# How to Build a Gravitational Wave Detector

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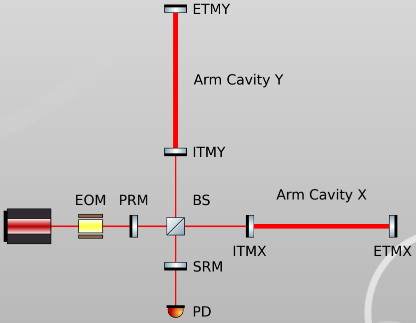
# Gravitational Wave Interferometry

# I am working on...

- Technical noise sources
- Actuation upon cavity mirrors
- New topologies
- Interferometer control



# Part 1
## Mitigating technical noise

### Technical Infrastructure
- **Materials and mirrors**
- Interferometer topology

### Make it Quiet
- Fundamental noise sources
- **Technical noise sources**

### Control Systems
- Test mass actuation
- Control schemes

# Technical Noise Sources

The interferometer needs to be quieter than the thing you want to measure

- **Thermal noise** in mirrors and suspensions
- **Seismic noise** around the site
- **Electronic noise** in controllers and readout
- Others: laser noise, oscillator noise, gravity gradient noise, and more...

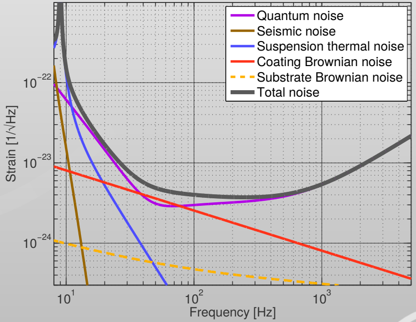
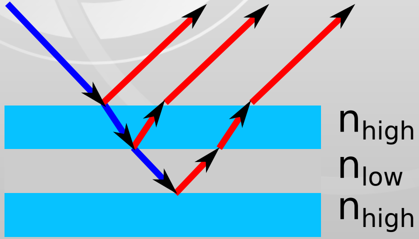



Figure : Advanced LIGO noise (arXiv: 1103.2728)

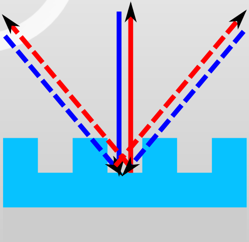
# Dielectric Mirrors

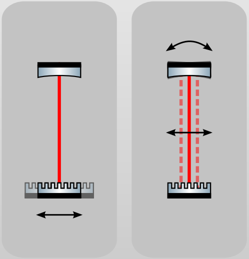


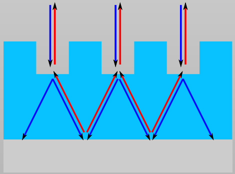

- Current detectors use dielectric mirrors
- Many (25-40) layers used to produce high reflectivity
- Each layer contributes thermal noise to signal
- **(Jointly) limits current generation detectors at some frequencies**

# Consider Waveguide Mirrors

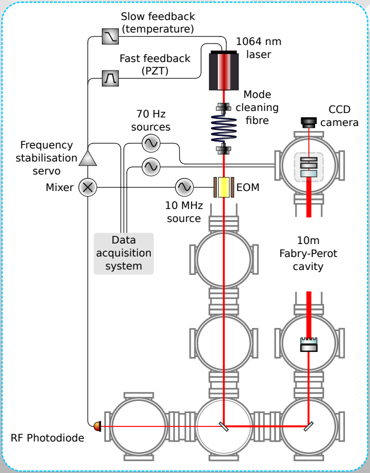
- Almost coating-free, thus reducing thermal noise
- **However,** gratings introduce noise in a different way, coupling seismic and thermal noise into the GW channel
- *Waveguide* mirrors should, in theory, cancel this additional noise term, but no experimental verification existed...







# Waveguide Mirrors

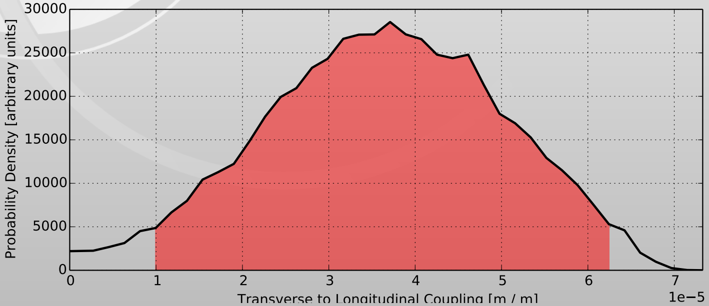



**...So we conducted an experiment in Glasgow to quantify this additional noise.**

Using the 10 m prototype facility, we built an optical cavity to measure this 'sidemotion' effect.

# Waveguide Mirrors

Measurement uncertainty made it difficult to quantify the exact level of coupling, but it is **orders of magnitude better than grating mirrors** in terms of noise performance.




**This work shows it might be possible to use these mirrors in future detectors to reduce thermal noise.**

# Part 2

Low noise actuation

### Technical Infrastructure

- Materials and mirrors
- Interferometer topology

### Make it Quiet

- Fundamental noise sources
- **Technical noise sources**

### Control Systems

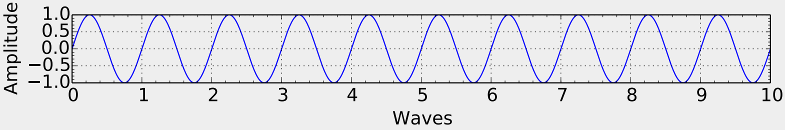
- **Test mass actuation**
- Control schemes

# Operating Point

A GW interferometer needs to be at its **operating point** to be optimally sensitive, with each mirror's position controlled to within as little as $10^{-12}$ m.

## Operating Point

**(Roughly speaking)** when each cavity within the interferometer is on resonance.

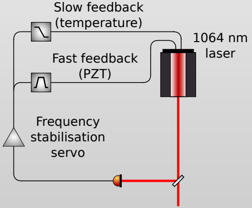


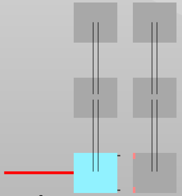

i.e. each cavity fits an integer number of half-wavelengths.

# Actuation

Cavities are kept on resonance by various means...

- (Slightly) change the laser's wavelength



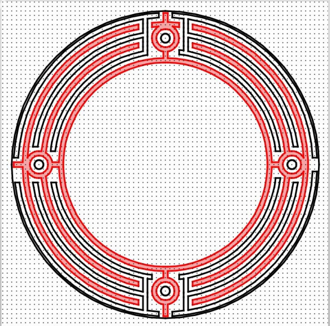



- Use voice coils and magnets on suspended optics and reaction masses

**Both are susceptible to certain types of environmental noise and technical challenges**

# Electrostatic Drives

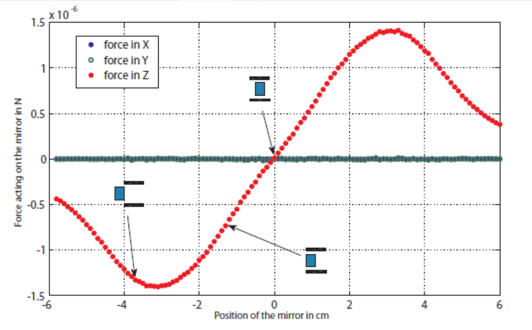
For low noise actuation directly on the test mass, electrostatic drives are used. These are low range but low noise actuators.

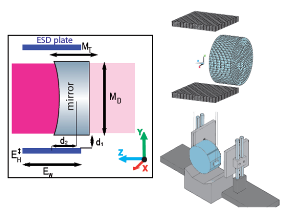


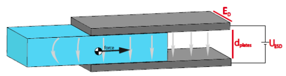
**However**, these introduce clipping losses due to the need to attach a pattern of conductive material onto the mirror.

# Electrostatic Drives

Another design, shown in simulations, is to use a **plate capacitor arrangement**. This has not yet been demonstrated experimentally...



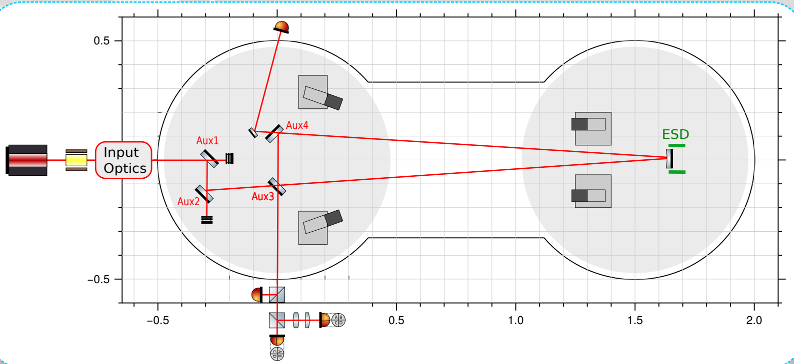




Credit: Wittel et. al. (arXiv)

# Electrostatic Drives

But we are currently building an experiment in Glasgow to demonstrate the plate capacitor concept. We hope to have results from this experiment in September 2015.



# Part 3

## Make it quieter than ever before

### Technical Infrastructure

- Materials and mirrors
- **Interferometer topology**

### Make it Quiet

- **Fundamental noise sources**
- Technical noise sources

### Control Systems

- Test mass actuation
- Control schemes

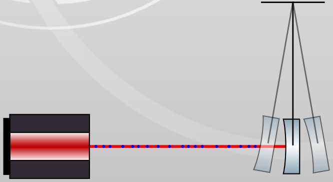
# The Standard Quantum Limit

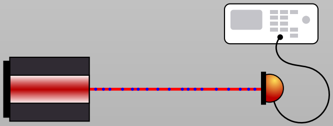
## Radiation Pressure Noise

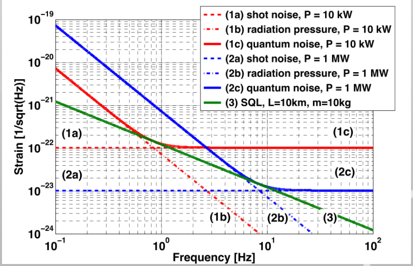
$$h_{RP}(f) = \frac{1}{mf^2L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$

## Shot Noise

$$h_S(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$







# Beating the Standard Quantum Limit

**Displacement** measurements are subject to Heisenberg's Uncertainty Principle. Thus:

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

and

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

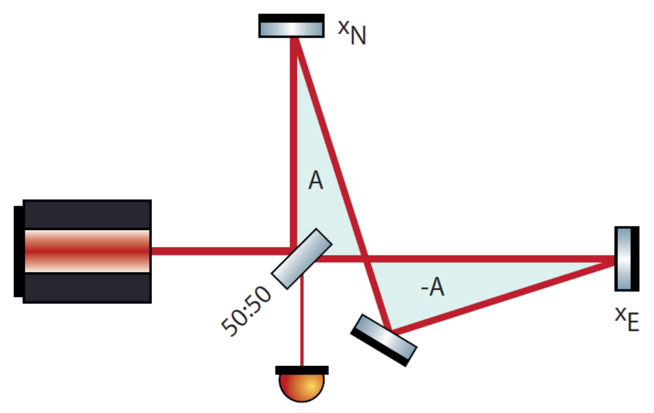
However, momentum, which manifests itself as the **speed at which a test mass moves**, *does* commute:

$$[\hat{p}(t), \hat{p}(t + \delta t)] = 0$$

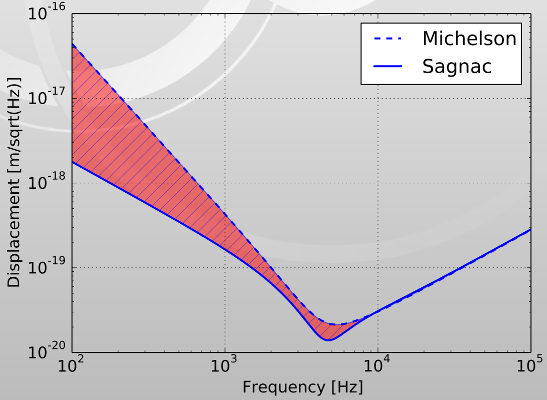
Figure : John von Neumann. By LANL [Public domain], via Wikimedia Commons

# Cancellation of Radiation Pressure Noise

It turns out that a zero-area Sagnac interferometer topology is automatically a speed-meter. **We can use it to cancel radiation pressure noise.**



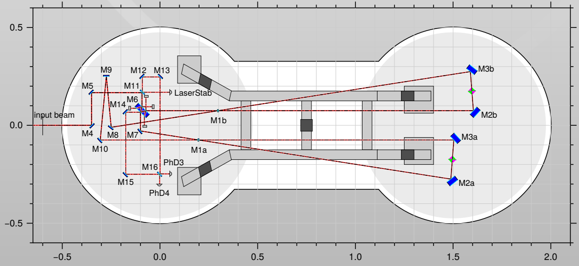
# Possible Sensitivity Improvement

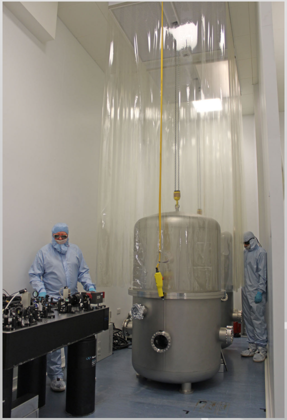



A factor of 10 improvement in sensitivity allows detectors to sense a factor 1000 more volume of our universe.

# The Glasgow Speed-Meter Experiment

- In vacuum, seismically isolated
- 1 g and 100 g cavity mirrors
- Electrostatic drives for direct actuation on test masses



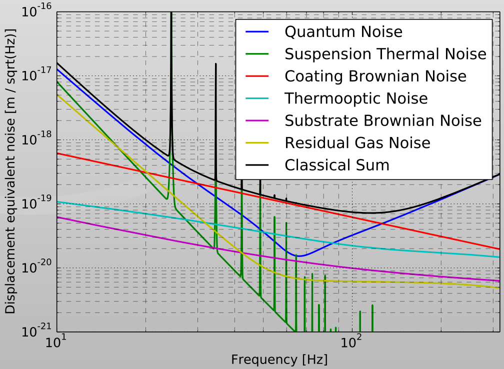



# Work So Far

Various technical and scientific aspects have been considered so far...

- Coil drivers
- Electronic wiring
- Vacuum infrastructure
- Noise budgeting
- Lock acquisition

**Five year** experiment
= lots of work!



# Part 4
## Control it

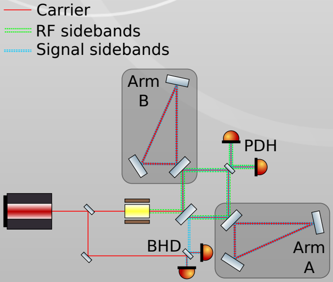
### Technical Infrastructure
- Materials and mirrors
- Interferometer topology

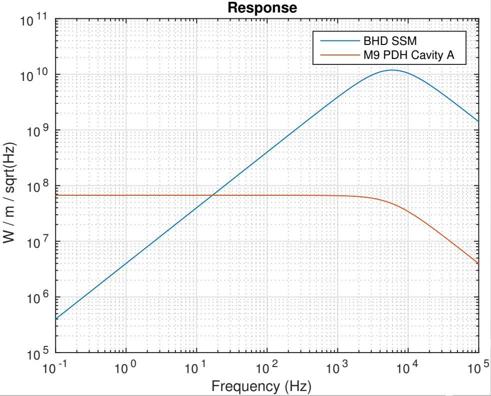
### Make it Quiet
- **Fundamental noise sources**
- **Technical noise sources**

### Control Systems
- **Test mass actuation**
- **Control schemes**

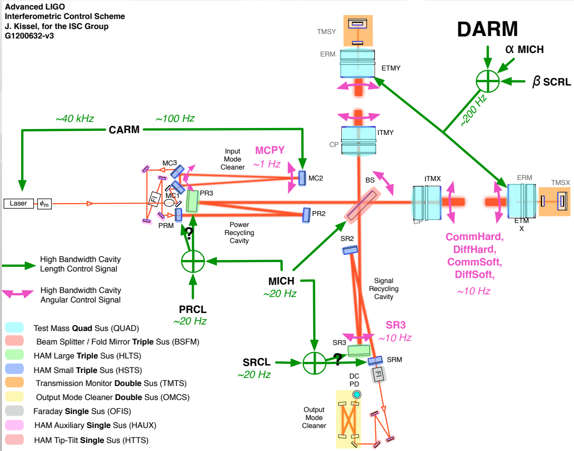
# Low Frequency Control

The speed-meter's 'velocity' response **vanishes at low frequencies**, so new control techniques are required.



# Sensing and Control




Sensing and control is a complicated business, even for 'standard' topologies!

**Work on the speed-meter's control scheme is on-going.**

Credit: Jeff Kissel (LIGO-G1200632)

# Thanks for listening!

http://speed-meter.eu/