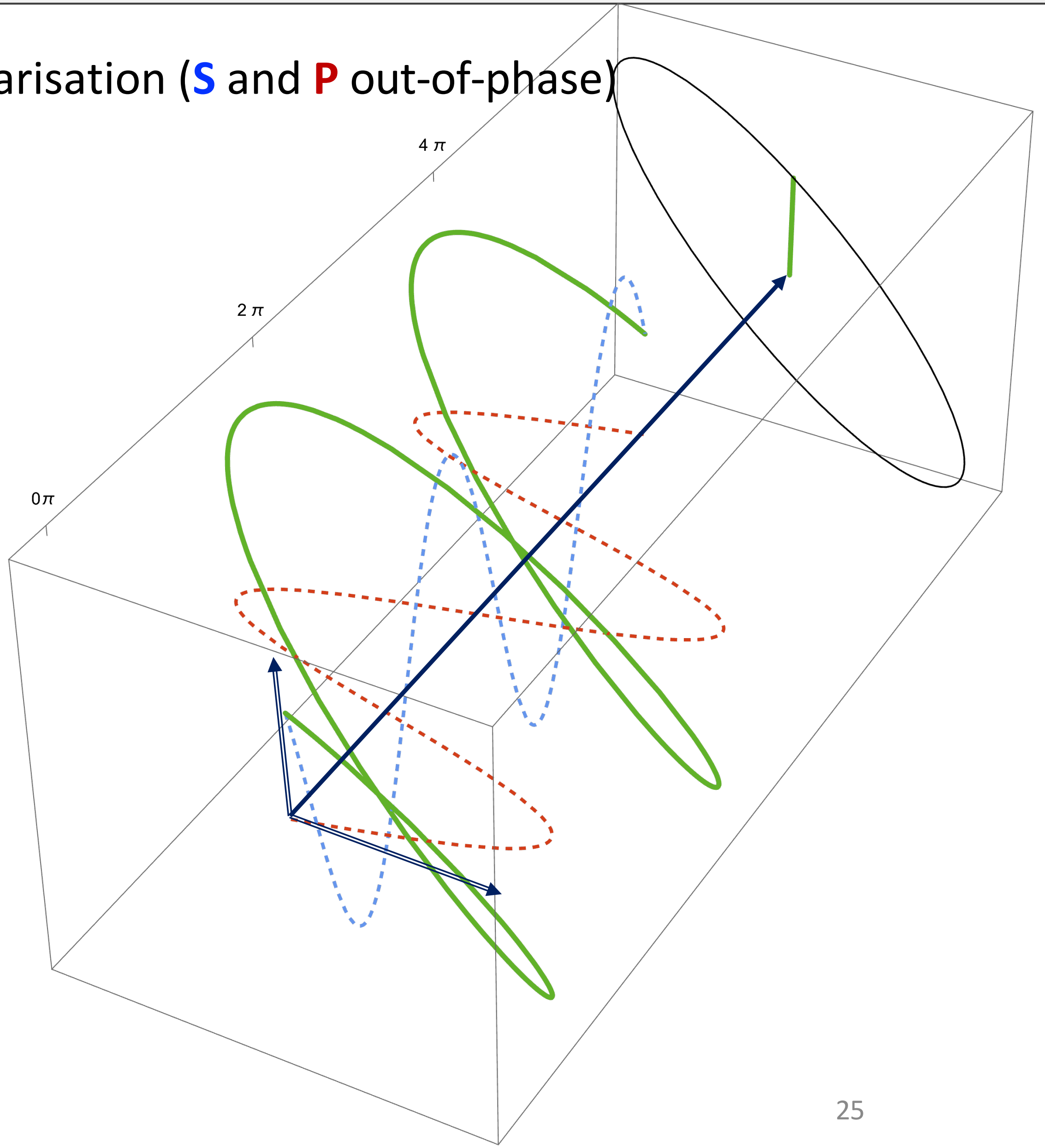
Linear Polarisation (S and P in-phase)



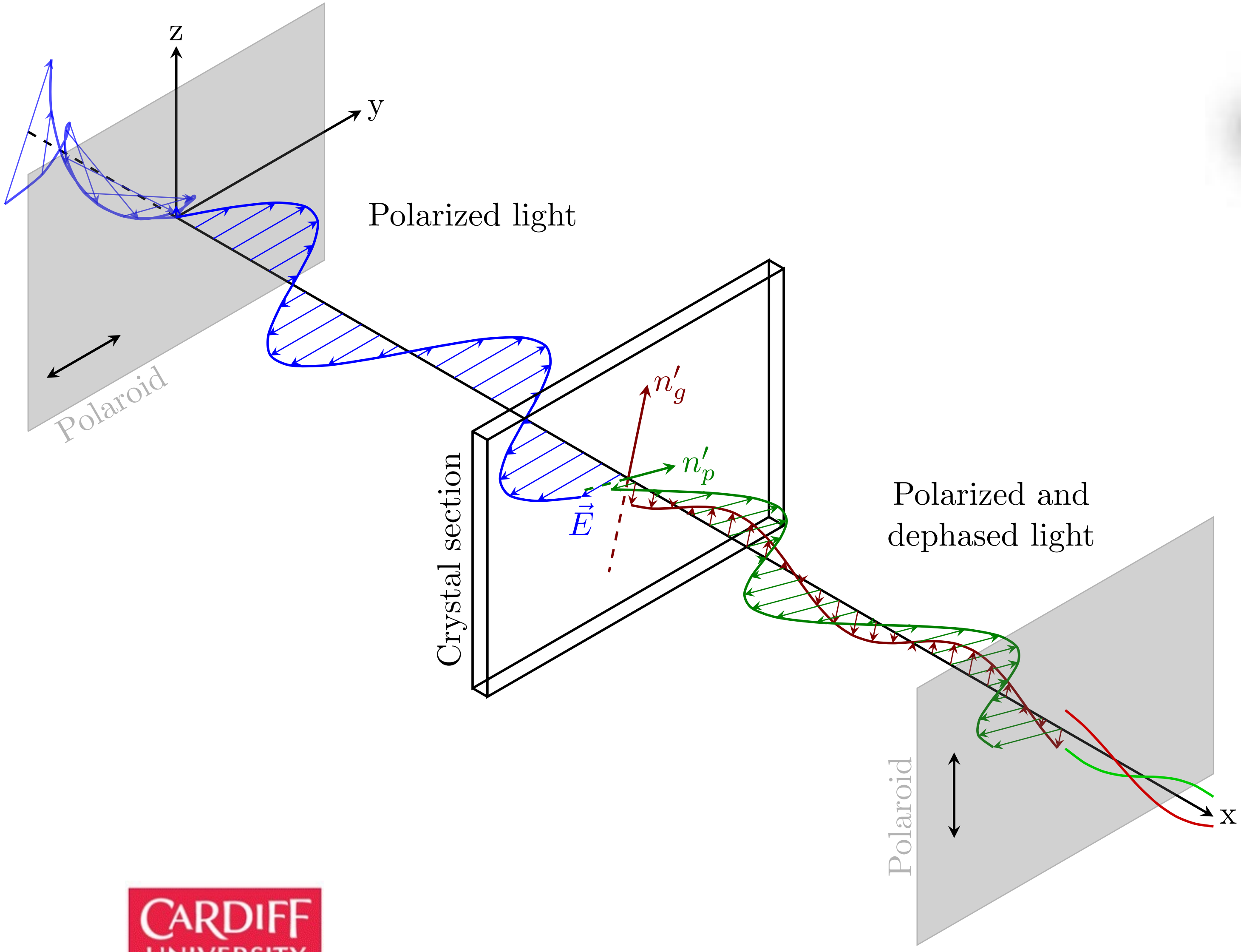
Polarimetry can probe ellipticity of the EM field

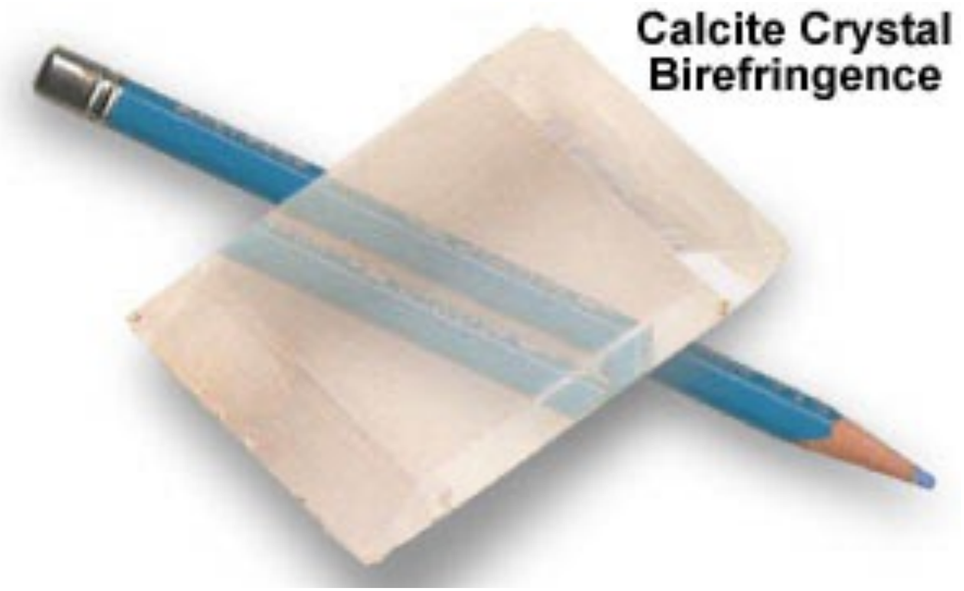


Elliptical Polarisation (**S** and **P** out-of-phase)



Birefringence generates ellipticity





$$\Delta n^{(\text{Calcite})} \approx 0.17$$

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Potential of Polarimetry Laser Interferometry

- Quantum spacetime
- **Fundamental physics**
- Dark matter

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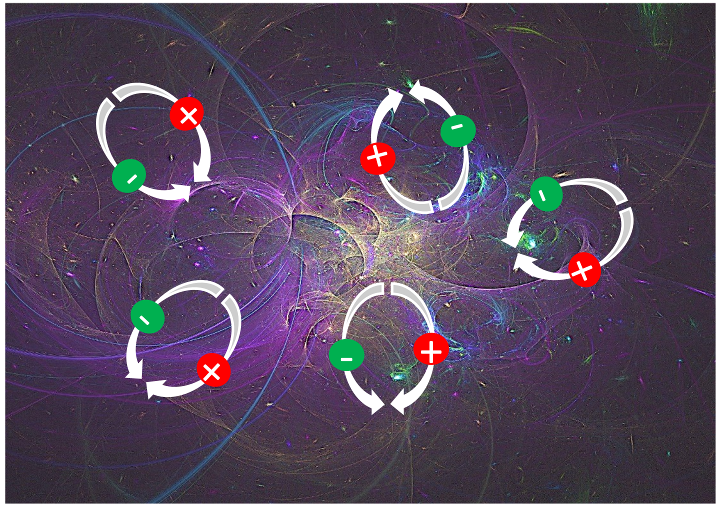
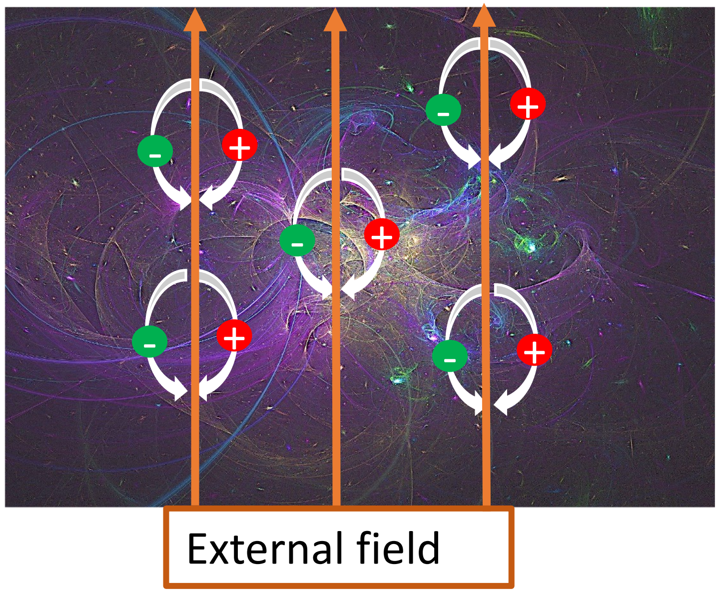
Vacuum in Quantum Electrodynamics (QED)

QED prediction

- Vacuum polarization

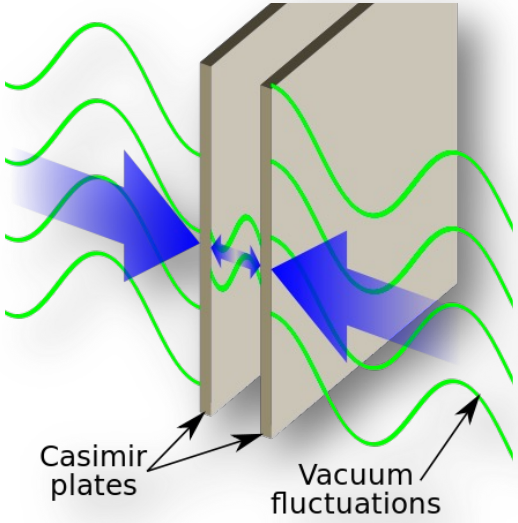
(lacking for direct detection)

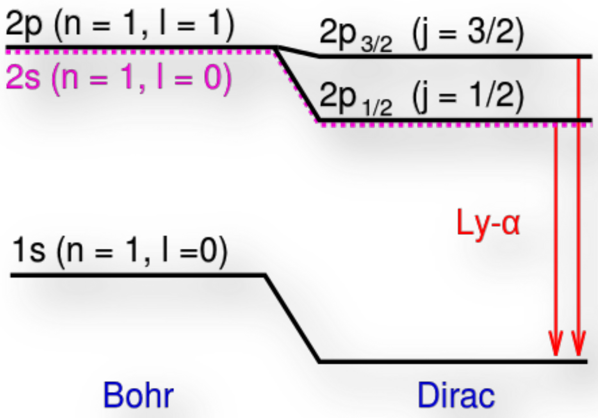




QED evidence

- g-2
- Casimir effect
- Lamb shift





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Nonlinear effects in vacuum

$$L_{\text{eff}} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\mathbf{E}}{c}\cdot\mathbf{B}\right)^2\right]$$

$A_e = \frac{2\alpha^2}{45\mu_0}\frac{(\hbar/m_e c)^3}{m_e c^2} = 1.32\times 10^{-24}\ \mathrm{T}^{-2}$, correction $\propto 1/m_e^4$, virtual pairs e^+e^-.

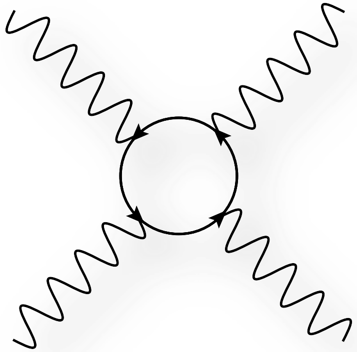
Consequences of Dirac's Theory of the Positron

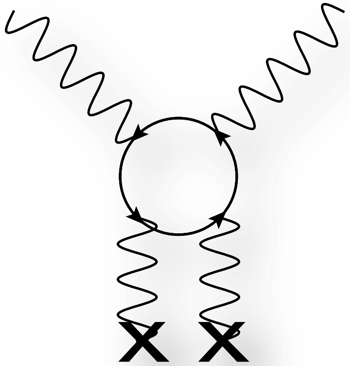
W. Heisenberg and H. Euler in Leipzig[1]

22. December 1935

Abstract

According to Dirac's theory of the positron, an electromagnetic field tends to create pairs of particles which leads to a change of Maxwell's equations in the vacuum. These changes are calculated in the special case that no real electrons or positrons are present and the field varies little over a Compton wavelength. The resulting effective Lagrangian of the





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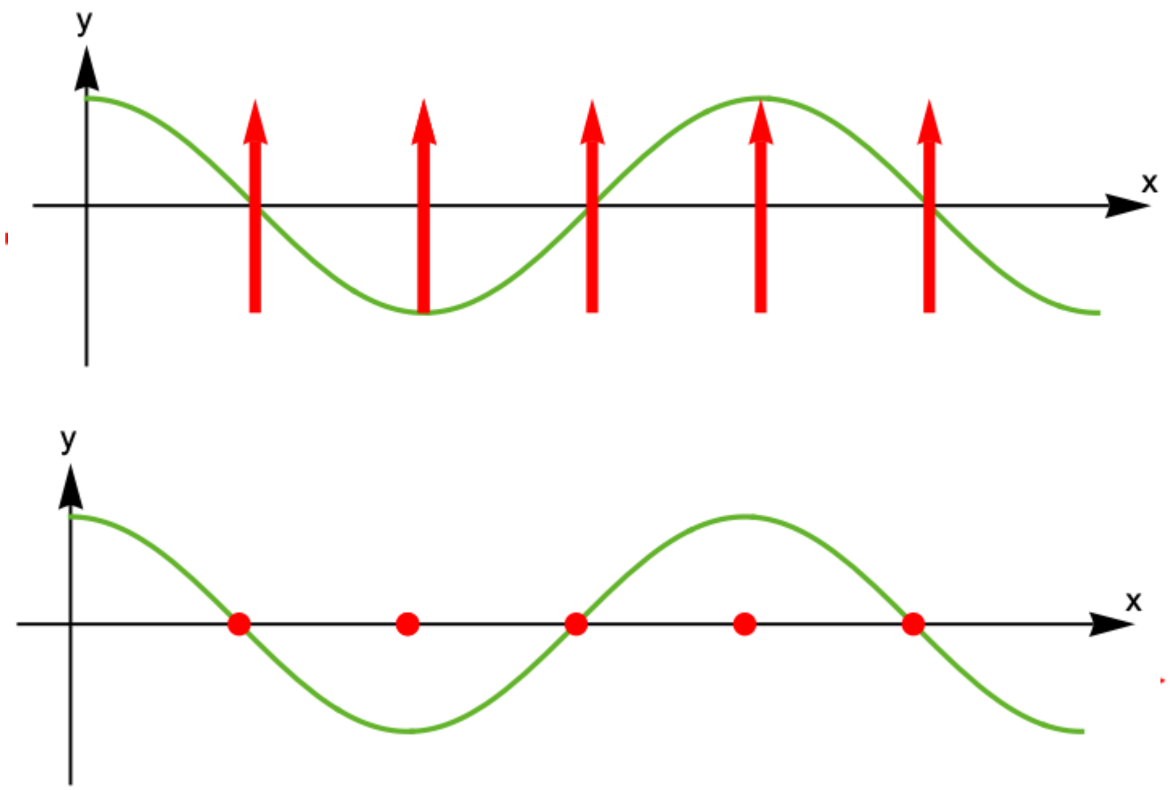
Vacuum polarization: vacuum magnetic birefringence



$$(n_{\parallel} - 1)/B^2 = 9.3 \times 10^{-24}\ \mathrm{T}^{-2}$$

$$(n_{\perp} - 1)/B^2 = 5.3 \times 10^{-24}\ \mathrm{T}^{-2}$$

$$\Delta n^{(\mathrm{QED})} = n_{\parallel} - n_{\perp} \approx 4 \times 10^{-24} [1/\mathrm{T}^2]$$

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Polarimetry for Vacuum Magnetic Birefringence

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

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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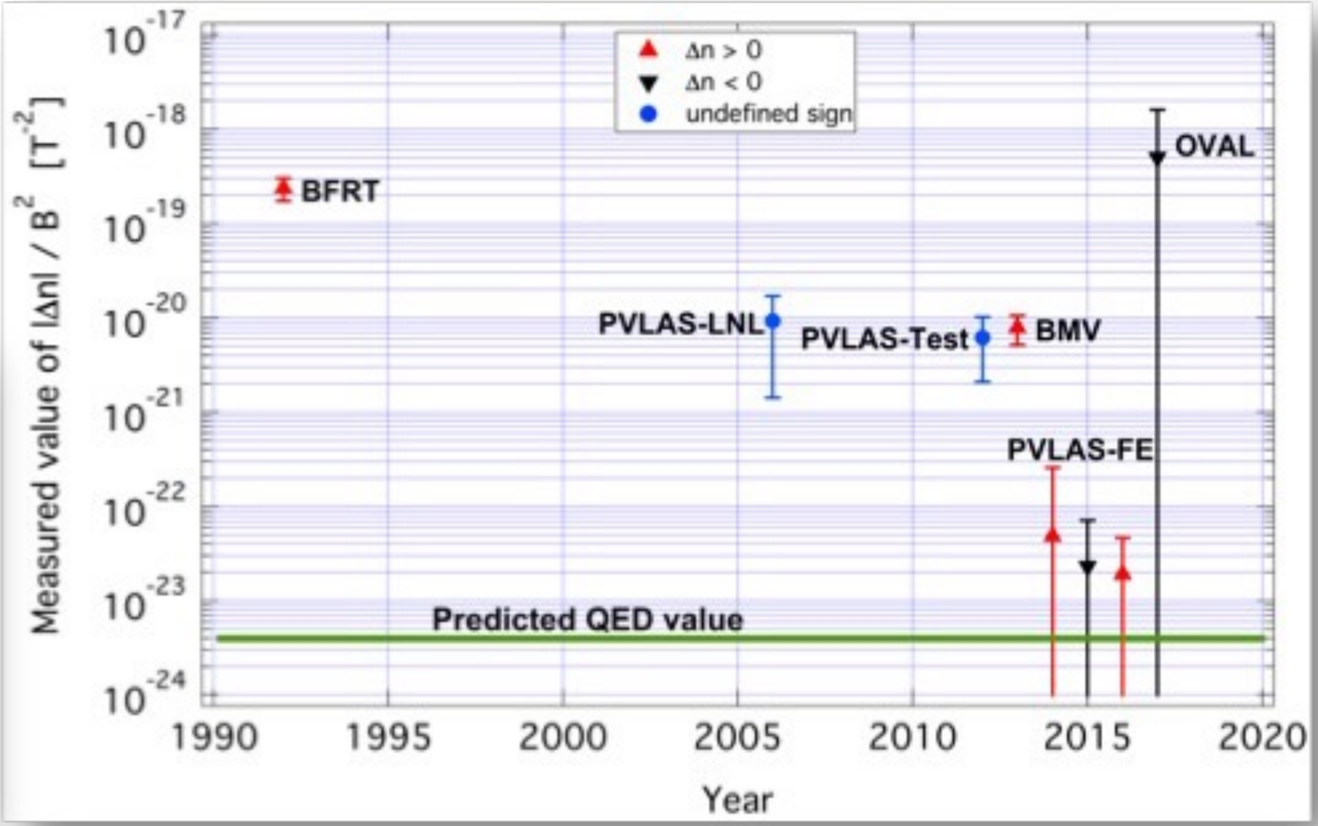

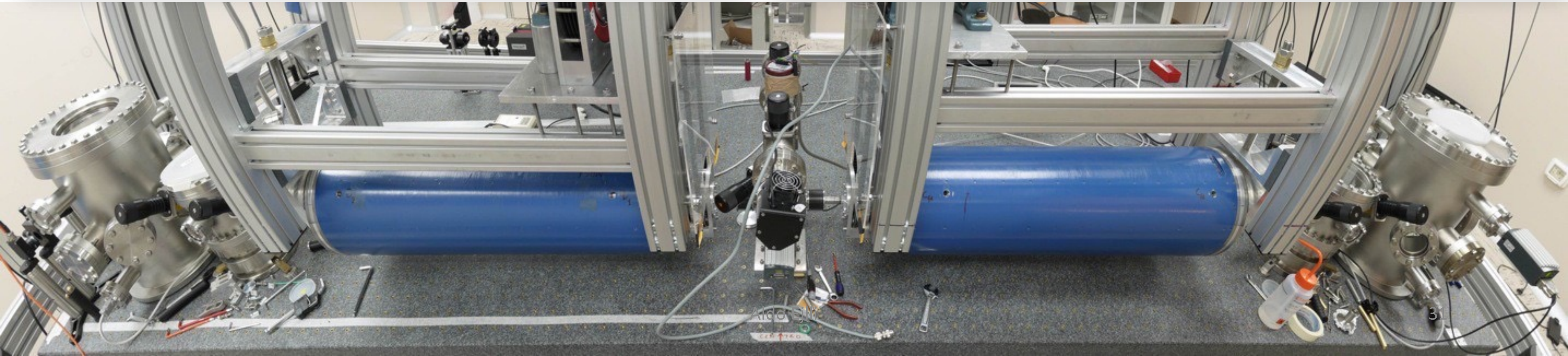

Potential of Polarimetry Laser Interferometry

- Quantum spacetime
- Fundamental physics
- **Dark matter**

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

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

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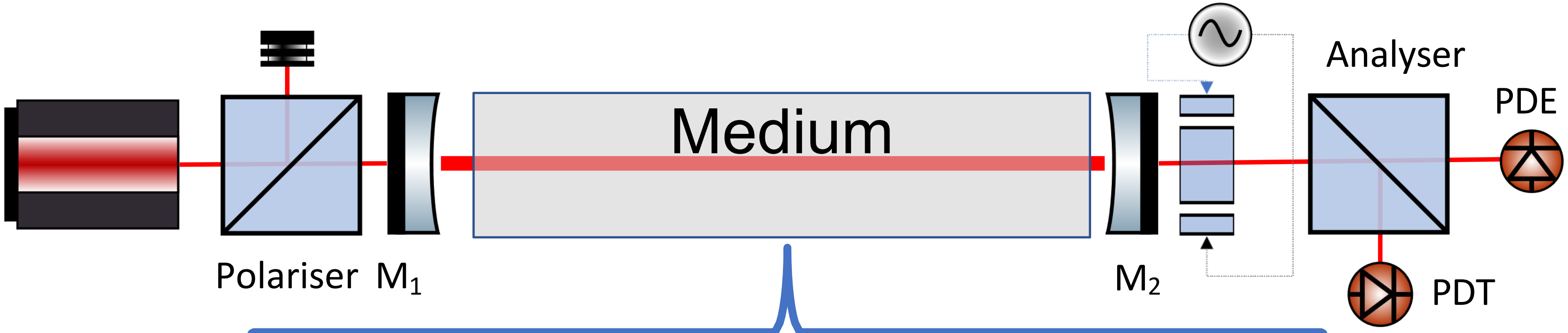
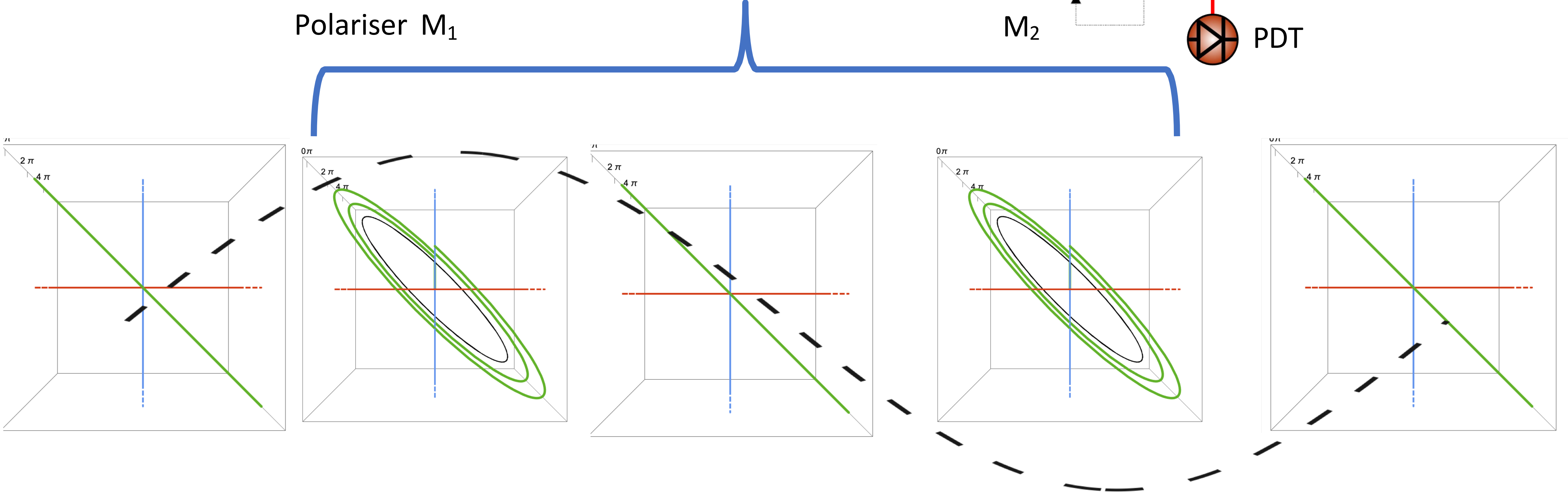
Polarimetry strategy for DM

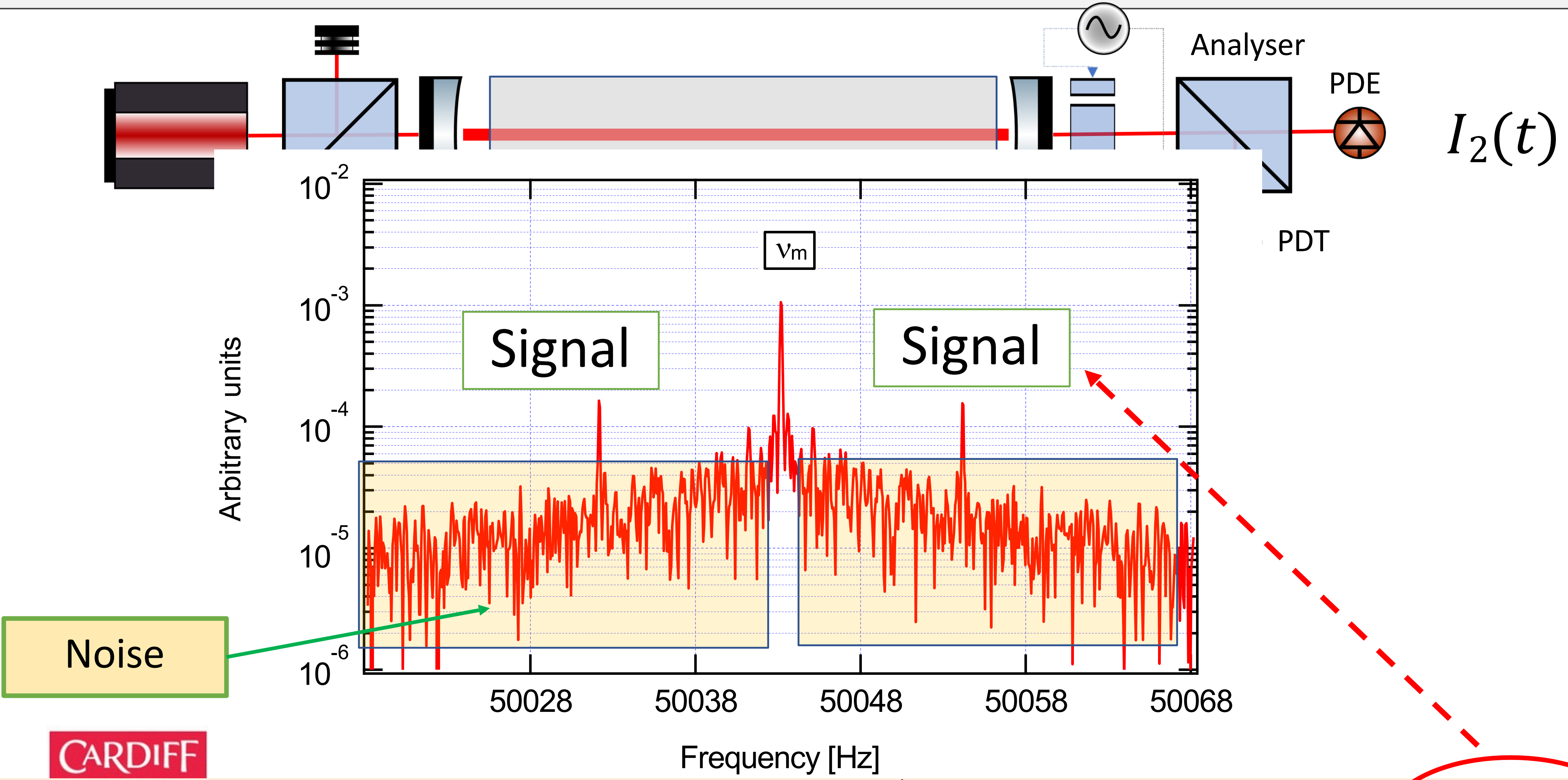


$I_2(t)$



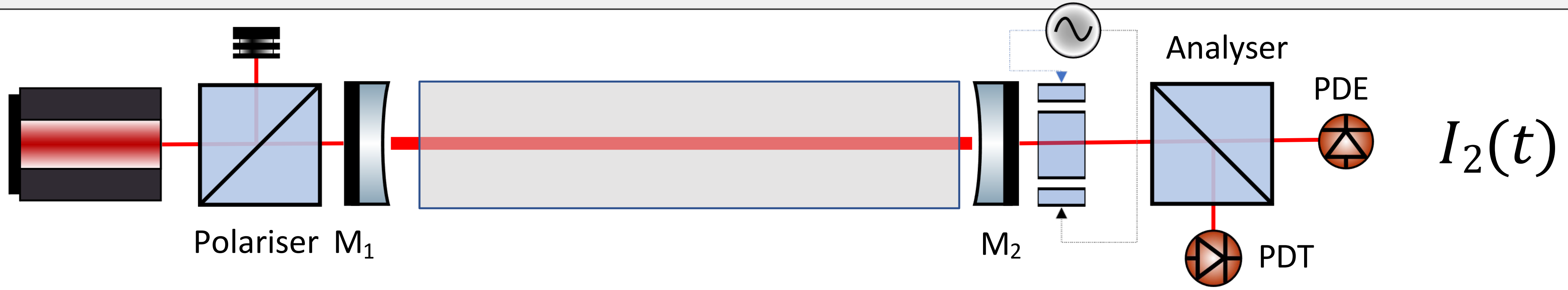
$$I_2(t) = I_0\left(\sigma^2 + |i\psi(t) + i\eta(t) + \epsilon(t)|^2\right) = I_0\left(\sigma^2+\psi^2(t)+\eta^2(t)+\epsilon(t)^2+2\psi(t)\eta(t)\right)$$

Polarimetry strategy: heterodyne



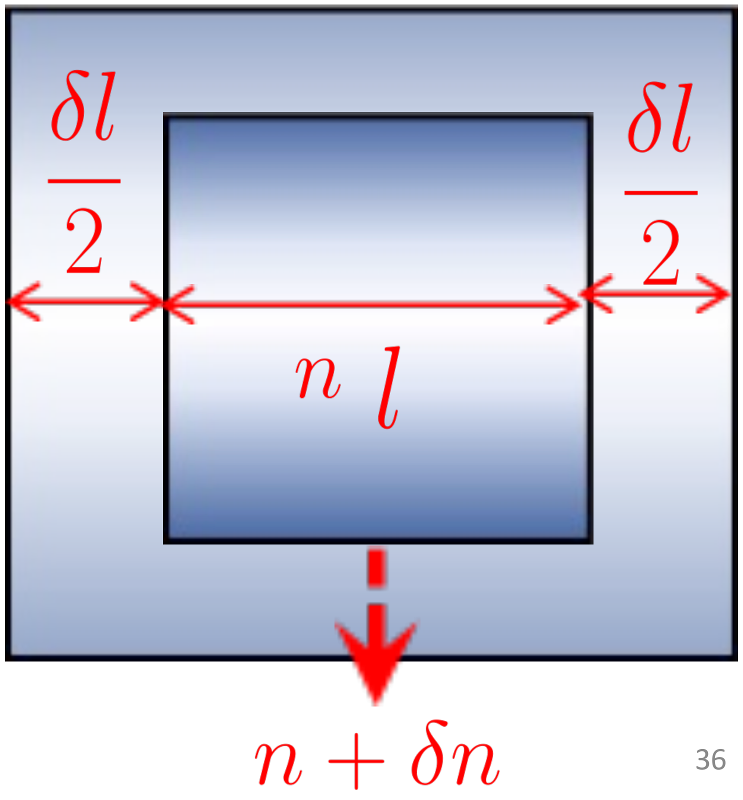
$$I_2(t) = I_0\left(\sigma^2 + |i\psi(t) + i\eta(t) + \epsilon(t)|^2\right) = I_0\left(\sigma^2+\psi^2(t)+\eta^2(t)+\epsilon(t)^2+2\psi(t)\eta(t)\right)$$

Scalar field dark matter

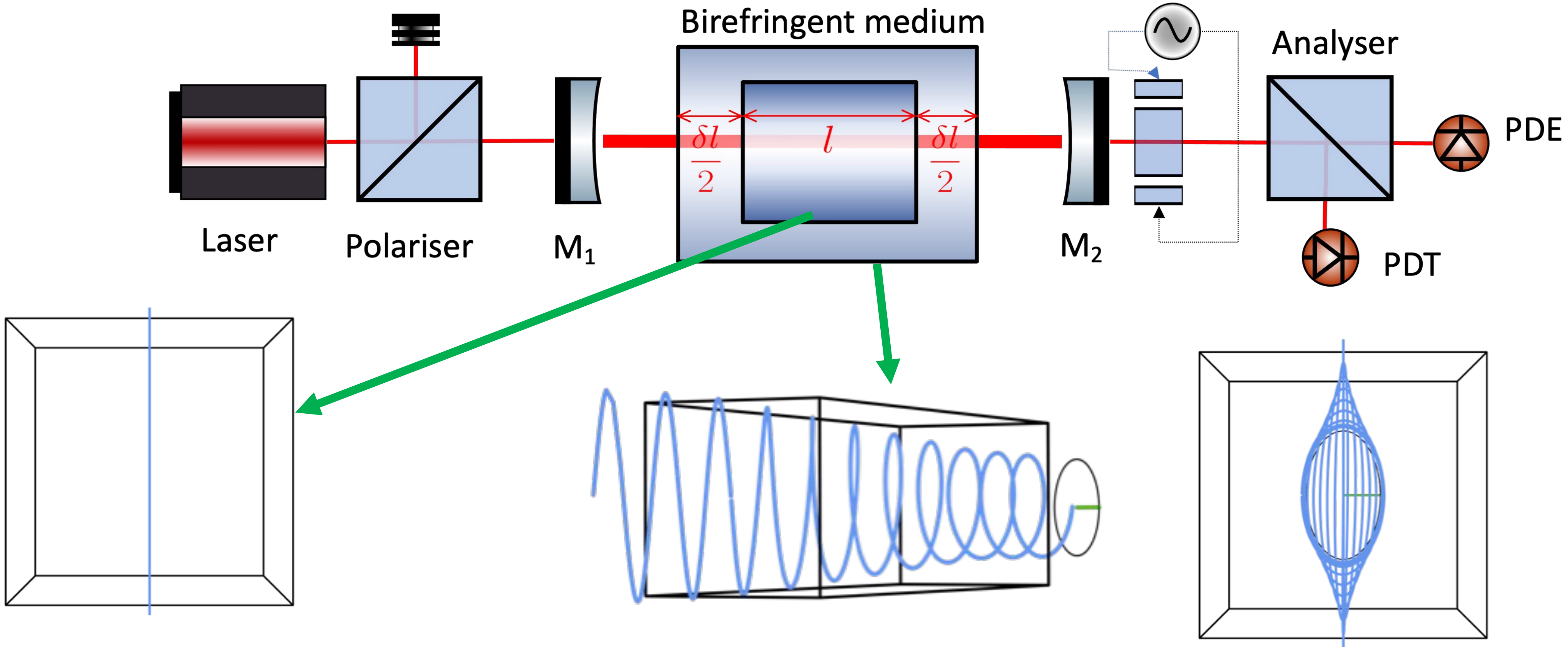


SDM Causes **oscillatory** changes:

- size *l*
- refractive index *n* of solids



Polarimetry for scalar filed DM



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

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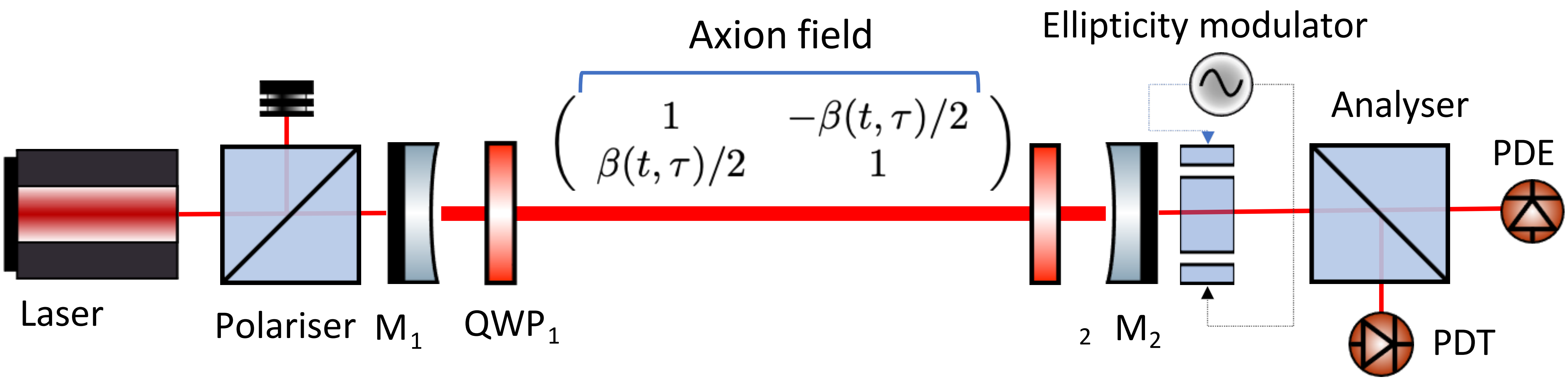
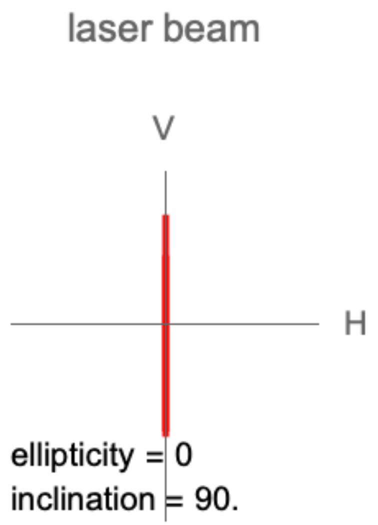
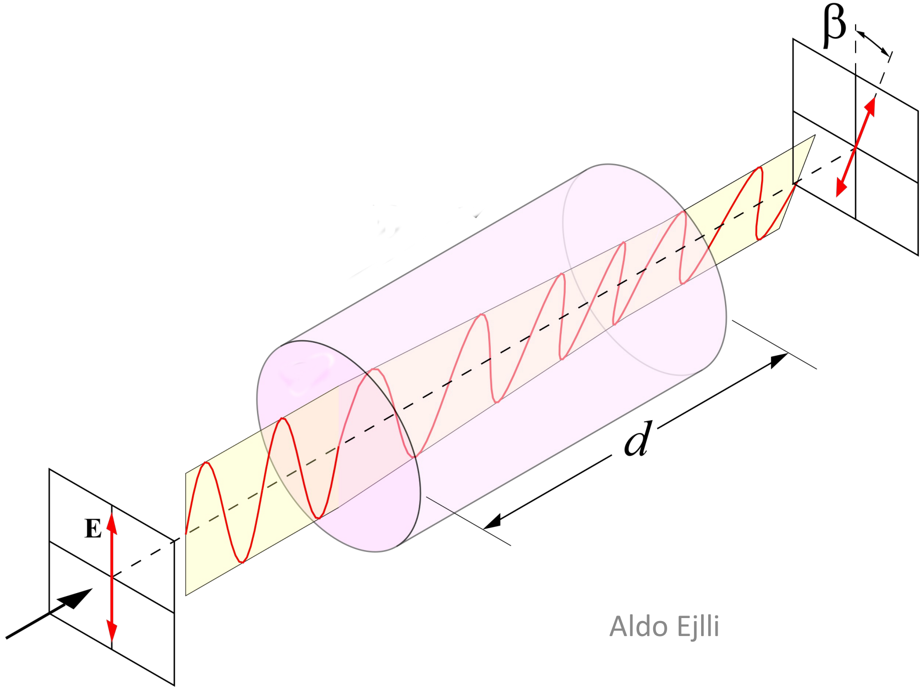
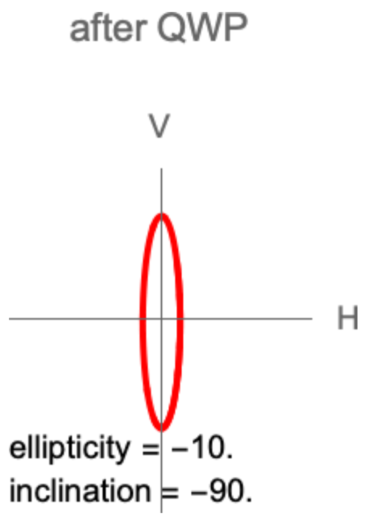
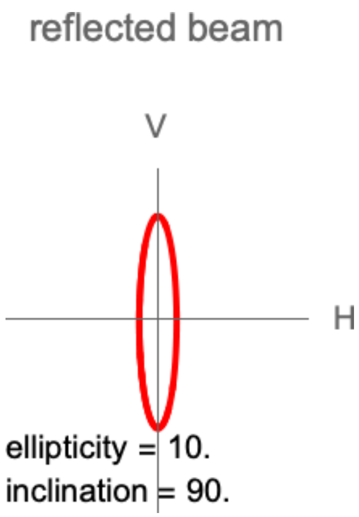
Polarimetry for Axion DM



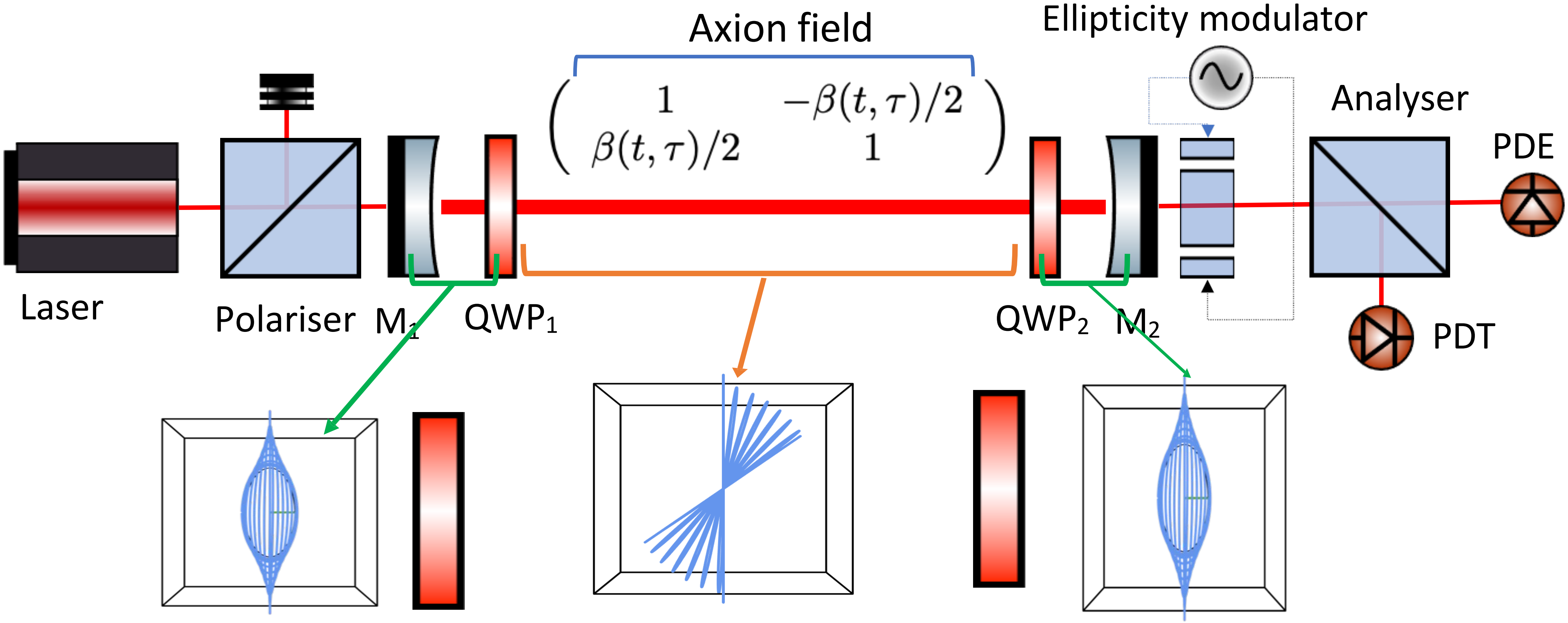








Polarimetry for Axion DM



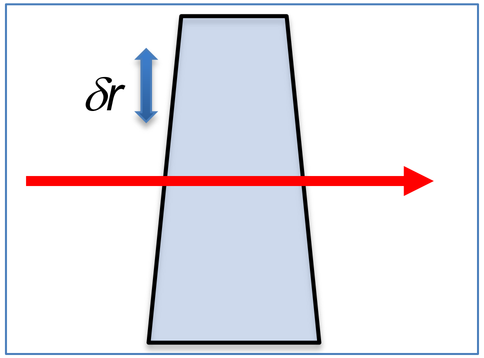
$$\begin{pmatrix} 1 & -\beta(t,\tau)/2 \\ \beta(t,\tau)/2 & 1 \end{pmatrix}$$

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

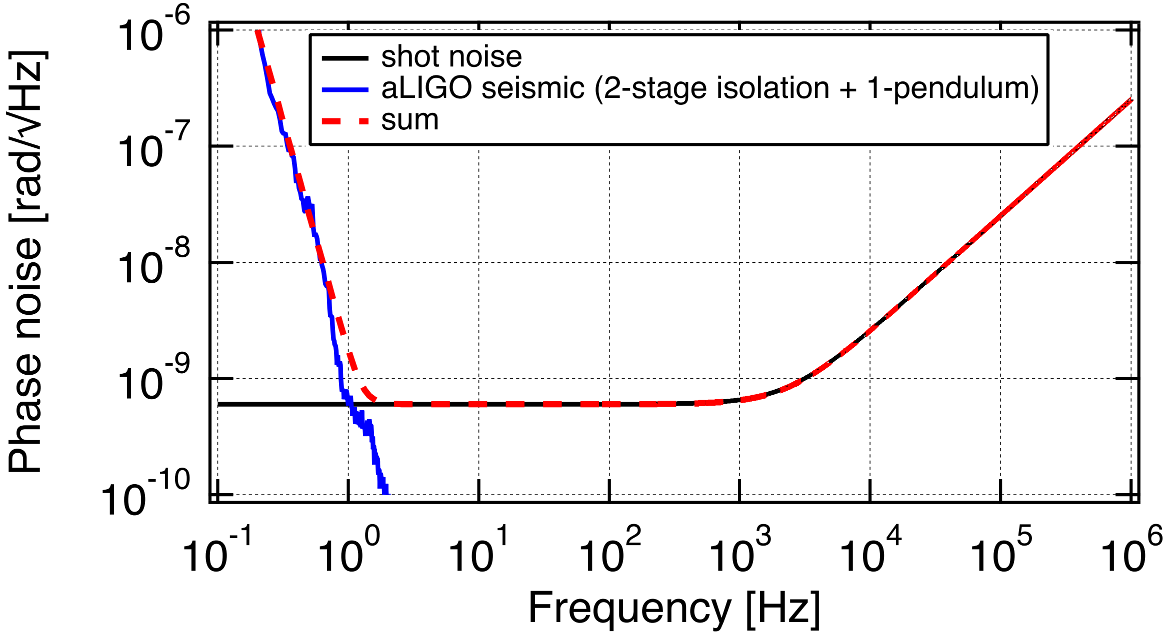
Noise budget

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

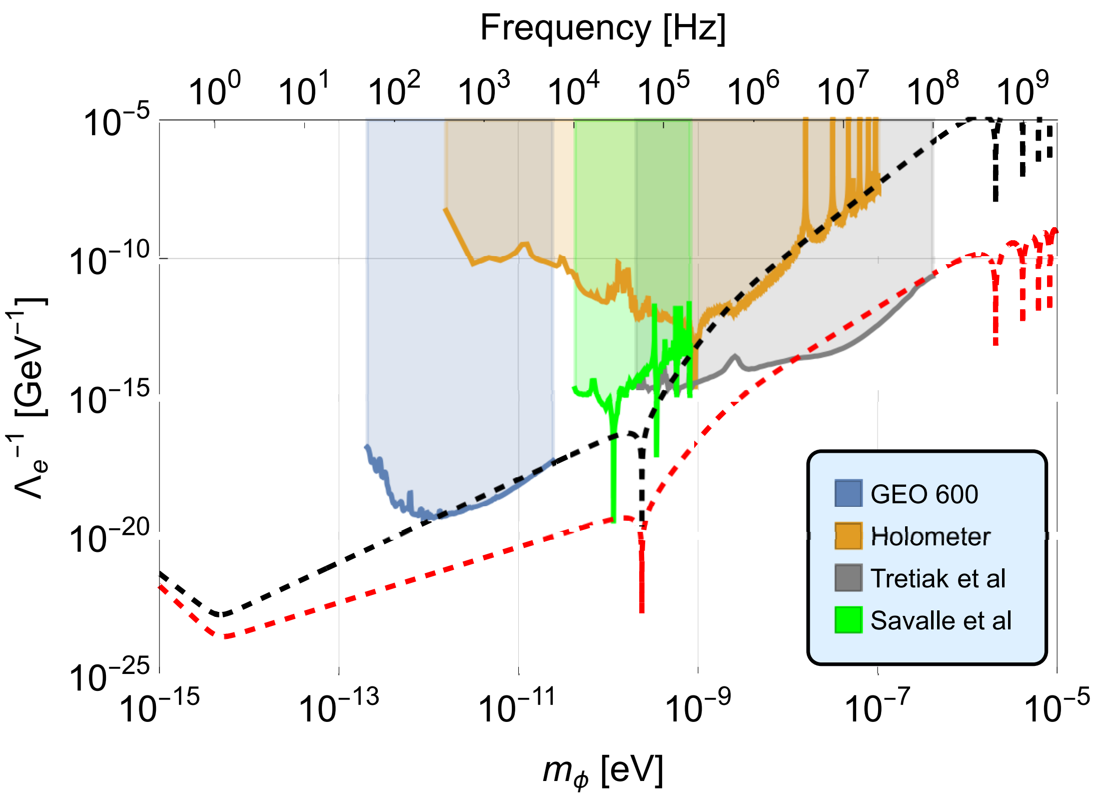
$$S_{\mathrm{P}}^{(\mathrm{seismic})} = 2\pi \frac{N\,\delta r\,\theta}{\lambda}\,\Delta n \gamma(L, f)$$

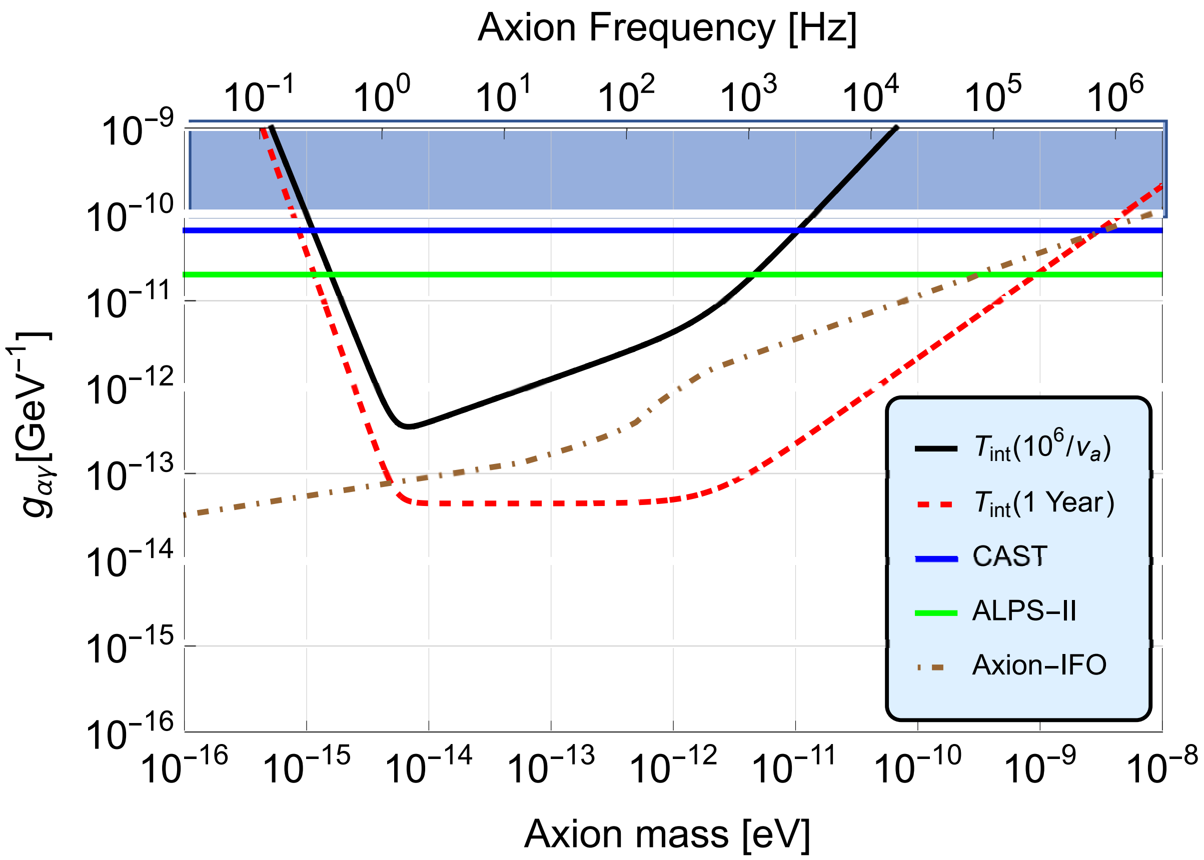


Input power	I_0	1 W
PDE quantum efficiency	q	0.7 A/W
PDE gain	G	$10^6\ \Omega$
Extinction ratio	σ^2	2×10^{-7}
Dark noise	i_{dark}	$25\ \mathrm{fA_{rms}}/\sqrt{\mathrm{Hz}}$
Modulation amplitude	η_0	1.5×10^{-3}
Modulation frequency	ν_{PEM}	50 kHz
RIN	$N_{\nu_{\mathrm{PEM}}}^{(\mathrm{RIN})}$	$3 \times 10^{-7}/\sqrt{\mathrm{Hz}}$
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}



Prospects for scalar and axion field dark matter





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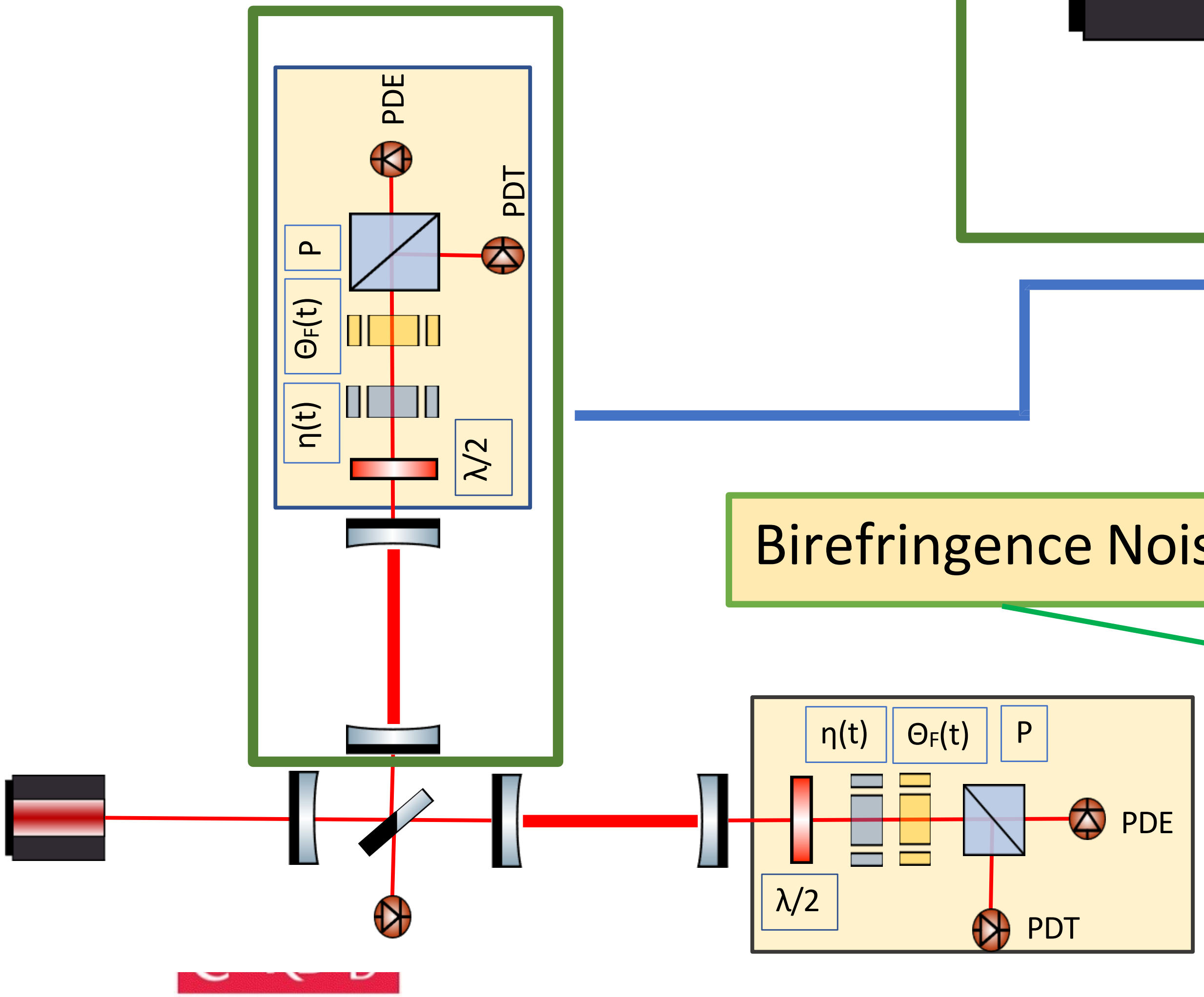
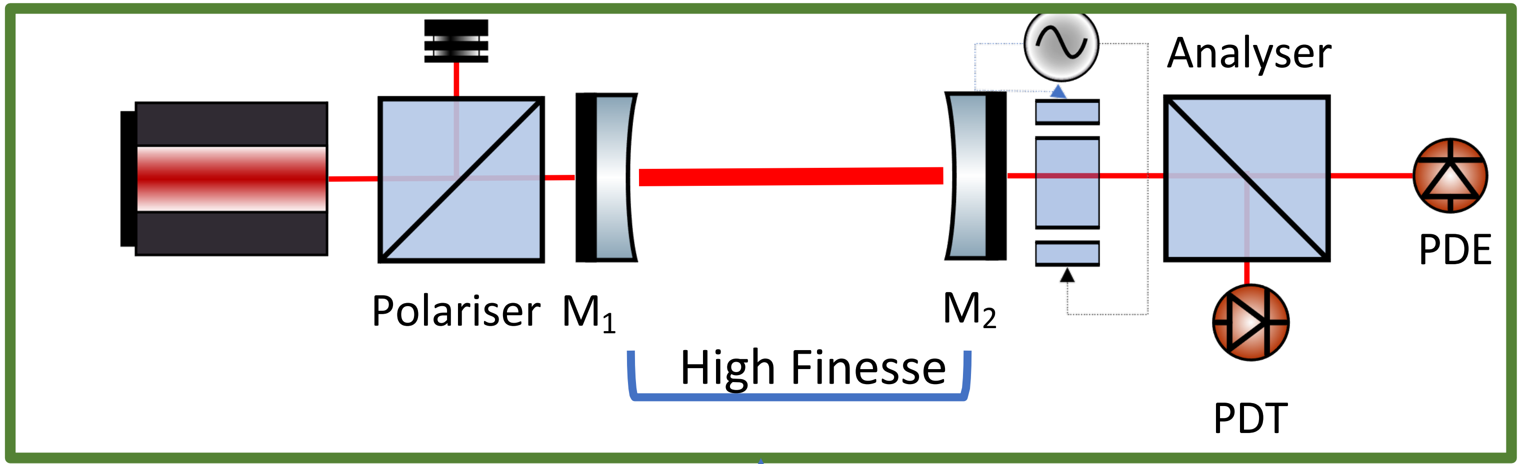
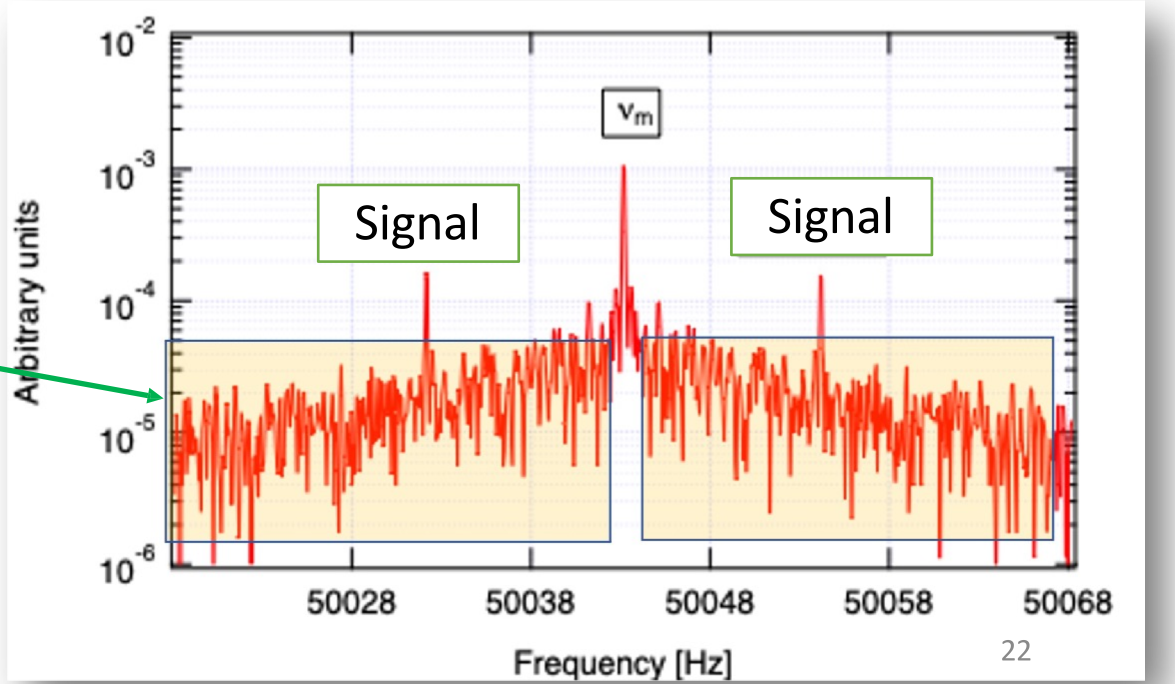
Polarimetry can mitigate birefringence noise in GW detectors

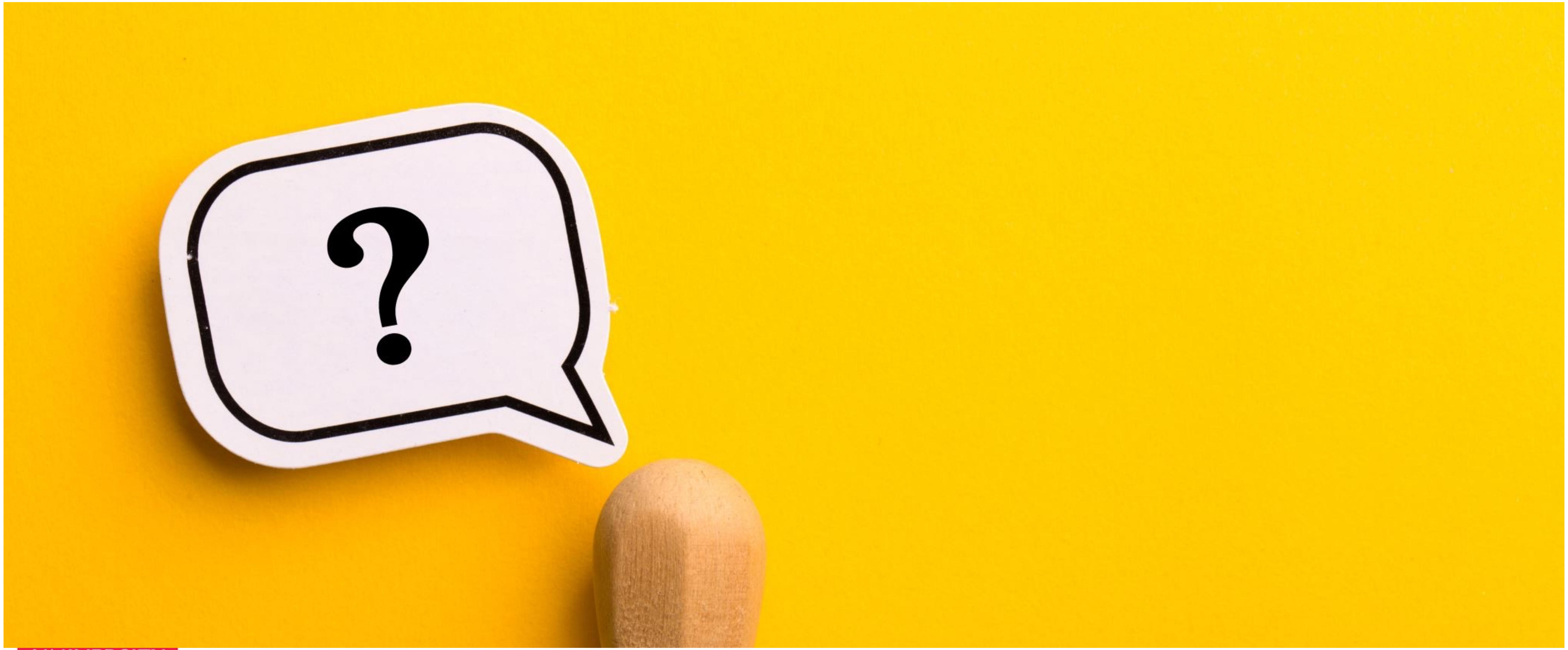




Birefringence Noise



Thank you for your attention



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