Quantum-enhanced Interferometry For New Physics

Hartmut Grote (PI)
on behalf of the QI consortium

UK - Quantum Technologies for Fundamental Physics programme

KITP workshop
April/05/2021

Our consortium

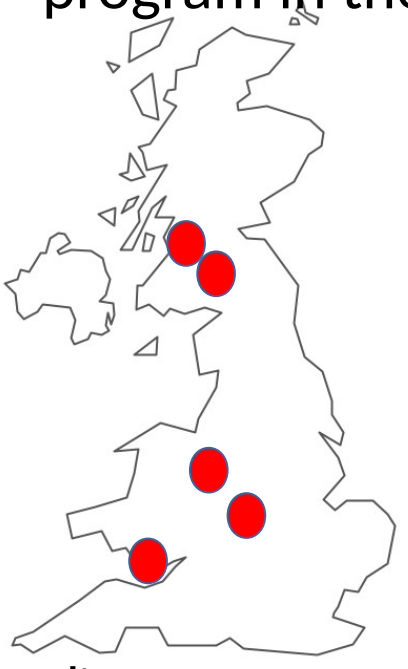
(one of 7 recently funded in the “Quantum Technologies for Fundamental Physics” program in the UK)

University of Birmingham

D. Martynov

H. Miao

V. Boyer



University of Glasgow

R. Hadfield

University of Warwick

Dr. A. Datta

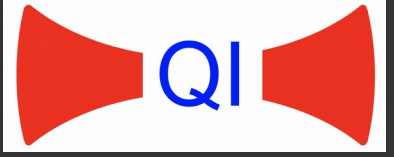
Cardiff University

H. Grote

K. Dooley

University of Strathclyde

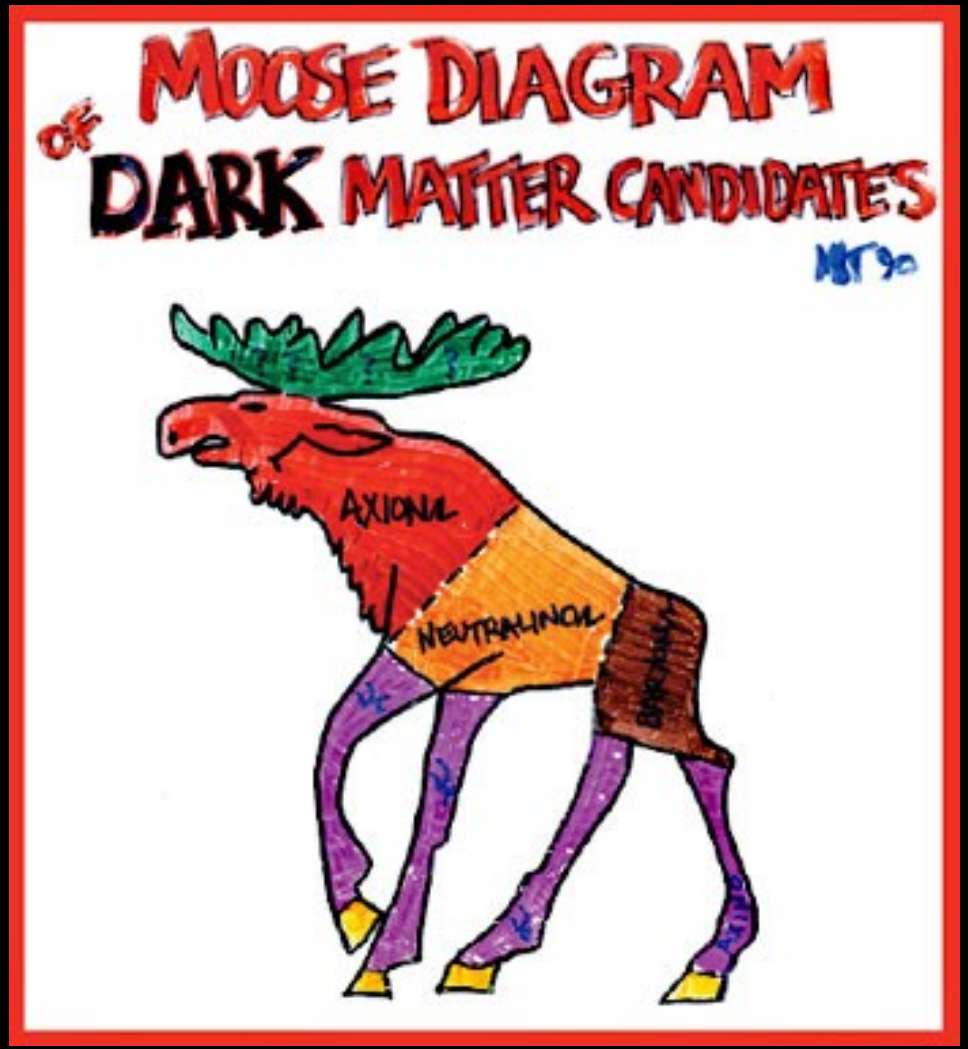
S. Reid



Two Themes

Theme 1: The nature of dark matter

Theme 2: The nature of space-time



Courtesy Michael Turner (1990)

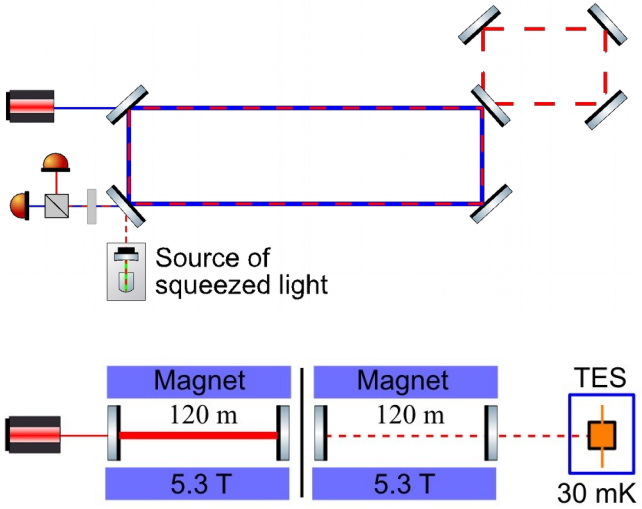
Experiments

Experiment 1: Axions in the galactic halo

- An ‘interferometry haloscope’
- Axions with masses from 10^{-16} eV up to 10^{-8} eV

Experiment 2: Light-shining-through-the-wall

- Making and detecting axion-like particles
- Transition edge sensor with background $<10^{-6}$/s



Exp1: Interferometry Haloscope

- Axion field behaves ‘classically’

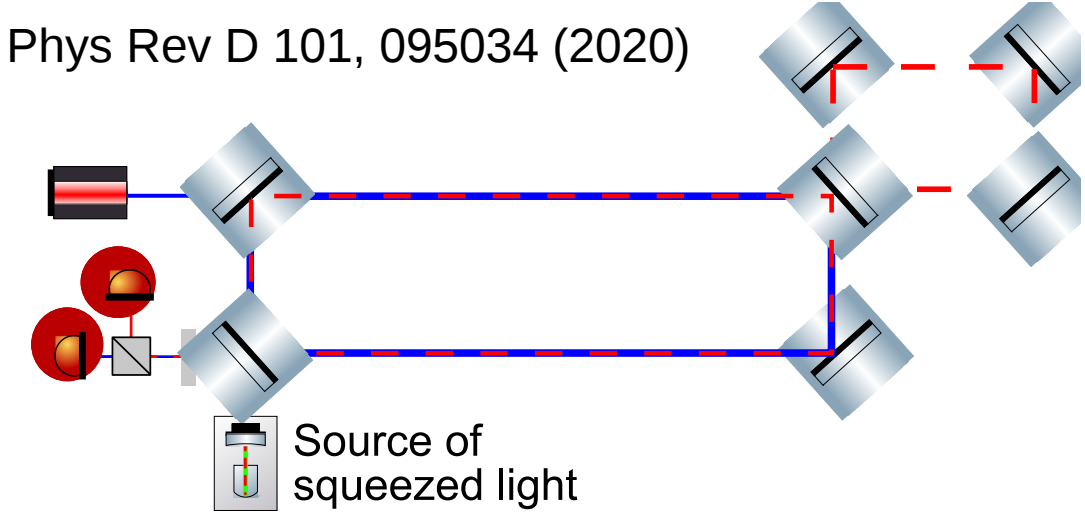
$$\mathrm{a(t)}=\mathrm{a_0}\cos(\Omega_a(t)+\Phi(t))$$

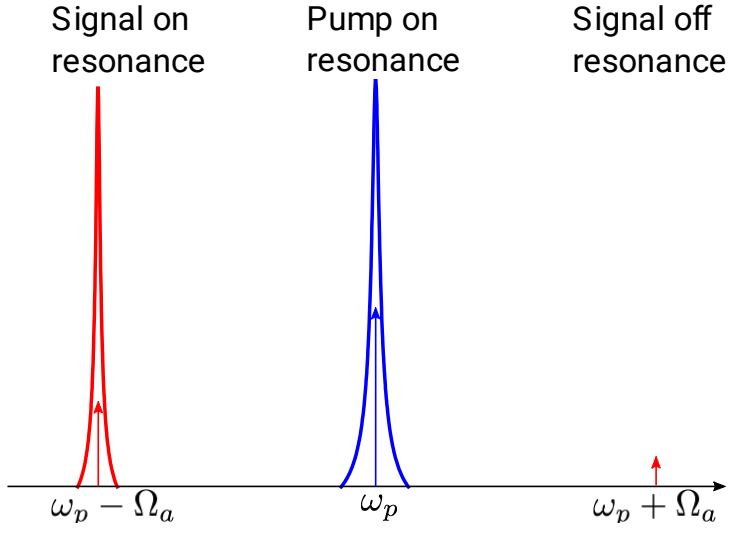
- Induces phase difference between left- and right-polarized light (no external magnetic field!)
- Can observe the phase interferometrically

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

Exp1: Interferometry Haloscope

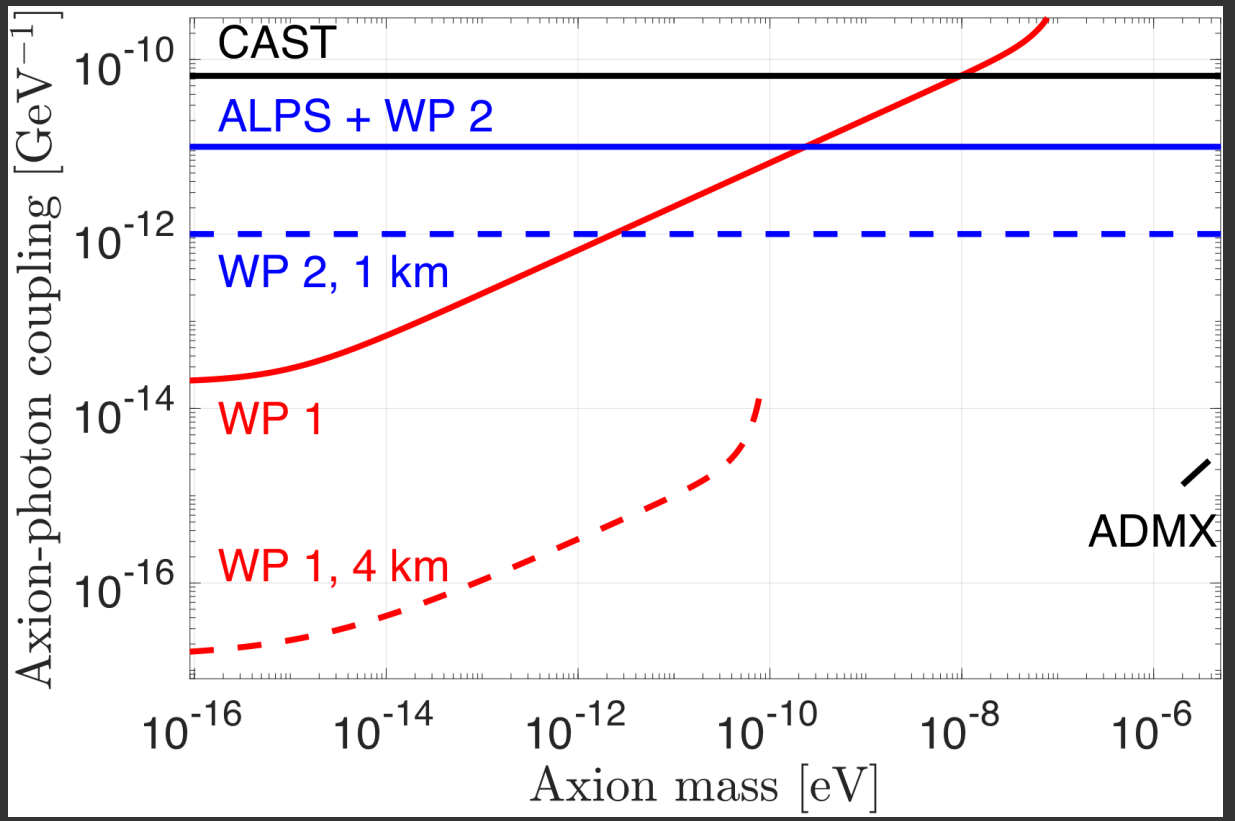
- Resonate the pump and signal fields in the main cavity
- Choose the axion mass by tuning the auxiliary cavity
- Squeezing enhances sensitivity



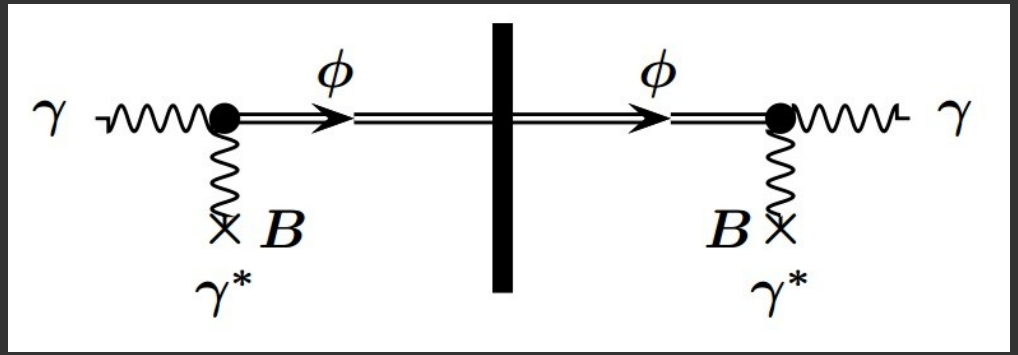


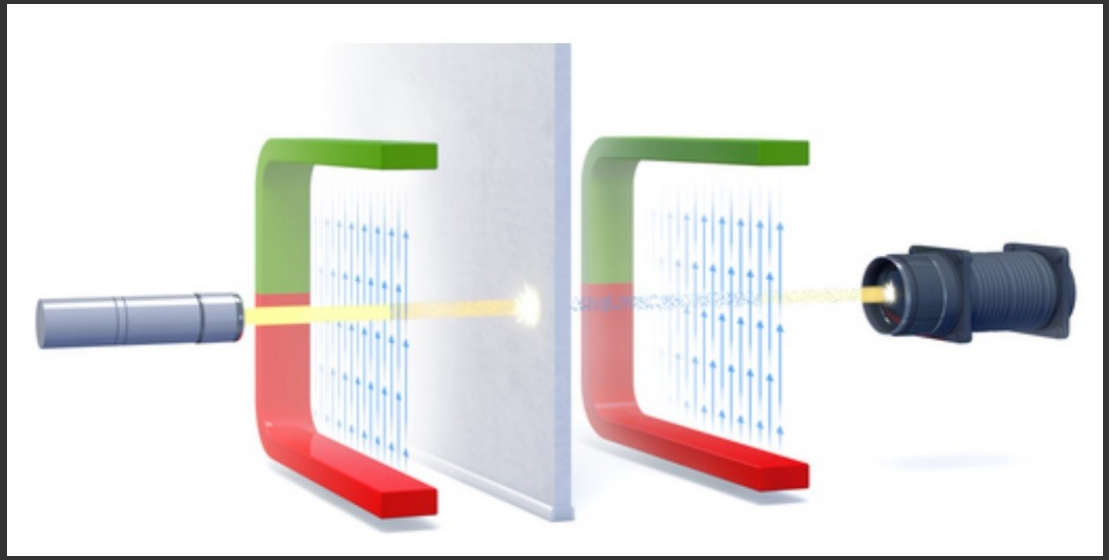
Exp1: Sensitivity

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



Light-shining-through-wall (LSW)



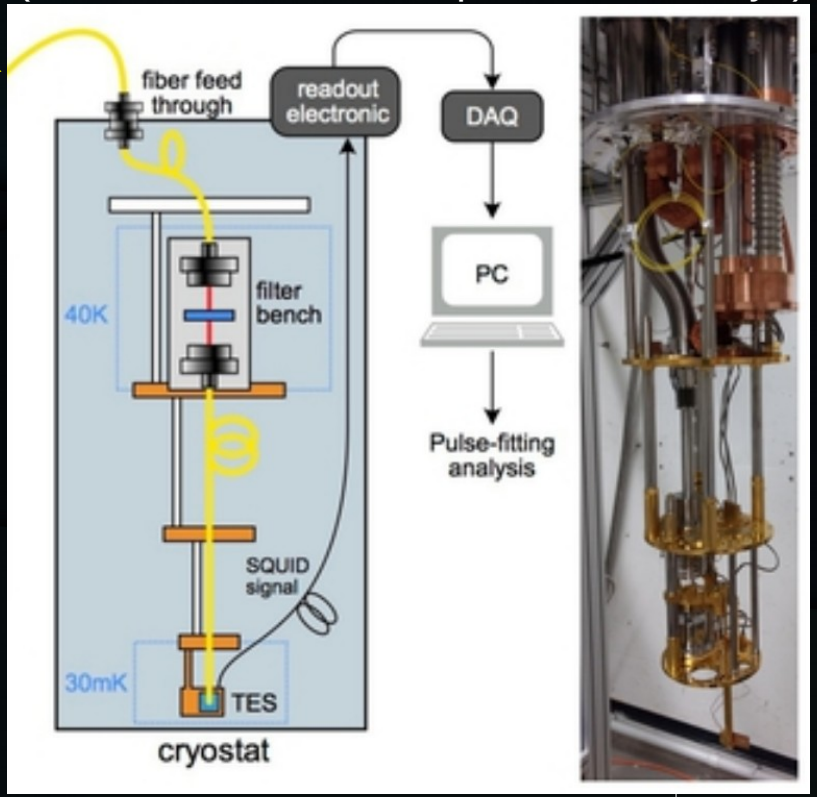


ALPS II at DESY

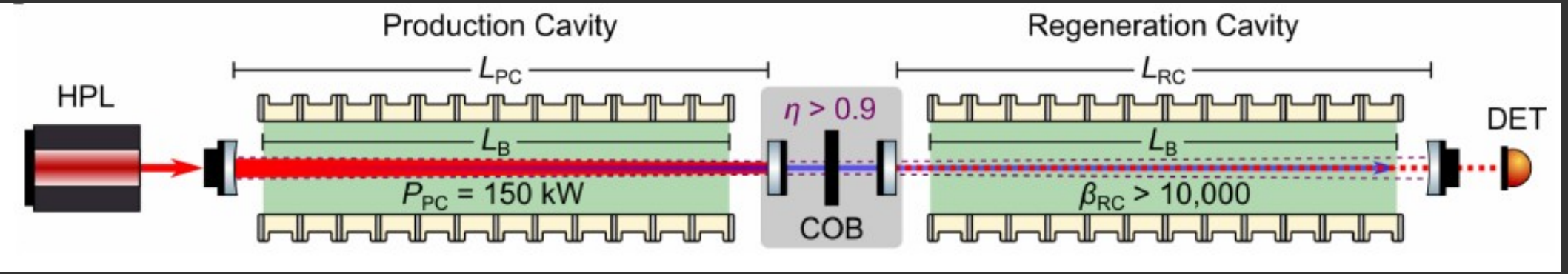
ALPS II at DESY

Copyright DESY / M.Mayer

Single photon detector
(noise of less than one photon in 10 days)



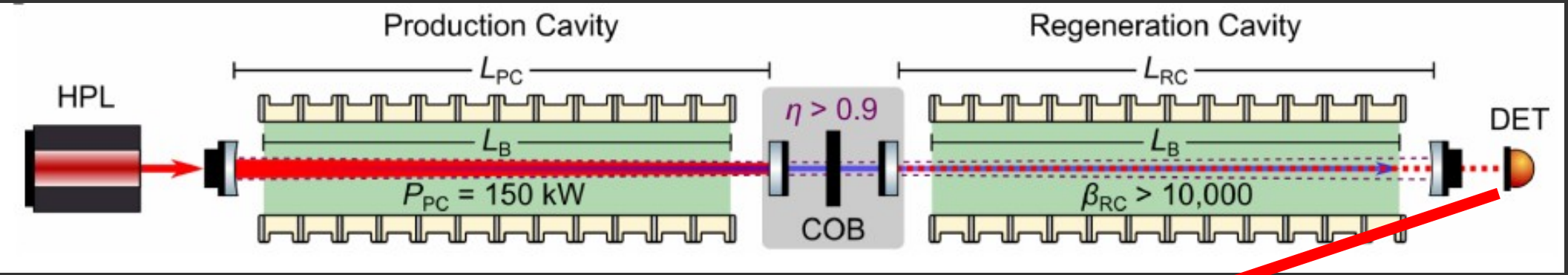
ALPS @ DESY, Germany



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

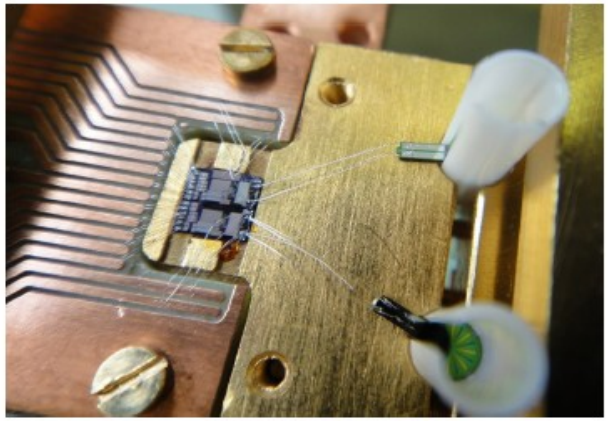
TES readout for ALPS

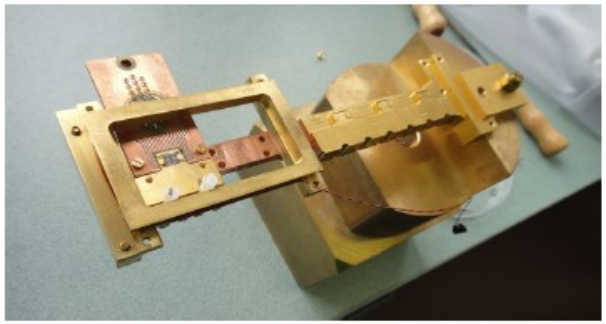


- Transition Edge Sensor: a micro-calorimeter
- Heat absorption brings superconductor to resistance increase
- Measure resulting current with SQUID
- Energy resolution to discriminate large green photon flux

TES readout for ALPS

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





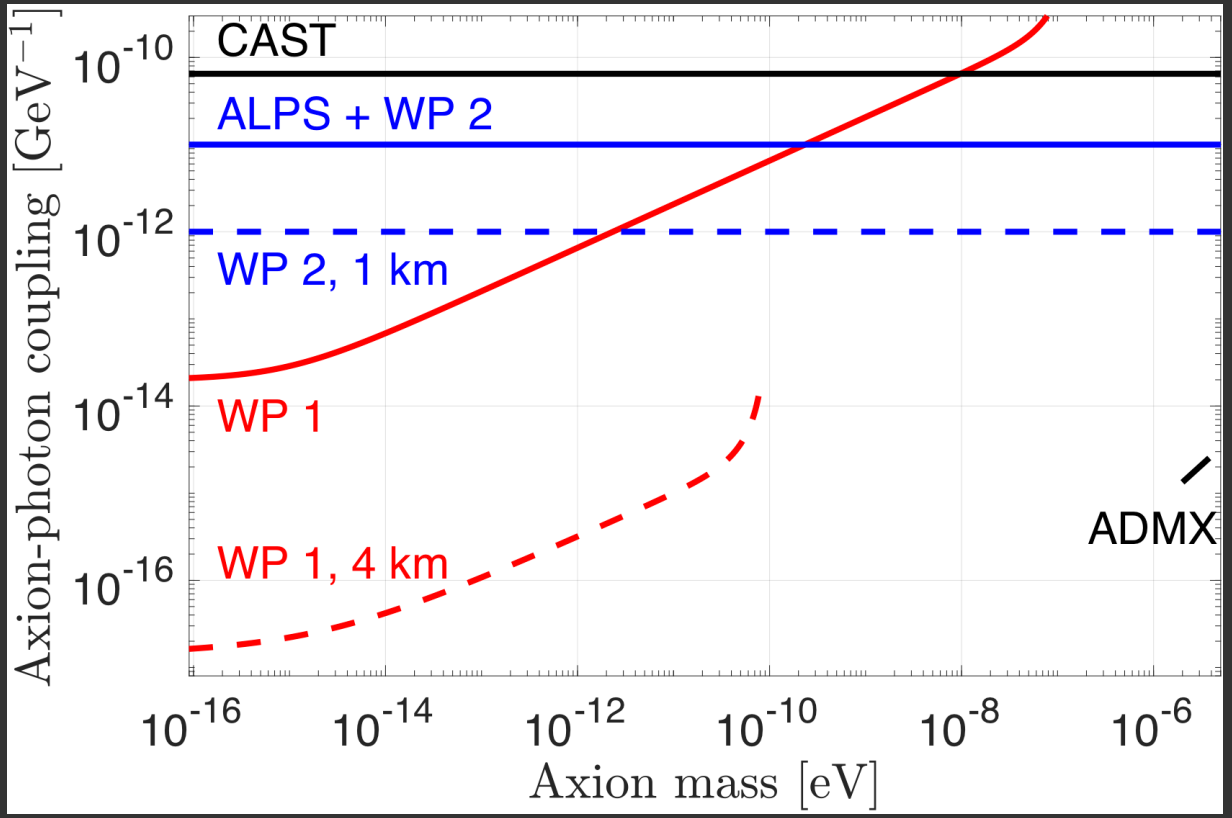
- Provide improved TES at 1064nm
- 30mK dilution refrigerator platform
- Next generation TES with SQUID readout (NIST/Magnicon)
- Target QE > 80%
- Target dark count < 10^{-6}/s
- Novel muon veto scheme with second on-chip detector
- Collaboration with NIST and PTB

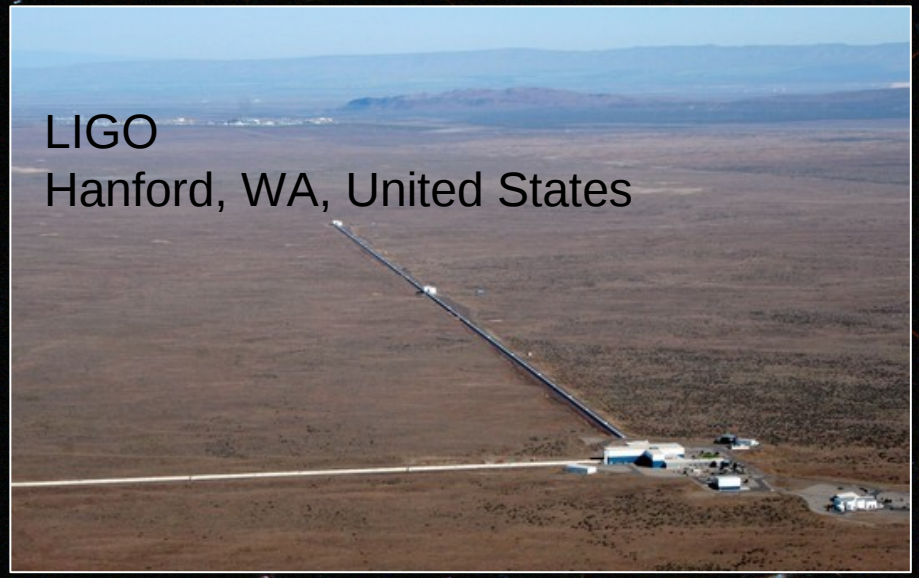
References:

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)

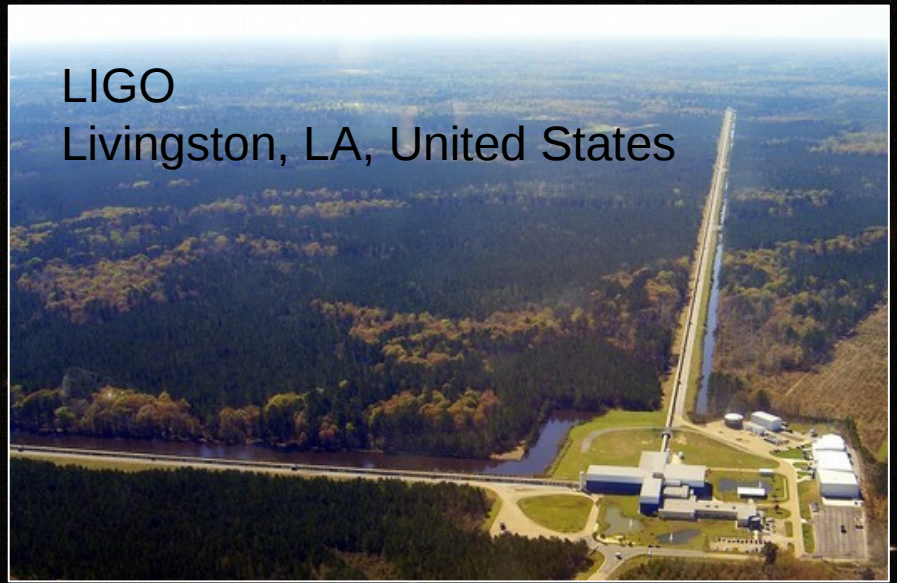
Exp1/Exp2: Sensitivity

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



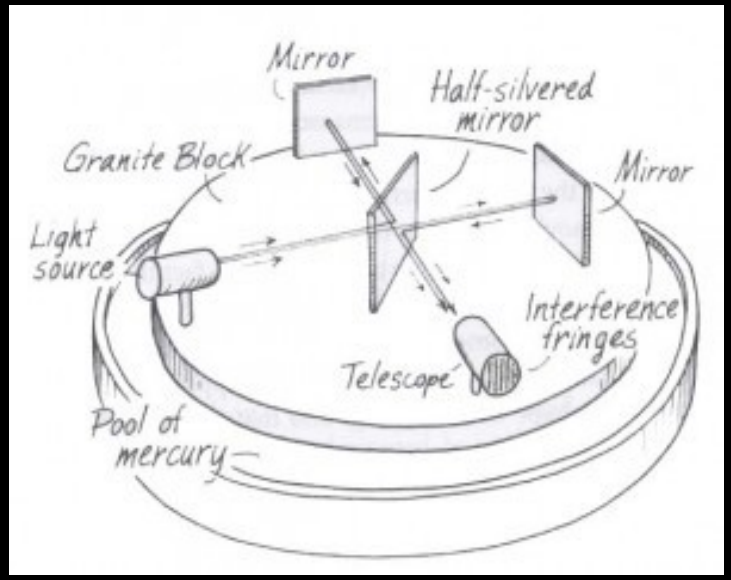

LIGO
Hanford, WA, United States


Virgo, Italy

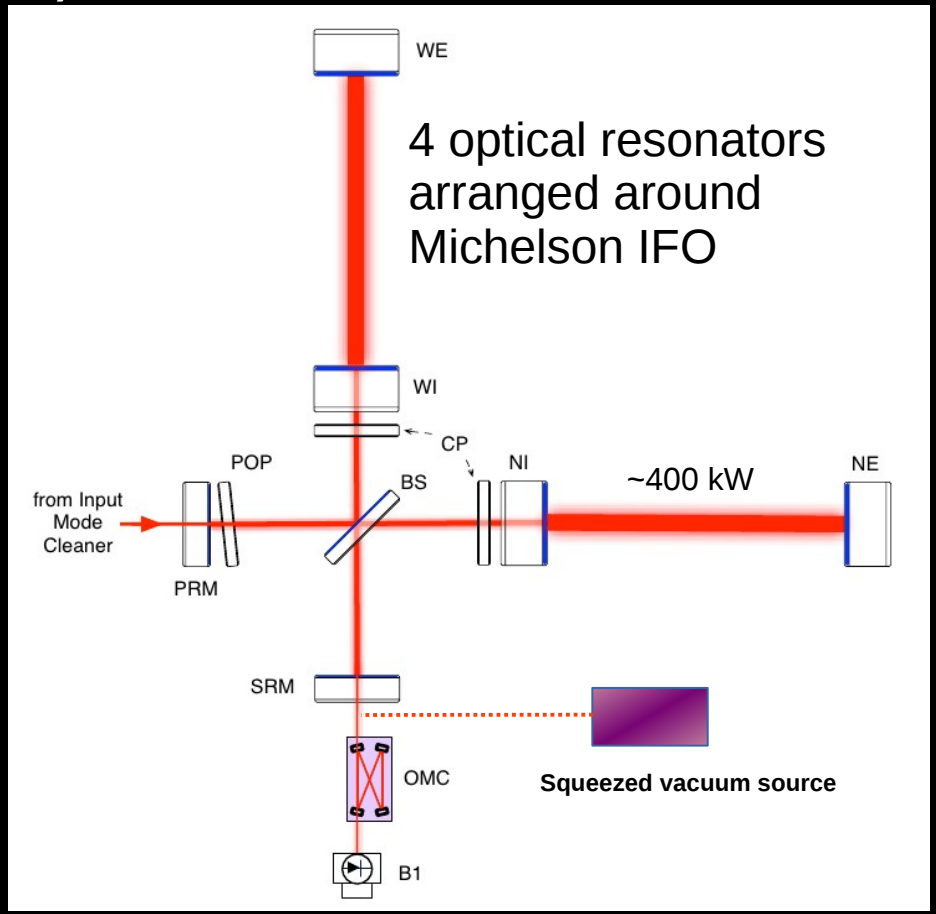

LIGO
Livingston, LA, United States


GEO600,
Germany

Michelson, with additions...

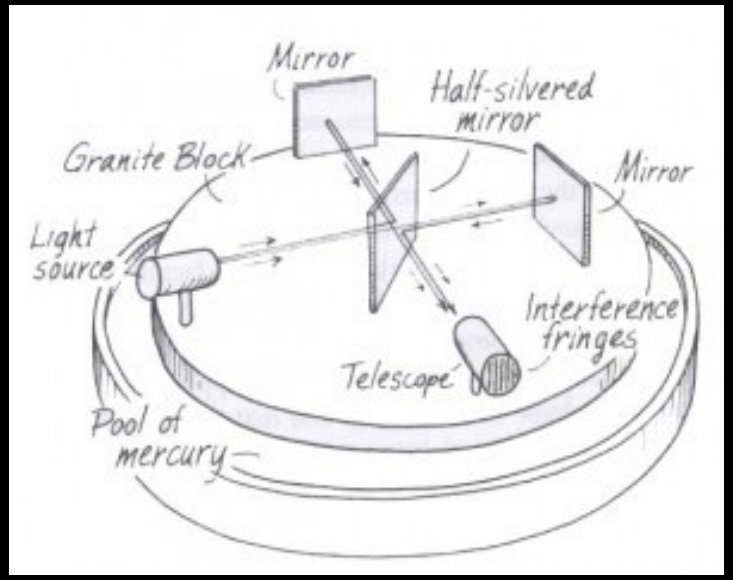


Michelson-Morley experiment:
Accuracy: 10^-8 m (10^-9 relative)
10m arm-length

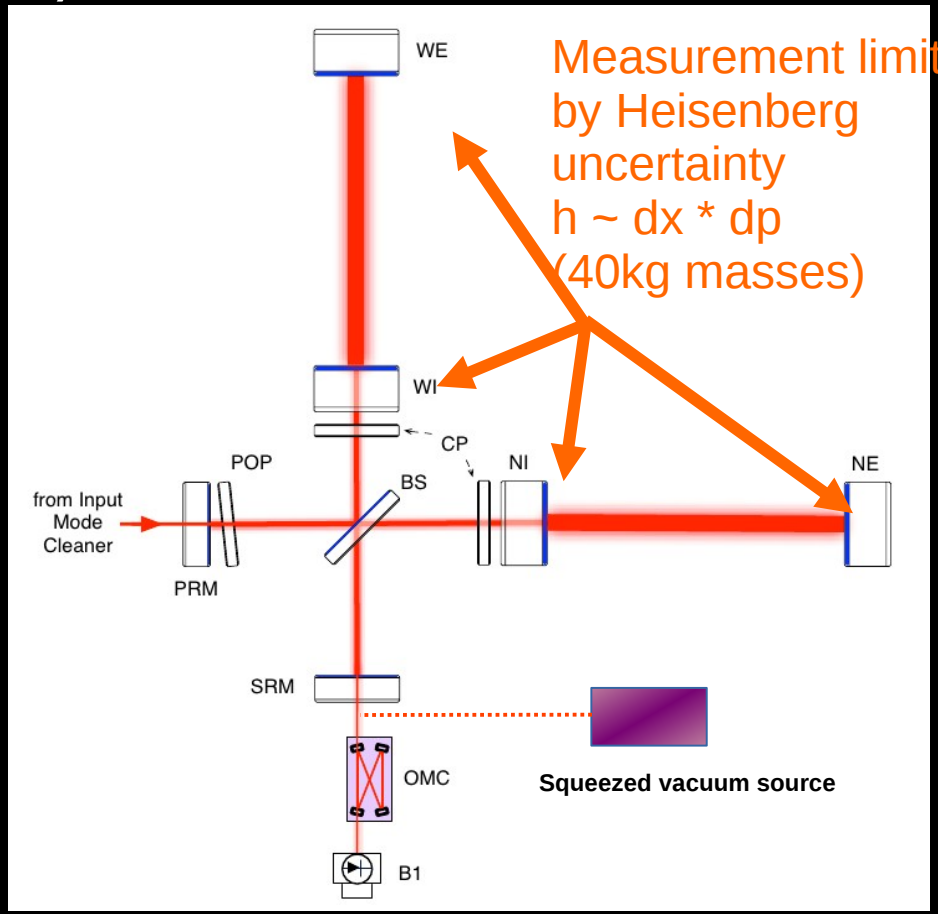


Advanced Interferometer: 3-4 km arm-length
Accuracy: 10^-19 m (3 x 10^-23 relative), 100Hz BW

Michelson, with additions...



Michelson-Morley experiment:
Accuracy: 10^-8 m (10^-9 relative)
10m arm-length



Advanced Interferometer: 3-4 km arm-length
Accuracy: 10^-19 m (3 x 10^-23 relative), 100Hz BW

Dark Matter and gravitational waves

- Mind map from: ArXiv 1907.10610

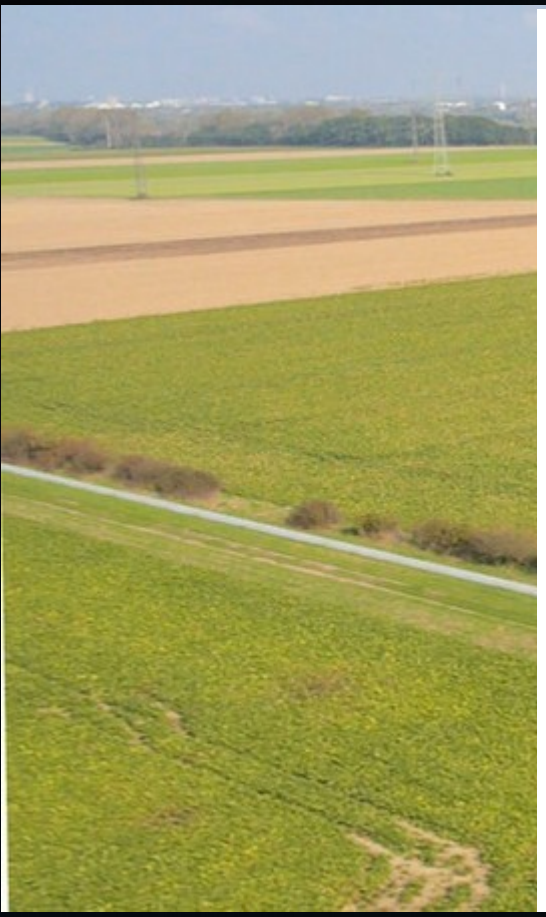
Dark Matter and gravitational waves

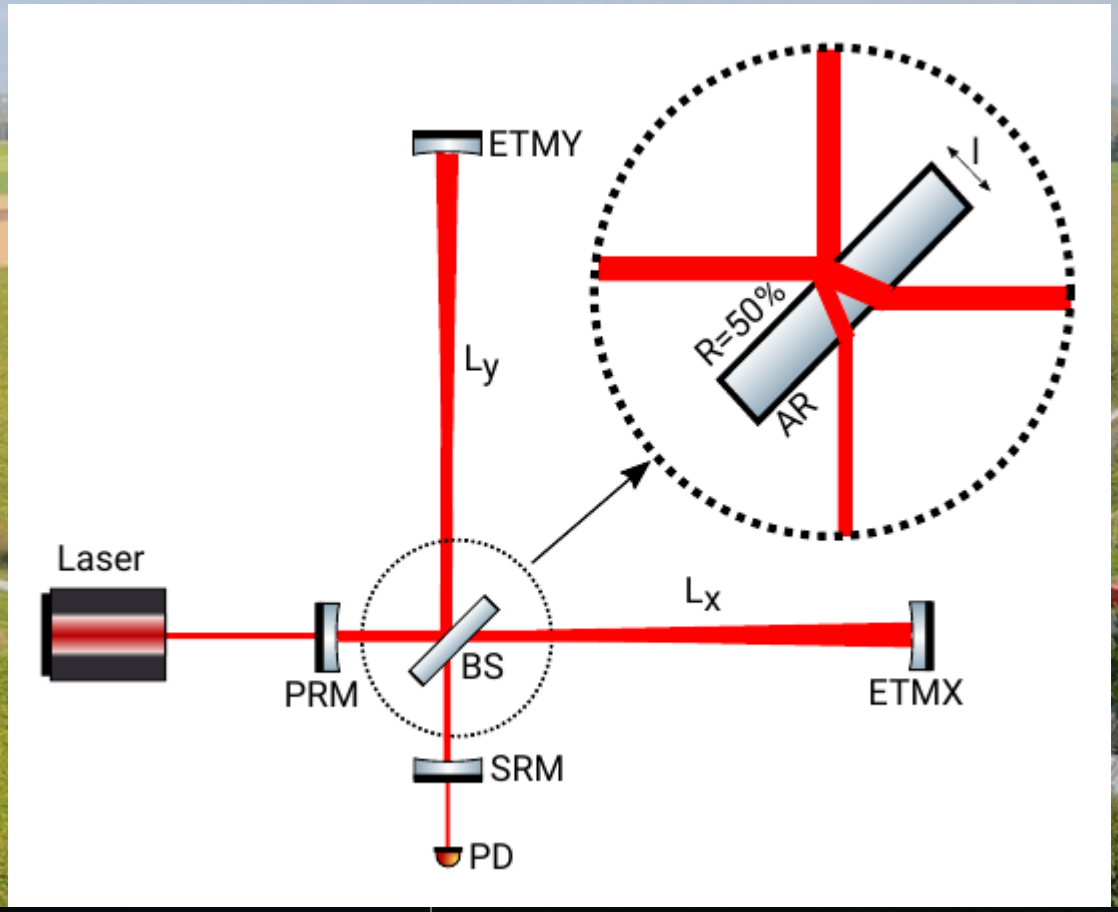
- Mind map from: ArXiv 1907.10610

- Scalar fields
- Dark photons
- Clumpy DM
- Domain walls
- ...

Scalar dark matter search with GEO600

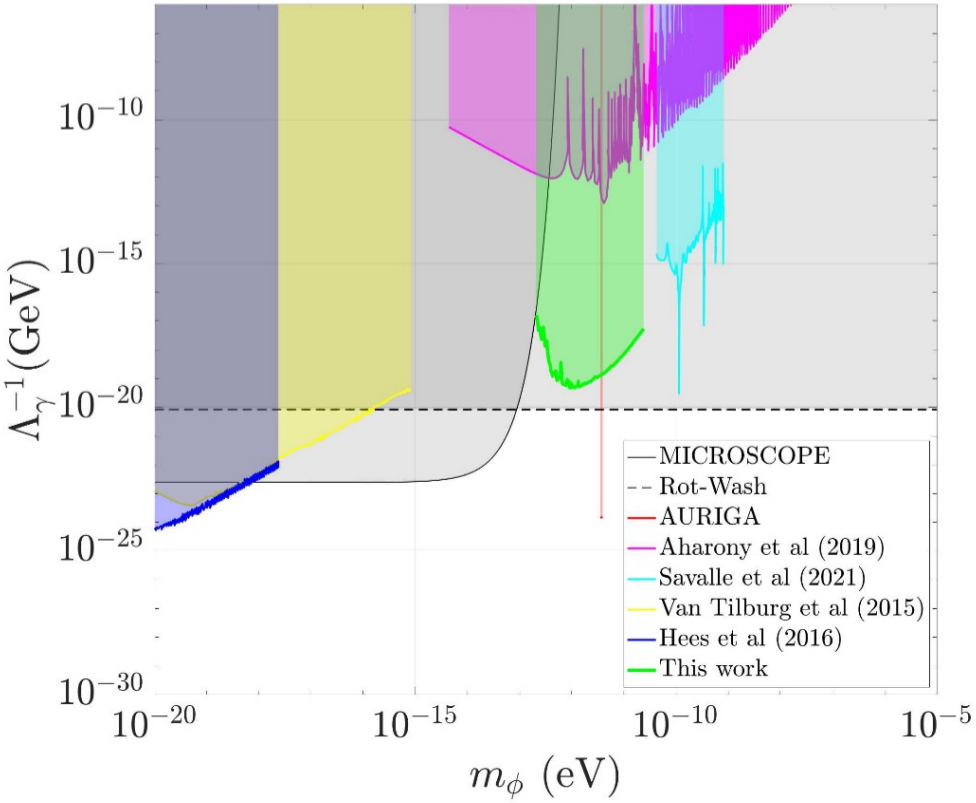
Scalar dark matter search with GEO600

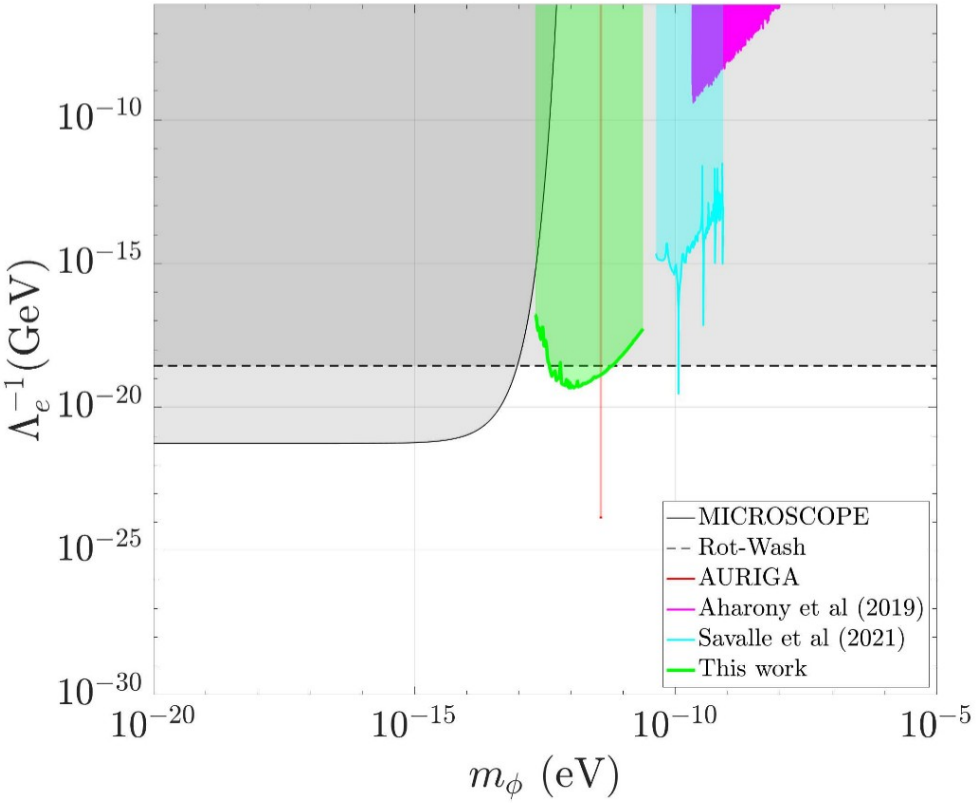




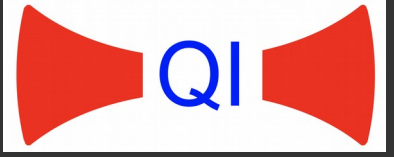
Limit on ‘scalar field’ dark matter from variation of fundamental constants

Scalar dark matter search with GEO600





ArXiv 2103.03783



Theme 2: Quantum aspects of space-time

Experiments

Experiment 1: Axions in the galactic halo

- An ‘interferometry haloscope’
- Axions with masses from 10^{-16} eV up to 10^{-8} eV

Experiment 2: Light-shining-through-the-wall

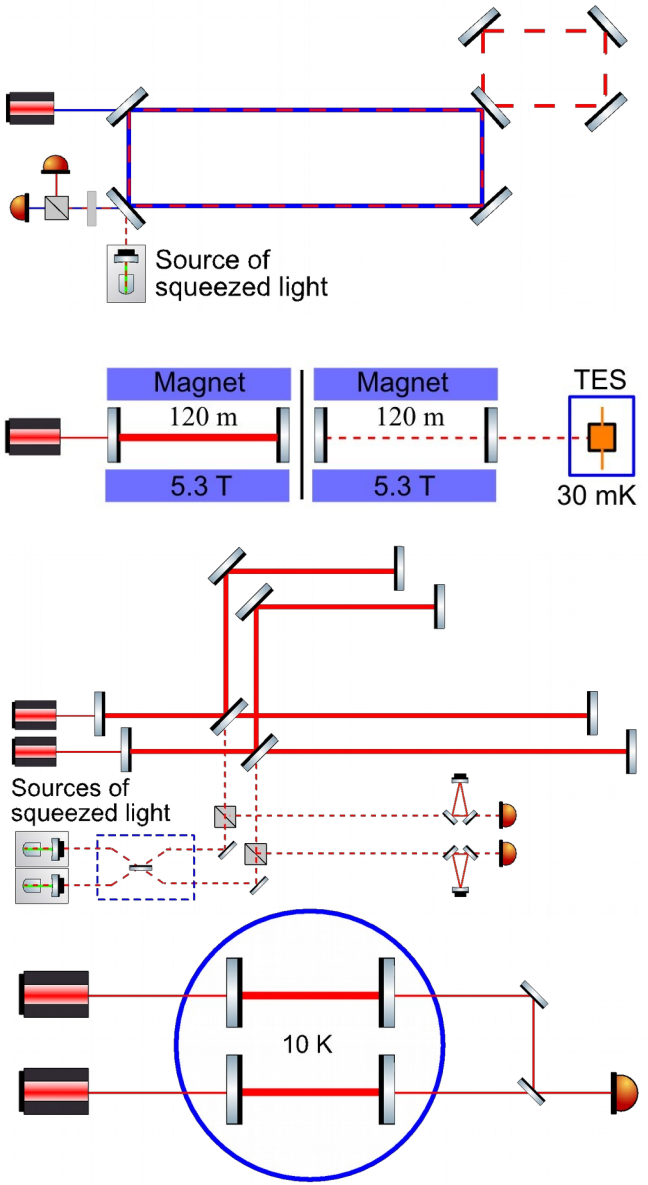
- Making and detecting axion-like particles
- Transition edge sensor with background $<10^{-6}$/s

Experiment 3: Quantisation of space-time

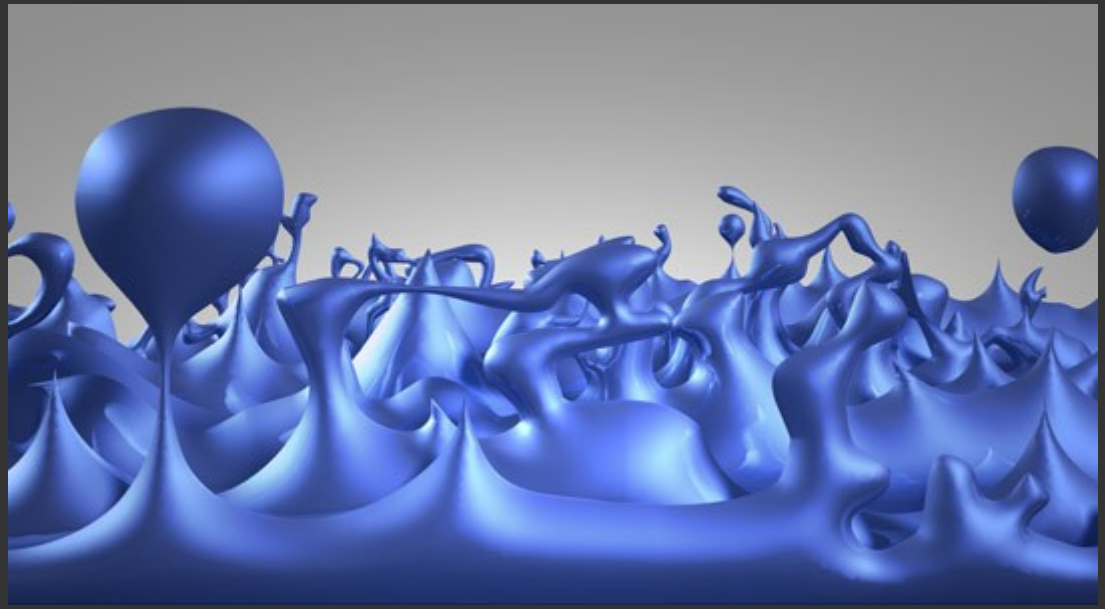
- Testing ideas on quantization of space-time
- Sensitivity of 2×10^{-19} m/rt(Hz) above 1 MHz

Experiment 4: Semiclassical gravity

- Testing semiclassical gravity predictions
- Expect to confirm or rule out



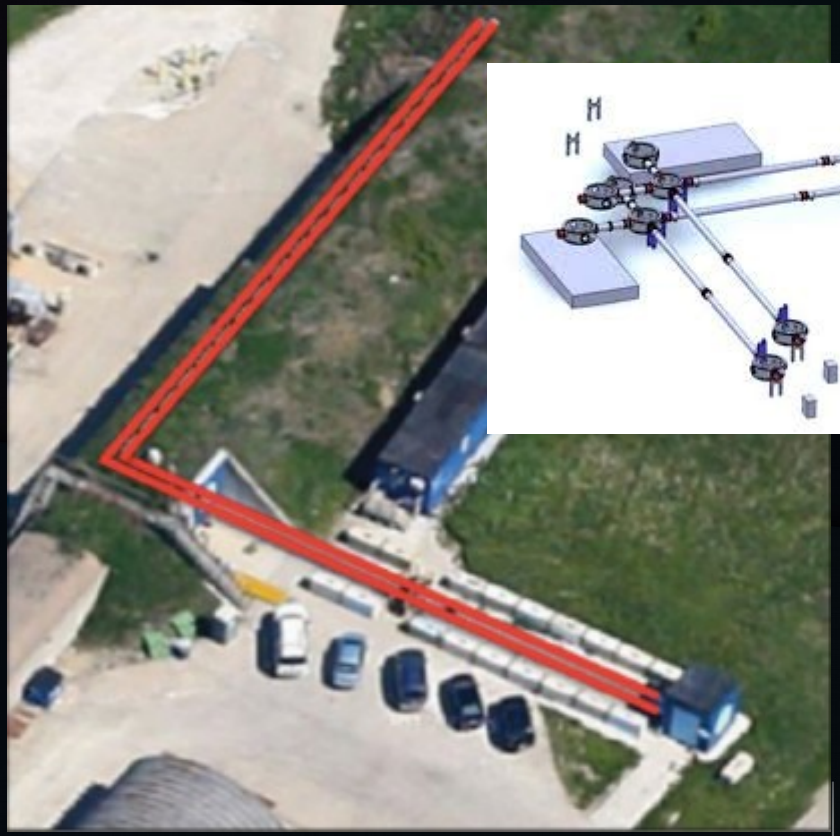
WP3: Quantization of space-time



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

Existing / past Laser-Interferometric experiment: “Holometer”

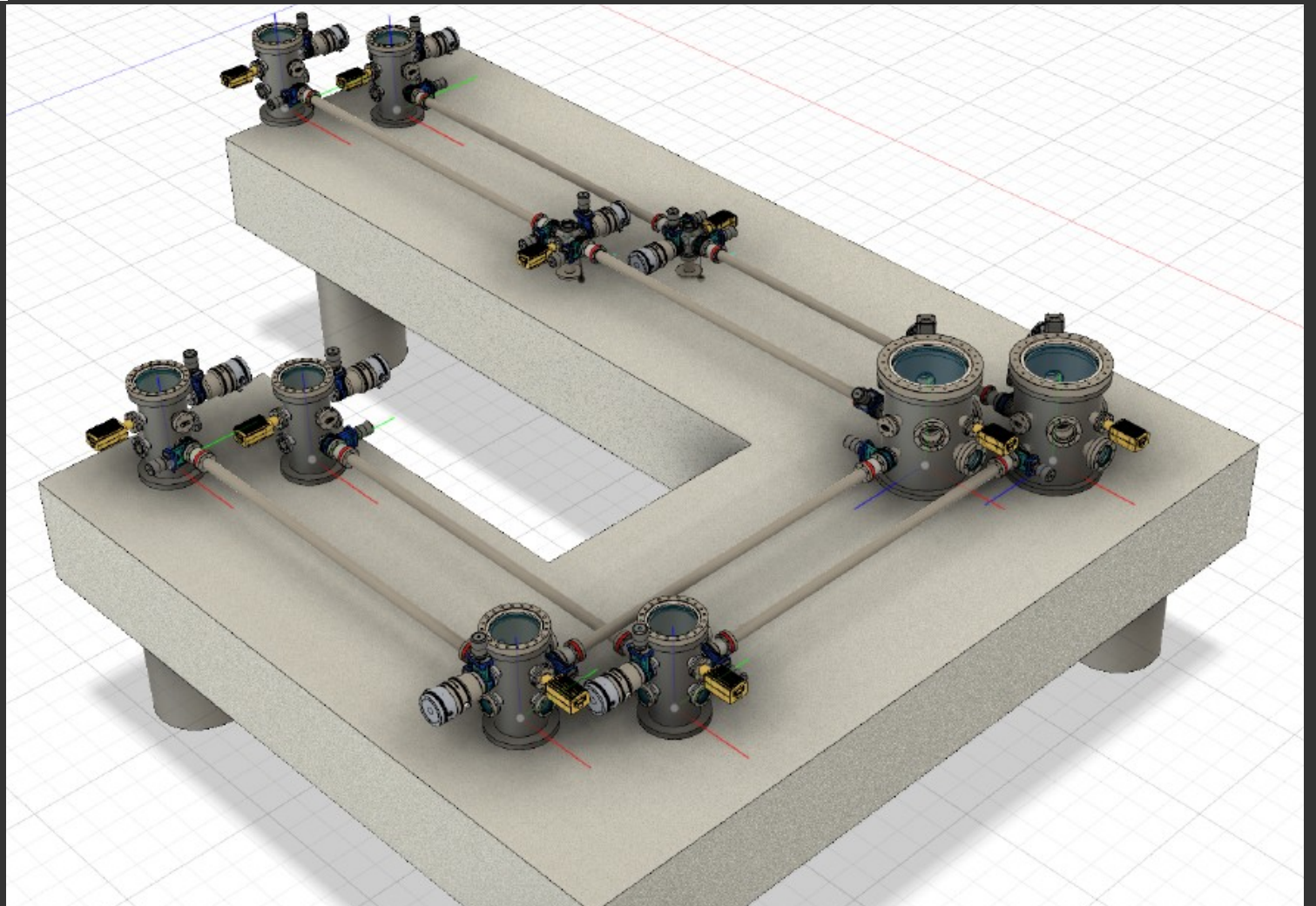


Co-located power recycled Michelson interferometers

PRL 117, 111102 (2016)
CQG 34, 065005 (2017) (Instrument)
ArXiv 2012.06939 (2020)

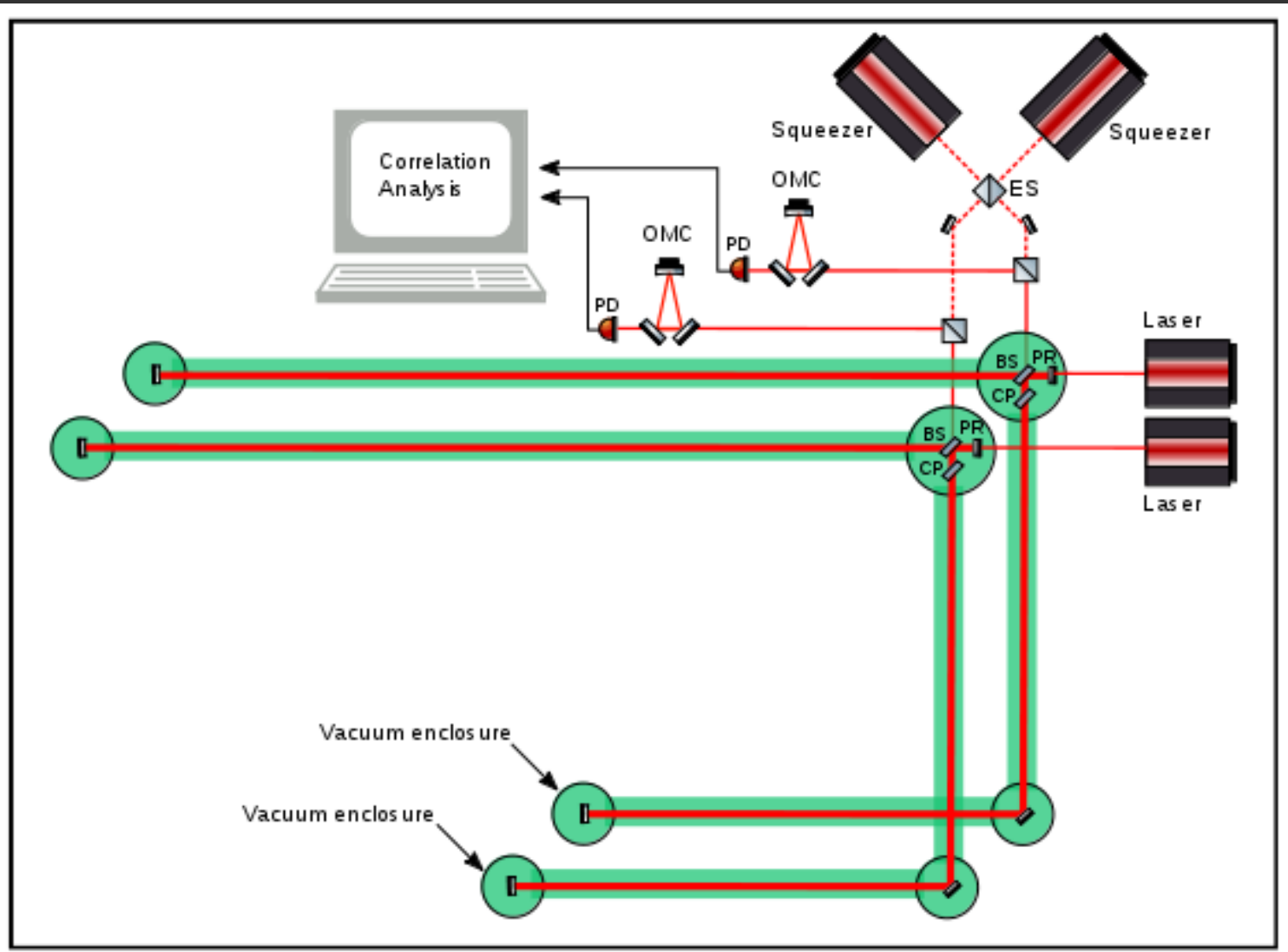
Exp1: co-located table-top interferometers

ArXiv
2008.04957

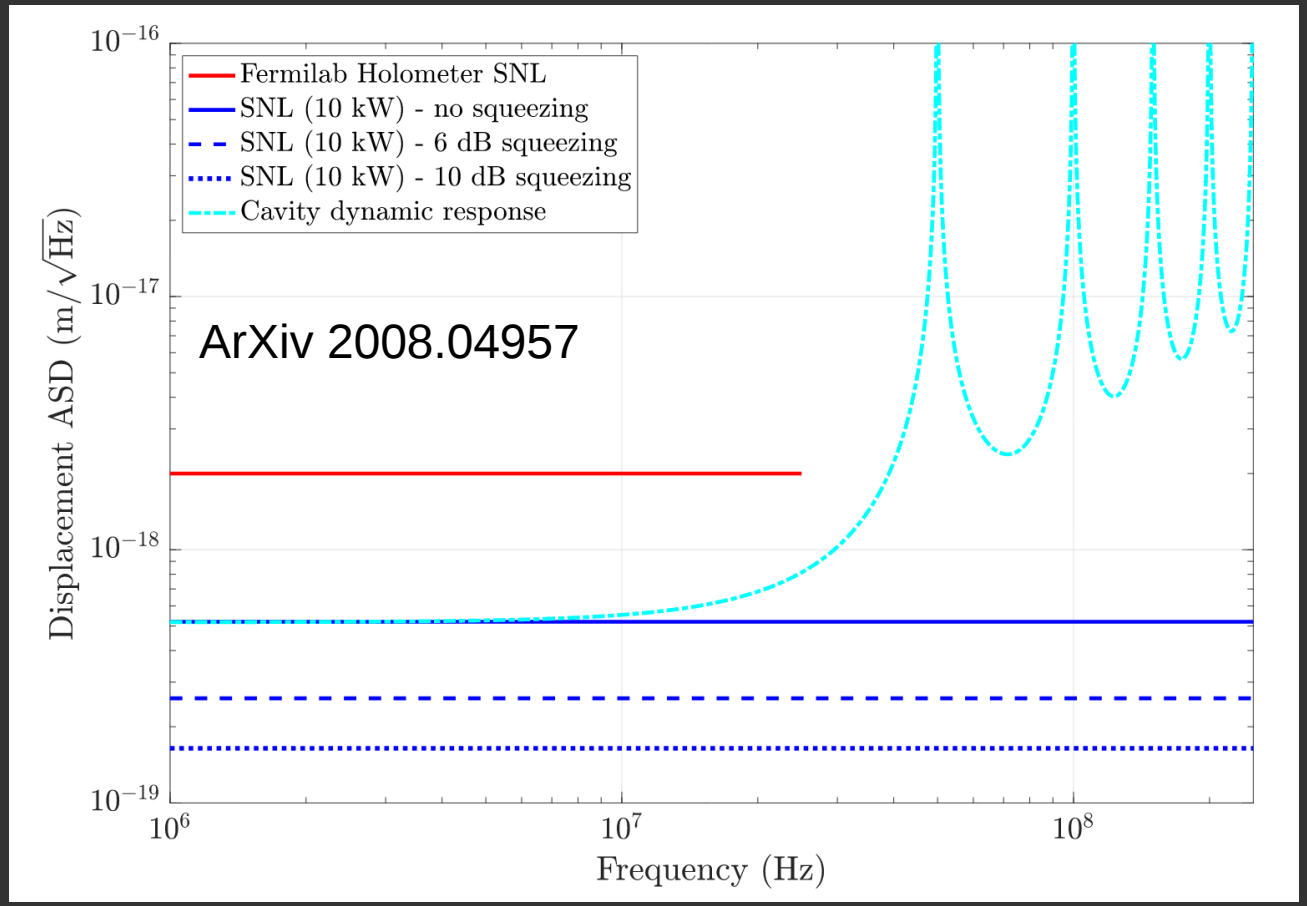


QI

- 10 kW in interferometer
- Output modecleaner
- 500MHz data sampling
- Squeezed light
- Can test new squeezing configurations
- Theory in development



Planned sensitivity for co-located interferometers

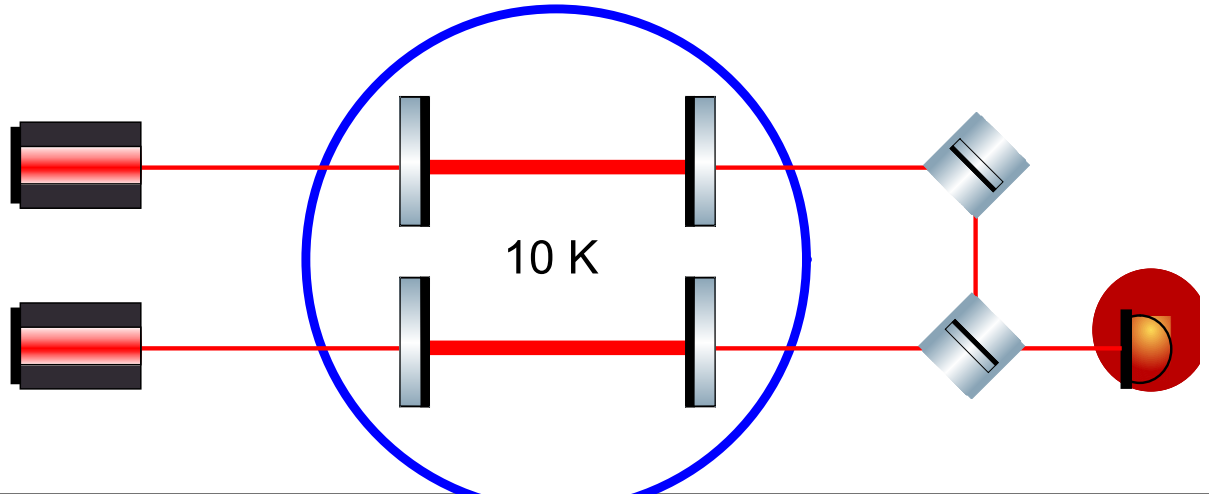


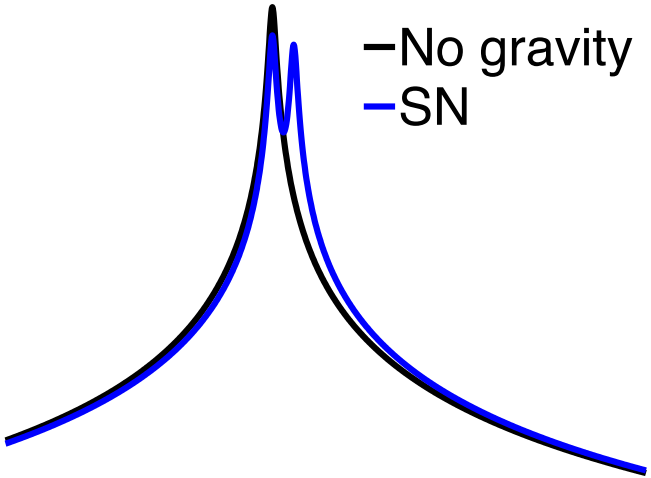
- A side remark:

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

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

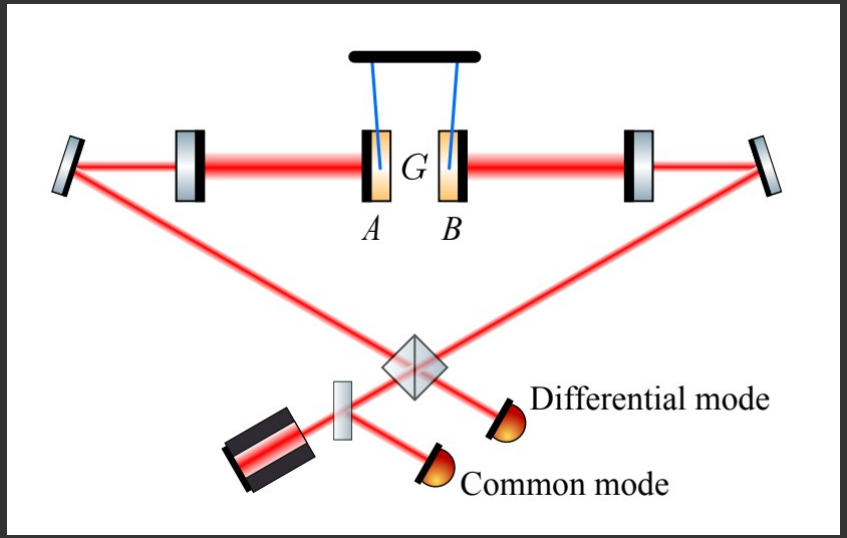
- Two cryogenic silicon cavities to suppress laser noise ϕ_{in}
- Observe a splitting of the resonance due to semiclassical gravity
- The mirror should be made out of a crystal for a test of coherent self gravitation of atoms in a lattice





Signatures of quantum nature of gravity

Measure differential motion of two masses
and observe squeezing as witness of entanglement.
Predicted different outcomes for linearized gravity and SN.



Parameters
-10 mK
-10 Hz
-Q~10^9
-rho~20g/cm^3

ArXiv 2104.04414
A. Datta, H. Miao

Optical coating facility + R&D

National Manufacturing Institute Scotland

EPOC
extreme performance in optical coatings

University of Strathclyde Glasgow

University of the West of Scotland

University of Glasgow

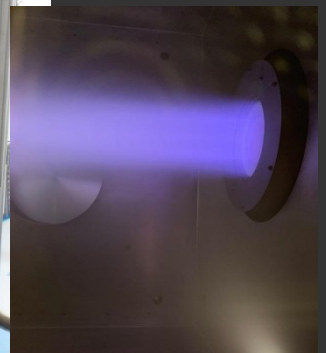
Gooch & Housego

HELIA PHOTONICS

Current state-of-the-art

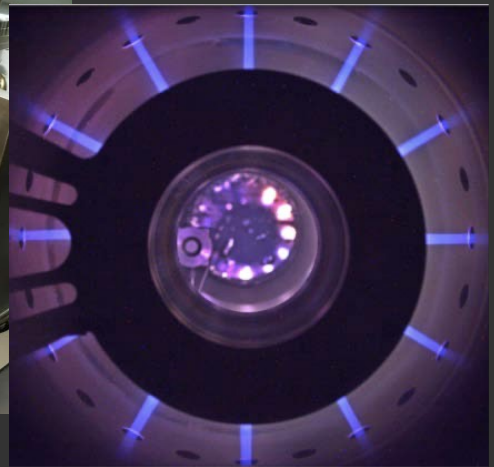
Industry best radio frequency (RF) ion beam deposition – second largest system in the world, hosted in SCAPA national laser/plasma facility in Strathclyde.

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

Summary

- Quantum-enhanced interferometry perfected for GW interferometers
- Dedicated interferometry experiments for fundamental physics

- Fundamental physics with gravitational wave detections
- Direct dark matter searches with GW detectors: scalar fields, dark photons…
- Axion search with interferometry Haloscope
- Axion search with LSW experiment (ALPS)
- Searches for quantization of space-time
- Search for semi-classical gravity
- Likely more is possible…