Interferometry beyond the Quantum Limit: **From Squeezed Vacuum, Stiff Photons and Other Ways to Trick Heisenberg.**

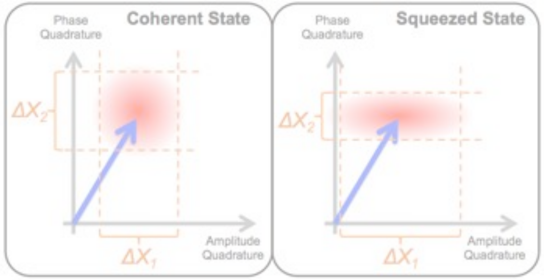
Stefan Hild

Overview

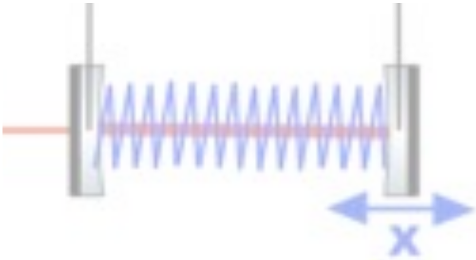
- Heisenberg, Braginsky and the Standard Quantum Limit

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

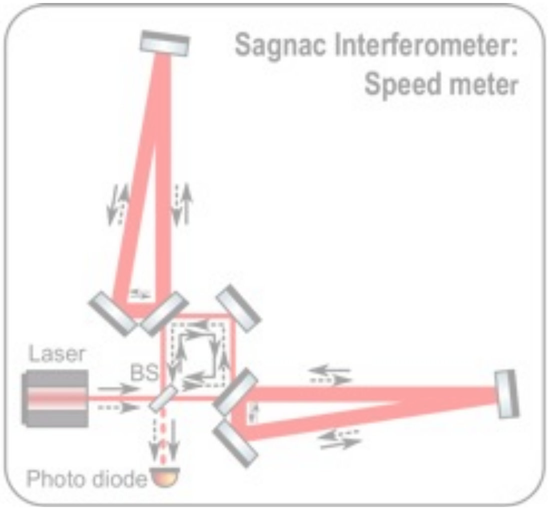
- Squeezed Vacuum



- Stiff Photons



- Why not measure observables that commute?

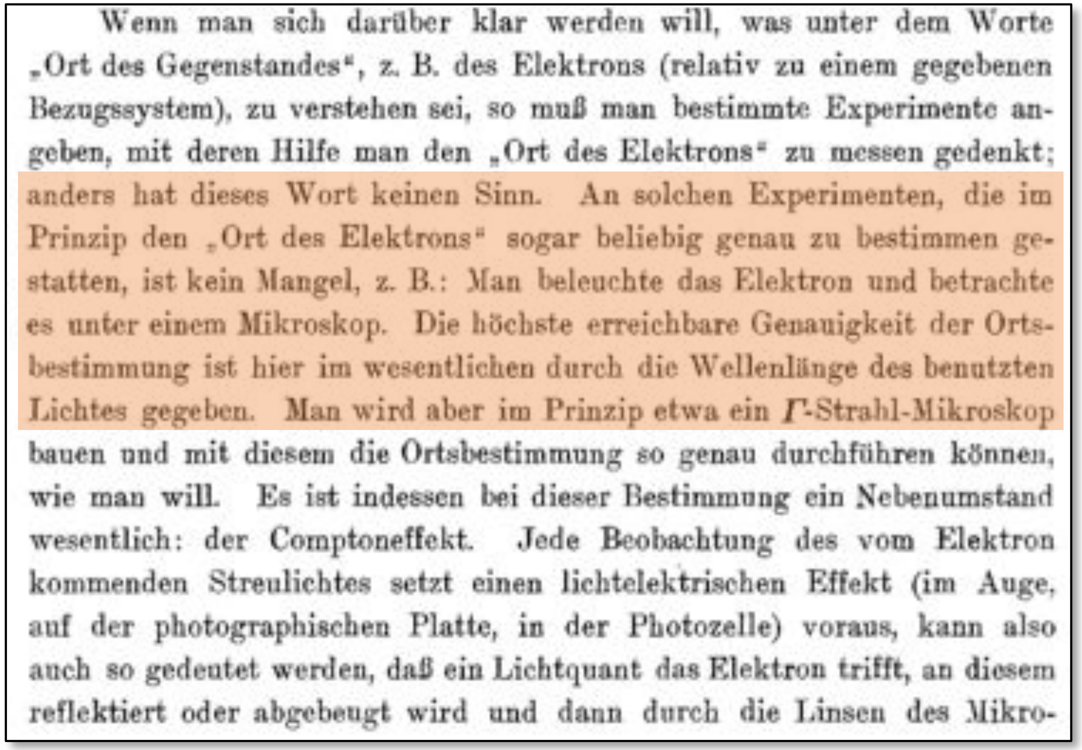


Heisenberg 1927

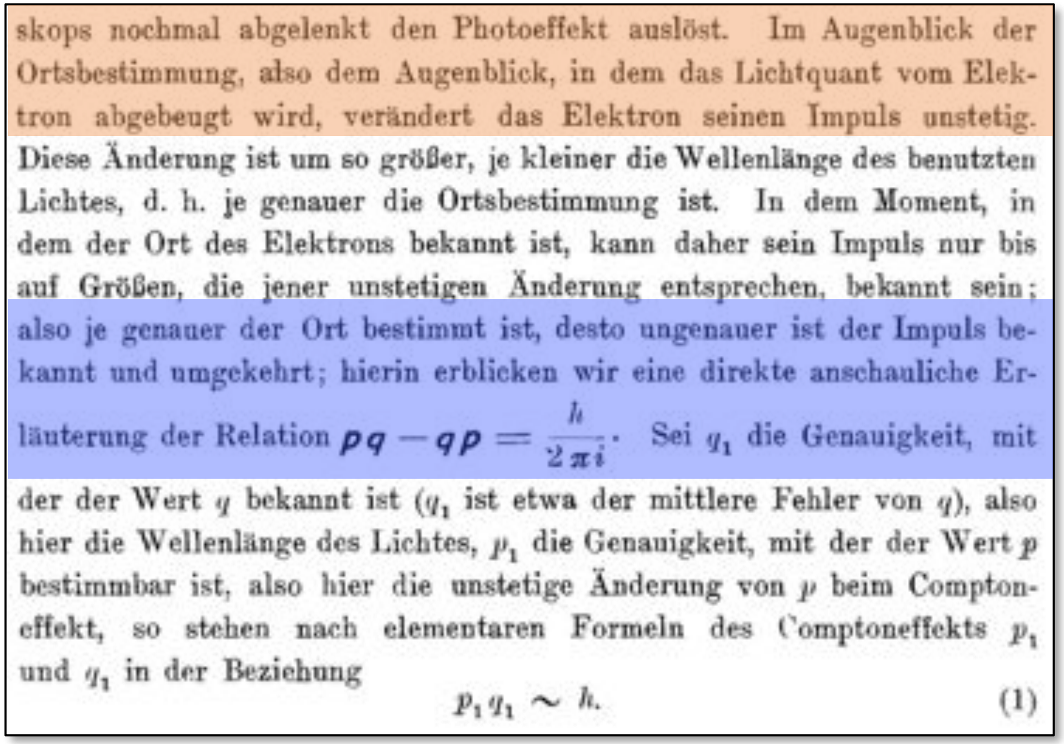
Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik.

Von **W. Heisenberg** in Kopenhagen.

Mit 2 Abbildungen. (Eingegangen am 23. März 1927.)



Wenn man sich darüber klar werden will, was unter dem Worte „Ort des Gegenstandes“, z. B. des Elektrons (relativ zu einem gegebenen Bezugssystem), zu verstehen sei, so muß man bestimmte Experimente angeben, mit deren Hilfe man den „Ort des Elektrons“ zu messen gedenkt; anders hat dieses Wort keinen Sinn. An solchen Experimenten, die im Prinzip den „Ort des Elektrons“ sogar beliebig genau zu bestimmen gestatten, ist kein Mangel, z. B.: Man beleuchte das Elektron und betrachte es unter einem Mikroskop. Die höchste erreichbare Genauigkeit der Ortsbestimmung ist hier im wesentlichen durch die Wellenlänge des benutzten Lichtes gegeben. Man wird aber im Prinzip etwa ein Γ-Strahl-Mikroskop bauen und mit diesem die Ortsbestimmung so genau durchführen können, wie man will. Es ist indessen bei dieser Bestimmung ein Nebenumstand wesentlich: der Comptoneffekt. Jede Beobachtung des vom Elektron kommenden Streulichtes setzt einen lichtelektrischen Effekt (im Auge, auf der photographischen Platte, in der Photozelle) voraus, kann also auch so gedeutet werden, daß ein Lichtquant das Elektron trifft, an diesem reflektiert oder abgebeugt wird und dann durch die Linsen des Mikro-



skops nochmal abgelenkt den Photoeffekt auslöst. Im Augenblick der Ortsbestimmung, also dem Augenblick, in dem das Lichtquant vom Elektron abgebeugt wird, verändert das Elektron seinen Impuls unstetig. Diese Änderung ist um so größer, je kleiner die Wellenlänge des benutzten Lichtes, d. h. je genauer die Ortsbestimmung ist. In dem Moment, in dem der Ort des Elektrons bekannt ist, kann daher sein Impuls nur bis auf Größen, die jener unstetigen Änderung entsprechen, bekannt sein; also je genauer der Ort bestimmt ist, desto ungenauer ist der Impuls bekannt und umgekehrt; hierin erblicken wir eine direkte anschauliche Erläuterung der Relation $pq - qp = \frac{h}{2\pi i}$. Sei q_1 die Genauigkeit, mit der der Wert q bekannt ist (q_1 ist etwa der mittlere Fehler von q), also hier die Wellenlänge des Lichtes, p_1 die Genauigkeit, mit der der Wert p bestimmbar ist, also hier die unstetige Änderung von p beim Comptoneffekt, so stehen nach elementaren Formeln des Comptoneffekts p_1 und q_1 in der Beziehung

$$p_1 q_1 \sim h. \qquad (1)$$

Detecting Gravitational Waves

- In order to detect GW you need to very accurately measure their effect onto the position of test masses.
- First you need to make your test masses quieter than what you want to measure.
- Secondly, you need to readout out the strain to the required precision without (!) introducing 'too much' additional noise.

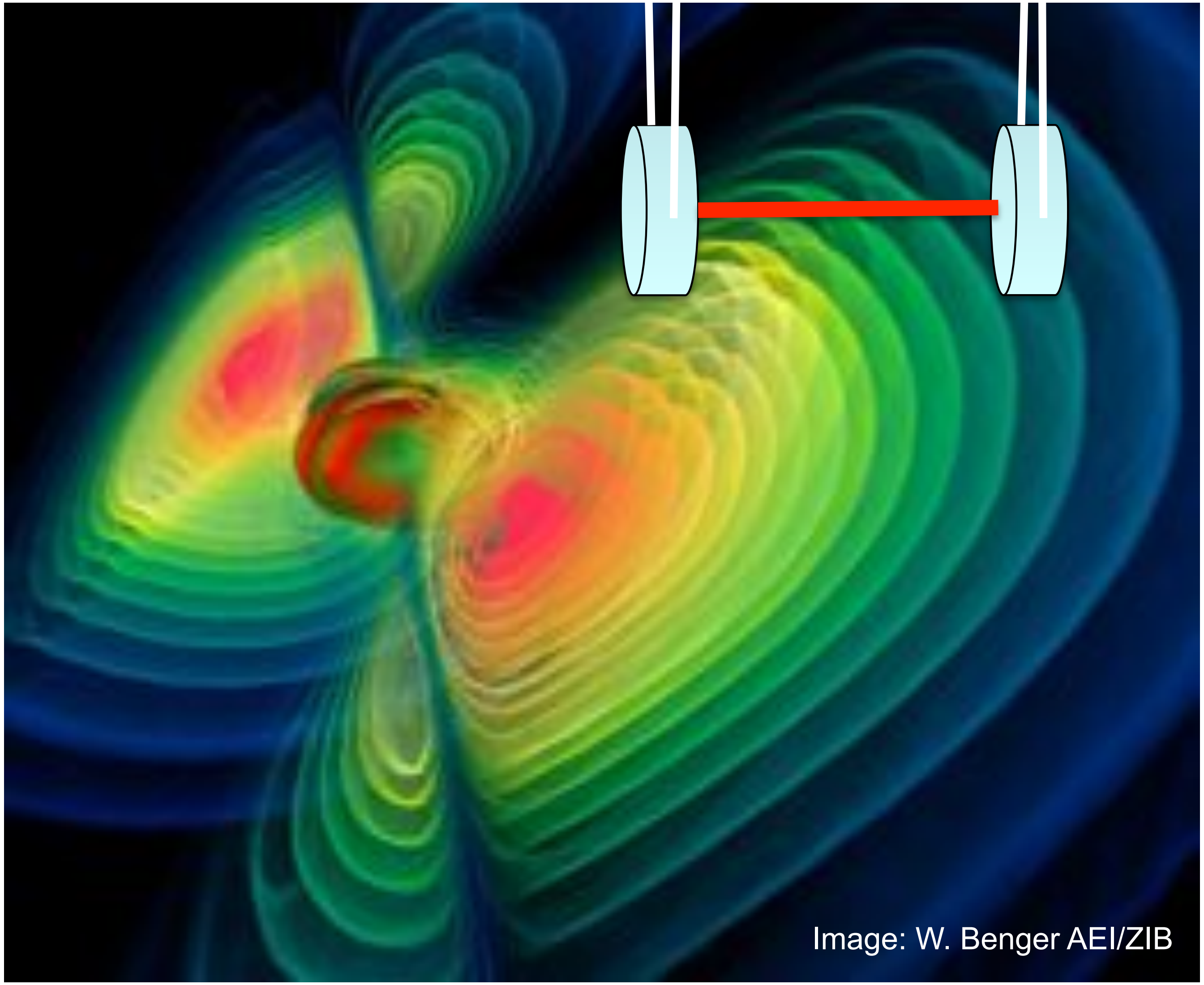


Image: W. Benger AEI/ZIB

The Standard quantum limit

- Standard Quantum Limit of a free mass is equivalent to Heisenberg uncertainty.
- Arises when one tries to detect gravitational wave by continuously measuring free-mass displacement, since

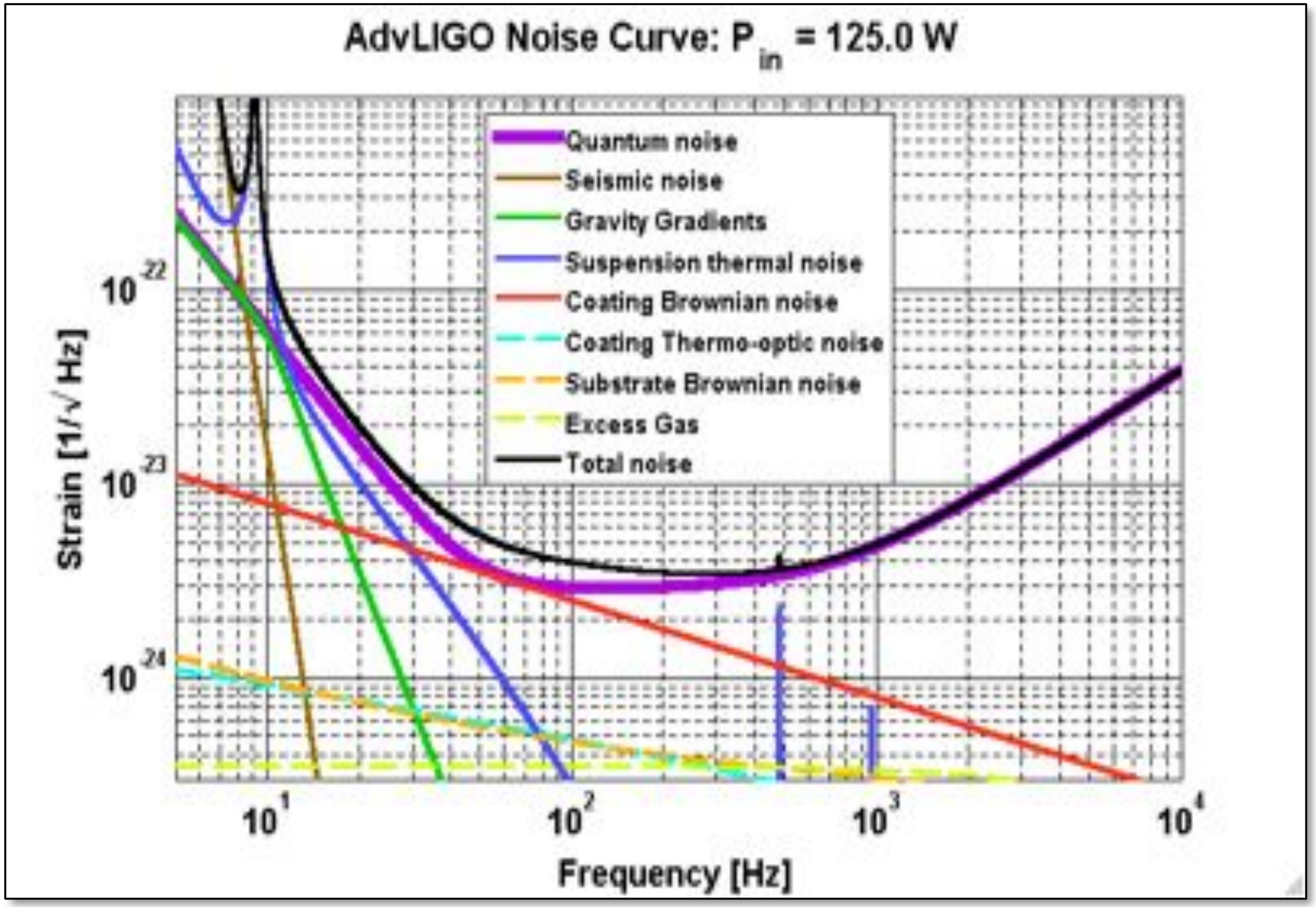
$$[\hat{x}(t),\hat{x}(t')]\neq 0$$

  - Precise measurement on x has to perturb p. Perturbation in p converts to future error in x.

- In our case: Light fields enforce Heisenberg uncertainty through complementarity between Shot noise and Radiation Pressure noise.

Why is Quantum Noise Reduction '*soooo*' important?

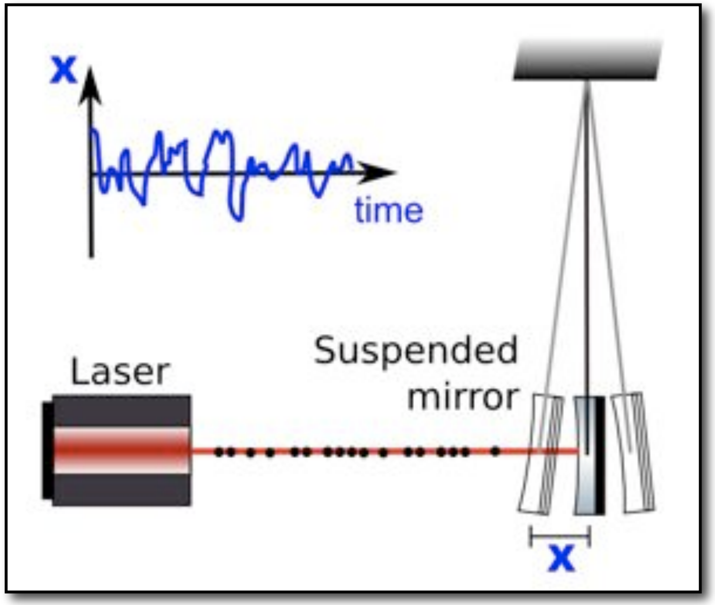
- For future interferometers Quantum noise is the ***main*** limiting noise source.
- Example: Broadband (tuned Signal Recycling) configuration of Advanced LIGO
- For all frequencies above 12Hz Quantum noise is the limiting noise.



Scenario 1b from LIGO-T070247-01-I

What is quantum noise?

- 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 radiation pressure noise

wavelength

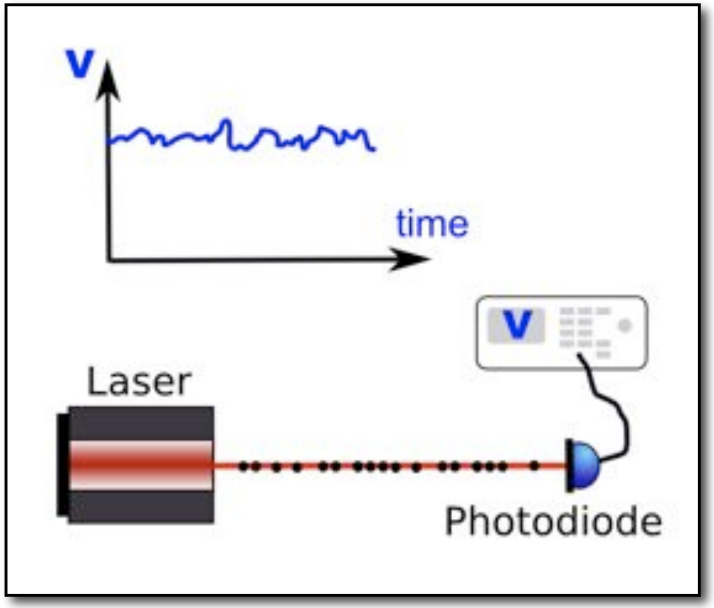
$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

optical power

Arm length

Mirror mass

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



photon shot noise

The Standard Quantum Limit (SQL)

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

wavelength

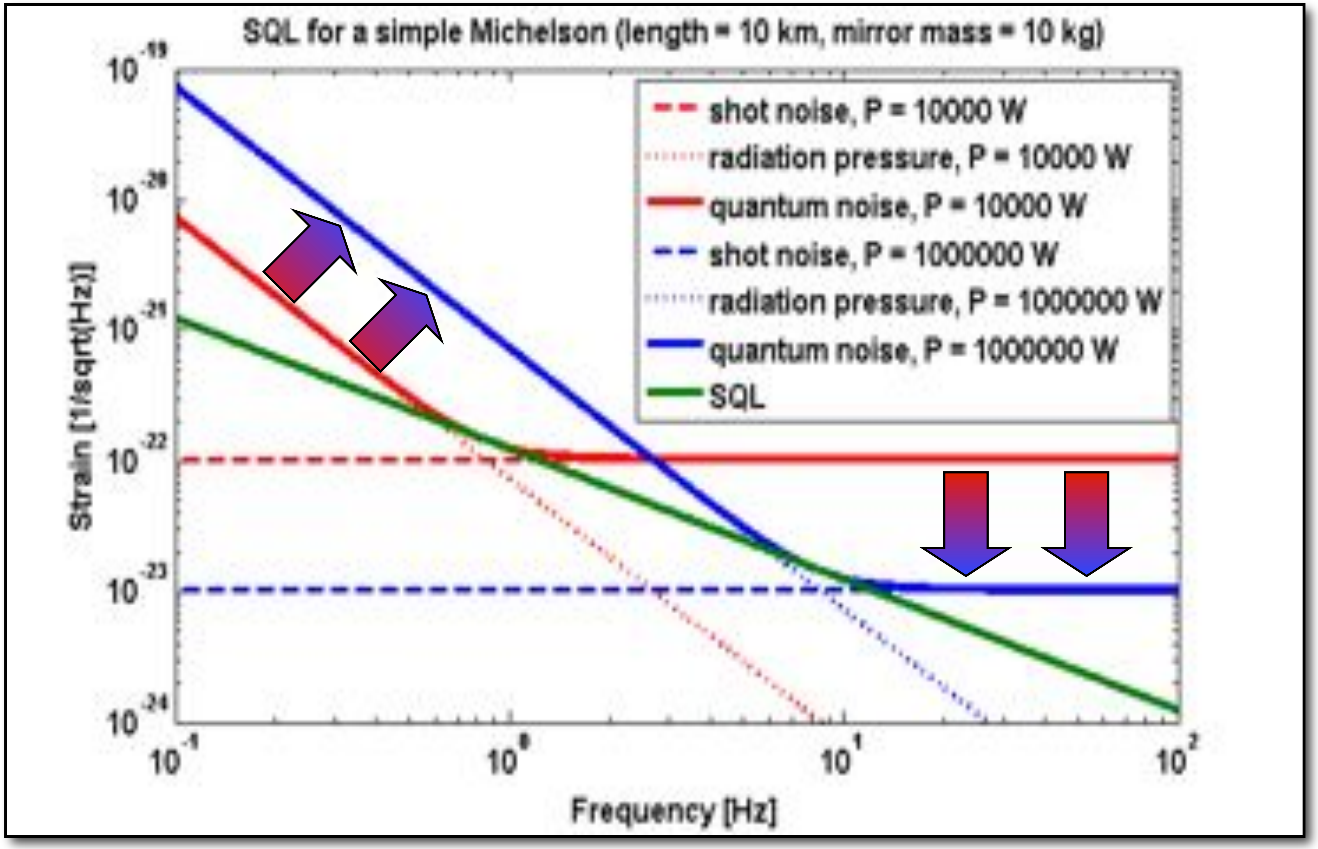
$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

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 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)

The Mathematical approach

- Quantitative description of an electrical field ***E*** at the position ***r*** and time *t*:

$$\boldsymbol{E}(\boldsymbol{r},t) = E_0\left[a(\boldsymbol{r})\mathrm{e}^{-\mathrm{i}\omega t} - a(\boldsymbol{r})^*\mathrm{e}^{+\mathrm{i}\omega t}\right]\boldsymbol{p}(\boldsymbol{r})$$

$$a(\boldsymbol{r}) = a_0(\boldsymbol{r})\mathrm{e}^{\mathrm{i}\phi(\boldsymbol{r})}$$

complex amplitude

angular frequency

polarisation

phase

- We can now introduce two new 'properties':

$$X_1(\boldsymbol{r}) = a^*(\boldsymbol{r}) + a(\boldsymbol{r})$$

$$X_2(\boldsymbol{r}) = \mathrm{i}\left[a^*(\boldsymbol{r}) - a(\boldsymbol{r})\right]$$

The Mathematical approach (2)

$$X_1(\boldsymbol{r}) = a^*(\boldsymbol{r}) + a(\boldsymbol{r})$$ amplitude quadrature

$$X_2(\boldsymbol{r}) = \mathrm{i}\,[a^*(\boldsymbol{r}) - a(\boldsymbol{r})]$$ phase quadrature

- Using X_1 and X_2 we can rewrite the electrical field:

$$\boxed{\boldsymbol{E}(\boldsymbol{r},t) = E_0\,[X_1 \cos{(\omega t)} - X_2 \sin{(\omega t)}]\,\boldsymbol{p}(\boldsymbol{r},\mathrm{t})}$$

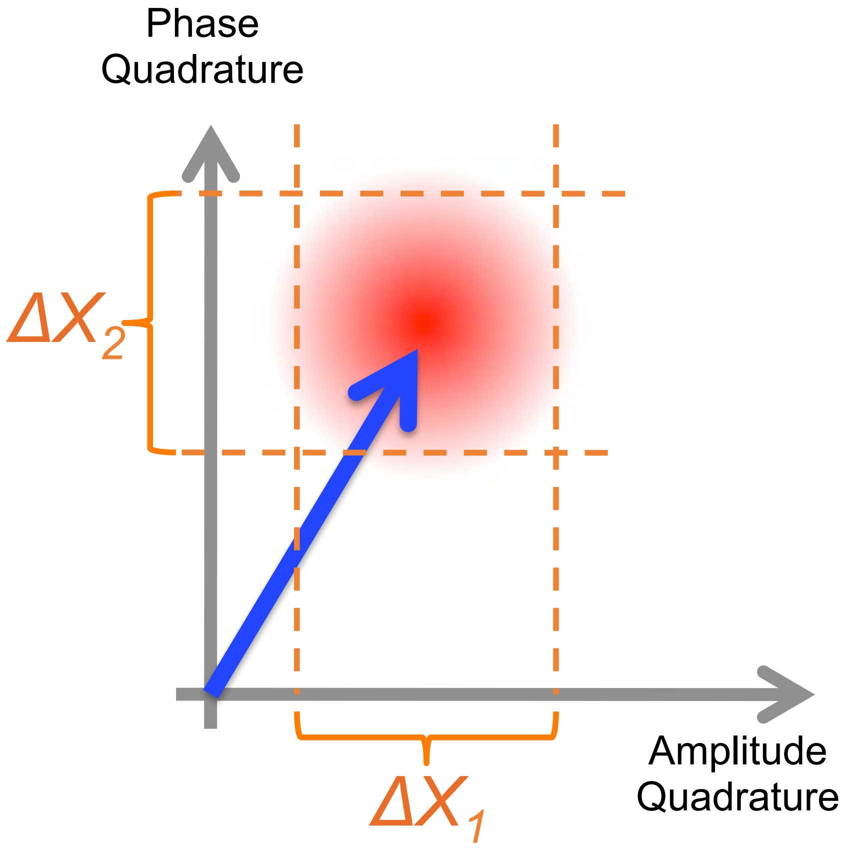
- Finally, we have to introduce a quantisation of the electrical field:

$$\hat{X}_1 = \hat{a}^\dagger + \hat{a}$$ amplitude quadrature operator

$$\hat{X}_2 = \mathrm{i}\left(\hat{a}^\dagger - \hat{a}\right)$$ phase quadrature operator

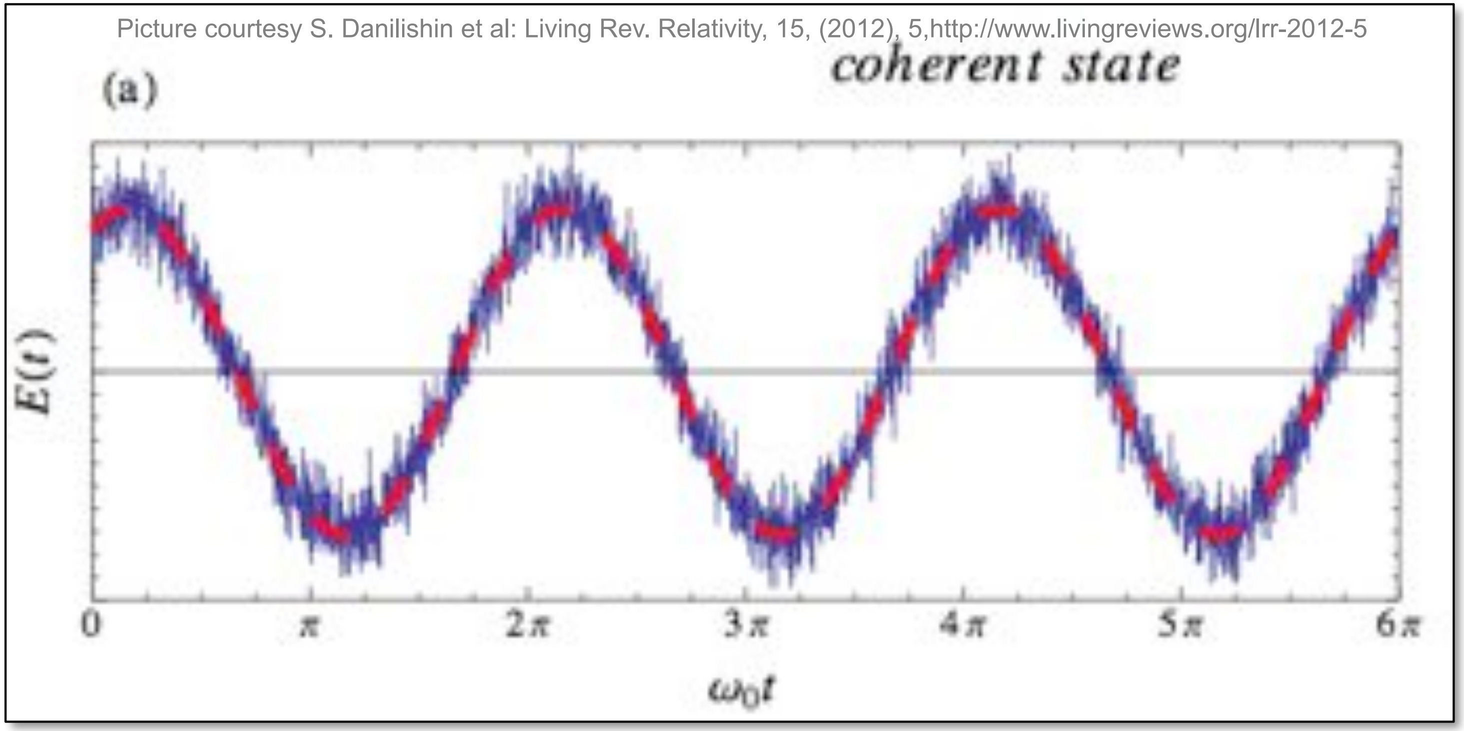
Introducing the Ball-on-a-stick concept

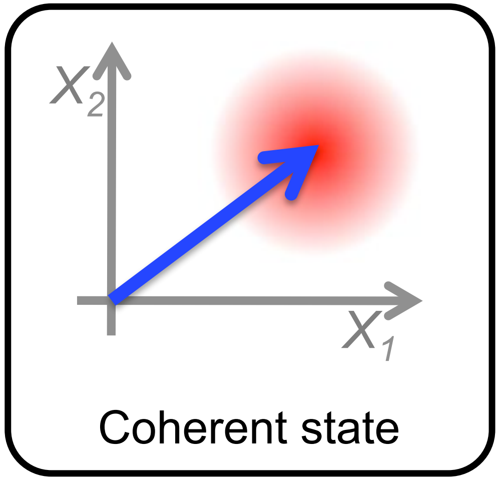
- Let’s try to convert the quadrature idea into a picture:
- A laser sends out light with an average frequency and amplitude. => This is the blue arrow.
- However, individual photons have a uncertainty, i.e. may have slightly different frequency or amplitude. => This is indicated by the red ball.



Ball-on-a-Stick vs Timeseries

Picture courtesy S. Danilishin et al: Living Rev. Relativity, 15, (2012), 5,http://www.livingreviews.org/lrr-2012-5

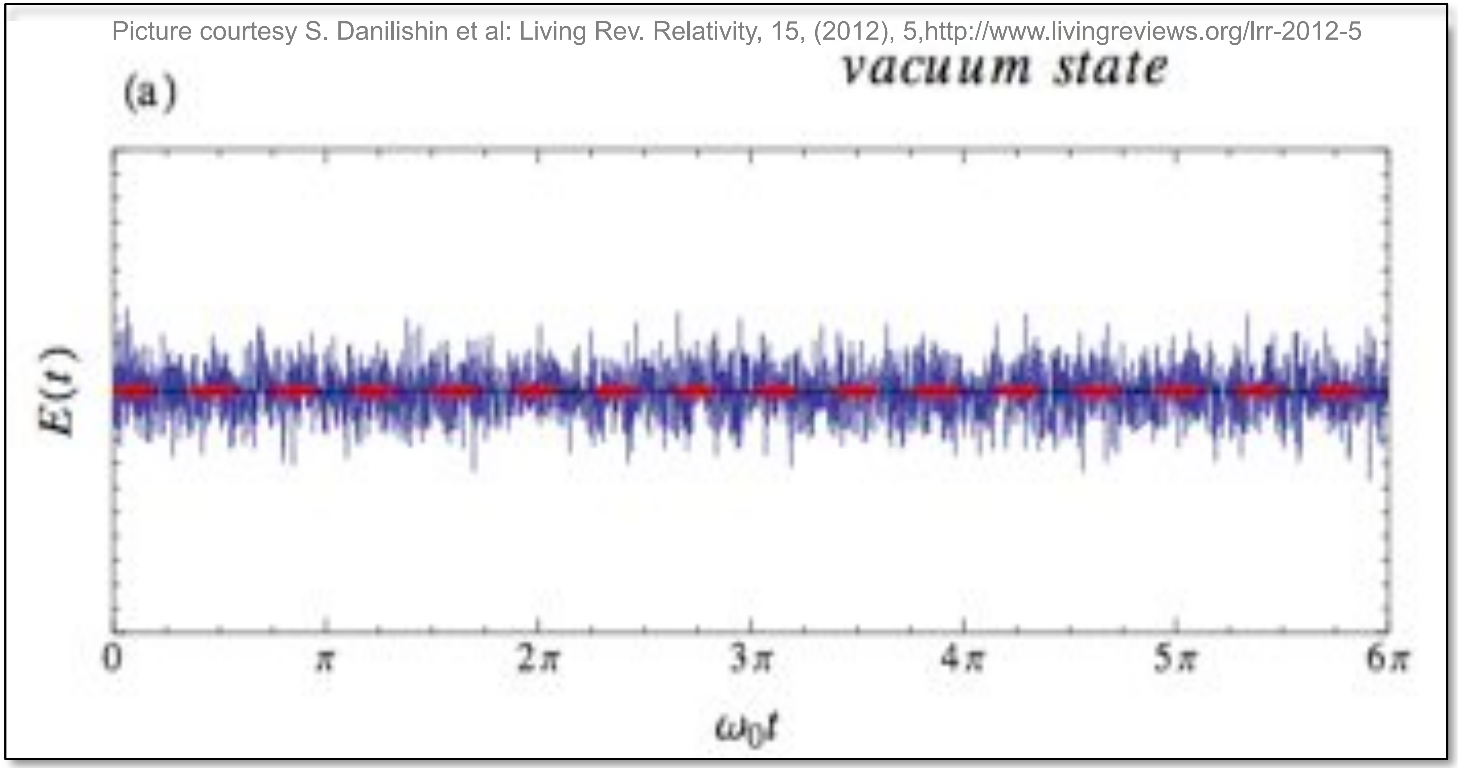


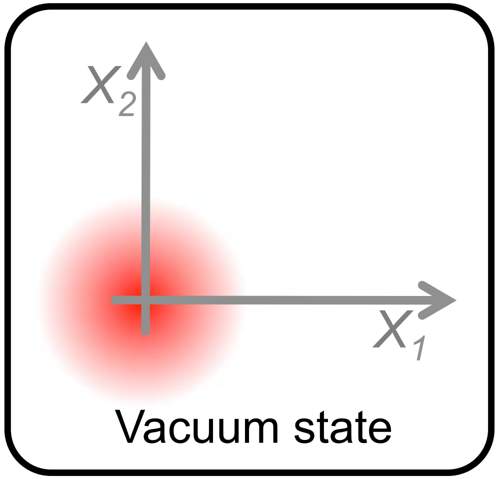


Coherent state

- The red dashed line in left hand picture corresponds to the blue arrow on the right hand plot.
- The fluctuations of the blue trace around the red-dashed curve in the left hand plot correspond to the red area in the right plot.

Vacuum fluctuations

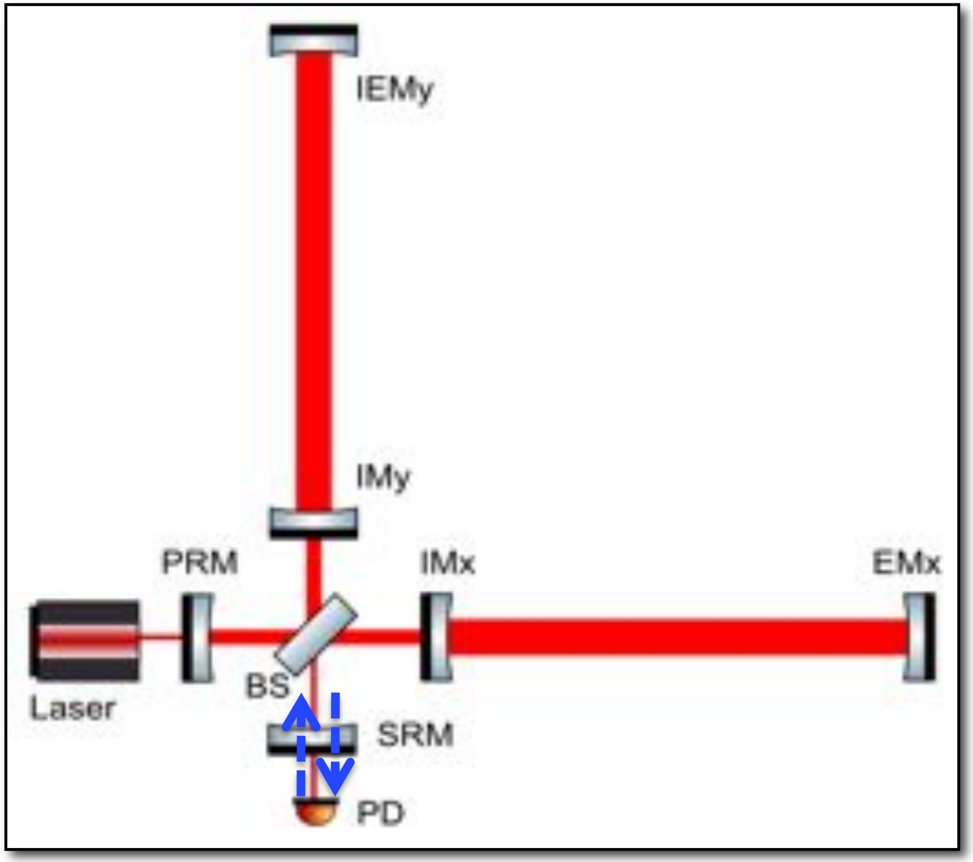

Picture courtesy S. Danilishin et al: Living Rev. Relativity, 15, (2012), 5,http://www.livingreviews.org/lrr-2012-5



- Even if there is 'no' light, vacuum fluctuations are always present.
- Vacuum fluctations enter our systems via any 'open port'.

Vacuum Fluctuations

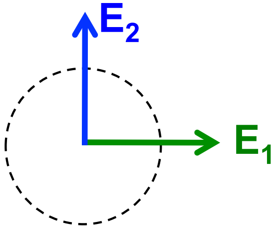
- How does 'Ball-on-the-stick' fits into the interferometer picture?
- An intuitive picture is to consider:
  - A vacuum state is entering the interferometer from the photodiode.
  - It is then 'reflected from the interferometer' and is detected together with the GW signal on the main photodiode.



Vacuum fluctuations

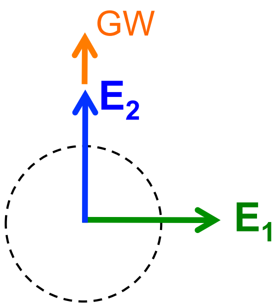
GW signal in Quadrature picture

Shot noise shows up in both quadratures

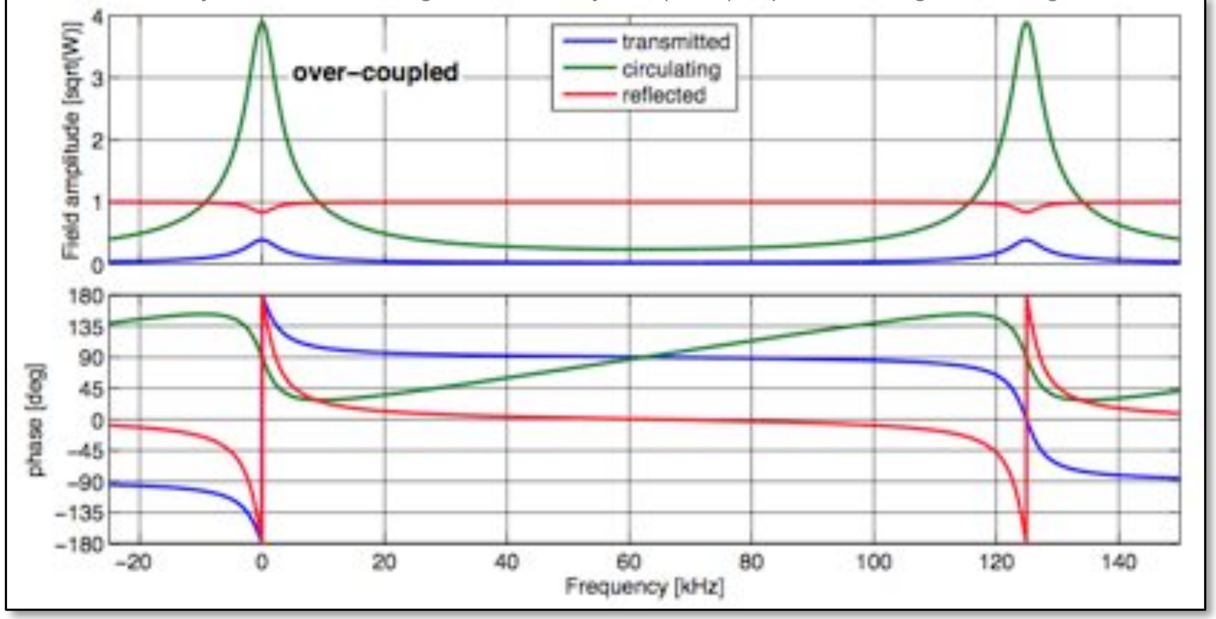


No correlations

GW signal shows up in phase quadrature



No correlations

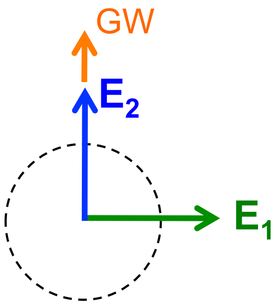


Picture courtesy of A. Freise: Living Rev. Relativity, 13, (2010),http://www.livingreviews.org/lrr-2010-1

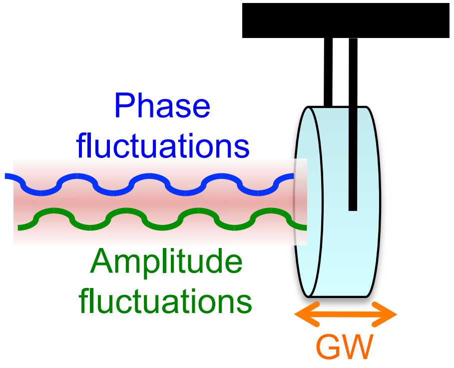
- ➲ If you change the length of a cavity around its resonance, the slope of the amplitude is zero, while the slope of the phase is maximal. Therefore, GW signal adds to phase quadrature.

Where does Radiation pressure noise come from?

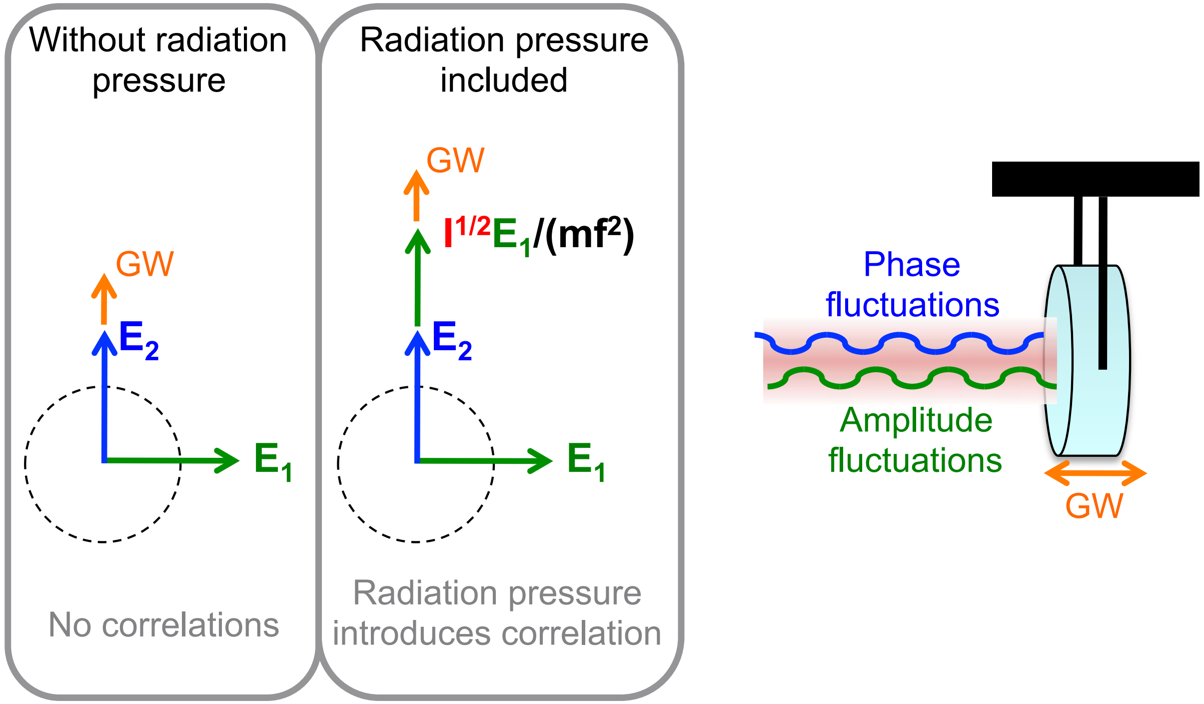
Without radiation pressure



No correlations

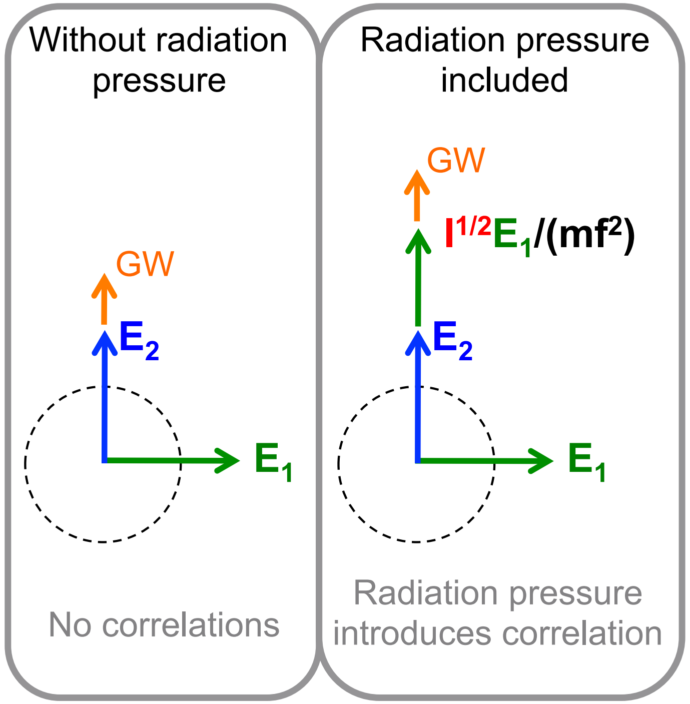


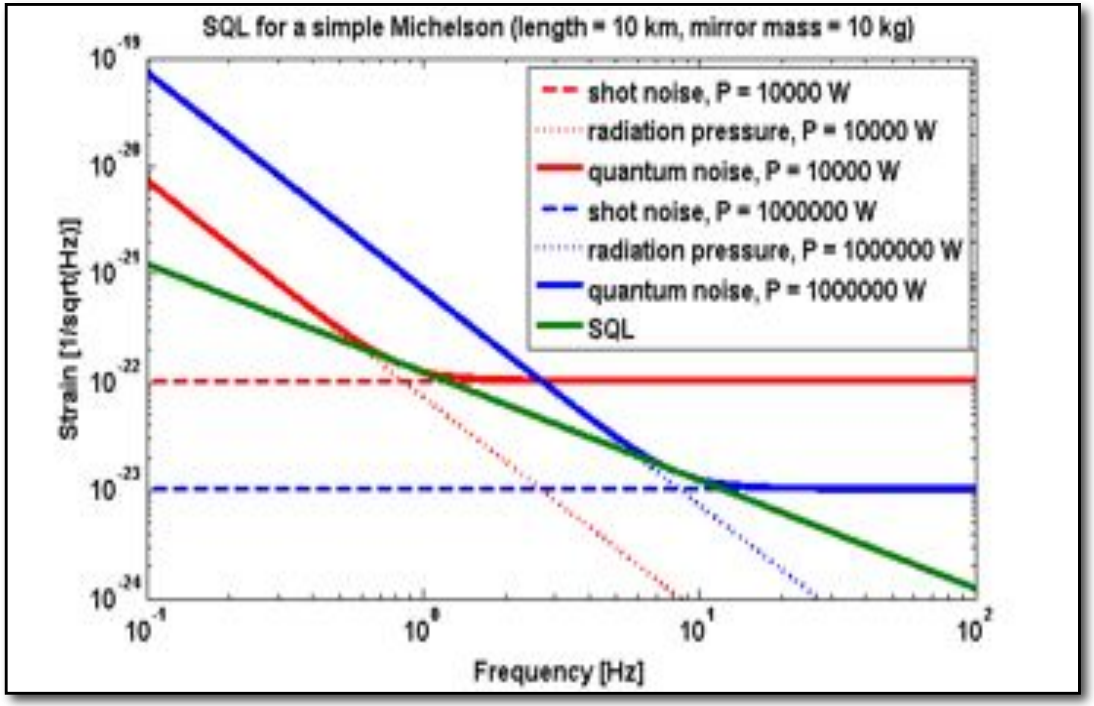
Where does Radiation pressure noise come from?



- Amplitude fluctuations act onto suspended mirror.
- Mirror is moved and gives contribution in the phase quadrature.
- This new contribution:
  - is correlated to E_1
  - depends on the mirror mass
  - Its magnitude goes with $1/f^2$

Where does Radiation pressure noise come from?





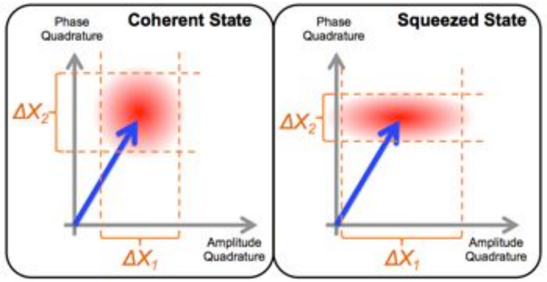
- At high frequencies radiation pressure is negilicable (due to $1/f^2$).
- At low frequencies radiation pressure is dominant

Overview

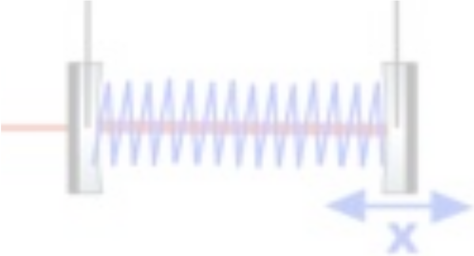
- Heisenberg, Braginsky and the Standard Quantum Limit

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

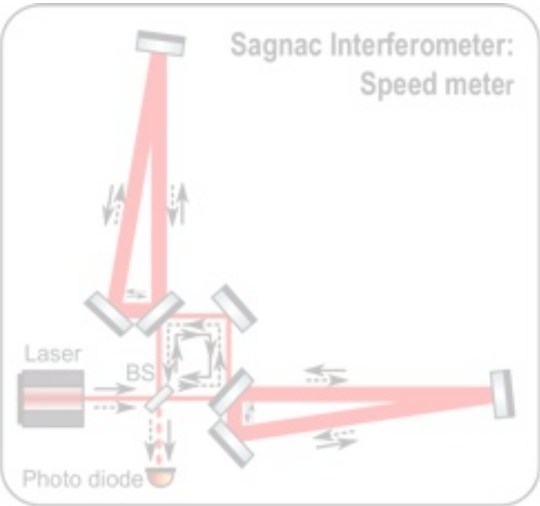
- Squeezed Vacuum



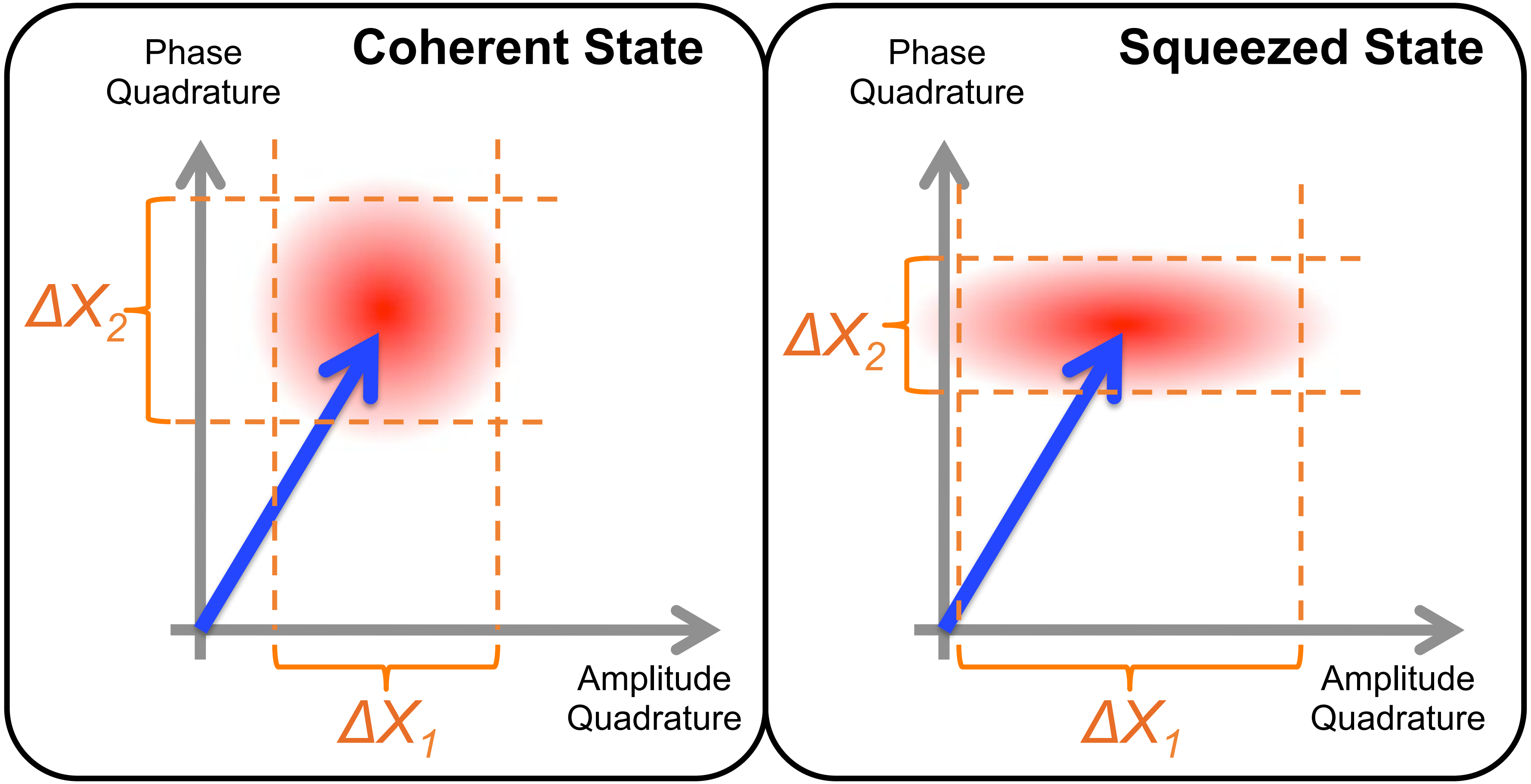
- Stiff Photons



- Why not measure observables that commute?



Ball on a stick and Heisenberg



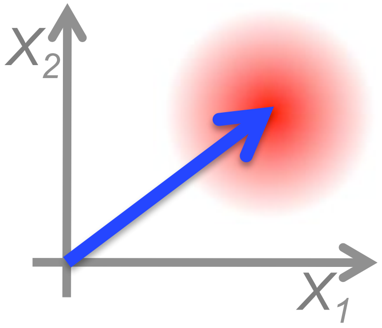
Heisenberg uncertainty principle: there is a minimal area of ball

$$\Delta\hat{X}_1\Delta\hat{X}_2 \geq 1$$

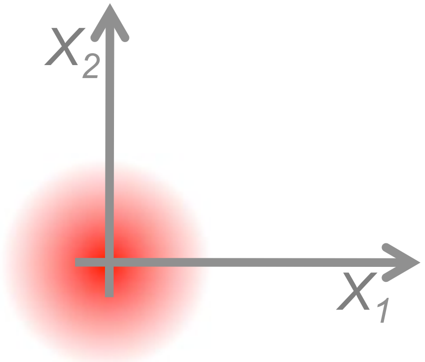
Time series of phase and amplitude squeezing

Task for you:
Sketch a time series of a) a phase squeezed state and b) of an amplitude squeezed state.

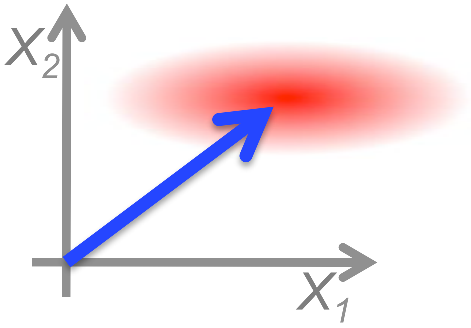
Examples of ball on the stick



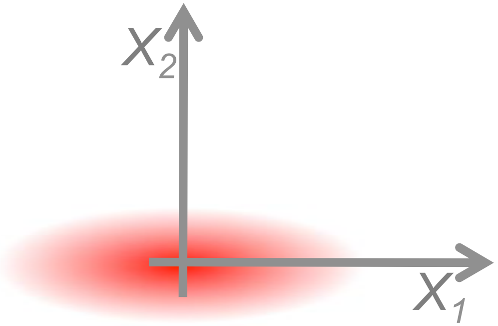
Coherent state



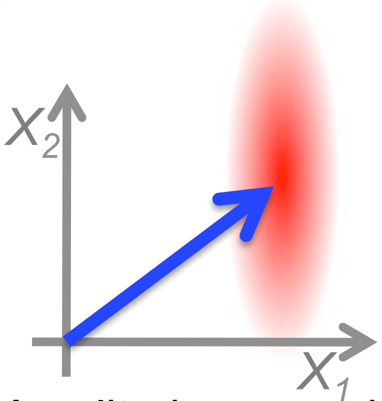
Vacuum state



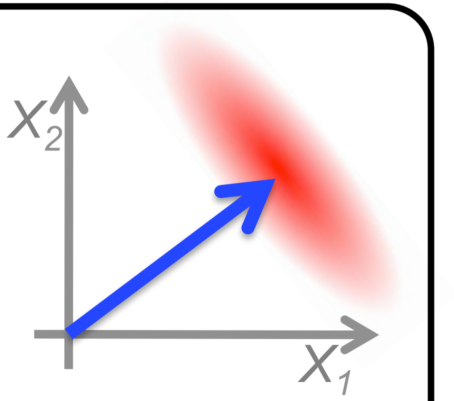
Phase squeezing



Phase squeezed vacuum



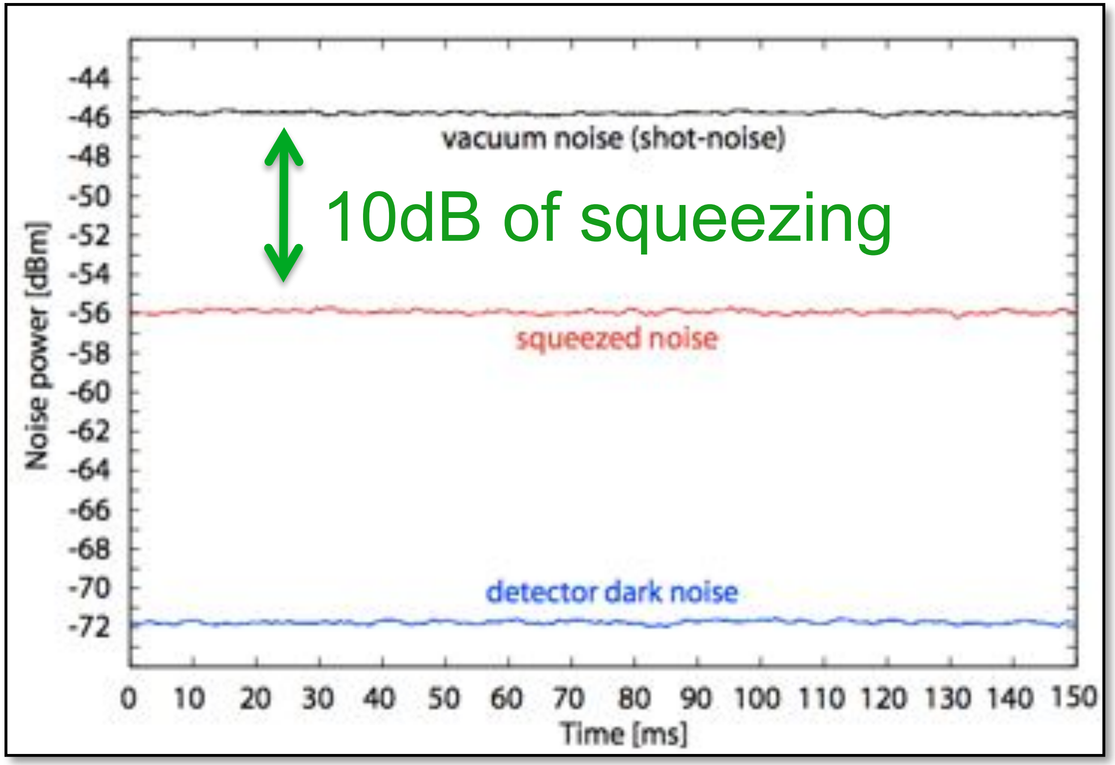
Amplitude squeezing



Quadrature squeezed

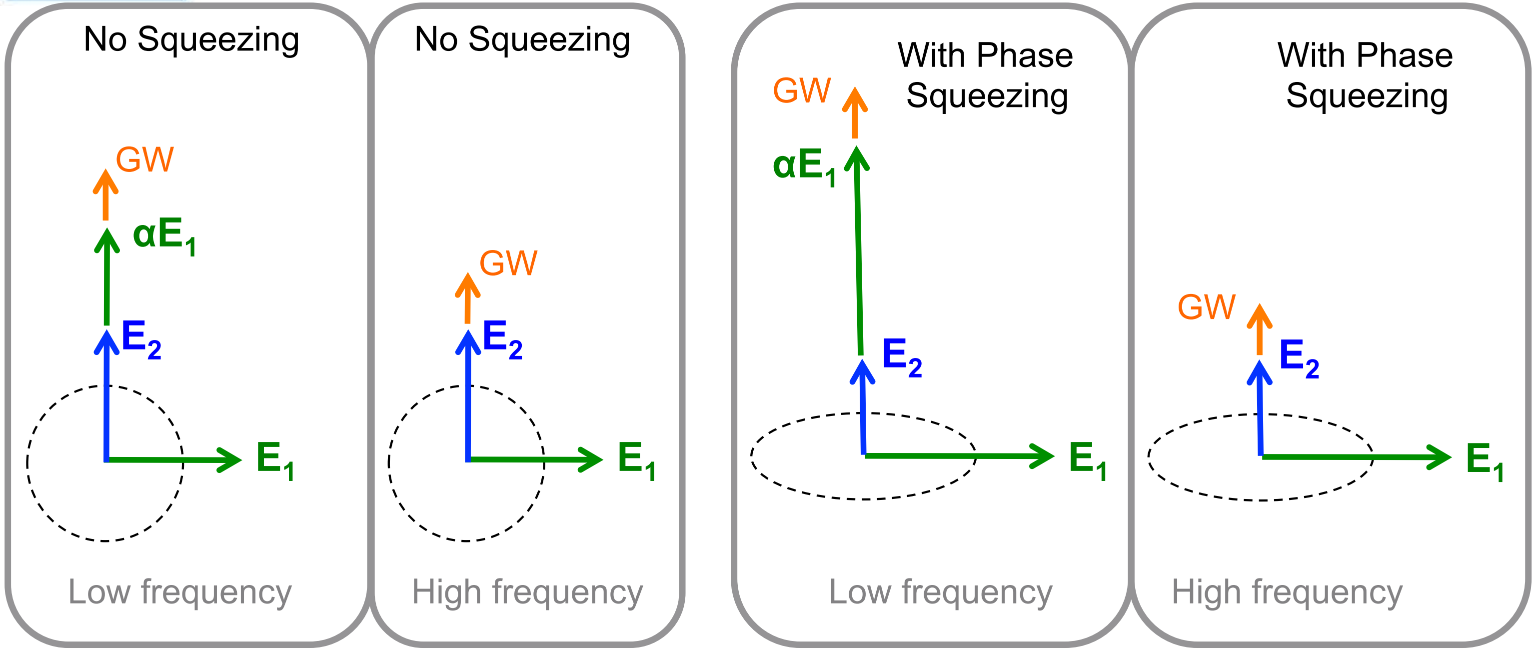
What squeezed light is available ?

- Over the past decade, squeezing made incredible progress.
- We have now all we need:
  - Squeezing at all frequencies of interest (as low as 1 Hz)
  - Squeezing factors > 10dB, improves the quantum noise by a factor 3 (or is equivalent to a power increase of 10)



Vahlbruch *et al.*, PRL. 100, 033602

Injecting squeezed light into an interferometer



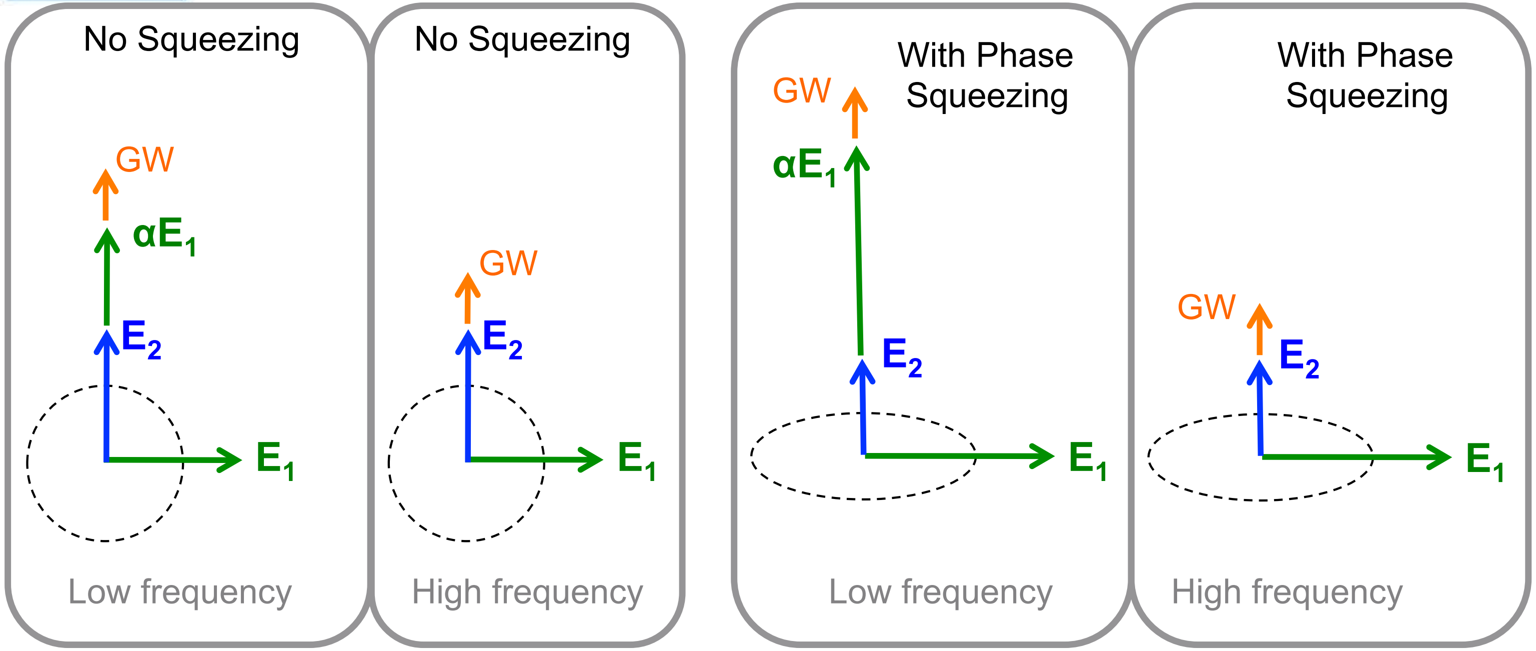
No Squeezing — Low frequency

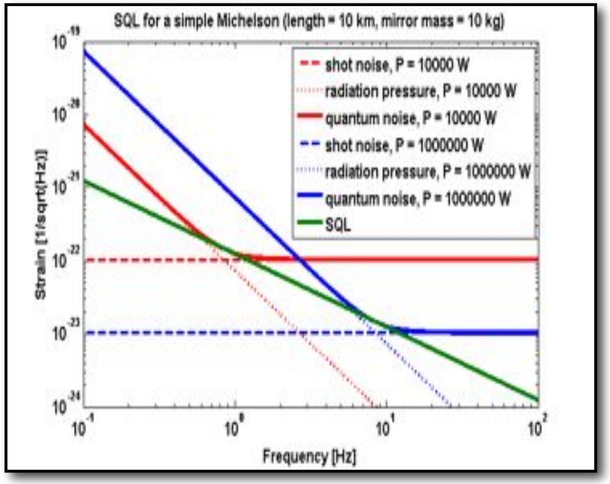
No Squeezing — High frequency

With Phase Squeezing — Low frequency

With Phase Squeezing — High frequency

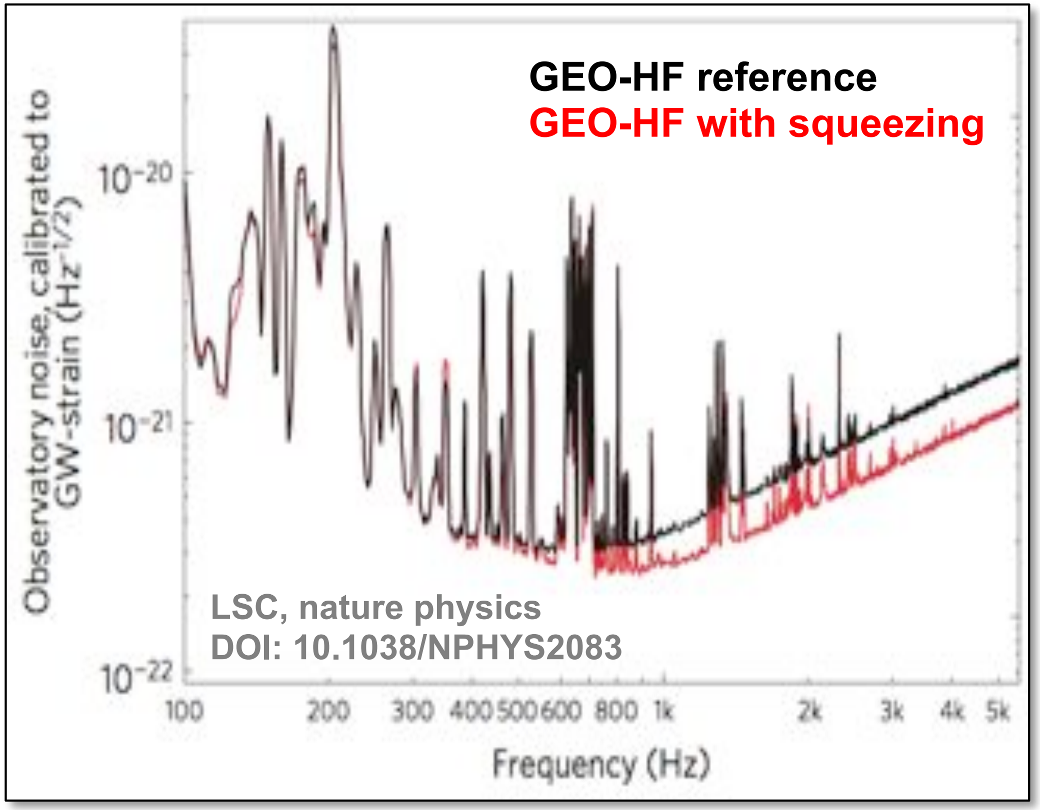
Injecting squeezed light into an interferometer



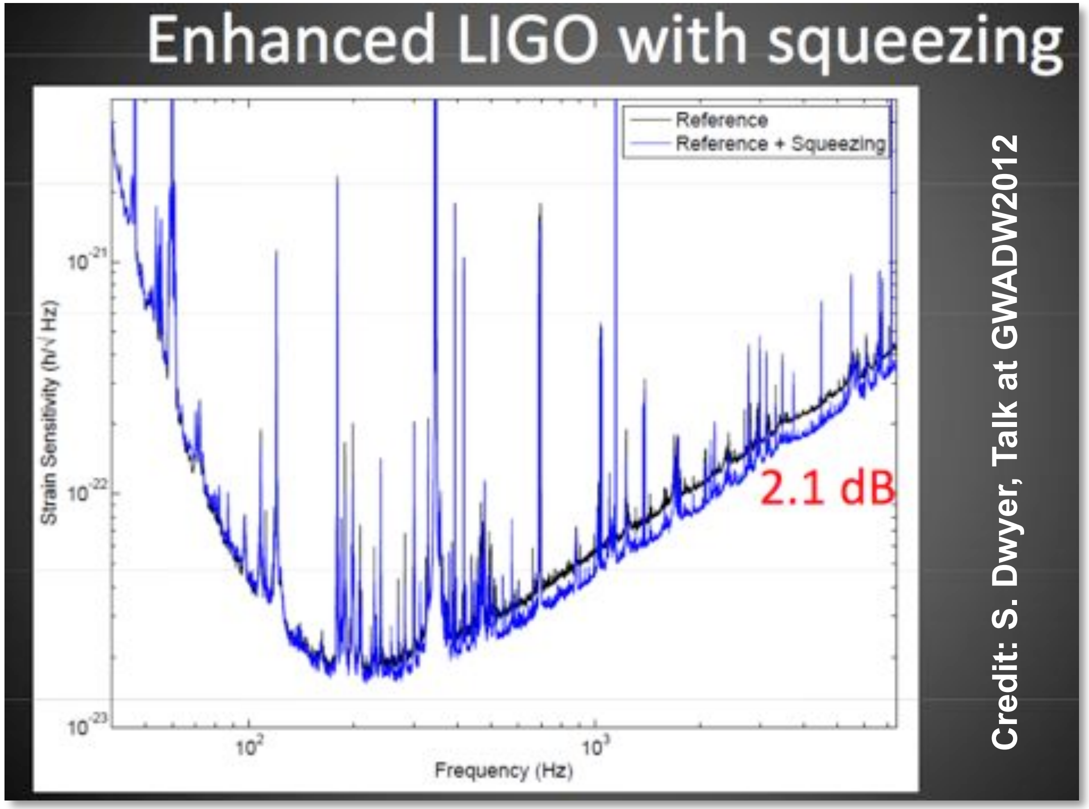


- Injecting phase squeezing into detector output:
  - High frequency sensitivity improved ☺
  - Low frequency sensitivity decreased ☹
- Phase squeezing gives in principle the same as a power increase.
- **With pure phase squeezing you cannot beat SQL!**

Squeezing is no Scifi. IT WORKS !!



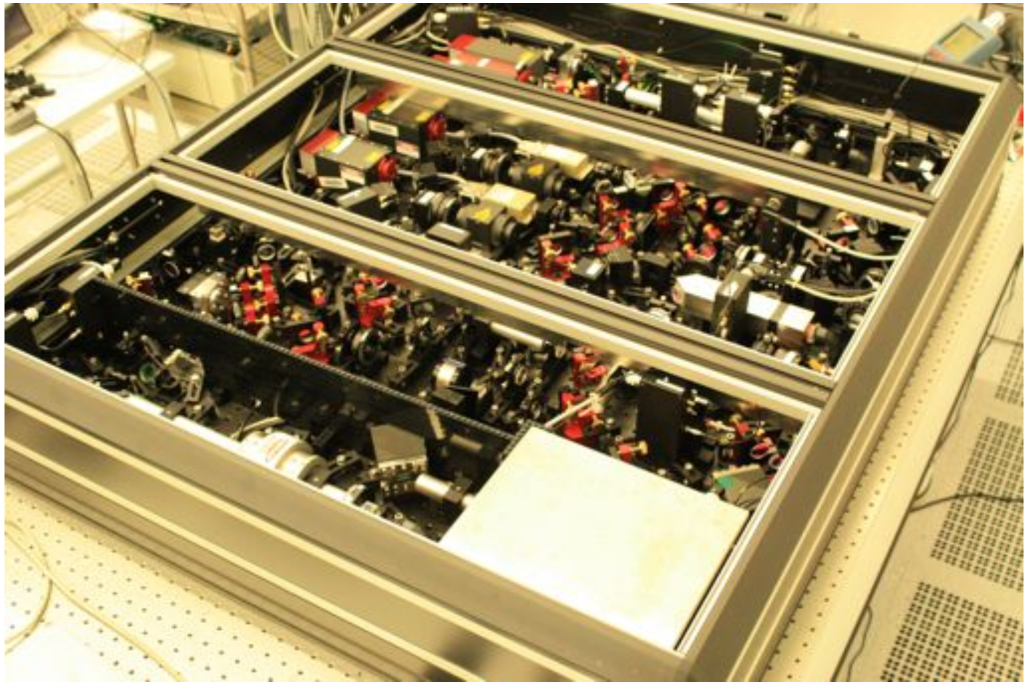
LSC, nature physics
DOI: 10.1038/NPHYS2083



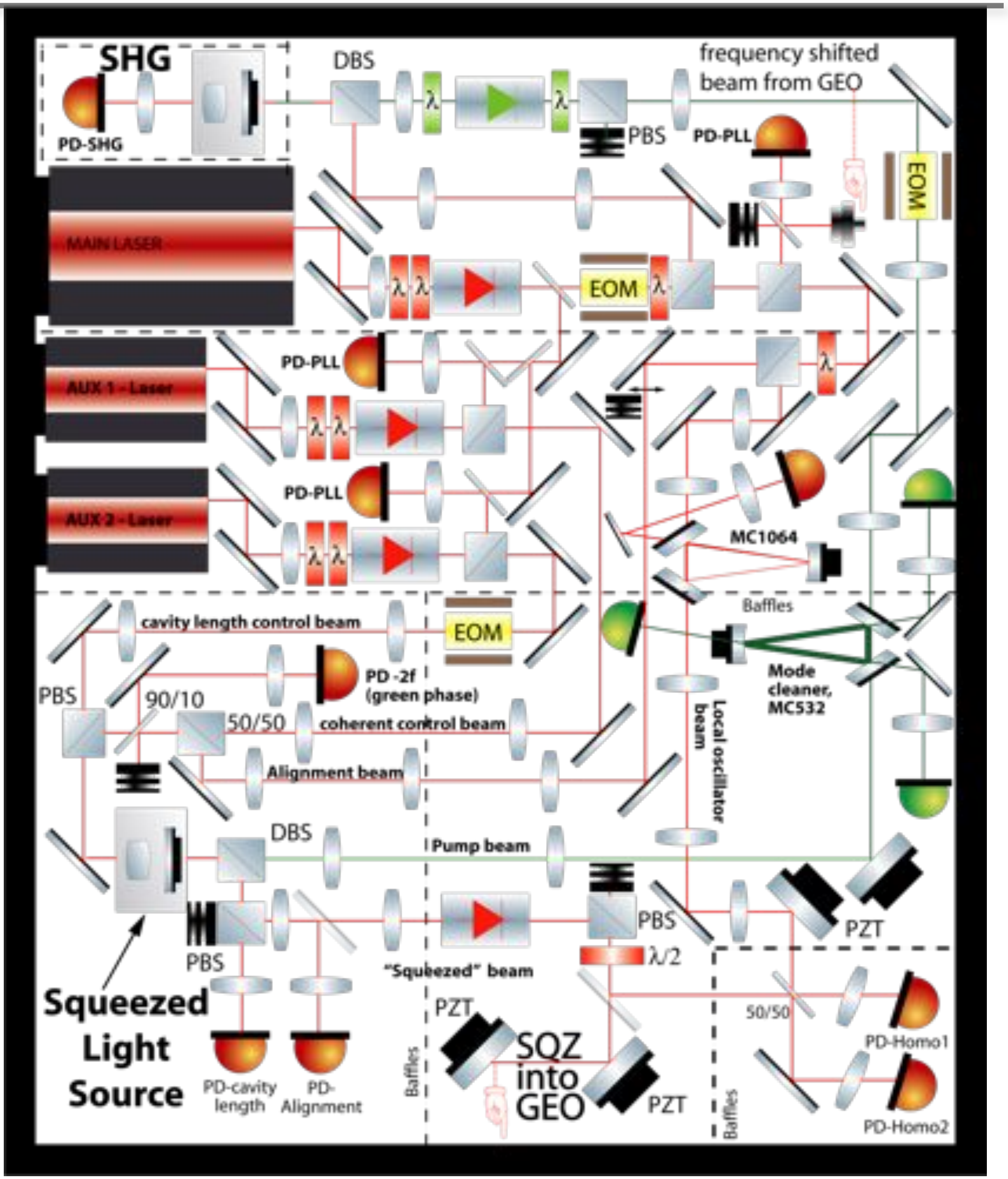
Credit: S. Dwyer, Talk at GWADW2012

- Recently squeezing of up to 3.5dB and at frequencies as low as a few 100Hz have been demonstarted in GEO600 and Enhanced LIGO.

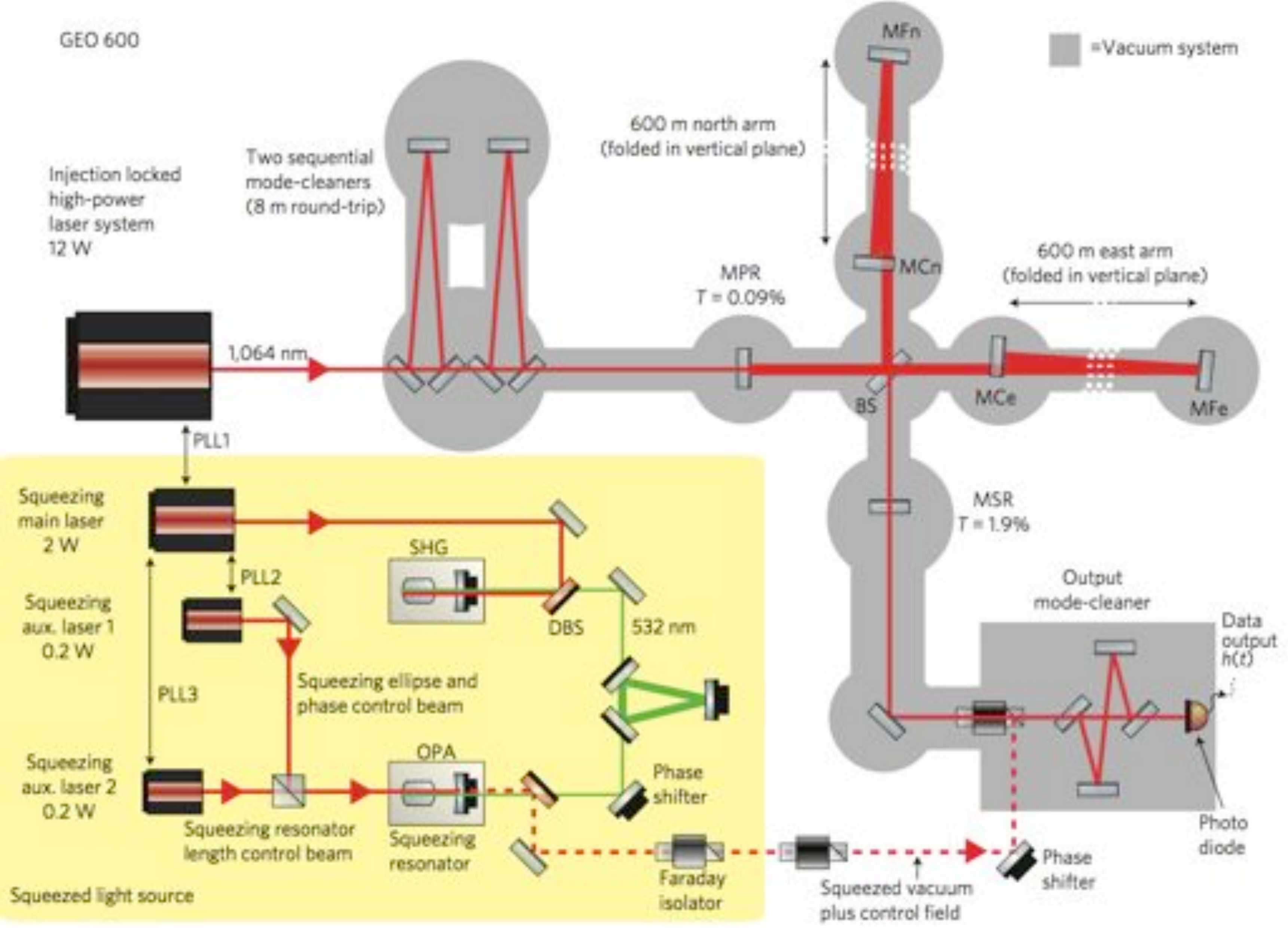
The GEO600 squeezer (schematic)



Images courtesy to GEO600 squeezing Group



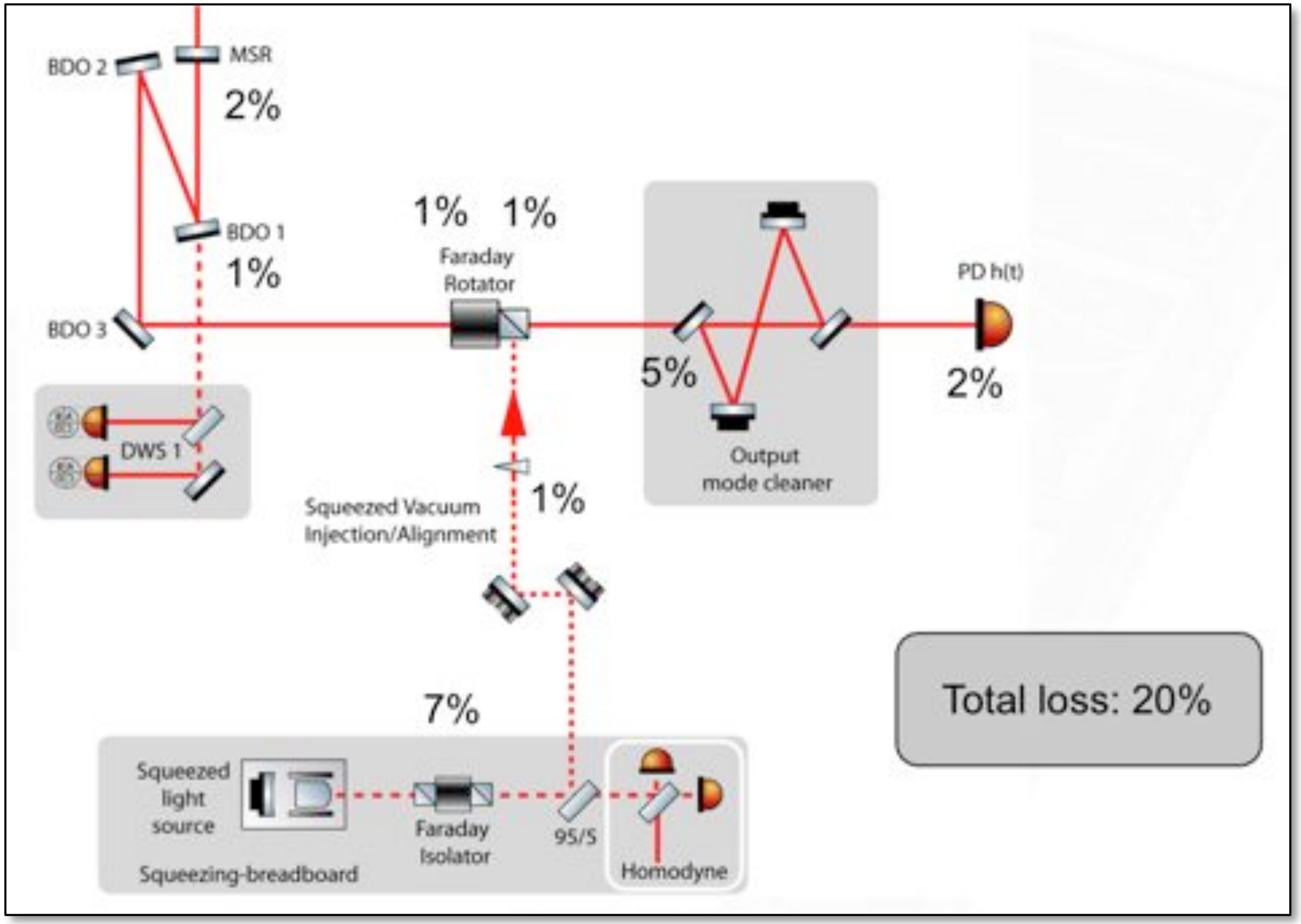
Squeezing injection in GEO



Picture taken from:
LSC, nature physics
DOI: 10.1038/NPHYS2083

How to inject squeezed light into GEO??

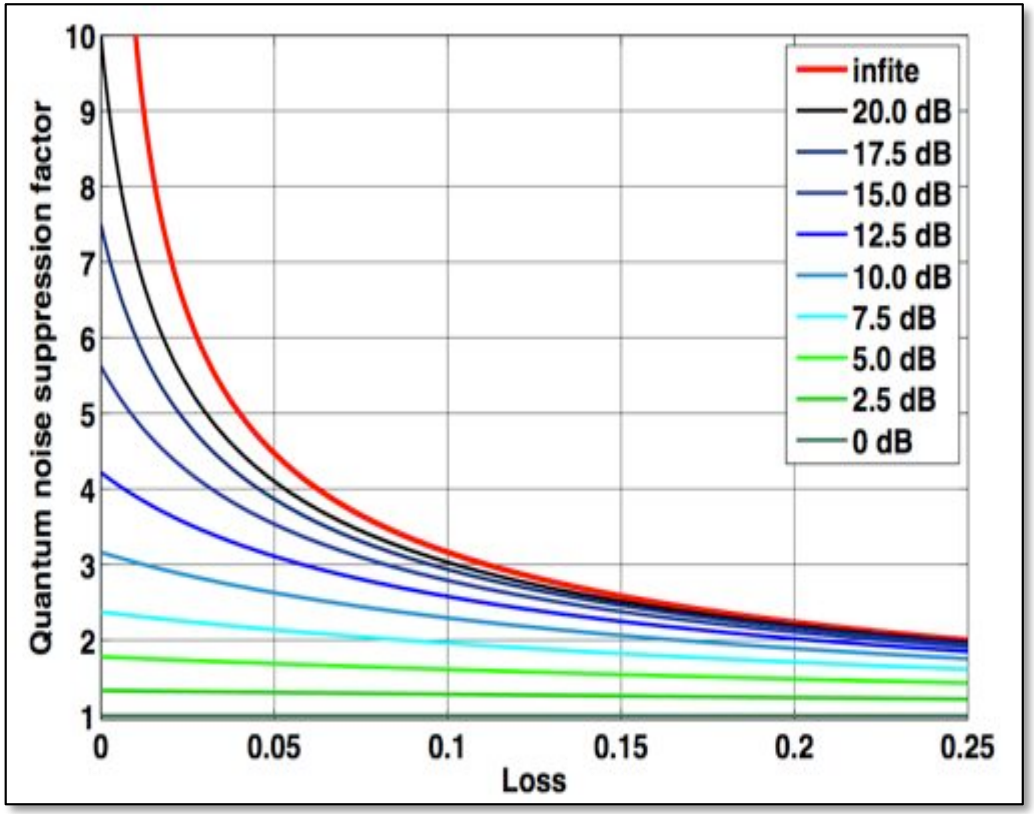
- Squeezed light is injected via a Faraday rotator into the back of the interferometer.
- It is then reflected from the signal recycling mirror (MSR) and detected at the main photodiode (PD).
- Squeezing requires low losses.



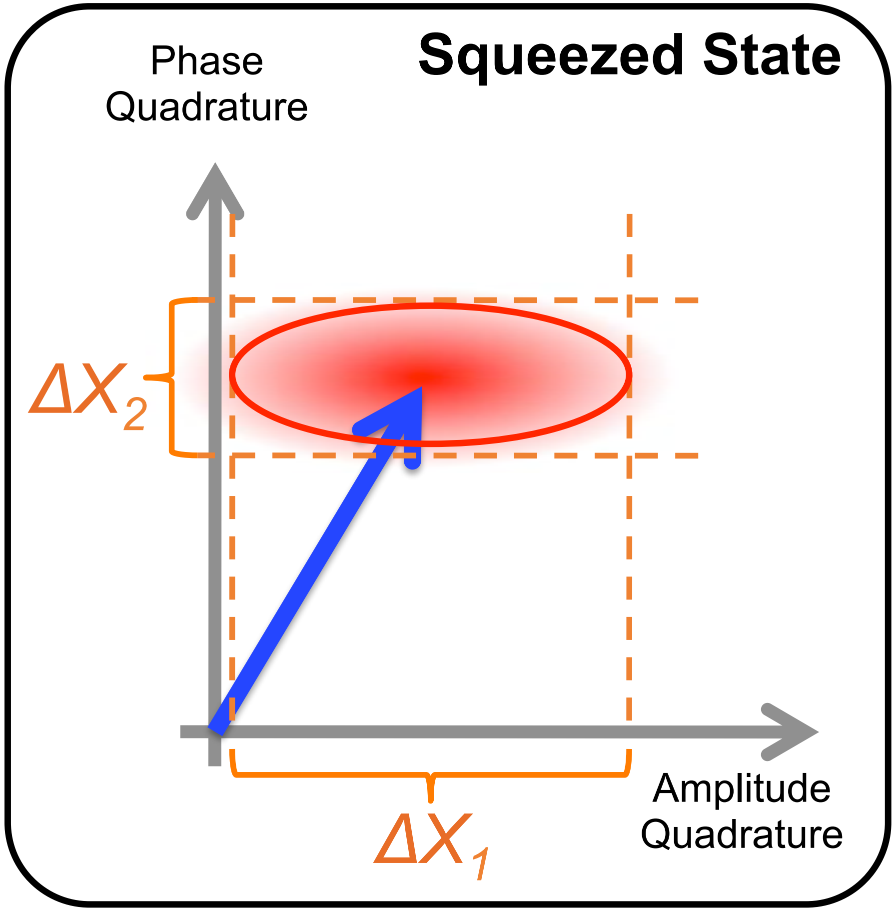
A. Khalaidovski: http://gw.icrr.u-tokyo.ac.jp/gwadw2010/program/2010_GWADW_Khalaidovski.ppt

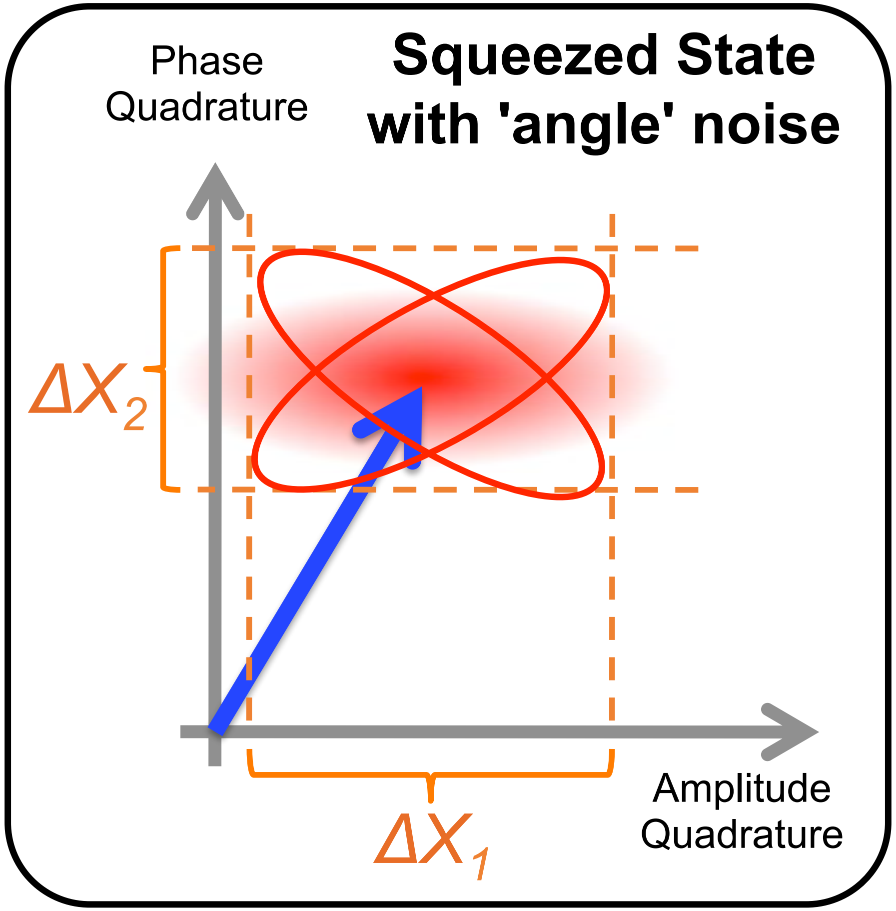
What is the maximum Squeezing ?

- What is the maximal noise reduction we will ever get from squeezing?
- With the current losses >0.2 we are not limited by the achievable squeezing of the sources.
- Even with an infinite squeezing level it seems hardly possible to get an improvement better than a factor 3.

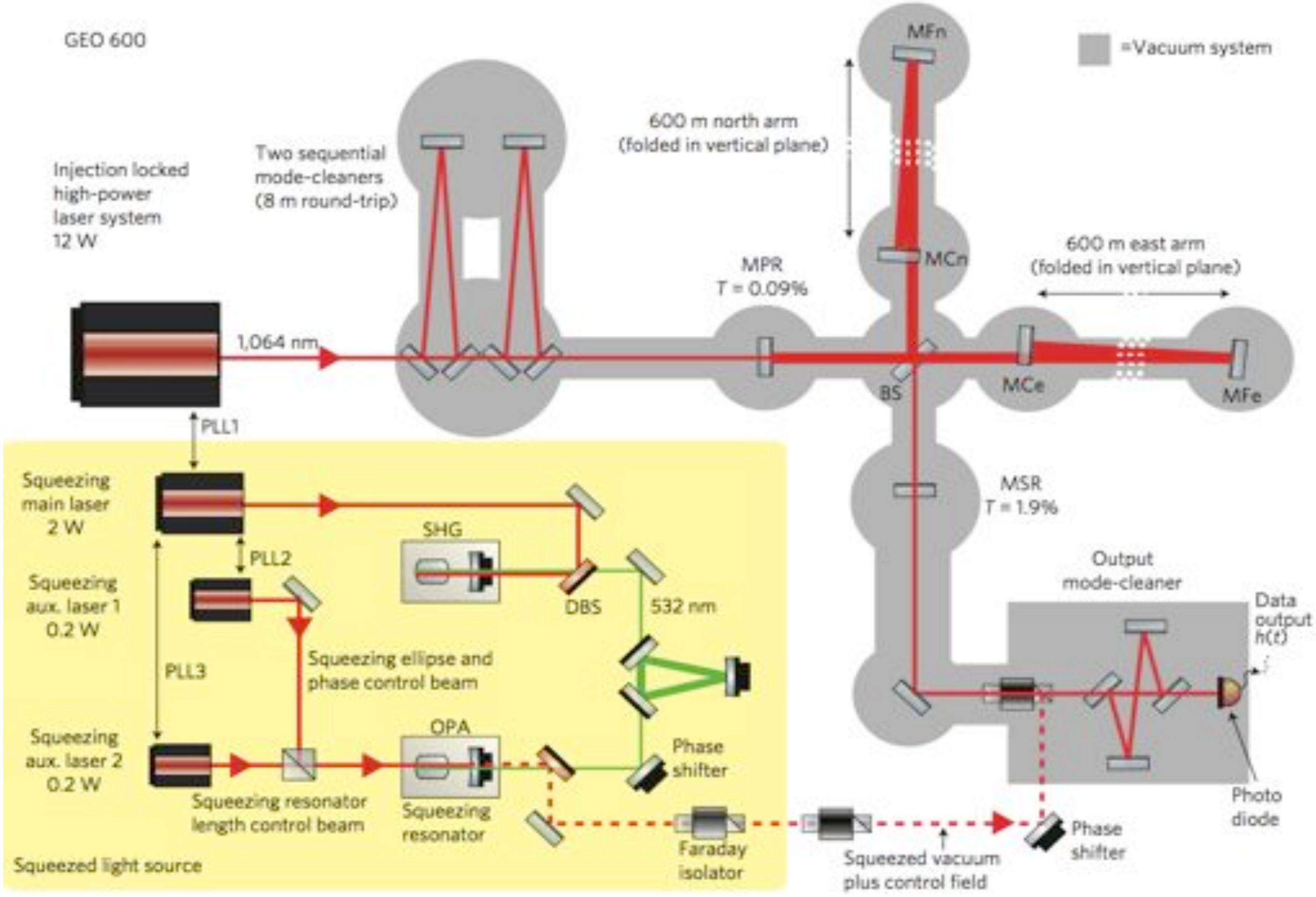


Wobbeling of the squeezing angle





Squeezing injection in GEO

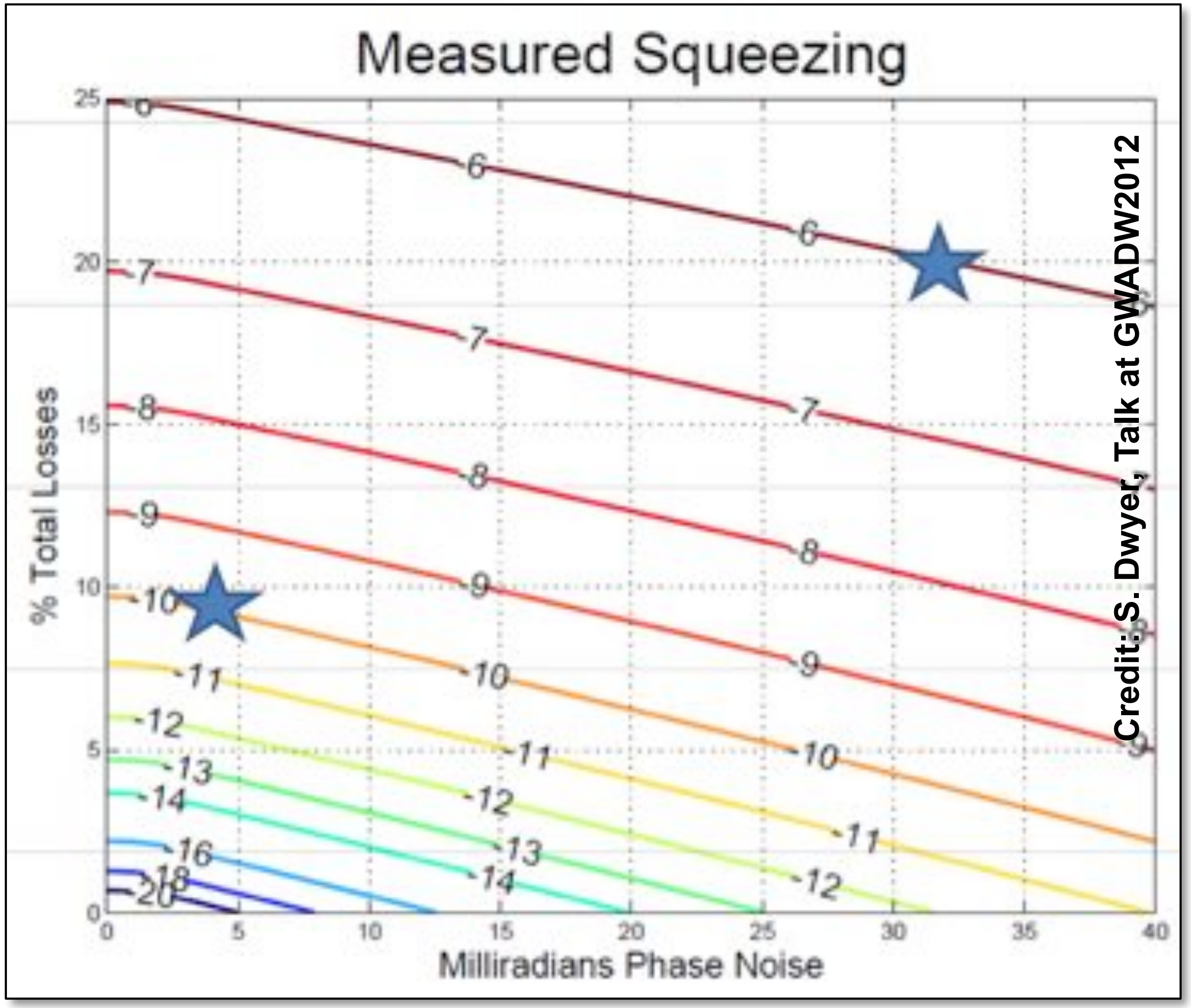


Picture taken from:
LSC, nature physics
DOI: 10.1038/NPHYS2083

Tasks for you:
1. Where in the drawing above do you think the phase noise is introduced?
2. Where do you think you can find the best error signal to correct it?

Phase noise on squeezed light

- Need to stabilise the squeezing angle very accurately.
- PLEASE NOTE: In this case it is not the audioband frequencies that are important, but the rms!
- Key-problem will be to find good error signals for this.



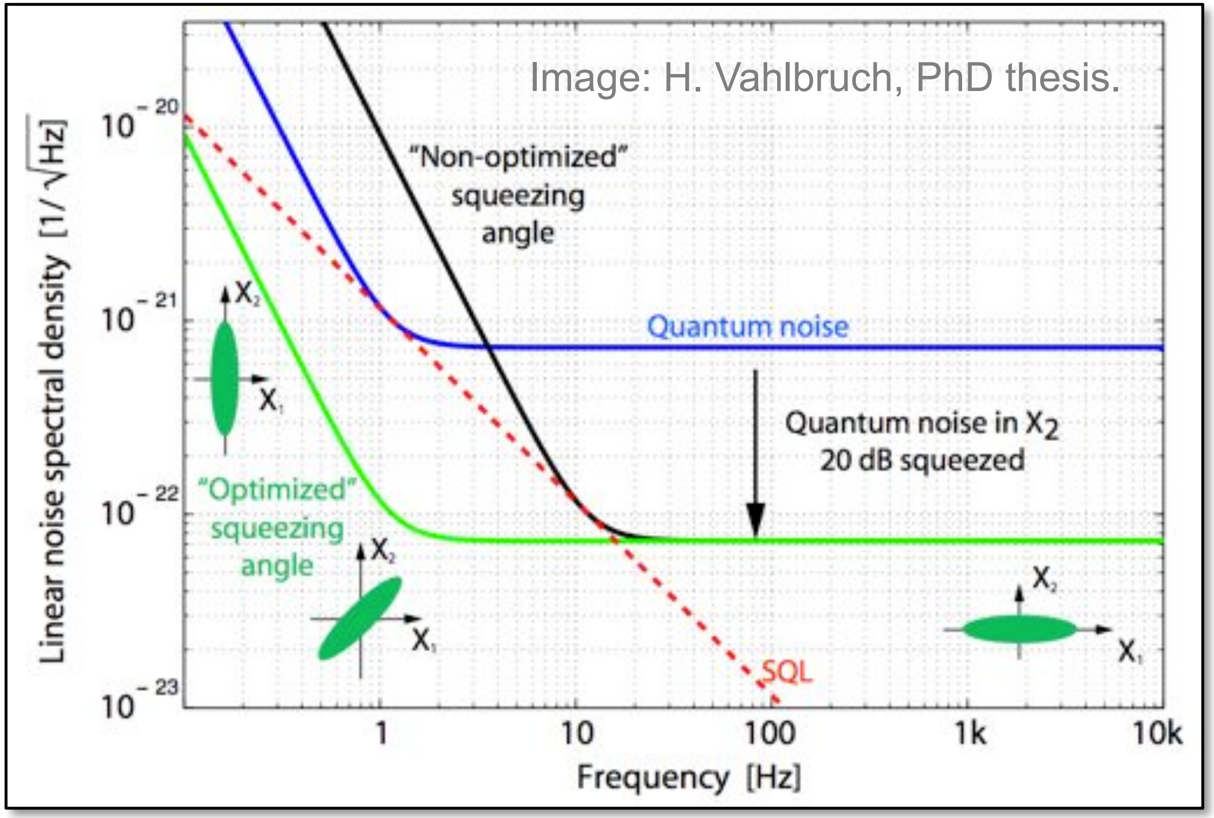
Credit: S. Dwyer, Talk at GWADW2012

Frequency dependent Squeezing

If squeezed light should reduce shot noise and radiation pressure noise, you need a frequency dependent squeezing angle:

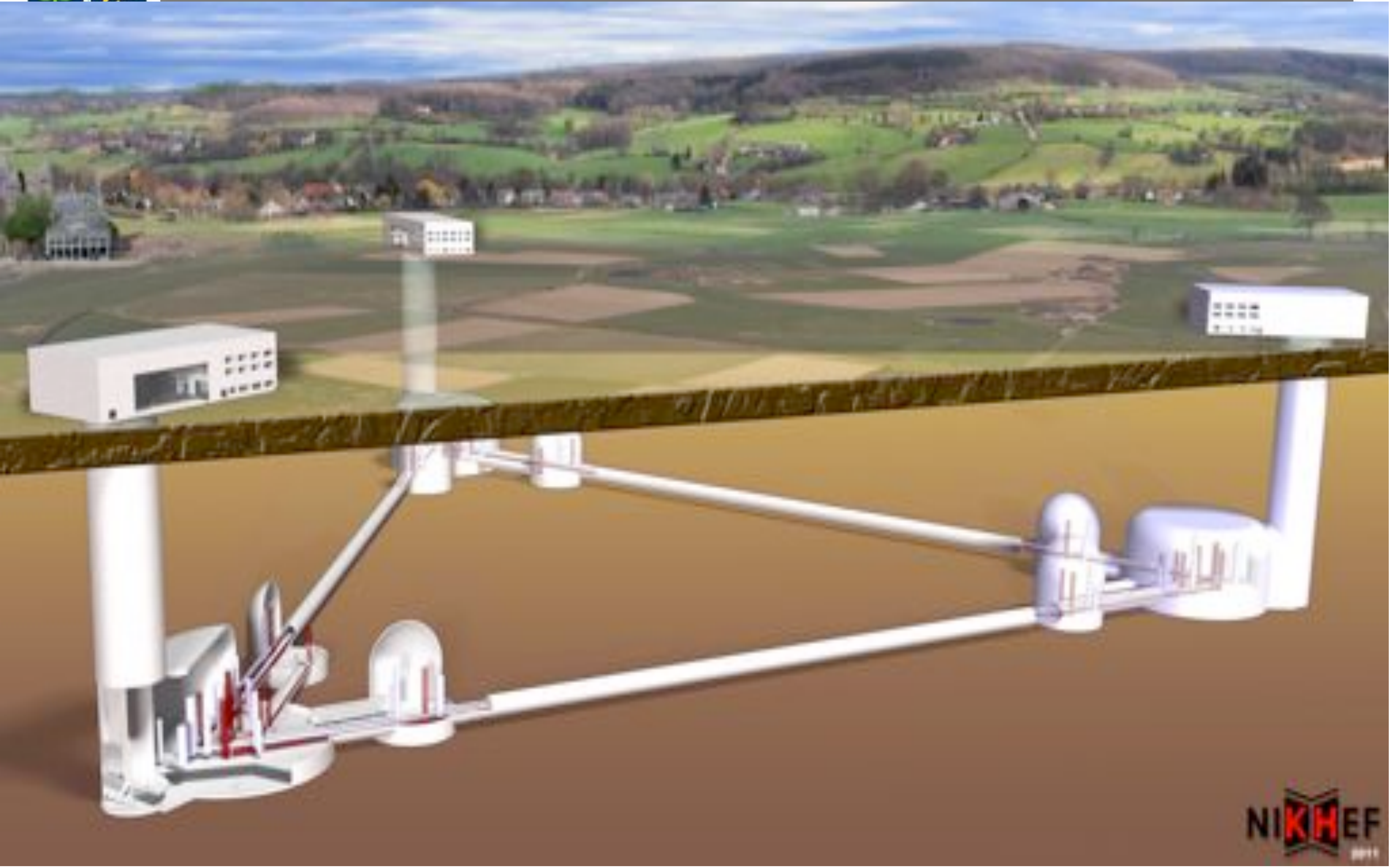
➲Phase squeezing at high frequencies.

➲Amplitude squeezing at low frequencies

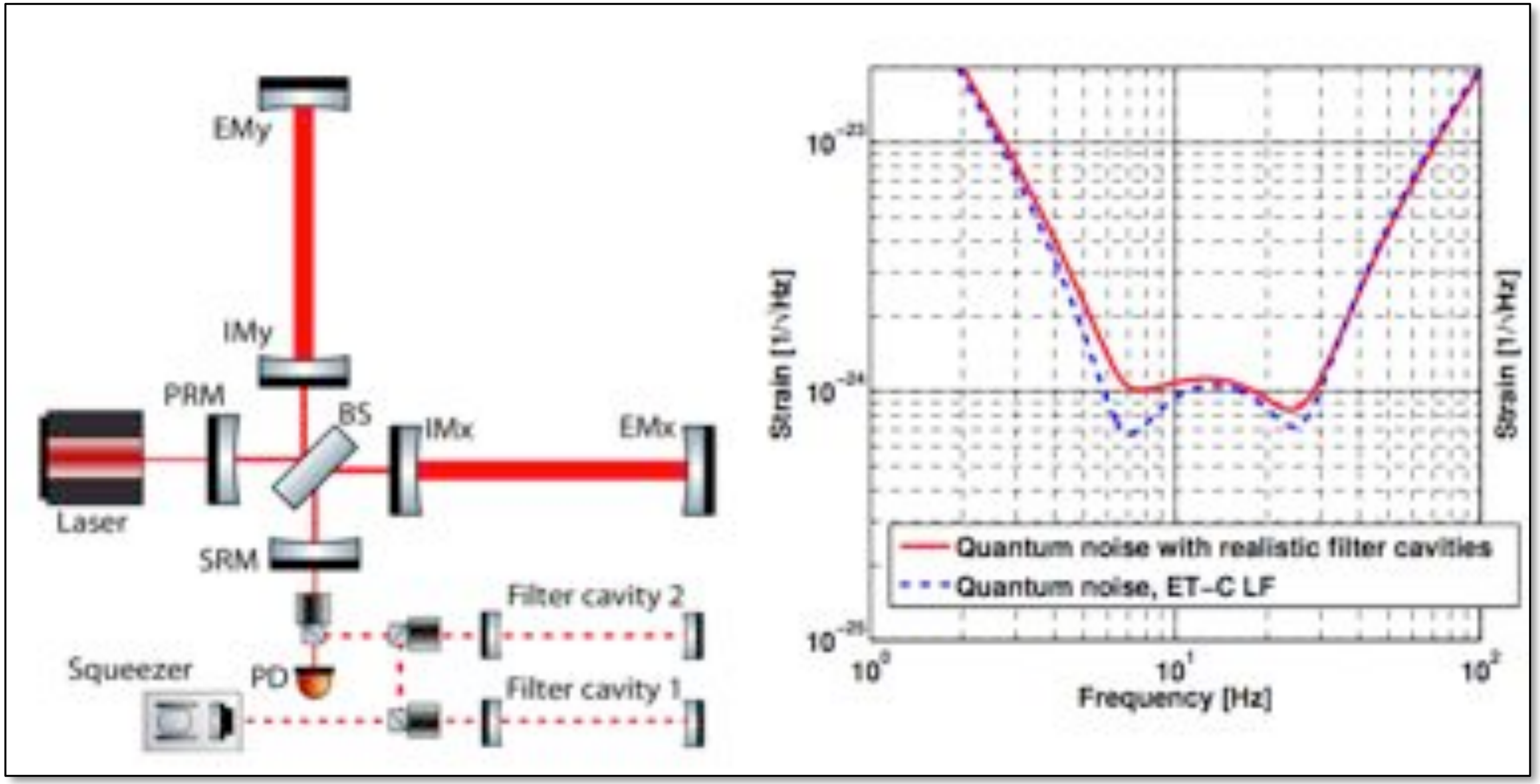


With frequency dependent squeezing it is possible to surpass the SQL.

Einstein Telescope

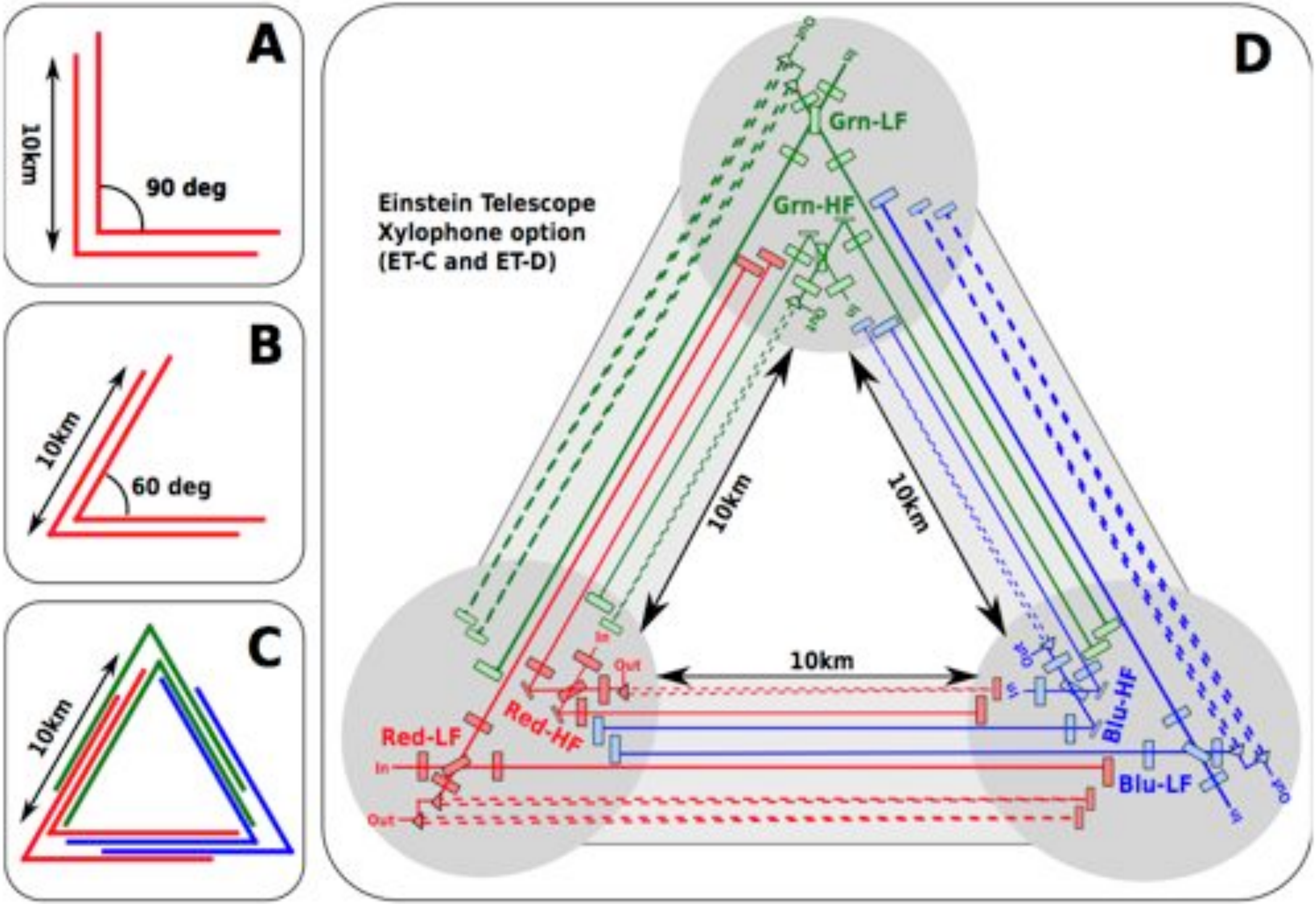


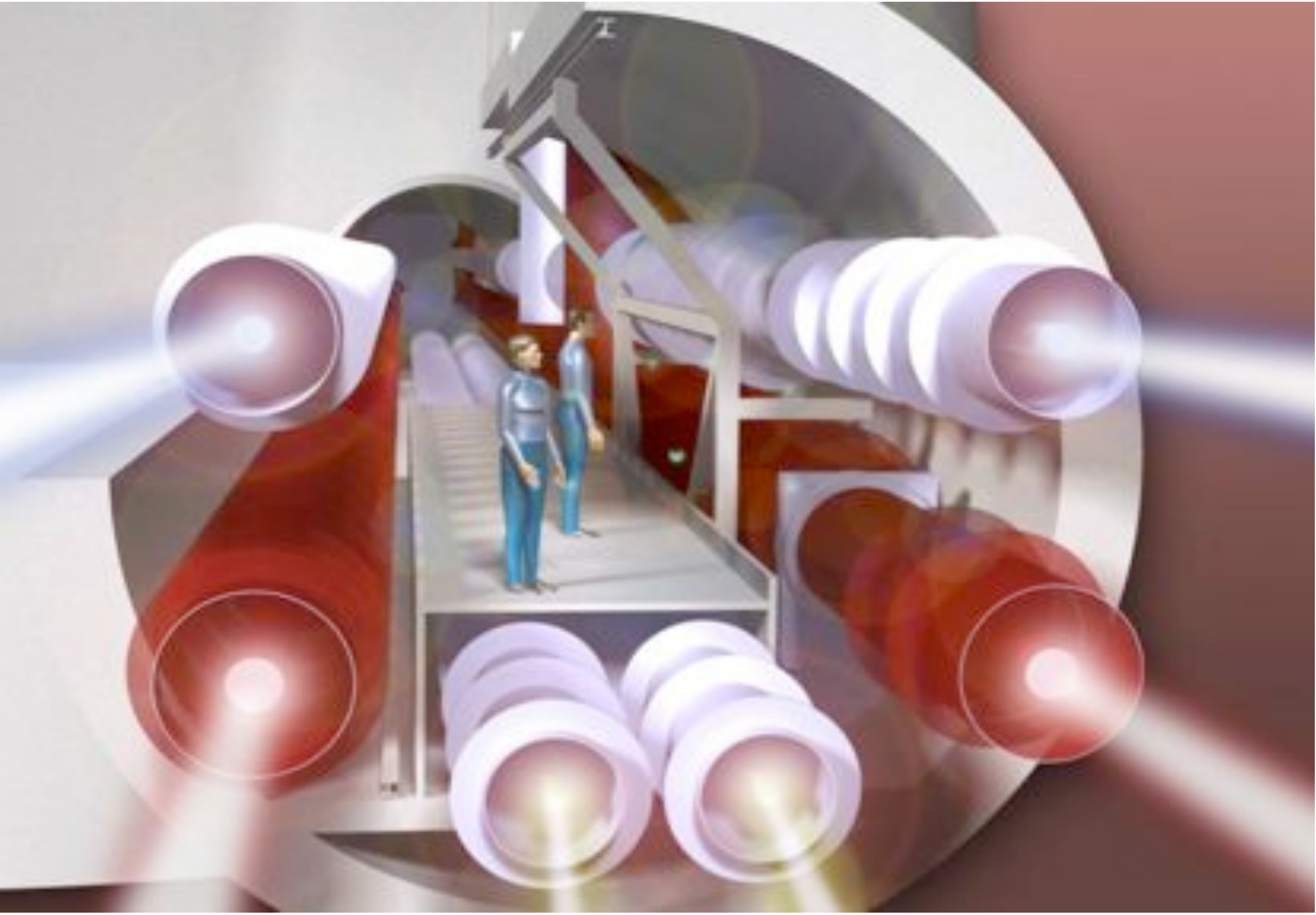
Creating frequency dependent Squeezing with filter cavities



- We can realise frequency dependent squeezing by reflecting it on a cavity, i.e. making use of the cavity's dispersion.

ET layout


A
10km
90 deg
B
10km
60 deg
C
10km
D
Einstein Telescope
Xylophone option
(ET-C and ET-D)
Grn-LF
Grn-HF
10km
10km
10km
Red-LF
Red-HF
Blu-HF
Blu-LF
In
Out
In
Out
In
Out



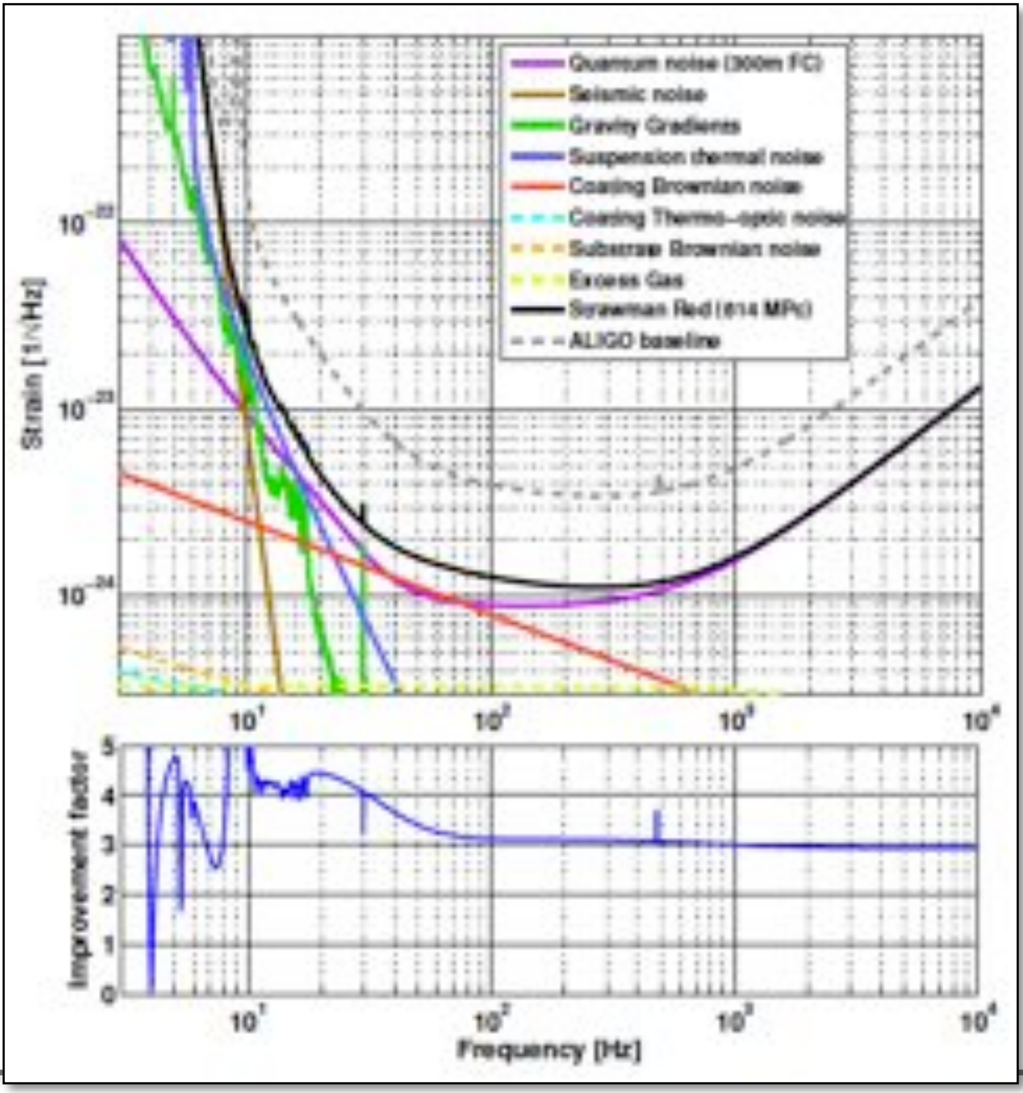
LIGO 3 Strawman Design, Team Red

B. Barr[1], A. Bell[1], C. Bell[1], C. Bond[2], D. Brown[2], F. Brueckner[2], L. Carbone[2], K. Craig[1], A. Cumming[1], S. Danilishin[3], K. Dooley[4], A. Freise[2], T. Fricke[4], P. Fulda[2], S. Giampsis[5], N. Gordon[1], H. Grote[4], G. Hammond[1], J. Harms[6], S. Hild[1,*], J. Hough [1], S. Huttner[1], R. Kumar[1], H. Lück[4], N. Lockerbie[7], J. Macarthur[1], I. Martin[1], P. Murray[1], S. Reid[1], S. Rowan [1], D. Shoemaker[8], B. Sorazu[1], K. Strain[1], S. Tarabrin[4], K. Tokmakov[7] and N. Voronchev[3] +H.Wittel

Photos by A. Freise

Example of frequency dependent Squeezing: LIGO3 Red

- During the last year people have started to investigate potential upgrades to the Advanced LIGO detectors.
- For details please see:
  - LIGO-T1200005-v2
  - LIGO-T1200031–v3
- Here we just want to take it as an example to look at the design of the frequency dependent squeezing

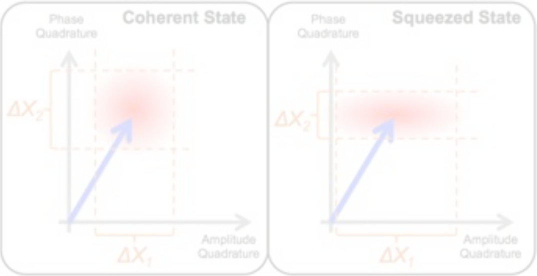


Overview

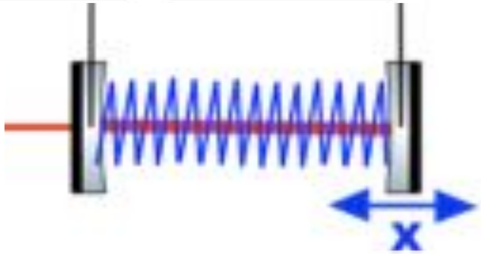
- Heisenberg, Braginsky and the Standard Quantum Limit

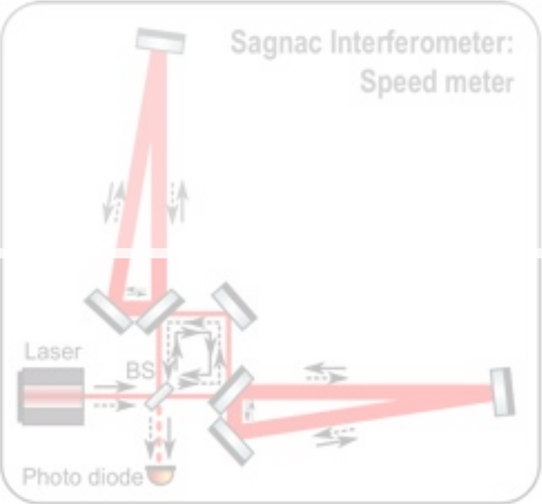
$$[\hat{x}(t),\hat{x}(t')]\neq 0$$
$$[\hat{p}(t),\hat{p}(t')]=0$$

- Squeezed Vacuum



- **Stiff Photons**

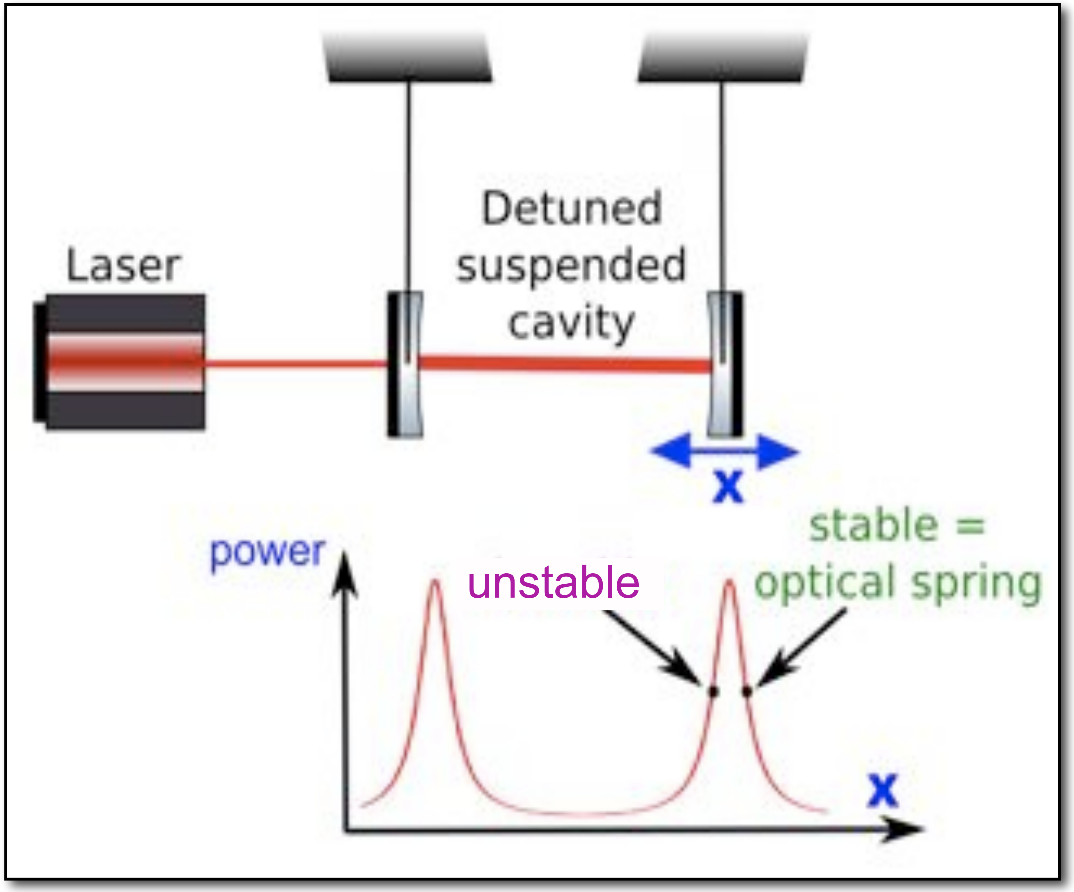




- Why not measure observables that commute?

What is an Optical Spring?

- Detuned cavities can be used to create optical springs.
- Position change of the mirror => power changes => radiation pressure force changes.
- Optical springs couple the mirrors of a detuned cavity with a spring made out of ‘stiff photons’
- Can be used as low-noise transducer for GW signals to mirror movement in the local frame.



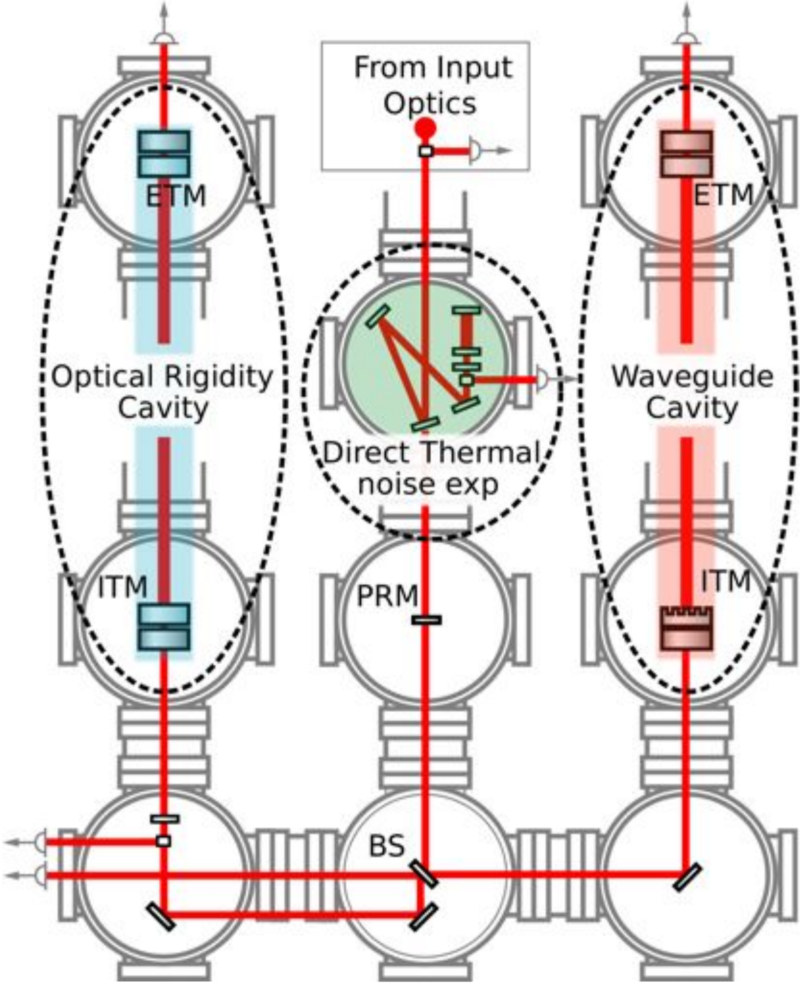
Glasgow 10m Interferometer

Overview of finished experiments:

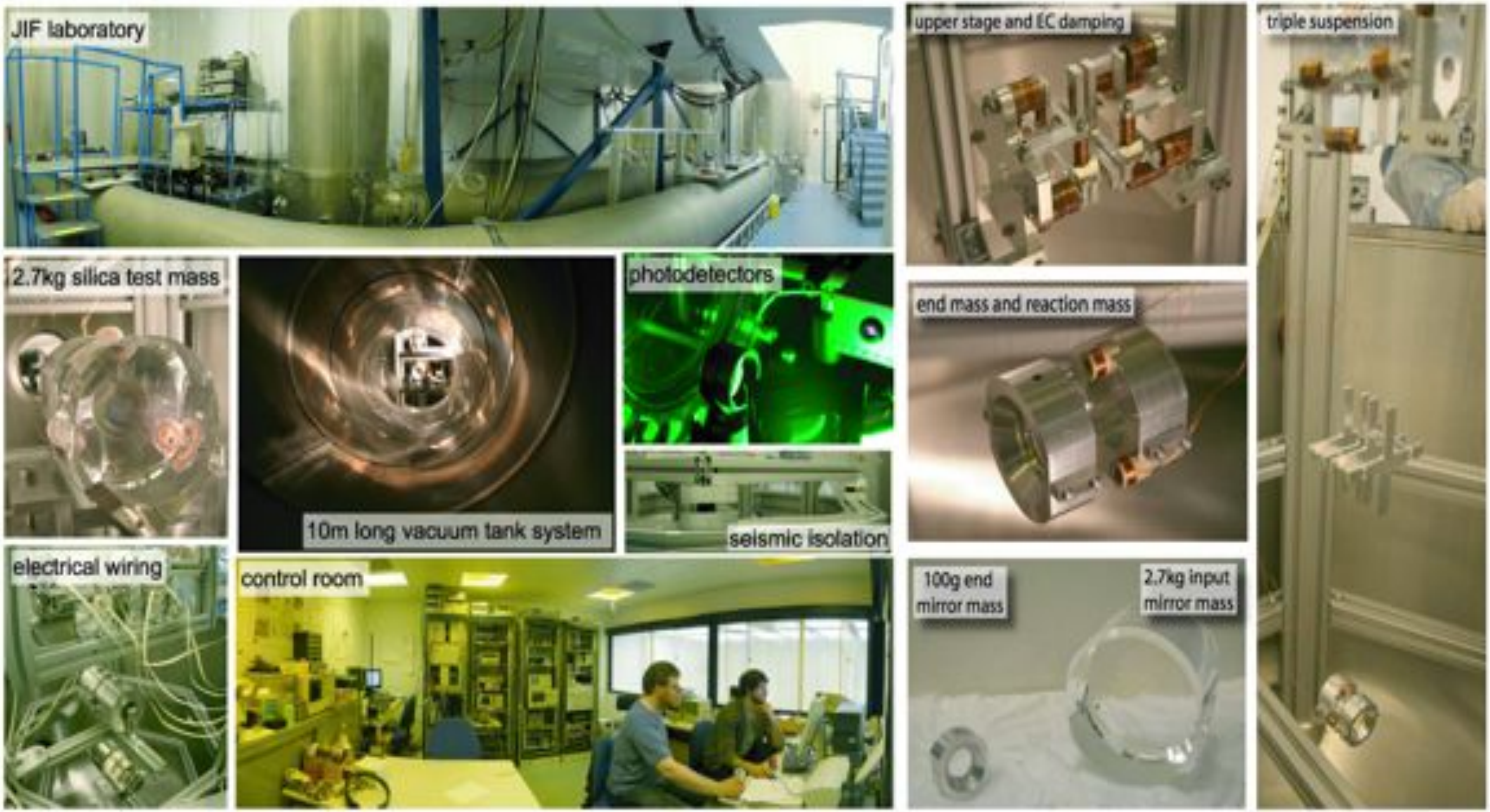
- Optical spring demonstration with 100g mirror
- First Demonstration of a waveguide mirror in a suspended cavity
- Injection of LG modes into a suspended 10m cavity

Overview of ongoing experiments:

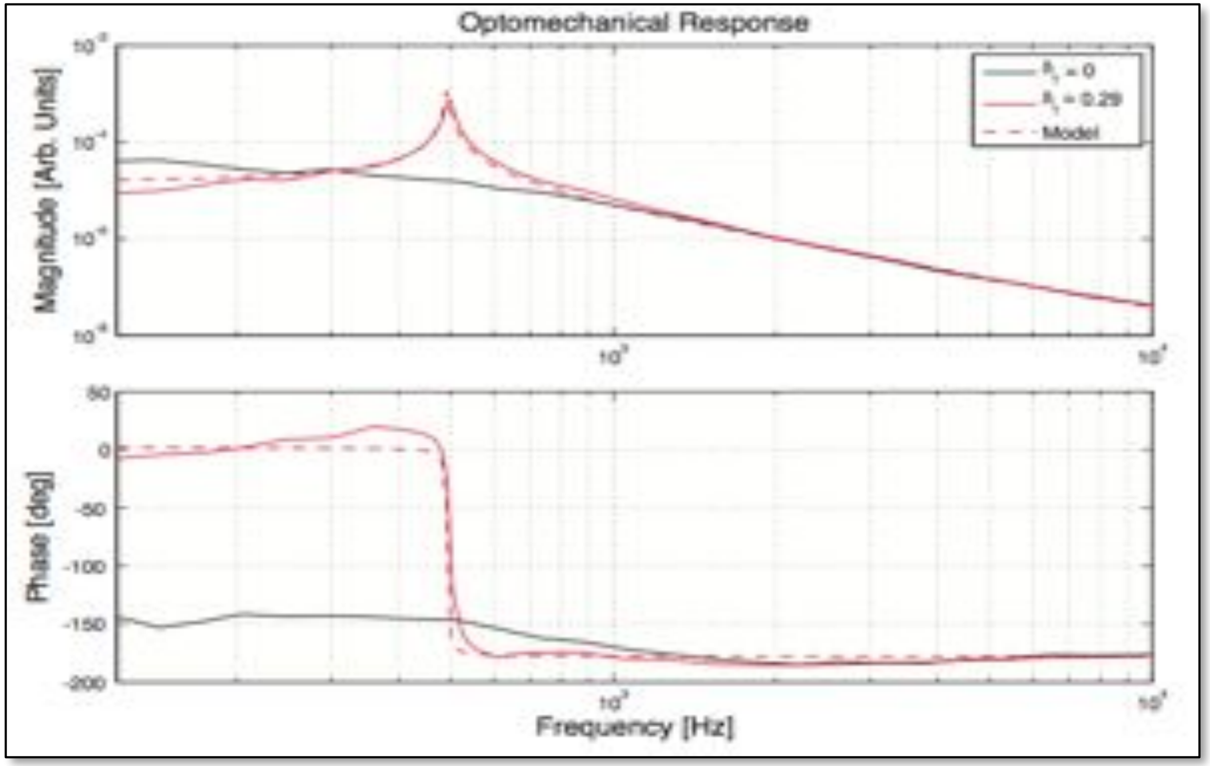
- Local Readout / Optical Bar experiment
- Dual Carrier Optical Springs and Quantum Control
- Waveguide mirror side motion noise
- Speedmeter proof of principle experiment

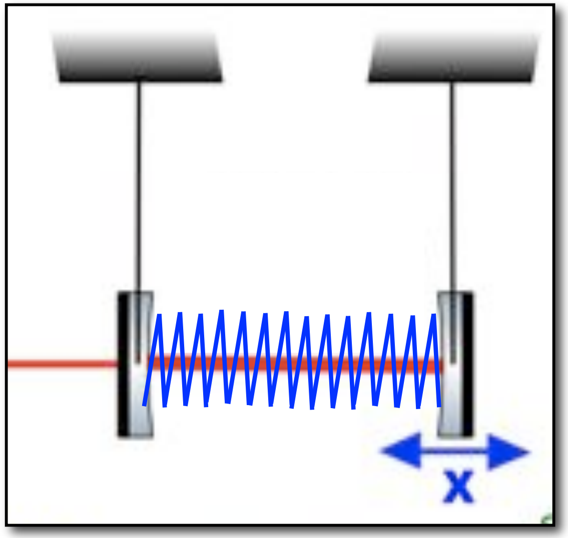


Glasgow 10m Interferometer



Stiffness of an optical spring in Glasgow 10m prototype





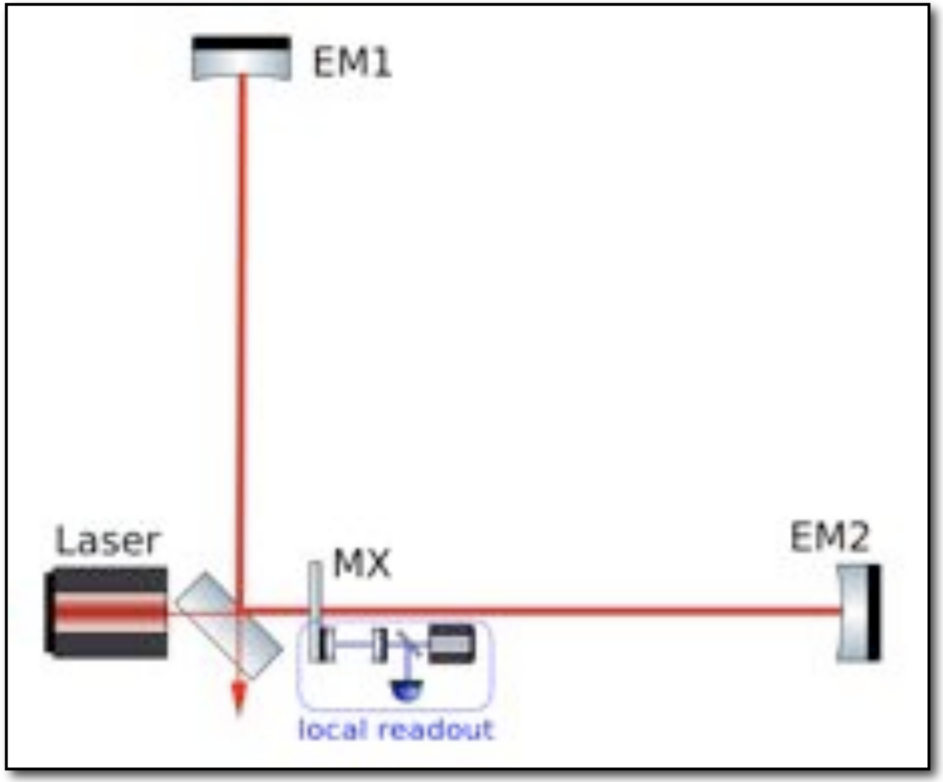
$$K = (2\pi f_{os})^2 m_r = 9.4 \times 10^5\,\mathrm{N/m}.$$

$$E = \frac{K L_{AC}}{A} \approx 1 \times 10^{12}\,\mathrm{Pa}.$$

Obtained a Youngs Modulus of optical spring similar to that of diamond

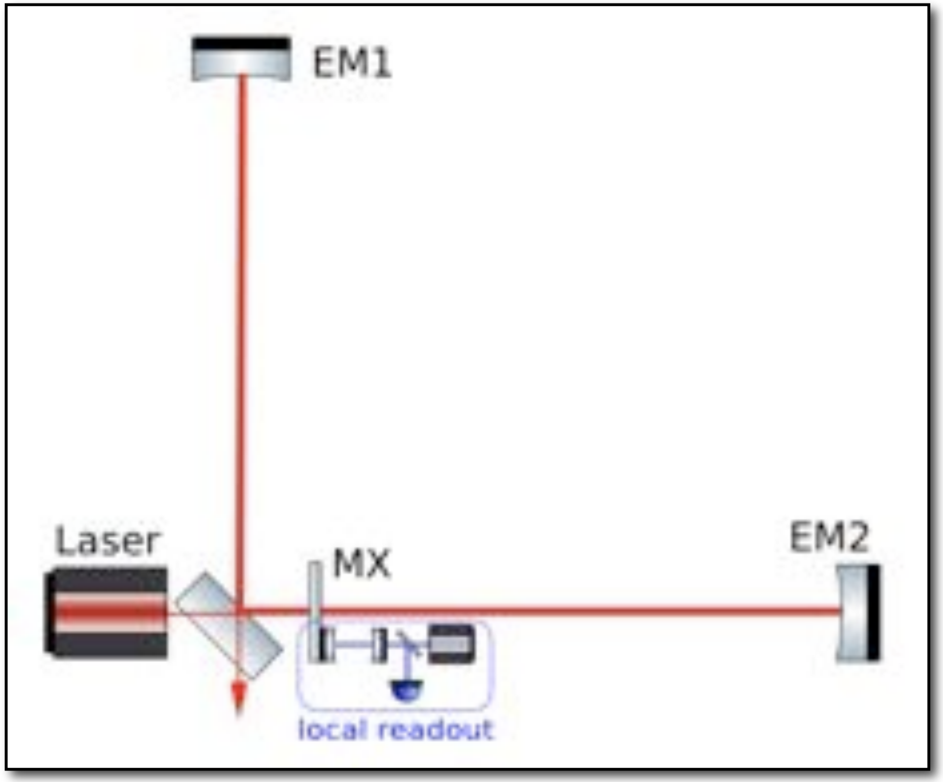
Optical Bars and 'moving mirrors'

Task for you:
Image there are 3 observers standing each next to EM1, EM2 and MX. A gravitational wave comes by. Which observer can 'see' which mirrors moving?



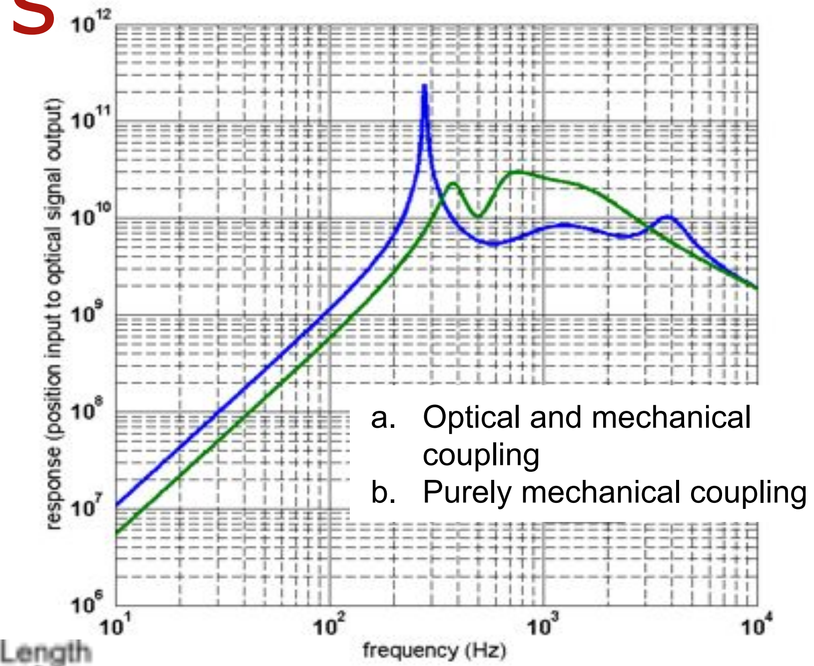
Optical Bar configurations

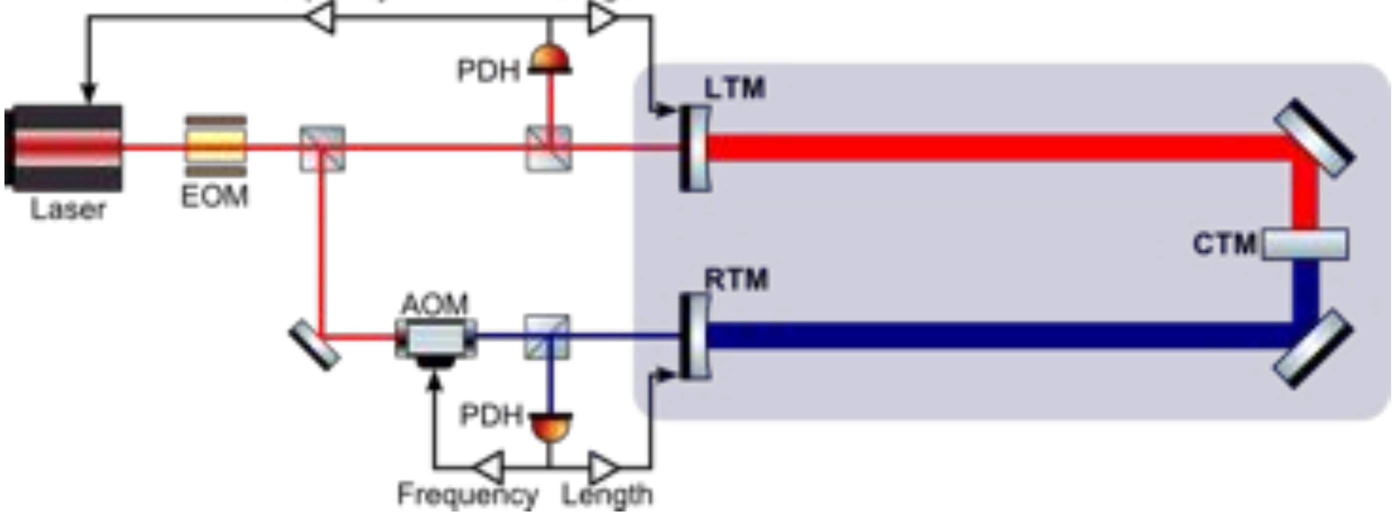
- Very light mirror (MX) is coupled to the movement of EM1 and EM2 via optical springs.
- MX can then locally read out by a small local meter without disturbing the quantum states in the main instrument (QND measurement).
- Split between GW transducer and readout allows separate optimisation of these two systems.



Multiple Optical springs in coupled cavities

- Experiment currently under construction.
- Use dual carrier systems in a coupled cavity systems.
- Initially only mechanical coupling, then mechanical+optical coupling.





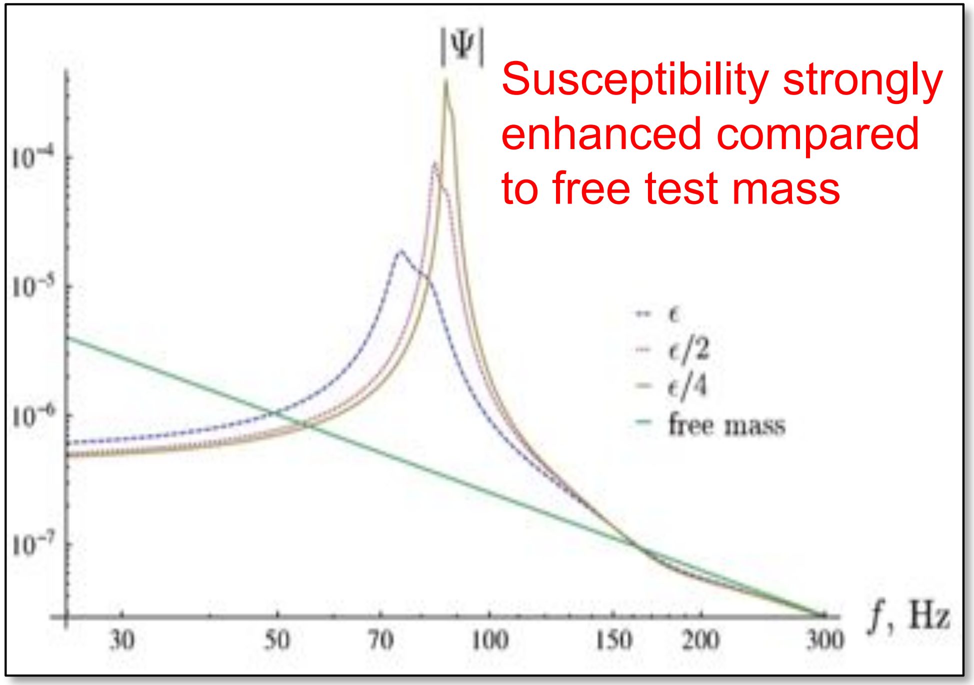
Double Optical Spring resonances

- What happens if the optical spring frequency coincides with the detuning frequency of the optical system?

PHYSICAL REVIEW D **84,** 062002 (2011)

Stable double-resonance optical spring in laser gravitational-wave detectors

Andrey A. Rakhubovsky,[1] Stefan Hild,[2] and Sergey P. Vyatchanin[1]



Susceptibility strongly enhanced compared to free test mass

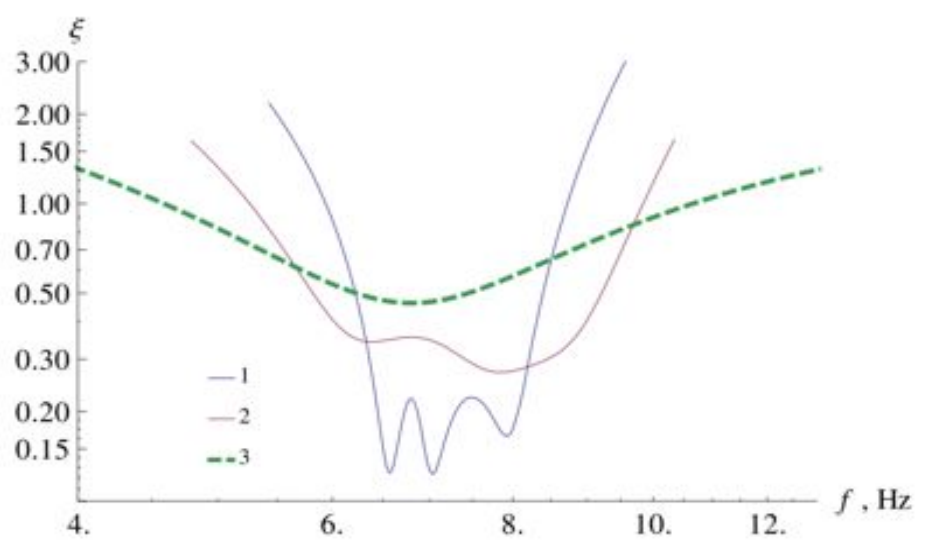


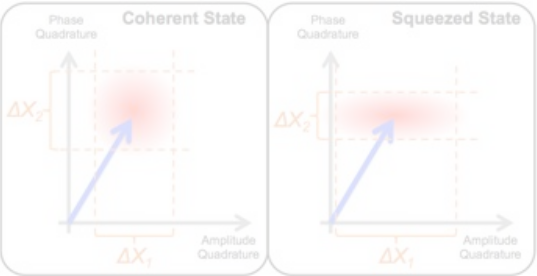
Fig. 4. Plots of sensitivity ξ of ET normalized to SQL versus frequency. Traces 1, 2: different regimes of optical rigidity. Trace 3: design sensitivity of ET without squeezing, no thermal noise present.

Overview

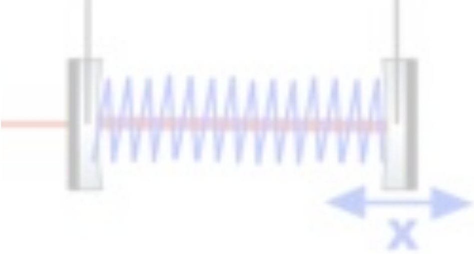
- Heisenberg, Braginsky and the Standard Quantum Limit

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

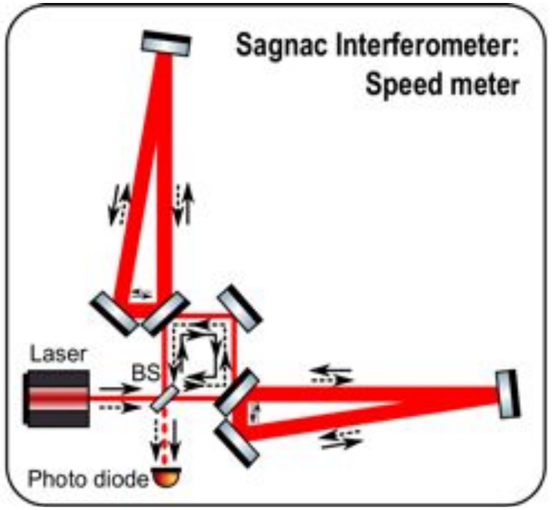
- Squeezed Vacuum



- Stiff Photons



- Why not measure observables that commute?

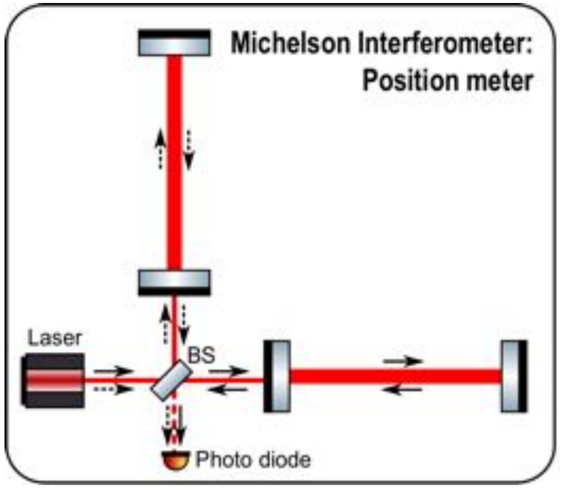


Are there better observables?

- 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:

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

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

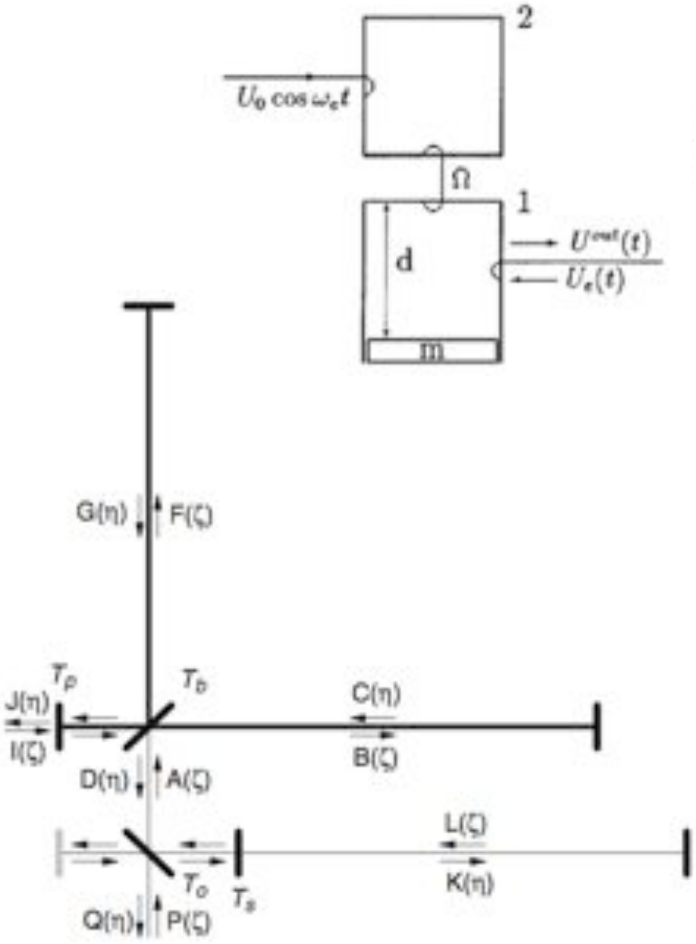


- However, already in 1930s John von Neumann told us that there are observables which can measured continuously without encountering the Heisenberg uncertainty. For example the momentum or speed of a testmass in our case.

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

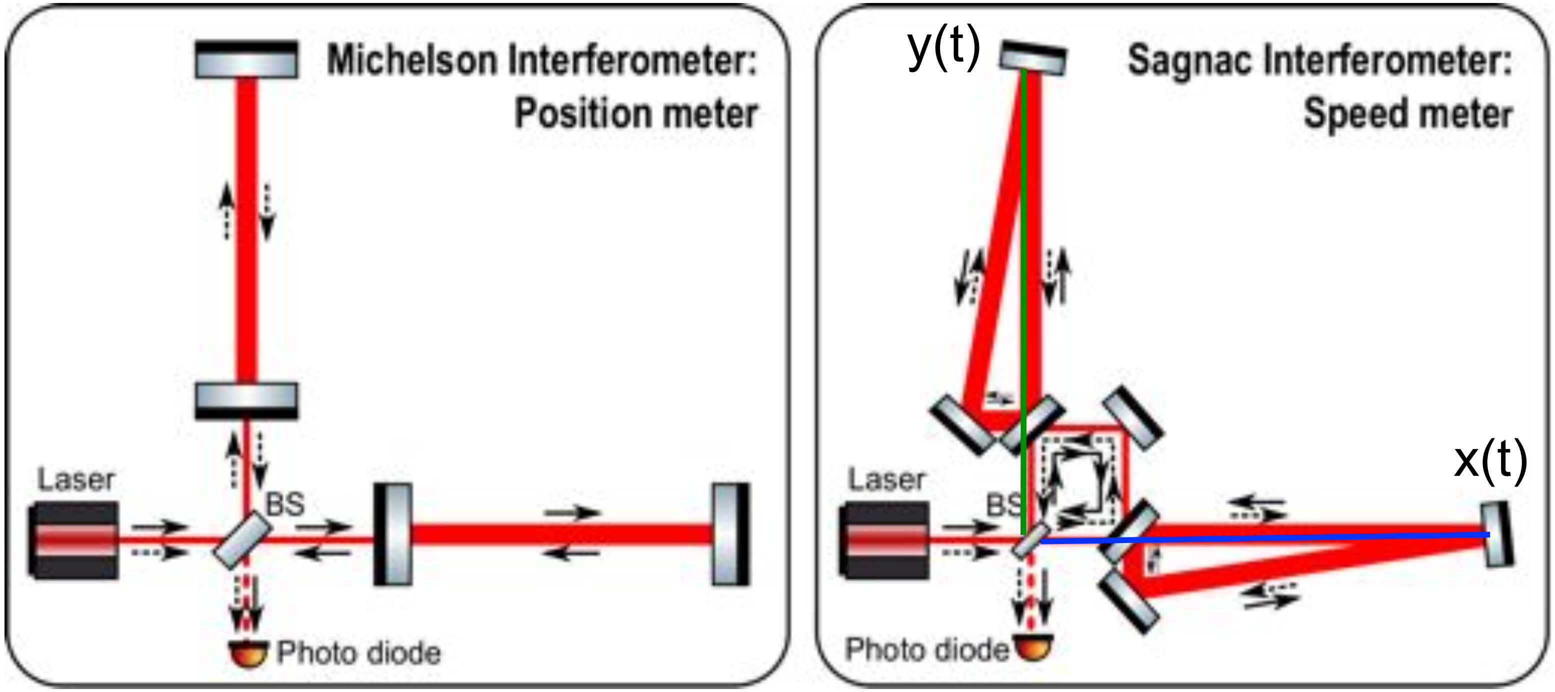
Speedmeter is not a new idea!

- 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 as Speedmeter

A Sagnac interferometer measures only (!) the speed of the mirrors, from which we can obtain the strain h(t). => No quantum limit.



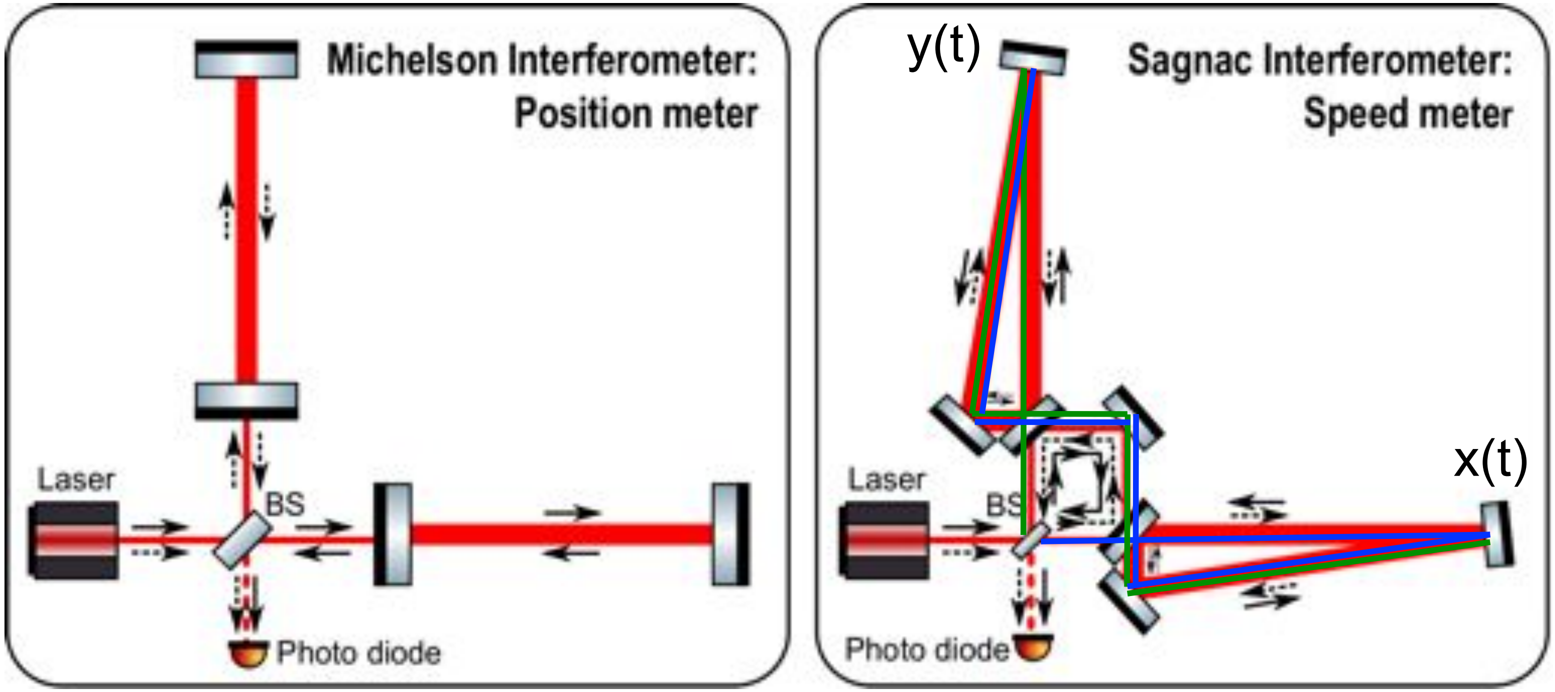
Each mirror is 'sensed' twice:

$y(t_1)$

$x(t_1)$

Sagnac as Speedmeter

- A Sagnac interferometer measures only (!) the speed of the mirrors, from which we can obtain the strain h(t). => No quantum limit.



Each mirror is 'sensed' twice:
$y(t_1)-y(t_2)$
$x(t_1)-x(t_2)$
Therefore on the photo diode we only have information on the mirrors velocity, but not their displacement.

- **A Sagnac speedmeter can avoid back action noise and therefore be limited entirely by shot noise. (= no quantum radiation pressure noise!)**

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?

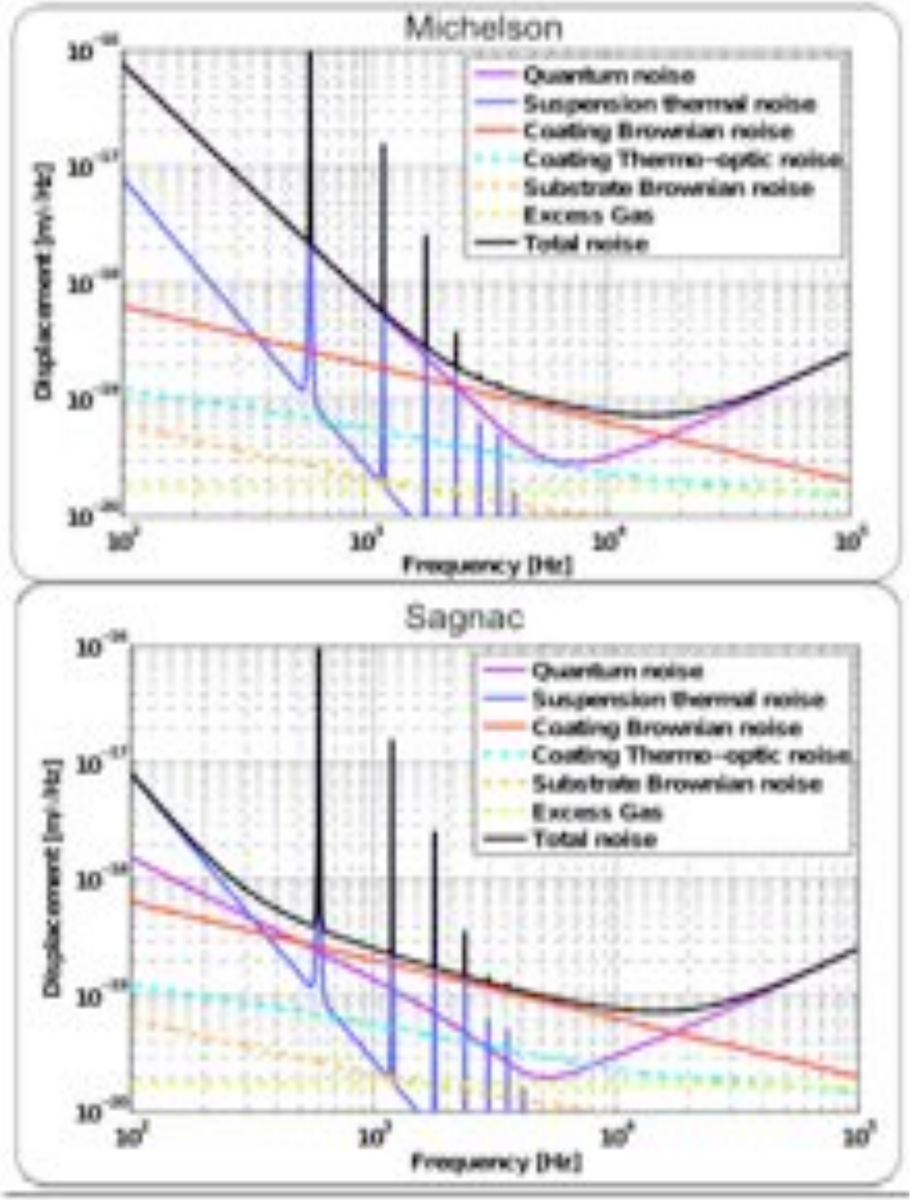
ERC grants aim to support 'Frontier Research', in other words the pursuit of questions at or beyond the frontiers of knowledge, without regard for established disciplinary boundaries. Applications may be made in **any field of research** covered by the Treaty on the Functioning of the European Union 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).

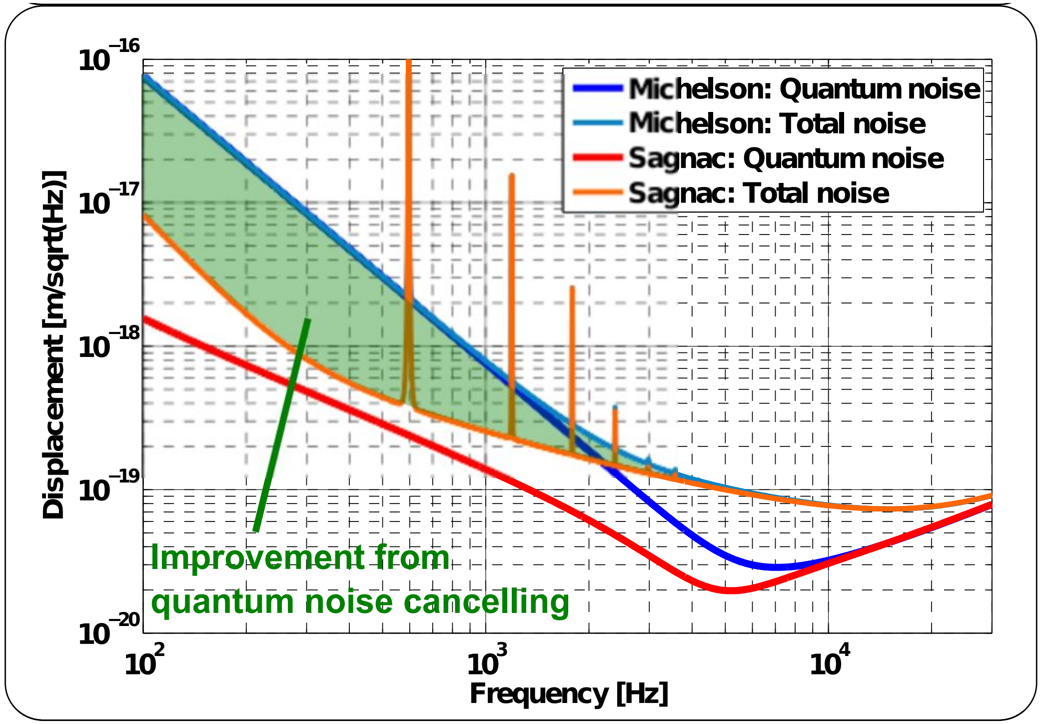
Aim of the Project

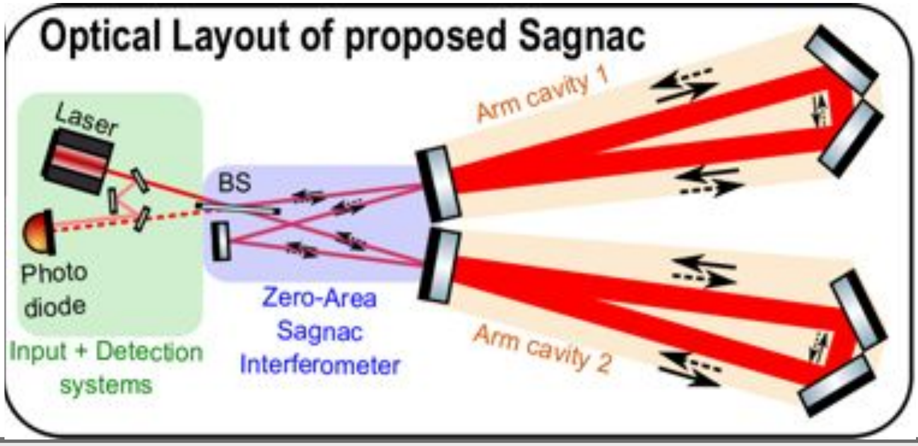


- 1g mirrors suspended in monolithic fused silica suspensions.
- 1kW of circulating power. Arm cavities with finesse of 10000. 100ppm loss per roundtrip.
- Sophisticated seismic isolation + double pendulums with one vertical stage.
- Large beams to reduce coating noise.
- Armlength = 1m. Target better 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.**



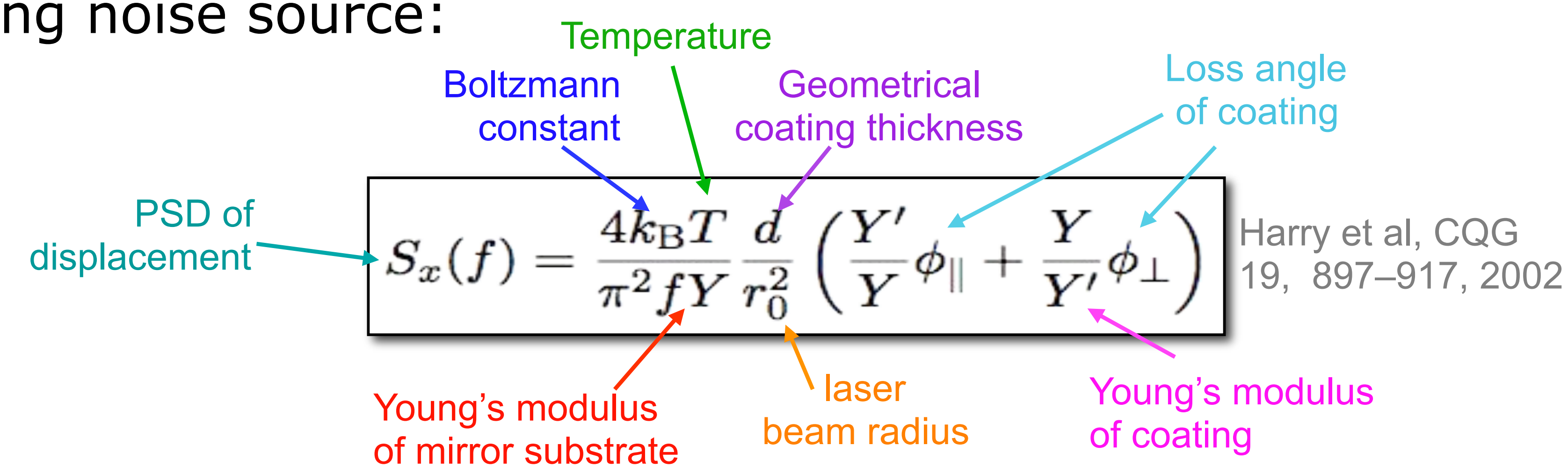


Thank you for your attention

EXTRA SLIDES

Mirror Thermal Noise

- Due to thermal fluctuations the position of the mirror sensed by the laser beam is not necessarily a good representation of the center of mass of the mirror.
- Various noise terms involved: Brownian, thermo-elastic and thermo-refractive noise of each substrate and coating (or coherent combinations of these, such as thermo-optic noise).
- For nearly all current and future designs coating Brownian is the dominating noise source:



Temperature

Boltzmann constant

Geometrical coating thickness

Loss angle of coating

PSD of displacement

$$S_x(f) = \frac{4k_{\mathrm{B}}T}{\pi^2 f Y}\frac{d}{r_0^2}\left(\frac{Y'}{Y}\phi_{\|} + \frac{Y}{Y'}\phi_{\perp}\right)$$

Harry et al, CQG 19, 897–917, 2002

Young's modulus of mirror substrate

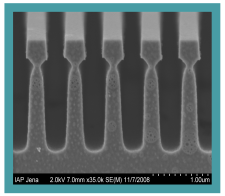
laser beam radius

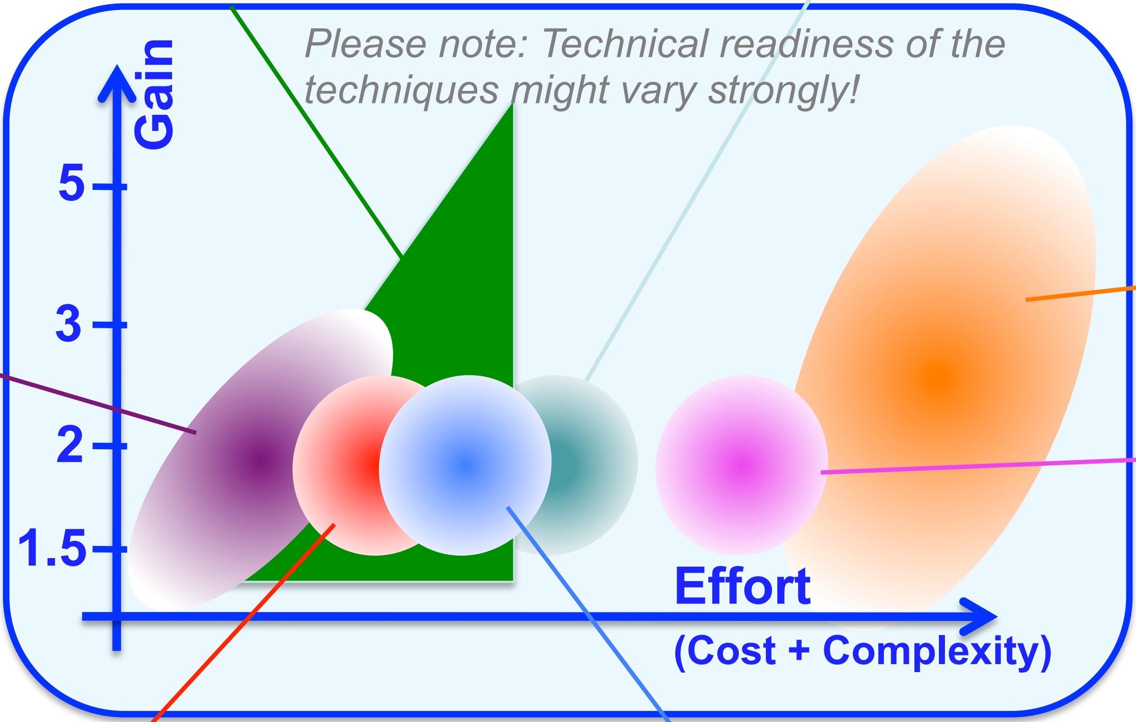
Young's modulus of coating

How to reduce Mirror Thermal Noise?

Improved coating materials (e.g. crystalline coatings like AlGaAs, GaPAs)
Cole et al, APL 92, 261108, 2008

Waveguide mirrors
Brueckner et al, Opt. Expr 17, 163, 2009
PhD thesis of D.Friedrich



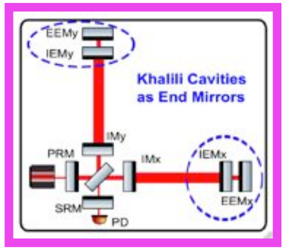


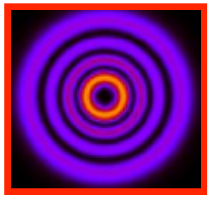
Please note: Technical readiness of the techniques might vary strongly!

Larger beam size (needs larger mirrors)
Harry et al, CQG 19, 897–917, 2002

Cryogenic mirrors
Uchiyama et al, PRL **108**, 141101 (2012)

Khalili cavities
Khalili, PLA 334, 67, 2005
Gurkovsky et al, PLA 375, 4147, 2011





Different beam shape
Mours et al, CQG, 2006, 23, 5777
Chelkowski et al, PRD, 2009, 79, 122002

Amorphous Silicon coatings
Liu et al, PRB 58, 9067, 1998

Suspension Thermal Noise

Temperature

Boltzmann constant

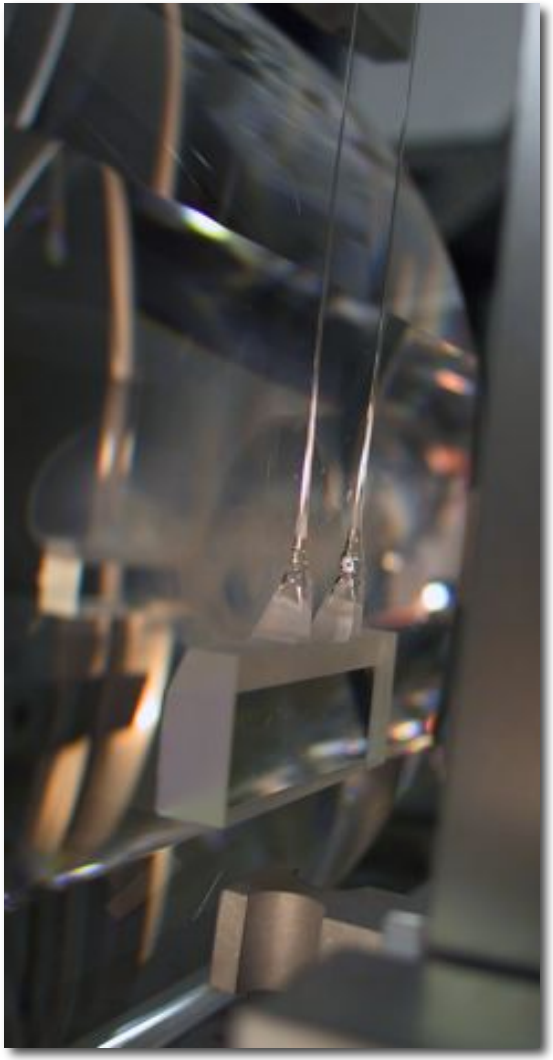
Loss angle

PSD of displacement

$$x^2(\omega) = \frac{4k_\mathrm{B}T\omega_0^2\phi(\omega)}{\omega m[(\omega_0^2-\omega^2)^2+\omega_0^4\phi^2(\omega)]}$$

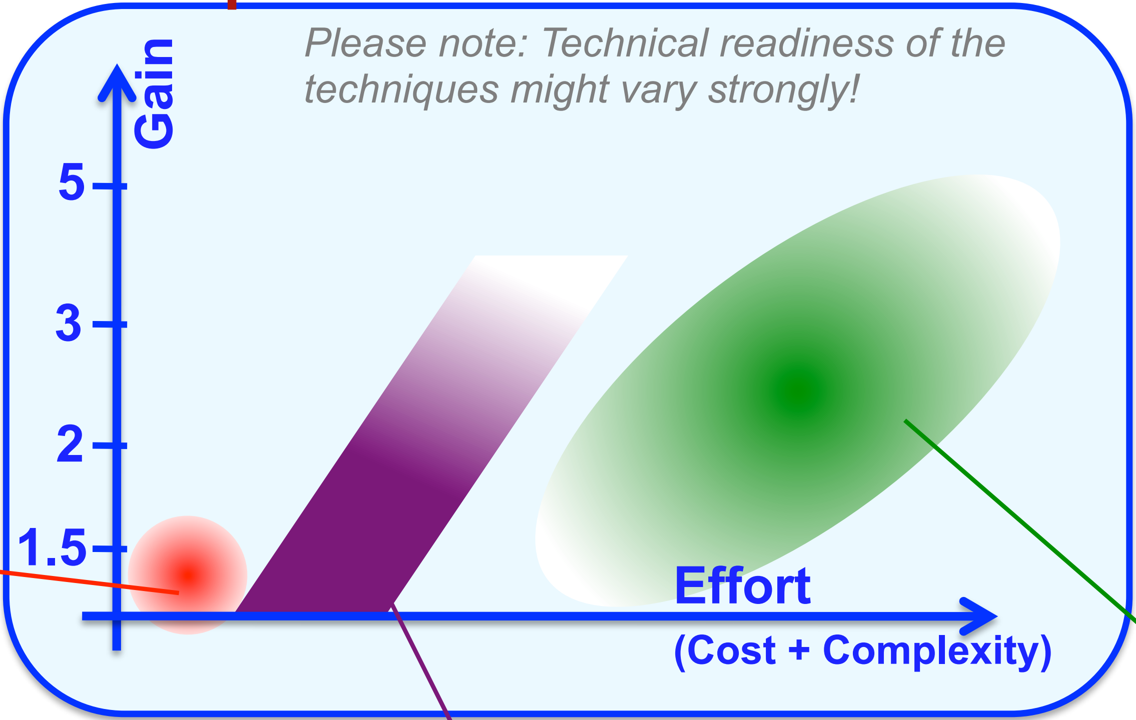
Mirror mass

Resonance frequency



- Mirrors need to be suspended in order to decouple them from seismic.
- Thermal noise in metal wires and glass fibres causes horizontal movement of mirror.
- Relevant loss terms originate from the bulk, surface and thermo-elastic loss of the fibres + bond and weld loss.
- Thermal noise in blade springs causes vertical movement which couples via imperfections of the suspension into horizontal noise.

How to reduce Suspension Thermal Noise?



Please note: Technical readiness of the techniques might vary strongly!

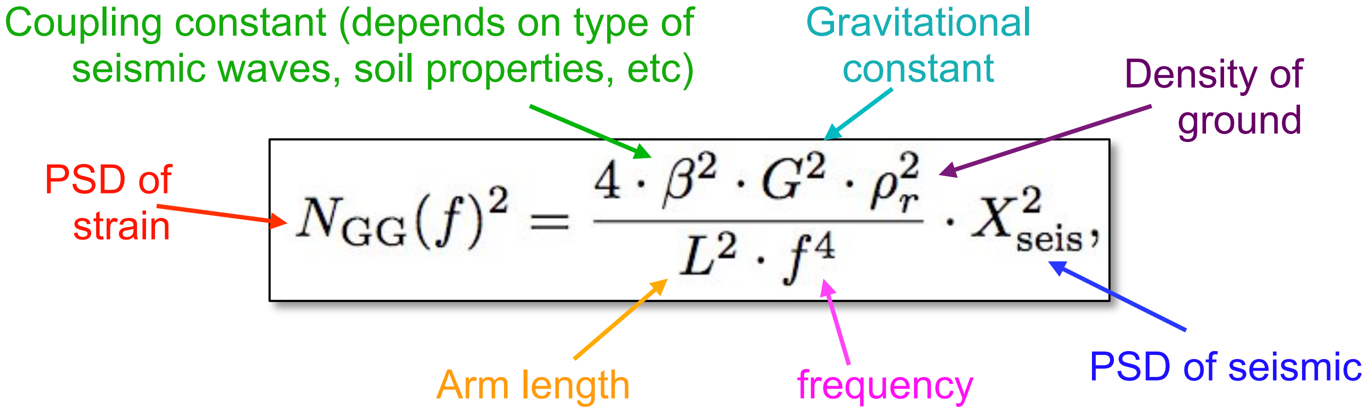
Improve fibre geometry/ profile
Bending points, energy stored via bending and neck profile can be potentially further optimised.

Increase length of final pendulum stage.
Allows the push suspension thermal noise out detection band.

Cooling of the suspension to cryogenic temperatures.
Usually also requires a change of materials.

Gravity Gradient Noise (also referred to as Newtonian noise)

- Seismic causes density changes in the ground and shaking of the mirror environment (walls, buildings, vacuum system).
- These fluctuations cause a change in the gravitational force acting on the mirror.
- Cannot shield the mirror from gravity. ☹



$$N_{\mathrm{GG}}(f)^2 = \frac{4\cdot\beta^2\cdot G^2\cdot\rho_r^2}{L^2\cdot f^4}\cdot X^2_{\mathrm{seis}},$$

Coupling constant (depends on type of seismic waves, soil properties, etc)

Gravitational constant

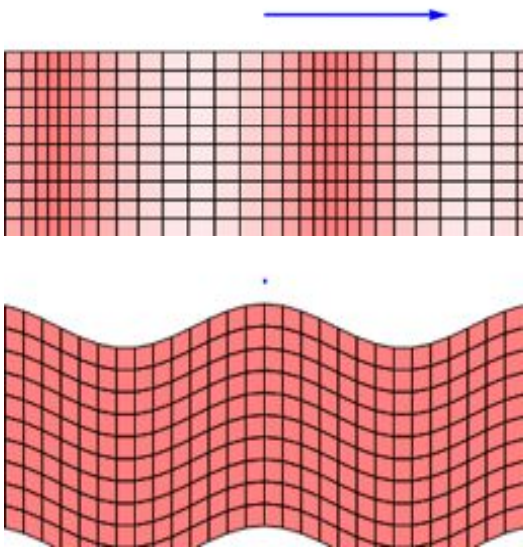
Density of ground

PSD of strain

Arm length

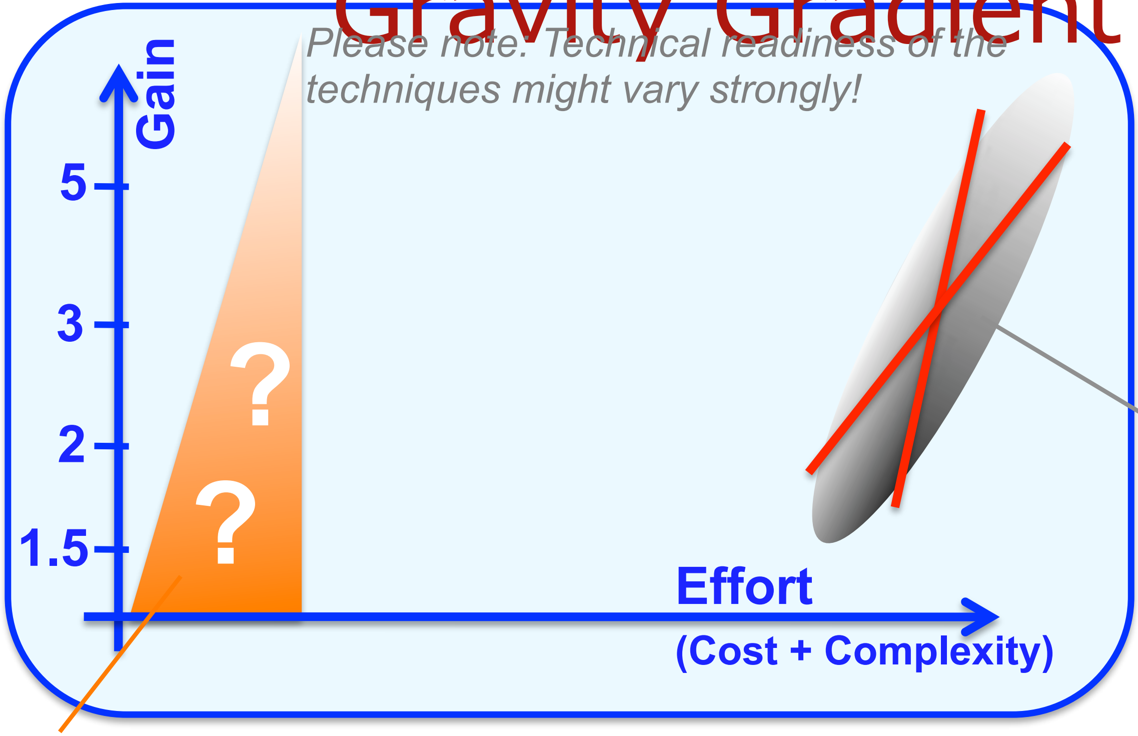
frequency

PSD of seismic



Images: courtesy G.Cella

How to reduce Gravity Gradient Noise?



Please note: Technical readiness of the techniques might vary strongly!

Subtraction of gravity gradient noise using an array of seismometers.

- Beker et al: General Relativity and Gravitation Volume 43, Number 2 (2011), 623-656
- Driggers et al: arXiv:1207.0275v1 [gr-qc]

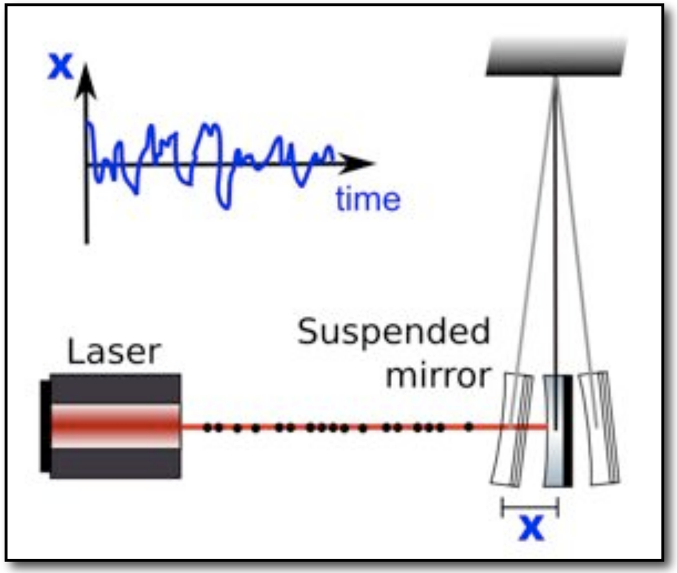
~~**Reduce seismic noise at site., i.e. select a quieter site, potentially underground.**~~

~~Beker et al, Journal of Physics: Conference Series 363 (2012) 012004~~

Obviously not possible within the LIGO infrastructure (but consider for other projects, see GW4 session tomorrow)

Quantum Noise

- Quantum noise is a direct manifestation of the **Heisenberg Uncertainty Principle**.
- It is comprised of **photon shot noise (sensing noise)** at high frequencies and **photon radiation pressure noise (back-action noise)** at low frequencies.



wavelength

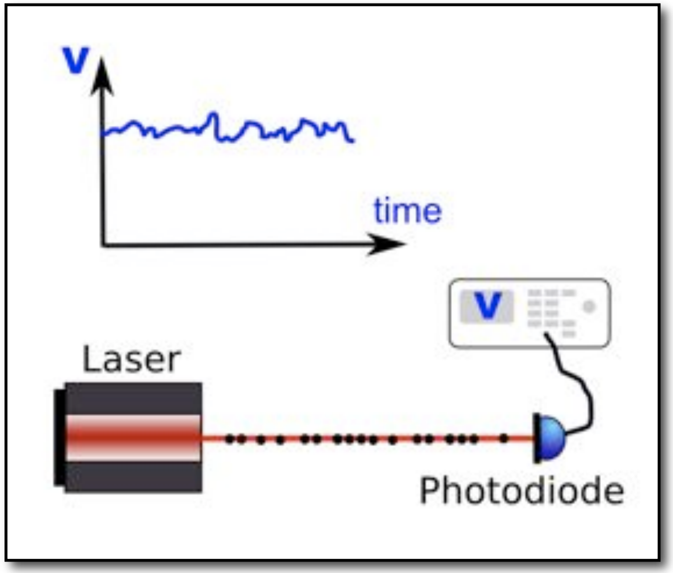
$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

optical
power

Mirror mass

Arm length

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



photon radiation pressure noise

photon shot noise

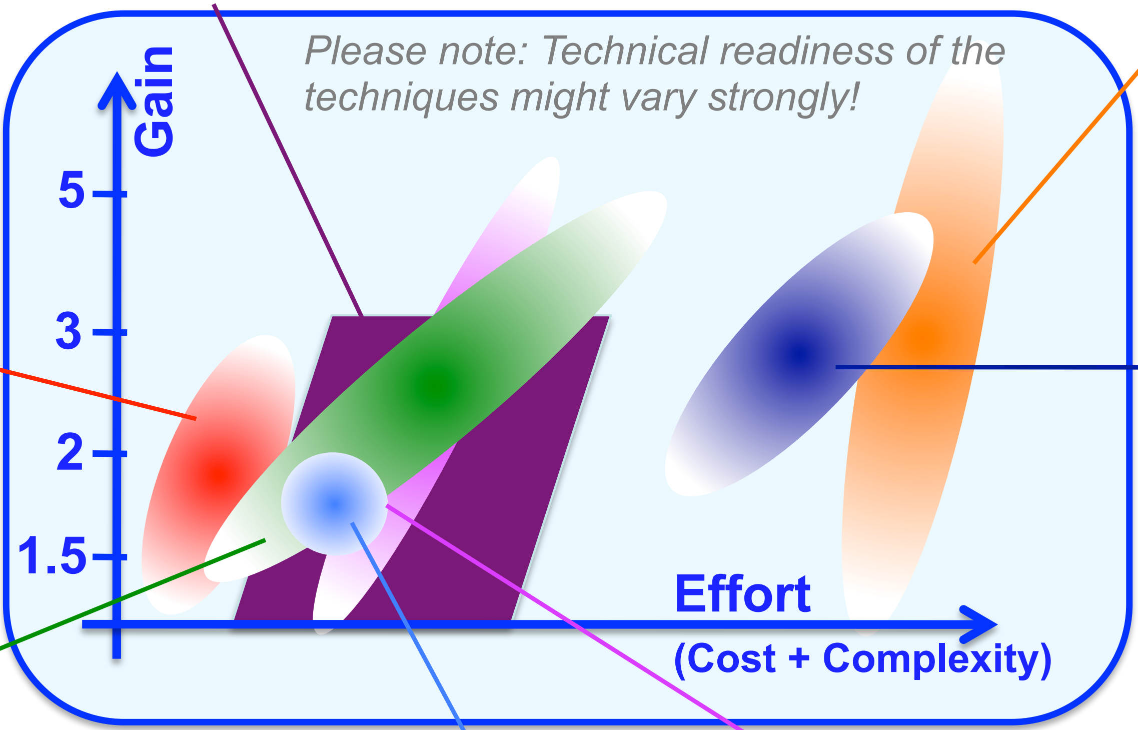
How to reduce Quantum Noise?

Squeezing with frequency dependent squeezing angle

Kimble et al, PRD 65, 2002

Speedmeter

Measures momentum of test masses and is therefore not susceptible to Heisenberg Uncertainity Principle.
Chen, PRD 67, 122004, 2003



Please note: Technical readiness of the techniques might vary strongly!

Squeezed Light

LIGO Scientific collaboration, Nature Phys. 7 962–65, 2011

Optical Bar + Optical Lever

Khalili, PLA 298, 308-14, 2002

Increased Laser Power

Need to deal with thermal problems and instabilities

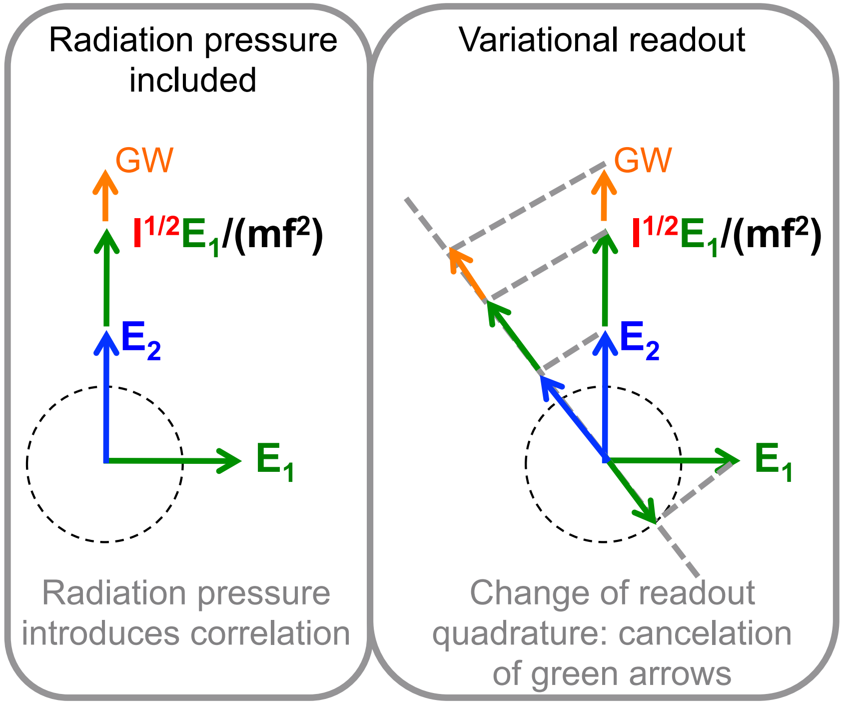
Local readout

Rehbein et al, PRD 78, 062003, 2008

Increased Mirror Weight

Need to deal with thermal problems and instabilities

Surpassing the SQL at AEI-10m: Variational Readout

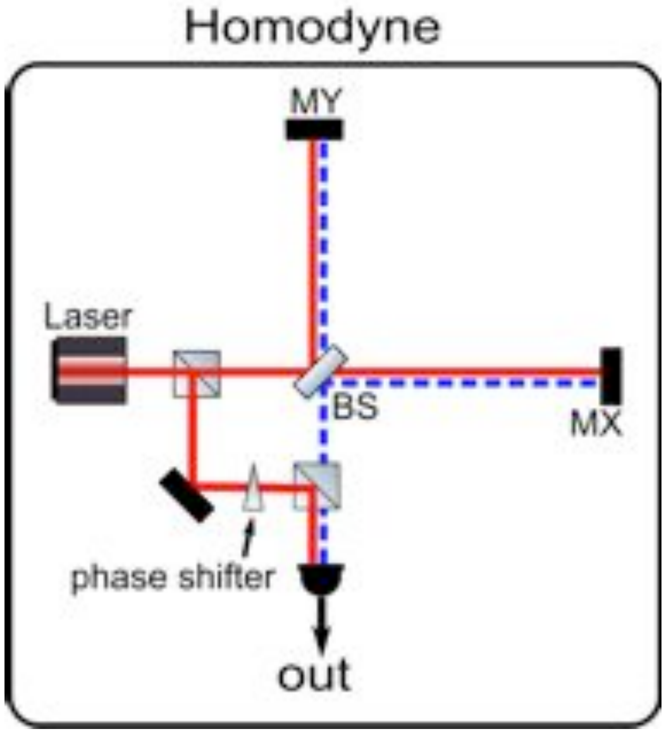


Radiation pressure included

Radiation pressure introduces correlation

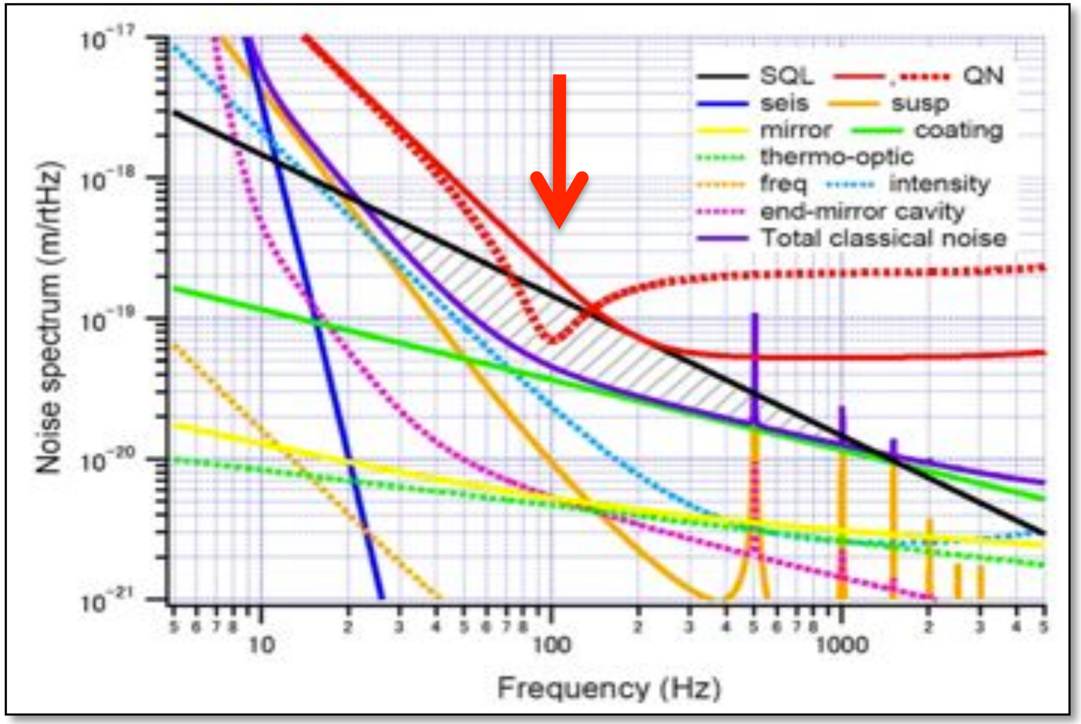
Variational readout

Change of readout quadrature: cancelation of green arrows

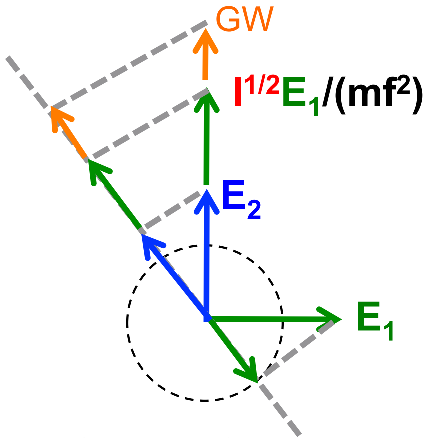


- Variational Readout enables us to partly cancel radiation pressure noise by selecting the appropriate readout quadrature.
- Readout quadarture (angle) can be chosen by phase shifter

Surpassing the SQL at AEI-10m-Interferometer



Variational readout

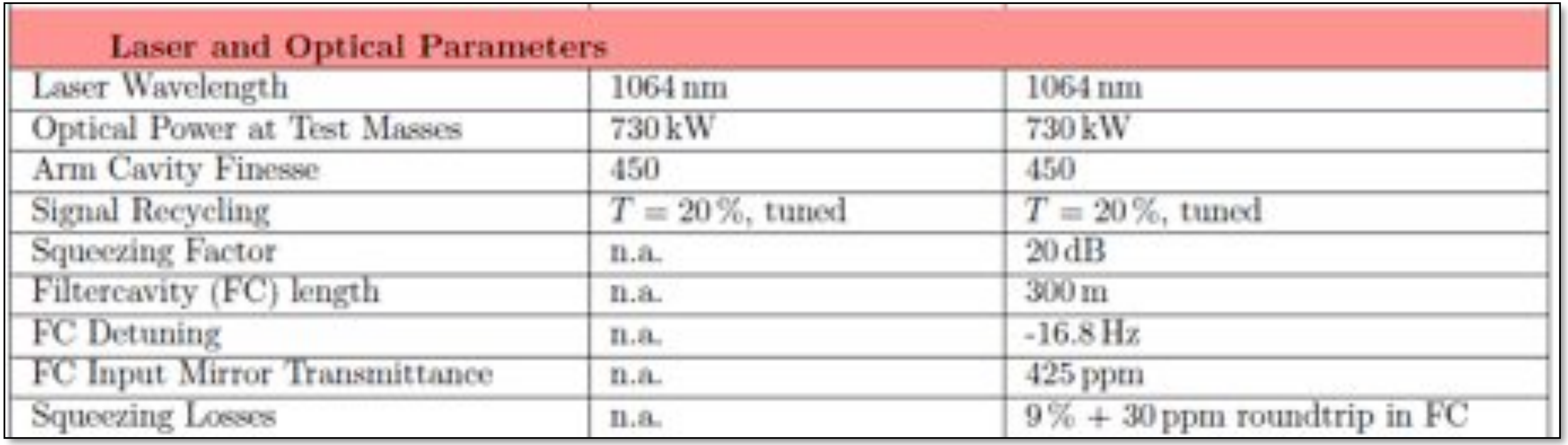


Change of readout quadrature: cancelation of green arrows

- Using Variational readout, we will be able to completely cancel the radiation pressure noise at **ONE** frequency (100Hz) and surpass the SQL a factor 2 to 3.
- To cancel the radiation pressure noise a all frequencies, we would need a frequency dependent angle of the readout quadrature

LIGO3-Red Quantum noise

- We kept the interferometer configuration and the mirror reflectivities the same as in aLIGO baseline.
- **Introduced frequency dependent input squeezing.**
- Key aspects: achievable squeezing level & required length of filter cavity



Laser and Optical Parameters		
Laser Wavelength	1064 nm	1064 nm
Optical Power at Test Masses	730 kW	730 kW
Arm Cavity Finesse	450	450
Signal Recycling	$T = 20\,\%$, tuned	$T = 20\,\%$, tuned
Squeezing Factor	n.a.	20 dB
Filtercavity (FC) length	n.a.	300 m
FC Detuning	n.a.	-16.8 Hz
FC Input Mirror Transmittance	n.a.	425 ppm
Squeezing Losses	n.a.	$9\,\% + 30$ ppm roundtrip in FC

Example: Squeez losses LIGO3 Red

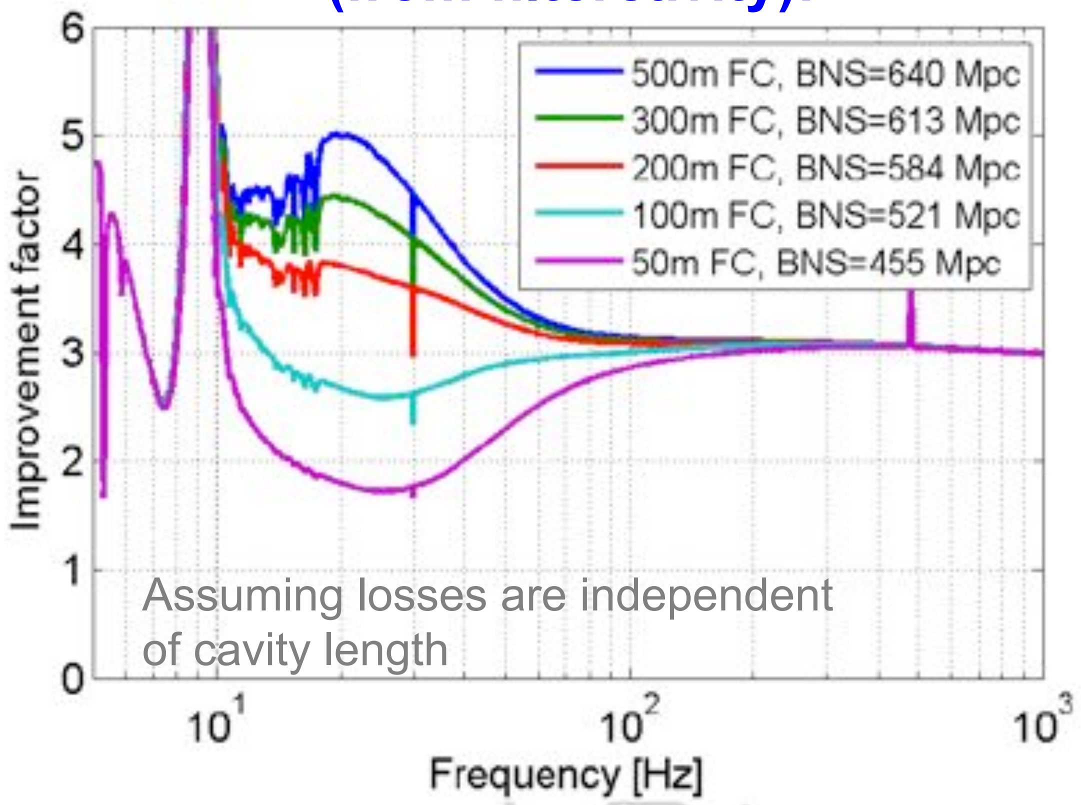
Frequency independent losses:

- Generation of squeezing: 3 %
- Optical isolation: 3 x 0.8 %
- Mode matching to IFO and to OMC: 2 x 1 %
- OMC loss and QE of PD: 2 x 0.5 %
- Mode matching to filter cavity: 1 %

= 9% in total

\+

Frequency dependent loss (from filtercavity):

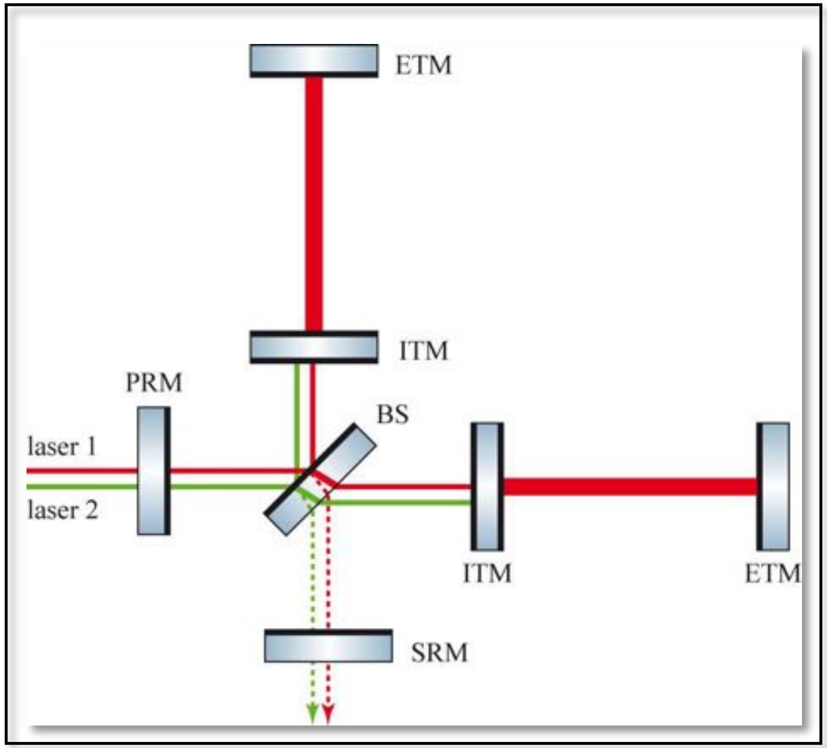


Assuming losses are independent of cavity length

Starting from 20dB squeezing inside the squeezing crystal the losses reduce the observed squeezing to about 9-10dB

Local Readout for Advanced LIGO

- While optical Bars and levers require a complete redesign of the interferometers, so-called 'local readout' is compatible within advanced LIGO infrastructure
- At low frequencies ITM and ETM are rigidly connected.
- At low frequencies GW signal is not in differential arm length, but in ITM movement (local frame).
- Use a separate laser system to read out the position of the ITM.

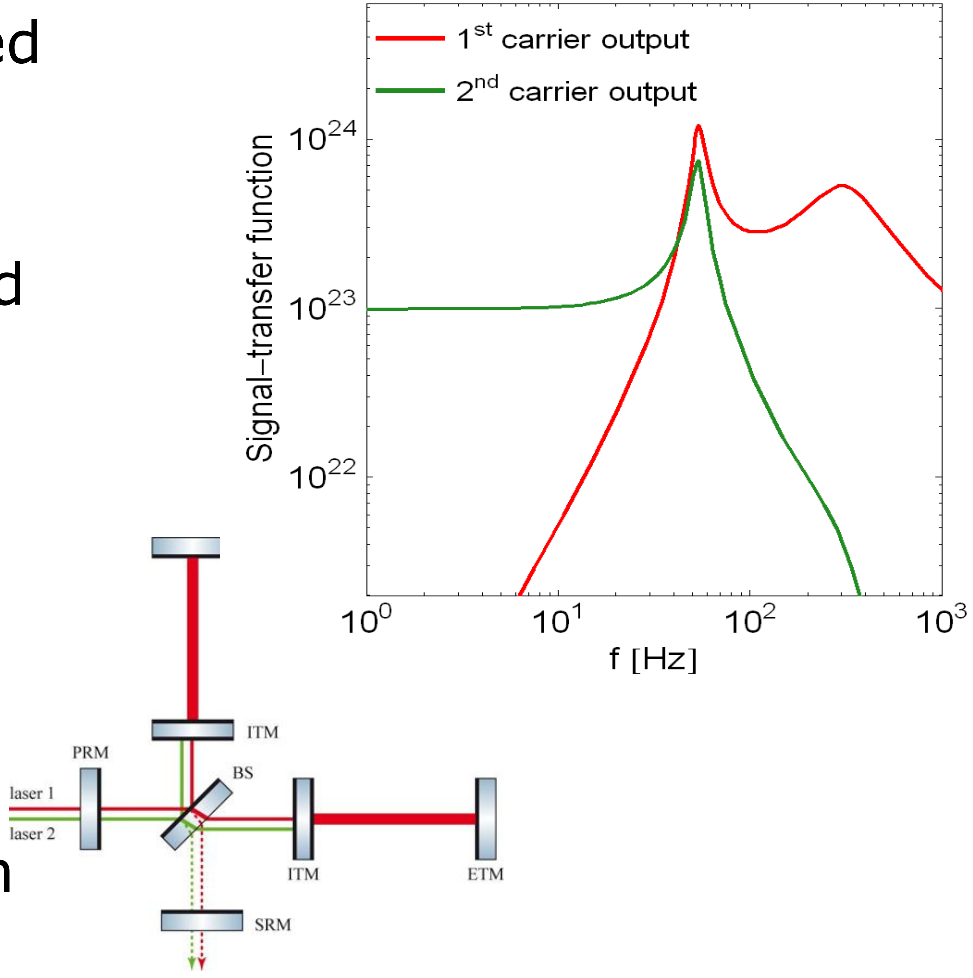


Rehbein et al: PRD ***76, 062002 (2007)***

Local Readout for Advanced LIGO (2)

How does local readout for Advanced LIGO work?

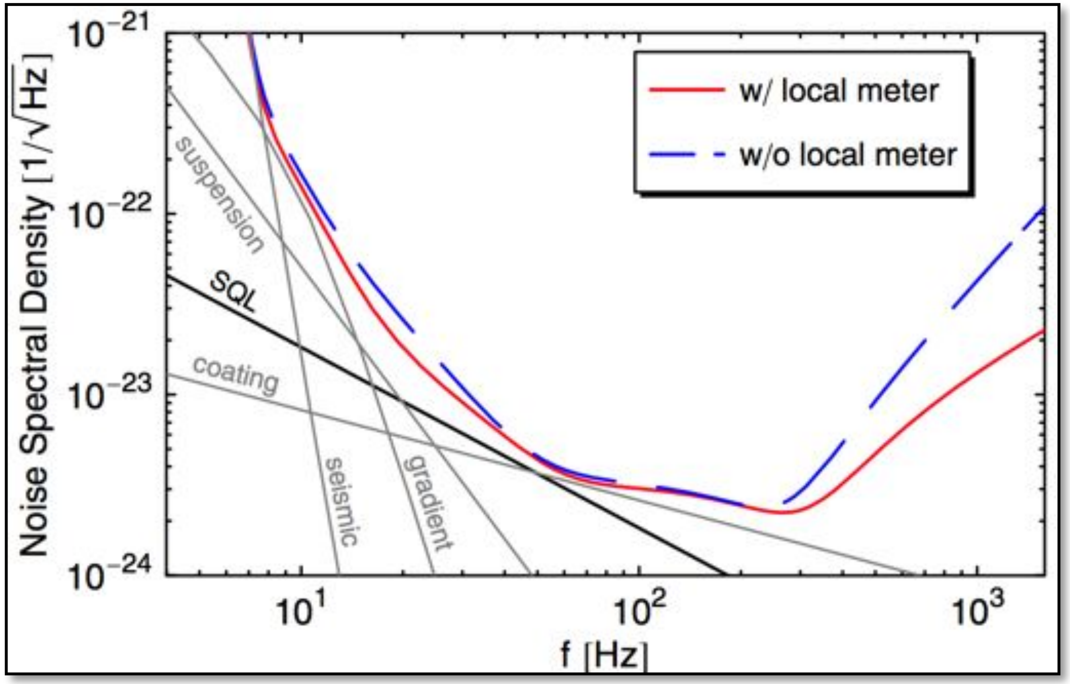
- **At low frequencies:** the arm cavity mirrors are 'rigidly' connected by optical springs => GW does not change the distance between ITM and ETM. However, GW signal is imprinted on ITM movement (in respect to BS), which and can be read out by additional green laser.
- **At high frequencies:** no optical spring present => ITM and ETM can move independently.



*Rehbein et al: PRD **76, 062002 (2007)***

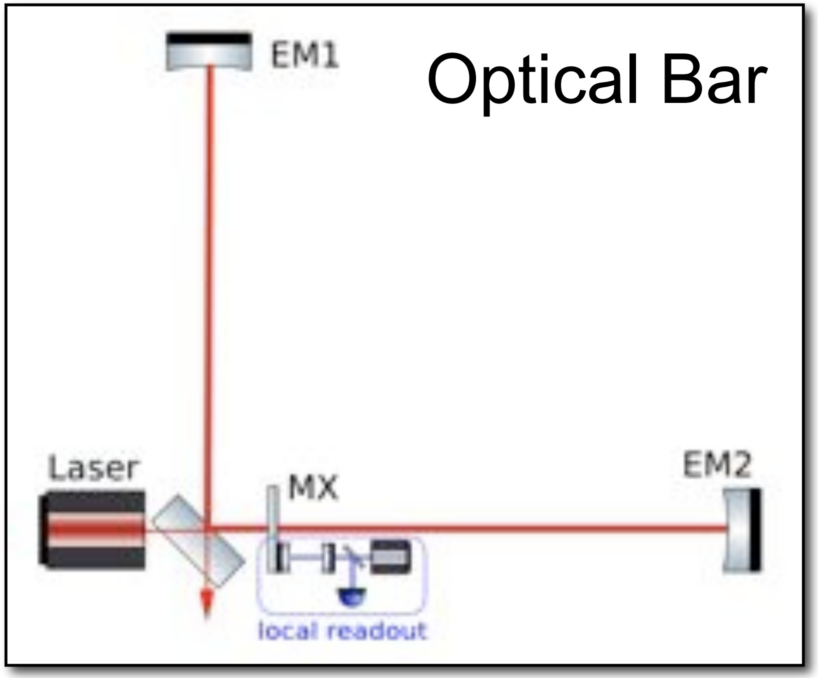
Local Readout for Advanced LIGO (3)

- Technique allows to increase low frequency sensitivity.
- In a second step the Signal-Recycling can then be re-tuned to slightly higher frequency.
- Win at low and high frequencies. =>

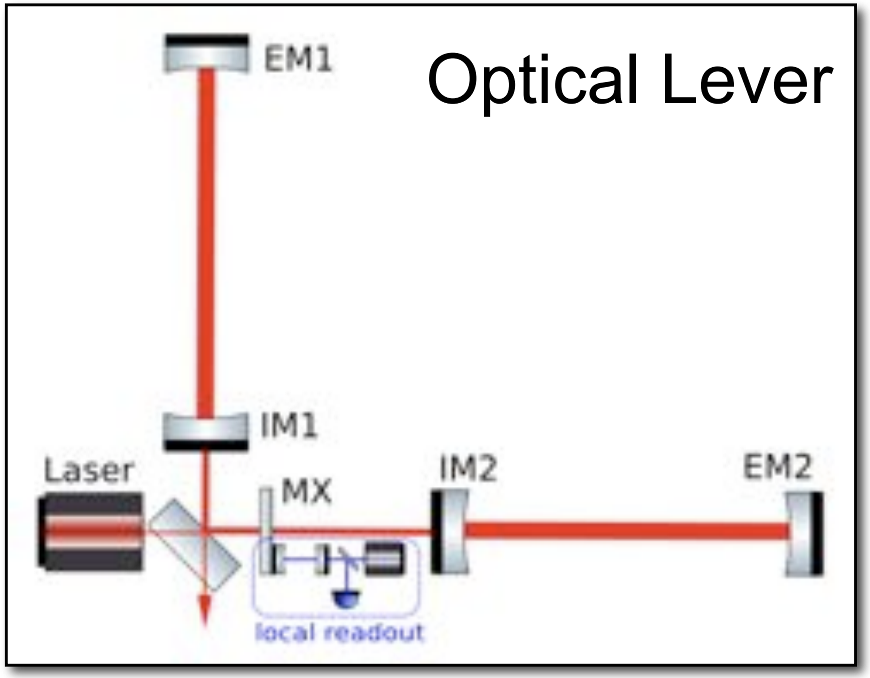


*Rehbein et al: PRD **76, 062002 (2007)***

Optical Bars and Optical Levers


Optical Bar

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


Optical Lever

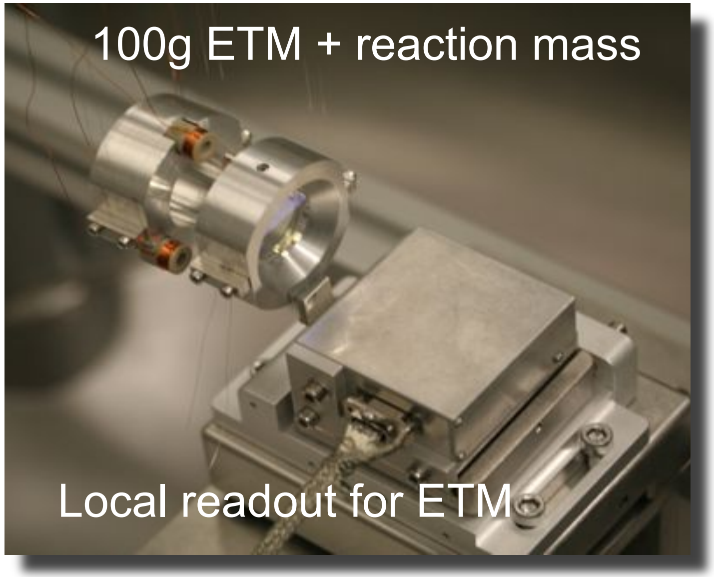
F.Y. Khalili: “The ‘ptical lever’ intracavity readout scheme for gravitational-wave antennae”,Phys. Lett. A 298 (2002).

- Optical lever: introducing arm cavities increases the movement of MX by the Finesse of the arm cavity.

Local Readout Demonstration

LONGTERM AIM: Pinning down of optical spring features to refine models and simulations to provide deeper understanding of system dynamics and control while maintaining low noise performance.

- 10m cavity with Finesse of 11000
- Input Power = 700mW (Laser amplifier addition will give up to 4W)
- **ETM (100g) coupled to ITM (3kg) with optical spring.**
- **Signal is applied to ETM, while ITM is read out in local frame with an independent interferometer.**
- EUCLID local readout: 10^{-13}m/sqrt(Hz) at 100Hz but poor dynamical range (limited to less than a micron)
- Beginning of Optical bar/Lever interferometer configurations



100g ETM + reaction mass

Local readout for ETM