Reaching the quantum limit with a gravitational wave telescope

Aspects of Quantum Information and Quantum Foundations
Feb 2023

Tokyo Tech
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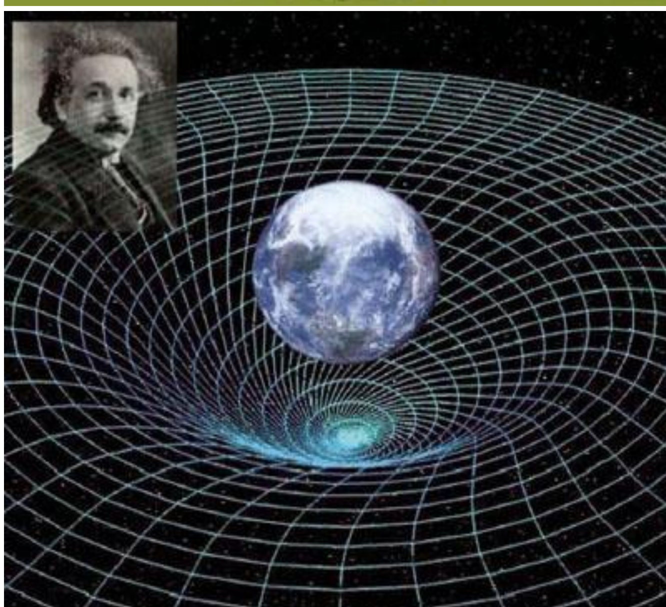
Gravitational waves



Newton's gravity
="distant force between an apple and Earth"

Einstein's gravity
="free fall in curved spacetime"

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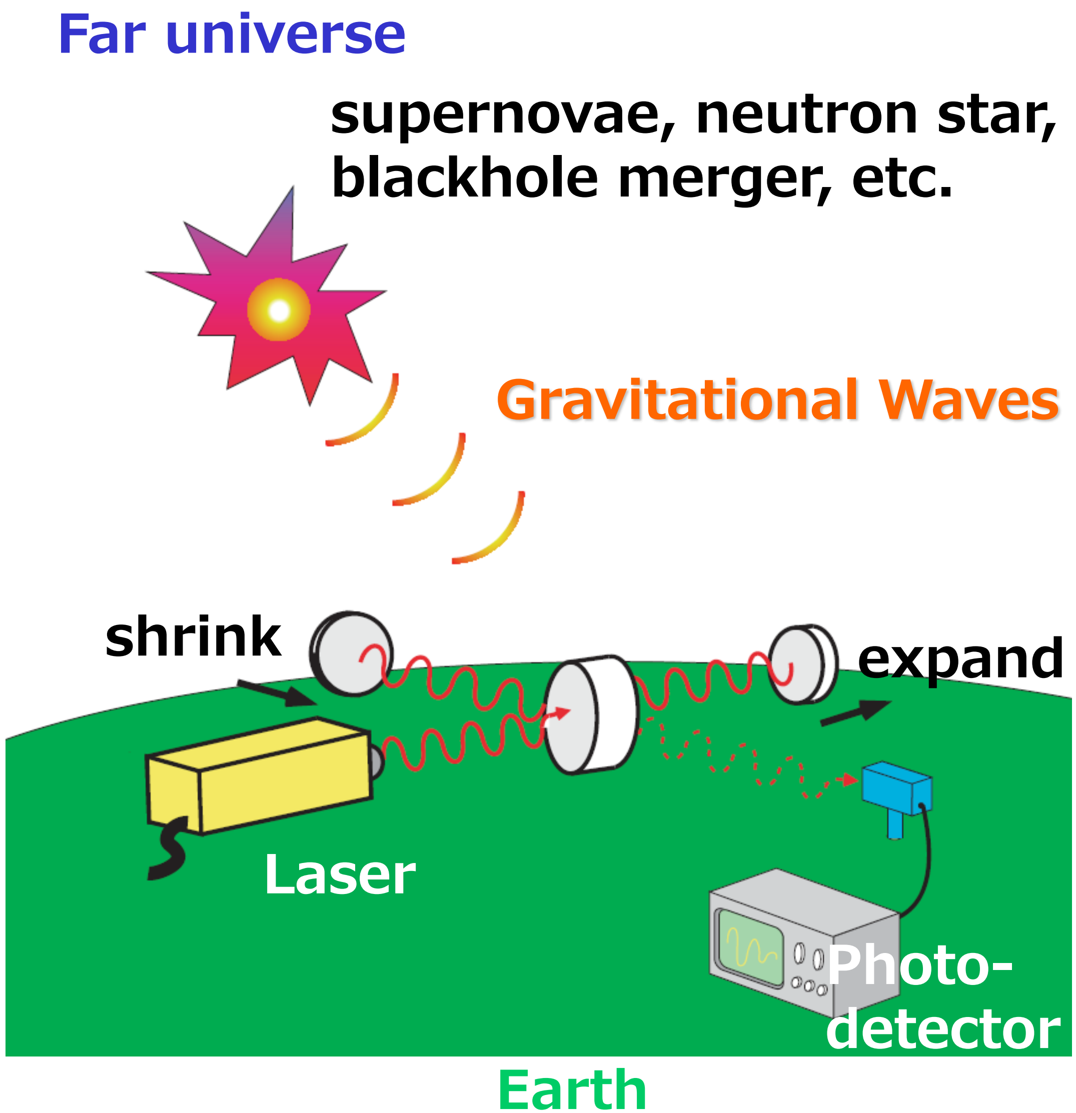
"dynamic change of spacetime must propagate as a wave"

Einstein's prediction of gravitational wave **(1916)**

Laser interferometric GW detector



Massive astronomical events

⇩

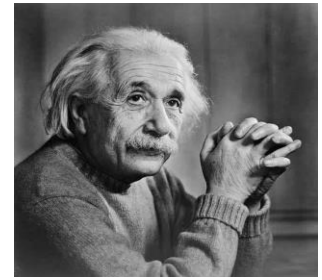
Optical path length changes

⇩

Can be observed by
a large interferometer

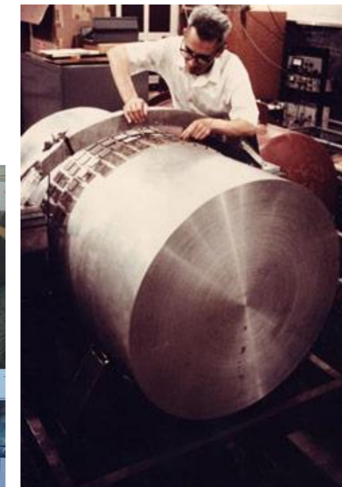
- LIGO in US [4km]
- Virgo in Italy [3km]
- GEO in Germany [600m]
- KAGRA in Japan [3km]

GW detector history



1916 Einstein's prediction of GW

1969 Weber's announcement of first detection
(considered as noise)



1974 Indirect measurement of GW by Hulse&Taylor
(1993 Nobel Prize)

1999 TAMA (JP) started observation

2002 LIGO (US) started observation

2005 GEO (GE/GB) started observation

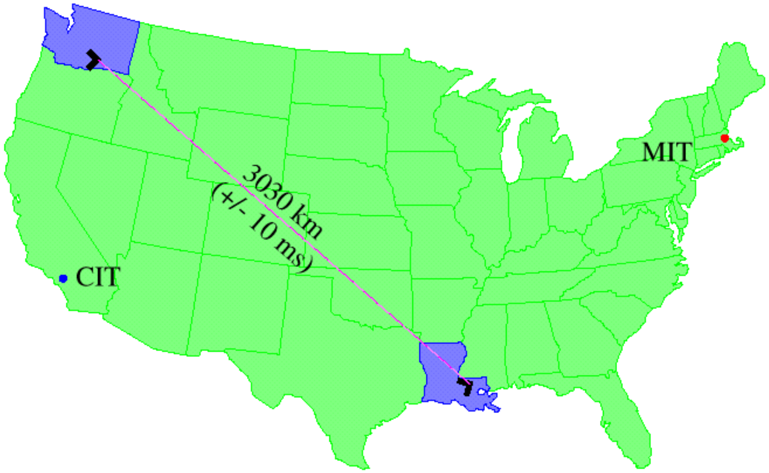
2007 Virgo (IT/FR) started observation

2009 LIGO-Virgo joint run for 1 year
(no GW detected)

2010 Upgrade to second generation GWs
KAGRA's construction started in Japan

2015 Advanced LIGO's first detection

Advanced LIGO



- 4km interferometer x2
- 10-times better sensitivity than LIGO
- Started obs. in 2015

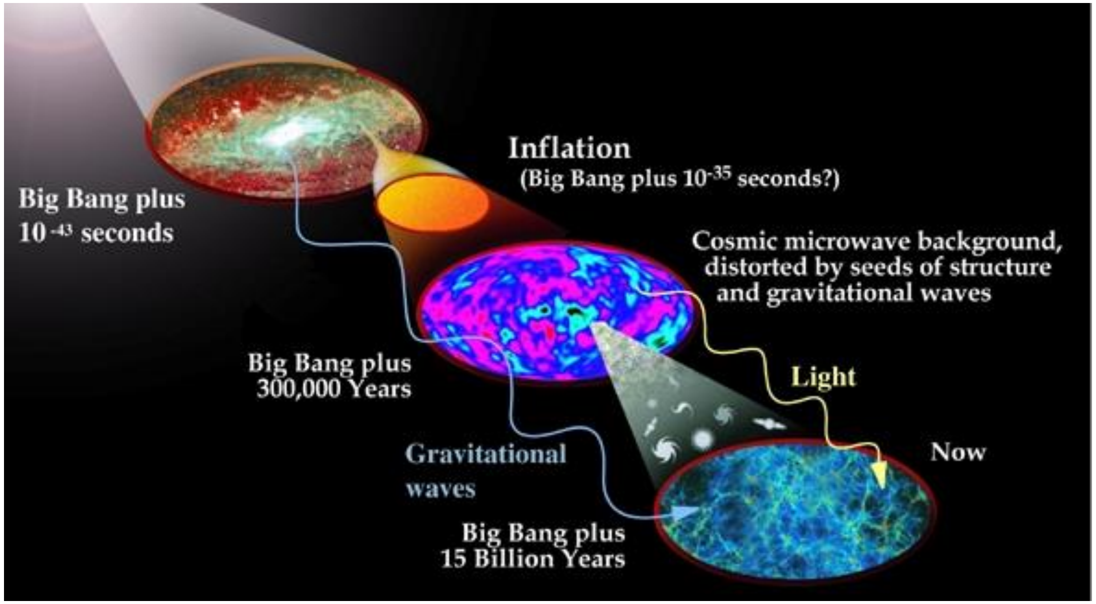
KAGRA

Kamioka, Gifu pref.

- 3km interferometer
- Underground
- Cryogenic mirrors
- Joined the observation run in 2020

What can we learn from GW?

[image:NASA]



Interaction with matter is weak

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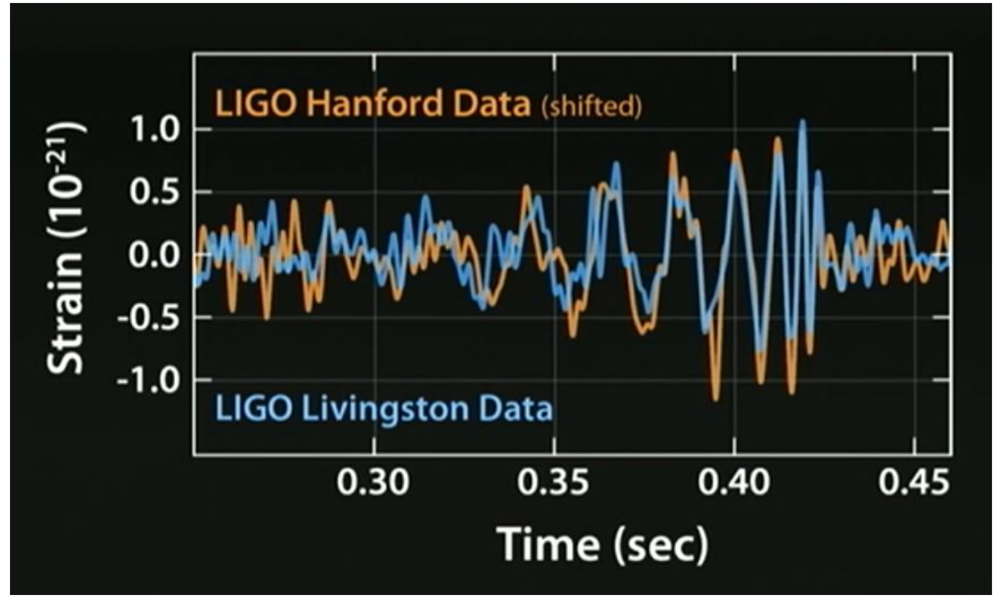
Information is different from EM

- Proof of Einstein's theory → GR
- Early universe → Cosmology
- Blackhole population → Astronomy
- Binary neutron star merger → Nuclear Phys

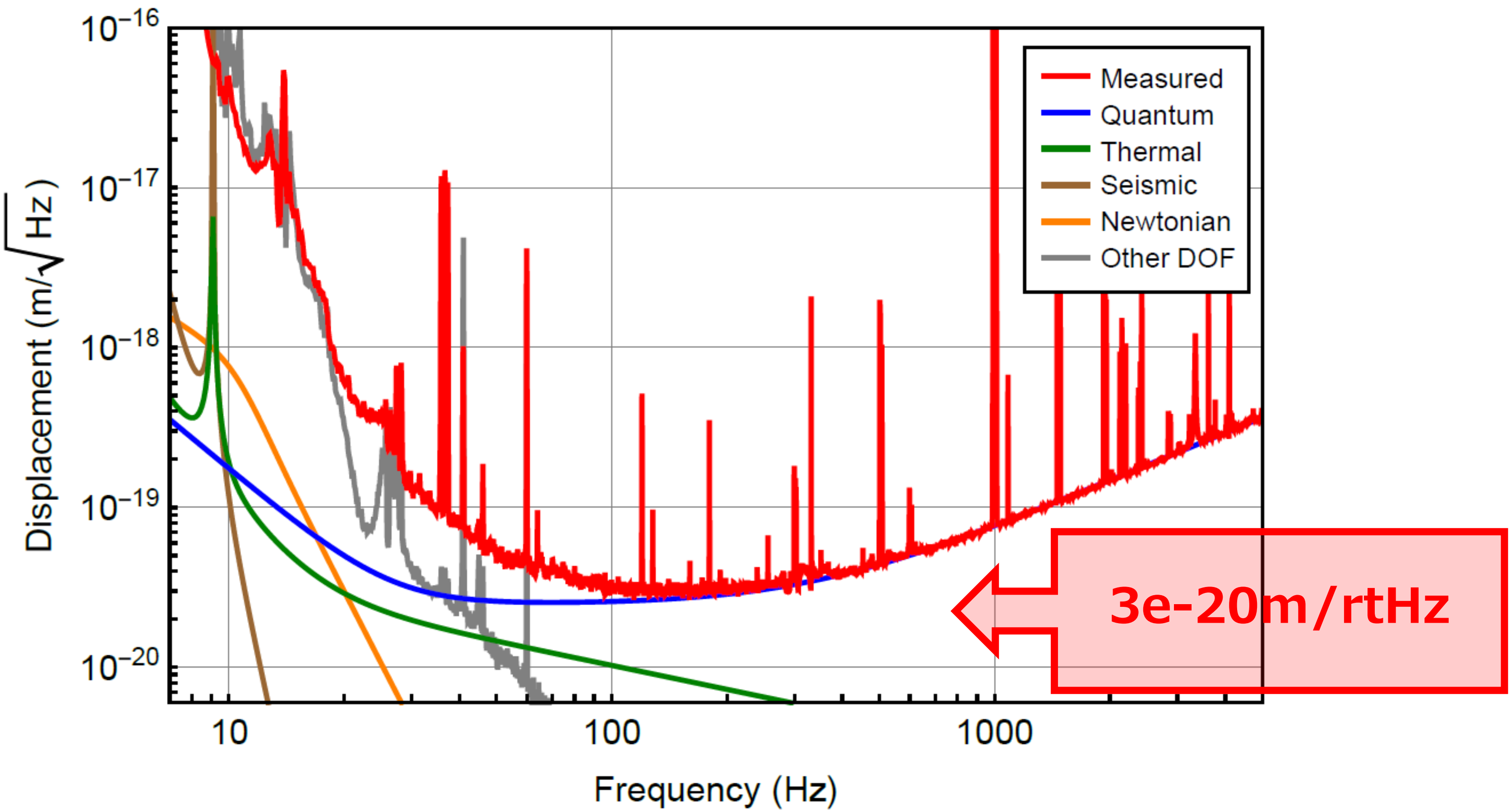
Advanced LIGO's first detection



- **Binary blackholes with 36 and 29 solar masses**
- **62 Ms BH was generated after the merger**
- **Two detectors observed it with a 10-ms time diff.**
- **Waveform matched to numerical relativity prediction**
- **The source is 1.3B light-years from Earth**
- **SNR was 24 and FAR was 1/200k-yrs or less**

(False Alarm Rate)

Sensitivity of Advanced LIGO in 2015



- **Mainly limited by quantum and control noises**
- **The sensitivity is x2 better in 2022**

Contents of the talk

1. Gravitational waves

2. Sensitivity of GW detectors
    2-1. Quantum noise (of light)
    2-2. Thermal noise
    2-3. Seismic+Newtonian noise

3. Toward the standard quantum limit

4. Summary

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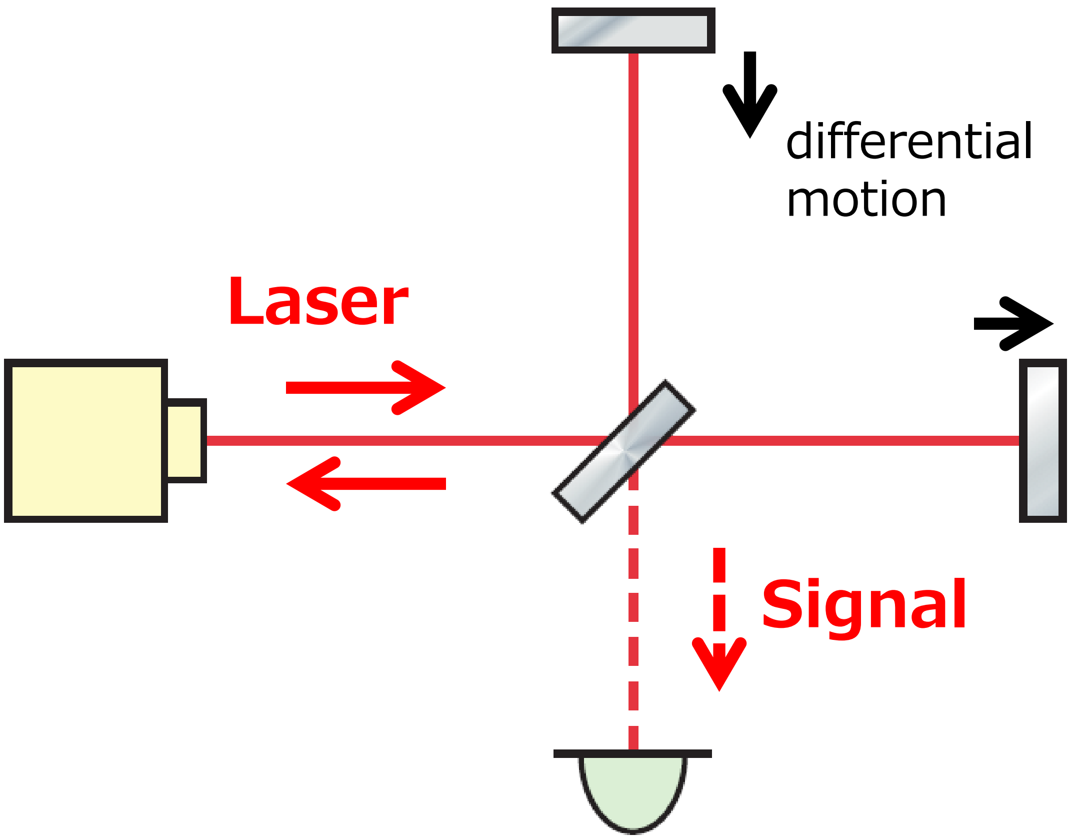
Quantum noise

(IFO=Interferometer
GW=Gravitational Waves)



Operating Michelson IFO at dark fringe
(Light goes back to laser)

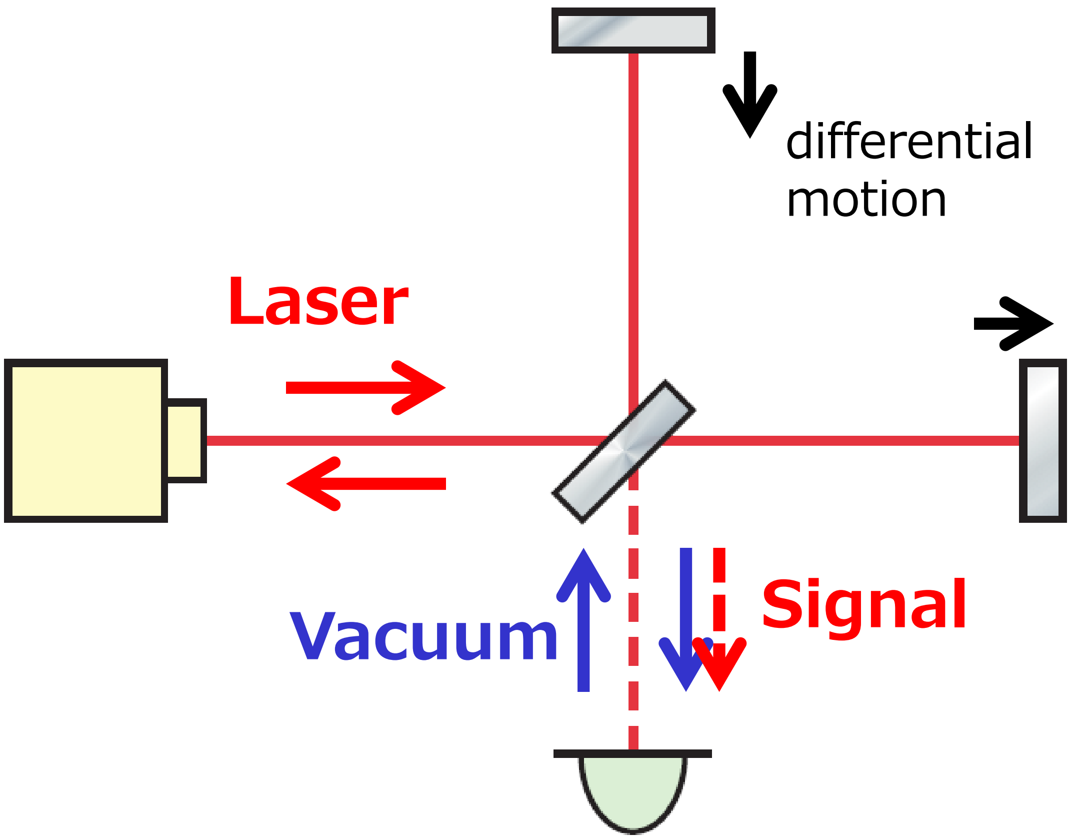
⇓

GW causes differential motion of the mirrors to send signal light to the dark port.

Laser fluctuation goes back to the laser.
⇒ What would be the noise source then?

Quantum noise

(QN=Quantum Noise
SNR=Signal-to-Noise Ratio)



Even without light, there exists vacuum
(zero mean, non-zero variance)

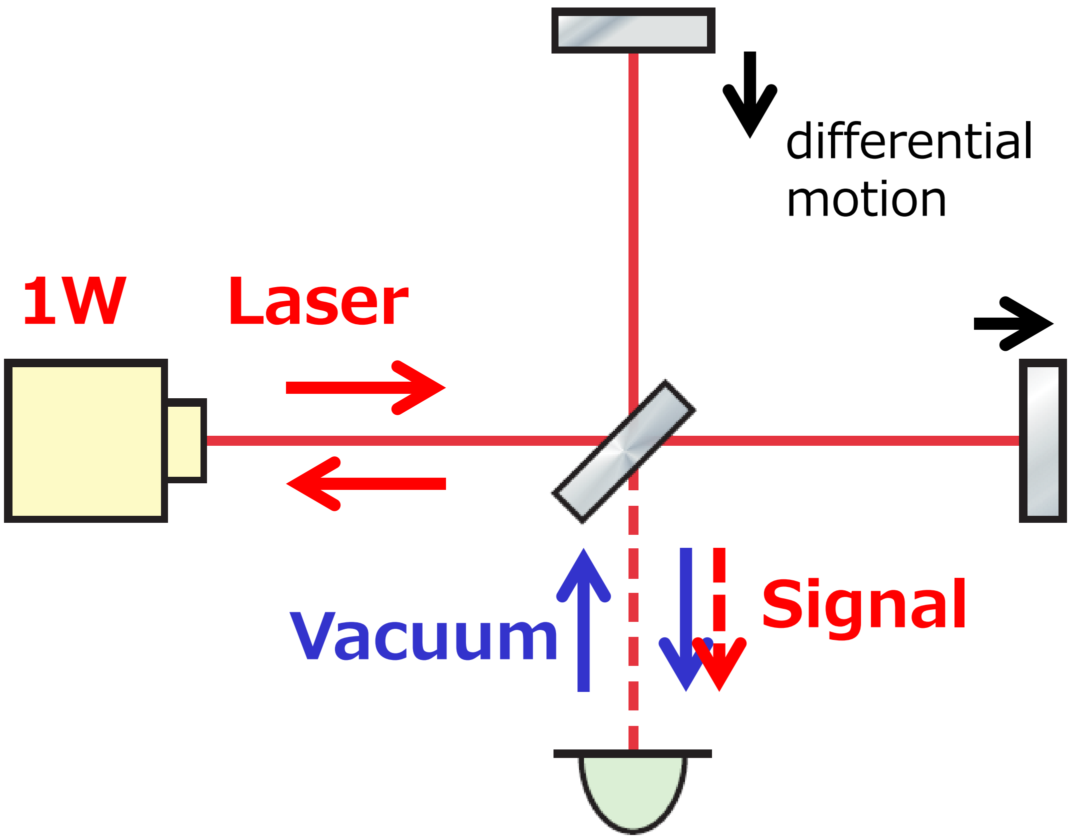
⇩

Vacuum field entering from dark port is the source of QN.

Vacuum fluctuation is equivalent to ½ photon
⇒ SNR is defined by the ratio to signal photons

Quantum noise

(IFO=Interferometer
GW=Gravitational Waves)



1W laser light contains N=5e18 photons/sec.

(λ is set to 1064nm)

⇩

As GW changes the path length by ΔL,

$\Delta N = \left(\sqrt{N}\frac{4\pi\Delta L}{\lambda}\right)^2$ **photons**

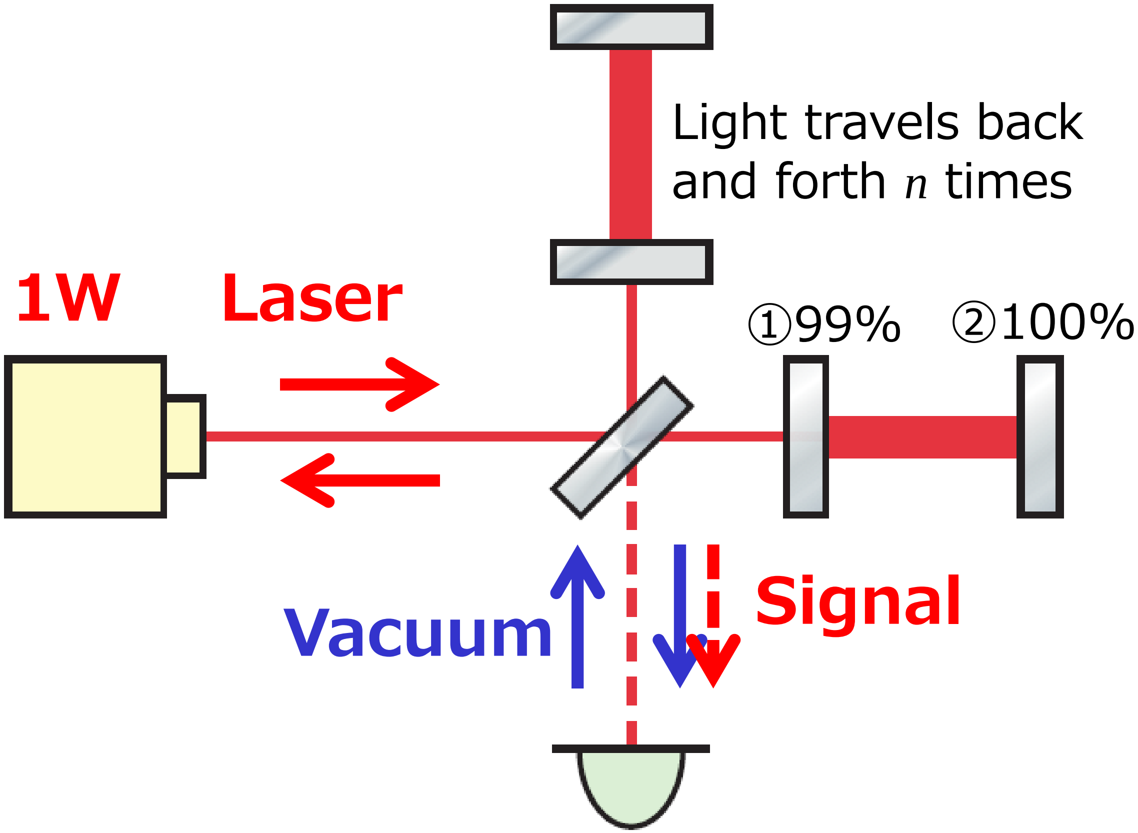
leak to the dark port

Sensitivity is given by solving $\Delta N \sim 1/2$

⇒ For 1W IFO, it is ΔL=5e-17(m/rtHz)

Optical cavity

(IFO=Interferometer)



With a cavity to circulate light 400 times, both $\sqrt{N}$ and ΔL increase by 400

$$\Delta N = \left(400^2 \times \sqrt{N}\,\frac{4\pi\Delta L}{\lambda}\right)^2$$

Sensitivity is given by solving $\Delta N \sim 1/2$

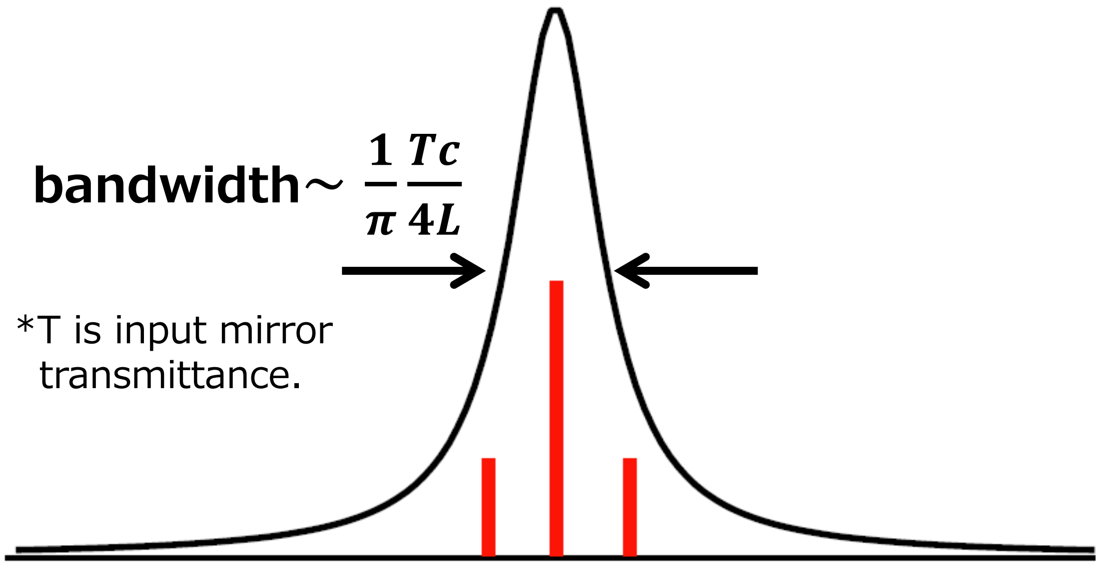
⇒ For 1W IFO, it is ΔL=1e-19(m/rtHz)

Optical cavity

(BW=Bandwidth)

bandwidth $\sim \frac{1}{\pi}\frac{Tc}{4L}$

*T is input mirror transmittance.



Signal outside bandwidth will not increase in cavity.

⇓

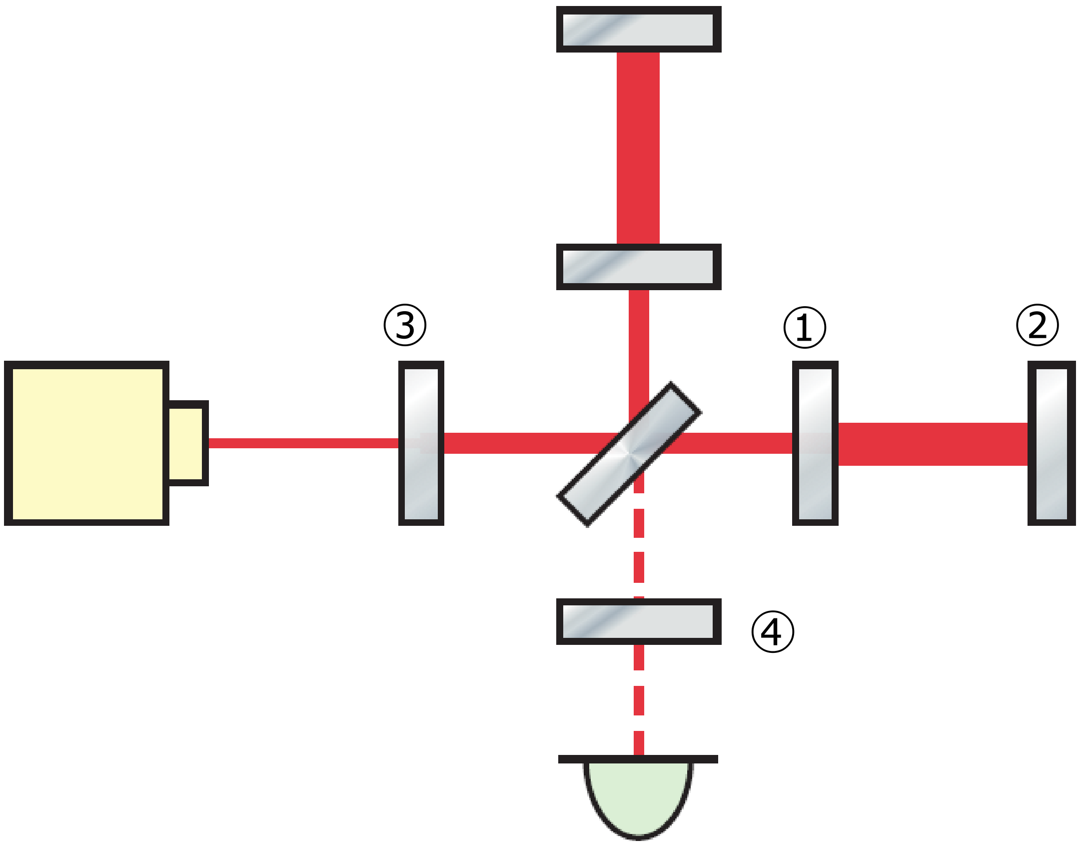
With 99% input mirror and L=4km, BW is~30Hz.

We like to have more light in the cavity but we do not want to decrease the BW

⇒ A coupled cavity

Coupled cavity

(BW=Bandwidth
BS=Beam Splitter)



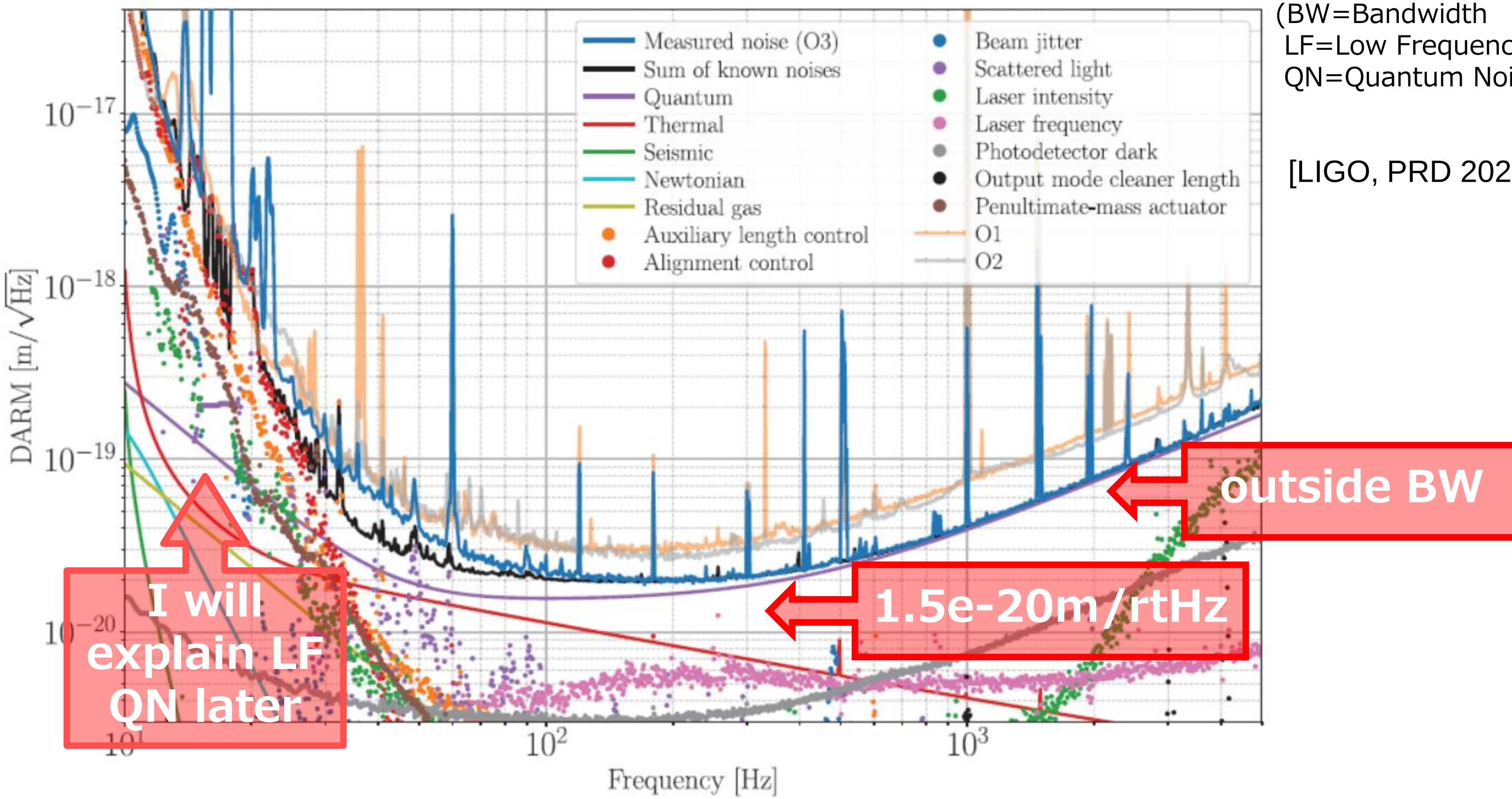
Coupled cavity w/①②③ determines the power.
Coupled cavity w/①②④ determines the BW.

"Power-recycled Resonant-sideband-extraction"

Both Advanced LIGO & KAGRA use this system.

Currently, Advanced LIGO uses ~1.5kW at BS and sensitivity reaches <u>ΔL=2e-20(m/rtHz).</u>

Quantum noise of LIGO in 2020



(BW=Bandwidth
LF=Low Frequencty
QN=Quantum Noise)

[LIGO, PRD 2020]

A 3dB squeezing was injected to effectively double the arm power (to be explained later).

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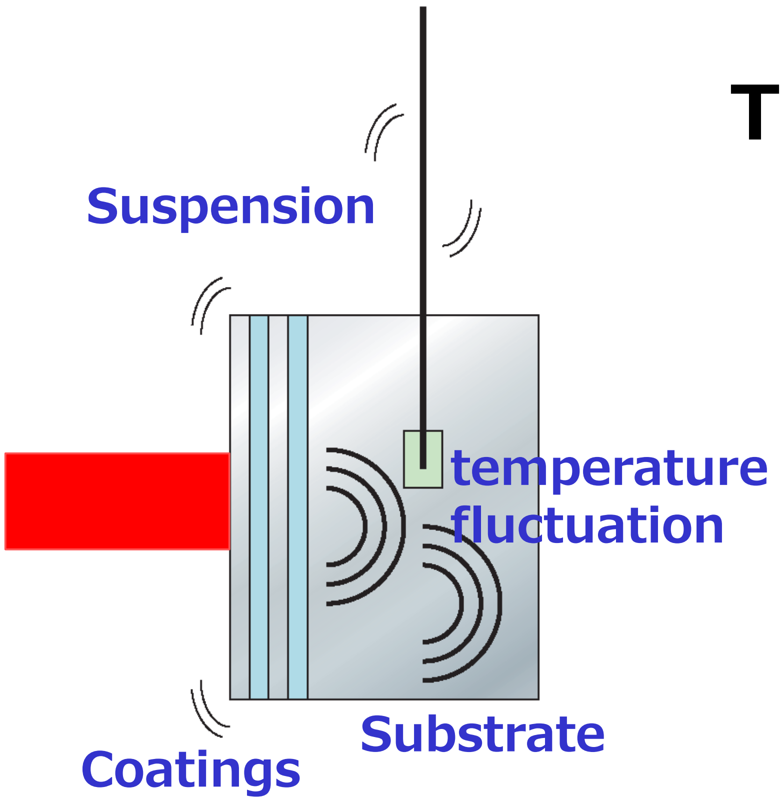
Thermal noise

(TN=Thermal Noise,
1/Q represents dissipation)



Thermal noise is given by

$$\frac{1}{2}mv^2 = \frac{k_B T}{Q}$$

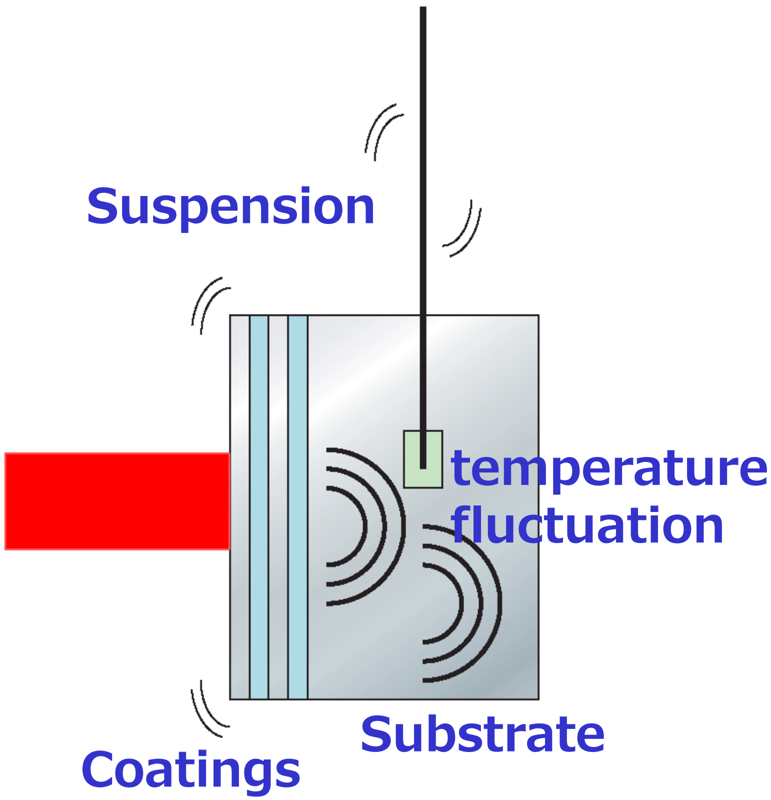
$$\tilde{x} \sim \sqrt{\frac{2k_B T}{Q m \Omega^3}} \sim 9 \times 10^{-21} (\mathrm{m/rtHz})$$

(Suspension TN at 100Hz)

Each thermal noise level is calculated with the fluctuation-dissipation theorem.

Thermal noise

※*expressed with a simple model*



- Coating Brownian TN [Harry, 2002]

$$S_x = \frac{4k_B T}{\Omega} \frac{(1+\sigma)(1-2\sigma)2d_{coa}}{\pi Y w^2} \phi_c$$

Decreases with a larger beam size (*w*)

- Suspension Brownian TN [Saulson, 1990]

$$S_x = \frac{4k_B T}{m\Omega^5} \sqrt{\frac{4\pi Y g}{m}} \left(\frac{d_{wire}}{4\ell} \right)^2 \phi_w$$

Decreases w/heavy mirror (m) and thin wire (d)

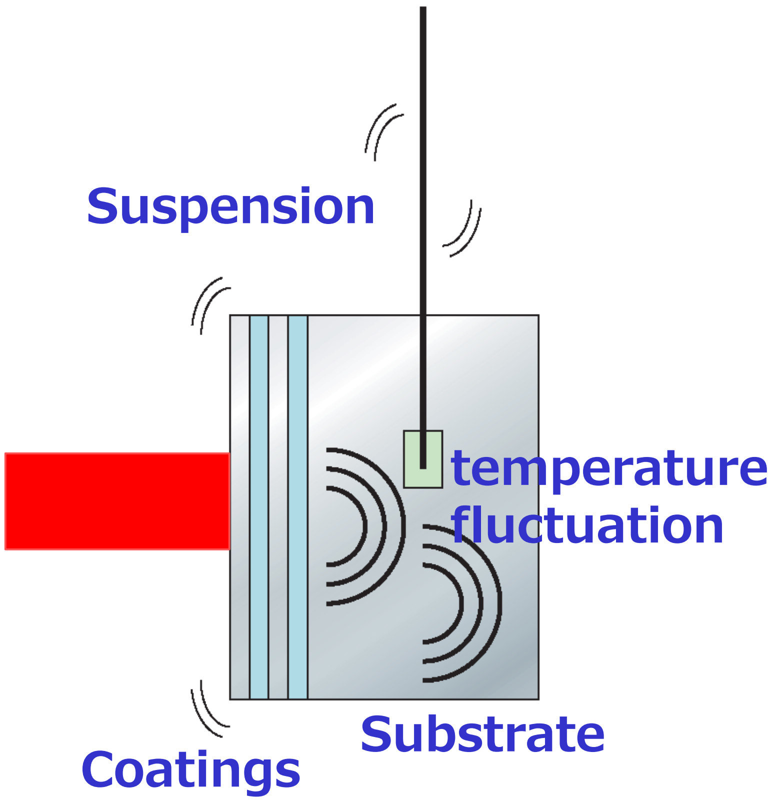
- Substrate thermoelastic noise [Braginsky, 2003]

$$S_x = \frac{16 k_B T^2 (1+\sigma)^2 \alpha_s^2 \kappa_s}{\sqrt{\pi} C_s w^3 \Omega^2}$$

Decreases w/low thermal expansion (α)

Y: Young's modulus
σ: Poisson ratio
C_s: heat capacity
ϕ: loss angle

Thermal noise



LIGO’s strategy

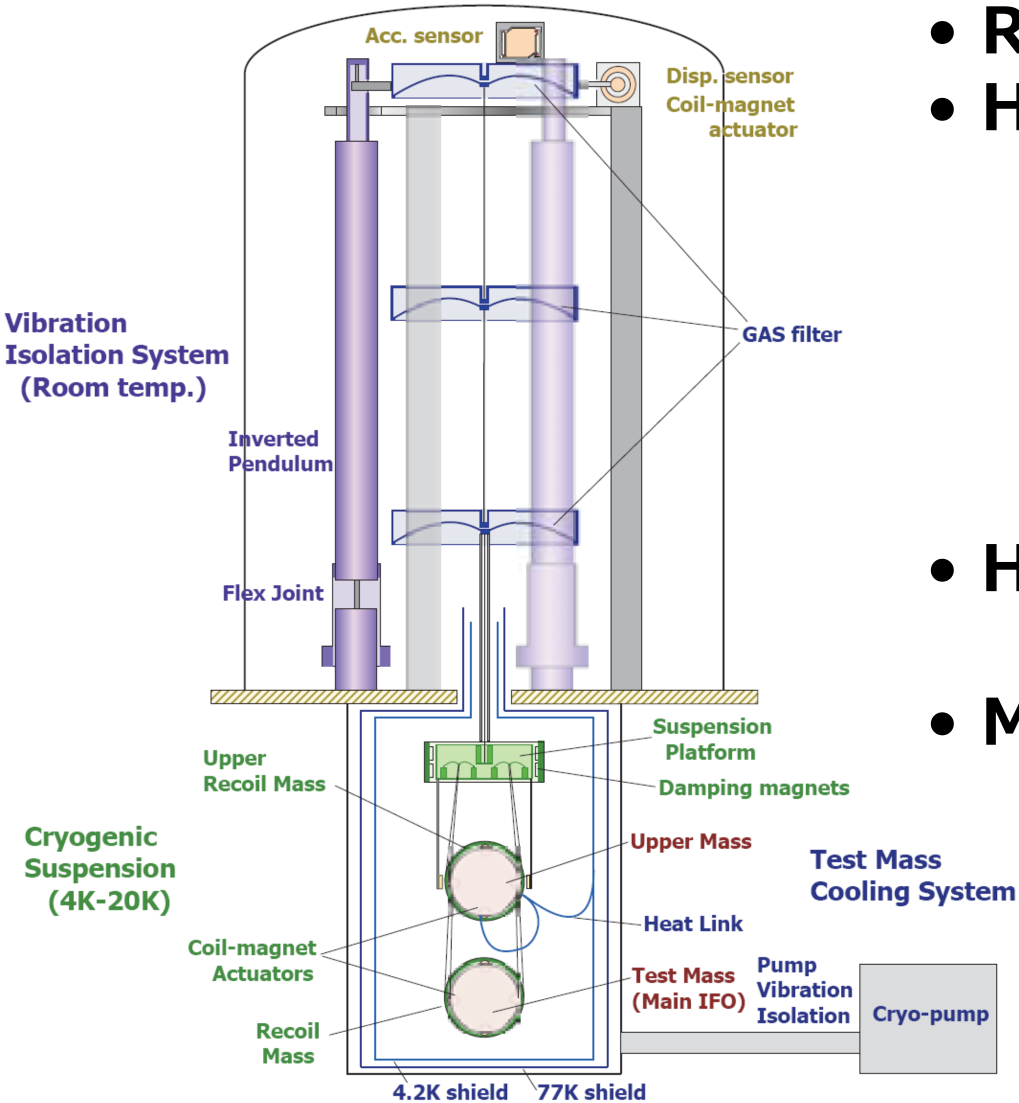
- Find a better coating material
- Increase the beam size
- Use thin monolythic wires
- Optimize the wire thickness

KAGRA’s strategy

- Cool the mirror down to 20K
- Use cryogenic sapphire wires

Choice of the strategy to reduce TN makes the difference between LIGO and KAGRA.

Cryogenic system



- **Radiation shields**
- **Heat transfer via heat links**

pure Al (99.999%)
ϕ=0.15mm

- **Heat transfer via sapphire wire**

ϕ=1.6mm

- **Mirror temperature 20~23K**

sapphire crystal
m=23kg, Q~1e8

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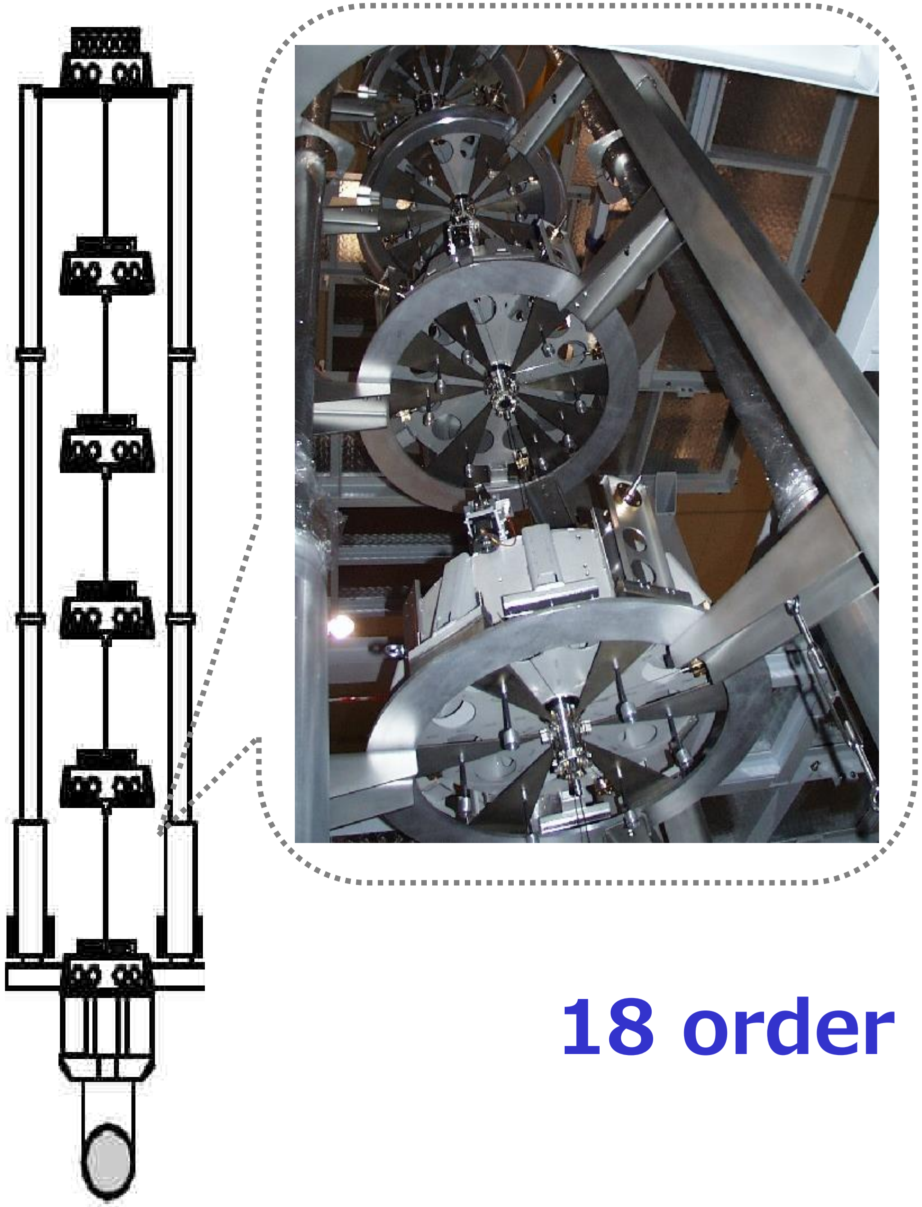
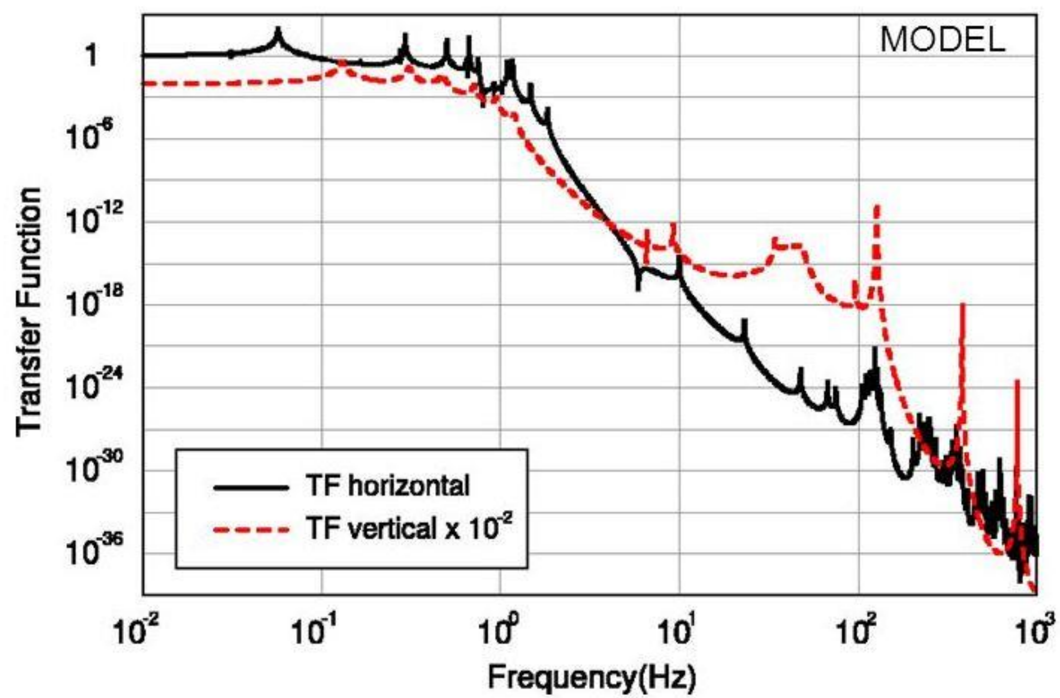
Multiple suspension in Virgo



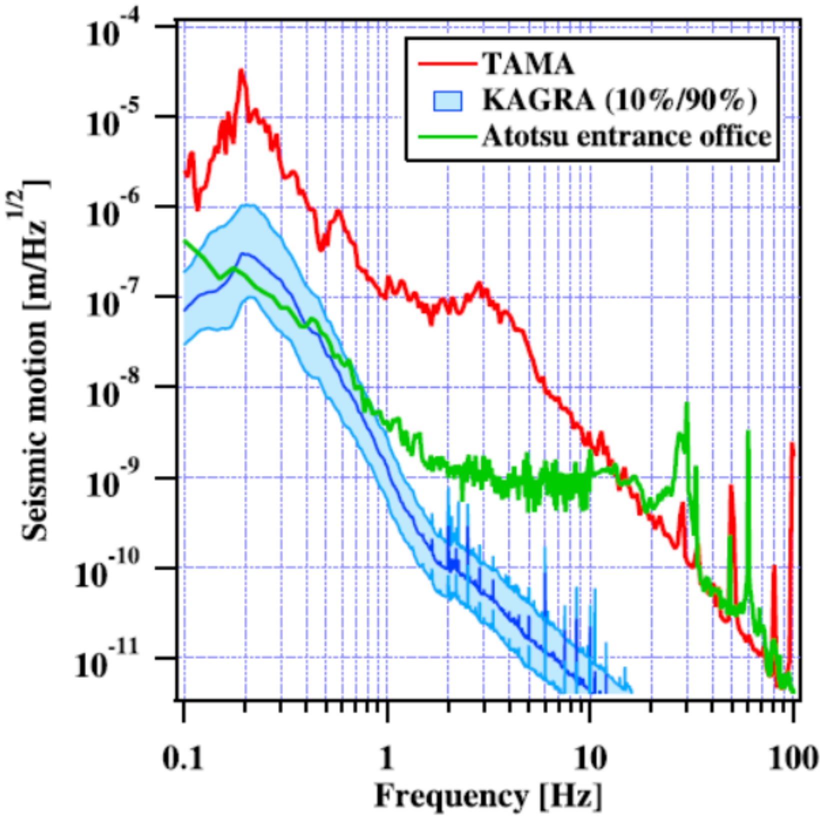
[Frasconi, APPEC Forum 2018]
[Ballardin, RSI 2001]

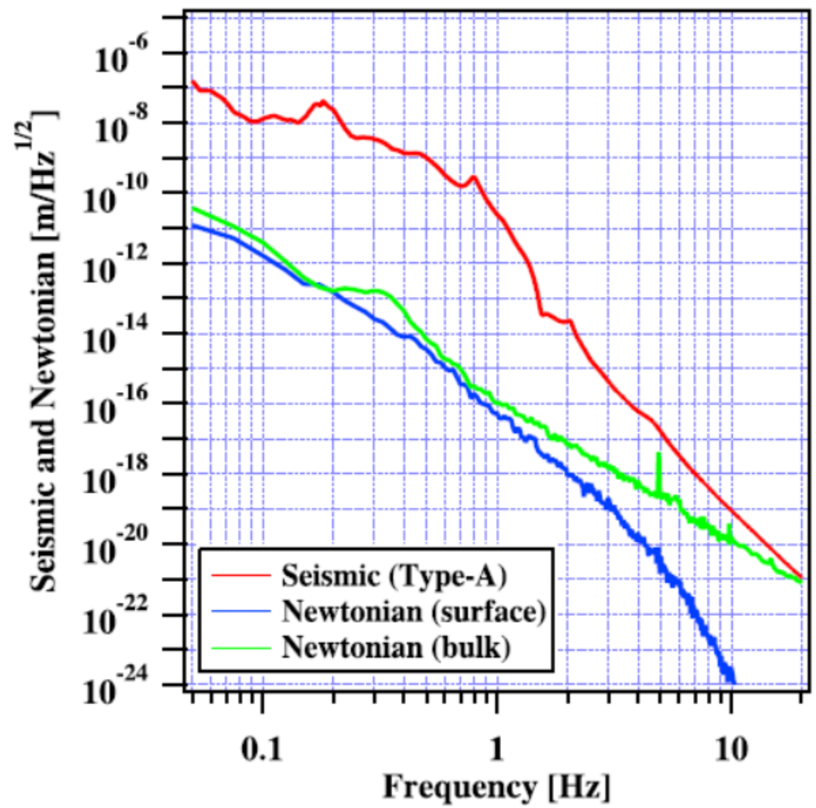


18 order seismic isolation at 100Hz

Underground

[KAGRA, PTEP 2020]





- **Seismic noise at 1Hz is low at a quiet place.**
- **Seismic noise above 10Hz is low in the underground.**
- **Surface Newtonian noise is low in the underground.**

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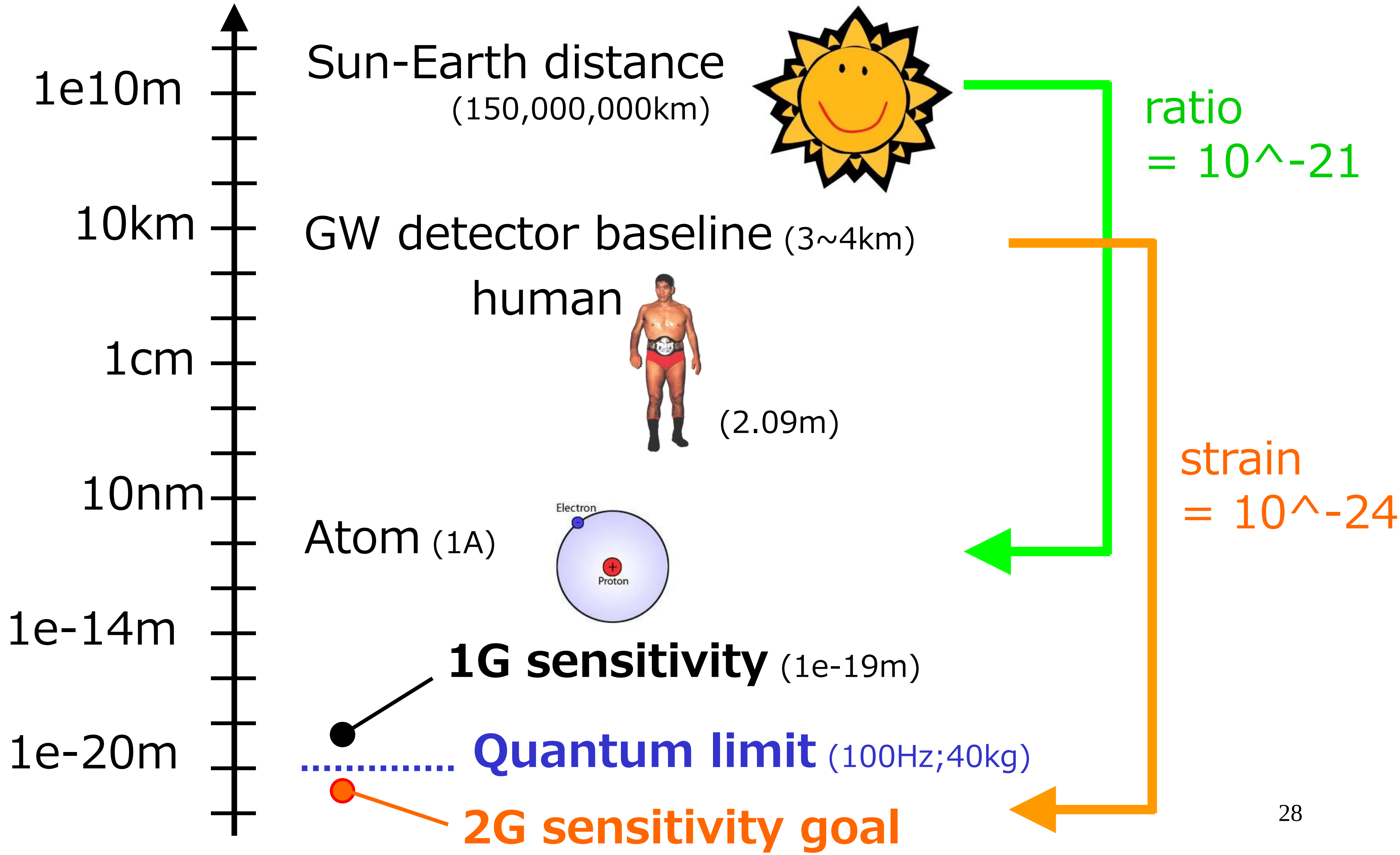
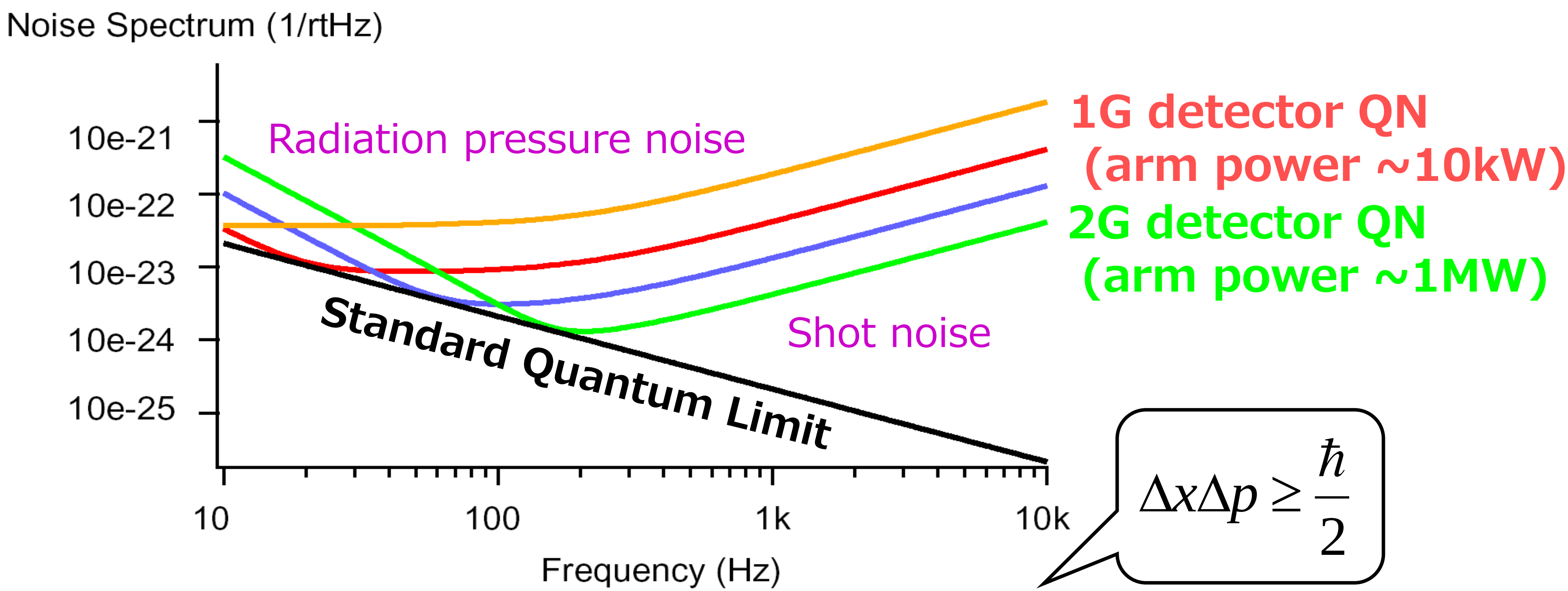
How small are we going to measure?



Quantum noise in GW detector



$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

Uncertainty Principle

High precision → Back action

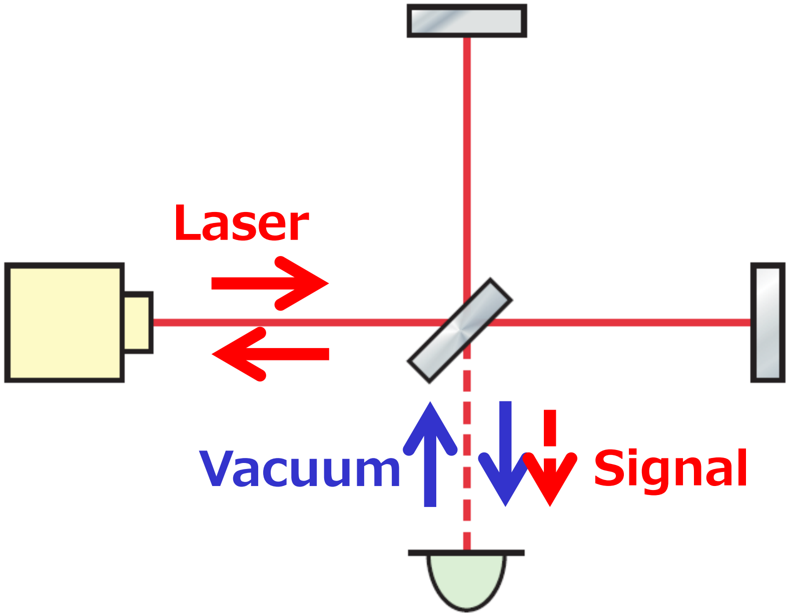
|| Shot noise reduction w/high power laser

|| Radiation pressure

There is a limit that cannot be exceeded by simply increasing laser power.

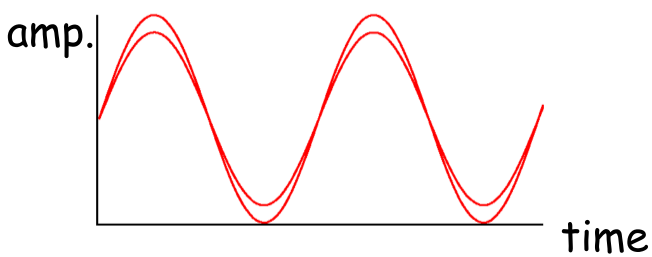
Source of quantum noise

(SQL=Standard Quantum Limit)



Vacuum field consists of amplitude and phase fluctuations.

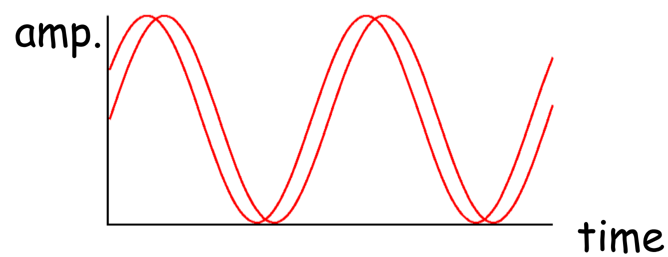
SQL derives from a commutator of these two components.



photon number fluctuation

↓

radiation pressure noise



phase fluctuation

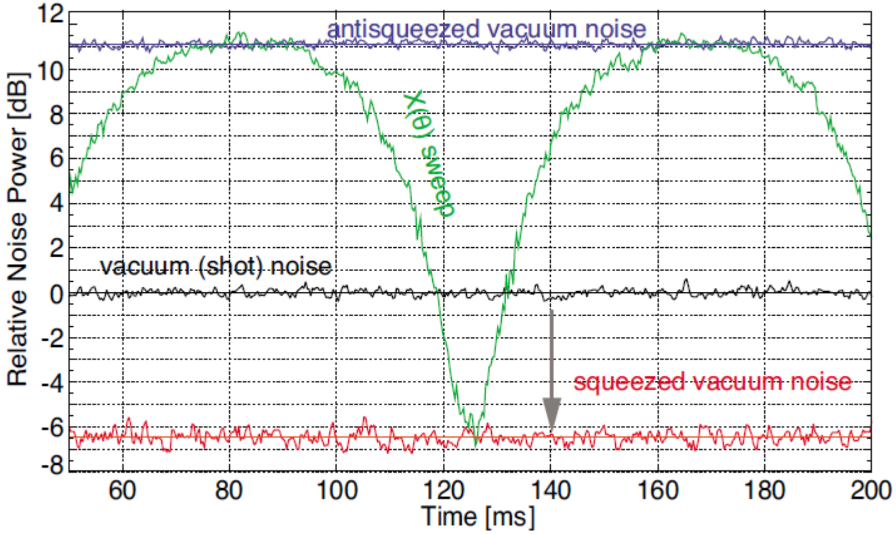
↓

shot noise

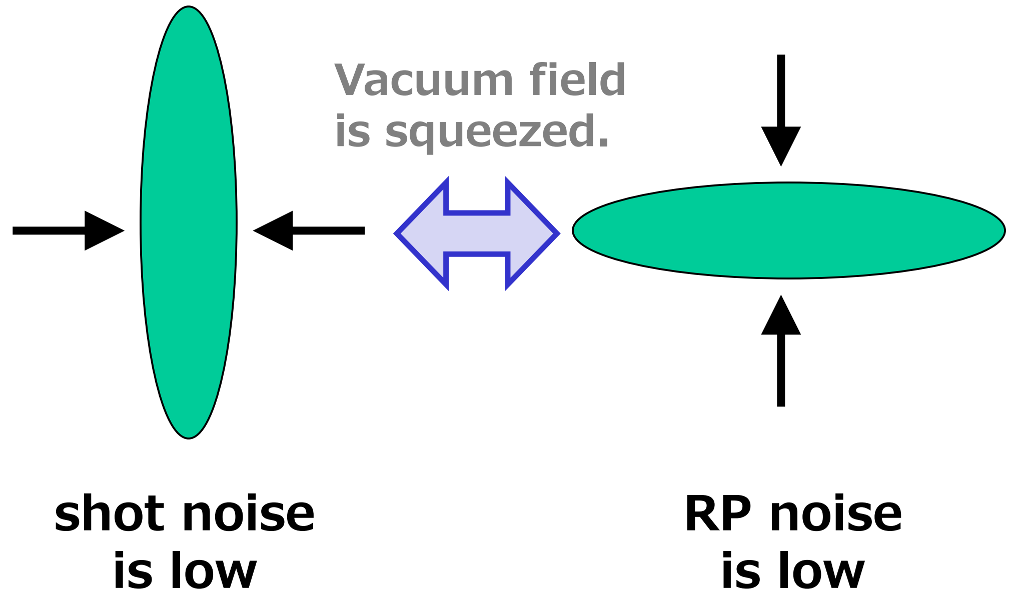
Optical squeezing

(RP=Radiation Pressure
LF=Low Frequency
HF=High Frequency)

[Mehmet, Opt.Lett. (2010)]



7dB squeezing

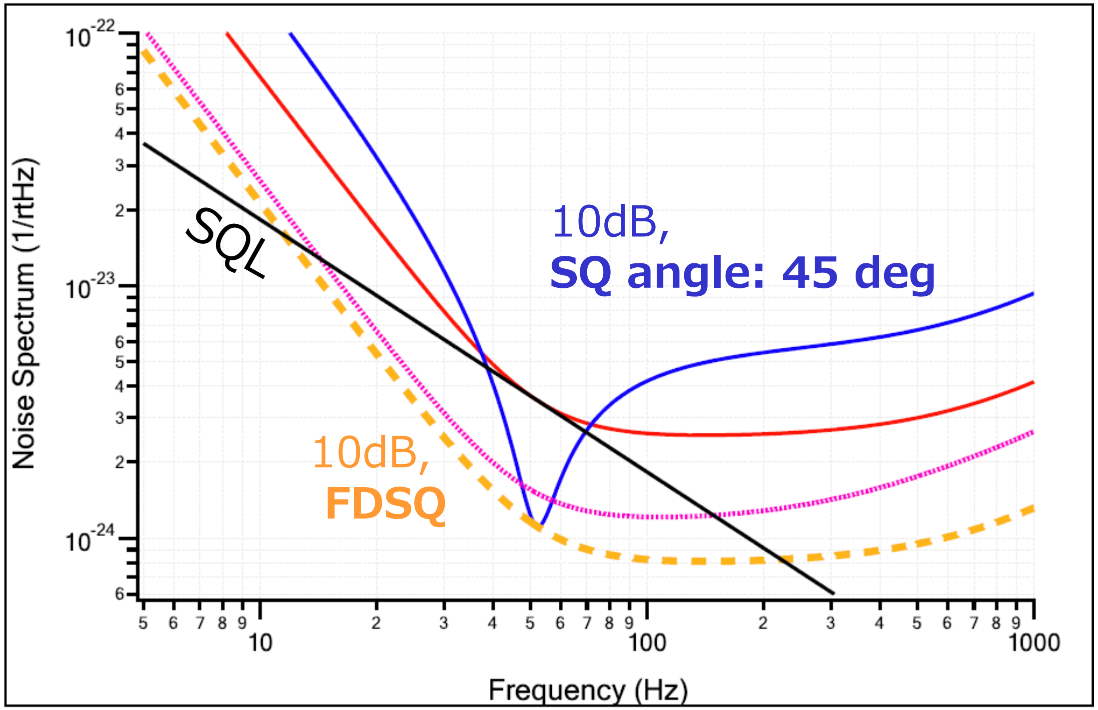


Optical parametric amplification process creates a correlation in upper and lower sidebands.

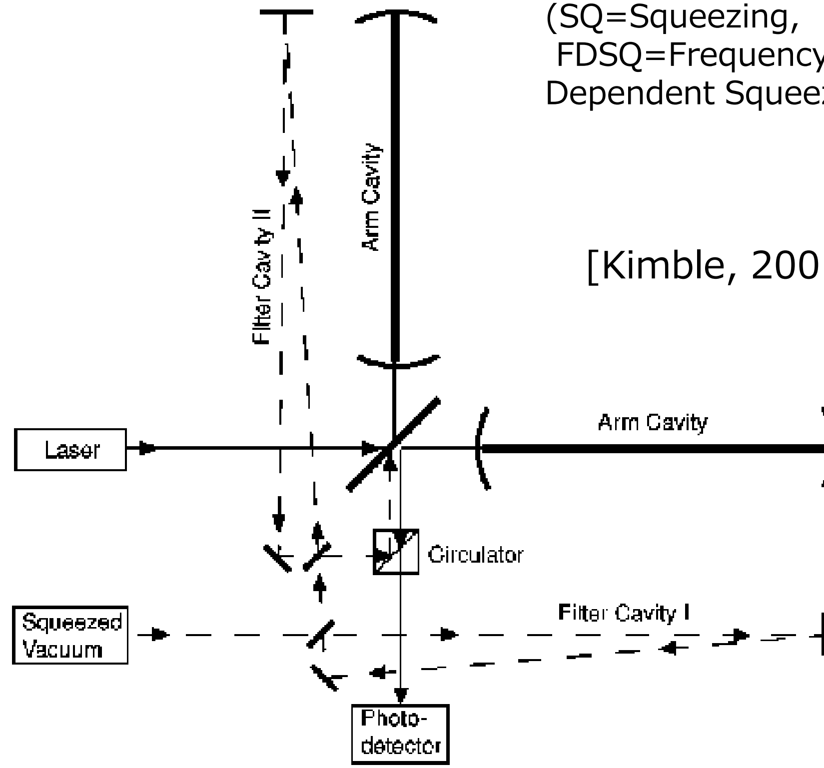
Sensitivity improves either at LF or HF according to the choise of the squeezing angle.

Frequency-dependent squeezing

orage: lossless, pink: with loss



(SQ=Squeezing,
FDSQ=Frequency-Dependent Squeezing)



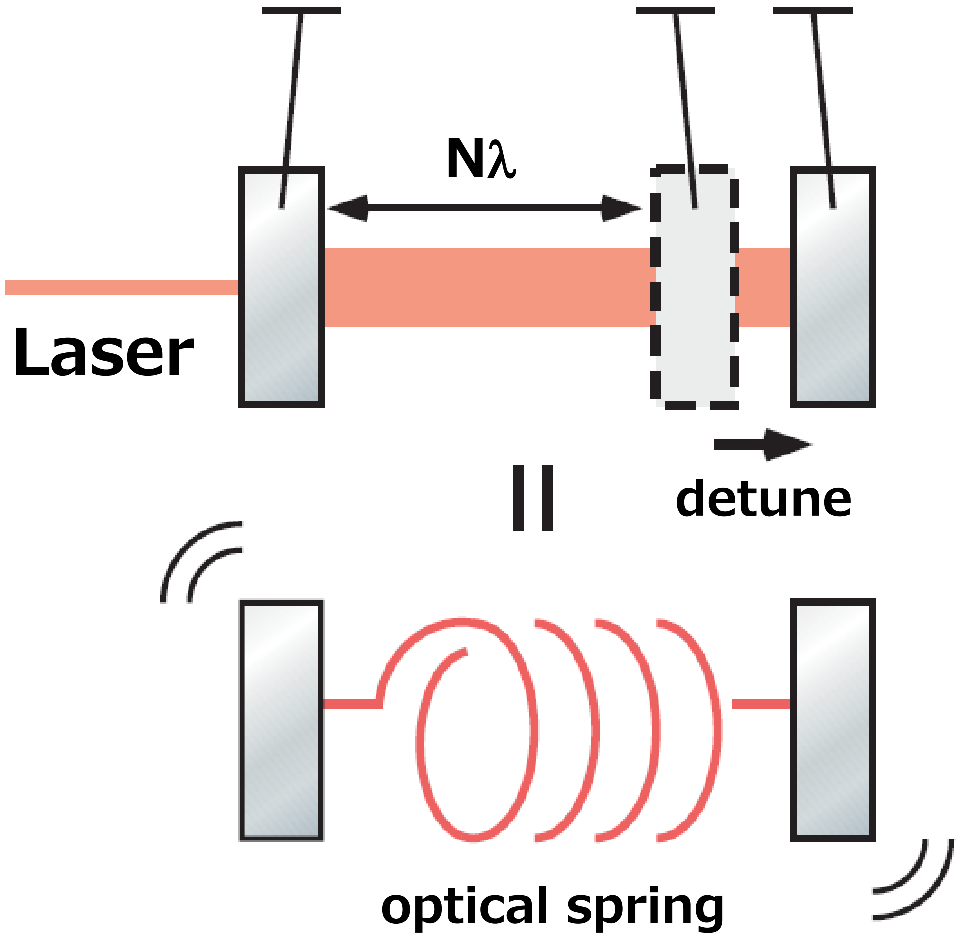
[Kimble, 2001]

- **SQ angle is rotated in filter cavities**
- **Rotation angle depends on the frequency**

This technique has been installed in LIGO & Virgo.

Optical spring

(RP=Radiation Pressure
GW=Gravitational Wave
OS=Optical Spring)



Far from reso → less RP

Approach to reso → more RP

⇩

Optomechanical restoring force

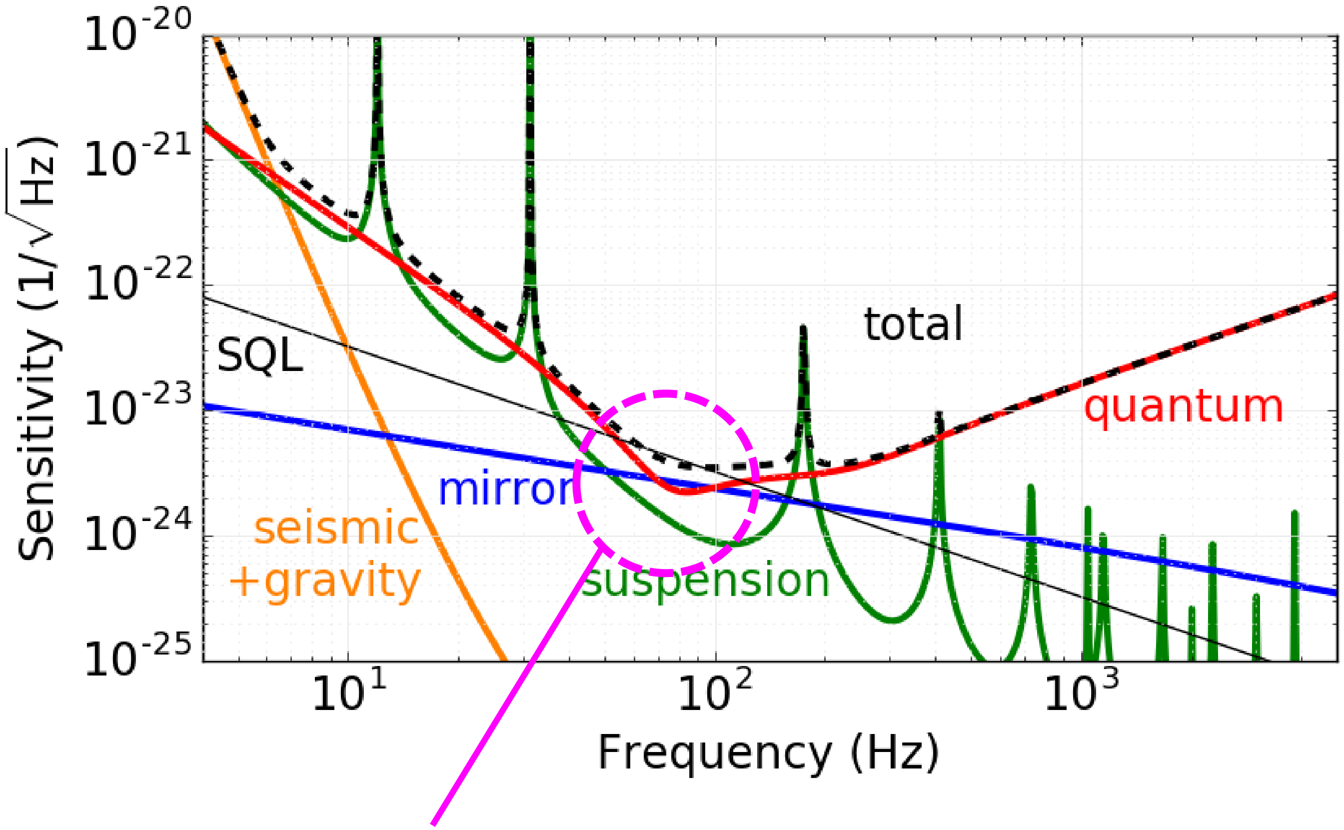
GW response increases at OS resonance.

KAGRA plans to implement this technique.

Optical spring

(QN=Quantum Noise
NS=Neutron Star
SQL=Standard Quantum Limit
HP=Home Page)

KAGRA design sensitivity

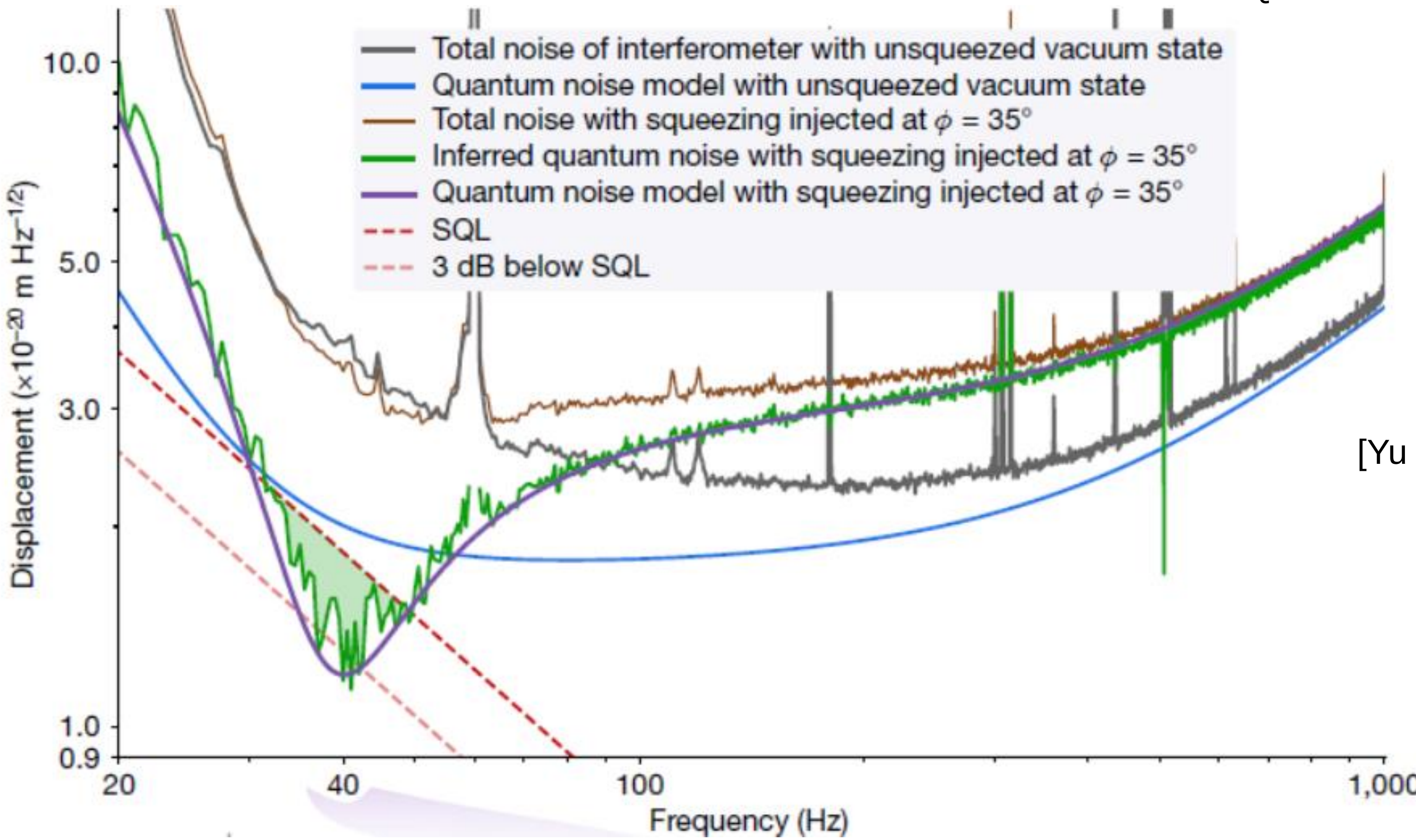


[KAGRA HP]

QN exceeds the SQL at the optical spring frequency.
⇒ 20% sensitivity improvement to observe binary NS.

Toward the SQL

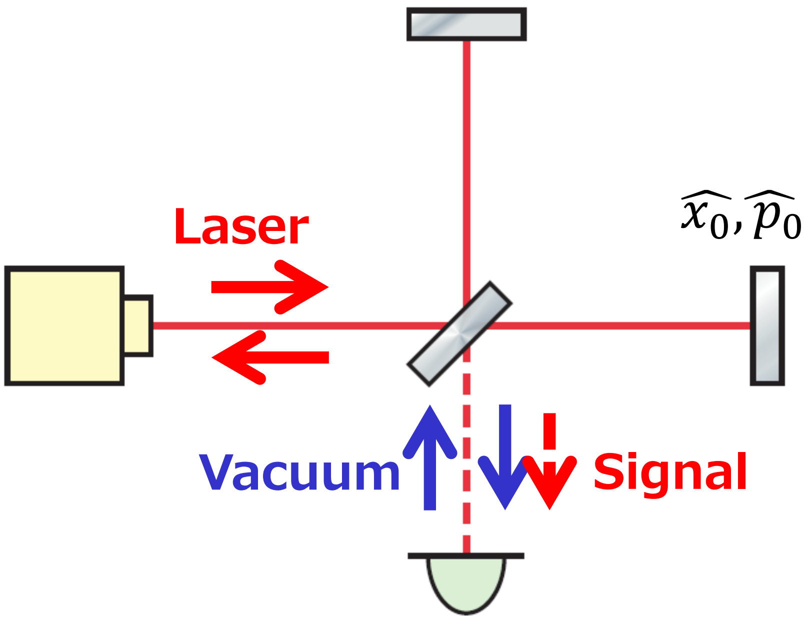
(QN=Quantum Noise
SQL=Standard Quantum Limit)



[Yu Nature 2020]

LIGO demonstrated their QN exceeds the SQL by 3dB with a post-processing removal of classical noise.

How come the sensitivity can go beyond the SQL?



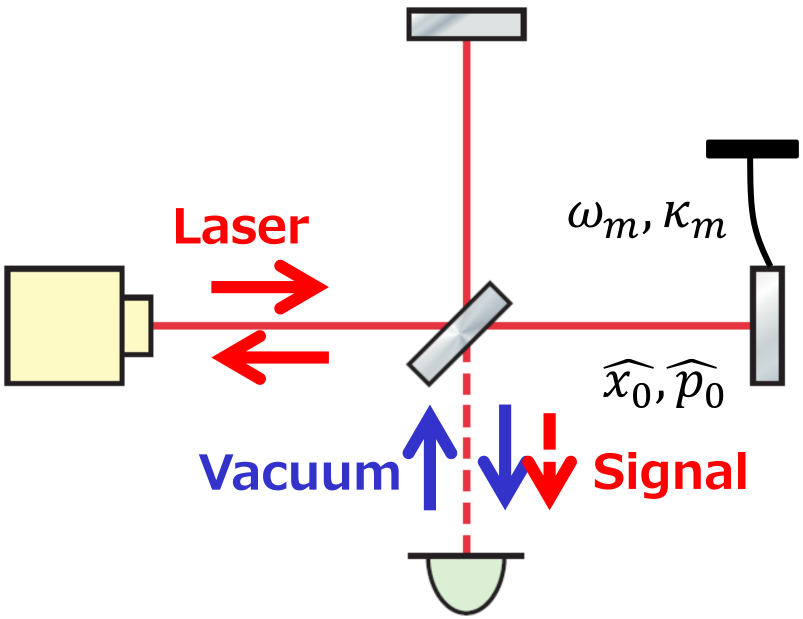
Brangisky's explanation in his paper, [PRD 67, 082001 (2003)] **is as follows:**

"GWD measures the external force on the mirror. Its initial position $\widehat{x_0}$ is not measured and remains quantum."

The mirror fluctuates with back action noise but one can measure the external force without seeing the fluctuation of the test mass.

In other words, the output field y(t) commutes at different times: $[y(t), y(t')] = 0$.

How come the sensitivity can go beyond the SQL?



Khalili's updated theory in his paper, [PRA 86, 033840 (2012)] **is as follows:**

"Oscillator's initial fluctuation $\hat{x}_0 \cos\omega_m t$ dissipates in time and a thermal field enters. If T is low, the zero-point fluctuation of the thermal field takes over the initial quantum fluctuation."

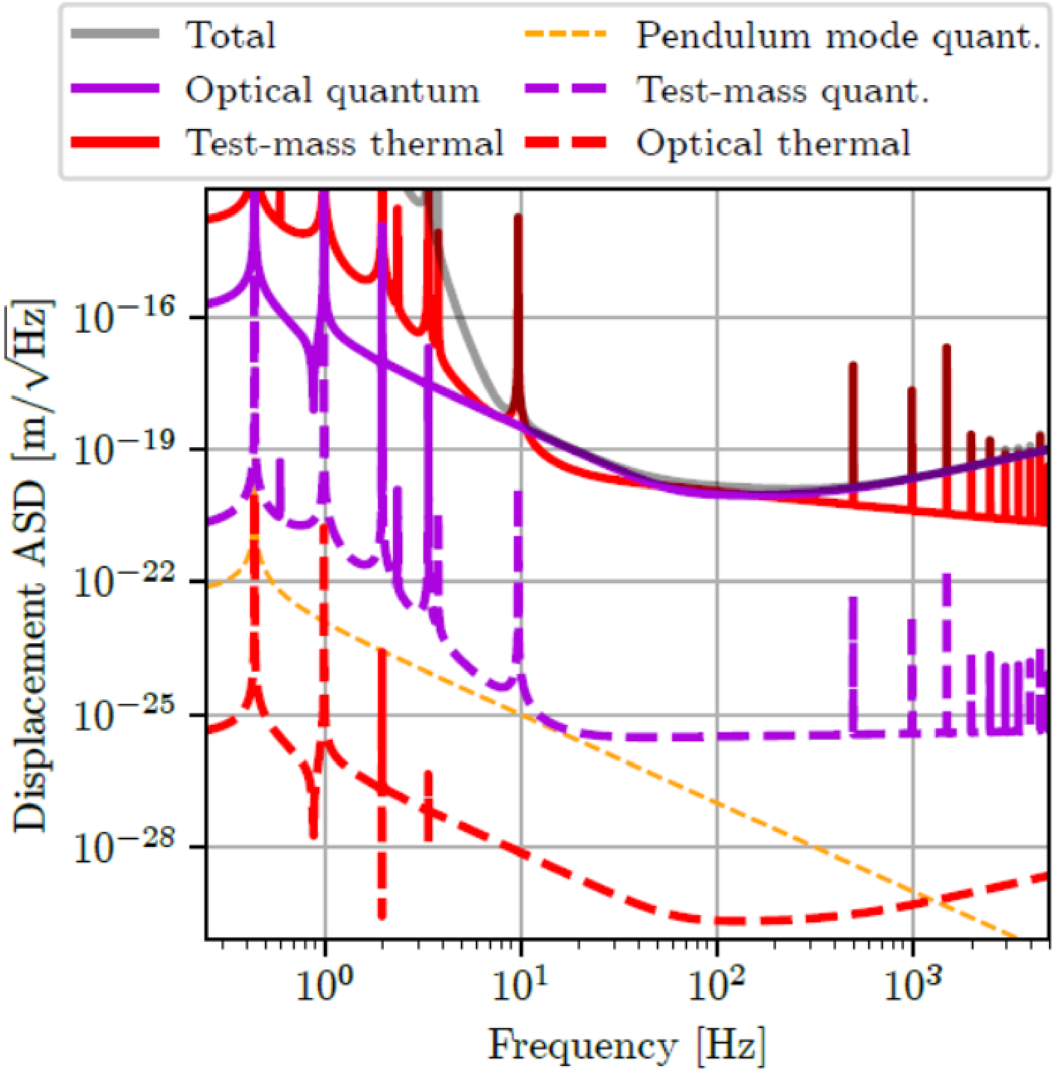
$$\hat{x}_q(t) = e^{-\frac{\kappa_m t}{2}}\left[\hat{x}_0 \cos\omega_m t + \frac{\hat{p}_0}{m\omega_m}\sin\omega_m t\right] + \int_{-\infty}^{t} e^{-\frac{\kappa_m (t-t')}{2}} \frac{\sin\omega_m (t-t')}{m\omega_m} F(t')\, dt'$$

$$\hat{y}(t) = \underline{\hat{z}(t)} + \underline{\hat{x}_{BA}(t)} + \underline{\hat{x}_q(t)}$$

shot noise — RPN — initial position

Either $z + x_{BA}$ or x_q does not commute at different times, but commutators cancel and y does commute at different times.

Zero-point fluctuation in GWD

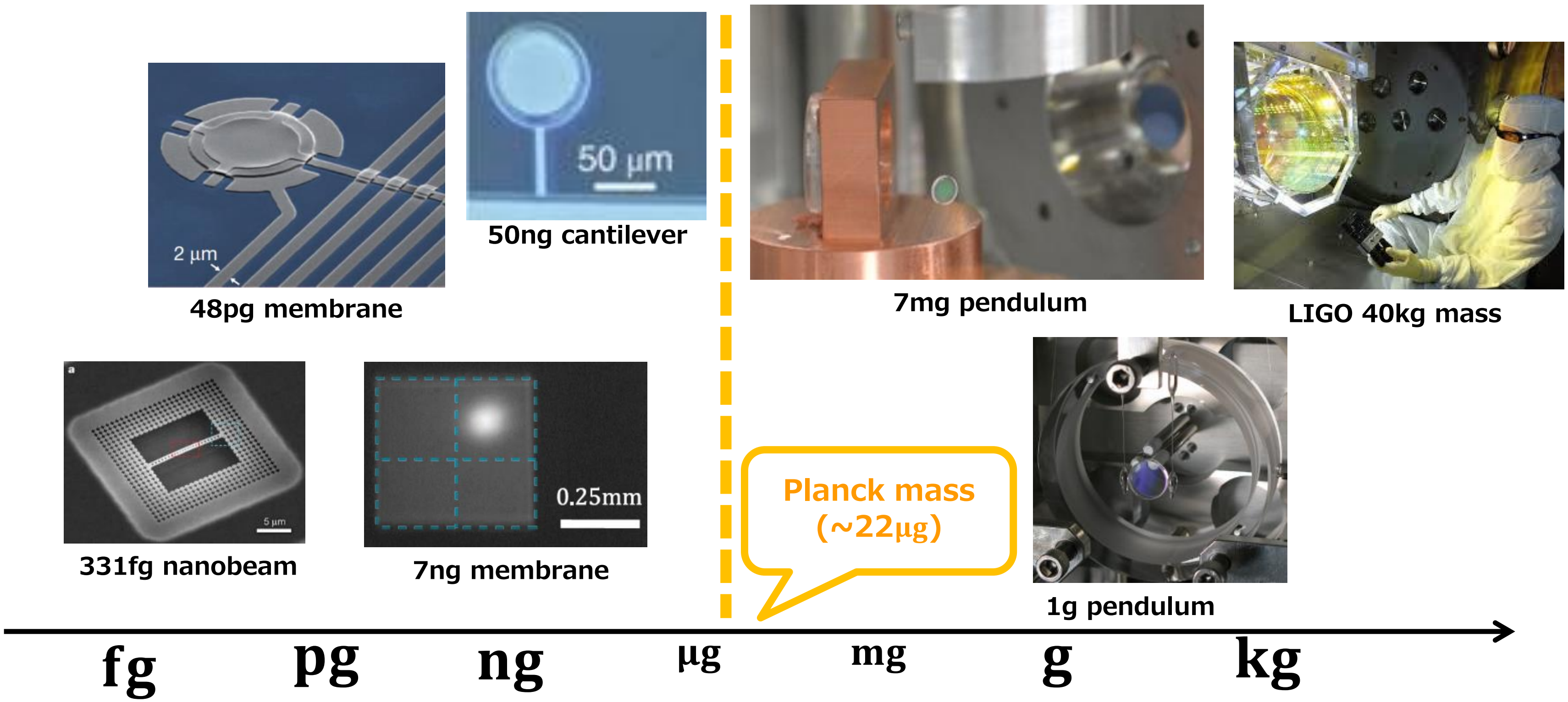


[Whittle, arXiv 2023]

Whittle et al. demonstrated to calculate test mass quantum fluctuation in Advanced LIGO, which is very low compared with quantum noise of light.

(dashed curves)
orange: pendulum mode only
purple: all mechanical modes
red: thermal fluctuation of photons

Macroscopic QM on various mass scales



Some microresonators have reached the SQL (not the zero-point fluctuation). None above the Planck mass has reached the SQL.

Reference

331fg nanobeam [Chan, Nature (2011)], 48pg membrane [Teufel, Nature (2011)], 7ng membrane [Peterson, PRL (2016)], 50ng cantilever [Cripe, Nature (2019)], 7mg pendulum [Matsumoto, PRL (2019)], 1g pendulum [Neben, NJP (2012)]

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Summary

(SQL=Standard Quantum Limit
GW=Gravitational Wave
QM=Quantum Measurement)

- **Quantum noise in GW detector consists of quantum fluctuation of light.**
- **SQL can be surpassed in several ways; (i) squeezing, and (ii) optical spring.**
- **Sensitivity of GW detector is quite close to exceed the SQL.**
- **Test mass quantum noise is a few orders below the quantum noise of light.**
- **Macroscopic QM experiments are going on in various mass scale.**