Large Interferometers for small displacements:

A technological view of Gravitational Wave detection

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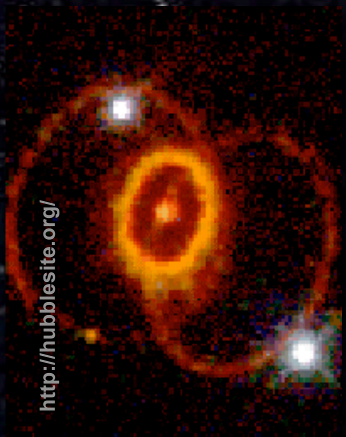
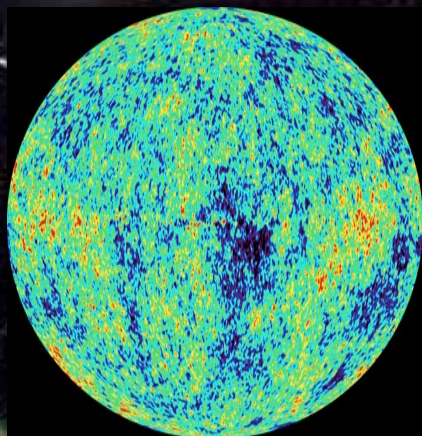
Outline

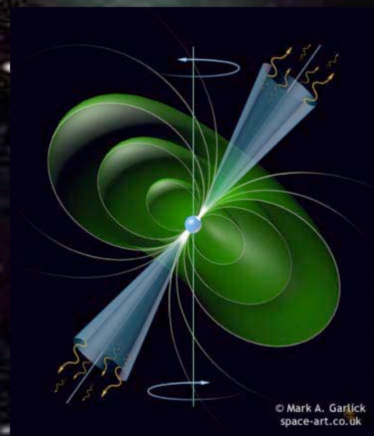
- Overview of Gravitational Wave detection
- Optical technology for high precision interferometry
  - Simple Michelson interferometer
  - Power Recycling
  - Arm cavities
  - Signal Recycling
  - Standard Quantum limit
- Examples of new technologies for future Gravitational wave detectors
  - High power laser, Laguerre Gauss modes, Quantum-non-demolition

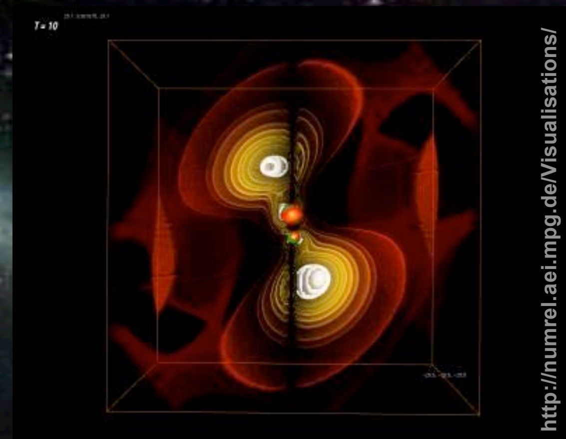
The most violent events in Universe are in our reach !

http://hubblesite.org/





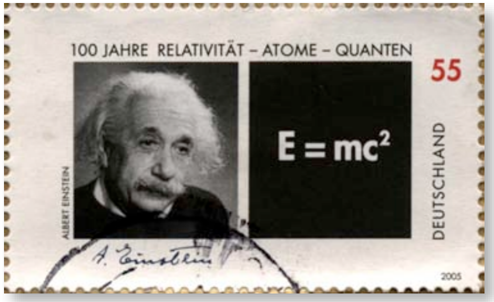


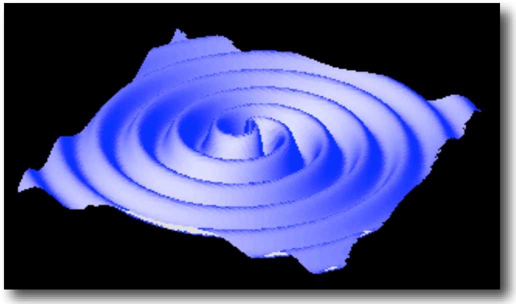


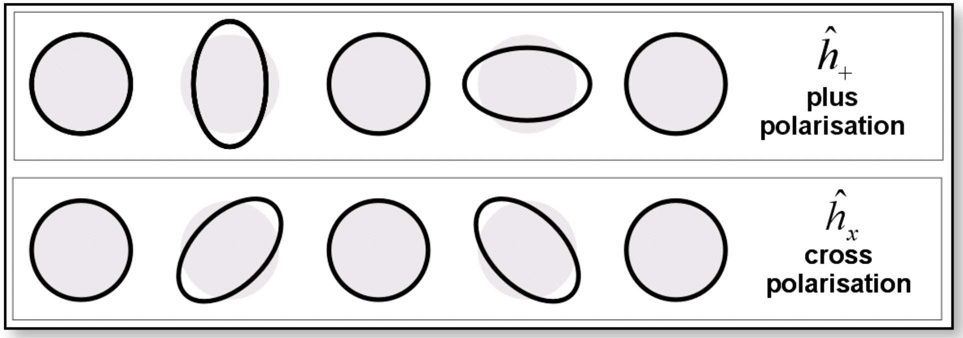
Soon we will be able to listen to Supernovae, colliding black wholes and even the aftermath of the Big Bang using Gravitational waves.

Gravitational Waves: Ripples in space time

- GW are consequence of General Relativity.
- GW are caused by asymmetric accelerated masses.
- GW change the metric of space time.
- Quadrupole waves.







- **We know that GW exist:** Indirect detection by Taylor and Hulse (1993 Nobel Price).
- **No direct detection so far**. On going search with kilometer-long Michelson interfero-meters looking for tiny length changes.

Why haven't we measured GW so far?

Stress Energy Tensor

Metric Tensor

$$\overline{\overline{T}} = \frac{c^4}{8\pi G}\overline{\overline{G}}$$

Analogon: Hooke's law

$$(\vec{F} = k\vec{x})$$

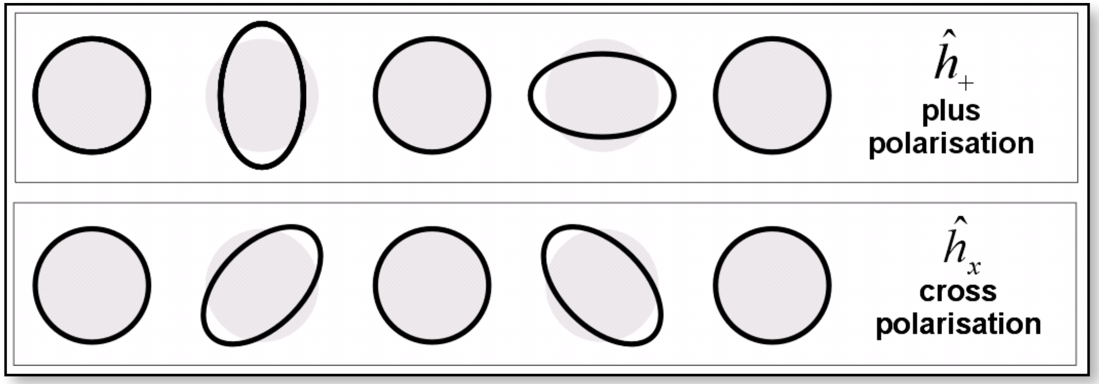
Stiffness of space time

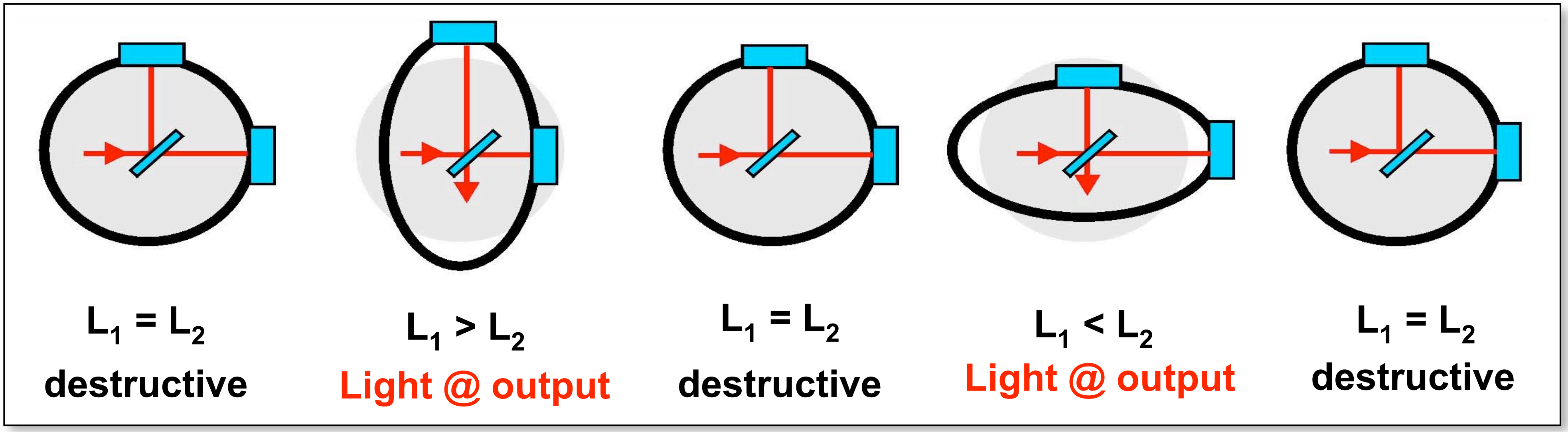
$$\frac{c^4}{8\pi G} \approx 5 \cdot 10^{42}$$

- Space time is extremely stiff !
- Length changes caused by GW are really tiny ($<10^{-21}$) !

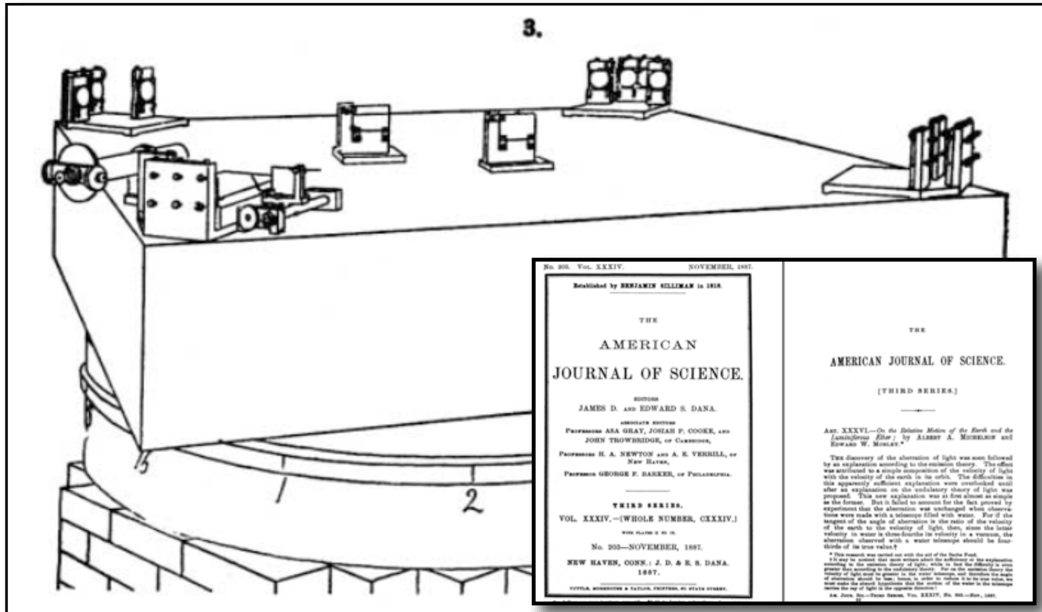
How can we detect gravitational waves?

A Michelson interferometer is the ideal instrument to measure relative length changes.





We have come a long way …



- The first Michelson interferometer: Experiment performed by Albert Michelson in Potsdam 1881.
- Measurement accuracy 0.02 fringe

- Michelson and Morley 1887 in Cleveland.

ART. XXXVI.—*On the Relative Motion of the Earth and the Luminiferous Ether*; by ALBERT A. MICHELSON and EDWARD W. MORLEY.*

State-of-the-art Michelson Interferometer

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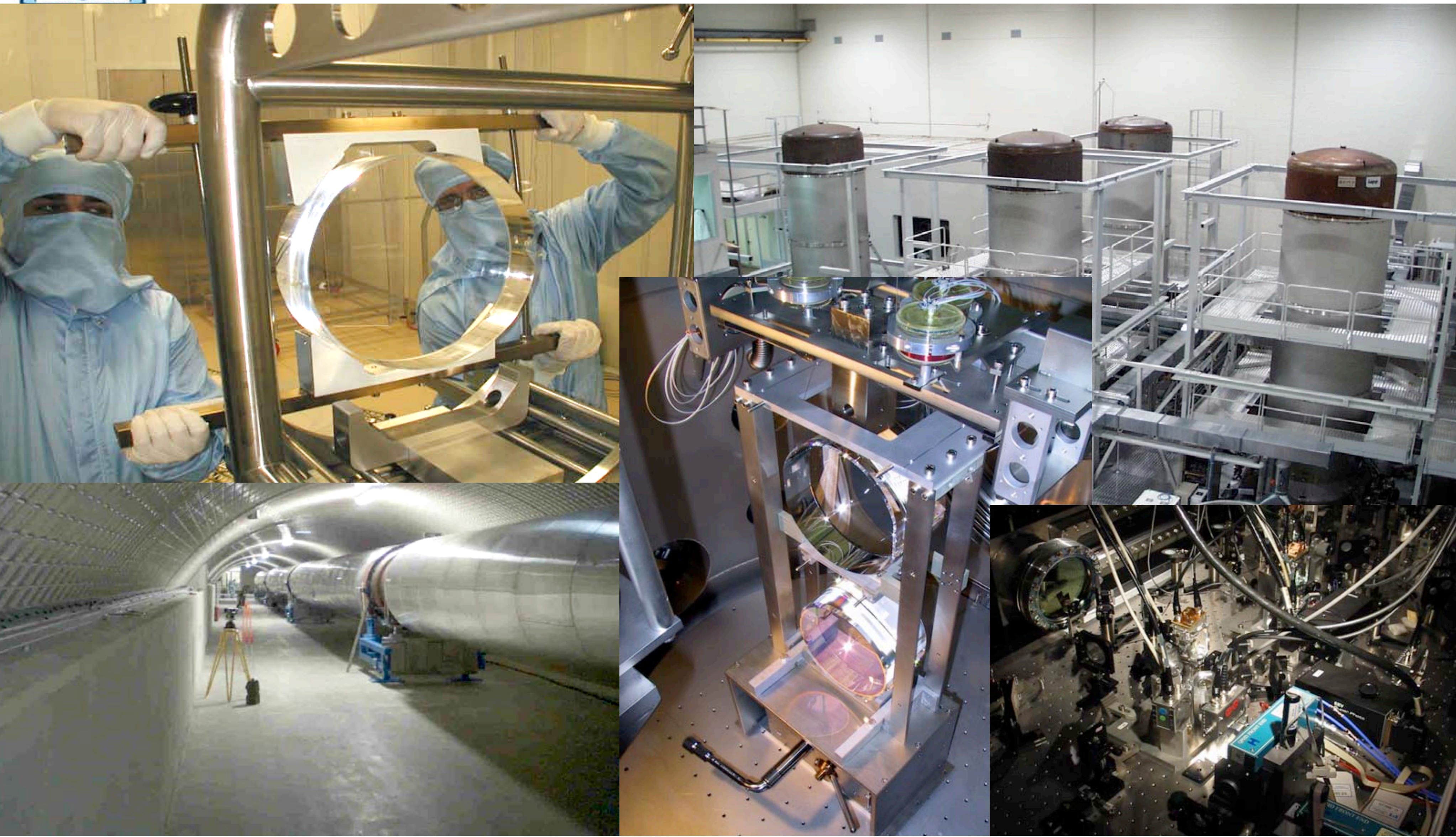
State-of-the-art Michelson Interferometer



Today’s network of GW detectors

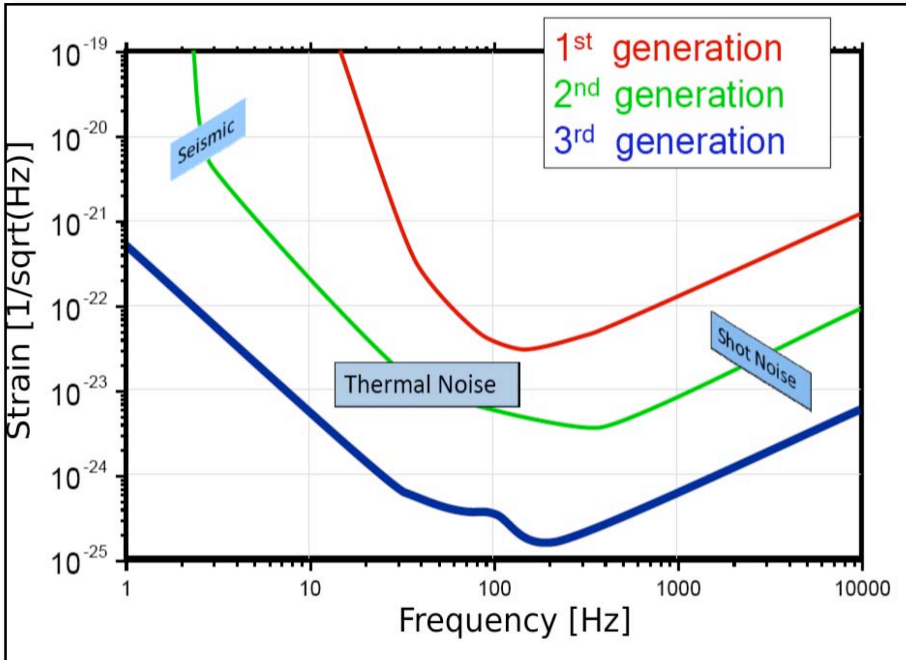
GEO600: measures the 600m long arms to an accuracy of 0.0001 proton diameter @ 500 Hz

S. Hild for the LSC: “The Status of GEO600”, Class. Quantum Gravity 23 (2006)

Status and future of GW observatories

- **1st** generation successfully completed:
  - Long duration observations (~1yr) in coincidence mode of 5 oberservatories.
  - Spin-down upper limit of the Crab-Pulsar beaten!
- **2nd** generation on the way:
  - End of design phase, construction about to start (or even 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



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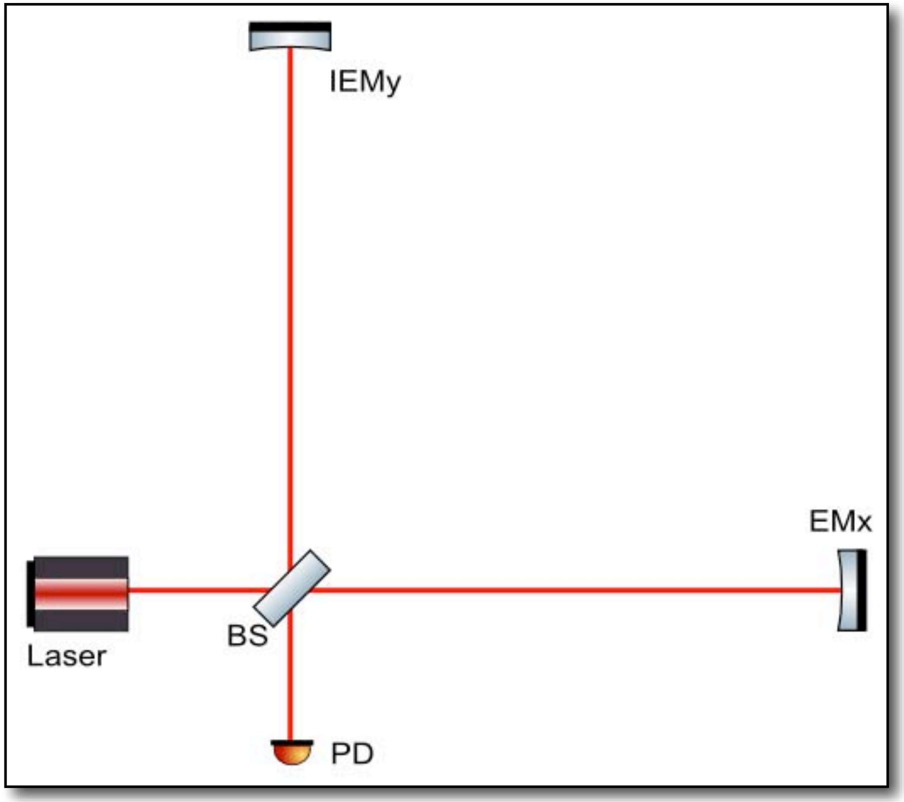
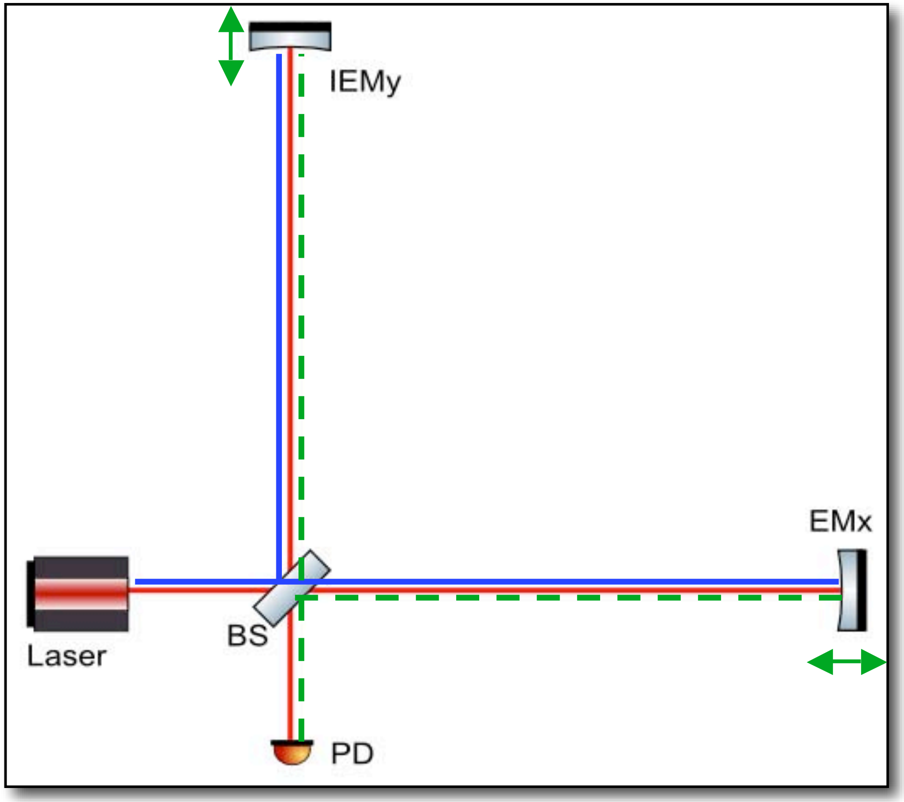
Interferometry: A simple Michelson

- How does a simple Michelson interferometer work?
- Aim: Measure lengths difference of the two perpendicular arms.
- Light from laser:
  - is split by beamsplitter,
  - travels along the arms,
  - bounces of the end mirrors
  - travels back beamsplitter
- Measurement is done by comparing the phase of the two returning beams.



Interferometry: A simple Michelson

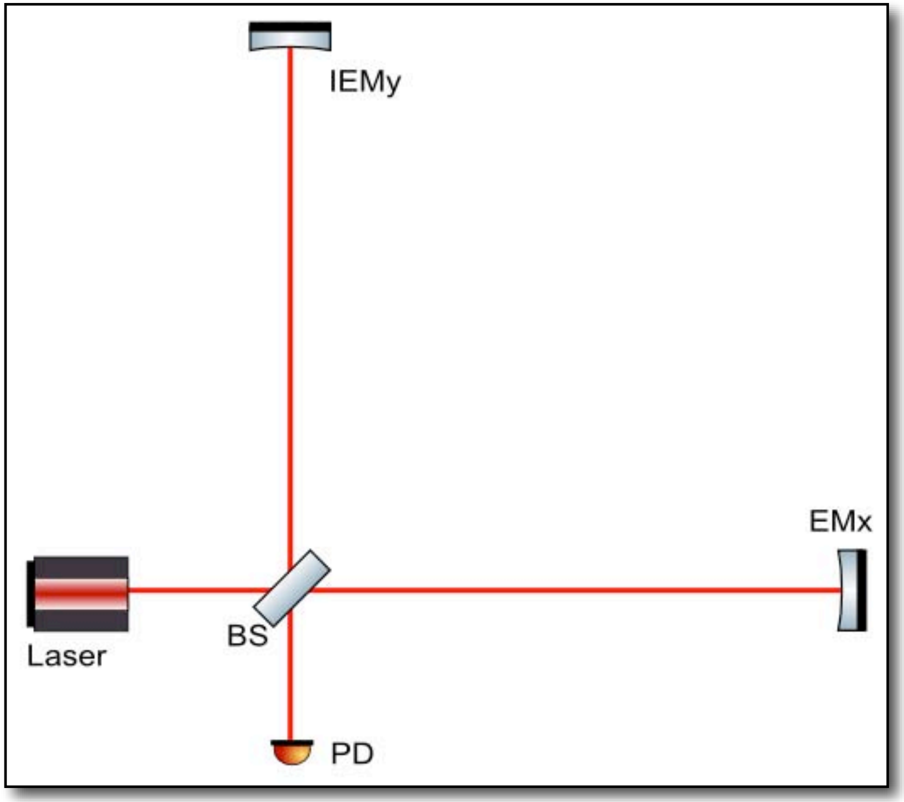
- Differential arm lengths changes can be described by the creation of phase modulation sidebands.
- Operation point = Dark fringe
  - Carrier light leaves the IFO towards the laser
  - Signal sidebands leaves towards the photodiode
- Many technical noises (frequency noise, laser amplitude noise) suppressed by common mode rejection.
- Null-measurement !!



Interferometry: A simple Michelson

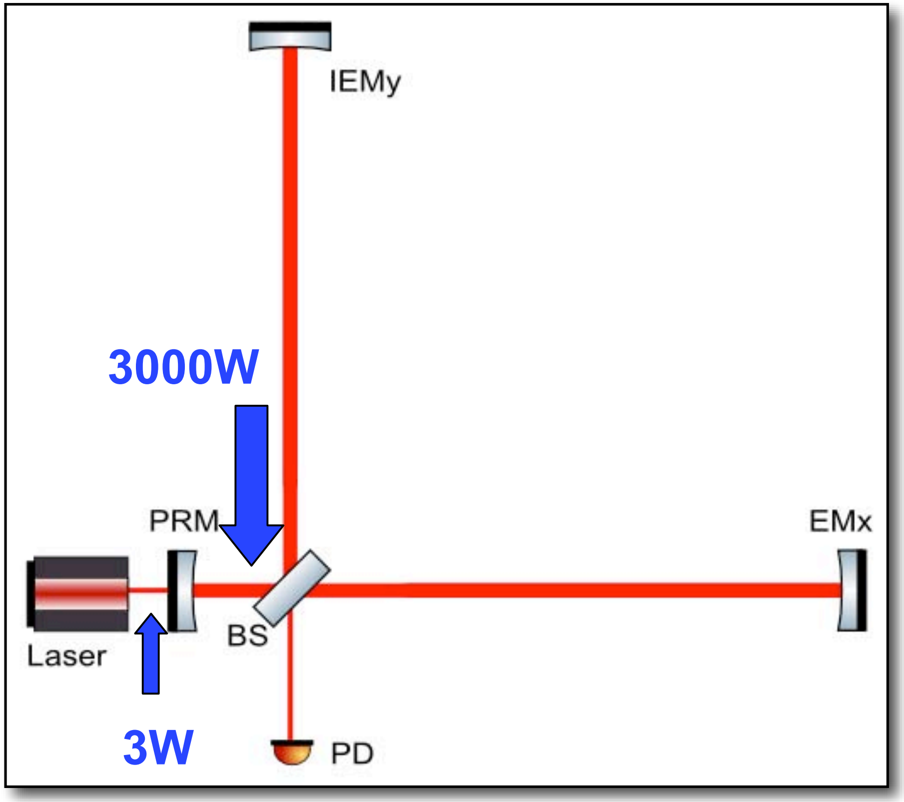
- Who can we improve our sensitivity to gravitational waves?
- GW signal scales with storage time of the light in the arms:
  - Increasing arm length
  - Make use of recycling techniques
- Major noise source limiting our sensitivity is shot noise.
  - Shot noise prop. sqrt(power)
  - GW signal scales linear with power

Our Goal:
• Increase storage time in the arms
• Increase circulating light power



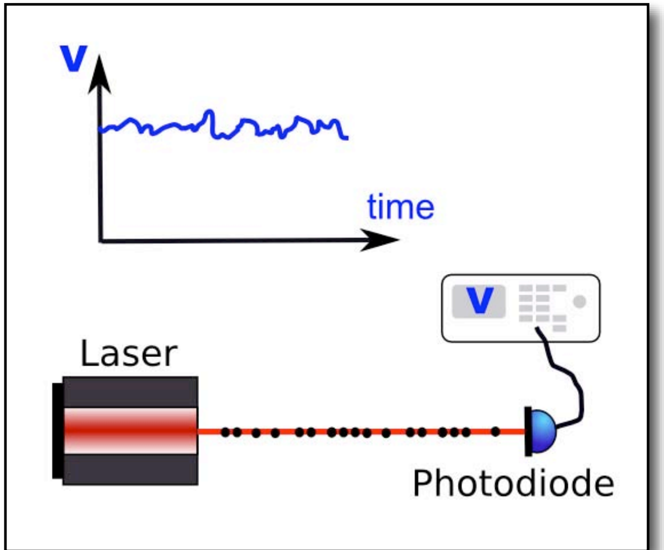
Interferometry: Power Recycling

- If operated on the dark fringe the Michelson looks from the laser like a mirror.
- Instead of 'wasting' light we insert a semi-transparent power-recycling mirror (PRM) to send the light back to the interferometer.
- In GEO600 a power recycling factor of 1000 is realised.

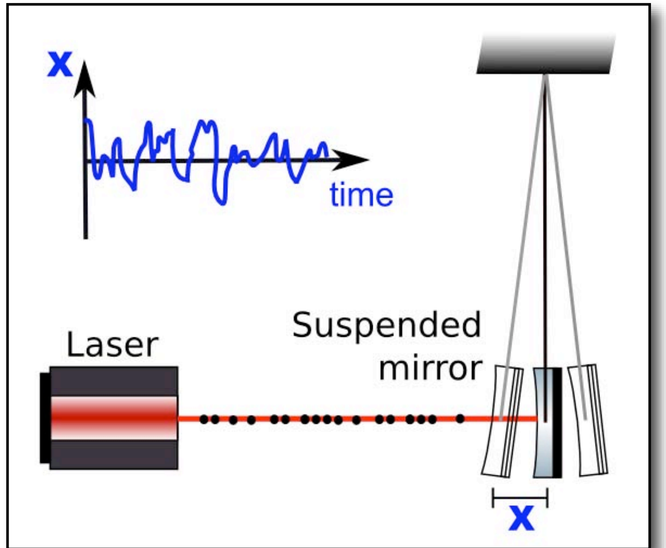


Quantum noise components

- 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

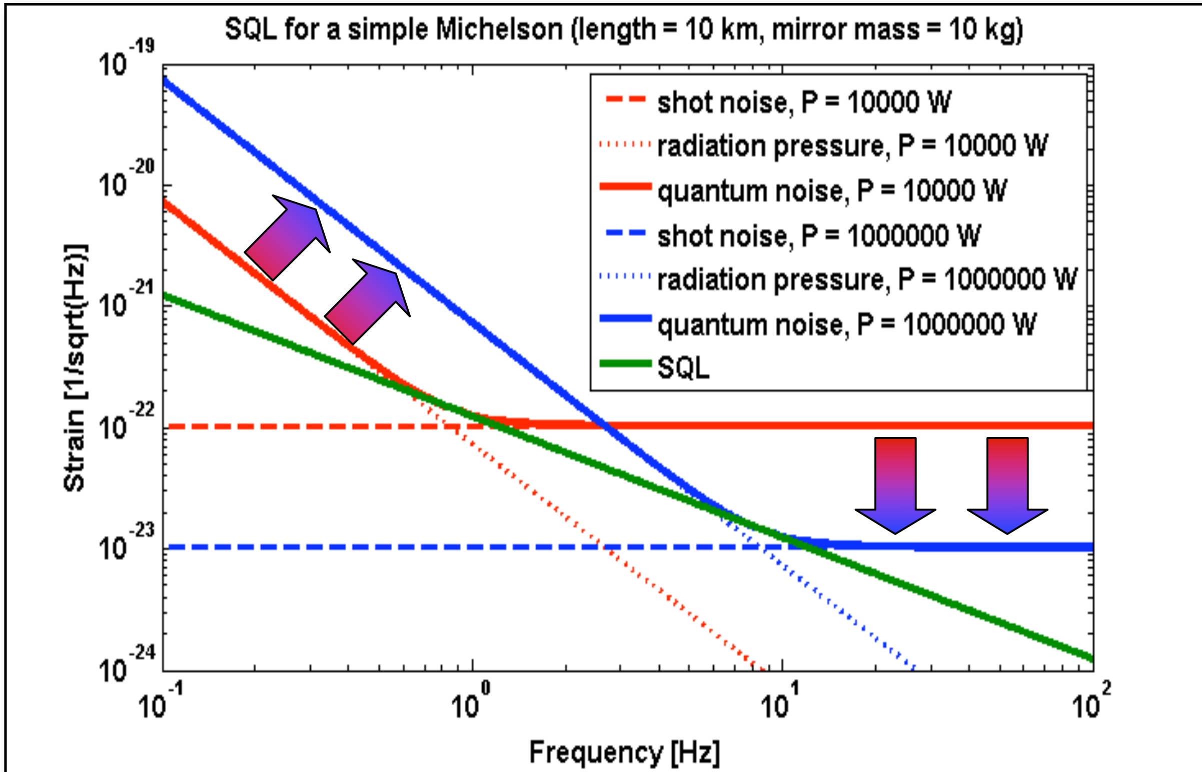
$$h_{sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$

optical power

Arm length

Mirror mass

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

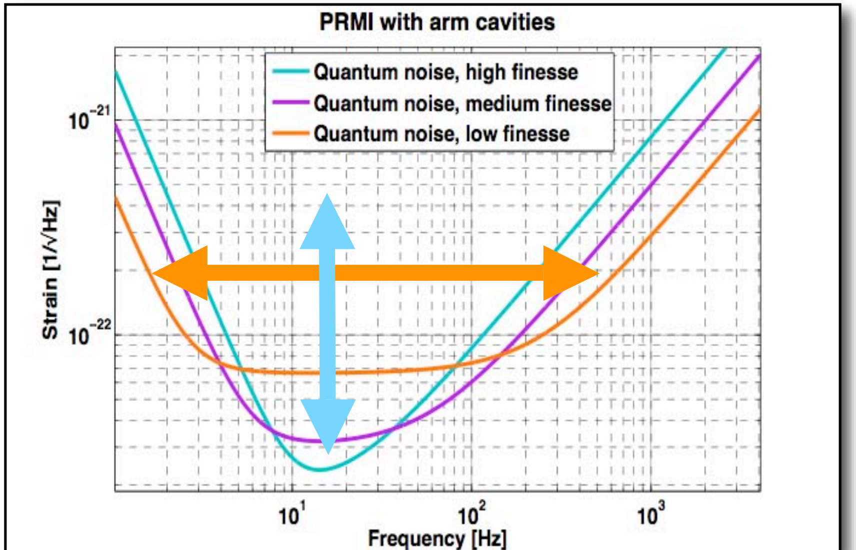


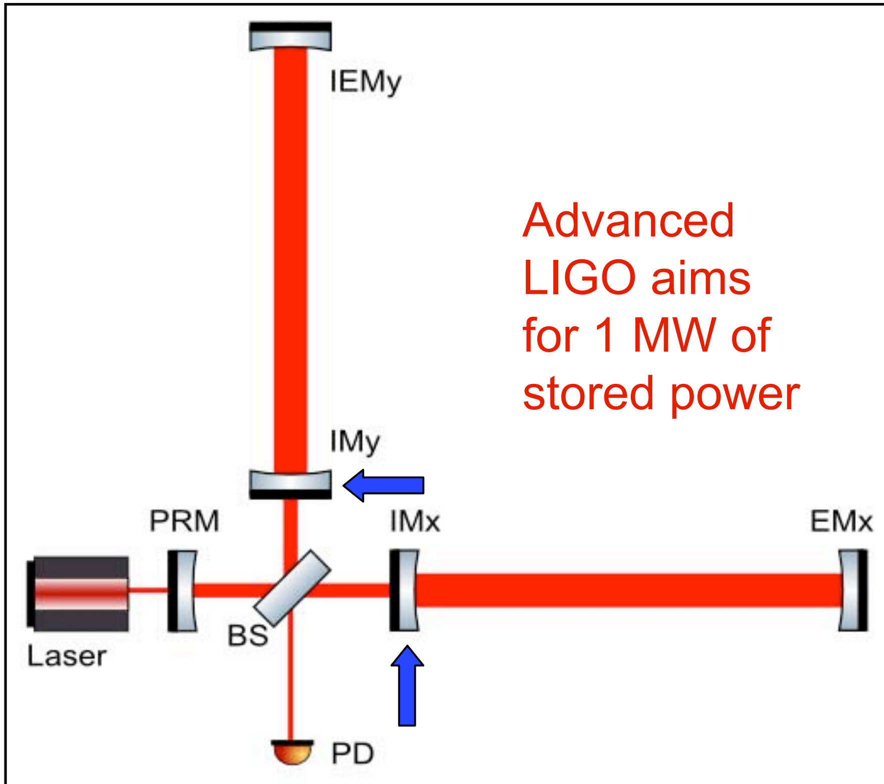
- The SQL is the minimal sum of shot noise and radiation pressure noise.
- Using a classical quantum measurement the SQL represents the lowest achievable noise.

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

Interferometry: Arm cavities

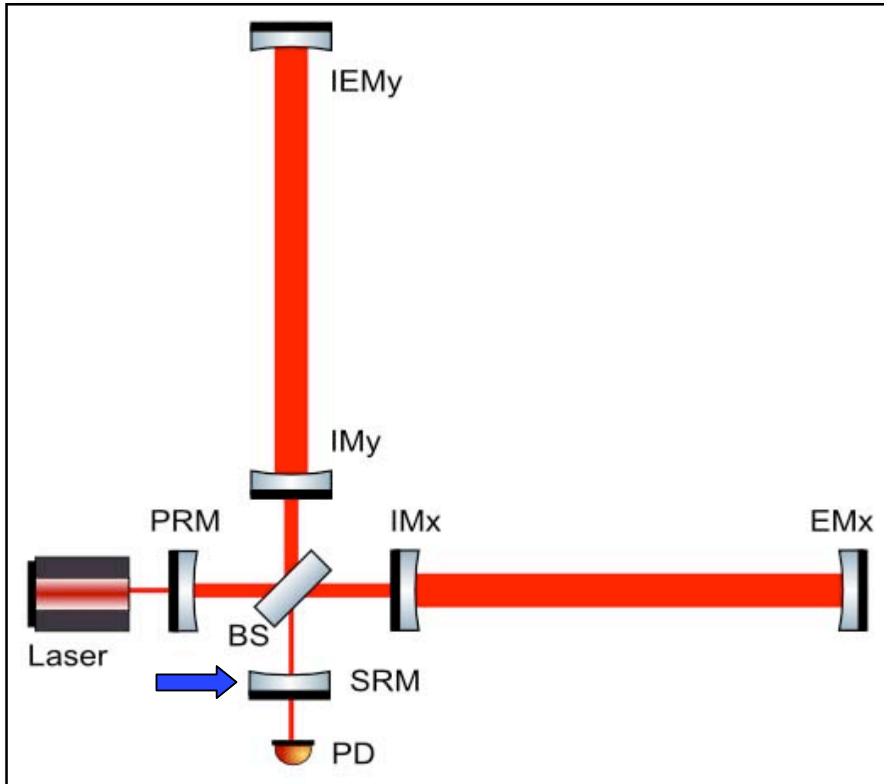
- Increasing the storage time in the arms by using arm cavities.
- Finesse of the arm cavities determines bandwidth of GW detector.



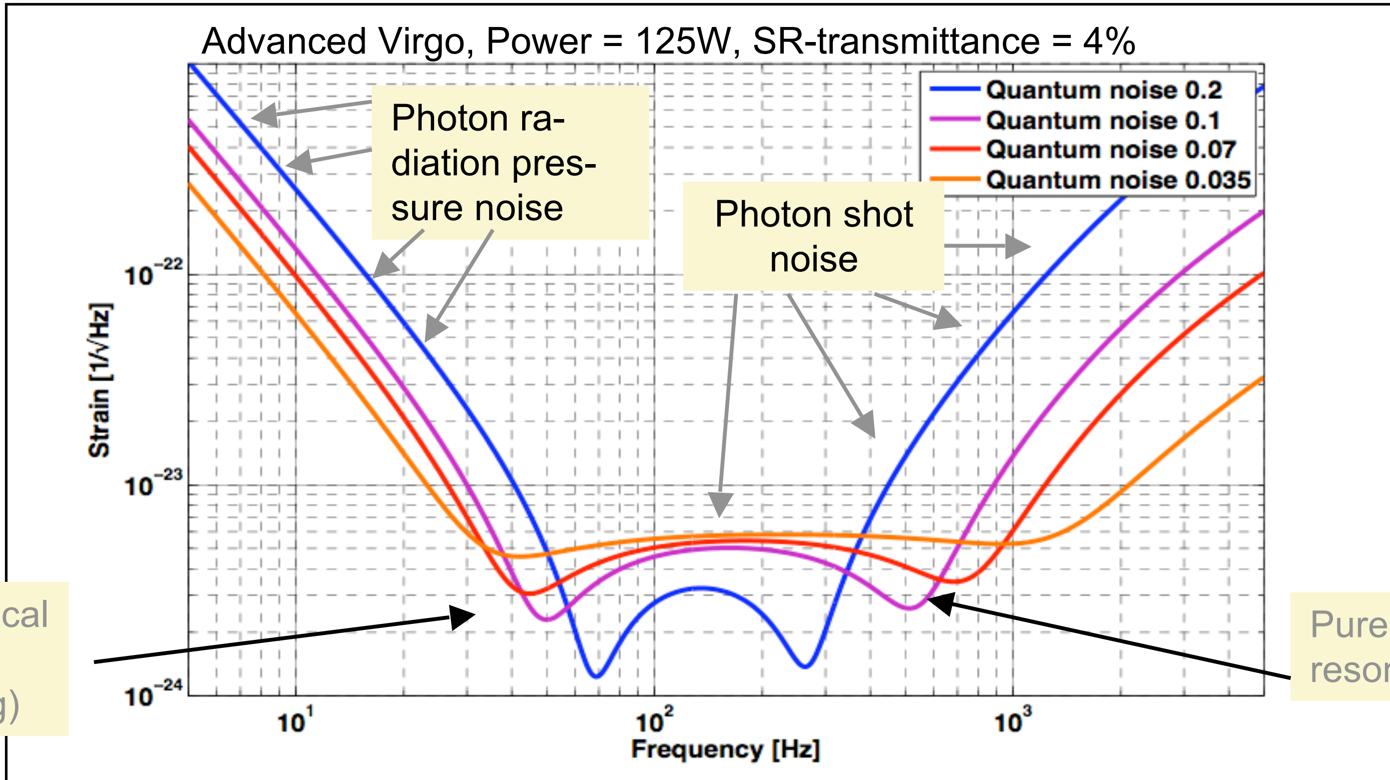


Interferometry: Signal Recycling

- Inserting a semi-transparent signal recycling mirror (SRM) at the output of the Michelson.
  - Increasing the signal storage time
- Signal Recycling allows to shape Quantum noise via two knobs:
  - Bandwidth
  - Frequency of maximal sensitivity
- Very handy for adjusting the detector sensitivity to astrophysical targets of interest.

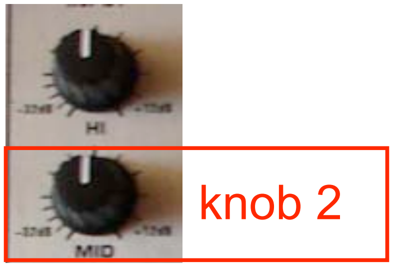


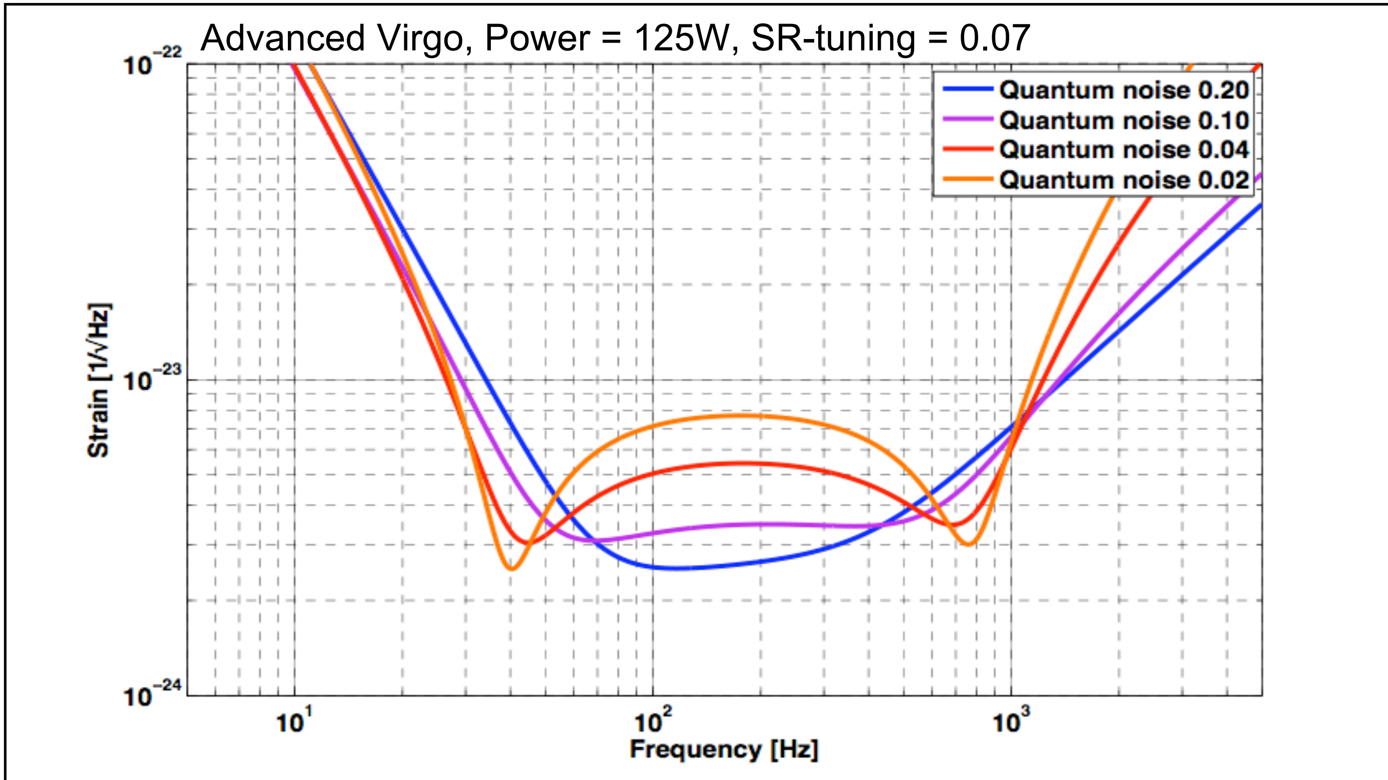
Signal-Recycling (de)tuning



➲ Modifying the Signal recycling detuning frequency by changing the position of the signal recycling mirror by a few nanometers.

Signal-Recycling mirror transmittance

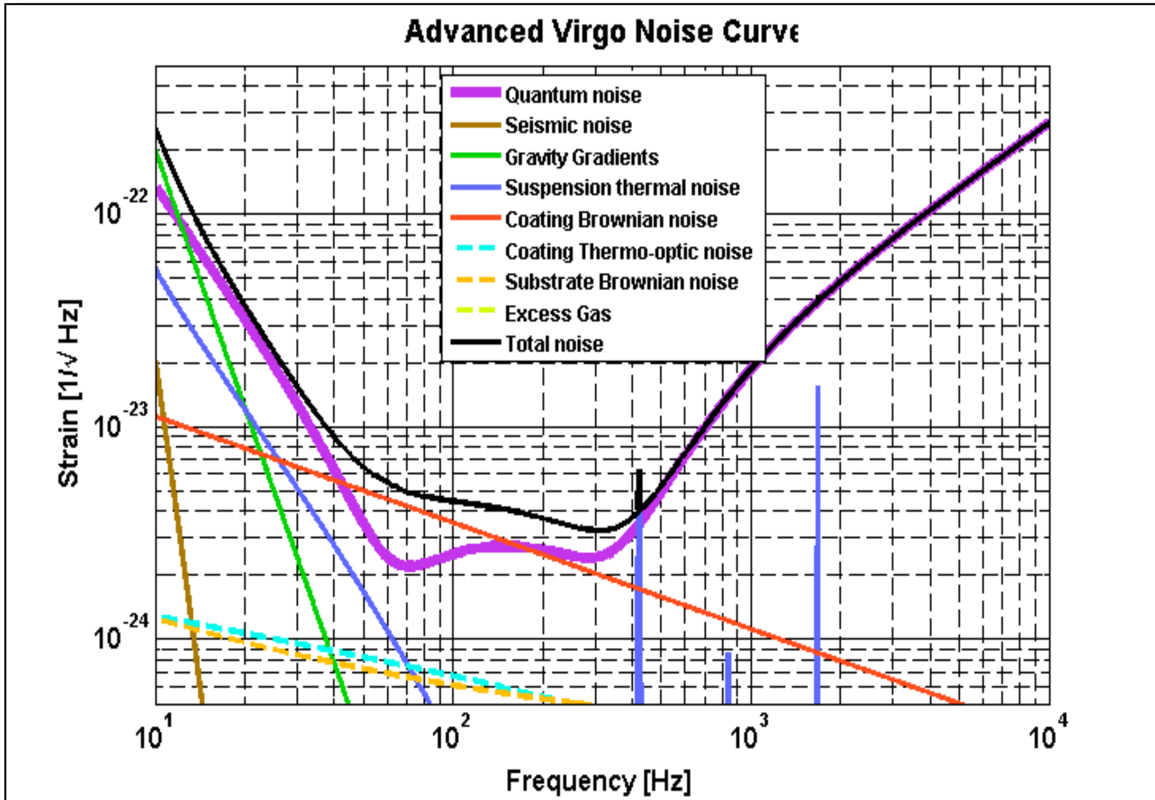




- Modifying the Signal recycling bandwidth by changing the reflectance of the signal recycling mirror by a few nanometers.

Fundamental noise limits for future GW detectors

- Future GW detectors (such as Advanced LIGO or Advanced Virgo) will be limited by **quantum noise** at nearly all frequencies of interest.
- The second major noise source is Brownian noise of the dielectric coating layers.
- Other noises that need to be treated with care:
  - Gravity gradient noise
  - Seismic noise
  - Suspension thermal noise



S. Hild et al: "Sensitivities curves for the Advanced Virgo Preliminary Design", Virgo note VIR-101A-08, available at https://pub3.ego-gw.it/codifier/index.php

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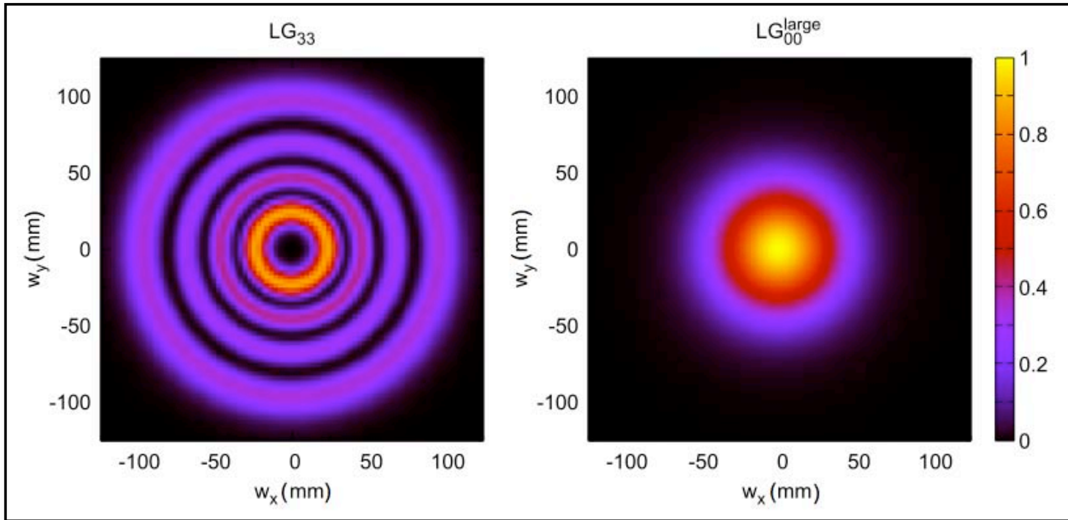
Laguerre Gauss modes to reduce thermal noise

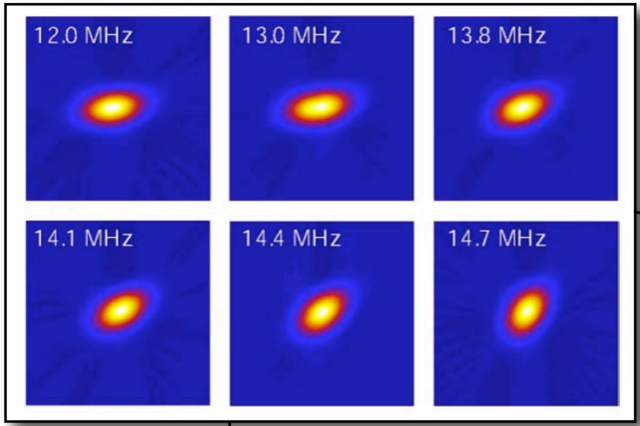
- Mirror thermal noise can be reduced by a factor of a few by using higher order LG modes instead of TEM_{00}
- By distribution the power more homogeneously over the mirror surface one can average better over the local thermal fluctuations
- We showed that interferometry (creation of errorsignal, misalignment effects etc) are similar for TEM_{00} and LG_{33}.



Chelkowski, Hild, Freise: PRD 79, 122002

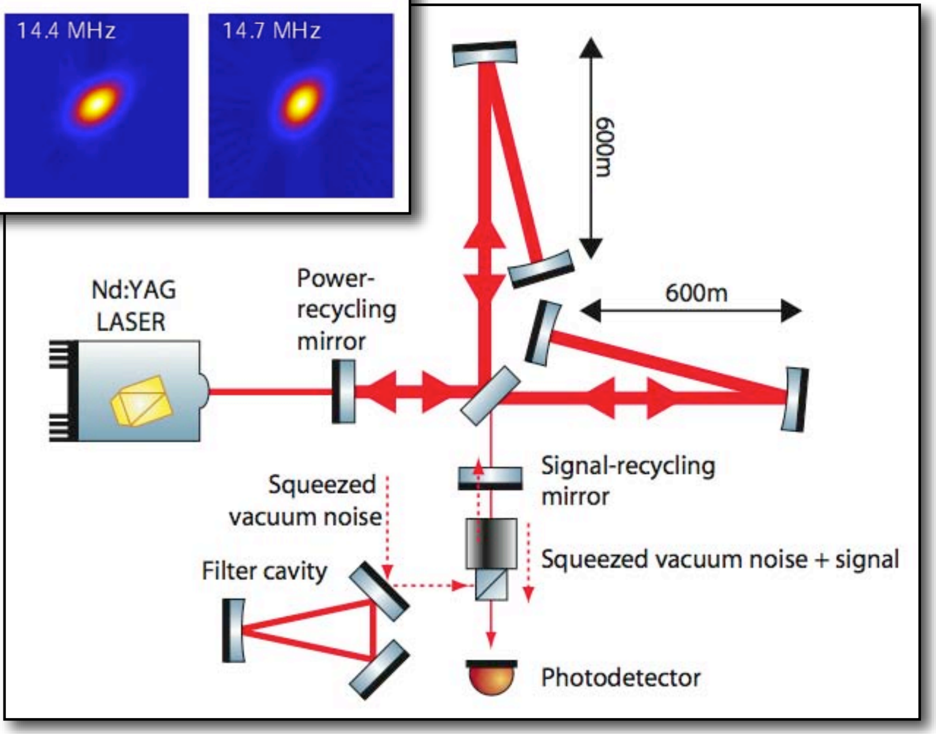
Injection of Squeezed Light

- 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.

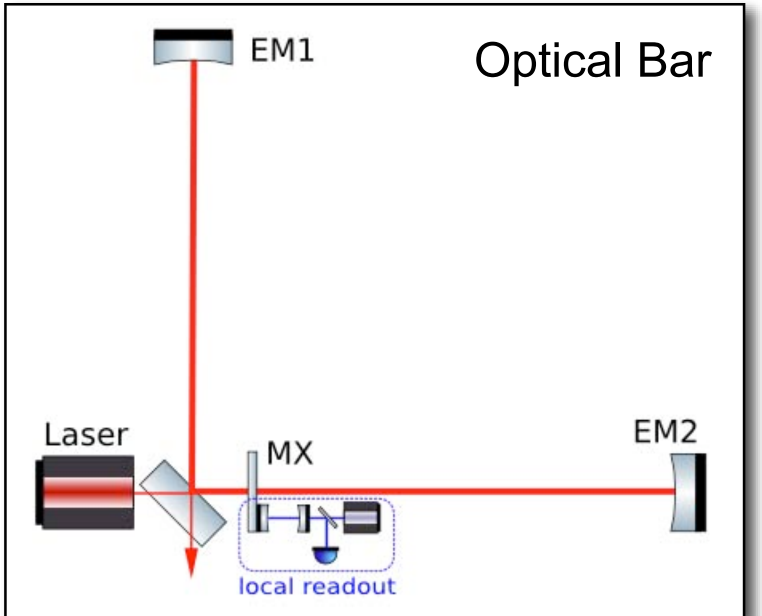


Chelkowski et al:

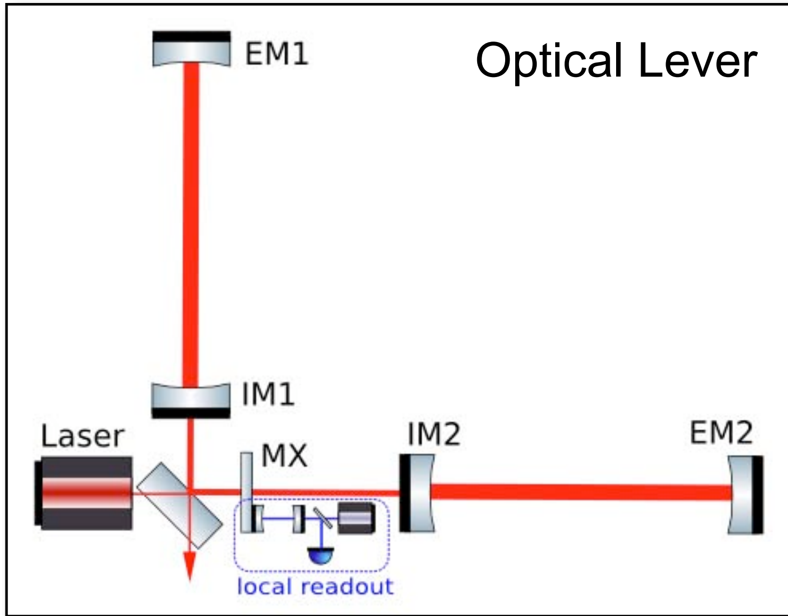
PRA 71, 013806



Qunatum-Non-Demolithion Techniques



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



F.Y. Khalili: "The 'ptical lever' intracavity readout scheme for gravitational-wave antennae",Phys. Lett. A 298 (2002).

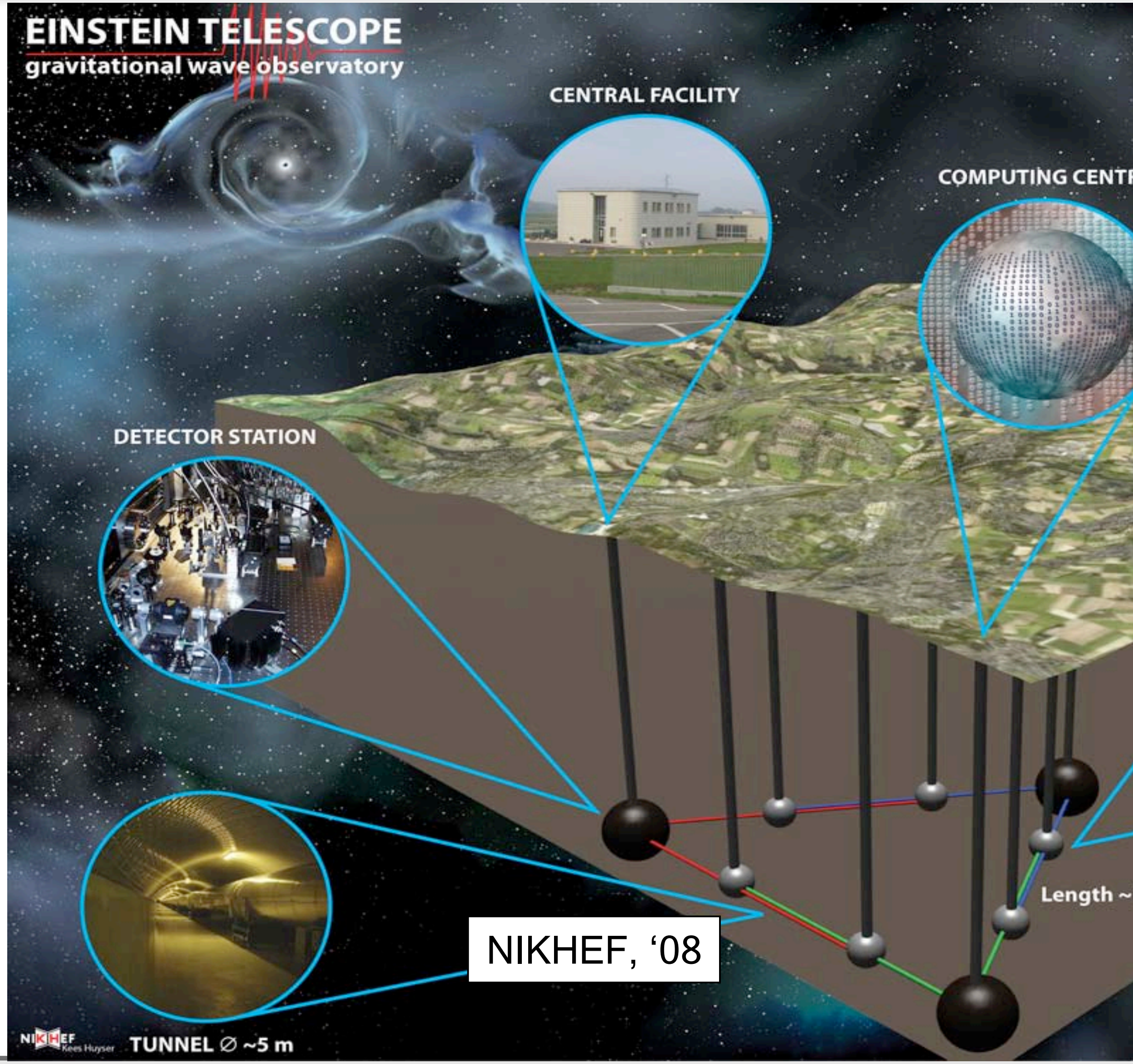
- Very light mirror (MX) is coupled to the movement of EM1 and EM2 via optical springs.
- MX can then locally read out by a small local meter without disturbing the quantum states in the main instrument (QND measurement).
- Optical lever: introducing arm cavities increases the movement of MX by the Finesse of the arm cavity.

Einstein Telescope

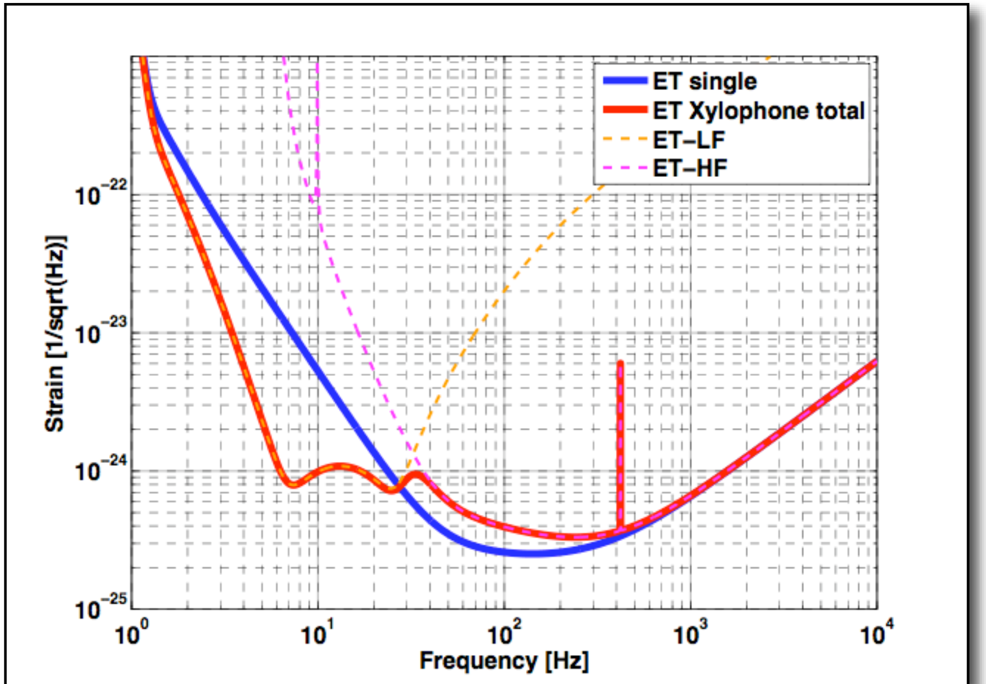
- Start around 2020(?)
- Underground location
- ~30km integrated tunnel length (?)
- Triangular shape

- **Myriads of new possibilities and challenges !!**

- **Plenty of new Science…**



Xylophone: More than one detector to cover the full bandwidth



S.Hild et al : arXiv:0906.2655

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Mirror material	Fused Silica	Silicon
Mirror diameter / thickness	62 cm / 30 cm	62 cm / 30 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	10 dB	10 dB
Beam radius	12 cm	12 cm
Beam shape	LG_{33}	TEM_{00}
Temperature	290 K	10 K
Suspension	Superattenuator	5 × 10 m
Seismic (for $f > 1$ Hz)	$1 \cdot 10^{-7}\,\mathrm{m}/f^2$	$5 \cdot 10^{-9}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	factor 50

Low Frequency IFO: low optical power, cryogenic test masses, sophisticated low frequency suspension, underground, heavy silicon test masses, laser at 1550nm.

High Frquency IFO: high optical power, room temperature, surface location, squeezed light

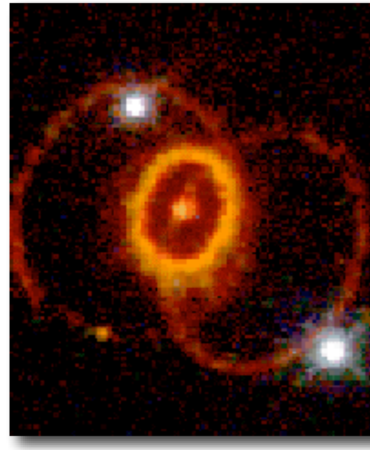
Summary

- Hunting gravitational waves requires plenty innovative optical technology.
- Pushing optics and interferometry towards their limits (and sometimes even beyond!) we set up an international network of extremely sensitive, km-long Michelson interferometers.
- There is an exciting future waiting for us. Many new optical technologies need to be developed, adapted, prototyped and implemented.

Thanks very much for your attention!

Gravitational waves: A new way of exploring the Universe

- Nearly all of our current knowledge of the cosmos is based on observation of electromagnetic radiation (visible light, radio astronomy, infrared, ...).
- Gravitational astronomy can provide completely new insight to the universe:
  - *Multimessenger observations:* We can learn more about things we already see in the electromagnetic spectrum by also seeing their GW emission (for instance supernovae).
  - *Exclusive GW observations:* There are objects that can only be seen by their GW emission



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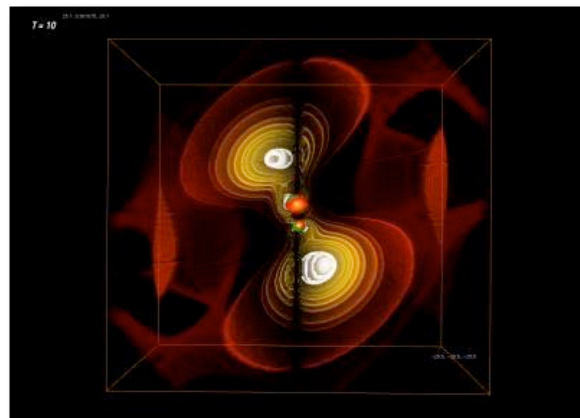
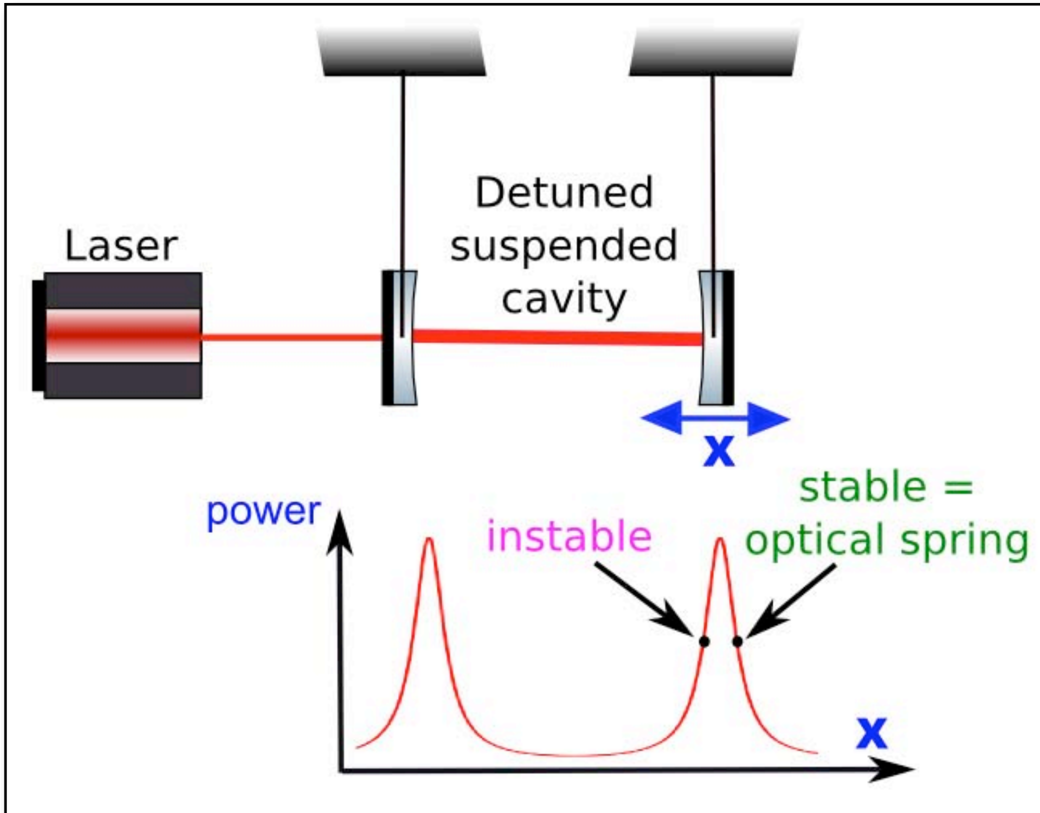


http://numrel.aei.mpg.de/Visualisations/

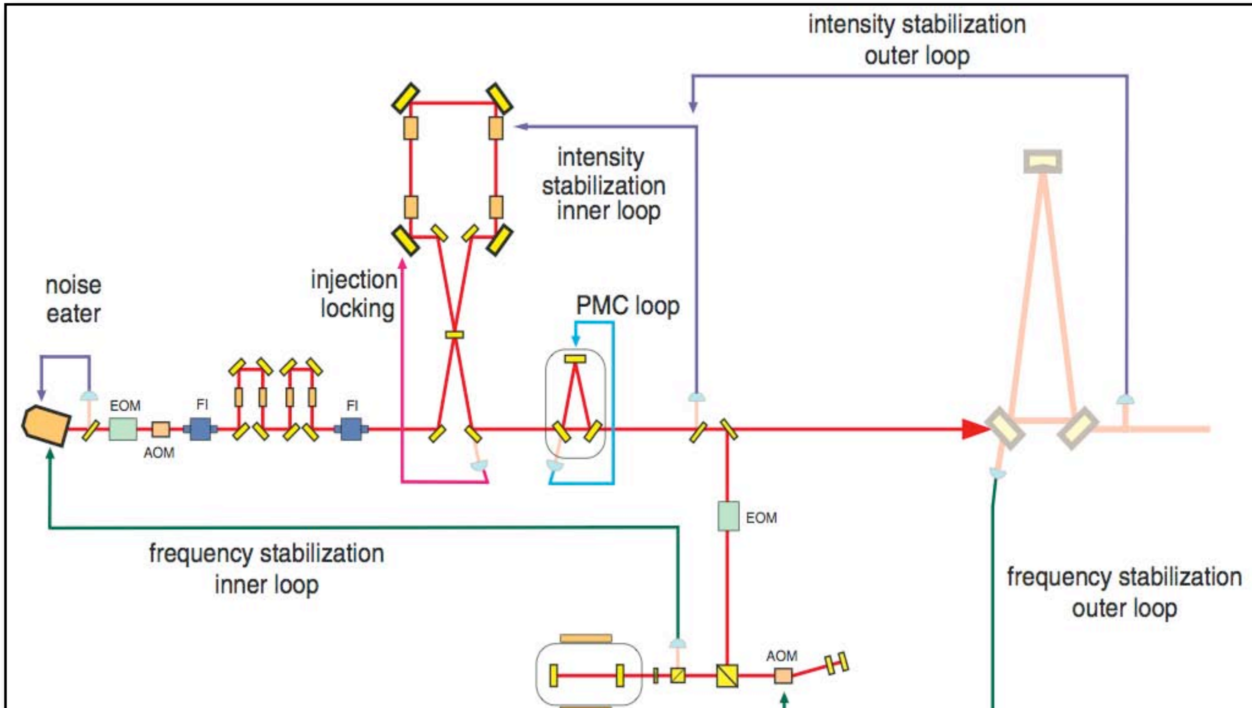
Optical Springs & Optical Rigidity

- 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.



High power lasers at 1064nm

- Advanced Ligo will feature a 200W laser.
  - Low power: NPRO
  - Medium power: amplifier
  - High power: Slave laser
- Prestabilized in in frequency and power
- Achieved RIN of about 3e-9.



B. Willke et al: CQG **25**, 114040