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EUROPEAN UNION

MINISTRY OF EDUCATION, YOUTH AND SPORTS

OP Education for Competitiveness

INVESTMENTS IN EDUCATION DEVELOPMENT

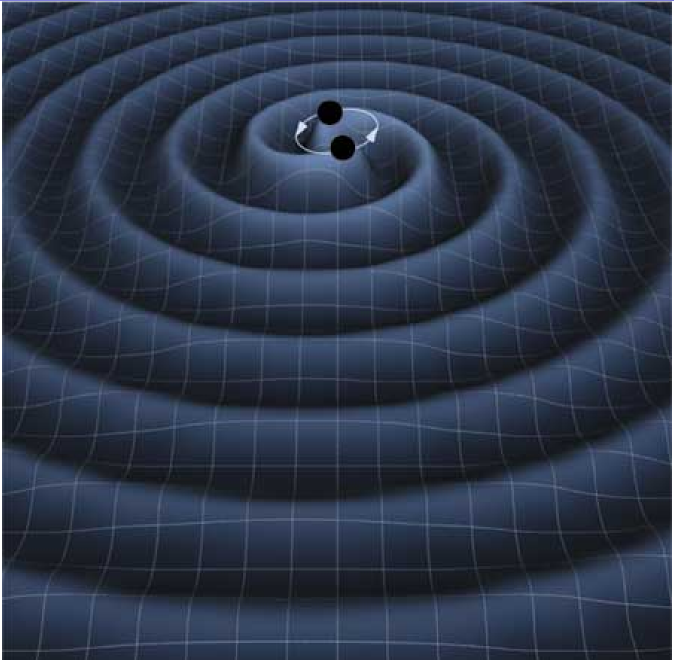
Quantum measurements in laser gravitation wave detectors

F.Ya.Khalili

February 4, 2013

1. Brief introduction into GW detectors
2. Brief theory of optical position meters
3. Standard Quantum Limit
4. Quantum noises cross-correlation
5. Quantum speedmeter

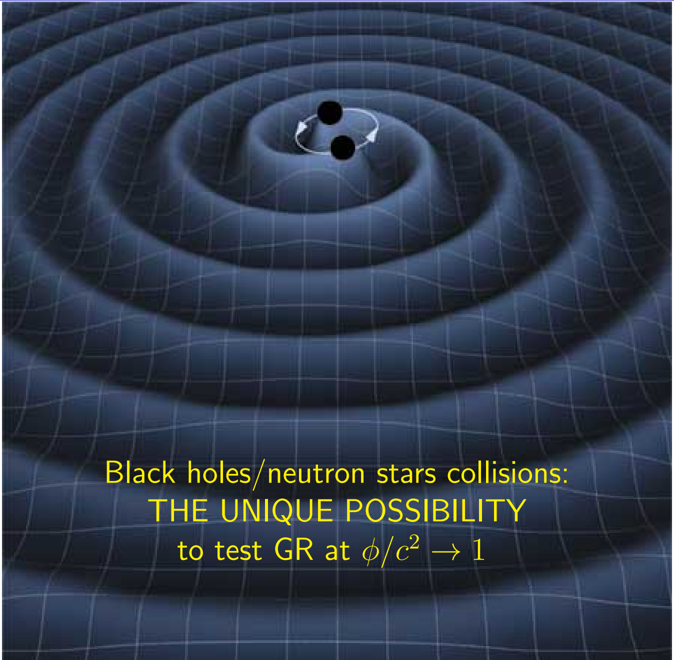
In some far far away galaxy...



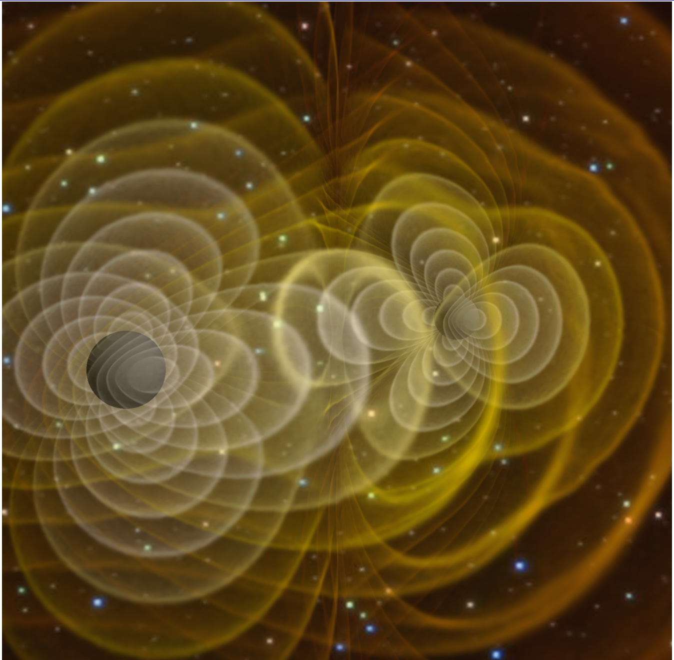
http://www.ligo.org/science.php

In some far far away galaxy...

http://www.ligo.org/science.php



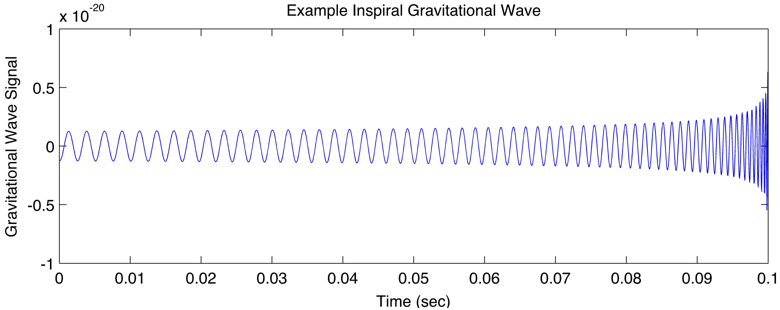
In some far far away galaxy...

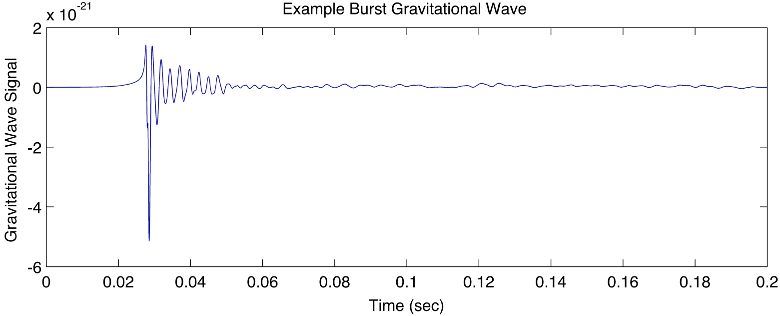


http://www.ligo.org/science.php

On Earth (some 100 000 000 years later)...

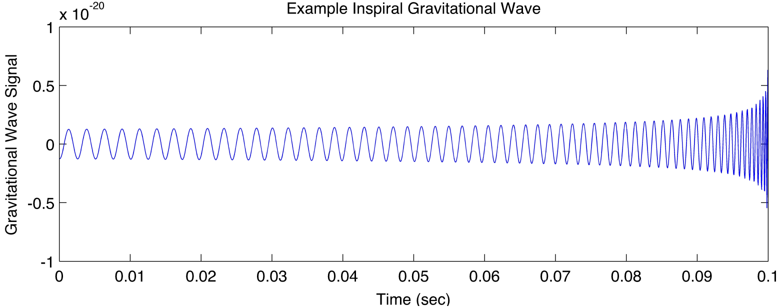
http://www.ligo.org/science.php

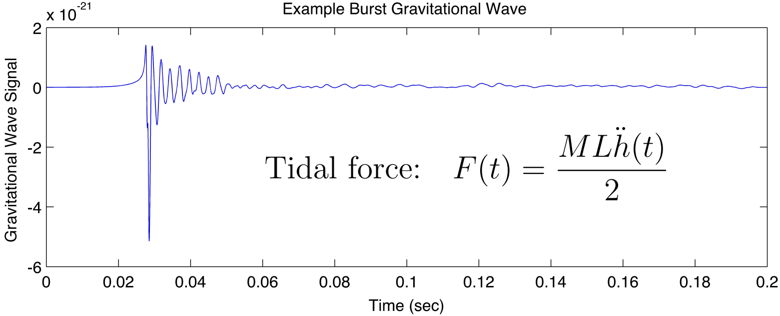




On Earth (some 100 000 000 years later)...

http://www.ligo.org/science.php



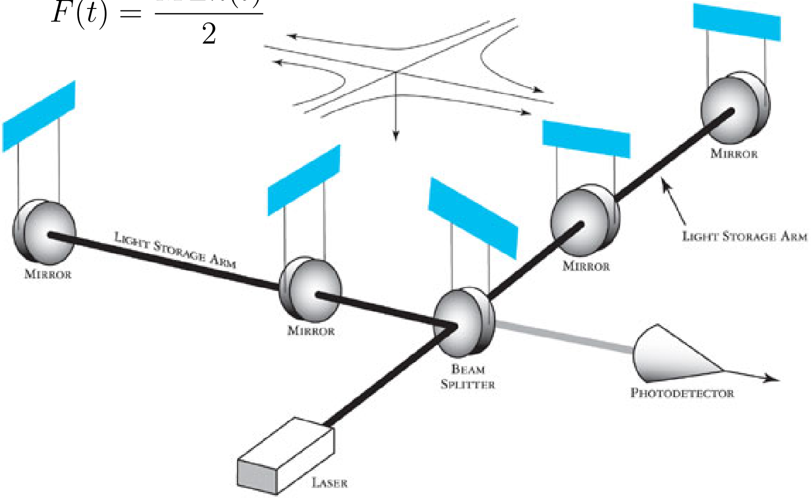


$$\text{Tidal force:} \quad F(t) = \frac{ML\ddot{h}(t)}{2}$$

On Earth (some 100 000 000 years later)...

http://www.ligo.org/science.php

$$F(t) = \frac{ML\ddot{h}(t)}{2}$$



The old good Michelson...

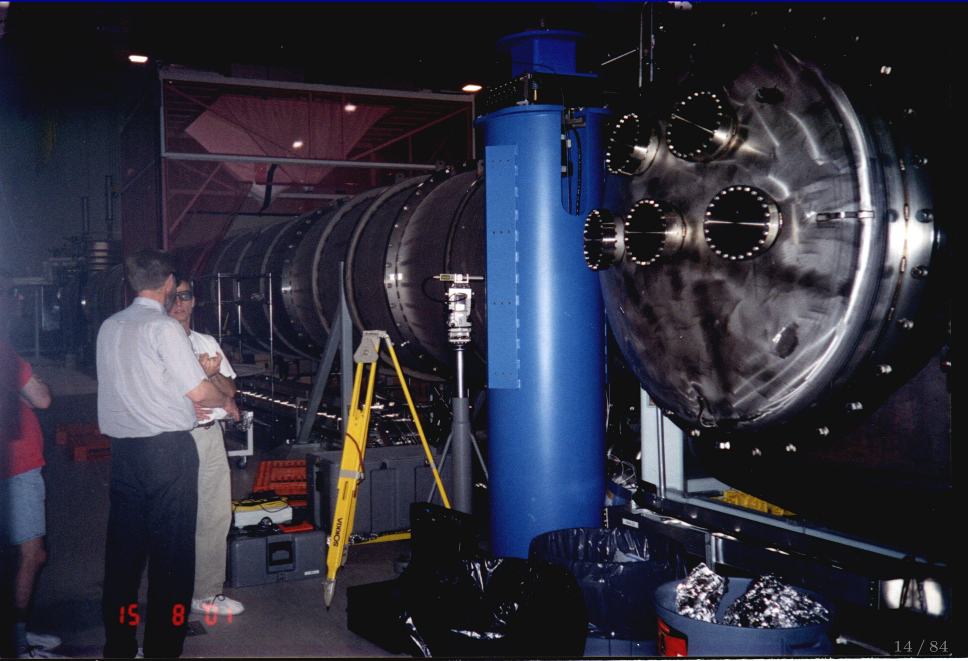
... but HUGE one!

Actually, four of them

Closer look

Closer look

Closer look



Weber's bar detector

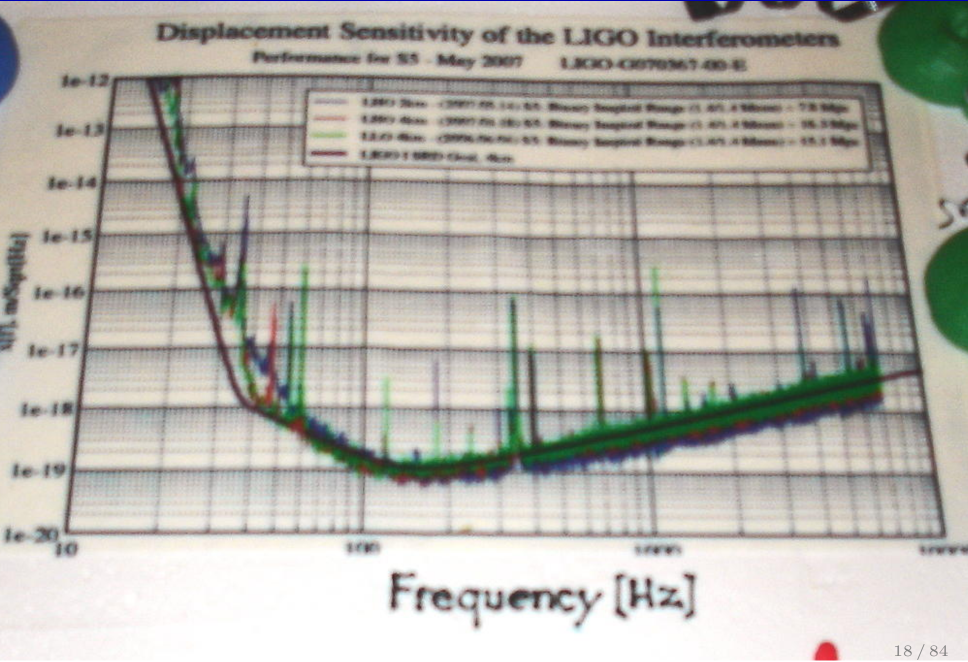
The results (for now)

Initial LIGO (2001-2009)

Sensitivity: $h \sim 10^{-21} \;\Rightarrow\; \delta x \sim 10^{-18}\,\mathrm{m}$
Prediction: ~ 0.5 events/year
Results: NONE

Nevertheless...

Nevertheless...



A new hope

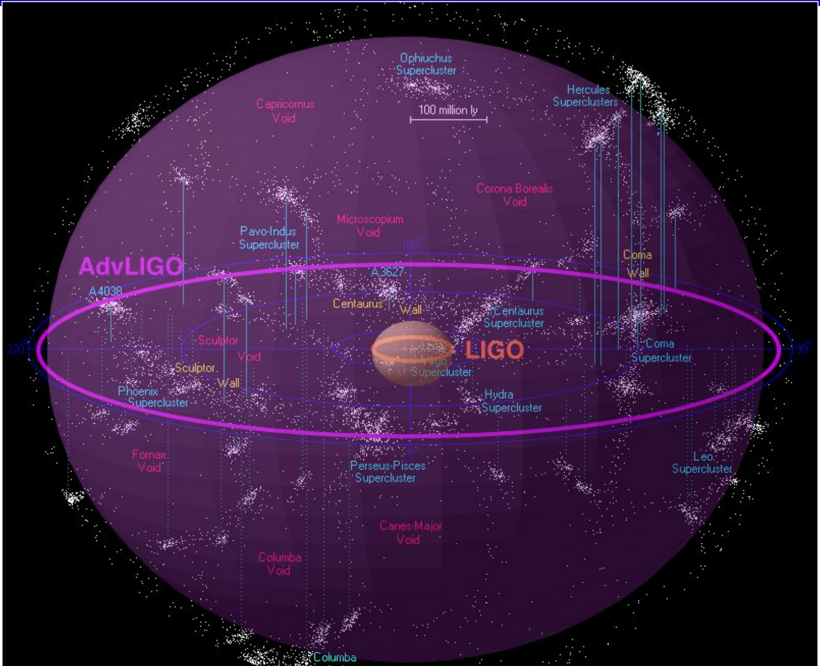
Initial LIGO (2001-2009)

Sensitivity: $h \sim 10^{-21} \ \Rightarrow \ \delta x \sim 10^{-18}\,\mathrm{m}$
Prediction: ~ 0.5 events/year
Results: NONE

Advanced LIGO (2014)

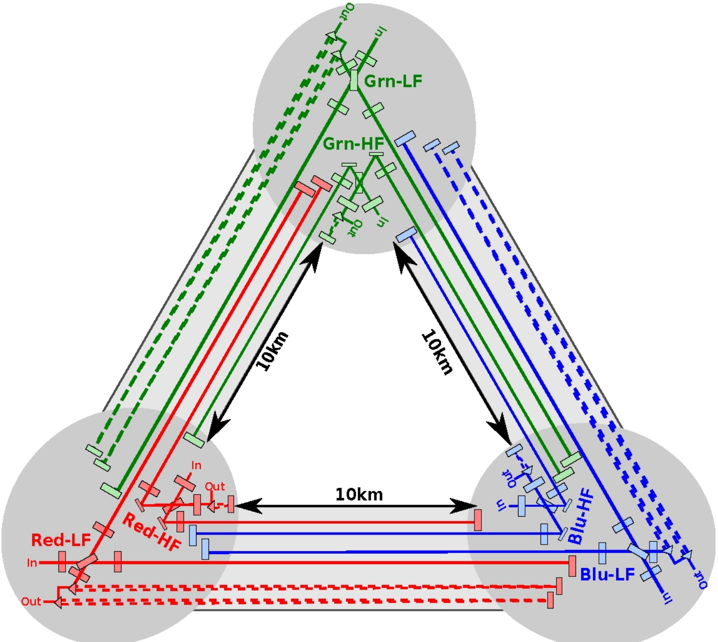
Sensitivity: $h \sim 10^{-22} \ \Rightarrow \ \delta x \sim 10^{-19}\,\mathrm{m}$
Prediction: up to $\sim 10^3$ events/year

A new hope

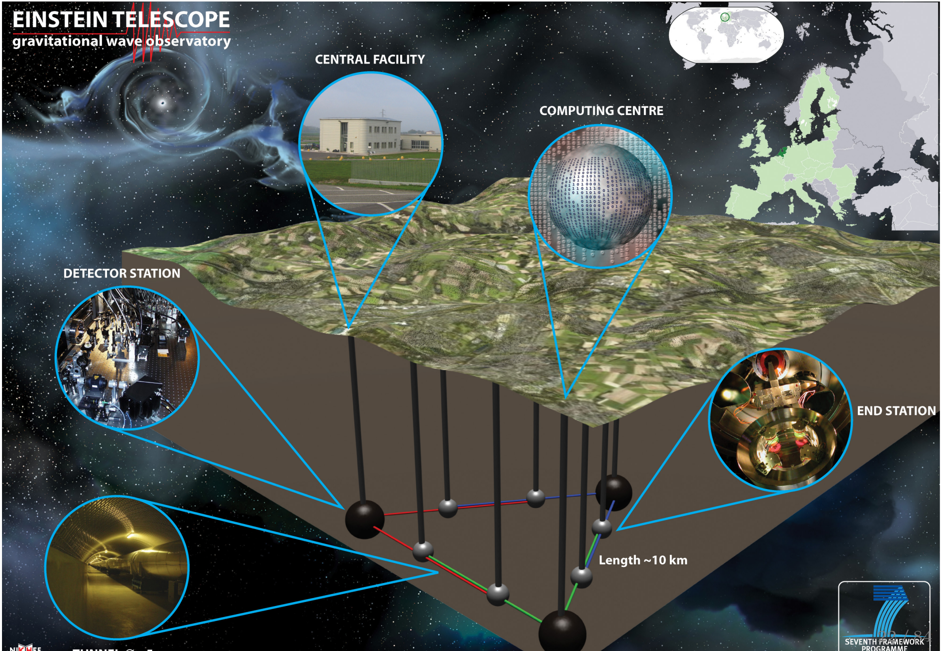


Ophiuchus Supercluster
Hercules Superclusters
Capricornus Void
100 million ly
Corona Borealis Void
Microscopium Void
Pavo-Indus Supercluster
AdvLIGO
A3627
A4038
Coma Wall
Centaurus Wall
Centaurus Supercluster
Sculptor Void
LIGO
Coma Supercluster
Sculptor Wall
Virgo Supercluster
Phoenix Supercluster
Hydra Supercluster
Fornax Void
Perseus-Pisces Supercluster
Leo Supercluster
Canes Major Void
Columba Void
Columba

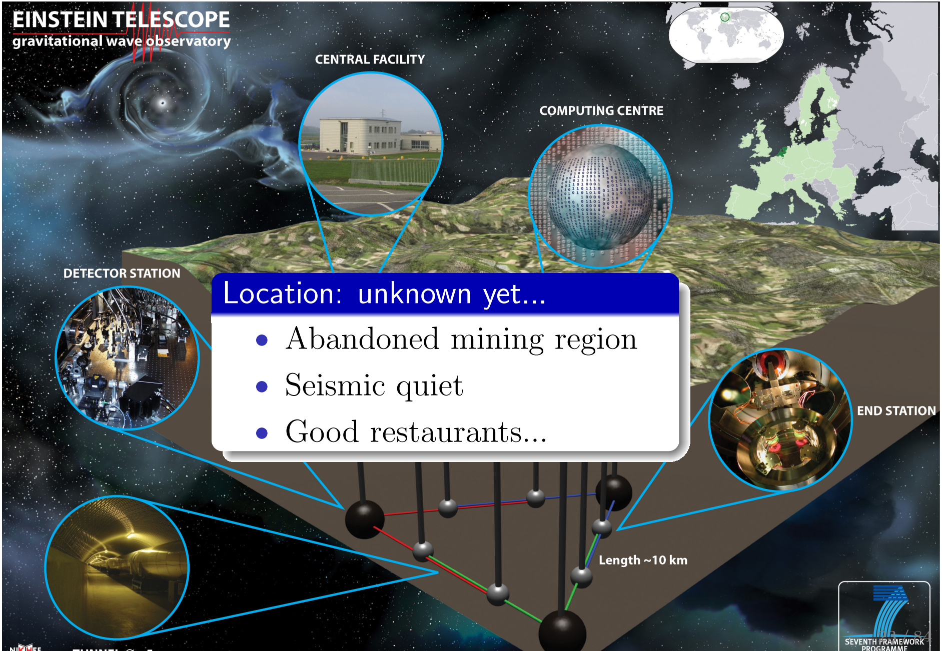
3rd generation (2020?): Einstein Telescope



3rd generation (2020?): Einstein Telescope



3rd generation (2020?): Einstein Telescope

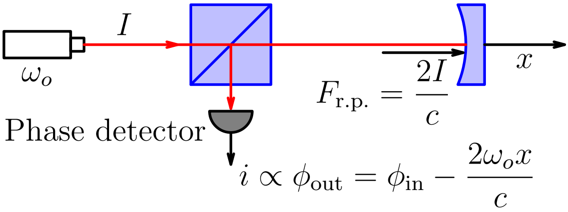


Location: unknown yet...

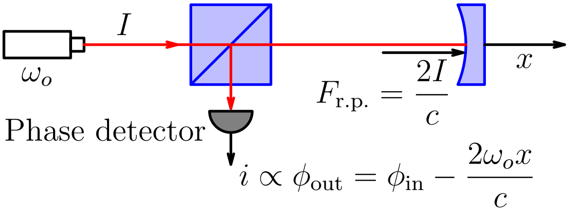
- Abandoned mining region
- Seismic quiet
- Good restaurants...

Questions?

Optical position meter (simplified version)



Optical position meter (simplified version)



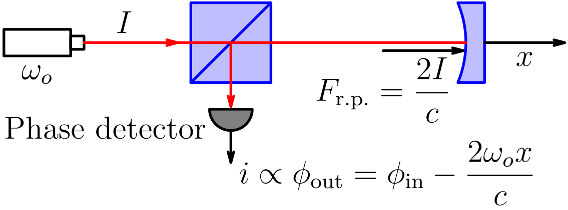
$$\hat{A}(t) = [A + \hat{a}_c(t)]\cos\omega_o t - \hat{a}_s(t)\sin\omega_o t$$

$$\approx [A + \hat{a}_c(t)]\cos[\omega_o t + \hat{\phi}(t)]$$

$$\hat{\phi}(t) = -\frac{\hat{a}_s(t)}{A}$$

$$S_c = \frac{e^{2r}}{2} \qquad S_s = \frac{e^{-2r}}{2}$$

Optical position meter (simplified version)



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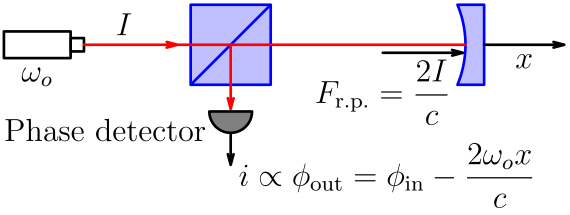
$$\hat{\phi}(t) = -\frac{\hat{a}_s(t)}{A}$$

$$S_c = \frac{e^{2r}}{2} \qquad S_s = \frac{e^{-2r}}{2}$$

Phase noise: $S_\phi = \frac{S_s}{A^2} = \frac{\hbar\omega_o}{4\langle I\rangle}\, e^{-2r}$

Intensity noise: $S_I = (\hbar\omega_o)^2 A^2 S_c = \hbar\omega_o \langle I\rangle e^{2r}$

Optical position meter (simplified version)



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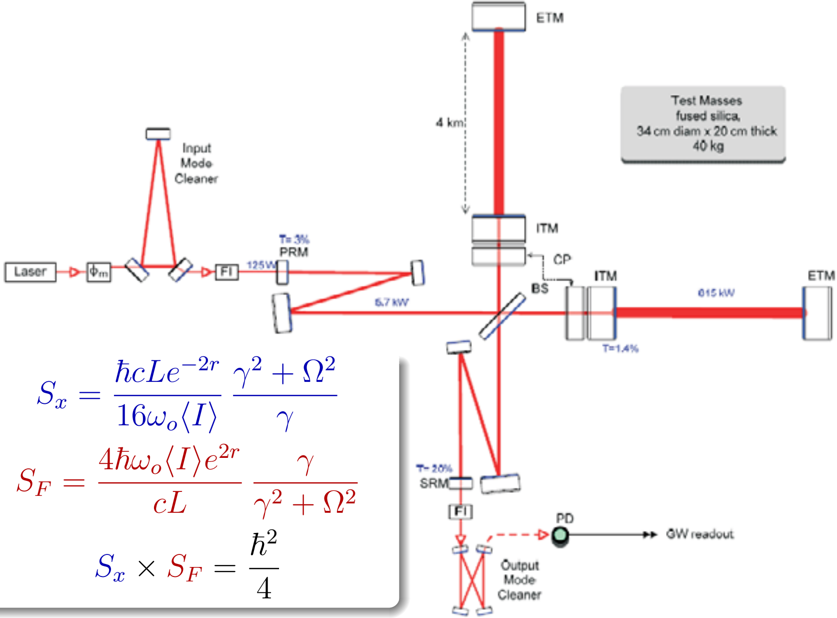
Intensity noise: $S_I = (\hbar\omega_o)^2 A^2 S_c = \hbar\omega_o\langle I\rangle e^{2r}$

Measurement noise: $S_x = \dfrac{c^2}{4\omega_o^2}\, S_\phi = \dfrac{\hbar c^2 e^{-2r}}{16\omega_o\langle I\rangle}$

Back-action noise: $S_F = \dfrac{4}{c^2}\, S_I = \dfrac{4\hbar\omega_o\langle I\rangle e^{2r}}{c^2}$

$$S_x \times S_F = \frac{\hbar^2}{4}$$

Optical position meter (real-world version)



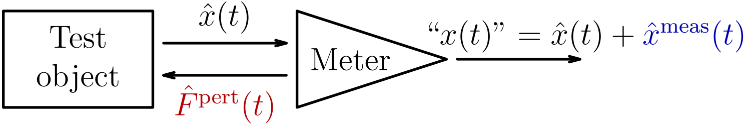
$$S_x = \frac{\hbar c L e^{-2r}}{16\omega_o\langle I\rangle}\,\frac{\gamma^2+\Omega^2}{\gamma}$$

$$S_F = \frac{4\hbar\omega_o\langle I\rangle e^{2r}}{cL}\,\frac{\gamma}{\gamma^2+\Omega^2}$$

$$S_x \times S_F = \frac{\hbar^2}{4}$$

G.Harry *et al*, Class. Quantum Grav. **27**, 084006 (2010)

Linear position meter: abstract model



S_x : spectral density of measurement noise $\hat{x}^{\text{meas}}(t)$

S_F : spectral density of back action noise $\hat{F}^{\text{pert}}(t)$

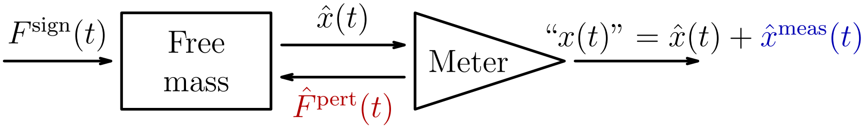
$$S_x \times S_F = \frac{\hbar^2}{4}$$

Questions?

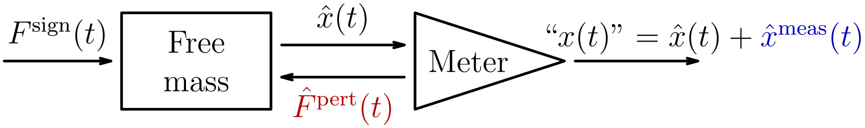
LENGTHY EQUATIONS AHEAD!

shortcut

Detection of classical force



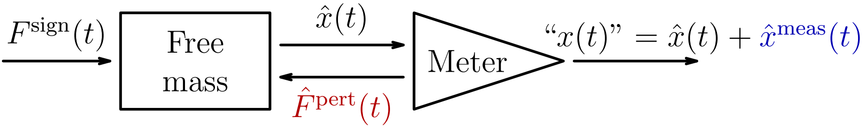
Detection of classical force



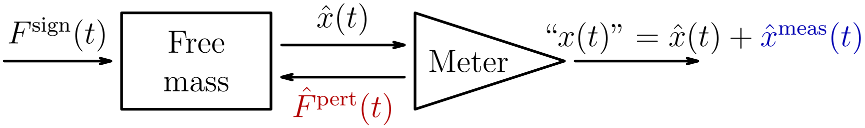
$$-m\Omega^2\hat{x}(\Omega) = F^{\mathrm{sign}}(\Omega) + \hat{F}^{\mathrm{pert}}(\Omega)$$

$$\text{“}x(\Omega)\text{”} = \hat{x}(\Omega) + \hat{x}^{\mathrm{meas}}(\Omega)$$

Detection of classical force



$$
\begin{aligned}
-m\Omega^2\hat{x}(\Omega) &= F^{\rm sign}(\Omega) + \hat{F}^{\rm pert}(\Omega) \\
\text{“}x(\Omega)\text{”} &= \hat{x}(\Omega) + \hat{x}^{\rm meas}(\Omega) \\
&= \frac{F^{\rm sign}(\Omega)}{-m\Omega^2} \quad + \quad \overbrace{\frac{F^{\rm pert}(\Omega)}{-m\Omega^2} + \hat{x}^{\rm sum}(\Omega)}^{\text{the sum noise}}
\end{aligned}
$$



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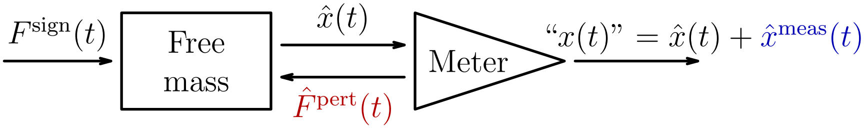
\end{aligned}
$$

$$
S_{\rm sum}(\Omega) = S_x + \frac{S_F}{m^2\Omega^4}
$$

Detection of classical force



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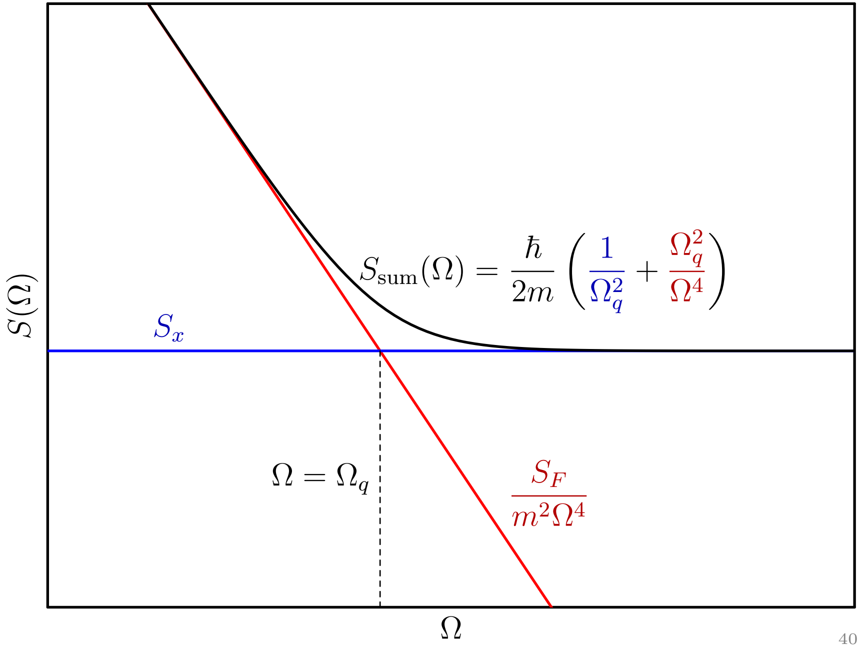
\end{aligned}
$$

$$
S_{\text{sum}}(\Omega) = S_x + \frac{S_F}{m^2\Omega^4} = \frac{\hbar}{2m}\left(\frac{1}{\Omega_q^2} + \frac{\Omega_q^2}{\Omega^4}\right)
$$

$$
\Omega_q = \left(\frac{S_F}{m^2 S_x}\right)^{1/4} \propto \sqrt{\frac{\langle I\rangle}{m}}\, e^r
$$

Sum noise spectral density



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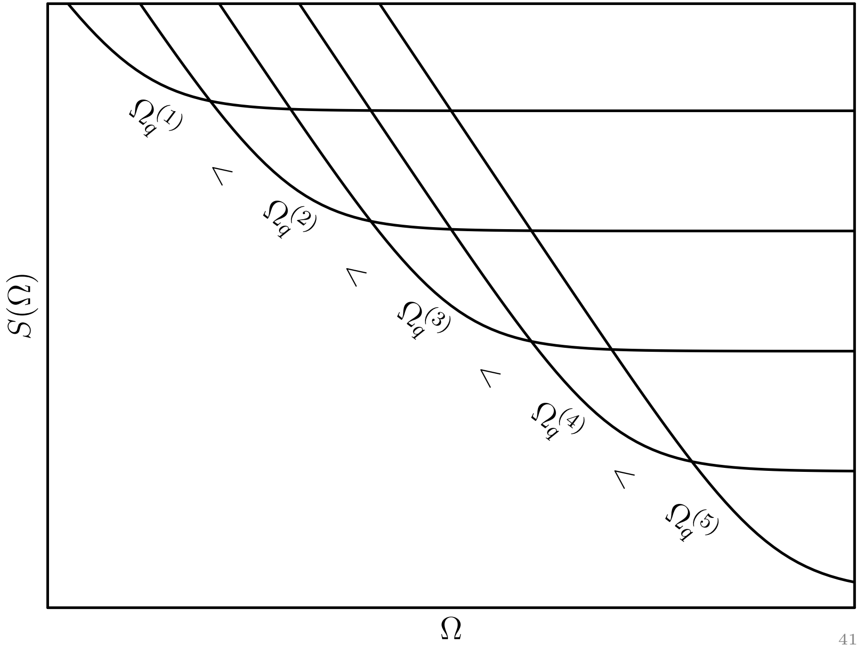
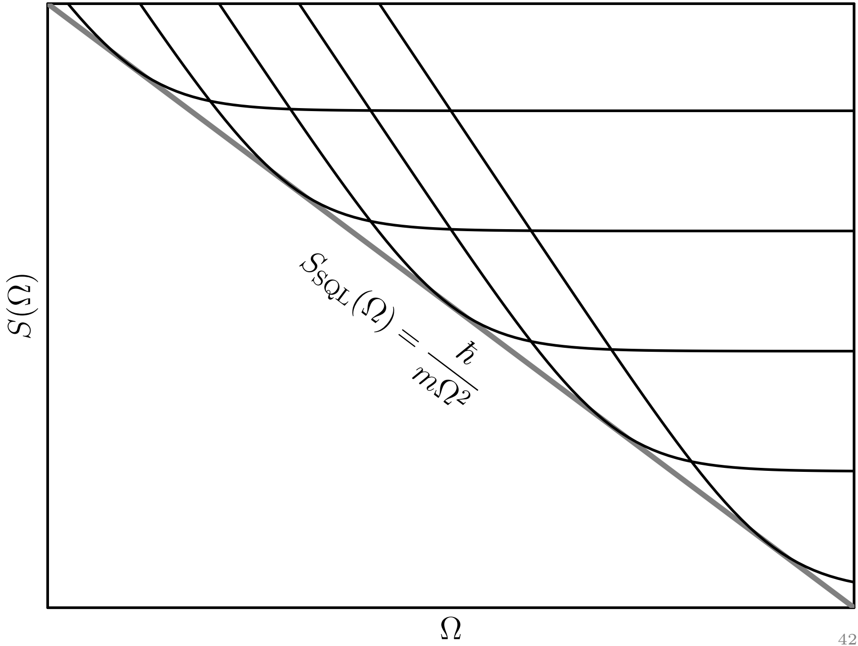


Standard Quantum Limit



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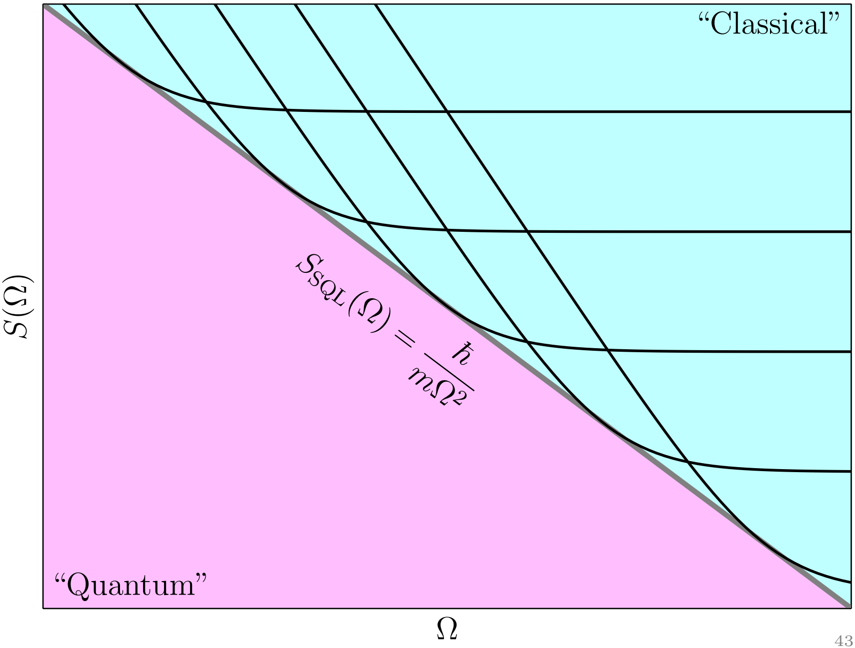

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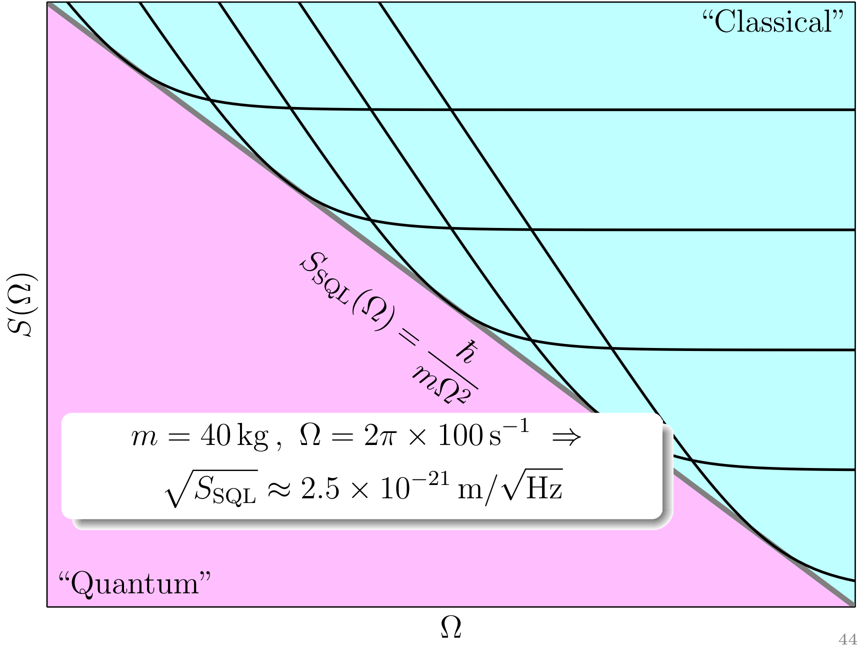


$$m = 40\,\mathrm{kg}\,, \;\; \Omega = 2\pi \times 100\,\mathrm{s}^{-1} \;\; \Rightarrow$$

$$\sqrt{S_{\mathrm{SQL}}} \approx 2.5 \times 10^{-21}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$$

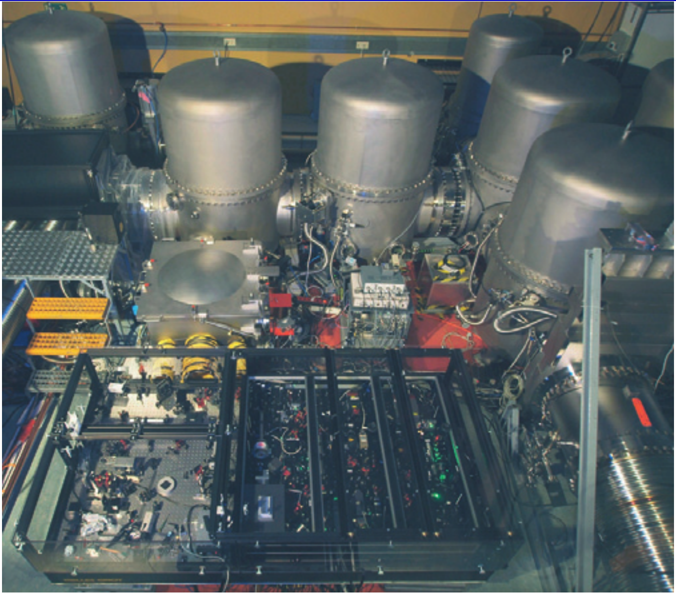
What about the light squeezing?

In all equations, we have only the combination

$$\langle I \rangle e^{2r}$$

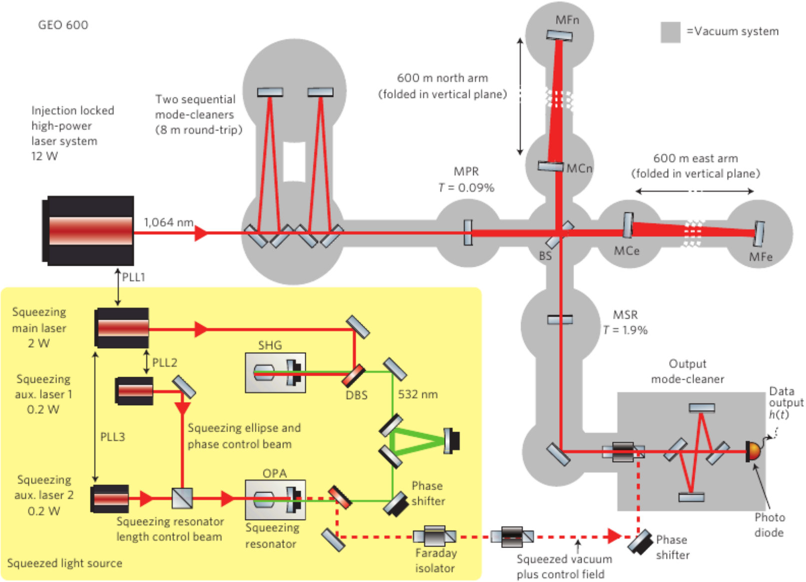
$\Rightarrow$ squeezing does not allow to overcome the SQL, but allows to decrease $\langle I \rangle$

Squeezing in GEO-600



The LSC, Nature Physics **7**, 962 (2011)

Squeezing in GEO-600



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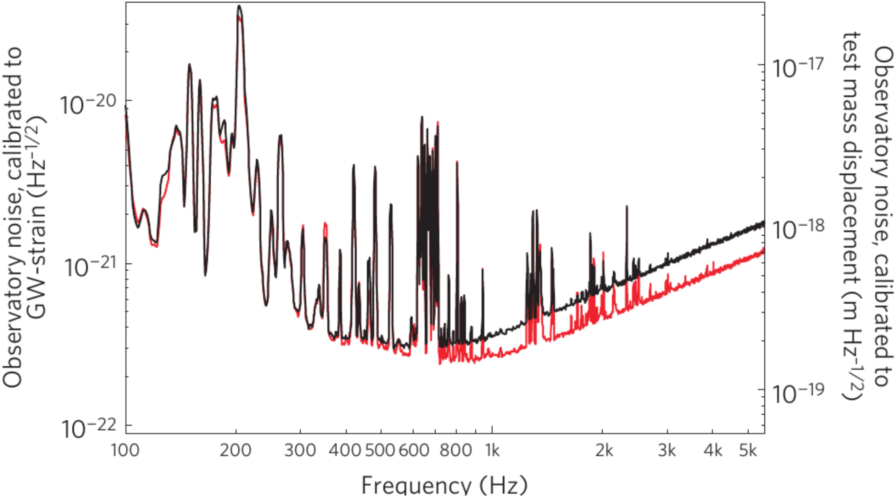
Squeezing in GEO-600



The LSC, Nature Physics **7**, 962 (2011)

How to overcome the SQL

Implicit assumptions that have been made:

1. The scheme is stationary (invariant with respect to time shift).
2. The noises are Markovian.
3. The noise are mutually uncorrelated.
4. The test object is a free mass.

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Number of schemes based on violation of some of these assumptions has been proposed.

Only one successful experiment was performed ☹ (for now).

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Number of schemes based on violation of some of these assumptions has been proposed.

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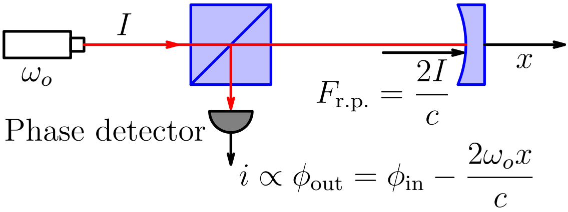
For the laser gravitation wave detectors, the way "2+3" is considered as the most promising.

Questions?

shortcut

Optical meter with homodyne detector



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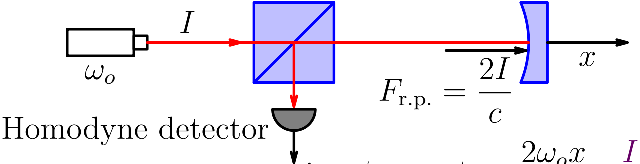
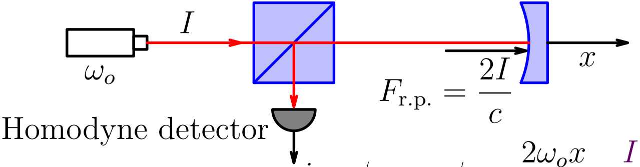


$$i \propto \phi_{\text{out}} = \phi_{\text{in}} - \frac{2\omega_o x}{c} - \frac{I - \langle I \rangle}{2\langle I \rangle} \tan\zeta$$

Optical meter with homodyne detector

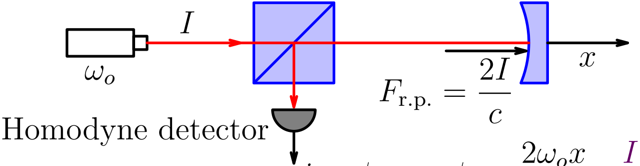


$$i \propto \phi_{\text{out}} = \phi_{\text{in}} - \frac{2\omega_o x}{c} - \frac{I - \langle I \rangle}{2\langle I \rangle} \tan\zeta$$

Measurement noise: $S_x = \dfrac{\hbar c^2}{16\omega_o \langle I \rangle \cos^2\zeta}$

Back-action noise: $S_F = \dfrac{4}{c^2} S_I = \dfrac{4\hbar\omega_o \langle I \rangle}{c^2}$

Cross-correlation: $S_{xF} = \dfrac{\hbar}{2} \tan\zeta$



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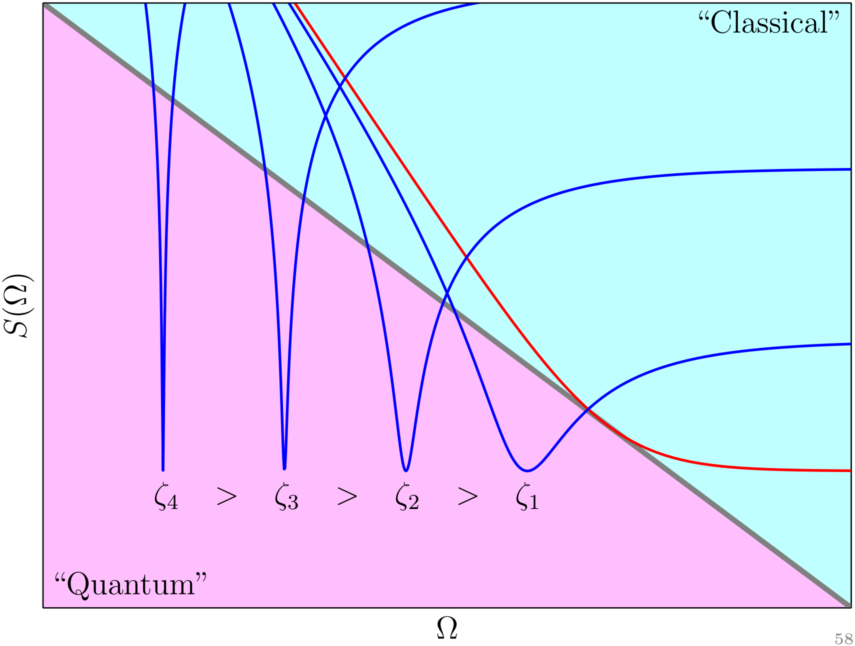
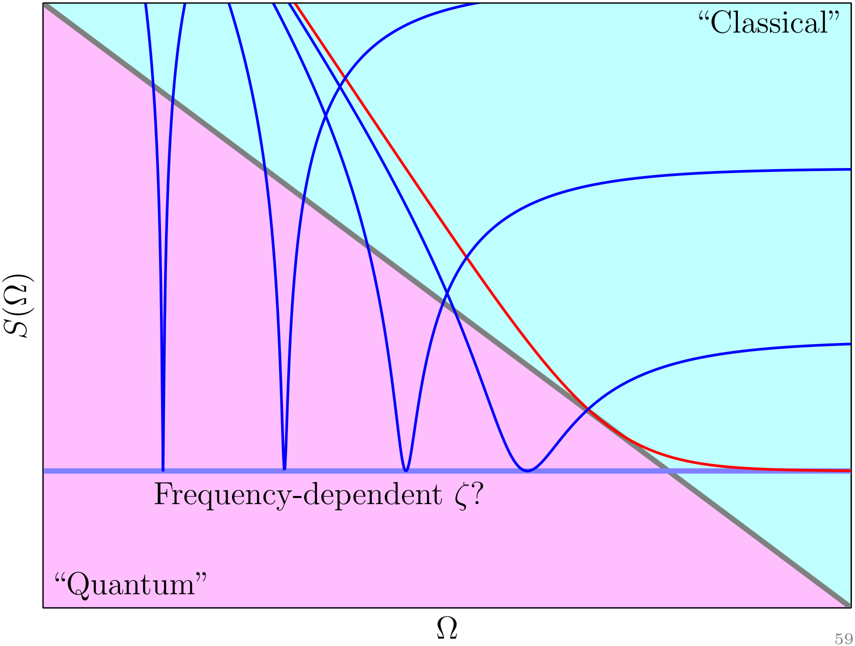
Cross-correlation: $\displaystyle S_{xF} = \frac{\hbar}{2} \tan\zeta$

$$S_x \times S_F - S_{xF}^2 = \frac{\hbar^2}{4} \qquad S_{\text{sum}}(\Omega) = S_x - \frac{2S_{xF}}{m\Omega^2} + \frac{S_F}{m^2\Omega^4}$$

Narrow-band gain



Broad band gain (?)



Broad band gain: options

$$S_{\rm sum}(\Omega) = \frac{\hbar}{2m}\left(\frac{1}{\Omega_q^2\cos^2\zeta} - \frac{2}{\Omega^2}\tan\zeta + \frac{\Omega_q^2}{\Omega^4}\right)$$

$$\Omega^2\tan\zeta = \Omega_q^2 \equiv \frac{2S_F}{\hbar m} \;\Rightarrow\; S_{\rm sum} = \frac{\hbar}{2m\Omega_q^2}$$

$$\boxed{\Omega_q^2 \propto I \to \infty \;\Rightarrow\; S_{\rm sum} \to 0}$$

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Option 1: variational readout

$$\tan\zeta \propto \frac{1}{\Omega^2} \qquad \Omega_q^2 = \text{const}$$

H.J.Kimble *et al*, Phys.Rev.D **65**, 022002 (2001)

Broad band gain: options

$$S_{\rm sum}(\Omega) = \frac{\hbar}{2m}\left(\frac{1}{\Omega_q^2\cos^2\zeta} - \frac{2}{\Omega^2}\tan\zeta + \frac{\Omega_q^2}{\Omega^4}\right)$$

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H.J.Kimble *et al*, Phys.Rev.D **65**, 022002 (2001)

Option 2: quantum speedmeter

$$\tan\zeta = \text{const} \qquad \Omega_q^2 \propto \Omega^2$$

V.B.Braginsky, F.Ya.Khalili, Phys.Lett.A **147**, 251 (1990)

Broad band gain: options

$$S_{\text{sum}}(\Omega) = \frac{\hbar}{2m}\left(\frac{1}{\Omega_q^2\cos^2\zeta} - \frac{2}{\Omega^2}\tan\zeta + \frac{\Omega_q^2}{\Omega^4}\right)$$

$$\Omega^2\tan\zeta = \Omega_q^2 \equiv \frac{2S_F}{\hbar m} \;\Rightarrow\; S_{\text{sum}} = \frac{\hbar}{2m\Omega_q^2}$$

$$\boxed{\Omega_q^2 \propto I \to \infty \;\Rightarrow\; S_{\text{sum}} \to 0}$$

Option 1: variational readout

$$\tan\zeta \propto \frac{1}{\Omega^2} \qquad \Omega_q^2 = \text{const}$$

H.J.Kimble *et al*, Phys.Rev.D **65**, 022002 (2001)

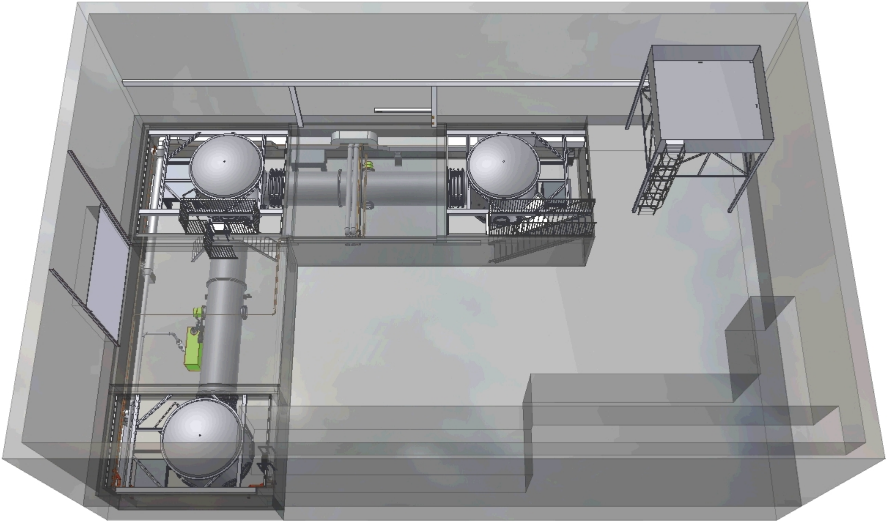
Option 2: quantum speedmeter

$$\tan\zeta = \text{const} \qquad \Omega_q^2 \propto \Omega^2$$

V.B.Braginsky, F.Ya.Khalili, Phys.Lett.A **147**, 251 (1990)

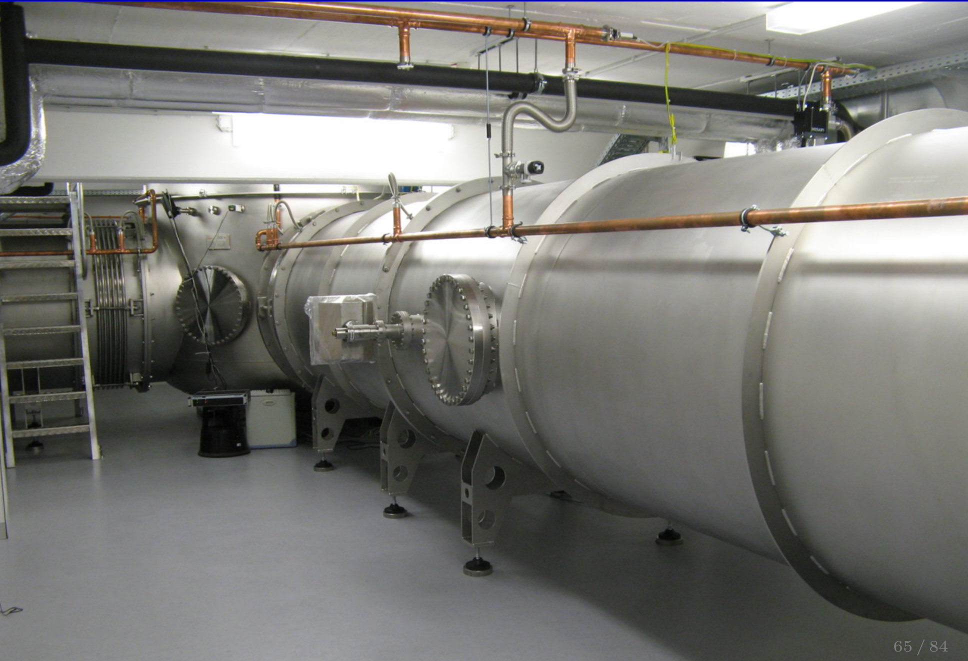
Optomechanical coupling $\Omega_q^2 \propto I \propto \Omega^2$: is it possible?

Hannover 10m prototype

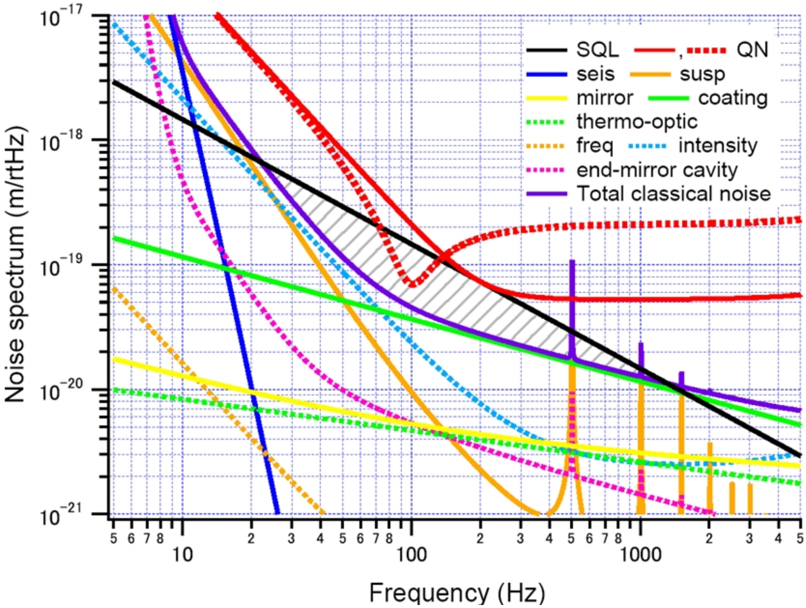


S.Goßler *et al*, Class. Quantum Grav. **27**, 084023 (2010)

Hannover 10m prototype



Hannover 10m prototype



S.Goßler *et al*, Class. Quantum Grav. **27**, 084023 (2010)

Questions?

SQL: simplified consideration

Position measurement

$$\hat{x}(t) = \hat{x} + \frac{\hat{p}t}{m}$$

$$\Delta x \times \Delta p \geqslant \frac{\hbar}{2}$$

$$\Delta x(t) \geqslant \sqrt{\frac{\hbar t}{m}} \sim \sqrt{\frac{\hbar}{m\Omega}} \ \Rightarrow\ S_{\text{sum}} \geqslant \frac{[\Delta x(t)]^2}{\Omega} = \frac{\hbar}{m\Omega^2}$$

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Momentum measurement

$$\hat{p}(t) = \text{const} \quad [\text{in the absence of } F(t)]$$

$$\Rightarrow \; \text{no uncertainty relation}$$

$$\Rightarrow \; \text{no SQL}$$

SQL: simplified consideration

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Momentum measurement

$$\hat{p}(t) = \text{const} \quad [\text{in the absence of } F(t)]$$

$$\Rightarrow \text{ no uncertainty relation}$$

$$\Rightarrow \text{ no SQL}$$

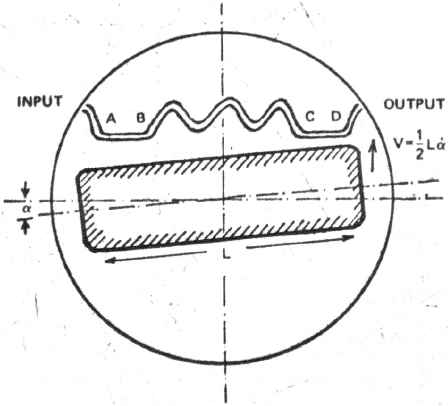
Velocity measurement

We can not measure momentum?

Let us measure velocity instead!

The idea

Light interacts with the probe twice:



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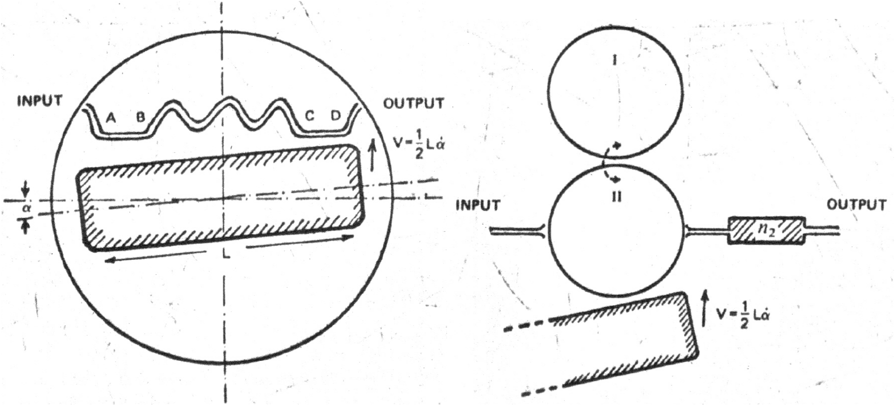

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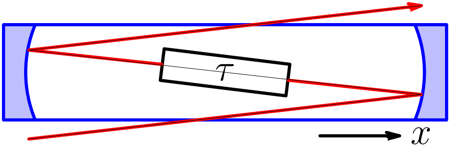

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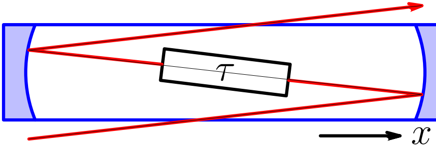
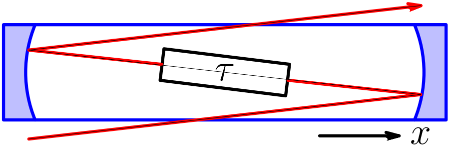


$$\phi_{\text{out}}(t) = \phi_{\text{in}}(t-\tau) + \frac{2\omega_o}{c}\left[x(t) - x(t-\tau)\right]$$

(quantum SPEED meter!) $$\approx \phi_{\text{in}}(t-\tau) + \frac{2\omega_o \tau}{c}\frac{dx(t)}{dt}$$

The idea

Light interacts with the probe twice:



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(quantum SPEED meter!) $\quad \approx \phi_{\text{in}}(t-\tau) + \frac{2\omega_o \tau}{c}\frac{dx(t)}{dt}$

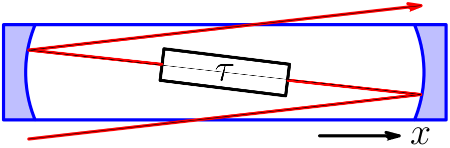
$$F_{\text{pert}}(t) = \frac{2}{c}\left[I(t+\tau) - I(t)\right] \approx \frac{2\tau}{c}\frac{dI(t)}{dt}$$

$$\Rightarrow\; p_{\text{pert}}(t) = \int_{-\infty}^{t} F_{\text{pert}}(t')\,dt' \approx \frac{2\tau I(t)}{c}$$

shortcut

The idea

Light interacts with the probe twice:



Fourier picture

$$\phi_{\text{out}}(\Omega) \approx \phi_{\text{in}}(\Omega) + \frac{2\omega_o \tau}{c} \times [-i\Omega x(\Omega)]$$

$$F_{\text{pert}}(\Omega) \approx \frac{2\tau}{c} \times [-i\Omega I(\Omega)]$$

The idea

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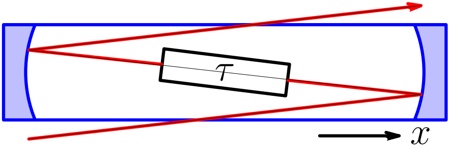

Spectral densities

Measurement noise: $S_x = \frac{\hbar c^2}{16\omega_o \langle I \rangle e^{2r} \cos^2 \zeta} \times \frac{1}{\Omega^2 \tau^2} = \frac{S_v}{\Omega^2}$

Back-action noise: $S_F = \frac{4\hbar\omega_o \langle I \rangle e^{2r}}{c^2} \times \Omega^2 \tau^2 = S_p \Omega^2$

Cross-correlation: $S_{xF} = \frac{\hbar}{2} \tan \zeta = -S_{vp}$

Note the requested frequency dependence!

The idea

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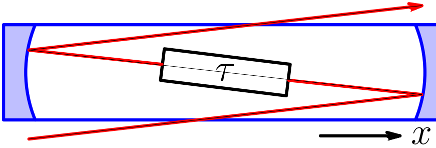

Detection of classical force

$$S_{\text{sum}} = \frac{1}{\Omega^2}\left(S_v + \frac{2S_{vp}}{m} + \frac{S_p}{m^2}\right); \qquad S_v S_p - S_{vp}^2 = \frac{\hbar^2}{4}$$

The idea

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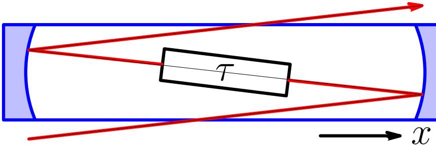

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$$S_{vp} = -\frac{S_p}{m}$$

$$\Rightarrow\ S_{\rm sum} = \frac{\hbar^2}{4S_p\Omega^2} = \left[S_{\rm SQL}(\Omega) = \frac{\hbar}{m\Omega^2}\right]\times\frac{mc^2}{16\omega_o\langle I\rangle e^{2r}\tau^2}$$

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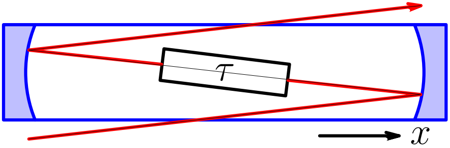

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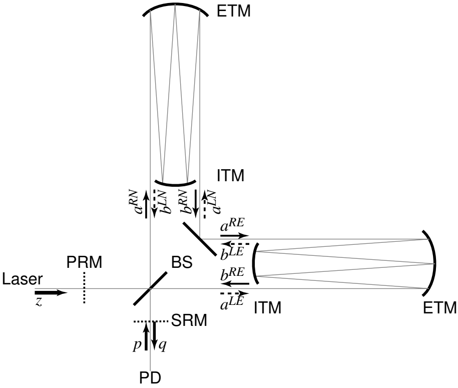
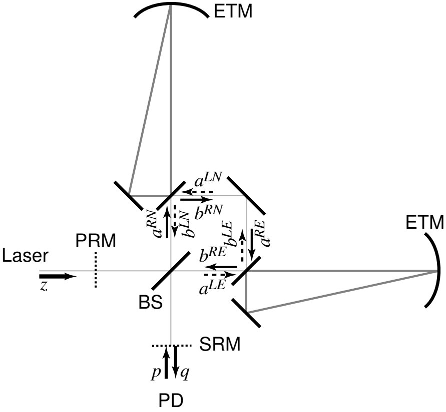
The factor $1/\tau^2$ calls for REALLY LARGE setups!

Practical variants for GW detectors: Sagnac interferometer

Delay lines implementation



Ring cavities implementation



Yanbei Chen, Phys.Rev.D **67**, 122004 (2003)

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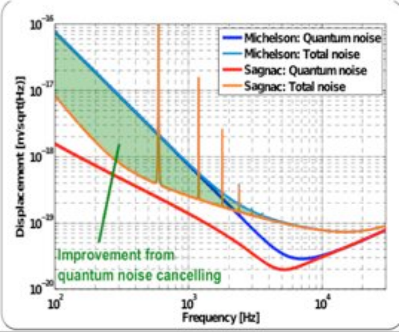
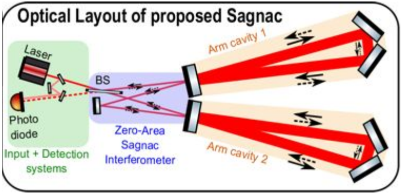
Overview of 1m speed meter experiment





- 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.
- No recycling, no squeezing, but plan to use homodyne detection.
- LOTS OF CHALLENGES! *(let me know if you want to help...)*

Questions?