Interferometric Haloscope

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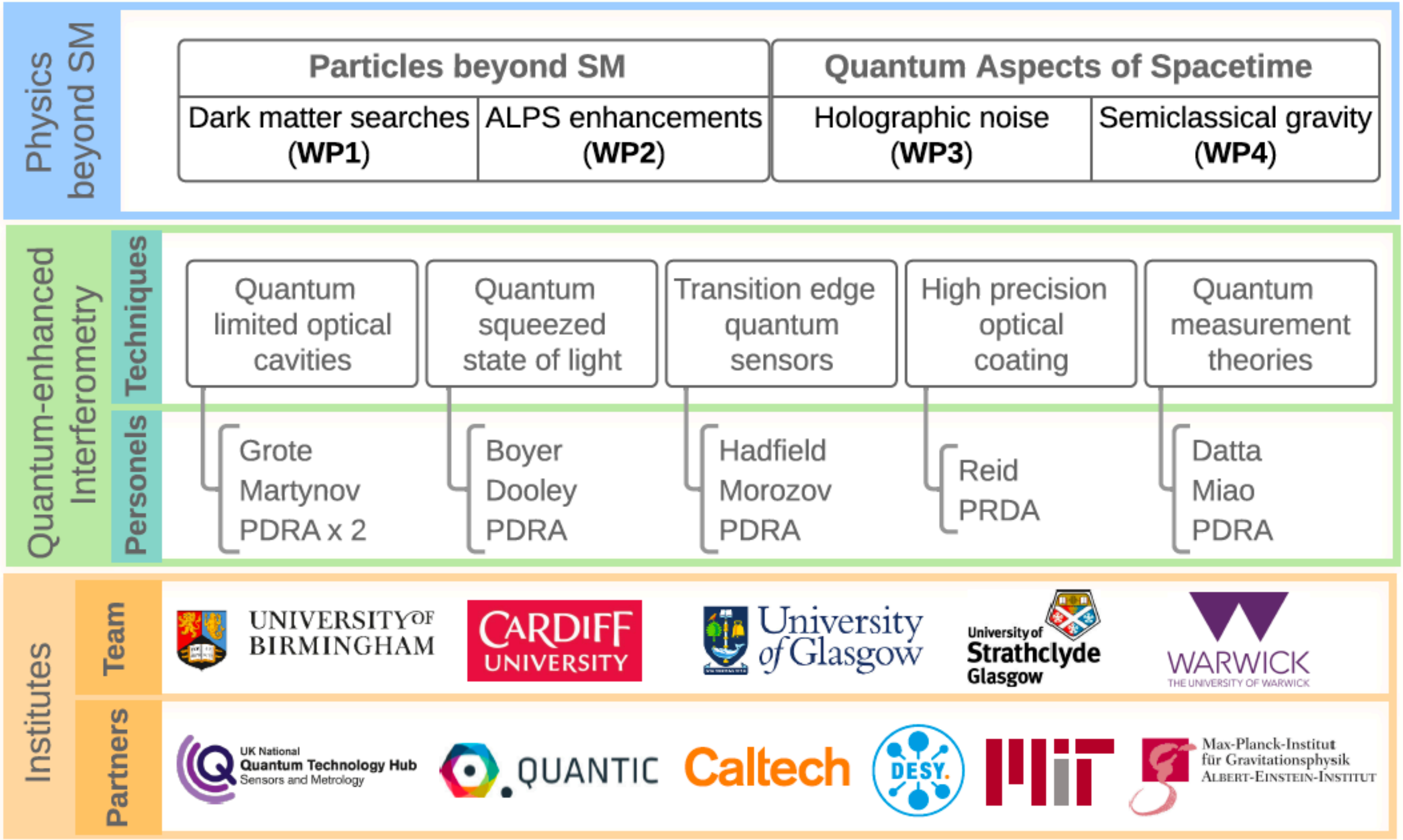
University of Birmingham

Member of **Quantum-enhanced Interferometer for New Physics** (QI) consortium

@ Beyond ALPS II Workshop

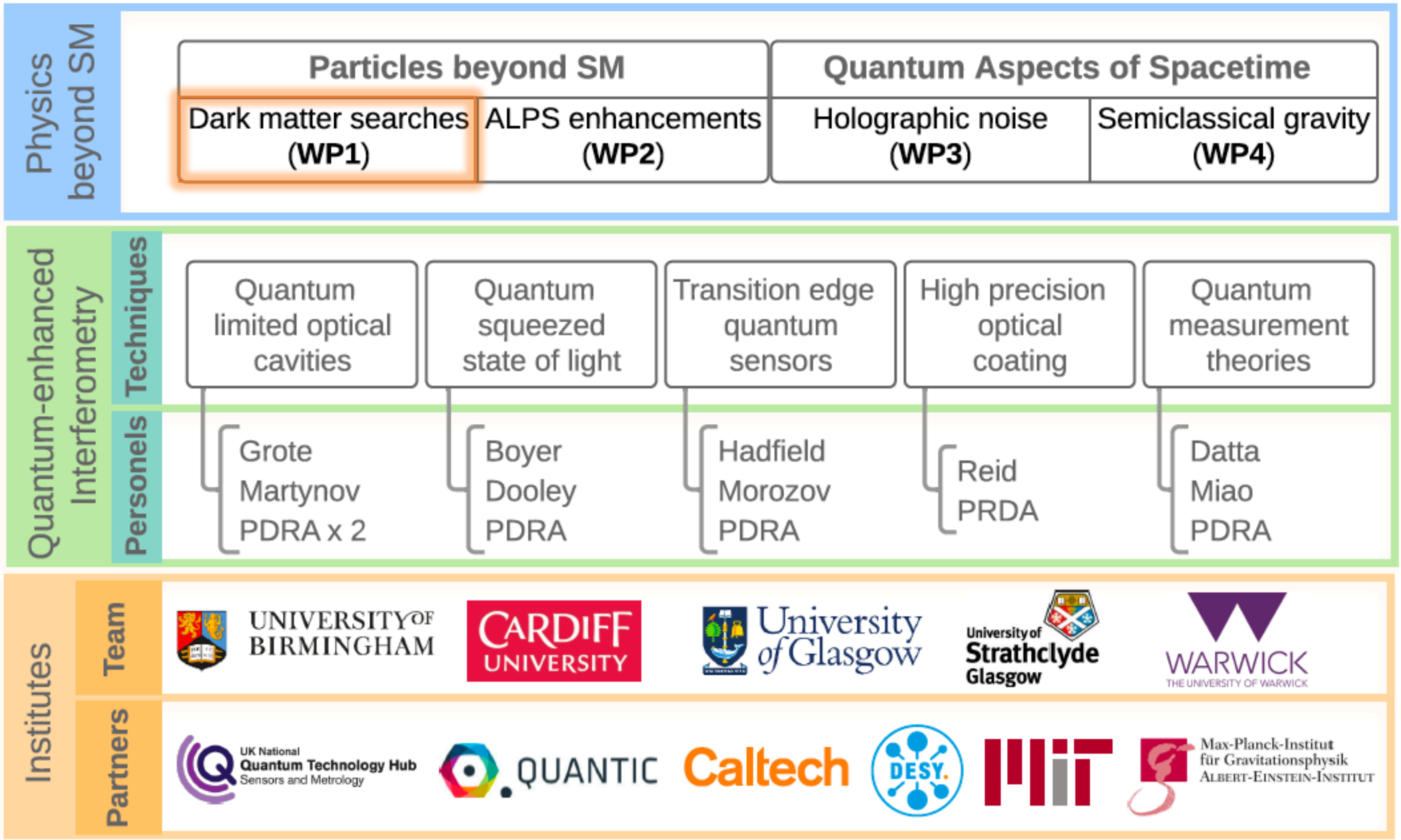
QI consortium overview



PDRA positions are now open. Please contact Hartmut Grote or Denis Martynov.

https://www.sr.bham.ac.uk/qi/

QI consortium overview



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Search Axion-Like-Particle (ALP) dark matter

Motivation for ALP:

- QCD Axion was proposed for solving the strong CP problem
- It has the right property as a dark-matter candidate
- Baryonic dark matter has issues with micro-lensing
- WIMPs: the detectors will face neutrino background soon

Theoretical Model:

$$\mathcal{L}_{\mathrm{int}} = -\frac{1}{4} g\, a(t) F_{\mu\nu} \tilde{F}^{\mu\nu} \propto a\, \mathbf{E} \cdot \mathbf{B}$$

Axion mean field amplitude

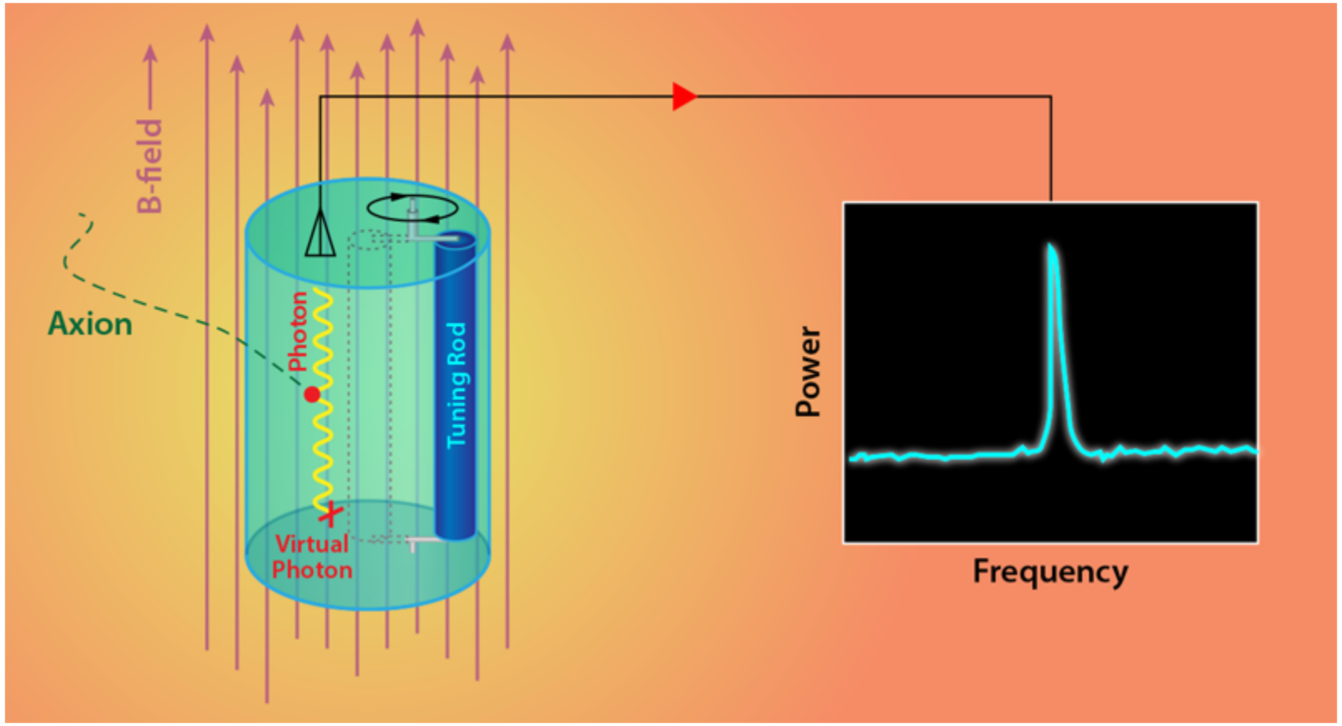
$$\bar{a}(t) = a_0 \cos(\Omega_a t + \phi)$$
$$(\Omega_a = m_a c^2 / \hbar)$$

- Breaking CP symmetry or T-reversal symmetry ($\mathbf{B} \rightarrow -\mathbf{B}$)
- Unlike QCD Axion, g is assume to be independent of the axion mass m_a [1, 2].

[1] P. Agrawal *et. al.*, *Experimental Targets for Photon Couplings of the QCD Axion*, JHEP 02(2018)006.
[2] W. DeRocco, and A. Hook, *Axion interferometry*, PRD **98**, 035021 (2018).

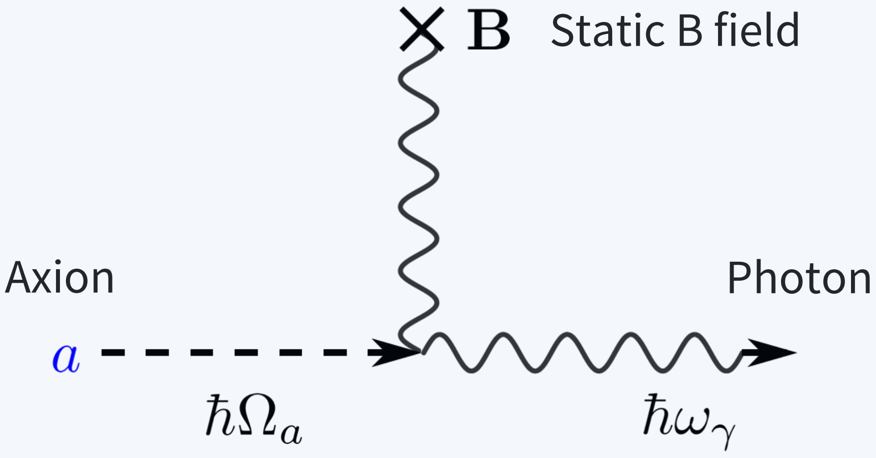
Detection Principle of Cavity Haloscope

Example: ADMX experiment [1]



[1] ADMX collaboration, *A SQUID-based microwave cavity search for dark-matter axions*, [Phys. Rev. Lett. 104, 041301 (2010)](https://doi.org/10.1103/PhysRevLett.104.041301).

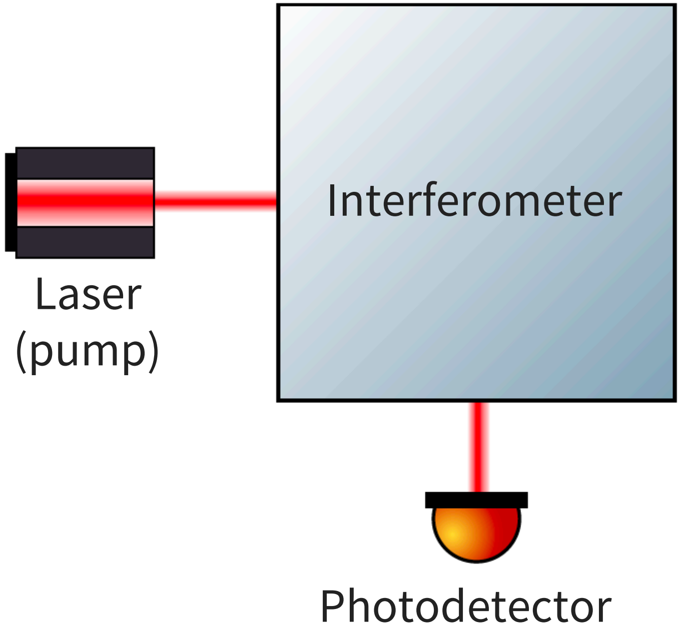
$$\mathcal{L}_{\text{int}} \propto a\,\mathbf{E}\cdot\mathbf{B}$$



$$\omega_\gamma = \Omega_a$$

μeV axions ⇒ Microwave photons

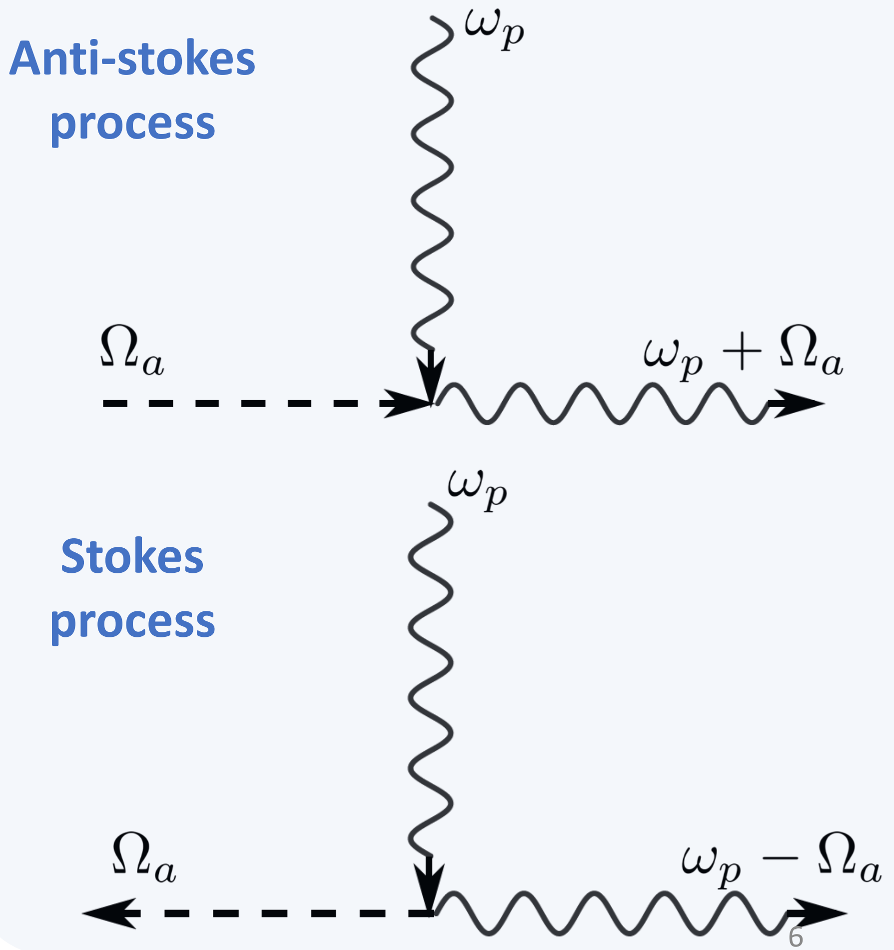
Interferometric Haloscope



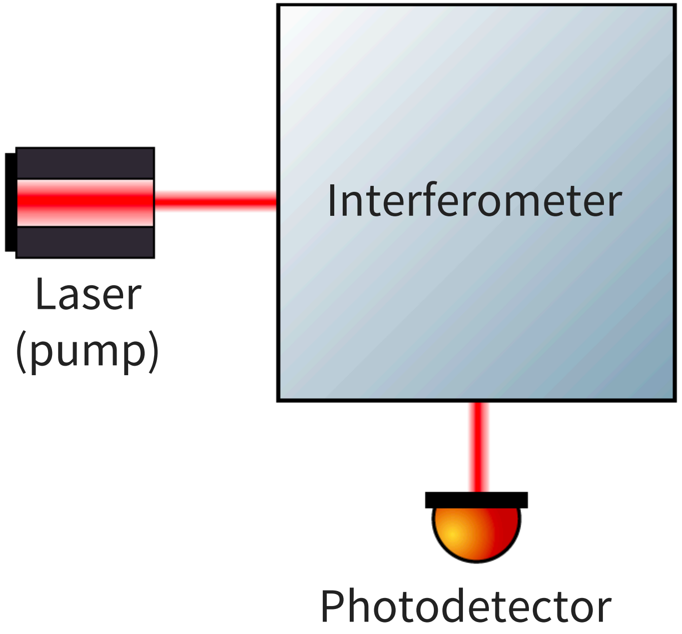
AC magnetic field
@ optical frequency

$$|\mathbf{B}| = \frac{|\mathbf{E}_0|}{c}$$

$$\mathcal{L}_{\rm int} \propto a\,\mathbf{E}\cdot\mathbf{B}$$



Interferometric Haloscope



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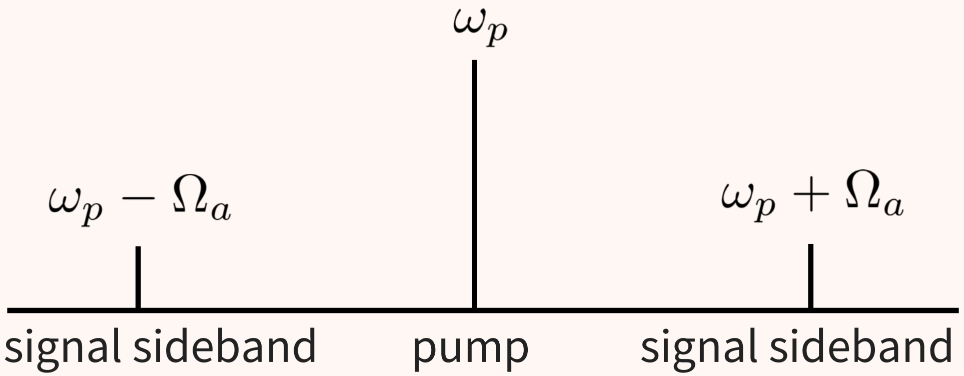
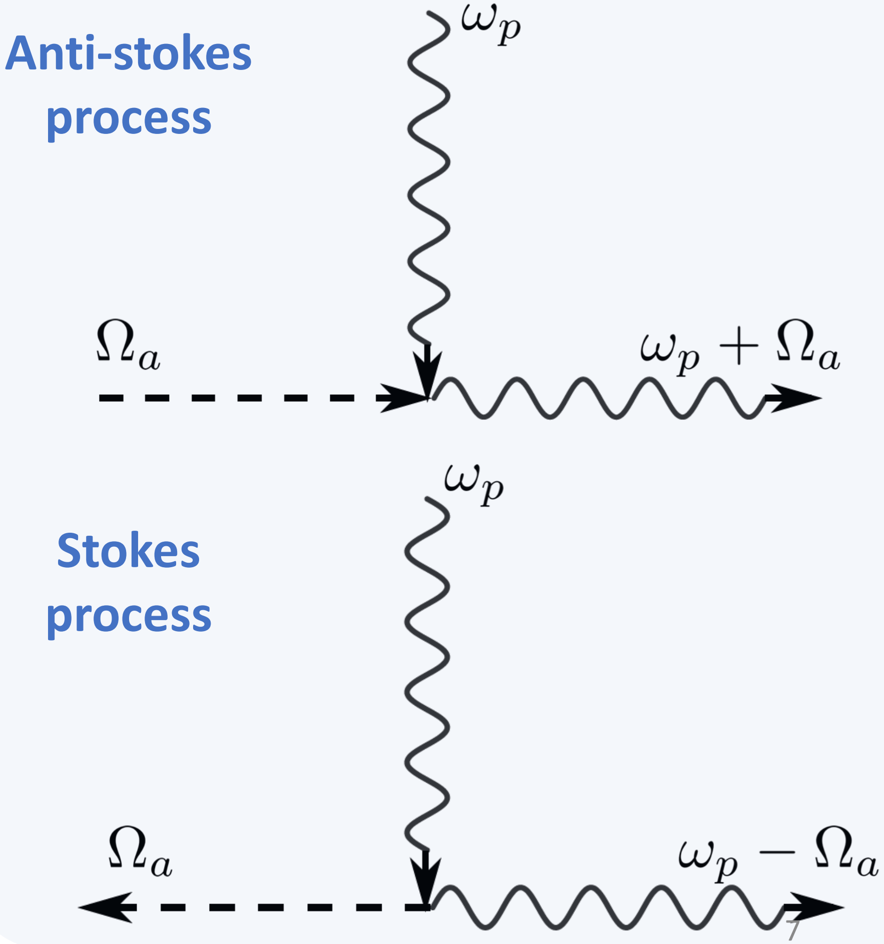
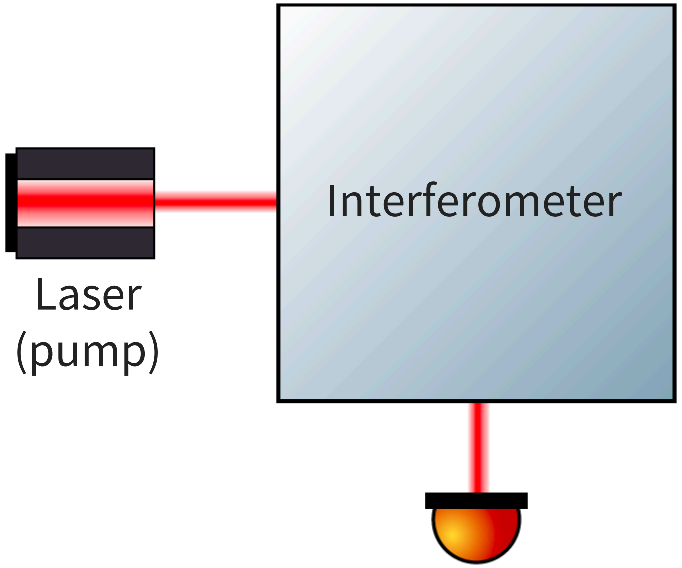
Experimental Signature:



$$\mathcal{L}_{\text{int}} \propto a\,\mathbf{E}\cdot\mathbf{B}$$



Interferometric Haloscope

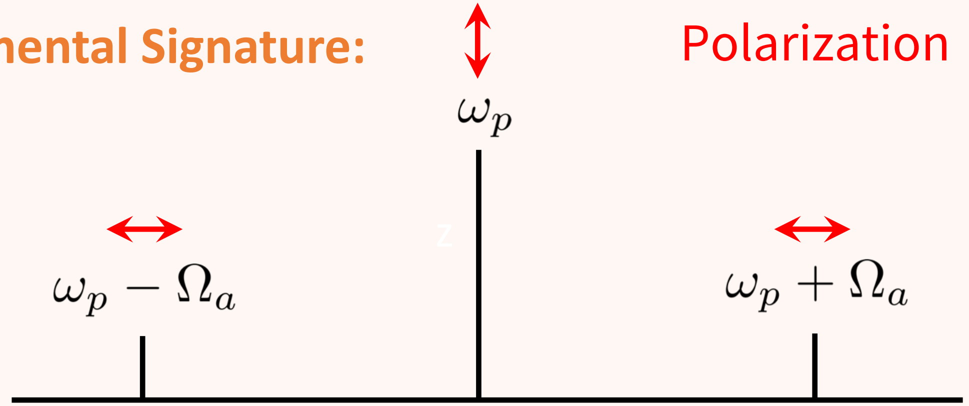


AC magnetic field
@ optical frequency

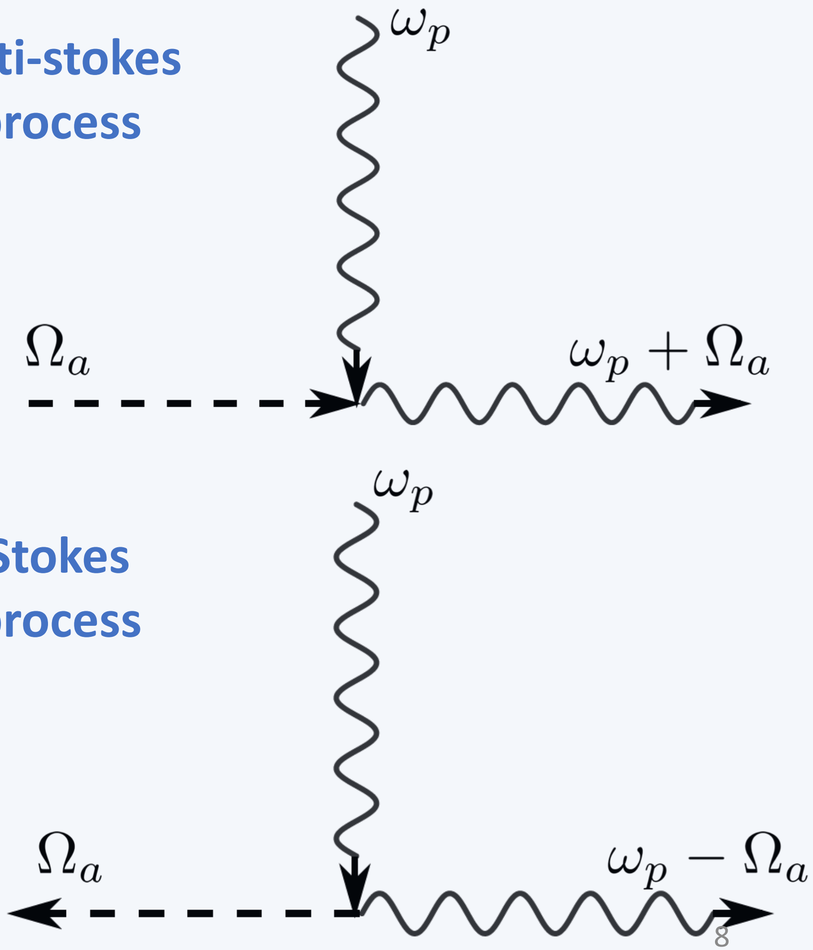
$$|\mathbf{B}| = \frac{|\mathbf{E}_0|}{c}$$

Experimental Signature:

Polarization

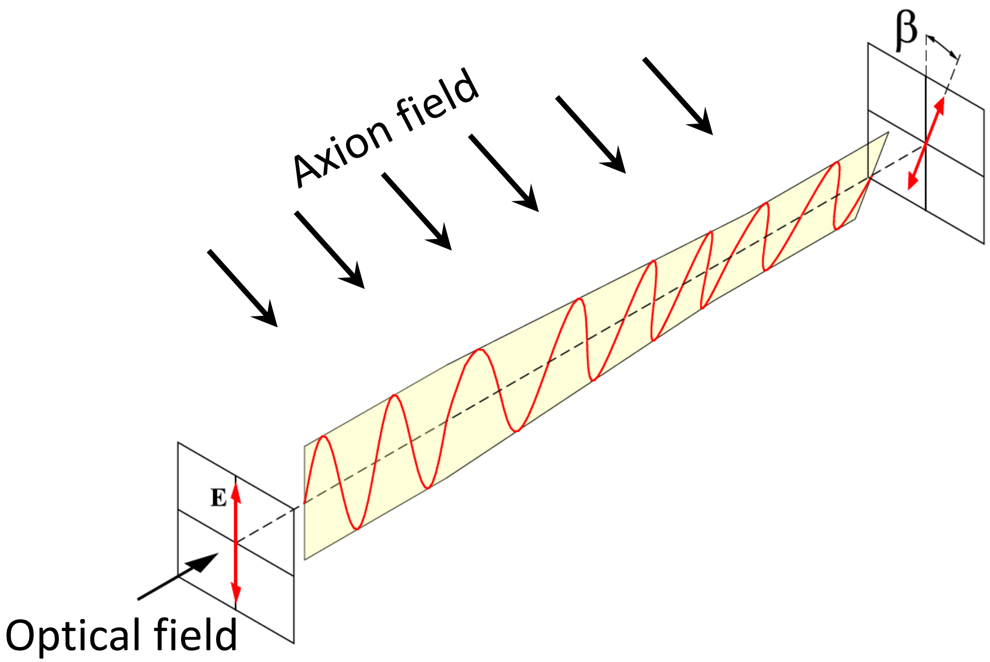


$$\mathcal{L}_{\text{int}} \propto a\, \mathbf{E} \cdot \mathbf{B}$$



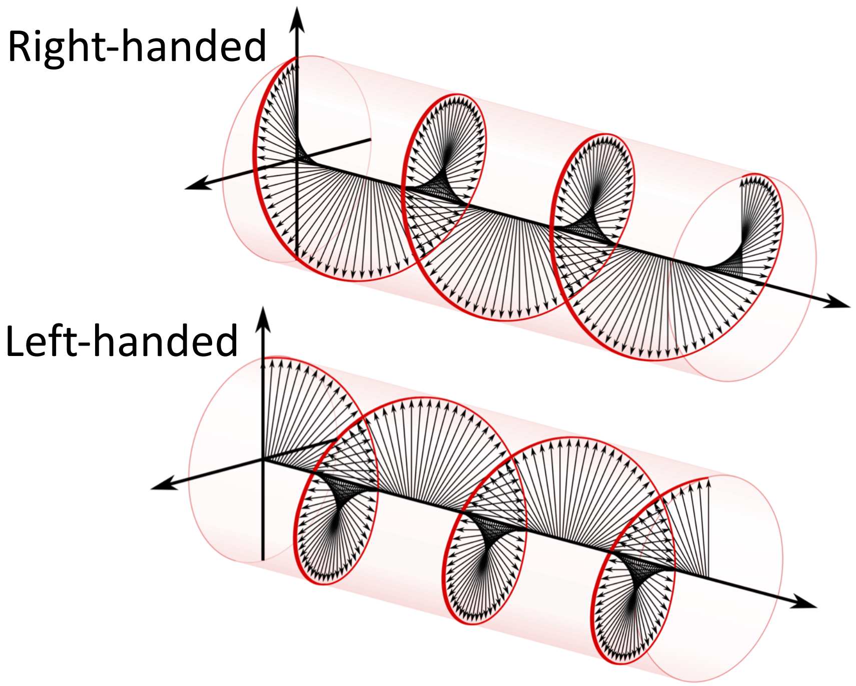
Two Equivalent Pictures

Linear polarization



A rotation of the polarization state
(converting a fraction of ↕ to ↔)

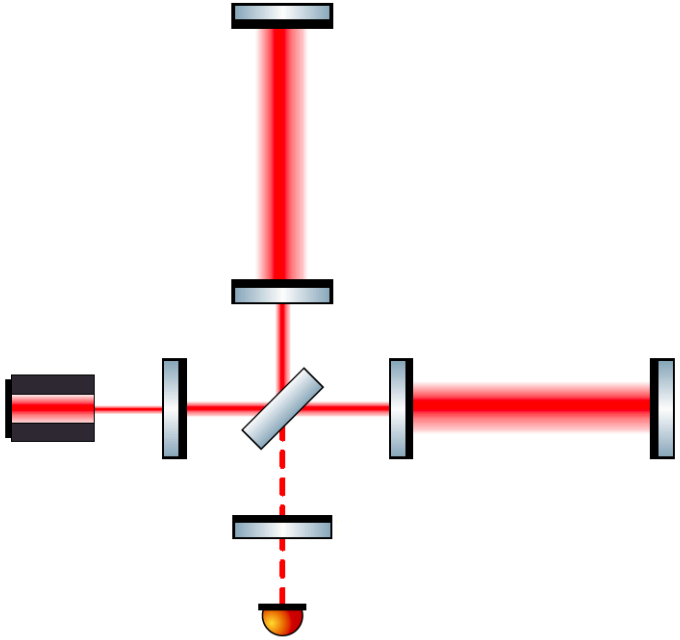
Circular polarization



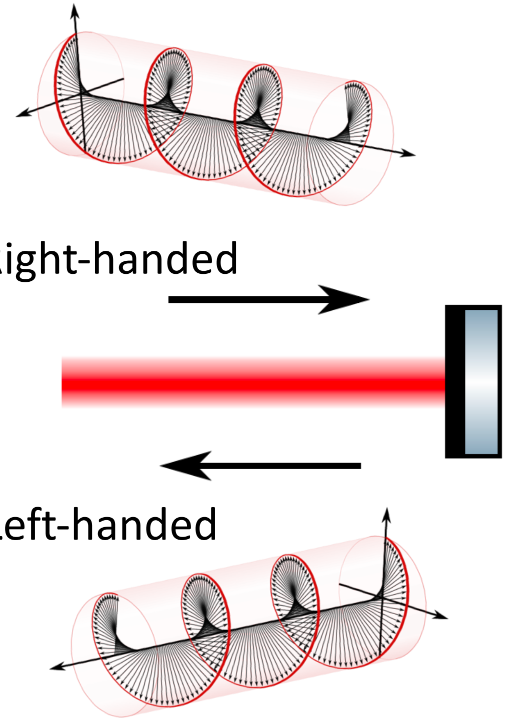
Their phase velocities are different

Analogous to the Faraday effect (circular birefringence)

Why LIGO-type interferometer insensitive to ALP?



Mirror reflection changes polarization state



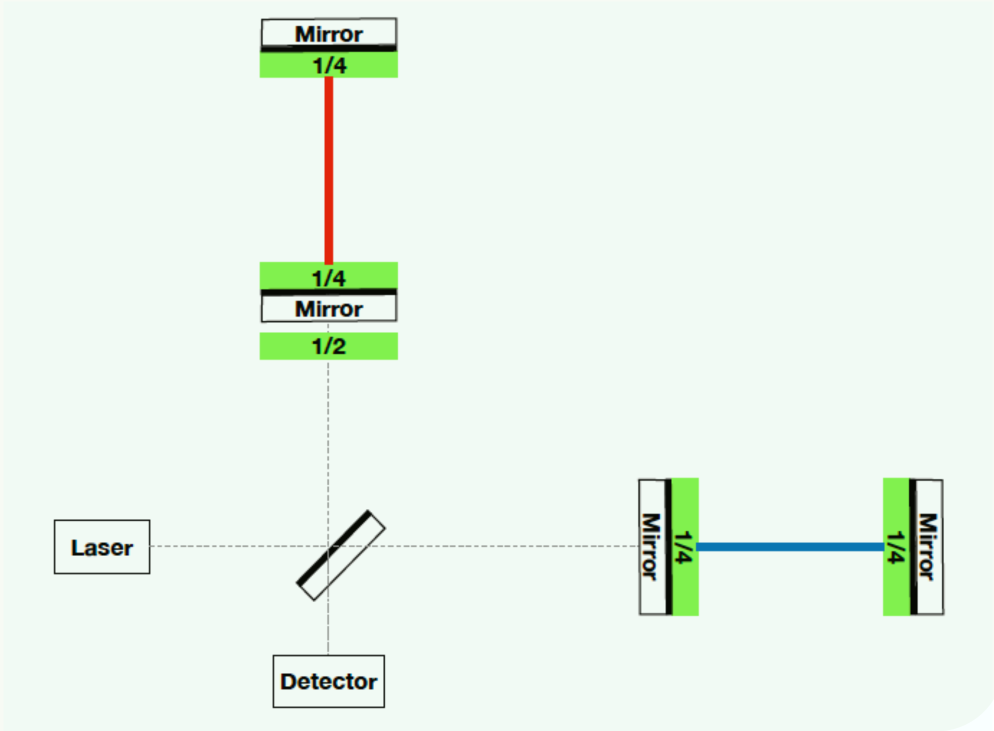
Or horizontal and vertical polarization have 180 degree phase difference after reflection

Axion effect cancels out after one round trip [1]

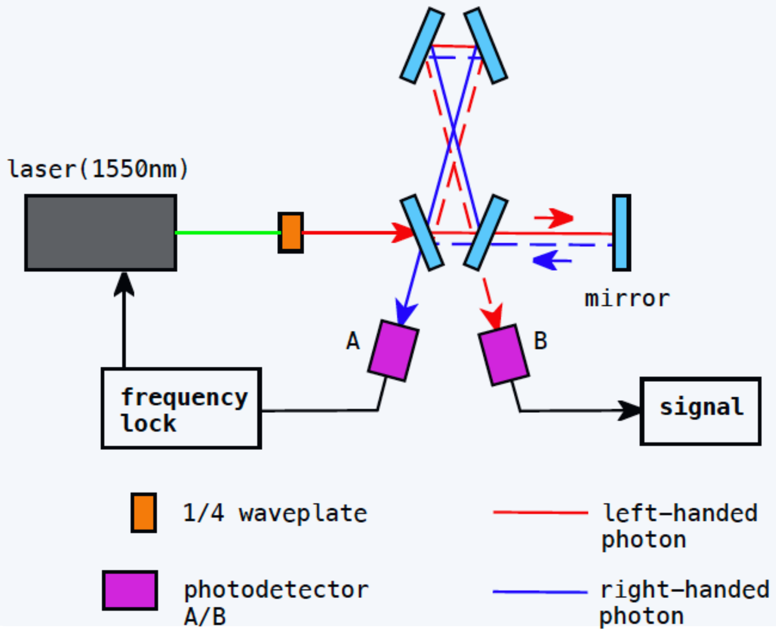
[1] W. DeRocco, and A. Hook, *Axion interferometry*, PRD **98**, 035021 (2018).

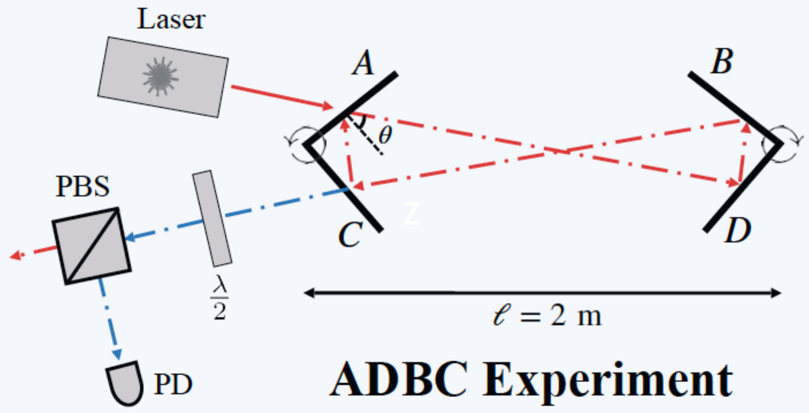
Different proposals

Michelson type [1]



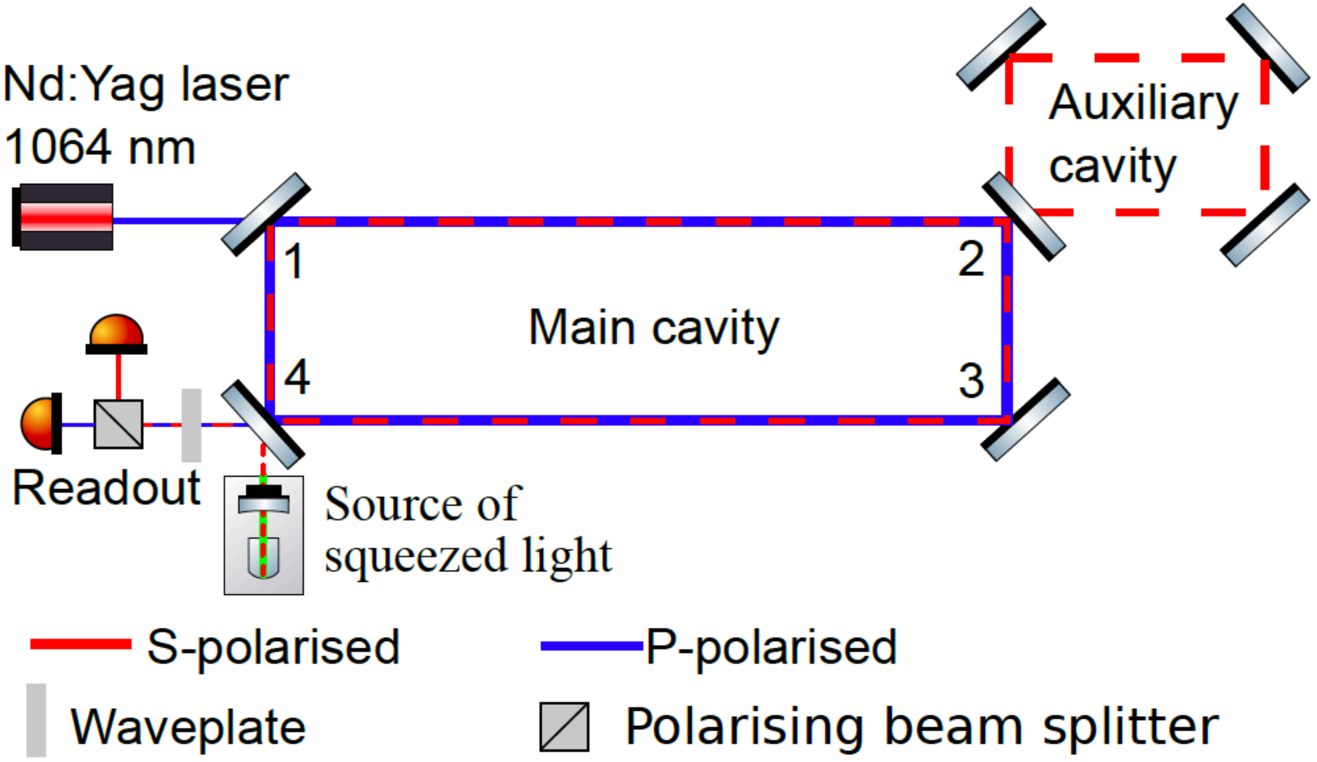
Ring-cavity type [2, 3]

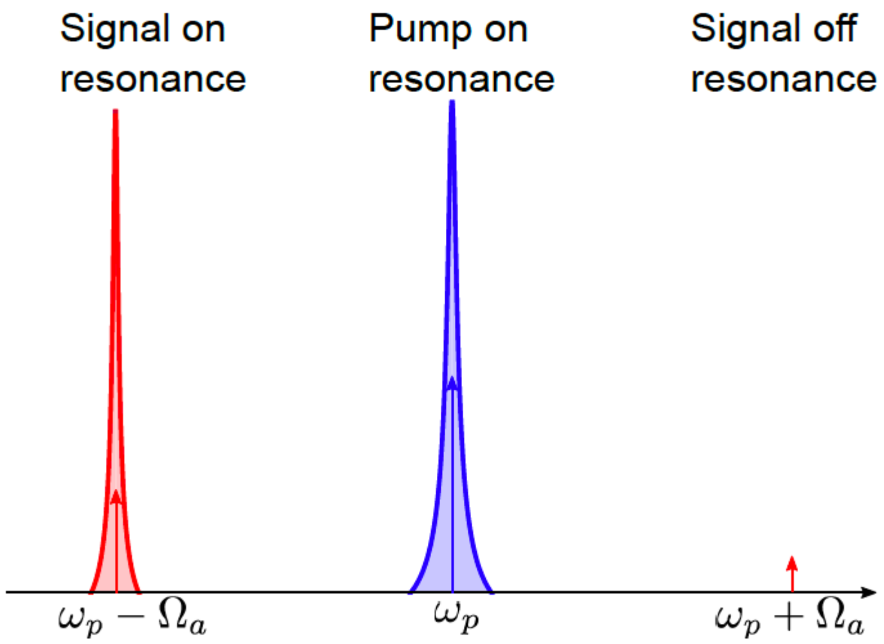




[1] W. DeRocco, and A. Hook, PRD **98**, 035021 (2018).
[2] I. Obata, T. Fujita, and Y. Michimura, PRL **121**, 161301 (2018).
[3] H. Liu, B. Elwood, M. Evans, and J. Thaler, PRD **100**, 023548 (2019).

Our proposed scheme

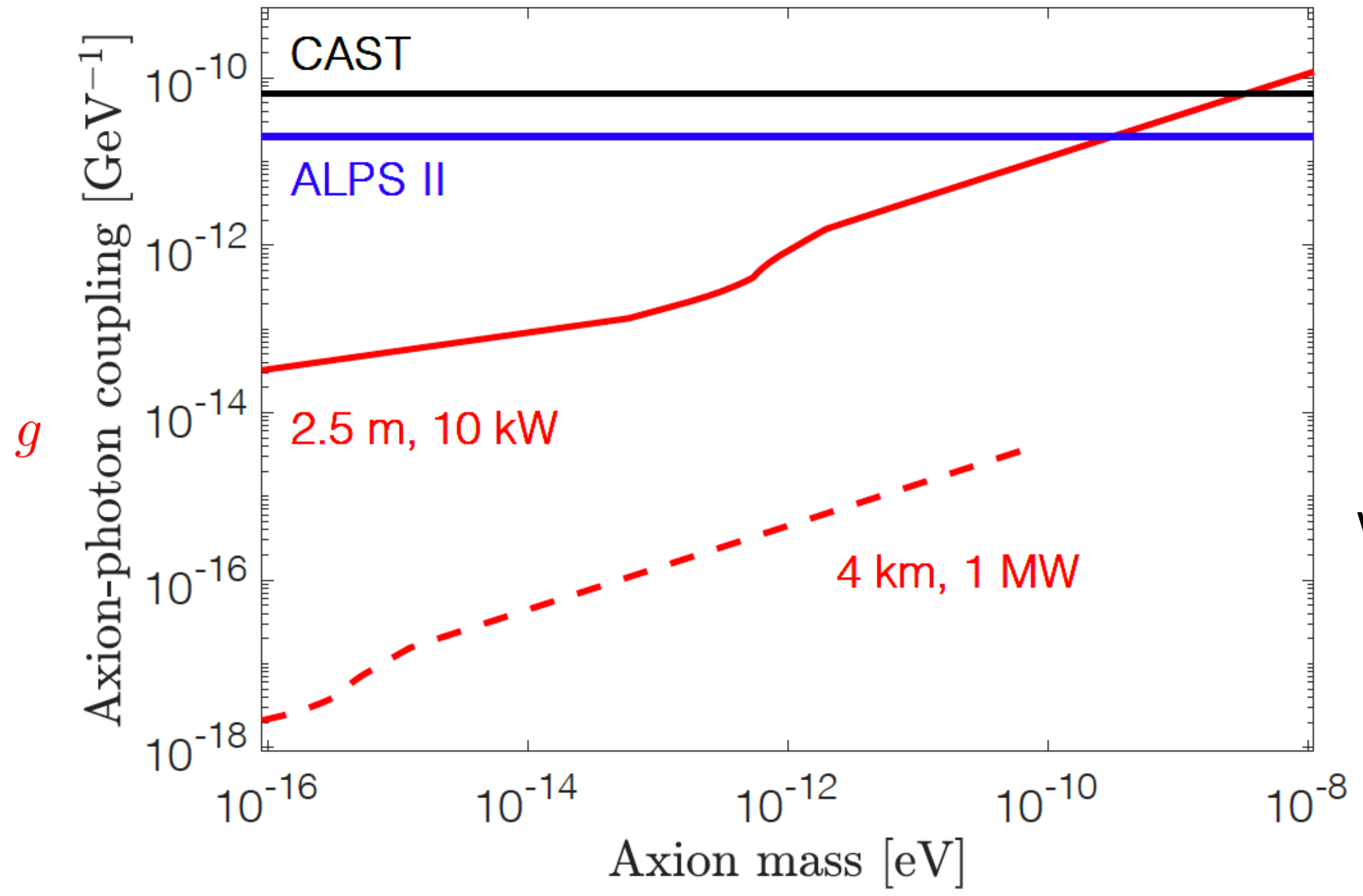




- Motivated by the Ring-cavity type design.
- Auxiliary cavity to tune the optical resonance for scanning the Axion mass.
- Quantum shot noise is the limiting source of noise.
- Squeezed light for reducing the quantum shot noise.

D. Martynov, and H. Miao, *Quantum-enhanced interferometry for axion searches*, PRD **101**, 095034 (2020)

Sensitivity (1 year observation)



ALPS hundred meter facility @ DESY may get down to 10^{-15} GeV^{-1} with this interferometric technique

Order of magnitude: $g \geq 10^{-13}\mathrm{GeV}^{-1}\left(\frac{\sqrt{S_{xx}}}{10^{-22}\,\mathrm{m}/\sqrt{\mathrm{Hz}}}\right)\left(\frac{10^6\,\mathrm{s}}{T_{\mathrm{int}}}\right)^{1/2}\left(\frac{1\,\mathrm{m}}{L}\right)$

Prospects

Experiments @ Birmingham:

- Setting up the proposed experiment (5 m scale).
- A parallel experiment exploring quantum amplification to reduce the quantum noise.
- PDRAs are needed!

Theoretical question:

- Is there any bound from below for ALP models?

  (Unlike QCD Axion which seems to have a limited mass range and coupling to test)

Thank you!