Quantum interferometry for new physics

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QI collaboration

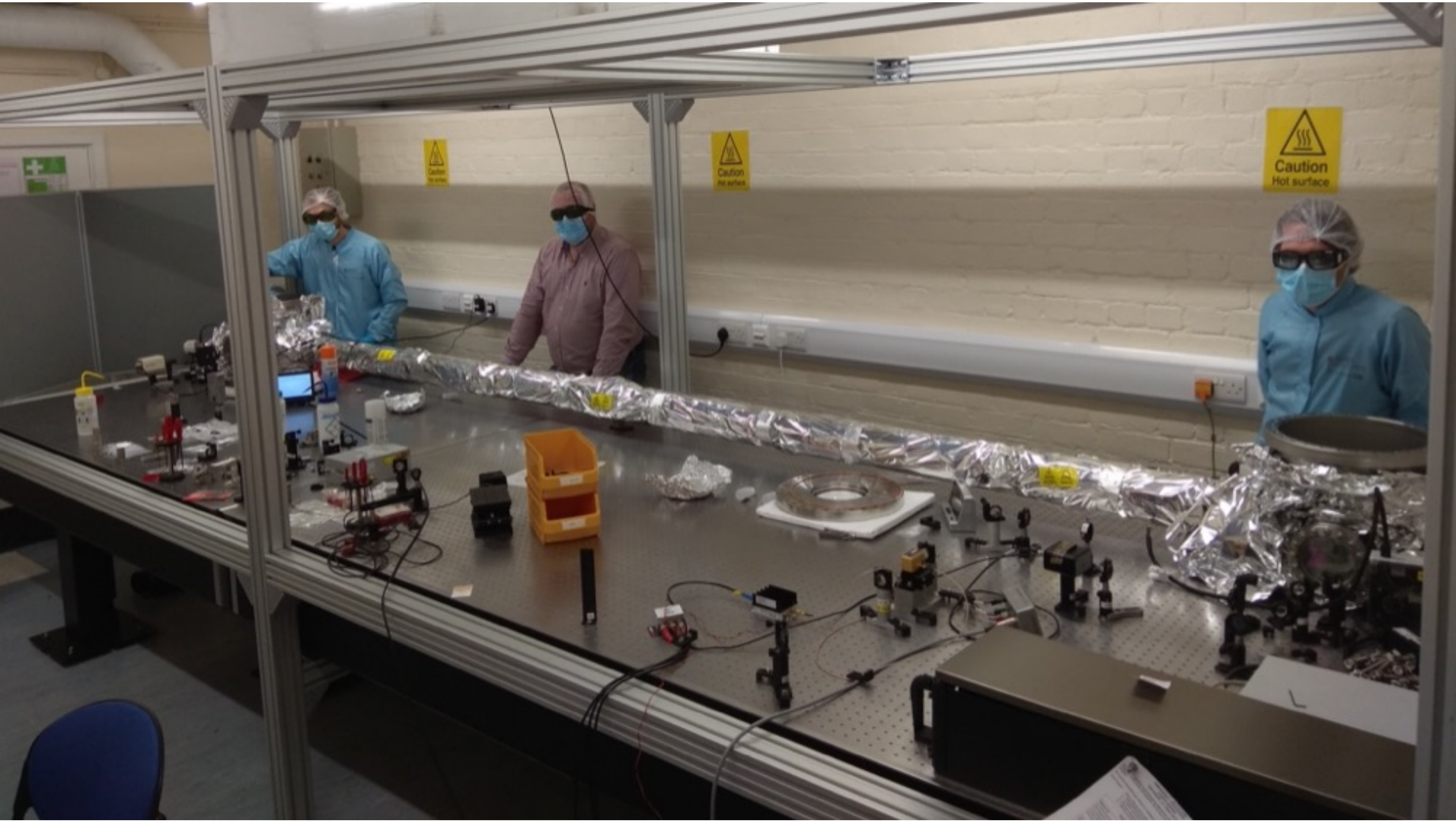
QTFP School, Cambridge, 2023

QI

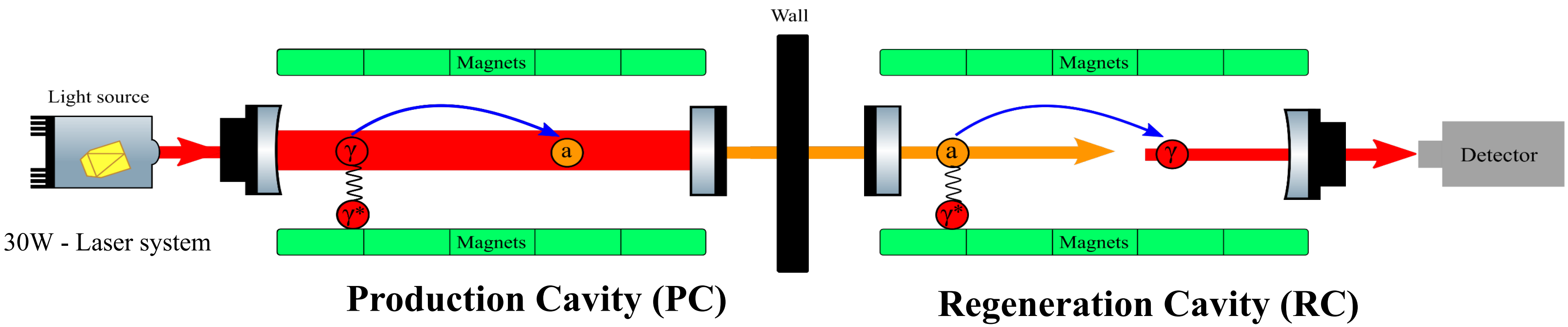
Overview

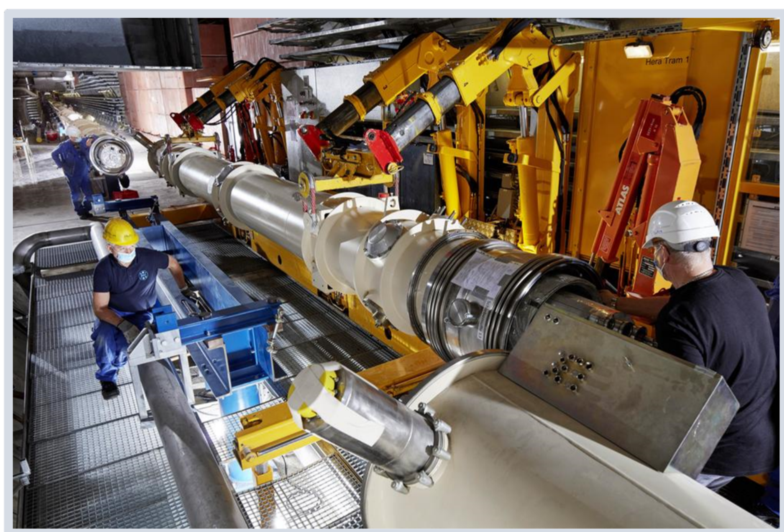
- Quantum Interferometry (QI) collaboration
  - Squeezed light
  - Single photon detectors
  - Quantum amplifiers
- Lecture 1: Dark matter
- Tutorial: optical cavities
- Lecture 2: Quantum measurements

WP 1: Laser Interferometric Detector for Axions (LIDA)



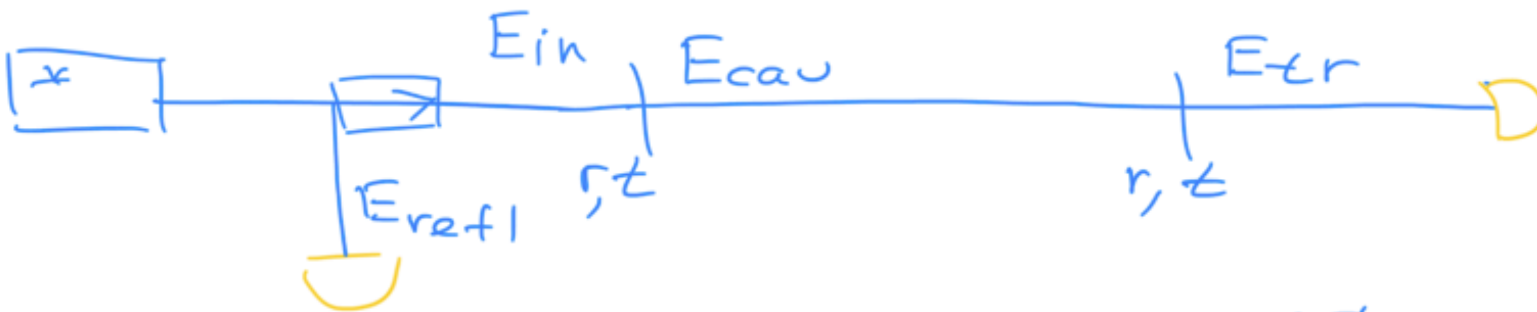
WP 2: contribution to ALPS II
Light-shining-through-a-wall





Photos: Marta Mayer DESY https//www.desy.de/news

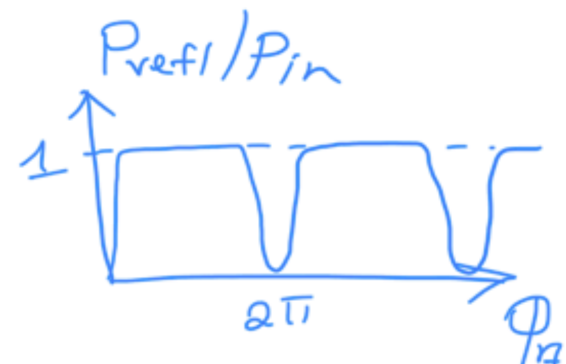
Fabry-Perot interferometer



$$E_{refl} = -r E_{in} + t E_{cav} r e^{-i\phi_{rt}}$$

$$E_{refl} = \left(-r + \frac{t^2 r e^{-i\phi_{rt}}}{1 - r^2 e^{-i\phi_{rt}}}\right) E_{in}$$

$$E_{refl} = \frac{-r + r e^{-i\phi_{rt}}}{1 - r^2 e^{-i\phi_{rt}}} E_{in}$$



Optical gain

$$E_{refl} = -\frac{i\varphi_{rt}}{T} E_{in}$$

$$P_{refl} = \frac{\varphi_{rt}^2}{T^2} P_{in}$$

$$\varphi_{rt} \ll T$$

$$\varphi_{rt}^{full} = 4\pi \frac{L}{\lambda} = 4\pi \frac{L_0 + X}{\lambda} = 2\pi N + 4\pi \frac{X}{\lambda}$$

$$P_{refl} = \left(\frac{4\pi X}{\lambda T}\right)^2 P_{in}$$

$$\frac{dP_{refl}}{dx} = \left(\frac{4\pi}{\lambda T}\right)^2 2x\, P_{in} = \frac{32\pi^2}{\lambda^2 T^2} P_{in} X$$

Shot noise

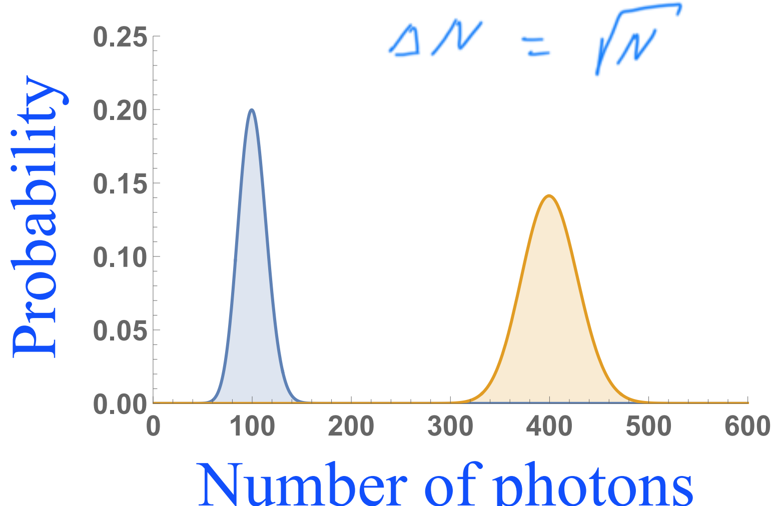
Measured power fluctuates due to the uncertain number of photons in the laser beam:

$$N = \frac{P \cdot \tau}{\hbar \omega_0}$$

← exposure time (τ)

↖ laser frequency (ω_0)

$$\Delta N = \sqrt{N}$$



Credit: Richard S. Wright Jr.

Shot noise

$$P_{refl}(x_0) = \left(\frac{4\pi x_0}{\lambda T}\right)^2 P_{in}$$

$$\Delta P_{refl}(x_0) = \sqrt{\frac{P_{refl}(x_0)\,\hbar\omega_0}{\tau}}$$

$$= \frac{4\pi x_0}{\lambda T}\sqrt{\frac{P_{in}\,\hbar\omega_0}{\tau}}$$

Shot-noise limited sensitivity

Shot noise limited resolution of a cavity with T=10 ppm. Input laser power is 1 W, wavelength if 1064 nm, measurement time is 1 msec.

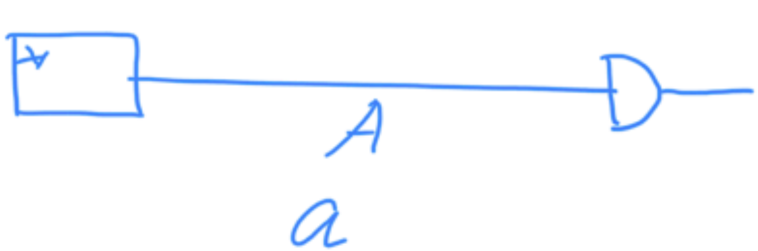
$$\Delta x = \frac{\Delta P_{refl}(x_0)}{\left.\frac{dP_{refl}}{dx}\right|_{x=x_0}} = \frac{\frac{4\pi x_0}{\lambda T}\sqrt{\frac{P_{in}\hbar\omega_0}{\tau}}}{\frac{32\pi^2}{\lambda^2 T^2} P_{in} x_0}$$

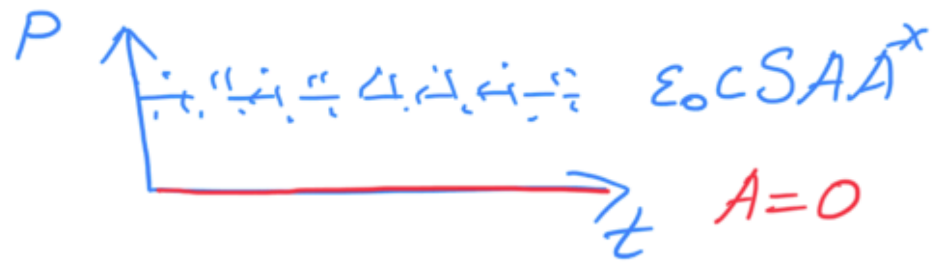
$$= \frac{\lambda T}{8\pi}\sqrt{\frac{\hbar\omega_0}{P_{in}\tau}} = 5.6\cdot 10^{-21}\ m$$

Lecture overview

- Quantum squeezing
- Optomechanical systems
- Quantum amplification
- Single photon detection

Heisenberg picture





Power operator:

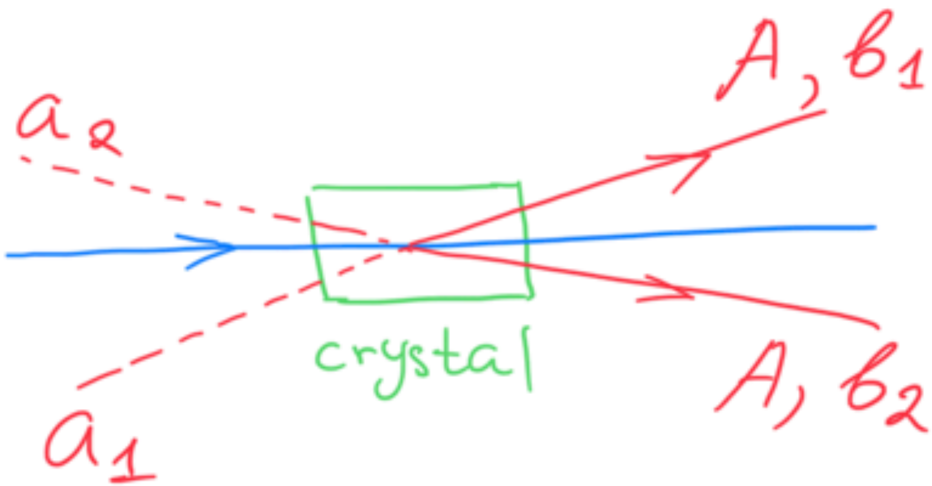
$$P = \frac{\varepsilon_0}{2} cS\left[(A+a)(A^*+a^\dagger)+h.c.\right]$$

$$P = \frac{\varepsilon_0}{2} cS\left[AA^* + \underbrace{Aa^\dagger + aA^*}_{\text{interference}} + aa^\dagger + h.c.\right]$$

Expectation value: $\langle 0|P|0\rangle$

Variance: $\langle 0|P^2|0\rangle - \langle 0|P|0\rangle^2$

Vacuum transformation

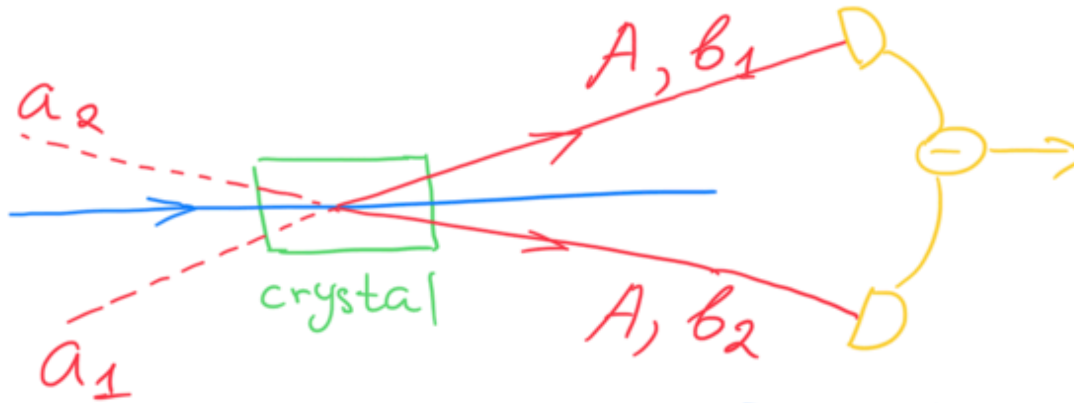


Squeezing transformation:

$$b_1 = \cosh r\, a_1 + \sinh r\, a_2^+$$

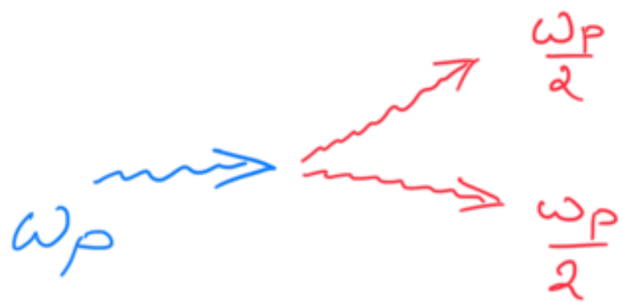
$$b_2 = \sinh r\, a_1^+ + \cosh r\, a_2$$

How is quantum entanglement achieved?



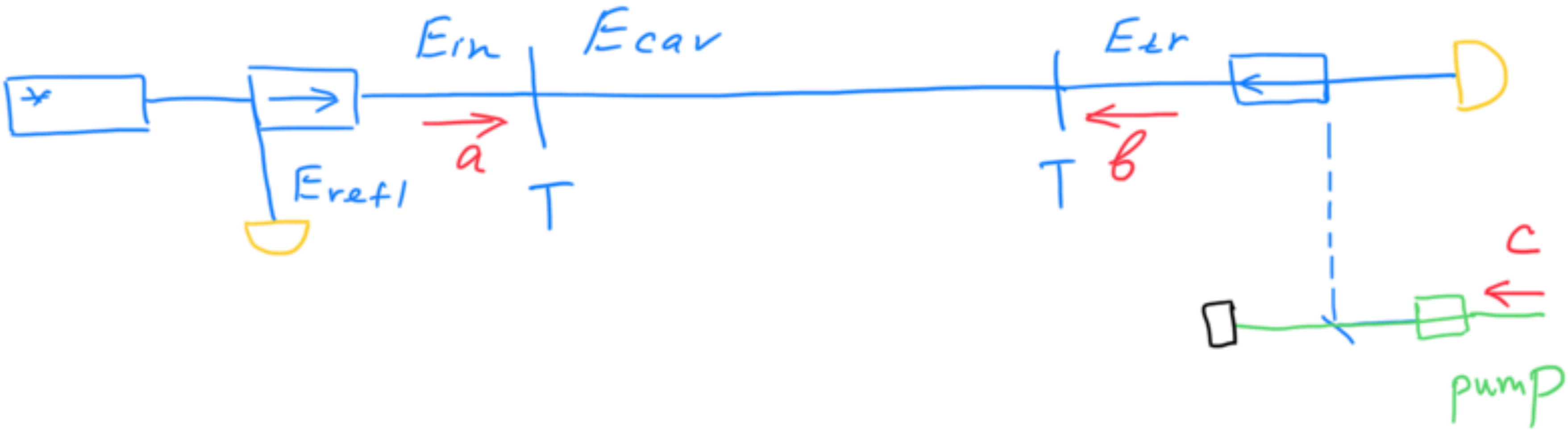
Nonlinear crystal: $\vec{P} = \varepsilon_0 \left(\chi^{(1)} \vec{E} + \chi^{(2)} \vec{E}^2 + \ldots \right)$

$$\nabla^2 \vec{E} - \frac{n^2}{c^2} \frac{\partial^2}{\partial t^2} \vec{E} = \frac{1}{\varepsilon_0 c^2} \frac{\partial^2}{\partial t^2} \vec{P}^{NL}$$

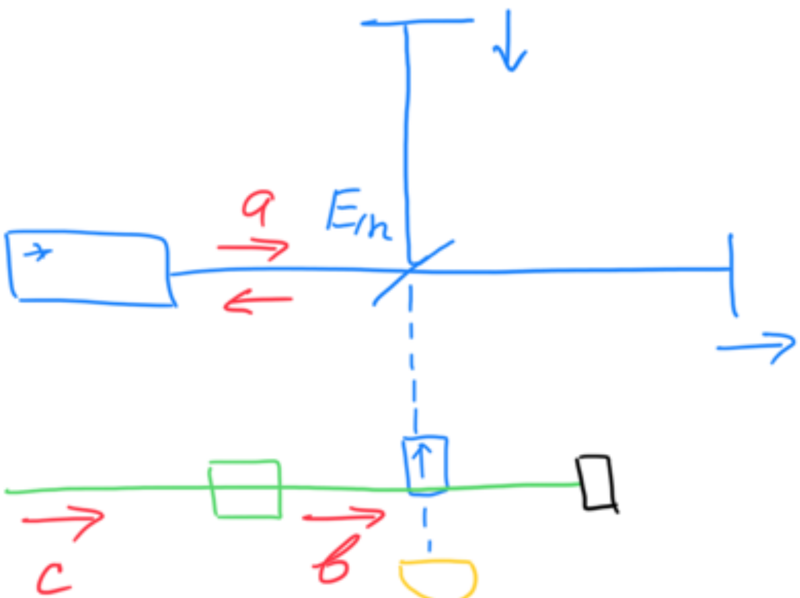


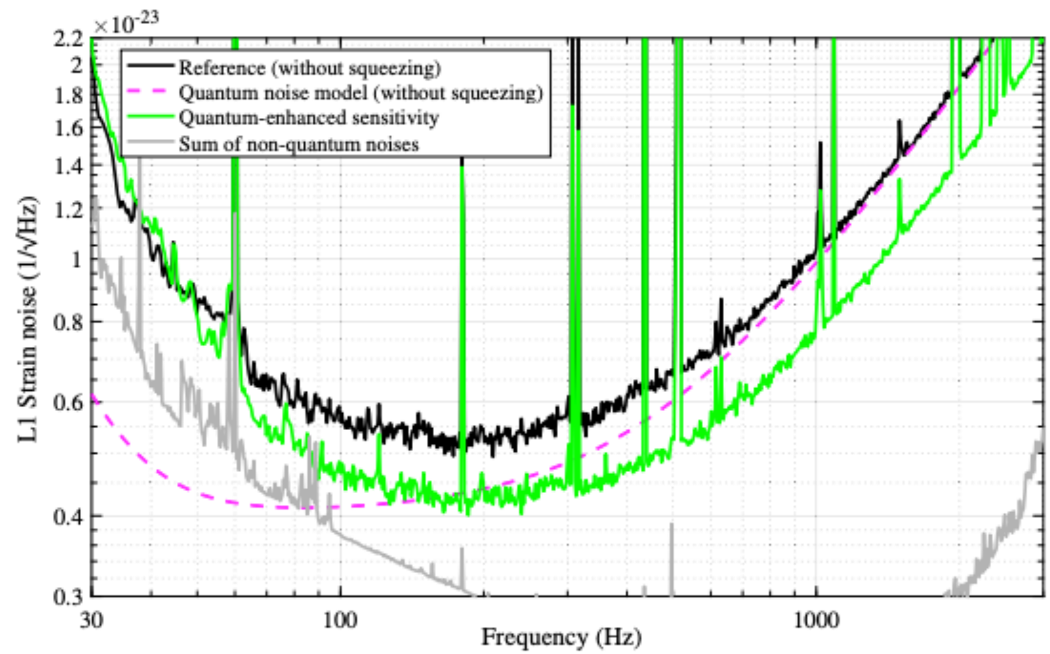
Open ports

- Need to find the port responsible for the quantum noise
- Inject squeezed states of light

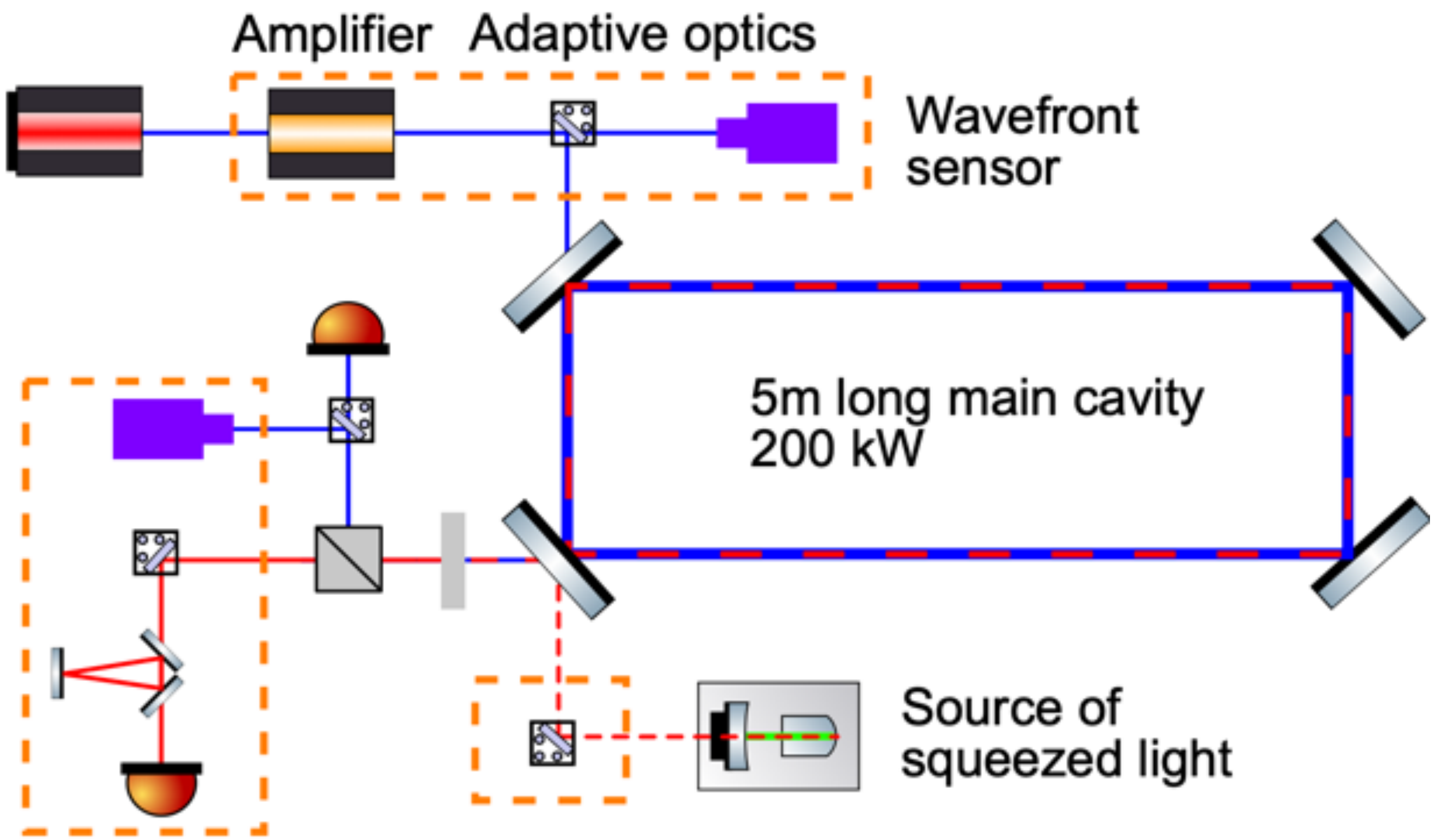


LIGO example



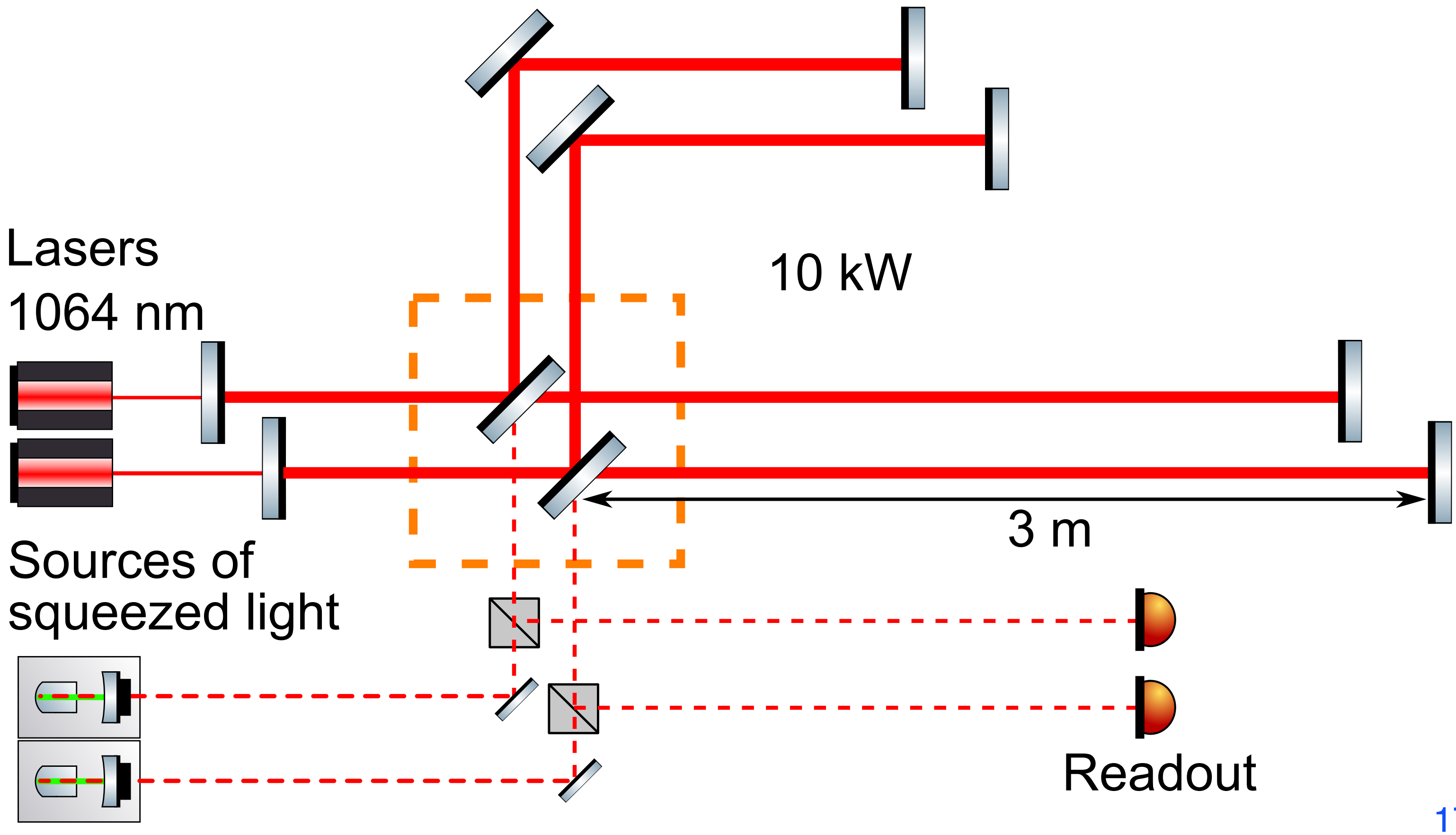


WP 1 example

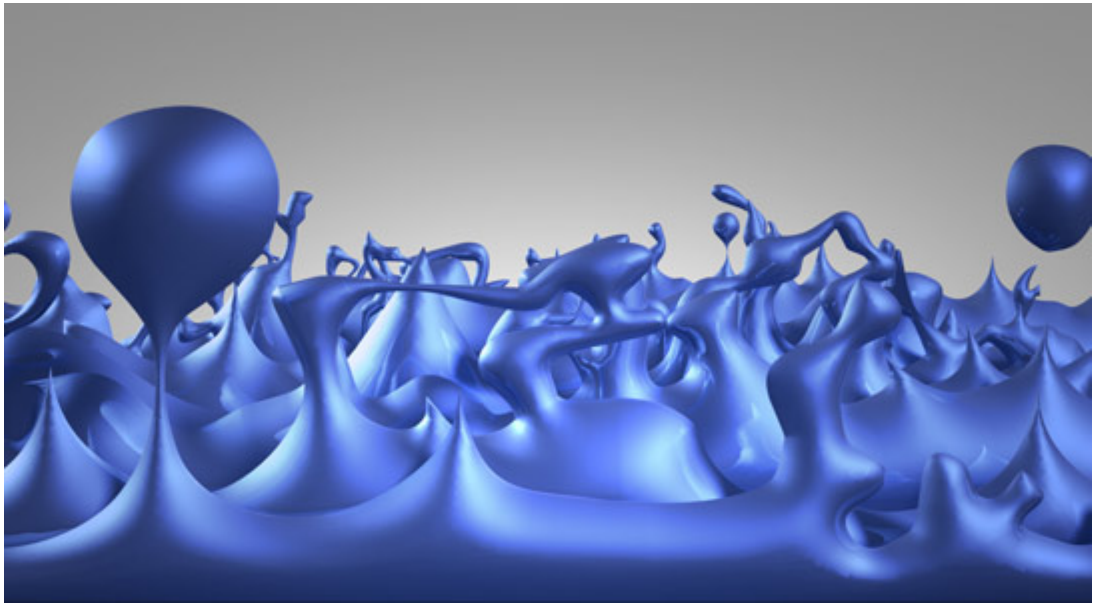


Amplifier
Adaptive optics
Wavefront sensor
5m long main cavity
200 kW
Source of squeezed light

WP 3 example



WP 3: space-time quantisation



Space-time foam?

Quantization of space-time at Planck scale of 10^{-35} m?

Holographic principle may make this accessible to interferometry

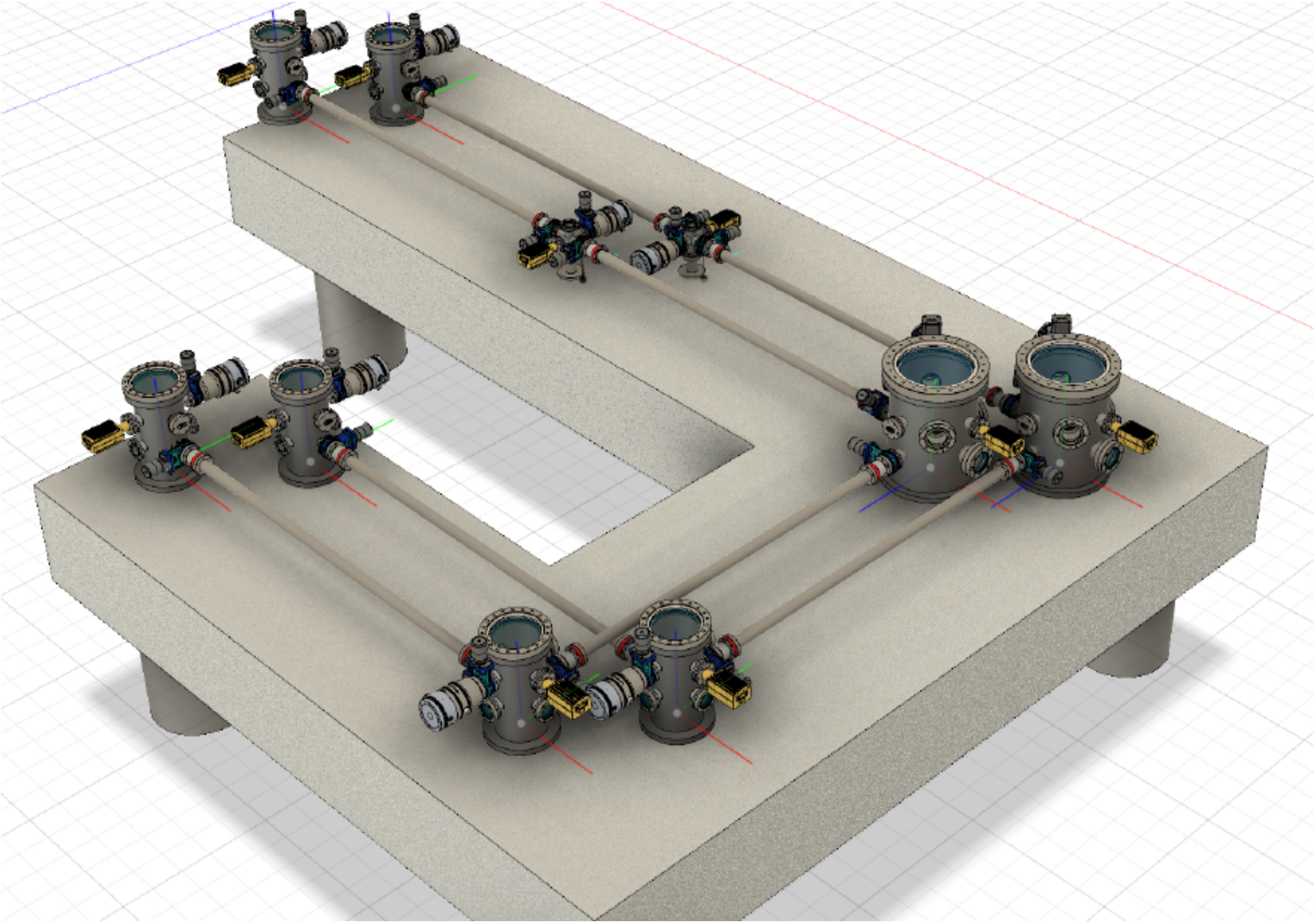
Flexible table-top to test different predictions

Fermilab holometer

Co-located Michelson interferometers.

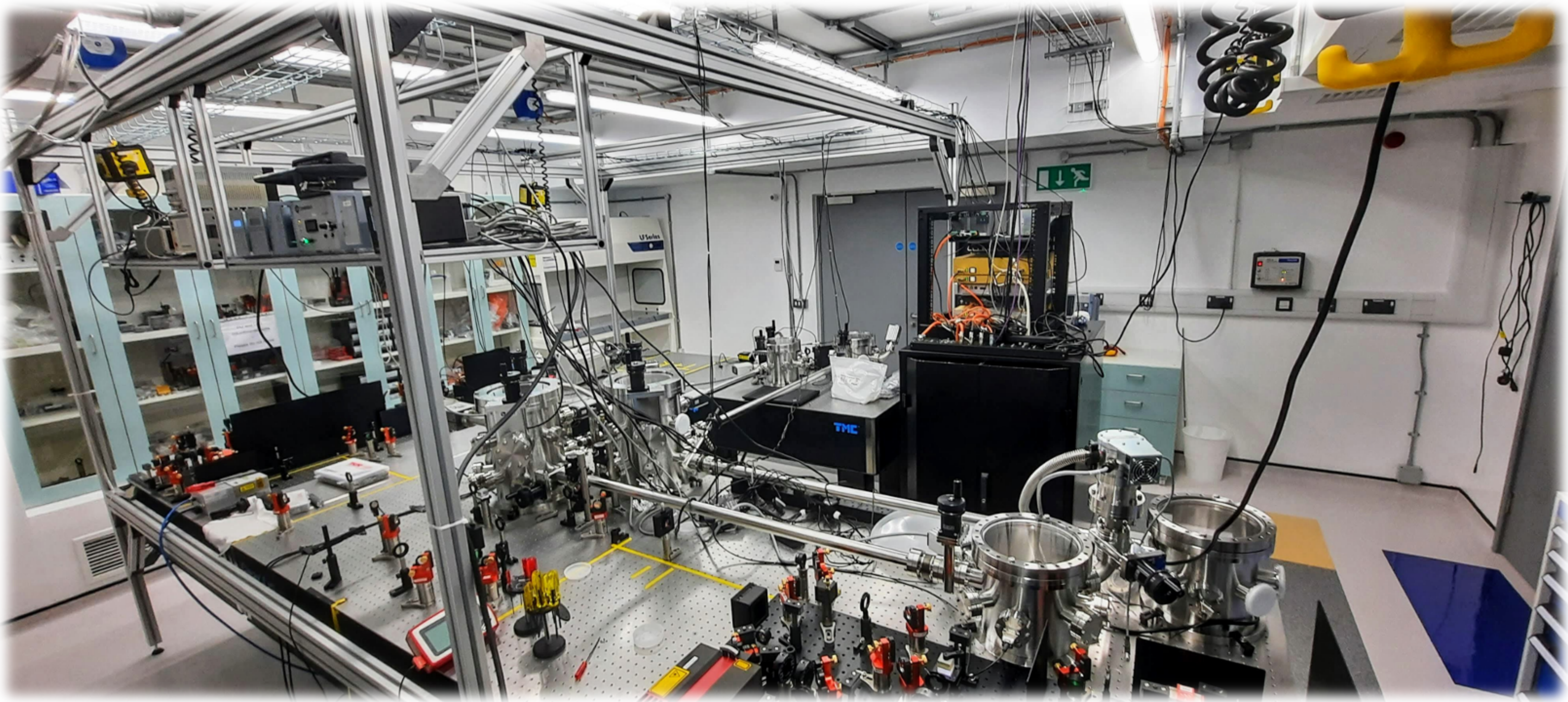
PRL 117, 111102 (2016)
CQG 34, 065005 (2017)
PRL 126, 241301 (2021)

Cardiff experiment

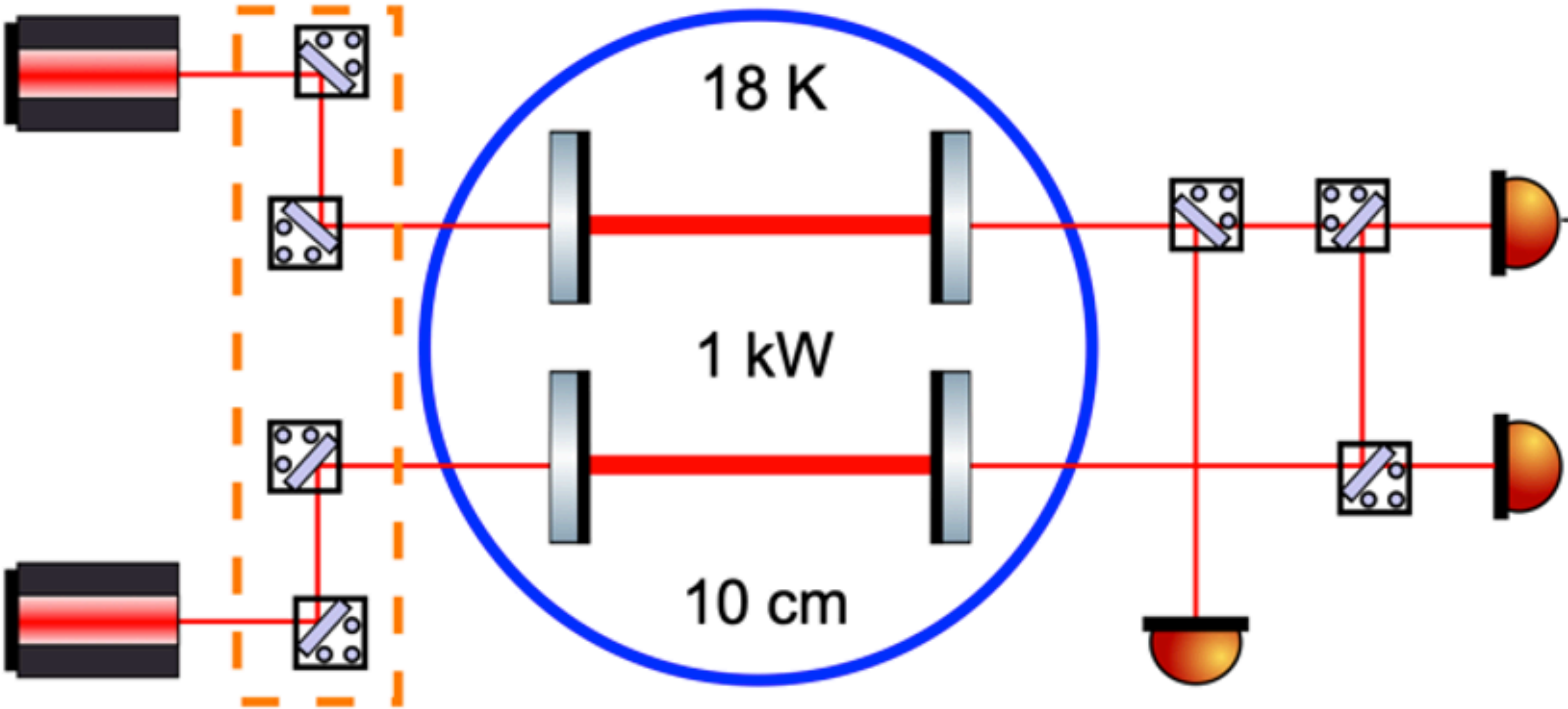


Class Quantum Grav. 38, 085008 (2021)

Commissioning of the experiment

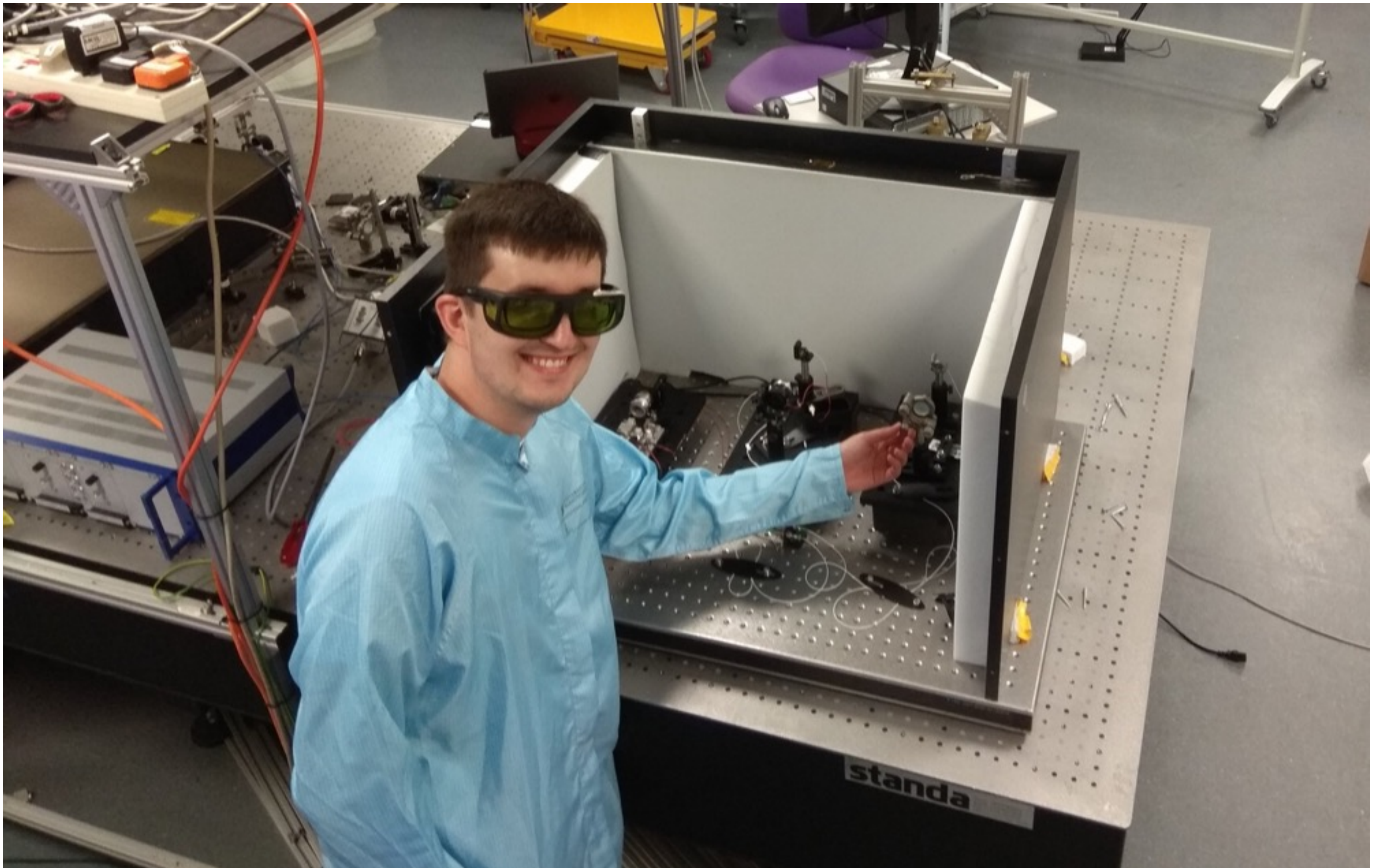


WP 4: quantum optomechanics

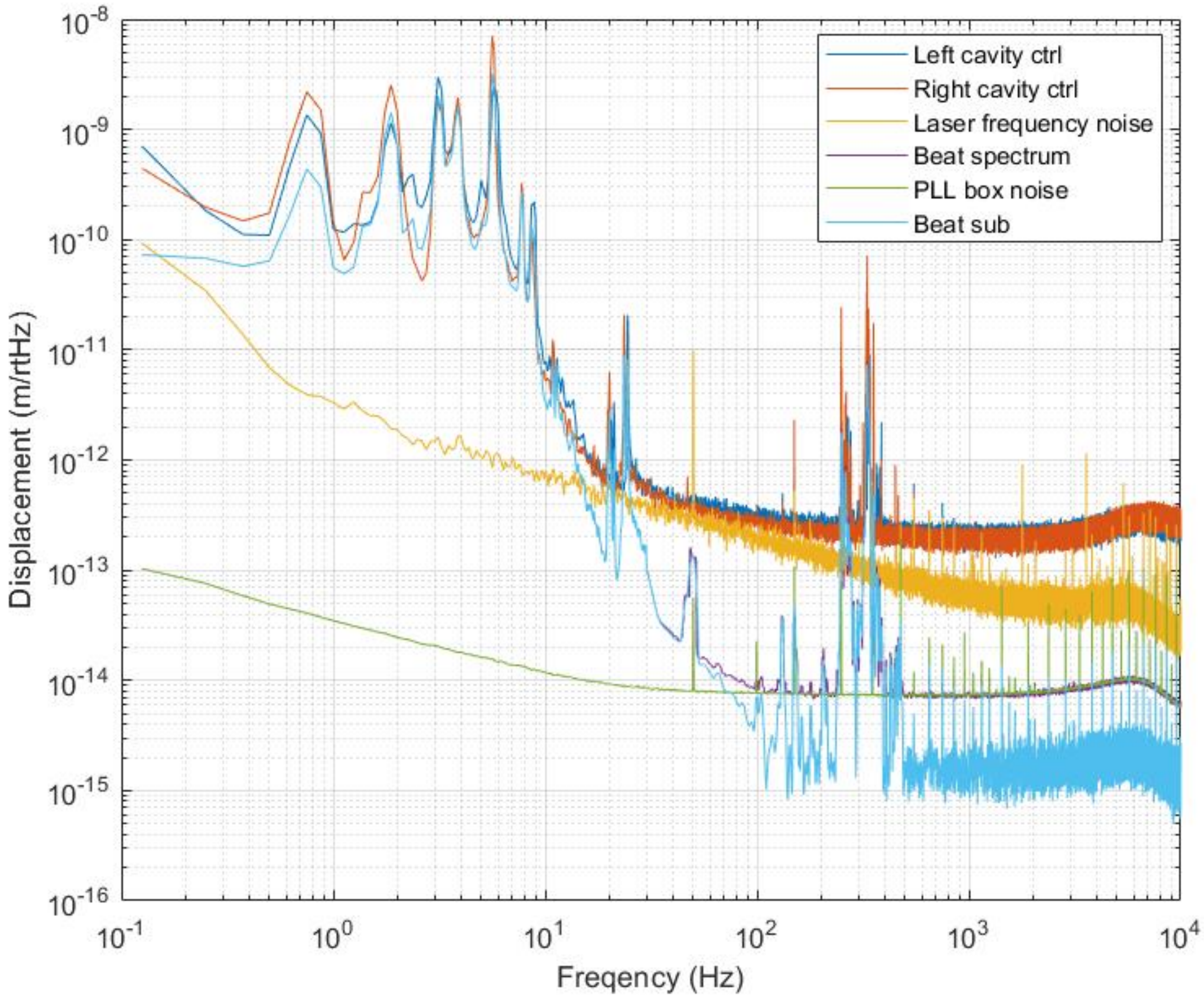


Birmingham experiment

Birmingham experiment

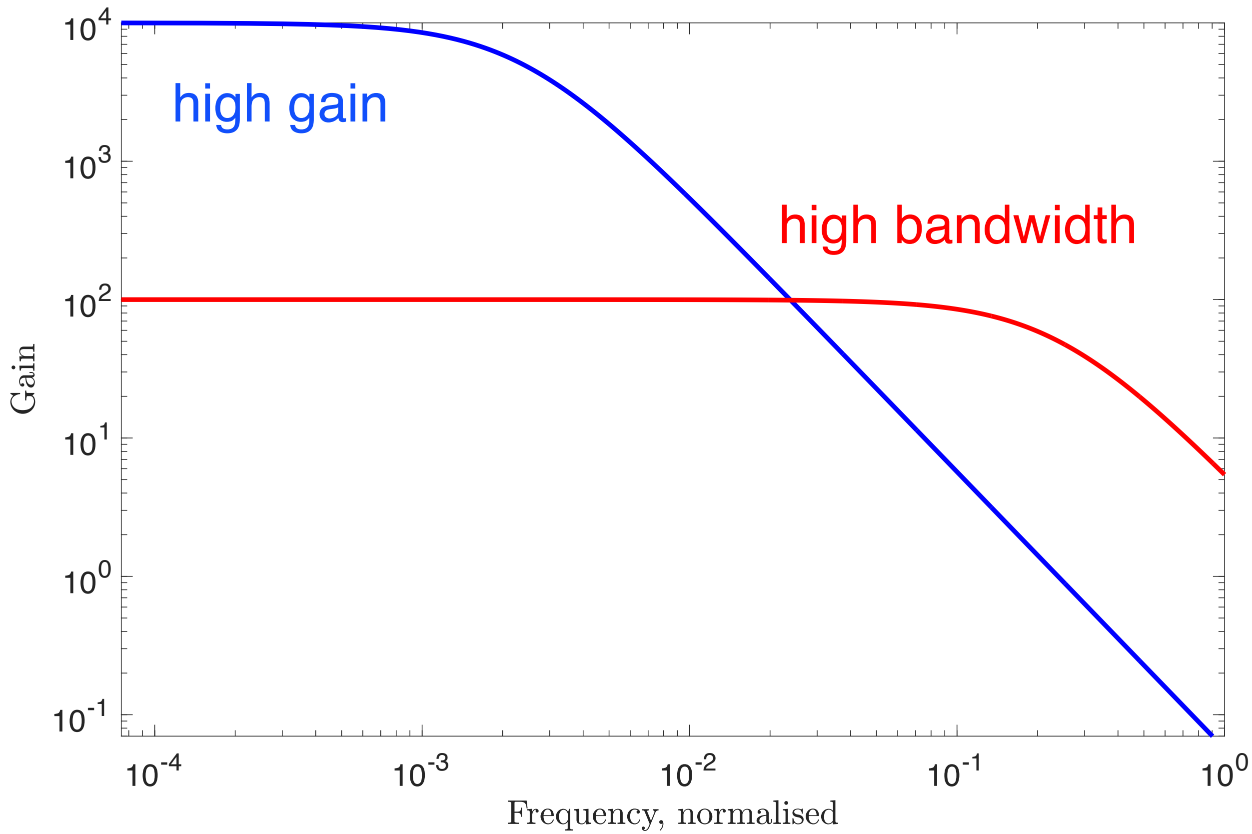


Both cavities locked, $F = 10^5$

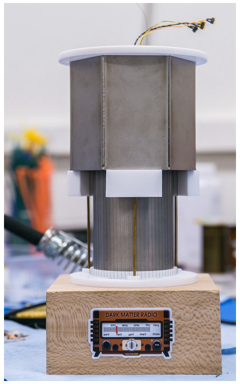


Resonant systems

Sensitive in a narrow frequency band



LIGO

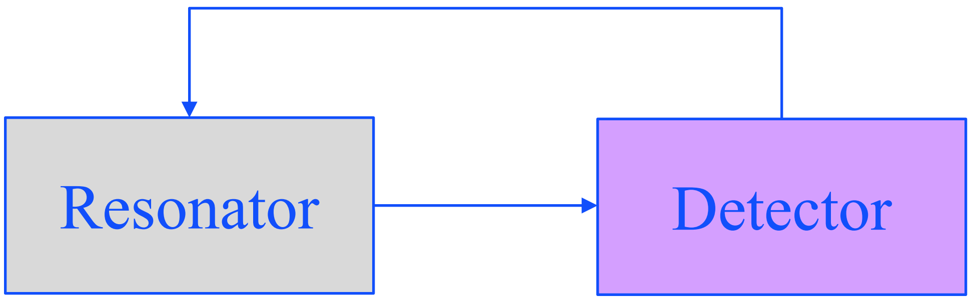


Dark matter radio

The fundamental question:

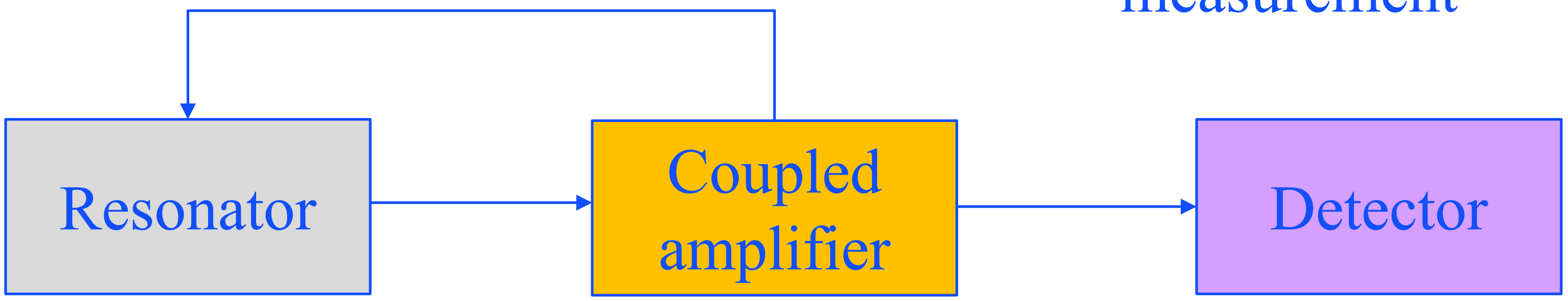
Is it possible to increase the gain-bandwidth product of resonant systems **at the quantum level**?

Quantum measurement



Classical feedback:
does not improve the quantum sensitivity

Coherent feedback:
works without making a measurement



Quantum amplification

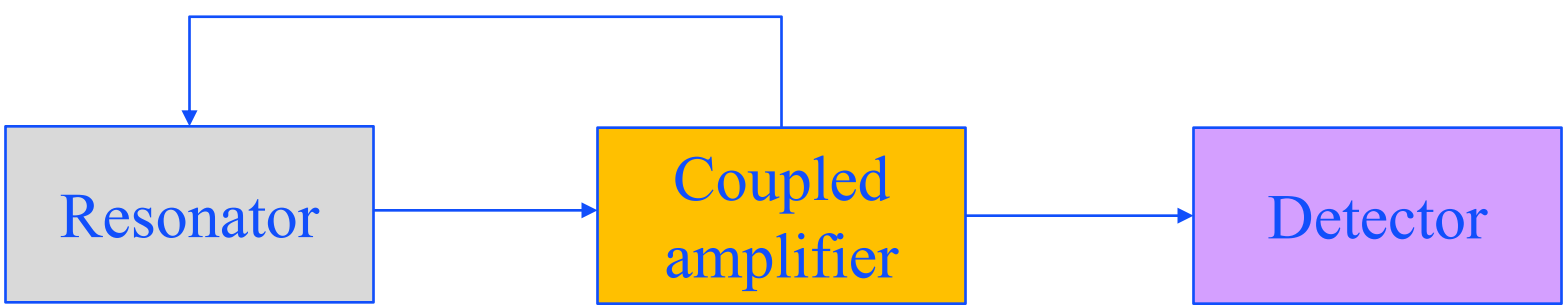
Caves theorem of signal amplification *:

$$\text{output} = G \times \text{input} + K \times \text{noise}$$

Gain $|G| >> 1$

SNR is preserved

This proposal:

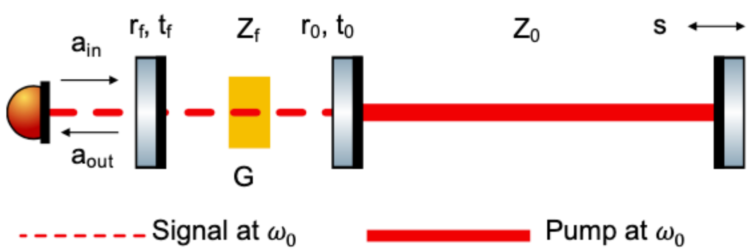


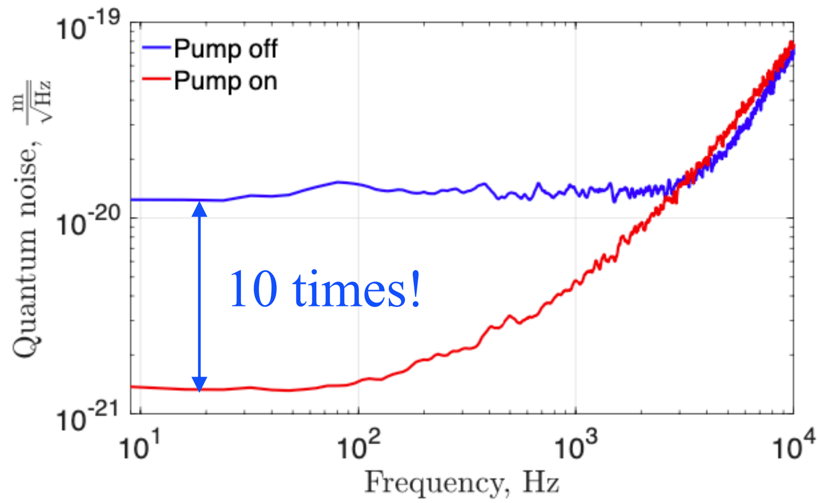
Gain $|G| \simeq 1$

* Phys. Rev. D **26**, 1817

Simulated improvements

- Derived the asymmetric signal and noise amplification
- Found a particular implementation of the amplifier

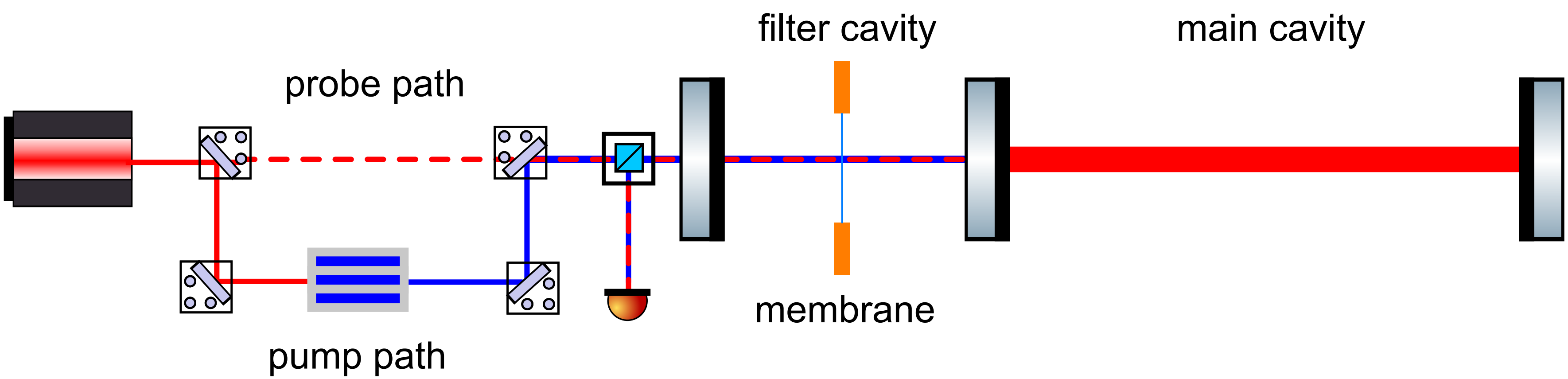




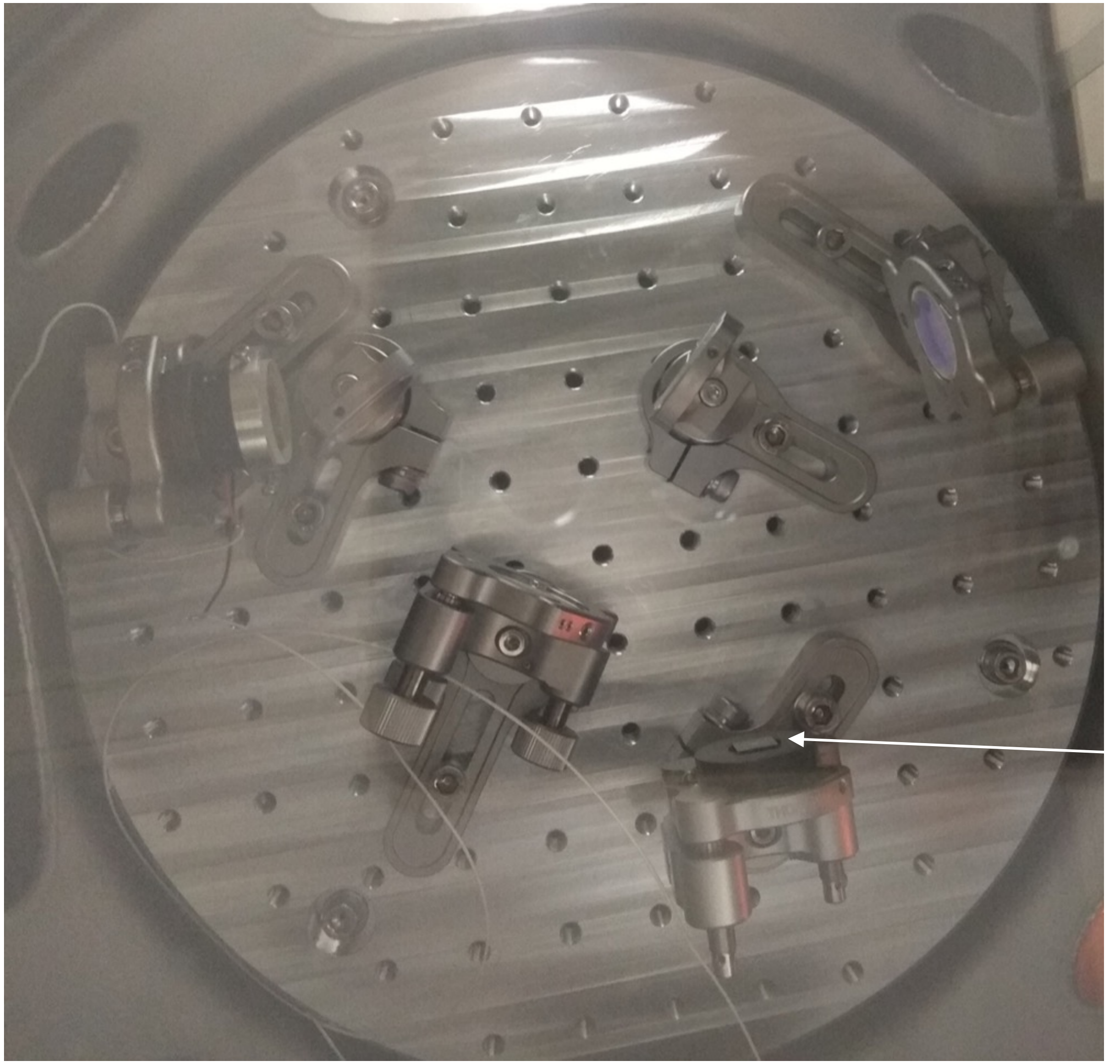
Phys. Rev. D 103,122001

Demonstration scheme

- Stabilisation of the coupled cavities
- Study of the system stability

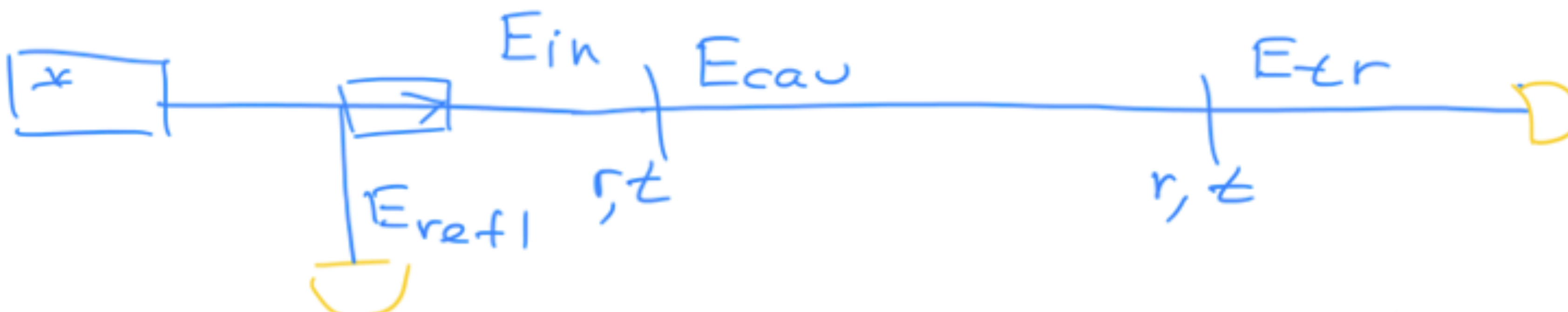


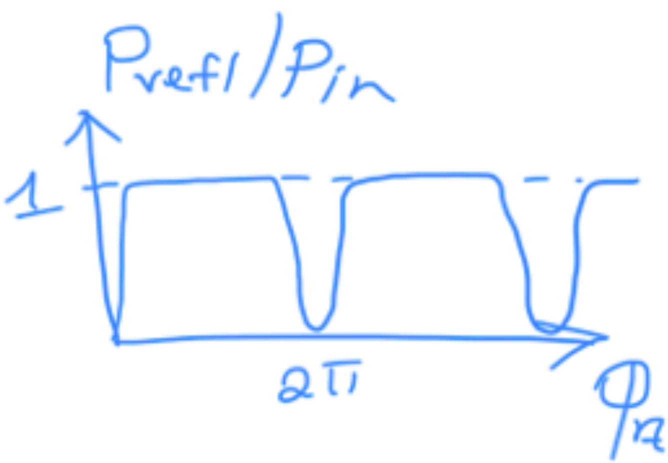
Current status



SiN
membrane

Continuous vs single photon readout





Continuous:

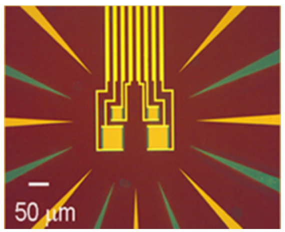
- Linear
- Simple
- But couples strong shot noise

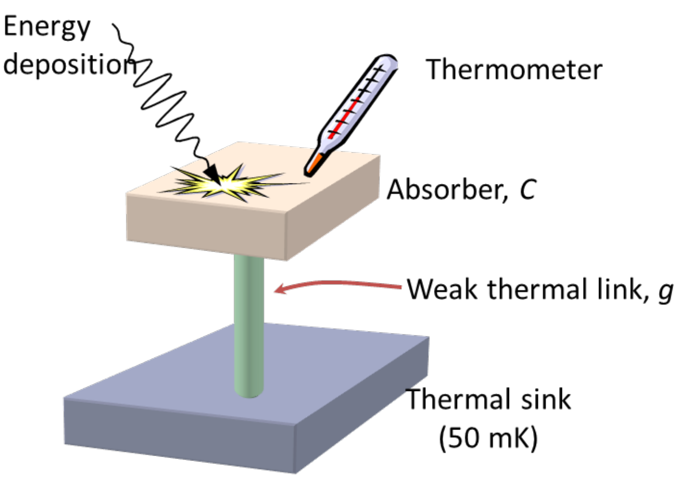
Single photon:

- Quadratic
- Complex
- Couples less shot noise

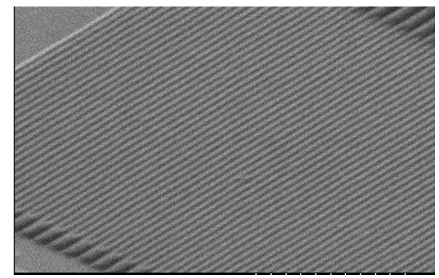
Single photon detectors

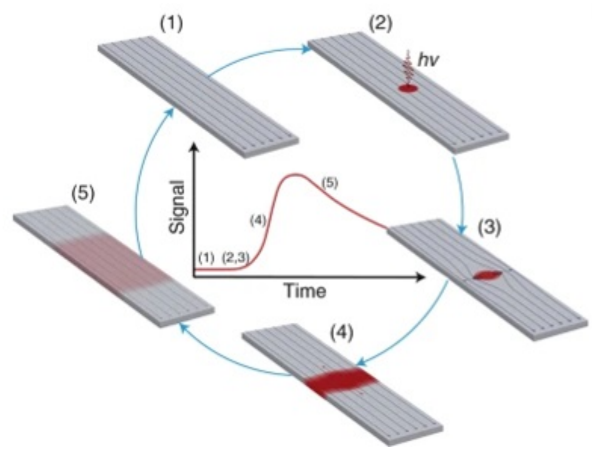
- TES (NIST)





- SNSPD (NIST & Glasgow)





D. Morozov, A Casaburi, RH Hadfield *Superconducting Photon Detectors* Contemporary Physics 1-23 (2022)

For more information visit

sr.bham.ac.uk/qi/