Proof-of–Principle Experiment for a Sagnac Speedmeter

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LVC meeting

Washington DC, March 2013

LIGO-G1300296

Overview

- Introduction / reminder of speedmeter concept
- Plans for a Proof-of-Principle Speedmeter Experiment
- Some examples of challenges that we will to investigate
- Outlook & Summary

Why Speedmeters?

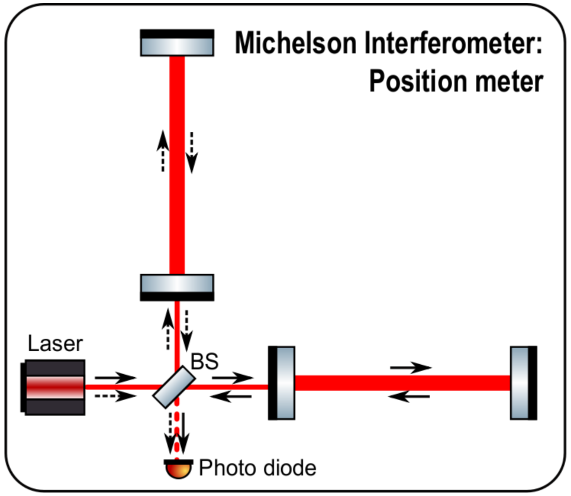
- So far we used Michelson interferometers to derive strain, by continuously measuring the displacement of the mirrors.
- However, quantum mechanics limits the accuracy of the measurement:

$$[\hat{x}(t), \hat{x}(t')] \neq 0$$

$$[\hat{x}(t), \hat{p}(t)] \neq 0$$

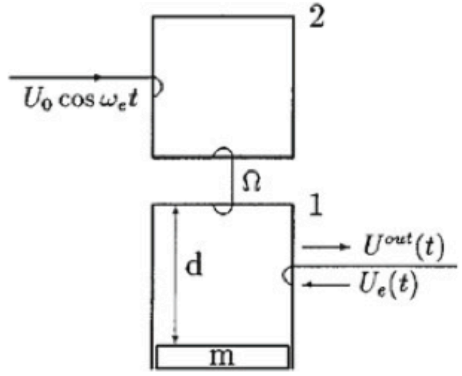
- However, already in 1930s John von Neumann told us that there are observables which can measured continuously without encountering the Heisenberg uncertainty. For example the momentum or speed of a testmass in our case.

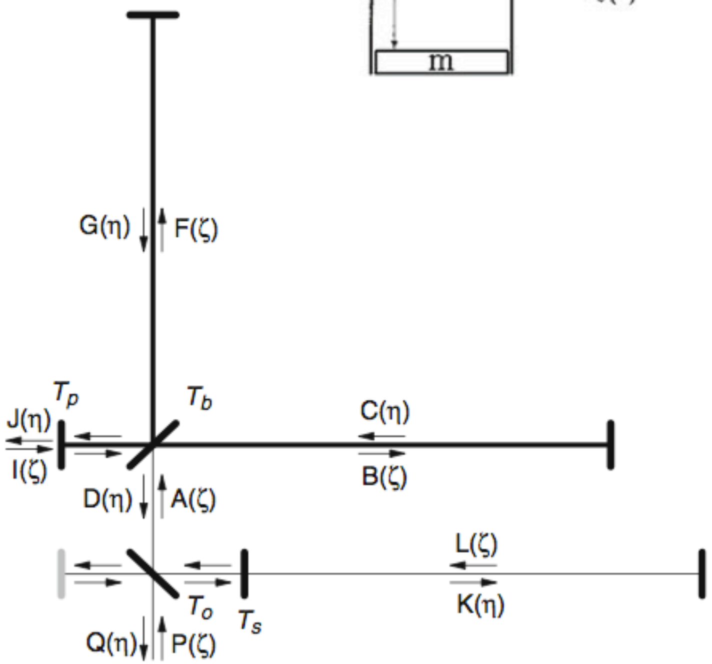
$$[\hat{p}(t), \hat{p}(t')] = 0$$



Speedmeter is not a new idea!

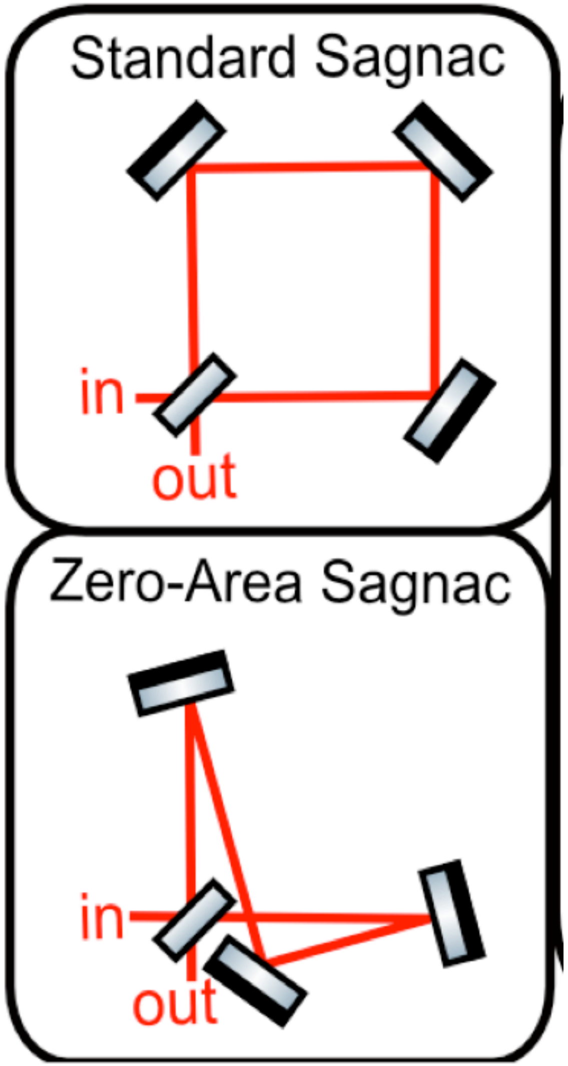
- Speedmeter originally suggested by Braginsky and Khalili in 1990.
- First suggestion to implement in a Michelson Interferometer (shloshing cavity) was in 2000 by Braginsky, Gorodetsky, Khalili and Thorne.
- Part of the signal is send back into the interferometer to cancel out displacement infromation.
- Purdue and Chen further developed shloshing cavity approach (2002).
- In 2003 Chen showed that a Sagnac interferometer is a speedmeter.



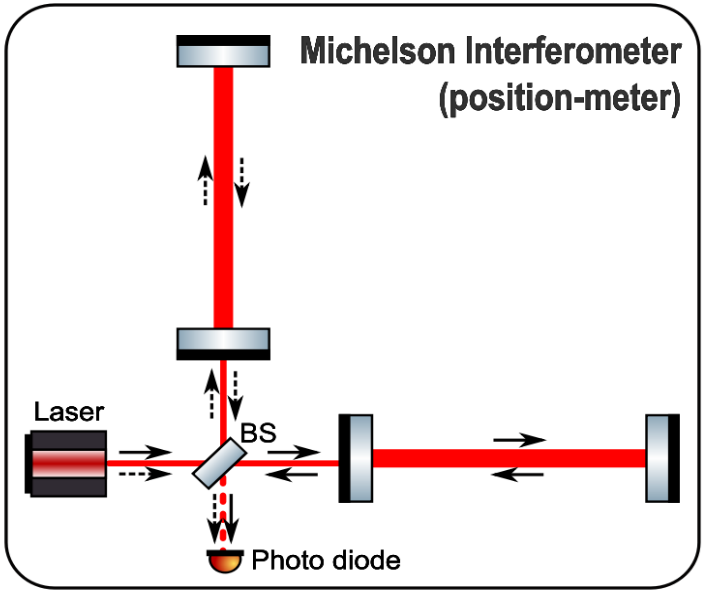


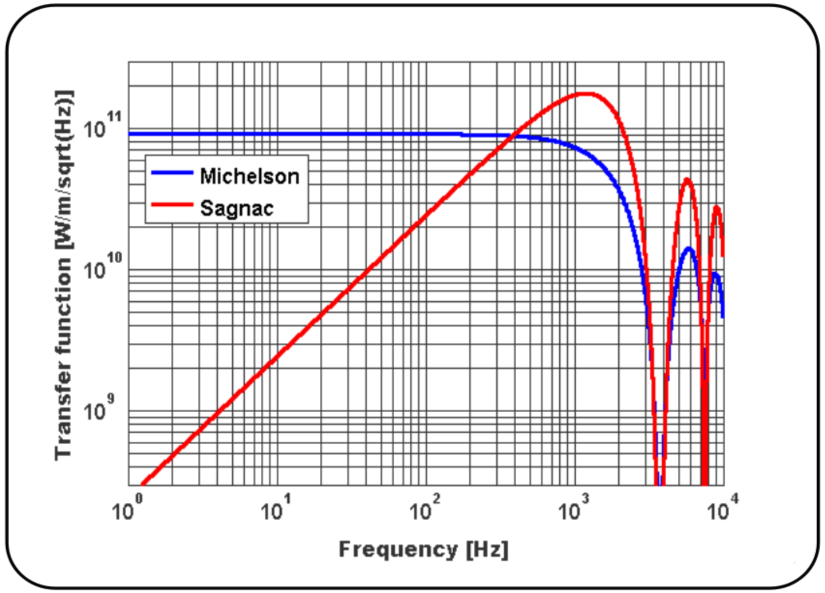
Sagnac Interferometer

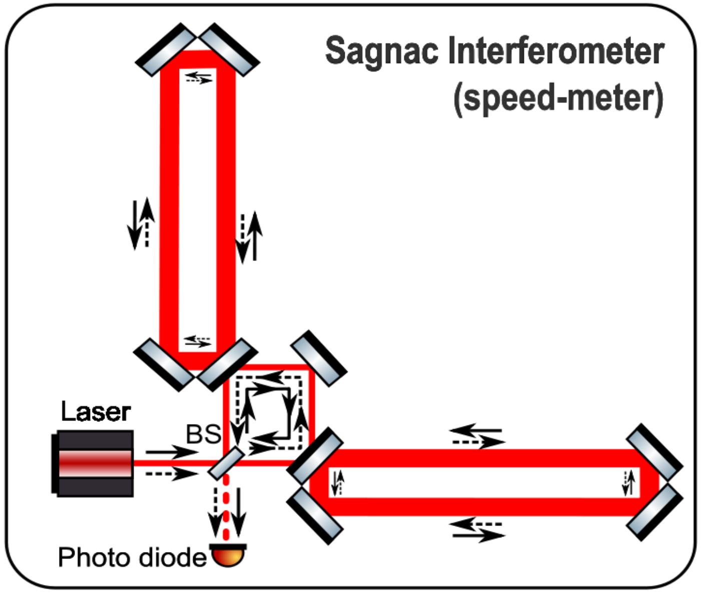
- Sagnac interferometer traditionally used for measuring rotation. See laser gyros etc.
- However we can build a zero-area Saganc interferometer. Rotation signals cancels out.
- Actually a zero-area Sagnac can be used to measure GW! (Lots of research at Stanford and ANU until about 10 years ago)
- Also Zero-Area Sagnac fits into the usual L-shaped vacuum envelop of GW detectors.

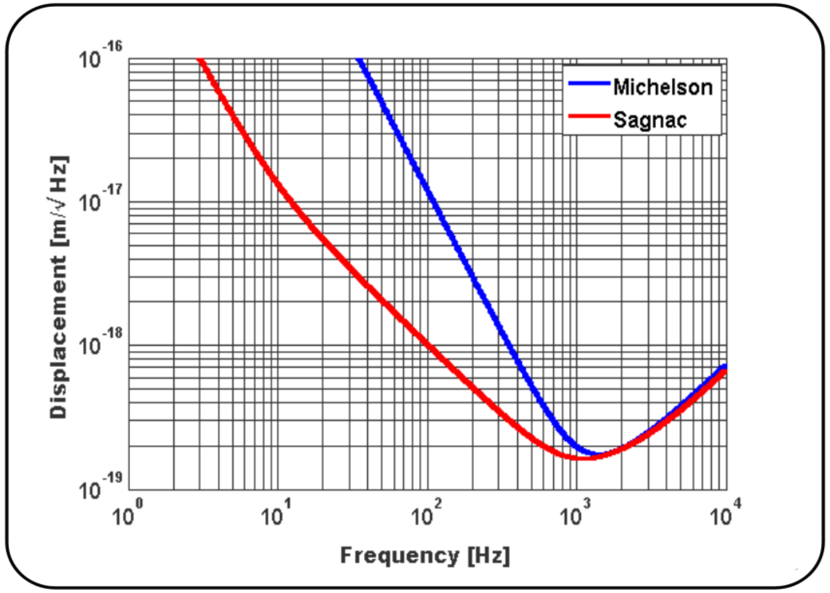


Michelson vs Sagnac



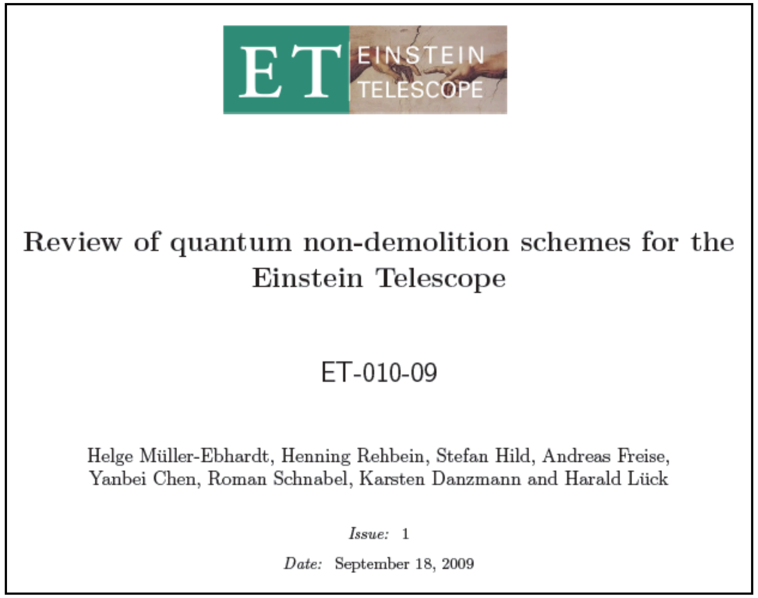






What is stopping us from using Sagnac speedmeters for future GWDs?

- So, we know that the speedmeter theoretically outperforms a Michelson interferometer.
- However, as we are lacking the experi-mental verification, for instance the ET standard design (ET-D) uses Michelson interferometers for both the LF and HF interferometers.
- **Since autumn 2012 the experimental verficiation is on the way as we started to build a proof-of-principle experiment of a Sagnac speedmeter in Glasgow.**


ET EINSTEIN TELESCOPE

Review of quantum non-demolition schemes for the Einstein Telescope

ET-010-09

Helge Müller-Ebhardt, Henning Rehbein, Stefan Hild, Andreas Freise, Yanbei Chen, Roman Schnabel, Karsten Danzmann and Harald Lück

Issue: 1

Date: September 18, 2009

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UNIVERSITY of GLASGOW

ERC Starting Grants

- Obtained 1,400,000€ from the ERC for the period of 2012-2017 to proof the speedmeter concept.
- Sufficent funding for required equipment + 4.5 FTE.

European Research Council

ERC Grant Schemes

Guide for Applicants for the Starting Grant 2012 Call

Version 14/07/2011

1.1.4 What kind of research can be funded?

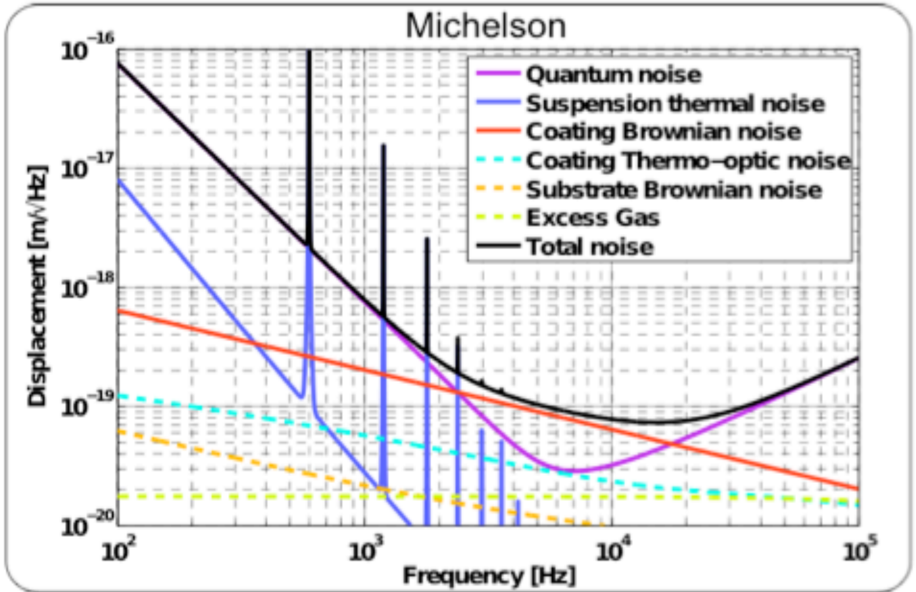
ERC grants aim to support 'Frontier Research', in other words the pursuit of questions at or beyond the frontiers of knowledge, without regard for established disciplinary boundaries. Applications may be made in **any field of research** covered by the Treaty on the Functioning of the European Union including physical sciences and engineering, life sciences, and social sciences and humanities. Please note that research proposals within the scope of Annex I to the Euratom Treaty, namely those directed towards nuclear energy applications should be submitted to relevant calls under the Euratom 7th Framework Programme[10].

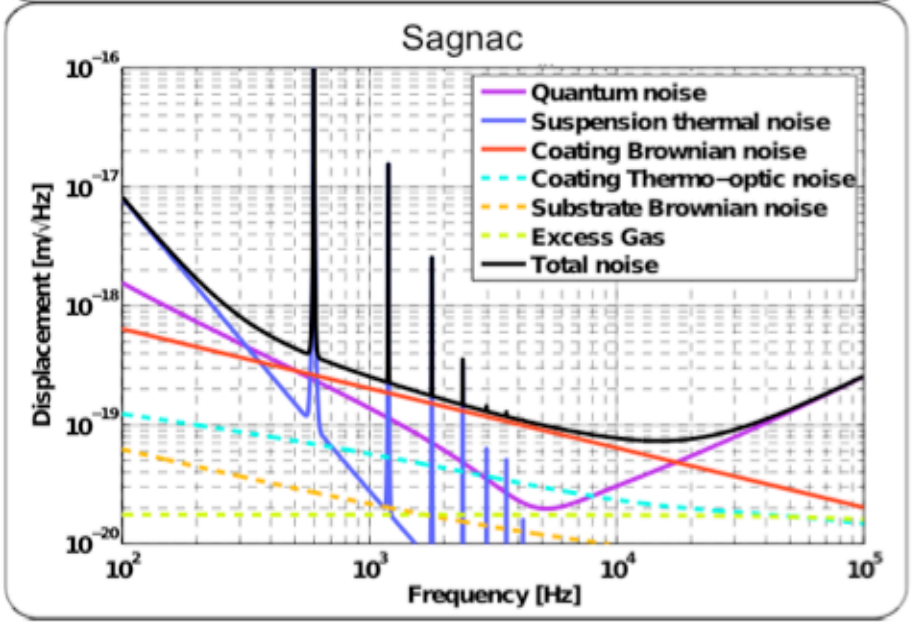
In particular, proposals of an interdisciplinary nature which cross the boundaries between different fields of research, pioneering proposals addressing new and emerging fields of research or proposals introducing unconventional, innovative approaches and scientific inventions are encouraged, as long as the expected impact on science, scholarship or engineering is significant.

The peer review evaluation of proposals will therefore give emphasis to these aspects, in full understanding that such research has a high-gain/high-risk profile, i.e. if successful the payoffs will be very significant, but there is a higher-than-normal risk that the research project does not entirely fulfil its aims.

Some frontier research activities and methodologies may have ethical implications or may raise questions which will require sound ethical assessment in order to ensure that research supported by an ERC grant respects the fundamental ethical principles (see Box 4 and Annex 2).

Aim of the Project

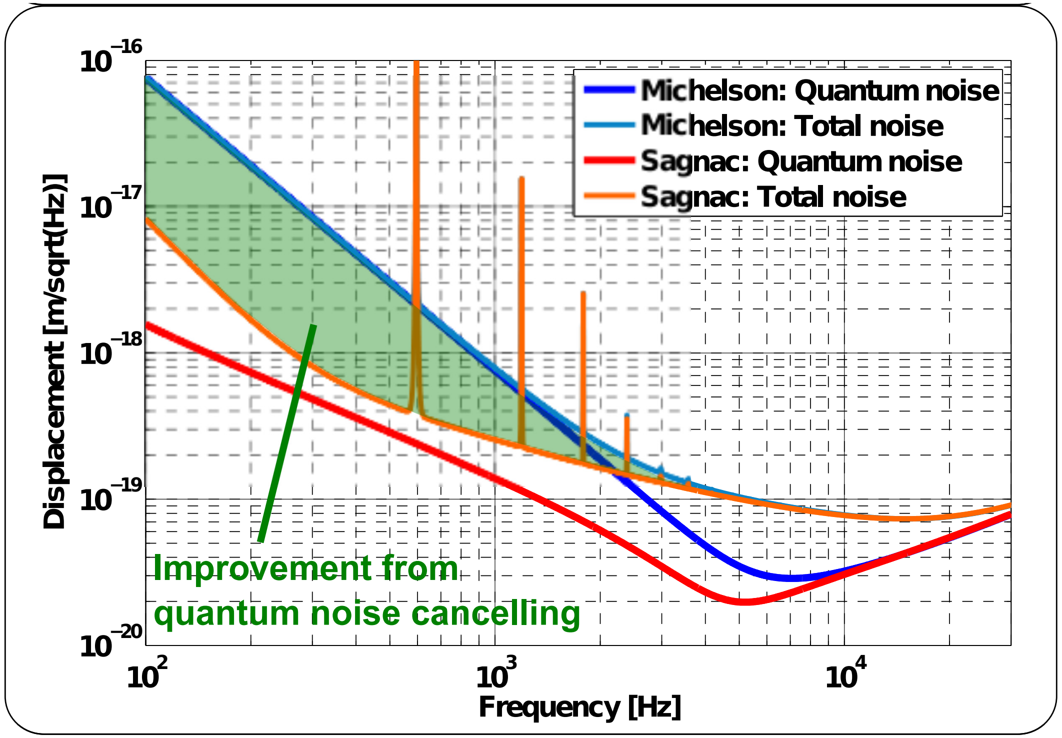


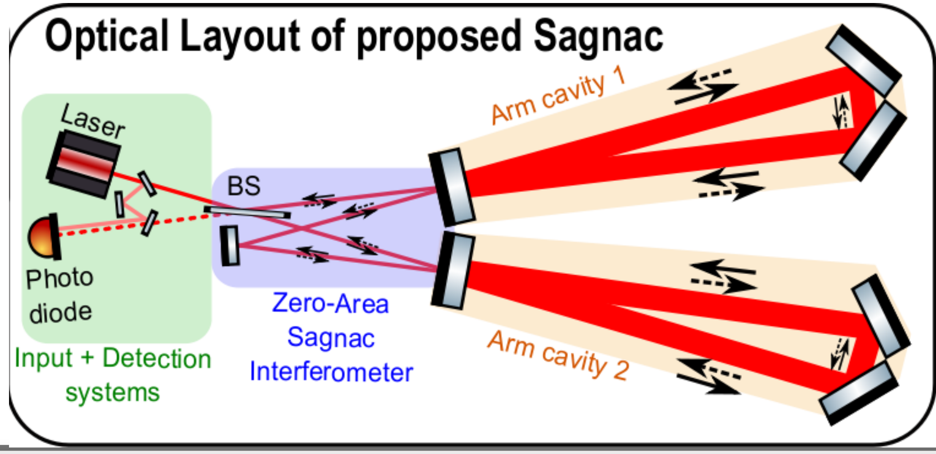


- 1g mirrors suspended in monolithic fused silica suspensions.
- 1kW of circulating power. Arm cavities with finesse of 10000. 100ppm loss per roundtrip.
- Sophisticated seismic isolation + double pendulums with one vertical stage.
- Large beams to reduce coating noise.
- Armlength = 1m. Target better than 10^{-18}m/sqrt(Hz) at 1kHz.
- In the initial stage no recycling and no squeezing will be used.
- Really just want to show the reduction of radiation pressure noise in a speedmeter compared to Michelson.

What are the aims of the project?

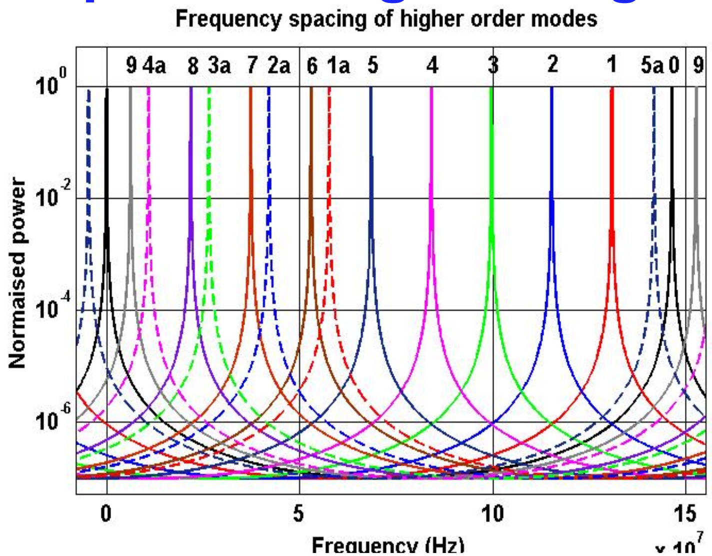
- Plan to setup an ultra-low noise Sagnac interferometer with high optical power and low-weight mirrors in order to demonstrate reduction/absence of back action noise and to test the Sagnac configuration for potential problems.
- Design optimised to achieve a factor 10 better sensitivity in the few 100Hz range, than an equivalent Michelson interferometer could achieve.
- **Proof of the speedmeter concept.**

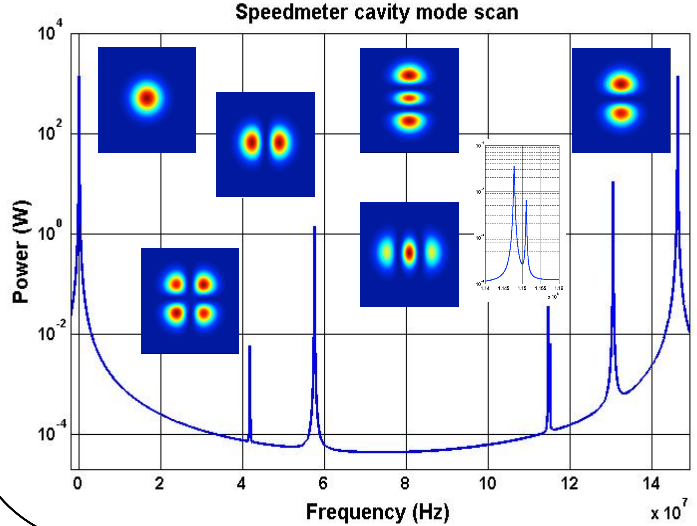




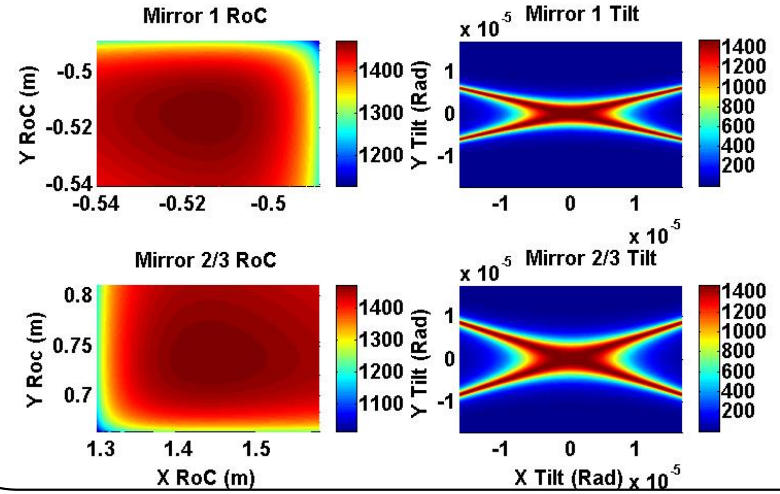
Current Status

Optical Design of Sagnac

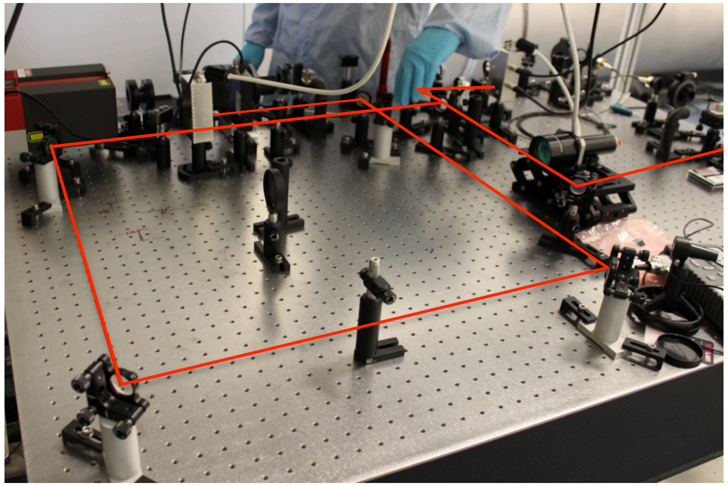




Tolerancing of Design Paramter



Pre-tests with in-Air tabletop



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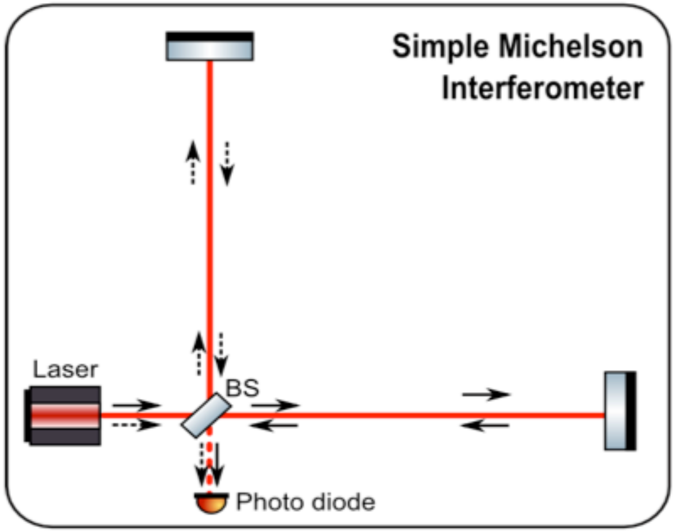
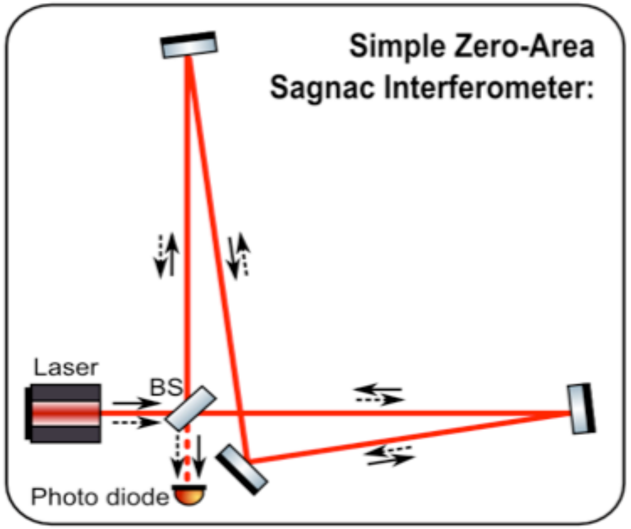
Different transfer functions

- A Michelson and a Sagnac have very different transfer functions from differential armlength to signal on the photodiode.



$$\varphi(t) = \frac{2L}{c}\omega_0 + \frac{\omega_0}{2}\int_{t-\frac{2L}{c}}^{t} h_+(t')dt'$$

$$= \underbrace{\tau_0\omega_0}_{(a)} + \underbrace{h_0\frac{\omega_0}{\omega_g}}_{(b)} \underbrace{cos\left(\omega_g\left(t-\frac{\tau_0}{2}\right)\right)}_{(c)} \underbrace{sin\left(\omega_g\frac{\tau_0}{2}\right)}_{(d)}$$

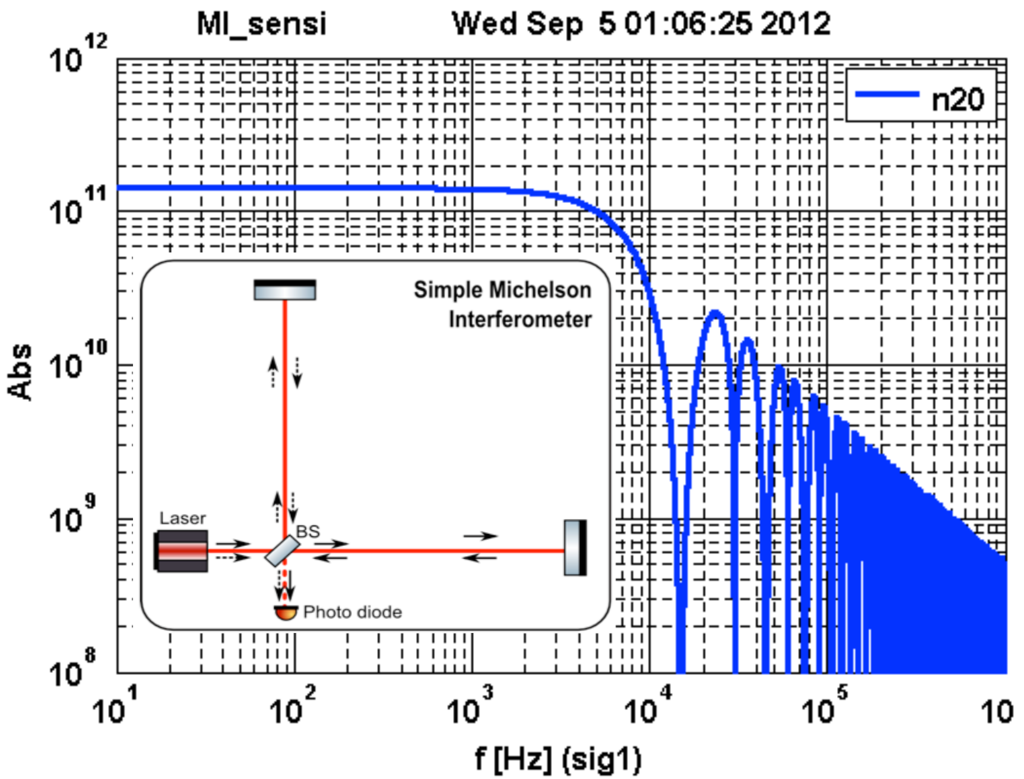


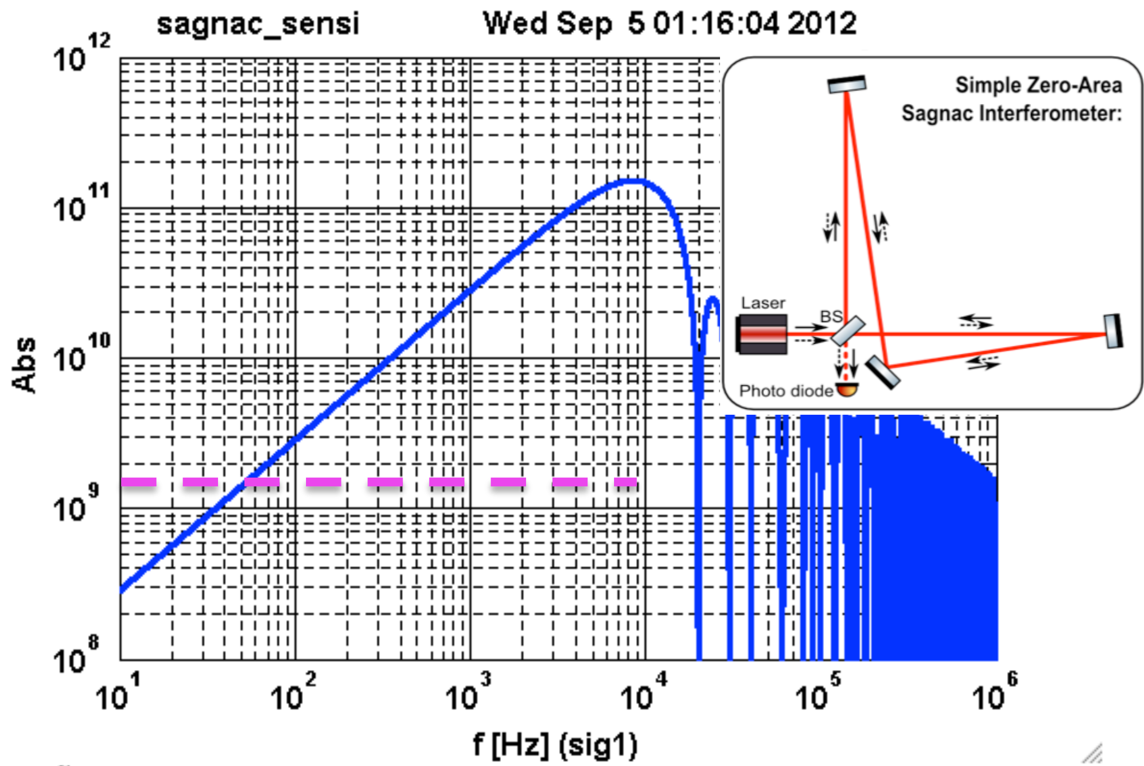
$$\varphi_1(t) = \frac{4L}{c}\omega_0 + \frac{\omega_0}{2}\left[\int_{t-\frac{4L}{c}}^{t-\frac{2L}{c}} h_+(t')dt' - \int_{t-\frac{2L}{c}}^{t} h_+(t')dt'\right]$$

$$|\Delta\varphi| = \underbrace{h_0\frac{4\omega_0}{\omega_g}}_{(a)} \underbrace{sin^2\left(\omega_g\frac{L}{c}\right)}_{(b)} \underbrace{sin\left(\omega_g t - \frac{2\omega_g L}{c}\right)}_{(c)}$$

Will we be able to cope with vanishing signal at low frequencies?

- For a Sagnac the optical gain (TF from differential arm length to voltage on readout photodiode) goes down towards lower freqs.

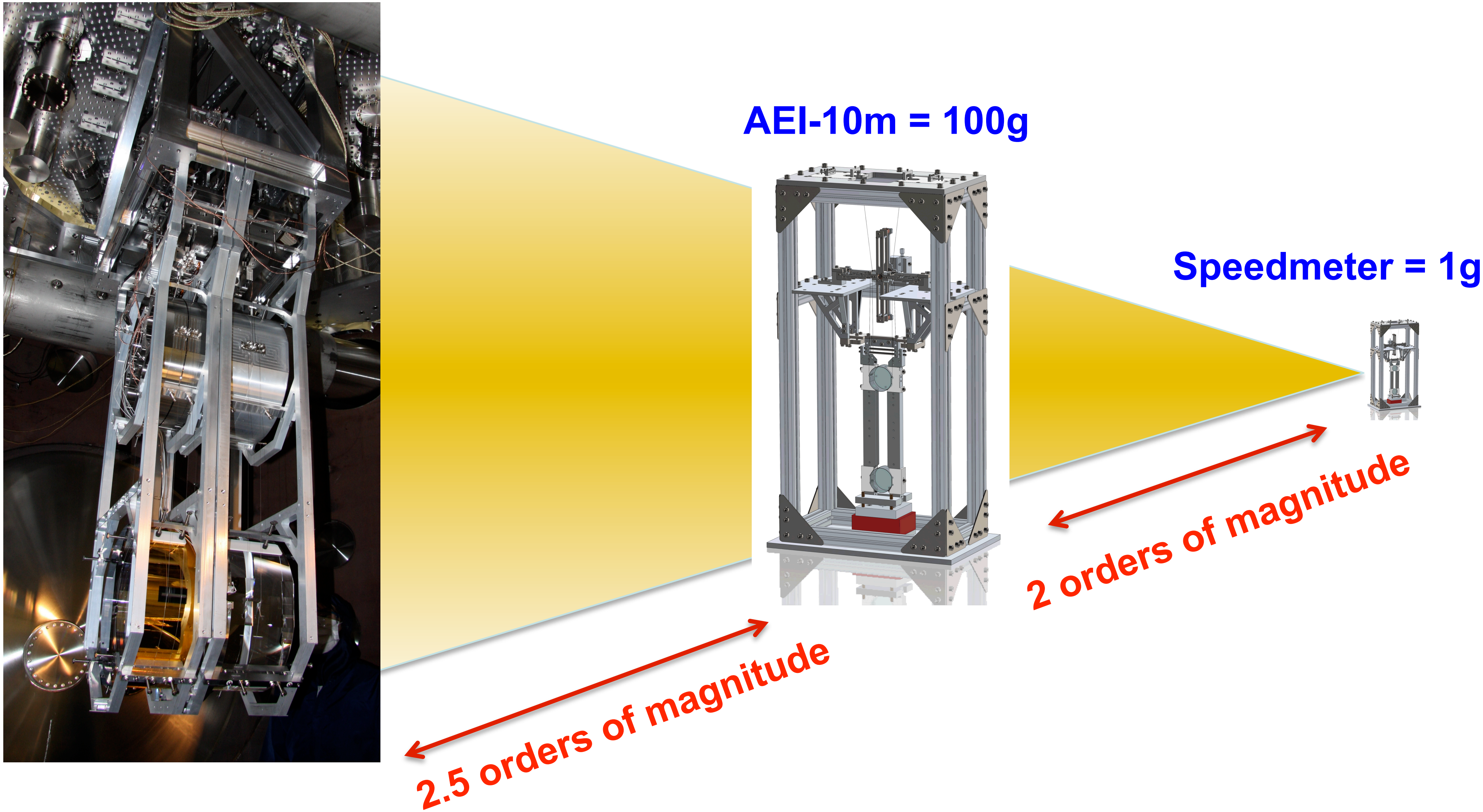




- Need to make sure that signal is still above the electronic noise for all frequencies of interest.

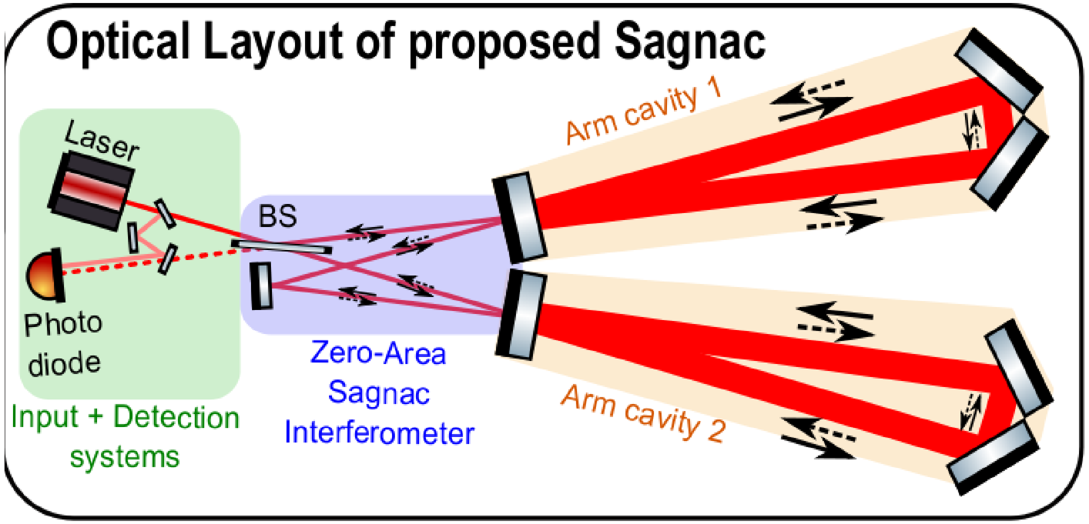
Monolithic 1 gram suspensions

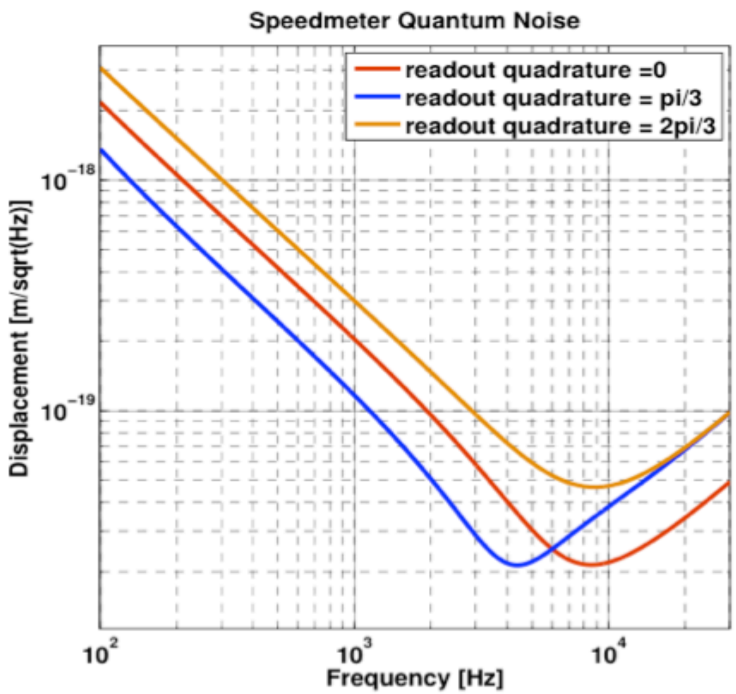
ALIGO = 42kg



Will Homodyne Readout at audio frequencies work?

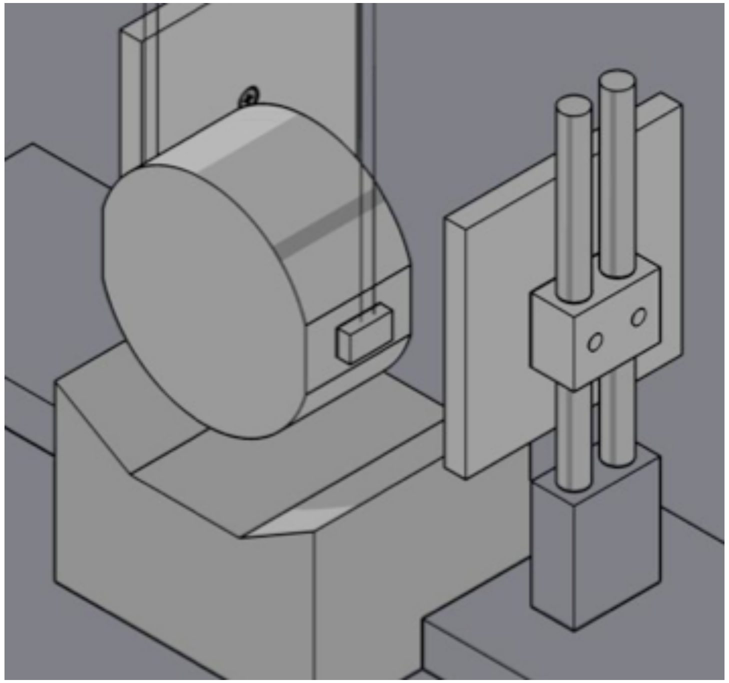
- Sagnac automatically on dark fringe. Cannot introduce dark fringe offset for DC-readout.
- Plan to try a real homodyne readout.
- Requires ultra-low noise and stable local oscillator path.
- Not been demonstrated so far!

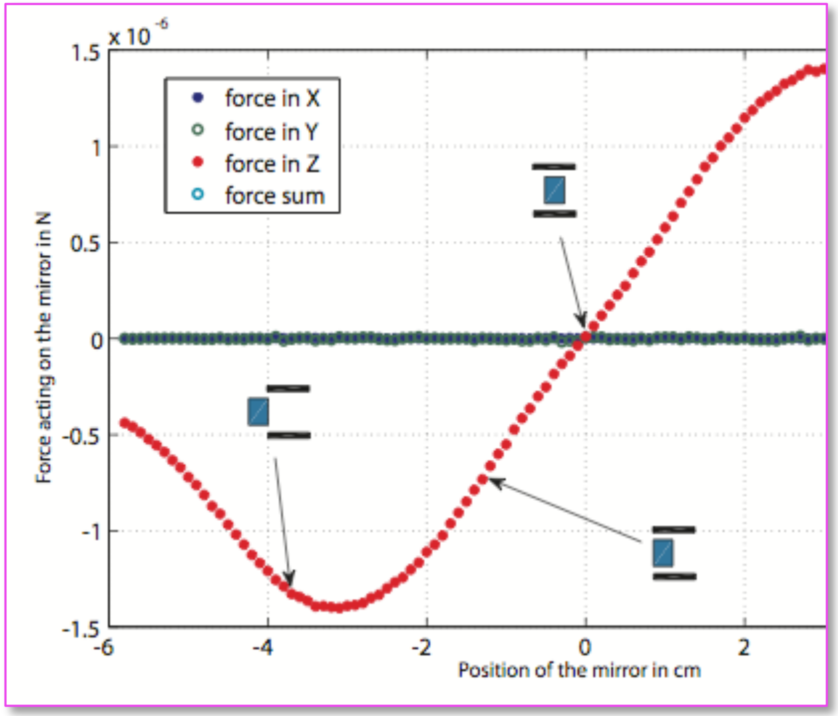




ESD actuators

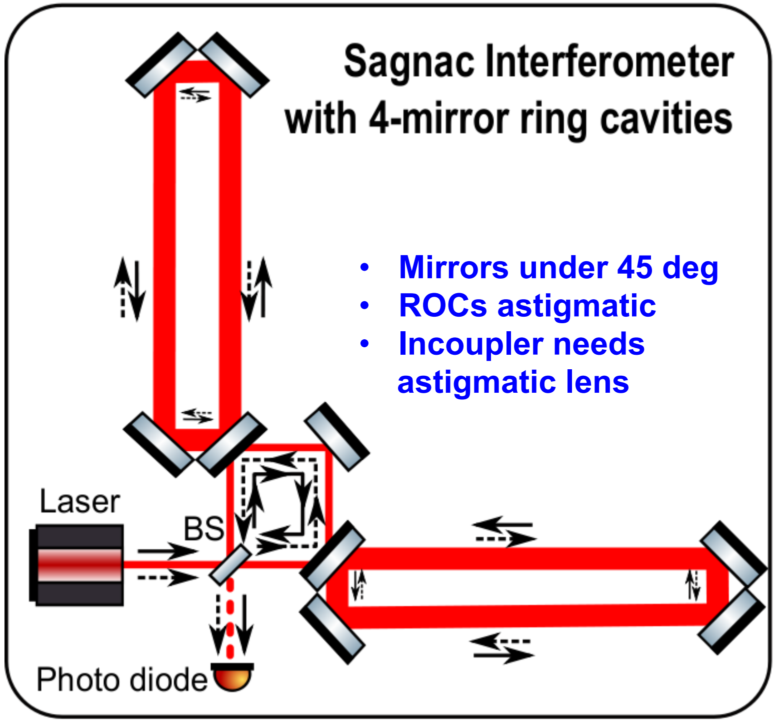
- New ESD concept. Force on mass only dependent on voltage and not distance between ESD and mirror.
- Investigated this concept for AEI-10m, but it will be even more useful for the speedmeter as it use lighter mirrors.

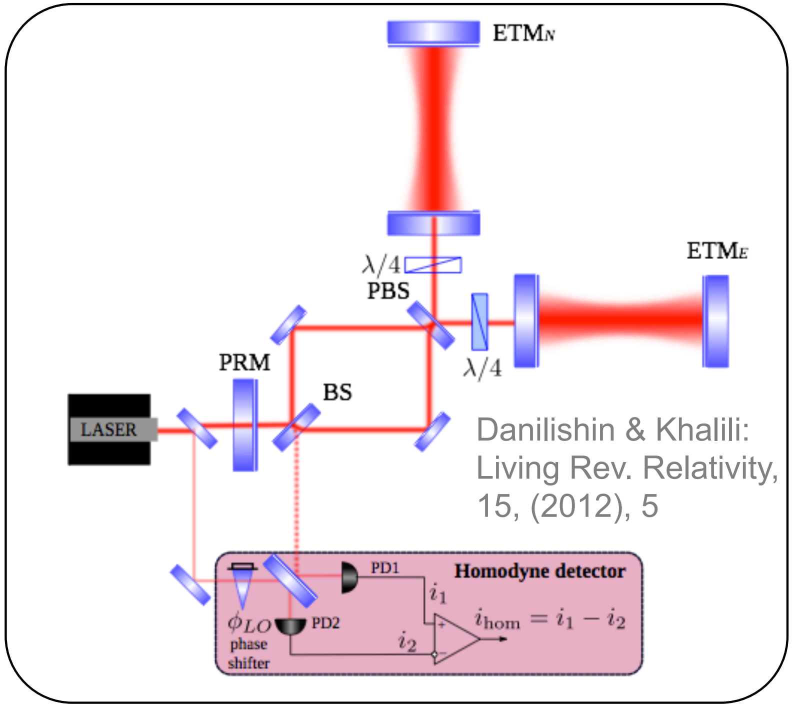




Arm cavity design

- Two different approaches under investigation:
  - 3-4 mirror ring cavities
  - Linear cavities using polarisation optics

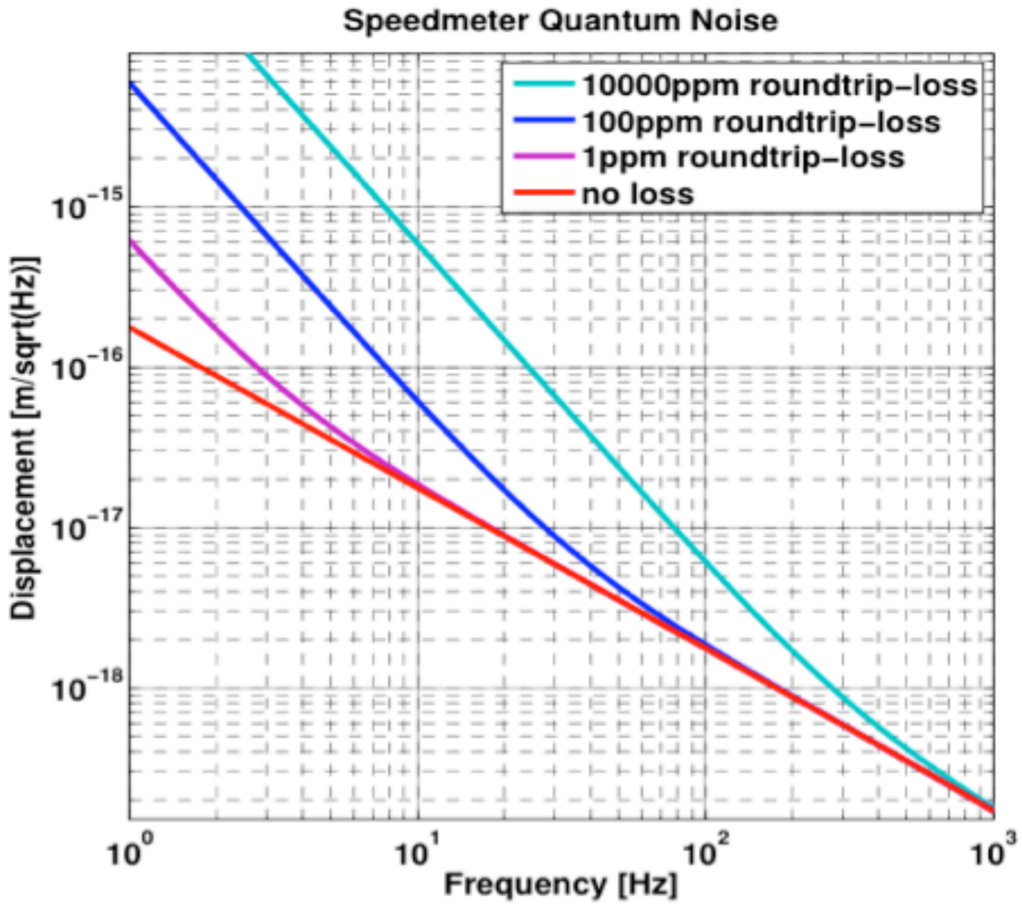




- So far not clear which concept would work better in a km-scale GW interferometer.

How do losses degrade the speedmeter performance?

- Losses degrade the speedmeter sensitivity.
- Losses introduce back-action noise again and we obtain again a quantum noise falling with $1/f^2$.
- Want to investigate how losses in different parts of the interferometer contribute.



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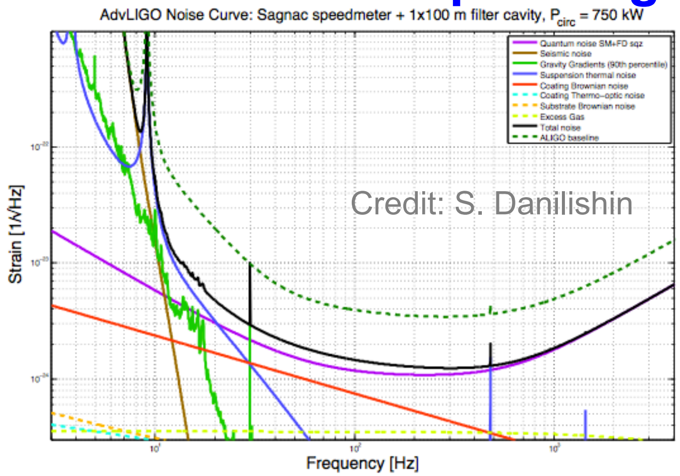
Discussion

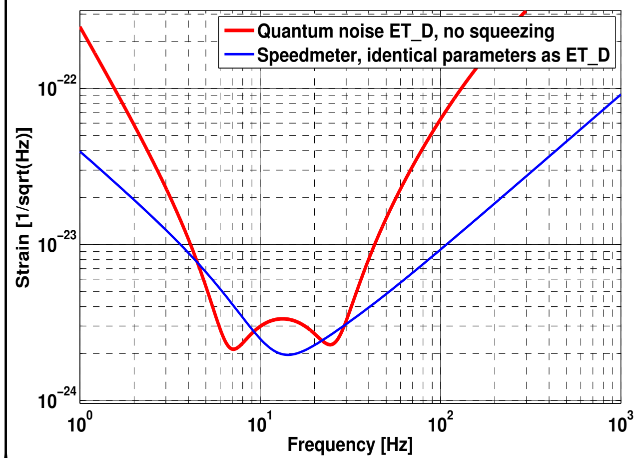
- So far concrete speedmeter analyses for future GW did not achieve significantly better sensitivity compared to Michelsons.

LIGO-3 with Squeezing



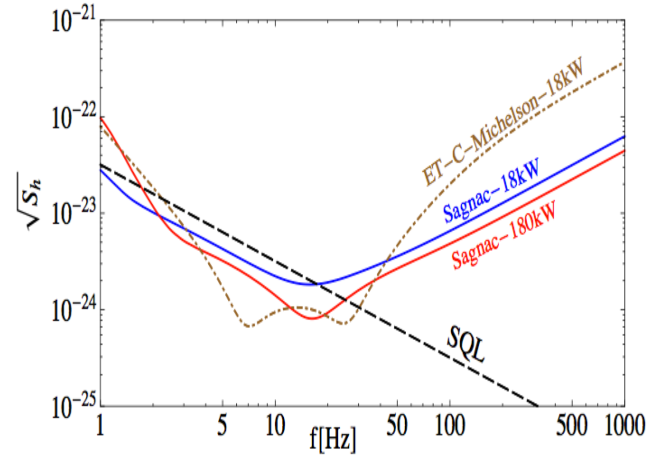
LIGO-3 Red design document: LIGO-T1200005-v2

ET-LF without Squeezing



Hild, CQG, 29, 12 pp. 124006 (2012)

ET-LF with Squeezing

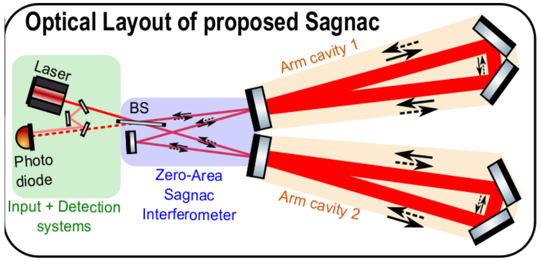


Wang et al: LIGO-P1300035-v1

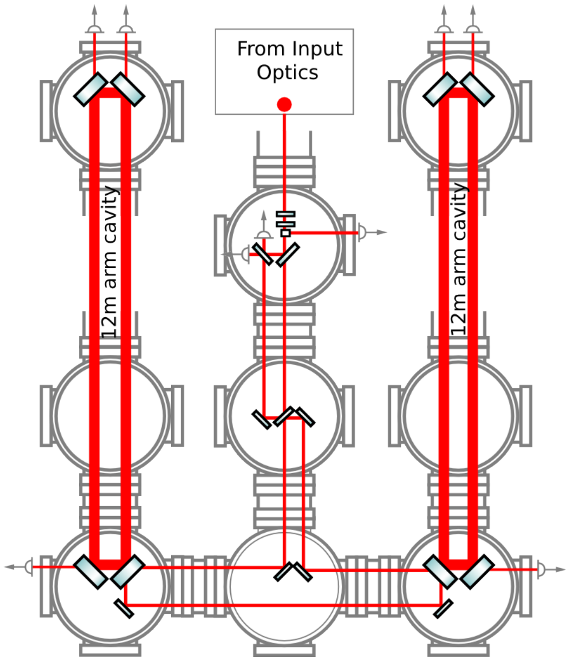
- Fair to compare Speedmeter to 30 years of Michelson optimisation?
- Sagnac might be simpler: Similar sensitivity than Michelson, but no need for signal recycling or frequency dependent squeezing.
- Also if coating noise is solved, Sagnac will allow to significantly reduce mirror size and weight.
- **In the long term: Speedmeter is the better measurement!**

3 Stage Plan to Investigate Sagnac Speedmeters in Glasgow for next 5+ years

- **Stage 1: 1m ERC-Sagnac-speedmeter**
  - Proof-of-principle of speedmeter concept
  - Show Back-action noise reduction



- **Stage 2: Set up a 10m arm cavity suitable for a speedmeter configuration**
  - 4 mirror ring cavity vs linear cavity using polarisation optics.
  - Control studies plus scattered light studies.
- **Stage 3: A full 10m Sagnac speedmeter**
  - Control and (homodyne)readout studies



Summary

- So far Michelson interferometers have been sufficient.
- However, we start to hit the quantum limit now.
- For the future measuring displacement would be the 'wrong measurement'!
- Now is the right time for an **exciting speedmeter experiment**. This is now on the way
- **Let's have some fun ...**

- If we do not find any showstoppers during our tests than it seems likely that over the next 10 years the Sagnac speedmeter will supersede the Michelson interferometer as state-of-the-art instrument for ultra-high sensitivity lengths measurements.

Please join if you are interested !!!

- **If you want to join this exciting project with your expertise you are more than welcome!**
- There is quite a lot of work involved in this project, - definitely more than my team on its own will be able to manage.
- **So everybody is welcome to join. Send us your interested students and postdocs or come along for a visit yourself.** ☺
- Also the ERC and NSF just initiated a program which allows NSF career awardees and NSF postdoctoral fellows to join ERC starting grant projects for periods from months up to a year.