High Precision Interferometry and Low-loss materials for future Gravitational Wave Observatories

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University of Glasgow

Today's network of GW detectors

These machines operate on a extremely high sensitivity !!!

Example GEO600: measures the 600m long arms to an accuracy of 0.0001 proton diameter @ 500 Hz.

Status of current and future GW detectors

1st generation successfully completed:

- Long duration observations (~1yr) in coincidence mode of 5 observatories.
- Spin-down upper limit of the Crab-Pulsar beaten!

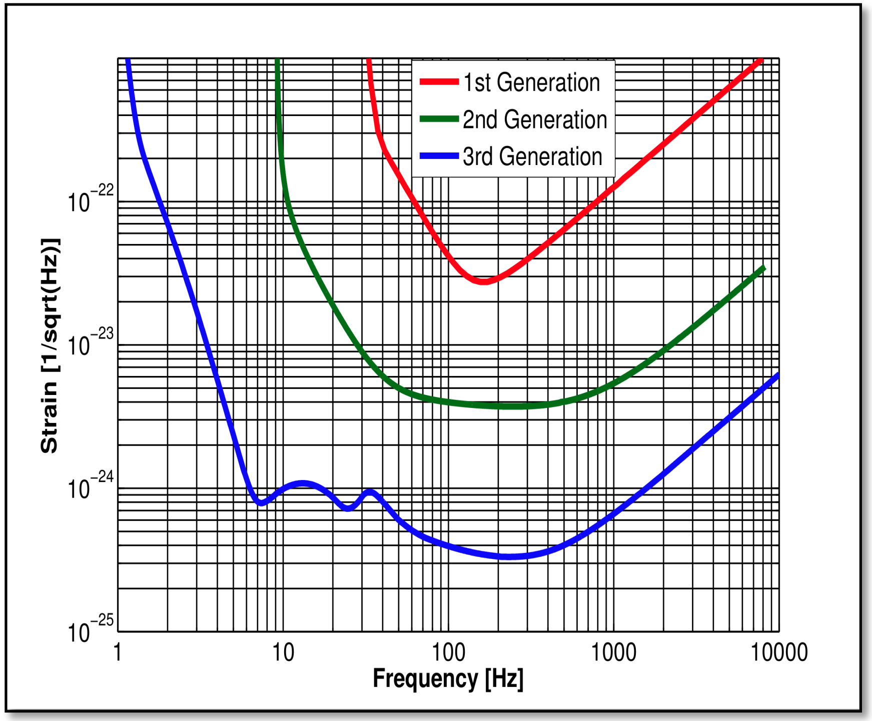
2nd generation on the way:

- End of design phase, construction started
- 10 times better sensitivity than 1st generation. => Scanning 1000 times larger volume of the Universe

3rd generation at the horizon:

- FP7 funded design study
- 100 times better sensitivity than 1st generation. => Scanning 1000000 times larger volume of the Universe

1G = GEO600 / LIGO / Virgo
2G = Advanced LIGO, GEO-HF, A-Virgo
3G = Einstein Telescope

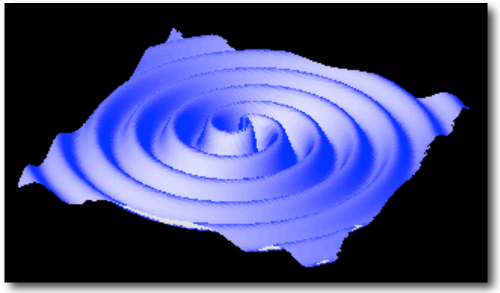


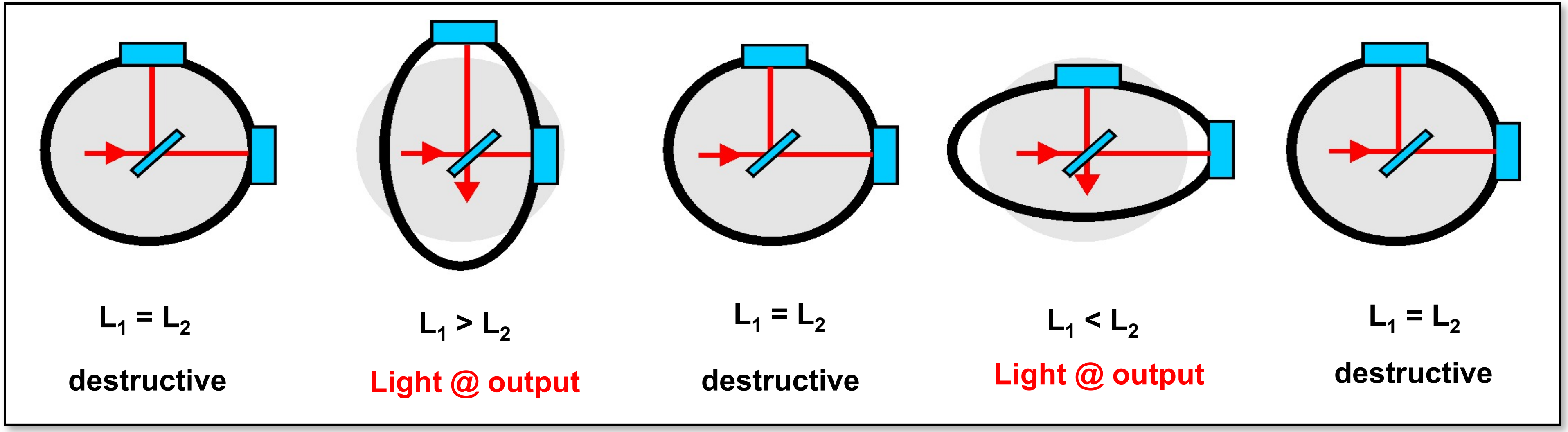
Simple Concept of a GW detector

Need to measure extremely accurate the distance between test masses!

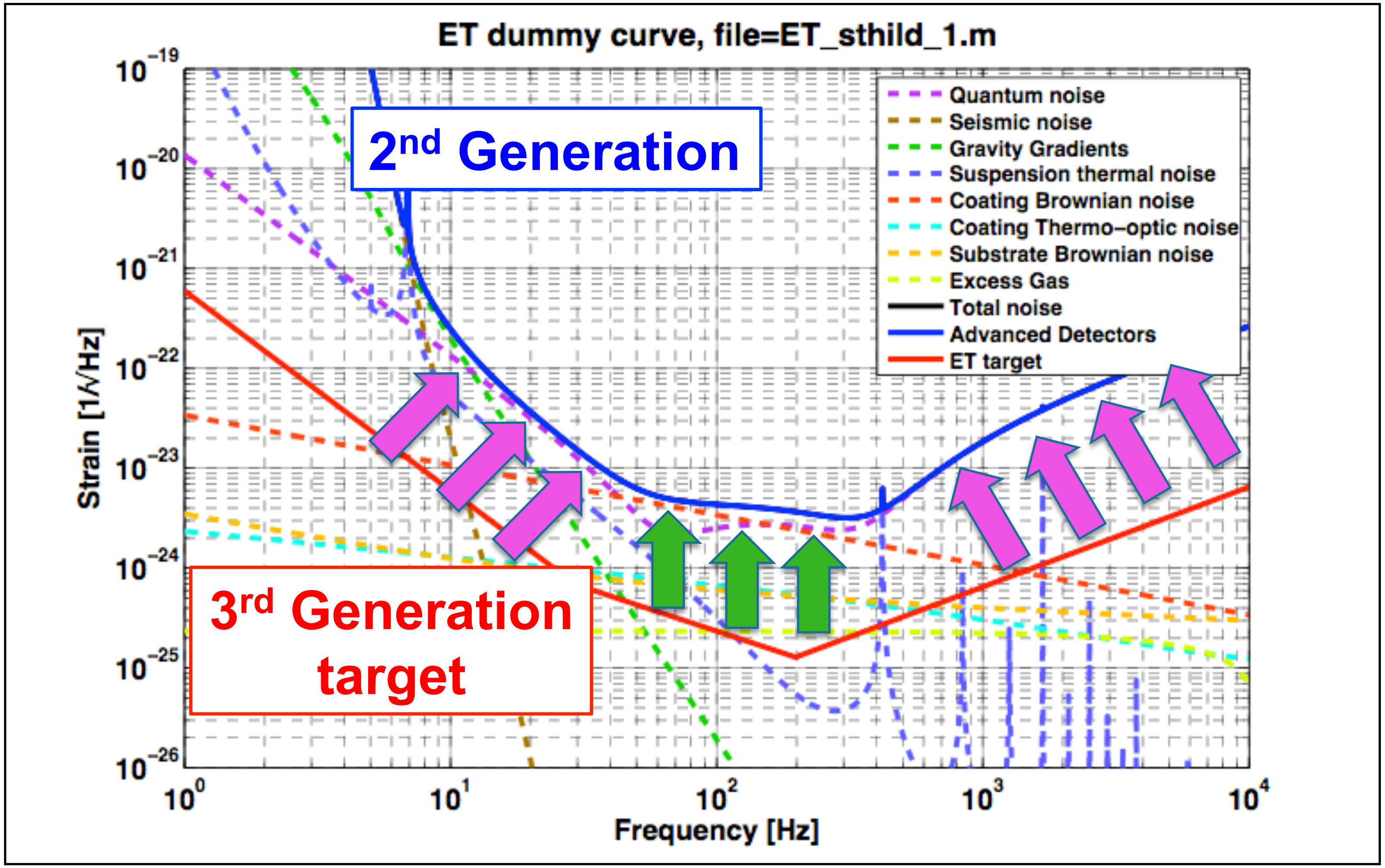
We have to make sure:

1. **That the test masses are quite enough (seismic isolation, thermal noise, gravity gradients)**
2. **That we can read out the test mass position to the required level without introducing noise.**





What is required to go from 2nd to 3r Generation ?



- Improve test mass quietness, i.e. reduce thermal noise
- Improve readout, i.e reduce quantum / back-action noise

Part 1 of this talk:

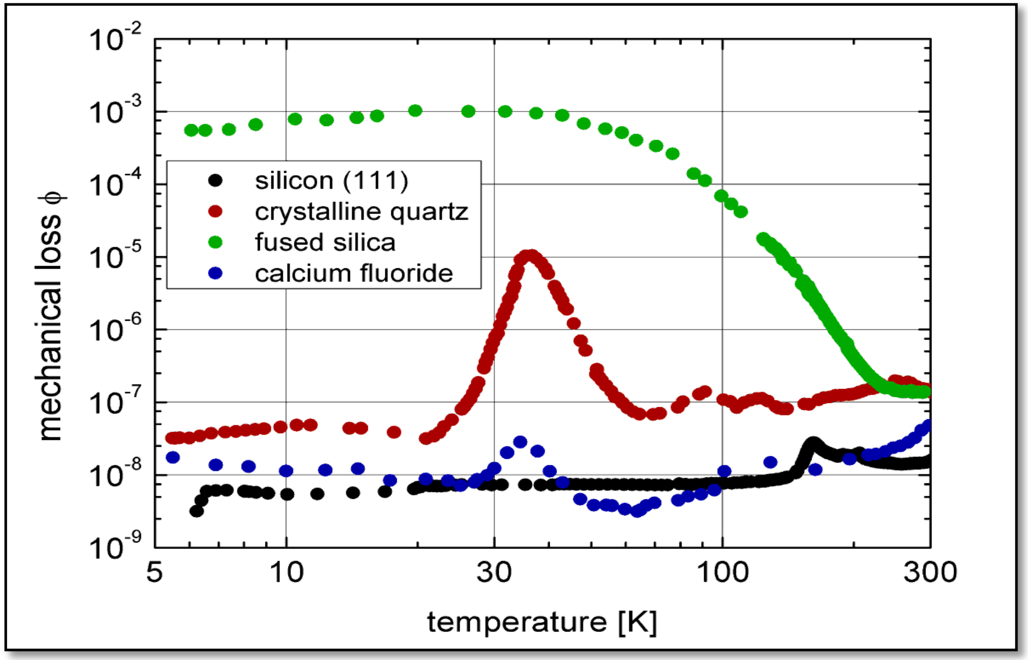
New Technologies to make the test masses quieter

How to reduce thermal noise

Thermal noise proportional to Temperature and mechanical loss of the test masses.

Improvements possible by:

reduction of temperature + reduce mechanical loss materials

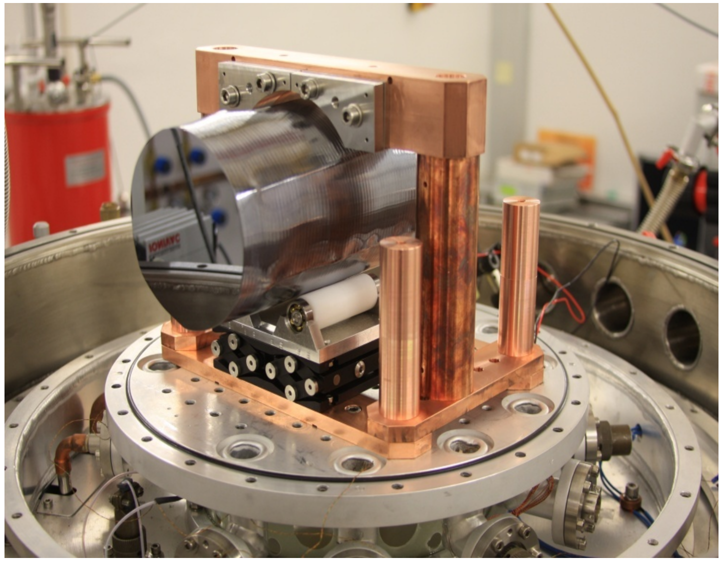


Fused silica – as the material currently in use – is not suited for cryogenic operation due to its large loss peak.

Silicon as a 3rd generation material

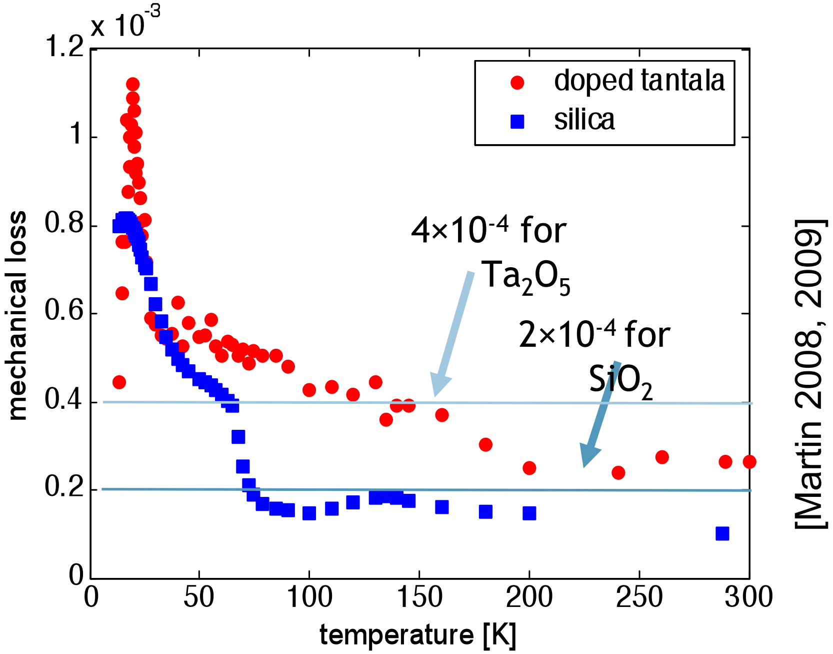
- **Silicon has several advantages as a test mass material for a 3rd generation detector**

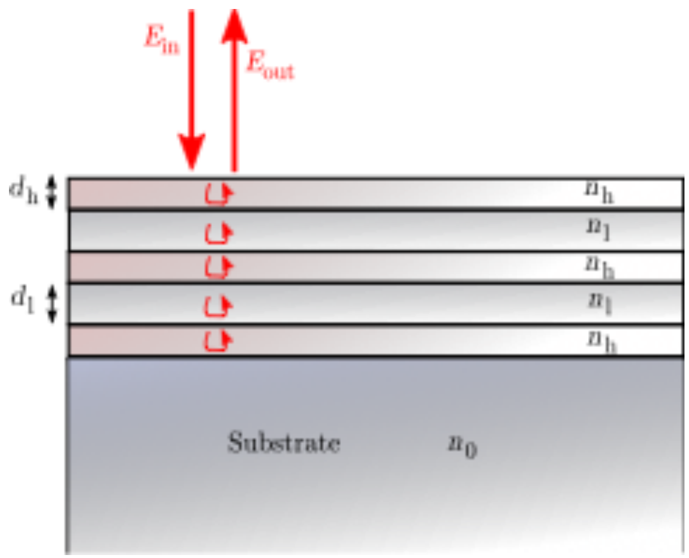
- **low mechanical loss**
- **low coefficient of thermal expansion**
- **excellent thermal conductivity (avoiding of thermal gradients)**
- **available in large pieces due to the demands of the semiconductor industry**



Optical coatings

There is not only thermal noise from the test mass substrates , but also from the mirror coatings (amorphous dielectric materials). This noise scales again with temperature and loss, but also with the number of the layers.

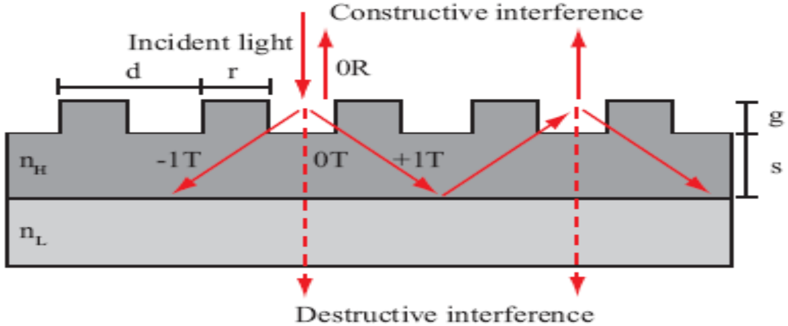




Idea: replacing the dielectric (lossy) multilayer stack by a mono-crystalline silicon micro structure

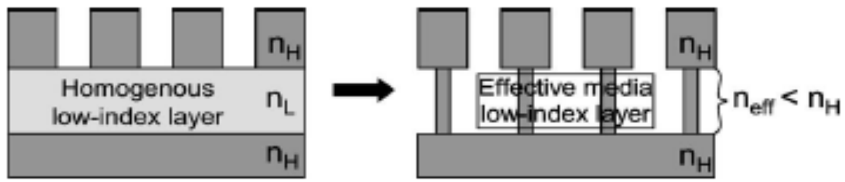
Novel Approaches

resonant waveguide



[Brückner et al., Optics Express 17 (2009) 163 – 169]

monolithic waveguide



[Brückner et al., Optics Letters 33 (2008) 264 - 266]

thickness of tantala by one order of magnitude smaller than in dielectric stacks

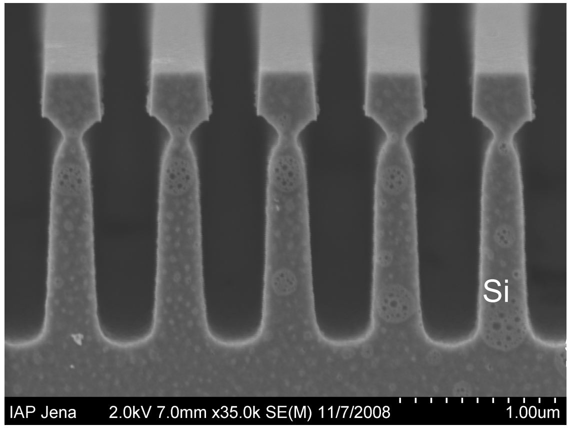
no lossy dielectric materials needed, no interfaces, excellent thermal properties

reduced thermal noise

reduced thermal noise

Reflective coatings based on micro structures

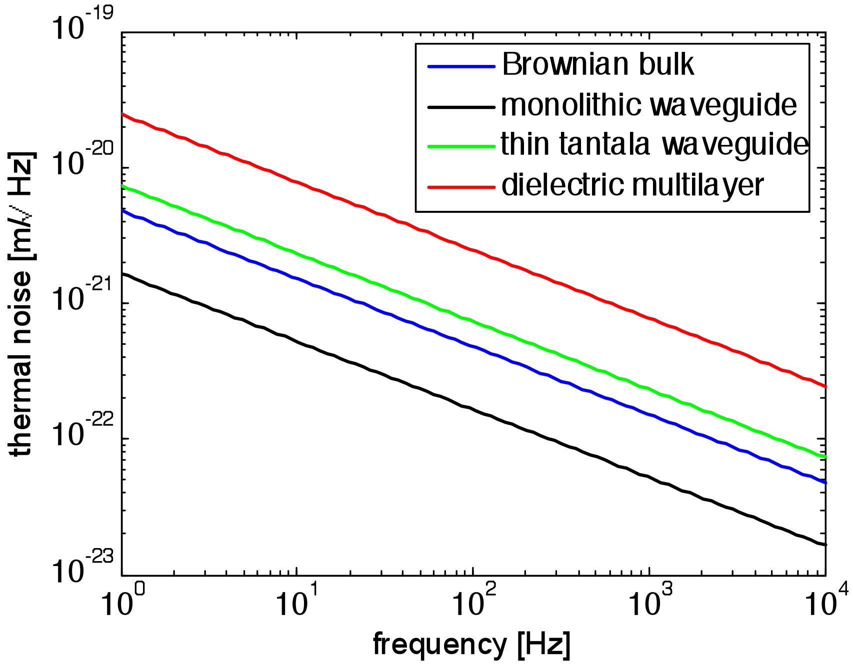
It is possible to fabricate such a reflector purely from silicon without any additional materials.



experimental realization [IAP Jena]

99.4% reflectivity demonstrated so far

Thermal noise potential of a T-shape micro structured mirror



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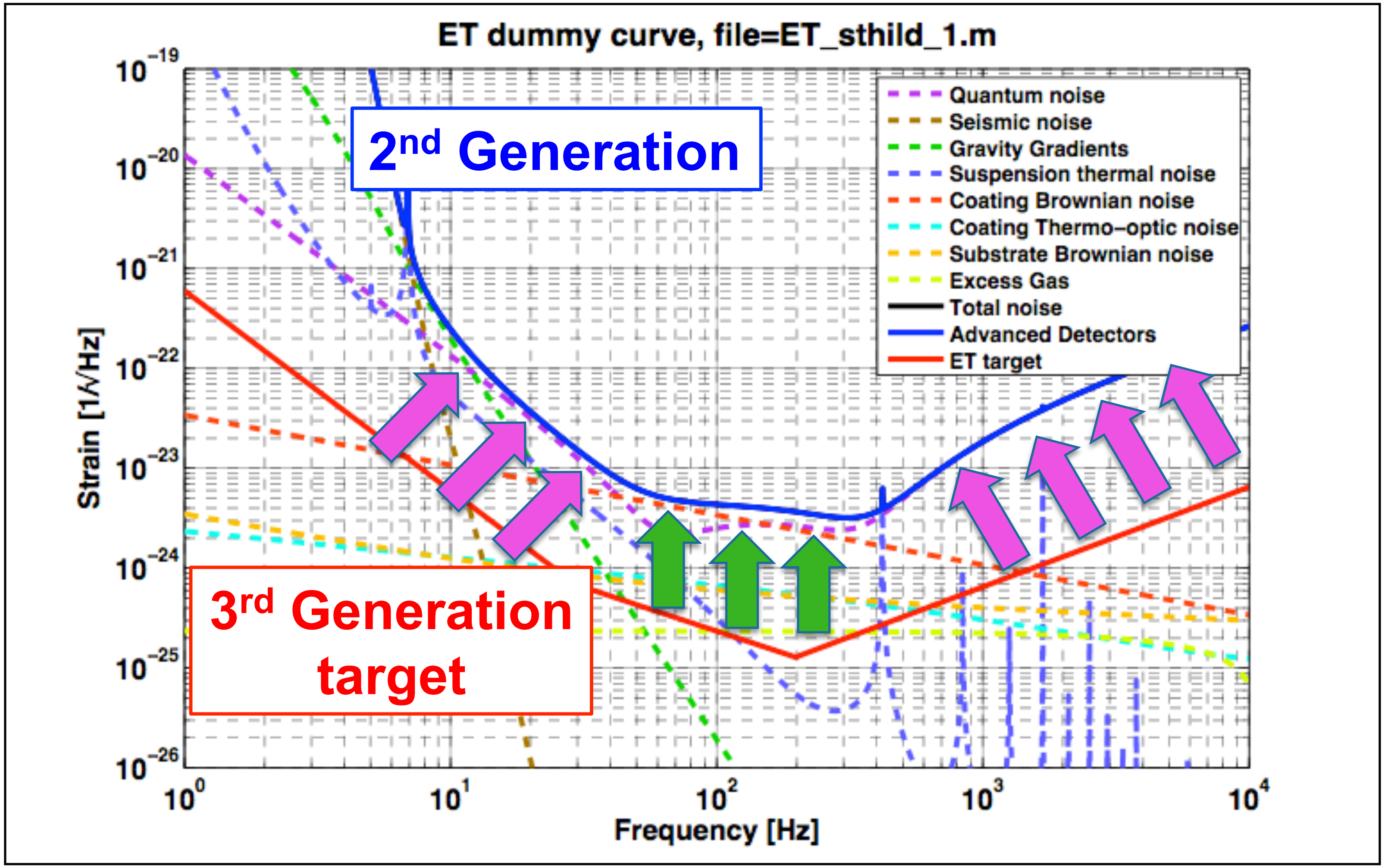


Improve test mass quietness, i.e. reduce thermal noise

Improve readout, i.e reduce quantum / back-action noise

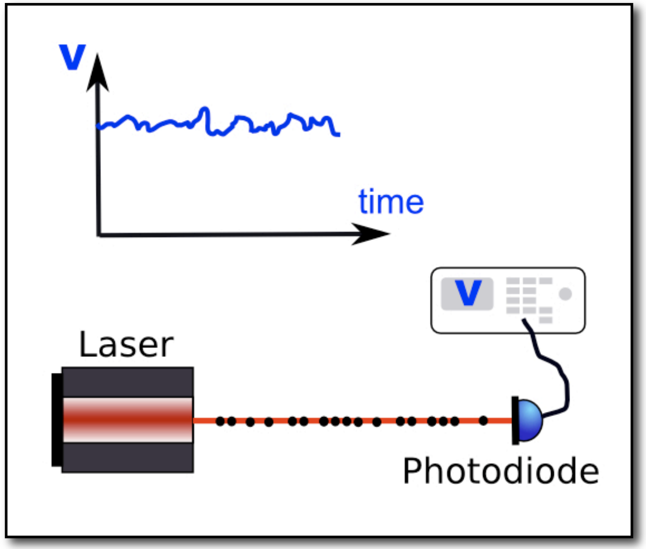
Part 2 of this talk:

New Technologies to reduce readout noise

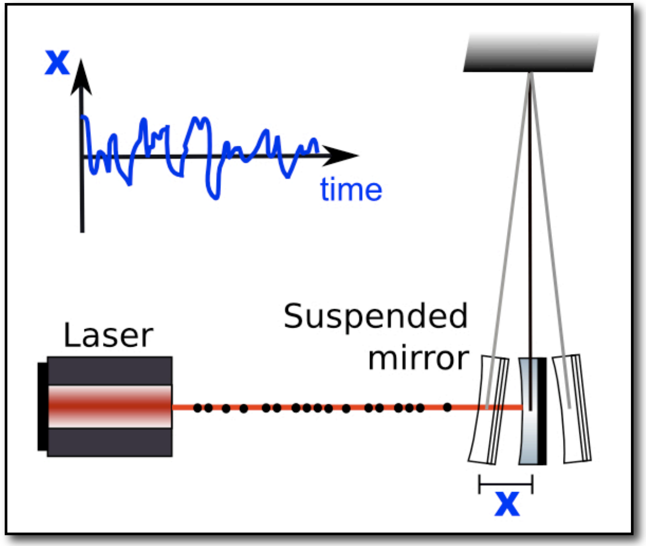
Quantum noise components

Quantum noise is comprised of photon shot noise at high frequencies and photon radiation pressure noise at low frequencies.

The photons in a laser beam are not equally distributed, but follow a Poisson statistic.



photon shot noise



photon radiation pressure noise

The Standard Quantum Limit (SQL)

While shot noise contribution decreases with optical power, radiation pressure level increases:

wavelength

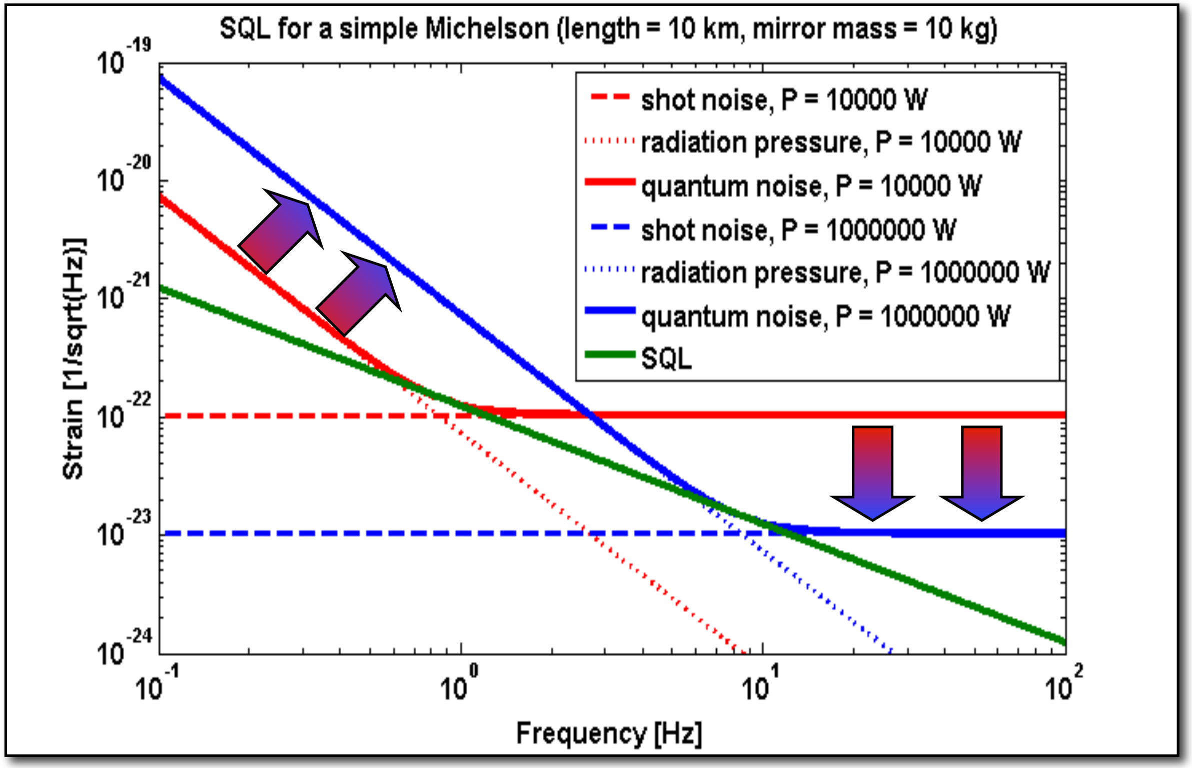
$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

optical power

Arm length

Mirror mass

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

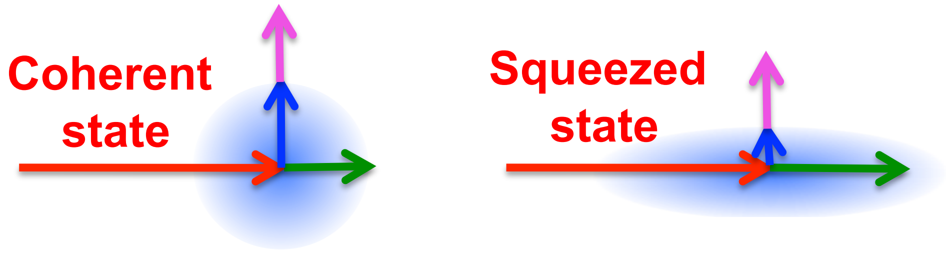


- **The SQL is equivalent to the Heisenberg uncertanty.**
- **Using a classical quantum measurement the SQL represents the lowest achievable noise.**

V.B. Braginsky and F.Y. Khalili: Rev. Mod. Phys. 68 (1996)

Injection of Squeezed Light

Quadrature picture of Heisenberg uncertainty:
horizontal = amplitude quadature
vertical = phase quadrature

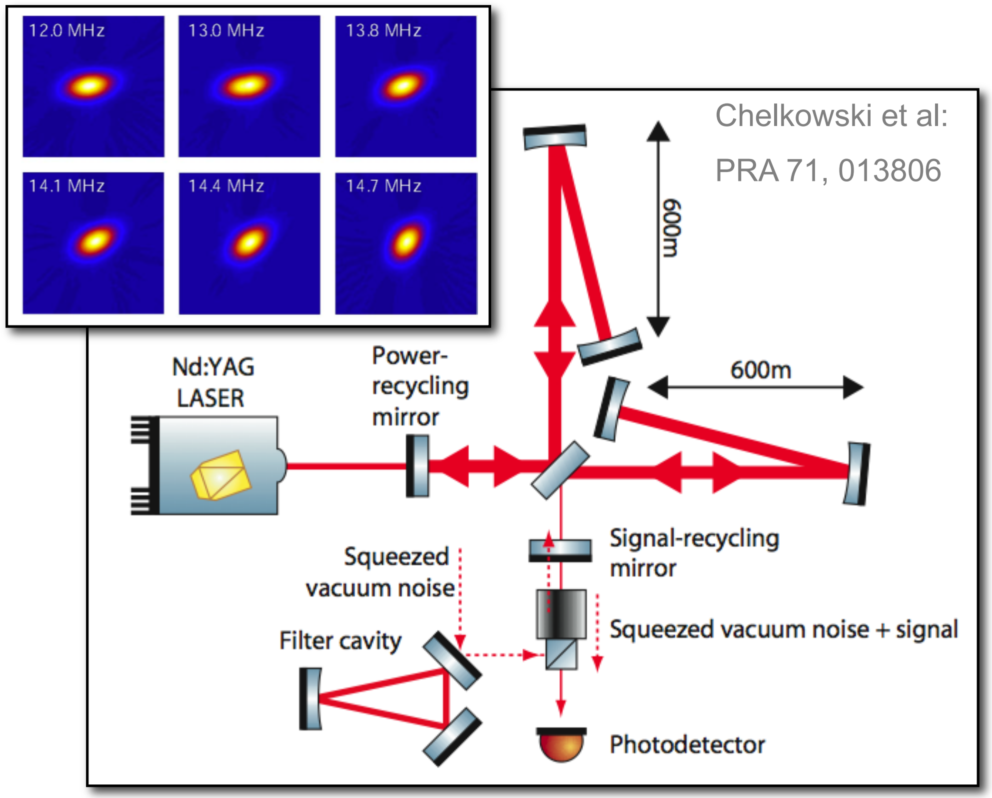


Injection of squeezed light will reduce photon shot noise / quantum noise.

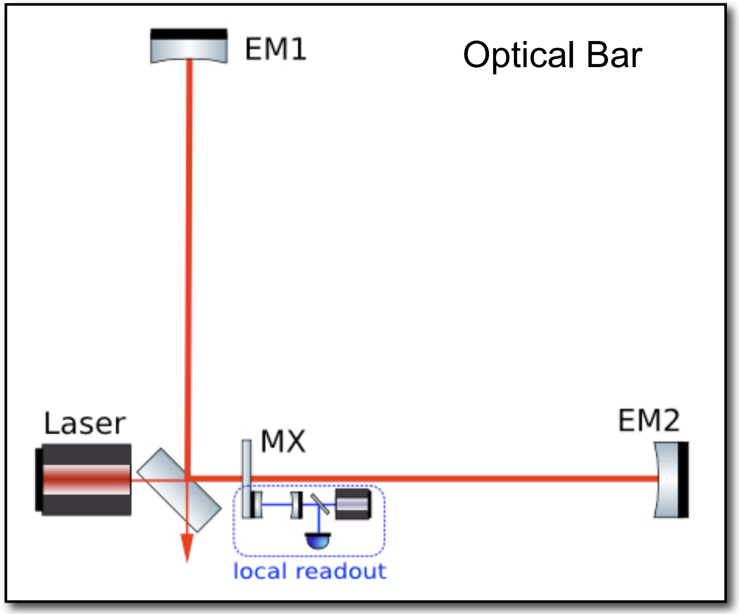
Squeezed light sources available now: 10dB squeezing + frequencies as low as 10Hz

Implementation of squeezing in GEO600 happing right now.

First time demonstration in a big interferometer.



Qunatum-Non-Demolithion Techniques



V.B. Braginsky and F.Y. Khalili: "Nonlinear meter for the gravitational wave antenna",Phys. Lett. A 218 (1996).

- **Optical rigidity can be used to surpass the Standard Quantum Limit. Optical springs allow to rigidly connect two mirrors with a spring made of photons, which is stiffer than diamond.**
- **Very light mirror (MX) is coupled to the movement of EM1 and EM2 via optical springs. MX moves in its local frame!**
- **MX can then locally read out by a small local meter without disturbing the quantum states in the main instrument (QND measurement).**

Summary

Future Gravitational Wave Observatories require many new technologies !

Development and prototyping of many innovative techniques is underway.

Two examples to make the test mass queiter:

- **Cryogenic silicon**
- **Waveguide coatings**

Two examples to reduce the readout noise:

- **Squeezed light**
- **Optical Rigidity / Qunatum non Demolition**

Many other interesting techniques around which I did not have the time to cover … (Speedmeter, frequency dependent variational readout, higher order Laguerre Gauss modes, xylophone detectors …)

E N D

Optical Springs & Optical Rigidity

Detuned cavities can be used to create optical springs.

Optical springs couple the mirrors of a cavity with a spring constant equivalent to the stiffness of diamond.

In a full Michelson interferometer detuned Signal Recycling causes an optical spring resonance.