Quantum-noise reduction techniques in a gravitational-wave detector

AQIS11 satellite session@KIAS
Aug. 2011

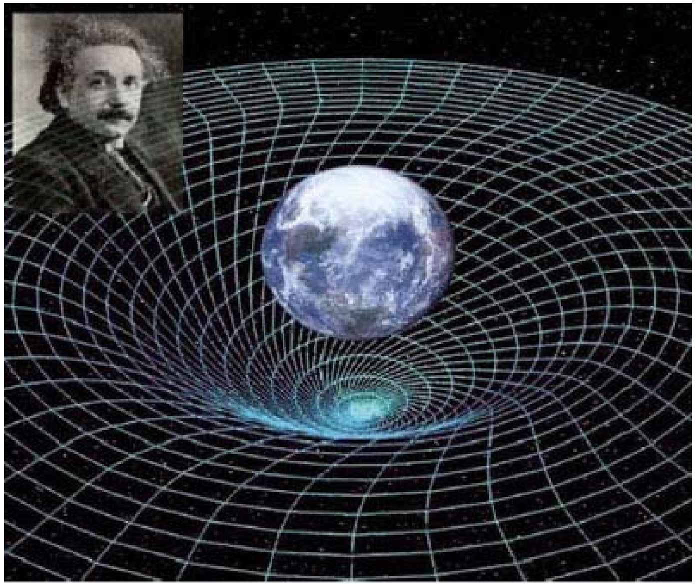
Tokyo Inst of Technology
Kentaro Somiya

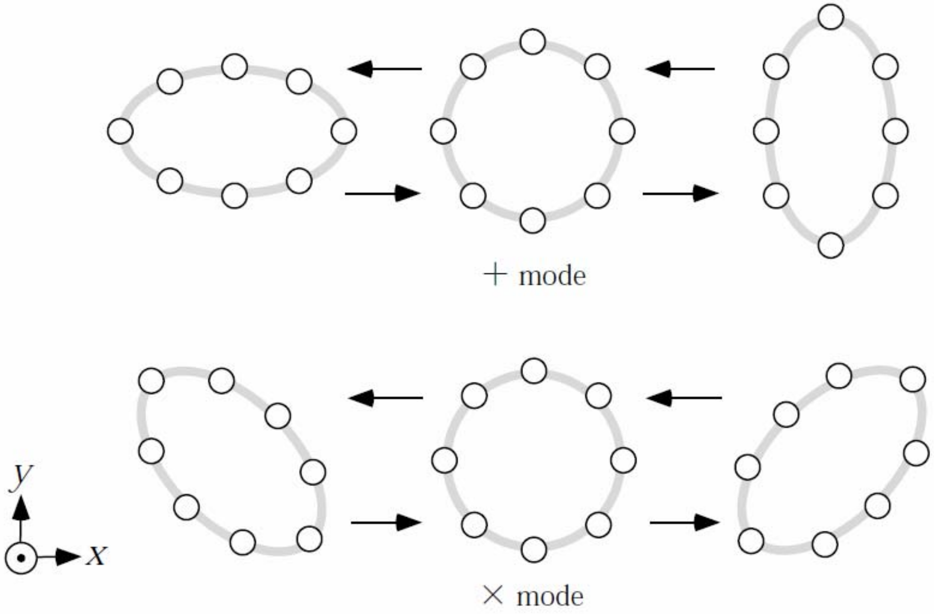
K.Somiya

Contents

- Gravitational-wave detector
- Quantum non-demolition techniques (QND)
- Macroscopic quantum measurement (MQM)

Gravitational waves





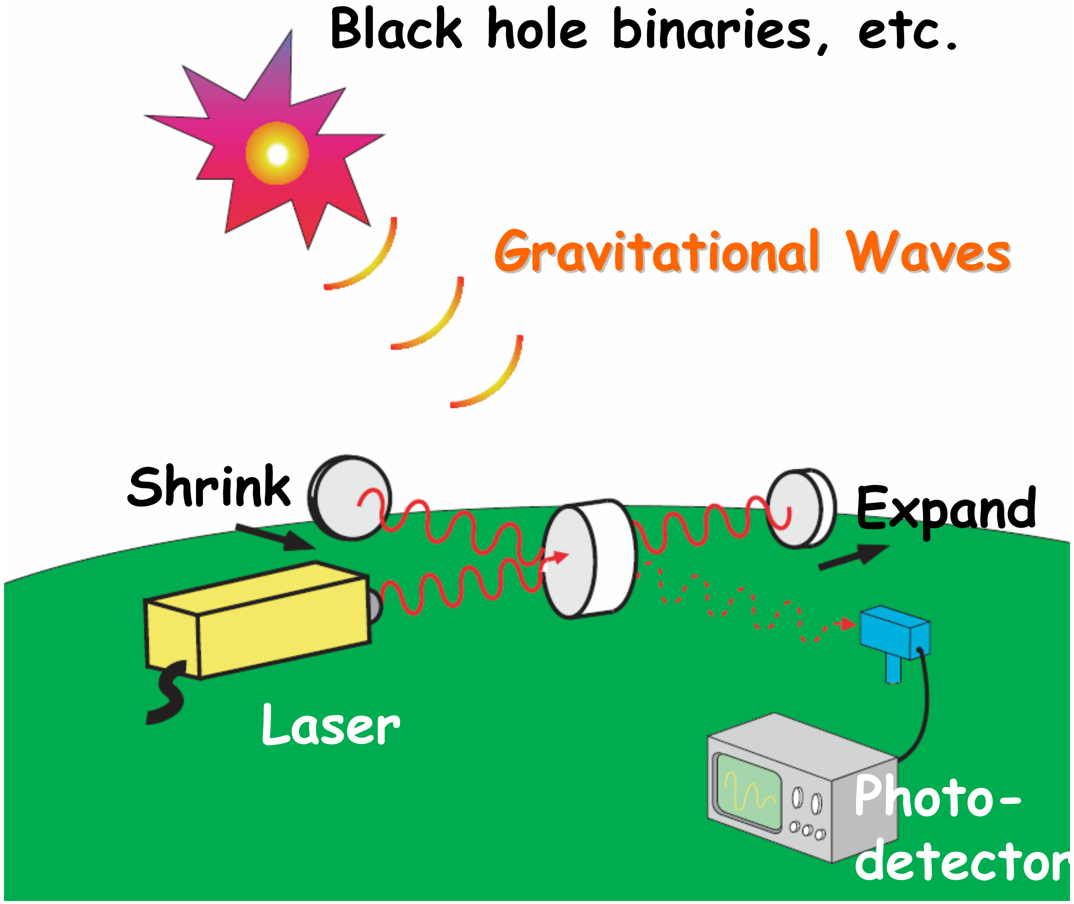
- **Einstein's prediction (1917)**
- **Spacetime ripple generated by BH mergers, supernovae, etc. propagates to the earth as a wave**
- **Unique information of the sources**
  (ex. Early Universe; ~10^-36 sec after the Big Bang)

$$h^{\mathrm{TT}}_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h^{\mathrm{TT}}_{xx} & h^{\mathrm{TT}}_{xy} & 0 \\ 0 & h^{\mathrm{TT}}_{xy} & -h^{\mathrm{TT}}_{xx} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Interferometric GW detector

Far Galaxy

Supernova explosion,
Black hole binaries, etc.



Earth

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]

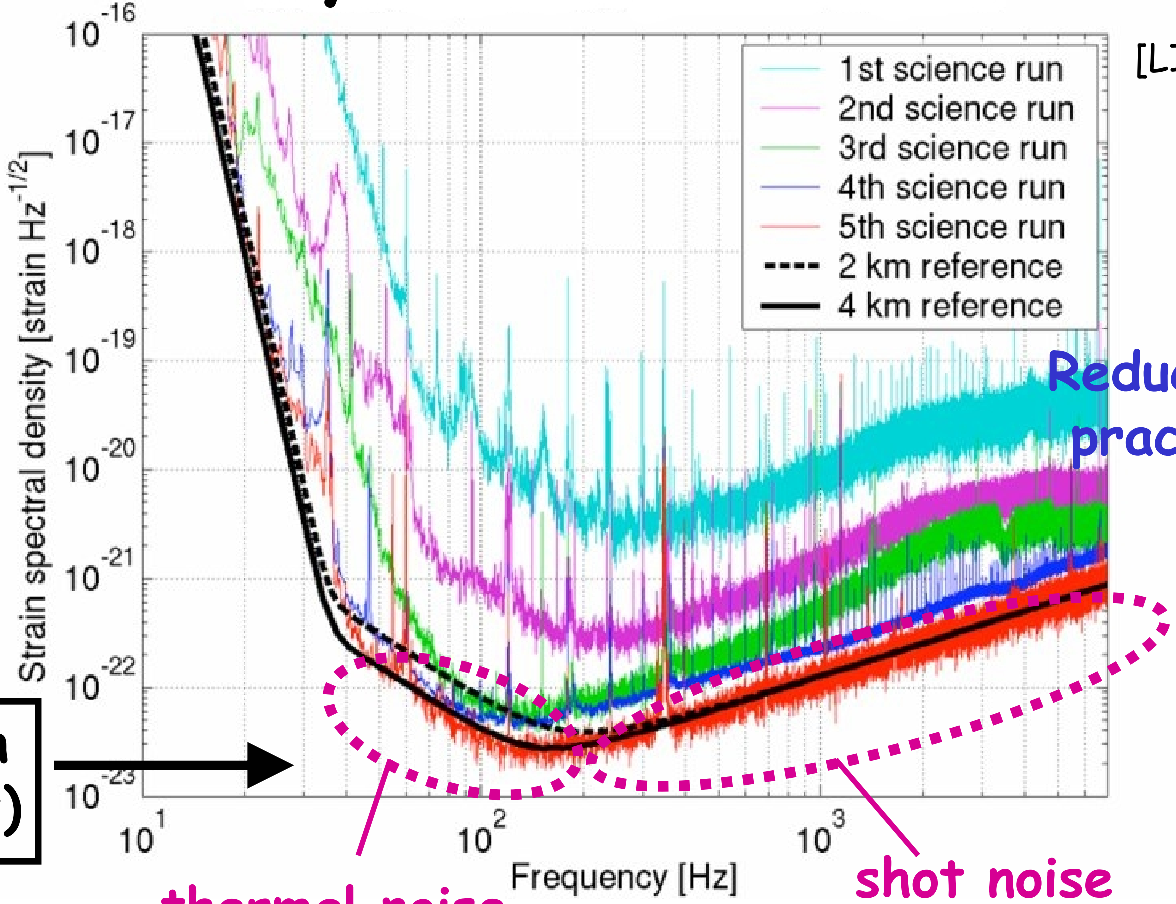
GW detectors in the world

- LIGO
- Virgo
- GEO

upgrade →

- Advanced LIGO
- Advanced Virgo
- GEO-HF

Sensitivity of a GW detector



[LIGO detector (US)]

Reduction of practical noise

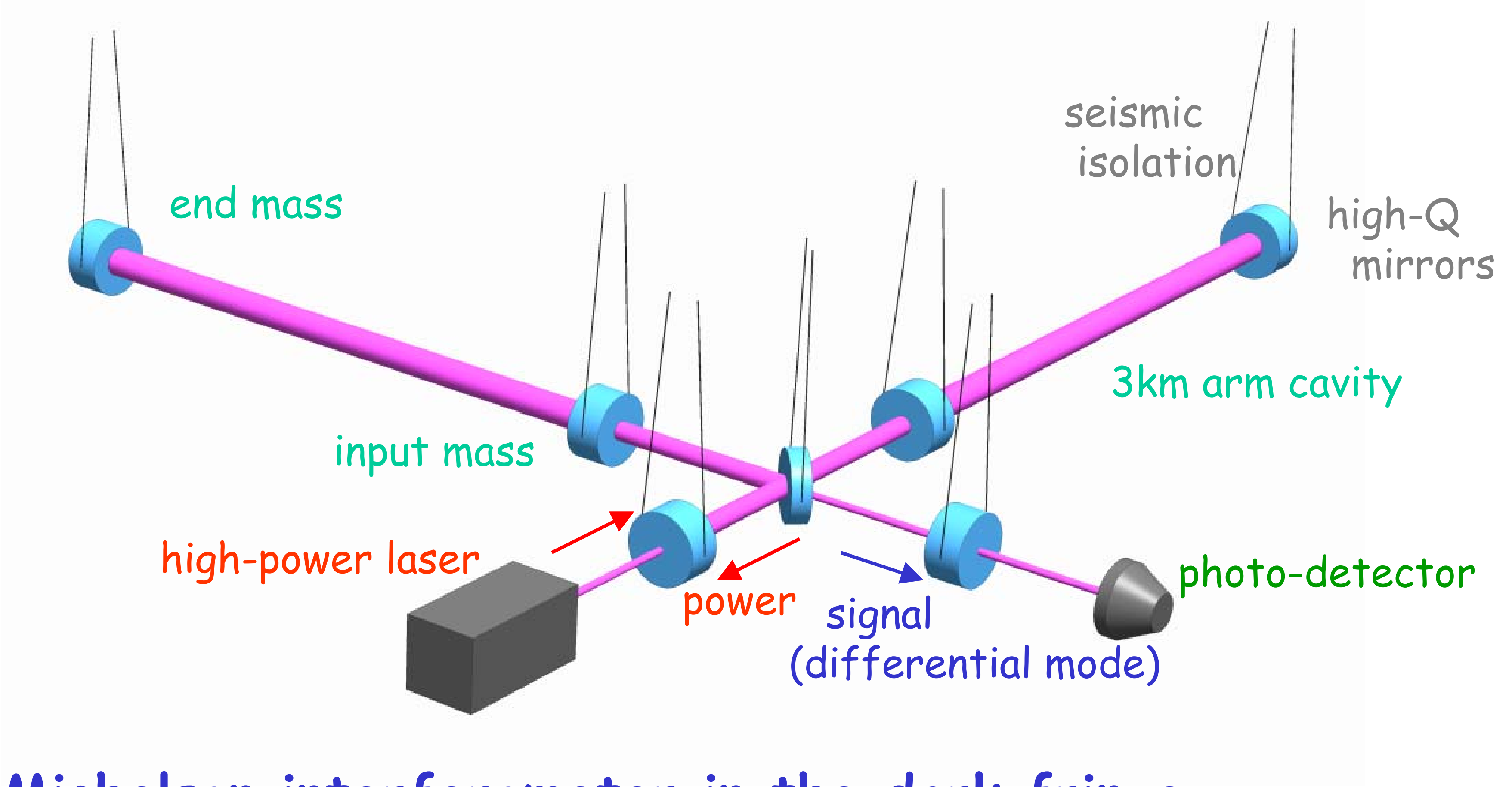
~2e-23 in strain (~1e-19m/rtHz)

thermal noise

shot noise (quantum noise)

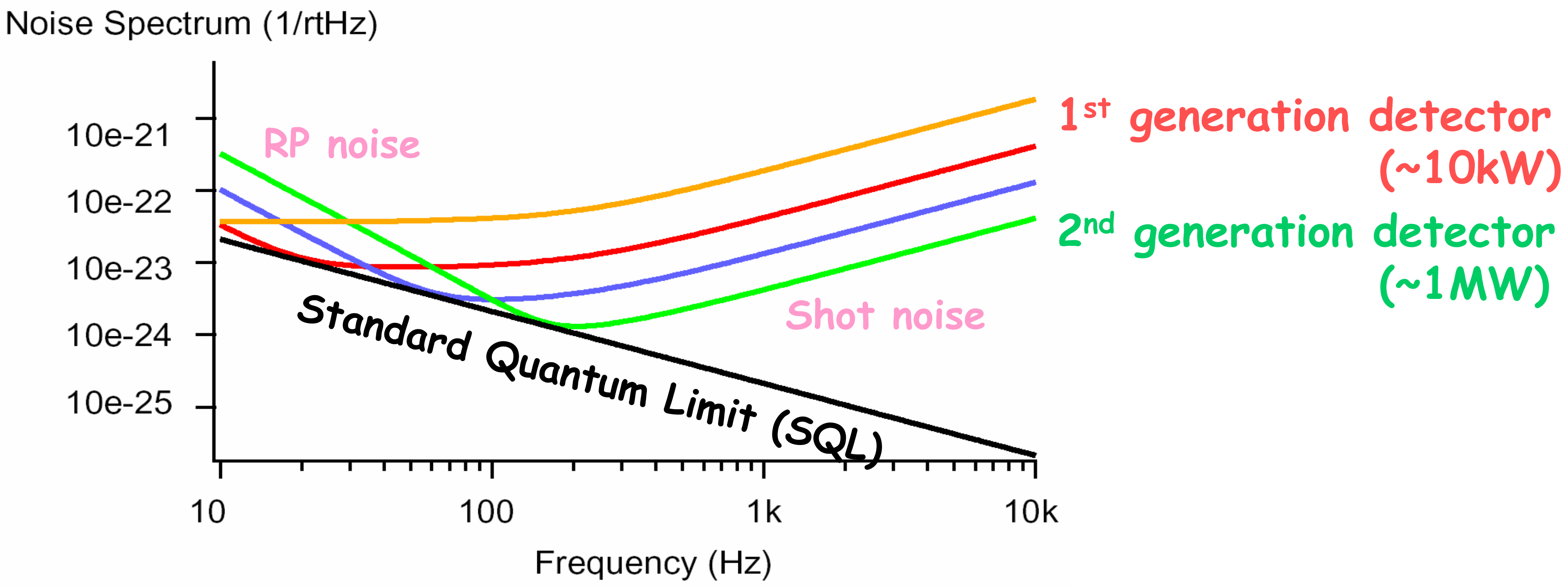
Extremely high sensitivity
(almost reaching the quantum limit)

Optical configuration



- **Michelson interferometer in the dark fringe**
- **Optical resonators in the arms**
- **Additional optical resonators for power/signal recycling**

Quantum noise in GW detector



High precision → **Back action**

Heisenberg's principle

||

Reduction of shot noise (high power)

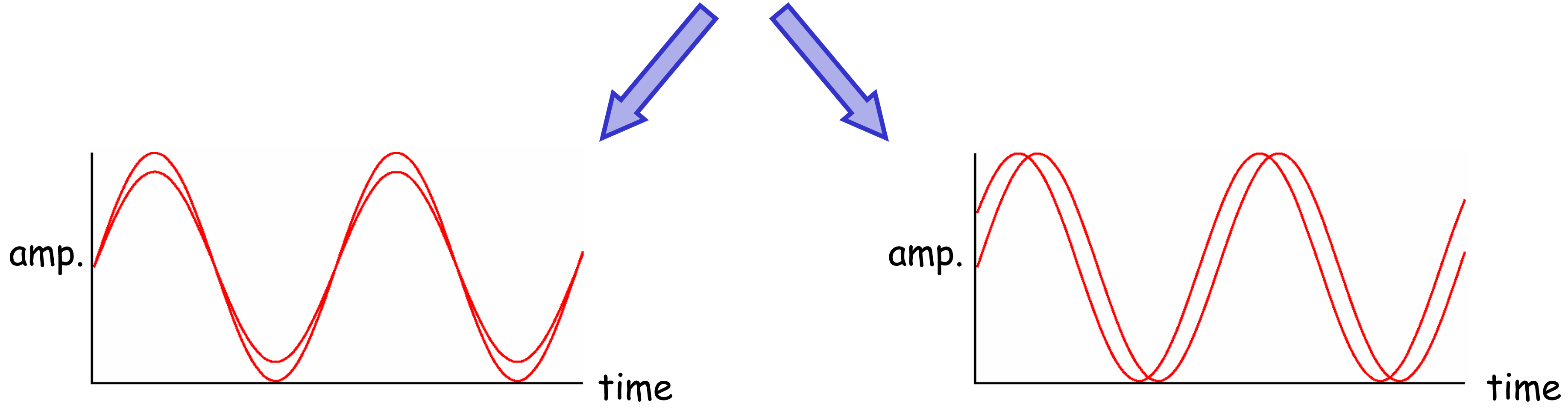
||

Radiation pressure noise

Sensitivity is limited by the SQL

Source of quantum noise

Quantum fluctuation of the light



AM noise

↓

Radiation pressure noise

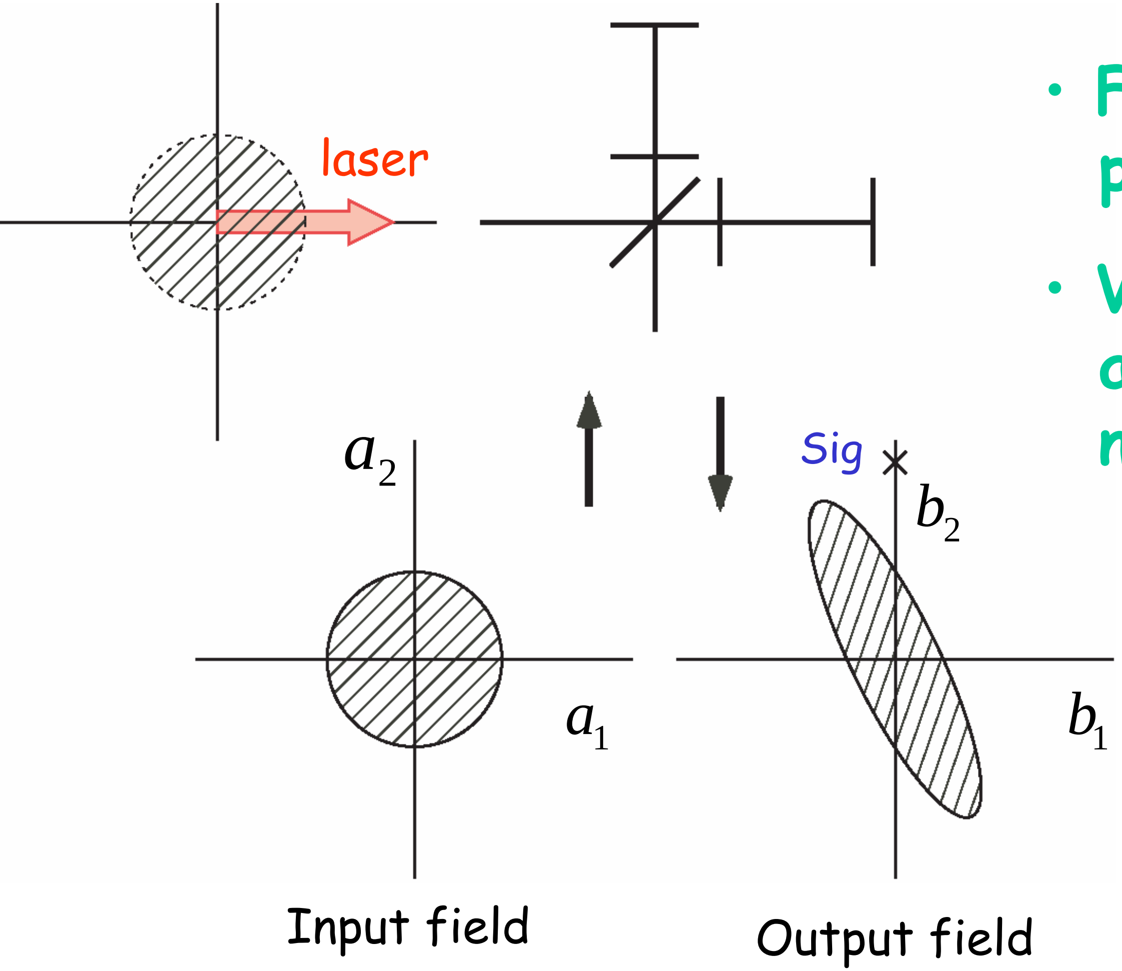
PM noise

↓

Shot noise

A quantum fluctuation field enters the interferometer through any open ports even if there is no light.

Ponderomotive squeezing



- Fluctuation from the symmetric port returns to the sym port
- Vacuum fluctuation from the anti-symmetric port is the noise source, and is squeezed

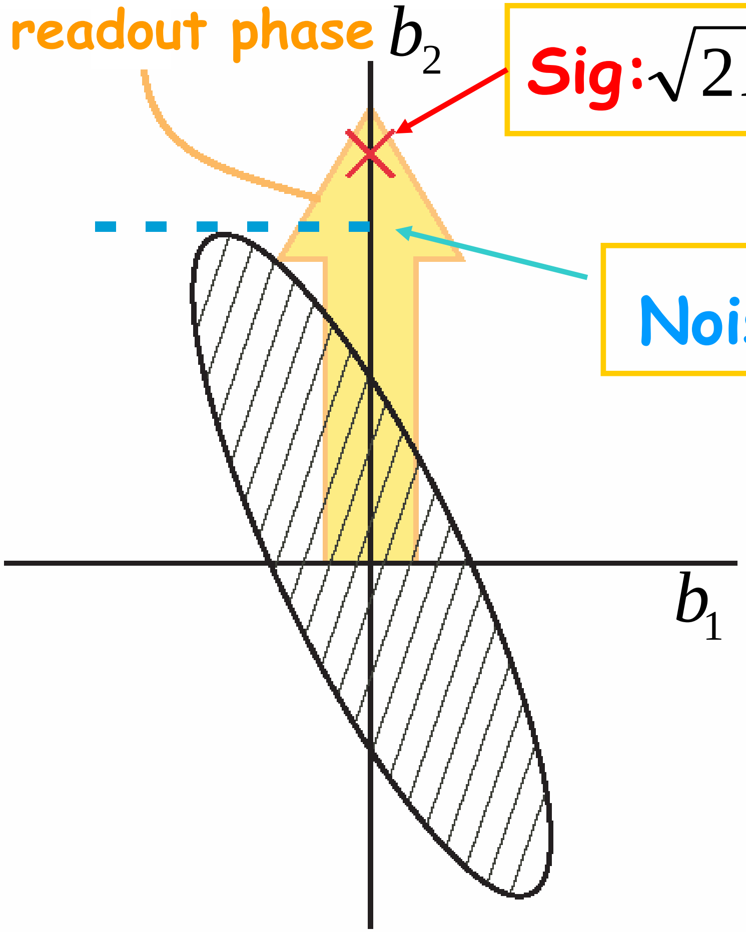
$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -K & 1 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} e^{2i\beta} + \text{signal}$$

K represents the opto-mechanical coupling.

SQL is determined with this *ponderomotive squeezing* and the measurement in the normal quadrature (=b_2)

Standard Quantum Limit (SQL)

Conventional readout phase



Sig: $\sqrt{2K}\,h$

Noise $\propto \sqrt{\underline{K^2} + \underline{1}}$

Shot noise

Radiation pressure noise

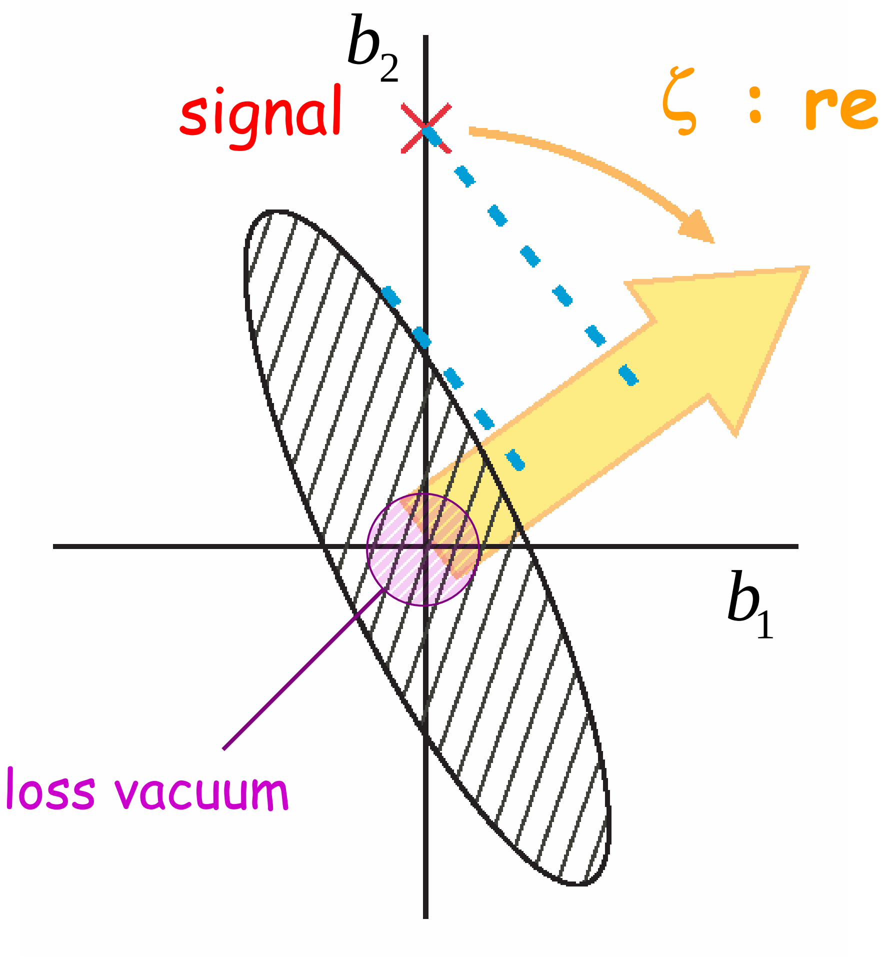
K represents the opto-mechanical coupling

Total quantum noise level

$$h_n = h_{SQL}\sqrt{\frac{K^2+1}{2K}} \geq h_{SQL}$$

With conventional readout we cannot exceed SQL

Back-action evasion technique



ζ : readout phase (homodyne phase)

Total quantum noise level

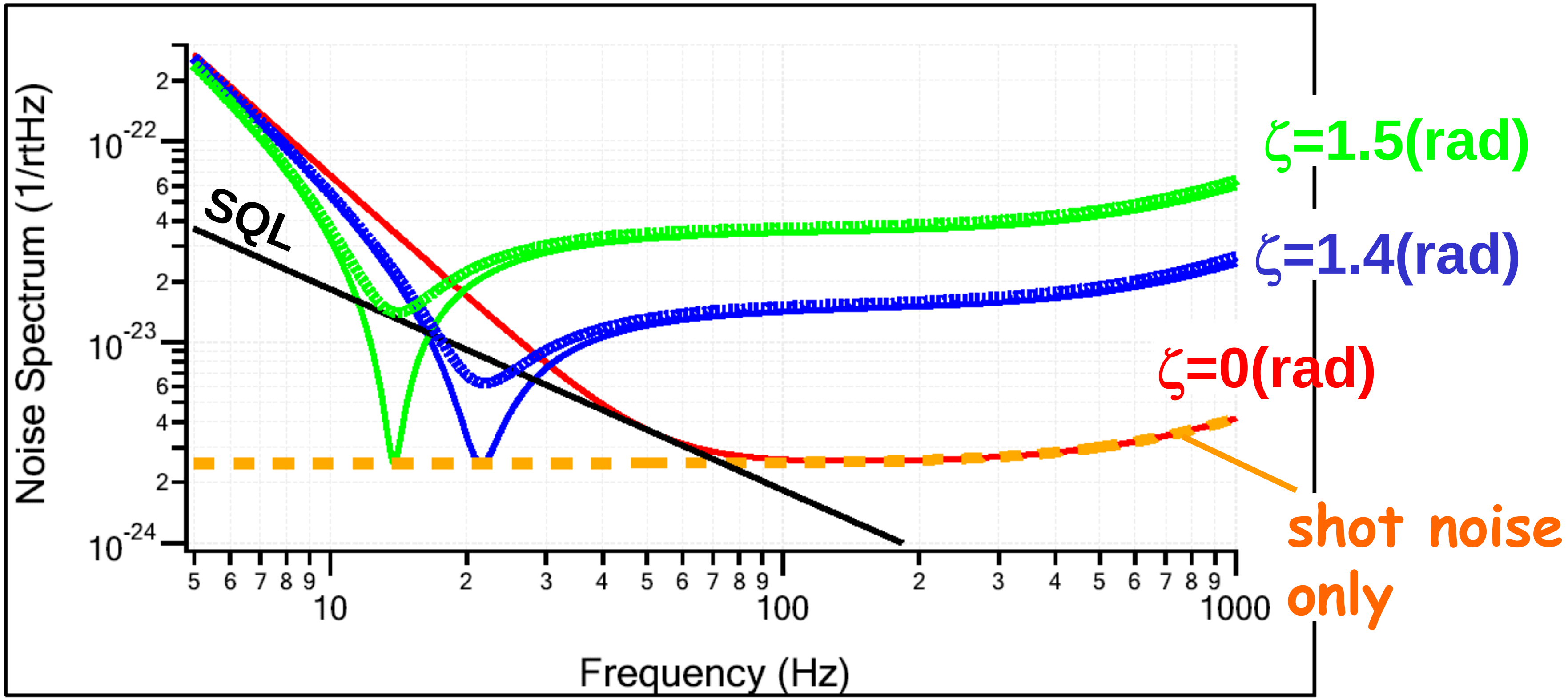
$$\boxed{h_n = h_{SQL}\sqrt{\frac{(K-\tan\zeta)^2+1}{2K}}}$$

$\left\{\begin{array}{l}\text{Readout phase is fixed.}\\ \text{K depends on signal freq.}\end{array}\right.$

⇨ QND at around a certain frequency

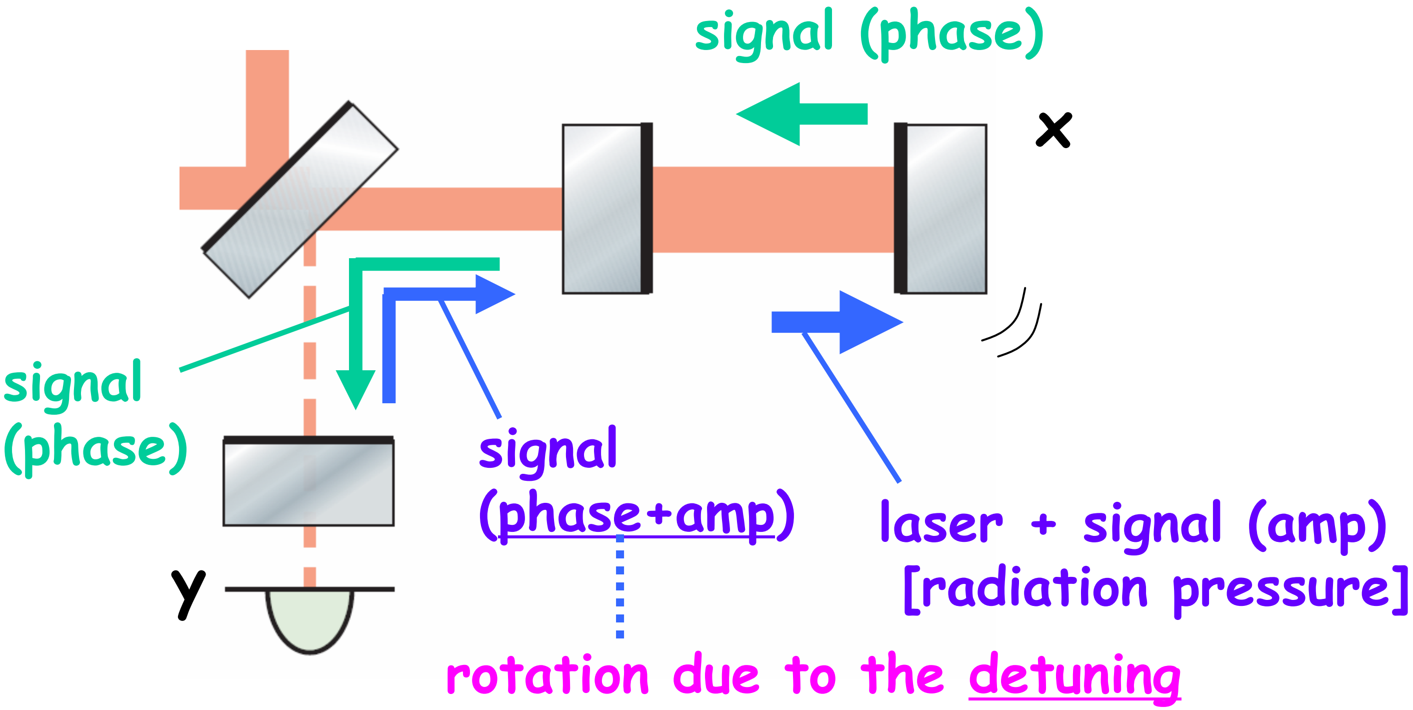
Sensitivity with BAE technique

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

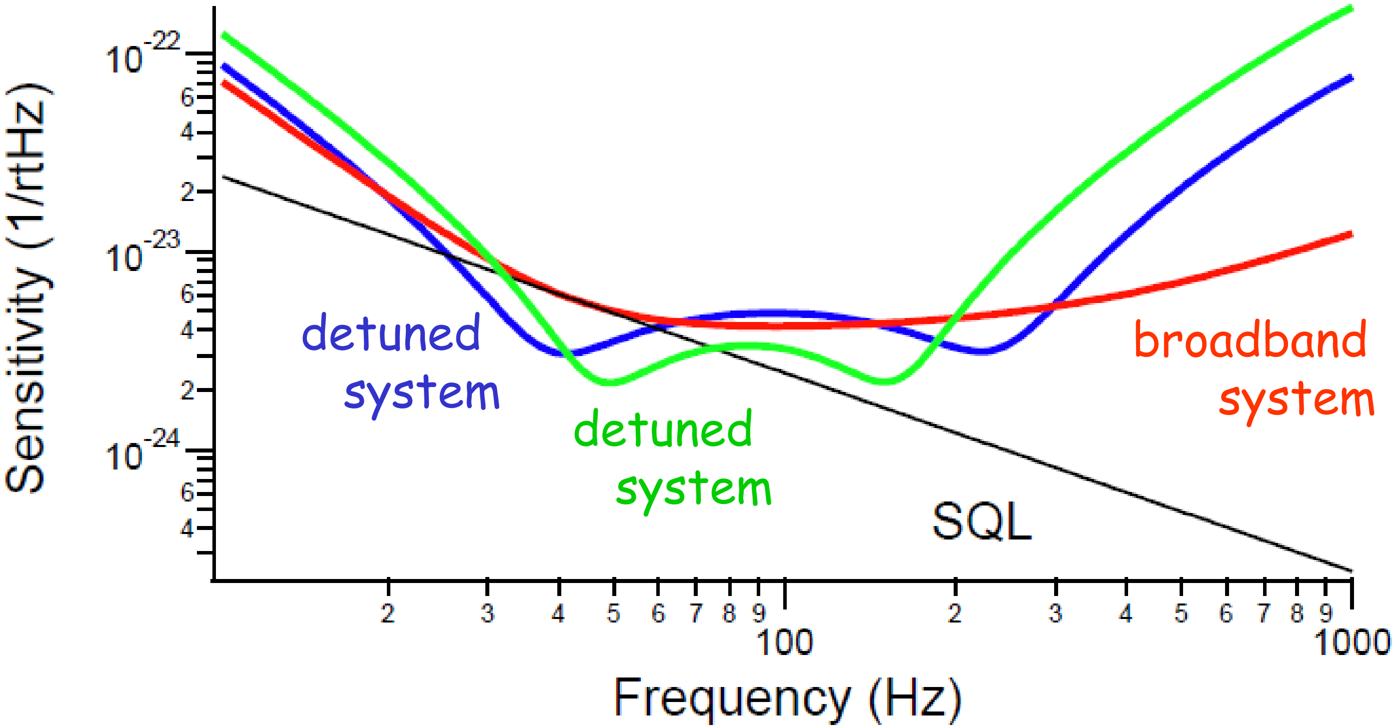
Another way is to use an optical spring



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

This loop makes an optical spring and allows us to overcome the SQL

Sensitivity with an optical spring



- **Beating the SQL helps improving the sensitivity to some GW sources**
- **BAE and optical spring are to be installed in LCGT**

By the way...

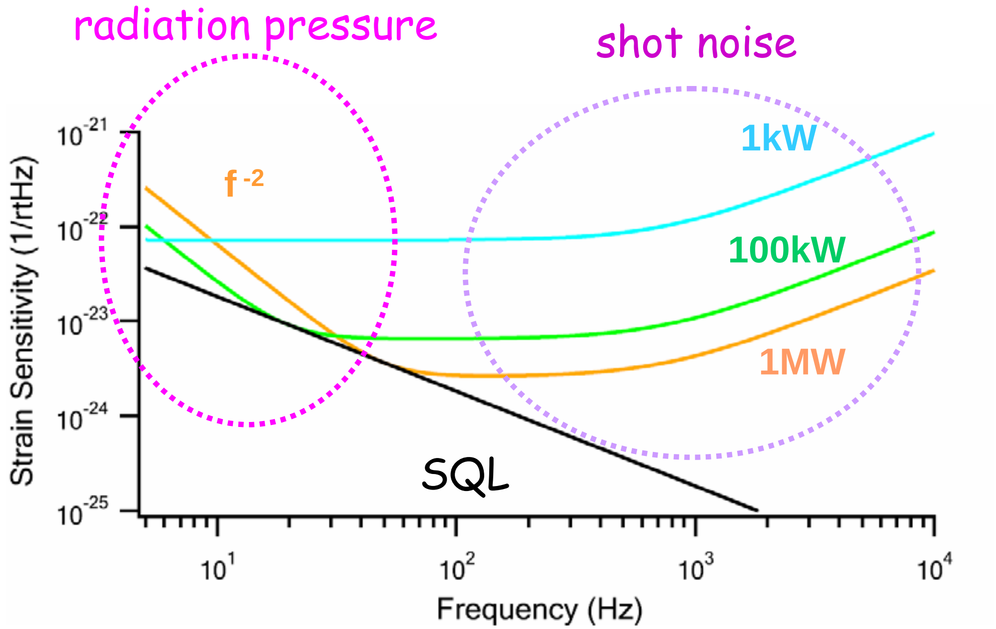
How come we are able to beat the SQL?

Is there a problem in the Uncertainty Principle?

SQL in GW detectors

Standard Quantum Limit

GWD sensitivity



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

Uncertainty Principle

position and momentum

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

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

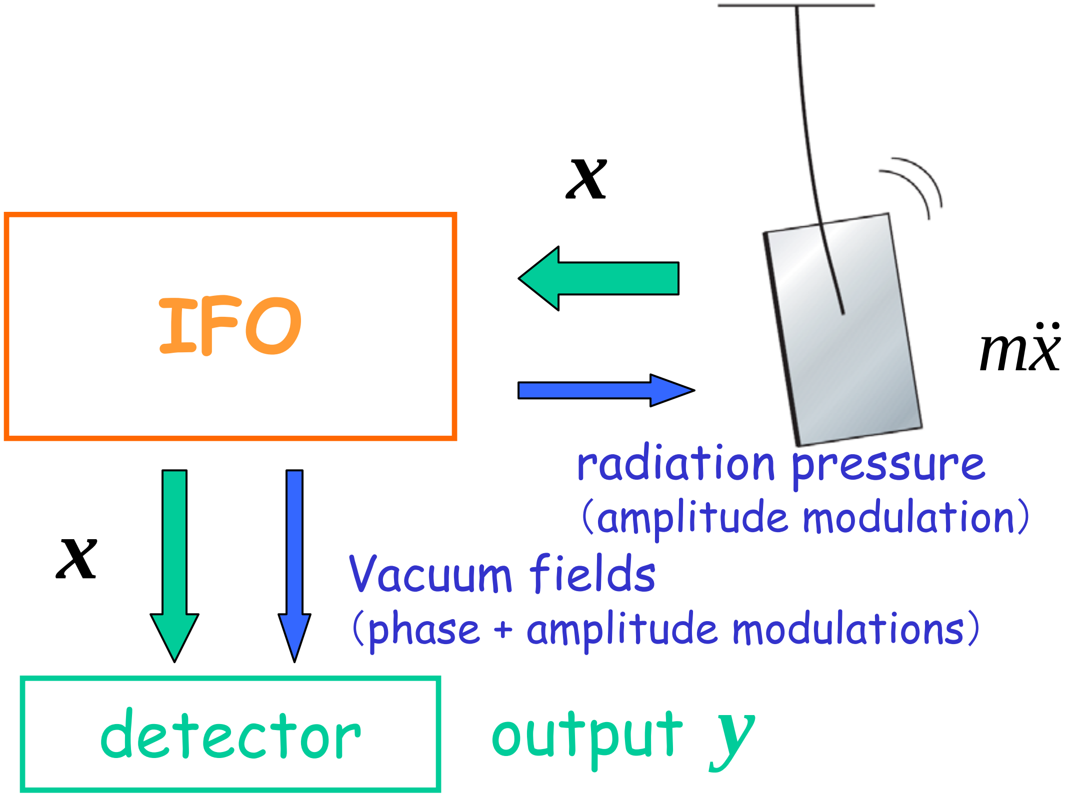
$$\Rightarrow \tilde{x}(f) \ge \sqrt{\frac{\hbar}{2m(\pi f)^2}}$$

clear coincidence

This can be beaten

This cannot be beaten

We measure "force" in GWD



x

IFO

radiation pressure
(amplitude modulation)

x

Vacuum fields
(phase + amplitude modulations)

detector

output *y*

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

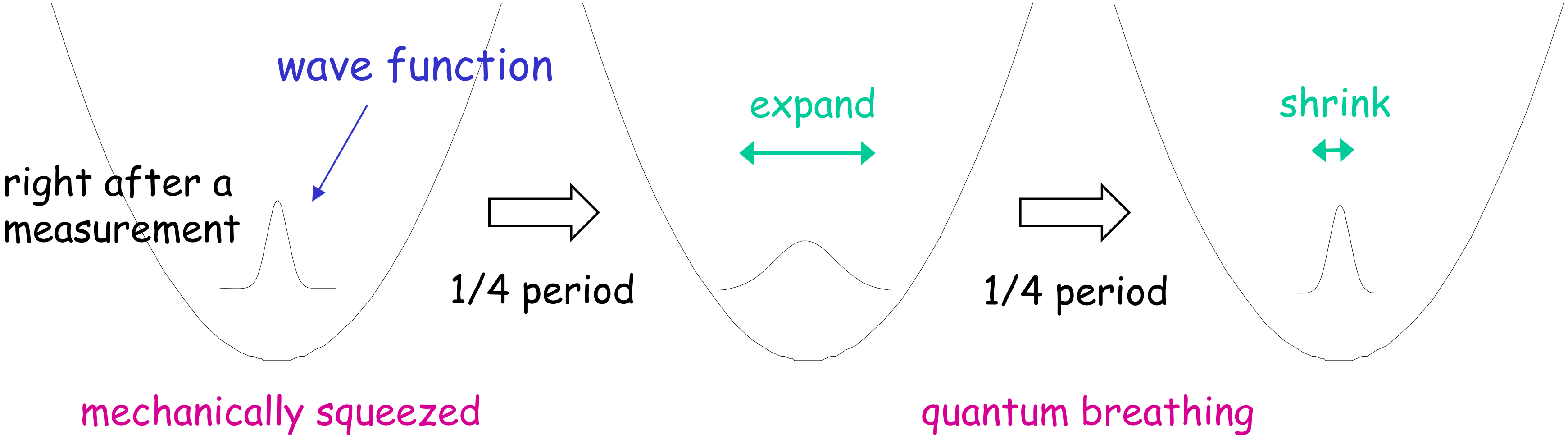
- **BAE: mirror is moving but we try not to see it**
- **Optical spring: mirror moves more for a GW force of the same strength**

Macroscopic Quantum Measurement

Here we are to measure the "position."

harmonic oscillator potential

$V = kx^2/2$



wave function

right after a measurement

1/4 period

expand

1/4 period

shrink

mechanically squeezed

quantum breathing

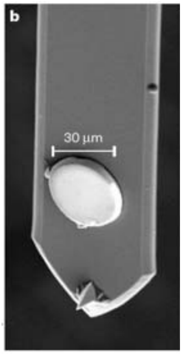
Quantum behavior of the test mass

(Note: the measured object is initial position of the test mass)

How can we observe such a thing?

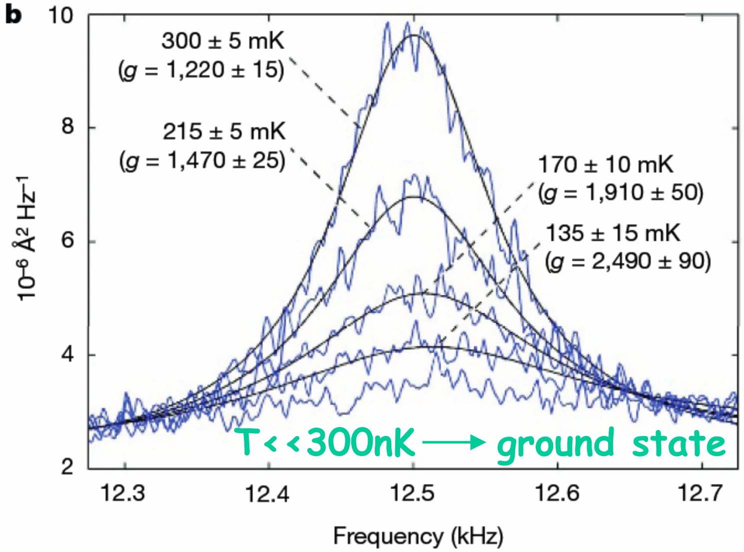
Harmonic oscillators for MQM

(1) mechanical oscillator (cantilever)



ex. Bouwmeester et al, 2004

20ng cantilever motion cooled by classical control using radiation pressure

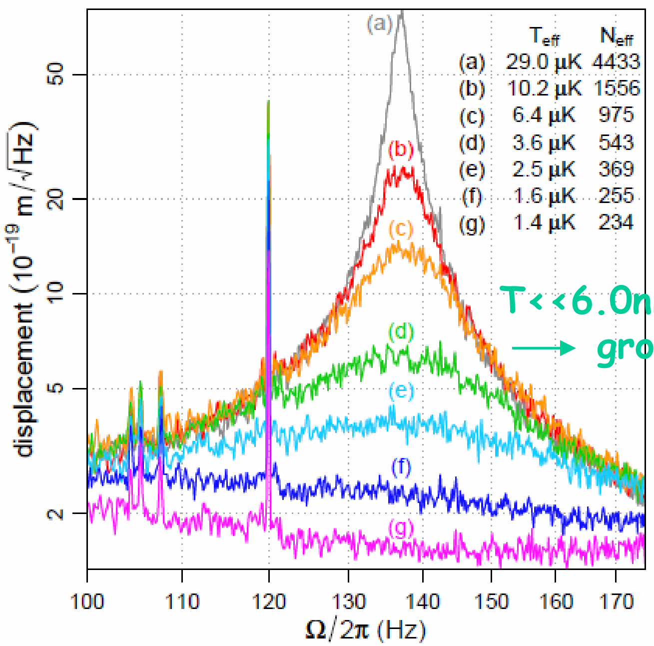


T<<300nK ⟶ ground state

(2) virtual spring (classic control)

LIGO scientific collaboration, 2009

Unstable feedback system creates a virtual spring. LIGO is used to demonstrate the lowest occupation number at the time.

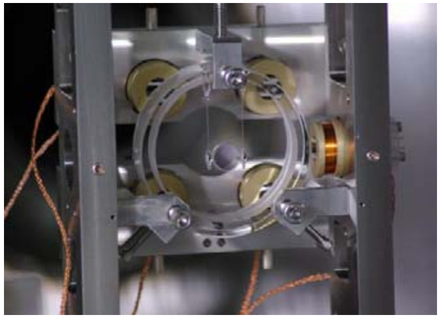


T<<6.0nK ⟶ ground state

In fact, these experiments wouldn't reach the ground state as they use classical control.

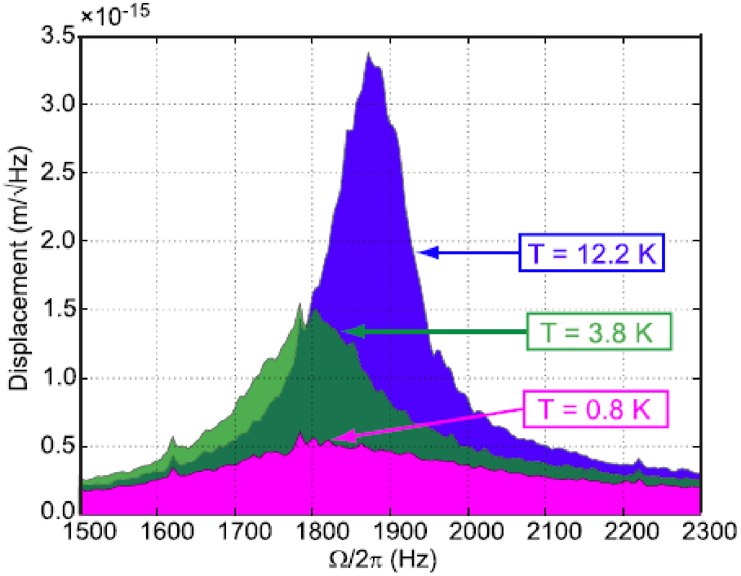
Harmonic oscillators for MQM

(3) optical spring



ex. Corbit et al, 2007

1g mirror is trapped and cooled by double optical spring system (no classical control used in the observation band).



(4) conditioning

For (1)-(3), it is assumed that the oscillator energy concentrate at around its resonant frequency.

In order to collect all the information, we should use the optimal filter and extract the information at all the frequencies.

We can even use a broadband interferometer with this method but the sensitivity has to be reaching the SQL.

Conditioning

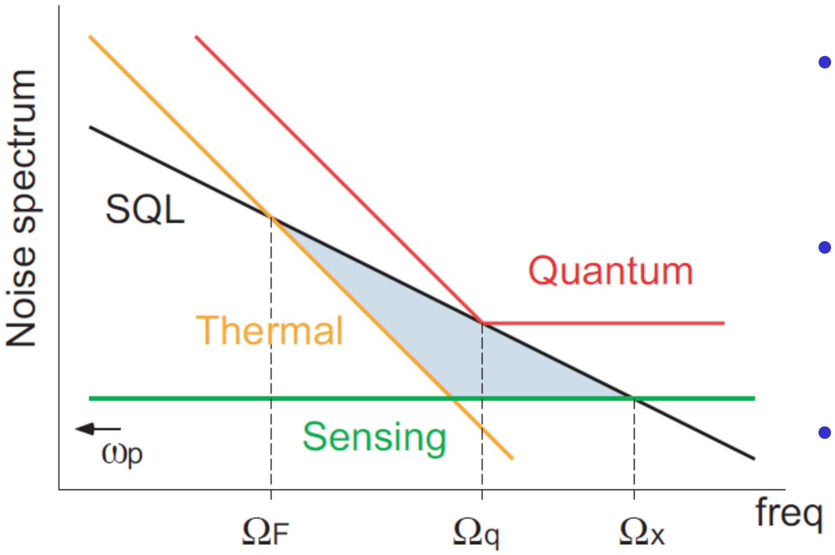
Optimal filter $A(t)$ to estimate $x(t)$ *from the output* $y(t)$

$$\begin{cases} x_c(t) = \int_{-\infty}^{t} A(t-t')y(t')dt' \\ \langle [x_c(t) - x(t)]y(t') \rangle = 0 \quad \forall t' < t \end{cases}$$

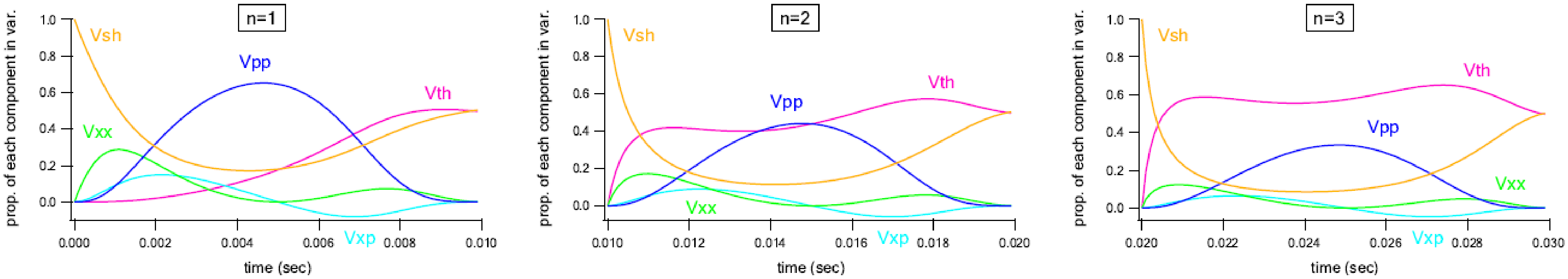
- *All the information in the past is used*
- Residual x_c-x is the quantum fluctuation
- $A(t)$ is uniquely determined
- The same will be done for $p(t)$ [filter is different]

Note: the measured object is the initial position x.
The quantum state is prepared at time t.

Simplified model of a conditioned state



- Assume there are white sensing noise and white force noise (thermal noise)
- Test mass information is collected mainly in the shaded triangle region
- Optimal filters are given analytically



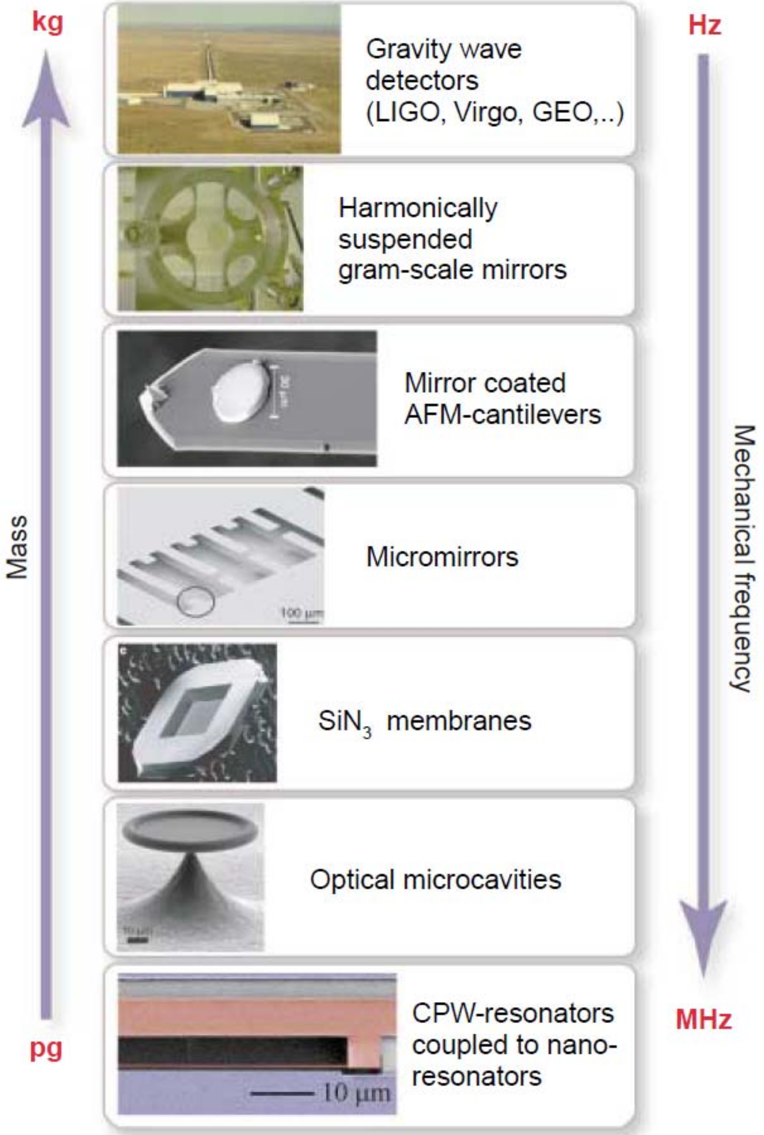
Δx and Δp are given by the covariance matrix;
thermal decoherence starts hiding the quantum behavior

Comparison of GWD and MQM

GW detector		MQM
external force	object	test mass position
beatable	SQL	unbeatable
$[y(t),y(t')]=0\ (t\neq t')$	commutator	$[x(t),x(t')]\neq 0\ (t\neq t')$
reduce TN and do QND	sensitivity	TN<SQL is required to see quantum behavior

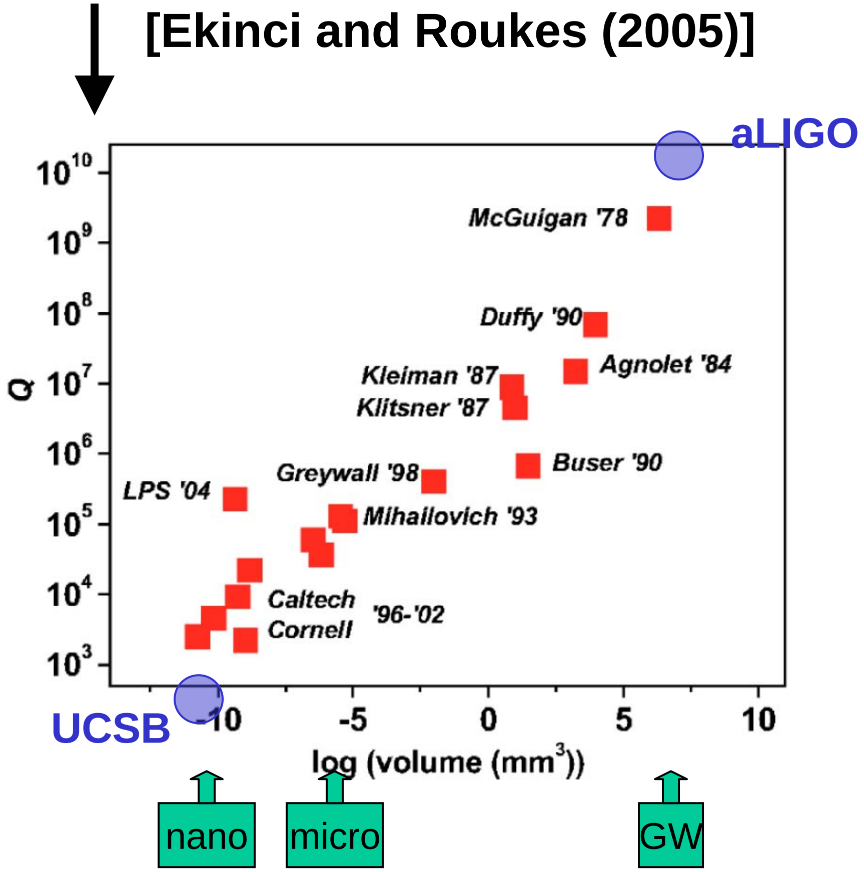
The purpose is different but the goal is the same: to reach and overcome the SQL

Broad spectrum of systems



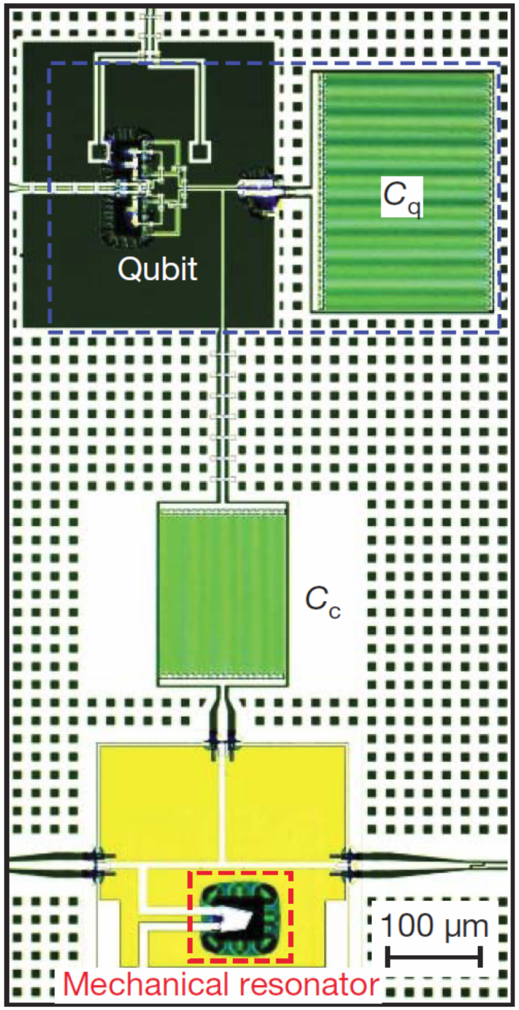
← [Kippemberg and Vahala (2010)]

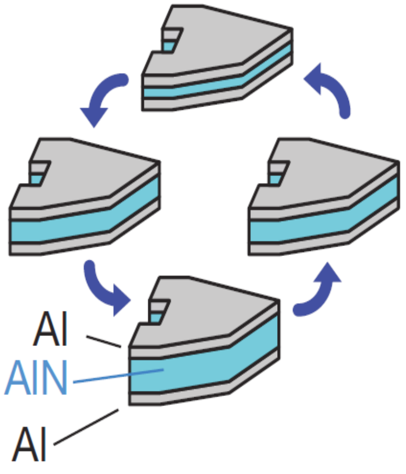
[Ekinci and Roukes (2005)]



Trade-off of mass and Q

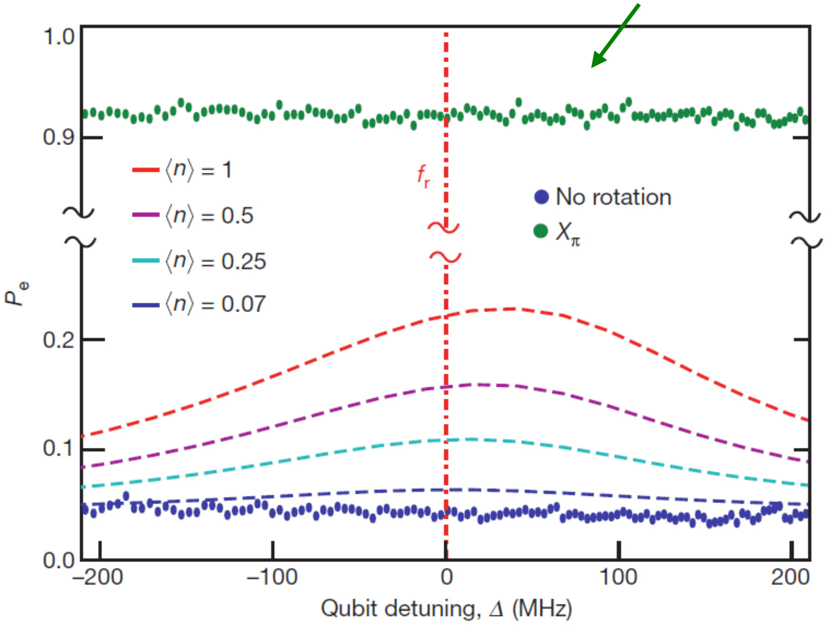
Connell et al (2010 March)





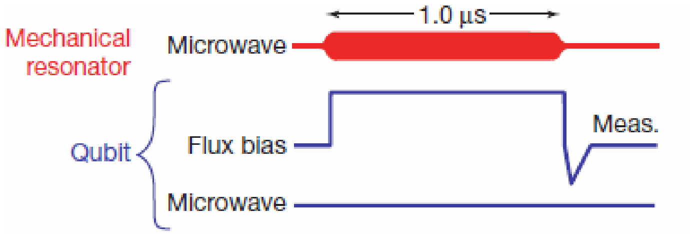
“quantum drum”

test with noise



n<0.07!

- Resonant frequency is 6GHz, Q=260
- Oscillator is coupled to a superconducting qubit



- 3.8ns to reach n<0.07
- Quantum breathing
- Decoherence

Comparison of UCSB and GWD-type MQM

UCSB		GWD-type
drum mode	object	center of mass
high	freq	low
low	noise	high
light	mass	heavy
qubit (binary)	probe	many photons
none	gravitational energy	maybe

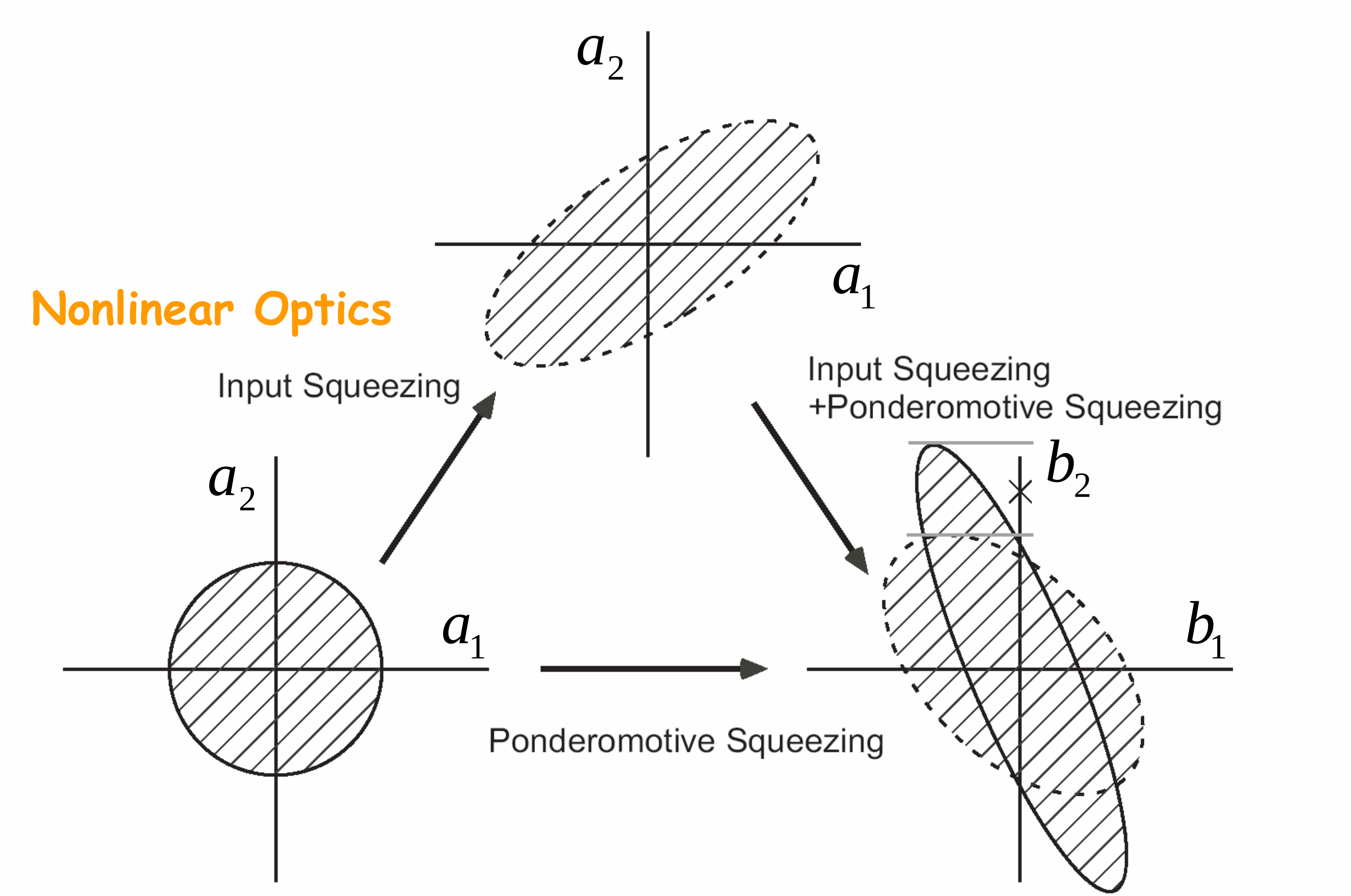
Gravity may have something to do with the difference of micro- and macroscopic objects

Summary

- 2nd generation GWDs are under construction
- The sensitivity is reaching the SQL
- Quantum non-demolition techniques
- MQM with a sub-SQL detector
- Quantum state recovery by conditioning
- Explore a difference of micro/macroscopic worlds

End

Another way is input squeezing



Nonlinear Optics

Input Squeezing

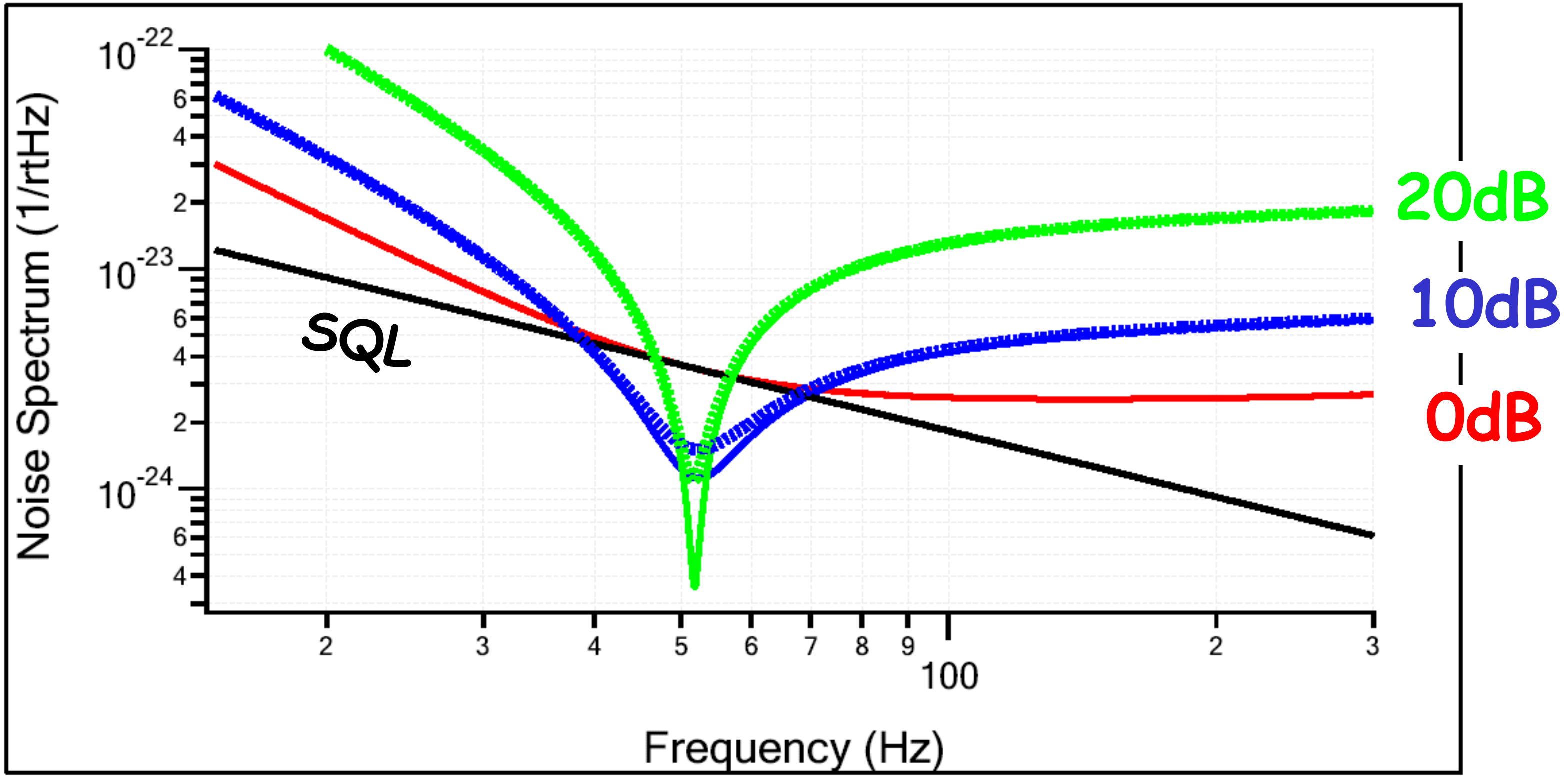
Input Squeezing
+Ponderomotive Squeezing

Ponderomotive Squeezing

Reshape the ellipse of ponderomotive squeezing!

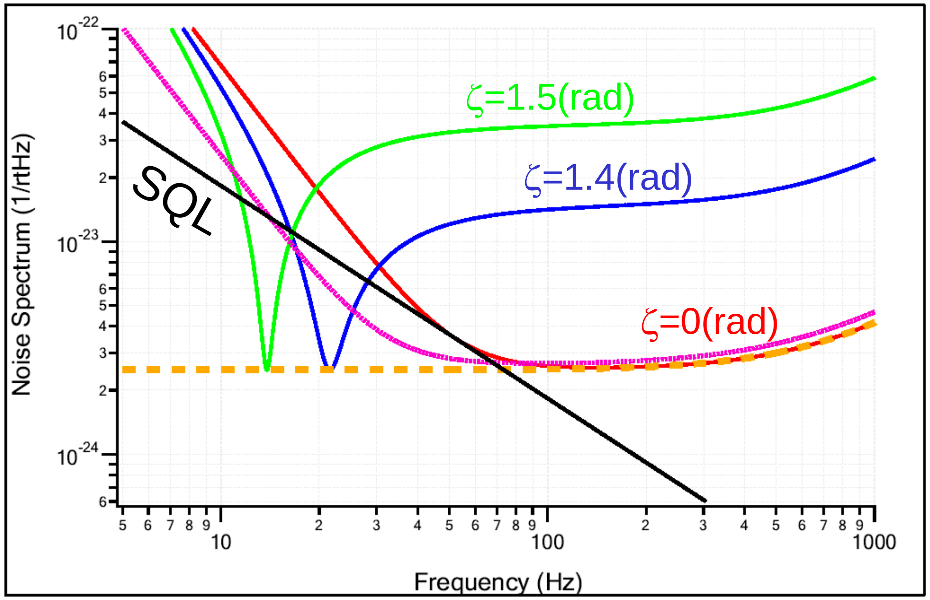
Sensitivity with input squeezing

solid : lossless, dashed : w/loss



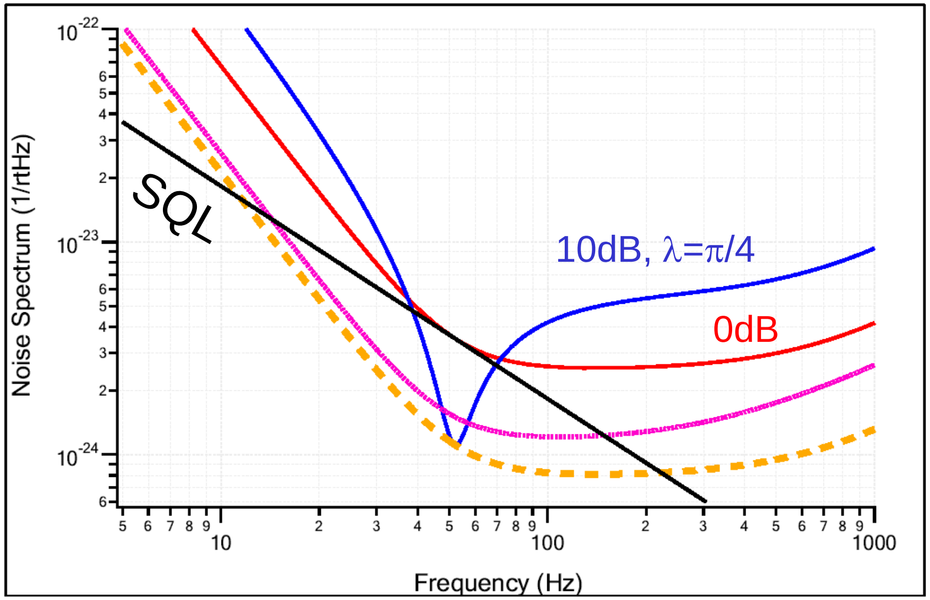
- SQL can be overcome at around a certain frequency
- Optical loss is critical with strong squeezing

Broadband QND



TOP: *variational readout*

Readout phase ζ is optimized at each frequency



BOT: *freq-dependent squeezing*

Squeeze angle λ is optimized at each frequency

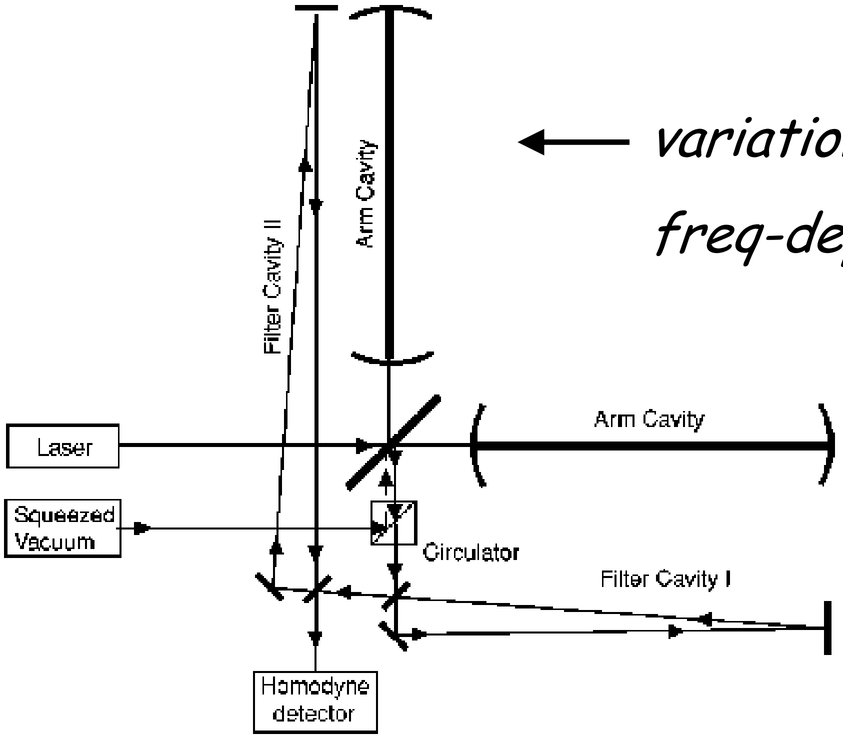
orange: without optical losses

pink: with optical losses

So, How can we realize these broadband QNDs?

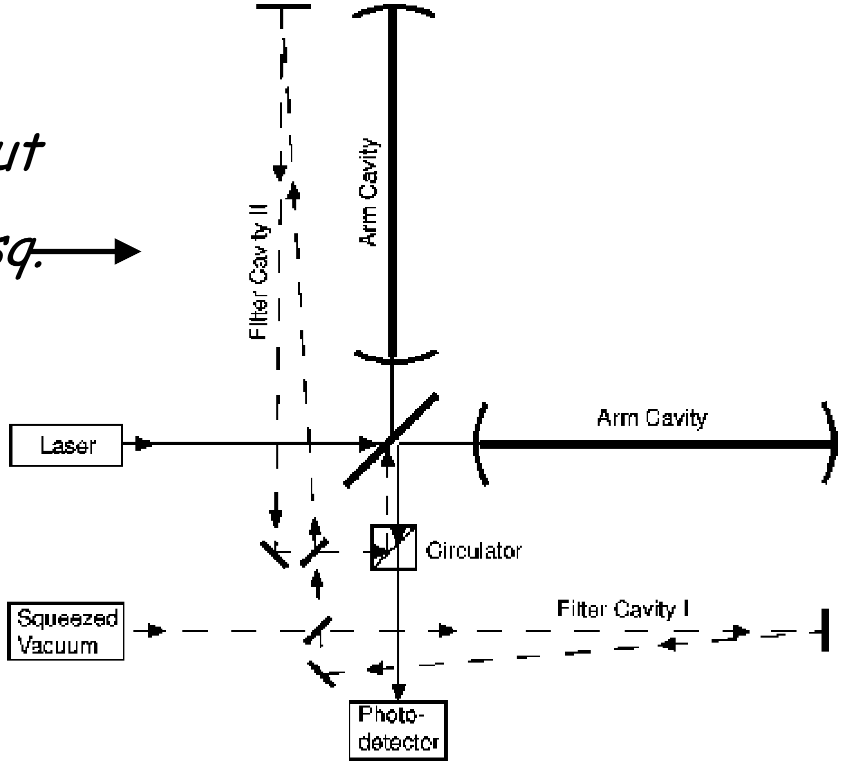
Filter-cavity ideas

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



← *variational readout*

freq-dependent sq. →

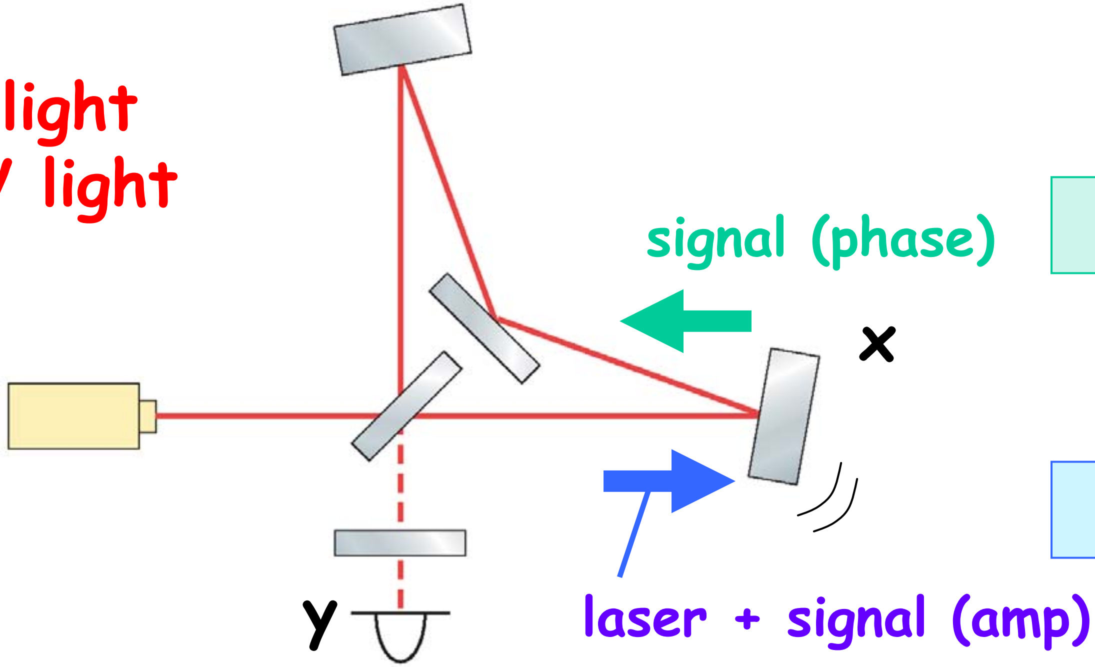


- Squeeze angle rotates slowly during a travel
- The rotation depends on the frequency

⇨ Noise ellipse can be optimally aligned at each frequency

Speed-meter (Sagnac interferometer)

CW light
CCW light



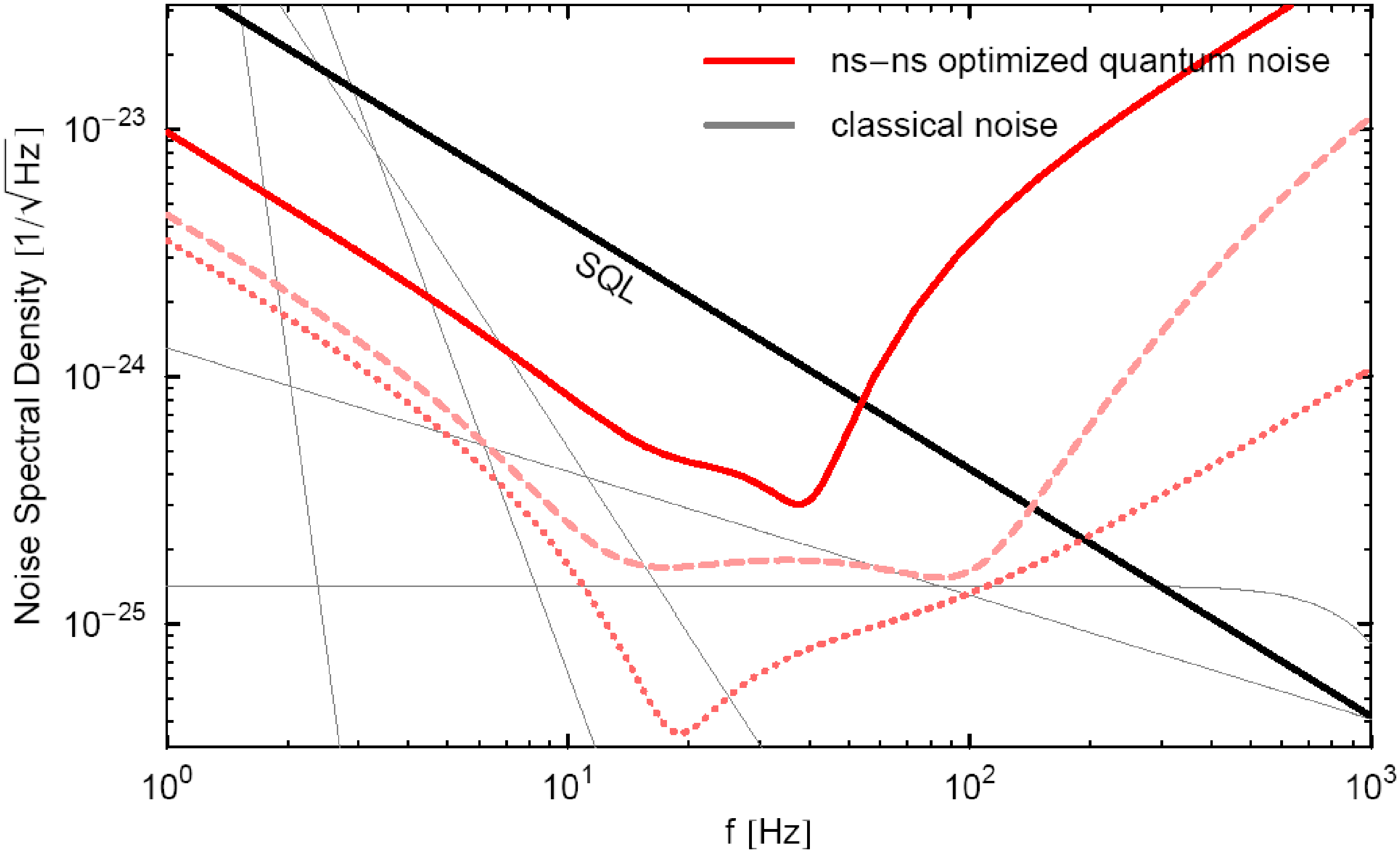
probed twice
→ derivative

pushes twice
→ derivative

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

Signal enhancement in broader frequency band

Speed-meter sensitivity



- QND in broadband
- Sensitivity curve in 1/f

Border of classical and quantum world

- UCSB's nano-oscillator drum acts like a qubit
- Would kg mass act like a qubit as well?
- CSL?
- Gravity decoherence?

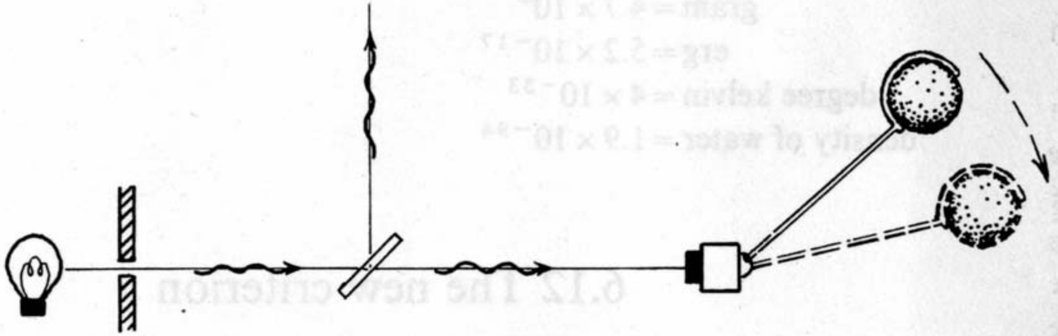


Fig. 6.4. Instead of having a cat, the measurement could consist of the simple movement of a spherical lump. How big or massive must the lump be, or how far must it move, for **R** to take place?

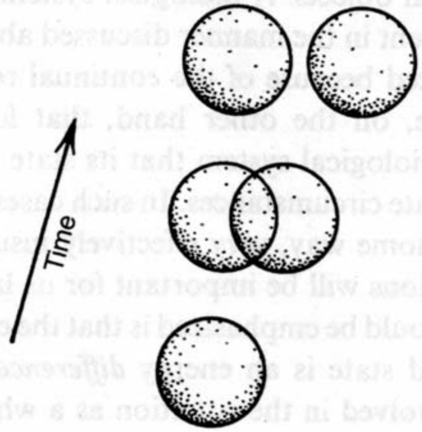


Fig. 6.6. To compute the reduction time $\hbar/E$, imagine moving one instance of the lump away from the other and compute the energy E that this would cost, taking into account only their gravitational attraction.

"SHADOWS OF THE MIND" (R.Penrose, 1994)