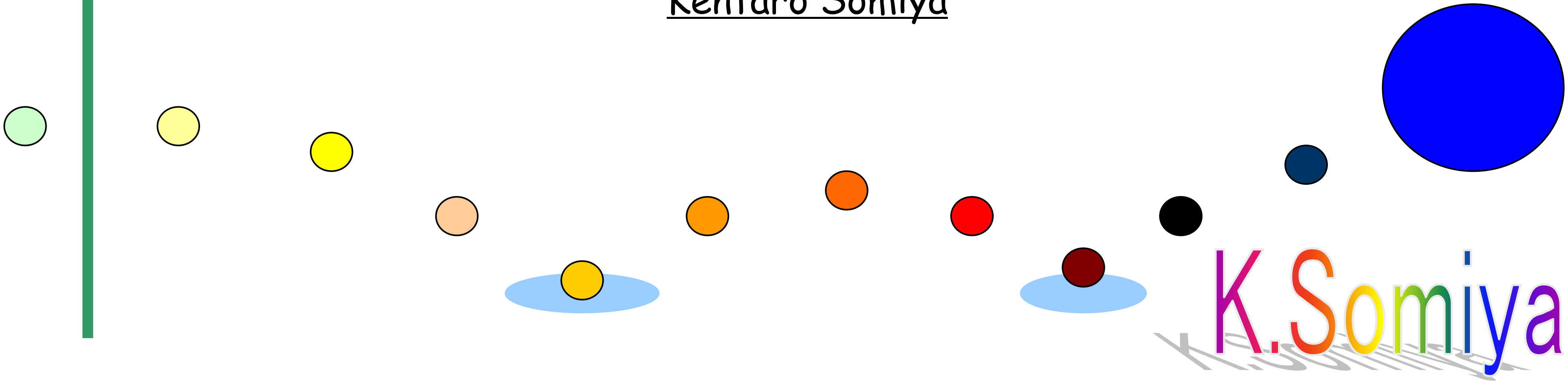
Gravitational-wave detectors

JFFoS Symposium @ Nice
Jan. 2012

Tokyo Inst of Technology
Kentaro Somiya



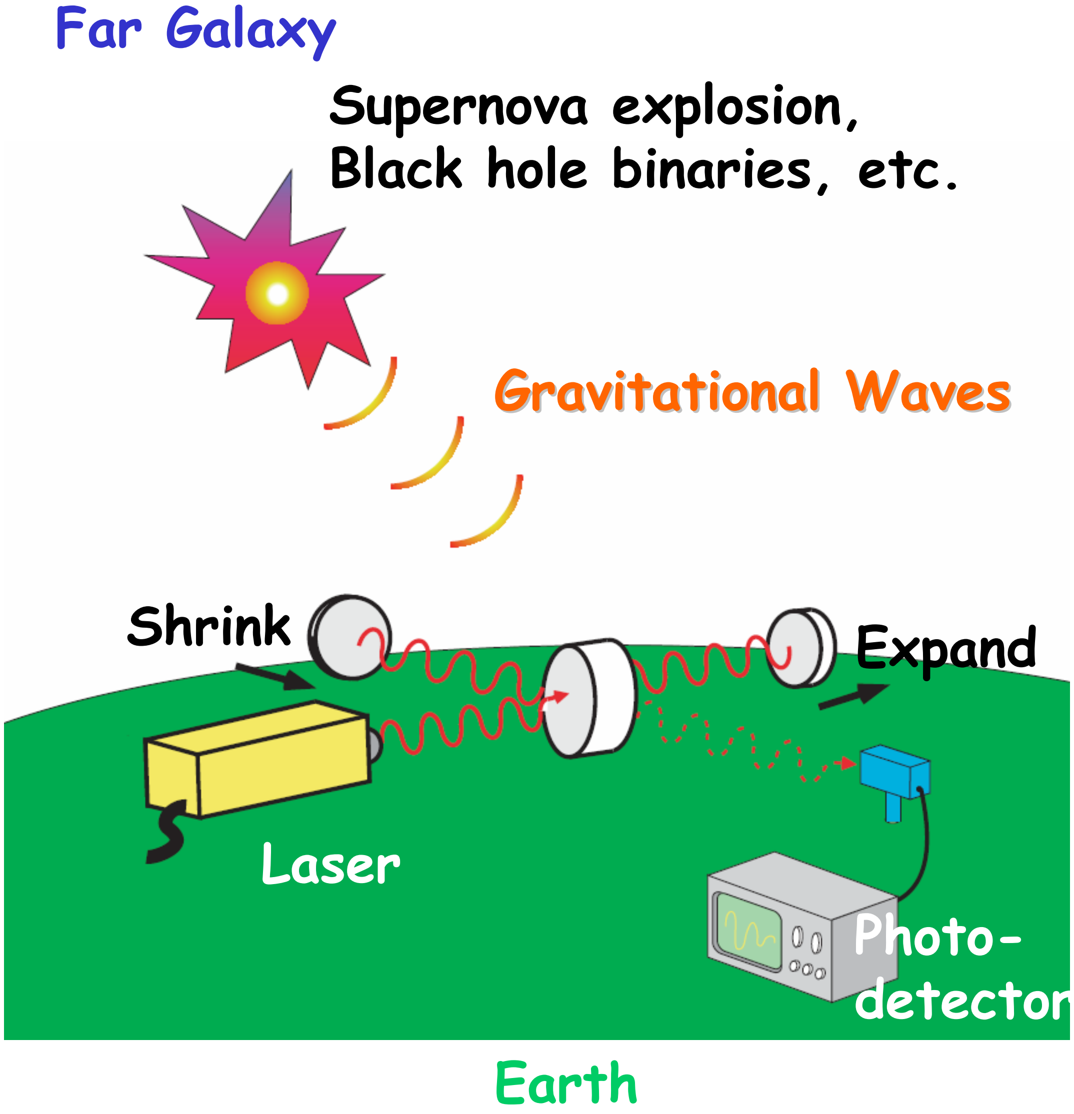
Contents

- Introduction of gravitational waves and gravitational-wave detectors in the world
  [Francois]

- Development of high-sensitivity detectors
  [Kentaro]

- Science from gravitational-wave signals
  [Tanya]

Interferometric GW detector



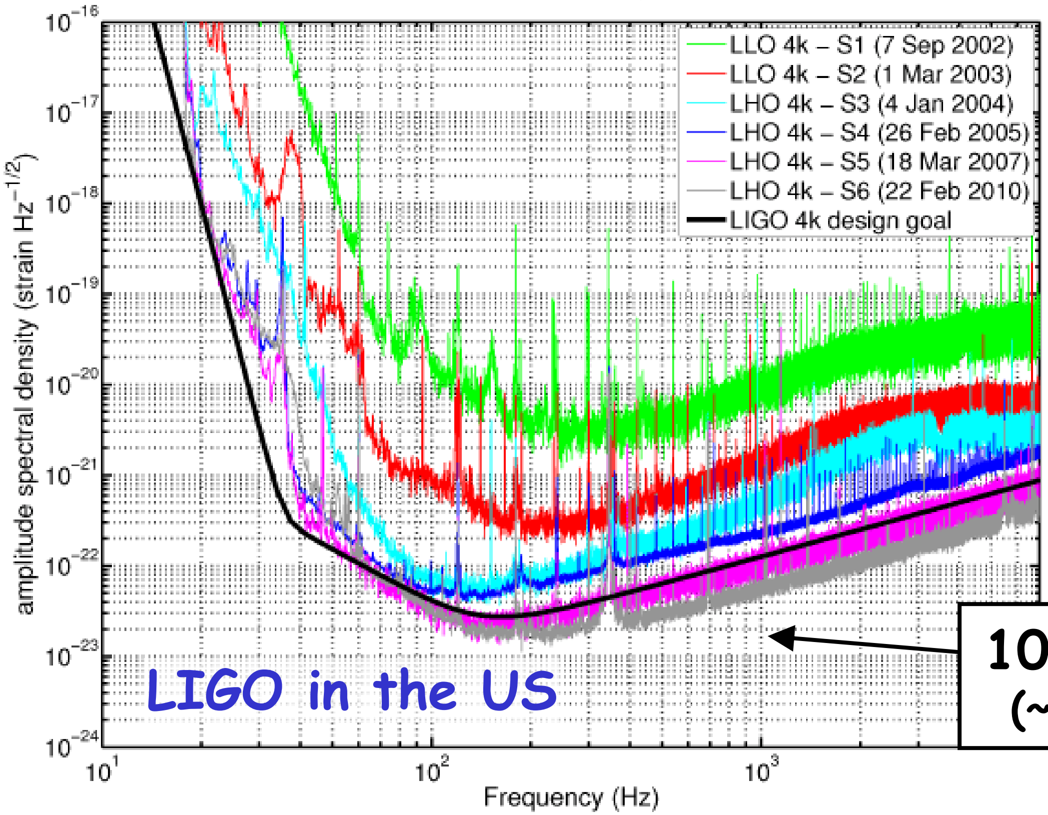
Massive Astronomical events.

Distance of two objects changes.

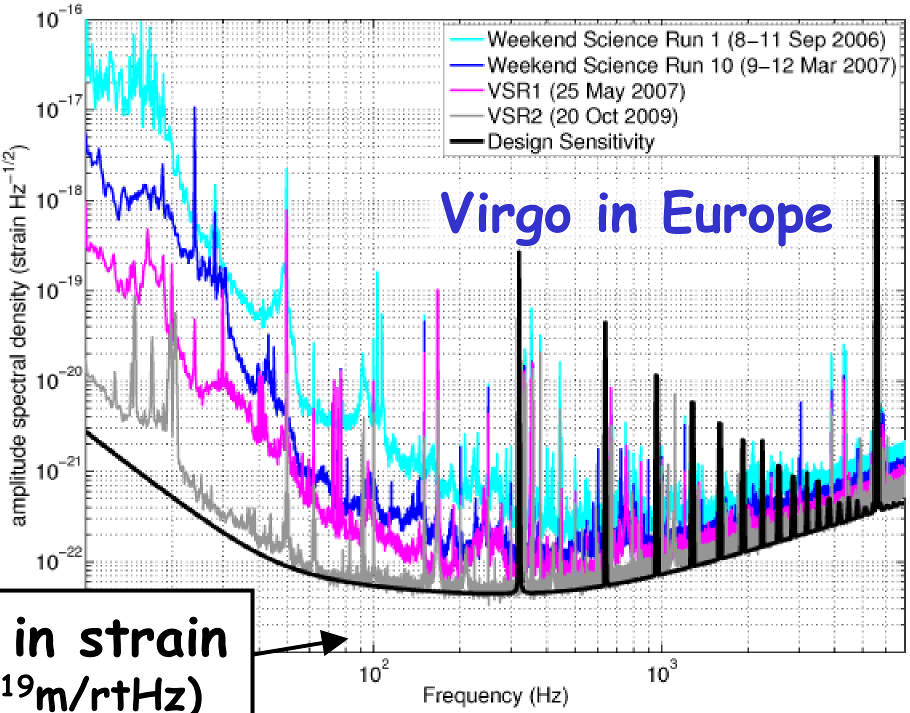
Observe the change with big high-power interferometers

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

Sensitivity of 1st generation detectors

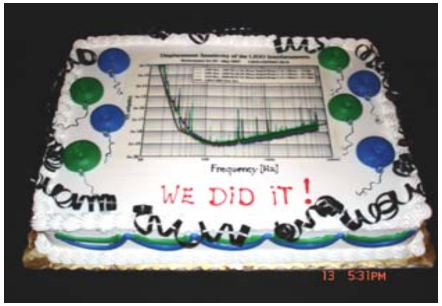


LIGO in the US



Virgo in Europe

10^{-23} in strain
(~10^{-19}m/rtHz)

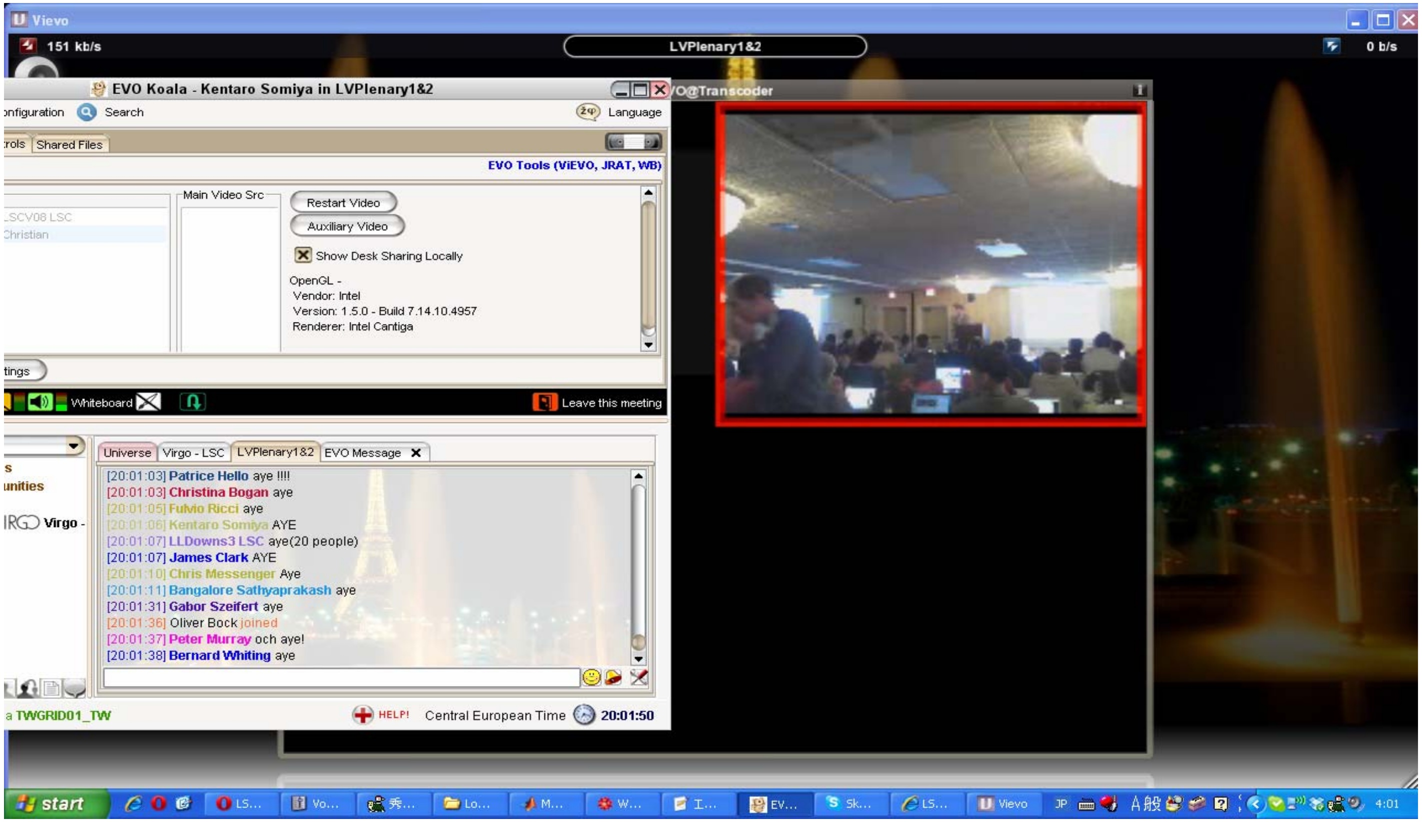


"Reached the design sensitivities"

- Unfortunately no GW found in the 2-year data
- But we proved we can make such good detectors

Big-dog event

In fact, there was a GW event found during a LIGO-Virgo observation in 2010.



☒ Show Desk Sharing Locally

```
OpenGL -
 Vendor: Intel
 Version: 1.5.0 - Build 7.14.10.4957
 Renderer: Intel Cantiga
```

```
[20:01:03] Patrice Hello aye !!!!
[20:01:03] Christina Bogan aye
[20:01:05] Fulvio Ricci aye
[20:01:06] Kentaro Somiya AYE
[20:01:07] LLDowns3 LSC aye(20 people)
[20:01:07] James Clark AYE
[20:01:10] Chris Messenger Aye
[20:01:11] Bangalore Sathyaprakash aye
[20:01:31] Gabor Szeifert aye
[20:01:36] Oliver Bock joined
[20:01:37] Peter Murray och aye!
[20:01:38] Bernard Whiting aye
```

It passed all the tests to be announced as the first detection of GW, except the last test, the blind injection: a fake signal added intentionally.

At last the big-dog event turned out to be a fake signal.

Science/lessons from the 1G detectors

[Science]

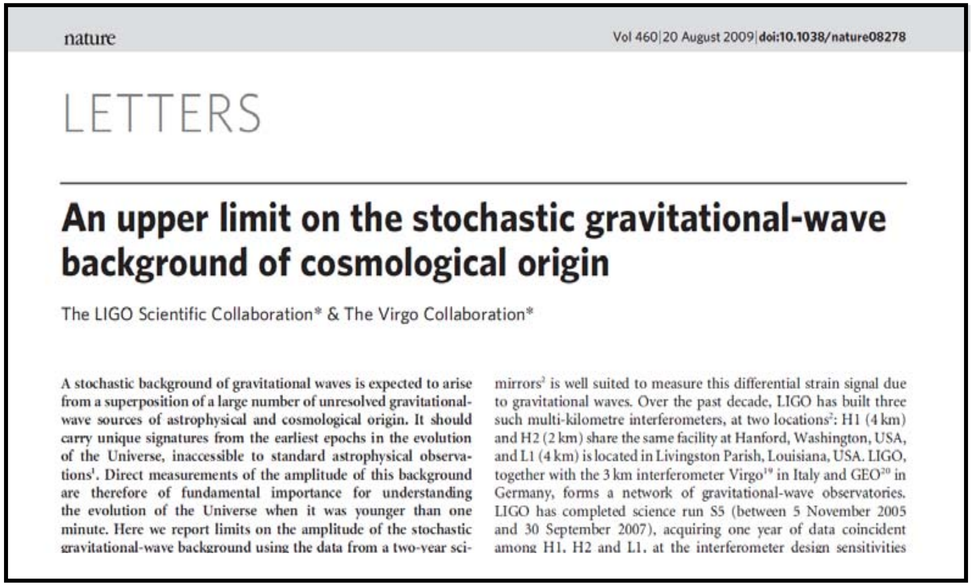
- **Upper limits**
  ~ ruling out exotic models

- **Multi-messengers**
  ~ neutrino, gamma-rays, etc.

[Instrument]

- **Confidence**
  ~ roadmap to next generations

- **Fundamental noise**
  ~ direct observation of noise
  ~ advanced configuration



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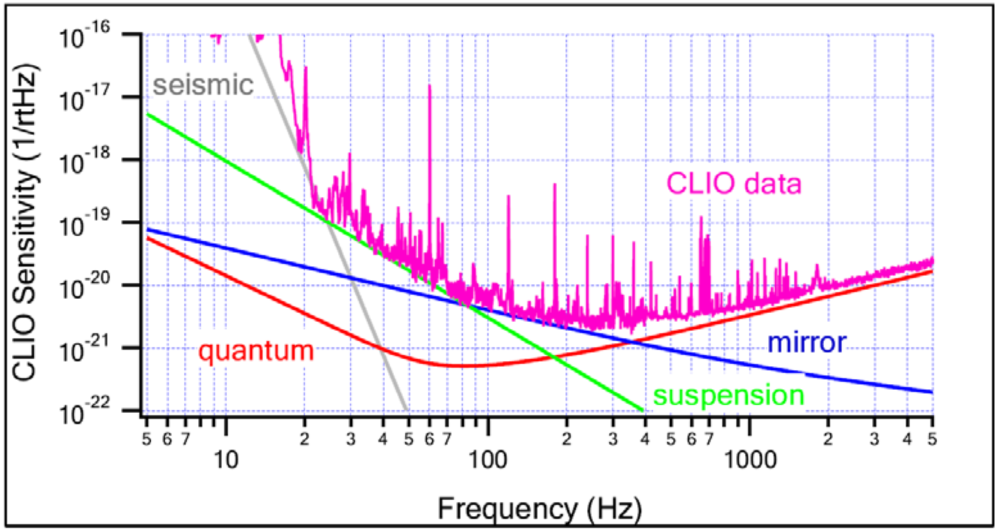
LETTERS

An upper limit on the stochastic gravitational-wave background of cosmological origin

The LIGO Scientific Collaboration* & The Virgo Collaboration*

A stochastic background of gravitational waves is expected to arise from a superposition of a large number of unresolved gravitational-wave sources of astrophysical and cosmological origin. It should carry unique signatures from the earliest epochs in the evolution of the Universe, inaccessible to standard astrophysical observations[1]. Direct measurements of the amplitude of this background are therefore of fundamental importance for understanding the evolution of the Universe when it was younger than one minute. Here we report limits on the amplitude of the stochastic gravitational-wave background using the data from a two-year sci-

mirrors[2] is well suited to measure this differential strain signal due to gravitational waves. Over the past decade, LIGO has built three such multi-kilometre interferometers, at two locations[2]: H1 (4 km) and H2 (2 km) share the same facility at Hanford, Washington, USA, and L1 (4 km) is located in Livingston Parish, Louisiana, USA. LIGO, together with the 3 km interferometer Virgo[19] in Italy and GEO[20] in Germany, forms a network of gravitational-wave observatories. LIGO has completed science run S5 (between 5 November 2005 and 30 September 2007), acquiring one year of data coincident among H1, H2 and L1, at the interferometer design sensitivities



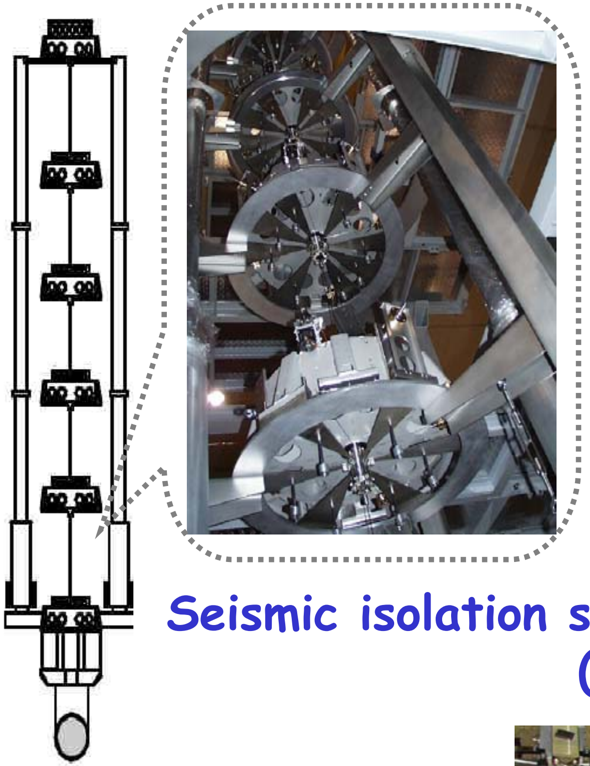
Upgrades to the 2G detectors

LIGO
Virgo
GEO

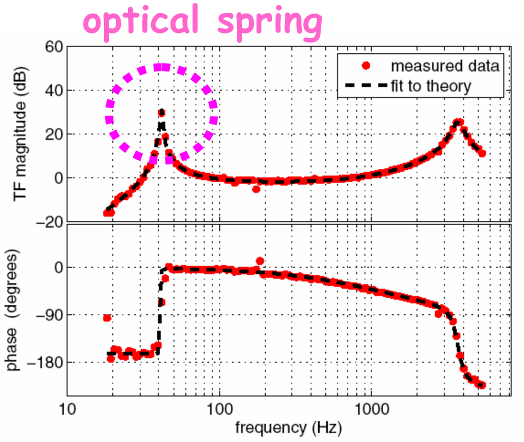
upgrade →

Advanced LIGO
Advanced Virgo
GEO-HF

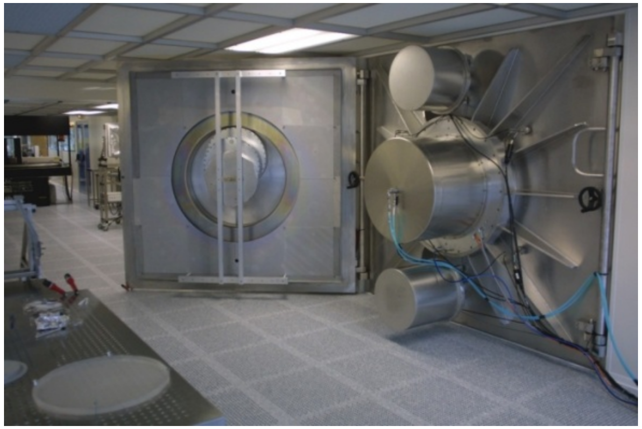
Advanced techniques



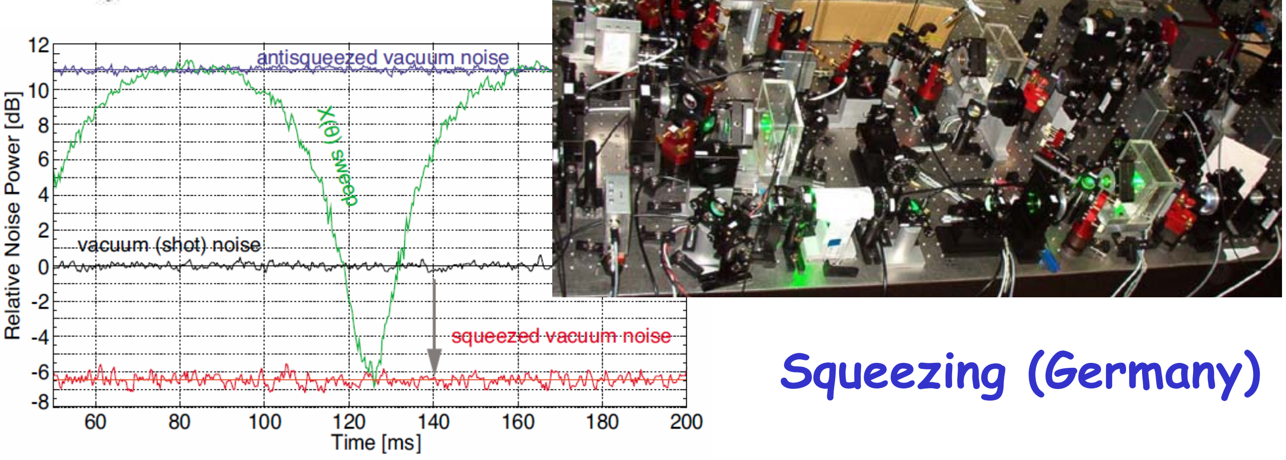
Seismic isolation system (Italy)



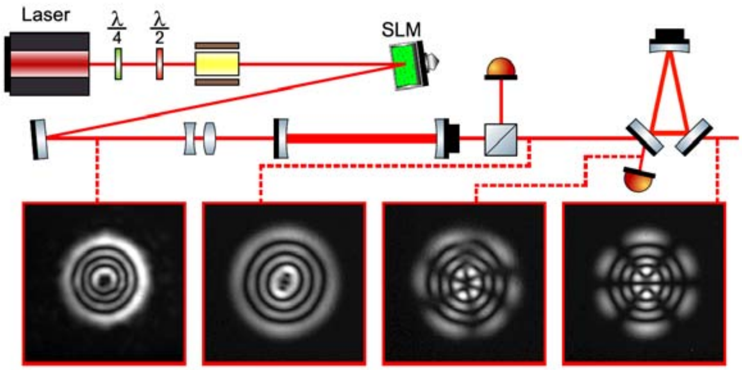
Optical-spring signal enhancement (USA)



Huge coating chamber for big mirrors (France)

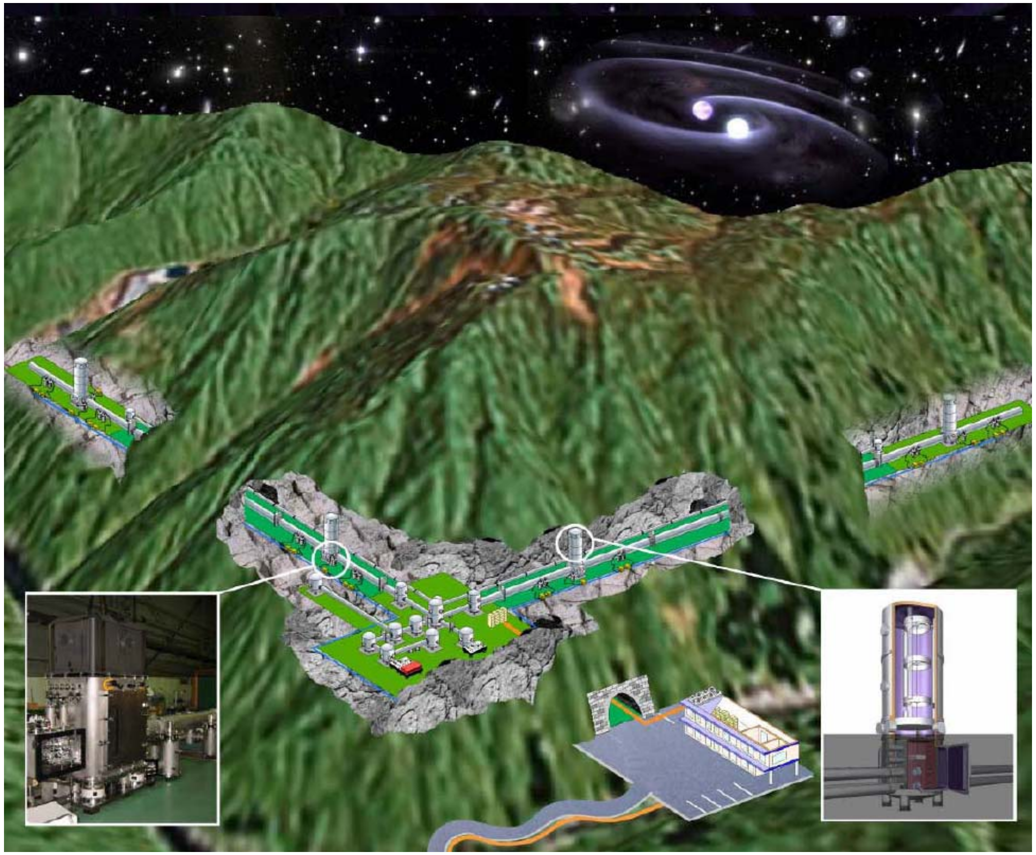


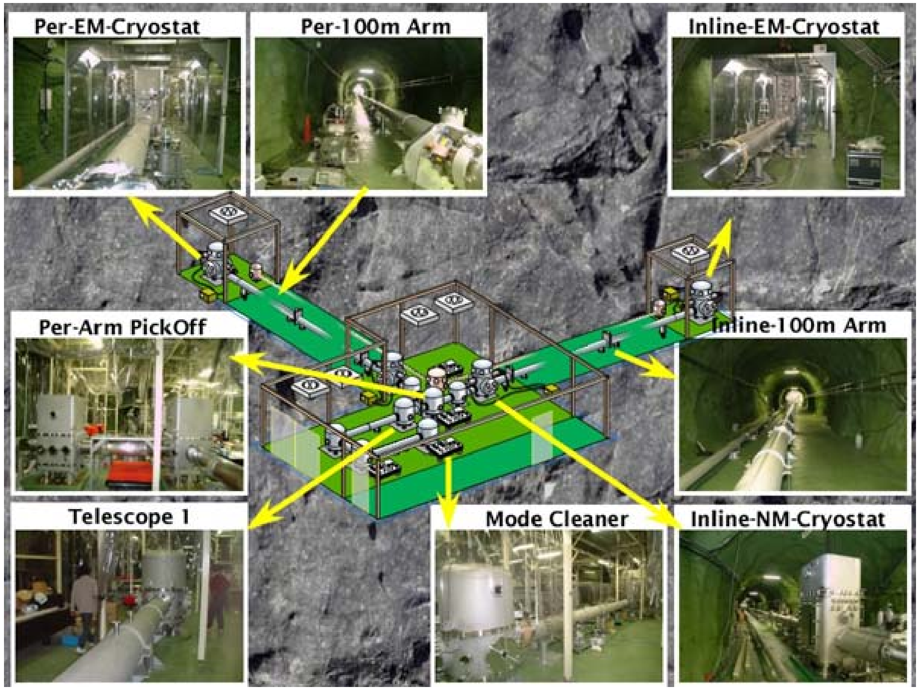
Squeezing (Germany)



Funny-shape beam to reduce thermal noise (UK, France)

Japanese cryogenic detectors



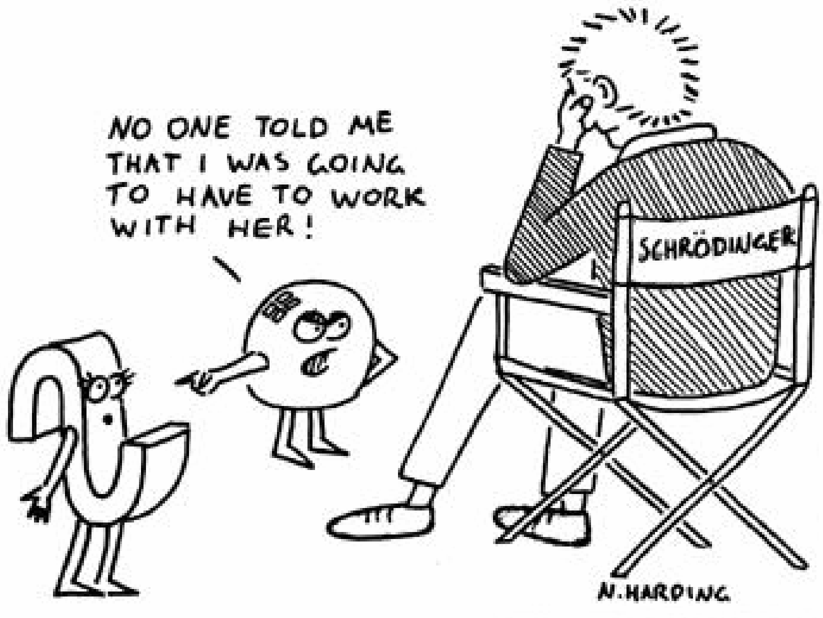


↑ 100m prototype CLIO

← 3km detector LCGT

- Sapphire mirrors cooled down to 20K
- Underground facility
- Quantum non-demolition techniques

GW detectors and Quantum Mechanics



Quantum Mechanics:

"All particles exhibit both wave and particle properties"

➡ Quantum uncertainty could be an issue in a GW detector.

Heisenberg's Uncertainty Principle

Quantum Mechanics tells us that the uncertainties of displacement x and momentum p satisfy

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

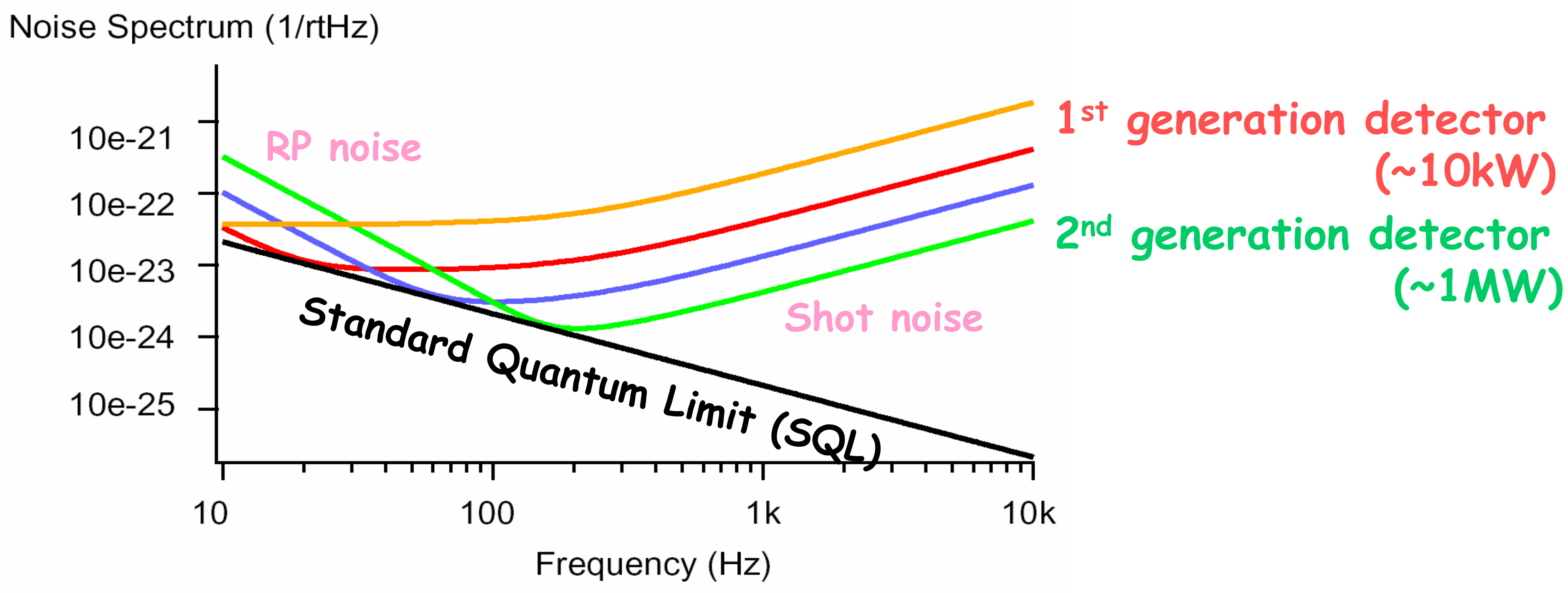
reduced Planck constant
(~1e-34 J*s)

This imposes the Standard Quantum Limit (SQL):

"If we try to increase the accuracy of measuring x, back action degrades the accuracy in later time."

$$\Rightarrow \quad \Delta x(\Omega) \geq \sqrt{\frac{2\hbar}{m\Omega^2}}$$

Quantum noise in GW detector



High precision → Heisenberg's principle → **Back action**

||

Reduction of shot noise (high power)

||

Radiation pressure noise

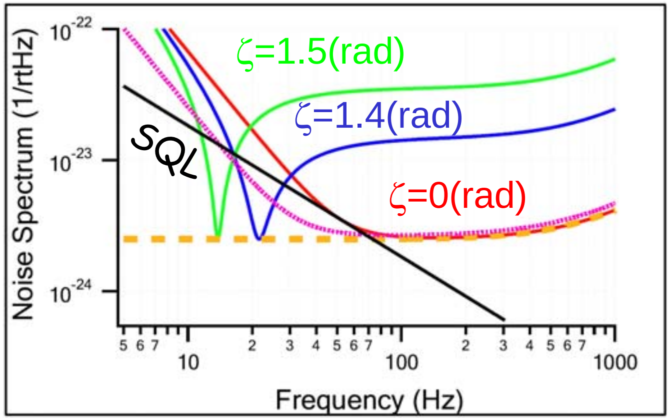
Sensitivity is limited by the SQL

There exist ways to overcome the limit

(1) Back-action evasion (BAE):

Measure amplitude vacuum fluctuation to compensate radiation pressure noise

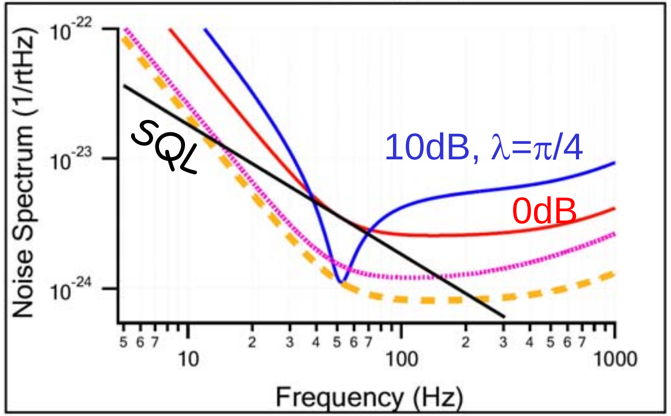
Quantum control



(2) Squeeze injection:

Change the balance of amp and phase fluctuations using non-linear crystal

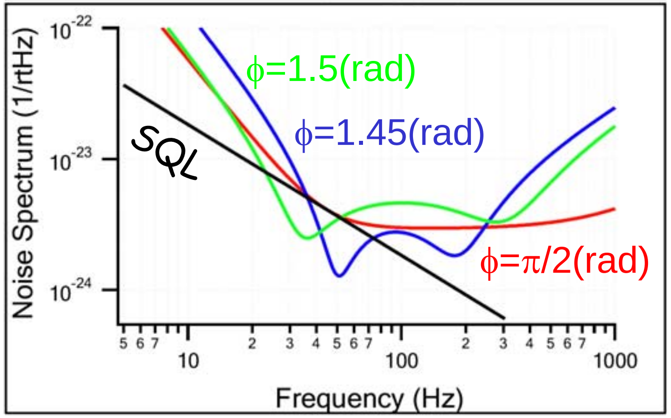
Application of quantum optics



(3) Optical spring:

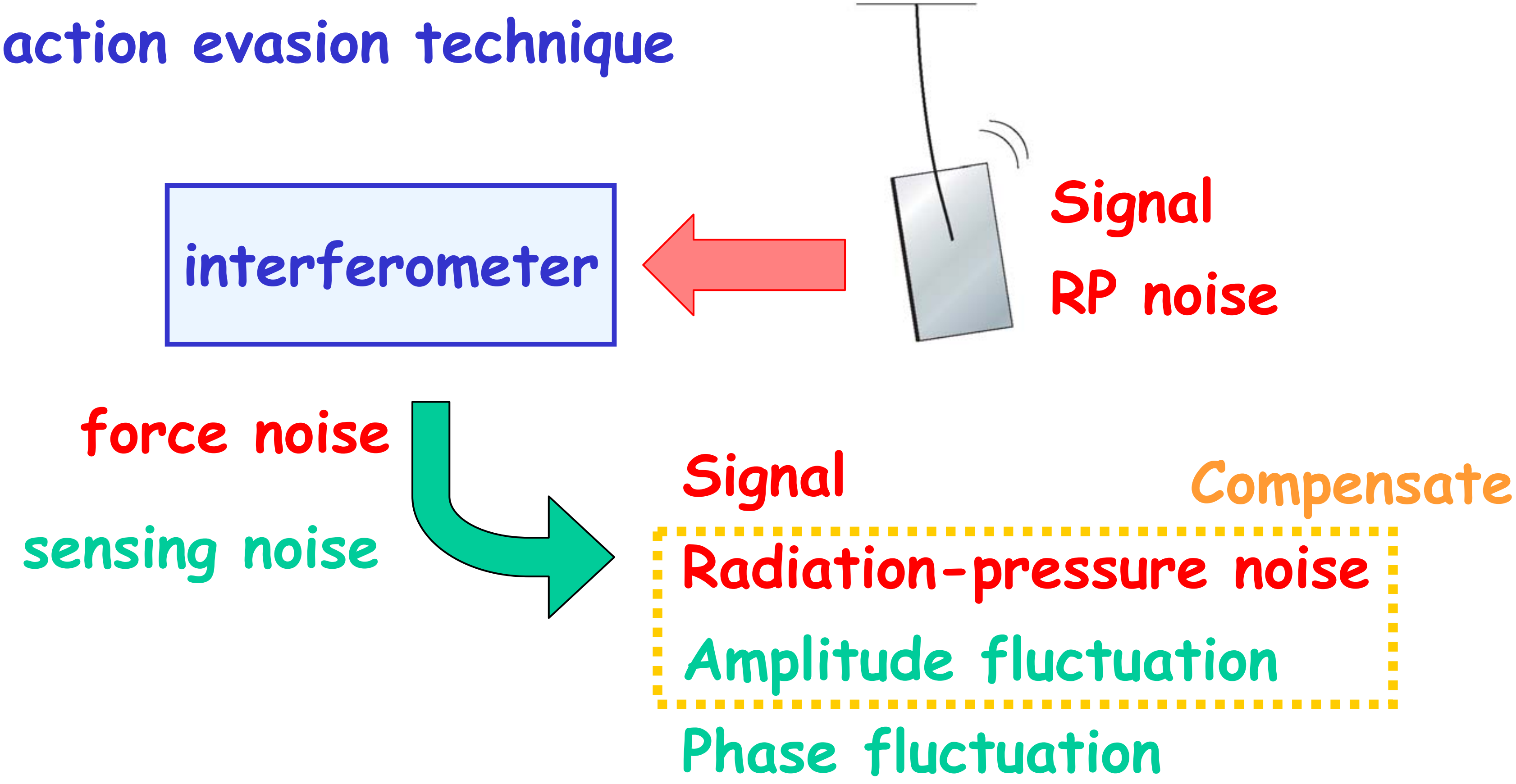
Re-inject the output field to the IFO to create a spring that enhances the susceptibility to gravitational waves

Optomechanical coupling



Why can we overcome the SQL?

ex.) back-action evasion technique



interferometer

Signal

RP noise

force noise

sensing noise

Signal

Compensate

Radiation-pressure noise

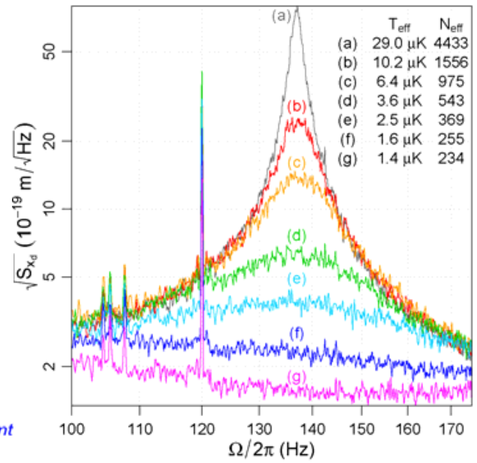
Amplitude fluctuation

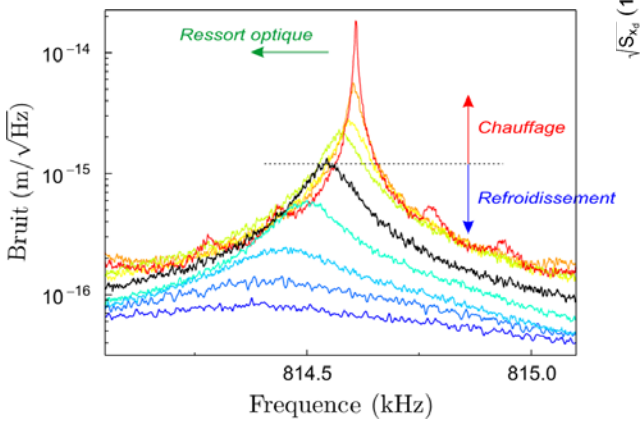
Phase fluctuation

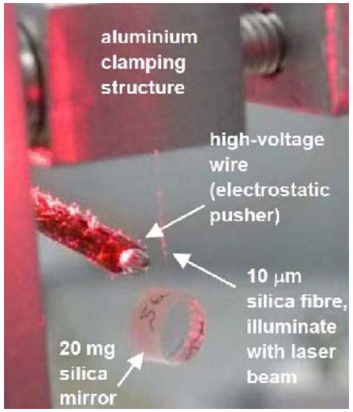
- We can try not to see the mirror motion (BAE)
- Or the mass moves more for the same force (Optical spring)

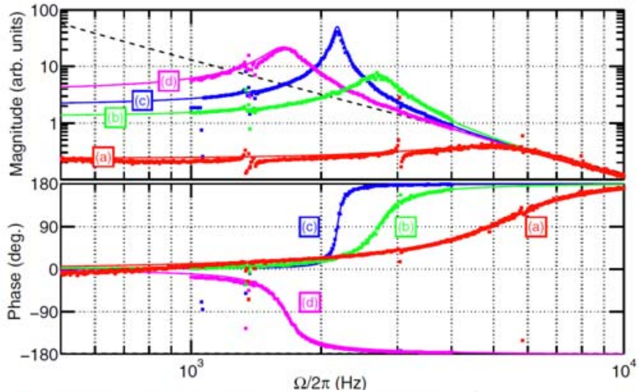
R&D experiments to see the quantum behavior

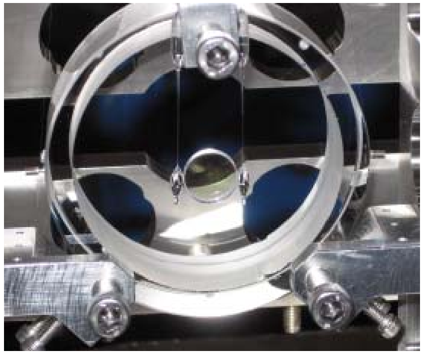
from right top to the left bottom
LIGO cooling, 20mg suspension, 10ng cantilever
LKB cooling, 1pg NEMS, 10ng membrane,
MIT 1g suspension, AEI 10m vacuum, MIT double optical spring, AEI 10m sensitivity

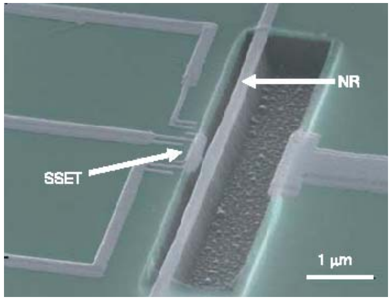


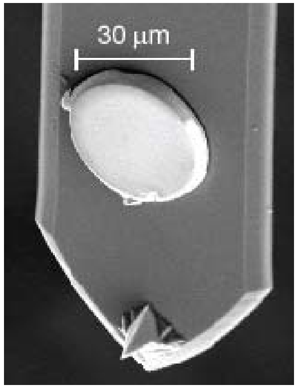


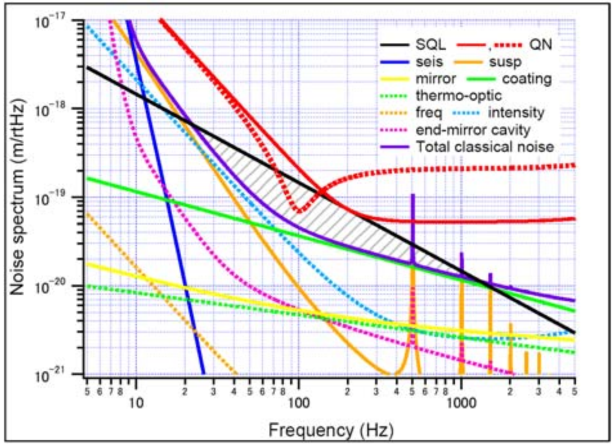




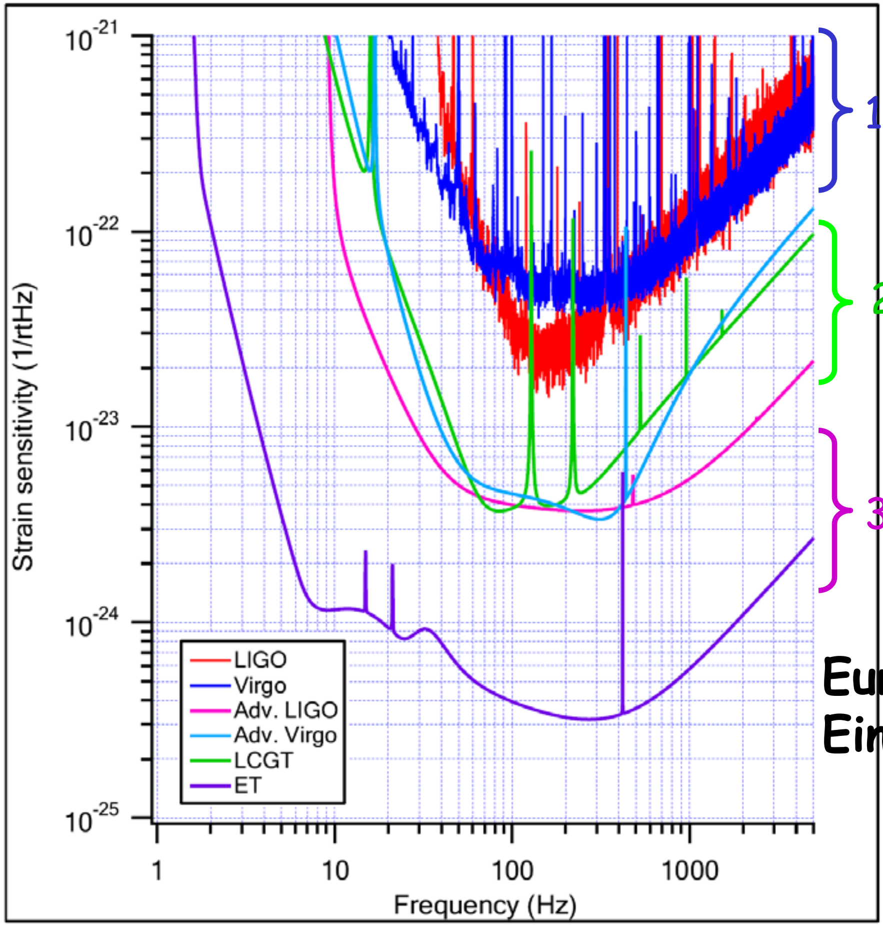








3rd generation and space detectors

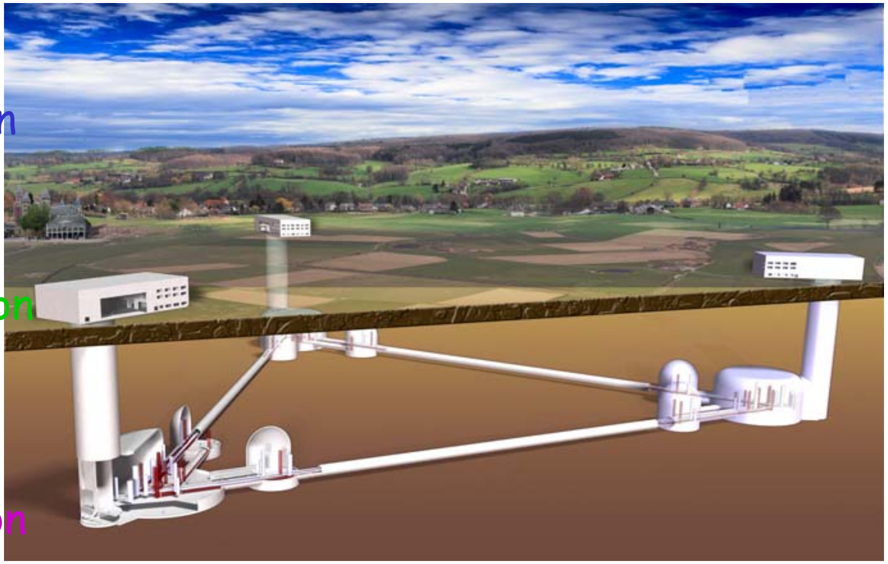


1st generation

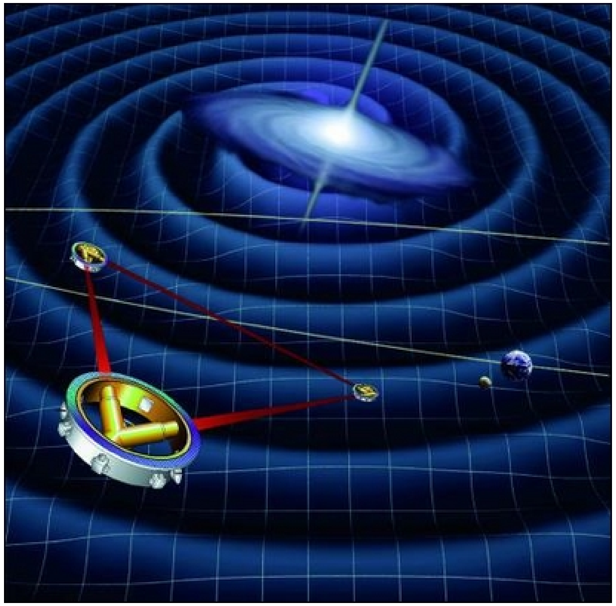
2nd generation

3rd generation

Sensitivities of the 1~3G detectors



European 3G detector
Einstein Telescope
(2025~?)



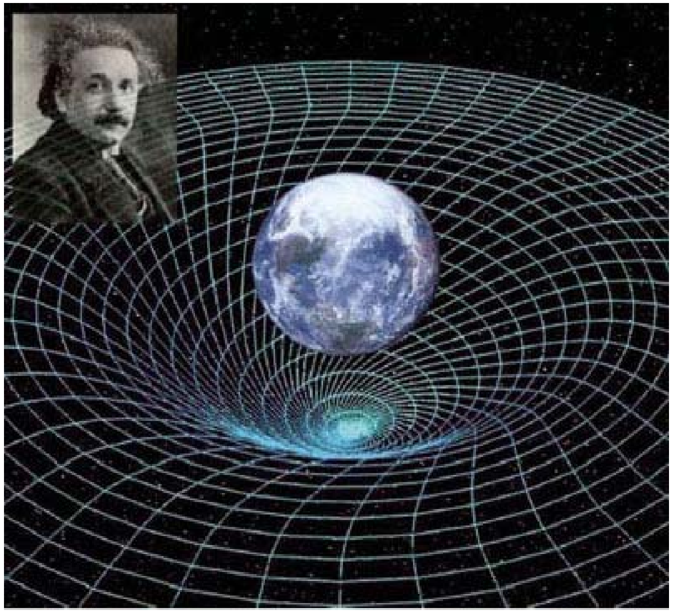
Space telescope LISA
(2030~?)

Summary

- 1st generation detectors observed no GW signals but proved that we can achieve such high-sensitivity.
- Various advanced techniques are to be equipped in 2nd and 3rd generation detectors.
- We can even achieve the sensitivity better than the quantum limit imposed by the uncertainty principle.

supplementary slides

Gravitational waves



Newton's gravity
"attracting force btw apple and earth"

Einstein's gravity
"free fall in a curved space-time"

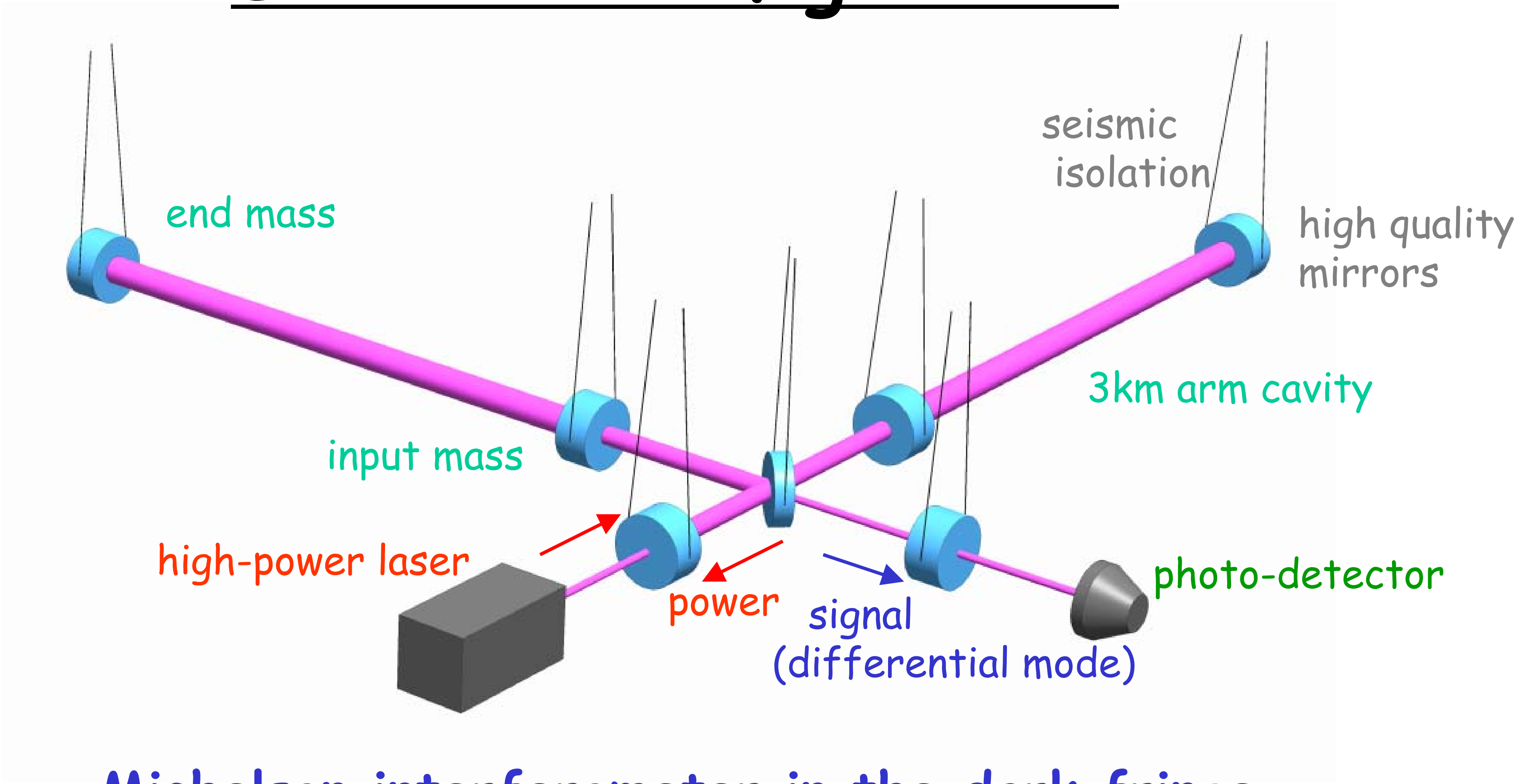
↓

"Dynamic change of the space-time
will propagate as a wave"

Prediction of GW
by Einstein

(1916)

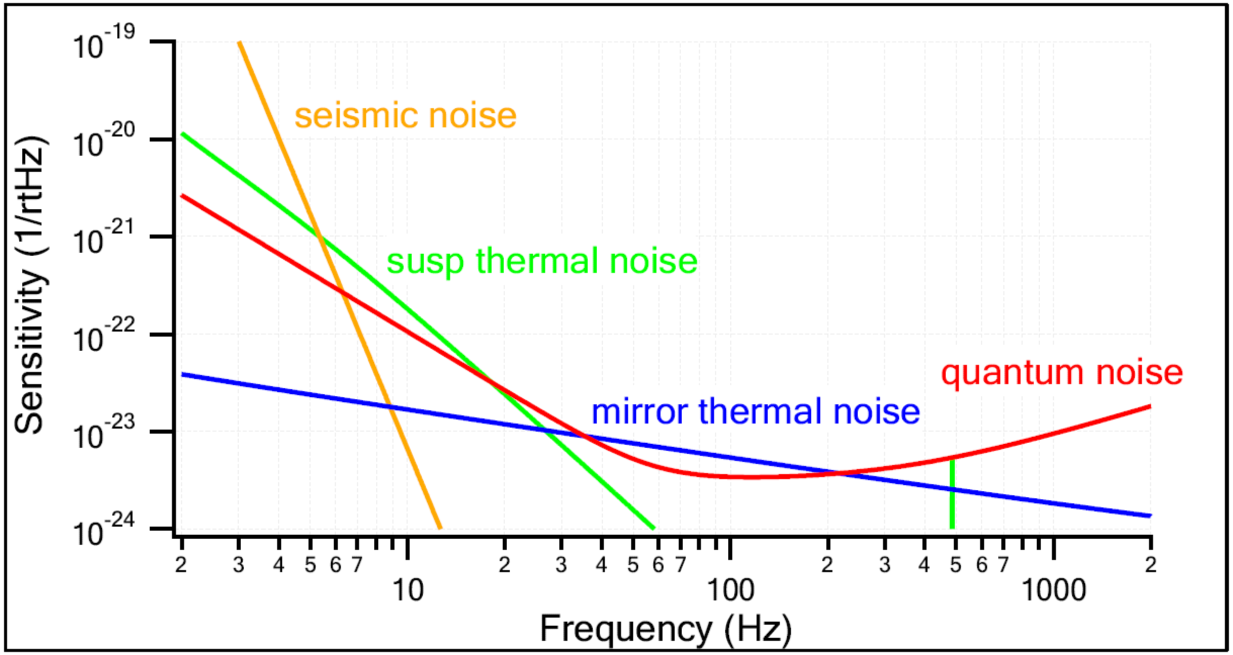
Detector configuration

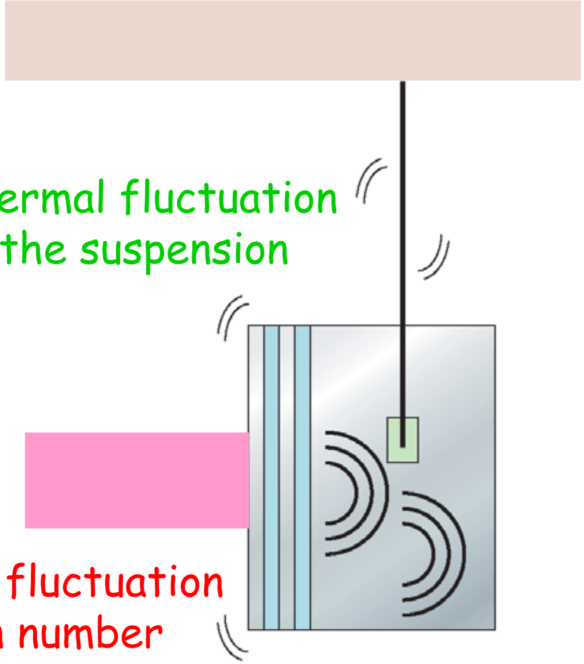


- Michelson interferometer in the dark fringe
- Optical resonators to enhance power/signal
- High quality mirrors to lower thermal fluctuations

Sensitivity of the detector

Typical sensitivity spectrum of a 2G detector (300K)





Seismic motion

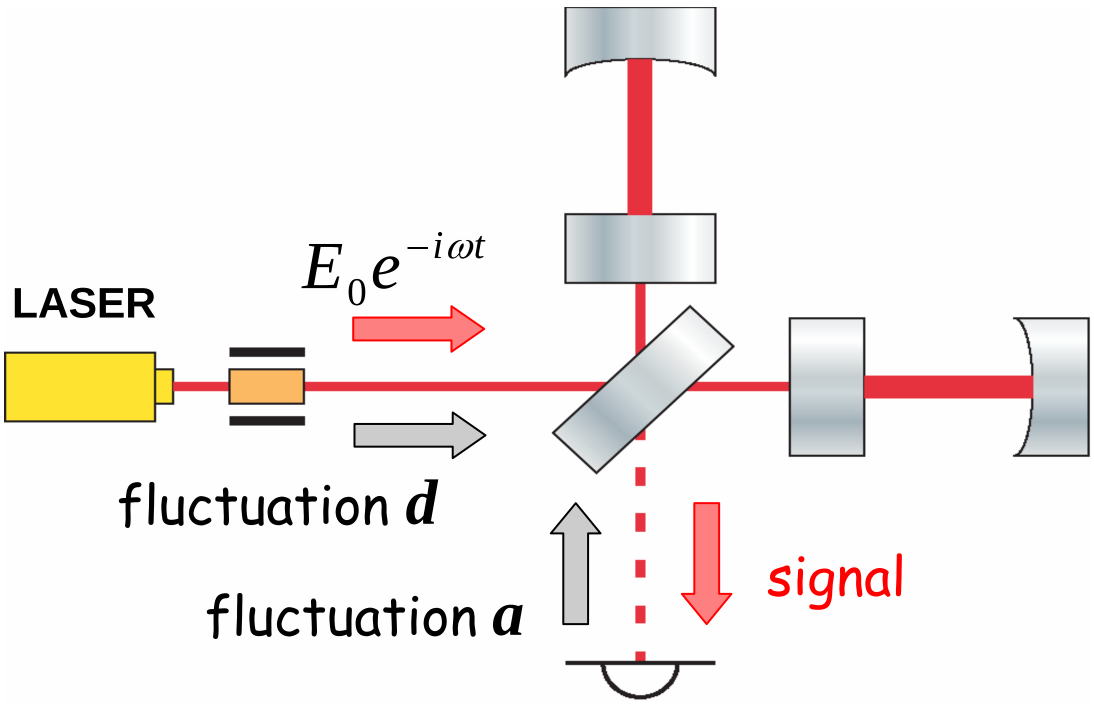
Thermal fluctuation of the suspension

Quantum fluctuation of photon number and phase

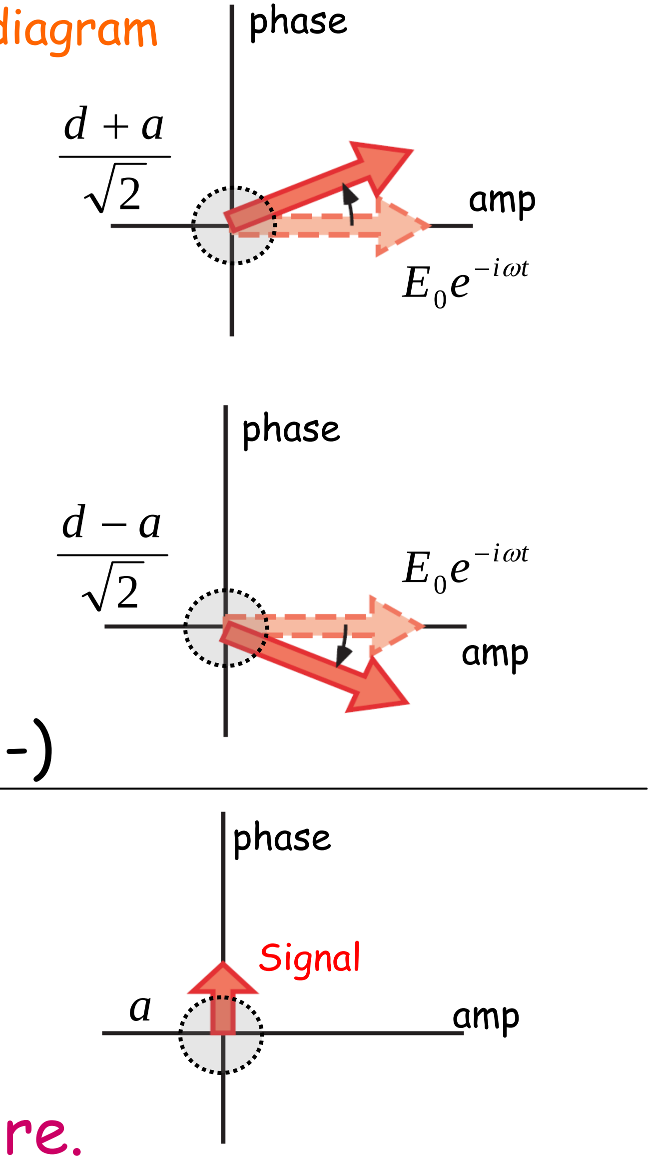
Thermal fluctuation of the mirror

- Seismic noise at low frequencies
- Thermal noise at middle frequencies
- Quantum noise at middle-high frequencies

Quantum noise

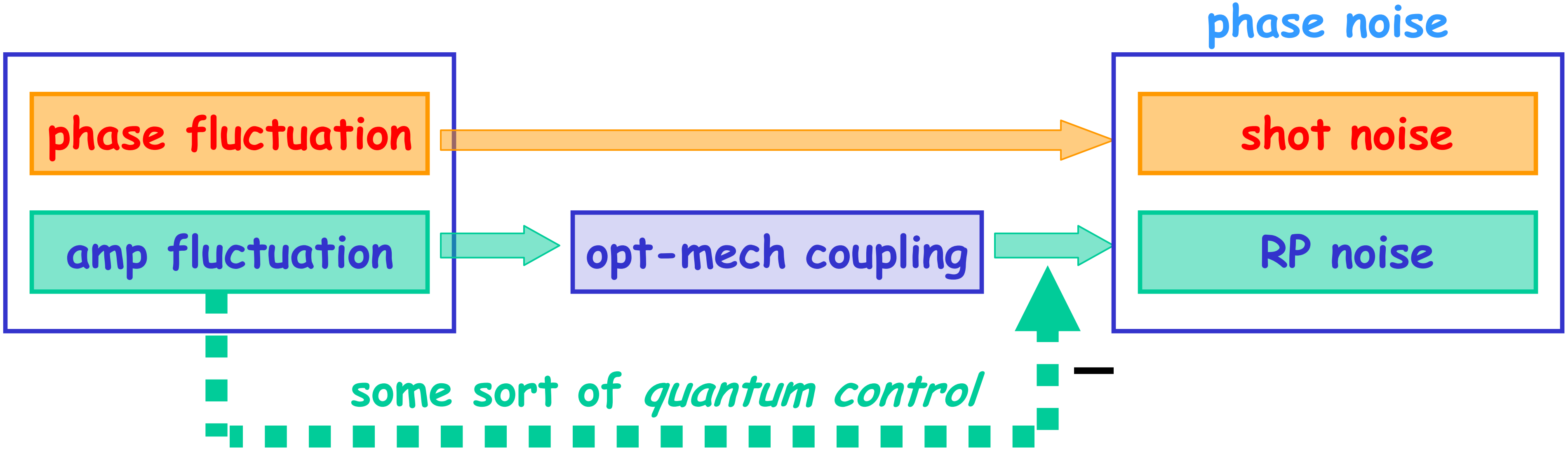


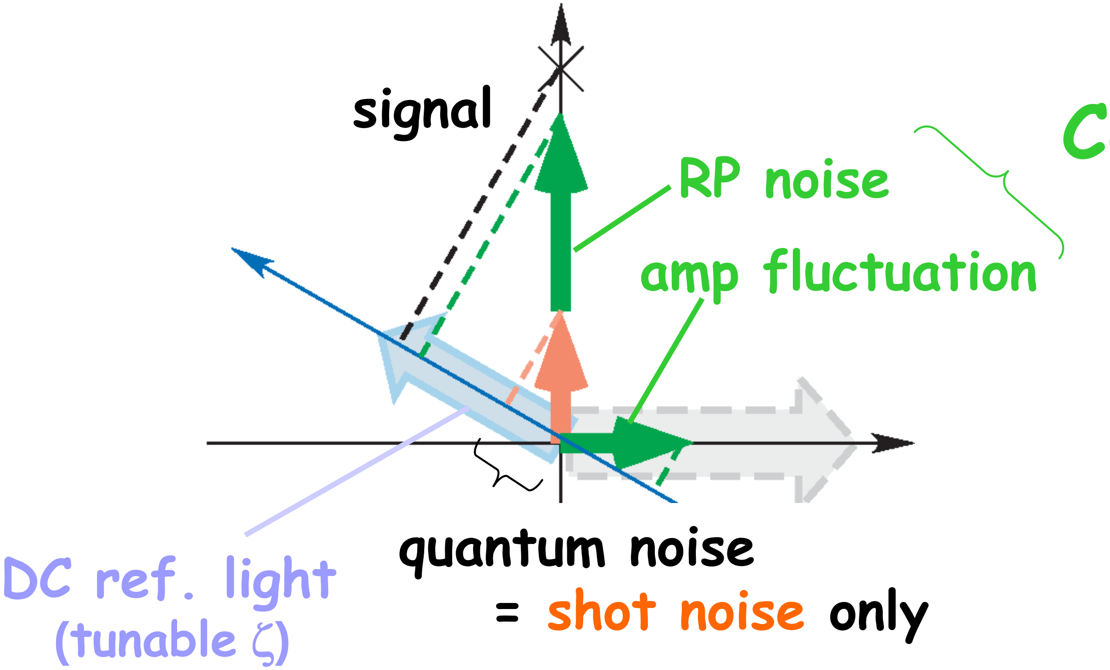
Phasor diagram



- Vacuum fluctuations entering from the signal extraction port is the noise source.
- The noise level corresponds to ½ photon.
- SNR is determined on the phase quadrature.

BAE = quantum control



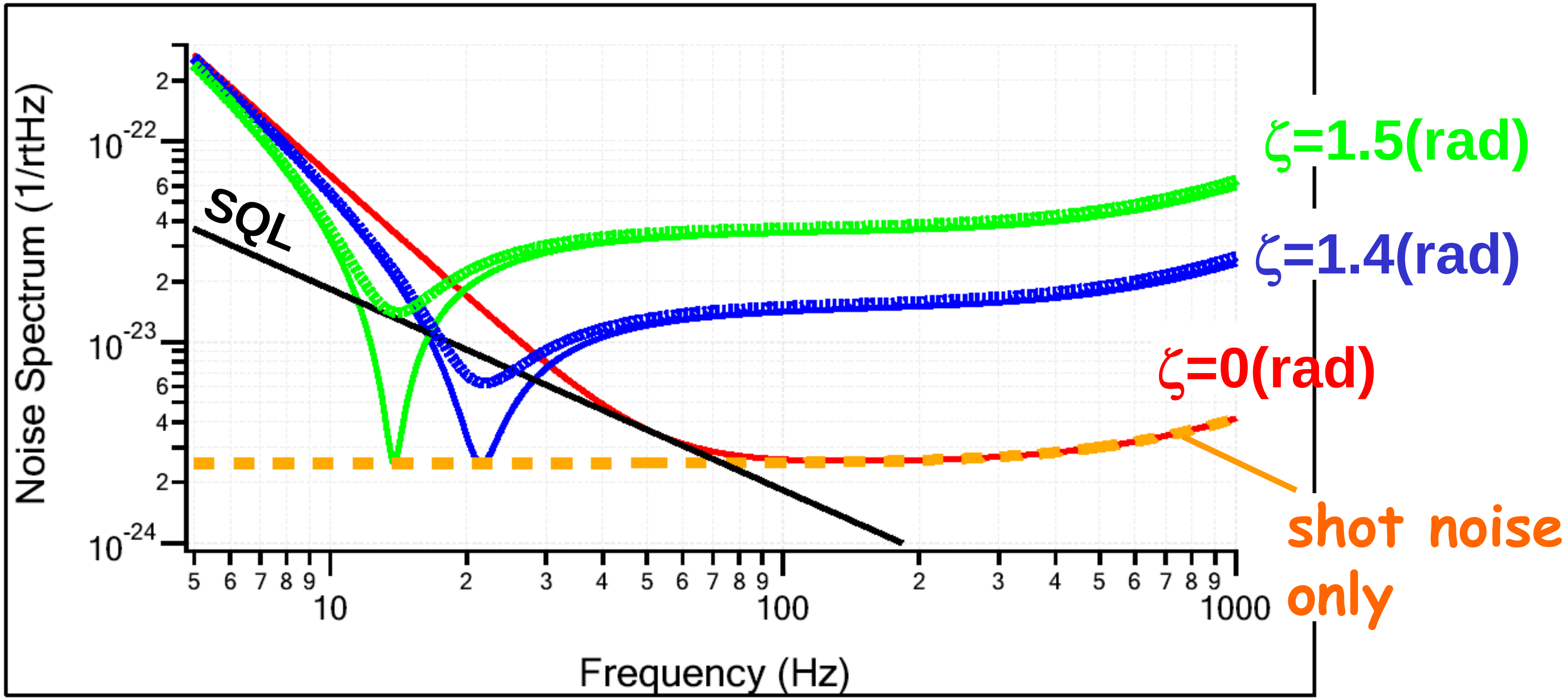


quantum noise
= shot noise only

Cancellation at
a single measurement
||
Quantum control

Sensitivity with BAE technique

solid : lossless, dashed : w/loss



- SQL can be overcome at around a certain frequency
- Optical loss is critical when ζ is far from 90 deg