Quantum-enhanced Interferometry

Hartmut Grote (PI)
on behalf of the QI consortium

Quantum Technologies for Fundamental Physics

UK HEP forum
10/Nov/2020

Our consortium

University of Birmingham


D. Martynov


H. Miao


V. Boyer

University of Glasgow


R. Hadfield

University of Warwick


Dr. A. Datta

Cardiff University


H. Grote


K. Dooley

University of Strathclyde


S. Reid

Two Themes

Theme 1: The nature of dark matter (UKRI/STFC C4)

Theme 2: The nature of space-time (UKRI/STFC C3))

Dark Matter: Why Axions?

- Baryonic dark matter inconsistent with CMB and micro-lensing
- Non-baryonic dark matter
    - WIMPs: the detectors will face neutrino background soon
    - Axions (and scalar and vector fields): large unexplored parameter space

    Can be tested using interferometric measurements

    - Sterile neutrinos: new experiments coming soon

...

Rev. Mod. Phys. 90, 045002

Axion searches using photon coupling

“Haloscopes”

ADMX
...
QI: WP1

P. Sikivie

“Helioscopes”

CAST
IAXO ?

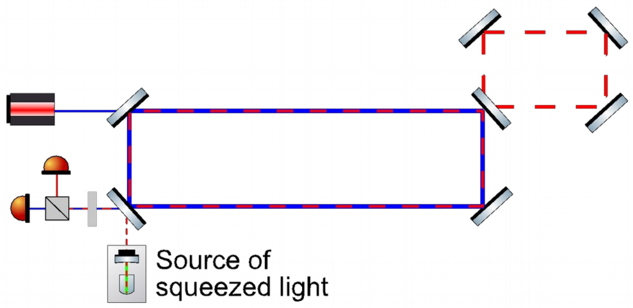
Lab
“Light-Shining
Through wall”

...
ALPS I
OSQAR
ALPS II, QI: WP2
JURA ?

Work packages

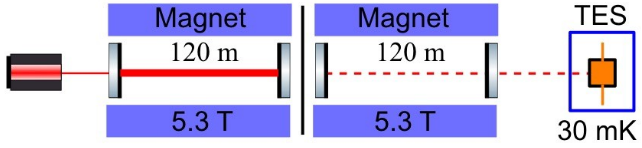
Work package 1: Axions in the galactic halo

- axions with masses from 10^{-16} eV up to 10^{-8} eV



Work package 2: Light-shining-through-wall

- transition edge sensor with background $<10^{-6}$/s



WP1: Interferometry Haloscope

- Axion field behaves classically

$$a(t)=a_0\cos(\Omega_a(t)+\Phi(t))$$

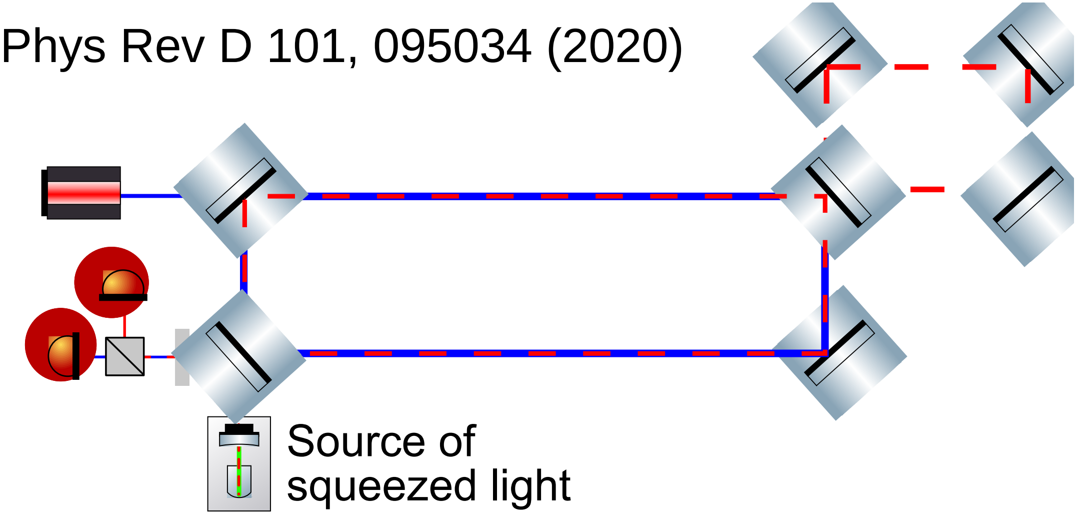
- Phase difference between left- and right-polarized light
- Can observe the phase interferometrically

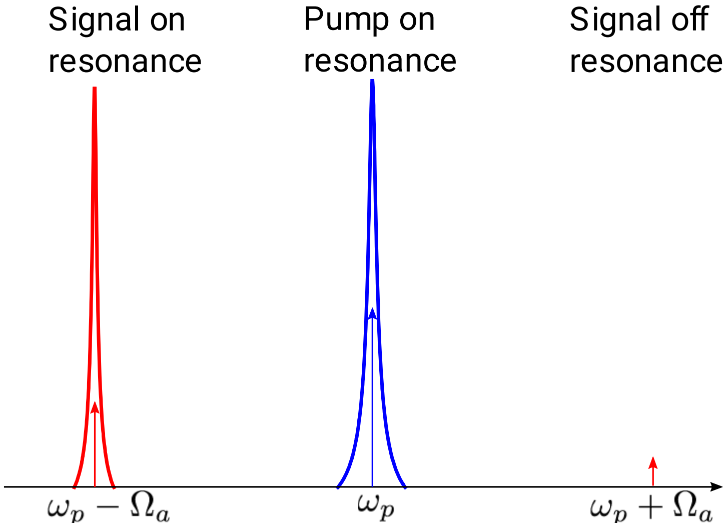
Phys. Rev. D **98**, 035021, Phys. Rev. Lett. **121**, 161301, Phys. Rev. D **100**, 023548

WP1: Interferometry Haloscope

- Resonate the pump and signal fields in the main cavity
- Choose the axion mass by tuning the auxiliary cavity
- Experimental support from MIT (Prof. M. Evans)

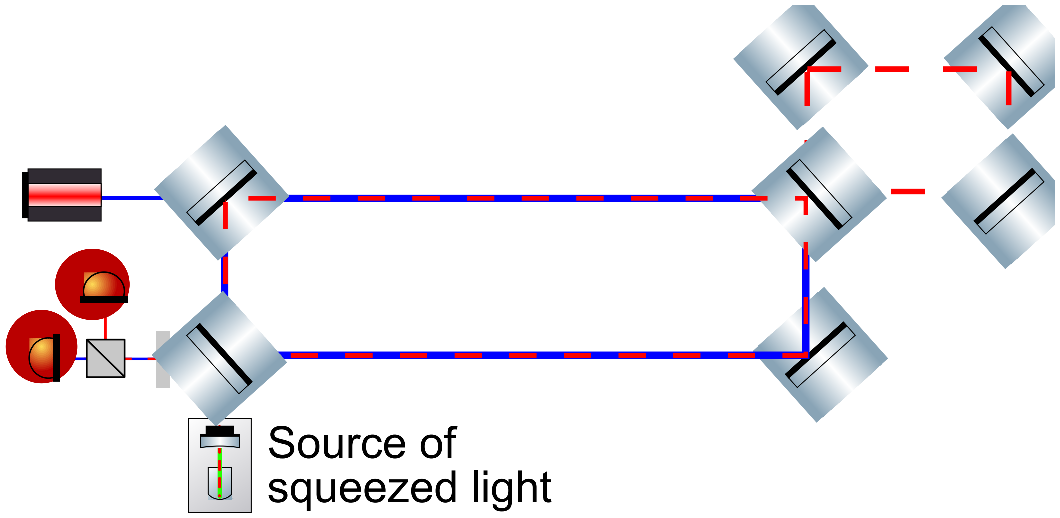
Phys Rev D 101, 095034 (2020)

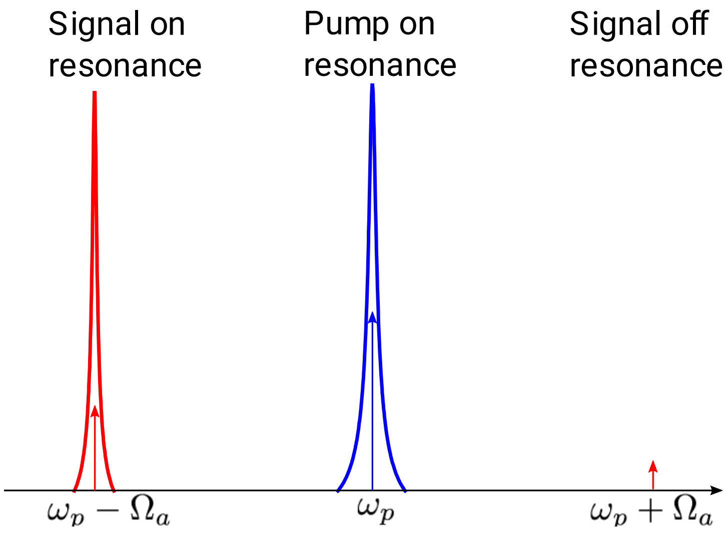




WP1: Quantum enhancement

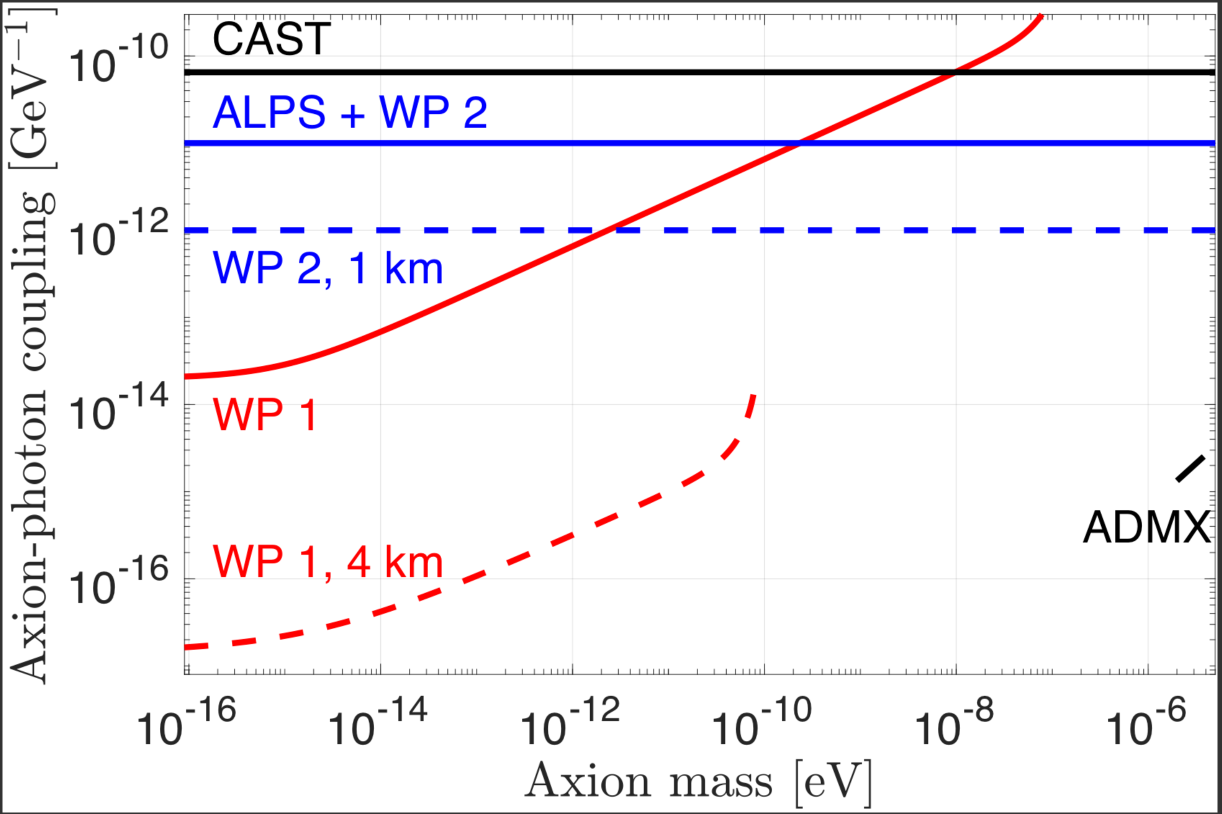
- The readout is limited by quantum shot noise
- Sources of squeezed states (developed by AEI Hannover) will reduce the noise (increase SNR) by a factor of 3





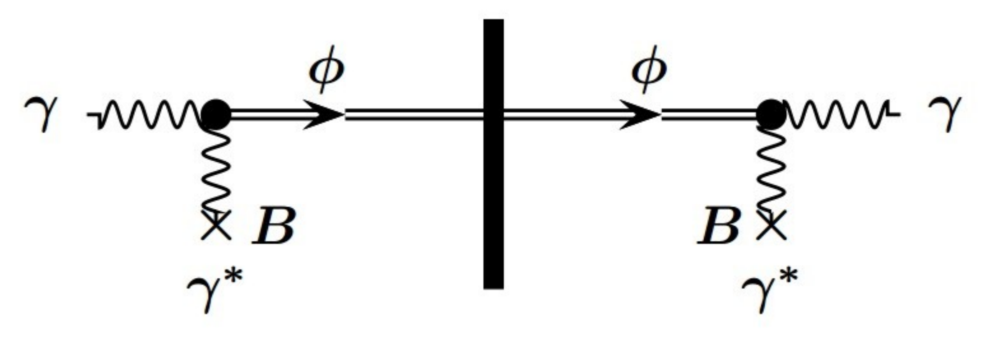
WP1: Sensitivity

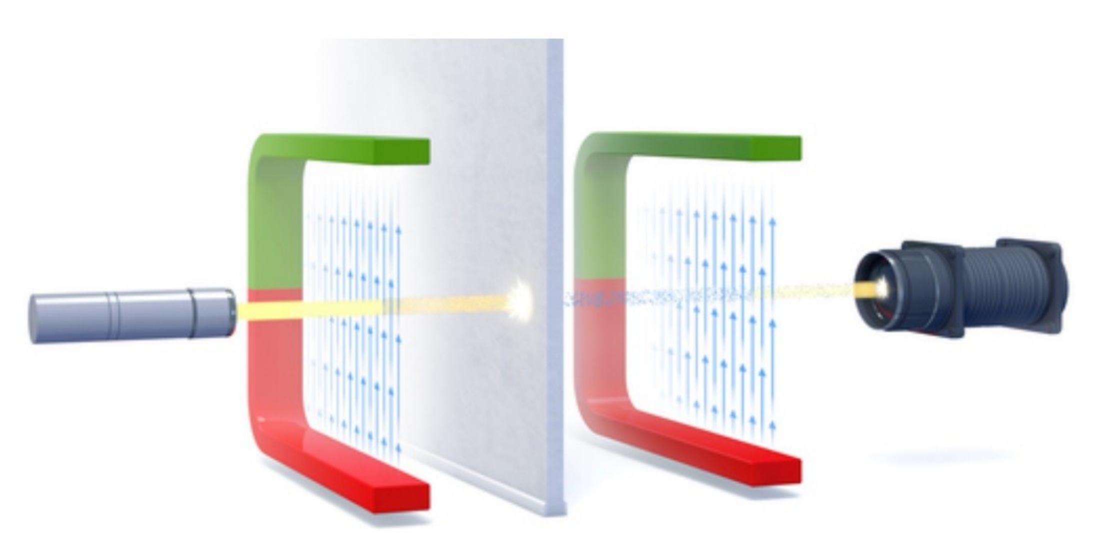
- Table top setups can provide new limits
- The layout can be potentially scaled to km lengths



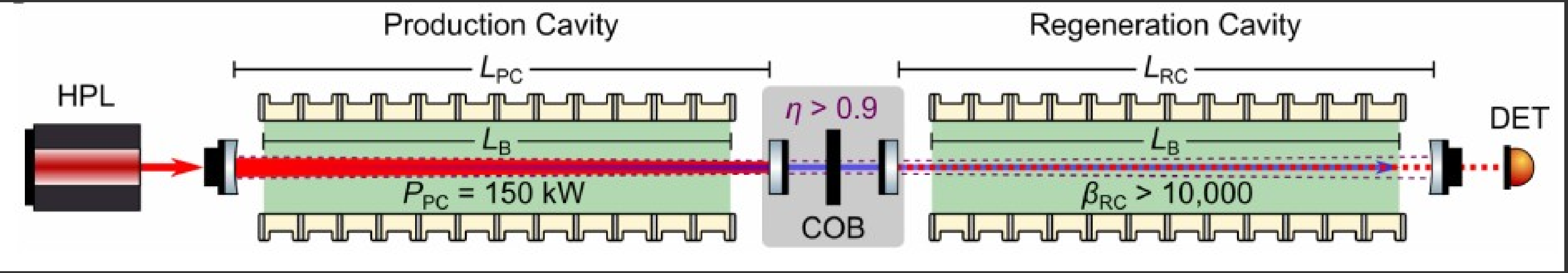
Light-shining-through-wall (LSW)

Lab
“Light-Shining
Through wall”





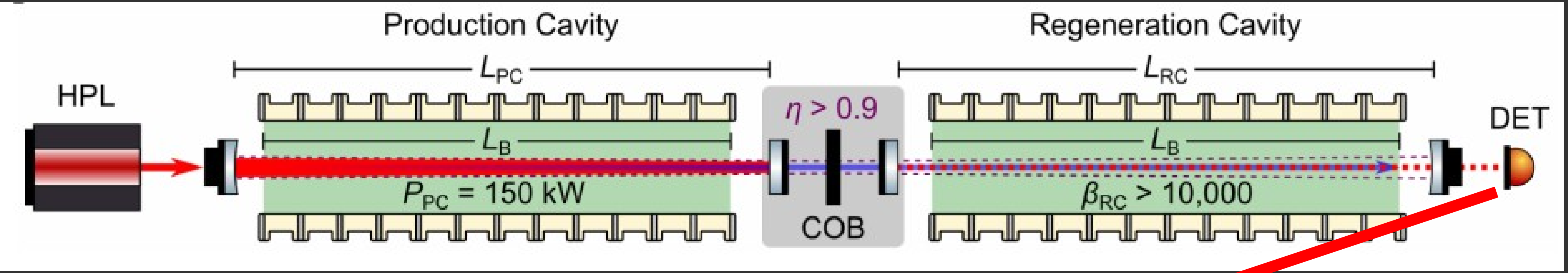
ALPS @ DESY, Germany



arXiv:2009.14294

- International collaboration (DESY, U Florida, AEI Hannover, Mainz, Cardiff)
- Under construction in former HERA accelerator tunnel at DESY
- WP2 contribution: improved TES and ALPS commissioning

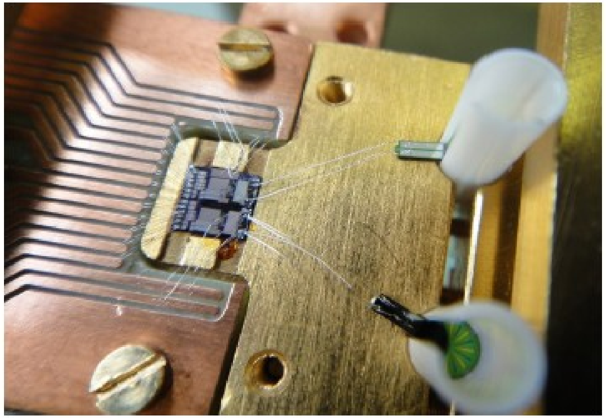
TES readout for ALPS

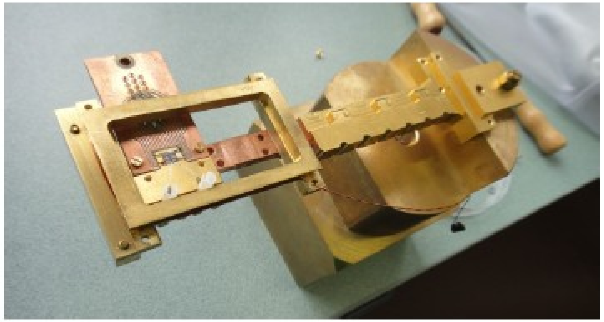


- Transition Edge Sensor: a micro-calorimeter
- Heat absorption brings superconductor to resistance increase
- Measure resulting current with SQUID
- Energy resolution to discriminate large green photon flux

TES readout for ALPS

NIST chips (W, Tc = 170 mK) with optical resonator and metallic mirrors reaching 98% quantum efficiency for 1064 nm





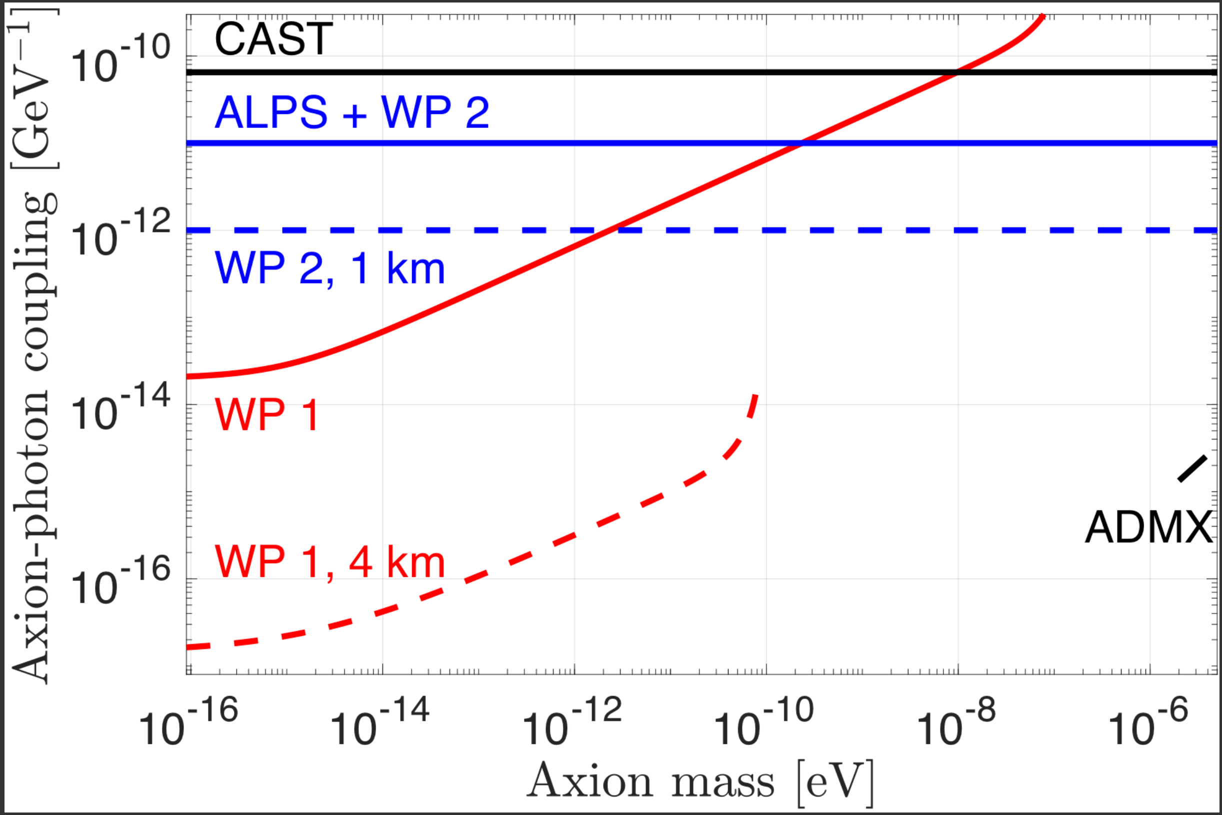
- Provide improved TES at 1064nm
- 30mK dilution refrigerator platform
- Next generation TES with SQUID readout (NIST/Magnicon)
- Target QE > 80%
- Target dark count < 10^{-6}/s
- Novel muon veto scheme with second on-chip detector
- Collaboration with NIST and PTB

References:

R. H. Hadfield Nat. Photon 3 696 (2009)
A. Lita et al. Optics Express 16 3032 (2008)
A. Lita et al. Proc. SPIE 7681 (2010)

WP1/WP2: Sensitivity

- “JURA” could be a next generation LSW experiment
- Km-long arms and higher power



ALPS: final magnet installation

Theme 2: Quantum aspects of space-time

- Quantum mechanics and general relativity passed all experimental tests to date.
    - Google's Sycamore quantum computer
    - Observation of gravitational waves by LIGO / Virgo
- How can gravity be united with the other fundamental forces?
- We pursuit the directions of search for quantization of space-time and quantum optomechanical tests

Phys. Rev. Lett. **110**, 170401, Phys. Rev. A **101**, 063804, Phys. Rev. D 100, 066020

Work packages

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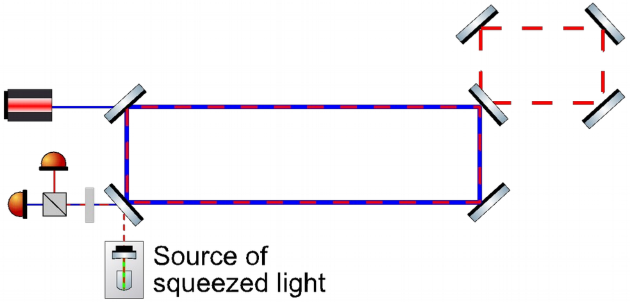
- axions with masses from 10^{-16} eV up to 10^{-8} eV



Work package 2: Light-shining-through-the-wall

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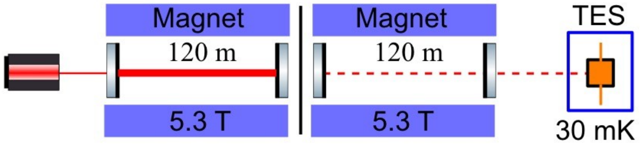
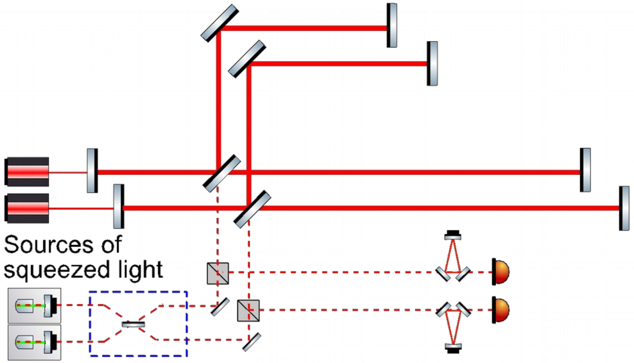


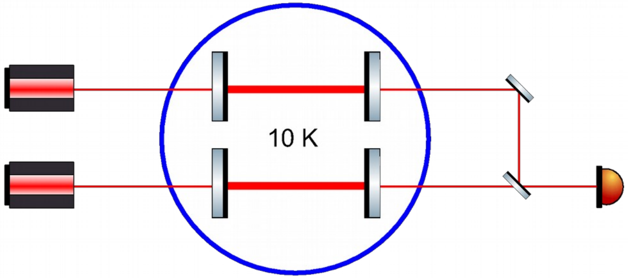
Work package 3: Quantisation of space-time

- sensitivity of 2×10^{-19} m/rt(Hz) above 1 MHz

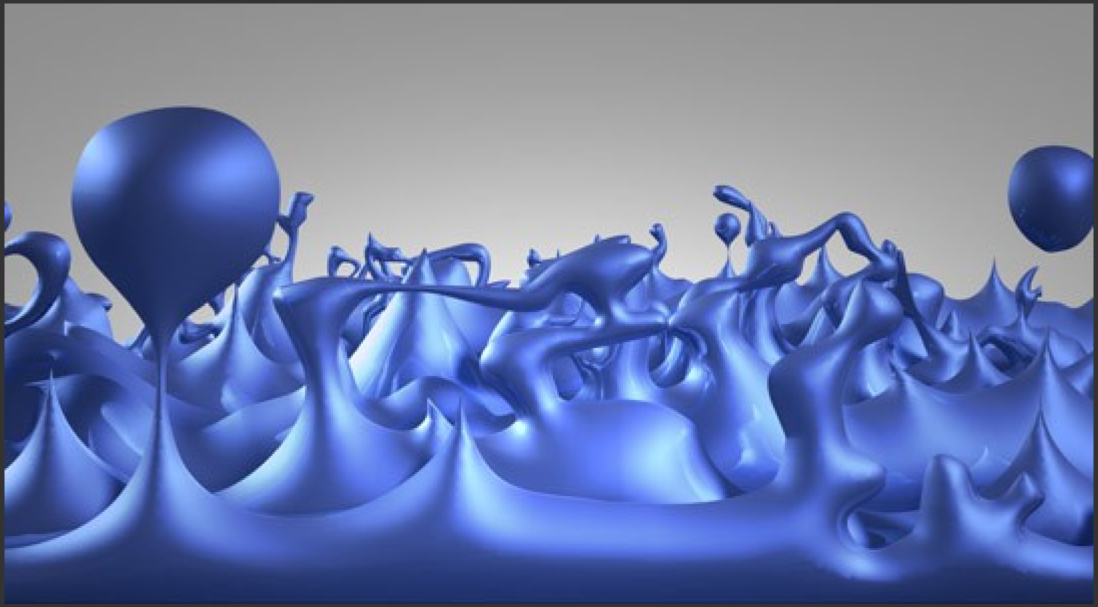


Work package 4: Semiclassical gravity

- confirm or rule out with 5 sigma precision



WP3: Quantization of space-time



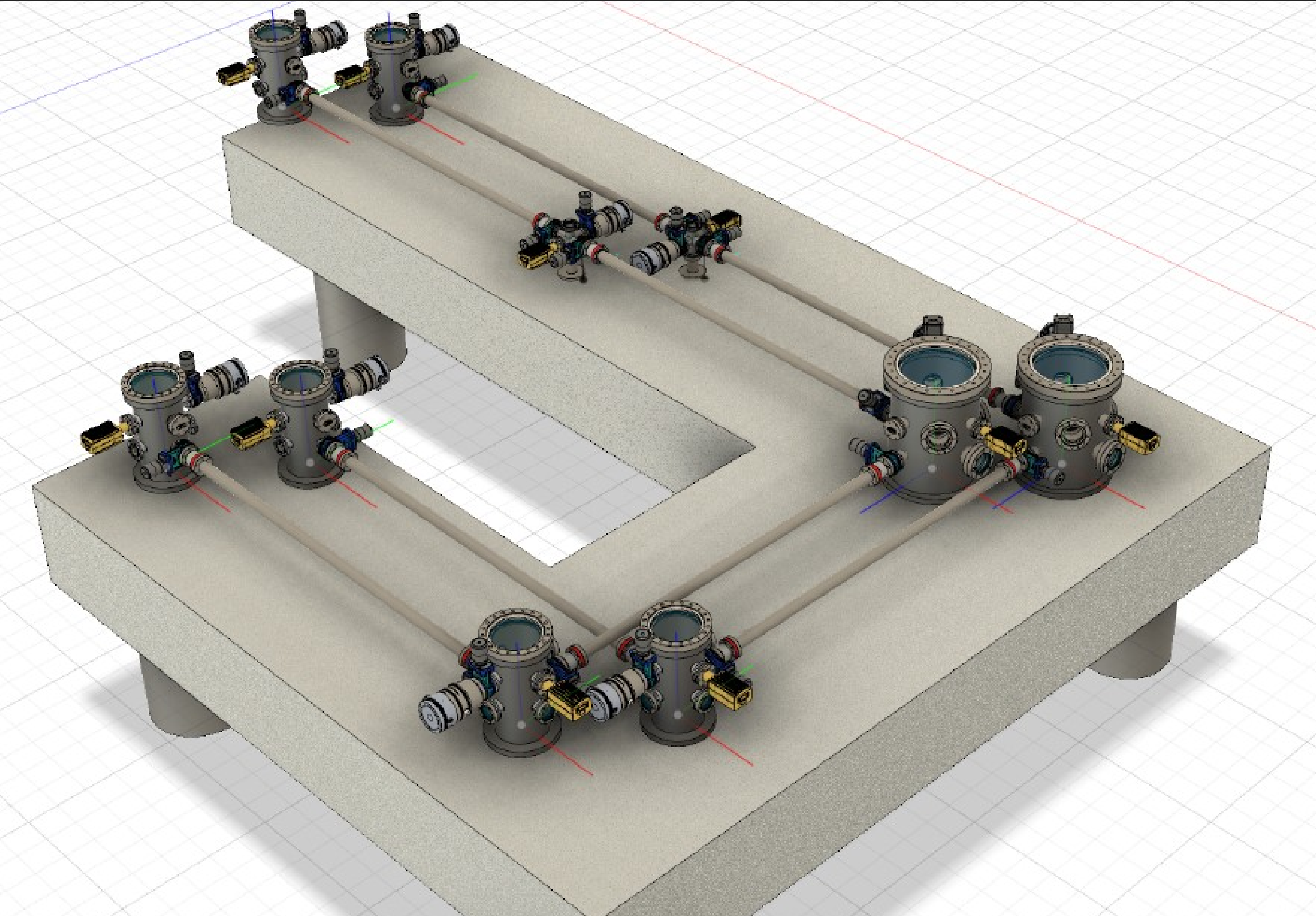
Space-time foam?

- 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

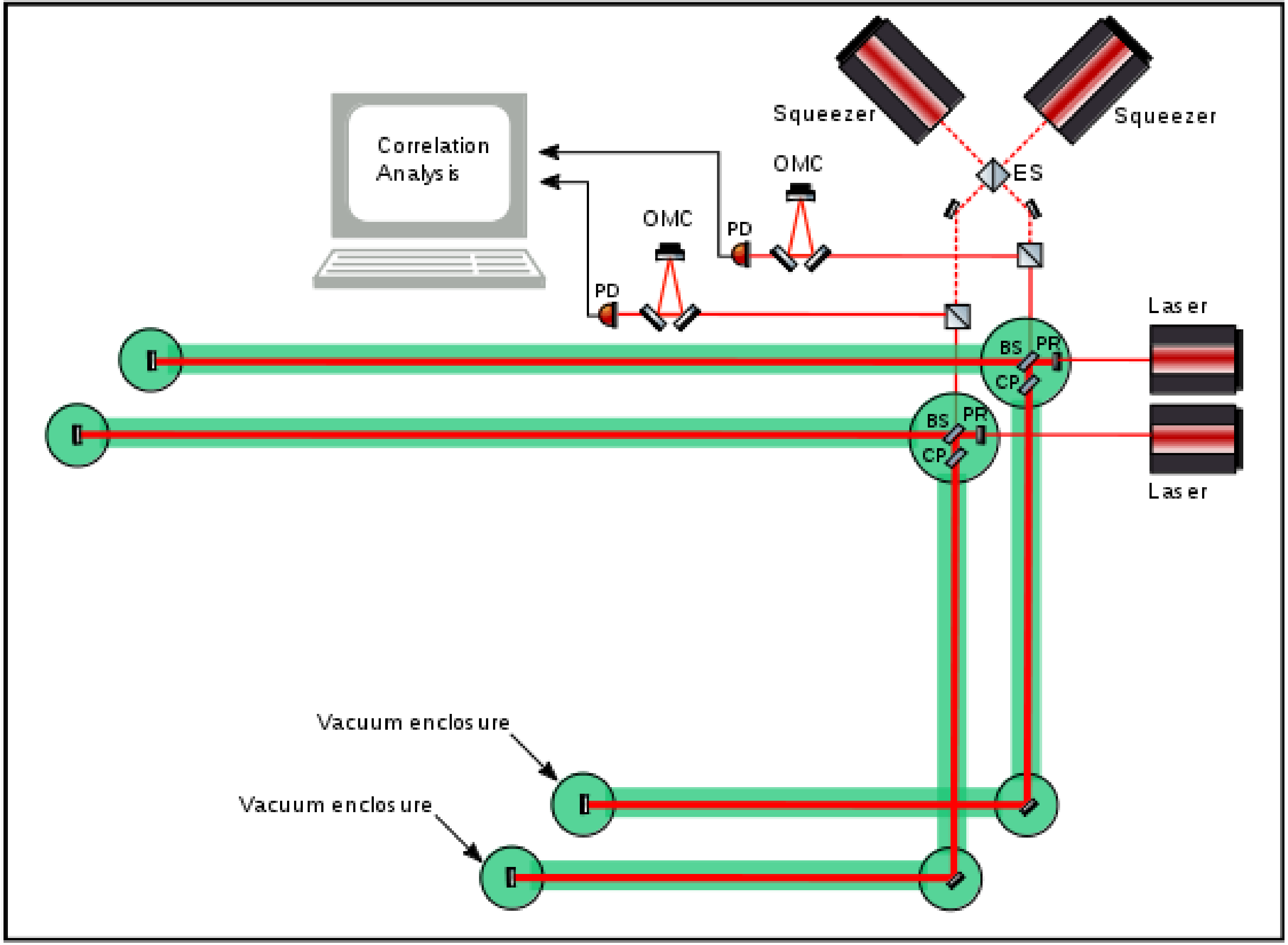
Before: Fermilab “Holometer”

PRL 117, 111102 (2016)
CQG 34, 6 (2017)

WP3: co-located table-top interferometers

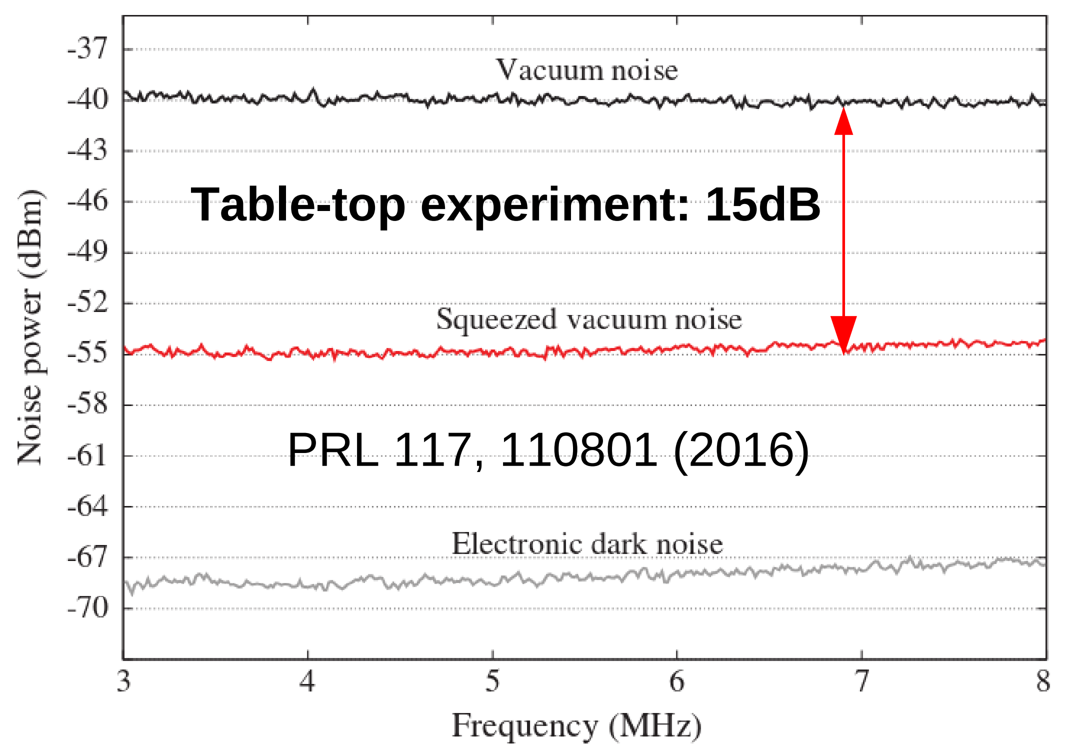


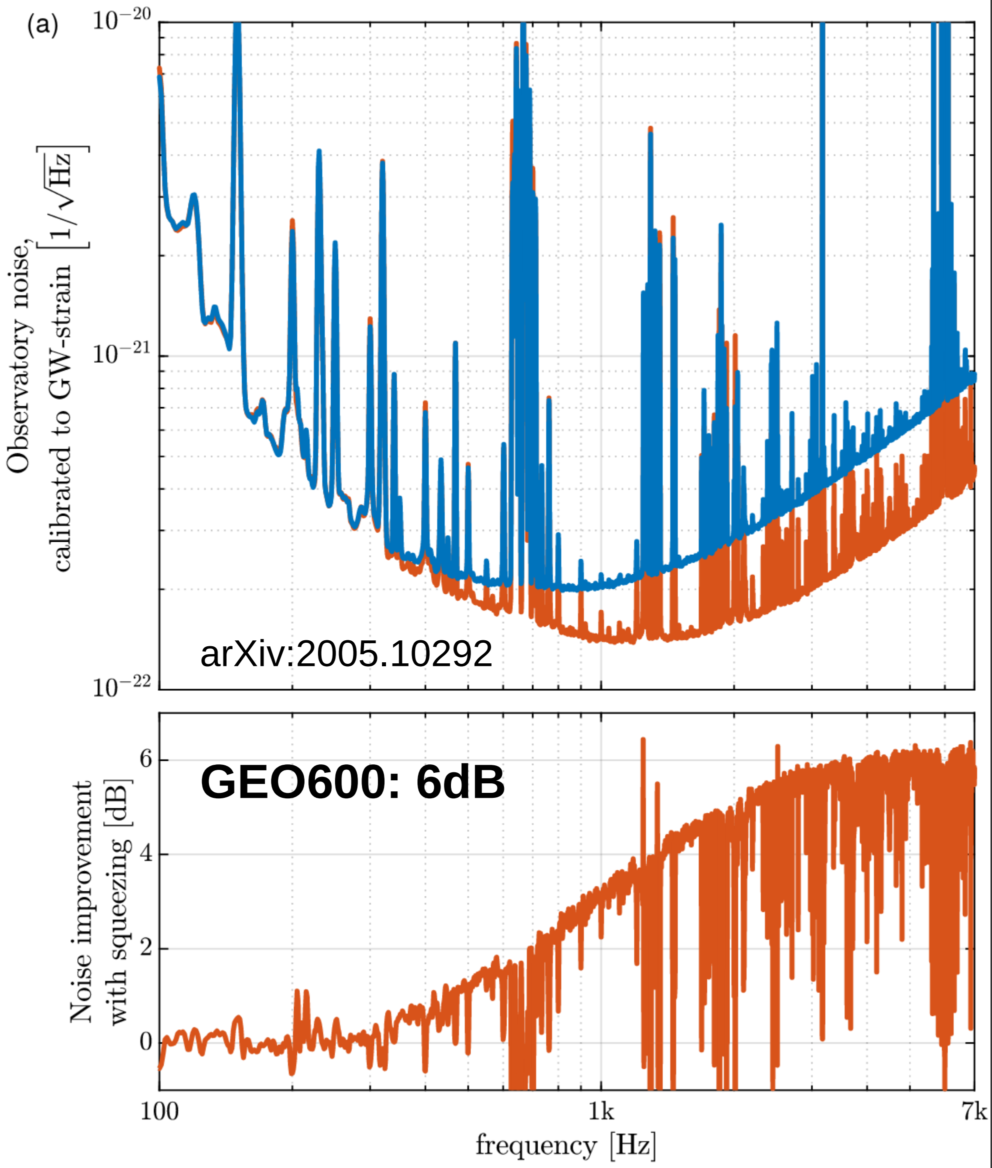
- 10 kW in interferometer
- Output modecleaner
- 500MHz data sampling
- Squeezed light
- Can test new squeezing configurations
- Theoretical support Fermilab



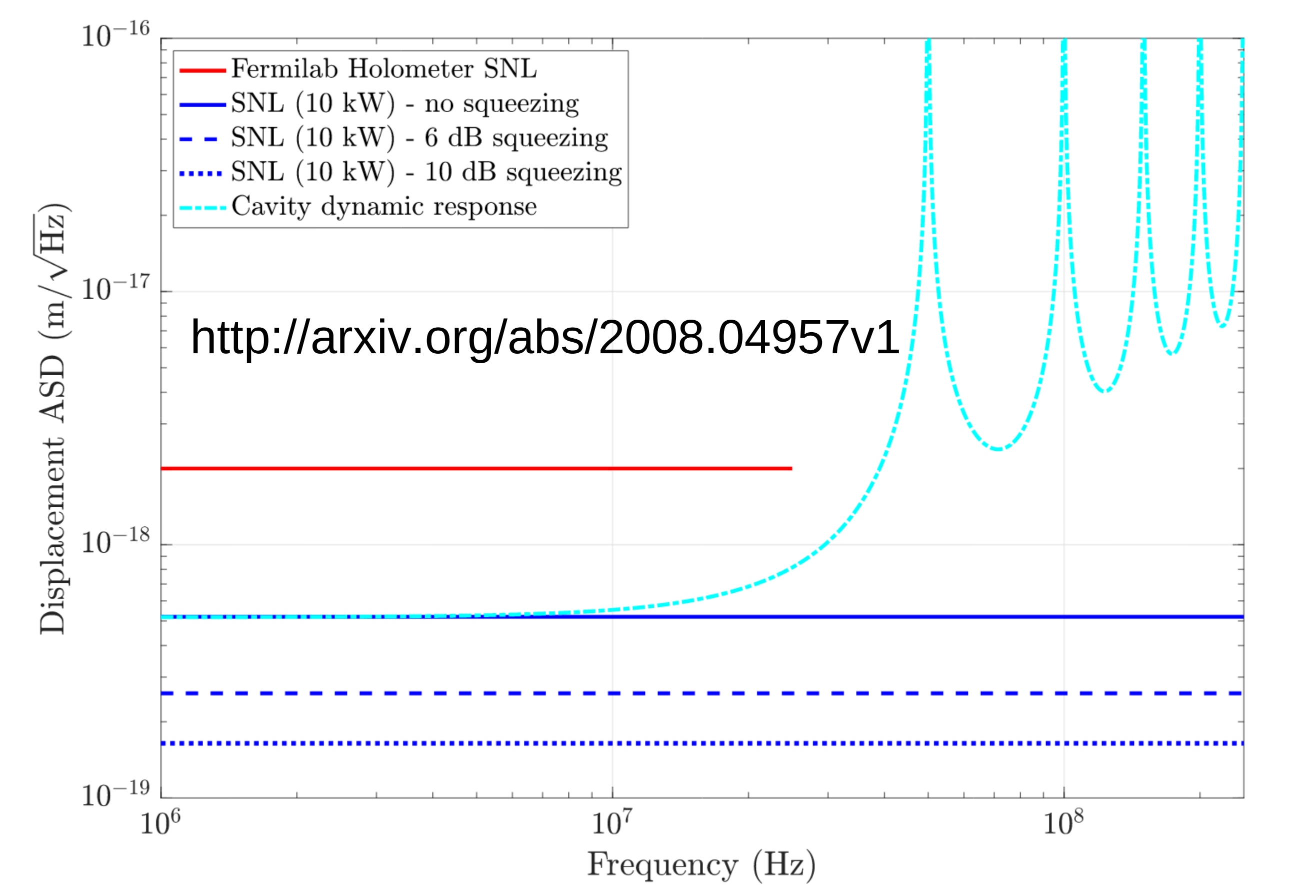
Squeezing shot noise

Two world records with squeezers from our AEI (Hannover, Germany) partners:





Aiming for World-best table-top sensitivity in interferometry



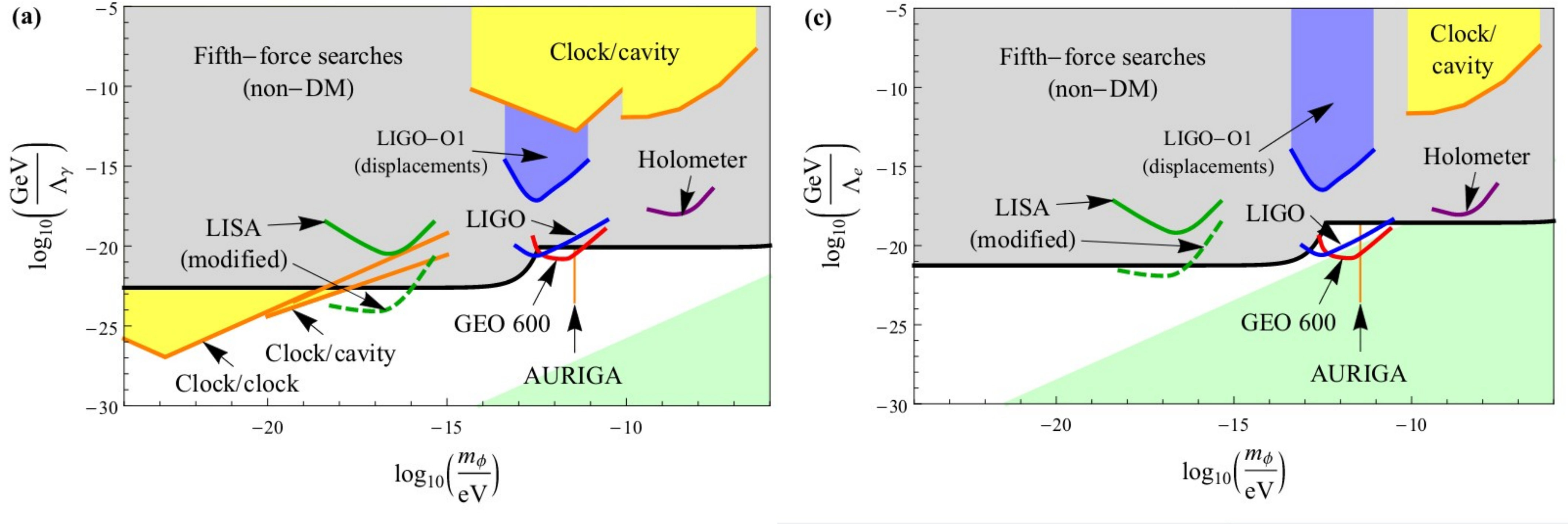
- A side remark:

  Also sensitive to very high frequency gravitational waves and scalar field dark matter

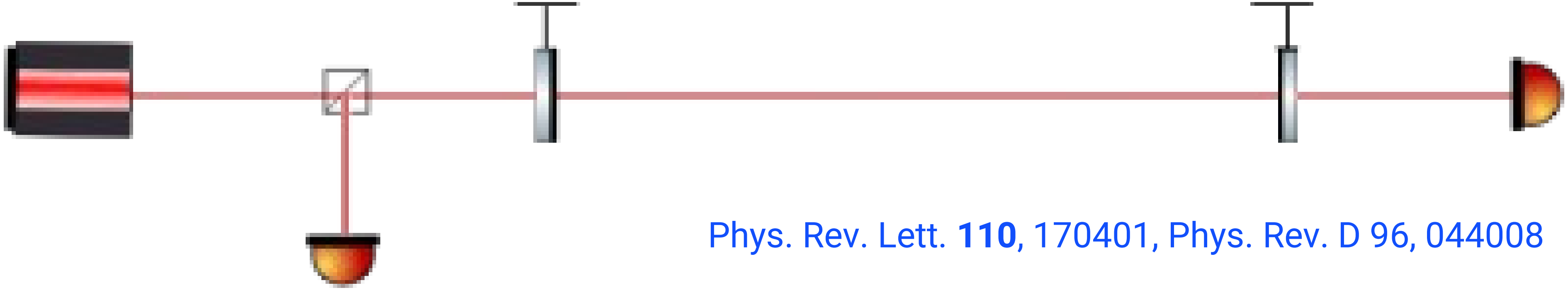
Scalar field DM with interferometry

- Scalar field DM (variation of fundamental constants) is searched for with atmic clocks and atom interferometry (in QTFP: Atomic clock network, AION)
- Also possible with precision interferometry (GW detectors and others)

PRR 1, 033187, 2019



WP4: Quantum-optomechanics

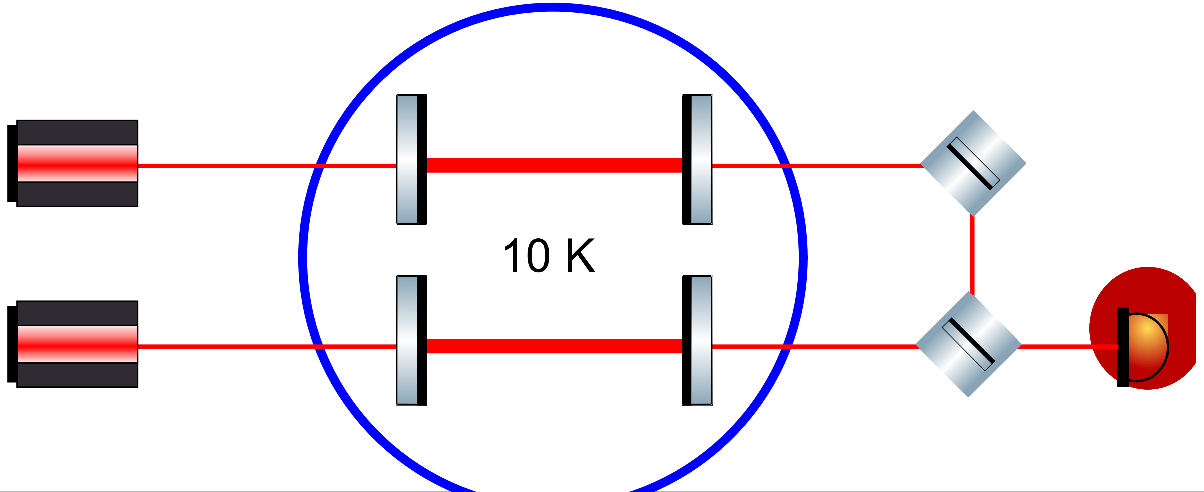


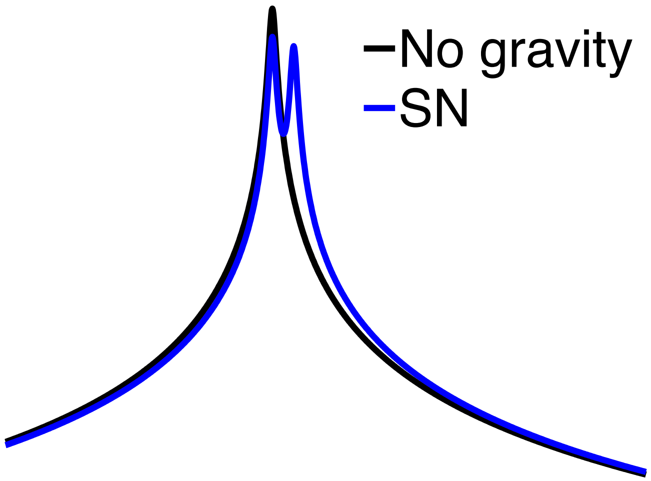
Phys. Rev. Lett. **110**, 170401, Phys. Rev. D 96, 044008

- Measured phase is $\phi_{\text{out}} = \phi_{\text{in}} + \phi_{\text{shot}} + \frac{8\,F}{\lambda}(x_{\text{cl}} + x_{\text{rad}})$
- x_{rad} is the quantum back action signal from the laser field to the mechanical oscillator
- x_{rad} may show gravity features in the spectrum
- Theoretical support from Prof Y. Chen (Caltech)

WP4: Test of semi-classical gravity (Schrödinger-Newton equation)

- Two cryogenic silicon cavities to suppress laser noise ϕ_{in}
- Observe a splitting of the resonance due to semiclassical gravity
- The mirror should be made out of a crystal for a test of coherent self gravitation of atoms in a lattice



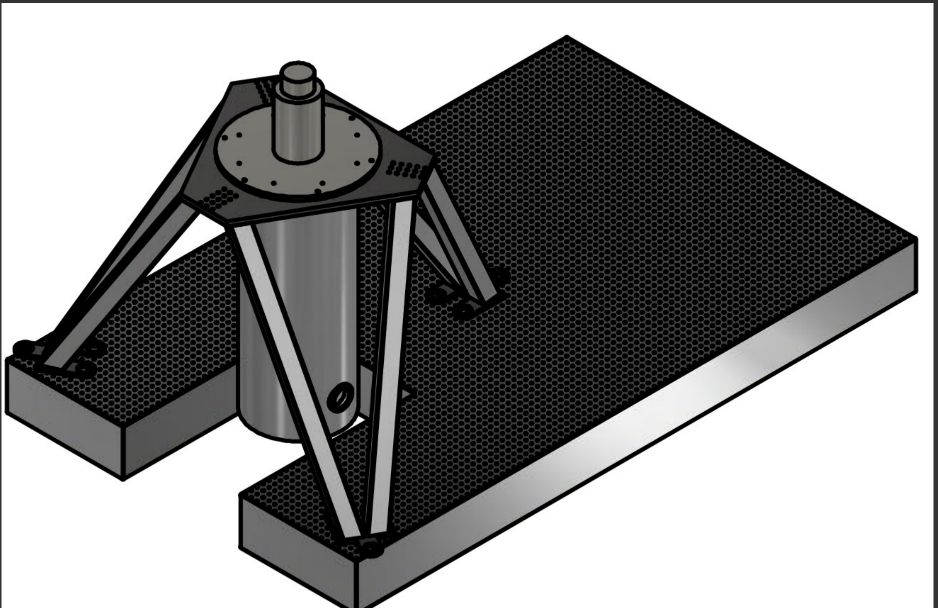


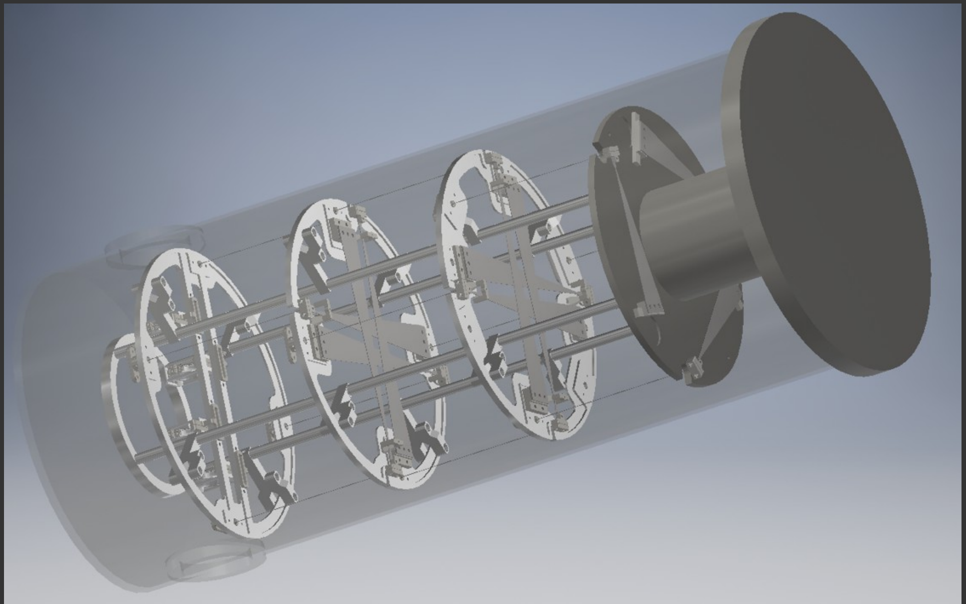
WP4: Cryogenic silicon

- Low thermal noises at 123 K and below 20 K
- Primary candidate for mirror substrate in future gravitational wave detectors
- The mirrors will be coated with custom coatings

WP4: Vibration isolation

- The tabletop will be isolated using commercial dampers
- Motion of the cryostat plate will be actively stabilised
- Vibrations will be further passively filtered via a suspension system





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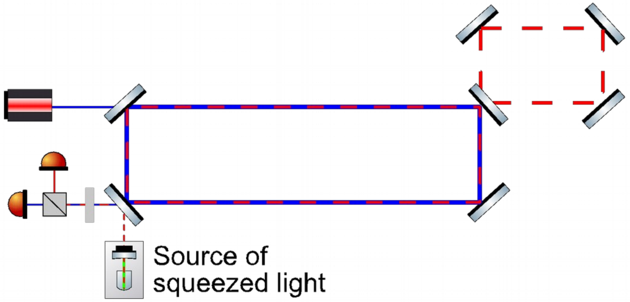

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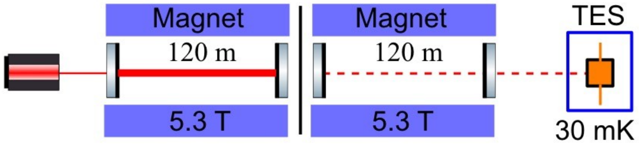

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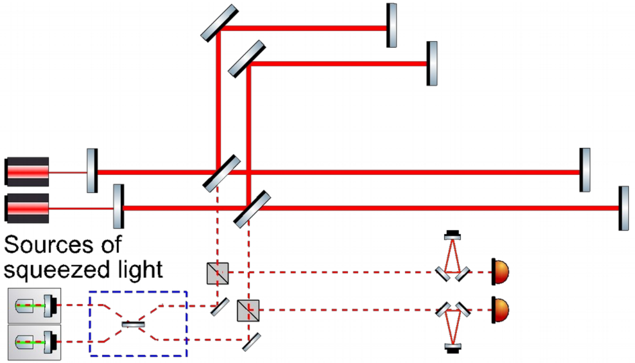

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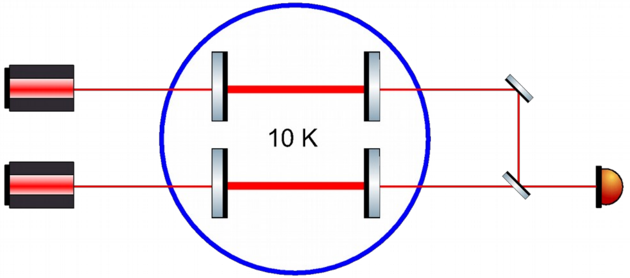


Work packages

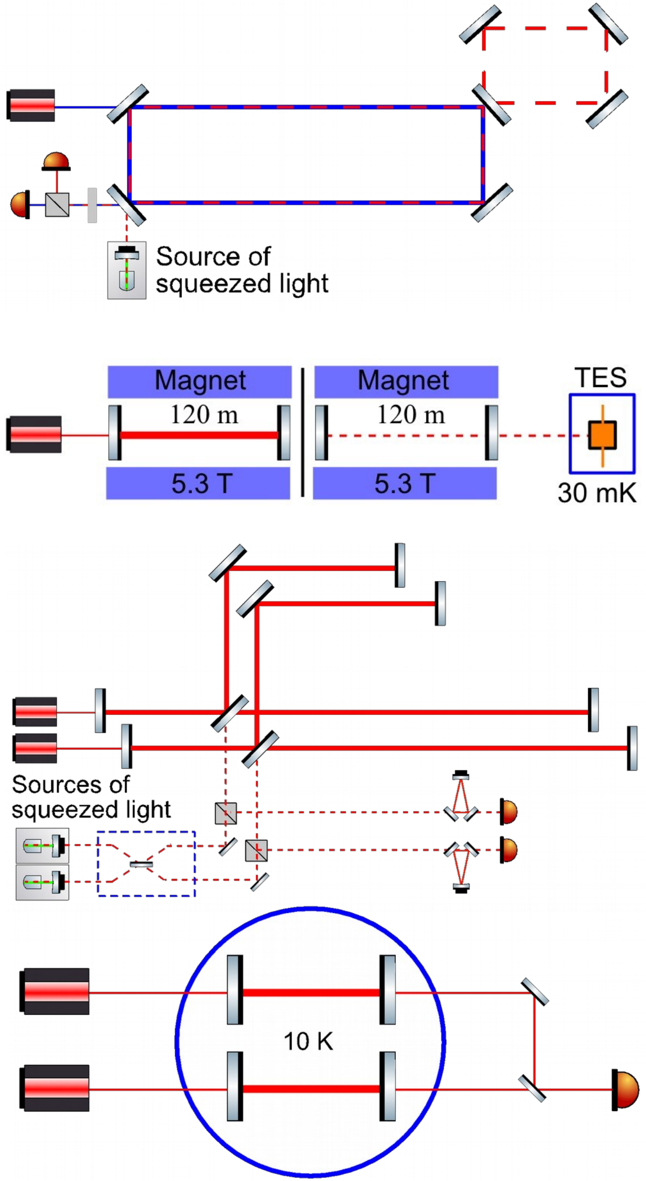
Two themes are united by quantum technologies

Optical cavities at their quantum limits

Sources of non-classical states of light

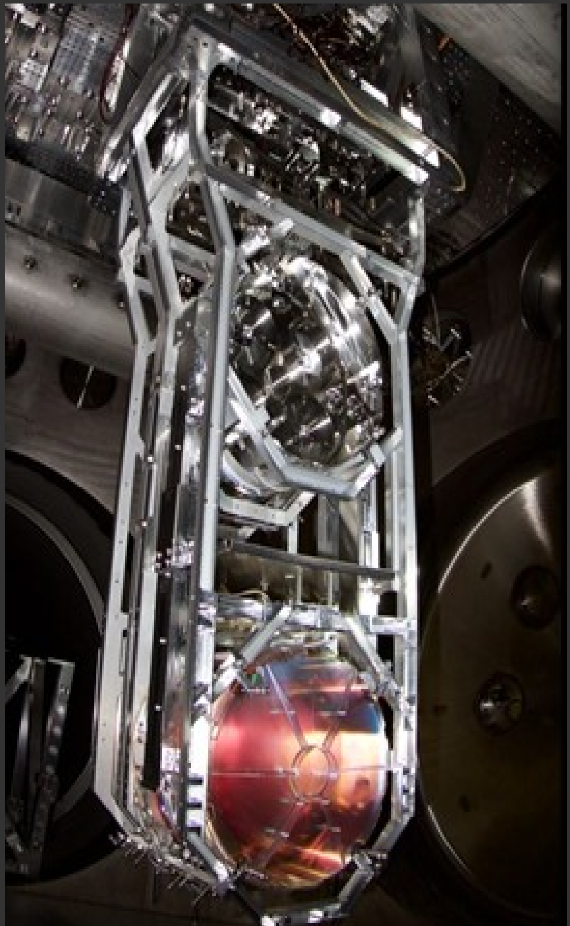
Transition edge sensors

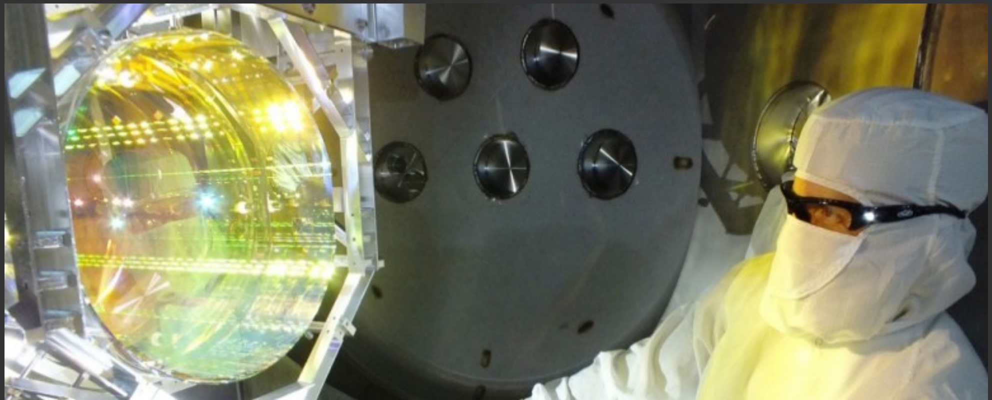
Extreme-performance optical coatings



Mirror Coating Requirements Driven by GW detectors

- Absorption <0.5 ppm
- Scatter <2 ppm
- ITM transmission: $(5 \pm 0.25) \times 10^{-3}$
- ETM transmission: <10 ppm
- Mechanical loss: 3×10^{-5} Goal (1×10^{-4})
- Uniformity +/- 0.5% over 34 cm





Optical coating facility + R&D

NMIS National Manufacturing Institute Scotland

EPOC extreme performance in optical coatings

University of Strathclyde Glasgow

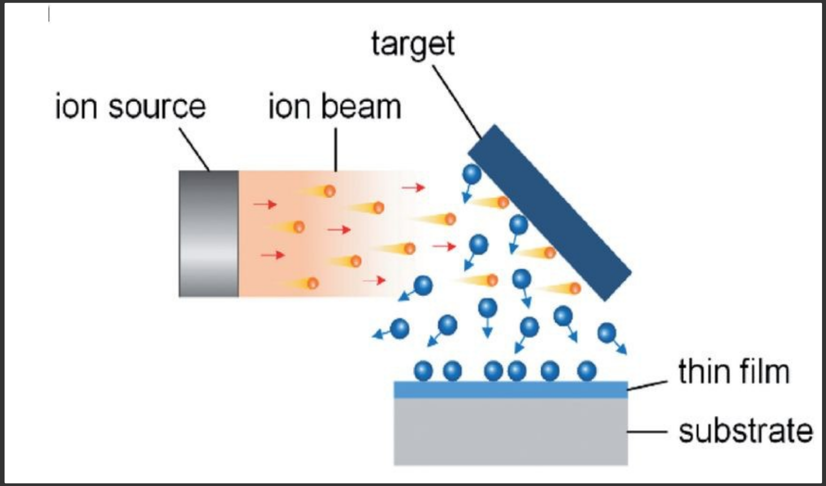
University of the West of Scotland UWS

University of Glasgow

Gooch & Housego

HELIA PHOTONICS

Ion beam deposition:



Optical coating facility + R&D

QI

NMIS
National Manufacturing Institute Scotland

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extreme performance in optical coatings

University of Strathclyde Glasgow

UNIVERSITY OF THE WEST of SCOTLAND UWS

University of Glasgow

Gooch & Housego

HELIA PHOTONICS

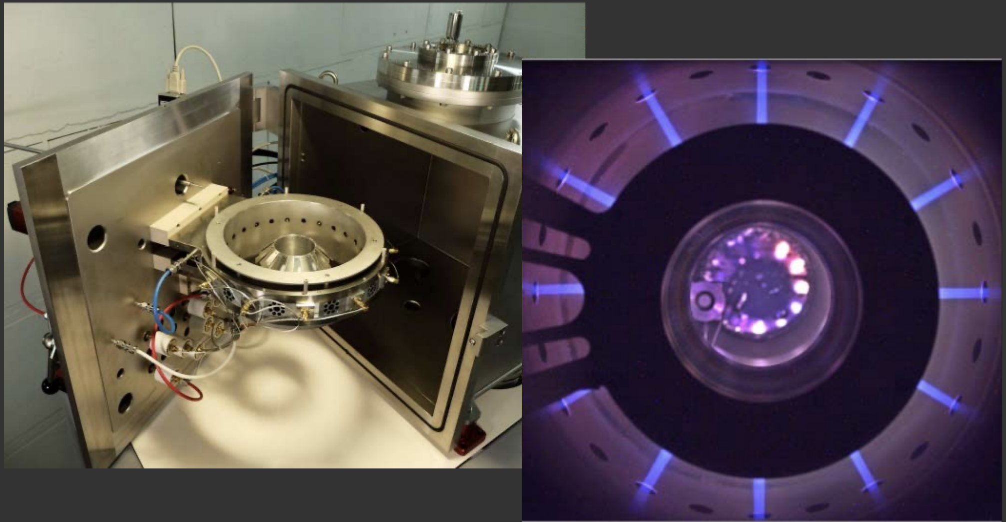
Current state-of-the-art

Industry best radio frequency (RF) ion beam deposition – second largest system in the world, hosted in SCAPA national laser/plasma facility in Strathclyde.

up to 62 cm diameter / 200 kg optics

Next-generation

Electron-cyclotron resonance (ECR) ion beam deposition for optical coatings – first demonstration in the world.



International + UK Project Partners

UK:

QUANTIC

Prof. S. Beaumont, WP 2

UK National Quantum Technology Hub in Sensors and Metrology

Prof. K. Bongs, WP 1, 4

Germany:

DESY.

Dr. A. Lindner, WP 2

Dr. H. Vahlbruch, WP 1,3

Dr. M. Mehmet, WP 1,3

USA:

NIST

Dr. S.W. Nam, WP 2

MIT

Prof. M. Evans, WP 1

Caltech

Prof. Y. Chen, WP 4

Fermilab

Prof. C. Hogan, WP 3

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