Ultralight Dark Matter Detection with Gravitational-Wave Interferometers

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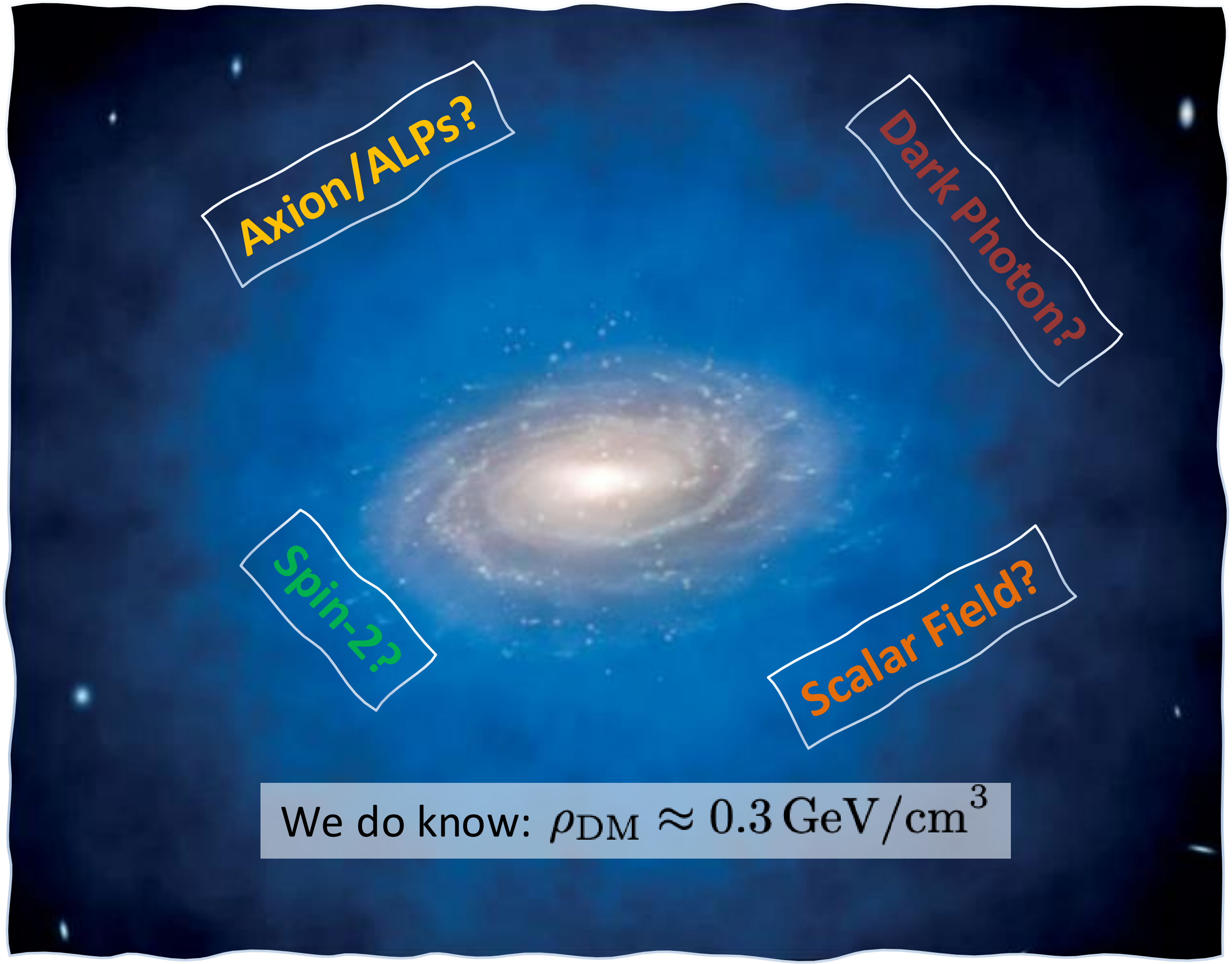
Introduction to Scalar Field Dark Matter

- Dark matter is one of the mysteries of modern physics.
- Scalar field dark matter is a theoretical candidate that could account for dark matter through low-mass fields.
- Why scalar fields?

Scalar Field Coupling

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



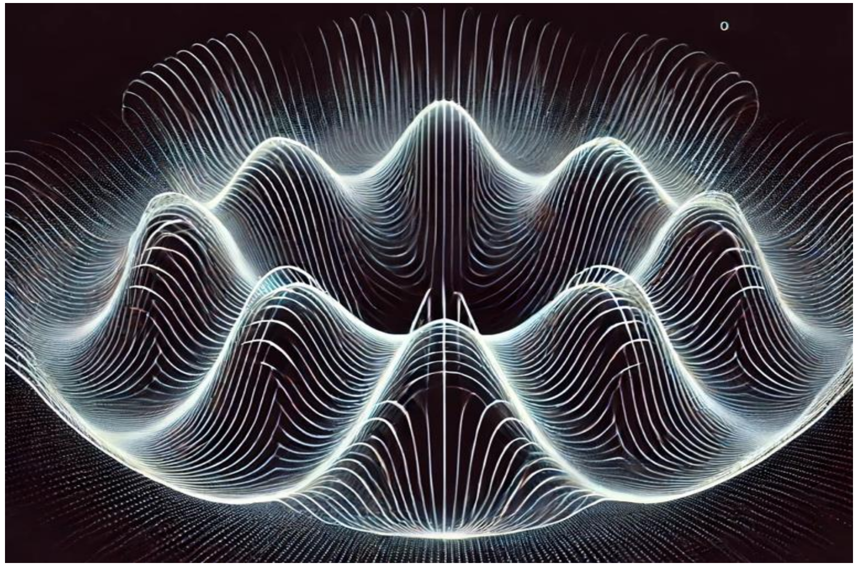
We do know: $\rho_{\text{DM}} \approx 0.3\,\text{GeV}/\text{cm}^3$

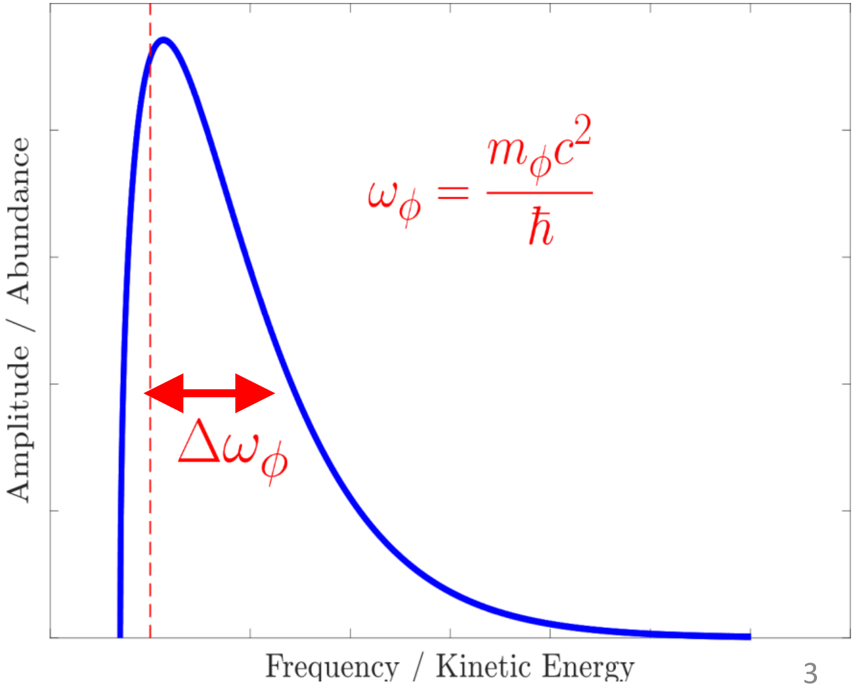
What is Scalar Field Dark Matter?

- Scalar field dark matter may have been created in the early universe.
- Coherently oscillating fields that can cause observable effects in physical systems.

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

$$\frac{\delta\omega_\phi}{\omega_\phi} \approx 10^{-6}$$





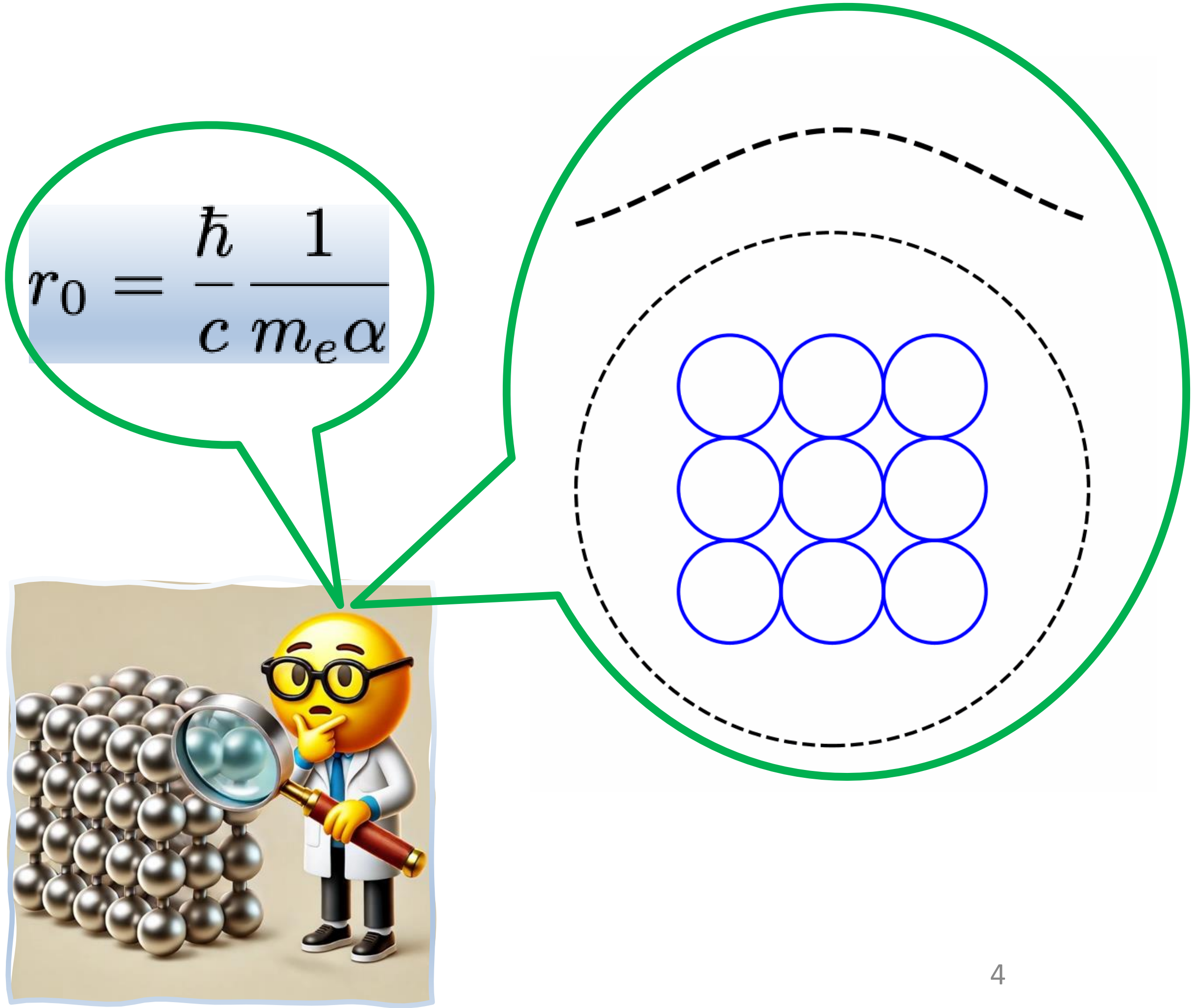
Expected Effects of Scalar Field Dark Matter

- Scalar field dark matter affects fine structure constant and electron mass.
- Modulations in the size and refractive index of materials.

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

$$\frac{\delta\alpha}{\alpha} = \frac{\phi}{\Lambda_\gamma} \qquad \frac{\delta m_e}{m_e} = \frac{\phi}{\Lambda_e}$$

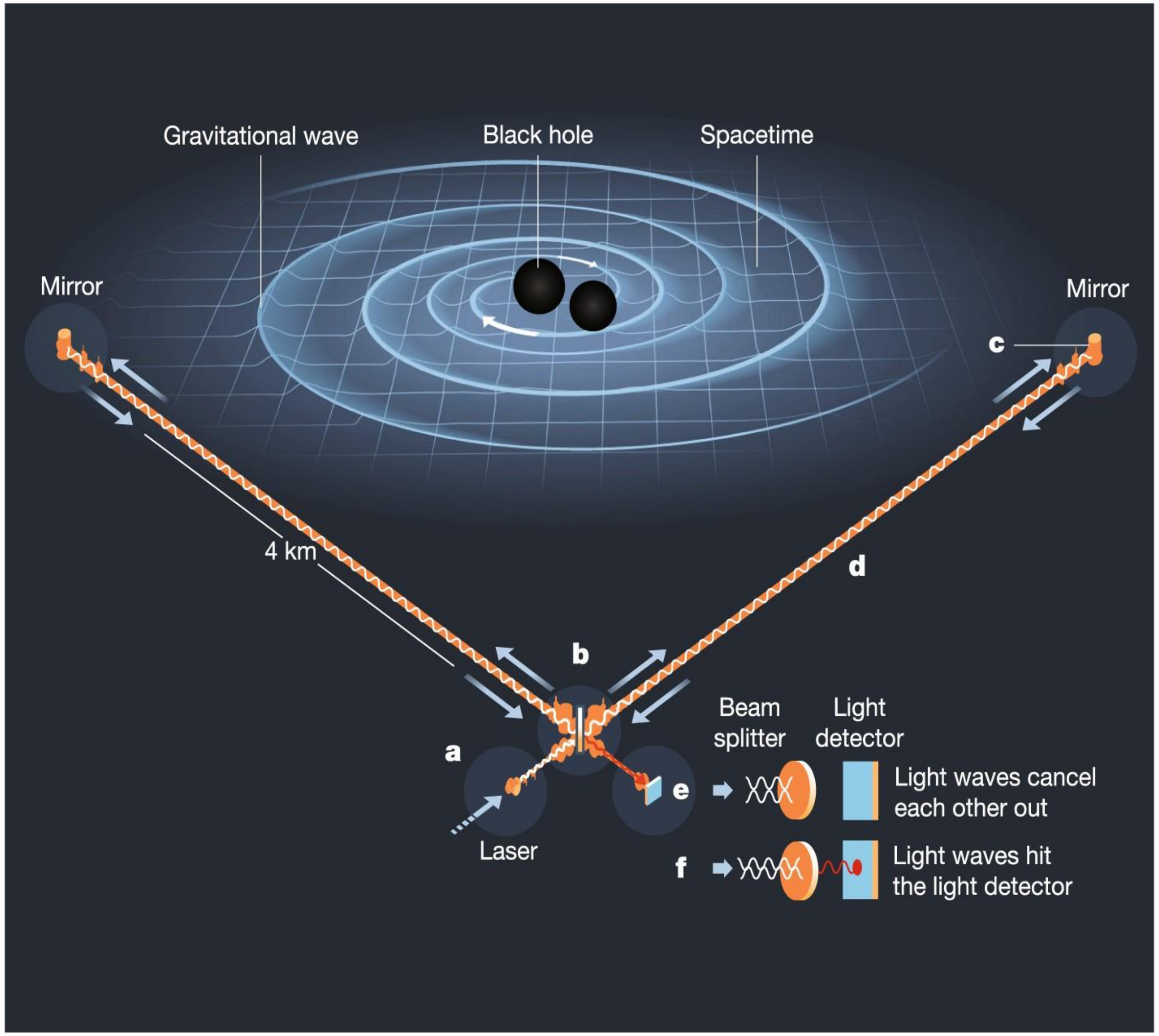
$$\phi(t, \vec{r}) = \left[\frac{\hbar\sqrt{2\,\rho_{\text{local}}}}{m_\phi\, c}\right] \cos\left(\omega_\phi\, t - \vec{k}_\phi \cdot \vec{r}\right)$$



$$r_0 = \frac{\hbar}{c}\frac{1}{m_e\alpha}$$

LIGO as a Detection Tool

- LIGO is a dual-recycled Fabry-Pérot Michelson interferometer designed to detect gravitational waves.
- Its extreme sensitivity to length changes makes it an ideal instrument for detecting scalar field dark matter.



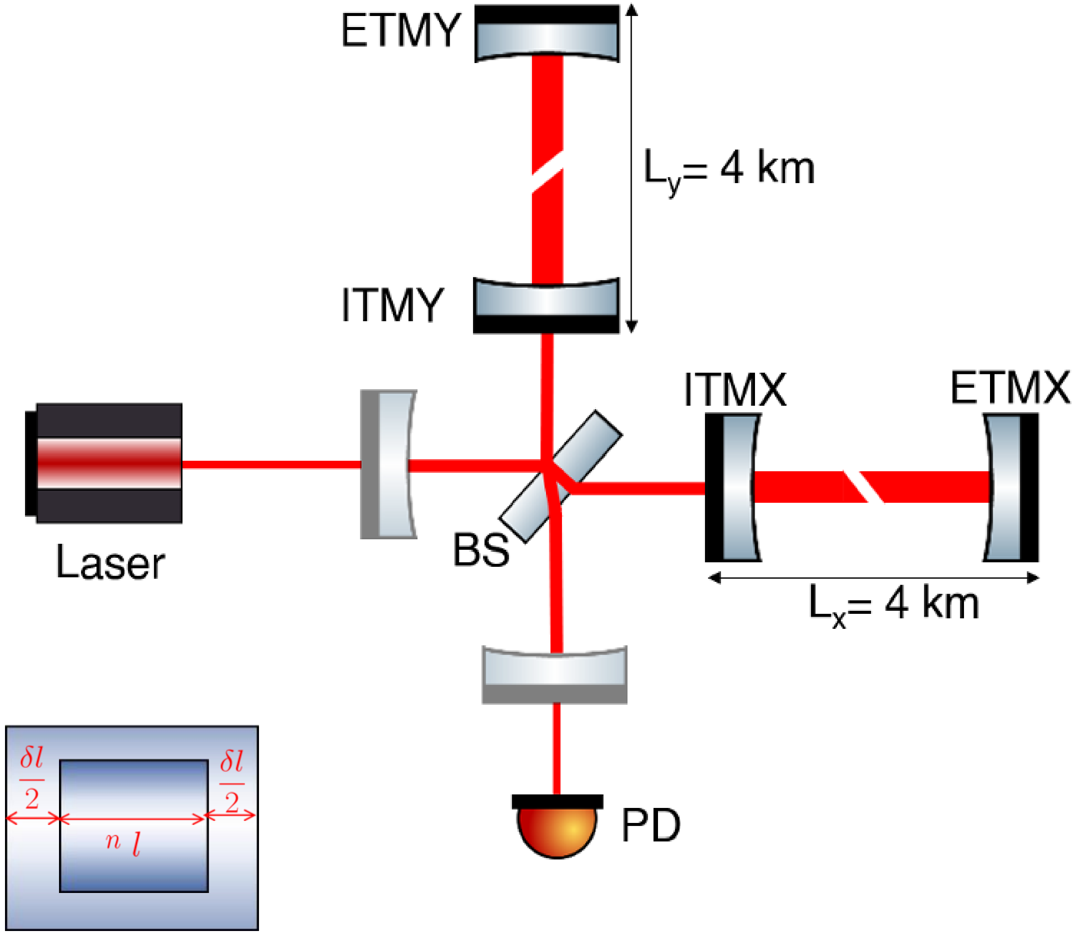
How Scalar Field Dark Matter Affects LIGO Measurements

- Oscillations in LIGO’s beamsplitter and test masses, leading to detectable path length differences.

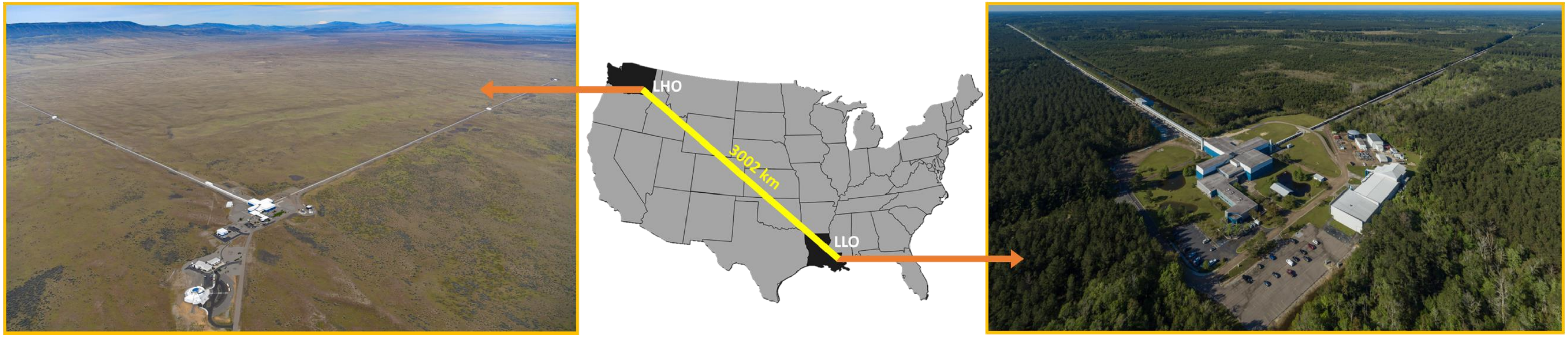
- These effects are measured through changes in the interferometer's output signal.

DM “size” effect only:

- Beamsplitter
- Splitting occurs far from the center of mass
- Test masses
- Asymmetry from thickness differences



LIGO's Dual Detectors



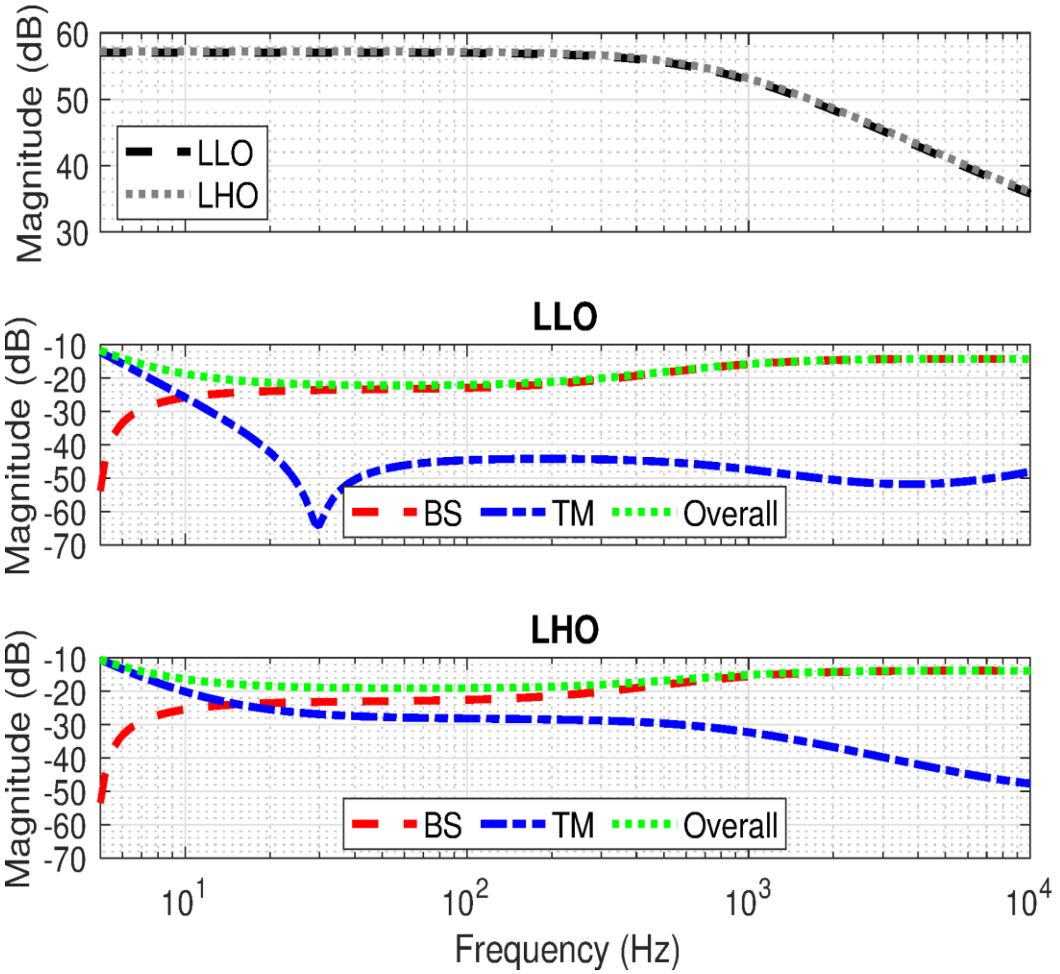
Calibrated Strain

- Available strain data is calibrated to gravitational waves:

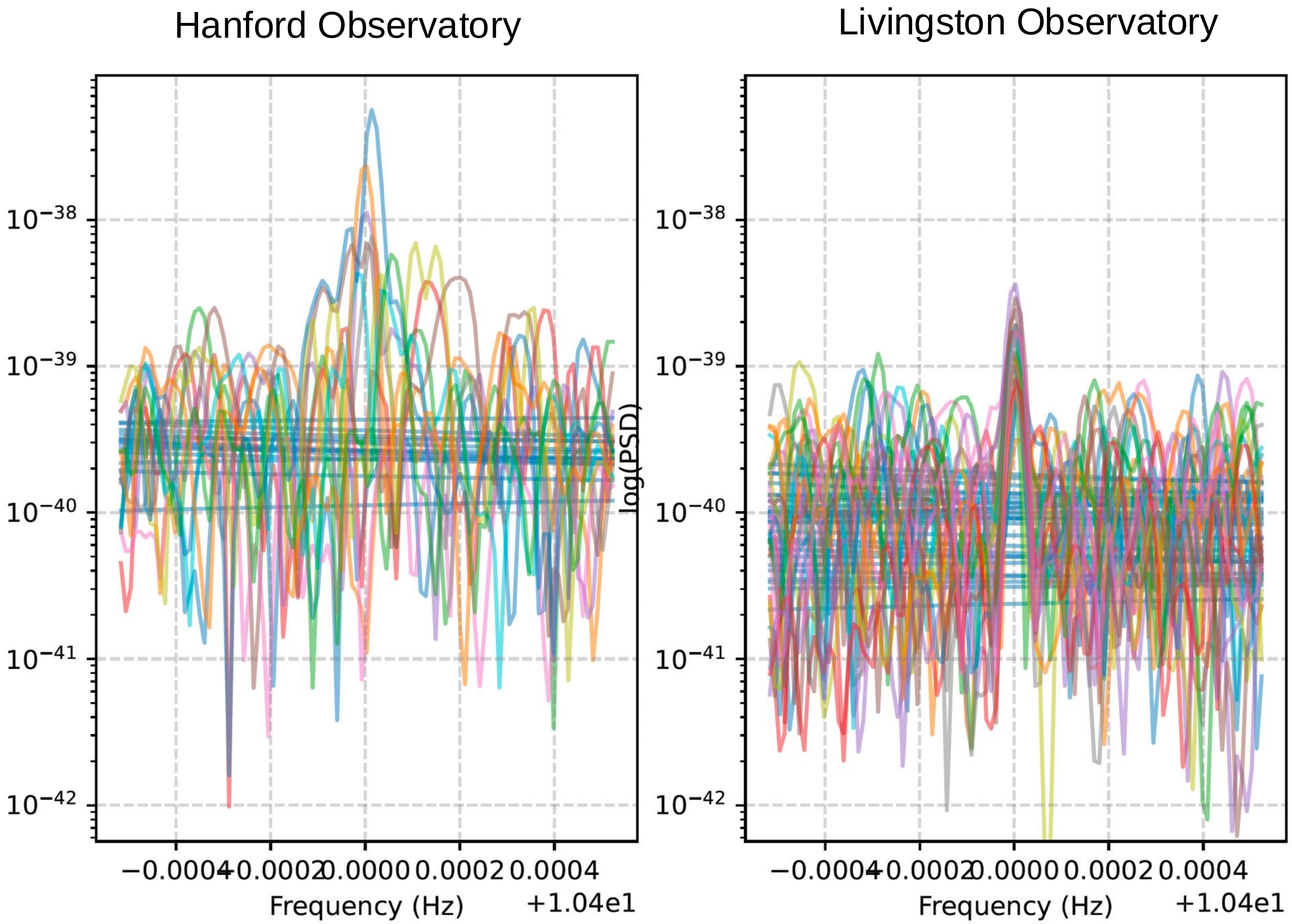
$$h(\omega) = \frac{I_{\rm PD}(\omega)}{L\,{\rm T}_{\rm GW}(\omega)\,e^{i\phi_{\rm GW}}}$$

- We are instead interested in DM-induced strain:

$$s_{\rm DM}(\omega) = \frac{I_{\rm PD}(\omega)}{|n\,t_{\rm B}{\rm T}_{\rm B}e^{i\phi_{\rm B}} + t_{\rm M}{\rm T}_{\rm M}e^{i\phi_{\rm M}}|}$$



10.4 Hz: **our best candidate**

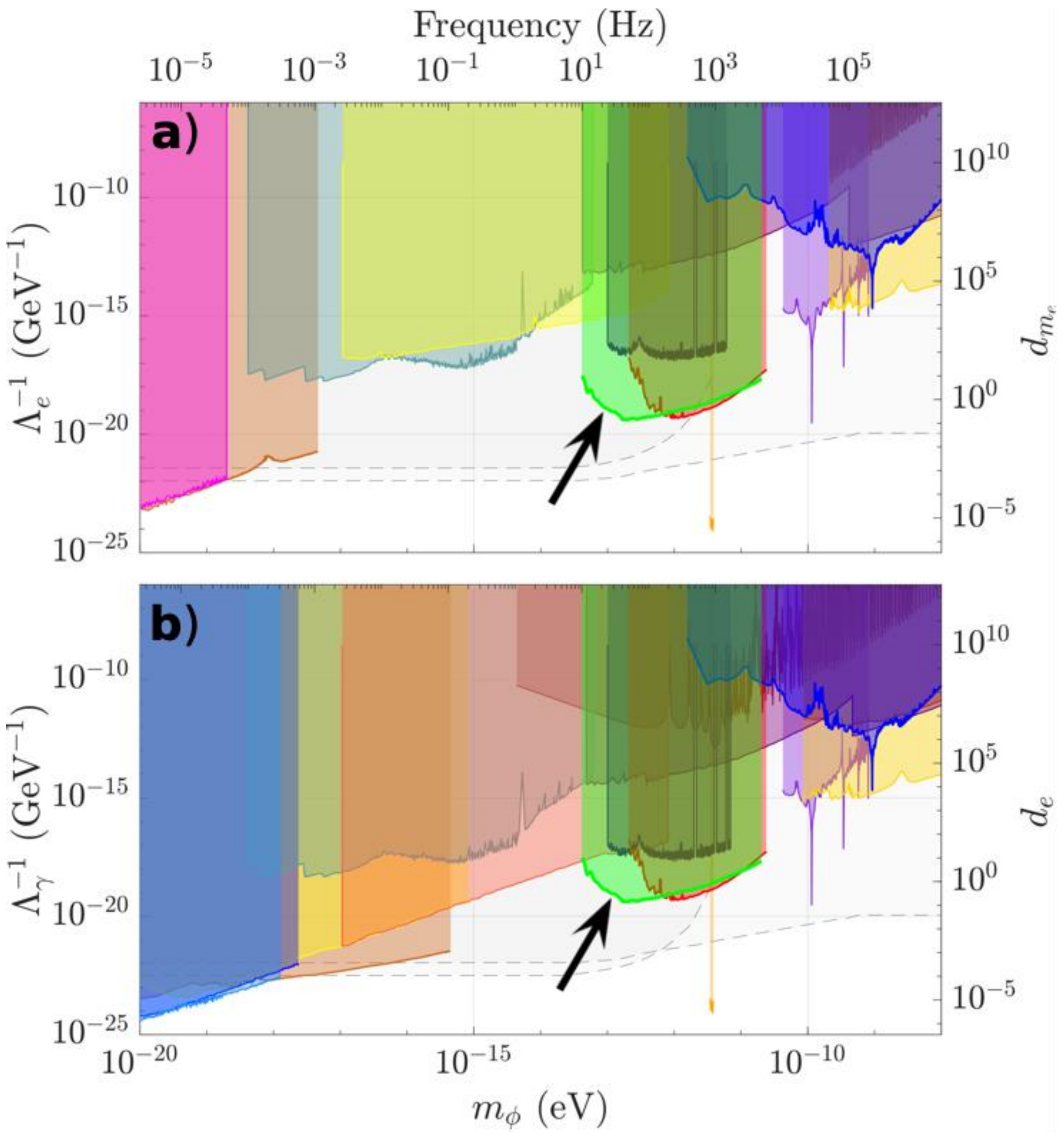


Hanford Observatory

Livingston Observatory

Upper Limits Results

- Our results in green
- Up to x1000 improvement below 180 Hz
- Competitive up to 5 kHz

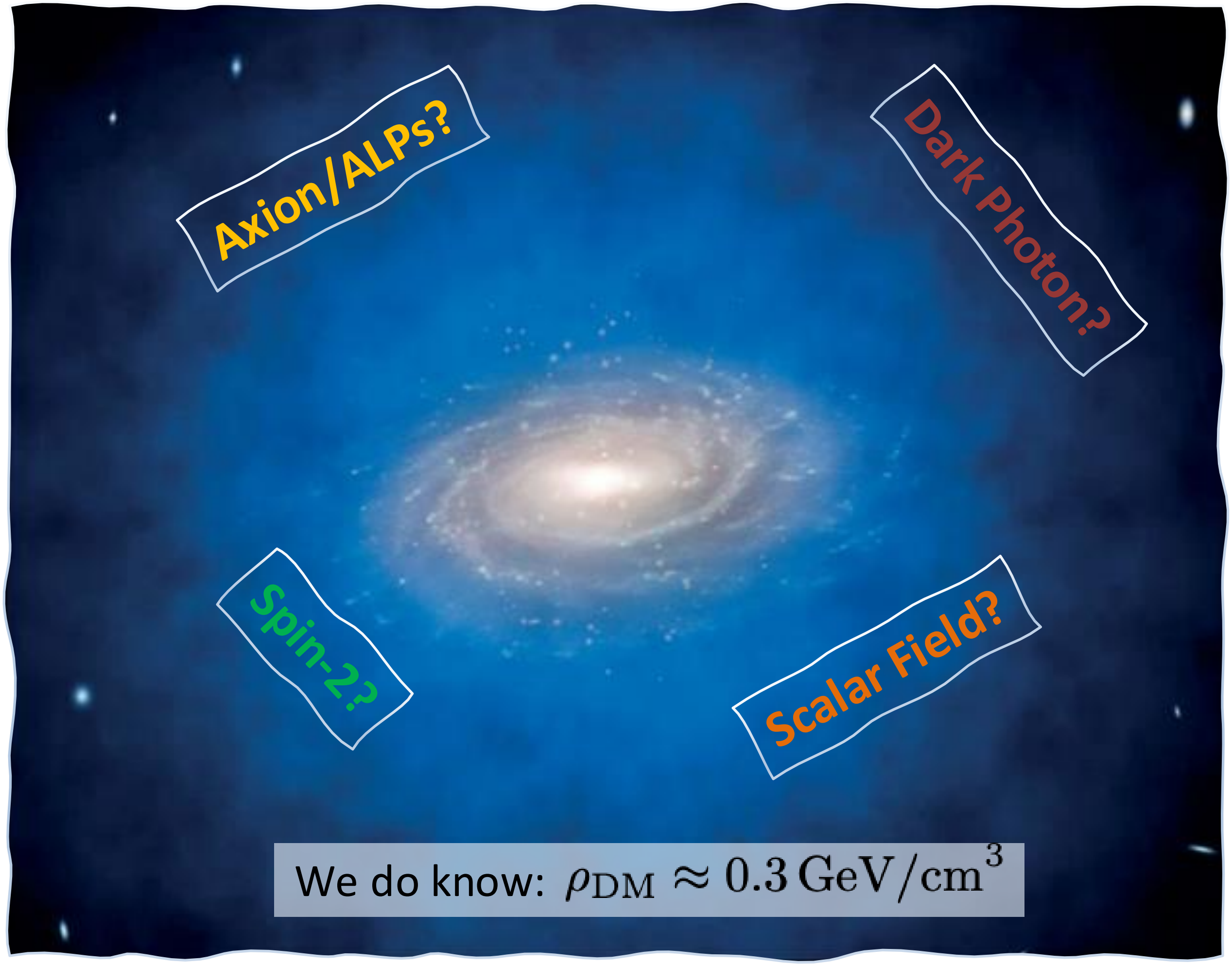


A.S. Göttel, A. Ejlli, K. Karan, S.M. Vermeulen, L. Aiello V. Raymond, H. Grote
https://arxiv.org/abs/2401.18076

Axion Field Dark Matter

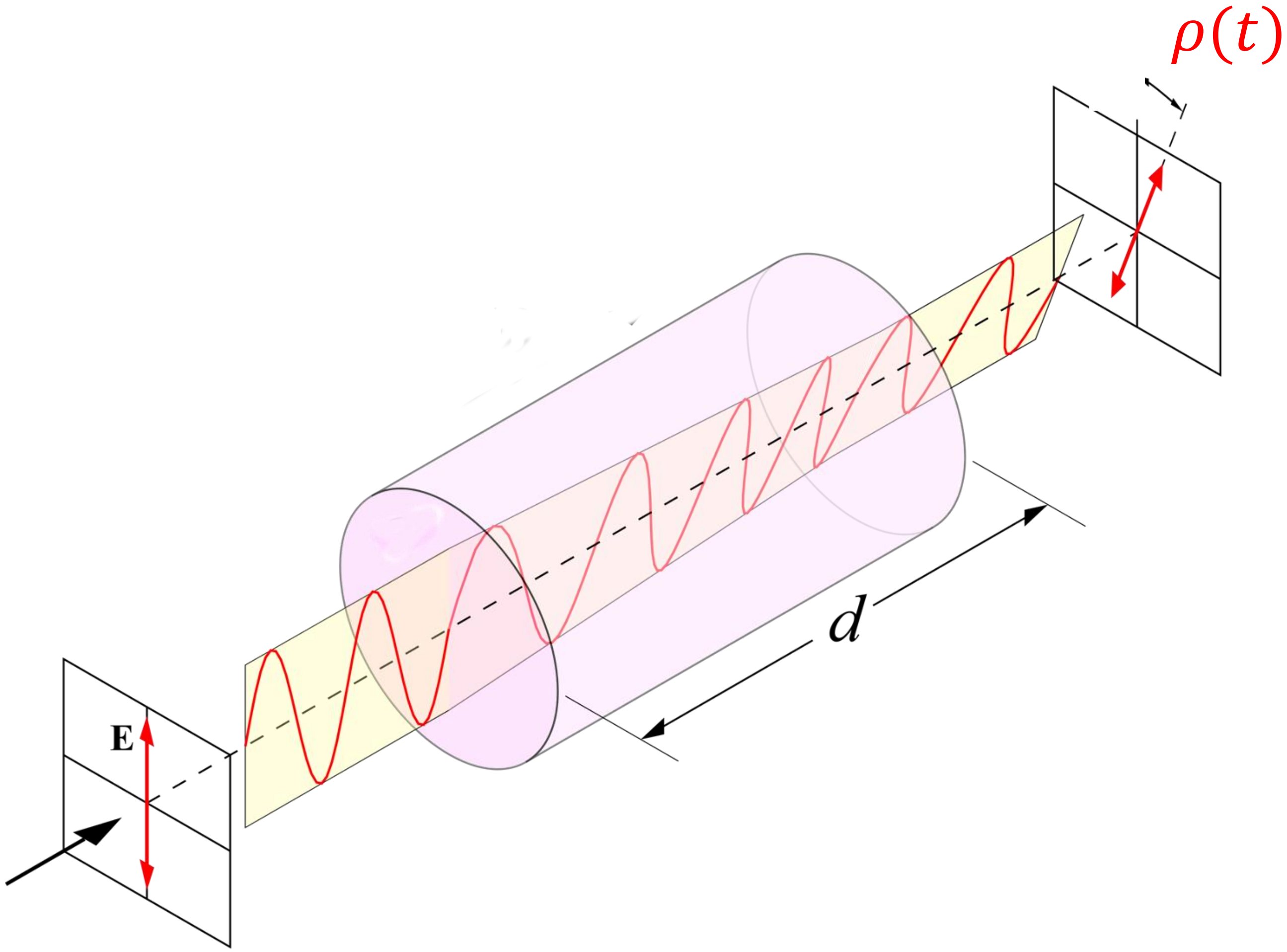
ALPs Coupling

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



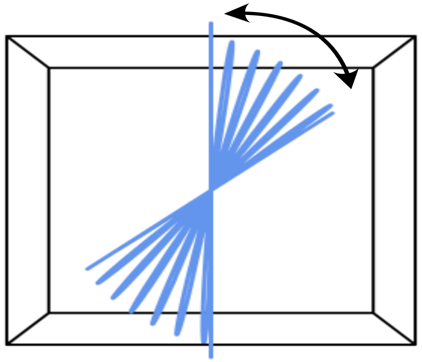
We do know: $\rho_{\text{DM}} \approx 0.3\,\text{GeV}/\text{cm}^3$

Effect of Axion Field on Polarization of Light

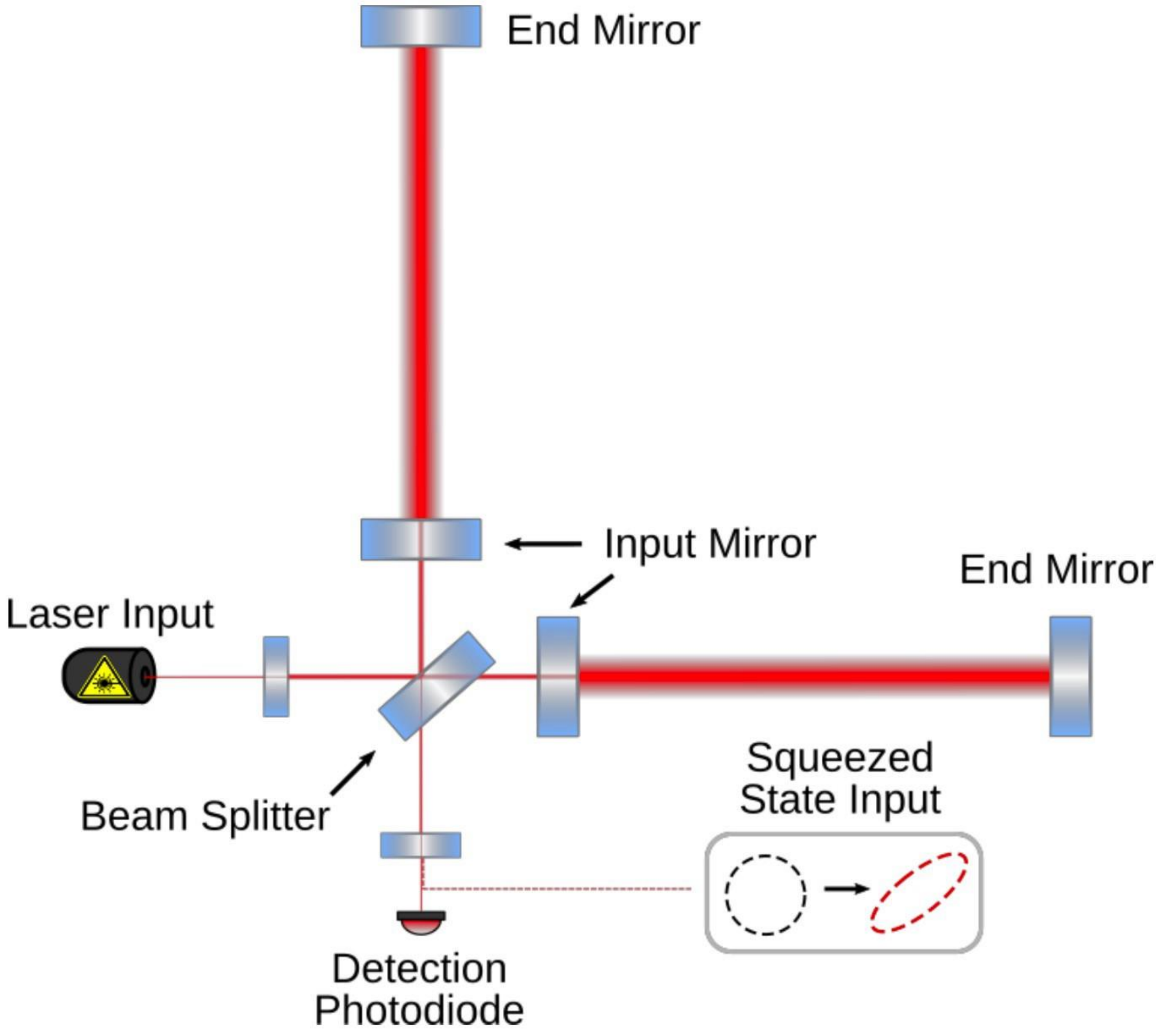


- Axion field rotates the polarization of linearly polarized light
- Angle of rotation oscillates with the frequency of Axion field

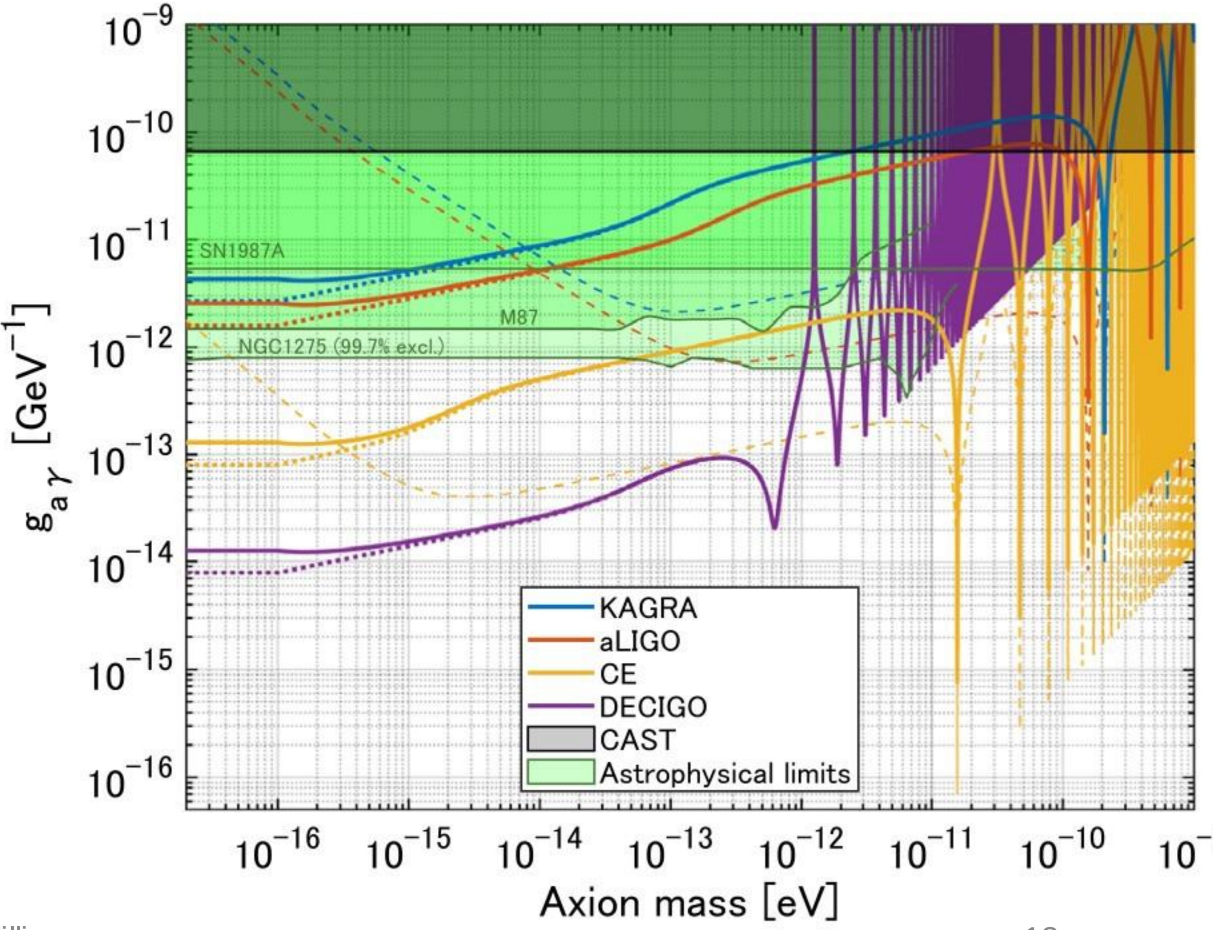
$$\rho(t) \propto \sin(\omega_{\text{Axion}} t)$$



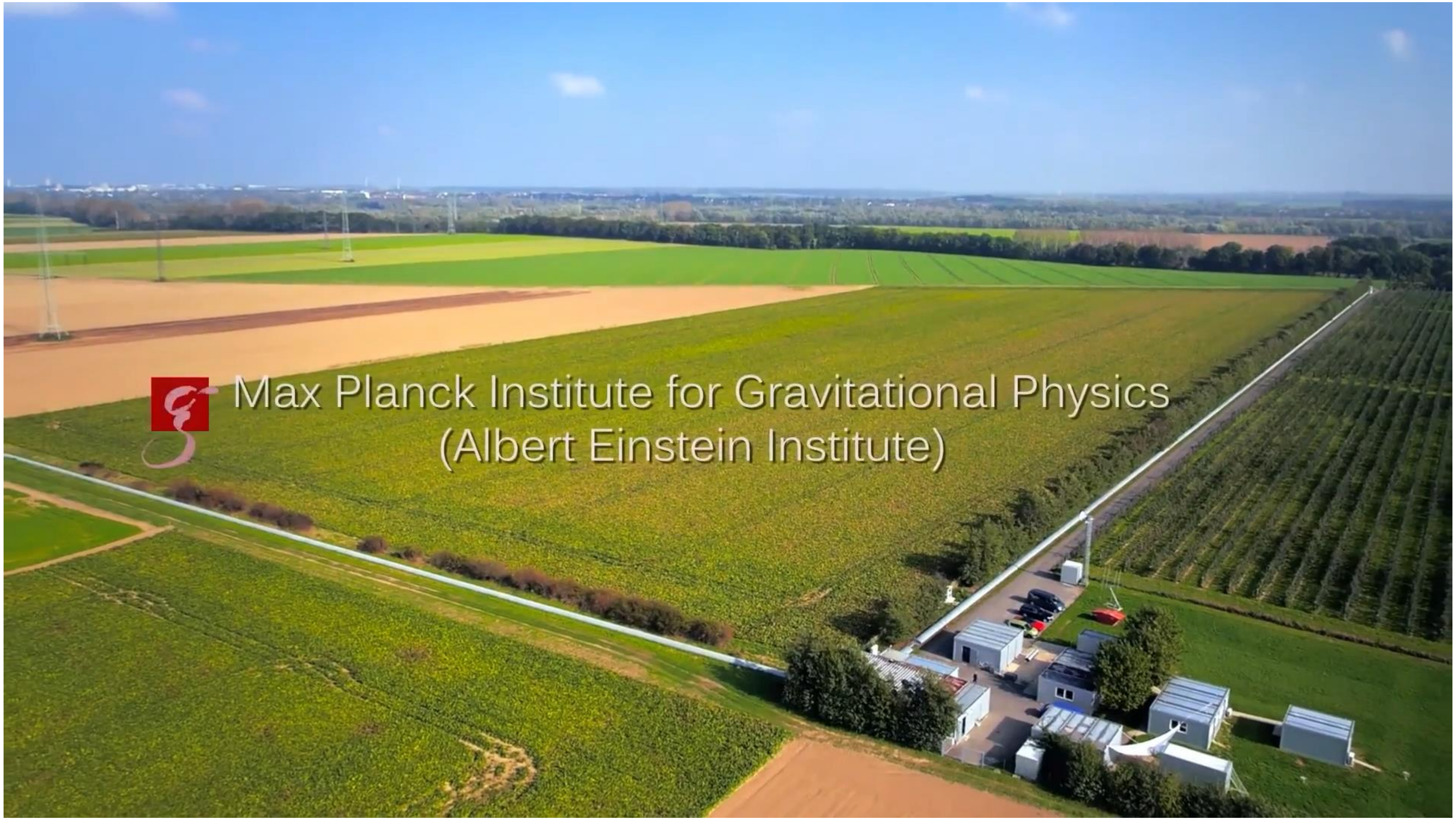
GW Detectors and Axion Search



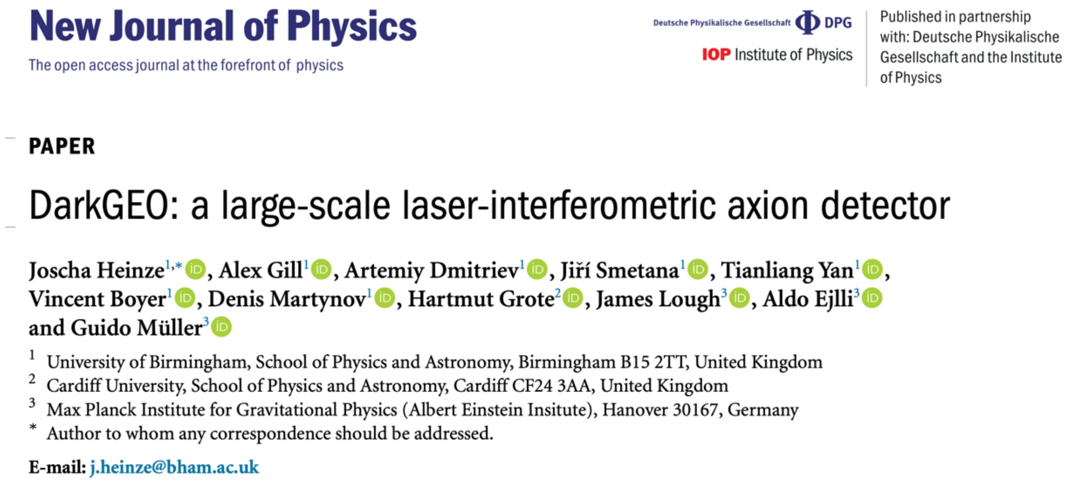
K. Nagano, *et al*
PRD 104, 062008 (2021)



GEO 600 – Gravitational Wave Detector



DarkGEO



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PAPER

DarkGEO: a large-scale laser-interferometric axion detector

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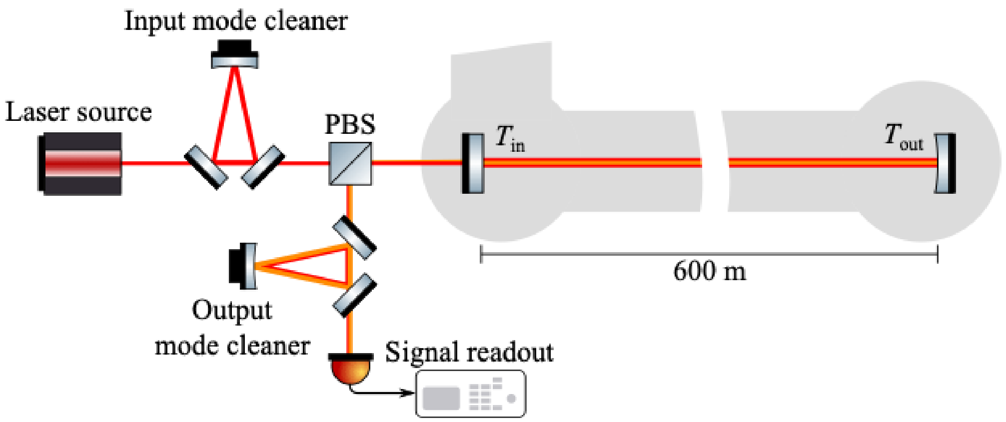
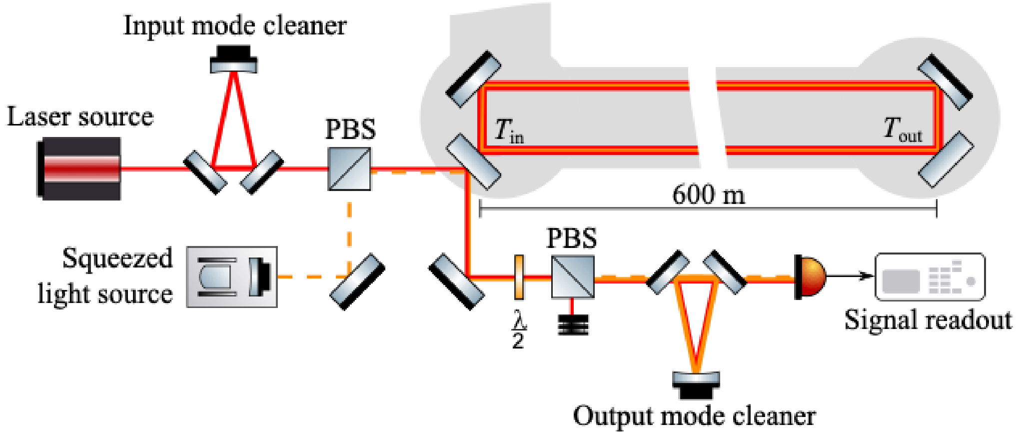
- **DarkGEO-I:** Linear Configuration
- **DarkGEO-II:** Rectangular Configuration
- **DarkGEO-III:** DarkGEO-III: Full Coincidence Search

DarkGEO-I: linear configuration

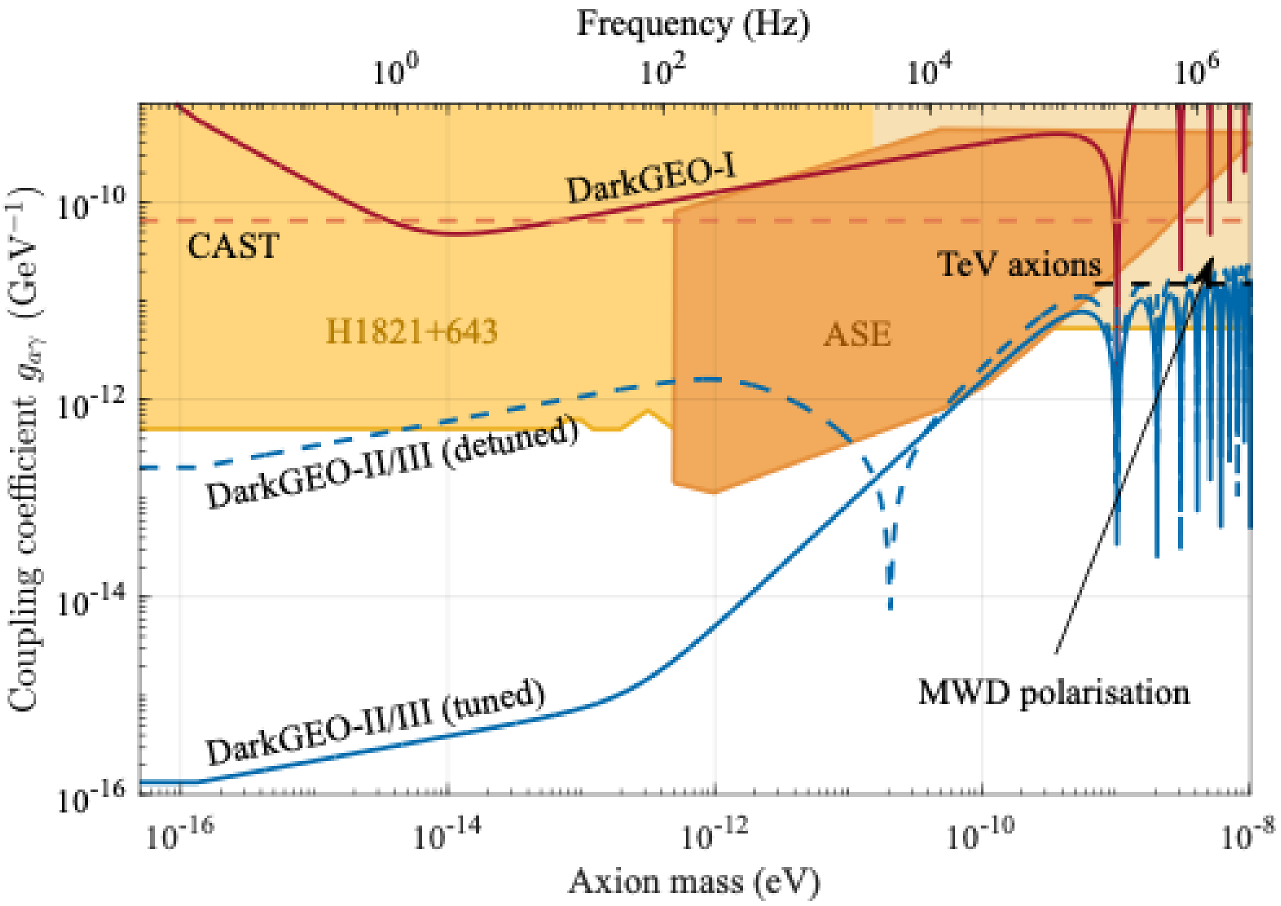


DarkGEO-II: rectangular configuration



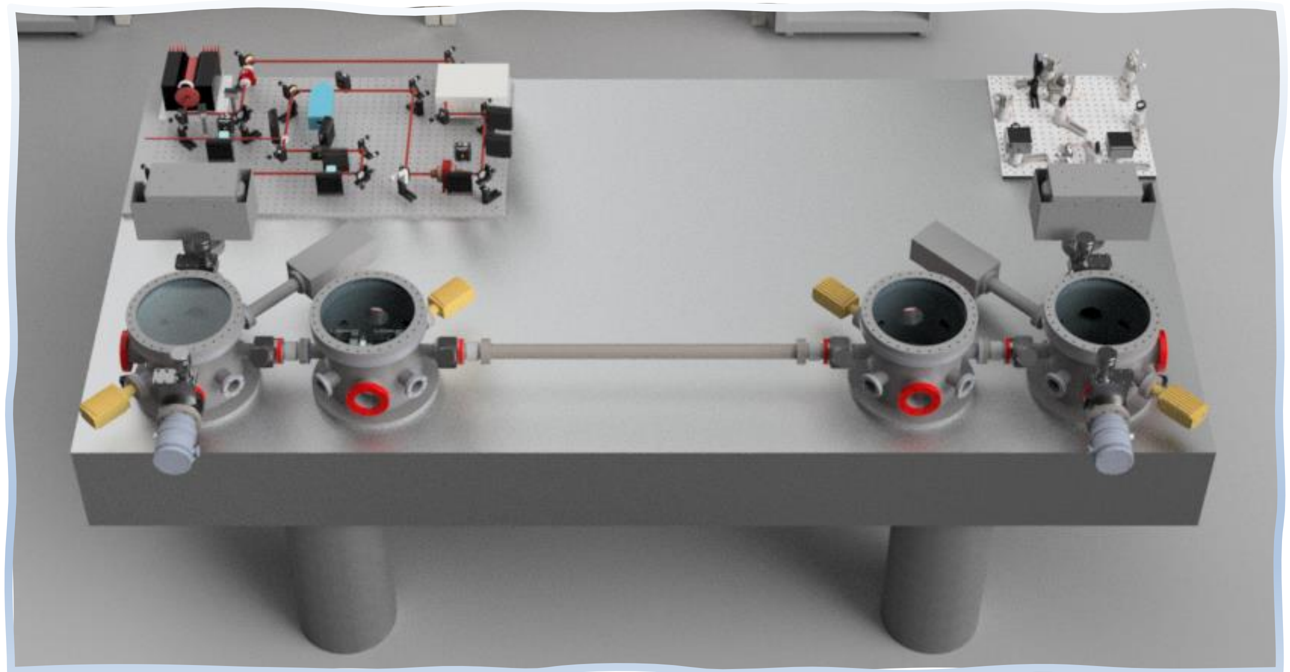
Potential of Large Scale Axion Polarimetry

- High Intra-Cavity Power 10 MW
- Squeezed Light at 10 dB to reduce quantum noise and enhance detection.
- Assumes shot-noise-limited performance across the measurement band for optimal signal-to-noise ratio.

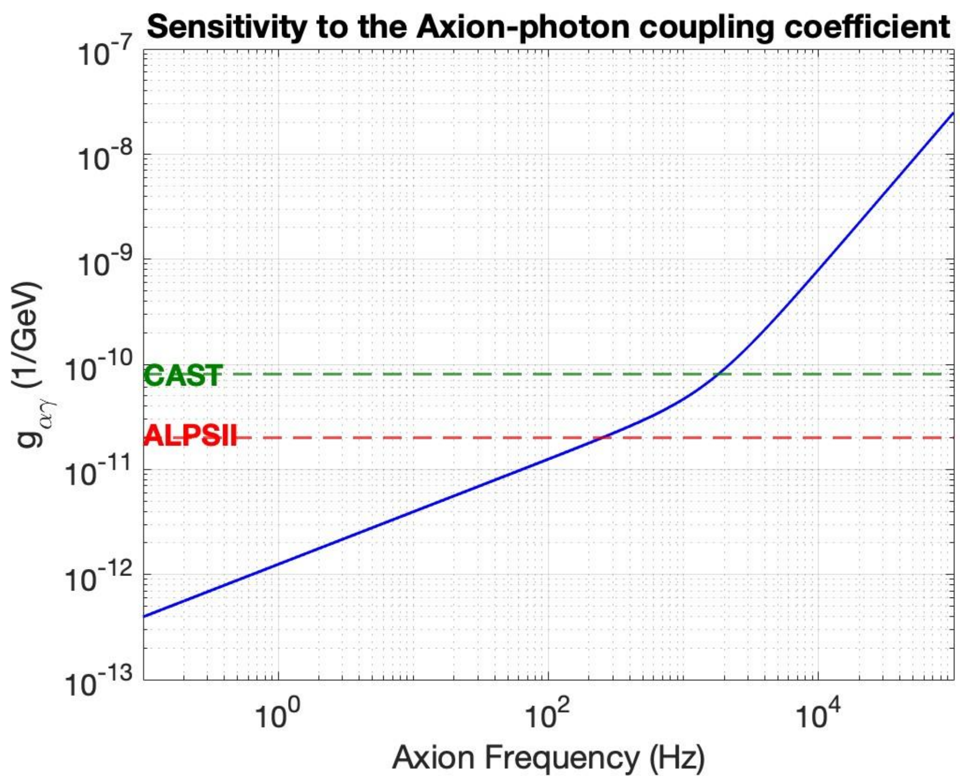


J. Heinze *et al*, *New J. Phys.* **26** (2024) 055002

Polarimetry-Prototype under construction at AEI MPG



$L = 1.5$ m

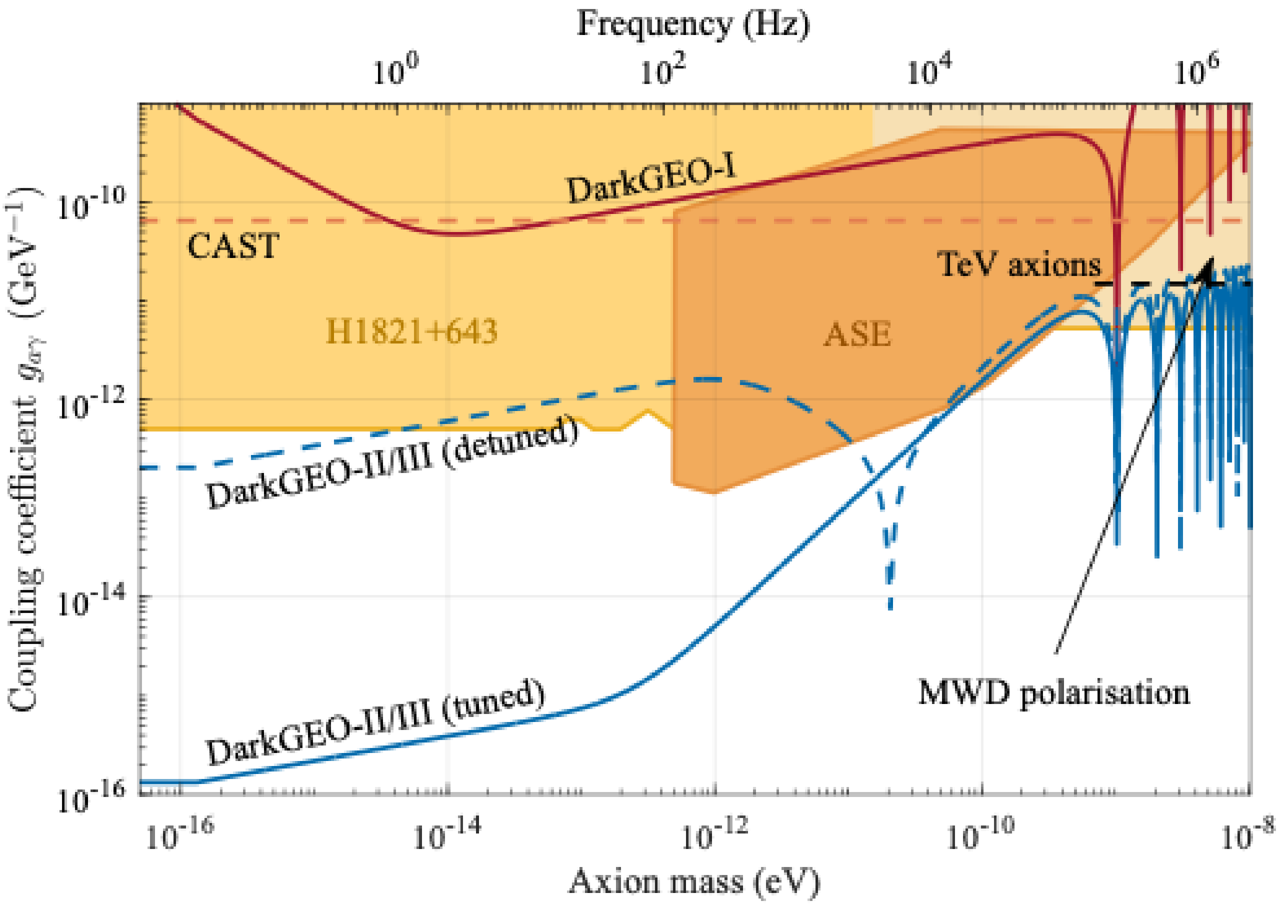


- ➢ **Sensitivity is proportional to the length!**

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

Discussion: Why targeting 10^{-16}-10^{-10} eV?

- Could this mass range validate multiple theoretical models of axions?
- Could the anomalies in cosmology and astrophysics are due to axions in this specific mass window?
- Could this experiment fill the critical gap left by other axion searches, making it a unique contribution to the field?



Thank you for your attention