Quantum noise reduction for the third-generation GW detector

YKIS
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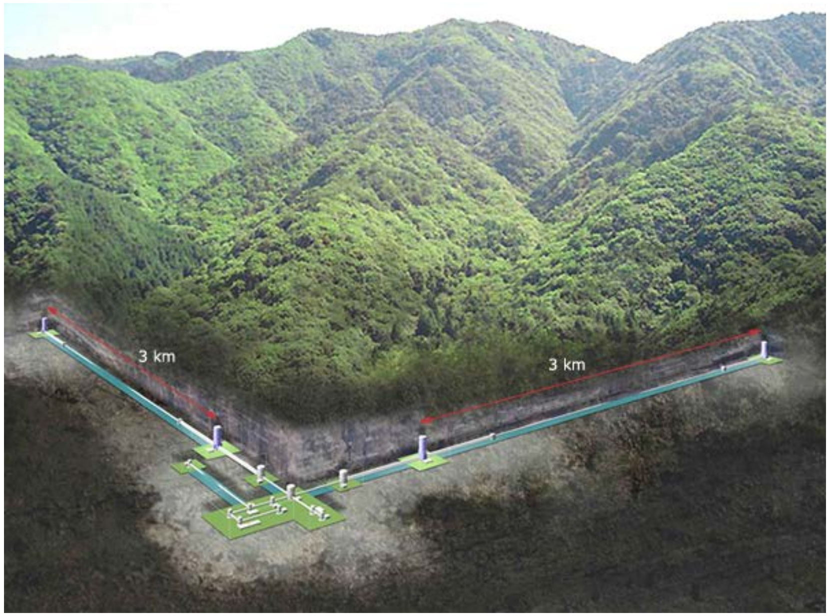
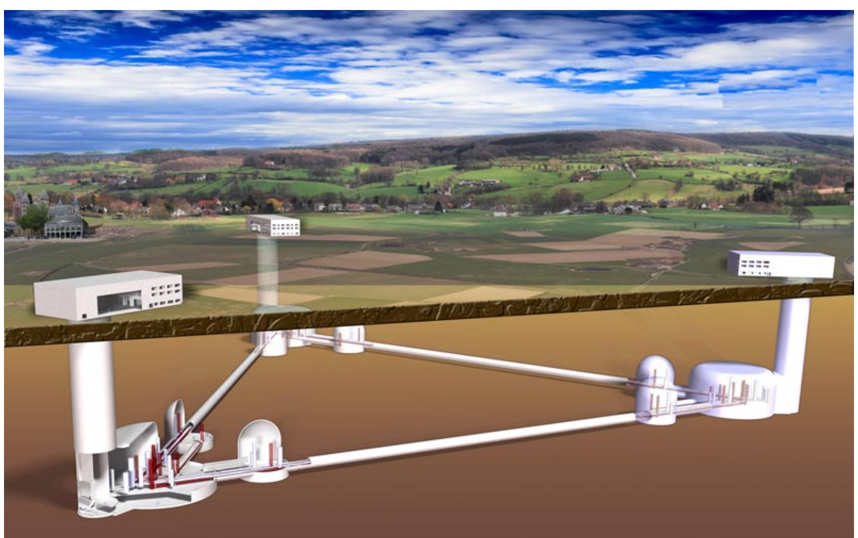
2nd generation to 3rd generation





2000-10: 1G detectors
TAMA, LIGO, Virgo, GEO

2015-25: 2G detectors
aLIGO, AdV, GEO-HF, KAGRA

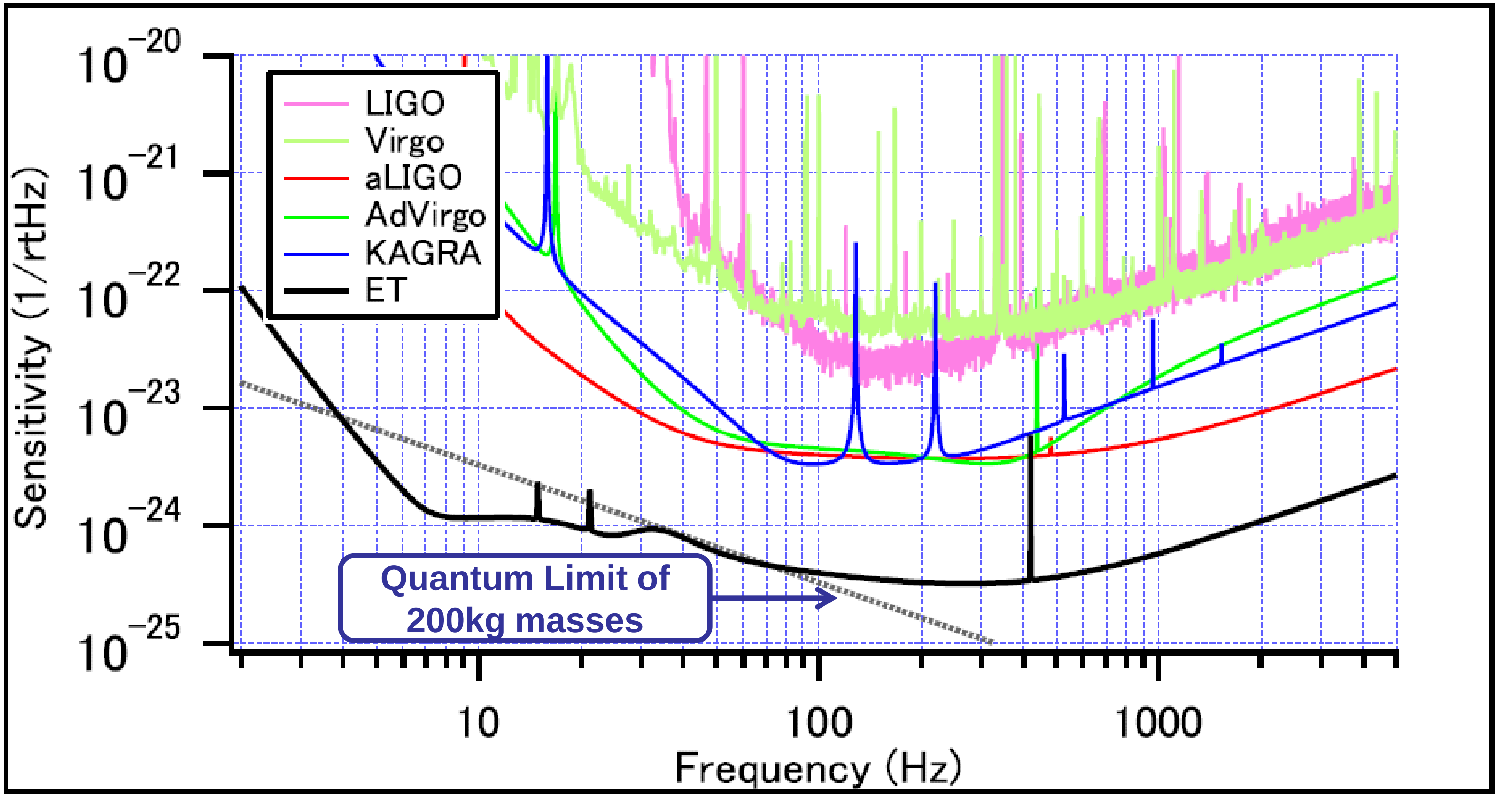
2030- : 3G detectors
ET, LIGO3

2030- : Space detectors
LISA, DECIGO

2nd generation to 3rd generation

	aLIGO	KAGRA	ET-LF
Baseline	4km	3km	10km
Facility	On ground	Underground	Underground
Test mass	40kg Silica	23~30kg Sapphire	~200kg Silicon
Laser	1064nm	1064nm	1550nm
Temperature	290K	20K	10K

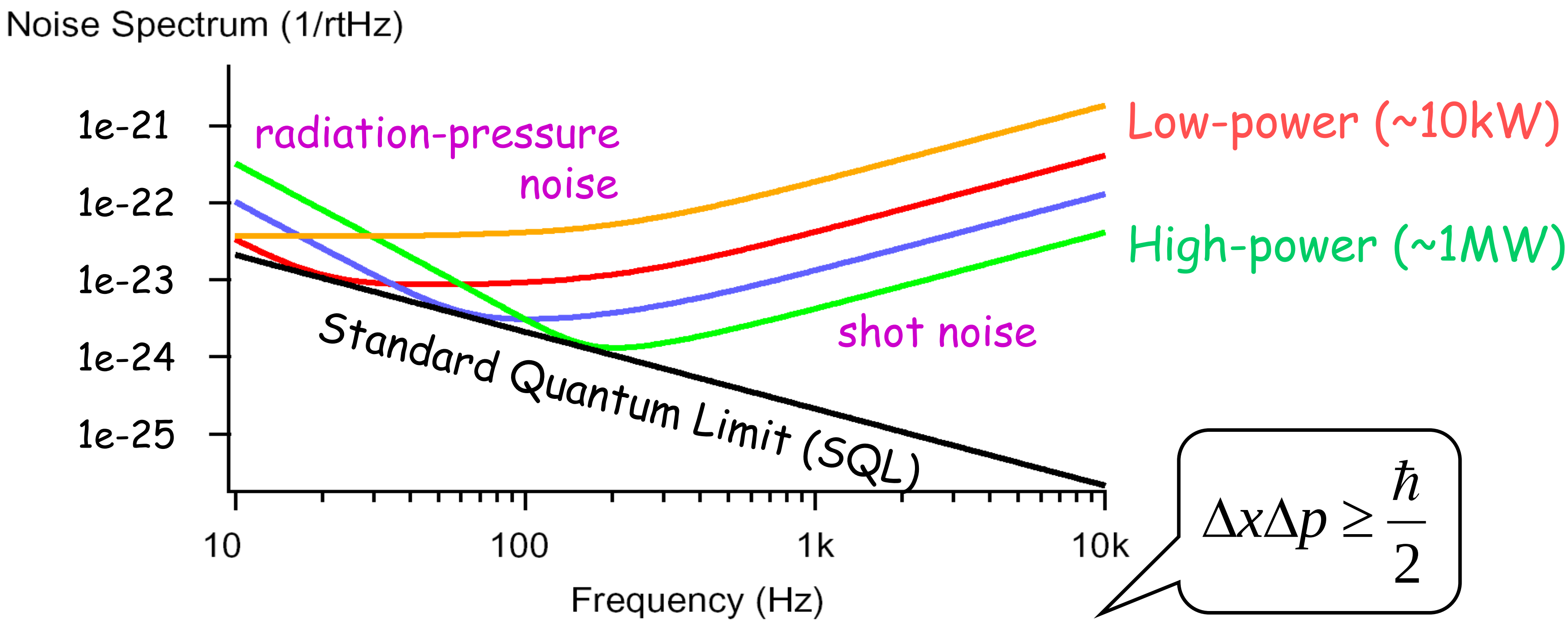
2nd generation to 3rd generation



ET sensitivity exceeds the limit determined by Heisenberg's Uncertainty Principle.

* KAGRA also exceeds the limit of its 23kg masses.

Standard Quantum Limit (SQL)



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

High precision → Back action

Uncertainty Principle

||

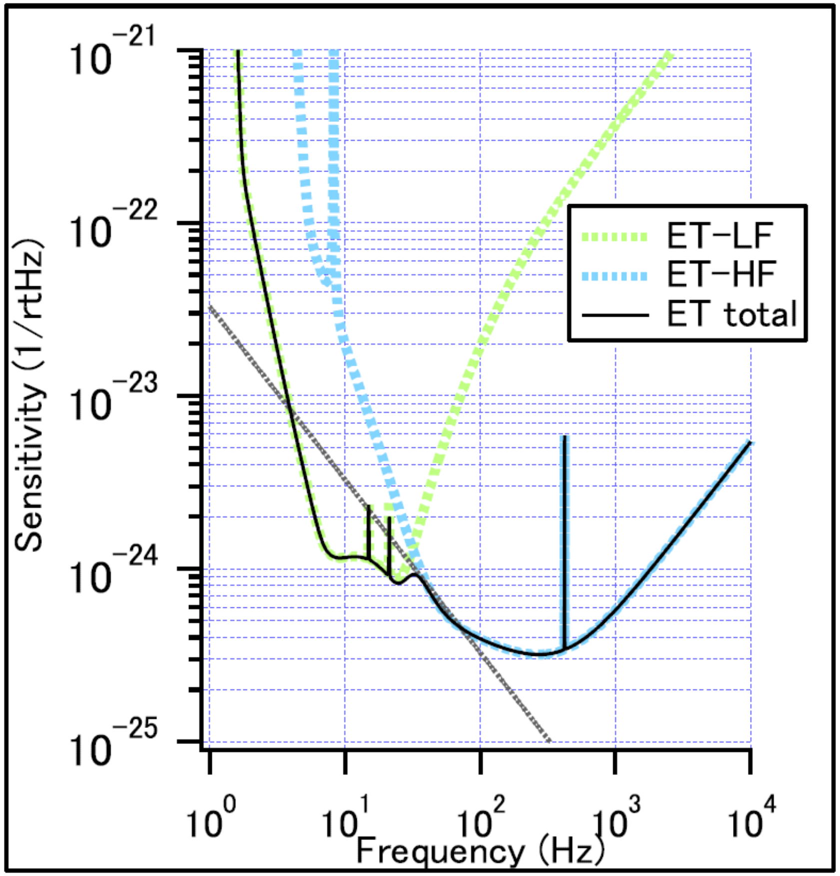
Shot noise reduction with more power in the detector

||

Radiation pressure moves the mirror away

The limit cannot be exceeded just by increasing the power.

How does ET beat the limit?



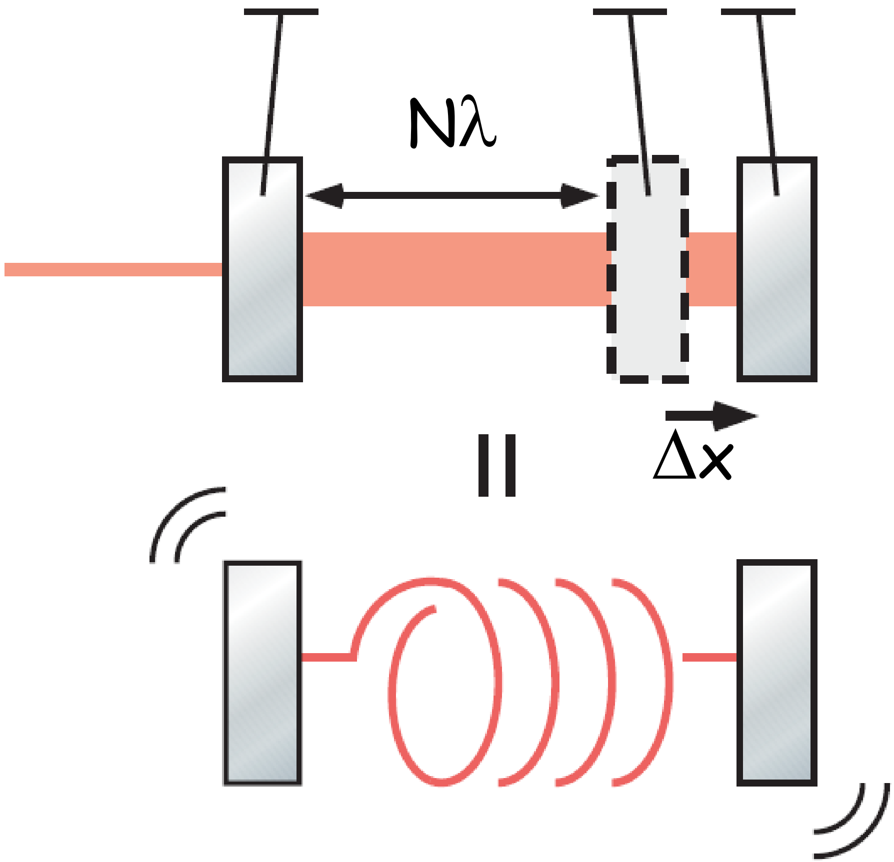
ET-LF: 20K, low power
ET-HF: 290K, high power

- ET is composed of 2 detectors: one at 290K and one at 20K
- Each of them beats the SQL with **freq-dependent squeezing**
- 20K ET-LF exceeds the SQL more for its **optical spring** (KAGRA employs the same technique)

2 important techniques to beat the SQL

Optical spring

[Buonanno and Chen (2001)]



Cavity is detuned from the resonance

Go further from the resonance

>> Less radiation pressure (pull)

Come closer from the resonance

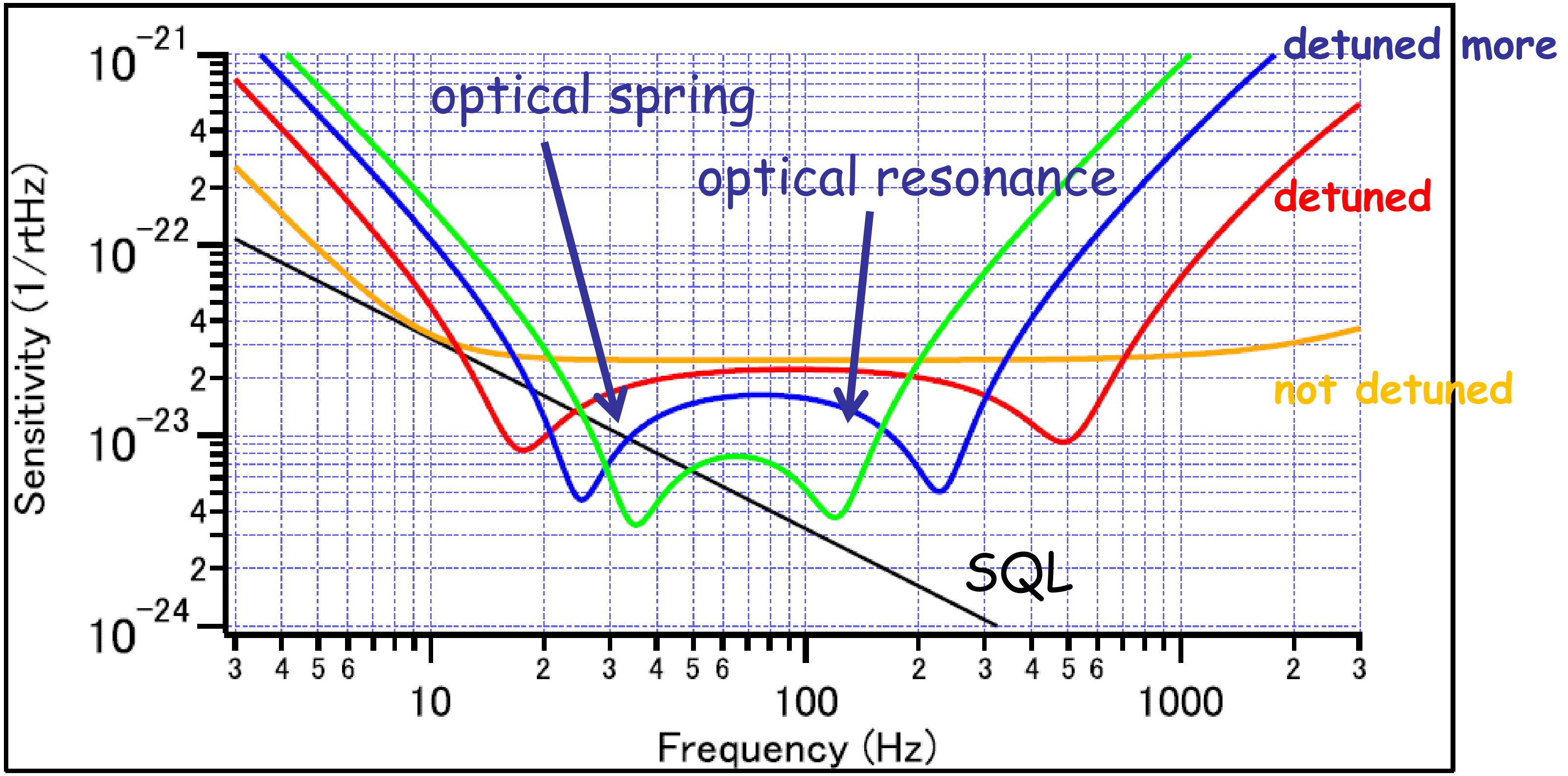
>> More radiation pressure (push)

Optical spring is created

Signal enhancement at the spring frequency

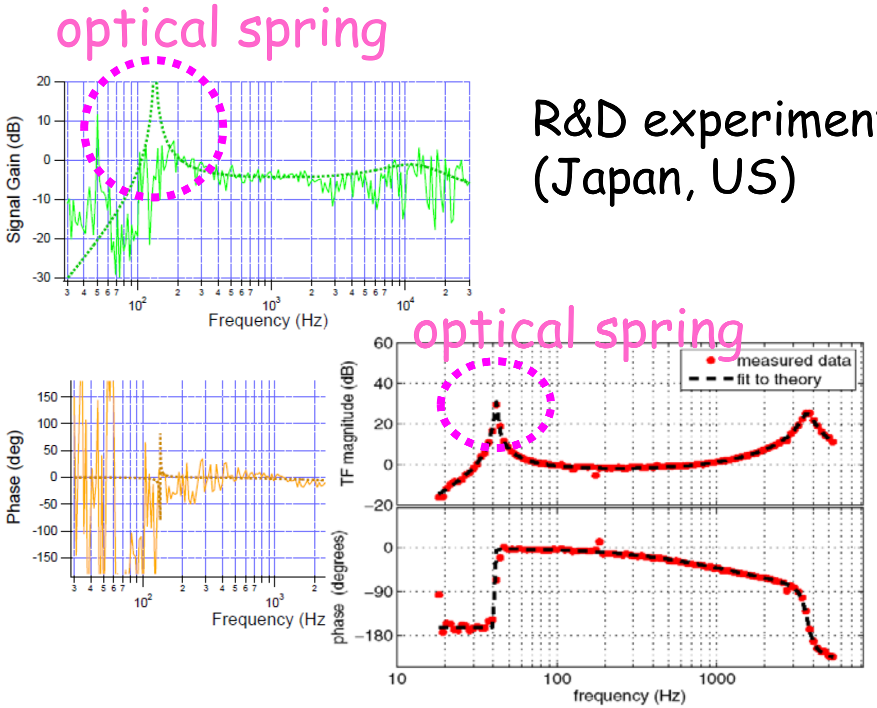
Optical spring

[Buonanno and Chen (2001)]



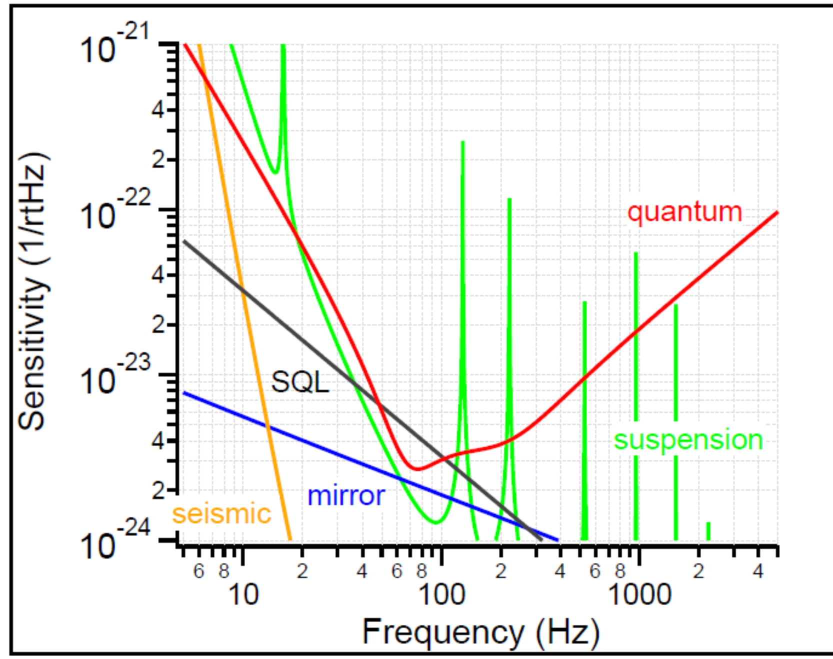
Sensitivity is given for force F_{GW}, not for displacement x.
-> SQL can be beaten at around the spring frequency.

Optical spring



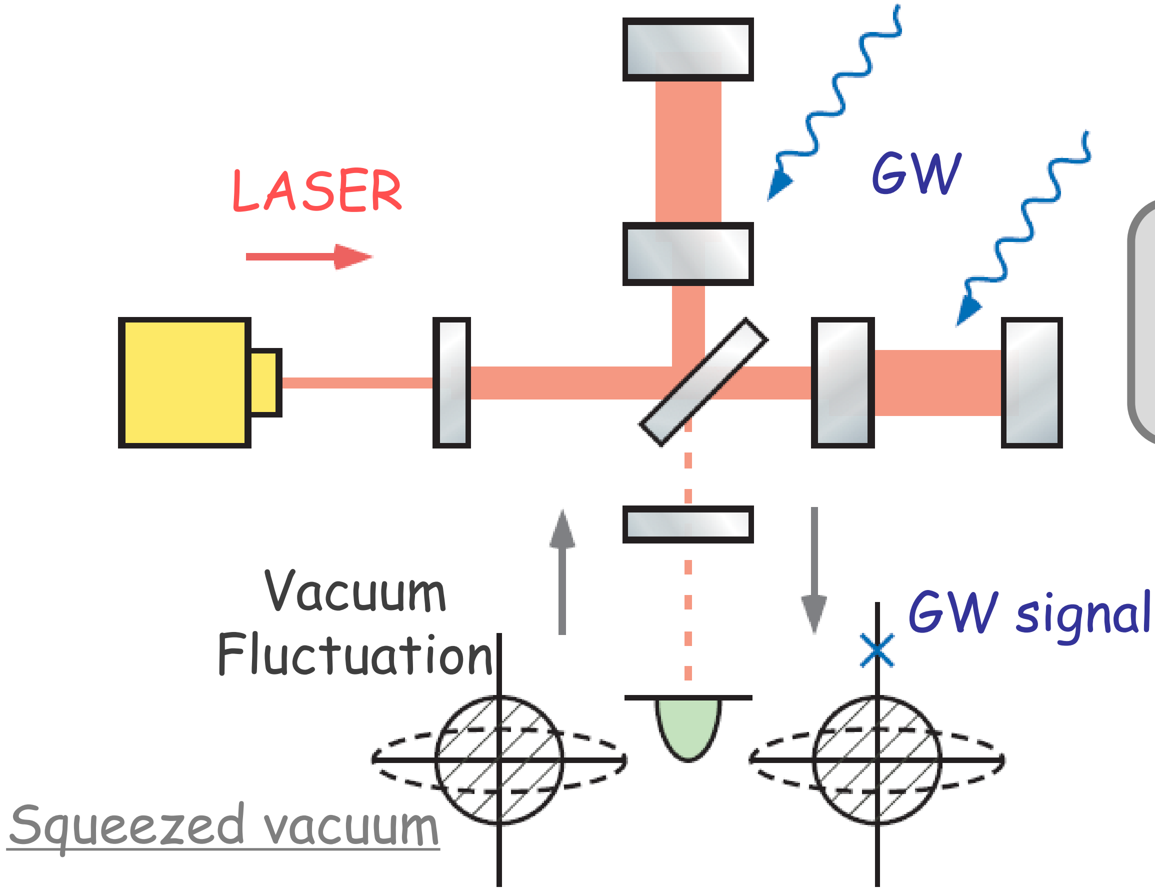
R&D experiments
(Japan, US)

KAGRA design sensitivity



Optical spring is ready to be used in 2G detectors.
(AdVirgo, KAGRA)

Squeezing

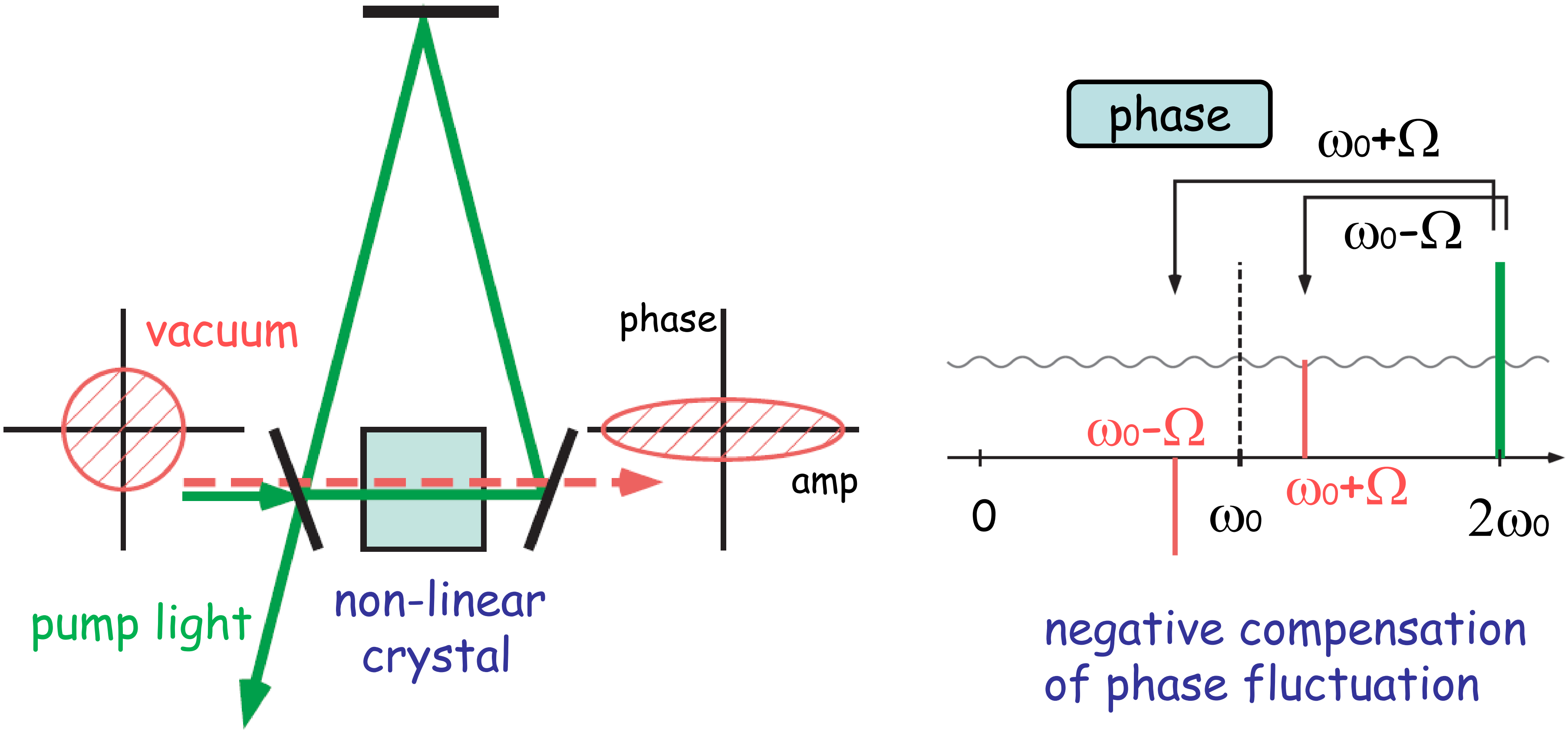


Photon's phase noise by vacuum fluctuation

Shot noise

Squeezing of the vacuum reduces phase noise
-> equivalent to the power increase

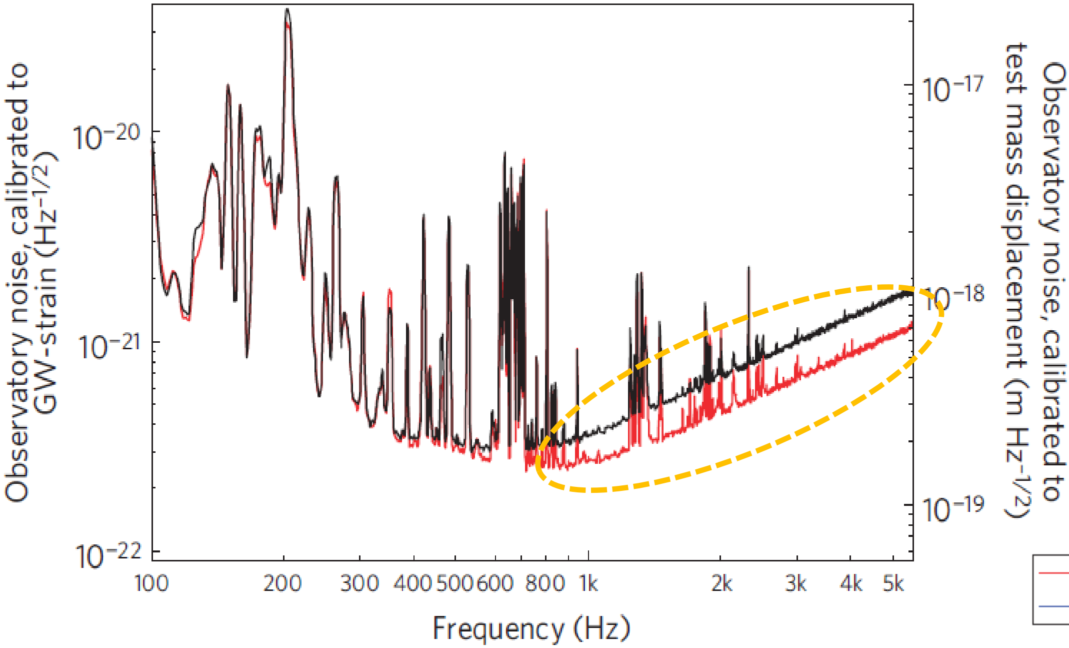
Squeezing

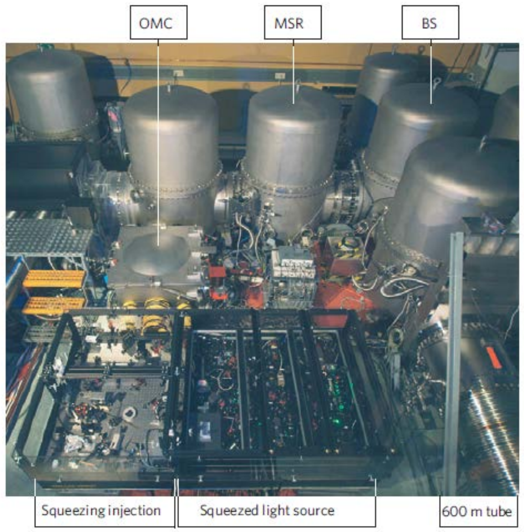


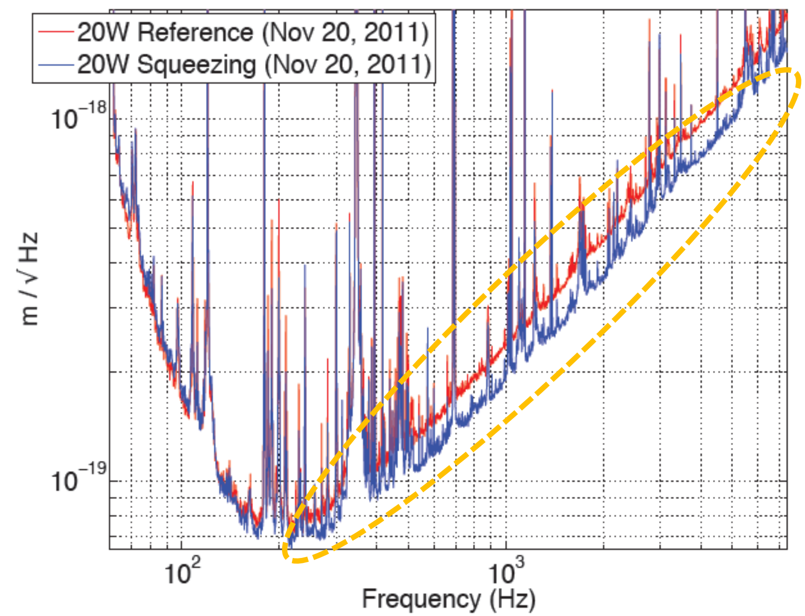
negative compensation
of phase fluctuation

Phase fluctuation is reduced by the non-linear crystal

Squeezing in GEO/LIGO





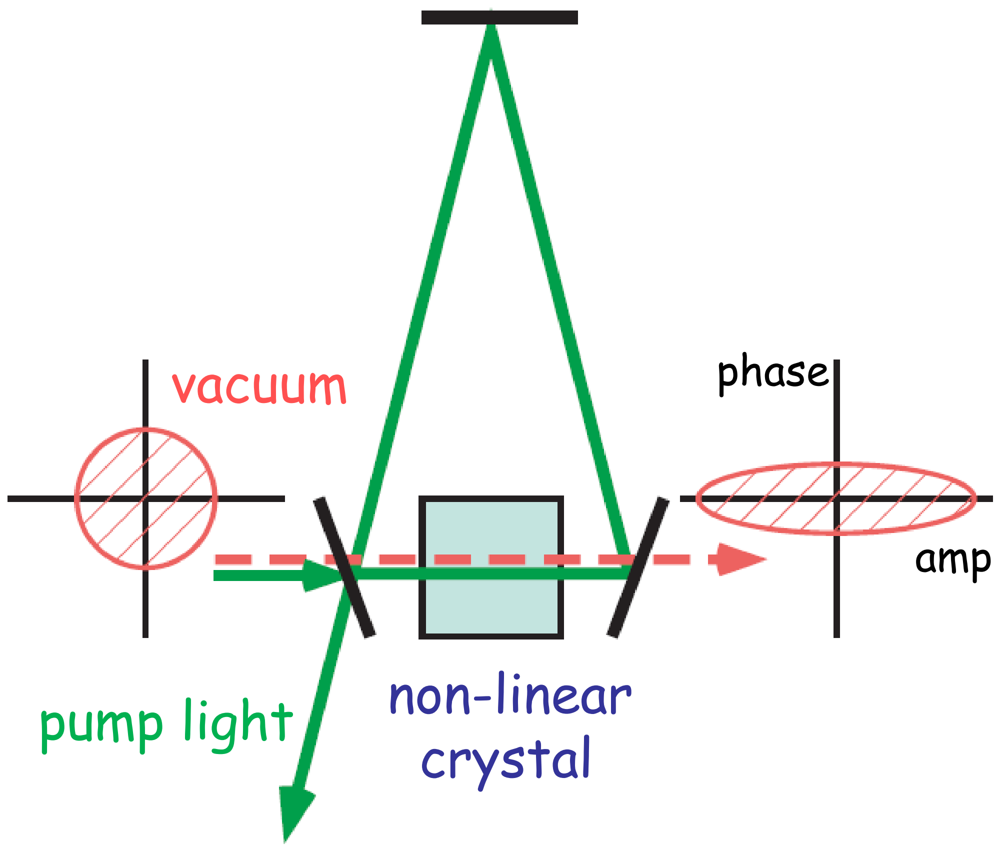


3.5dB squeezing above 500Hz in GEO

2dB squeezing above 200Hz in LIGO

[LSC, Nature Phys 2083]
[Barsotti, LIGO-G1101263]

Squeezing in high-power detectors



phase fluctuation of vacuum

⇩

shot noise

amplitude fluctuation of vac.

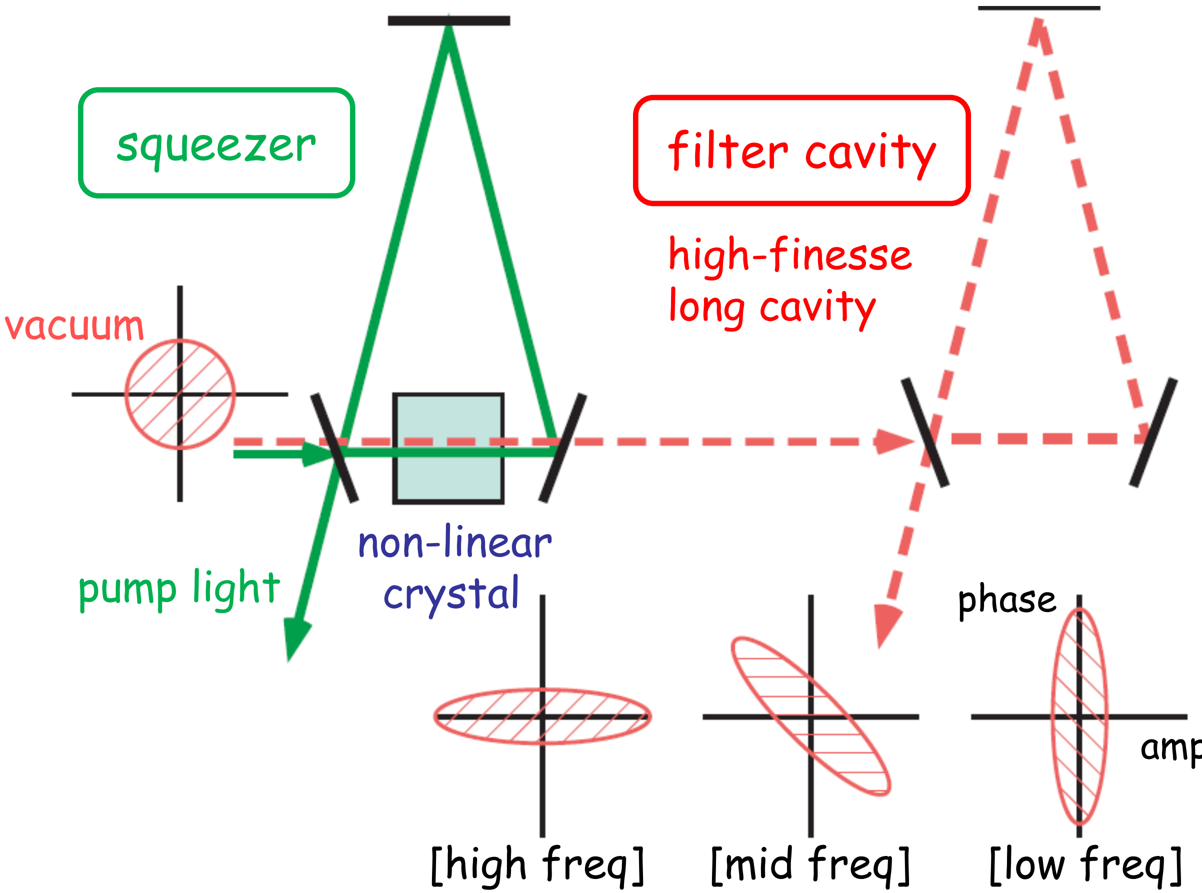
⇩

radiation pressure noise (RPN)

In high-power detectors, increase of RPN is not good...

Frequency-dependent squeezing

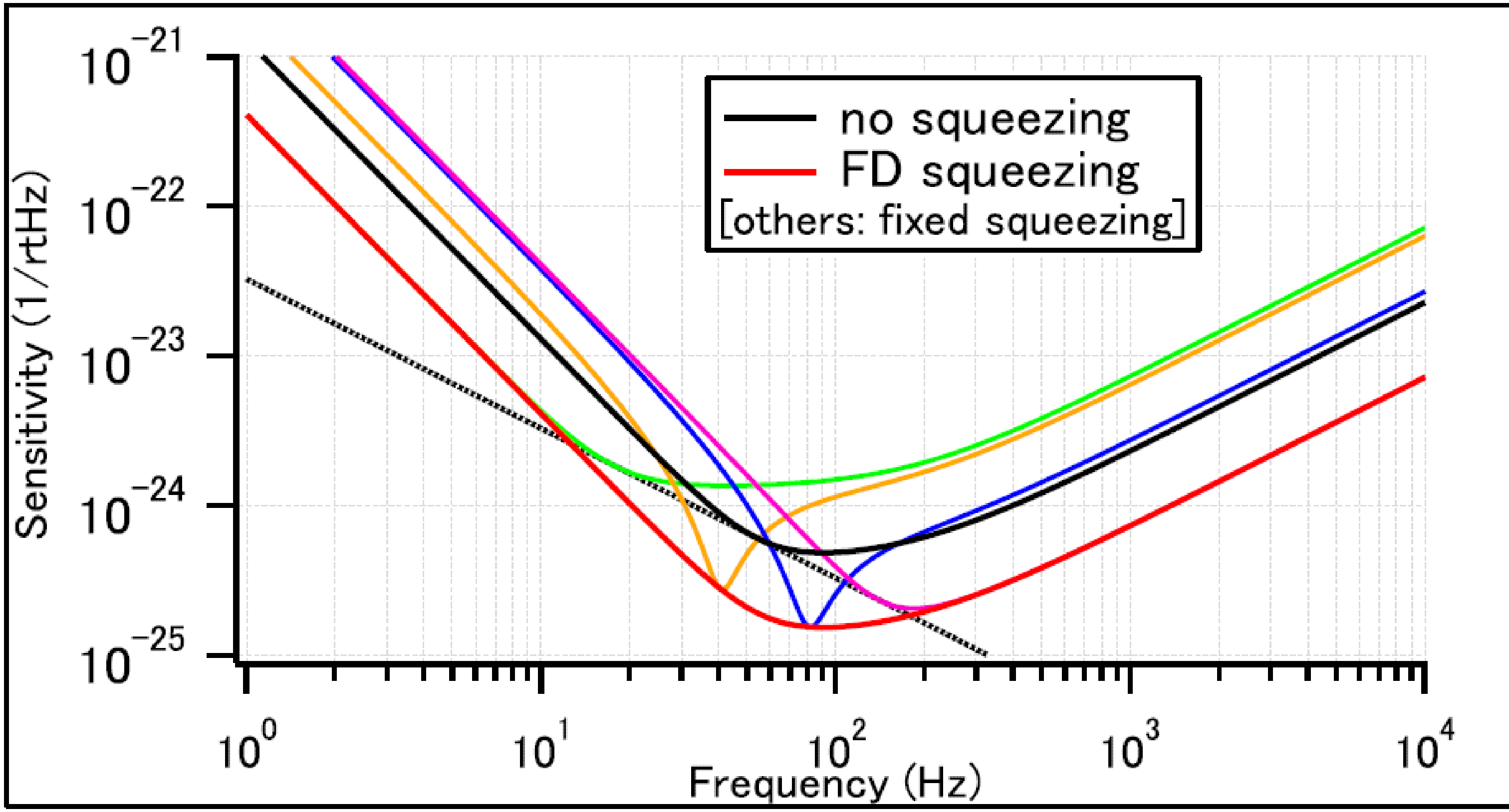
[Kimble et al (2001)]
[LIGO-T1200024]



Low shot noise at high freq and low RPN at low freq.

Sensitivity with FD squeezing

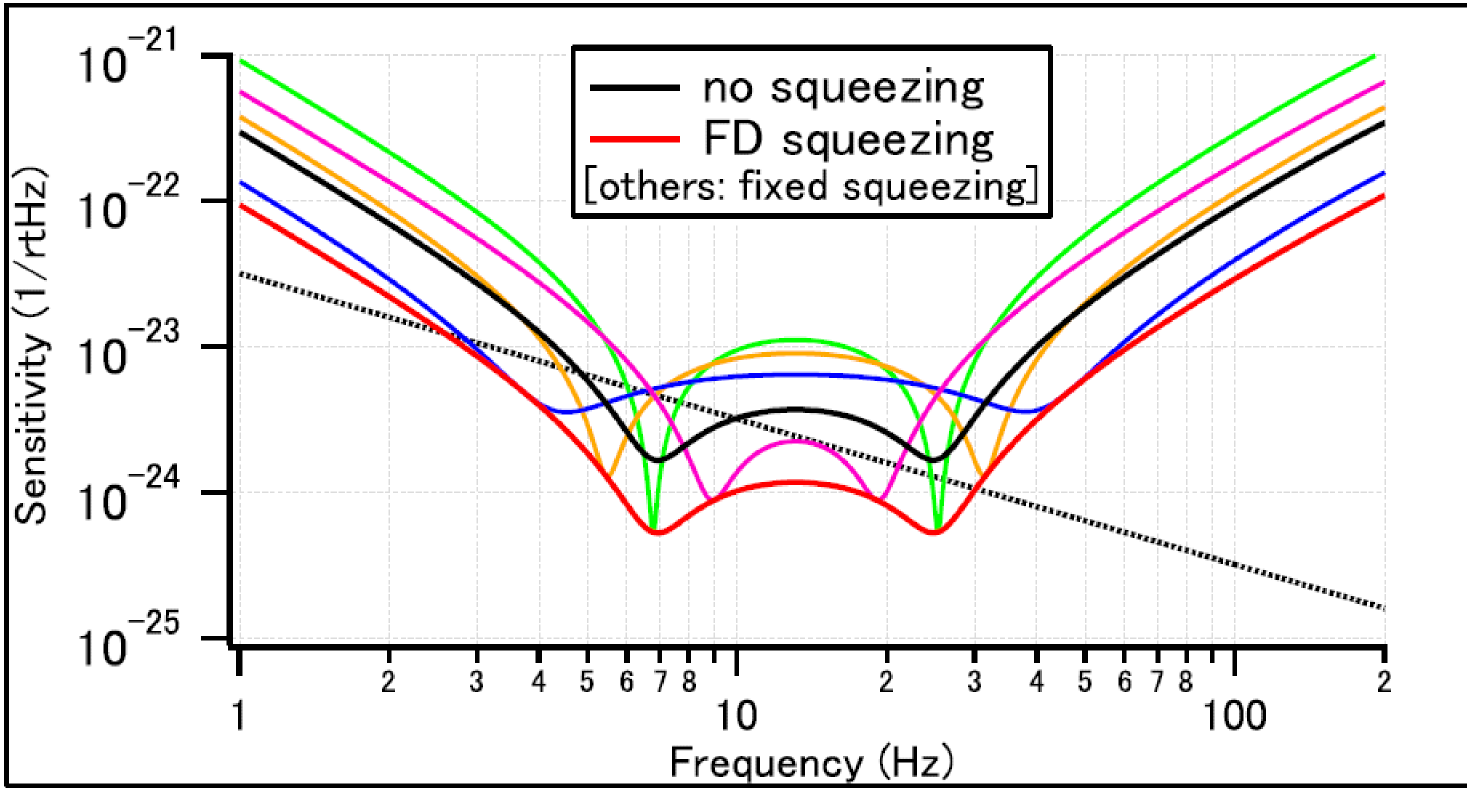
(broadband detector)



10dB FD squeezing makes the sensitivity sqrt 10 times better at all the frequencies.

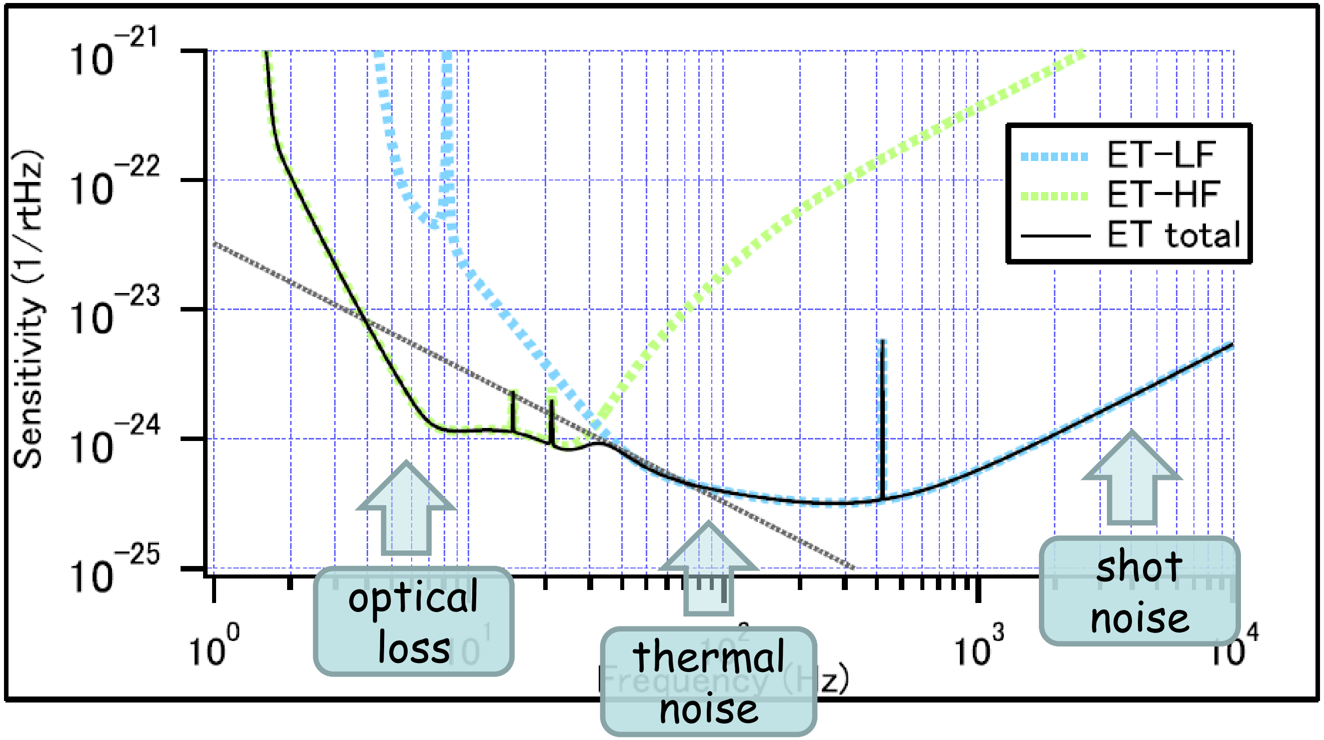
Sensitivity with FD squeezing

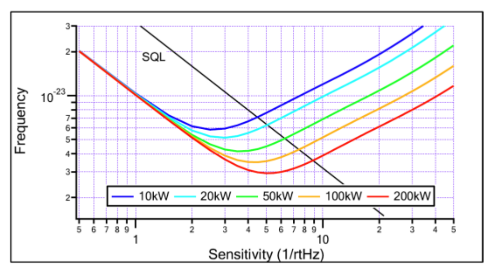
(detuned detector)

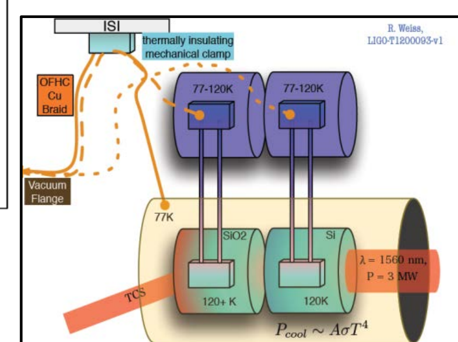


10dB FD squeezing makes the sensitivity sqrt 10 times better at all the frequencies.

Some rooms for further improvement







Other possibilities:

- low freq: speedmeter
- mid freq: many ideas
- high freq: 120K Silicon

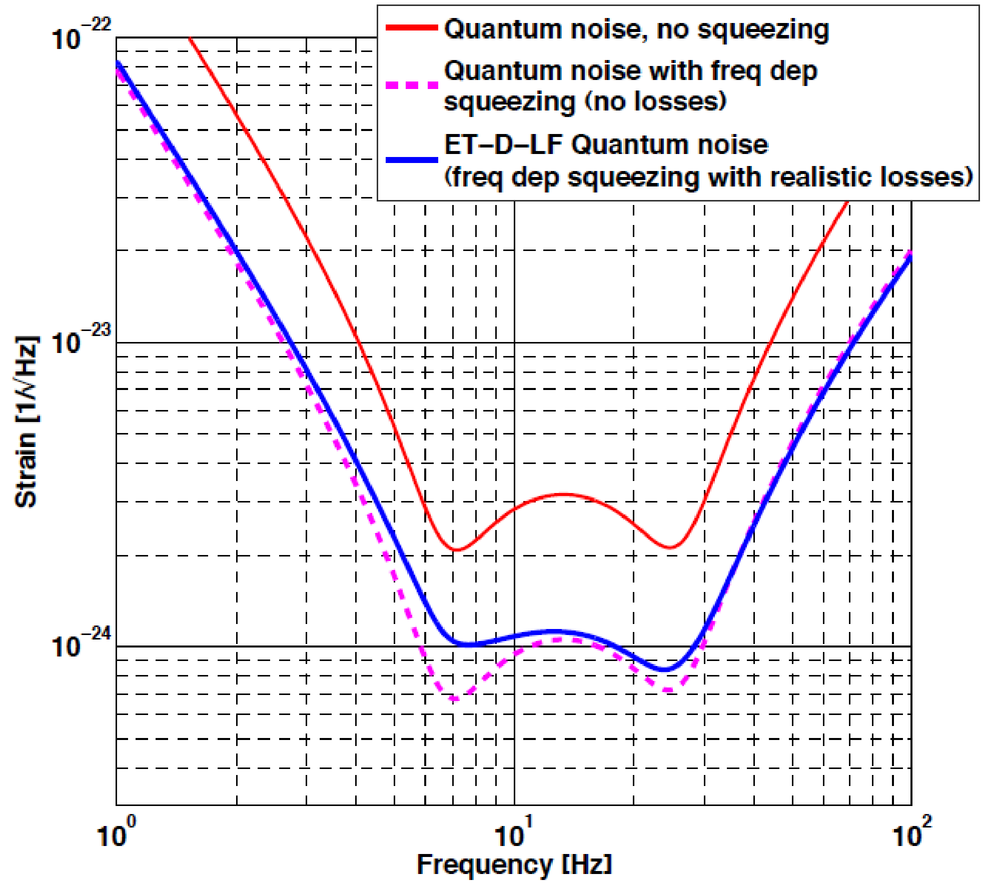
Summary

- Einstein Telescope composed of 2 detectors
- ET-LF employs the optical spring
- Both ET-LF and HF employ the FD squeezing
- Sensitivity exceeds the SQL of 200kg masses
- Some rooms for further improvements

Supplementary slides

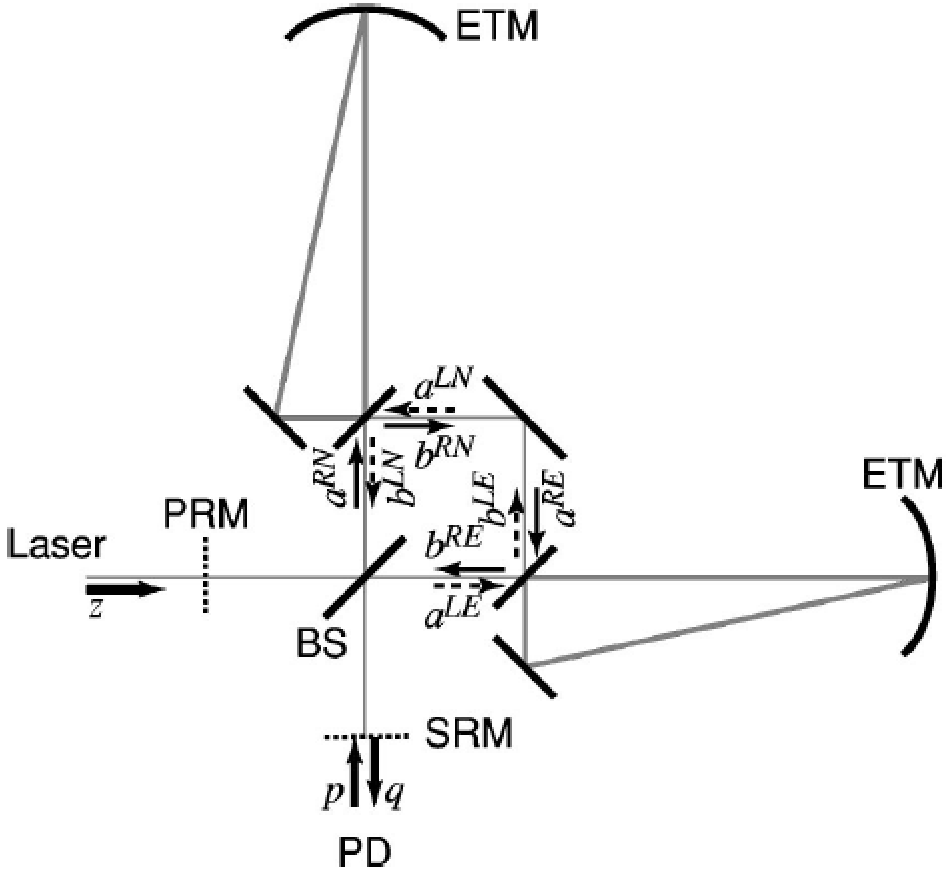
ET-LF sensitivity with losses

[S.Hild]



Some deterioration at the resonances.
This is due to optical losses (scattering, absorption, etc.).

Alternative configuration for ET-LF



[Chen (2003)]

Sagnac Speedmeter

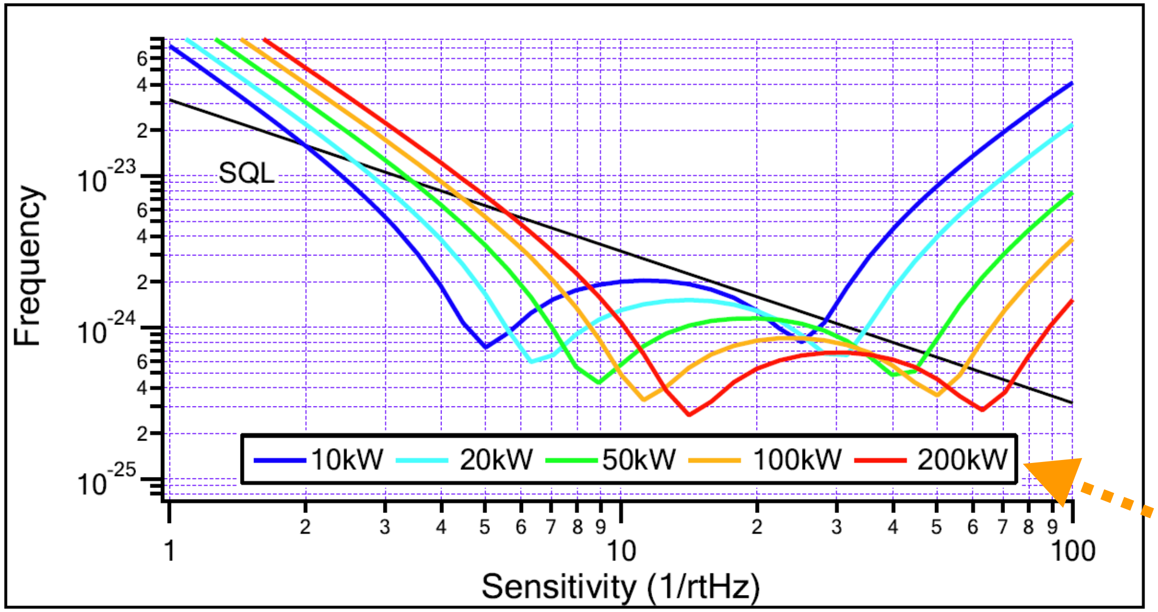
$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

➡ displacement measurement induces momentum kick

➡ momentum measurement induces no back action

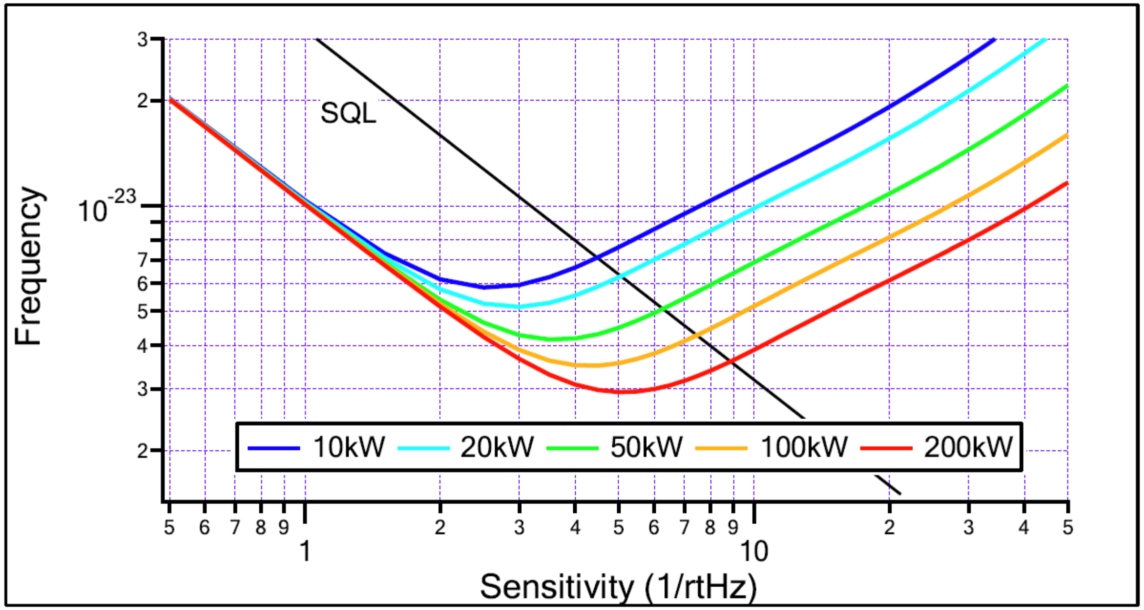
Speedmeter beats the SQL in broadband w/o filter cavities.

Optical spring vs speedmeter



Optical spring with FD squeezing:
narrow but deep

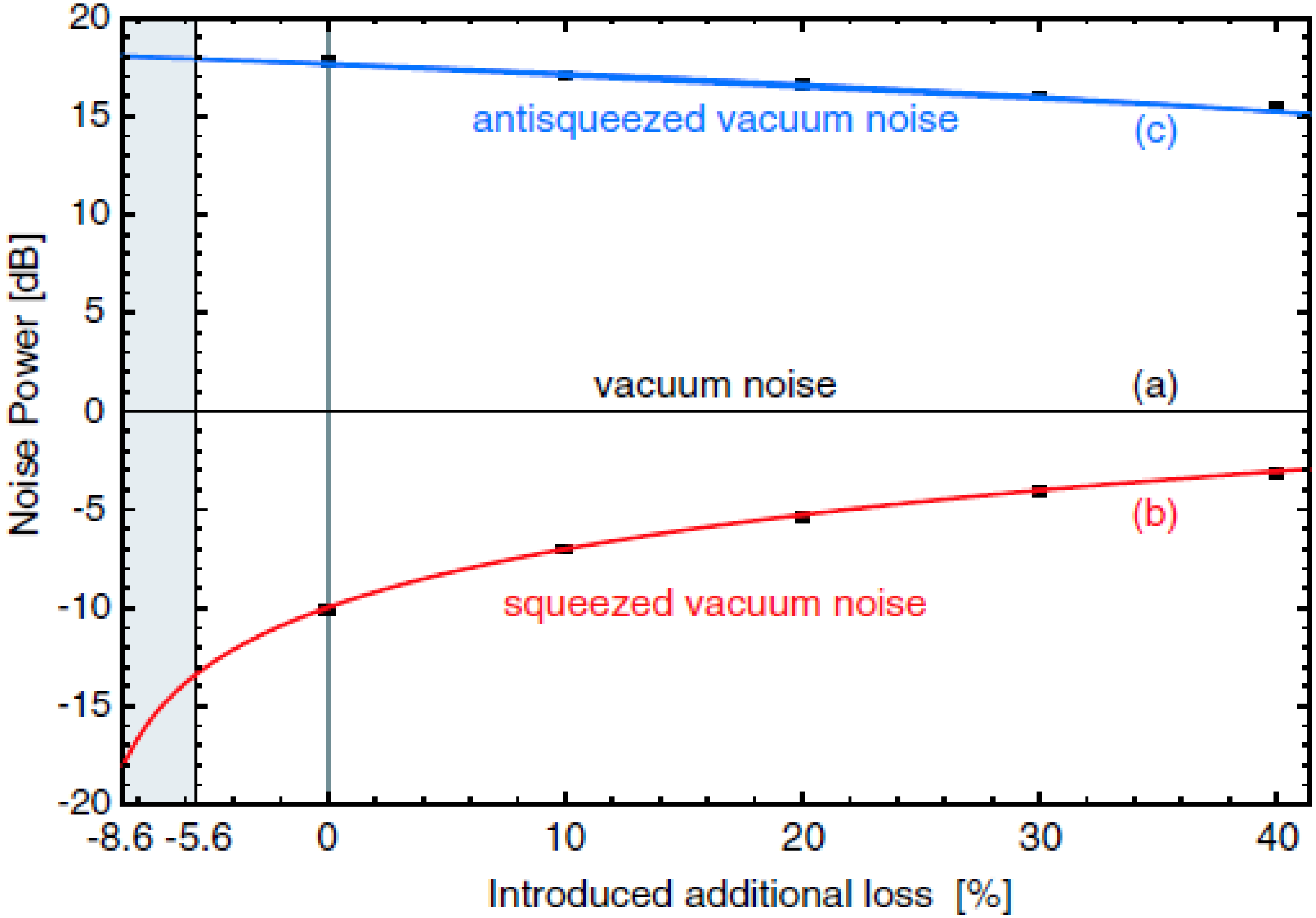
power in arm cavities



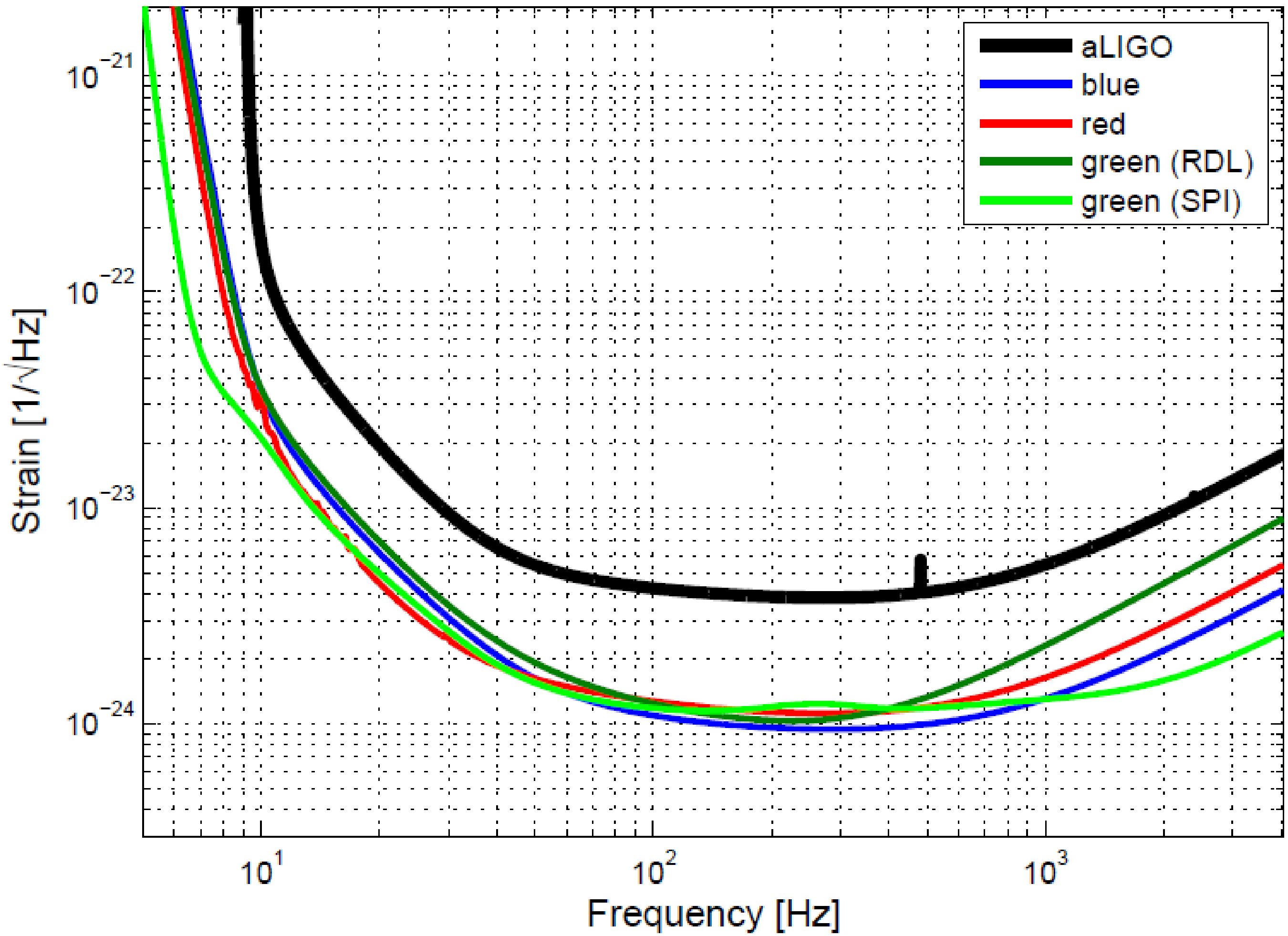
Speed-meter with fixed squeezing:
good only with power

Optical losses and squeezing

[Vahlbruch et al (2008)]



LIGO3



aLIGO
blue
red
green (RDL)
green (SPI)
10^{-21}
10^{-22}
10^{-23}
10^{-24}
Strain [1/√Hz]
10^{1}
10^{2}
10^{3}
Frequency [Hz]