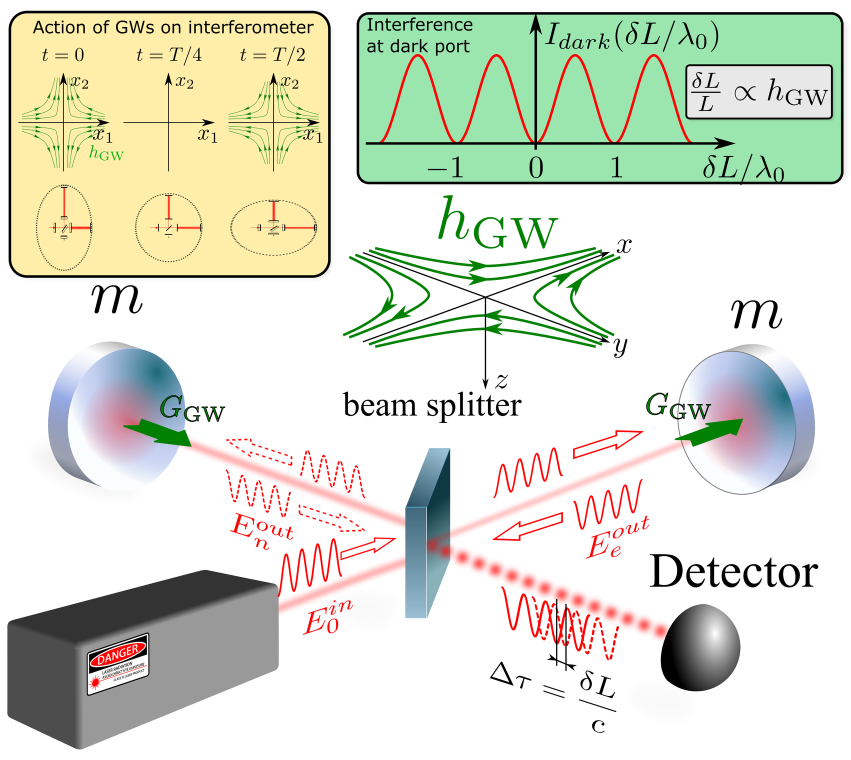
Quantum non-demolition speed measurement with the proof-of-concept Sagnac speed meter interferometer.

S.L. Danilishin, C. Gräf, A. Gläfke, S.S. Leavey, J.-S. Hennig, E.A. Houston, D. Pascucci, S. Steinlechner, J. Wright and S. Hild

MOTIVATION

- Quantum non-demolition (QND) measurement techniques are the future of quantum sensors with measurement precision below the Standard Quantum Limit (SQL) [1, 2].
- The two 4-km long gravitational wave laser interferometers of the Advanced LIGO project are the most sensitive measurement devices ever built, capable of measuring the relative motion of its 40-kilogram mirrors with up to $\sim 10^{-19}$ m precision [3].
- Quantum fluctuations of light phase and amplitude dominate their sensitivity over almost all of detection frequency band (~ 10–10^4 Hz). The Heisenberg uncertainty principle, these fluctuations obey, gives rise to the **Standard Quantum Limit**, *the lower bound of sensitivity for any displacement measurement set by the fundamental laws of Quantum Mechanics*.
- Next generation of GW interferometers **must** have at least **10 times better sensitivity**, to allow for precise parameter estimation of the astrophysical sources. This calls for a new design of the detector, based on QND measurement techniques.
- **The most promising way:** QND measurement of speed with zero area Sagnac interferometer, rather than displacement measurement per formed by conventionally used Michelson interferometers.

DETECTION OF GRAVITATIONAL WAVES

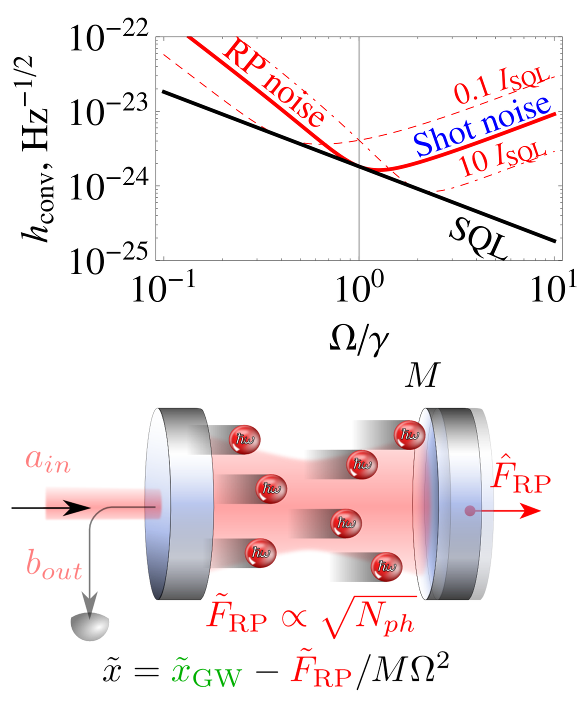


△ Detection of GWs with Michelson interferometer.

- **Gravitational waves (GWs)** are tiny ripples of space-time fabric that pervade our universe;
- **GW astronomy opens up a new window to the universe.** We will start "hear" the universe, not only "see" it!
  - **Astrophysics**: (i) compact binaries (NS, BH), (ii) catch SNe in the act (iii) reveal GRB progenitors, *etc.*
  - **Fundamental physics**: (i) testing GR at its extreme, in BHs; (ii) nuclear physics: probe NS cores;
  - **Cosmology**: seeds of supermassive BHs in galactic cores.
- **Light is a yardstick** to sense these ripples $\Rightarrow$ large-scale laser interferometers. (aLIGO)

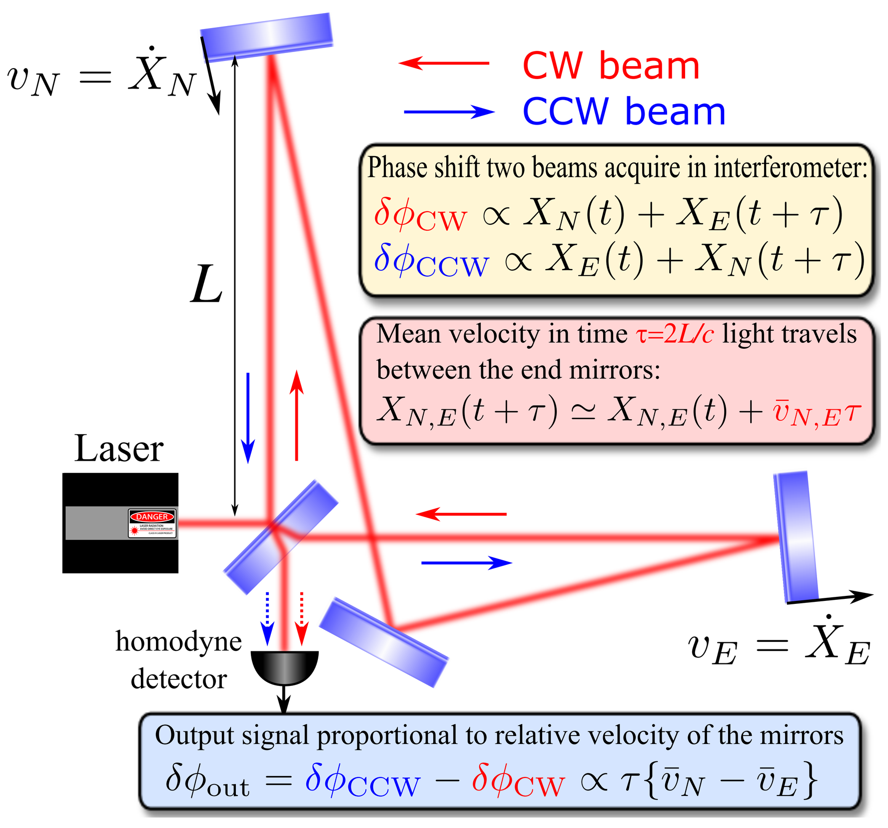
QUANTUM NOISE IN OPTOMECHANICAL INTERFEROMETERS

- **Quantum noise** in optomechanical sensors comprises of phase and intensity fluctuations [2];
- **Shot noise (SN)** component refers to fluctuations of laser light phase;
- **Radiation pressure noise (RPN)** component comes from intensity fluctuations that produce random radiation pressure gorse pushing the suspended mirrors around any mimicking weak GW force;
- **Standard Quantum Limit** originates from the trade-off between the RPN and SN components, where the former is proportional to the light power, circulating in the interferometer, and the latter one is inversely proportional to it.



△ Typical quantum noise spectrum (upper) of a simple Fabry-Pérot interferometer with moving mirrors (lower).

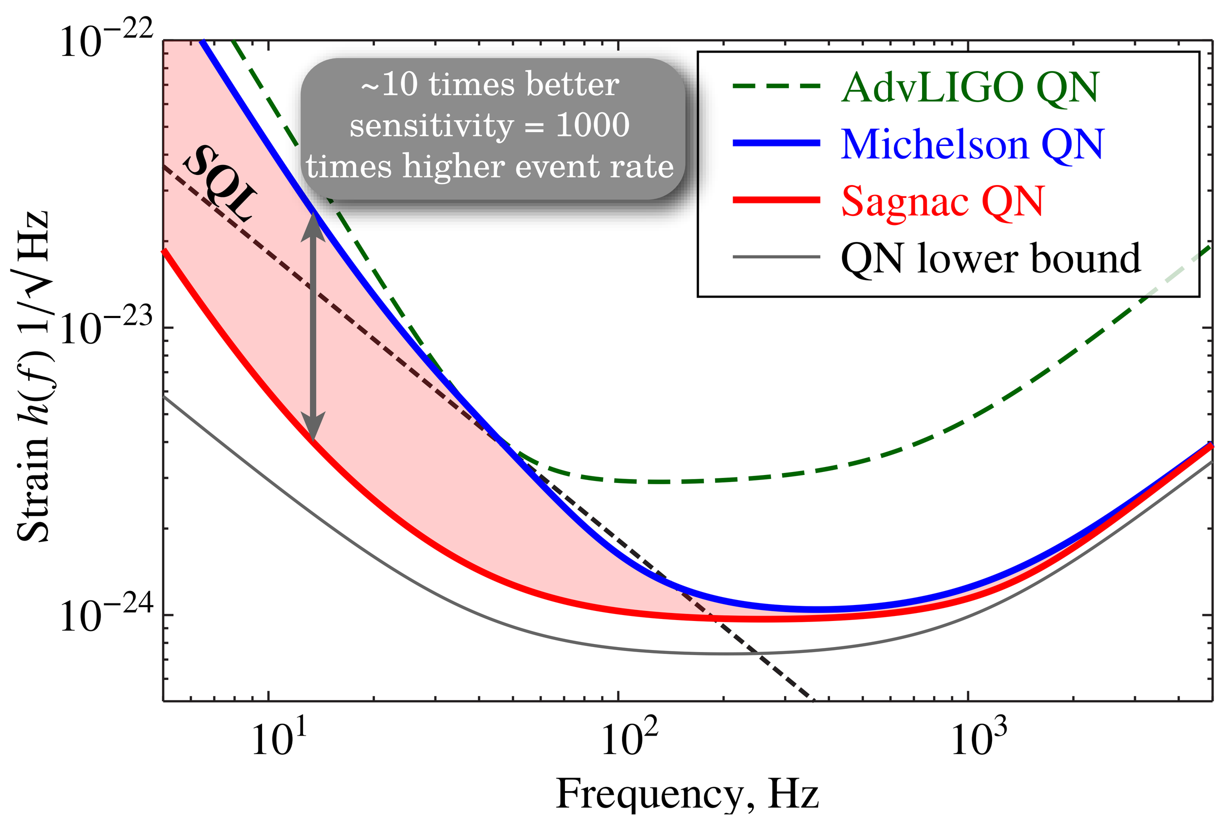
SPEED MEASUREMENT WITH ZERO-AREA SAGNAC INTERFEROMETER



△ Principle of speed measurement with zero-area Sagnac interferometer

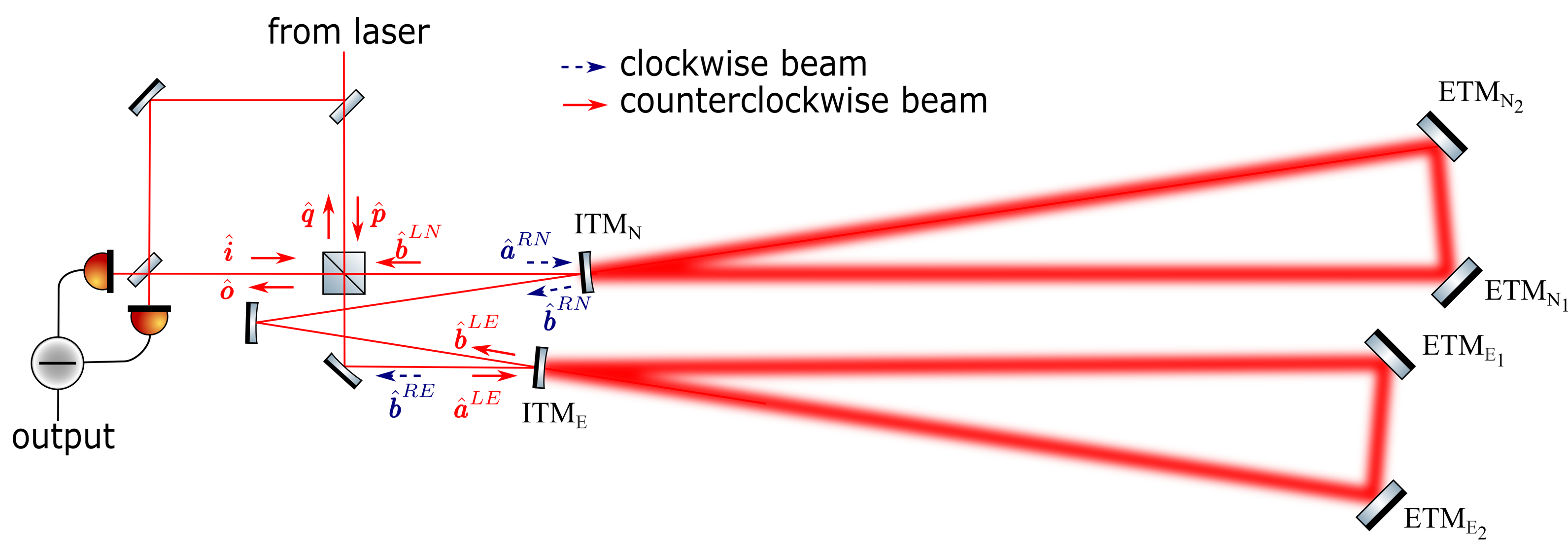
- **Michelson interferometers** we used so far to measure GW strain **are sensitive to displacement** of the mirrors.
- Displacement operator **does not commute with itself** at different times, $[\hat{x}(t),\,\hat{x}(t')] \neq 0$, **therefore it cannot be measured with arbitrary precision** $\Rightarrow$ SQL ;
- But zero-area **Sagnac interferometer senses velocity**, $\hat{v}(t)$, which is proportional to the momentum of the mirrors, $\hat{p}(t) = m\hat{v}(t)$, which is a **QND observable** $\Rightarrow$ no back action (ideally);

Sagnac interferometer has significantly lower RPN, if compared to the equivalent Michelson interferometer, thereby giving access to all the fascinating GW sources that emit mostly in this frequency band [6].



△ Optimised QN of Sagnac and Michelson interferometers vs. AdvLIGO baseline QN.

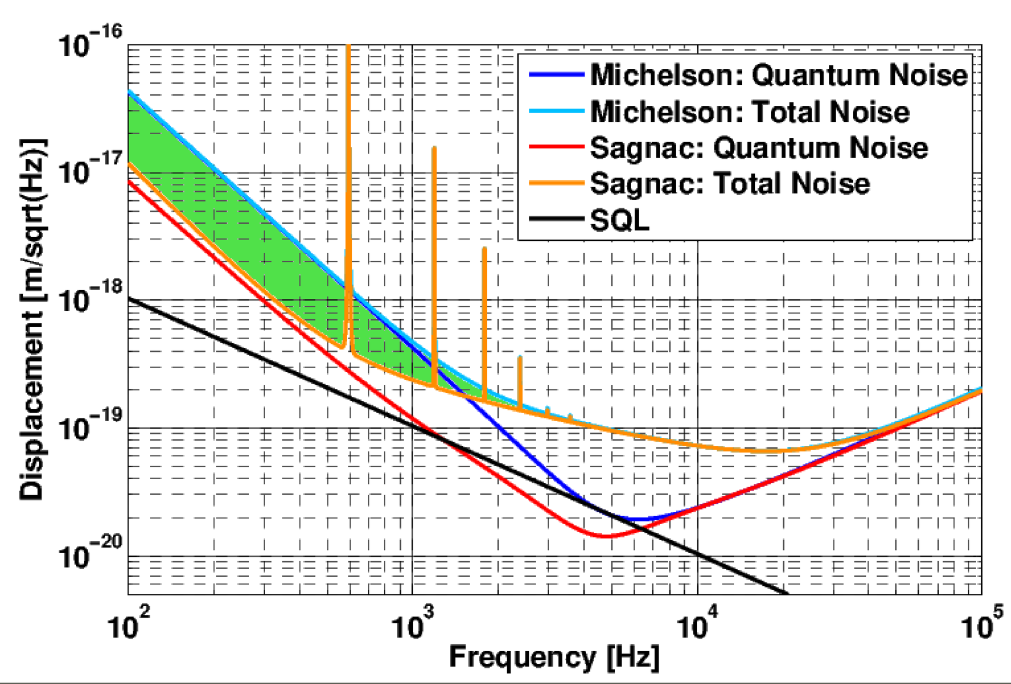
GLASGOW PROOF-OF-CONCEPT SAGNAC SPEED METER INTERFEROMETER



△ Simplified optical layout of the proof-of-concept Sagnac speed meter interferometer which construction is underway in the University of Glasgow.

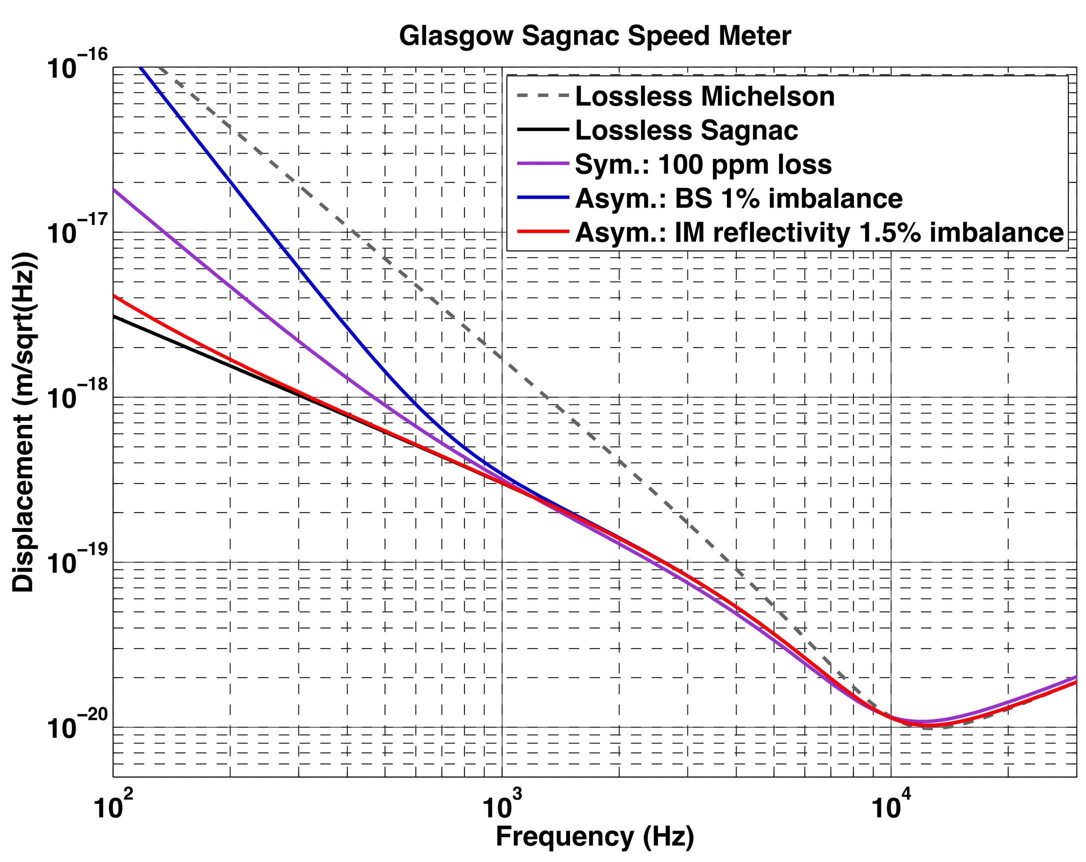
The construction of prototype Sagnac speed meter interferometer, funded by the ERC Starter Grant, is currently underway in the Institute for Gravitational Research of the University of Glasgow [4]. This interferometer will have quantum radiation pressure noise much lower than the equivalent Michelson interferometer, thereby, for the first time, demonstrating QND measurement of speed.

Planned QN sensitivity of the Glasgow proof-of-concept Sagnac speed meter interferometer and QN of the equivalent Michelson interferometer ▷

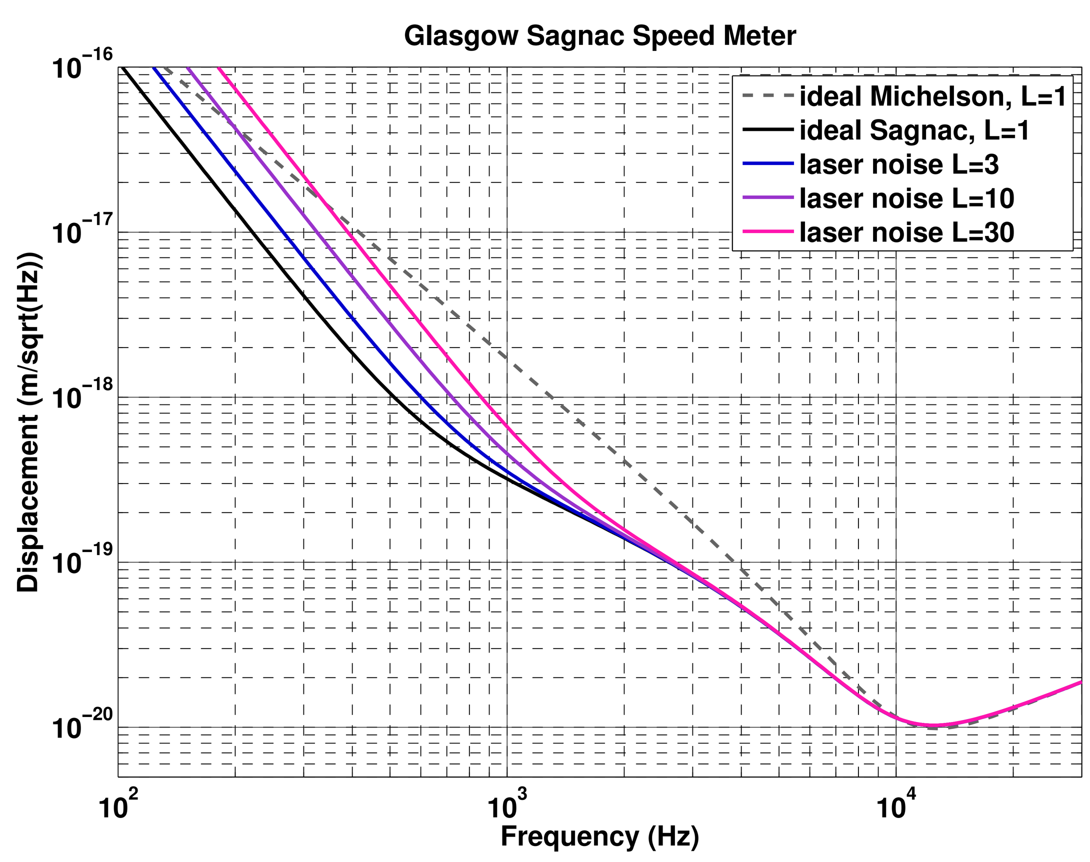


QUANTUM NOISE OF REALISTIC SAGNAC INTERFEROMETER

A real experimental setup is always non-symmetric and imperfect in many different ways. In order to rank those imperfections and asymmetries we built a numerical model of imperfect Sagnac interferometer. The results published in [5] are summarised below.



△ Impact of optical loss, beam splitter (BS) imbalance and asymmetry of the arms.



△ Impact of excess laser noise in the presence of 1% imbalance of the BS.

Summary

- The Sagnac speed meter interferometer suppresses quantum radiation pressure noise and allows to beat the SQL in broad frequency band;
- Among imperfections of the real experiment, optical loss in the arms, imbalance of the beam splitter and laser noise leakage into the readout port are most damaging;
- However, imperfections do not prevent Sagnac interferometer to beat the equivalent Michelson interferometer at low frequencies in terms of quantum noise.

References

[1] V.B. Braginsky and F.Y. Khalili, *Quantum Measurement*, Cambridge Univ. Press (1996).

[2] S.L. Danilishin and F.Y. Khalili, Living Rev. Relativity **15**, 5 (2012), `http://www.livingreviews.org/lrr-2012-5`.

[3] Advanced LIGO web-page: `https://www.advancedligo.mit.edu/`.

[4] C. Gräf *et al.*, Class. Quant. Grav **31**, 15009 (2014), `http://arxiv.org/abs/1405.2783`.

[5] S.L. Danilishin, New J. Phys. *accepted* (2015), `http://arxiv.org/abs/1412.0931`.

[6] N.V. Voronchev, S.P. Tarabrin and S.L. Danilishin, Phys. Rev. D *submitted* (2015), `http://arxiv.org/abs/1503.01062`.

Institute for Gravitational Research, School of Physics and Astronomy, University of Glasgow