Advanced techniques to reduce quantum noise

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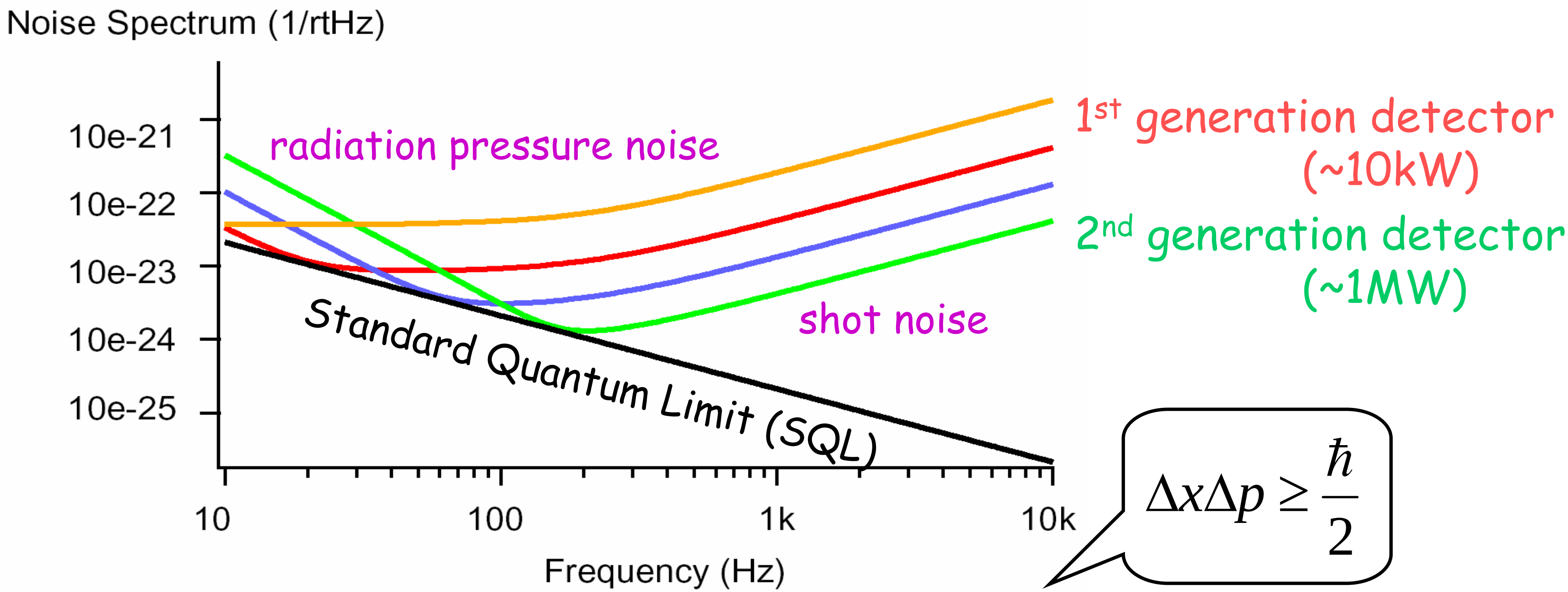
Quantum Limit in GW detectors



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

High precision — Uncertainty Principle → **Back action**

‖ Shot noise reduction

‖ Radiation pressure noise

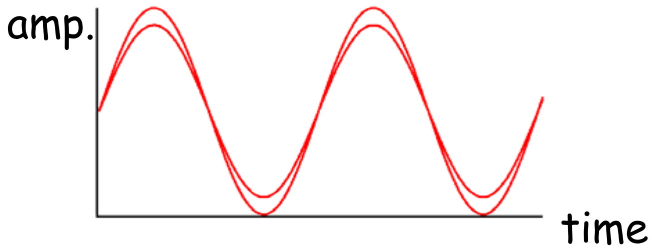
A limit that cannot be exceeded by simply increasing power

However, the limit can be circumvented

Several ways to overcome the limit

- Back-action evasion with quantum control
- Application of optical squeezing
- Change of dynamics with an optical spring

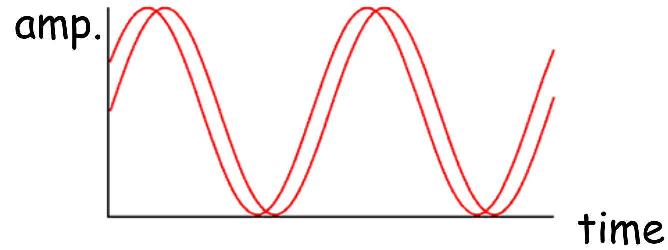
Source of quantum noise



Photon number fluctuation

↓

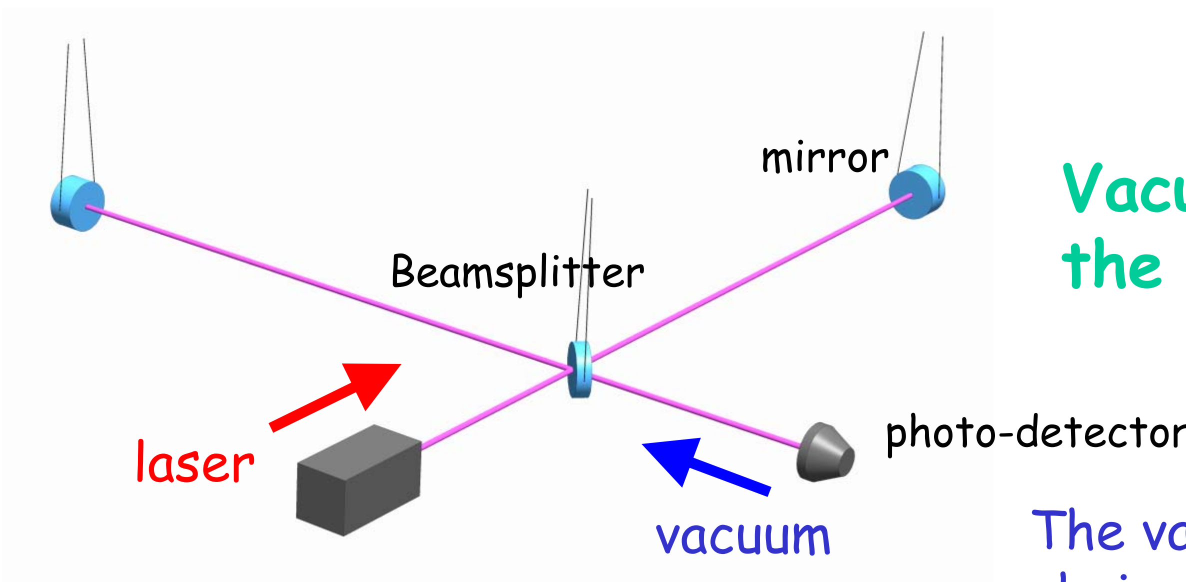
radiation pressure



Photon phase fluctuation

↓

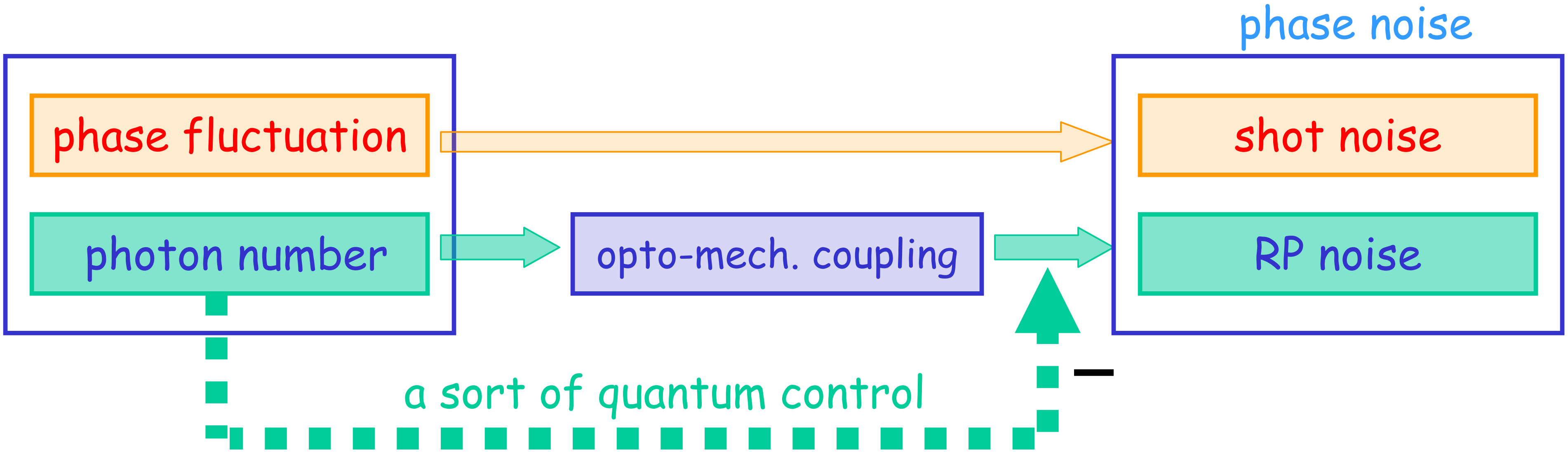
Shot noise

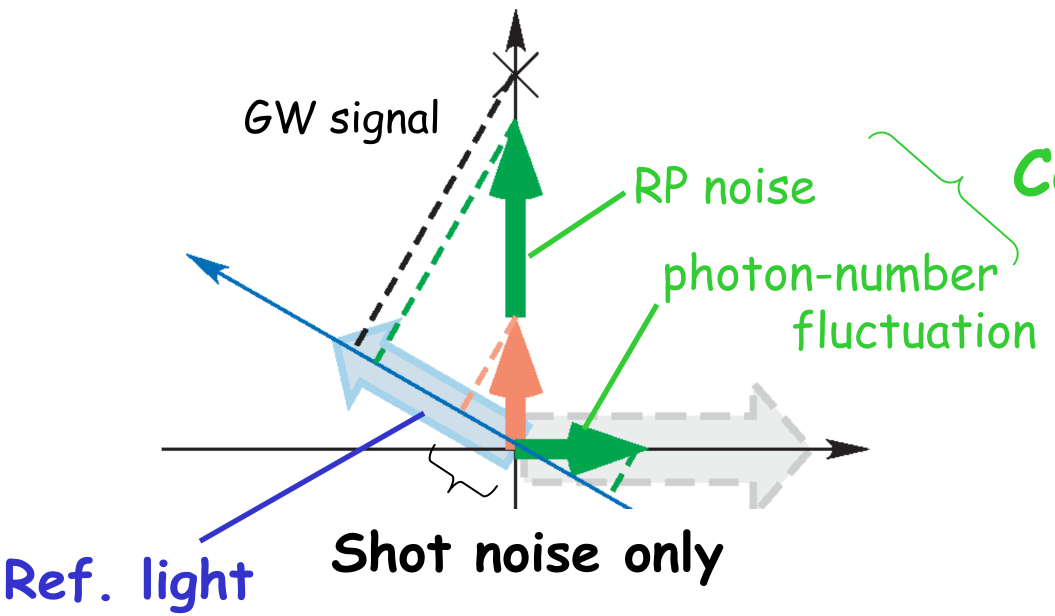


Vacuum fluctuation from the dark port causes QN

The vacuum is the source of random choice of photons on the BS.

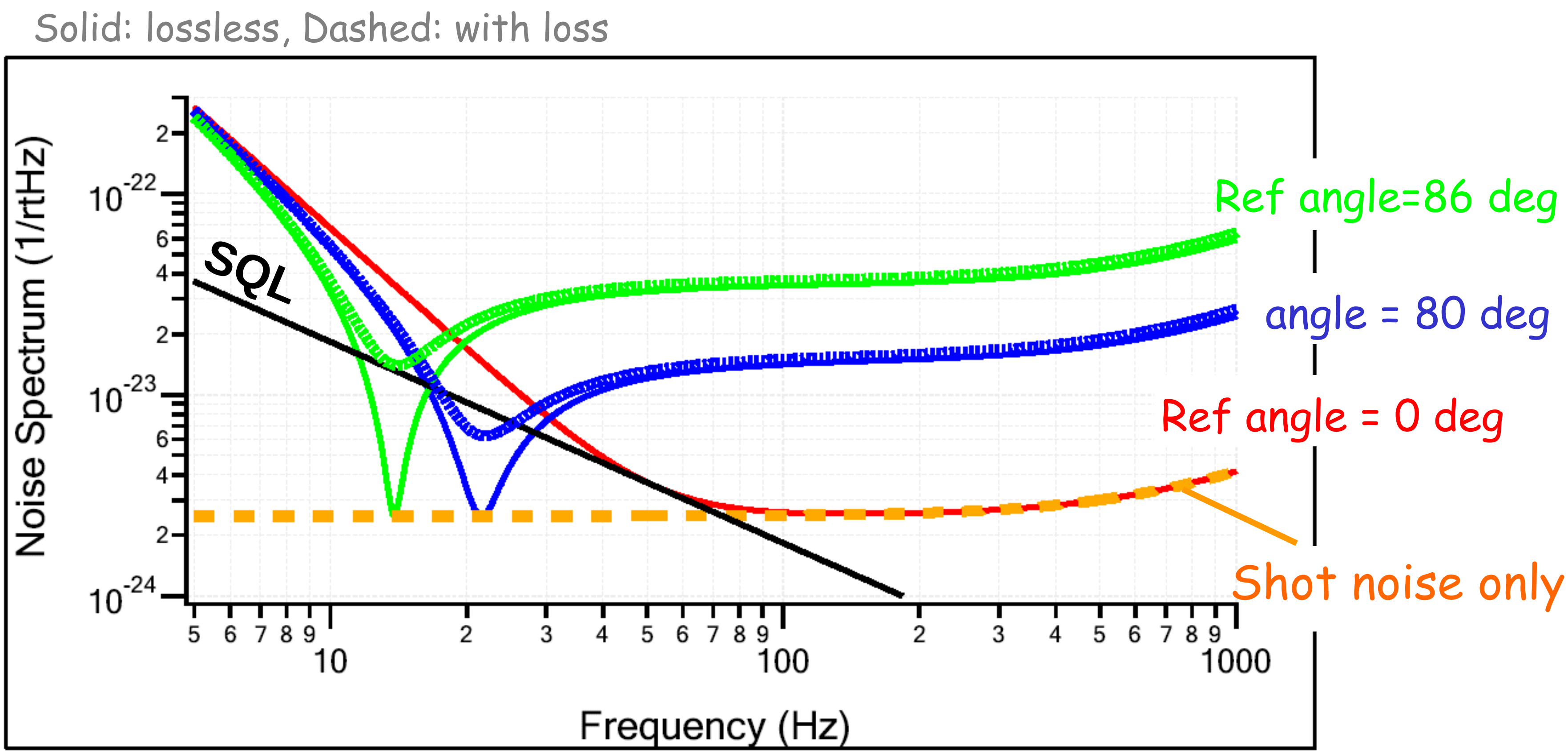
Back-action evasion





Compensation of noise by a simultaneous measurement

Sensitivity with Back-action evasion



- Exceeding SQL in a narrow band
- Weak against optical losses

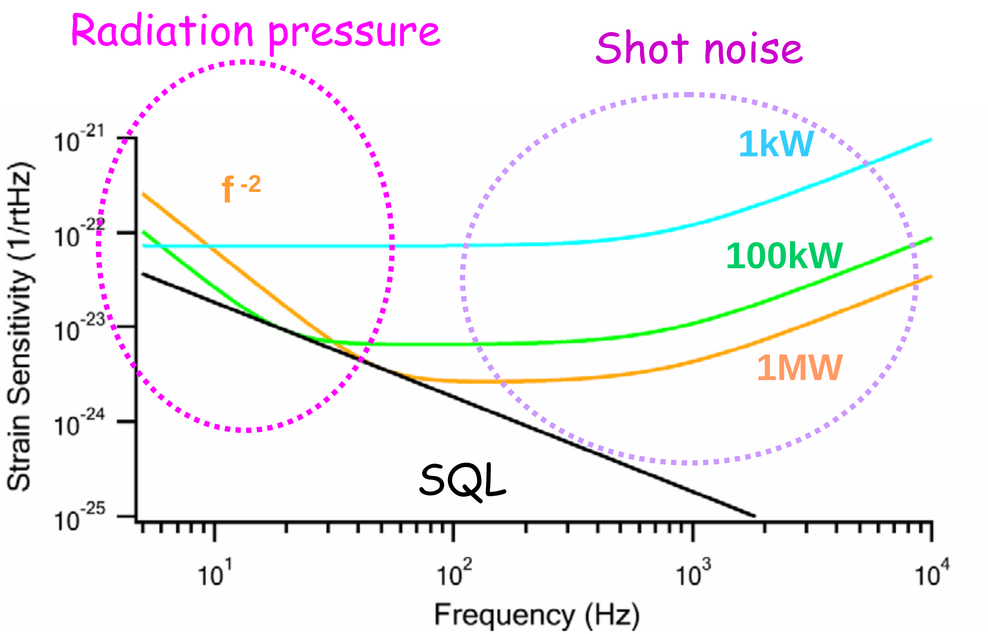
By the way...

How come we can exceed the SQL?

Was Heisenberg wrong??

SQL in a GW detector

GW detector



$$\sqrt{\text{RP Noise}^2 + \text{Shot Noise}^2} \geq \sqrt{\frac{2\hbar}{m'(\pi f)^2}}$$

Heisenberg

Uncertainty Principle

$$\Delta x(t)\Delta p(t) \geq \frac{\hbar}{2}$$

$$\Rightarrow \Delta x(t)\Delta x(t+\tau) \geq \frac{\hbar\tau}{2m}$$

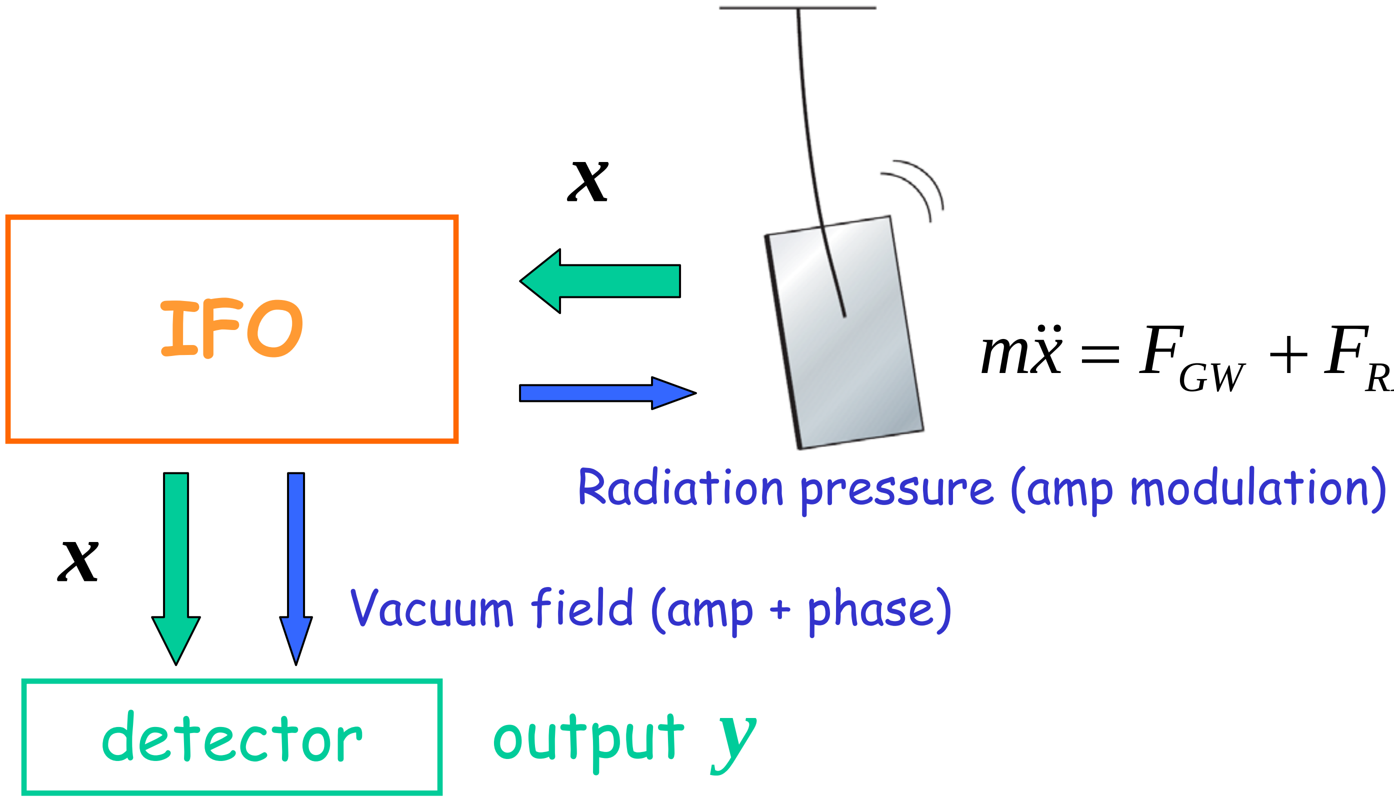
$$\Rightarrow \tilde{x}(f) \geq \sqrt{\frac{\hbar}{2m(\pi f)^2}}$$

identical

Beatable

Unbeatable

GW detectors see the "force"



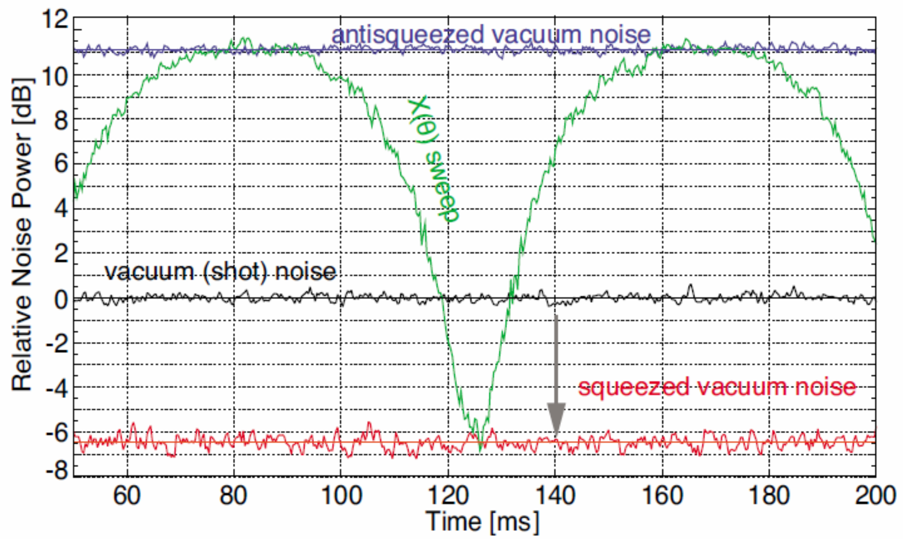
$$m\ddot{x} = F_{GW} + F_{RP}$$

We can try not to see the radiation pressure motion (though the mirror IS moving).

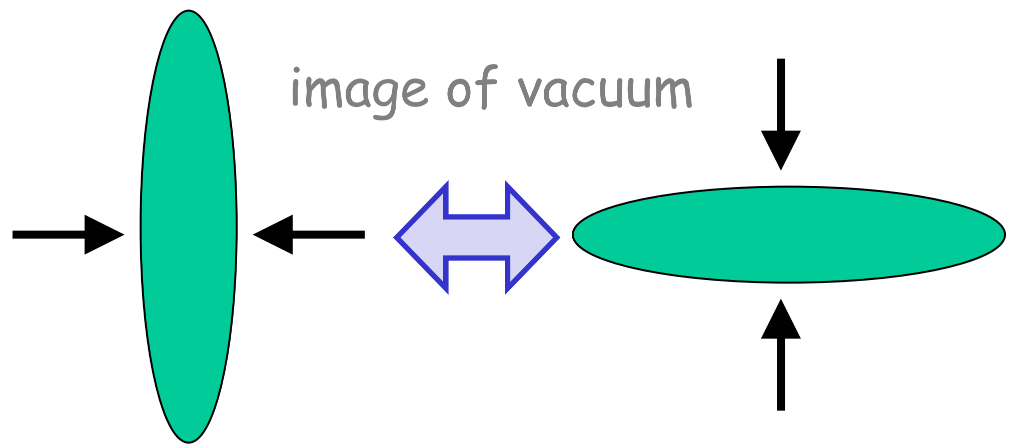
Various ways to overcome the SQL

- Back-action evasion
- Squeezed vacuum injection
- Optical spring
- Optical inertia

Squeezing



7dB squeezing



less fluctuation of light phase

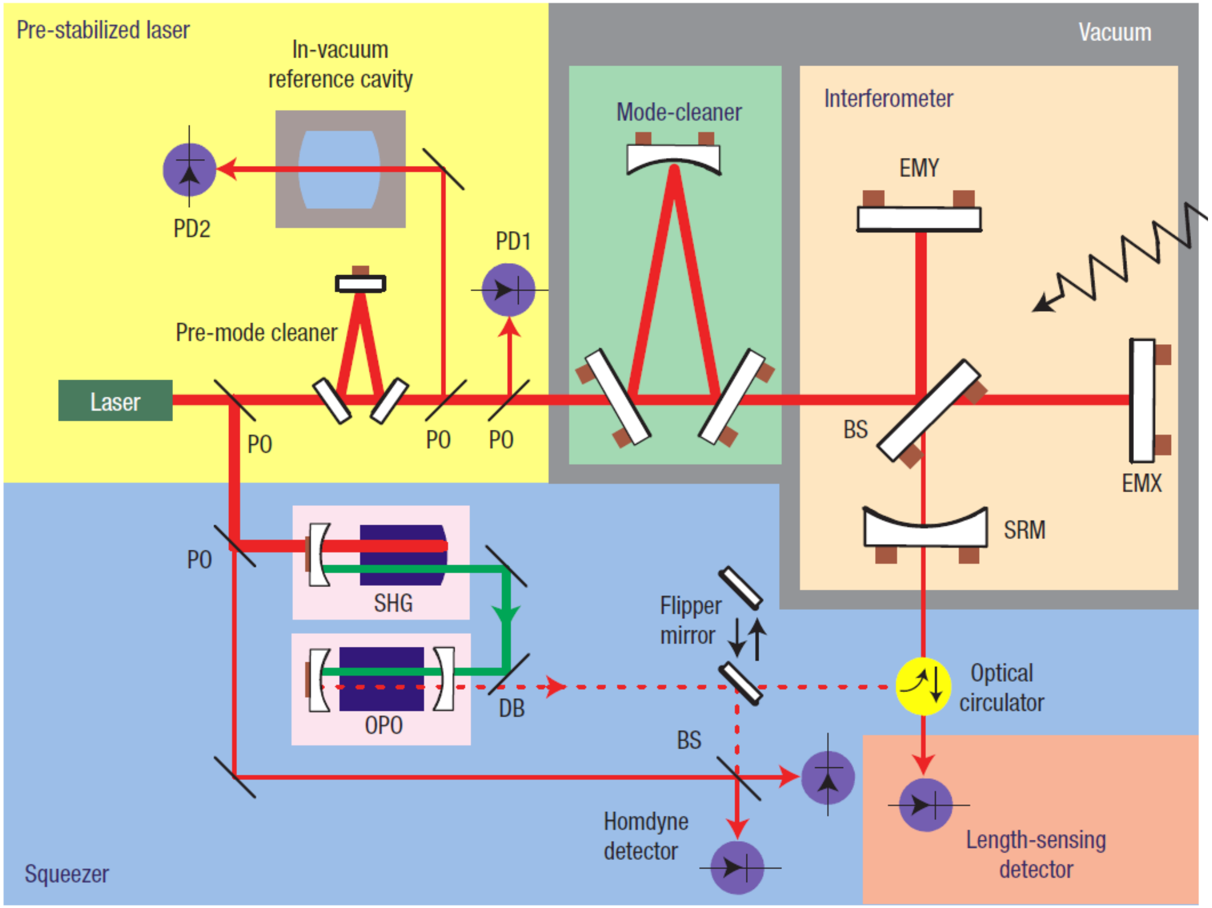
less fluctuation of photon number

Make an imbalance between photon-number fluctuation and phase fluctuation using a non-linear crystal.

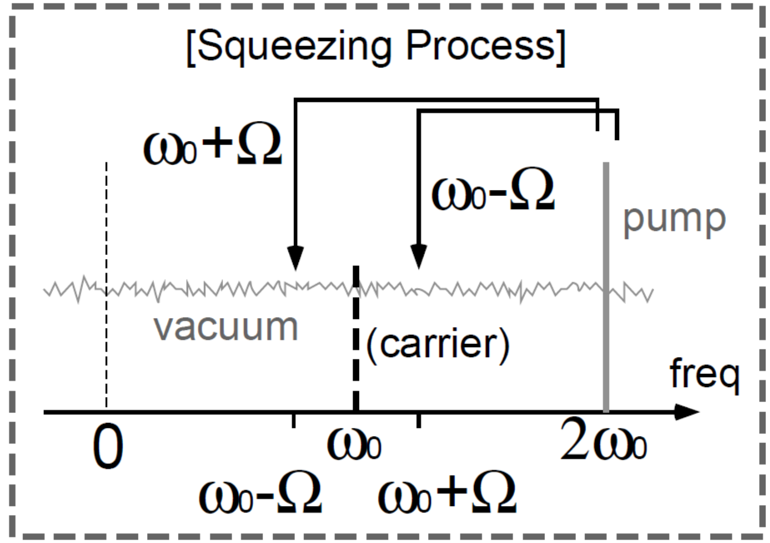
Sensitivity depends on the shape of vacuum:

~ low shot noise (left)
~ low radiation pressure (right)
~ overcoming SQL (intermediate)

How to make squeezing



Goda et al, Nature Physics 2008



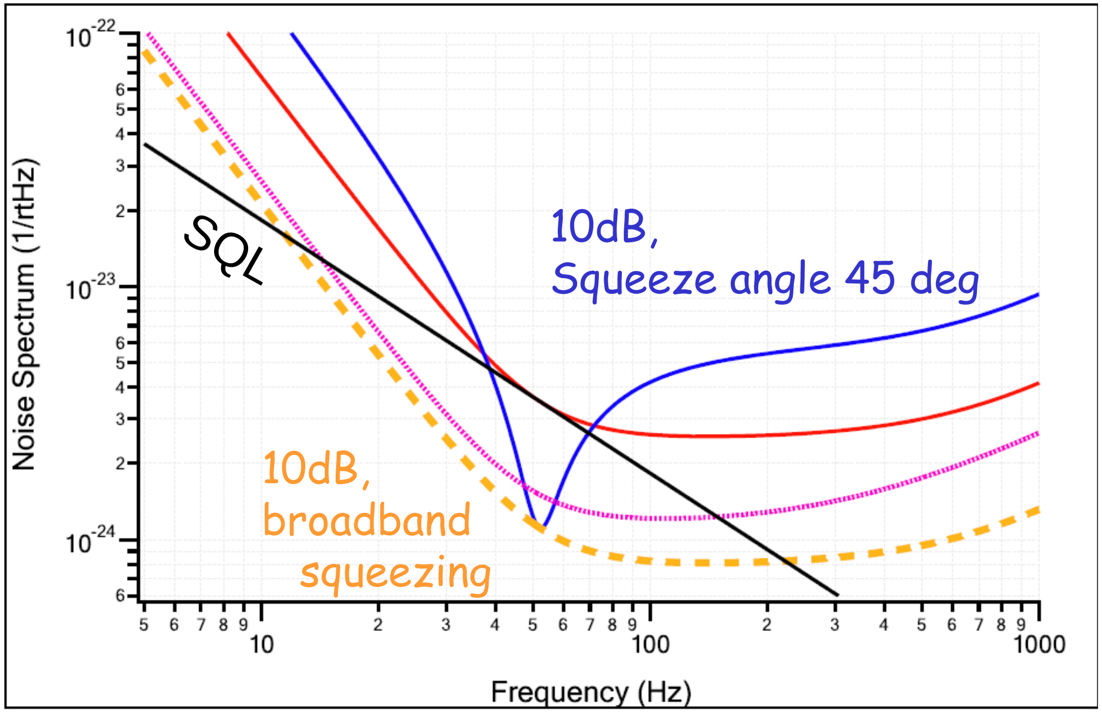
Squeezer makes a correlation btw vacuum fields at $\omega+\Omega$ and $\omega-\Omega$.

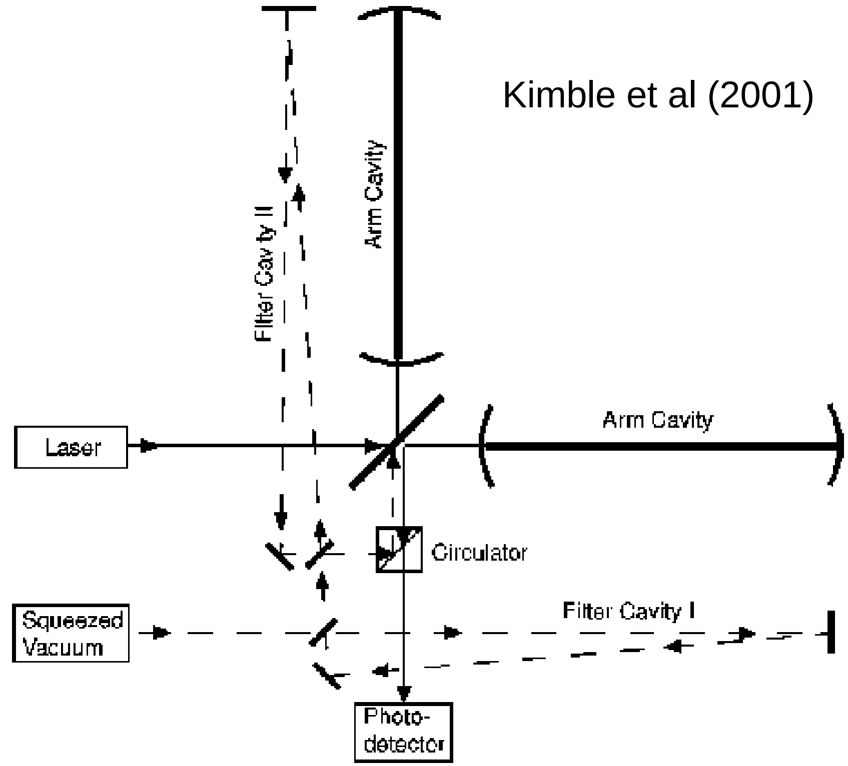
Differential-mode field decreases while common mode increases.

- Has been implemented in GEO and LIGO
- An issue is the optical loss

Broadband squeezing

orange: lossless, pink: with loss

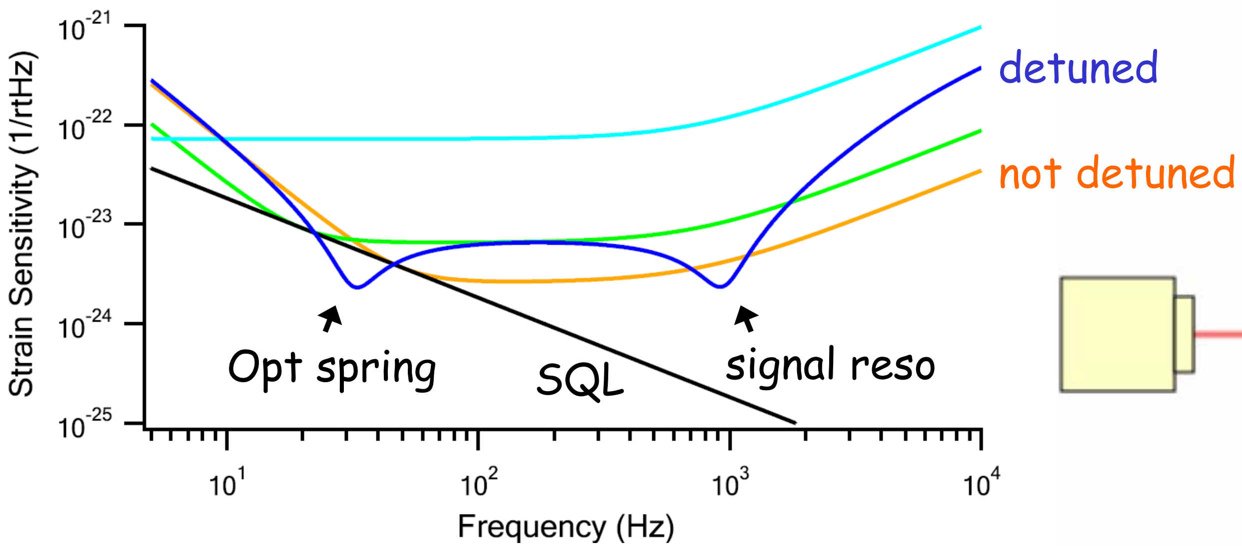


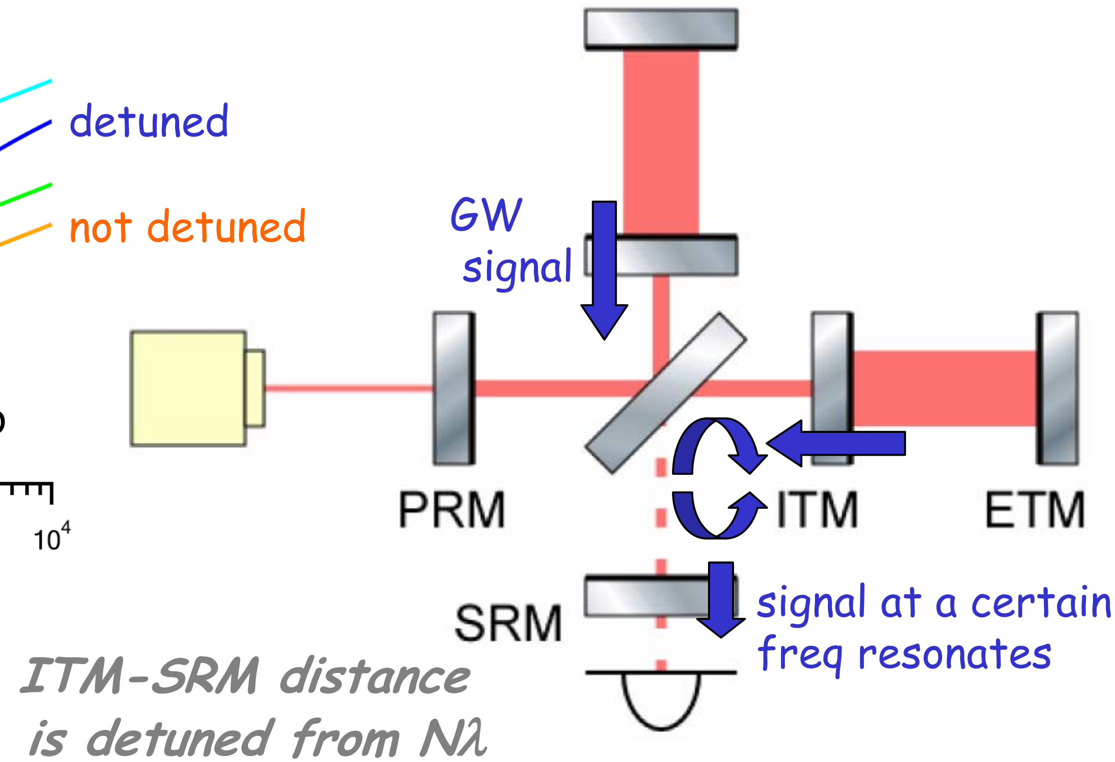


- Rotation of the squeeze angle in the filter cavity
- Frequency-dependent squeezing can be realized

➡ Optimal squeezing at each frequency

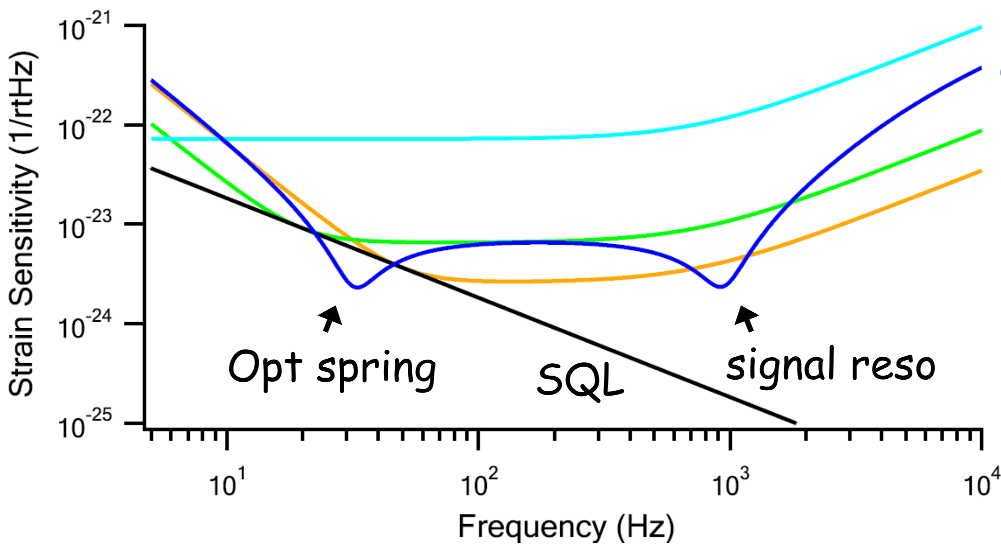
Optical spring

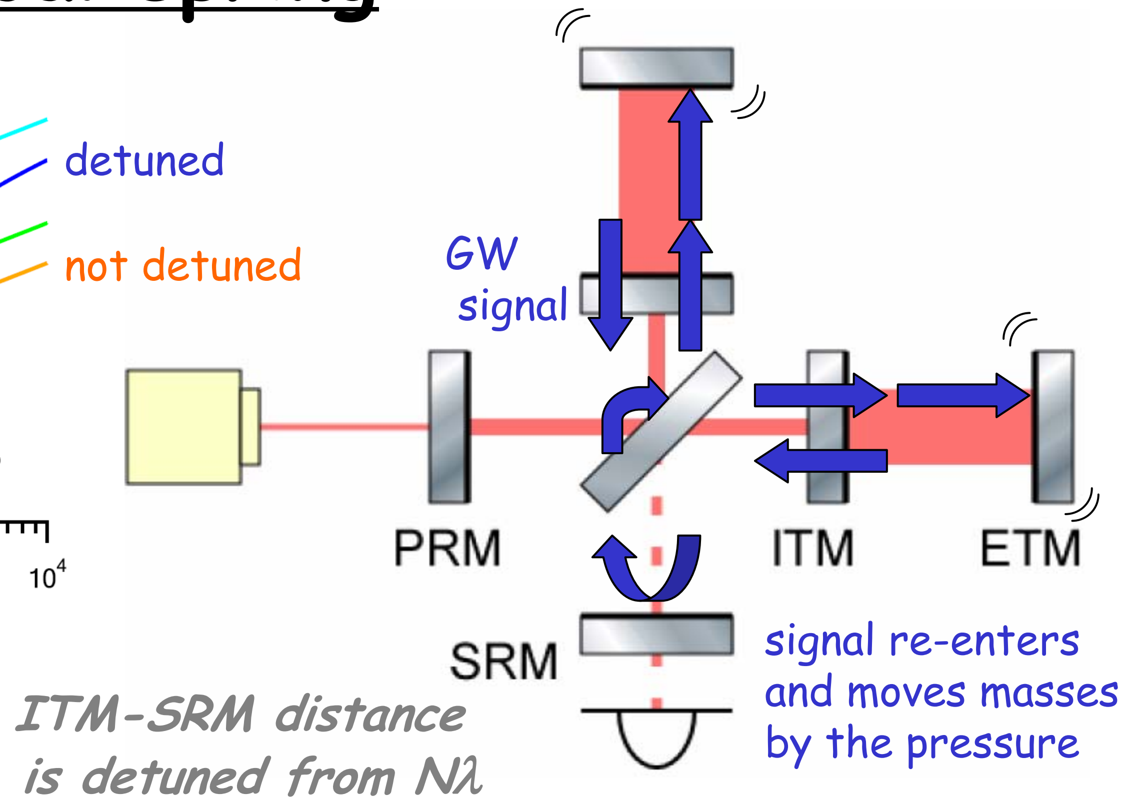




- High freq peak: signal resonance

Optical spring





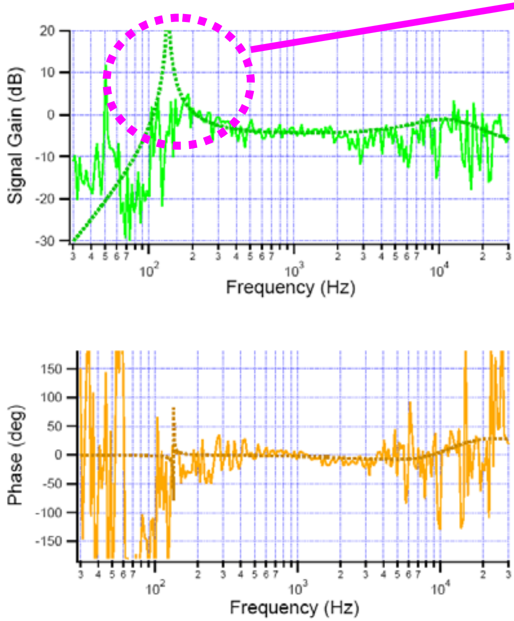
- High freq peak: signal resonance
- Low freq peak: radiation pressure causes optical spring

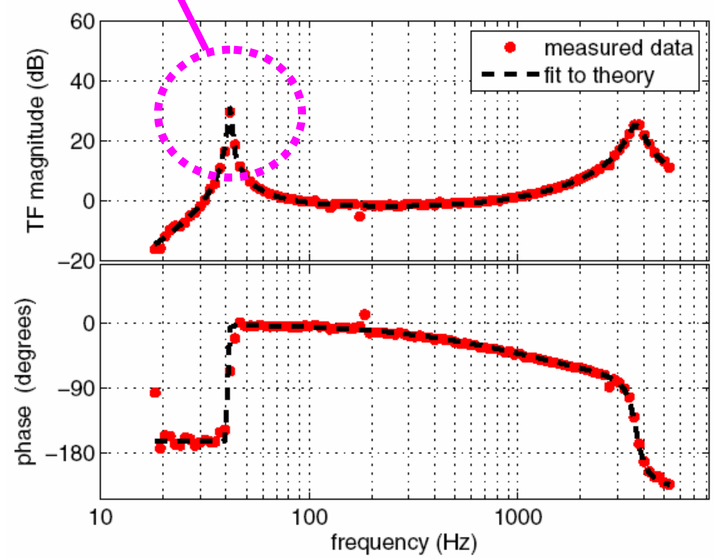
Susceptibility to GW increases so one can exceed the SQL defined for free mass measurement.

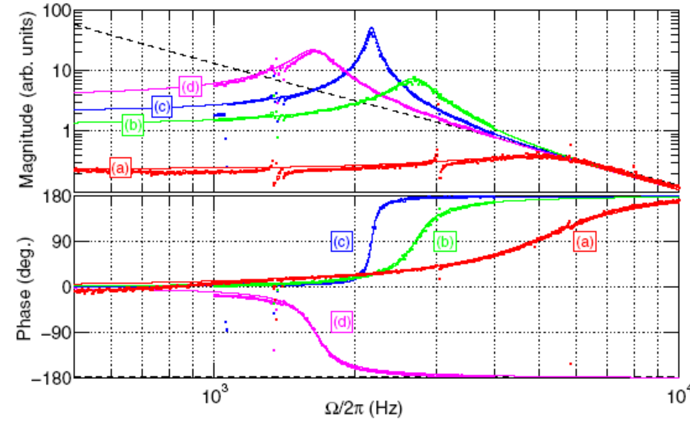
Optical spring experiments

Somiya et al, Appl. Opt. 44, 16 (2005)
Miyakawa et al, Phys. Rev. D 74, 022001 (2006)
Corbitt et al, Phys. Rev. Lett. 98, 150802 (2007)

optical spring

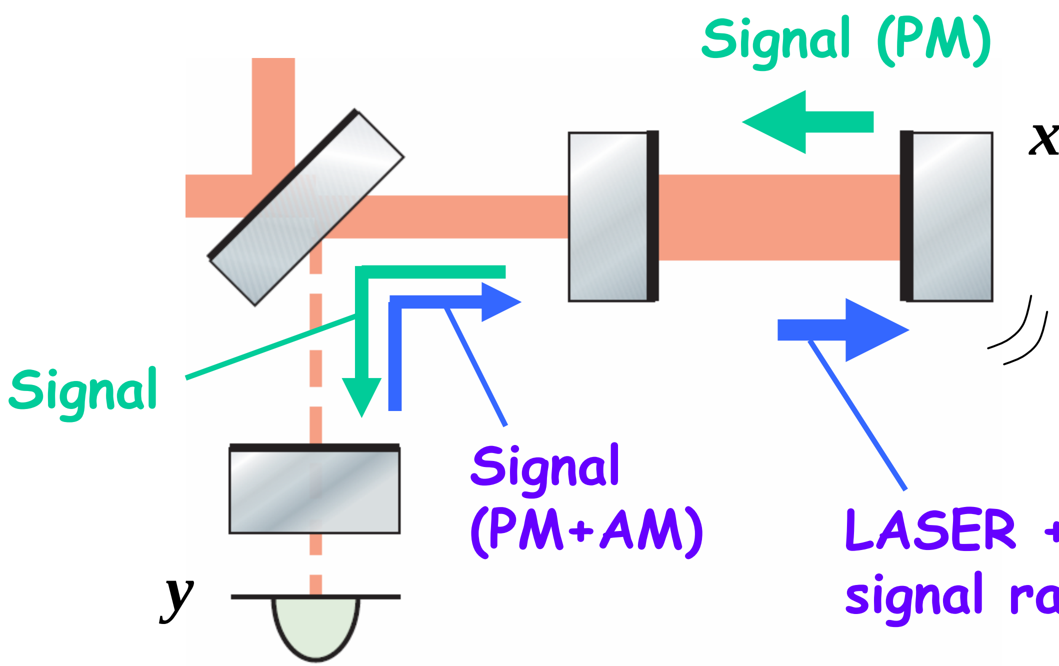






- Signal amplification can be tested by TF measurement
- Spring freq is determined by mirror weight and power
- Optical spring system is to be implemented in KAGRA

Optical spring response



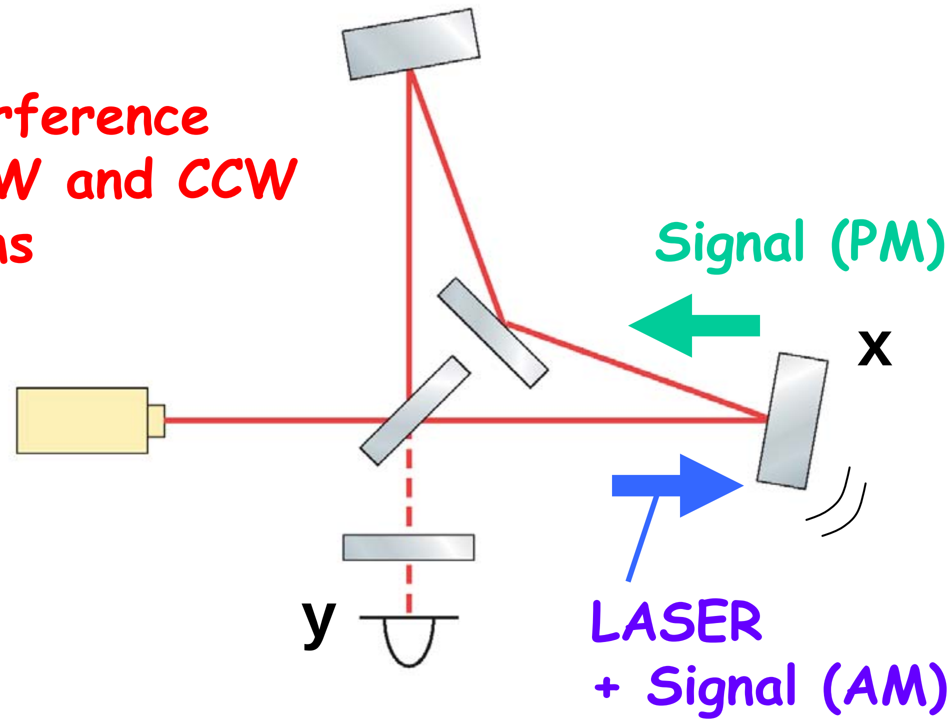
LASER + Signal (AM) generates signal radiation pressure force

$$\begin{cases} y \sim Ax \\ x'' \sim x''_{GW} - By \end{cases} \rightarrow \tilde{y}(\Omega) \sim \frac{A\Omega^2}{\Omega^2 - AB} x_{GW}$$

Amplification in narrowband

Optical inertia in a Sagnac interferometer

Interference of CW and CCW beams



Differential probe

→ time derivative

Differential force

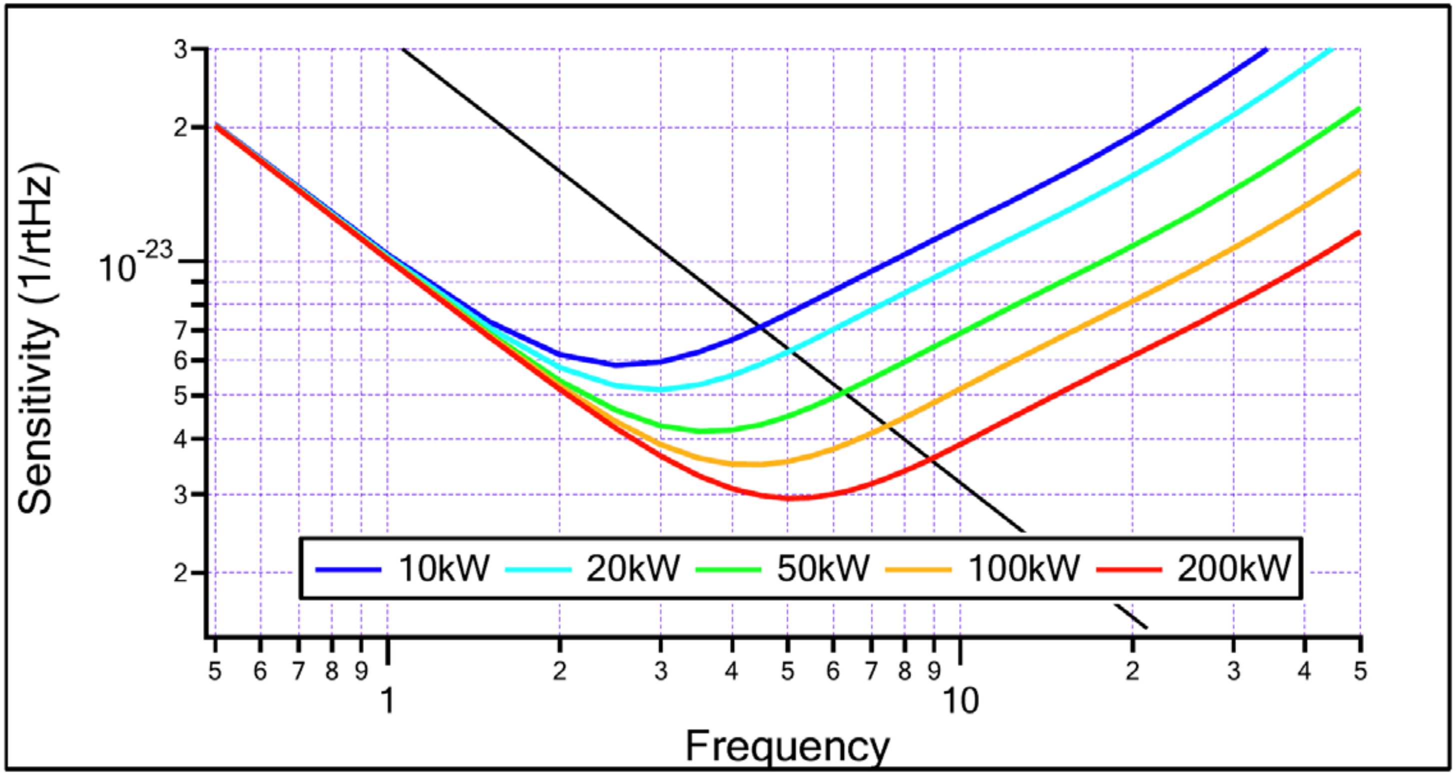
→ time derivative

$$\begin{cases} y \sim Ax' \\ x'' \sim x''_{GW} + By' \end{cases} \rightarrow \quad \tilde{y}(\Omega) \sim \frac{Ai\Omega}{1-AB} x_{GW}$$

Broadband amplification

Quantum noise spectrum of Sagnac

* With arm cavities; optical parameters are well tuned



- Exceeding SQL in broadband
- Bandwidth depends on the input power

Theme of the quantum noise reduction

(1) We need a regime that is strong against losses

(2) Exceeding the SQL in broadband would be good

(3) We need a regime to do so with low power

New ideas are welcome!!